ND280 upgrade

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T2K Cross-Section workshop

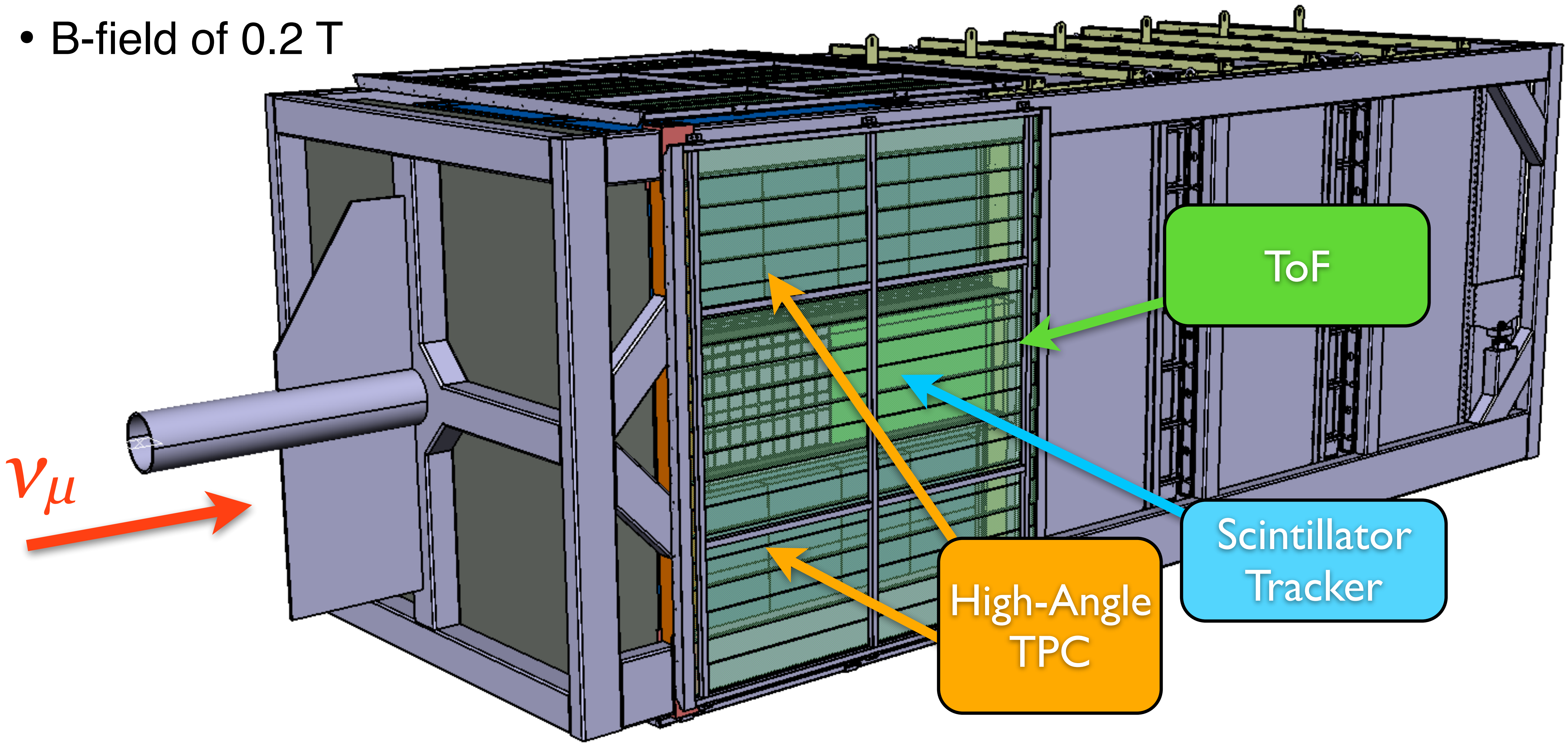
16th October 2019

The T2K Near Detector upgrade

- Keep the electromagnetic calorimeter
- Horizontal active target detector (2x2x0.6 m^3)
- Two High-Angle TPCs
- Time-of-Flight detector around new tracker
- B-field of 0.2 T

	Current	Upgrade
Target Mass (tons)	~2	~4

CERN-SPSC-2018-001 / SPSC-P-357



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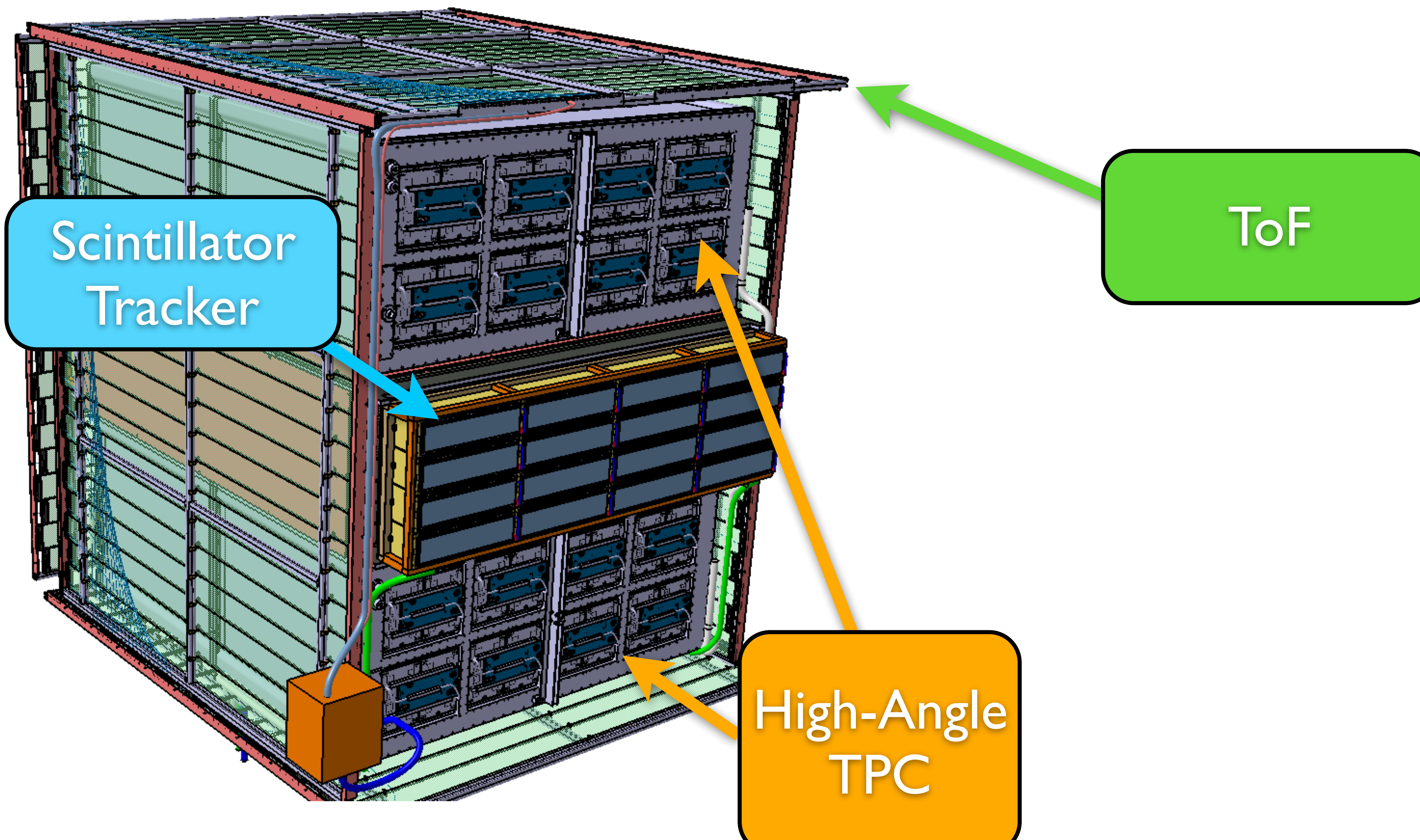
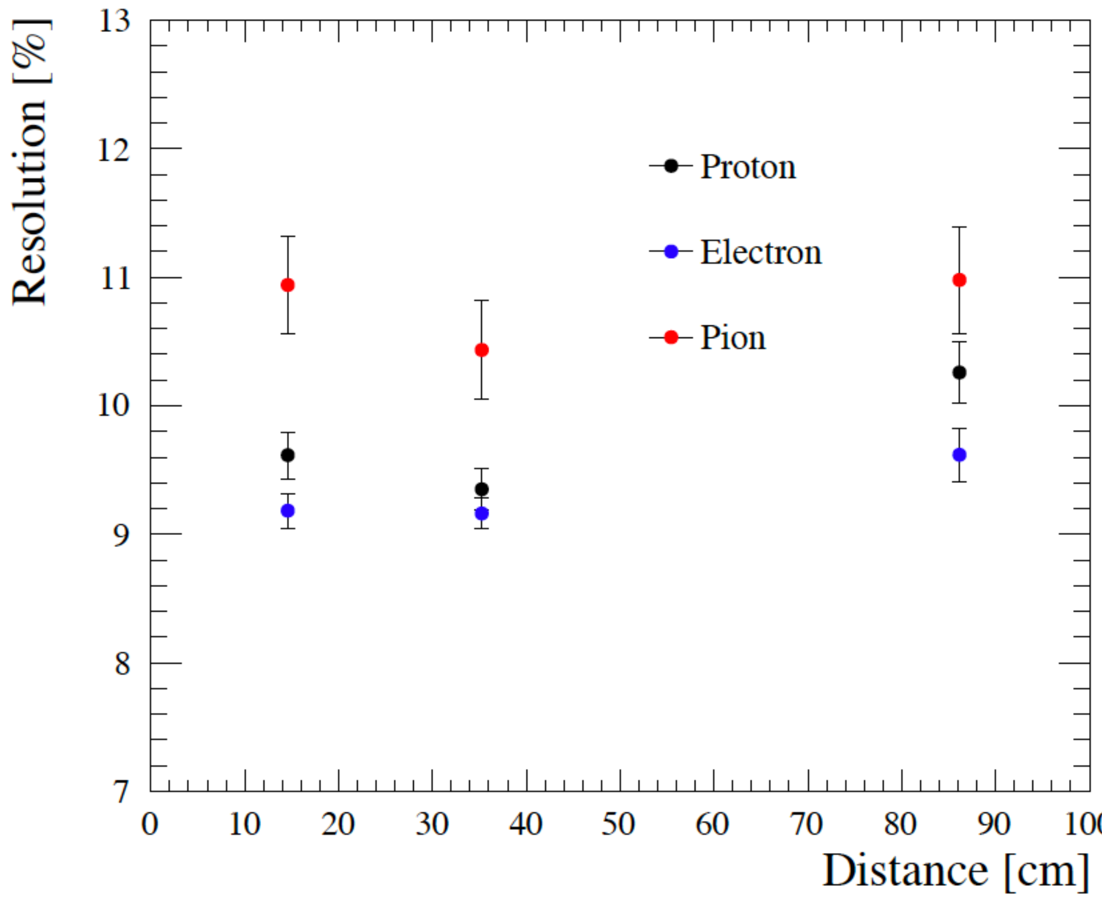


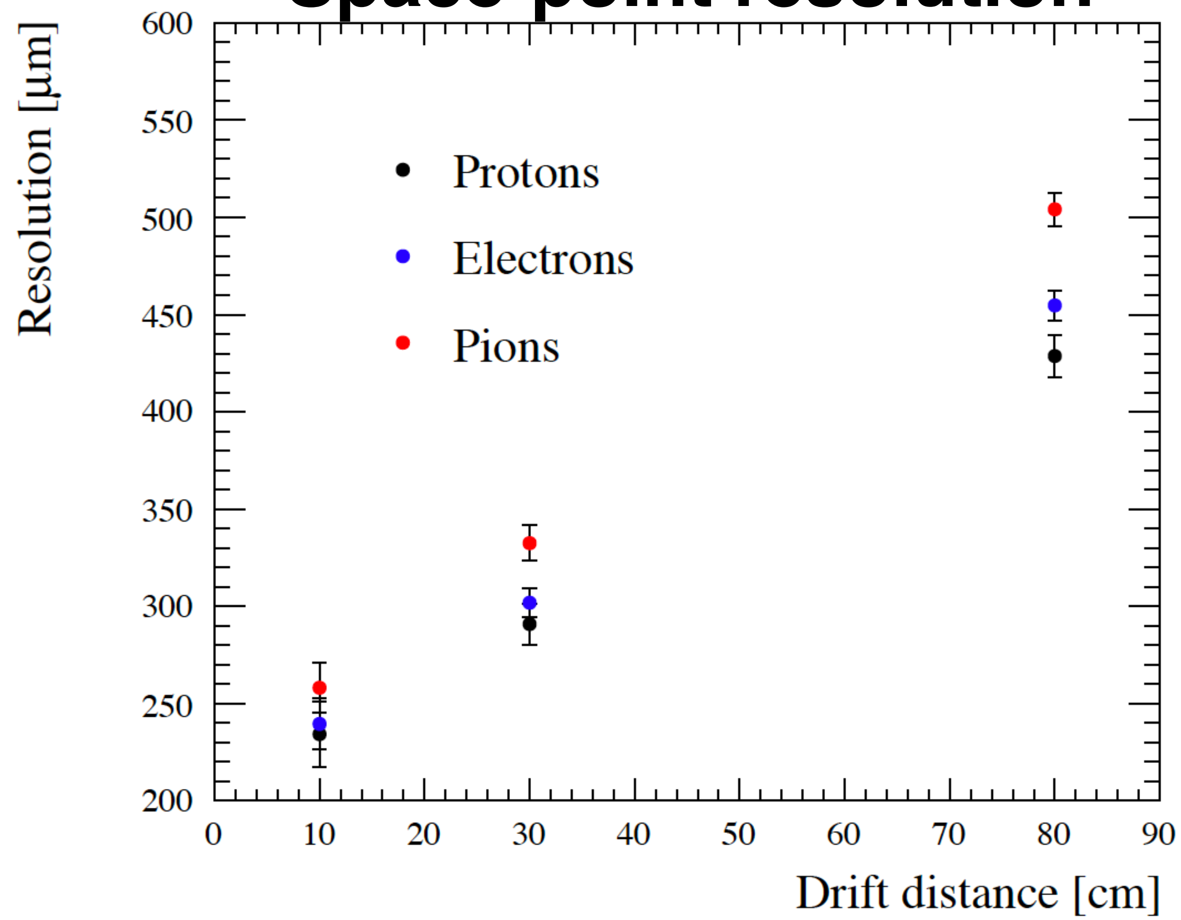
High-Angle TPCs

- Performance for 0.8 GeV/c particles (2018 beam tests @CERN)

dE/dx resolution



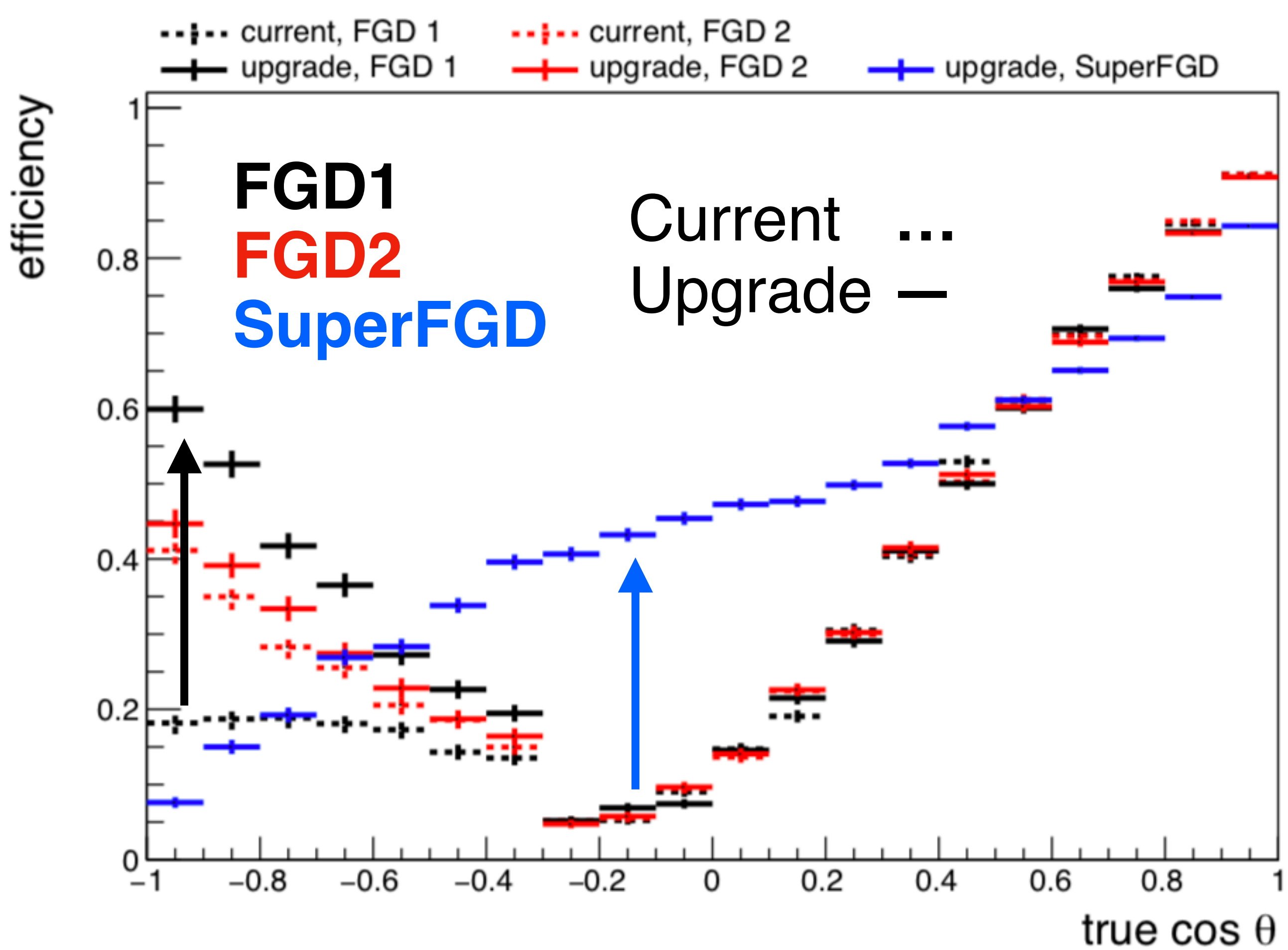
Space-point resolution

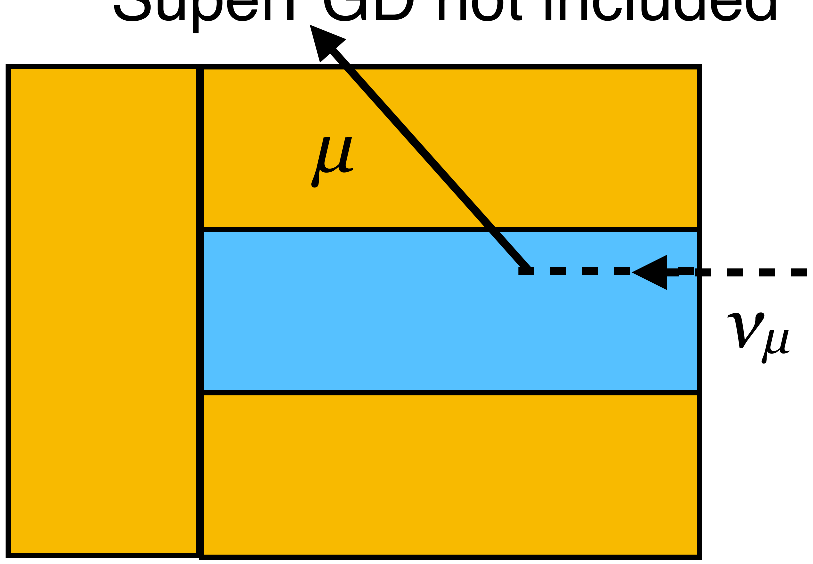


- Large fraction of the charge is deposited in one pad, but on average at least 20% of the charge is spread over the adjacent pads
- Space-point resolution improved by a factor ~2 compared to current TPCs
- Expect momentum resolution improved by about x2

CC 4pi NuMu Inclusive selection

- Selection of CC-ν_μ 4π events: compare ND280 current vs upgraded
- We tried to implement in a modified version of highland (smear truth information) the same analysis as implemented by Alfonso (TN-245)
- ν_μ interactions in FGD / SuperFGD —> muon detected in TPC or ECAL





This analysis would be the first milestone obtained with the ND280 upgrade data

- TPCs provide a precise measurement of the particle kinematics
- ToF detectors precisely determine the track direction (neither ECAL nor the TPC can determine it) and reject the Out-of-Fiducial Volume events (<1%)

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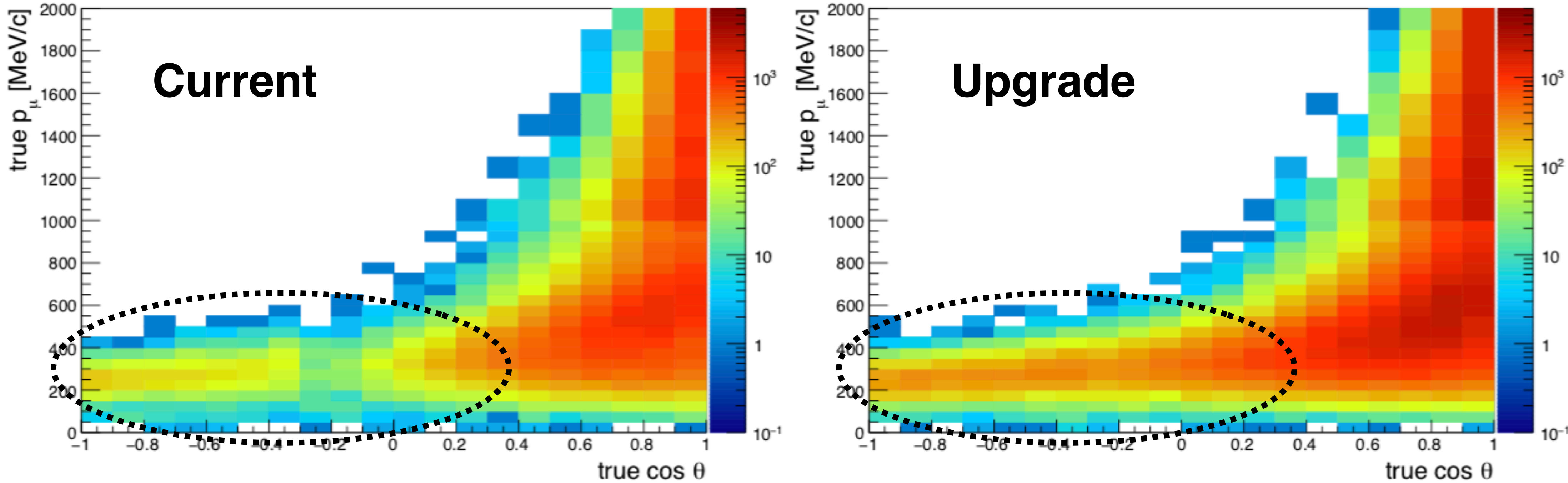
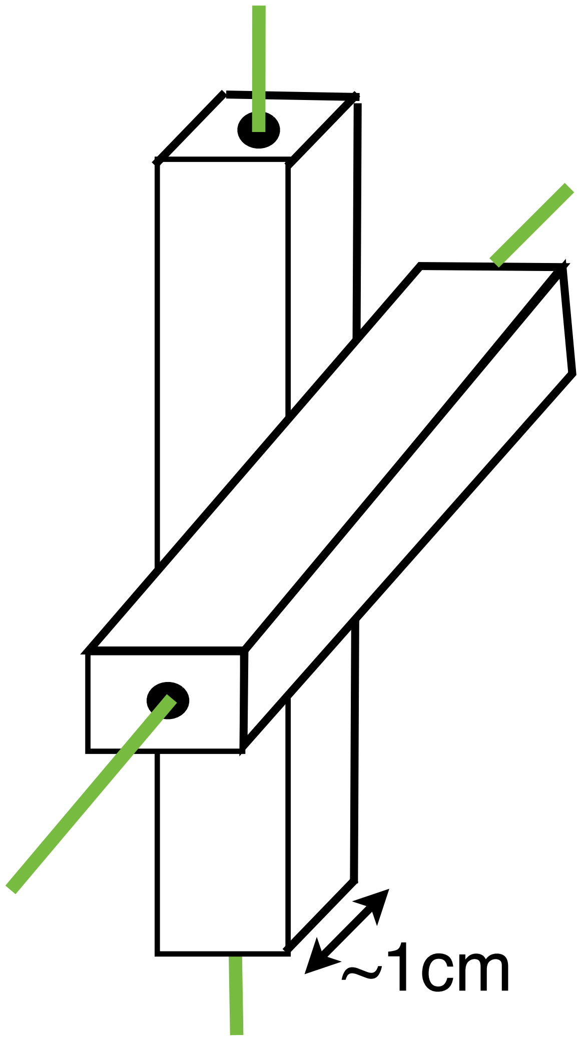


10^{21} protons on target (POT)

Selection	Current-like	Upgrade-like
ν_μ (ν beam)	100632	199605
$\bar{\nu}_\mu$ ($\bar{\nu}$ beam)	32671	60763
ν_μ ($\bar{\nu}$ beam)	16537	29593

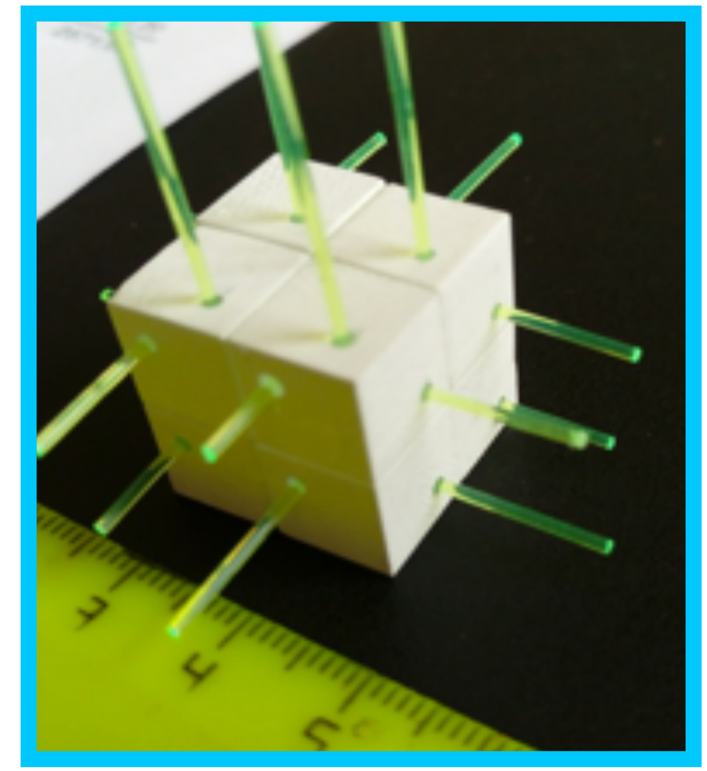
- Upgrade: factor x2 higher statistics
- Sensible statistics for wrong-sign background —> very important to search for CP violation (not-magnetized far detector)
- Another difference is that detector systematic uncertainties at high-angle are TPC ones, much smaller than 20-30% as in ND280 current

Fully active FGD with three views: SuperFGD



2018 JINST 13 P02006

This detector opens many windows on more selection / physics analyses compared to ND280 current



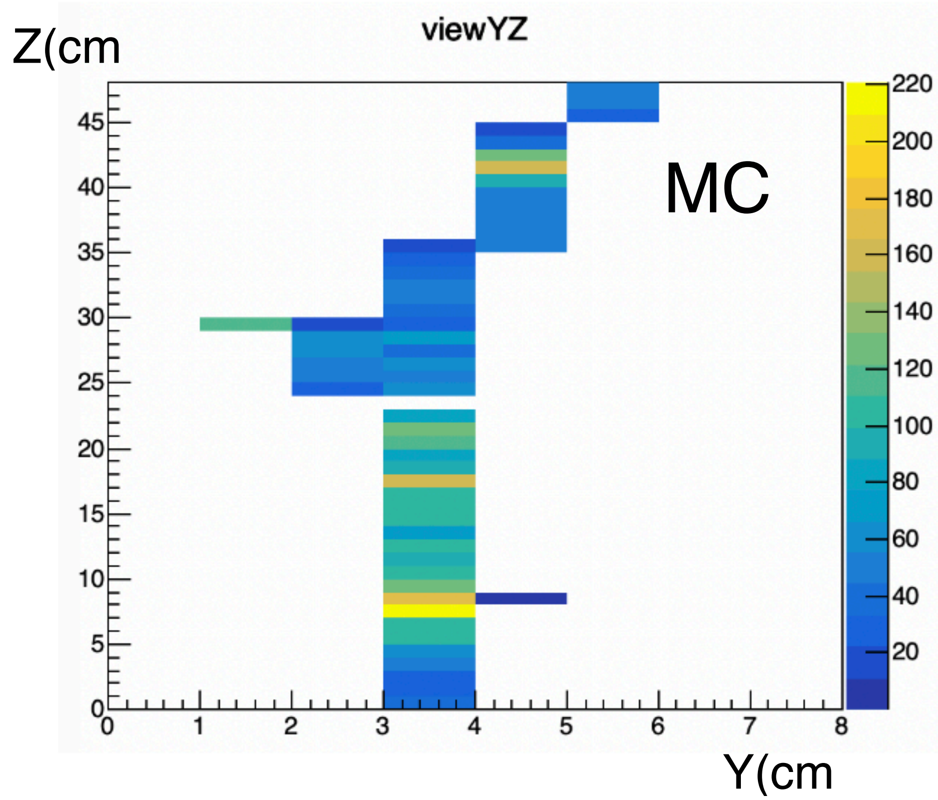
- Lower momentum threshold: 1 single hit gives immediately XYZ
- Uniform material (just plastic) —> no systematics from different nuclei
- Very good time resolution: ~0.9ns / channel / MIP
- Light yield ~ 40 p.e. / channel / MIP

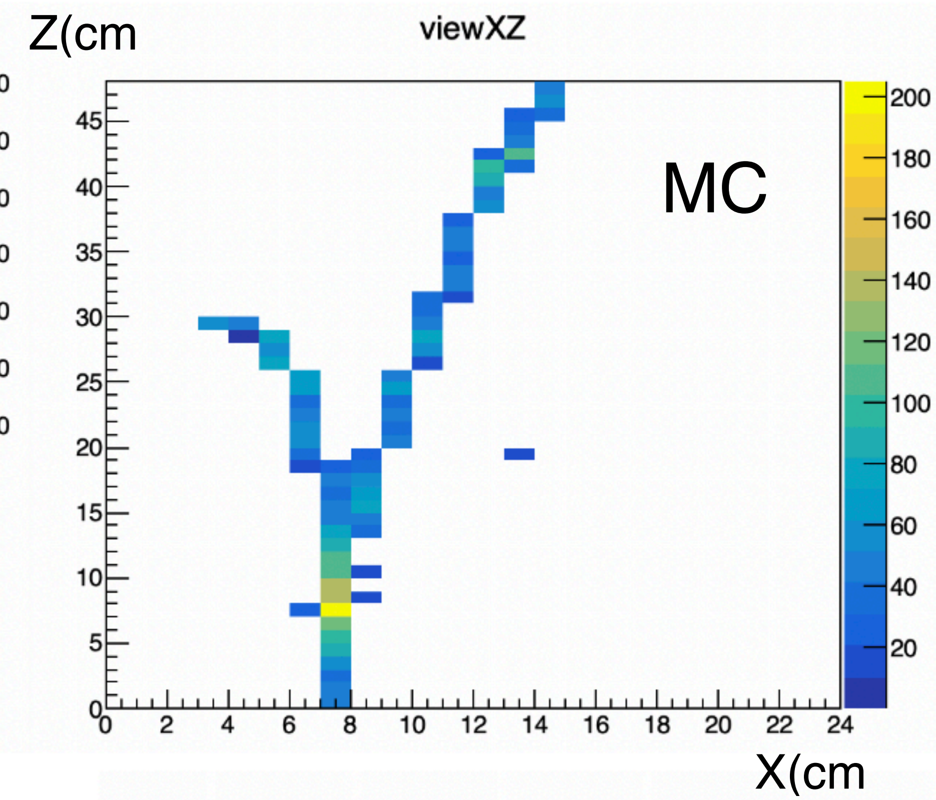
Fully active FGD with three views: SuperFGD

- Three views from XYZ WLS fibers —> 4π acceptance, 3D reconstrution

2D projections

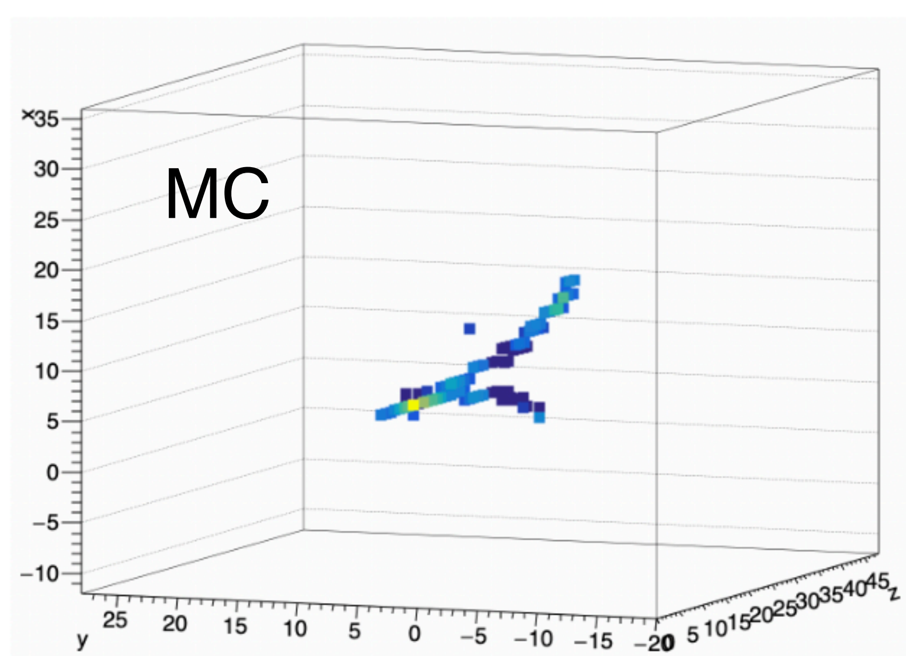
XY projection not shown

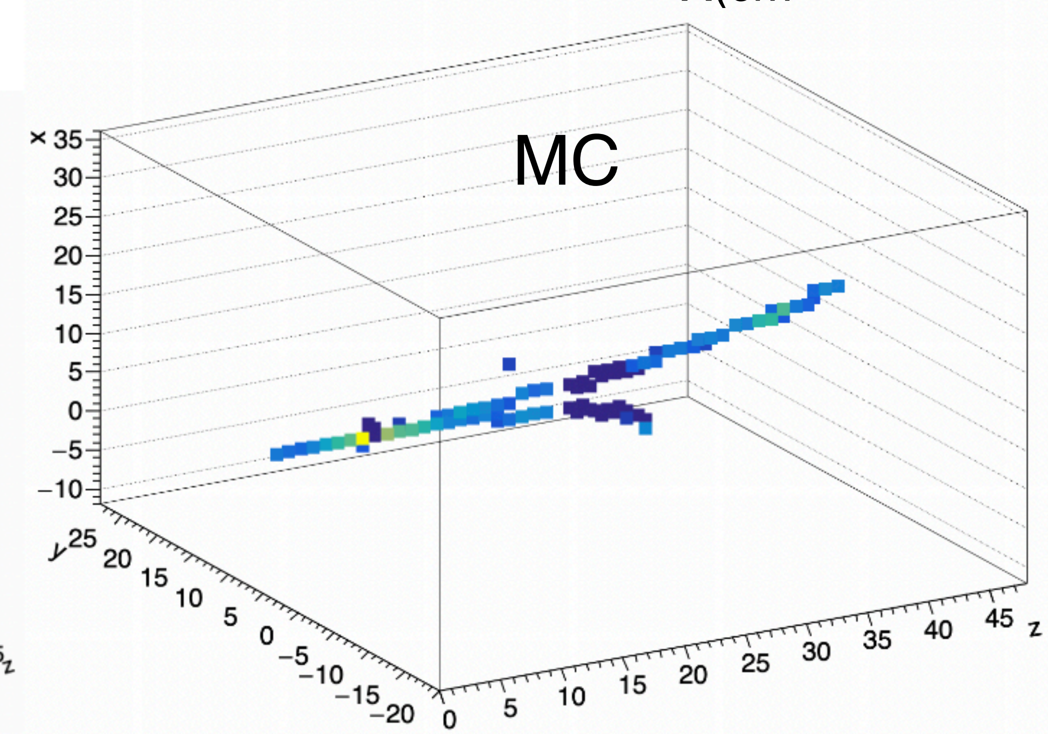




3D rotated views

Example of a photon converting in SuperFGD



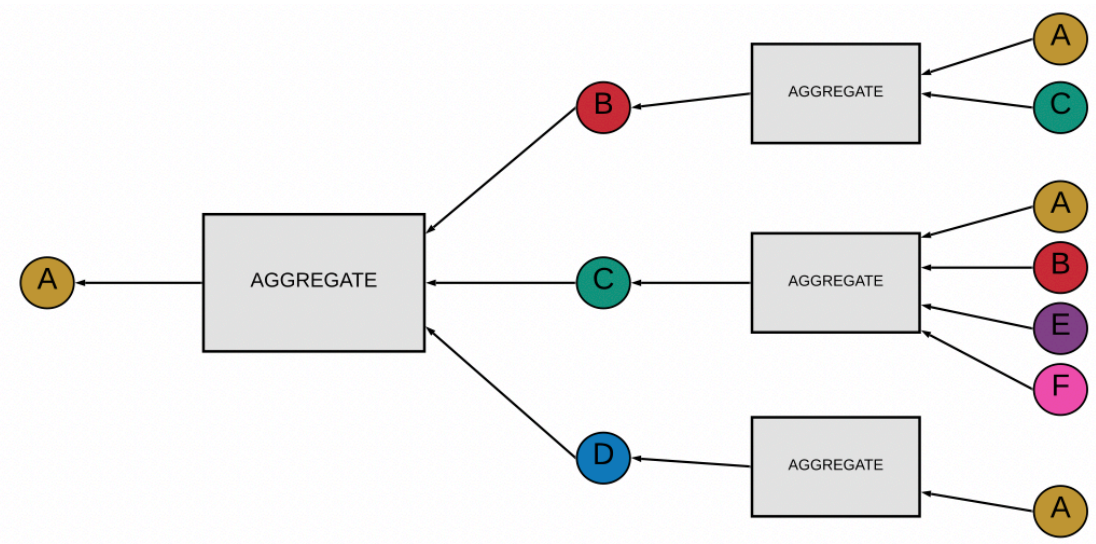


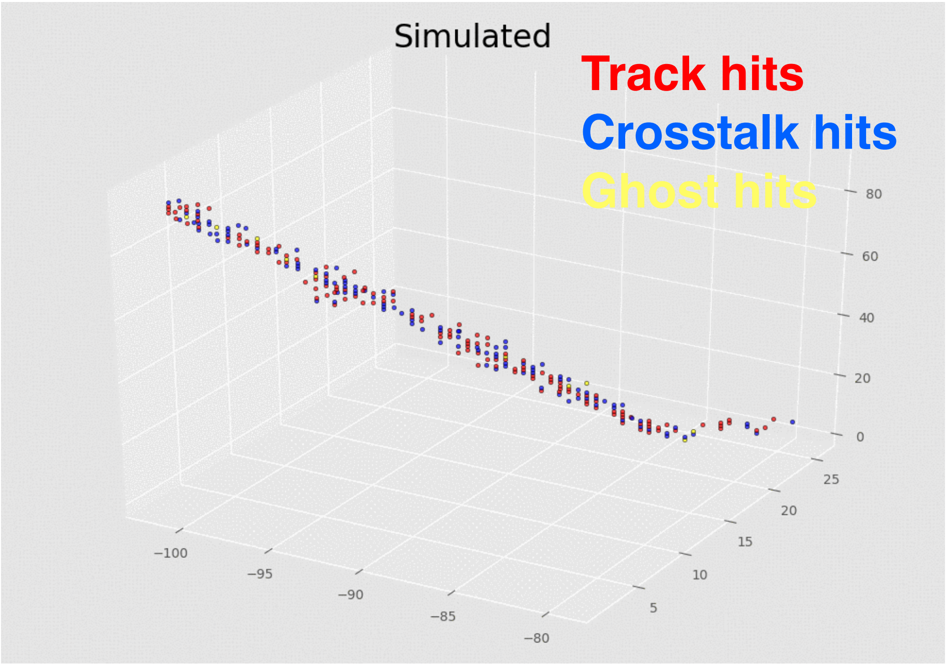
- Working on the event reconstruction within the Soft&Reco working group

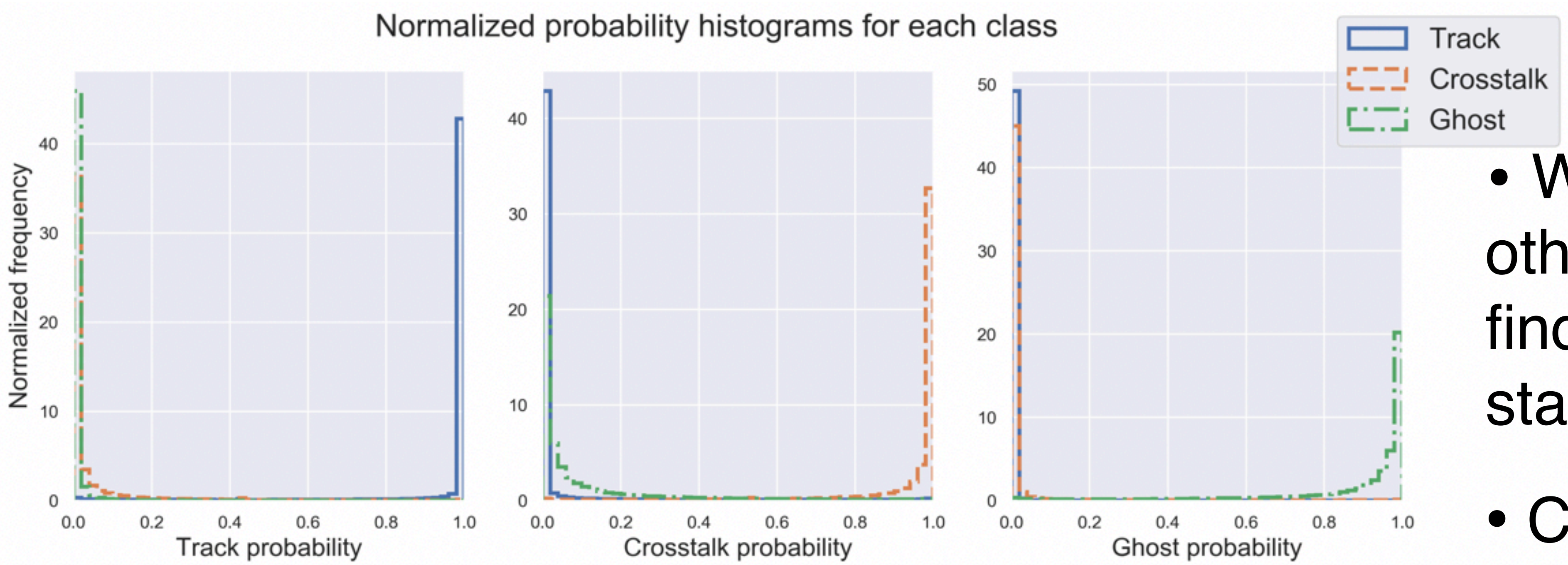
See S.Monsalve's talk on Friday

Machine Learning techniques

- Testing ML techniques to tag hits: track, cross talk and ghost hits



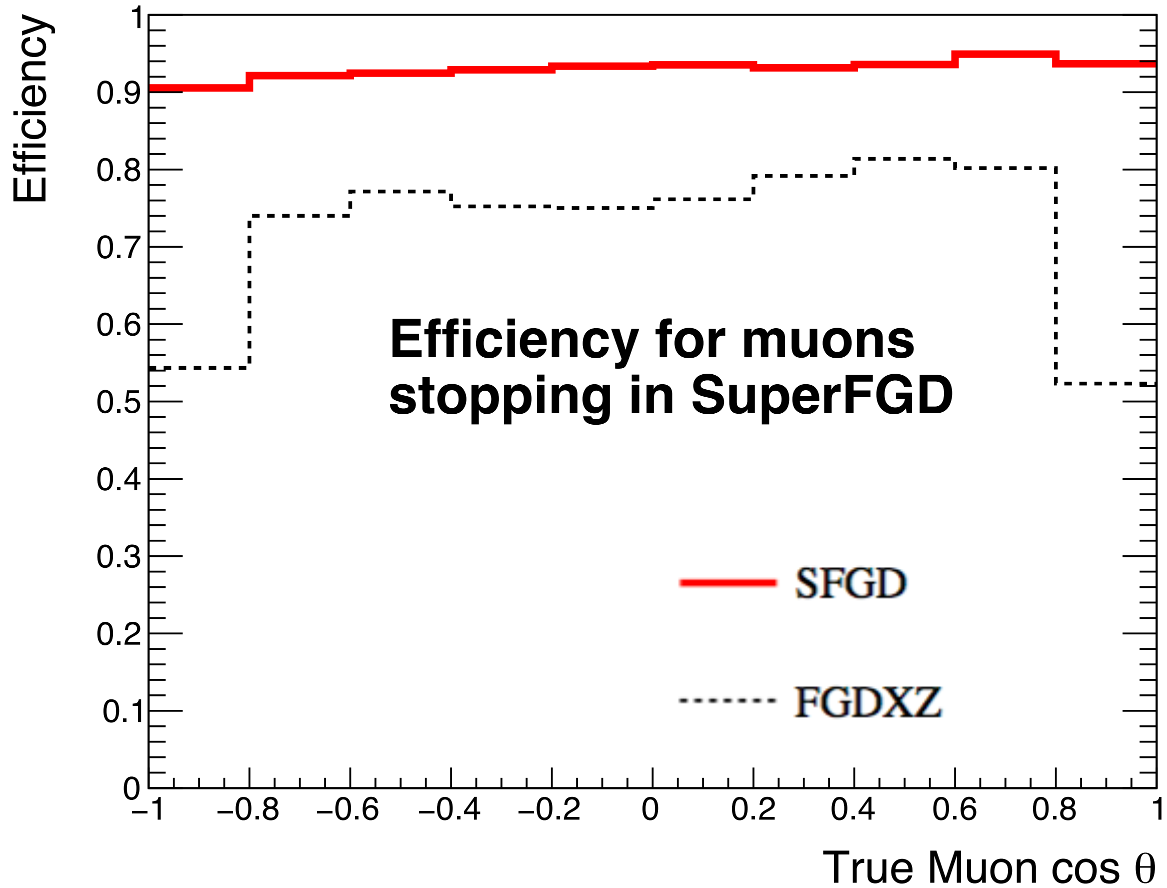


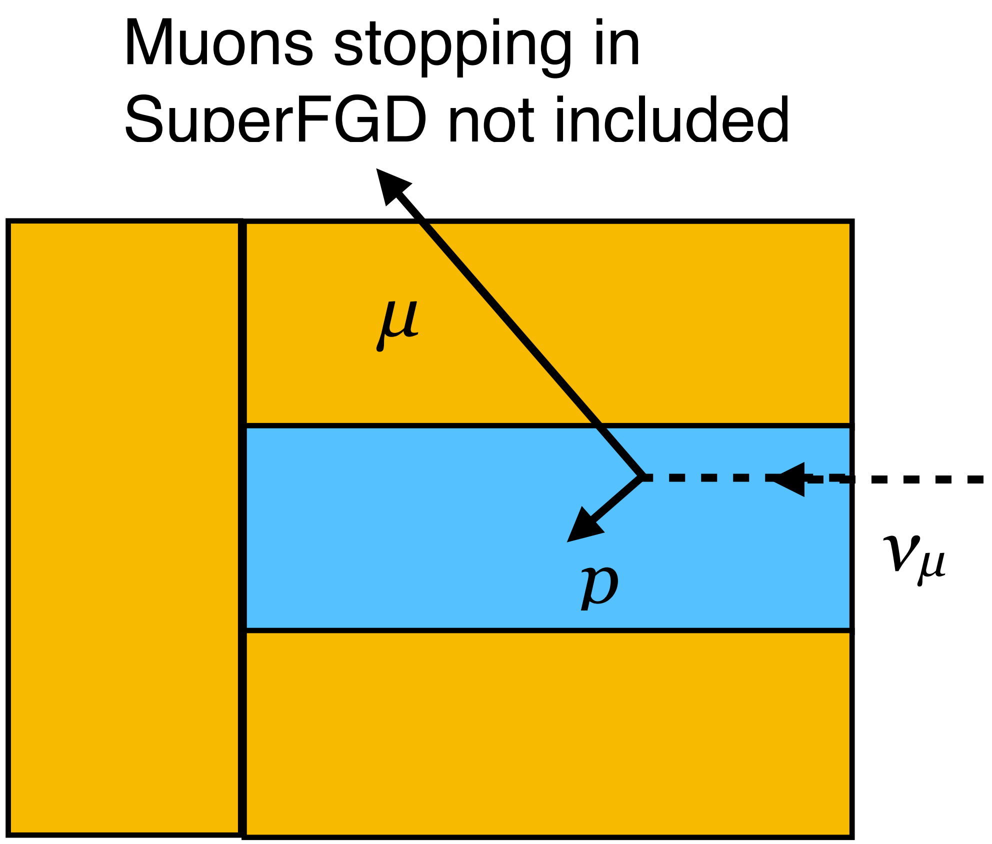


- We are going to test other features, like vertex finding, etc, to help the standard reconstruction
- Choosing a good validation sample is the key

Exclusive selection with SuperFGD

- Cubic granularity allows to detect shorter tracks
- Three WLS fibers provides high efficiency at any angle





- By detecting muons stopping in SuperFGD expect ~15-20% more events
- Momentum resolution ~3% or better for stopping muons (by range)
- To exploit all these informations we need to develop an exclusive muon+proton analysis. Then same for muon+proton+pion —> high priority

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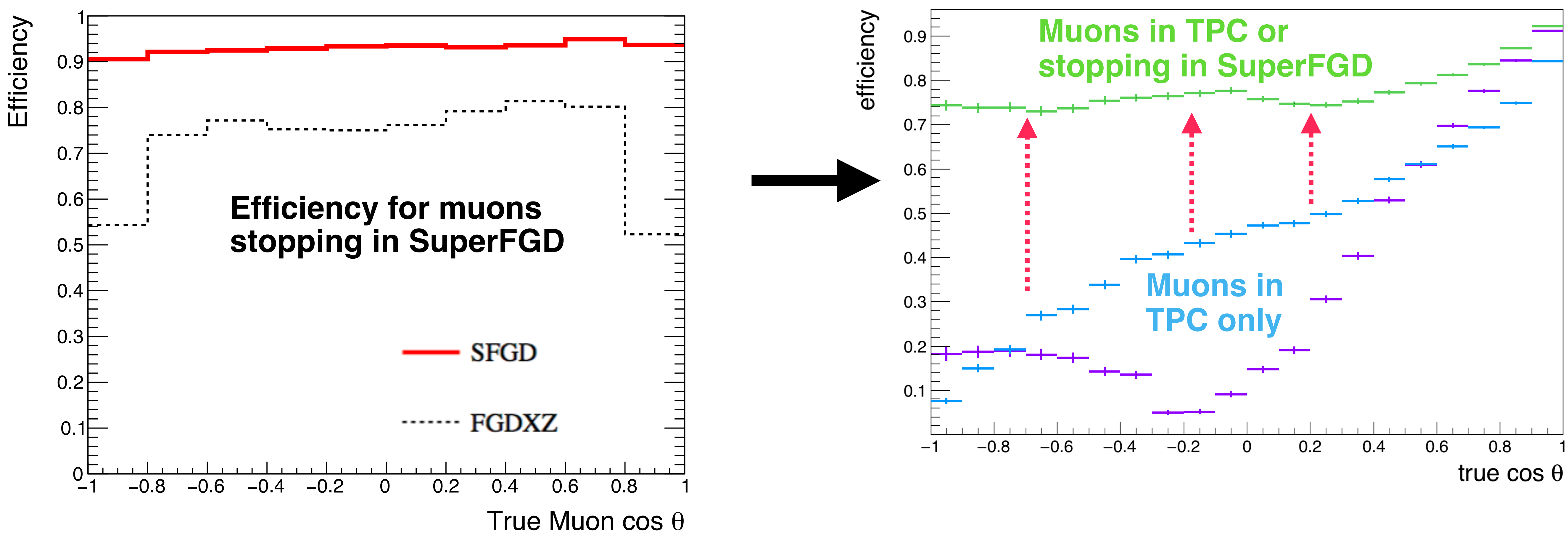

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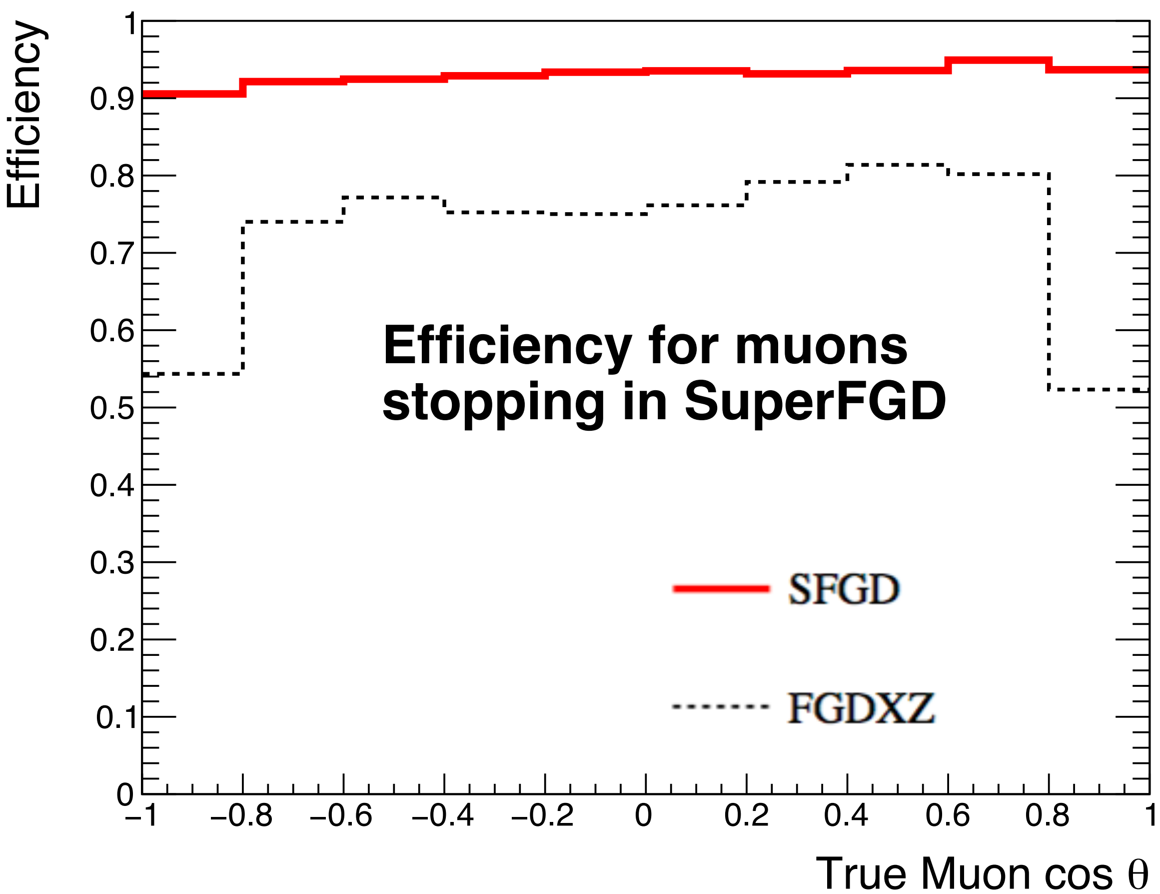
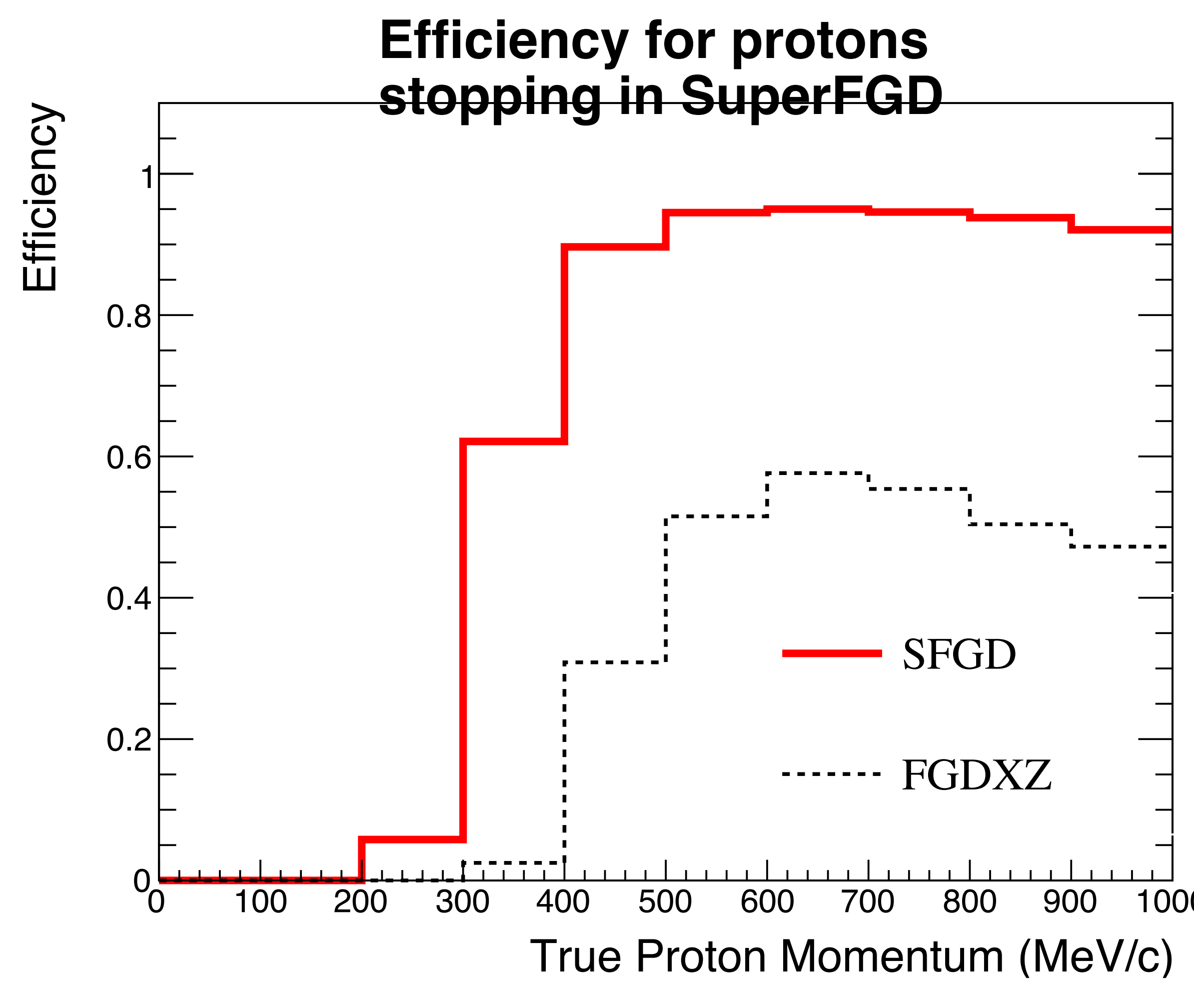
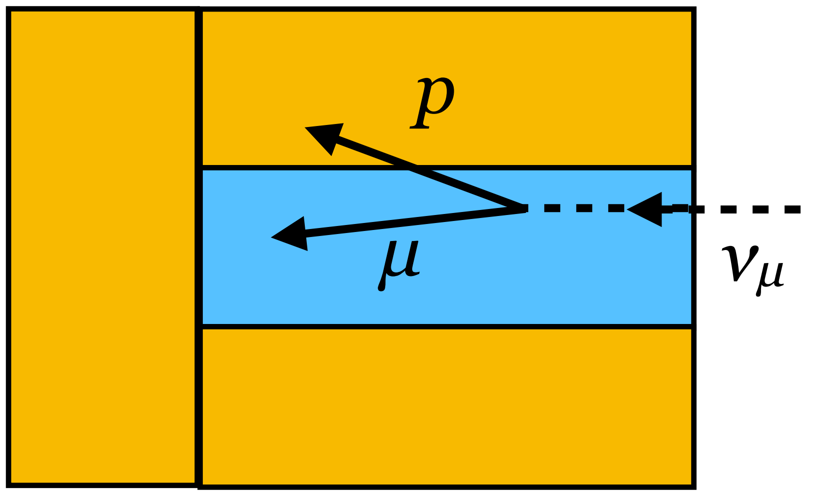


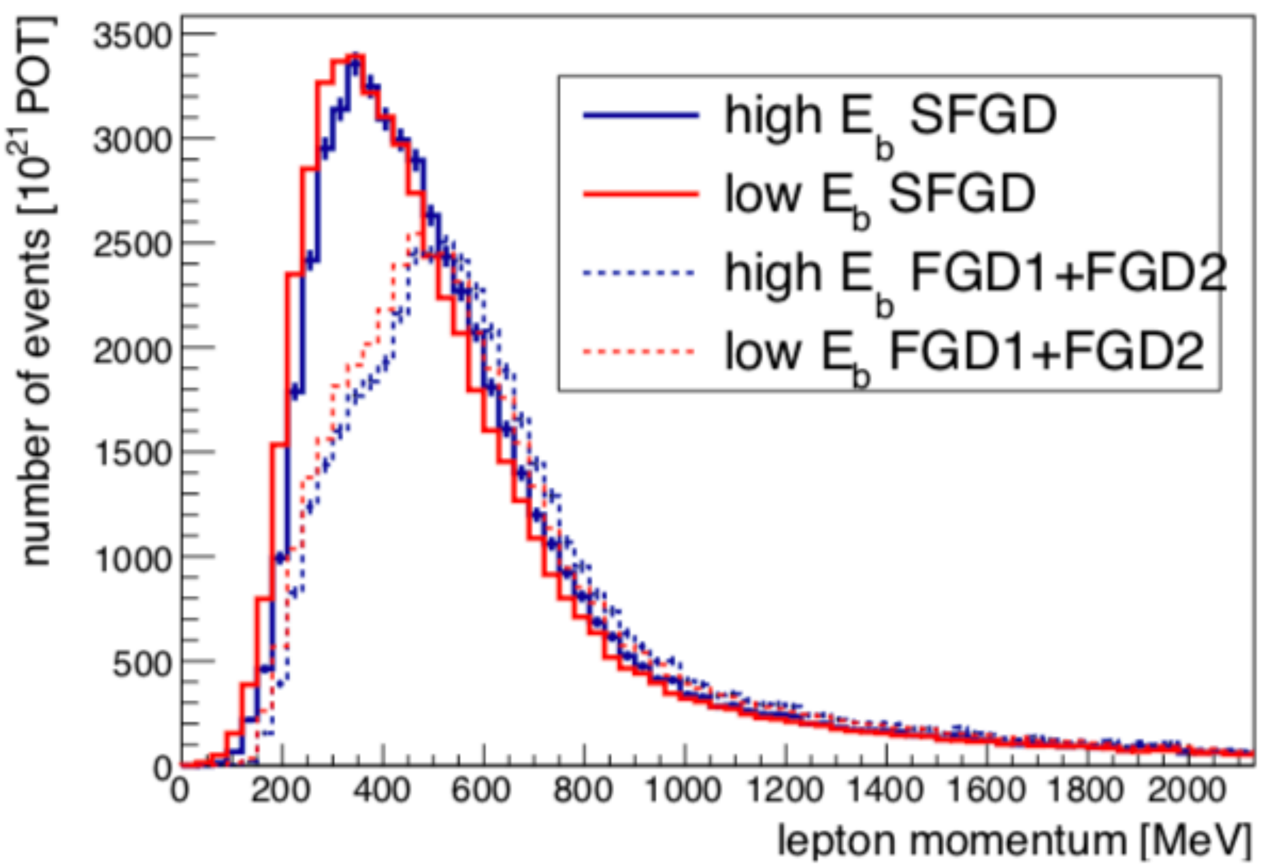


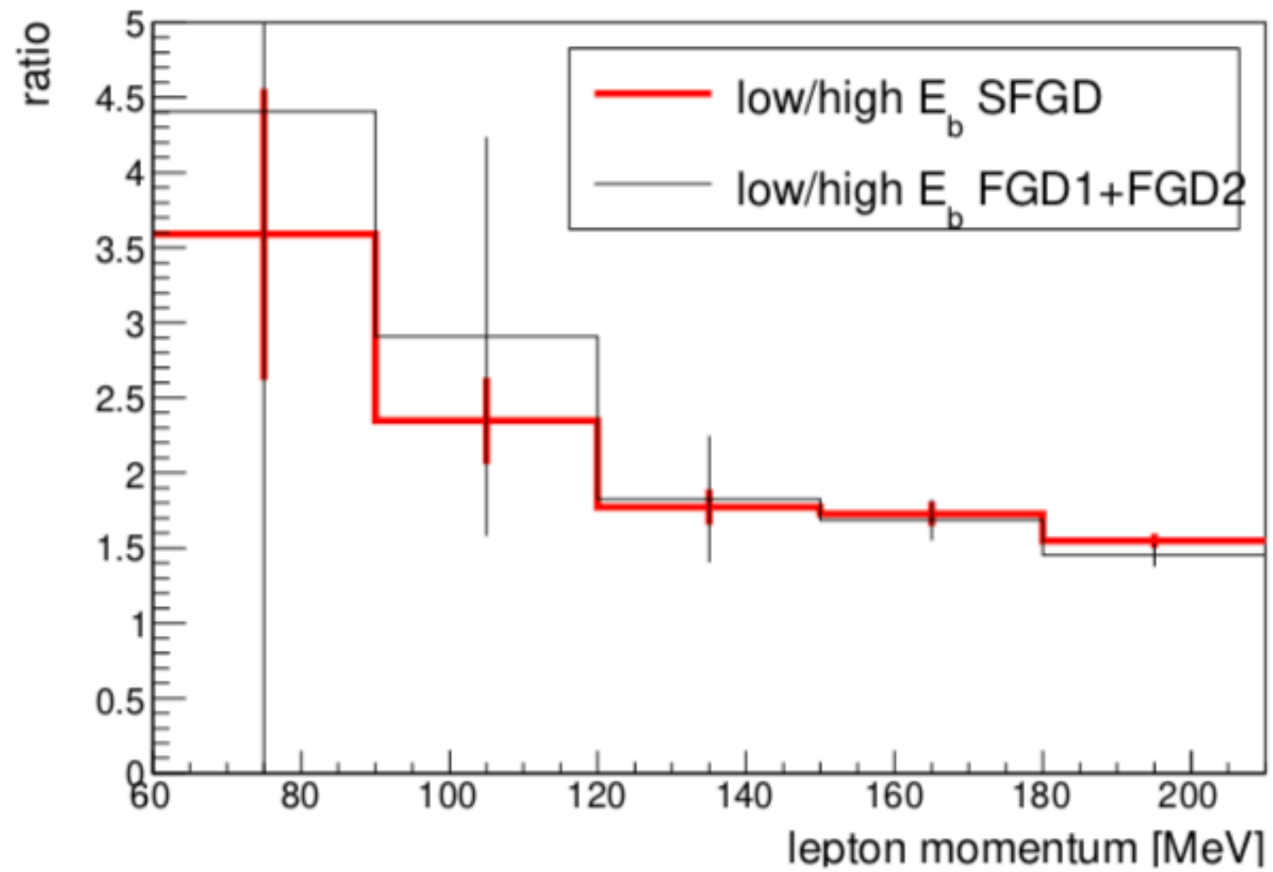
- Lower momentum detection threshold: ~300 MeV/c for protons (~450 MeV/c for current ND280 scintillator)
- Better than 90% efficiency for stopping-muons at any angle

CC 4pi NuMu selection with low-momentum muons

- Low momentum muons will help on the constraining of binding energy systematics (and similar)
- Binding energy effect more visible for low neutrino / momentum energies
- Lower statistics (tail of the flux) but much larger difference between different models



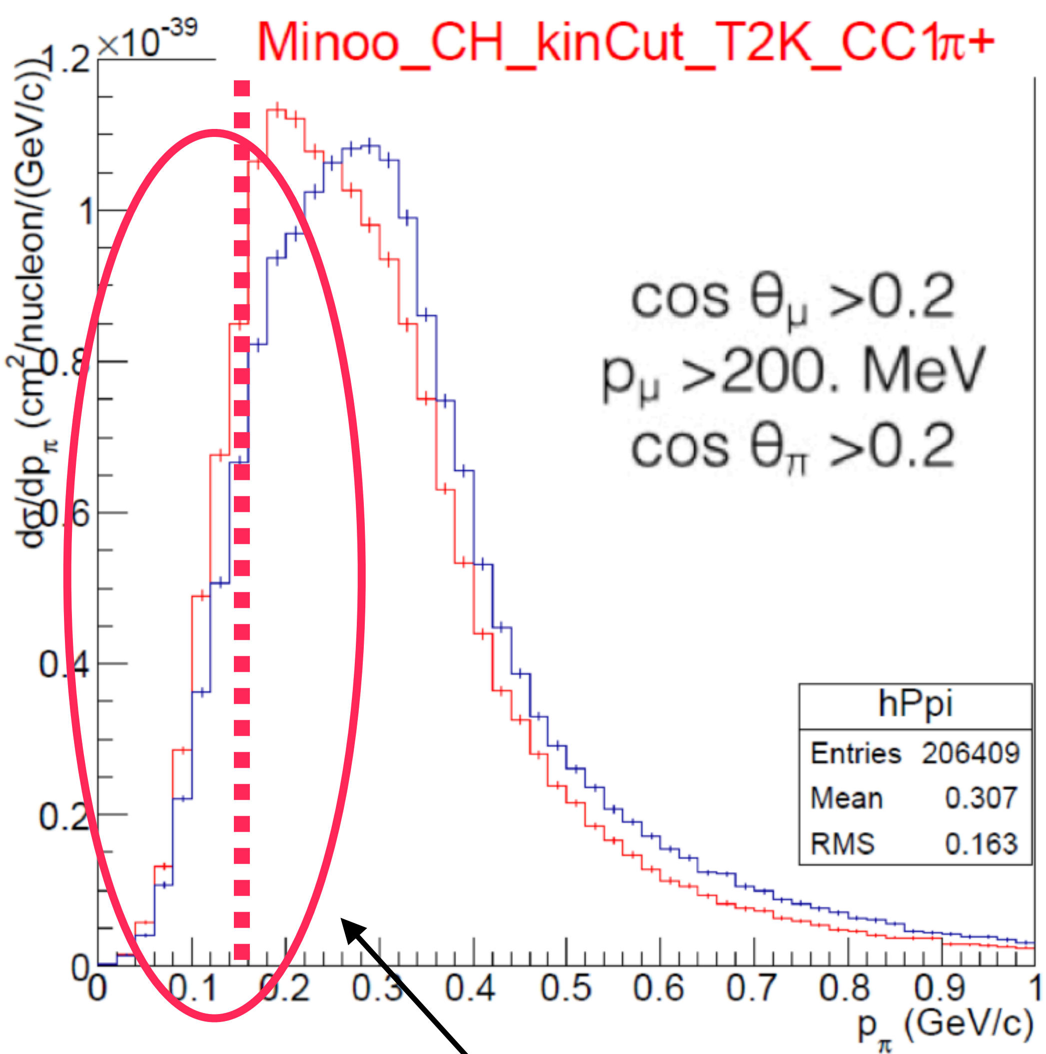


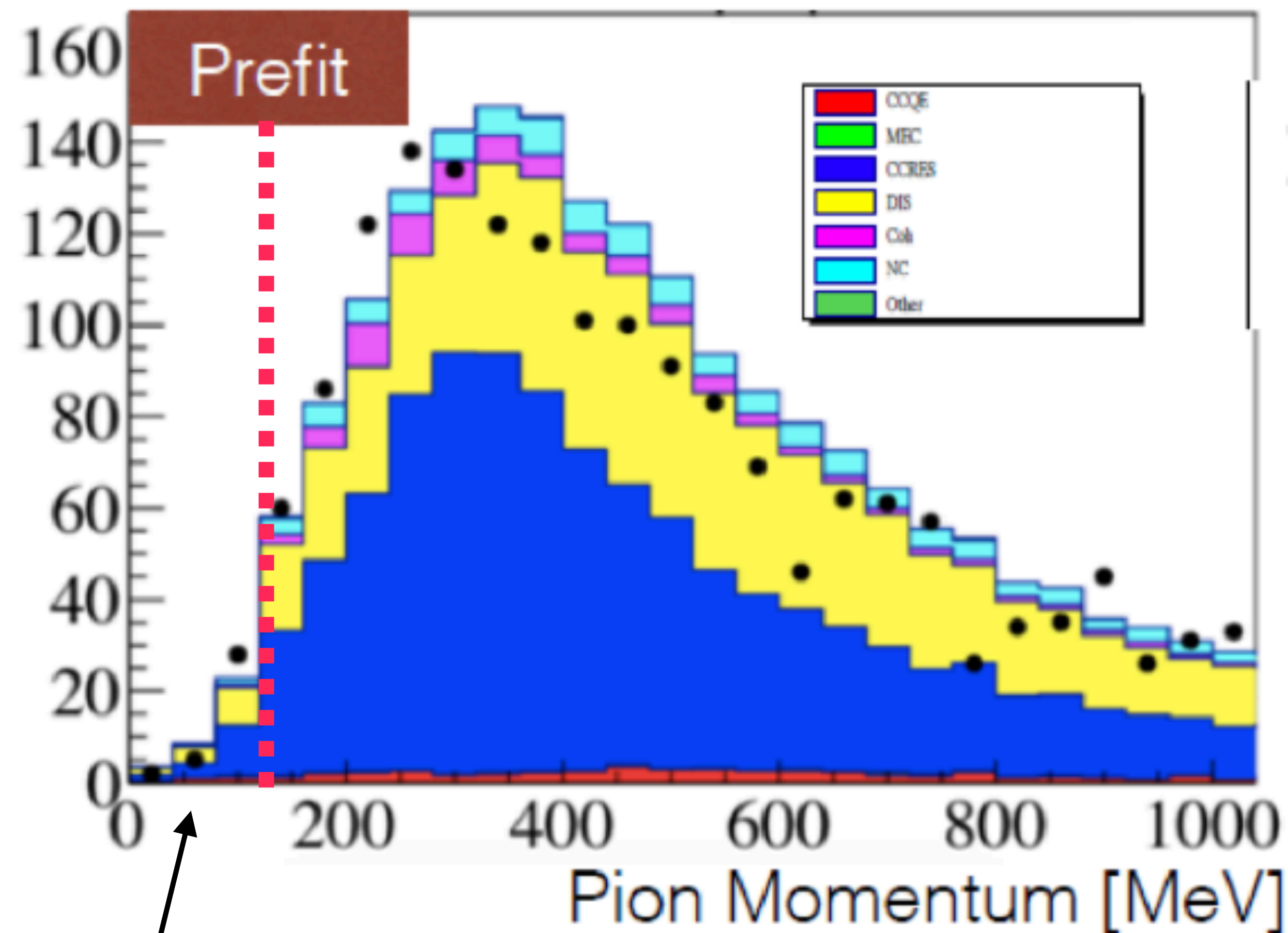


- Momentum resolution ~3% or better for stopping muons (by range)
- High priority, as Eb is one of the major systematic uncertainties

What about pion-production models ?

- We will be able to look to this discrepancy at many different angles

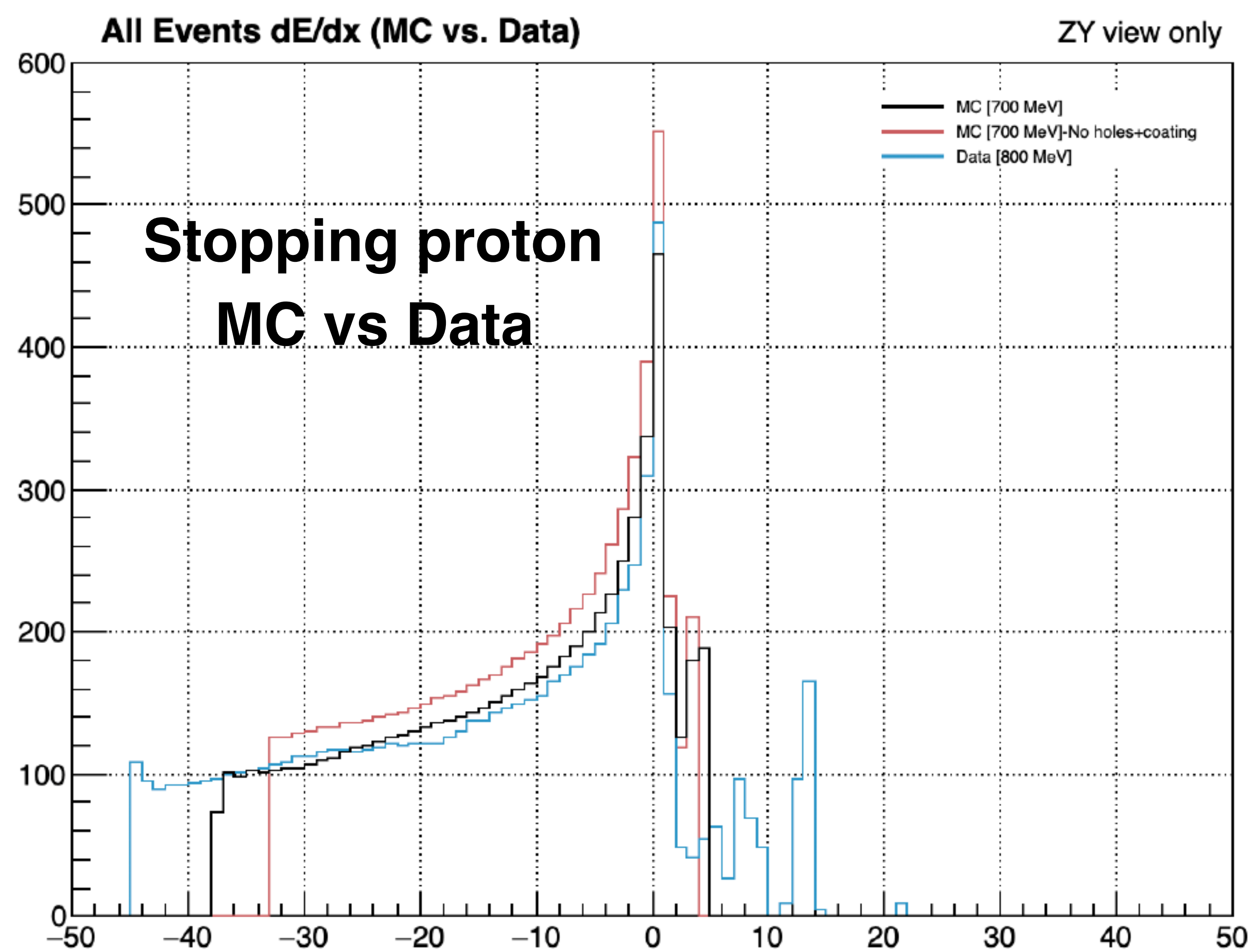




- What about current systematic uncertainties (e.g. momentum scale) in this steep region ?
- Reducing the pion threshold and higher statistics may help

Vertex Activity

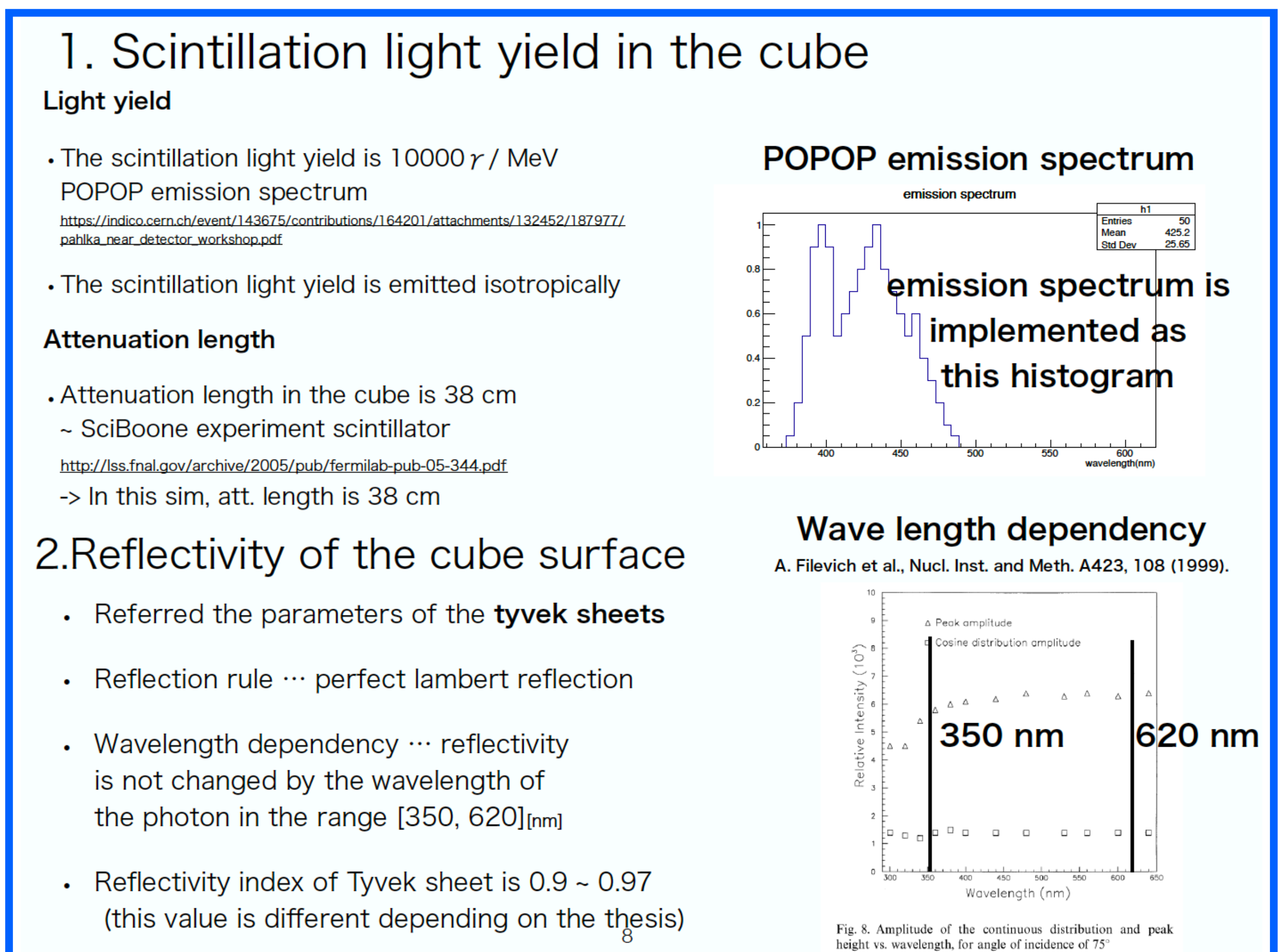
- Better granularity and higher light yield gives also better sensitivity to the vertex activity
  - ✦ Some particles, that in FGD gives just "activity", in SuperFGD can become tracks

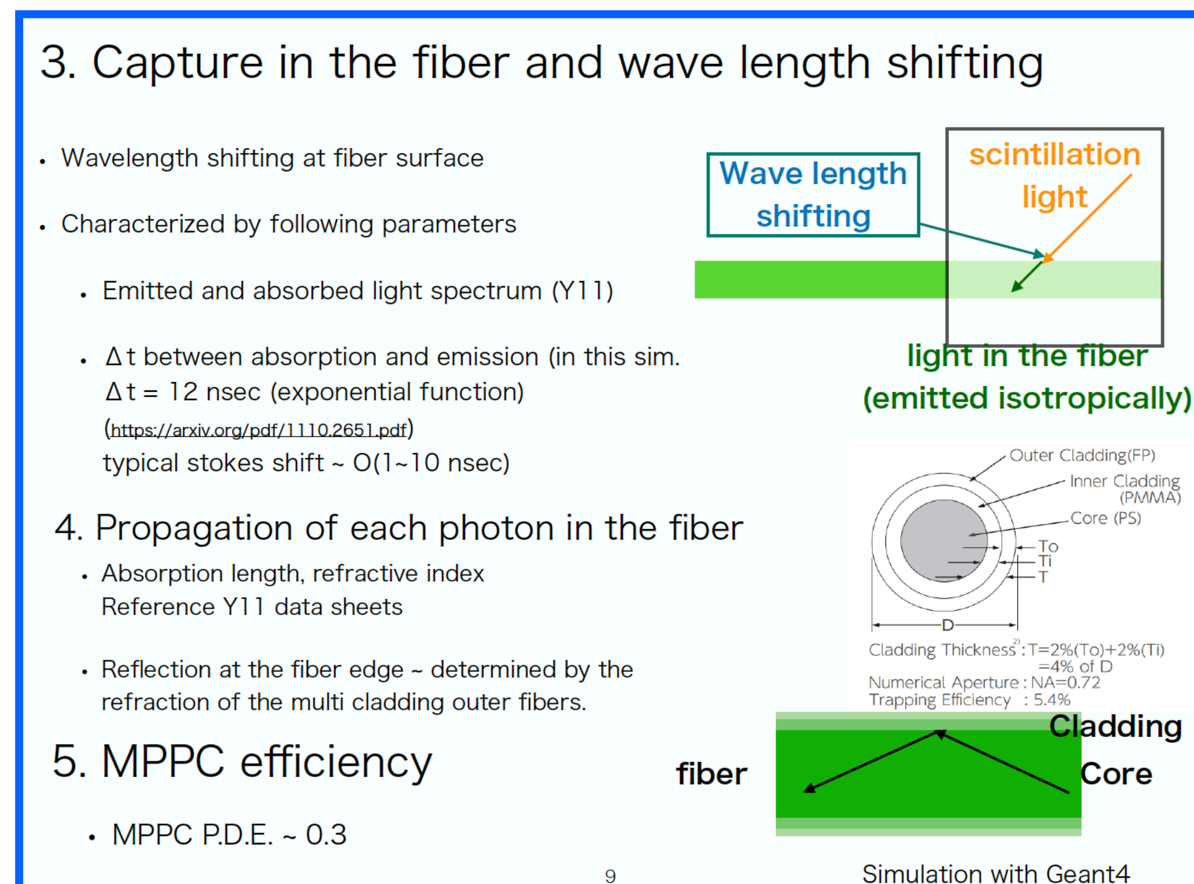


- Need to develop a detailed vertex activity analysis in SuperFGD

Vertex Activity and Light Optical simulation

- A detailed simulation is mandatory to characterize the observed vertex activity
- We are currently working on the optical simulation from scintillation in the cube to MPPC
- The simulation is implemented. Validation with test beam data is ongoing
- The goal is to improve the simulation of the detector response after GEANT4
  - ✦ Parametrize it as a function of the particle topology, energy deposited and position of particle interaction inside the cube (i.e. distance from the WLS fiber)

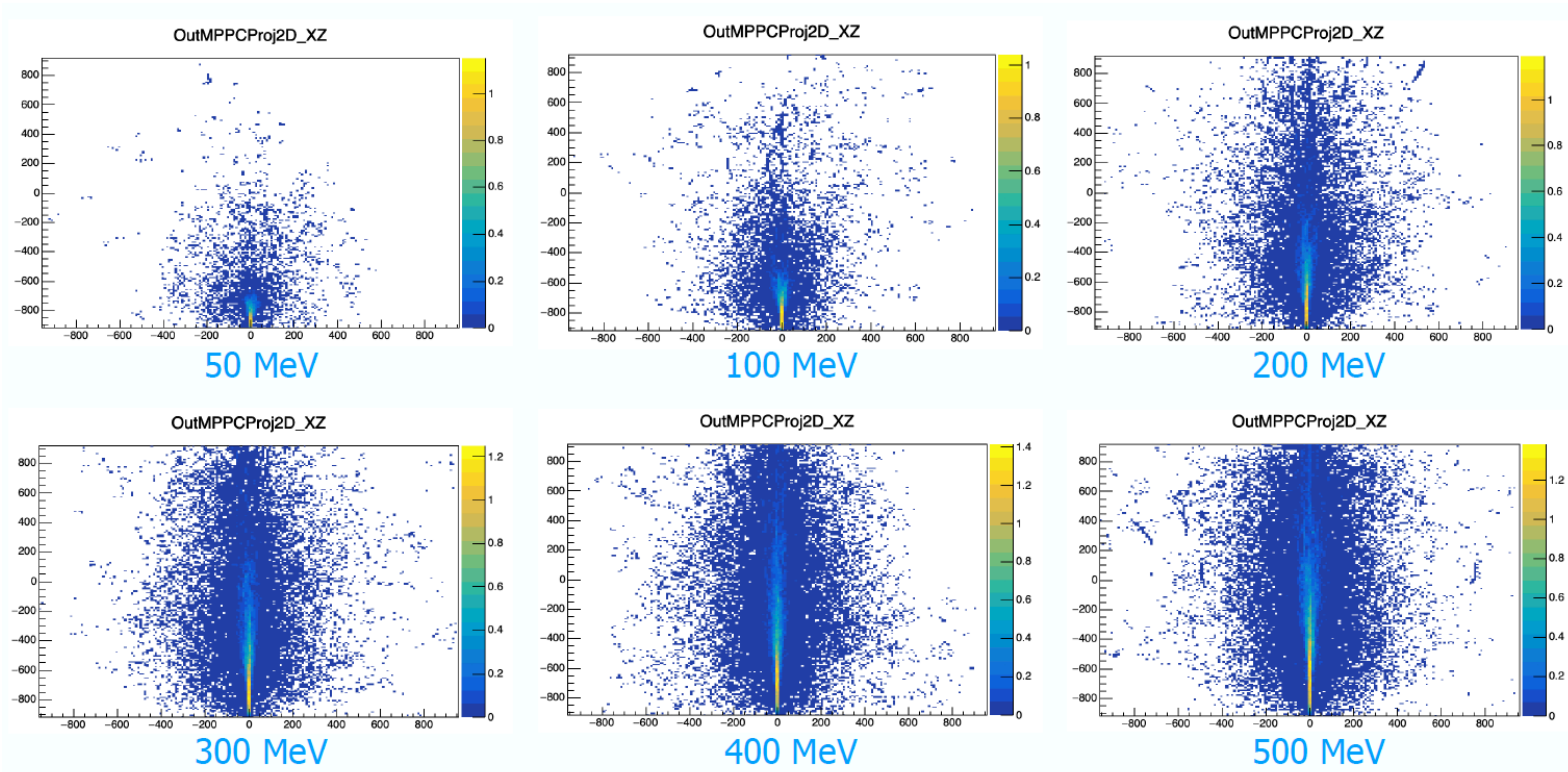




E.M. shower containment and energy resolution

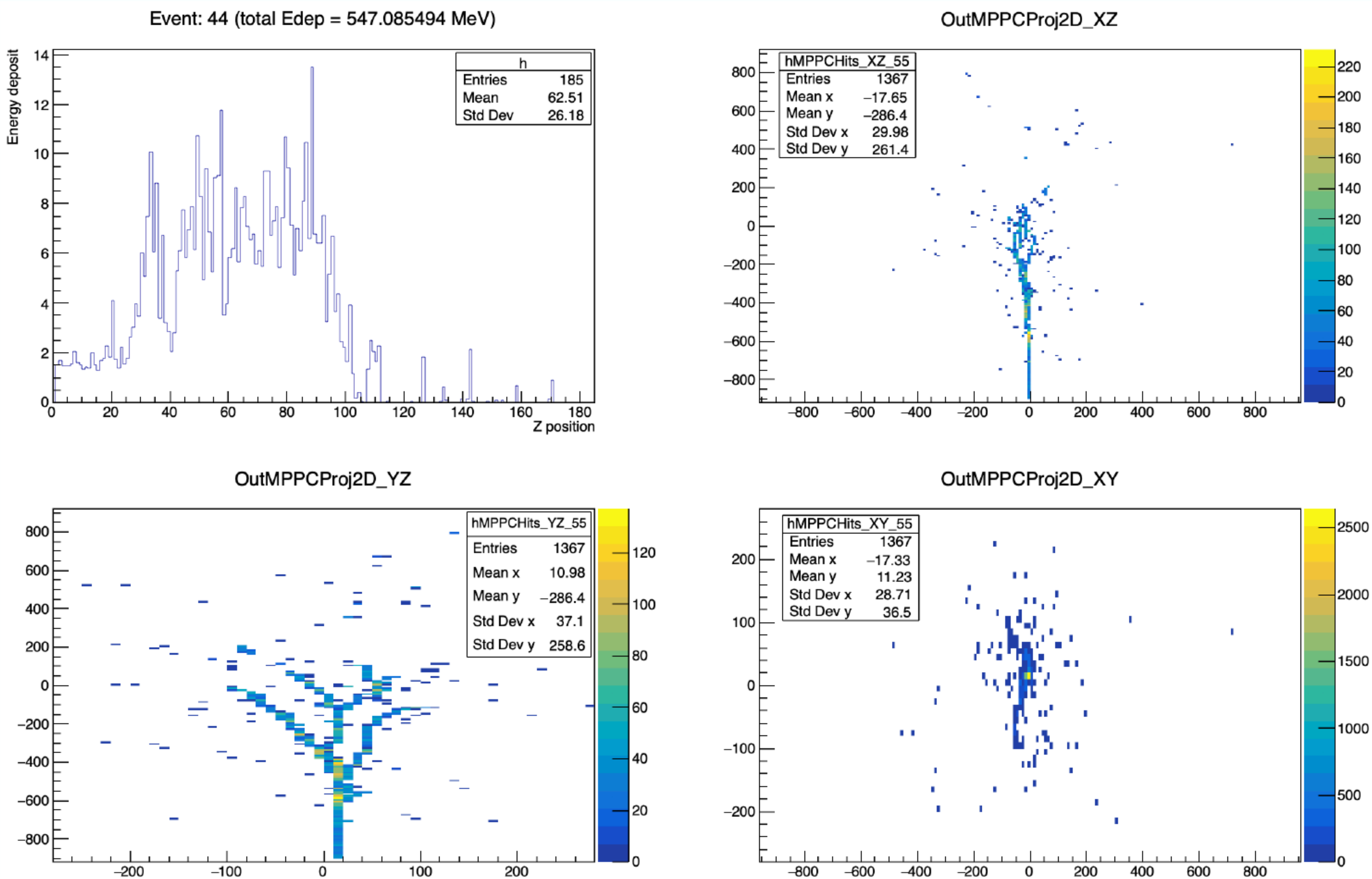
- We started to look at EM shower reconstruction in sFGD

Average distributions of EM showers for different energies



- In order to achieve a good energy resolution we have to contain most of the EM shower in the “solid” detectors (sFGD and ECAL)

Result (600 MeV; maximum Edep)



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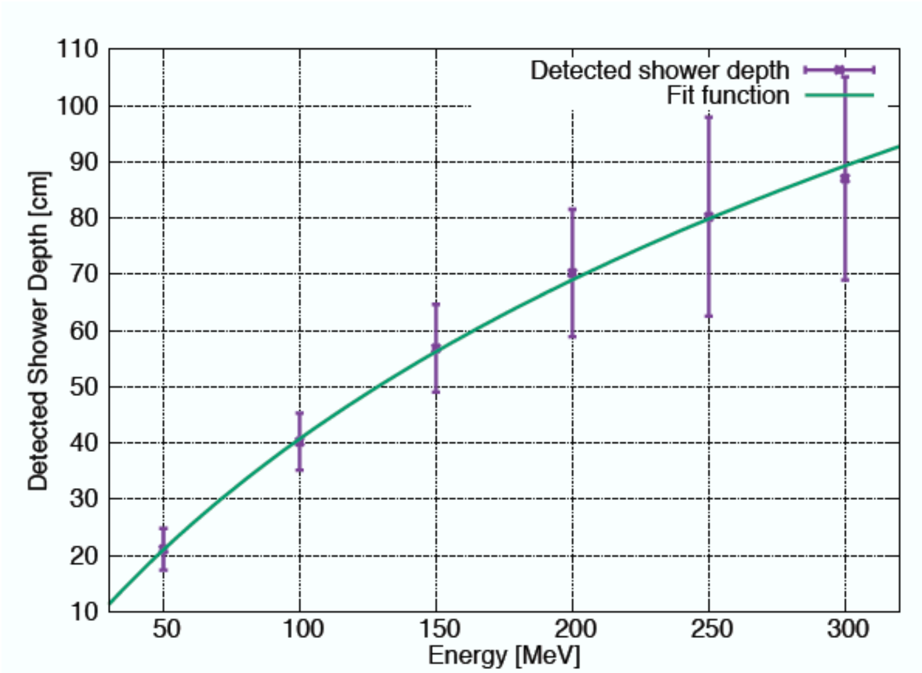
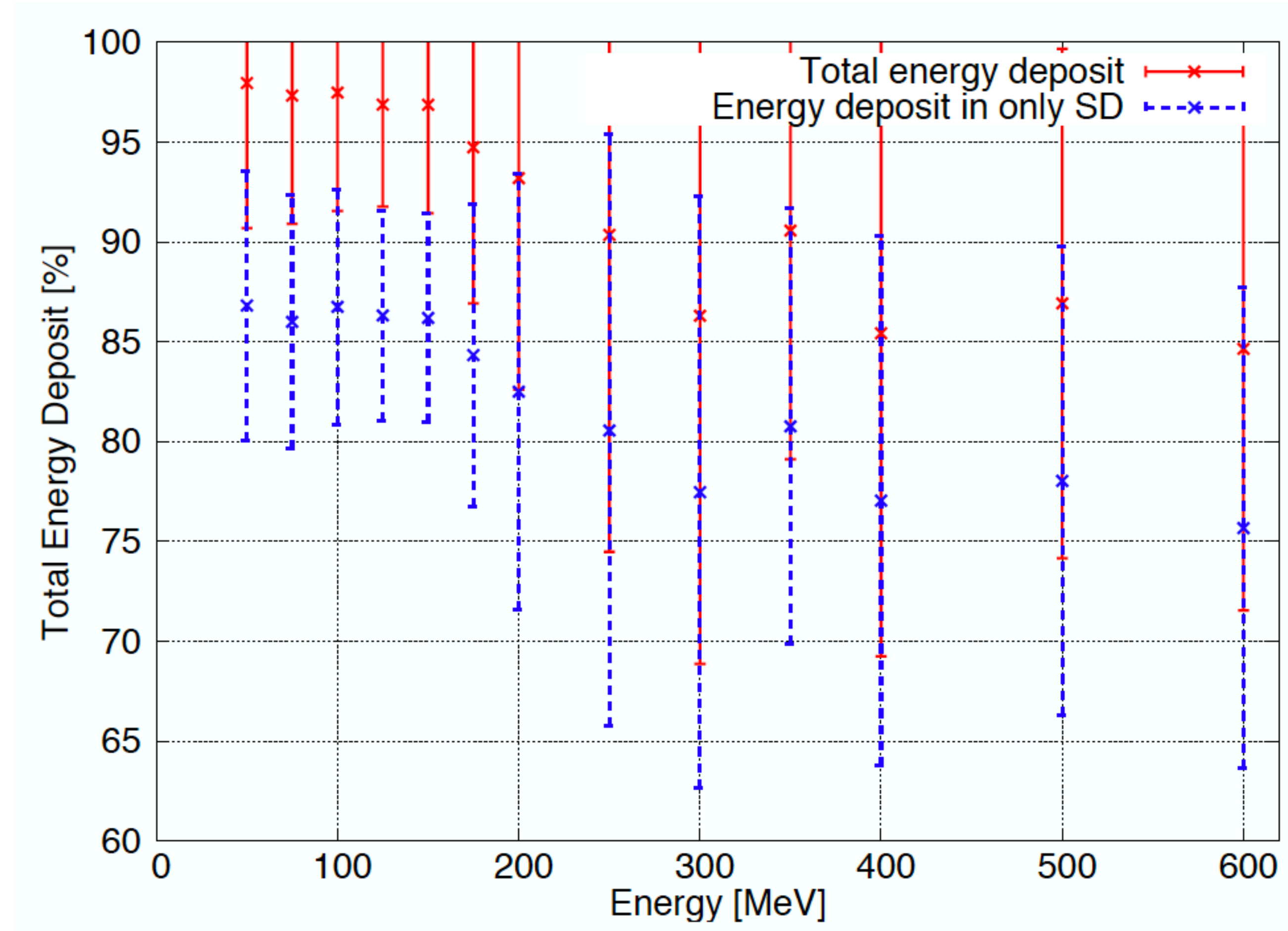
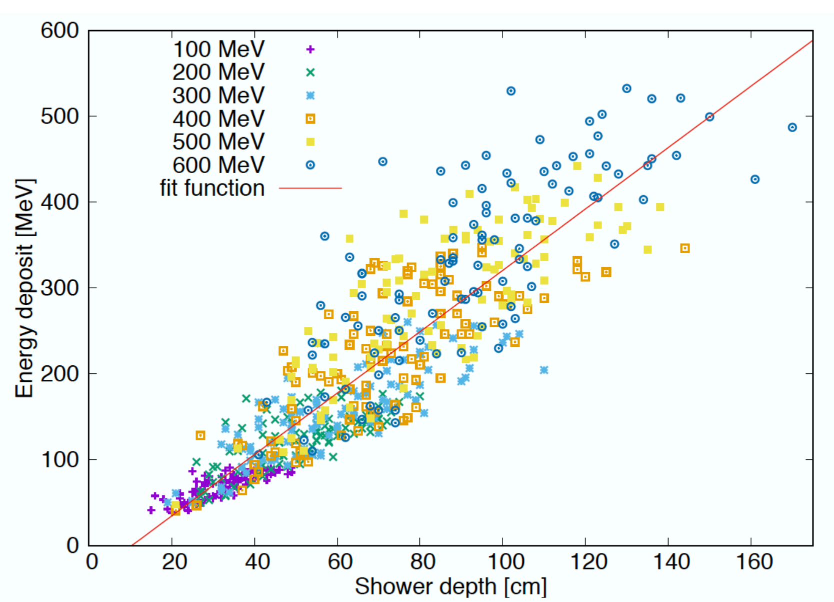






Energy [MeV]	50	100	150	200	250	300	350	400
Mean (total) [MeV]	49	97	145	186	226	259	317	342
Mean (SD only) [MeV]	43	87	129	165	201	232	283	308

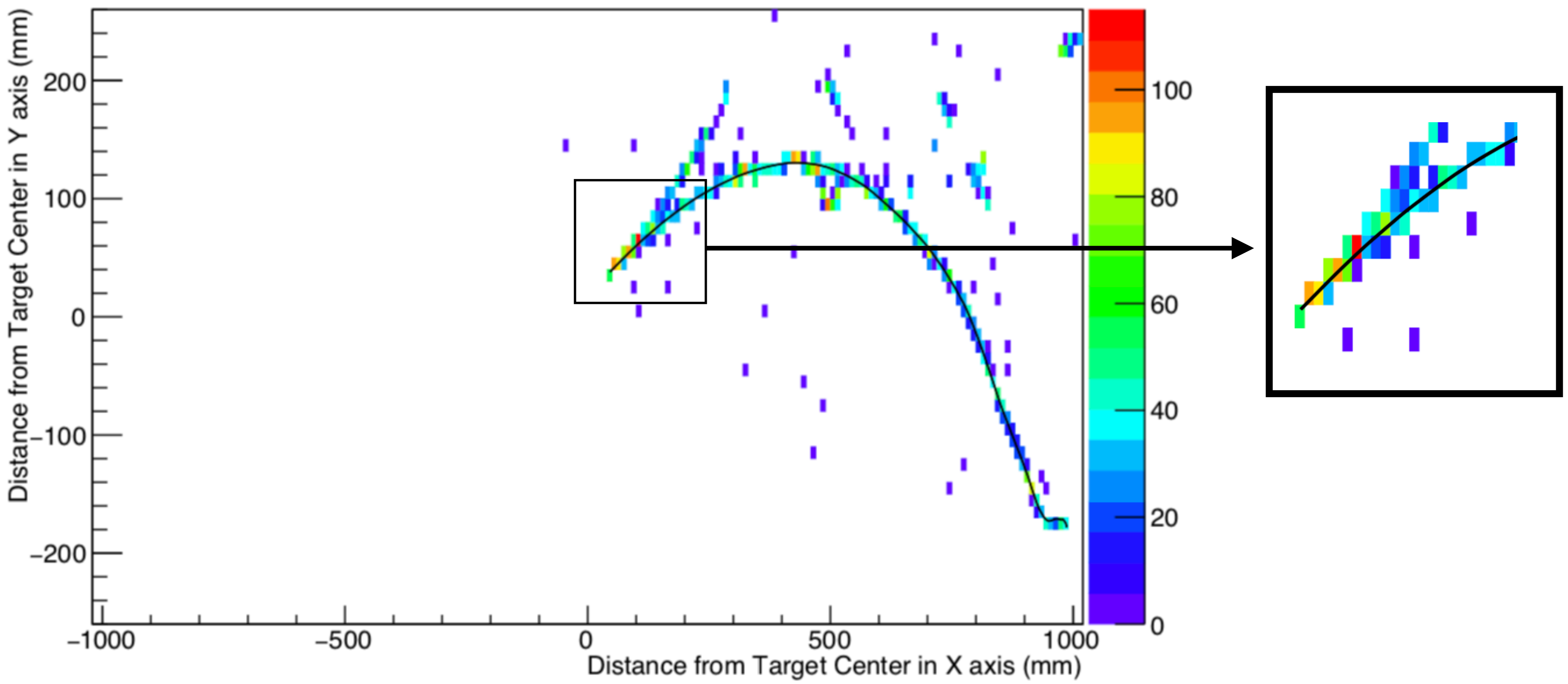
- sFGD can't contain all the EM shower, i.e. bad resolution at high energy
- Can P0D-ECAL do the job? Only 5 X_0, only bars along 1 direction

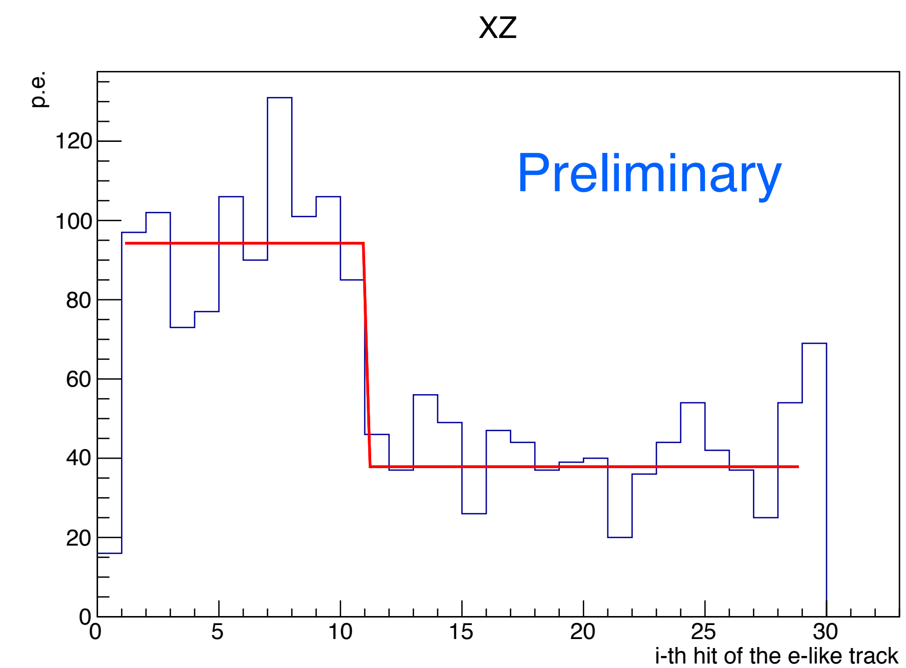
Toward a hybrid tracking + calorimetric measurement

- The event reconstruction strategy has to change
- ND280 current:
  - ✦ particles mostly detected by TPCs, FGD is not a tracker
  - ✦ Only forward, so particle energy resolution depends on phase space
- ND280 upgrade:
  - ✦ sFGD is also a tracker and will contain most of the low-energy particles
  - ✦ TPC will detect particles exiting sFGD
  - ✦ Tracking can be done at any angle
  - ✦ Move the “edge” between what is a track and what is deposited energy (e.g. vertex activity, showers)
- We should aim to a hybrid tracking + calorimetric measurement, where calorimetry is not done only at the vertex but within hadronic e.m. interactions
- Not easy, but this must be the future goal

CC 4pi NuE selection and gamma bkg rejection

- Background from $\gamma \to e^+e^-$ is the major background ν_e interactions at ND280

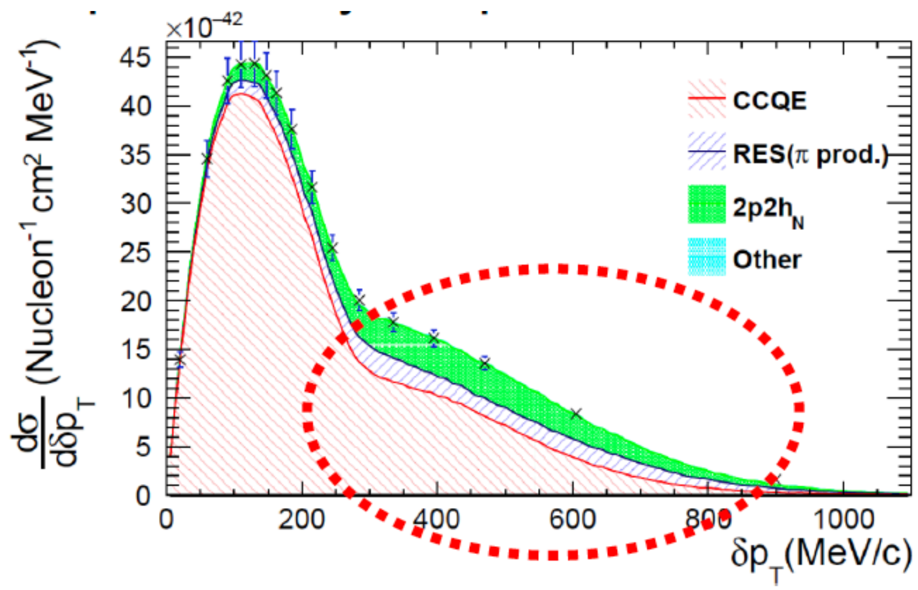




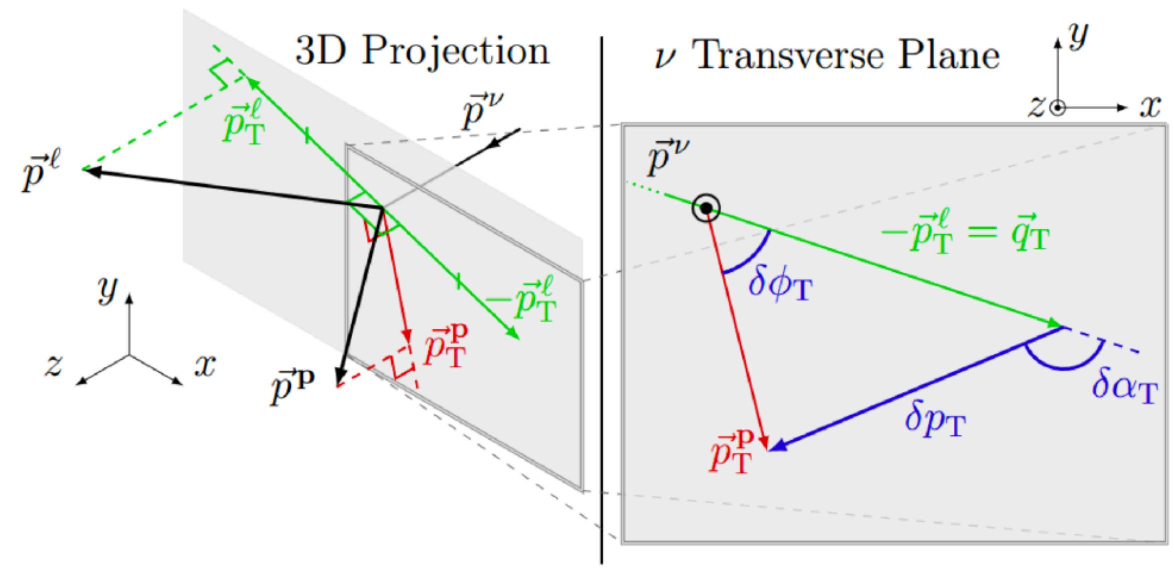
- Reject the $\gamma \to e^+e^-$ background by tracking and light yield discrimination
  - ✦ Light deposited by $e^+ e^-$ is double than the light deposited by e^+ only
- ~68% of $\gamma \to e^+e^-$ rejected w/o using TPC (a lot of room for improvement)
- Nue CC 4π analysis is high priority. We developed a signal-only one, but proper estimation of the bkg and e-shower reconstruction performance in SFGD performance is necessary and very important. Lot of efforts are needed

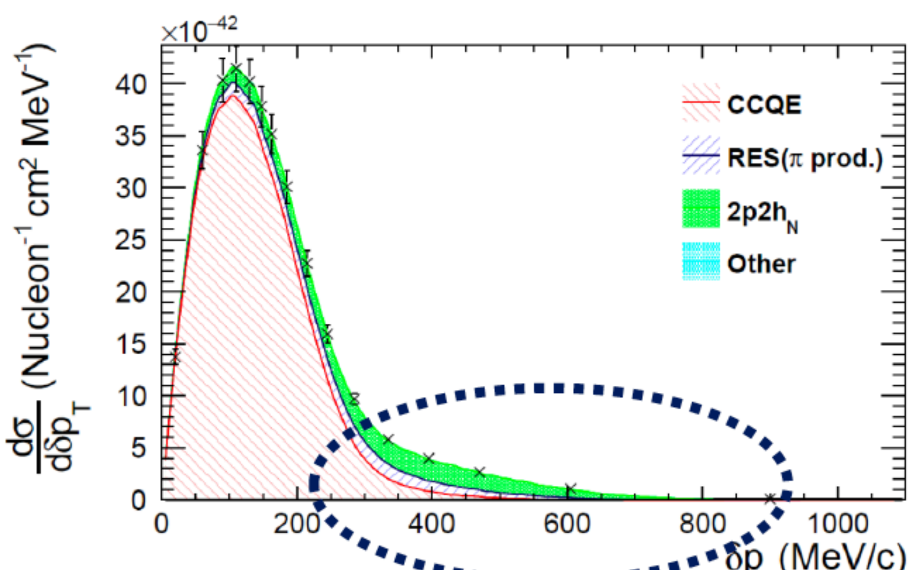
Single Transverse Variables at ND280 upgrade

- Look at the transverse plane to probe nuclear effects (PRC 94,015503 2016)
  - ✦ δp_T —> sensitive to "invisible" processes
  - ✦ $\delta \alpha_T$ —> Acceleration of the system
- The development of a sample with STV will become mandatory (soon?)

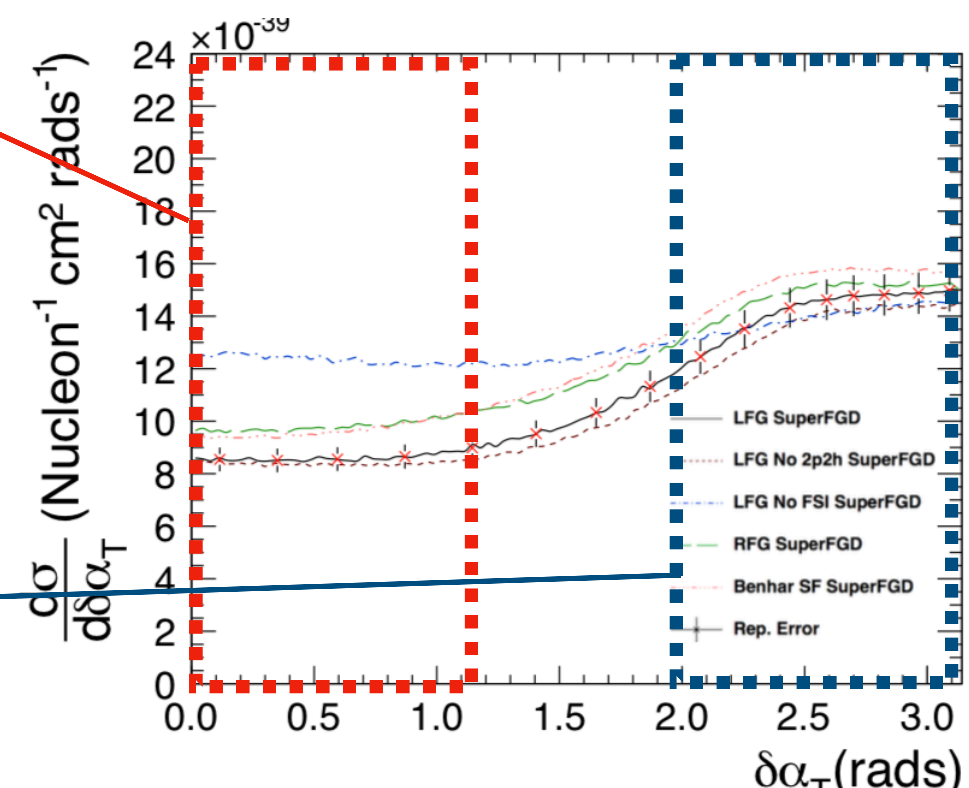


δp_T **tail dominated by FSI**



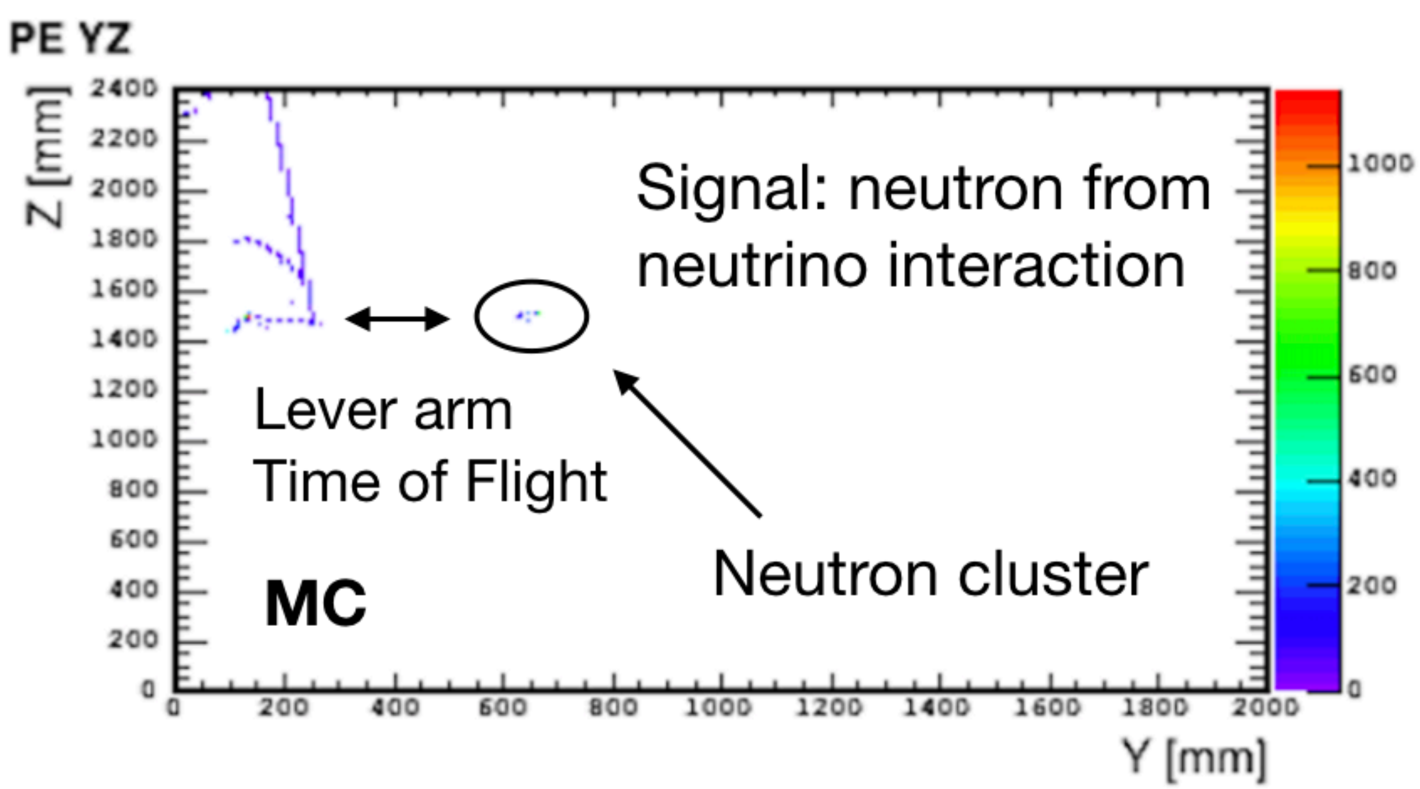


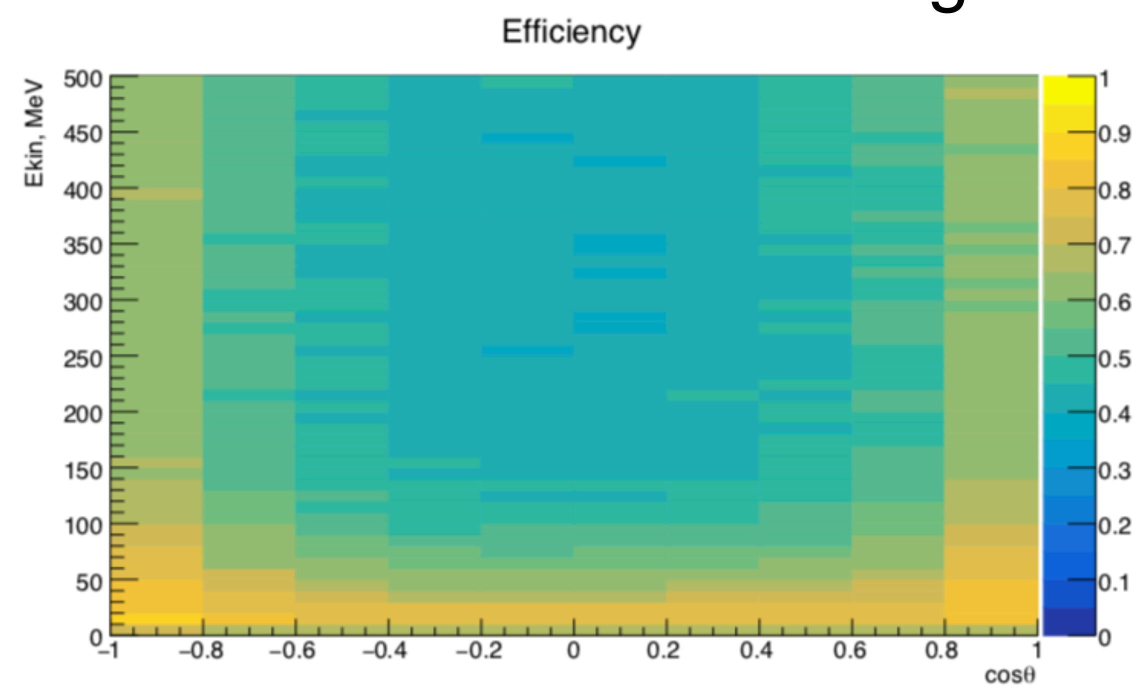
δp_T **tail dominated by 2p2h**

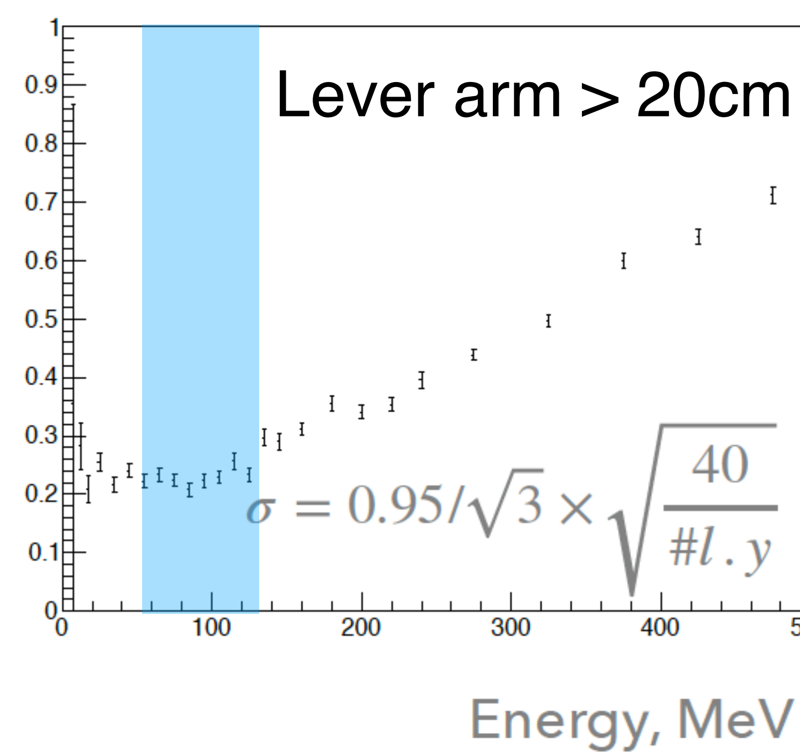


Neutron Detection in SuperFGD

- Minerva experiment has demonstrated the potential of detecting neutrons produced by ν interactions in scintillator (arXiv:1901.04892)
- SuperFGD has 3D granularity, much better spatial and timing resolution
- Precise neutron detection is a very powerful tool for the understanding of the ν interaction processes (e.g. 2p2h)
- Neutron kinetic energy by time-of-flight



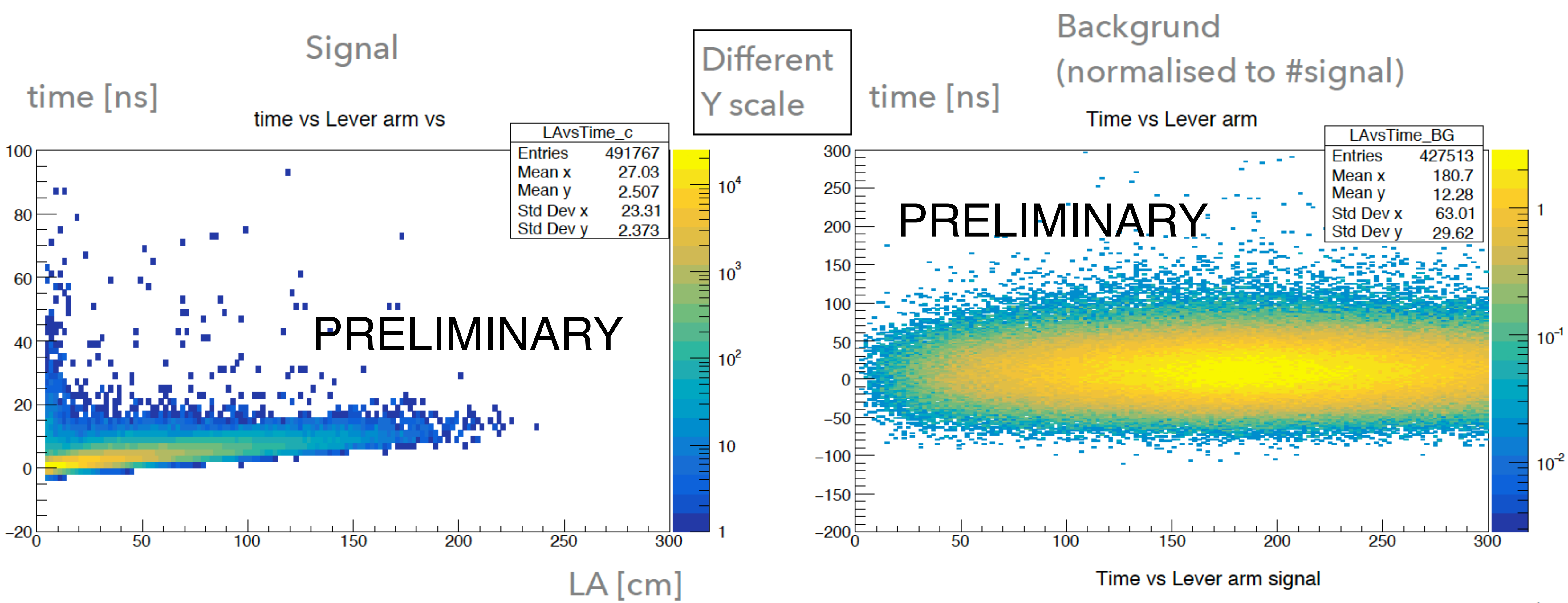




- Very important as SuperFGD may be the first neutrino detector measuring precisely the neutron kinematics
- Neutron beam test in Los Alamos in fall this year

Neutron Background

- The out-FV neutron background is the most dangerous one
- Very large (unknown?) systematic uncertainties —> it must be very low

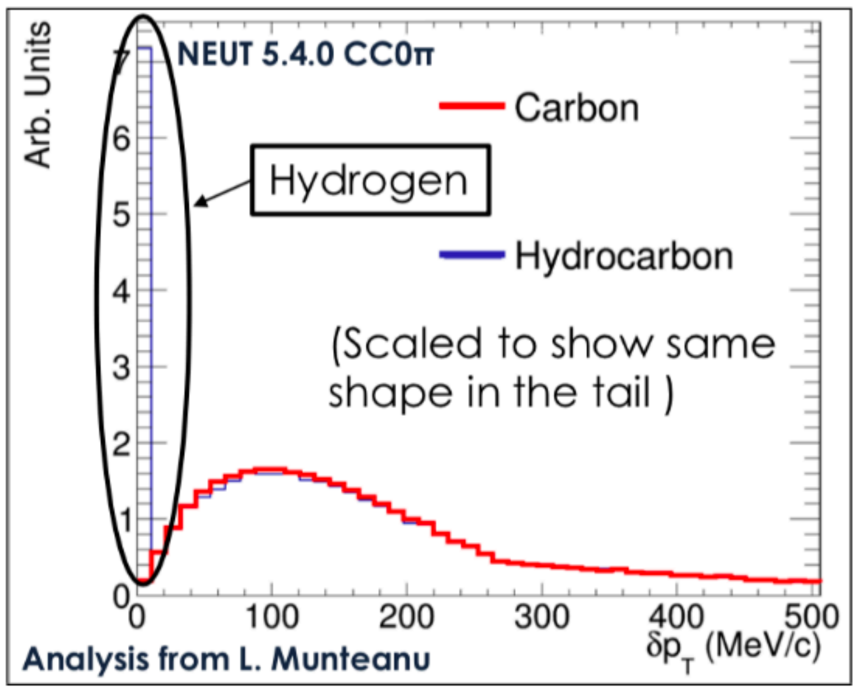


- Another source of bkg is secondary neutrons, i.e. produced by proton, pion, neutron interactions
- Hard to get rid of it. However it's physics and it could be studied with a proper test beam

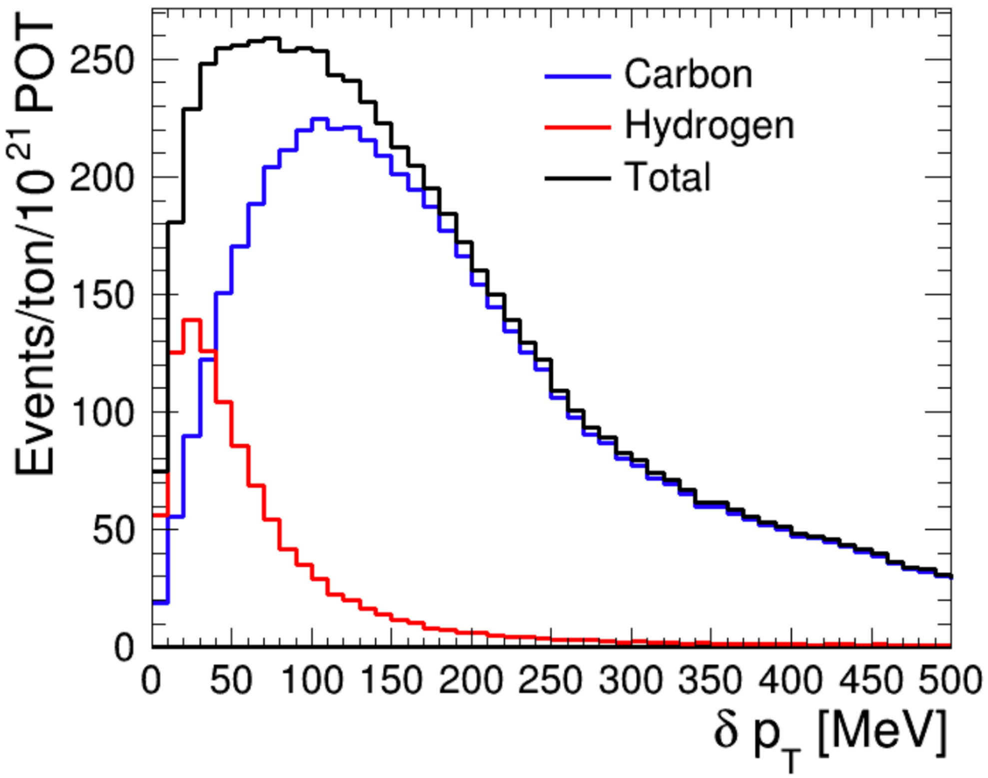
New method to infer $\overline{\nu}_\mu$ flux

• At T2K energies it’s hard to use independent methods to infer the neutrino flux (e.g. nu+e scattering, low-nu)

• We are developing a new method that may directly infer the antineutrino flux by looking at the transverse momentum imbalance



Detector smearing

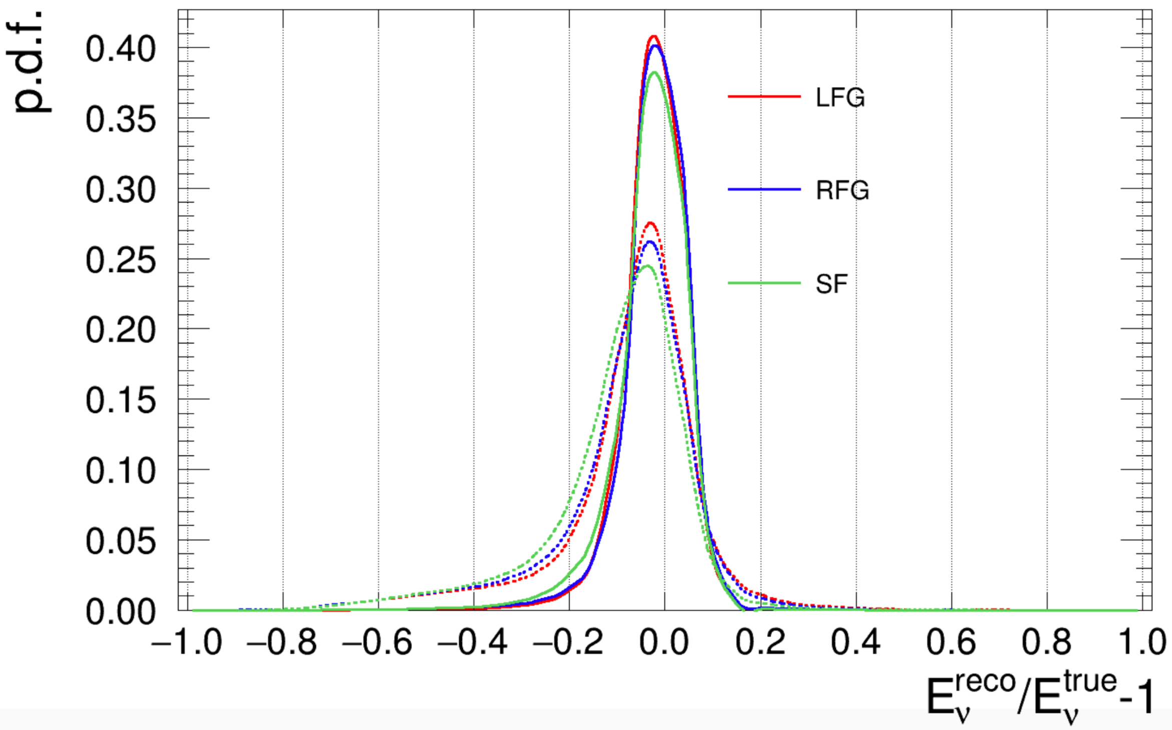


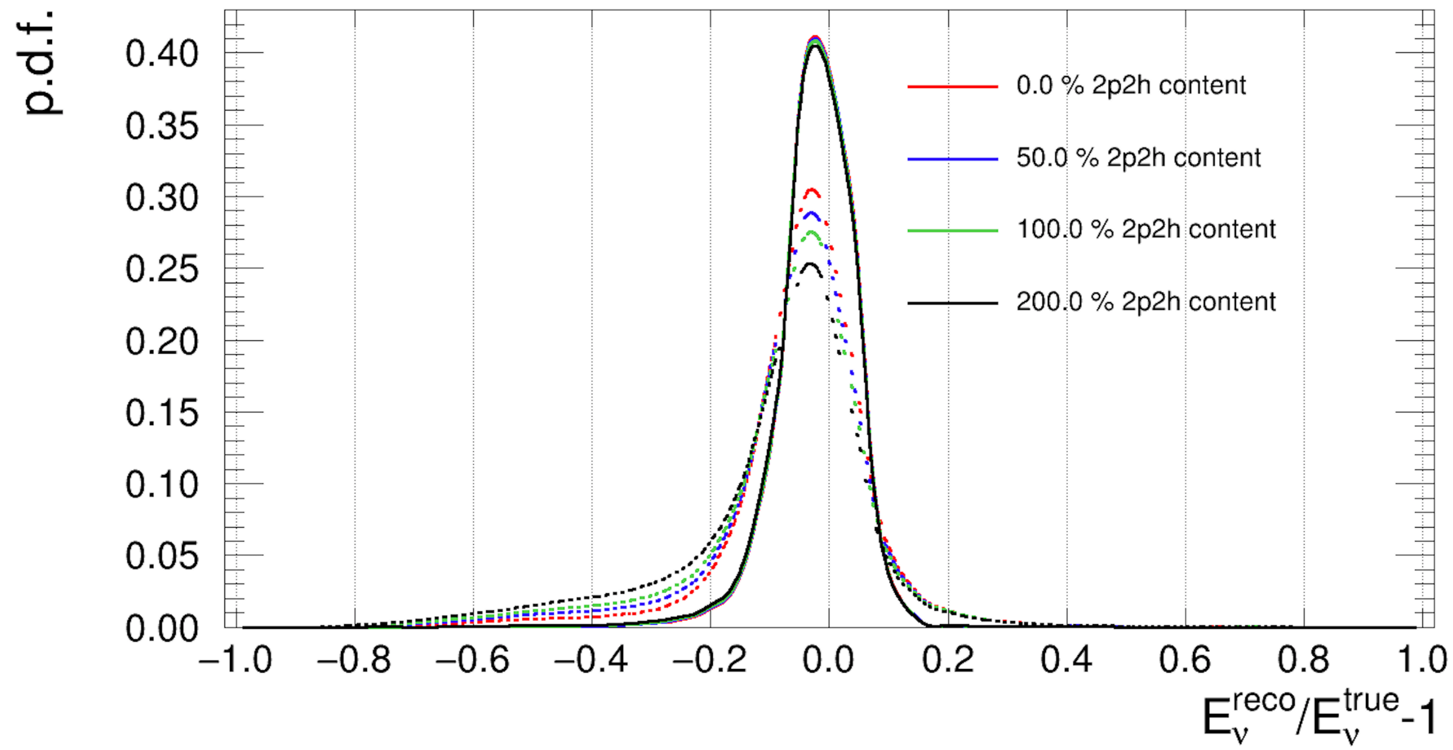
• Detect both the muon and the neutron

• No vertex activity —> quite trivial as the detector is fully active and energy threshold is low

•Cut on dp_T to isolate a hydrogen-enriched / low-nuclear effect carbon sample

New method to infer $\bar{\nu}_\mu$ flux





- NuBar energy resolution is reduced from ~15% to ~7%
- Almost no bias on the reconstructed energy
- Energy reconstruction only weakly dependent on the interaction model
- This analysis is weakly dependent from out-FV neutron bkg and secondary neutrons as they would prefer high dp_T values

What about a test beam program ?

- We aim to very precise measurements of nuclear effects

- Should we think about a test beam program already now ?

- Characterization of detector response to low-momentum muons and pions (e.g. Osaka University) ?

- Neutron test beam with bigger prototype to measure secondary neutrons for constraining SI ?

    - ✦ Beam test in Los Alamos can tell us a lot about what we can do

- Any suggestion is welcome

Summary of the possible new event samples

- List of possible event samples we may develop with higher priority
  - ✦ CC NuMu 4pi Inclusive —> first milestone with ND280 upgrade data
  - ✦ CC NuMu 4pi Exclusive —> almost in // —> first upgrade samples in ND-OA
  - ✦ CC NuE 4pi Inclusive / Exclusive —> ND280up shower reconstruction performance is important
  - ✦ Vertex Activity —> model comparison / hybrid (tracks + calorimetric) energy reconstruction
  - ✦ CC NuMu 4pi Low momentum Muon sample —> Constrain Eb
  - ✦ STV analysis —> make it ready for ND-OA
  - ✦ CC NuMu 4pi + Neutron selection —> multiplicity and ToF
  - ✦ STV+neutrons —> NuBar flux constraint
  - ✦ Many other things, e.g. pion resonance, NCE, etc.
- First data coming in 2022
- Feedbacks and ideas are very welcome