Note: This file contains five separate 3DST talks.

Report on the 3D-projection Scintillator Tracker (3DST) as part of the DUNE Near Detector Concept Study

1. Overview – C. K. Jung, Stony Brook
2. Simulation and Characterization – G. Yang, Stony Brook
3. Angular Resolution Studies – K. Wood, Stony Brook
4. Physics Studies – S. Manly, Rochester
5. R&D – D. Sgalaberna, CERN

Report on the 3D-projection Scintillator Tracker (3DST) as part of the DUNE Near Detector Concept Study

Direct Contributions from:
D. Sgalaberna (CERN), R. Gran (U. of Minnesota, Duluth),
S. Fedotov, A. Khotjantsev, Y. Kudenko, A. Mefodev, and O. Mineev (INR),
H. Su (U. of Pitzburgh), Tejin Cai, , S. Manly, A. Olivier (U. of Rochester),
C. McGrew, J. Palomino, Kevin Wood, G. Yang (Stony Brook U.),
M. Kordosky, E. Valencia (College of William and Mary)

Overview

Chang Kee Jung, Stony Brook U.

4th DUNE ND Workshop
March 23, 2018
Fermilab,Batavia, Illinois

Conveners Questions
(to be answered at this ND Workshop)

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- Q-A: What is the angular/energy resolutions of the 3DST for photons, muons and electrons?
- Q-B: How well can it do electron-neutrino scattering?
- Q-C: How big does the 3DST target have to be do reasonably well with pi0 topologies and neutrons?
- Q-D: Can it do something with neutron counting/angles?
- Q-E: Does it have to be in the B-field?
- Q-F: What is the complementary physics to the other trackers that can be addressed with the 3DST?

3DST Report
(DUNE Docdb #7686)

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Report on the 3D-projection Scintillator Tracker (3DST) as part of the DUNE Near Detector Concept Study

- Answers all conveners' questions
  - Continuing work to refine answers
- Contains additional materials
  - Synergy between DUNE 3DST and T2K SuperFGD, and Potential U.S.-Japan Cooperation funding
  - R&D Status
- Signed by 35 members from 12 institutions in 4 countries and CERN
  - BNL; Chung-Ang, Korea; CERN; Lisbon, Portugal; LSU; Minnesota, Duluth; Pittsburgh; Rochester; Pennsylvania; Stony Brook; INR Russia; and William&Mary

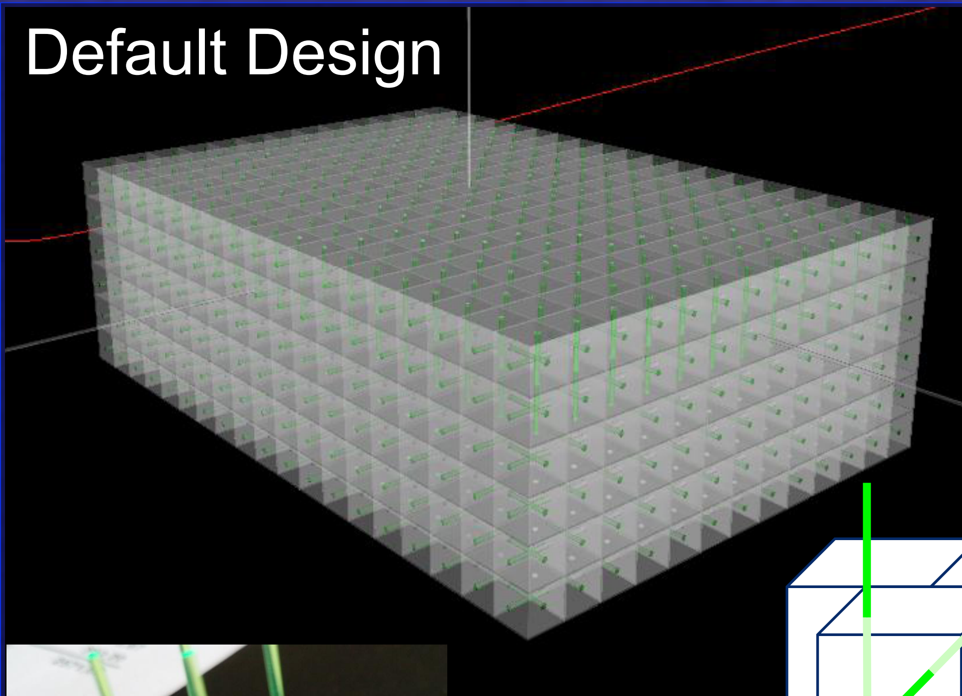
3DST Talks

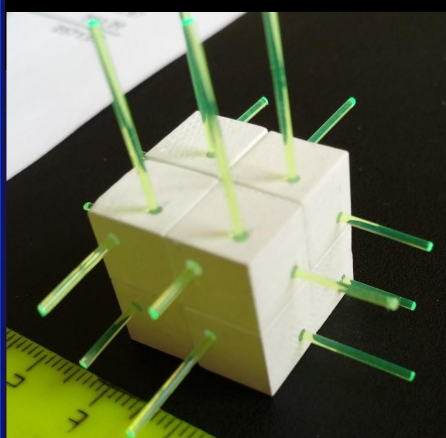
- Overview - ckj
  - ¬Introduction: General layout and design
  - ¬Statistics
  - ¬Synergy between DUNE 3DST and T2K SuperFGD, and potential US-JAPAN cooperation funding
- Simulation and Characterization - G. Yang
  - ¬Detector simulation
  - ¬Tracking efficiency
  - ¬Answers to: Q-A (energy resolutions), Q-C and Q-E (Charge separation efficiency)

3DST Talks

- Angular Resolution (Answer to Q-A) - K. Wood
- Physics studies - S. Manly
  - ¬Answers to Q-B, Q-D, Q-E (Wrong sign background and low energy muons and CP violation), Q-F
  - ¬Selected physics processes
  - ¬Other geometries
- R&D - D. Sgalaberna
  - ¬Detector R&D and beam test results

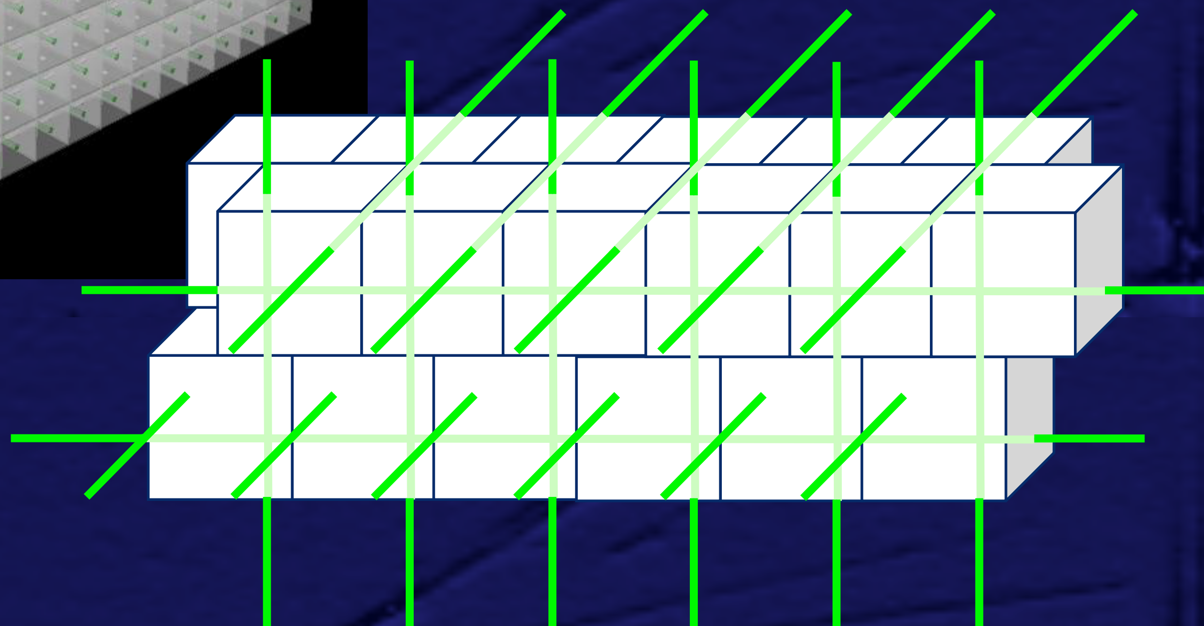
SuperFGD/3DST Design





1x1x1 cm^3 scintillator cubes

Possible “Staggered” Design



A Possible DUNE ND
Hybrid-Detector Configuration w/ 3DST

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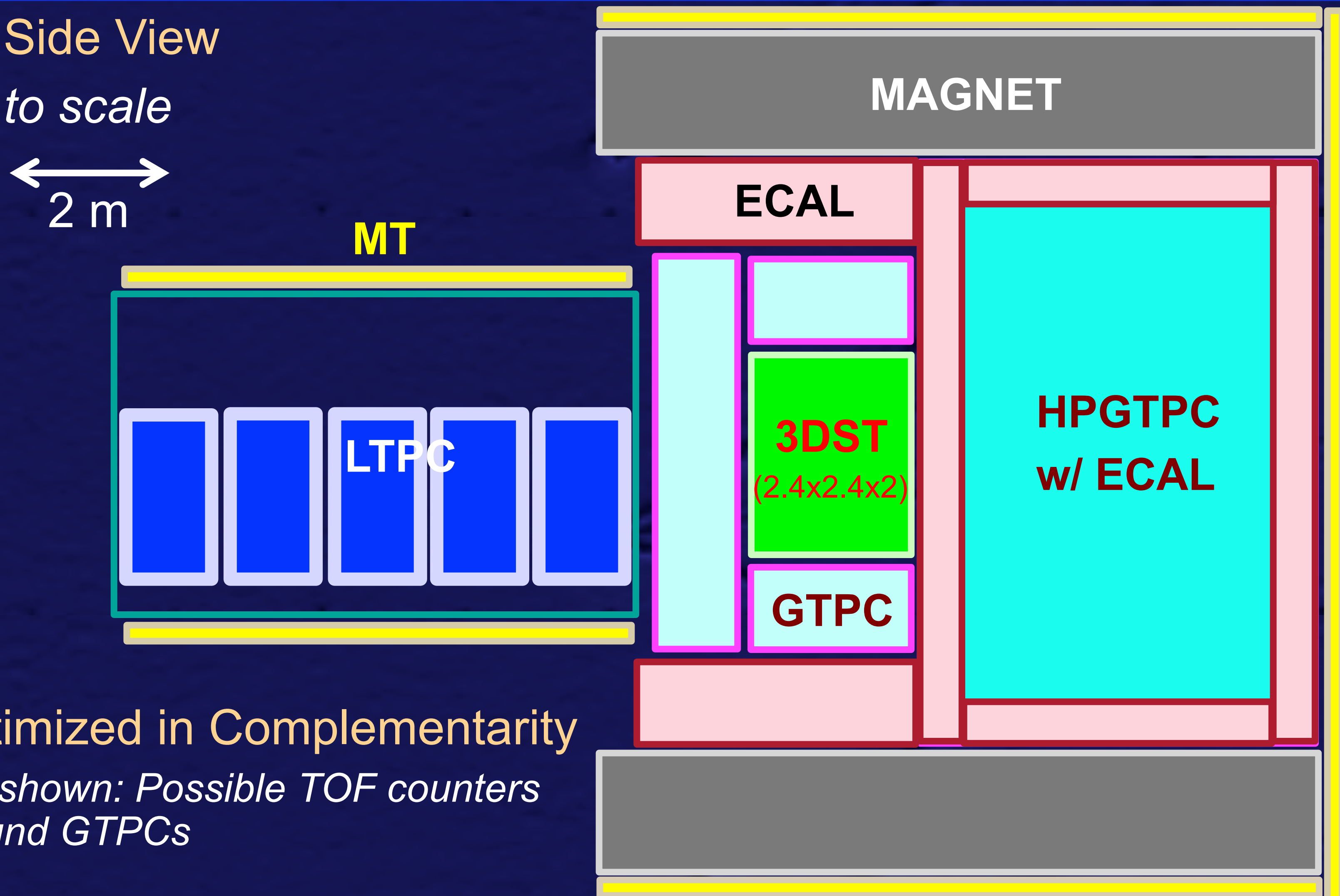
Side View

to scale



Optimized in Complementarity

Not shown: Possible TOF counters around GTPCs

Summary of 3DST Features

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- A large statistics sample w/ true 4π coverage & B-field
  - e.g.) possible differentiation of various 2p2h models
    - Martini vs Valencia (Nieves) vs GiBUU
- A fine-grained detector w/ good spatial resolution (~3 mm)
- A transparent connection (directly comparable) to other scintillator experiments (MINERvA, NOvA and T2K)
- A functionally identical detector to the T2K SuperFGD
  - T2K's narrow band, low energy (peaked at ~0.6 GeV) beam
    - Near the DUNE 2^{nd} oscillation maximum, critical for CPV measurement
    - Reduced feed-down background from high energy interactions

Summary of 3DST Features

- A fast detector (< 1 ns timing resolution)
  - ¬Less backgrounds
- A detector w/ substantial sensitivity to neutrons
- Containment of substantial fraction of photons from π^0 decays

For DUNE oscillation analysis, some level of reliance on neutrino interaction models is unavoidable!

- Different ND and FD
  - Magnet field in ND Tracker
  - High flux in ND → smaller drift region LArTPC
  - Limited ND LArTPC muon kinematic coverage
  - Different detector efficiencies

SuperFGD/3DST NUINT Model Tuning

DUNE
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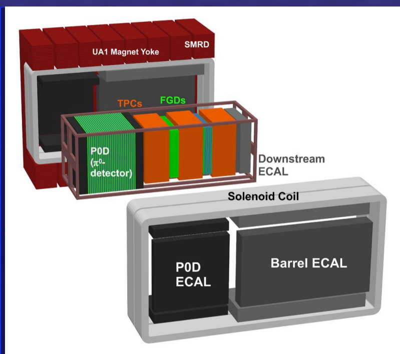
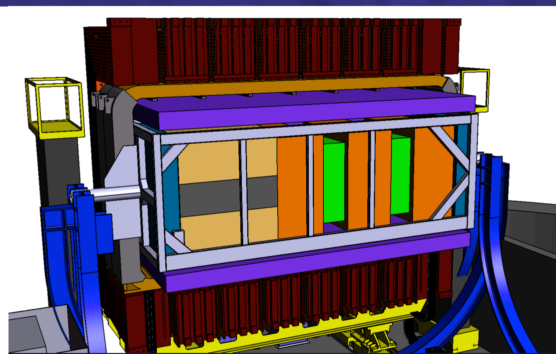
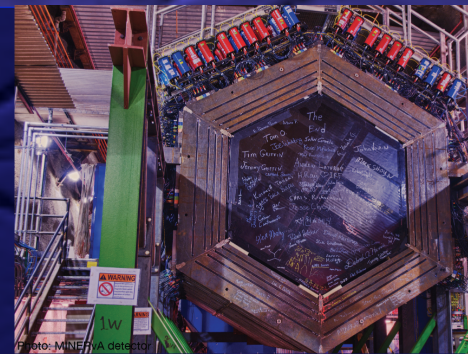


T2K ND280

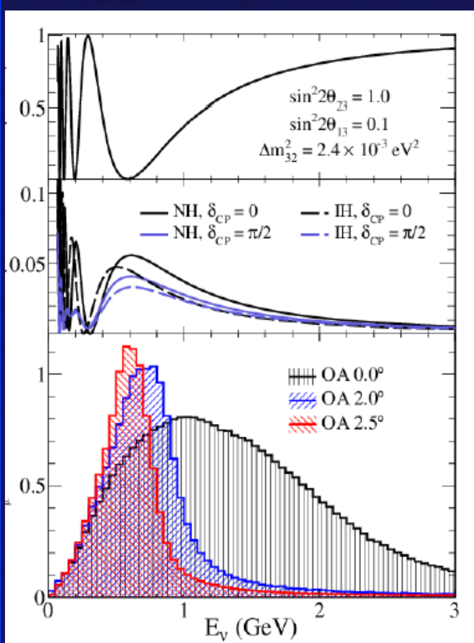


T2K ND280 Upgrade

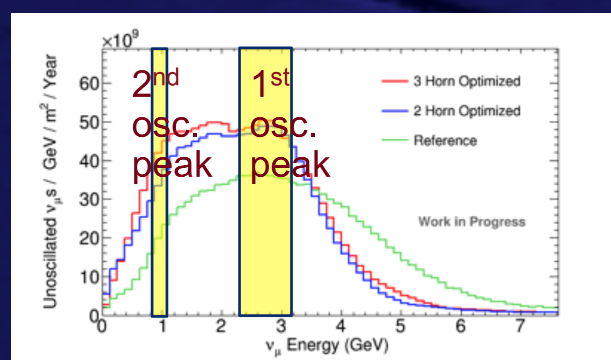


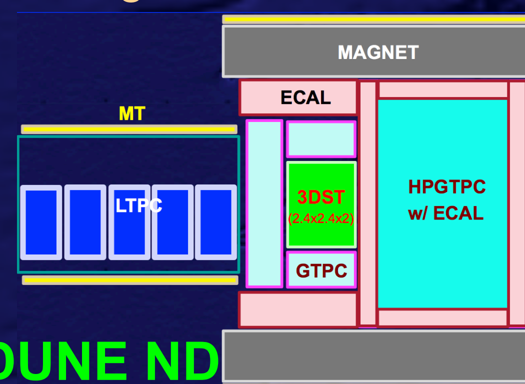
MINERvA

NOvA ND



- Huge amount data on scintillator target (~2027)
  - Precision xs measurements & NUINT model tuning
- T2K osc. peak ~600 MeV → ~2nd osc. peak of DUNE
  - SuperFGD identical to 3DST (little high E feed down BG)





DUNE ND

Statistics – Event Rates

Channel	FHC	RHC
ν_μ CC inclusive	8.4×10^6	3.1×10^6
CCQE	1.8×10^6	1.0×10^6
CC π° inclusive	2.4×10^6	0.6×10^6
NC total	3.0×10^6	1.3×10^6
ν_μ-e^- scattering	960	660
ν_e CC inclusive	1.6×10^5	0.35×10^5

- Default detector size: 2.4(w) x 2.4(h) x 2.0(d) m^3

  ¬ 12.2 t

- GENIE w/ DUNE flux @80 GeV, 1.06 MW, 3-horn optimized
- 1-yr sample (1.46 x 10^{21} POT)
- Fiducial Volume: 25 cm veto region at each side (à la MINERvA)

  ¬ 5.7 t

US-Japan Proposal

- ~$500k proposal to build 25 x 25 x 25 cm^3 prototype in 2018

U.S. Collaboration Members			
No.	**Name**	**Affiliation**	**Position**
1	Elizabeth Worcester	Brookhaven National Lab	Scientist (PI)
2	Steve Kettell	Brookhaven National Lab	Senior Scientist
3	Thomas Kutter	Louisiana State U.	Professor (Co-I)
4	Martin Tzanov	Louisiana State U.	Associate Professor
5	Christopher Mauger	U. of Pennsylvania	Associate Professor (Co-I)
6	Vittorio Paolone	U. of Pittsburgh	Professor (Co-I)
7	Donna Naples	U. of Pittsburgh	Professor
8	Steven Manly	U. of Rochester	Professor (Co-I)
9	Kevin McFarland	U. of Rochester	Professor
10	Howard Budd	U. of Rochester	Research Scientist
11	Chang Kee Jung	Stony Brook U.	SUNY Distinguished Professor (Co-I)
12	Clark McGrew	Stony Brook U.	Associate Professor
Japanese Collaboration Members			
No.	**Name**	**Affiliation**	**Position**
1	Masashi Yokoyama	U. of Tokyo	Associate Professor (PI)
2	Akihiro Minamino	Yokohama National U.	Associate Professor (Co-I)
3	Takashi Kobayashi	KEK	Professor (Co-I)
4	Takeshi Nakadaira	KEK	Associate Professor
5	Toshifumi Tsukamoto	KEK	Associate Professor
6	Tsuyoshi Nakaya	U. of Kyoto	Professor (Co-I)
7	Atsuko Ichikawa	U. of Kyoto	Associate Professor

The SuperFGD/3DST Group (14 institutions, 5 countries + CERN)

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CERN

Japan
KEK
U. Kyoto
U. Tokyo
Yokohama National U.

Korea
Chung-Ang U.

Russia
INR

Switzerland
U. Geneva

USA
BNL
Louisiana S. U.
Stony Brook U.
U. Pennnsylvania
U. Pittsburgh
U. Rochester

Some Concluding Comments

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- 3DST will provide high statistics sample w/ full 4π coverage for precision xs measurements and neutrino interaction model tuning
  - Contribute to reduce model dependent sys. errors
    - Especially, in the beginning of the data taking and combined with T2K SuperFGD
  - Provide a large number of thesis topics
    - Critical for the vibrancy of the collaboration
  - Could contribute to the advancement in nuclear physics
- Strong interest in the international community
  - Synergy between 3DST and SuperFGD
    - Efficient use of community resources

Some Concluding Comments

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- The 3DST group has produced a DUNE Docdb report (#7686)
  - ¬Answered all conveners' questions at some level (not perfect)
  - ¬Greatly benefited from the work at MINERvA and T2K
  - ¬Work still on-going to improve the studies

Considering the difficulties we face in detailed simulation, full event reconstruction and evaluating impact on the δ_{CP} measurement of various detector designs and variations, we should position ourselves erring on the "over-designing" side than erring on the "under-designing" side unless the cost is prohibitively large.

The End

3DST simulation and characterization

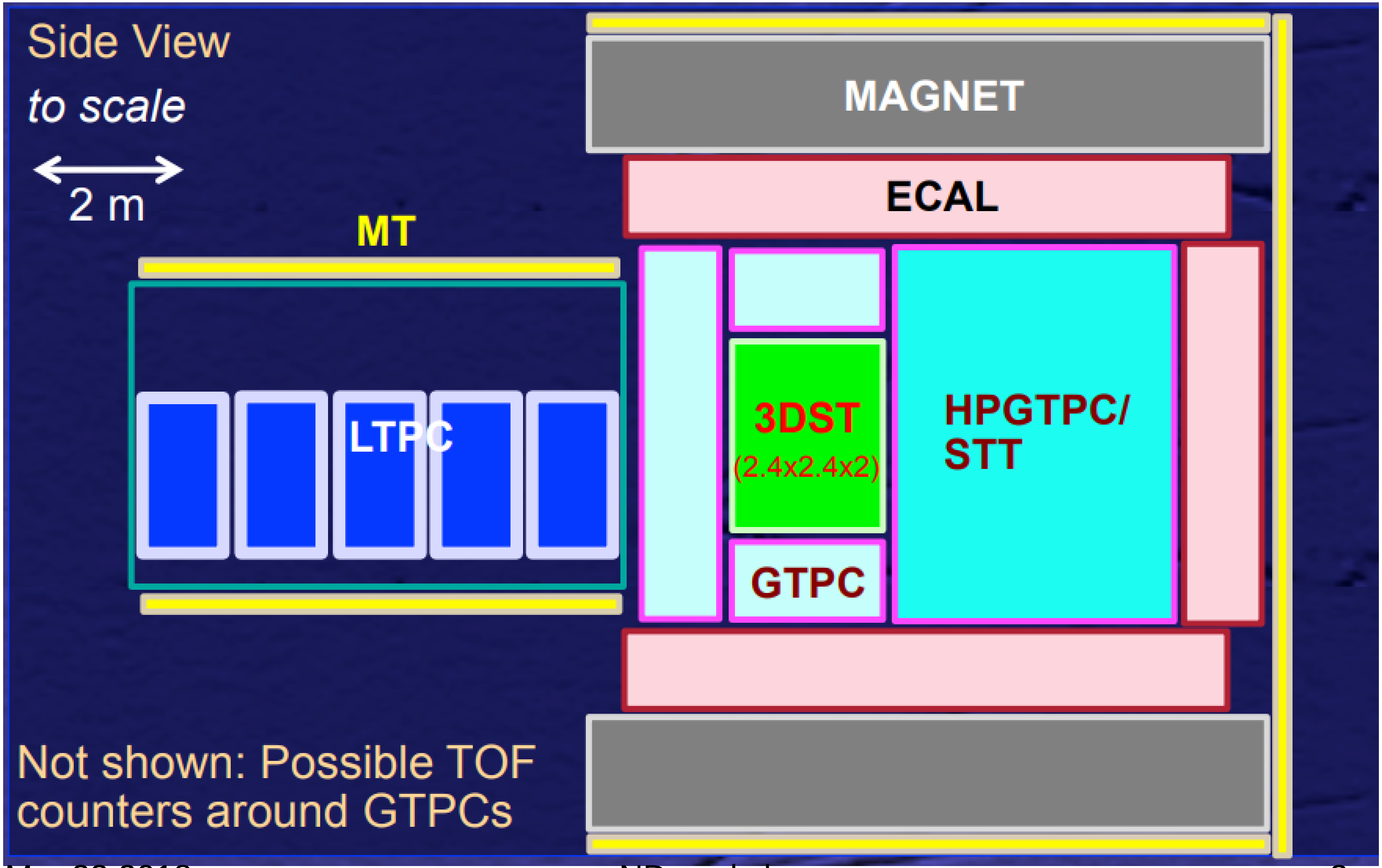
Guang Yang (Stony Brook University)
On behalf of 3DST working group

Outline

- 3DST simulation flow

- Answers to 3DST questions
    - Tracking efficiency and muon containment
    - Energy resolution → Q-B
    - Detector size → Q-D
    - Charge separation and wrong-sign background → Q-E

Possible ND design



Simulation framework

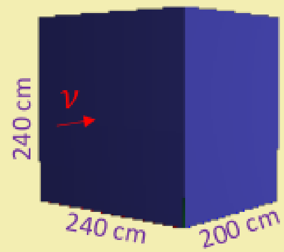
Stony Brook University

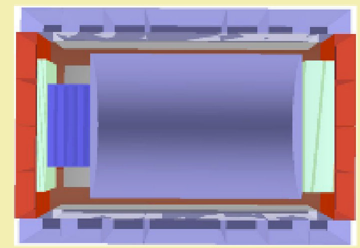
Dune-ND-GGD

https://github.com/gyang9/dunendggd

Generate (.gdml) geometry files and build detector complex

Multiple layers:
Boxes → row → plane → 3D

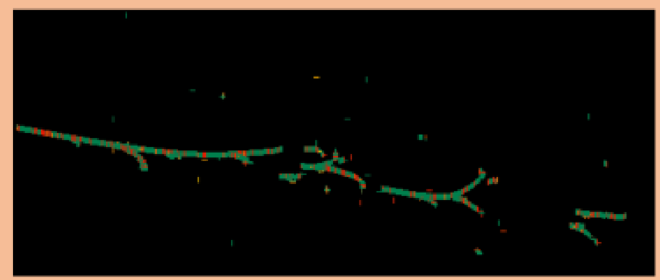




edep-sim

https://github.com/ClarkMcGrew/edep-sim

Geant4-based simulation of particle interactions inside the detector volume

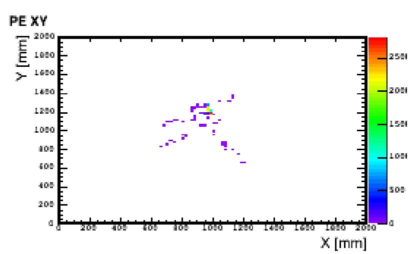


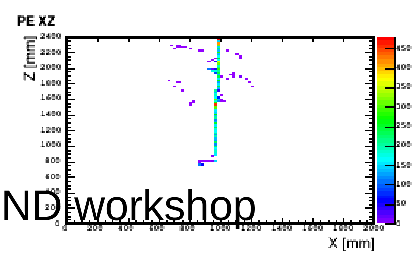
3DSTSim

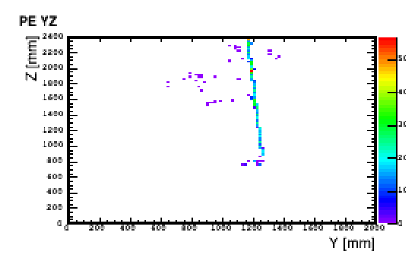
https://github.com/gyang9/3DSTSim

Hit simulation

- 1 cm scintillator cube
- Birk's saturation (dedx)
- PE yield in scintillator
- light collection in each fiber
- light attenuation in fiber (11926 mm)
- MPPC efficiency (0.38)
- ADC response (including noise)







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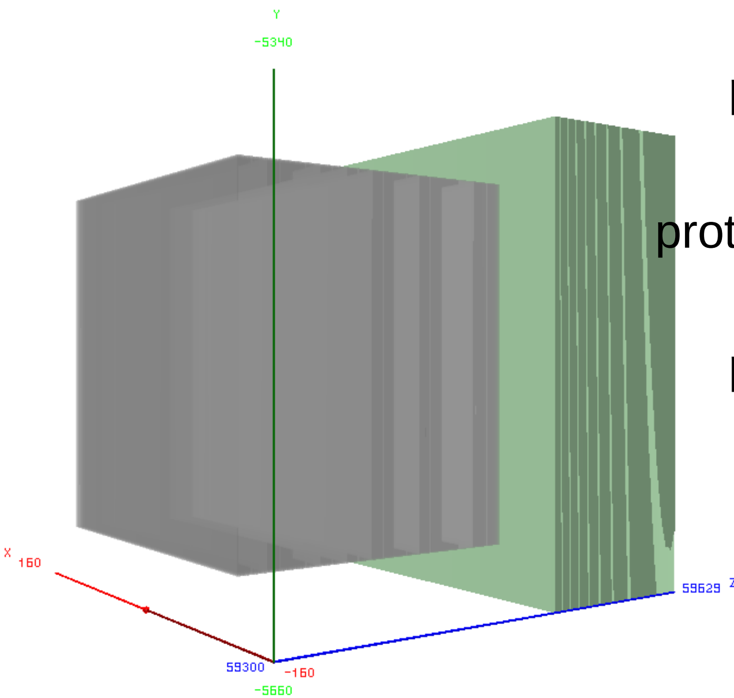
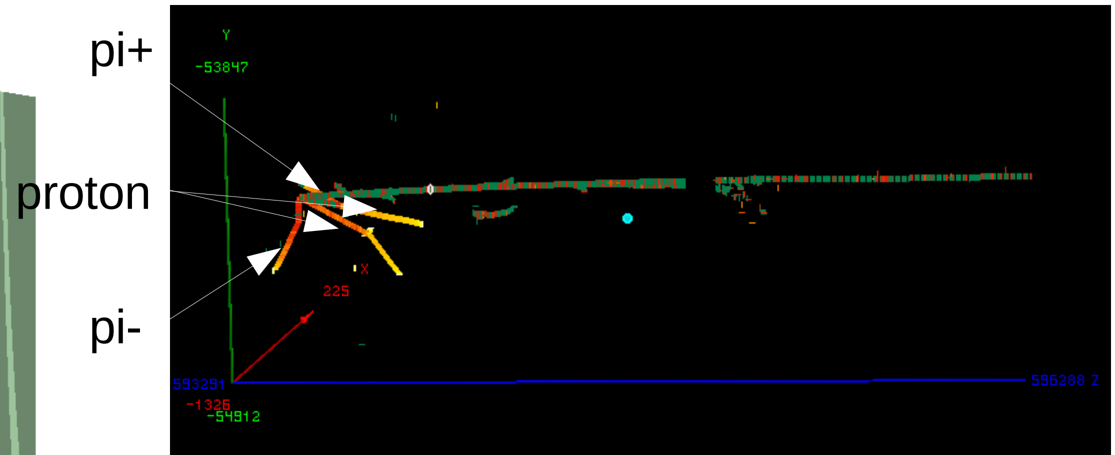
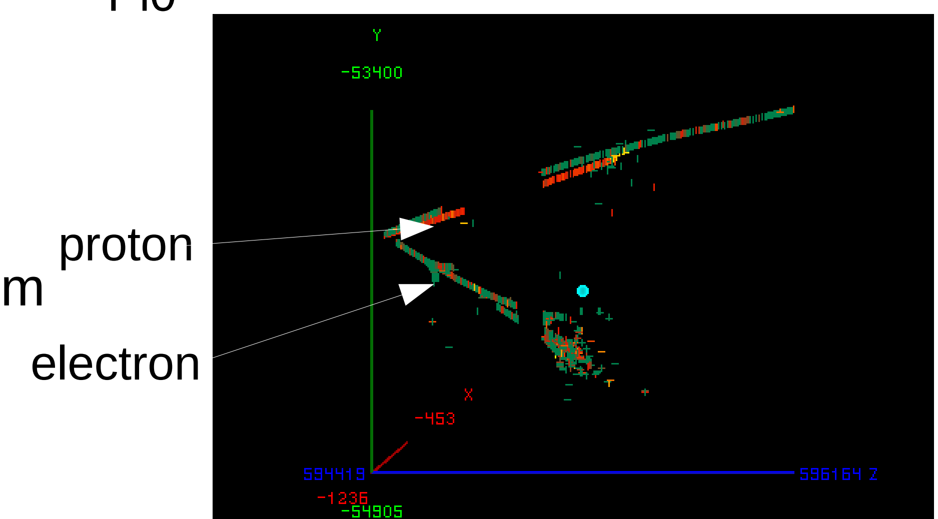
3DST Geometry and event generation



Pion production



Pi0

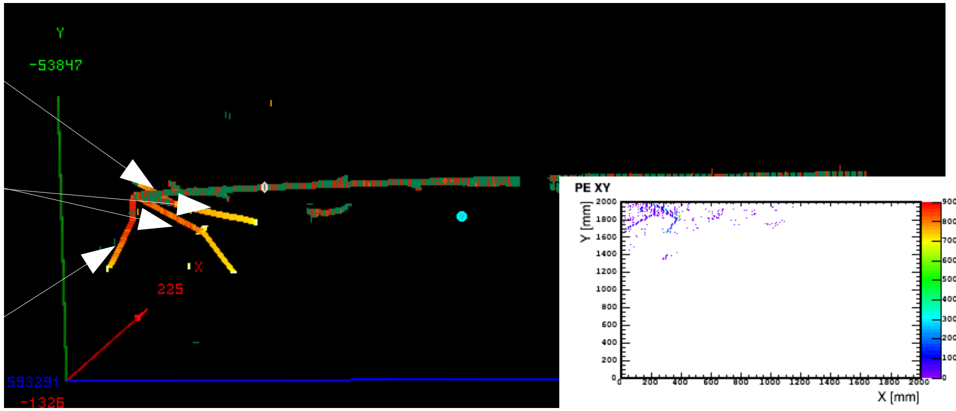


3DST : 2.4 x 2.4 x 2 m^3
ECAL : 1.75mm lead layer and 1cm scintillator layer
(radiation length ~ 3.5 cm)

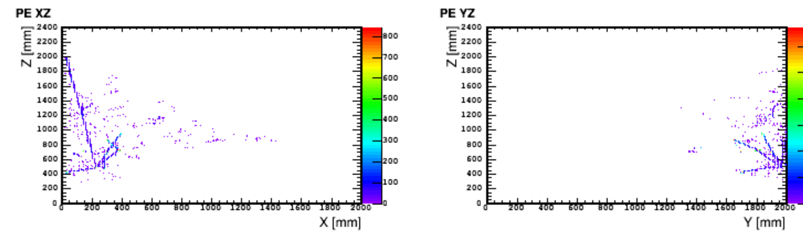
DUNE Geometry and event generation

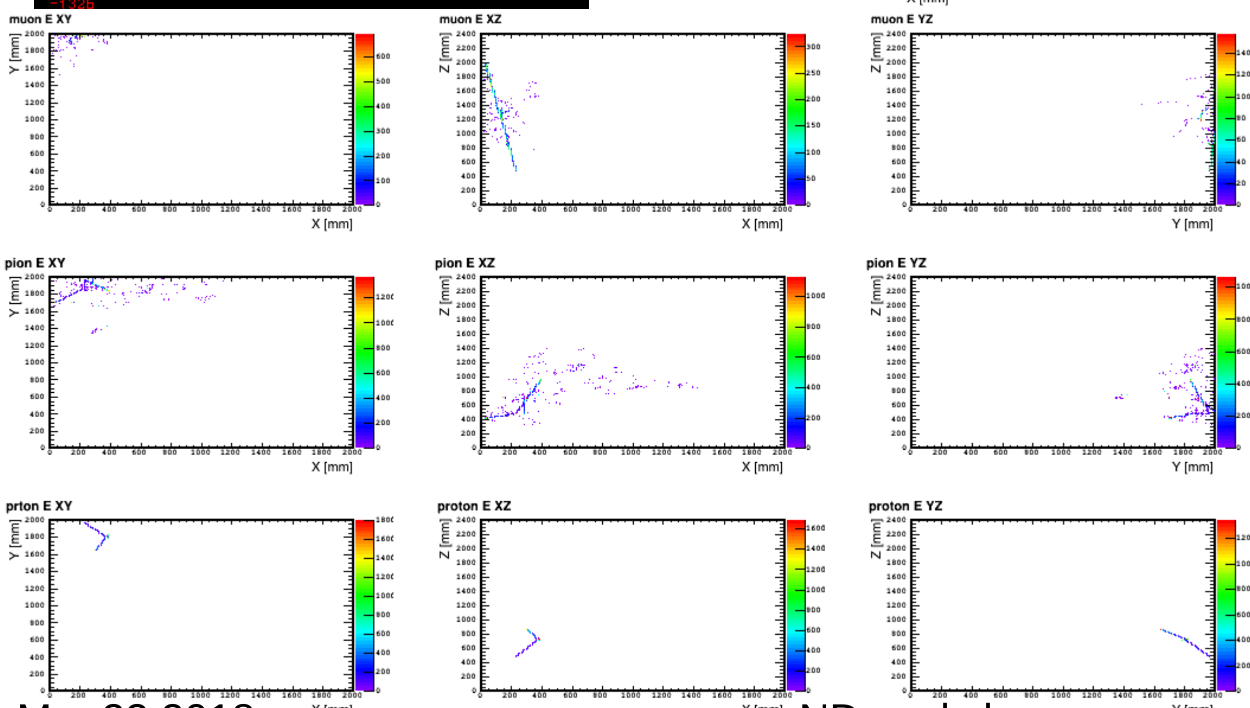
pi+

pi-



Hit simulation: energy deposit
→ light yield → shadowing
→ PE calibration → MPPC efficiency





- Events go into cube hits.
- Separate particles based on true info.
- Do analysis on different events.

Tracking efficiency

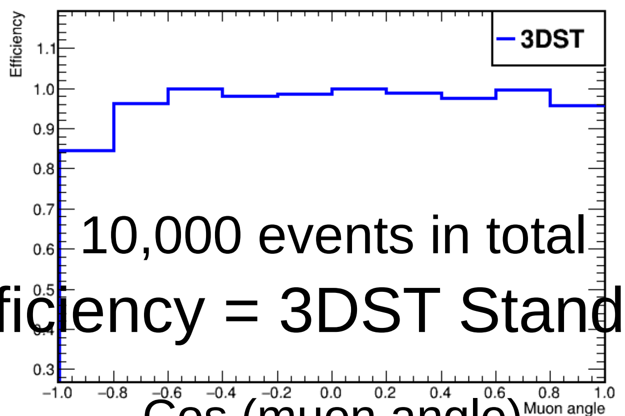
Stony Brook University

Defining the efficiency for muon CC events:

Cuts:

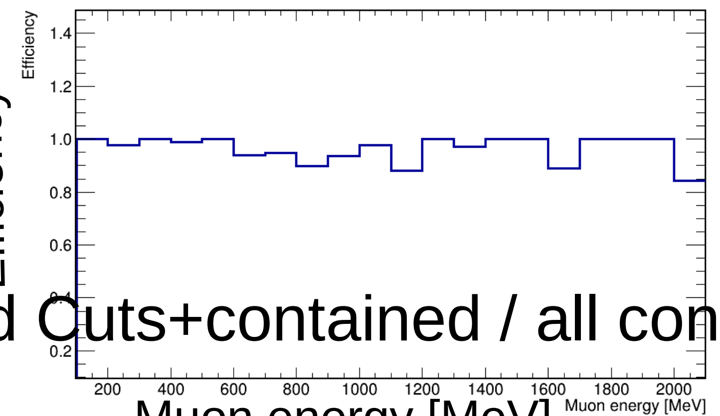
- Events that have two 2D projections that have at least 3 hits.
- All three 2D projections have at least 6 hits.
- second long track is separated from the longest one.

Efficiency



Cos (muon angle)

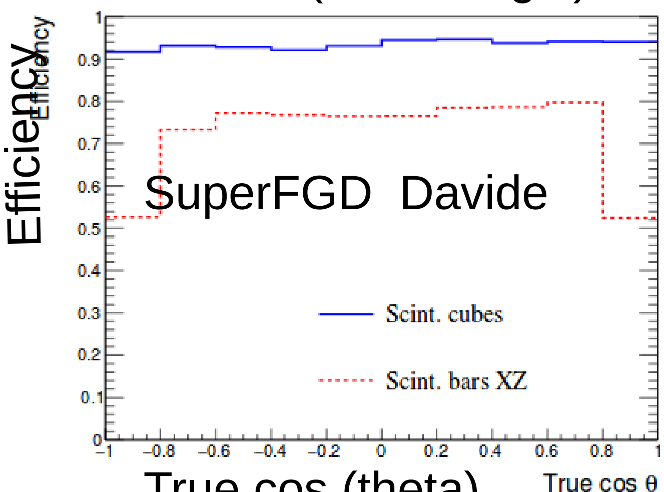
Efficiency



Muon energy [MeV]

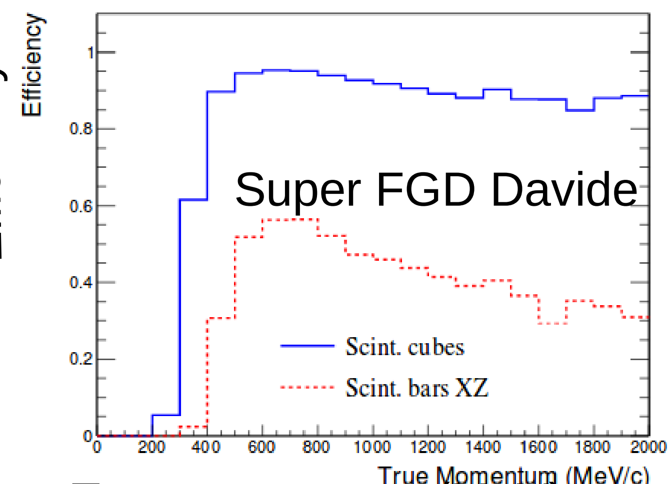
Efficiency = 3DST Standard Cuts+contained / all contained

Efficiency



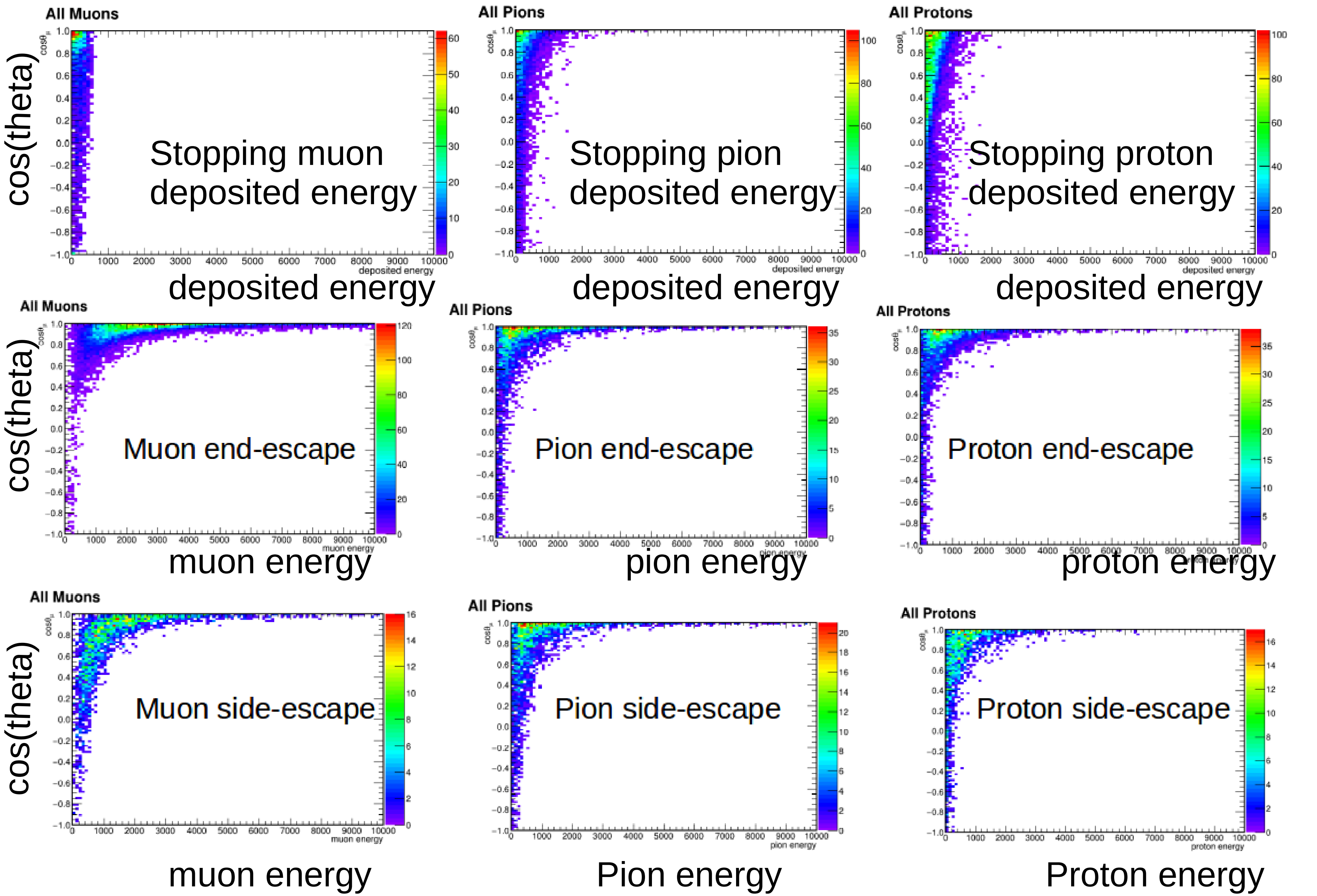
True cos (theta)

Efficiency



True momentum (MeV)

Event containment



Muon energy resolution Q-B

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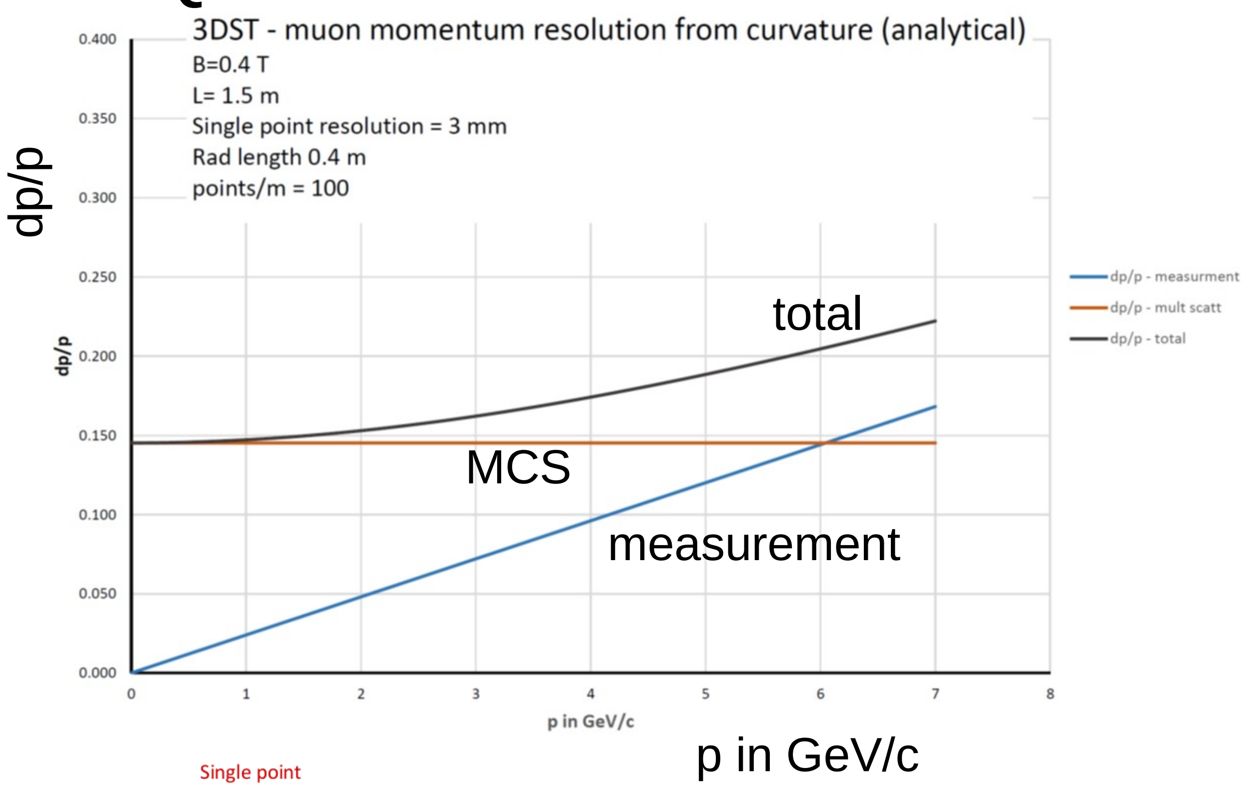


$$\left(\frac{\delta p}{p}\right)^2 = \left(\frac{\sigma_s p}{0.3BL^2}\sqrt{\frac{720}{N+4}}\right)^2 + \left(0.045\frac{1}{B\sqrt{LX_o}}\right)^2$$

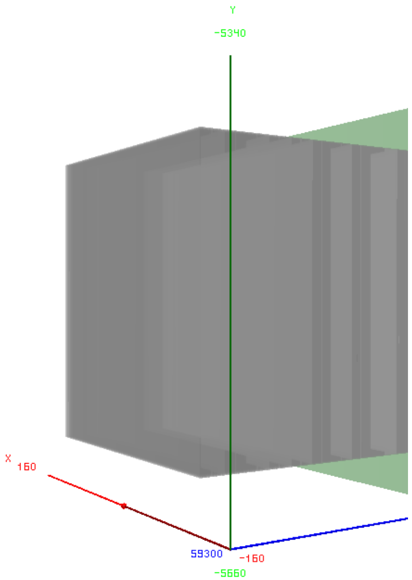
Single point measurement resolution (m); Track length in m; Track momentum in GeV/c; B field strength in T; Number of measurement points; Radiation length of medium (m)

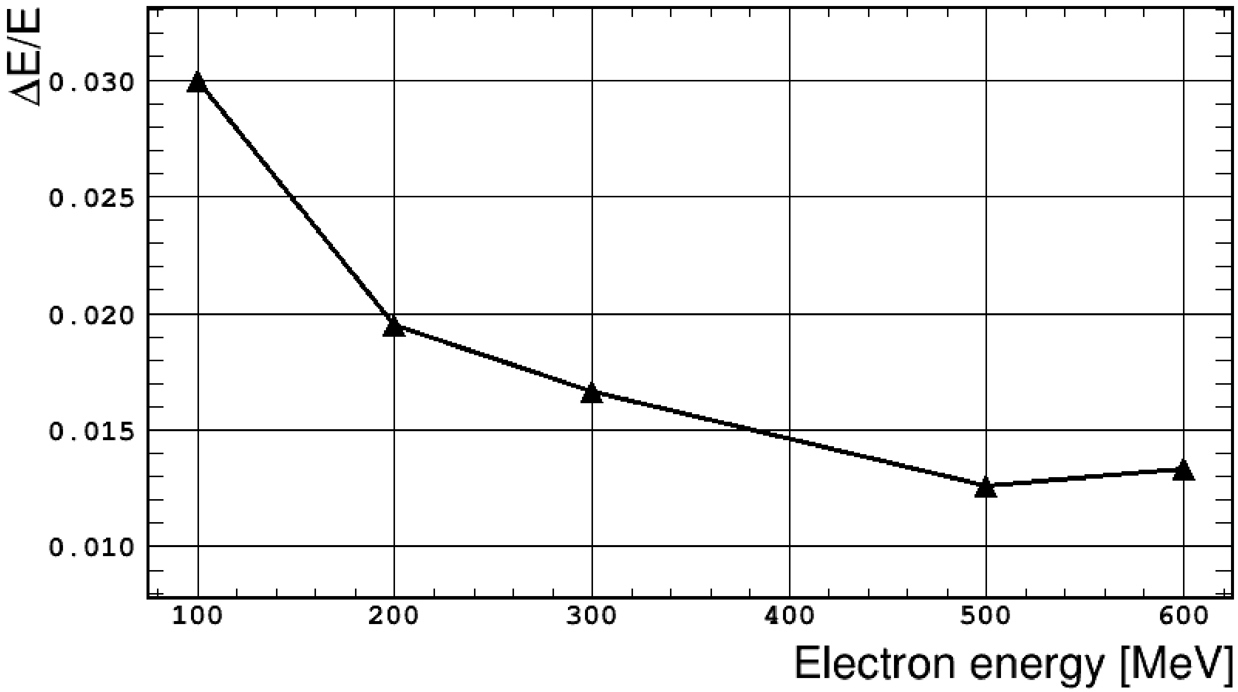
Measurement term; Multiple scattering term

- Should be done with bending curvature. The algorithm is still being developed. Use an analytical result here.
- Consider the point resolution and multiple scattering affecting the bending curvature.
- Analytical plot shows ~15% dp/p for contained part of muons.

Stony Brook University

Electron energy resolution Q-B



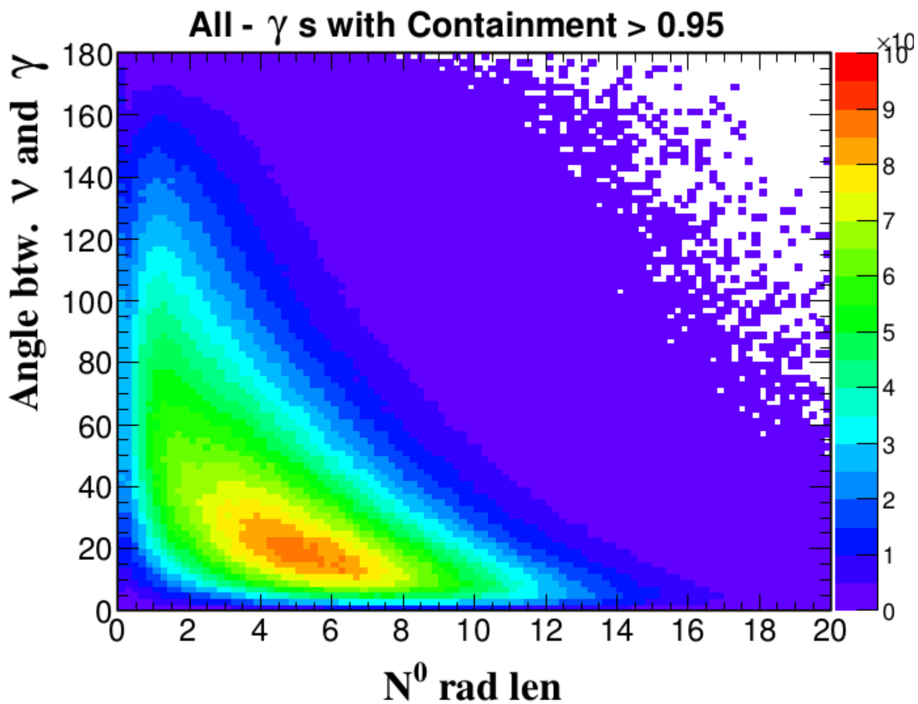


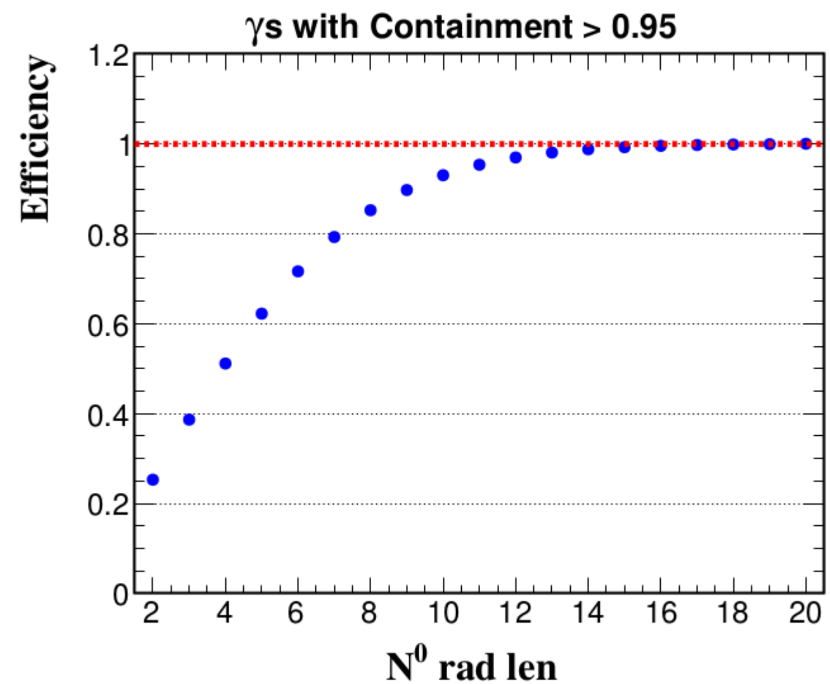
- Particle gun is used for various energy electrons.

- Only use 3DST (no ECAL) and this is done only for contained electrons so did not go to high energy. Will update with ECAL included.

- few percents resolution can be achieved for contained electrons.

Detector size → pi0 containment Q-D

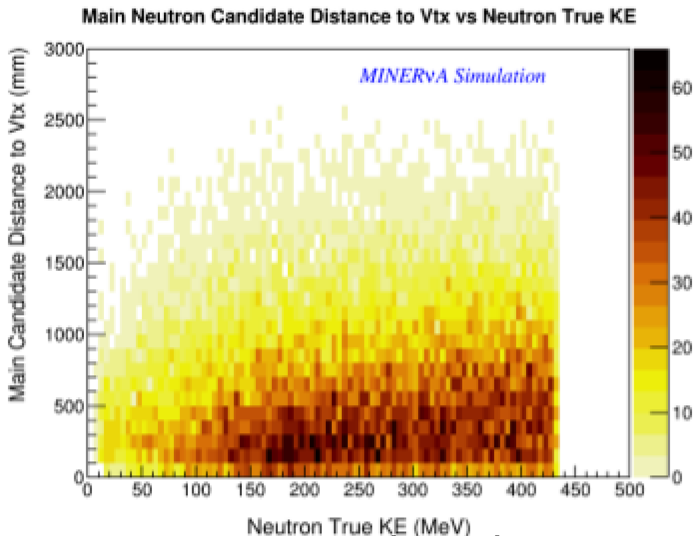




- A large detector is used to consider the containment of the pi0 (20 radiation length)
- Most of events that deposit > 95% energy can be contained with 10 radiation length.
- 5 radiation length contains 60% pi0 which deposits > 95% energy.

Detector size → neutron containment Q-D

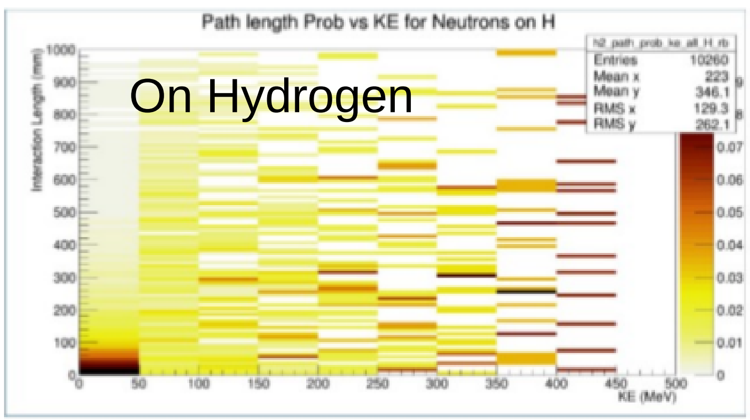
Candidate distance to Vtx (mm)



Neutron KE (MeV)

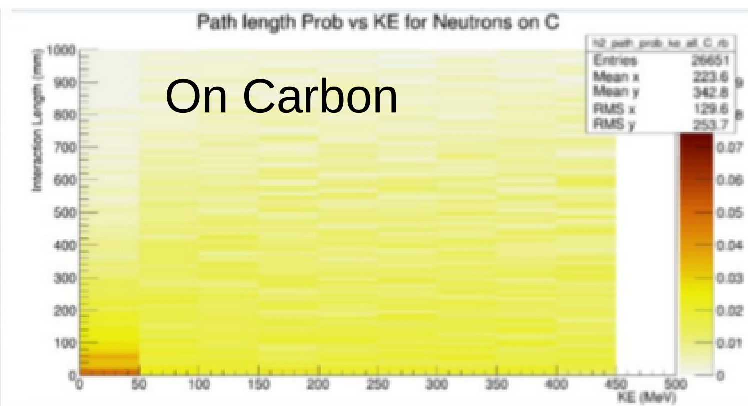
- Most energetic interaction (would leave energy deposit points) locations to the Interaction vertex. (left plot)
- All interaction locations to the vertex (many of them leave energy deposits) in bottom two plots.
- We don't have air gap, so 1 m will contain most of the interactions.

Interaction length (mm)



On Hydrogen

KE (MeV)

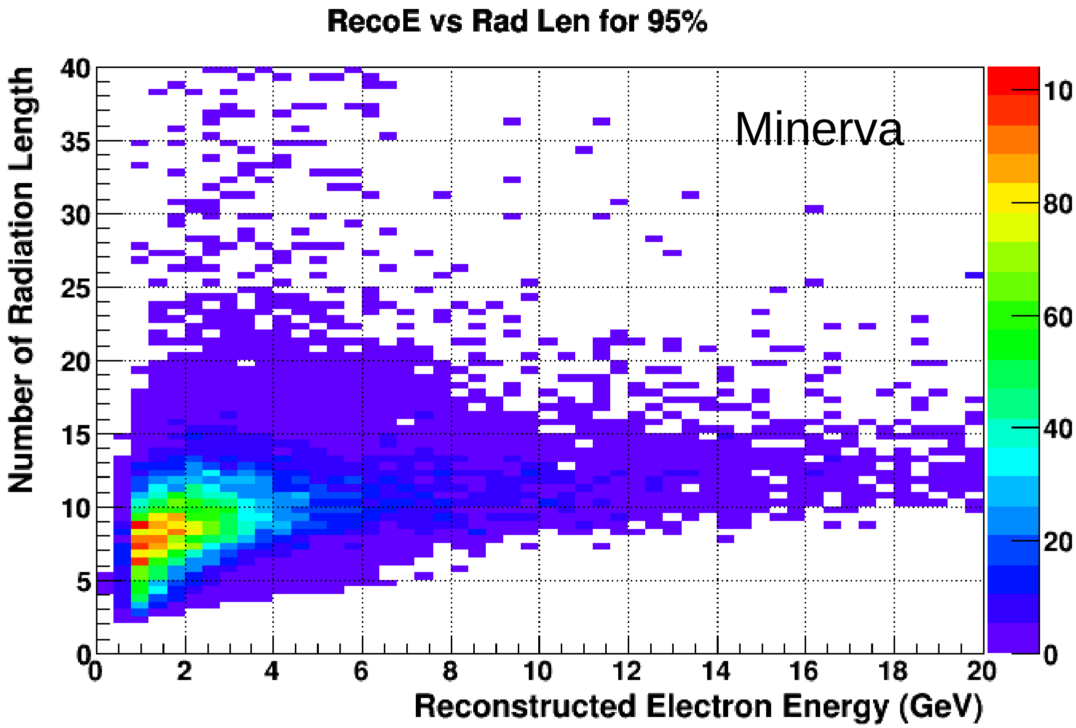


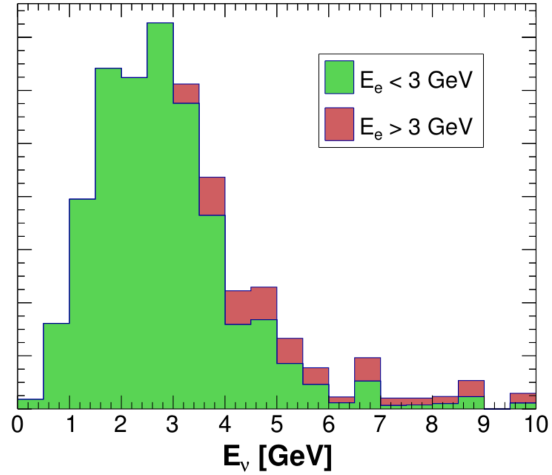
On Carbon

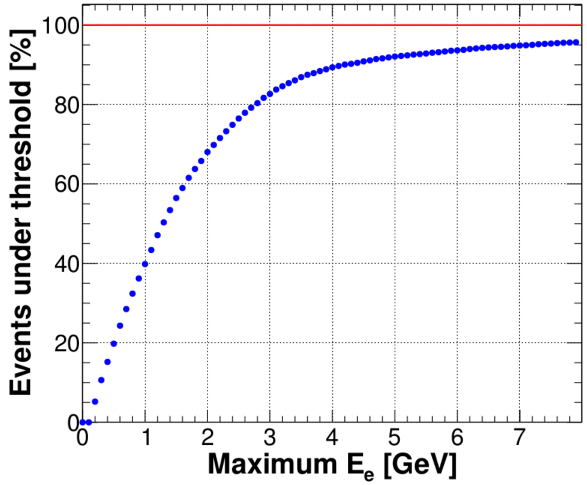
KE (MeV)

Detector size → nu+e electron containment

O-D





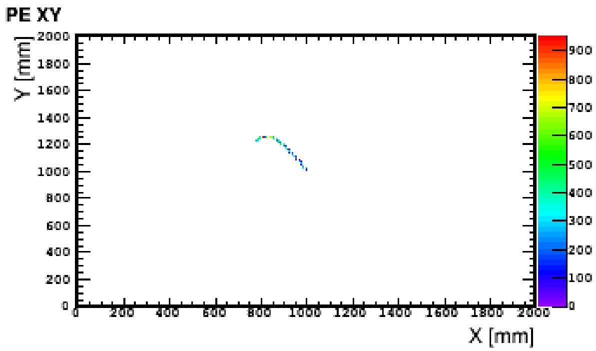


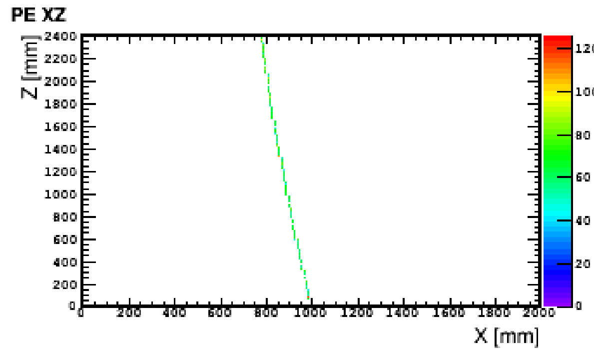
. Minerva is used as a reference.

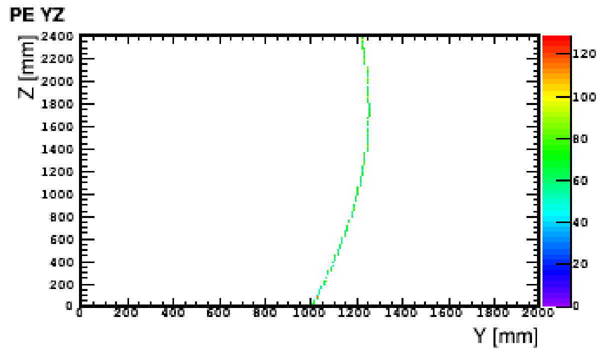
- Tested with B-field and without B-field cases: They are very similar.
- By measuring <3 GeV, we can cover large neutrino spectrum.

Charge separation Q-E

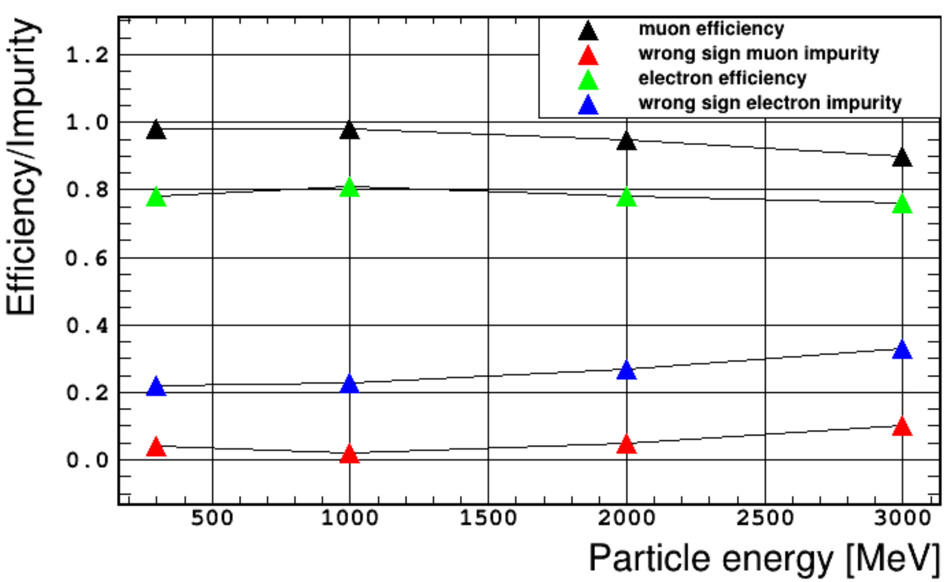
0.4 T B-field 1 GeV muon example



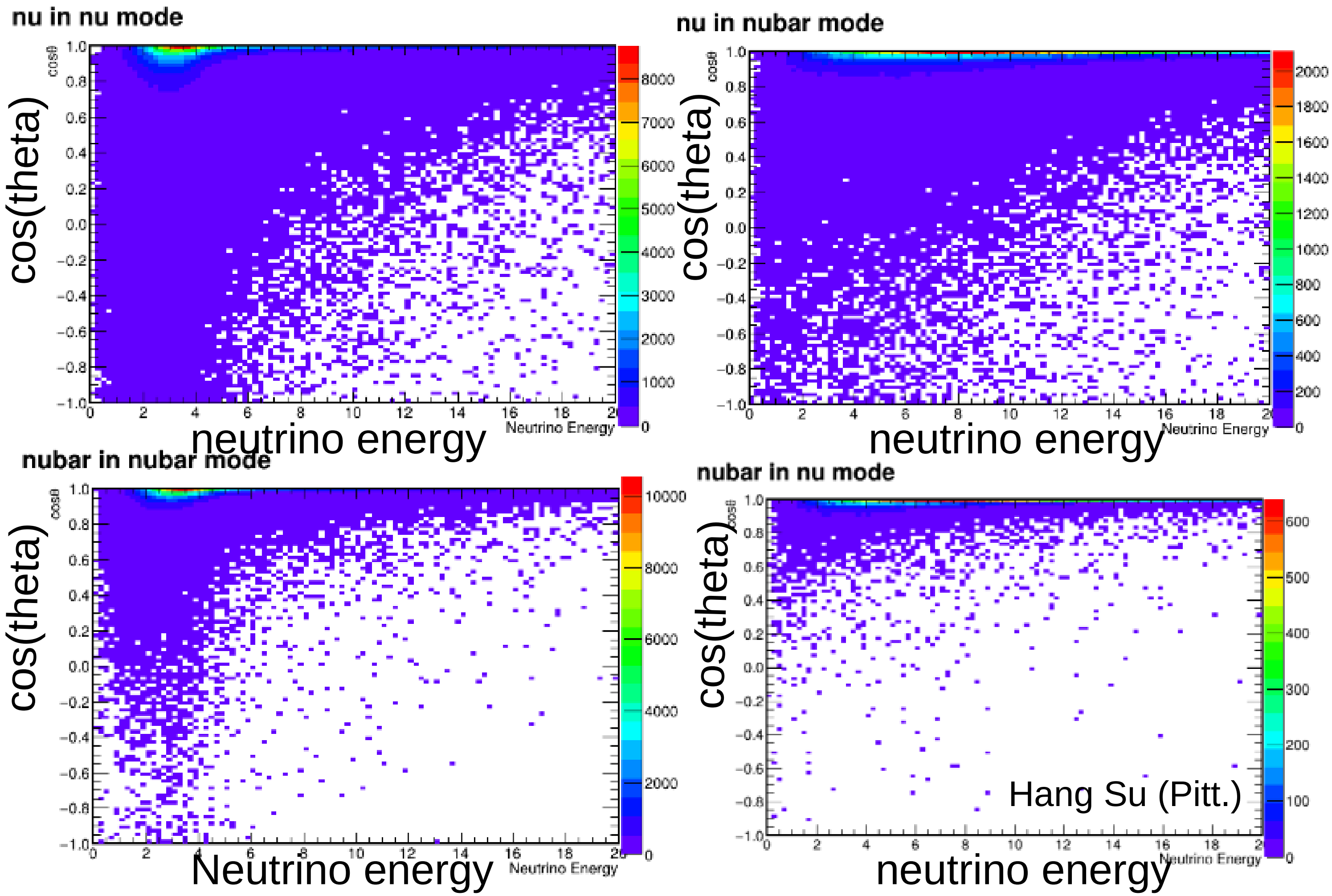




- Fit a straight line and count event number on sides to decide charge.
- More sophisticated algorithm will Do better.
- Muons can be separated clearly.
- Efficiencies are obtained by generating right sign events and impurities By generating wrong-sign events.



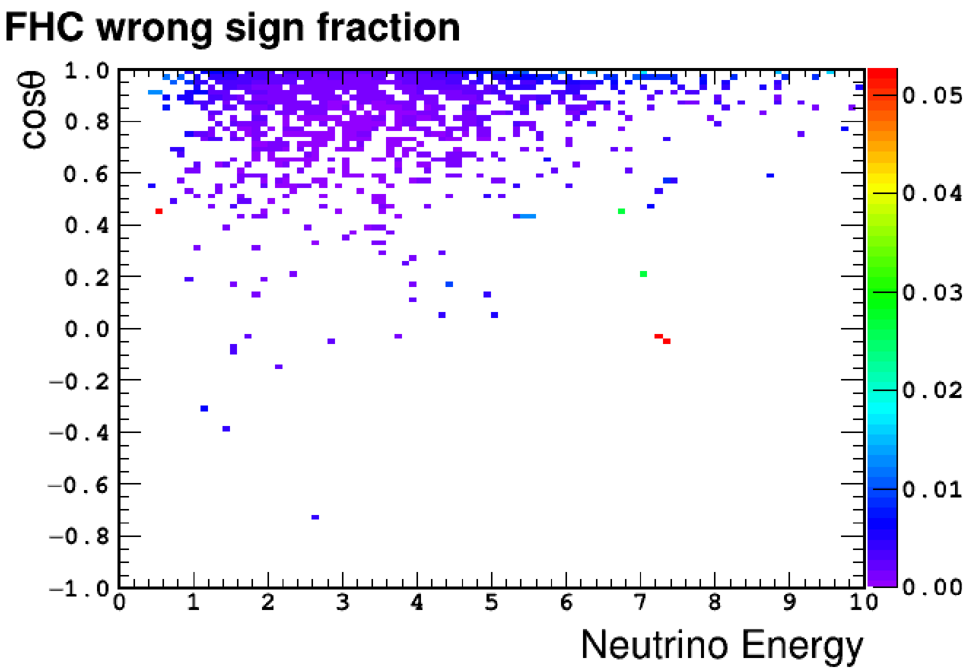
Wrong sign background

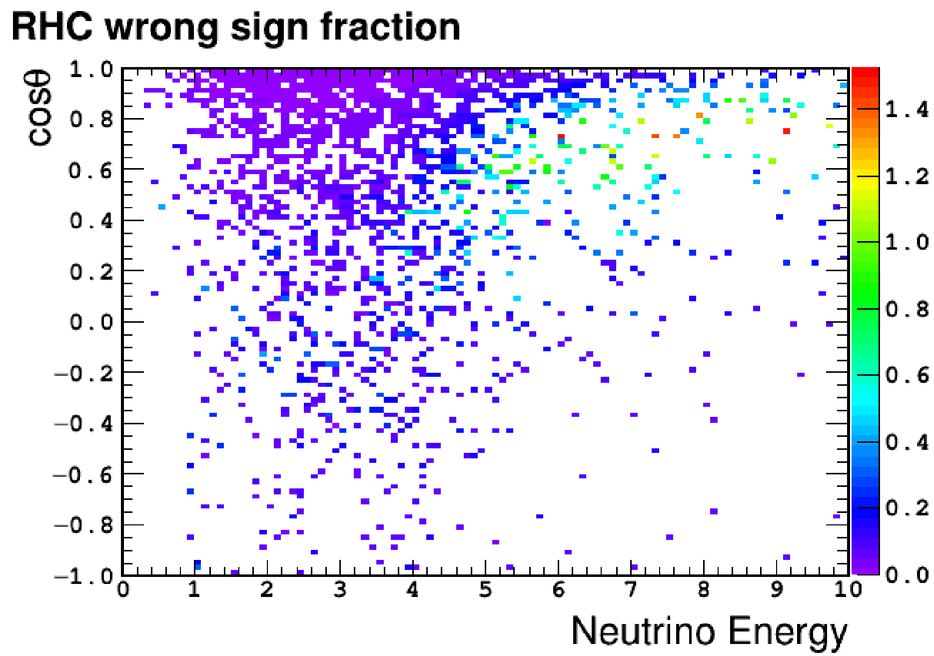


- Use charge separation efficiencies and purities to obtain wrong-sign background inside 3DST.
- NuMI LE fluxes.

Wrong sign background Q-E

$$\epsilon_b = \frac{F(b) \times containment(b) \times \epsilon_{reco.}(b) \times \epsilon_q(b)}{F(s) \times containment(s) \times \epsilon_{reco.}(s) \times \epsilon_q(s)},$$





- For escaping events, sign separation should be very good.
- For contained events, < 2% for FHC and <20% for RHC.

Conclusion

- 3DST has great angle coverage and low particle thresholds.

- Q-B: Particle containments and stopping energy resolutions have been estimated.

- Q-D: We propose a 2.4 x 2.4 x 2 m^3 3DST.

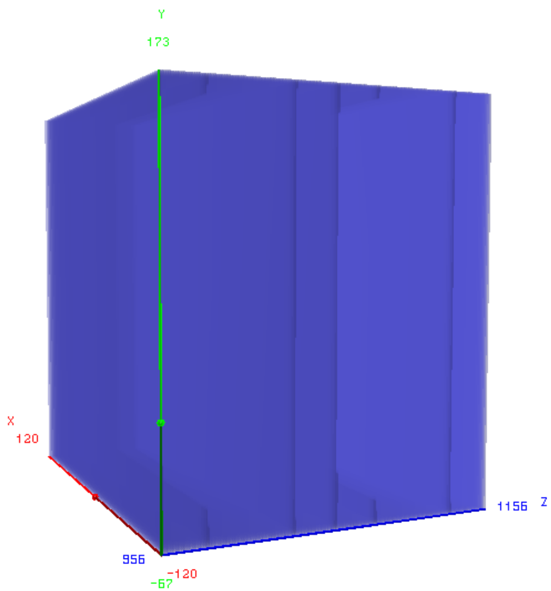
- Q-E: 3DST has good charge separation and low wrong-sign background.

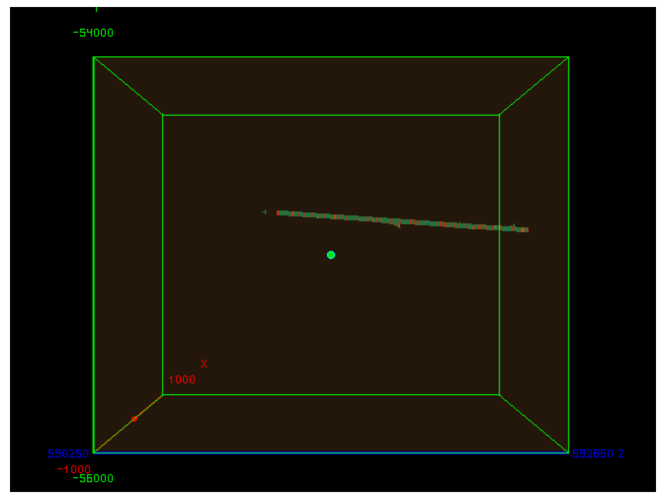
BACKUPS

3DST Geometry and event generation

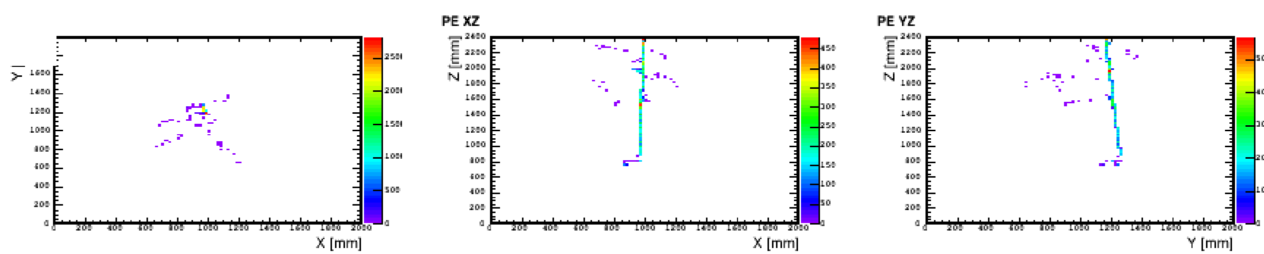
GENIE events

DUNENDGG → **EDEP-SIM** → **3DSTHIT-SIM**





Multiple layers:
Boxes → row → plane → 3D



3DST Angular Resolution

Kevin Wood

4th DUNE Near Detector Workshop

March 23, 2018

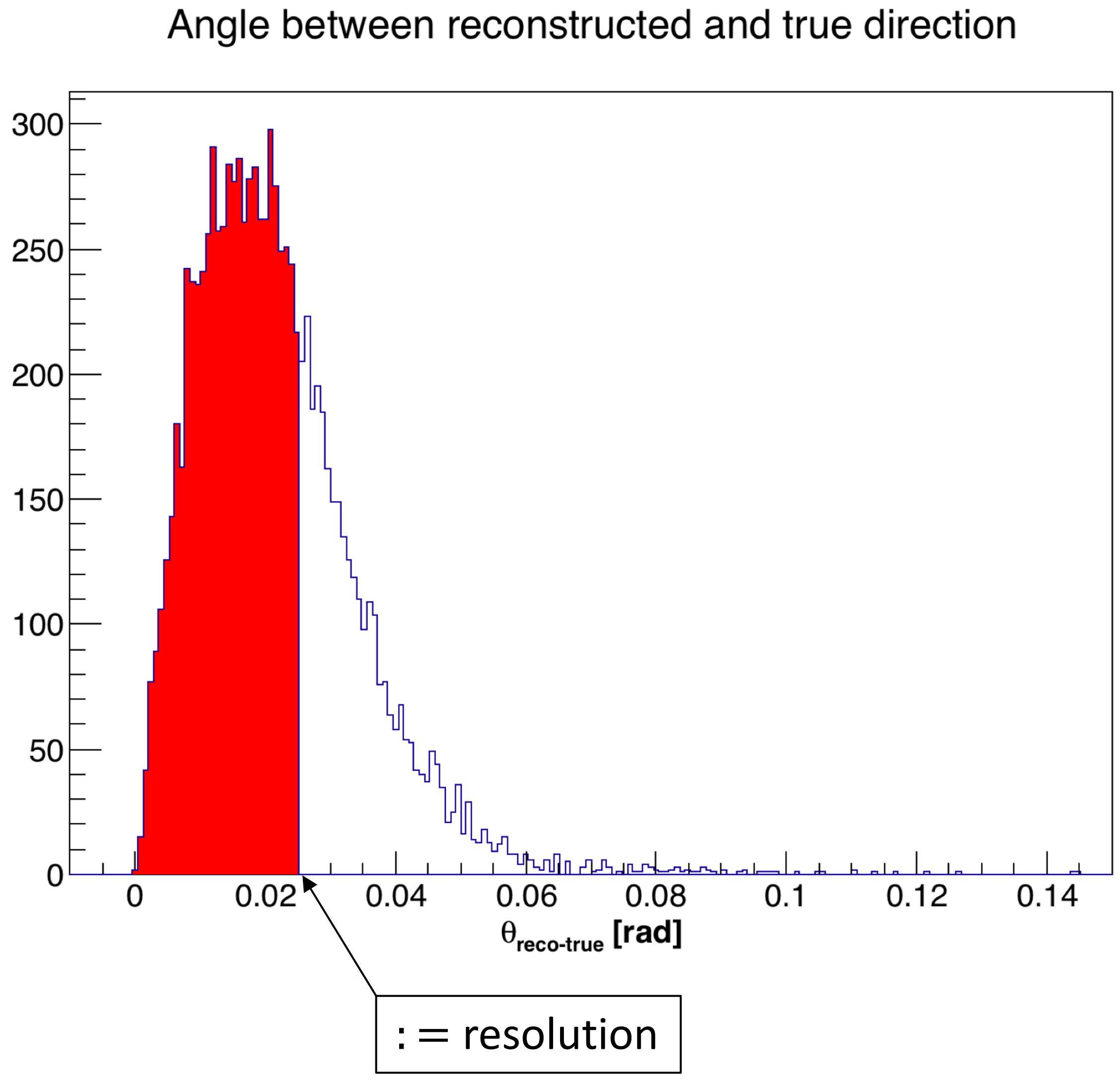
Stony Brook University

DUNE

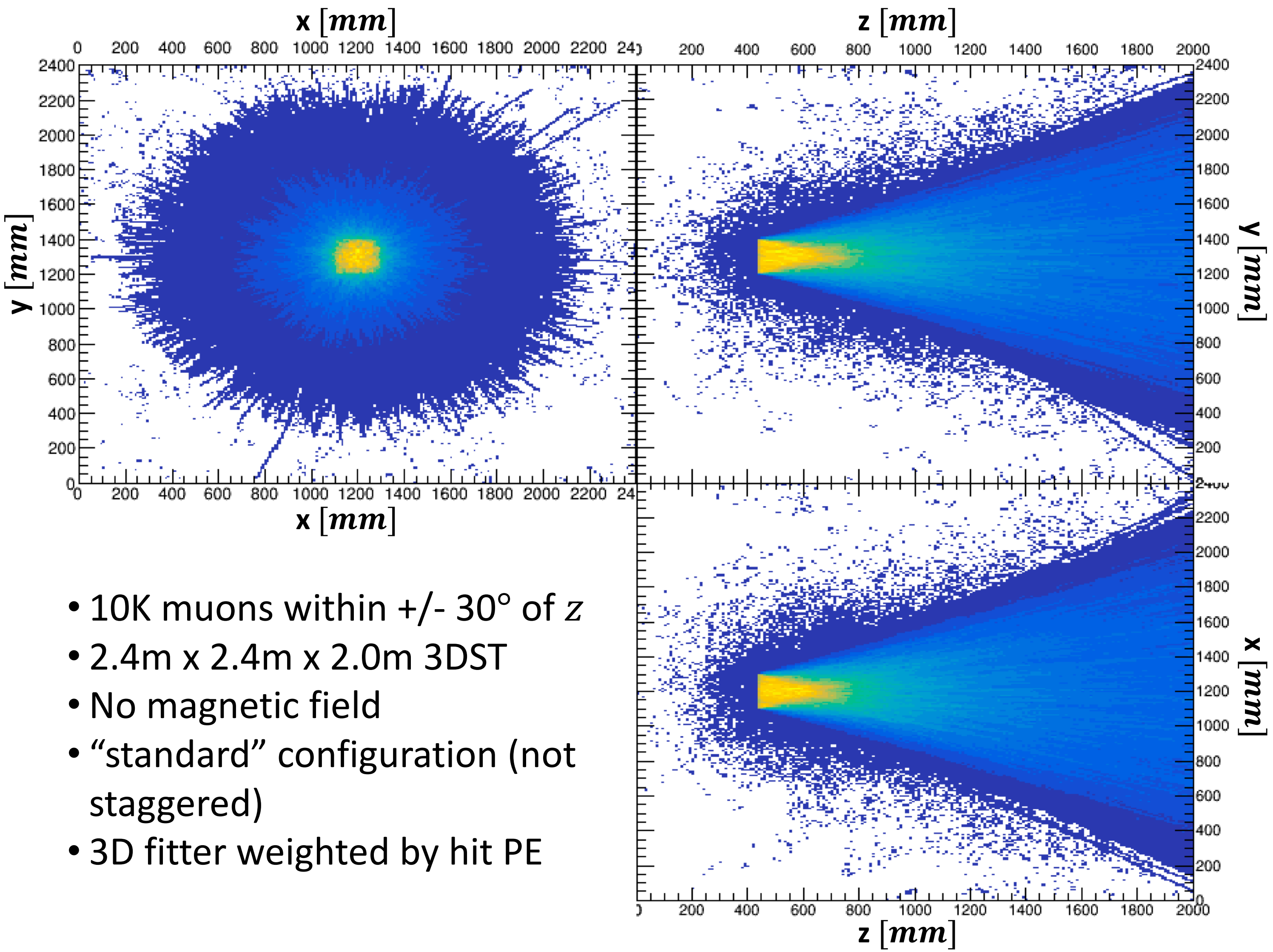
Angular Resolution

- Reconstructed event direction vector, $\hat{\boldsymbol{r}}$, obtained with a 3D fit, weighted by PE
  - Using different track lengths to optimize resolution.
  - Resolution suffers from the geometrical effect if the track length is too short and from multiple scattering if too long
- Angle between $\hat{\boldsymbol{r}}$ and the initial momentum vector, $\boldsymbol{p_0}$, obtained for 10K events

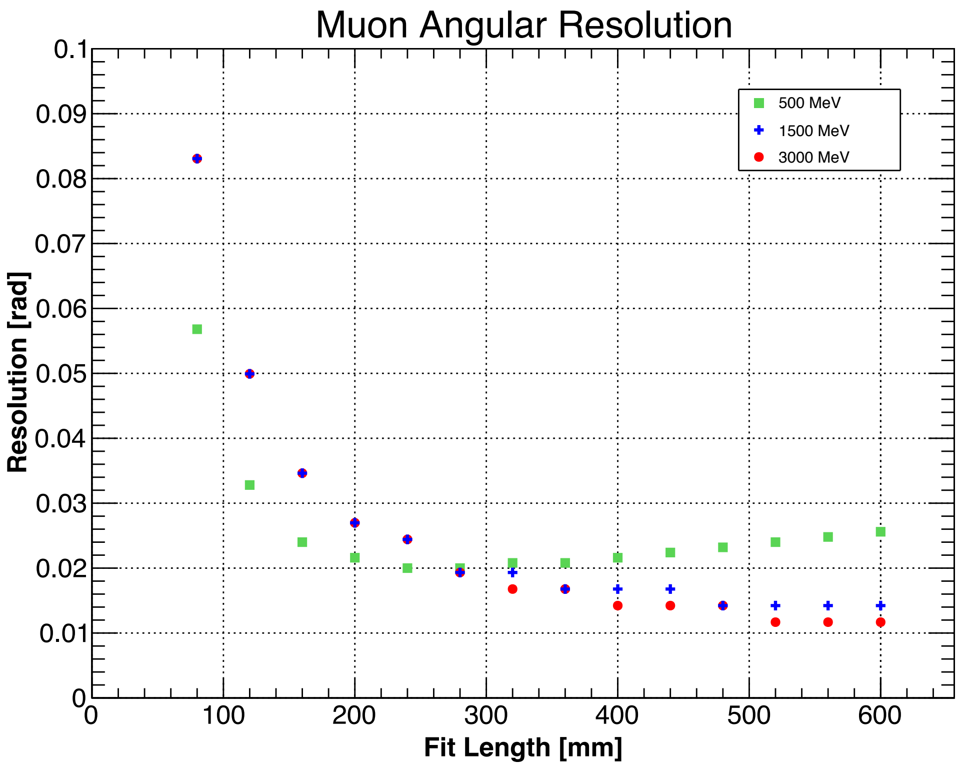
$$\theta_{true-reco} = \cos^{-1}\left(\frac{\hat{\boldsymbol{r}} \cdot \boldsymbol{p_0}}{|\boldsymbol{p_0}|}\right)$$



Muons

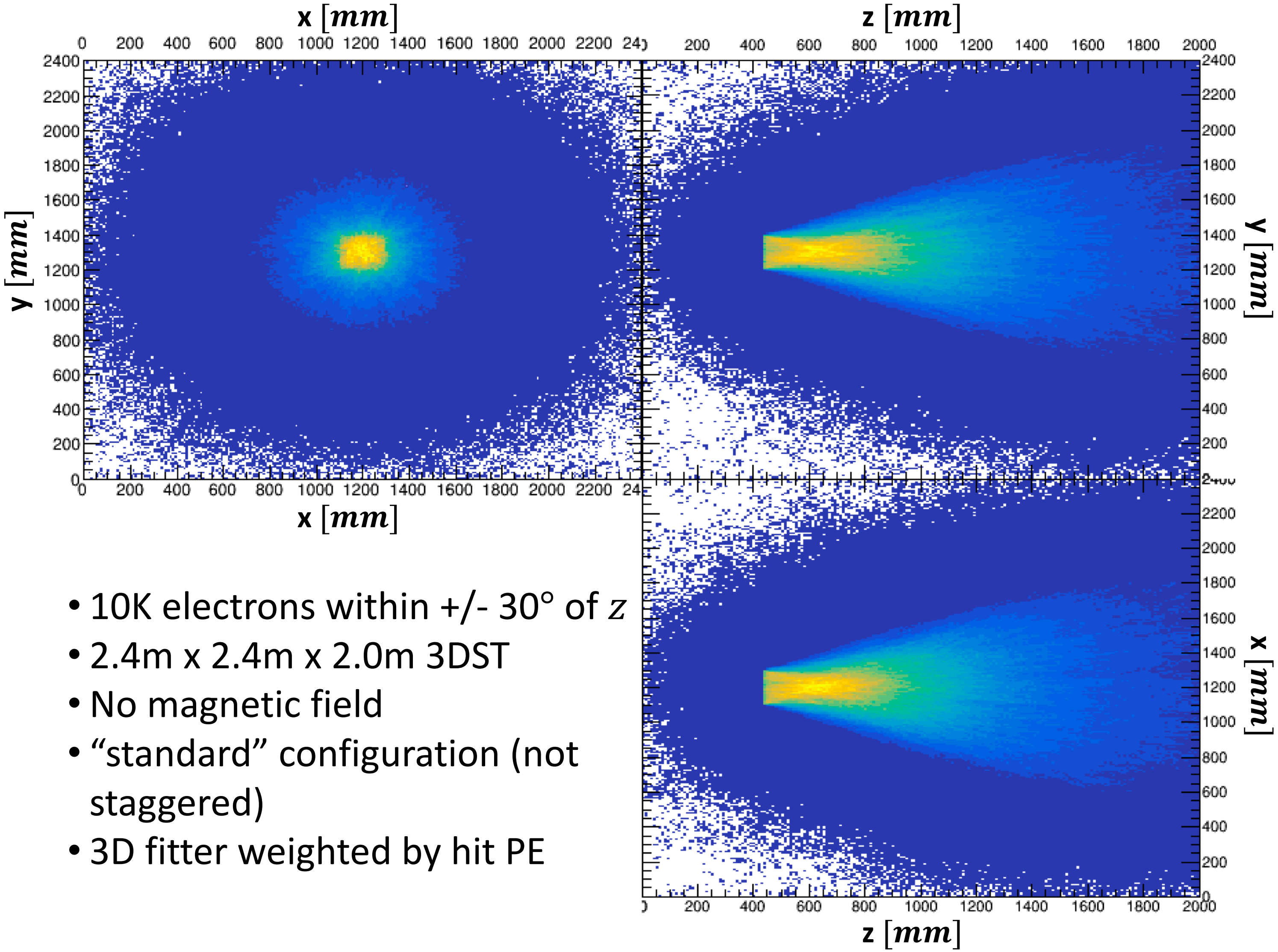


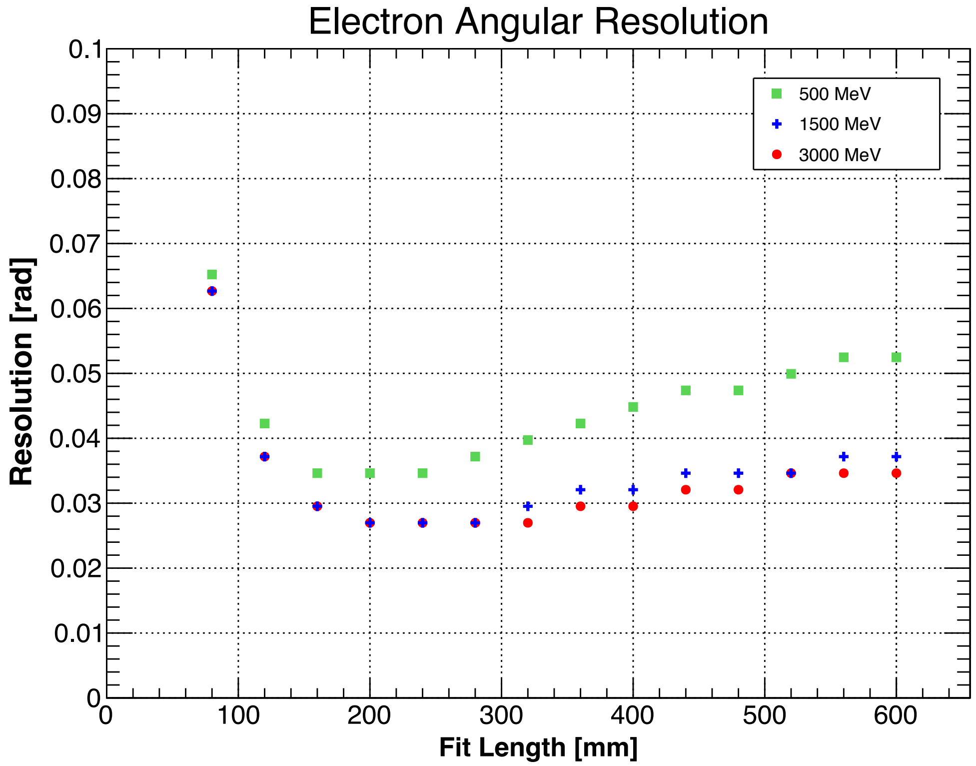
- 10K muons within +/- 30° of z
- 2.4m x 2.4m x 2.0m 3DST
- No magnetic field
- “standard” configuration (not staggered)
- 3D fitter weighted by hit PE



~12 mrad angular resolution

Electrons



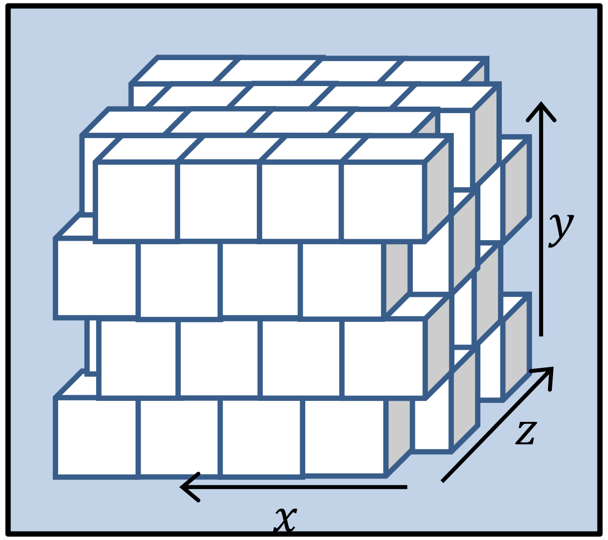


- 10K electrons within +/- 30° of z
- 2.4m x 2.4m x 2.0m 3DST
- No magnetic field
- “standard” configuration (not staggered)
- 3D fitter weighted by hit PE

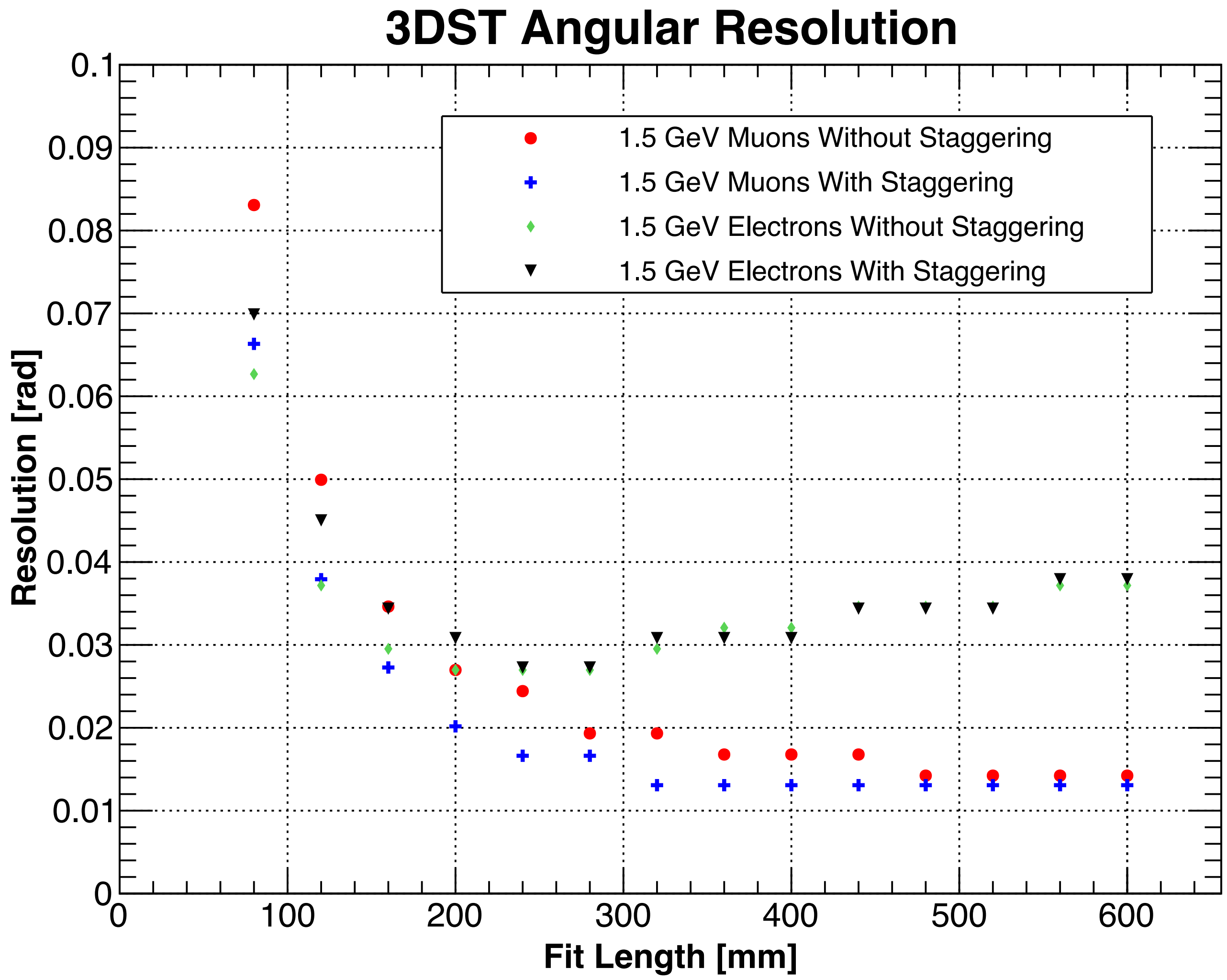
~27 mrad angular resolution

Stony Brook University

Staggered Geometry

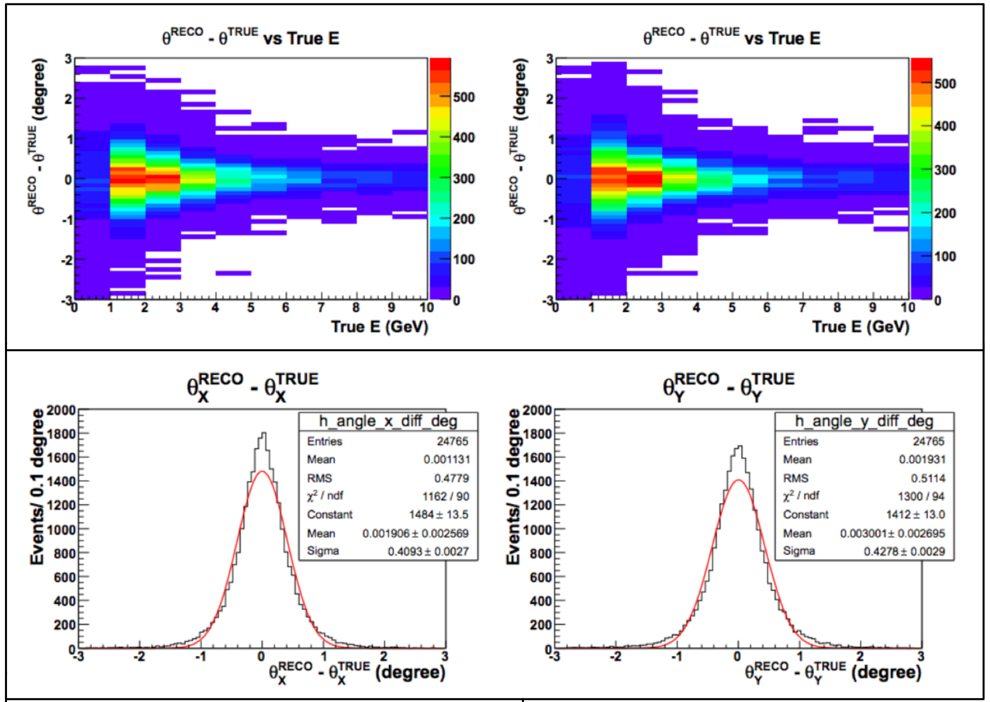


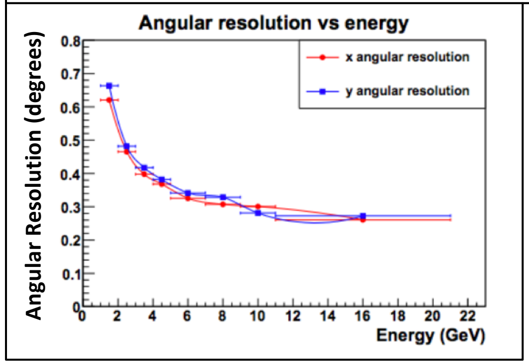
- Improvement for muons but not for electrons
- Here the staggered case uses the same PE-weighted 3D fitter (with appropriate binning) as the non-staggered case
- Maybe a more sophisticated reconstruction algorithm can help us exploit the effectively higher granularity in the xy- and yz-planes



Minerva Comparison

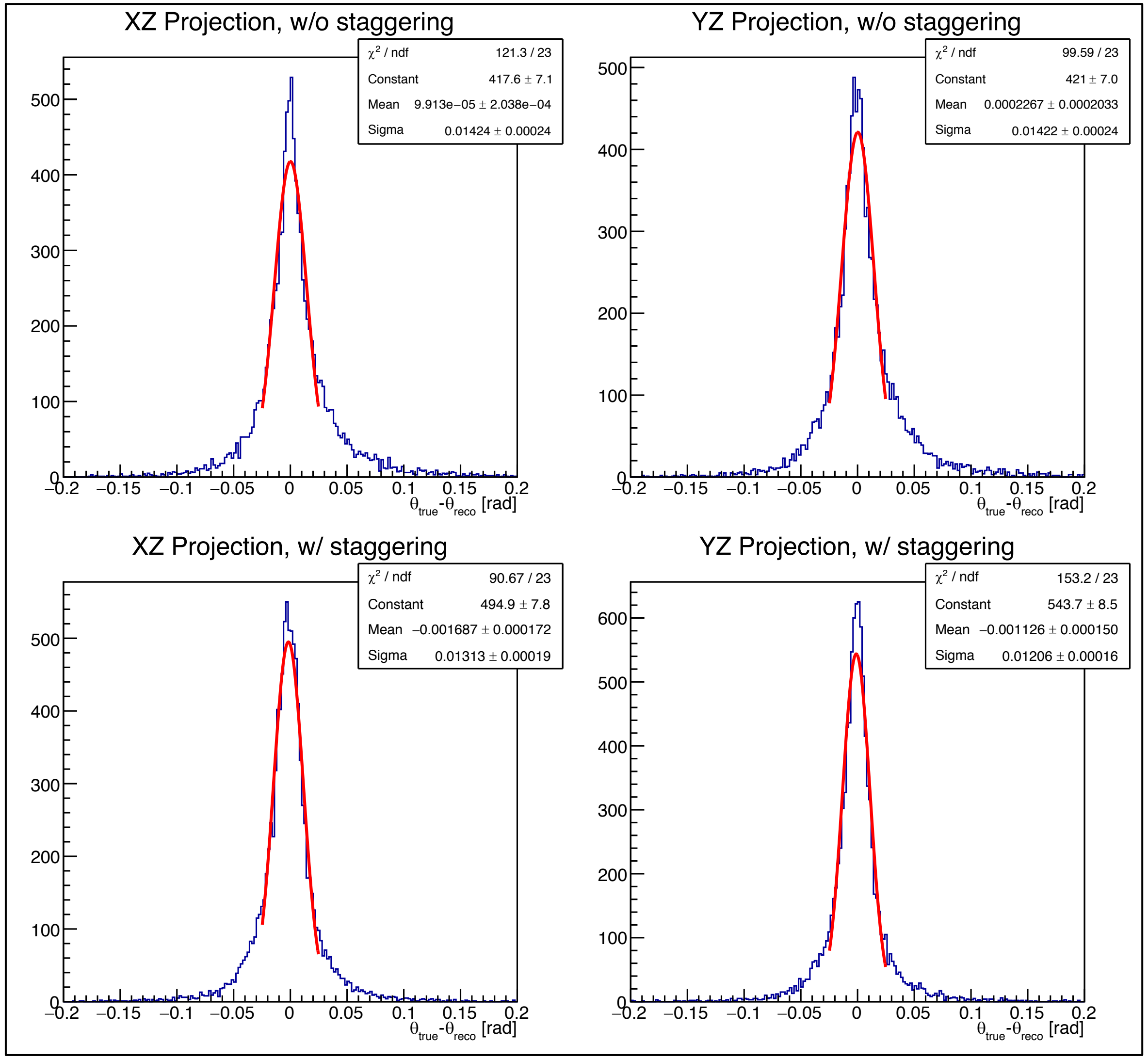
J. Park, Neutrino-Electron Scattering in MINERvA for Constraining the NuMI Neutrino Flux, thesis, 2013.





Jaewon Park finds ~0.65° = 11.3 mrad (2D) angular resolution for 1-2 GeV electrons

3DST Simulation – 2.0 GeV electrons



Summary

- Q-A: What is the angular resolution of 3DST?
  - ~12 mrad for muons and ~ 27 mrad for electrons

Physics studies for 3DST as part of DUNE near detector

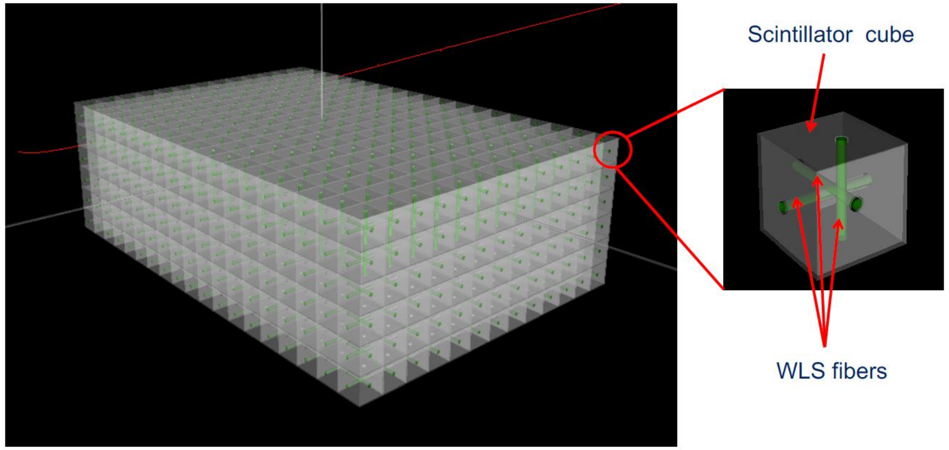
S. Manly, Univ. of Rochester
DUNE Near Detector Workshop
March 22-24, 2018
Fermilab

Outline:

- Need for statistics
- Q1: How well can 3DST do for ν-e^- scattering?
- Q2: How well can 3DST do with neutrons?
- Q3: Does 3DST need to be in B field?
- Physics process studies:
  - Neutrino-electron scattering
  - Coherent charged and neutral pion production
  - Low-recoil (low-ν) technique to measure flux
  - ν_μ CC inclusive production
  - NC and CC neutral pion production
- Q4: How does 3DST complement other parts of the ND and how does it help CP sensitivity
- Option with 3DST inside the HPTPC

Slides included. Will skip. MINERvA and T2K experience show these should not pose a problem.

Moved to backup



Statistics: how much is enough?

Need stats in FD
Need stats in ND to constrain flux and xsec models at FD
Need stats in LAr part of ND to help constrain FD detector model

- Typical start-
  - high interest in early results
  - intensity starts out low
- Differential analyses
- Exclusive morphologies
- Tight cuts for transverse variables
  - exciting recent results, very promising
  - excellent resolution also important
- Beams change
  - Target
  - Alignment
  - intensity-dependent effects
- If DUNEprism, LAr moves off-axis 50%-ish of time (and beams change)

- ν_μ CC
  1. 1-track 0π (μ^- only)
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  5. $1\pi^\pm$ ($\mu^- + 1\pi^\pm +$ X)
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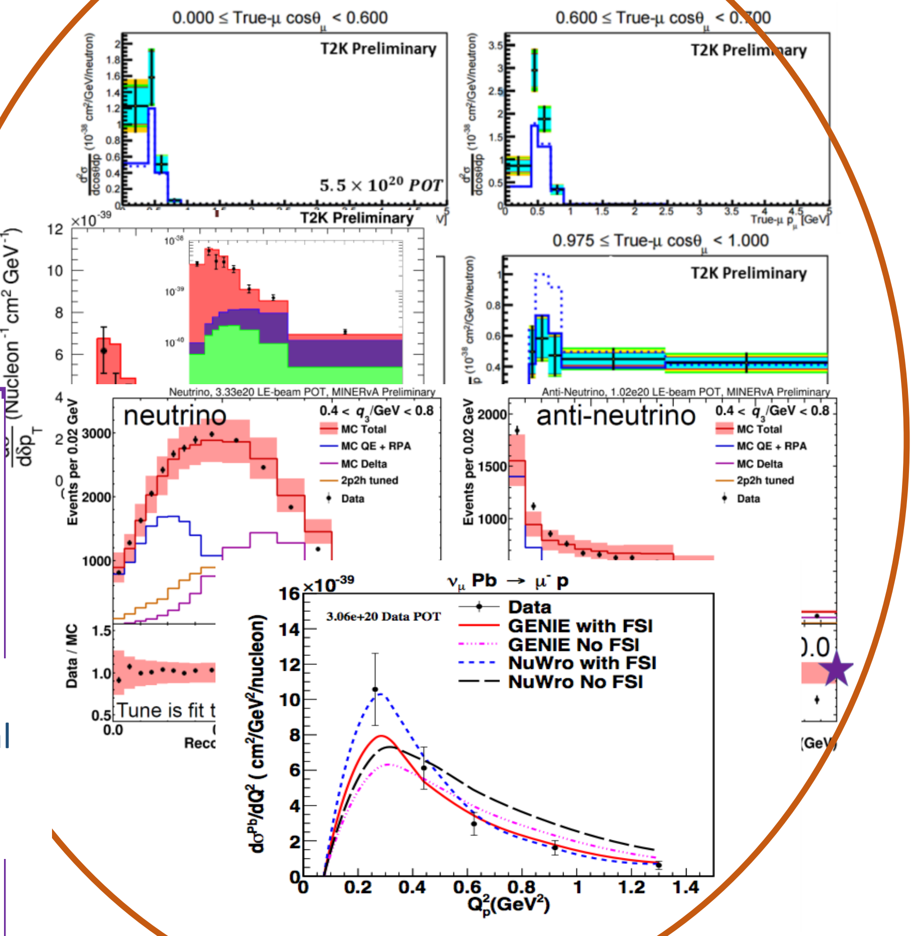
  14. $1\pi^\pm$ ($e^- + \pi^\pm +$ X)
  15. $1\pi^0$ ($e^- + \pi^0 +$ X)
  16. Other

NDTF Valor experimental data sets considered

Plus more



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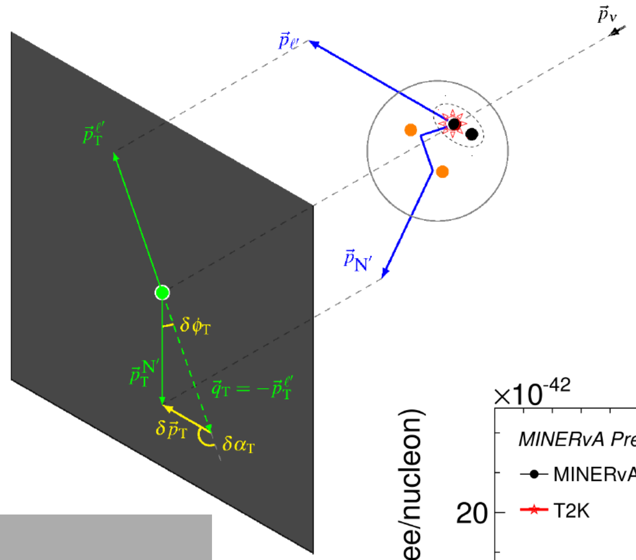
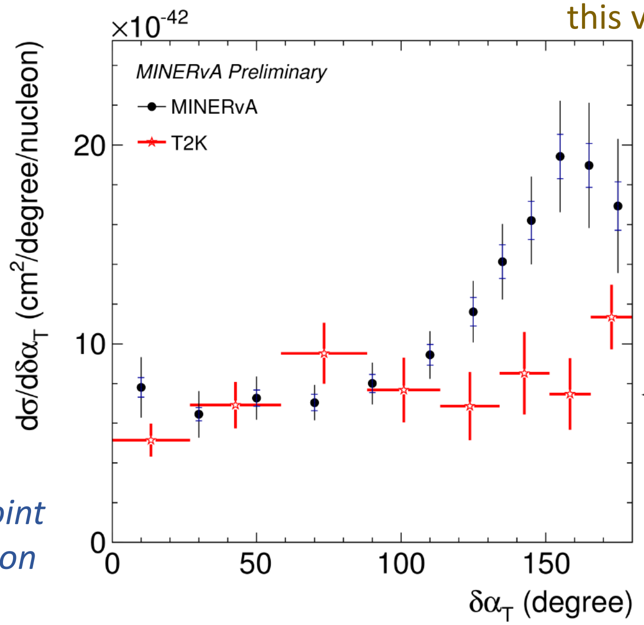


Cuts on proton reconstruction, muon reconstruction, vertex activity, Michel
→ 9% efficient for CCQE

At MINERvA, resonance production is present and there is an enhancement in this variable thought to be due to FSI



At T2K, resonance production is small and this variable is expected to be flat and reflects the isotropic effect of Fermi smearing

Presented by Xianguo Lu at Fermilab Joint Experimental and Theoretical Seminar on March 2, 2018

Statistics: how much is enough?

Need stats in FD
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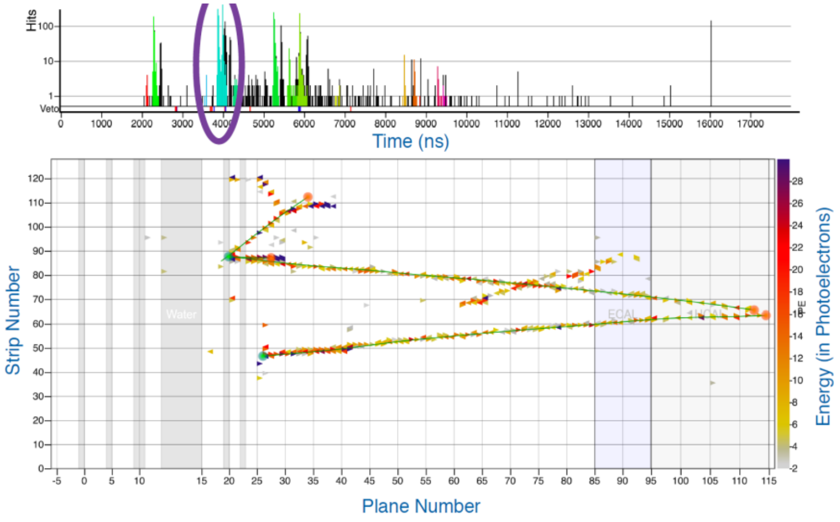
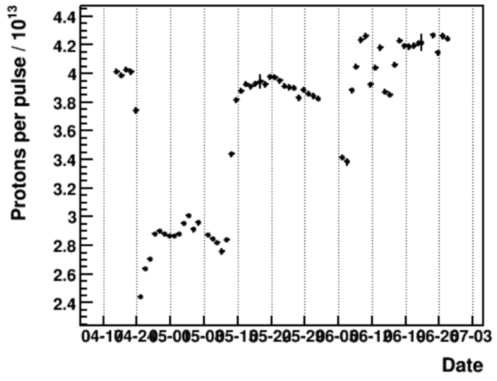
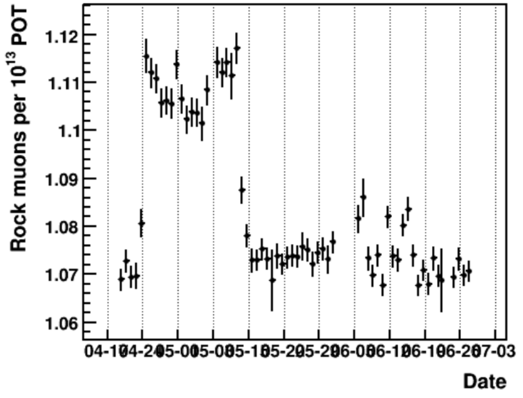




0+6
to
4+6
to
6+6



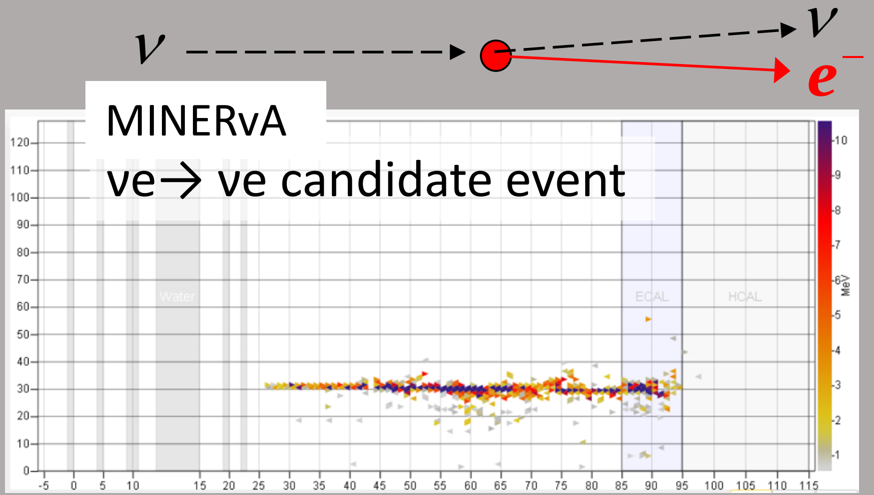
2016

Q1: How well can the 3DST do using ν-e⁻ scattering for a flux constraint?

$$\frac{d\sigma(\nu_\mu e^- \rightarrow \nu_\mu e^-)}{dy} = \frac{G_F^{\,2} m_e E_\nu}{2\pi}\left[\left(\frac{1}{2} - \sin^2\theta_W\right)^2 + \sin^4\theta_W (1-y)^2\right]$$

G_F and θ_W: well-known electroweak parameters

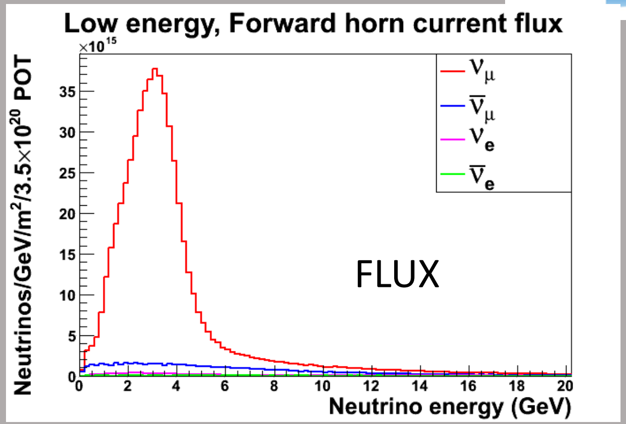
Very forward single electron final state $E_e\theta^2 < 2m_e$

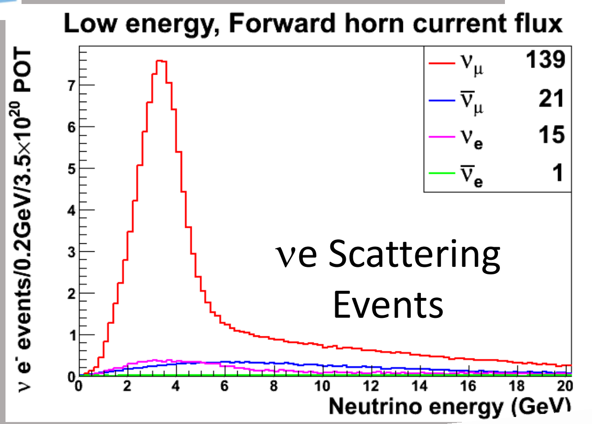


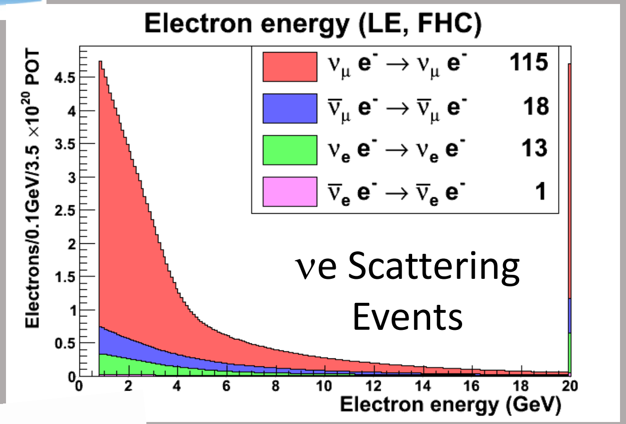
$\sigma(\nu e) \propto E_\nu$

$\frac{d\sigma}{dy}$

$y = \frac{\text{(electron KE)}}{\text{(neutrino energy)}}$



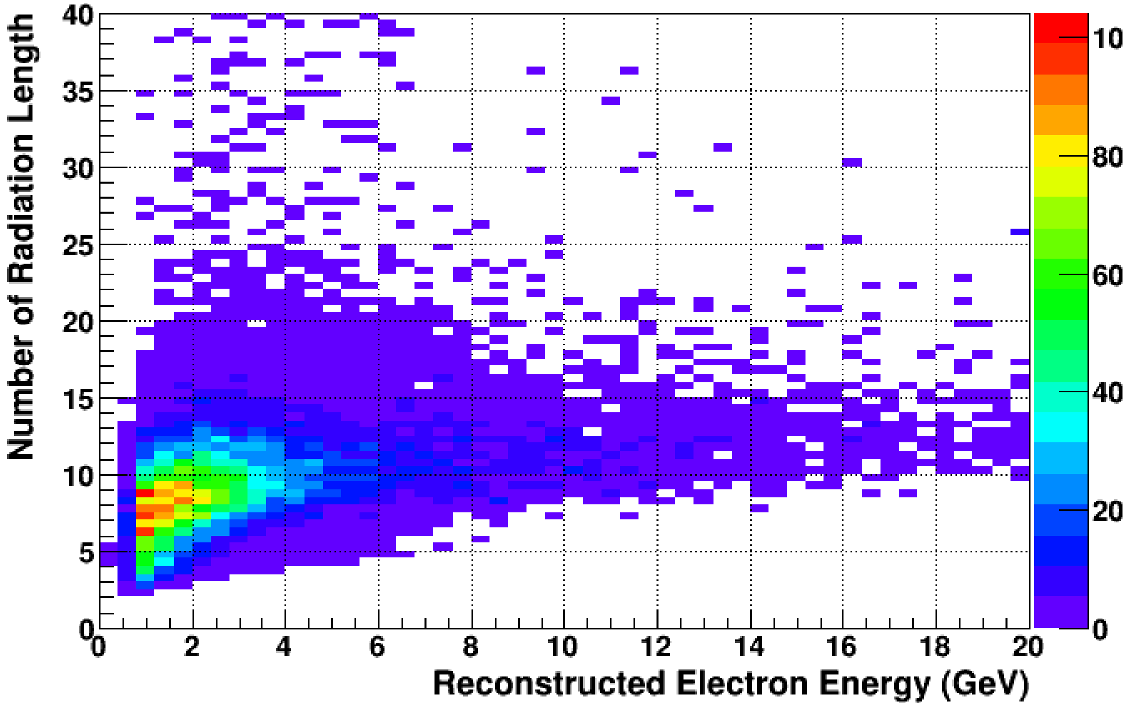


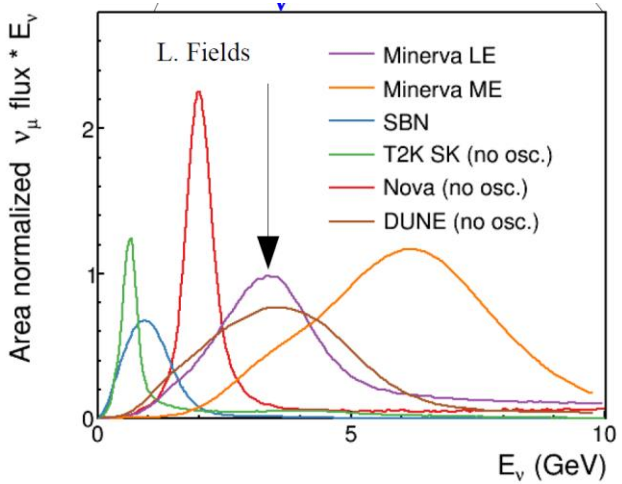


Q1: How well can the 3DST do using ν-e^- scattering for a flux constraint?

~1000 events per year with FHC for 80 GeV, 3-horn, optimized beam and 2.4x2.4x2.0 m^3 3DST with 25 cm fiducial volume cut around all edges

Edgar Valencia



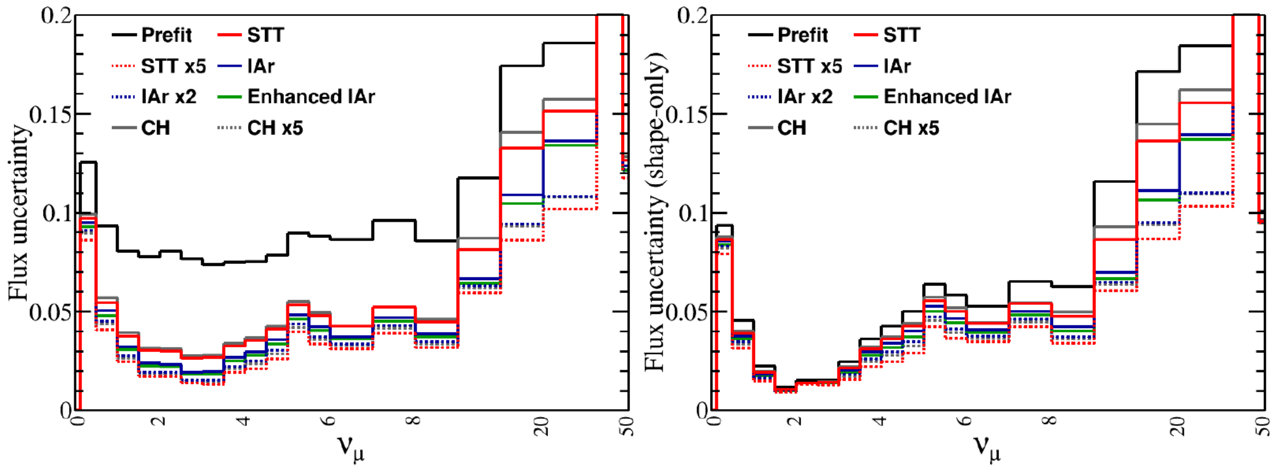


- MINERvA simulation
- NuMI medium energy flux
- Reweighted to low energy flux shape (very similar to DUNE)
- Events passing MINERvA ν-e^- scattering event selection

For those paying close attention, have only shown ME flux results in the past (SM mistake). This is first time we've shown this study for LE flux.

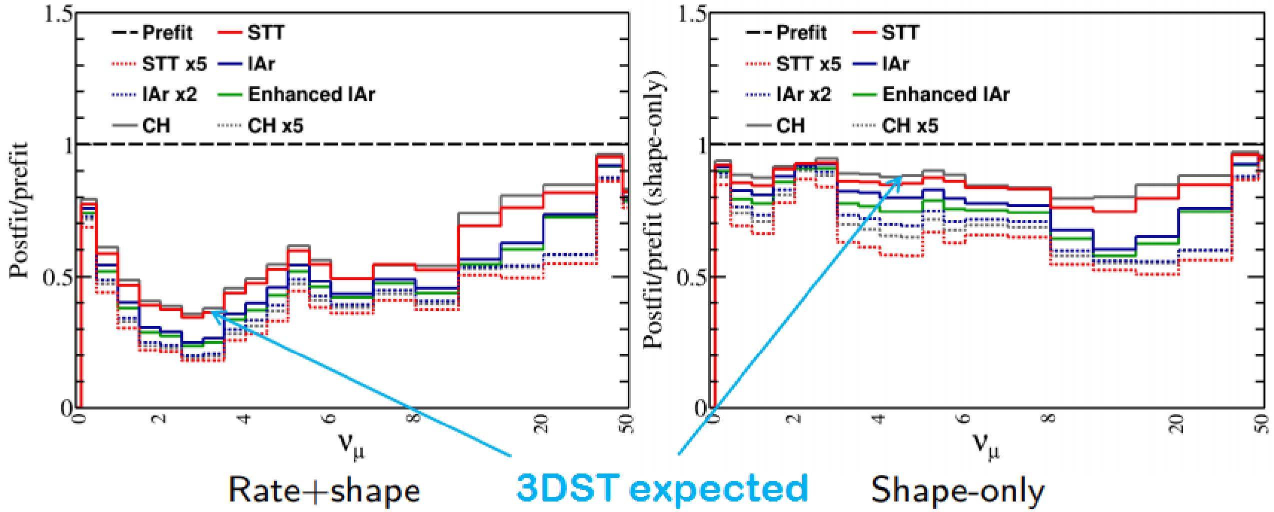
From study by Chris Marshall, Callum Wilkinson, Kevin McFarland, Steve Dennis
Presented by Chris and Callum at Nov. 2017 ND workshop

- Aim: test how well we can constrain the flux normalization and shape from E_e,θ_e distributions
  - Include beam divergence
  - Include realistic detector smearing from previous studies
  - Include beam related backgrounds ν_e and γ
- Use 2D template fit, where each E_ν template is required to have $\geq$500 events (Gaussian)



Rate+shape Shape-only

- CH is MINERvA-like detector
- 3 mm hit resolution with 2 cm spacing
- 3DST similar, 1 cm spacing
- Assumed 5 tons, 5 years: 4250 events
- 2.4x2.4x2.0 m^3 3DST has 5.7 ton FV
- Expect ~5000 events in 5 years



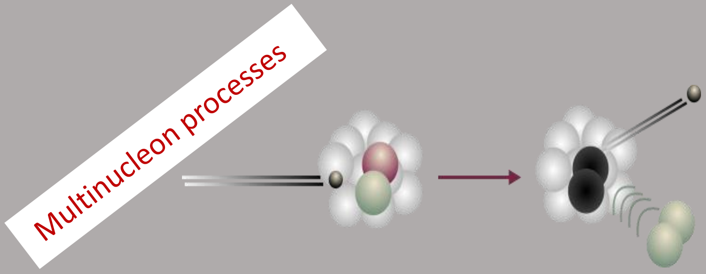
Rate+shape Shape-only

- Mass is the critical thing here
- Different systematics from LAr

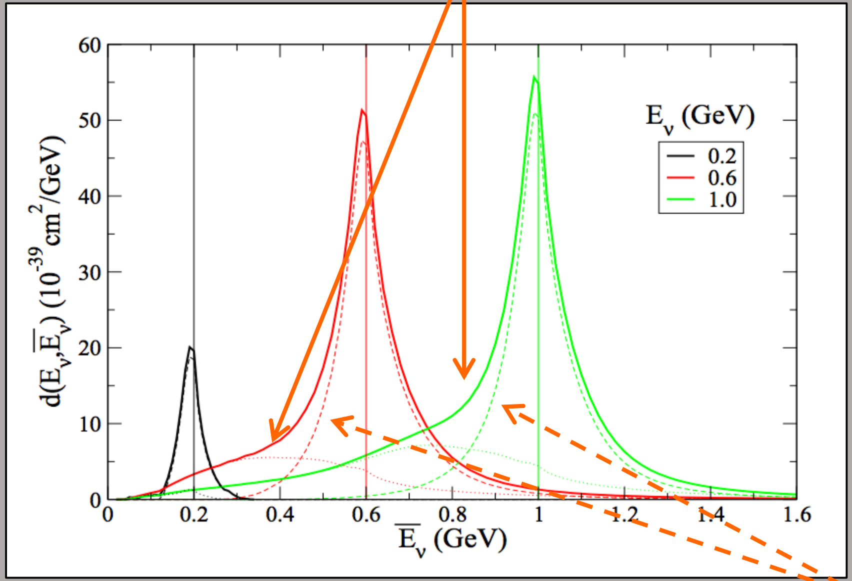
3DST or STT both gives capability to make this measurement on-axis when LAr might be off-axis

How well can the 3DST do with neutrons?

Can we use neutron tag to improve neutrino reconstruction in the CCQE-like sample?



Multinucleon events reconstructed as quasielastic



Martini, Ericson, Chanfray, Phys. Rev. D87, 013009, 2013

Genuine quasielastic events

NDTF: Final states used by VALOR for the ND constraint of FD fluxes

- ν_μ CC
  1. 1-track 0π (μ^- only)
  2. 2-track 0π (μ^- + nucleon)
  3. N-track 0π (μ^- + (>1) nucleons)
  4. 3-track Δ-enhanced ($\mu^- + \pi^+$ + p, with $W_{reco} \approx 1.2$ GeV)
  5. $1\pi^\pm$ ($\mu^- + 1\pi^\pm$ + X)
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  7. $1\pi^\pm + 1\pi^0$ ($\mu^- + 1\pi^\pm + 1\pi^0$ + X)
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- Wrong-sign ν_μ CC
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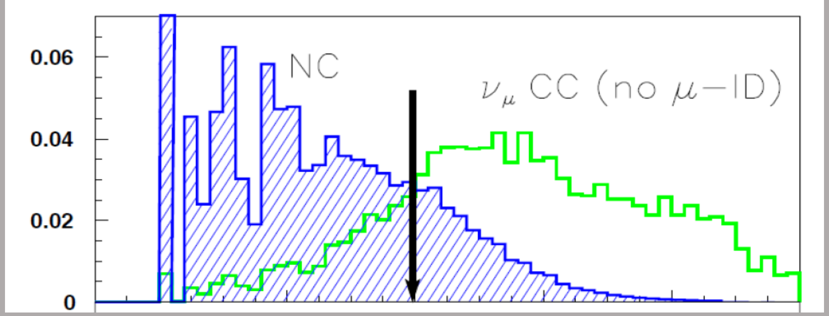
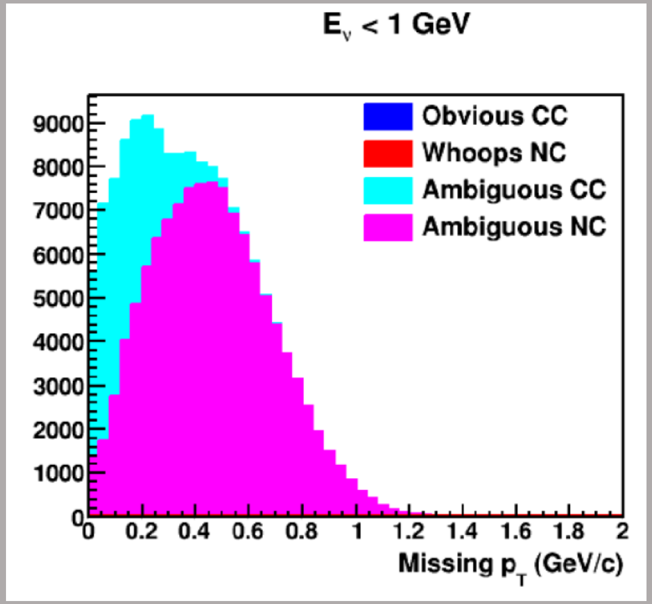
  12. Other
- ν_e CC
  13. 0π (e^- + X)
  14. $1\pi^\pm$ ($e^- + \pi^\pm$ + X)
  15. $1\pi^0$ ($e^- + \pi^0$ + X)
  16. Other
- Wrong-sign ν_e CC
  17. Inclusive
- NC
  18. 0π (nucleon(s))
  19. $1\pi^\pm$ ($\pi^\pm$ + X)
  20. $1\pi^0$ (π^0 + X)
  21. Other
- ν-e
  22. $\nu_e + e^-$ elastic
  23. Inverse muon decay $\bar{\nu}_e + e^- \to \mu^- + \bar{\nu}_\mu$ (including the annihilation channel $\nu_\mu + e^- \to \mu^- + \nu_e$).

With neutron tagging, can we expand list of processes used to constrain the flux?

Can neutron tagging be used to improve our ability to use transverse momentum balance variables?

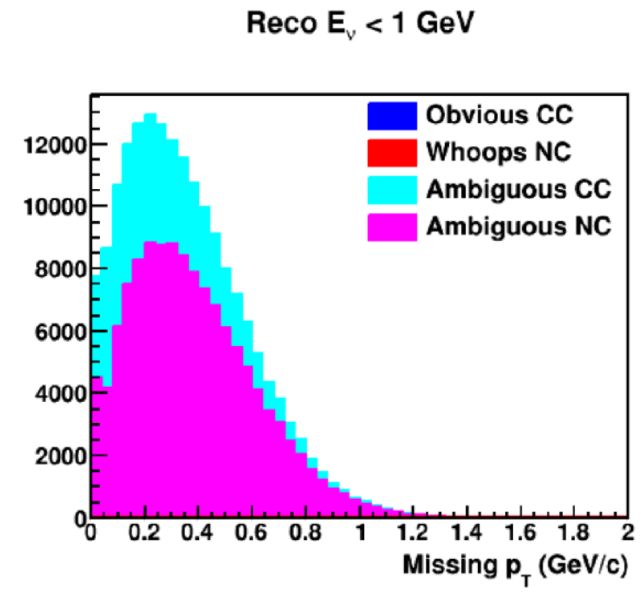
NC and CC separation works fairly well at NOMAD
-R. Petti





Perfect reconstruction

Chris Marshall, shown at March 2017 DUNE ND workshop

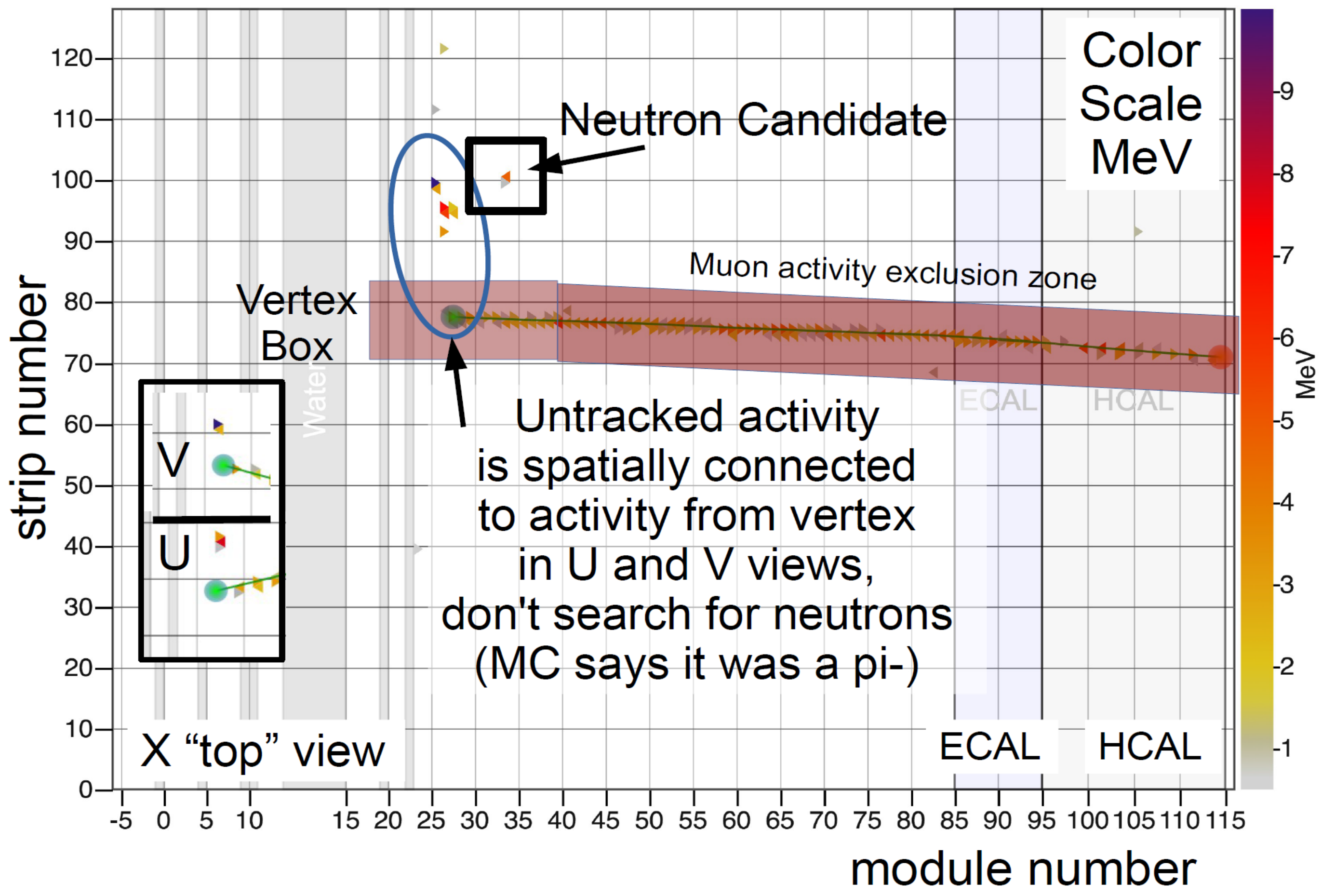


Remove neutrons

Separation between cyan (CC) and pink (NC) is reduced dramatically with missing neutrons

Q2: How well can the 3DST do with neutrons?

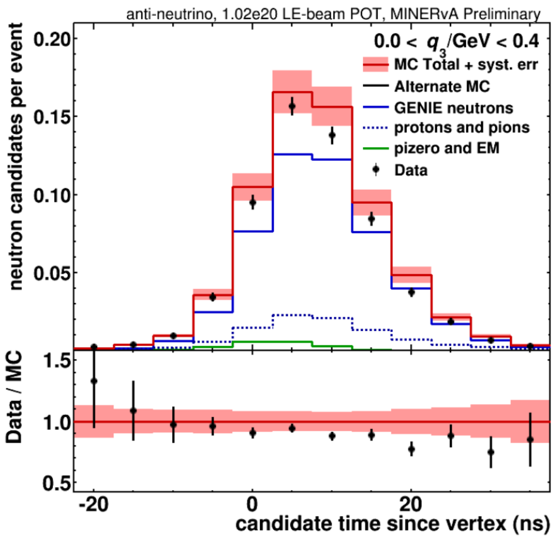
MINERvA sees neutrons



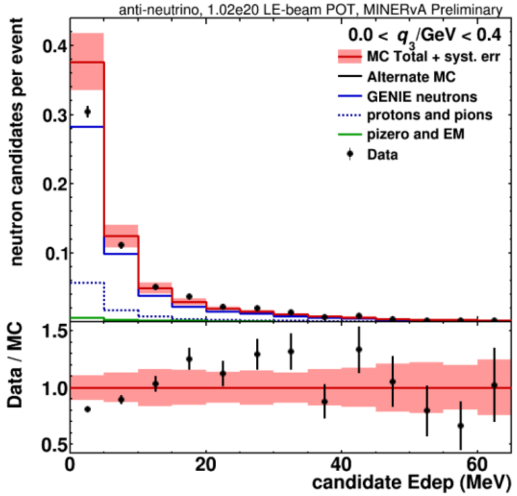
From MINERvA (R. Gran), FNAL Joint Experimental and Theoretical Seminar, Nov. 3, 2017

MINERvA data

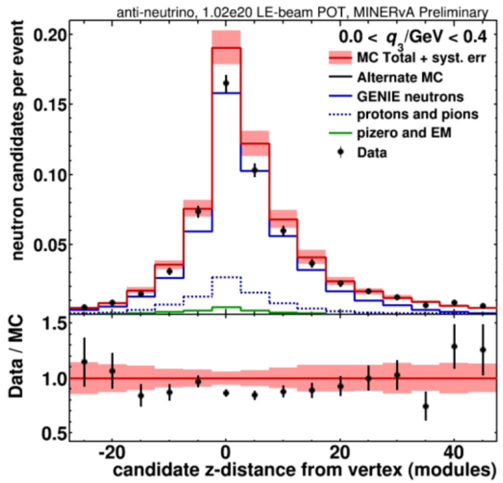
From MINERvA (R. Gran), FNAL Joint Experimental and Theoretical Seminar, Nov. 3, 2017



Time since interaction



Deposited energy per candidate

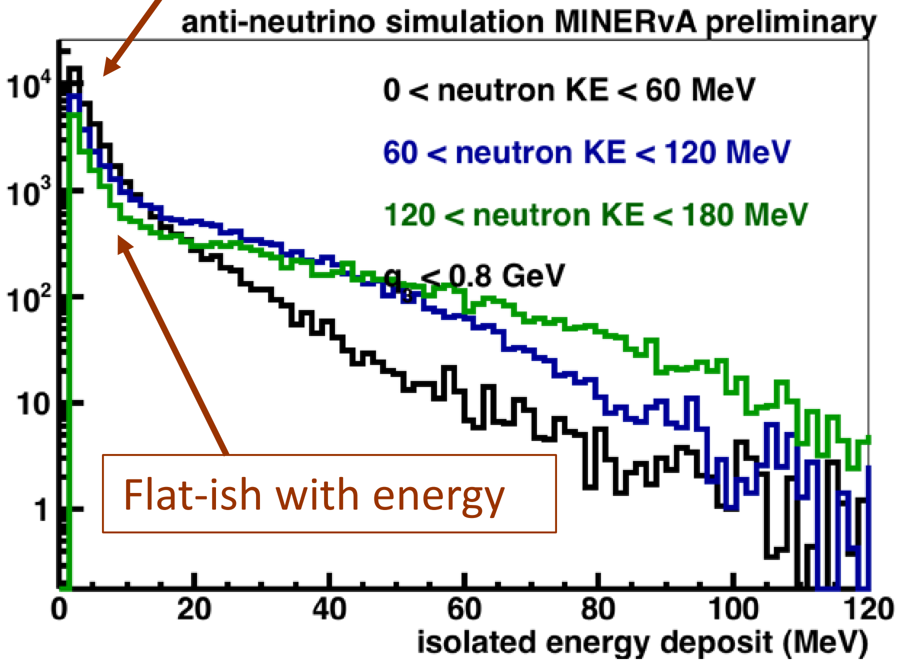


Position relative to interaction (upstream vs. downstream)

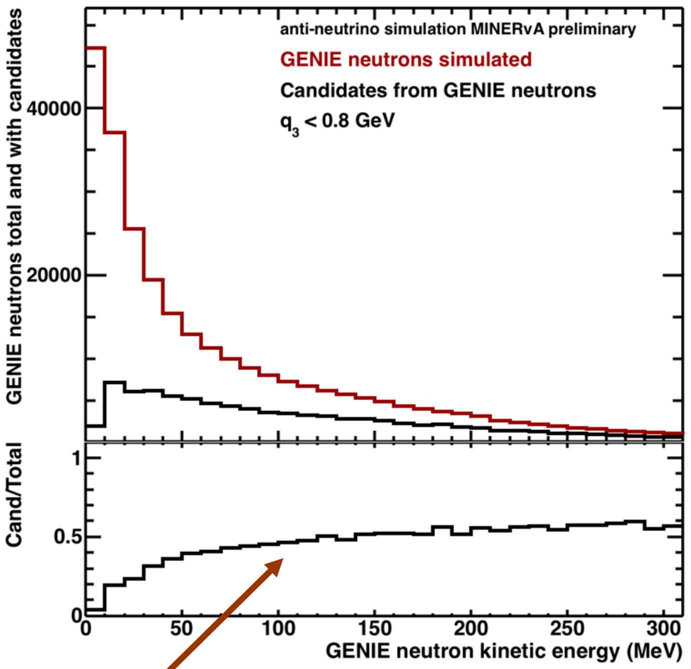
- MINERvA seems to see the neutrons.
- Dominated by the low energy (2-6 MeV) candidates in this analysis
- Data-MC agreement not so bad (surprisingly?)
- MINERvA only able to get Z position for the low energy candidates
- Can get 3D reconstruction only for higher energy candidates (multiple planes)
- 3DST expected to get 3D position for these candidates

Expectation from MINERvA GENIE/GEANT simulation

Bulk of neutron energy depositions are small (2-6 MeV) – Note log scale



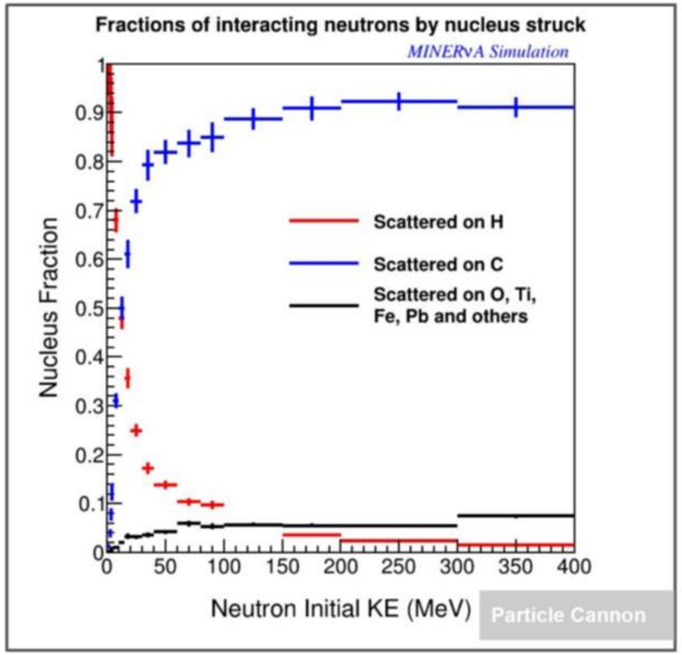
Flat-ish with energy

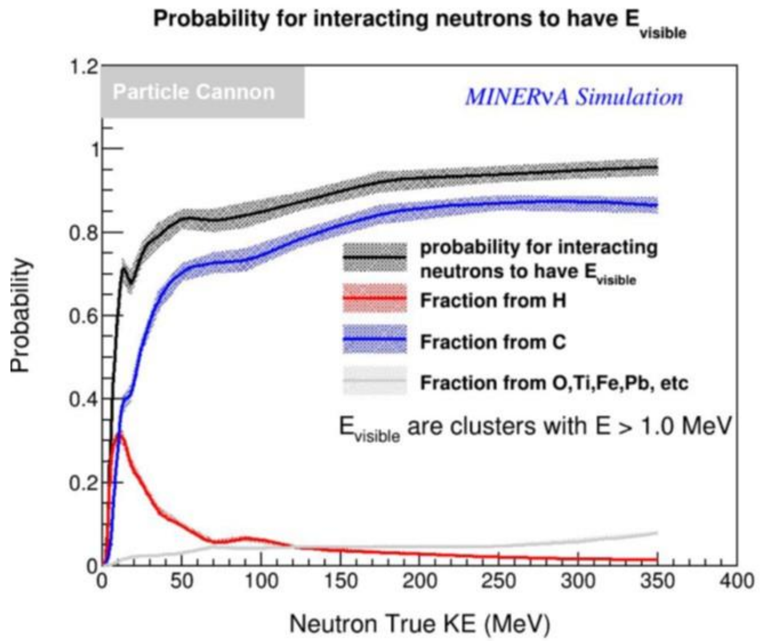


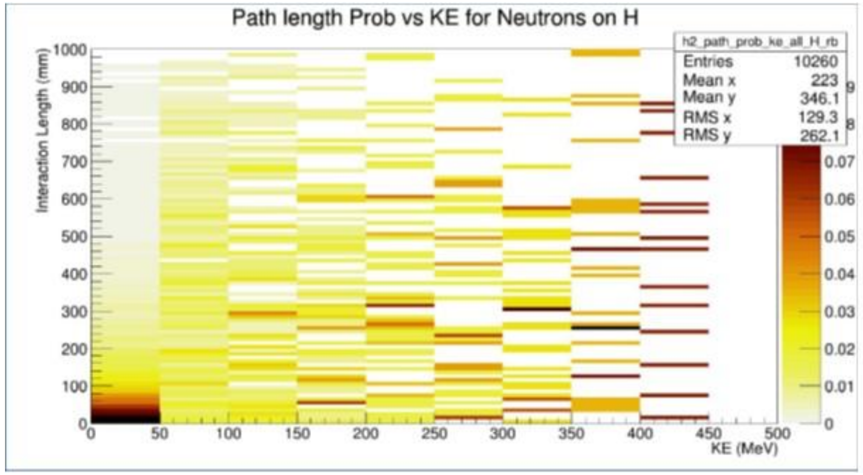
Neutron detection efficiency rises with neutron KE and reaches 50-60% for KE>50 MeV

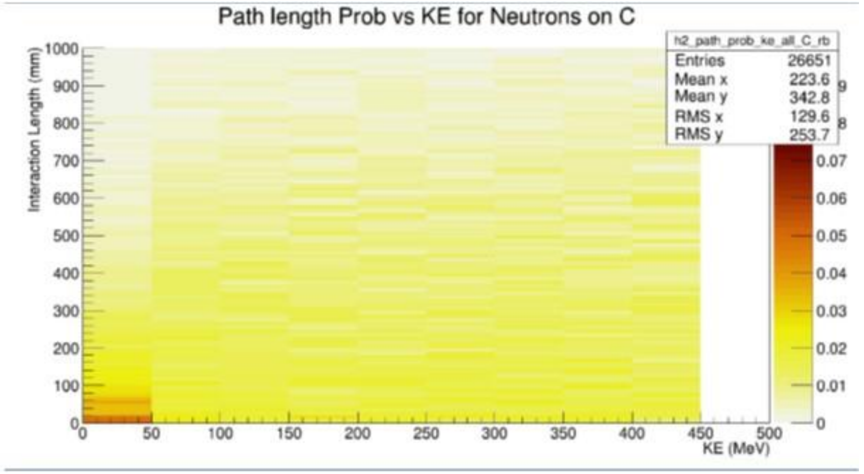
Particle gun studies from MINERvA (Tejin Cai), presented at Xsec workshop at FNAL, March 13, 2018

- Low n KE, more likely to interact on H
- Interactions on C more likely to leave visible energy
- Energy deposits happen fairly close to interaction vertex



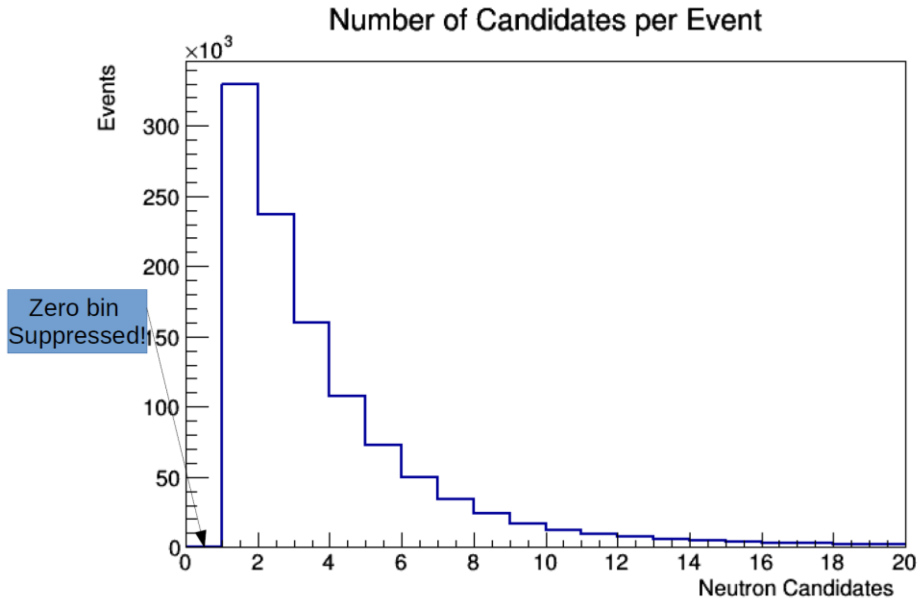


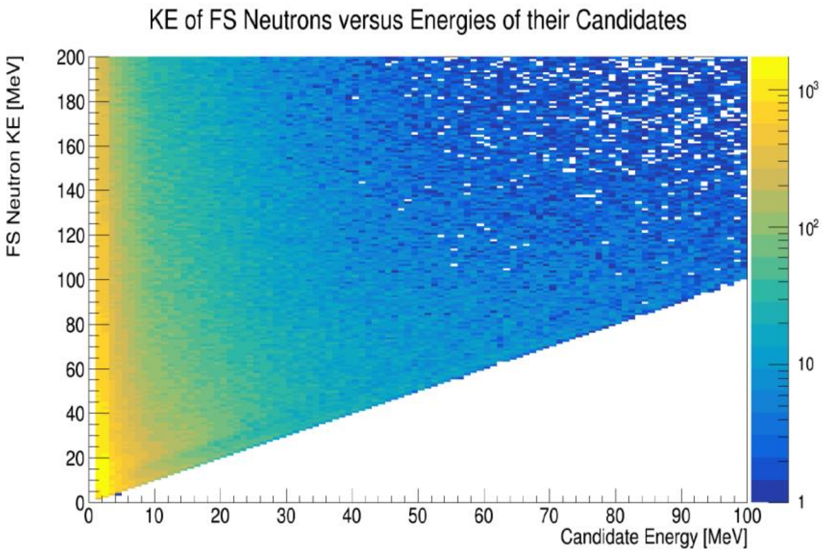


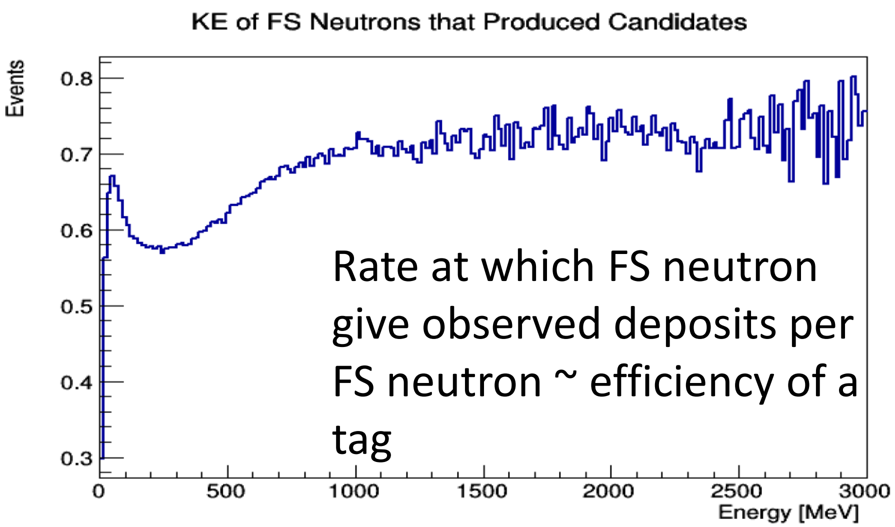


- 3DST simulation
- Clustering algorithm not optimized

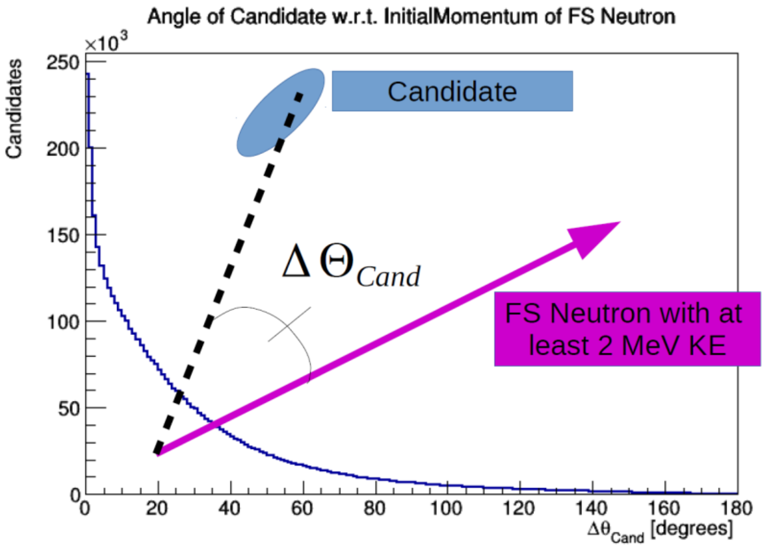
Andrew Olivier





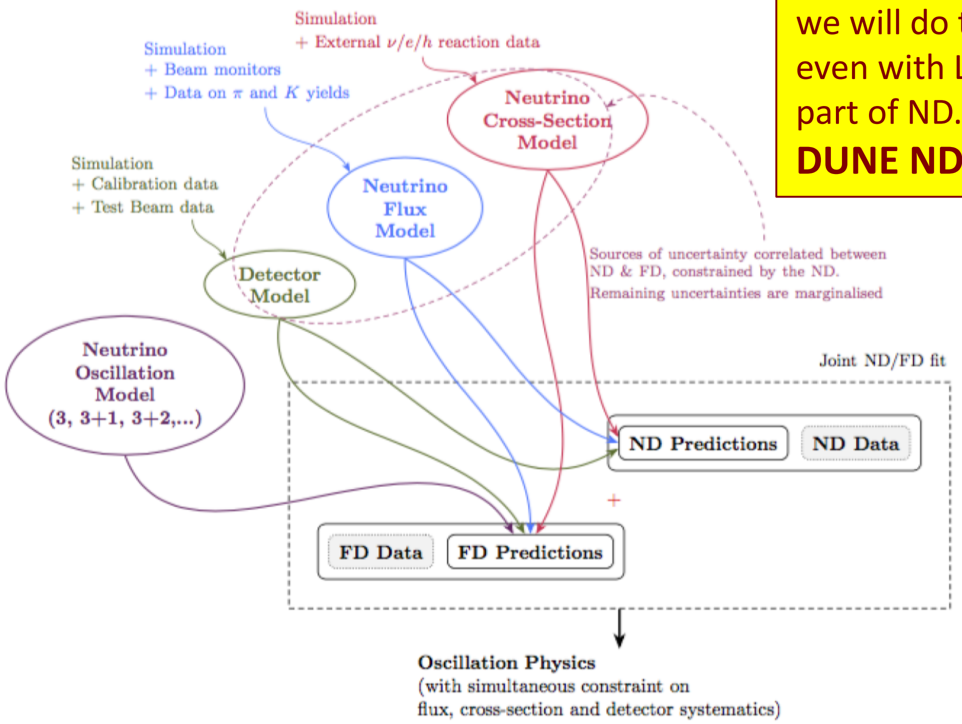


Rate at which FS neutron give observed deposits per FS neutron ~ efficiency of a tag



Q3: Does the 3DST need to be in a magnetic field?

- Primary mission of the non-LAr part of the ND is to fine tune the neutrino interaction model used in ND to FD constraint
- Want to measure many channels with sign separation for neutrinos and anti-neutrinos



Note: No question we will do this even with LAr as part of ND.
DUNE ND≠FD!

- ν_μ CC
  1. 1-track 0π (μ^- only)
  2. 2-track 0π (μ^- + nucleon)
  3. N-track 0π (μ^- + (>1) nucleons)
  4. 3-track Δ-enhanced ($\mu^- + \pi^+ + p$, $W_{reco} \approx 1.2$ GeV)
  5. $1\pi^\pm$ ($\mu^- + 1\pi^\pm + X$)
  6. $1\pi^0$ ($\mu^- + 1\pi^0 + X$)
  7. $1\pi^\pm + 1\pi^0$ ($\mu^- + 1\pi^\pm + 1\pi^0 + X$)
  8. Other
- Wrong-sign ν_μ CC
  9. 0π ($\mu^+ + X$)
  10. $1\pi^\pm$ ($\mu^+ + \pi^\pm + X$)
  11. $1\pi^0$ ($\mu^+ + \pi^0 + X$)
  12. Other
- ν_e CC
  13. 0π ($e^- + X$)
  14. $1\pi^\pm$ ($e^- + \pi^\pm + X$)
  15. $1\pi^0$ ($e^- + \pi^0 + X$)
  16. Other
- Wrong-sign ν_e CC
  17. Inclusive
- NC
  18. 0π (nucleon(s))
  19. $1\pi^\pm$ ($\pi^\pm + X$)
  20. $1\pi^0$ ($\pi^0 + X$)
  21. Other
- ν-e
  22. $\nu_e + e^-$ elastic
  23. Inverse μ decay $\bar{\nu}_e + e^- \rightarrow \mu^- + \bar{\nu}_\mu$ and annihilation channel $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$

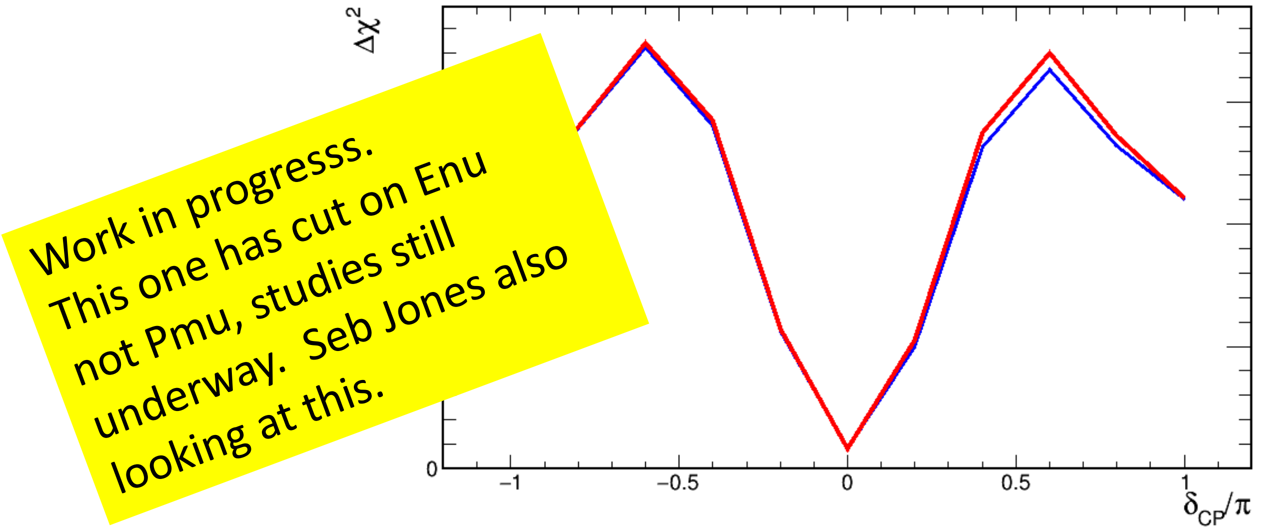
Steve Dennis
January 2017
NDTF era

Q3: Does the 3DST need to be in a magnetic field?

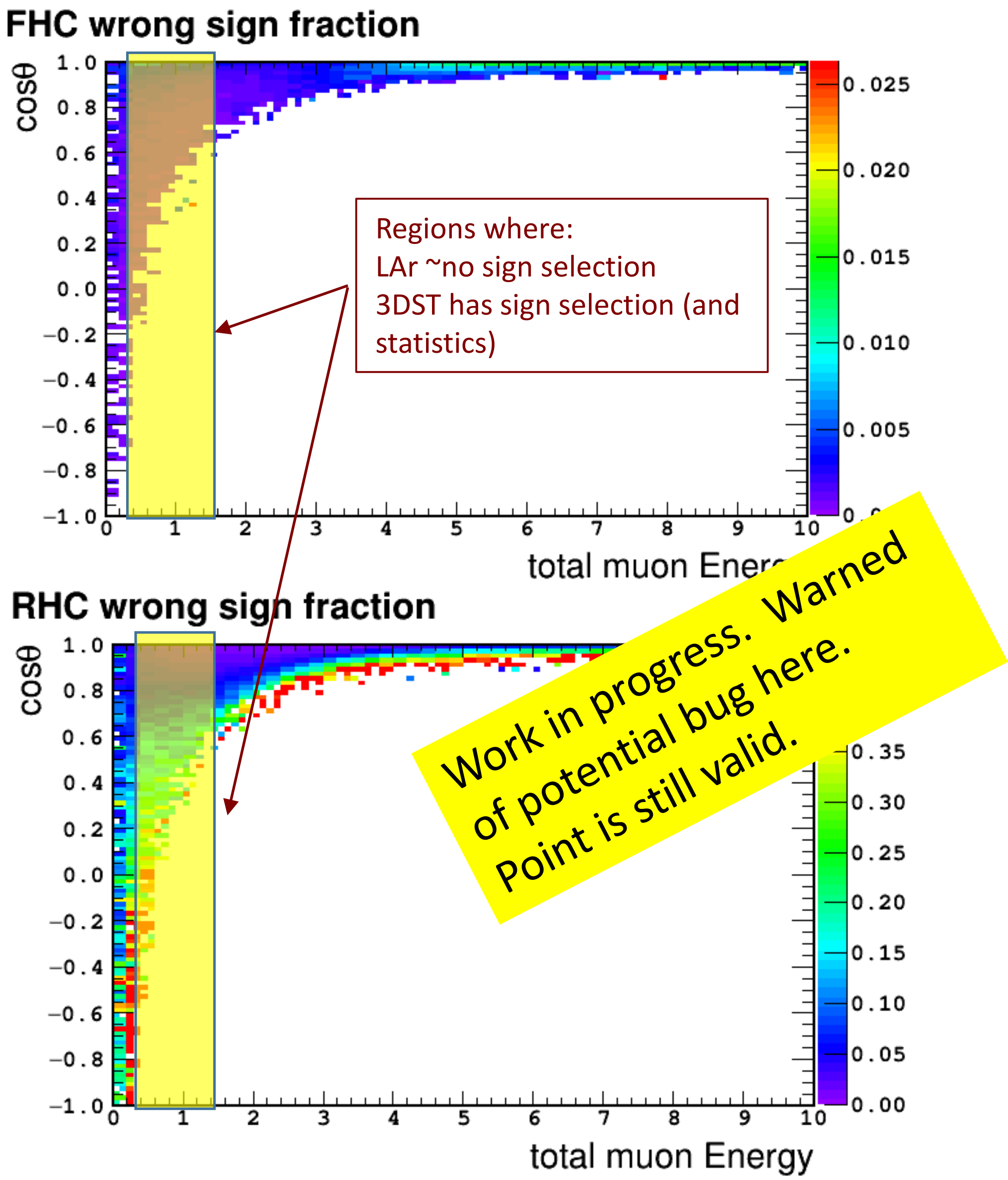
Guang Yang, Hang Su

- LAr has no sign separation for events where muon is not energetic enough to make it into an analyzing magnet, loss of information that can have bearing on CPV sensitivity
- Experimental constraint on wrong-sign background for CPV at low momentum

Guang Yang



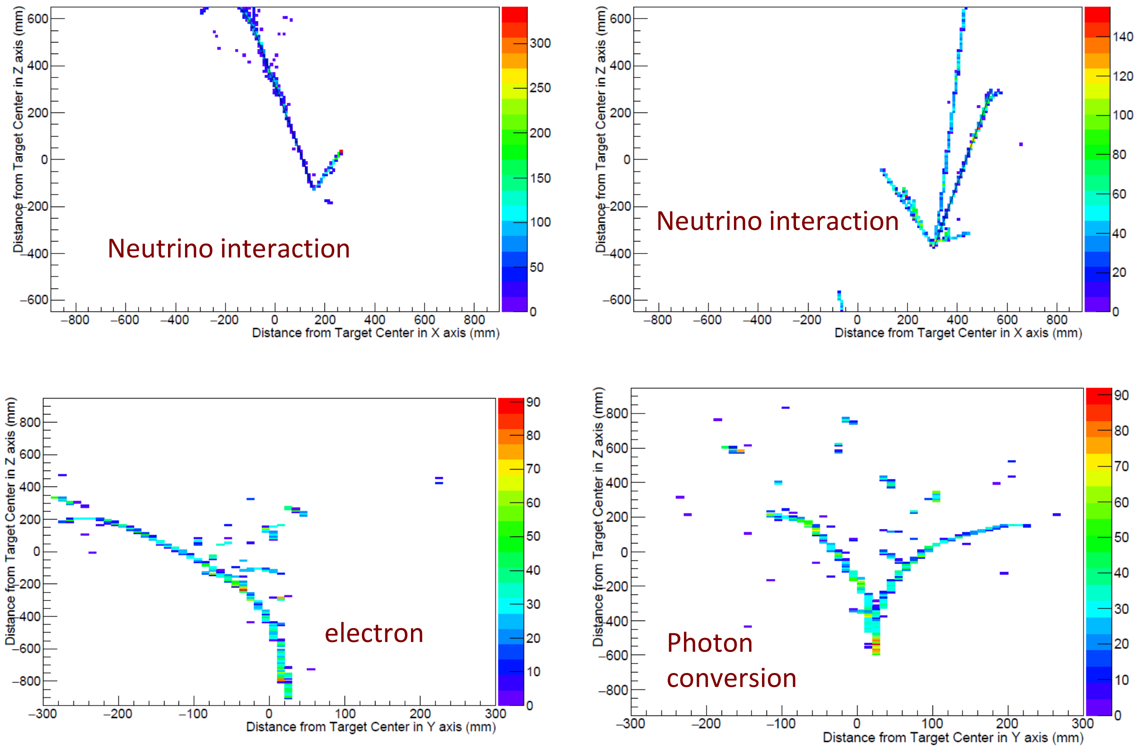
CAFana study using LAr sample with 32 valor xsecs, 5 largest flux, energy resolution and energy scale errors
Red: E_{μ}>0.15 GeV, θ_{μ}<40 degrees
Blue: E_{μ}>1.5 GeV, θ_{μ}<20 degrees



Q3: Does the 3DST need to be in a magnetic field?

- NC/CC separation, particularly at lower energy range (think second maximum region)
  - higher energy protons sometimes mistaken as muon (can eliminate with charge determination)
  - NC1$\pi^{\pm}$ background to CC0π
- $\pi^{\pm}$ reconstruction harder without B, can use Michel electron to ID π^{+}, but π^{-} contribution leads to systematic
- Helpful with electron-photon separation

Note: This kind of stuff is important when the mission is to tune the neutrino interaction model



SuperFGD simulation plots from the ND280 upgrade document, CERN-SPSC-2018-001 (SPSC-P-357)

Coherent charged and neutral pion production

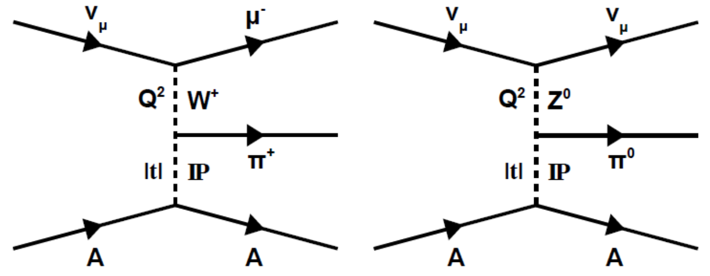


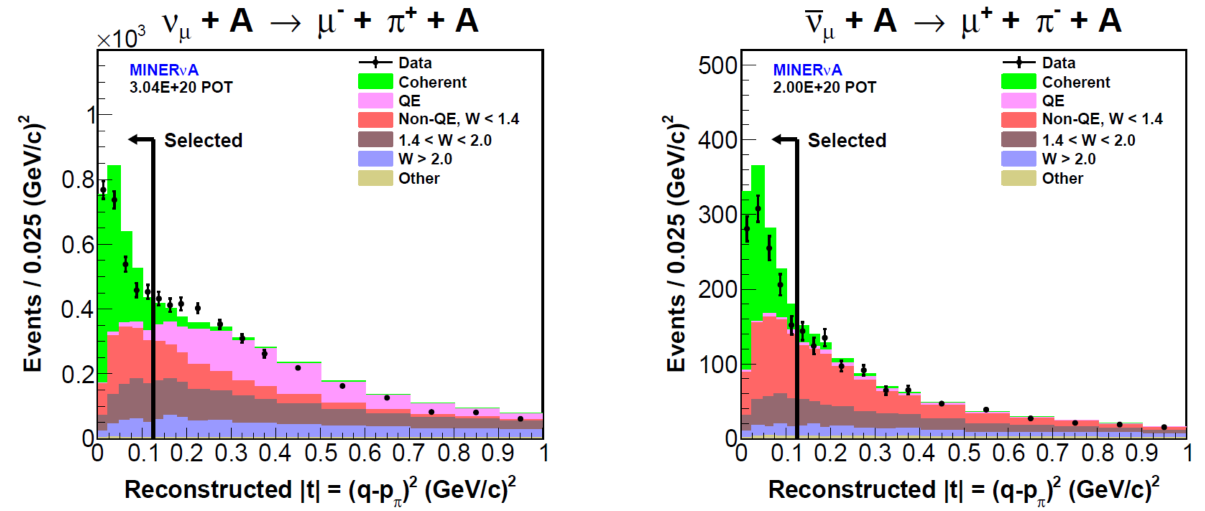
FIG. 1. CC (left) and NC (right) neutrino-nucleus coherent pion production in the PCAC picture.

From MINERvA - A. Mislivec et al., Phys. Rev. D97, 032014 (2018)

$$|t| = \left|\left(p_\nu - p_\mu - p_\pi\right)^2\right|$$

4-momentum transfer to the nucleus is small

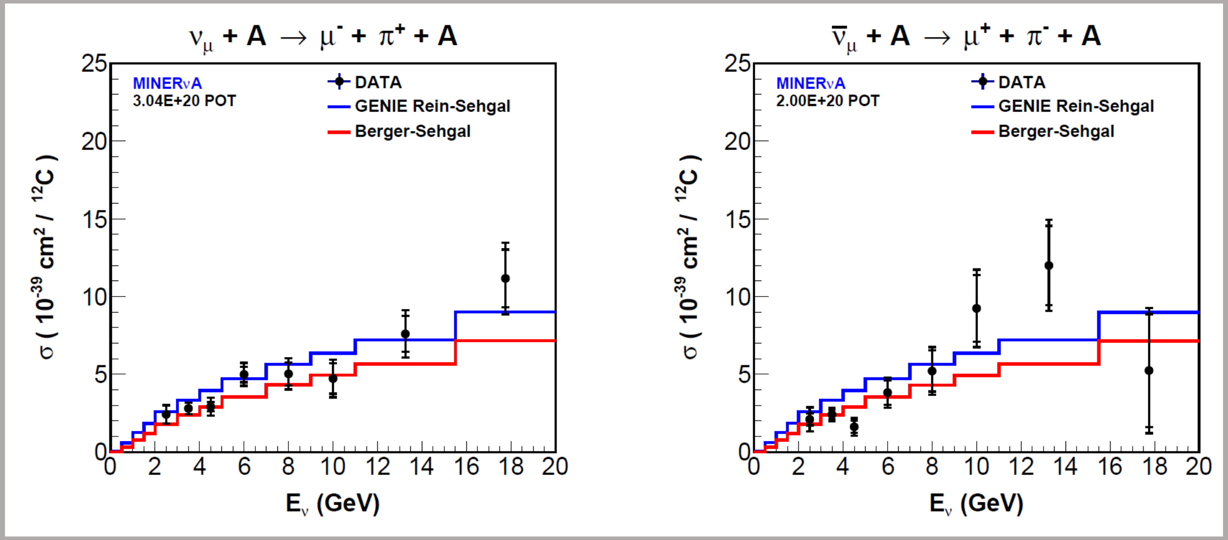
- Nuclear state unchanged
- No vertex activity
- $\mu^-\pi^+$ final state for CC coh signal, use small |t| to isolate signal
- NC coh has only the pizero, no E_ν or |t| reconstructed



NC coherent pizero is a dangerous appearance oscillation signal background.

CC coherent pi$^+$ can be used to help understand the NC coherent signal and can be measured in a less model-dependent fashion

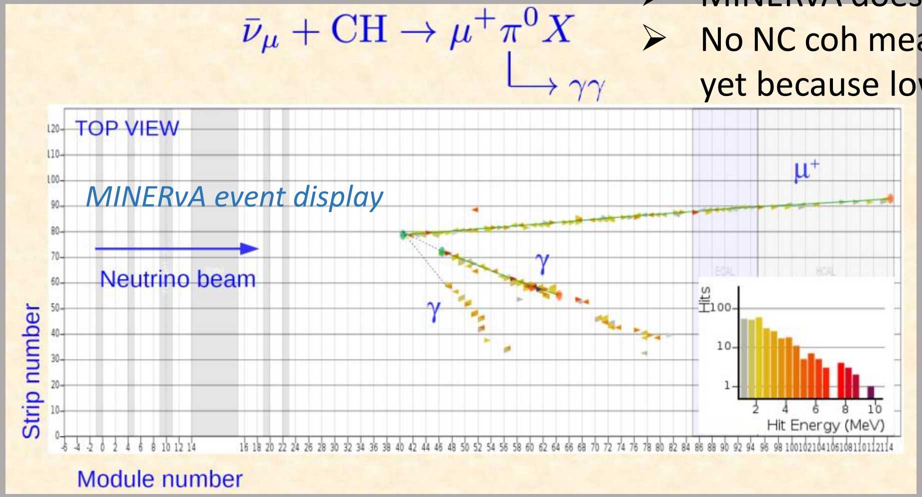
MINERvA CC coherent pion cross section results
(also presented as functions of E_π, θ_π, Q^2)



To do this well, need:

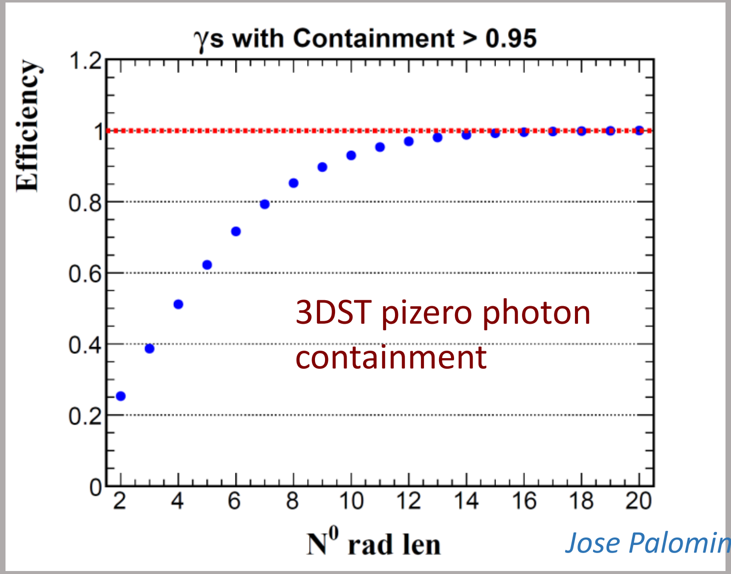
- ➢ Good sensitivity to vertex activity
- ➢ Good reconstruction of pion

- ➢ 3DST should be better than MINERvA by these measures
  - Good at 90 degrees
  - Real 3D readout with fine segmentation
  - B field tracking pions



- ➢ MINERvA does pizeros well
- ➢ No NC coh measurements yet because low priority

- ➢ For pizeros, 3DST has good photon containment
- ➢ Clustering for showers should be significantly better than MINERvA since it is true 3D (MINERvA – XUV planes – requires multiple layers)



Jose Palomino

Low-ν (nu) technique to measure flux

For muon (anti-)neutrinos

Let nu = energy transfer to the recoil system

nu = $E_{neutrino} - E_{lepton}$

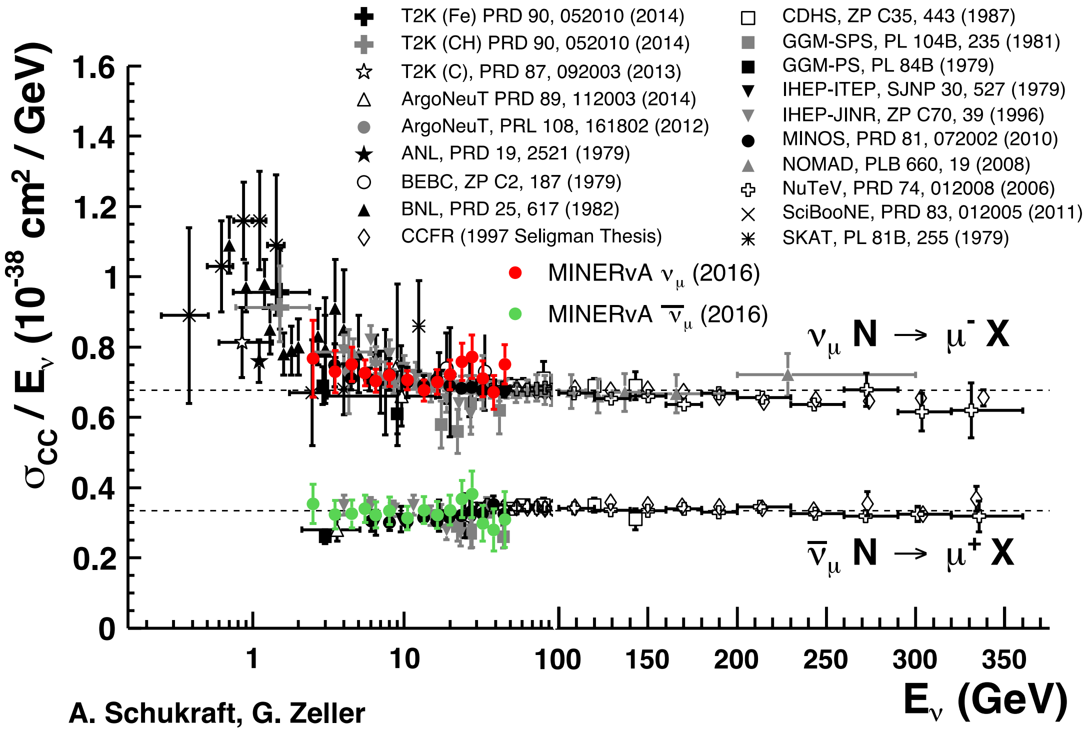
S. Mishra, Proc. of the workshop on hadron structure functions and parton distributions, 84 (1990).

- In limit of low-nu, the (anti-)neutrino xsec ~constant with (anti-)neutrino energy
- Measurement of low-nu event rate is a measure of the flux shape
- Normalize to precise measurement at high energy to get absolute flux

Done most recently by MINERvA, point of comparison for 3DST

From MINERvA – J. Devan et al., Phys. Rev. D94, 112007 (2017)
And J.Nelson, FNAL JETP seminar, Jan. 8, 2016

- Validated flux model
- Helped choose central value for flux (out of calculations that disagreed)
- Used to extract CCinclusive xsec



From MINERvA

Have cutoff, nu_o, below which is defined low-nu sample

Cutoff optimization →

Low, less energy dependence in xsec
High, avoids CCQE and resonance mismodeling in correction
High, need statistics fo rthe low-nu sample

Caution:
Low-nu sample has a large overlap with the CC0pi sample. Best to extract low-nu with sample independent of CCQE analysis.

3DST:

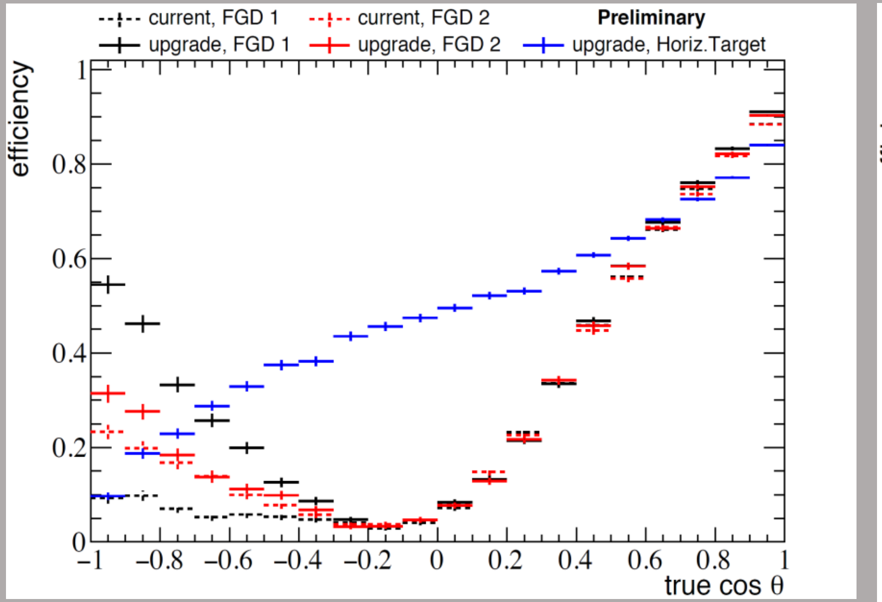
- Good vertex activity sensitivity, short tracking
- Expect recoil resolution to be similar to better than MINERvA
- Muon resolution and acceptance better than MINERvA
- High statistics
- Much work in CC0pi modeling and resonance, perhaps go to lower nu_o
  (at lower nu_o, include lower neutrino energies, lower p_μ reach is good)
- Can provide good, independent low-nu flux for use in LAr CCQE analyses

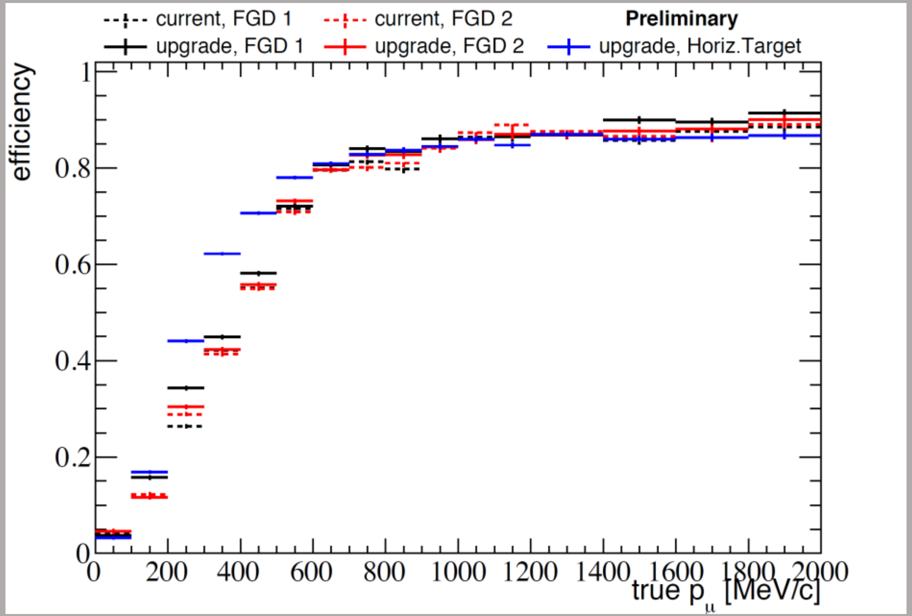
- 3DST may be able to do low-nu for ν_e and get an independent measure of the ν_e flux
  Needs study

ν_μ CC inclusive production

- Expect 8.4×10^6 events per year
- Performance depends to some extent on detectors outside 3DST

From T2K upgrade proposal

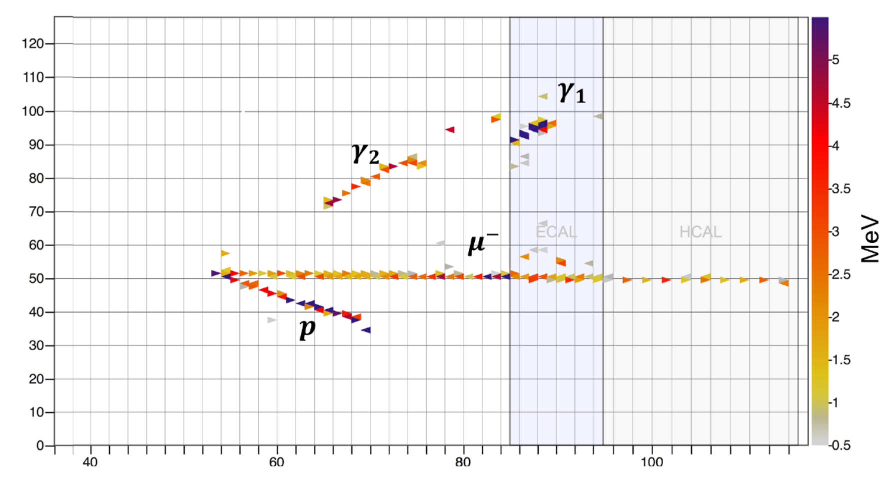


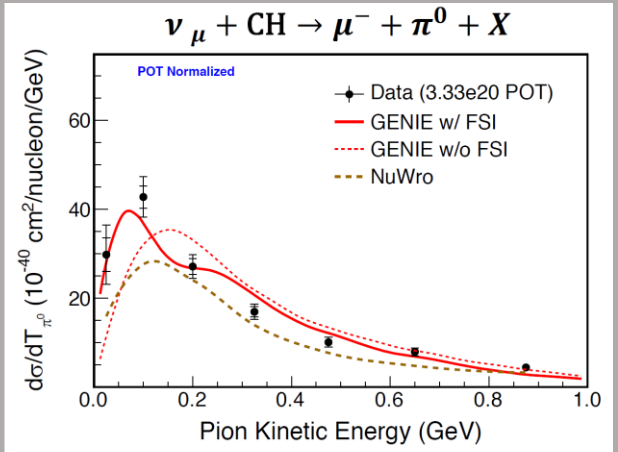


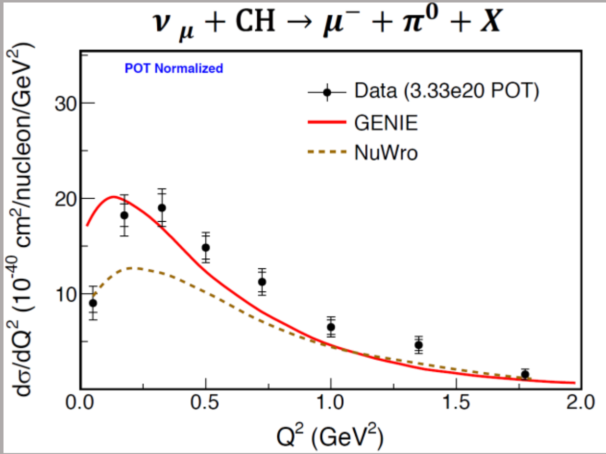
SuperFGD efficiency (with side TPCs) shown as function of cosθ and pμ
(T2K flux is at low neutrino energy compared to DUNE, B higher for DUNE ND)
SuperFGD curves are blue

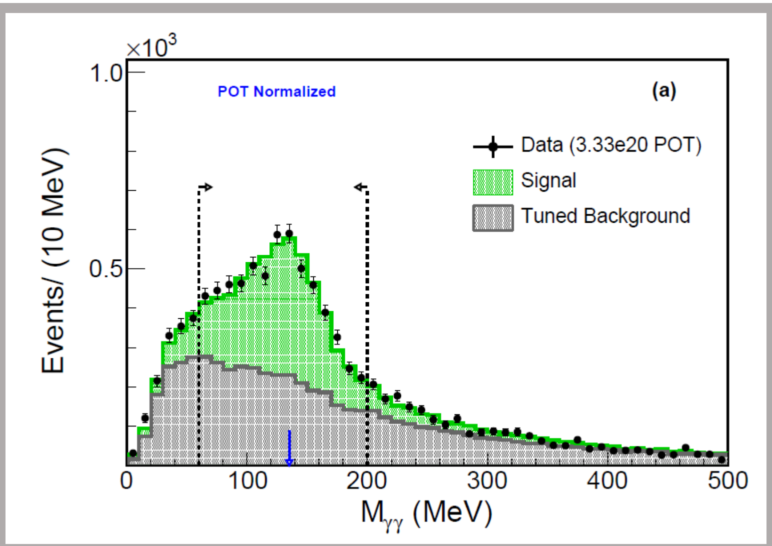
NC and CC neutral pion production

From MINERvA – Ccprotonpizero
O. Altinok et al., Phys. Rev. D96, 072003 (2017)



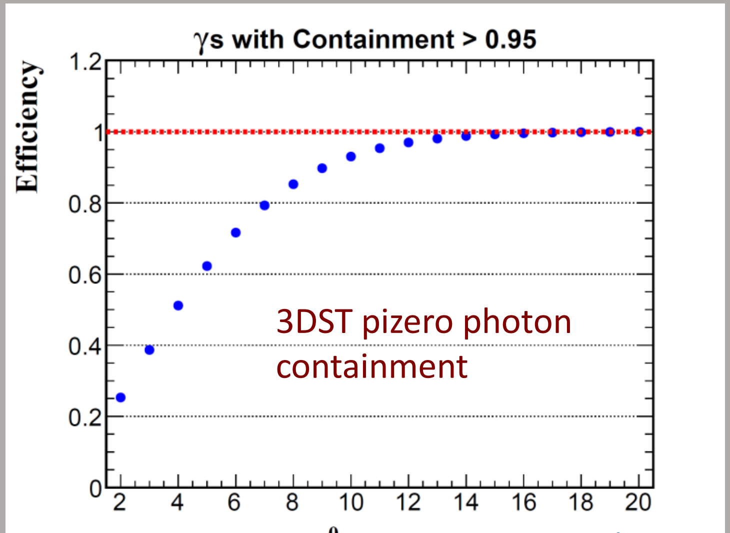






3DST:

- ➢ Fast timing
- ➢ True 3D and fine segmentation (shower clustering/pointing should be better than MINERvA)
- ➢ Photon containment
- ➢ Expect decent performance



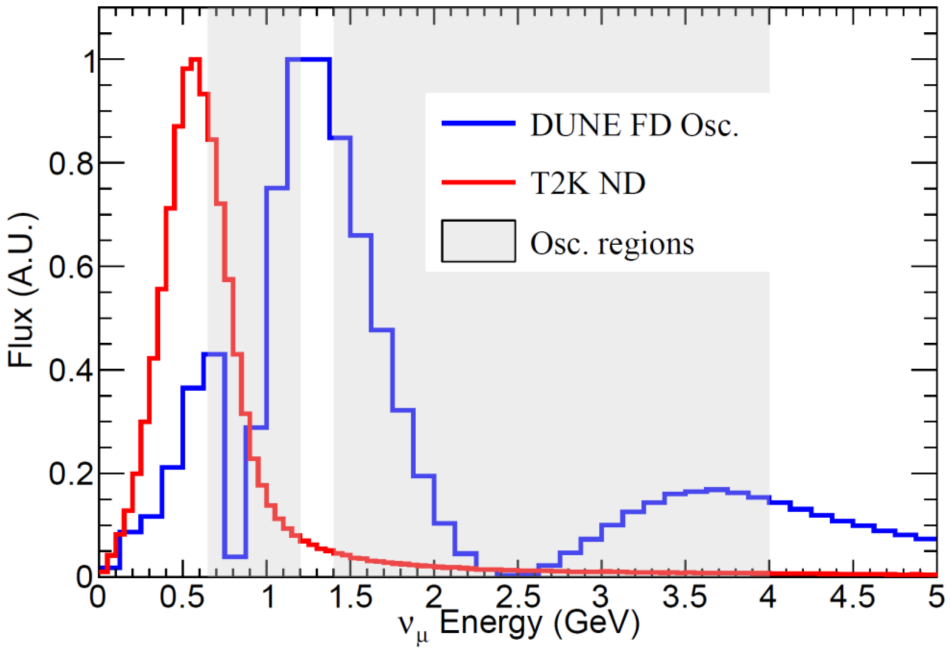
Jose Palomino

Q4: What is the physics complementarity of the 3DST to the other detectors and how does it improve to CP sensitivity?

Unique features:

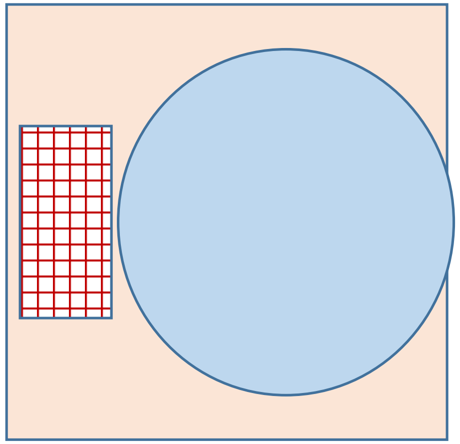
Transparent connection to vast plastic data trove from MINERvA, T2K

Able to compare to functionally identical detector (SuperFGD) in T2K narrow-band beam that is situated conveniently in the region of the DUNE second oscillation max.

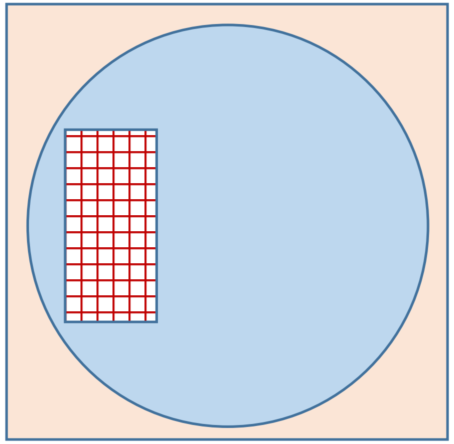


10 cm FV cut at upstream side and sides of 3DST
no FV cut at downstream side

3dst								1.64E+06
Height	width	depth	Mass	FV mass	3DST CC numu ev/year	CC numu ev in FV/year	Frac TPC vol removed	TPC CC numu per year
2	2	2.5	10.6	8.2	1.55E+07	1.20E+07	0.47	8.69E+05
2	2	2	8.48	6.5	1.24E+07	9.53E+06	0.35	1.07E+06
2	4	2.5	21.2	17.4	3.10E+07	2.54E+07	0.47	8.69E+05
2	4	2	16.96	13.8	2.48E+07	2.01E+07	0.35	1.07E+06
1.5	2	2	6.36	4.7	9.29E+06	6.88E+06	0.33	1.10E+06
1.5	4	2	12.72	9.9	1.86E+07	1.45E+07	0.33	1.10E+06
1.5	4	1.5	9.54	7.3	1.39E+07	1.07E+07	0.21	1.30E+06
1.5	2.5	1.5	5.96	4.4	8.71E+06	6.48E+06	0.21	1.30E+06



2 m 3DST depth removes 63% TPC active volume



2 m 3DST depth removes 35% TPC active volume (for 2 m high 3DST)

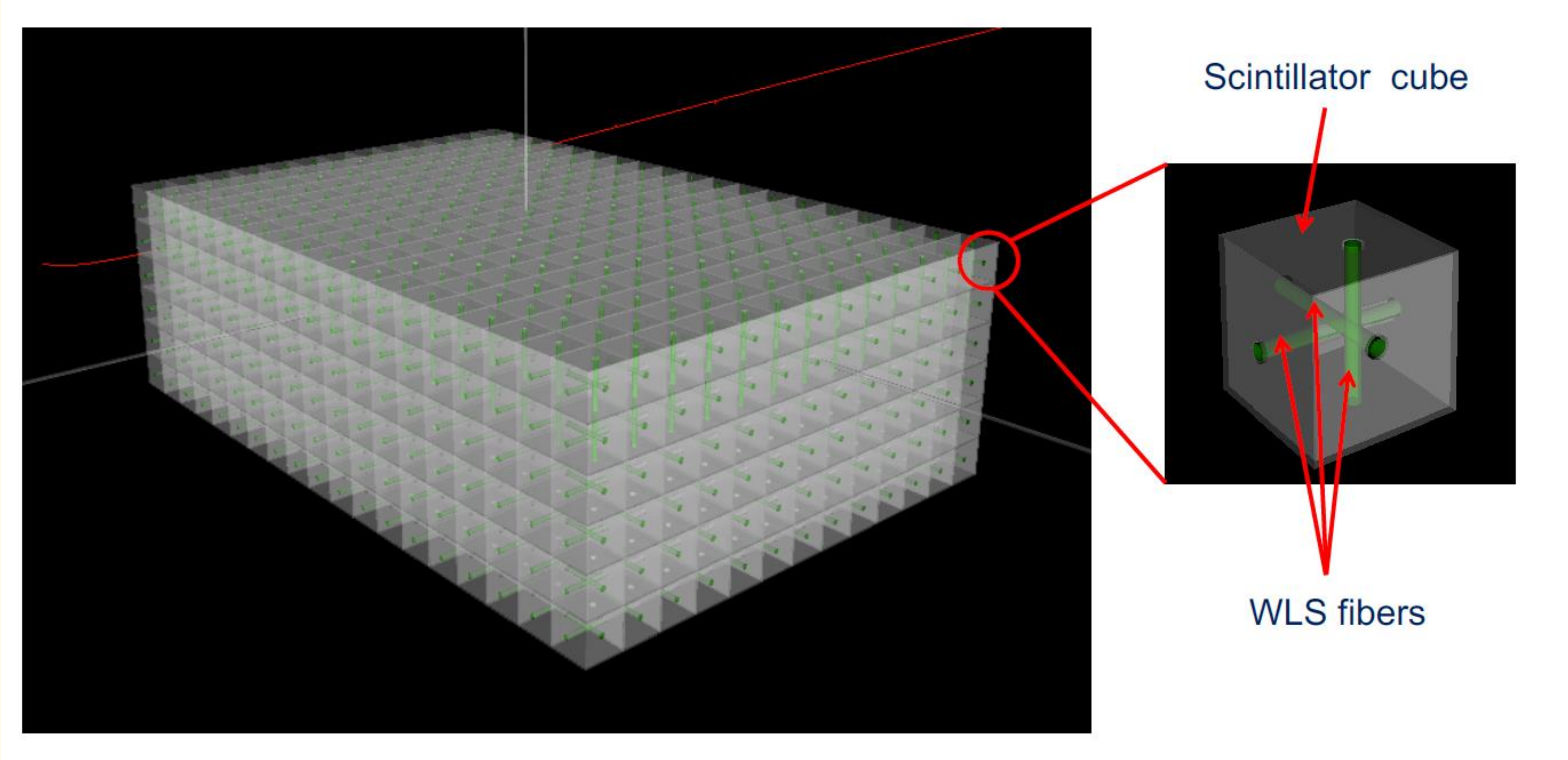
Scaling 1t FV events in TPC by the fraction of active volume retained after removal of 3DST region, ignoring region to transverse sides of 3DST, not adjusting TPC FV cuts

For illustration, could insert a 2x4x2 m^3 3DST in HPTPC and get 20 million events in the 3DST FVwith a loss of 1/3 of the high resolution vertex events

Overview of 3DST complementarity to other potential parts of ND

	3DST gives additional capability relative to or when coupled with		
Characteristic	LAr	HPTPC	STT
Photon conversion in tracker (help understand backgrounds and pizeros)		●	
Fast timing	●	●	
Neutron sensitivity	●	●	●
Sign selected low Pmu included in flux constraint	●	●	
Larger angular acceptance (good Pmu) in flux constraint	●		
Tracking at 90 degrees			●
High stats when LAr off axis	NA	●	●
neutrino-electron scattering with different systematics	●	●	●
low-nu flux determination with sample independent of LAr CCQE	●	●	●
Sign separate pions for xsec	●		
High stats connection to plastic data	●	●	●
Detector similar to superFGD in T2K beam	●	●	●

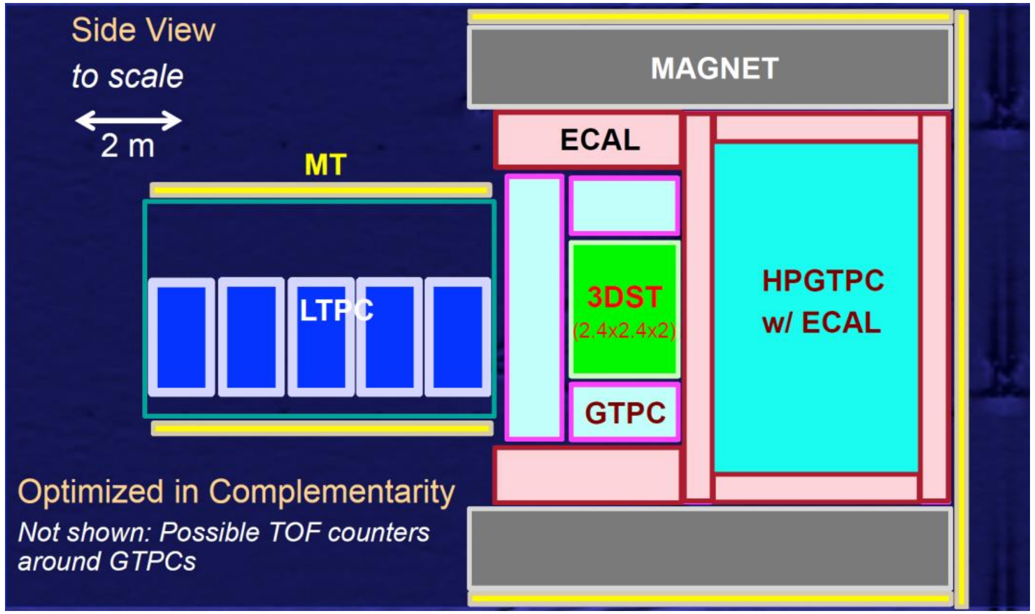
Backups



Sharing of the magnetic volume

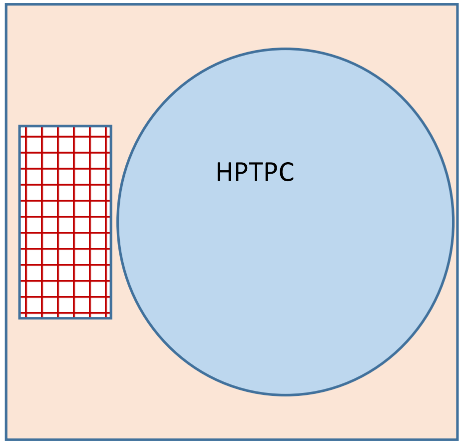
For concept study: inner volume = 4.5x4.5x8 m^3

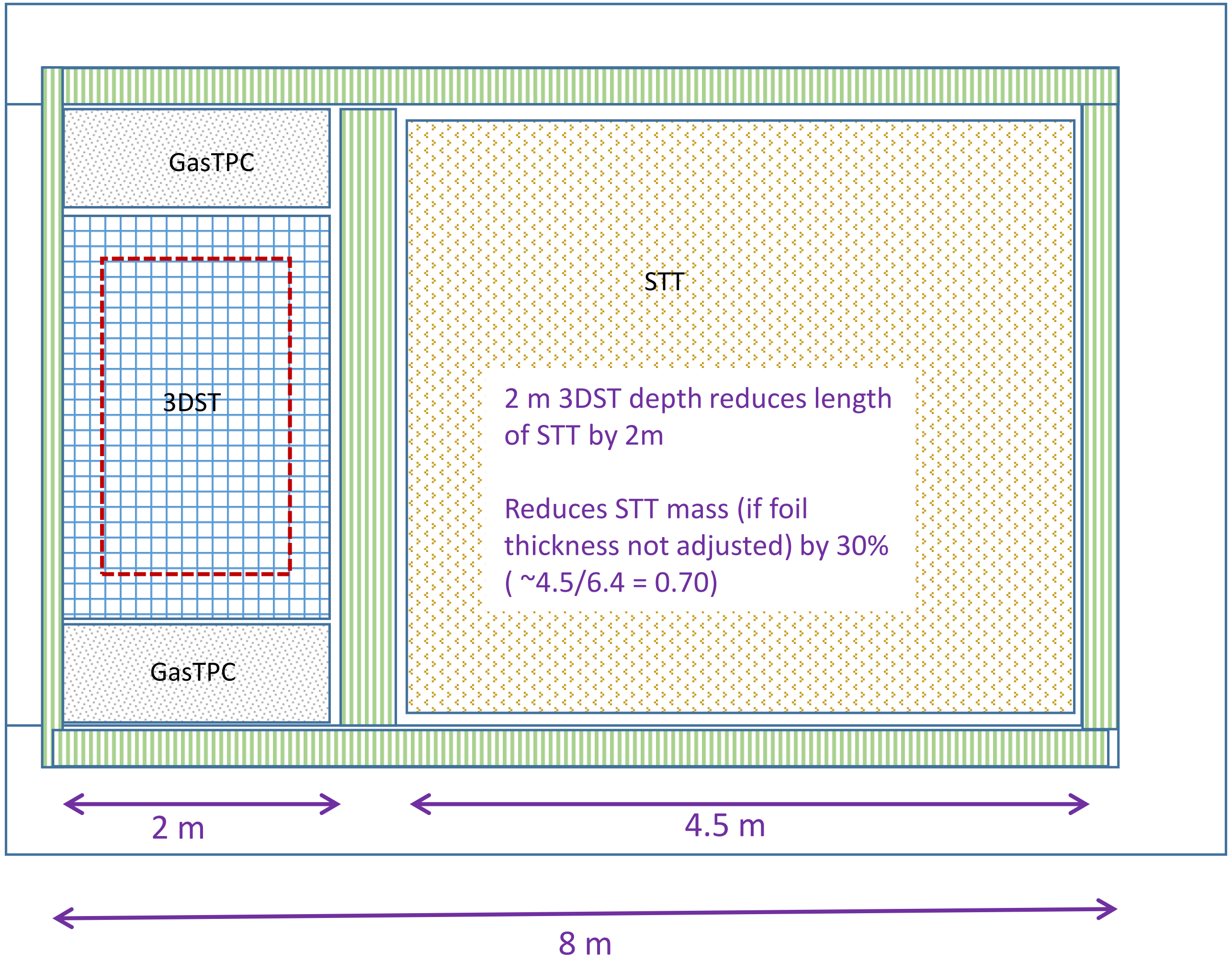
New build dipole, dimensions not yet fixed, but what are tradeoffs if we use concept study dimensions?

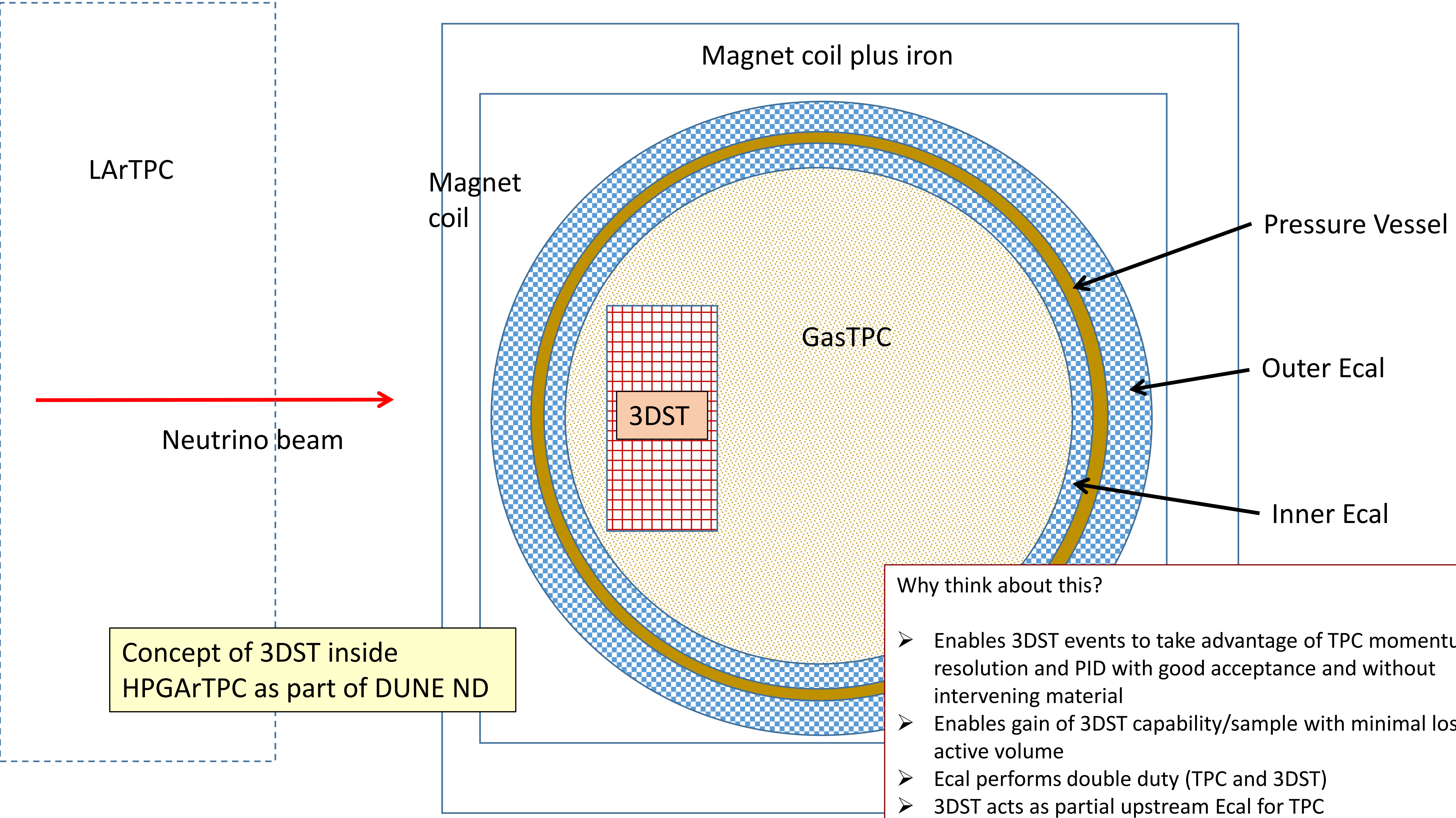


2 m 3DST depth reduces diameter of HPTPC by 2m

removes 63% TPC active volume



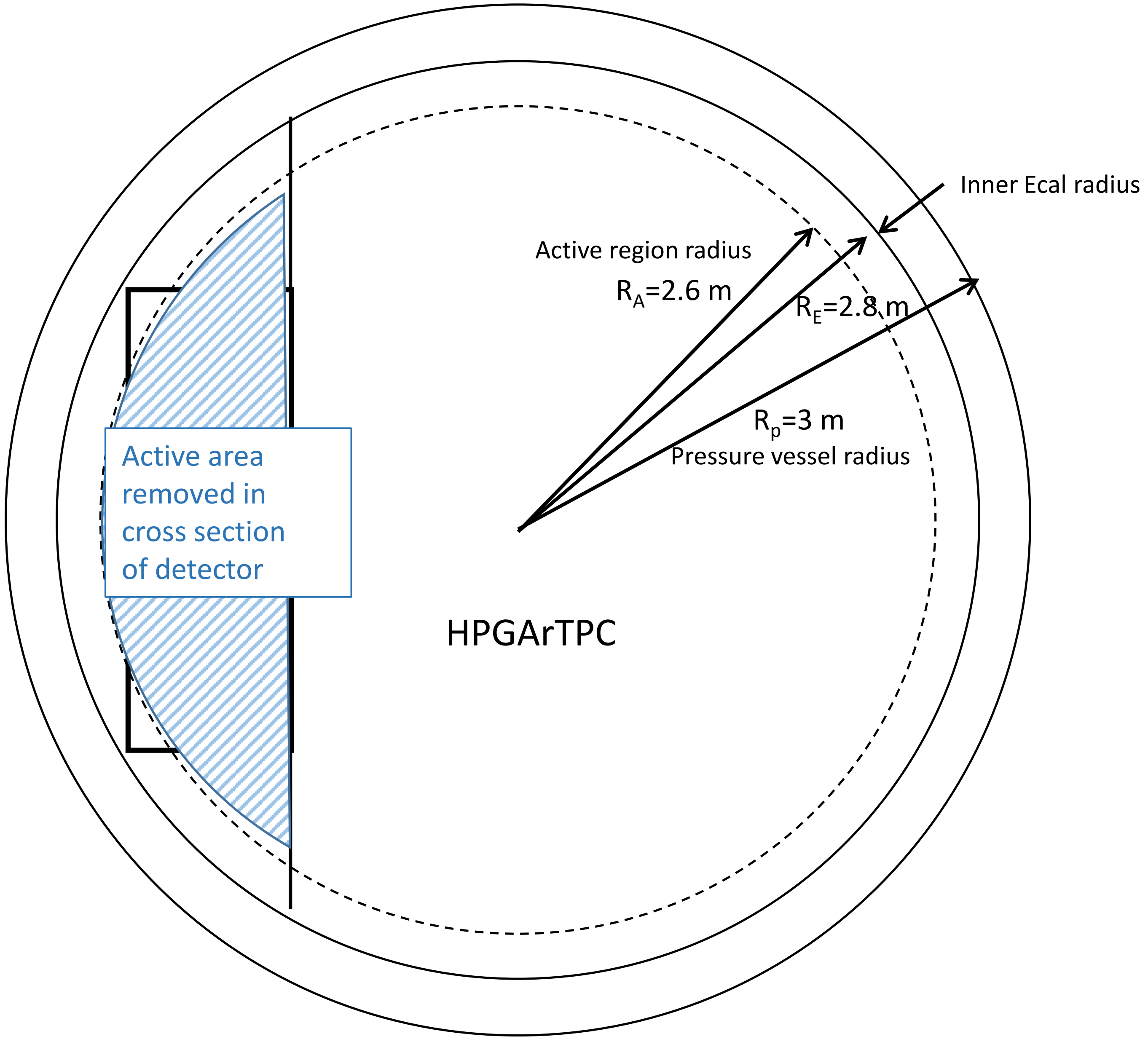


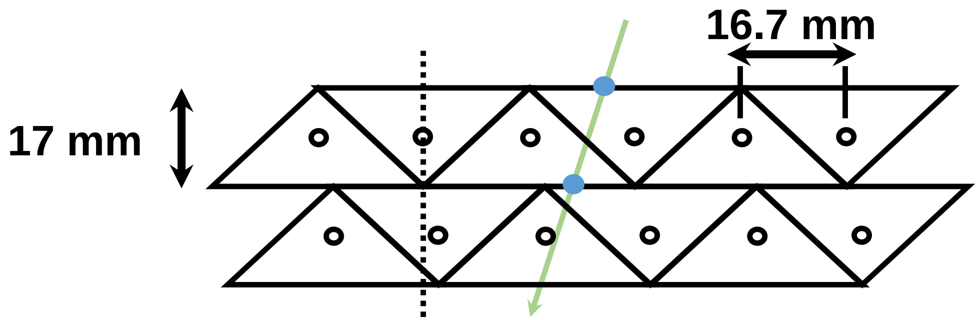


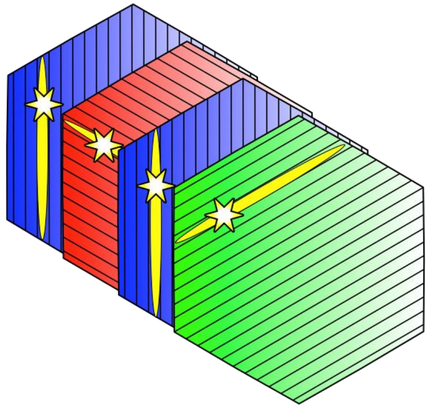
Concept of 3DST inside HPGArTPC as part of DUNE ND

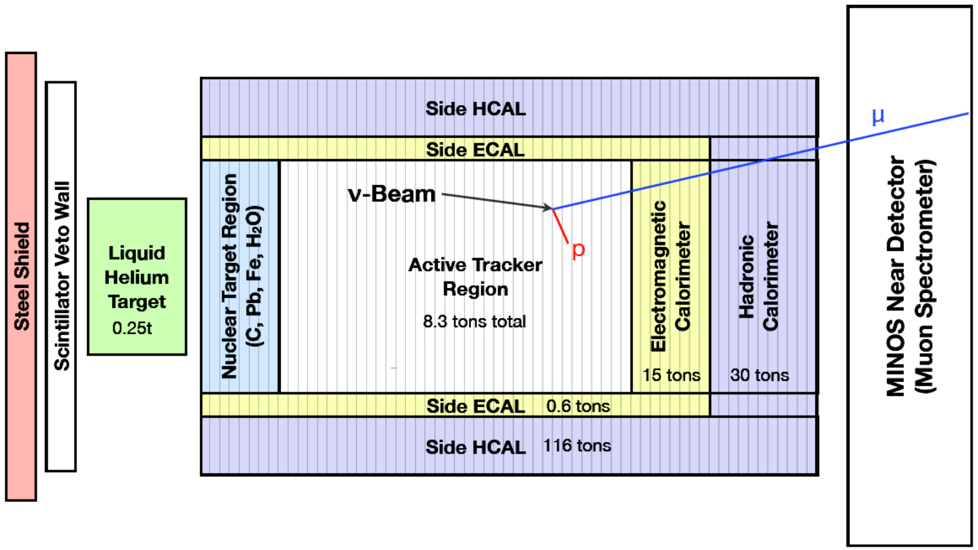
Why think about this?

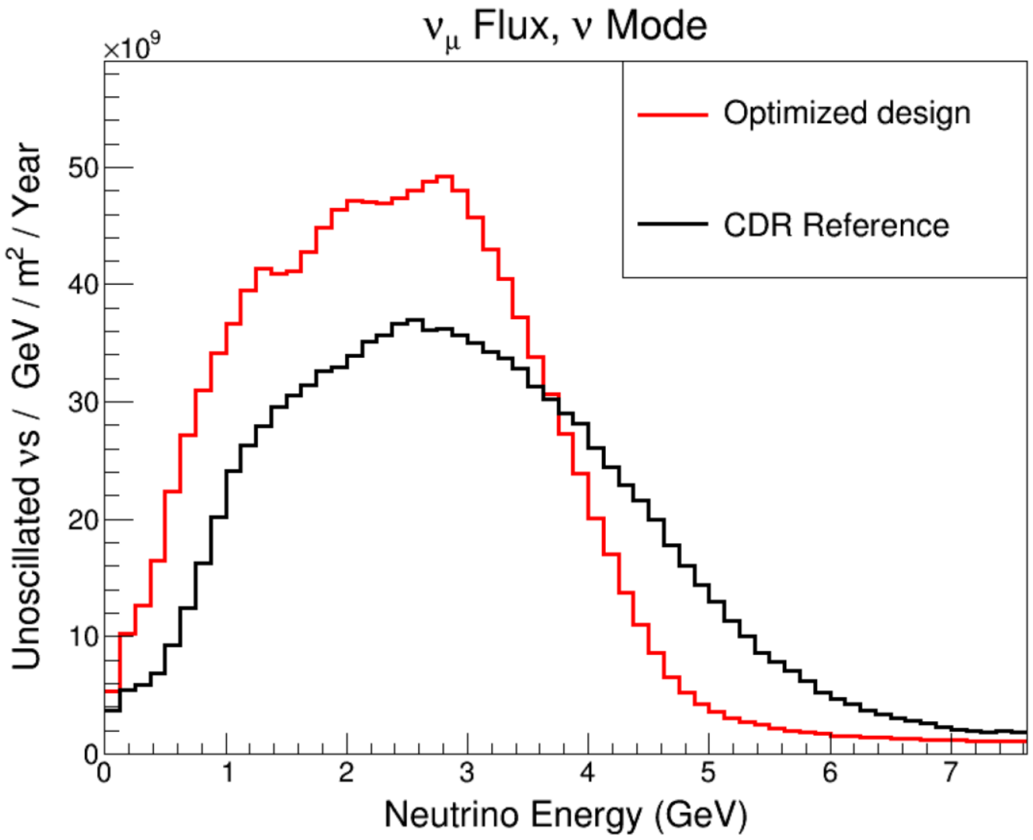
- Enables 3DST events to take advantage of TPC momentum resolution and PID with good acceptance and without intervening material
- Enables gain of 3DST capability/sample with minimal loss in TPC active volume
- Ecal performs double duty (TPC and 3DST)
- 3DST acts as partial upstream Ecal for TPC


Inner Ecal radius
Active region radius
R_A=2.6 m
R_E=2.8 m
R_p=3 m
Pressure vessel radius
Active area removed in cross section of detector
HPGArTPC

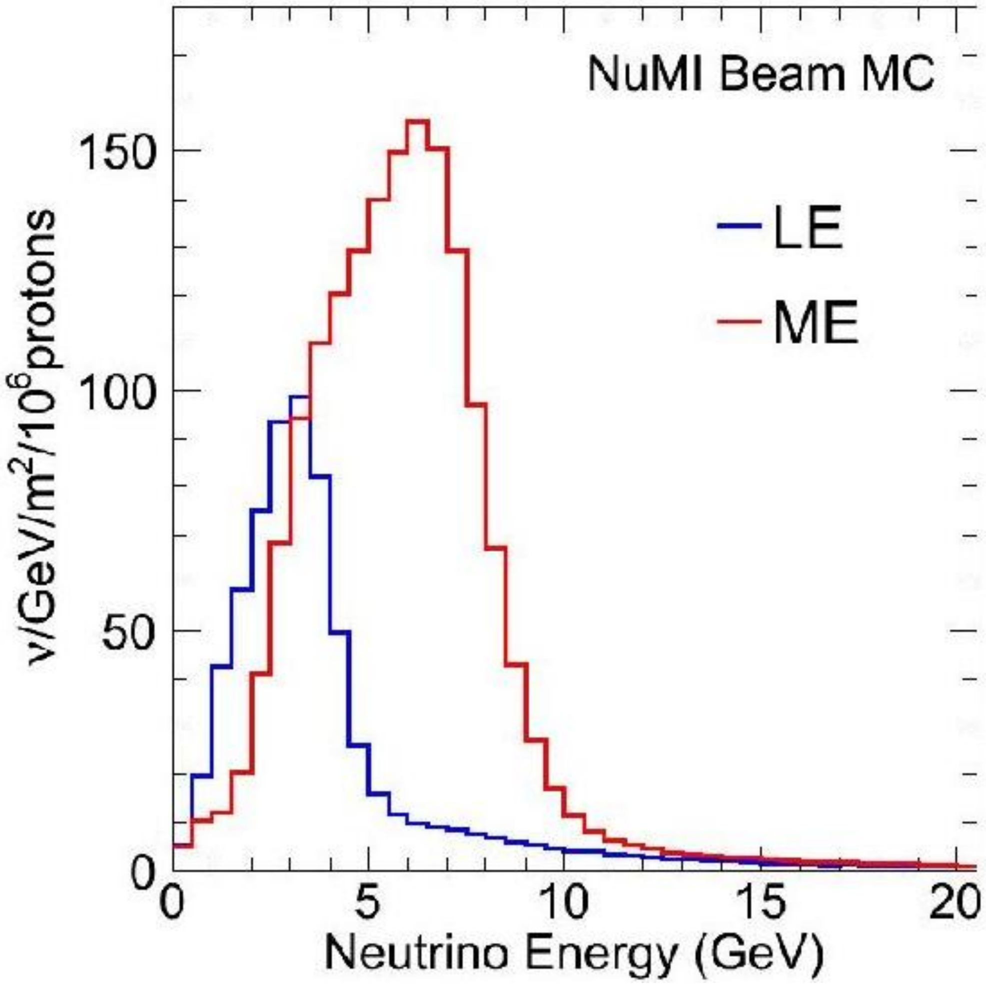

16.7 mm
17 mm




Steel Shield
Scintillator Veto Wall
Liquid Helium Target
0.25t
Nuclear Target Region
(C, Pb, Fe, H2O)
Side HCAL
Side ECAL
ν-Beam
p
μ
Active Tracker Region
8.3 tons total
Electromagnetic Calorimeter
15 tons
Hadronic Calorimeter
30 tons
Side ECAL 0.6 tons
Side HCAL 116 tons
MINOS Near Detector
(Muon Spectrometer)

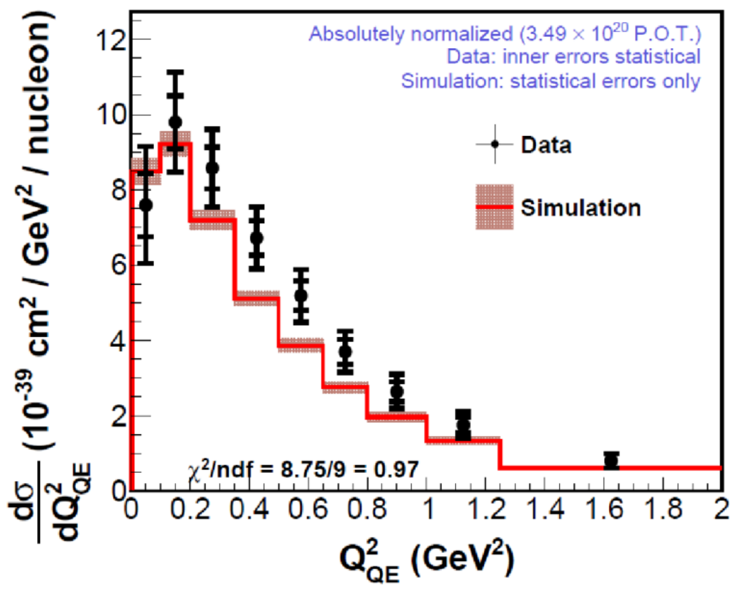


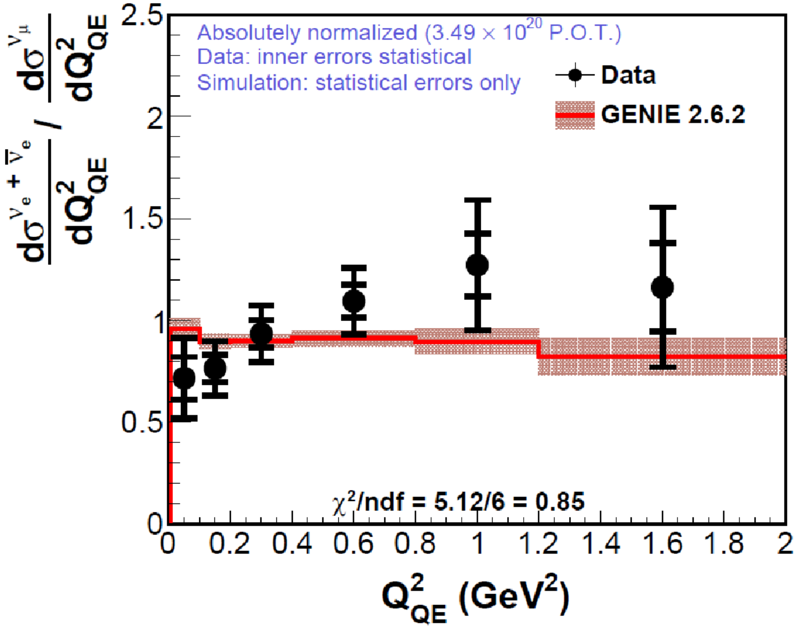
νμ Flux, ν Mode
×10^9
Optimized design
CDR Reference
Unoscillated νs / GeV / m^2 / Year
Neutrino Energy (GeV)
0
1
2
3
4
5
6
7
10
20
30
40
50

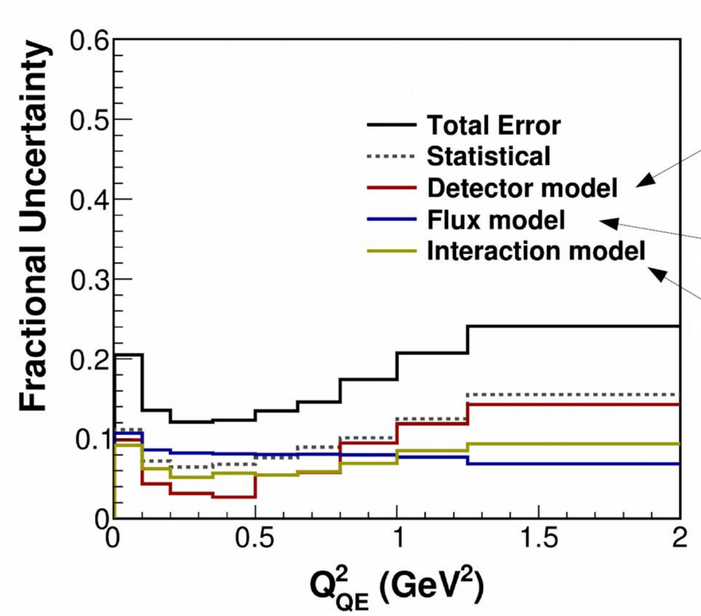


NuMI Beam MC
LE
ME
ν/GeV/m^2/10^6protons
Neutrino Energy (GeV)
0
5
10
15
20
50
100
150

nue/numu <1%?



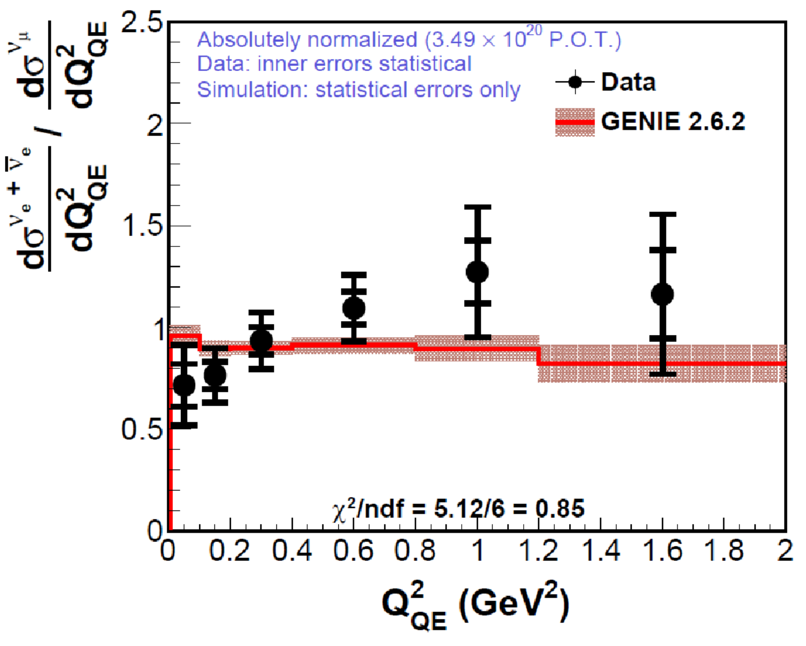


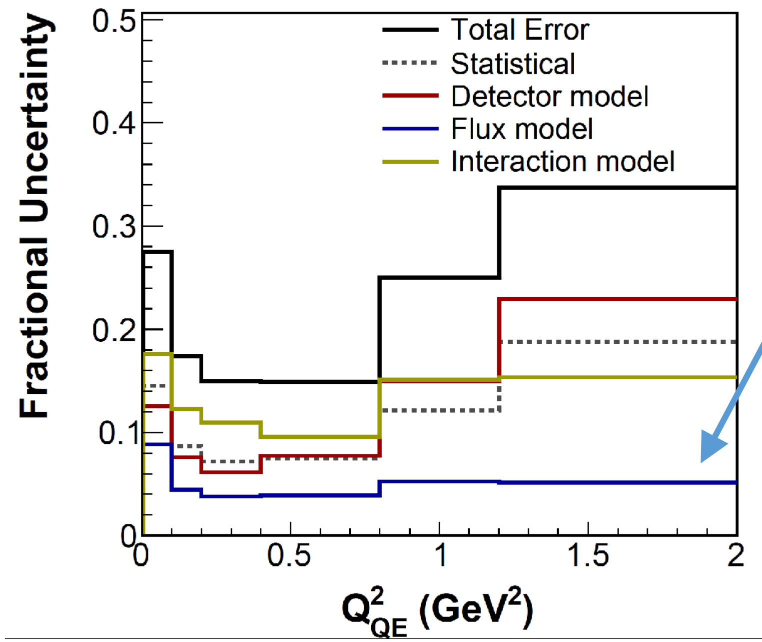


Includes energy scale estimated using the π^0 mass peak in a separate measurement; resolutions; other detector effects

Constrained as noted previously

Mostly enters in background subtraction (from GENIE 2.6.2)





Flux model error is dominated by kaon production and tertiary production (re-interactions upstream of neutrino production, say in the horns)

1% is an aggressive goal. If LBNF post-horn hadron measurements happen, seems hopeful. Also the nue, nuebar separation with DUNE and maybe the NC pizero and nue-, nuebar-CC separation will help.

SuperFGD / 3DST R&D and test beam plans

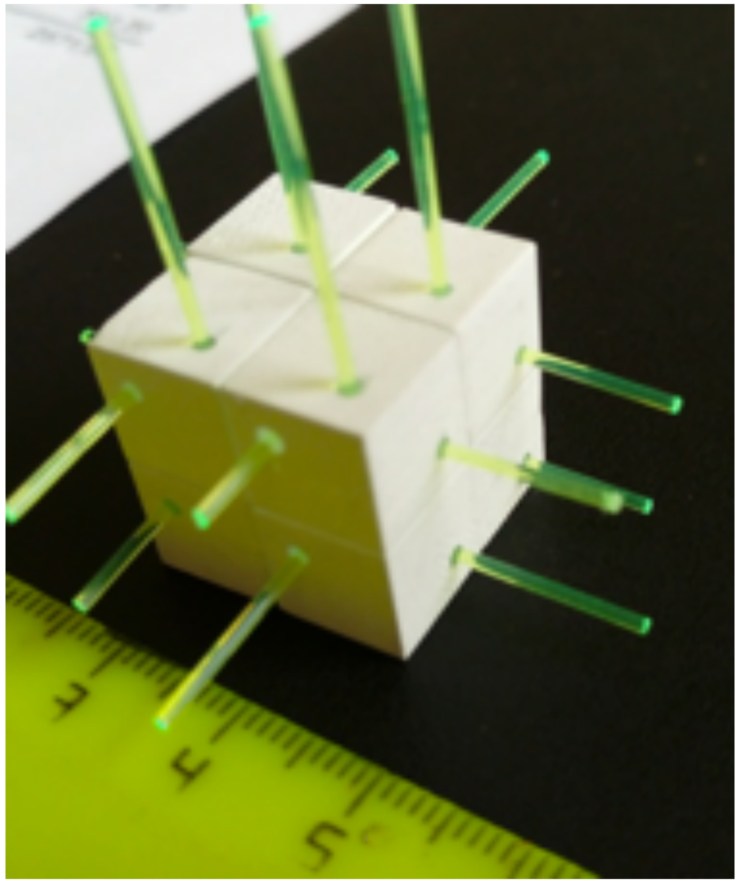
Davide Sgalaberna (CERN)

DUNE-ND workshop

23rd of March 2018

Introduction

- New detector concept for active targets in neutrino experiments
  - T2K is going to install this detector in the upgraded ND280 (SuperFGD)
  - institutes from both Japan and Europe are involved
- Same detector (3DST) proposed for the DUNE ND
- T2K has started an extensive R&D program in 2017
  - R&D with cosmics at INR Moscow and Japan
- Test beam at CERN in October 2017 lead by INR group
- Results useful for both DUNE and T2K projects
  - plan for joint US / Japan efforts on R&D



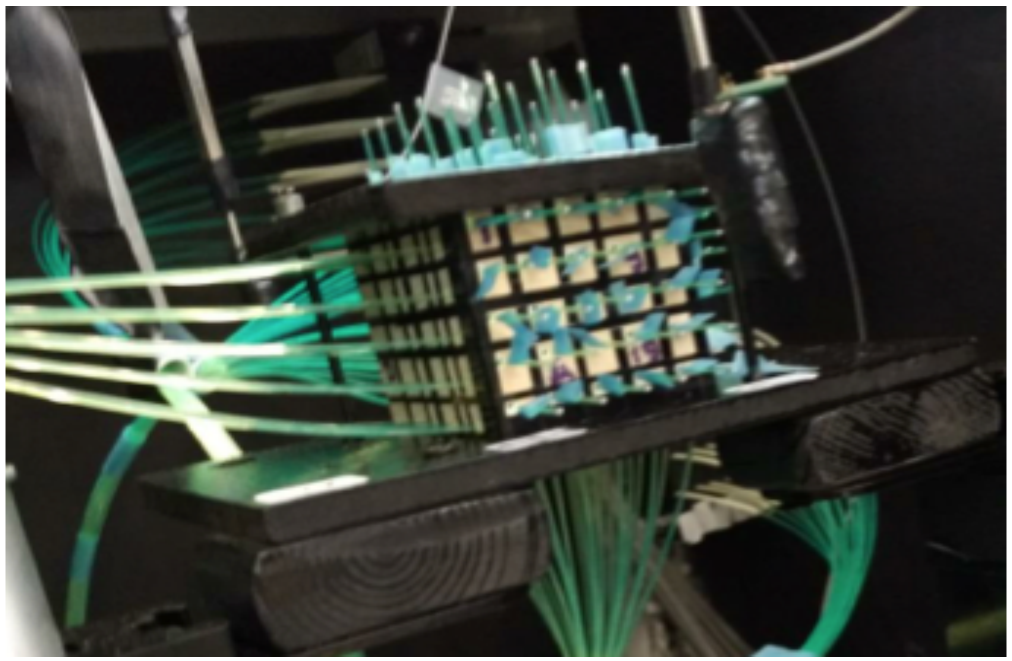
Extruded plastic scint. 1x1x1 cm^3 cube
Chemical etching as reflector (~50-100 mum thick)
3 WLS fibers (Kuraray Y11, 2-clad, 1mm) along XYZ

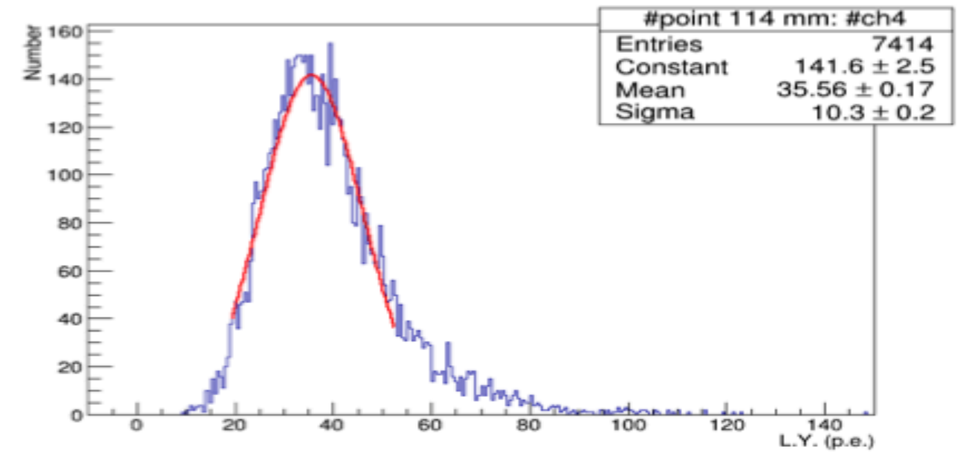
Concept described in 2018 *JINST* **13** P02006

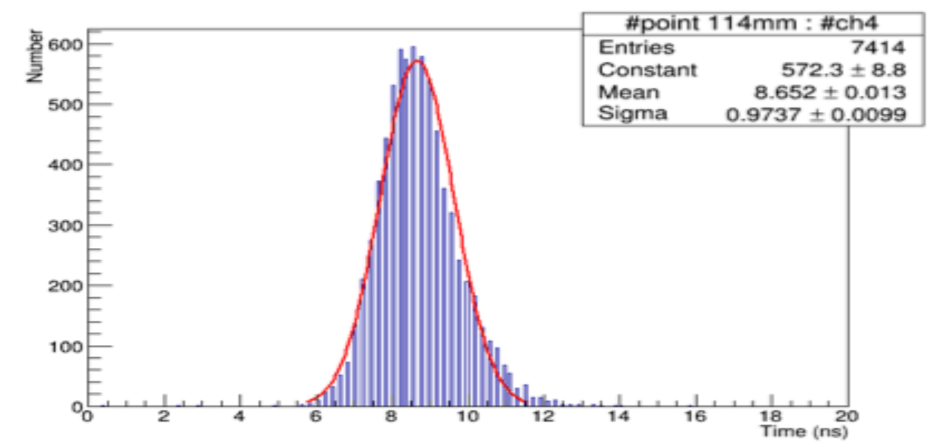
Summary of October 2017 test beams

- Prototype 5x5x5 cm^3, 6 GeV pion beam
- Test the light yield in WLS fibers transverse to beam direction

A.Khotjantsev, O.Mineev

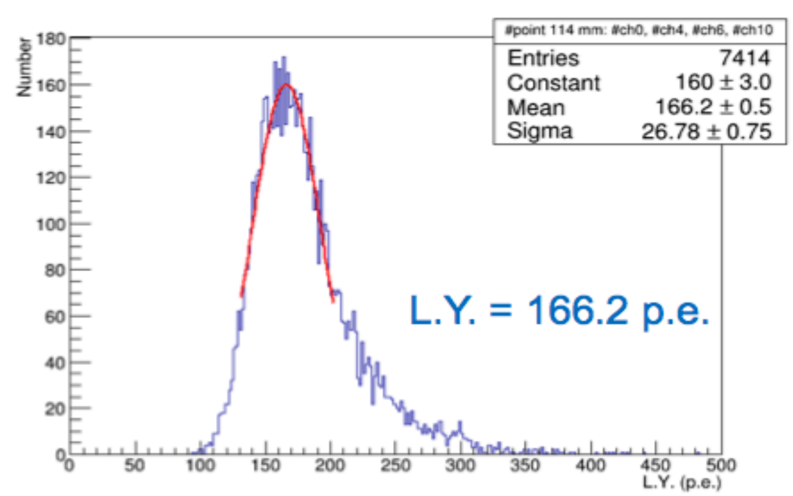


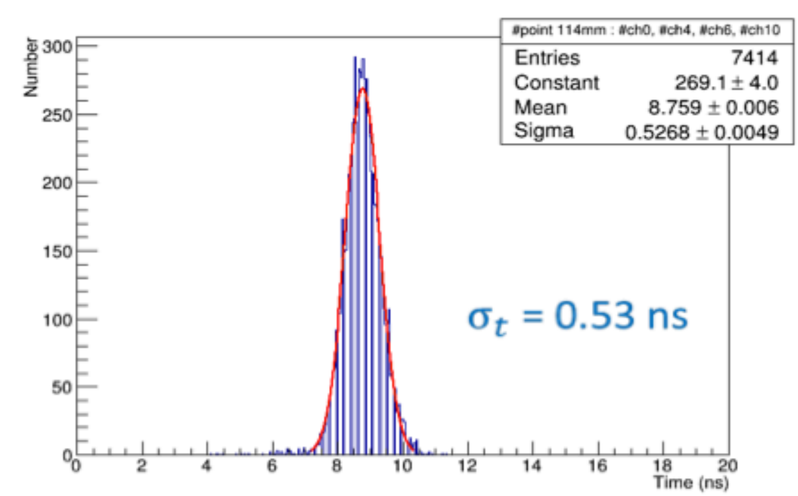




- Cross talk measured upper value ~3.7%
- Average L.Y. ~ 41 p.e. / fiber

- Very good time resolution
- Average $\sigma_t \sim$ 0.92 ns / fiber
- Average $\sigma_t \sim$ 0.53 ns / 4 fibers (2 cubes)

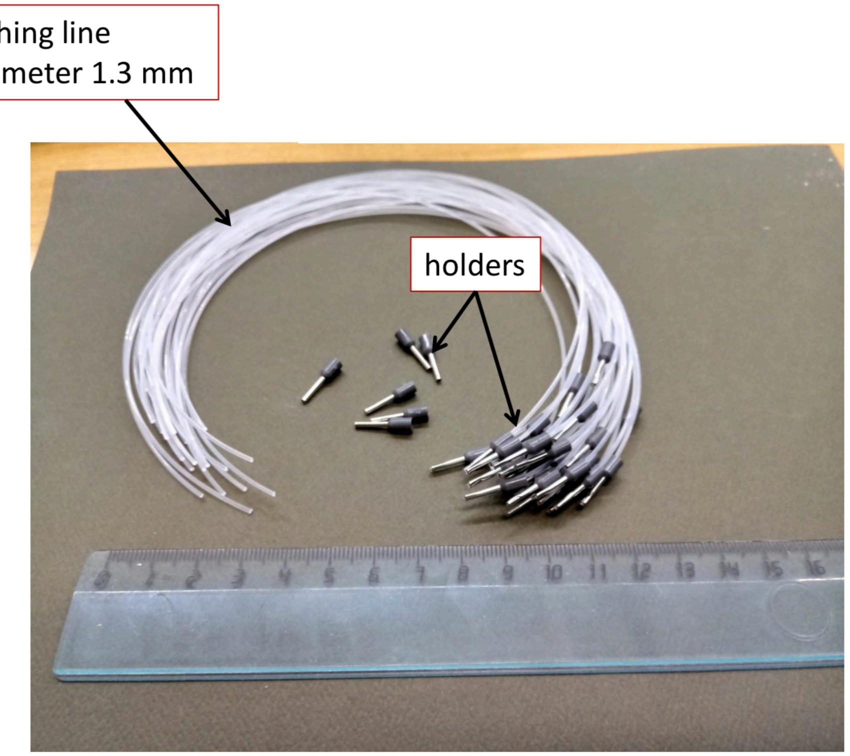


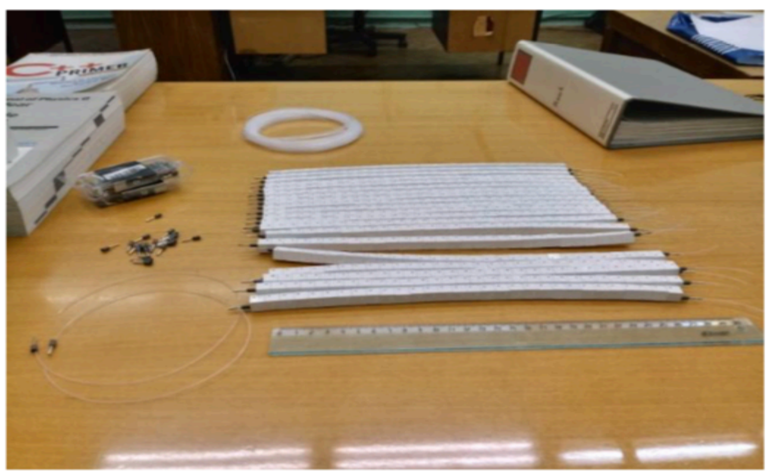


- Results are very promising and show unprecedented performances
- More details in https://indico.fnal.gov/event/14581/session/5/contribution/80/material/slides/0.pdf

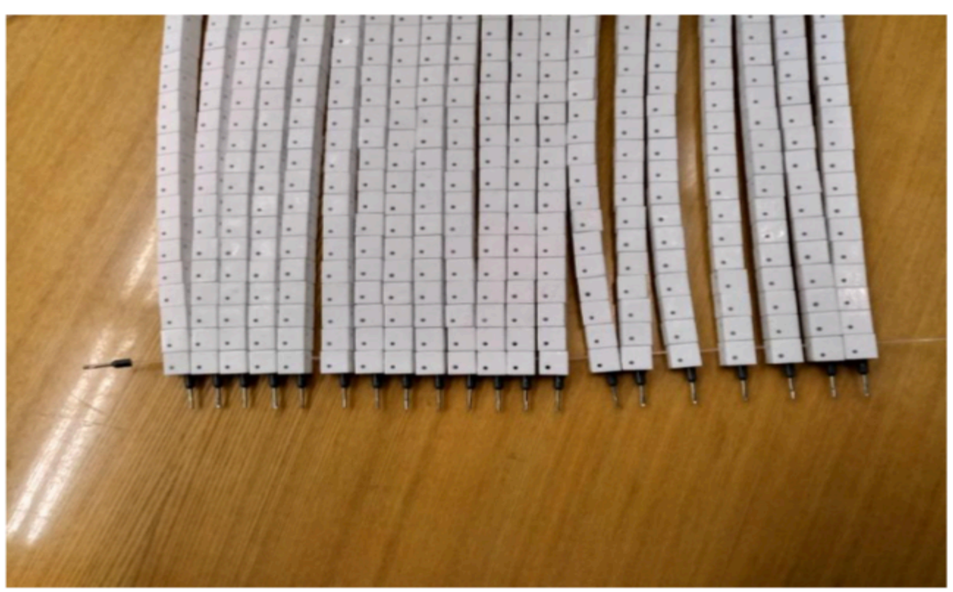
R&D on detector assembly

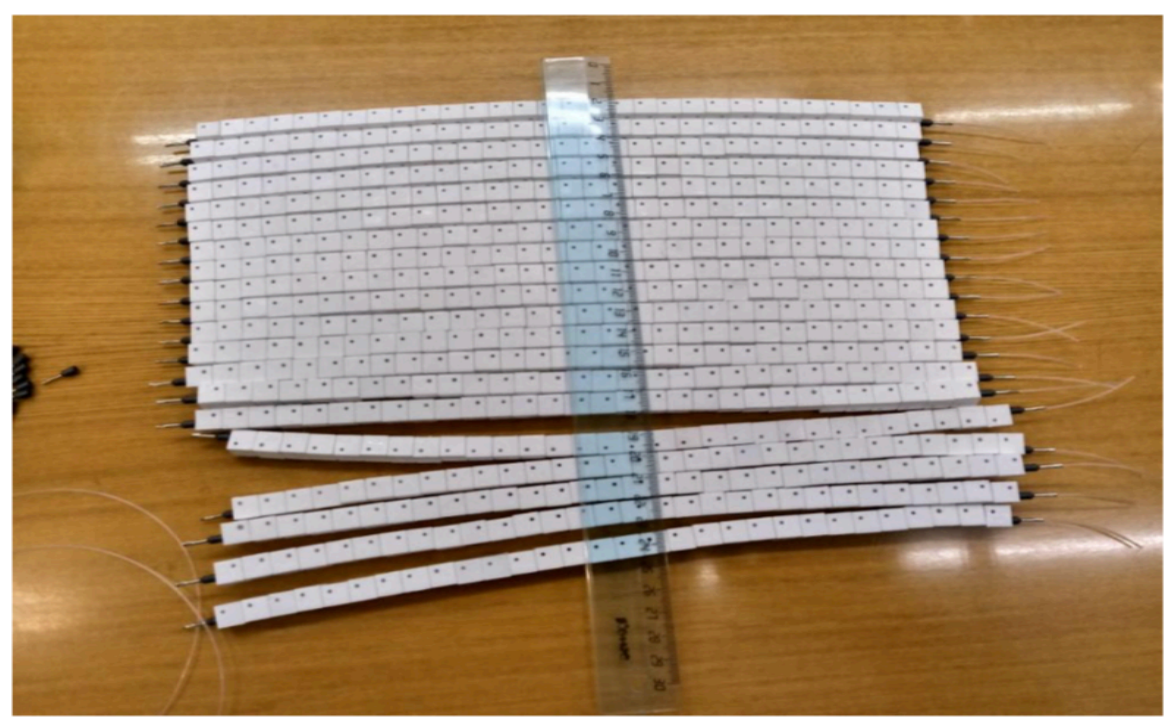
- Studies performed at INR Moscow
- Method:
  - use fishing lines for assembly to align the cubes
  - replace fishing line by WLS fibers





- Method tested with cubes of ~100 microns tolerance
- R&D ongoing to lower tolerance down to ~30 microns

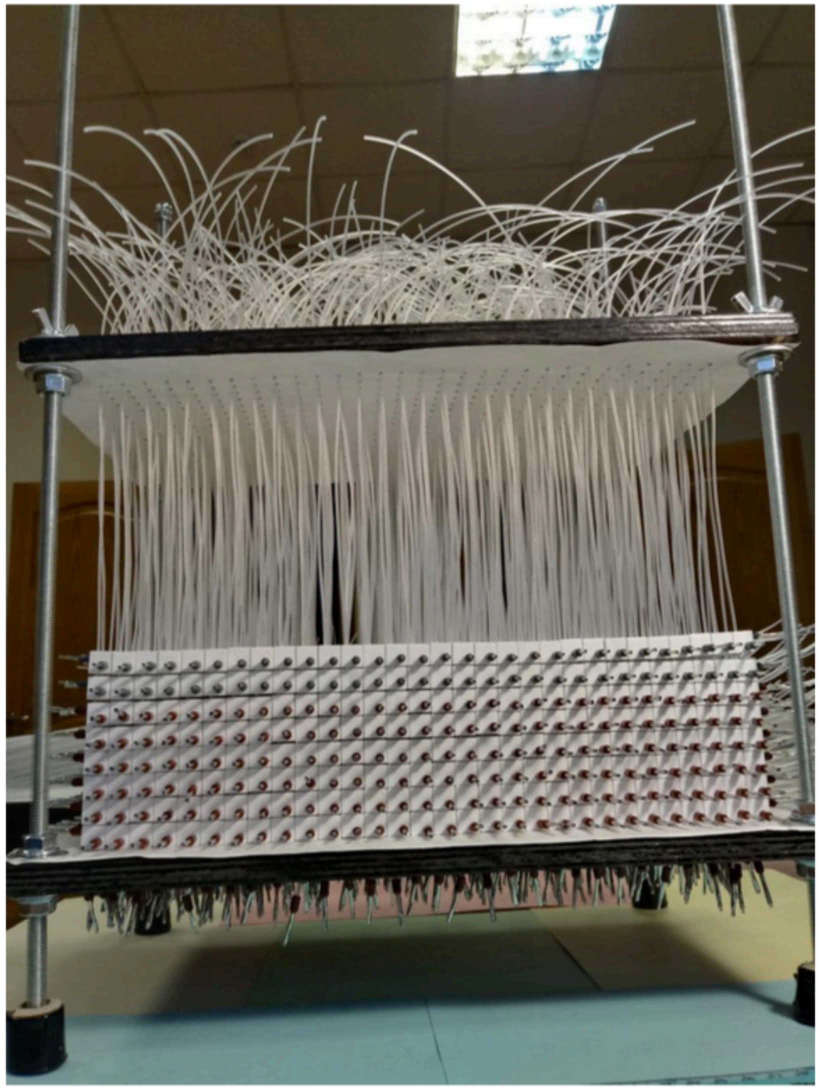


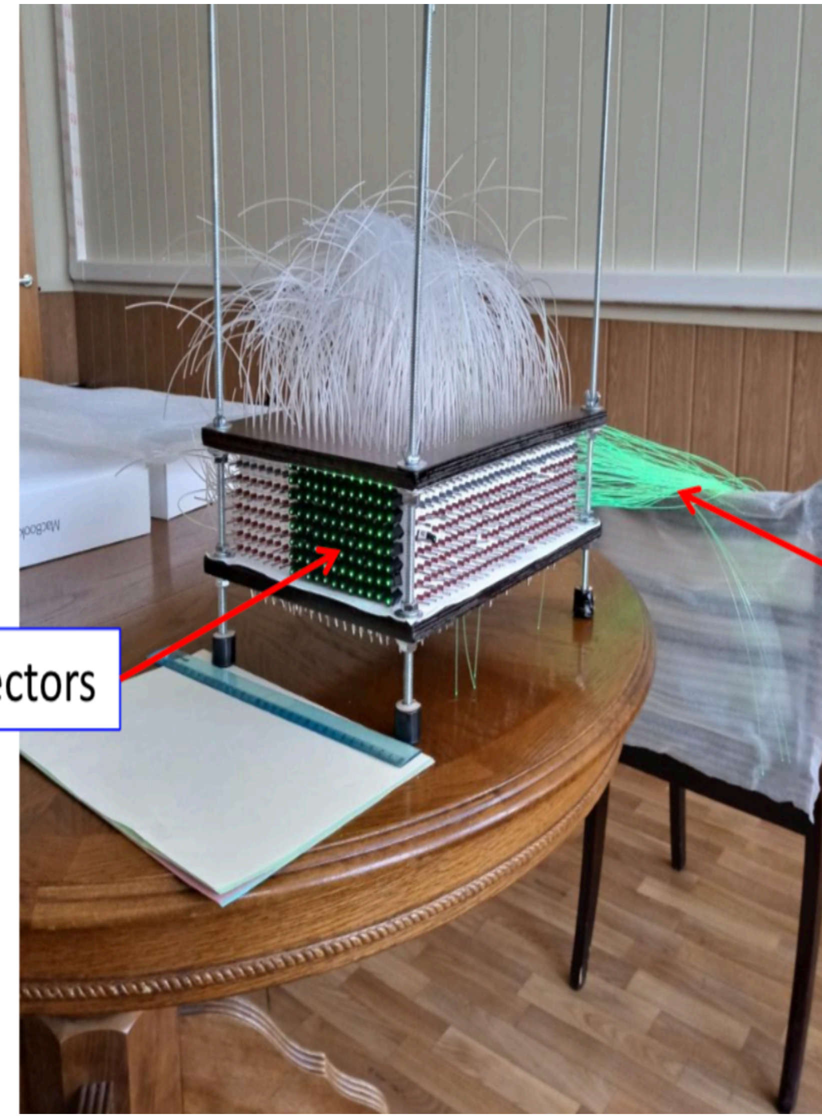


R&D on detector assembly

- One plane consists of 600 cubes (20x30 cm^2)
- Speed of assembly ~ 1.5 hours / person (not trained), quite fast
- It can be easily parallelized with more people

R&D on detector assembly

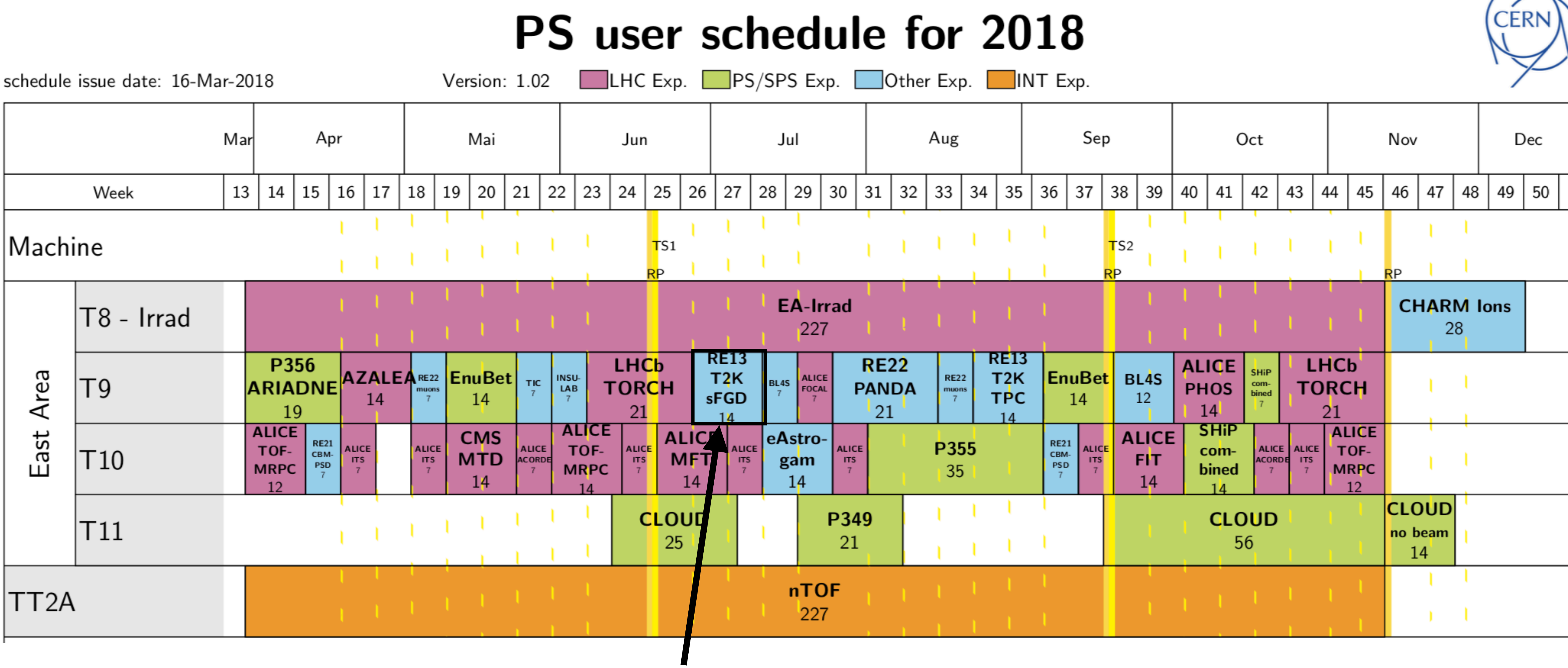




$20x30x8\ cm^3$

- Procedure tested with available cubes (~5k) —> works fine
- Insertion of WLS fibers is straightforward: cubes are aligned by fishing lines
- Assembly procedure not difficult and relatively fast (can be done in parallel)
- More tests with longer piles of cubes (up to 2m) are ongoing
- Expect assembly procedure even easier with improved tolerance

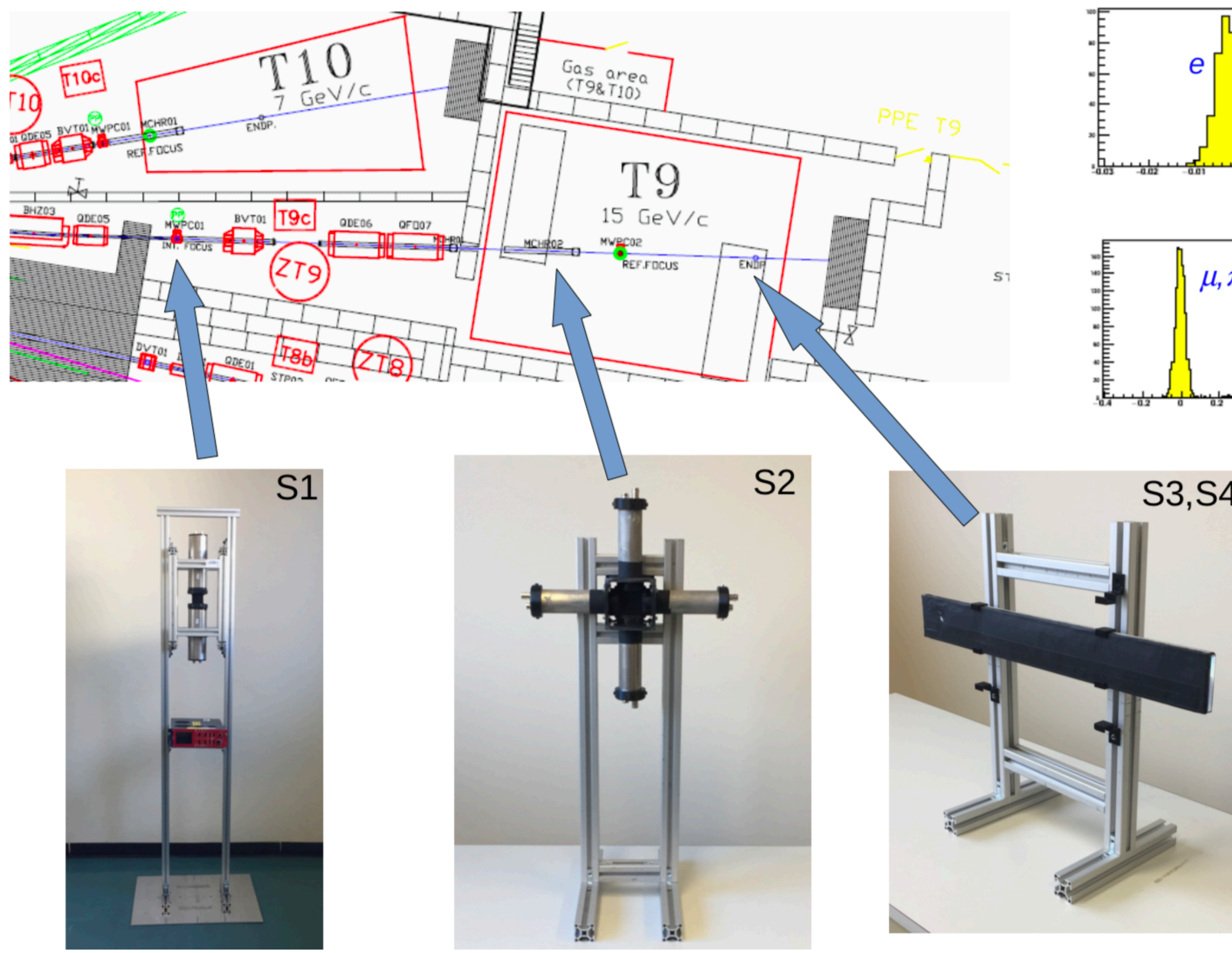
Beam test program at CERN

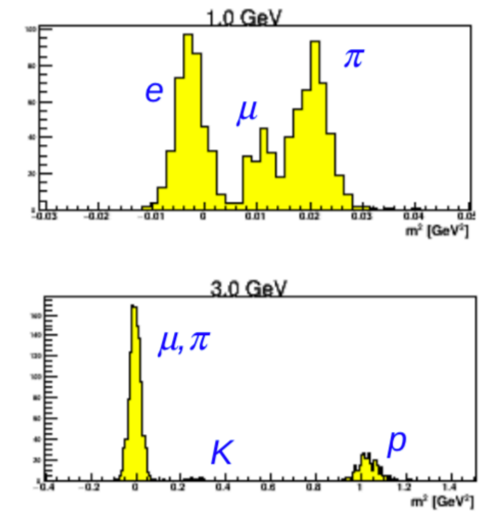


- Beam tests will be made by T2K-ND upgrade collaboration
- 2 weeks assigned in June/July in T9 area
- More precise characterization of SuperFGD / 3DST wrt previous test beams with a bigger prototype
- Wide participation to test beams from Europe, Japan and US, also from institutes not joining the T2K-ND project
- Results will be useful also for DUNE (exactly same detector but bigger)

Beam test program at CERN

- The prototype is now being assembled for the test beam
  - 10k cubes: 52 (width) x 22 (length) x 8 (height) cm^3
  - aim to instrument all the 1.7k channels
  - the prototype will be put in a B-field: MNP17 magnet (0.2 - 1 T)
  - Hodoscope, Cherenkov, ToF to provide elec / proton / muon (pion) PID





2 bars:
50x6x1 cm^3
δt = 60 ps

To be set up- and downstream of SuprFGD

Beam test program at CERN

- Aim to perform the following measurements:

  - exposure to muons, electrons, pions and protons down to 0.5 GeV/c

  - response of the detector (pulse height, time resolution, tracking)

  - stopping pions / protons —> MPPC saturation

  - $\pi^+ p$ scattering to test tracking of many particles

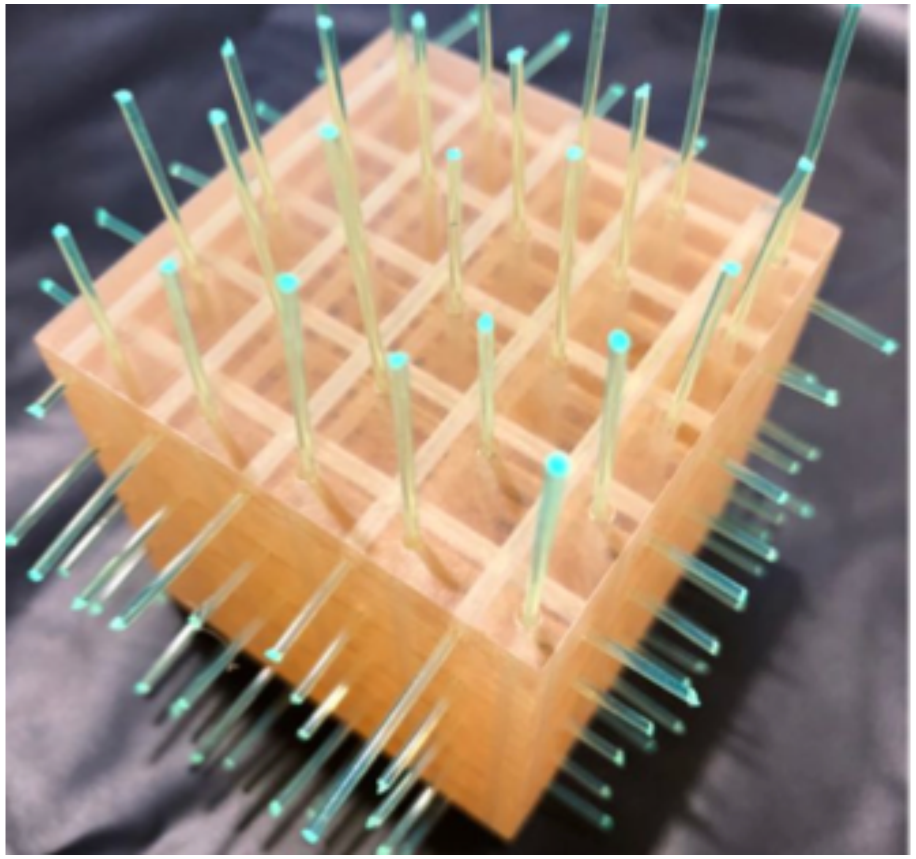
  - possibility to produce a photon beam to test e^- / gamma separation

- Wide participation to test beams from Europe, Japan and US
- Results will be useful also for DUNE (exactly same detector but bigger)

Long-term options

- Demonstrated the feasibility to assemble several thousands cubes detector
- R&D is still ongoing to further improve the cube tolerance
- Expect to scale it up to larger dimensions (at least 60x60x60 cm^3) quite easily
- Assembly time is not prohibitive and can be easily parallelized
- Another option that could be tested in the future is 3D printing of detector modules
- In arXiv:1406.4817 it's shown an example
- 3D print the scintillator and the coating
- Technique not yet established that needs R&D
- Fund request for R&D will be submitted by Stony Brook and BNL with participation of CERN and, possibly, other institutes

Matsubara-san



Conclusions

- 3DST is a high-performance detector

  - keeps all the advantages of plastic scintillators (very good PID, very good time resolution, fast, etc…)

  - enlarge the angular acceptance to 4π, reduce the particles momentum threshold, improve the time resolution

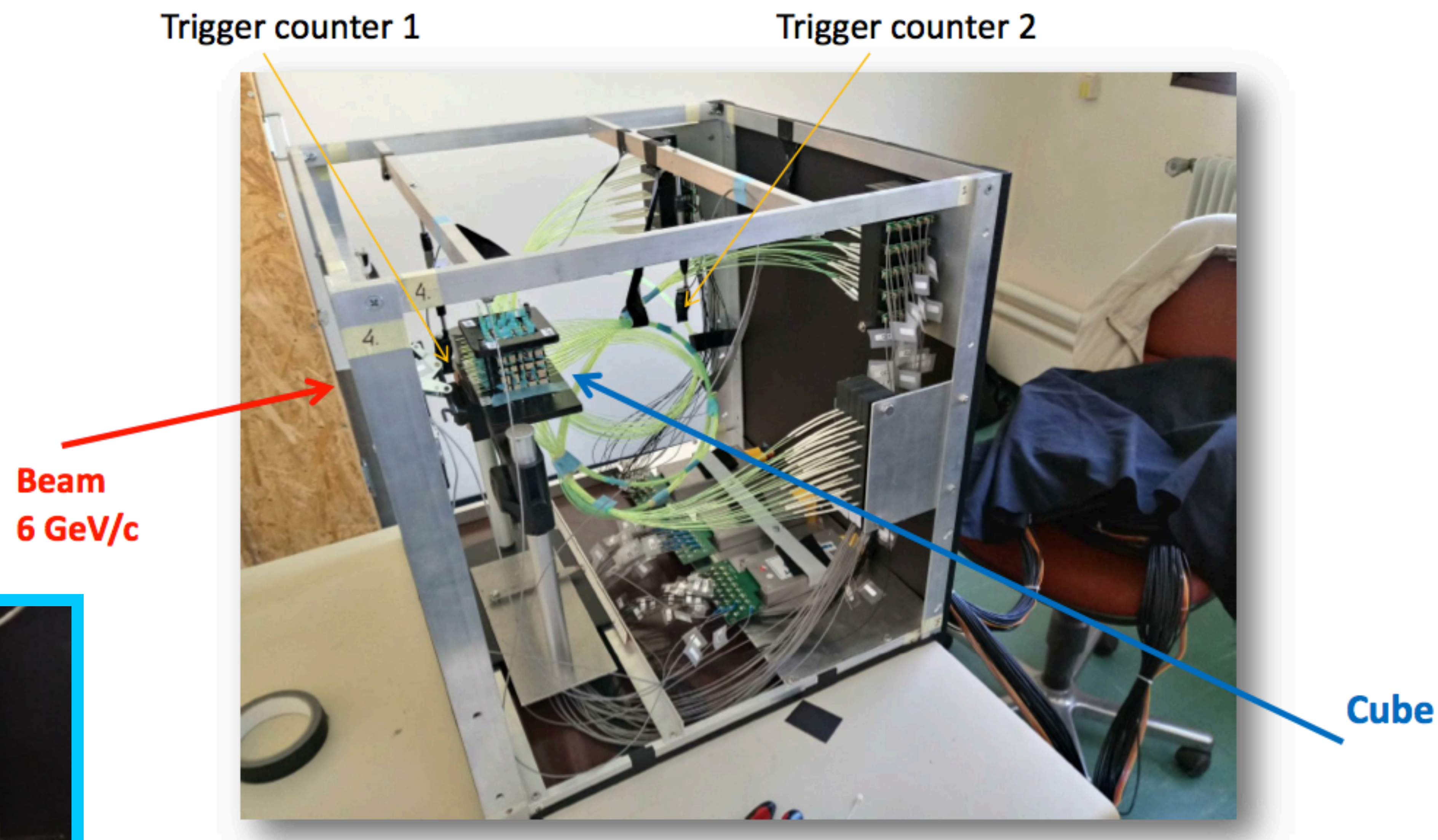
  - fine granularity (1cm^3) provides a single hit spatial resolution ~3mm

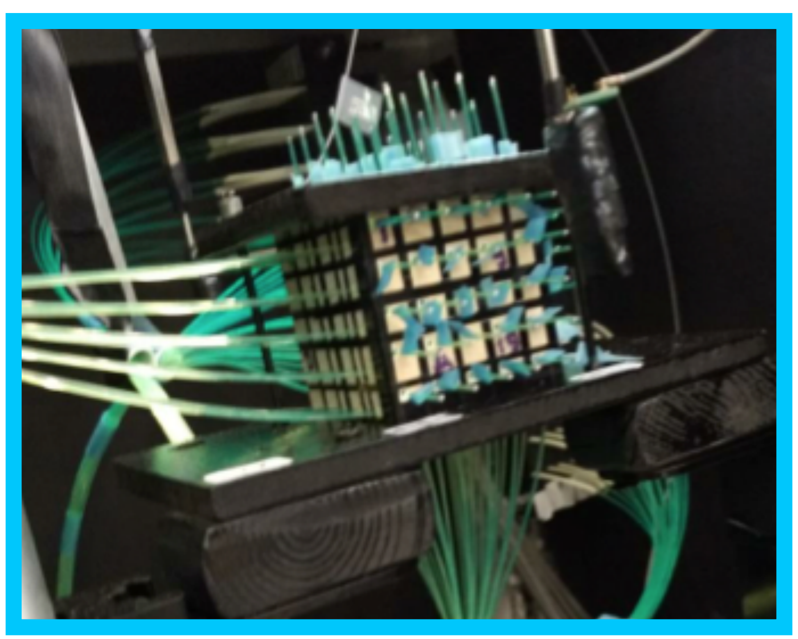
- First test beams in October 2017 confirmed the very good performances
- The assembly procedure has been demonstrated and R&D is ongoing to improve the precision on the cubes dimensions
- Test beams with a bigger prototype (10k cubes, ~1.7k channels) will be performed in June/July at CERN for the T2K-ND upgrade but common to 3DST

BACKUP

The prototype

- Prototype 5x5x5 cm^3 --> 125 cubes and 75 readout channels
- Hamamatsu MPPC S12571-025C for light readout
  - 1x1 mm^2 active area
  - 1600 pixels, each of 25x25 mum^2





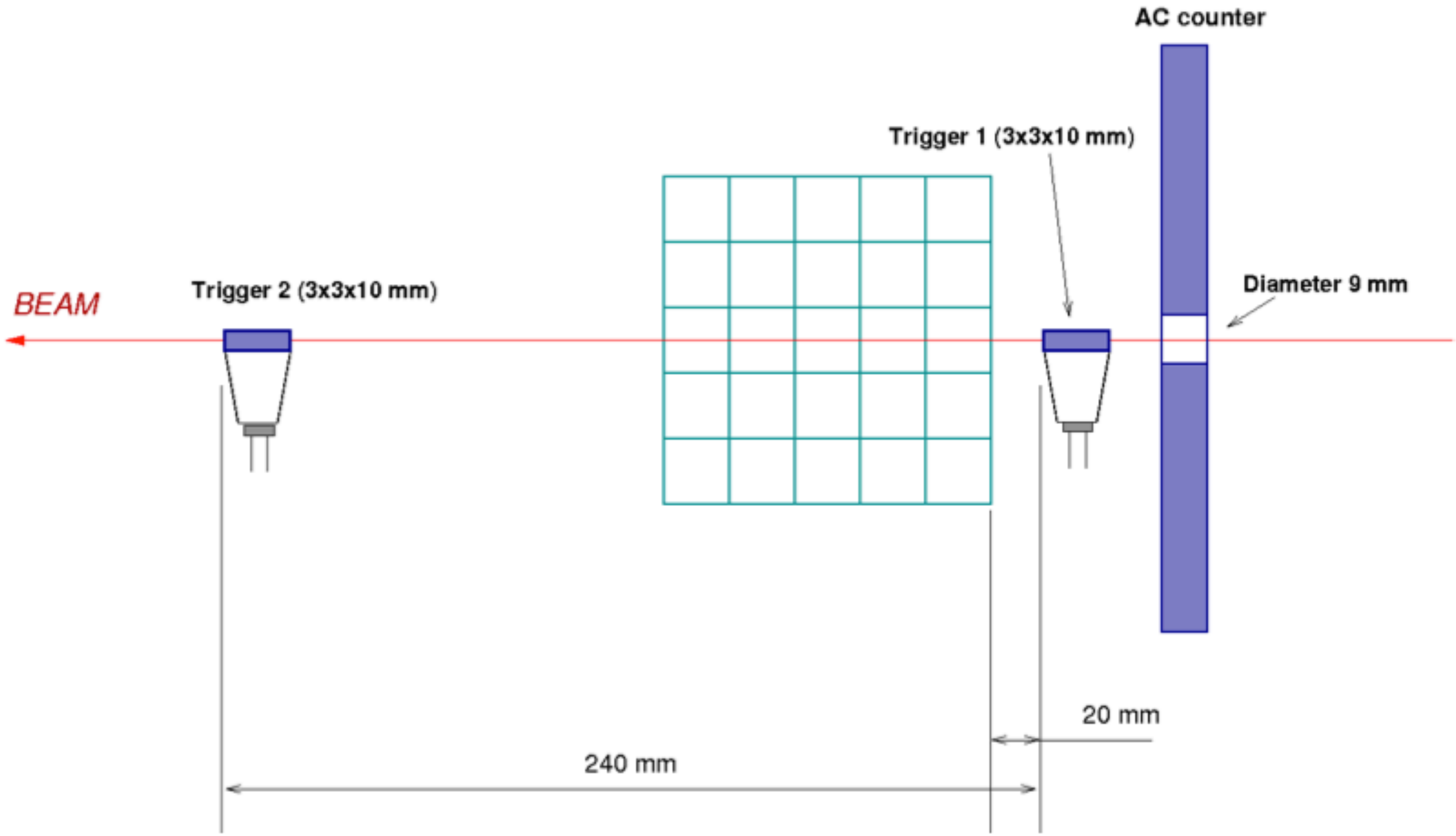
Everything covered by a black box

CERN T10 test beam area

Beam test at T10: 28 October - 1 November 2017
p (π, μ) = 6 GeV/c
Beam spot ~3 cm (horiz)x 6 cm (vert)
Trigger counters (in front/behind prototype) 3 x 3 mm2
Veto counter : beam hole 9 mm diameter

Trigger setup

Trigger counters: direct readout of scintillator with MPPC through a lightguide.
AC counter: readout with S-shaped WLS fiber and 2 MPPC's.
AC counter has a 9 mm diameter hole in the center.



- Readout electronics:
  - digitizer --> a few channels to test the intrinsic time resolution
  - CITIROC --> multichannel data taking (used in Baby MIND detector)