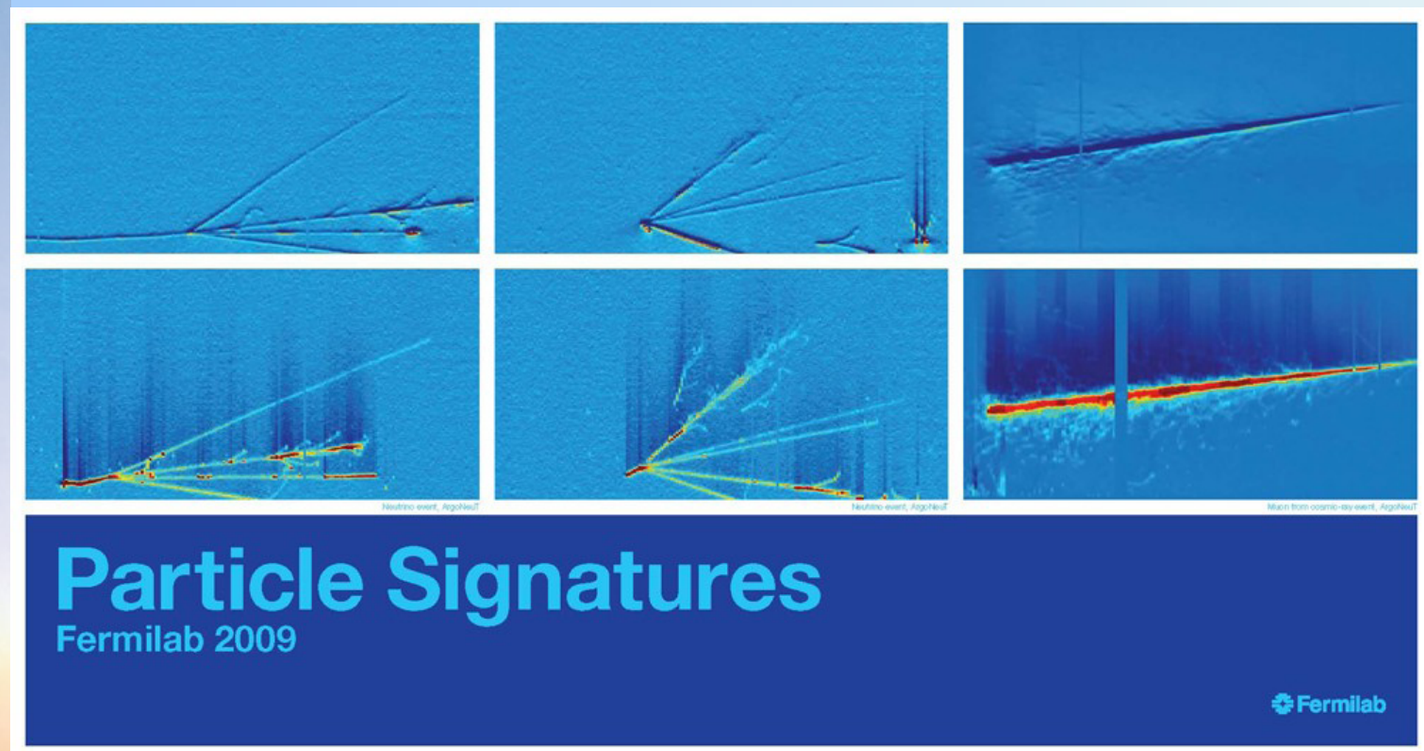
Exclusive 1 μ+Np Topologies in ArgoNeuT



Kinga Partyka

Yale University

Outline

- LArTPC technique
- Argon Neutrino Test (ArgoNeuT)
- Topological Analysis 1μ+Np

  (rates only, cross-section calculations are in progress)
- Energy Reconstruction
- Conclusions

Liquid Argon Time Projection Chamber (LArTPC) technique

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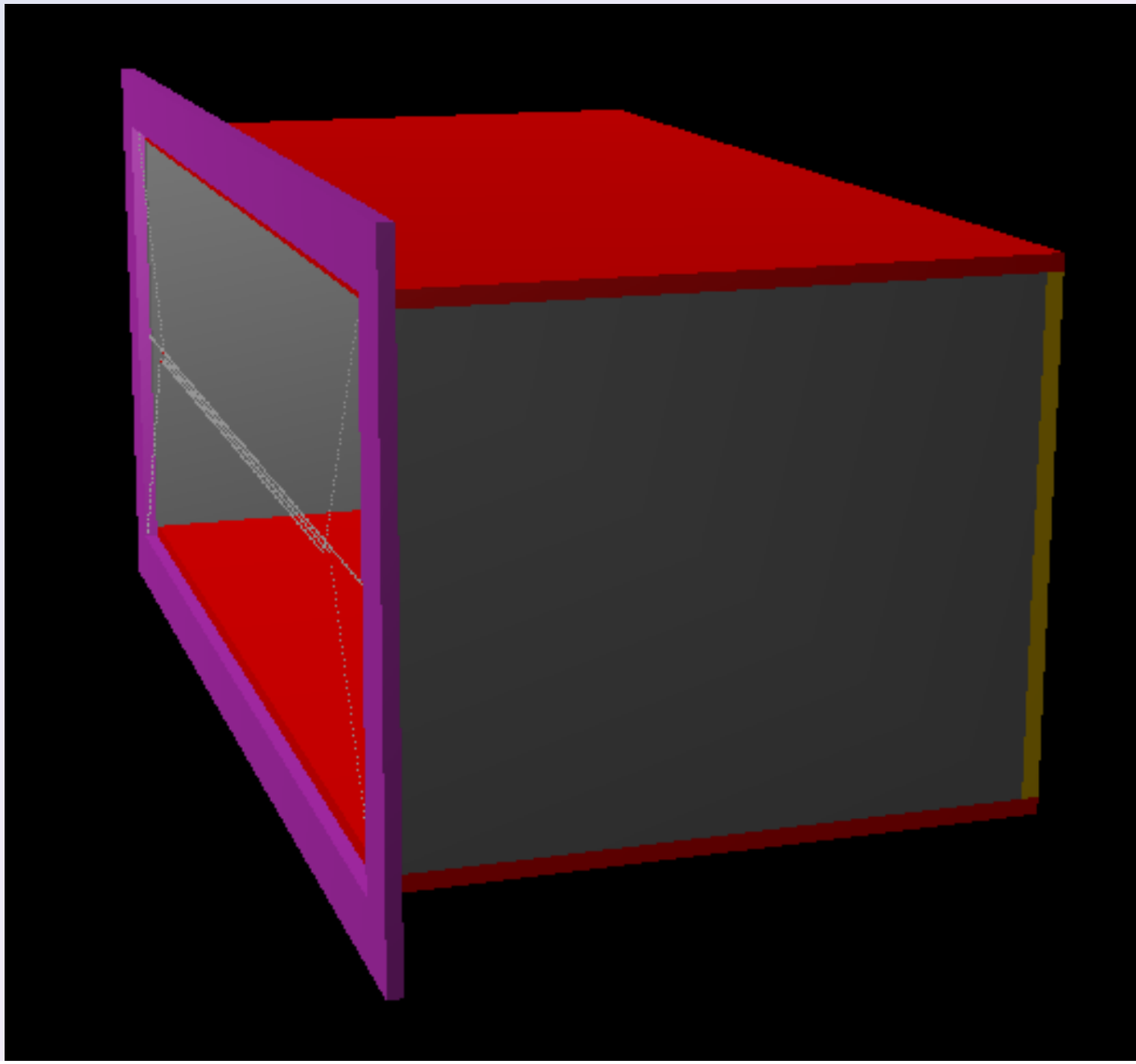
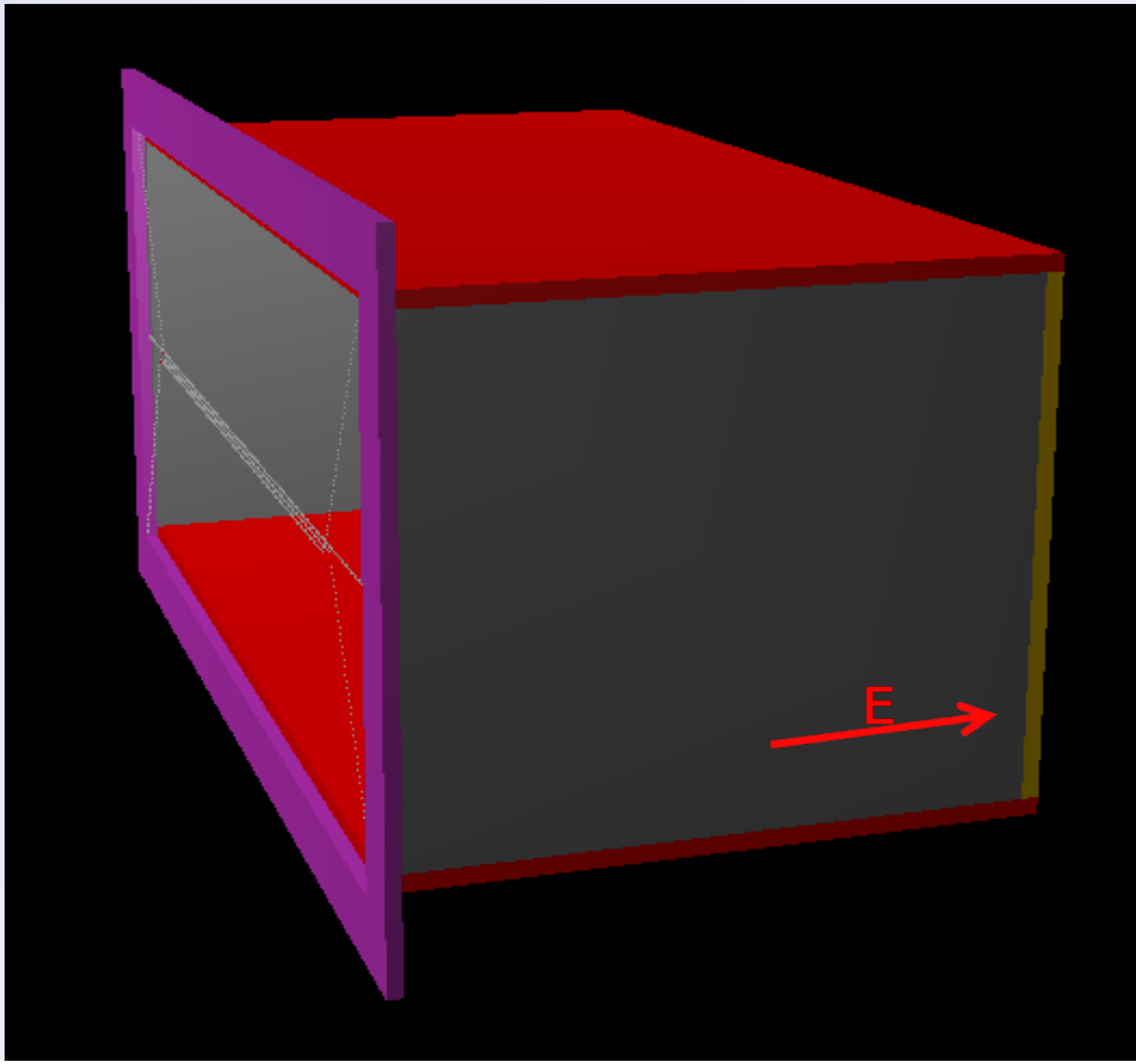


Liquid Argon Time Projection Chamber (LArTPC) technique



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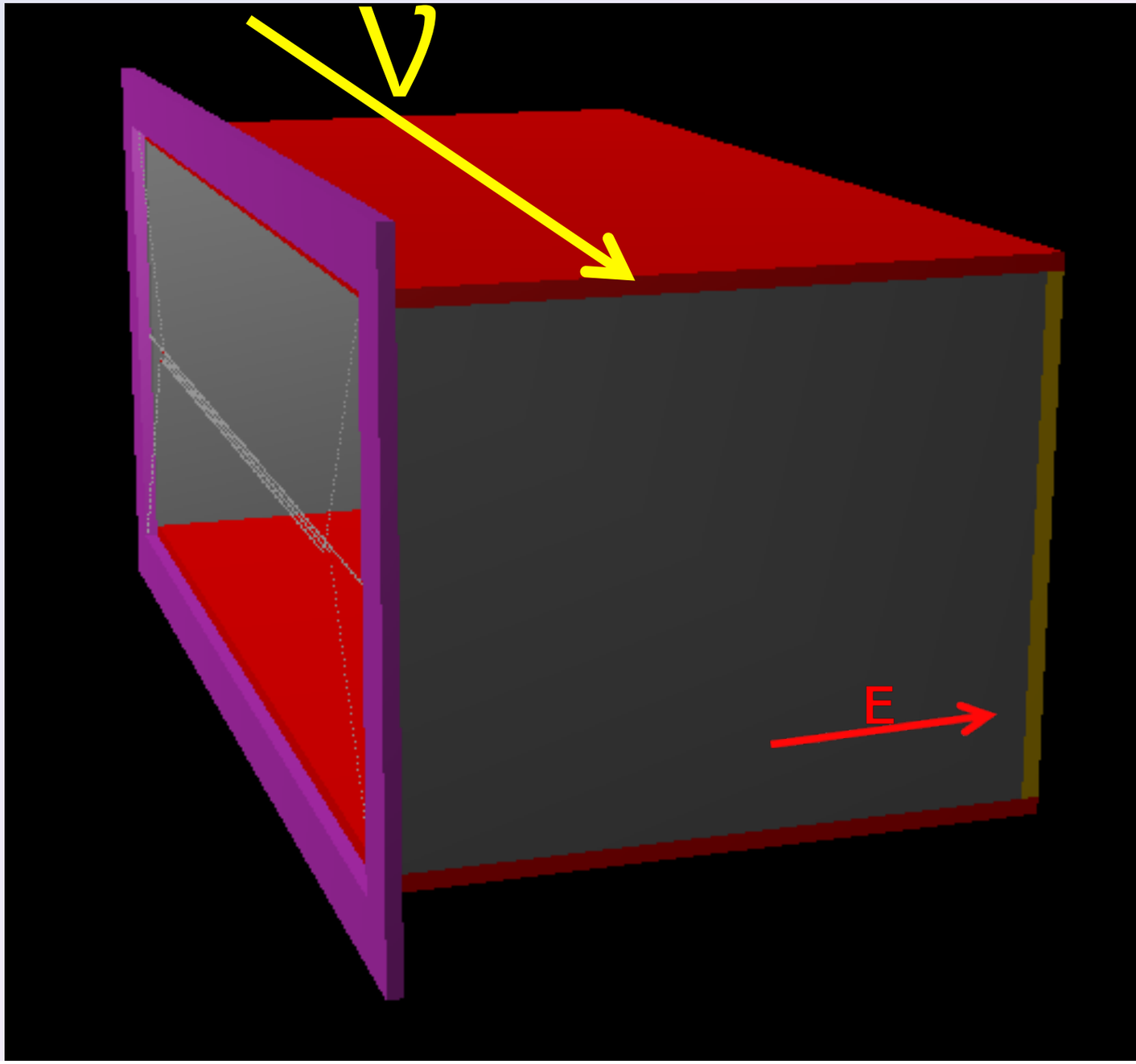

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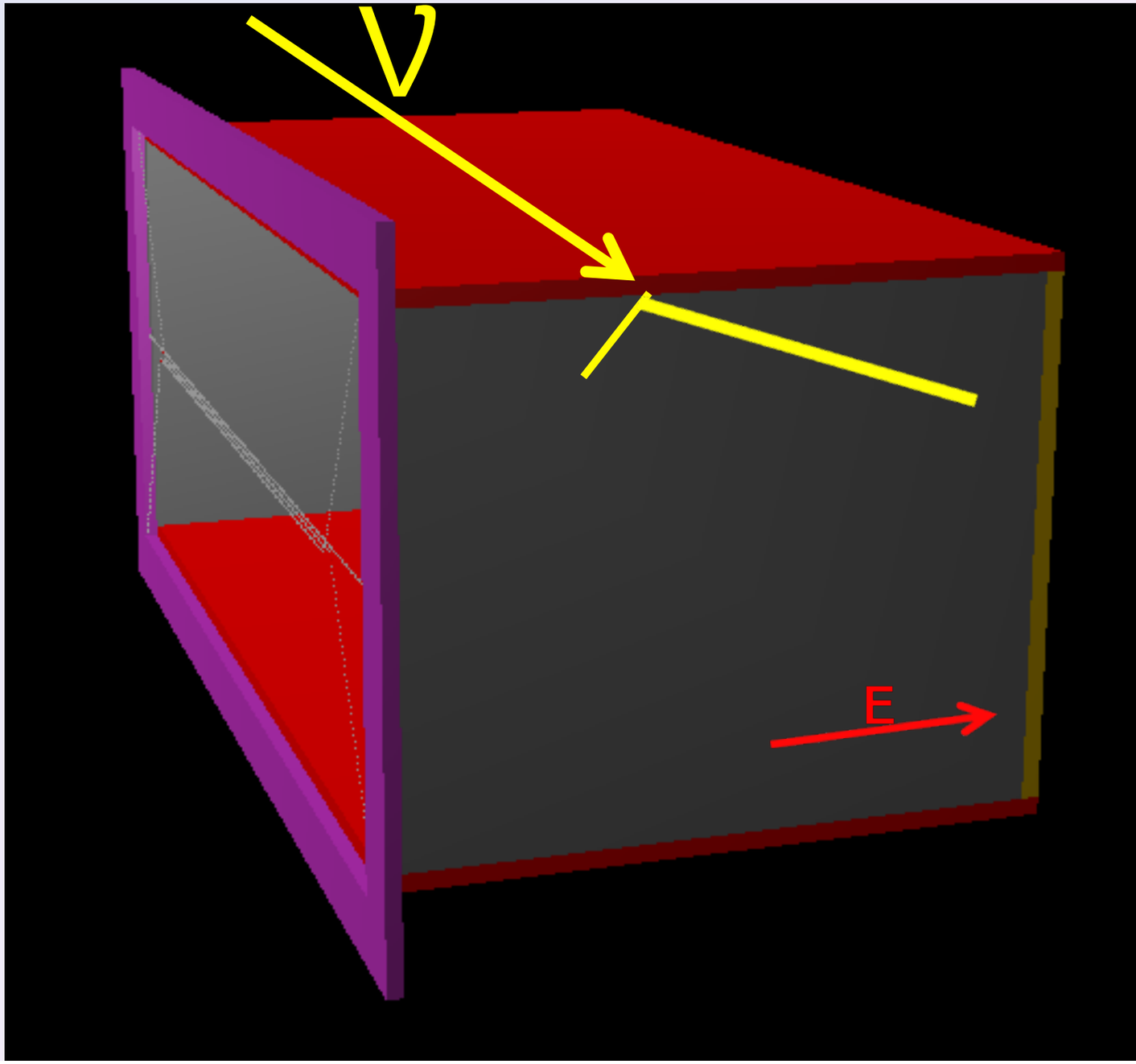

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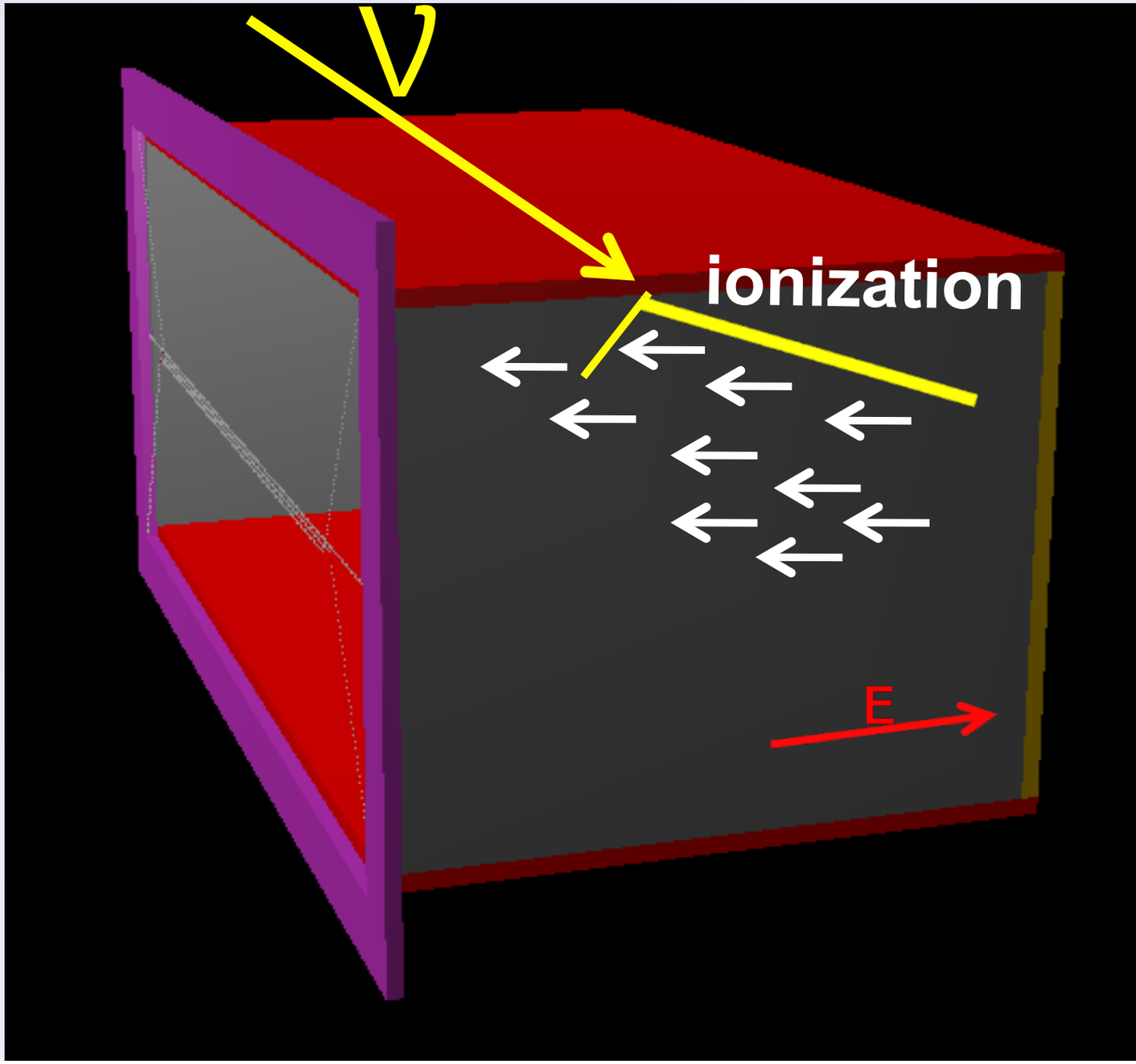

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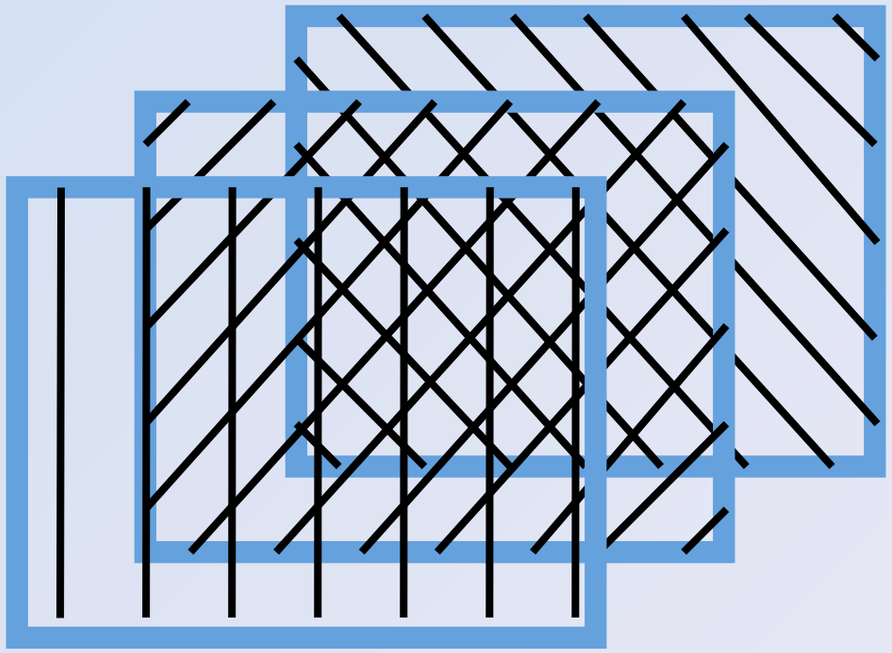

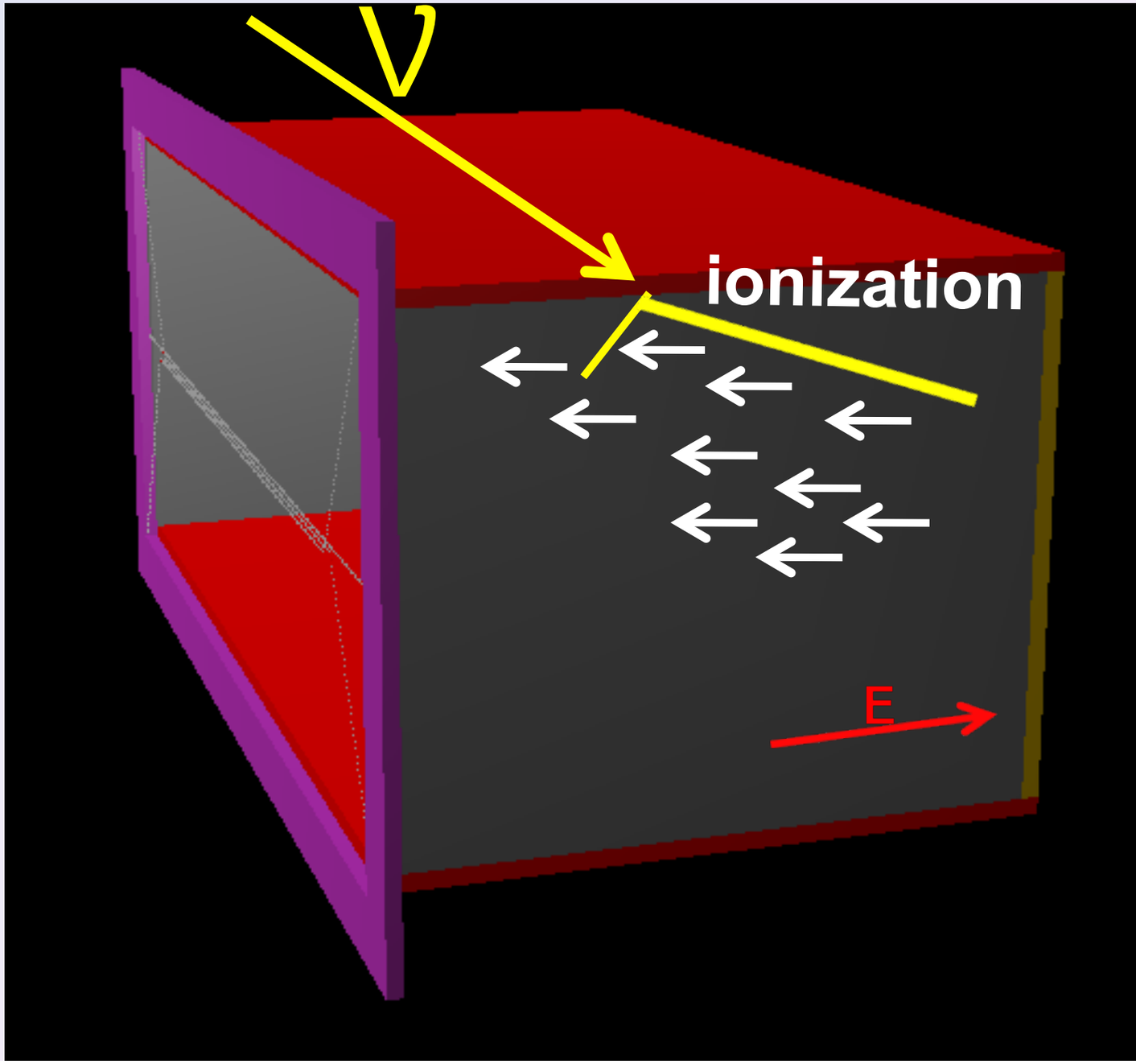

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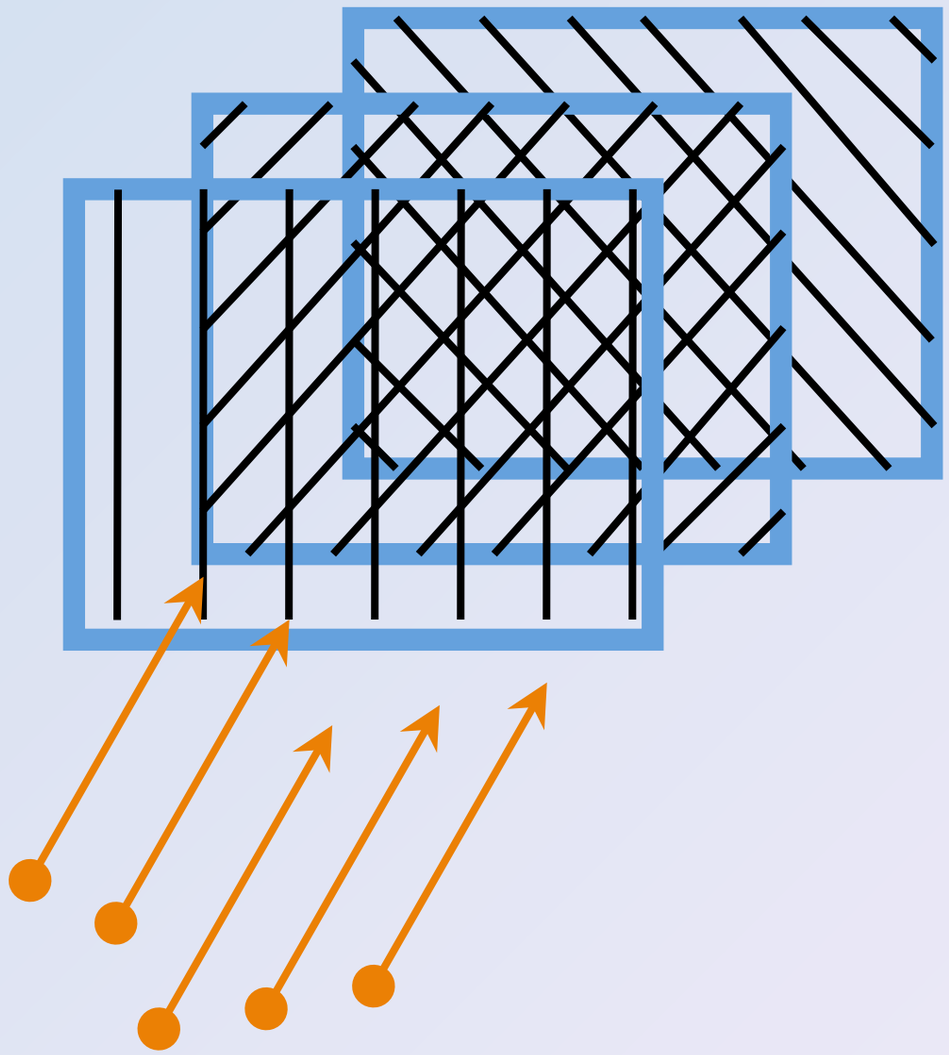

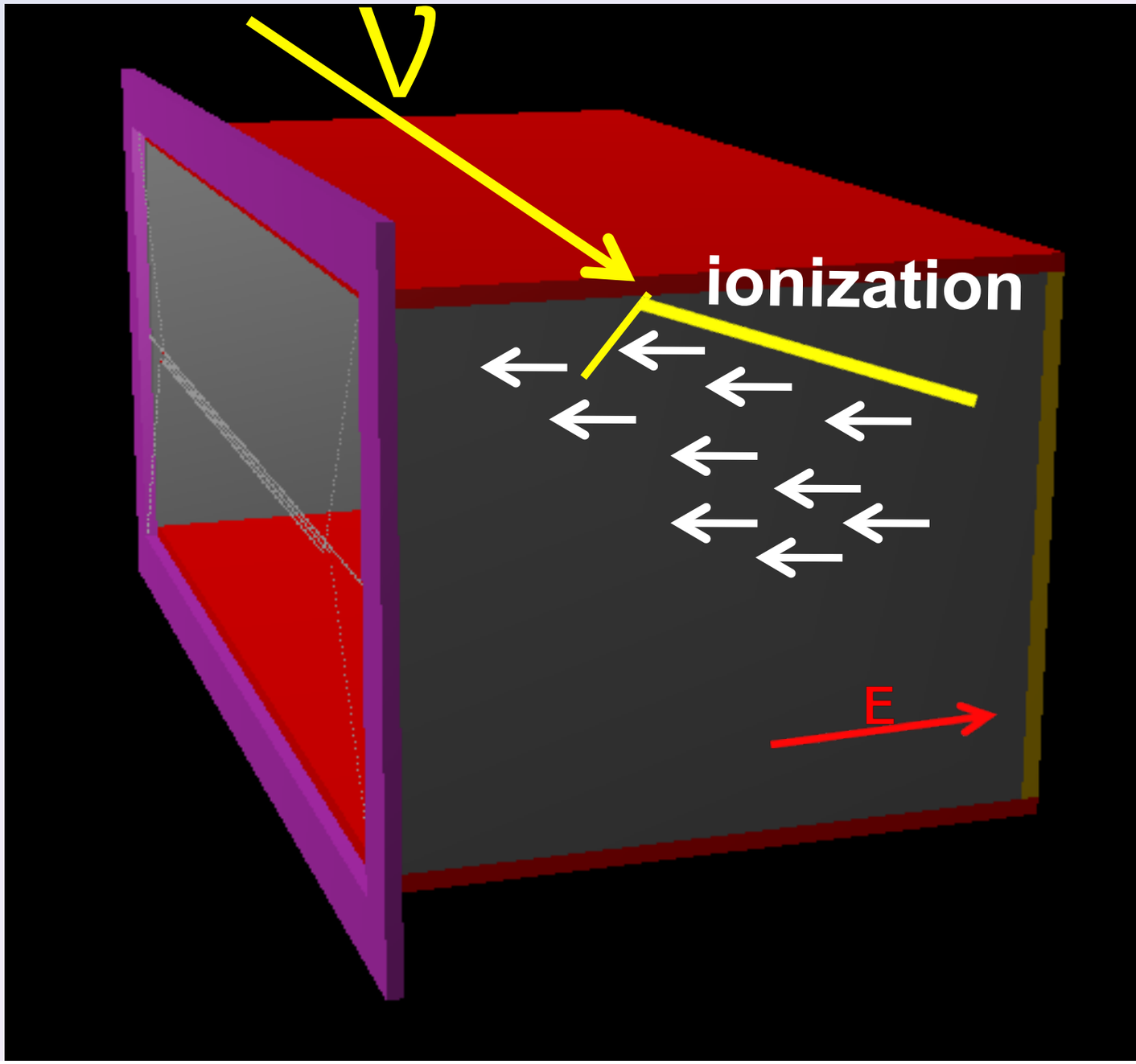

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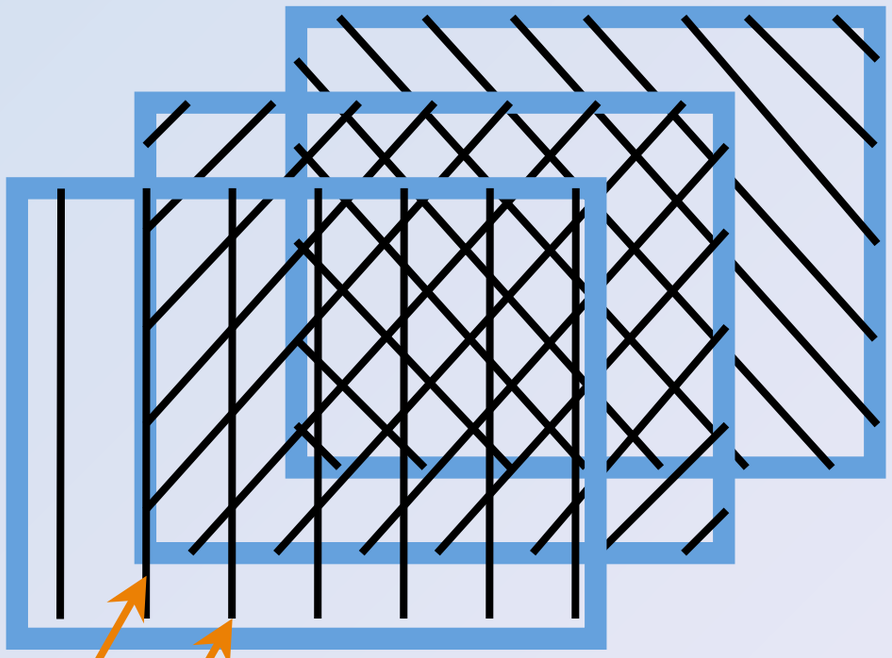

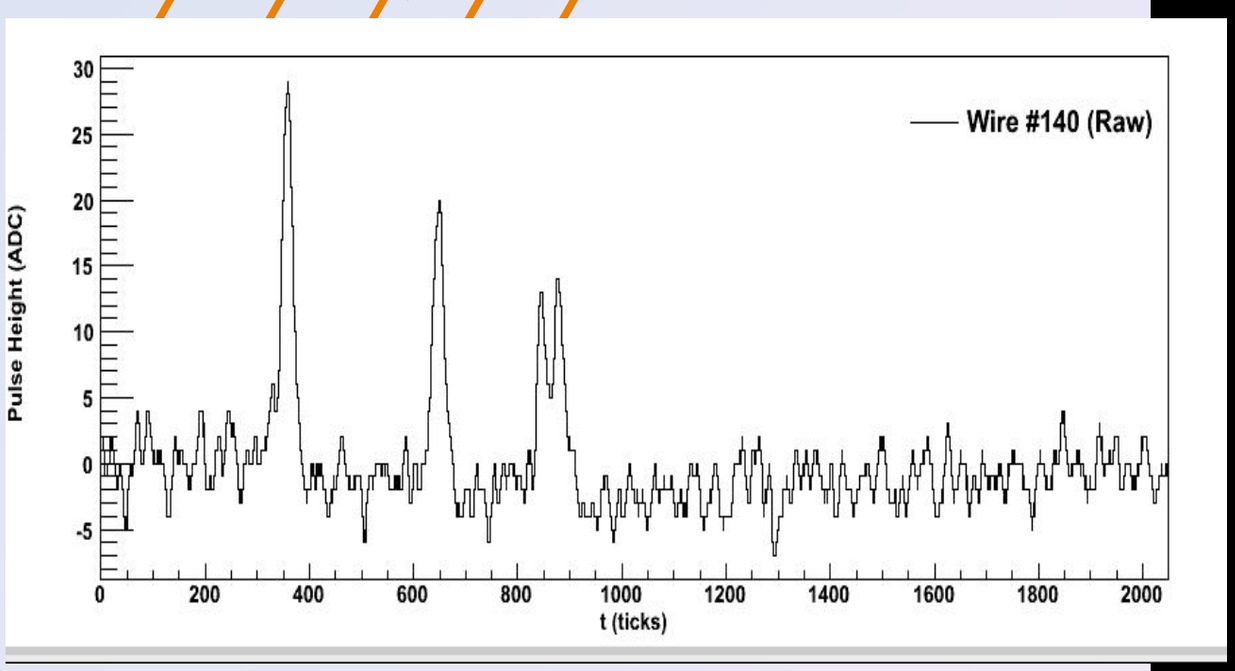

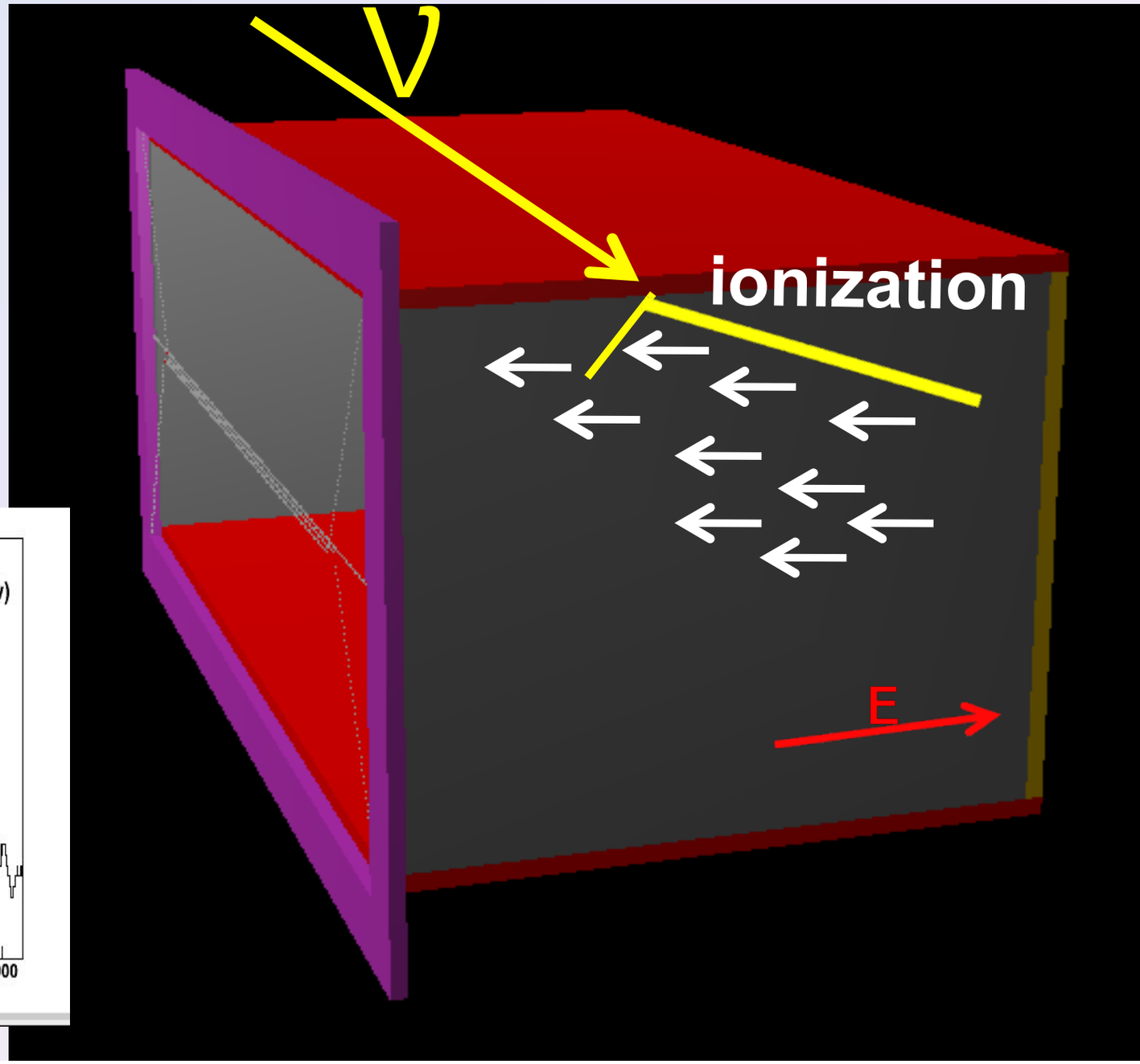

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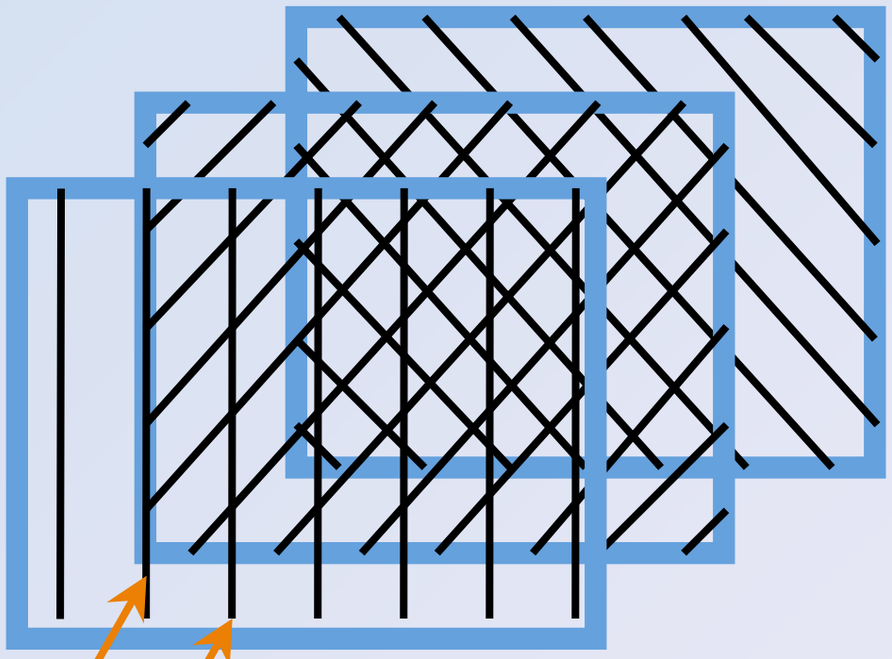
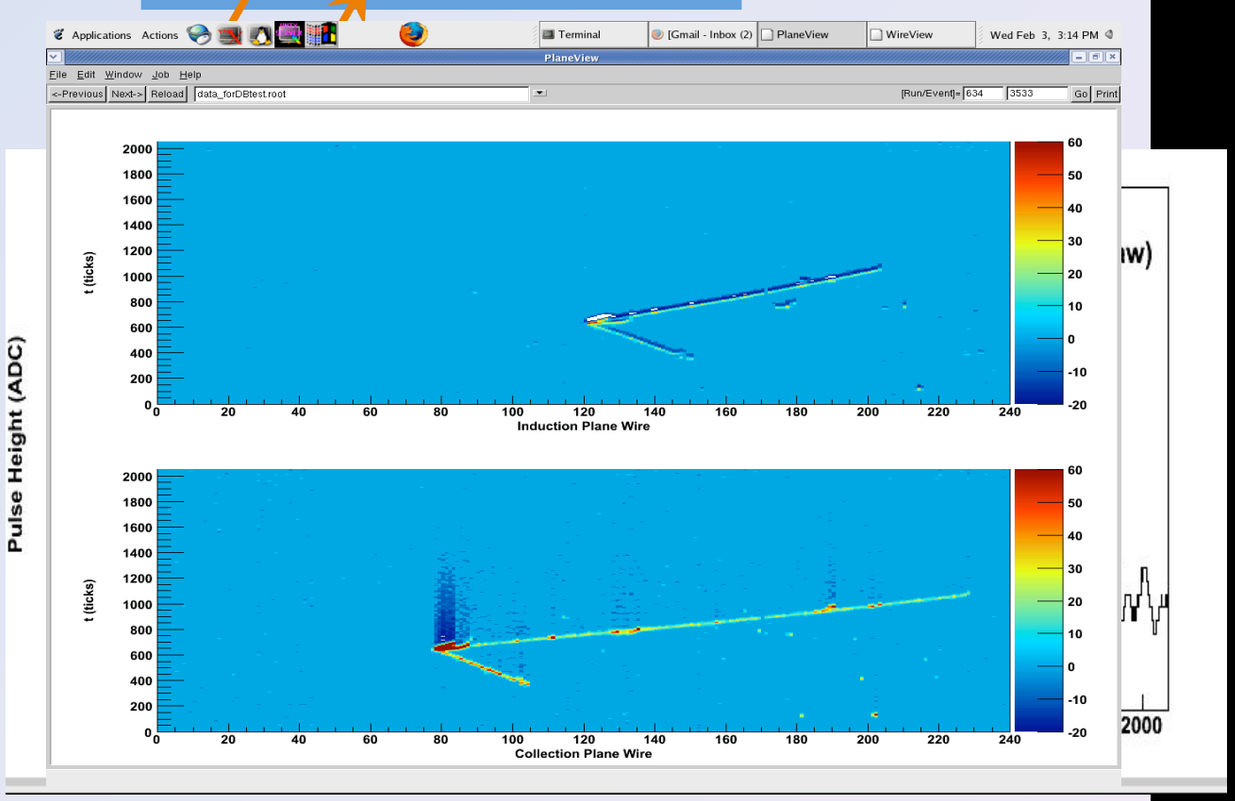
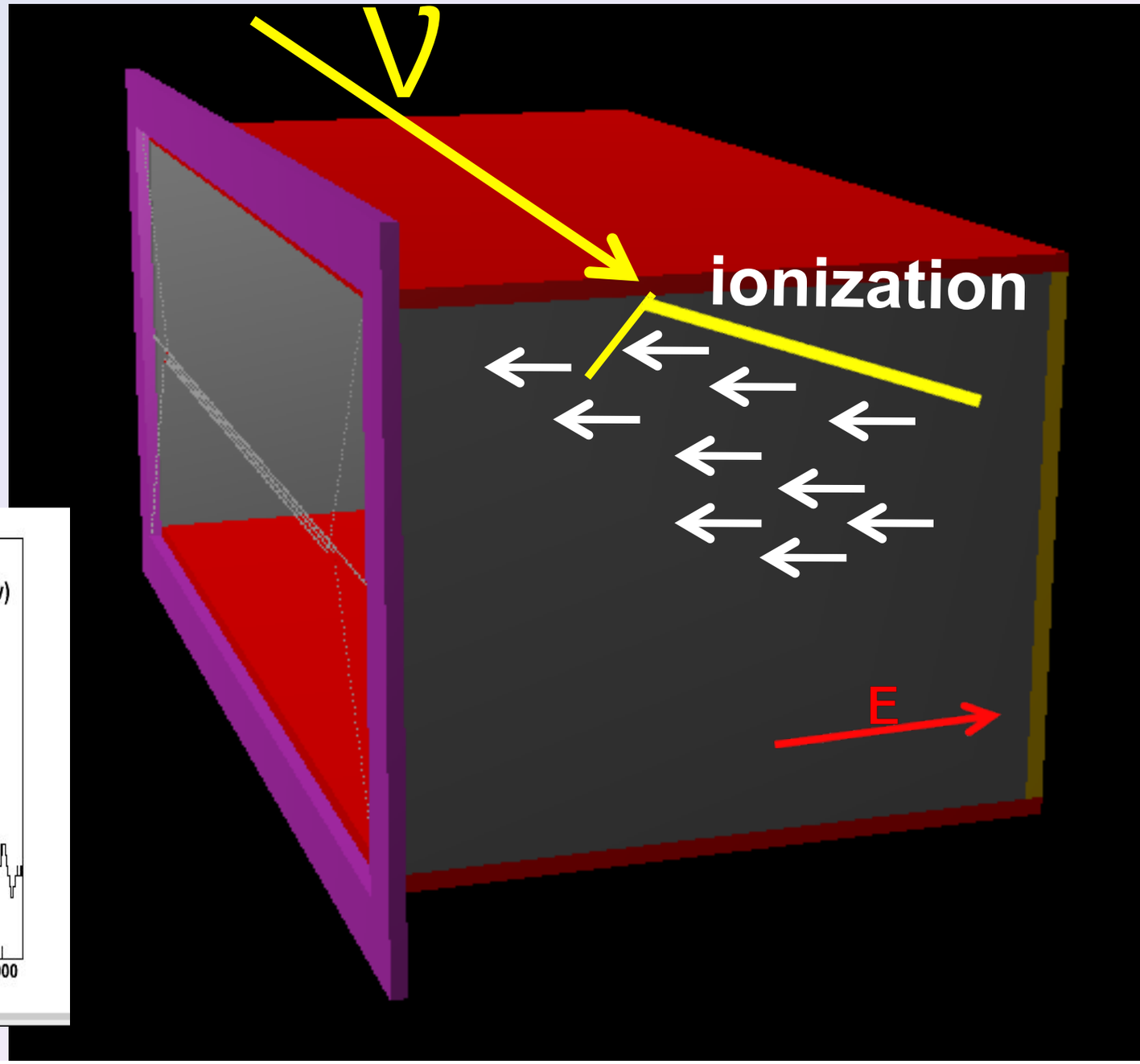




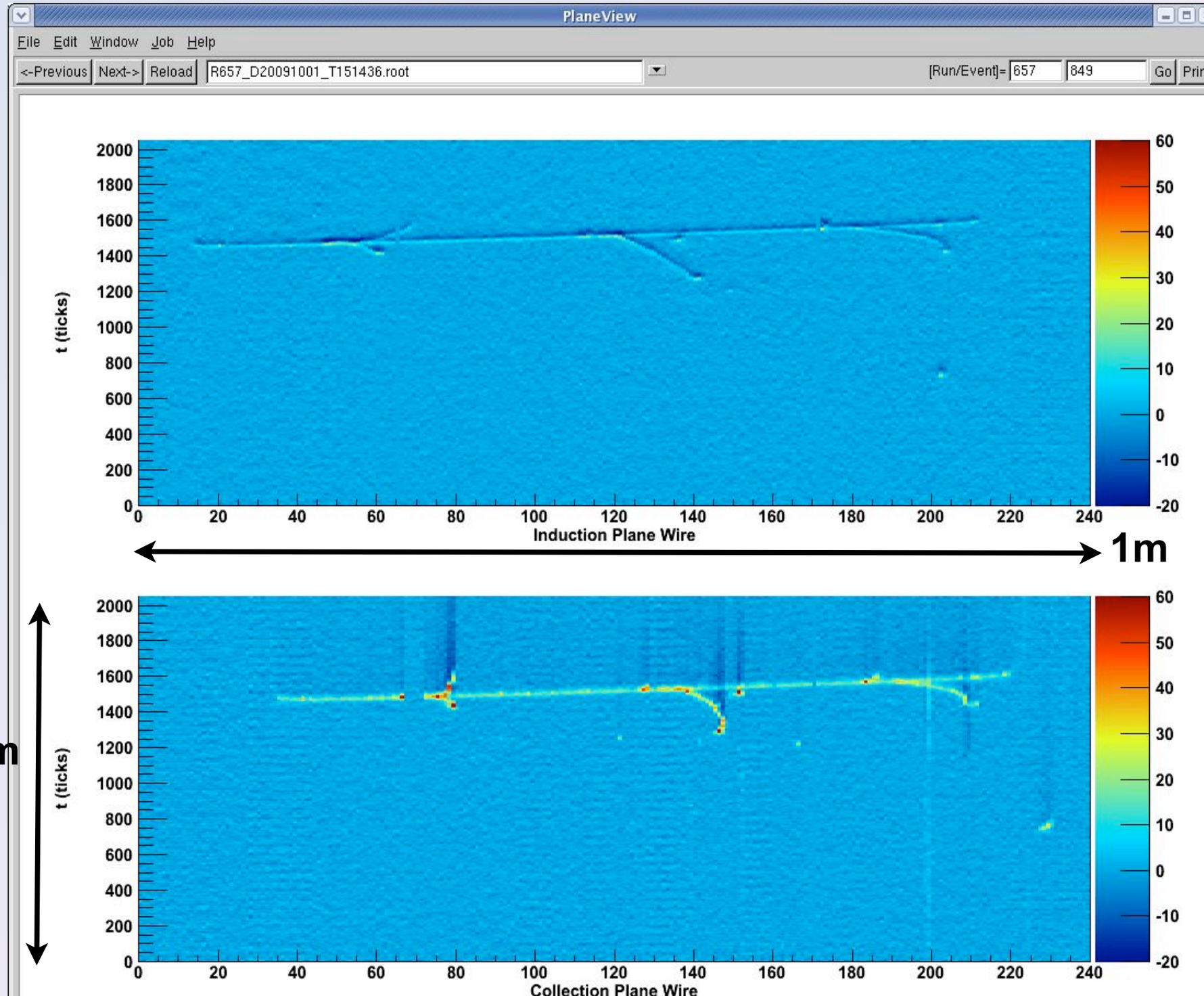


Event Display

- **Bubble chamber quality!**
- **Pixel size of (4.0 x 0.3) mm^2**

4mm wire pitch

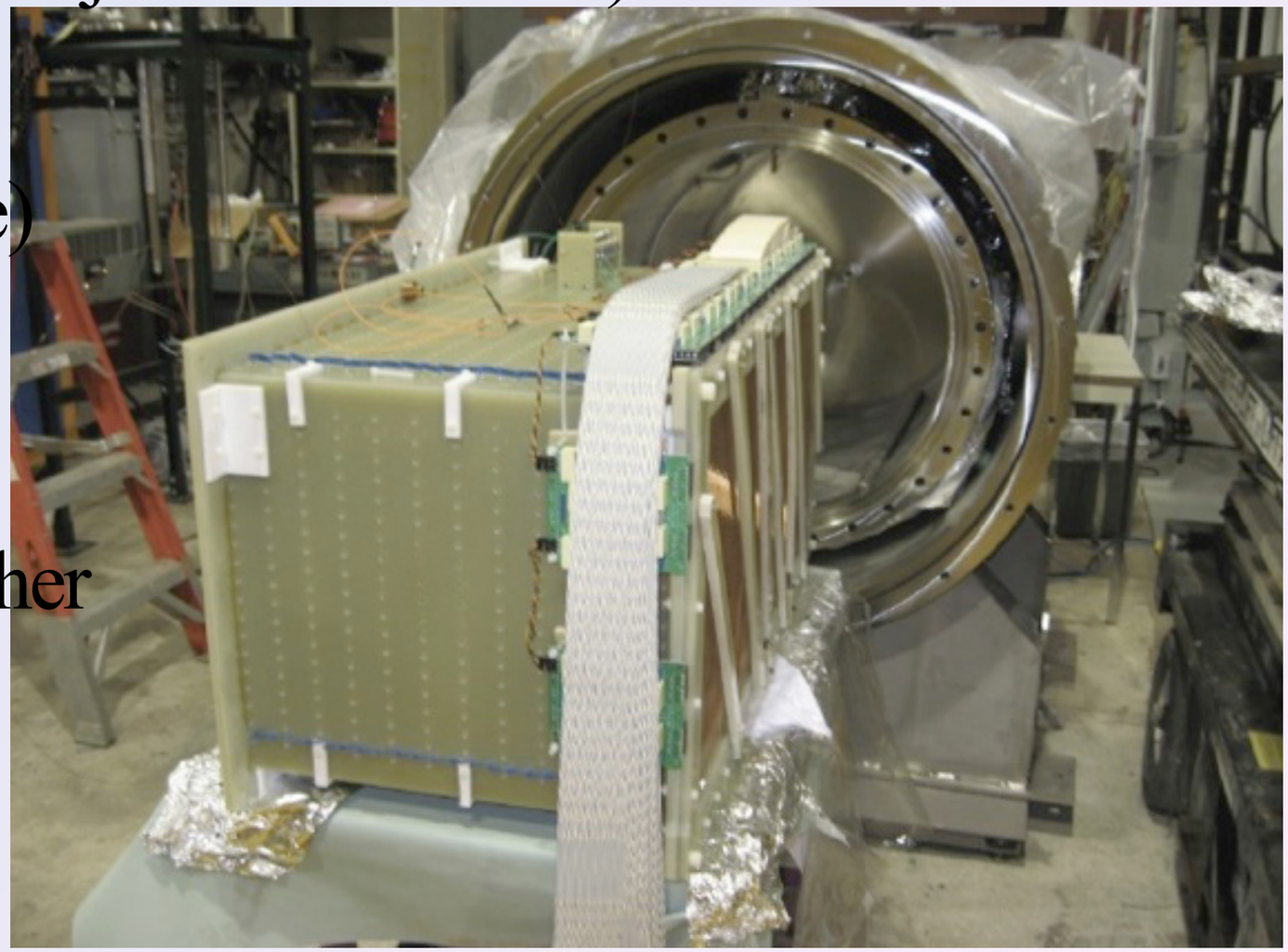
198 ns sampling time

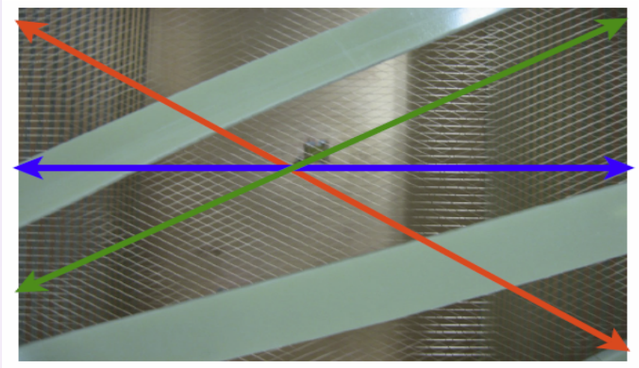


ArgoNeuT Introduction

- NSF/DOE R&D project at Fermilab
- LArTPC (Liquid Argon Time Projection Chamber)
- 175L active volume
- 480 channels - (240 wires/plane)
- ~ Max 50cm drift-distance
- ~ 500 V/cm E field
- two wire planes at 60^0 to each other
- T_0 from beam information

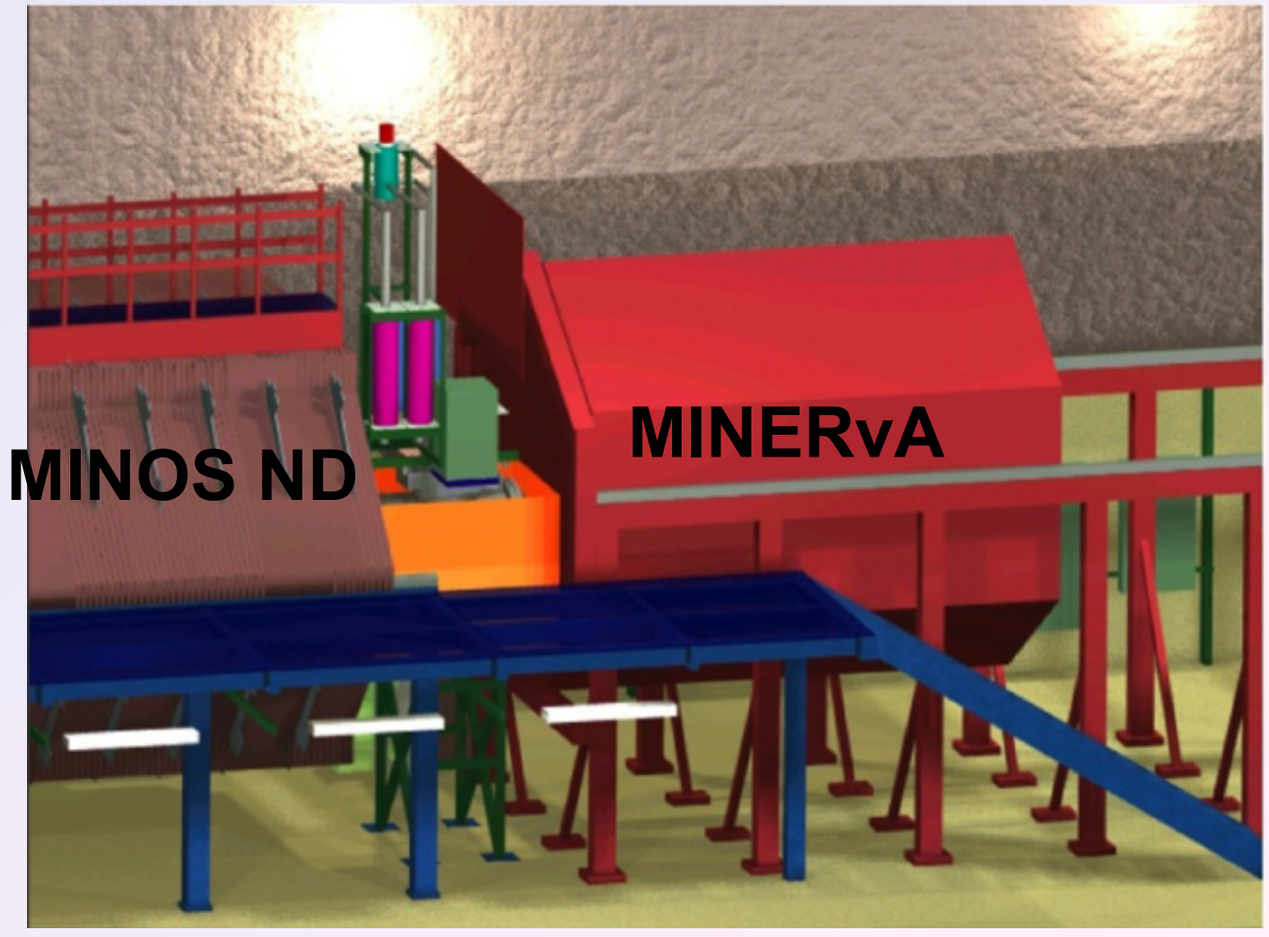
"The ArgoNeuT detector in the NuMI low- energy beamline at Fermilab" JINST 7 P10019 (2012)



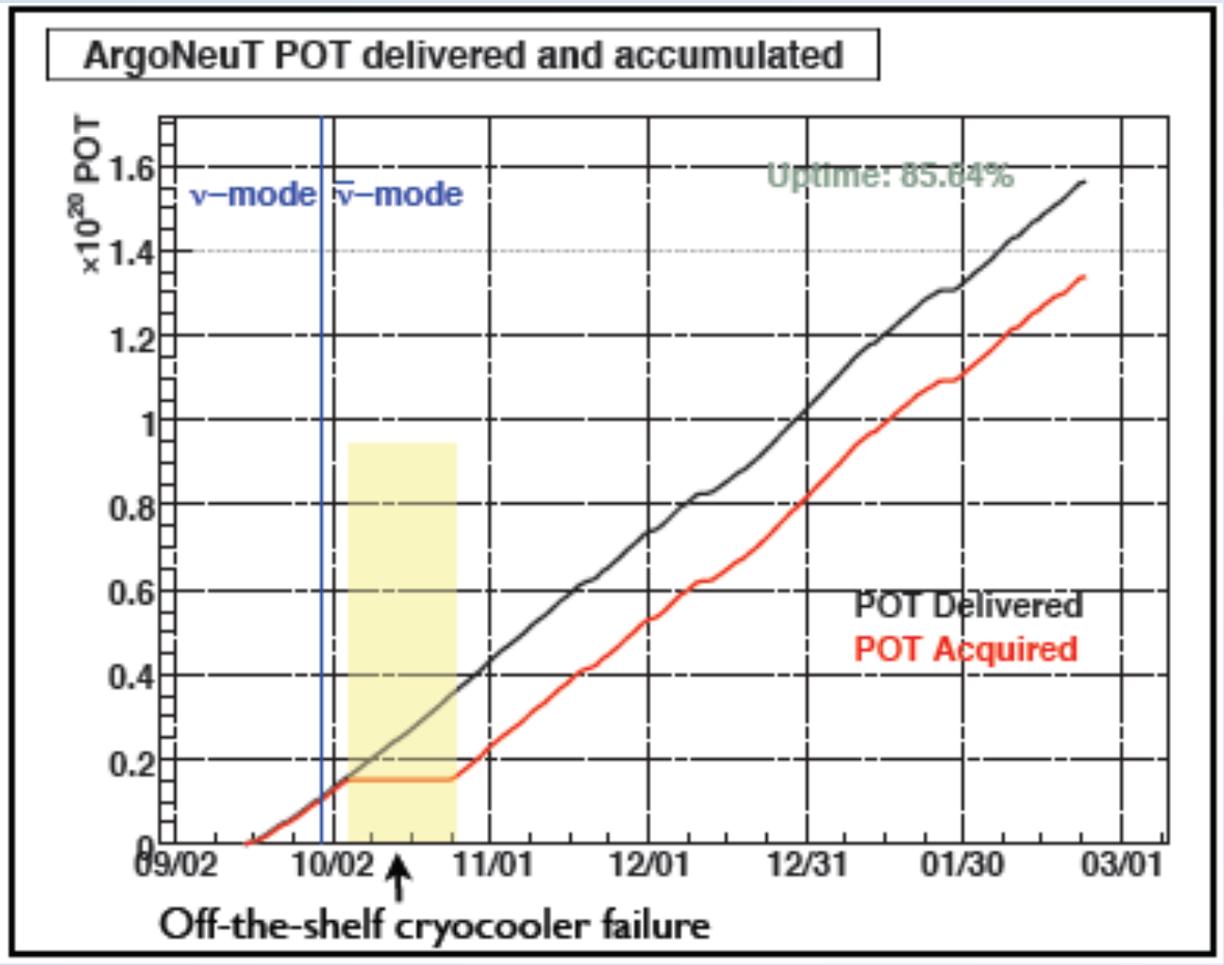


ArgoNeuT

- Located underground on NuMI Beamline between MINOS ND and MINERνA
- MINOS helps with reconstruction of muons

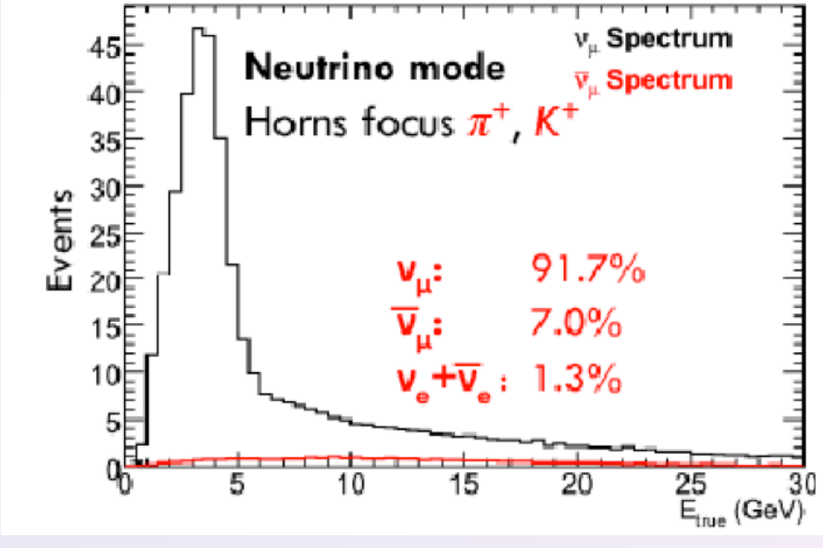


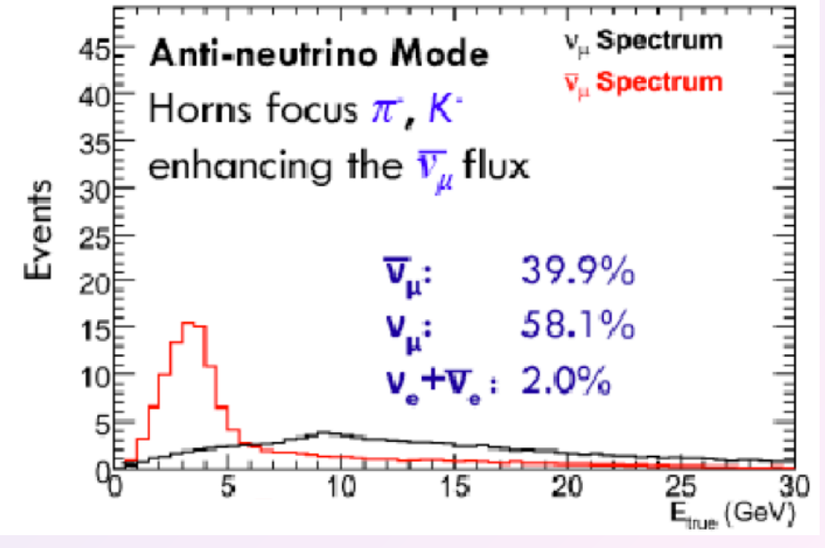
ArgoNeuT's Physics Run



- ArgoNeuT completed its phase I physics run (9/14/2009-2/22/2010)
- Collected events in the 0.1 to 10 GeV range, ArgoNeuT produced the first ever data for low energy neutrino interactions within a LArTPC.
- Stable, shift-free operation
- Goals:
- Multiple neutrino cross sections
- demonstration of dE/dx particle separation capabilities
- Developing automated reconstruction techniques for all future LArTPCs

POT with MINOS present:
anti-nu mode 1.20e20
nu-mode: 8.5e18





Outline

- LArTPC technique
- Argon Neutrino Test (ArgoNeuT)
- Topological Analysis 1μ+Np

  (rates only, cross-section calculations are in progress)
- Energy Reconstruction
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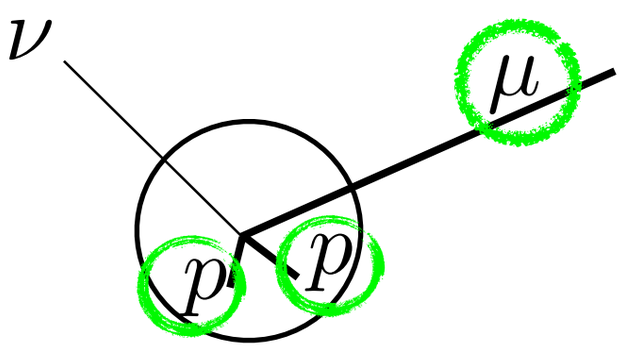
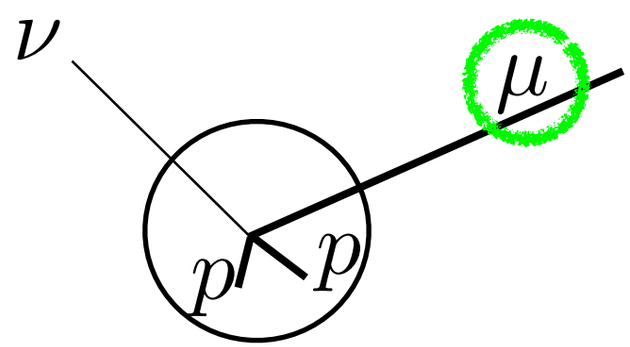
Philosophy





• initial state σ's
(corrected back to initial state)

• final state σ's
(do not correct out FSI)

LAr

don't have to be restricted to measuring "QE", "CCπ^+", ... cross sections

Instead: Topological Analysis
- 1μ+Np where N=0,1,2...
- $1\mu+\pi$+Np
- etc.

Neutrino channel definitions are largely ill defined given the effects of FSI
We want to report what our detector actually sees!

How is it done?

- Automatic reconstruction+visual scanning

  - Particle Identification
  - Proton threshold
  - Matching with MINOS Near Detector
  - final scanned sample includes events with contained protons in fiducial volume

- Efficiency and Purity for different proton multiplicities evaluated using a full MC simulation (GENIE/Geant4/Larsoft)

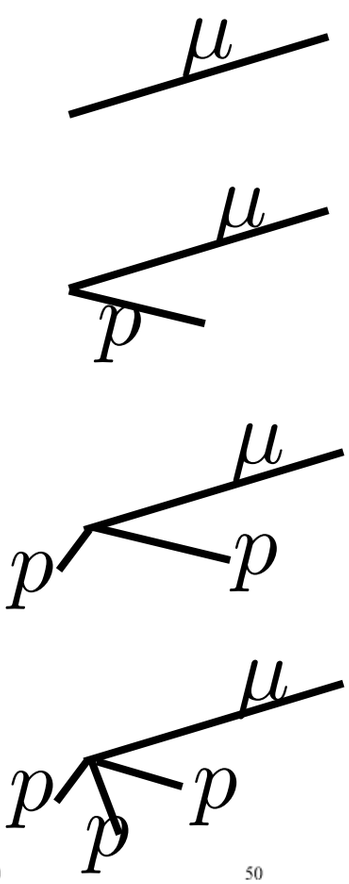
  - take proton containment into account

- Energy reconstruction with muon kinematics.

  (Analysis including proton kinematics in progress)

$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

Topology appearance

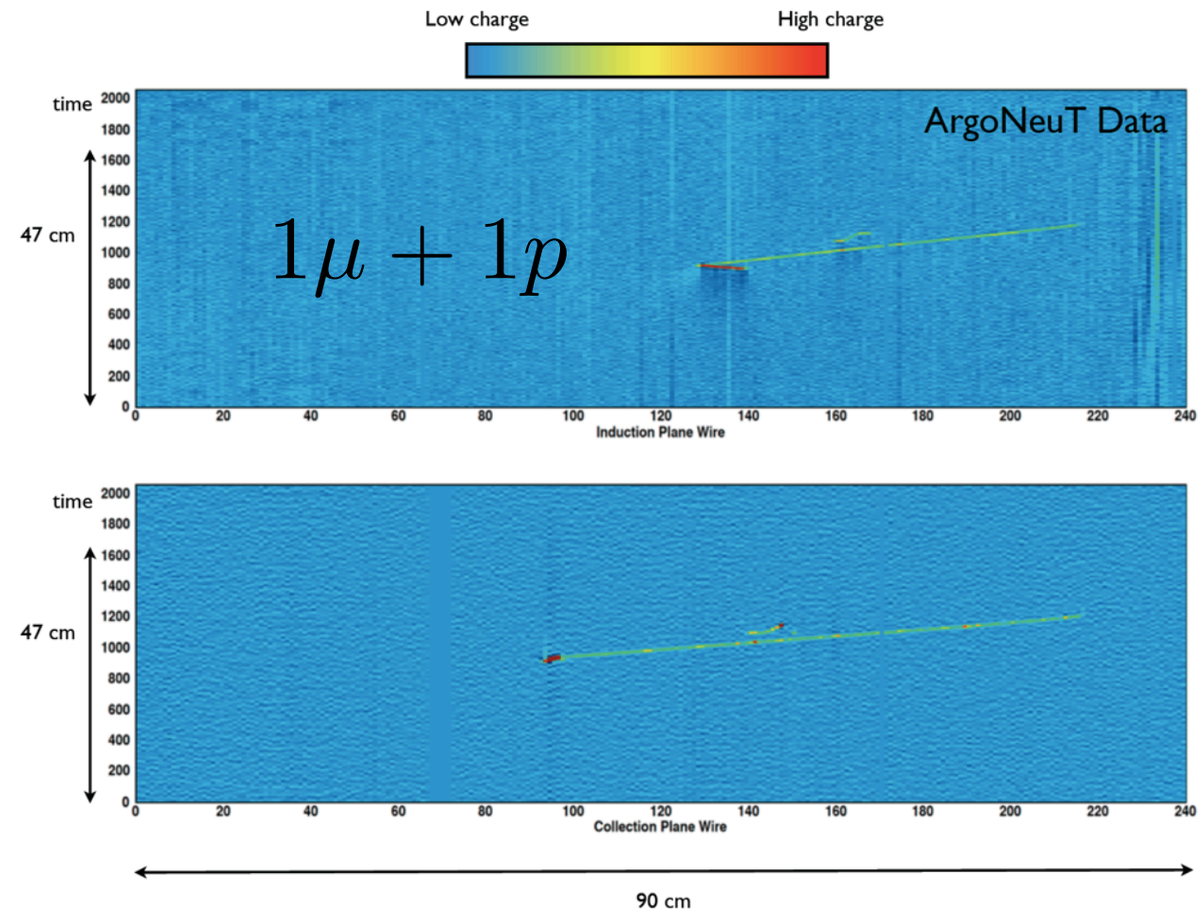


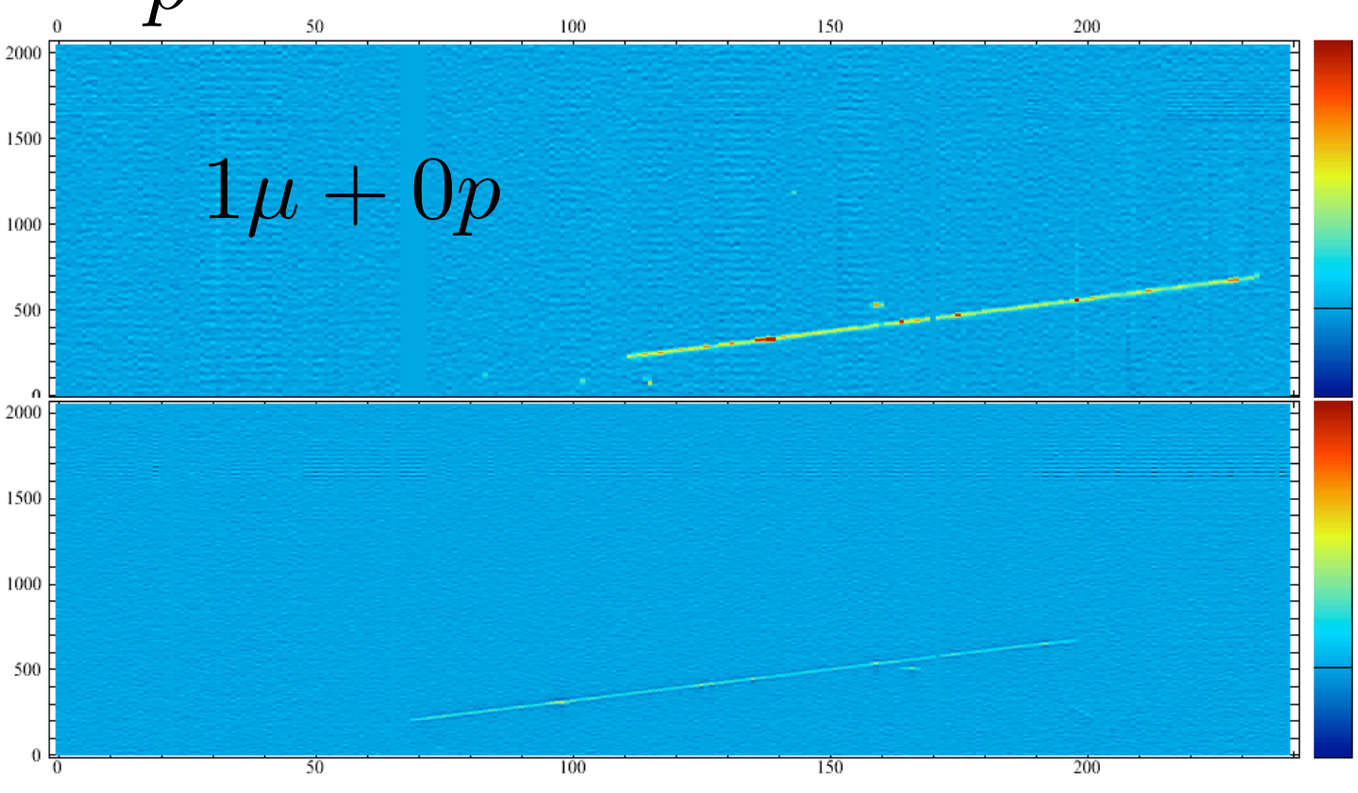
$1\mu + 0p$

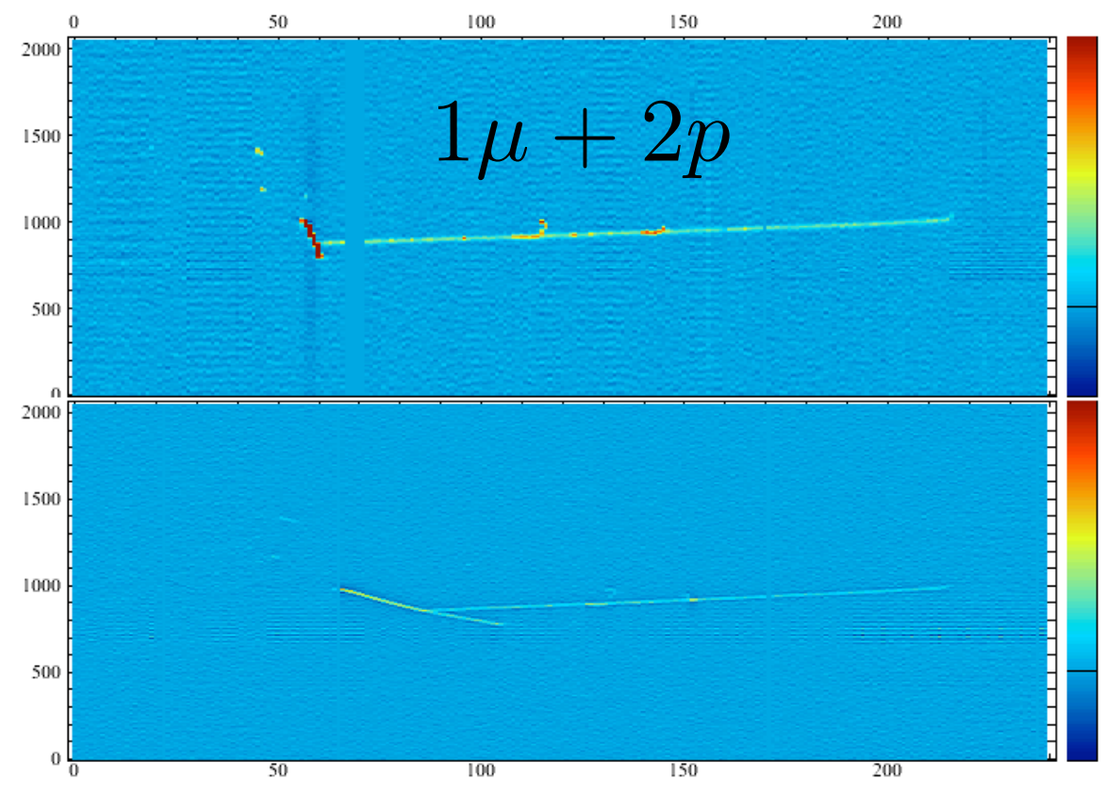
$1\mu + 1p$

$1\mu + 2p$

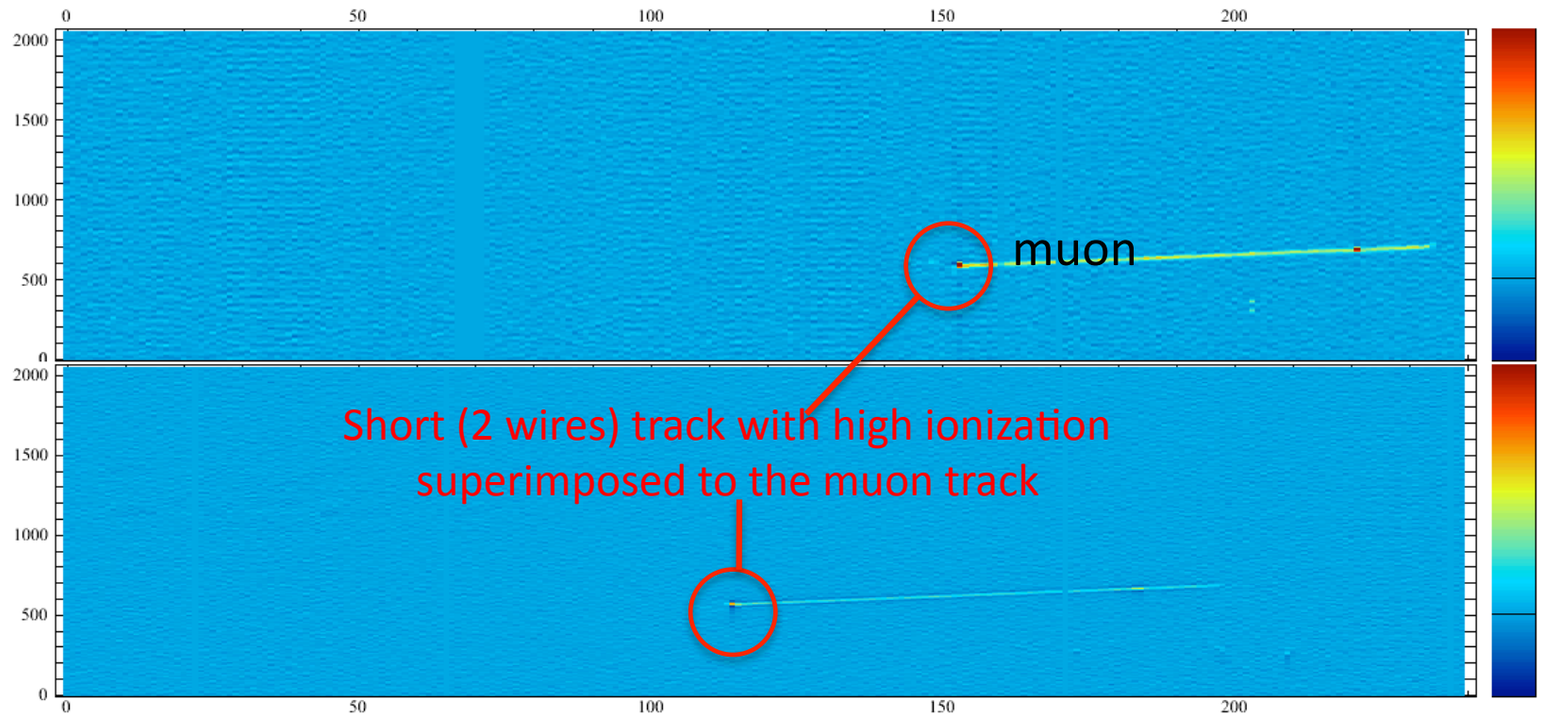
$1\mu + 3p$







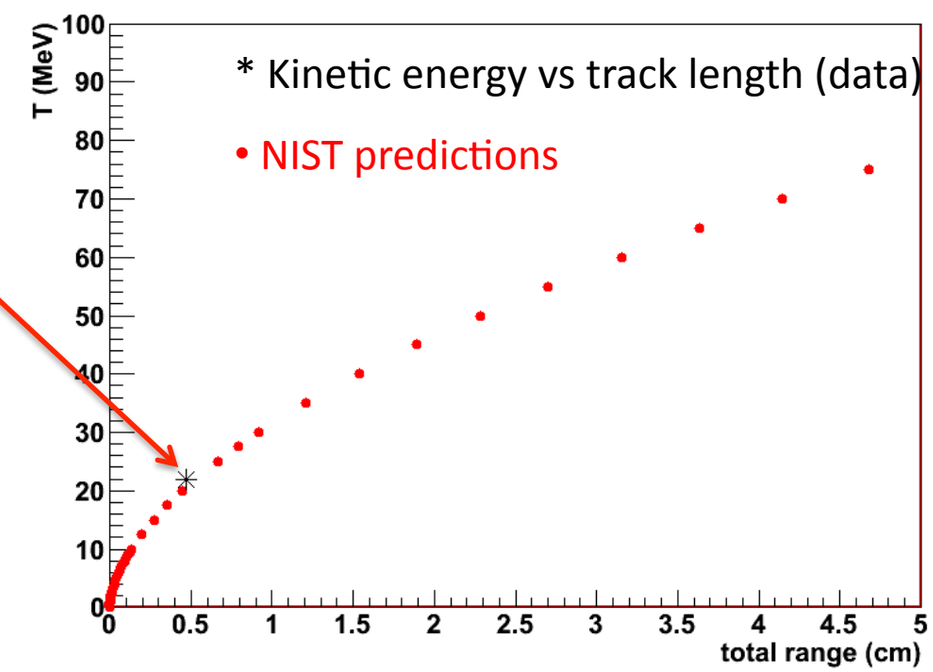
Example of Low energy proton reconstruction



The short track behaves like proton

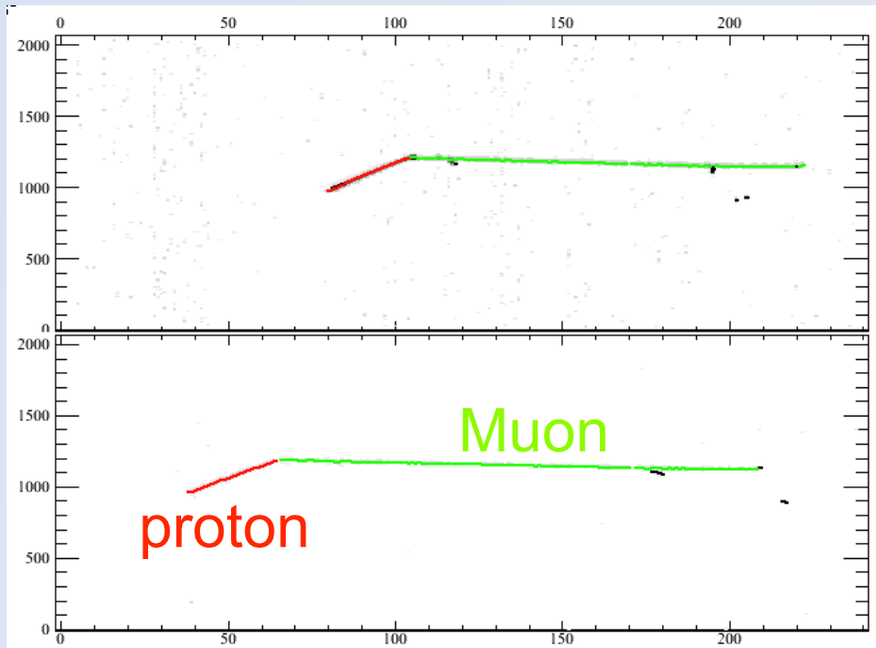
Length=0.5 cm

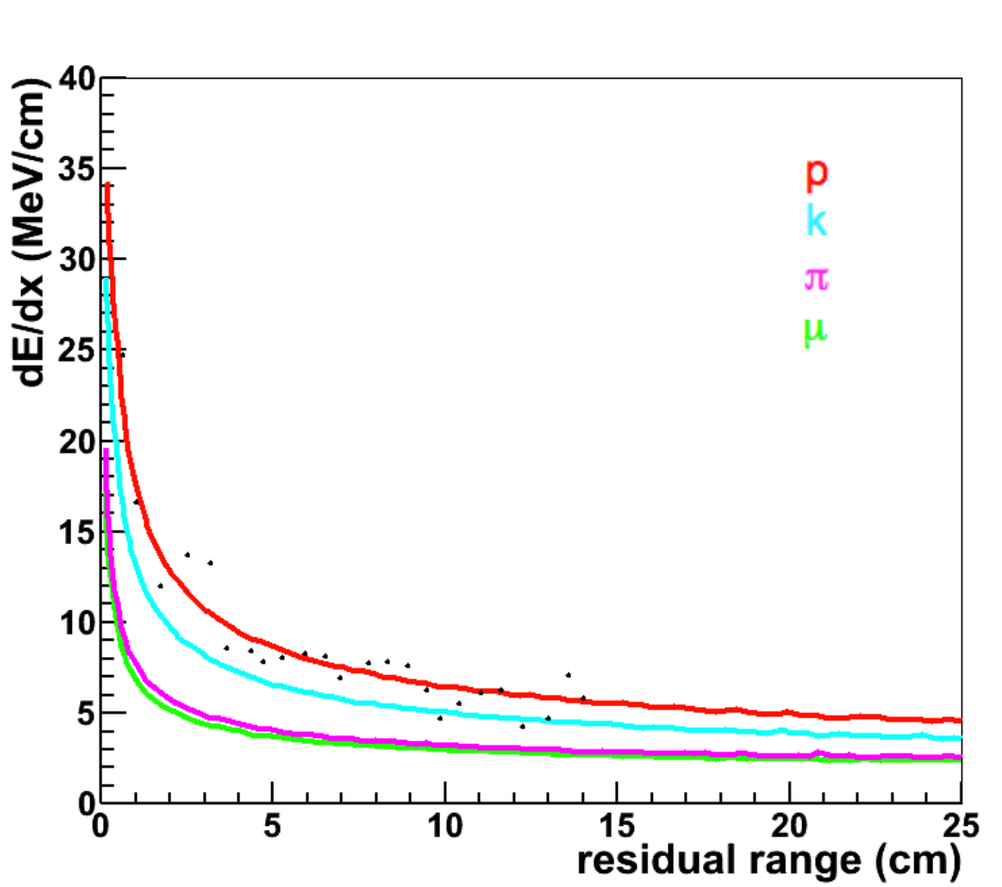
KE=22±3 MeV

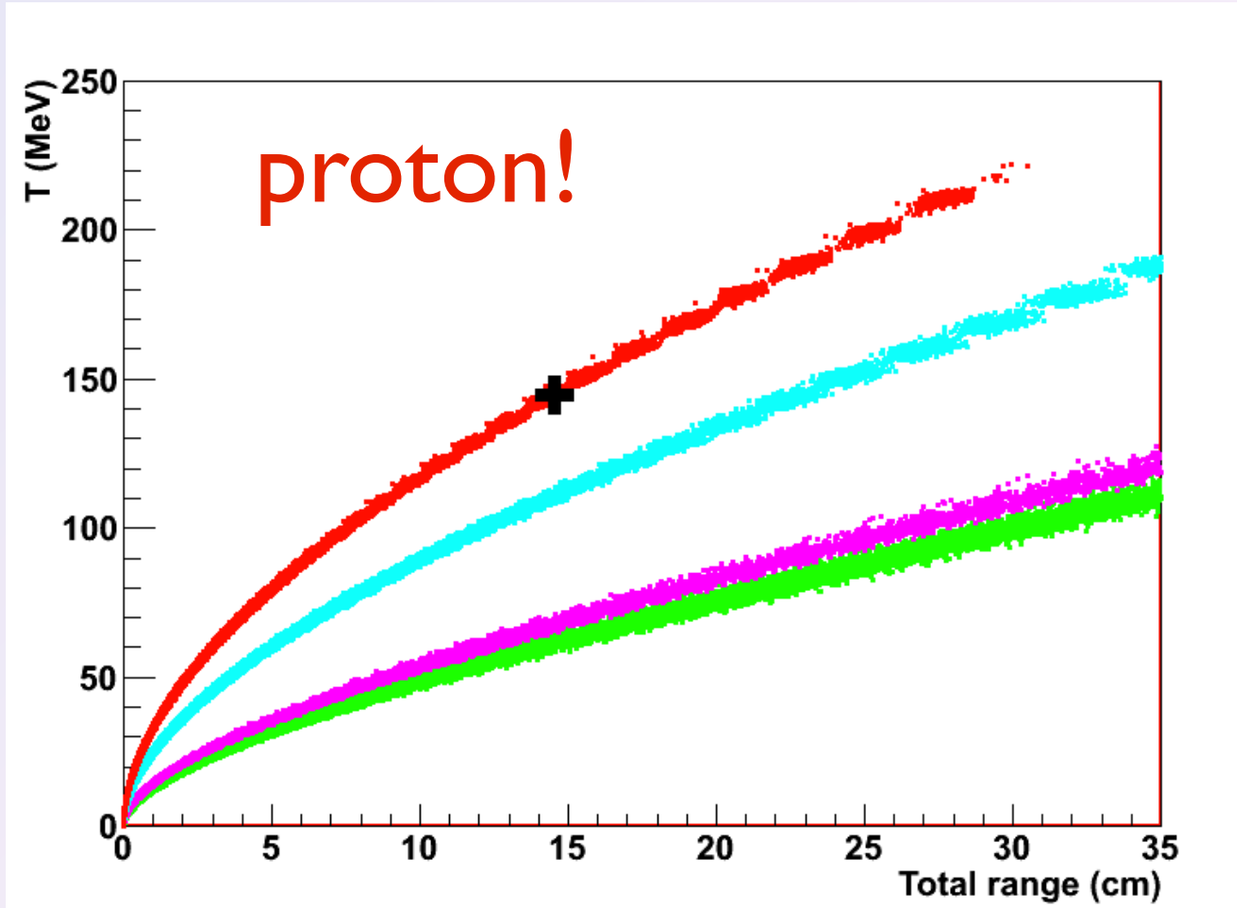


proton threshold is 21 MeV of Kinetic Energy

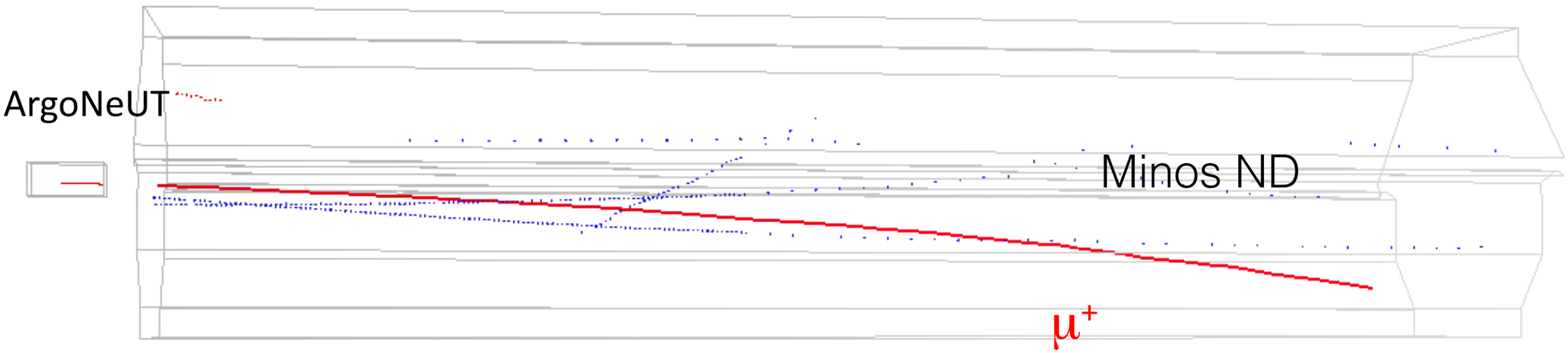
Calorimetry Example

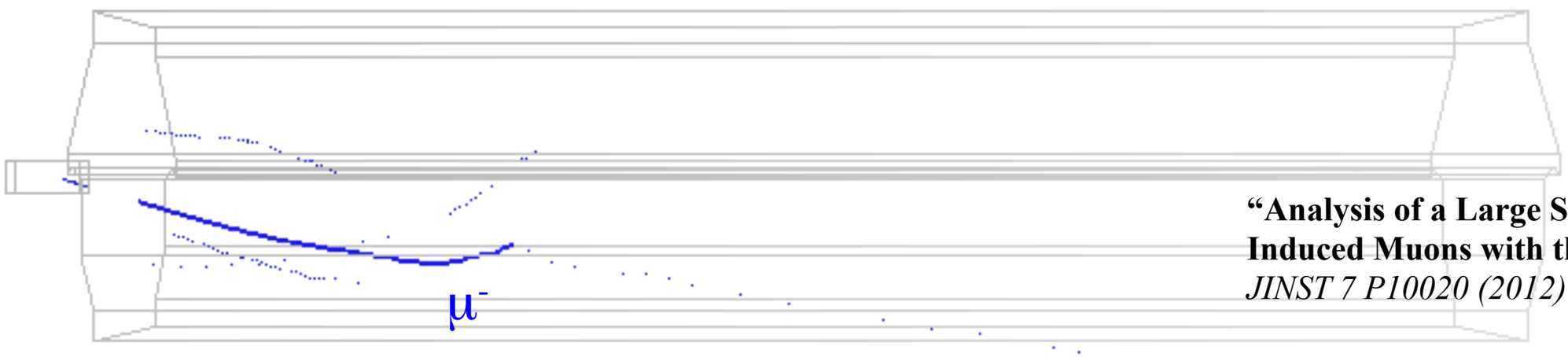






Muon Reconstruction





"Analysis of a Large Sample of Neutrino-Induced Muons with the ArgoNeuT Detector"
JINST 7 P10020 (2012)

muon kinematics: ArgoNeuT 3D, ArgoNeuT calorimetric reconstruction + MINOS ND measurement (momentum and sign)

Data Analysis still in progress
Preliminary Results!

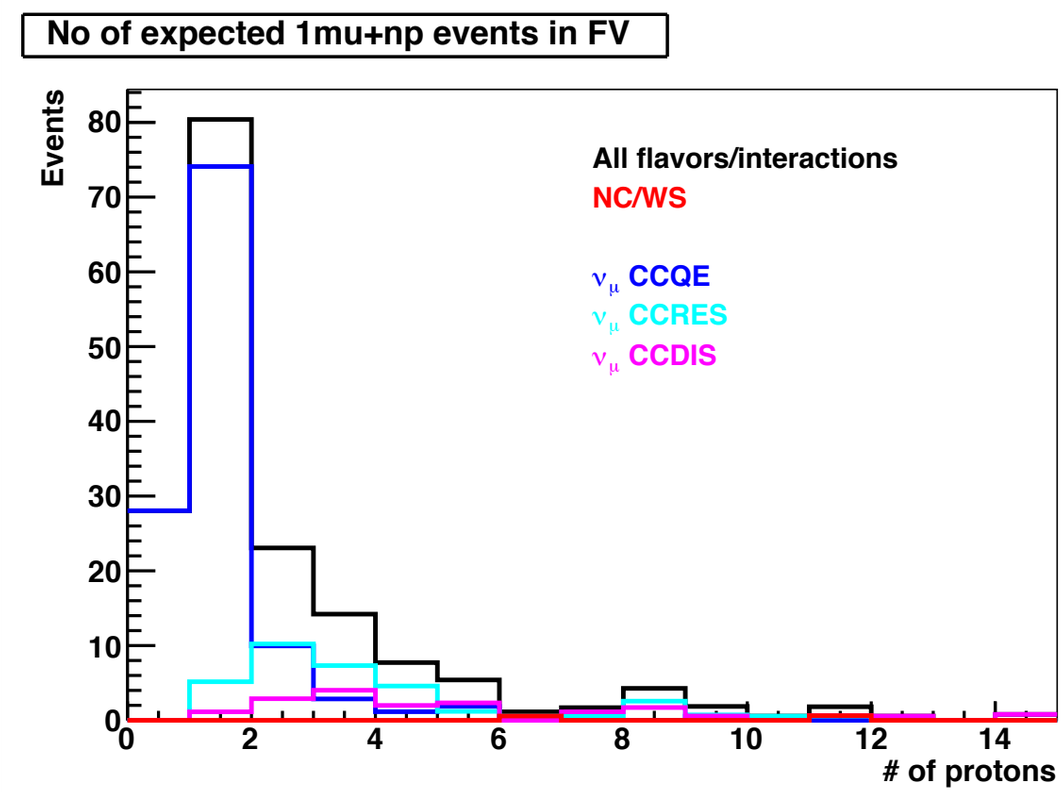
Note: Flux in anti-neutrino needs to be studied (no uncertainties included)
MC used for comparison with data: GENIE v3665
Analysis has been focused on lower multiplicity proton events!
(No optimization for higher multiplicities at the moment)
More in depth studies of background effects are ongoing and will be finalized soon

Data-MC comparison

ν_μ - neutrino mode run

Multiplicity	Genie Expectation *	Genie % of Total	DATA**	DATA % of Total
0p+1mu	28±4	16%	15±3	14%
1p+1mu	80±7	47%	51±10	48%
2p+1mu	23±4	13.4%	28±6	26%
3p+1mu	14±3	8.3%	13±3	12%
4p+1mu	8±2	4.5%	0	0
TOTAL (including >4p)	172±10	-	107±12	-

Data 38% lower



*statistical errors
** stat.+syst. errors- preliminary

Data-MC comparison

μ^-/μ^+(DATA)=0.36

μ^-/μ^+(MC)=0.36

$\bar{\nu}_\mu$ - anti-neutrino mode

Multiplicity	Genie	Genie % of Total	DATA	DATA % of Total
0p+1mu	553±11	60%	422±42	58%
1p+1mu	160±6	17%	266±53	37%
2p+1mu	68±4	7%	30±6	4%
3p+1mu	50±3	5%	3±1	0.4%
4p+1mu	32±3	4%	3±1	0.4%
TOTAL (including >4p)	925±15	-	727±68	-

data 21% lower

ν_μ - anti-neutrino mode run

Multiplicity	Genie	Genie % of Total	DATA	DATA % of Total
0p+1mu	46±3	14%	60±12	23%
1p+1mu	163±6	48%	154±31	59%
2p+1mu	46±3	13.6%	33±7	13%
3p+1mu	23±2	7%	9±2	3.5%
4p+1mu	16±2	5%	4±1	1.5%
TOTAL (including >4p)	337±9	-	260±34	-

data 23% lower

Data-MC comparison

μ^-/μ^+(DATA)=0.36

μ^-/μ^+(MC)=0.36

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← this is closest to MINERvA $\bar{\nu}$ QE selection (μ^+ and no vertex activity)

← this is closest to MiniBooNE selection (muon and any # nucleons)

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4p+1mu	16±2	5%	4±1	1.5%
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} ← this is closest to NOMAD and SciBooNE selection (1+2 track QE)

← this is closest to MiniBooNE selection (muon and any # nucleons)

Data-MC comparison

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For more discussion see O.Palamara's talk

ν_μ - anti-neutrino mode run

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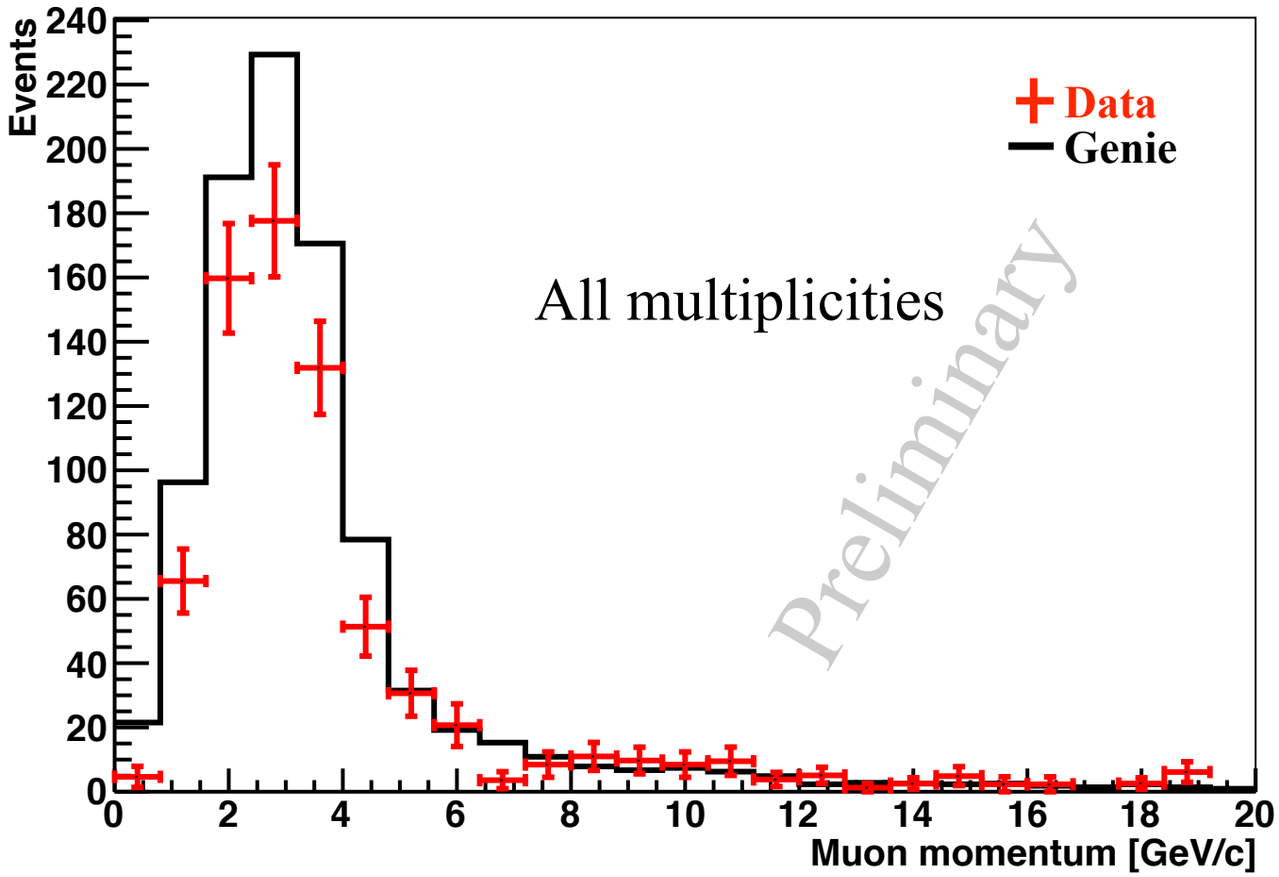
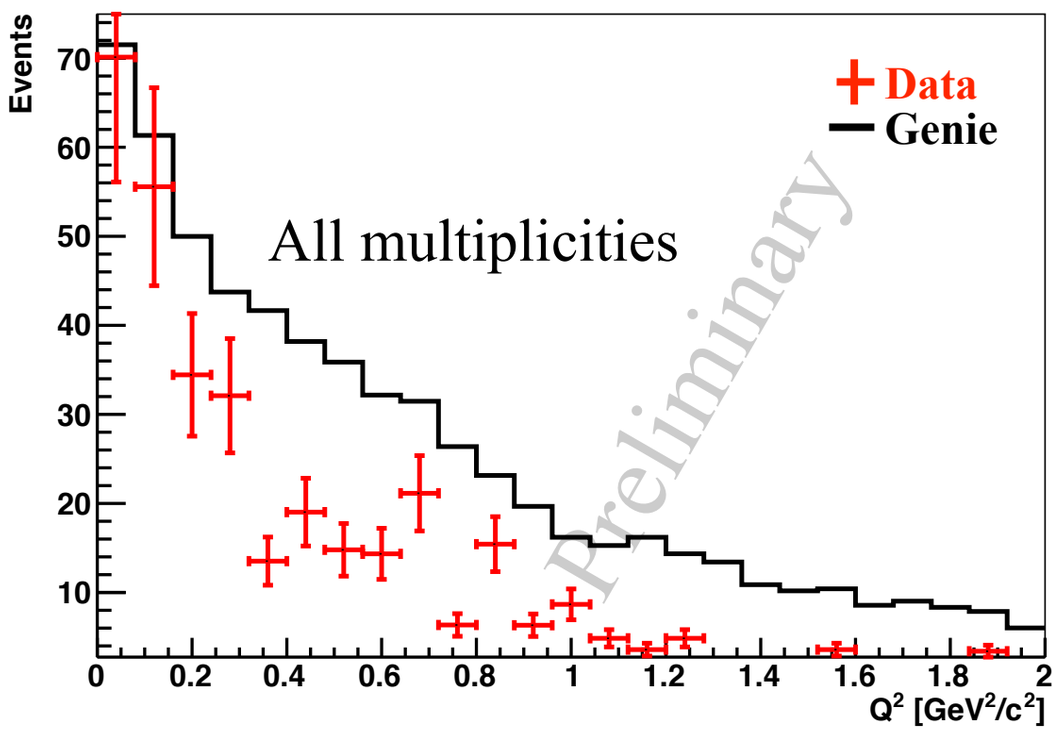
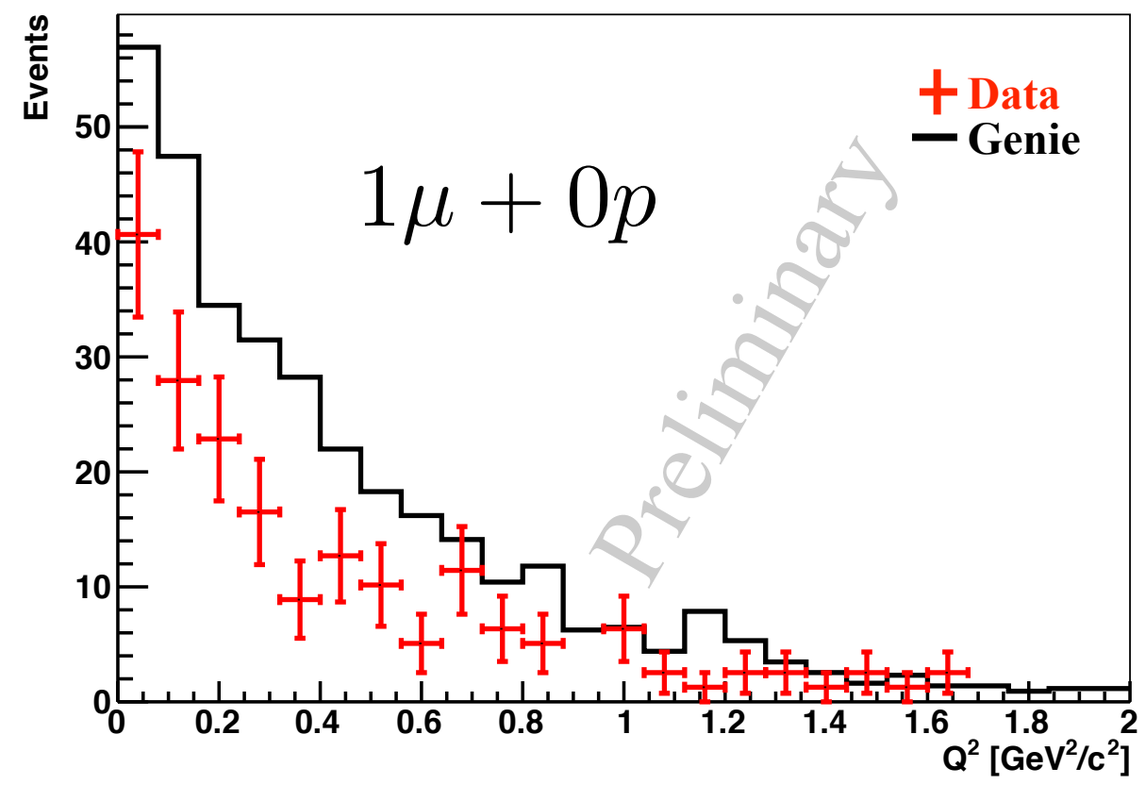
Muon Momentum and Q^2



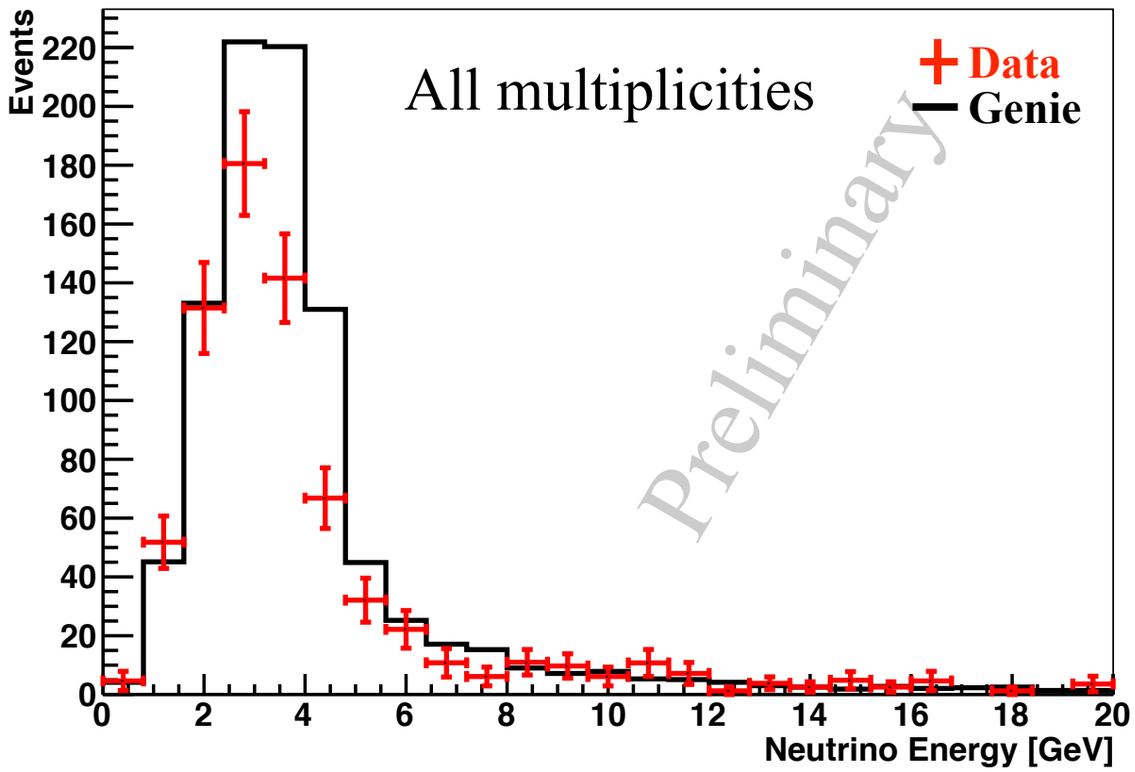
$\overline{\nu}_\mu$ - anti-neutrino mode run



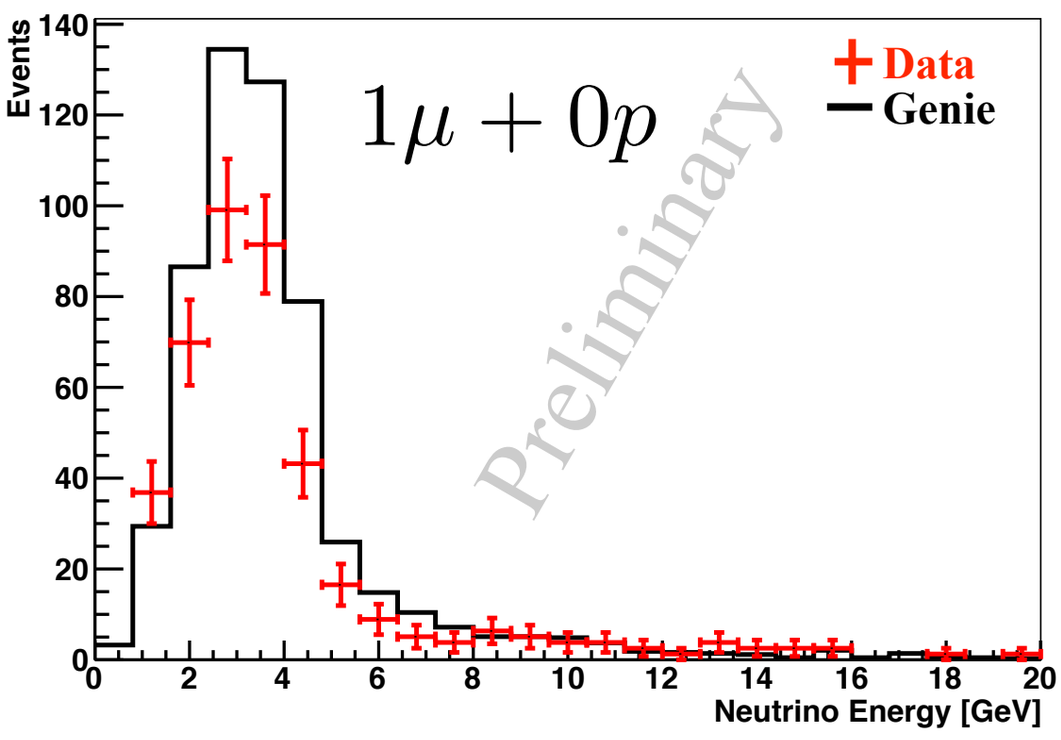


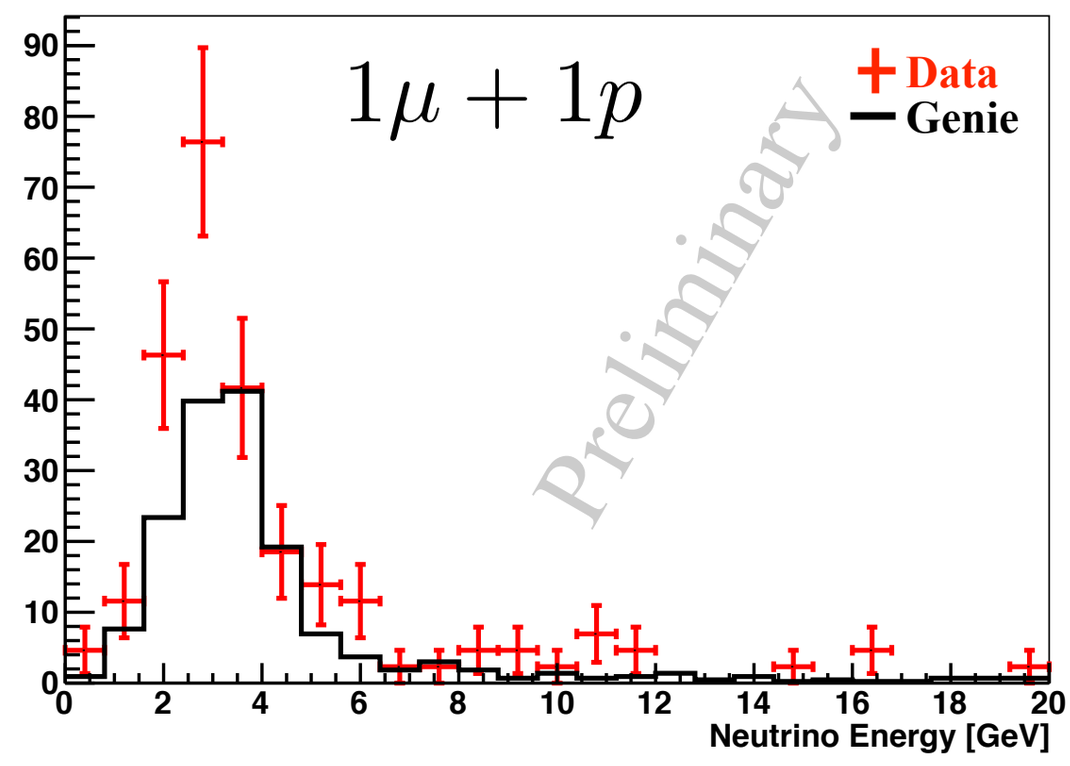
All plots normalized to absolute POT

Neutrino Energy $\bar{\nu}_\mu$ - anti-neutrino mode run



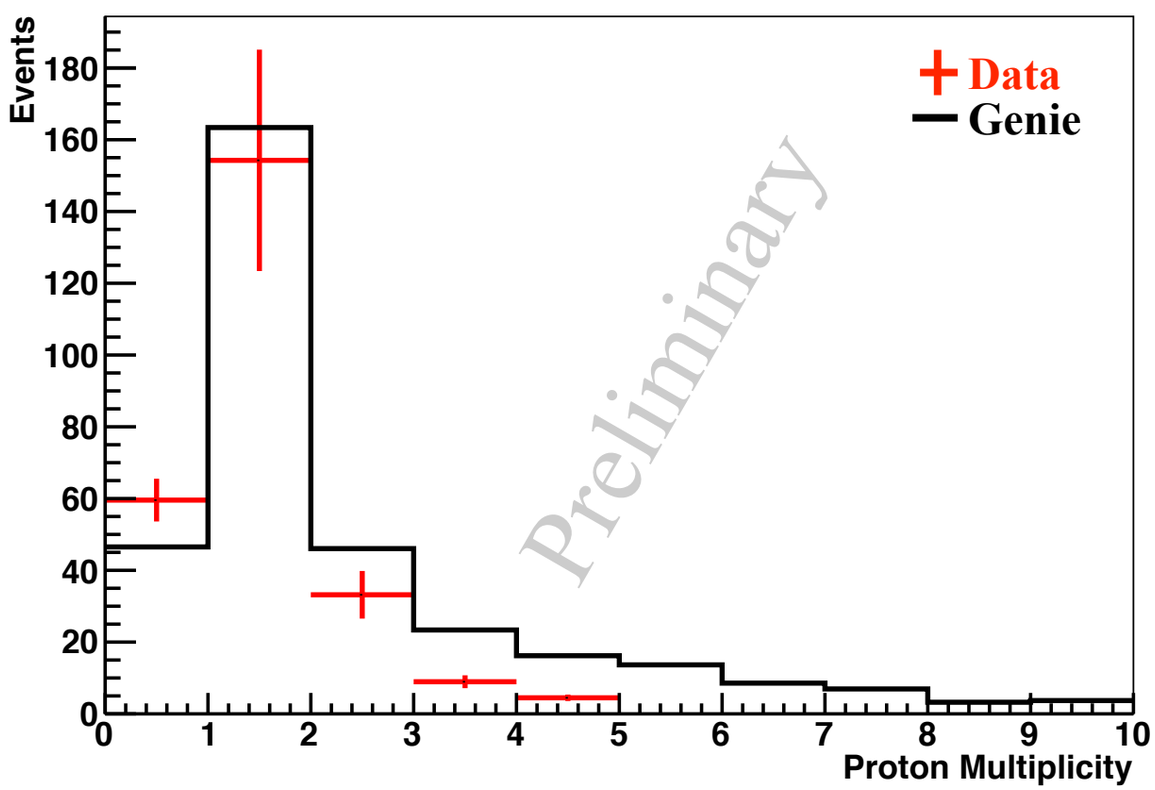
$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$



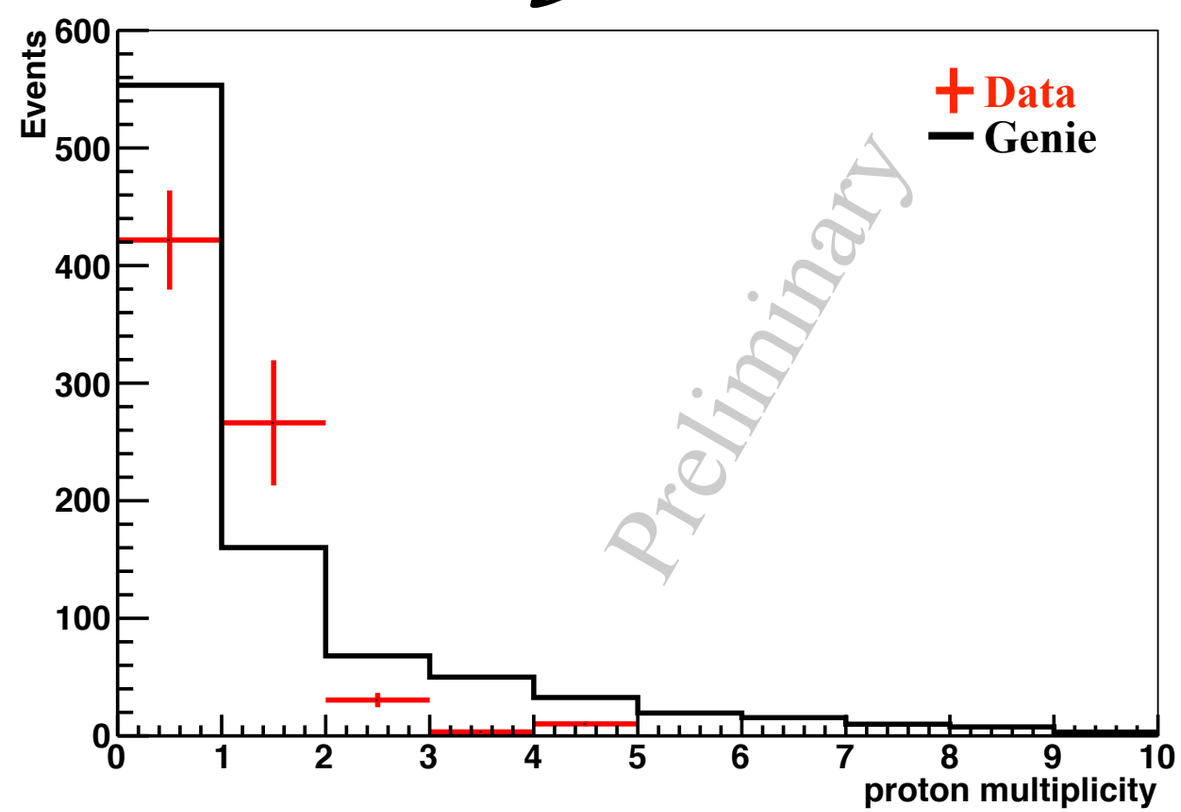


Proton Multiplicities in Anti-nu mode:

ν



$\bar{\nu}$



Besides absolute normalization the shape is better reproduced for neutrinos

Neutrino Energy Reconstruction

$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

μ kinematics

automatic reconstruction

$$p_h = \sqrt{(E_\nu - p_\mu cos\theta_\mu)^2 + p_\mu^2 sin^2\theta_\mu}$$

assumes QE events!

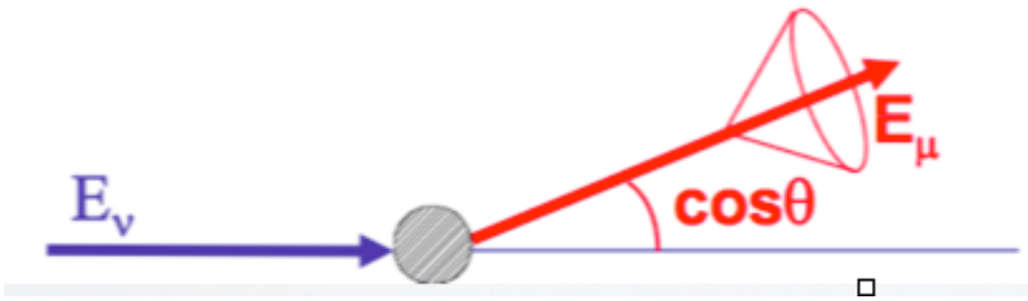
$$cos\theta_h = (E_\nu - p_\mu cos\theta_\mu)/p_h$$

$$E_\nu = p_\mu \cos\theta_\mu + p_h \cos\theta_h$$

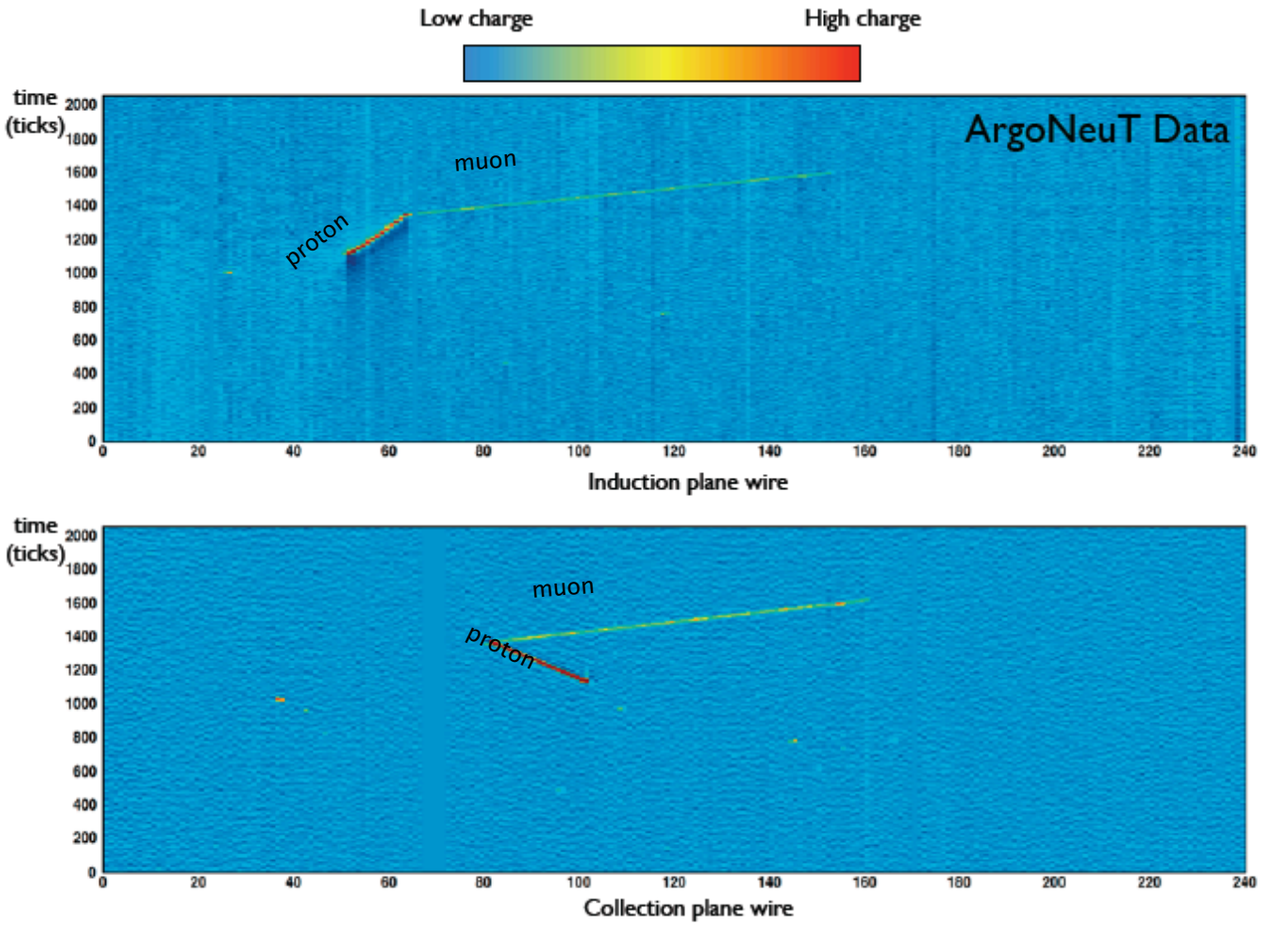
μ + p kinematics

semi-automatic reconstruction

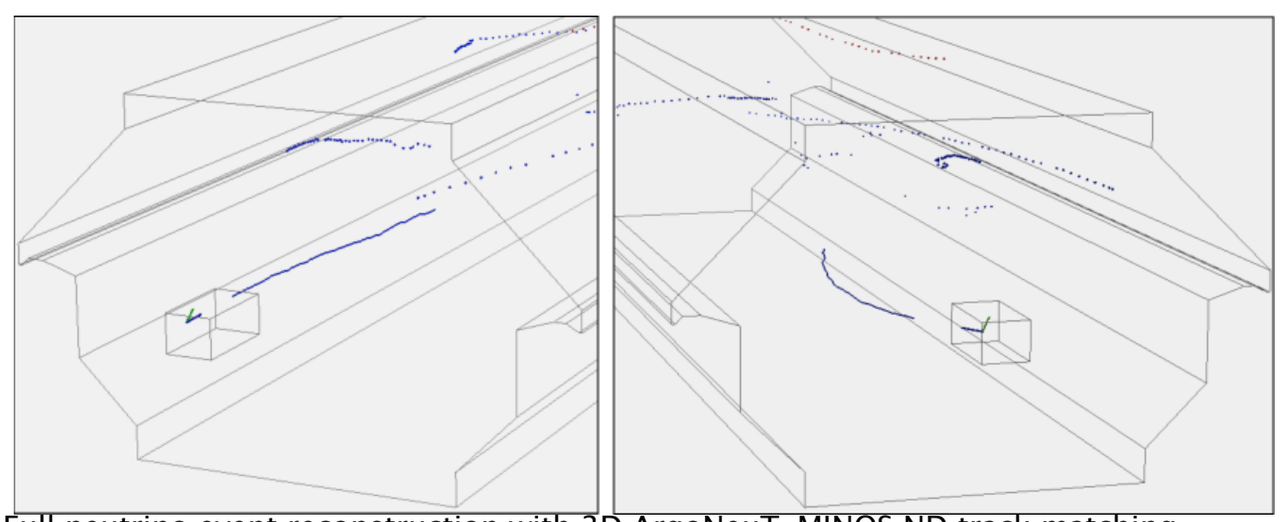
We can compare the two methods!



Reconstruction of $1\mu 1p$ events

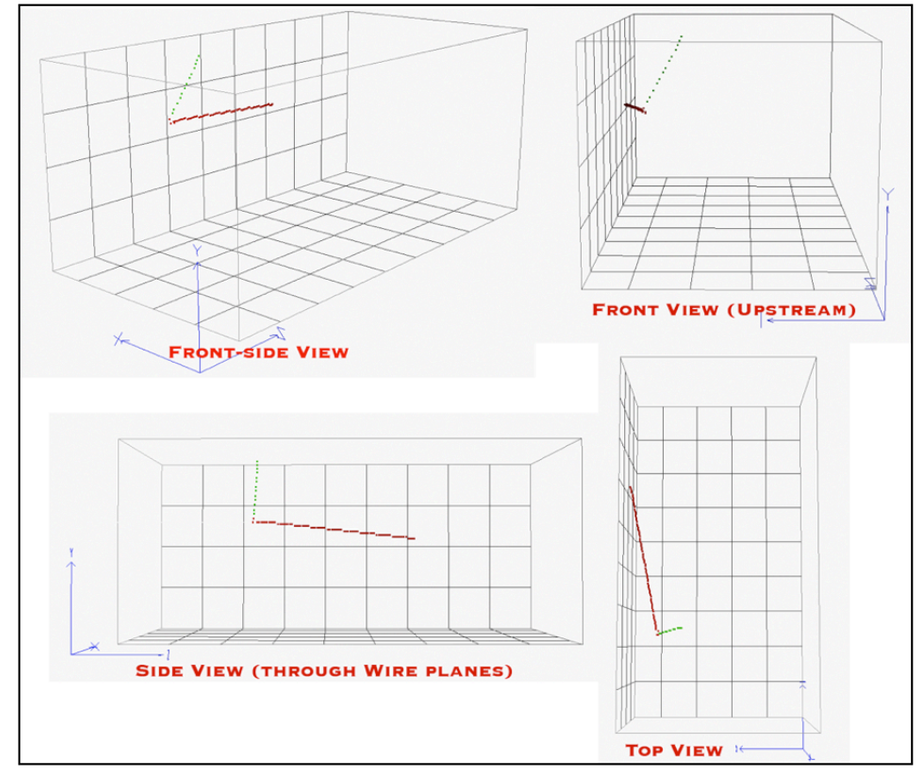


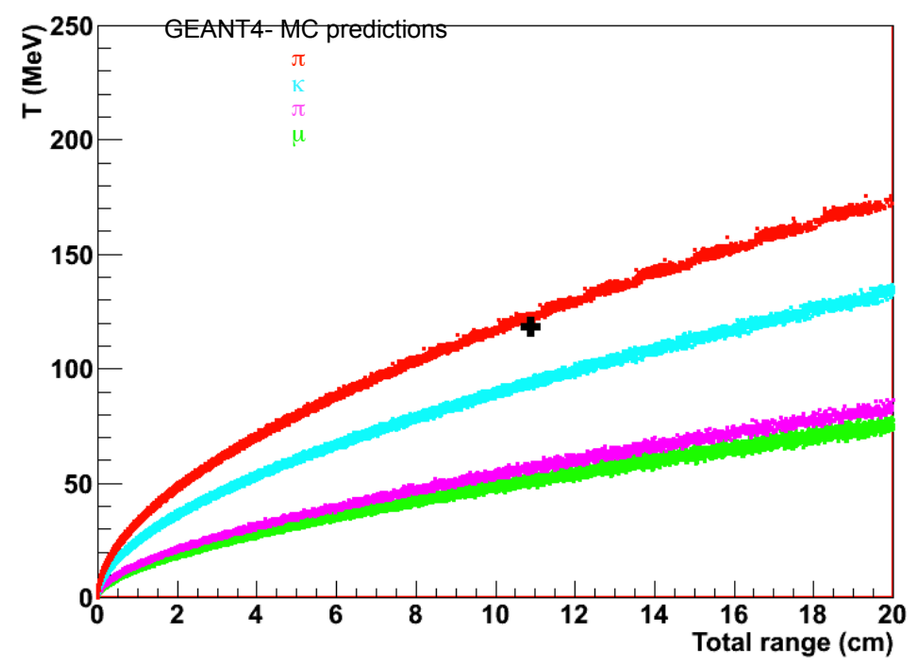
μ- escaping ArgoNeuT (and reaching MINOS-ND downstream)



Full neutrino event reconstruction with 3D ArgoNeuT-MINOS ND track matching

Neutrino event reconstructed in 3D space



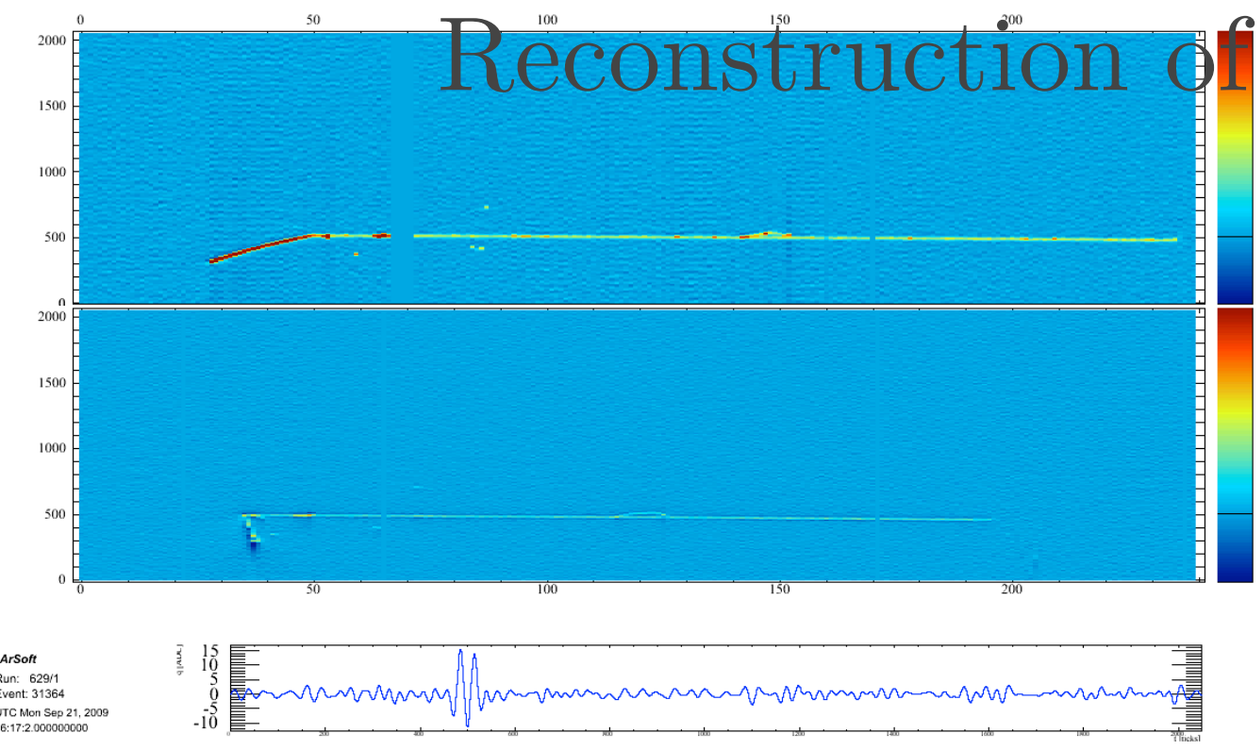


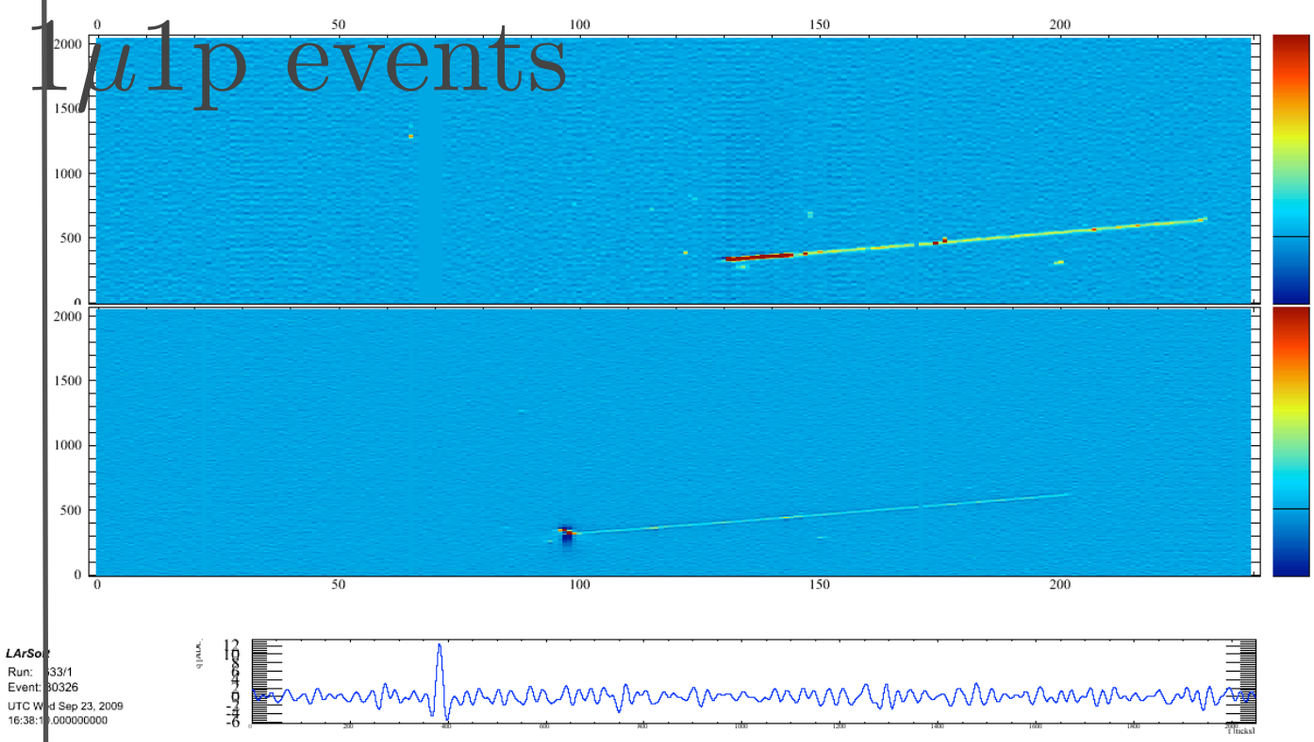
Proton (ArgoNeuT reconstruction):
track length= 10.88 cm,
T=118 MeV, p=0.485 GeV/c

$\mu + p$ kinematics — Reconstructed Neutrino Energy= 3.1 GeV

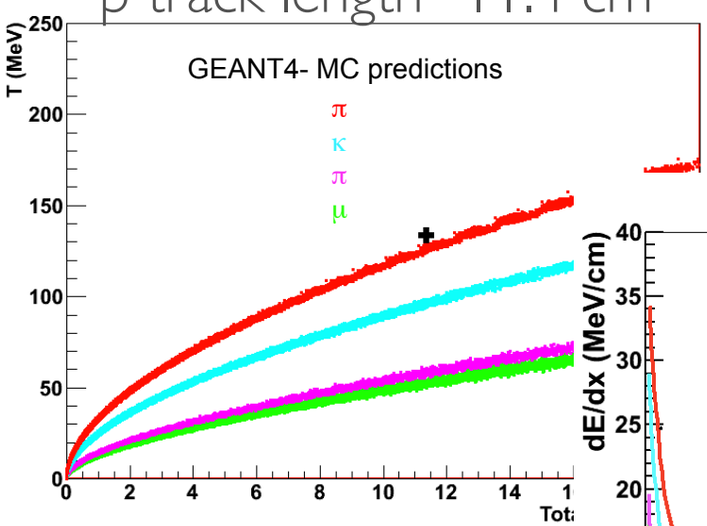
μ kinematics — Reconstructed Neutrino Energy= 3.0 GeV

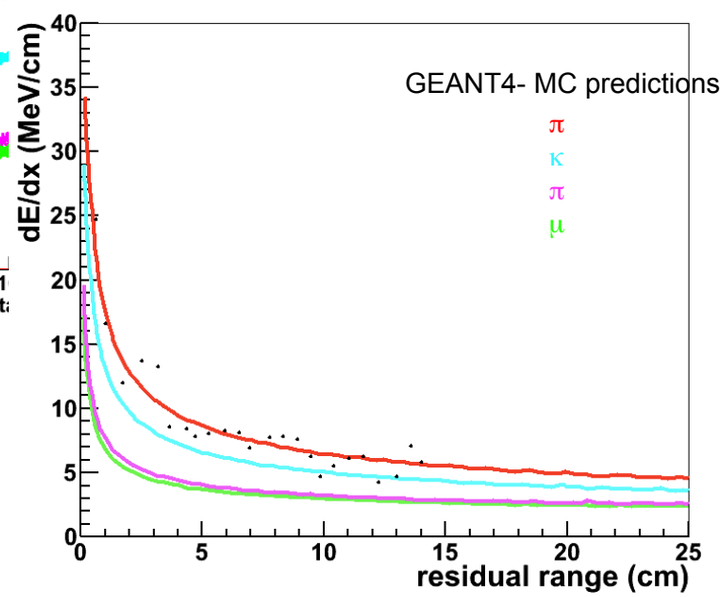
Reconstruction of 1μ1p events

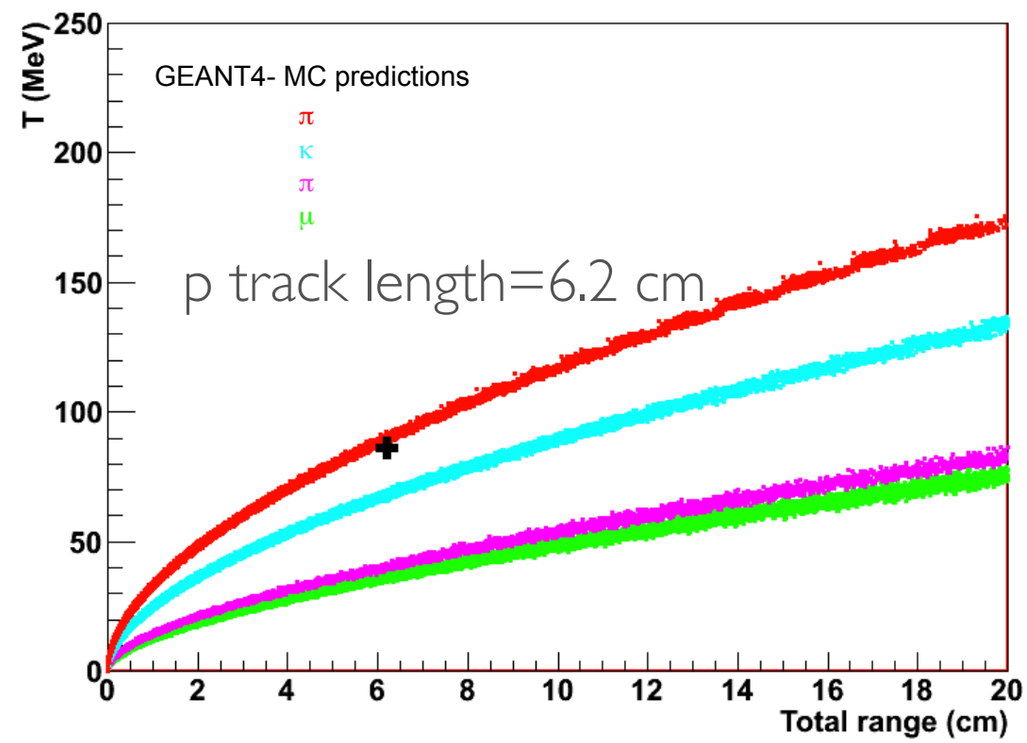




p track length=11.4 cm







μ+p kinematics	Reconstructed Neutrino Energy=3.3 GeV
μ kinematics	Reconstructed Neutrino Energy=3.3 GeV

μ+p kinematics	Reconstructed Neutrino Energy=6.5 GeV
μ kinematics	Reconstructed Neutrino Energy=6.0 GeV

Conclusions and Next Steps

- ArgoNeuT collected first ever data for low energy neutrino interactions with a LArTPC.
- Performed preliminary topological analysis of 1μ+Np in terms of rates. Cross section calculations are in progress.
- We need to be careful about what we call “QE” and how we compare these samples with other experiments.
- Energy reconstruction with the inclusion of proton kinematics is in progress.

ArgoNeuT Collaboration

F. Cavanna

University of L'Aquila

A. Ereditato, S. Haug, B. Rossi, M. Weber

University of Bern

B. Baller, H. Greenlee, C. James, S. Pordes, G. Rameika, B. Rebel, T. Yang, G. Zeller

Fermi National Accelerator Laboratory

M. Antonello, O. Palamara

Gran Sasso National Laboratory

T. Bolton, S. Farooq, G. Horton-Smith, D. McKee

Kansas State University

C. Bromberg, D. Edmunds, P. Laurens, B. Page

Michigan State University

M. Soderberg*

Syracuse University

K. Lang, R. Mehdiyev

The University of Texas at Austin

E. Church, B. Fleming, R. Guenette, A. Patch, K. Partyka, J.Spitz, A. Szelc

Yale University

* spokesperson