Perspectives from an Augmented Scintillation Light Detection System

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LArIAT Collaboration Meeting, July 2014

Based on arXiv:1405.0848 (submitted to JINST)

Scintillation light in standard LAr neutrino detectors

Useful for:

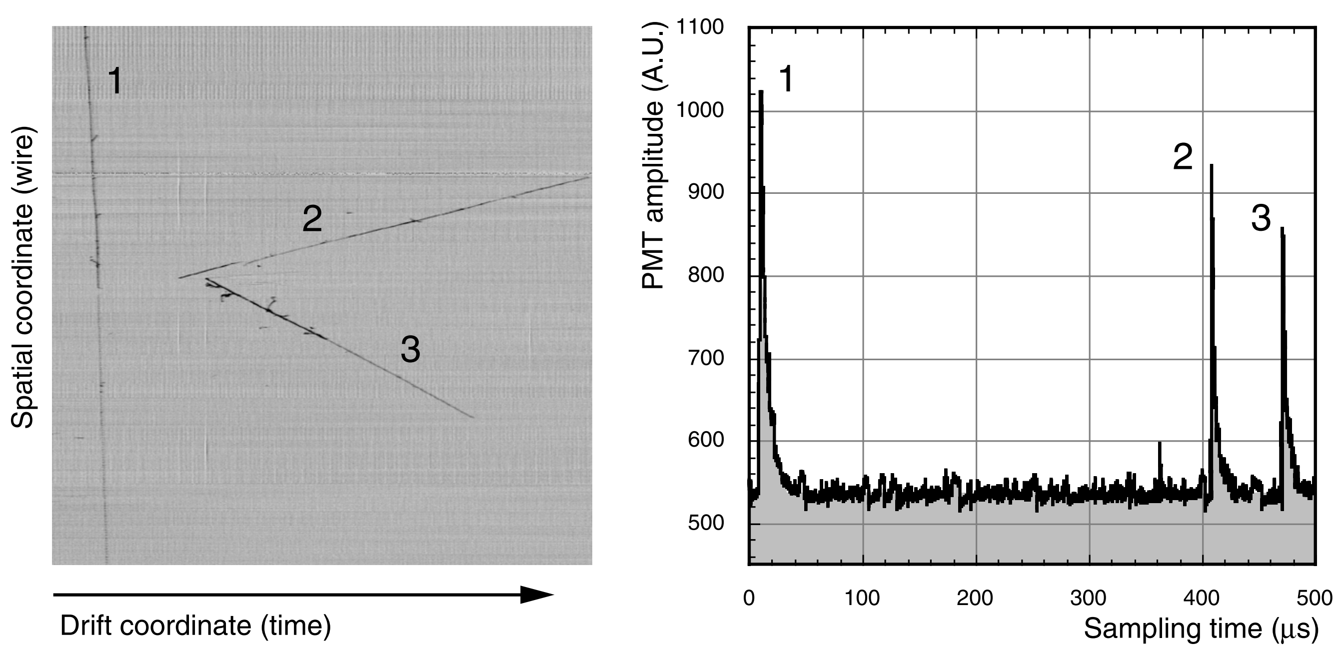
1. Trigger signal
2. t0 determination
3. Cosmic background rejection

Essential for non-beam physics (1, 2)

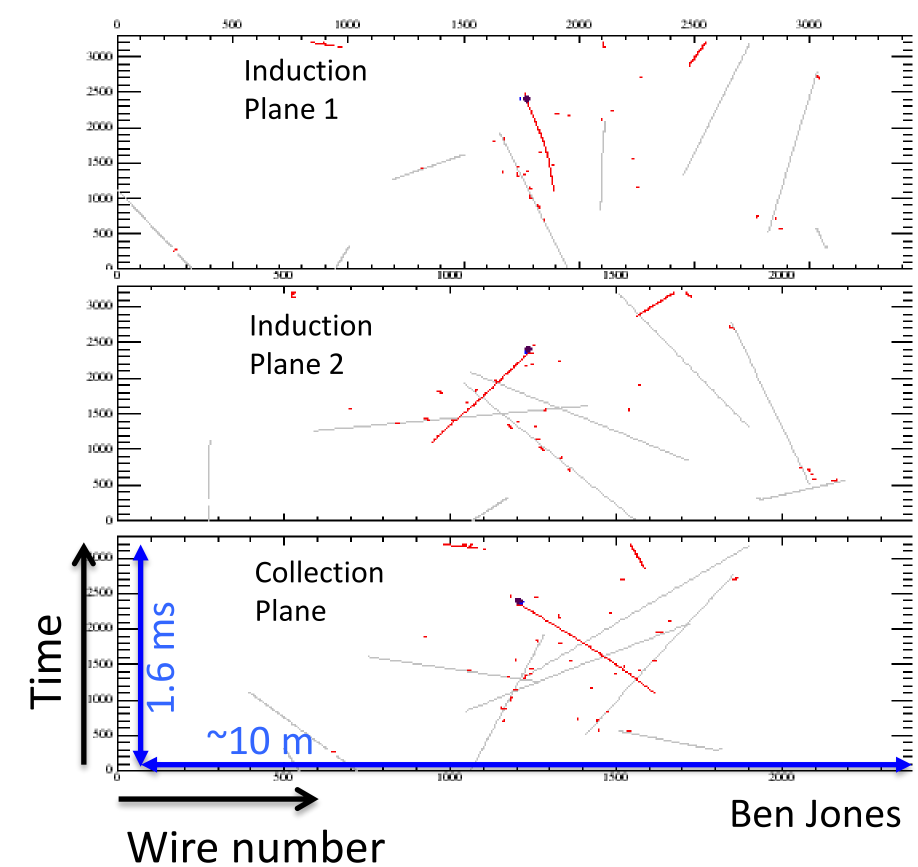
Essential for surface detectors (3)

Low (10^{-5}-10^{-4}) light detection efficiency sufficient

ICARUS T600 cosmic muons: charge and light signals

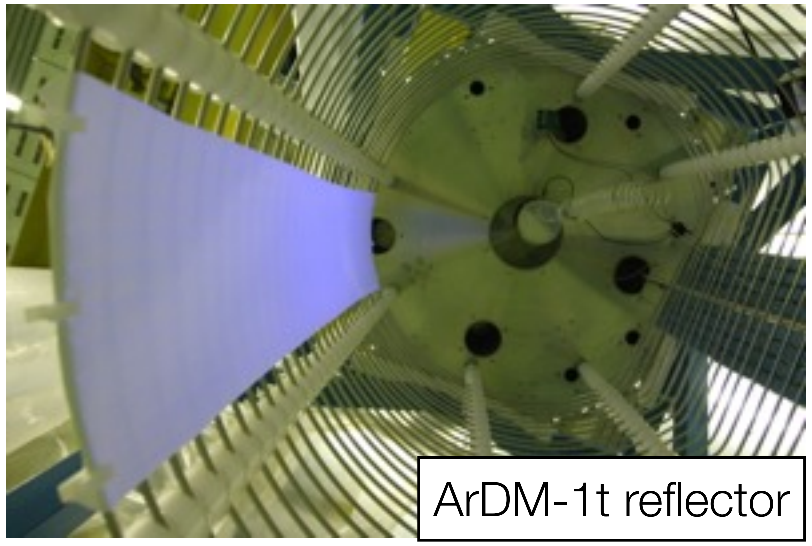


MicroBooNE simulation

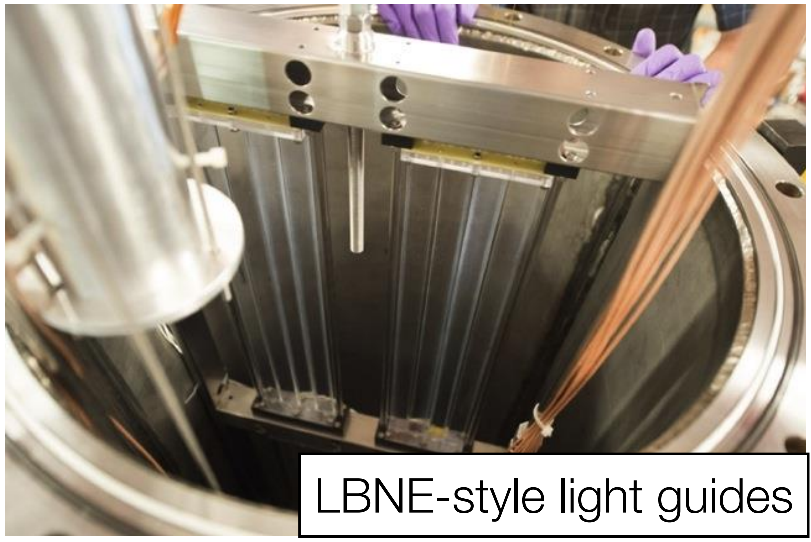


More efficient light detection systems are possible

Experiment	Fiducial mass (tons)	Coverage (%)	Reflecting surfaces	Light yield (PEs/MeV)	Detection efficiency
ICARUS T600	476	0.5	No	$\sim$1 at 0.5 kV/cm [56]	$\sim 6 \cdot 10^{-5}$
LBNO-DEMO	300	0.5	No	$\sim$1 at 0.5 kV/cm [14]	$\sim 6 \cdot 10^{-5}$
MicroBooNE	70	0.9	No	$\sim$2 at 0.5 kV/cm [57]	$\sim 1.3 \cdot 10^{-4}$
CAPTAIN	5	0.5	No	2.2 at 0.5 kV/cm [58]	$1.4 \cdot 10^{-4}$
LArIAT-1	0.24	0.3	Yes	$5 \cdot 10^1$ at 0 kV/cm [59]	$9.8 \cdot 10^{-4}$
ArDM-1t	0.85	18	Yes	$2 \cdot 10^3$ at 0 kV/cm [60]	$4 \cdot 10^{-2}$
DEAP-3600	1	75	Yes	$8 \cdot 10^3$ at 0 kV/cm [61]	$1.6 \cdot 10^{-1}$
DarkSide-10	0.01	22	Yes	$9 \cdot 10^3$ at 0 kV/cm [62]	$1.8 \cdot 10^{-1}$


ArDM-1t reflector


DEAP-3600 PMTs


LBNE-style light guides

Opportunities offered by enhanced light detection

Enhanced ↔ 10^{-3} detection efficiency or higher (see arXiv:1405.0848)

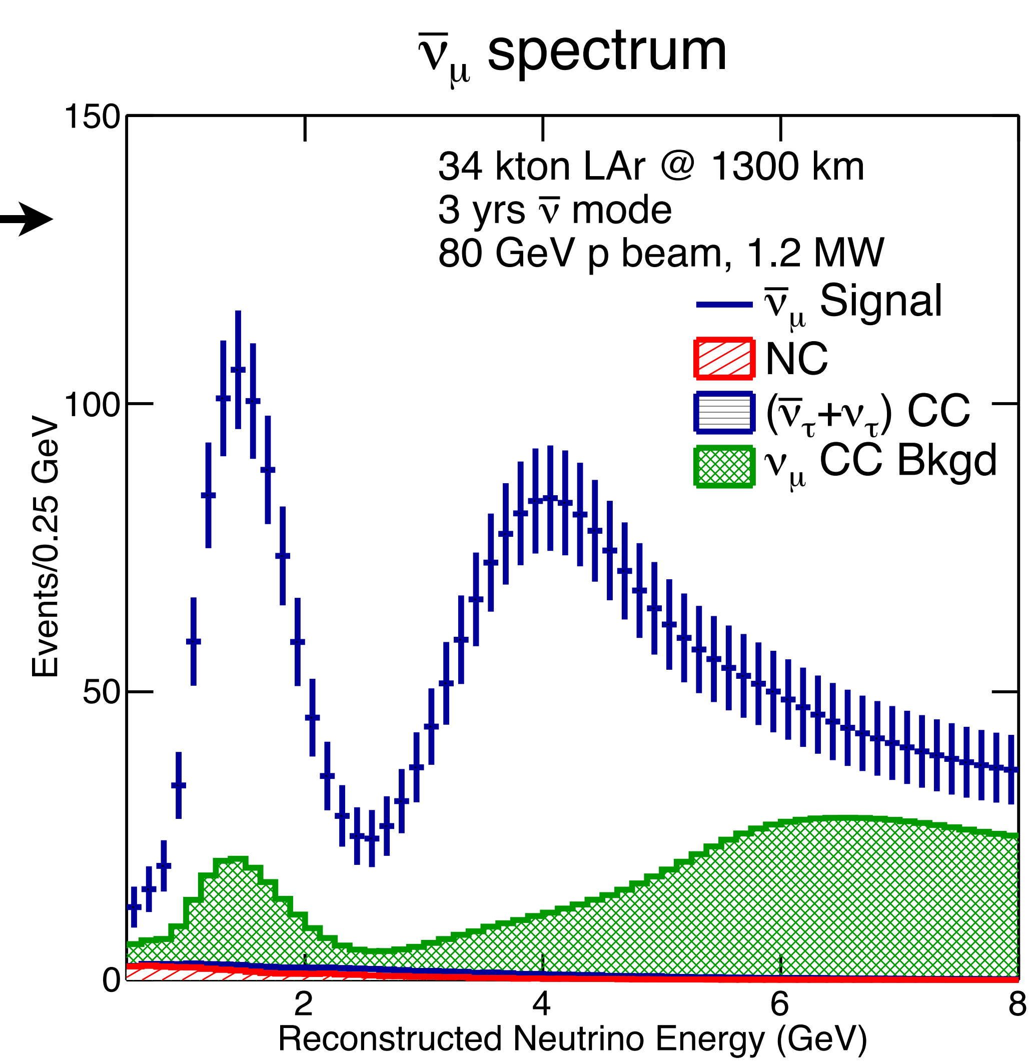
Focus on two key performance indicators for neutrino oscillation physics:

Neutrino energy resolution

Muon charge identification

Parameter	Range of Values	Value Used for LBNE Sensitivities
	For ν_e-CC appearance studies	
ν_e-CC efficiency	70-95%	80%
ν_μ-NC misidentification rate	0.4-2.0%	1%
ν_μ-CC misidentification rate	0.5-2.0%	1%
Other background	0%	0%
Signal normalization error	1-5%	1-5%
Background normalization error	2-15%	5-15%
	For ν_μ-CC disappearance studies	
ν_μ-CC efficiency	80-95%	85%
ν_μ-NC misidentification rate	0.5–10%	1%
Other background	0%	0%
Signal normalization error	1-10%	5–10%
Background normalization error	2-20%	10-20%
	For ν-NC disappearance studies	
ν-NC efficiency	70-95%	90%
ν_μ-CC misidentification rate	2-10%	10%
ν_e-CC misidentification rate	1-10%	10%
Other background	0%	0%
Signal normalization error	1-5%	under study
Background normalization error	2-10%	under study
	Neutrino energy resolutions	
ν_e-CC energy resolution	$15\%/\sqrt{E(GeV)}$	$15\%/\sqrt{E(GeV)}$
ν_μ-CC energy resolution	$20\%/\sqrt{E(GeV)}$	$20\%/\sqrt{E(GeV)}$
E_{ν_e} scale uncertainty	under study	under study
E_{ν_μ} scale uncertainty	1-5%	2%

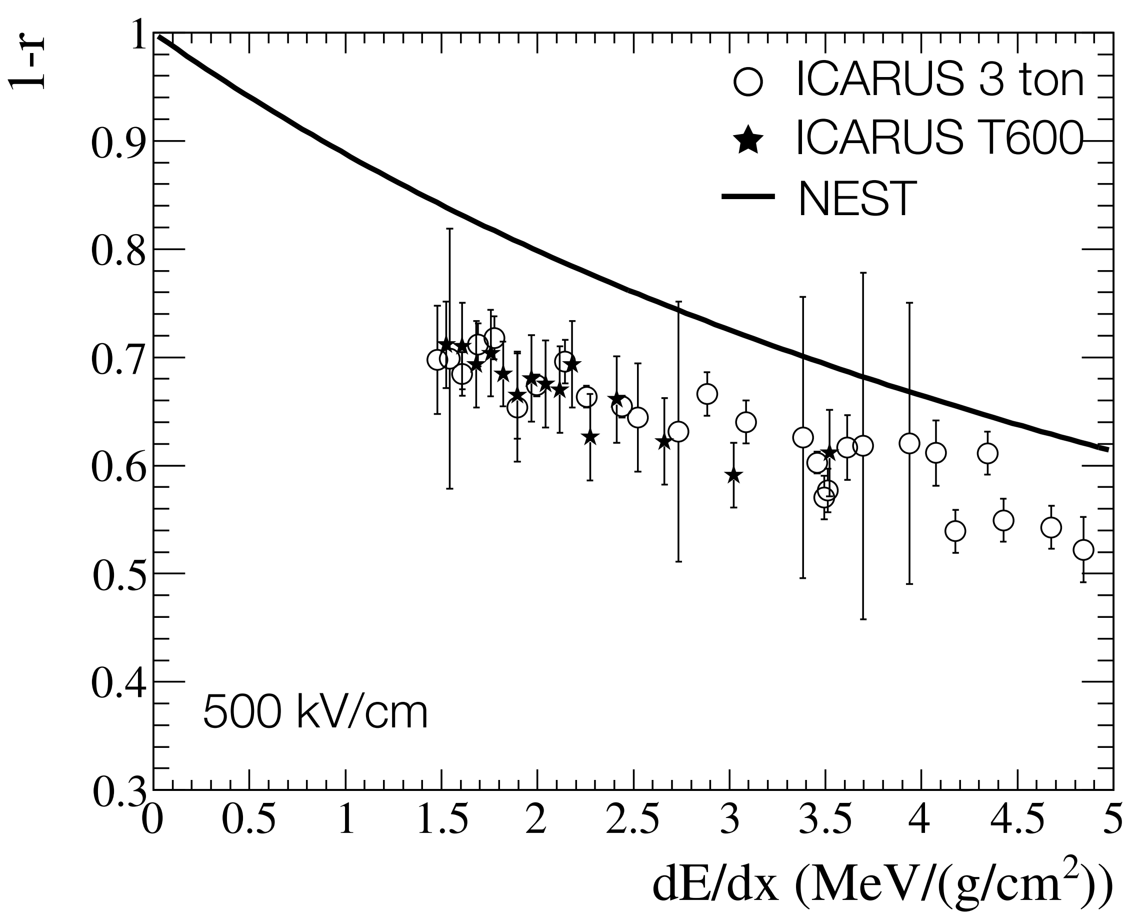
← LBNE assumptions and simulations →



Simulation tool: LArSoft

ν-Ar interactions simulated with GENIE
- ν_e, ν_μ, $\bar{\nu}_\mu$ CC interactions
- 1-6 GeV energy range

Passage of particles in LAr simulated with Geant4
- LBNE-10kt geometry
- Neutrino interactions only near detector center
- QGSP_BERT physics list
- NeutronTrackingCut turned <u>off</u>



Charge/light production simulated with NEST
- Energy partitioning between Ar ionization and excitation
- Quenching of charge/light for highly ionizing nuclear fragments
- Recombination (r) of ionization electrons

Neutrino energy resolution

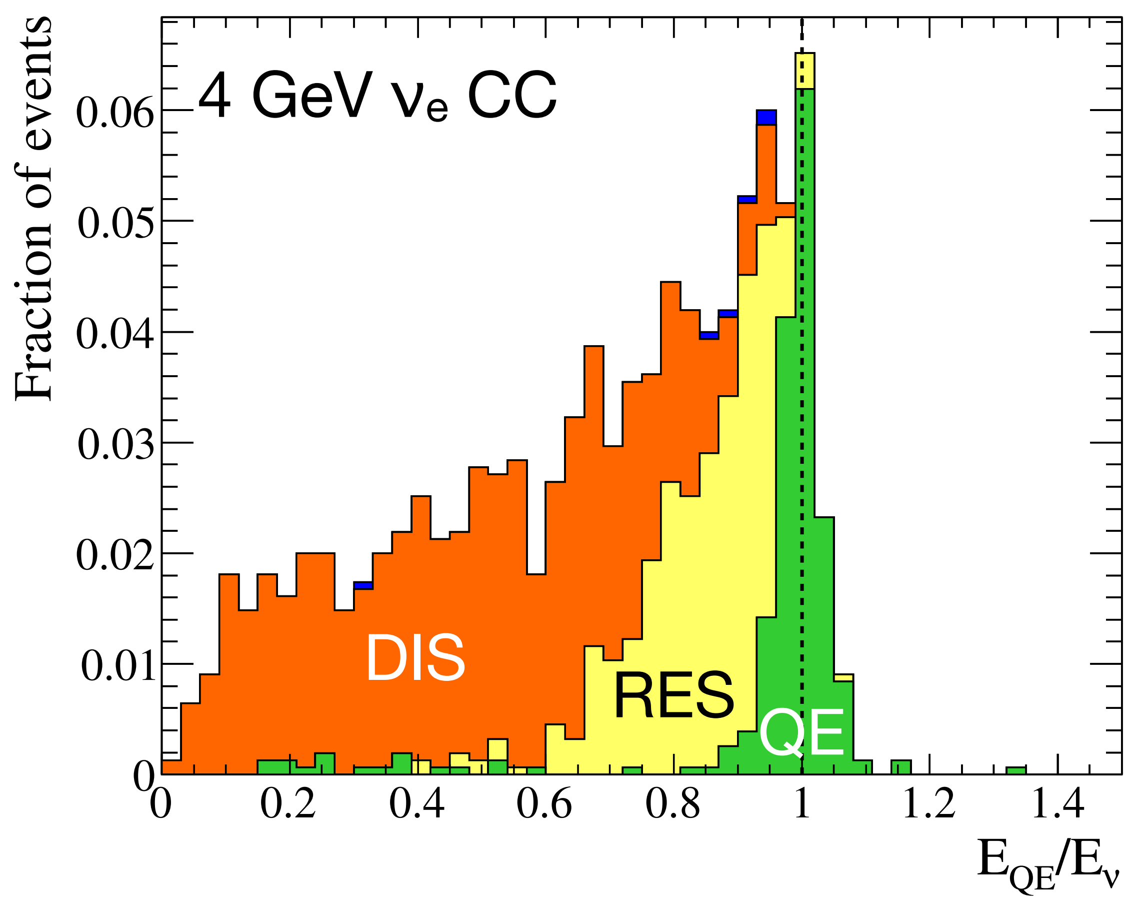
Limitations of quasi-elastic neutrino energy reconstruction

- QE reconstruction: neutrino energy by measuring energy/direction of outgoing lepton

Assumptions:

- $\nu_l + n \rightarrow l^- + p$ reaction
- neutron at rest
- neutrino direction known

$$E_{QE} = \frac{1}{2} \frac{m_n^2 - (m_p - V)^2 - m_l^2 + 2(m_p - V)E_l}{(m_p - V) - E_l + |\vec{p}_l| \cdot \cos\vartheta_l}$$



- Very poor performance for inelastic interactions, which are dominant above few-GeV

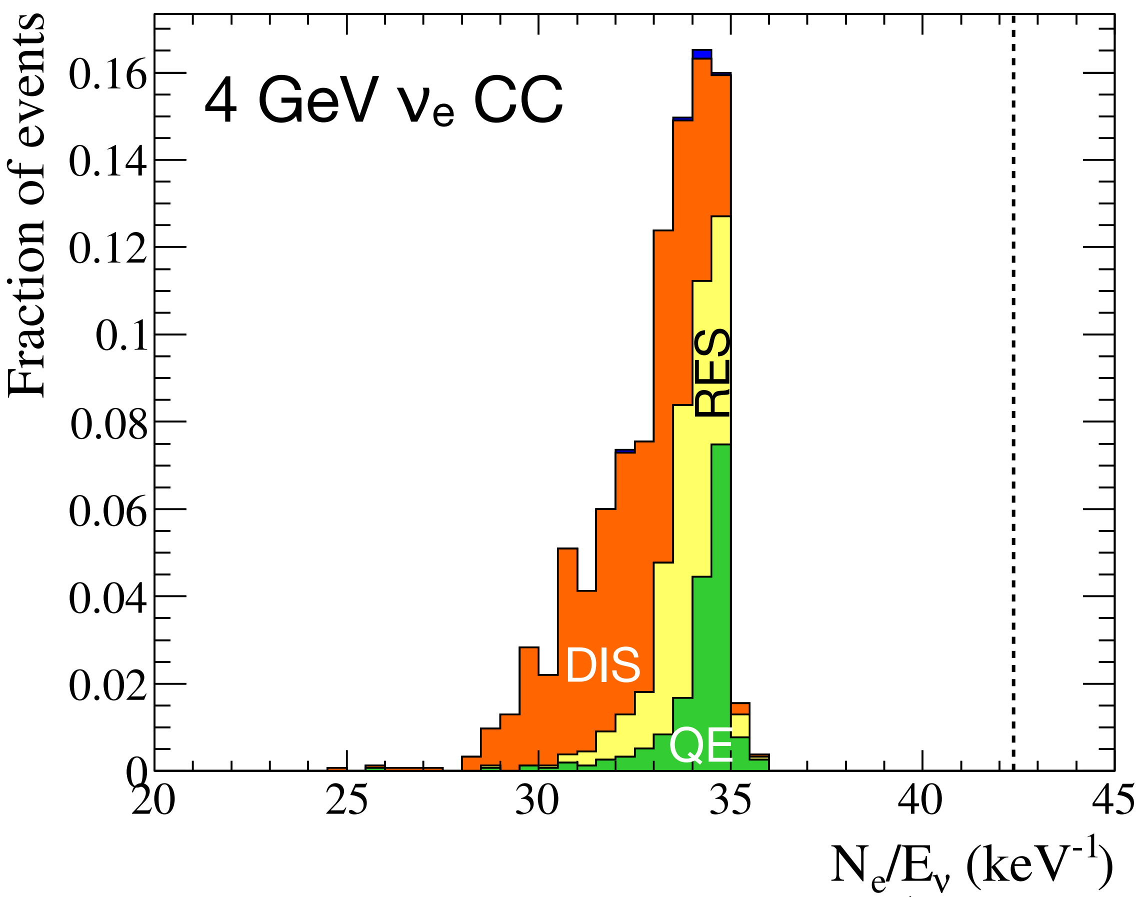
Calorimetric neutrino energy reconstruction

Contributions to resolution

- Calorimetric reconstruction: add all energy deposited in active volume, as estimated from ionization electrons reaching readout planes (N_e)

- Effects limiting calorimetric measurement:

1. Nuclear effects in neutrino interactions
2. Non-deposited energy carried away by neutrinos
3. Particle (other than ν) leakage out of active volume
4. Quenching of ionization/excitation from nuclear fragments
5. Electron-ion recombination
6. Electron attachment along drift
7. Electronic noise



True neutrino energy

Calorimetric neutrino energy reconstruction

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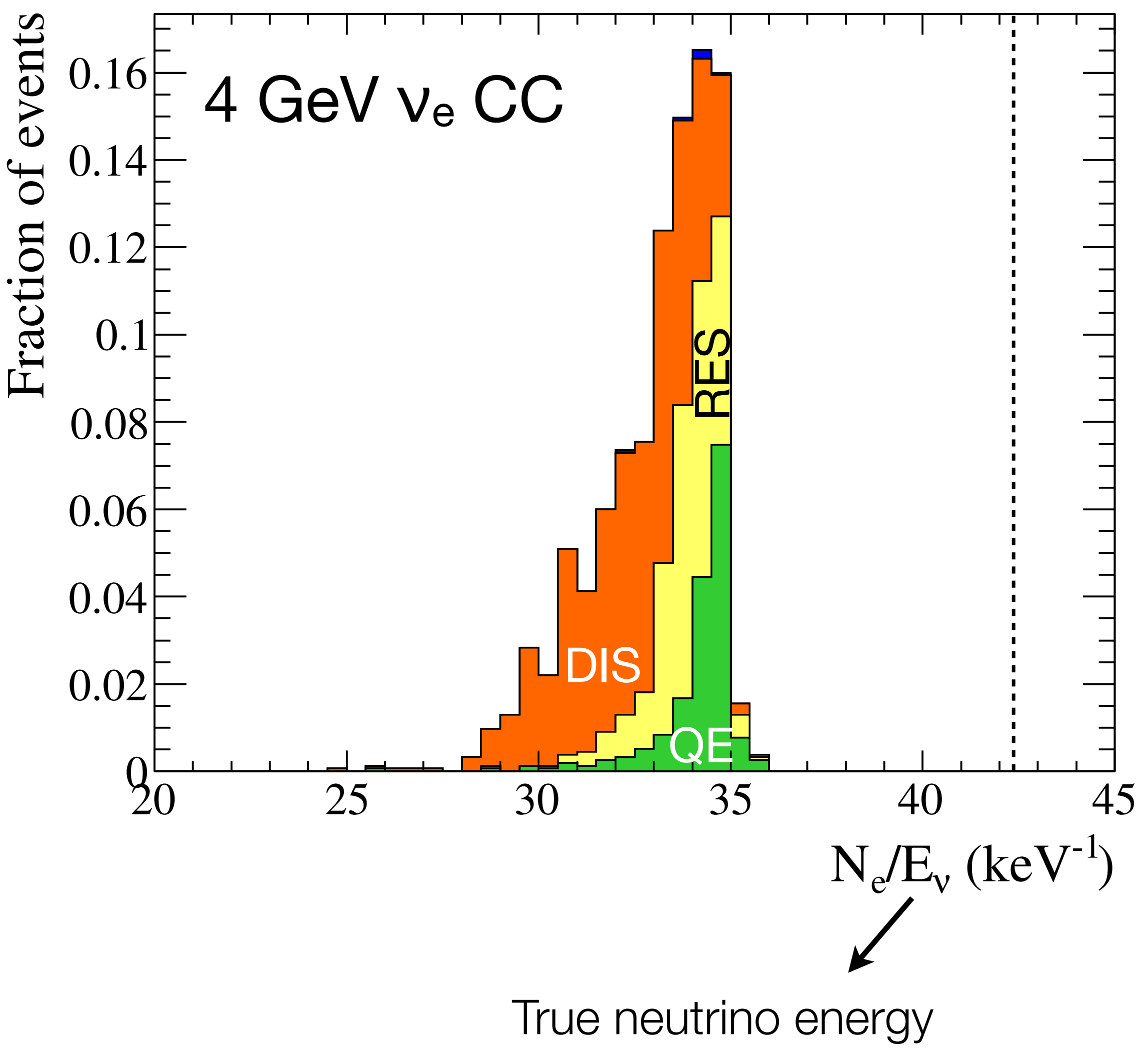
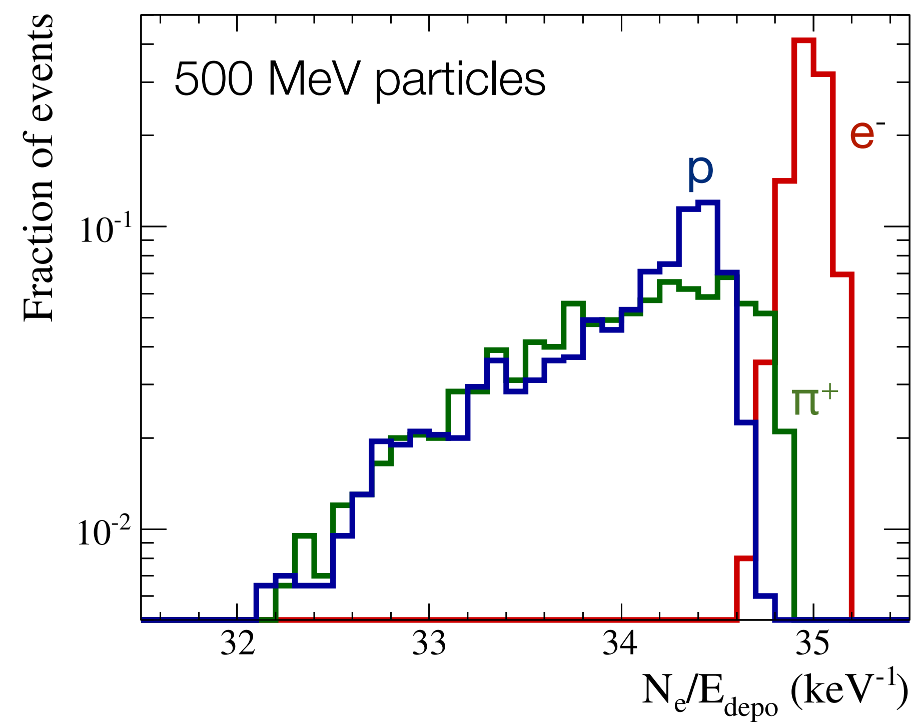
not considered here
(detector-dependent and can be made small)



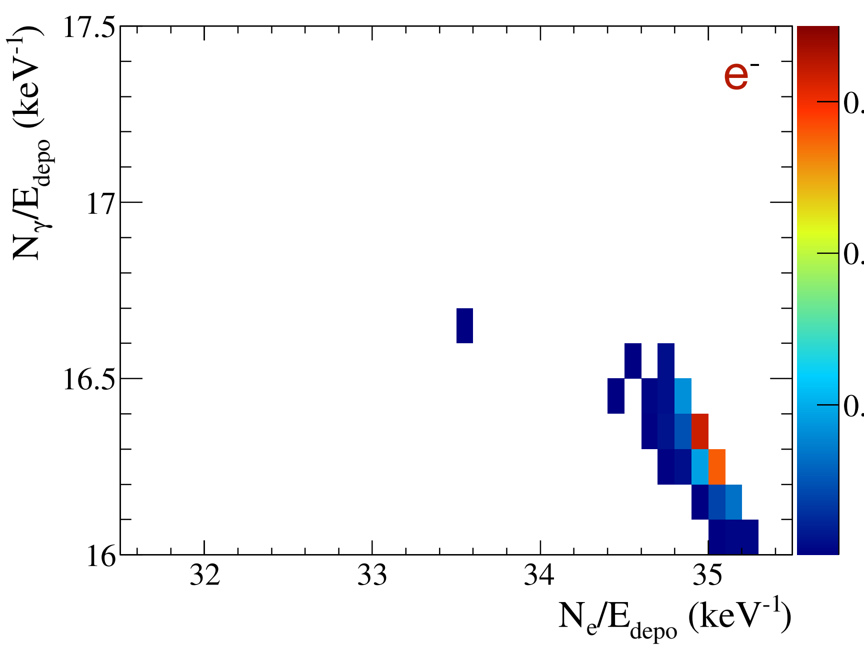
Electron-ion recombination

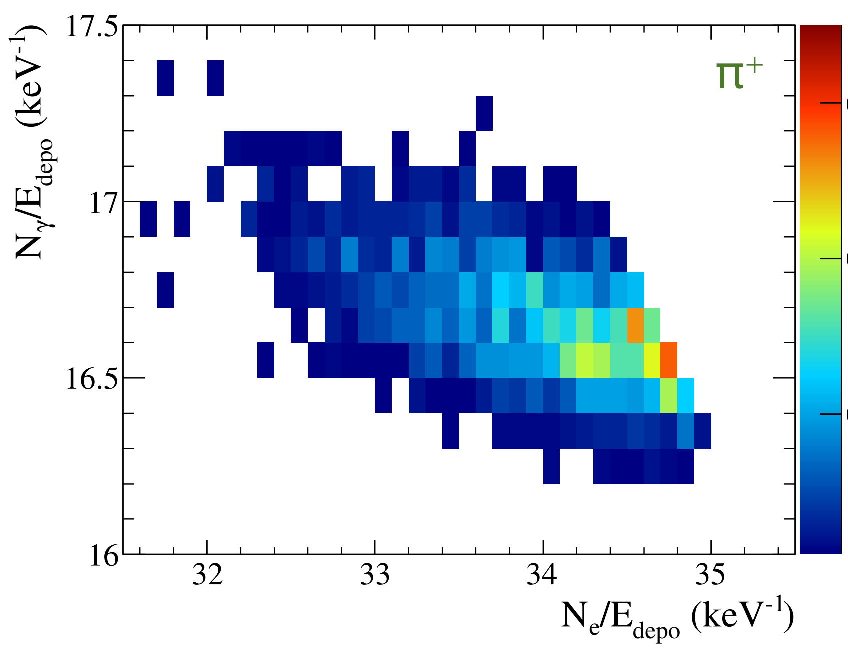


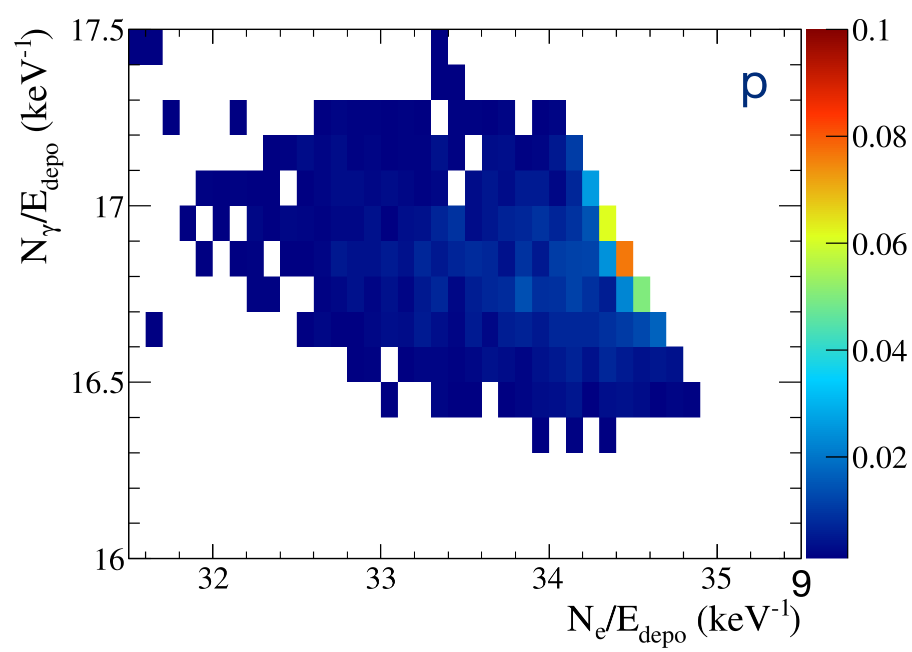
- Charge per deposited energy depends on recombination (and quenching) effects

- Different charge response for different particles

- Anticorrelation between charge and light, since each recombined electron (N_e) gives rise to one photon (N_γ)



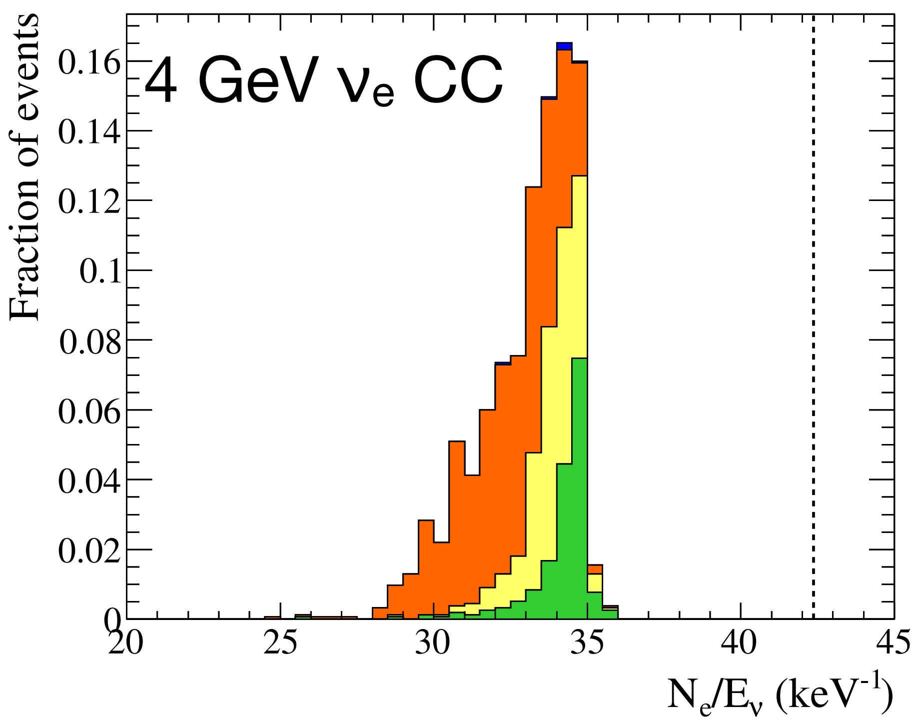




Calorimetric neutrino energy reconstruction

Impact of electron-ion recombination

- Use $N_q = N_e + N_\gamma$ instead of N_e



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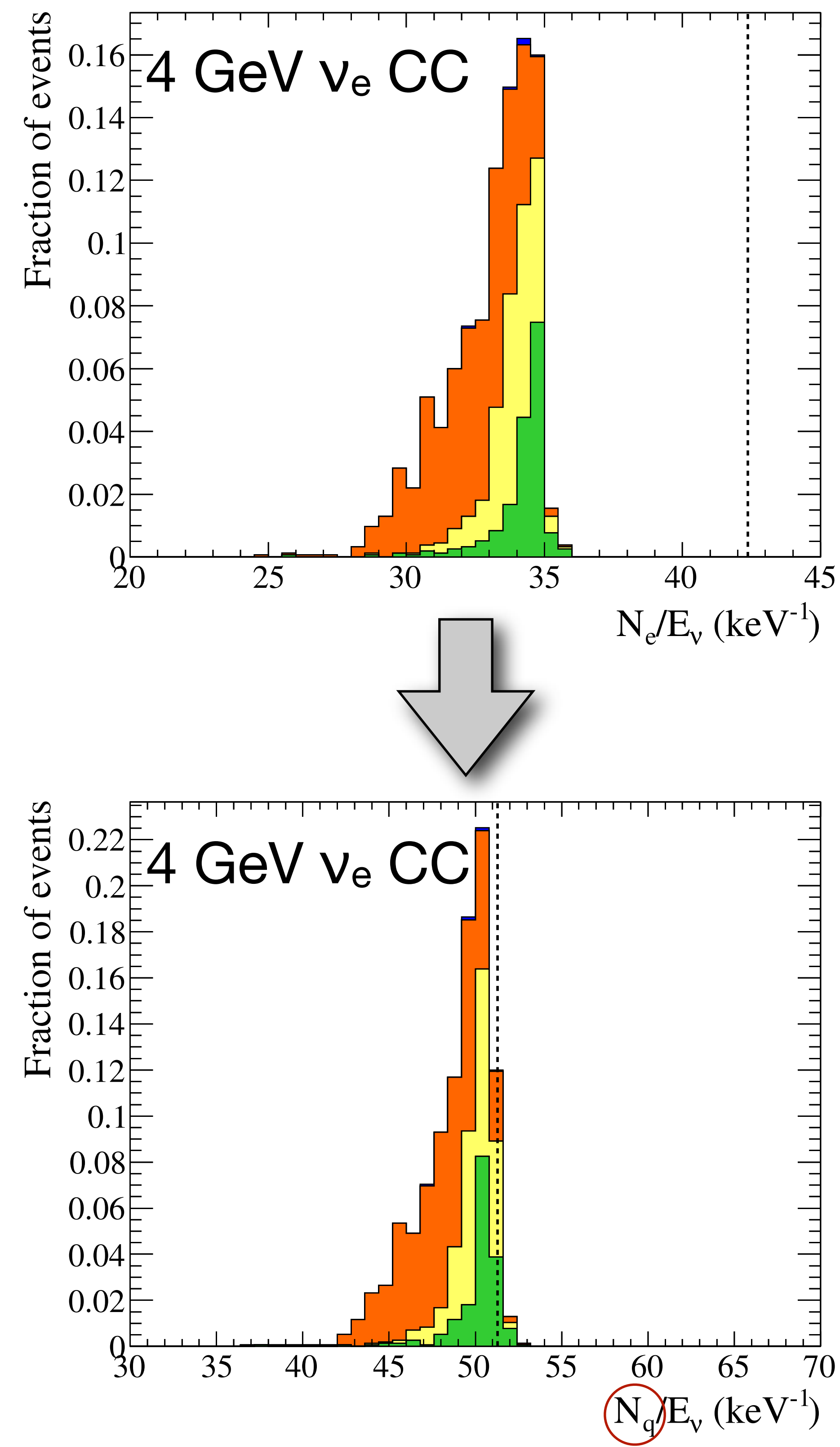
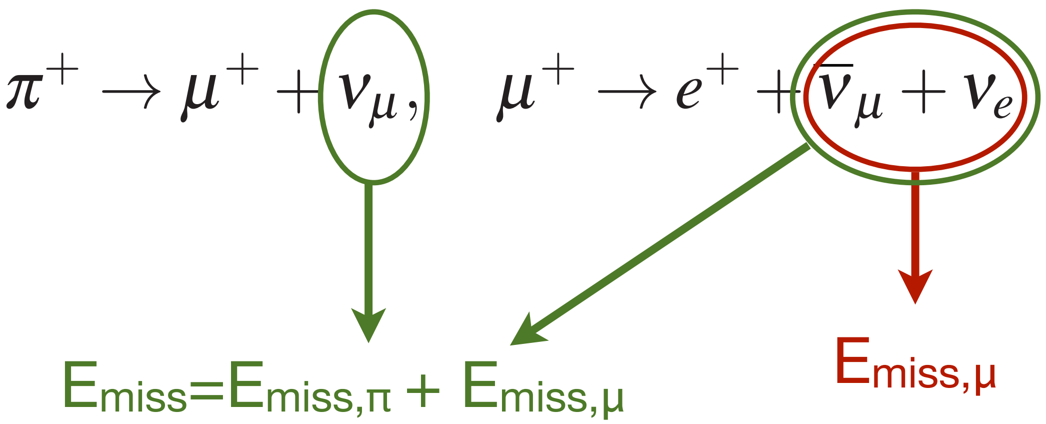
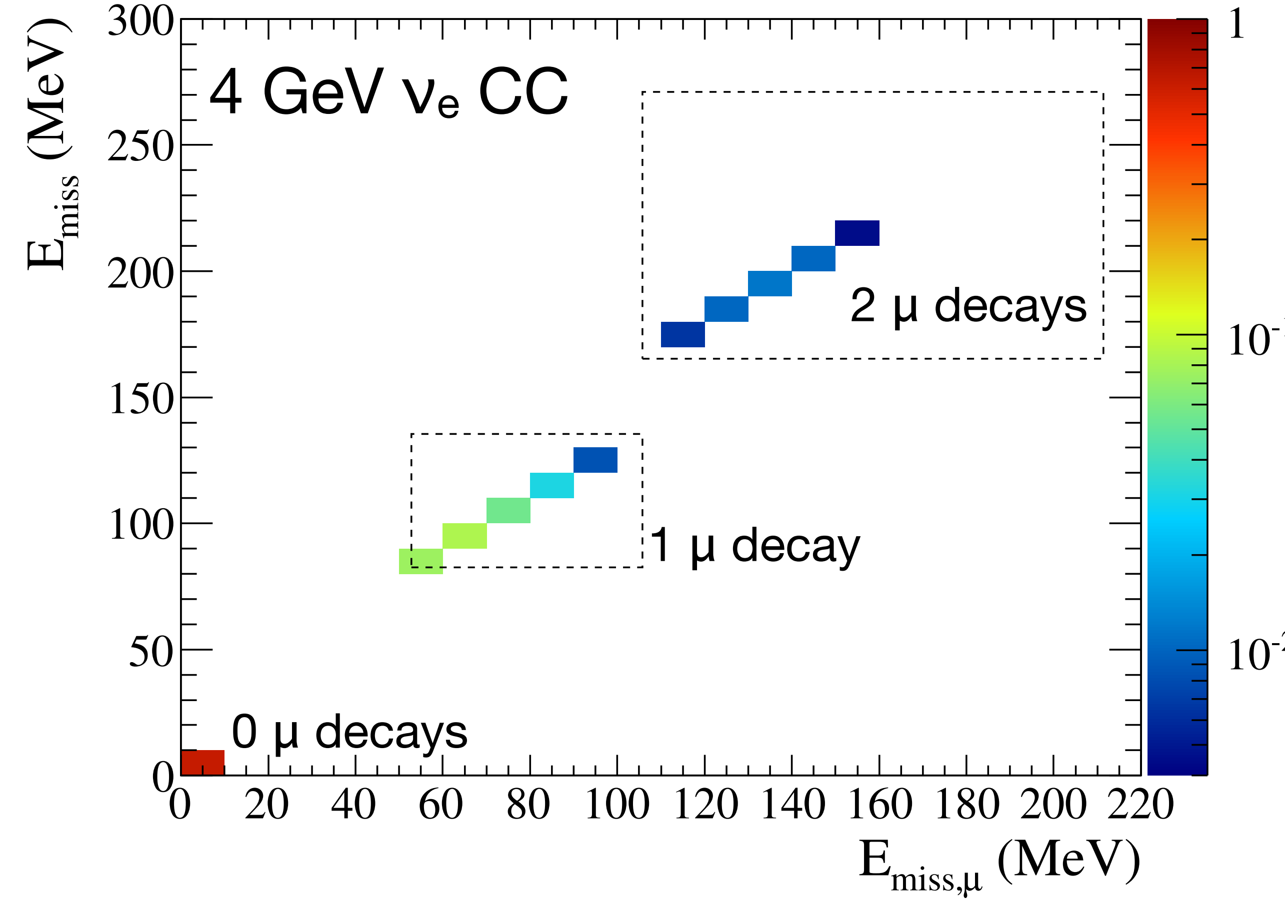


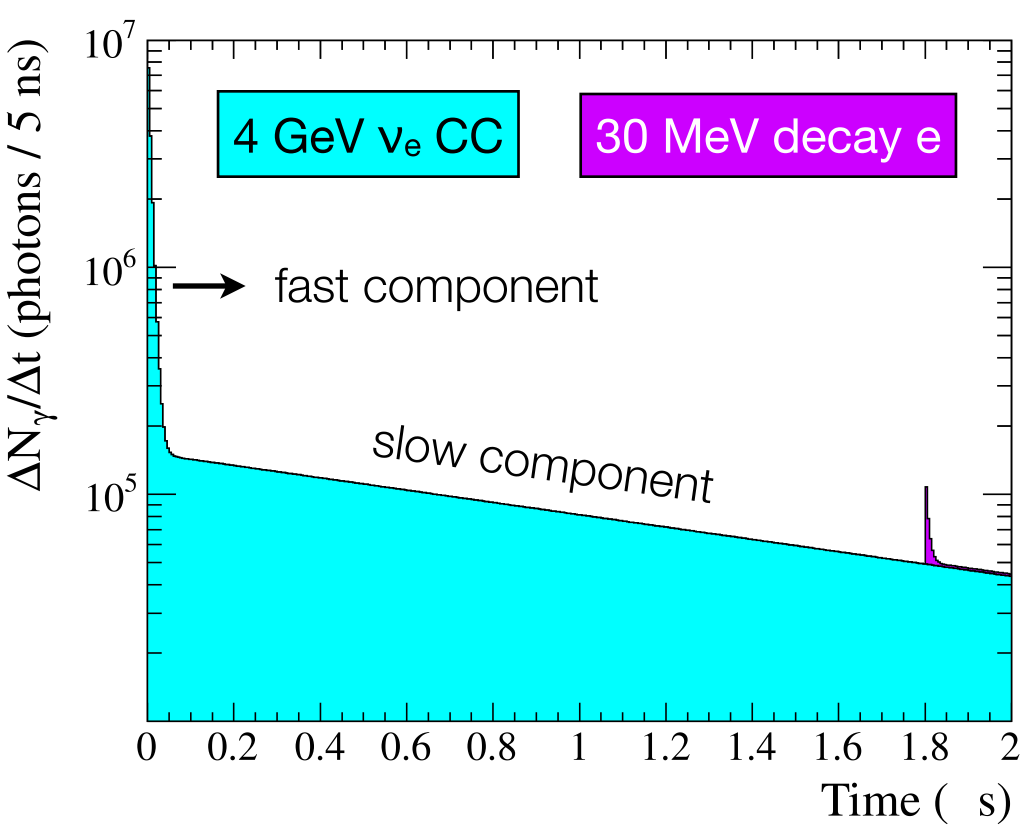
Missing energy from secondary neutrinos

- Missing energy from secondary neutrinos:





- $E_{miss,\mu}$ is good estimator for E_{miss}



- Fast scintillation light provides one way to measure Michel electron energy

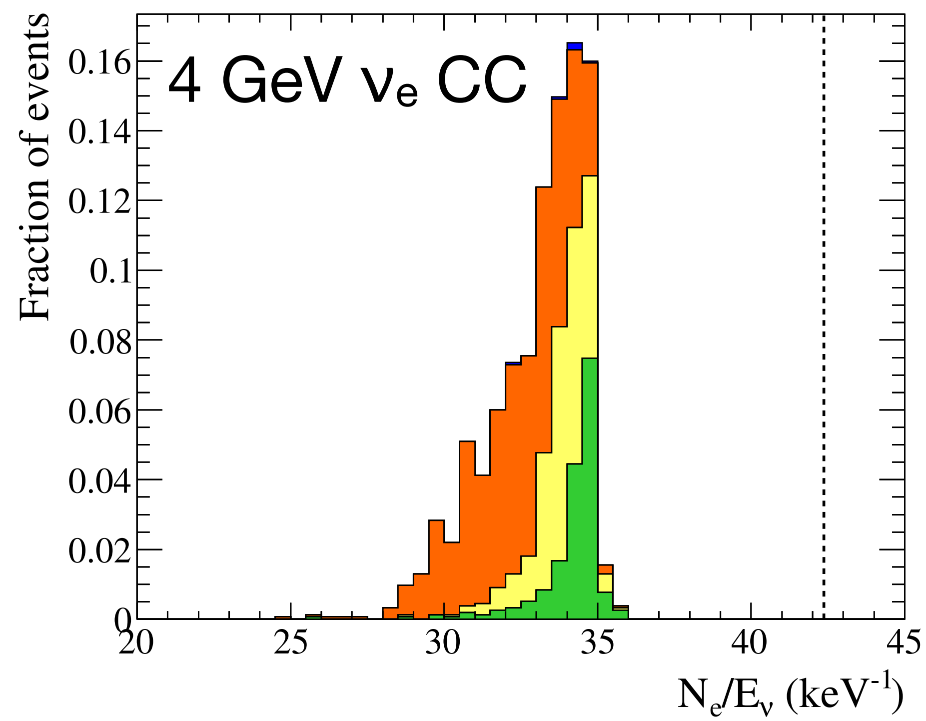
- Numbers on the left for 100% light detection efficiency

Calorimetric neutrino energy reconstruction

Impact of secondary neutrinos

- Sum E_{miss} to charge-based energy measurement

Equivalent in plot here: subtract E_{miss} from E_ν



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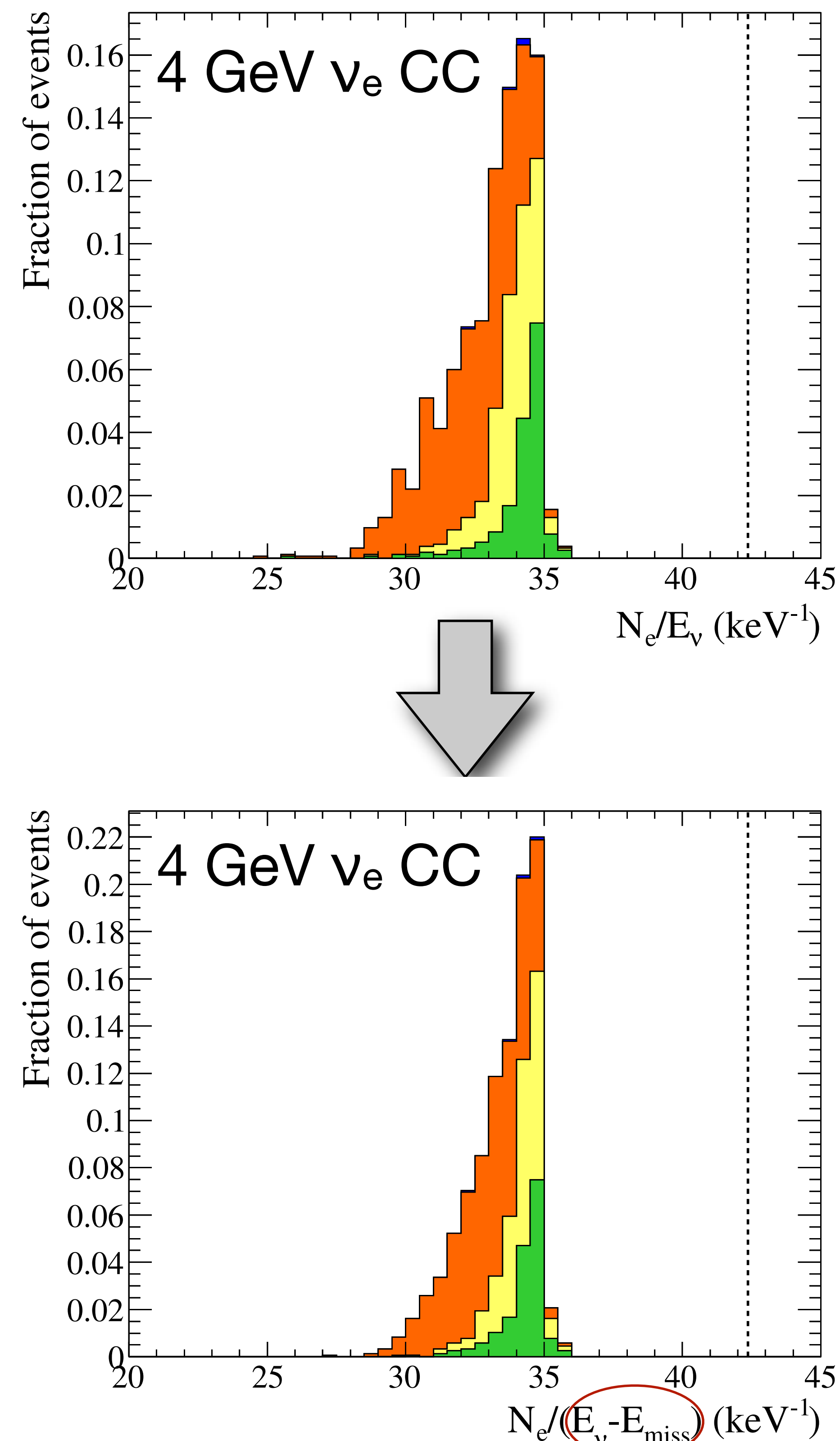
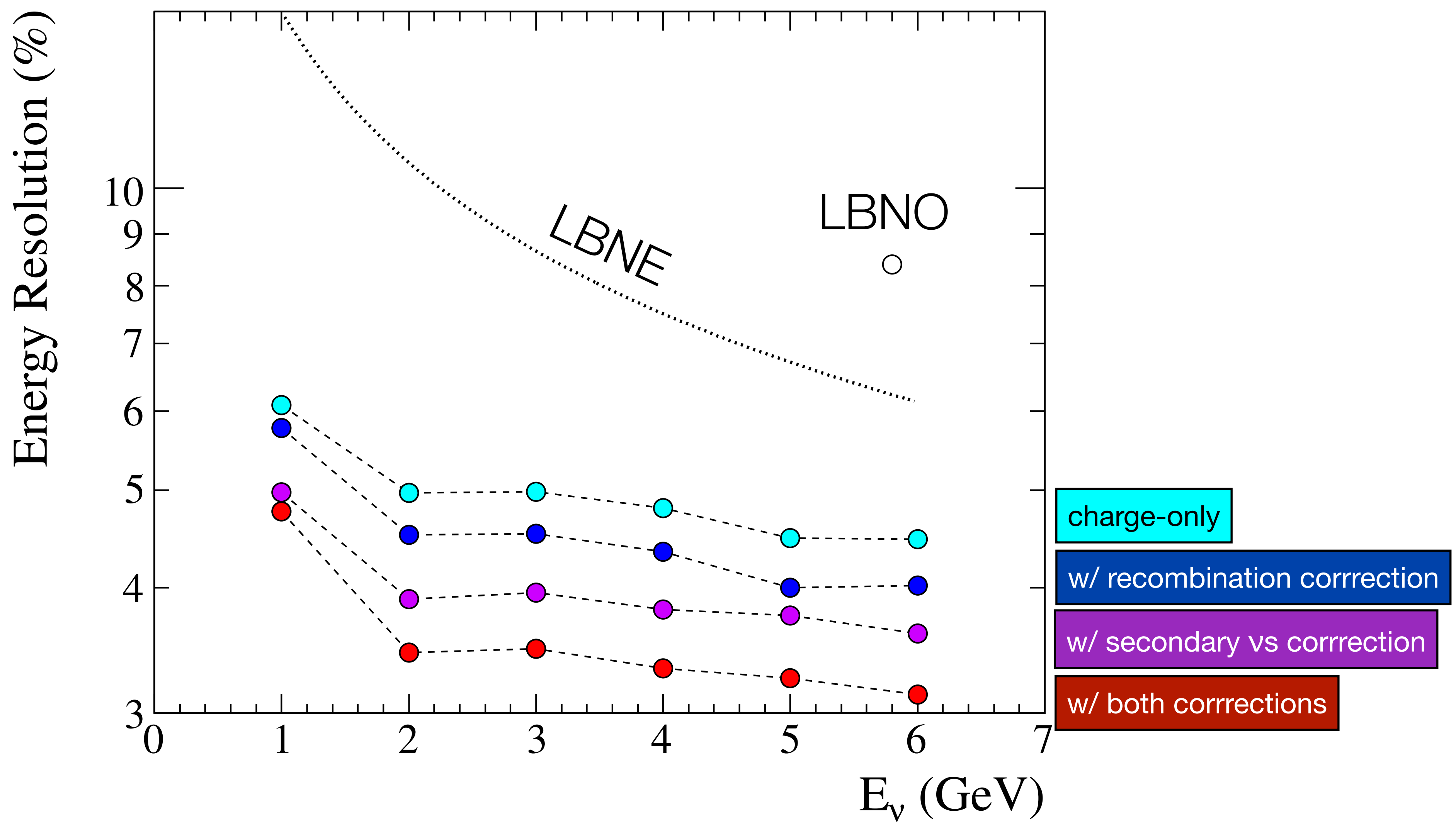


Calorimetric neutrino energy reconstruction

Achievable resolution



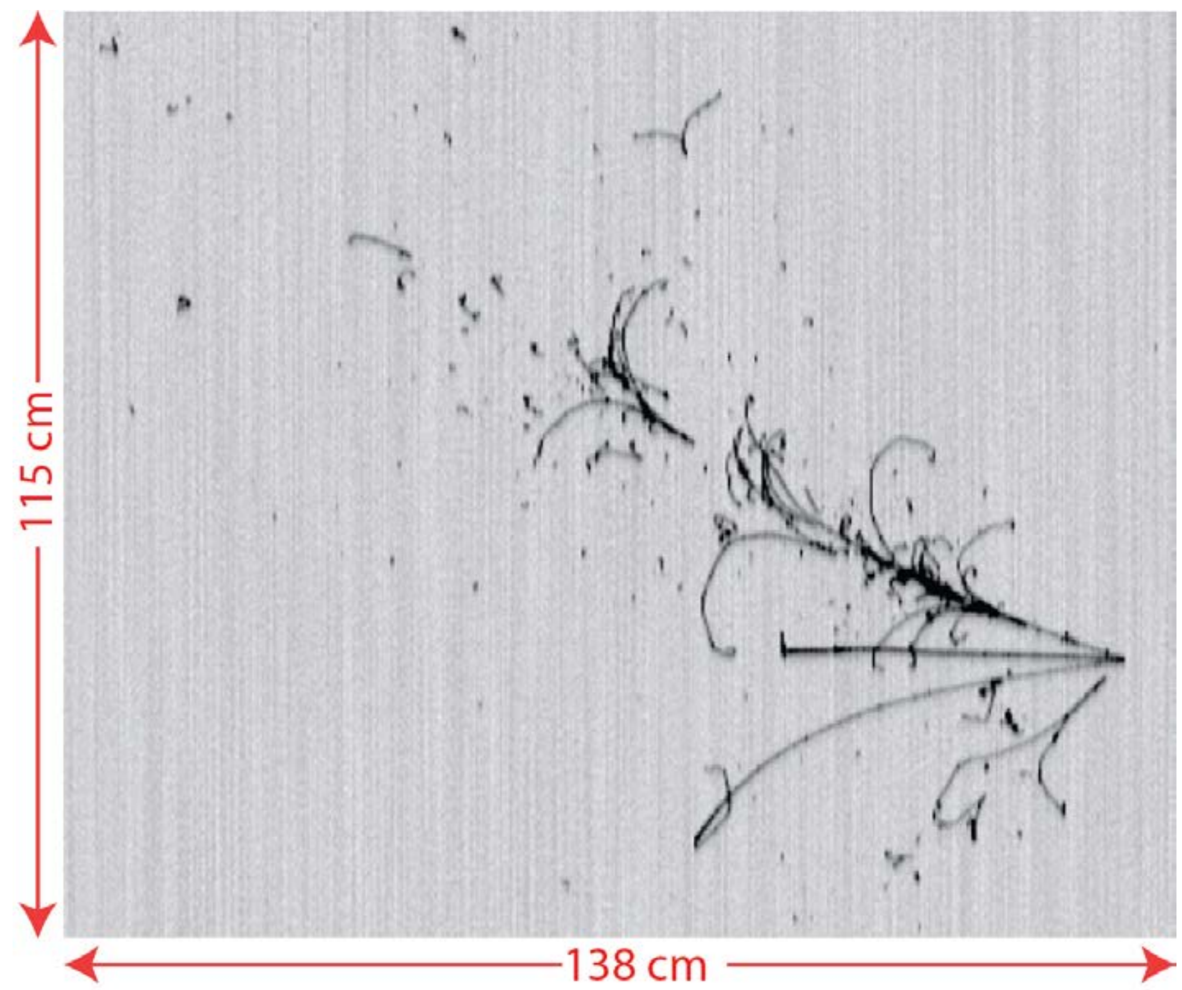
- 3-4% RMS neutrino energy resolution for few-GeV ν_e CC in ideal LAr possible
- Limited by nuclear and quenching effects
- Large differences between charge-only LArSoft-based estimate, and LBNE/LBNO assumptions

Likely due to treatment of low-energy neutrons, maybe other hadronic physics aspects

Muon charge identification

Ideal case: LAr magnetization

- Measure track curvature in magnetic field is best
- Best charge ID, and not only for muons
- Figure shows MC simulation of 4 GeV ν_e CC in magnetized LAr TPC (ICARUS at FNAL proposal)
- But... technically challenging and expensive



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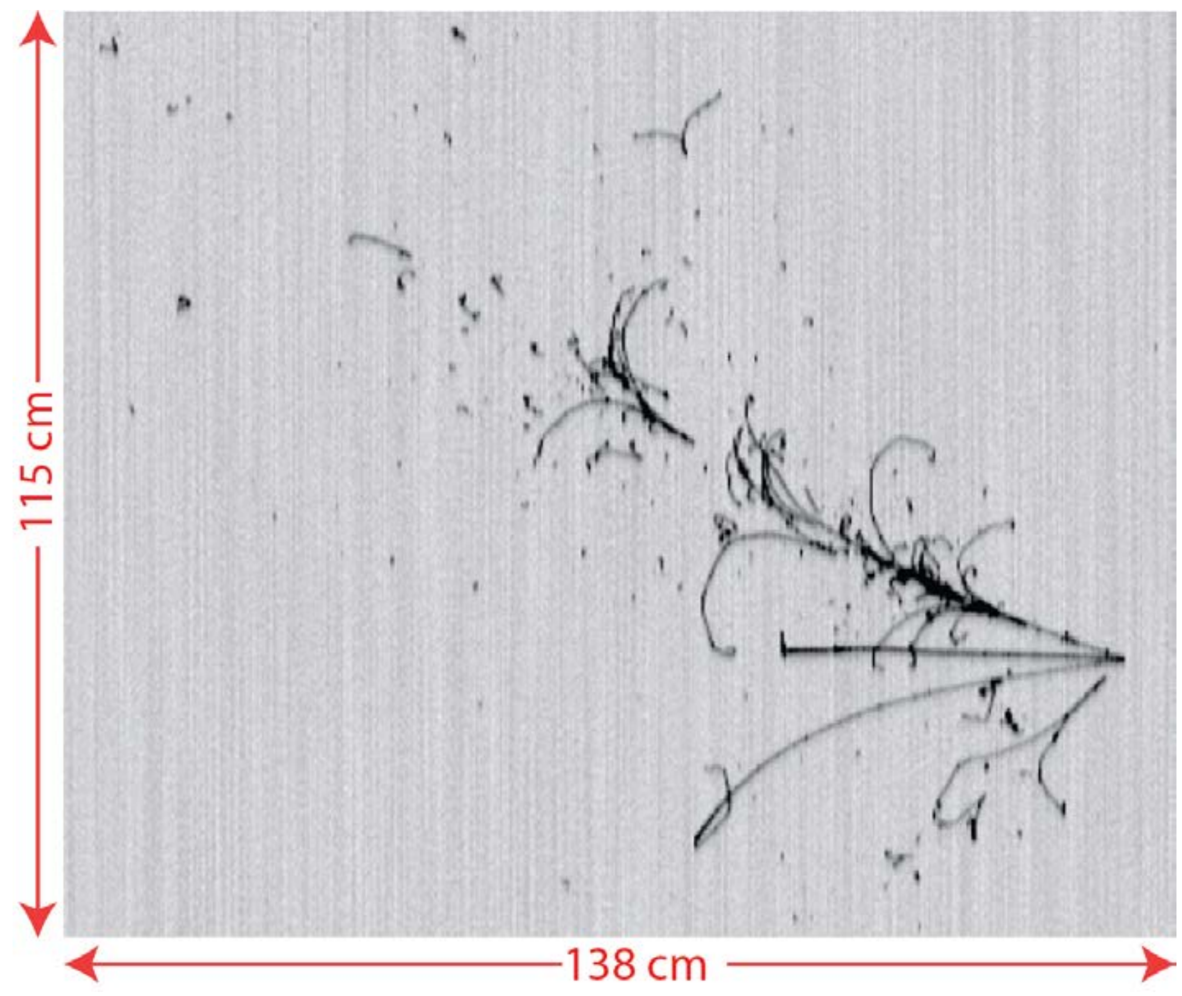


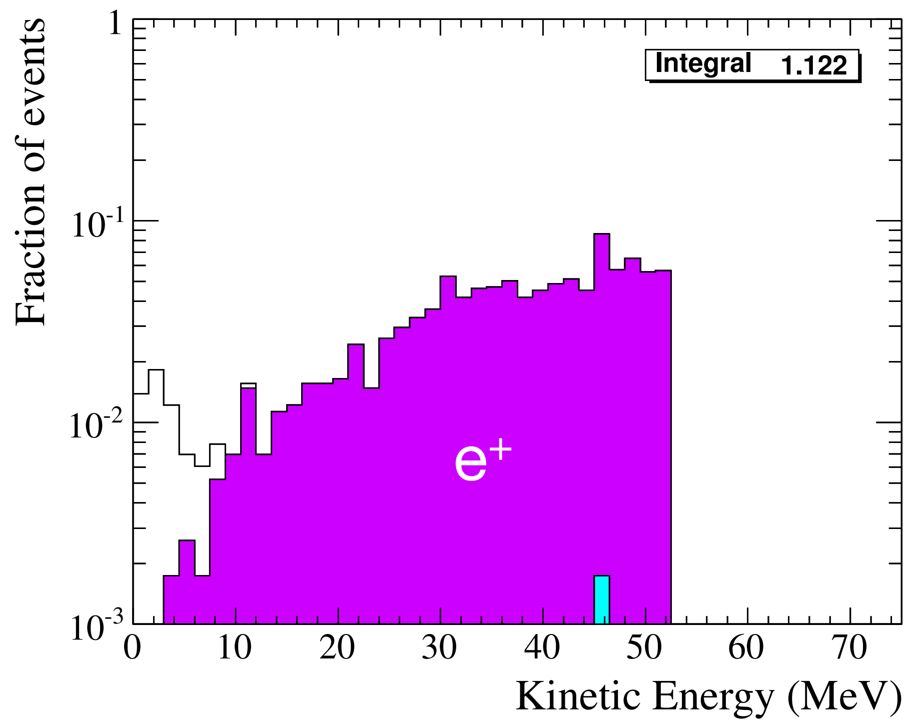
What can be done on muon charge ID without magnetization, particularly exploiting high (74%) μ^- capture on Ar?

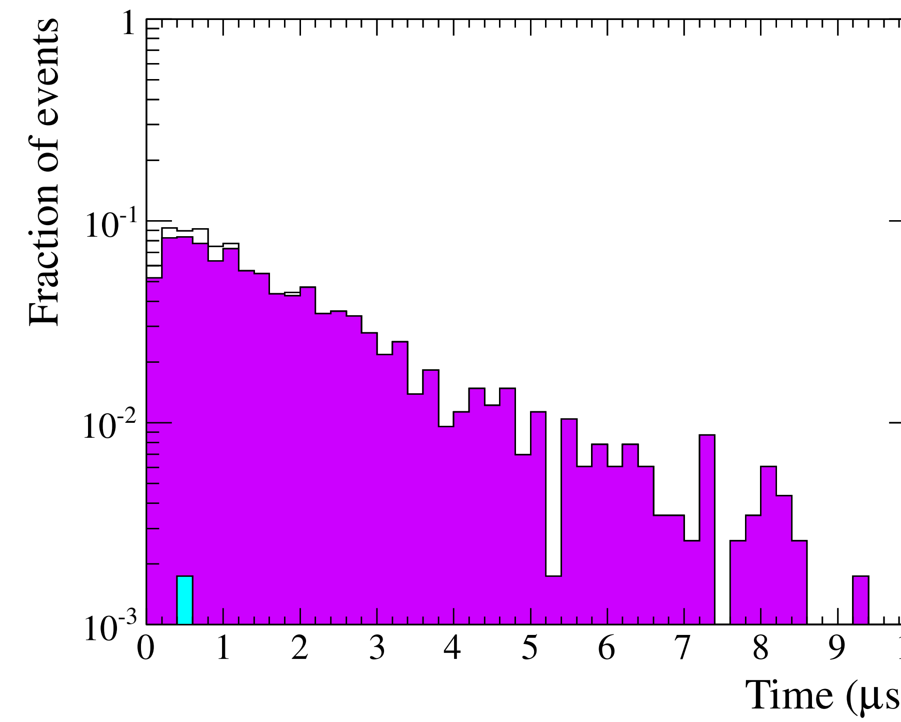
Particles produced in muon decay or capture

Kinetic energy and time distributions

4 GeV $\bar{\nu}_\mu$ CC:

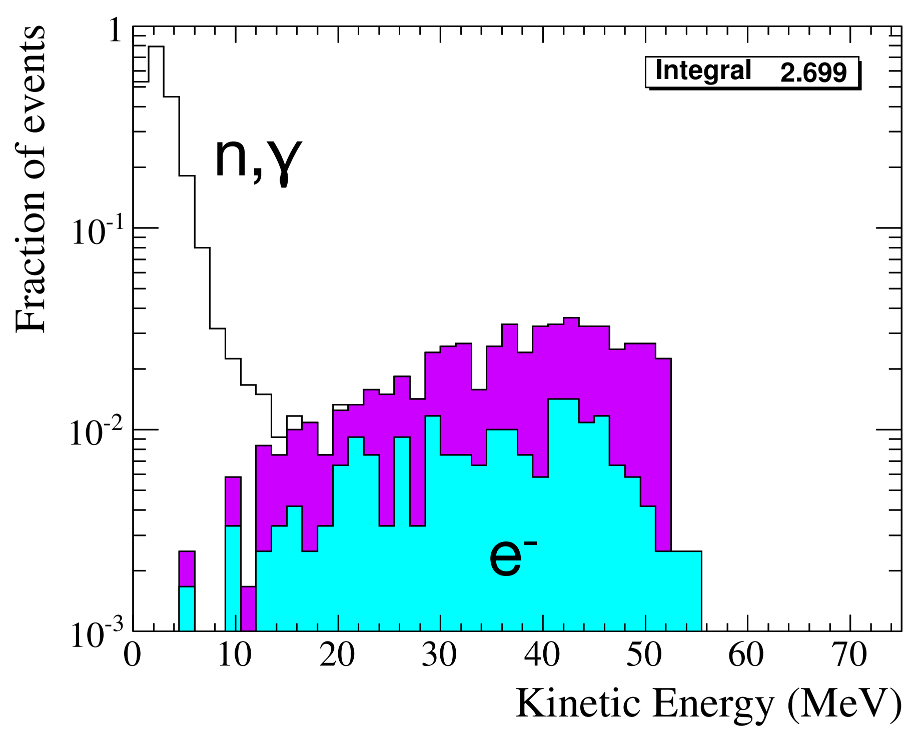
- Little capture
- More decay $e^{\pm}$

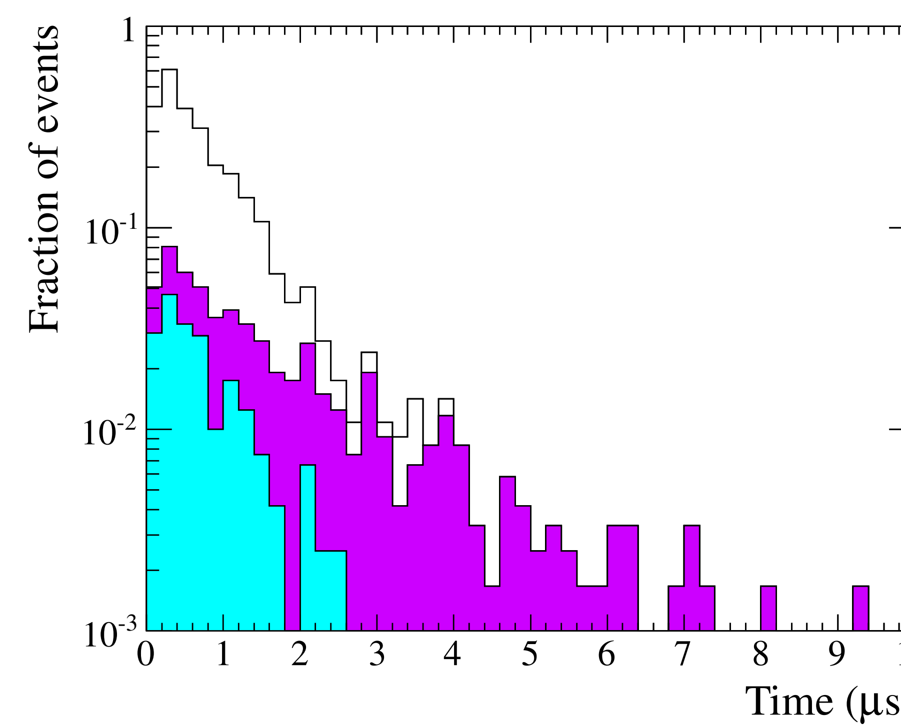




4 GeV ν_μ CC:

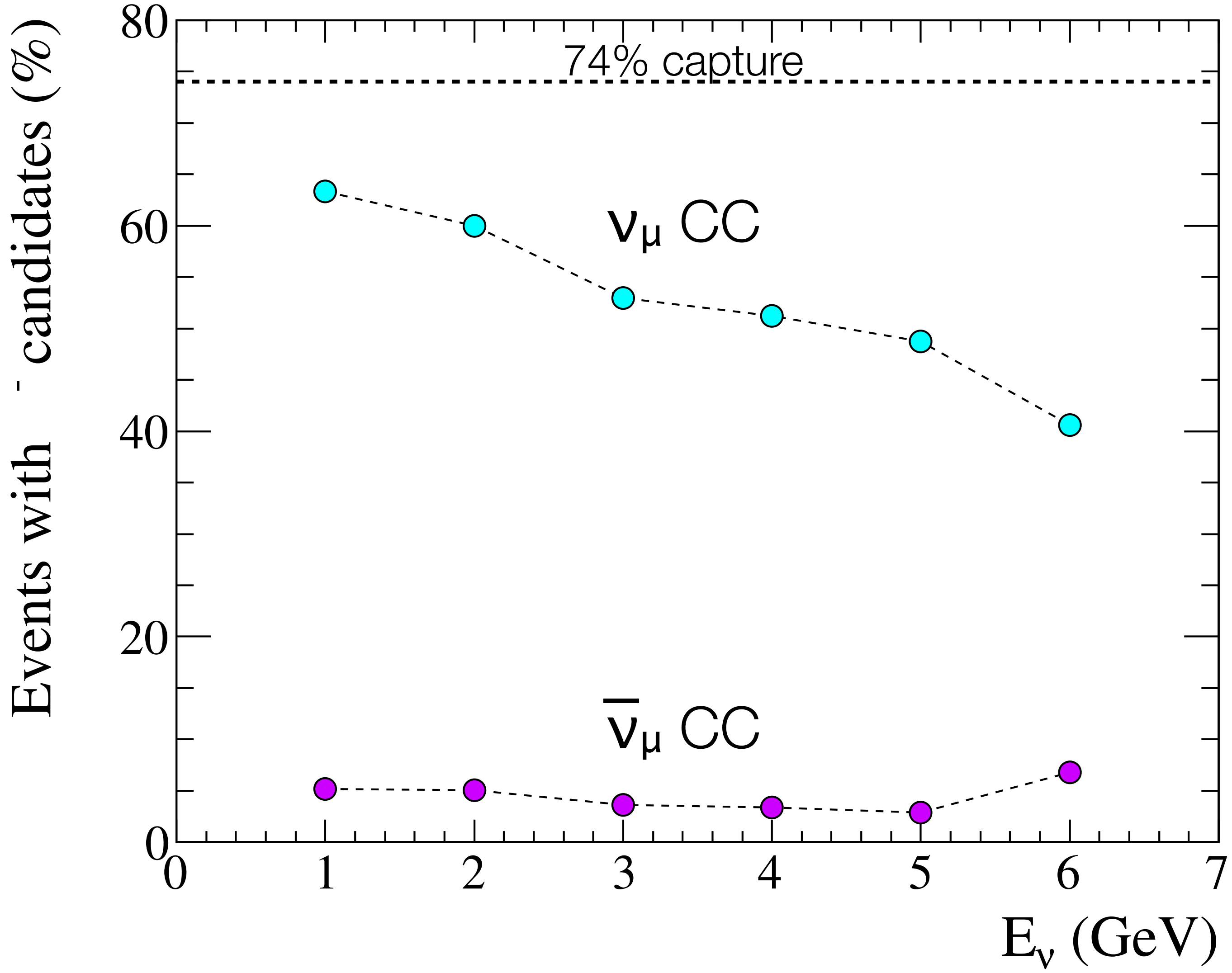
- More capture
- Fewer decay $e^{\pm}$





Muon charge ID performance

- Michel electron (mostly e^+) candidate: >10 MeV kinetic energy and >100 ns decay time
- μ^- (ie, ν_μ CC) candidate events: events with no Michel electron candidates
- ν_μ CC ID efficiencies of about 50%, and $\bar{\nu}_\mu$ CC mis-ID rates of few %, for fully contained muon events



- ν_μ CC ID efficiency bounded from above at 74% capture probability
- Efficiency decreases with energy because π^+ production increases
- Mis-ID rate entirely driven by dead time (100 ns assumed here)

LArIAT measurements exploiting light

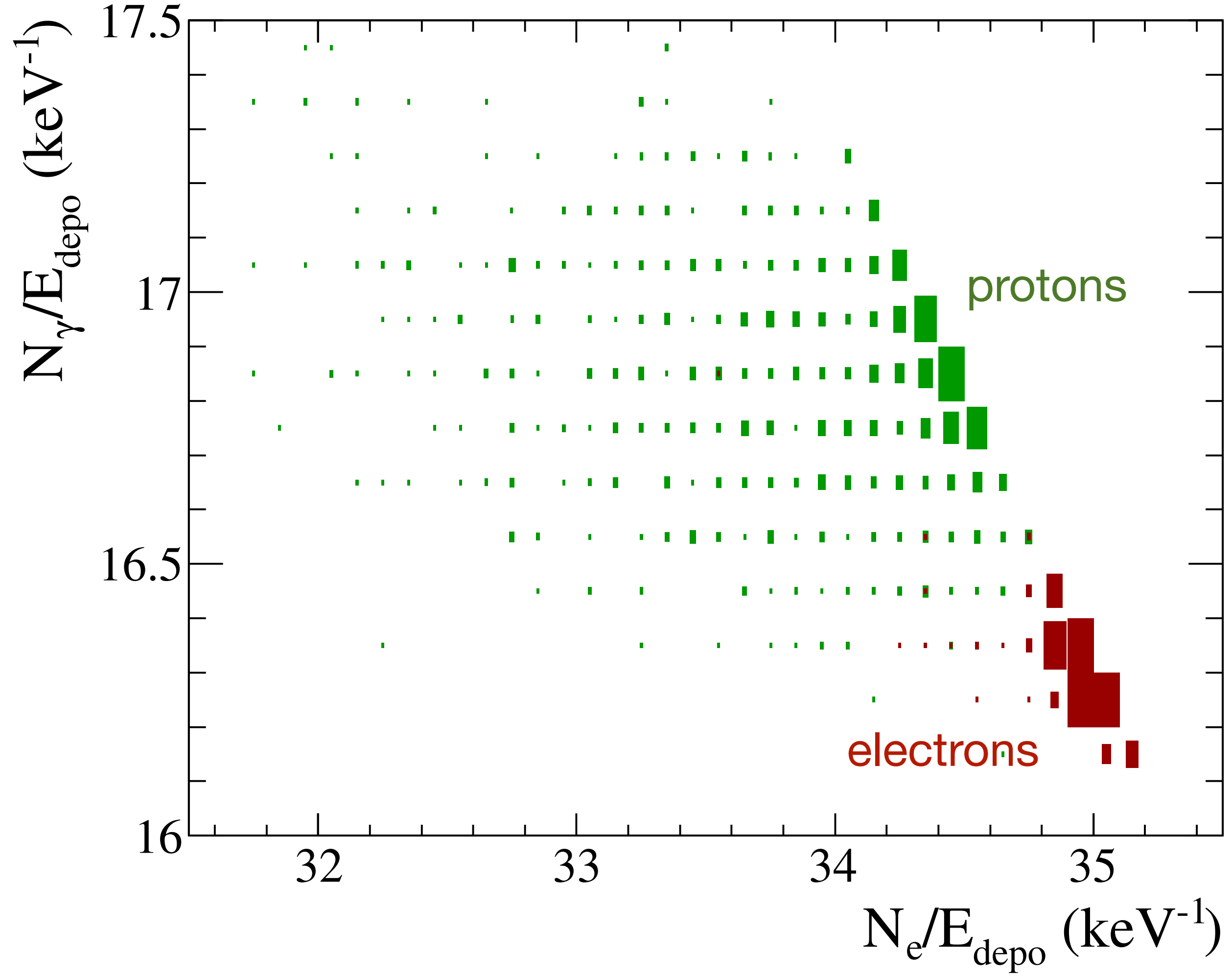
Some examples: there are much more, I am sure!

Recombination studies and calorimetry

- Measure charge and light signals per deposited energy for different stopping particle types

- Few percent effects (not easy!) on:
  - Average charge and light signals
  - Charge-light anticorrelation

- LArIAT would be first LAr-based detector studying this!



Michel electron and muon charge identification

- Use stopped muon sample to quantify:
  - Michel electron tagging efficiency
    → μ^- ID efficiency, muon charge mis-ID rate
  - Michel electron energy resolution

using light information (and other techniques?)

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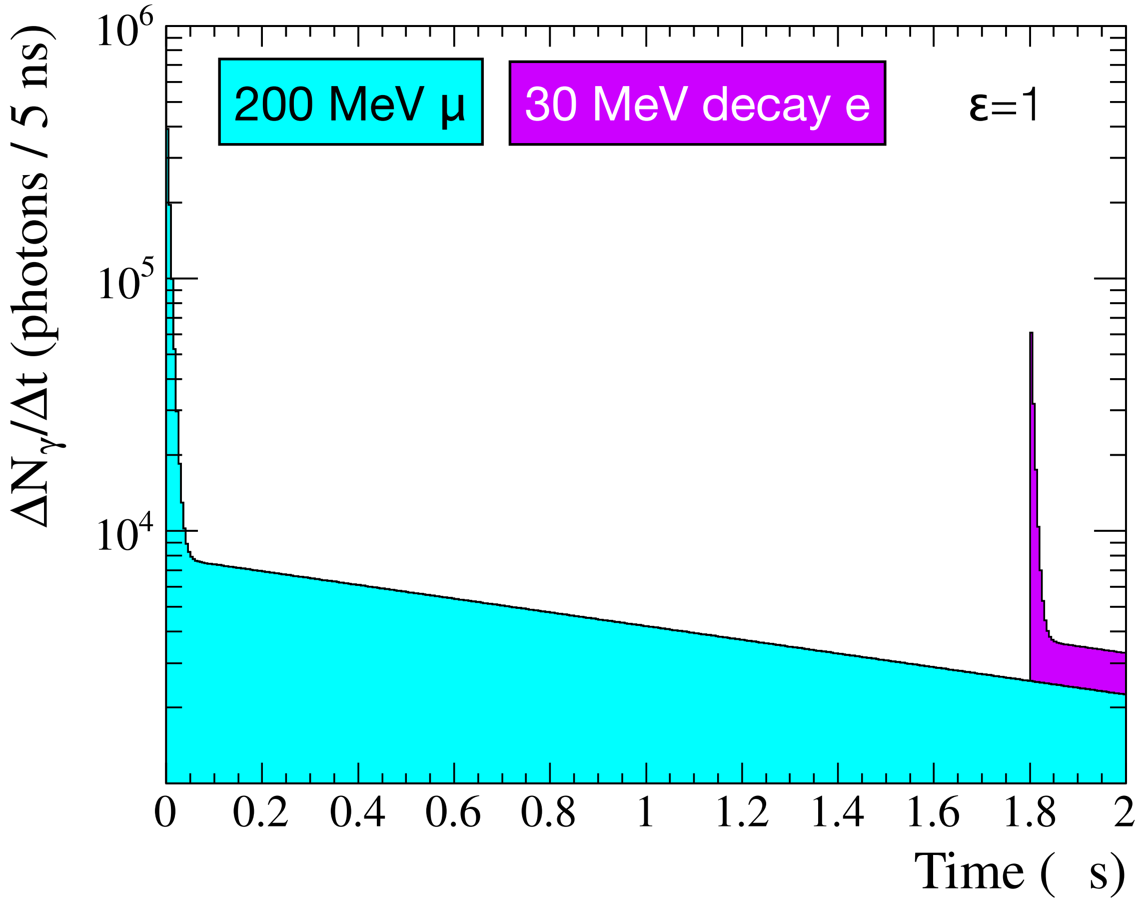

Conclusions

- LAr detectors with enhanced sensitivity to scintillation light could offer additional opportunities, such as superior neutrino energy reconstruction or muon charge ID

- These conclusions are based on detailed charge and light production simulation in LAr, but rather idealized detector response modeling
  - Would be nice study whether main conclusions hold in more realistic detector simulation

- In fact, even better: LArIAT is the perfect detector to actually <u>measure</u> (much of) this!
  - I hope it can be done