High Pressure Gaseous TPC Overview and Summary of Performance

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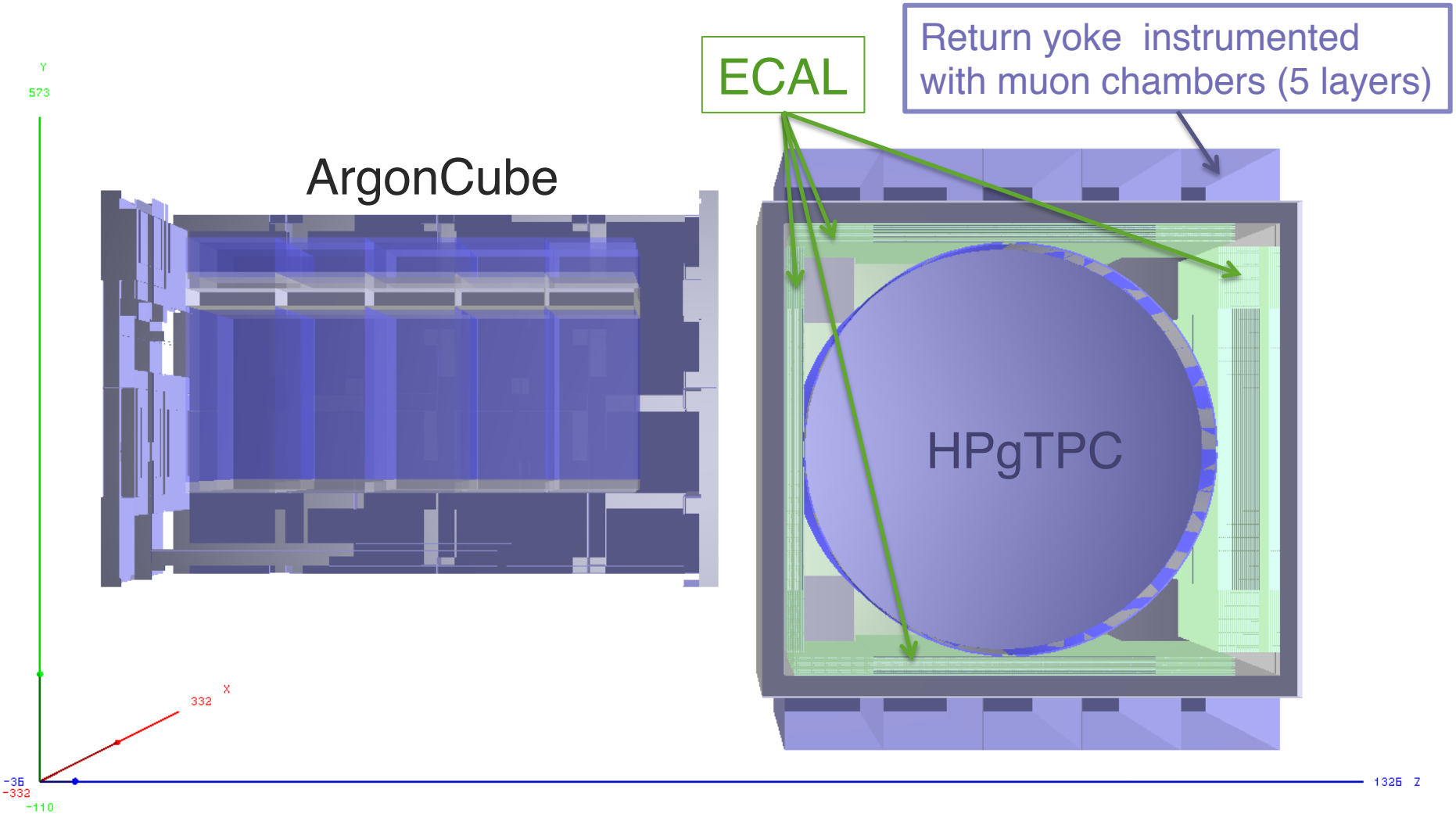
4th DUNE Near Detector Workshop

2018 March 22-24

High-pressure gaseous TPC (HPgTPC): Overview

- The HPgTPC provides two functions
  - Aids in event containment for ArgonCube
  - Very-high resolution stand-alone experiment (1t fiducial target mass)
    - ~ 4M ν_μ CC events in 3 years of ν running
- Build copy of ALICE TPC
  - Repurpose ALICE readout chambers (available in 2019)
  - Represents significant savings in both hardware and engineering (big!)
- Synergy with ArgonCube
  - Target nucleus:
    - 100% Ar in LAr and 97% Ar in gas
  - Raw 3D data
  - Similar FE electronics architecture
    - Front-end chip design
  - Same DAQ
  - Common data structure
  - Reconstruction algorithms may be similar & help reduce systematics

Simulated configuration



Performance Questions

The questions to be answered are

✔ 1. What is the tracking efficiency as a function of track angle, especially when the track is along the wire in the case of the STT?

✔ 2. What is the energy threshold for detecting protons/pions and how important is this to reduce systematics?

✔ 3. Momentum/angular resolution of all particles;

✔ 4. Pi0 energy resolution and efficiency in neutrino interactions (overlays, multiple interactions & background from rock);

✔ 5. What are the uncertainties in energy scale for e/mu?

✔ 6. What are the uncertainties in angular resolution?

✔ 7. What are the key performance parameters for the ECAL to detect NC pi0?

✔ 8. Can neutrons be detected in the tracker?

✔ 9. What is the expected performance for key channels (see appendix A) including yields?

You should update the docdb document detailing the final answers to these questions and the physics processes before the workshop. Please do not change the field volume of the dipole in your simulation for any new study. We need to compare the performance of the HPAr TPC and the STT as directly as possible.

Answers documented in detail in DUNE DocDB 6652
https://docs.dunescience.org/cgi-bin/private/ShowDocument?docid=6652

1. Tracking Efficiency vs. Angle

What is the track efficiency as a function of track angle?

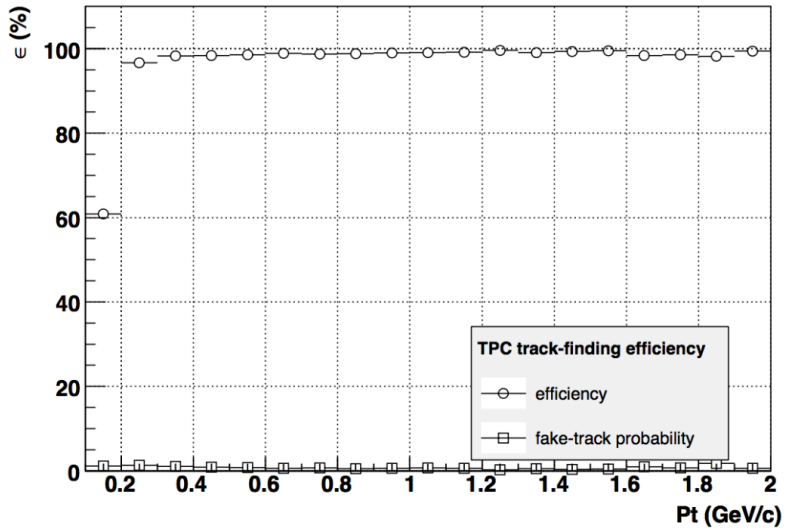


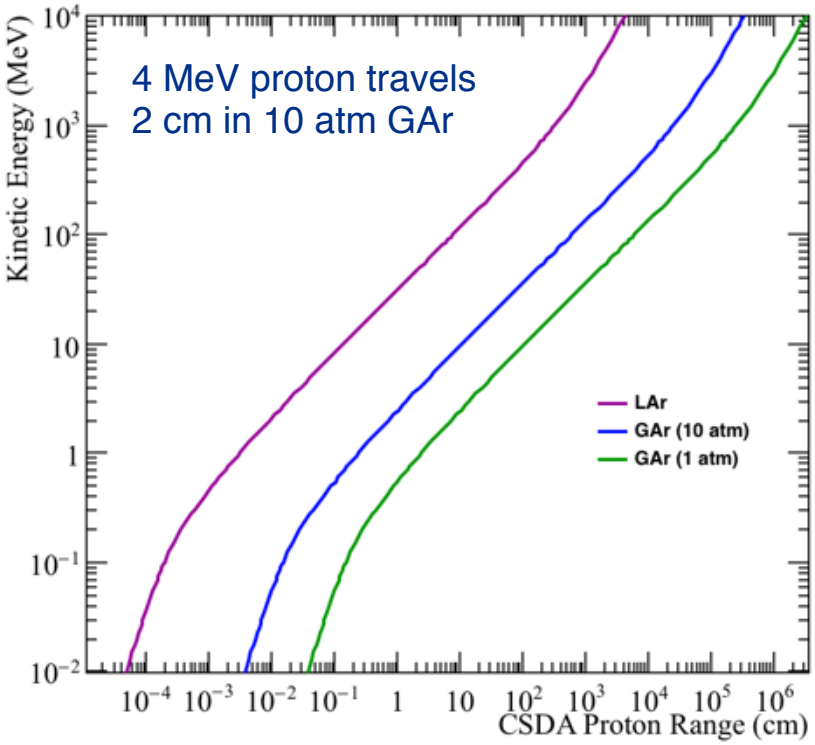
Figure 2: From Ref. [1]. Efficiency of the ALICE TPC track-finding software as a function of track transverse momentum for event multiplicity of 6000 tracks per unit of rapidity in Pb-Pb collisions (open circles), and corresponding fake track candidates (open squares).

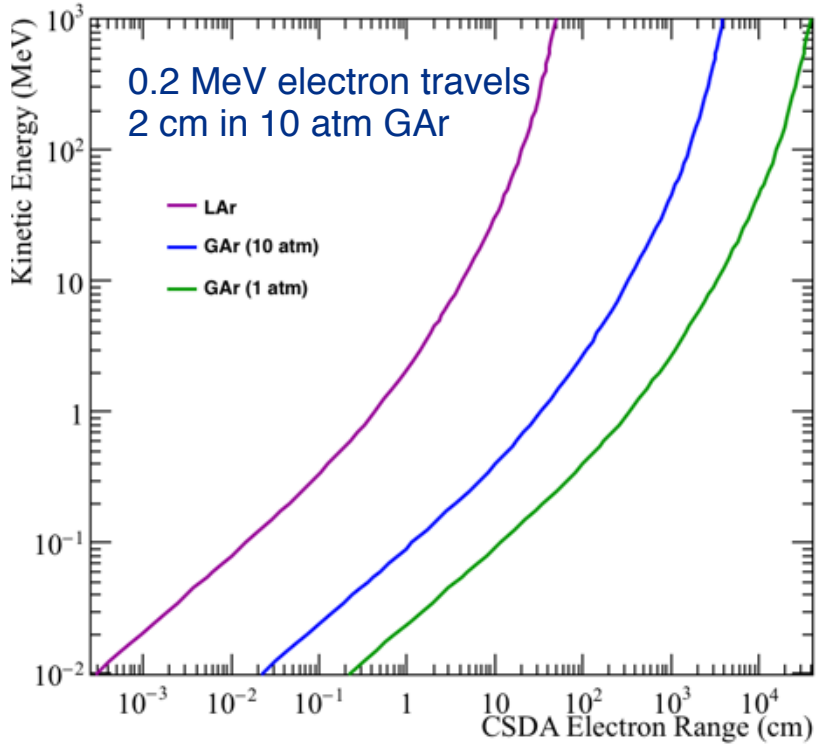
- High tracking efficiency vs. p_T for central region of pseudorapidity ($-1 < \eta < 1$)
- Within TPC fiducial volume, charged particles can be tracked over the full 4π solid angle
  - No direction is particularly affected, but need different algorithms to reconstruct with high efficiency in full η range (i.e., not collider-centric algos)
  - Tom Junk will show more details later in this session

2. Energy Thresholds

What is the energy threshold for protons and pions, and how important is this to reduce systematics?

- No inherent energy thresholds in TPC
- Reconstruction thresholds related more to track length





2. Energy Thresholds, cont'd.

What is the energy threshold for protons and pions, and how important is this to reduce systematics?

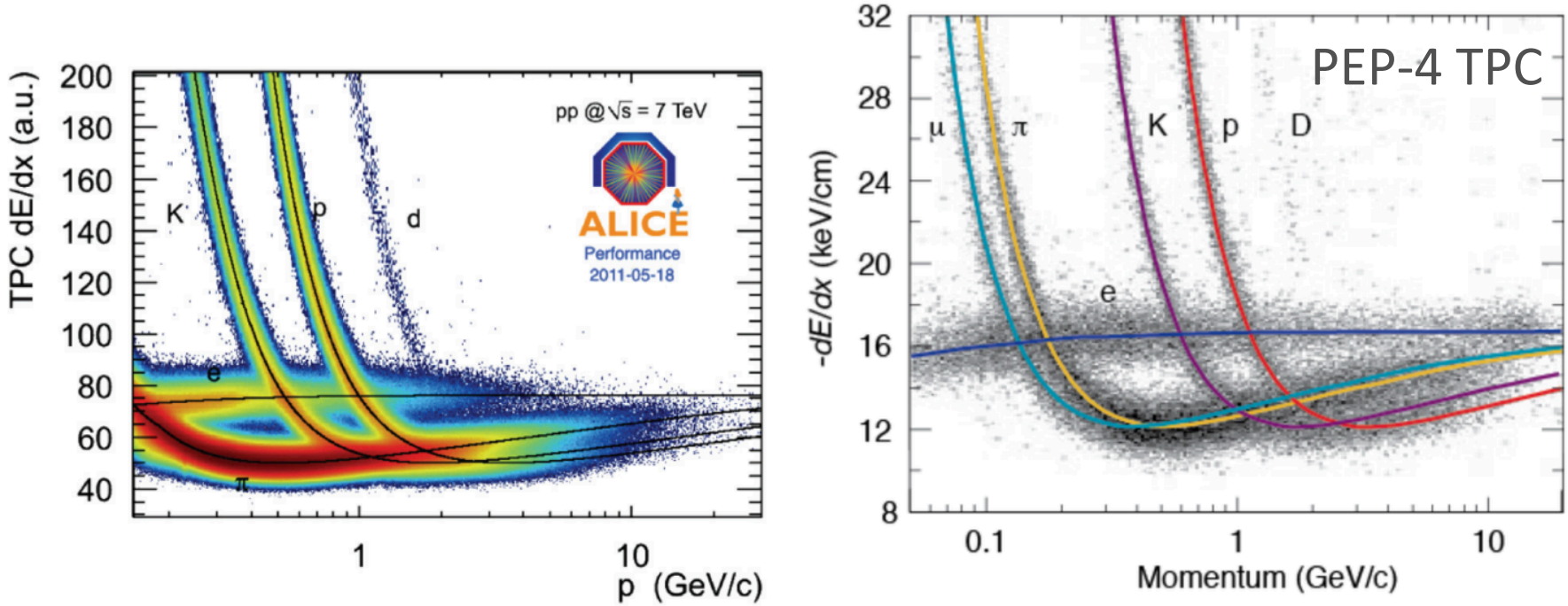
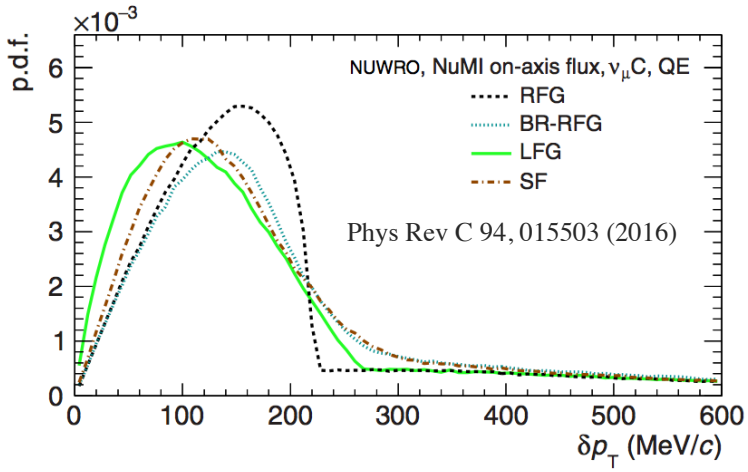


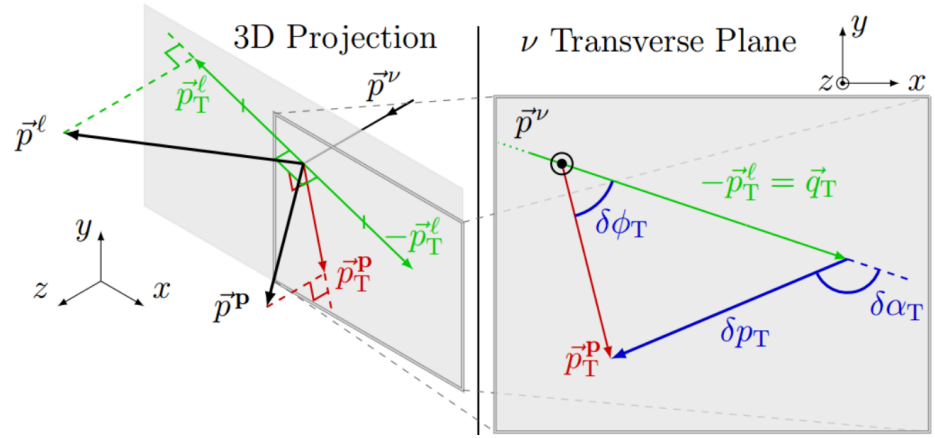
Figure 3: Left: ALICE TPC dE/dx-based particle identification as a function of momentum (from [6]). Right: PEP-4/9 TPC (80:20 Ar-CH4, operated at 8.5 Atm) dE/dx-based particle identification.

2. Energy Thresholds & Systematics

Dominant systematic in current LBL experiments is due to nuclear effects/ final state hadronic system

- Gas TPC gives the best measurement of hadronic activity at vertex on <u>same target nucleus</u> as FD, in both resolution and threshold
- À la recent T2K and MINERvA measurements: probe nuclear effects by looking at transverse kinematics for CCQE-like events



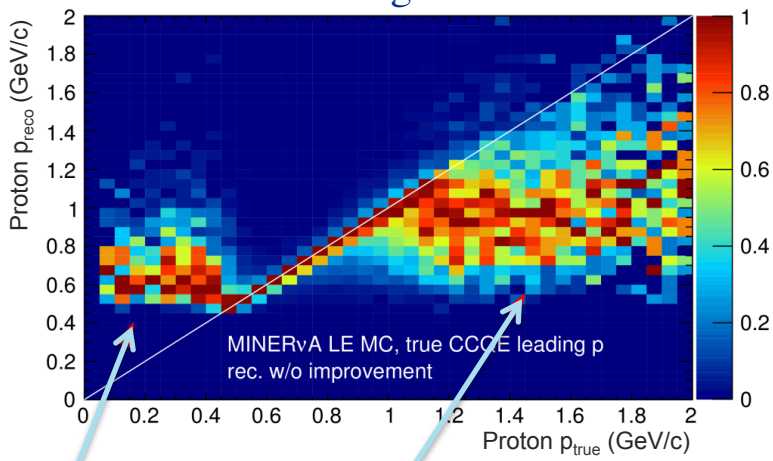


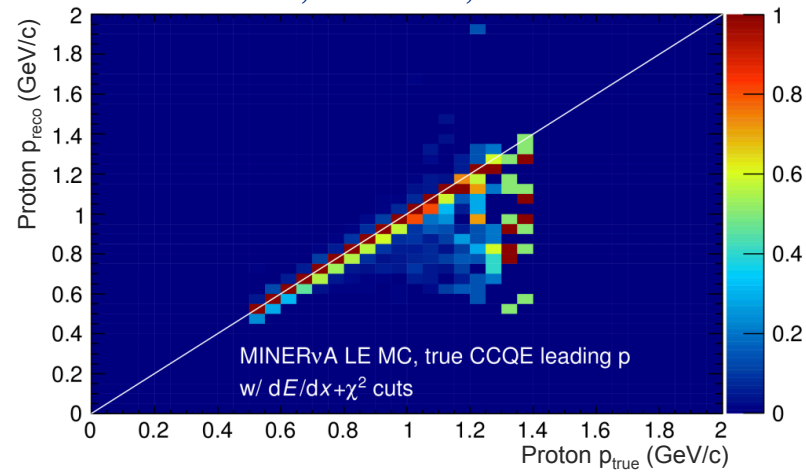
T2K measurement limited by momentum resolution:

- T2K: ~9% (proton momentum resolution)
- HPgTPC: ~1-2% below 1 GeV
- T2K did this analysis with ~3500 events, HPgTPC will have ~240k evts/ton-yr with better momentum resolution and 4π angular coverage

2. Energy Thresholds & Systematics

From Xianguo Lu @ FNAL Wine & Cheese Seminar, March 2, 2018





Short tracks at vertex

Inelastically scattered protons

Event sample can be cleaned up by dE/dx and χ^2 cuts, but loss of statistics

For same analysis in MINERvA, the limiting factor is hadron rescattering

- Improve momentum resolution by selecting only elastically scattered contained protons, but lose ~70% of statistics

HPgTPC:

- Much (x50) lower density: less rescattering, but when it does happen we measure it
- Much lower momentum threshold (MINERvA threshold 500 MeV/c)

If desired, study of nuclear effects on various nuclei could also be done in HPgTPC, by running the TPC with <u>other gas options</u>: H_2, D_2, Ne, CF_4, Xe…

3. Momentum/Angular Resolution

What is the momentum and angular resolution of all particles?

Table 1: HPgTPC performance.

Parameter	Value	units
σ_x	250	μm
σ_y	250	μm
σ_z	1500	μm
$\sigma_{r\phi}$	<1000	μm
Two-track separation	1	cm
Angular resolution	2-4	mrad
σ(dE/dx)	5	%
σ_{p_T}/p_T	0.7	% (10-1 GeV/c)
σ_{p_T}/p_T	1-2	% (1-0.1 GeV/c)
Energy scale uncertainty	$\lesssim 1$	% (dominated by δ_p/p)
Charge particle detection thresh.	5	MeV (K.E.)
ECAL resolution	$5\text{-}7/\sqrt{E/\text{GeV}}$	%
ECAL pointing resolution	$\simeq$ 6 at 500 MeV	degree

Based on previously operated TPCs such as PEP-4 and ALICE

3. Momentum/Angular Resolution, cont'd

What is the momentum and angular resolution of all particles?

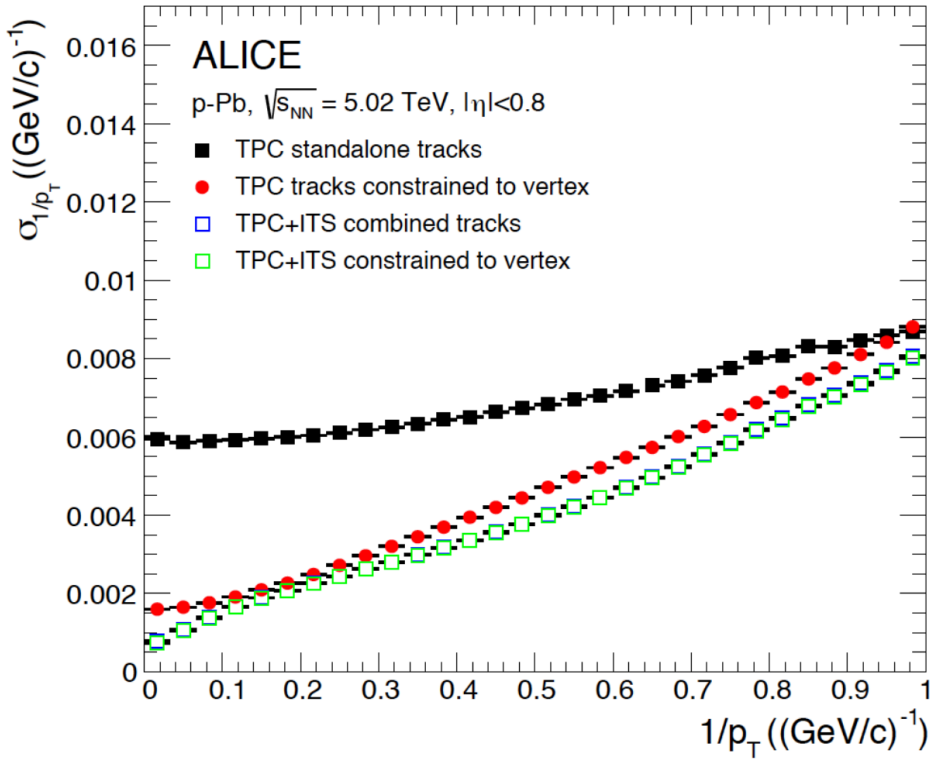


Figure 7: Black squares show the TPC stand-alone p_T resolution in ALICE for p–Pb collisions.

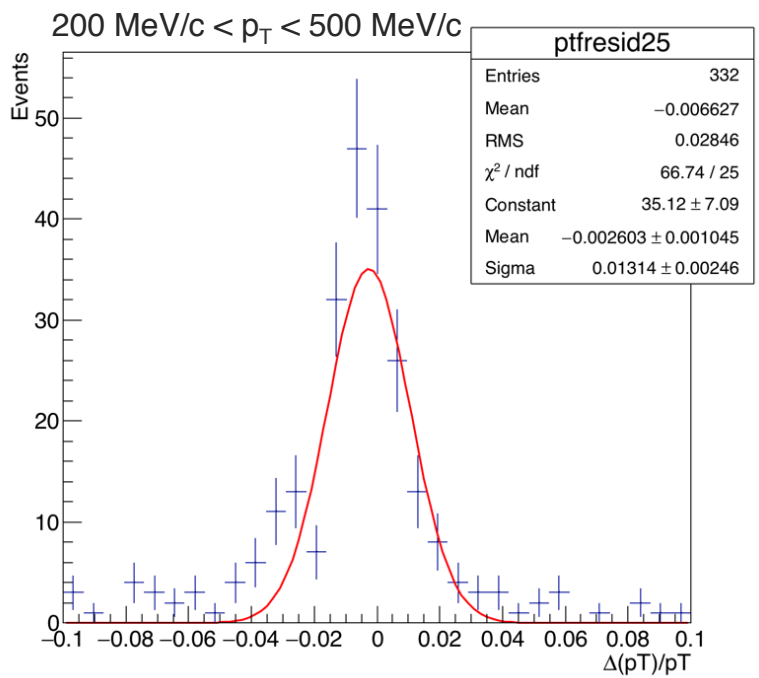
Momentum determined by bending radius of particle trajectory.
Limited by:

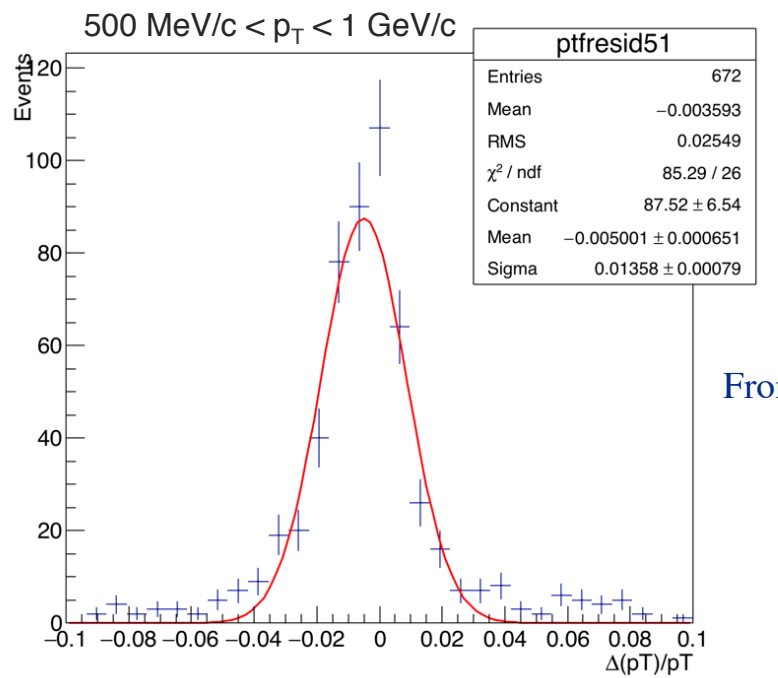
- Spatial resolution of measured drift points in plane perpendicular to B field (dominant effect)
- Multiple Coulomb Scattering (negligible in gas)

Visibility of track curvature depends on p_T and multiplicity and proximity of nearby tracks

3. Momentum/Angular Resolution, cont'd

What is the momentum and angular resolution of all particles?





From T. Junk

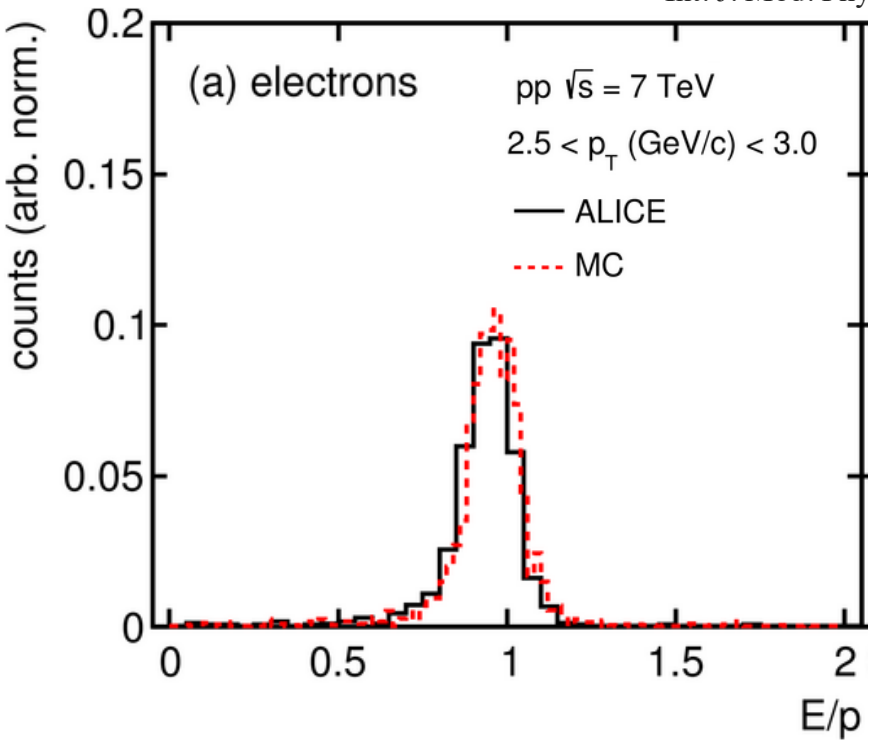
Muons simulated/reconstructed with ALICE software:
$\sigma(p_T)/p_T \sim 1.3\%$ ($p_T < 500$ MeV/c)

More details in Tom's talk later in this session

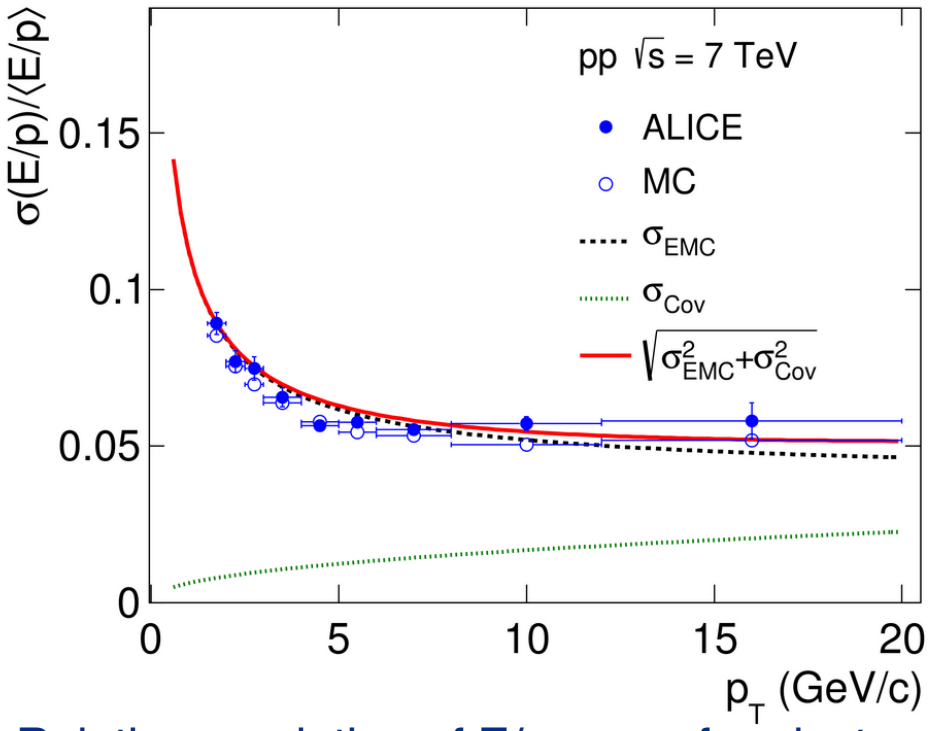
3. Momentum/Angular Resolution, cont'd

- ALICE electron data vs. MC

Int. J. Mod. Phys. A 29 (2014) 1430044



E/p distributions for electrons



Relative resolution of E/p vs. p_T for electrons

ECAL energy resolution added in quadrature to the TPC p_T resolution (green-dash-dotted line)

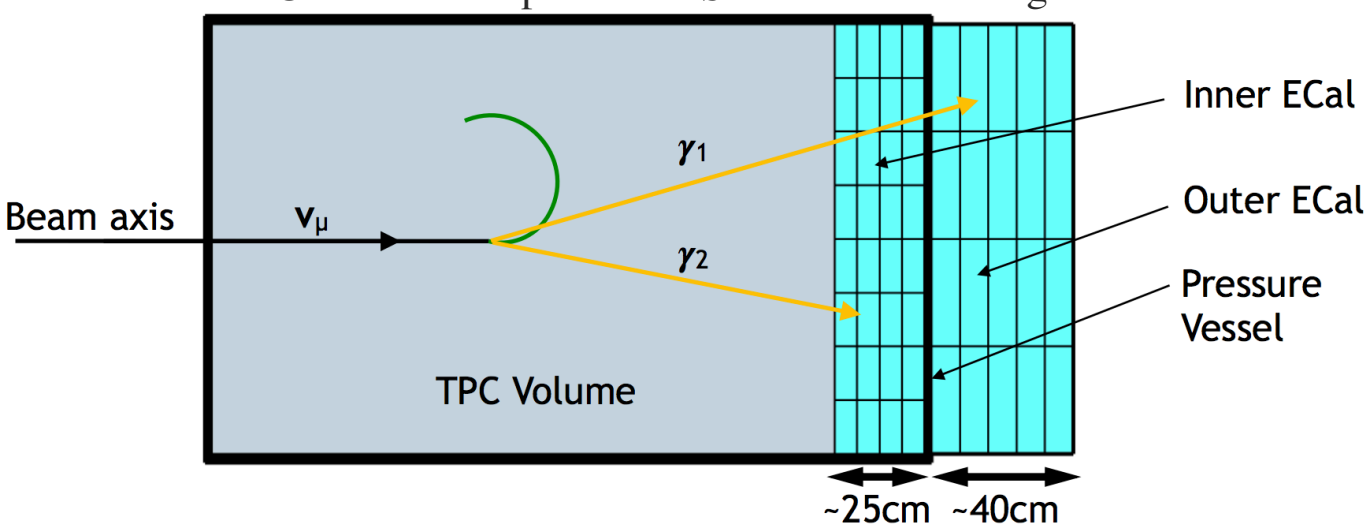
4. π^0 Energy Resolution & Efficiency

What is the π^0 energy resolution and efficiency in neutrino interactions (overlays, multiple interactions, background from rock)?

For the HPgTPC option, π^0s are detected in the ECAL

- Not a background for HPgTPC measurements (veto ECAL activity)
- In ALICE full detector simulation of 1M π^0s, ~12% of photons convert, ~2% Compton scatter

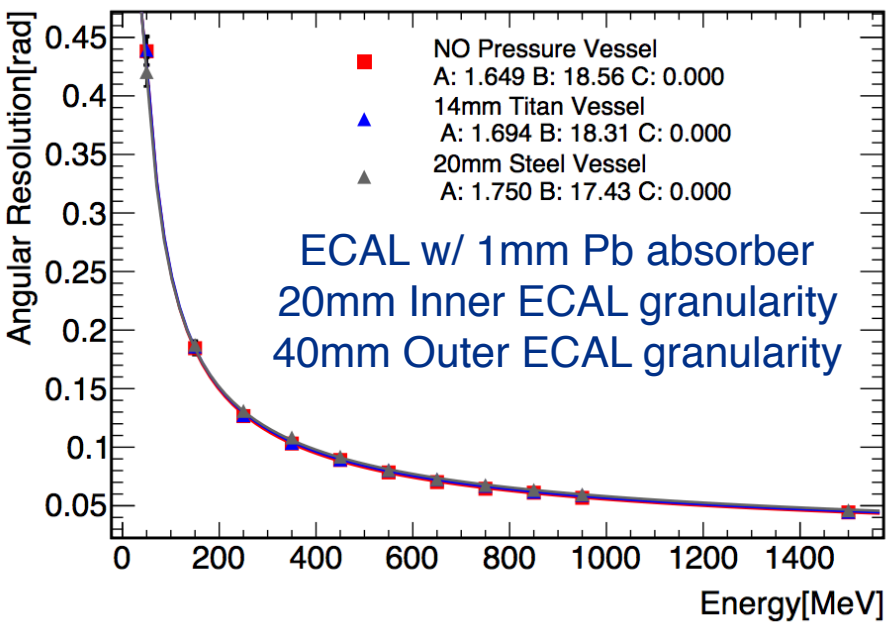
Cartoon concept from F. Simon & L. Emberger

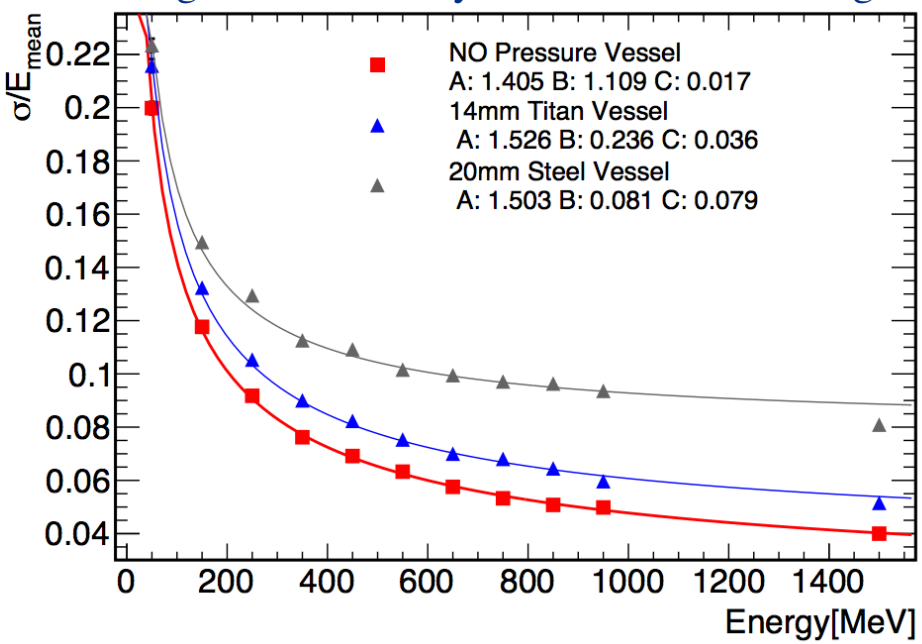


4. π^0 Energy Resolution & Efficiency

What is the π^0 energy resolution and efficiency in neutrino interactions (overlays, multiple interactions, background from rock)?

Design and studies by F. Simon & L. Emberger





Single photon energy and angular resolutions.
More information in F. Simon's ECAL talk on Friday.

5. Energy scale uncertainties for e/μ

- Muons and charged pions: 1-2%, solely determined by σ_p/p. No scale offset, per se.
  - HPgTPC is a magnetic spectrometer:
    - p = 0.3 Bρ/cosλ (ρ: track radius of curvature; λ: helix pitch angle)
  - Must know magnetic field and geometry/alignment of tracker. Calibration needed at a level that should be perfectly achievable, based on previous experiments' experience:
    - B: detailed field map and in-situ Hall probe and/or NMR probe
    - ρ: alignment procedures (survey, laser, in-situ tracking), laser calibration for v_{drift}

5. Energy scale uncertainties for e/μ, cont'd

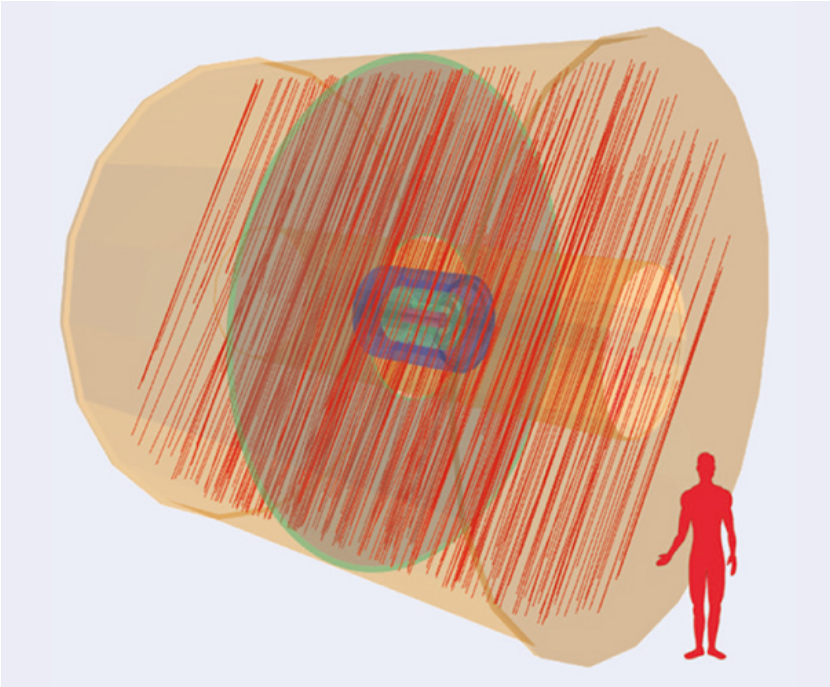
- Electrons/positrons: 1-2%
  - Same uncertainties as for μ/π, but also needs correction for bremsstrahlung radiation in a subset of $e^{\pm}$ events
  - Bremsstrahlung energy loss increases linearly with E_e
  - For 10atm GAr
    - No correction needed for 60% of electrons with $0.5 < E_e < 4$ GeV
      - Lose < 1% of energy in 1.5m of track length
    - For remaining 40% of electrons:
      - ECAL detection of brem (ECAL E scale becomes 2nd order correction)
        - t_0 provided by electron → precise match to brem photon
      - Full Kalman fit including Bethe-Bloch E loss and E-loss straggling, multiple scattering, and bremsstrahlung
      - Note: ALICE achieves 1-2% without ECAL correction for $\sim 0.5 < p_T < 5$ GeV/c

6. Uncertainties in angular resolution

What are the uncertainties in angular resolution?

- Related to alignment uncertainties
- Measure using cosmic rays and/or laser system

ALICE: 276 reconstructed muons from air shower



ALICE laser calibration system

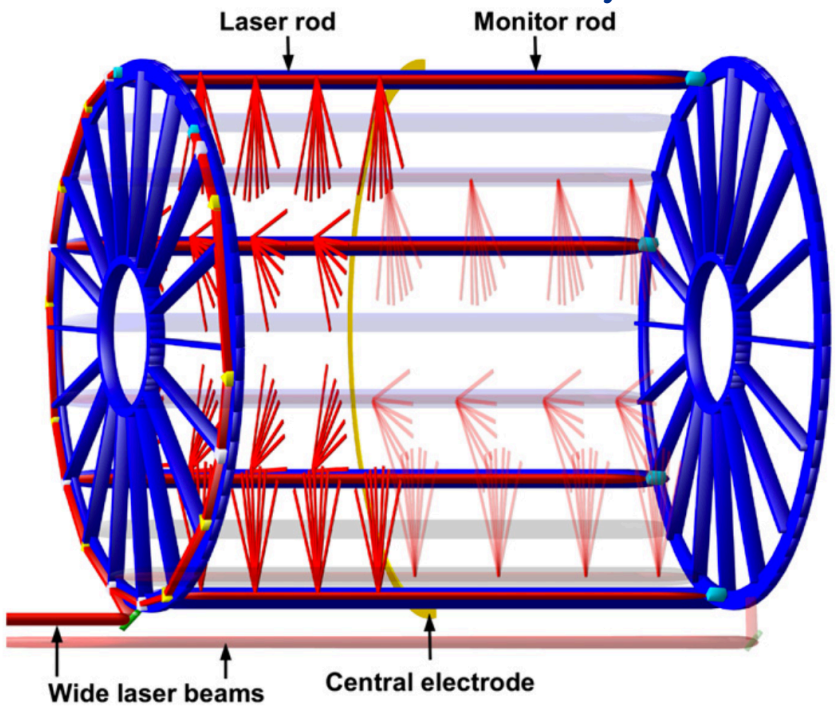


Fig. 45. Schematic 3D view of the TPC and the laser system. Two wide pulsed laser beams enter horizontally at the bottom of the TPC and are guided around the two end-caps by mirrors, prisms and beam splitters before entering the TPC. Bundles of micromirrors in the hollow laser rods intersect the beams and generate a large number of thin rays in the TPC drift volume. The undeflected part of the beams continue through the monitor rods to cameras at the far end. All elements are fixed mechanically, except for the remote controllable entrance mirrors at the bottom.

7. Key Performance Parameters for ECAL NCπ^0

The ECAL performance requirements:

- Good energy resolution
- Good angular resolution
- Good timing
- Fine segmentation

In HPgTPC, γ's rarely convert, so these should not contribute to background

If ECAL pointing accuracy is good enough, can tag NCπ^0 and look for vertex activity in correct region of TPC to get a pure sample of NCπ^0

HPgTPC will have ~200k ν_μ NCπ^0 events per year

- 1% of π^0's will Dalitz decay ($\pi^0 \rightarrow \gamma e^+e^-$)
- If we misidentified 10% of Dalitz decays, this would leave us with a 1% BG contribution to ν_e CC
  - We believe most Dalitz decays can be rejected in TPC by looking for oppositely bending track pairs

8. Neutrons

Can neutrons be detected in the tracker?

Not in a way that is very useful for neutrino event reconstruction (no detector does this well…)

- Some information may be determined by tagging/tracking recoil protons and deuterons from neutron scatters, and HPgTPC will have capability to measure the energy and direction of the recoils, but efficiency is very low.

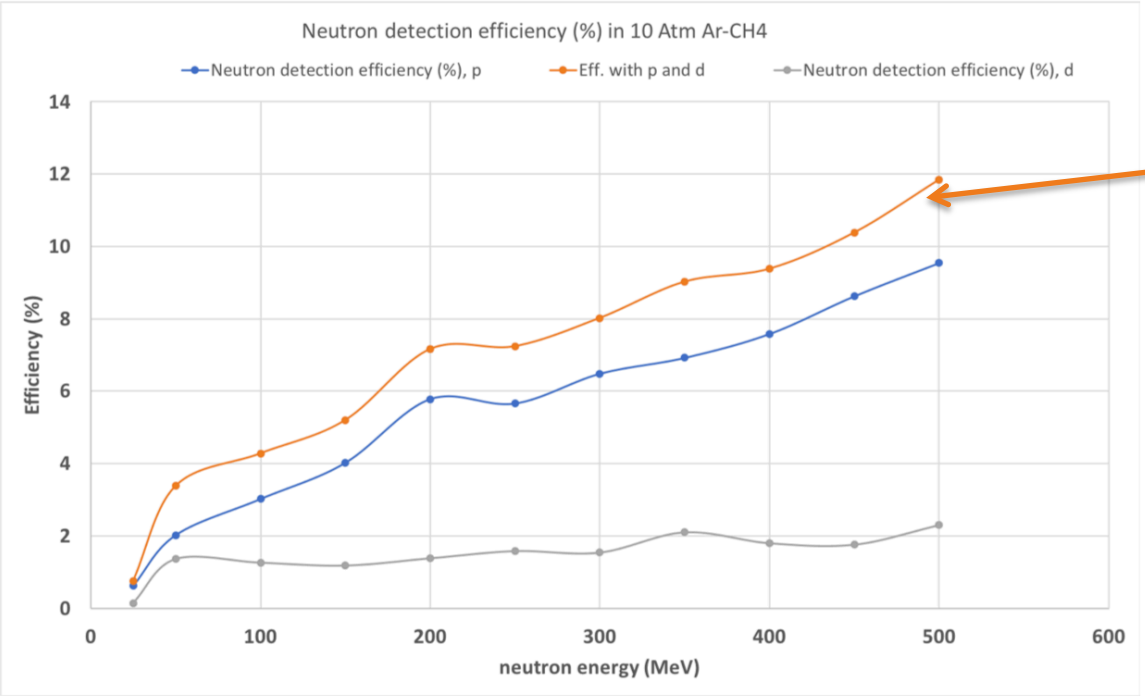


Figure 18: Neutron detection efficiency.

~5-10% efficiency to tag a neutron by detection of recoil proton or deuteron

Low stats, but clean event sample

Proton/neutron multiplicity analysis may be another probe of FSI

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9. Key Channels

What is the expected performance for key channels, including yields?

Table 2: Number of events for 1 year of neutrino running in HP GAr TPC with 1 t fiducial mass.

Event class	Number of events per ton-year
ν_μ CC Total	1.64×10^6
ν_μ NC Total	5.17×10^5
ν_μ CC Coherent	8.35×10^3
ν_μ NC Coherent	4.8×10^3
ν_μ - electron elastic	135
ν_μ CC π^0 inclusive	4.47×10^5
ν_μ NC π^0 inclusive	1.96×10^5
ν_μ Low v (250 MeV)	2.16×10^5
ν_μ Low v (100 MeV)	7.93×10^4
$\bar{\nu}_\mu$ CC Coherent ($\bar{\nu}$ mode)	6.90×10^3
ν_e CC Total	1.89×10^4
ν_e NC Total	5.98×10^3
ν_e CC Coherent	93
ν_e NC Coherent	52

High stats

Clean sample

Clean samples

Sign-selected BG-free beam ν_e measurement

Too low stats for HPgTPC, but LArTPC can do this without help.

See C. Marshall's talk from earlier today

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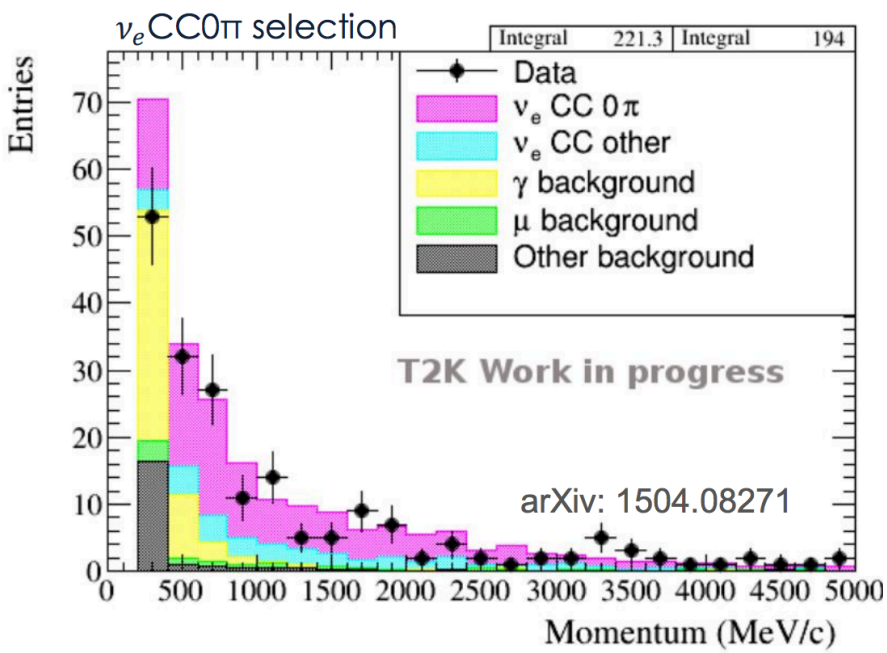
9. Key Channels: ν_e / $\bar{\nu}_e$ CC (intrinsic beam ν_e's)

T2K experience (measured with FGDs as target):

- Largest background to ν_e appearance measurement at far detector is intrinsic beam ν_e's
- Constrain by measuring ν_e-*like* events in the ND, but T2K still has large γ BG, especially at low momentum



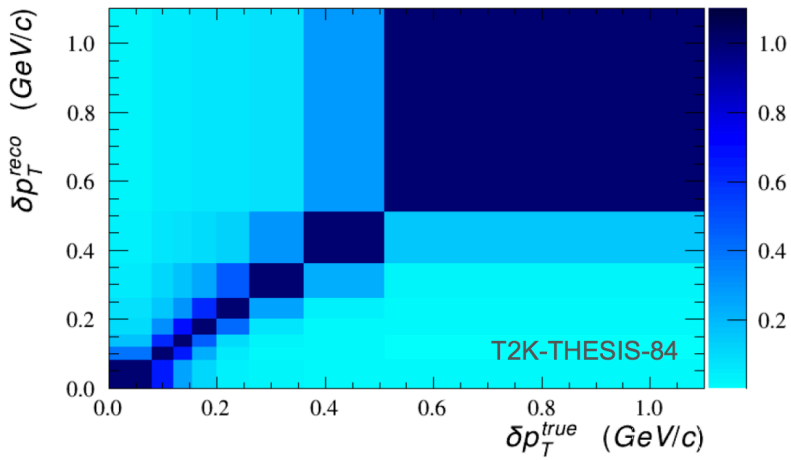
Clean measurement of intrinsic beam ν_e rate in HPgTPC constrains backgrounds to LArTPC ν_e CC-*like* measurement

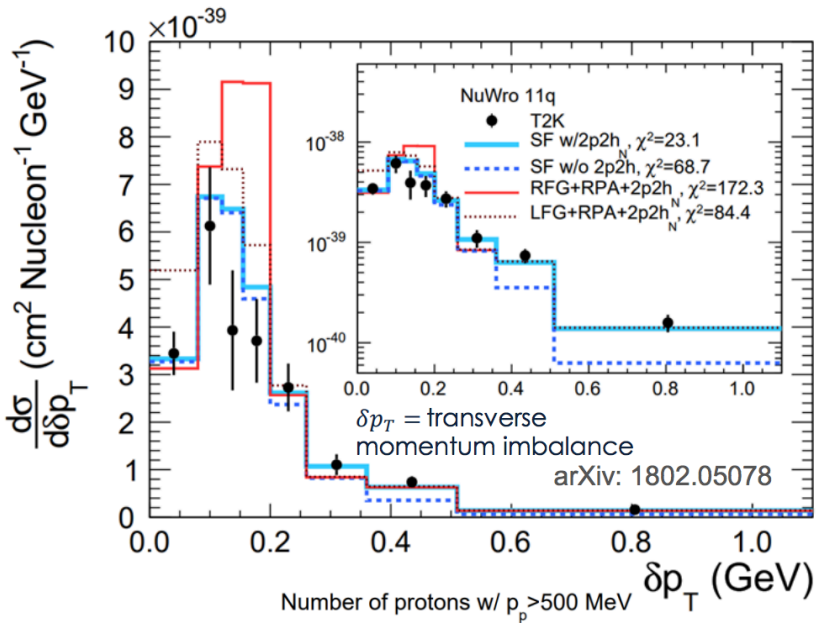
- 18,900 events/year in FV
- GArTPC measurement will not have backgrounds from γ's
- Wrong-sign tagging/rejection of anti-ν_e's

9. Key Channels: Probe Nuclear Effects w/CC 0πNp

Charged current interactions with no pions and at least one proton are a very sensitive probe of final state interactions

T2K analysis: hep-ex/1802.05078
Limited by detector resolution.





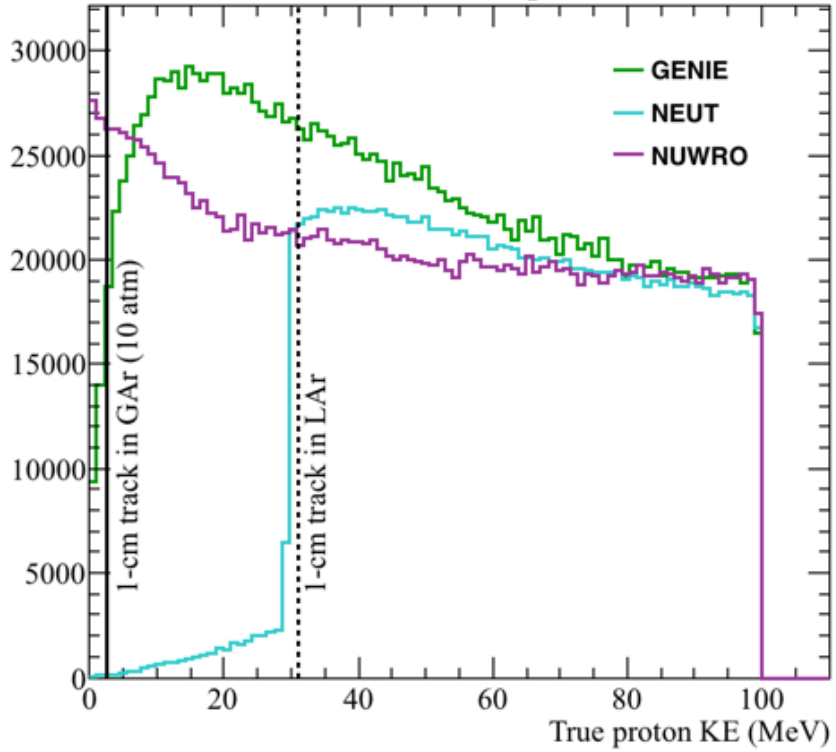
Better momentum resolution and higher statistics in HPgTPC will improve sensitivity

- T2K: ~9% momentum resolution, ~3500 events
- HPgTPC: ~1-2% momentum resolution, ~244,000 events/year

9. Key Channels: Probe Nuclear Effects

Proton multiplicities and energy spectra may also help to distinguish among nuclear models

Generator samples from J. Calcutt



HPgTPC's very low reconstruction/PID threshold enhances ability to distinguish among models

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Participants (alphabetical by institution)

Aachen	P. Hamacher-Baumann, S. Roth
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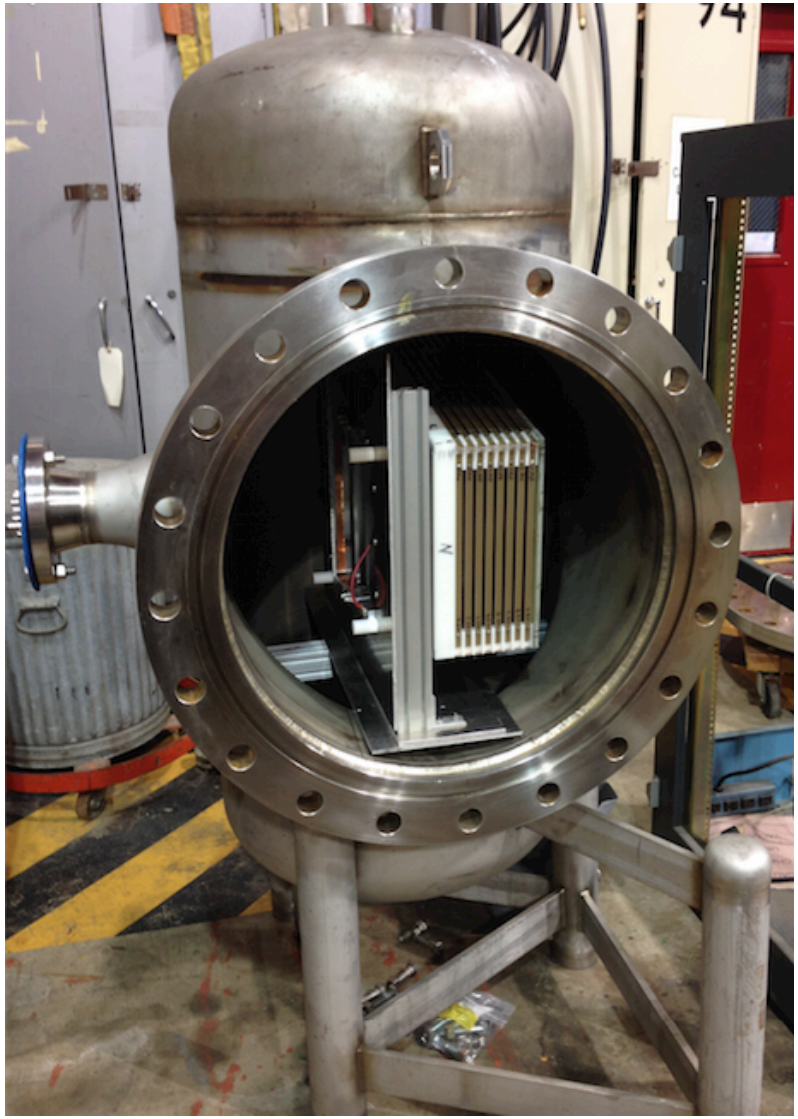
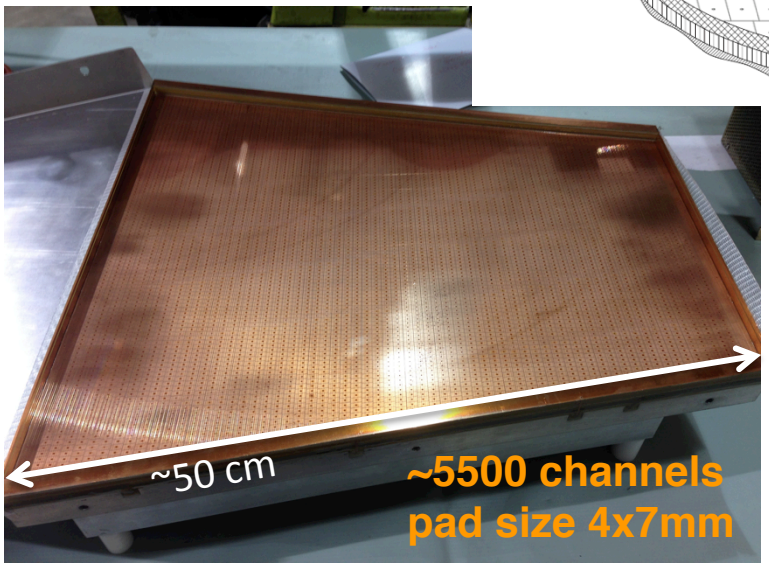
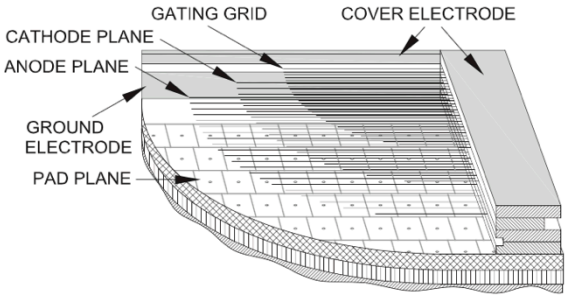
Fermilab	A. Bross, K. Duffy, G. Fernández-Moroni, T. Junk, J. Raaf, A. Schukraft
Harvard	J. Martín-Albo
Indiana	G. Davies
LBNL	D. Dwyer
Max Planck	L. Emberger, F. Simon
Michigan State	J. Calcutt, K. Mahn, L. Pickering
SLAC	H. Tanaka

Great team that is fully capable of building this detector.

Ongoing R&D: ALICE IROC





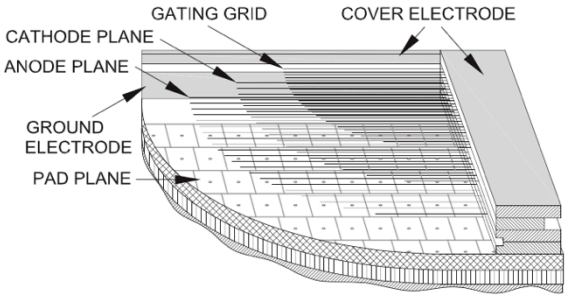


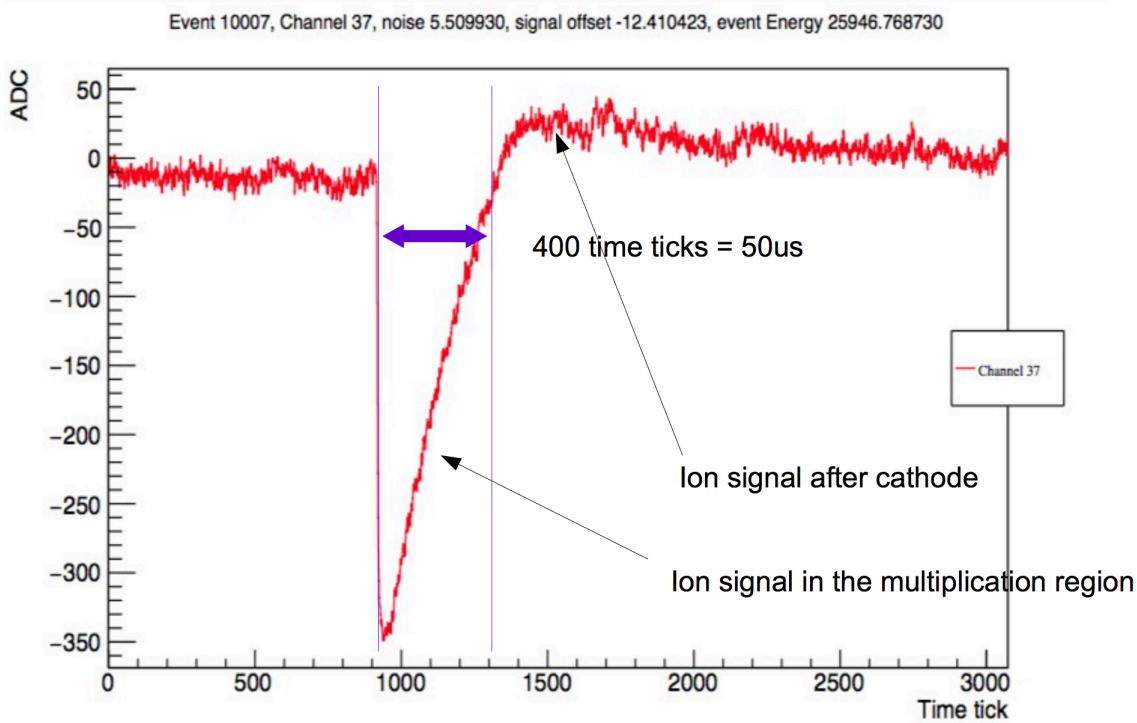
Pad readout w/ amplification by wire planes

Test stand at Fermilab

- Demonstrate operation of ALICE readout chamber at higher pressures & characterize performance
- Test chamber performance in various gases
- Develop/extend use of LArPix ASIC (LBNL design) to HPgTPC; synergistic with ArgonCube

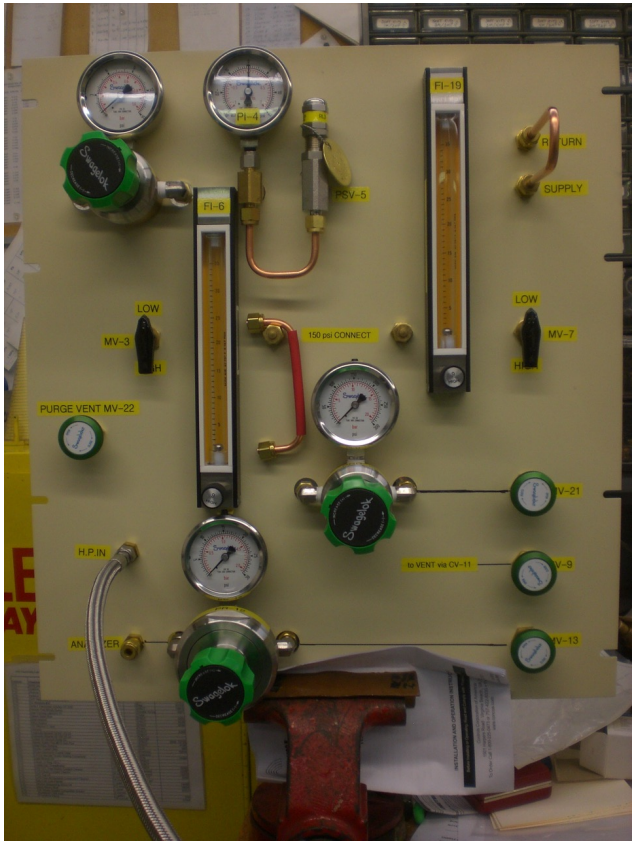
Ongoing R&D: ALICE IROC





First signals in the IROC at 1 atm!

Newly built gas panel



Next steps:

- Higher pressure
- Pad readout via LArIAT motherboards (BNL ASIC)
- Pad readout via LBNL LArPix ASIC

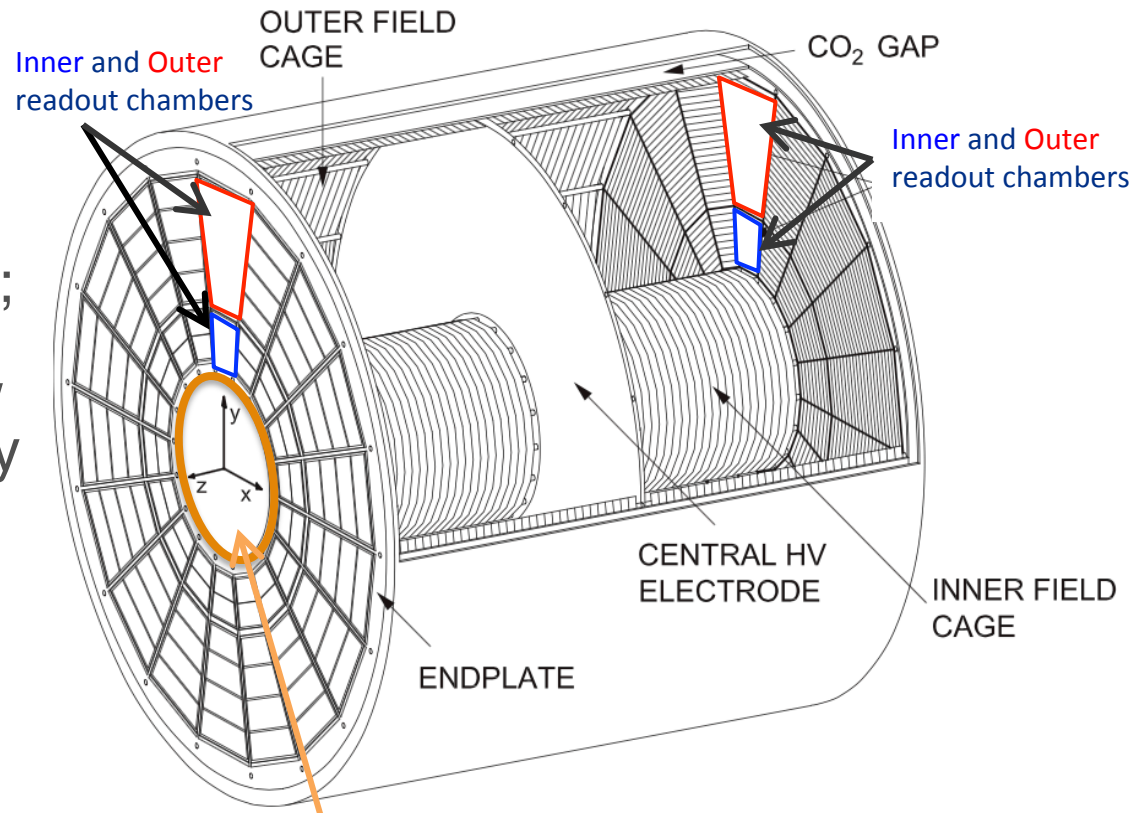
Summary

- An integrated argon detector (ArgonCube + HPgTPC) gives the best chance to measure what is needed for oscillation analyses
  - HPgTPC enhances LAr measurements by constraining backgrounds (intrinsic beam ν_e's)
  - HPgTPC's low thresholds, excellent momentum and angular resolutions, and 4π angular coverage also give the opportunity to probe FSI via analyses similar to T2K and MINERvA
  - Totally active detector, no dead material
- Synergies in LAr & GAr: readout, DAQ, data structure, reconstruction...
- Want to measure things on other nuclear targets? Ok! Just put a different gas in the TPC...
- Great team of people fully capable of building this detector, and R&D to make it happen is well underway

Thank you

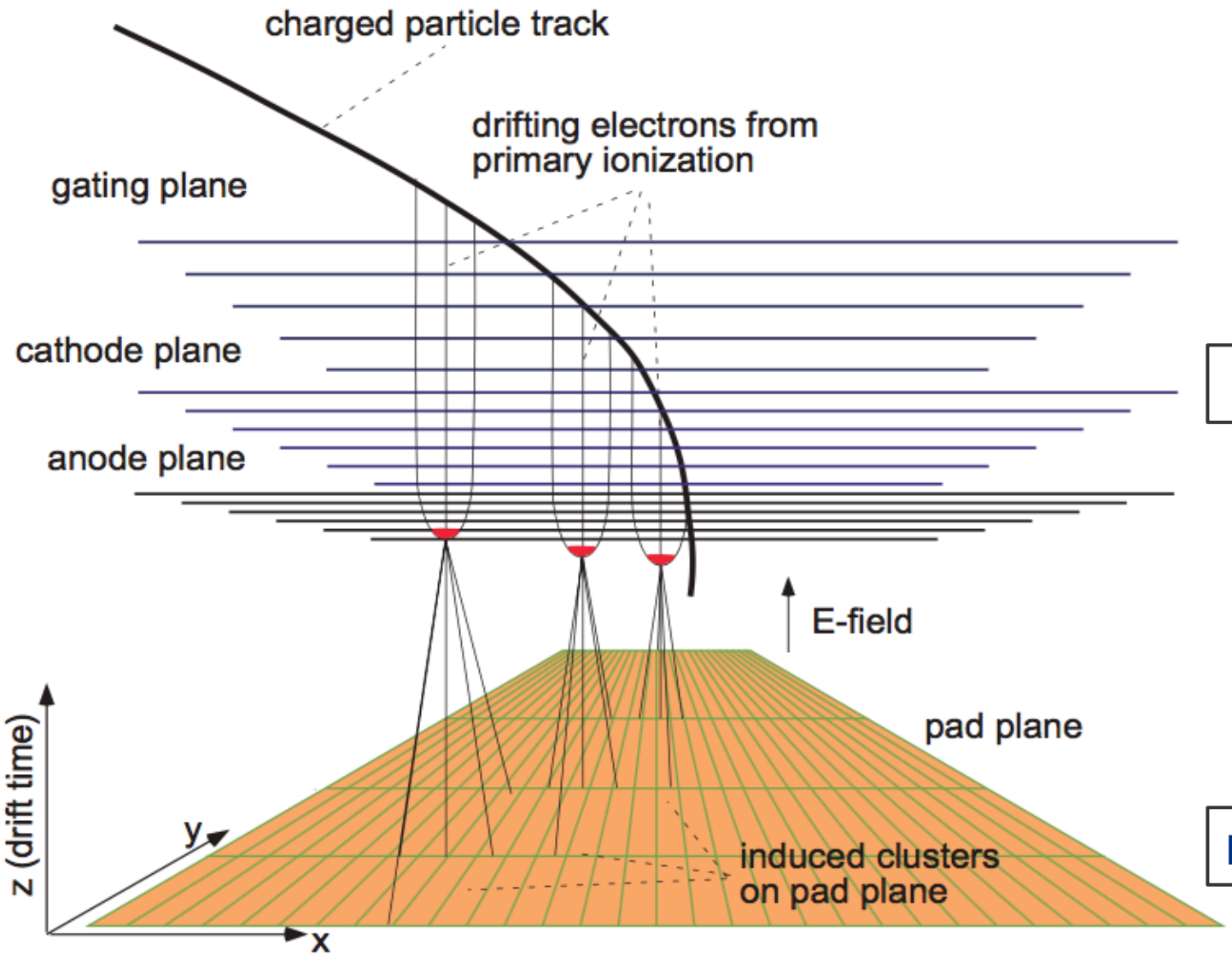
ALICE TPC

- Chambers work very well; ALICE collaboration has just decided to make new readout chambers so they can handle higher multiplicity:
  - Current: 6000 tracks per unit rapidity
  - Upgrade: 8000 tracks per unit rapidity
- ALICE operated at 1 atm, but would need to run at higher pressure (density) to collect enough stats for neutrino interactions



Also will need to build new readout chambers to fill central regions (in ALICE, this is instrumented with a silicon vertex tracker)

ALICE Readout Chambers



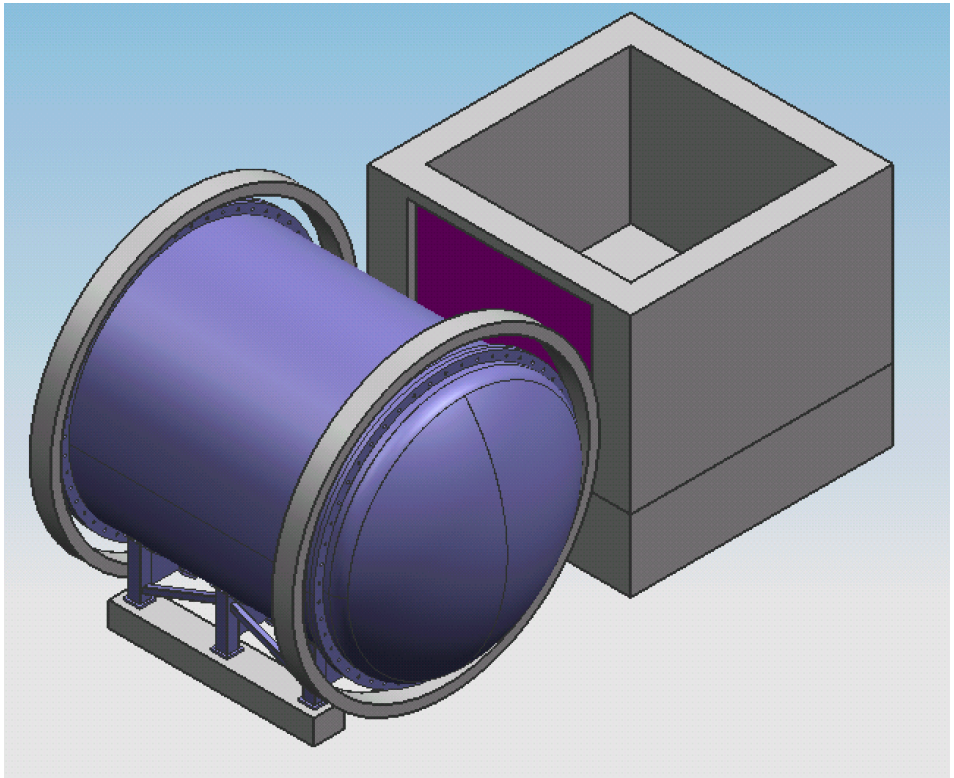
gain = ~2×10^4

Readout plane

Fermilab

Alternative configuration (for future consideration)

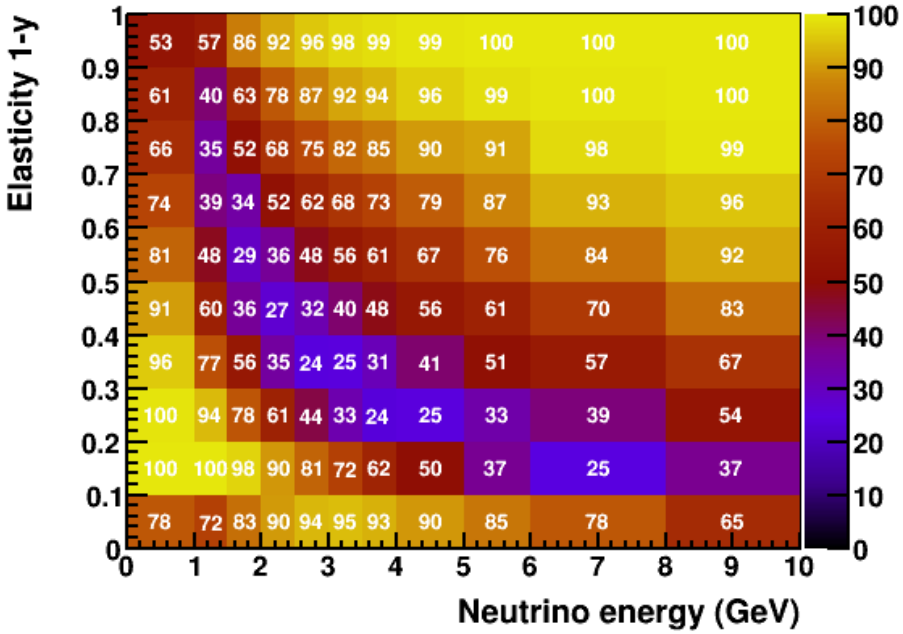
- *All studies for this STT vs. HPgTPC comparison were done with the magnet configuration shown earlier*
- Improved configurations that will give even better acceptance should be considered in the future:



GAr Acceptance: Dipole vs. “Open Magnet” design

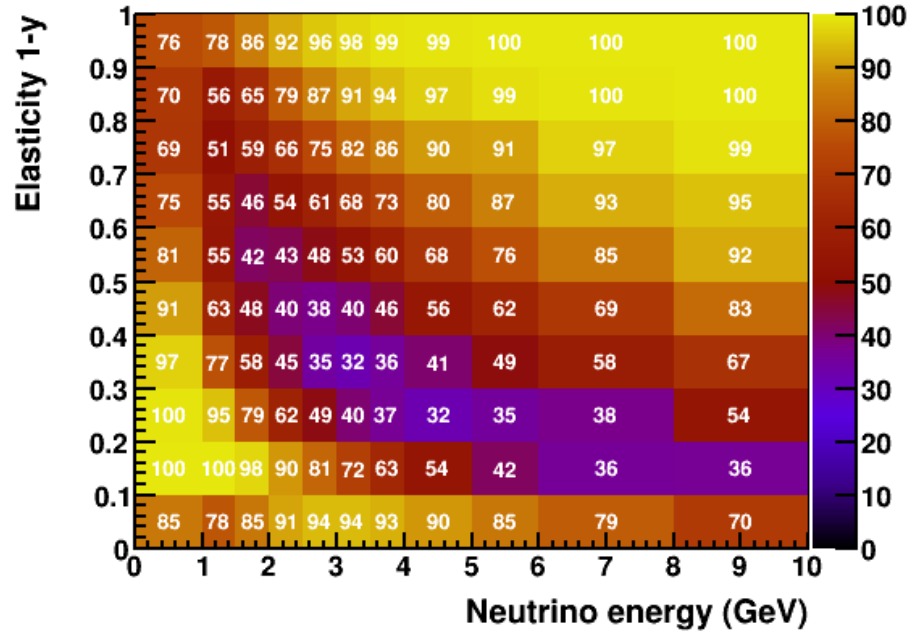
Dipole

Contained + Tracker + ECAL



“Open Magnet”

Contained + Tracker + ECAL



Study by C. Marshall & J. Martín-Albo

For future consideration

- Modified design with thin-wall downstream face of LAr cryostat + “open magnet” gives better acceptance
- See Justo’s talk later in this session for more details.