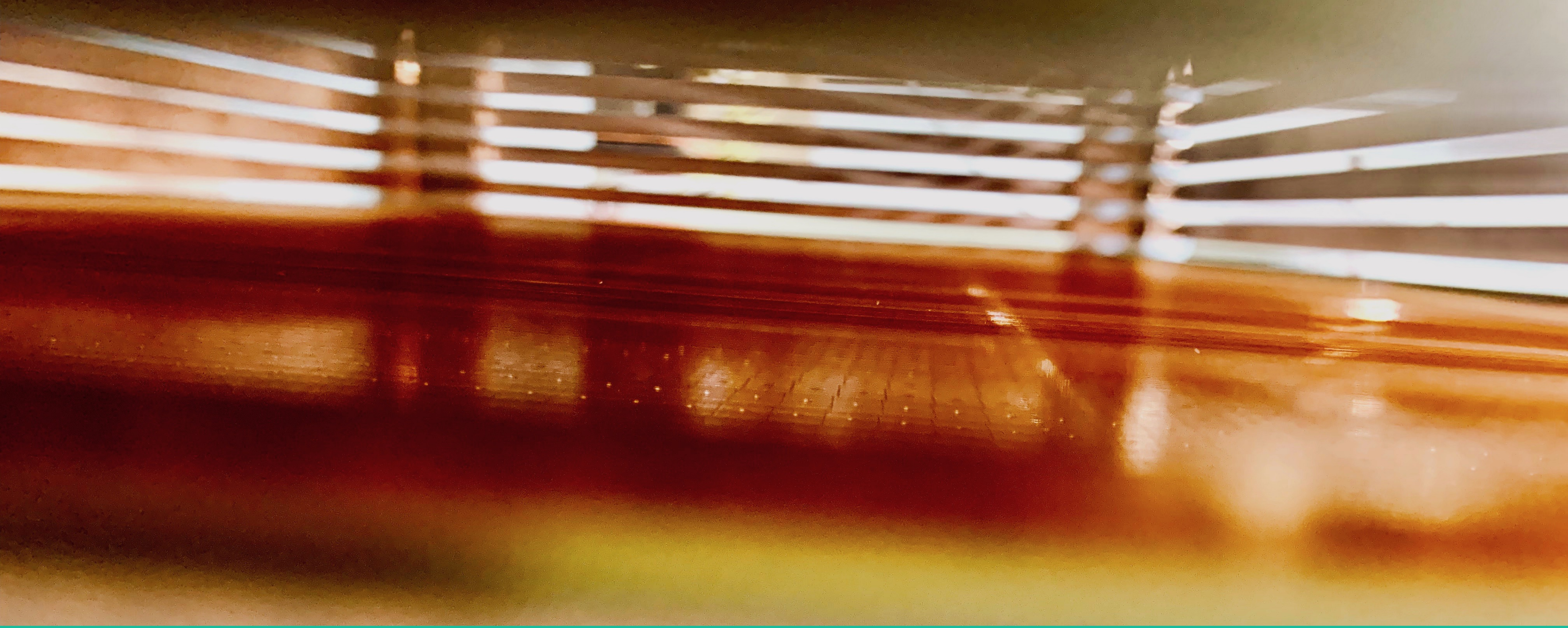


Neutrino Detectors and Detection Techniques

Tanaz Angelina Mohayai
Fermilab Neutrino University
June 17, 2021

Fermilab

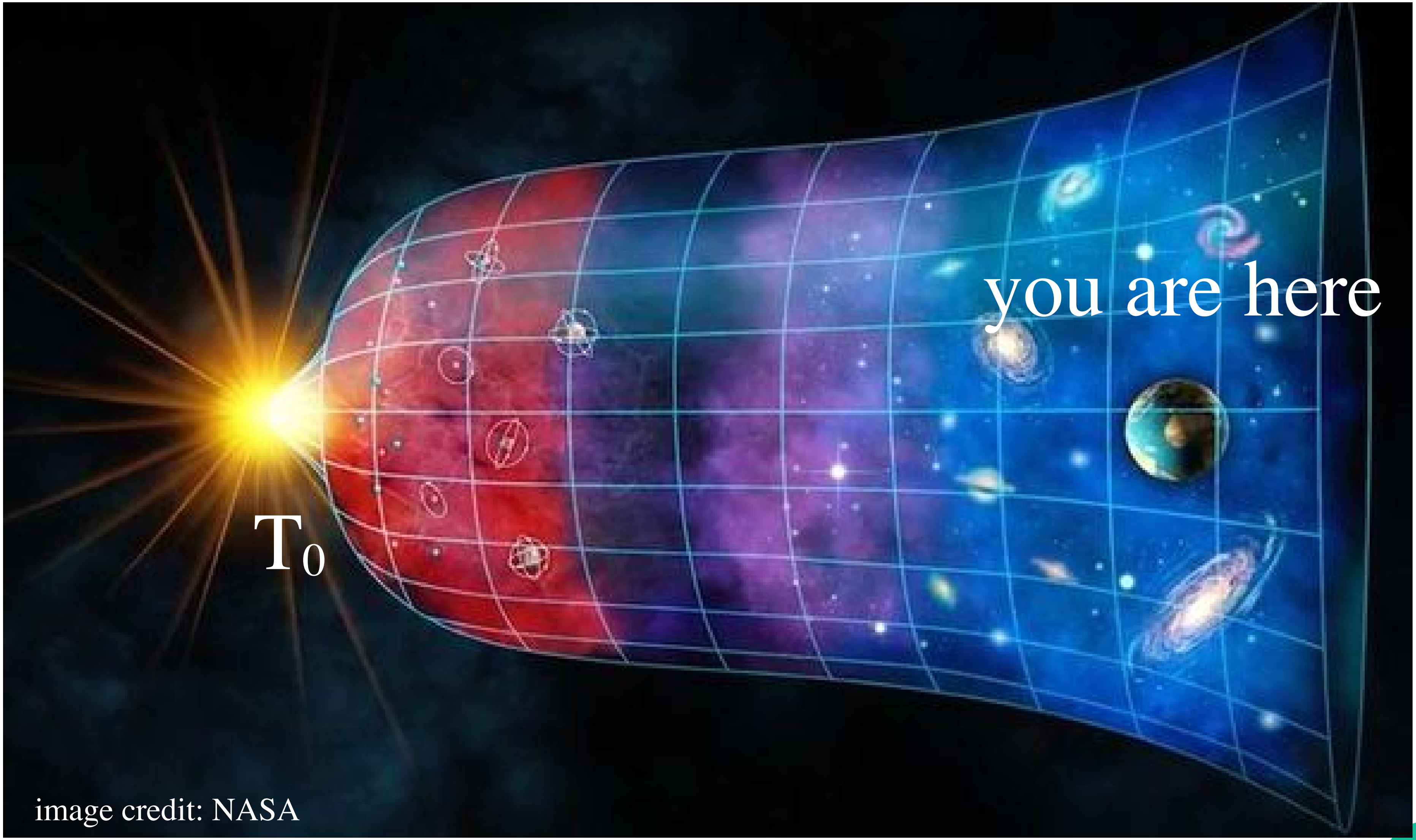
Disclaimer

I am giving an overview of a subset of neutrino detectors, with more emphasis on neutrino detectors at Fermilab (sorry if your favorite experiment is missing)!

I am also giving an overview of detection techniques relevant to the subset of detectors that I cover.

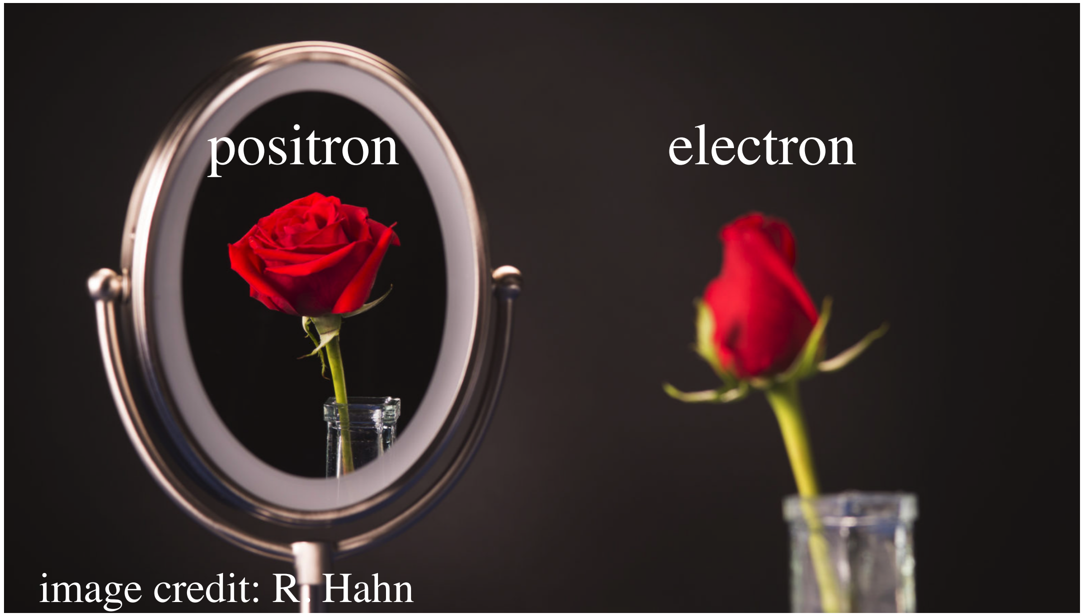
Big Picture – Why Study Neutrinos

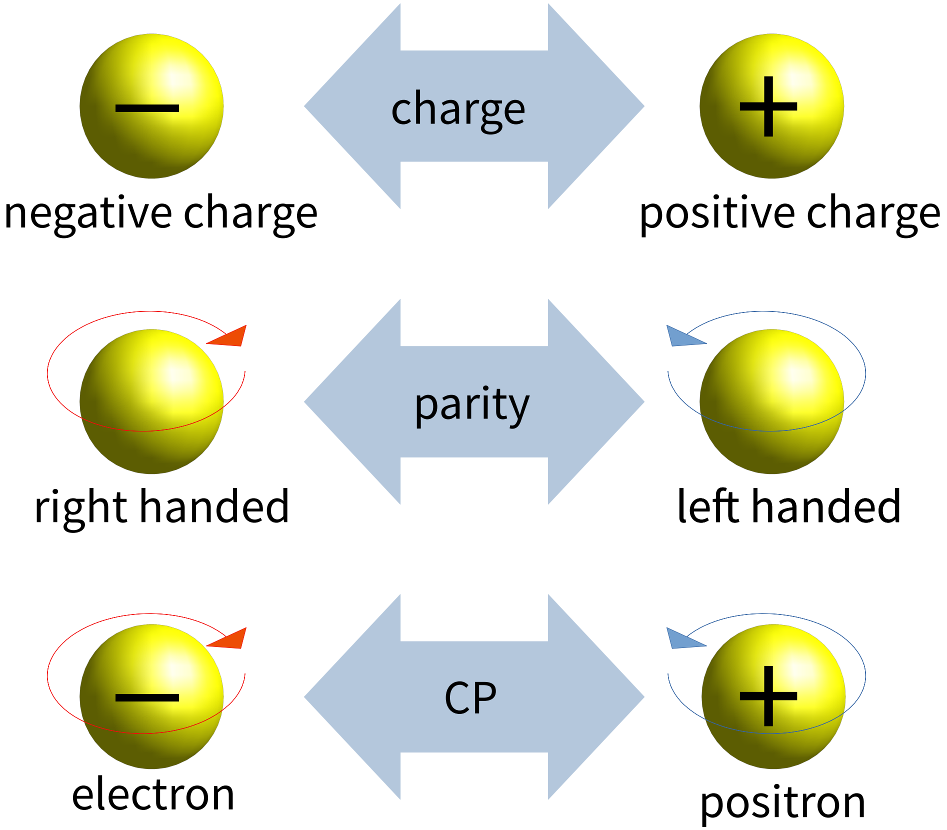
Matter and anti-matter were produced in equal quantities at big bang, but, today, we live in a matter-dominated universe



Big Picture – Why Study Neutrinos

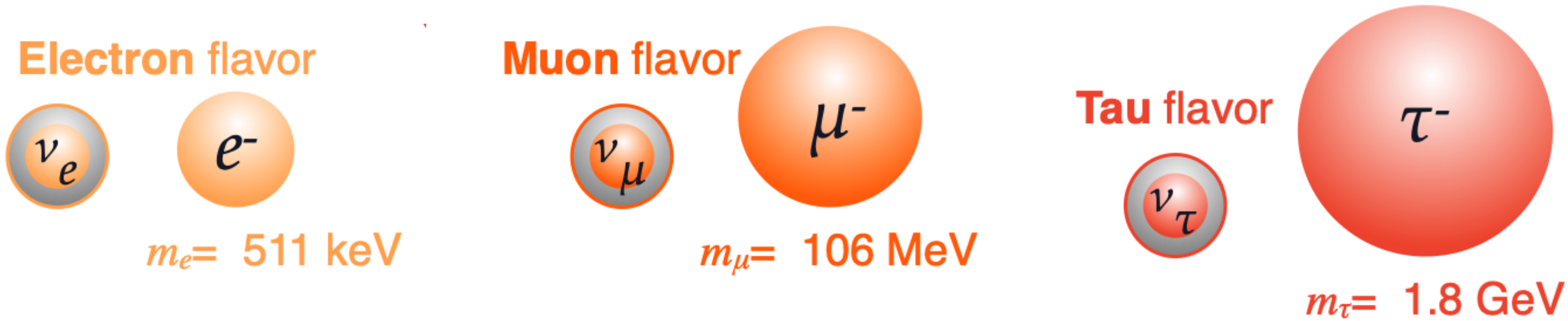
- To have a matter dominated universe, matter and anti-matter must behave differently
  - ★ In specific, Charge-parity, CP symmetry must be violated
- If neutrinos violate CP, they could be the key to explaining the matter-antimatter asymmetry in the universe





A Quick Recap of Neutrinos

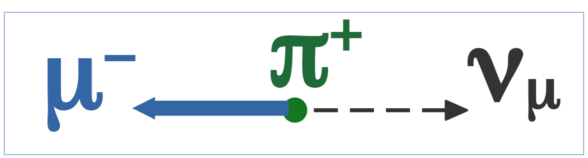
- Neutrinos are neutral leptons and have 3 types/flavors:



C. Patrick

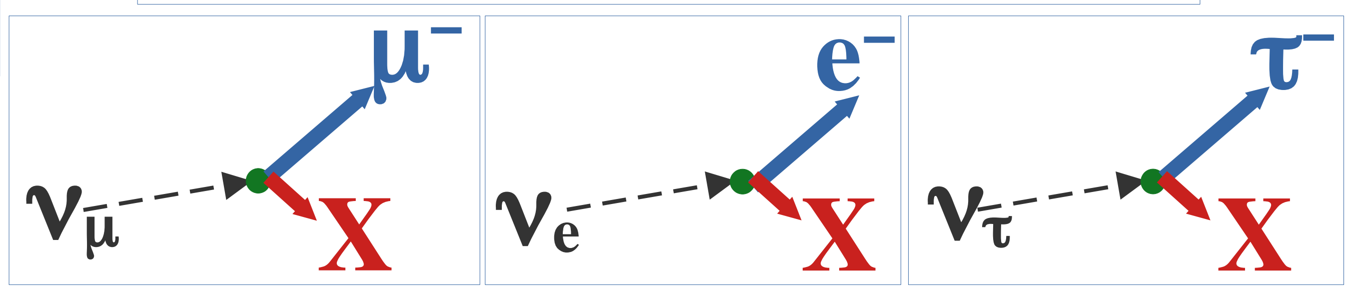
★ Generally, produced along with or interact to produce a charged lepton

ν_μ produced along with a μ



See Mark Messier's Talk on Neutrino Sources

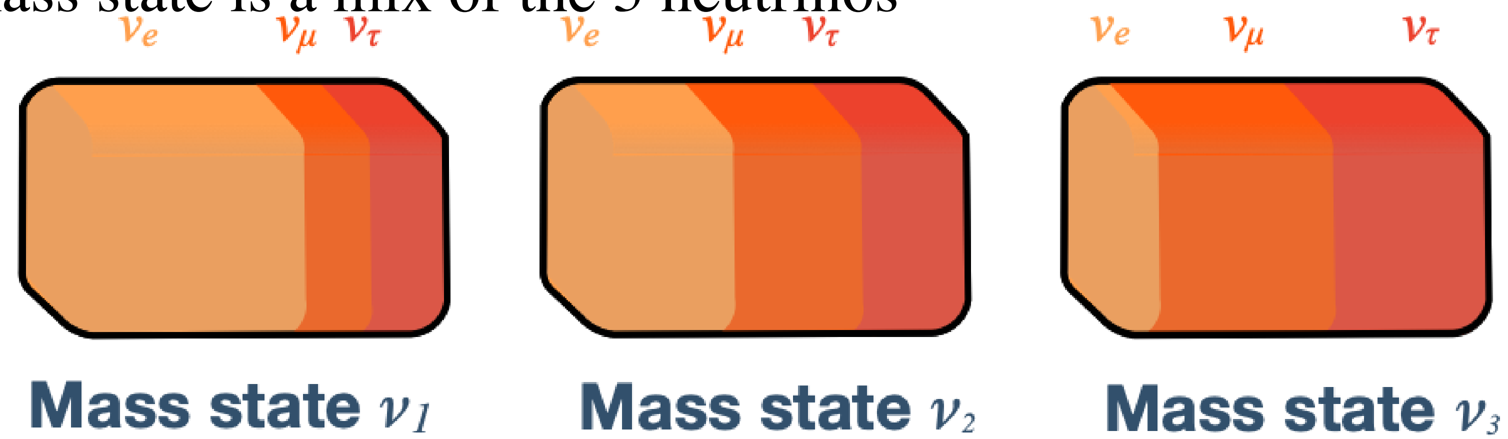
νs interact to produce a charged lepton



See Adi Ashkenazi's Talk on Neutrino Cross Sections

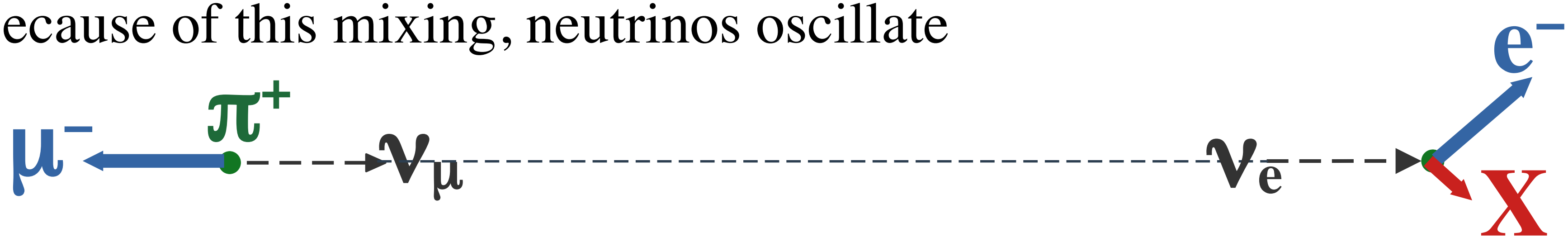
A Quick Recap of Neutrinos

- 3 definite, non-zero mass states (unlike the standard model neutrinos which are massless):
  - Each mass state is a mix of the 3 neutrinos



C. Patrick

  - Because of this mixing, neutrinos oscillate



More about Neutrino Interactions

- Neutrinos don’t interact appreciably with another constituent of matter

More about Neutrino Interactions

- Neutrinos don’t interact appreciably with another constituent of matter

More about Neutrino Interactions

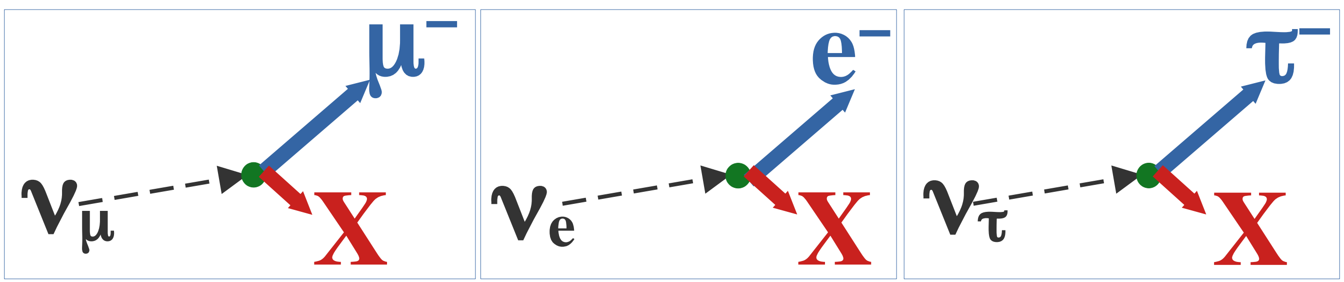
- We can only detect a neutrino if it interacts in our detectors:
  - ★ Build a massive detector that is also highly efficient
  - ★ If producing the neutrinos artificially, produce a lot of them (refer to M. Messier's talk for more info)

$$N_{\text{obs}} \propto \underbrace{\boxed{M}}_{\text{detector mass}} \underbrace{\boxed{T}}_{\text{exposure time}} \int \underbrace{\boxed{\phi(E_\nu)}}_{\text{neutrino flux}} \underbrace{\boxed{\sigma(E_\nu)}}_{\text{neutrino cross section}} \underbrace{\boxed{\epsilon(E_\nu)}}_{\text{detector efficiency}} dE_\nu$$

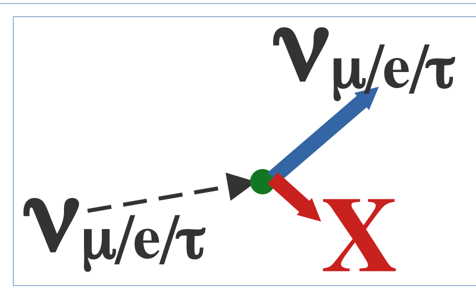
More about Neutrino Interactions

- And when the neutrinos are able to interact in our detector
  - We still don’t directly see them!!
  - Have to rely on the outgoing charged particles
  - We also don’t see the outgoing charged particles, directly!
  - Have to rely on charged particles losing energies in the detector medium via various processes

neutrino charged current interactions



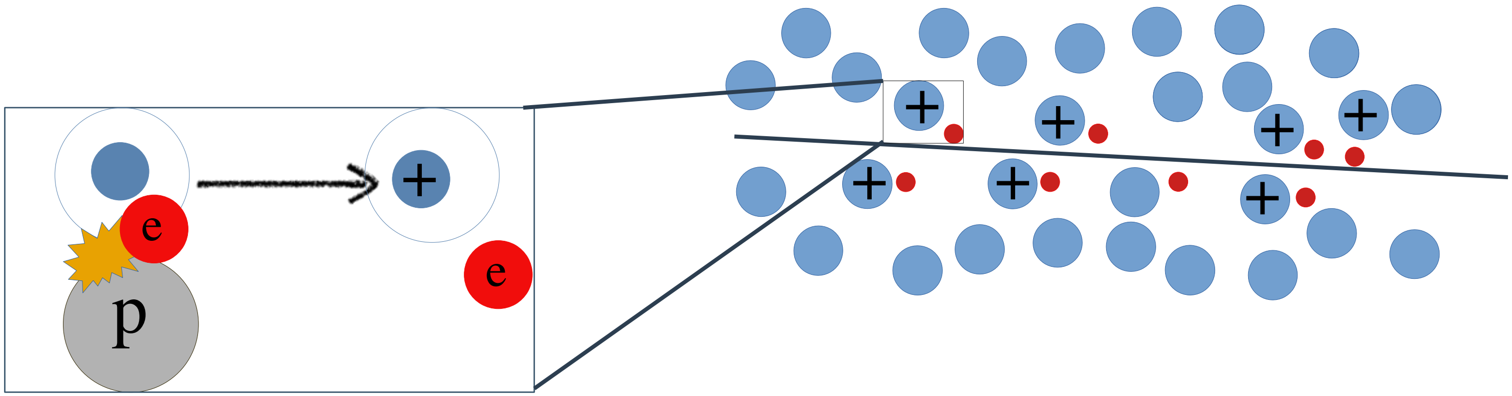
neutrino neutral current interactions



See Adi Ashkenazi’s Talk on Neutrino Cross Sections

Charged Particle Interactions – Inelastic Collisions with Atomic Electrons

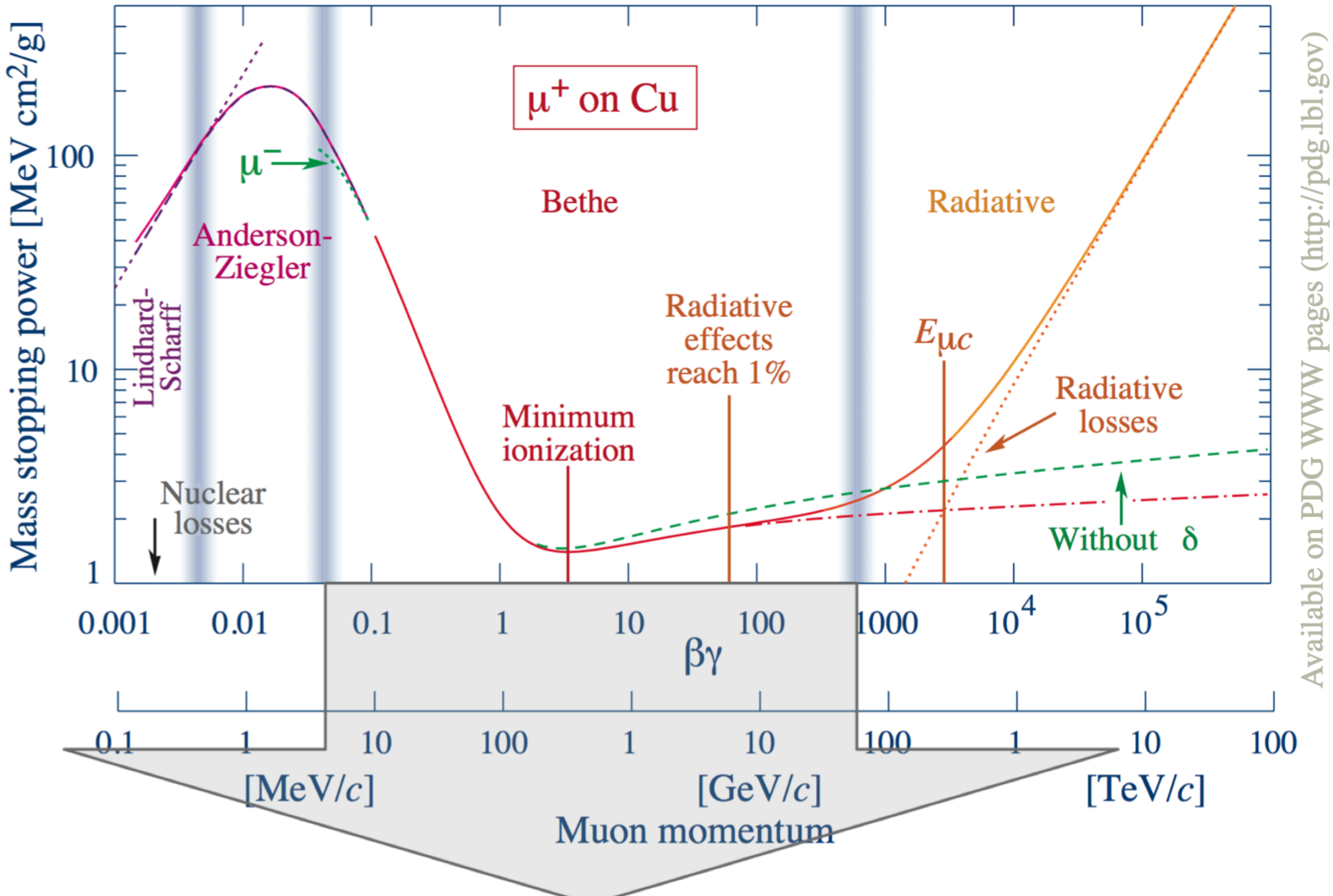
- One process by which charged particles lose energy in detectors is inelastic collisions with atomic nuclei:
  - ★ When energy of charged particle is larger than electron binding energy, it can ionize the atom & knock out the electron



  - ★ Sometimes the knocked out electron can have enough kinetic energy to further ionize the surrounding atoms (delta rays)
  - ★ When the energy of charged particle is not larger than electron binding energy, excitation can occur – when the atom de-excites, photon (light) is released

Ionization Energy Loss

mean ionization energy loss for a heavy charged particle, e.g. muon



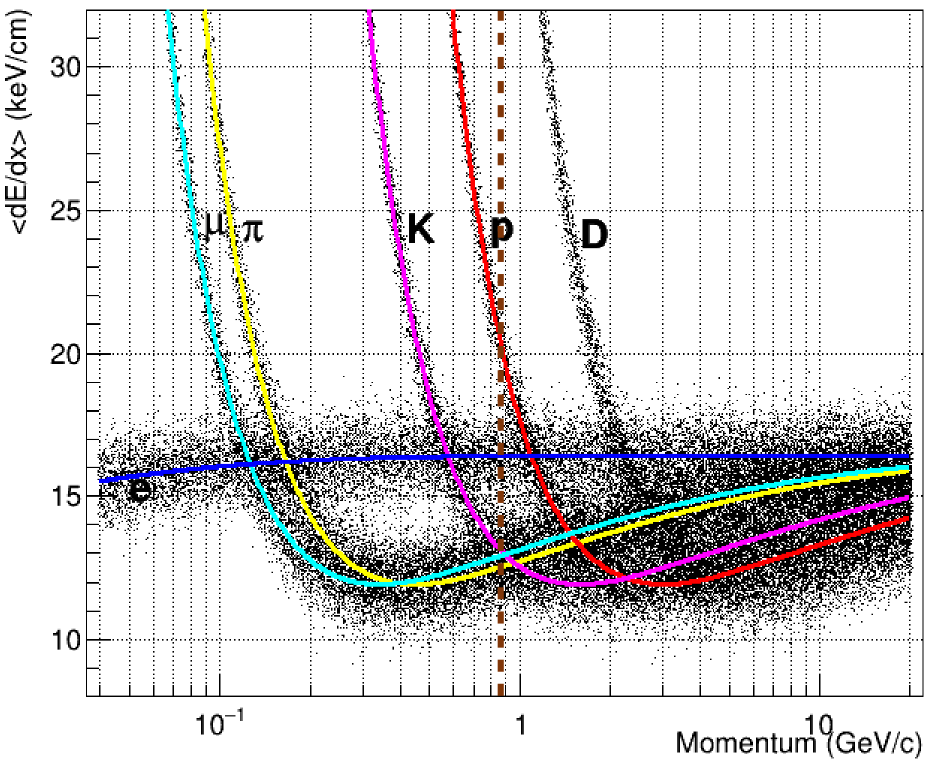
$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

J. Raaf

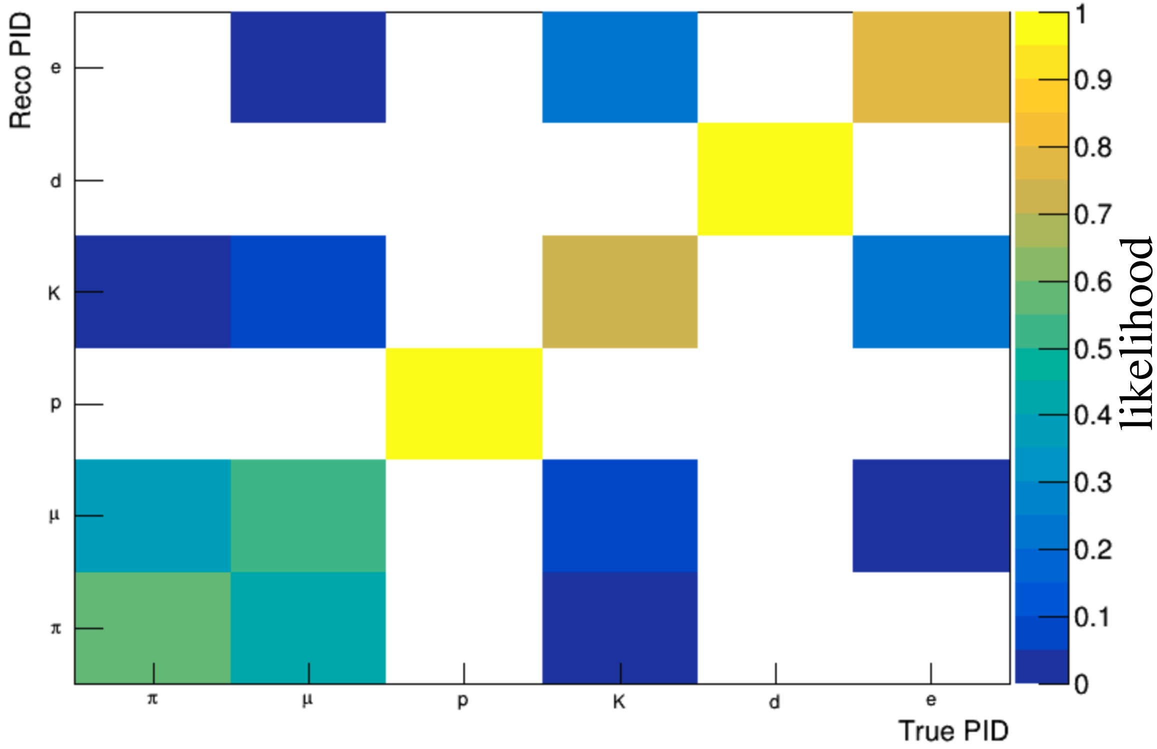
Ionization Energy Loss

- Used as a common particle identification approach
- Particles with different masses at various momentum values lose different amount of ionization energy loss

dE/dx based on PEP-4 detector

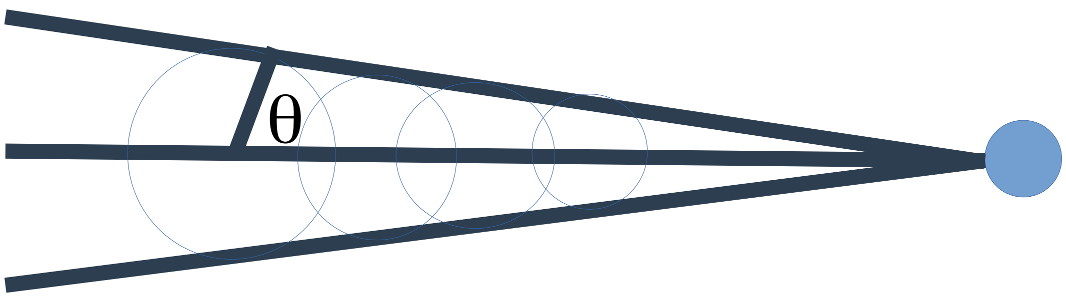


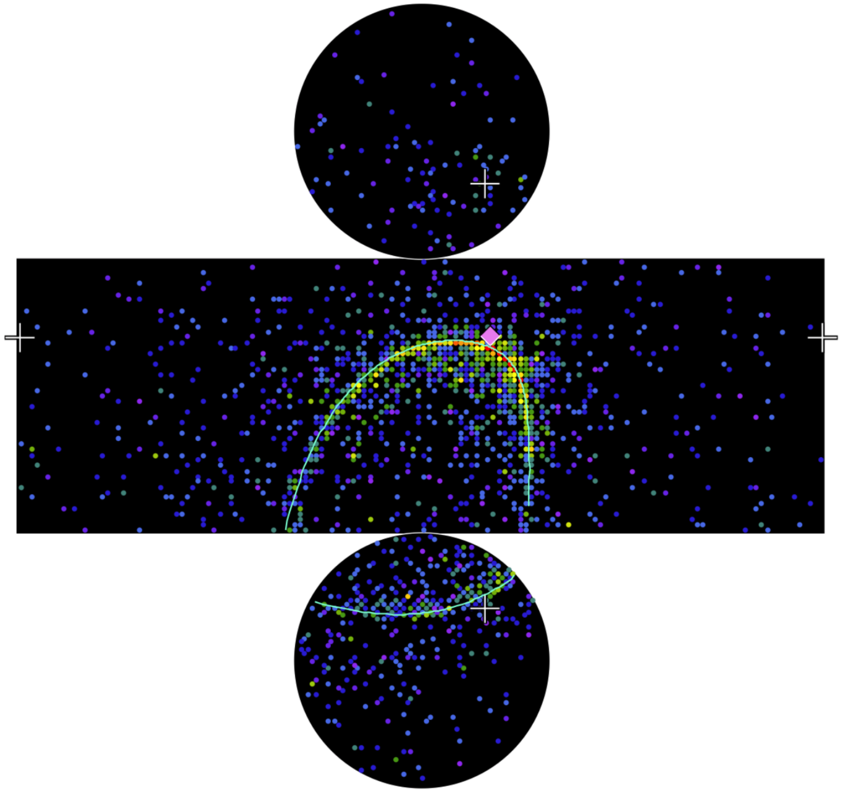
Momentum = 0.647 GeV/c



Other Relevant Charged Particle Interactions

- Cherenkov radiation:
  - Photons released at an angle θ when the particle's velocity is larger than the speed of light in the detecting medium – similar to a sonic boom from an airplane that goes faster than the speed of sound
  - Number of photons is dependent on the angle, $N_\gamma \propto \sin^2(\theta)$

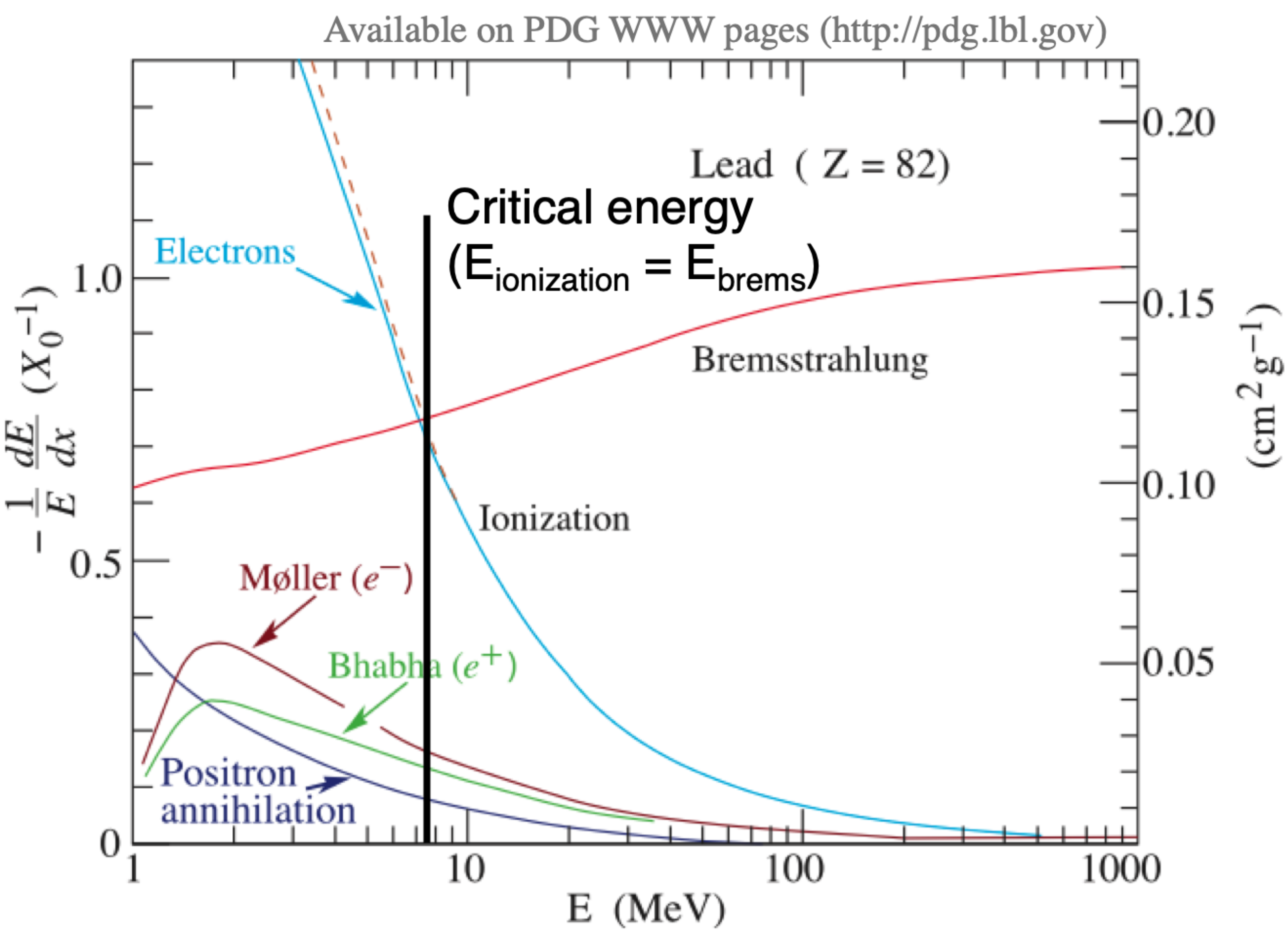




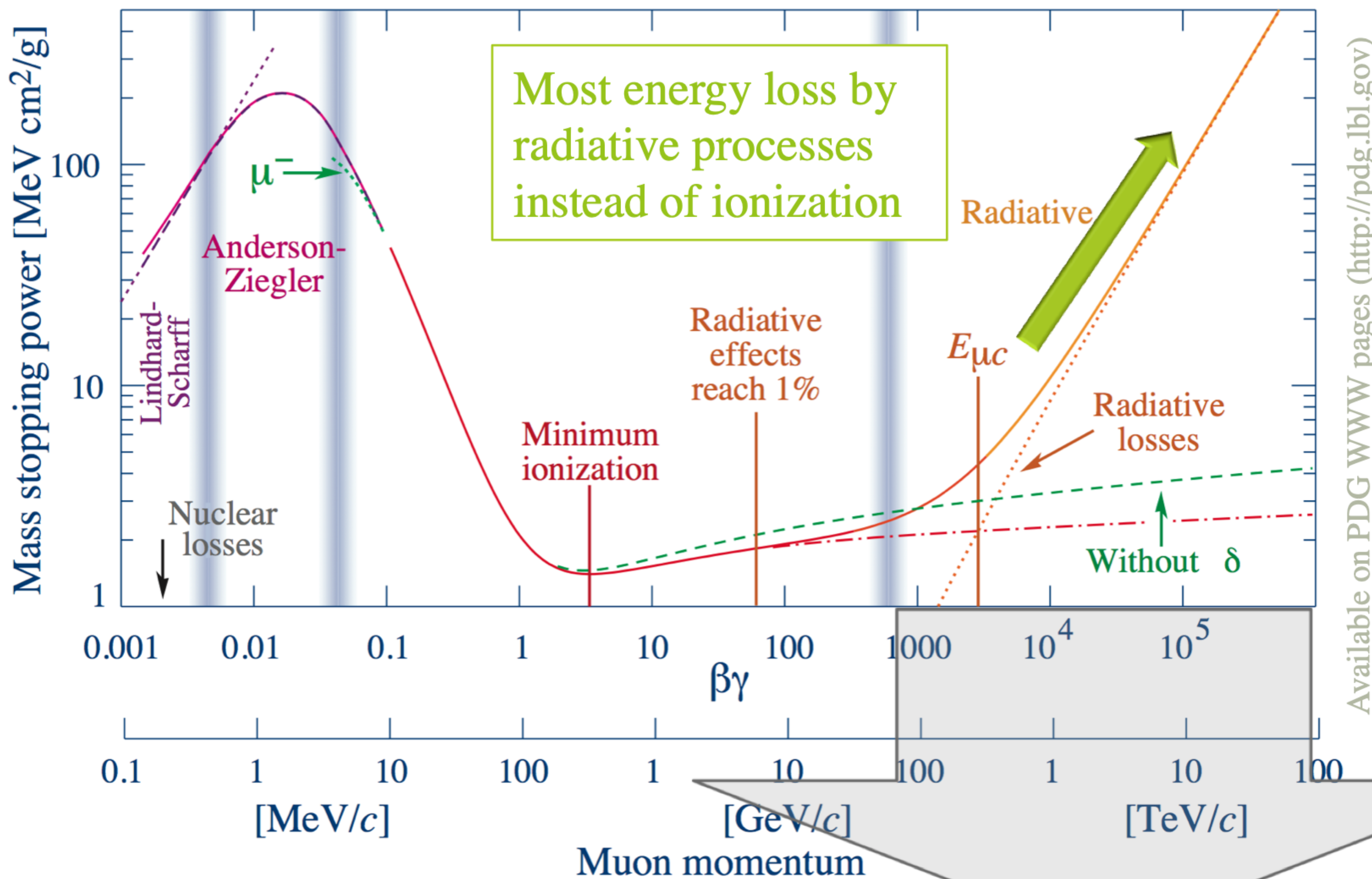
Super-Kamiokande event display

Other Relevant Charged Particle Interactions

- Bremsstrahlung:
  - When photons are emitted from a charged particle scattering in electric field of a nucleus
  - Dependent on detecting material, it is the dominant energy loss process for electrons in energies between 10 and 100 MeV



Other Relevant Charged Particle Interactions



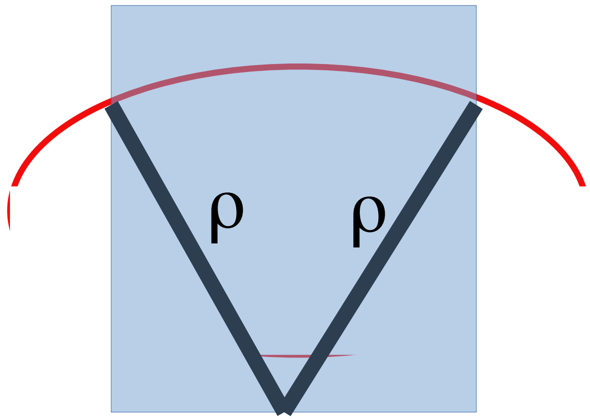
Energy losses due to things like bremsstrahlung and knock-on electrons (delta rays)

J. Raaf

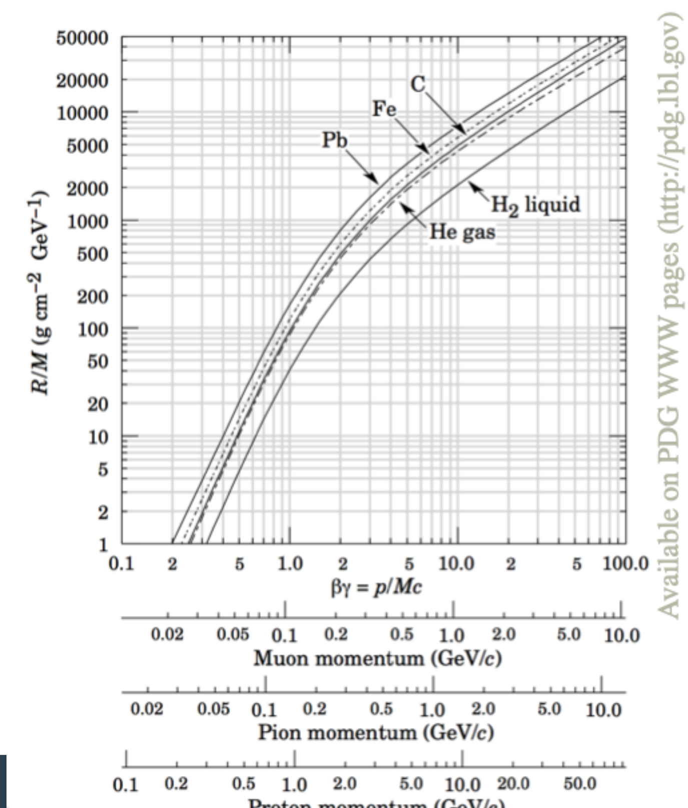
How to Reconstruct Charged Particles in Detectors

- We can reconstruct the momentum of charged particles
  - In magnetized detector, we can reconstruct momentum and charge of particles using the magnetic field

$$p[GeV/c] = 0.3B[T]\rho[m]$$



  - In non-magnetized detector, we measure the range of the particle if it stops in the detector

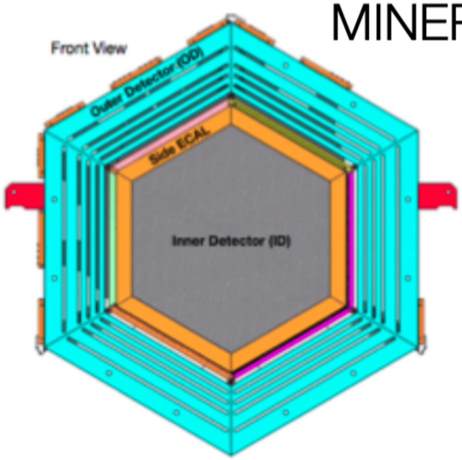


Neutrino Detectors at Fermilab

- Most past, current, and future Fermilab experiments use heavy targets in their detectors

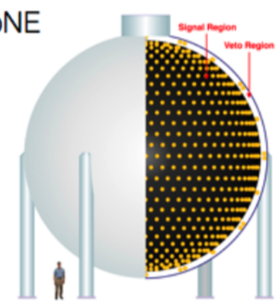
Carbon

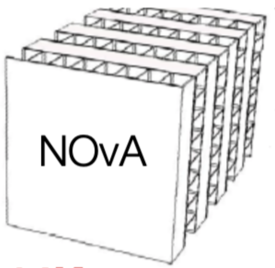
MINERvA



Carbon, iron, lead, helium, water

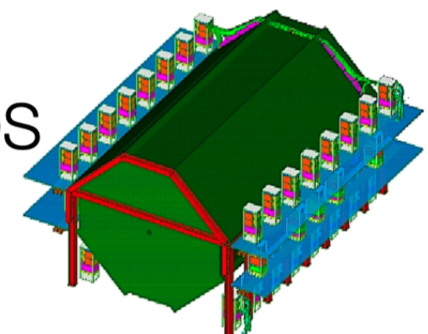
MiniBooNE





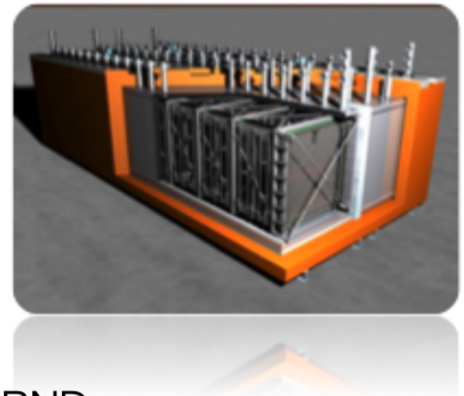
14Kton

MINOS

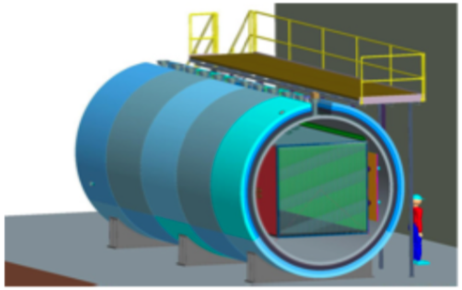


Liquid Argon

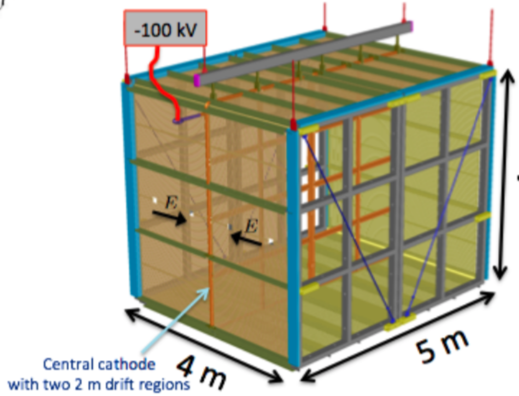
ICARUS



MicroBooNE

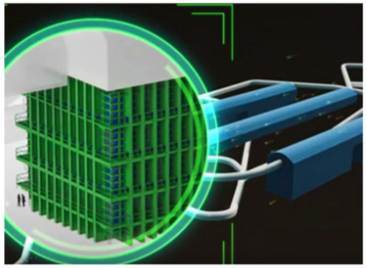


SBND

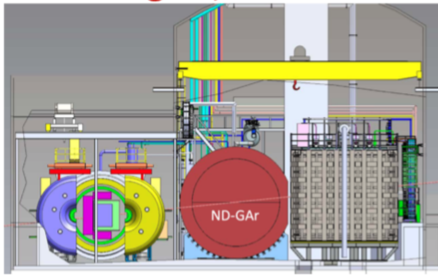


DUNE

40Kton



Liquid and Gaseous Argon, carbon

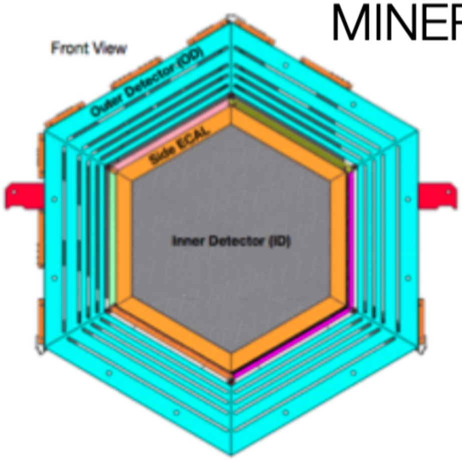


Neutrino Detectors at Fermilab

- Most past, current, and future Fermilab experiments use heavy targets in their detectors and most are **time projection chambers**

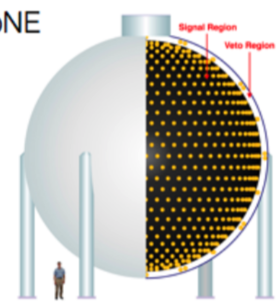
Carbon

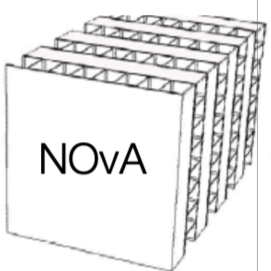
MINERvA



Carbon, iron, lead, helium, water

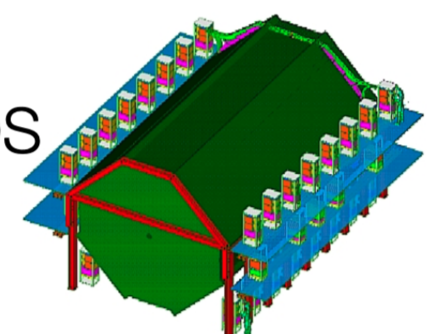
MiniBooNE





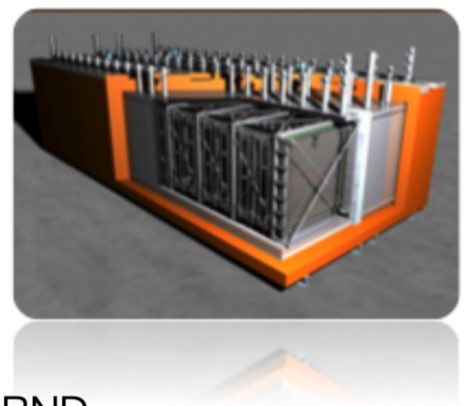
14Kton

MINOS

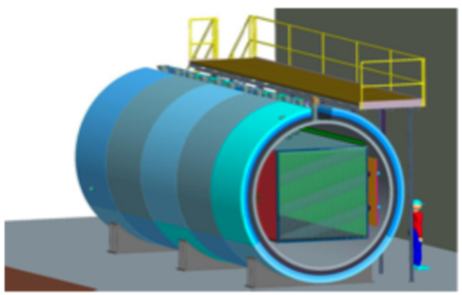


Liquid Argon

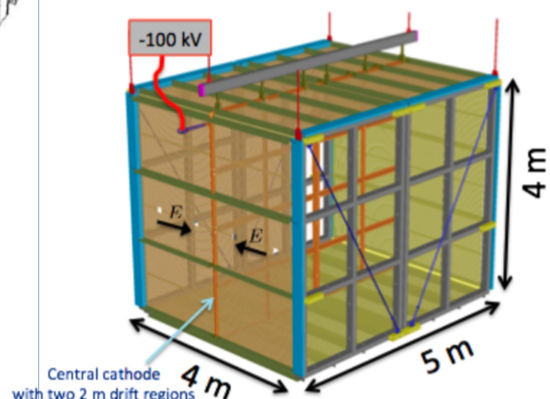
ICARUS



MicroBooNE

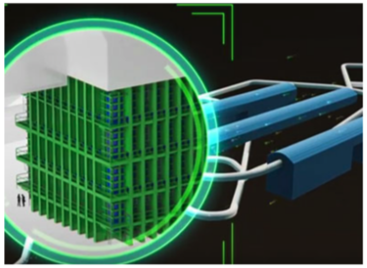


SBND

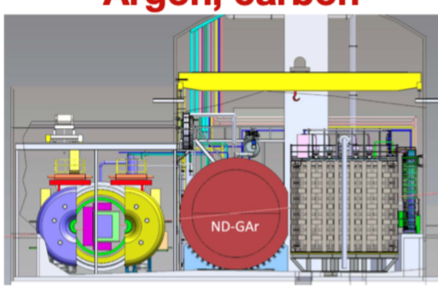


DUNE

40Kton

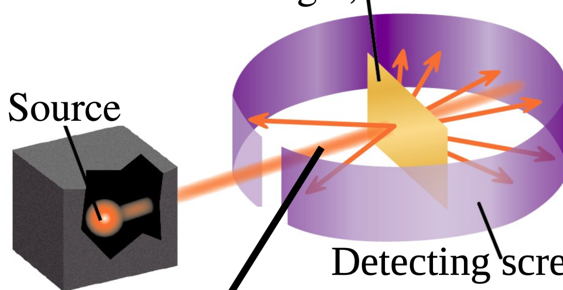


Liquid and Gaseous Argon, carbon



How Time Projection Chambers Started

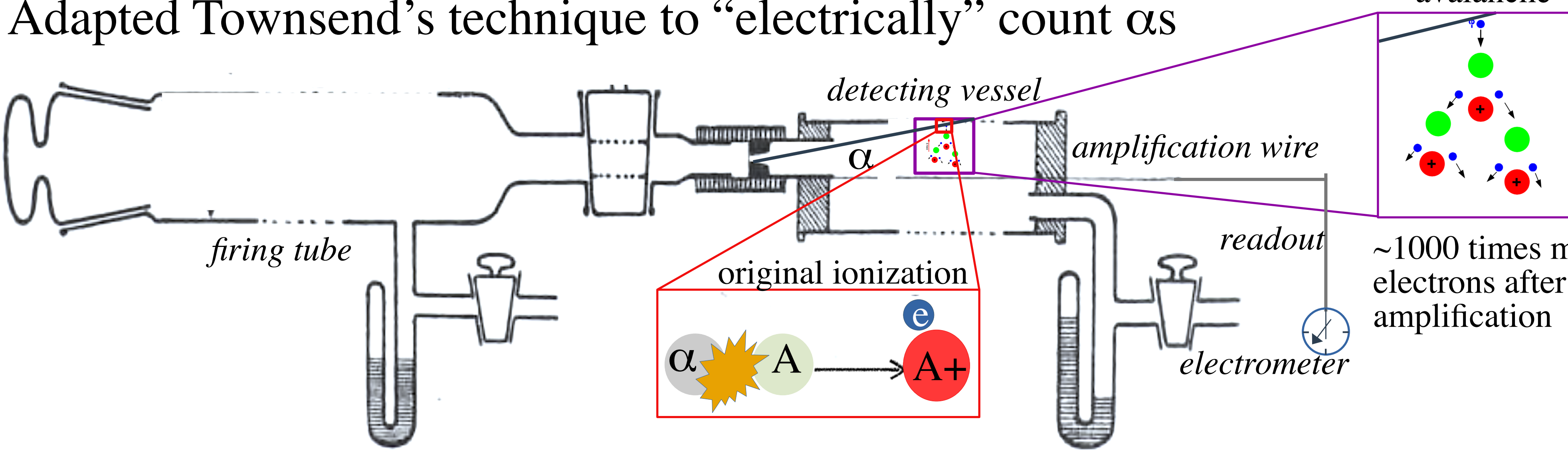
- J. S. Townsend:
  - ★ Signal amplification via secondary ionization electron-ion pairs*
- Ernest Rutherford + Hans Geiger:
  - ★ Extended the scintillation signal count approach as done with Rutherford + Geiger + Marsden setup



Encyclopedia of Science

  - ★ Adapted Townsend's "electrically" count αs

Townsend avalanche

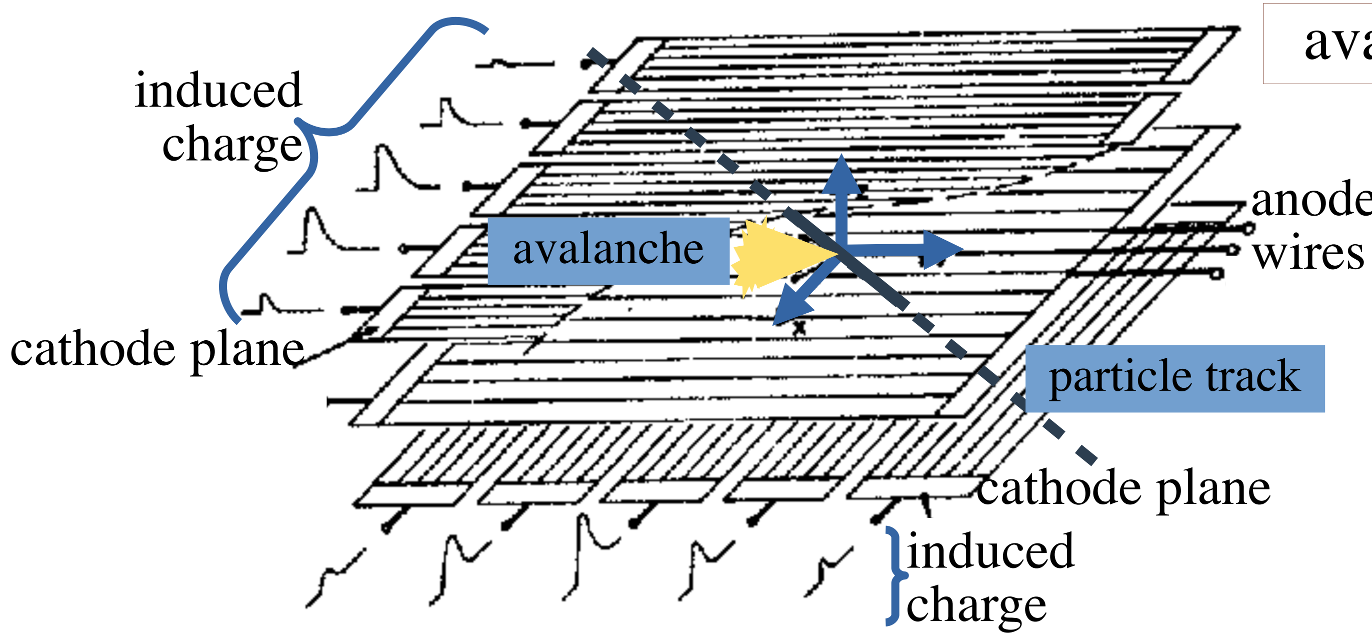


~1000 times more electrons after amplification

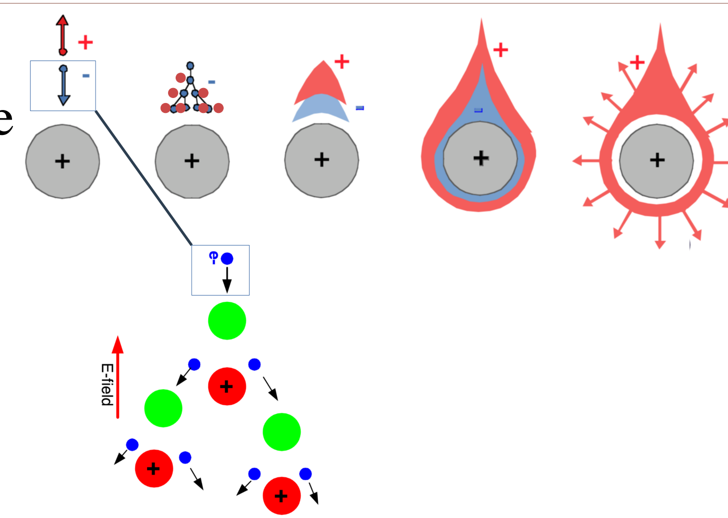
* E. Rutherford, F.R.S., H. Geiger, An electrical method of counting the number of α-particles from radio-active substances, Proc. Roy. Soc. 81 (546) (1908) 27.
J.S. Townsend, On the conductivity of gases exposed to negative ions, Proc. Roy. Soc. 1 (sixth series, #2) (1901). Also in issues of June 1902; April, Sept., Nov., 1903.

How Time Projection Chambers Started

- Invention of Multi-wire Proportional Chamber, **MWPC** by Georges Charpak et al.:
  - ★ Amplification wires ("anode") sandwiched between two cathode planes
  - ★ Signal read out is typically induced charge on the pads

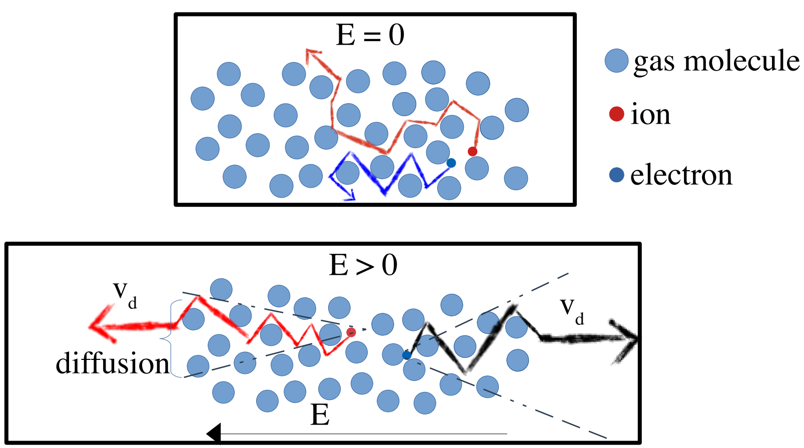


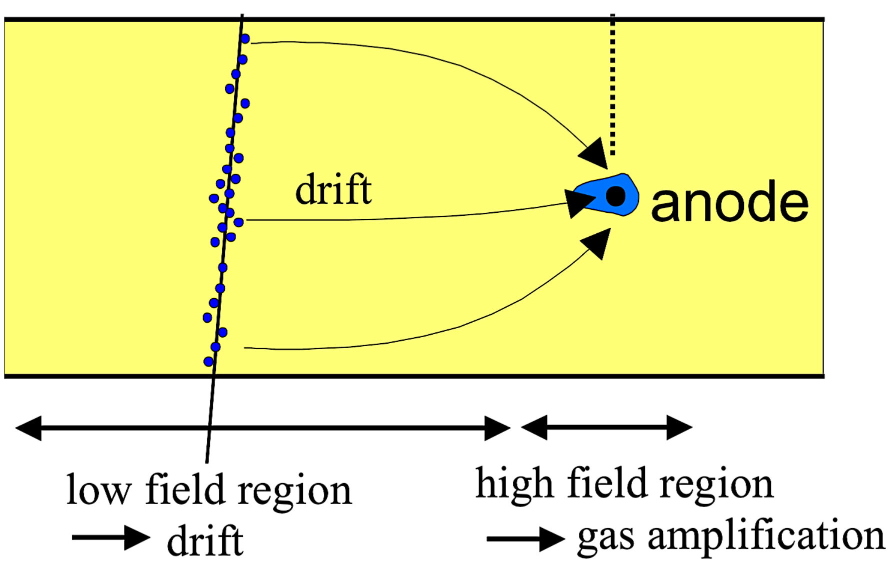
avalanche formation & readout



How Time Projection Chambers Started

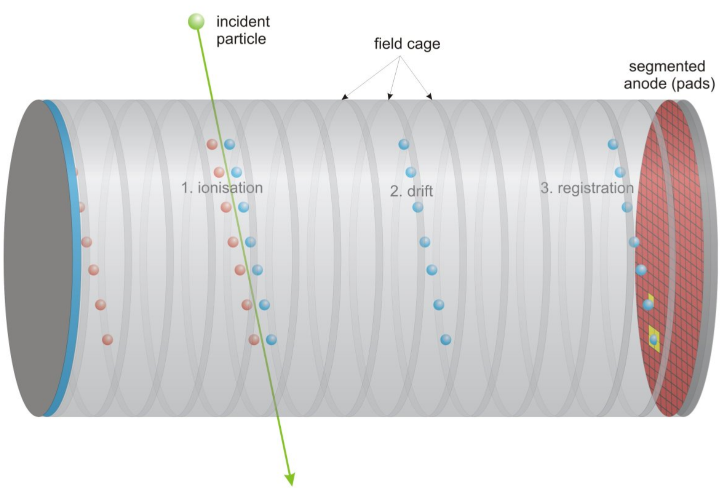
- Parallel to MWPC, invention of **drift chamber** by Georges Charpak et al.:
  - Allowing ionization electrons to drift before reaching a MWPC – as much of a high-res image of the tracks (minimized diffusion) transported over as large a distance as possible (acceptance)

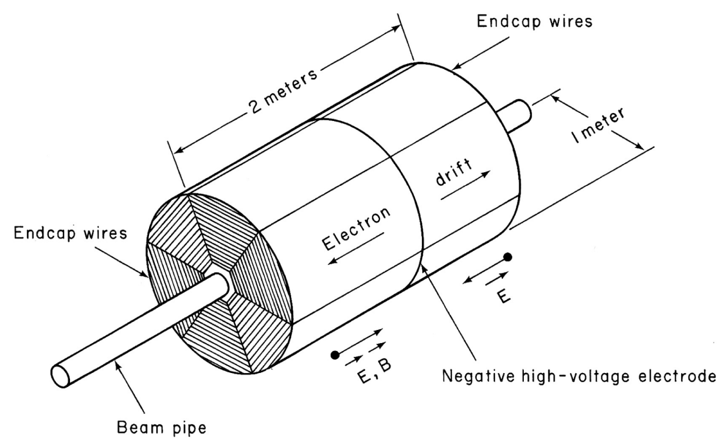


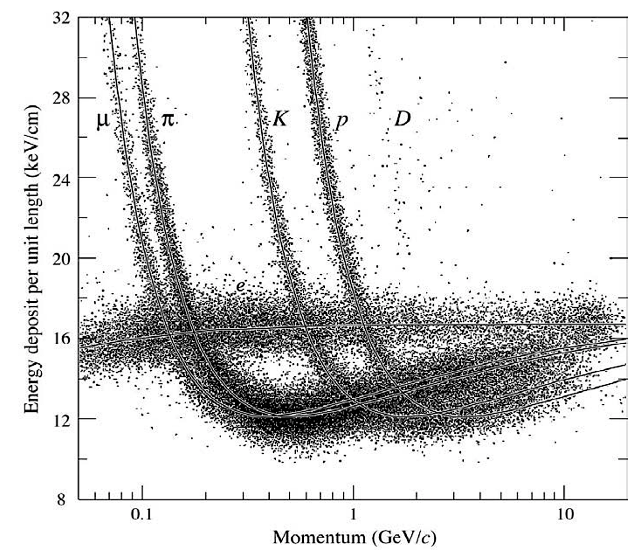


How Time Projection Chambers Started

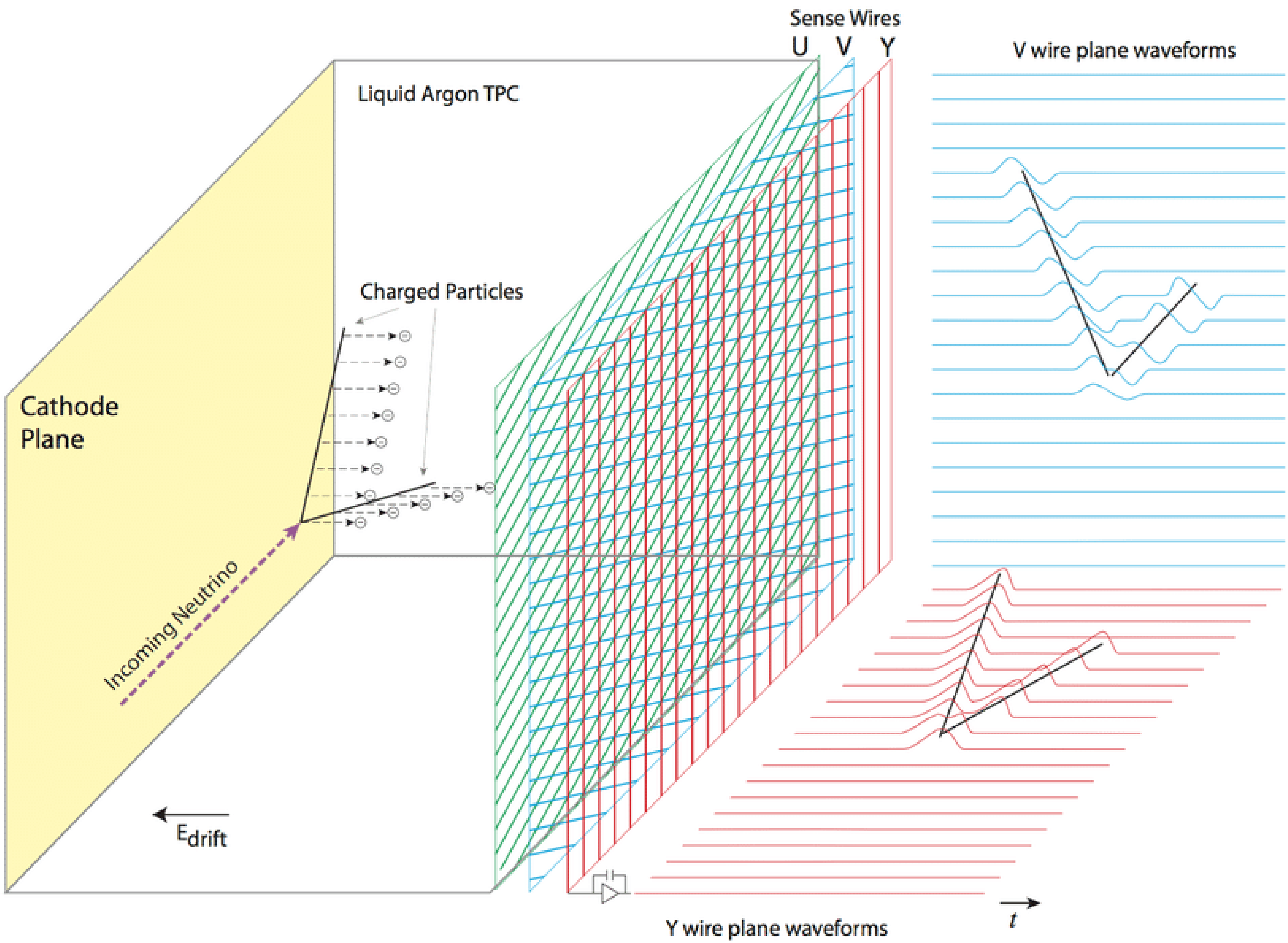
- Invention of Time Projection Chamber, TPC by David Nygren:
  - B-field oriented ll to E-field, readout chambers placed at the ends
  - Reduced diffusion & simultaneous (multiplicity) reco of particle type, momentum & position in full 3D space
  - First large-scale realization in Positron Electron Project, PEP-4 TPC at SLAC:
    - Pressurized gas medium @ 8.5 bar, excellent PID



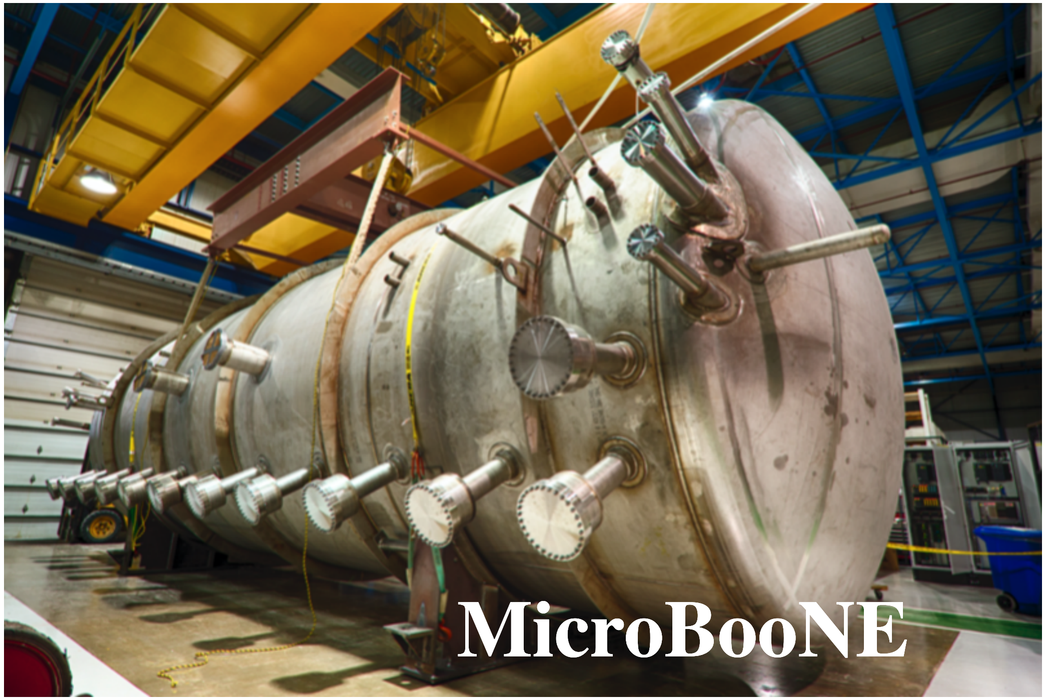




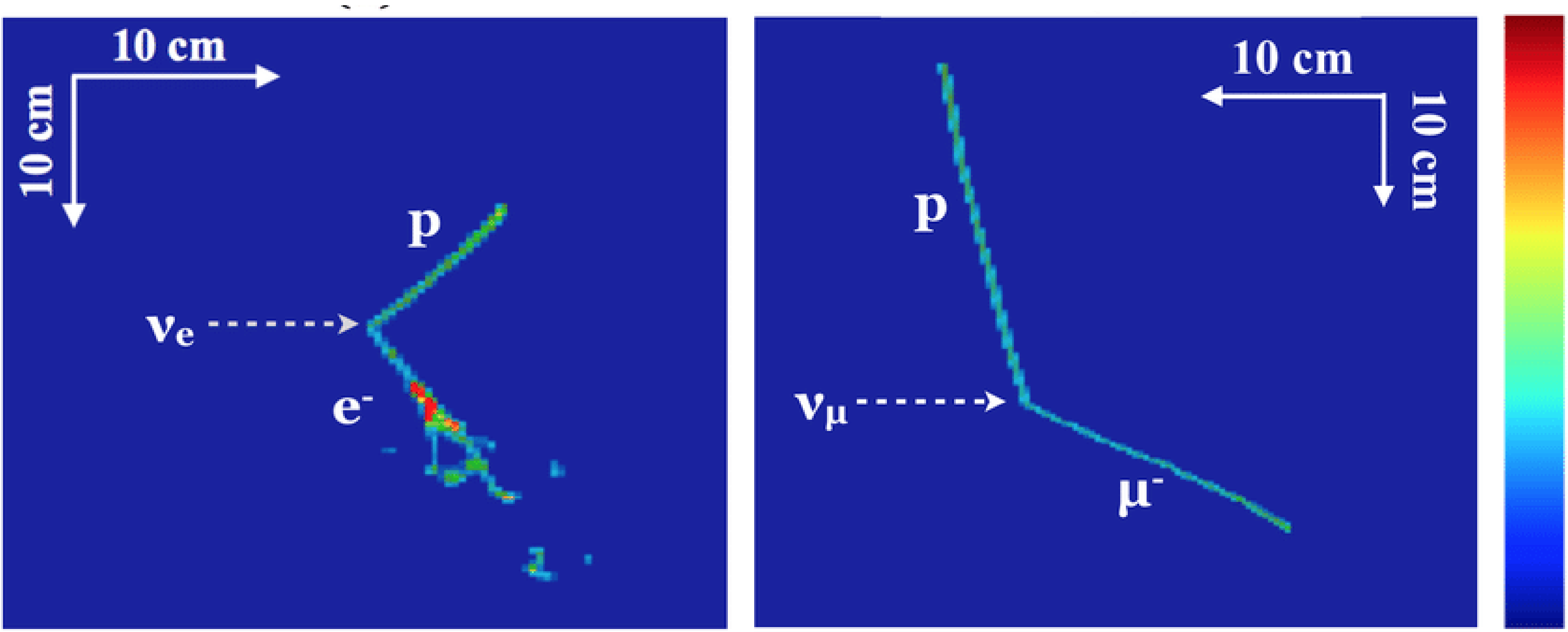
Liquid Argon Time Projection Chambers



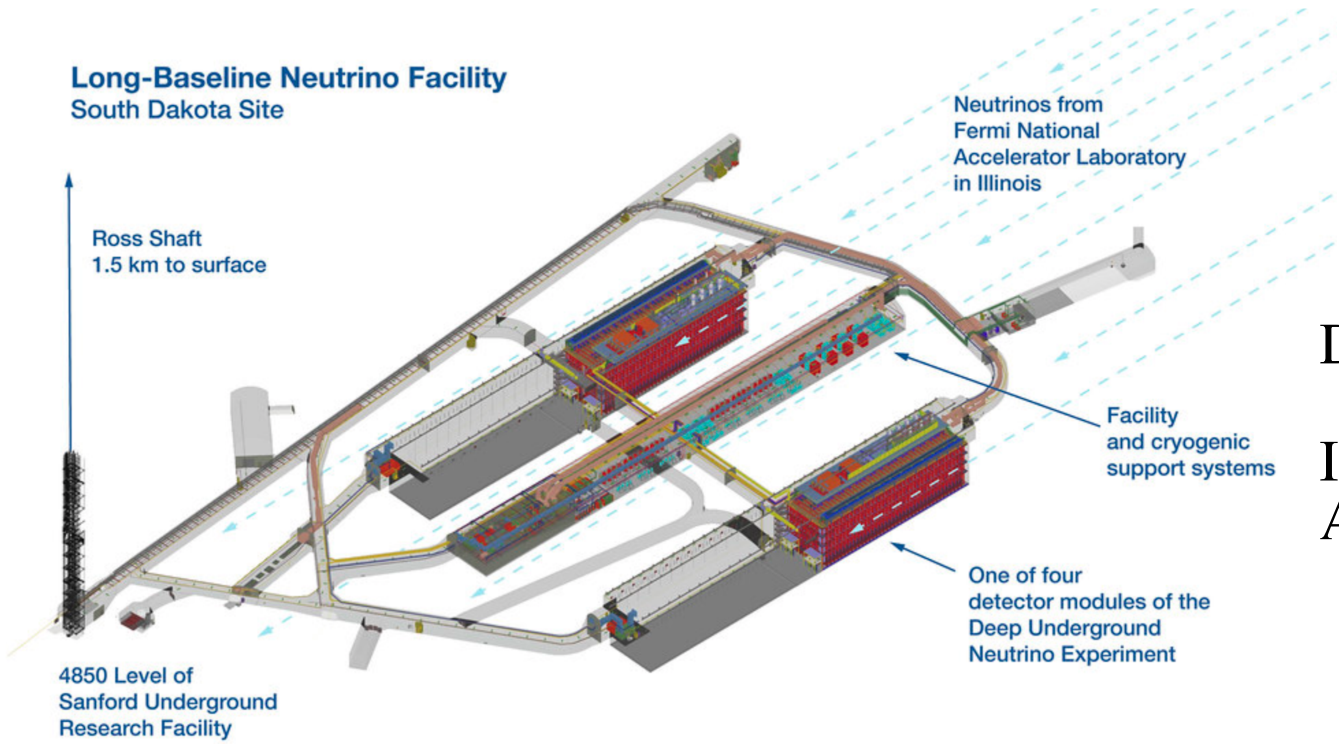
Liquid Argon Time Projection Chambers



Liquid Argon Time Projection Chambers

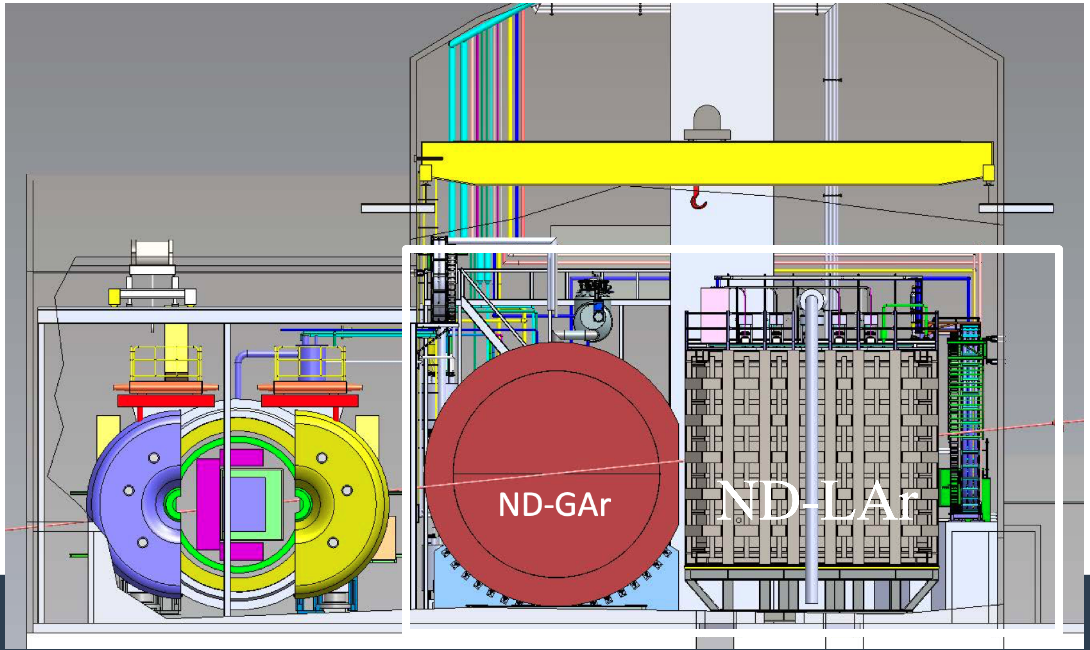


Liquid Argon Time Projection Chambers



DUNE Far Detector

Includes Liquid Argon TPC Modules

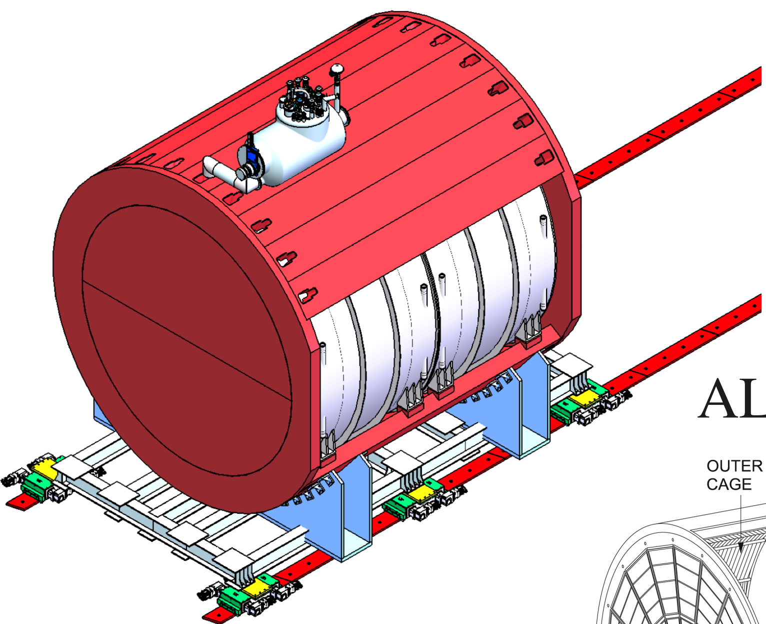


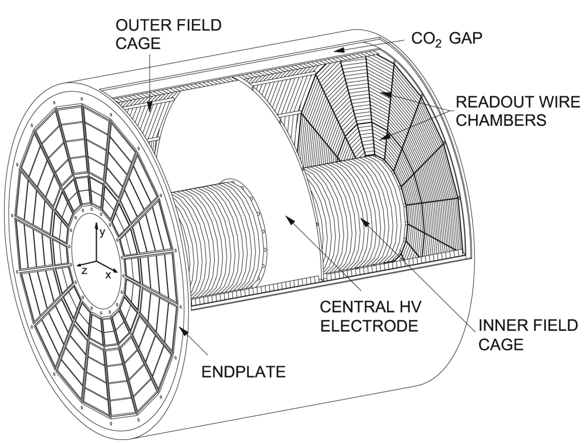
DUNE Near Detector

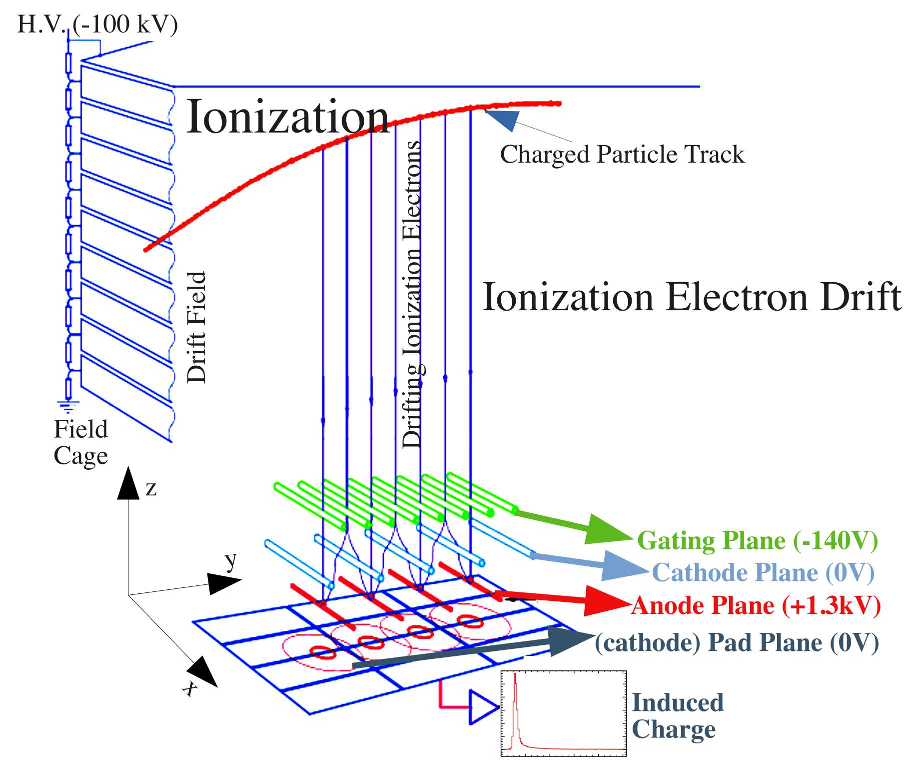
Includes 2 TPCs both with Ar as their target

Gaseous Argon Time Projection Chamber

- DUNE ND-GAr Key design features:
  - Has a High Pressure Gas Argon TPC (HPgTPC) at its core; will be a copy of ALICE TPC
  - Actually uses Ar-CH_4 90-10 gas mixture instead of pure Ar (97% Ar interactions) at 10 atm & is surrounded by calorimeter and magnet

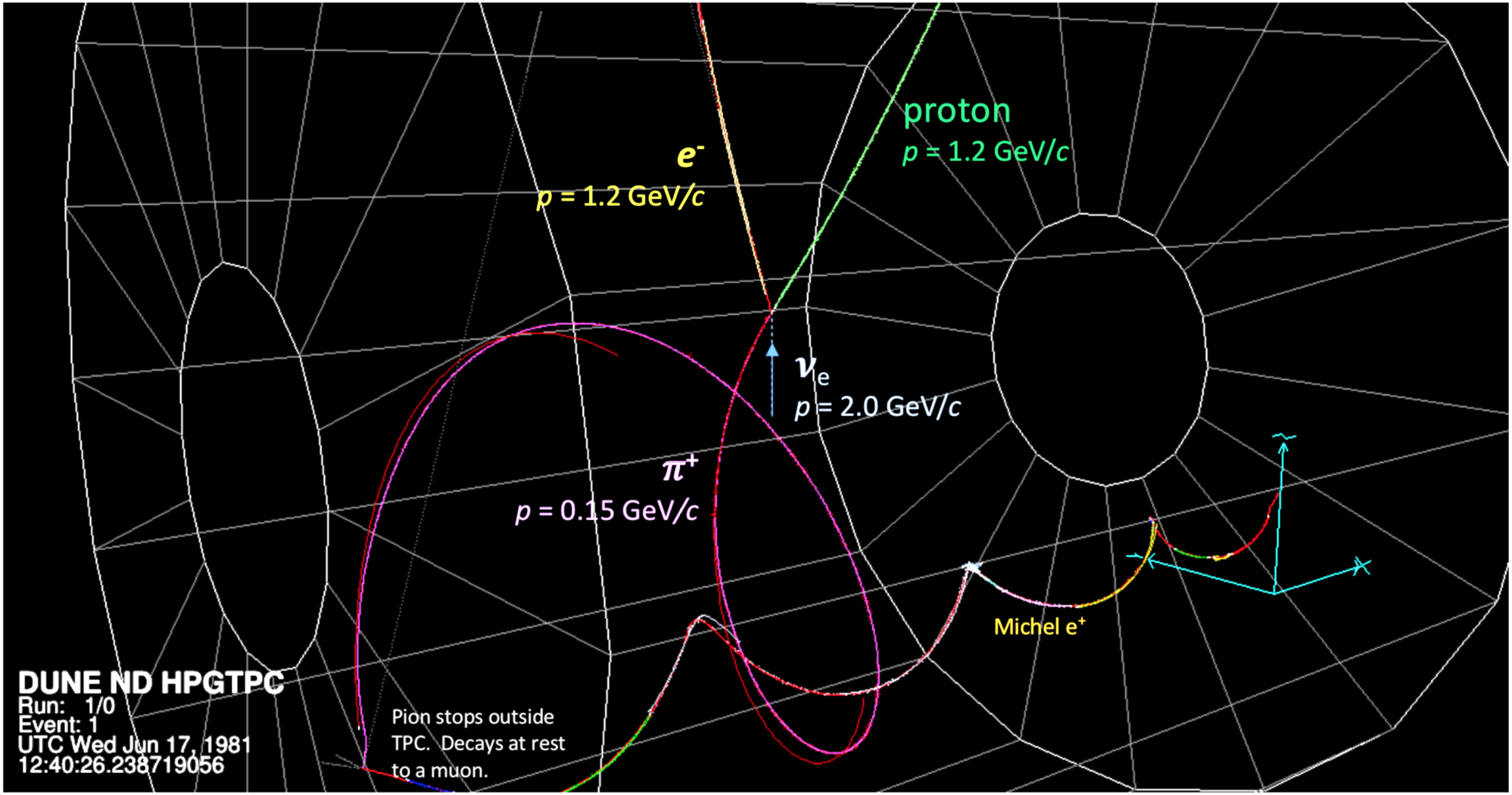






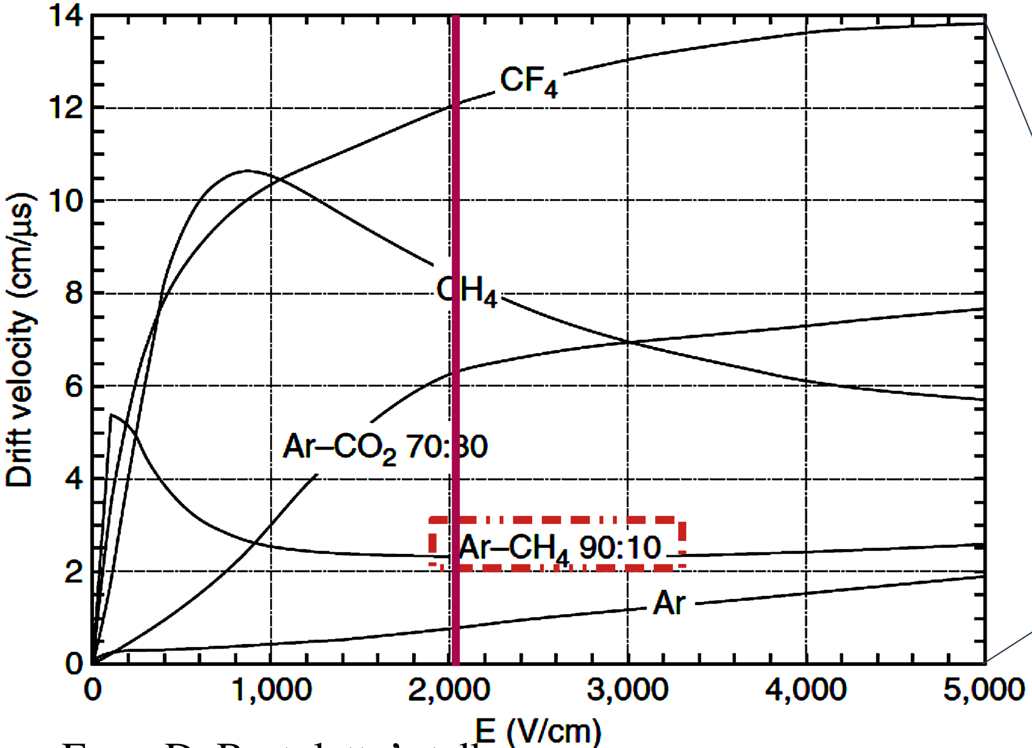
Gaseous Argon Time Projection Chamber

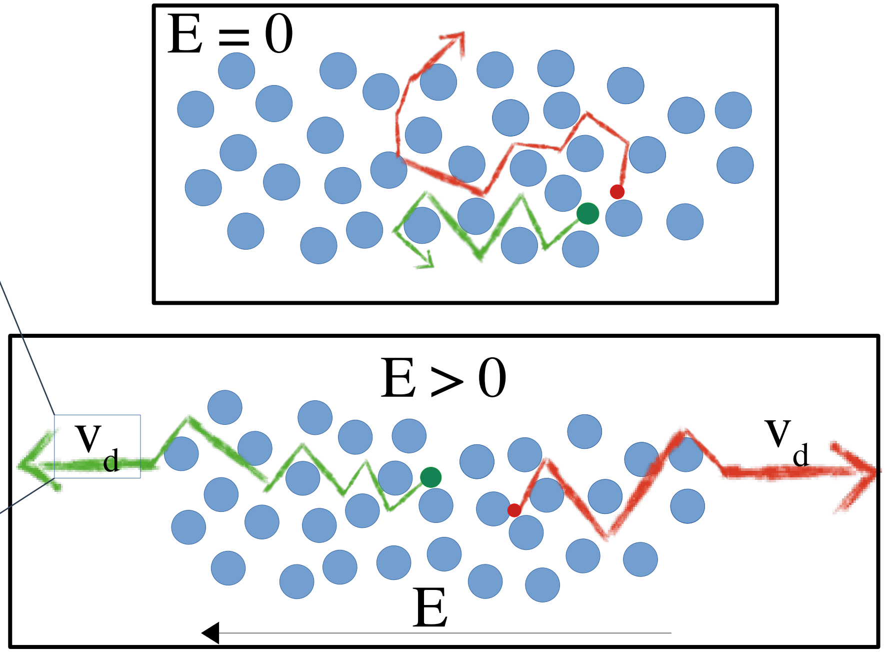
- ND-GAr simulated event display of a ν_e CC interaction using an end-to-end simulation and reconstruction software, GArSoft



Example of Detector R&D

- Mainly in the context of ND-GAr
- Optimize the mobility/drift velocity of the ionization electrons:
  - Need for highest possible drift velocity to prevent pile up
  - Slowest drift velocity in pure Ar, add admixtures (e.g. CH_4 or CO_2) to Ar to increase the drift velocity

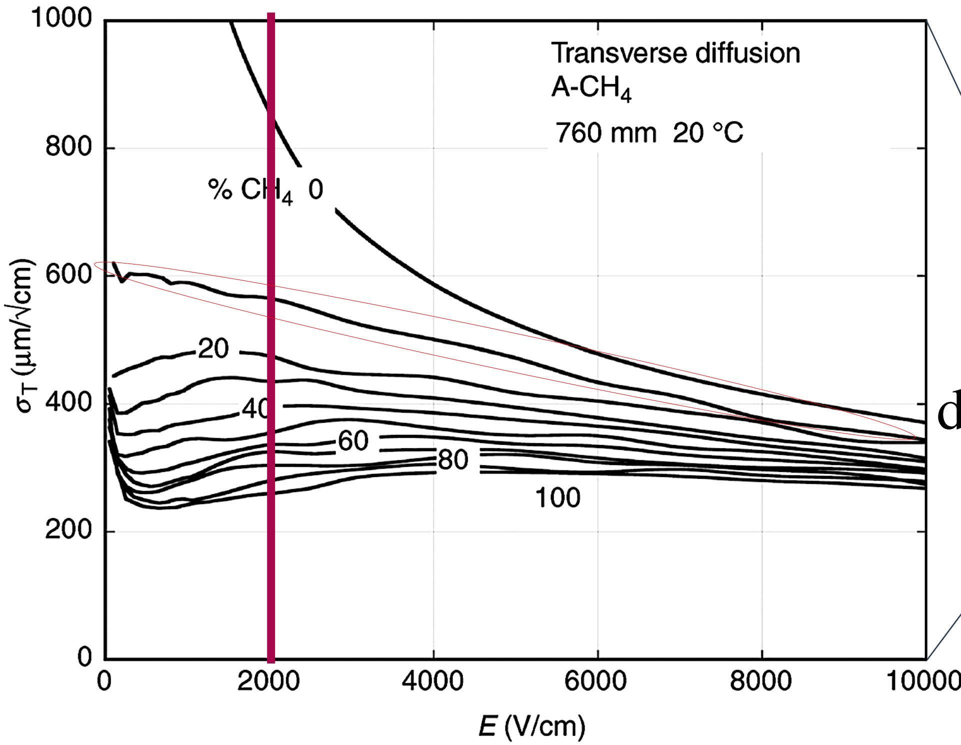


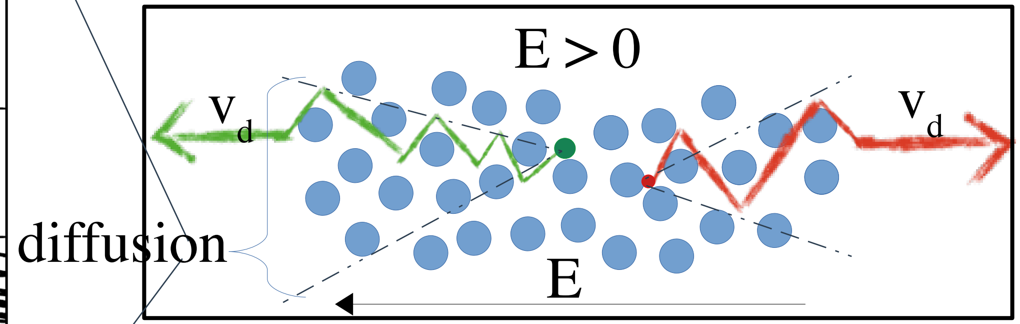


From D. Bortoletto's talk:
https://indico.cern.ch/event/318529/attachments/612837/843122/daniela_l3.pdf

Example of Detector R&D

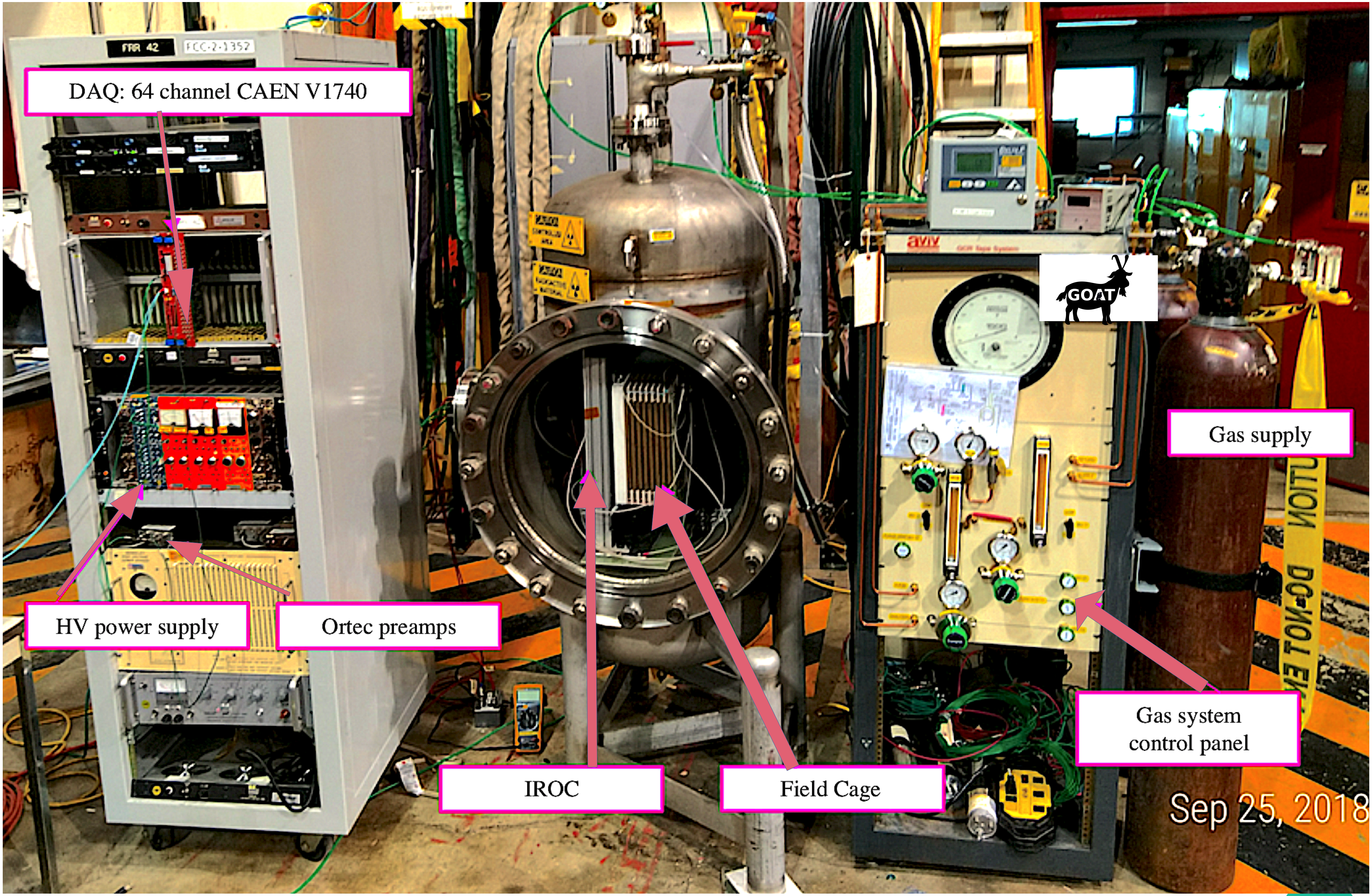
- Minimize diffusion:
  - High diffusion degrades spatial resolution – similar to drift velocity, soln is to add admixtures/quenching gases
  - Pure Ar has highest diffusion





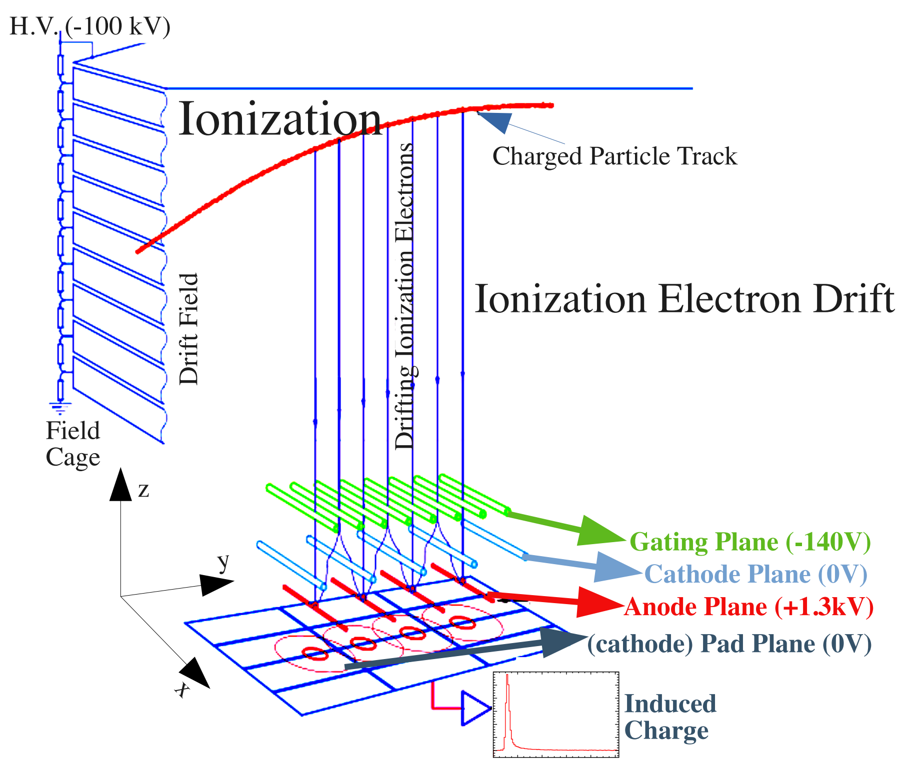
Sauli, F. "Gaseous Radiation Detectors: Fundamentals and Applications," Cambridge: Cambridge University Press. doi:10.1017/CBO9781107337701.006

We Build Test Stands and Prototypes

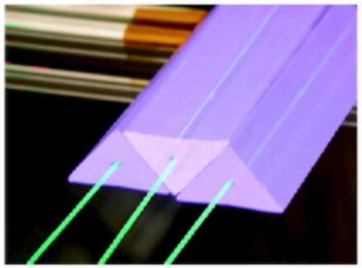


Aim of the Test Stand

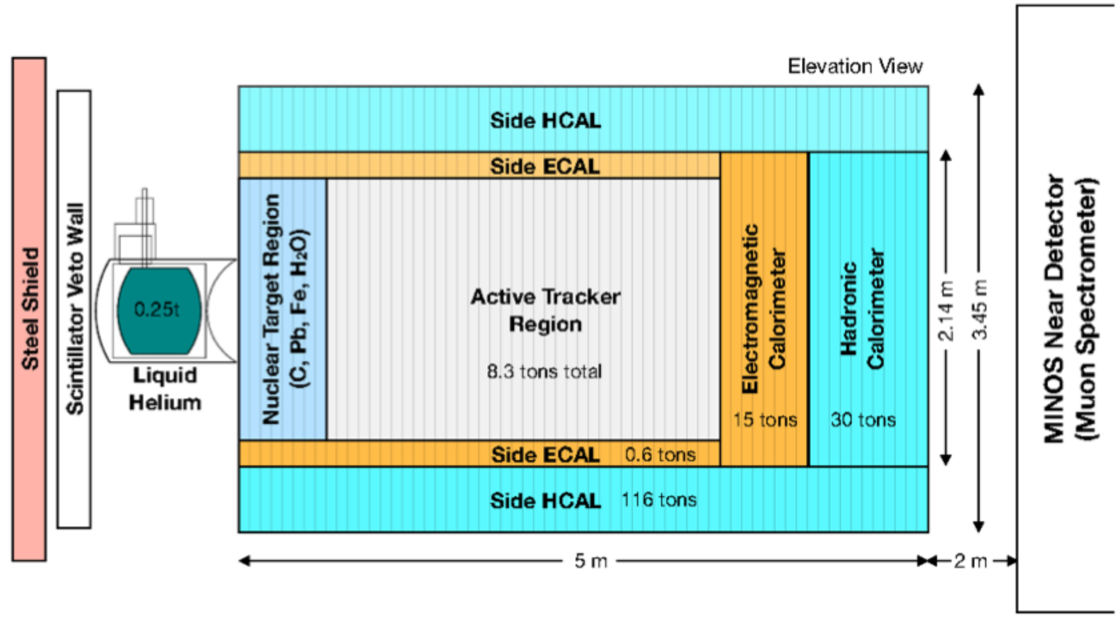
- Maximize amplification gain and the output signal (gain as the figure of merit for testing the operation of the chambers before their use in ND-GAr):
  - Pressure affects the gain – gain goes down as pressure goes up
  - Since amplification gain scales linearly with anode voltage scales, need higher anode voltage to compensate for lower gain at higher pressure

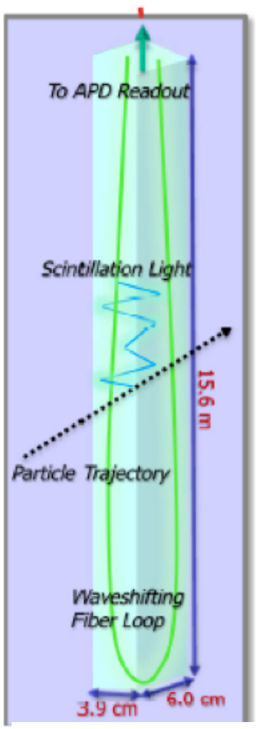


Segmented Scintillation Detectors

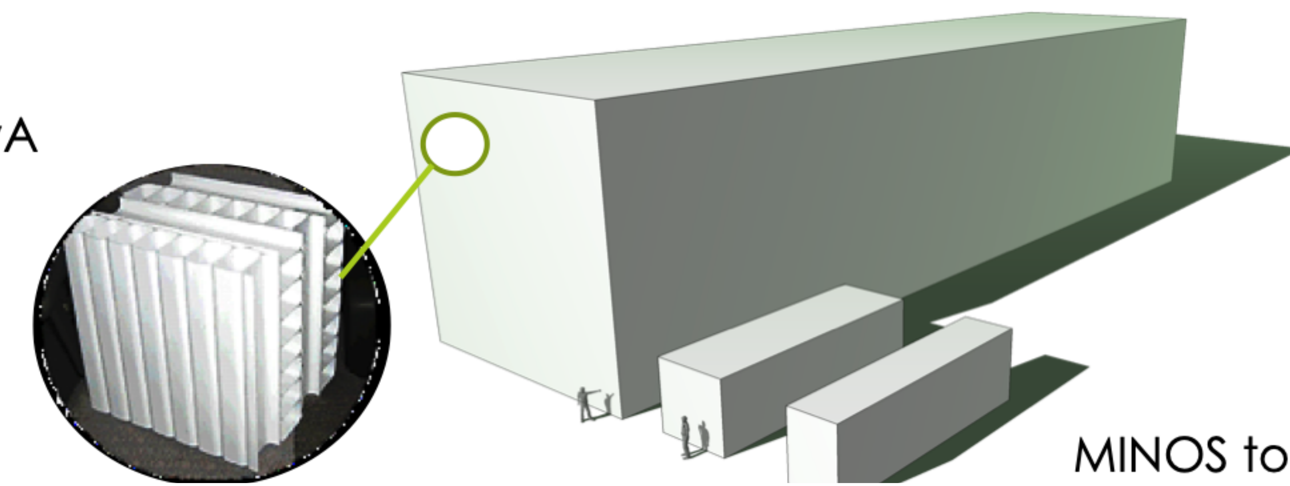


MINERvA





NOvA

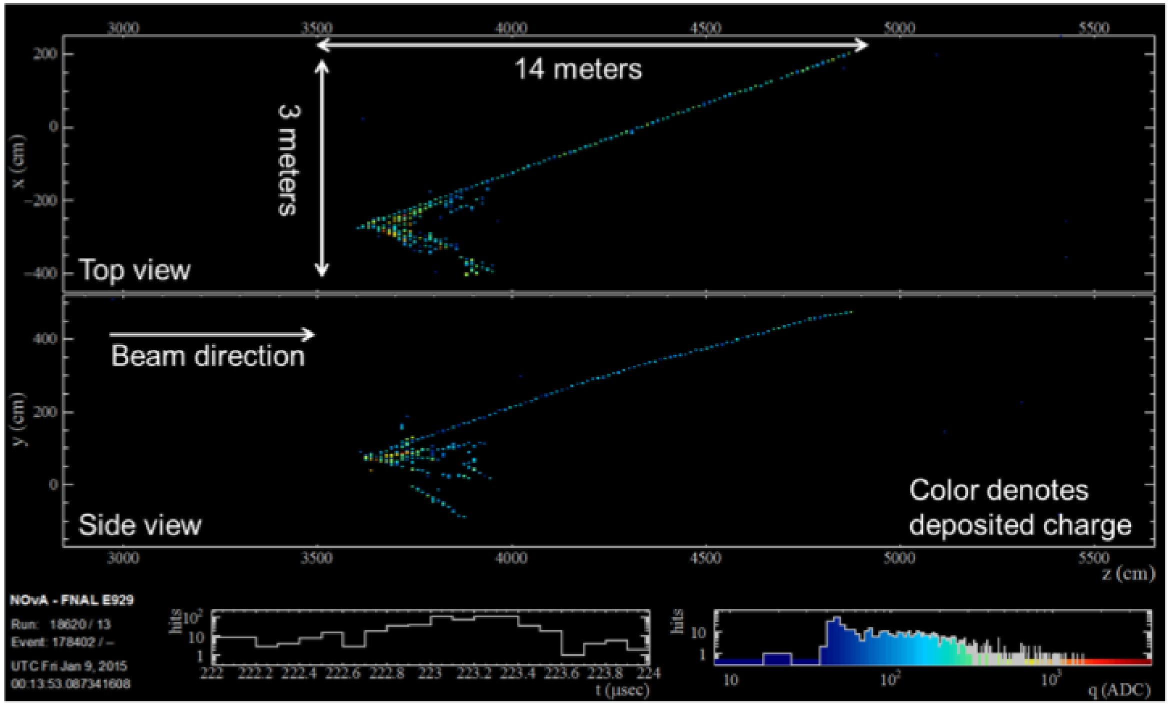


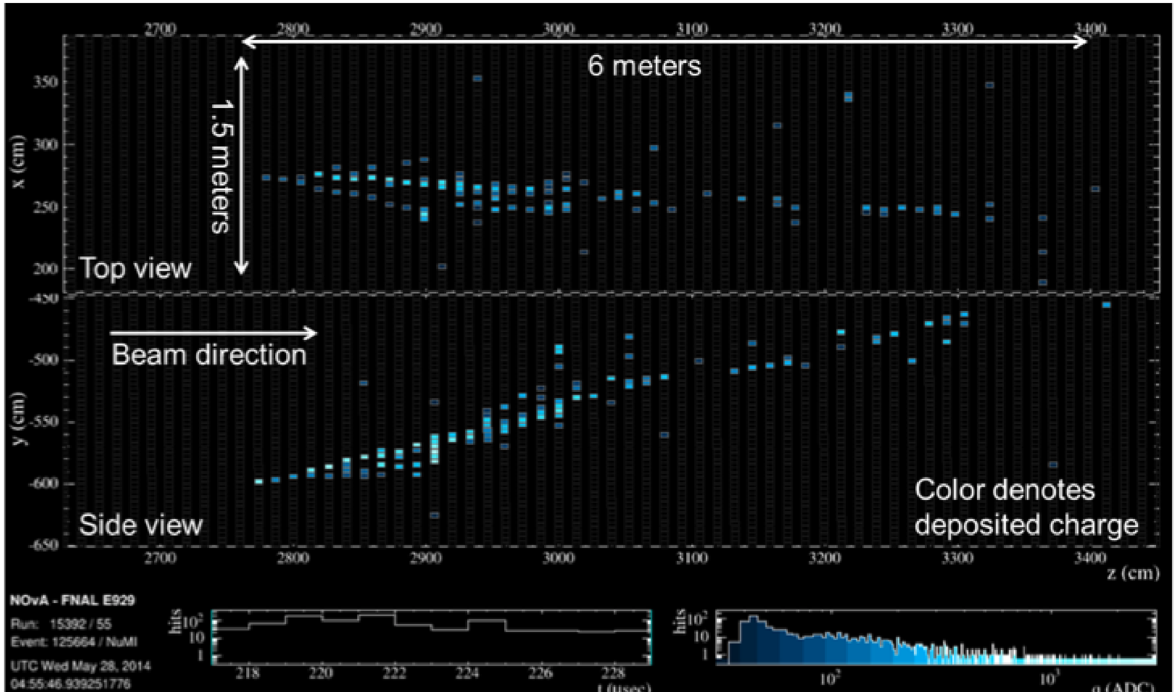
MINOS too!

J. Raaf

Segmented Scintillation Detectors

From http://novaexperiment.fnal.gov





Summary and Conclusion

- We cannot observe neutrinos directly in our detectors
  - We have to rely on outgoing charged particles
  - Even the charged particles have to undergo extra processes for our detectors to detect them
  - These processes mainly include ionization energy loss, scintillation, and bremsstrahlung
  - Our detectors make use of these processes to detect neutrinos
  - Various detector technologies are used to be able to detect neutrinos; I have covered a subset of them

Thank You!
Questions are welcome!

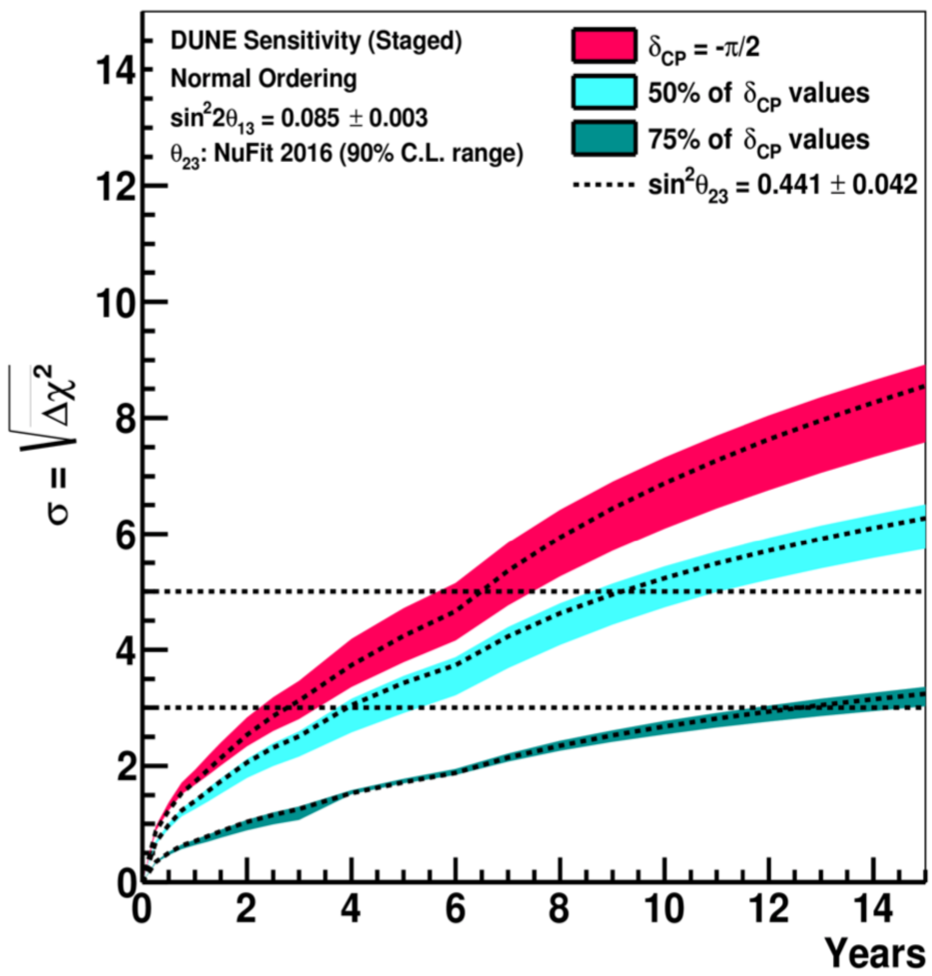
contant: mtanaz@fnal.gov

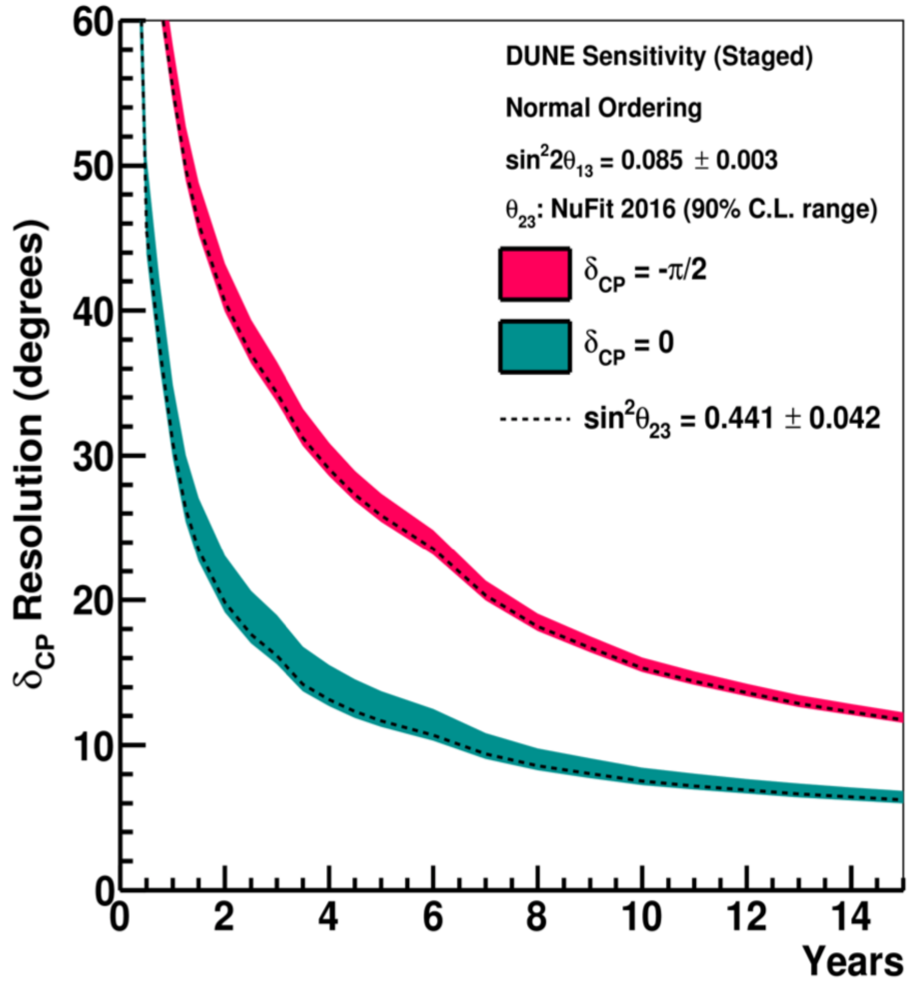
Additional Slides

A subset of currently-running or previously operation Gas TPCs

over the years, various gas mixtures and pressures were used

Parameter/Experiment	PEP4	TRIUMF	TOPAZ	AlEPH	DELPHI	STAR	ALICE[a]
Operation	1982/1984	1982/1983	1987	1989	1989	2000	2009
Inner/Outer radius (m)	0.2/1.0	$\sim$ 0.15/0.50	0.38/1.1	0.35/1.8	0.35/1.4	0.5/2.0	0.85/2.5
Max. driftlength ($L/2$) (m)	1	0.34	1.1	2.2	1.34	2.1	2.5
Magnetic field (T)	0.4/1.325	0.9	1	1.5	1.23	0.25/0.5	0.5
Gas :	Ar/CH_4	Ar/CH_4	Ar/CH_4	Ar/CH_4	Ar/CH_4	Ar/CH_4	$Ne/CO_2/N_2$
Mixture	80/20	80/20	90/10	91/9	80/20	90/10	90/ 10/ 5
Pressure (atm)	8.5	1	3.5	1	1	1	1
Drift field (kV cm^{-1} atm^{-1})	0.088	0.25	0.1	0.11	0.15	0.14	0.4
Electron drift velocity (cm μs^{-1})	5	7	5.3	5	6.69	5.45	2.7
$\omega\tau$ (see section 2.2.1.3)	0.2/0.7	2	1.5	7	5	1.15/2.3	<1
Pads: Size $w \times L$ (mm × mm)	7.5 × 7.5	(5.3–6.4) × 19	(9–11) × 12	6.2 × 30	~7 × 7	2.85 × 11.5 6.2 × 19.5	4 × 7.5 6 × 10/15
Max. no. 3D points	15—straight	12	10—linear	9 + 12—circular	16—circular	13 + 32—straight	63 + 64 + 32
dE/dx: Max. no. samples/track	183	12	175	148 + 196	192	13 + 32	63 + 64 + 32
Sample size (mm atm); w or p	4 × 8.5; wires	6.35; wires	4 × 3.5; wires	4; wires	4; wires	11.5 + 19.5; pads	7.5 + 10 + 15; pads
Gas amplification	1000	50 000		3000–5000	5000	3000/1100	20 000
Gap a–p; a–c; c–gate[b]	4; 4; 8	6	4; 4; 8	4; 4; 6	4; 4; 6	2; 2; 6/4; 4 ; 6	2; 2; 3/3; 3; 3
Pitch a–a; cathode; gate	4; 1; 1		4; 1; 1	4; 1; 2	4; 1; 1	4; 1; 1/ 4; 1; 1	2.5; 2.5; 1.5
Pulse sampling (MHz/no. samples)	10/455, CCD	only 1 digitiz., ADC	10/ 455, CCD	11/ 512, FADC	14/300, FADC	9.6/400	5–10/500–1000, ADC
Gating[c]	⩾1984 o.on tr.	⩾1983 o.on tr.	o. on tr.	synchr. cl.wo.tr	static	o.on tr.	o.on tr.
Pads, total number	15 000	7800	8200	41 000	20 000	137 000	560 000
Performance							
Δx_T (μm)-best/typ.	130–200	200/	185/230	170/200–450	180/190–280	300–600	spec:800–1100
Δx_L (μm)-best/typ.	160–260	3000	335/900	500–1700	900	500–1200	spec:1100–1250
Two-track separation (mm), T/L	20		25	15	15	8 - 13/30	
$\partial p/p^2$ (GeV/c)$^{-1}$: TPC alone; high p	0.0065		0.015	0.0012	0.005	0.006	spec:0.005
dE/dx (%) Single tracks/ in jets	2.7/4.0		4.4 /	4.4 /	5.7/7.4	7.4/7.6	spec:4.9/6.8
Comments		a in single PCs strong $E \times B$ effect	chevron pads	circular pad rows	circular pad rows	No field wires >3000 tracks	No field wires ⩽20 000 tracks


DUNE Sensitivity (Staged)
Normal Ordering
$\sin^2 2\theta_{13} = 0.085 \pm 0.003$
θ_{23}: NuFit 2016 (90% C.L. range)
$\delta_{CP} = -\pi/2$
50% of δ_{CP} values
75% of δ_{CP} values
$\sin^2\theta_{23} = 0.441 \pm 0.042$
$\sigma = \sqrt{\Delta\chi^2}$
Years


DUNE Sensitivity (Staged)
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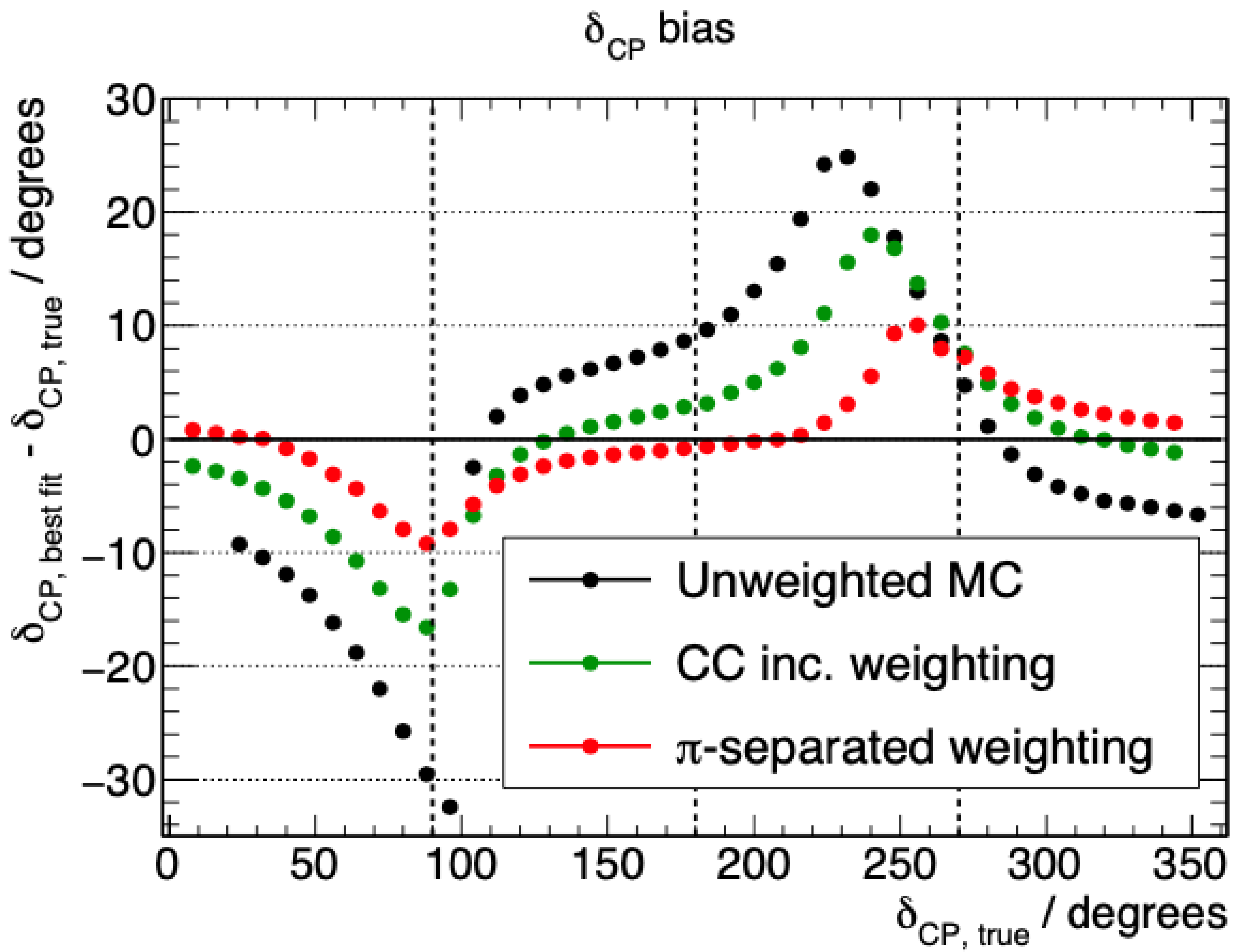
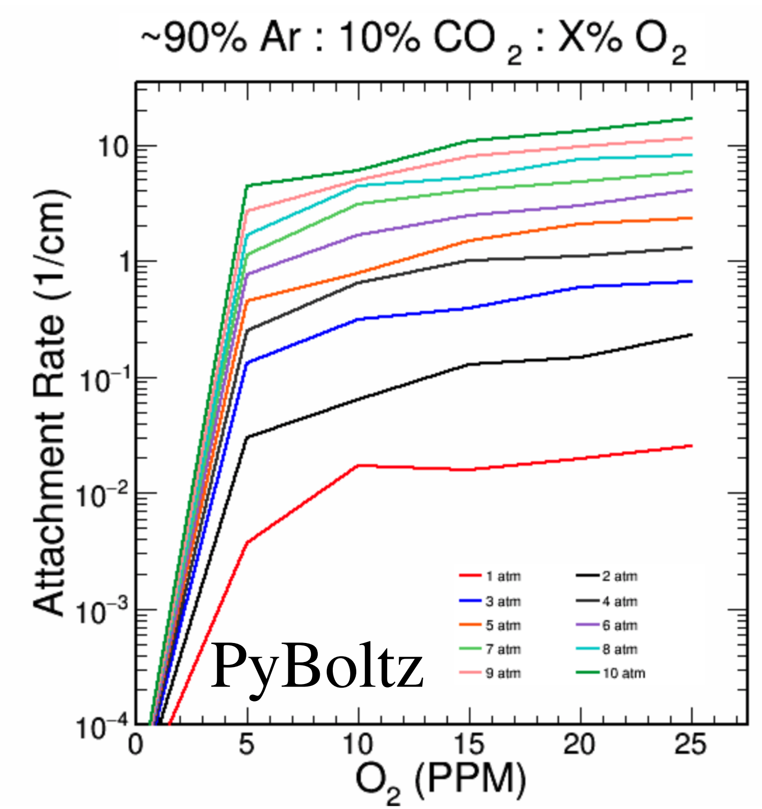
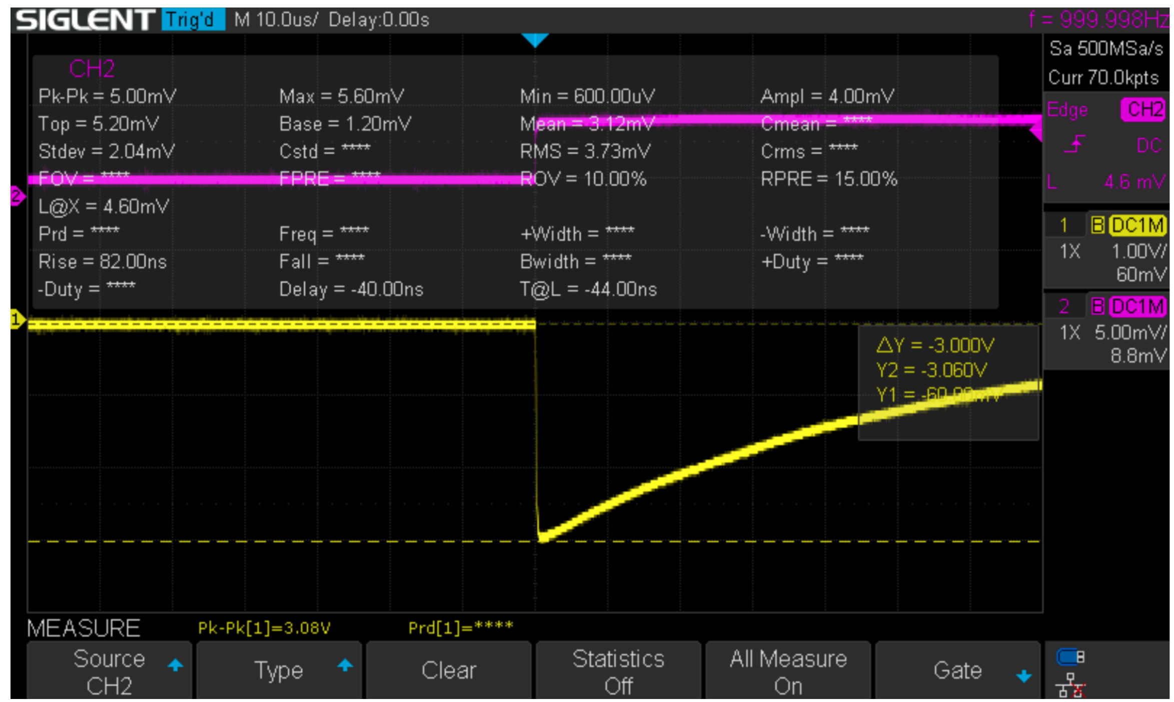
θ_{23}: NuFit 2016 (90% C.L. range)
$\delta_{CP} = -\pi/2$
$\delta_{CP} = 0$
$\sin^2\theta_{23} = 0.441 \pm 0.042$
δ_{CP} Resolution (degrees)
Years


δ_{CP} bias
$\delta_{CP,\ best\ fit} - \delta_{CP,\ true}$ / degrees
30
20
10
0
−10
−20
−30
0
50
100
150
200
250
300
350
$\delta_{CP,\ true}$ / degrees
Unweighted MC
CC inc. weighting
π-separated weighting

Gain at 1 atm





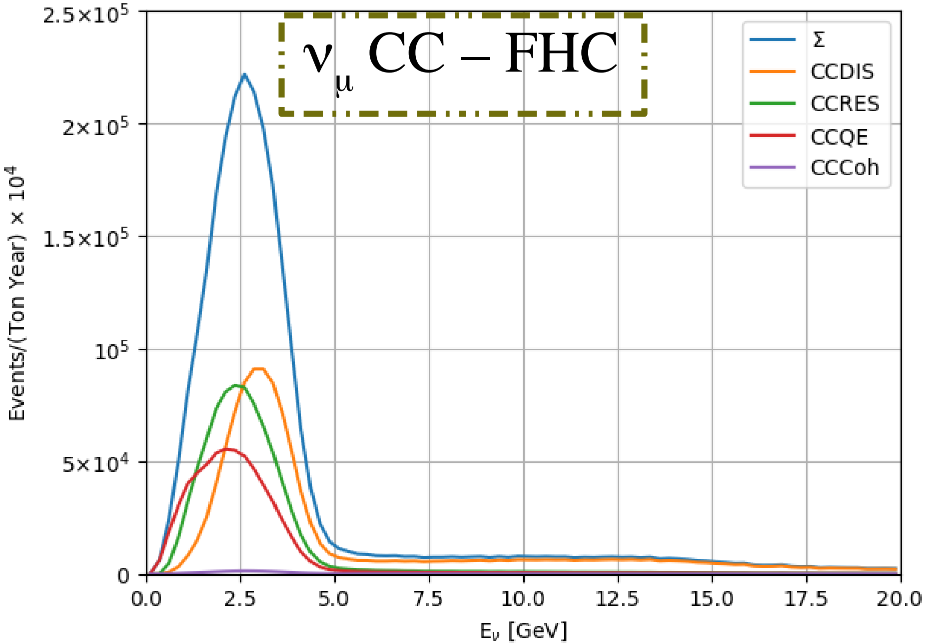
- Also corrected for preamp gain and electron attachment in gain = N/N_0 so N = actually number of **measured** electron-ion pairs after corrections = $N_{raw}/(G_c\, e^{-\alpha d})$, α = attachment rate & Ortec preamp gain (G_c)

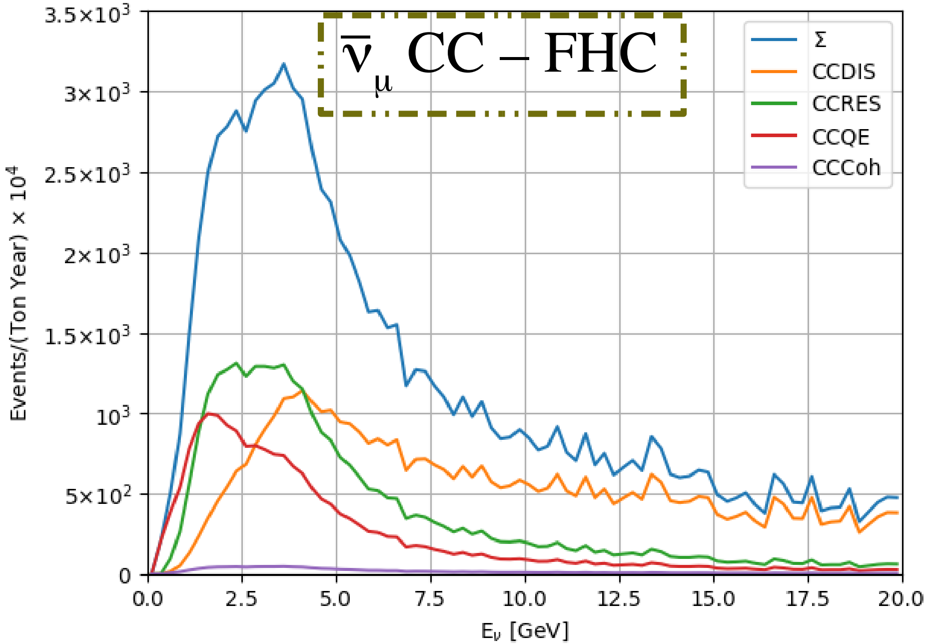
Test Stand at Fermilab

- Recent set up with pressure-rated components
- Purge lines help rapidly remove impurities
- Monitoring H_2O in addition to O_2 impurities to account for e-attachment

FHC Mode, Optimized DUNE flux (Oct 2017), GENIE v2.12.10

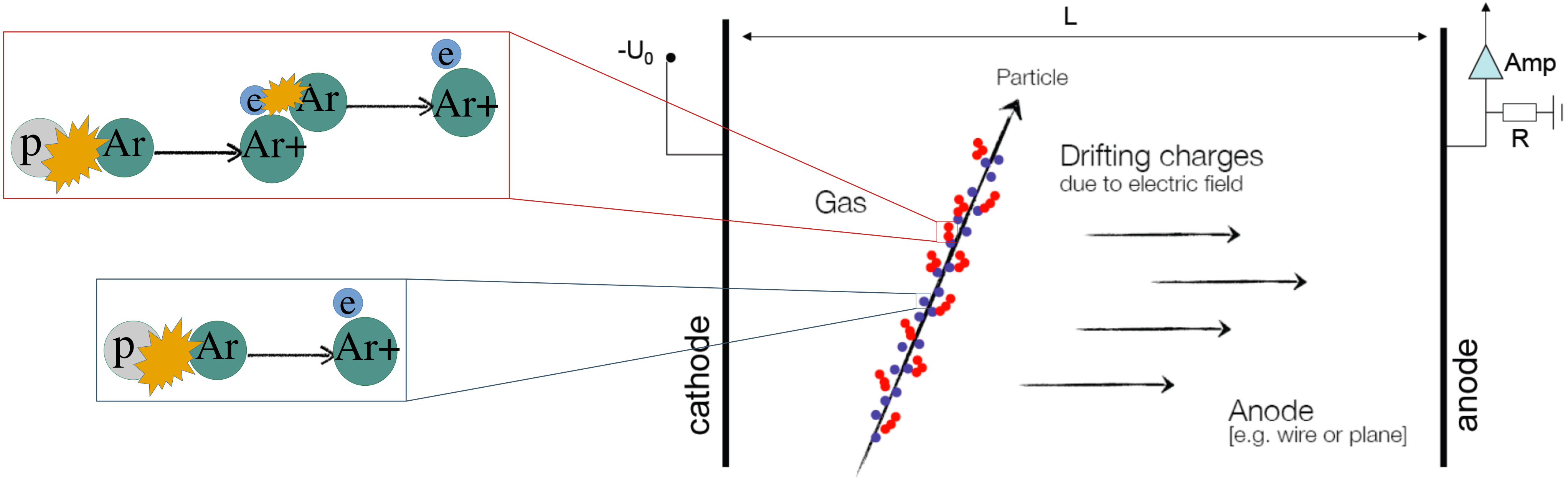
Event Category	Events/Ton-year	Event Category	Events/Ton-year
ν_μ CC total	2.54E+06	$\bar{\nu}_\mu$ CC total	2.43E+02
ν_μ NC total	1.69E+02	$\bar{\nu}_\mu$ NC total	9.83E+01



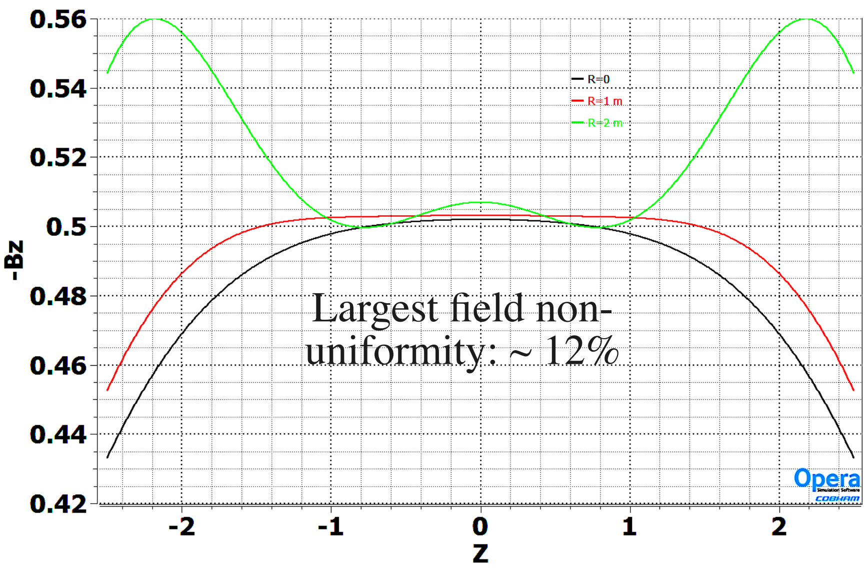


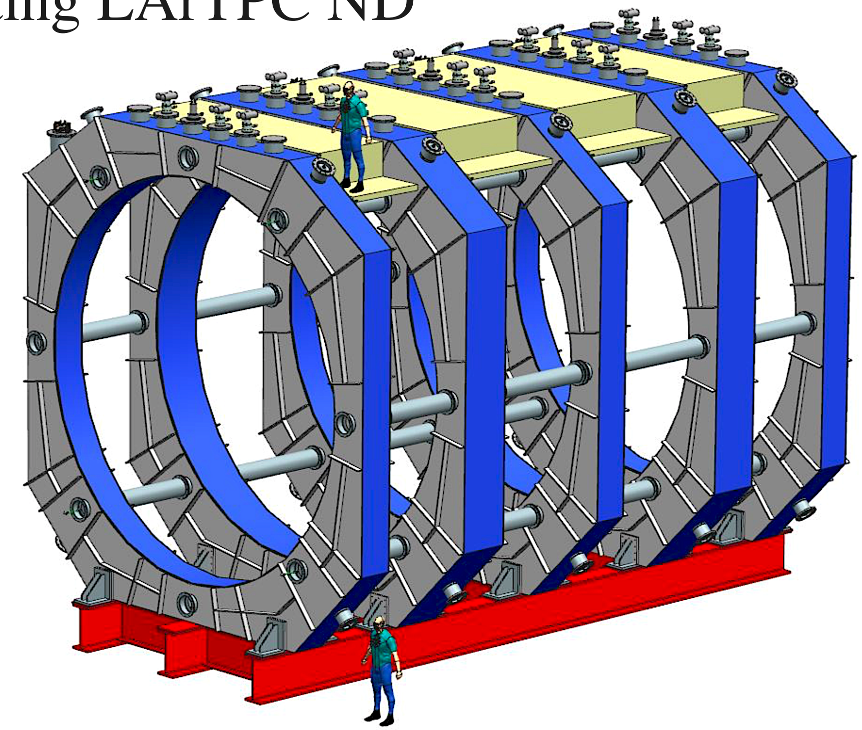
- **As an independent magnetized tracker**:
  - ν-interactions on a gaseous Ar target

- More on step 1 – I am biased to talk about ionization electron-ion pair production:
  - **Primary pair** liberated from the Coulombic interactions between the particle and the molecules of the detecting medium
  - **Secondary pair** liberated if the primary electron (called δ-electron) has enough energy to further liberate more electron-ion pairs



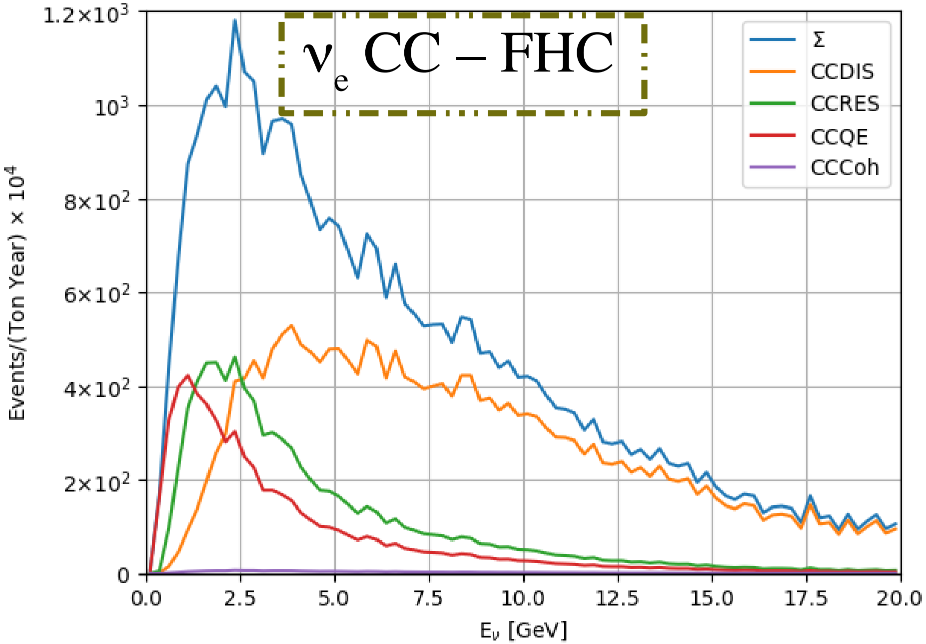
- Reference design:
  - 3 superconducting Helmholtz & a pair of trim/bucking (added for field uniformity) coils
  - Achieves 0.5 T central field
- Meets requirements:
  - Uniformity in central field + minimized fringe field
  - Maximized acceptance for particles exiting LArTPC ND
  - Minimized mass (X_0)

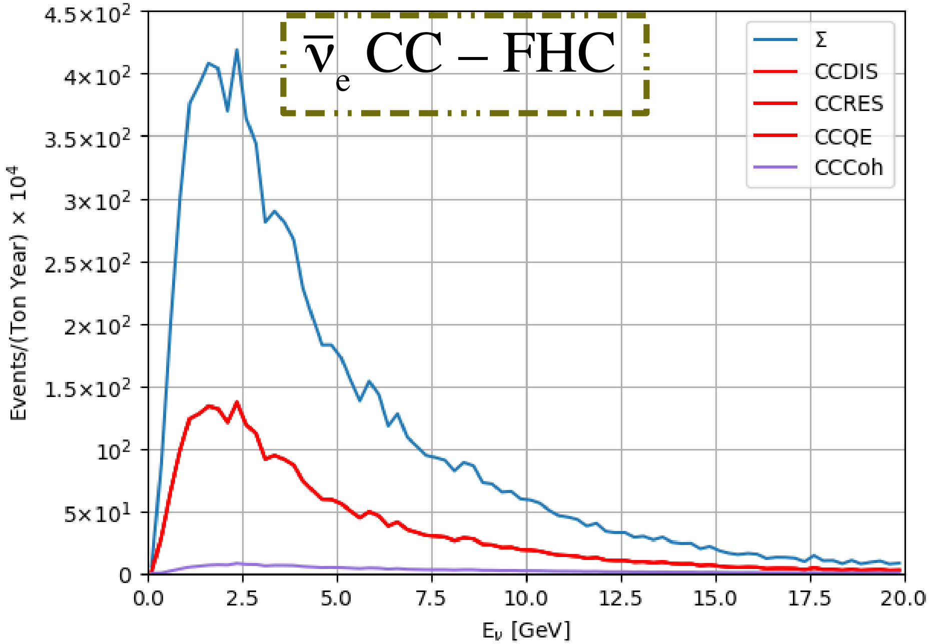




FHC Mode, Optimized DUNE flux (Oct 2017), GENIE v2.12.10

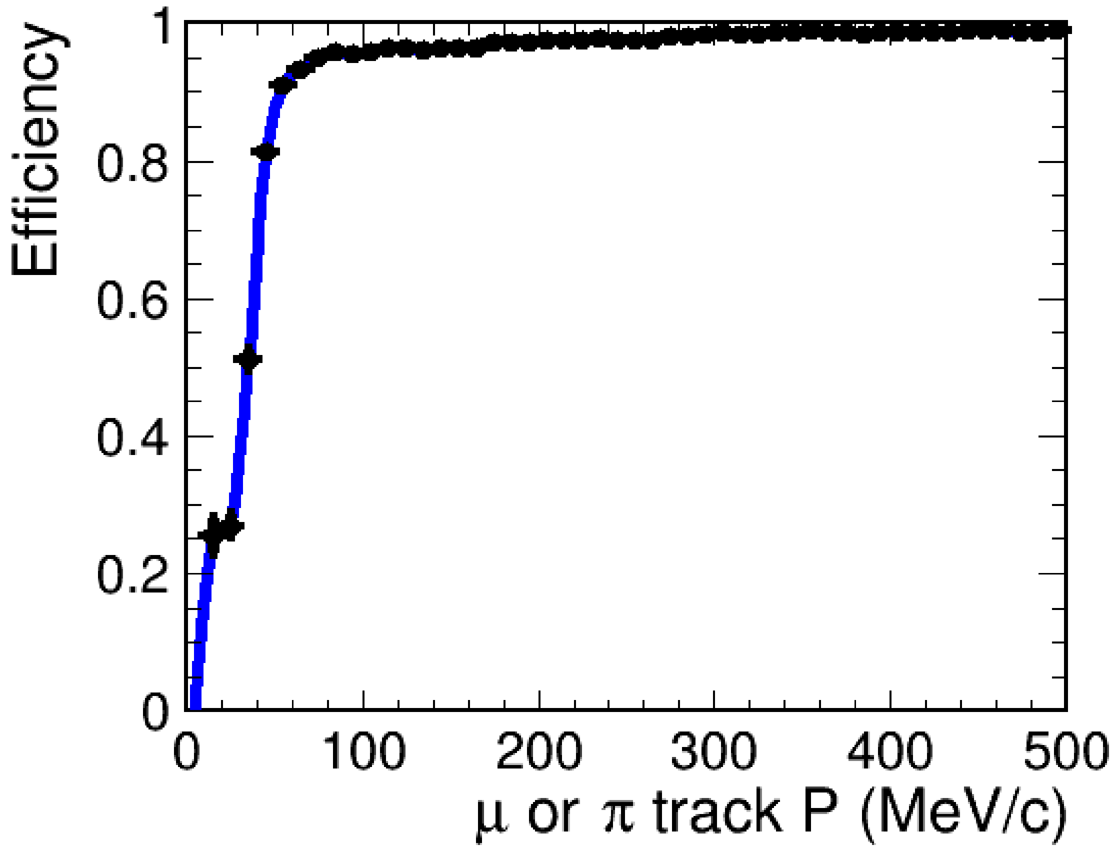
Event Category	Events/Ton-year	Event Category	Events/Ton-year
ν_e CC total	3.62E+04	$\bar{\nu}_e$ CC total	8.62E+03
ν_e NC total	6.05E+01	$\bar{\nu}_e$ NC total	9.83E+01



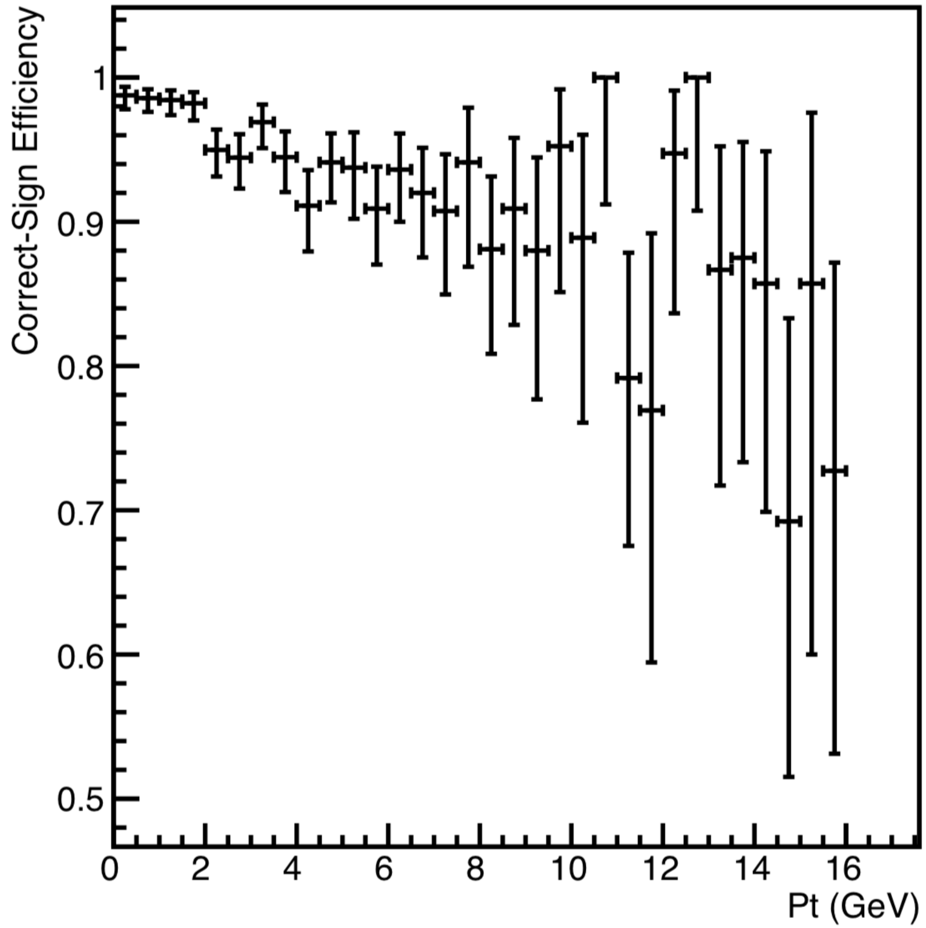


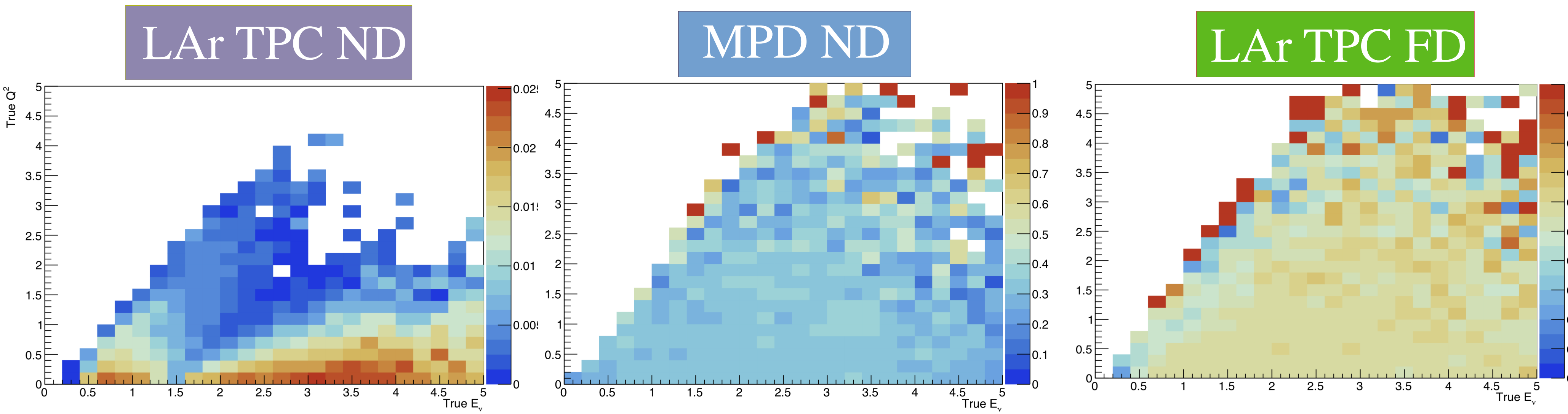
- **As an independent magnetized tracker**:
  - ν-interactions on a gaseous Ar target

- $> 90\%$ efficiency for tracks with p > 40 MeV/c
- As momentum $\uparrow$ so does the efficiency



- Sign-tagging capability illustrated for e- and e+

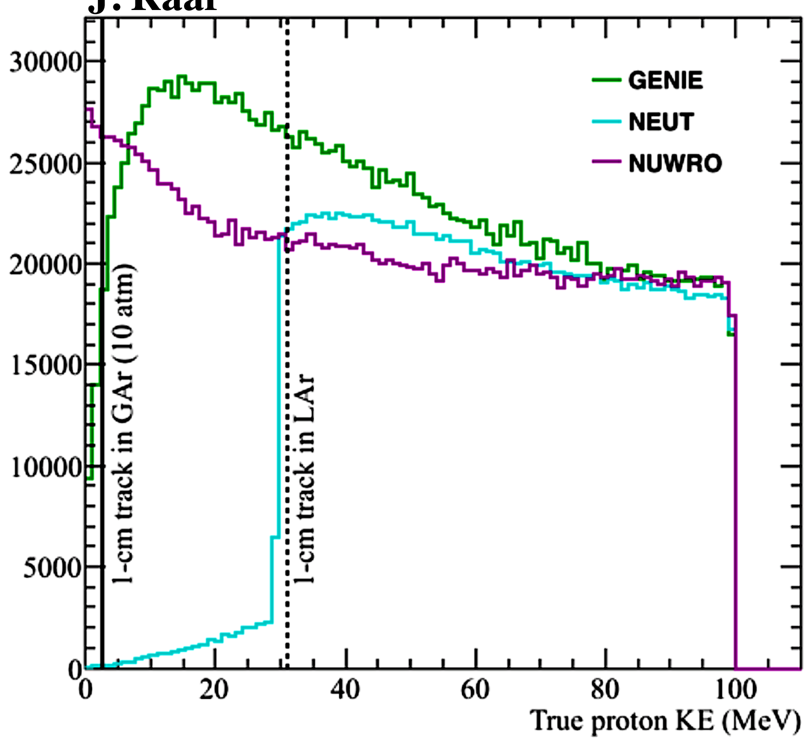




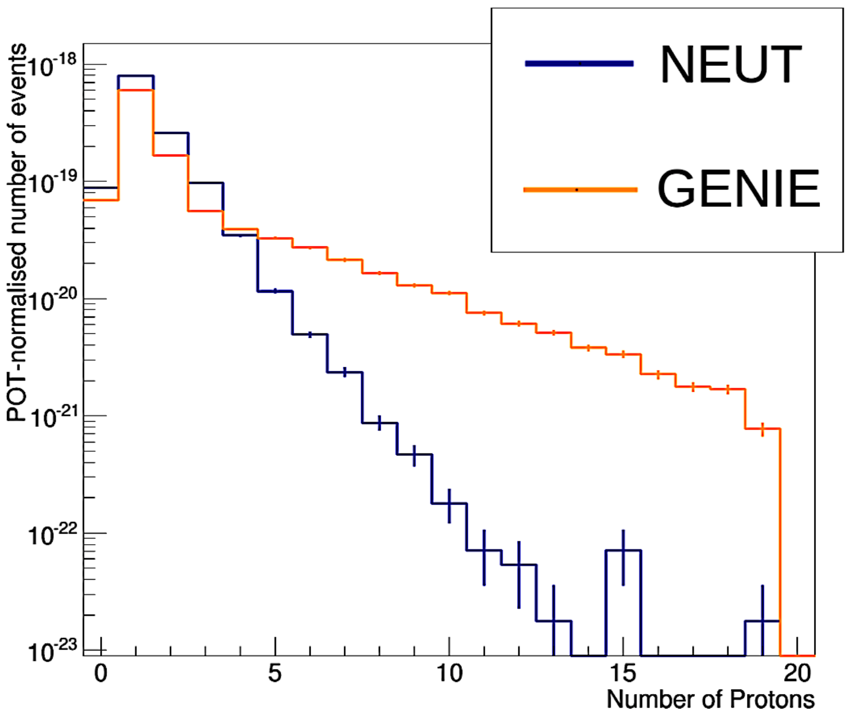
- **As an independent magnetized tracker**:
  - Full 4π coverage
    - Nearly identical acceptance as FD

- Need to understand discrepancies between event generators at lower energies
  - Lower detection threshold (than in LAr) in HPgTPC is critical for this

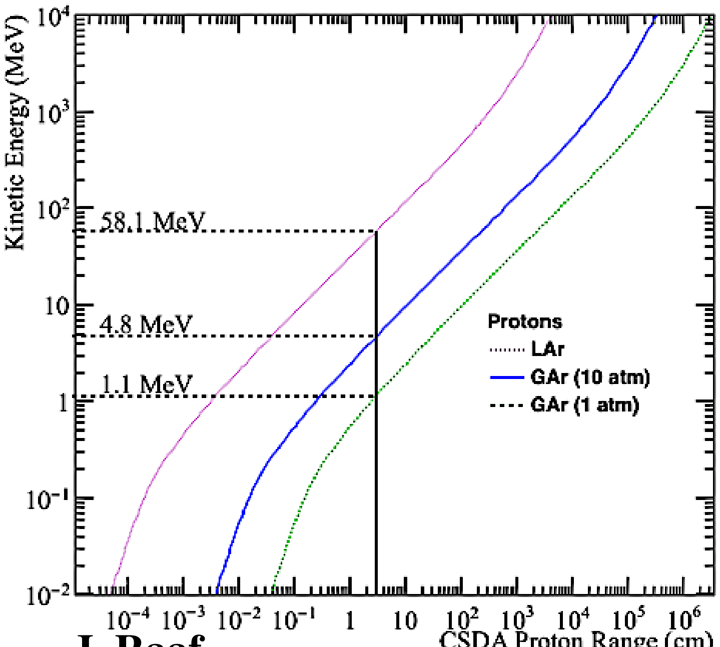
J. Raaf



P. Hamilton T2K-Thesis-062



- So, how low is the threshold for 10 atm GAr?
  - Range of a 5 MeV proton: 3 cm!
  - Ranges of less heavily ionizing particles (π, μ, e) >> proton range
- Assuming a 5 MeV detection threshold is conservative; may be able to go even lower



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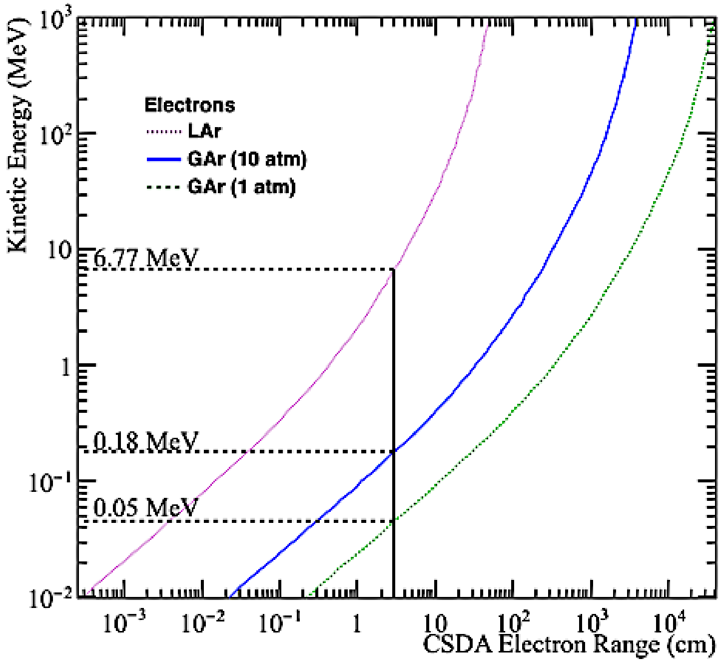

5 MeV K.E. particles

Species	Length (cm)
Protons	3
π^+	10
π^-	10
μ^+	15