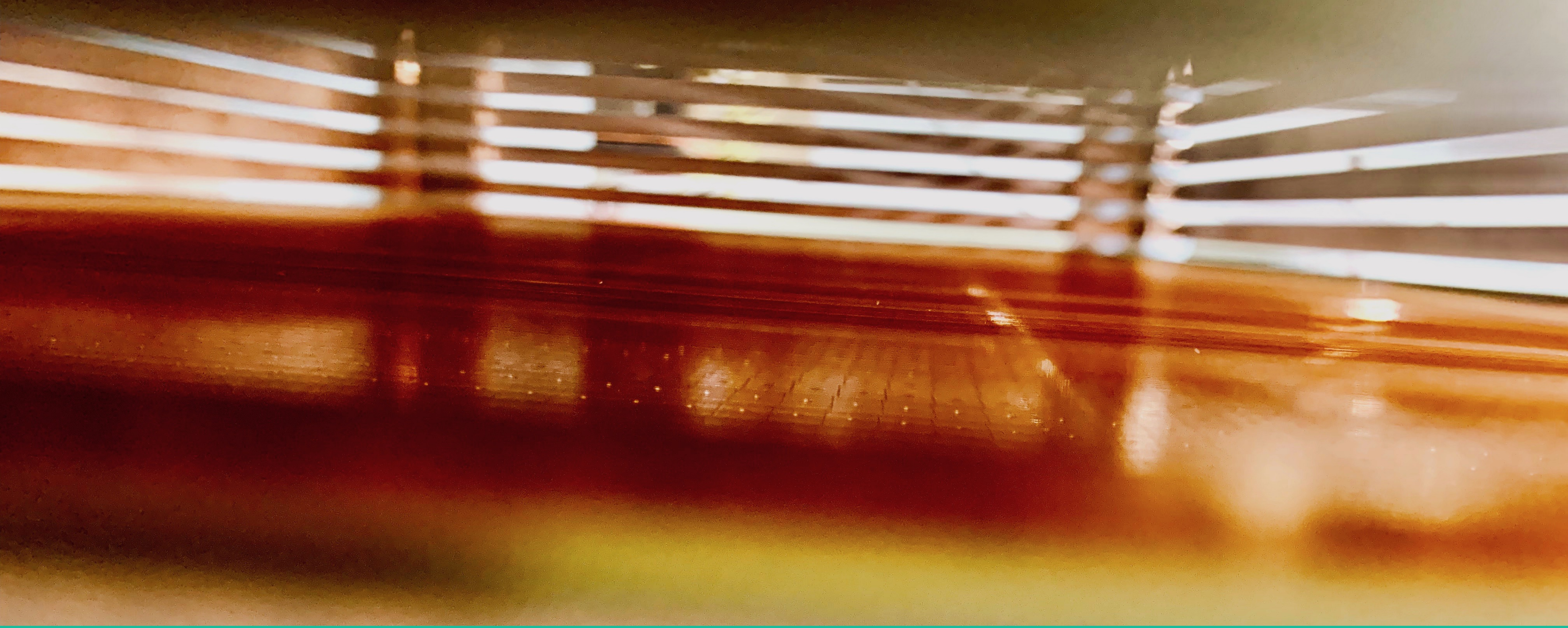


How do we detect neutrinos?

Tanaz Angelina Mohayai
Fermilab Neutrino University

July 5, 2023

Fermilab

Neutrino Detectors Through a Biased Lens

- I had my first experience in detector physics with a liquid argon time projection chamber, a dark matter experiment called DarkSide
- I came back to the world of detector physics as a postdoc at Fermilab, working on both liquid & gaseous argon time projection chambers in the context of DUNE and MicroBooNE, and I will continue in this world as a faculty at Indiana University
- Also, I wrote a thesis on a novel approach to producing an intense beam of neutrinos, an R&D experiment named MICE, which was a proof-of-principle for building a future neutrino factory and a muon collider

- Bottom line & disclaimer: I'll talk a lot about time projection chambers and experiments that use accelerator neutrinos as a source!

To Detect Neutrinos

- Get them to interact first!
- But **neutrinos rarely interact**...
  - The mean free path of a few GeV neutrino

$$d \approx 1.5 \times 10^{12} \text{meters}$$

about a light year of lead

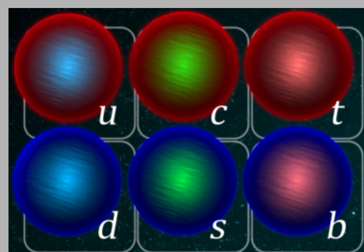
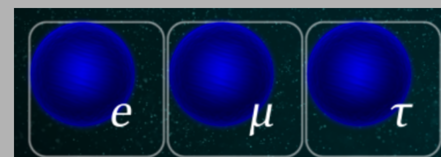
  - Compared to a few GeV proton:

$$d \approx 10 \text{ centimeters}$$

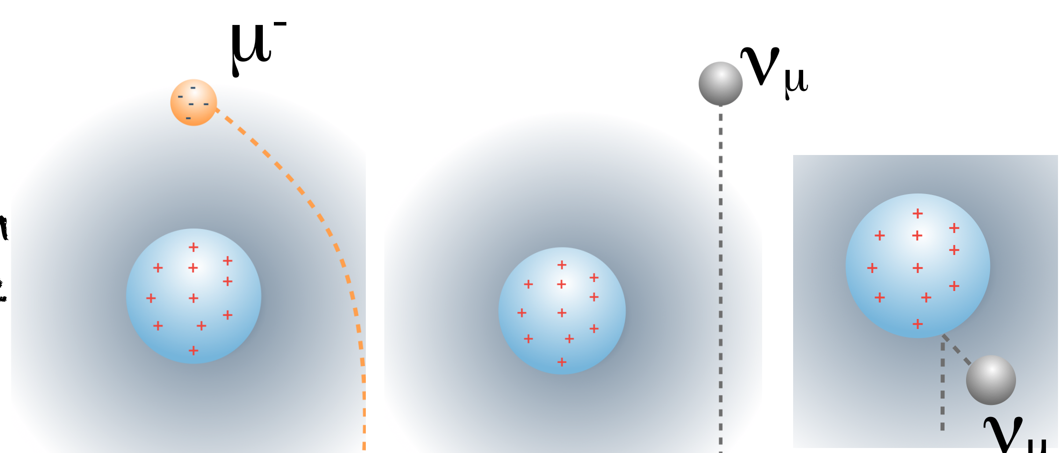
smaller than the length of an average human step

What makes νs so rarely interacting

- Neutrinos are neutral & interact with nuclei only via the weak force

	 quarks	 charged Leptons	 neutrinos (neutral leptons)
Weak			
Strong			
Electro-magnetism			

electromagnetism interaction range is not limited



weak force has a interaction range of ~10^{-18} m

image credit: Cheryl Patrick

- Neutrinos are neutral & interact with nuclei only via the weak force

quarks

charged Leptons

neutrinos (neutral leptons)

We

Str

Ele
ma

i.e. neutrinos require an almost direct strike or they quietly slip by!

electromagnetism interaction range is not limited

weak force has a interaction range of ~10^{-18} m

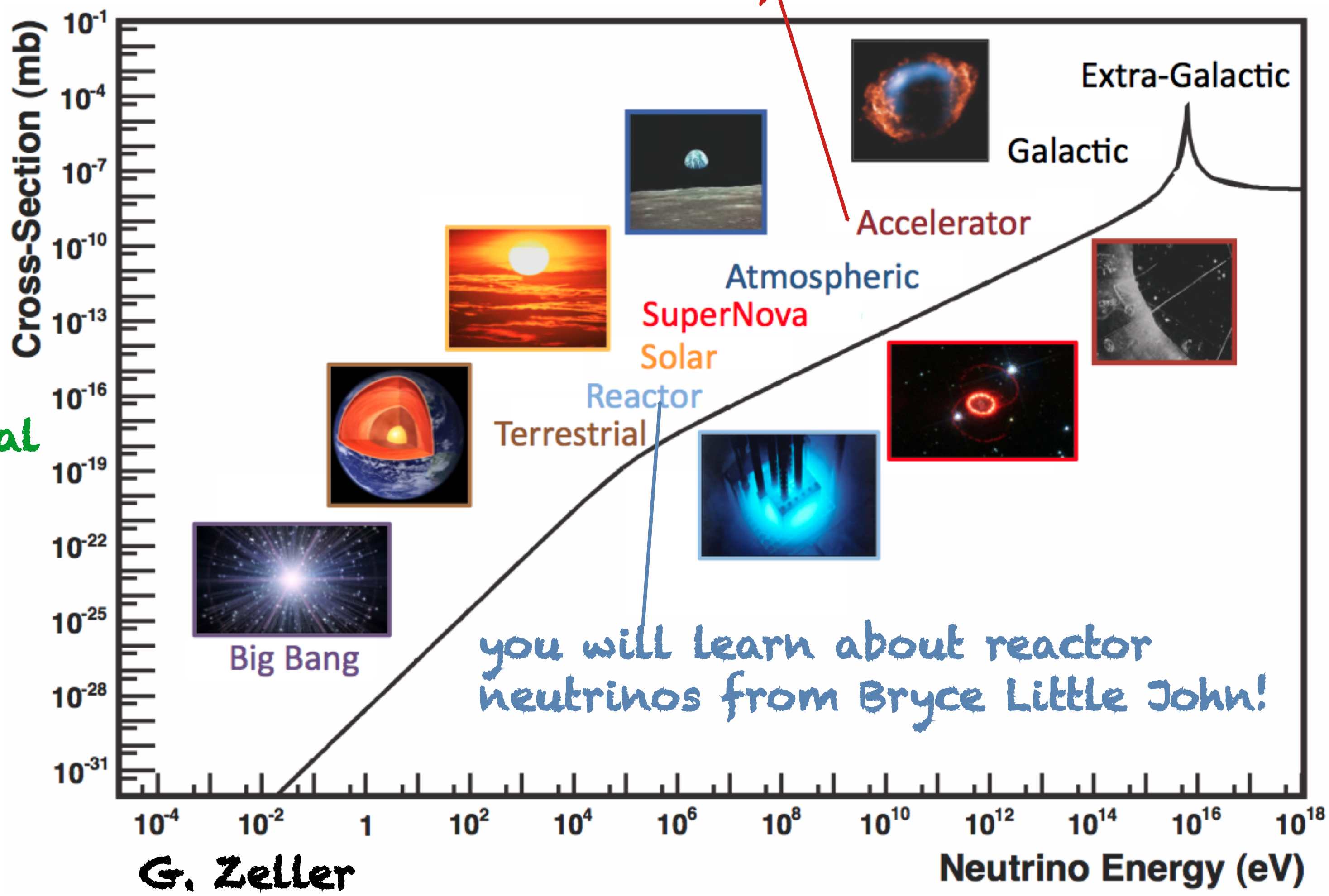
image credit: Cheryl Patrick

Origin Stories

- Despite their ghostly nature, we've unveiled them from every corner!
- Can also make our own, e.g. reactor or accelerator νs
- Generally, the chance of a ν interacting, or ν cross-section, increases with increasing ν energy

Reminder: you learned about accelerator neutrinos from Louise Suter!

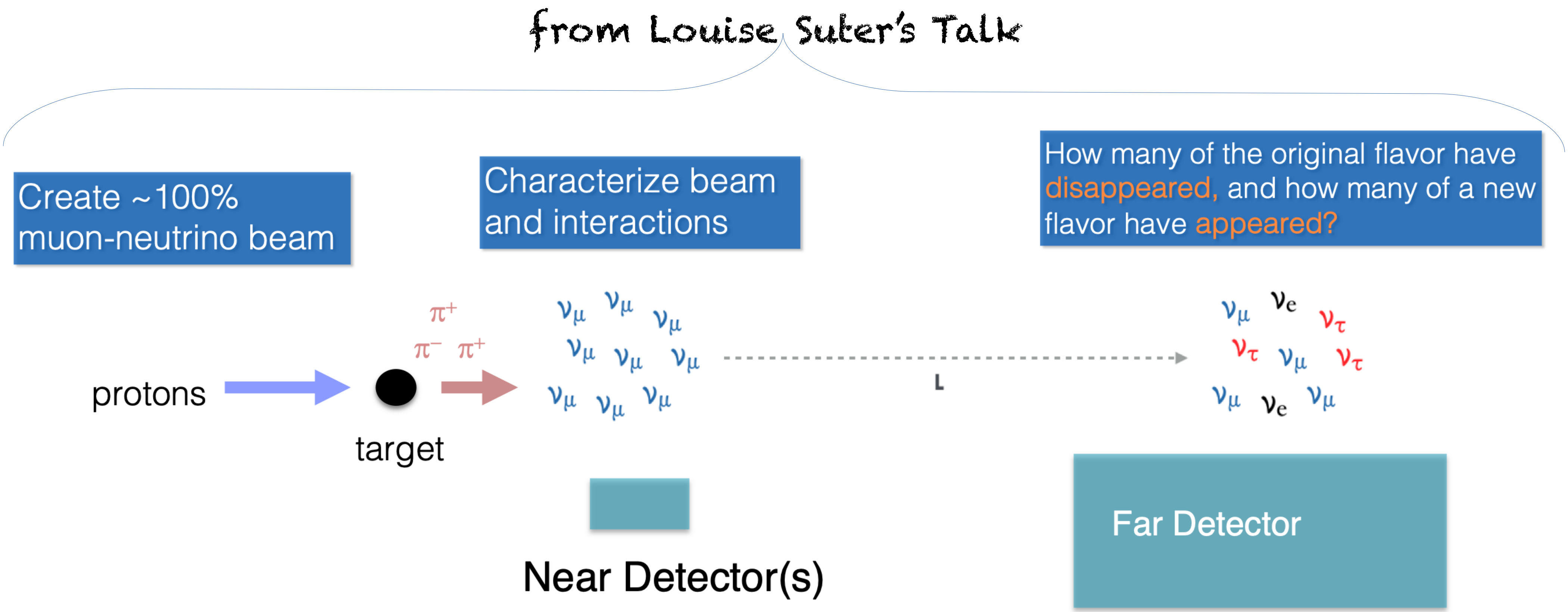
Reminder: astrophysical sources covered by Shirley Li!



you will learn about reactor neutrinos from Bryce Little John!

Some Essential Ingredients for ν Detection

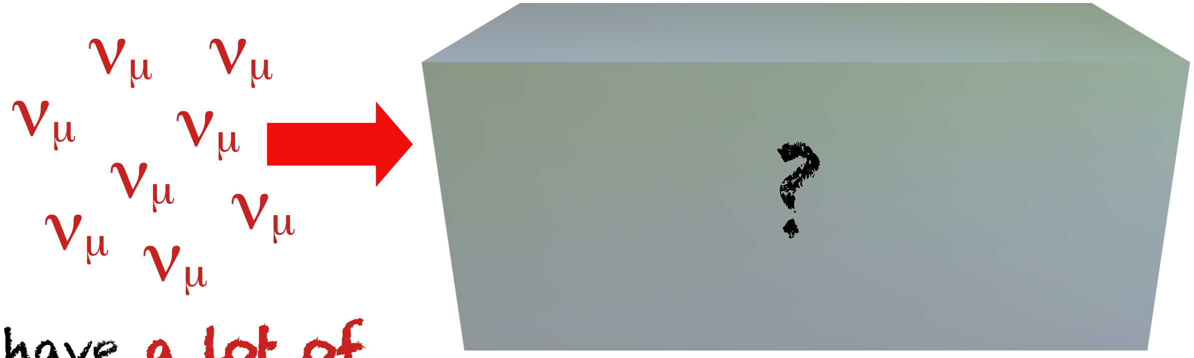
- Choice of neutrino sources and ultimately the detector technology depends on the **physics** being pursued
  - ★ e.g. we use **accelerator νs** for **ν oscillation** analyses & place **two sets of (almost identical) detectors**, one near the source of neutrinos and one some distance away



Some Essential Ingredients for ν Detection

- Once the physics is defined, we build ν detectors that:
  - Put a **lot of target material (large nuclei) in the path of νs & have good acceptance**
  - Can **efficiently** see outgoing particles from a neutrino interaction; **we don't see the νs directly!**

increase the chances of νs interacting or the ν cross section



we can only know if a ν interacted if we can see what comes out

have a lot of neutrinos or increase the ν flux

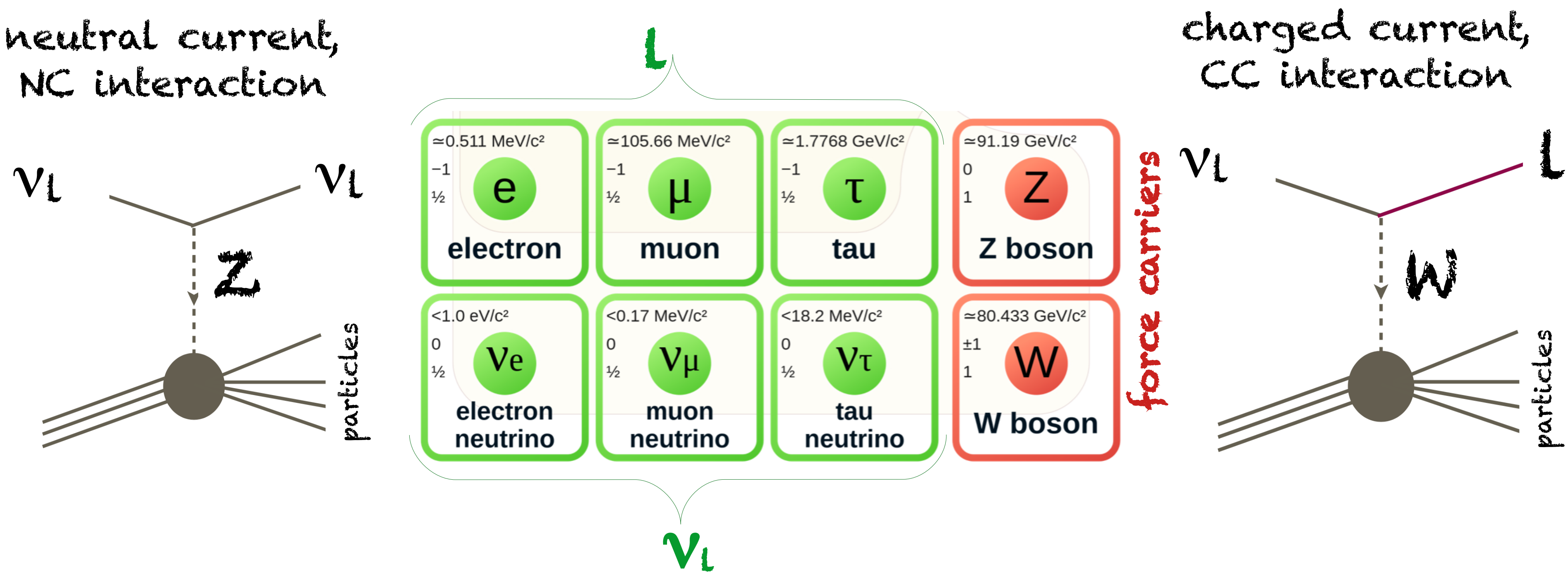
make the nuclear target heavy

# of νs interacting ≈ flux X cross section X target X detector efficiency

we should also determine what count of νs we want

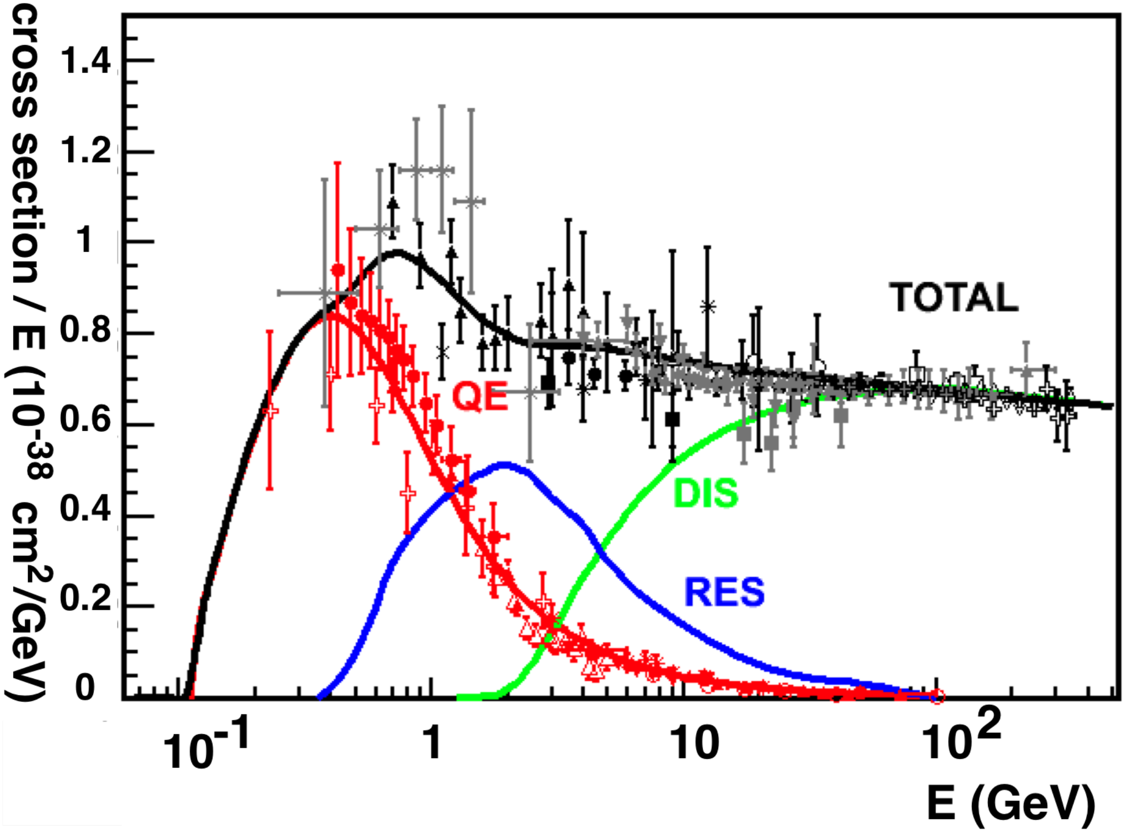
Modes of Interactions

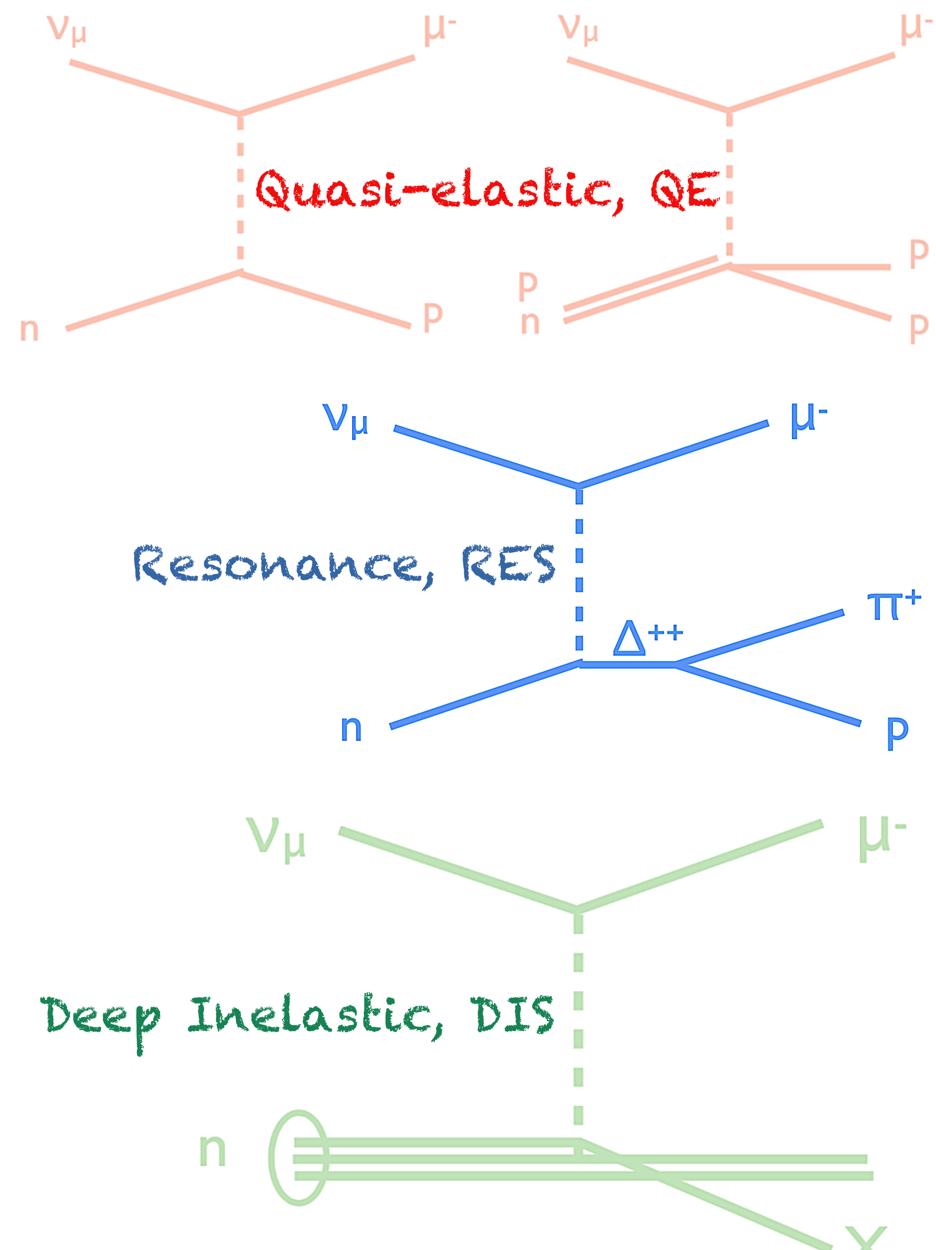
- Charged current
  - ★ Exchanges a W boson, produces a charged lepton of same flavor as ν
- Neural current
  - ★ Exchanges a Z boson, no charged leptons produced
- Other particles also get produced:
  - ★ Can be neutrons, protons, or hadrons (e.g. pions, kaons)



Example of Charged Current Interactions

neutrinos interact in many different ways depending on their energy





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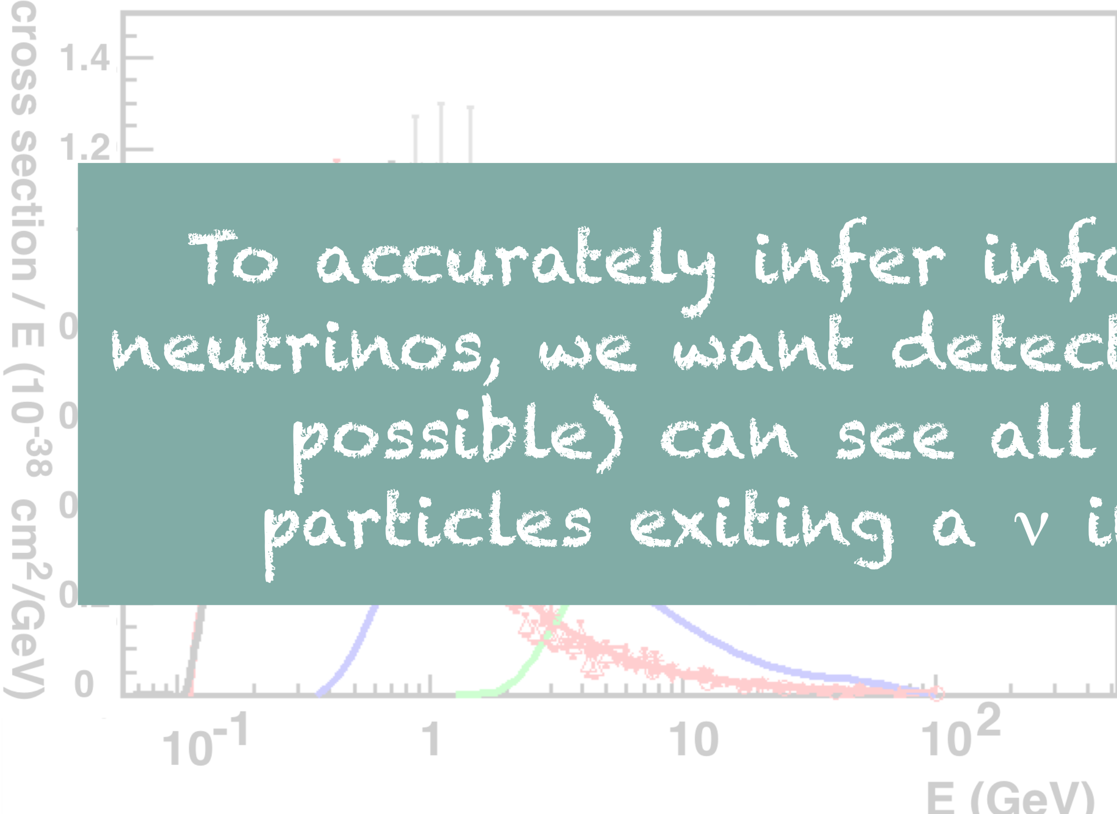
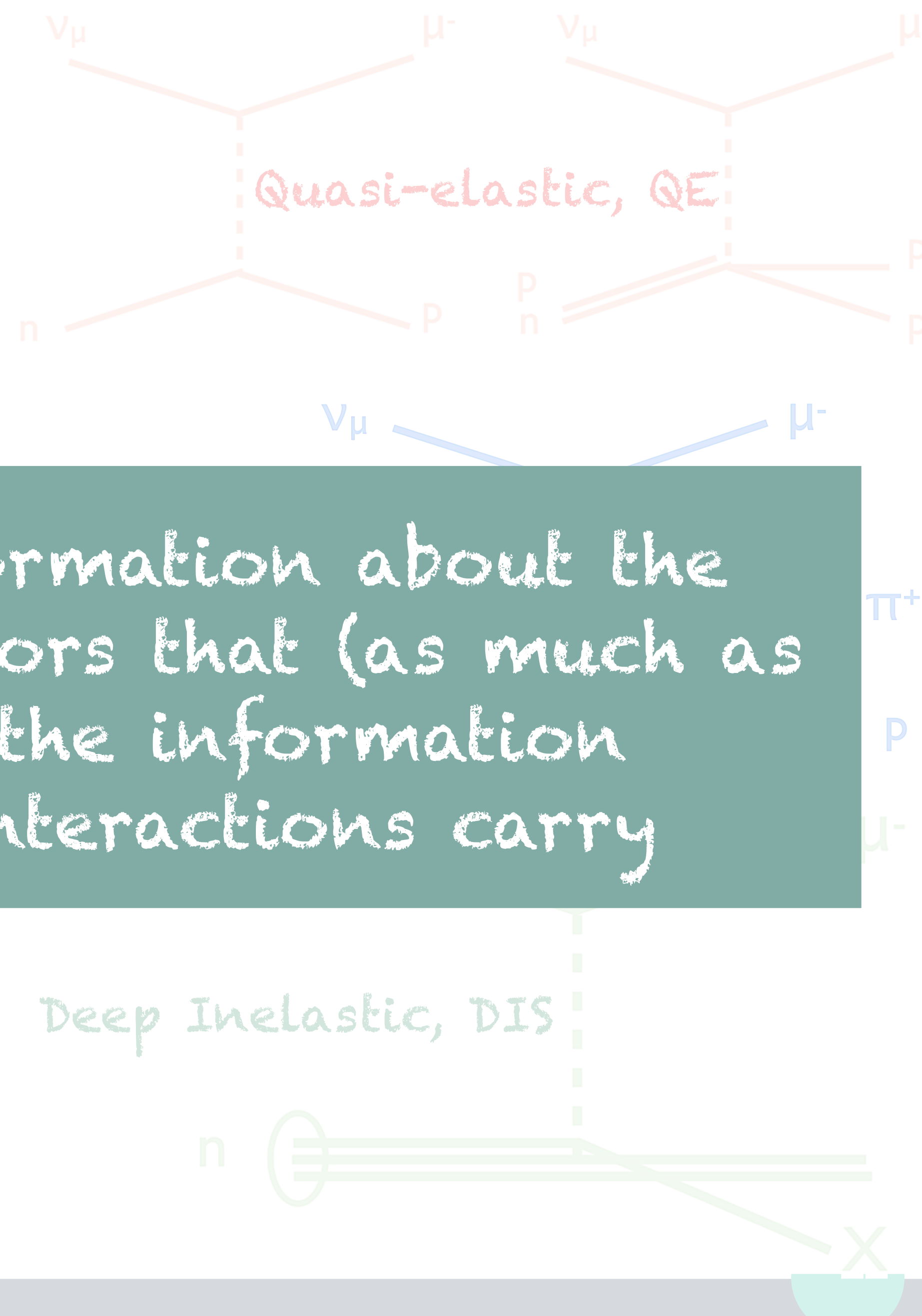
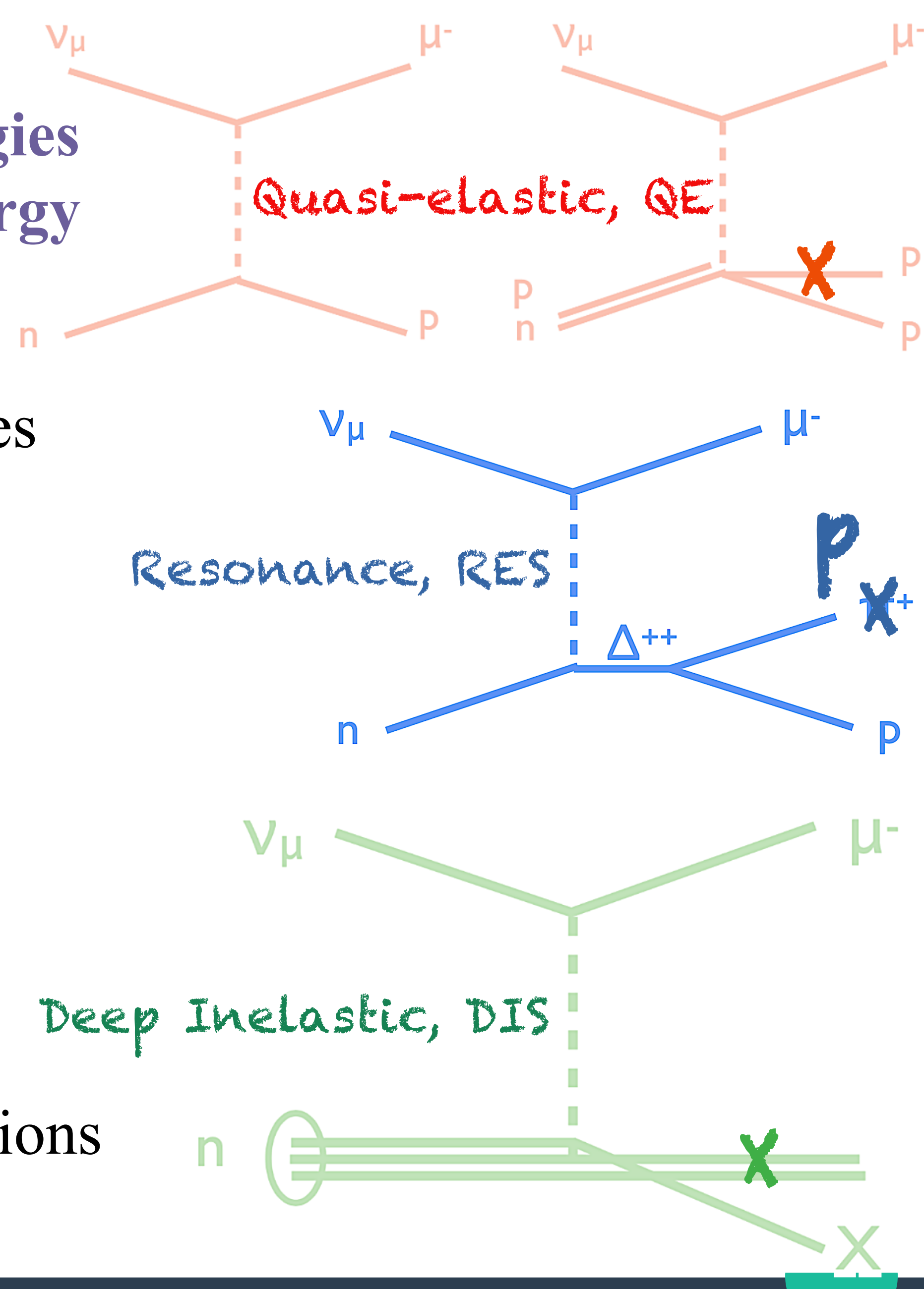




To accurately infer information about the neutrinos, we want detectors that (as much as possible) can see all the information particles exiting a ν interactions carry

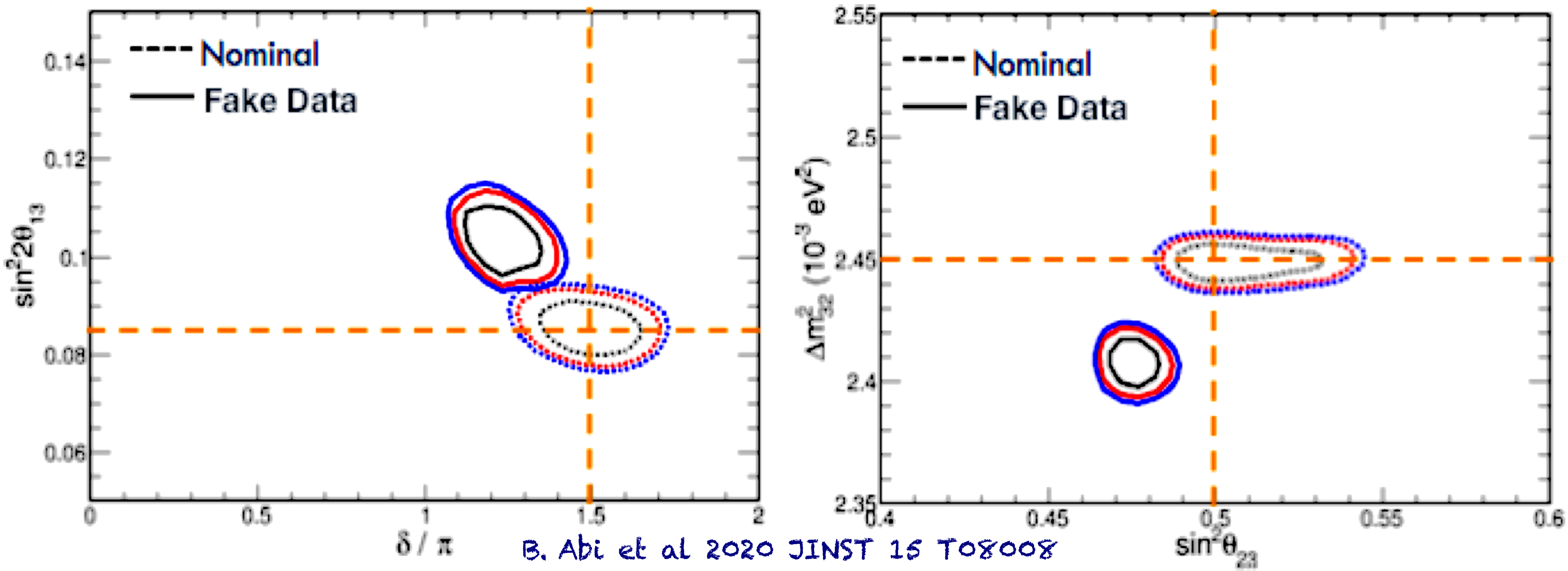
Challenges

- e.g. from Louise Suter's lecture: goal of oscillation experiments is to measure oscillation parameters at specific **ν energies**
- The need to accurately reconstruct **ν energy** amounts to using the kinematic info:
  - ★ e.g. energy contributions from all the particles exiting a ν interaction, includes leptons, protons (or neutrons), hadrons
- Scenarios where we will lack the right calorimetric info:
  - ★ **In QE**, one proton is below threshold and/or not correctly reconstructed
  - ★ **In RES**, a proton is misIDed as a pion
  - ★ The hadronic activity **in DIS** misIDed or is below threshold
  - ★ Backgrounds can also mimic ν interactions



Impact on Oscillation Parameters

- To emphasize: ν energy is **incorrectly** estimated if particles emerging from a ν interaction are **unaccounted for**
- A simple case study:
  - Getting only 20% of the proton energy wrong, shown as Fake Data on the plot, can have significant impacts on the measurements of the oscillation parameters



B. Abi et al 2020 JINST 15 T08008

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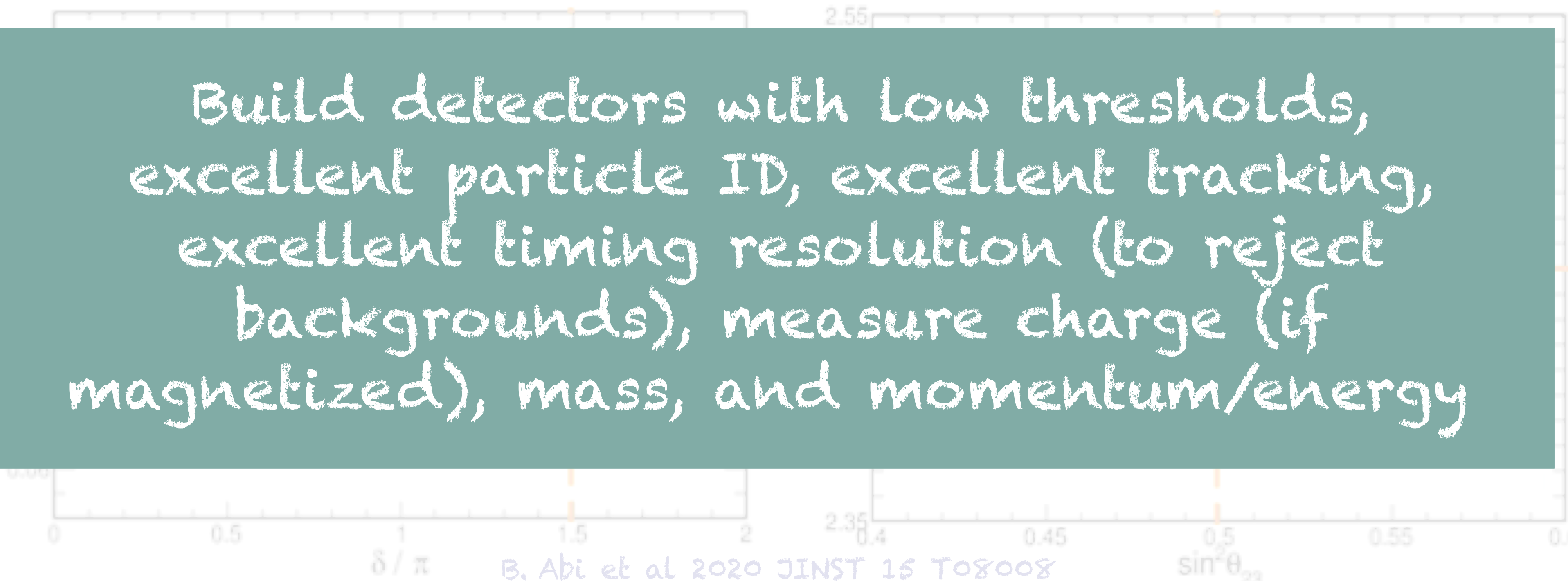
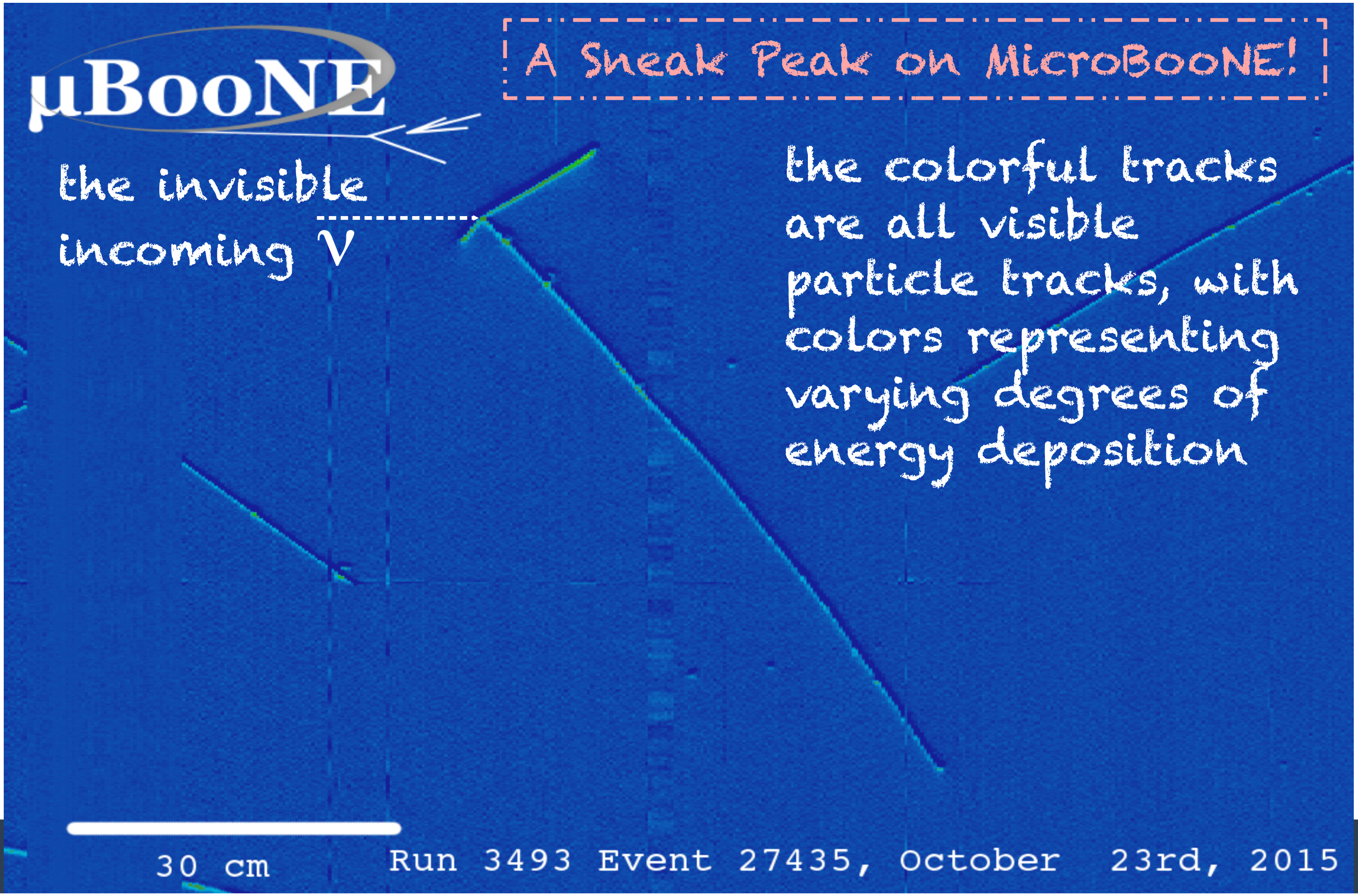


Build detectors with low thresholds, excellent particle ID, excellent tracking, excellent timing resolution (to reject backgrounds), measure charge (if magnetized), mass, and momentum/energy

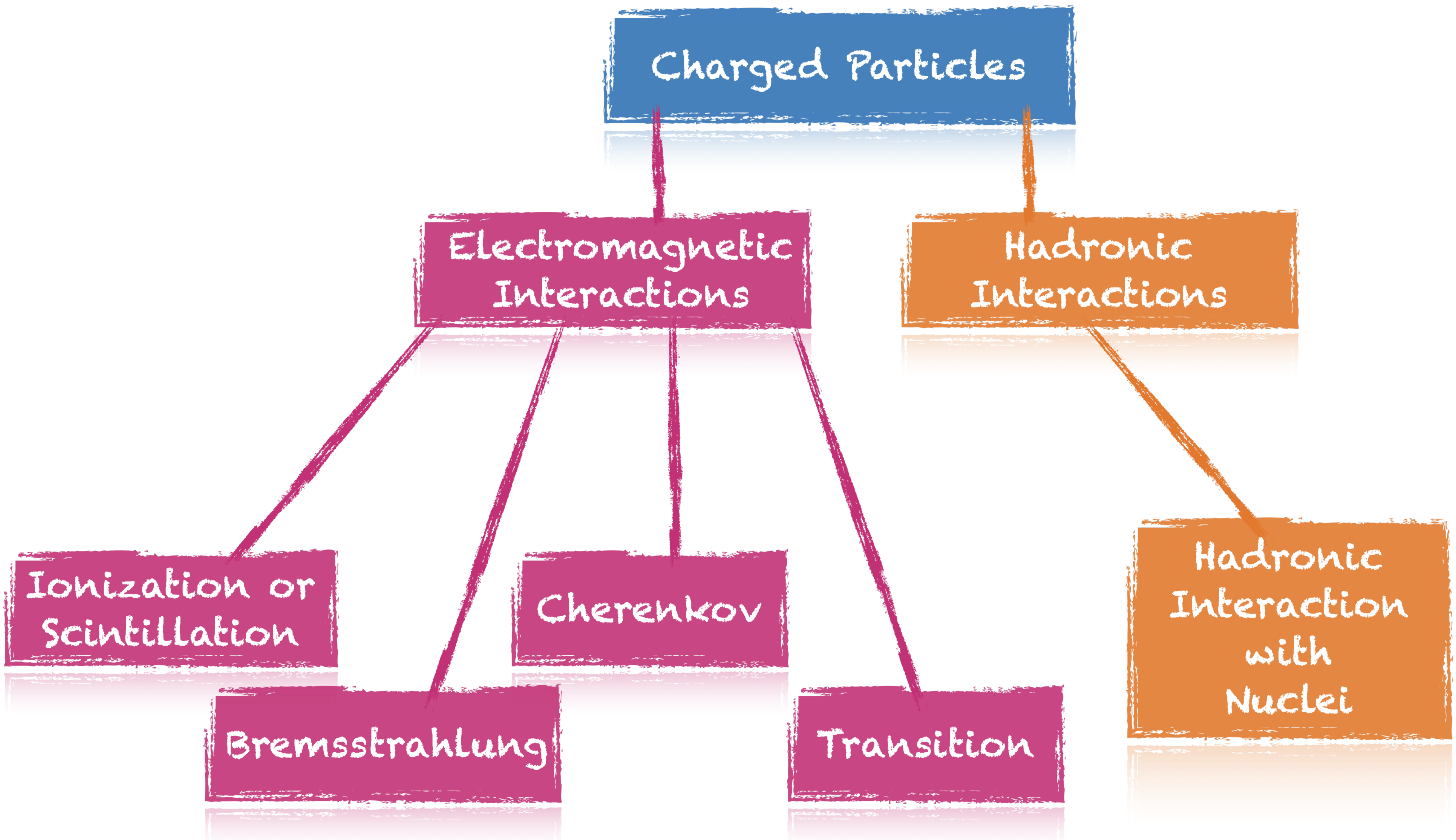
B. Abi et al 2020 JINST 15 T08008

Quick Recap

- So far, we learned:
  - If neutrinos interact in our detector, we won't see them directly! Have to rely on the leptons, hadrons, nucleons emerging from a ν interaction (and it's important to be able to see these emerging particles!)
- We also won't see the outgoing particles, directly! Have to rely on the them **losing energies in the detector medium via various processes**

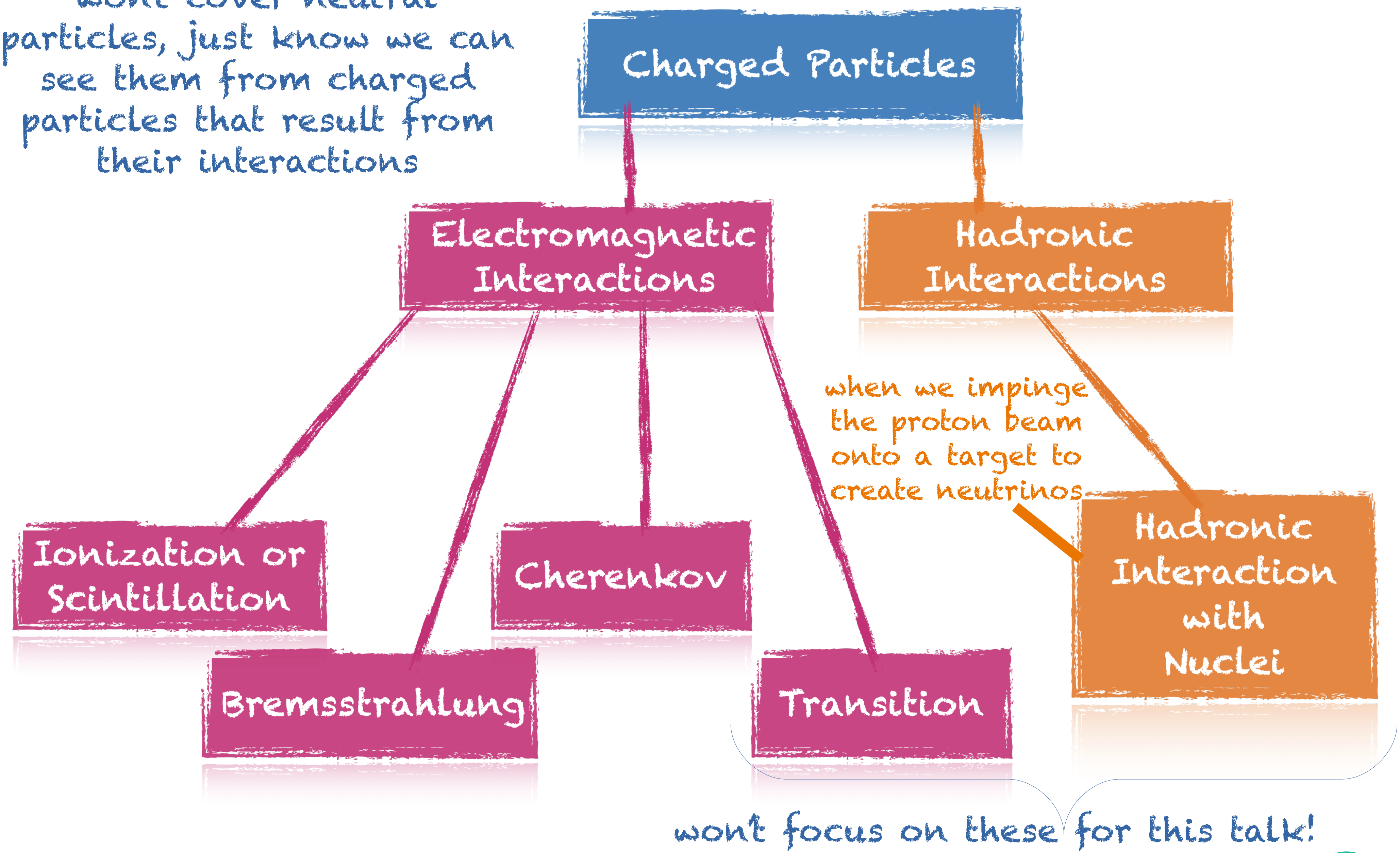


Energy Loss Mechanisms – Charged Particles



Energy Loss Mechanisms – Charged Particles

wont cover neutral particles, just know we can see them from charged particles that result from their interactions



Energy Loss Mechanisms – Charged Particles

Charged Particles

Electromagnetic Interactions

Hadronic Interactions

Ionization or Scintillation

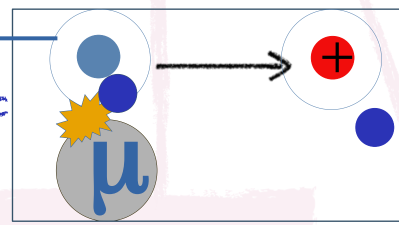
Cherenkov

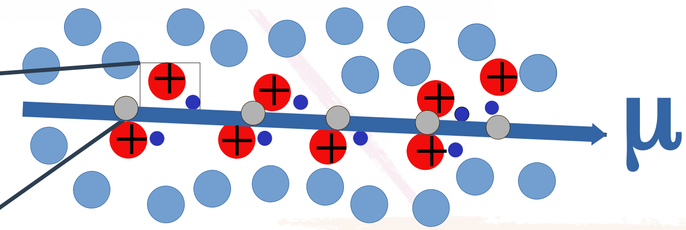
Bremsstrahlung

Transition

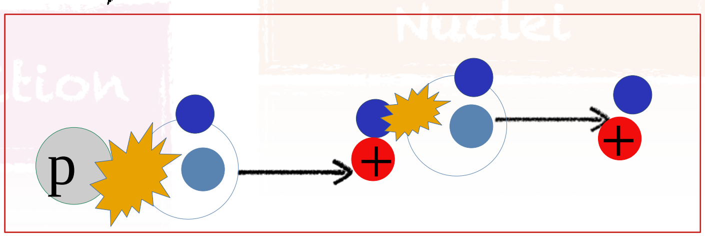
detecting medium releases an atomic electron

ionization

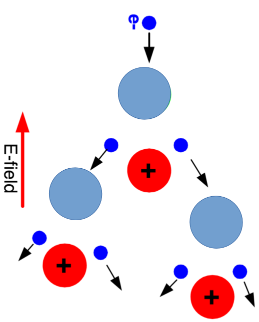




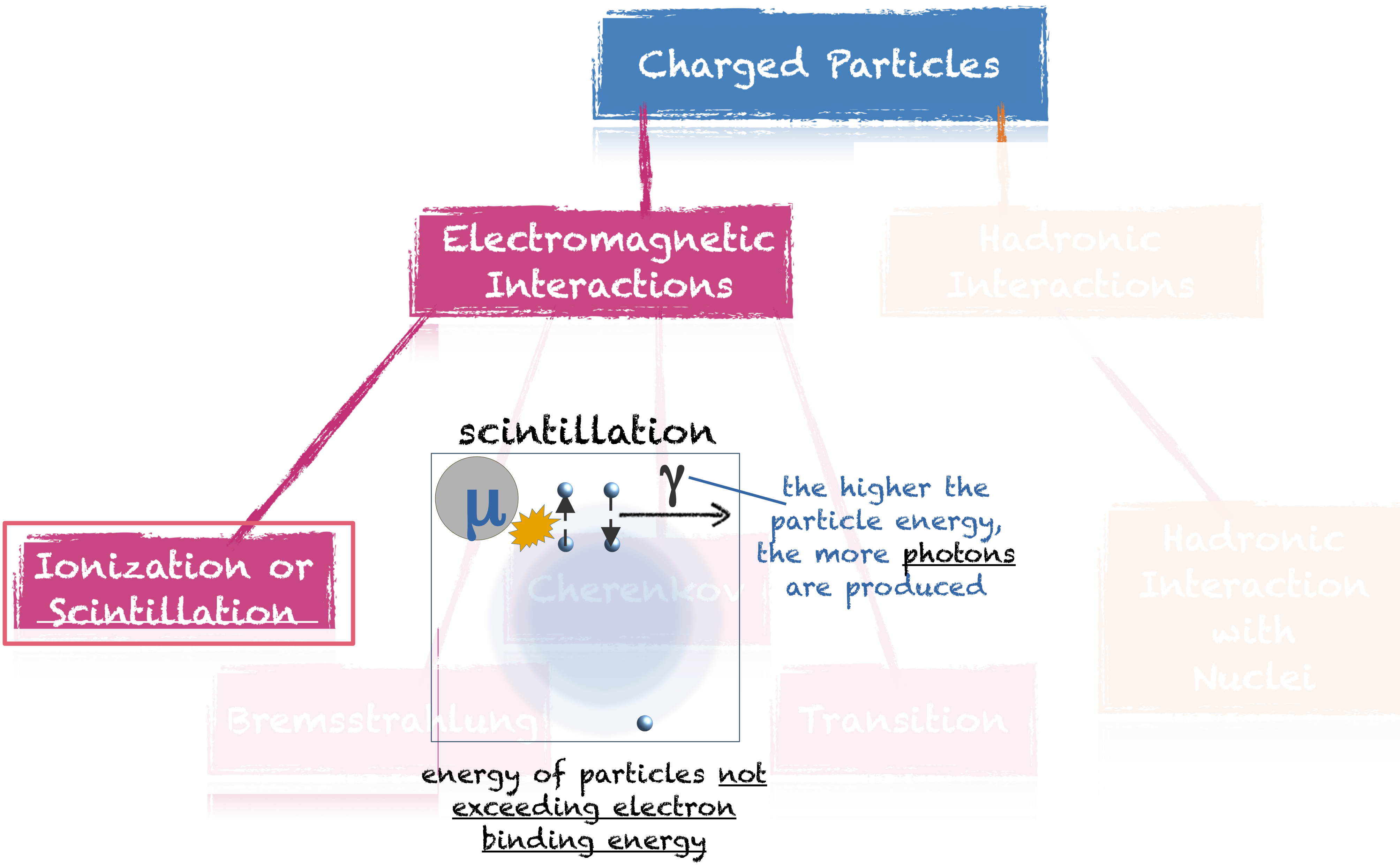
sometimes the released electrons have enough energy to further ionize the detector medium, referred to as δ electrons



or get an exponential increase in electrons under the influence of high electric fields, a process known as Townsend Avalanche



Energy Loss Mechanisms – Charged Particles



Energy Loss Mechanisms – Charged Particles

Charged Particles

Electromagnetic Interactions

Hadronic Interactions

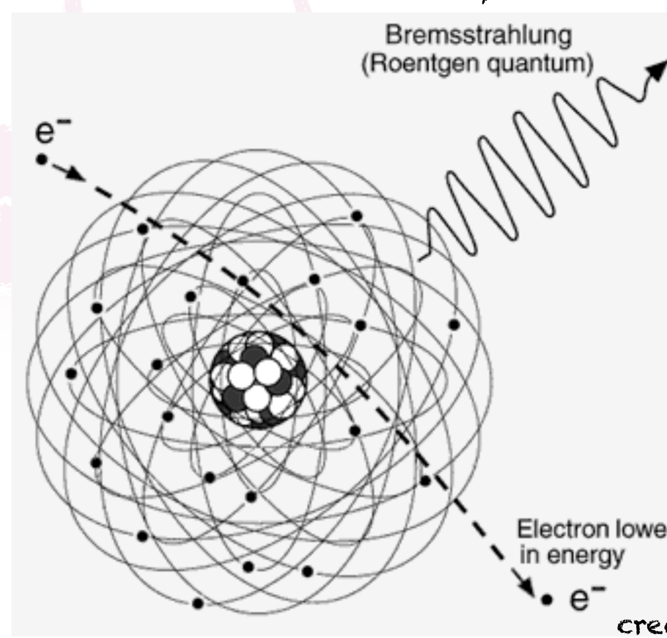
Ionization or Scintillation

Cher

Bremsstrahlung

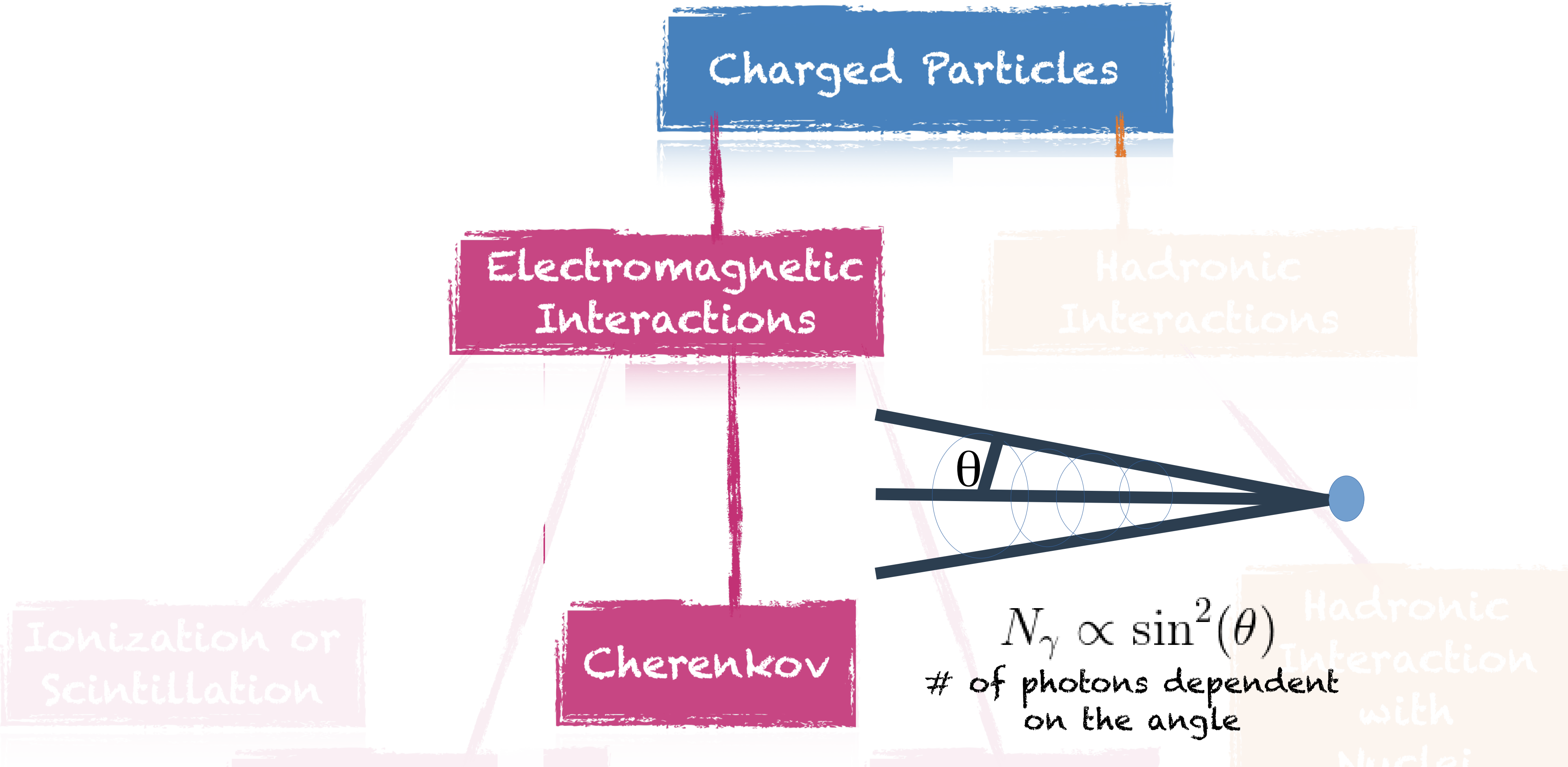
Hadronic Interaction with Nuclei

charged particles scattering in a nucleus' electric field emit photons



credit: www.euronuclear.org

Energy Loss Mechanisms – Charged Particles



$$N_\gamma \propto \sin^2(\theta)$$

# of photons dependent on the angle

photons released when the particle's velocity is larger than the speed of light in the detecting medium

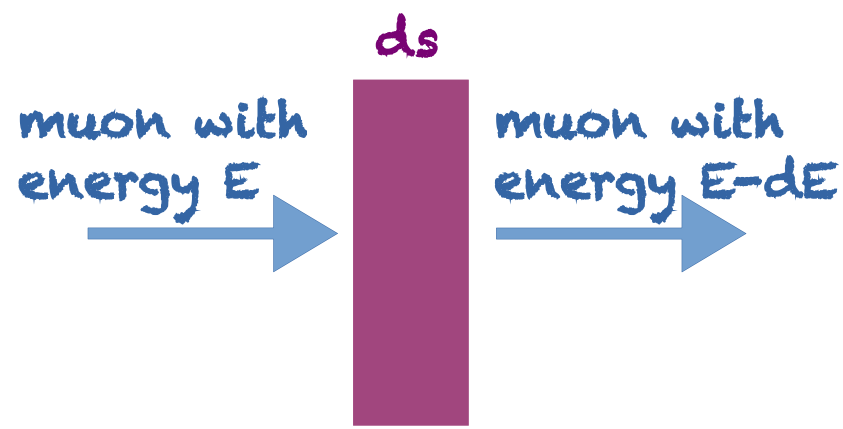
Specifically, Heavy Charged Particles

- i.e. heavy charged leptons and hadrons, so not electrons
- In the 0.1-1000 βγ range, they lose energy by ionization
  - Described by the Bethe-Bloch relation

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

e.g. in the case of a muon passing through an absorbing material, dx is the thickness (ds) times destiny of material

dE/dx (the stopping power) therefore has the units of MeV cm^2 g



*note: Bethe-Bloch relation considers the average energy loss

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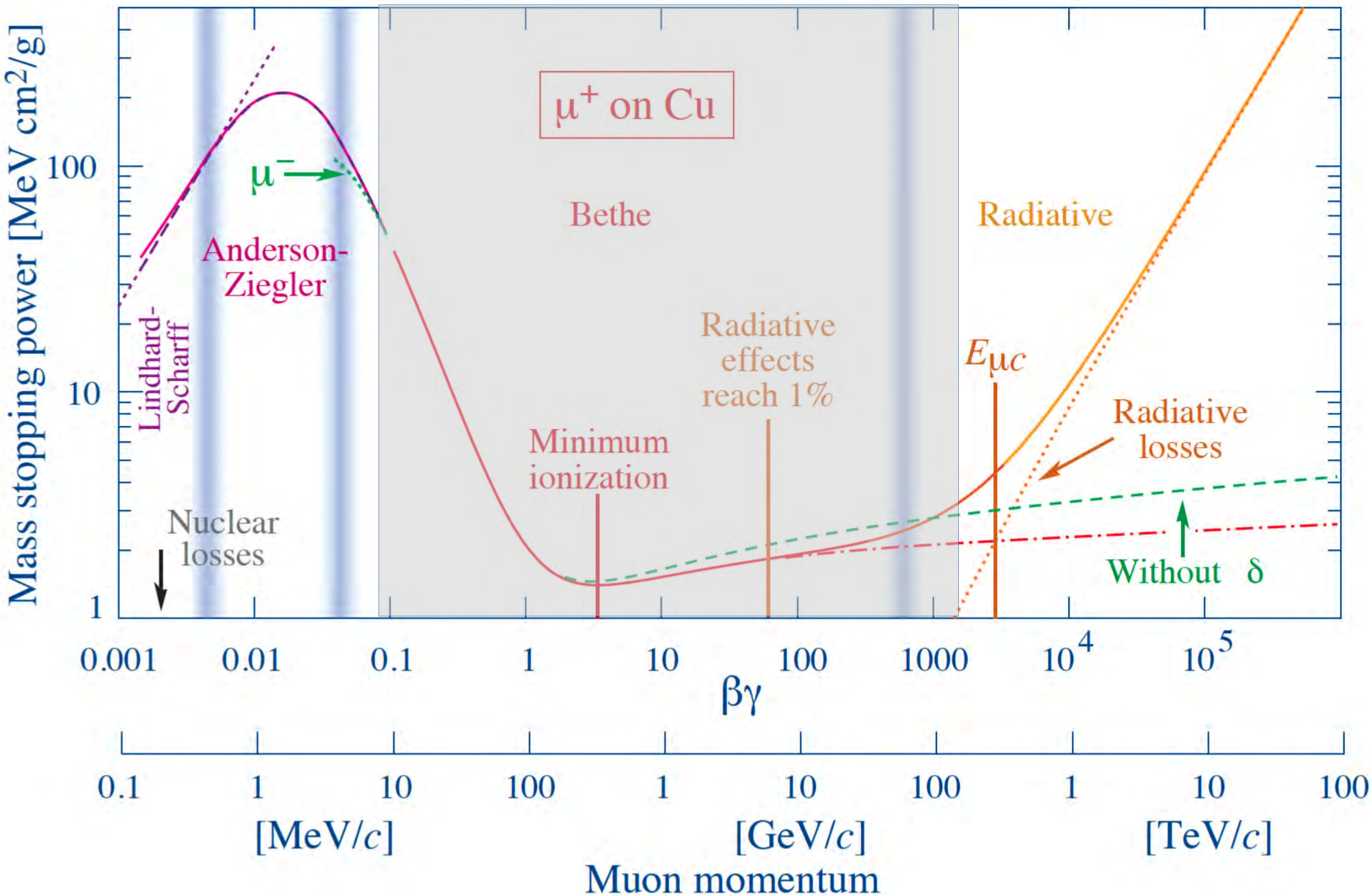
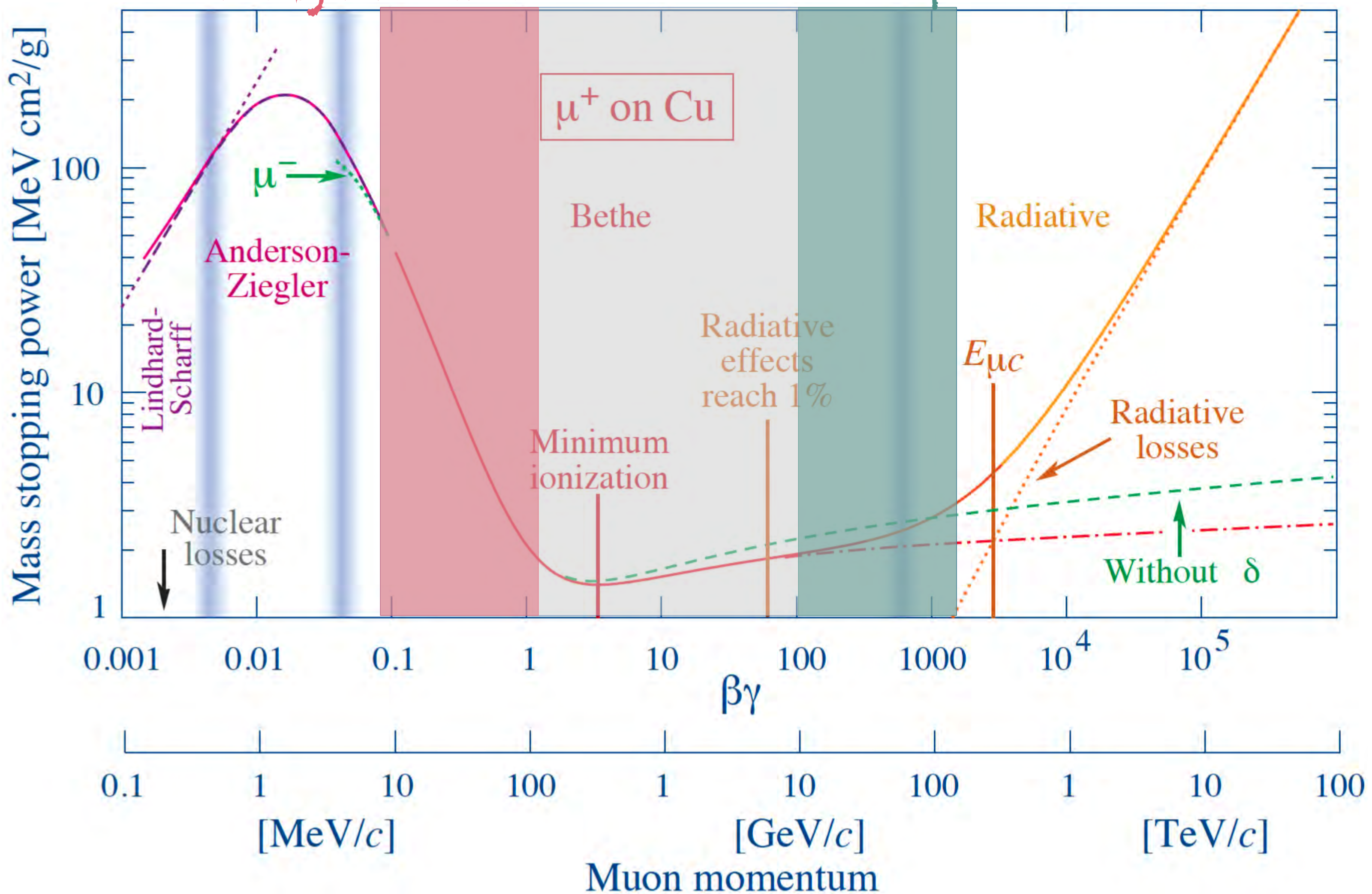


Specifically, Heavy Charged Particles

There are distinct subregions within the region where Bethe-Bloch relation holds true

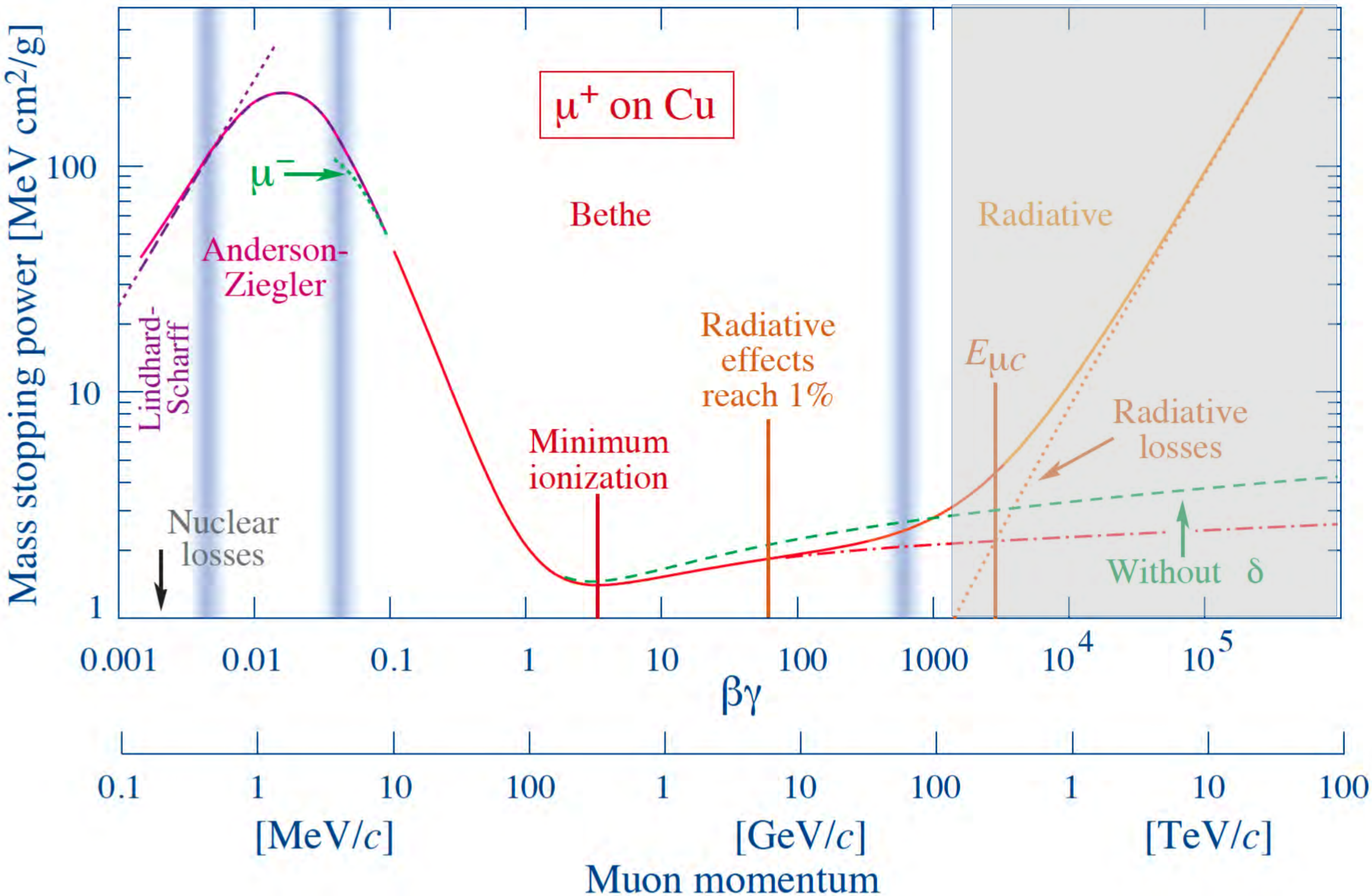
a $1/\beta^2$ dependence, particles lose more energy to ionization as they slow down

a $\ln(\beta)$ dependence, called the relativistic rise region where dE/dx plateaus



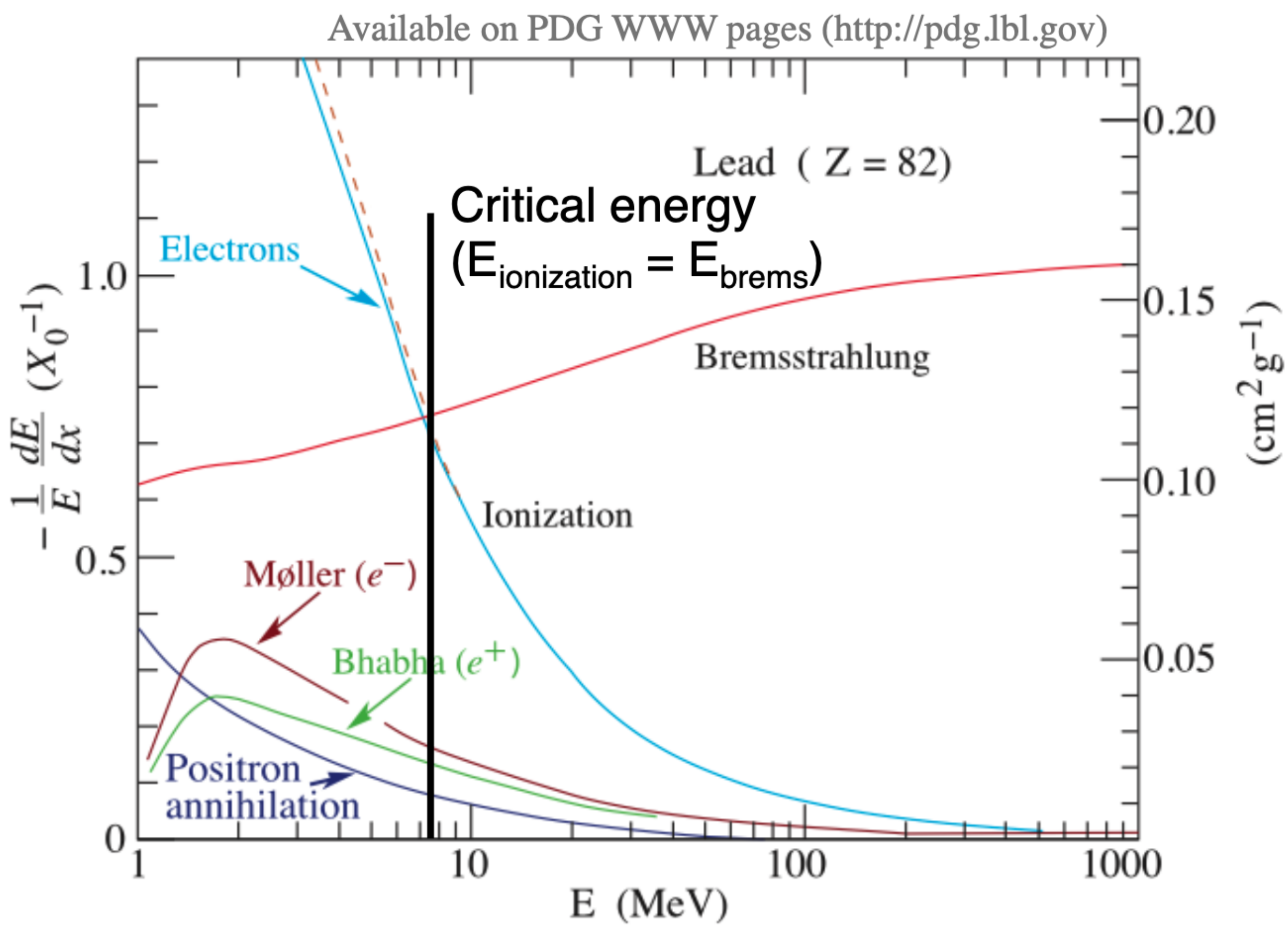
Specifically, Heavy Charged Particles

- When βγ > 1000 & radiative energy losses dominate, energy is lost through other dominant processes, e.g. Bremsstrahlung
  - ★ Bethe-Bloch relation no longer holds



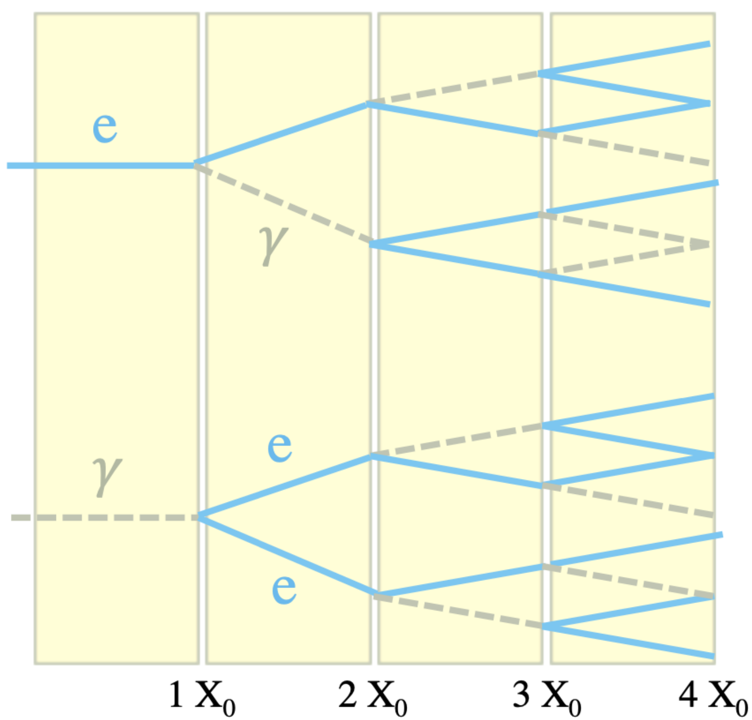
What about Light Charged Particles

- aka electrons or positrons:
  - Bremsstrahlung is a dominant mechanism for energy loss for electrons at energies above 10 MeV

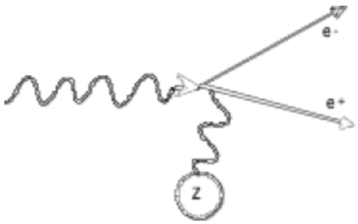


What about Light Charged Particles

- aka electrons or positrons:
  - Bremsstrahlung is a dominant mechanism for energy loss for electrons at energies above 10 MeV
- Electrons travel 1 radiation length, X_0 before emitting a Bremsstrahlung photon, after passing through many X_0s, it forms an electromagnetic shower
  - X_0, distance at which the particle's energy is reduced by 1/e, 63%

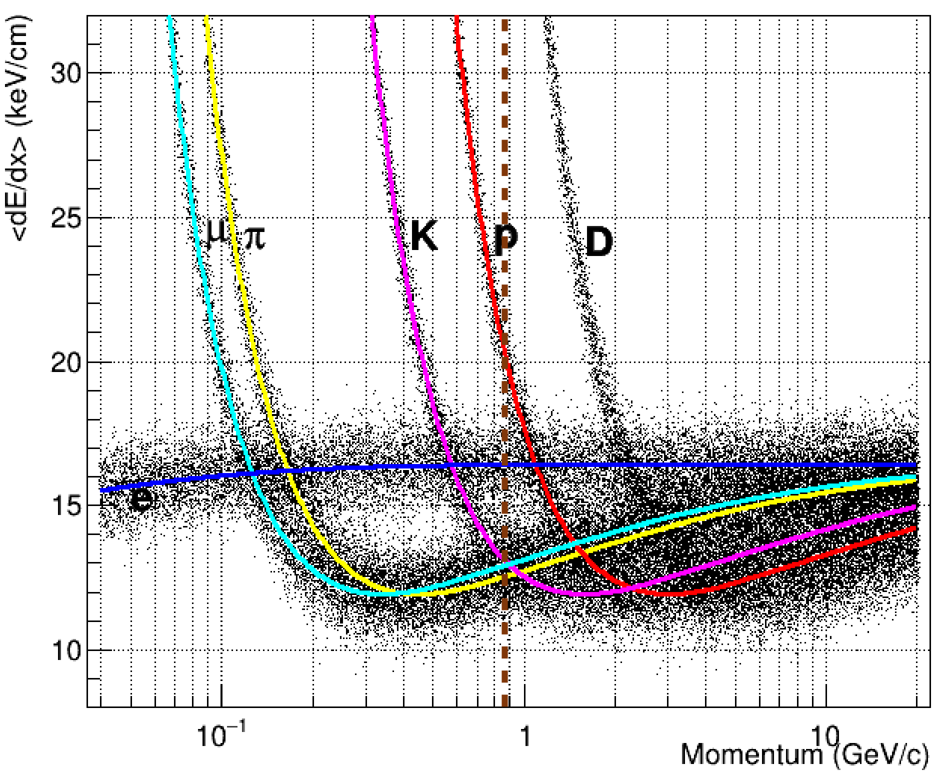


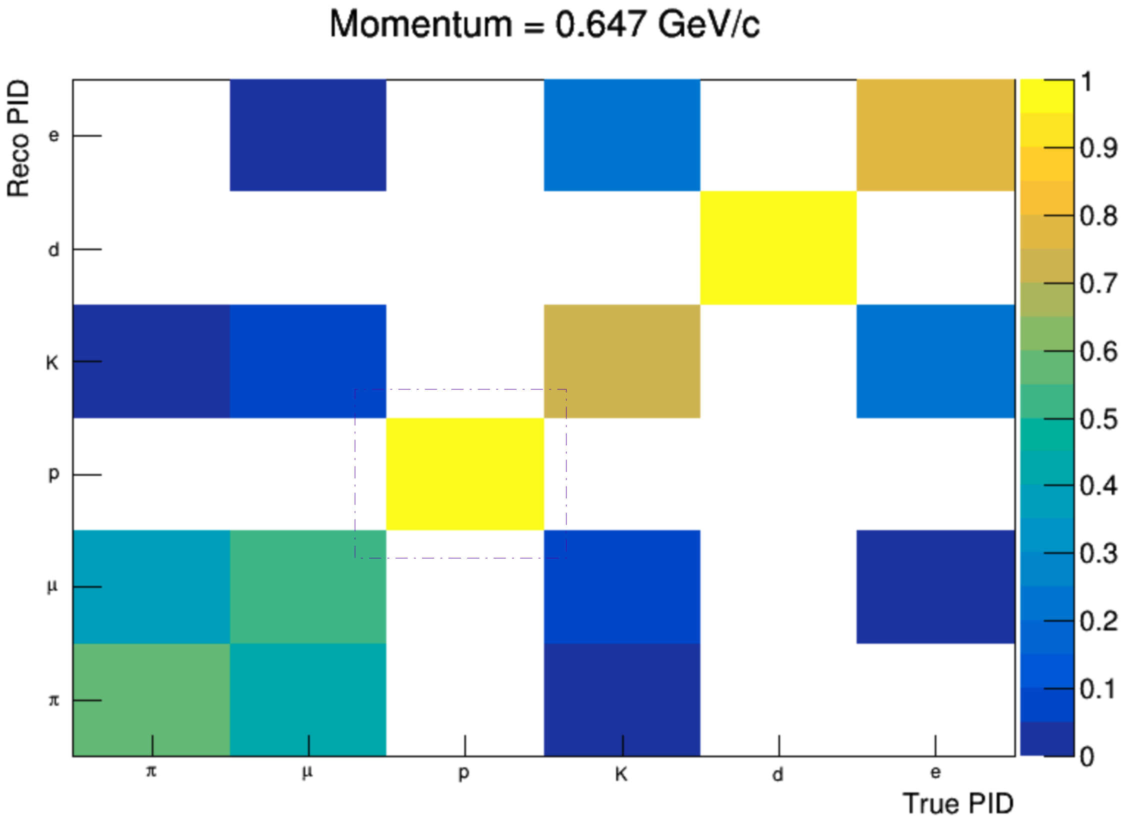
photons also form a shower, travel $1X_0$ before pair produce



Particle ID using dE/dx & Particle Momentum

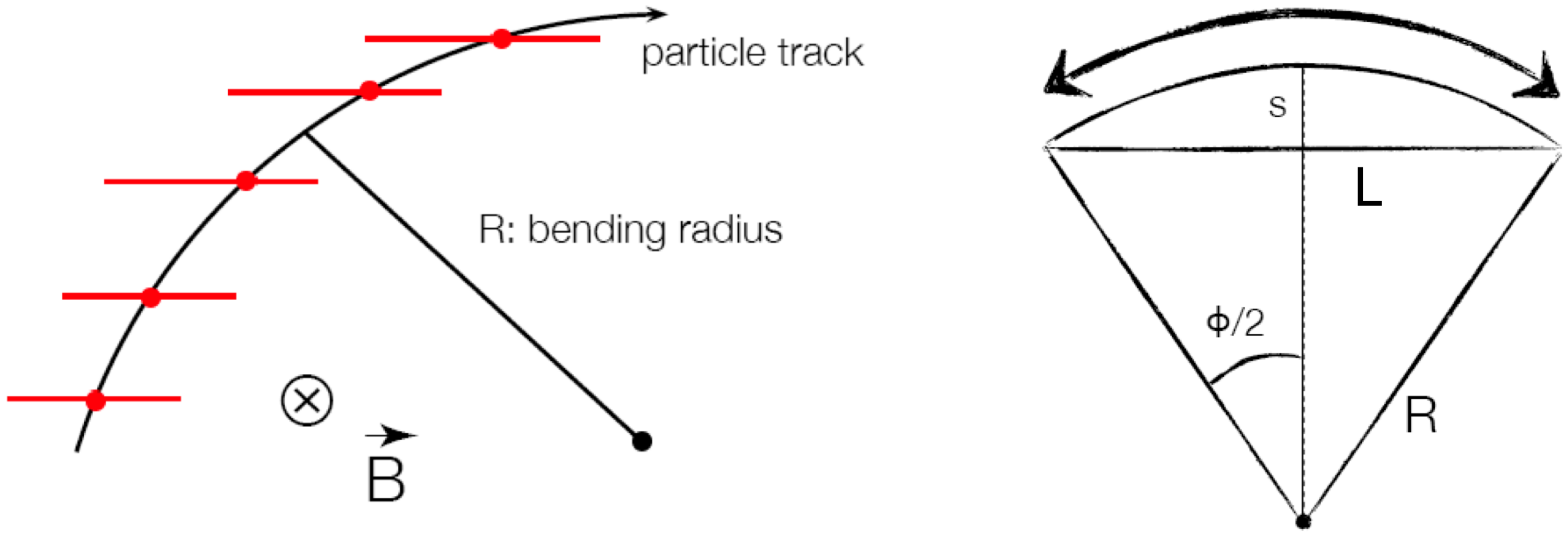
- Bottom line: to accurately infer incoming ν, we rely on particles losing energy as they exit a ν interaction
- e.g. for a given momentum (in a given momentum range), different particles with different masses will lose energy differently
  - ★ Use that to tell the particles apart, perform PID





Measuring the Particle Momentum I

- Using curvature in a magnetic field:
  - When a uniform transverse magnetic field is present, a particle with momentum p bends by a radius R



  - We solve for p using this relation:

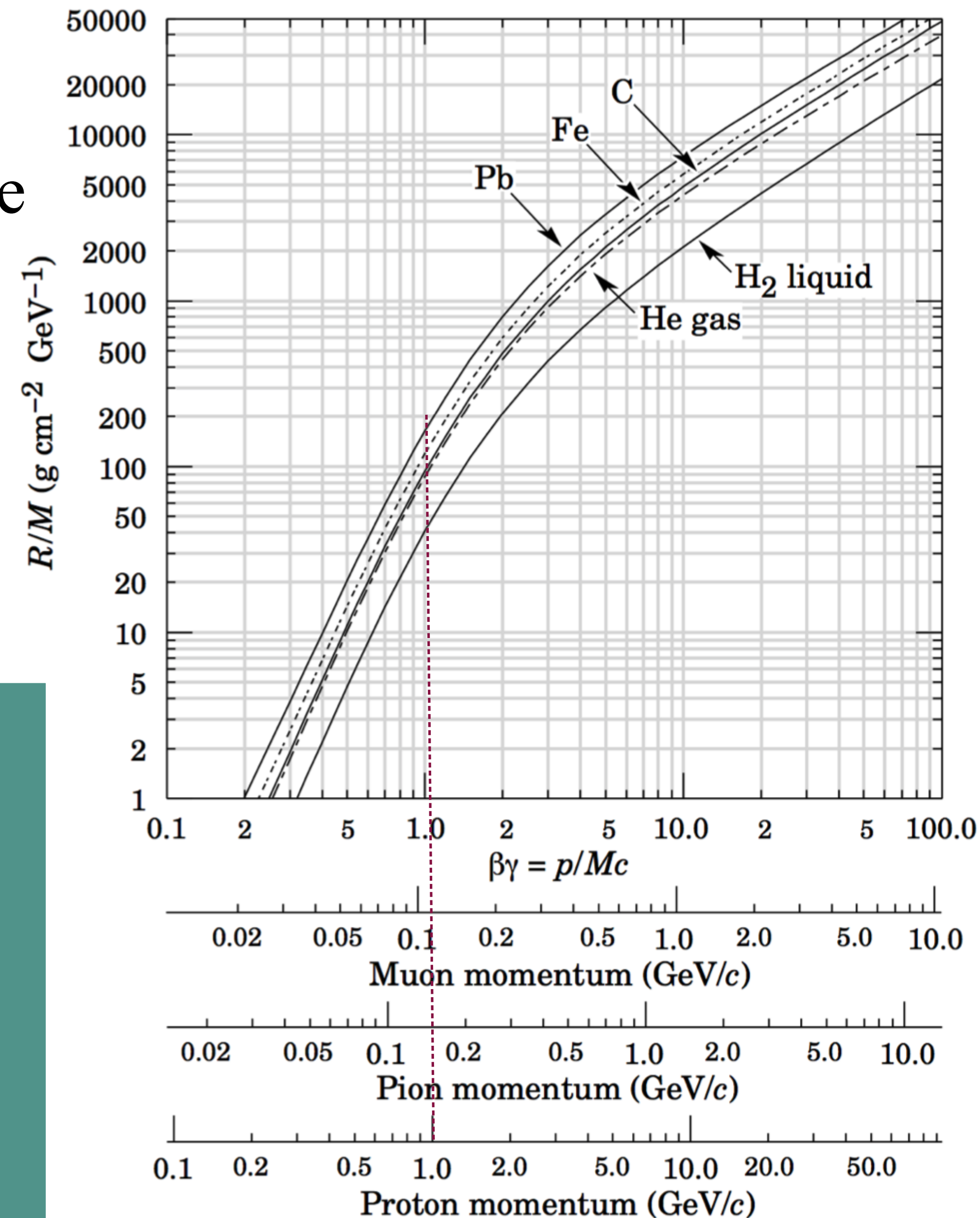
$$p\left[\frac{GeV}{c}\right] = 0.3\ \mathrm{B[T]\ R[m]}$$

B field is known, radius is obtained by fitting a circle to **measurement points** along the particle's track

Measuring the Particle Momentum II

- Using range:
  - If we can get a particle to stop in the detector, we can use range to measure its momentum
- e.g. what range would a 1 GeV/c proton in Pb (with a density of ~11.3 g/cm^3) have? From the plot, R is range

problem set time!



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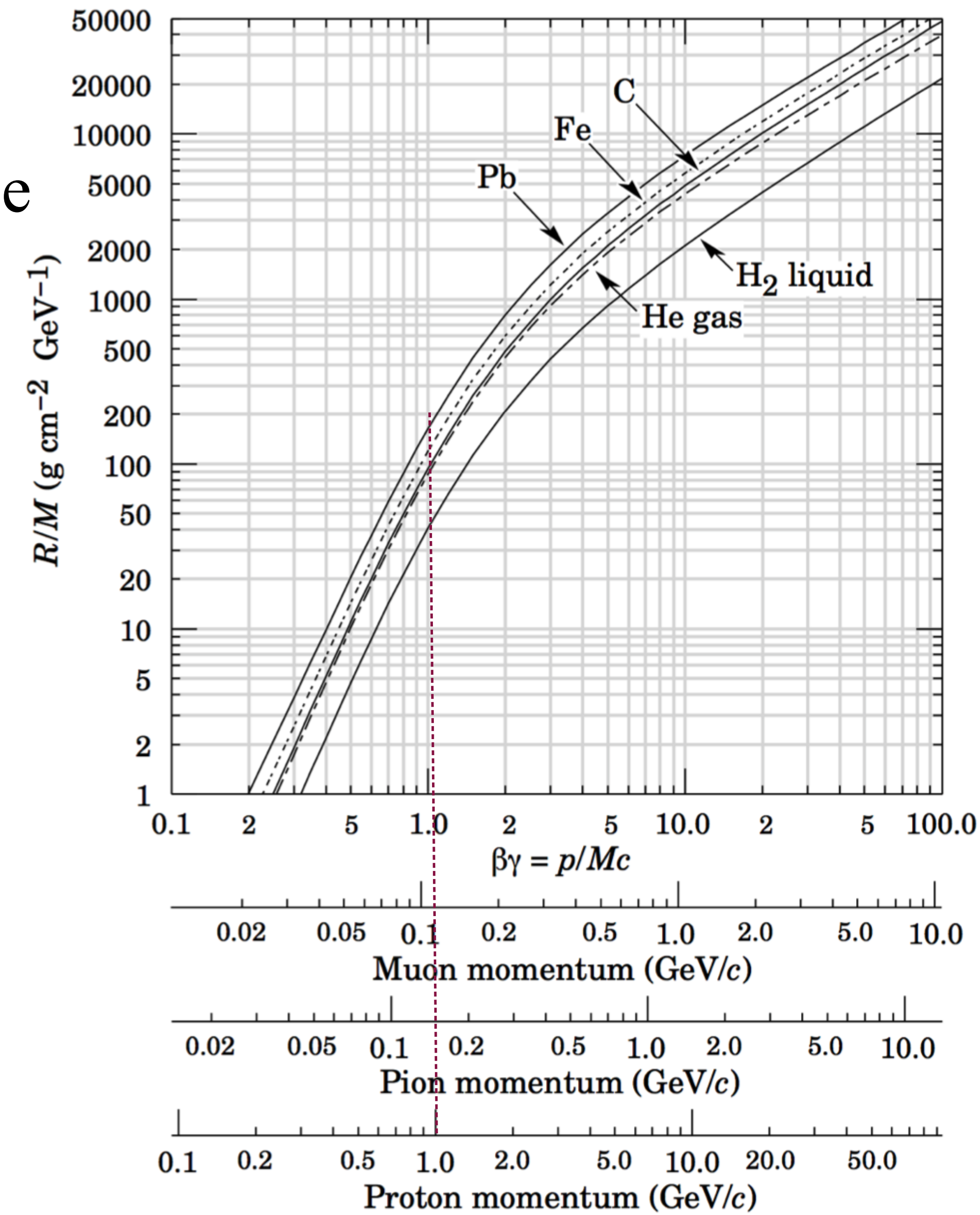


$R/M \approx 200$ g cm^{-2} GeV^{-1}

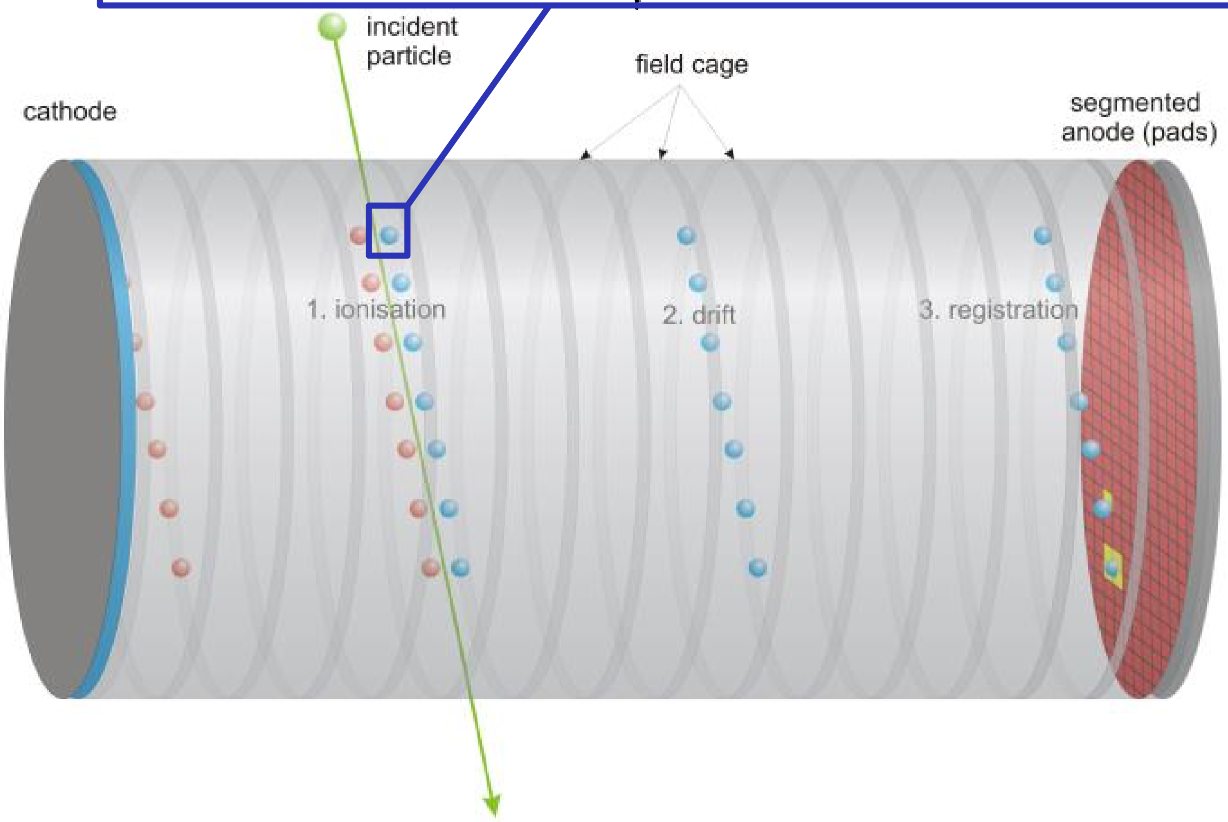
$\Rightarrow R = 200/11.3$ cm $\approx$ 18 cm

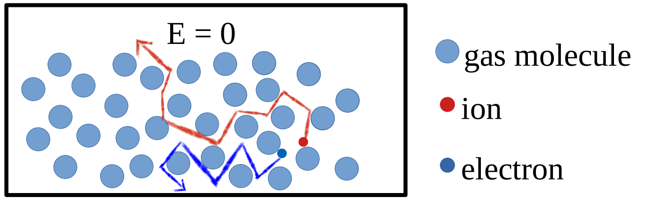
How do we see particles using energy deposition

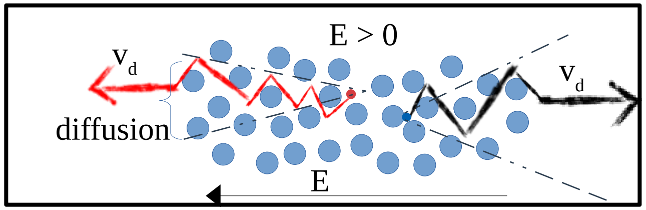
*disclaimer: only focusing on what's relevant to accelerator neutrino experiments

- Read out (ionization) electrons
  - e.g. in gaseous or liquid time projection chambers

a wish-list: make sure drift electrons are not lost (via attachment or recombination), that they travel fast (minimized pile up), won't diffuse much (need excellent point resolution), and we produce enough of them





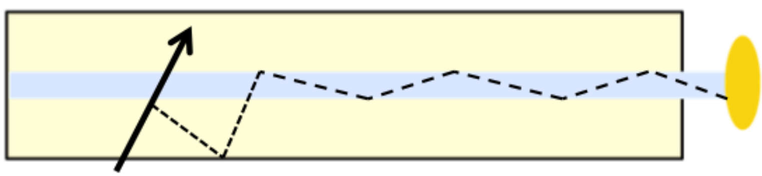


How do we see particles using energy deposition

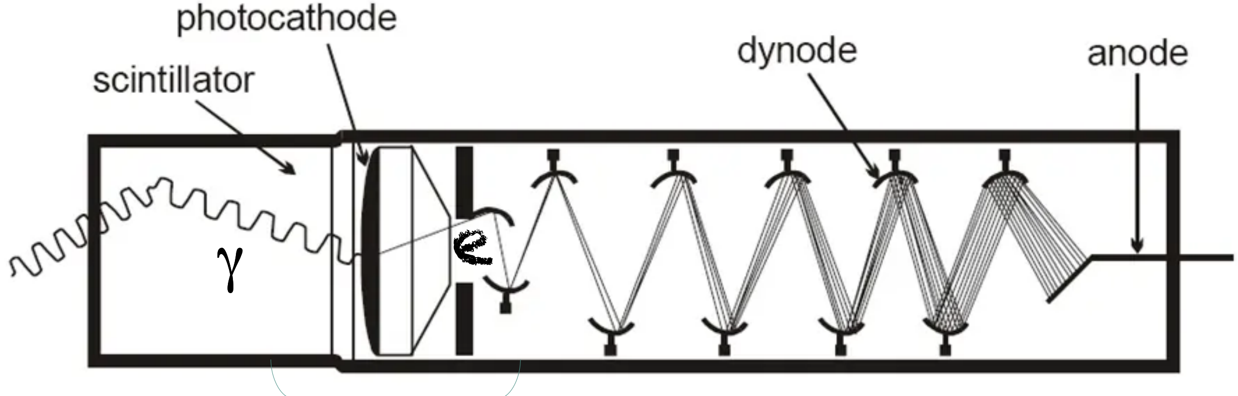
*disclaimer: only focusing on what's relevant to accelerator neutrino experiments

- Read out (scintillation) light
  - e.g. in detectors that use organic or in-organic scintillators as their detecting medium, and in gaseous or liquid time projection chambers

example of a light readout system



typically, there are wavelength shifting fibers embedded in the scintillating material that guide the signal to light readout systems



from your modern physics, what is the name of this effect?

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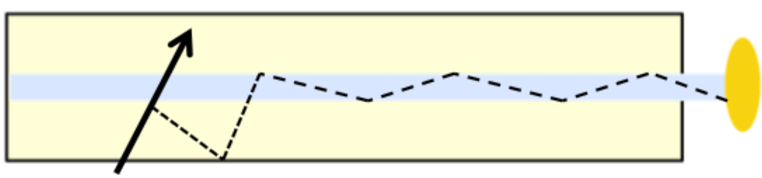

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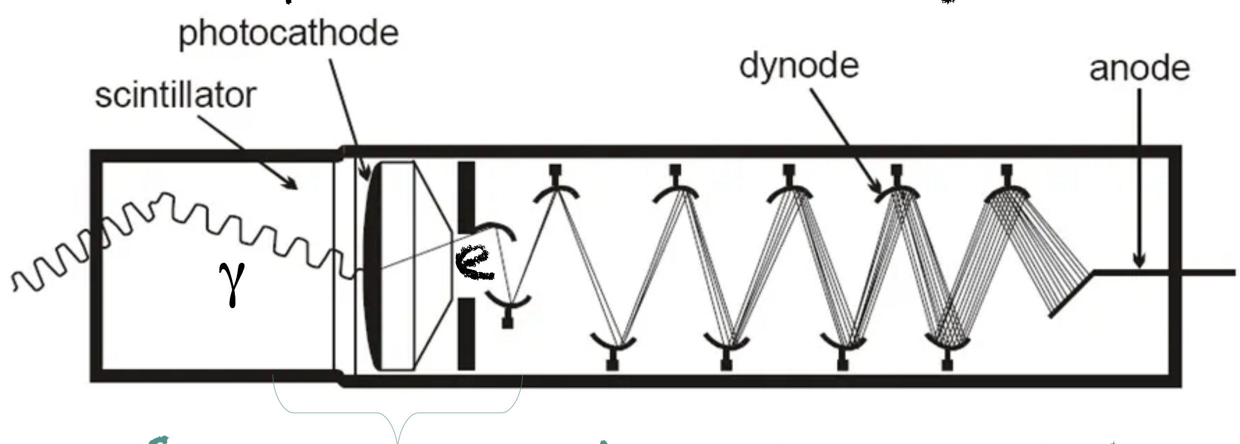
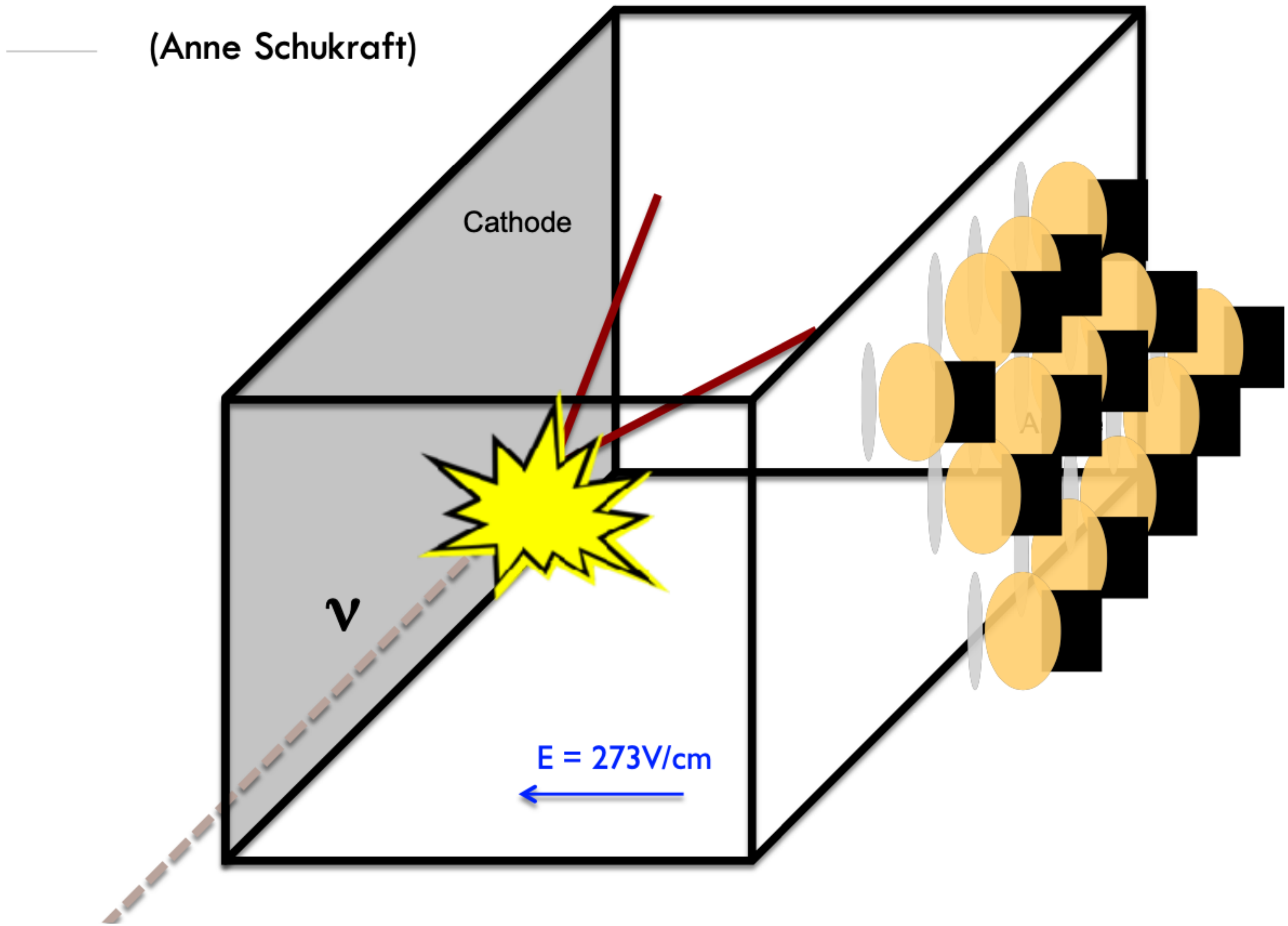
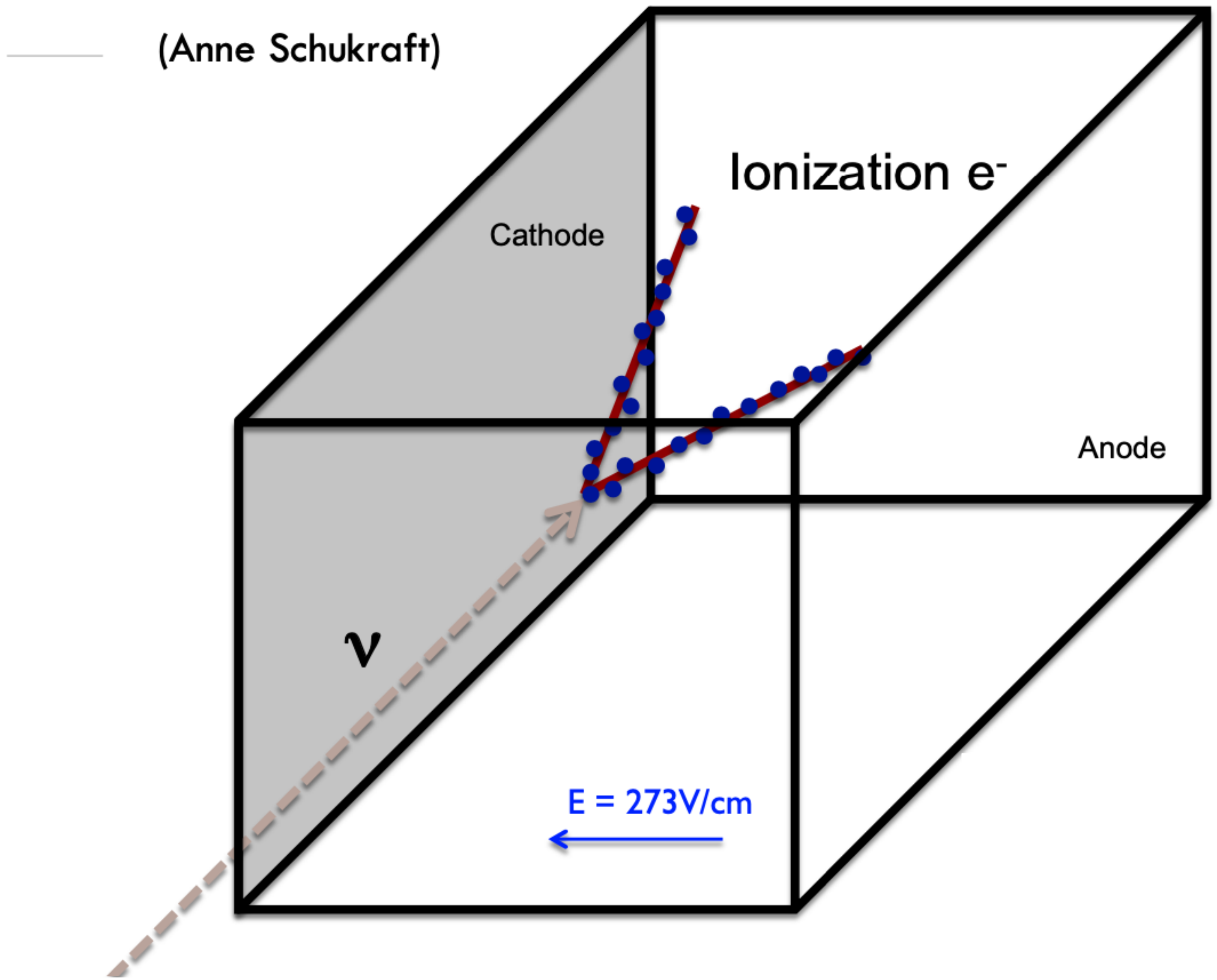


from your modern physics, what is the name of this effect?
photoelectric effect!

Liquid Argon Time Projection Chamber Example



Liquid Argon Time Projection Chamber Example



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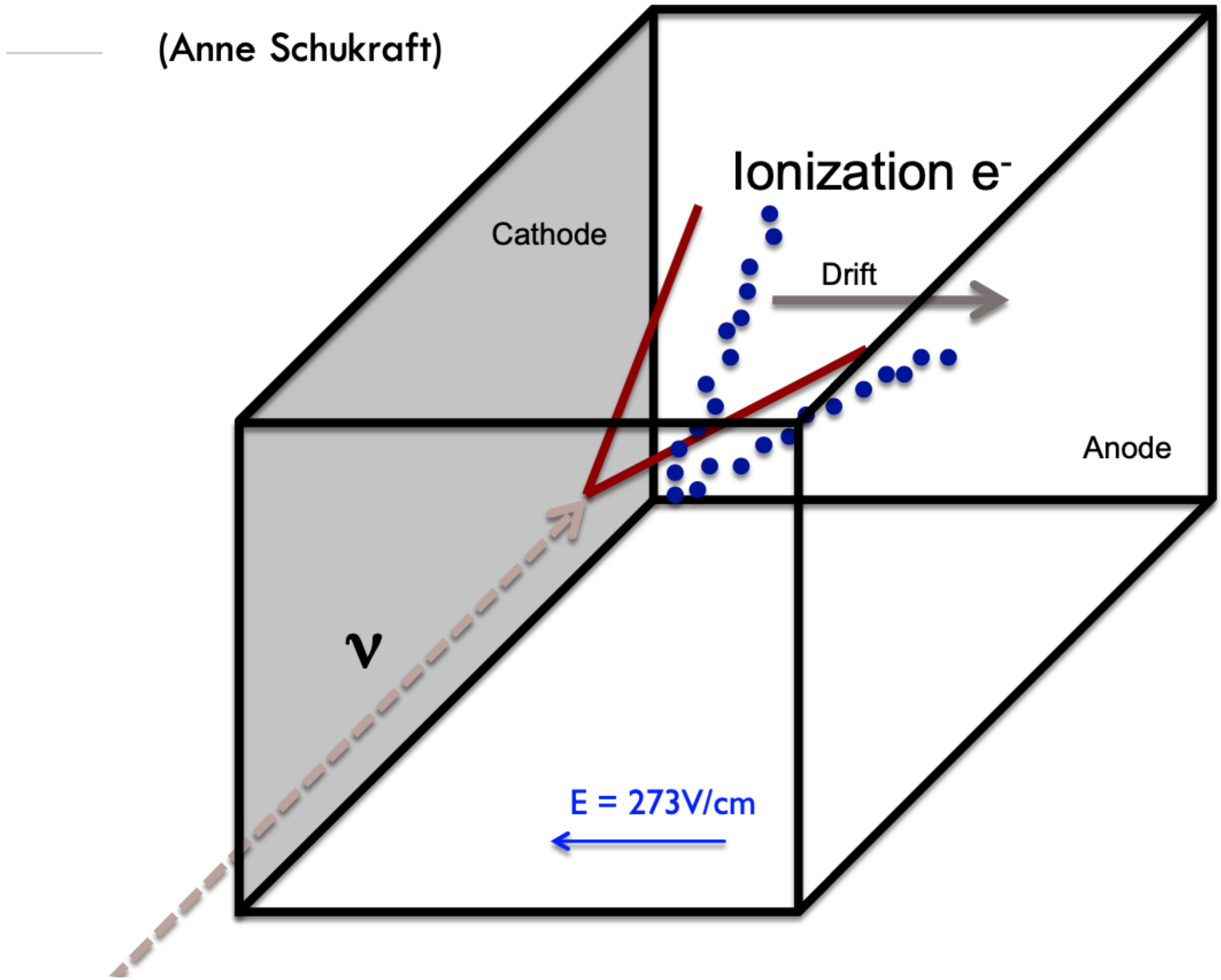
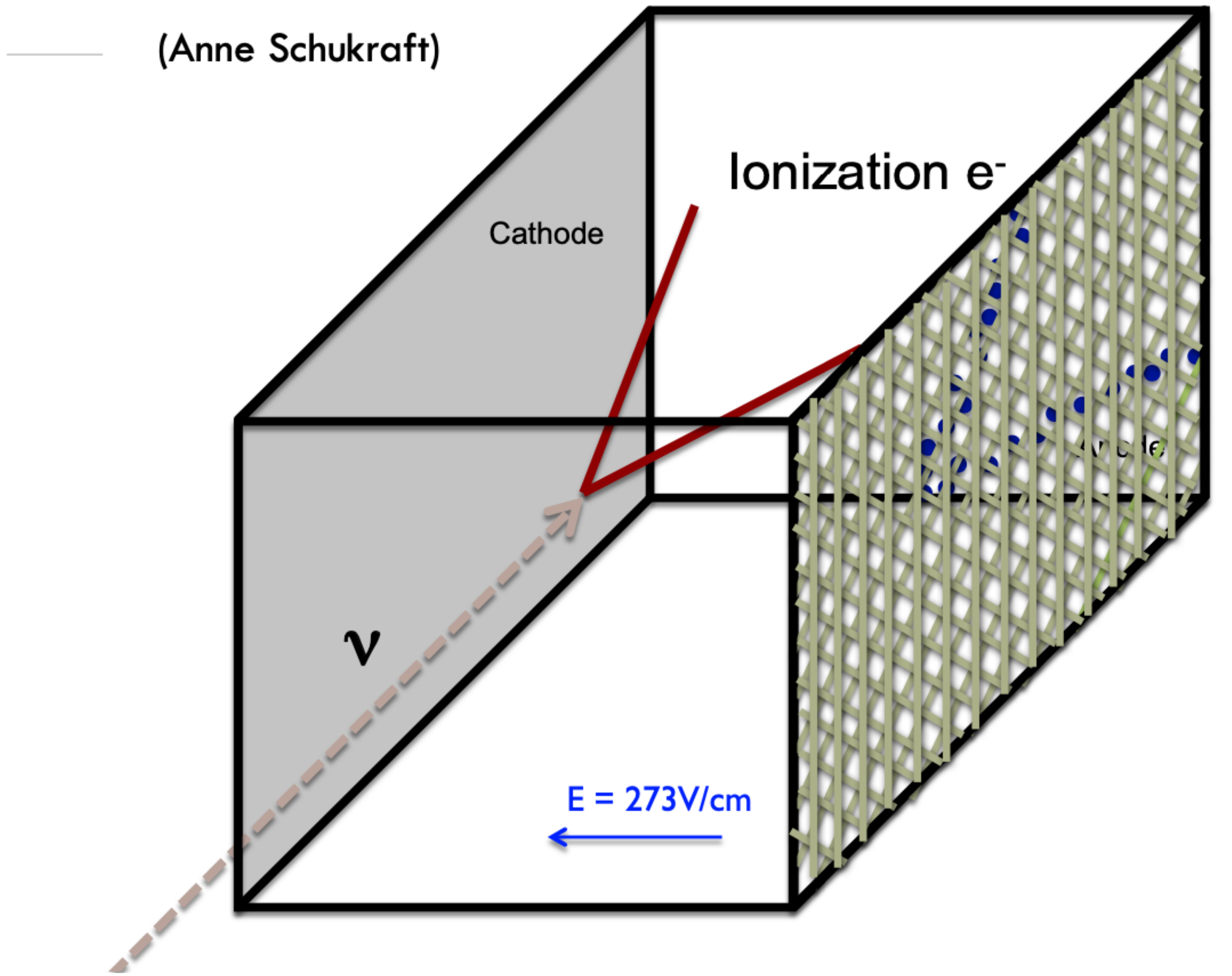


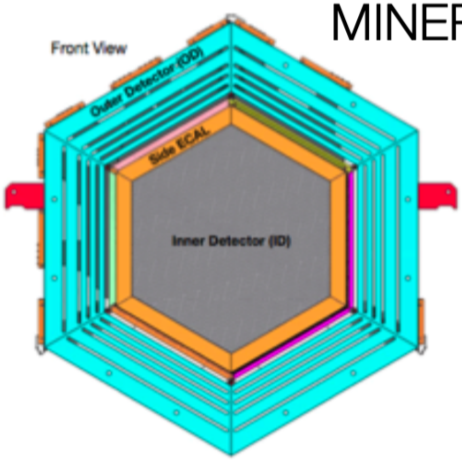
Liquid Argon Time Projection Chamber Example



Neutrino Detectors at Fermilab

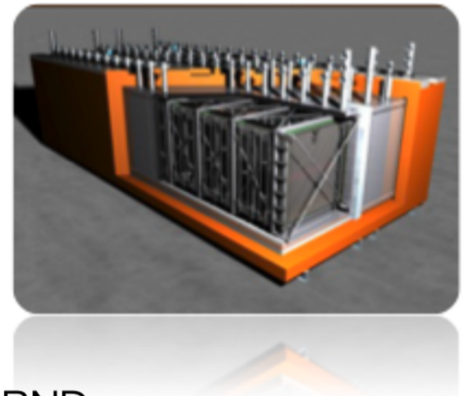
- Most of the existing and future Fermilab experiments use time projection chamber, TPC detector technologies & scintillators

MINERvA

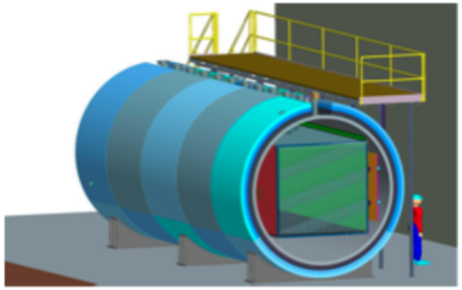


Carbon, iron, lead, helium, water

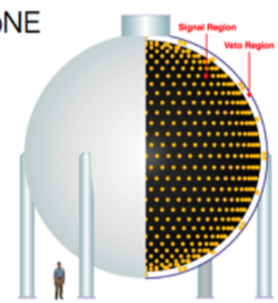
ICARUS

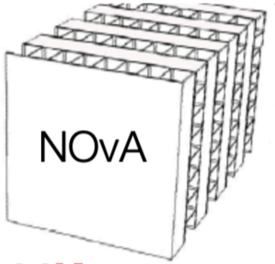


MicroBooNE



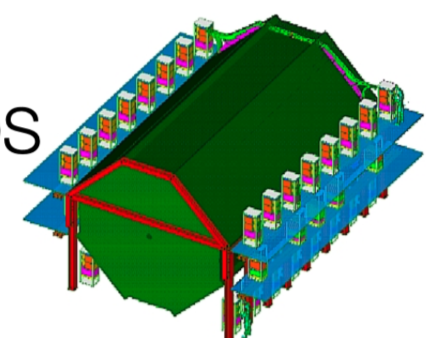
MiniBooNE



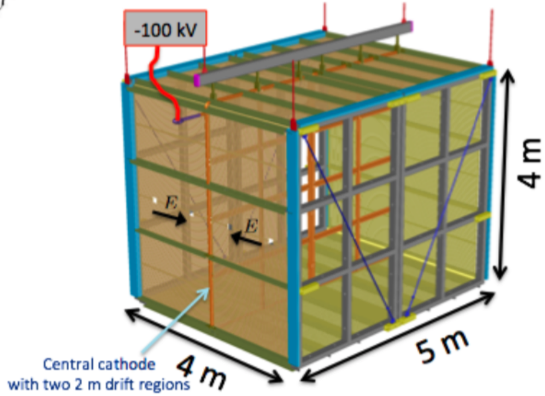


14Kton

MINOS



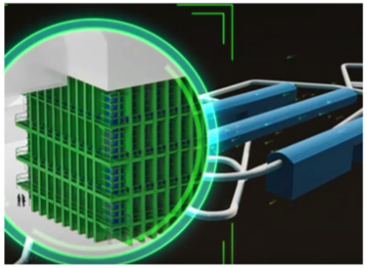
SBND

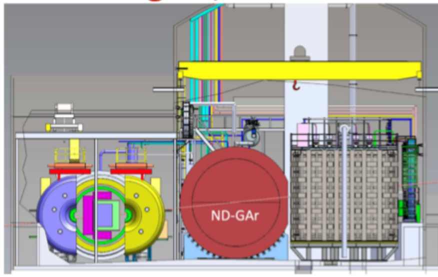


DUNE

40Kton

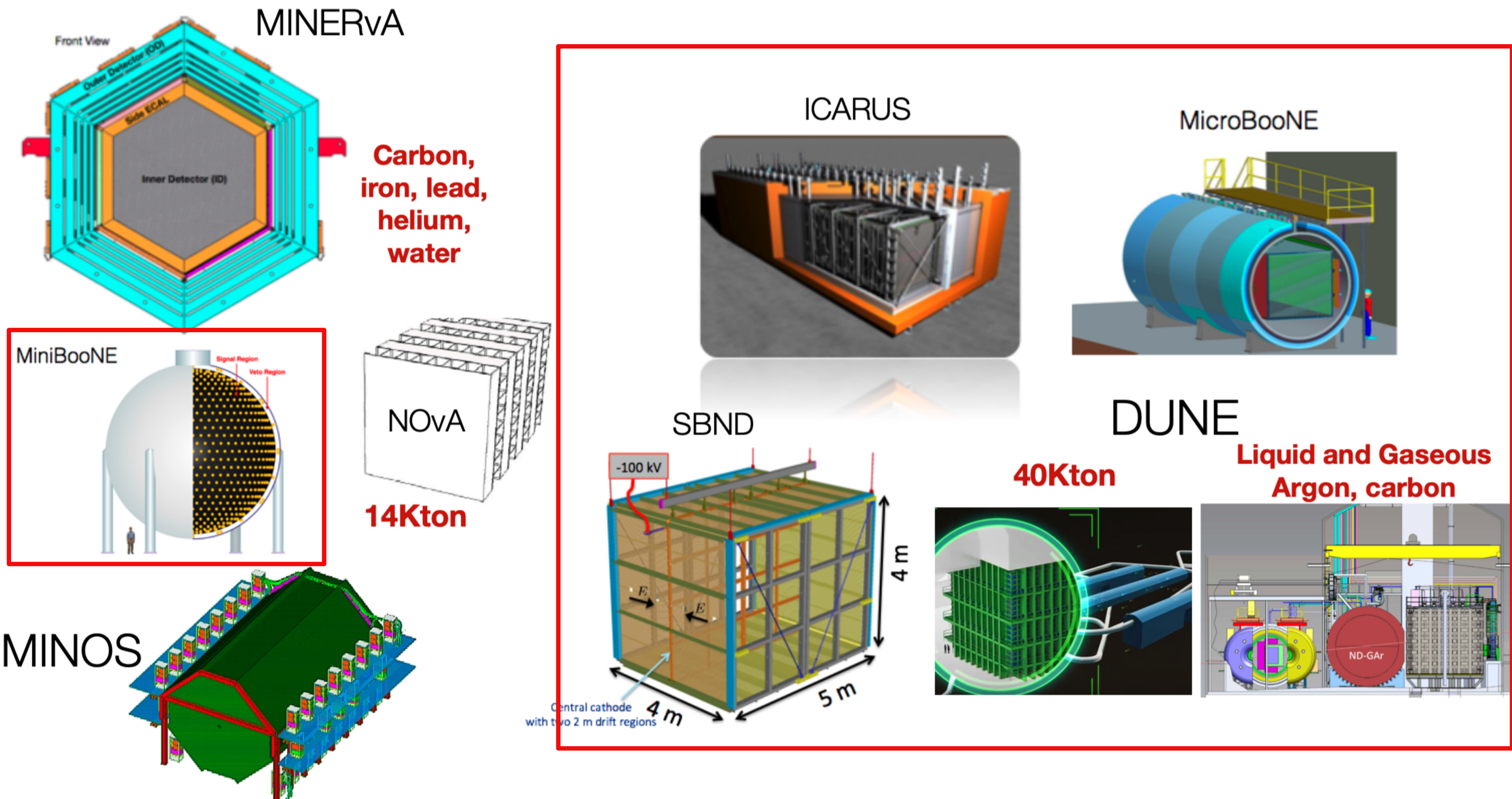
Liquid and Gaseous Argon, carbon





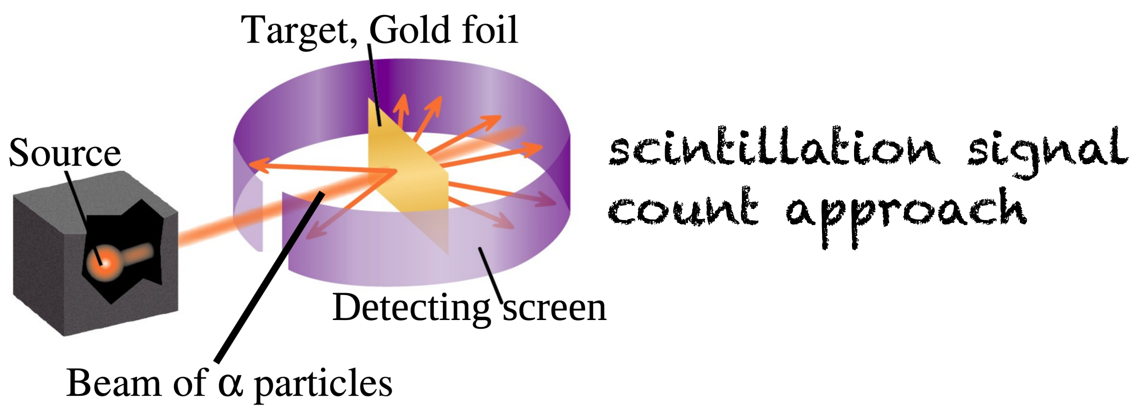
Neutrino Detectors at Fermilab

- Most of the existing and future Fermilab experiments use **time projection chamber, TPC detector technologies** & scintillators

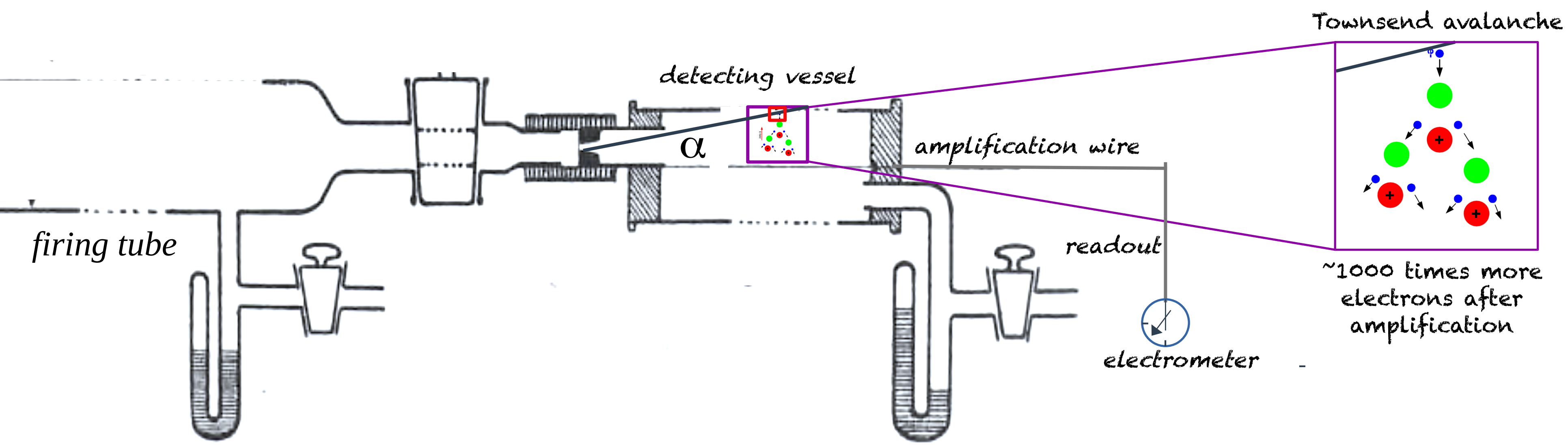


A History of Time Projection Chambers

- Everything started from Ernest Rutherford + Hans Geiger:
  - Extended the scintillation signal count approach as done with Rutherford + Geiger + Marsden setup



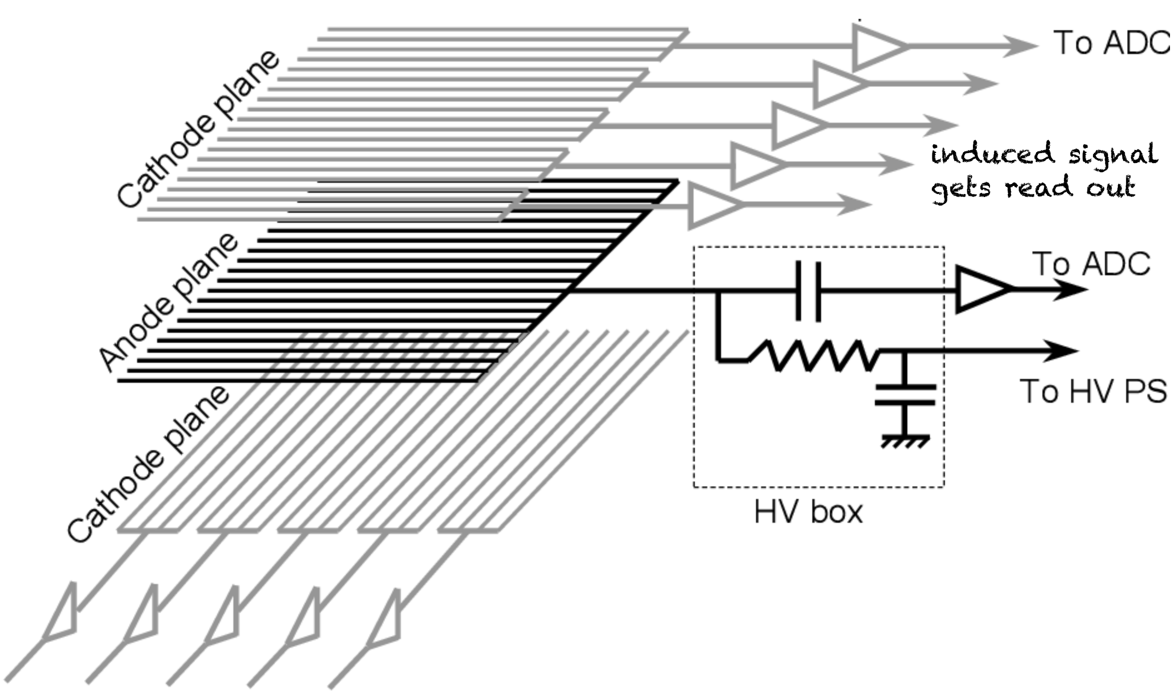
  - Adapted the technique from Townsend to amplify the ionization electron & "electrically" count αs

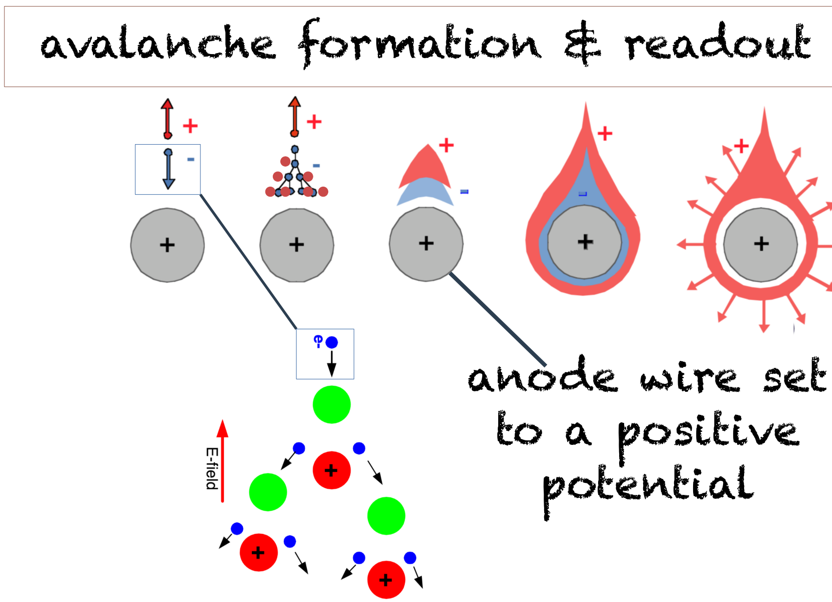


*J.S. Townsend, On the conductivity of gases exposed to negative ions, Proc. Roy. Soc. 1 (sixth series, #2) (1901). Also in issues of June 1902; April, Sept., Nov., 1903.
E. Rutherford, F.R.S., H. Geiger, An electrical method of counting the number of α-particles from radio-active substances, Proc. Roy.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

A History of Time Projection Chambers

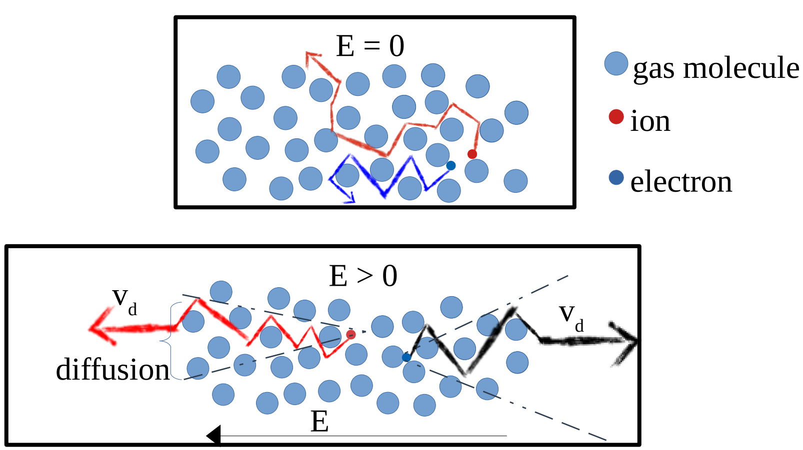
- Invention of Multi-wire Proportional Chamber, **MWPC** by Georges Charpak:
  - Amplification wires (“anode”) sandwiched between two cathode planes
  - Signal read out is typically induced charge on the pads

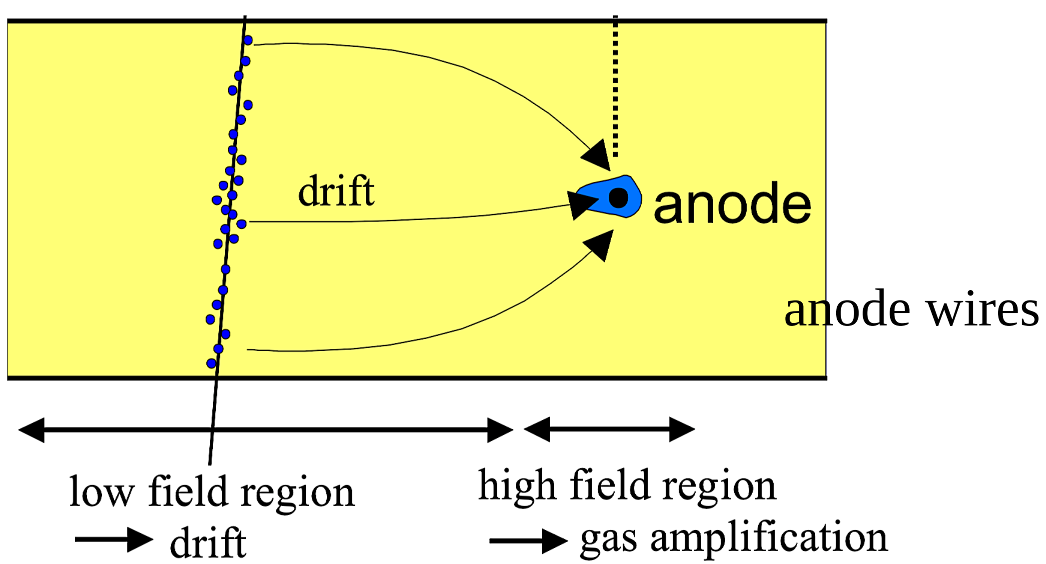




A History of Time Projection Chambers

- 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)

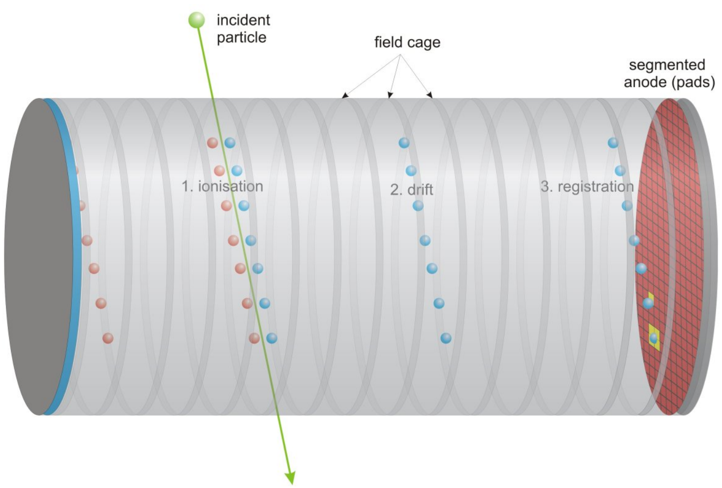


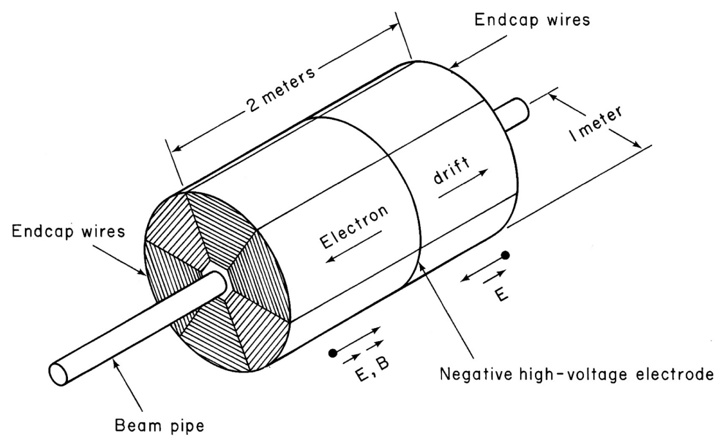


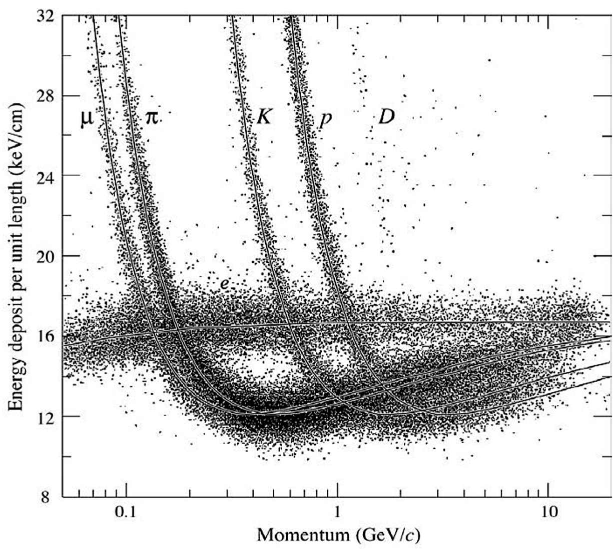
A History of Time Projection Chambers

Townsend + Rutherford-Geiger 1903 1908 — next breakthroughs — Charpak et al. 1968-69 — Nygren 1976

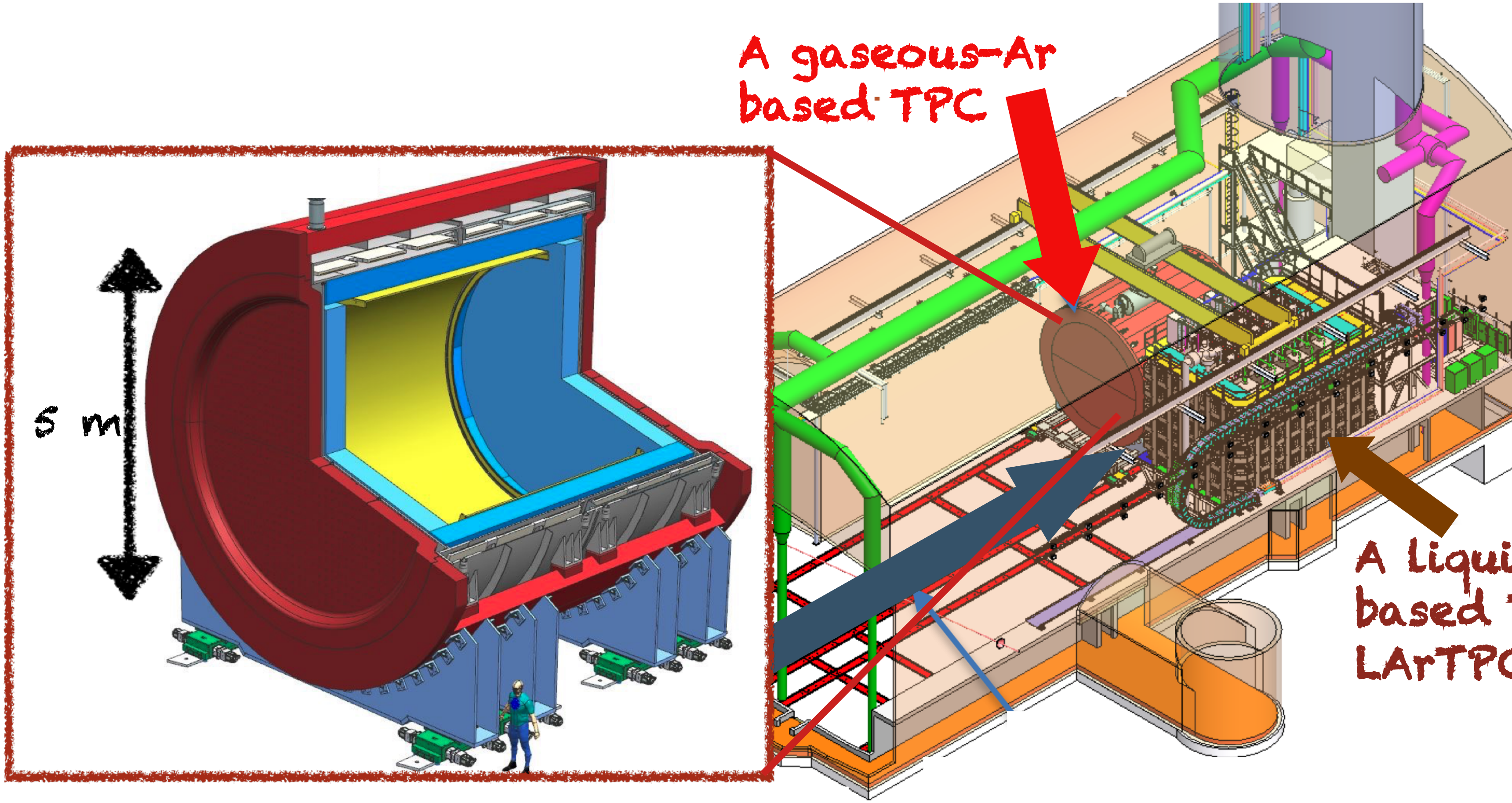
- Invention of Time Projection Chamber, TPC by David Nygren:
  - B-field oriented || to E-field, readout chambers placed at the ends
  - First large-scale realization in Positron Electron Project, PEP-4 TPC at SLAC:
    - Pressurized gas medium @ 8.5 bar, excellent PID







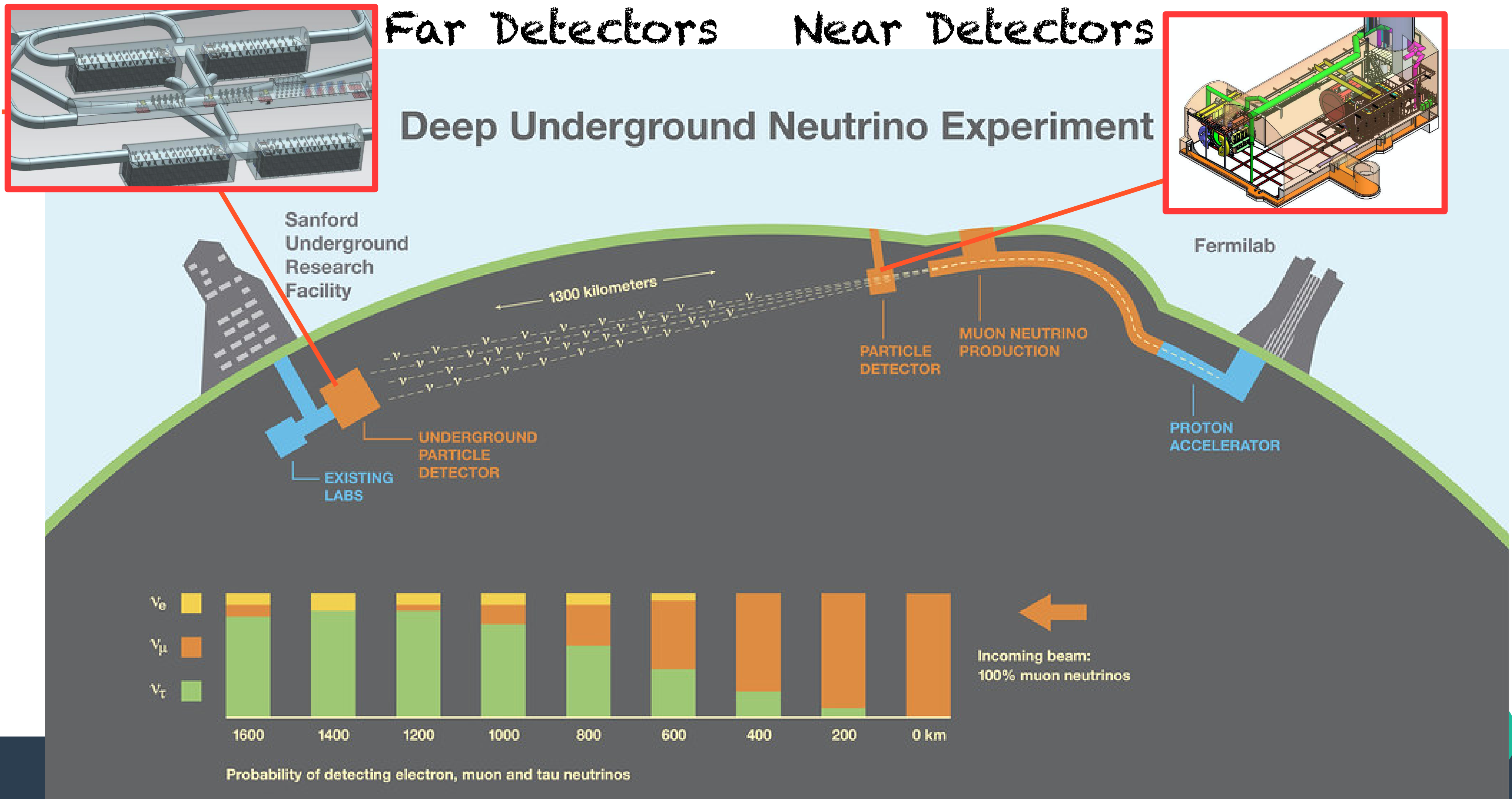
A Gaseous Argon-based TPC for DUNE



- An elaborate near detector complex for DUNE includes **a high pressure (similar pressure to the PEP-4 TPC) gaseous argon time projection chamber (HPgTPC)** surrounded by a another detector component and a magnet

DUNE's LArTPCs

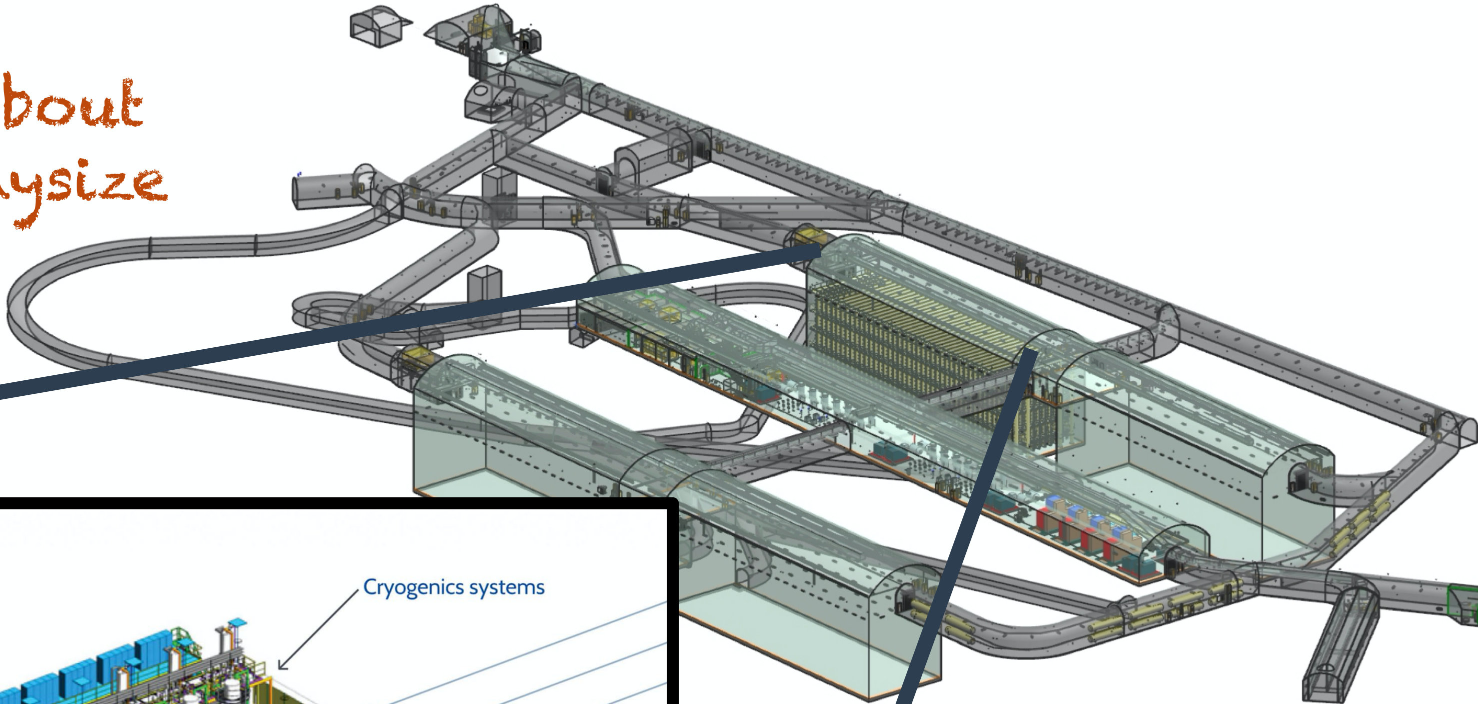
- DUNE is a neutrino oscillation experiment (as introduced by Louise Suter!) with two sets of detectors
  - ★ Far detectors are four LArTPC modules
  - ★ Near detector, in addition to a gaseous-Ar based TPC, includes a LArTPC

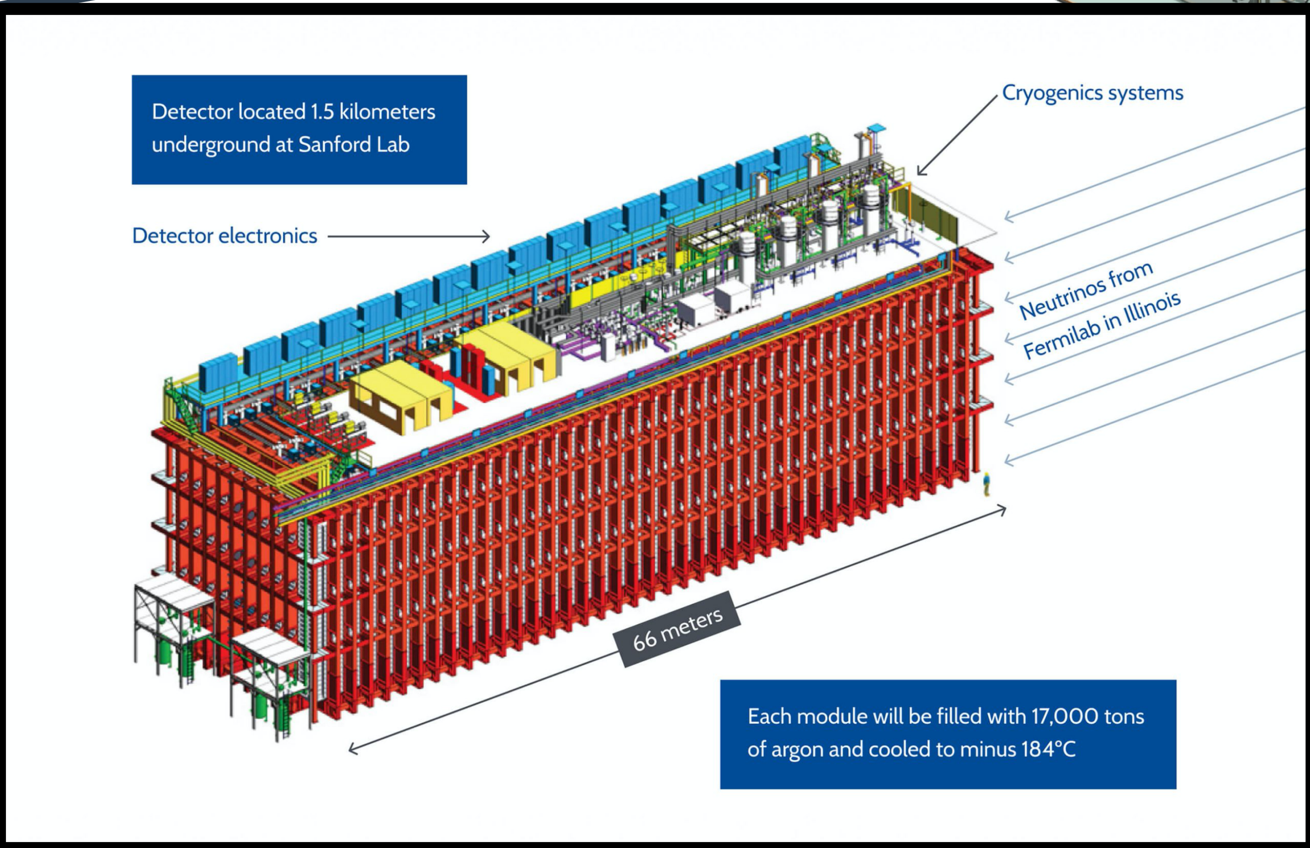


DUNE’s LArTPCs

Liquid Argon Time Projection Chamber, LArTPC modules

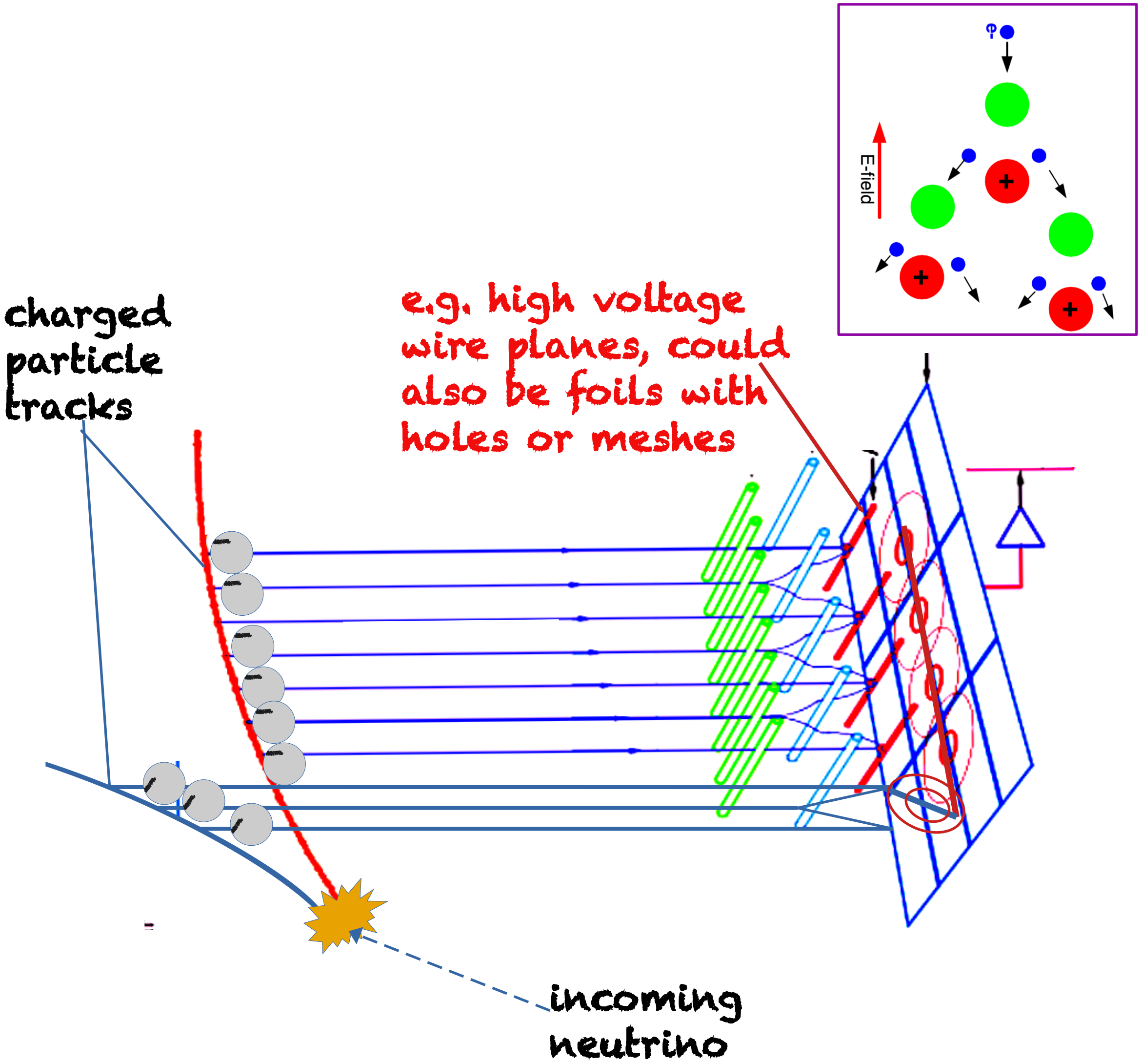
Each module is about the size of a Handysize Cargo ship





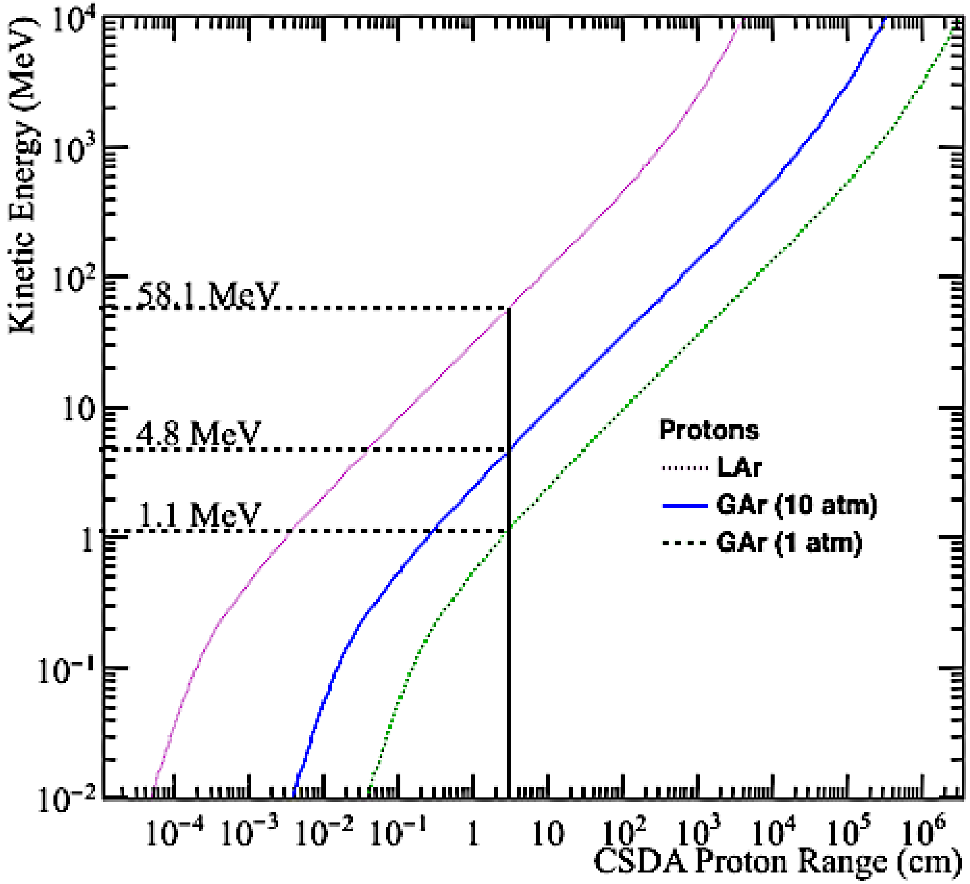
LArTPC and HPgTPC

- As you've already heard, gaseous TPCs, they are similar to a liquid argon TPC, but can be magnetized & have a readout system that can be tuned to multiply the original ionization electron by a certain factor, the larger the factor, the lower the threshold of the detector



LArTPC and HPgTPC

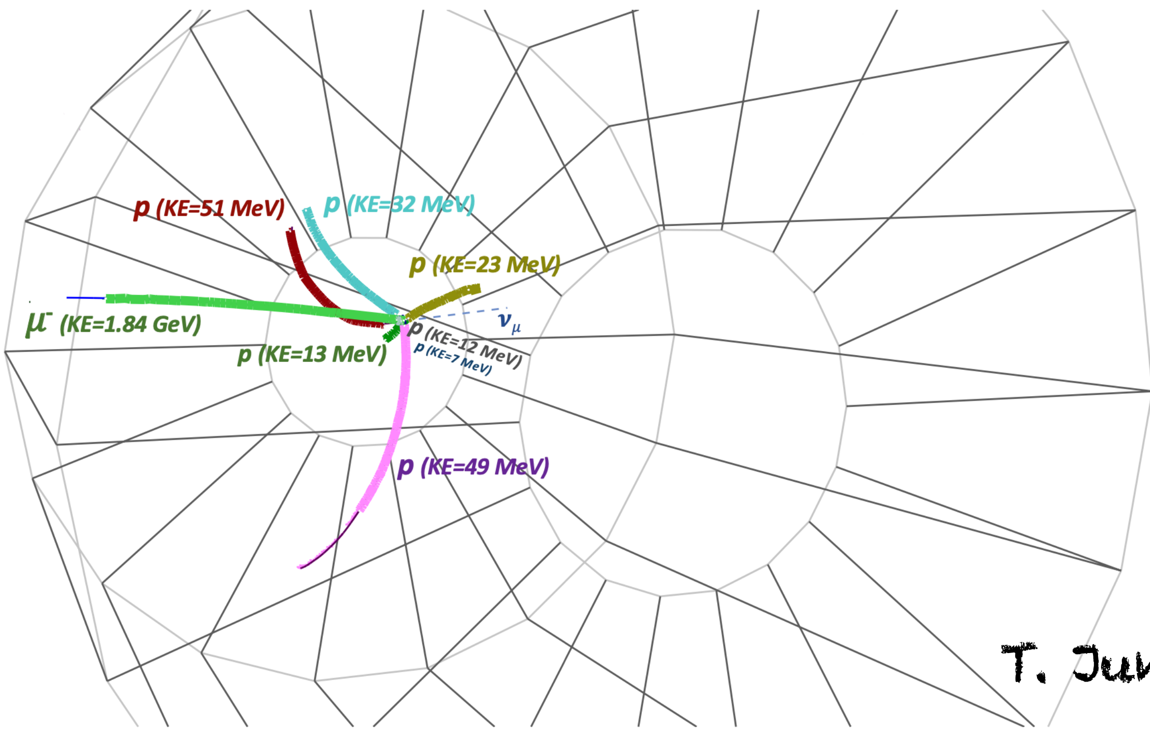
- Thanks to its low density medium ($\rho_{LAr}/\rho_{GAr} \approx 85$ for pressurized gas argon), **HPgTPC** will have a lower detection threshold than a **LArTPC:**
  - ★ Leads to high sensitivity to low energy protons or pions



LArTPC and HPgTPC

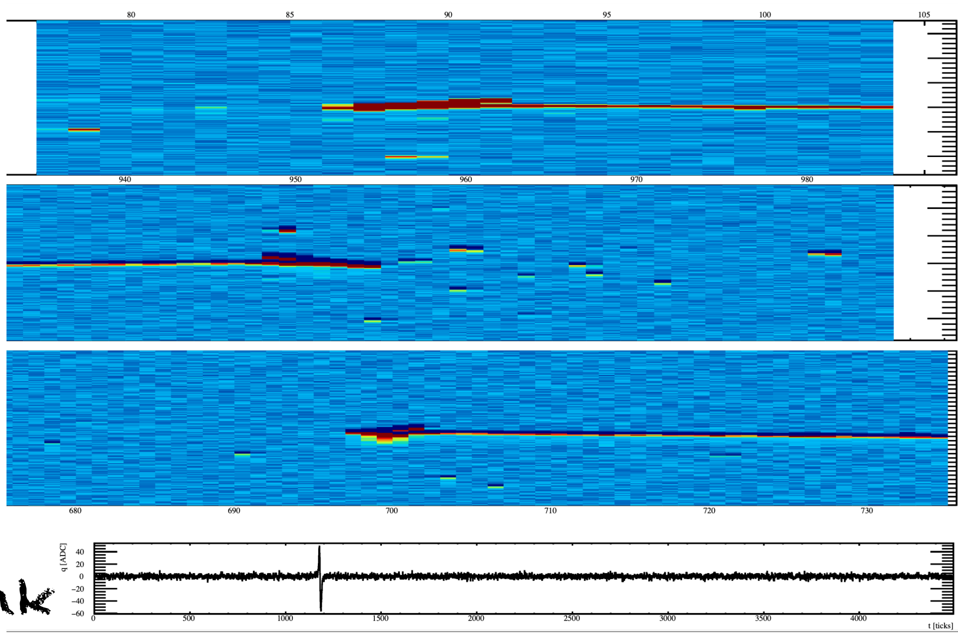
- Comparing the same neutrino interaction that results in 7 protons
  - In HPgTPC, we can reconstruct low energy protons that escape detection in a LArTPC, provides a data-driven constraint on uncertainties in estimating the neutrino energy

DUNE's High Pressure gas TPC



from the DUNE software, GArSoft with end-to-end reconstruction

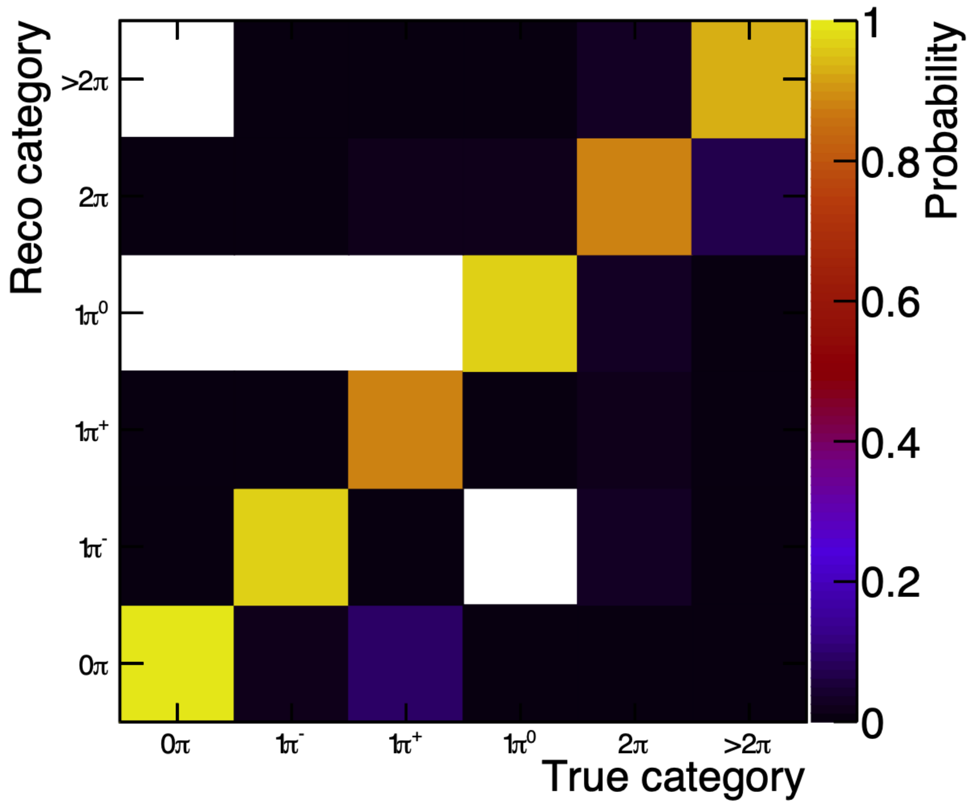
same simulated neutrino event with 7 protons in a LArTPC

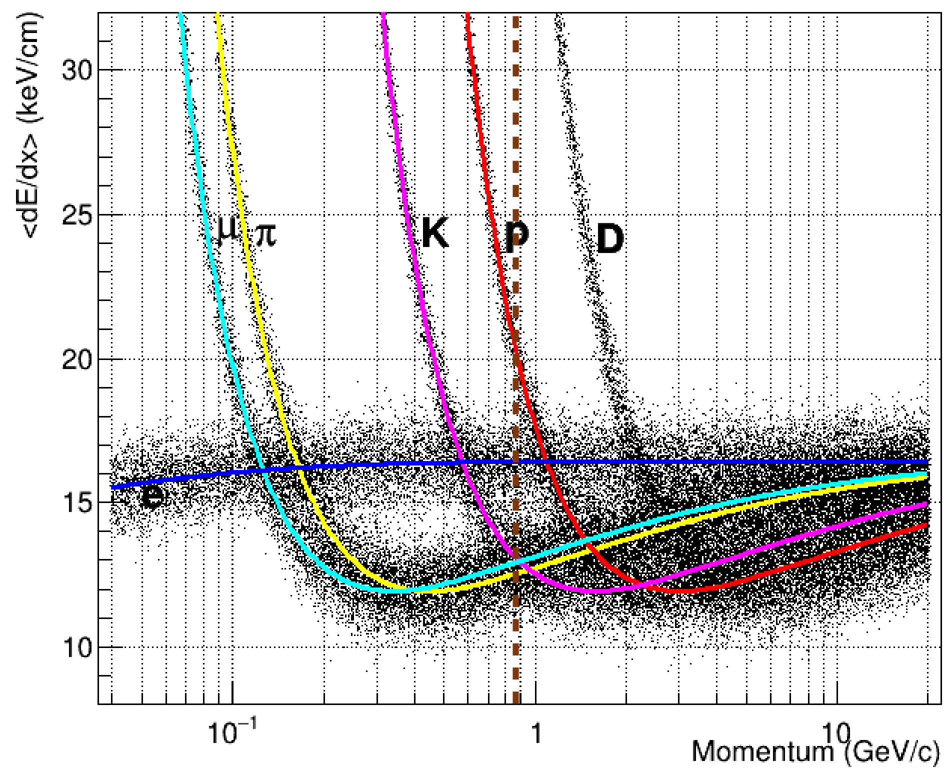


T. Junk

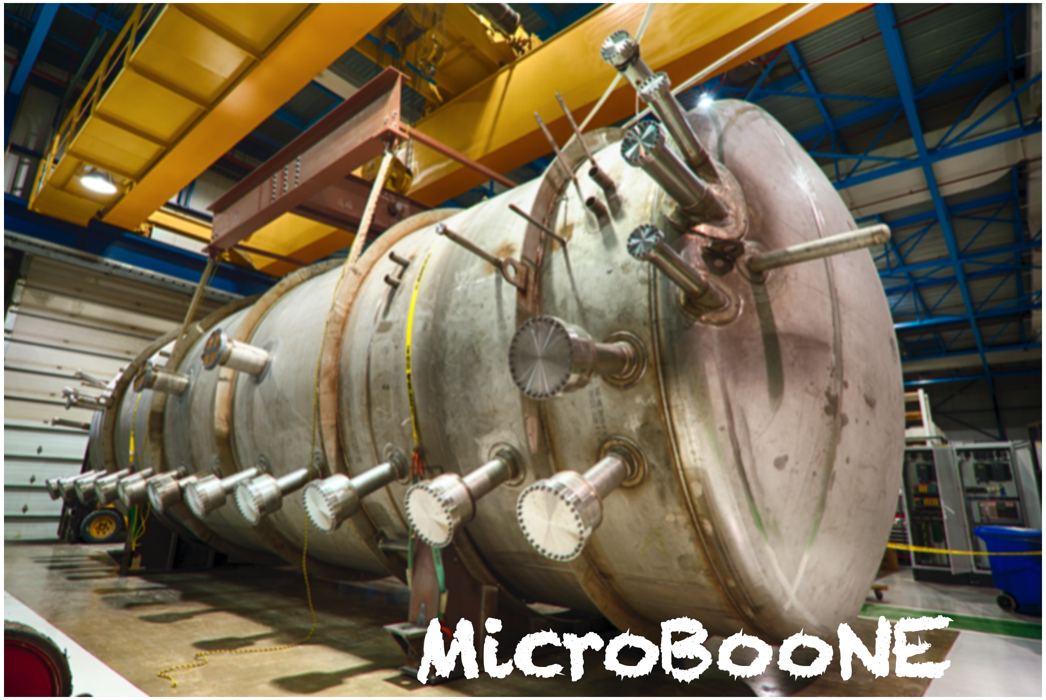
LArTPC and HPgTPC

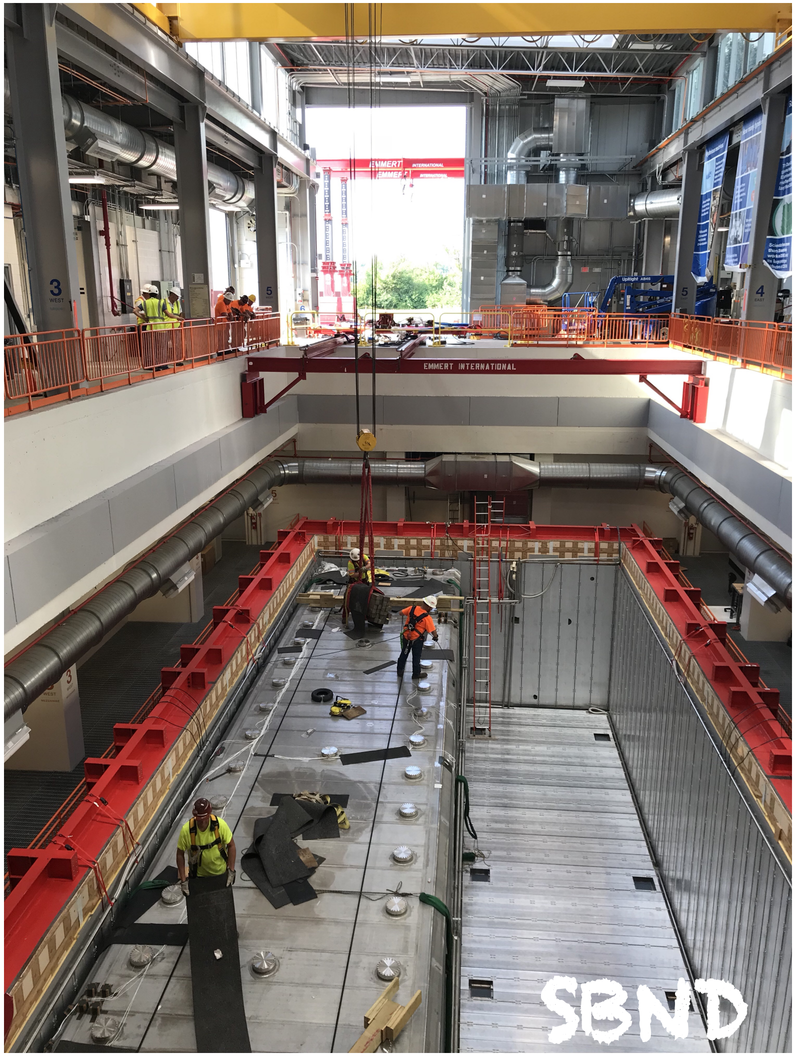
- Excellent PID capabilities:
  - PEP-4-like:
    - e.g. can be used to select ν interactions with multiple πs in the final states of the interaction





Existing LArTPCs @ Fermilab





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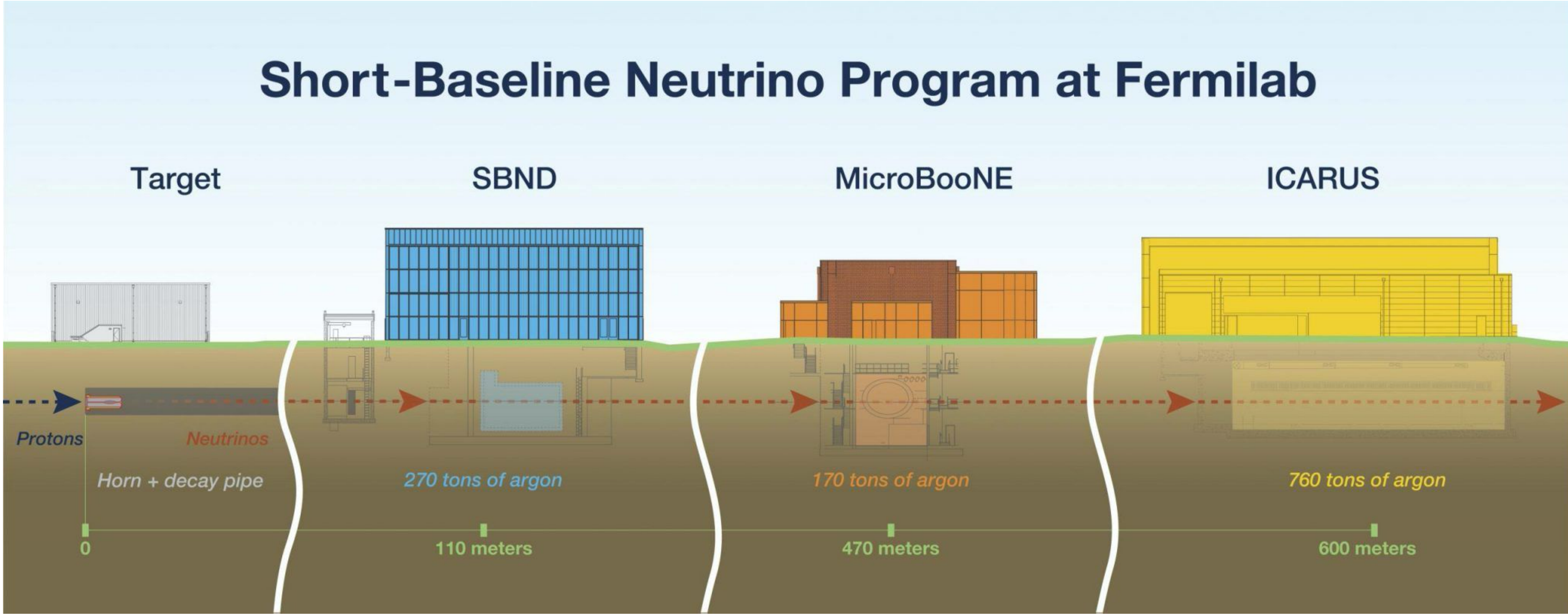
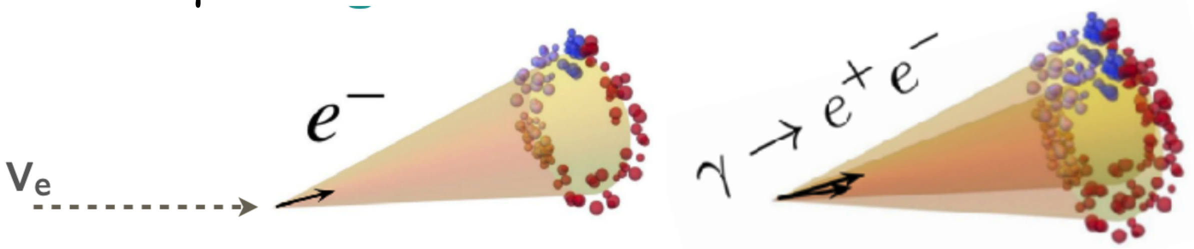
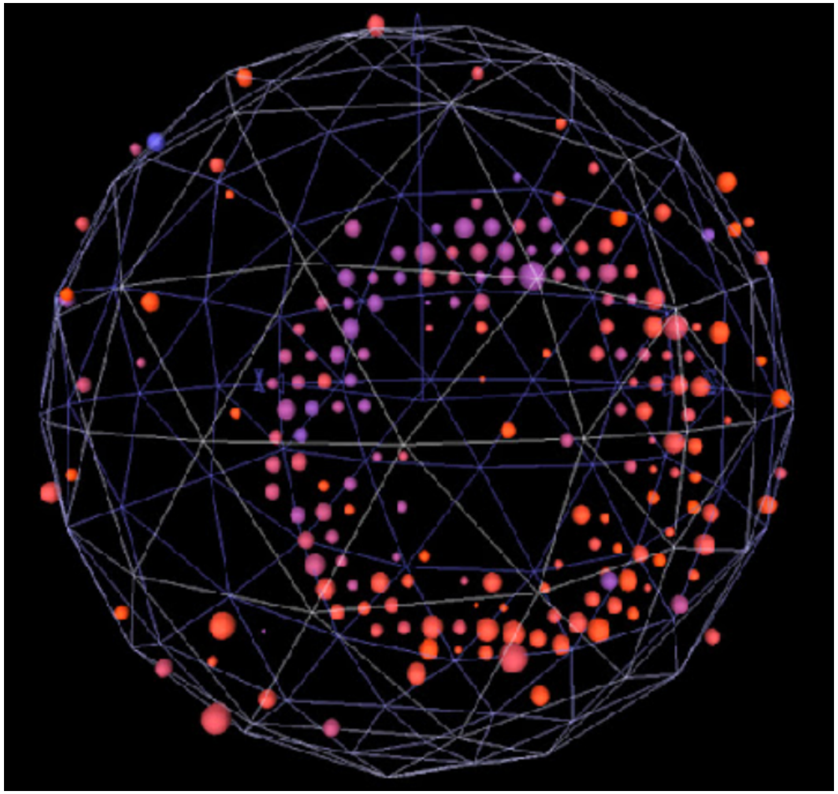
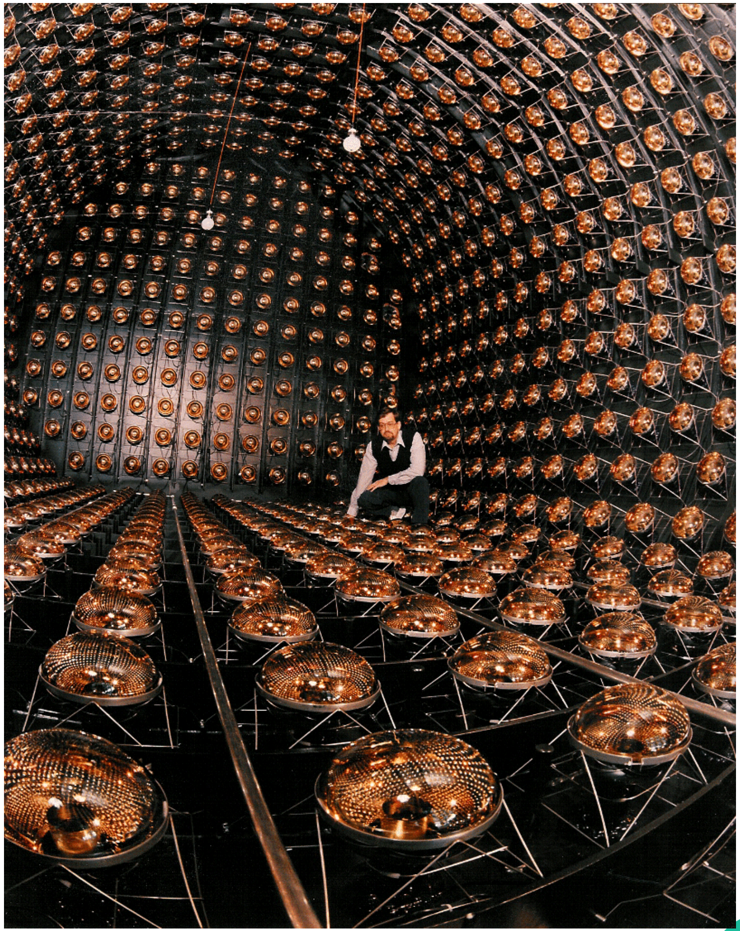


SBN Program Goal

- The MiniBooNE experiment, an experiment in the same ν beam as the SBN program, used Cherenkov detector technology and was filled with mineral oil
  - Observed excess of electron events, but was unable to distinguish between electrons and γs to determine the source of the excess







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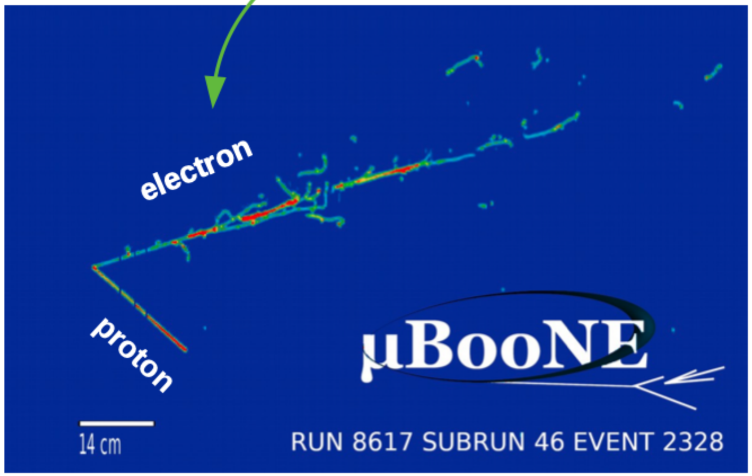
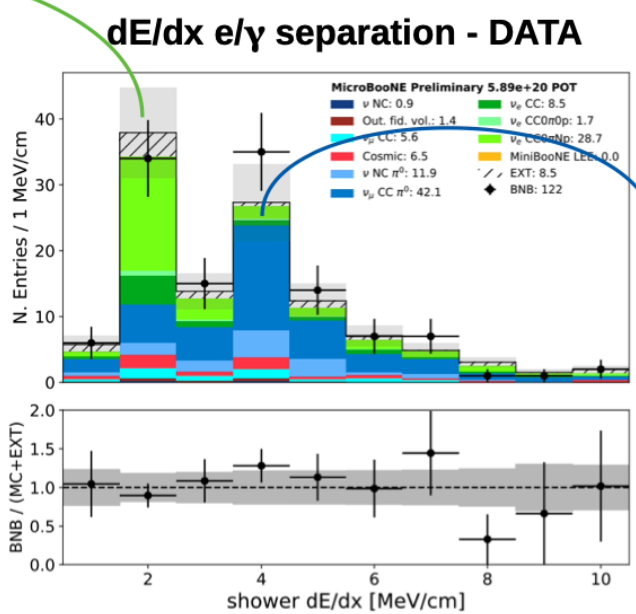
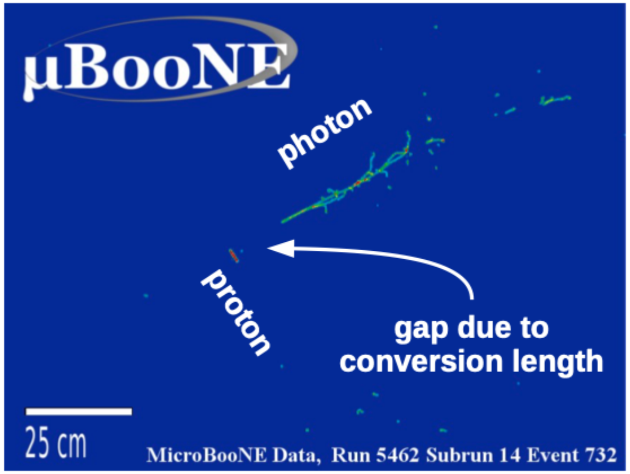
- SBN experiments rely on LArTPC technology which can more efficiently make the distinction between electrons and photons



D. Caratelli's talk at ICHEP20





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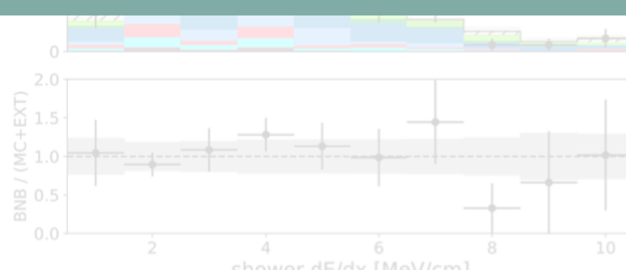


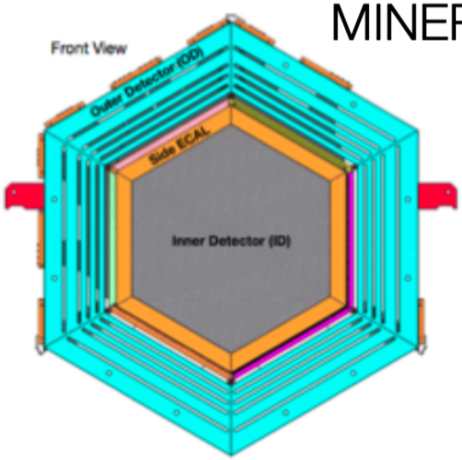
D. Caratelli's talk at ICHEP20

The impact of the choice of detector technology becomes evident in the example of the SBN detectors at Fermilab

Neutrino Detectors at Fermilab

- Most of the existing and future Fermilab experiments use time projection chamber, TPC detector technologies & **scintillators**

MINERvA



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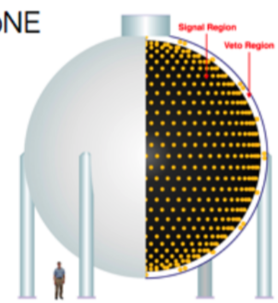
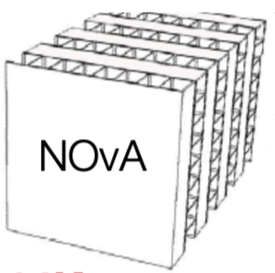
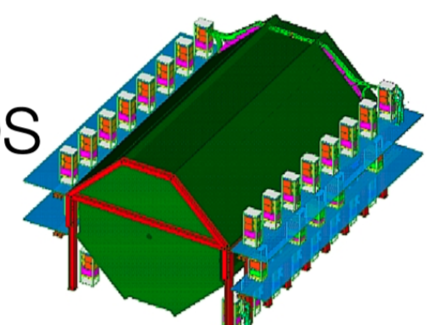




14Kton

MINOS



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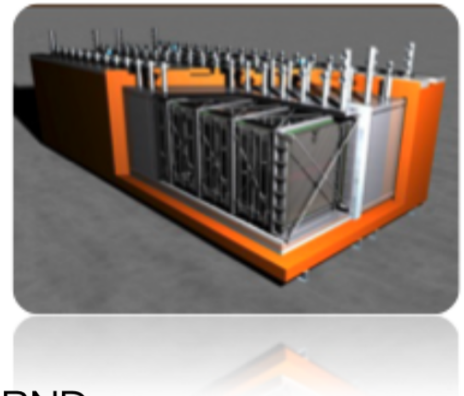

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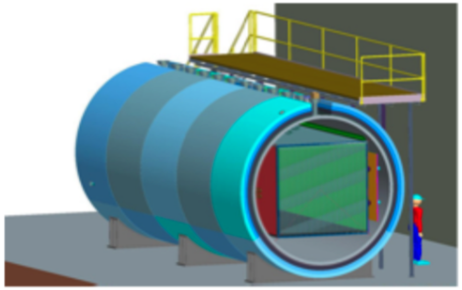

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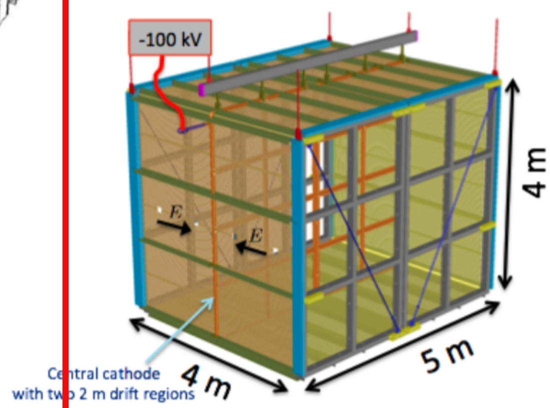

DUNE

40Kton

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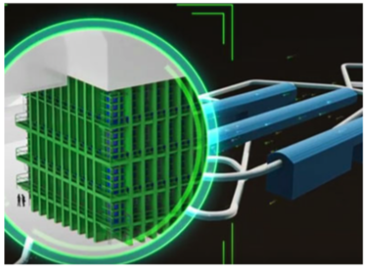
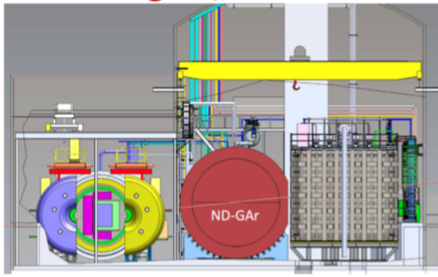
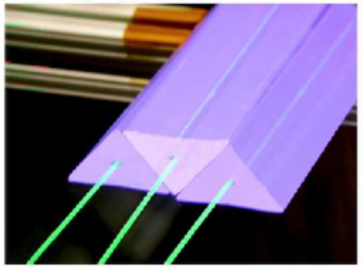
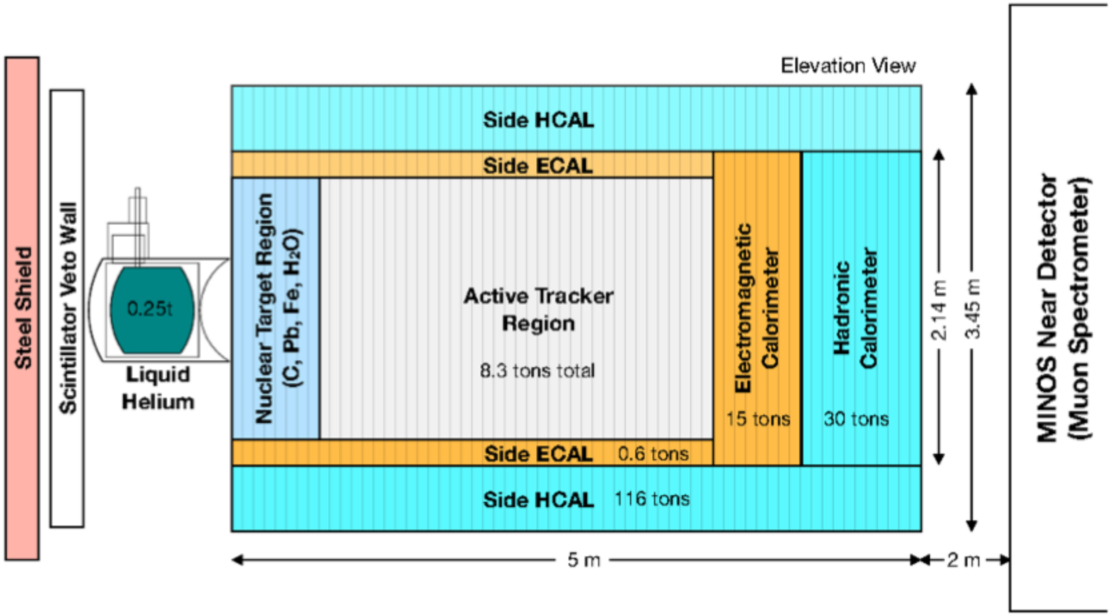


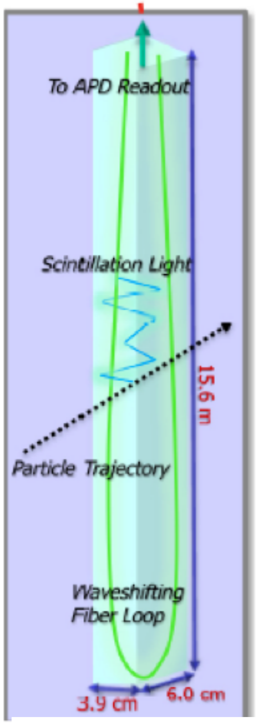


Other Detector Technologies @ Fermilab

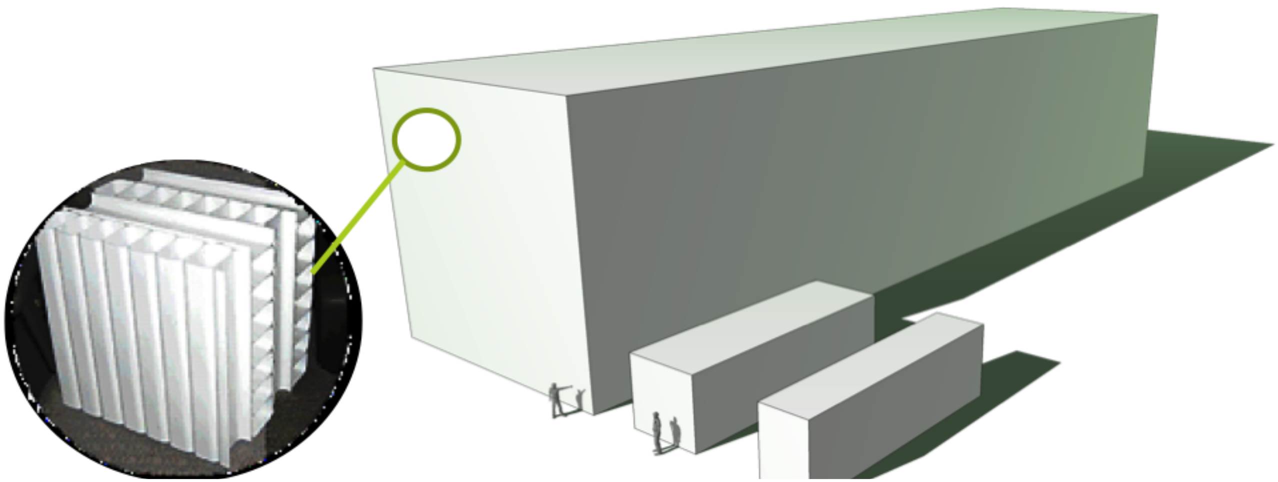


MINERvA



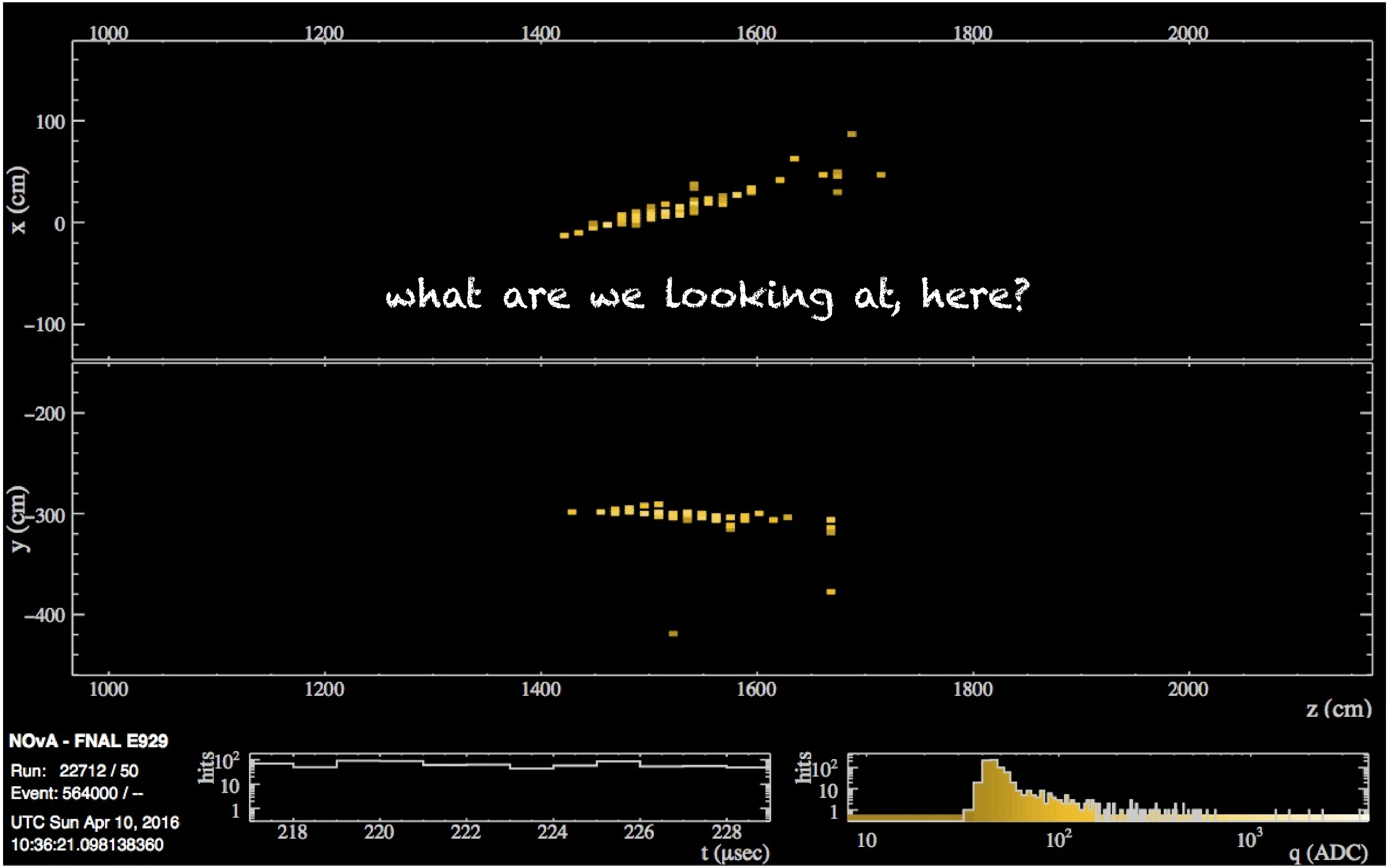


NOvA



Other Detector Technologies @ Fermilab

Electromagnetic shower in NOvA



Other Detector Technologies @ Fermilab

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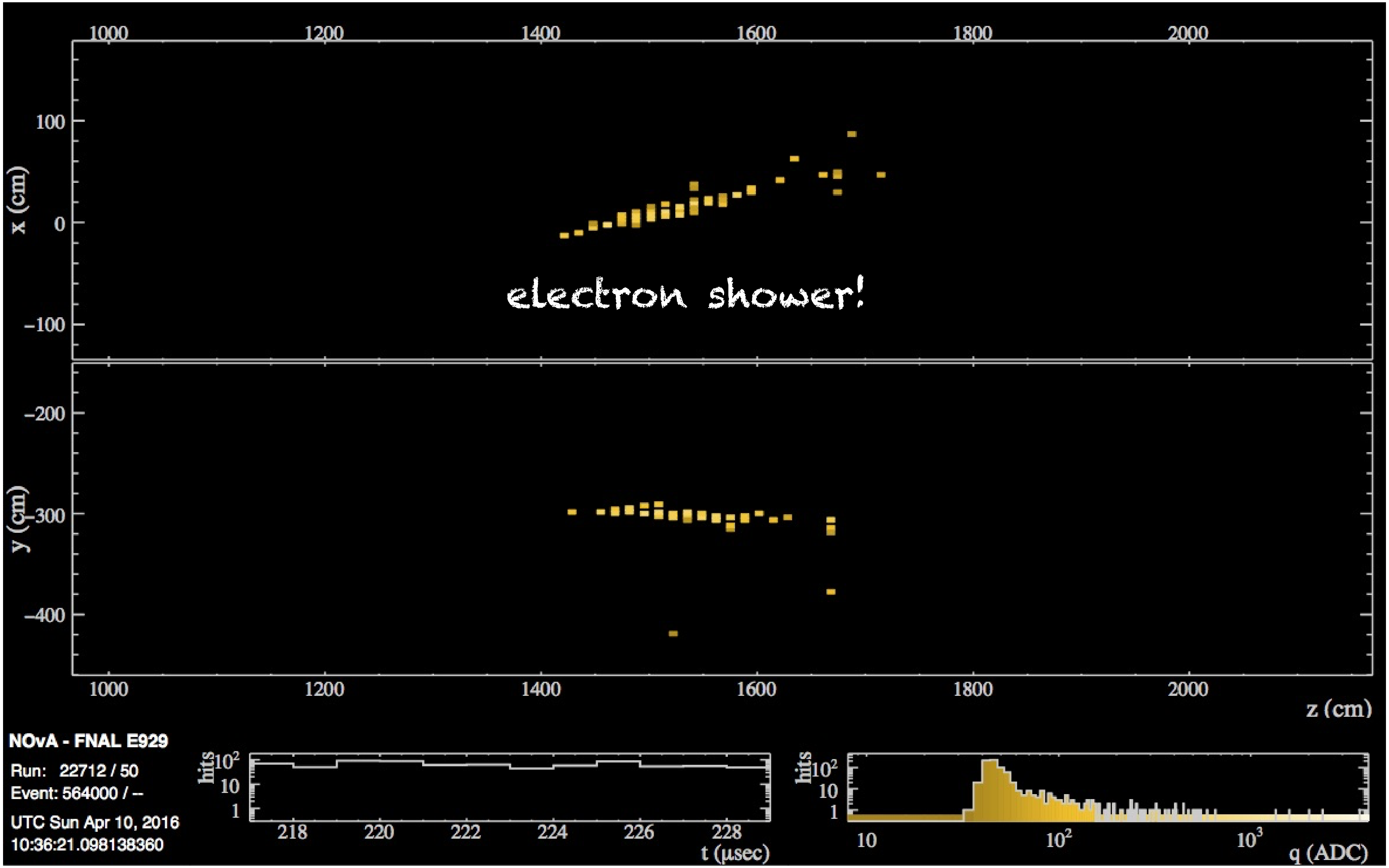

A few things to remember

- We cannot see neutrinos directly, instead we rely on outgoing particles losing energy via various processes in the detecting medium:
  - By extracting info such as energy loss per unit track length, track curvature, and particle's range, we can tell what type of particle we saw and what its momentum or energy was, thereby helping us determine the type and energy of the ν that interacted

- Depending on the physics that we're after and what source of neutrinos we want to see, we can build detectors that can enable a very precise look into these neutrino interactions & enable discovery-level physics:
  - Come build your favorite detector!

Questions are welcome!

contant: mtanaz@fnal.gov

Additional Slides