Time Projection Chambers (TPCs) and applications

Ezra D. Lesser

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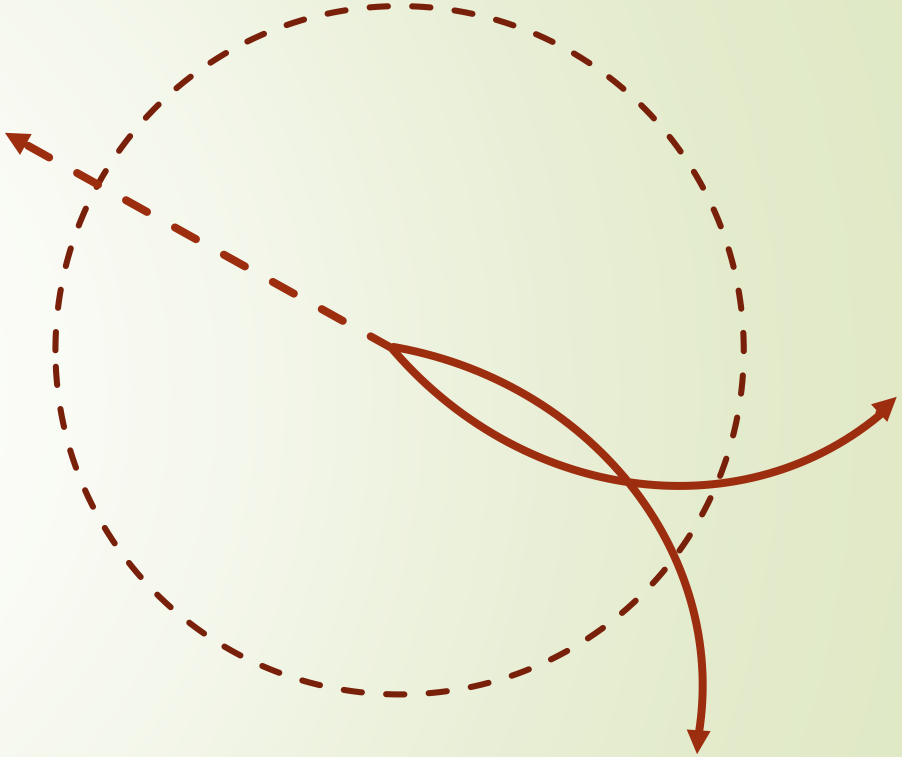
Physics 290E Seminar – Detectors & Experiments

Goals of particle detection & tracking

- Was there a particle(s)?
- What was its trajectory (position)?
- What was its 4-momentum?
- What was its charge?
- With what uncertainty do we know the answer to these questions?



Some historical particle detectors

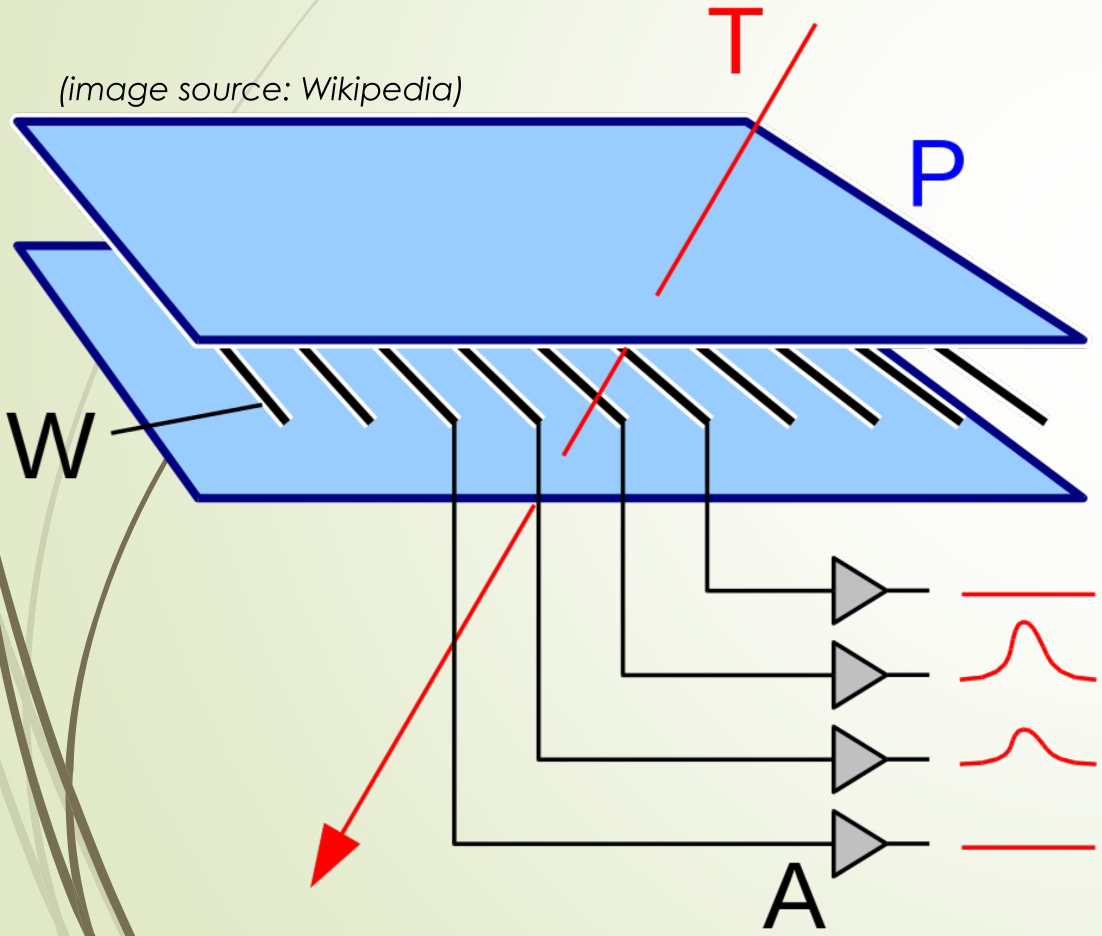
BEBC

- Cloud chamber (1920s-50s)
  - Discovery of positron, muon, & K meson
- Spark chamber (1930s-60s)
  - Layers of parallel plates which can be triggered to spark via HV along ionized tracks through gas
- Bubble chamber (1952-present)
  - Invented by Donald A. Glaser (Nobel Prize 1960)
  - Big European Bubble Chamber (BEBC) at CERN in use until 1984
    - Discovery of D meson
  - Used in some modern experimental searches for dark matter / WIMPs

Example cloud chamber

Wire chambers

- Developed by Georges Charpak at CERN in 1968 (Nobel Prize 1992)



(image source: Wikipedia)

- Gas ionization detector
  - Charged particle (T) traversing gas interacts electromagnetically with gas molecules
  - Creation of ion/electron pairs
  - Approximately constant applied electric field between wires (W) and grounding plates (P)
  - Electron/ions drift to wires, which is amplified and read out as a signal (A)
- Second plane of wires can be added in transverse direction to get 2D information

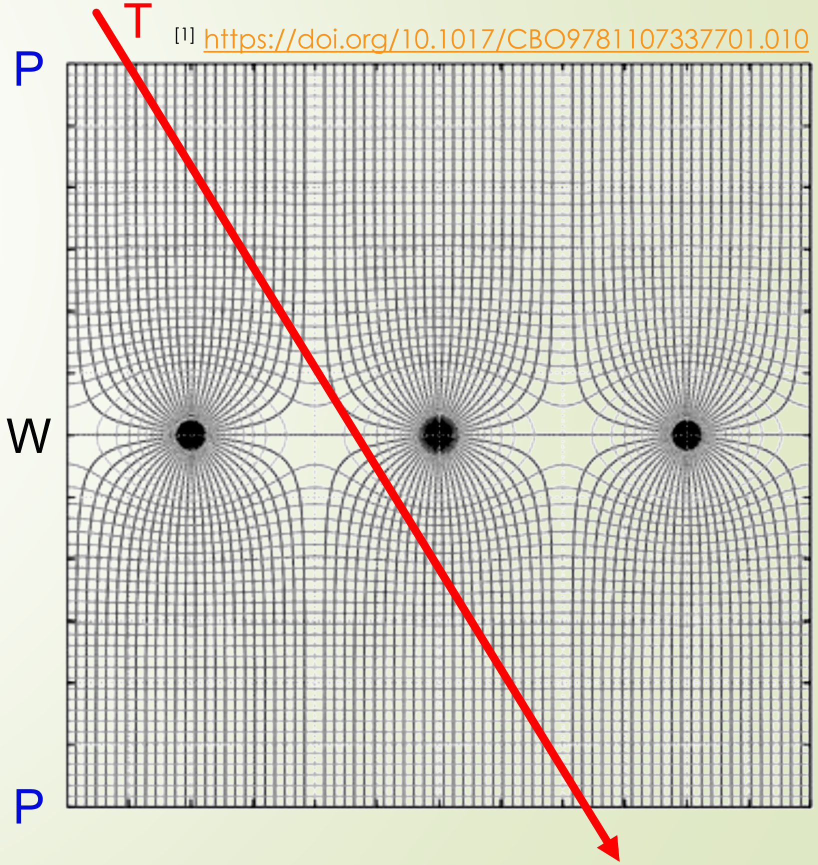
Signal amplification

- Electrons/ions first drift along approximately straight field lines

- Amplification happens in high-gradient area near the wires

- **Electron avalanche**
  - Original e^- has enough energy to create additional electron/ion pairs

- Capacitive coupling between nearby wires is largely negated by the positive signal induced on those wires by the avalanche [1]

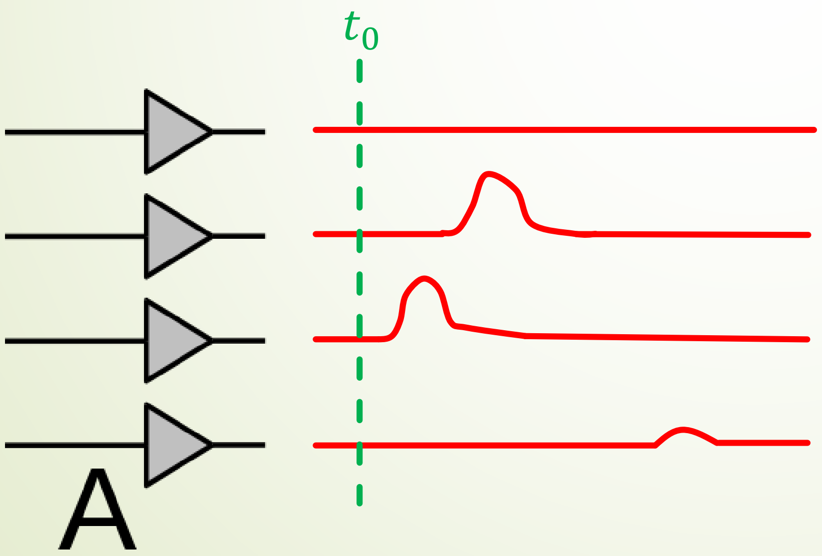


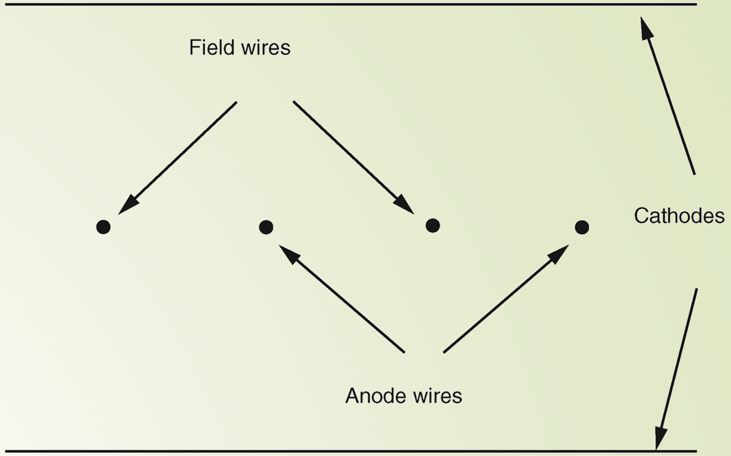
[1] https://doi.org/10.1017/CBO9781107337701.010

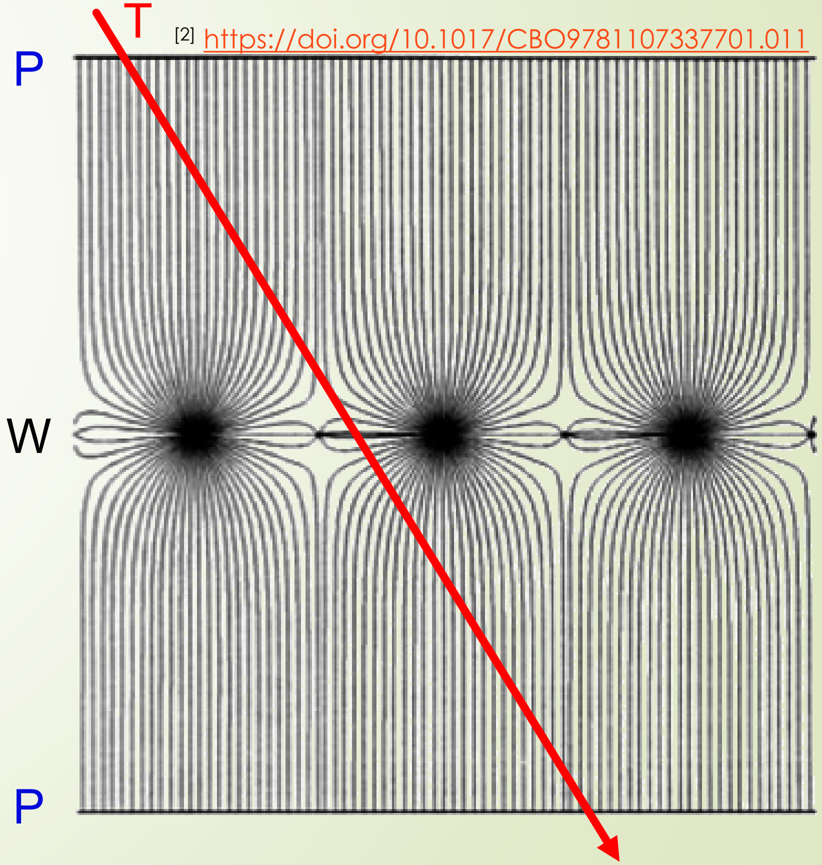
Drift chamber

- Also utilize the **timing** which is required for the electrons/ions to drift to the nearest wire

- Increases the accuracy of path reconstruction





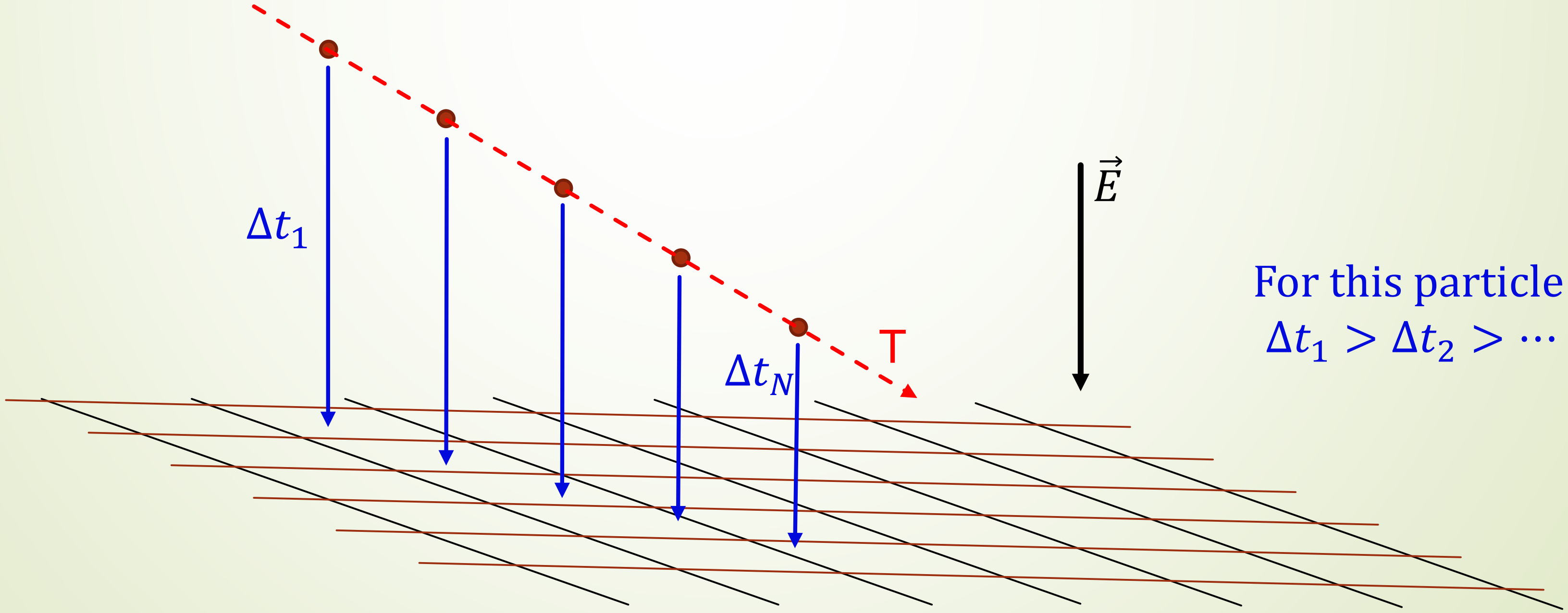


[2] https://doi.org/10.1017/CBO9781107337701.011

But how can we create a 3D image?

- Several layers of wire chambers
  - Can be expensive to reproduce the N chambers required for z-resolution

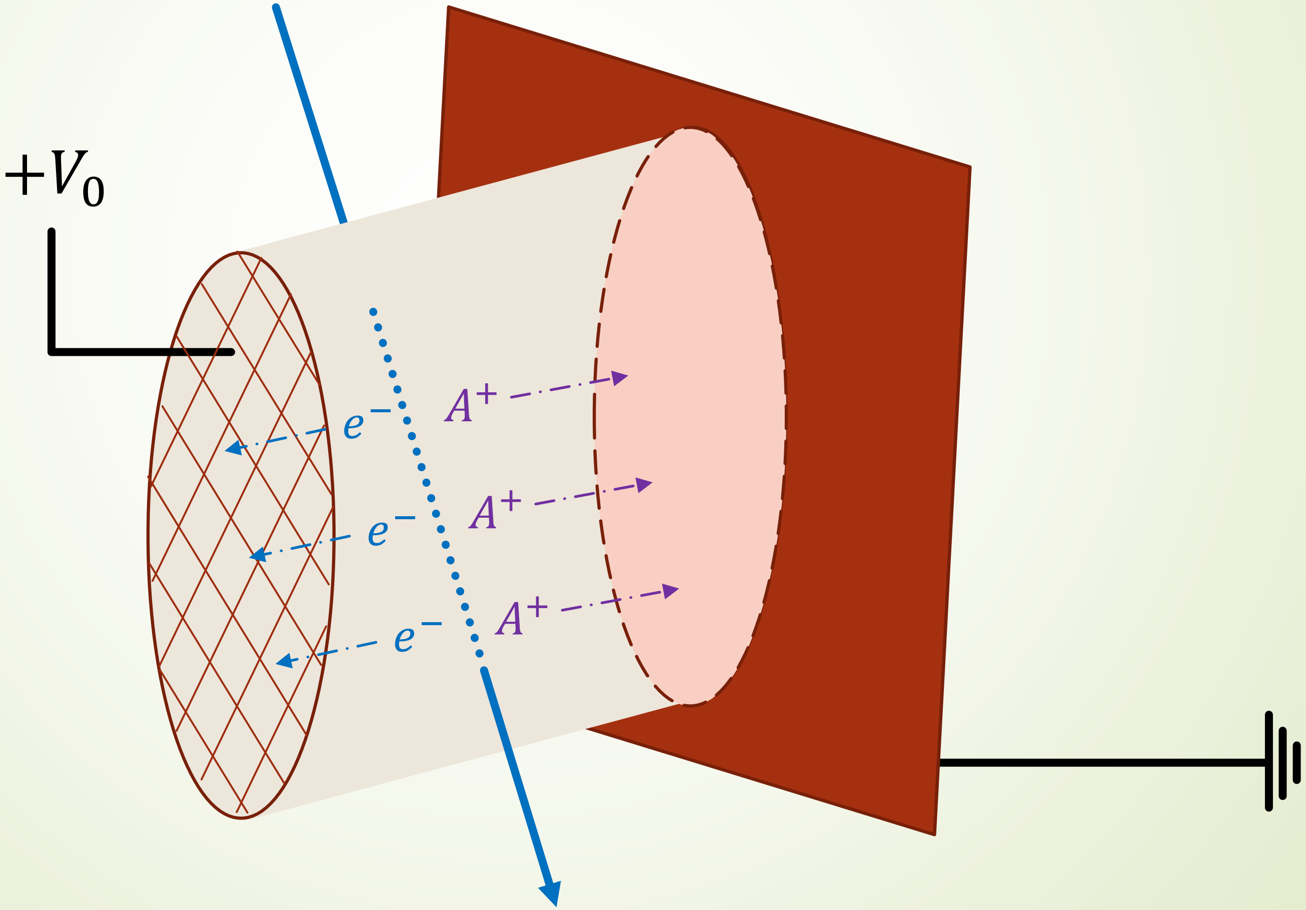
- Utilize the **timing of drift** in the z-direction



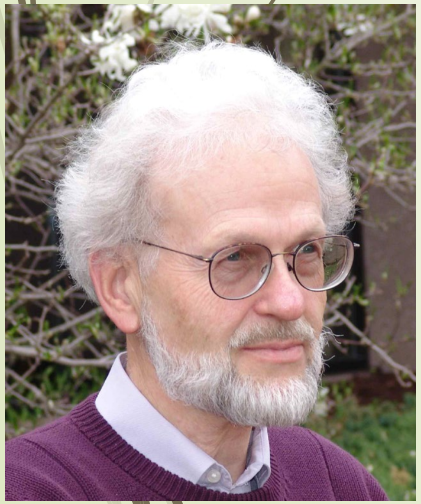
For this particle track,
$\Delta t_1 > \Delta t_2 > \cdots > \Delta t_N$

The Time Projection Chamber (TPC)

- First proposed by David R. Nygren at LBNL in 1974 [3]



V_0 can be $O(100\ \mathrm{kV})$!



[3] https://cds.cern.ch/record/1734475

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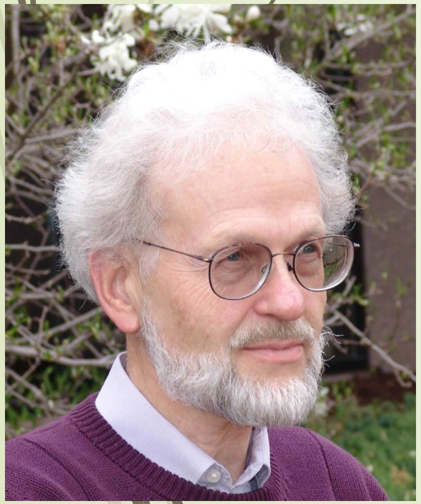
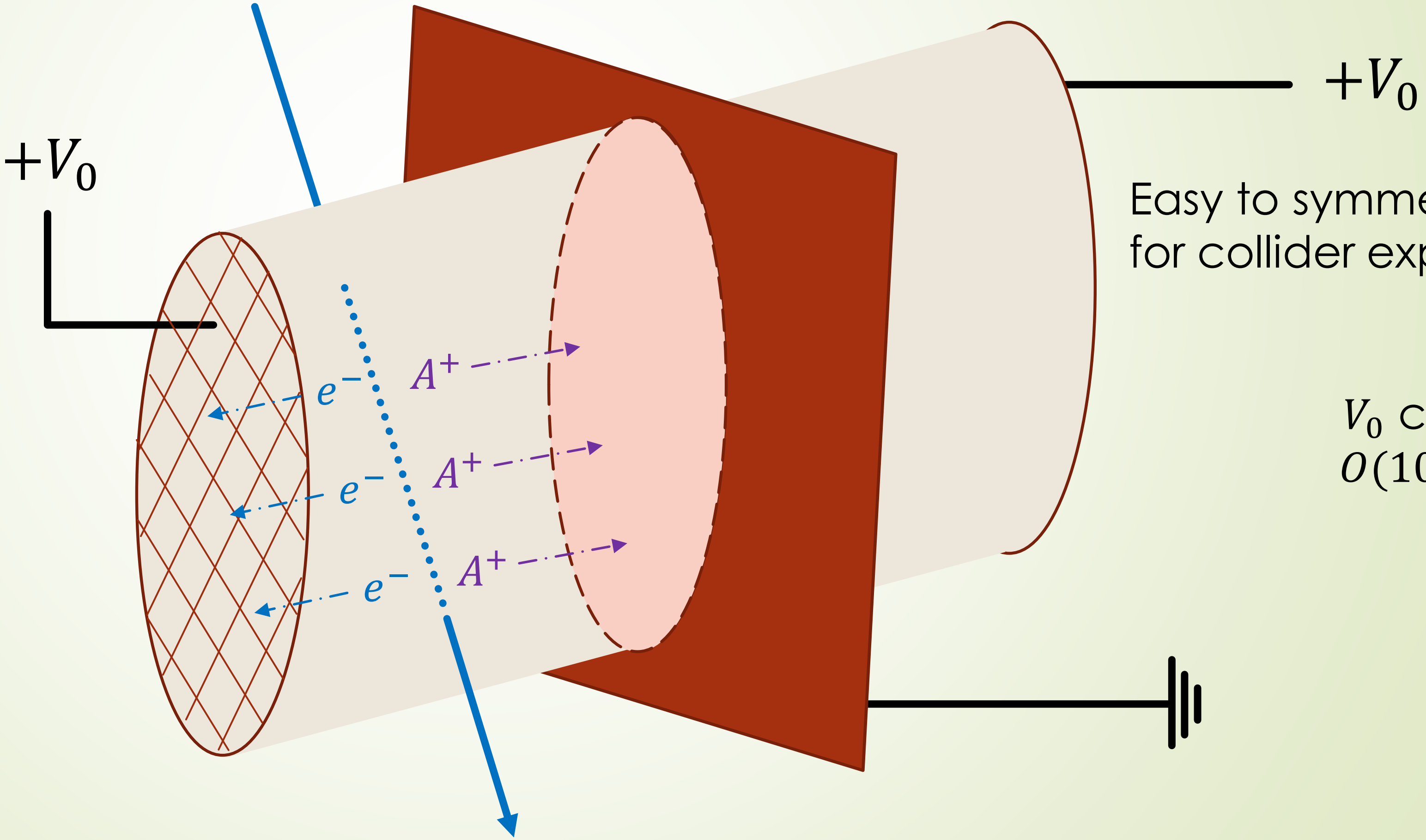


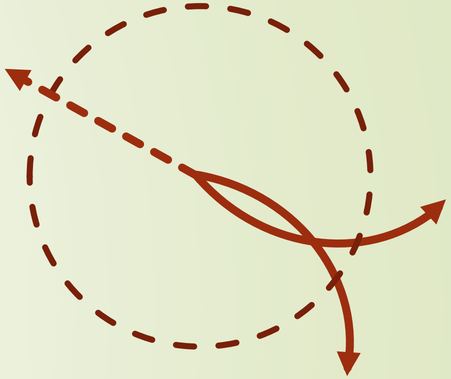


Easy to symmetrize for collider experiments

V_0 can be $O(100\text{ kV})$!

[2] https://cds.cern.ch/record/1734475

How to tell if particle has +/- charge?
How to identify the particle's momentum?



- Add a **magnetic field** parallel to the electric field direction
  - Charged particles traversing the TPC will have their bent
  - Thinking classically:

$$\vec{F} = q\left(\vec{v} \times \vec{B}\right) = m\vec{a} \;\rightarrow\; qvB\sin(\theta) = \frac{mv^2}{r} \;\rightarrow\; r = \frac{p}{qB\sin(\theta)}$$

  - **Radius** of curvature is proportional to the **momentum** with known prefactor
  - **Direction** of curvature tells us about the **sign** of q versus $\vec{B}$

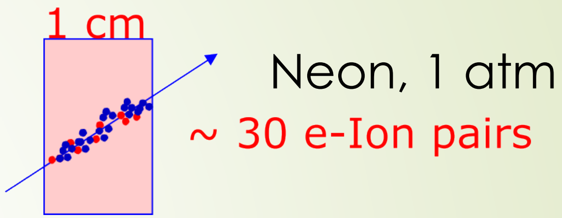
- Magnitude of magnetic field has to be chosen carefully
  - Larger magnetic field increases curvature → improves resolution for high-momentum tracks, but limits the minimum momentum that can successfully transverse the field

Proportional counter

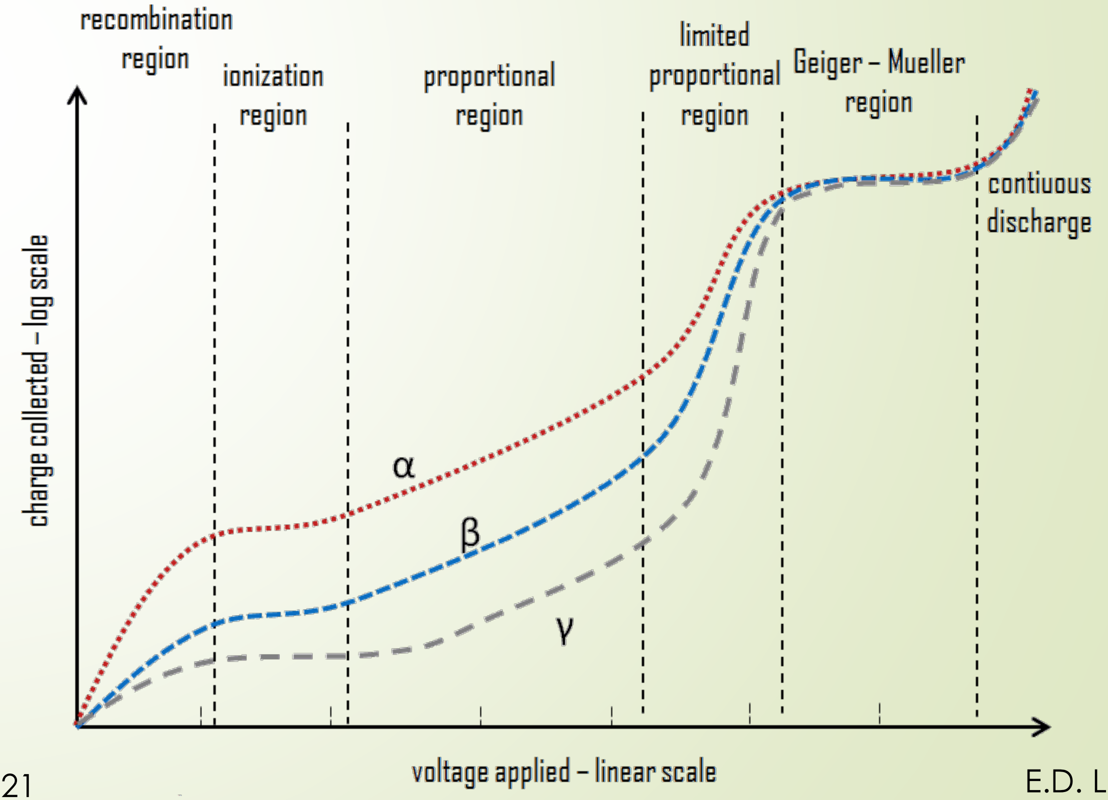
- Electrical noise in readout electronics can be quite high [4]:

● = **primary** ionization (from original atom)

● = **secondary** ionization (from e^- with $E > 100\ \text{eV}$)



  - Equivalent noise charge (ENC) is $O(1000\ e^-)$!
  - Need a noise-free amplification → **gas amplification**
- TPC has applied voltage high enough that each ionization e^- causes a Townsend avalanche
- Amplification $O(10^5)$ for $|\vec{E}| \sim 10\ \text{kV/cm}$
- Pulse height is proportional to the energy deposited ($\mathrm{d}E/\mathrm{d}x$)



https://www.radiation-dosimetry.org/what-is-proportional-counter-proportional-detector-definition/

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[4] https://www.desy.de/~garutti/LECTURES/ParticleDetectorSS12/L4_gasDetectors.pdf

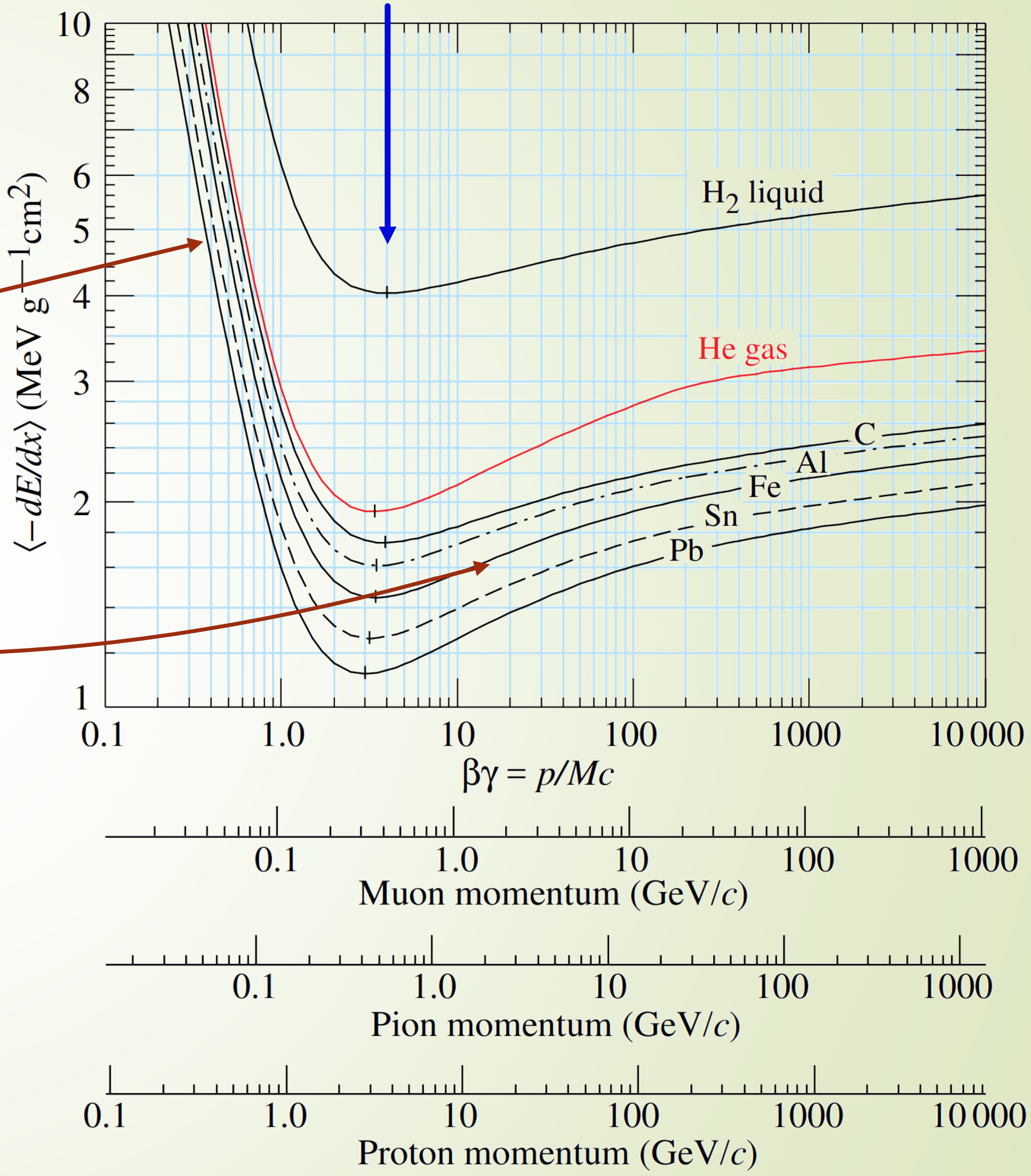
Measuring $\mathrm{d}E/\mathrm{d}x$

- Energy loss given by Bethe-Bloch formula:

$$\left\langle -\frac{\mathrm{d}E}{\mathrm{d}x}\right\rangle = 4\pi N_A \rho m_e c^2 z^2 \frac{Z}{A}\boxed{\frac{1}{\beta^2}}\times \left[\frac{1}{2}\boxed{\ln\frac{2m_e c^2\beta^2\gamma^2}{I^2}} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

for $0.1 \lessapprox \beta\gamma \lessapprox 1000$.

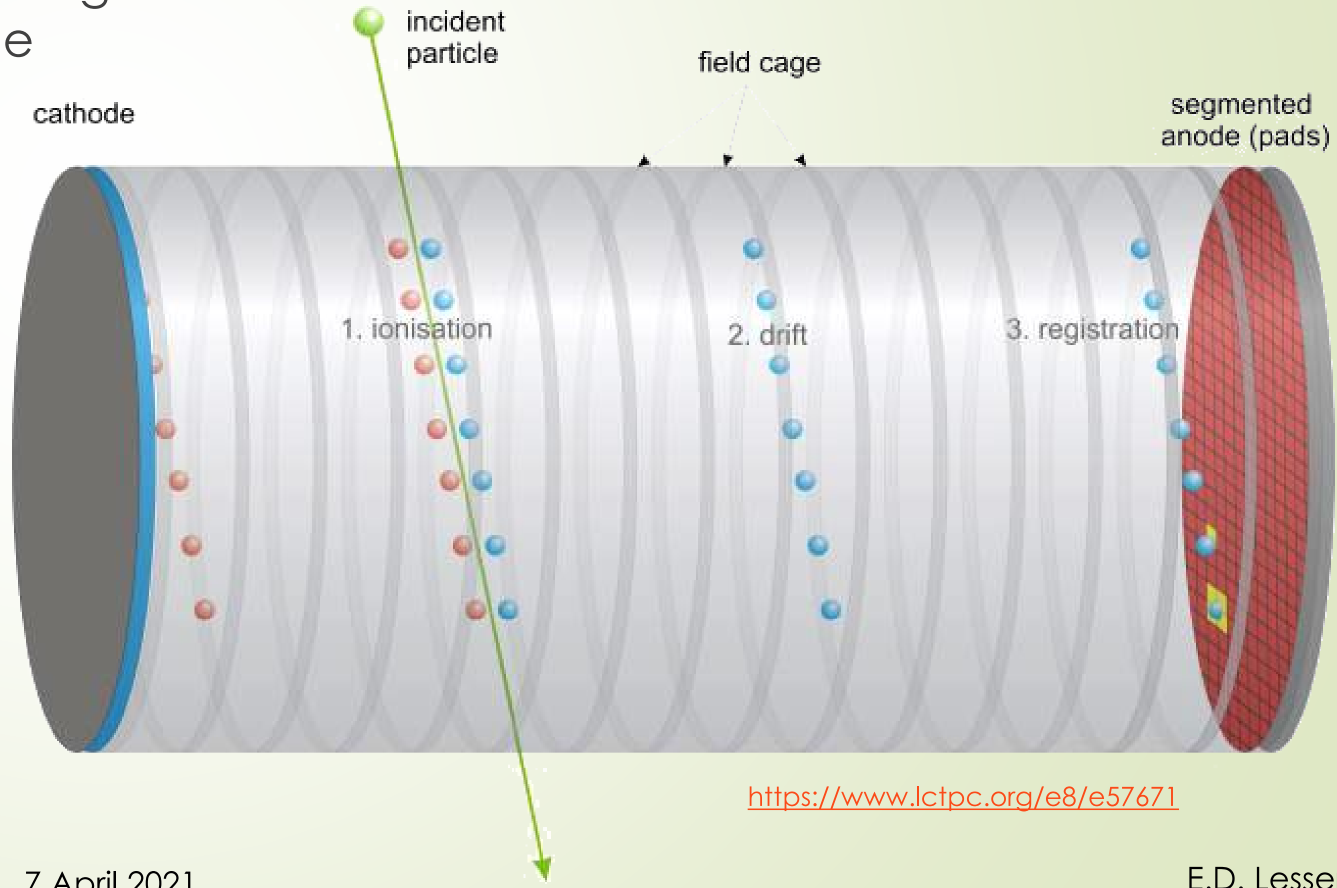
- e^- shape is different (dominated by bremsstrahlung)
- With access to the particle speed β, and its momentum p from the curved tracking, one can find the mass → **can identify the particle type (PID)**



[6]: PDG (2018 rev), sect. 33

Controlling the electric field

- Knowledge of $\vec{E}$ is required to get an accurate $\mathrm{d}E/\mathrm{d}x$ calibration
- Add a **field cage** – several metal rings of ΔV between anode & cathode
- Usually must be kept thin to limit the radiation length for incoming/outgoing radiation
- Each ring must be well-insulated from each other and from the outside environment to prevent discharges
  - Must consider charge build-up and breakdown voltages



https://www.lctpc.org/e8/e57671

Gas selection

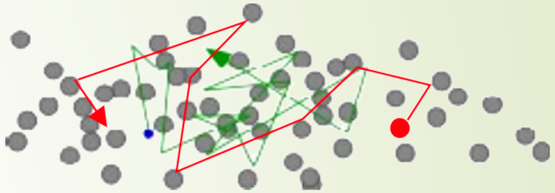
- Need an **inert gas** which is ionized by the radiation
  - Noble gasses are an obvious choice: Argon, Neon, Xenon *[expensive!]*, …
- e^- move much faster than A^+ → build up a net positive charge in the bulk
  - Distorts the field, and can cause fake secondary pulses when ions reach cathode
- Add **quench gas** to ensure each discharge terminates
  - Hydrocarbons (e.g. methane CH_4), carbon dioxide (CO_2), carbon tetrafluoride (CF_4)
  - Lower affinity to electrons than inert gas; "donates" electrons to positive ions
  - Usually added in a mixture of about ~10% to the inert gas
- This process of adding some small amount of a secondary to a main active bulk is commonly called **doping**

Electron diffusion

- **Diffusion constant** is one of the essential parameters in choice of gas mixture [4]
  - Important for separation of tracks & position resolution

$\left|\vec{E}\right| = 0$ → thermal diffusion

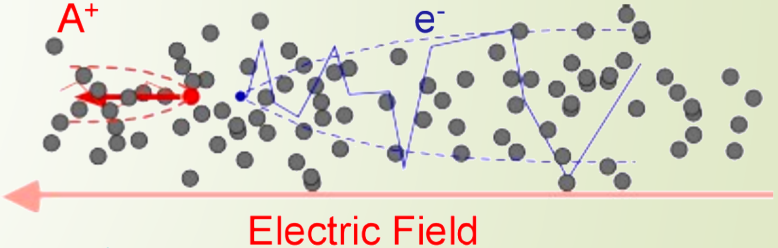
$$\langle v \rangle_t = 0$$



[4]

$\left|\vec{E}\right| > 0$ → transport & diffusion

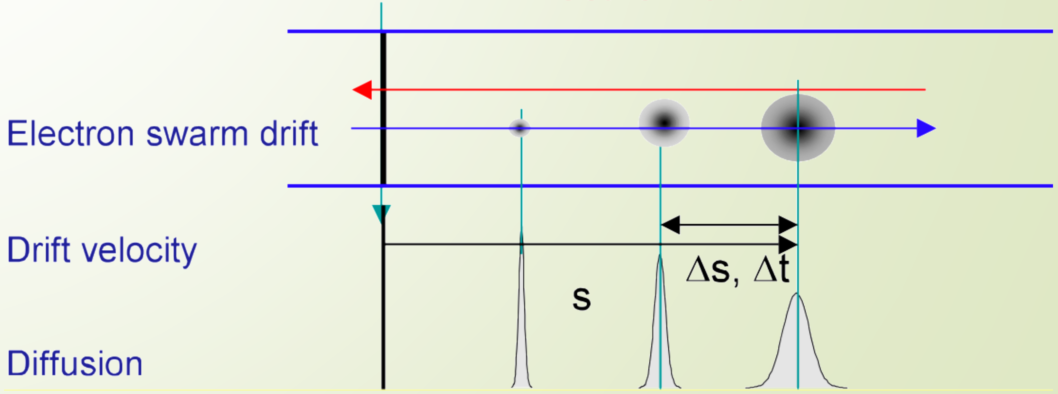
$$\langle v \rangle_t = v_D$$



- Transverse electron motion is limited in part by the magnetic field

$$\boxed{\begin{aligned} \sigma_{\parallel} &= \sqrt{2dt} \\ \sigma_{\perp} &= \frac{\sigma_{\parallel}^2}{1+\omega^2\tau^2} \end{aligned}}$$

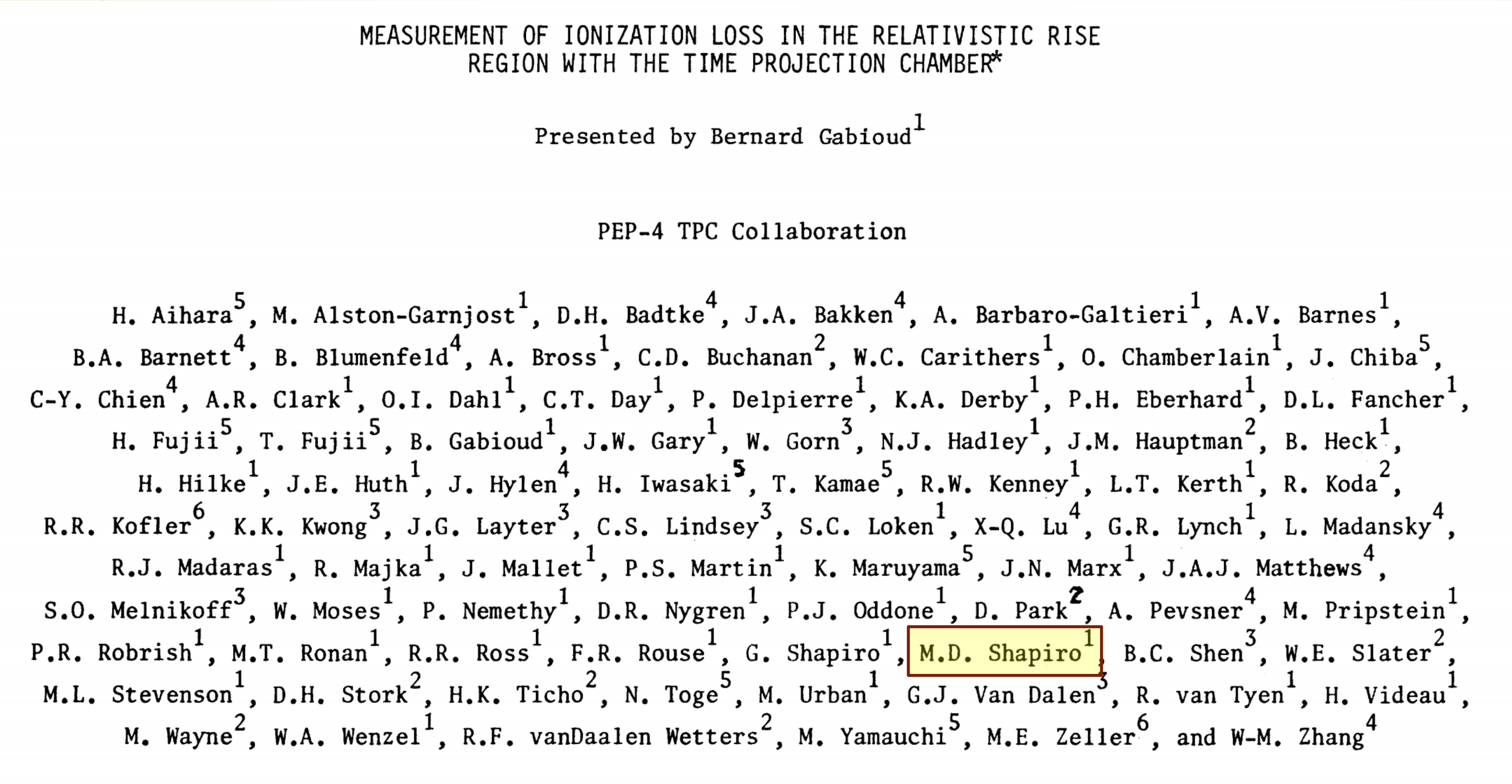
σ = r.m.s. normal distance
$d = vl/3$ = diffusion coeff.
$l = e^-$ mean free path
$v = e^-$ speed $\quad t$ = total time
$\omega = eB/m_e$ = cyclotron frequency
τ = mean collision time



D.R. Nygren's original paper:
https://lss.fnal.gov/conf/C740805/p58.pdf

The first major TPC application

- Installed in the PEP-4 experiment at SLAC
  - Studied $\sqrt{s} = 24\ \mathrm{GeV}\ e^+e^-$ collisions in PEP storage ring



MEASUREMENT OF IONIZATION LOSS IN THE RELATIVISTIC RISE
REGION WITH THE TIME PROJECTION CHAMBER*

Presented by Bernard Gabioud[1]

PEP-4 TPC Collaboration

H. Aihara[5], M. Alston-Garnjost[1], D.H. Badtke[4], J.A. Bakken[4], A. Barbaro-Galtieri[1], A.V. Barnes[1], B.A. Barnett[4], B. Blumenfeld[4], A. Bross[1], C.D. Buchanan[2], W.C. Carithers[1], O. Chamberlain[1], J. Chiba[5], C-Y. Chien[4], A.R. Clark[1], O.I. Dahl[1], C.T. Day[1], P. Delpierre[1], K.A. Derby[1], P.H. Eberhard[1], D.L. Fancher[1], H. Fujii[5], T. Fujii[5], B. Gabioud[1], J.W. Gary[1], W. Gorn[3], N.J. Hadley[1], J.M. Hauptman[2], B. Heck[1], H. Hilke[1], J.E. Huth[1], J. Hylen[4], H. Iwasaki[5], T. Kamae[5], R.W. Kenney[1], L.T. Kerth[1], R. Koda[2], R.R. Kofler[6], K.K. Kwong[3], J.G. Layter[3], C.S. Lindsey[3], S.C. Loken[1], X-Q. Lu[4], G.R. Lynch[1], L. Madansky[4], R.J. Madaras[1], R. Majka[1], J. Mallet[1], P.S. Martin[1], K. Maruyama[5], J.N. Marx[1], J.A.J. Matthews[4], S.O. Melnikoff[3], W. Moses[1], P. Nemethy[1], D.R. Nygren[1], P.J. Oddone[1], D. Park[2], A. Pevsner[4], M. Pripstein[1], P.R. Robrish[1], M.T. Ronan[1], R.R. Ross[1], F.R. Rouse[1], G. Shapiro[1], M.D. Shapiro[1], B.C. Shen[3], W.E. Slater[2], M.L. Stevenson[1], D.H. Stork[2], H.K. Ticho[2], N. Toge[5], M. Urban[1], G.J. Van Dalen[3], R. van Tyen[1], H. Videau[1], M. Wayne[2], W.A. Wenzel[1], R.F. vanDaalen Wetters[2], M. Yamauchi[5], M.E. Zeller[6], and W-M. Zhang[4]

David Nygren (LBNL) &
Fred Catania (SLAC)

IEEE Transactions on Nuclear Science, Vol. NS-30, No. 1, February 1983

The first major TPC application

- Installed in the PEP-4 experiment at SLAC
  - Studied $\sqrt{s} = 24\ \text{GeV}\ e^+e^-$ collisions in PEP storage ring

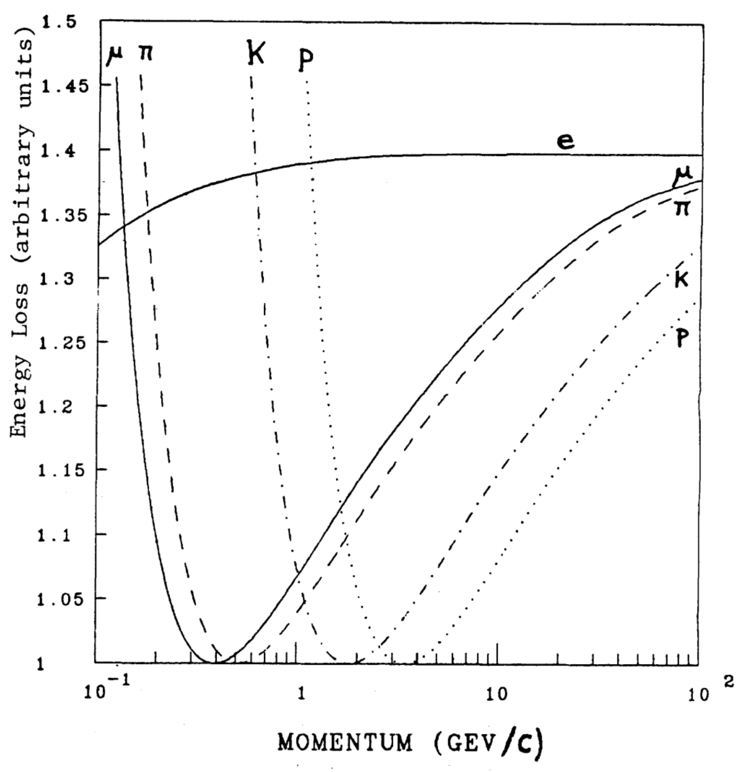


Fig. 3. The most probable Energy Loss versus Momentum, for the TPC detector, at 8.5 atmospheres.

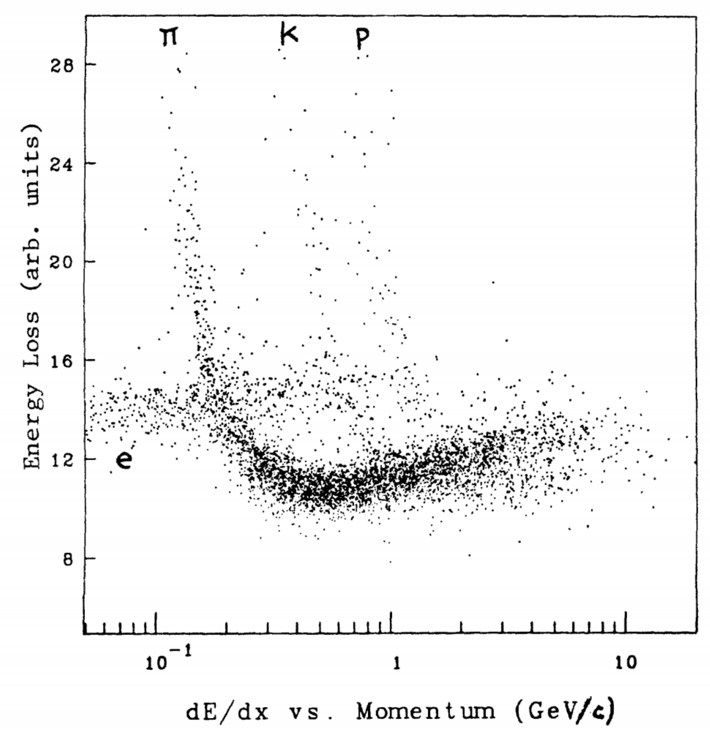


Fig. 5. dE/dx versus Momentum for tracks in a sample of 1000 Multihadron Events at E_{cm} = 29 GeV.

David Nygren (LBNL) &
Fred Catania (SLAC)

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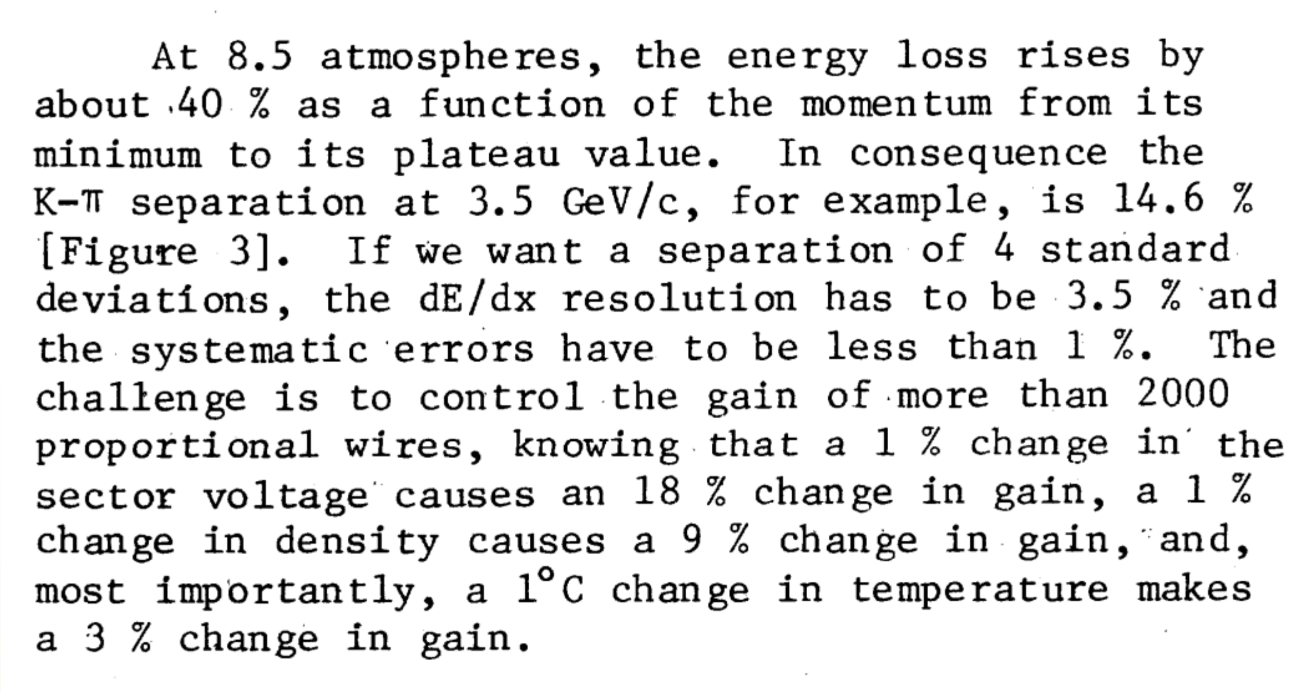
Temperature & pressure stability

- **Increased pressure** → increased density → **higher energy loss** $(\mathrm{d}E/\mathrm{d}x)$

- Generally a positive pressure is maintained ($> 1\ \mathrm{atm}$), meaning leaks have gas moving *out* instead of *in*, though there are low-pressure TPCs

- Front-end electronics use power and generate heat
- Resistors between HV have some dark current that generates heat
- Heat radiation can be absorbed from the surrounding environment
- → need cooling systems to maintain stability

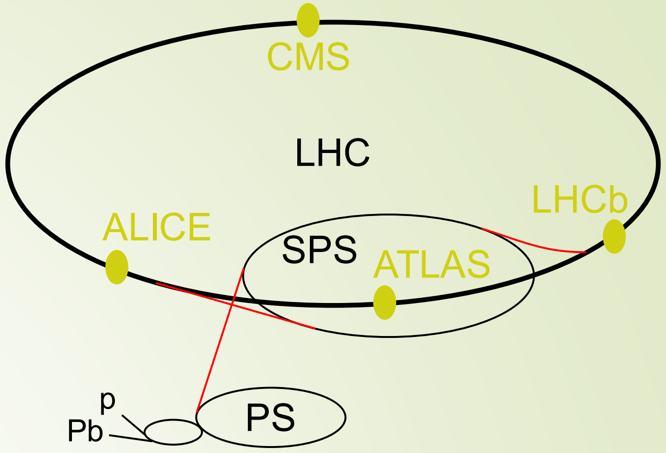


At 8.5 atmospheres, the energy loss rises by about 40 % as a function of the momentum from its minimum to its plateau value. In consequence the K-π separation at 3.5 GeV/c, for example, is 14.6 % [Figure 3]. If we want a separation of 4 standard deviations, the dE/dx resolution has to be 3.5 % and the systematic errors have to be less than 1 %. The challenge is to control the gain of more than 2000 proportional wires, knowing that a 1 % change in the sector voltage causes an 18 % change in gain, a 1 % change in density causes a 9 % change in gain, and, most importantly, a 1°C change in temperature makes a 3 % change in gain.

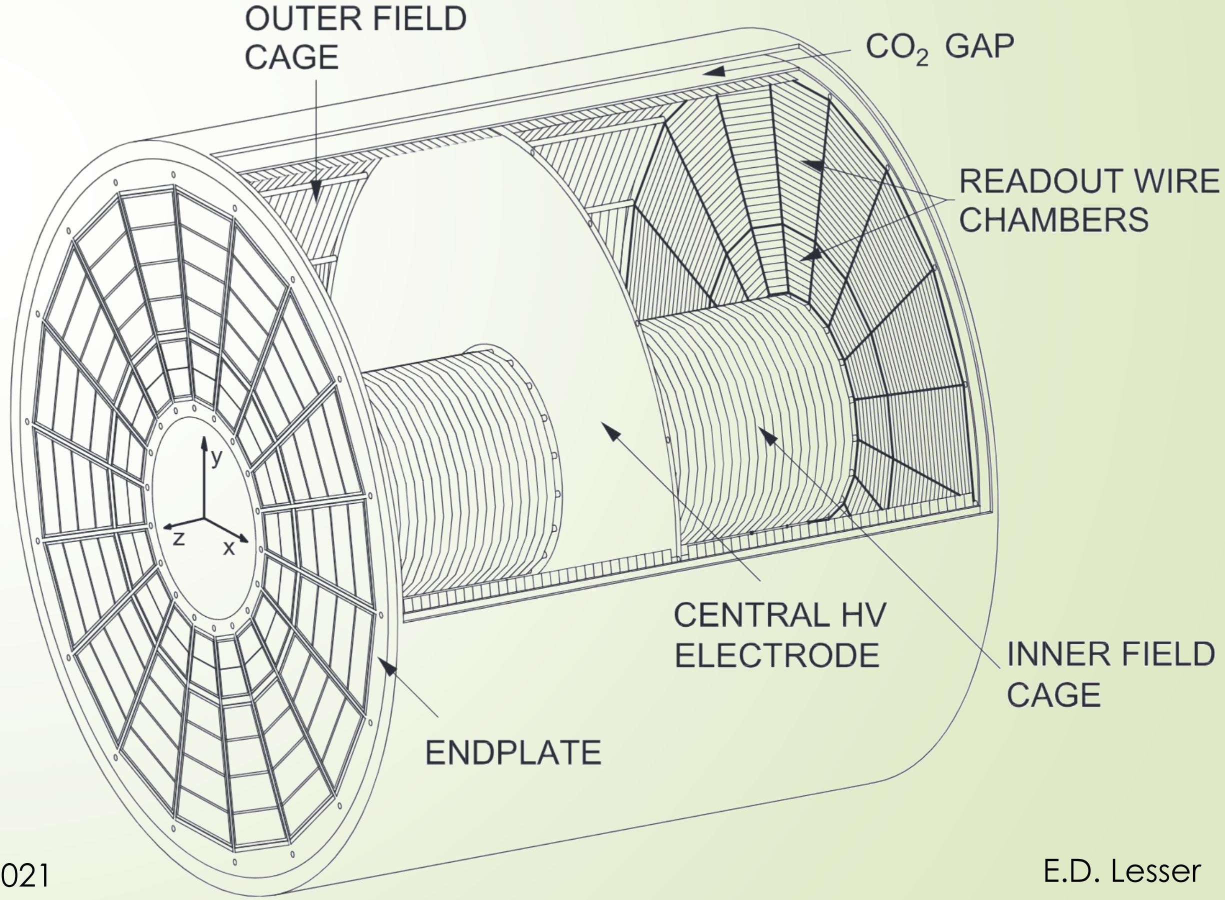
IEEE Transactions on Nuclear Science, Vol. NS-30, No. 1, February 1983

ALICE TPC [4] [5]

- Dimensions: $5\ \mathrm{m}$ length, $2.5\ \mathrm{m}$ radius → $88\ \mathrm{m}^3$ of $\mathrm{Ne/CO_2/N_2}$ (90-10-5) gas mixture
- High voltage: $-100\ \mathrm{kV}$ at a central electrode ($400\ \mathrm{V/cm}$ throughout)
- Total drift time: $92\ \mathrm{\mu s}$
- End-cap detectors: $32\ \mathrm{m}^2$ with 557 568 readout pads
- Gain: $> 10^4$
- Diffusion: $\sigma_\perp = 250\ \mu\mathrm{m}$
- Resolution: $\sigma_x \approx 0.2\ \mathrm{mm}$; $\sigma_p/p \approx 1\%\ p$; $\sigma_{\mathrm{d}E/\mathrm{d}x}\ /\ (\mathrm{d}E/\mathrm{d}x) \approx 5\%$
- Magnetic field: $\left|\vec{B}\right| = 0.5\ \mathrm{T}$
- Temperature control: $\mathrm{d}T < 0.1\ \mathrm{K}$

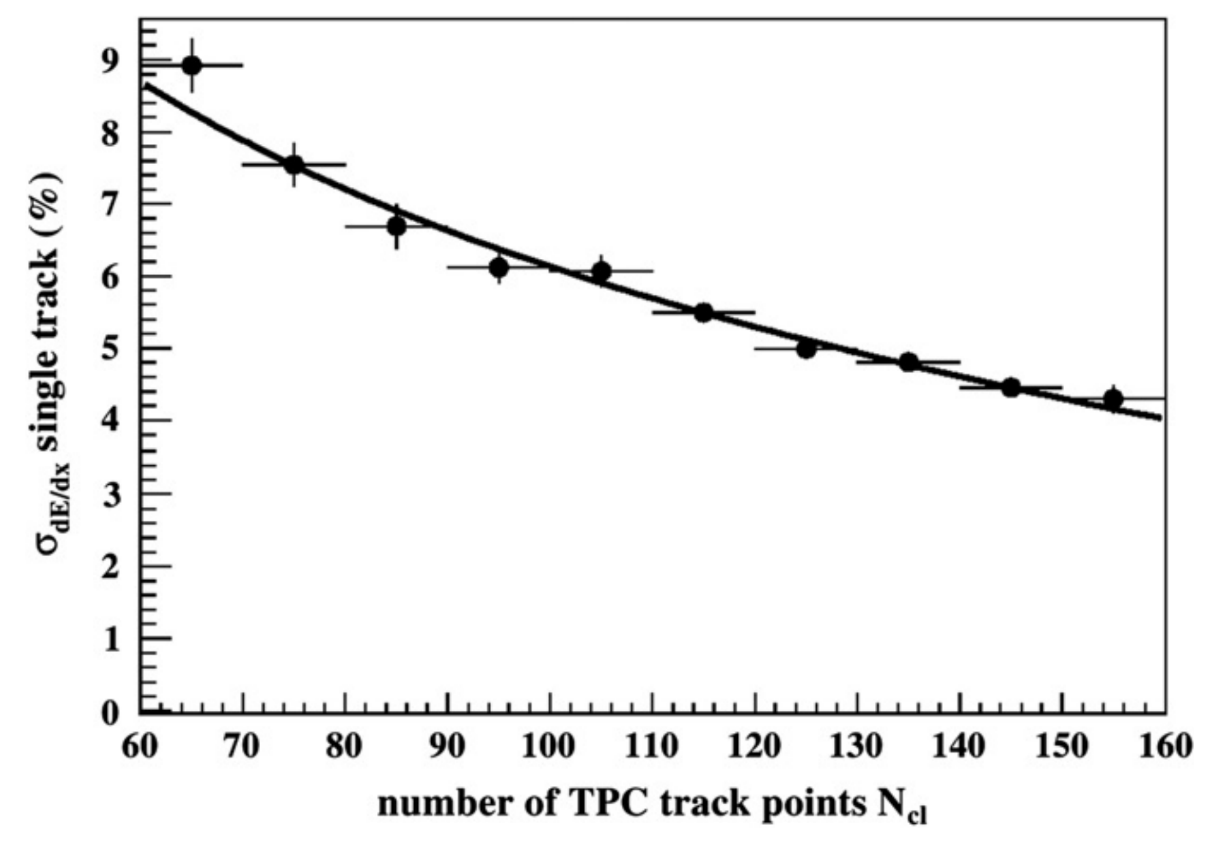


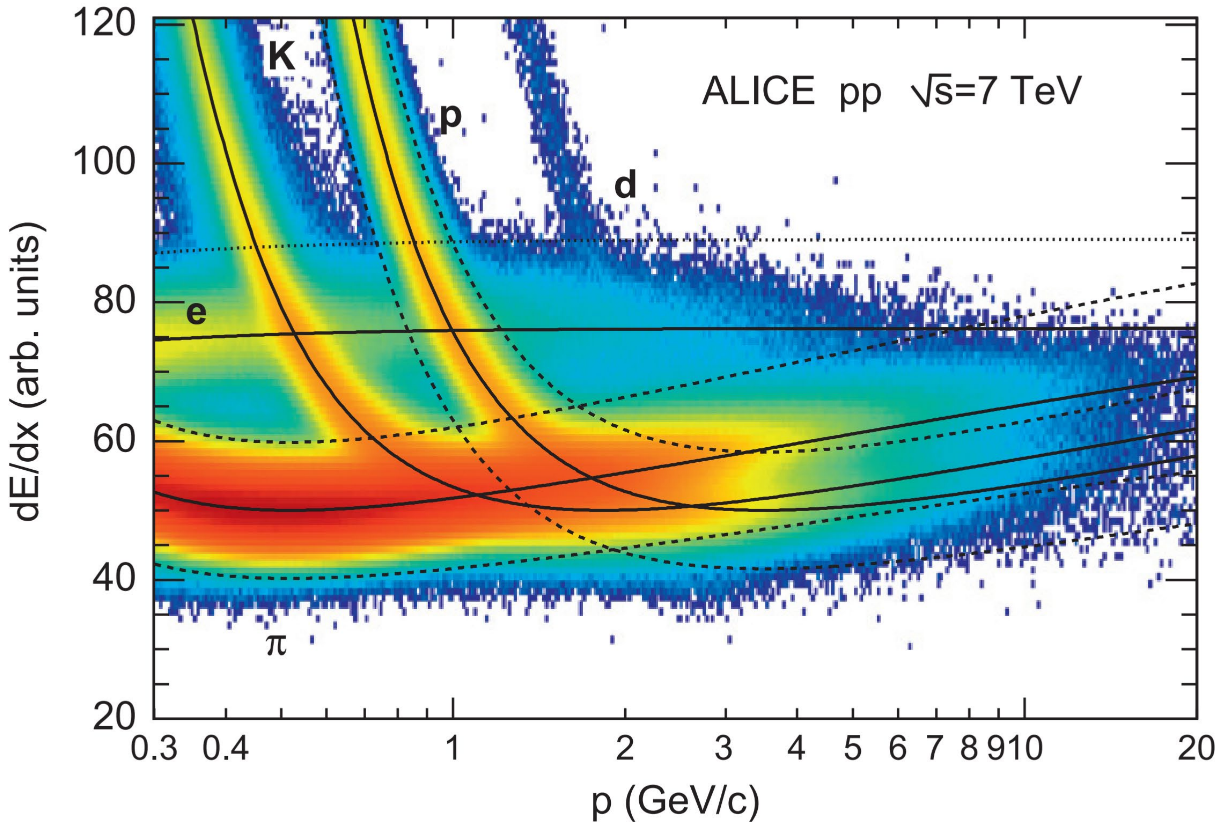
[5] https://doi.org/10.1016/j.nima.2010.04.042



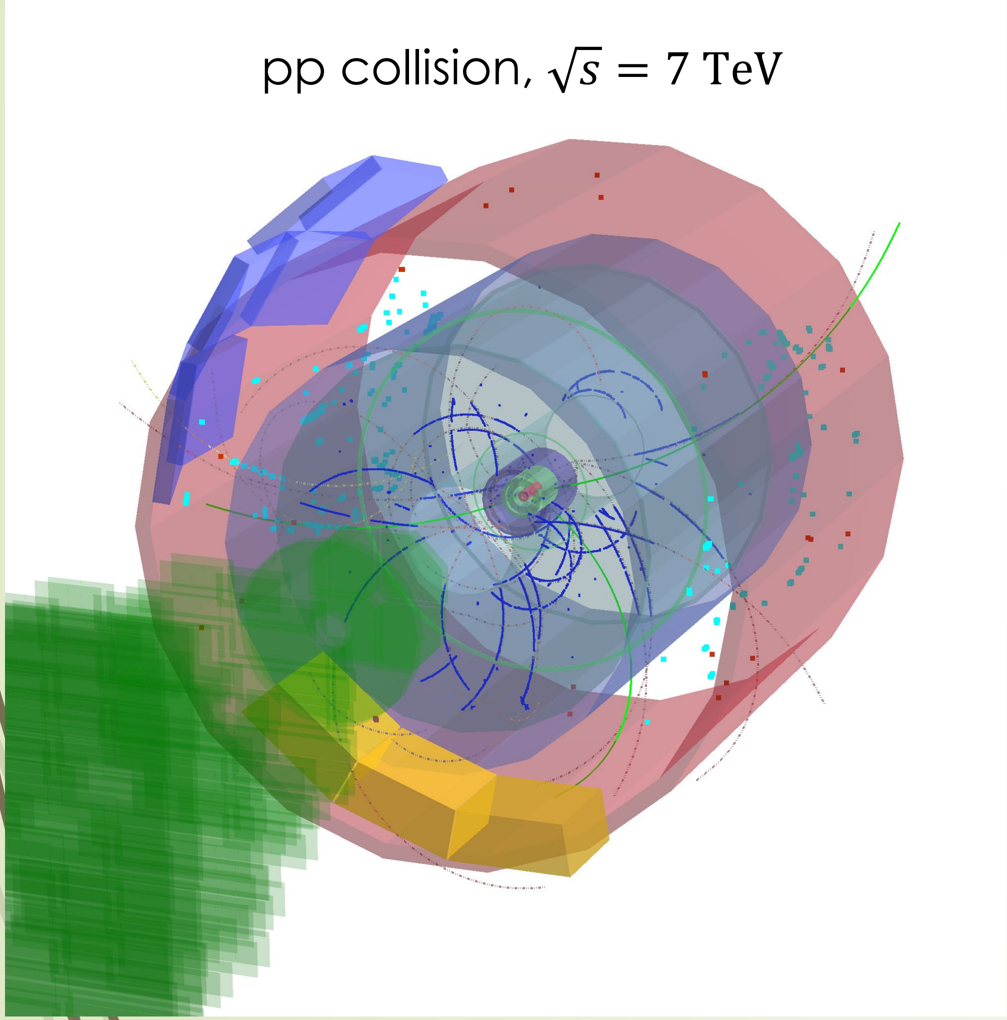
ALICE TPC [4] [5]

- $\mathrm{d}E/\mathrm{d}x$ resolution depends on the number of space points (159 radial pads)

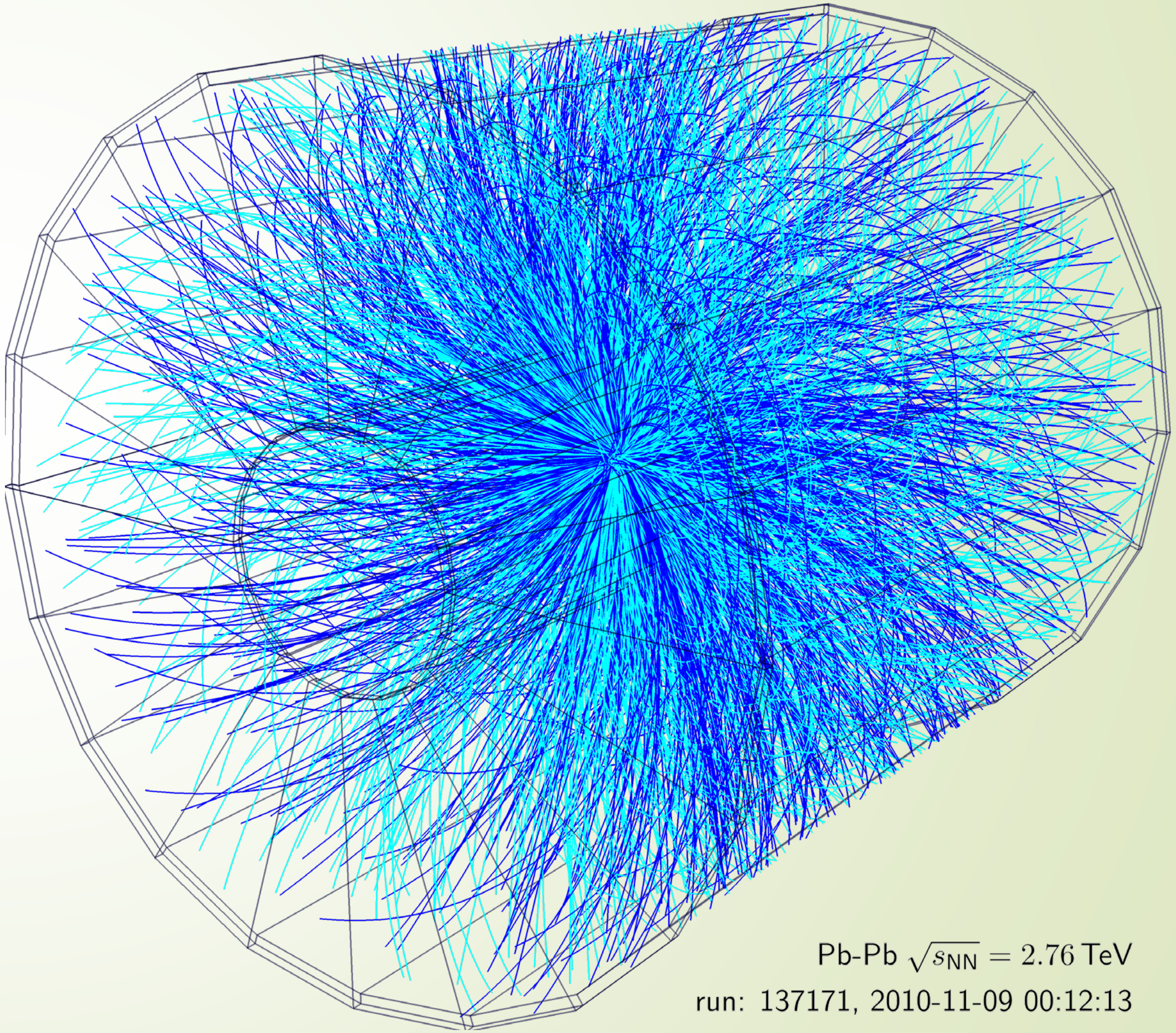




ALICE TPC [4] [5]



1209 positively-charged (darker tracks) and 1197 negatively-charged (lighter tracks) particles are produced, about 80 percent are π mesons.

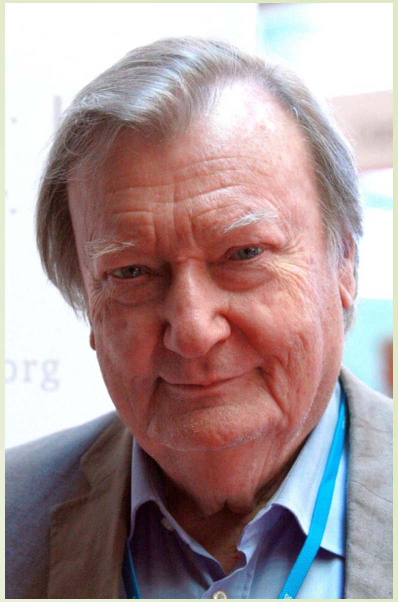


https://cds.cern.ch/record/2032743

Pros/cons of using a TPC for tracking [4]

- Advantages:
  - Reconstruct complete tracks with a single detector
    - Almost the whole volume is active detector region
  - Good momentum resolution (many space points)
  - Minimal radiation length (field cage + gas)
  - Proportional counter, so gives $\mathrm{d}E/\mathrm{d}x$ → good particle identification
  - Excellent for track reconstruction in high-density environments (e.g. heavy-ions)
- Challenges:
  - Long drift time → limited rate capabilities
  - Large volume → precision
  - Large ΔV gradient → discharges
  - High data rates
  - Extreme load at high luminosity
    - Need to apply gating to select on specific, triggered events

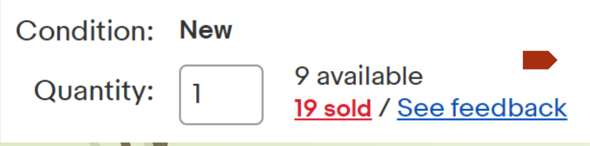
Liquid scintillator TPCs



- Liquid Argon (LAr) TPC proposed by Carlo Rubbia in 1977
- In addition to ionization electrons, excited Argon will scintillate at $\lambda_{\text{peak}} = 127\ \text{nm}$
  - Quartz glass only transparent to $\sim 170\ \text{nm}$ → require wavelength shifter
    - Tetraphenyl butadiene (TPB) is often used (peak at $430\ \text{nm}$)
  - Liquid Xenon (LXe) is also used (*expensive*!) → $\lambda_{\text{peak}} = 178\ \text{nm}$
- Light collection improves energy resolution and can be used as a trigger
- Much higher density (order ~1000x) → useful for detecting neutral particles
  - Neutral particle (e.g. neutron or neutrino) must scatter off of a charged particle (e.g. Argon nucleus) which then ionizes / excites the LAr

On eBay today:

$2,000
50L (at 1 atm)



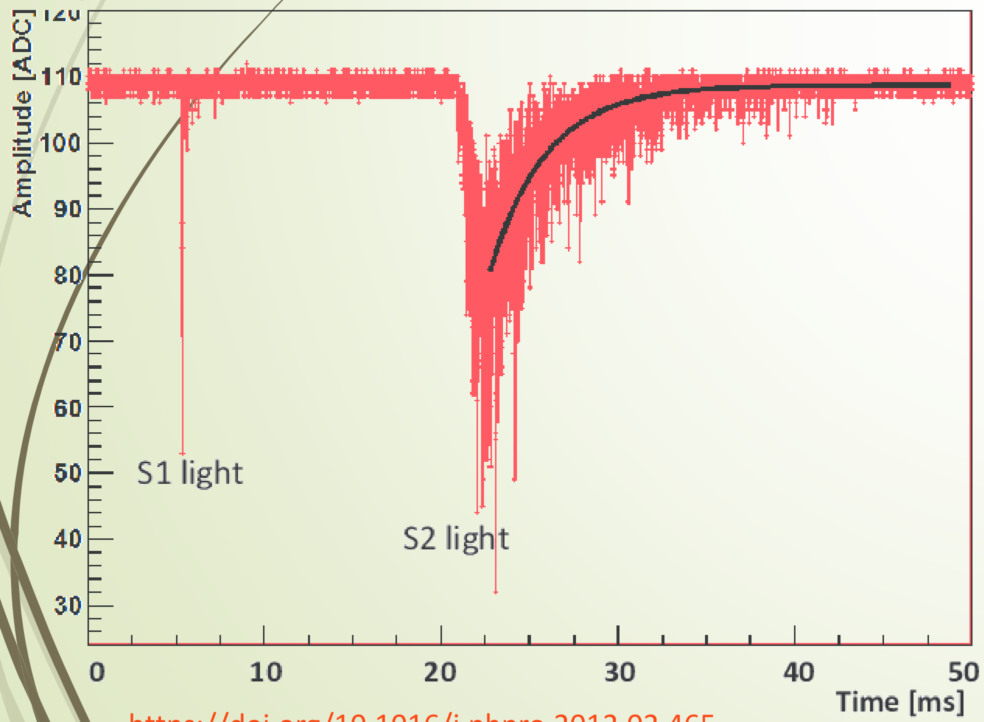
Condition: **New**

Quantity: 1 9 available
19 sold / See feedback

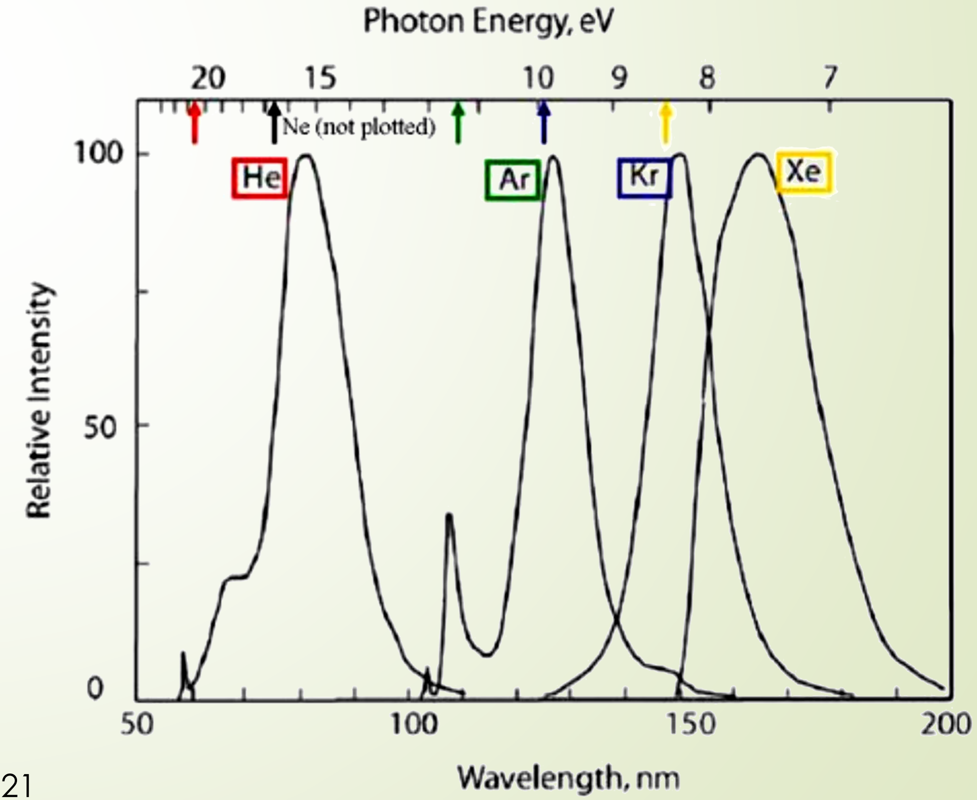
Scintillation light

- **Prompt** ("S1") scintillation signal
  - Light emitted from atoms excited by the original ionizing particle
- **Secondary** ("S2") scintillation signal
  - Light emitted from atoms excited by the electron avalanche

^{57}Co (γ source)
dual-phase Ar detector



https://doi.org/10.1016/j.phpro.2012.02.465



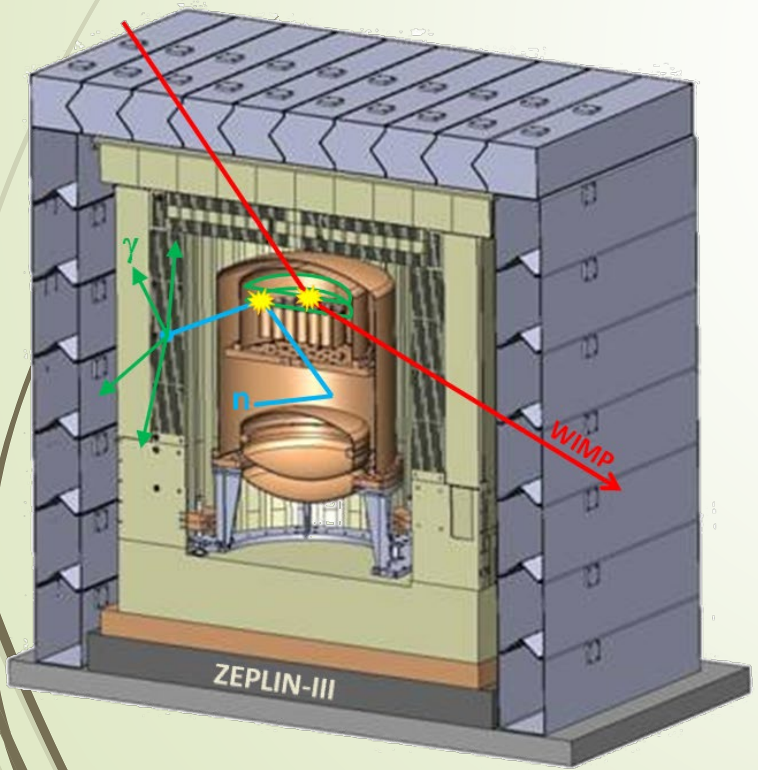
Large Underground Xenon (LUX) experiment

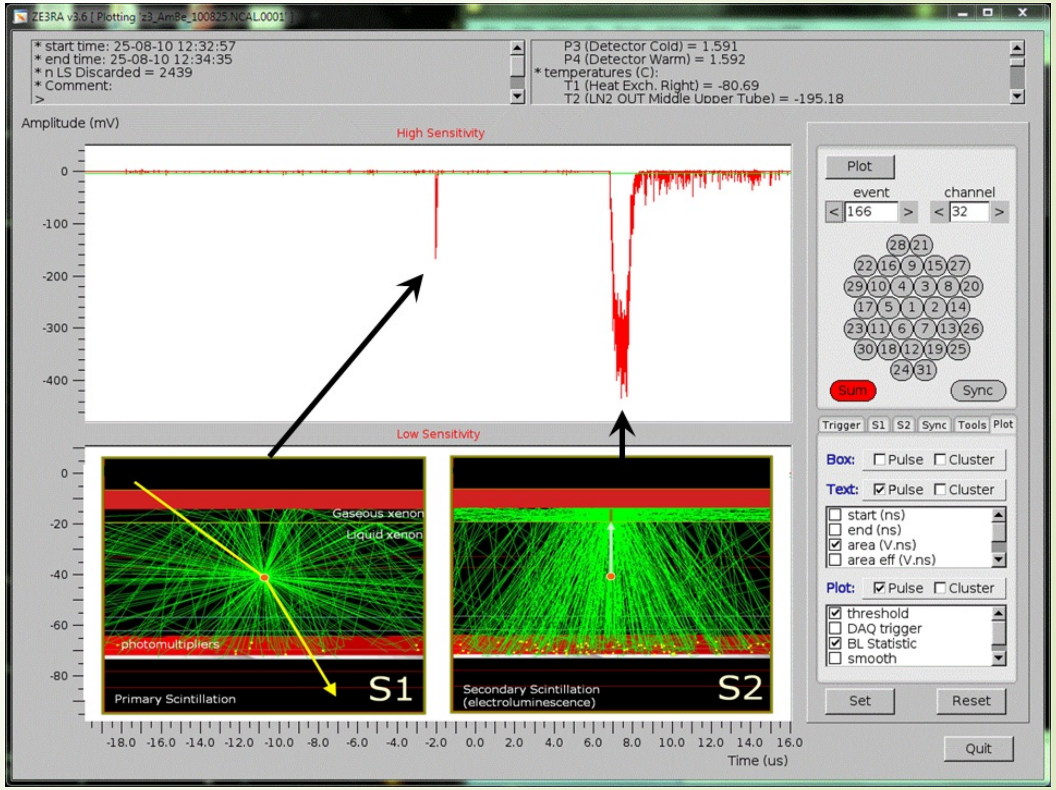
- 370 kg LXe (!) TPC for searching for WIMP dark matter candidates
- Began running April 2013 → decommissioned 2016
  - Detector now on display at Sanford Underground Research Facility (SURF) in SD

- White material seen in the photo is PTFE (Teflon), which is used to reflect scintillation light and thus improve light yield
- Detector was submerged in 71600 gallons (271 kL) of de-ionized water; 4850 ft (1480 m) underground

ZEPLIN-III experiment

- Third generation of **Z**on**E**d **P**roportional scintillation in **LI**quid **N**oble gases
- 12 kg LXe TPC for searching for WIMP dark matter, based in UK
- ZEPLIN-II was the very first dual-phase TPC (both gas & liquid)
- Ran in 2008, 2010-2011




ZE3RA v3.6 [Plotting 'z3_AmBe_100825.NCAL.0001']

```
* start time: 25-08-10 12:32:57
* end time: 25-08-10 12:34:35
* n LS Discarded = 2439
* Comment:
>
```

```
    P3 (Detector Cold) = 1.591
    P4 (Detector Warm) = 1.592
* temperatures (C):
    T1 (Heat Exch. Right) = -80.69
    T2 (LN2 OUT Middle Upper Tube) = -195.18
```

event: 166
channel: 32

Box: ☐ Pulse ☐ Cluster
Text: ☑ Pulse ☐ Cluster
☐ start (ns)
☐ end (ns)
☑ area (V.ns)
☐ area eff (V.ns)
Plot: ☑ Pulse ☐ Cluster
☑ threshold
☐ DAQ trigger
☑ BL Statistic
☐ smooth

https://en.wikipedia.org/wiki/ZEPLIN-III

LUX-ZEPLIN (LZ) experiment

- "Next generation" dark matter search using 7000 kg (!!!) LXe TPC