A re-appraisal of delta rays (“the TPC project”)

Frank Filthaut

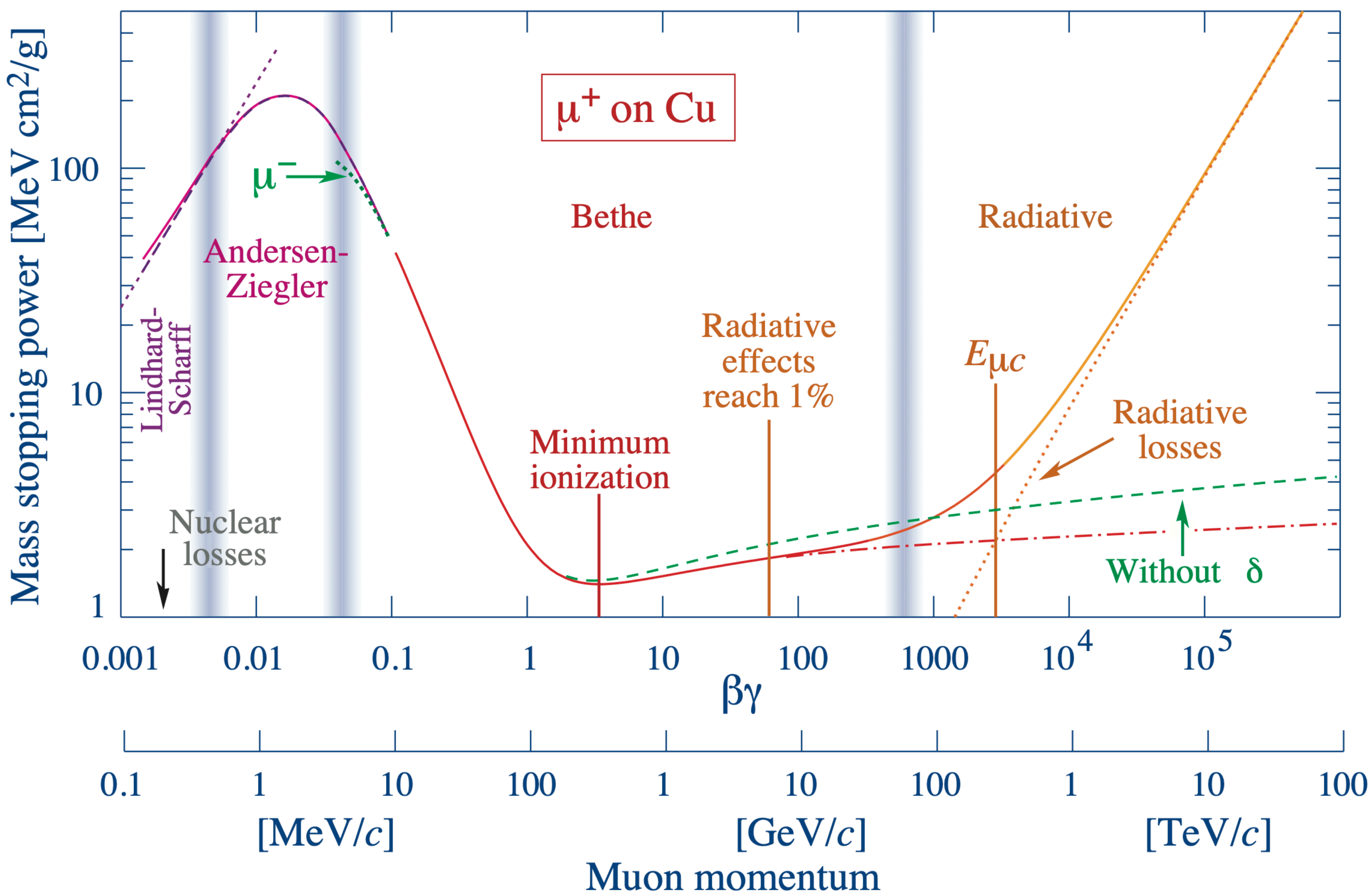
RU HEP seminar, February 7, 2022

Introduction: ionisation energy losses

Ionisation energy losses of charged particles in matter: well understood theoretically as electromagnetic interactions with atomic electrons

- collisions with atomic nuclei ➠ multiple Coulomb scattering (mostly small changes of direction)

Well-known Bethe-Bloch curve describing <u>average</u> E loss of relativistic charged particles:



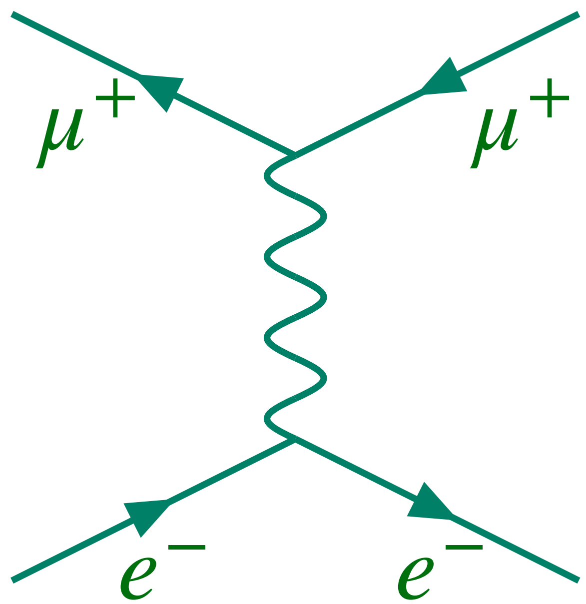
(2020 RPP)

Energy loss as a scattering process

Energy loss is dominated by scatterings with $W \equiv -\Delta E \lesssim$ 50 keV: long-range interaction ➠ affected by interactions with atoms as a whole + screening effects by vicinity of other atoms

At higher W, interactions can be described as with free electrons: Rutherford scattering process

- for a particle with mass m, charge $z\,e$:



$$\frac{d\sigma}{dW} = z^2 \frac{2\pi r_e^2 m_e c^2}{\beta^2} \frac{1 - \beta^2 W / W_{\max}}{W^2}$$

(technically, for $S = 0$)

$$W_{\max} = \frac{2 m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/m + (m_e/m)^2}$$

e.g. for μ with $E = 1$ GeV: $W_{\max} \approx 100$ MeV

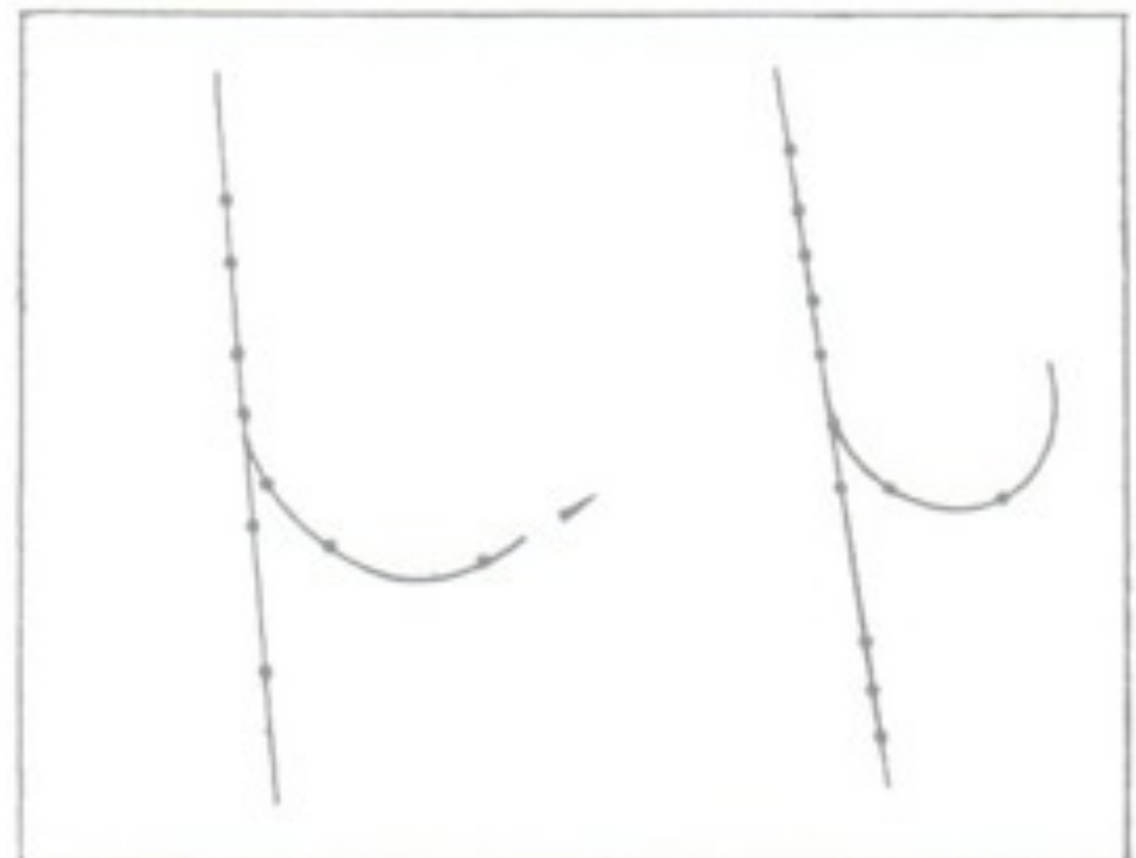
δ rays

Sufficiently high energy transfer ➠ e^- causes further ionisation: delta ray

Important because also kinematics is simple: E, θ of e^- related

$$m^2 \approx p^2 \left(\frac{E_e + m_e}{E_e - m_e} \cos^2 \theta - 1 \right)$$

- used by Leprince-Ringuet and l'Héritier (1944) to identify the charged kaon ($m(K^{\pm})$ = 494 MeV) as having a mass of 870 — 1110 m_e (inconsistent with μ, p)
  - even if not credited for discovery



Dessin stéréoscopique de la collision.

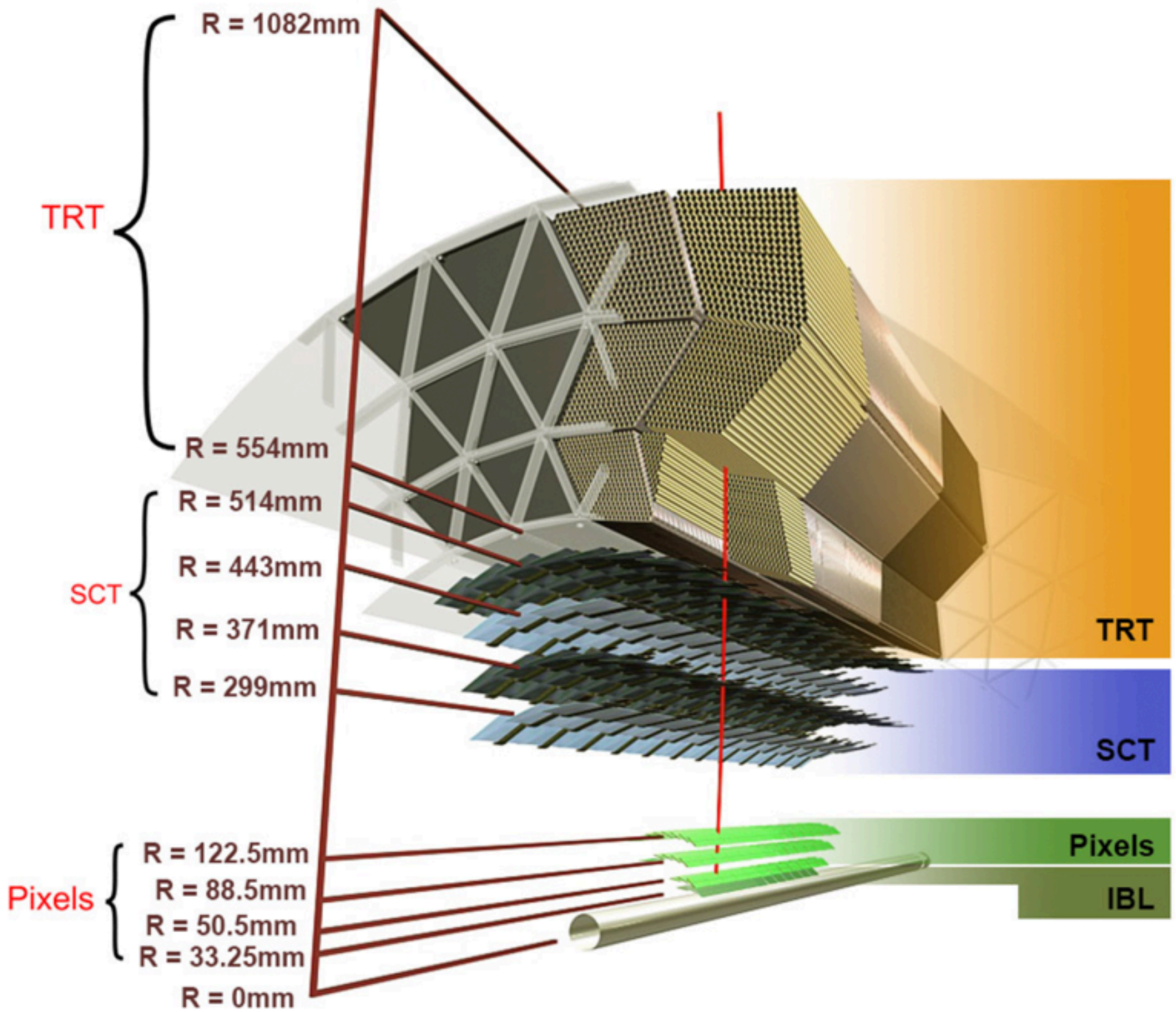
Cloud chamber photograph, redrawn

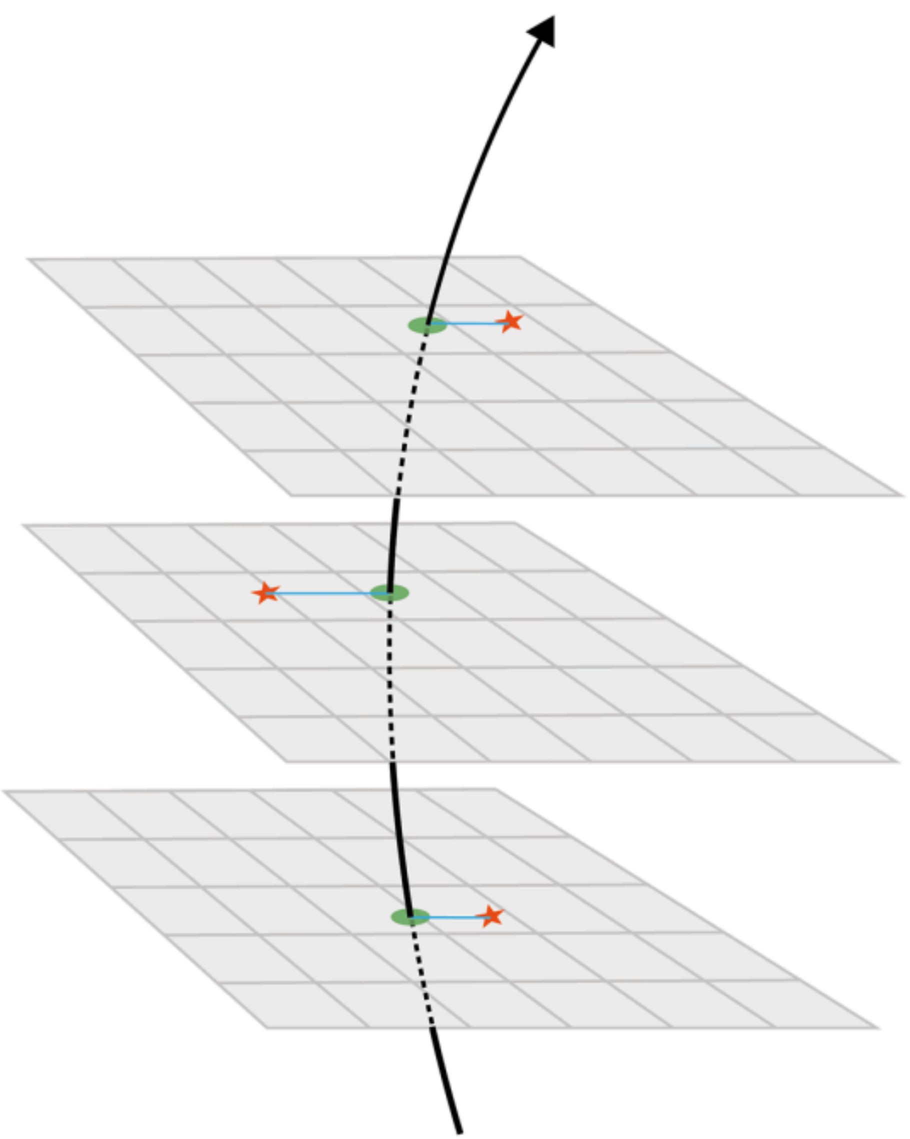
If both e^- E, θ well measured ➠ relation between m, p

Silicon-based charged-particle tracking

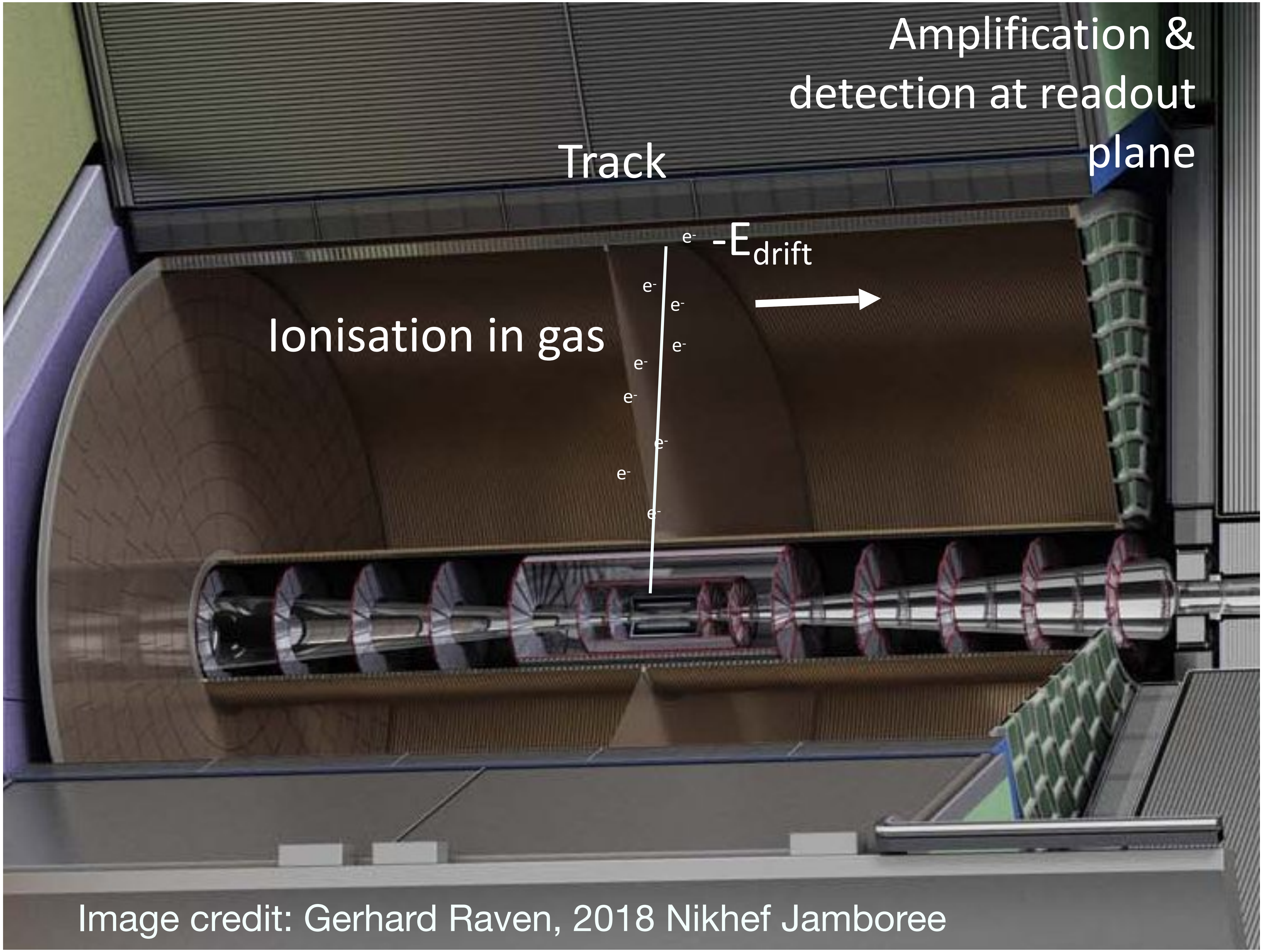
Amount of detail visible in cloud chamber (and bubble chamber) photographs can be impressive… but the technique is too slow

Present-day charged-particle detectors typically use thin Si sensors instead: t ~ ns





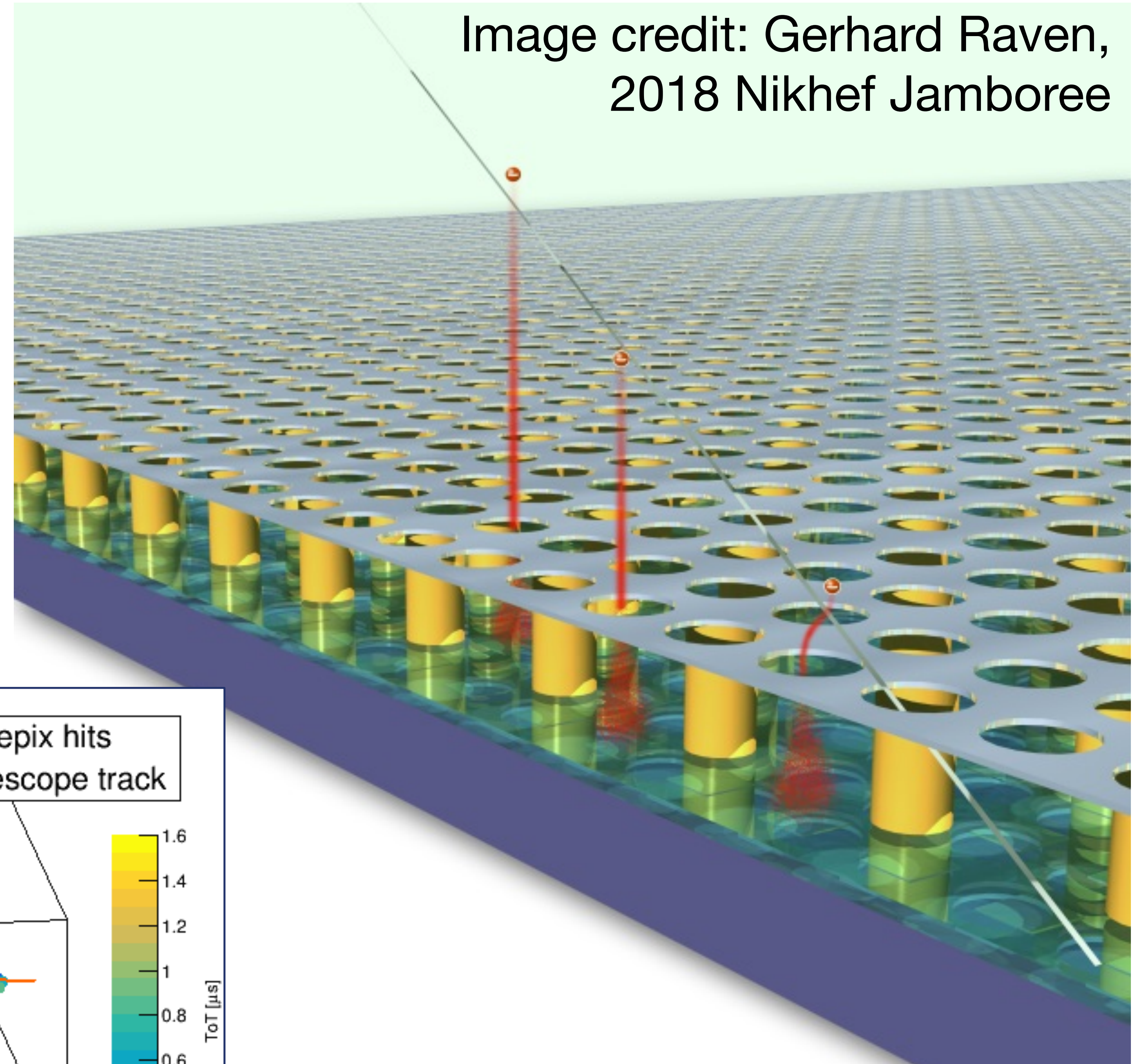
(Prospective) ILD: Time Projection Chamber

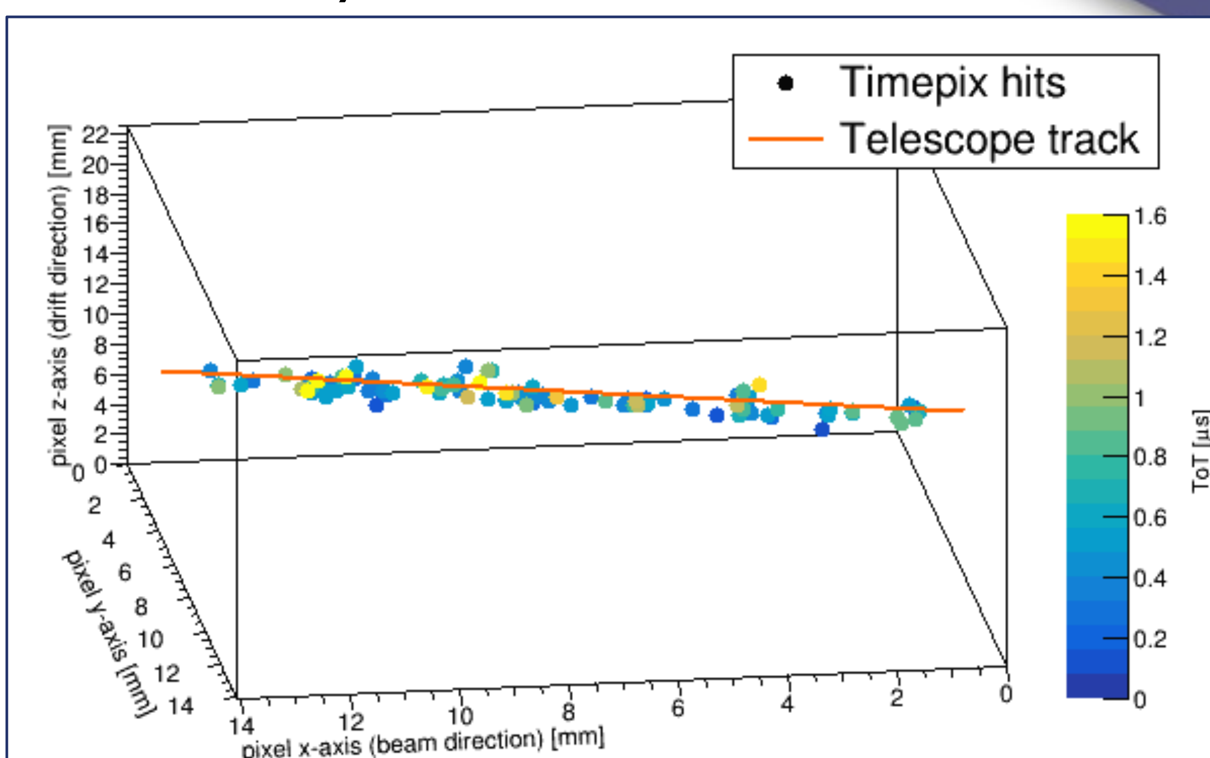


GridPix development (Nikhef + Bonn U)

Combination of Si sensor & gaseous detection medium:

- pillar height ~ 50 μm, to support Al grid maintaining V difference: 300—500 V ➠ signal amplification
- (TimePix3) pixel size: $55 \times 55 \mu$m





Quasi-continuous sampling of particle trajectories!

“Particle identification” using δ rays

Using such GridPix detectors it should be possible to (once more) use δ rays for particle ID

- estimate m, given p

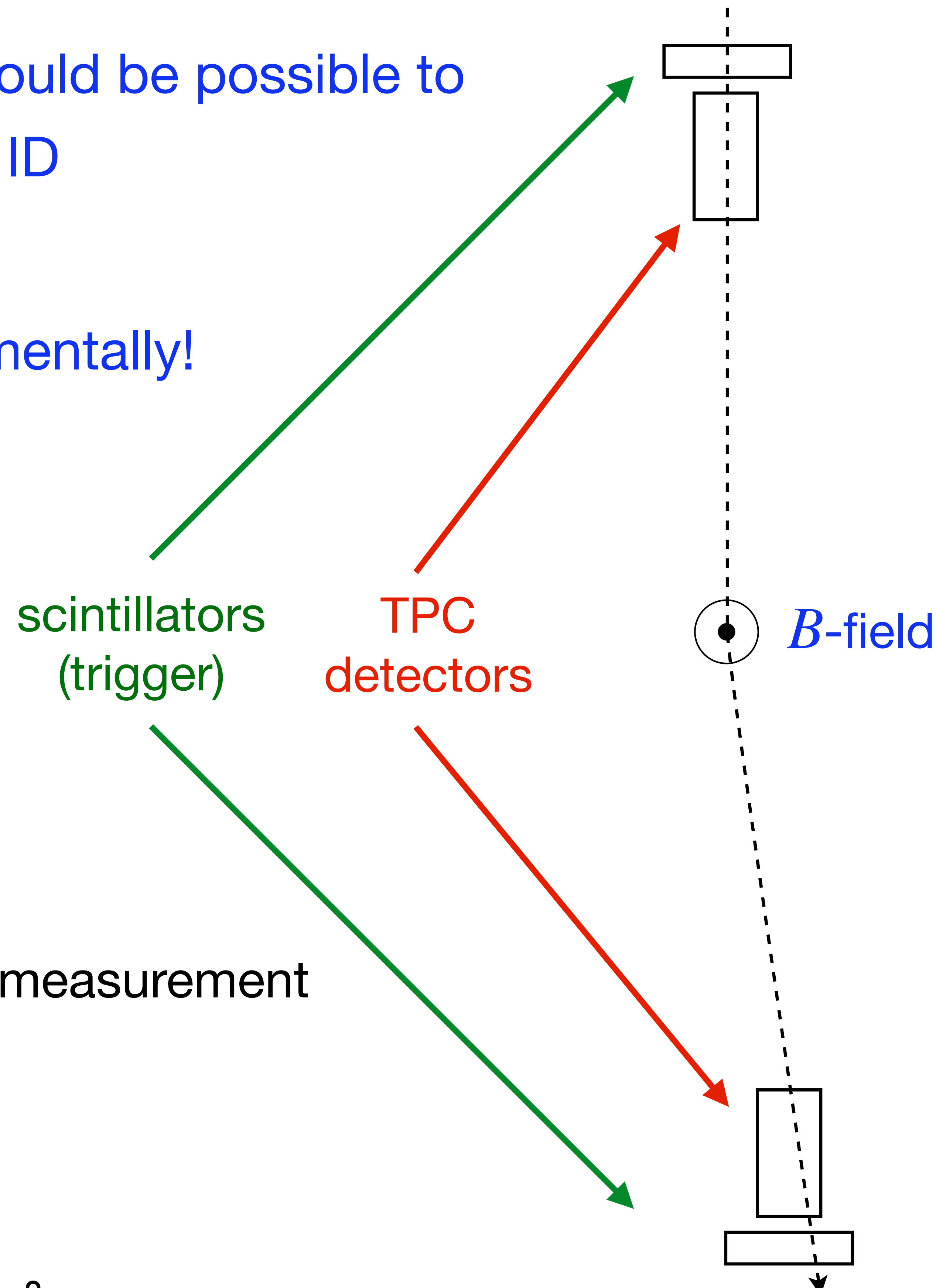
I’d like to demonstrate this experimentally!

Concrete idea:

- use (abundantly available) CR μ^+ to estimate p (for assumed m_μ)
- needs independent momentum measurement ➠ bending in B-field

Ingredients:

- 2 TPC detectors: δ rays + direction measurement
- 2 scintillator triggers
- one magnet
- electronics

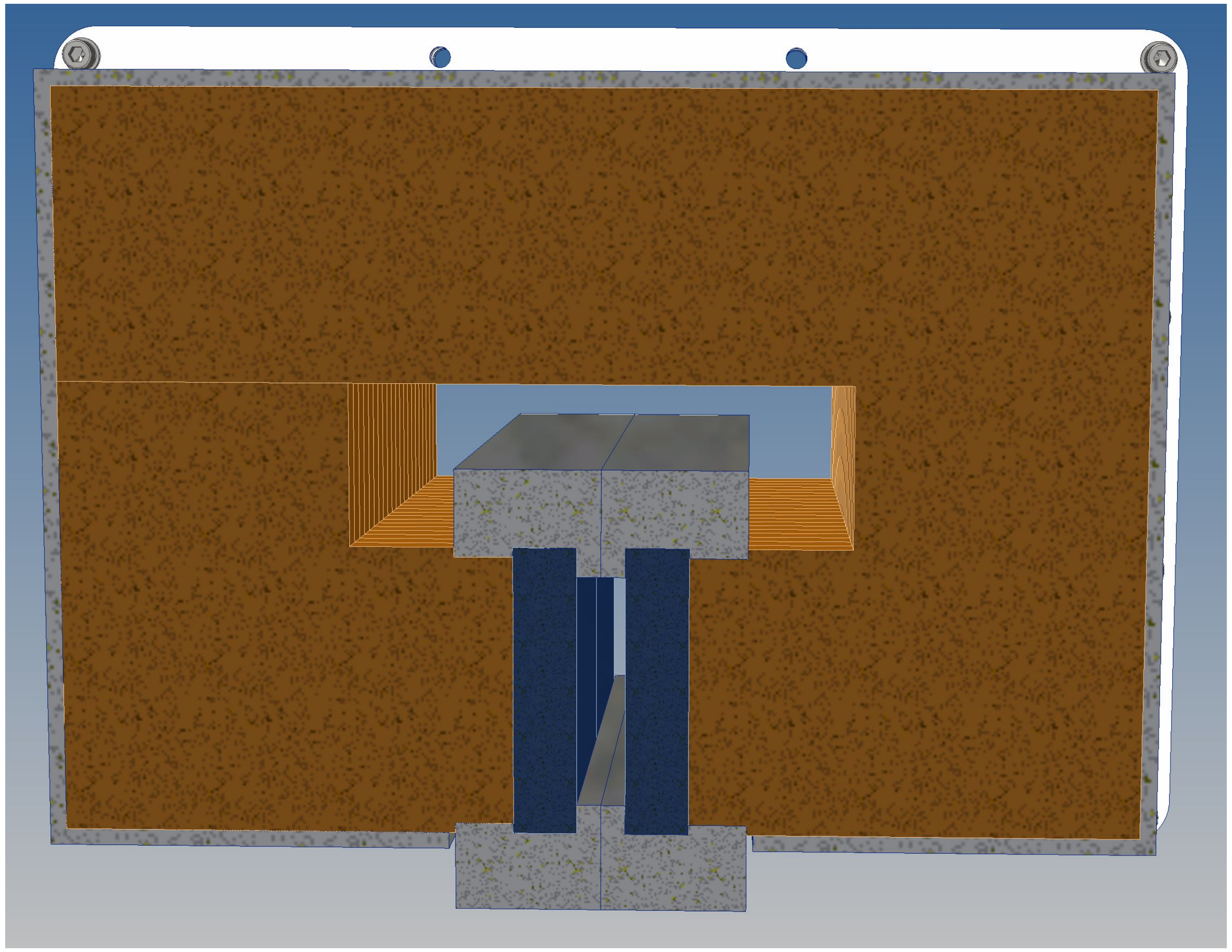


Work plan: magnet

Key quantity: "bending power" $\int B\,\mathrm{d}l$ ➠ need either a very large or a very strong magnet (or both!)

- converged on neodymium permanent magnets in horse-shoe configuration: field ~ 1 T in 1.5 cm gap
  - design is a compromise between field uniformity (~ 15%) and acceptance
  - extensive FEA studies by Daniel

Design (by Arno Engels, Techno-Centre) ready; to be produced in near future



- considerable forces
- to be done: *verify* FEA results with actual measurements
  - not easy in confined space

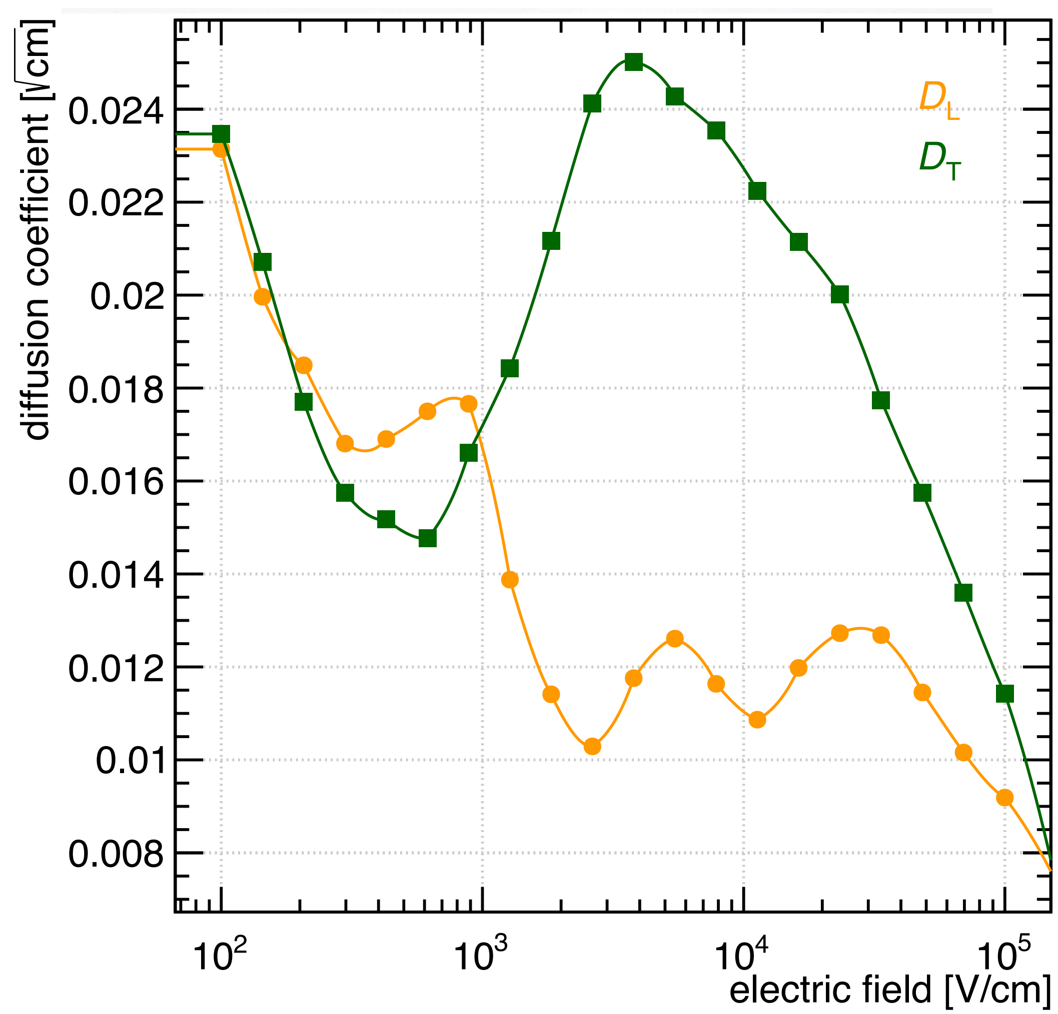
Work plan: TPC detectors

Sensors + readout scheme exist

- but are scarce & expensive — at present I don't have any in hand, and the promise from the Nikhef / Bonn side (1 for longer-term use, 1 for limited time)

Still need to design & construct small (~ 3cm × 5cm) TPCs

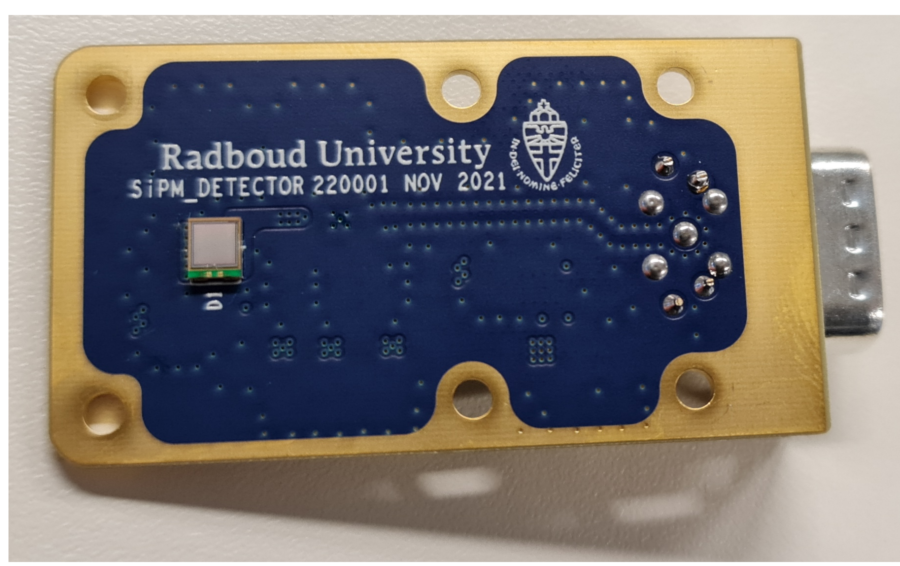
- electrically, sensor is anode; need cathode + electrodes shaping the electric field
  - $\vec{E}$ should be perfectly $\perp$ sensor
    - measurement of longitudinal coordinate
- need to converge on gas mixture & pressure (simulation studies)
  - diffusion: $\sigma_{\mathrm{T,L}} = D_{\mathrm{T,L}} \cdot \sqrt{\ell}$ ➠ challenging to keep this low enough. Possible solutions:
    - special gas mixtures (often flammable, toxic, …)
    - $\vec{B} \parallel \vec{E}$ ➠ reduced D_{T}
    - **high pressure** ➠ reduced D_{T}, D_{L}: investigate option of operating at 10 bar

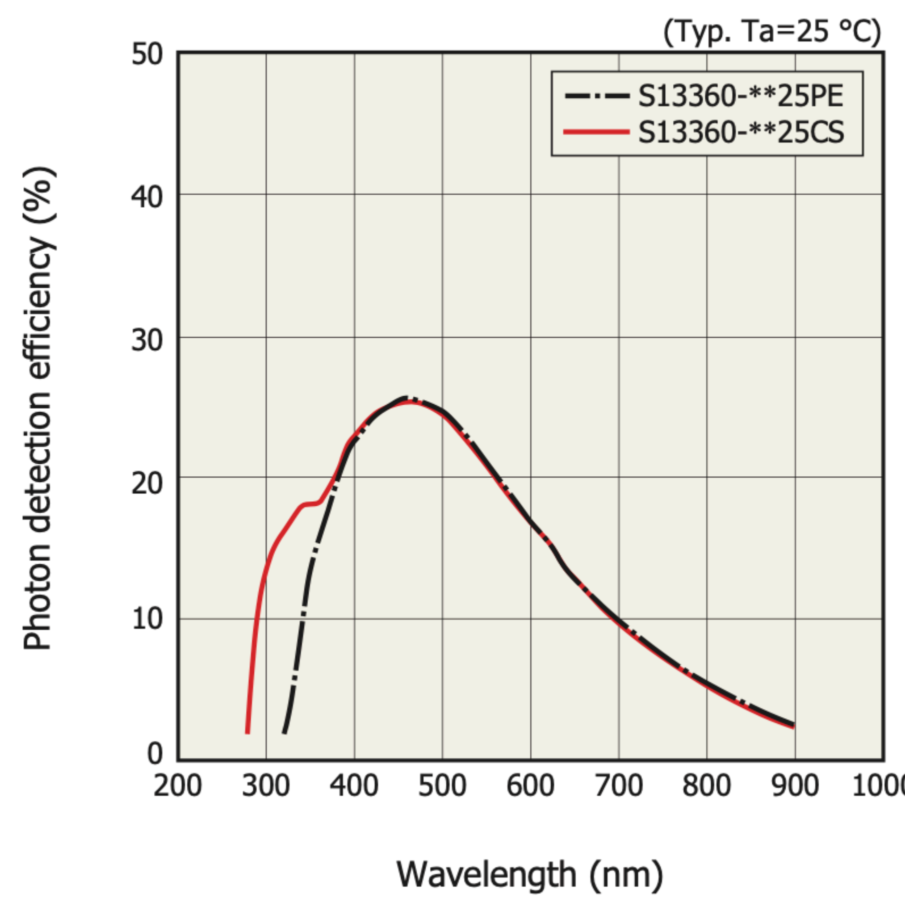


Work plan: scintillators

Data rate coming from the detector will be high if operated continuously, so the plan is to have a trigger

- data from individual TPC detectors will be useful for in-situ calibration purposes; coincidences will be useful especially to collect the tracks of primary interest
- organic scintillators: readily available & good γ yield. Rather than using traditional PMTs, opted for use of SiPMs (suggestion by Charles)
  - good spectral sensitivity
  - board designed by Daniel
- to be done: characterise once scintillator has been converged on





Prospective student projects

Multiple items will benefit from detailed studies that can be tailored for Bachelor or Master students:

- simulation studies of diffusion as a function of gas mixture, pressure, magnetic field
- development of reconstruction algorithms for
  - muon direction in TPC detectors ➠ independent momentum estimate
  - identification of δ rays & measurement of their E, θ
- characterisation of triggers

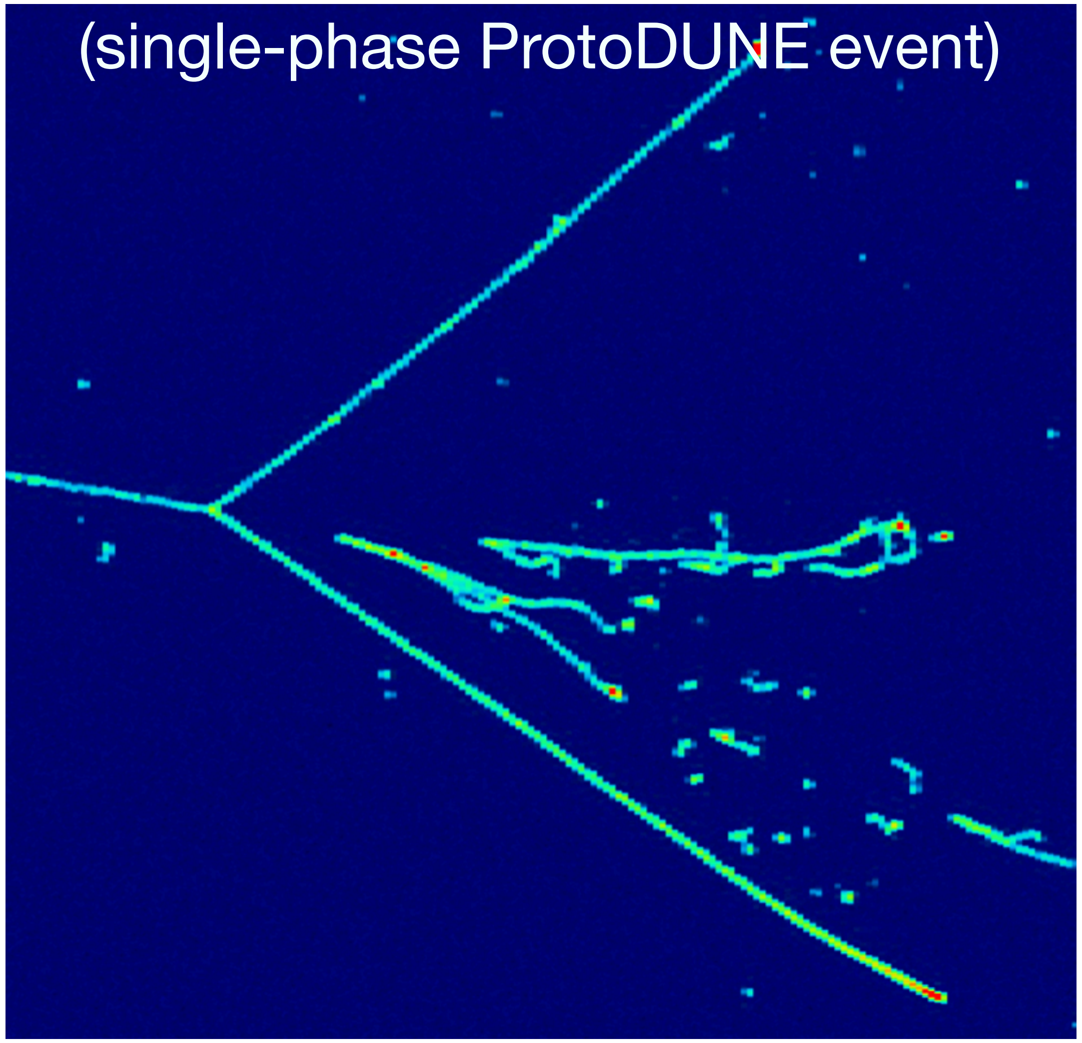
DUNE & δ rays

Deep Underground Neutrino Experiment (DUNE): study of $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations to discover and measure CP violation in the lepton sector (among many other topics)

- based on liquid argon (LAr): target as well as detection medium (both ionisation & excitation)

Essential for proper understanding: measurement of muon energy

- no B-field ➟ from range in LAr



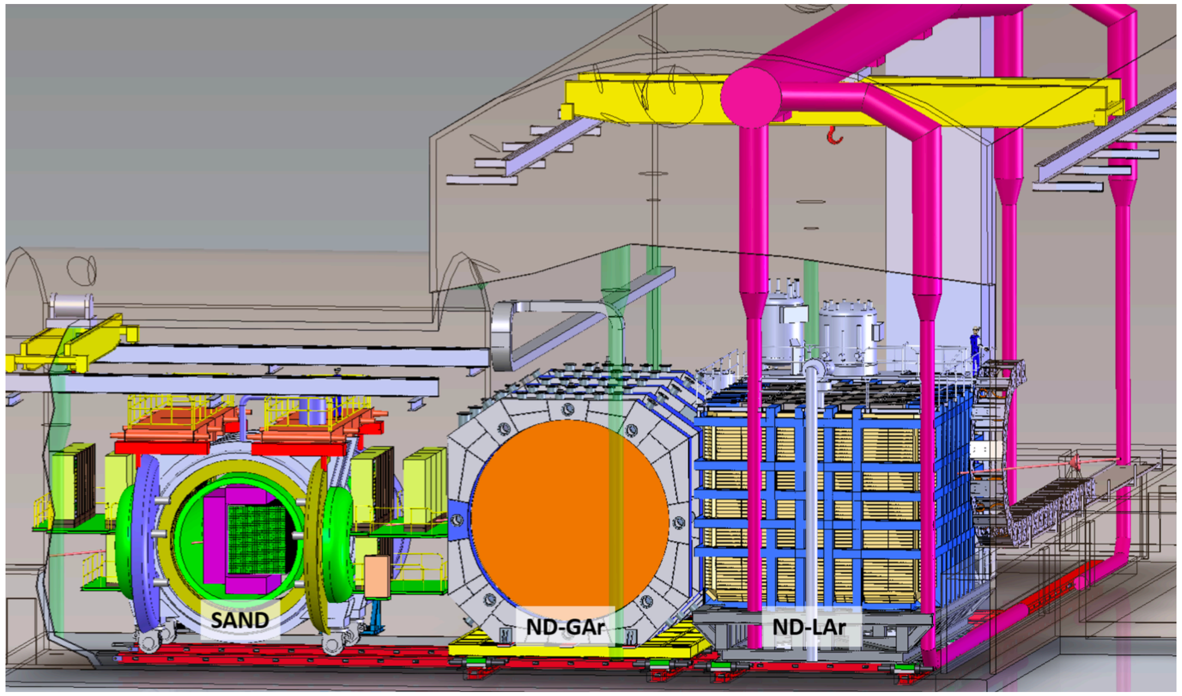
DUNE & δ rays (2)

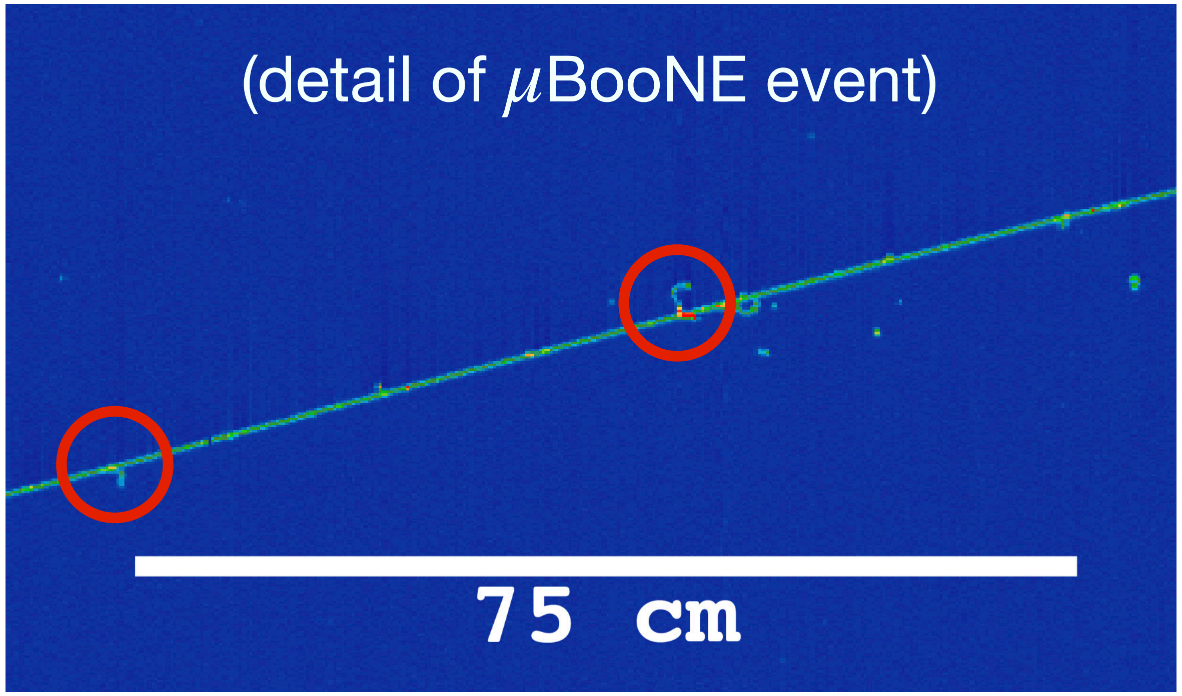
Near Detector (~ 500 m from source) will be too small to contain most of the $\mu^{\pm}$ ➠ addition of gaseous Ar TPC in B-field

- not just a "tail catcher": allows for more precise studies of ν-Ar interactions

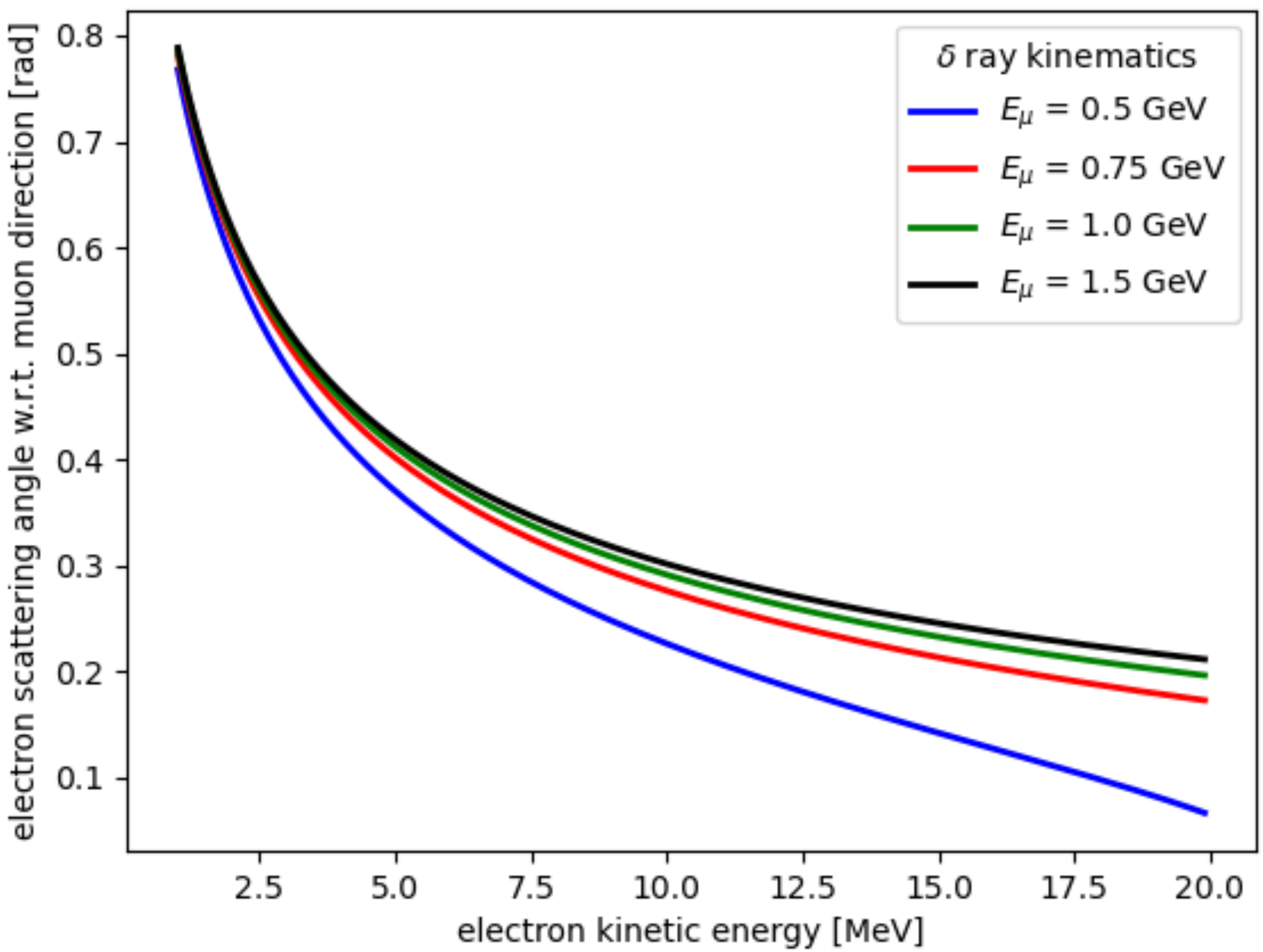
However, funding is insufficient (for now) to have this system in place at the start of beam data taking ➠ construction of temporary muon spectrometer

Aim to investigate whether δ-ray construction is a sufficient alternative





Backup



δ ray kinematics
E_μ = 0.5 GeV
E_μ = 0.75 GeV
E_μ = 1.0 GeV
E_μ = 1.5 GeV
electron scattering angle w.r.t. muon direction [rad]
electron kinetic energy [MeV]
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0