How can physicists explore the particle world? (II)

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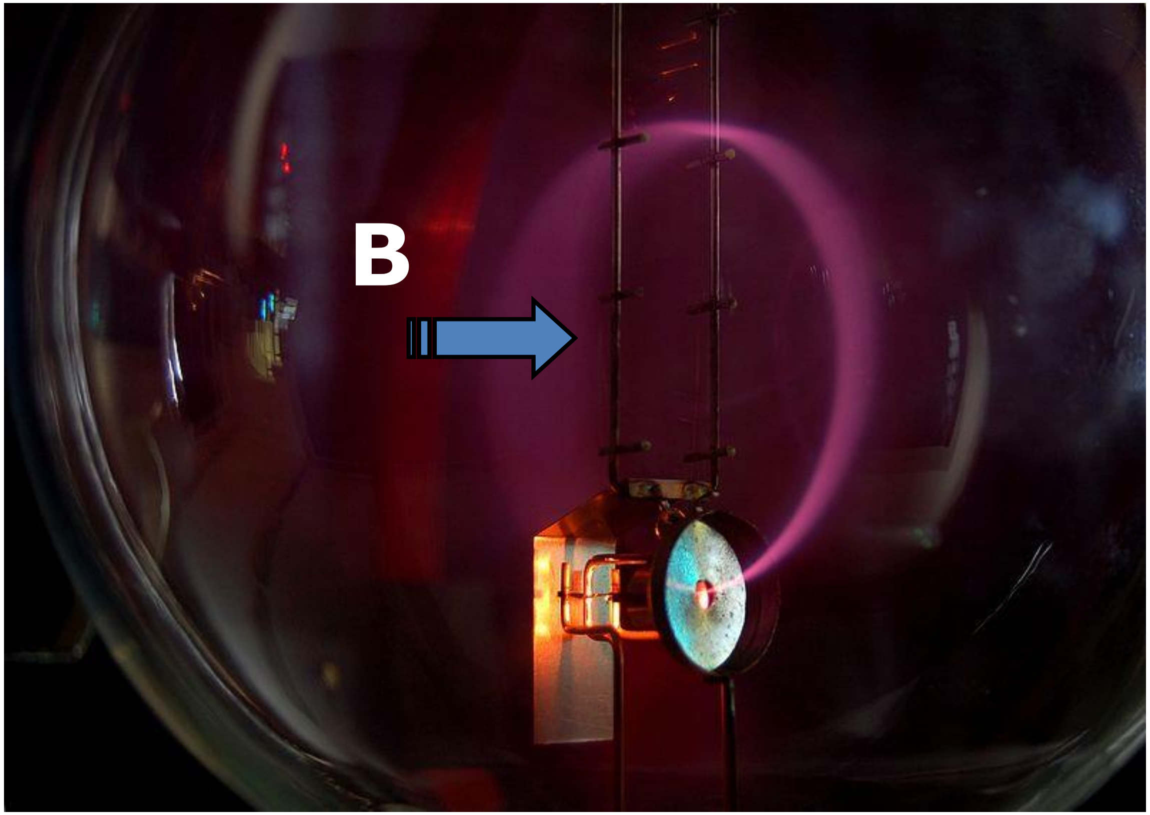
The 4th Asia Europe Pacific School of HEP @Quy Nhon, Vietnam

The 2nd step

- Measuring four momentum of particles combining the information from detectors….

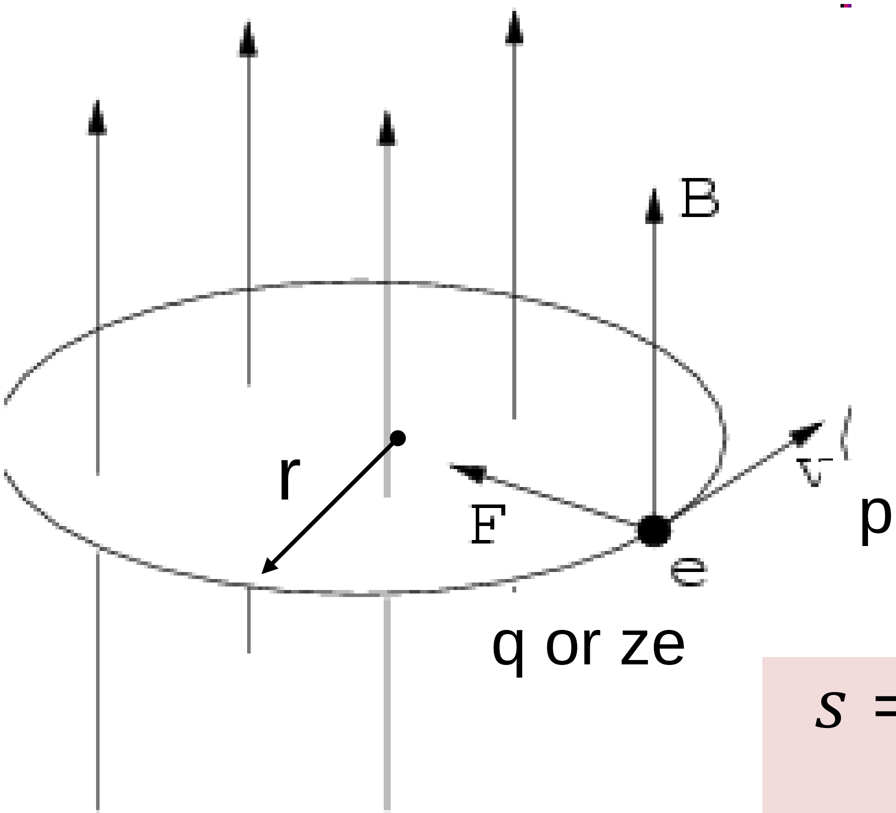
Momentum

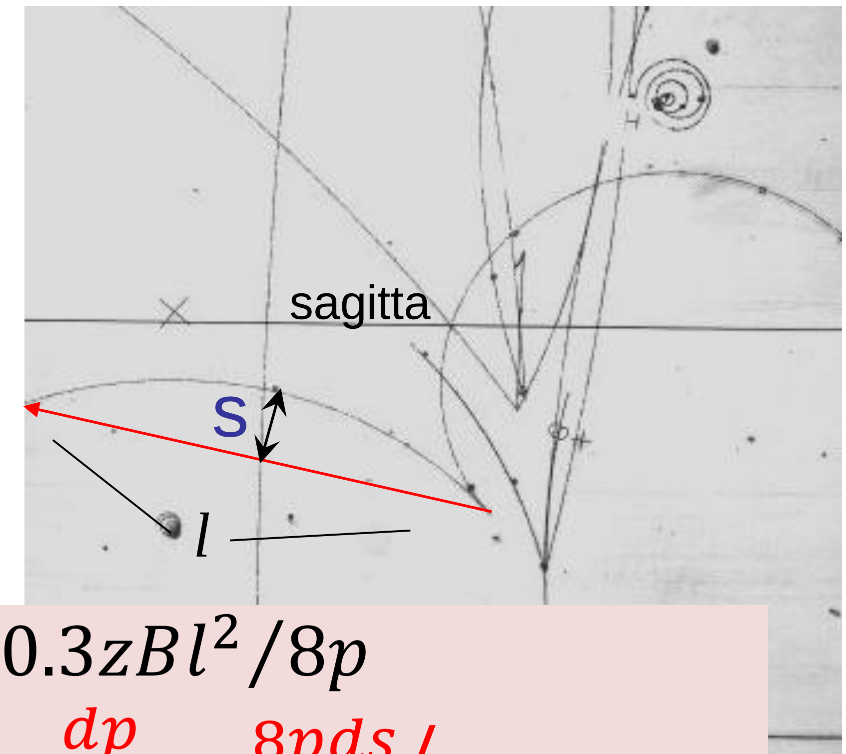
- *Momentum* can be measured as a radius of circular motion in a magnetic field



Lorentz force and momentum measurement

$$p = qrB \quad or \quad p = 0.3zBr \qquad (\mathrm{GeV, m, Tesla})$$



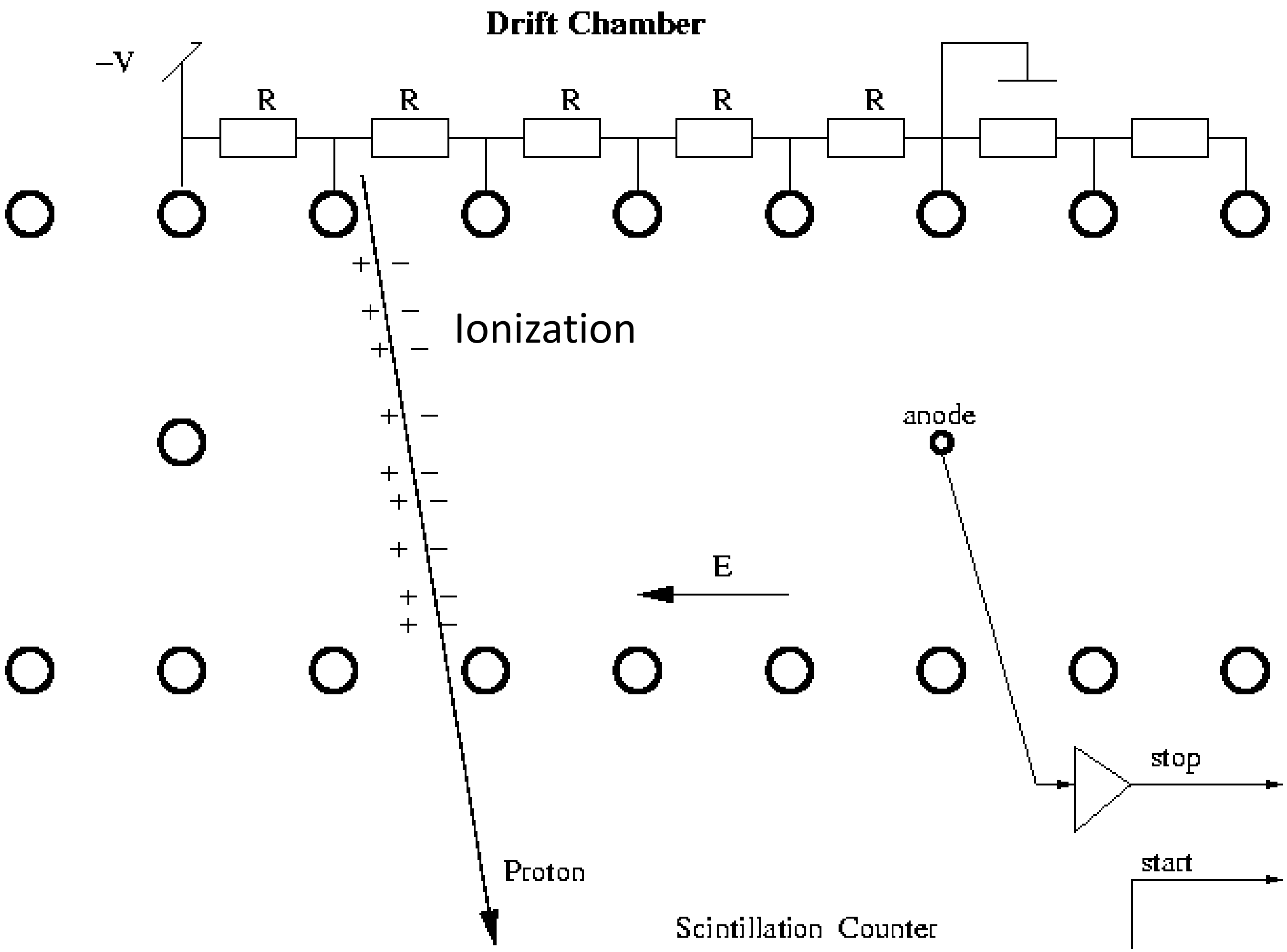


$$s = 0.3zBl^2/8p$$

$$\rightarrow \quad \frac{dp}{p} = {8pds}/{0.3zBl^2}$$

$$ds^2 = \sigma^2_{tracking} + (\sigma_{MS}/p)^2$$

Wire chambers invented by Charpak



Drift velocity

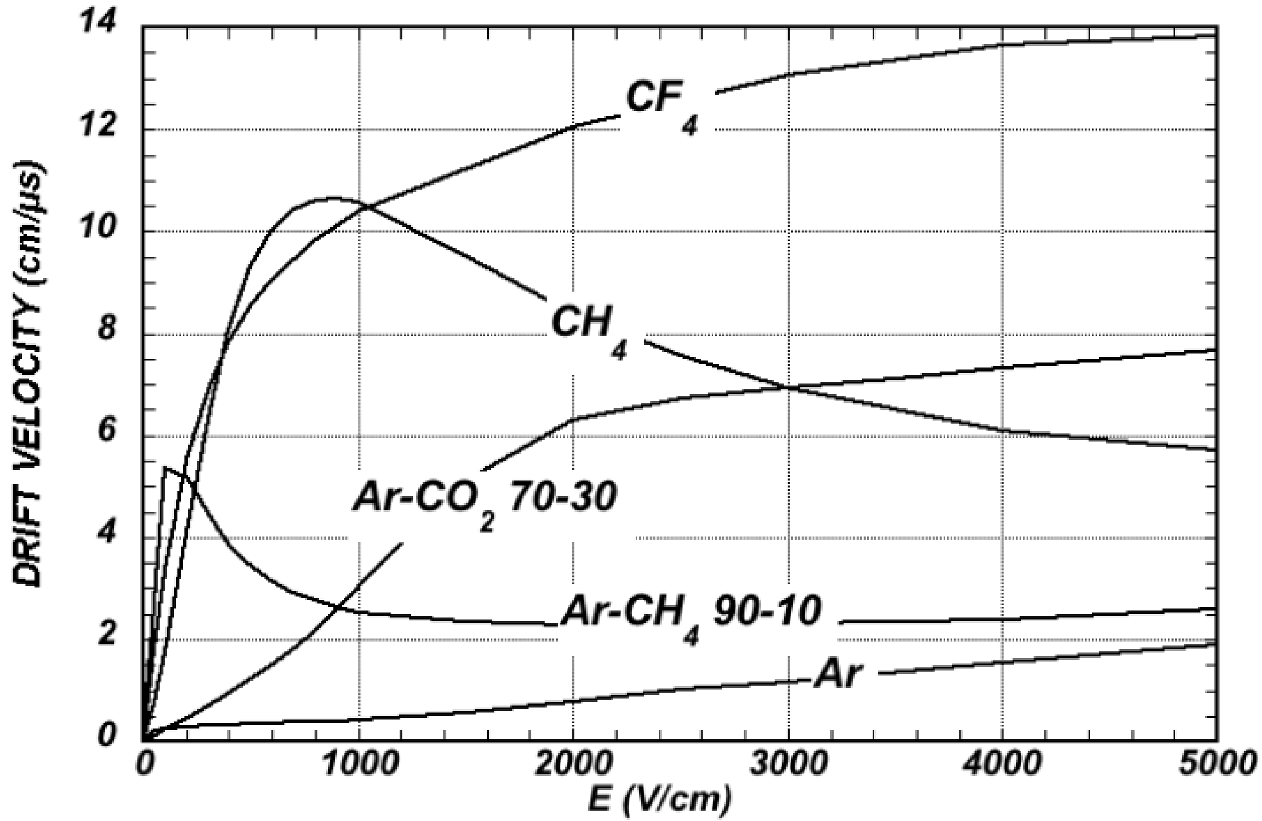
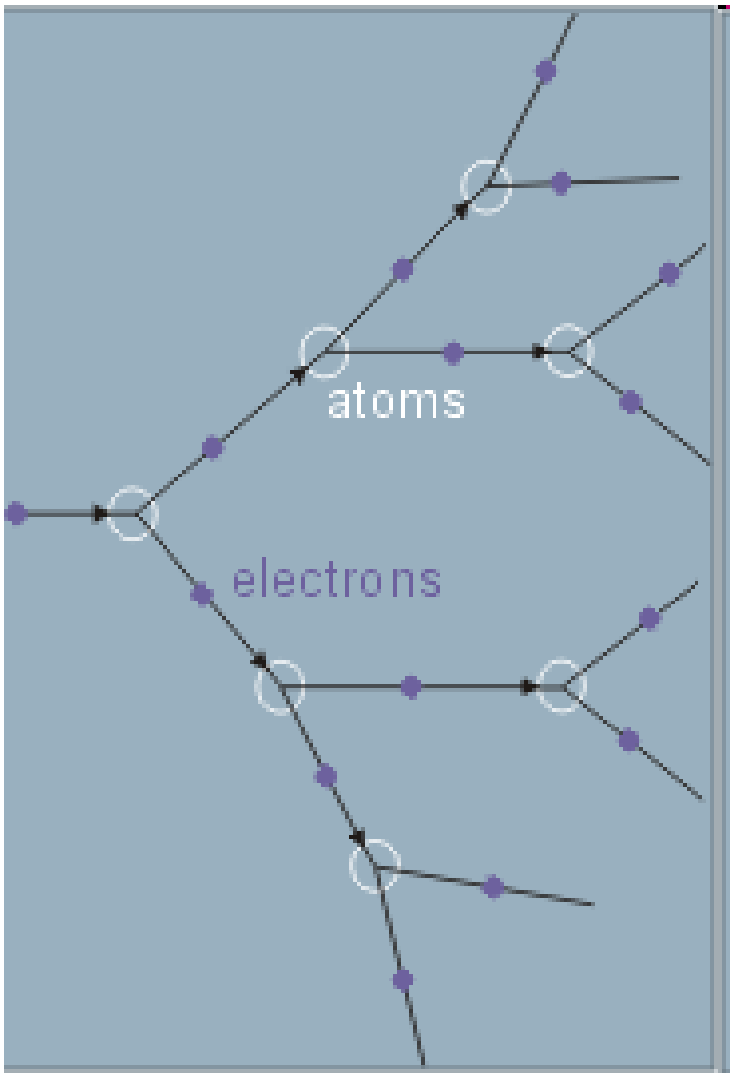
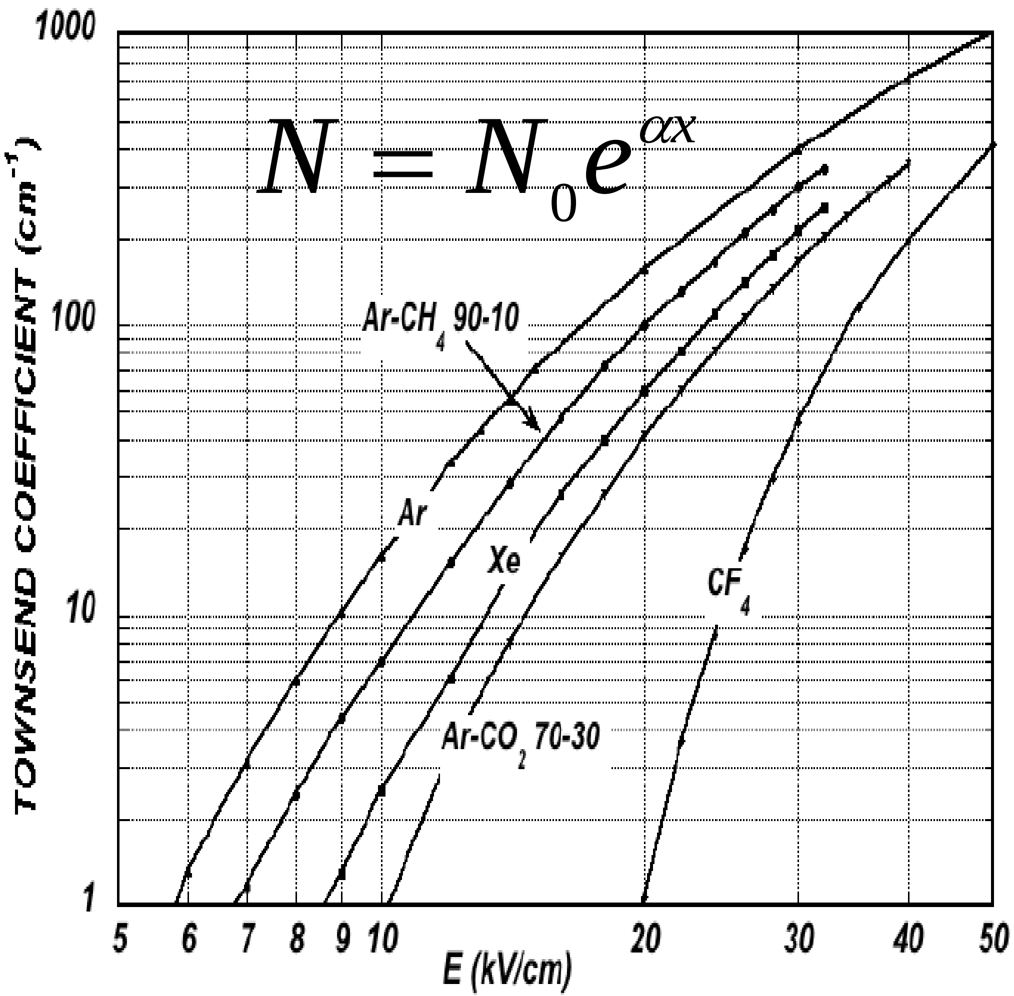


Figure 28.4: Computed electron drift velocity as a function of electric field in several gases at NTP [67].

Electron avalanche multiplication



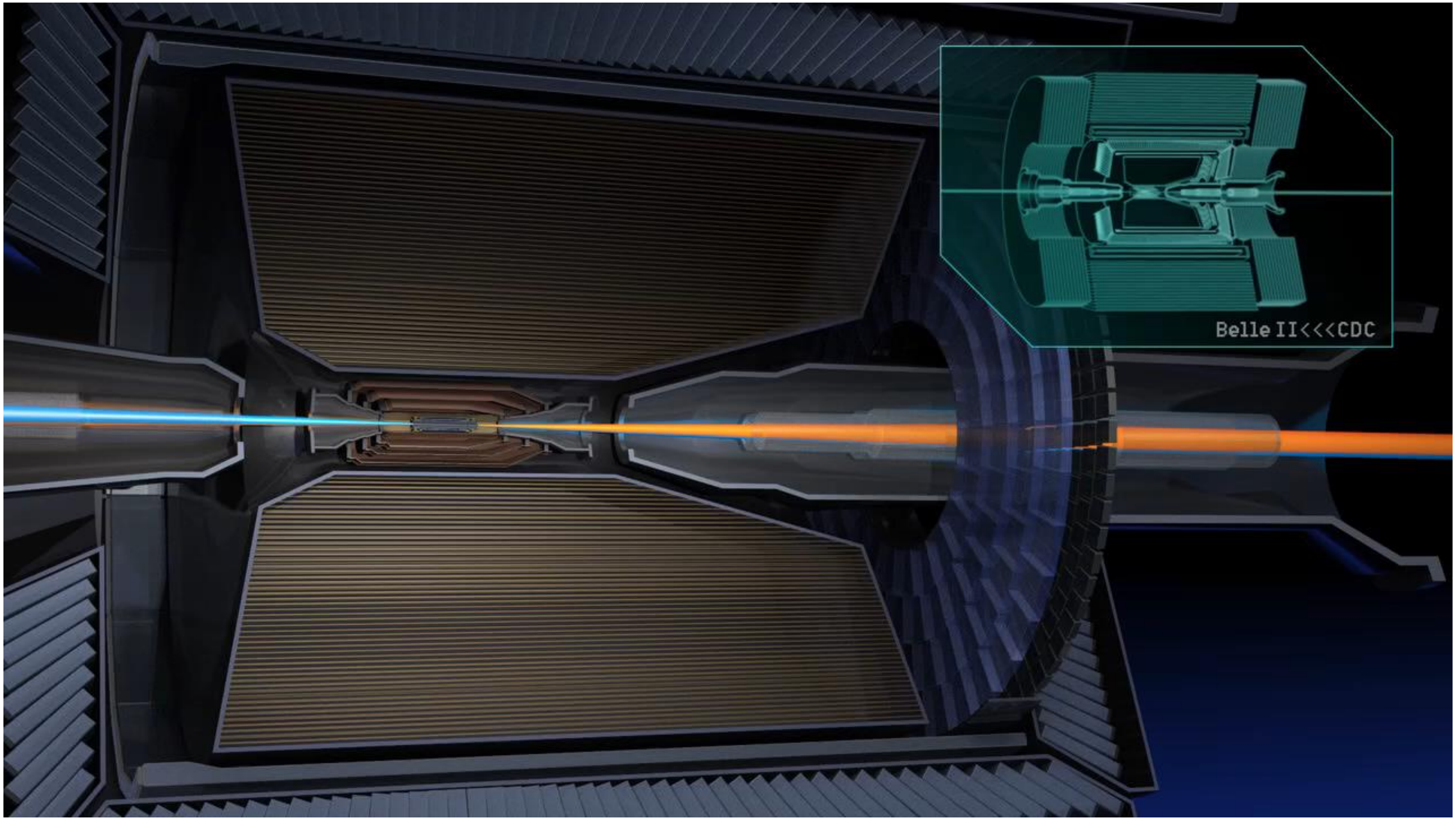


$$N = N_0 e^{\alpha x}$$

Electric field around a thin wire is extremly high

$$\varepsilon(r) = \frac{V}{r \ln(b/a)}$$

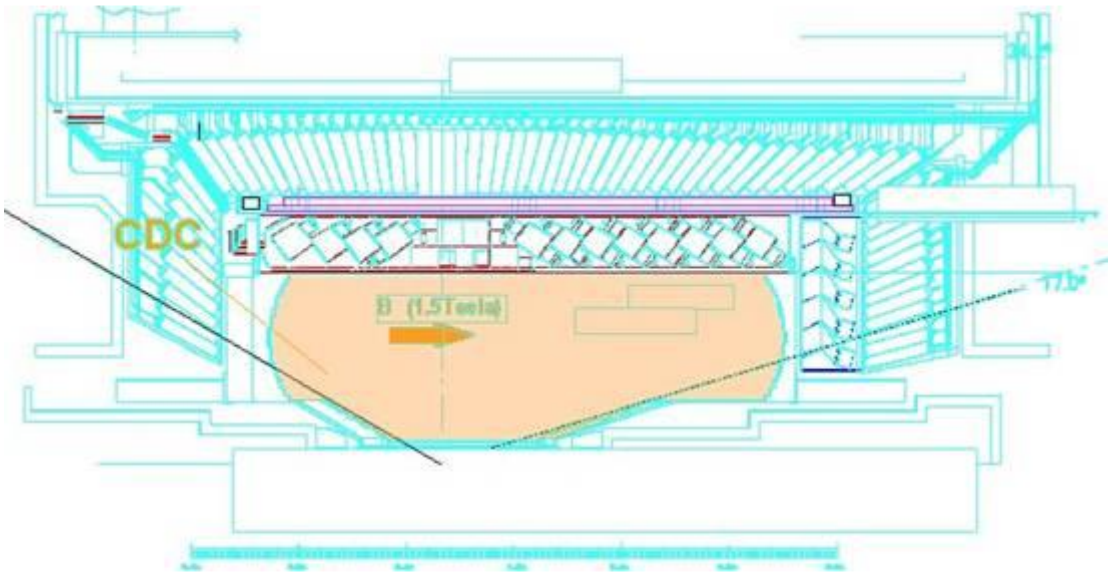
Central Tracker

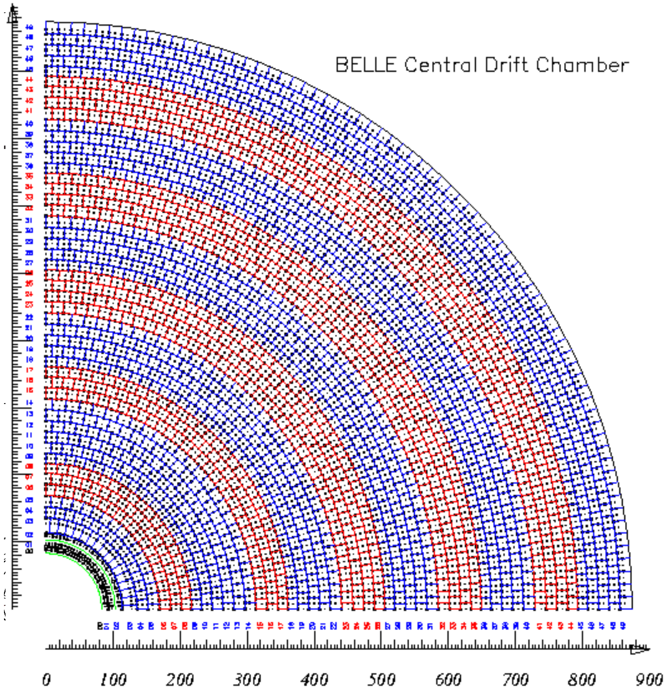


Drift Chamber

(momentum,PID)

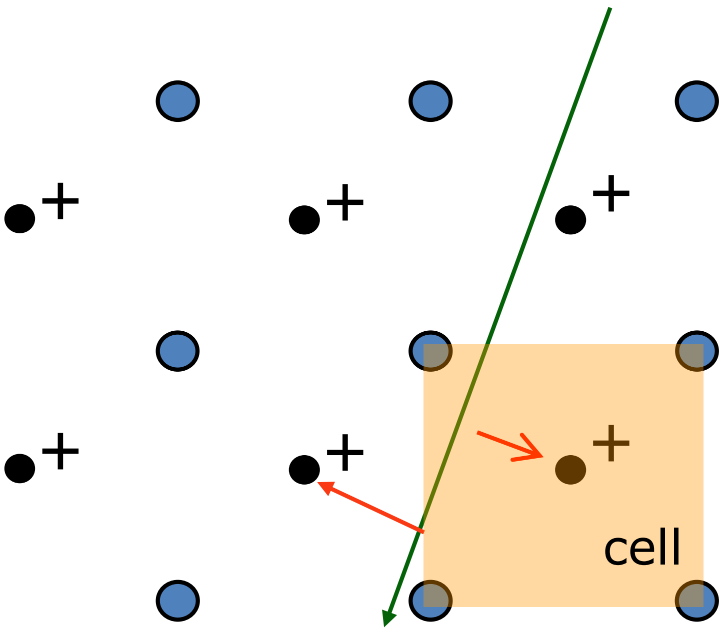
- Belle CDC consists of three parts(Main, Inner and Cathode).
- Curved Aluminum enplates for the main part.
  - Thickness : $10mm^t$
- Conical endplates for the inner part to give a space for accelerator components.

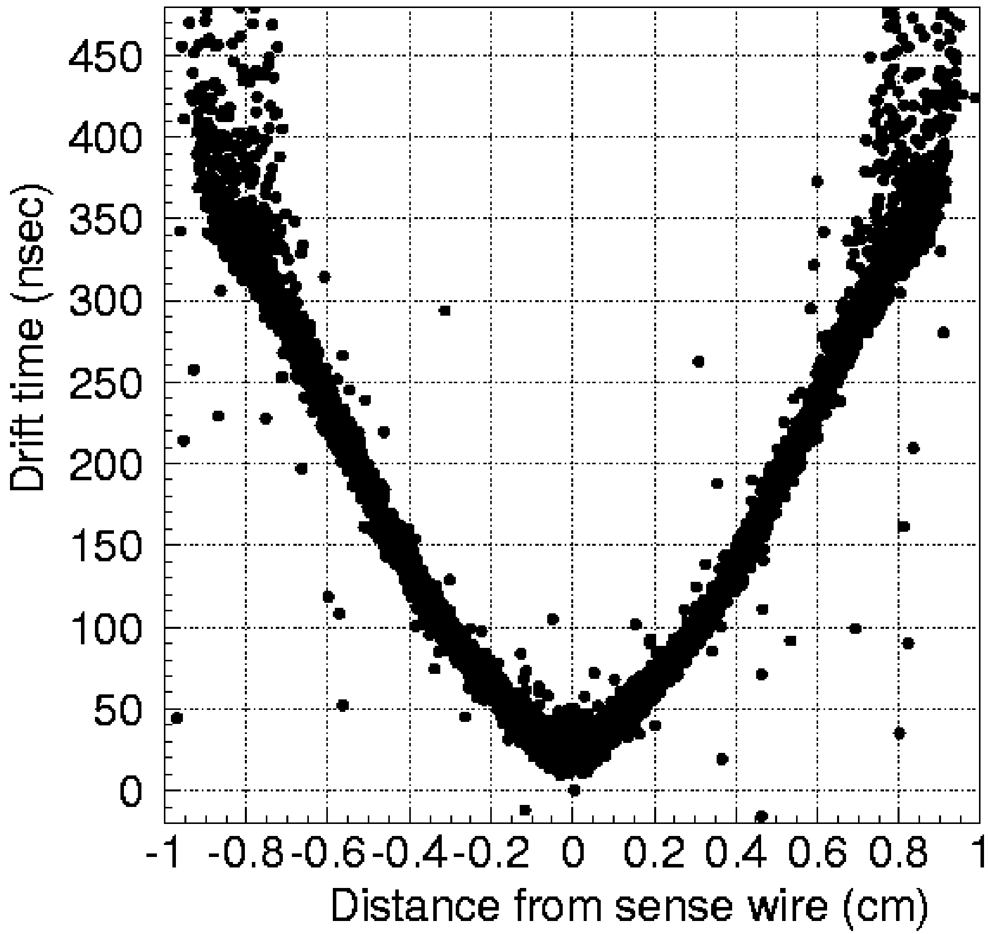




X-T relation
(drift time vs position)

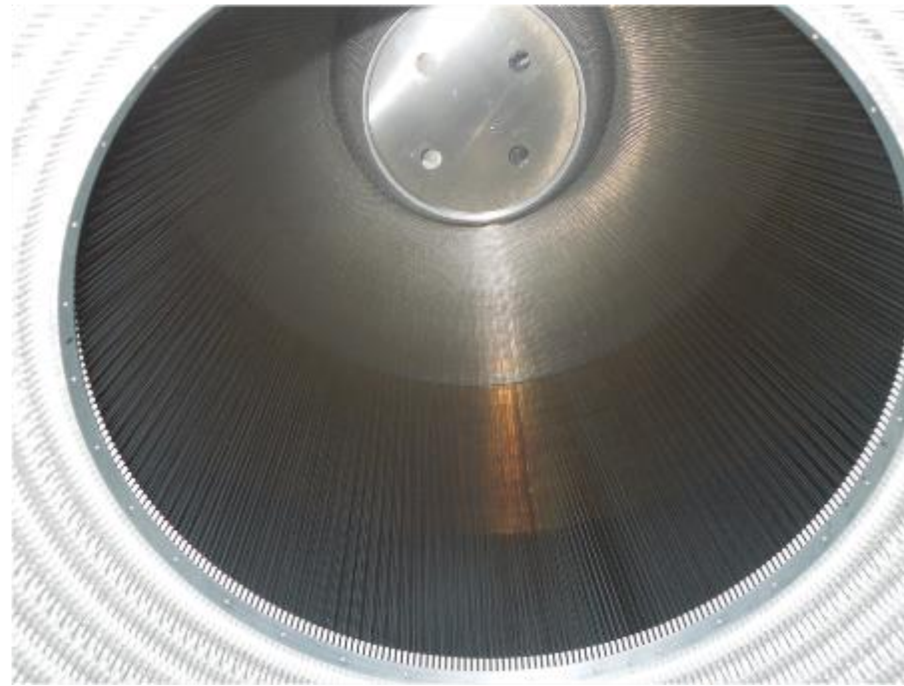
- $He(50\%)-C_2H_6(50\%)$
- B=1.5Tesla
- HV : 2.3KV
- Cell Size:18mm
- Maximum Drift Time : ~400nsec





Wire stringing for BelleII central drift chamber

Inner part
5120 wires



Outer part
43,776 wires

It took more than 5 years to complete

P_t resolution of BelleII CDC
(Big contribution of Vietnamise students in KEK)

$$\frac{\sigma_{P_t}}{P_t} = \left(\frac{\sigma_{P_t}}{P_t}\right)_{\text{meas}} \oplus \left(\frac{\sigma_{P_t}}{P_t}\right)_{\text{MS}}$$

$$\left(\frac{\sigma_{P_t}}{P_t}\right)_{\text{meas}} = \frac{P_t \sigma_{r\phi}}{0.3 L^2 B}\sqrt{\frac{720}{N+4}}$$

$$\left(\frac{\sigma_{P_t}}{P_t}\right)_{\text{MS}} = \frac{0.05}{L B \beta}\sqrt{1.43\frac{L}{X_0}}\left[1 + 0.038 \ln\frac{L}{X_0}\right]$$

$\sigma_{r\phi}$: position resolution

B: magnetic field (1.5 T).

X_o: radiation length.

L: lever arm.

N: number of measurement point

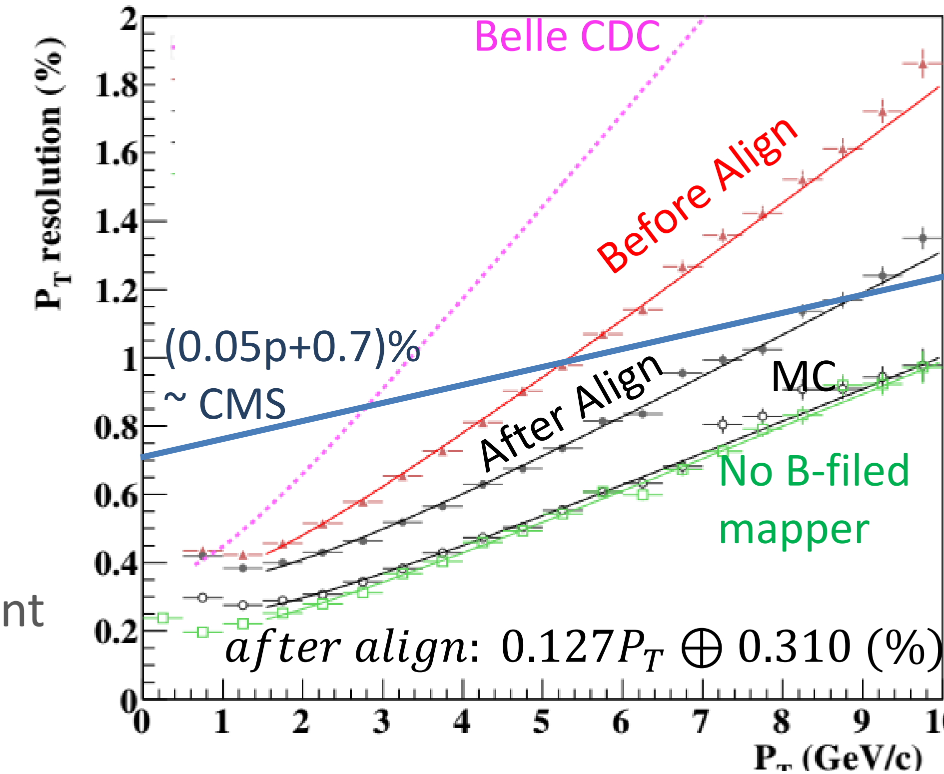
$$\frac{\sigma_{Pt}}{Pt} = \sqrt{(aP_t)^2 + b^2}$$

	Belle	→ Belle II
L:	77.5	→ 94.84 cm
N:	50	→ 56

Belle CDC only: $0.28P_t \oplus 0.35\ (\%)$

=> Estimate for Belle II : $0.19Pt \oplus 0.32(\%)$

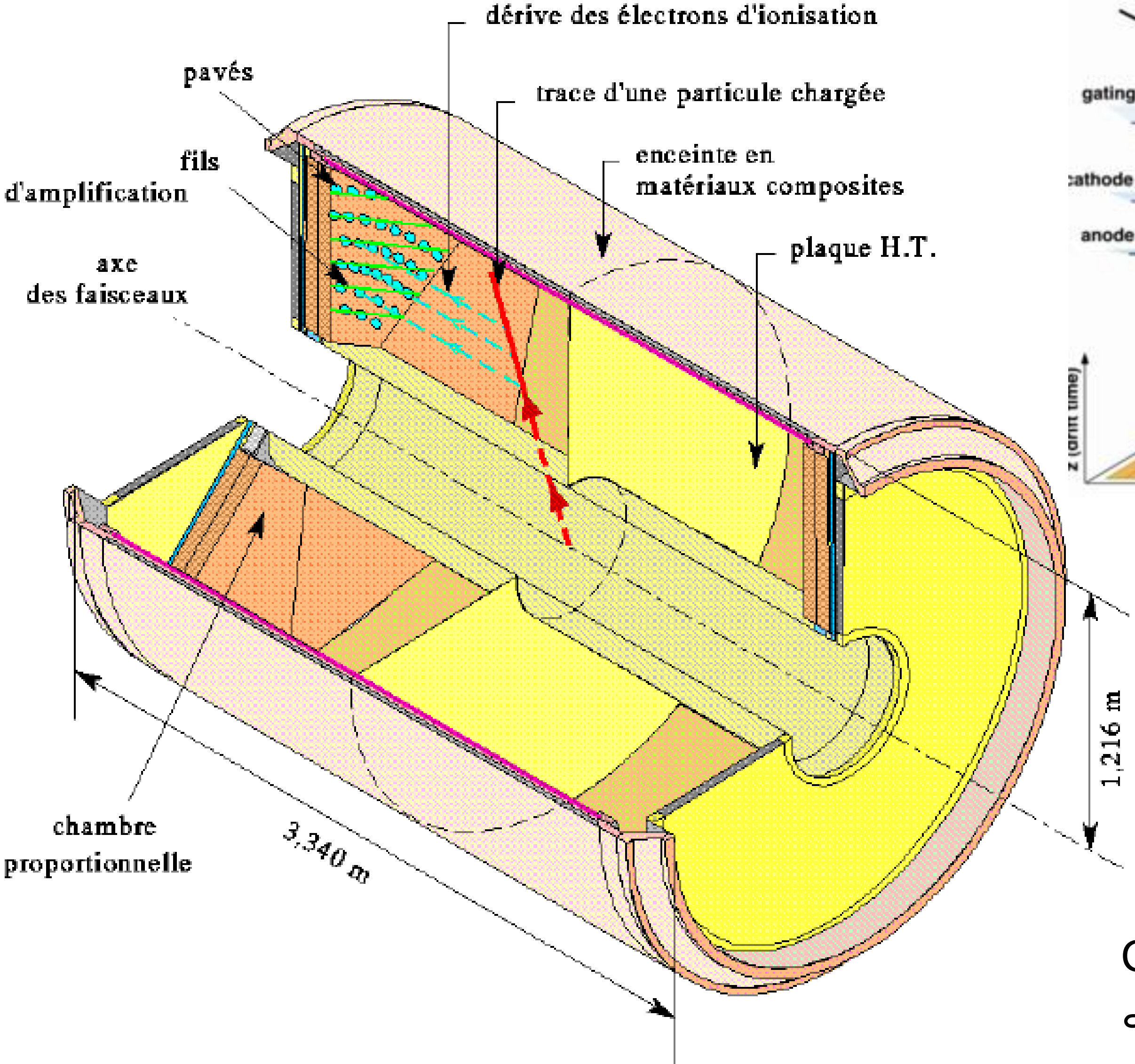
Obtained : $0.127P_t \oplus 0.310(\%)$

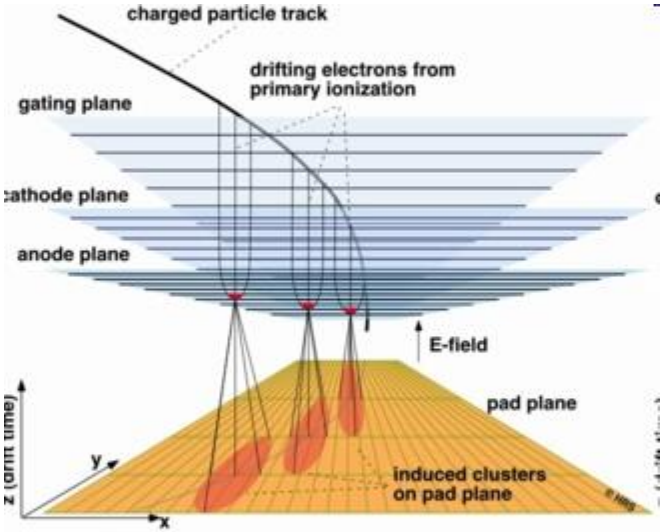


- P_T resolution is much improved compare with Belle CDC.
- Much better than the expectation (extrapolation from Belle CDC)
- Observed constant term is not improved as expected because of the multiple scattering on the B-field mapper

P_T (GeV/c) D.V.Thann

TPC(Time Projection Chamber)





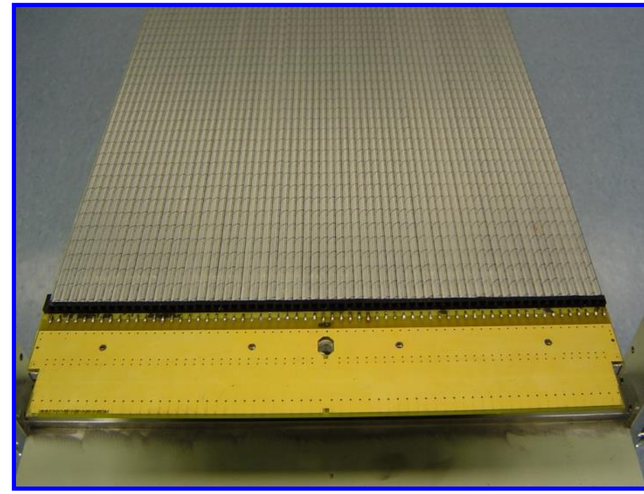
Z座標をドリフト時間で

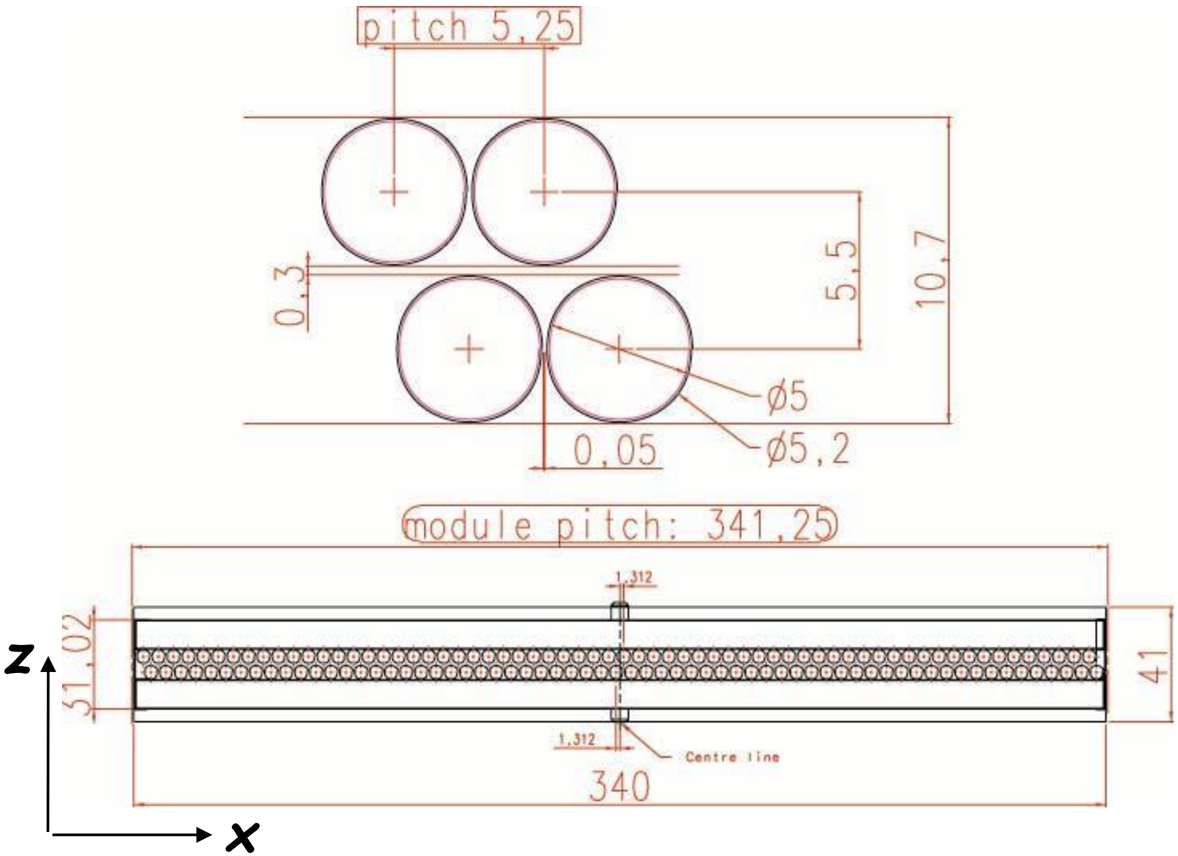
３次元の空間測定

CERN/ALICEウェブページ
より抜粋

Straw Tubes Modules

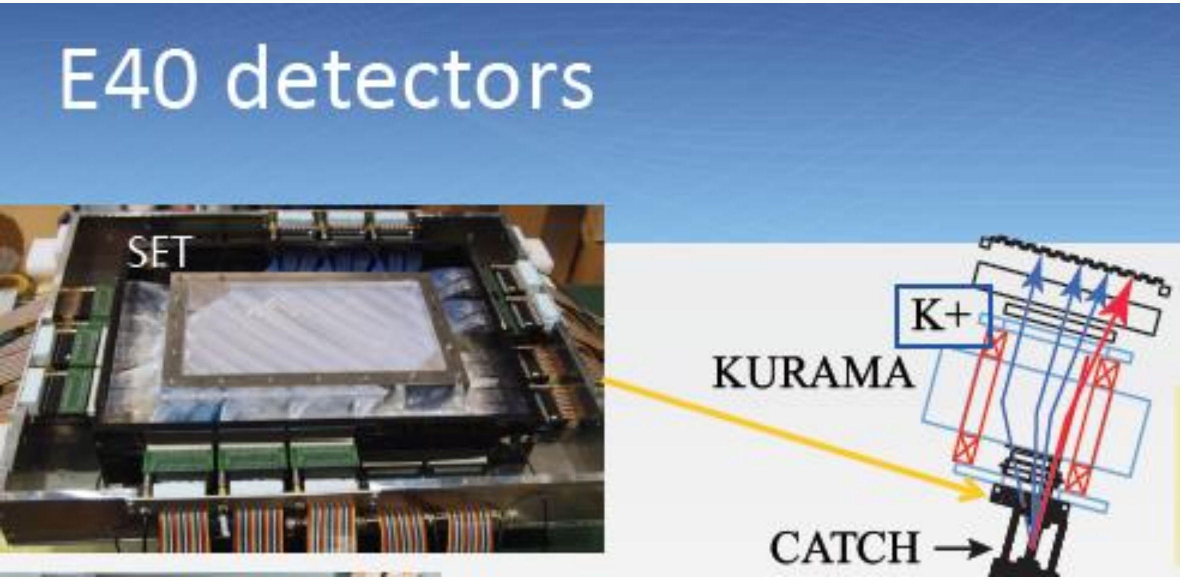
Straw Tubes packed in double-layered modules



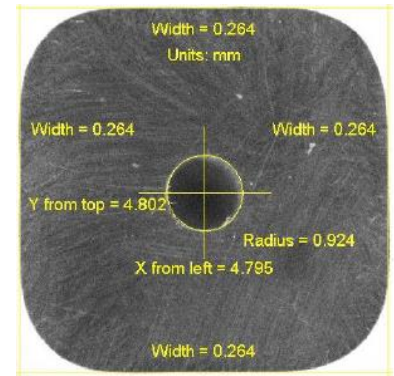


- modules 64-cells wide
- modules only ~0.37% of 1 X_0
  - "light" panels (Rohacell core with carbon fiber skins)
  - "light" straws

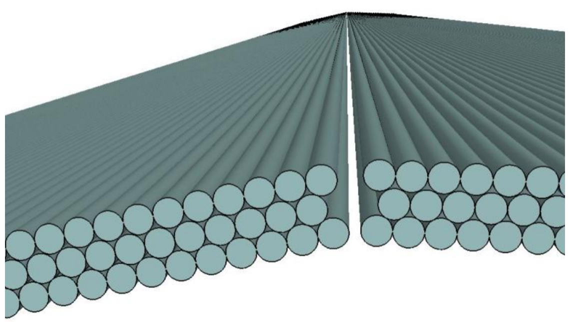
Scintillation strip/fiber tacker



0.5 – 1 mmϕ

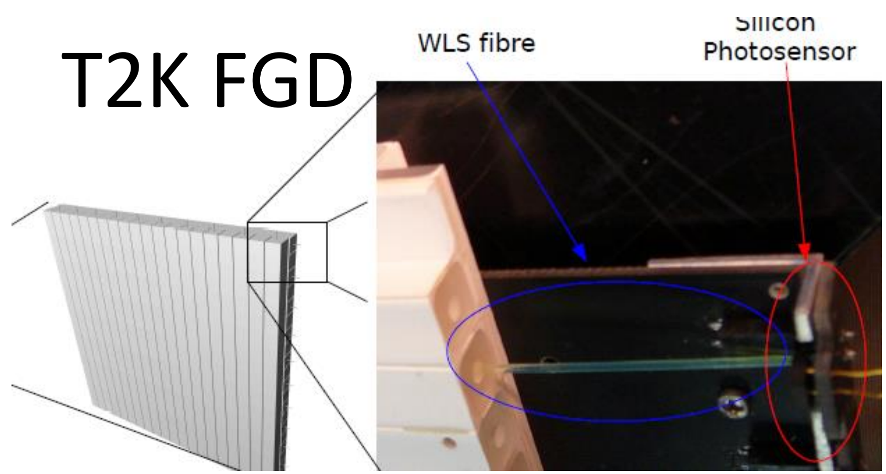


Mu3e



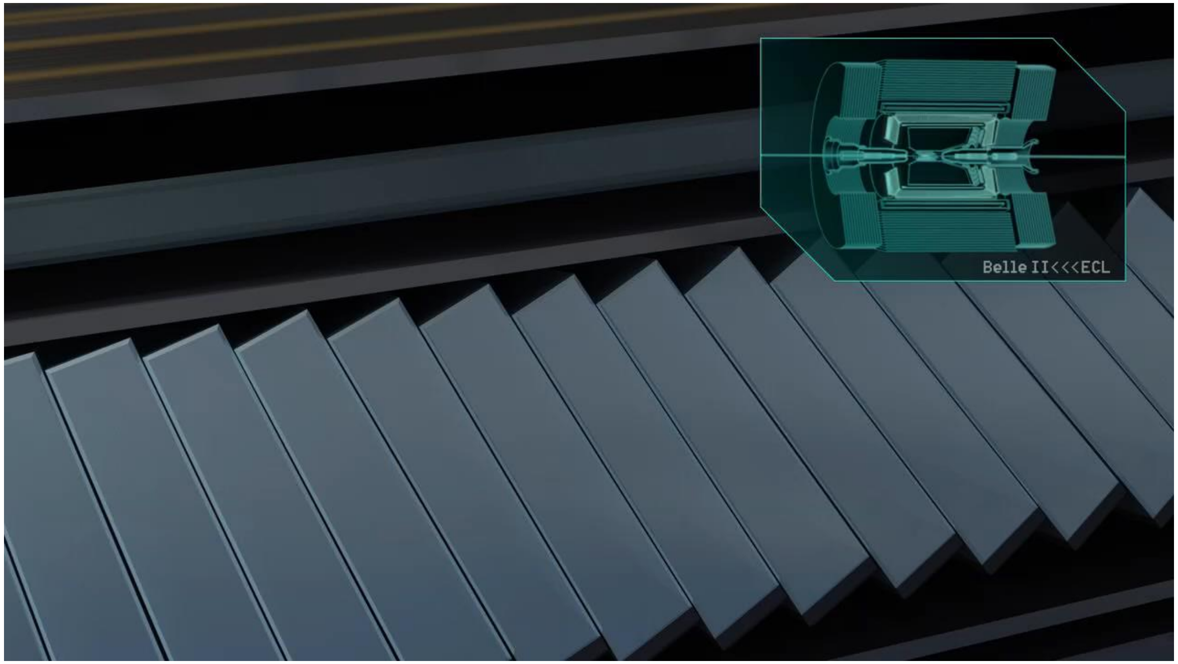
0.25 mmϕ

T2K FGD



Energy measurement

Energy can be measured
by a total absorption calorimeter,
in which all the energy are released
through cascading shower.



Energy measurement

- Energy measurement with calorimetry is a powerful technique especially for higher energy experiment at hadron colliders.

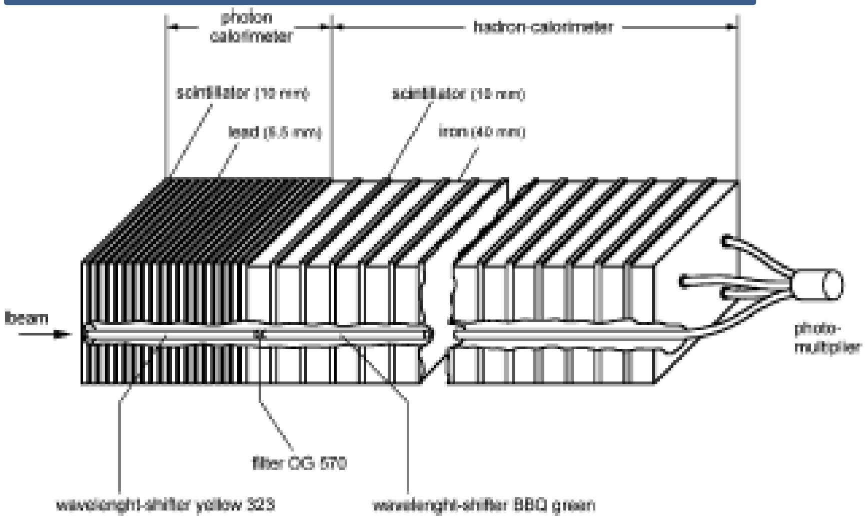
E ~ Number of particles generated in a shower (N)

$$E = CN$$

$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = \frac{1}{\sqrt{N}} = \frac{\sqrt{C}}{\sqrt{E}}$$

Cf. $$\frac{dp}{p} = {}^{8pds}\!/_{0.3zBl^2}$$

Traditional sampling calorimeter

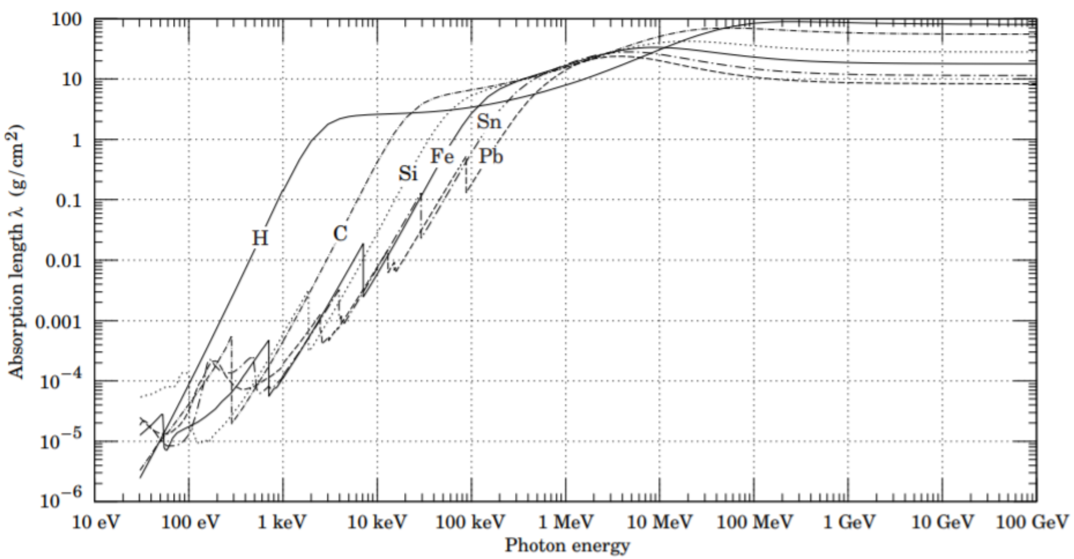


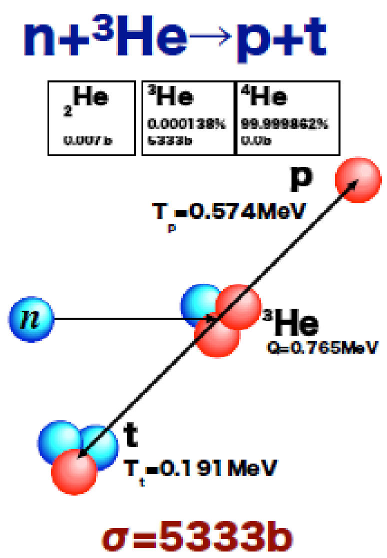
Klaus Pretzl 2005 *J. Phys. G: Nucl. Part. Phys.* **31** R133

Question given yesterday: How to distinguish photon from neutron?

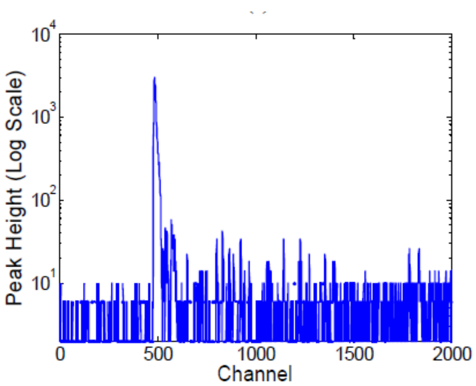
Photon vs neutron For low energy area

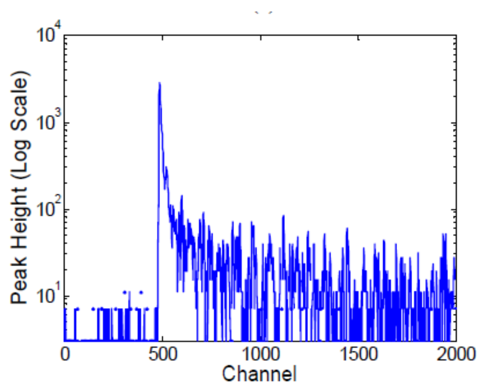
– Material with high Z for photon, high absorption cross section (like 3He) for neutron

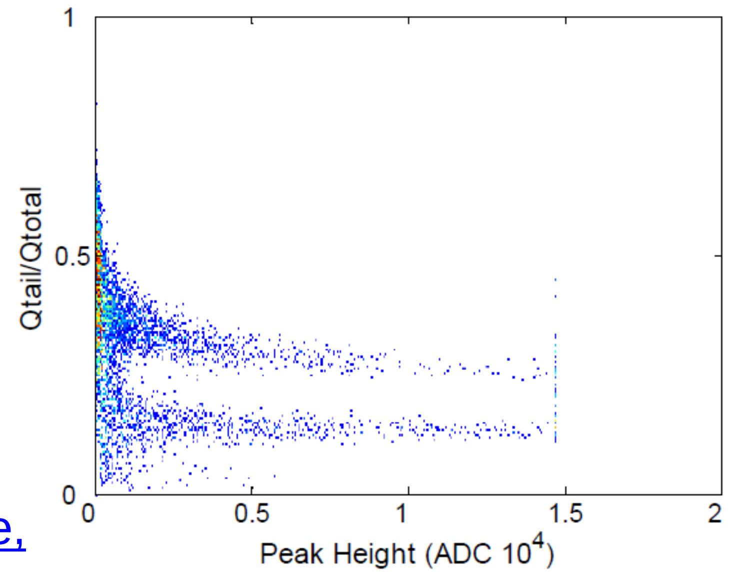




– Pulse shape discrimination in scintillation device, very important technique in low energy neutrino experiment or DM search





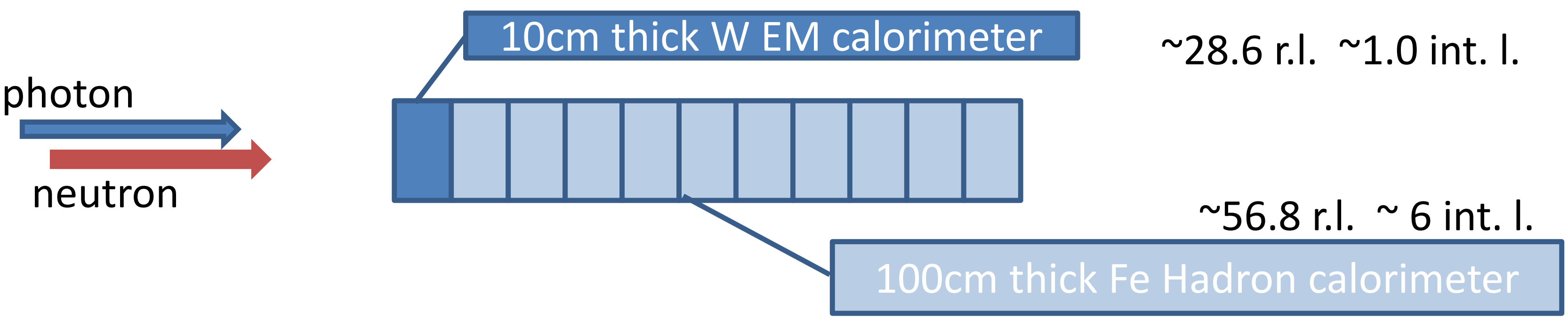


Lintereur, Azaree T.; Ely, James H.; Stave, Jean A.; McDonald, Benjamin S. PNNL-21609

For high energy area

- Radiation length, interaction length (~ mean free paths of photon or neutron, respectively)

	Radiation length	Nuclear interaction length	Density
W	6.76 (g/cm^2)	191.9 (g/cm^2)	19.3 g/cm^3
	0.35 cm	9.94 cm	
Fe	13.84(g/cm^2)	132.1(g/cm^2)	7.87 g/cm^3
	1.76 cm	16.8cm	



Organic scintillator and WLS

Scintillator	Emission spectrum（nm）	Decay time （ns）	Light yield wrt NaI
Naphthalene	348	96	0.12
Anthracene	440	30	0.5
p-Terphenyl	440	5	0.25
PBD	360	1.2	
POPOP	420	1.6	
bis-MSB	420	1.2	

Particle identification

- ***Particle identification (mass)*** can be made from its veolocity（β=*v/c*）, which can be measured through time of flight, Cherenkov radiation or energy loss rate.
- Life time (flight distance) of particle is another very important characteristics.

	$\mu^{\pm}$	$e^{\pm}$	γ	$\pi^{\pm}$	K^0	$K^{\pm}$	p	n
Mass (MeV/c^2)	106	0.511	0	140	498	494	938	940
Detection	Charge	Charge Shower	Shower	Charge Strong	Strong	Charge Strong	Charge Strong	Strong
Life time（$c\tau$ m）	659	--	--	7.8	0.027 (15.3)	3.7	--	2.7 $\times 10^{11}$

Some theorists know better….

The Standard Model: Matter

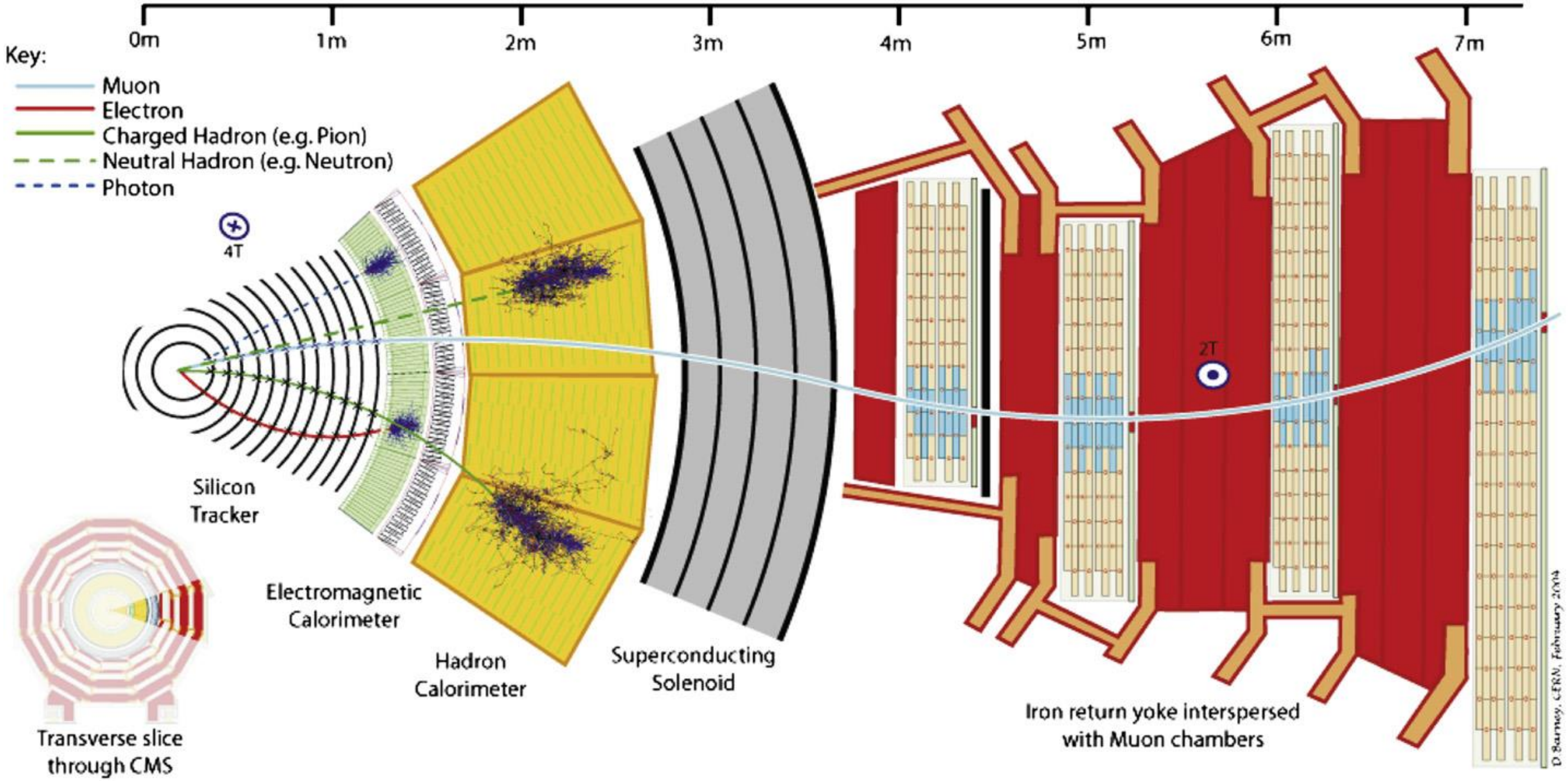
~~The particles seen in a detector~~

Absolutely stable particles	Collider stable particles	Sort of stable particles	Displaced vertex particles
γ (m=0) (G (m=0)) (ν (m~0)) e^- (m=511keV) p (m=938MeV)	n (m=940MeV, ct=10^{14}mm) μ (m=940MeV, ct=10^{6}mm) K_L (m=500MeV, ct=10^{4}mm) $\pi^\pm$ (m=140MeV, ct=10^{4}mm) $K^\pm$ (m=500MeV, ct=10^{3}mm)	Ξ, Λ, Σ, Ω (m=1-2GeV, ct=10-100mm) K_S (m=500MeV, ct=30mm)	B, D $\Xi_{c,b}$, $\Lambda_{c,b}$ (m=2-5GeV, ct=0.1-0.5mm)

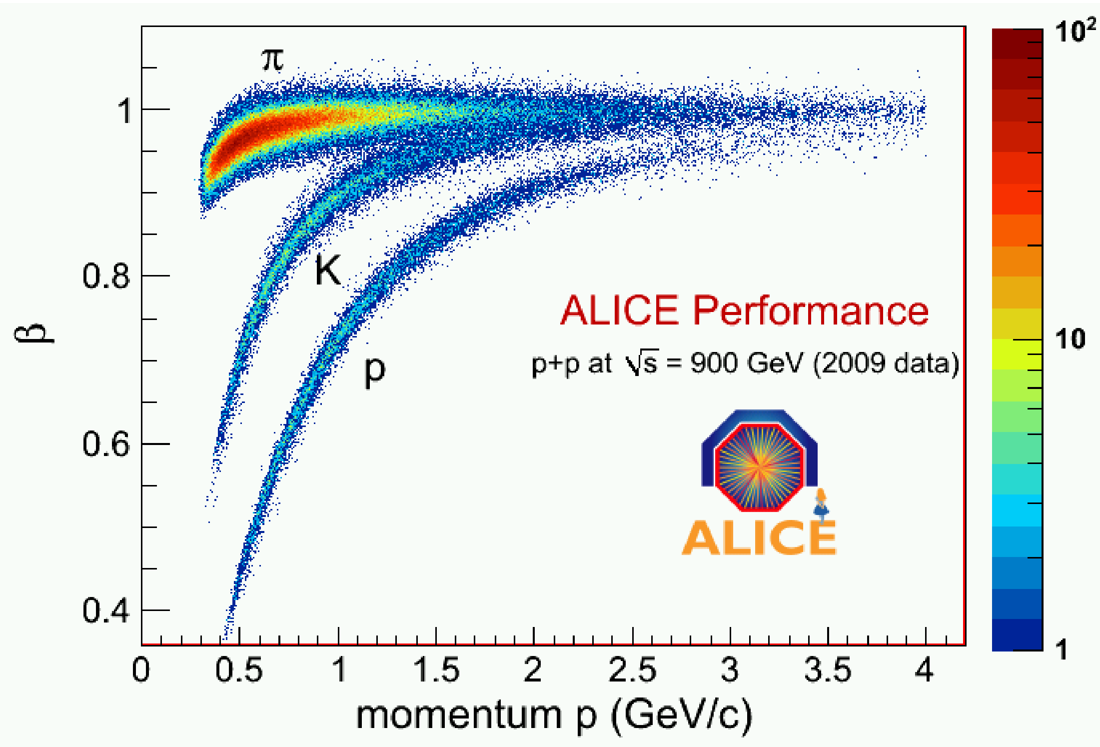
You don't "see" most of the SM particles!
You have to infer their existence

Test: have you ever seen dinosaurs? You "reconstruct" them from their decay products

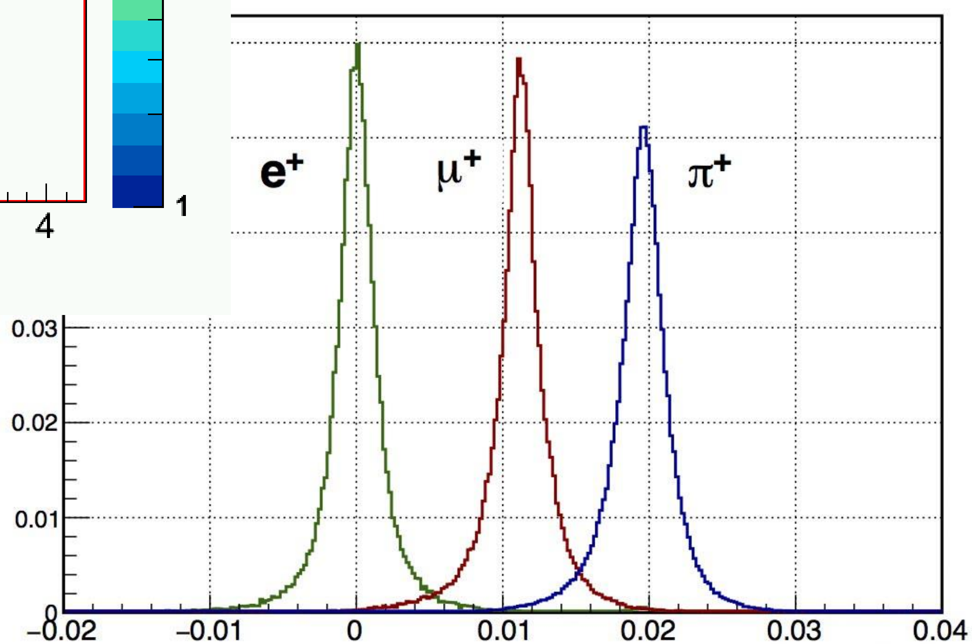
How modern detector measrue them? Higher energy collider



Direct β measurement: ToF (Time of Flight)



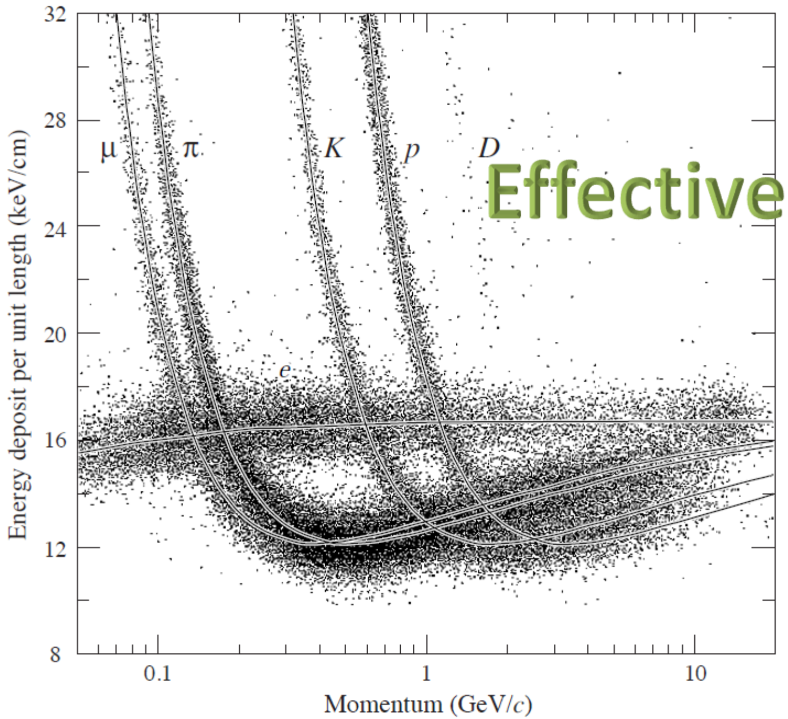
$$c\beta = \frac{flight\ distance}{flight\ time}$$



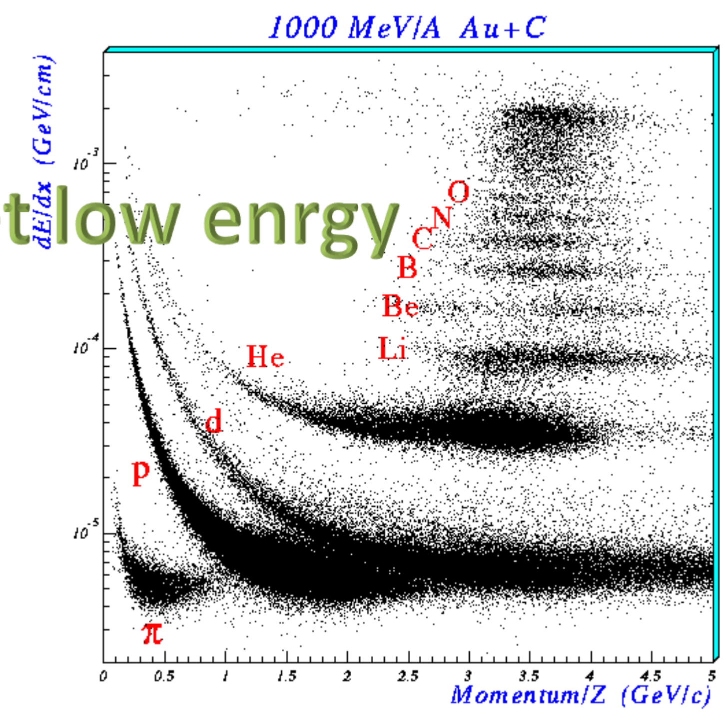
β measurement through energy loss information

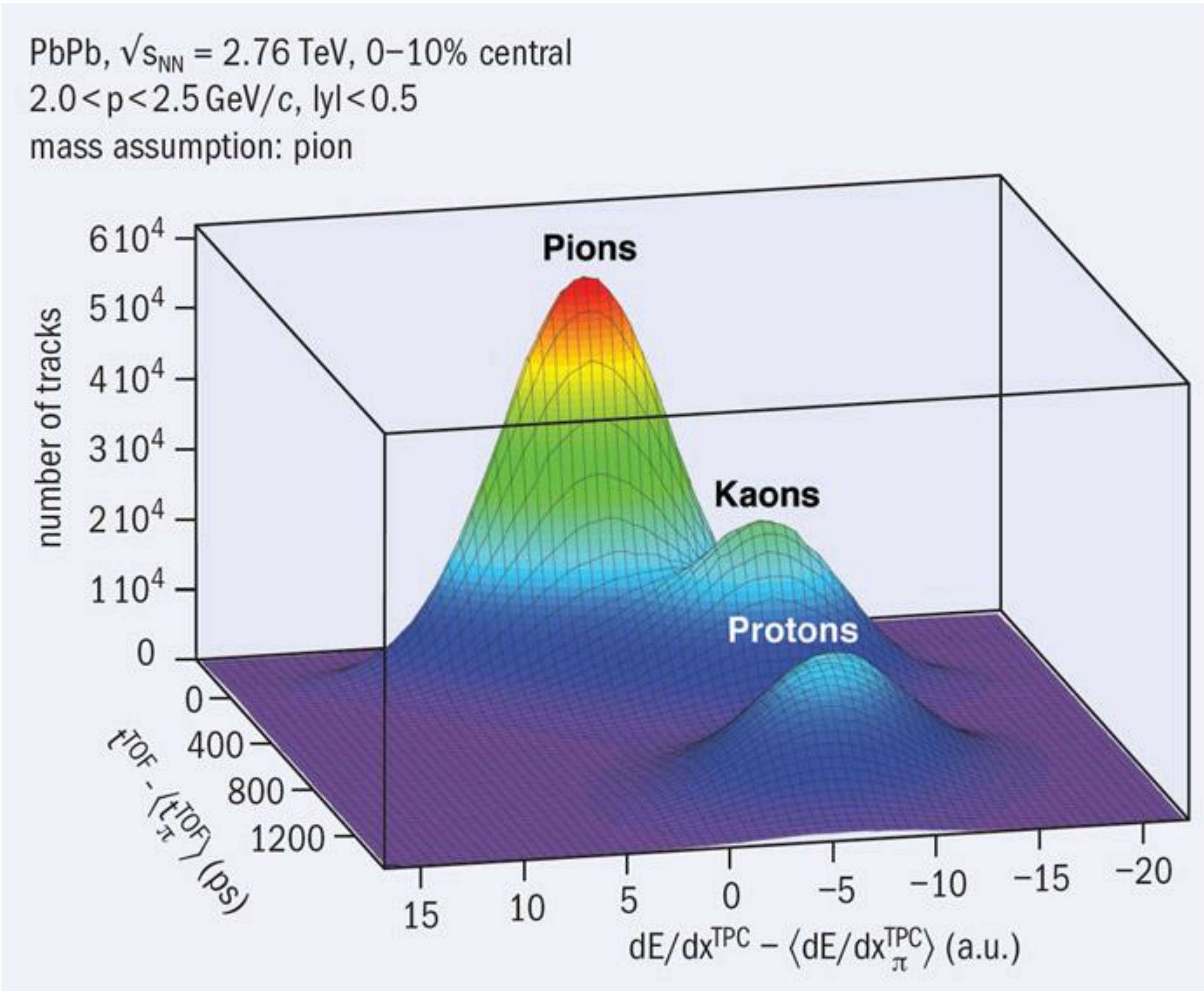
- Remember Bethe-Bloch formulation

$$\frac{\overline{\Delta E}}{\Delta x} = 2C\frac{m_e c^2}{\beta^2}\frac{Zz^2}{A}\rho\left[\frac{1}{2}\ln\left(\frac{2\gamma^2\beta^2 m_e c^2 E_{\max}}{I_0^2}\right) - \beta^2 - \frac{\varepsilon}{2} - \frac{\delta(\beta)}{2}\right]$$



Effective aet low enrgy

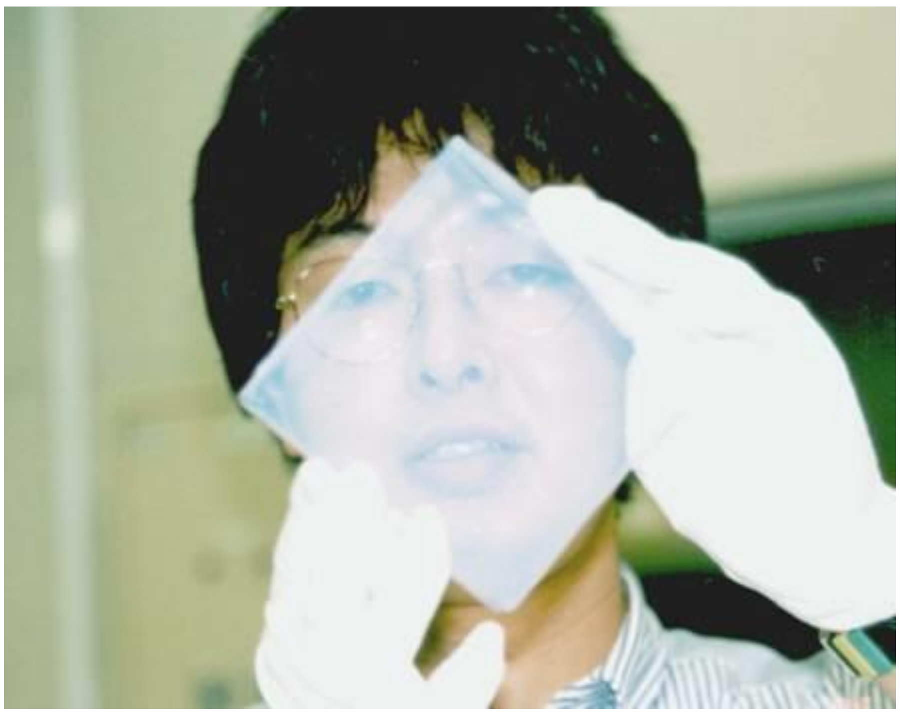




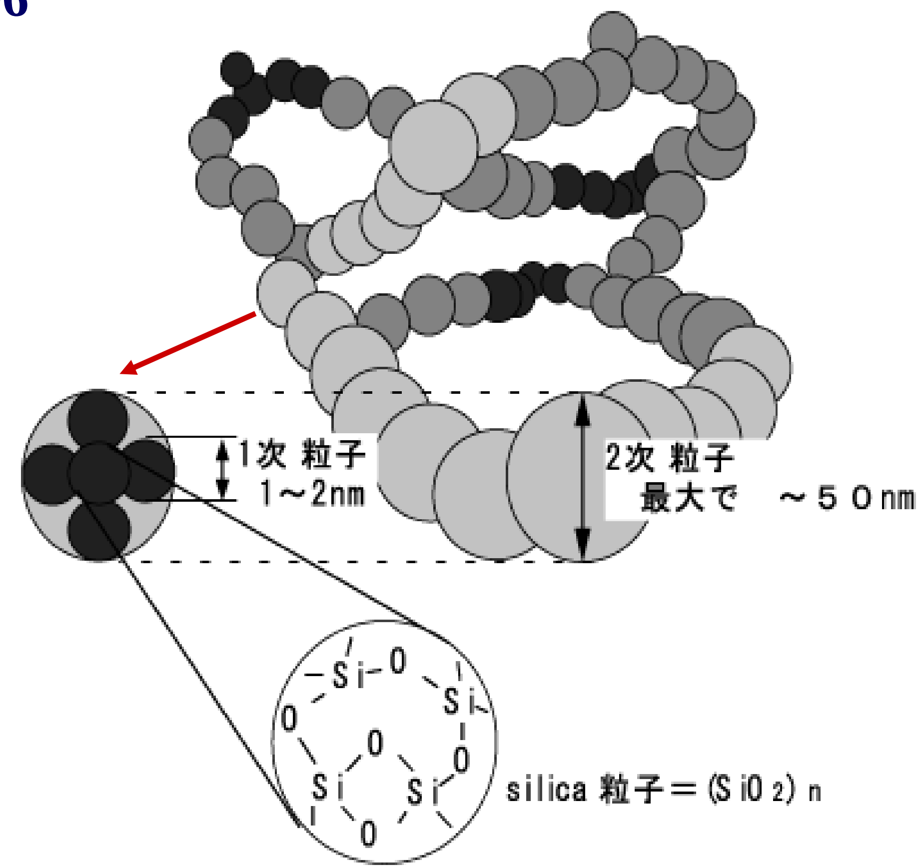
PbPb, √sNN = 2.76 TeV, 0–10% central
2.0 < p < 2.5 GeV/c, |y| < 0.5
mass assumption: pion
Pions
Kaons
Protons
number of tracks
0
1 10^4
2 10^4
3 10^4
4 10^4
5 10^4
6 10^4
t^TOF - ⟨t_π^TOF⟩ (ps)
0
400
800
1200
dE/dx^TPC – ⟨dE/dx_π^TPC⟩ (a.u.)
15
10
5
0
−5
−10
−15
−20

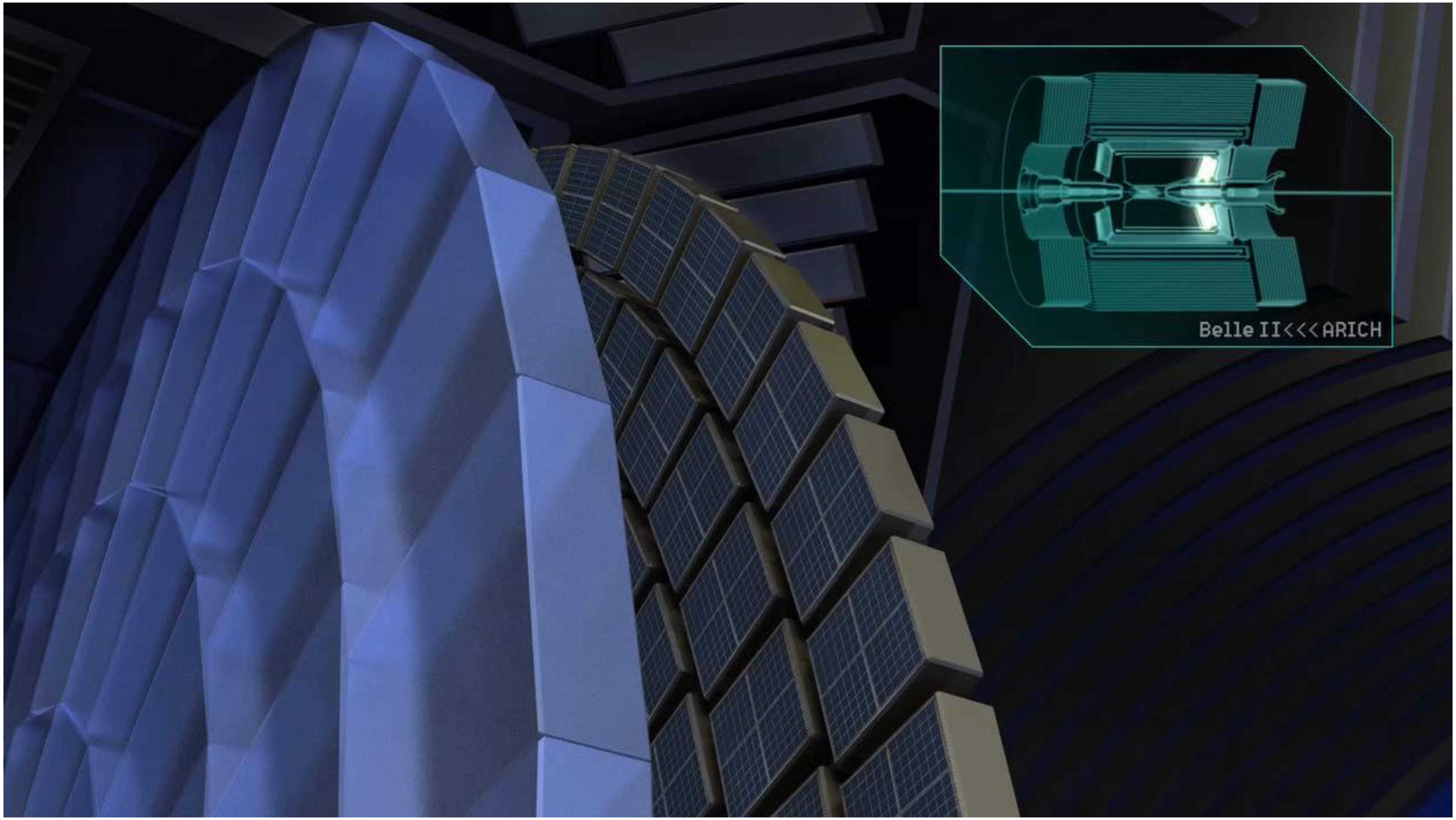
Particle identification with Silica Aerogel Cherenkov radiator

Colloidal form of SiO_2. Very special refractive index of n=1.006 ~ 1.06 with ρ=0.1g/cc. Hydrophobic

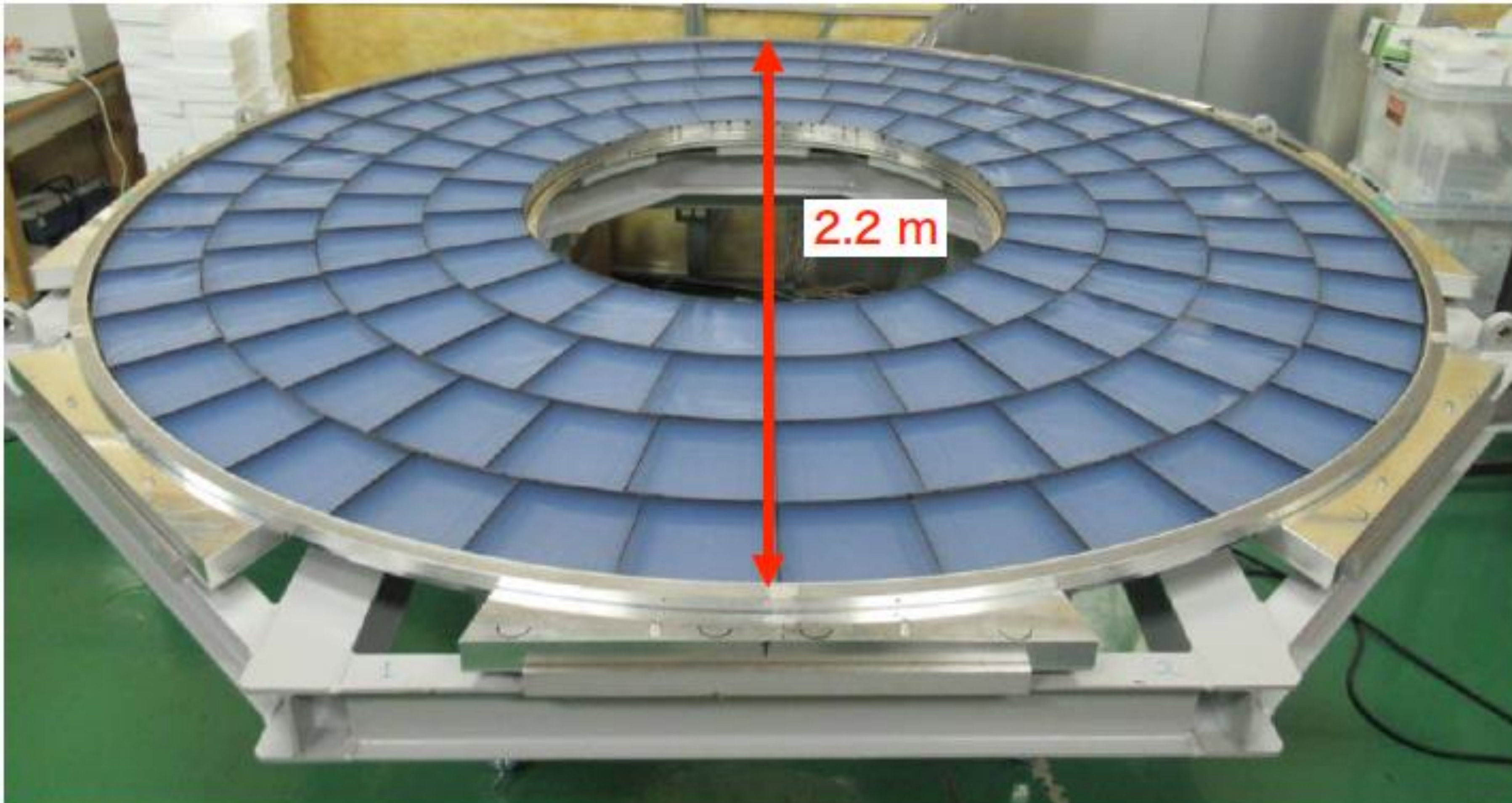


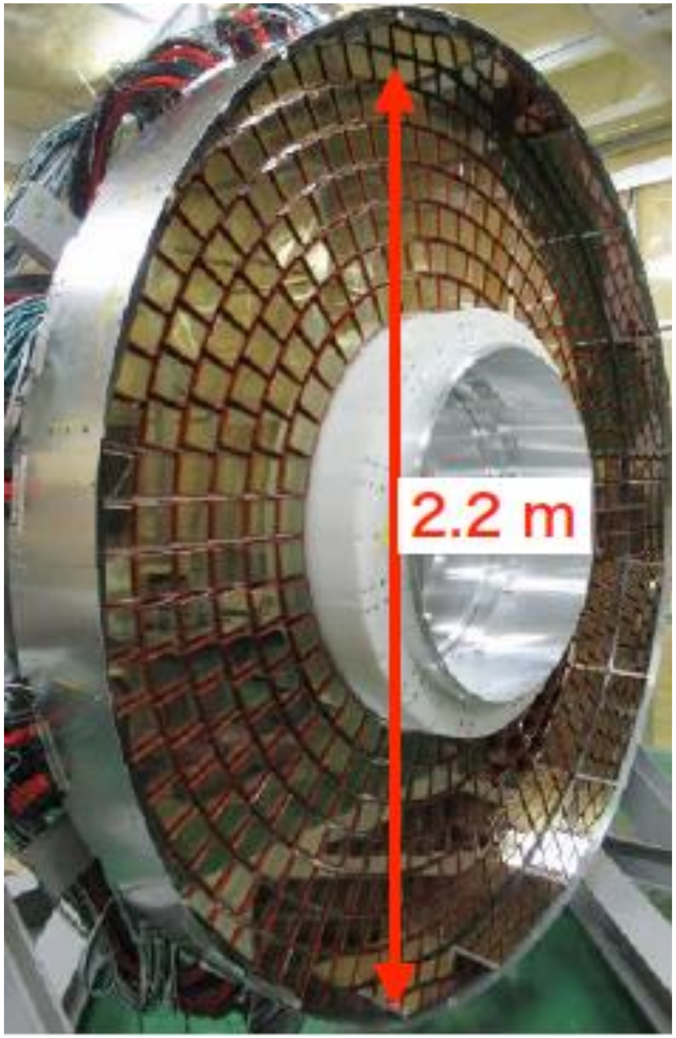
Fractal structure

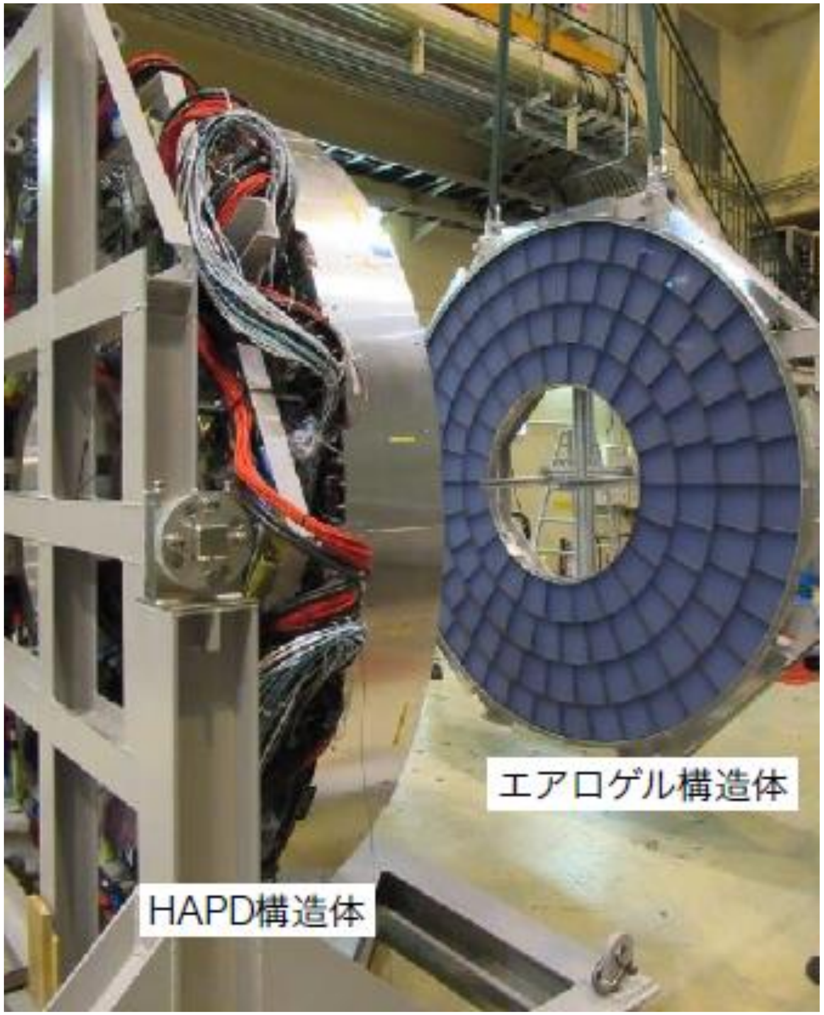



Belle II<<<ARICH

Belle II A-RICH




2.2 m

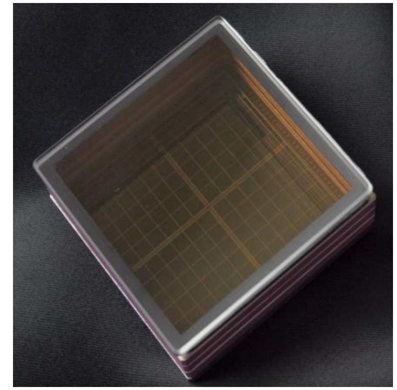

エアロゲル構造体
HAPD構造体

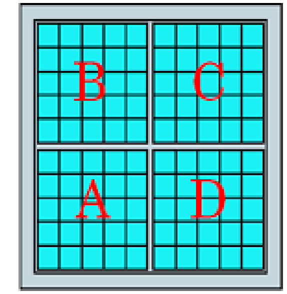
HAPD Belle II

Photo-detector

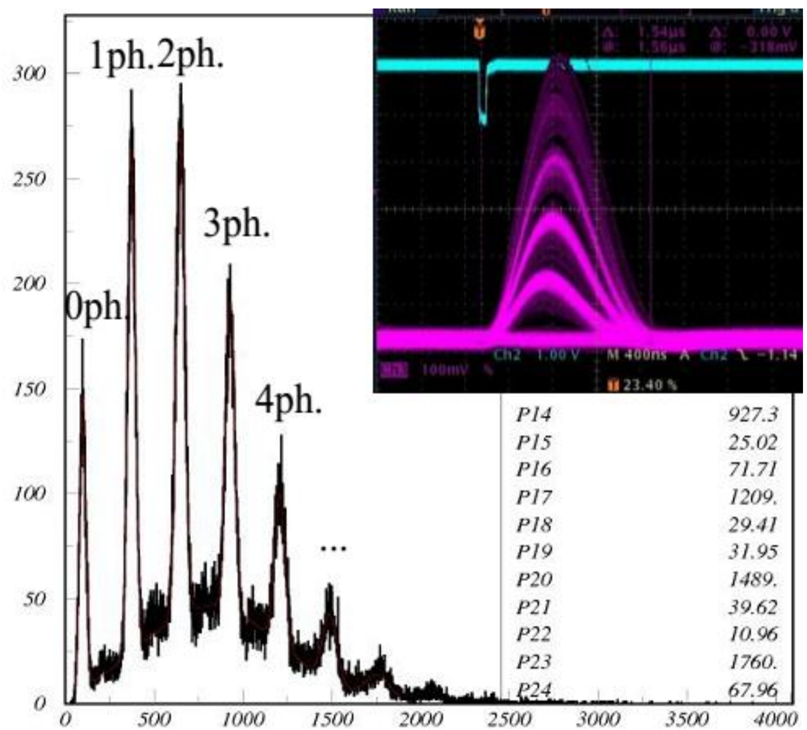
- ~5mm pixel size. Large coverage.
- Immune to 1.5T magnetic field.
- Radiation tolerance (neutron, gamma).

⇨ HAPD (Hybrid Avalanche Photo-Detector)





□4.9 [mm]

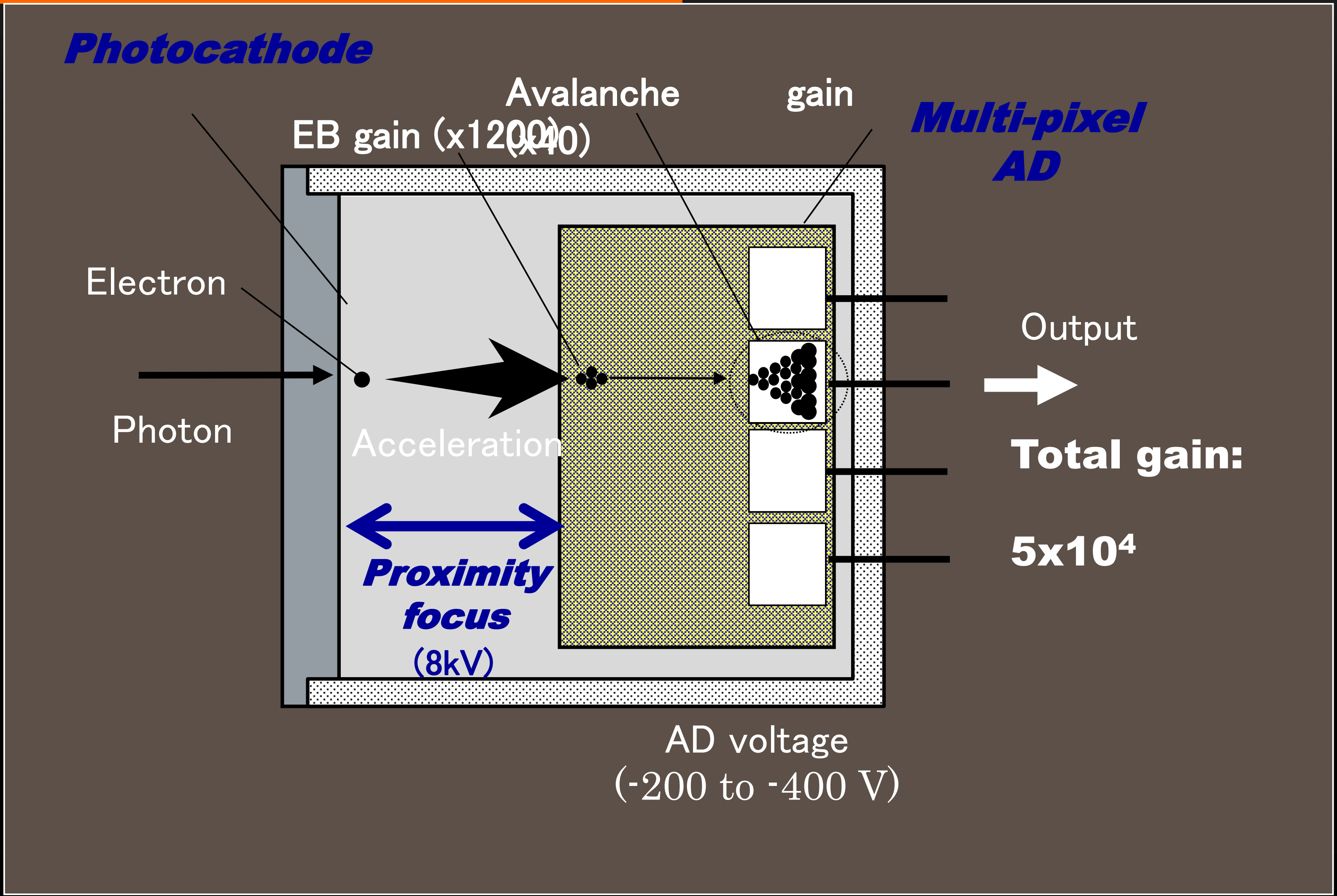


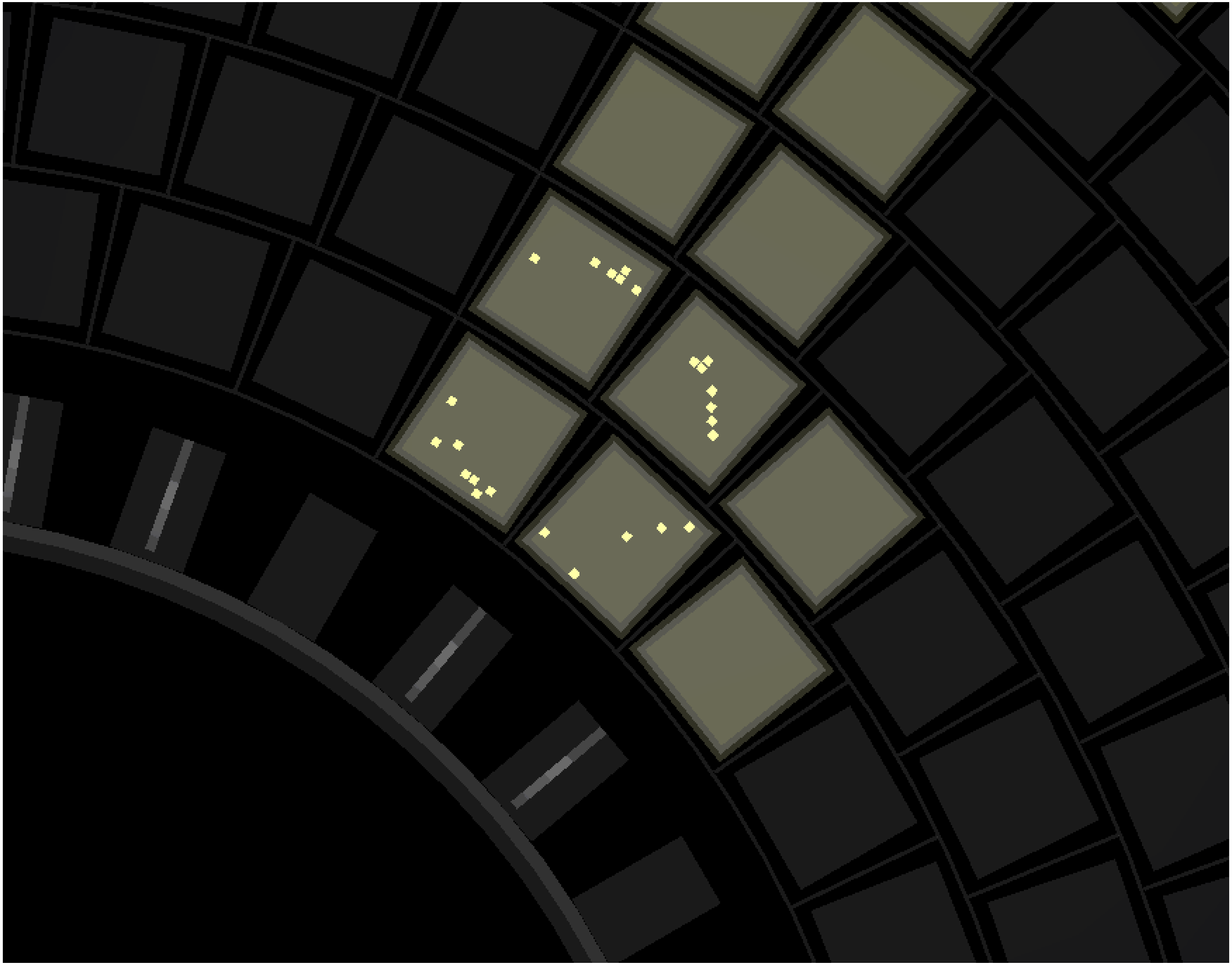
- Developed with Hamamatsu Photonics.
- 144 channels (36-ch APD chip × 4).
- Gain ≥45000.
- Peak QE ~28%
- Size 73mm × 73mm.
- Effective area 63mm×63mm (65%).

Total 420 HAPDs

POSSIBLE SOLUTION

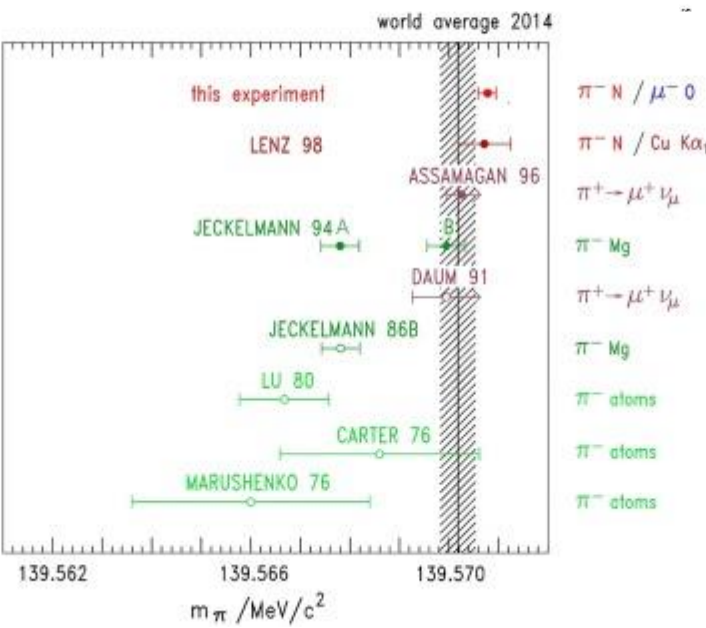
HPD with Multi-pixel Avalanche Diode (AD-HPD)

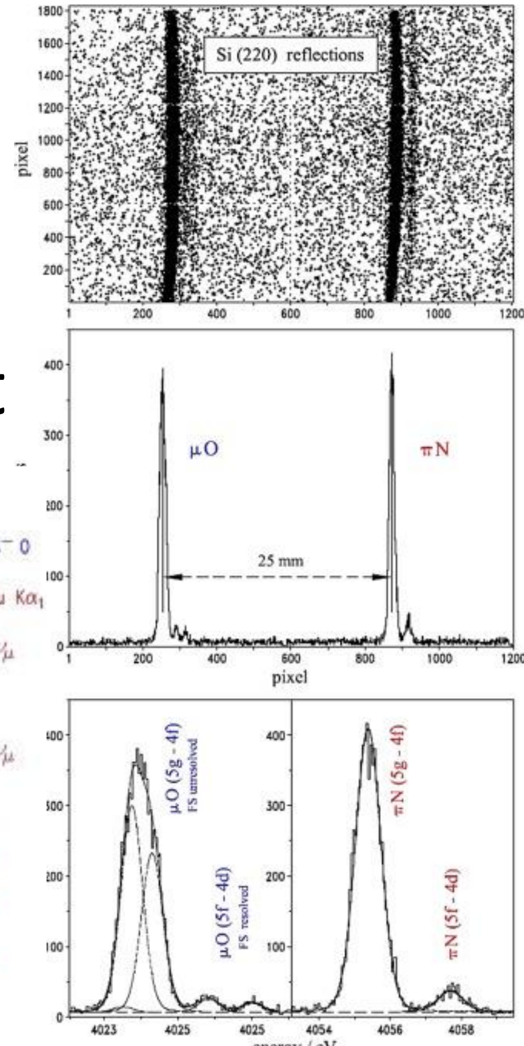




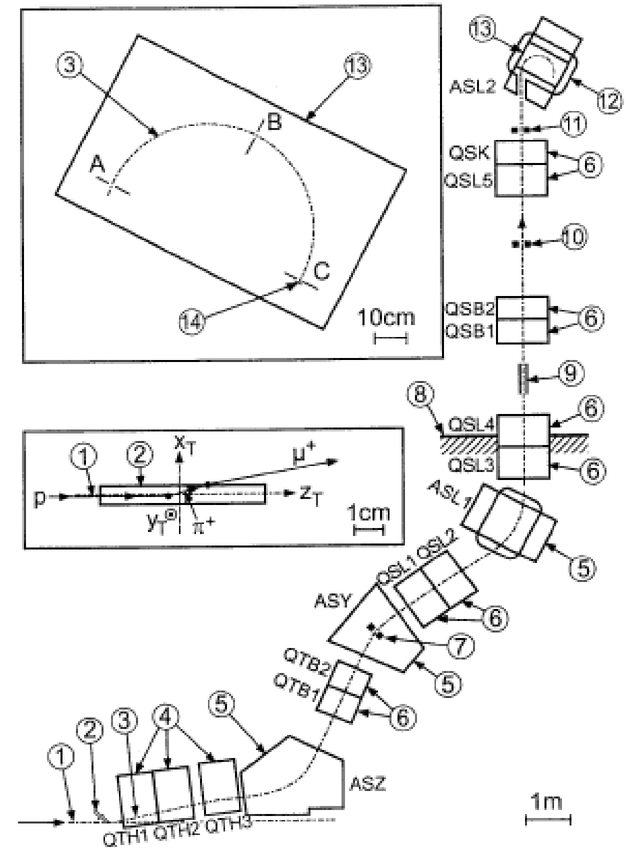
cf Serious mass measurement beyond particle identification..

- Example of
  π mass
  measurement





X-ray spectrum from pionic atom

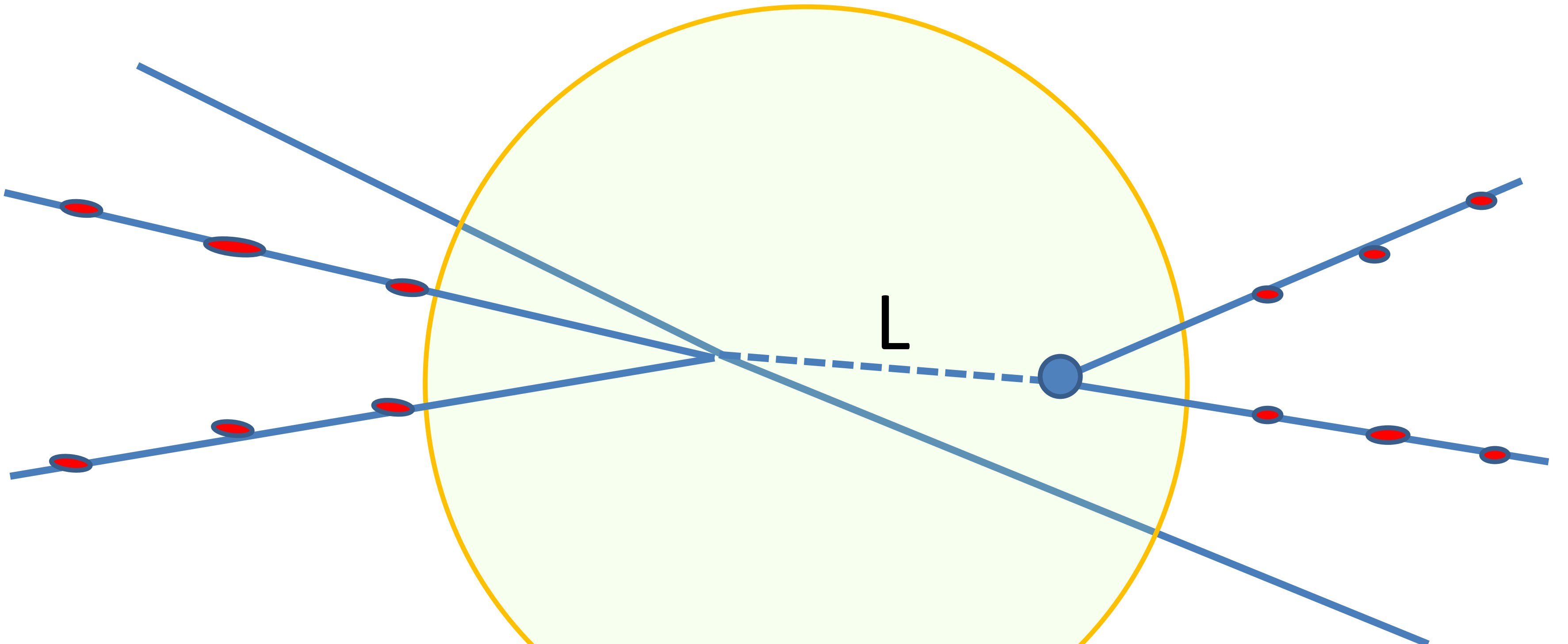


μ spectrum from π decay at rest

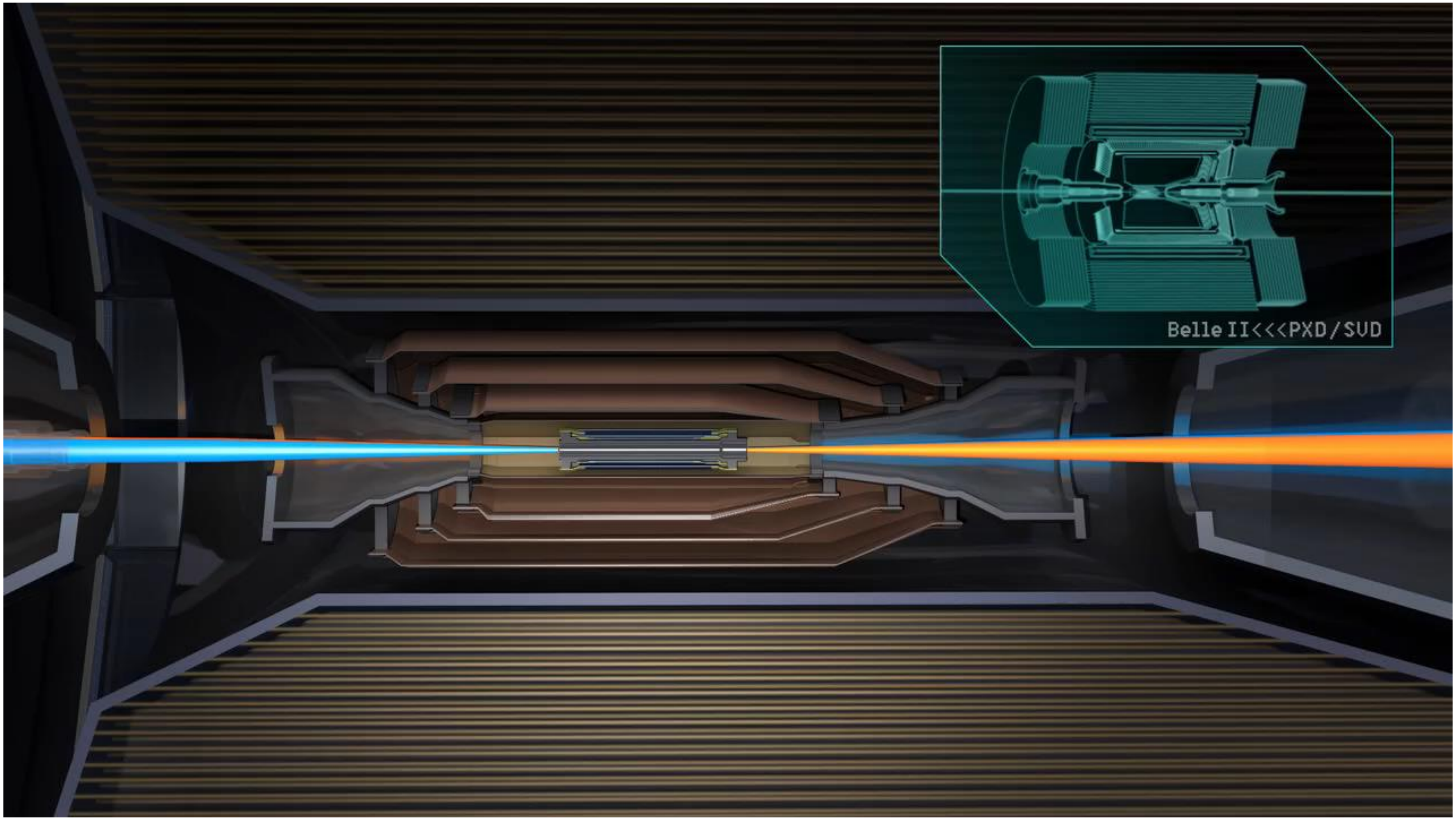
Life time measurement using decay vertex

Life time is measured through "decay length " L,

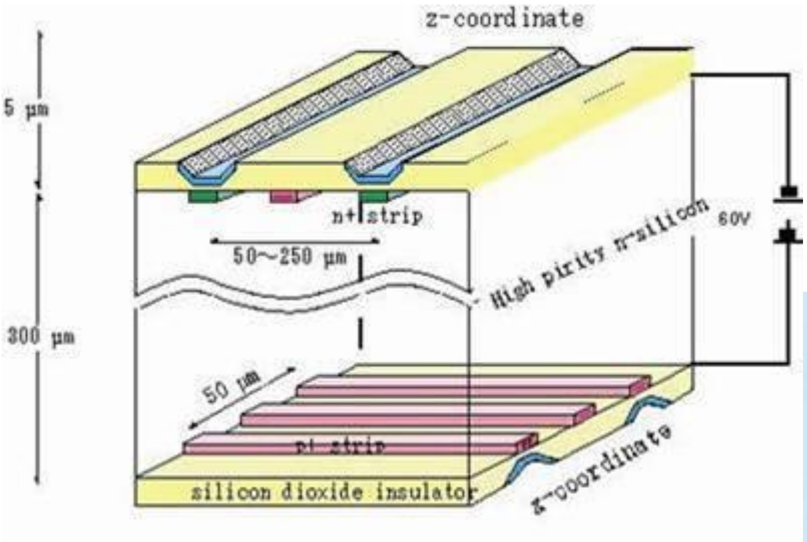
$$L = c\,\beta\,\gamma\,\tau$$

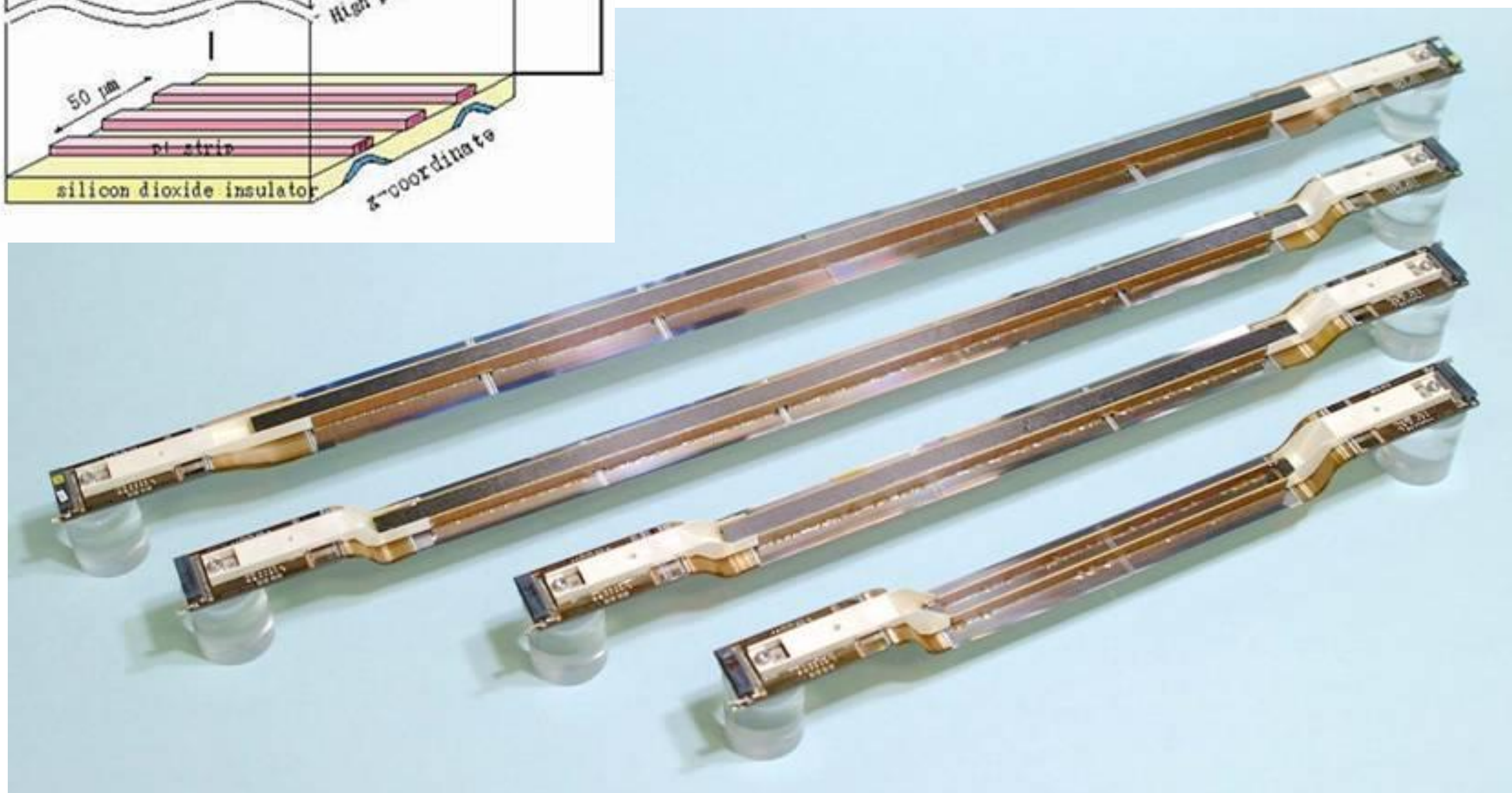


Vertex detector



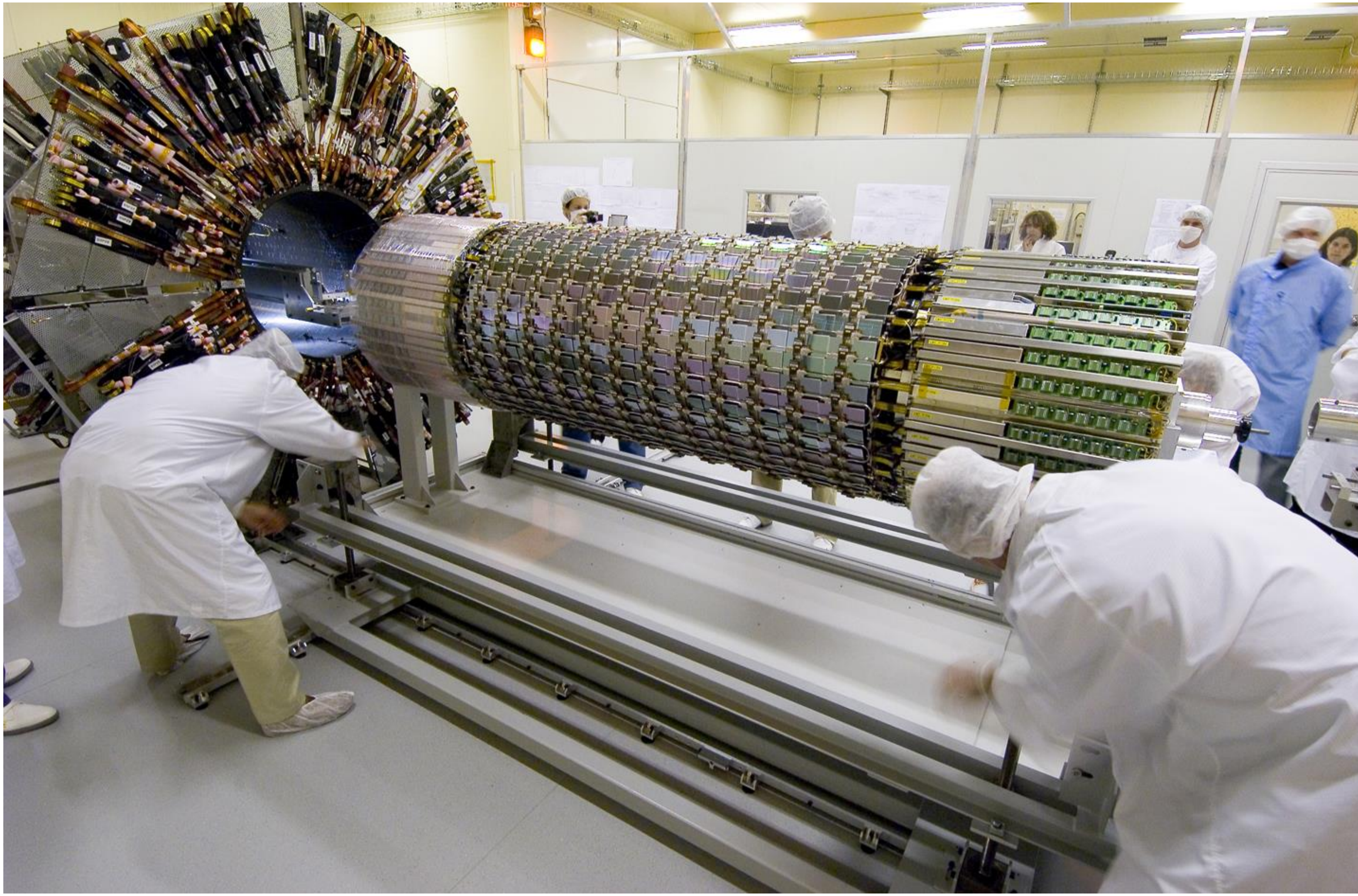
Silicon vertex detector

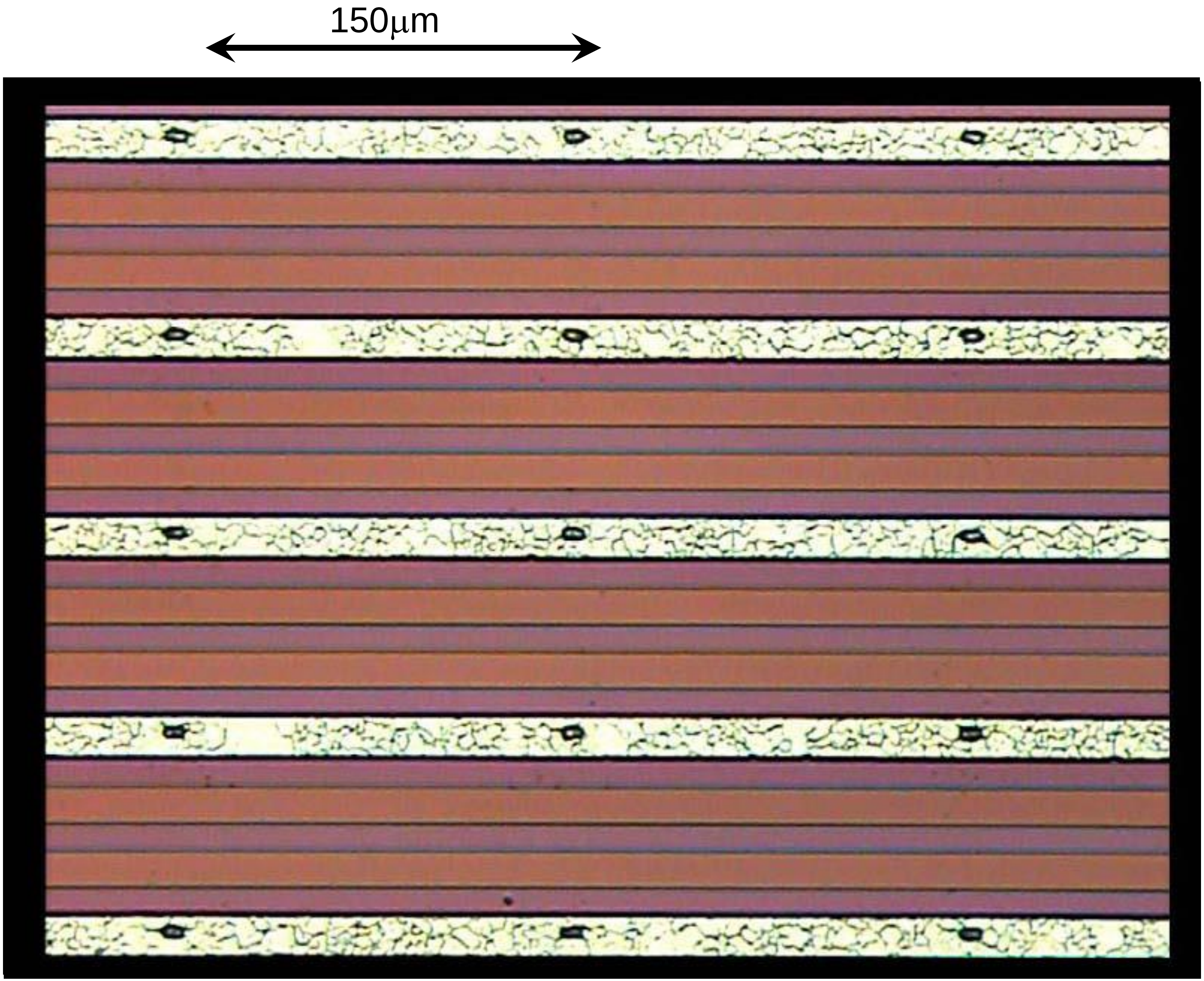




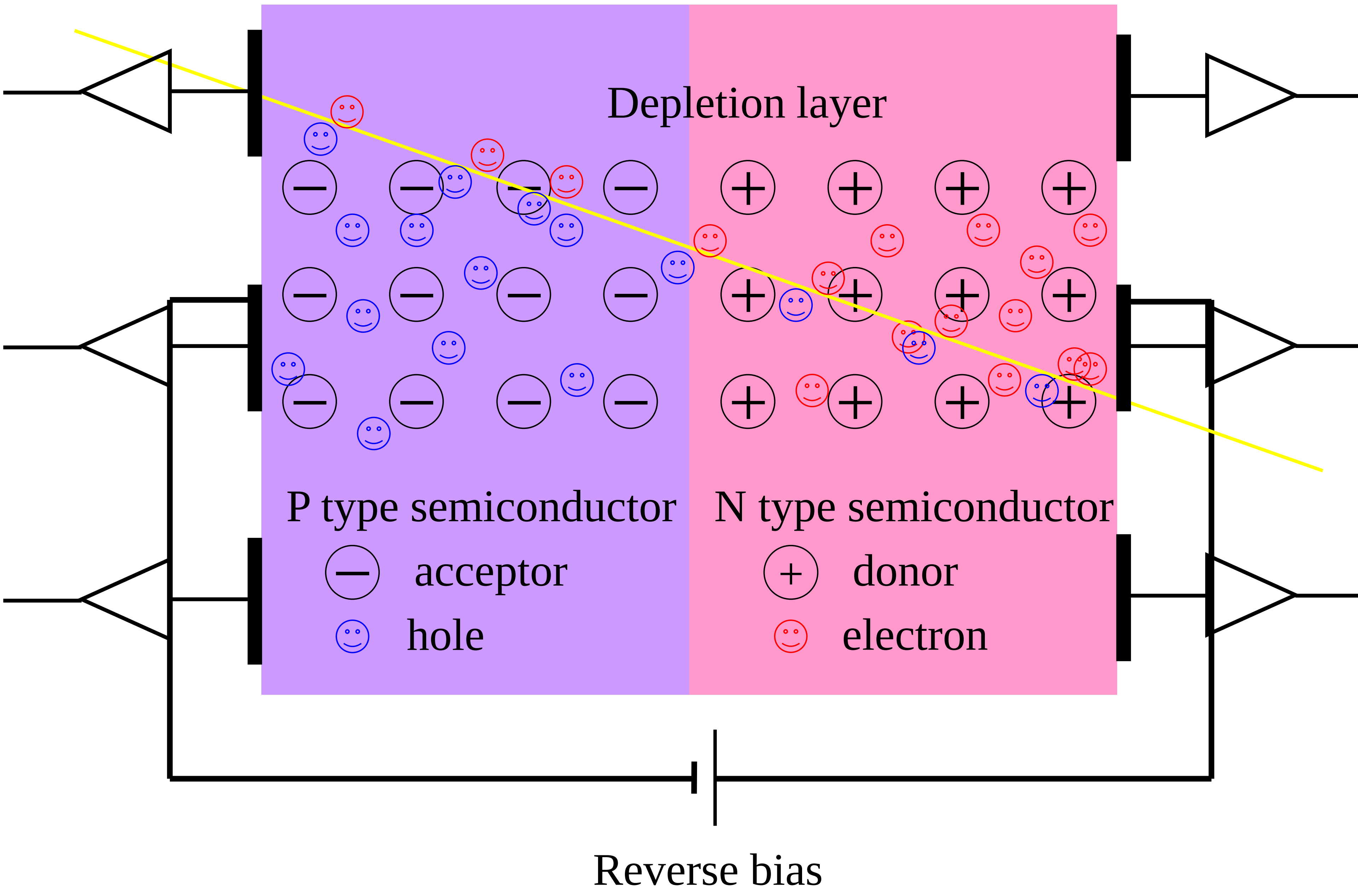
ATLAS SCT

ATLAS
Web page





Principle of semiconductor detector



No big difference from old leaf electroscope shown yesterday!