How can physicists explore the particle world?

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The 2\textsuperscript{nd} 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

\[ p = qrB \quad \text{or} \quad p = 0.3zBr \quad \text{(GeV, m, Tesla)} \]

\[ s = \frac{0.3zBl^2}{8p} \]

\[ \frac{dp}{p} = \frac{8pds}{0.3zBl^2} \]

\[ ds^2 = \sigma_{\text{tracking}}^2 + \left(\frac{\sigma_{\text{MS}}}{p}\right)^2 \]
Wire chambers invented by Charpak
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 extremely 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
- Conical endplates for the inner part to give a space for accelerator components.
X-T relation (drift time vs position)

- He(50%)-C$_2$H$_6$(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
$\sigma_{PT} = \sqrt{(aPT)^2 + b^2}$

Belle CDC only: $0.28P_T \oplus 0.35 \%$

Estimate for Belle II: $0.19P_T \oplus 0.32 \%$

Obtained: $0.127P_T \oplus 0.310 \%$

- $P_T$ resolution is much improved compared to 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.

$\sigma_{P_t}$: position resolution
$B$: magnetic field (1.5 T).
$X_0$: radiation length.
$L$: lever arm.
$N$: number of measurement points.

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

before align: $0.28P_T \oplus 0.35 \%$

after align: $0.127P_T \oplus 0.310 \%$

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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

T2K FGD

0.25 mmϕ
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.

\[ E \sim \text{Number of particles generated in a shower (N)} \]

\[ E = CN \]

\[ \frac{\Delta E}{E} = \frac{\Delta N}{N} = \frac{1}{\sqrt{N}} = \frac{\sqrt{C}}{\sqrt{E}} \]

Cf. \[ \frac{dp}{p} = 8pds / 0.3zBl^2 \]
Question given yesterday: How to distinguish photon from 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)

<table>
<thead>
<tr>
<th></th>
<th>Radiation length</th>
<th>Nuclear interaction length</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>6.76 (g/cm²)</td>
<td>191.9 (g/cm²)</td>
<td>19.3 g/cm³</td>
</tr>
<tr>
<td></td>
<td>0.35 cm</td>
<td>9.94 cm</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>13.84(g/cm²)</td>
<td>132.1(g/cm²)</td>
<td>7.87 g/cm³</td>
</tr>
<tr>
<td></td>
<td>1.76 cm</td>
<td>16.8cm</td>
<td></td>
</tr>
</tbody>
</table>

10cm thick W EM calorimeter ~28.6 r.l. ~1.0 int. l.

100cm thick Fe Hadron calorimeter ~56.8 r.l. ~ 6 int. l.
## Organic scintillator and WLS

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Emission spectrum (nm)</th>
<th>Decay time (ns)</th>
<th>Light yield wrt NaI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naphthalene</td>
<td>348</td>
<td>96</td>
<td>0.12</td>
</tr>
<tr>
<td>Anthracene</td>
<td>440</td>
<td>30</td>
<td>0.5</td>
</tr>
<tr>
<td>p-Terphenyl</td>
<td>440</td>
<td>5</td>
<td>0.25</td>
</tr>
<tr>
<td>PBD</td>
<td>360</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>POPOP</td>
<td>420</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>bis-MSB</td>
<td>420</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>
Particle identification

- **Particle identification (mass)** can be made from its velocity ($\beta = v/c$), 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.

<table>
<thead>
<tr>
<th>Mass (MeV/c$^2$)</th>
<th>$\mu^\pm$</th>
<th>$e^\pm$</th>
<th>$\gamma$</th>
<th>$\pi^\pm$</th>
<th>$K^0$</th>
<th>$K^\pm$</th>
<th>$p$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>106</td>
<td>0.511</td>
<td>0</td>
<td>140</td>
<td>498</td>
<td>494</td>
<td>938</td>
<td>940</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Detection</th>
<th>Charge</th>
<th>Charge Shower</th>
<th>Shower</th>
<th>Charge Strong</th>
<th>Strong</th>
<th>Charge Strong</th>
<th>Charge Strong</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life time (c$\tau$ m)</td>
<td>659</td>
<td>--</td>
<td>--</td>
<td>7.8</td>
<td>0.027</td>
<td>3.7</td>
<td>--</td>
<td>2.7 x10$^{11}$</td>
</tr>
</tbody>
</table>
Some theorists know better....

### The Standard Model: Matter

~~The particles seen in a detector~~

<table>
<thead>
<tr>
<th>Absolutely stable particles</th>
<th>Collider stable particles</th>
<th>Sort of stable particles</th>
<th>Displaced vertex particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ (m=0)</td>
<td>$n$ (m=940MeV, ct=10^{14}\text{mm})</td>
<td>$\Xi, \Lambda, \Sigma, \Omega$ (m=1-2GeV, ct=10-100mm)</td>
<td>$B, D$</td>
</tr>
<tr>
<td>(G (m=0) )</td>
<td>$\mu$ (m=940MeV, ct=10^{6}\text{mm})</td>
<td></td>
<td>$\Xi_{c,b}, \Lambda_{c,b}$ (m=2-5GeV, ct=0.1-0.5mm)</td>
</tr>
<tr>
<td>(\nu (m\sim0) )</td>
<td>$K_L$ (m=500MeV, ct=10^{4}\text{mm})</td>
<td>$K_S$ (m=500MeV, ct=30mm)</td>
<td></td>
</tr>
<tr>
<td>$e^-$ (m=511keV)</td>
<td>$\pi^\pm$ (m=140MeV, ct=10^{4}\text{mm})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p$ (m=938MeV)</td>
<td>$K^\pm$ (m=500MeV, ct=10^{3}\text{mm})</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 measures them?
Higher energy collider
Direct $\beta$ measurement: ToF (Time of Flight)

$\beta = \frac{c}{\text{flight distance}} / \text{flight time}$
\[ \frac{\Delta E}{\Delta x} = 2C \frac{m_e c^2}{\beta^2} \frac{Z z^2}{A} \rho \left[ \frac{1}{2} \ln \left( \frac{2\gamma^2 \beta^2 m_e c^2 E_{\text{max}}}{I_0^2} \right) - \frac{\beta^2}{2} - \frac{\varepsilon}{2} - \frac{\delta(\beta)}{2} \right] \]

**\( \beta \) measurement through energy loss information**

- Remember Bethe-Bloch formulation

**Effective at low energy**
PbPb, $\sqrt{s_{NN}} = 2.76$ TeV, 0–10% central
$2.0 < p < 2.5$ GeV/$c$, $|y| < 0.5$
mass assumption: pion
Particle identification with Silica Aerogel Cherenkov radiator

Colloidal form of SiO$_2$. Very special refractive index of $n=1.006 \sim 1.06$ with $\rho=0.1$g/cc. Hydrophobic
Belle II A-RICH
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)

- 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)

- Photocathode
- Multi-pixel AD
- Proximity focus (8kV)
- Electron
- Photon
- EB gain (x1200)
- Acceleration
- AD voltage (-200 to -400 V)
- Output

Total gain: $5 \times 10^4$
cf  Serious mass measurement beyond particle identification..

- Example of \( \pi \) mass measurement

X-ray spectrum from pionic atom

\[ \mu \text{ spectrum from } \pi \text{ decay at rest} \]
Life time measurement using decay vertex

Life time is measured through “decay length “ $L$, 

$L = c \beta \gamma \tau$
Vertex detector
Silicon vertex detector
Principle of semiconductor detector

- **P type semiconductor**
  - acceptor
  - hole

- **N type semiconductor**
  - donor
  - electron

Depletion layer

Reverse bias
No big difference from old leaf electroscope shown yesterday!