Detector Basics & ILC Detectors

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1. Detector basics
2. ILC detectors
3. Detector electronics

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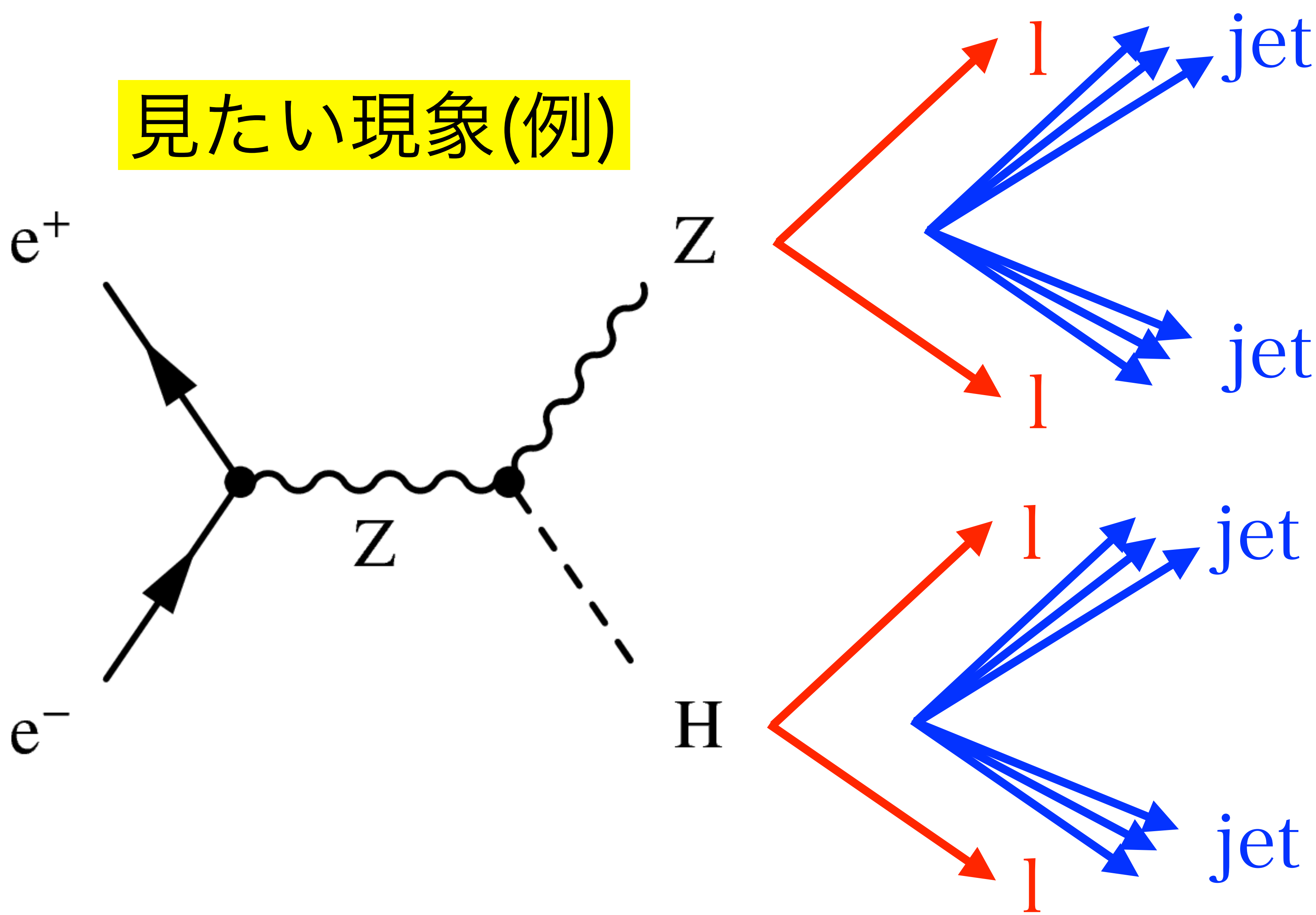
測定器の役割

見える(測定できる)事象

見たい現象(例)

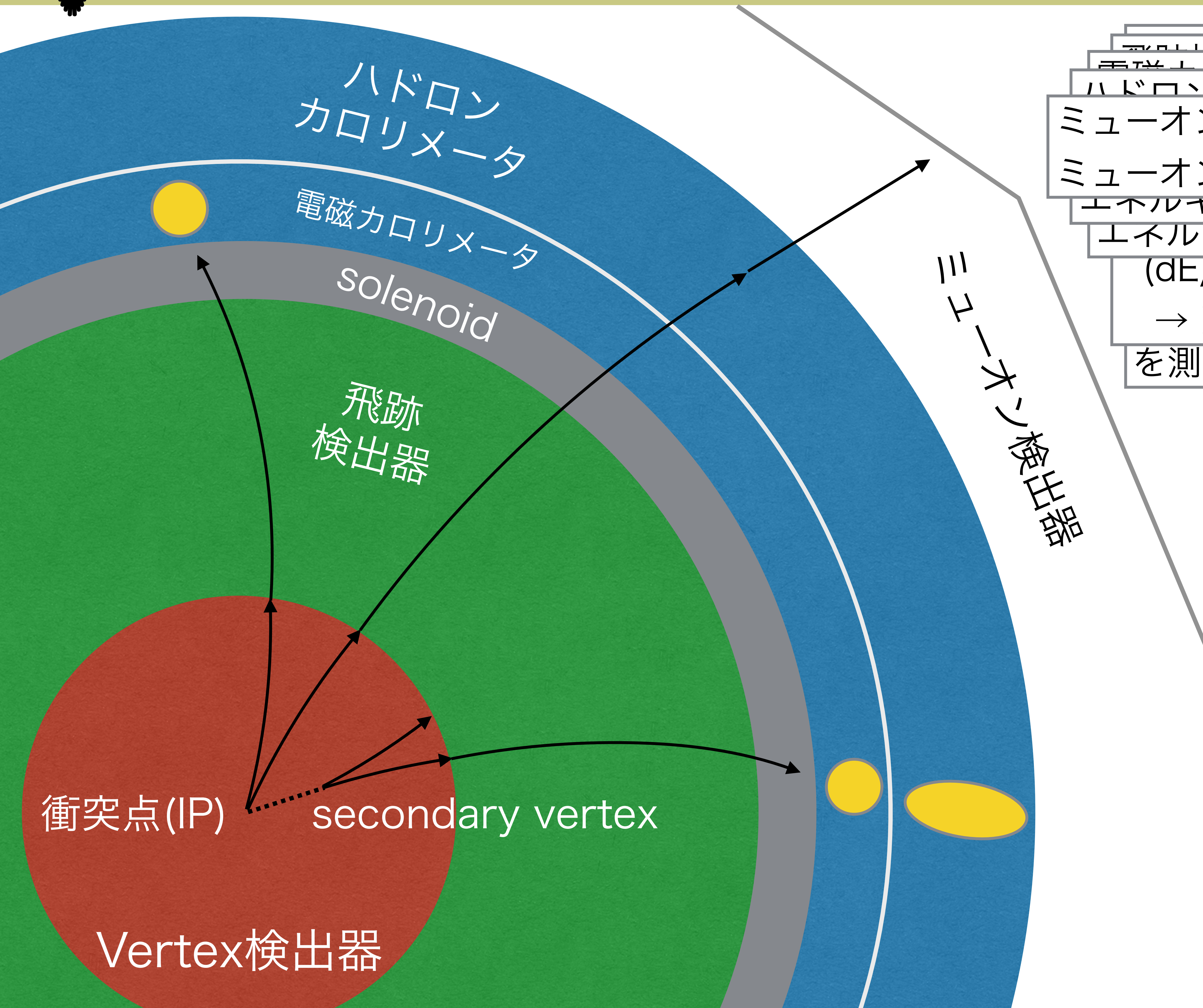


PID (μ, b-tag, etc.)
4-mom (E, $\vec{p}$)

「見たい現象」を再現

測定器： Decay生成物の4-momentum (E, $\vec{p}$) 測定
およびParticle ID

高エネルギー実験用測定器の基本形



ミューオン検出器
ミューオンのID

(dE/dx)
→ Particle ID
を測定

粒子の物質との相互作用

粒子の検出は、粒子と物質との間の多様な相互作用を利用

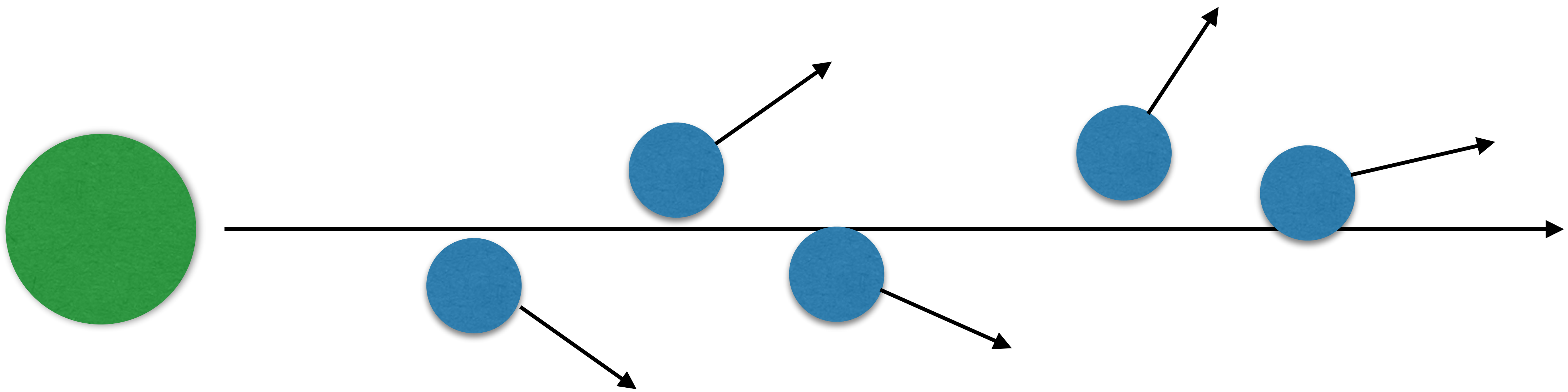
■荷電粒子
- 電離、励起
- 制動放射
- チェレンコフ放射

■光子
- 光電効果
- コンプトン散乱
- 電子陽電子対生成

■中性ハドロン
- 核破砕

■中性パイ粒子
- ２光子崩壊

電離：電子より重い荷電粒子の場合



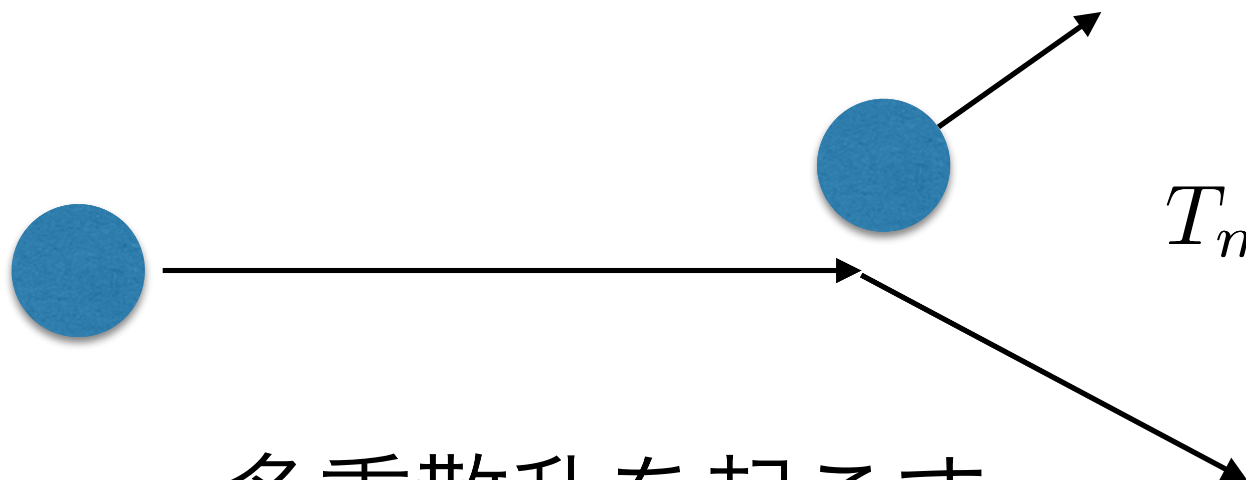
1回の散乱で電子に移行する運動エネルギーは、
入射粒子の運動エネルギーに対して最大でも (θ =0)

$$T_{max} = \frac{4m}{M\left(1+\frac{m}{M}\right)^2}E_{in} \rightarrow \frac{4m}{M}E_{in}$$ (とても小さい)

この場合のenergy deposit (dE/dx) は、
Bethe-Blochの式として良く知られている (後述)。

荷電粒子の物質との相互作用

電離：電子の場合



$$T_{max} = \frac{4m}{M\left(1+\frac{m}{M}\right)^2} E_{in} \to E_{in}$$

多重散乱を起こす

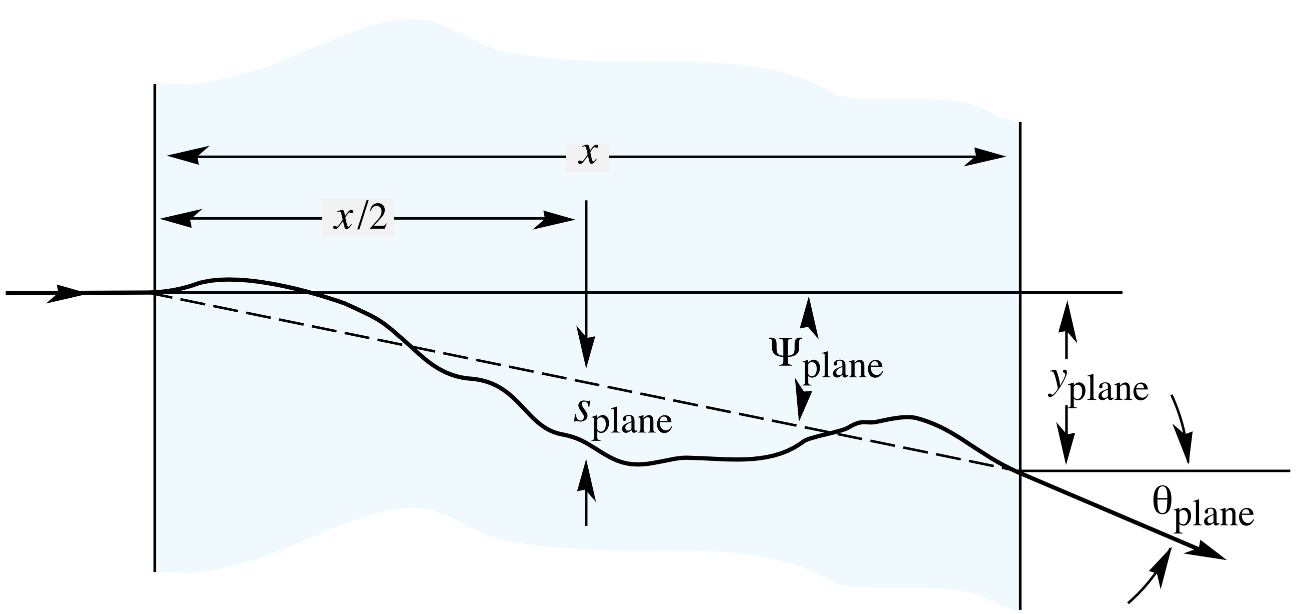


Figure 33.10: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

Bethe-Blochの式 (dE/dx) に修正が必要

制動放射 (Bremsstrahlung) を起こすため。

飛跡検出器でのdE/dxを用いた粒子識別

- 磁場中での飛跡により p_T[GeV] = 0.3B[Testa]R[m]
  → $p = p_T / \sin\theta$
- dE/dx (飛跡単位長あたりの energy deposit) 測定
  → 速度 β=v/c の関数

静止質量 m が (原理的には) 得られる (= 粒子識別)

$$p = \gamma m v = \frac{mc\beta}{\sqrt{1-\beta^2}}$$

※precise “tracking” also requires understanding on charge (∝energy) deposit (and drift).
→ We need to know “how” charges are deposited.

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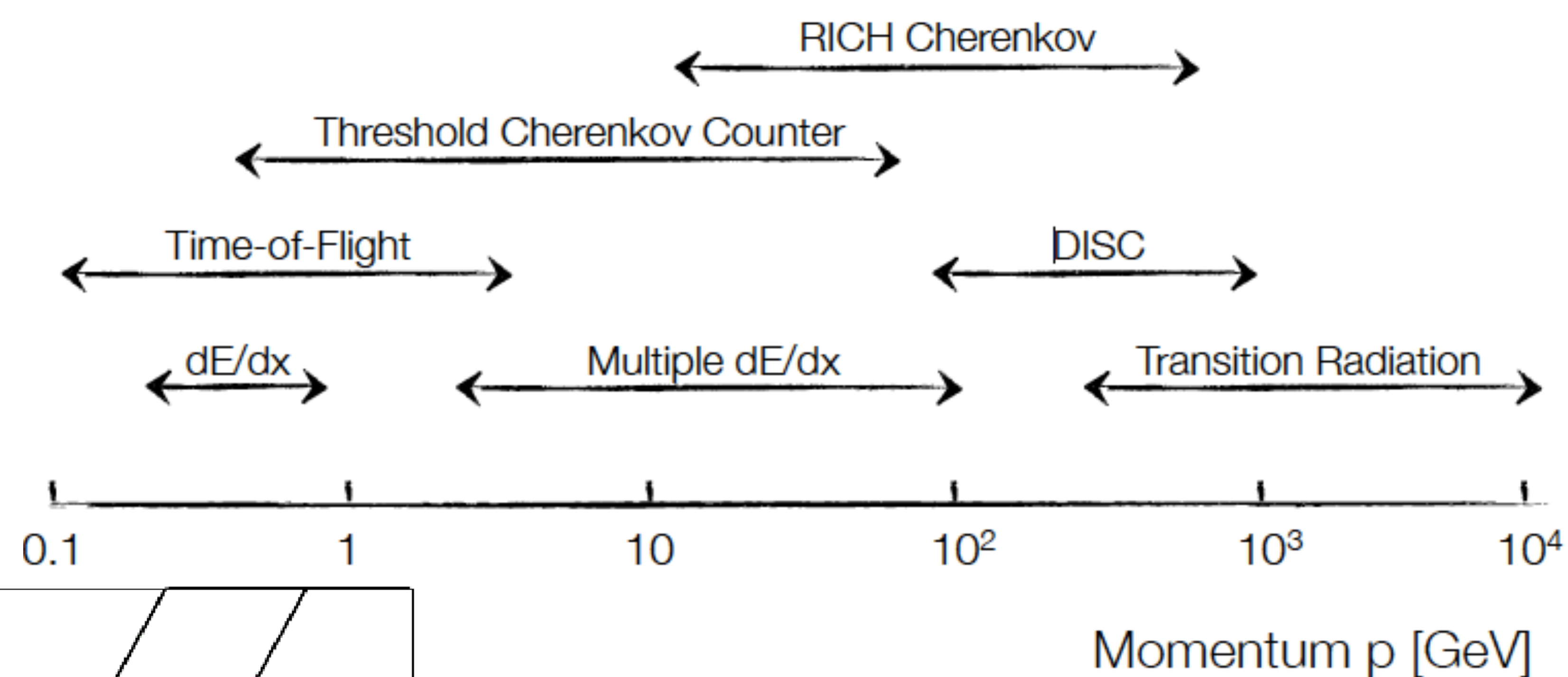
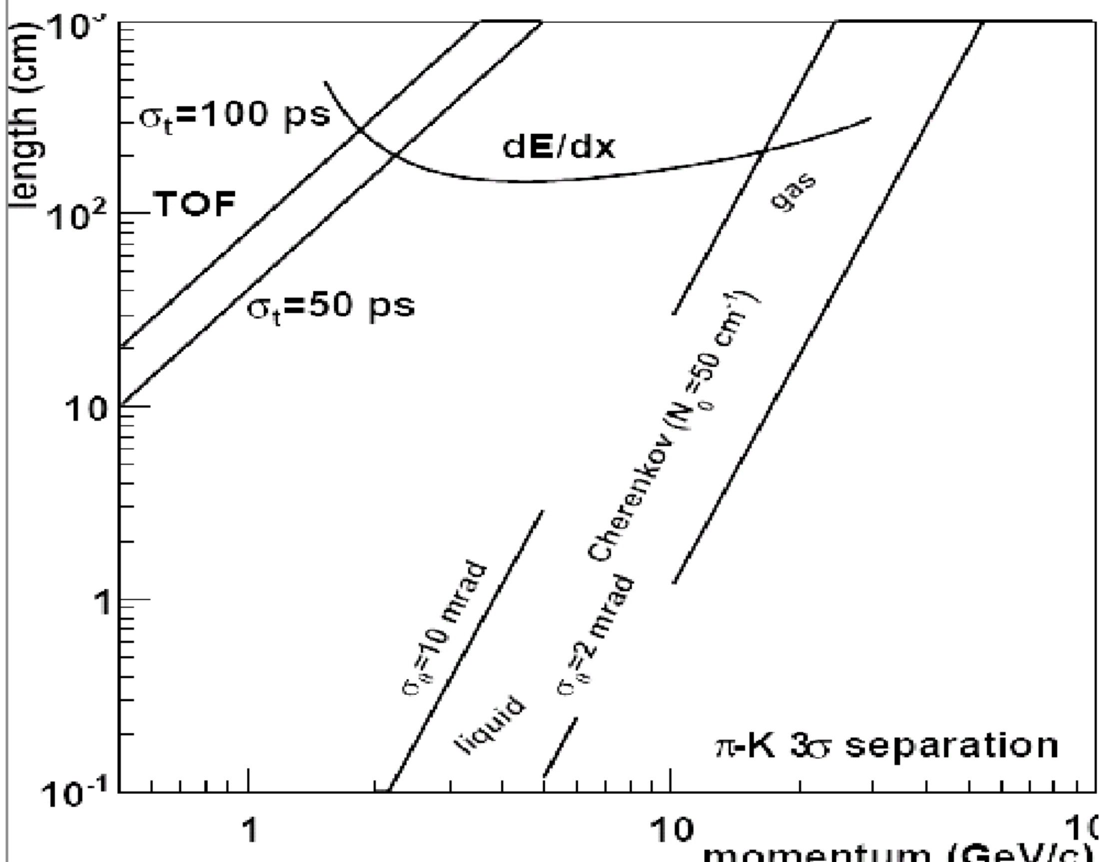
実際には目的に応じて異なるPID手法

PID methods - compare

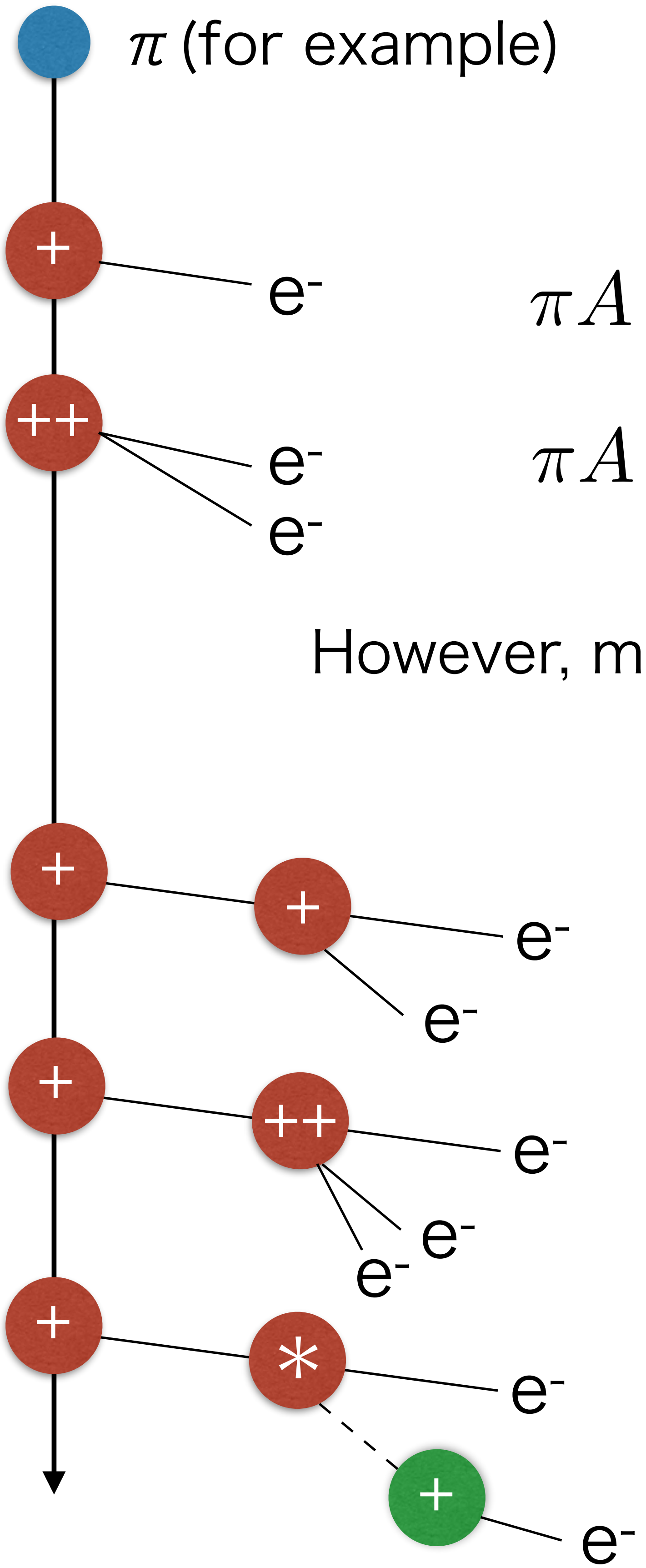
π/K Separation with different PID methods





Alternatively topological techniques can be used …

Gas ionization processes



primary ionizations

$$\pi A \rightarrow \pi A^{+} e^{-}$$

$$\pi A \rightarrow \pi A^{++} e^{-} e^{-}$$

However, most of deposited charge comes from ...

secondary ionizations

$$\pi A \rightarrow \pi A^{+} e^{-}, \quad e^{-} A \rightarrow e^{-} A^{+} e^{-}$$

$$\pi A \rightarrow \pi A^{+} e^{-}, \quad e^{-} A \rightarrow e^{-} A^{++} e^{-} e^{-}$$

$$\pi A \rightarrow \pi A^{+} e^{-}, \quad e^{-} A \rightarrow e^{-} A^{*}, \quad A^{*} B \rightarrow A B^{+} e^{-}$$

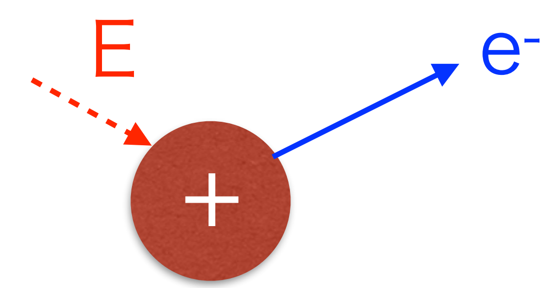
exited state of noble gas atom

“quencher” gas atom with ionization potential lower than A

Charge due to ionization processes

- Amount of charge deposit is a result of those independent processes.
- However, the “total amount” of ionization from all such complicated processes is know to be characterized by the paramter “W”.

$$W = \frac{\langle E \rangle}{\langle N \rangle}$$



W is the “energy spent”, on the average, on the creation of “one free electron”.

- Note that only a certain fraction of all the energy lost by the charged track is spent in ionization.

$$W > E_{\text{ionization}}$$

- We can write

$$W \langle N \rangle = L \left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle$$

- Experimentally, W is known to be almost “independent” of the track energy. It’s remarkable! → We can estimate dE from N (=charge) measurement.

W = energy spent for one ionization

Table 1.3 Energy W spent, on the average, for the creation of one ionization electron in various gases and gas mixtures [CHR 71]; W_α and W_β are from measurements using α or β sources, respectively. The lowest ionization potential is also indicated

Gas	W_α(eV)	W_β(eV)	I(eV)	Gas mixture[a]	W_α(eV)
H_2	36.4	36.3	15.43	Ar (96.5%) + C_2H_6 (3.5%)	24.4
He	46.0	42.3	24.58	Ar (99.6%) + C_2H_2 (0.4%)	20.4
Ne	36.6	36.4	21.56	Ar (97%) + CH_4 (3%)	26.0
Ar	26.4	26.3	15.76	Ar (98%) + C_3H_8 (2%)	23.5
Kr	24.0	24.05	14.00	Ar (99.9%) + C_6H_6 (0.1%)	22.4
Xe	21.7	21.9	12.13	Ar (98.8%) + C_3H_6 (1.2%)	23.8
CO_2	34.3	32.8	13.81	Kr (99.5%) + C_4H_8-2 (0.5%)	22.5
CH_4	29.1	27.1	12.99	Kr (93.2%) + C_2H_2 (6.8%)	23.2
C_2H_6	26.6	24.4	11.65	Kr (99%) + C_3H_6 (1%)	22.8
C_2H_2	27.5	25.8	11.40		
Air	35.0	33.8	12.15		
H_2O	30.5	29.9	12.60		

[a] The quoted concentration is the one that gave the smallest W.

W = energy spent for one ionization

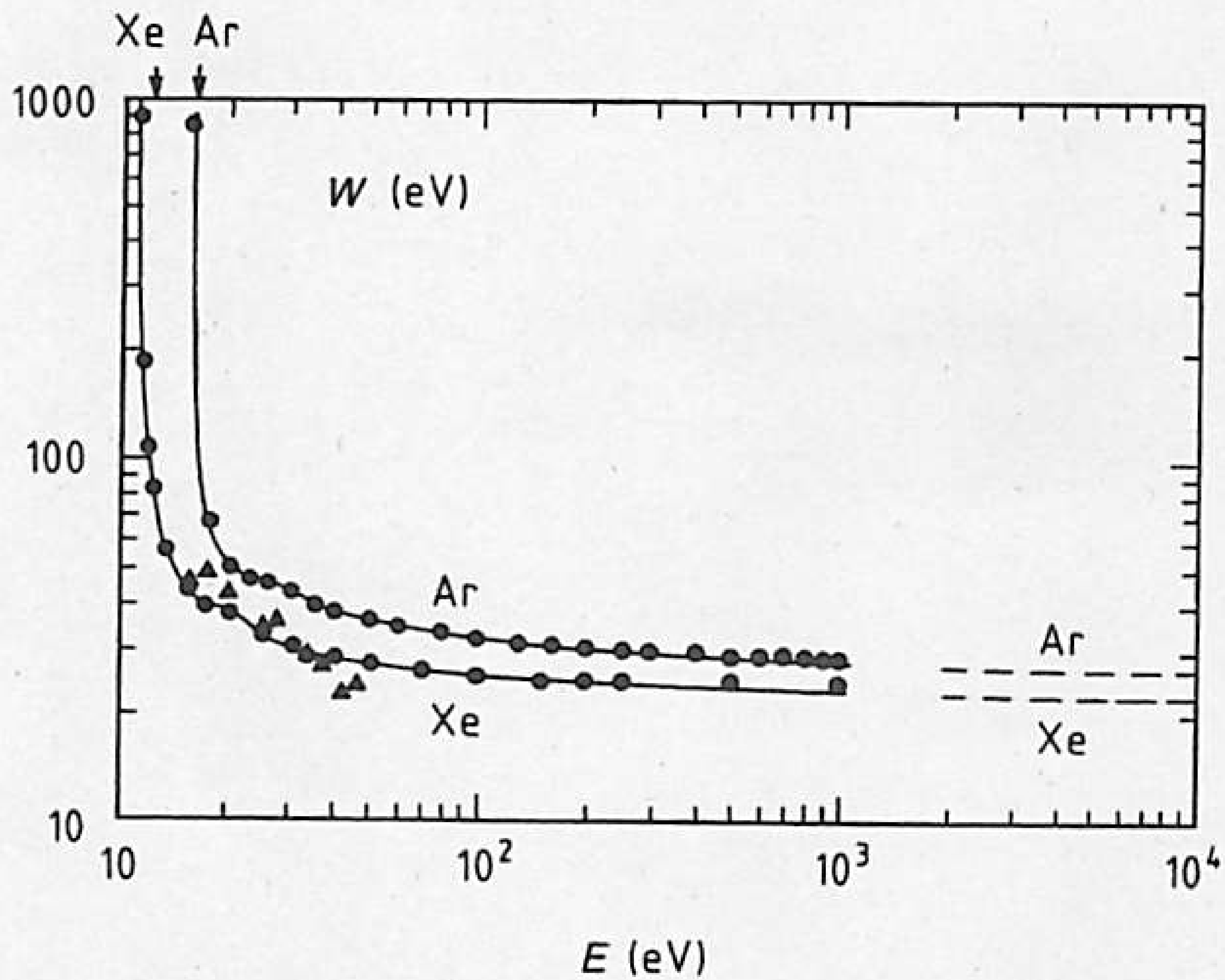


Fig. 1.2 Average energy W spent for the creation of one ionization electron in pure argon and in pure xenon as a function of the energy E of the ionizing particle, which is an electron fully stopped [COM 77]. The *dashed lines* represent the values W_β from Table 1.2 measured at larger E

Bethe-Bloch formula (dE/dx)

- The formula, famous for experimentalists, is given by

velocity

$$\left\langle -\frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = \frac{4\pi N e^4}{m_e c^2 \boxed{\beta^2}} z^2 \left(\ln \frac{2 m_e c^2 \boxed{\beta^2 \gamma^2}}{I} - \beta^2 \right)$$

velocity

Function of particle velocity!!

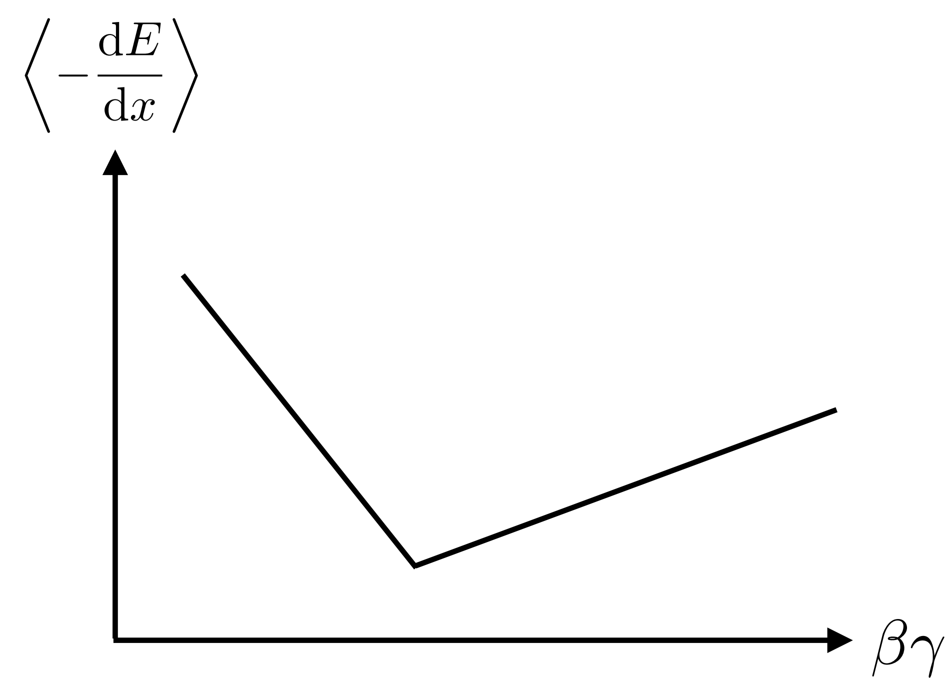
N : number density of electron, m_e : electron mass,
β and γ : relativistic velocity parameters.

when the particle is slow

$$E \propto \frac{1}{\beta^2 \gamma^2}$$

when the particle is fast

$$E \propto f(\beta^2 \gamma^2)$$



dE/dx vs. particle velocity

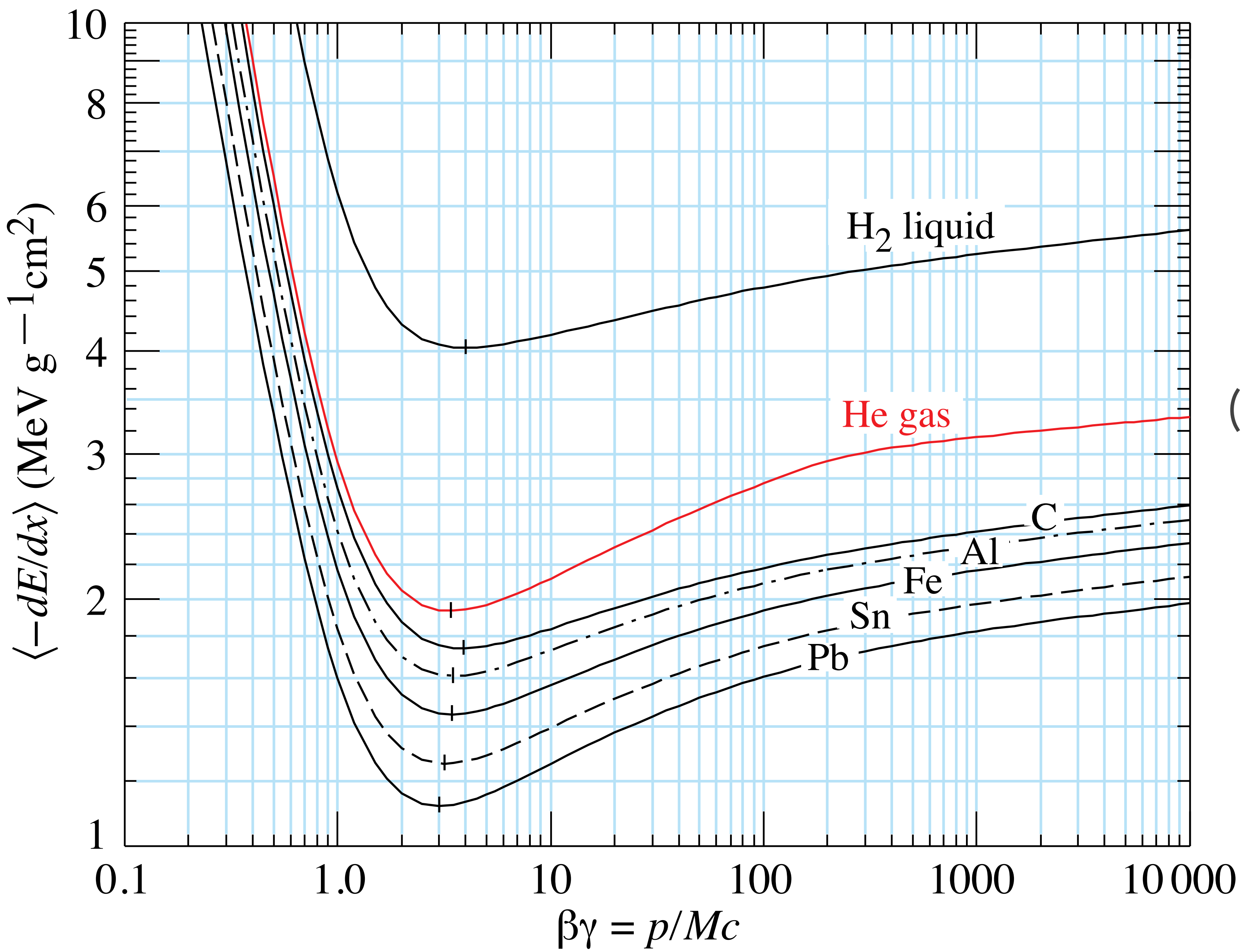


Figure 33.2: Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminum, iron, tin, and lead. Radiative effects, relevant for muons and pions, are not included. These become significant for muons in iron for $\beta\gamma \gtrsim 1000$, and at lower momenta for muons in higher-Z absorbers. See Fig. 33.23.

Minimum at βγ~4
(Minimum Ionizing Particle
: MIP)

dE/dx vs. track momentum

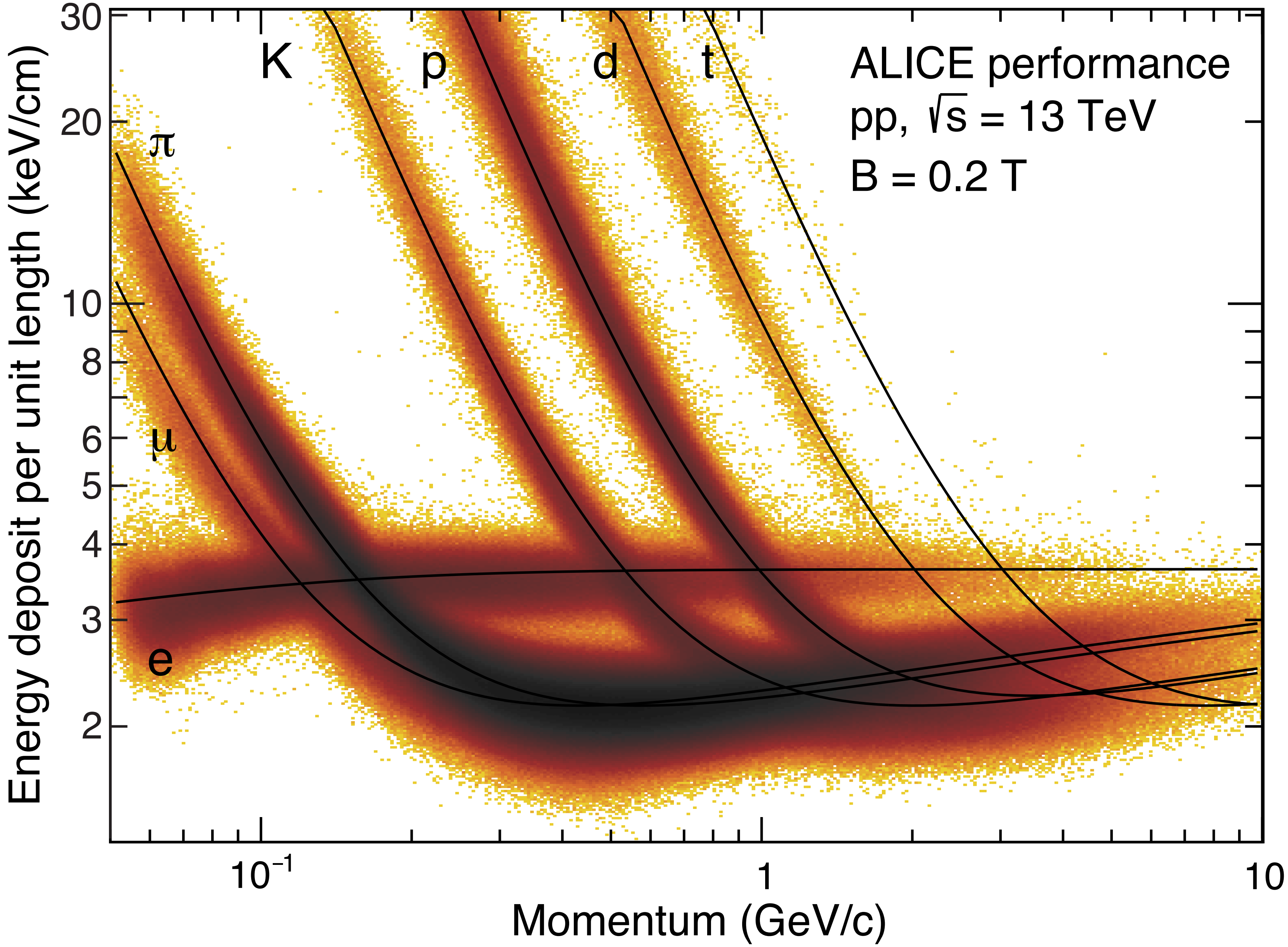


Figure 33.15: Energy deposit versus momentum measured in the ALICE TPC [108].

$$p = \gamma m v = \frac{mc\beta}{\sqrt{1-\beta^2}}$$

光子と物質の相互作用

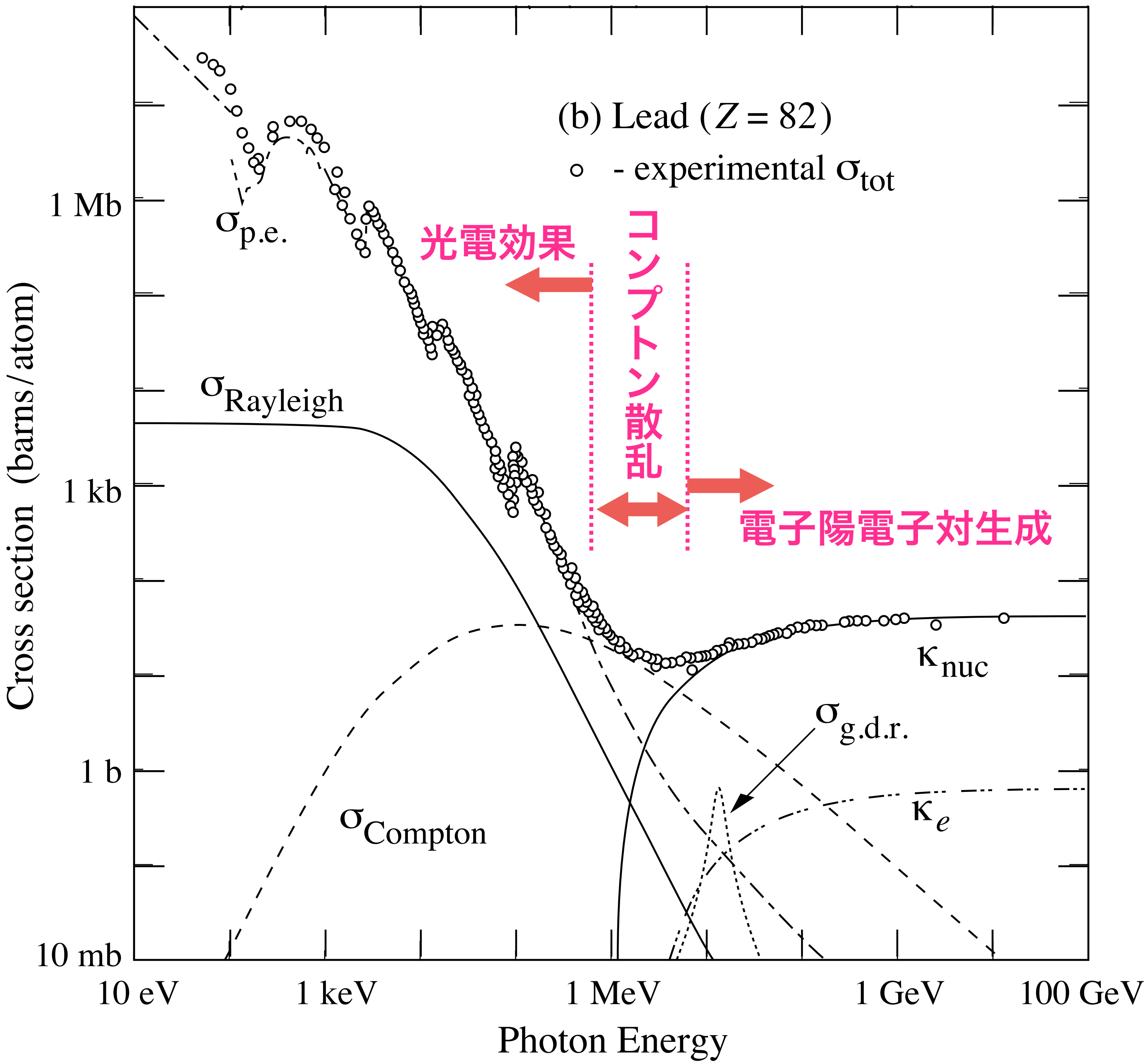
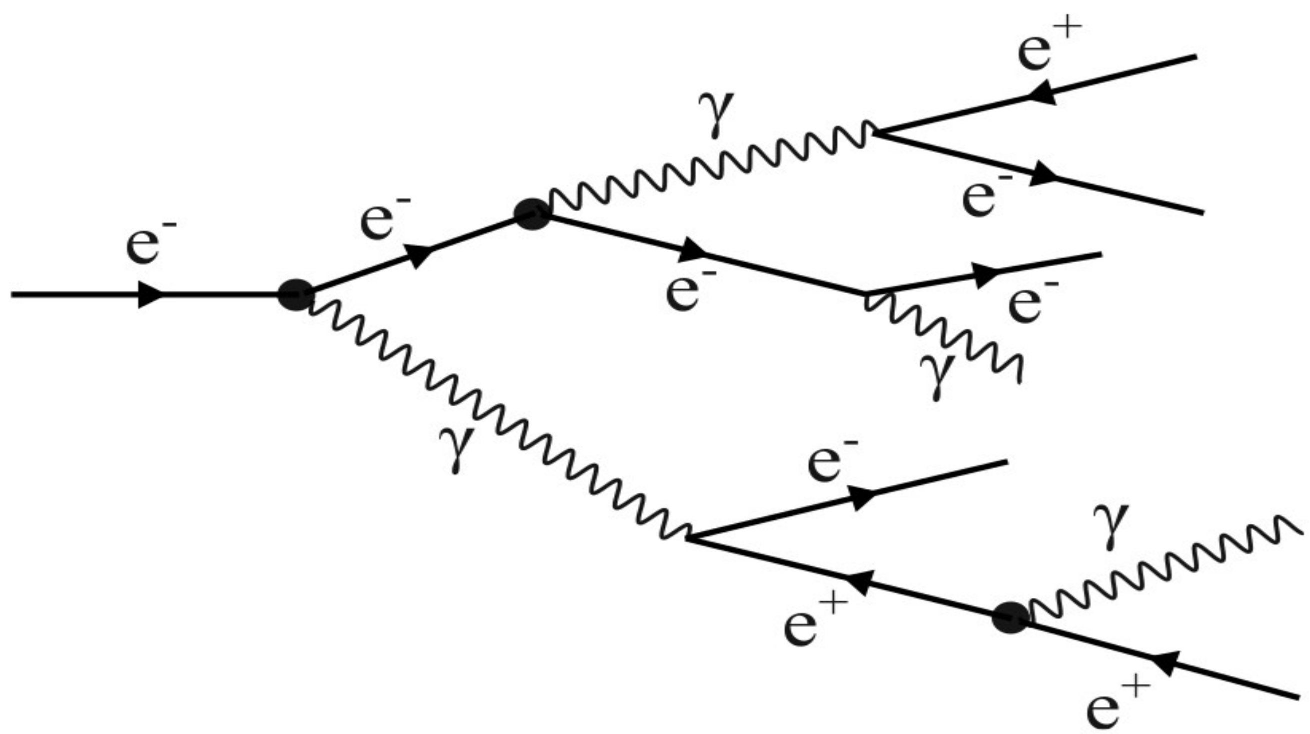


Figure 33.15: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes [50]:

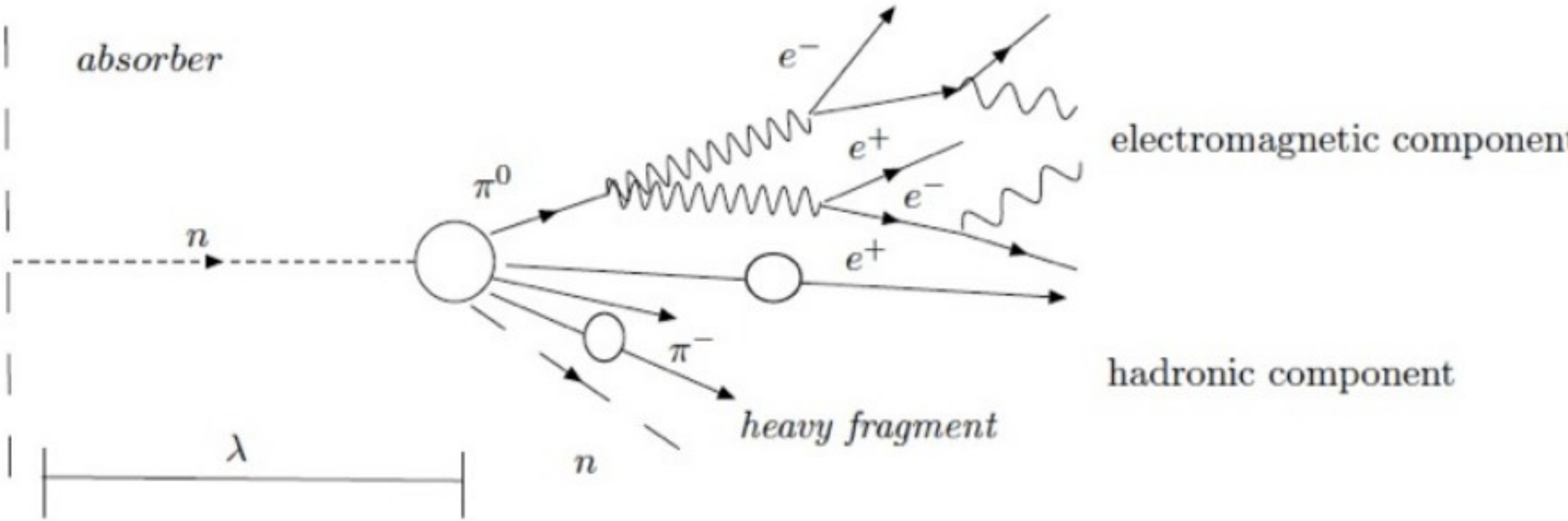
- 光子は荷電粒子に変換することで測定できる。
- 1点で変換するので、荷電粒子のような連続的な飛跡は得られない。
- 高エネルギーでは、電子陽電子対生成がほとんど。

Electromagnetic Showers



- High-energy electron loose its energy mostly through bremsstrahlung.
- This leads to high-energy photons.
- If >1MeV, the photon converts to an e^+e^- pair.
- Then, the cascade creates electromagnetic shower.

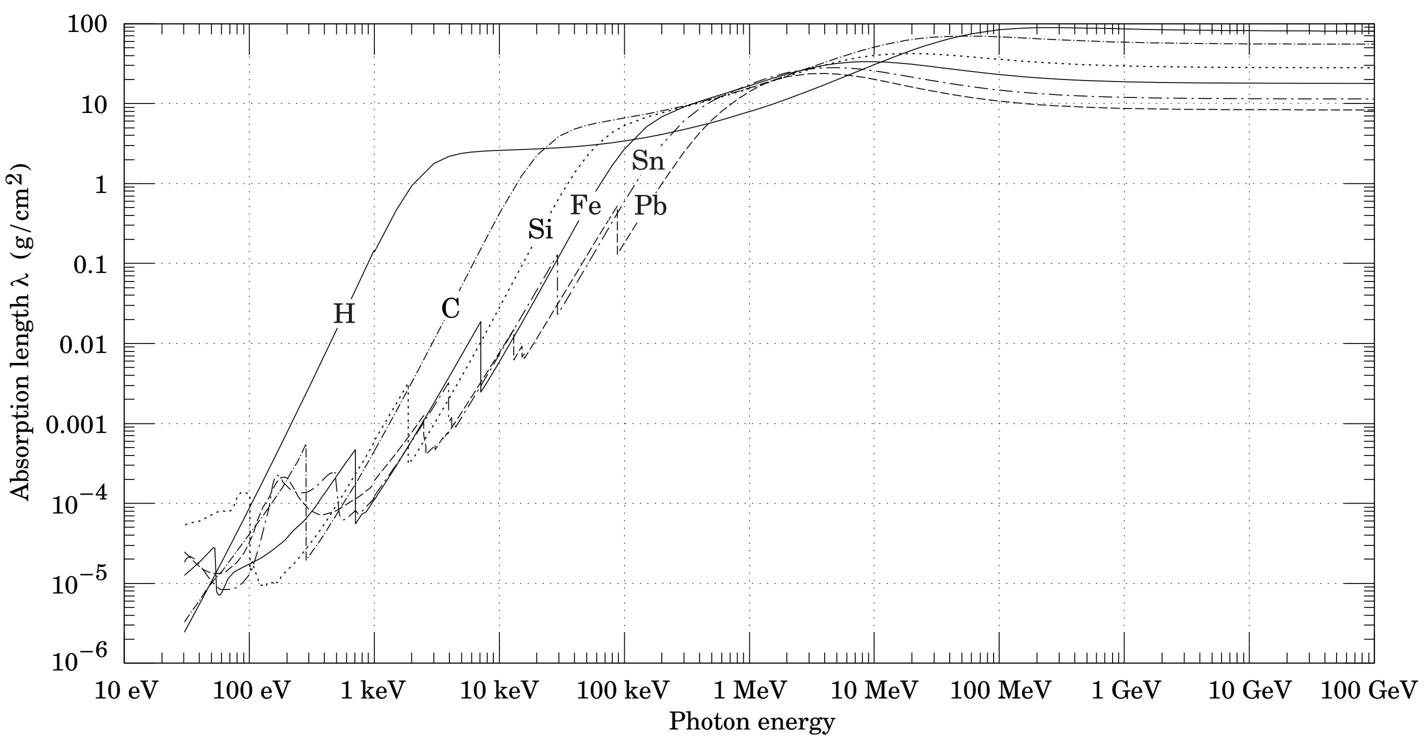
Hadronic Showers

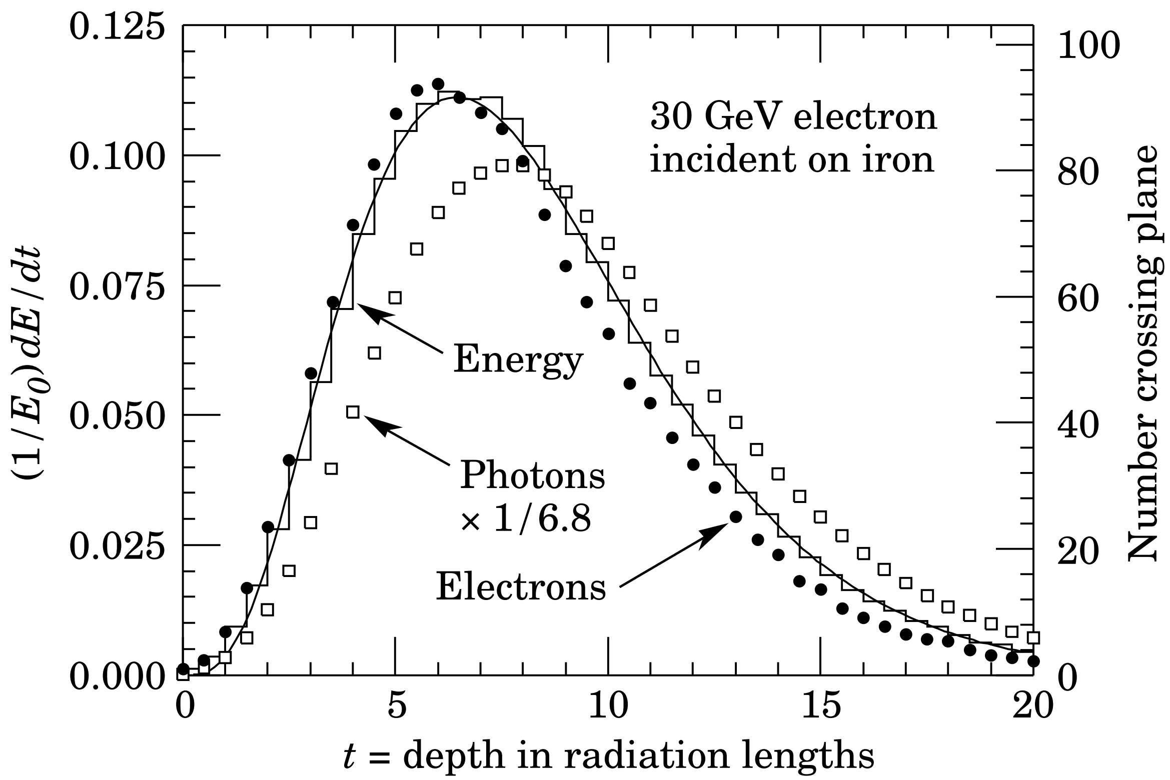


- High-energy hadrons produce hadronic shower when interacting with matter.
- Includes nuclear and strong interactions.
- Shower range is longer than EM showers.
  → hadronic calorimeter is larger than EM cal.

Radiation Length X_0

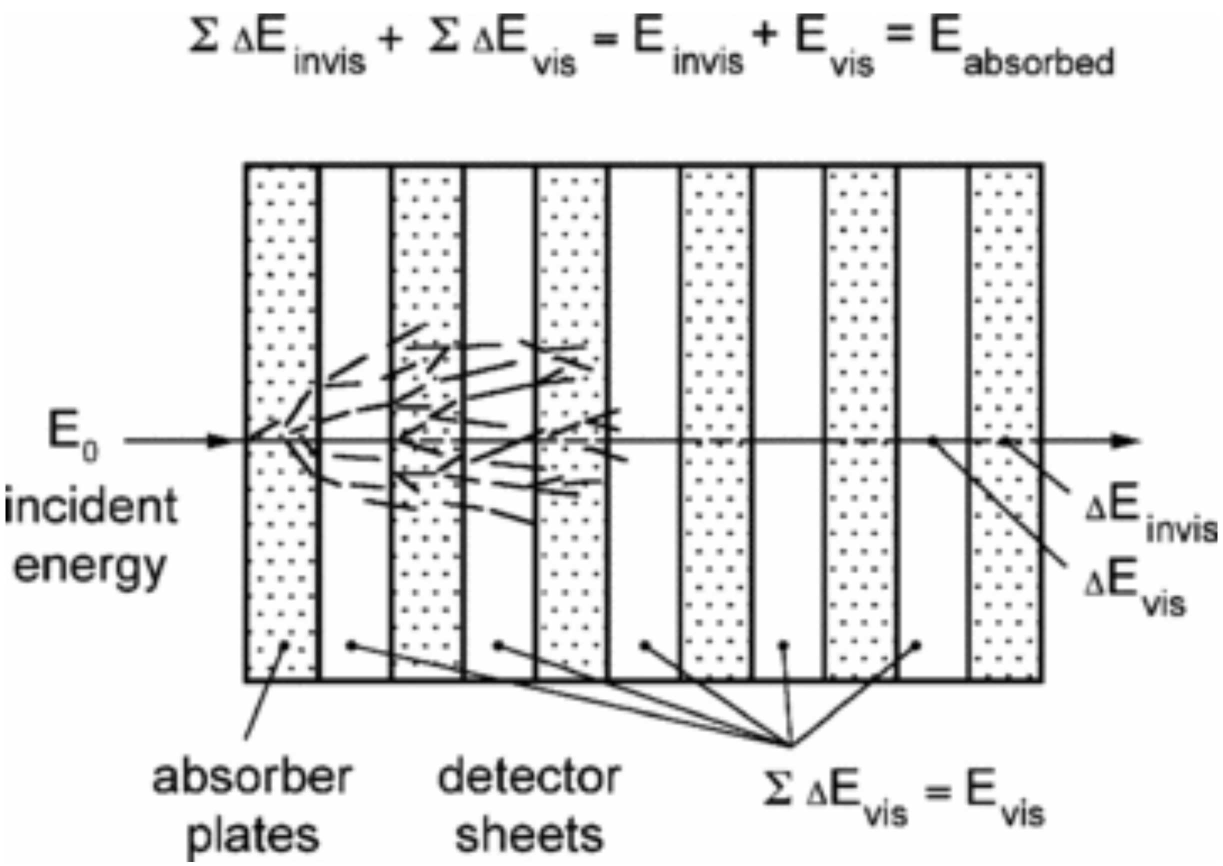
- Radiation Length (放射長) X_0 :
  Length the electron energy becomes 1/e by bremsstrahlung.
- Photon flux decreases to 1/e at $(9/7)X_0$
- Depends on energy and material.
- To absorb whole EM shower, one needs ~$25X_0$





- For hadrons, λ is similarly defined.
- $\lambda \gg X_0$ → hadron needs longer material for full absorption.

Sampling Calorimeter



- If the shower is fully contained in a “scintillator”, incident energy is converted to the amount of excitation light.
- But, for this, “scintillator” should be too large.
- Usually, heavy material (absorber plates) are sandwiched with scintillator sheets (sampling calorimeter).
- Need to know E_{vis} : $E_{absorbed}$.

Contents

1. Detector basics
2. ILC detectors
3. Detector electronics

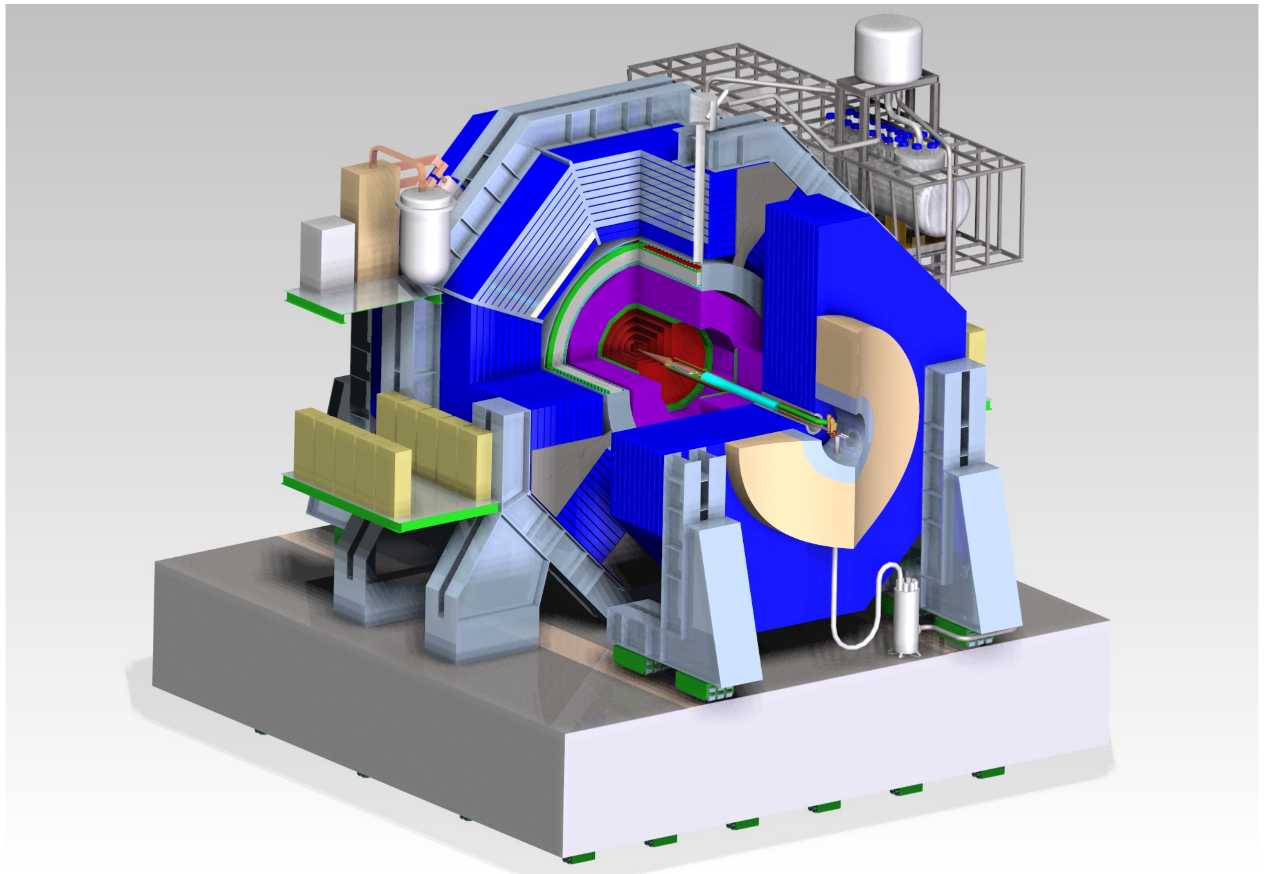
(Refer 5/Sep lectures for detailed and recent topics)

ILC Detector Requirements

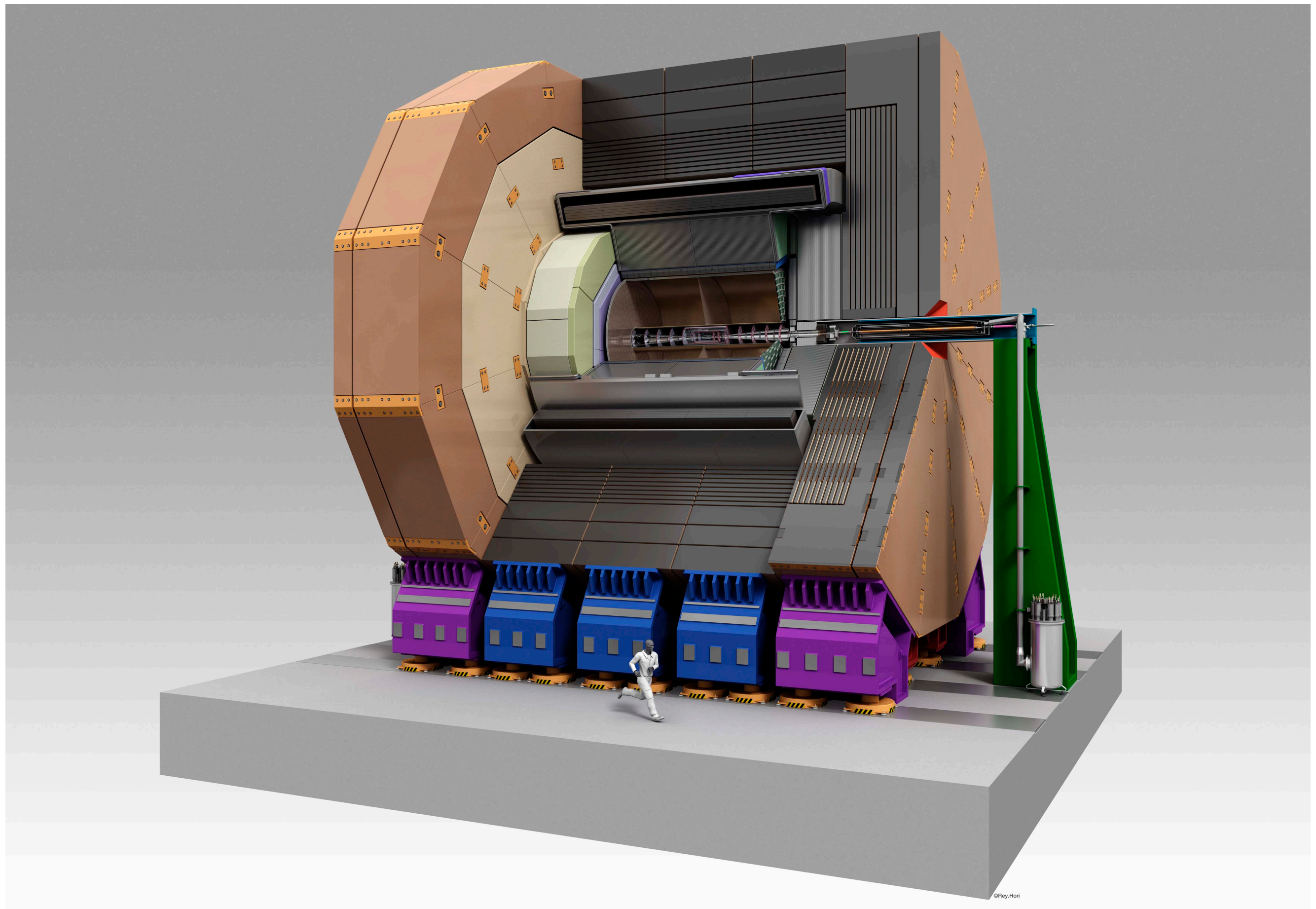
- High jet energy resolution for W/Z invariant mass separation
  $\sigma/E_{jet} <= 30\%/\sqrt{E_{jet}}(GeV)$ Calorimeter
- Impact parameter resolution for efficient jet flavor identification
  $\sigma <= 5 \oplus 10/p\beta \sin^{3/2}\theta\ (\mu m)$ Vertex
- High momentum resolution for Higgs recoil mass measurement
  $\sigma/p_t^2 <= 5 \times 10^{-5}\ (GeV/c)^{-1}$ Tracker

Needs advanced detectors
with high resolution sensors!!

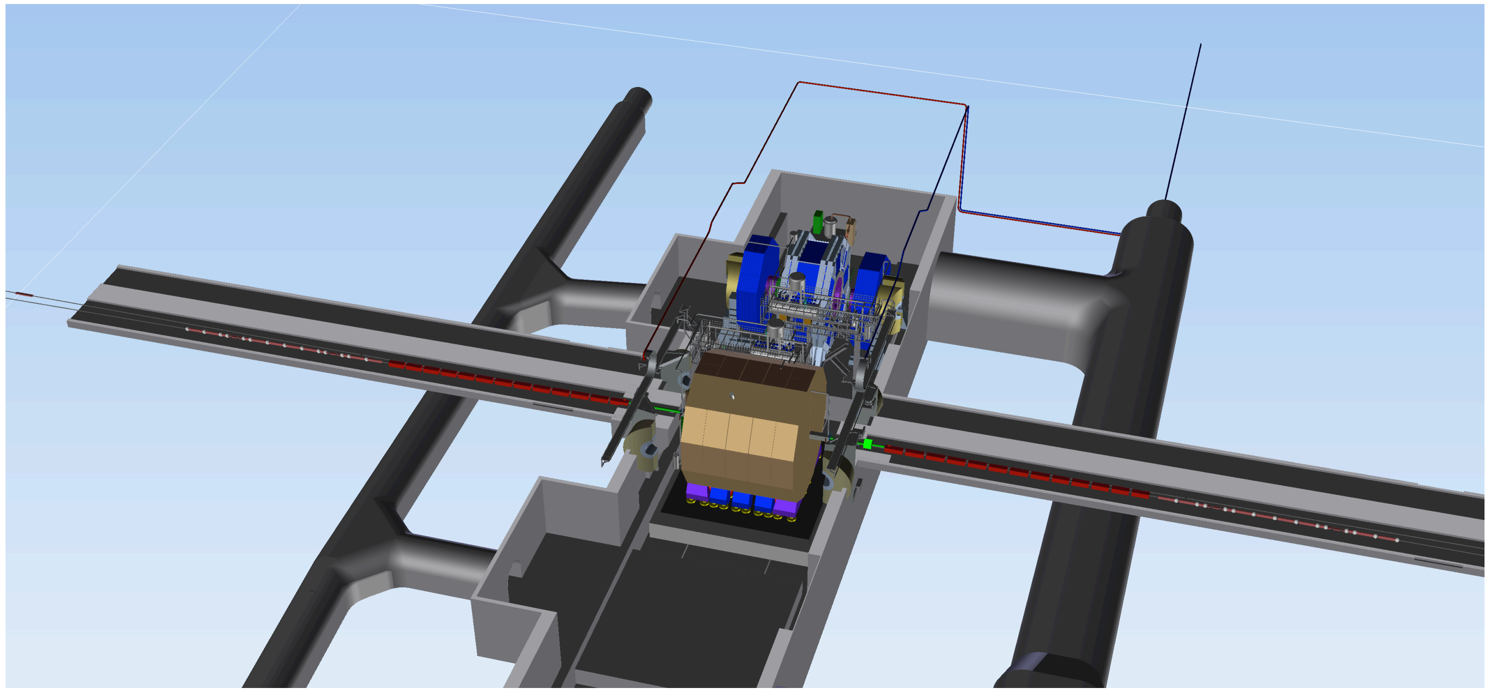
ILC detectors — SiD and ILD



SiD (Silicon Detector)



ILD (International Large Detector)



Each detector is alternatively moved to the beam-line by way of the “push-pull” system.

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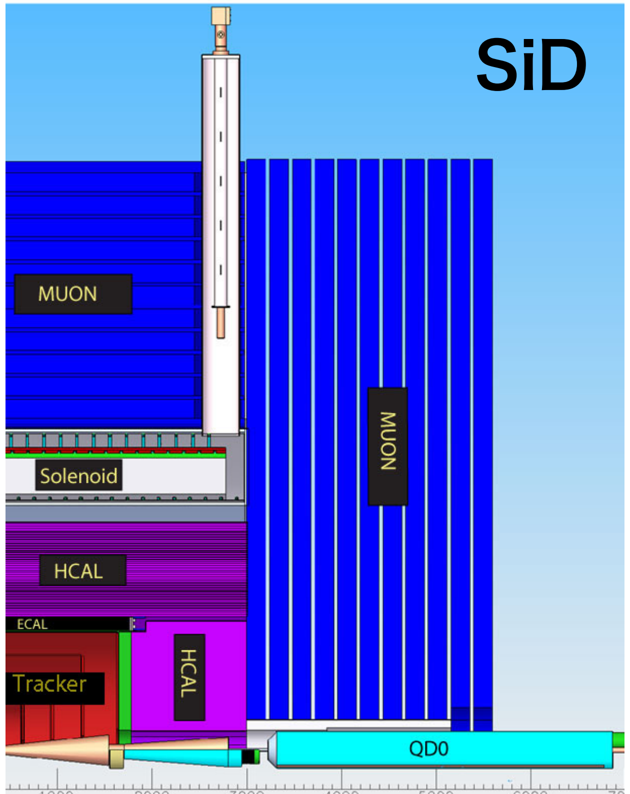
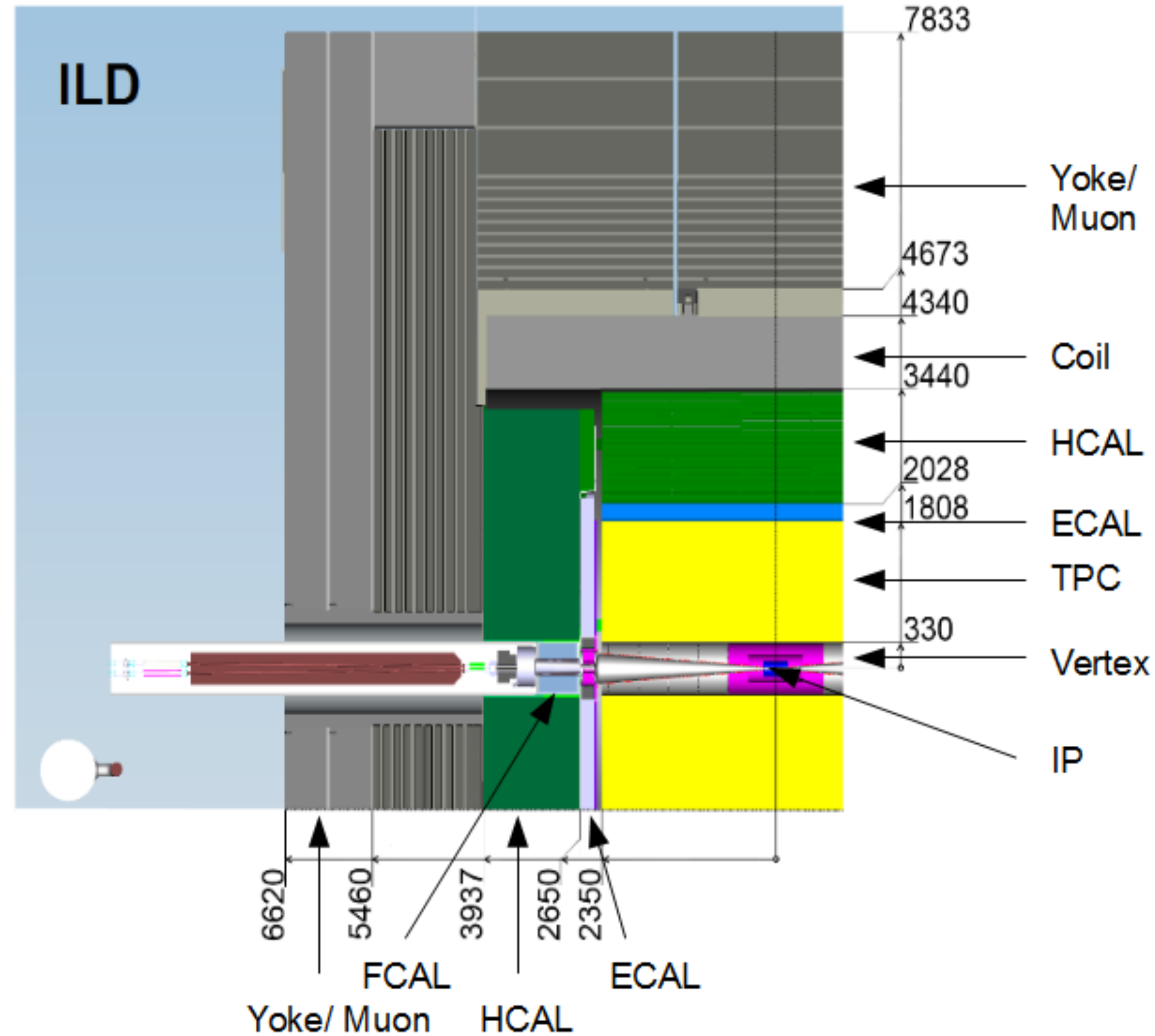
Comparison of SiD and ILD



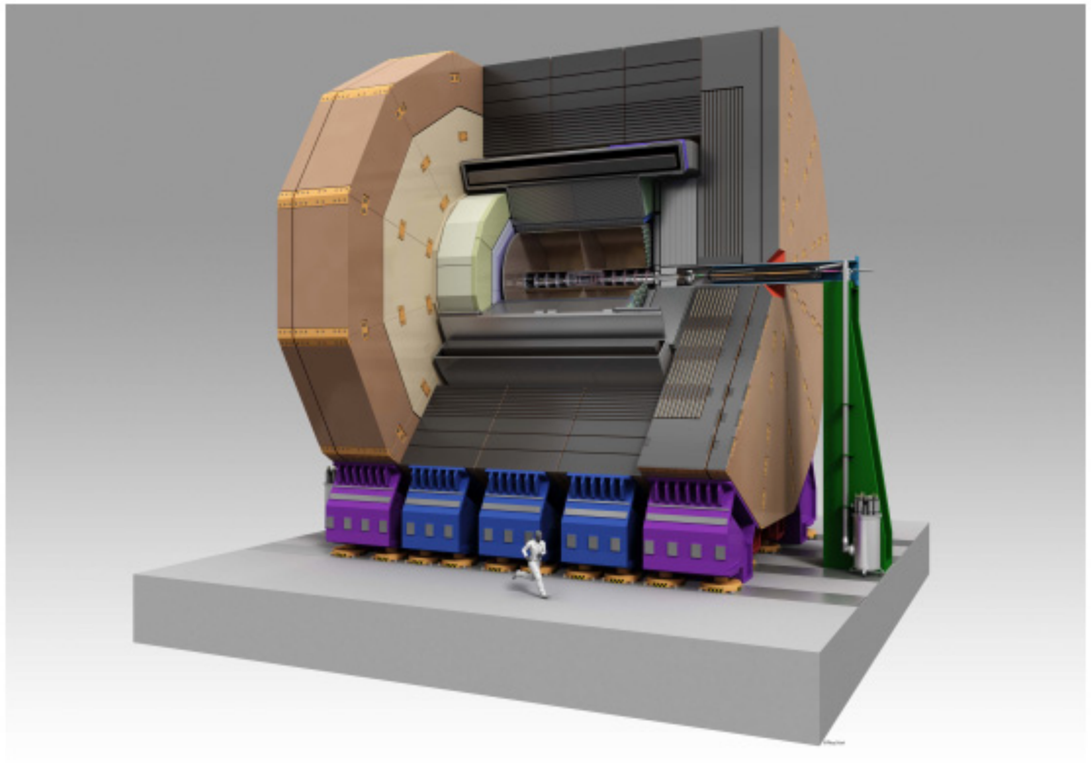


SiD
smaller
↓
low cost

	SiD	ILD
Height x Length	14m x 11m	16m x 14m
Weight	10,100t	14,000t
B Field	5T	3.5T
ECAL inner R	1.3m	1.8m
Tracker	silicon strip	TPC

ILD
gas tracker
↓
continuous
tracking,
low material

ILC detector granularity (ILD case)



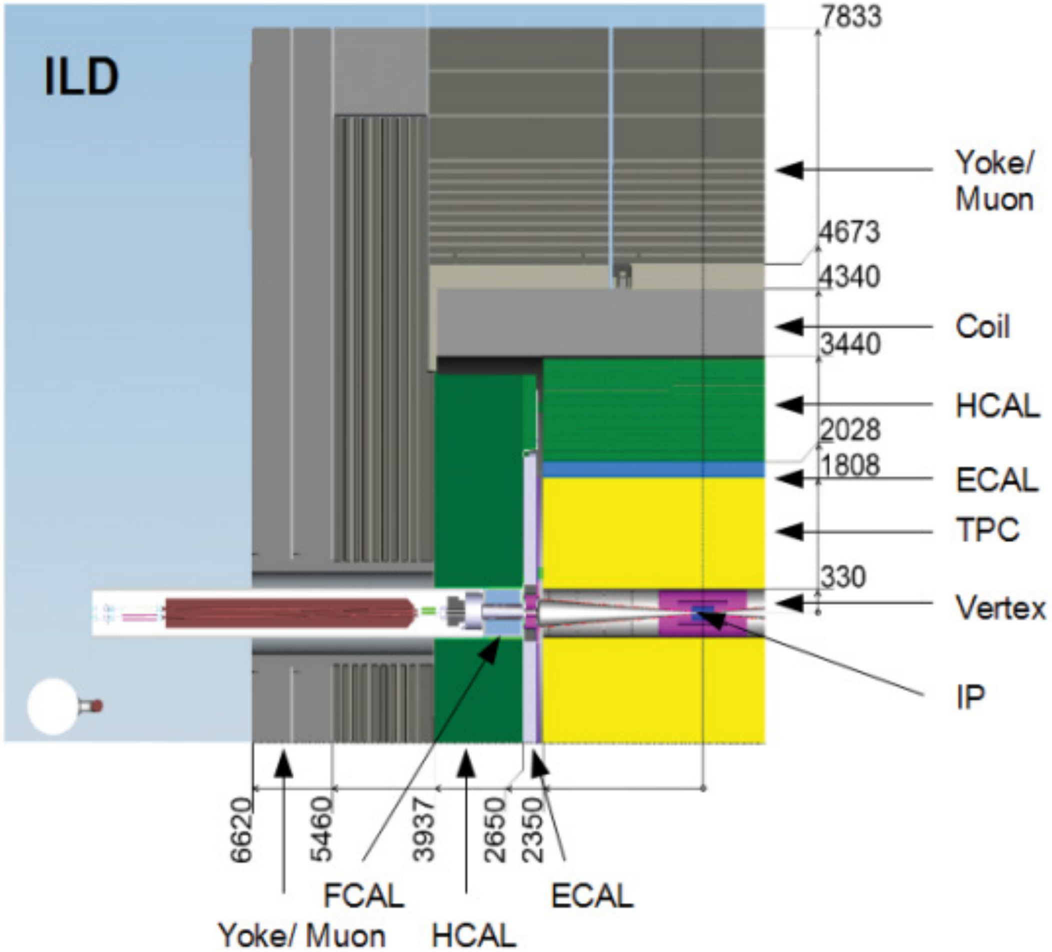
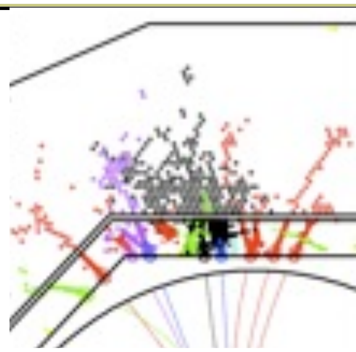


Figure 4.6. Views of the ILD detector concept. The interaction point in the quadrant view (right) is in the lower right corner of the picture. Dimensions are in mm.

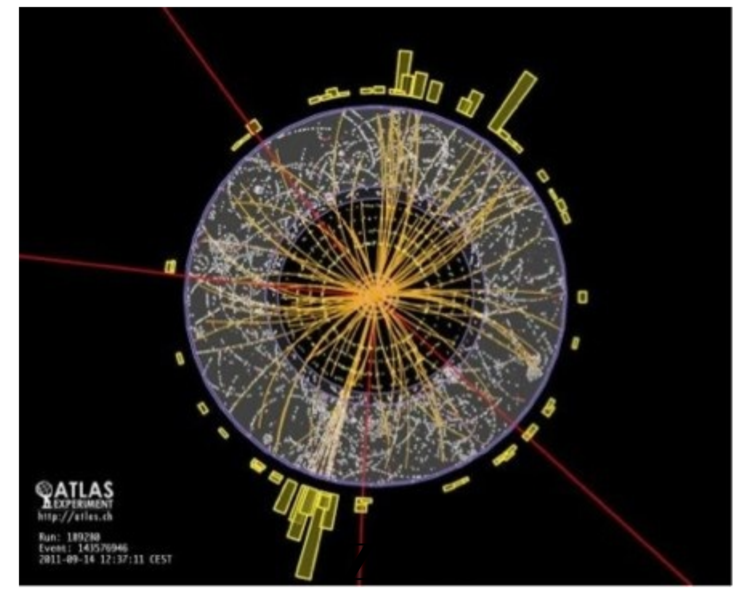
	ILC	ATLAS	granularity ratio
vertex	5x5 um²	400x50 um²	x800
tracker	1x6 mm²	13 mm²	x2.2
ECAL	5x5 mm²	39x39mm²	x61

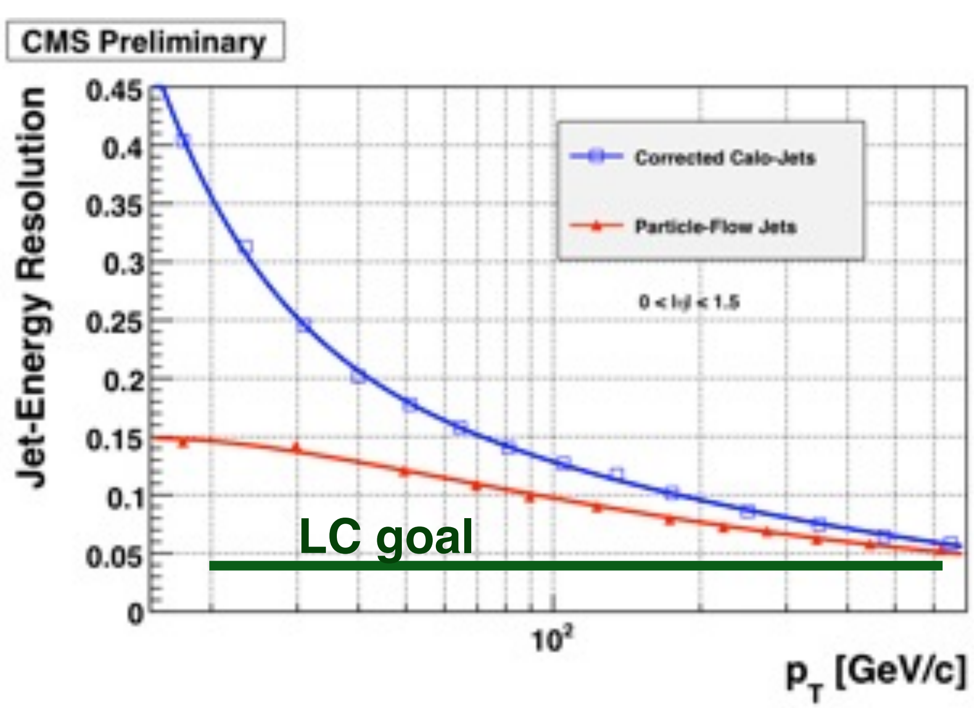
Particle Flow Algorithm (PFA)



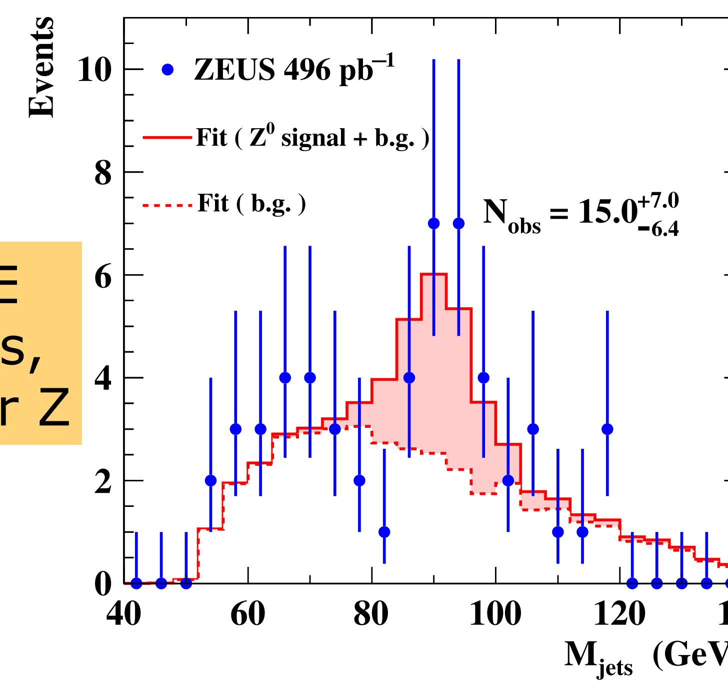
The jet energy challenge

- Jet energy performance of existing detectors is not sufficient for W Z separation
- E.g. CMS: ~ 100%/√E, ATLAS ~ 70%/√E
- Calorimeter resolution for hadrons is intrinsically limited
- Resolution for jets worse than for single hadrons
- It is not sufficient to have the world best calorimeter





35%/√E
for pions,
6 GeV for Z



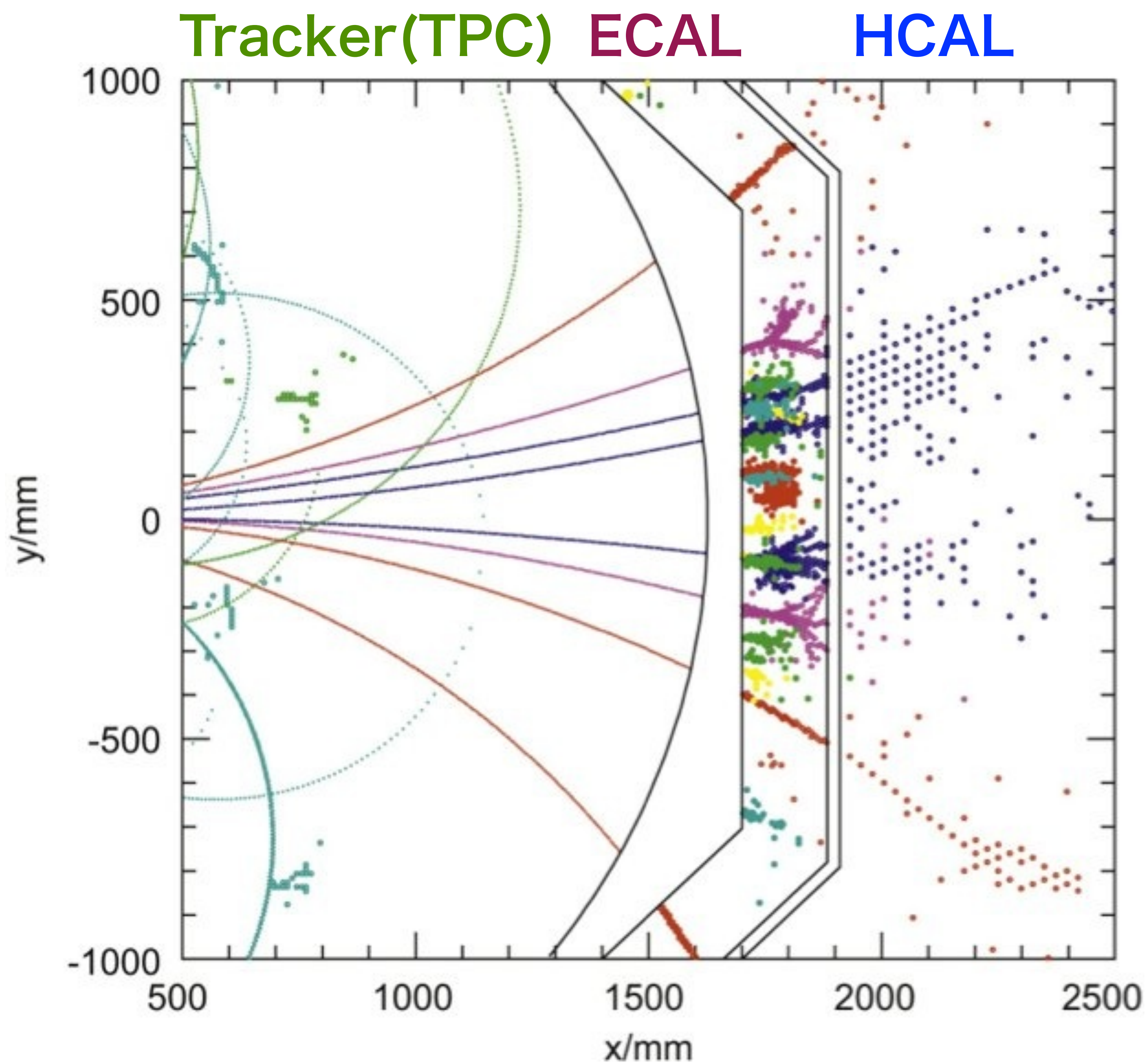
Slides by F. Sefkow

Particle Flow Algorithm (PFA)

Separate hit of each particle in calorimeter. Then, measure the particle energy using the detector with the best resolution for the particle.

- charged particles
  → Tracker
- photons
  → ECAL
- neutral hadrons
  → HCAL

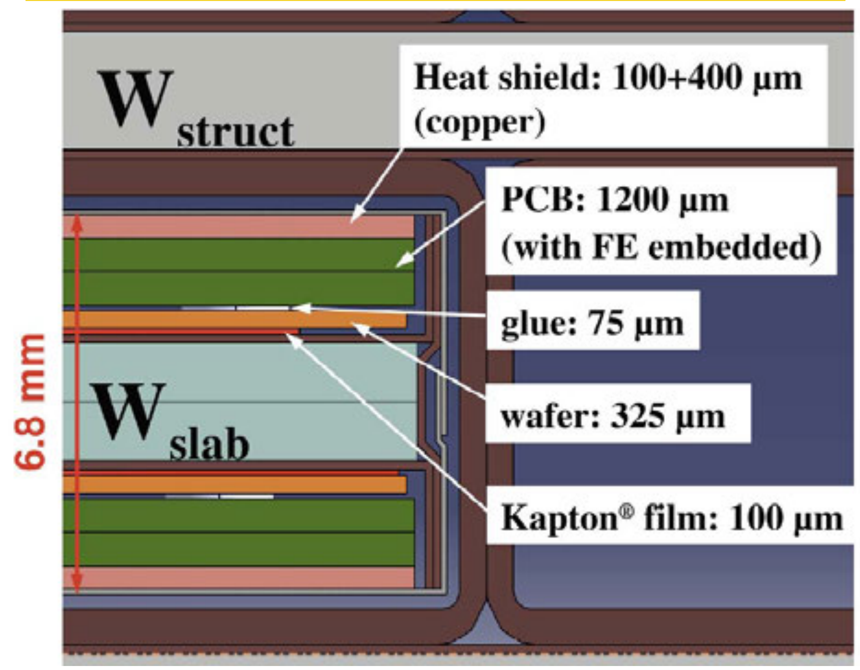
For this purpose, there is no solenoid inside calorimeters.



ILD Calorimeter

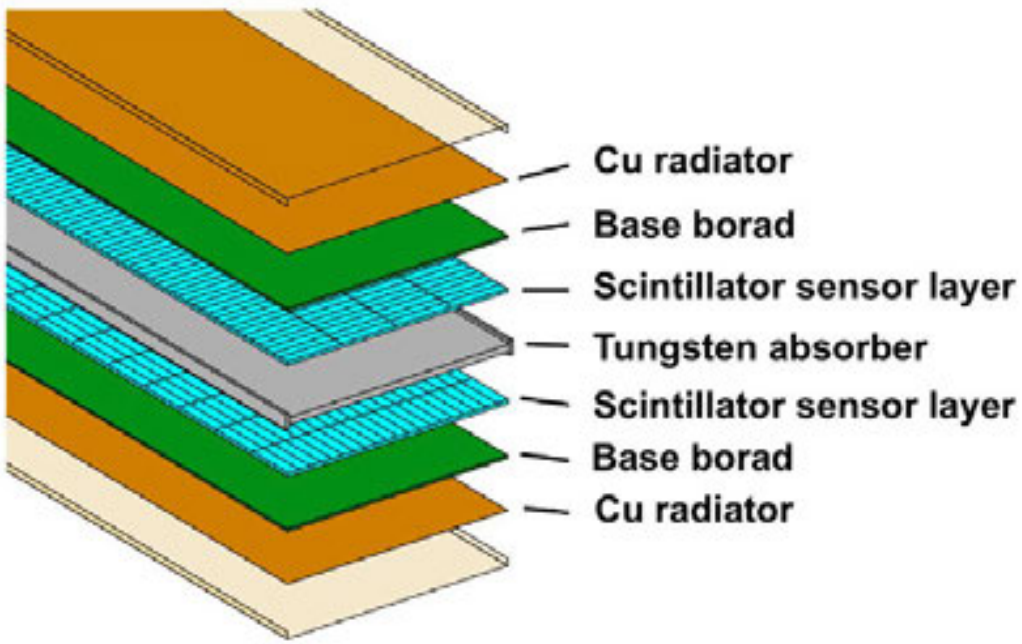
- ILC calorimeter development is carried by the CALICE Collaboration.
- ECAL (EM shower) / HCAL (Hadron shower) / FCAL (near beam axis direction)
- σ (jet) = σ (CAL energy) + σ (PFA particle separation)
  → needs precise segmentation.
- ECAL → 30 layers of tungsten absorbers and sensors.

SiECAL (sensor = silicon)



silicon sensors w. 5x5mm² pads

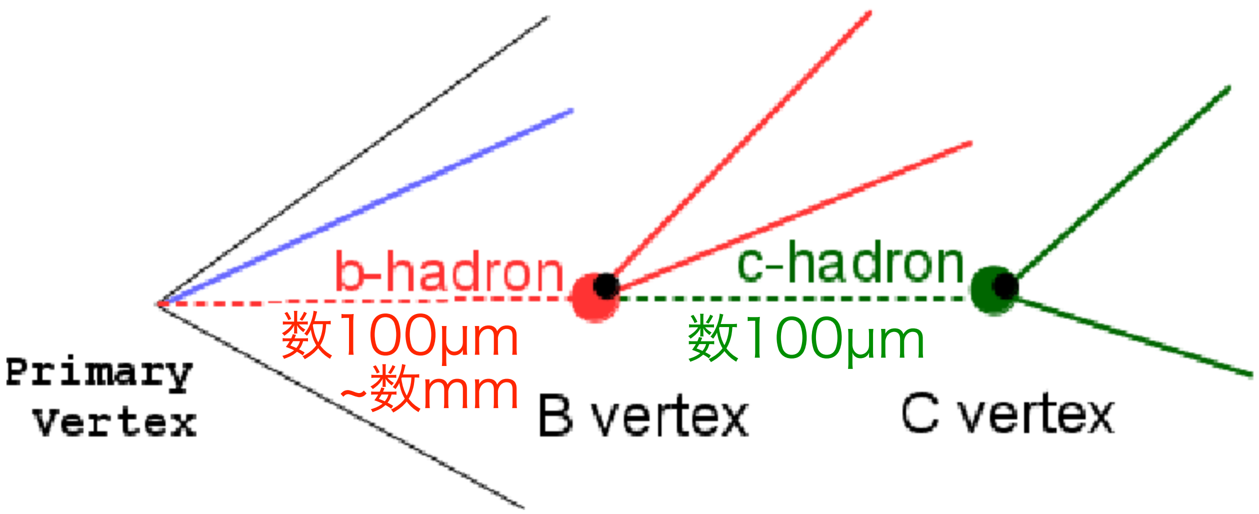
ScECAL (sensor = scintillator)



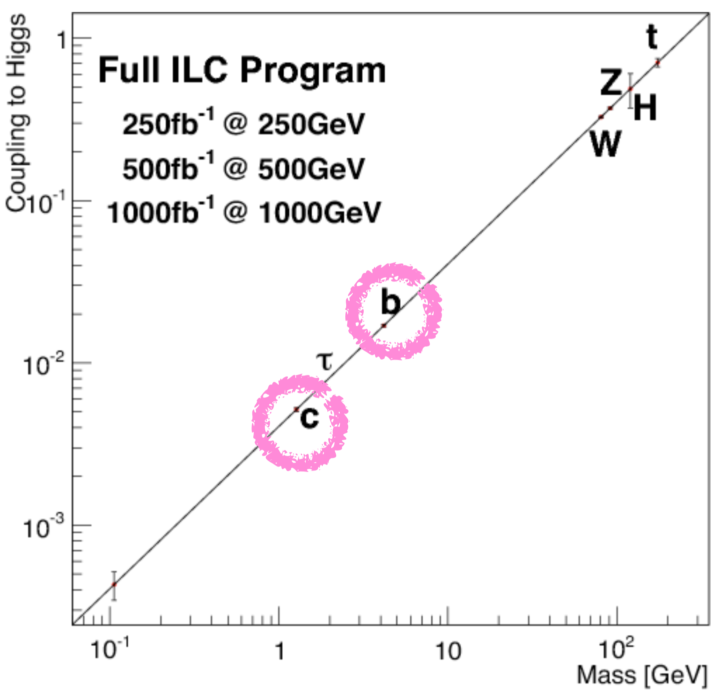
45x5mm² strip plastic scintillators
read by PPD (pixelated photon detector)

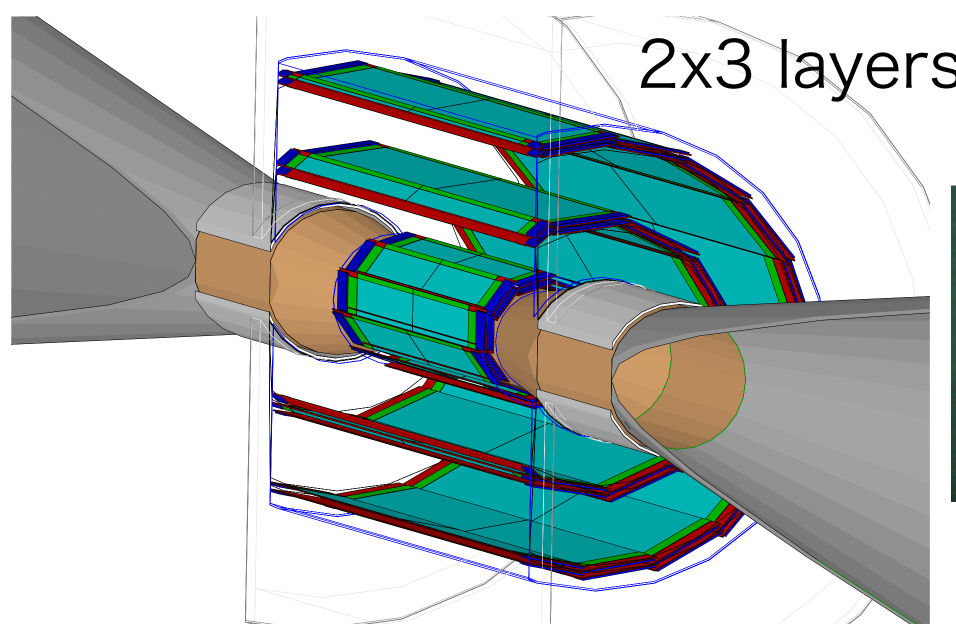
- HCAL → two concepts:
  AHCAL (analog HCAL) : similar to ScECAL w. 30x30mm² tiles.
  SDHCAL (semi-digital HCAL) : 2-bit digital readout from 10x10mm² gas detector.

ILD Vertex Detector

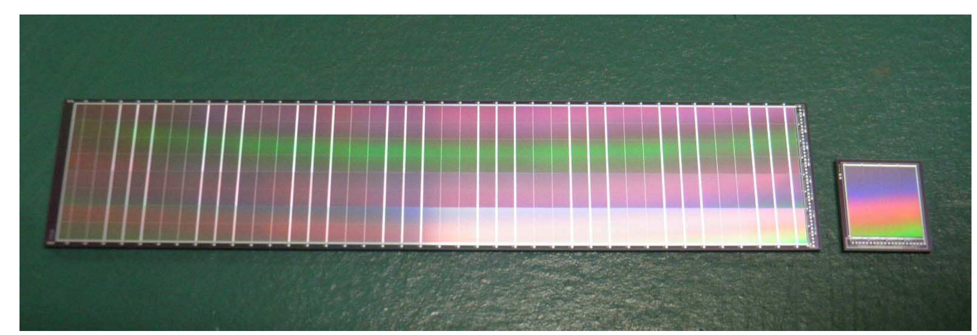


- Separate b-hadron jets and c-hadron jets from u, d, s-hadron/gluon jets.
- C-vertex: only possible at clean lepton collider → important to measure coupling to Higgs.





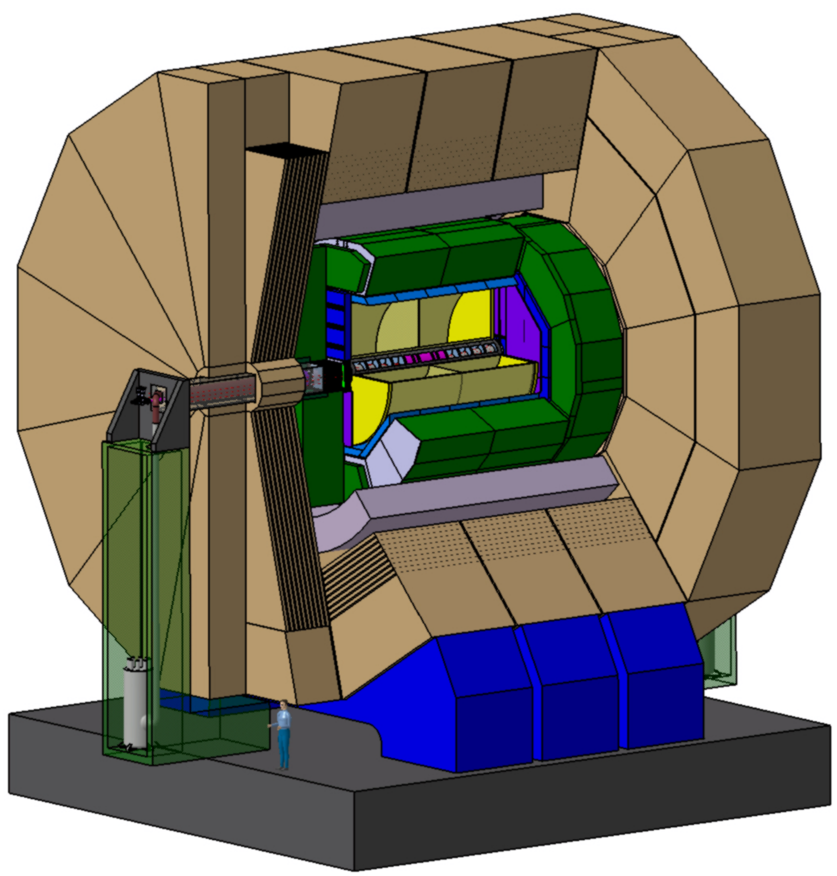
FPCCD prototype



$62.4 \times 12\ \mathrm{mm}^2$ and $6 \times 6\ \mathrm{mm}^2$

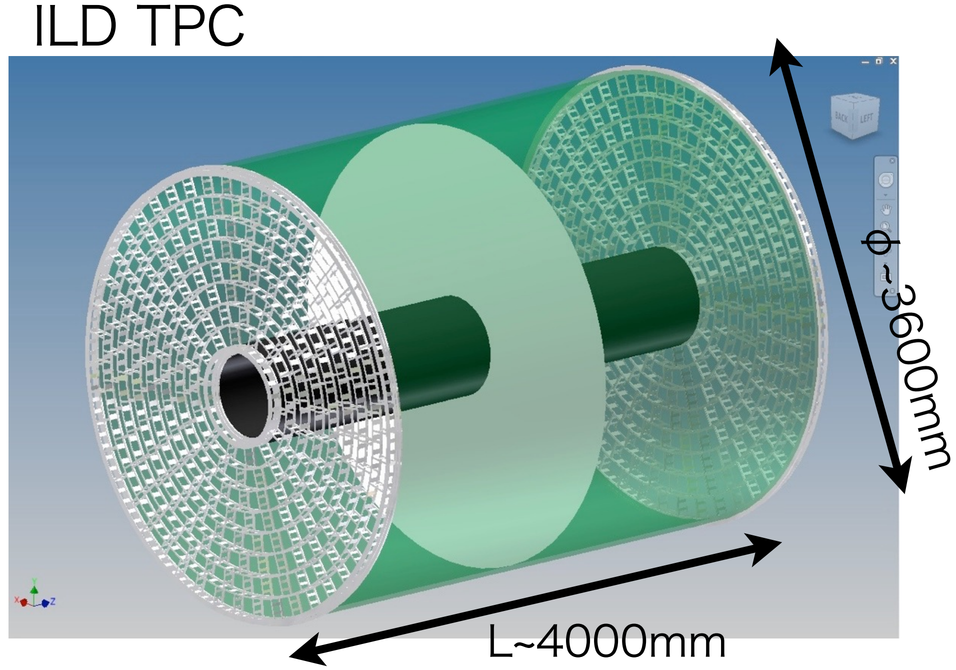
- Development groups: MIMOSA/AROM (仏), DEPFET (独), FPCCD (日).
- Position resolution <= 3μm → FPCCD (Fine Pixel CCD) users finer pixels (5x5μm²).
- Suppress multiple coulomb scattering → thin layer ~50μm.
- FPCCD readout btw. trains (199ms) → free from beam EMI noise.
- Low temperature (-40℃) and thin pipe → CO_2 cooling.

ILD Tracker: TPC

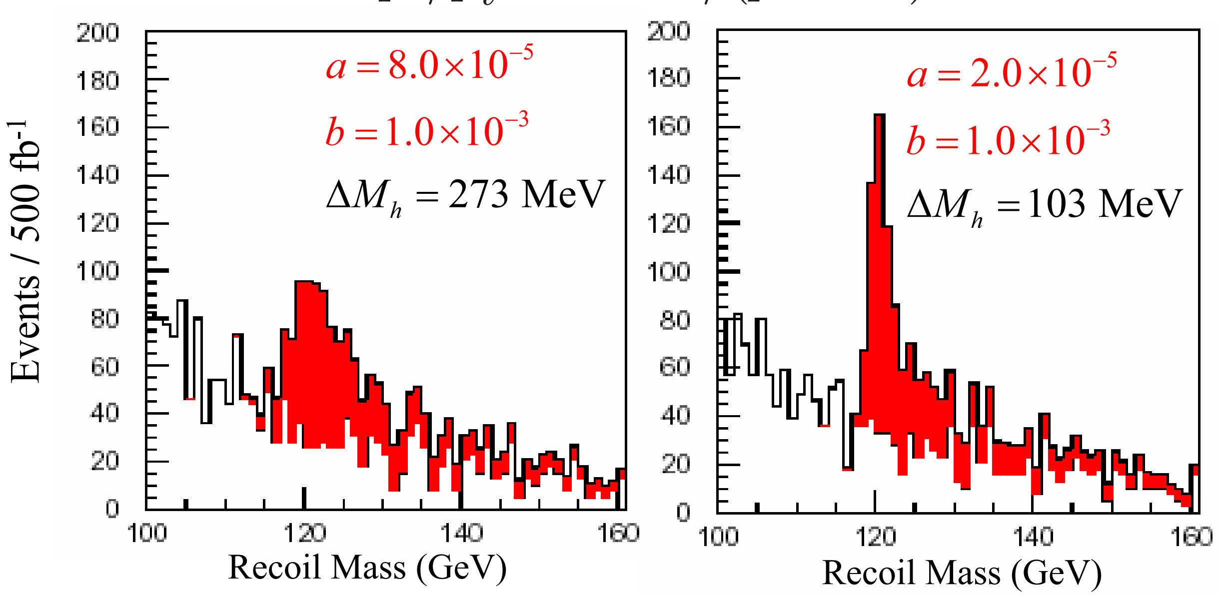


- Why TPC as the ILD central tracker?
  - Good momentum resolution and pattern recognition with ~200 measurement points per track.
  - Low material budget provides good energy resolution in calorimeters.
- MPGD (GEM or Micromegas) as amplification device.
- Good spatial resolution
  σ_{point} in rϕ < 100μm @ 3.5T

ILD TPC



$$\delta p_t/p_t^2 = a \oplus b/(p_t \sin\theta)$$

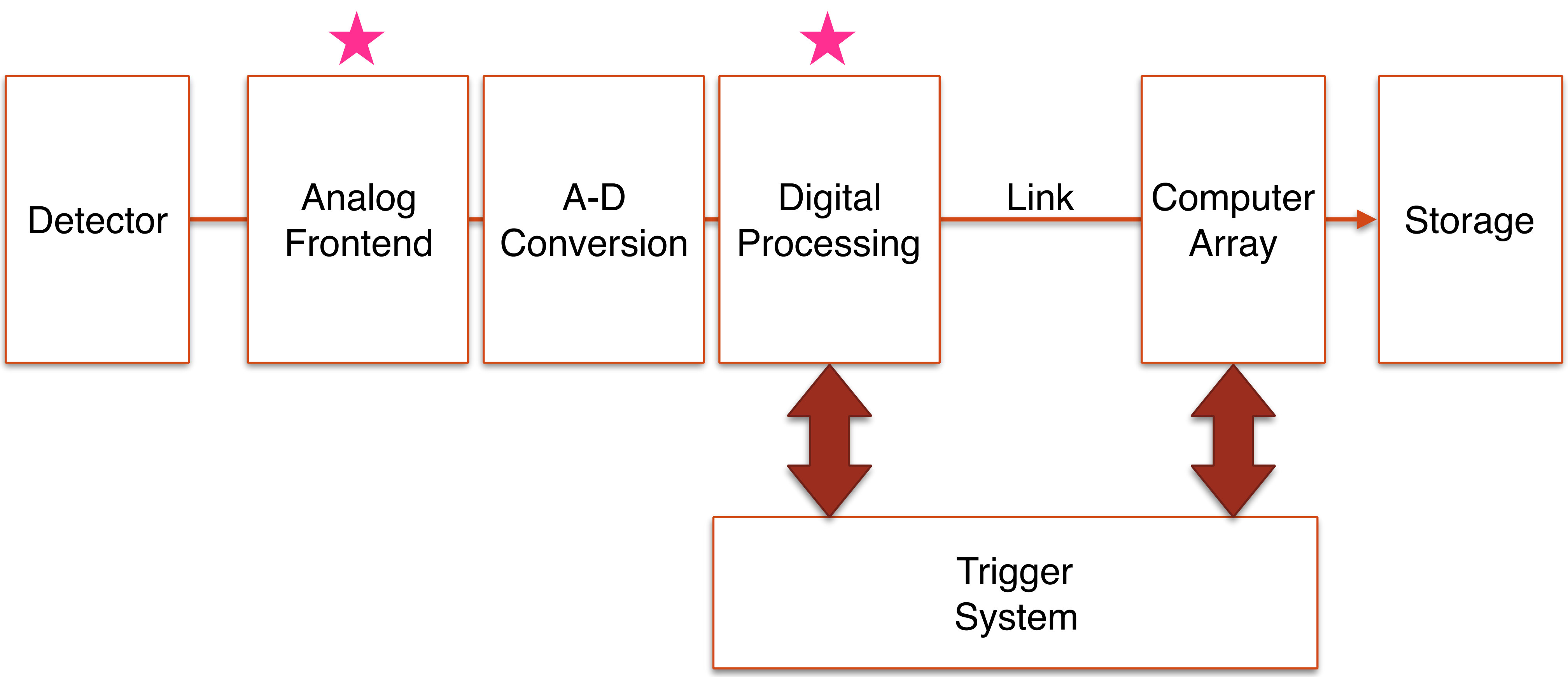


Higgs recoil mass reconstruction from muon pair decay of Z for different momentum resolution (ILC Reference Design Report Vol.4)

Contents

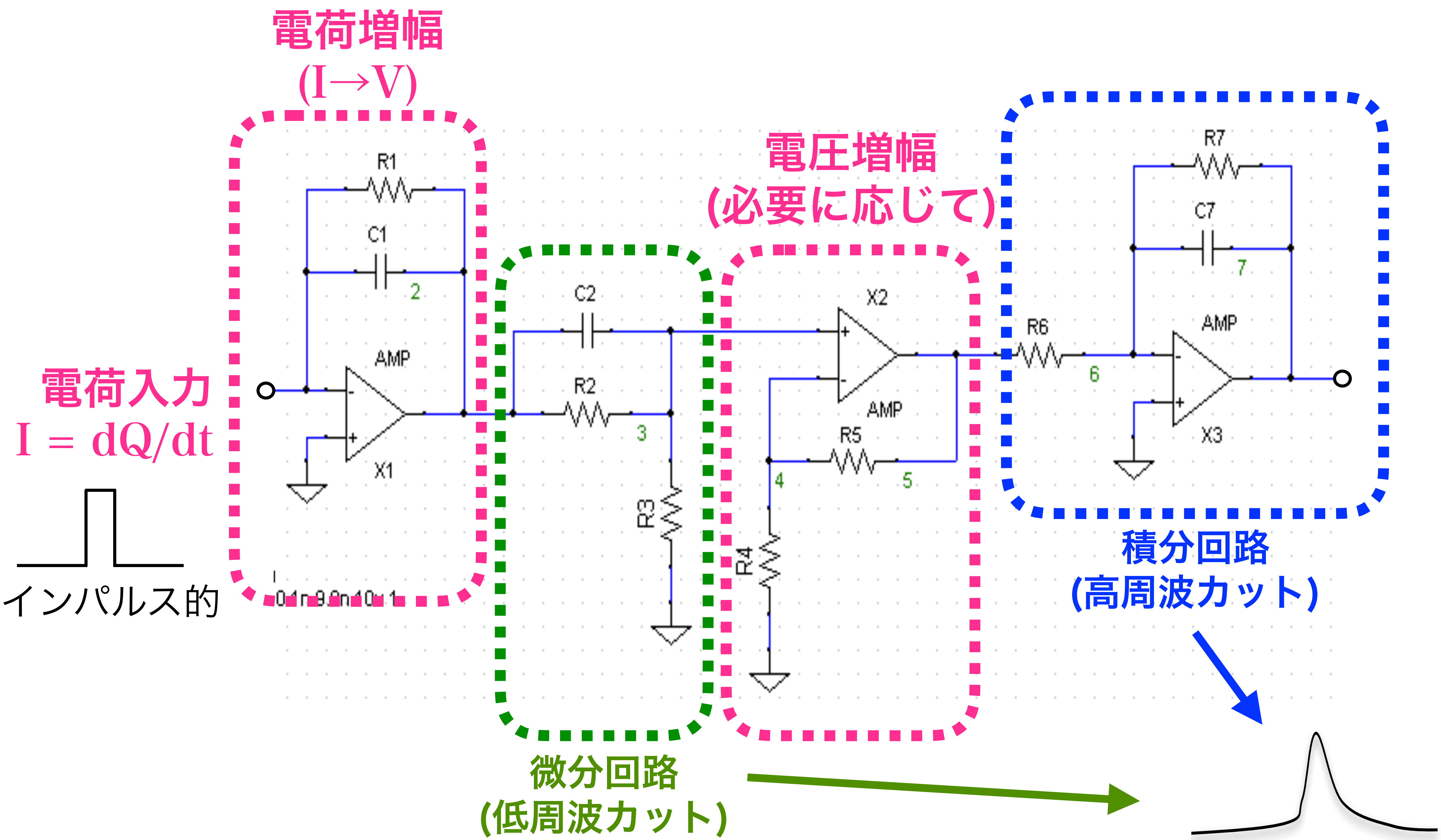
検出器読み出しシステム (一般論)

- 検出器信号はアナログ（多くの場合、電荷信号）
- 信号劣化を防ぐため、検出器にできるだけ近い所にアナログフロントエンド
- アナログ回路で適切な信号整形を行った後、A/D変換
- デジタル回路でData Reduction等の信号処理（トリガーとのやり取り）
- 光リンク等でコンピュータ、ストレージに送る
- ここでは★について解説



フロントエンド回路の役割

回路の議論はここではしないとして、何をやってるかだけ簡潔に・・。



- 一定の波形に整形
- 低周波・高周波ノイズをカット

検出器周りのノイズ

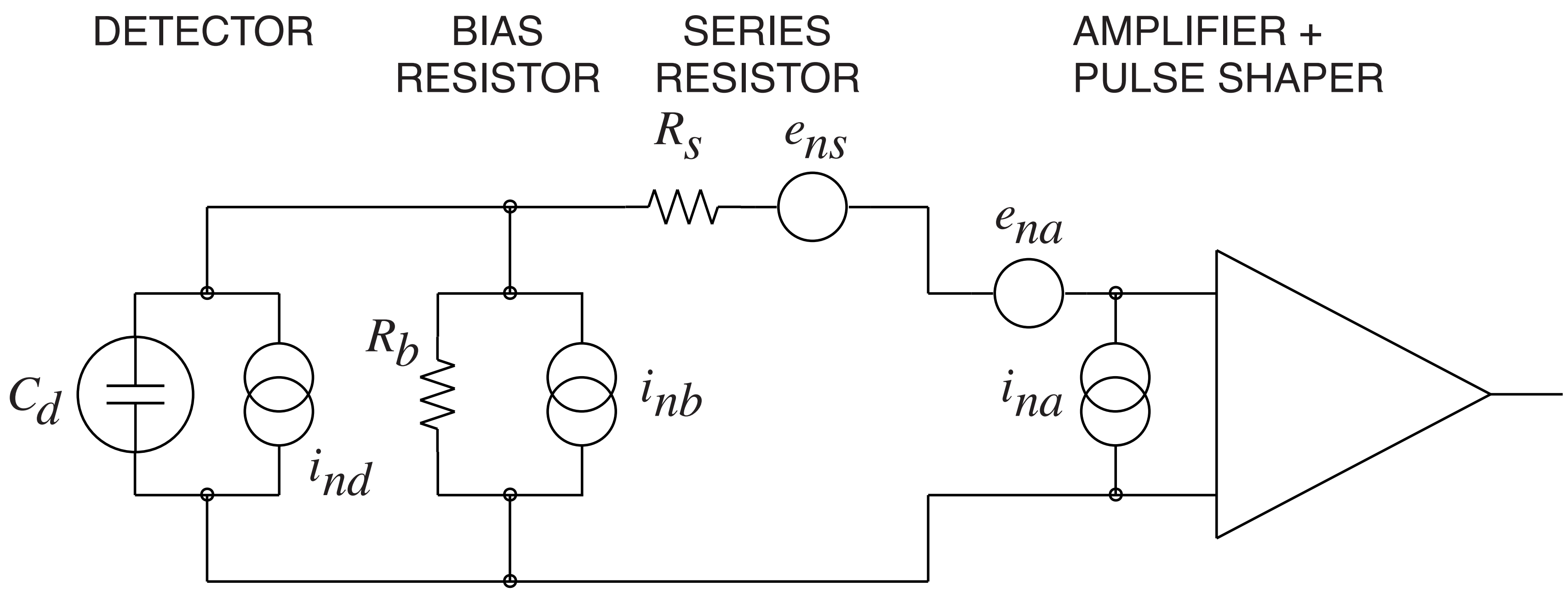


Figure 34.19: Equivalent circuit for noise analysis.

- 多くの検出器は容量(C_d)で記述できる。
- 検出器での電荷ゆらぎ（ショットノイズ）は電流源(i_{nd})で記述できる。
- 直列/並列抵抗成分は、電圧源(e_{ns})、電流源(i_{nb})で記述できる。
- アンプのノイズ(e_{na}, i_{na})も考慮。

要は電圧性のノイズと電流性のノイズに分類される。

Detector Noise and Shaping Time

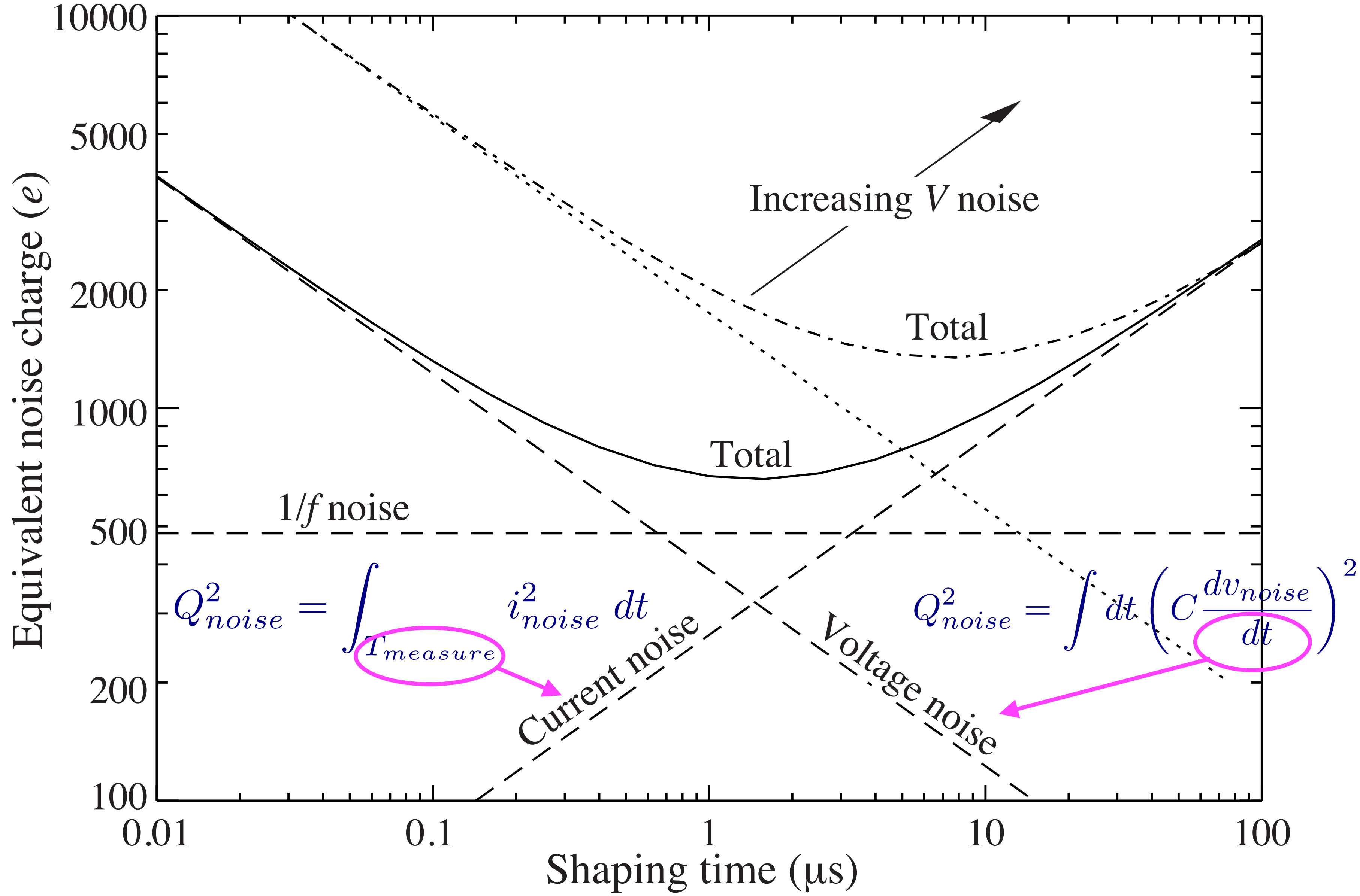
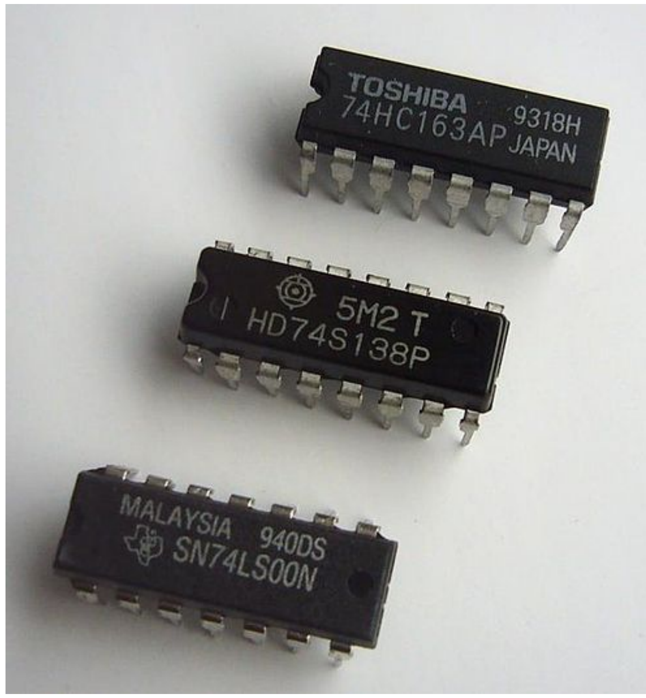


Figure 34.20: Equivalent noise charge *vs* shaping time. Changing the voltage or current noise contribution shifts the noise minimum. Increased voltage noise is shown as an example.

- 残留する電流性ノイズと電圧性ノイズは、Shaping Time (パルス波形の減衰時定数) に対して逆特性となることに注目。
- 例えば、電圧性ノイズが増えると、最適なShaping Timeは増加。

Digital Circuit — FPGA



https://ja.wikipedia.org/wiki/汎用ロジックIC

https://ph.rs-online.com/web/p/fpgas/0134093/

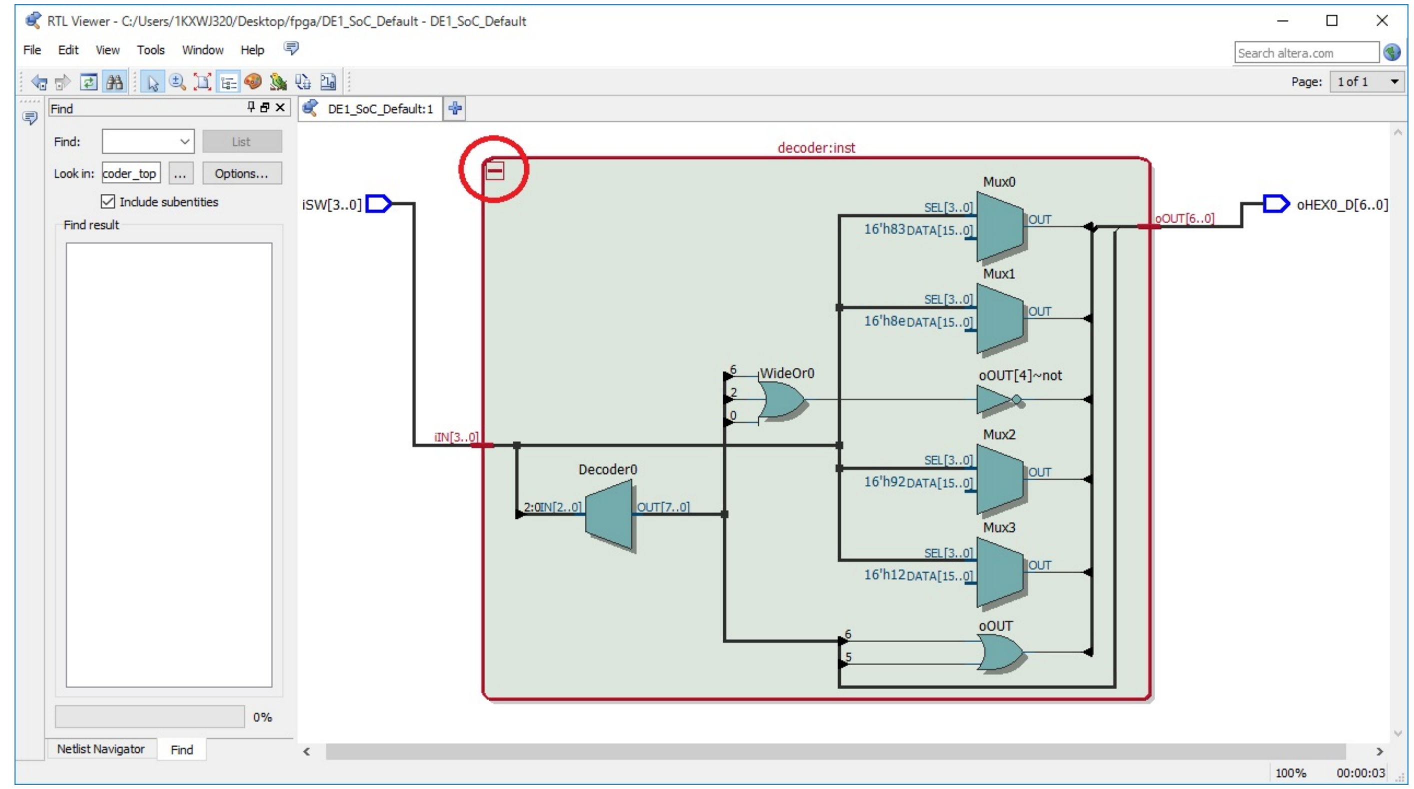
- 現在では、FPGA (Field Programmable Gate Array) を用いたデジタル回路開発が主流。
- PCで設計したデジタル回路をFPGAにダウンロードすると、FPGA内のスイッチが切り替わり、所望の回路がチップ内に構成される。何回でも書き換えられる。

Takahiro Fusayasu
ILC Summer Camp 2019

Digital Circuit — FPGA

```vhdl
--  counter_10.vhd

library IEEE;
use IEEE.std_logic_1164.all;
use IEEE.std_logic_unsigned.all;

entity counter_10 is
    port
    (
        CLK   : in  std_logic;
        Q     : out std_logic_vector(3 downto 0)
    );
end counter_10;

architecture RTL of counter_10 is
signal COUNT : std_logic_vector(3 downto 0);

begin
    process(CLK)
    begin
        if (CLK'event and CLK = '1') then
            if(COUNT = "1001") then
                COUNT <= "0000";
            else
                COUNT <= COUNT + 1;
            end if;
        end if;
    end process;
    Q <= COUNT;
end RTL;
```

http://www7b.biglobe.ne.jp/~yizawa/logic2/chap10/index.html



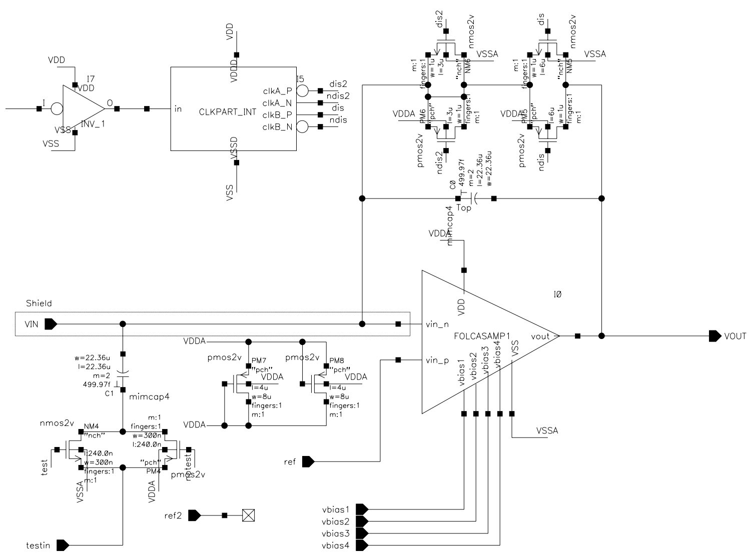
http://www.ee.tcu.ac.jp/lectures/fpga/Verilog_compile.html

- 現在ではHDL (ハードウェア記述言語) でコードを記述。
  →コンパイルしてトランジスタレベルに落とし込み、自動配置配線。
- FPGAで確認した後、フロントエンドASICに組み込む事もある。

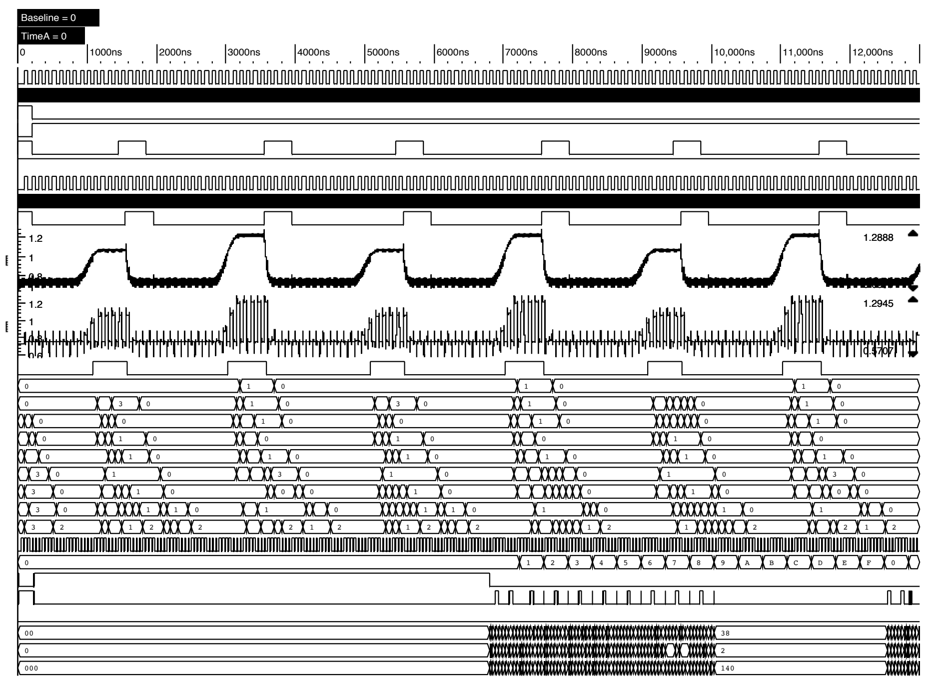
ASIC production

ASIC = Application Specific Integrated Circuit (特定用途向け集積回路)

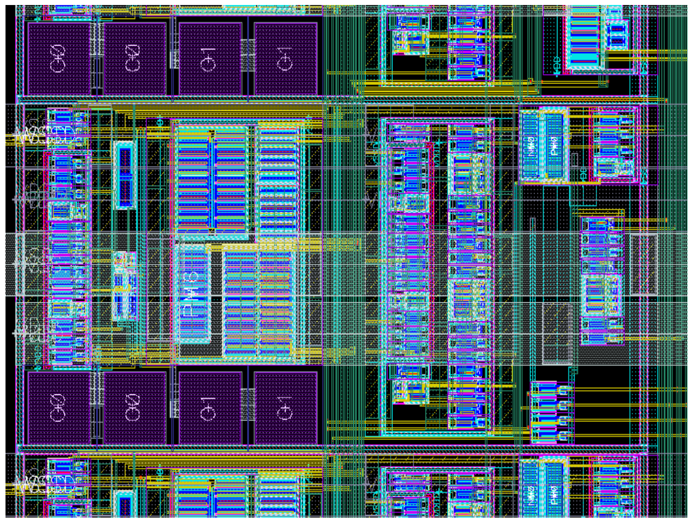
汎用の売り物ではなく、自分たちの用途向けに小規模に生産。



Circuit Design



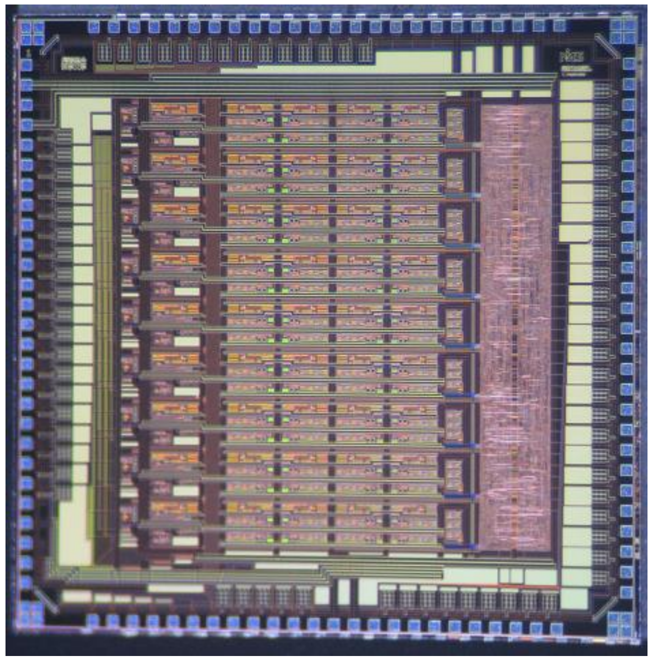
Simulation



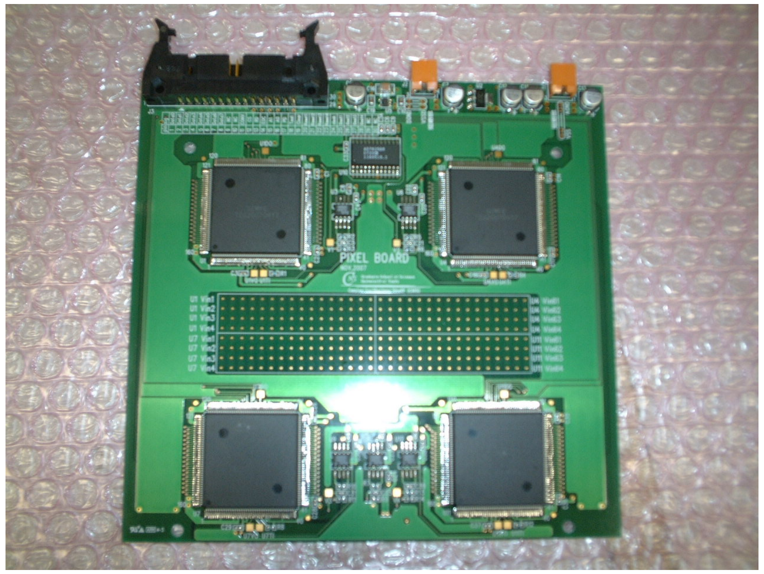
Layout Design

IBM tsmc UMC

Foundry



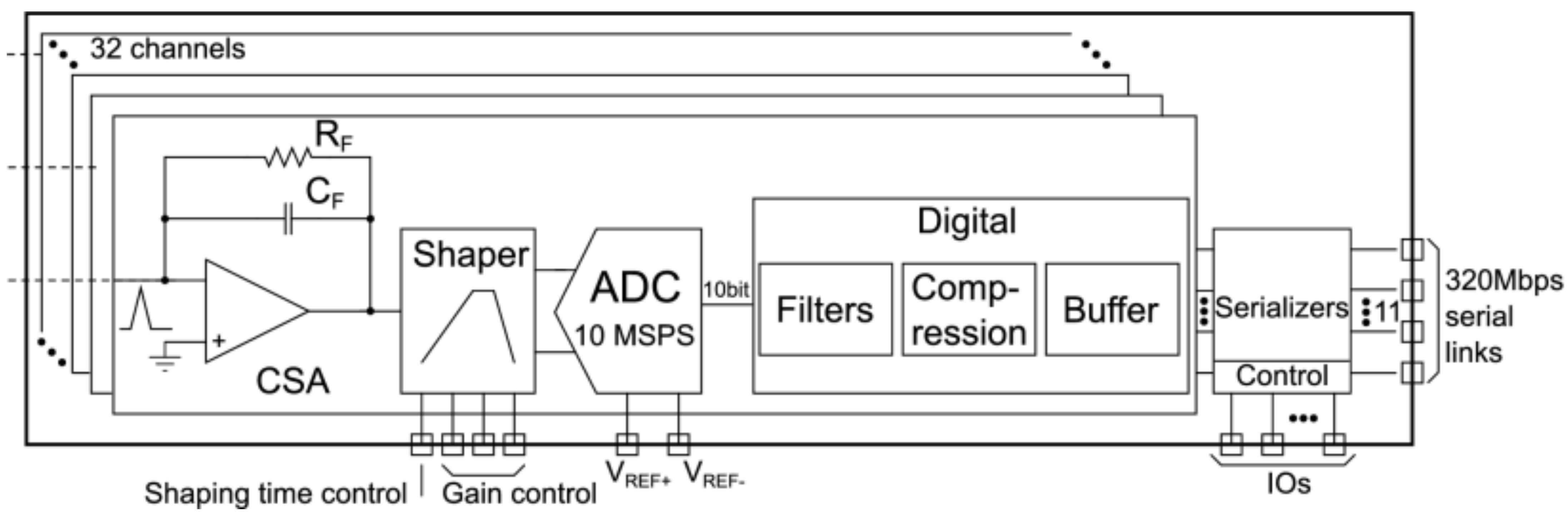
Delivery



Test

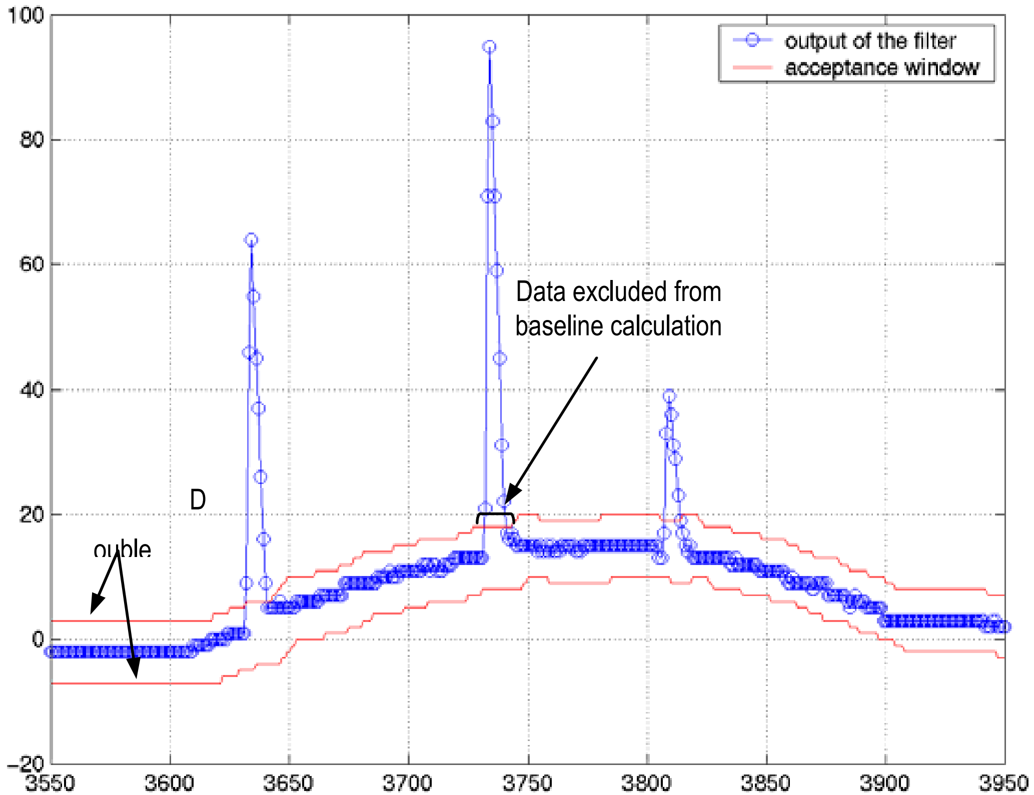
ASIC example — SAMPA

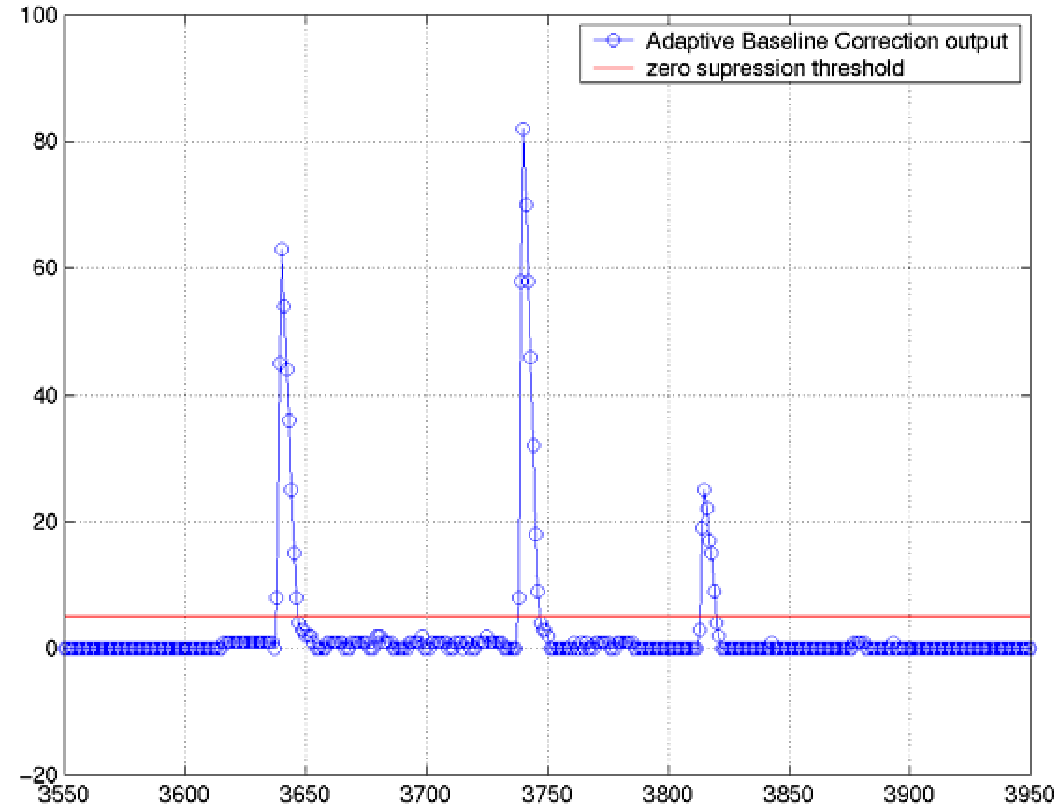
- 原型はLHC/ALICE重イオン実験でTPC検出器向けに開発された PASA (Pre-Amplifier and Shaping Amplifier) アナログチップと、ALTROチップ (A/D変換 + デジタル回路)。
- ALTROはデッドタイムによるロスが大きかった。
- ALICE-TPCの連続読み出しのために、PASAとALTROを合体して高機能化したのがSAMPAチップ。
- なお、ILC TPC向けにも、PASA + ALTRO から S-ALTRO16が開発され、プロトタイプ試験の読み出しに使われている。



Takahiro Fusayasu

ASIC example — SAMPA



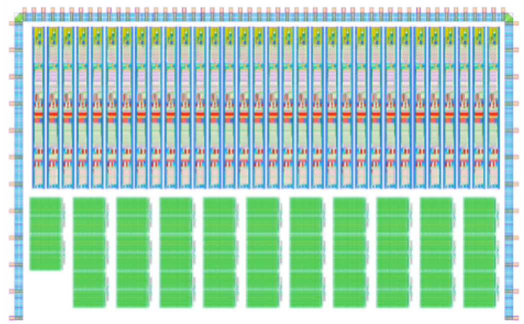


Digital Signal Processing
(Figures from S-ALTRO16 document)

- baseline correction
- overlap signal separation

SAMPA ASIC Specification

SAMPA ASIC



- ALICEの複数検出器共通 読み出しASIC
- 32 ch. charge sensitive preamplifiers with ADC
- programmable shaping time (80 to 300 ns) & charge sensitivity
- bipolar
- 10, 20 and now 5 MHz
- デッドタイム無し連続読み出しをサポート (320 Mbps x 10 serial links) to SERDES (GBT)
- トリガモードもサポート
- on chip DSP and Zero Suppression (他の検出器向け)
- 2018年2月大量生産スタート

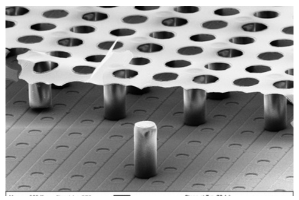
Specification	**TPC**	**MCH**
Voltage supply	1.25 V	1.25 V
Polarity	Negative	Positive
Detector capacitance (Cd)	18.5 pF	40 pF–80 pF
Peaking time (ts)	160 ns	300 ns
Shaping order	4th	4th
Equivalent Noise Charge (ENC)	< 600e@ts=160 ns*	< 950e @ Cd=40 pF* < 1600e @ Cd=80 pF*
Linear Range	100 fC or 67 fC	500 fC
Sensitivity	20 mV/fC or 30 mV/fC	4 mV/fC
Non-Linearity (CSA + Shaper)	< 1%	< 1%
Crosstalk	< 0.3%@ts=160 ns	< 0.2%@ts=300 ns
ADC effective input range	2 Vpp	2 Vpp
ADC resolution	10-bit	10-bit
Sampling Frequency	10 (20) Msamples/s	10 Msamples/s
INL (ADC)	<0.65 LSB	<0.65 LSB
DNL (ADC)	<0.6 LSB	<0.6 LSB
ENOB (ADC)**	> 9.2-bit	> 9.2-bit
Power consumption (per channel) CSA + Shaper + ADC	< 15 mW	< 15 mW
Channels per chip	32	32

*: R_{esd} = 70Ω
**: @ 0.5MHz, 10Msamples/s

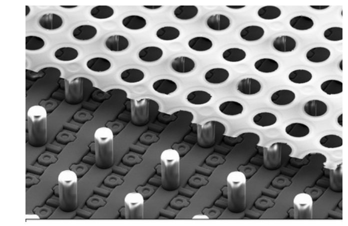
S.H.I. Barboza et.al, 2016 JINST 11 C02088.

Slide by Ken Oyama, 7/Feb/2018, at Nagasaki Inst. of Ap[l. Sci.

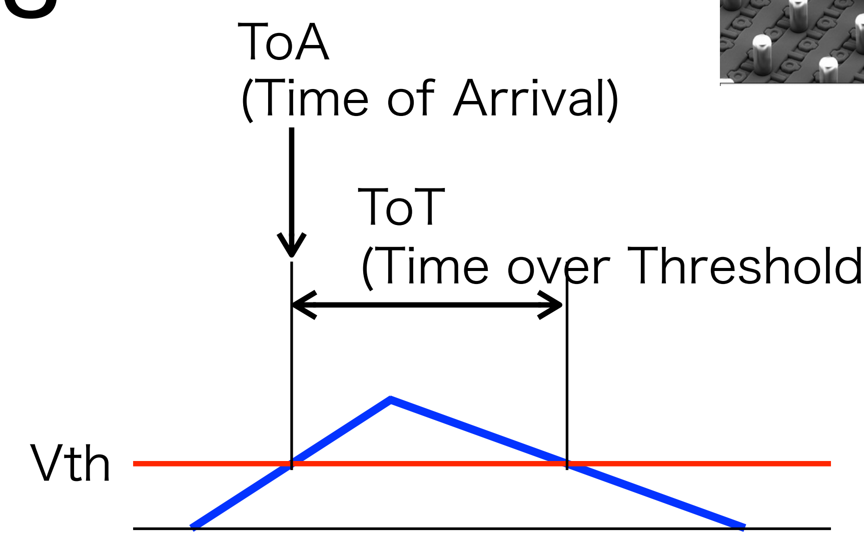
ASIC example — Timepix3



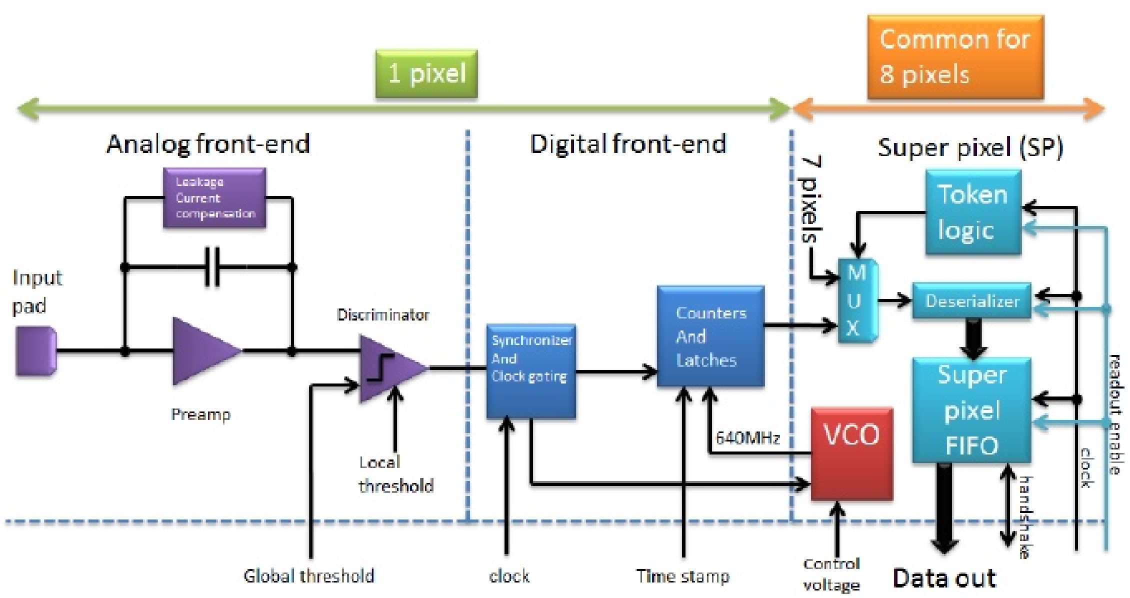
Timepix3

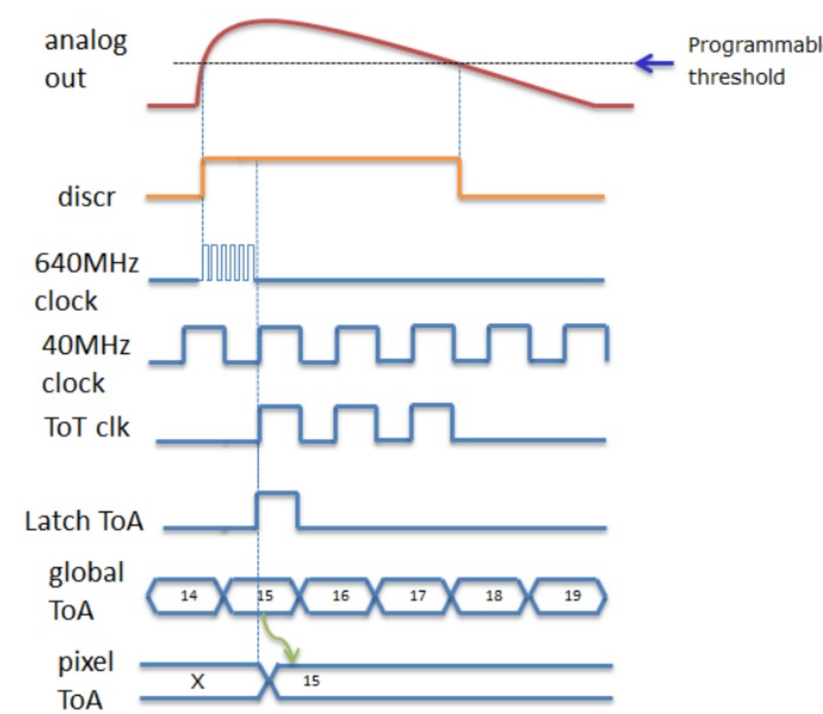


CMOS technology	130 nm, 8-metal stack
Pixels	256 × 256
Pixel size	55 × 55 μm^2
Acquisition modes	Charge and time Time only Event counting and integral charge
Zero suppressed readout	YES
Dead time per pixel	ToT Pulse time + 475 ns
Timing resolution	1.5625 ns (640 MHz)
On-chip power pulsing	YES
Output bandwidth	Up to 5.12 Gbps (8 × 640 Mbps)
I/O	SLVS, 8b/10b, 8 output links for data



※ToA/ToT同時計測が可能





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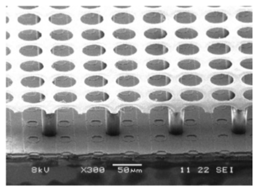
J. Kaminski
MPGD2017

Candidate of pixel readout TPC

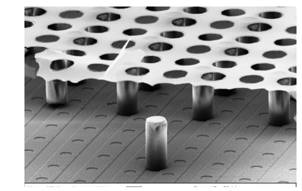
ASIC example — Timepix3

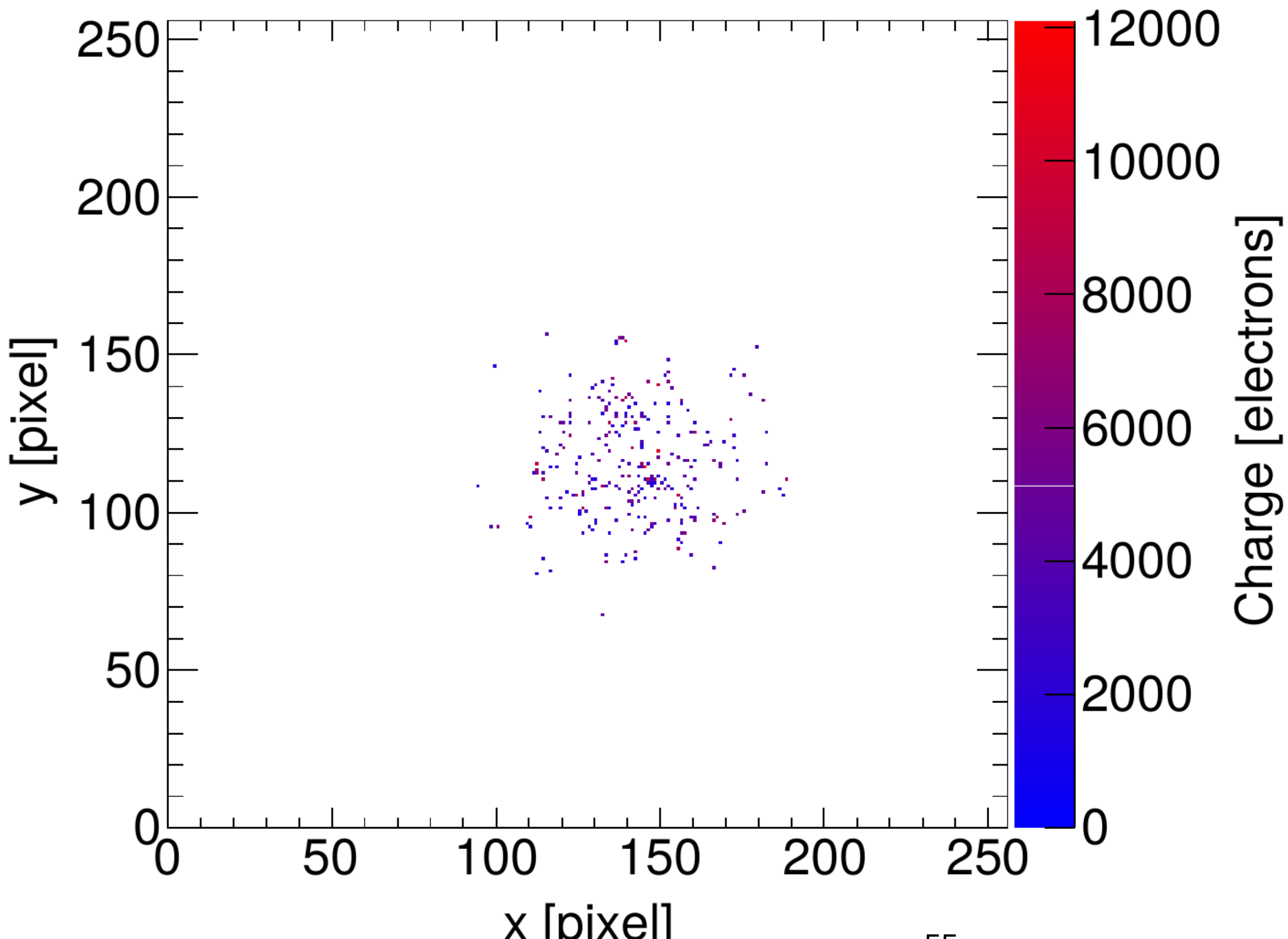
イオン化電子ごとのヒット情報を高効率に再構成

単電子毎の検出例



1 Event





^{55}Fe decay: 5.9 keV photon
→ ~225 electrons

universitätbonn

J. Kaminski
Instrumentation Seminar
15. April 2016, DESY

OpenIt introduction

ログイン

サイトを検索 検索
現在のセクション内のみ

Open Source Consortium of Instrumentation(osc)

ホーム | About Open-It | Technologies | R&D Project | Education | Workshop | F.A.Q. | For Members

ナビゲーション
- About Open-It
- Technologies
- R&D Project
- Education
  - 若手の会
  - 不定期開催セミナー情報
  - VPN及びネットワーク接続について
  - コンソーシアム拠点リスト
  - Intro_Verilog-HDL
- Workshop
- F.A.Q.
- For Members

"openit.kek.jp"を新規タブで開く

現在位置: ホーム / Education

Education

Upcoming seminar

JFY 2019

- FPGA training course 2019/9/10~11 @NIFS(National Institute for Fusion Science)
- ASIC training course 2019/25~27 @Tohoku Univ.
- DAQ-Middleware training course 2019/9/25 - 27 @KEK Tsukuba campus
- FPGA training course 2019/10/24~25 @NiAS(Nagasaki Institute of Applied Science)

開催日は変更される可能性があります。

開催が確定した時点で告知ページへのリンクを張ります。遅くとも開催一か月前に告知ページを開設します。

セミナーやトレーニングコースを主催していただける方を募集しています。
詳細はメールでosc-mgrs#ml.post.kek.jp(#は@へ書き換えてください）までお問い合わせください。

Meeting for young researchers

Meeting for young researchers is a place to interaction among young researchers. Share information with mailing lists and workshops.
This meeting can participate non-members of Open-It. For details, please refer to the following link.

- FPGA training course 2019/9/10~11 @
- ASIC training course 2019/25~27 @
- DAQ-Middleware training course 201
- FPGA training course 2019/10/24~25

※Electronics DAQ seminar in July every year

※DAQ = Data AcQuisition

Summary

1. Detector basics

   Charged particle dE/dx, photon interactions,
   EM and hadronic showers, radiation length, sampling calorimeter

2. ILC detectors

   SiD/ILD, PFA, ILD CAL/Vertex/TPC

3. Detector electronics

   Frontend electronics functions and noise, FPGA, ASIC examples