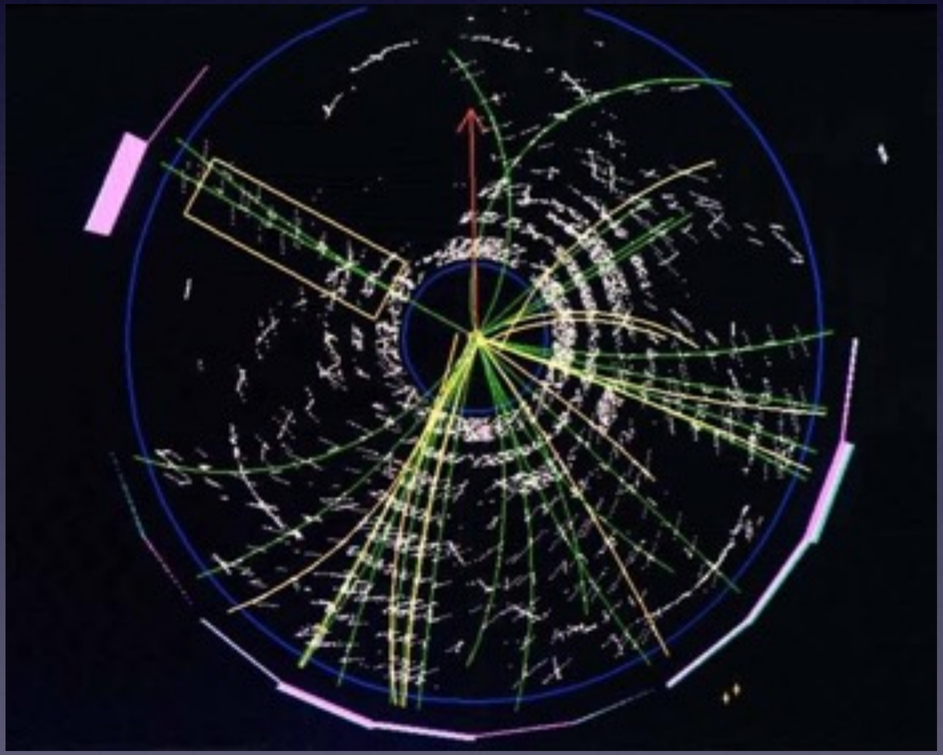
粒子物理

第二节 粒子探测器



曹庆宏

北京大学物理学院

PDG综述：

1) Passage of particles through matter
2) Particle detector at Accelerators
3) Particle detector at Non-Accelerators

为什么研究粒子探测

粒子物理发展史不仅仅是理论物理的历史，同时也是实验物理（特别是对撞机和探测器技术）的发展史。

理论物理学家应该了解简单的实验，

1）可以判断实验学家工作的正确与否

2）可以建议实验检验方案

好的理论物理学家一定了解实验

爱因斯坦
海森堡
费米 (Fermi)
盖尔曼
费曼
。。。

温伯格
李政道
杨振宁
威特曼（Veltman）
威特 (Witten)
。。。

好的实验物理学家也应该了解理论

今日的探测器

希格斯粒子产生等稀有事例是难以寻找的。

需要更好的探测器、触发器和存储器来将残骸遗迹还原出真正的物理。

粒子探测器

目的：探测粒子并尽可能精确地测量粒子的属性

物理可观测量：

1）电荷　　2）磁矩

3）寿命　　4）速度、动量和能量

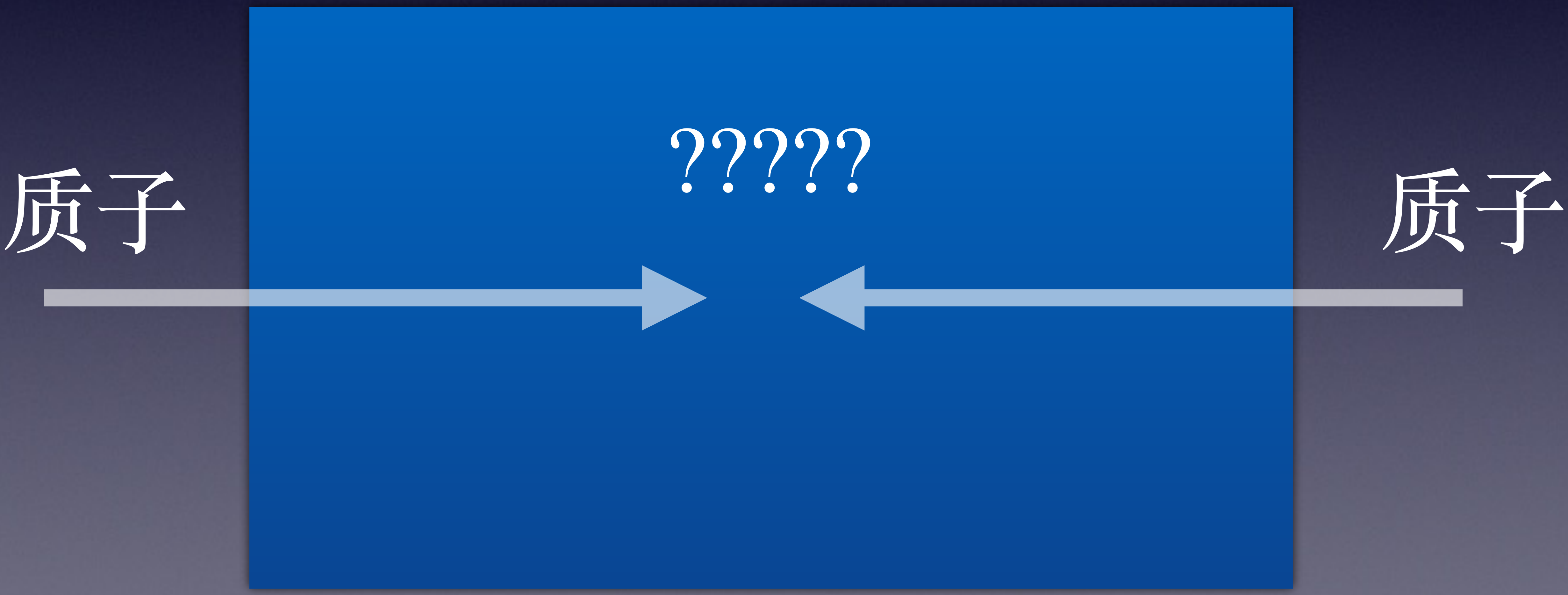
注意：质量不是直接观测量

$p = m\gamma\beta \qquad E = m\gamma \qquad m^2 = E^2 - p^2$

请设计一个探测器，可测量

1）电荷　　2）磁矩

3）寿命　　4）速度、动量和能量



质子

?????

质子

现代探测器

可探测的粒子要取决于粒子的寿命和相互作用

现代探测器可以探测6种“稳定”粒子：

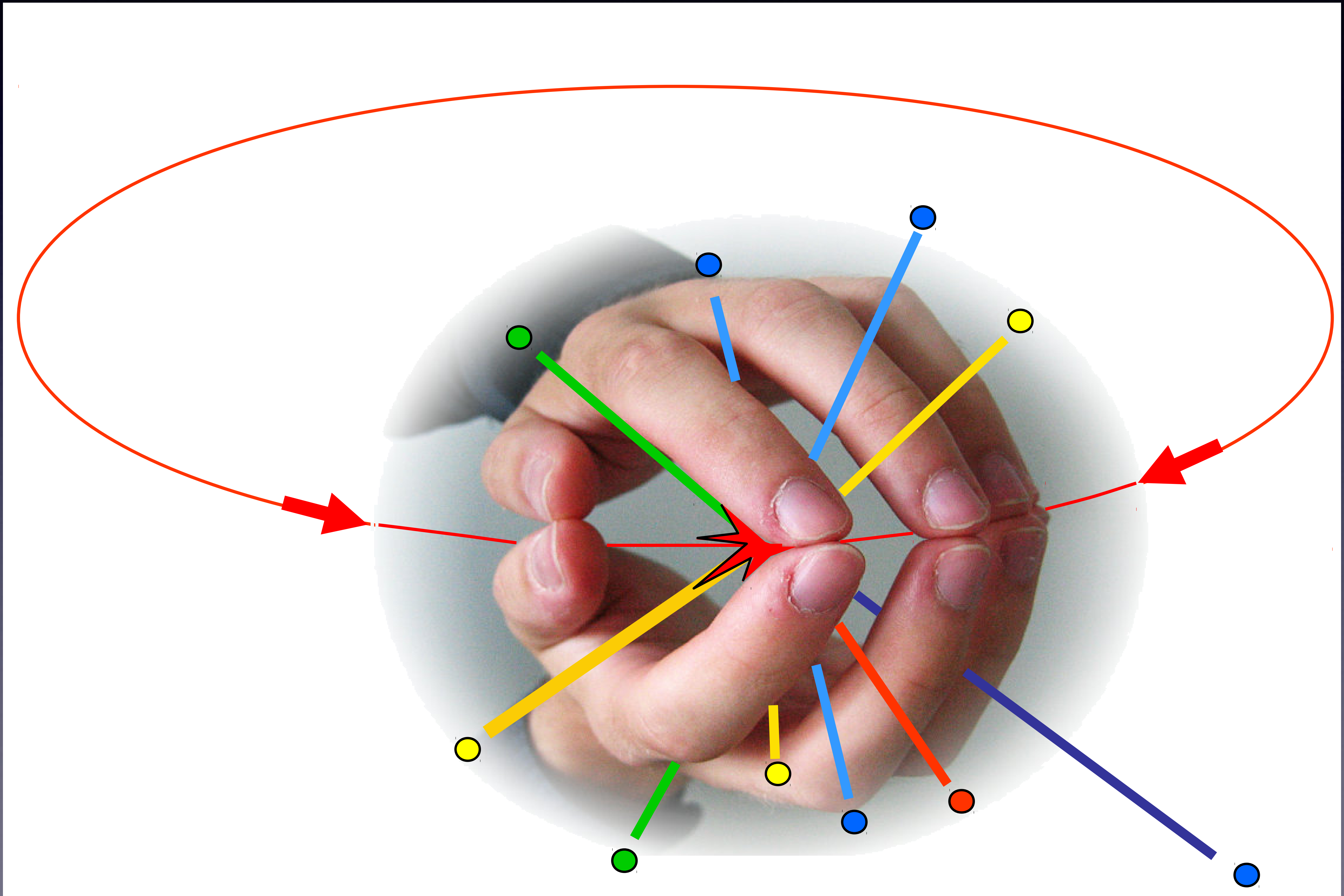
$$\gamma, e^{\pm}, p^{\pm}, \pi^{\pm}, n, \mu^{\pm}$$

和中微子 （表现为丢失能量或动量）

稳定：$\tau \geq 10^{-10} s$

大型强子对撞机

探测器围绕对撞点，探测次级粒子



设计探测器：妥协的艺术

理想的探测器：

1. 尽可能覆盖所有方位
   捕获所有粒子，没有漏洞或盲点
2. 尽可能提高精度
   分辨所有粒子，精确测量能量和动量
   可以分析每一次对撞（高速无遗漏）

现实测量的局限性：

1. 设备成本和实验技术的局限性
2. 辅助设备、电源线和信号线、冷却设备
3. 不可避免的辐射

加速器和对撞机

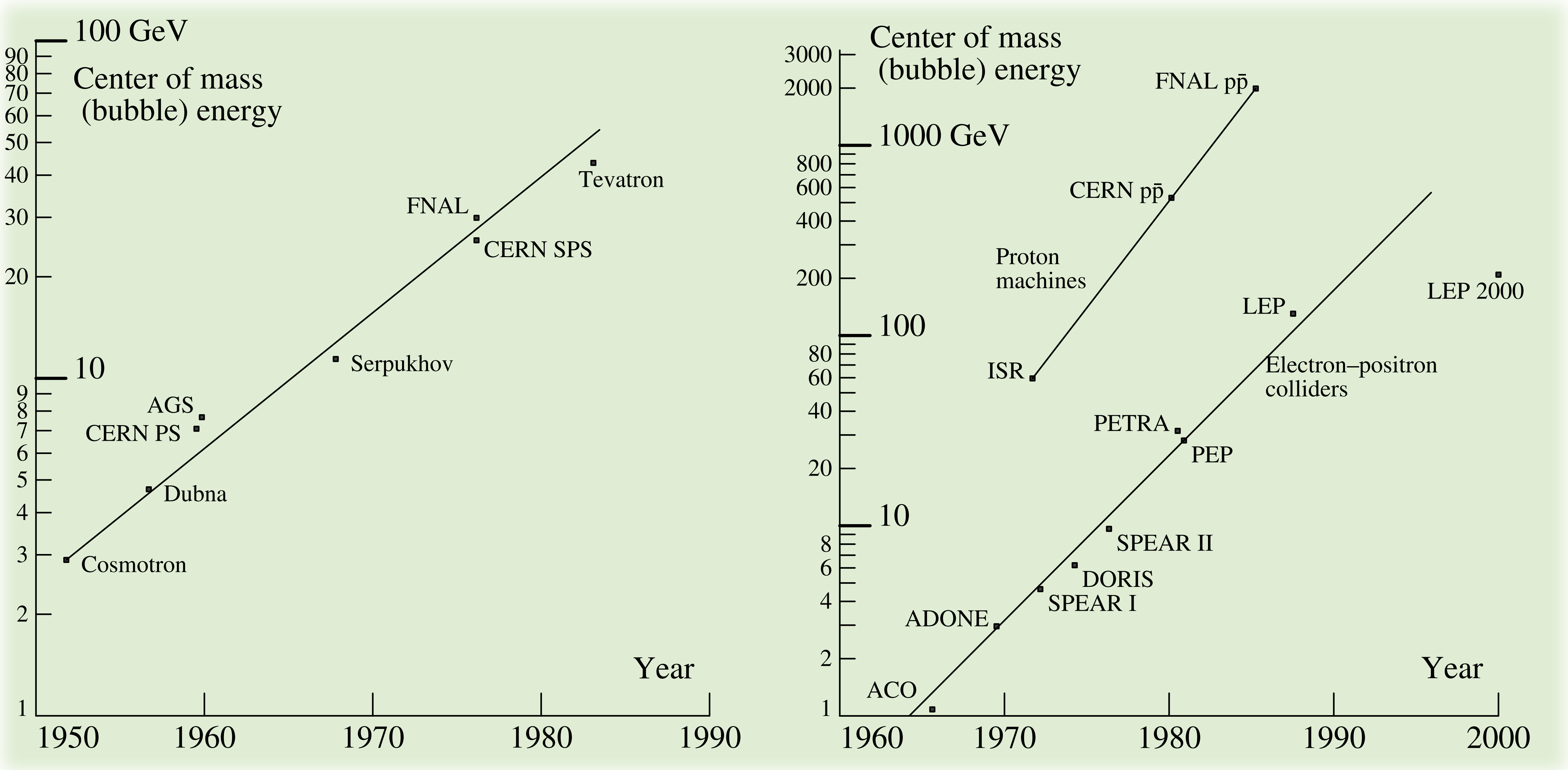
二战之后高能物理才成为一门公认的学科

（富人的游戏）

能量上限由机器的环半径和磁场强度决定

- 上世纪50年代，半径~10-20米（房子中）
- 上世纪60年代，半径~100米　（地下）
- 上世纪70年代，半径~1000米（地下）
- 上世纪80年代，半径~4000米（地下）

对撞机年表


100 GeV
Center of mass
(bubble) energy
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
Tevatron
FNAL
CERN SPS
Serpukhov
AGS
CERN PS
Dubna
Cosmotron
Year
1950
1960
1970
1980
1990
Center of mass
(bubble) energy
3000
2000
1000 GeV
800
600
400
200
100
80
60
40
20
10
8
6
4
2
1
FNAL pp̄
CERN pp̄
Proton
machines
ISR
LEP 2000
LEP
Electron–positron
colliders
PETRA
PEP
SPEAR II
DORIS
SPEAR I
ADONE
ACO
Year
1960
1970
1980
1990
2000

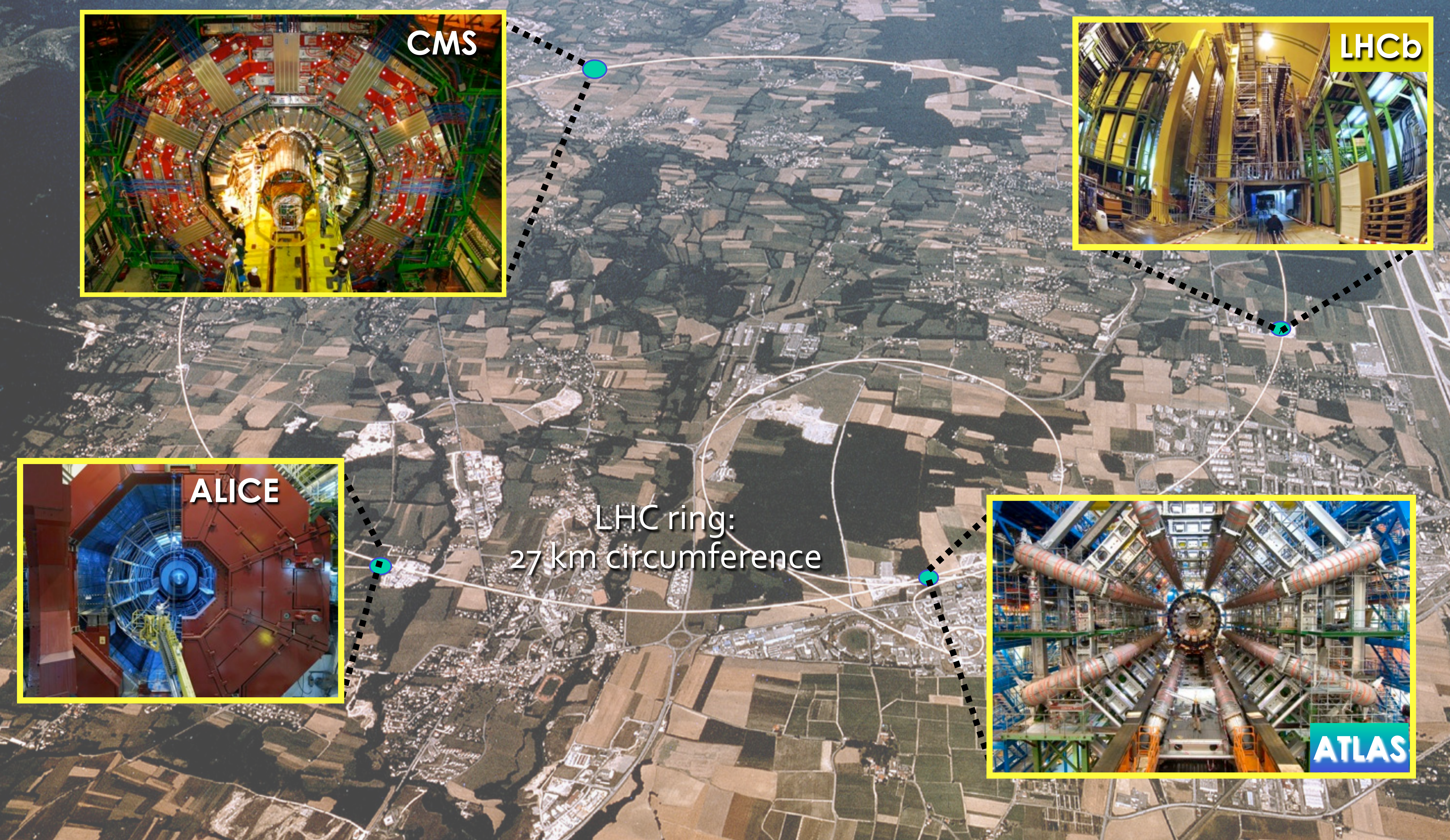
大型强子对撞机

质心系能量14TeV

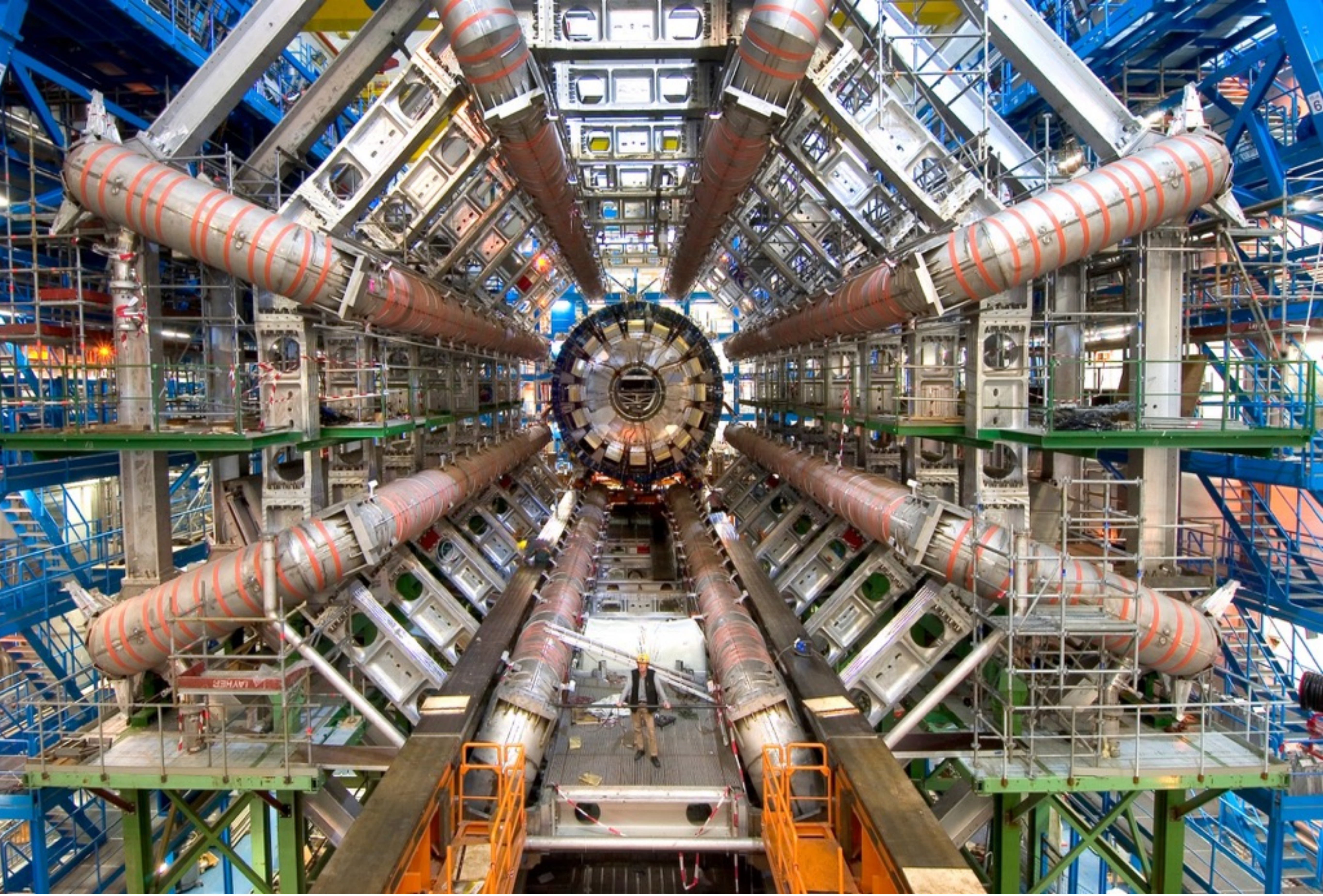
LHC ring:
27 km circumference

大型强子对撞机

质心系能量14TeV

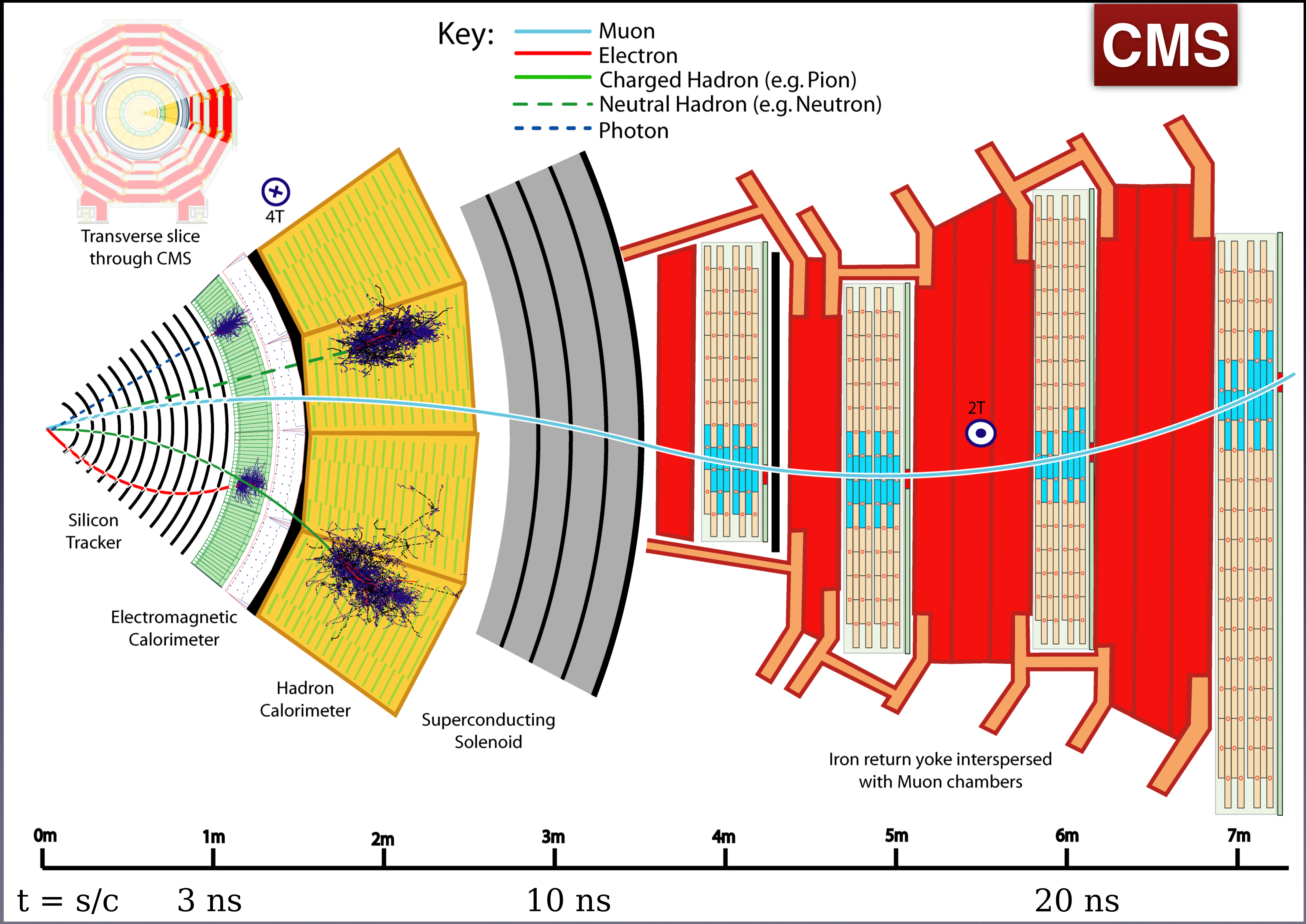


CMS： 长21米，高15米，宽15米，12.5千吨



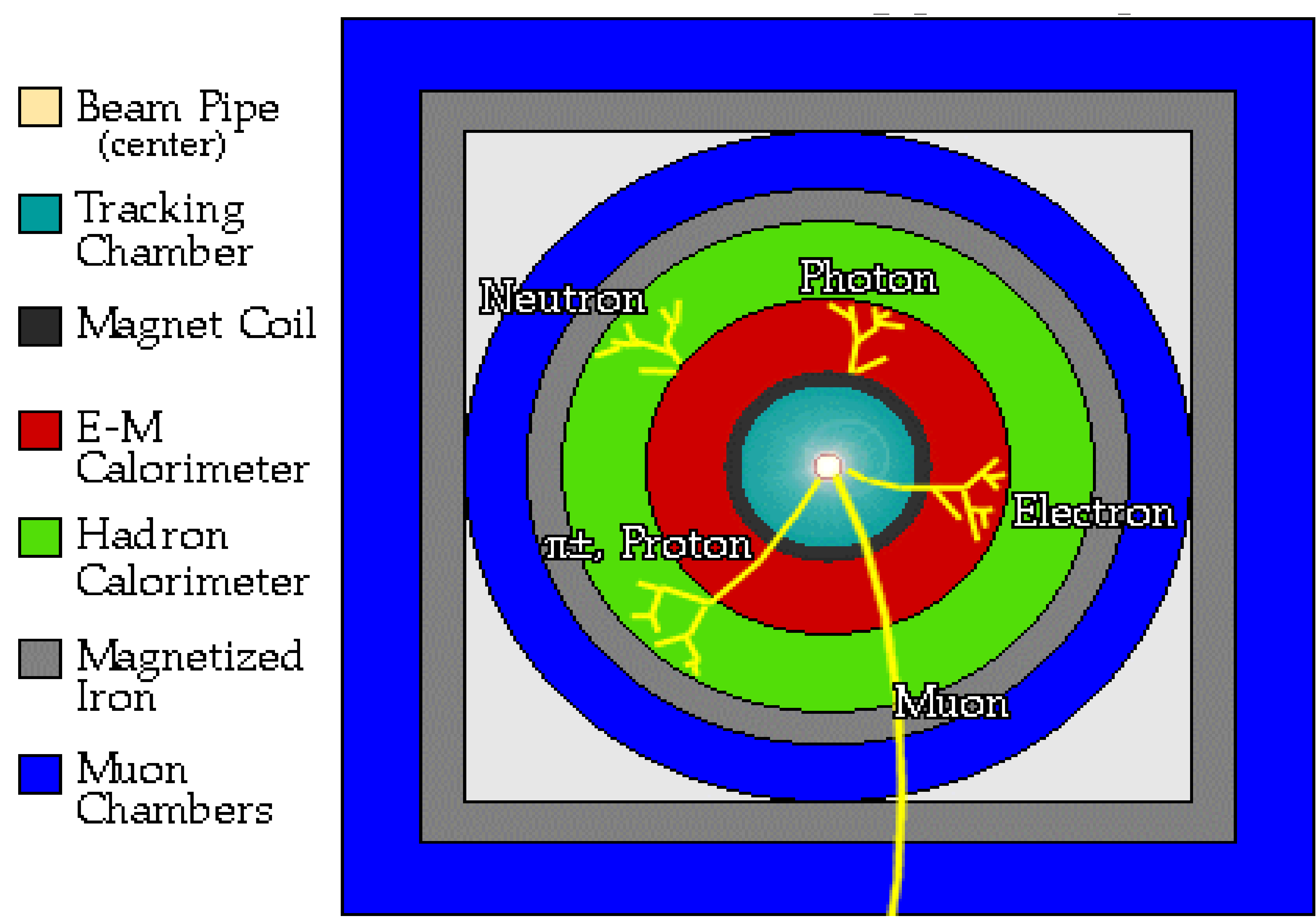
ATLAS： 长**46**米，高**25**米，宽**25**米，**7**千吨

现代探测器： 洋葱圈结构

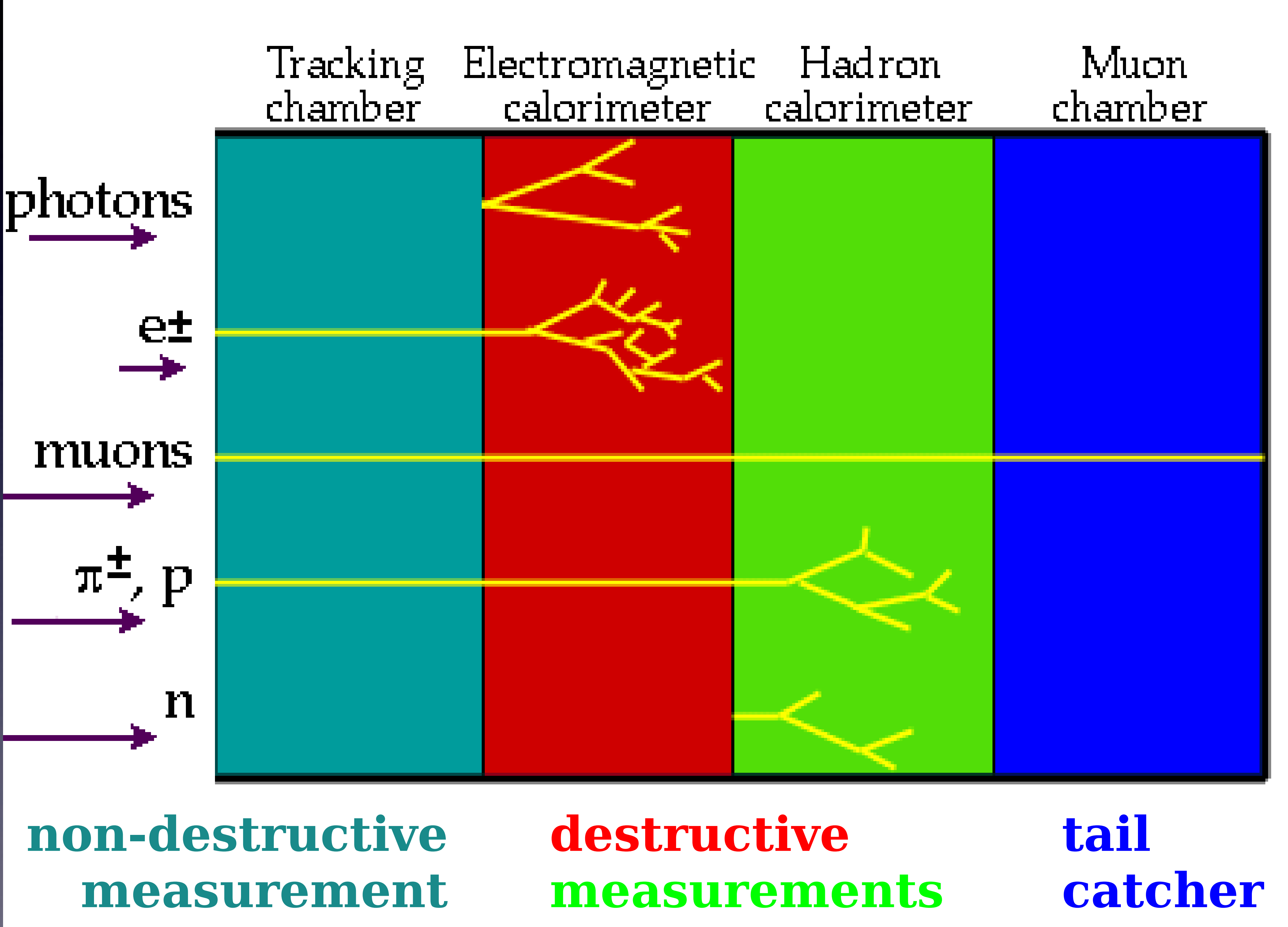

Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
CMS
Transverse slice through CMS
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0m
1m
2m
3m
4m
5m
6m
7m
t = s/c
3 ns
10 ns
20 ns

大型强子对撞机的探测器

在对撞点附近



剖面图


Tracking chamber
Electromagnetic calorimeter
Hadron calorimeter
Muon chamber
photons
e±
muons
π±, p
n
non-destructive measurement
destructive measurements
tail catcher

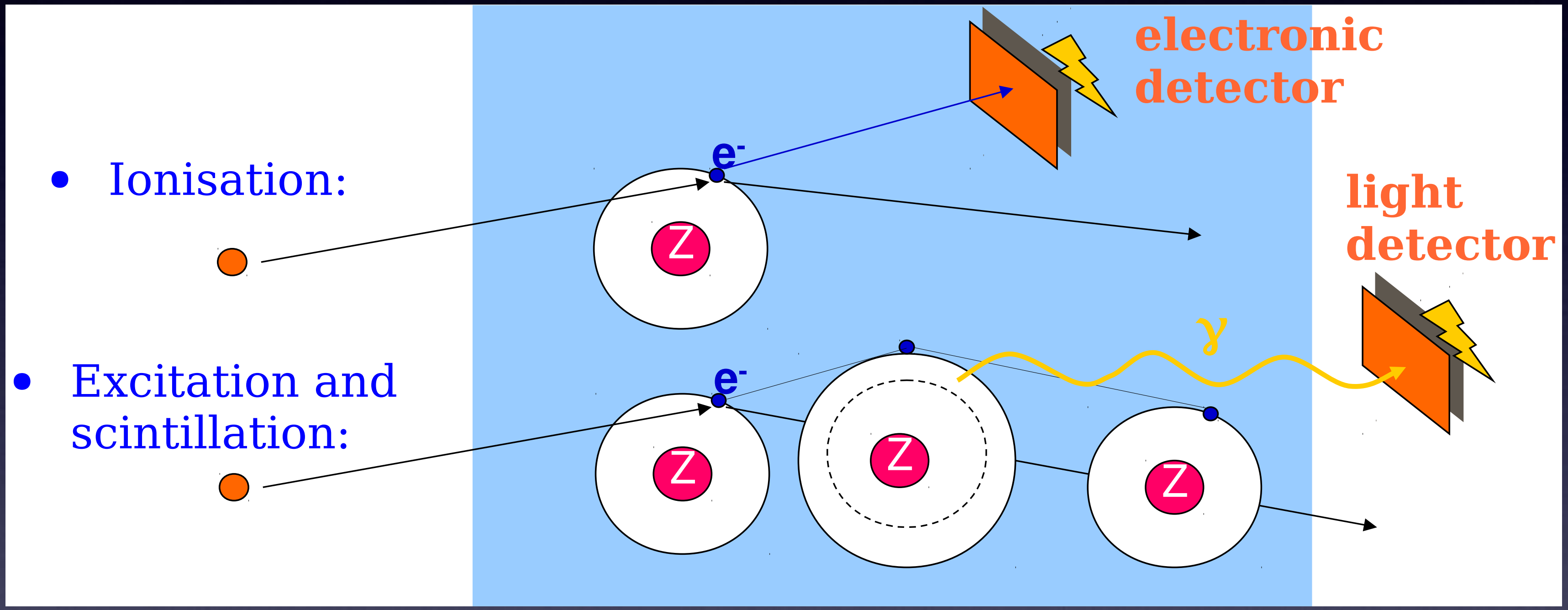
为什么这么摆放?

带电粒子如何通过探测物质

电中性粒子怎么测量?

测量原理

1. 粒子必须与探测物质发生相互作用
2. 此相互作用要能够被测量到



- Ionisation:
- Excitation and scintillation:

离子化过程可能会在物理上或化学上改变测量物质

云雾室、气泡室、感光乳剂

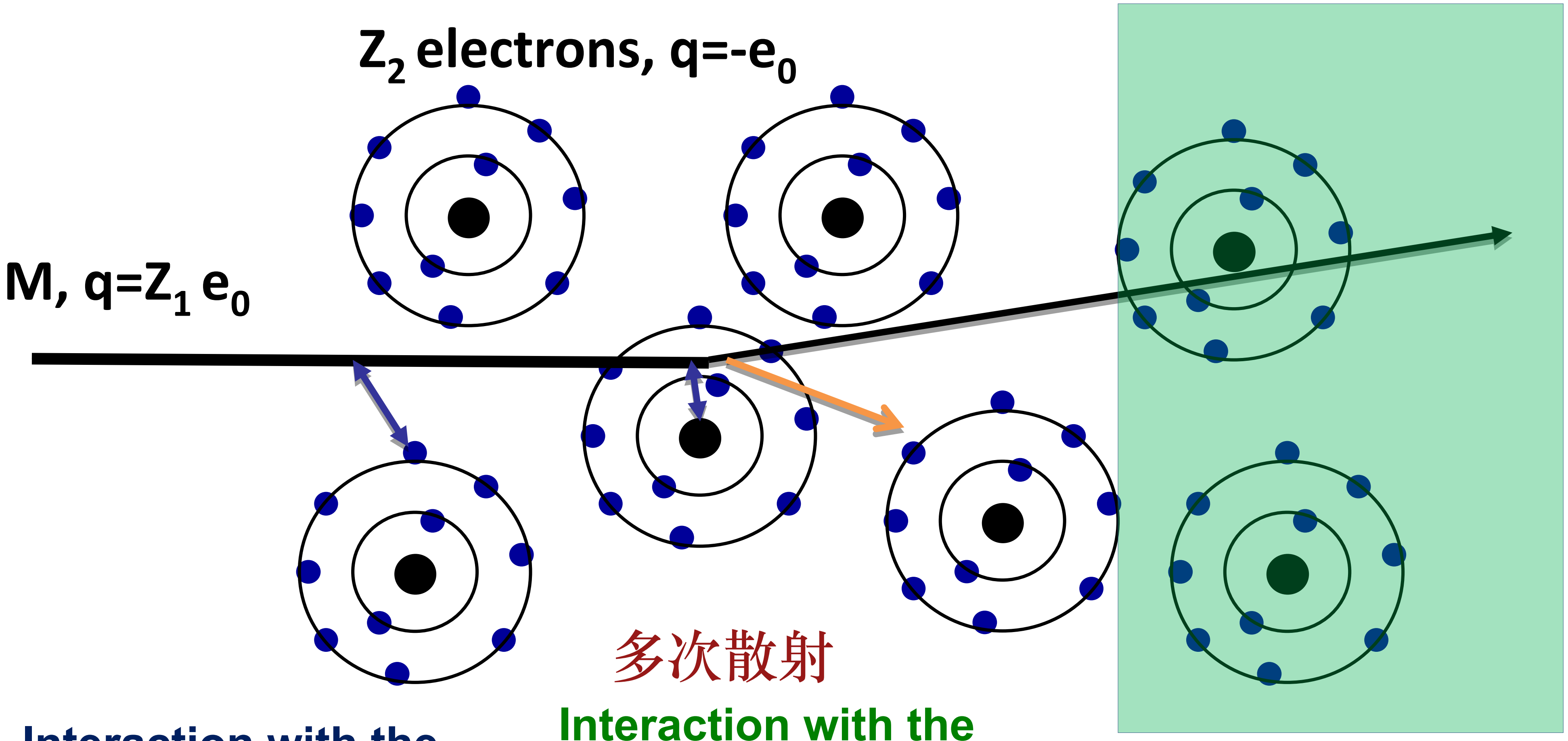
不可避免地是，待测量粒子性质也会被测量过程改变

能量损耗、运动方向改变

If you want to measure something…

it has to interact!

em-interaction of a charged particle



多次散射

离子化或激发

Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized
➔process used to produce measureable signals

Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted
➔ shower production

If the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation ➔ used to measure the energy of atmospheric showers by "Astrophysics Calorimeter"

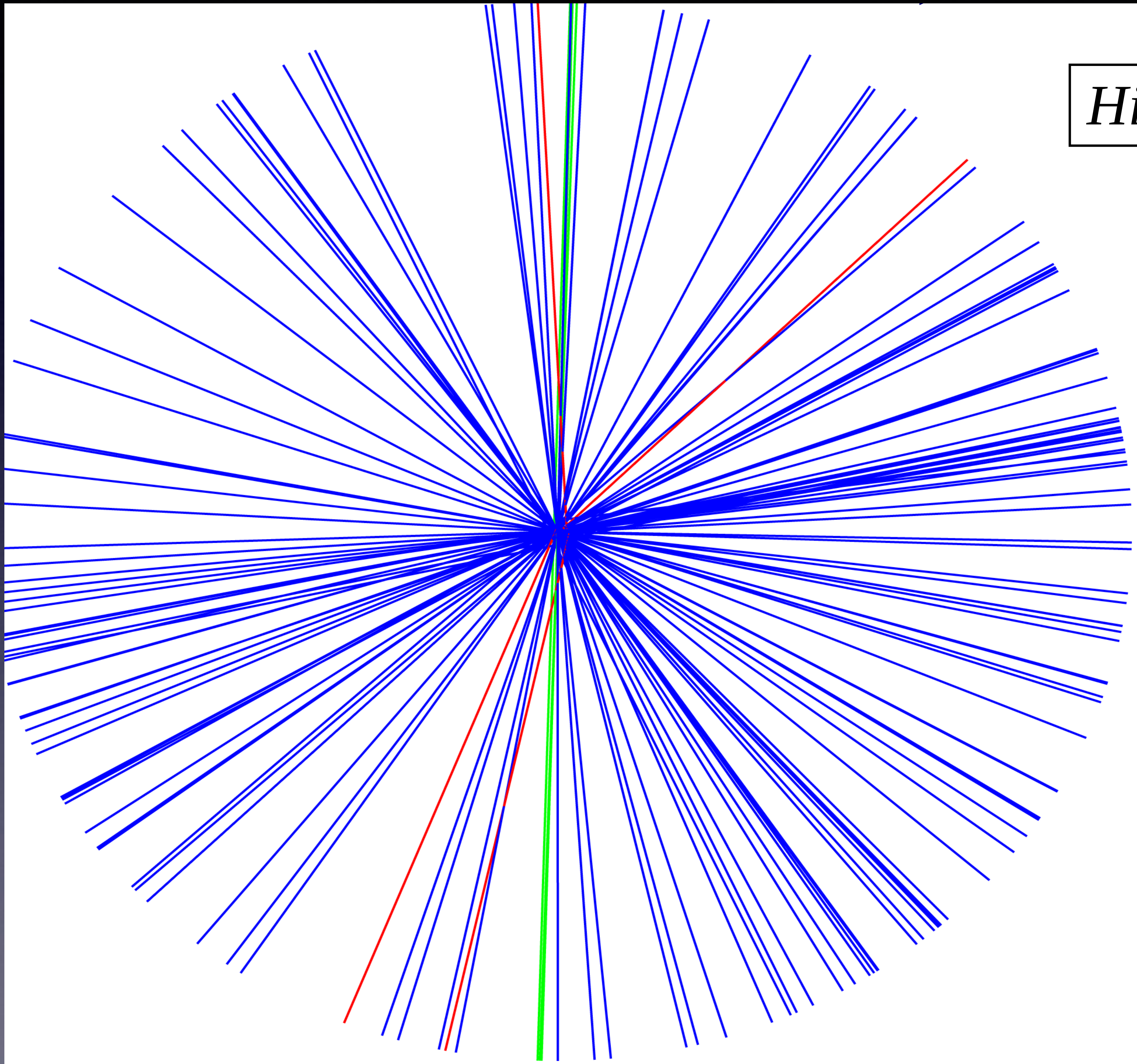
1）径迹探测器

(最内层的探测器)

电荷和动量

气体或硅探测器（离子化）测量带电粒子轨迹

示例：LHC上希格斯衰变



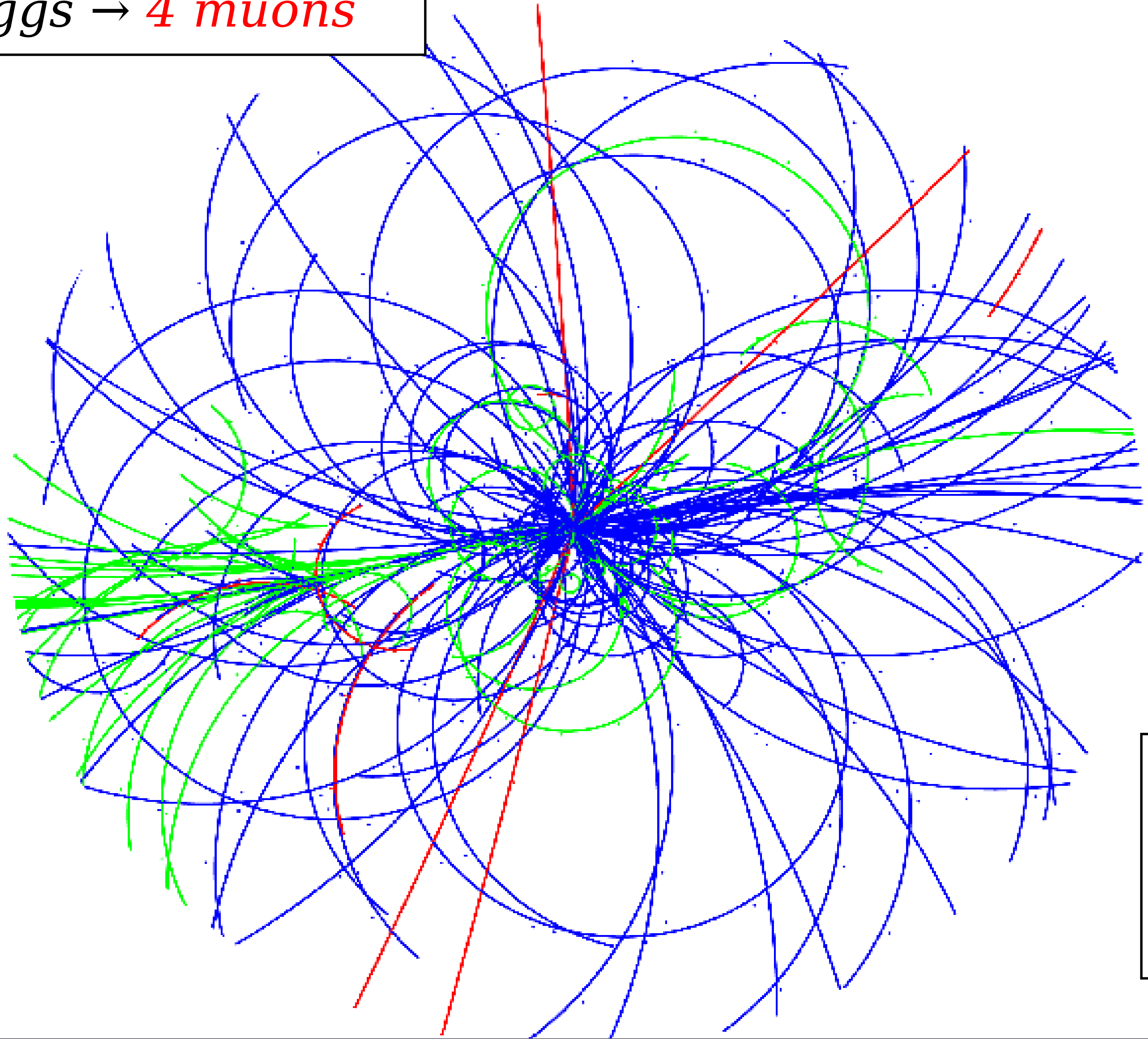
Higgs → 4 muons

Where are the muons?

Red lines show the muons (simulation!)

在探测器中心施加强磁场

Higgs → 4 muons

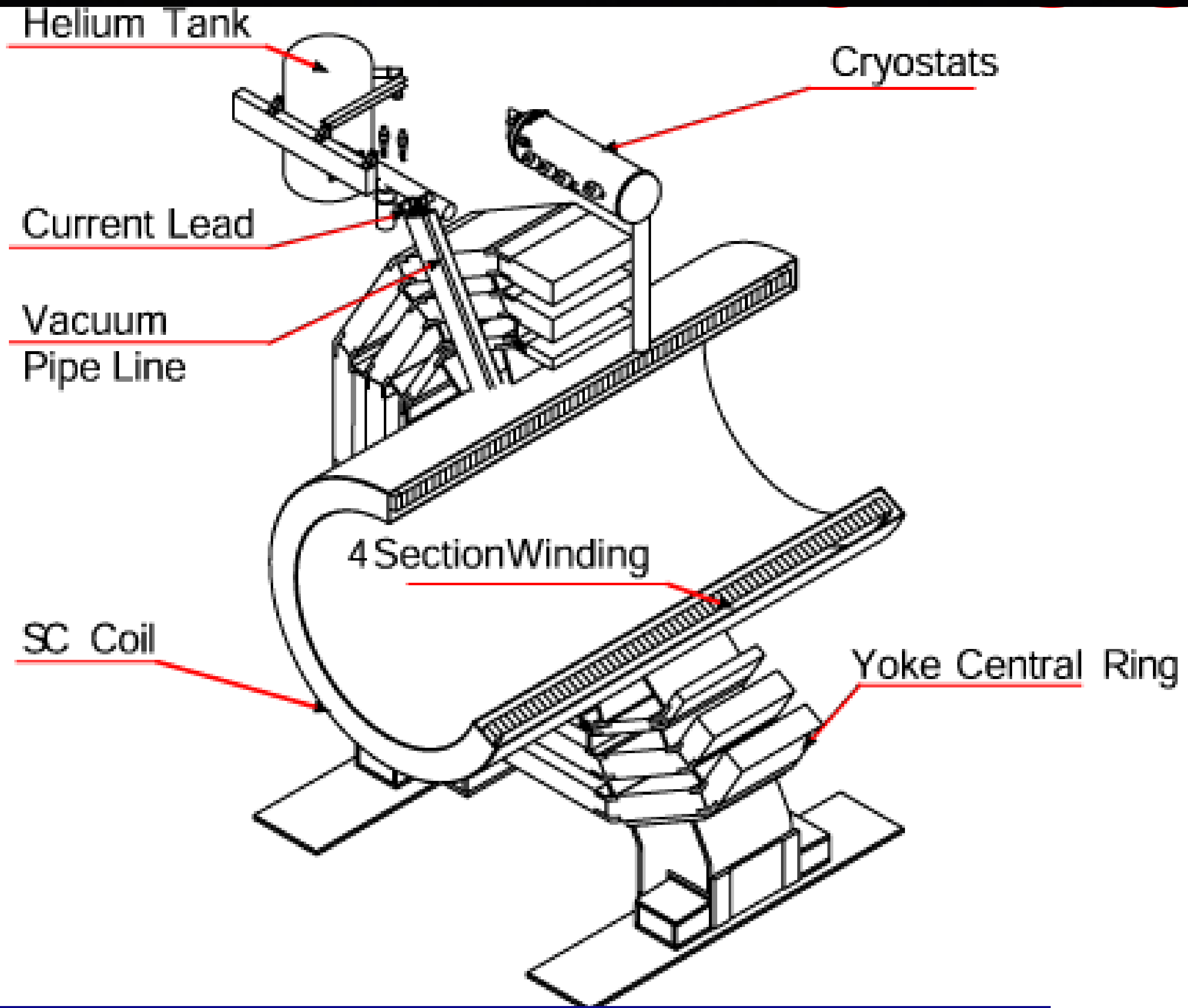


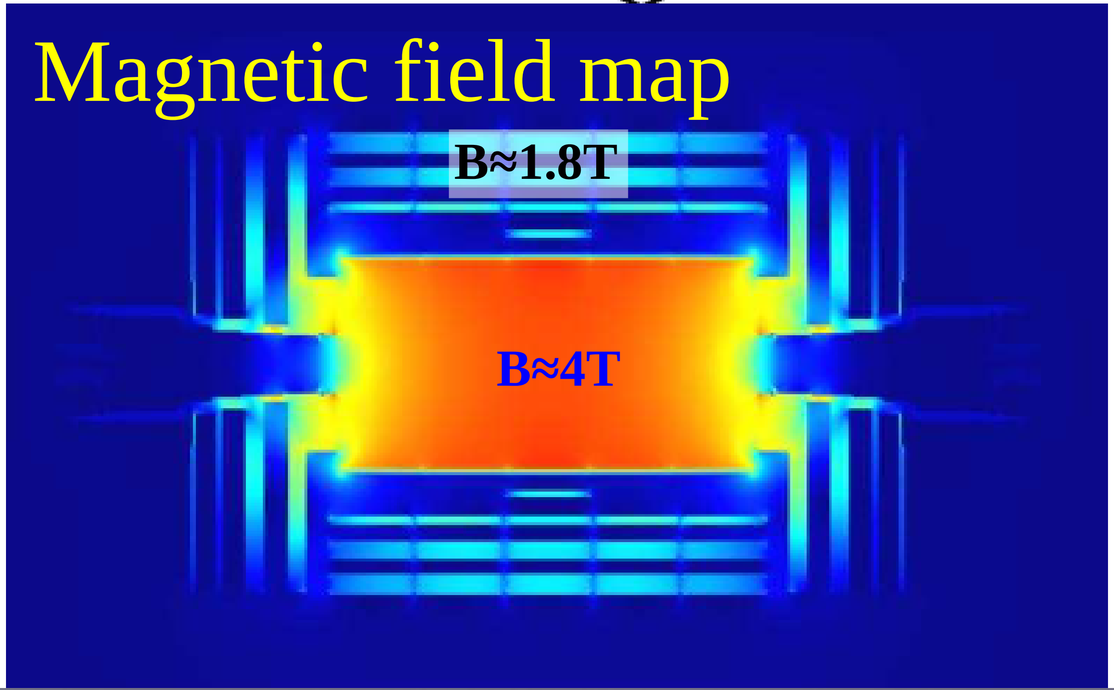
Charged particles bend in the magnetic field

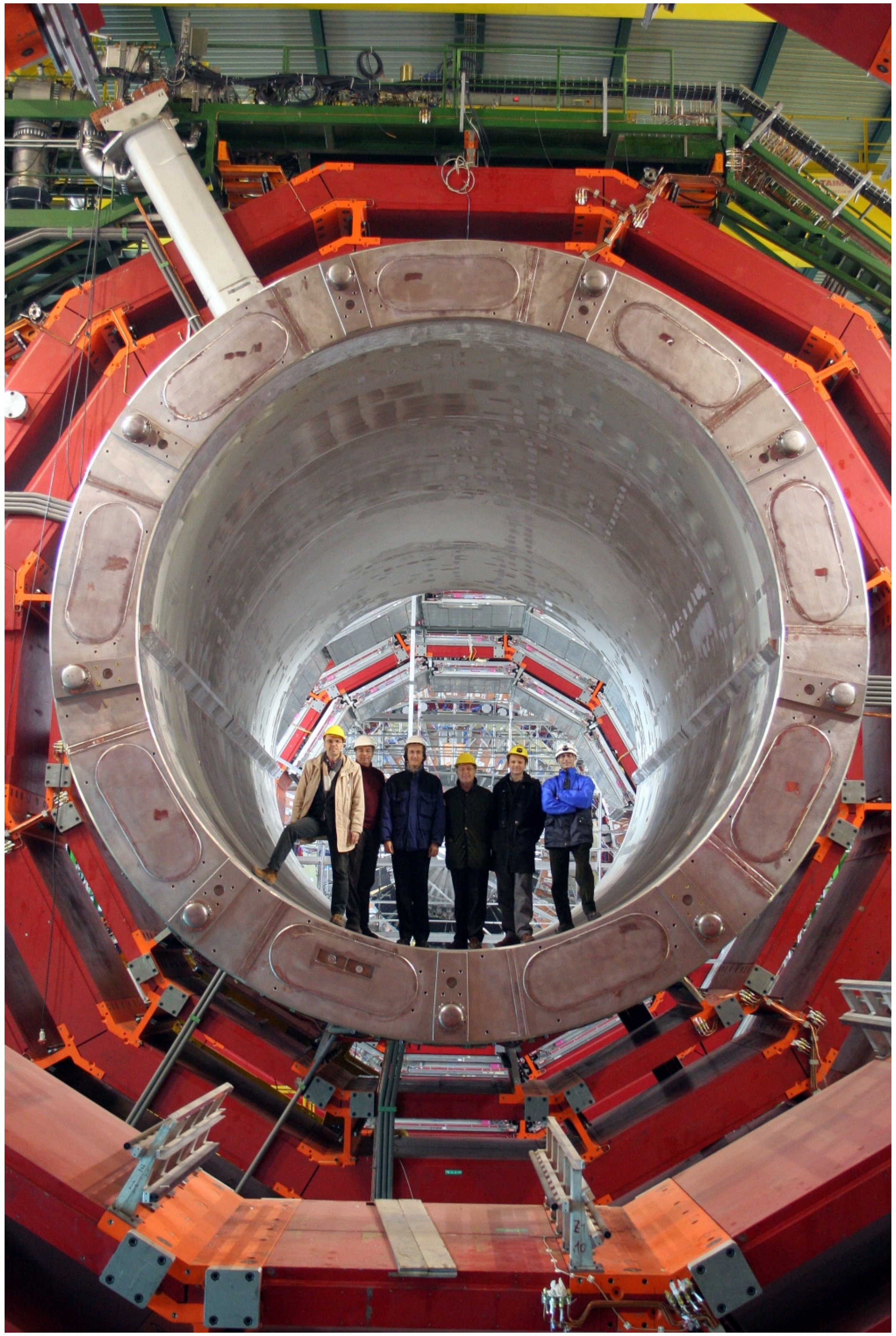
The lower the particle momentum the more they bend.

Straight tracks from high momentum particles are the most interesting!

CMS螺线管强磁场


Helium Tank
Cryostats
Current Lead
Vacuum Pipe Line
4 Section Winding
SC Coil
Yoke Central Ring

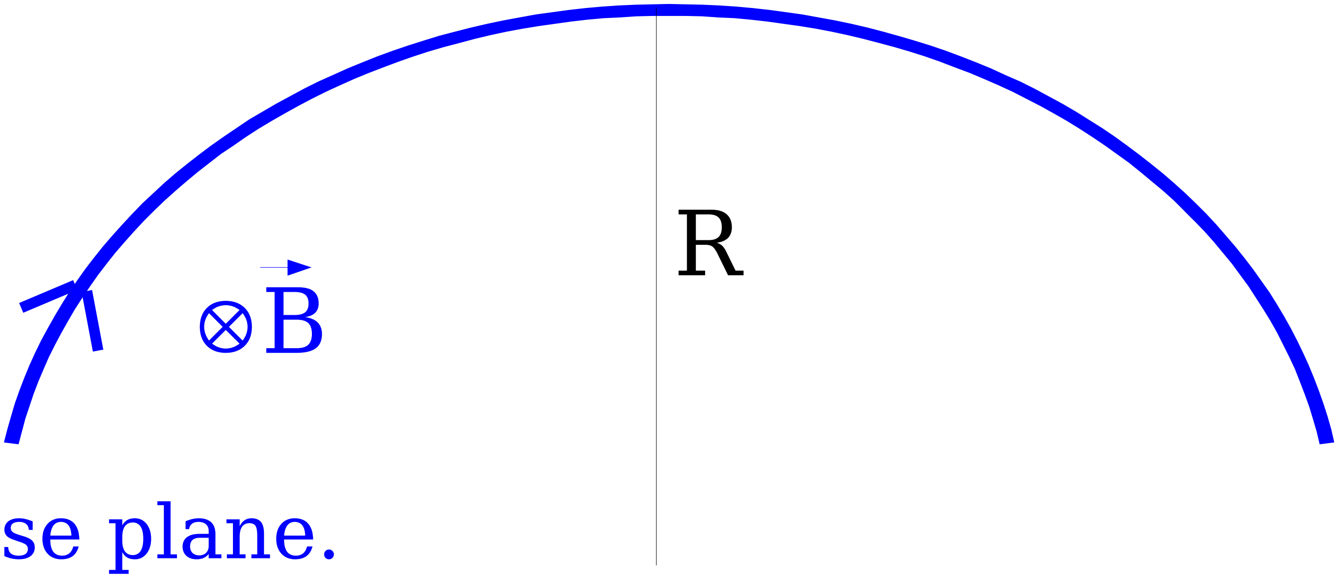

Magnetic field map
B≈1.8T
B≈4T



磁场中带电粒子运动

Lorentz Force:

$$\vec{F}_L = q\,\vec{v} \times \vec{B}$$



For B = constant:
circular motion in the transverse plane.
Equation of motion:
Lorentz force balanced by centrifugal force: $q\,v_t\,B = m\,v_t^2/R$

$p_t = m\,v_t \qquad \Rightarrow \boxed{p_t = qRB}$ also holds relativistically.

$$\boxed{c p_t\,[GeV] = 0.3\,R\,[m]\,B\,[T]}$$

for q = e

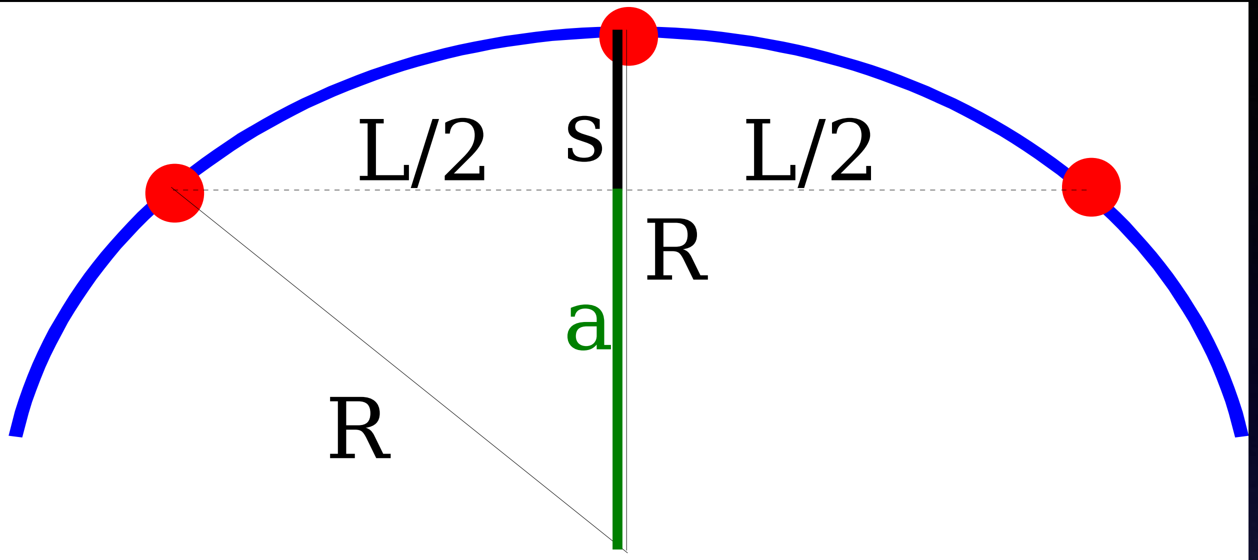
CMS: B = 3.8 T

p_t [GeV/c]	R [m]
100	87.72
10	8.77
1	0.88

Low p_t tracks curl up
inside the tracker if 2R < L

700　　614米

弧高(sagitta)测量



1. Pythagoras: $a^2 + L^2/4 = R^2$

$$\Rightarrow a = R\sqrt{1 - L^2/4R^2}$$

Taylor: $\sqrt{1-x} \approx 1 - x/2$

$$\Rightarrow a \approx R\left(1 - L^2/8R^2\right)$$

2. Sagitta: $s = R - a$, insert a

$$\Rightarrow \boxed{s = L^2/8R}$$

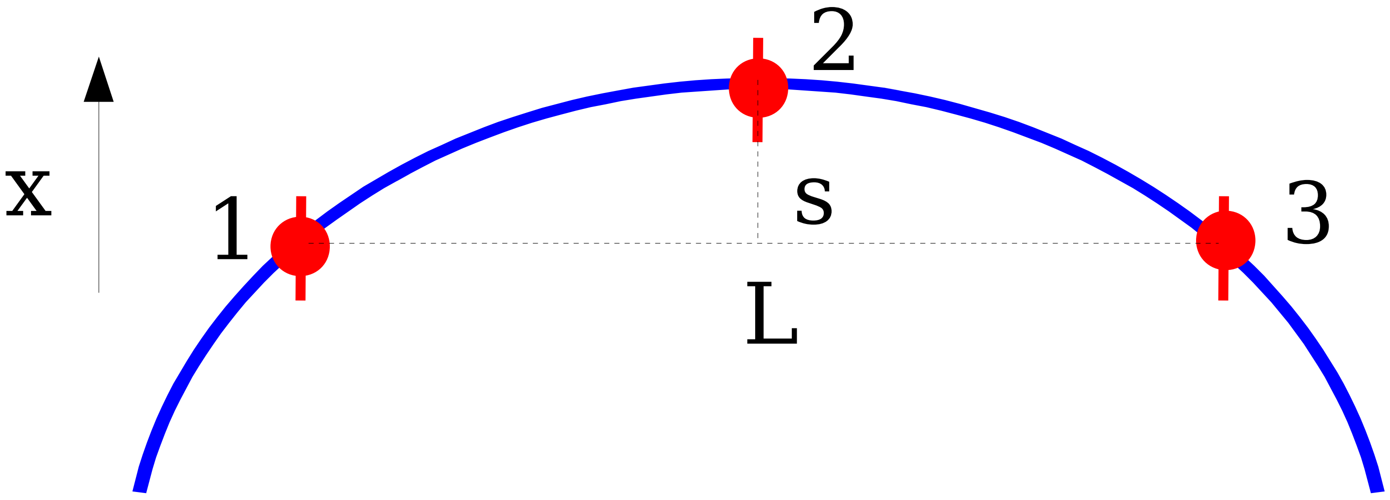
$$\Rightarrow p_t = qBL^2/8s$$

CMS: B = 3.8 T, L = 1 m

P_t [GeV/c]	s [**cm**]
100	0.15
10	1.50
1	15.00

动量测量精度

Sagitta: $s = x_2 - \frac{x_1 + x_3}{2}$



Error propagation: $\sigma_s^2 = \sigma_2^2 + \sigma_1^2/4 + \sigma_3^2/4$ (usually Gaussian)

All σ equal: $\sigma_s = \sqrt{3/2}\,\sigma_x$ $p_t = qBL^2/8s$

$\Rightarrow \sigma_{p_t}/p_t = \sigma_s/s = \sqrt{96}\,\sigma_x\, p_t/qBL^2$ (always non-Gaussian)

N equidistant measurements: $\boxed{\sigma_{p_t}/p_t = \sqrt{720/(N+4)}\,\sigma_x\, p_t/qBL^2}$

(Glückstern 1964)

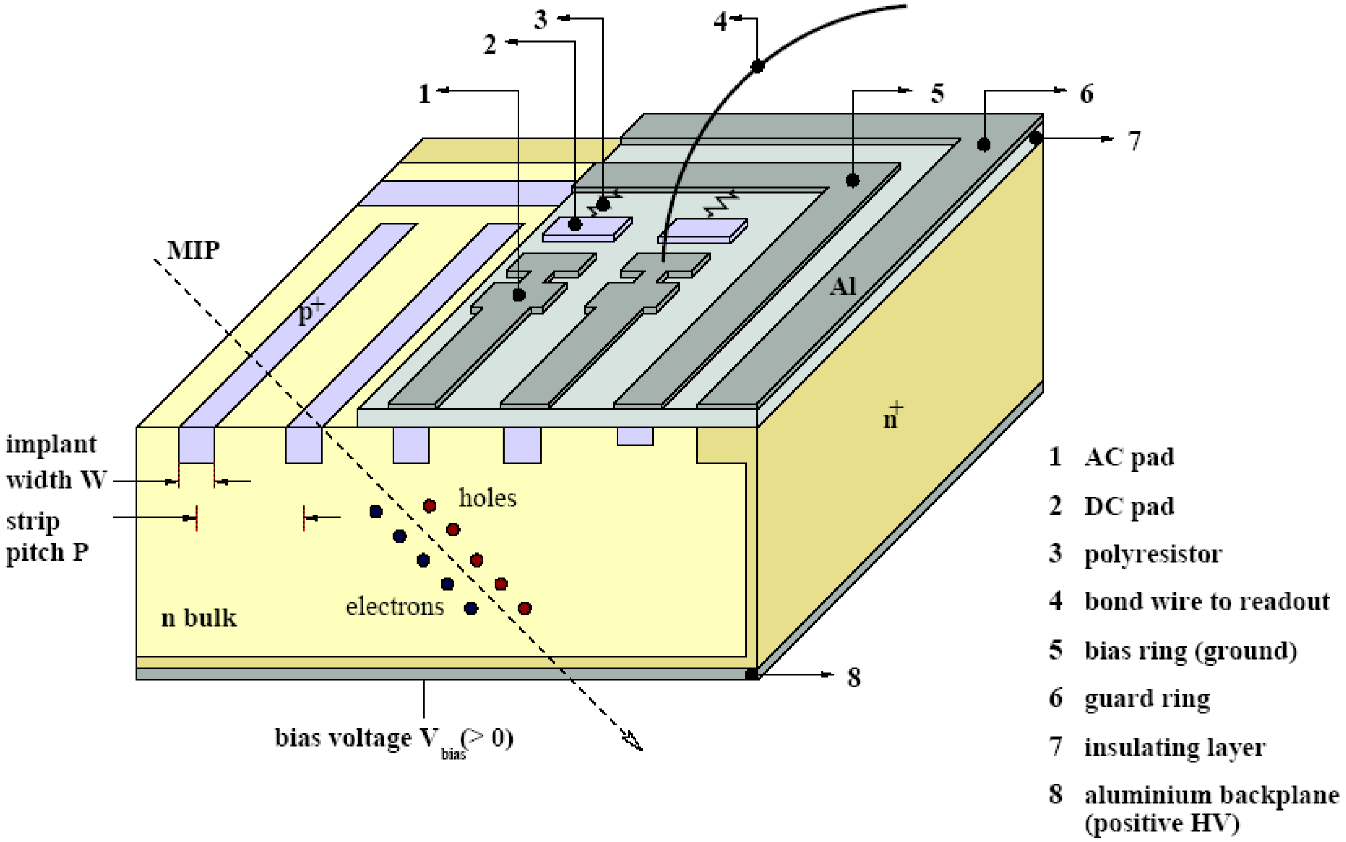
Note: $\sigma_{p_t}/p_t \sim p_t$ worse resolution at high p_t.

$\sigma_{p_t}/p_t \sim \sigma_x/BL^2$ want large, precise tracker, strong field.

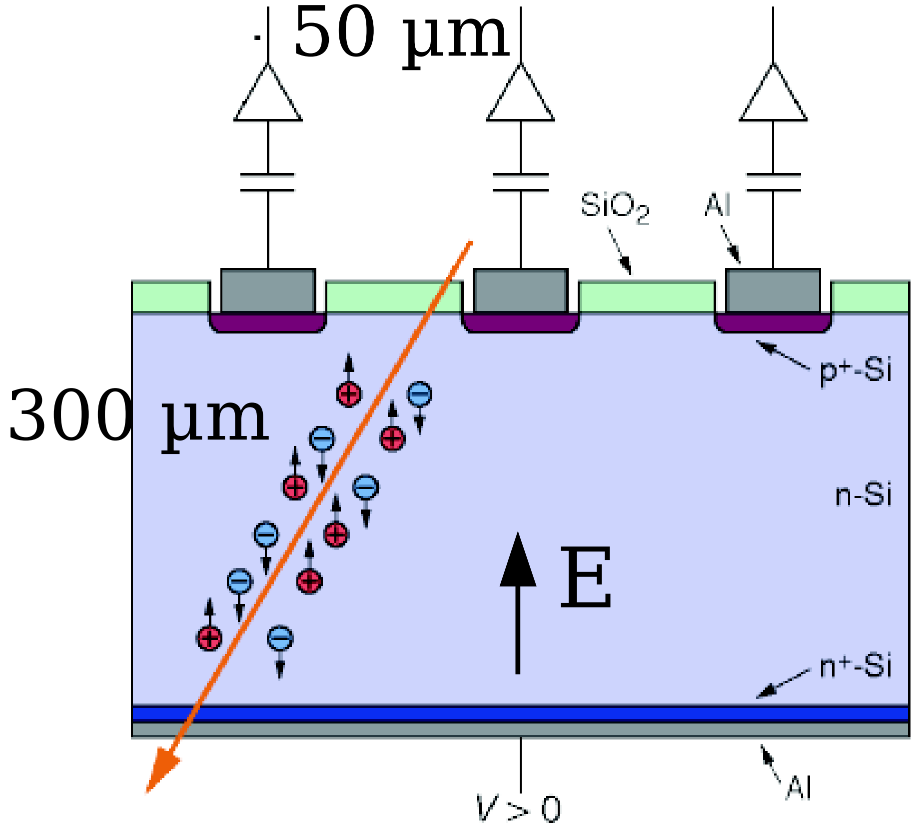
如何测量带电粒子的等距位置?

Silicon strip detectors

- Planar sensor from a high-purity silicon wafer (here *n*-type).
- Segmented into strips by implants forming *pn* junctions.
- Strip pitch 20 to 200 μm, high precision photolithography (expensive).
- Bulk is fully depleted by a reverse bias voltage (25-500V).
- Ionizing particle creates electron-hole pairs (25k in 300 μm).

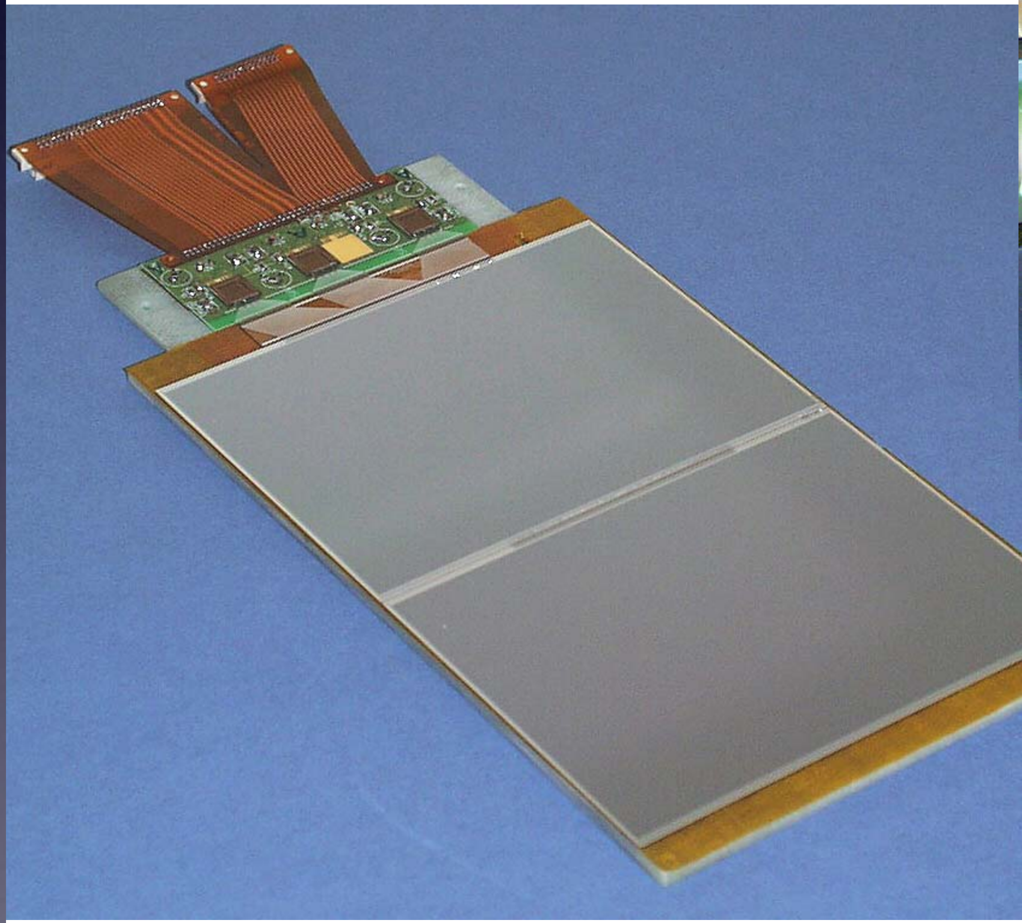


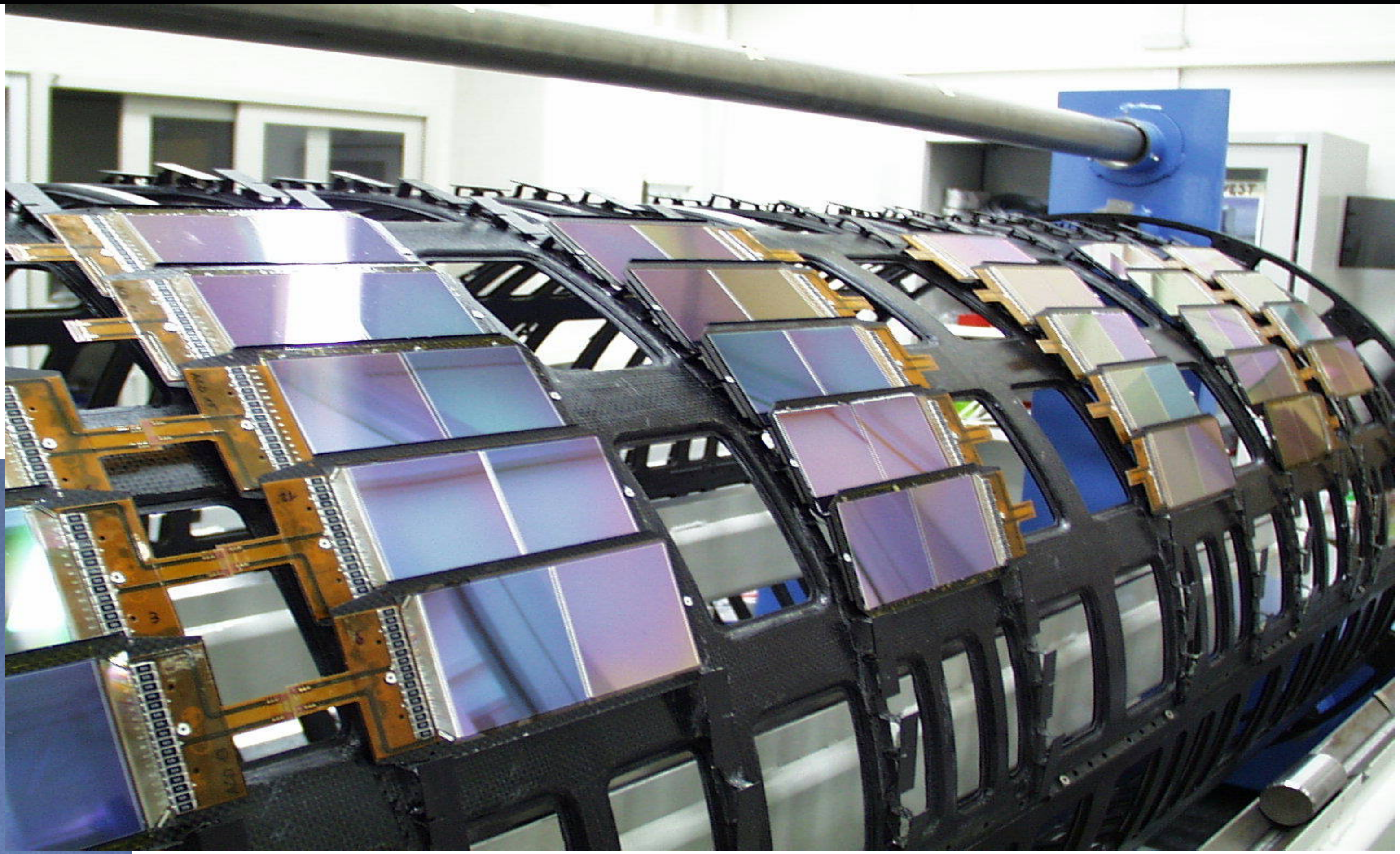
1 AC pad
2 DC pad
3 polyresistor
4 bond wire to readout
5 bias ring (ground)
6 guard ring
7 insulating layer
8 aluminium backplane (positive HV)



CMS Silicon tracking

One outer barrel module:



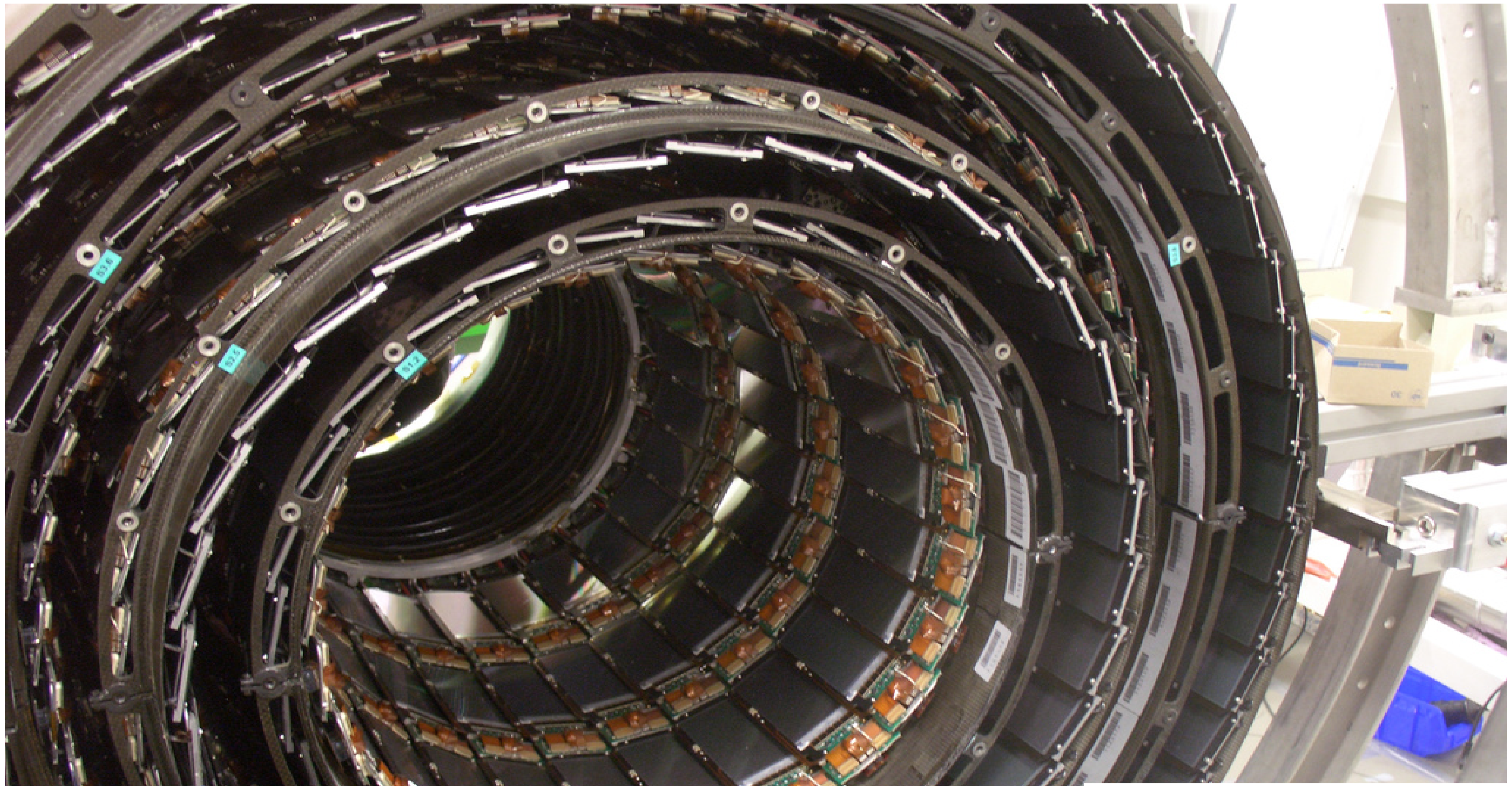


Carbon-fibre support structure. Stable.

Software alignment needed, despite tight mechanical tolerances and accurate placement.

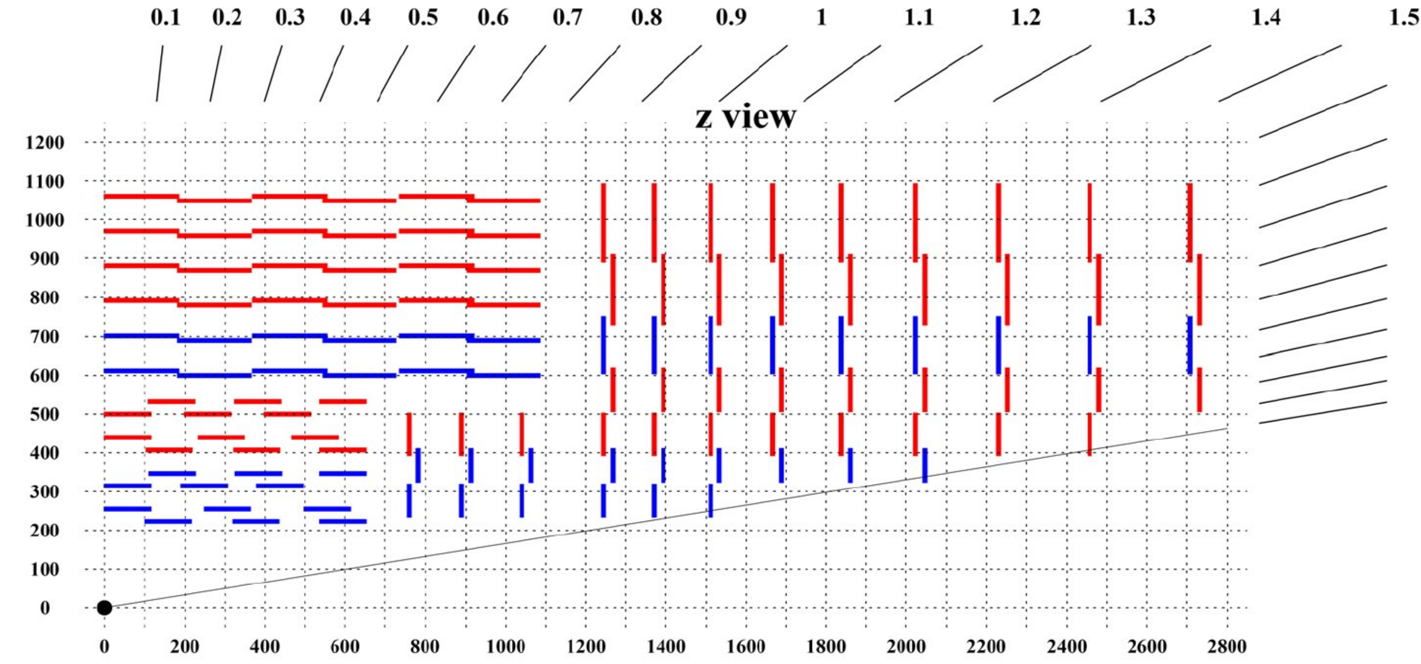
±5 µm reached so far.

CMS Silicon Tracker



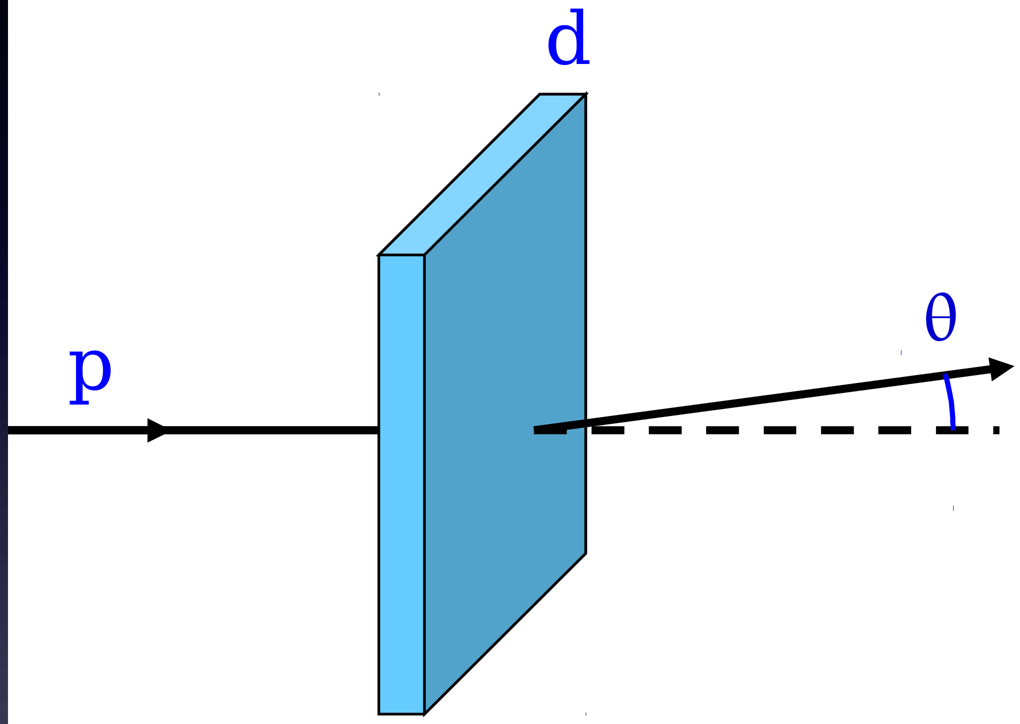
Inner barrel

10^7 channels
200 m^2



Multiple Coulomb scattering

Multiple elastic scattering from nuclei causes angular deviations:



$$\langle \theta \rangle [rad] \approx \frac{0.014}{p\,[GeV/c]} \sqrt{d/X_0}$$

X_0 = radiation length

9.4 cm for silicon

18.8 cm for carbon

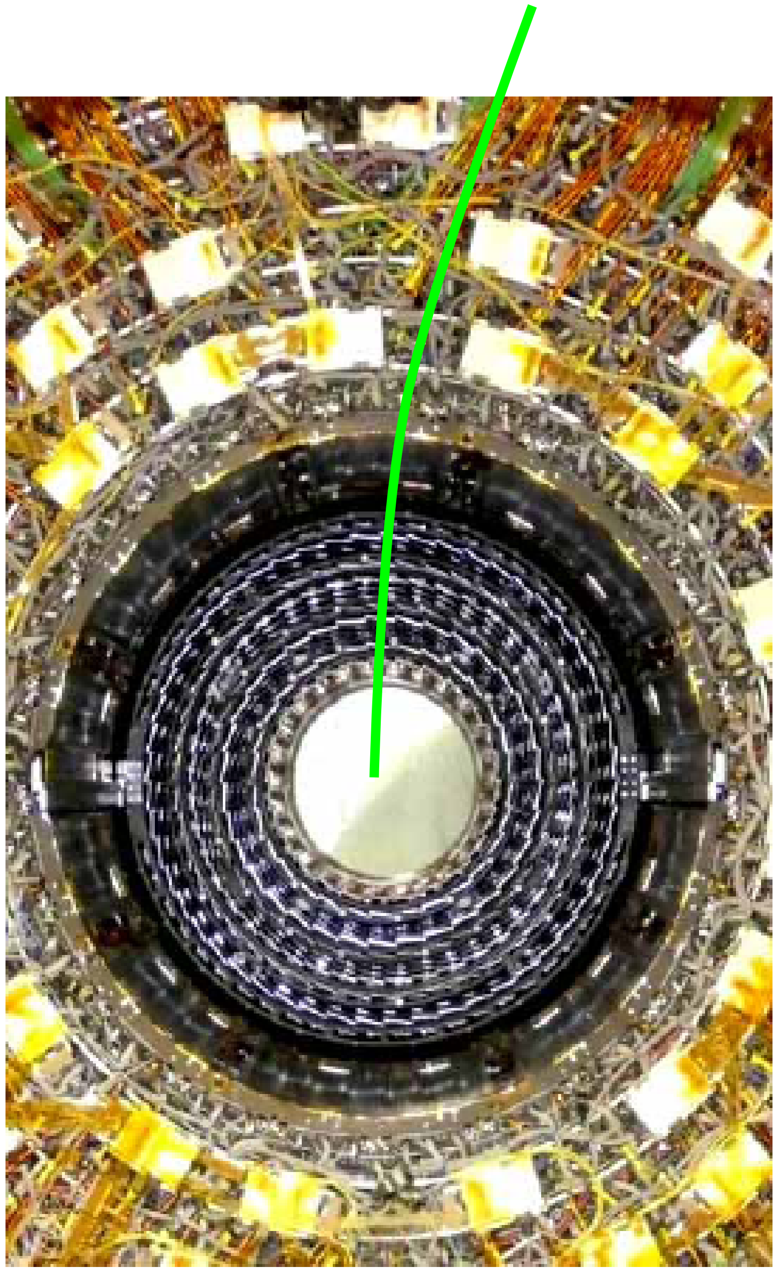
Number of scatterings is Poisson process

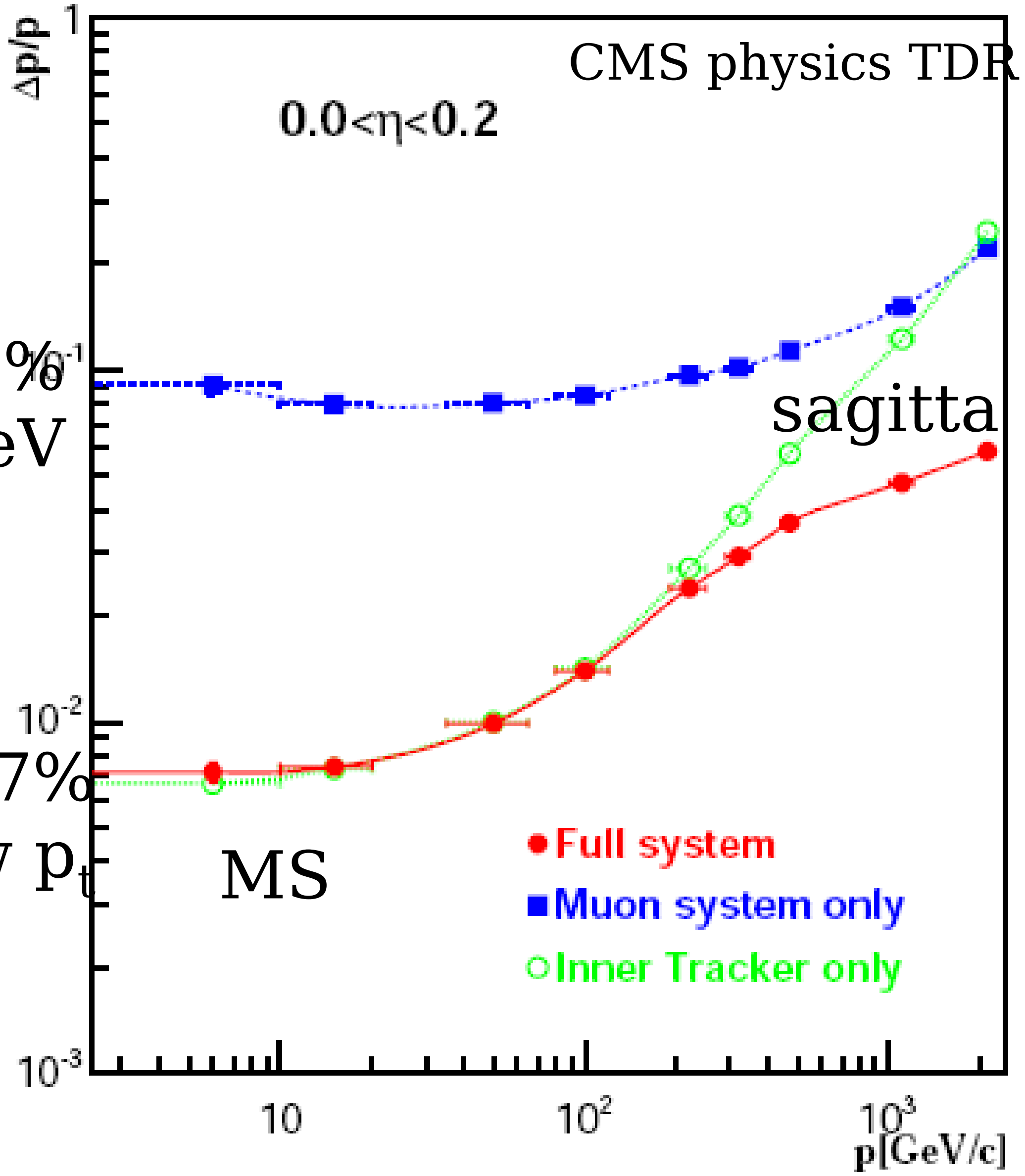
⇒ RMS ~ √d

Important at low momentum: ~1/p

CMS momentum resolution

Multiple scattering and momentum resolution: $\sigma^{MS}_{p_t}/p_t \approx \frac{0.016}{BL}\sqrt{\sum d/X_0}$





CMS physics TDR

10%
at 1000 GeV

sagitta

0.7%
at low p_t

MS

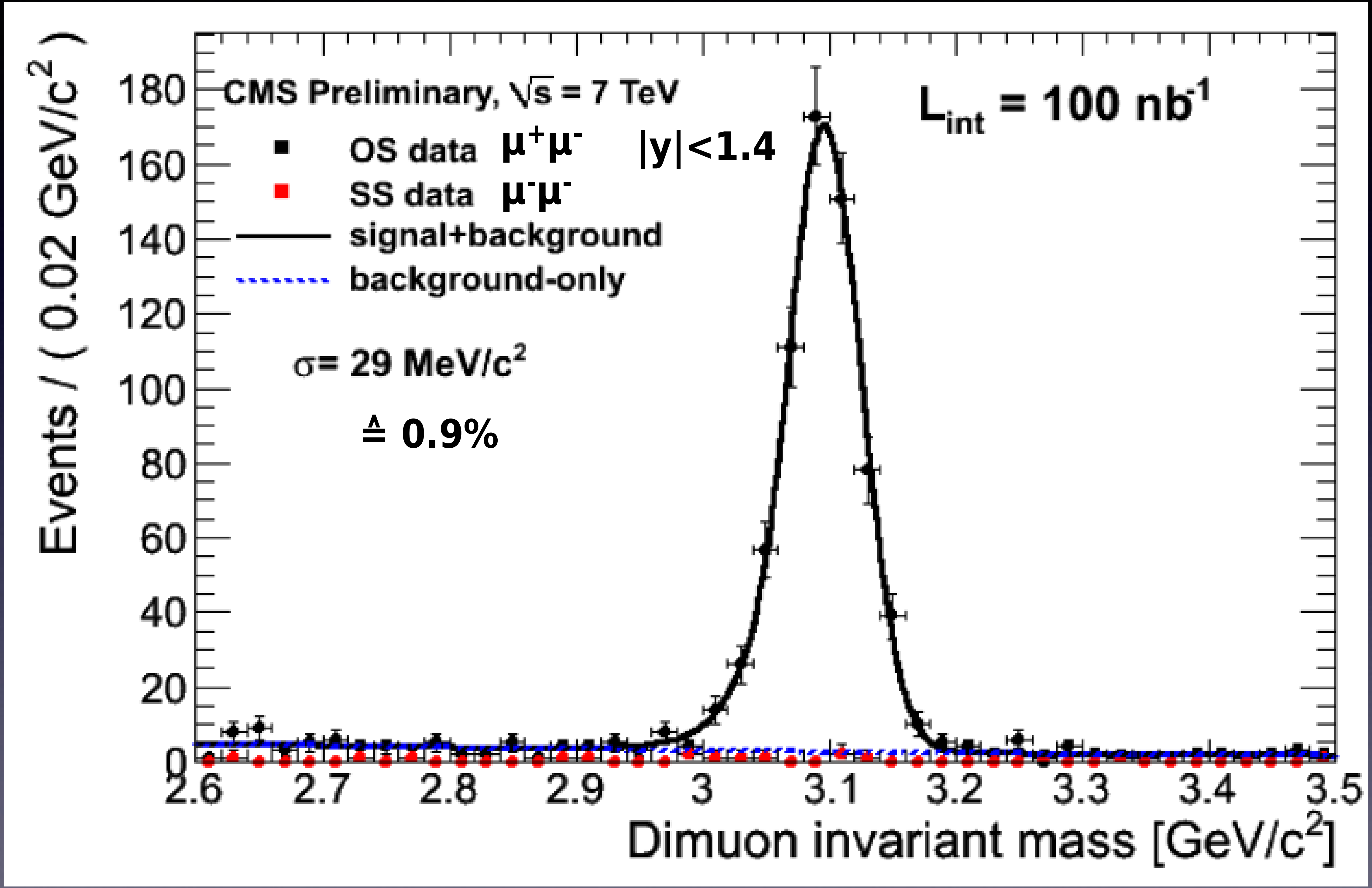
$$\frac{\sigma_{p_t}}{p_t} \sim \frac{\sigma_x}{\sqrt{N}}\,\frac{p_t}{BL^2} \oplus \frac{\sqrt{d/X_0}}{BL}$$

$\sigma_x \approx 10-20\mu m$

$X_0 = 9.4\mathrm{cm}$

Silicon detectors

CMS mass resolution



$$m_{\mu\mu} = \sqrt{(p_{\mu^+} + p_{\mu^-})^2}$$

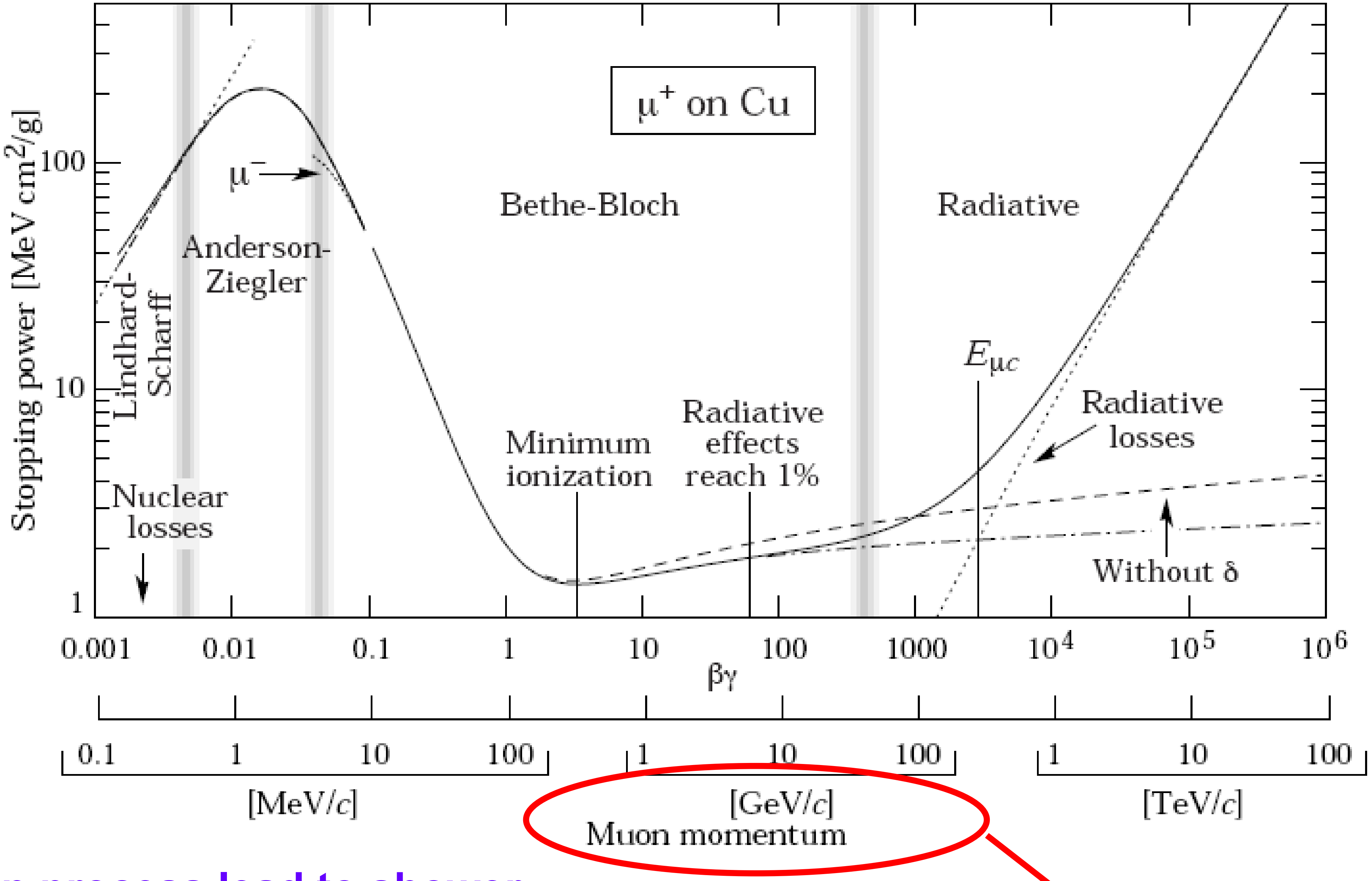
2）电磁量能器

电磁级联簇射（EM shower)

高能散射过程的次级衰变产物将被量能器完全吸收，从而测得这些粒子的能量和位置。所有（或大部分）入射能量都以激发或离子化探测材料的原子的形式记录下来。

Calorimeter

Energy loss of particles in matter



5 50 500

[MeV/c]

Electron Momentum

➔ radiation process lead to shower developments,

➔ ionization and atomic excitation lead to measurable signals (light or charge)

μ are essentially considered as mip, but radiative effects have to be taken into account, in particular at LHC!

Bethe-Bloch公式

1930年

$$
\boxed{\begin{aligned} -\frac{dE}{dx} &= Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\ln\left(\frac{2m_ec^2\gamma^2\beta^2}{I}\right)-\beta^2-\frac{\delta}{2}\right] \\ &= Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\ln\frac{T_{\max}}{I}-\beta^2-\frac{\delta}{2}\right] \end{aligned}}
$$

$$x = \rho\ell$$

$$\frac{K}{A} = \frac{4\pi N_A r_e^2 m_e c^2}{A} = 0.307\ \mathrm{MeV}g^{-1}\mathrm{cm}^2 \ \ \textit{if}\ \ A = 1g\ \mathrm{mol}^{-1}$$

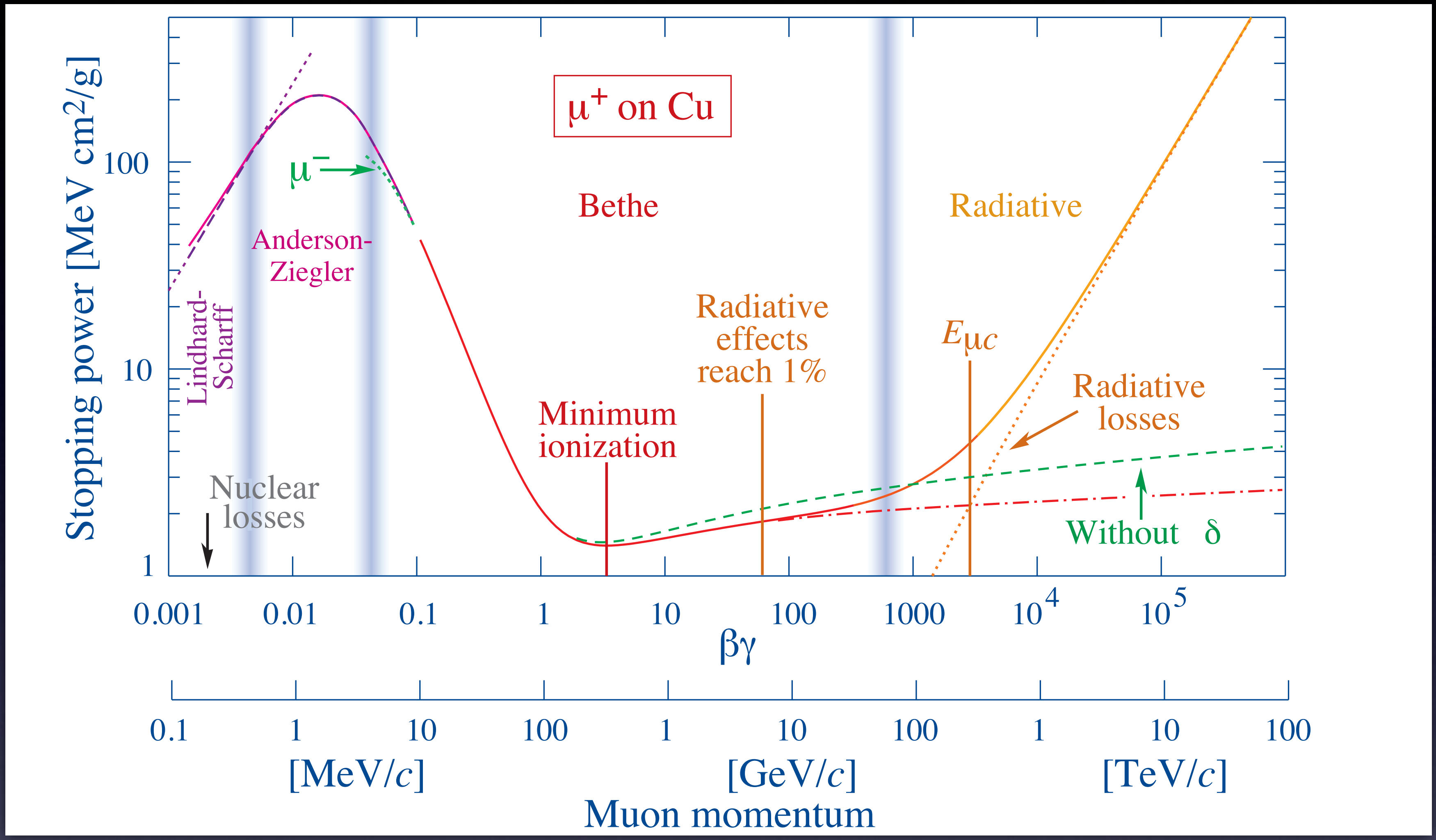
$T_{\max}$： 单次散射传递给自由电子的最大能量

z 入射粒子电荷 Z 测量媒介的原子数

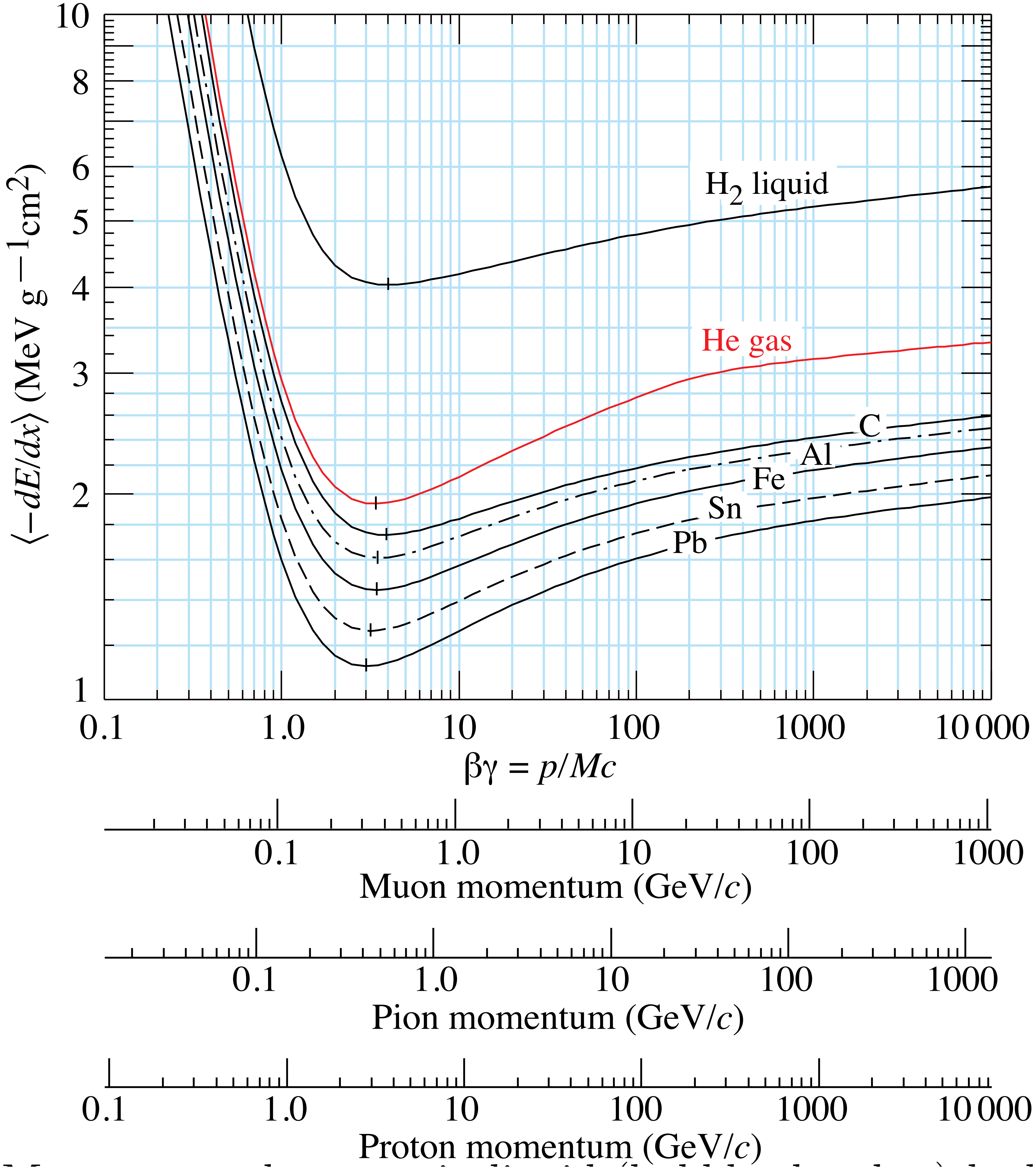
I 离子化的势能，通常 $I = 10 \times Z\ (\mathrm{eV})$

δ 测量媒介的密度修正项

Bethe-Bloch公式

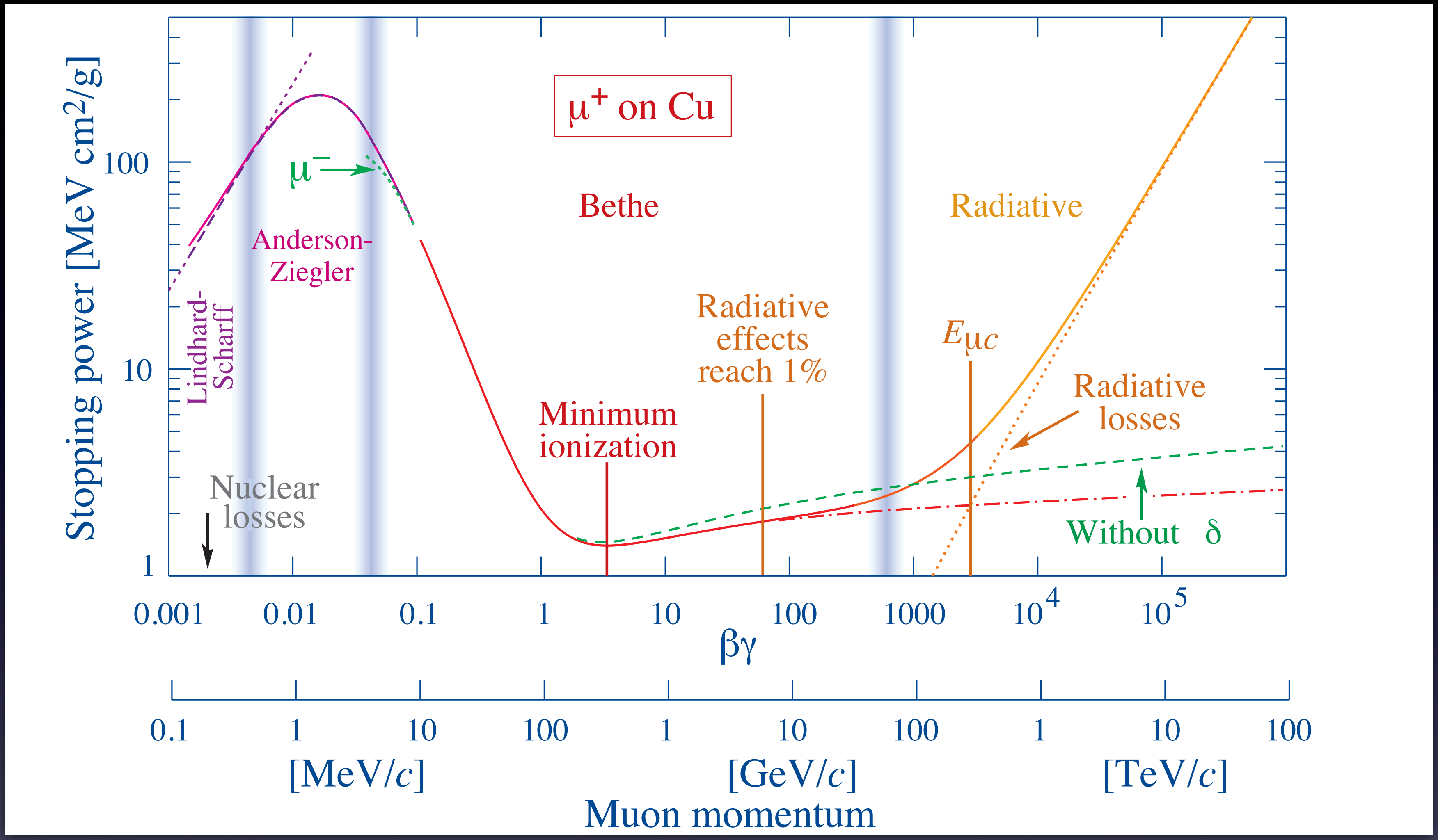


1. 离子化能量损失不依赖于入射粒子质量，对具体的探测材料也不太敏感，因为大部分材料都满足 $Z/A \sim 0.5$
2. 离子化能量损失依赖于入射粒子速度 β
3. B-B公式给出的是平均的能量损失，其统计方差(通常被称作straggling)是很大的。



$\langle -dE/dx \rangle$ (MeV g^{-1}cm^2)
10
8
6
5
4
3
2
1
H$_2$ liquid
He gas
C
Al
Fe
Sn
Pb
0.1
1.0
10
100
1000
10 000
$\beta\gamma = p/Mc$
0.1
1.0
10
100
1000
Muon momentum (GeV/c)
0.1
1.0
10
100
1000
Pion momentum (GeV/c)
0.1
1.0
10
100
1000
10 000
Proton momentum (GeV/c)

Bethe-Bloch公式



4. 离子化能量损失随入射粒子速度减小而平方增加 $\sim \beta^{-2}$

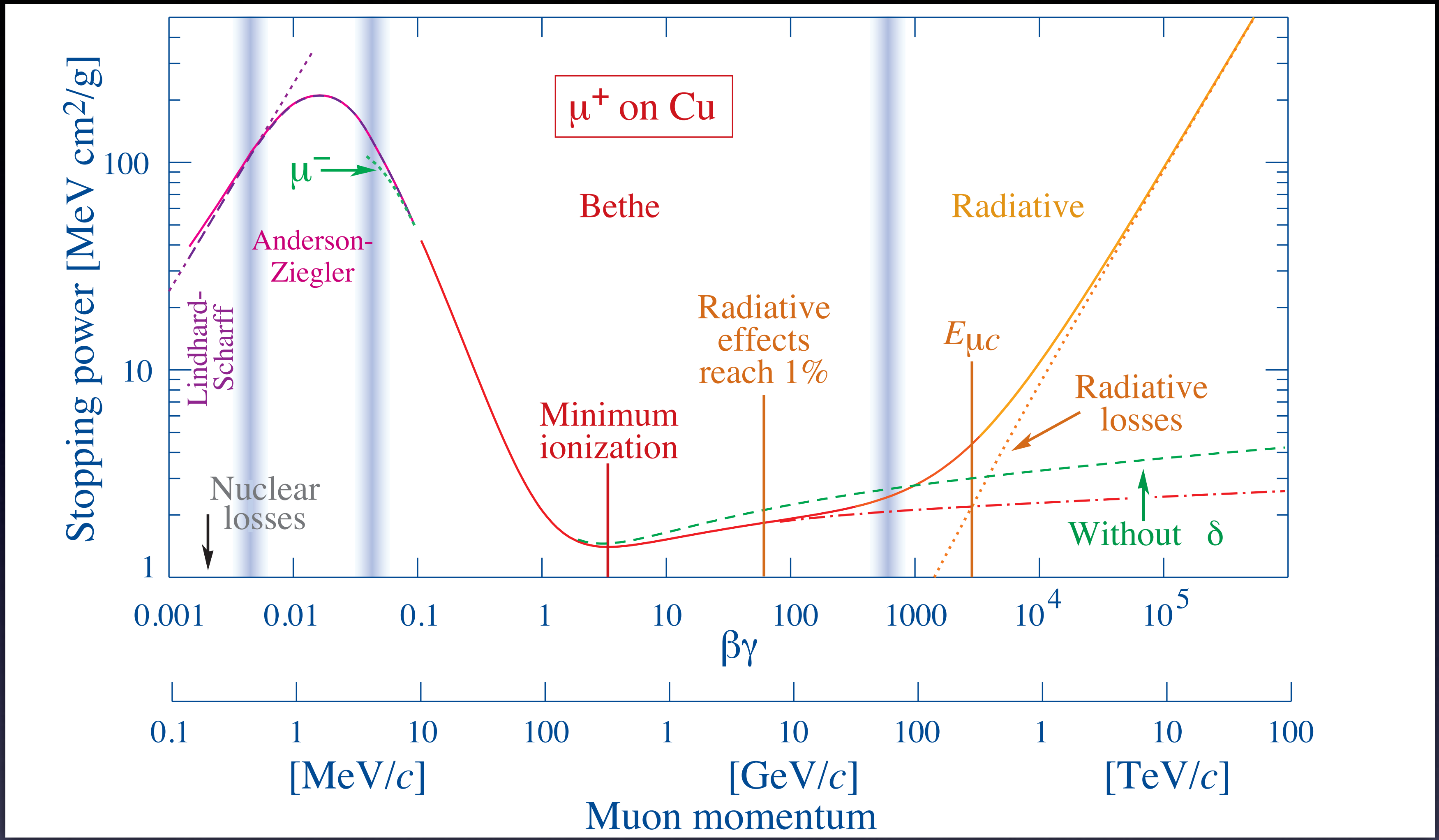
   入射粒子越慢，能量损失越快 => 慢粒子更快离子化

5. 最小离子化粒子（$\beta\gamma \sim 3$）

10 GeV Muon在铁中能损约为13MeV/cm，
因此可以跑大约10米，穿行无阻

$$\frac{dE}{dx} \times \rho$$

Bethe-Bloch公式



6. 相对论性增加 $(3 \leq \beta\gamma \leq 800)$：带电粒子电场随其速度增强, β^{-2} 可以看到更远处的原子中的电子，从而损失更多的能量

$$-\frac{dE}{dx} \propto \ln \frac{2m_e c^2 \beta^2 \gamma^2}{I} \sim \ln \frac{2m_e c^2}{I} + \ln\left(\beta^2\gamma^2\right) \sim \ln \frac{p}{m}$$

练习：考虑一个动能80MeV的pion粒子通过碳媒介物。估算一下，需要多厚的碳板才可以将此pion粒子停住。

$$\rho_C = 2.265 g/\mathrm{cm}^3$$

$$K.E. = E - M \qquad 80\ \mathrm{MeV} = E - 140\ \mathrm{MeV}$$

$$E = 220\ \mathrm{MeV}$$

$$P = \sqrt{E^2 - M^2} = 170\ \mathrm{MeV} \qquad \beta\gamma = \frac{P}{M} = \frac{170}{140} \simeq 1.21$$

查图可知：$-\left.\frac{dE}{dx}\right|_{\beta\gamma=1.21} = 2\ \mathrm{MeV}\frac{\mathrm{cm}^2}{g}$

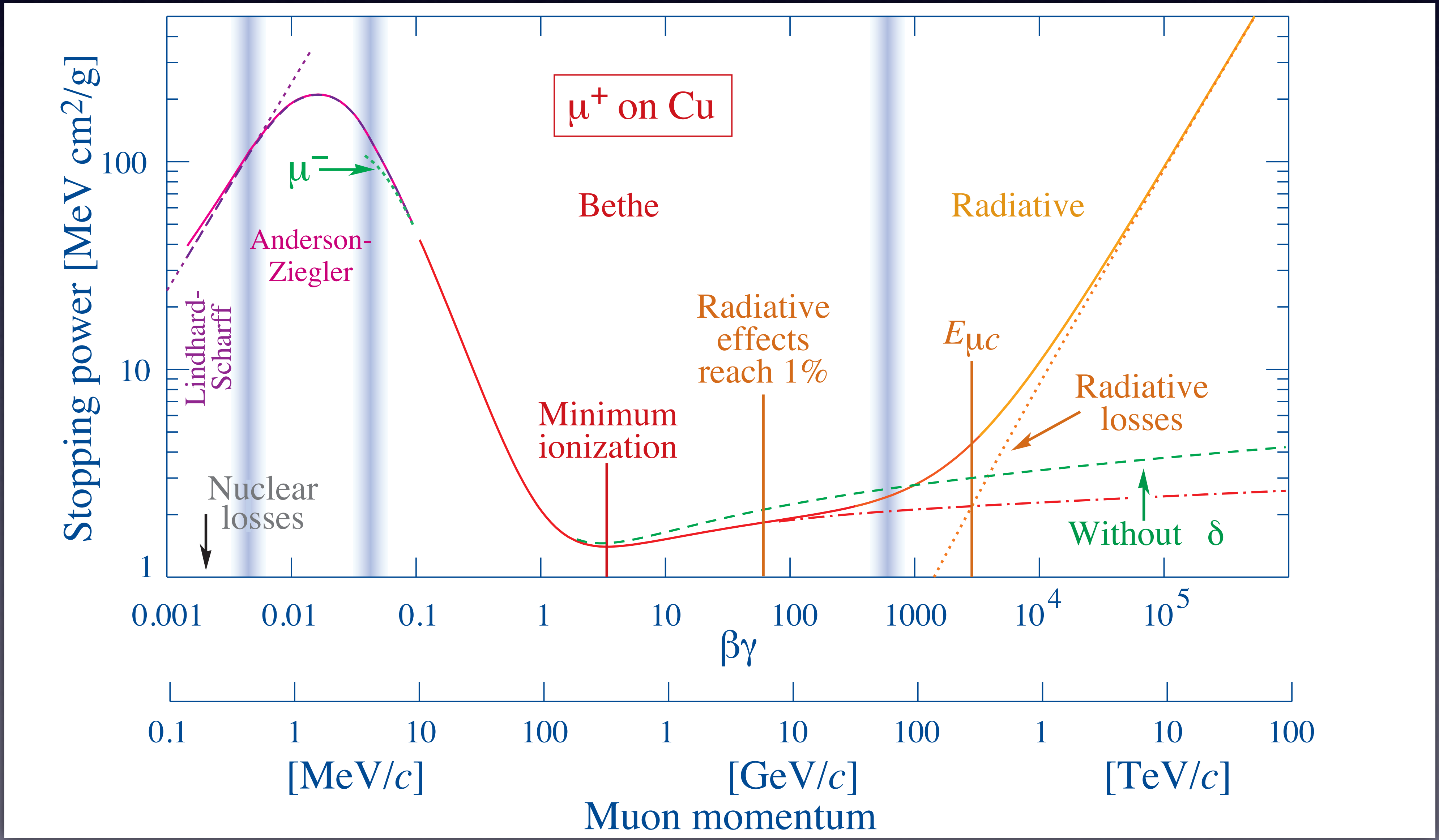
→ $$\frac{\Delta E}{\Delta x} = 2.265\frac{g}{\mathrm{cm}^3} \times 2\ \mathrm{MeV}\frac{\mathrm{cm}^2}{g} = 4.5\frac{\mathrm{MeV}}{\mathrm{cm}}$$

→ $$L = \frac{80\ \mathrm{MeV}}{4.5\ \mathrm{MeV/cm}} = -18\ \mathrm{cm}$$

电子和光子的能量损失

电子质量非常轻 ($m_{\mu^\pm} = 206 m_{e^\pm}$)，主要通过在核子的库仑场中发生韧致辐射损失能量

离子化能量损失是次要的



电子的韧致辐射

电子辐射光子的几率正别于加速度的平方，从而当电子靠近核子附近时的韧致辐射更加重要。

（核子附近电场要大于原子核附近电子的电场）

→ 测量材料的原子数越大时，韧致辐射越重要

当核子电场给定时，韧致辐射几率反比于入射粒子质量平方

$$\text{Prob} \propto \frac{1}{m^2}$$

$$\Rightarrow \frac{\text{Prob}(\mu)}{\text{Prob}(e)} \propto 10^{-4}$$

$$\Rightarrow \text{Prob}(\mu) \sim \text{Prob}(e) \quad \rightarrow \quad E_\mu \sim 10^4 E_e$$

Bethe-Heither公式

$$-\frac{dE}{E} = \frac{dX}{X_0}$$

X_0 ： 辐射长度 (radiation length)，定义为电子能量减少为初始值的1/e时的距离

$$X_0 \sim 1/Z \sim 1/\rho$$

空气 (n.t.p.) $X_0 \simeq 300\ \mathrm{m}$

水 $X_0 \simeq 0.36\ \mathrm{m}$

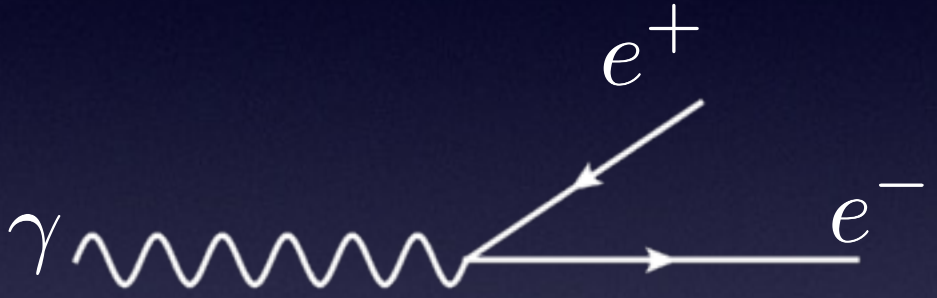
碳 $X_0 \simeq 0.2\ \mathrm{m}$

铁 $X_0 \simeq 2\ \mathrm{cm}$

铅 $X_0 \simeq 5\ \mathrm{mm}$

光子的能量损失

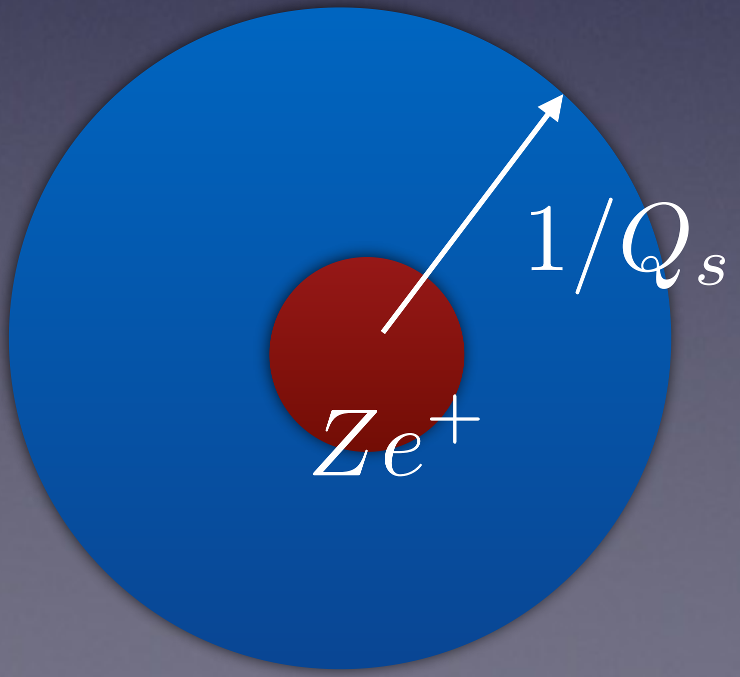
$$-\frac{1}{E}\frac{dE}{dX\,dZ}=\frac{1}{X_0}\frac{1}{Z}\left[\frac{4}{3}(1-Z)+Z^2\right]$$



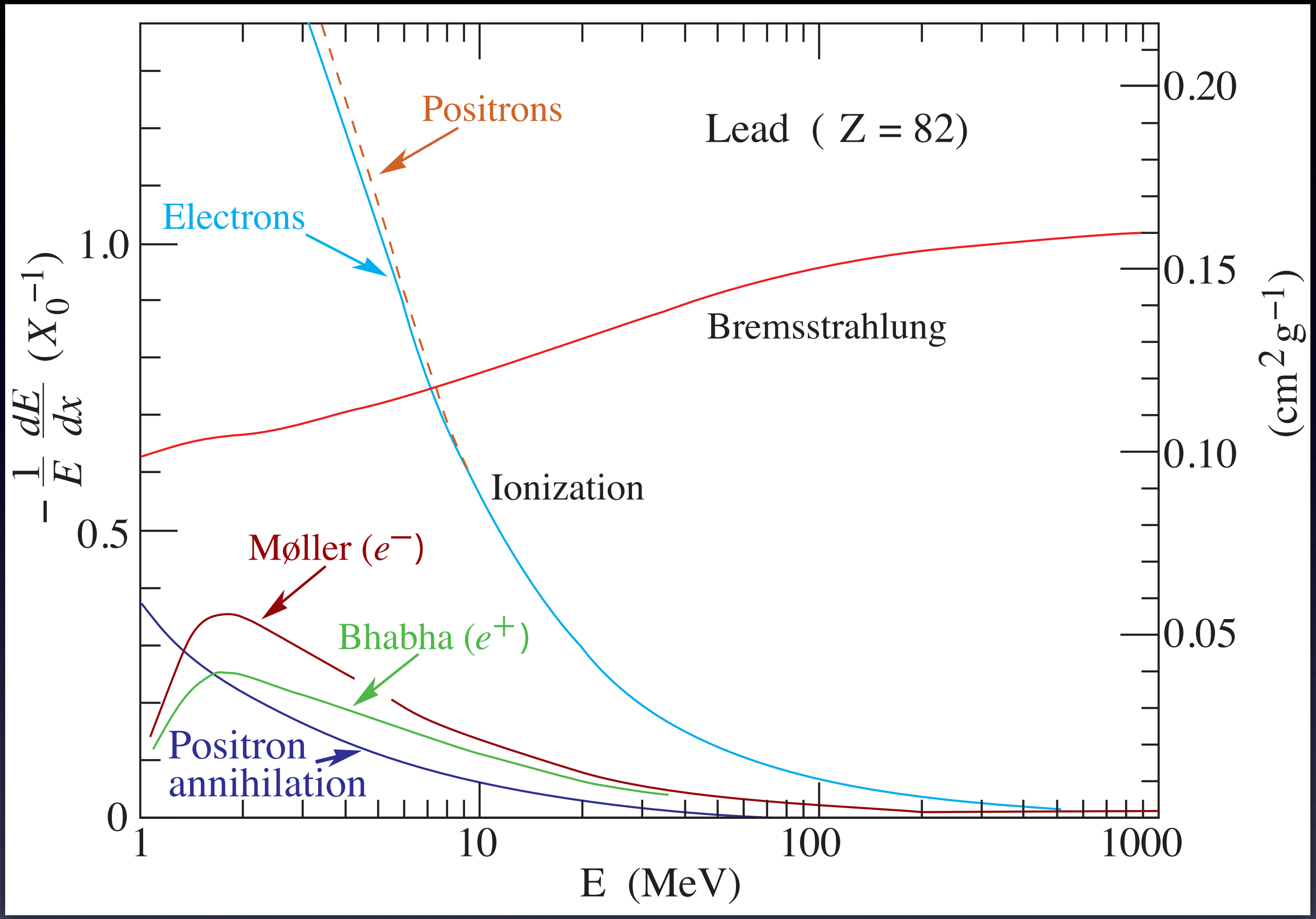
$$-\frac{1}{E}\frac{dE}{dX\,dZ}=\frac{1}{X_0}\left[1-\frac{4}{3}Z(1-Z)\right]$$

$$\frac{1}{X_0}=\frac{4\alpha^3}{m_e^2}nZ^2\ln\frac{m_e}{Q_s}$$

screening length $\frac{1}{Q_s}=1.4Z^{-1/3}a_B$



铅板中电子的相对能量损失

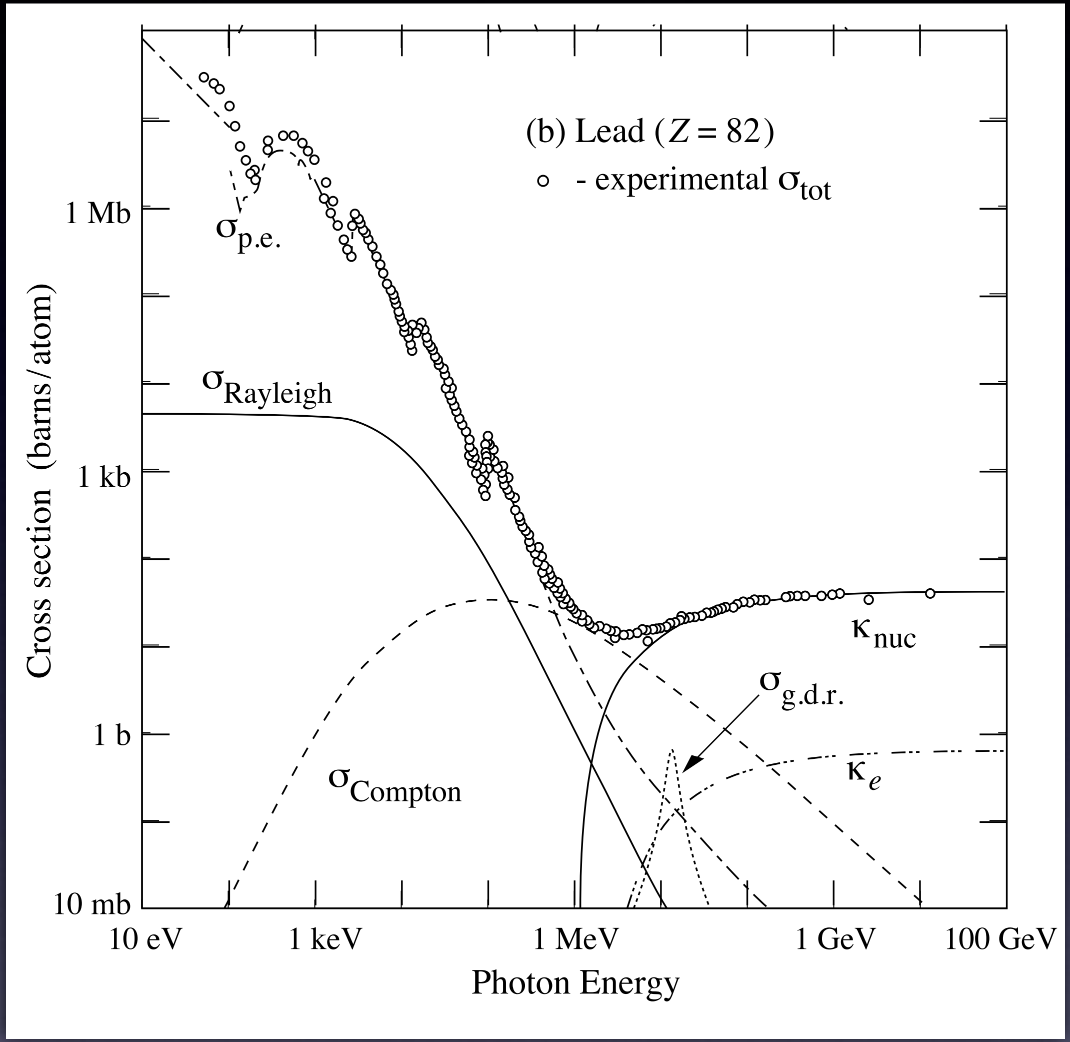


临界能量： $E_c \approx \frac{800}{Z}$ MeV $\qquad E_c(\mathrm{Lead}) = 7$ MeV

我们通常遇到的电子的能量远远大于此临界能量

→ 韧致辐射占主导

光子的能量损失



依赖光子的能量：

1. ~ eV

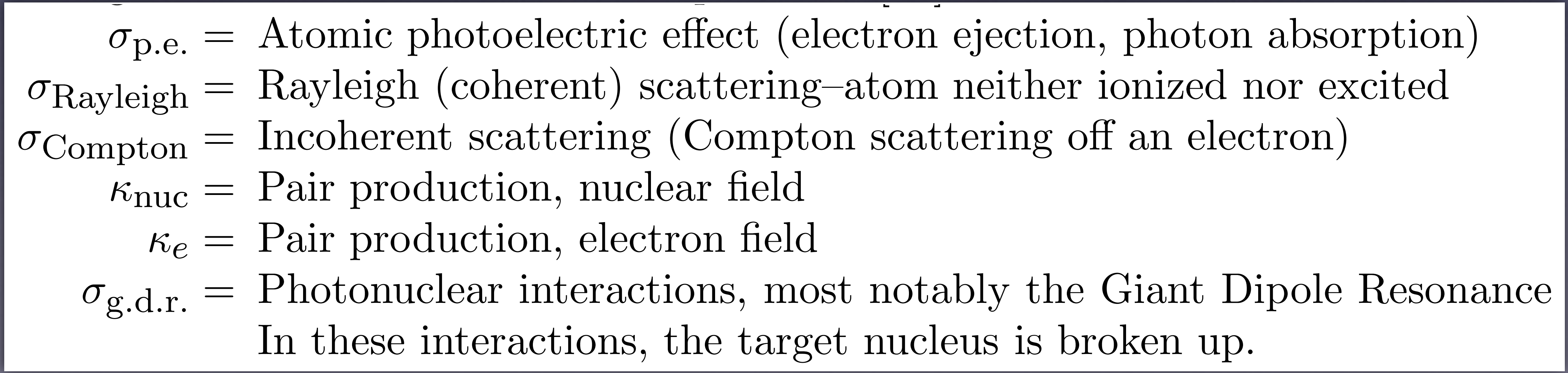
   与原子中电子发生光电效应

2. ~ keV

   康普顿散射

3. >1.022 MeV

   e^+e^-对产生



$\sigma_{\text{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)
σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited
σ_{Compton} = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_e = Pair production, electron field
$\sigma_{\text{g.d.r.}}$ = Photonuclear interactions, most notably the Giant Dipole Resonance
In these interactions, the target nucleus is broken up.

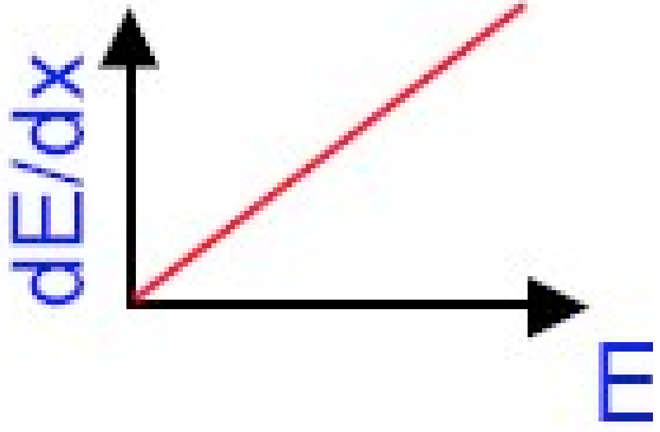
em interactions with matter

Process taking place during EM Shower development

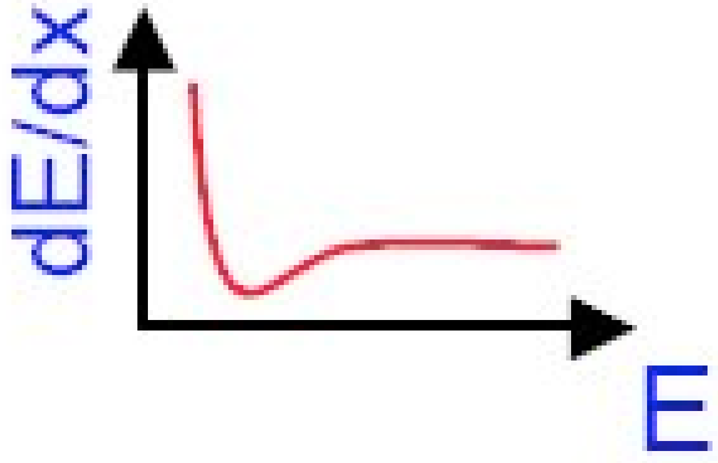
Electrons:

- **High energy: Bremsstrahlung**
  - photon radiation close to an atom
- **Low energy: ionization**
  - energy dissipation by creating free electrons

Bremsstrahlung

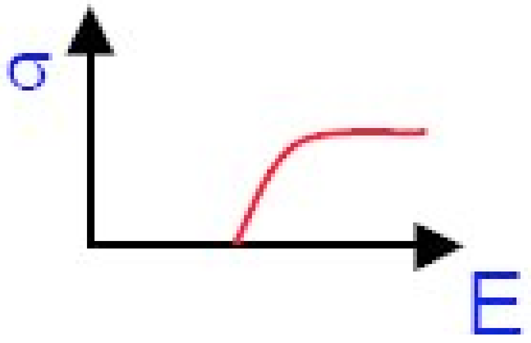


Ionization

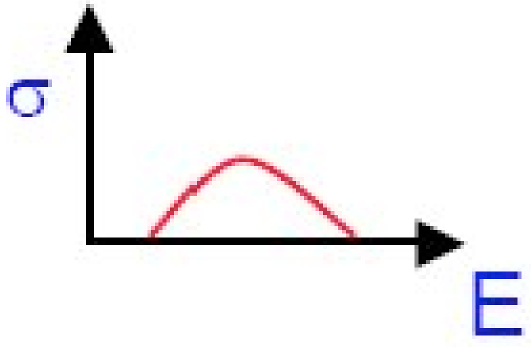


Photons:

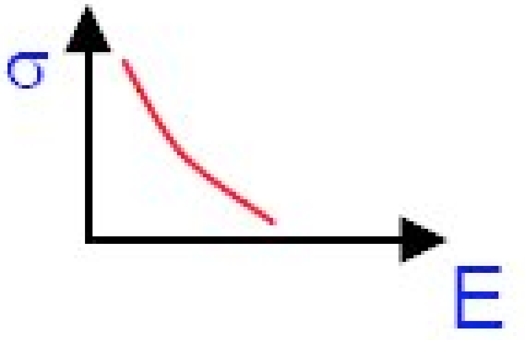
- **High energy : e$^+$/e$^-$ pair production**
  - materialization of photons
- **Medium energy: Compton effect**
  - photon diffusion liberating an electron from the atomic cortex
- **Low energy: photoelectric effect**
  - photon absorption liberating an electron from the atomic cortex



Pair production

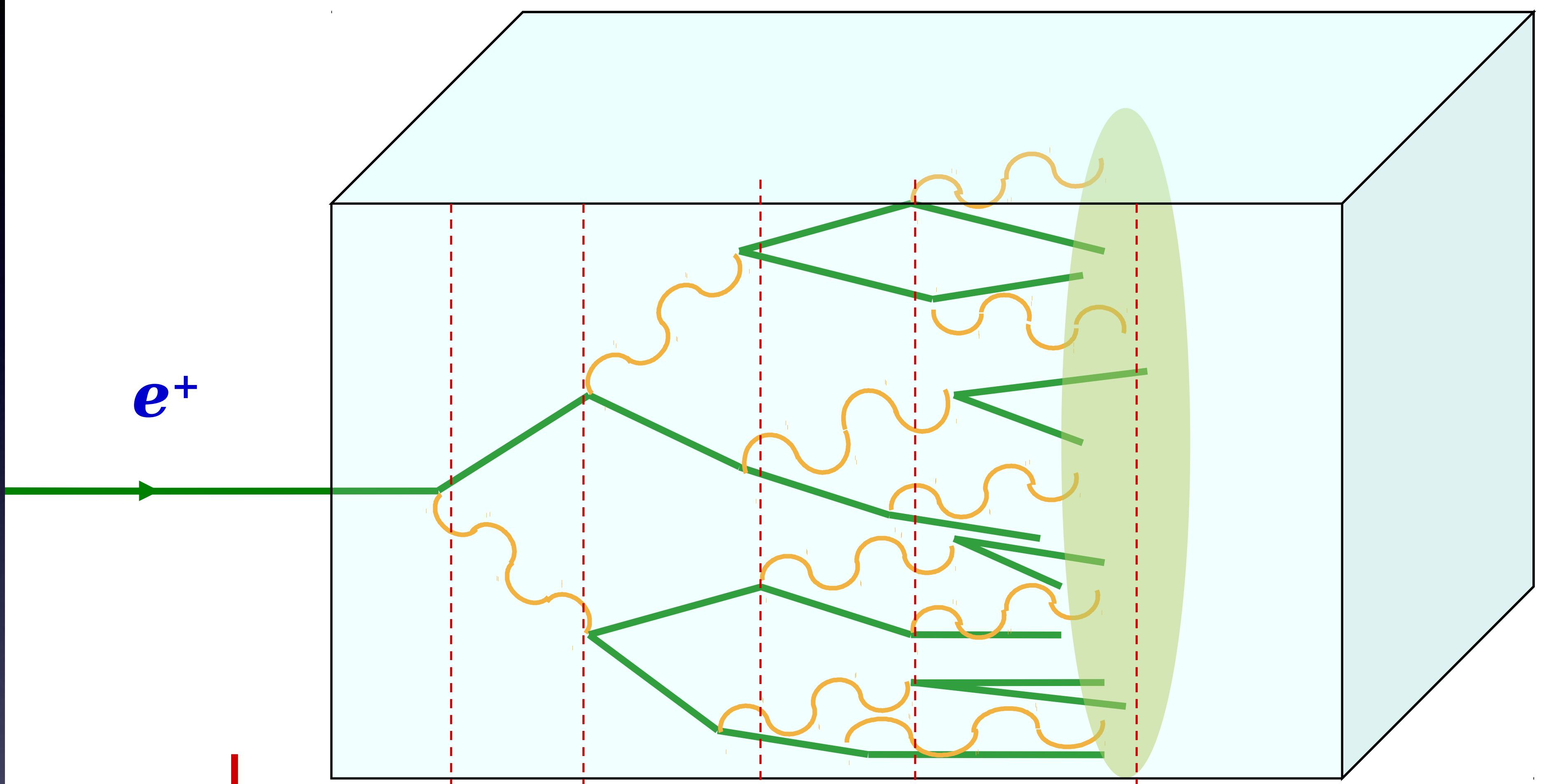


Compton effect



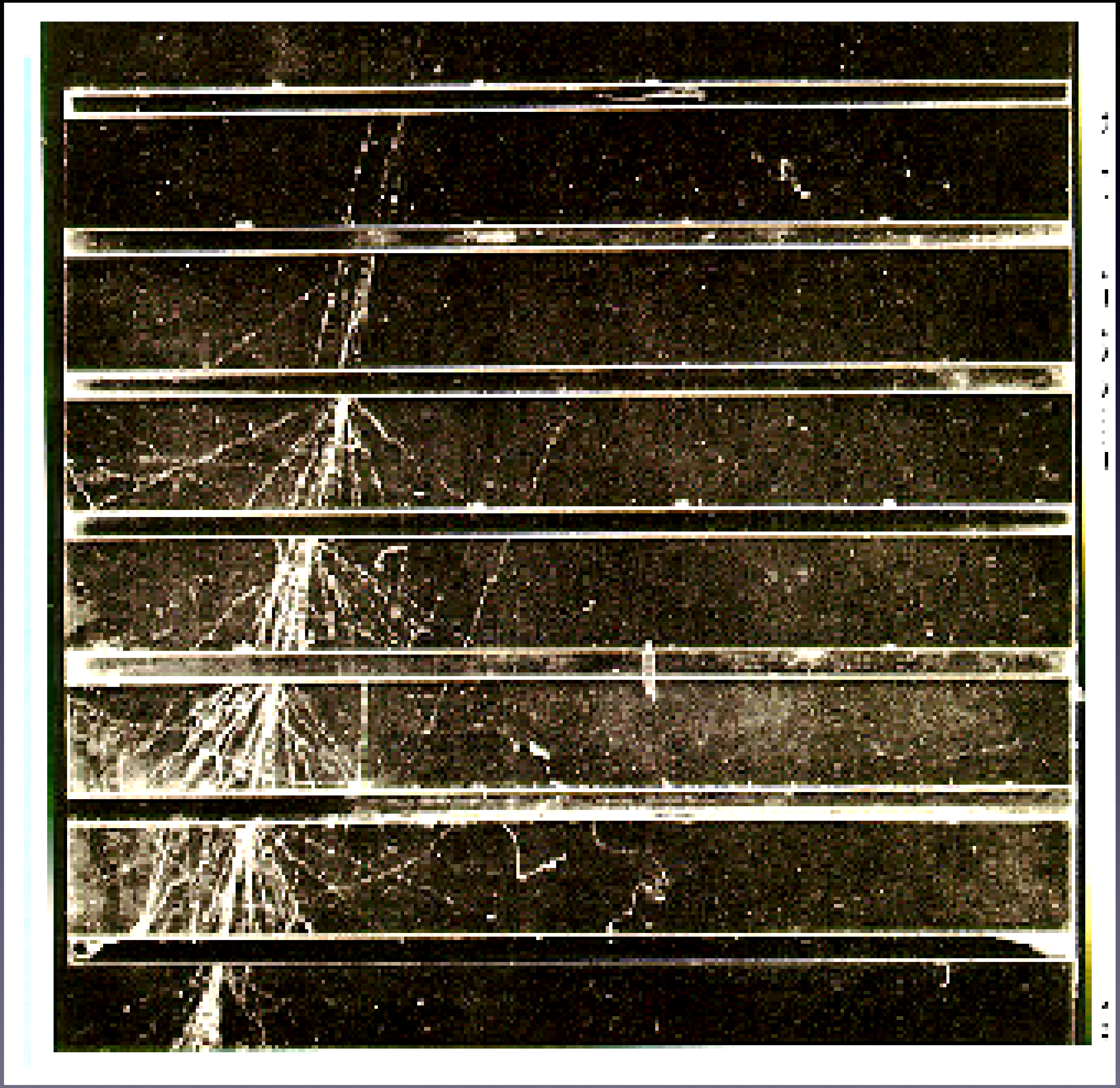
Photoelectric effect

Electromagnetic Shower



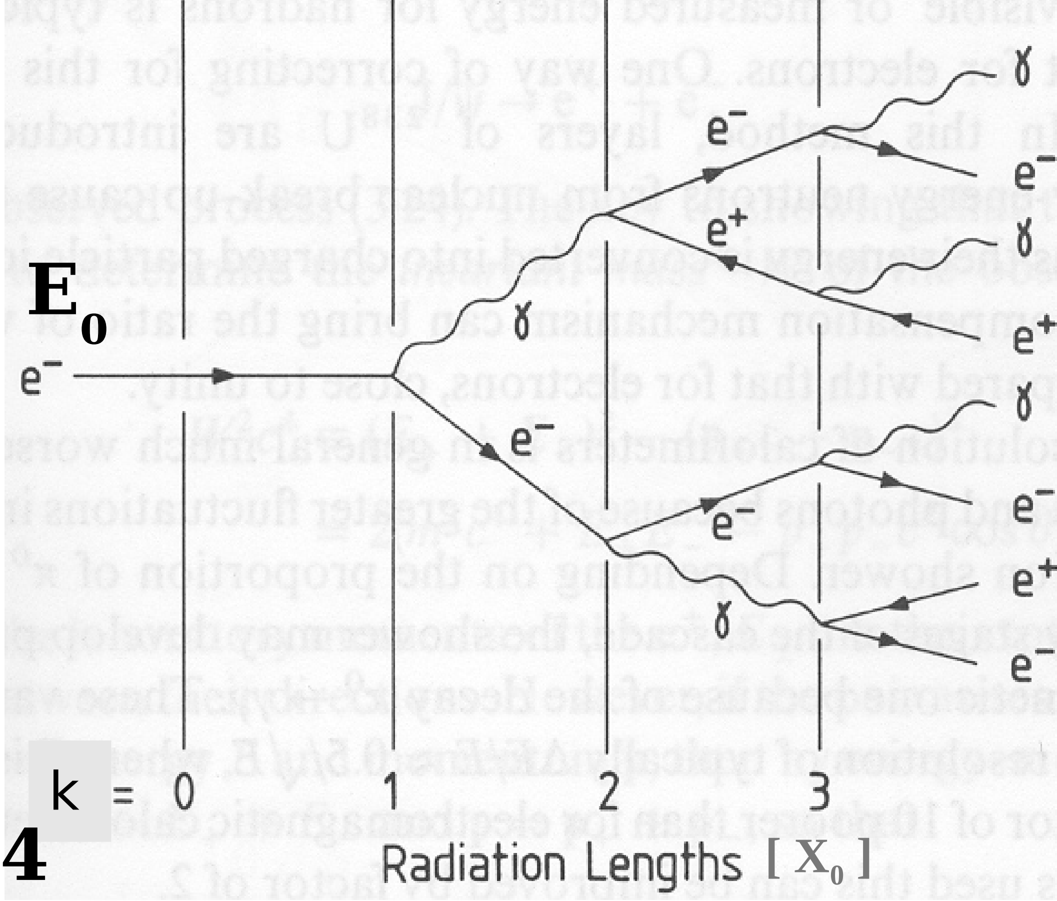
x	0	X_0	$2X_0$	$3X_0$	$4X_0$	
N	1	2	4	8	16	0
$\langle E \rangle$	E_0	$E_0/2$	$E_0/4$	$E_0/8$	$E_0/16$	$<E_c$

Shower in a cloud chamber



铅板之间的
级联簇射

A simple shower model



Start with a high energy electron: $\mathbf{E_0}$

⇒ After $\mathbf{1X_0}$: $\mathbf{1\ e^-}$ and $\mathbf{1}\gamma$, each with $\mathbf{E_0/2}$

⇒ After $\mathbf{2X_0}$: $\mathbf{2\ e^-}$, $\mathbf{1\ e^+}$ and $\mathbf{1}\ \gamma$, each with $\mathbf{E_0/4}$

⇒ After $\mathbf{kX_0}$: total $\mathbf{N = 2^k}$, each with $\mathbf{<E> = E_0/2^k}$

At $\mathbf{<E> = E_c}$ pair production and bremsstrahlung stop.

Compton- or photoeffect and ionization take over. The shower ranges out.

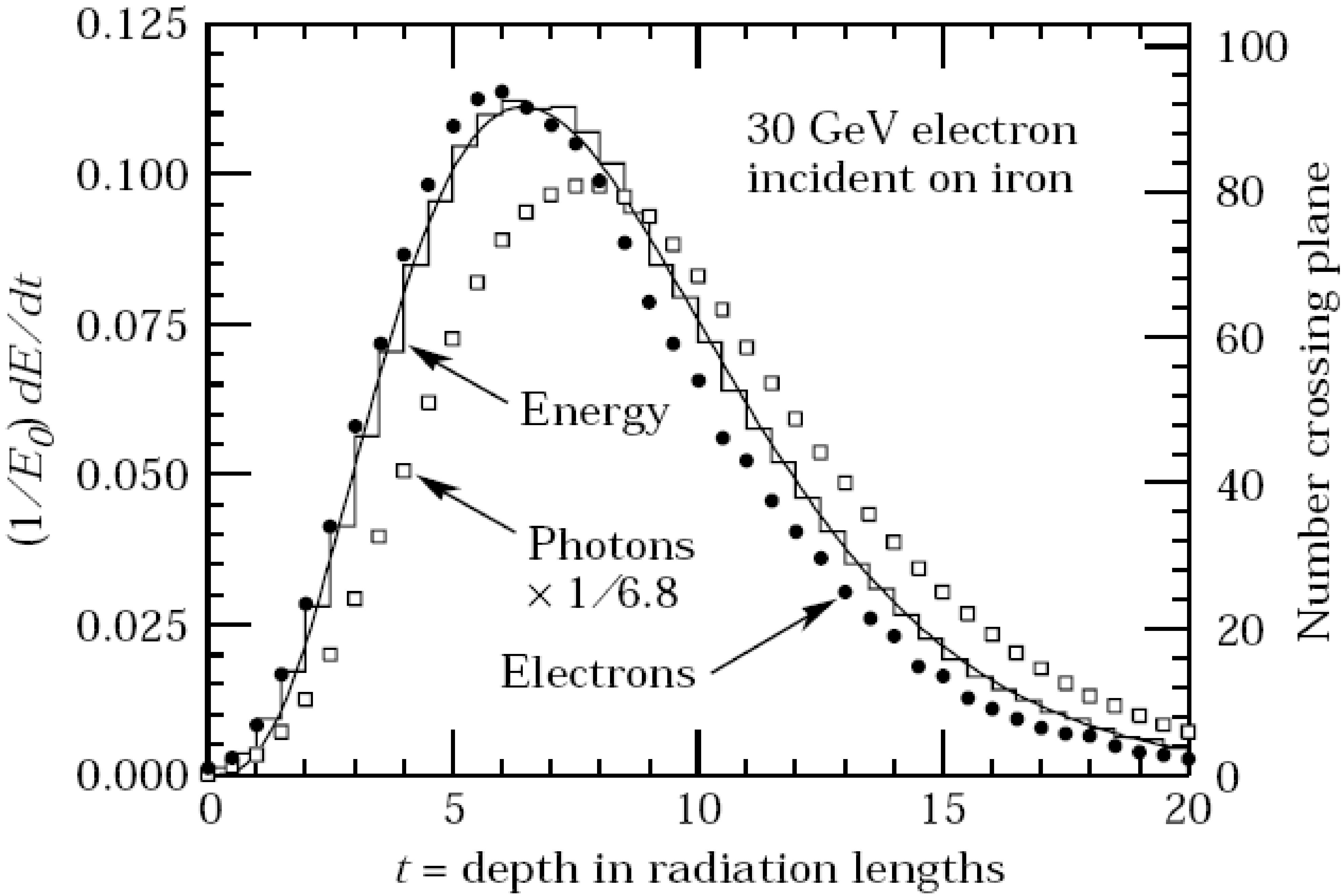
E_c = 0.6 GeV / (Z+1.24) = 7 MeV for lead. (empirical fit by the PDG)

⇒ $\mathbf{k_{max} = lg_2(E_0/E_c)}$. **Shower depth grows logarithmically with $\mathbf{E_0}$.**

⇒ $\mathbf{N_{max} = 2^{kmax} = E_0/E_c}$. **Number of particles grows linearly with $\mathbf{E_0}$.**

A sophisticated shower simulation

Energy profile

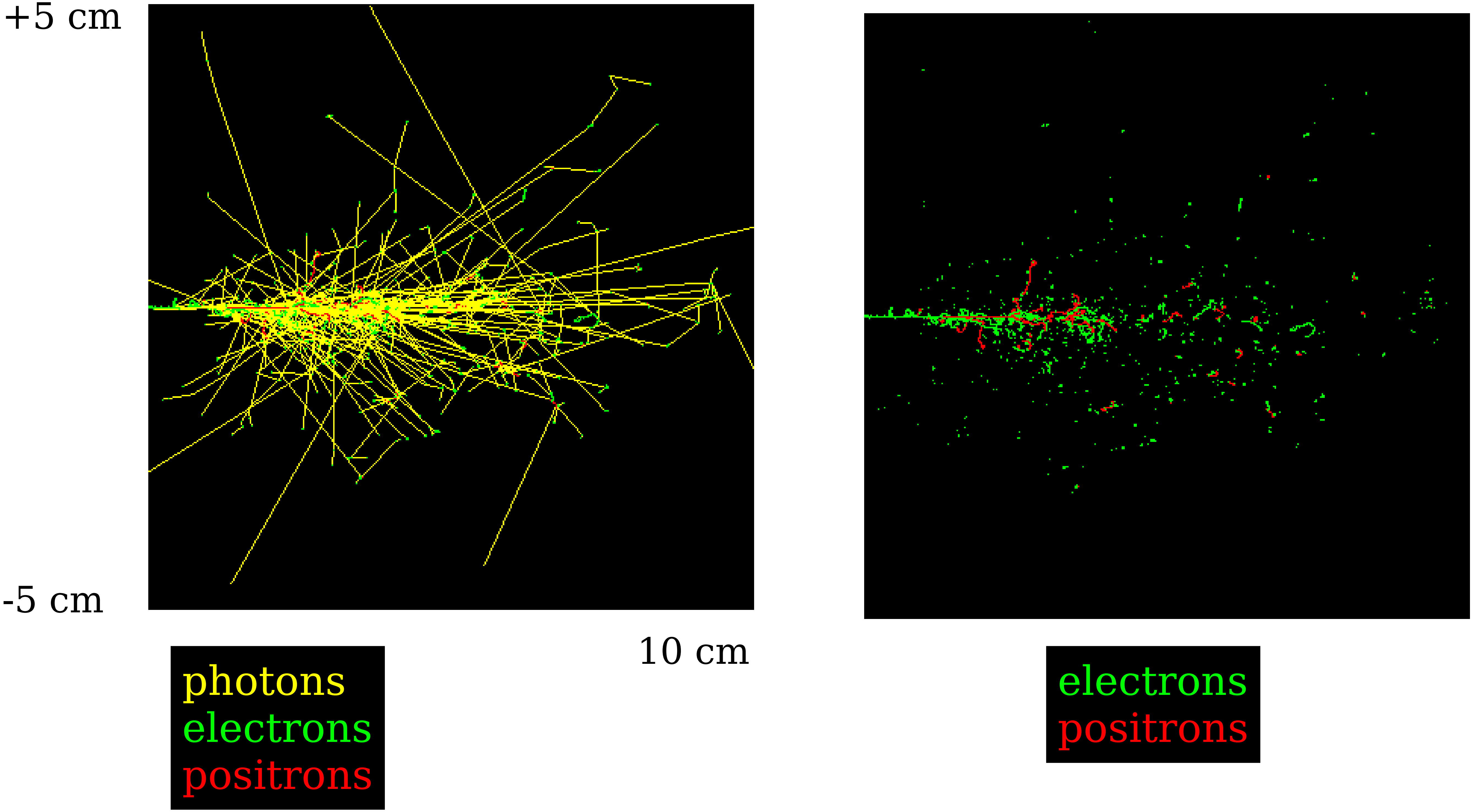


particle flow

longitudinal shower profile: $\frac{dE}{dt} = E_0\, b\, \frac{(bt)^{a-1}\, e^{-bt}}{\Gamma(a)}\,,\ t = \frac{x}{X_0}$

Shower simulation

1 GeV e^- in lead



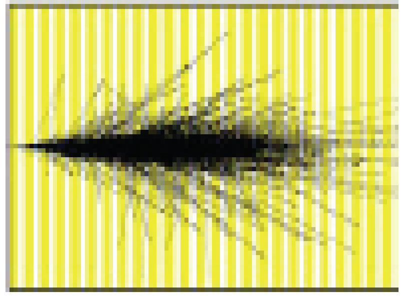
Energy measurement

Total number of particles in the shower in the simple model:

$\mathbf{N_{tot} = \sum_k 2^k = 2\ k_{max} - 1 \approx 2\ E_0 / E_c}$

2/3 of N_{tot} are charged ($e^+ + e^-$).

$\Rightarrow \mathbf{N_{ch} \approx 4/3\ E_0 / E_c}$



Each *e* travels 1 X0 between interactions.

⇒ **total path length:** $\mathbf{L_{ch} \approx 4/3\ X_0\ E_0 / E_c}$

Electrons and positrons also **ionize** the medium.

Collect the charge or the fluorescent light signal: $\mathbf{S \sim X_0\ E_0 / E_c}$

After calibration, S is an energy measurement!

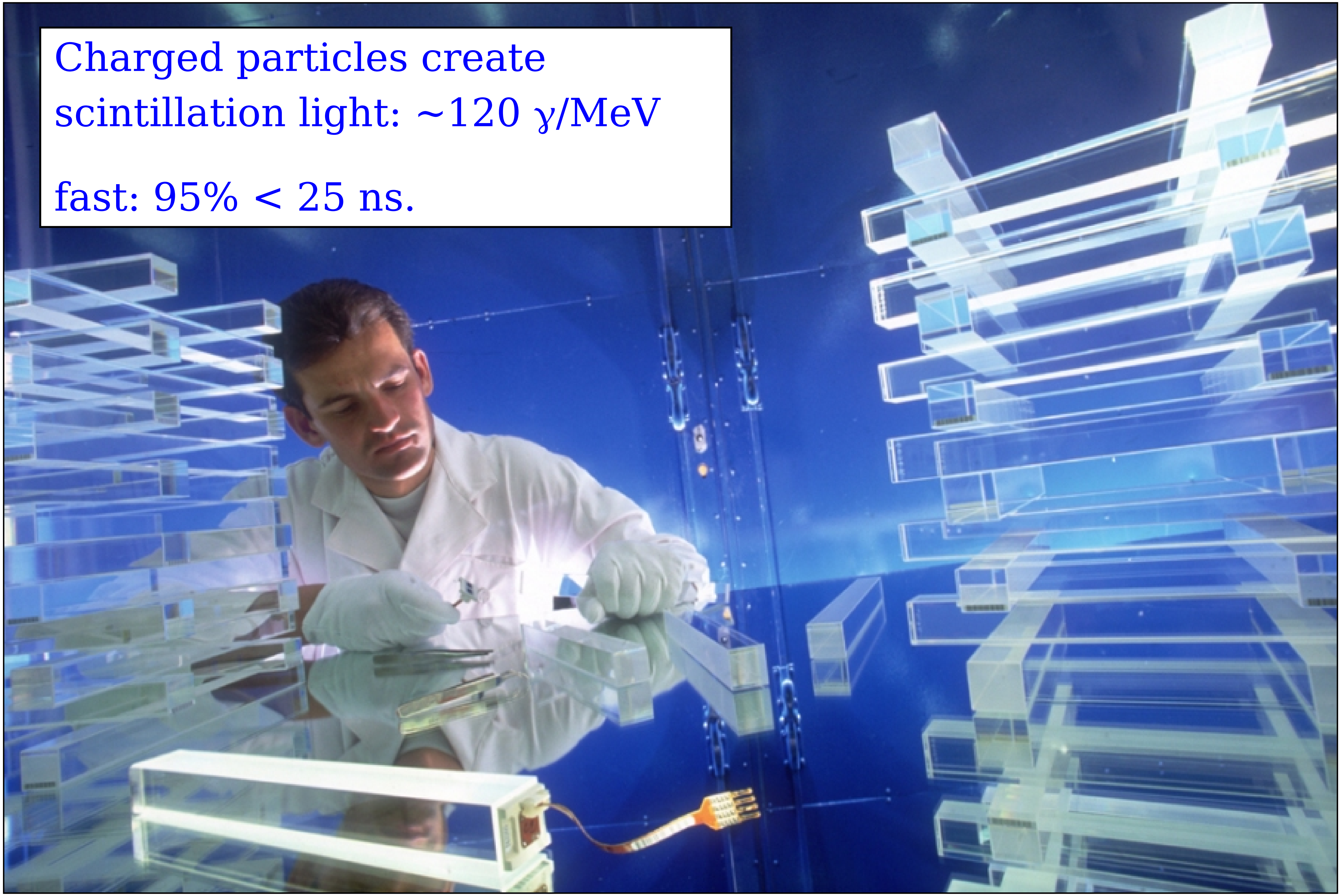
Shower fluctuations: particle production is a Poisson process.

$\Rightarrow \sigma(\mathbf{N}) = \sqrt{\mathbf{N}}$

$\Rightarrow \sigma(\mathbf{S}) / \mathbf{S} = 1 / \sqrt{\mathbf{S}}$

The relative energy resolution improves as $\mathbf{1/\sqrt{E_0}}$.

CMS PbWO Crystals

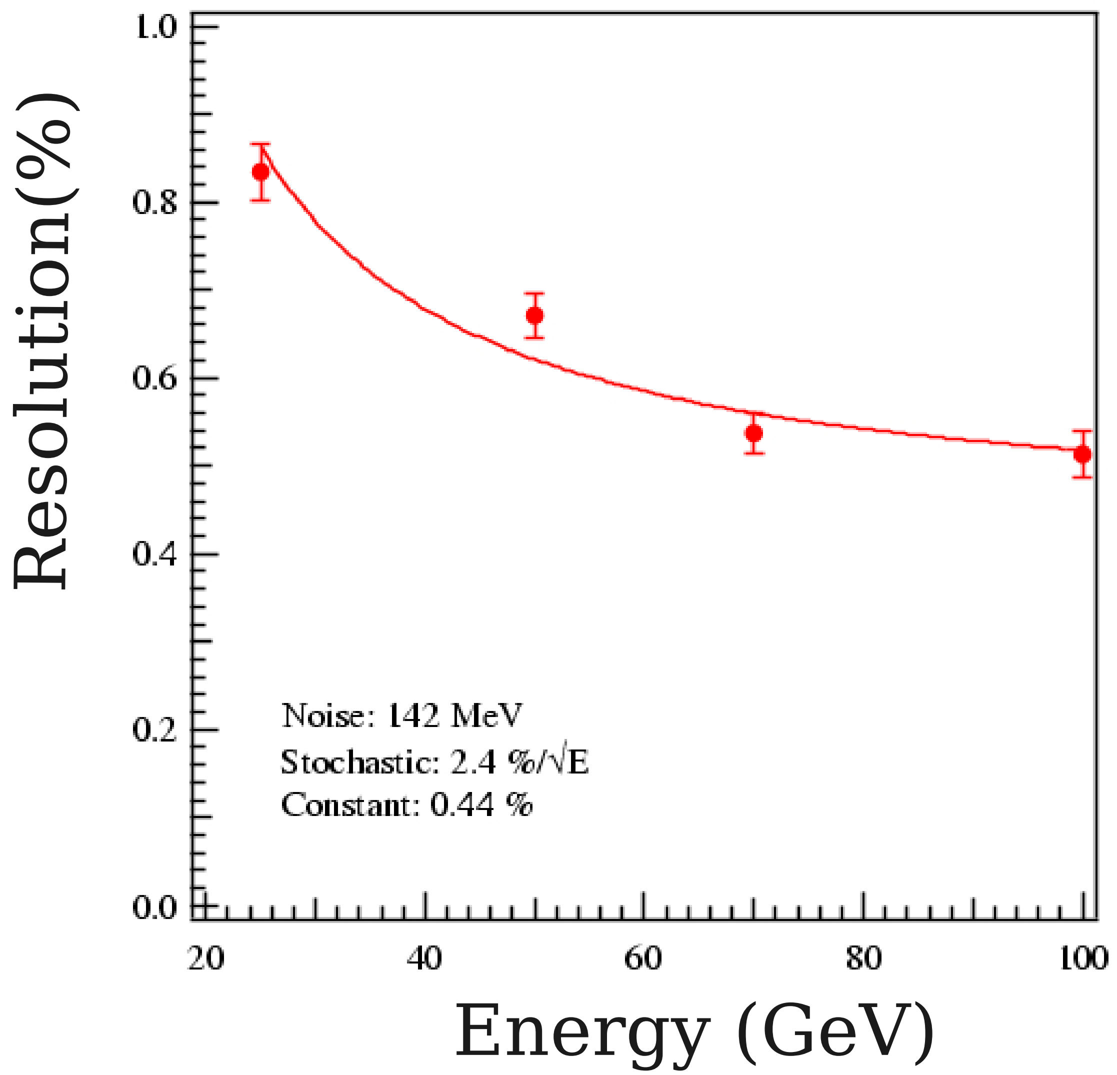


Charged particles create scintillation light: ~120 γ/MeV

fast: 95% < 25 ns.

CMS ECAL Test beam with final electronics

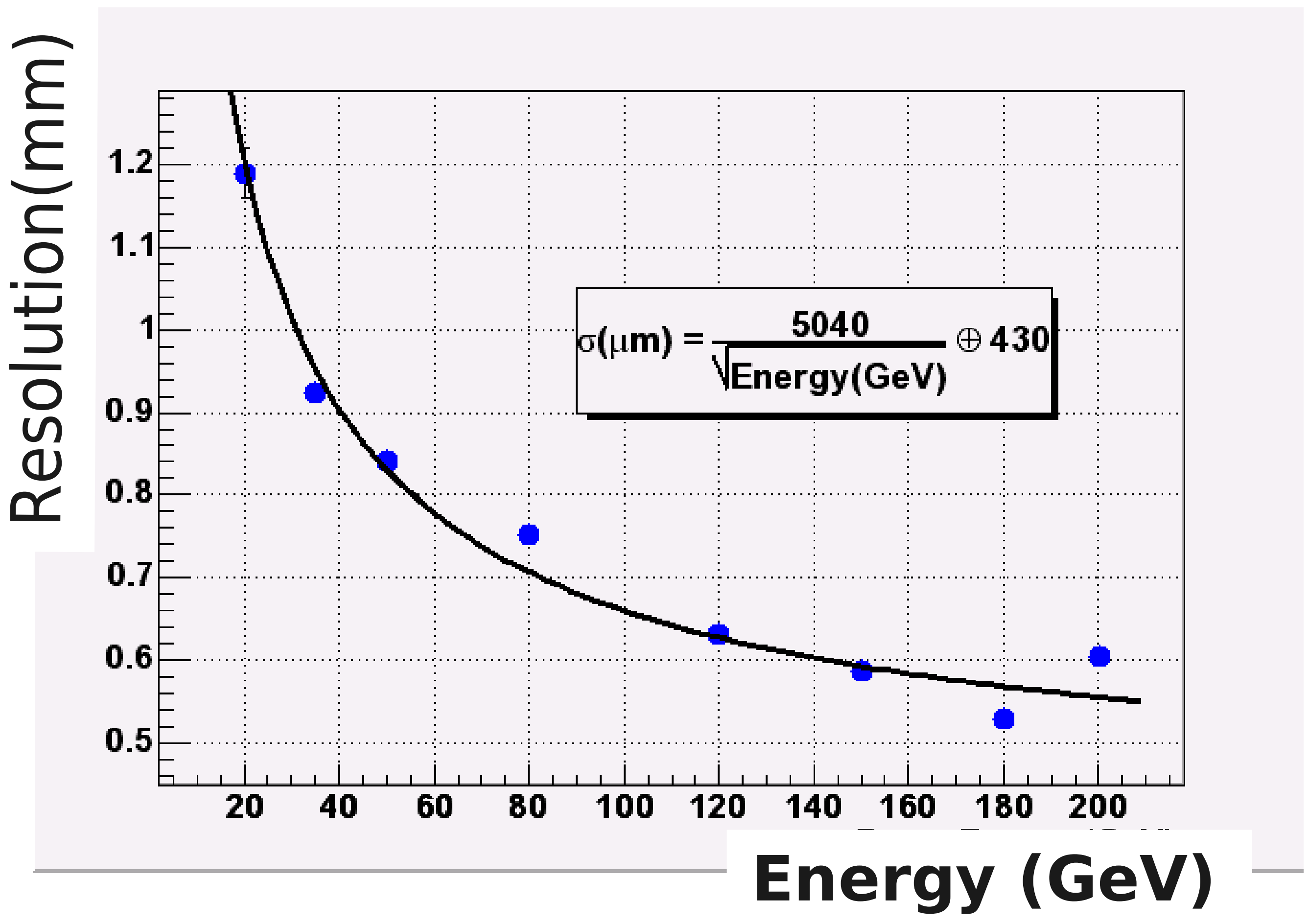
Energy



$$\frac{\sigma(E)}{E} = \frac{2.4\,\%}{\sqrt{E}} \oplus \frac{142\ \text{MeV}}{E} \oplus 0.44\ \%$$

0.6% at 50 GeV.

Position

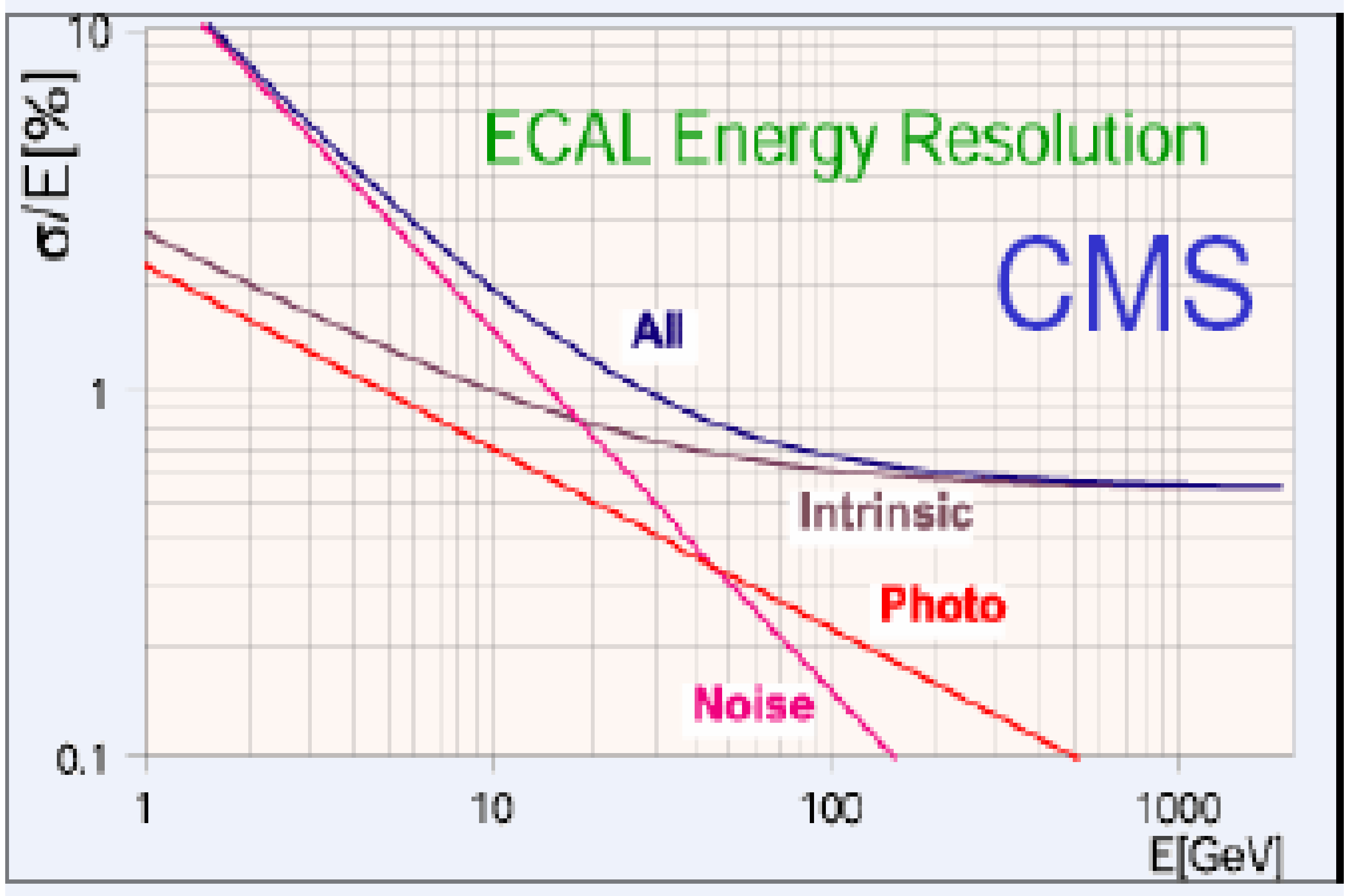


$$\sigma_Y\,(\mu m) = \frac{5040}{\sqrt{E}} \oplus 430$$

0.85 mm at 50 GeV.

Energy resolution terms

- The intrinsic shower fluctuations give σ(E) ~ √E
- Fluctuations in the photo-electron yield also give σ(E) ~ √E
- Noise (electronics, radiation) gives a constant term: σ(E) = c
- Inhomogeneities and leakage give σ(E) ~ E



$$\frac{\sigma(E)}{E} = \frac{2.4\,\%}{\sqrt{E}} \oplus \frac{142\ \mathrm{MeV}}{E} \oplus 0.44\ \%$$

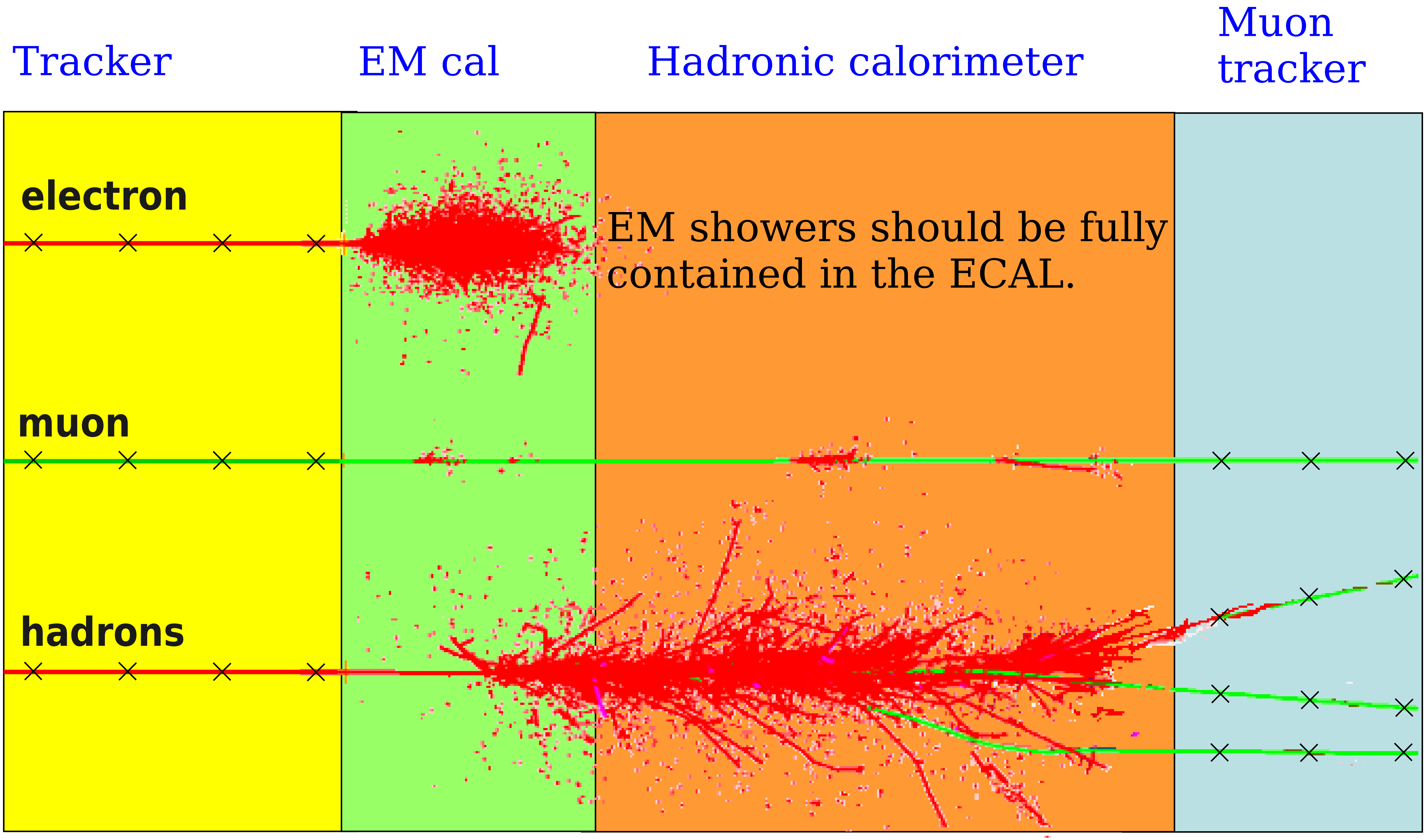
3）强子量能器

强子级联簇射 (Hadron shower)

高能散射过程的次级衰变产物将被量能器完全吸收，从而测得这些粒子的能量和位置。所有（或大部分）入射能量都以激发或离子化探测材料的原子的形式记录下来。

Calorimeter

Hadronic showers



EM showers should be fully contained in the ECAL.

Hadronic showers may already start in the ECAL and extend into the HCAL.

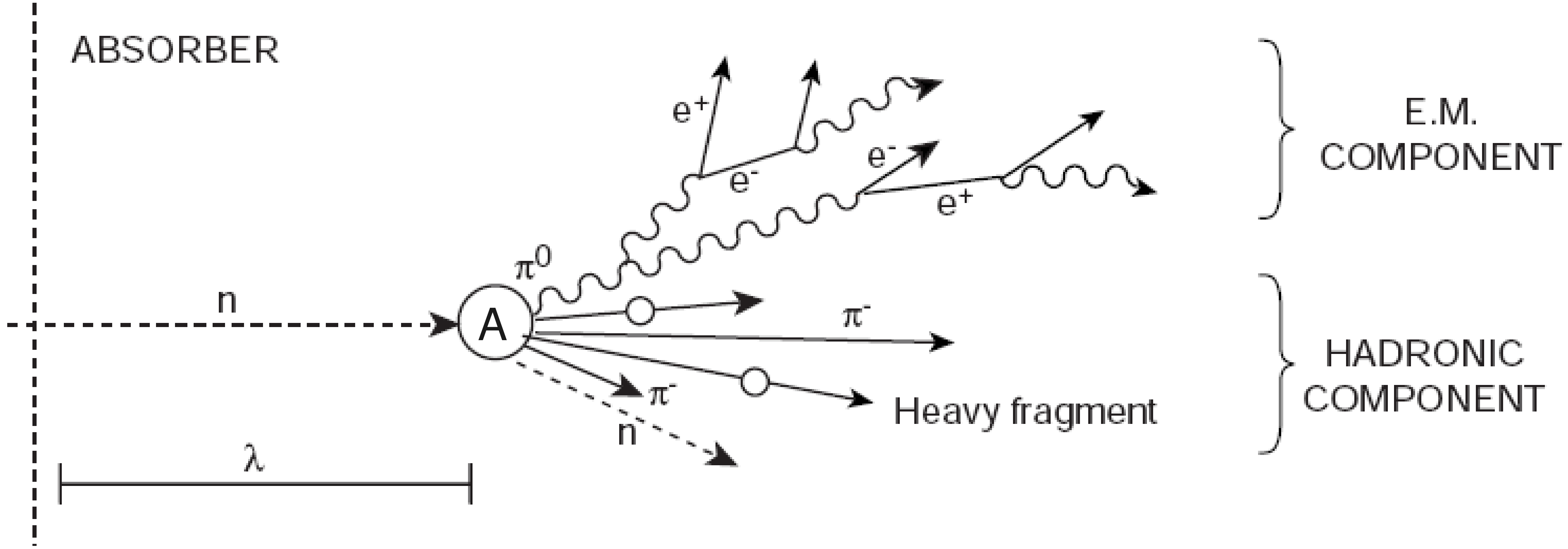
Hadronic interaction length

- Pion-proton cross section σ(πp) ≈ 25 mbarn above a few GeV.
- σ(πA) ≈ σ(πp) $A^{2/3}$ (black disk limit).
- ⇒ hadronic interaction length:

$$\lambda_I = \frac{A}{\sigma N_A \rho} = \frac{35\,cm}{\rho} A^{1/3}$$

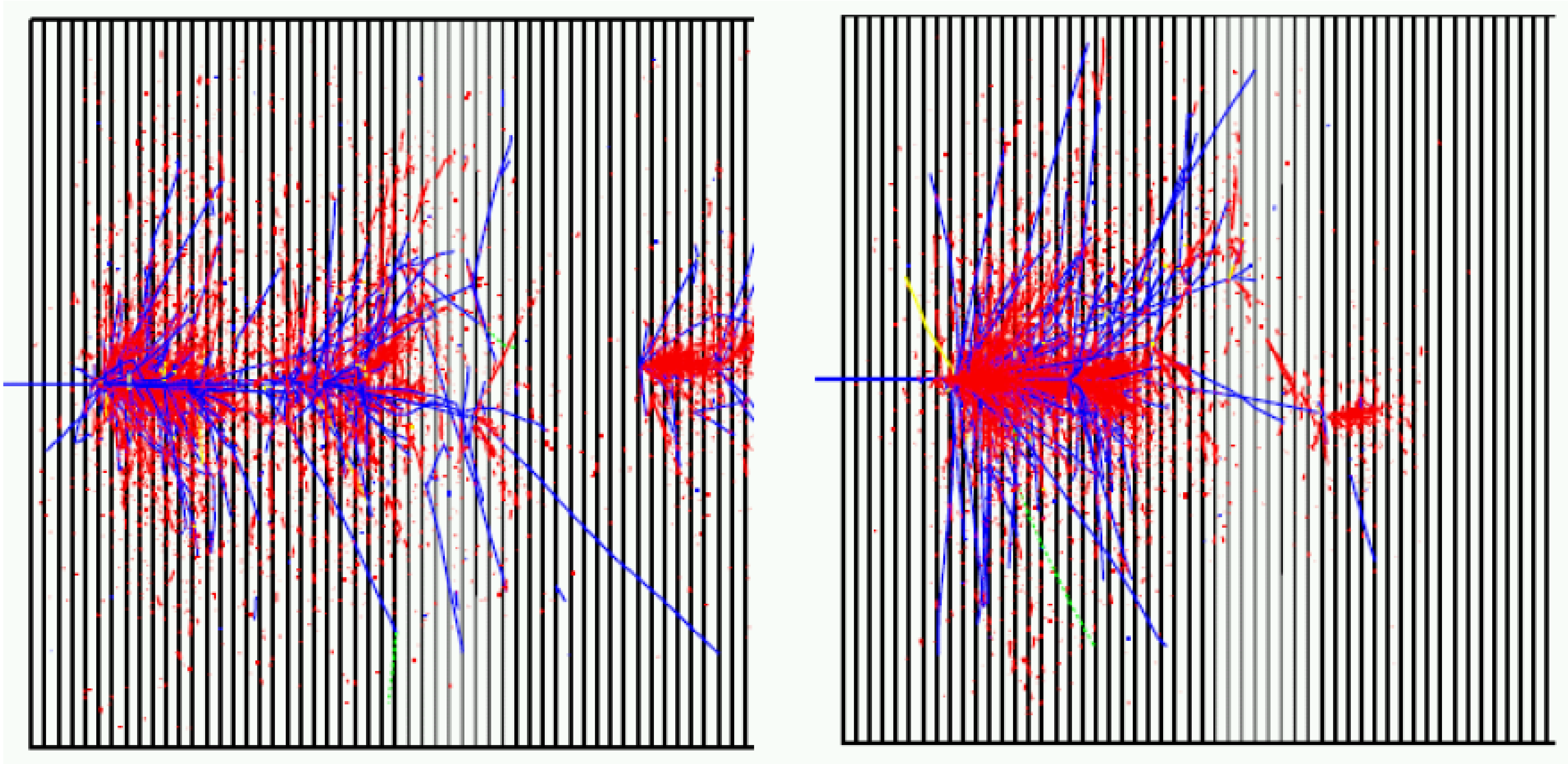
- λ_I = 17 cm in Fe or Pb.
- Much larger than X_0.

Hadronic showers



- Hadronic interaction have high multiplicity:
  - Shower is to 95% contained in ~7λ at 50 GeV (1.2m of iron).
- Hadronic interactions produce π^0:
  - $\pi^0 \rightarrow \gamma\gamma$, leading to local EM showers ('hot spots', ~30%)
- Some energy lost in nuclear breakup and neutrons ('invisible energy', 15-35%).
- Stronger fluctuations in a hadronic shower:
  - Worse energy resolution.

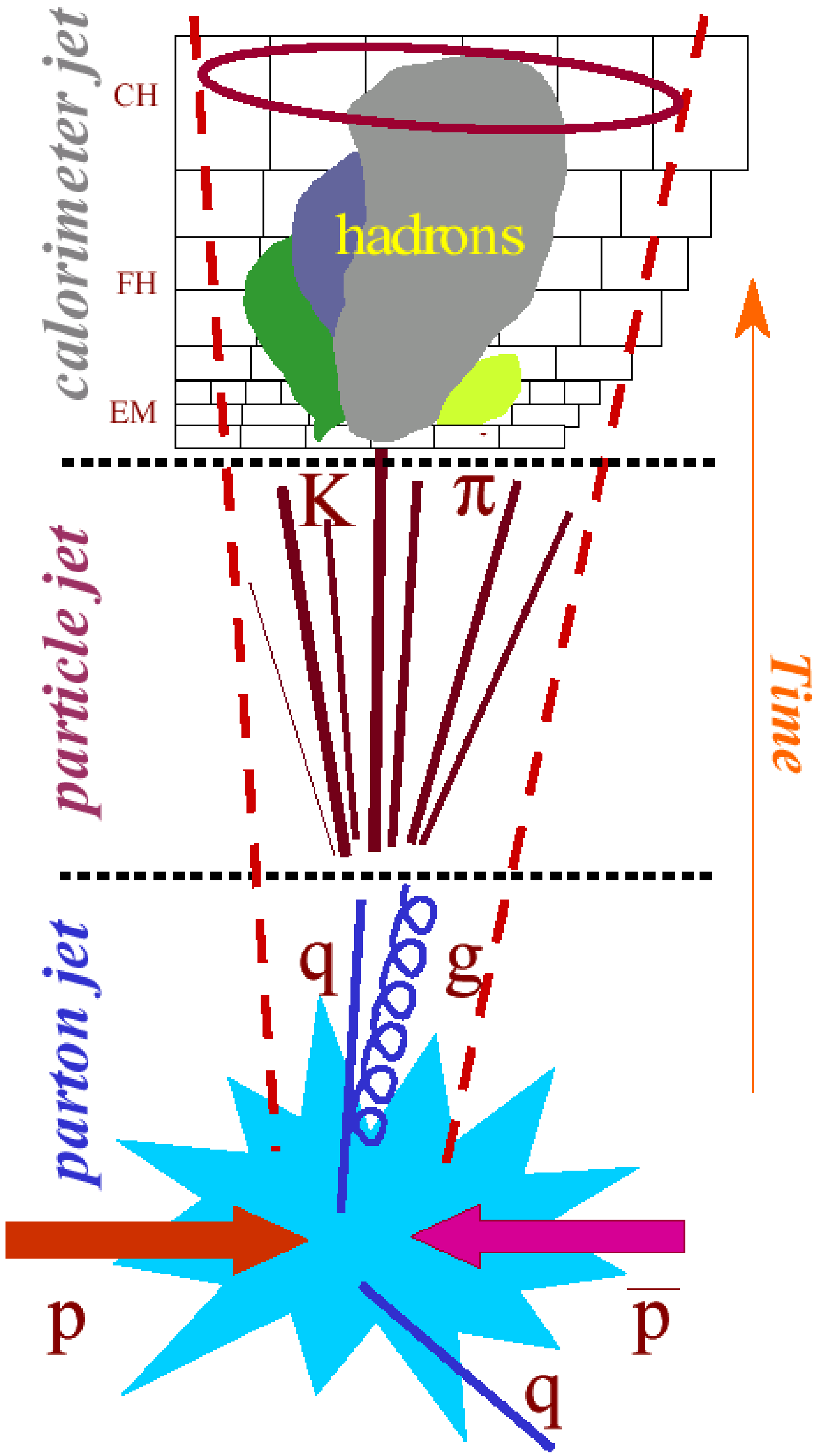
2 hadronic showers



blue = hadronic component red = electromagnetic component

A good hadron calorimeter should have
equal response to hadrons and electrons ('hardware compensation')
or high granularity to isolate the hot spots ('software compensation')

Jet Finding

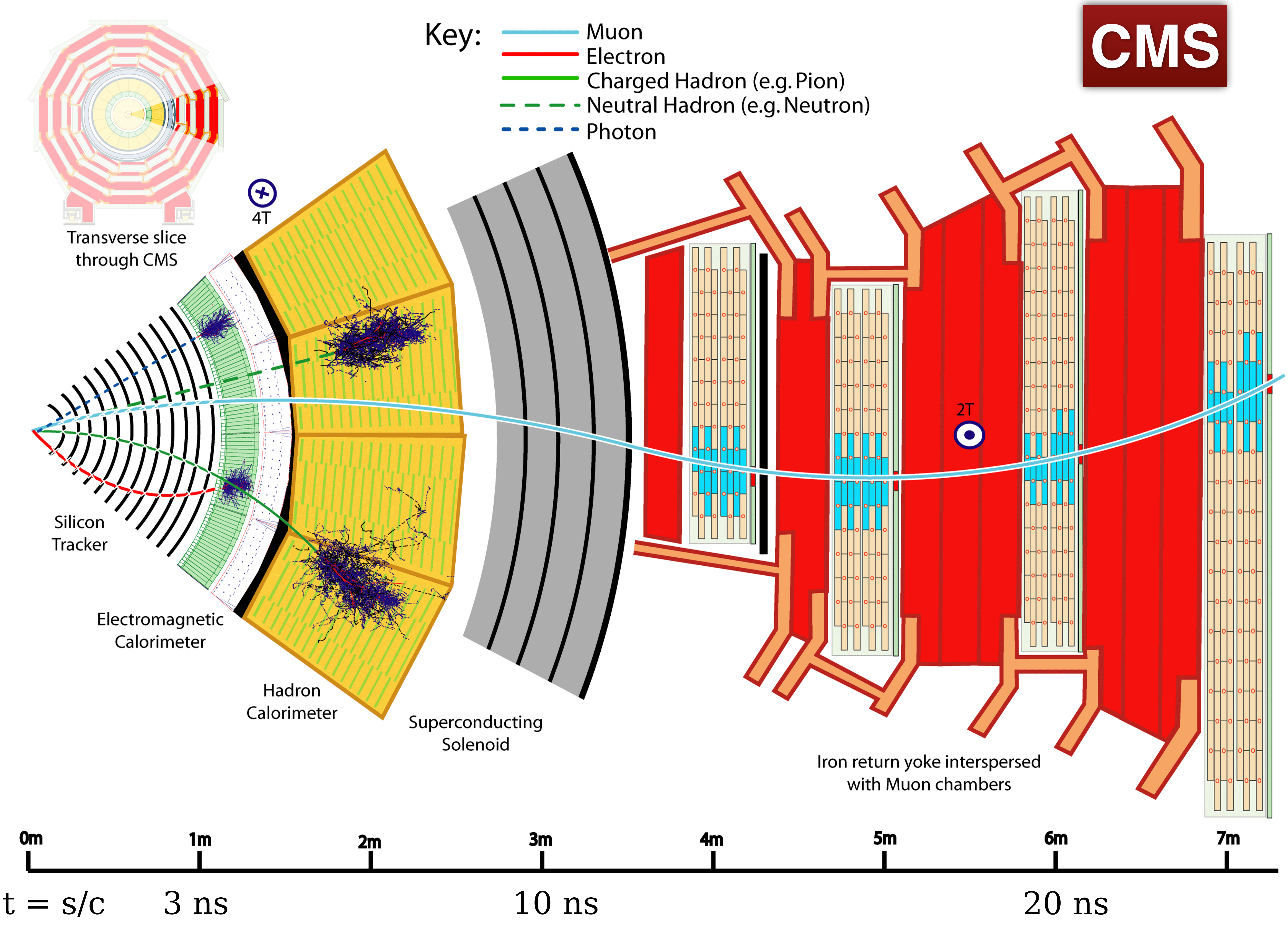


- **Calorimeter jet (cone)**
  - jet is a collection of energy deposits with a given cone *R*: $R = \sqrt{\Delta\varphi^2 + \Delta\eta^2}$
  - cone direction maximizes the total E_T of the jet
  - various clustering algorithms

→ correct for finite energy resolution
→ subtract underlying event
→ add out of cone energy

- **Particle jet**
  - a spread of particles running roughly in the same direction as the parton after hadronization

Transverse slice through CMS detector



Key:
- Muon
- Electron
- Charged Hadron (e.g. Pion)
- Neutral Hadron (e.g. Neutron)
- Photon

CMS

Transverse slice through CMS

4T

2T

Silicon Tracker

Electromagnetic Calorimeter

Hadron Calorimeter

Superconducting Solenoid

Iron return yoke interspersed with Muon chambers

0m 1m 2m 3m 4m 5m 6m 7m

t = s/c 3 ns 10 ns 20 ns

Summary

1. 粒子电荷和动量测量
   弧高测量和偏转
2. 电子和光子能量测量
   韧致辐射 + 离子化
3. 强子能量测量
   粉碎核 + 核子碰撞
   + 离子化
4. muon子动量测量
   偏转
5. 中微子动量
   丢失动量