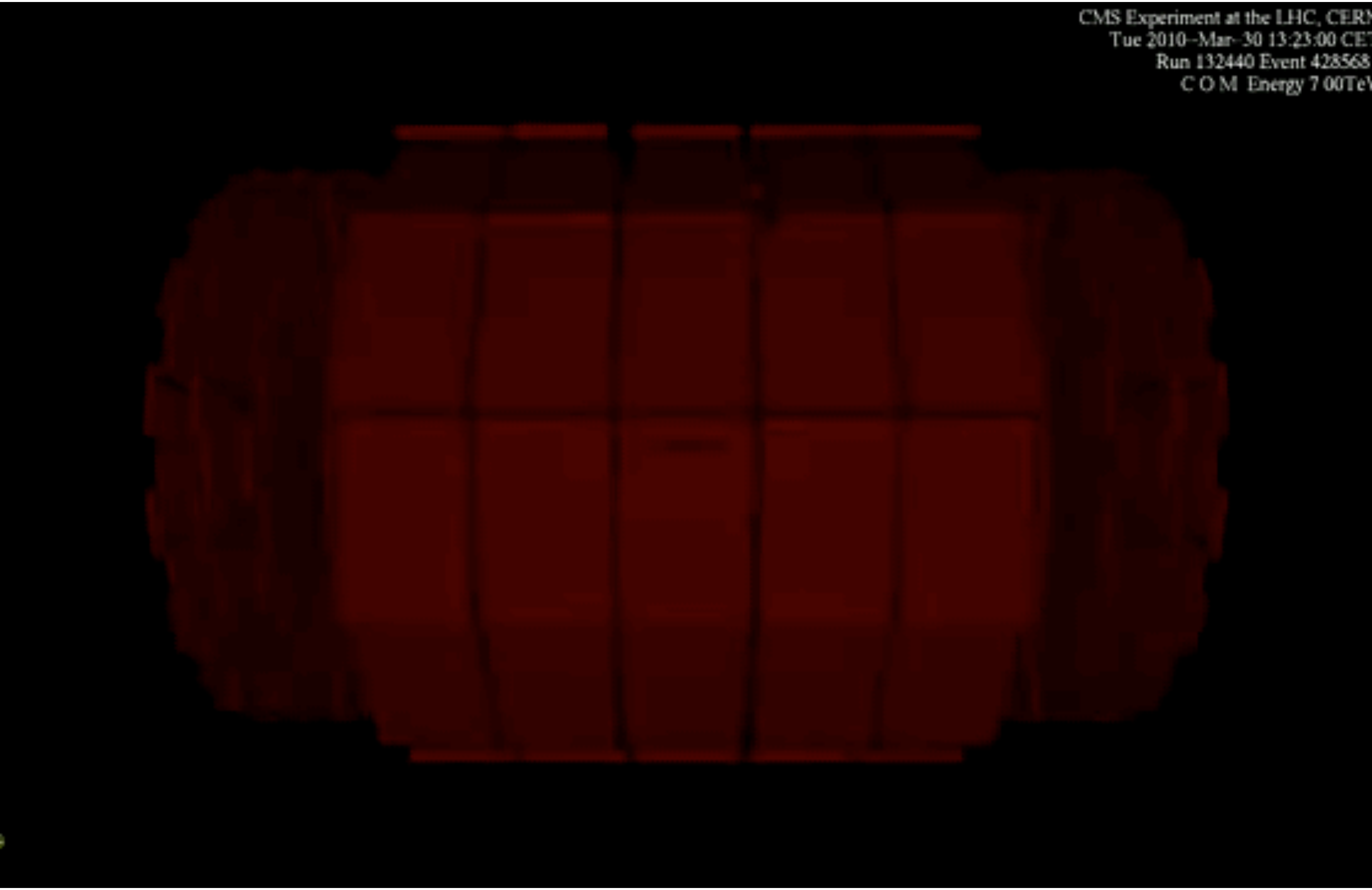
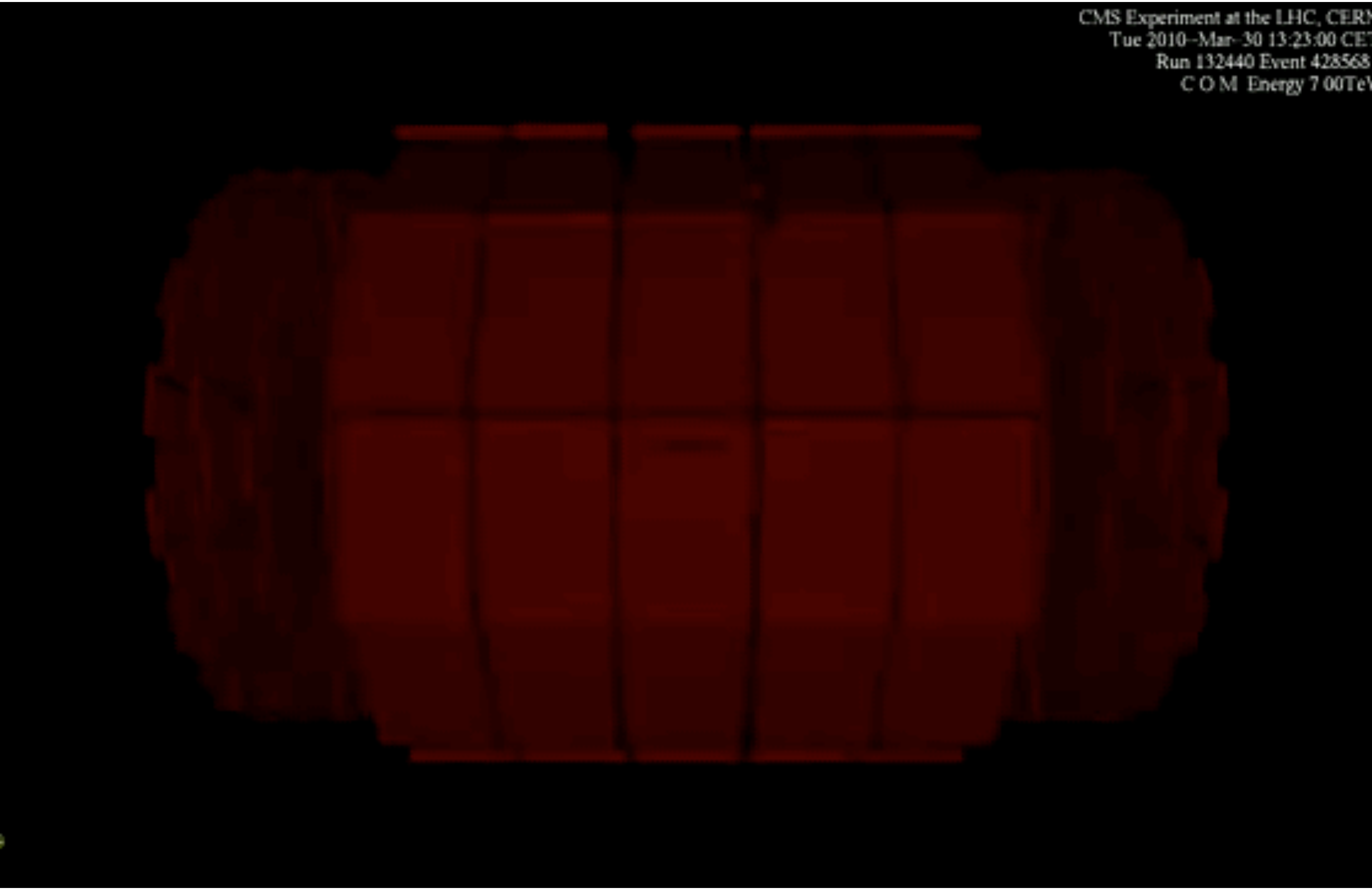
Introduction to Sub-detectors


CMS Experiment at the LHC, CERN
Tue 2010-Mar-30 13:23:00 CET
Run 132440 Event 428568
C O M Energy 7 00TeV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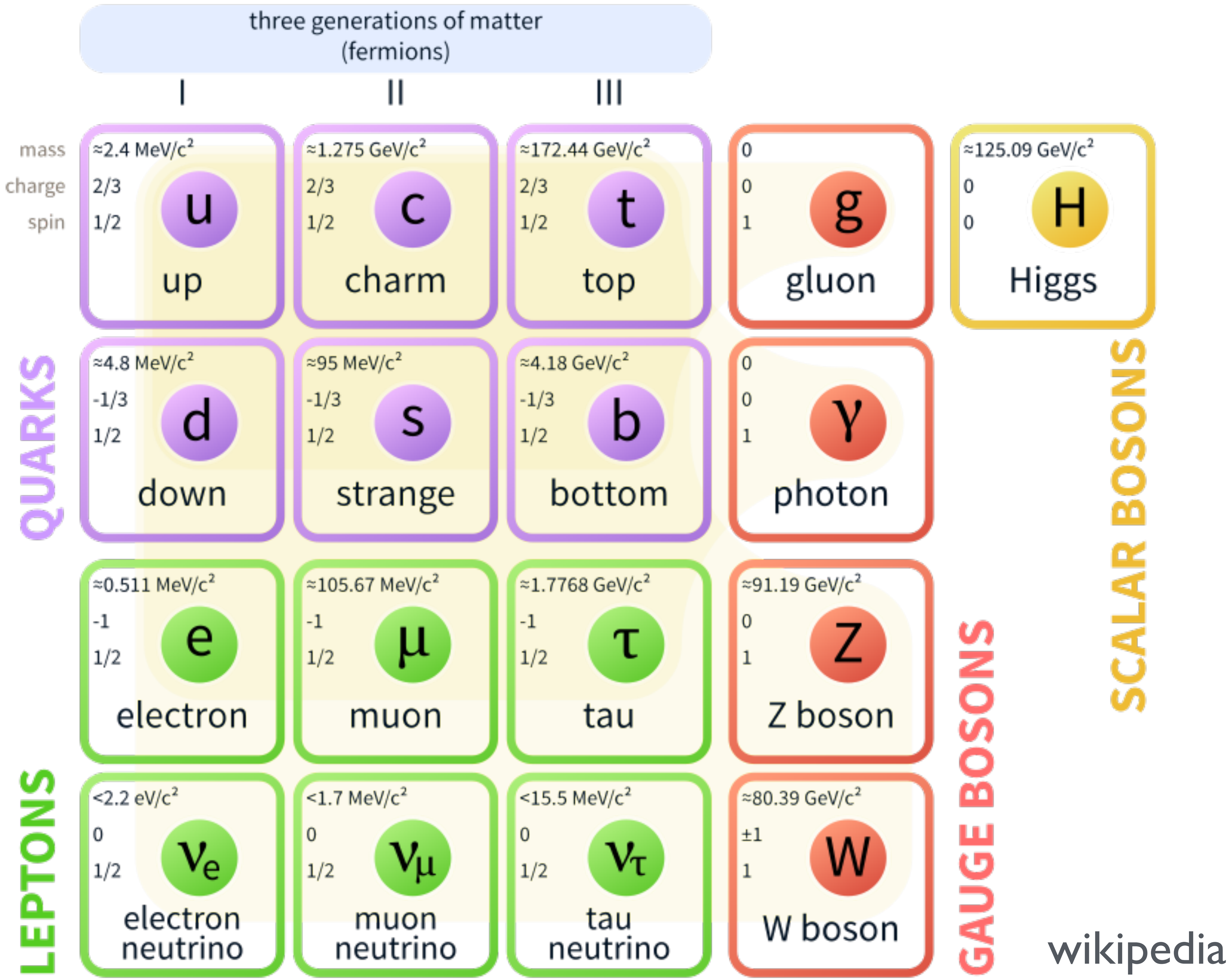
Standard Model of Elementary Particles



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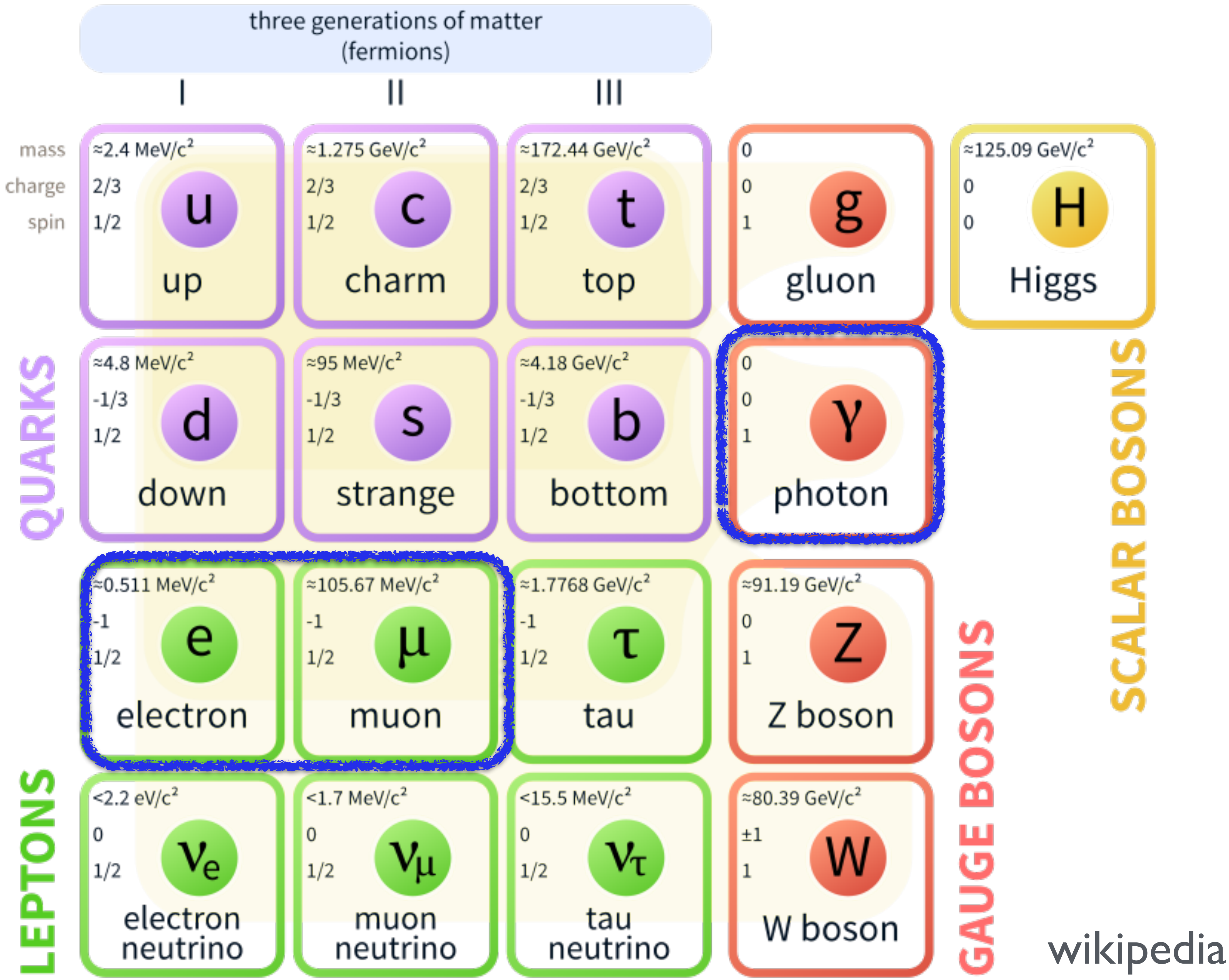

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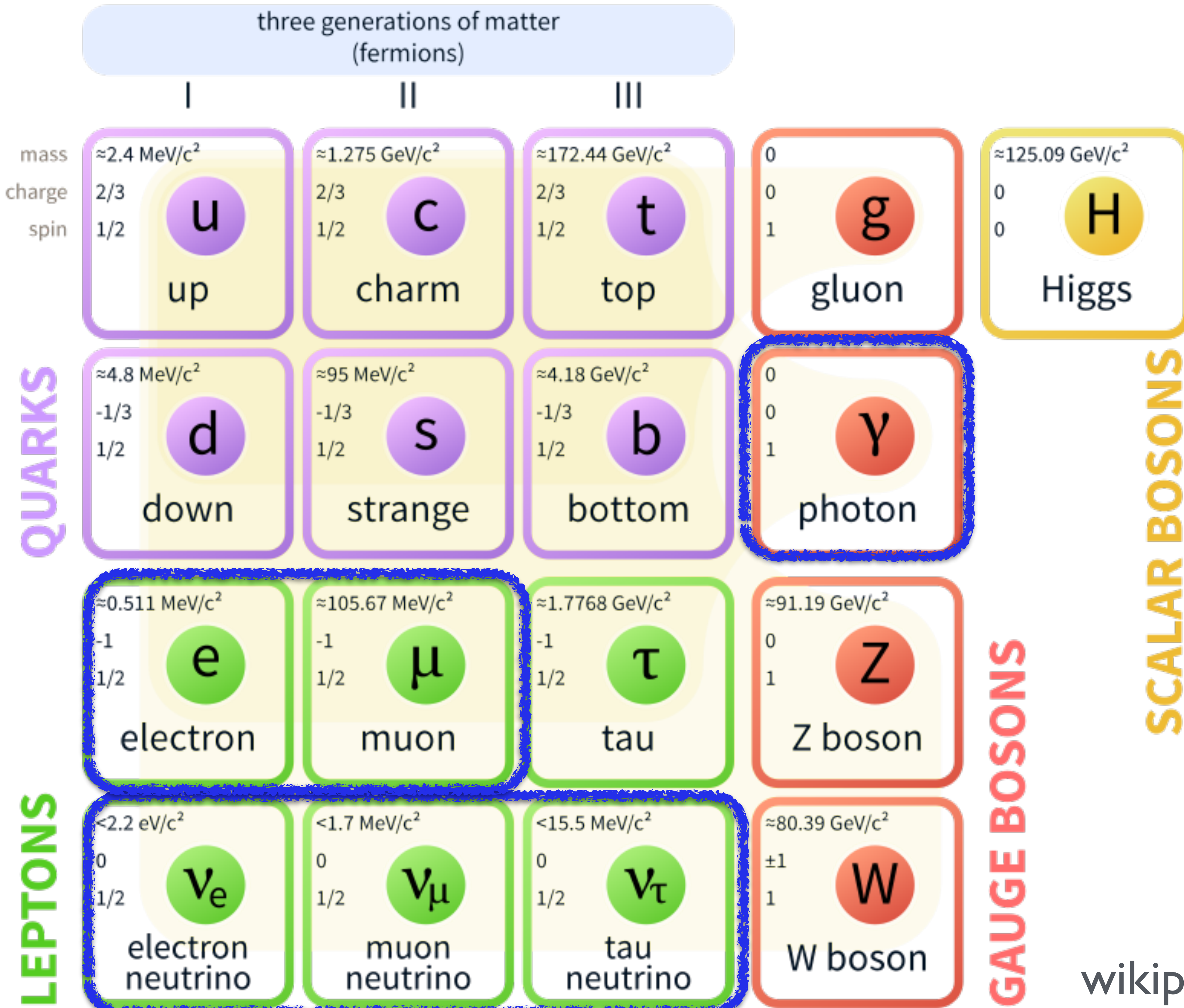

wikipedia

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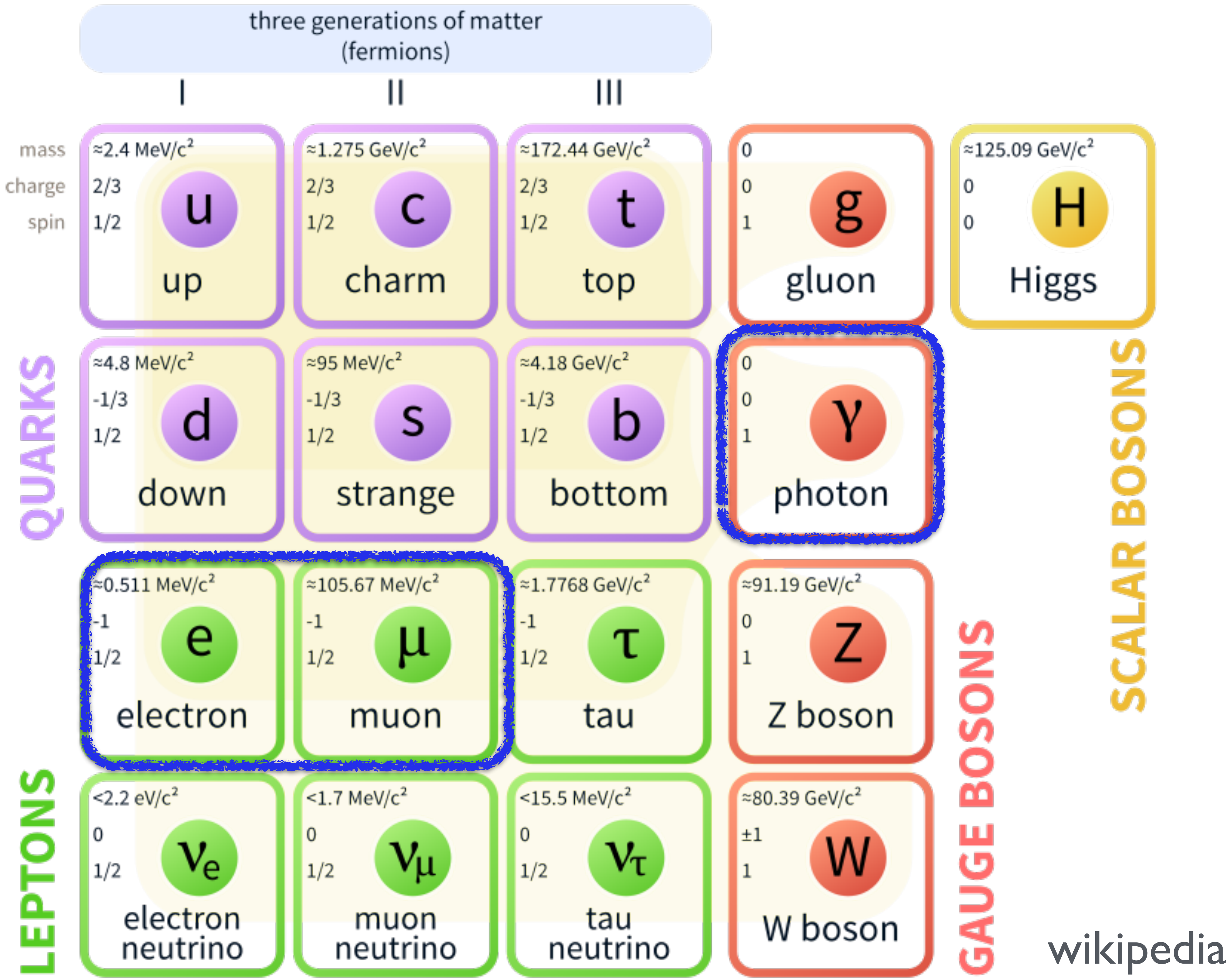

Particles in the Detector

Name	Mass (MeV)	Lifetime	Travel for 1 GeV [m]
e	0.51	$>4.6\times10^{26}$ year	$>8.5\times10^{45}$
μ	105.66	2.2×10^{-6} sec	6250
τ	1776.82	2.9×10^{-13} sec	4.9×10^{-5}
π^0	134.98	8.4×10^{-17} sec	1.9×10^{-7}
$\pi^\pm$	139.57	2.6×10^{-8} sec	56
$K^\pm$	493.68	1.2×10^{-8} sec	7.5
B^0	5279.5	1.5×10^{-12} sec	8.7×10^{-5}
p	938.27	$>2.1\times10^{29}$ year	$>2.1\times10^{45}$
n	939.57	885.7 sec	2.8×10^{11}
W	80399	10^{-25} sec	3.7×10^{-19}
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Jets

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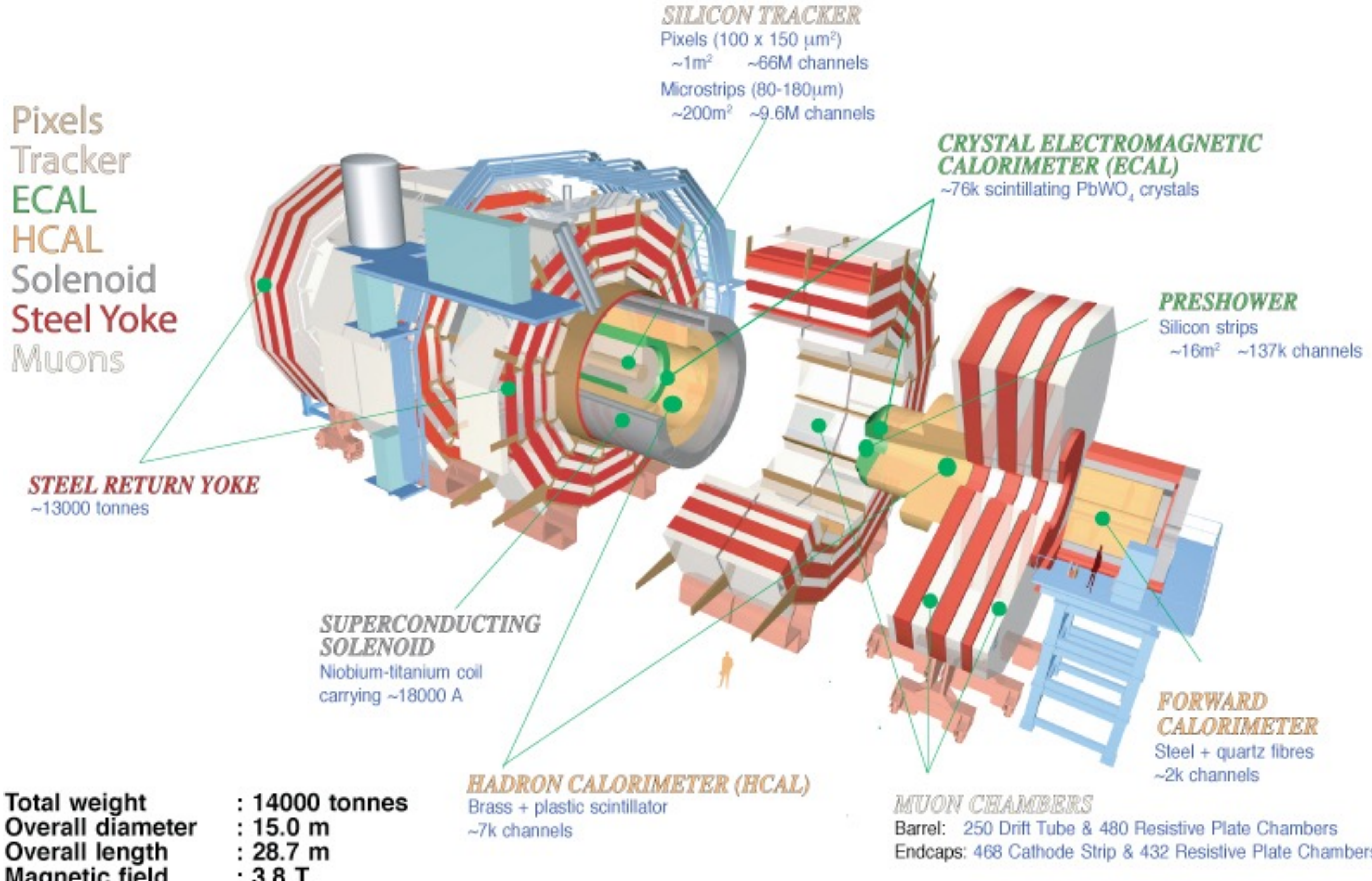
    - γ, e, μ, charged hadrons, neutral hadrons

CMS Detector Sketch



A Standard Collider Detector

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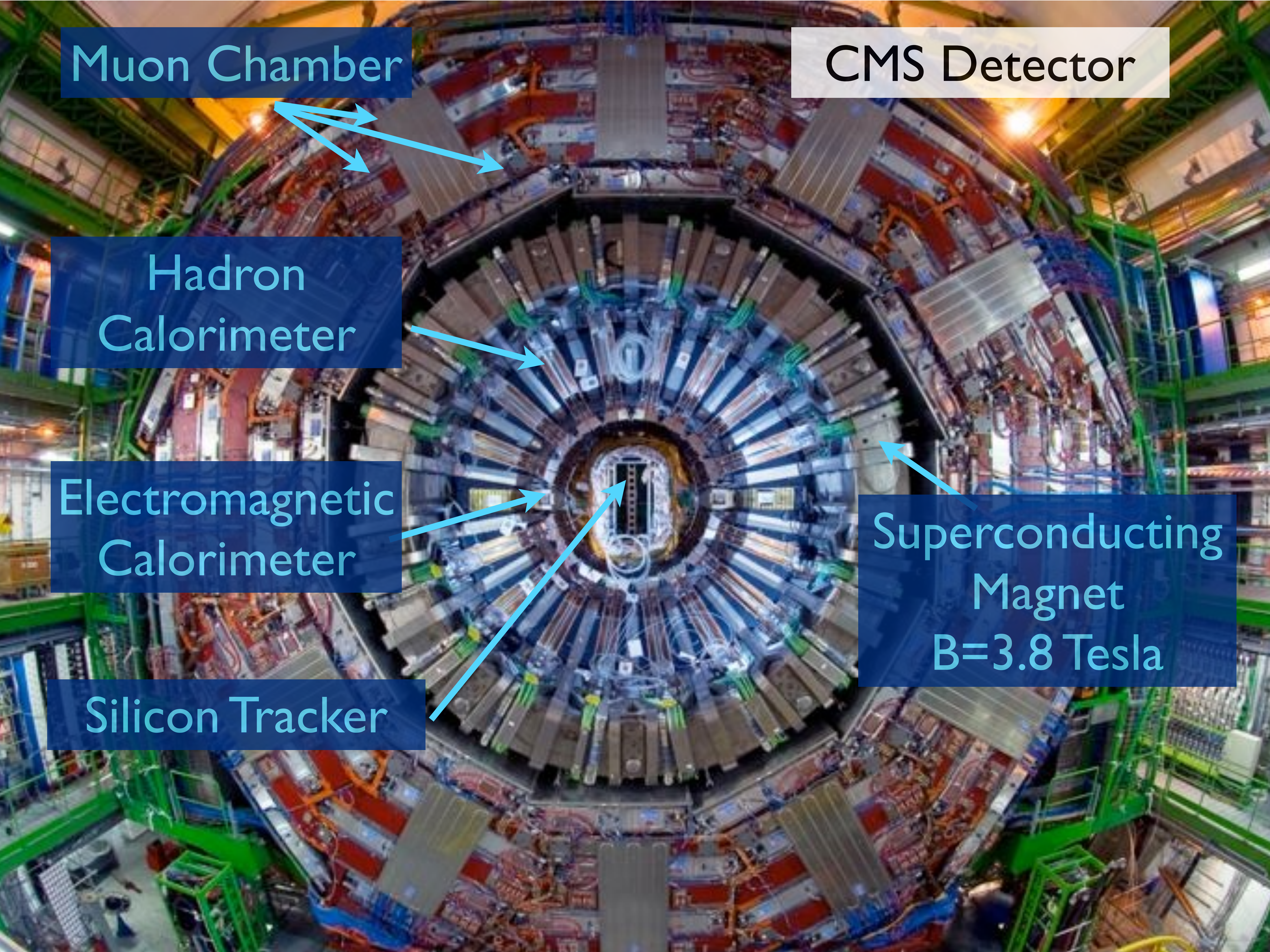
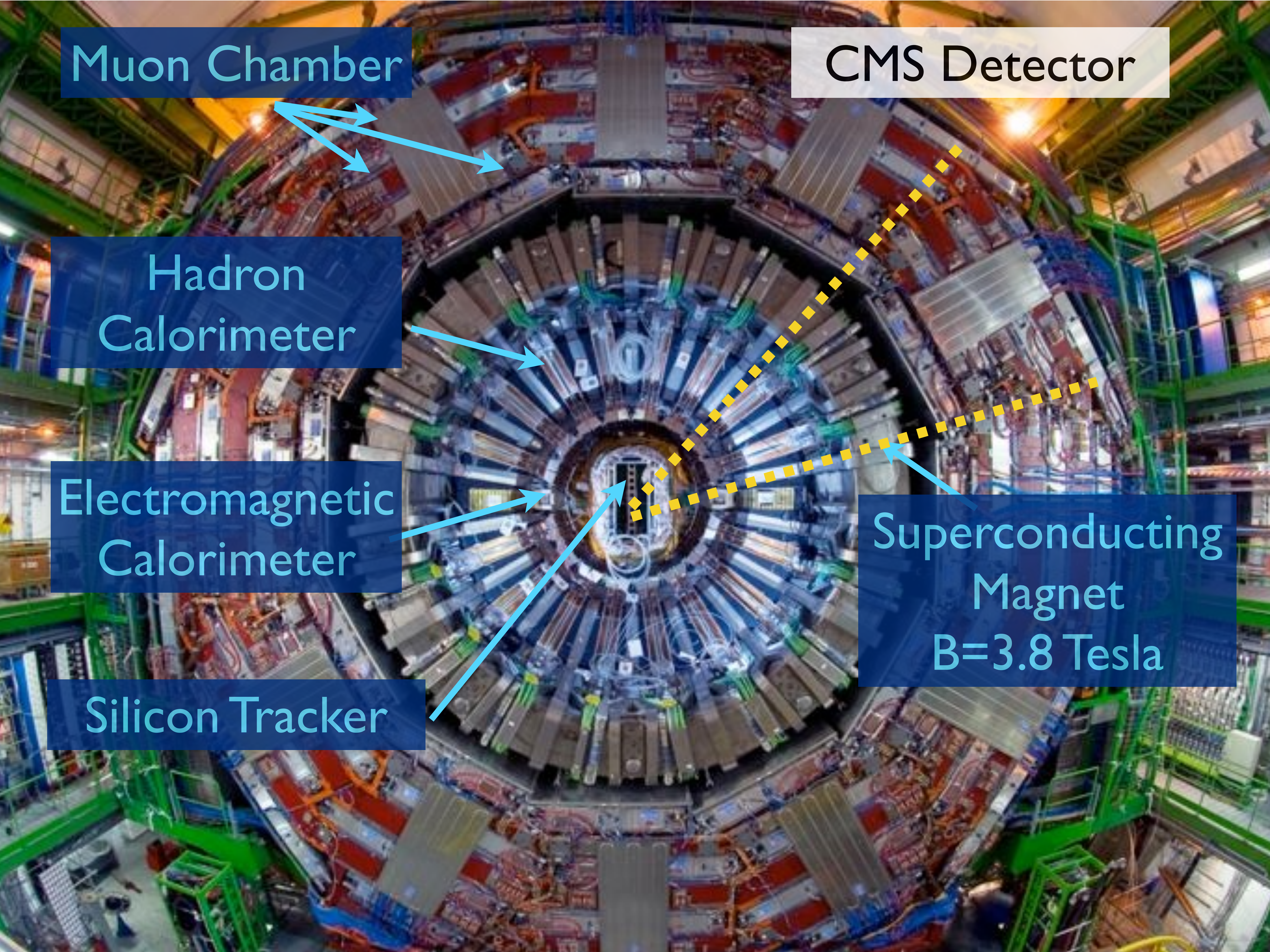
  - Muon chamber: drift tubes, cathode strips →detect and (possibly) measure momentum of muons


CMS Detector
Muon Chamber
Hadron Calorimeter
Electromagnetic Calorimeter
Silicon Tracker
Superconducting Magnet
B=3.8 Tesla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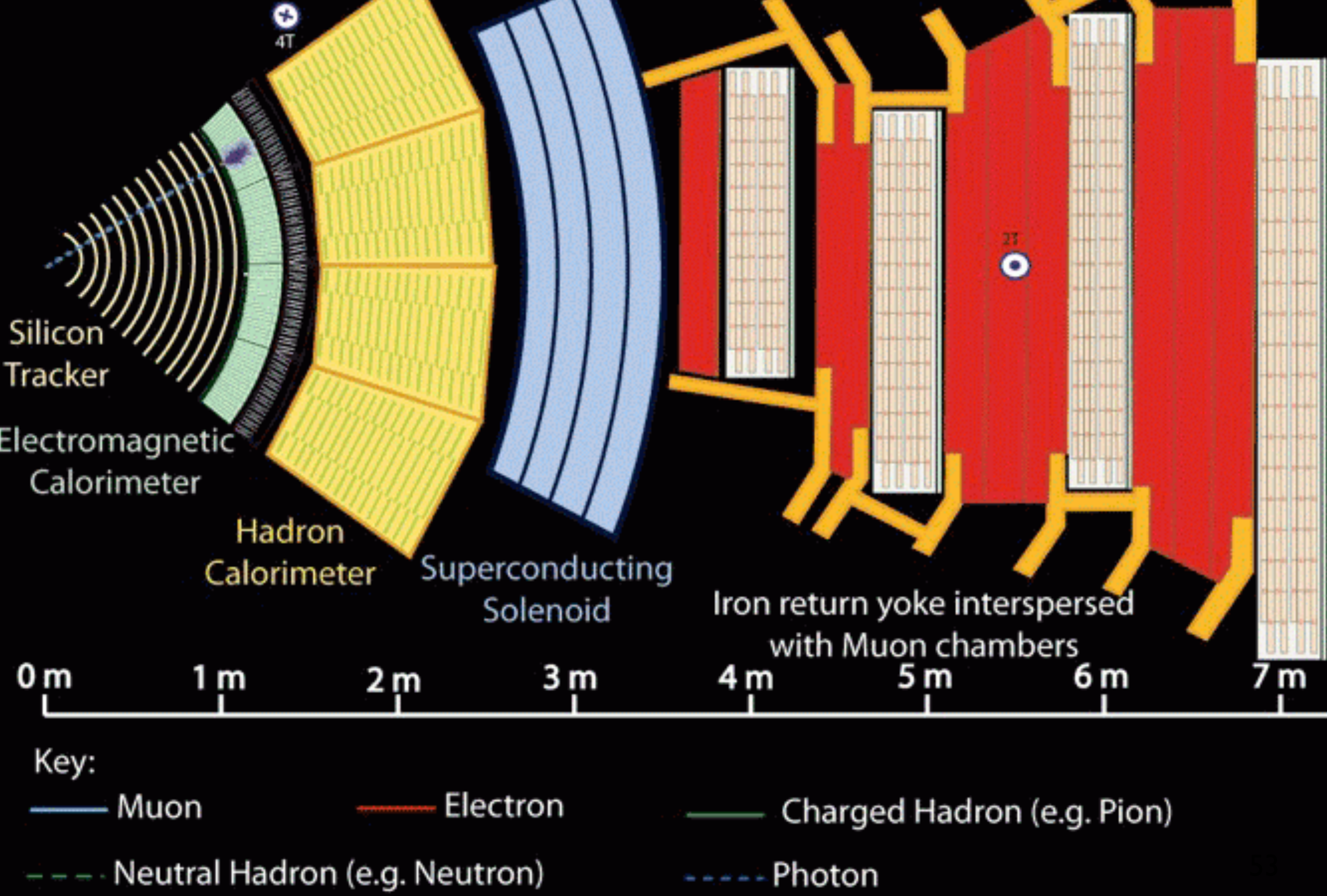
Path of Various Particles



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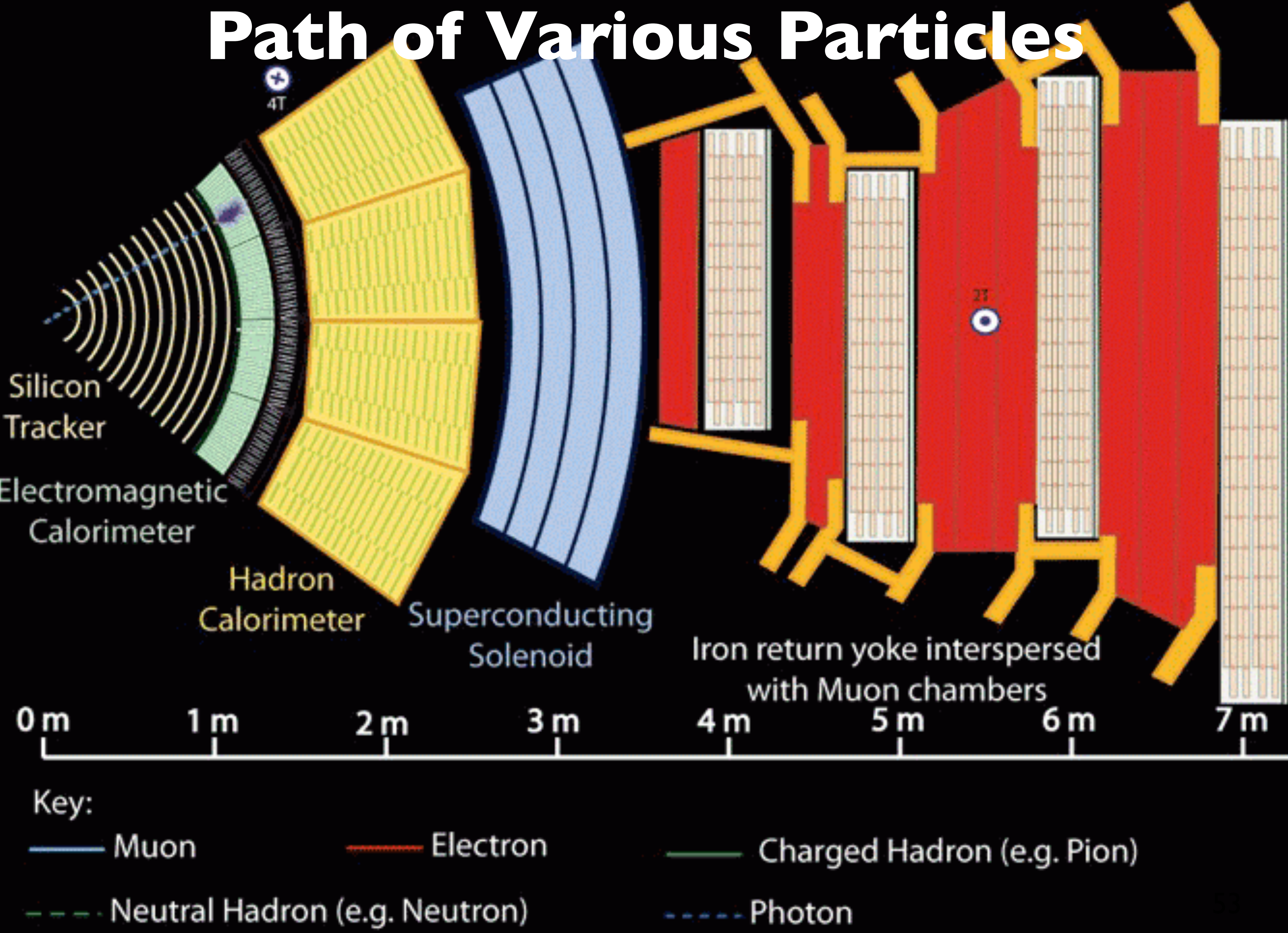

What Do We Need to Know?

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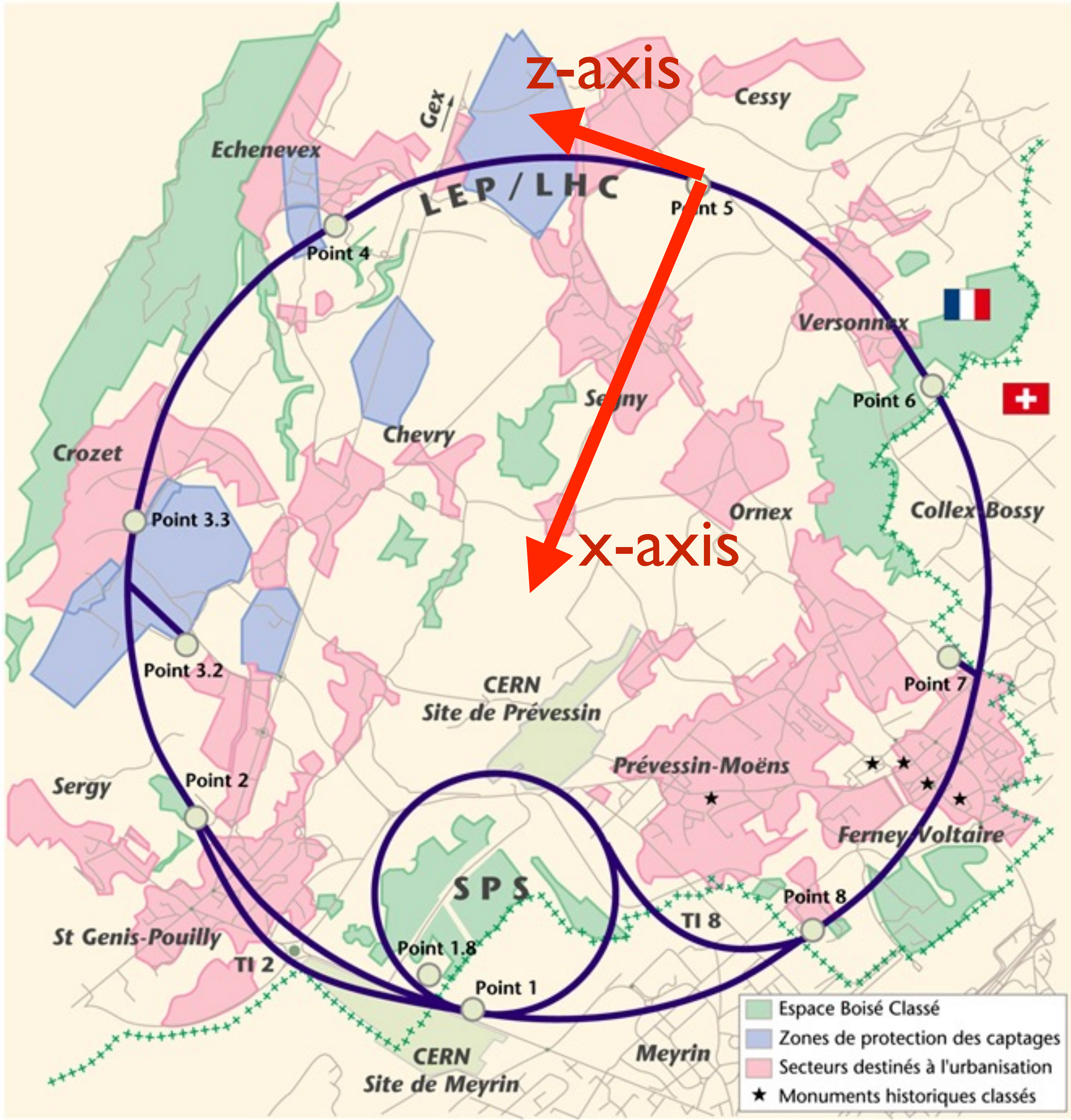
- All above require interaction of particles with detectors
- Particle detectors always rely on electromagnetic interaction
    - photons, charged particles

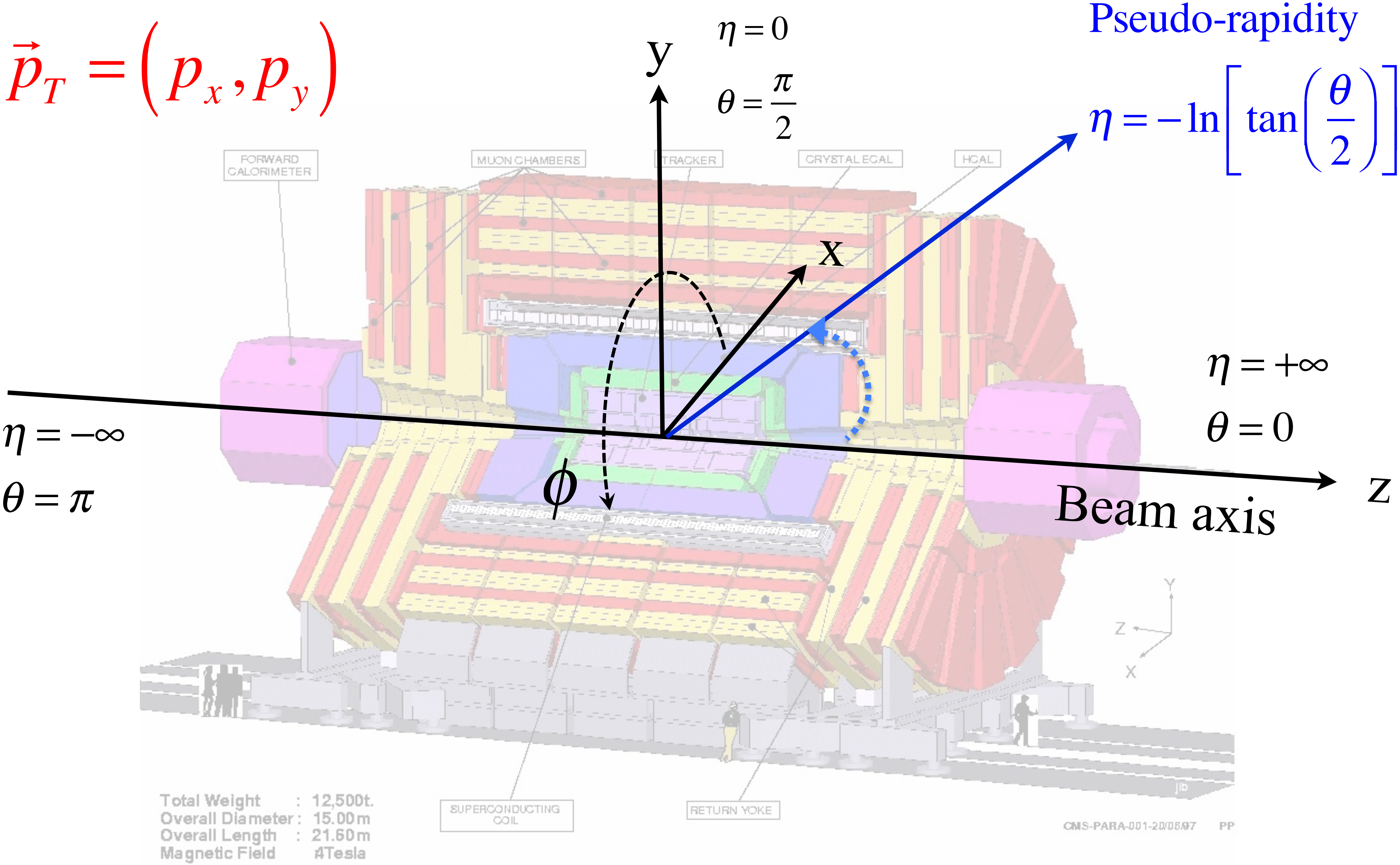

z-axis
x-axis
Cessy
Gex
Echenevex
LEP / LHC
Point 5
Point 4
Versonnex
Point 6
Segny
Chevry
Crozet
Ornex
Collex Bossy
Point 3.3
Point 3.2
Point 7
CERN
Site de Prévessin
Prévessin-Moëns
Sergy
Point 2
Ferney Voltaire
SPS
Point 8
TI 8
St Genis-Pouilly
TI 2
Point 1.8
Point 1
CERN
Site de Meyrin
Meyrin
Espace Boisé Classé
Zones de protection des captages
Secteurs destinés à l'urbanisation
★ Monuments historiques classés

Standard Collider Kinematic Variables

$$\vec{p}_T = \left(p_x, p_y\right)$$

Pseudo-rapidity

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



η-θ Conversion

Pseudo-rapidity

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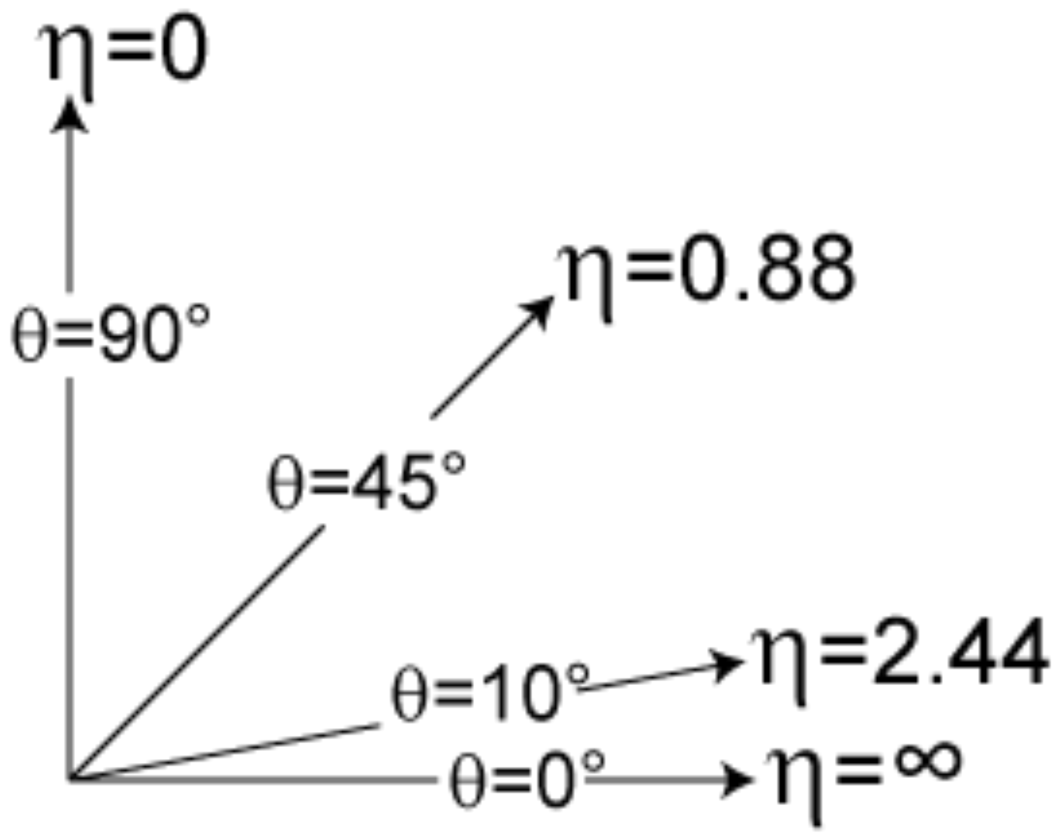

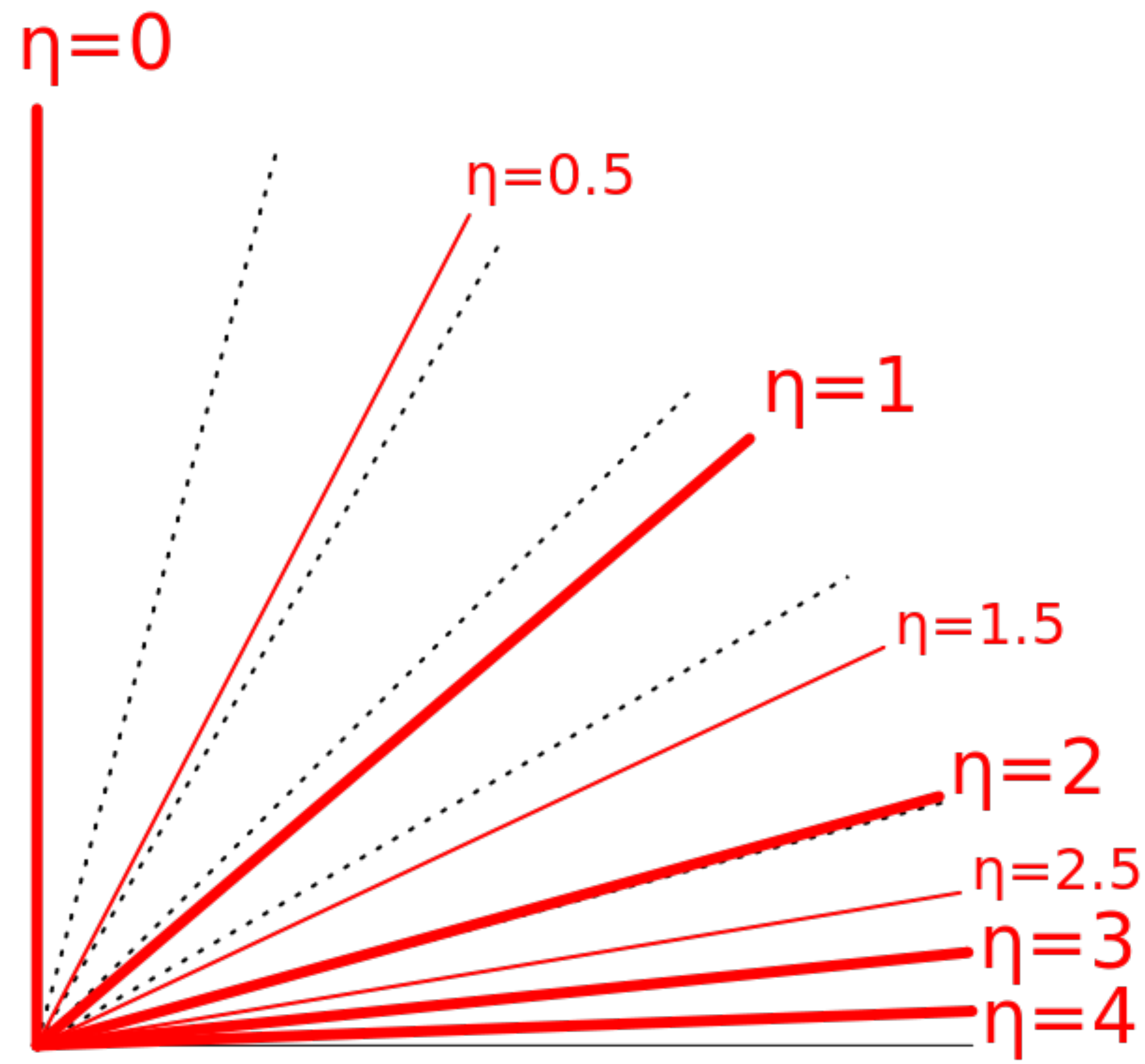

Charge Hadron Multiplicity

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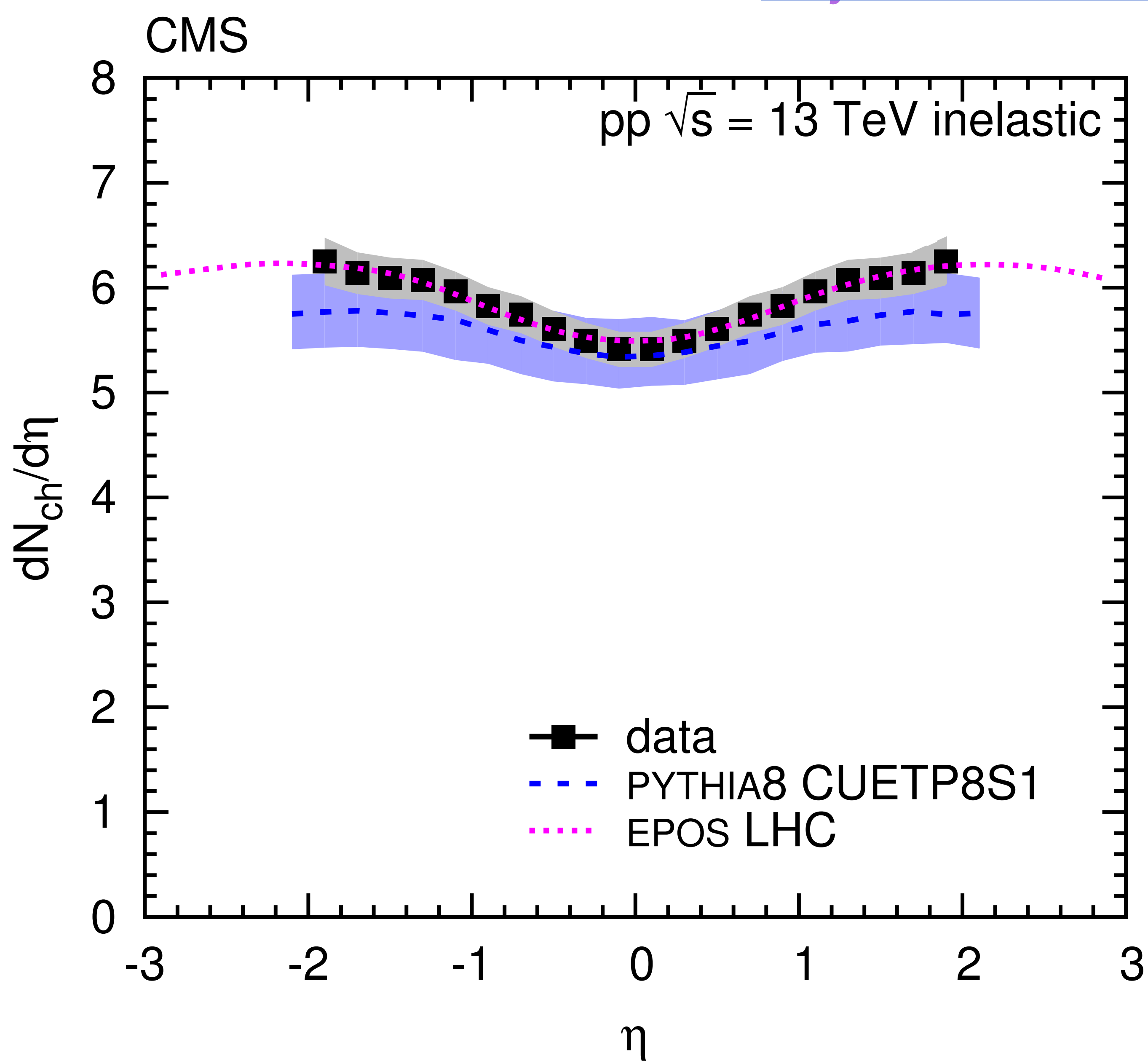
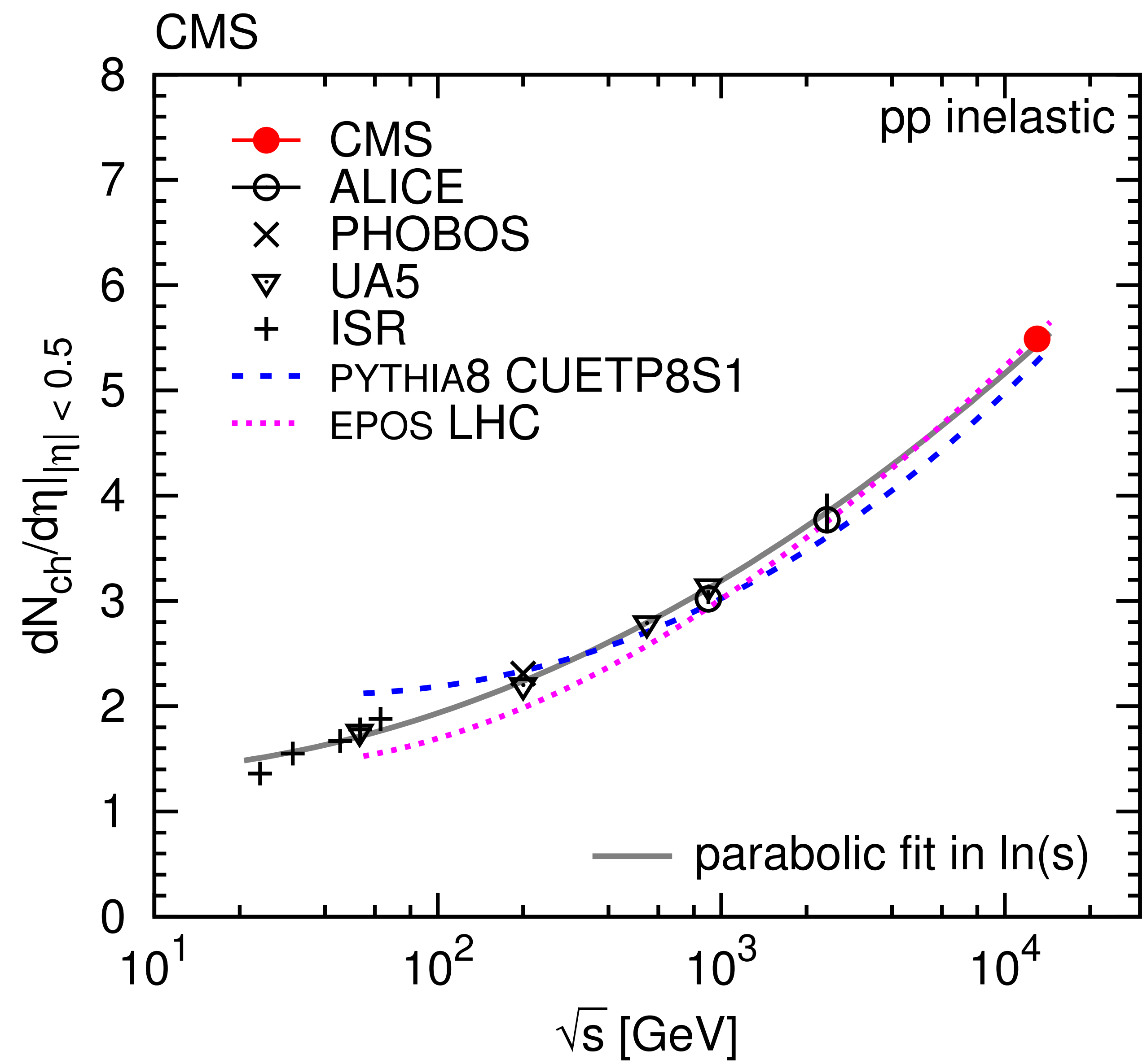


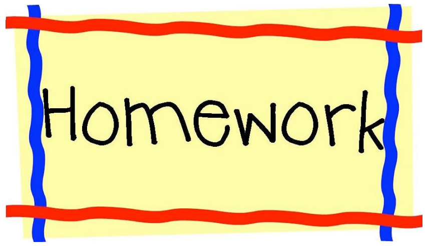


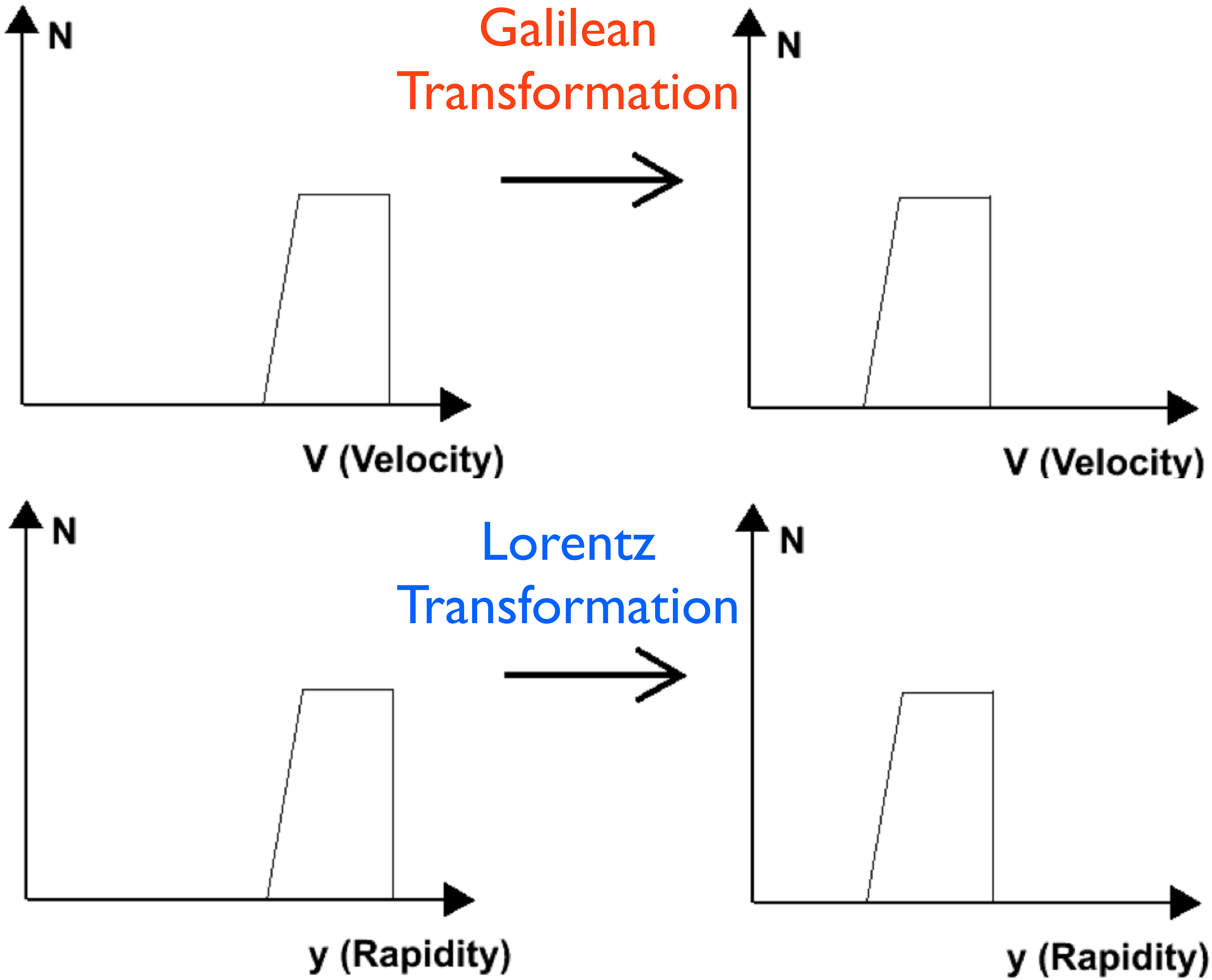
Kinematic Variables

$$\text{rapidity } y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

Under boost along the z direction

$$y \rightarrow y + \Delta y_b$$




N
Galilean
Transformation
N
V (Velocity)
V (Velocity)
N
Lorentz
Transformation
N
y (Rapidity)
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Kinematic Variables

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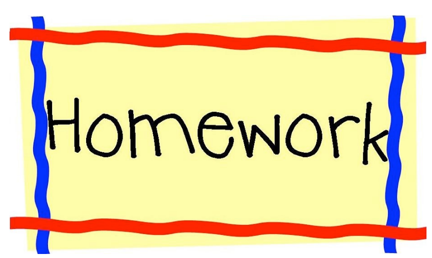
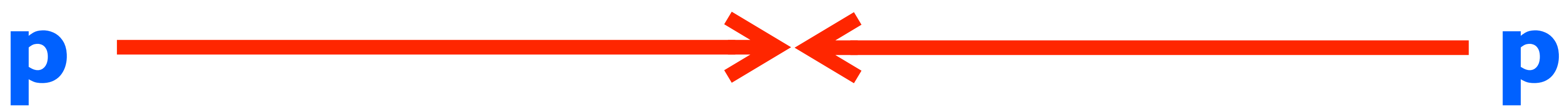
For relativistic particle, $p \gg m$

$$y \rightarrow \eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



Center of Momentum Frame

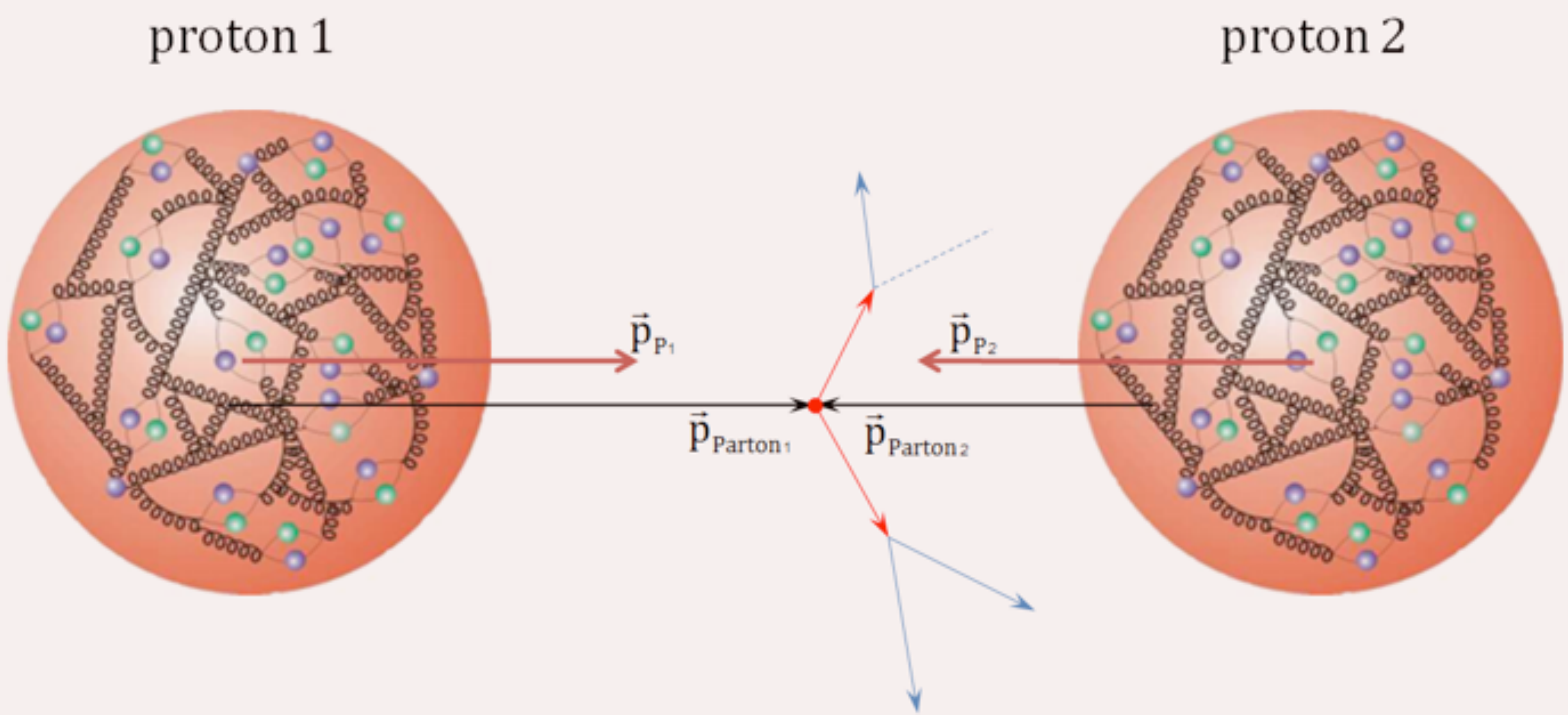
If proton were a point-like particle, lab frame is also the center of momentum frame of the hard scattering.



Proton Is Not an Elementary Particle

Interactions of constituents of the colliding protons, the so called partons (quarks, gluons)

Mostly u, d, s, and gluon



$\vec{p}_{P_1}$ ... momentum proton 1

$\vec{p}_{P_1}$ ... momentum proton 2

• interaction vertex

$\vec{p}_{Parton_1}$ ... momentum parton 1

$\vec{p}_{Parton_2}$ ... momentum parton 2

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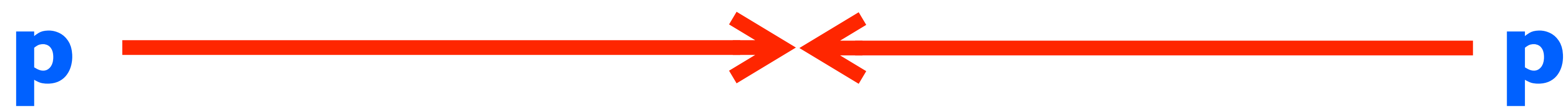
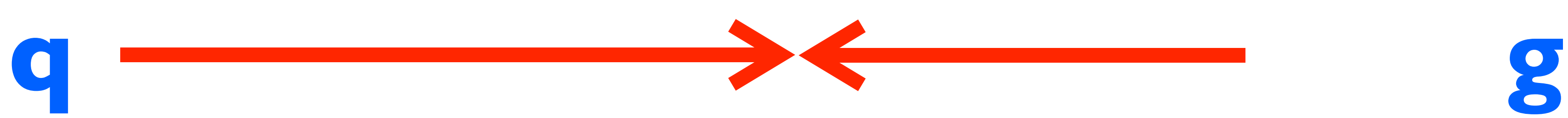


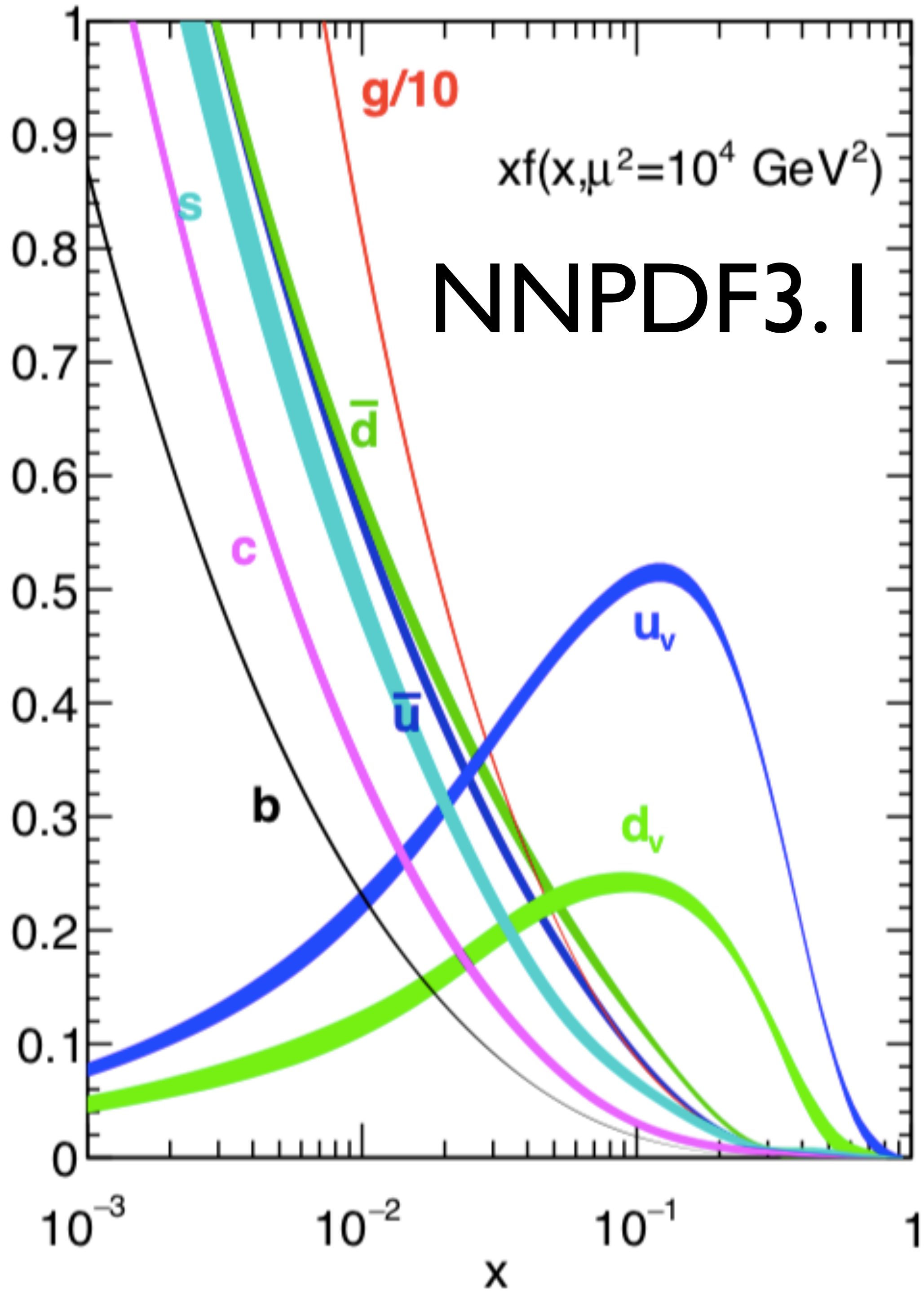
But ... proton has substructure, and the scattering constituents are partons inside proton (quarks and gluons). Therefore, the center of momentum frame varies event by event and does not coincide with the lab frame.

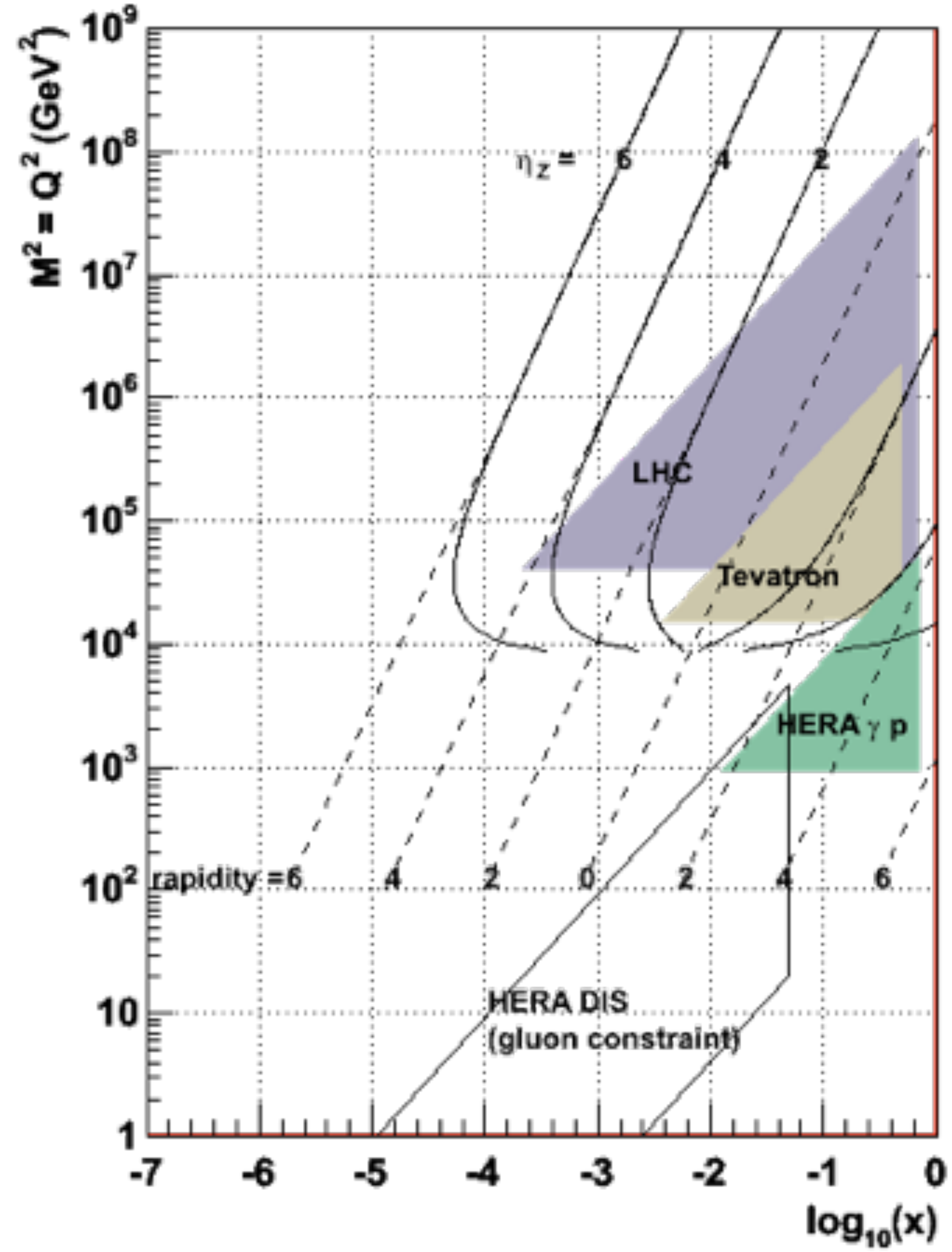


Therefore, we want to use kinematic variables that are invariant under the boost along the z direction.

Parton Distribution Function

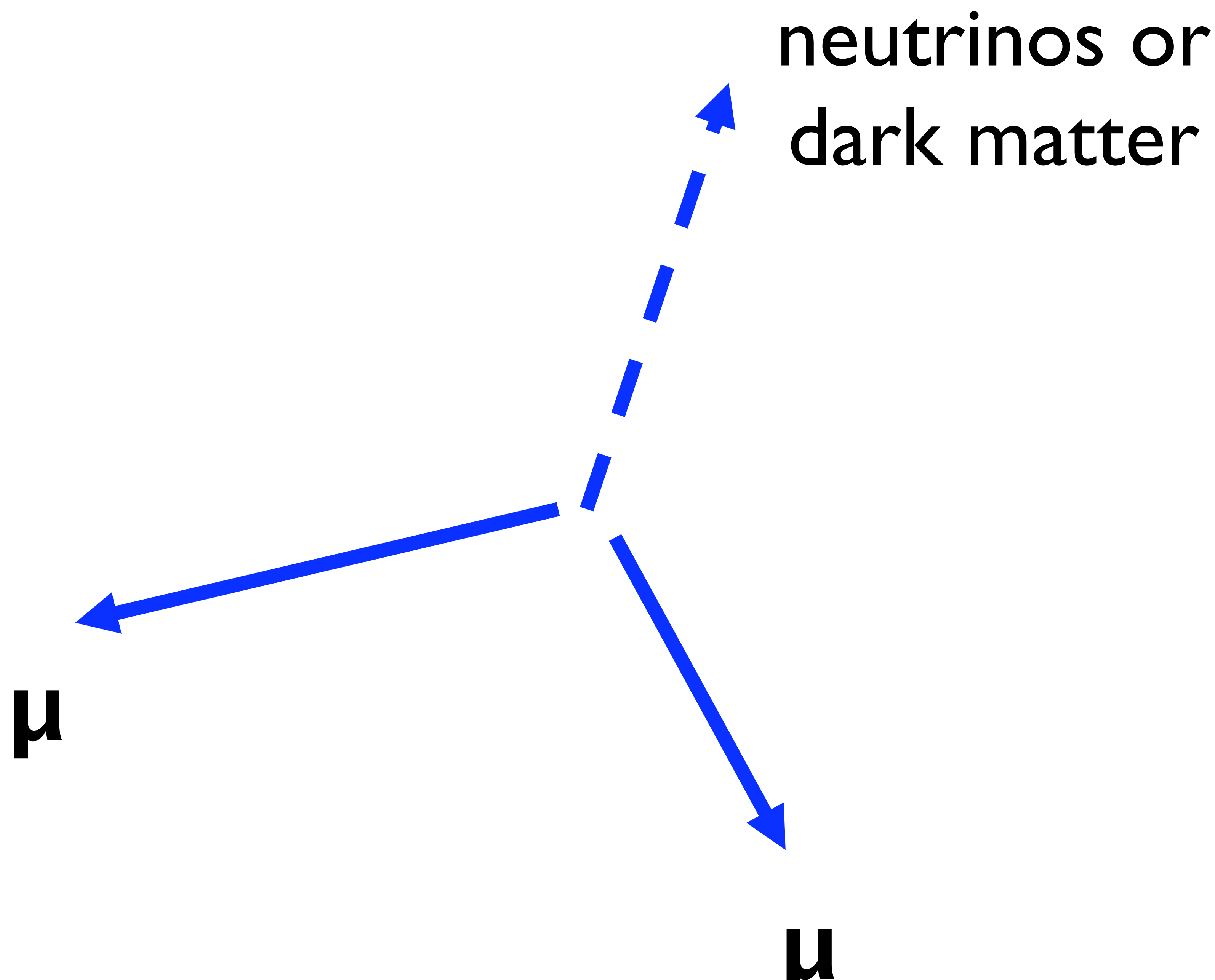
$$\sigma(pp \to X) = \sum_{i,j} \int dx_1 dx_2\, f_{i,p}(x_1, \mu_F^2)\, f_{j,p}(x_2, \mu_F^2)\, \hat{\sigma}_{ij\to X}(x_1 x_2 s, \mu_R^2, \mu_F^2)$$



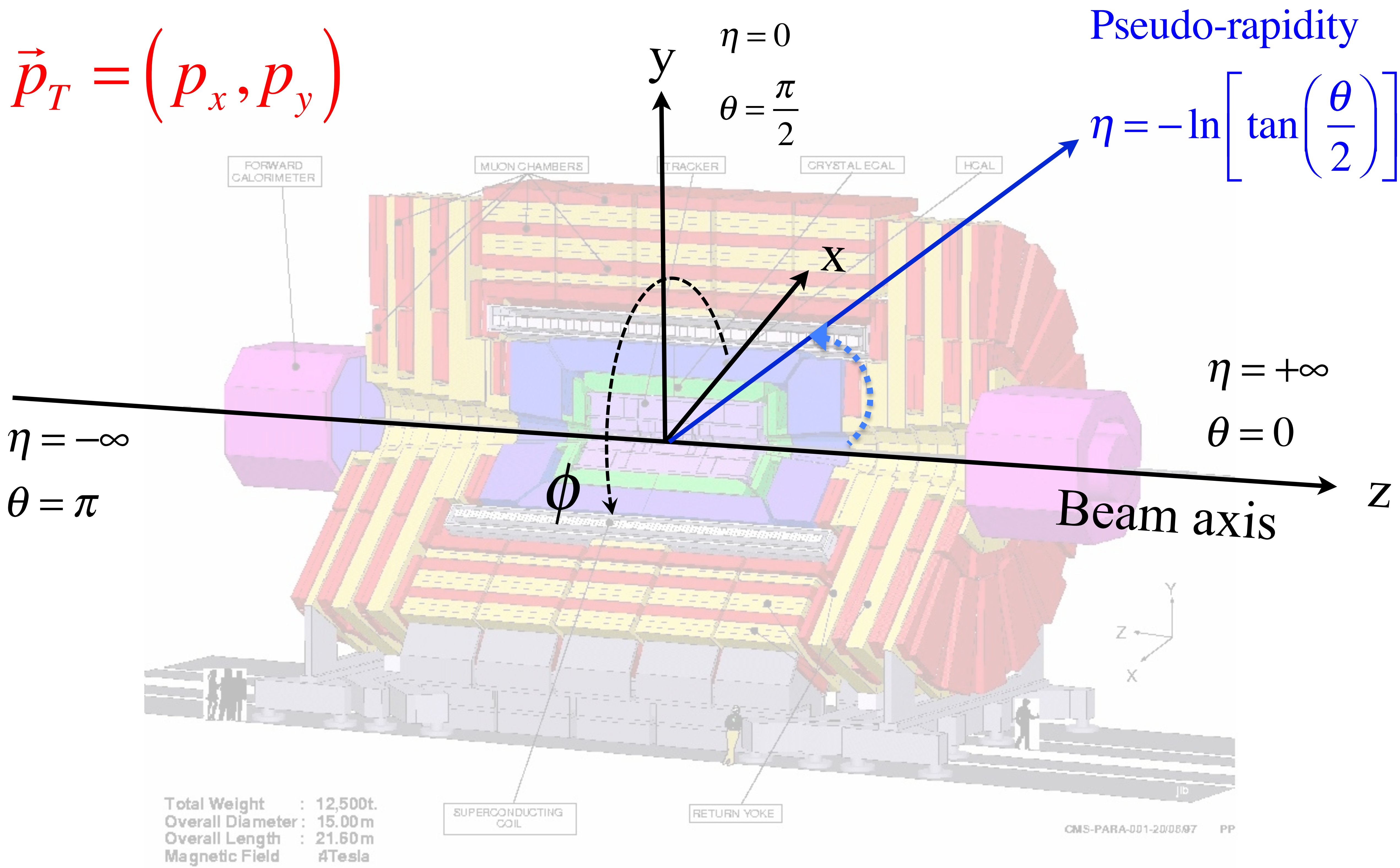


Missing Transverse Momentum

- The negative of the total transverse momentum of all observed particles in the detector



Standard Collider Kinematic Variables



Kinematic Variables We Use

$$\Rightarrow \ \phi, \ p_T , \ \eta$$

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Kinematic Variables We Use

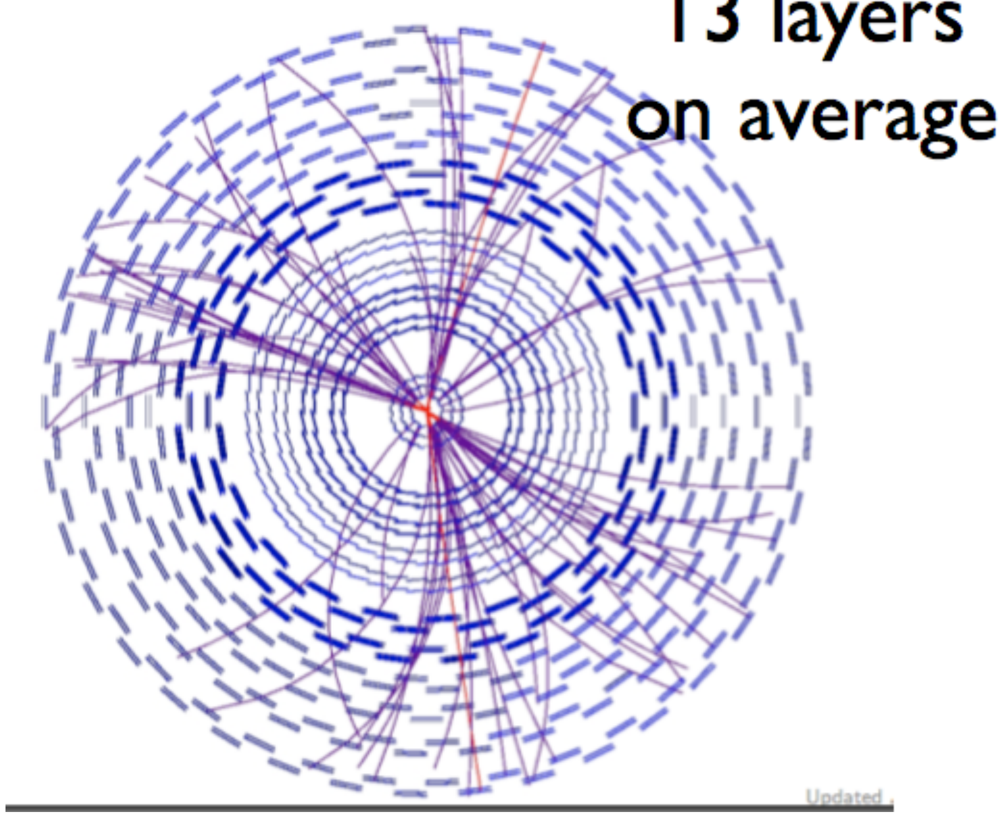
$$\Rightarrow \ \phi, \ p_T, \ \eta$$

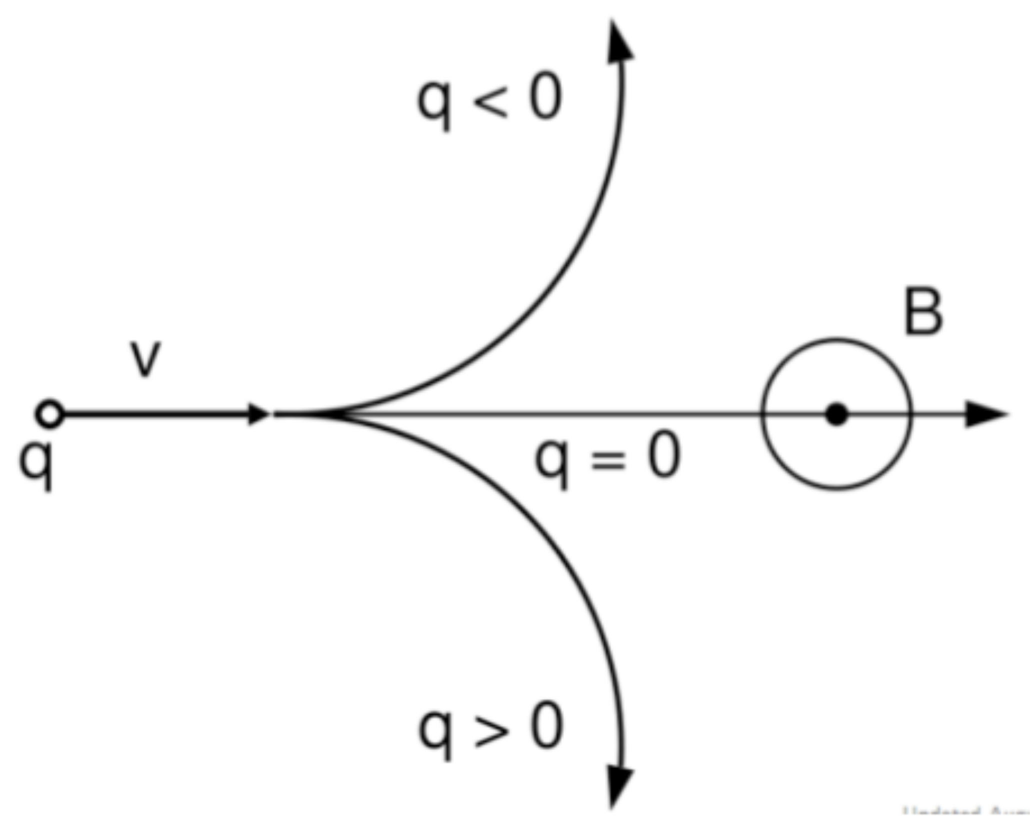
- How do we measure these quantities?
  - Basically, we need to measure the direction of momentum and the magnitude of transverse momentum.
- Which variable(s) will not change as particles travel through the detector?

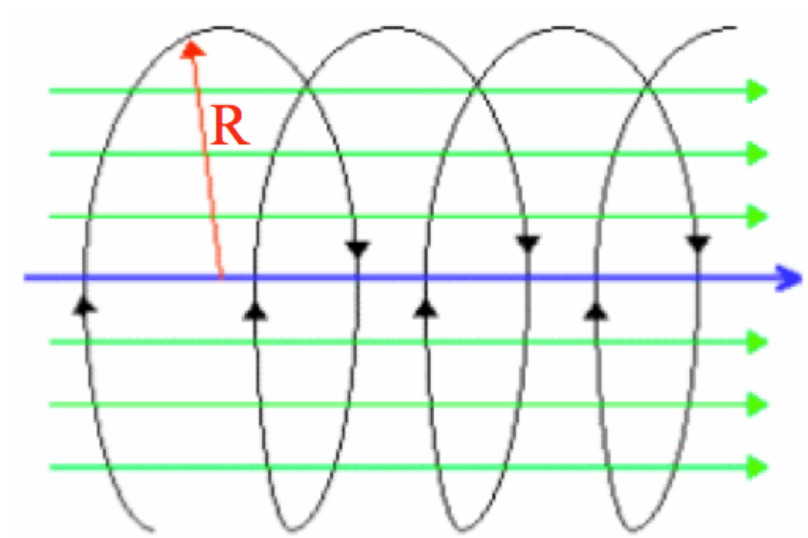
How to Measure Momentum?

- Charged particle

  ➡ Measure trajectory with tracker (silicon detector, gas chamber) + a magnetic field

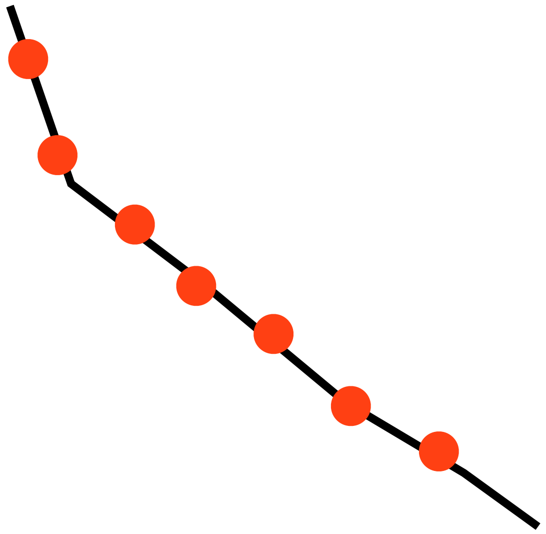






Tracks

- Trajectory of charged particles
- Only possible for charged particle due to their ionization loss



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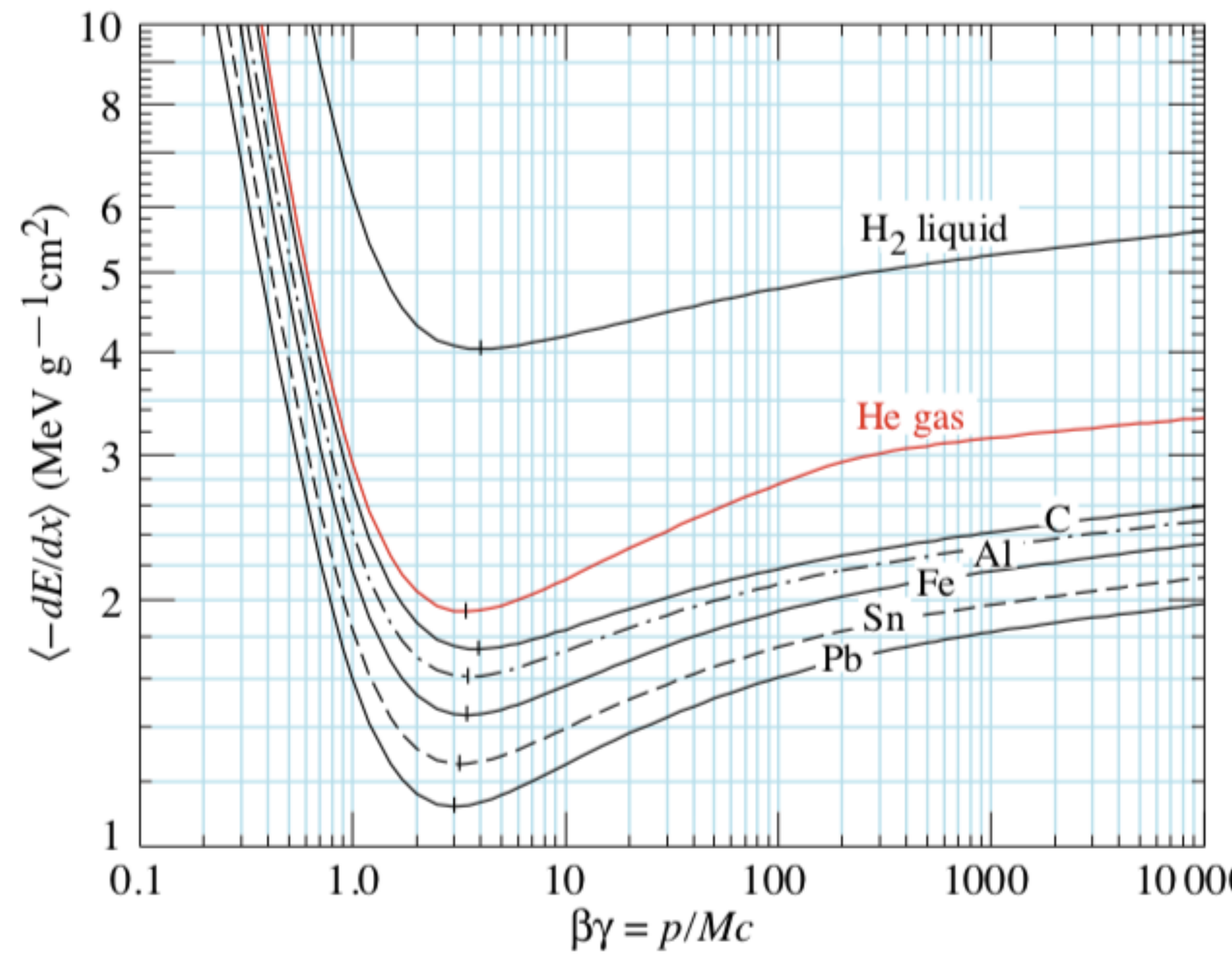
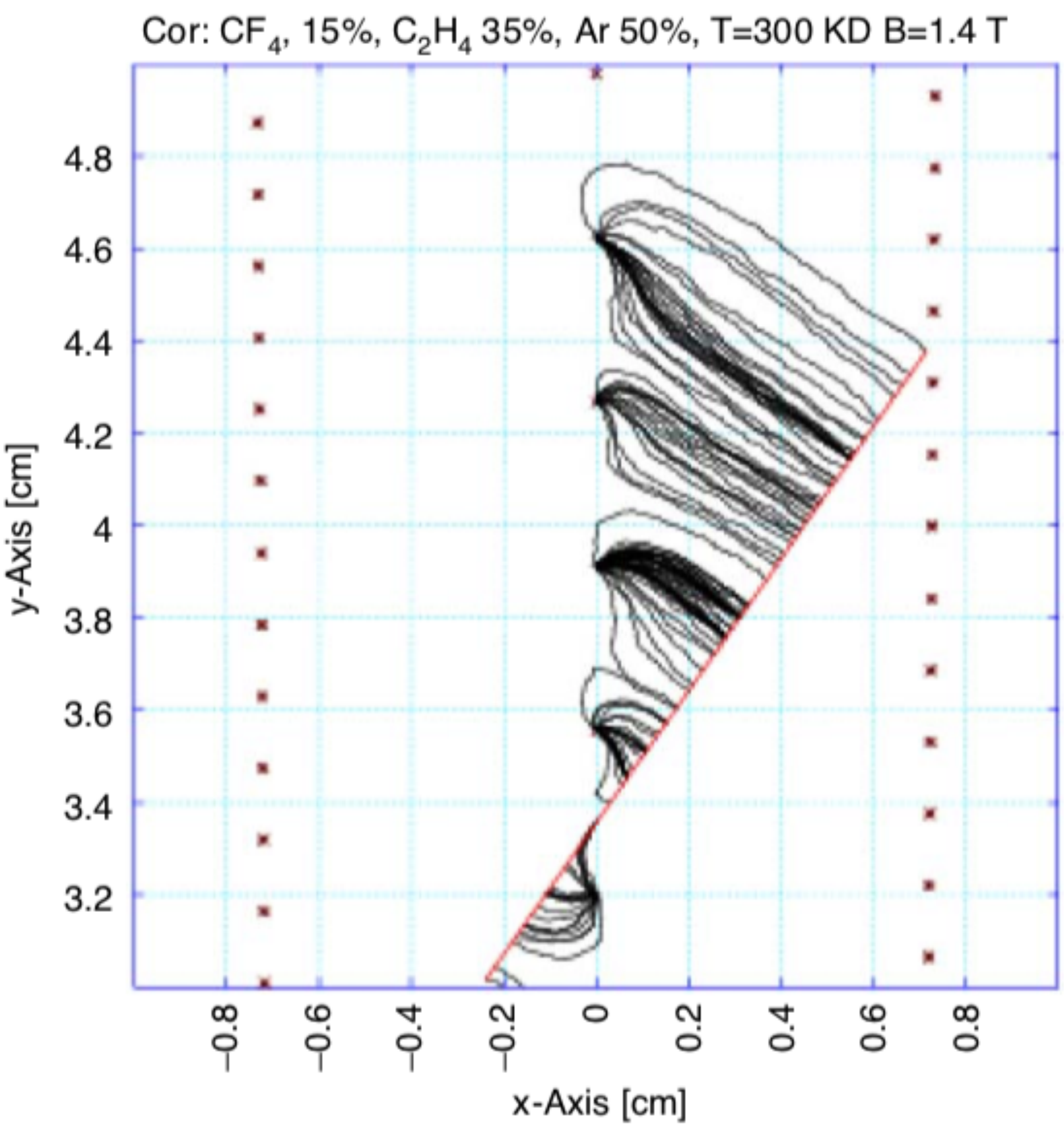


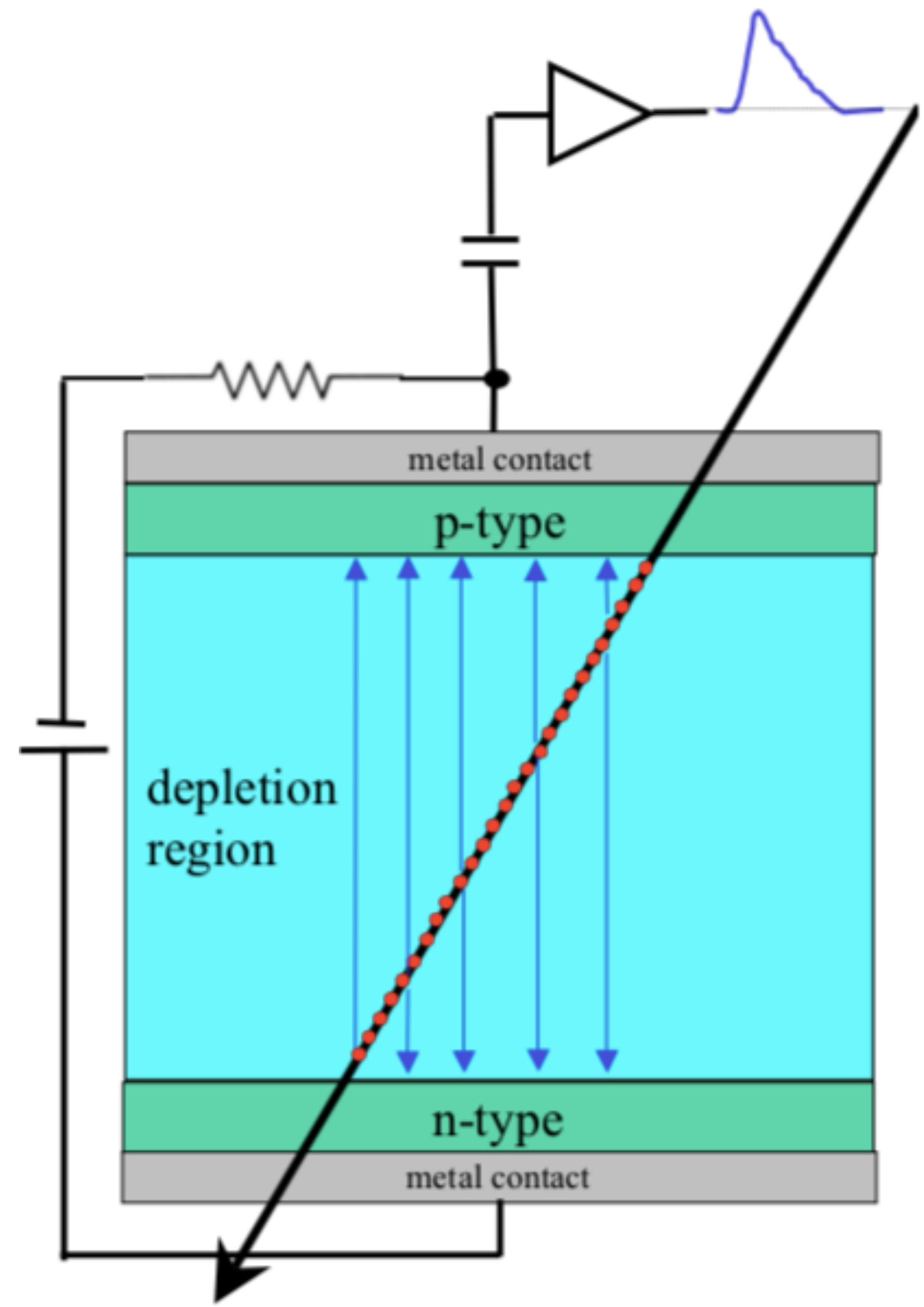
Gas:	~0.5 keV/cm
Liquid:	~300 keV/cm
Solid:	~4 MeV/cm

Relative energy loss for 10 GeV particle:
< 0.001% for a gas detector,
~ 5% for a solid detector

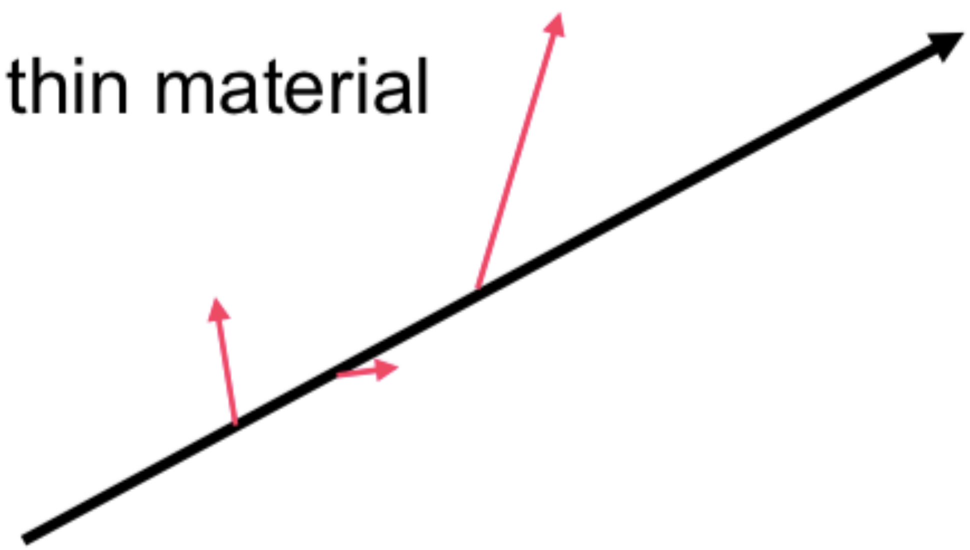
$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

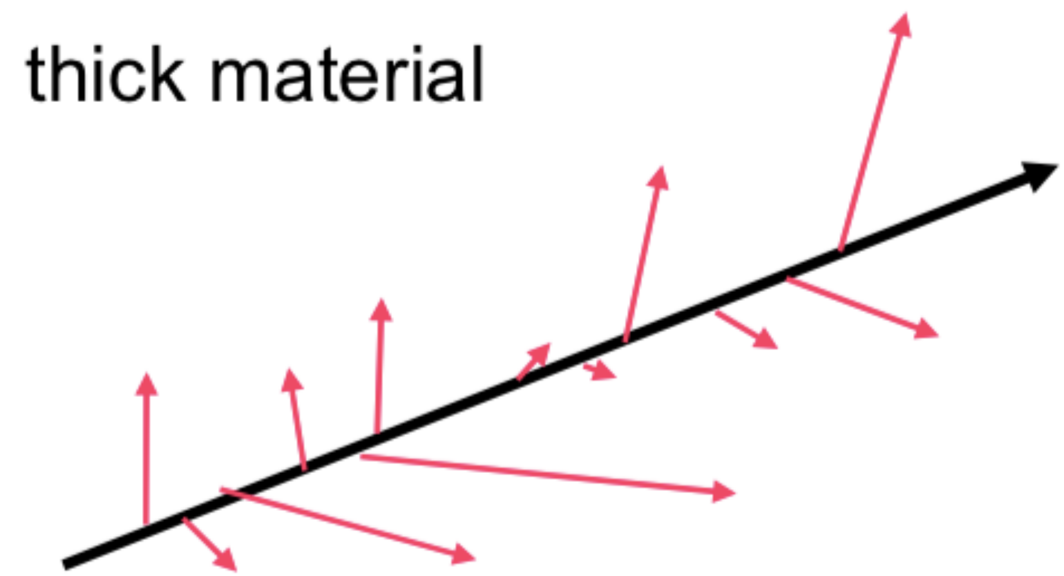
Gas vs. Semiconductor

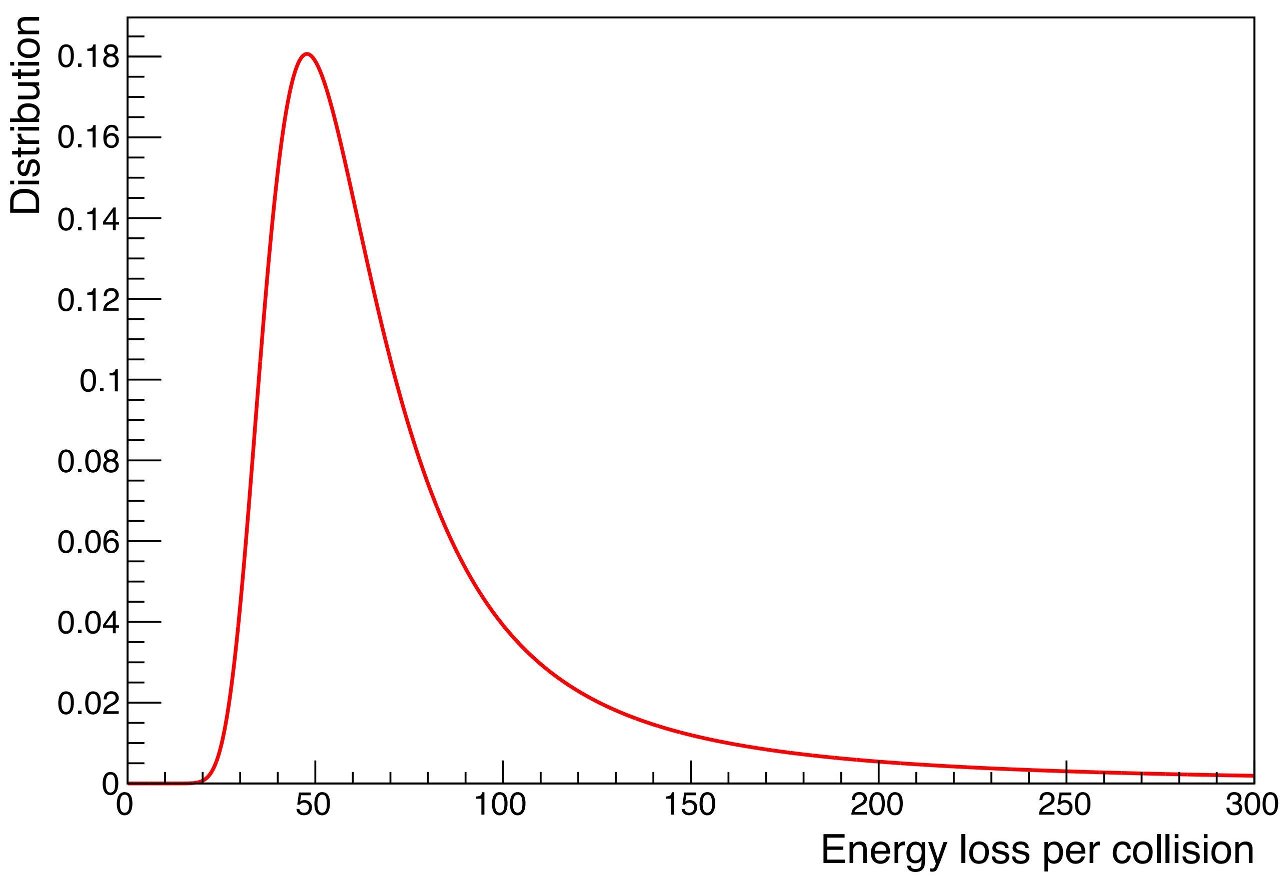


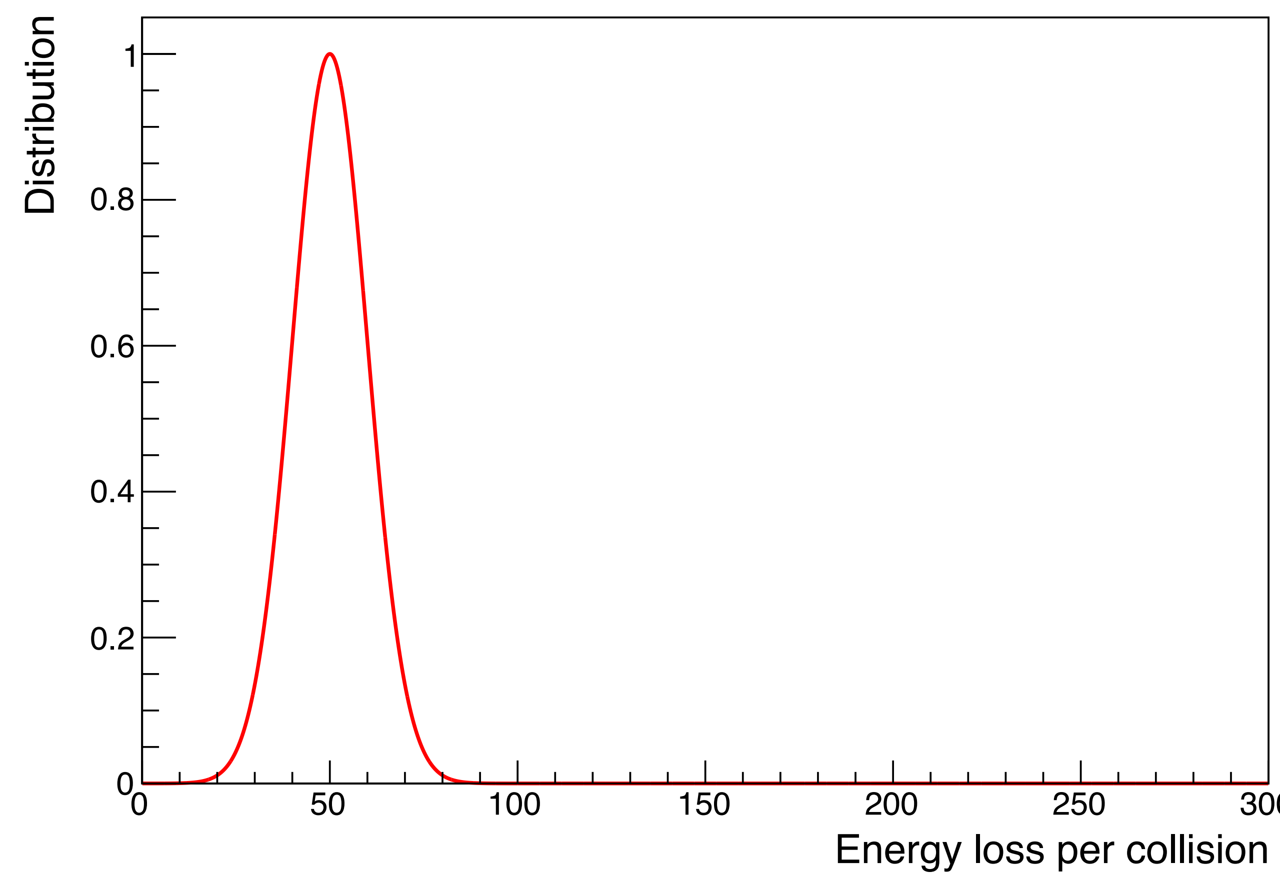


Average Energy Loss per Unit Length

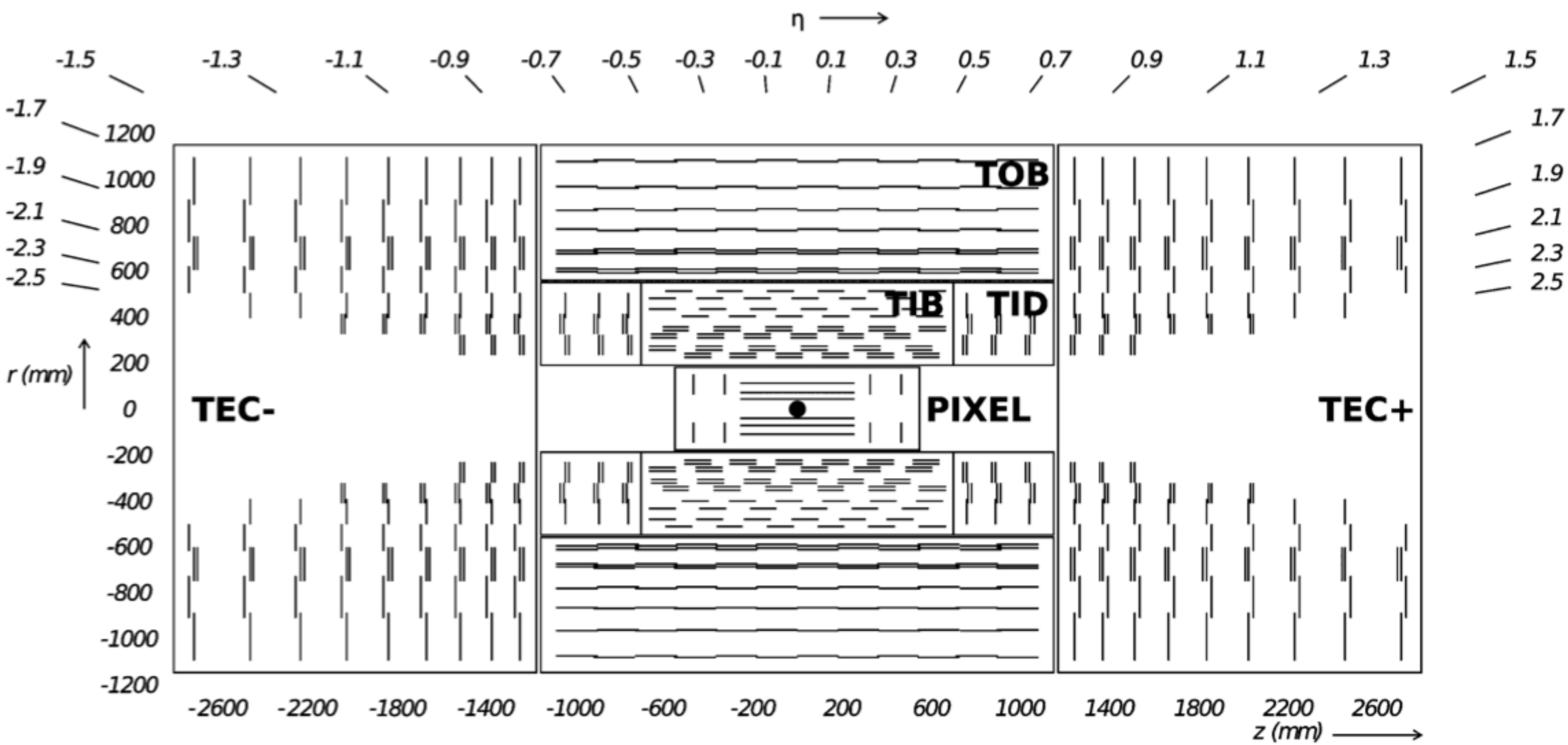






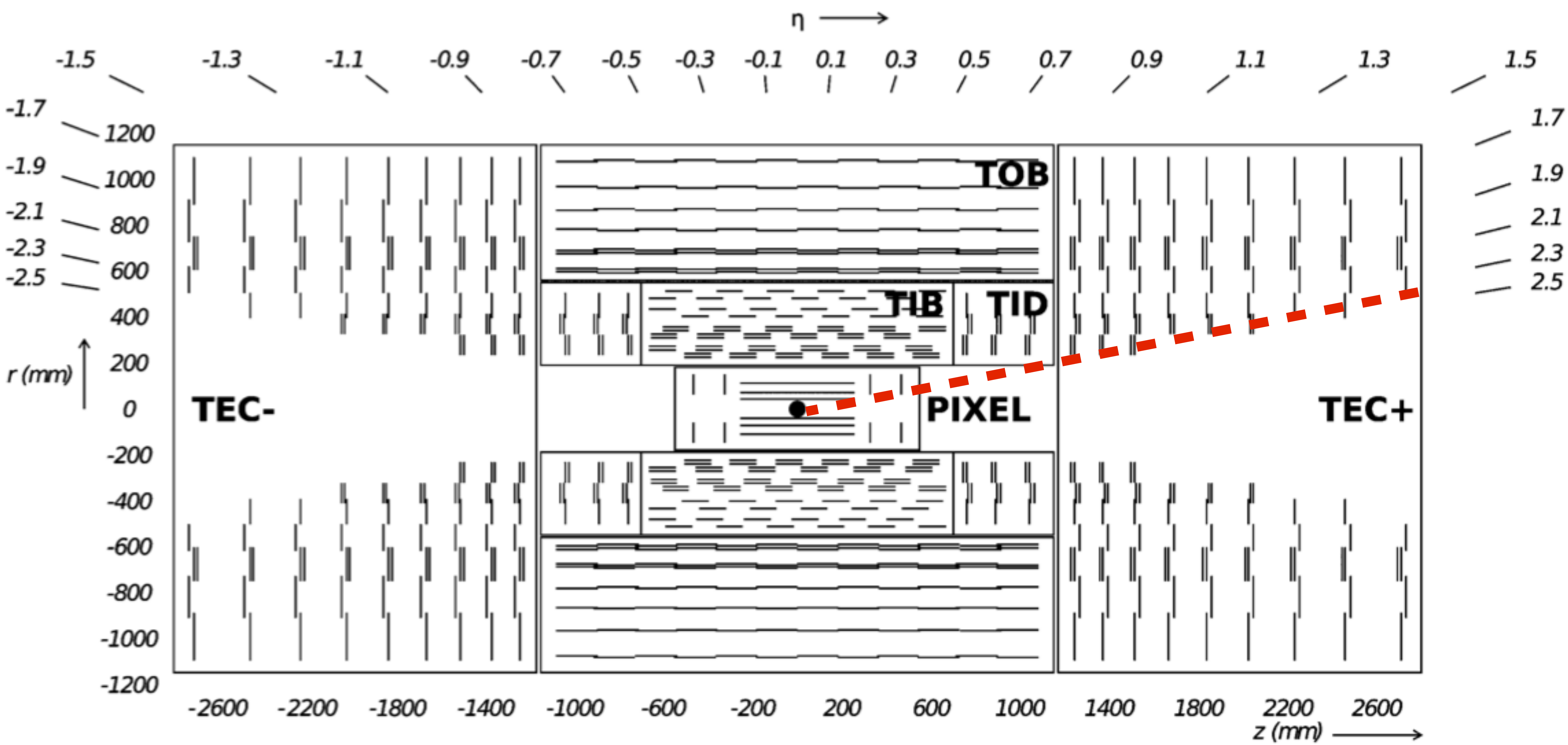


CMS Tracker



η
-1.5
-1.3
-1.1
-0.9
-0.7
-0.5
-0.3
-0.1
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
-1.7
-1.9
-2.1
-2.3
-2.5
1.7
1.9
2.1
2.3
2.5
1200
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
-1200
r (mm)
TOB
TIB
TID
PIXEL
TEC-
TEC+
-2600
-2200
-1800
-1400
-1000
-600
-200
200
600
1000
1400
1800
2200
2600
z (mm)

CMS Tracker



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0.3
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2.1
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1200
1000
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200
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-200
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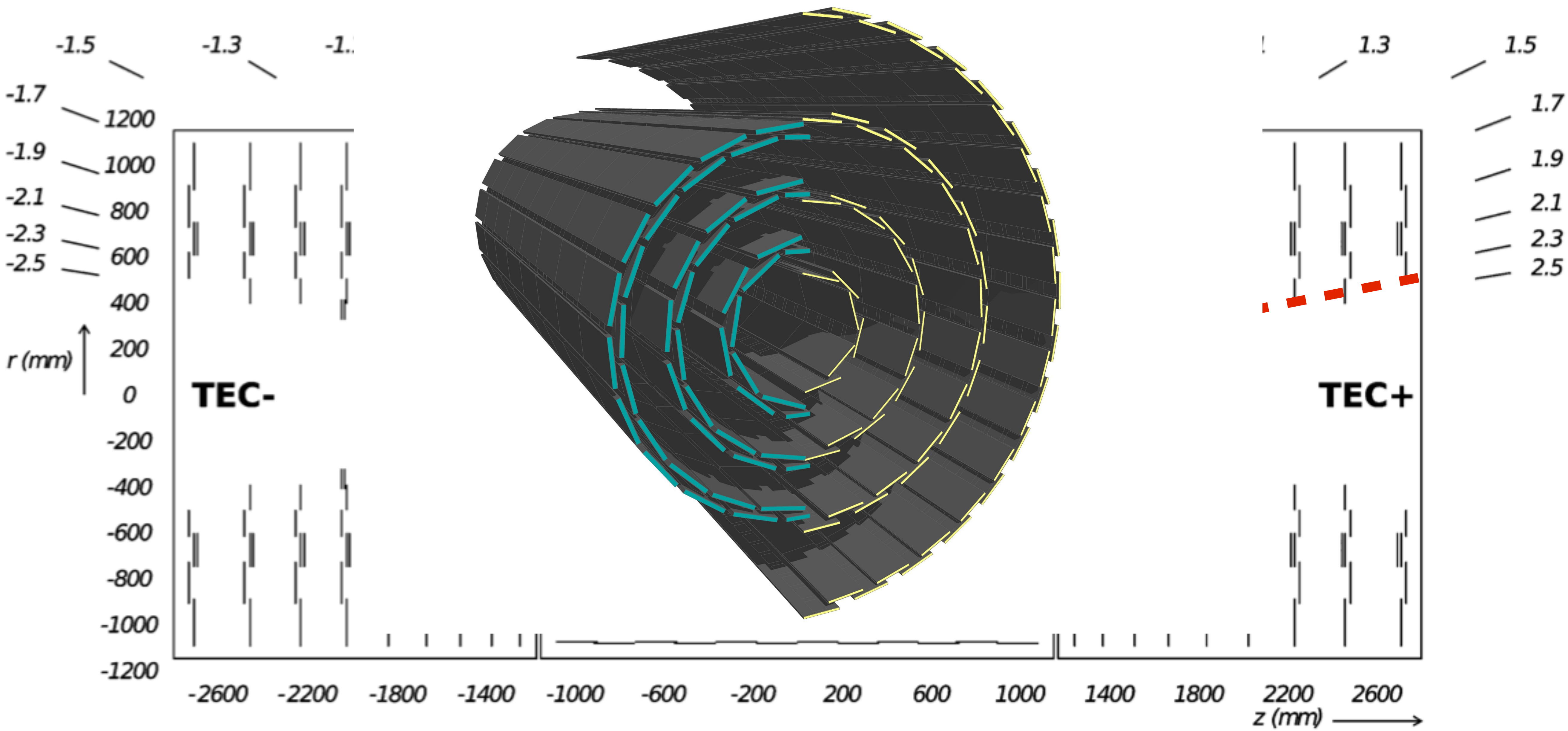
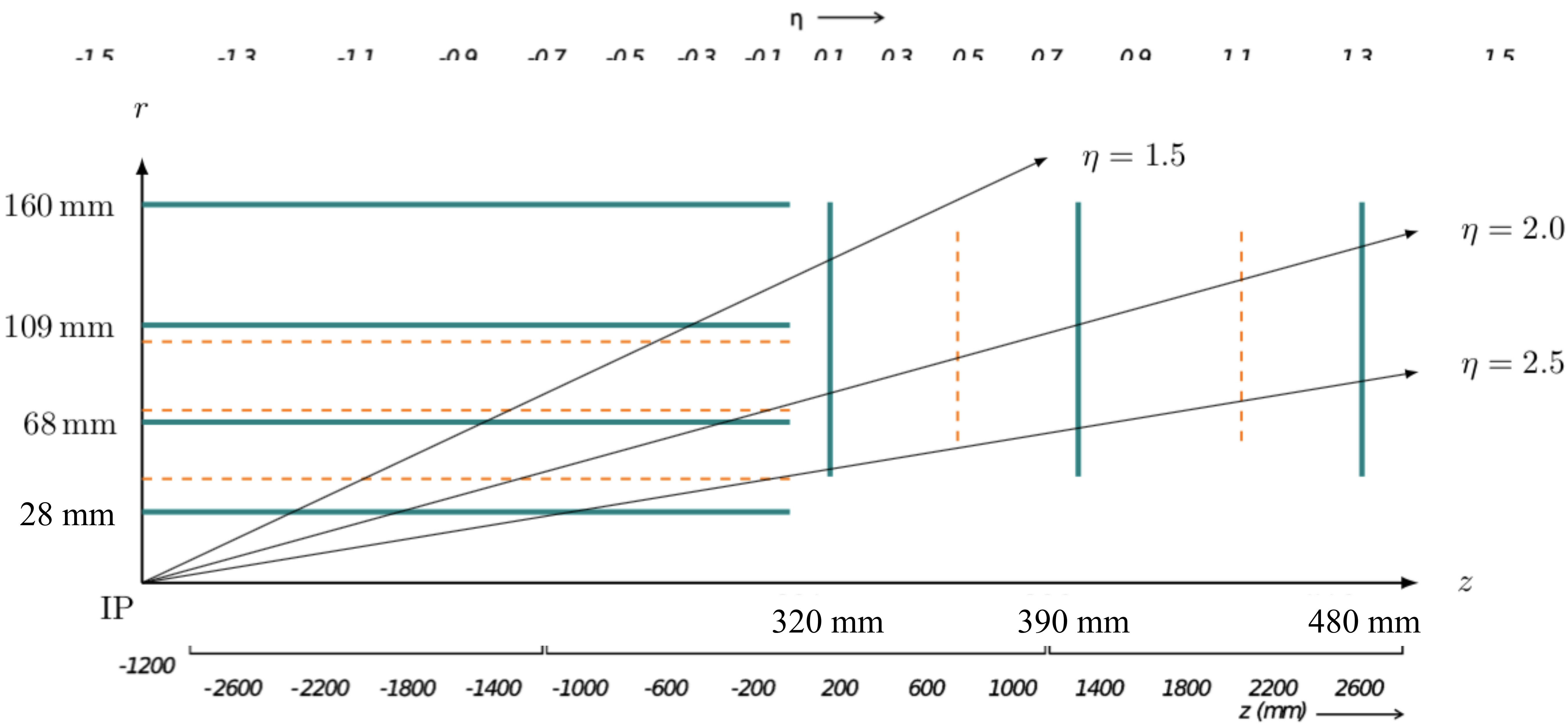
-600
-800
-1000
-1200
r (mm)
TOB
TIB
TID
PIXEL
TEC-
TEC+
-2600
-2200
-1800
-1400
-1000
-600
-200
200
600
1000
1400
1800
2200
2600
z (mm)

CMS Tracker



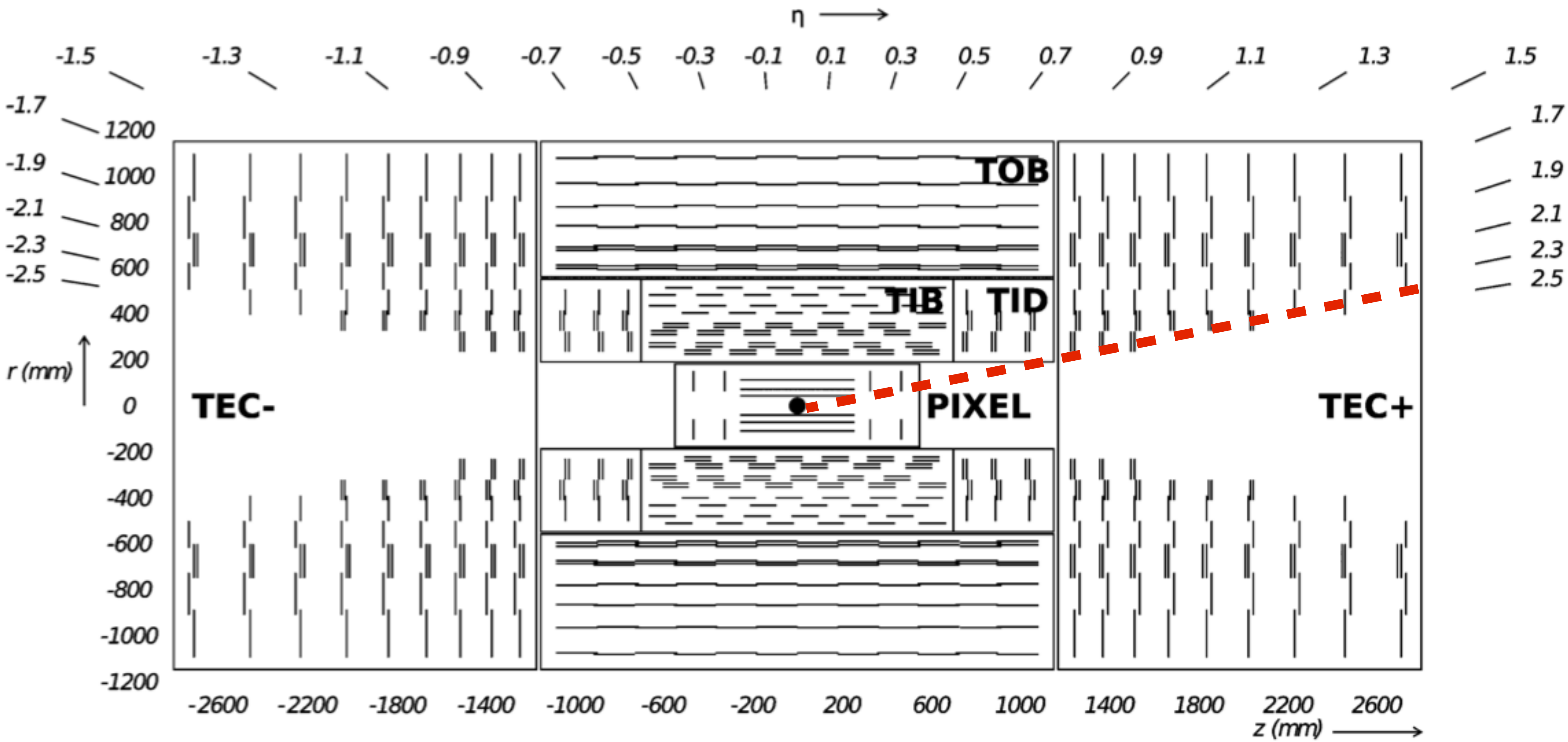
-1.5
-1.3
1.3
1.5
-1.7
-1.9
-2.1
-2.3
-2.5
1.7
1.9
2.1
2.3
2.5
1200
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
-1200
r (mm)
TEC-
TEC+
-2600
-2200
-1800
-1400
-1000
-600
-200
200
600
1000
1400
1800
2200
2600
z (mm)

CMS Tracker

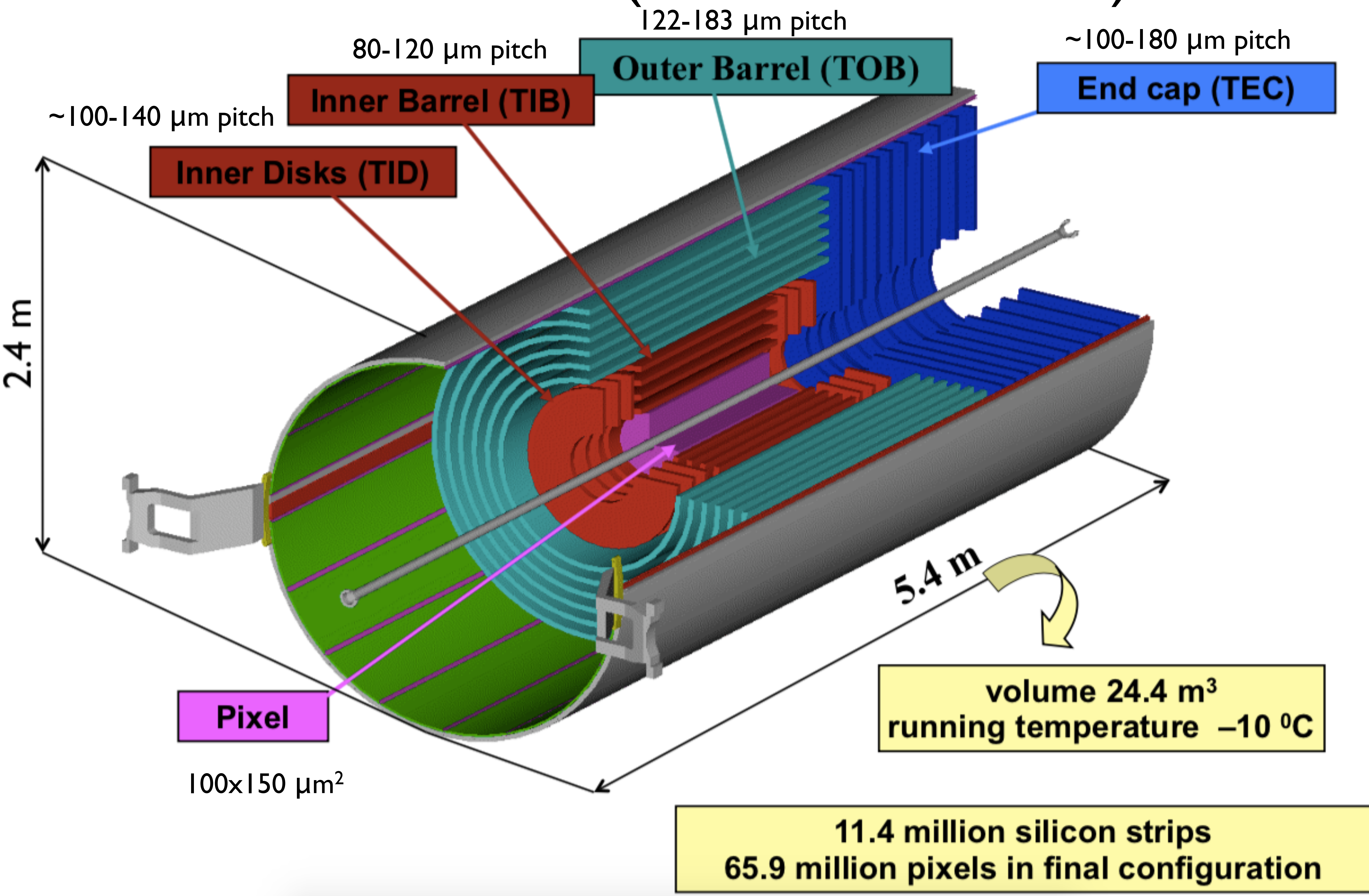


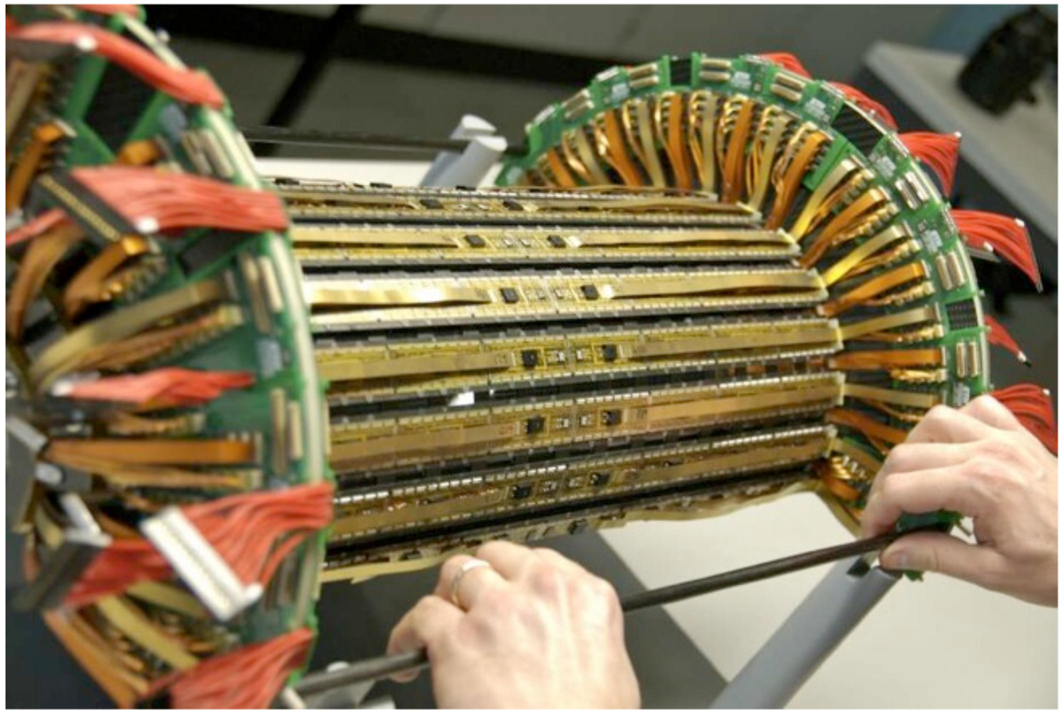
η
r
160 mm
109 mm
68 mm
28 mm
IP
$\eta = 1.5$
$\eta = 2.0$
$\eta = 2.5$
z
320 mm
390 mm
480 mm
-1200
-2600 -2200 -1800 -1400 -1000 -600 -200 200 600 1000 1400 1800 2200 2600
z (mm)

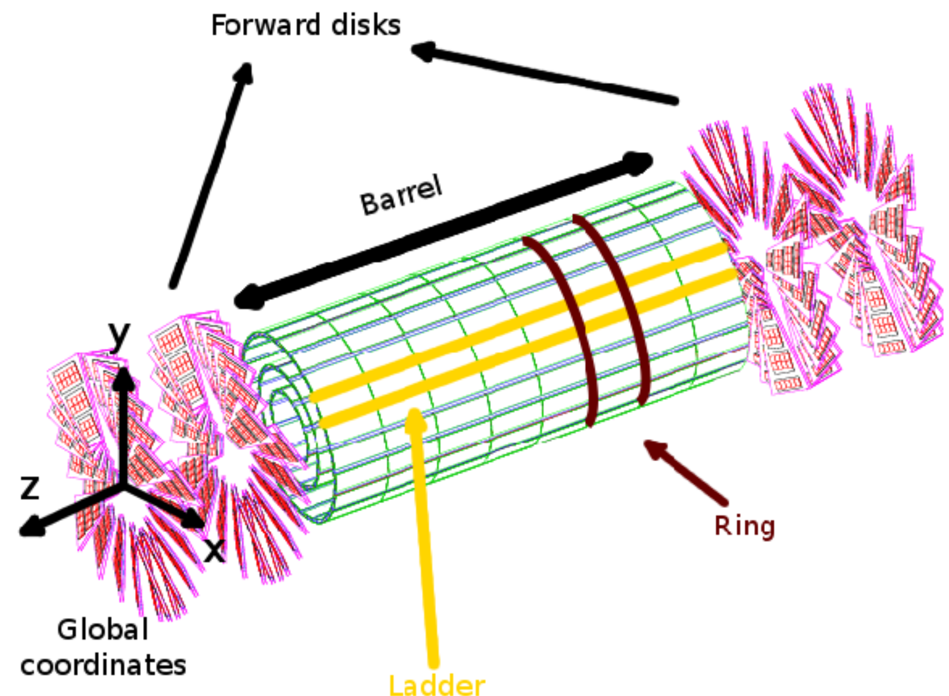
CMS Tracker

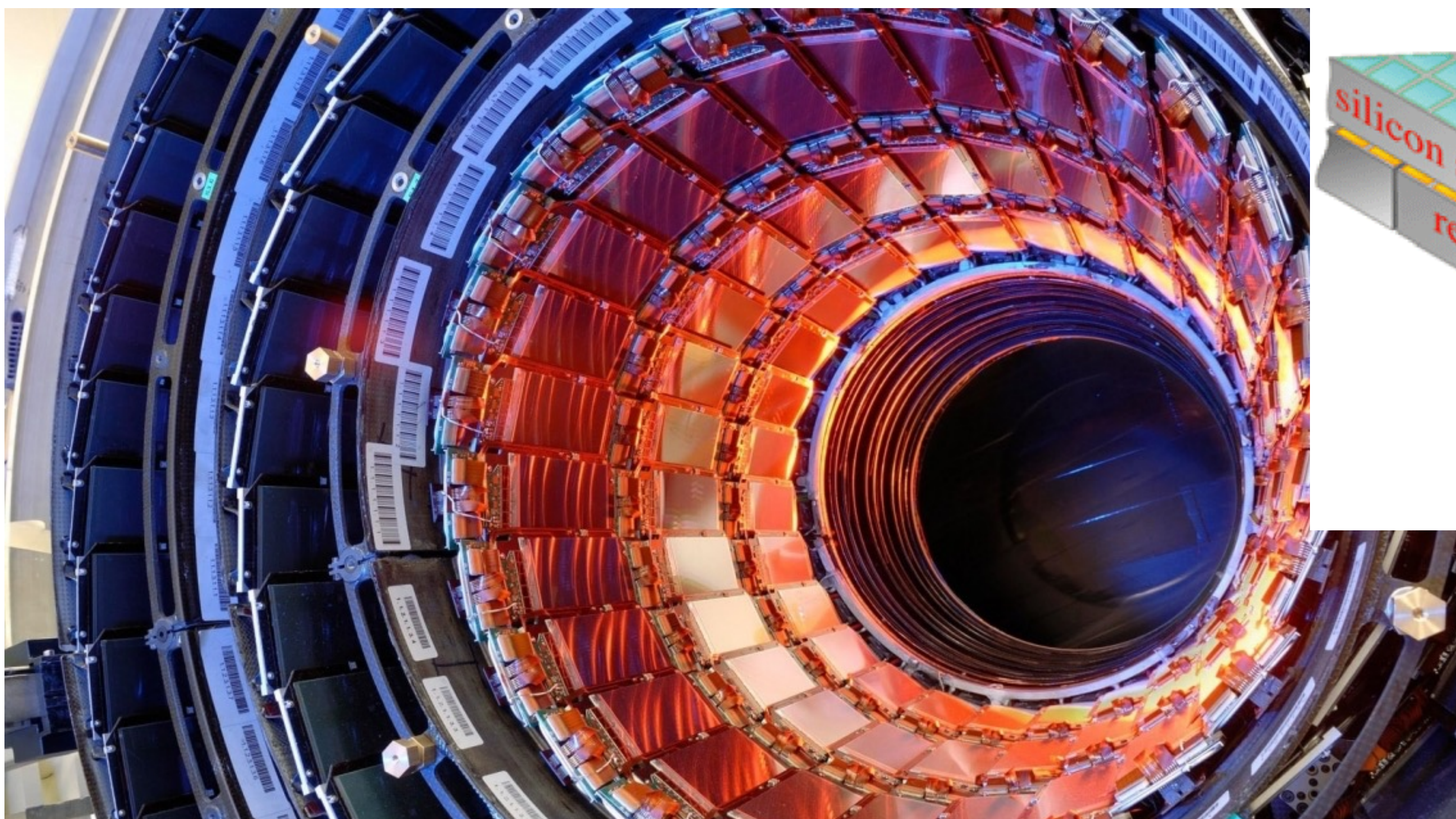

η
-1.5
-1.3
-1.1
-0.9
-0.7
-0.5
-0.3
-0.1
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
-1.7
-1.9
-2.1
-2.3
-2.5
1.7
1.9
2.1
2.3
2.5
1200
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
-1200
r (mm)
TOB
TIB
TID
PIXEL
TEC-
TEC+
-2600
-2200
-1800
-1400
-1000
-600
-200
200
600
1000
1400
1800
2200
2600
z (mm)

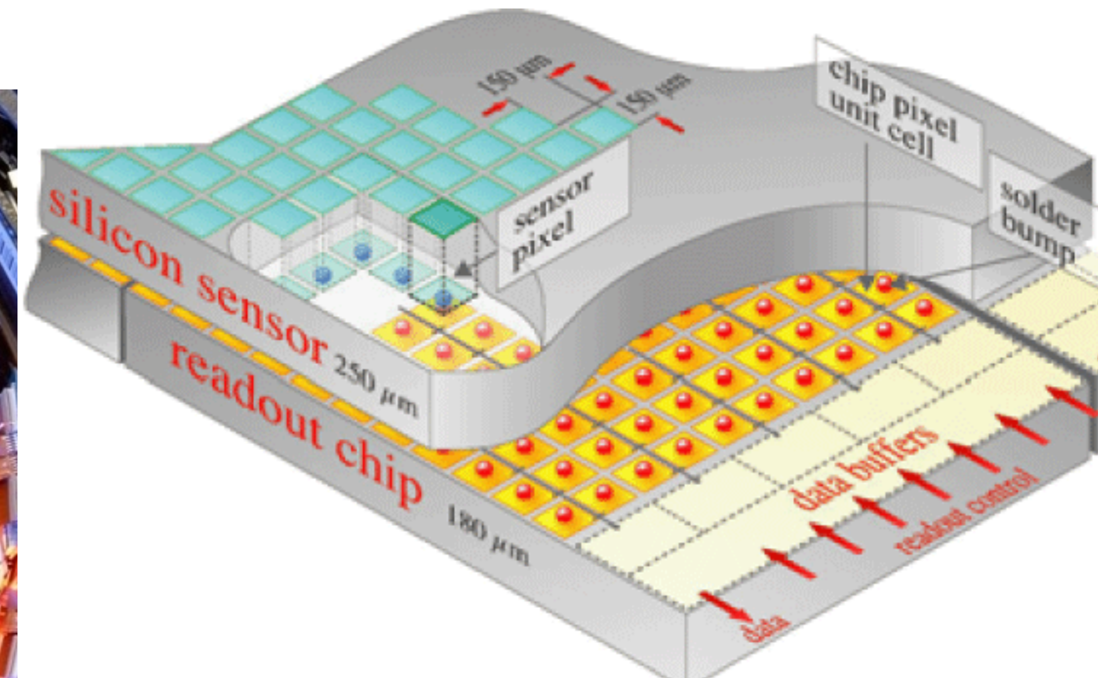
CMS Tracker (Before Phase-1)





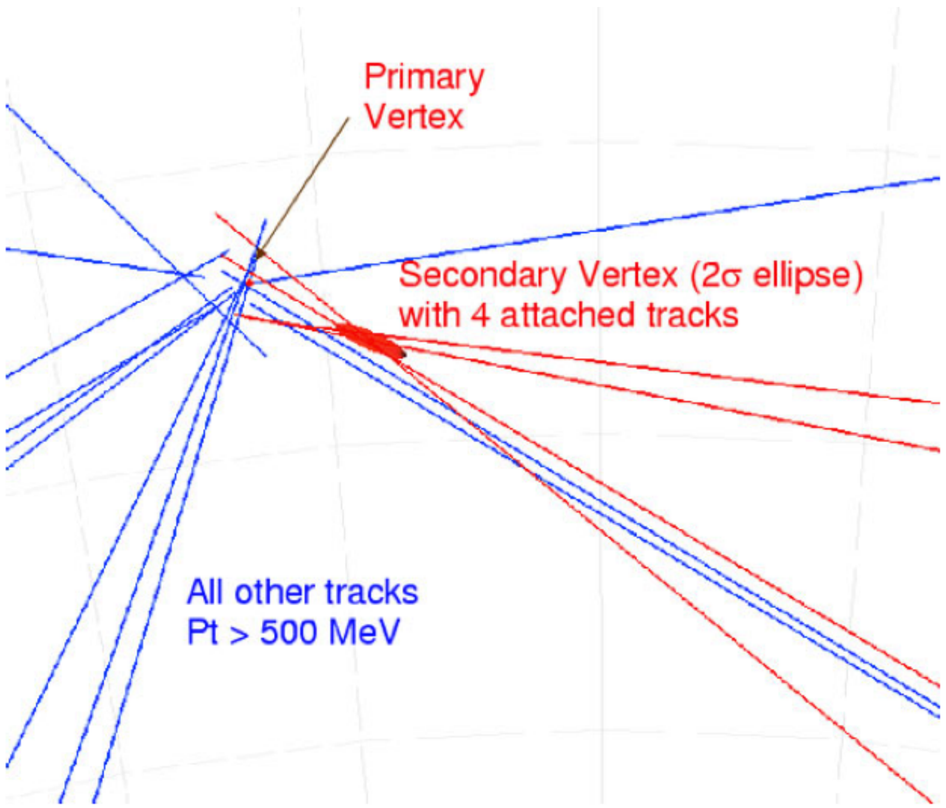

Forward disks
Barrel
y
z
x
Global
coordinates
Ladder
Ring




150 μm
150 μm
chip pixel
unit cell
sensor
pixel
solder
bump
silicon sensor 250 μm
readout chip 180 μm
data buffers
readout control
data

What Could We Do with Tracks?

- Charge of a particle
  - Knowing they originate from the collision point, not from the sky
- Momentum of a particle (direction and magnitude)
- Reconstruct primary vertex
  - Momentum for neutral particles
  - pileup removal
- Reconstruct secondary vertex
  - b-tagging



Typical Track Parameters

Five helix parameters:

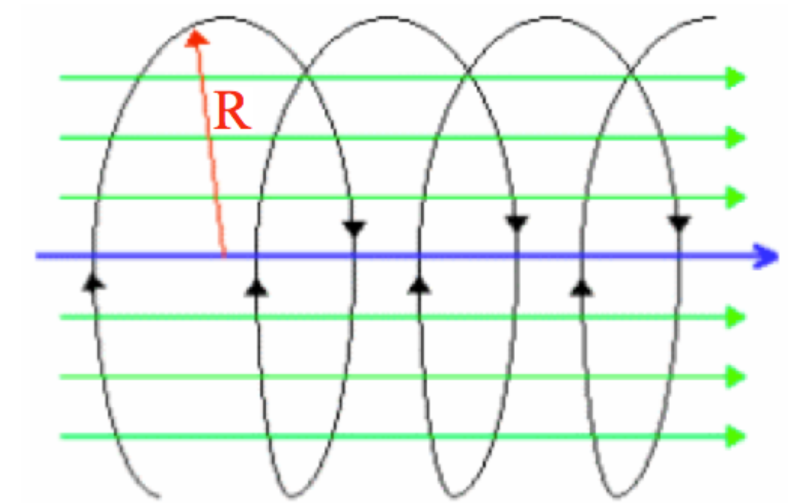
C: [half] curvature, signed

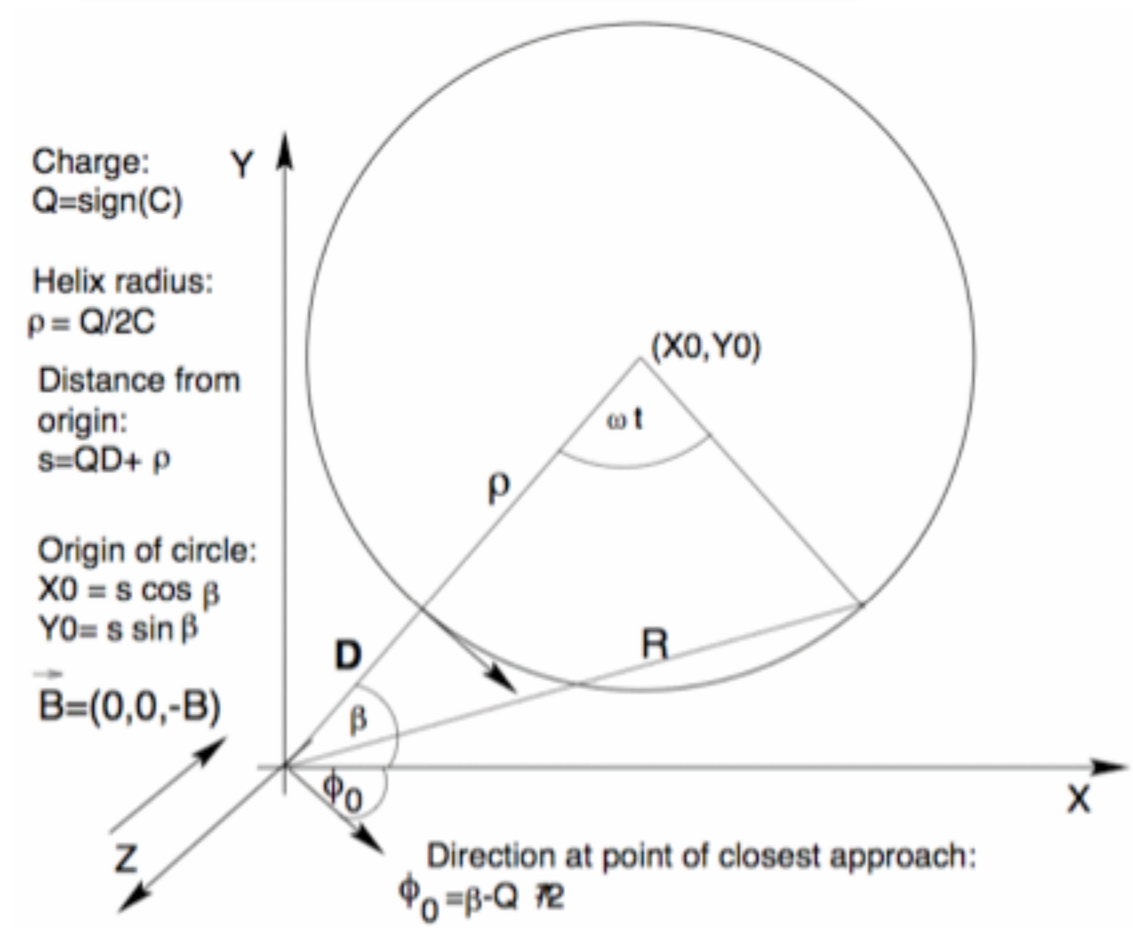
cot(θ): polar angle

D: Distance of closest approach to orign. (Also called impact parameter, d_0).

ϕ_0: Phi at closest approach

z_0: z at closest approach





Hanz Wenzel, CDF Note 1790

How to Obtain p_T

Homework

$$p_T = qBR \xrightarrow{\substack{\text{Singly charged,} \\ \text{in units of GeV/c,} \\ \text{meter, and Tesla}}} p_T = 0.3\ BR$$

Example: The CMS magnetic field is 3.8 Tesla. The trajectory of a 10 GeV charged particle at CMS is a helix with a radius of 8.8 m.

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Example: The CMS magnetic field is 3.8 Tesla. The trajectory of a 10 GeV charged particle at CMS is a helix with a radius of 8.8 m.

A typical tracker has an outer radius of 1~1.5 m. ➡ Its trajectory is an arc (rather than a full circle)!

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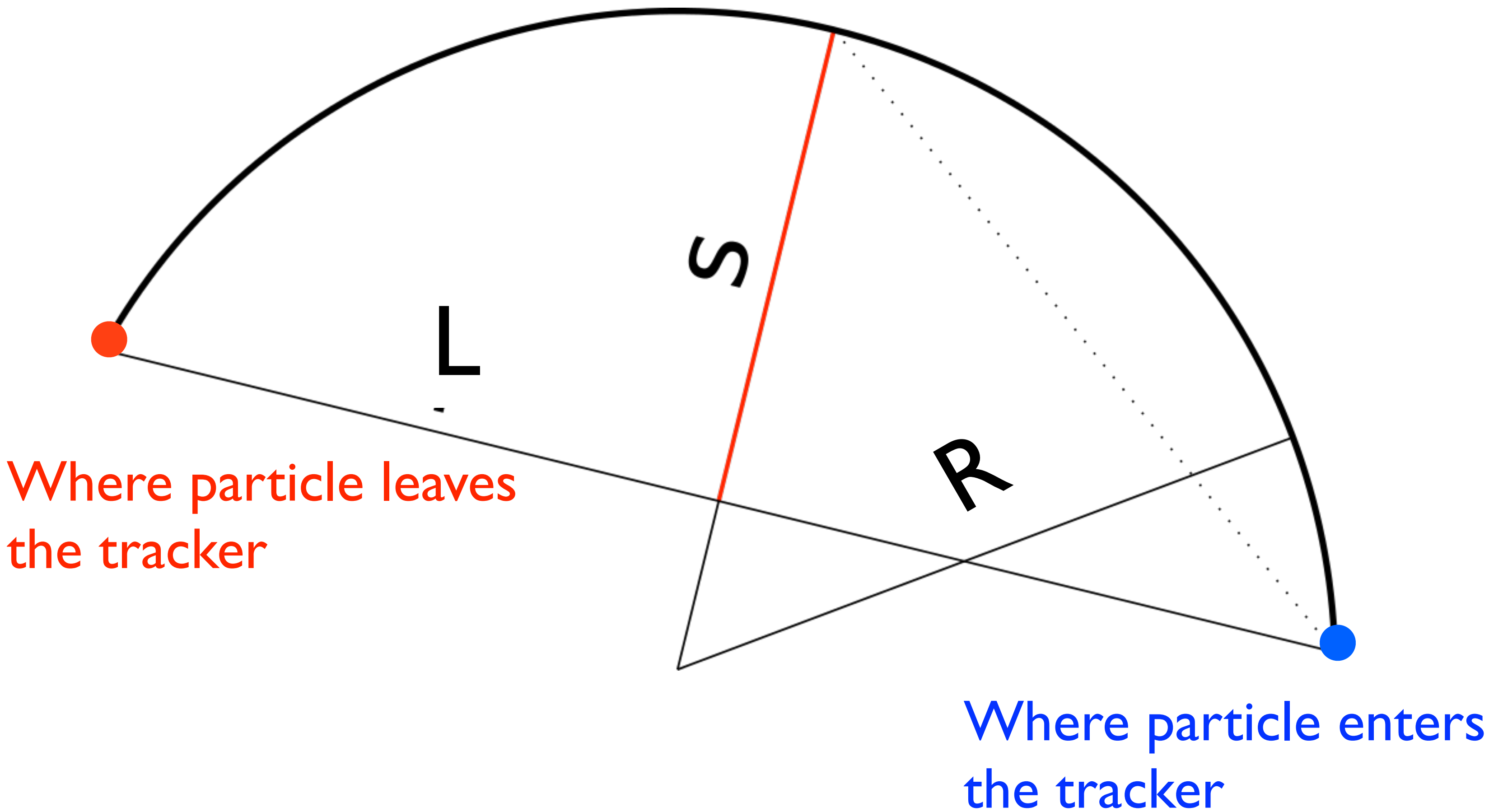
Example: The CMS magnetic field is 3.8 Tesla. The trajectory of a 10 GeV charged particle at CMS is a helix with a radius of 8.8 m.

(1) What happens to a 0.1 GeV or 1 GeV charged particle?
(2) How do we obtain p_z?

Homework

Sagitta and Momentum Resolution

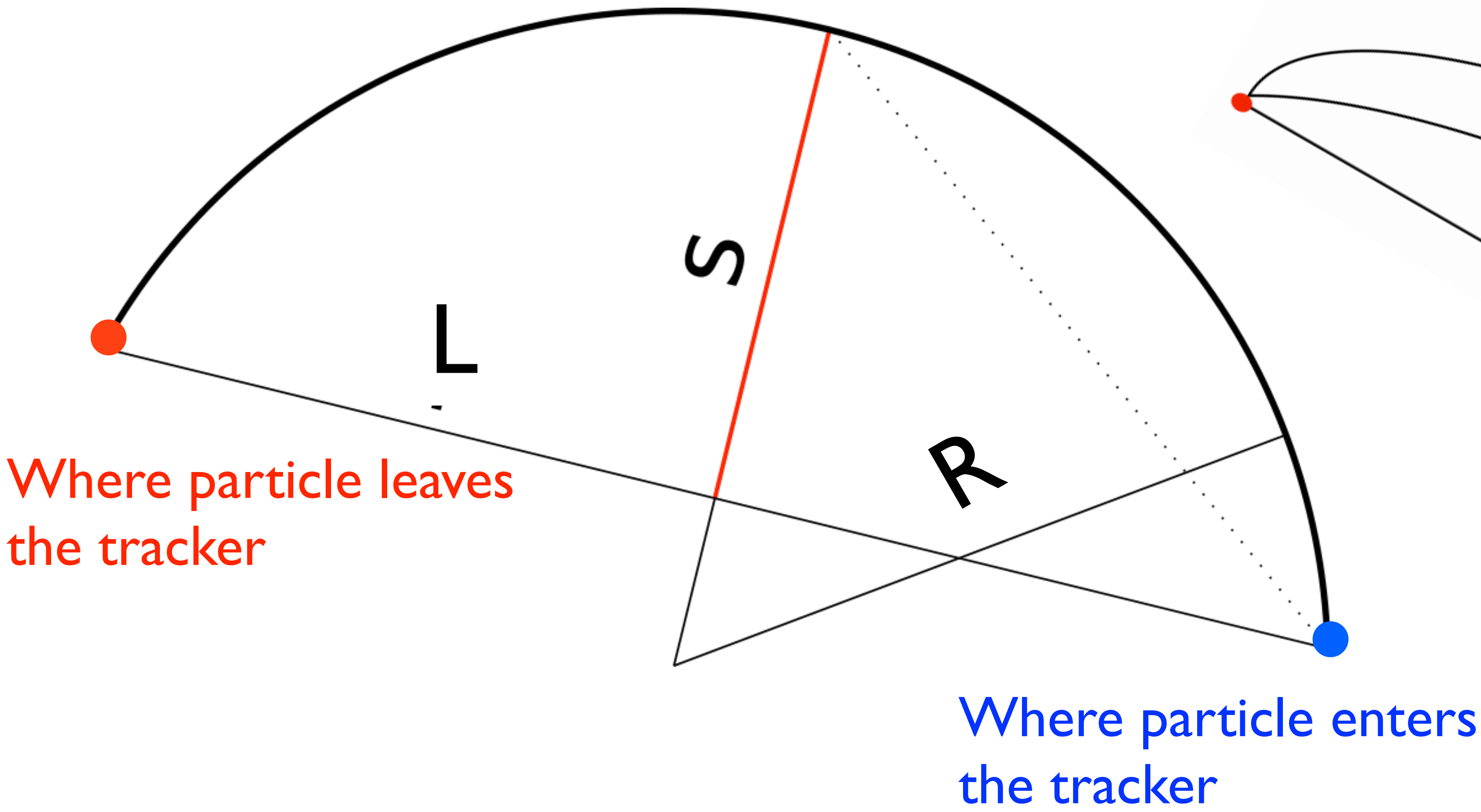


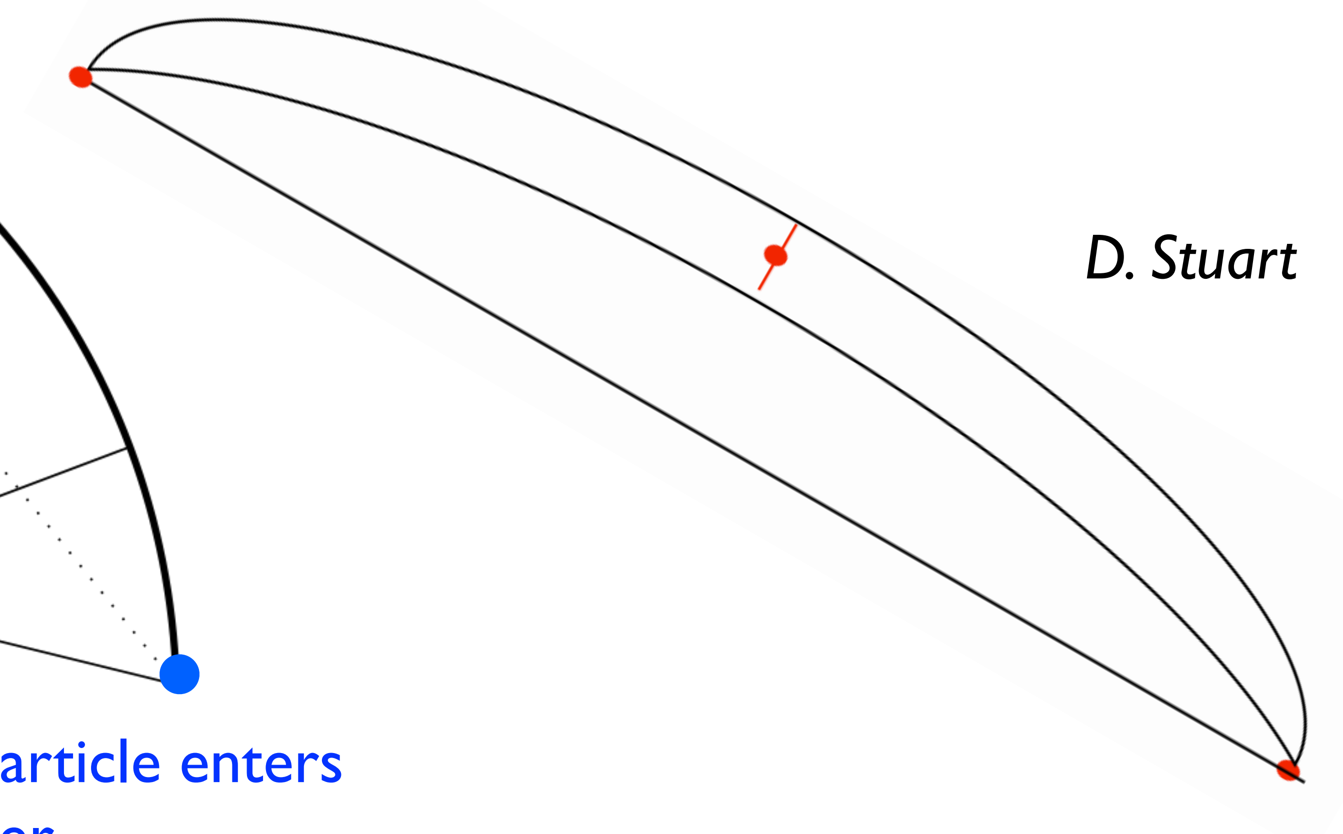
L (level arm): tracker outer-inner radius

Usually s (sagitta) $\ll R$

$$\Rightarrow R \cong \frac{L^2}{8s}, \;\; p_T \cong \frac{qBL^2}{8s} = \frac{0.3\, BL^2}{8s}$$ Homework

Sagitta and Momentum Resolution





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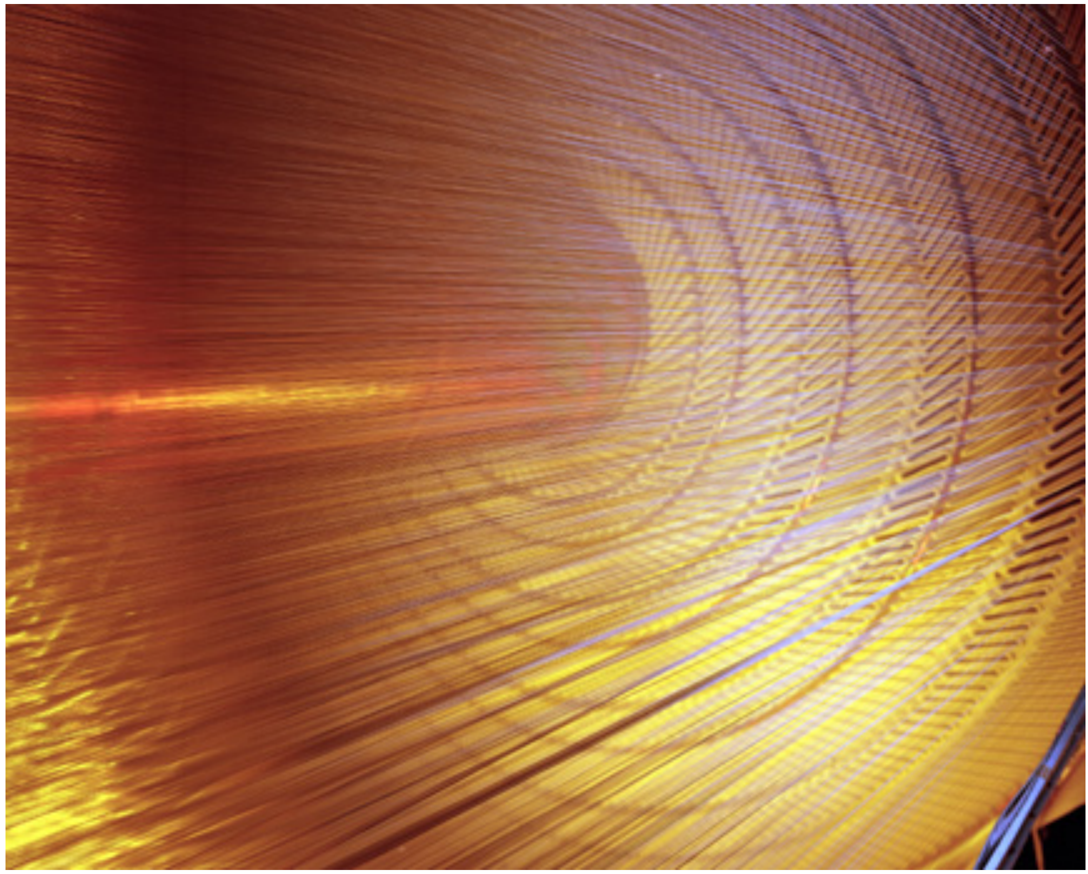
$$\boxed{\frac{\delta p_T}{p_T} \propto \frac{\delta x}{BL^2} \frac{1}{\sqrt{(N+4)}} \times p_T}$$

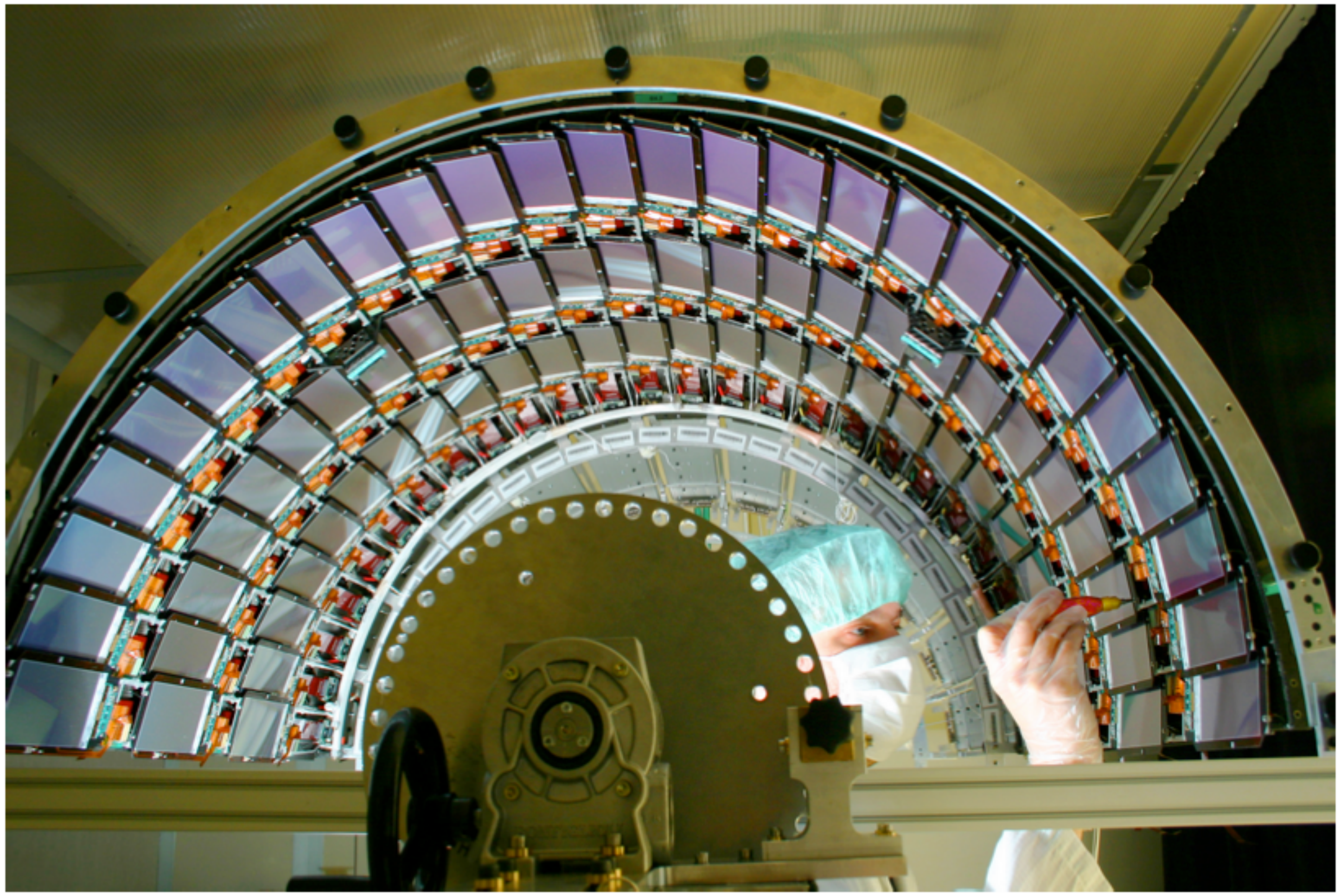
ATLAS and CMS Trackers

	ATLAS	CMS
Tracker Radius	110 cm	115 cm
Tracker Length	7 m	5.4 m
Solenoid Field	2T	4T
Pixels		
# Barrel Layers	3	3
Barrel Radii	5.05, 9.85, 12.25	4.4, 7.5, 10.2
#Fwd Disks	3	2(3)
Disk Positions	49.5, 56.0, 65.0 cm	35.5, 48.5, 61.5 cm
Microstrips		
#Barrel Layers	4	10
# Disk Layers	9	9
Radial Span	25-50 cm	20-110 cm
Measurement points in central region	7 precision + 36 TRT	13 precision

Tracking Resolution

$$\frac{\delta p_T}{p_T} \propto \frac{\delta x}{BL^2} \frac{1}{\sqrt{(N+4)}} \times p_T$$





Hit position resolution

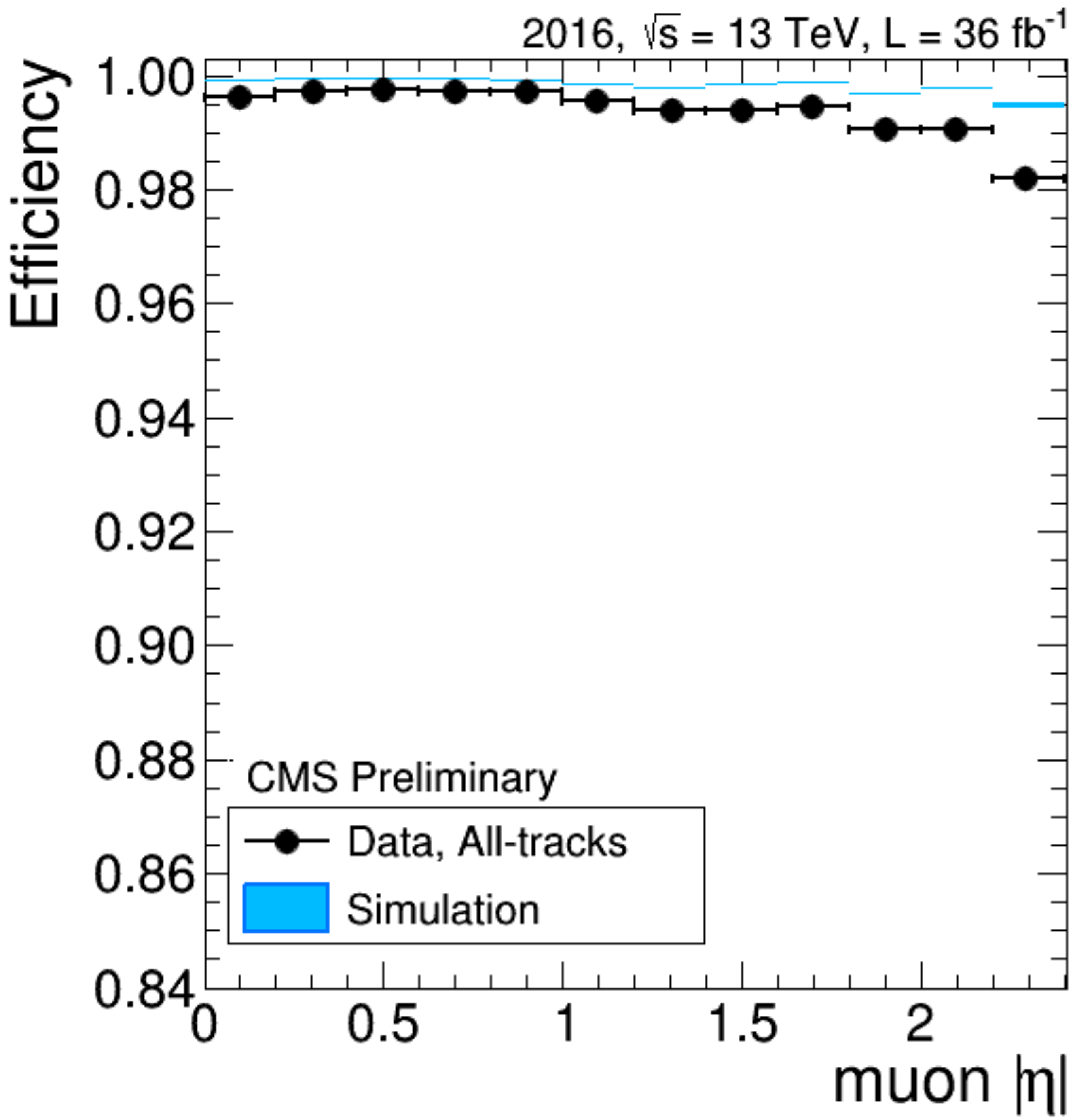
Gas: $\delta x \sim 150\ \mu\text{m}$

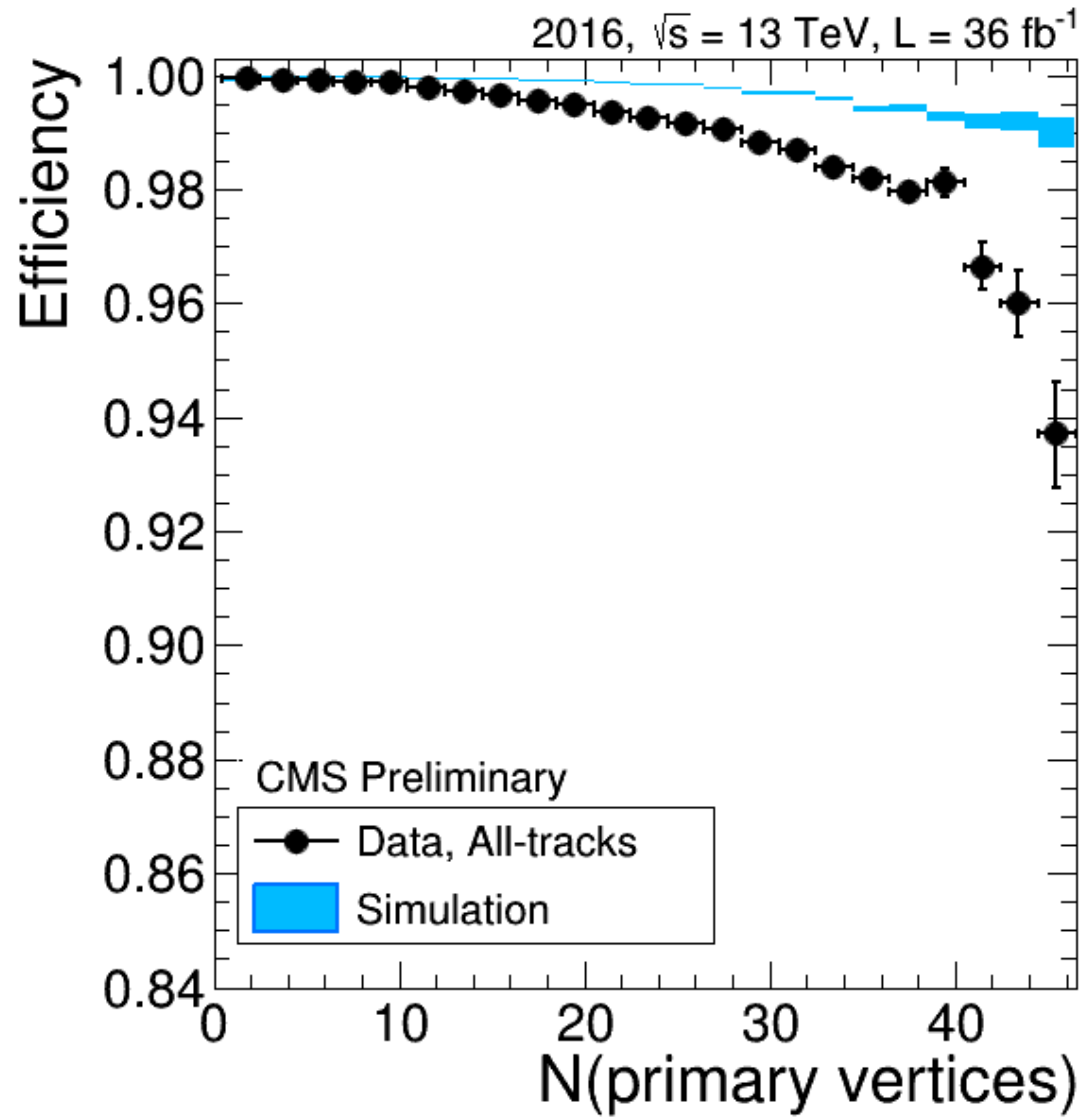
Silicon: $\delta x \sim 10-20\ \mu\text{m}$

Typical Tracking Resolution

- ATLAS has similar performance
- p_T resolution for 1 GeV (TeV) particle is 0.7% (5%)
- Impact parameter resolution is 10 (15) μm in xy (z) direction for high momentum tracks

Typical Tracking Efficiency

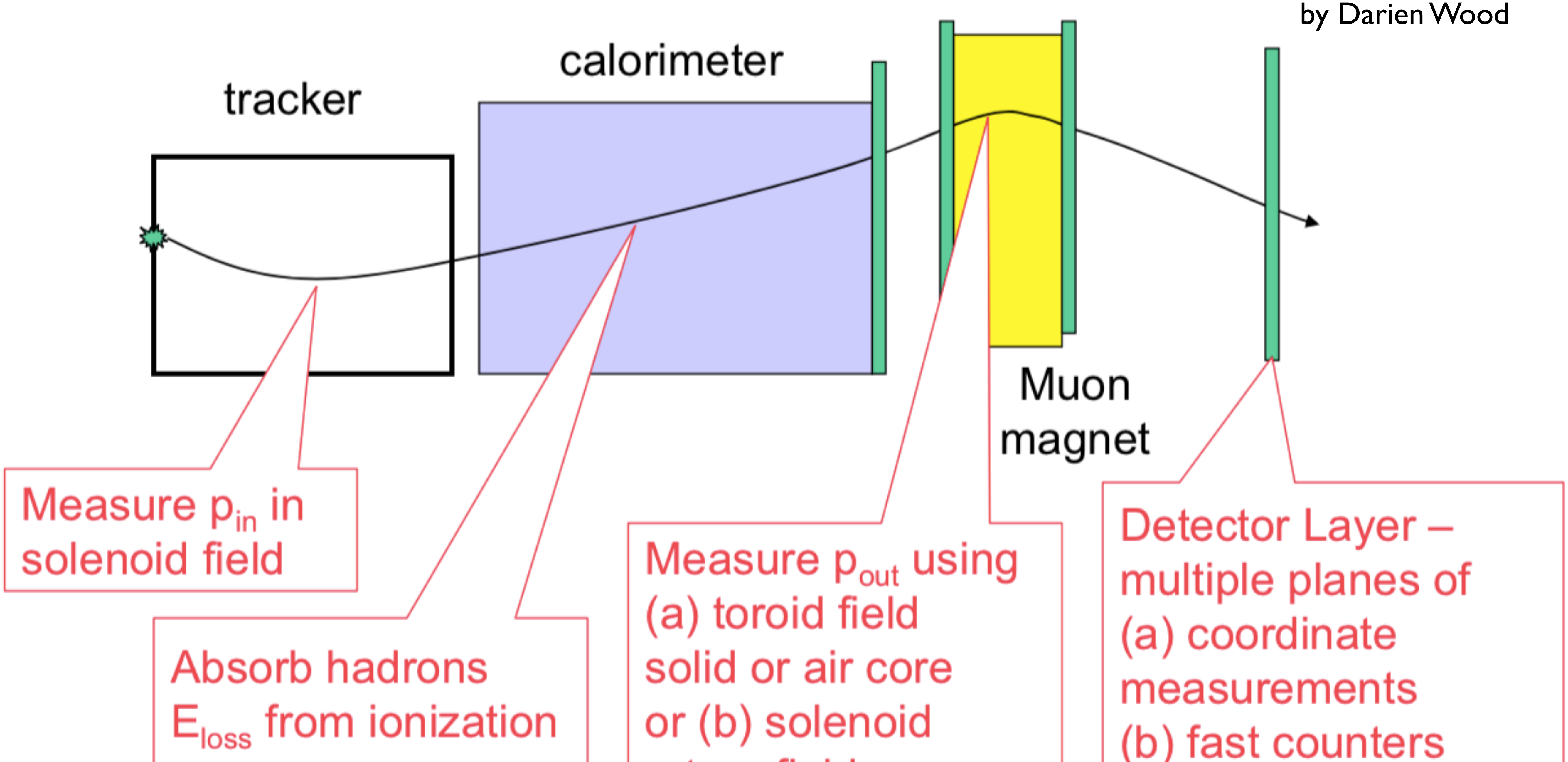




Muon Chamber

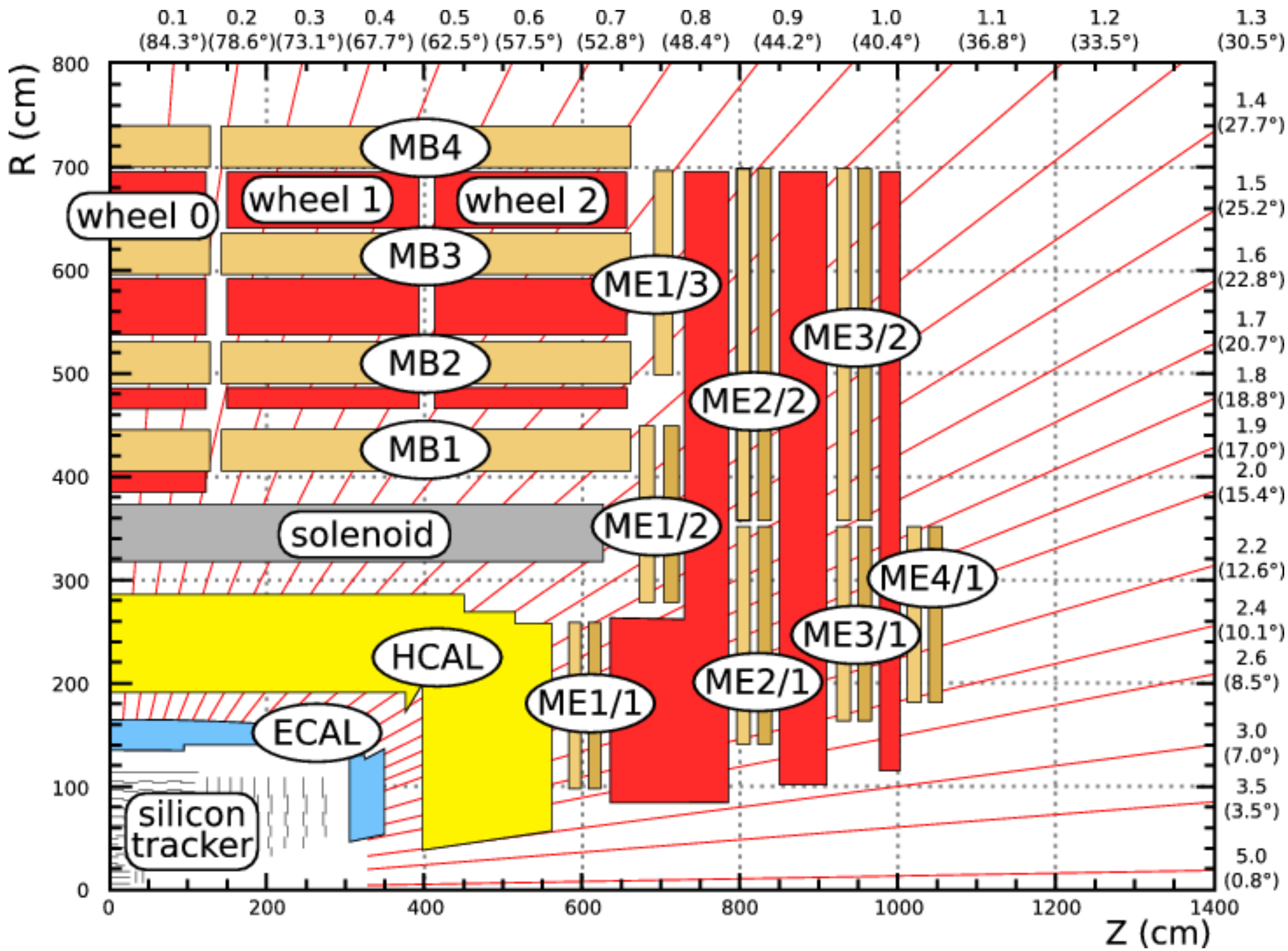
- Muon is a charged particle
  - Leaves signal in the tracker and the muon chamber, with small energy deposit in the calorimeter

by Darien Wood



CMS Muon System

- Drift tubes (DTs), resistive plate chambers (RPCs), cathode strip chambers (CSCs)



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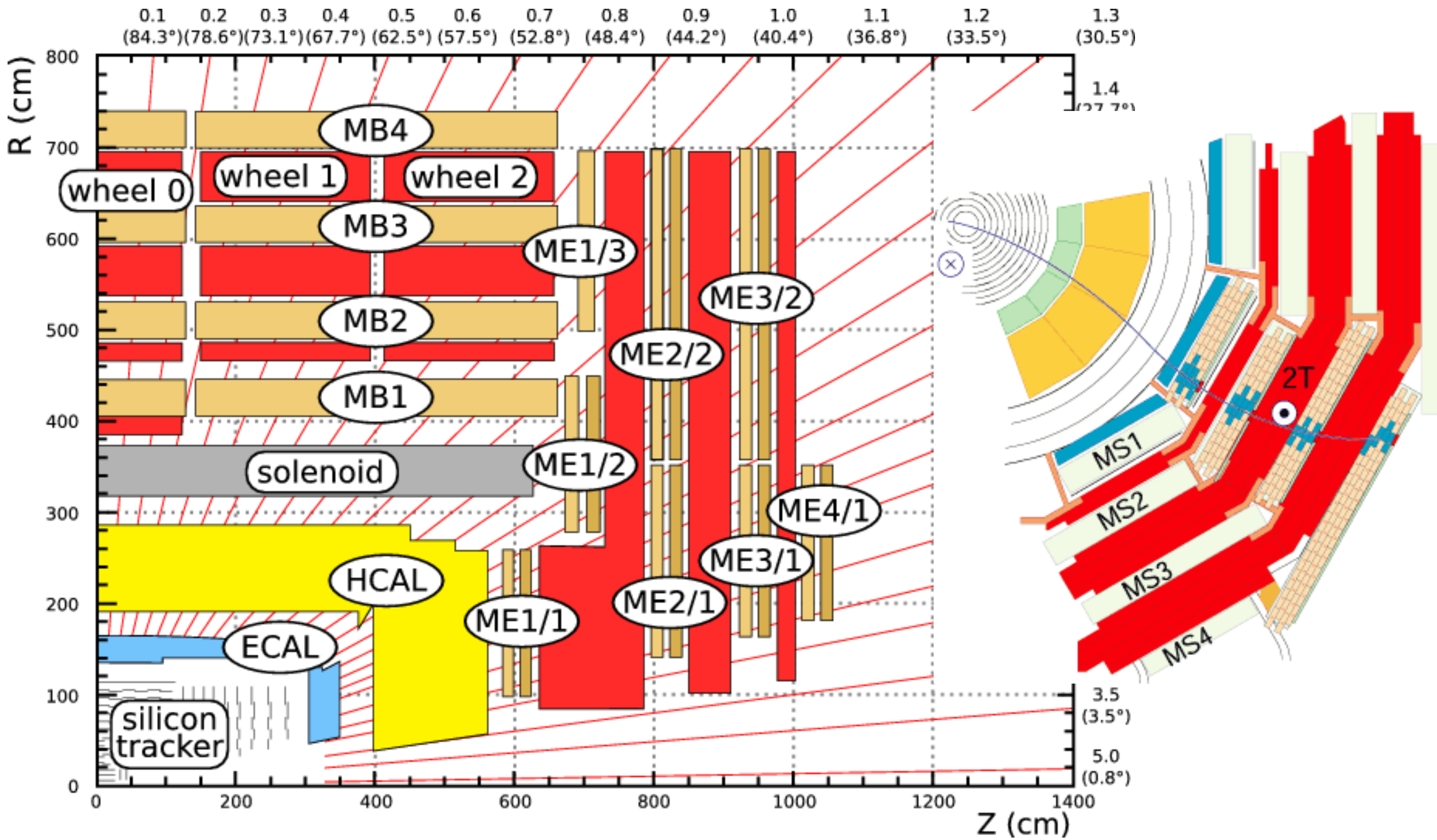

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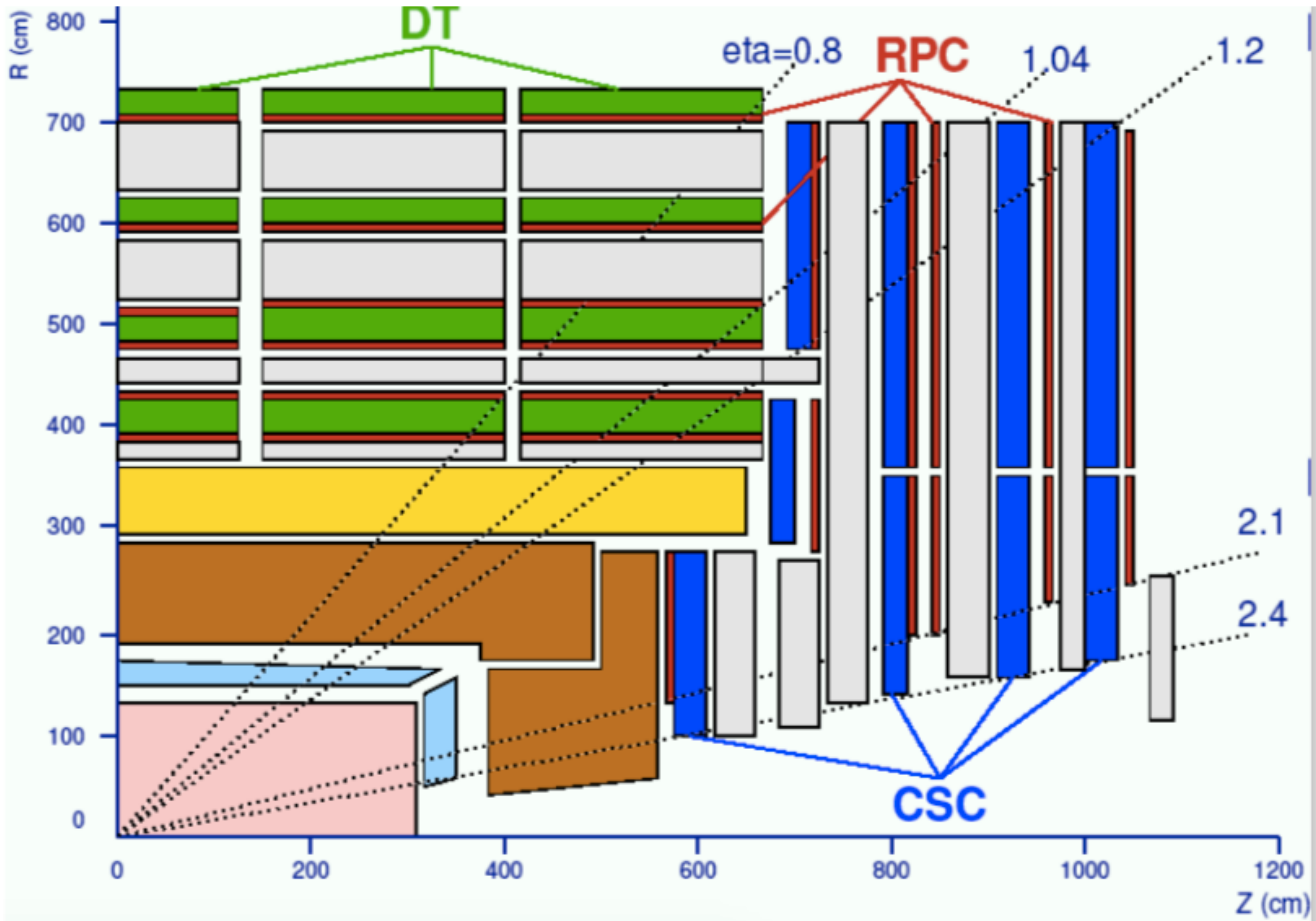
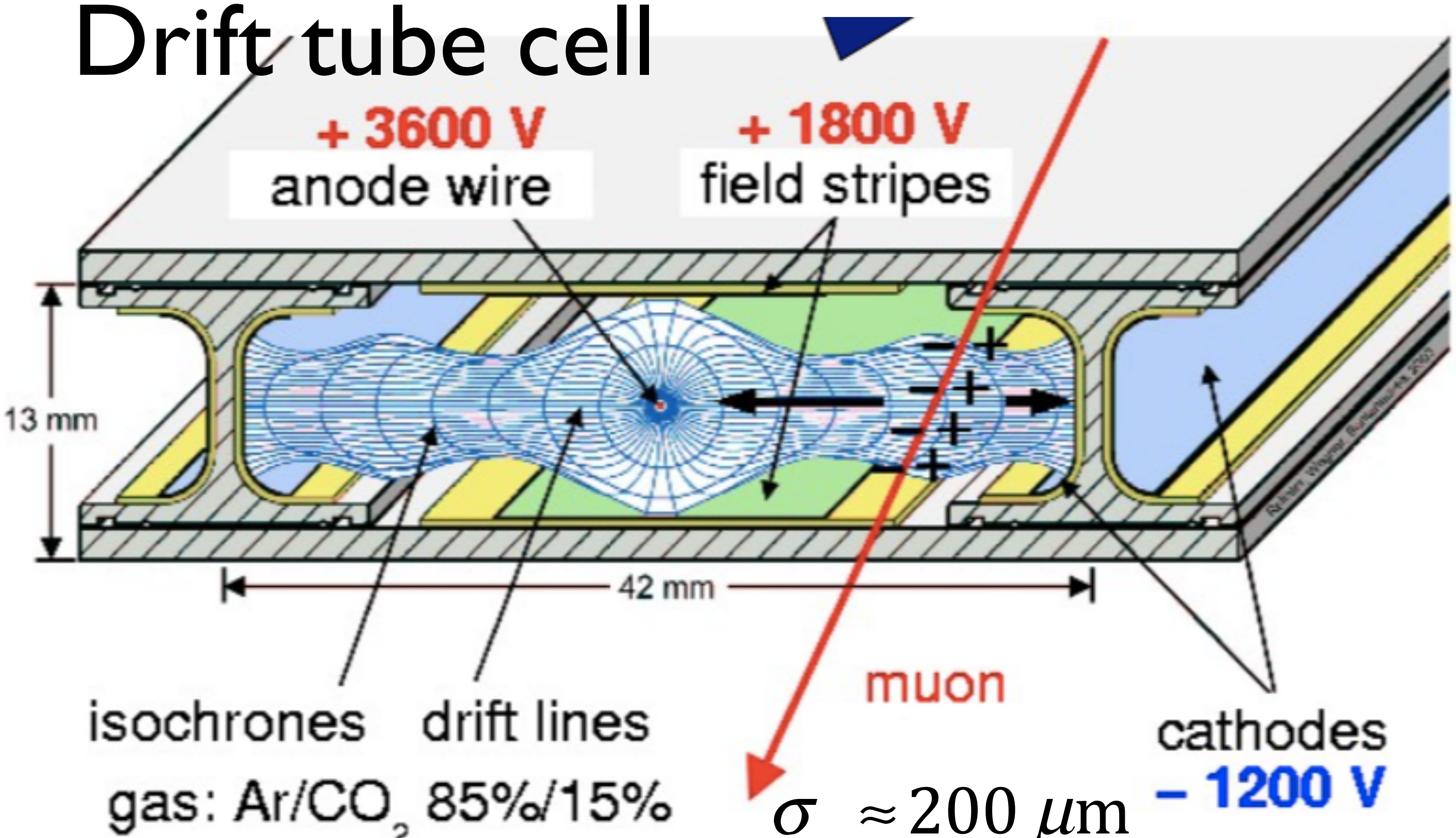


CMS Muon System

Drift tube cell



$\sigma_x \approx 200\ \mu\text{m}$

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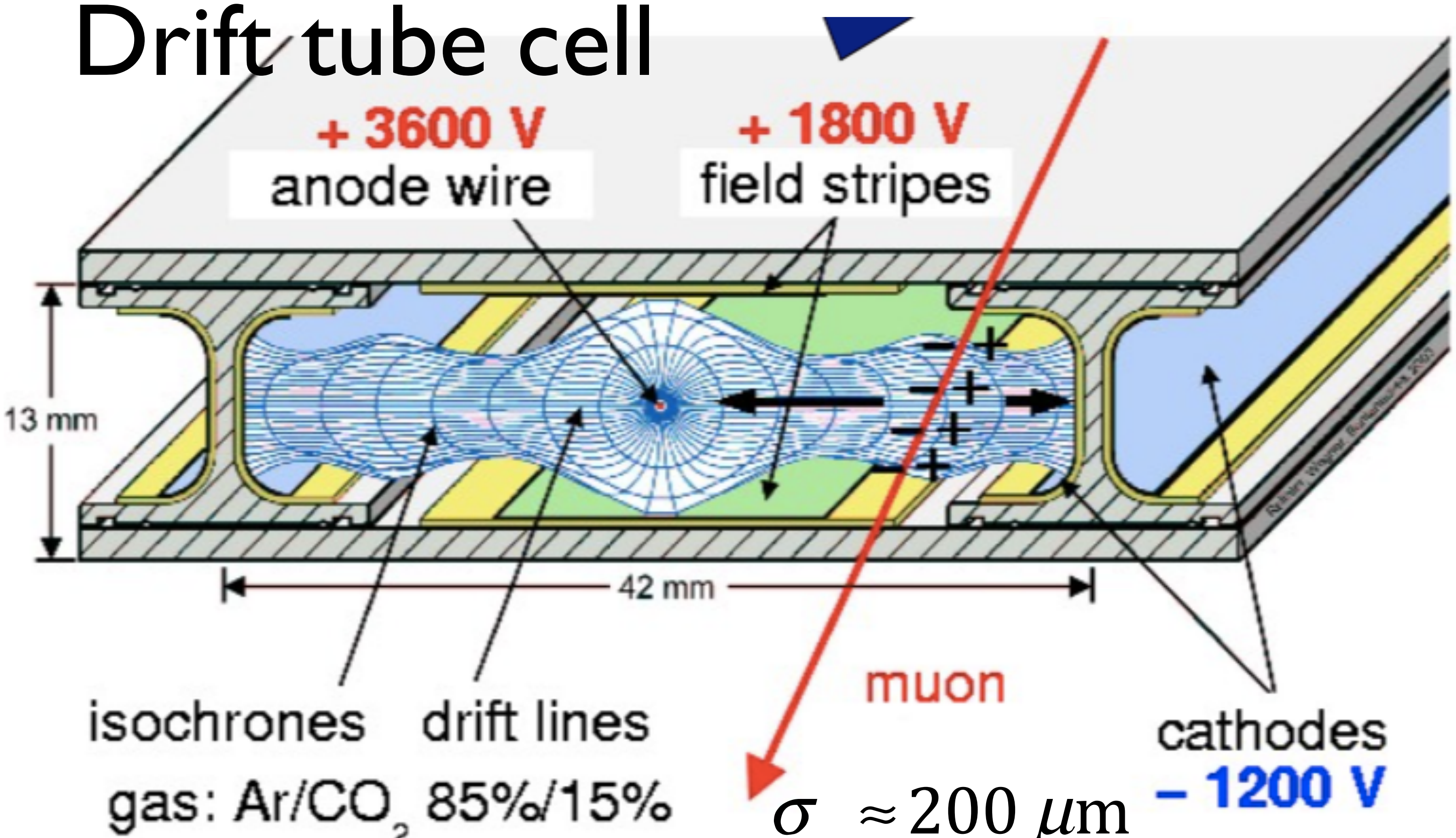

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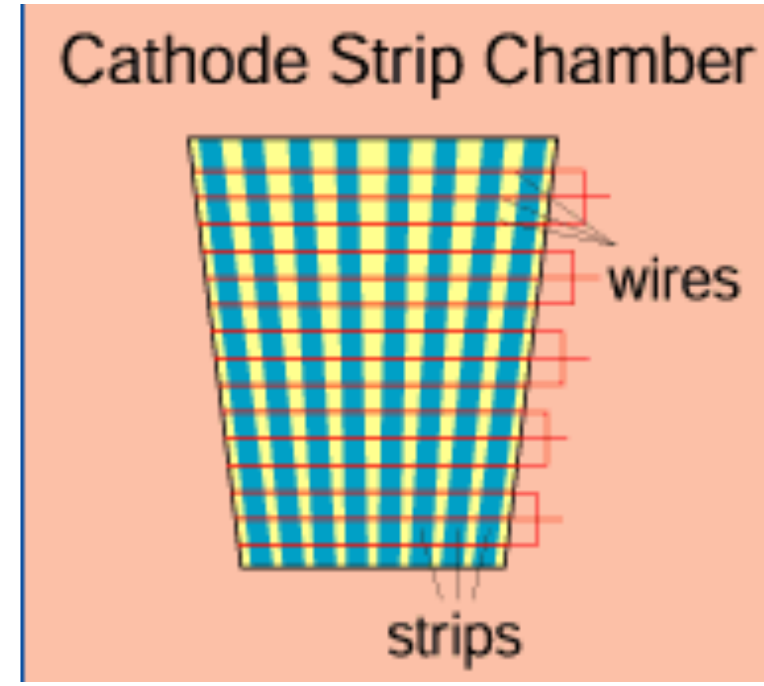
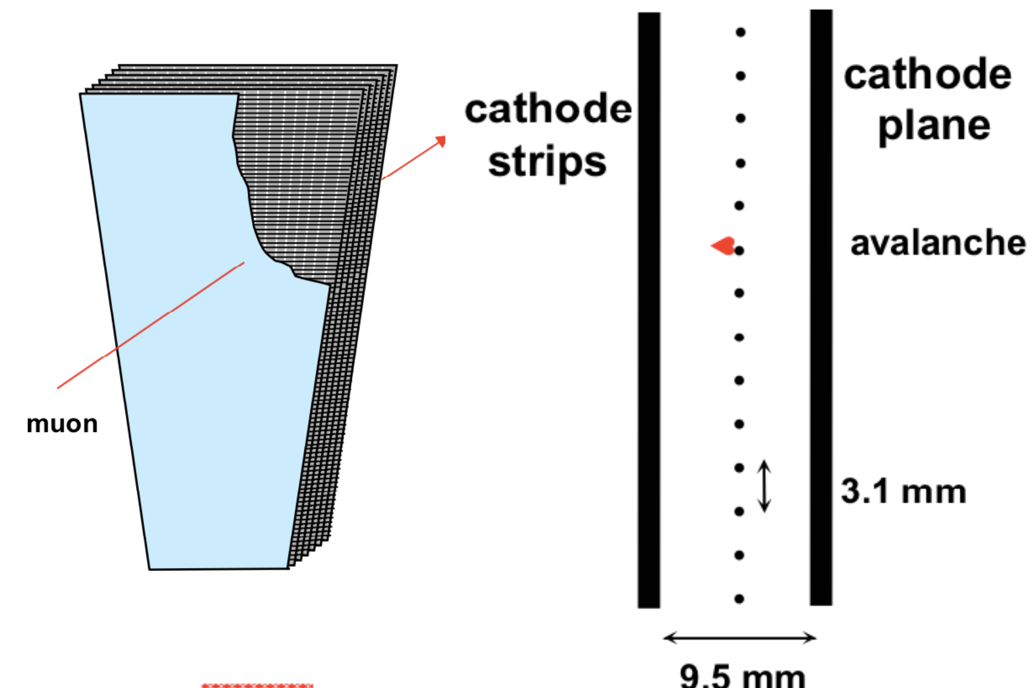
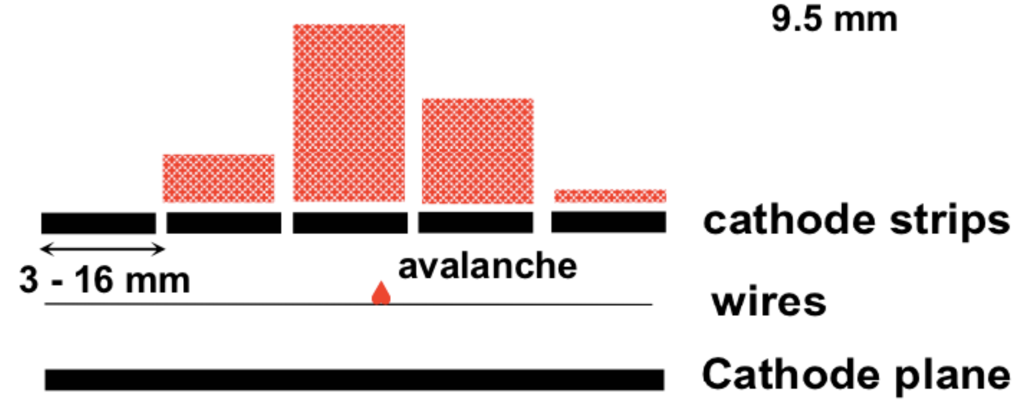


$\sigma_x \approx 100-240\ \mu m$





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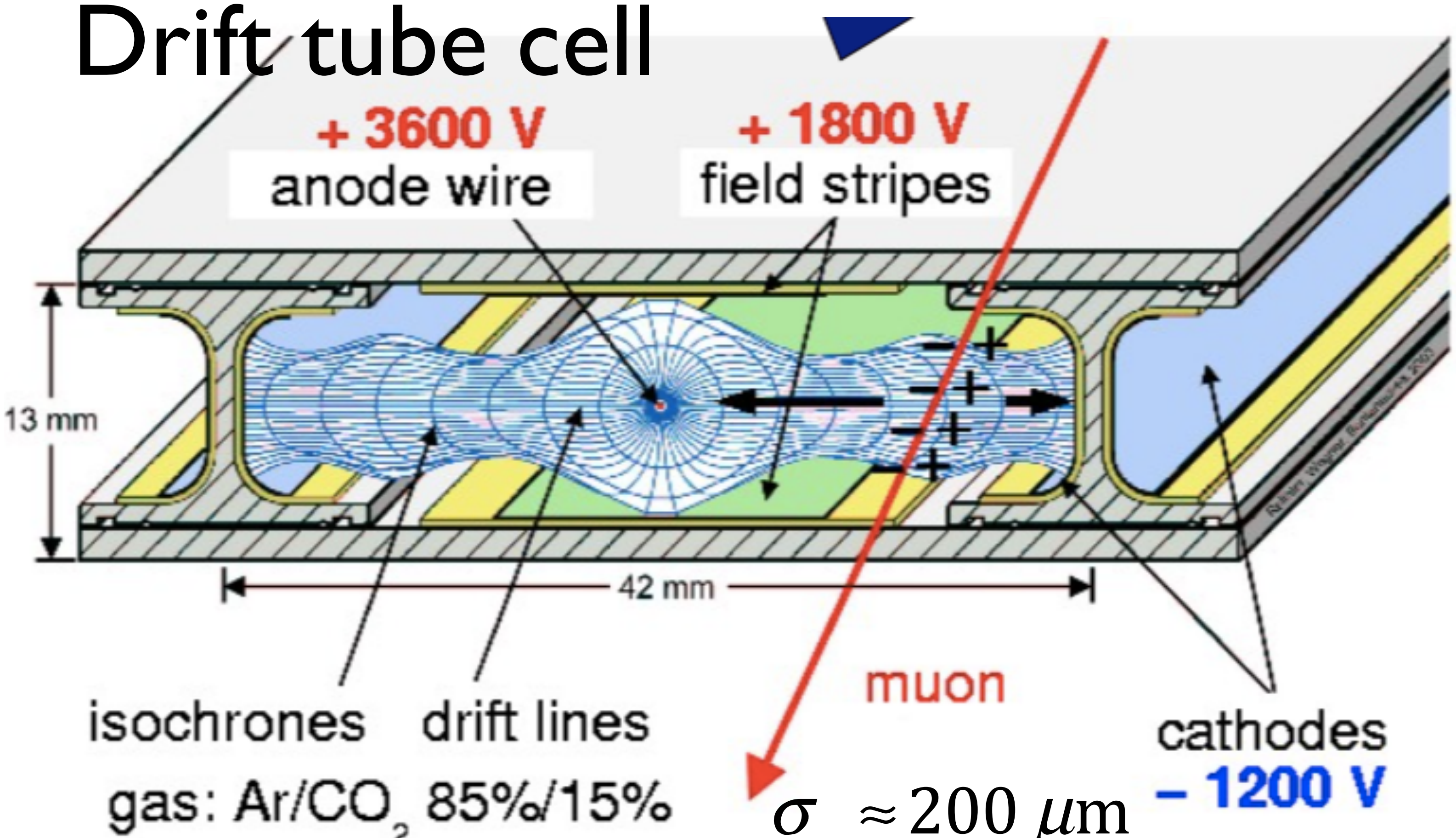

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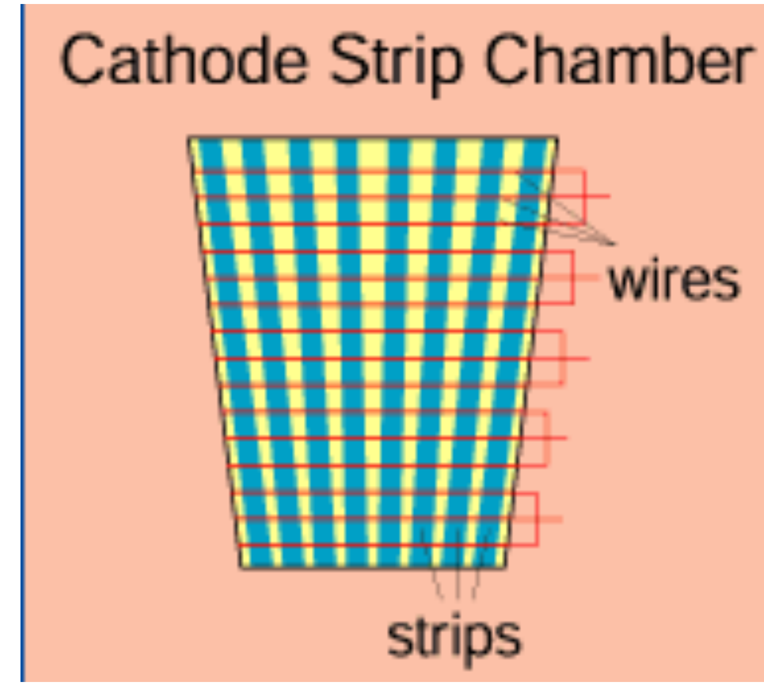

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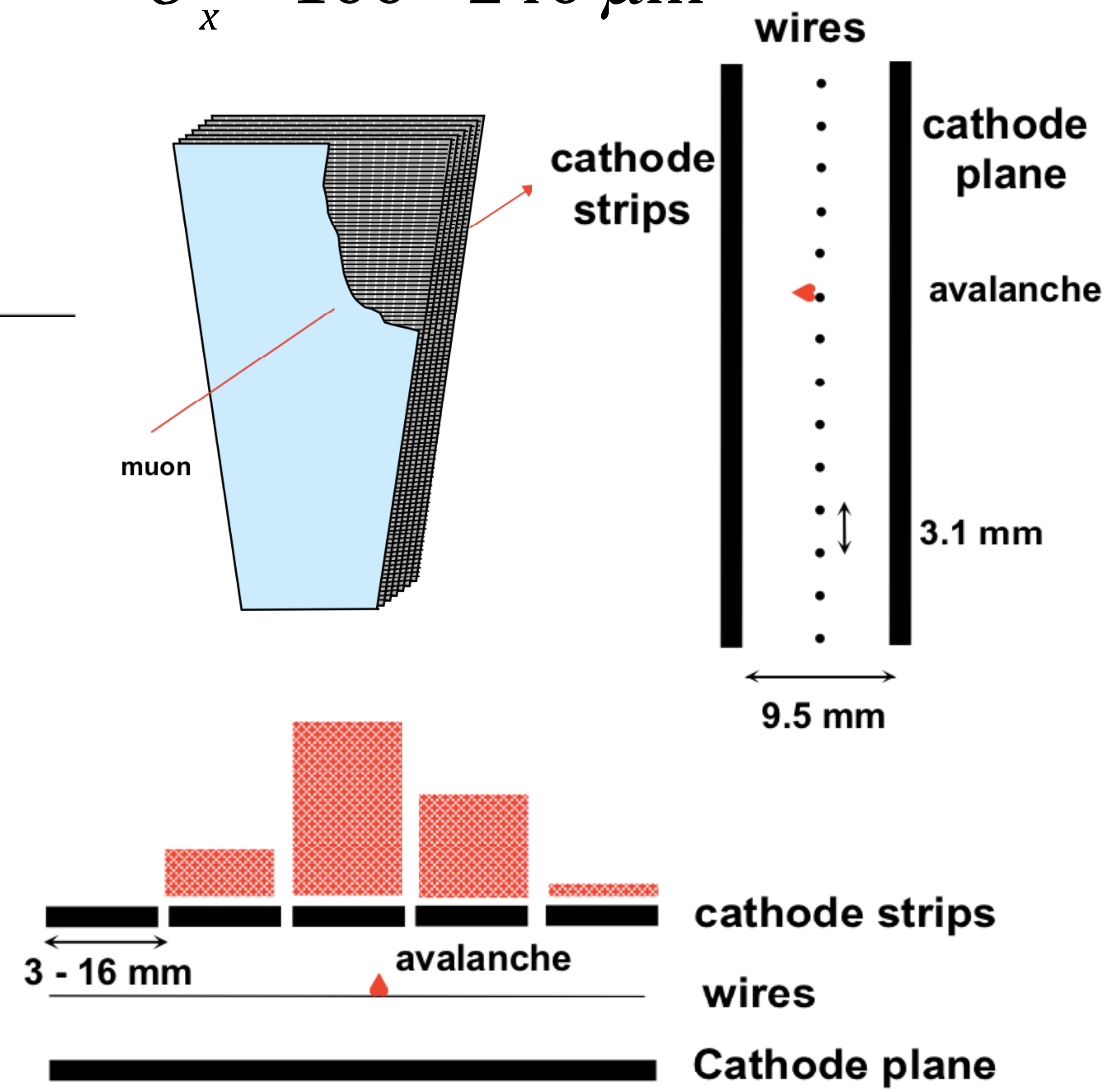
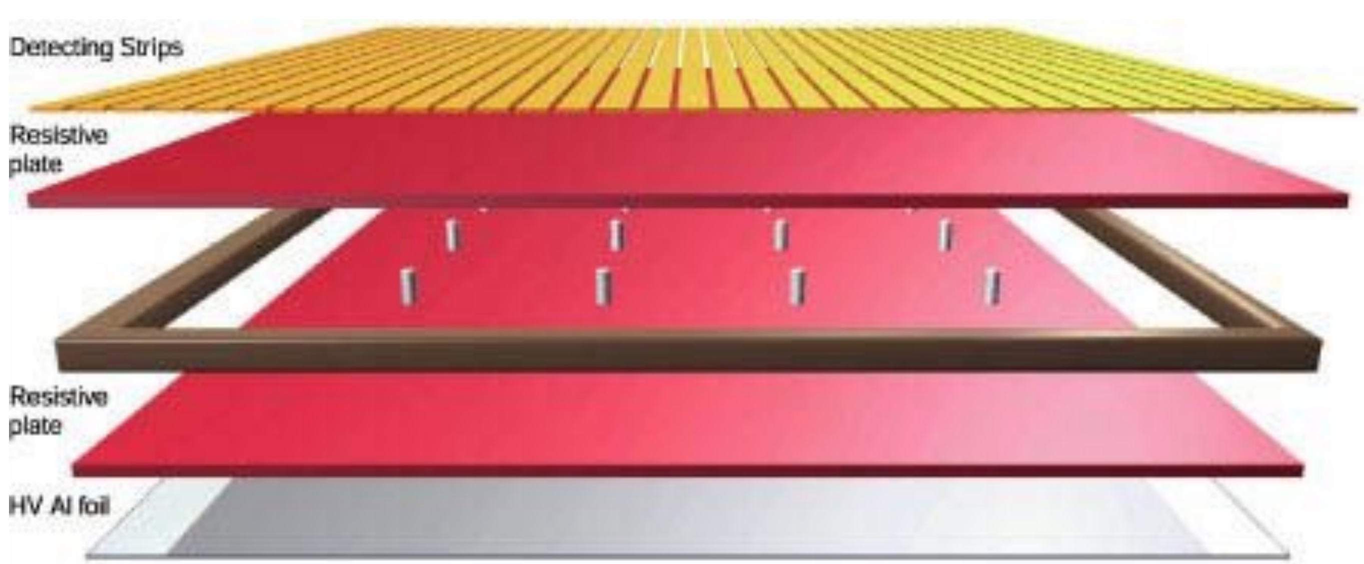
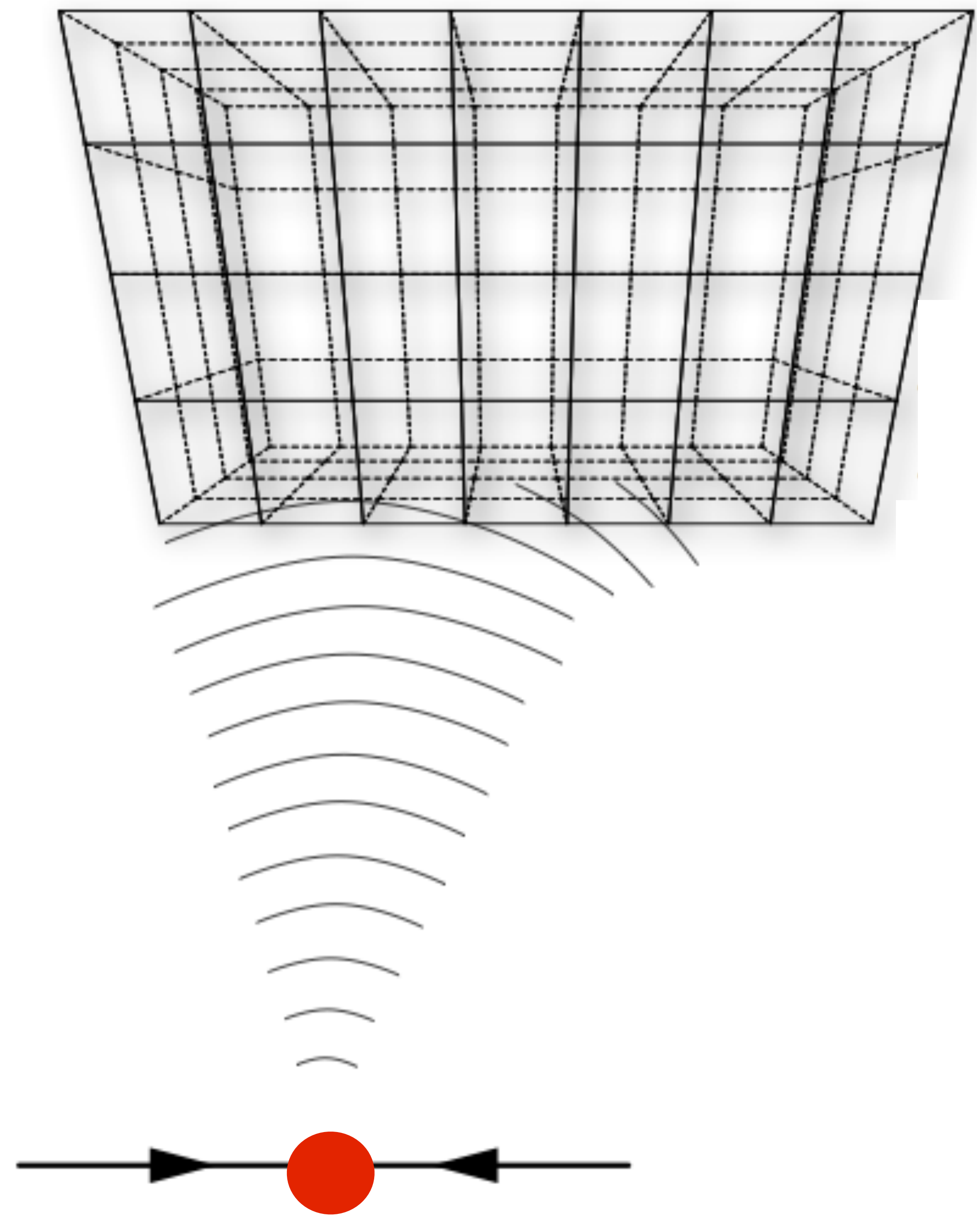




$\sigma_t \approx 2\ \text{ns}$

How to Measure Momentum?

- Neutral and interacting particle(s)
  - ➡ Connect the spot of energy deposit in calorimeter with primary interaction point
  - ➡ Due to the poor segmentation of hadron calorimeters, most of the time we are studying momentum of merged hadrons



R. Cavanaugh

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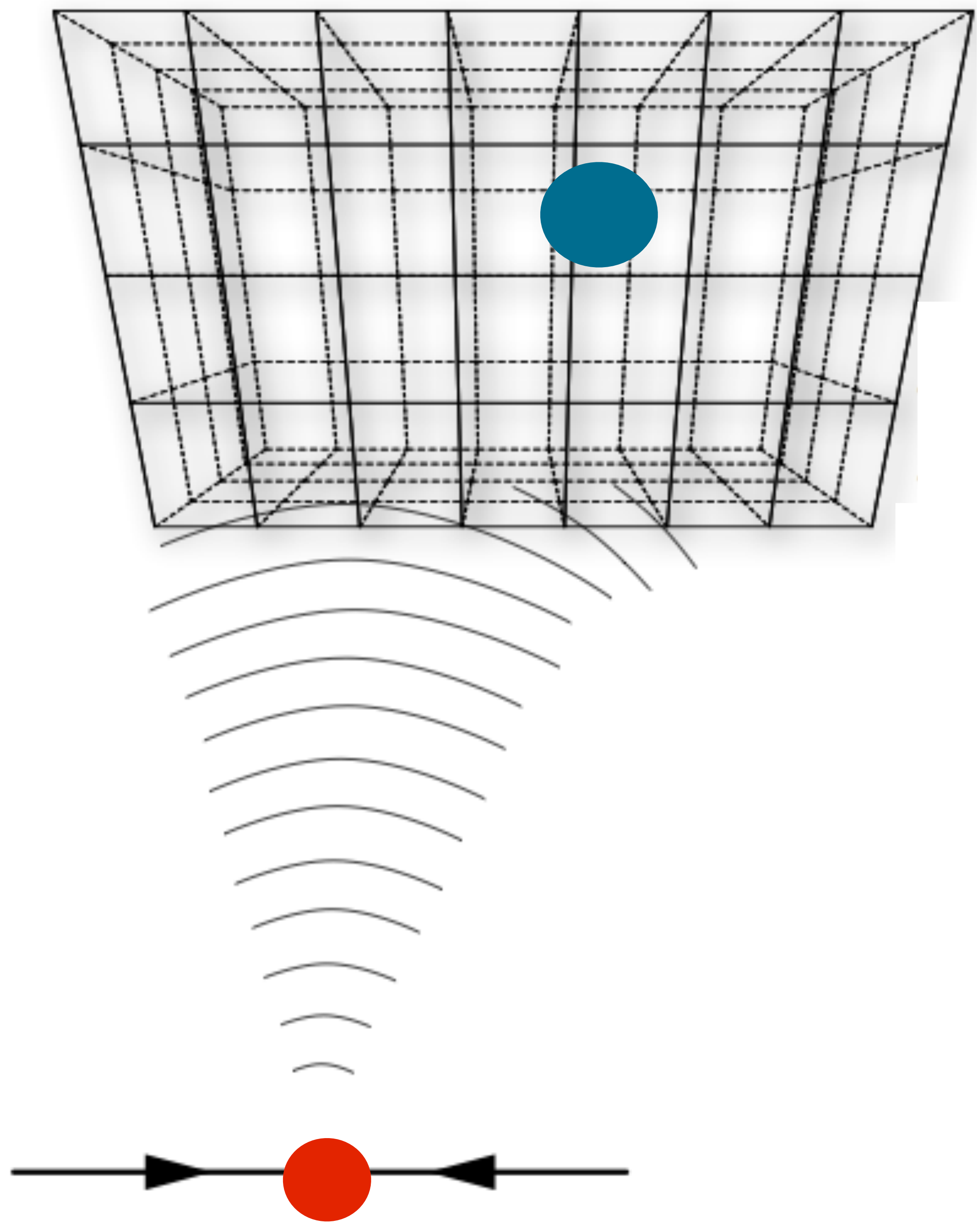

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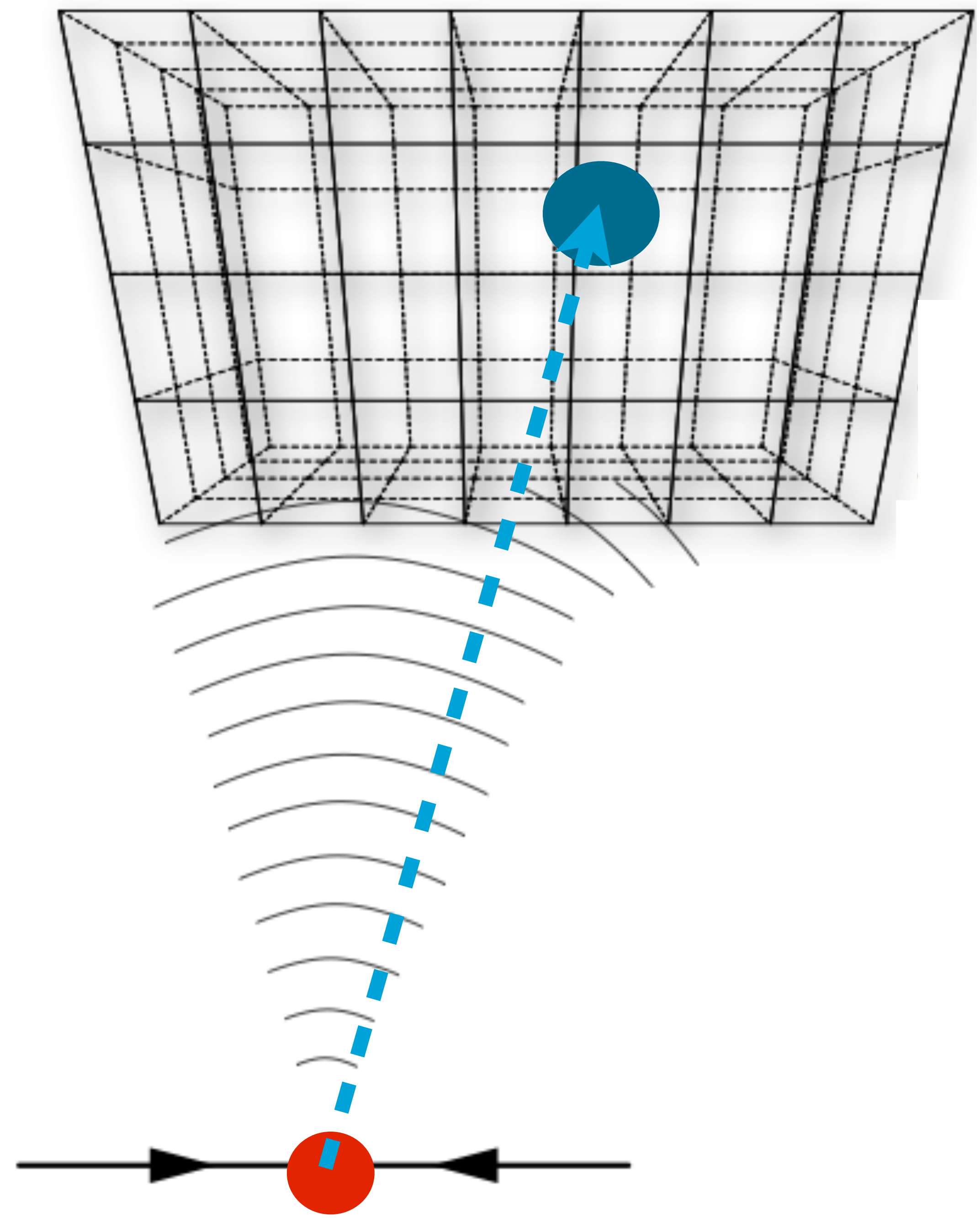

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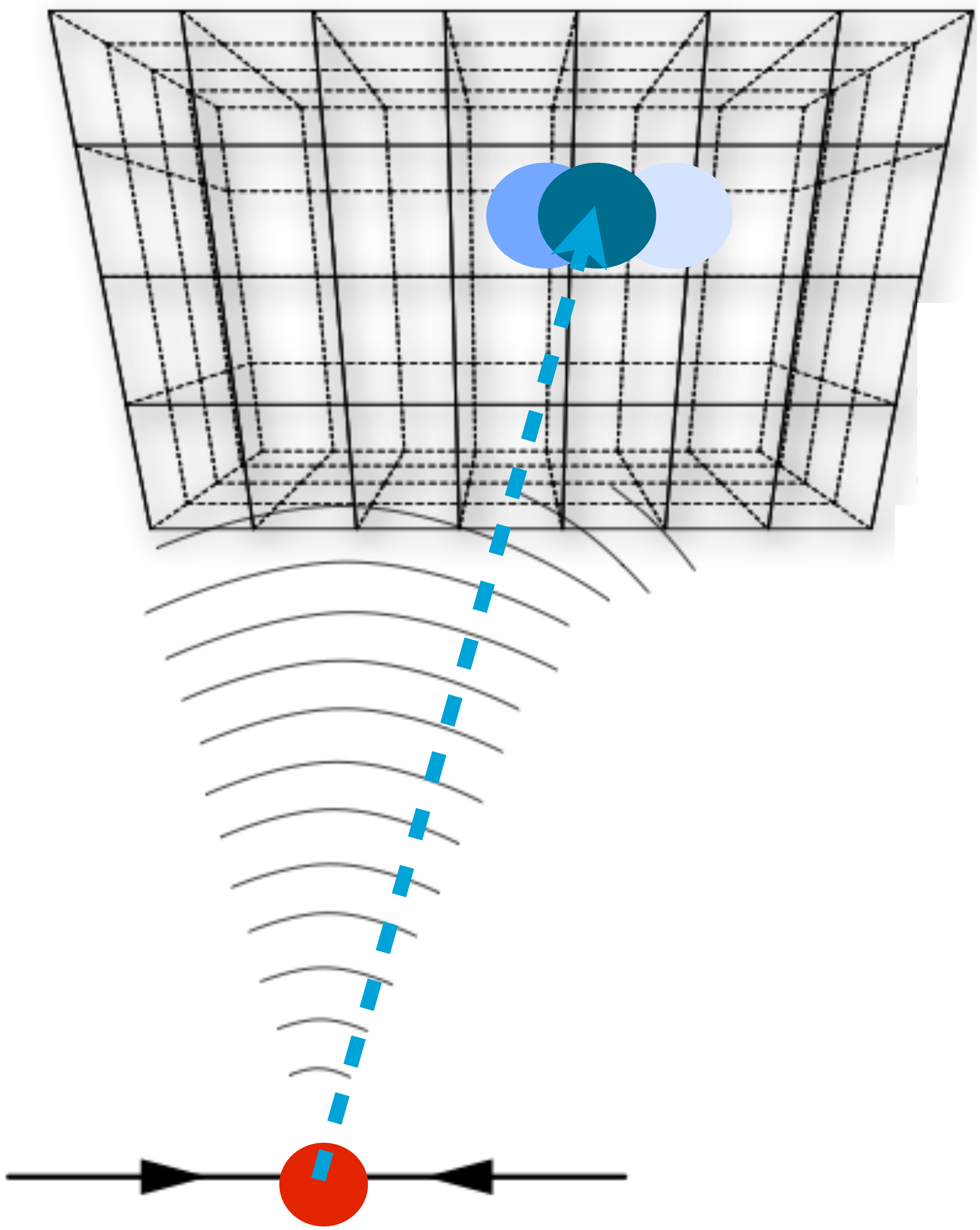

R. Cavanaugh

Basic Principle of Calorimeter

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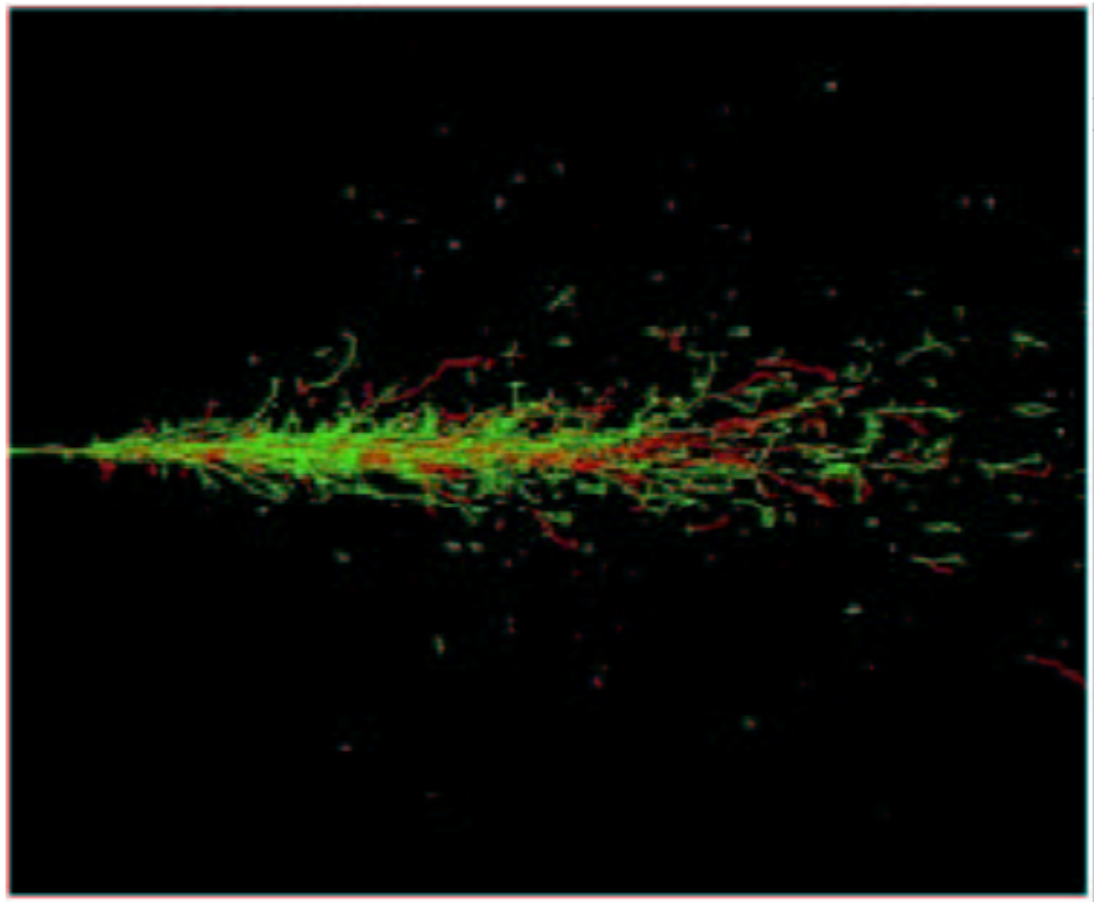
  - Shower products deposit energy in the detector via ionization or excitation
- Passive material (absorber) and active material

Electromagnetic Shower Cascade



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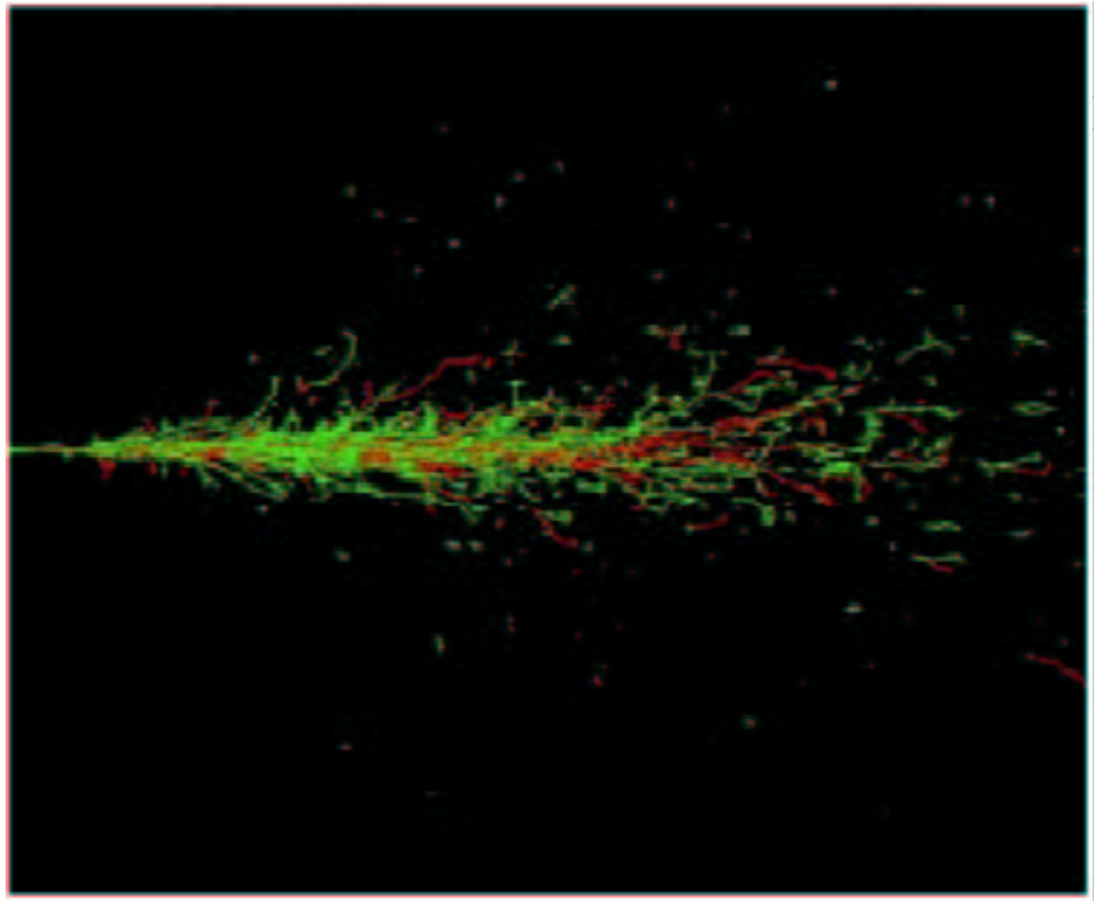

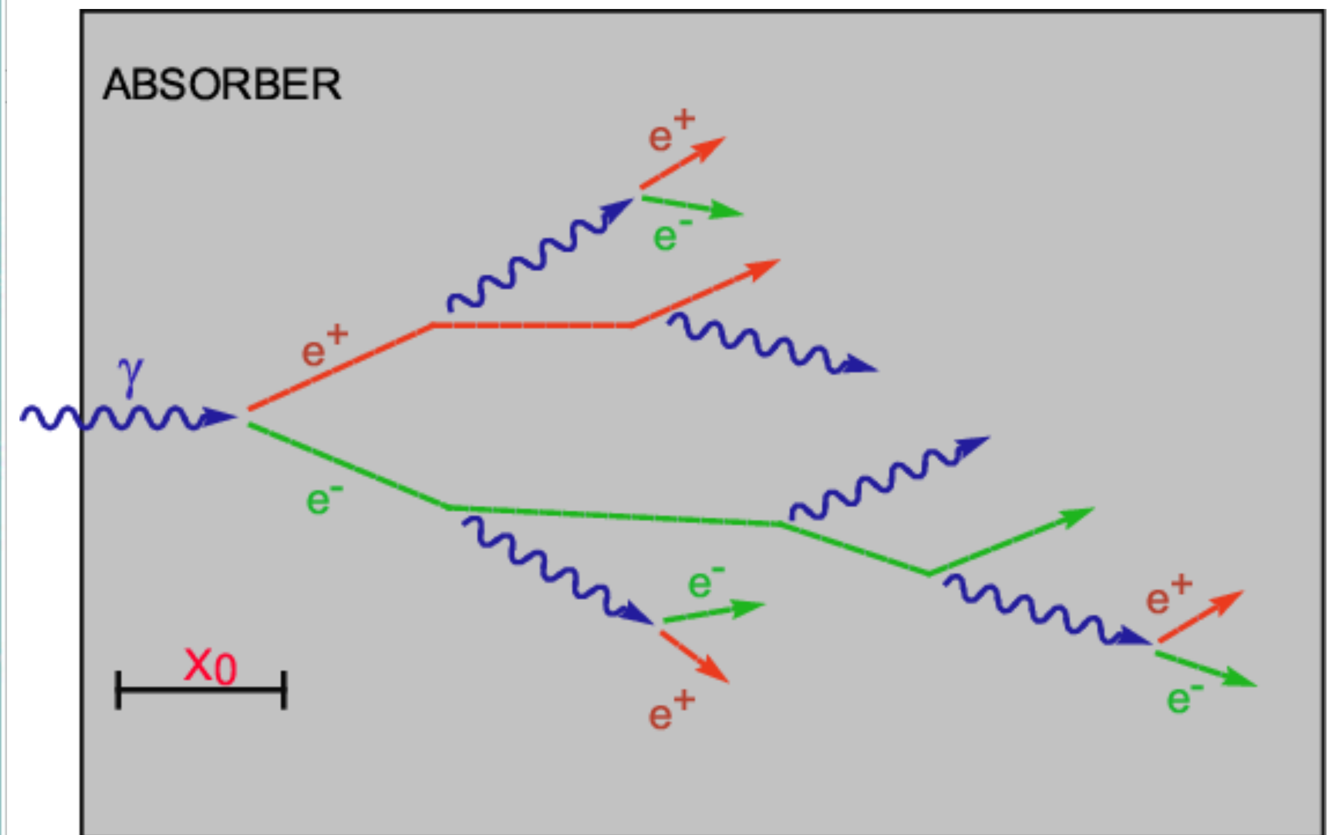

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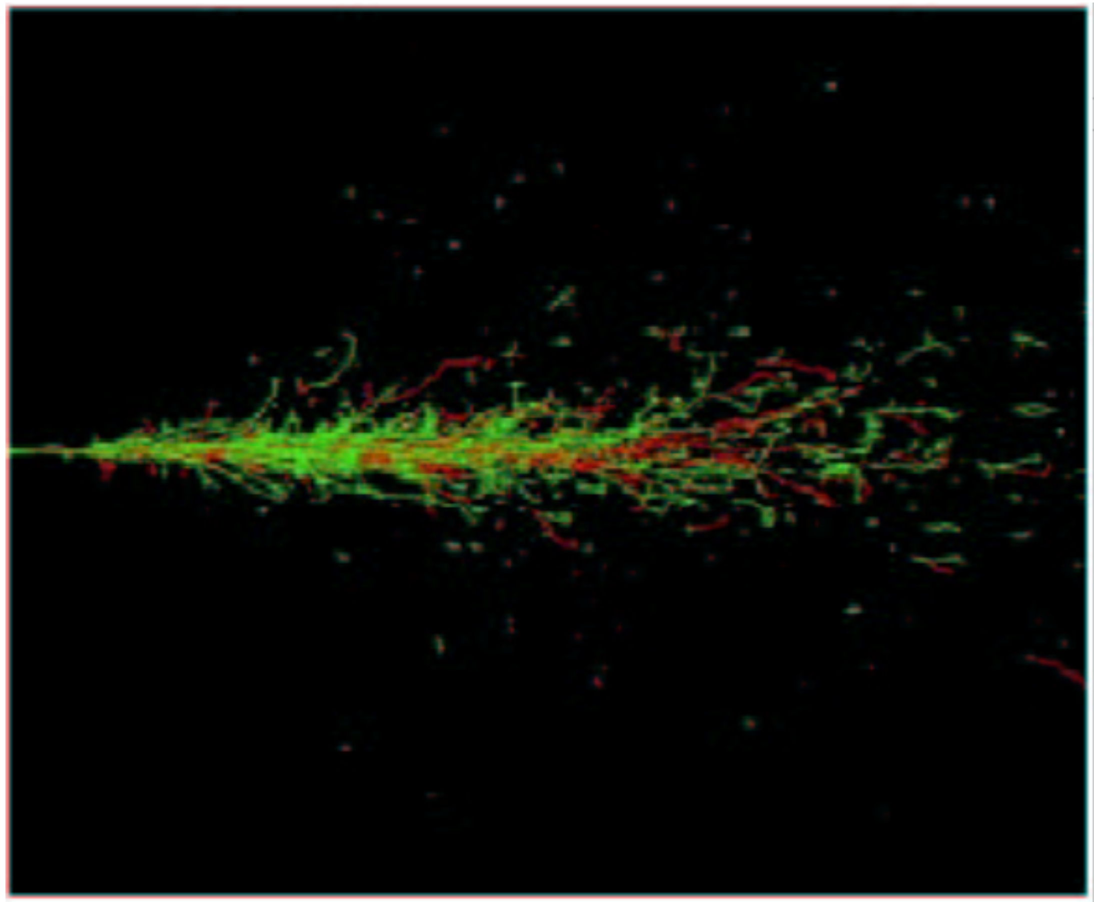

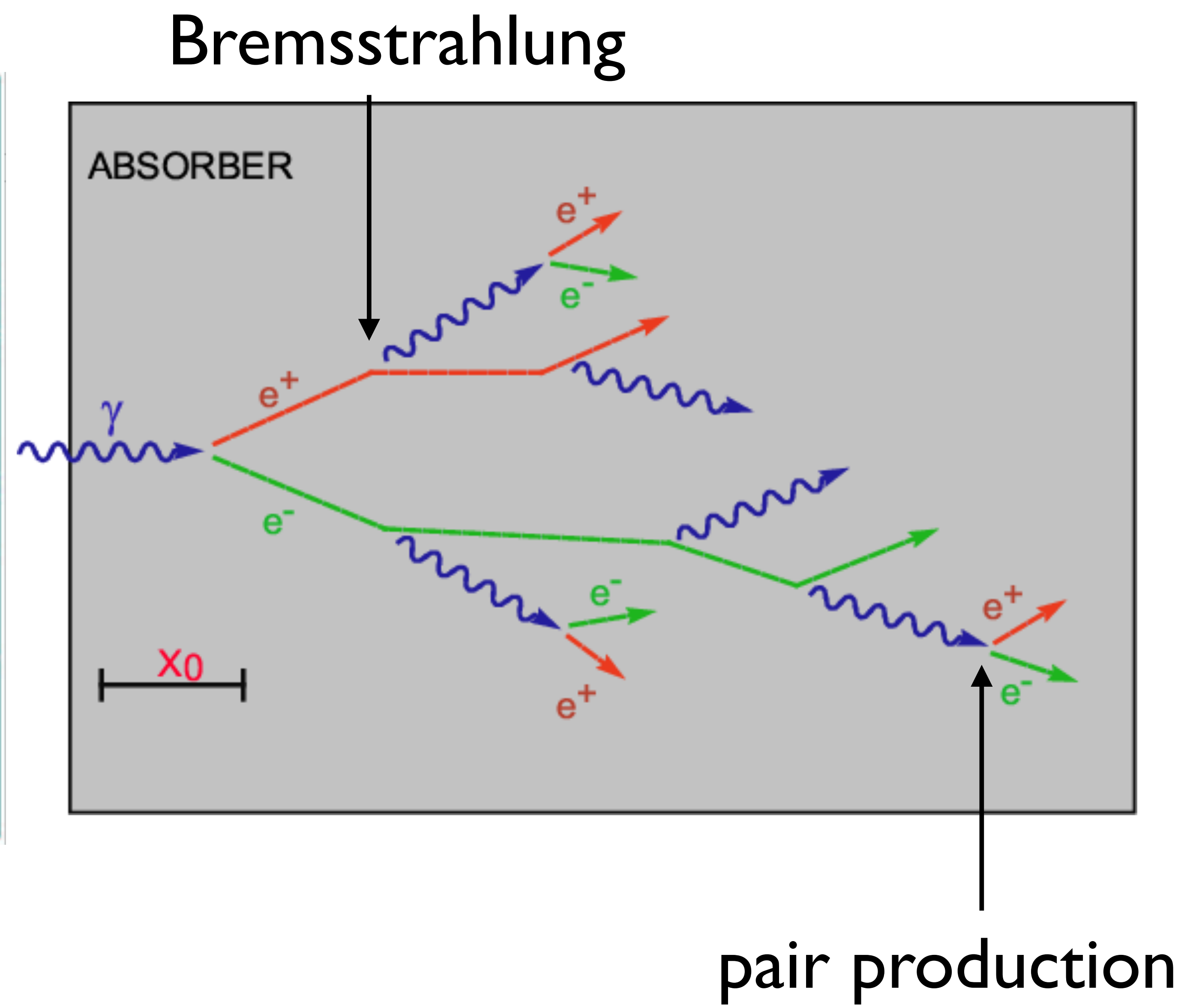

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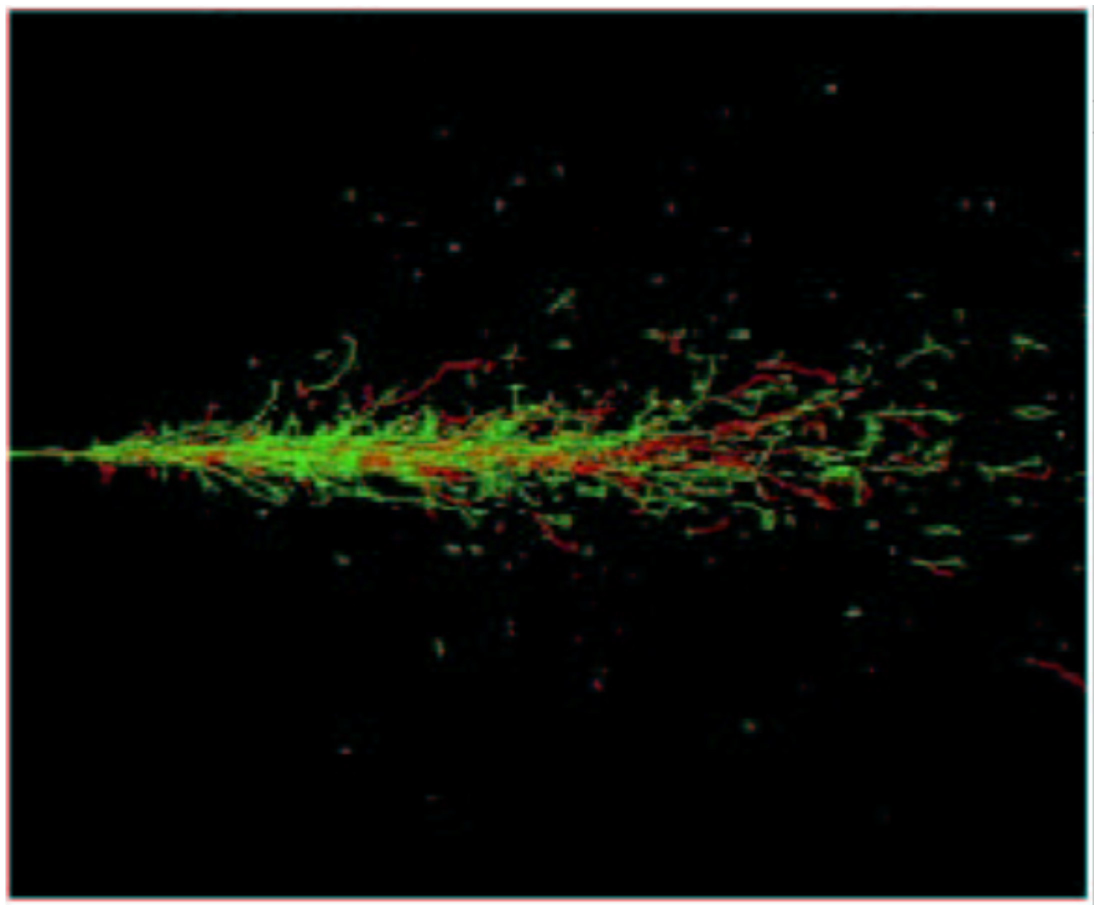
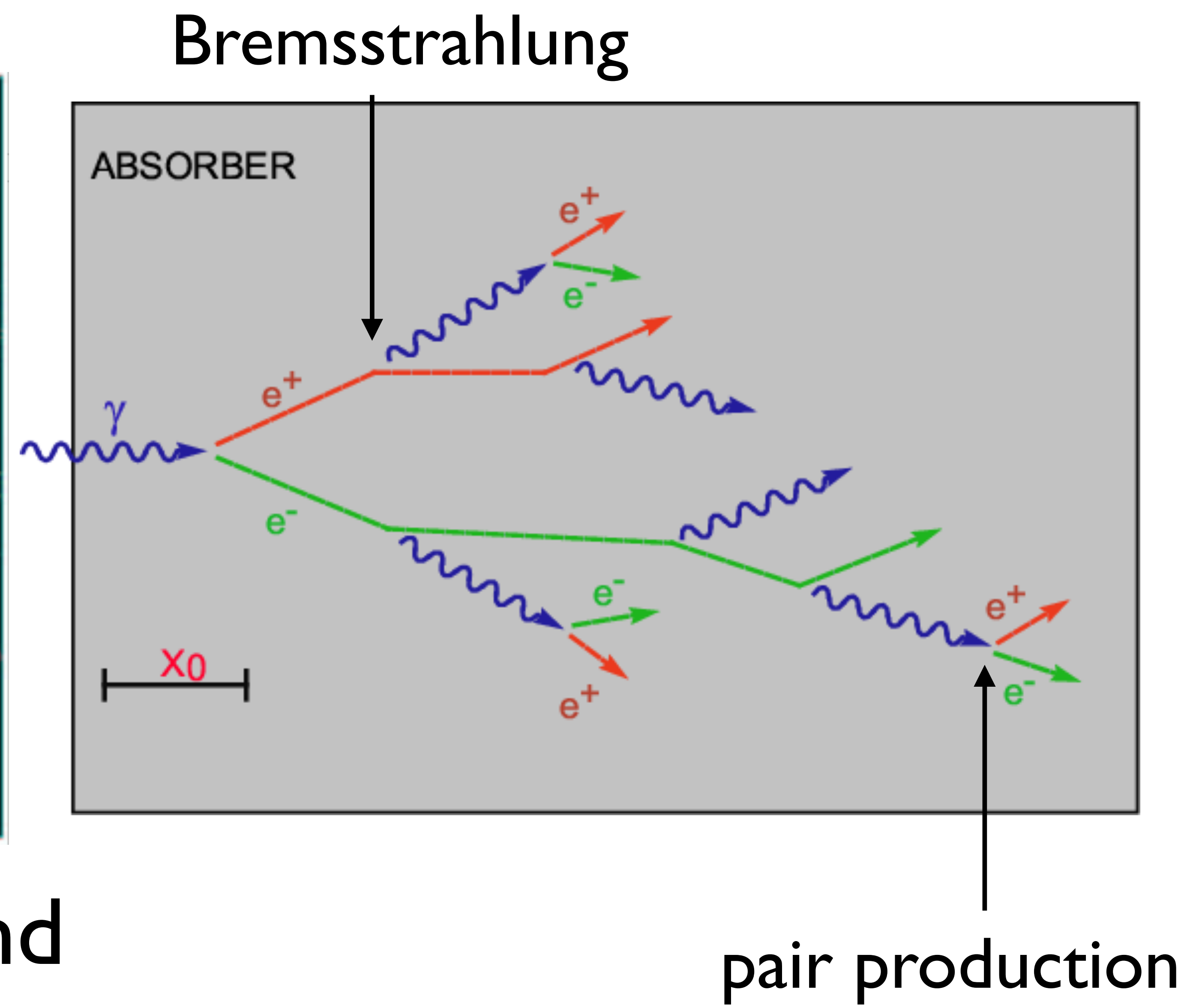
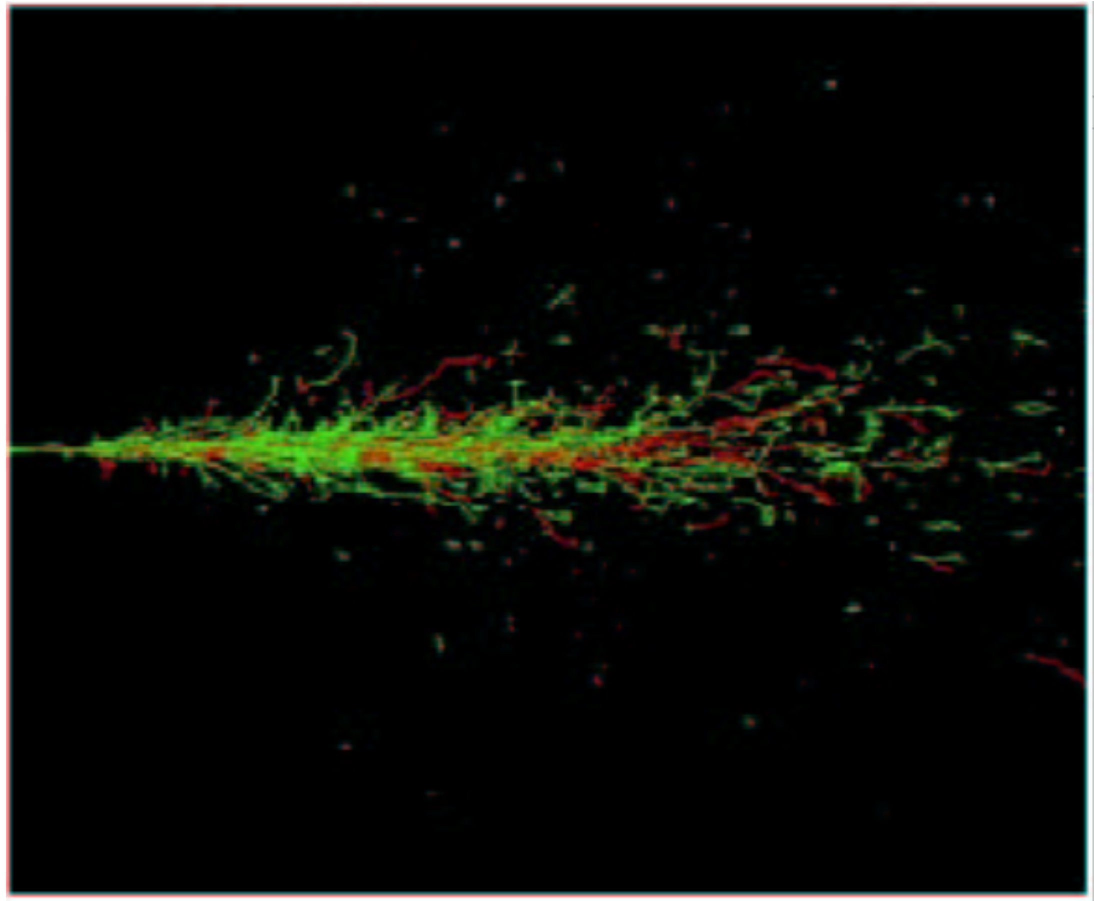
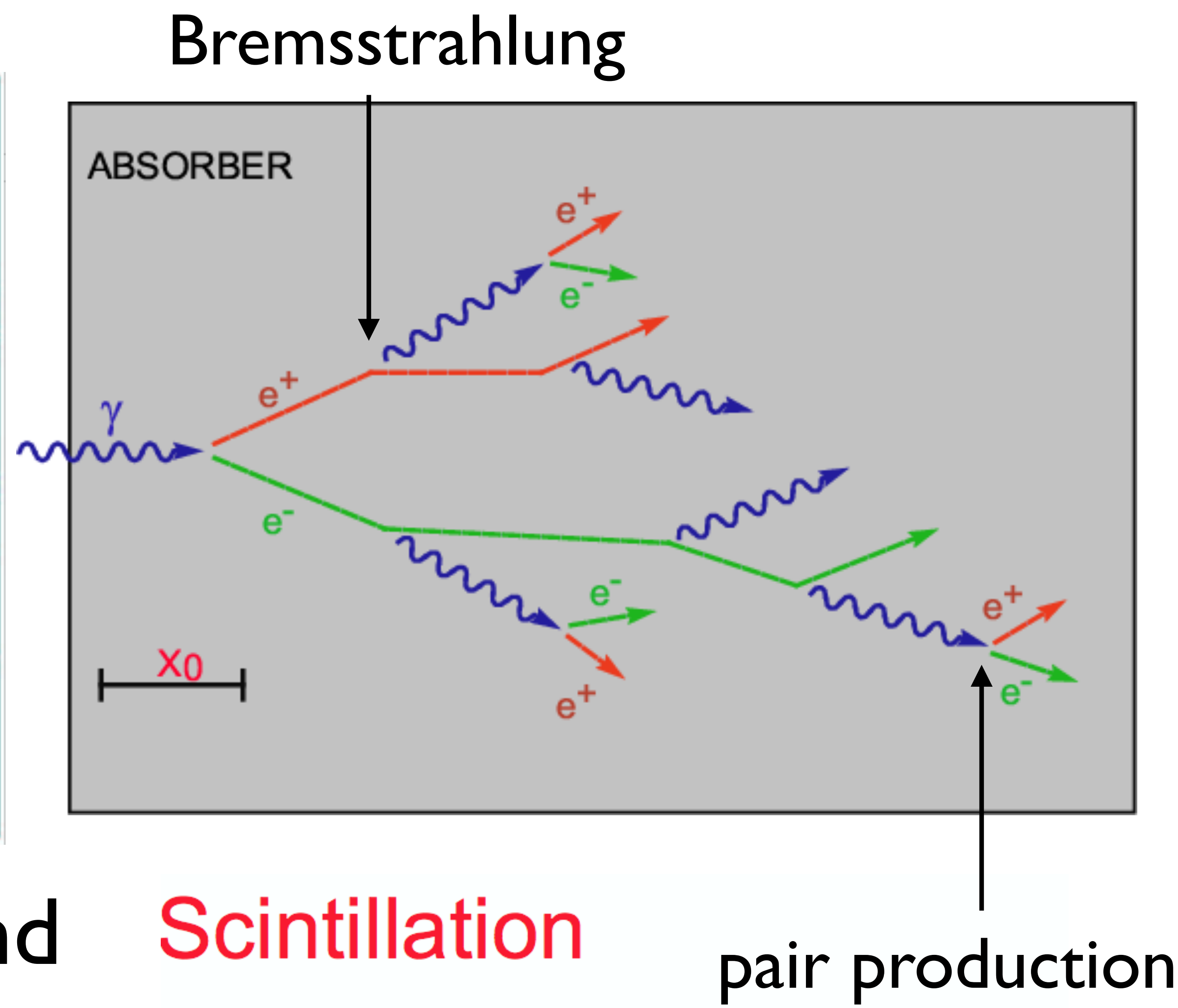




- Showers are induced and detector material are excited and produced scintillation light
- Radiation length X_0

Electromagnetic Shower Cascade





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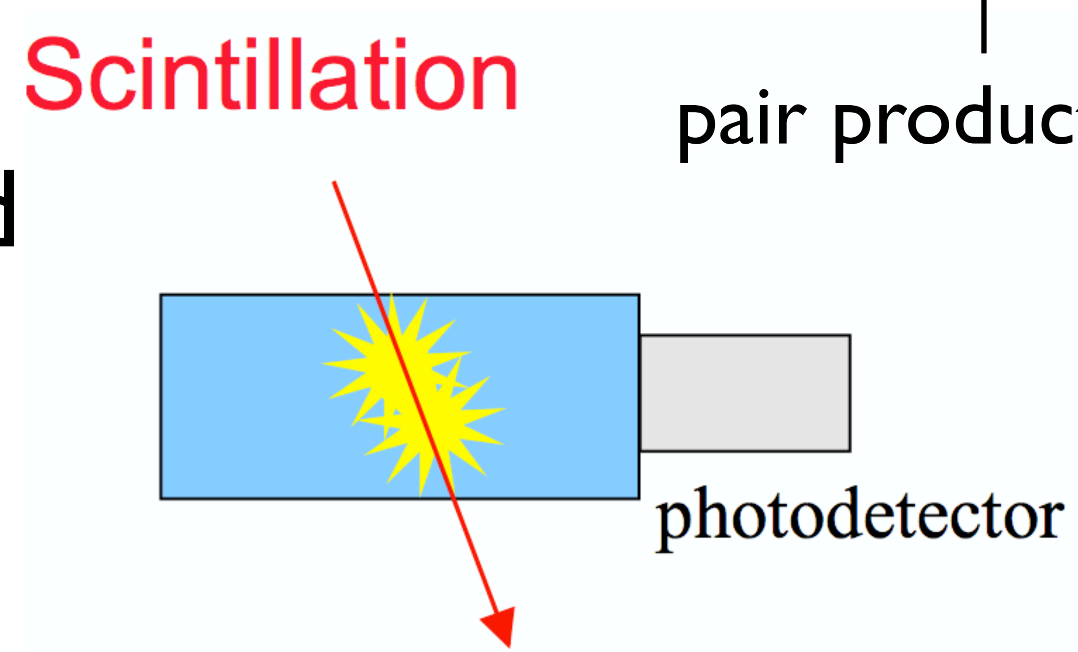

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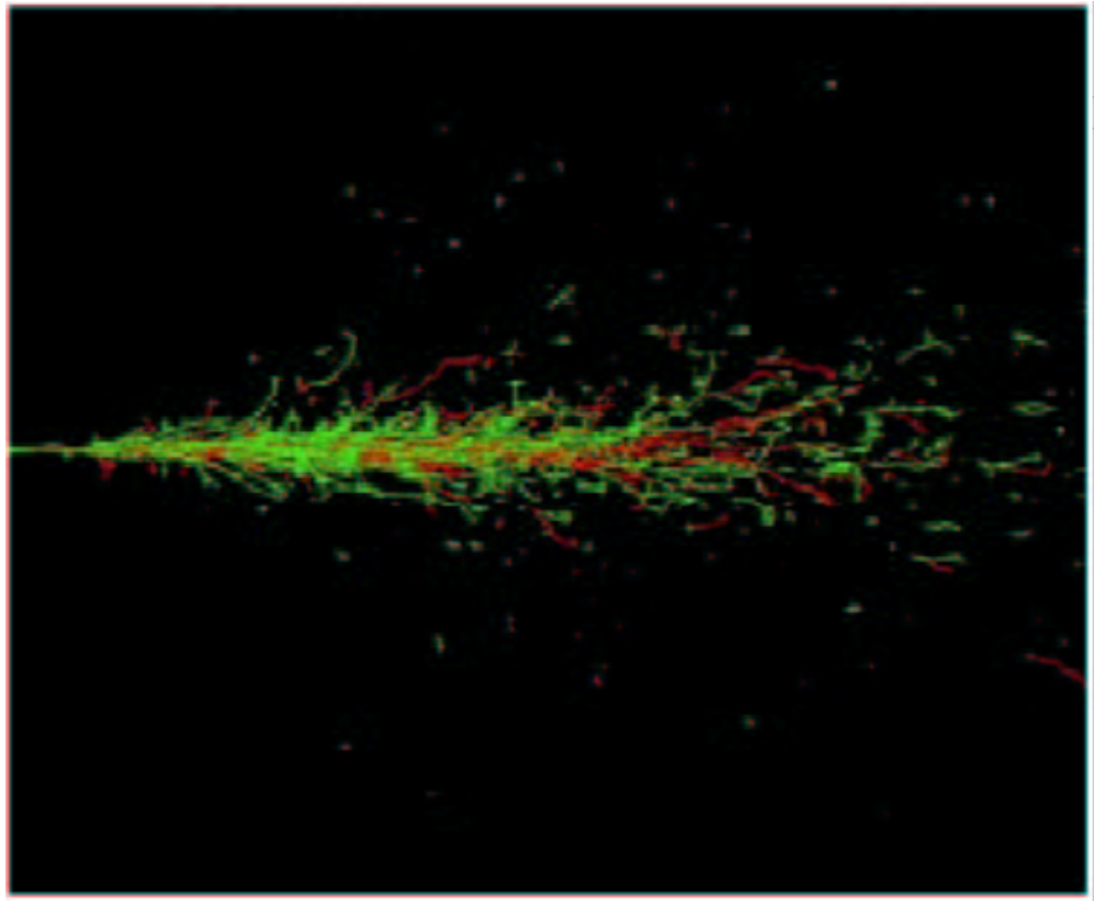
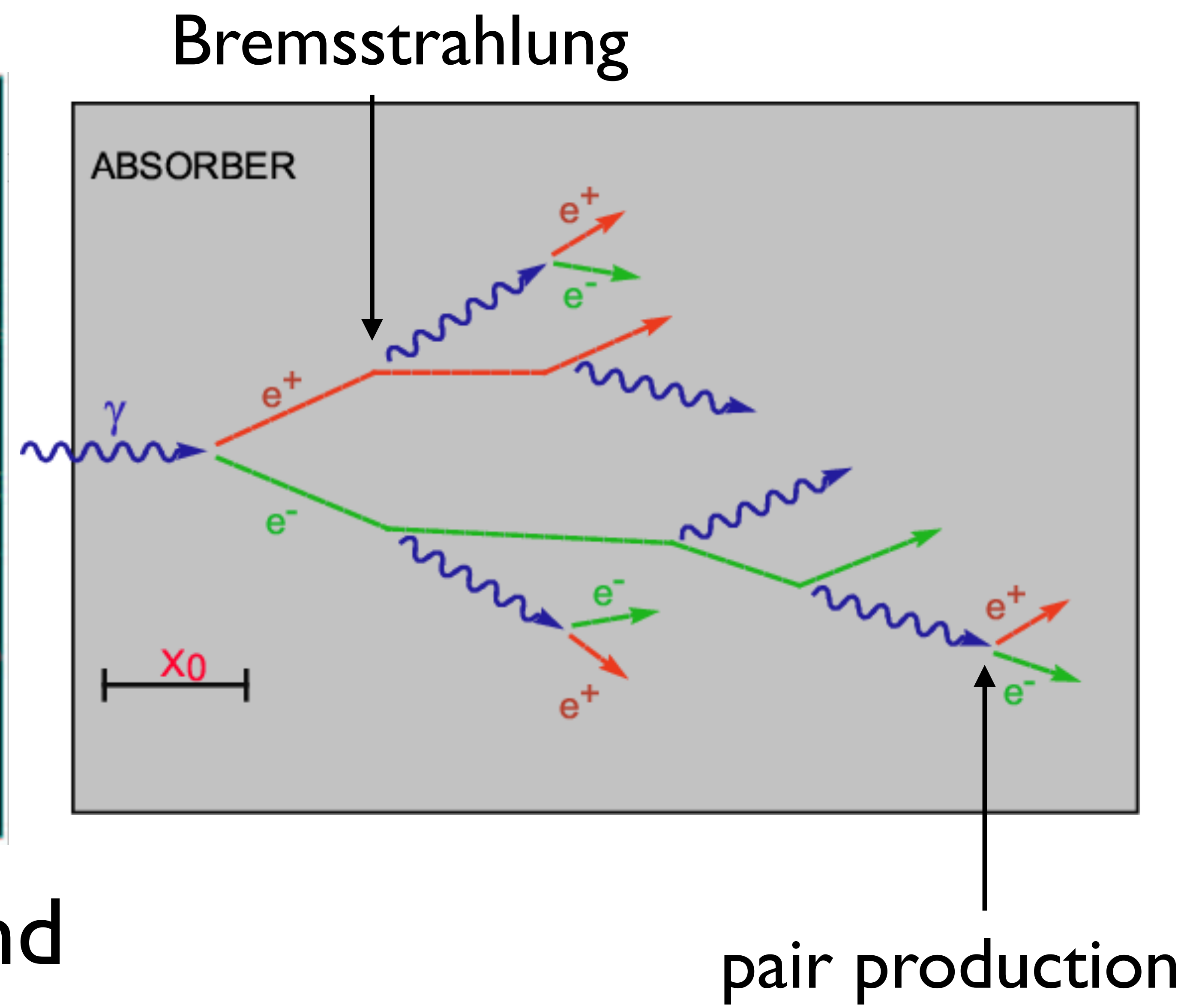




- Showers are induced and detector material are excited and produced scintillation light
- Radiation length X_0

$$\frac{1}{X_0} = \frac{4\alpha N_A Z(Z+1) r_e^2 \log(183 Z^{-1/3})}{A}$$

CMS Electromagnetic Calorimeter

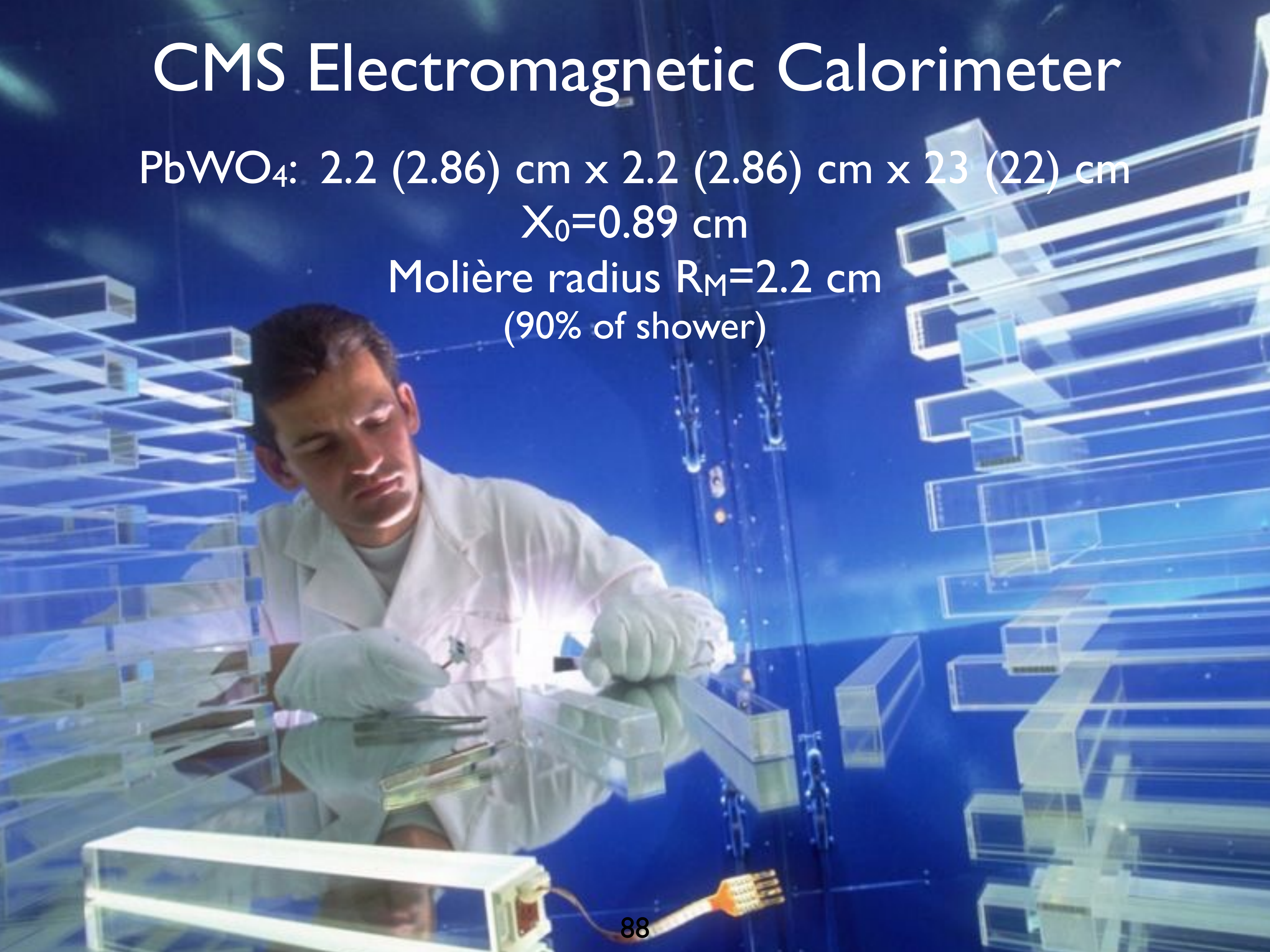
CMS Electromagnetic Calorimeter

$PbWO_4$: 2.2 (2.86) cm x 2.2 (2.86) cm x 23 (22) cm

X_0=0.89 cm

Molière radius R_M=2.2 cm

(90% of shower)



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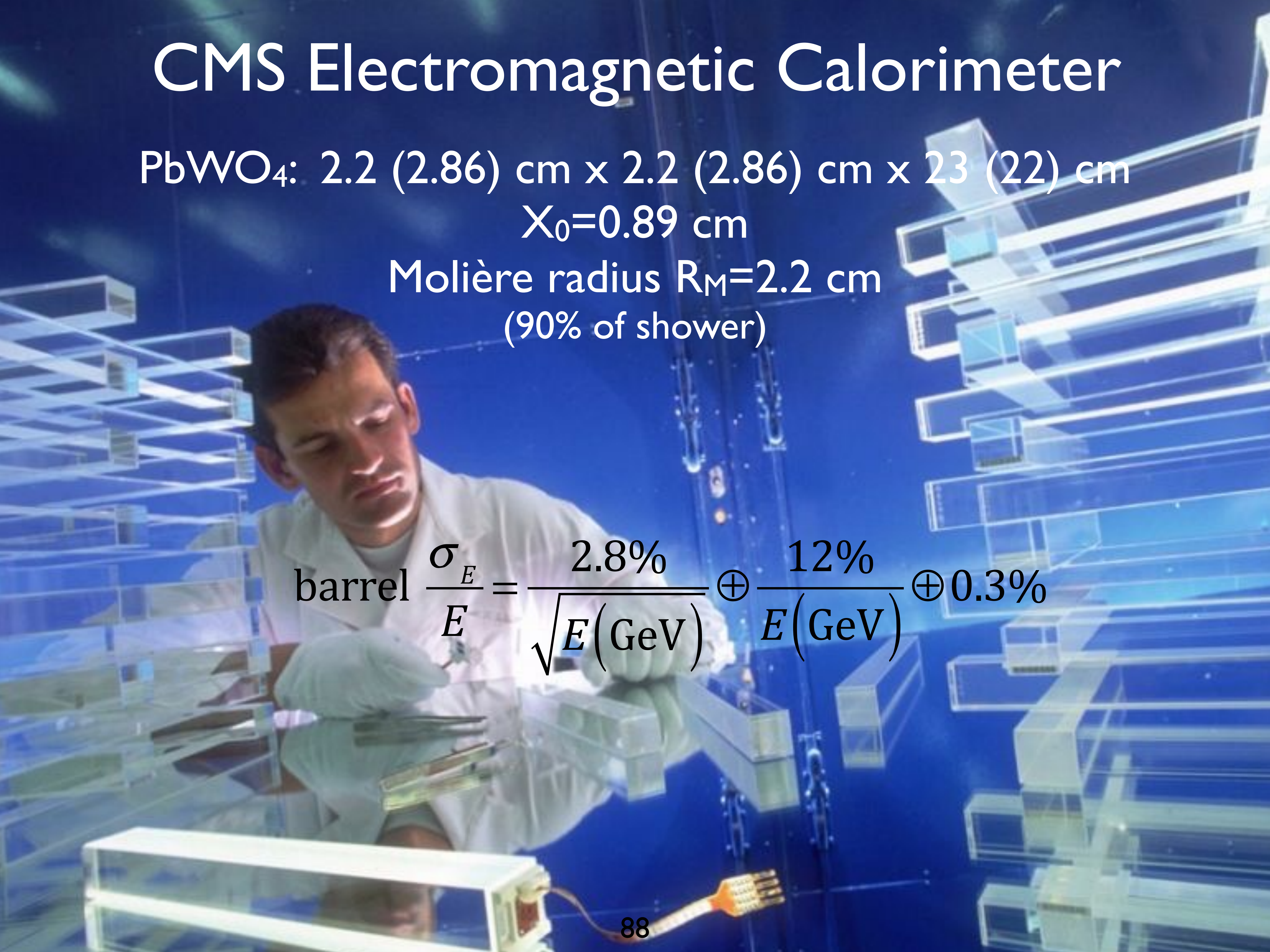
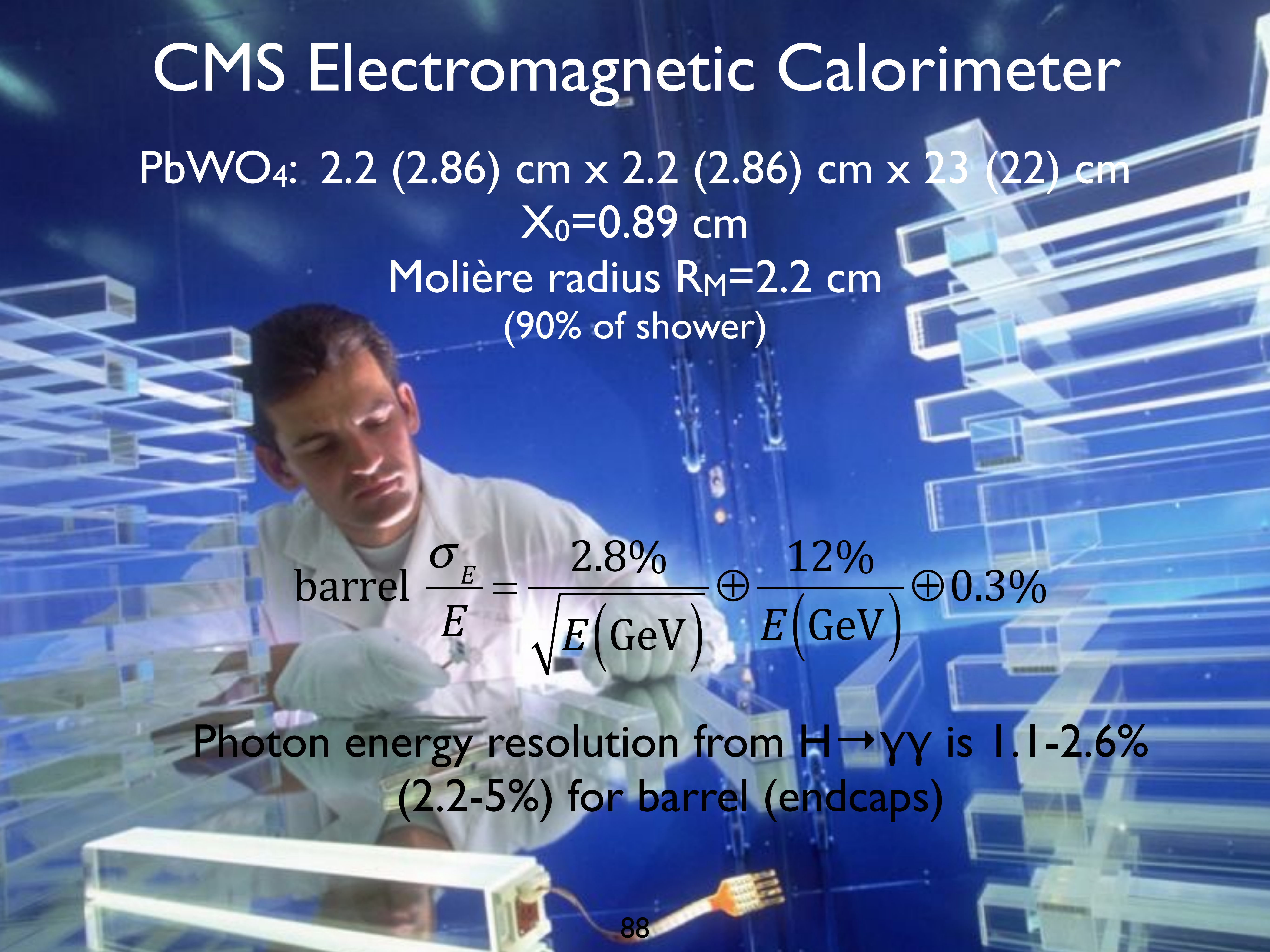


barrel $\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{12\%}{E(\mathrm{GeV})} \oplus 0.3\%$



CMS Electromagnetic Calorimeter

$PbWO_4$: 2.2 (2.86) cm x 2.2 (2.86) cm x 23 (22) cm

X_0=0.89 cm

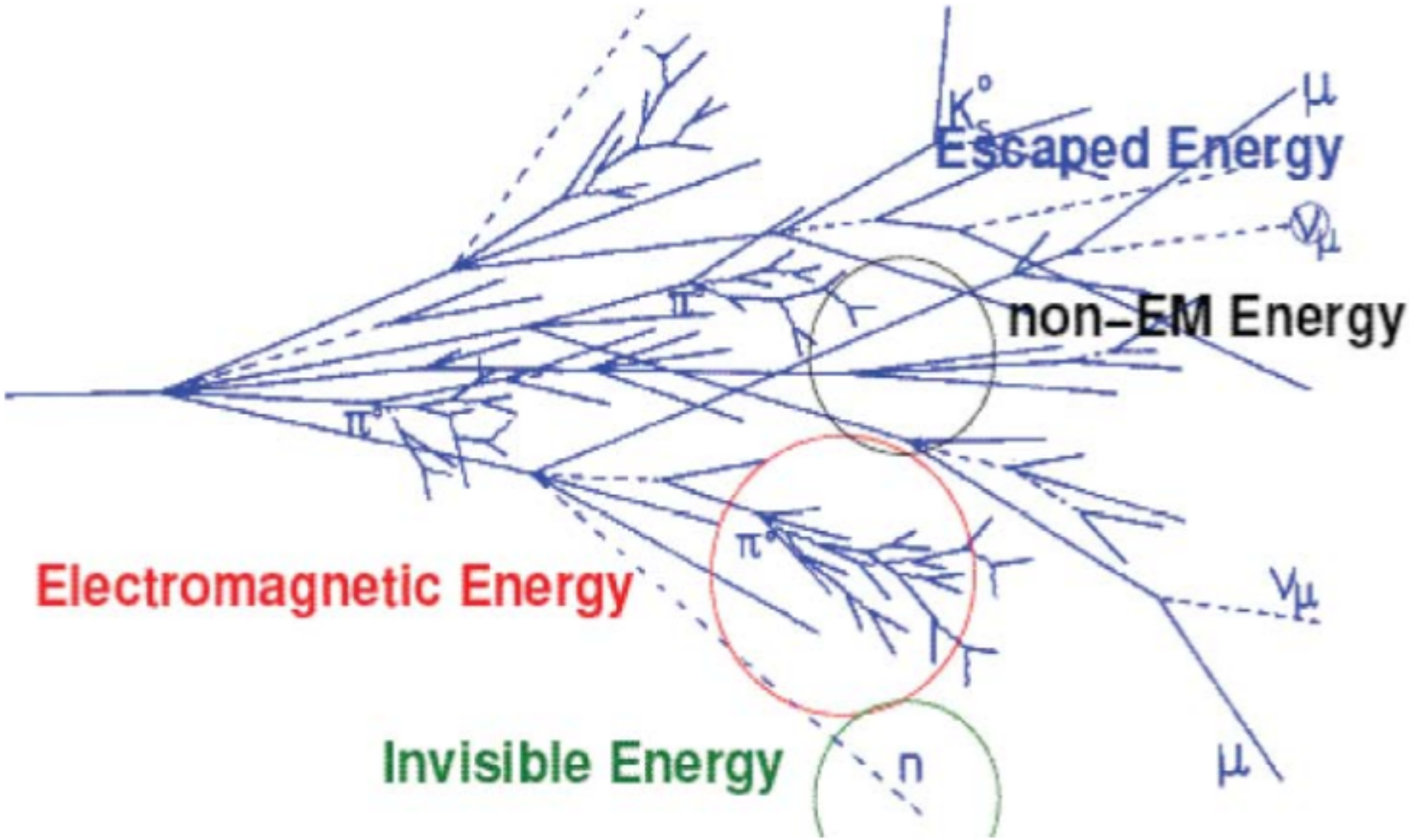
Molière radius R_M=2.2 cm

(90% of shower)

$$\text{barrel } \frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E(\text{GeV})}} \oplus \frac{12\%}{E(\text{GeV})} \oplus 0.3\%$$

Photon energy resolution from $H \rightarrow \gamma\gamma$ is 1.1-2.6% (2.2-5%) for barrel (endcaps)

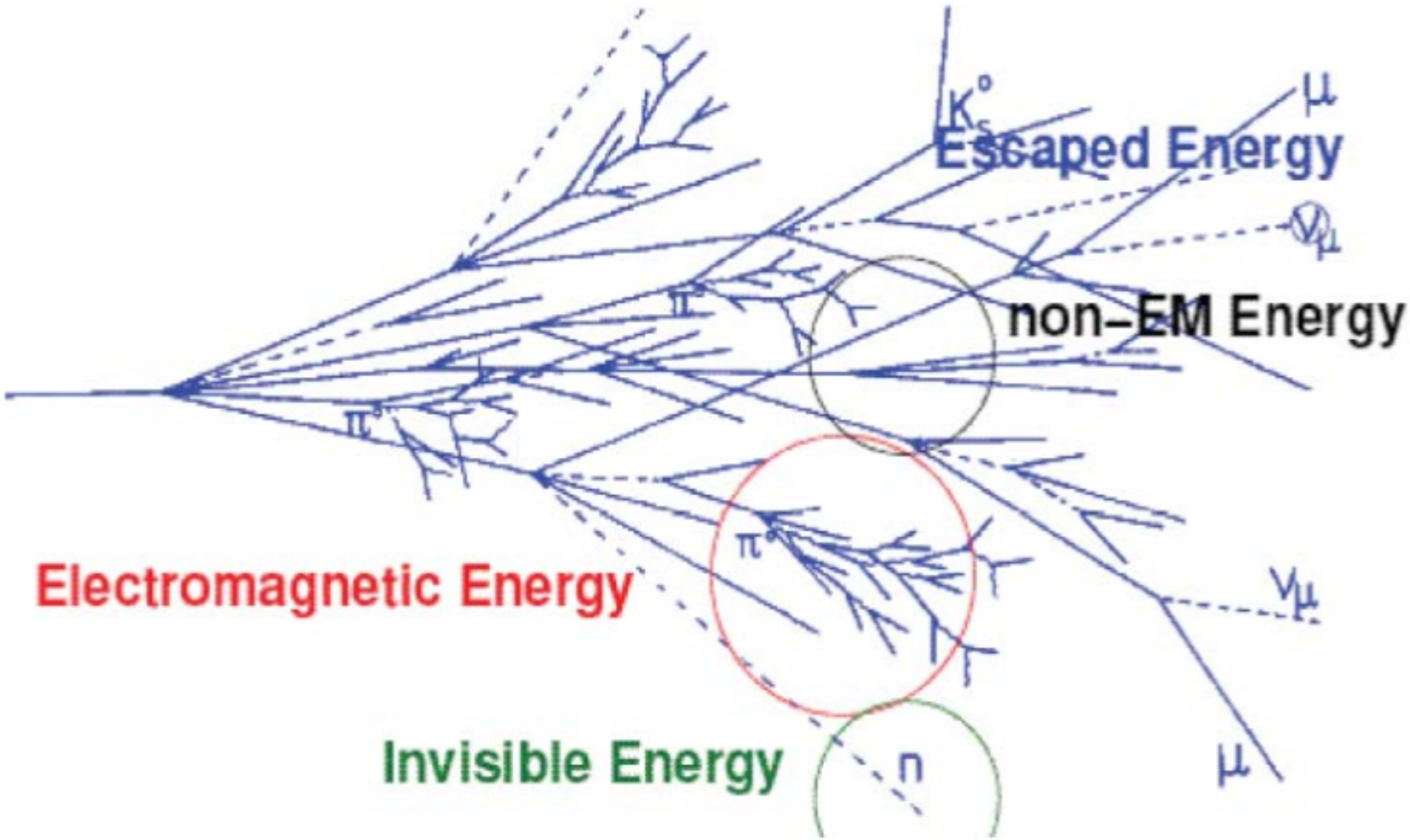
Hadronic Shower Cascade



Good reference book: Calorimetry by Richard Wigman

Hadronic Shower Cascade

- Interaction length $\lambda_I \approx 35\ \mathrm{g\,cm^{-2}} A^{\frac{1}{3}}$



Good reference book: <u>Calorimetry by Richard Wigman</u>

CMS Hadronic Calorimeter

Sampling calorimeter:
scintillator+ brass/steel

CMS Hadronic Calorimeter

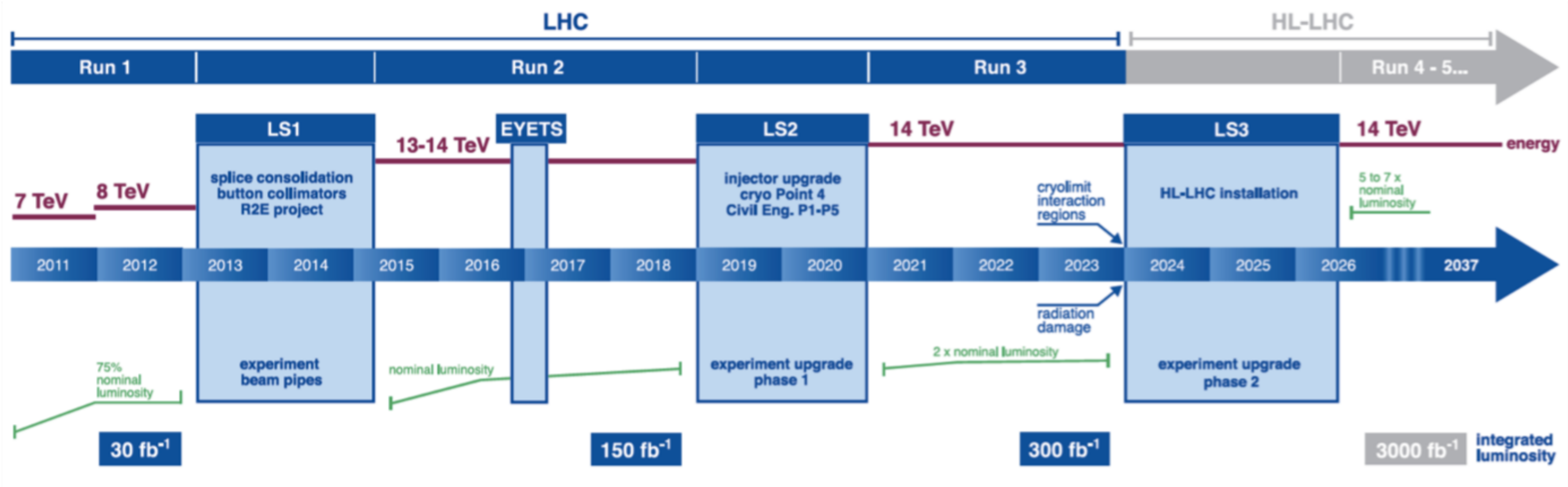
Sampling calorimeter:
scintillator+ brass/steel

CMS Hadronic Calorimeter

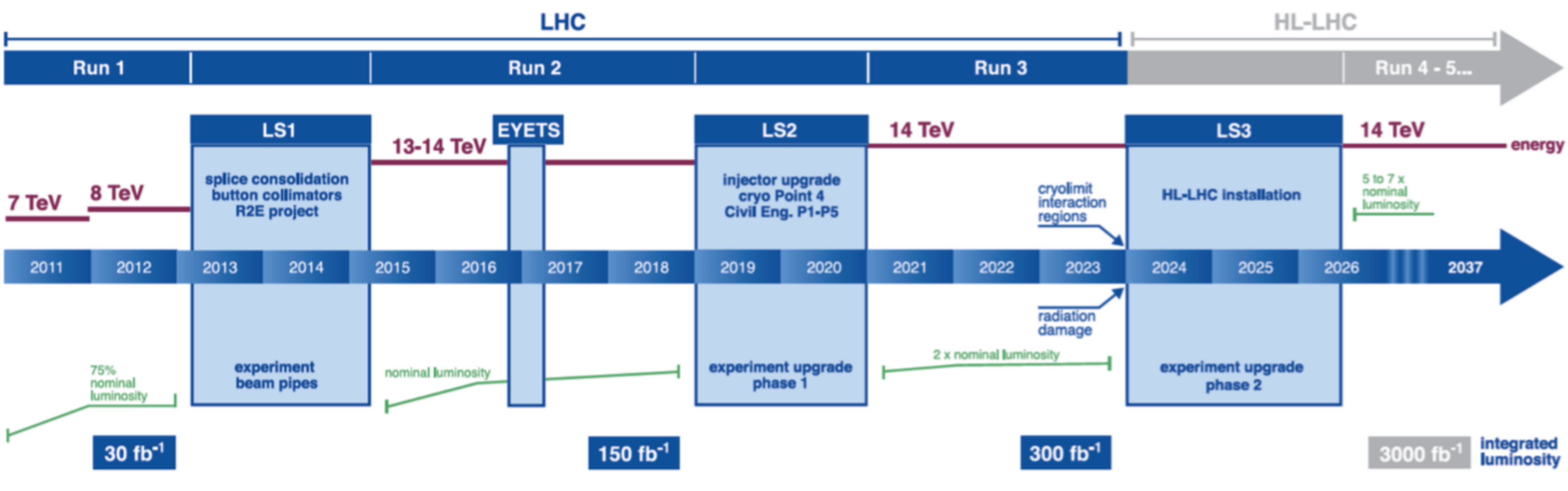
$$\frac{\sigma_E}{E} = \frac{110\%}{\sqrt{E(\mathrm{GeV})}} \oplus 9\%$$

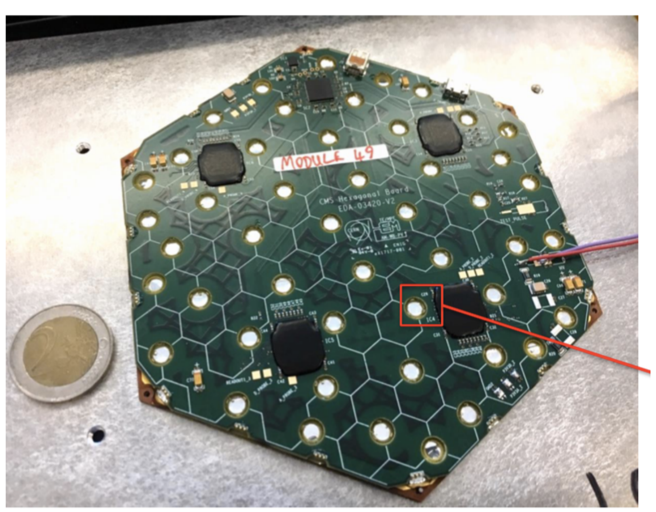
Sampling calorimeter:
scintillator+ brass/steel

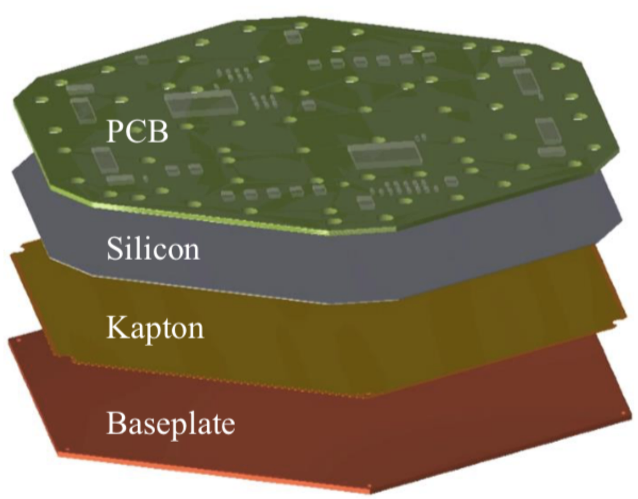
Upgraded Endcap Calorimeter

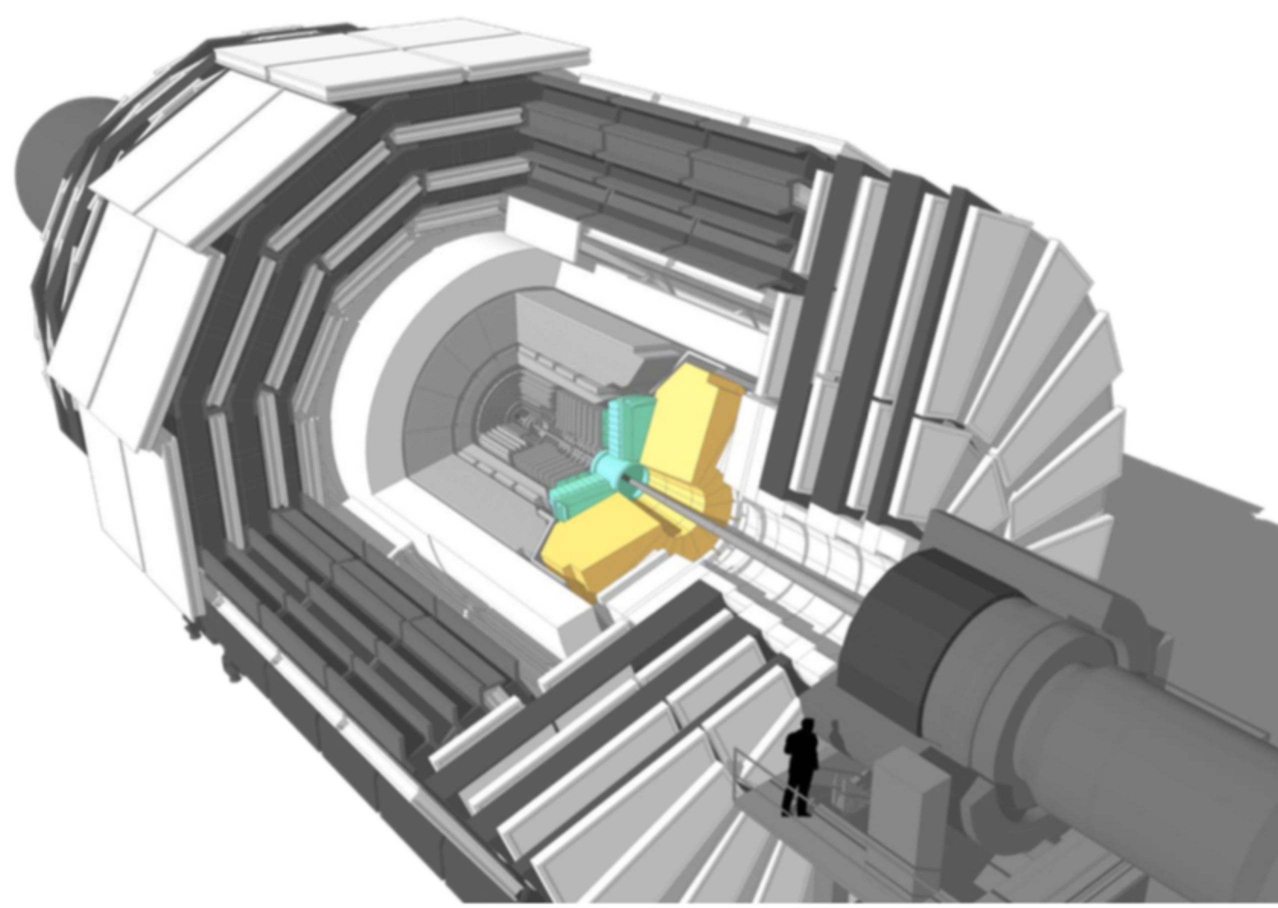


Upgraded Endcap Calorimeter





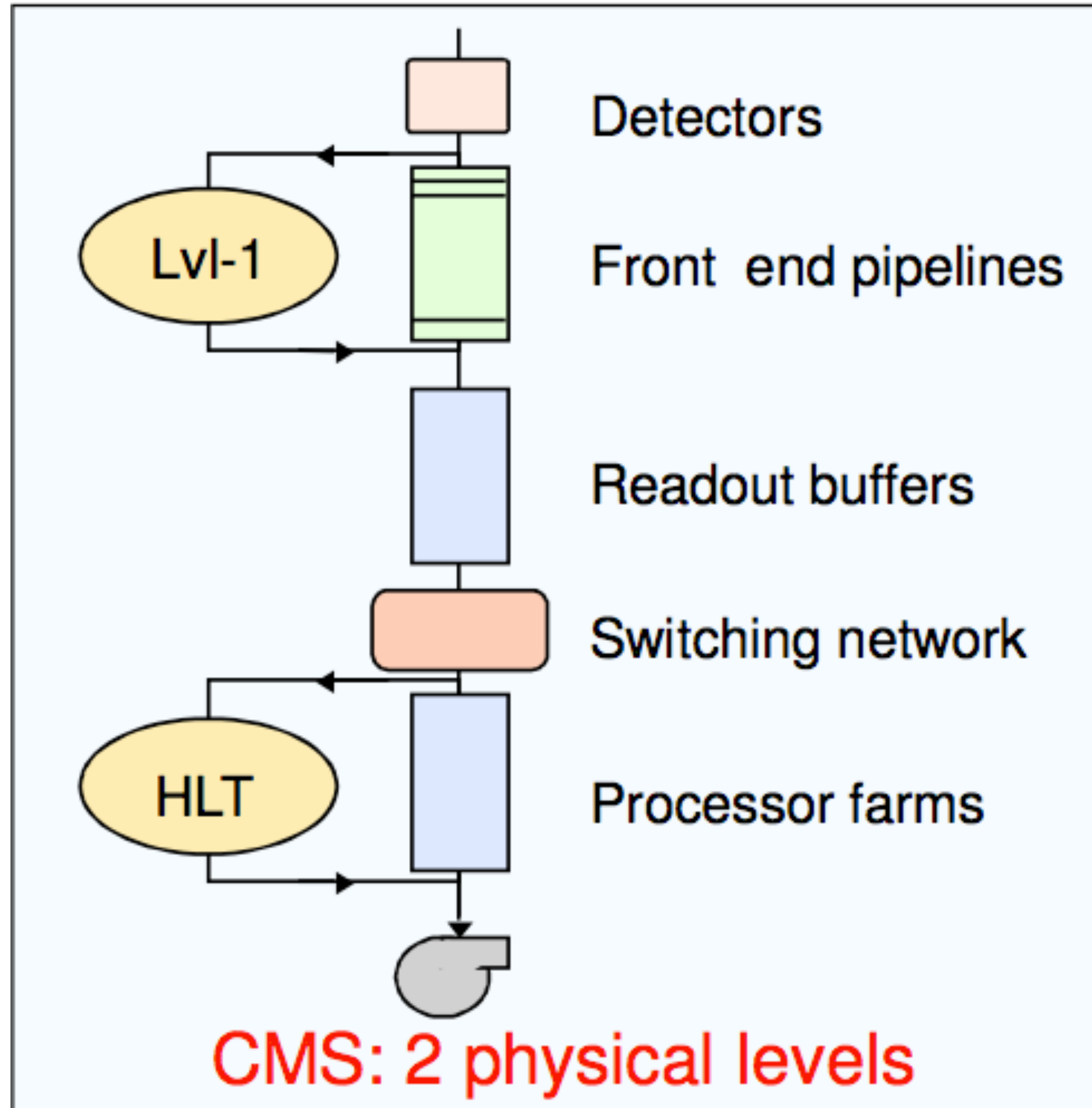




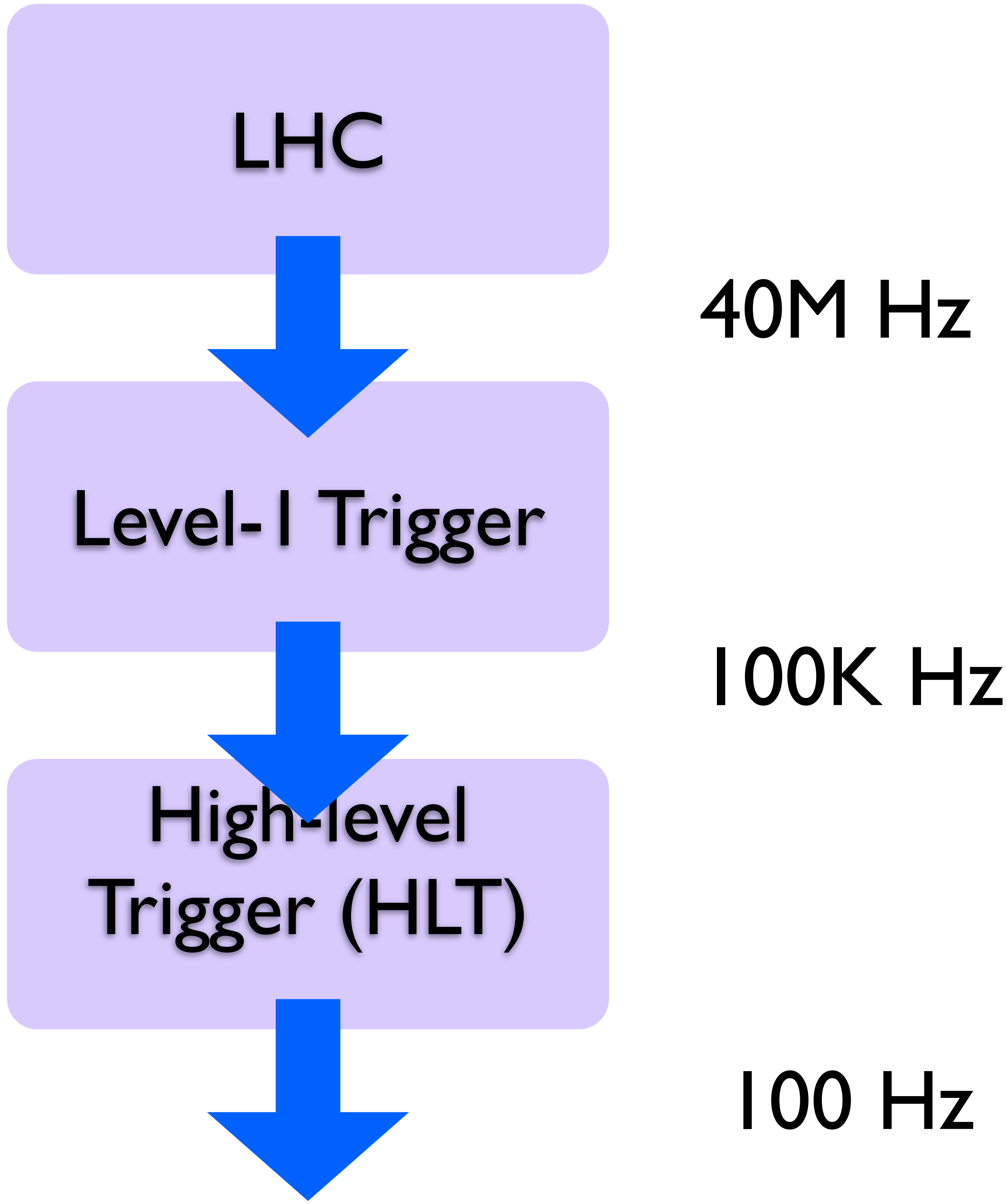
Brief Story of the Trigger

Trigger Philosophy

- Two-level system
  - Hardware trigger at L1
  - Software trigger (computer clusters, 1000 nodes) at high-level
- Reduction factor ~ 1000
- Event size ~ 1 MB, can handle 300 MB/sec
- Fast response, but still keep interesting physics

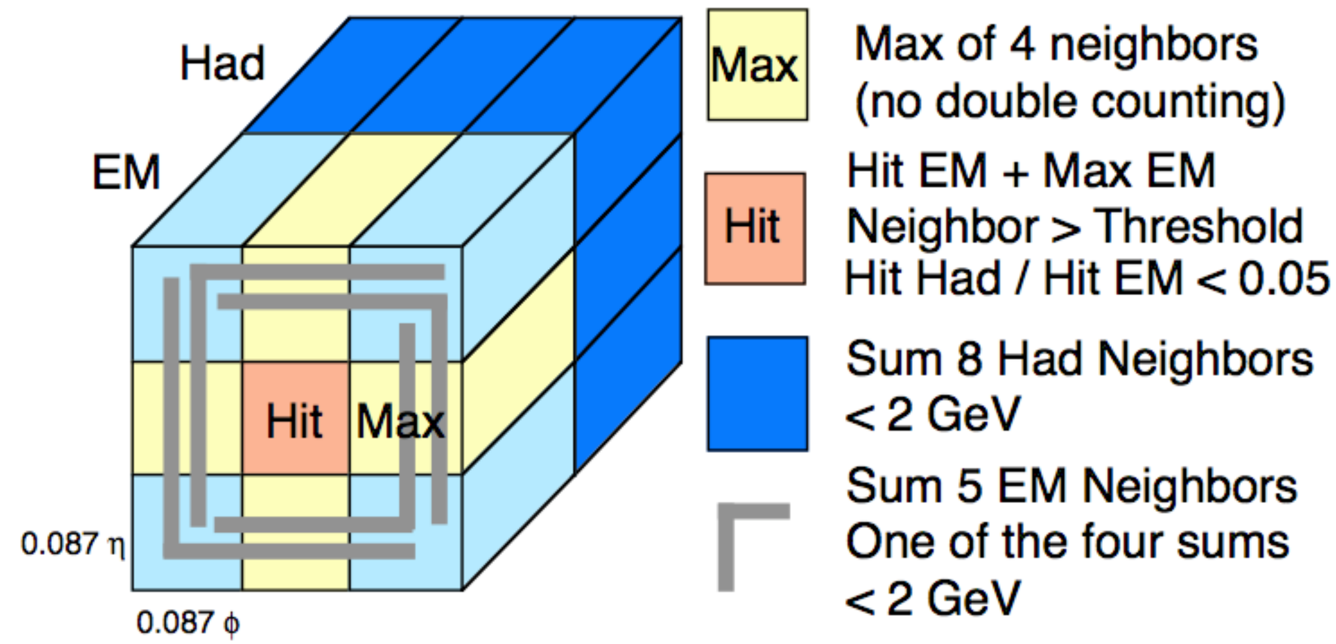


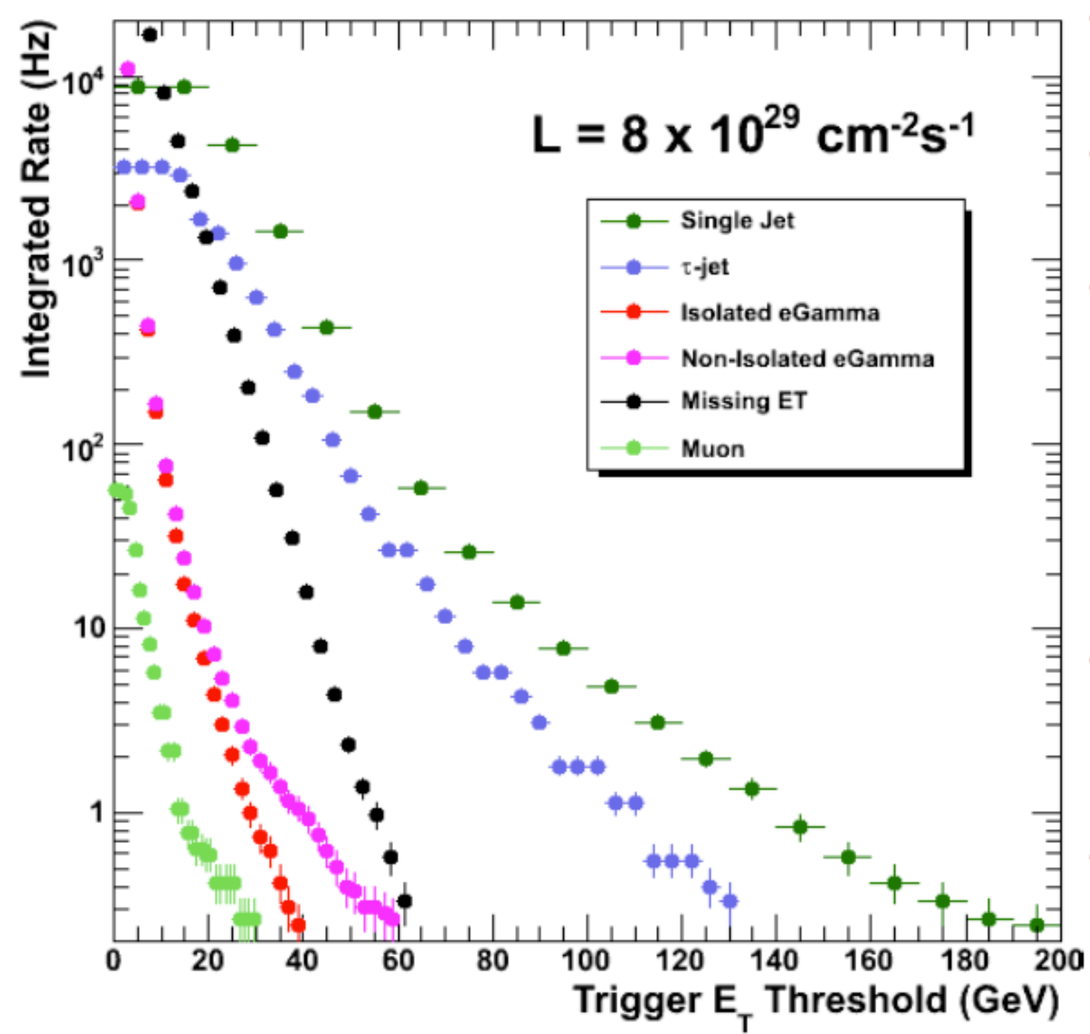
Trigger Reduction Rates



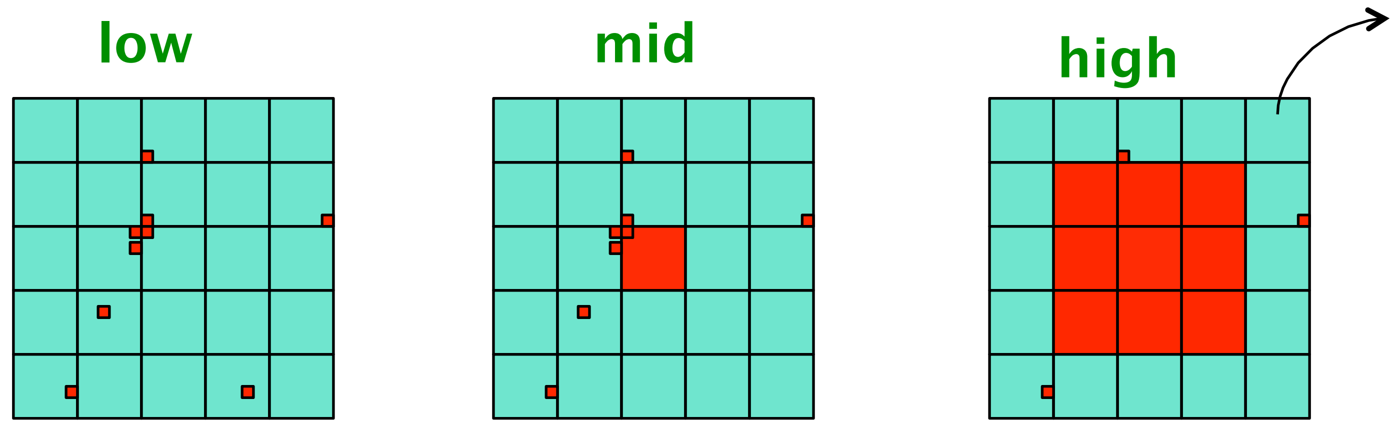
Level-1 Trigger

- Based on calorimeters and muon chambers only
- Simple algorithms
  - objects' E_T (Hit+Max E_T), location, Had/EM
- Group smaller cells into larger ones
  - 5 x 5 crystals in ECAL barrel →trigger tower (level-1 trigger primitives)





Data Reduction



Each box is a 5x5 crystal

- Employ selective readout (ECAL and HCAL for CMS)
- Only active part of the calorimeter could be readout (full ECAL: 2MB/event, 100kB/event allocated)
- Use trigger primitives (TP) generated at Level-1 to identify region of interest (Here, use ECAL as an example.)
  - Low interest: TP < 1 GeV (Zero suppression at 3σ noise-level)
  - Medium interest: 1 < TP < 2 GeV (Full readout the TP)
  - High interest: TP > 2 GeV (Full readout the 3x3 trigger towers)

High-level Trigger

- Almost offline reconstruction with faster algorithms
- Apply isolation, shower shape ID cuts
- Include tracking to form electron and muon
    - Matching between tracker and calorimeter/ muon chamber