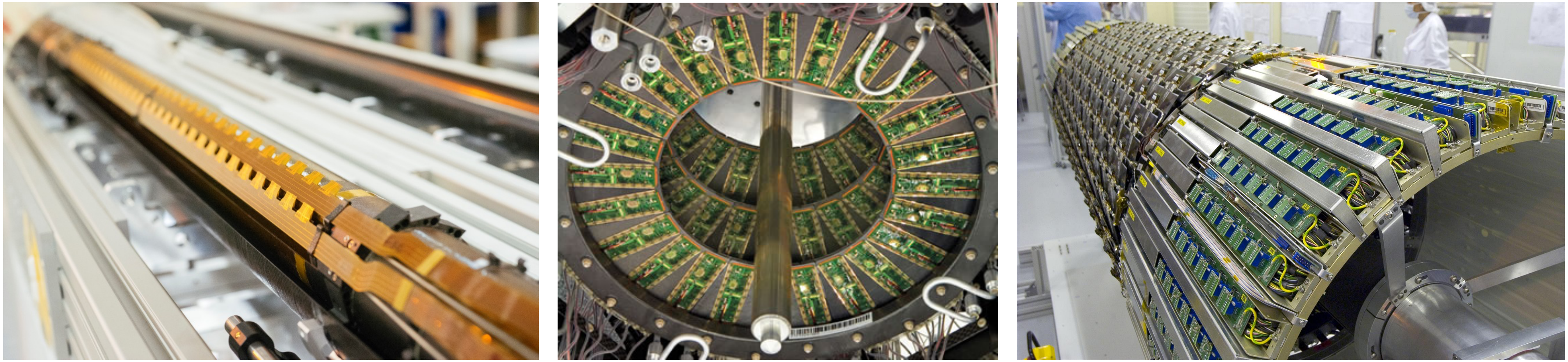
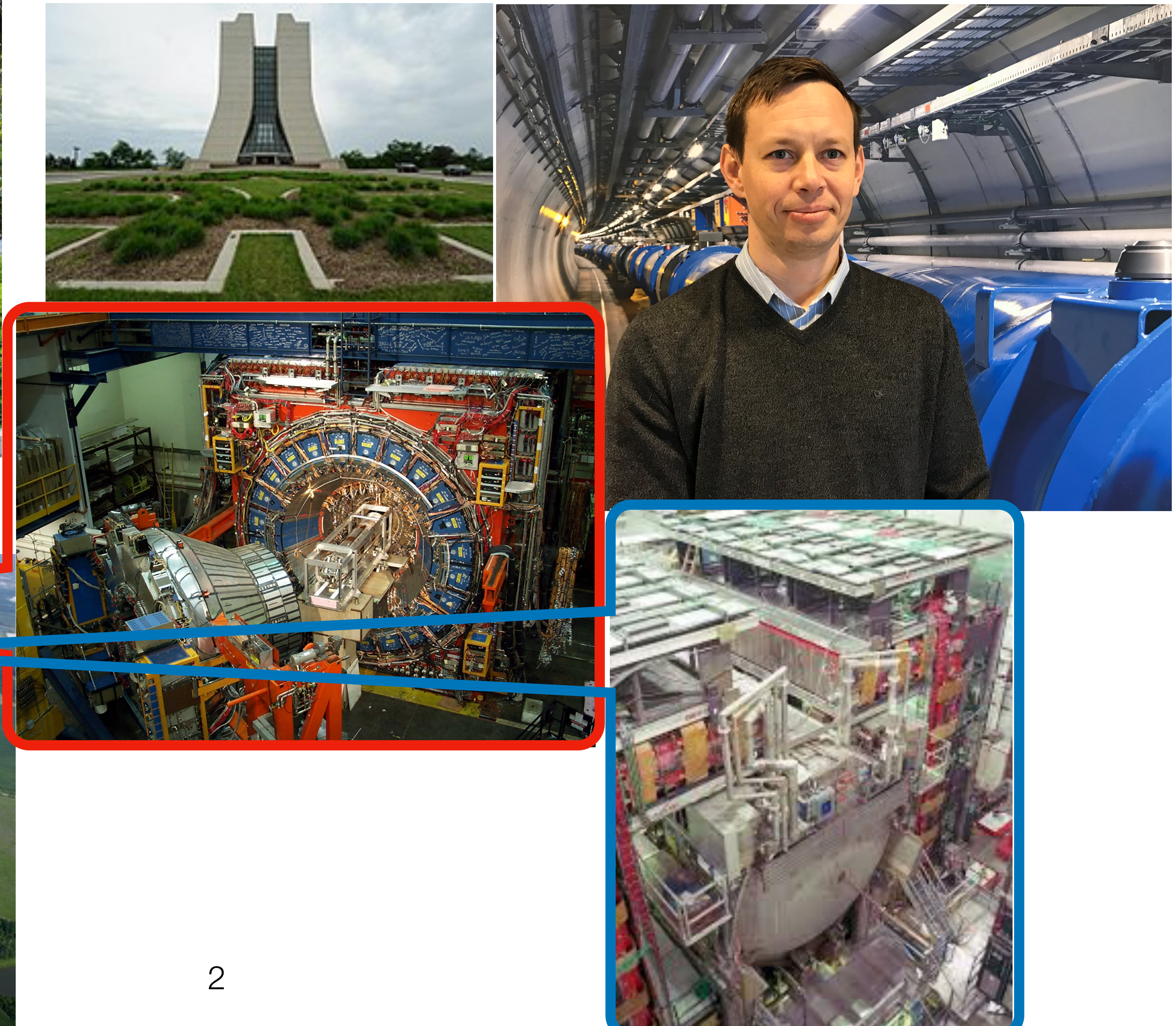
Introduction to Particle Detectors

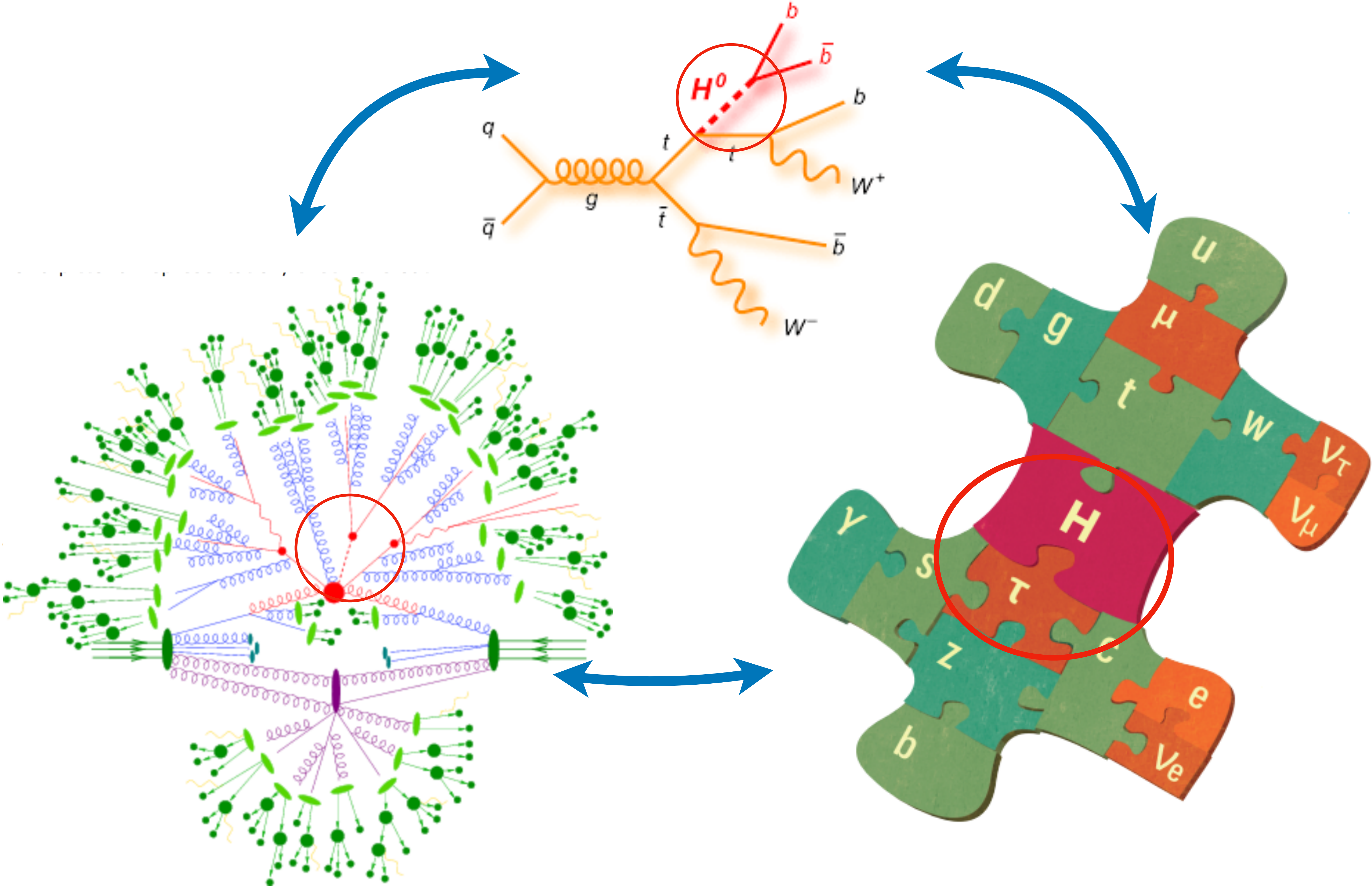
Dmitri Tsybychev
Stony Brook University



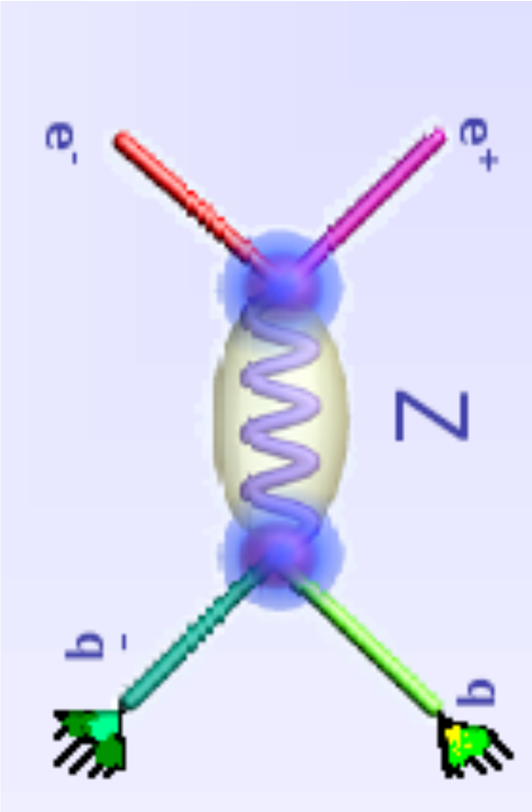
- Always wanted to be a scientist or an engineer
- Diploma, Moscow State University (1997, IHEP Protvino)
- PhD, University of Florida (2004, CDF, Fermilab)
- Postdoctoral Fellow, Stony Brook (D0, Fermilab)
- Professor, Stony Brook University (2008 - present, ATLAS, D0)
- More than 1000 publications



Discovery Process

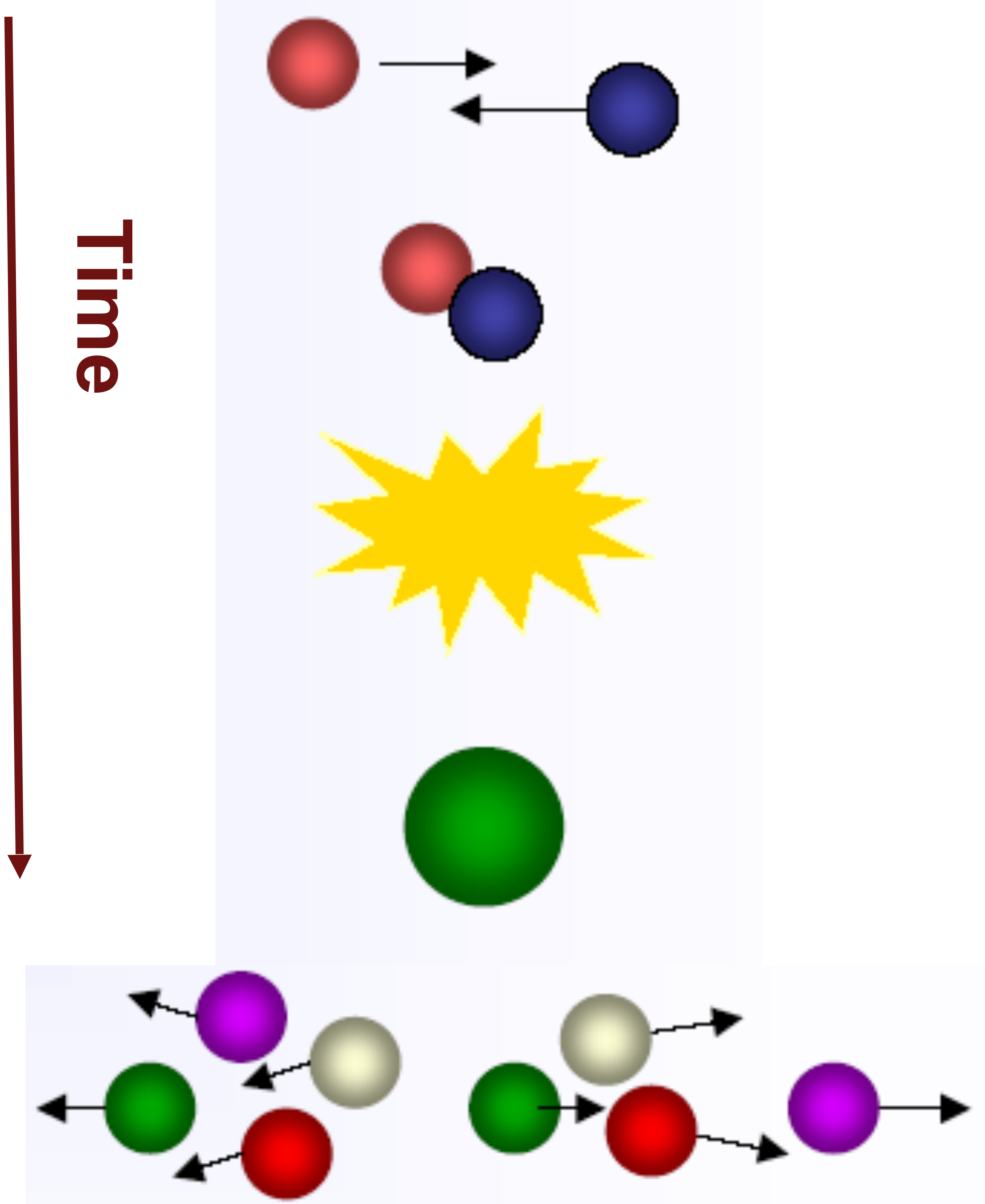


Particle Physics Experiment



$$e^+ + e^- \to Z^0 \to q\bar{q}$$

$$(+\,\text{hadronization})$$



Idealistic View:

Elementary Particle Reaction

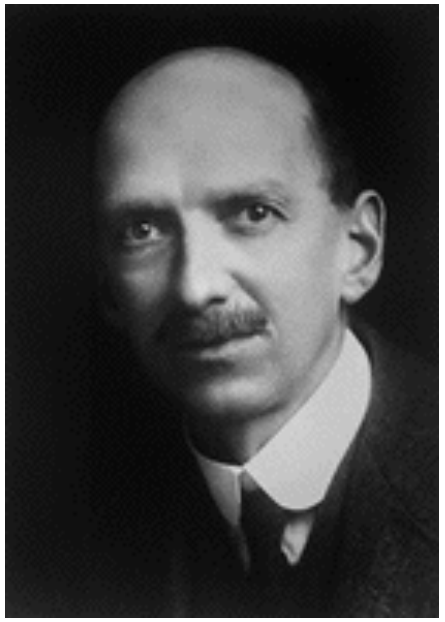
- Usually cannot “see” the reaction itself
- To reconstruct the process and the particle properties, need maximum information about end-products

Particle Detection

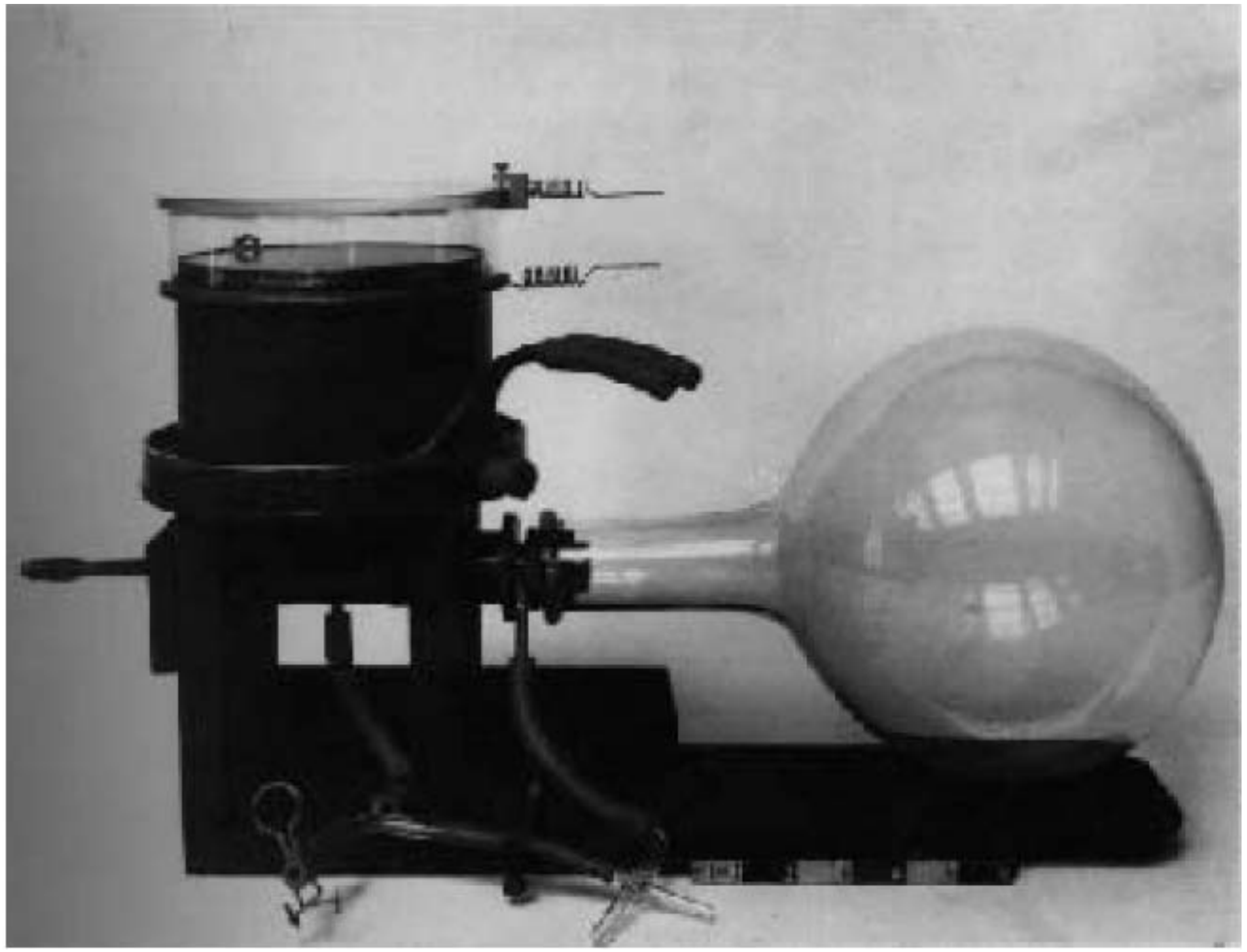
- Basically, everything interesting happens within the first ~10^{-12} seconds after the beams collide
  - we can only see "final-state" particles
  - our physics knowledge is based on "working backwards in time" to infer what actually happened in the initial collision
  - the more precisely the final-state particles are measured, the more accurately we can determine the parameters of their parents
- In order to detect a particle it has to interact and deposit energy
  - Measure charge, momentum, energy
  - Particle ID (γ, e, μ, π, K, p)
  - Reconstruct decay vertices of short lived particles (origin of jets -charm, bottom or light quarks, τ - leptons) and identify them probabilistically

The First Particle Detector

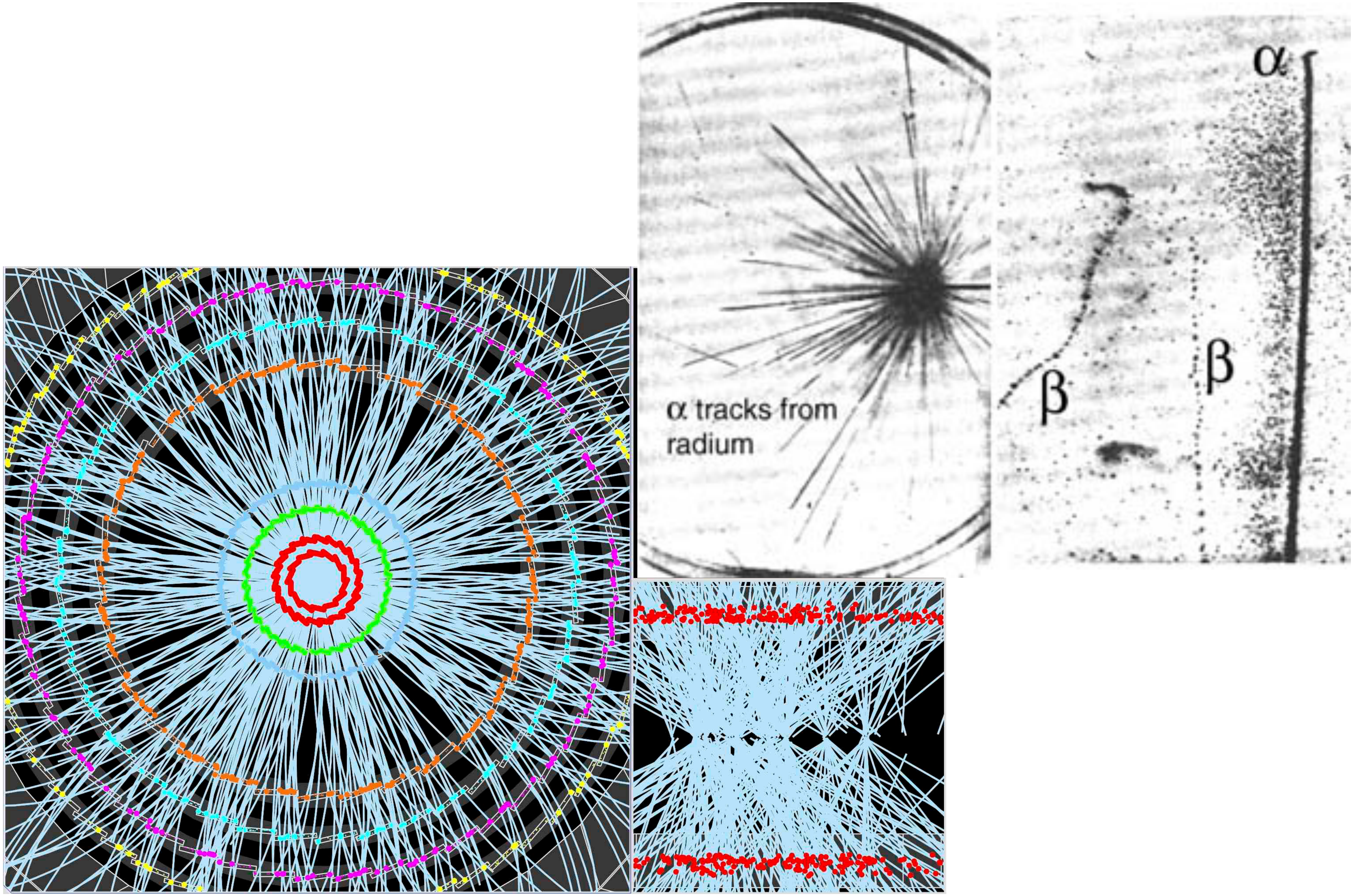
The Cloud Chamber (C.T.R. Wilson)



- an air volume saturated with water
- lower pressure to generate a super-saturated air volume
- charged particles cause condensation of vapour into small droplets
- droplets form along particle trajectory and are observed
- photographs allow longer inspections



The First Particle Detector



Definitions and Units

Energy of a particle: $E^2 = \vec{p}^2 c^2 + m^2 c^4$

- energy, E, measured in eV (MeV, GeV)
- momentum, p, measured in eV/c
- mass, m, measured in eV/c^2
- Natural units h=c=1
  - $E^2 = p^2 + m^2$

From special relativity

$$\frac{v}{c} = \beta \quad (0 \leq \beta < 1) \quad \text{and} \quad \gamma = 1/\sqrt{1-\beta^2} \quad (1 \leq \gamma < \text{inf})$$

Things we want to know

A particle detector is an instrument to measure one or more properties of a particle …

Properties of a particle:		Type of detection principle:
- position and direction	$x, \vec{x}$	position and tracking
- momentum	$\|\vec{p}\|$	tracking in a magnetic field
- energy	E	calorimetry
- mass	m	Spectroscopy and PID
- velocity	β	Cherenkov radiation or time of flight
- transition radiation	γ	TRD
- spin, lifetime		

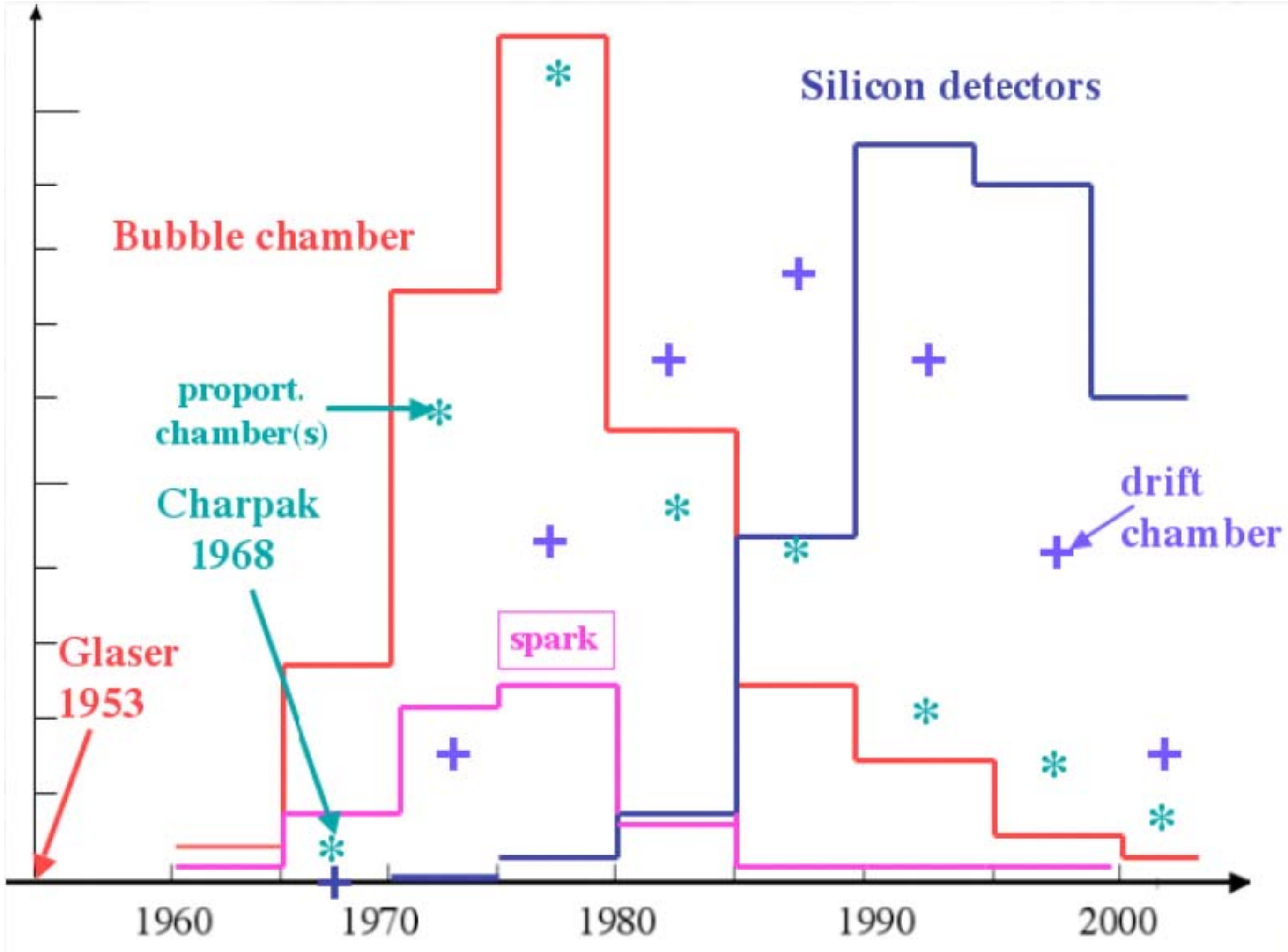
History of Detectors

- **Cloud Chambers dominating until the 1950s**
➔now very popular in public exhibitions related to particle physics

- **Bubble Chambers had their peak time between 1960 and 1985**
➔ last big bubble chamber was BEBC at CERN (Big European Bubble Chamber), now in front on the CERN Microcosm exhibition

- **Wire Chambers (MWPCs and drift chambers) started to dominate since 1980s**

- **Since early 1990s solid state detectors are in use started as small sized vertex detectors**
➔ now ~200 m^2 silicon surface in CMS tracker

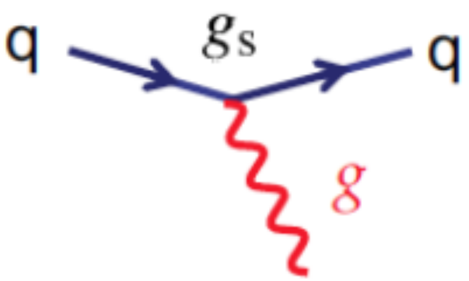


Slide credit E. Garutti, H. Graafsma

Standard Model Interactions

The interaction of gauge bosons with fermions is described by the Standard Model

STRONG

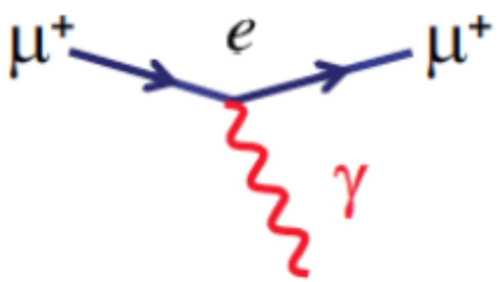


Only quarks

Never changes flavour

$\alpha_S \sim 1$

EM

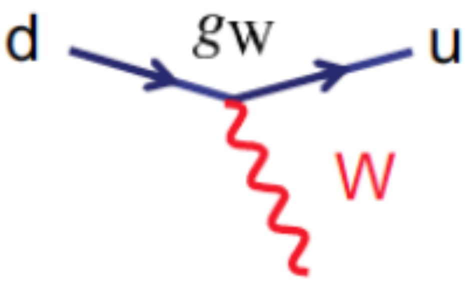


All charged fermions

Never changes flavour

$\alpha \simeq 1/137$

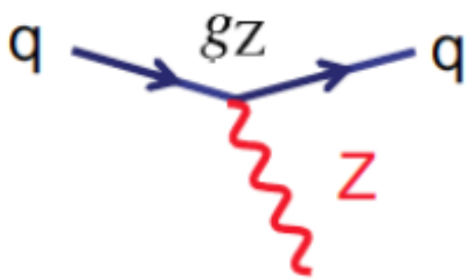
WEAK CC



All fermions

Always changes flavour

WEAK NC



All fermions

Never changes flavour

$\alpha_{W/Z} \sim 1/40$

Gluons
massless

Photon
massless

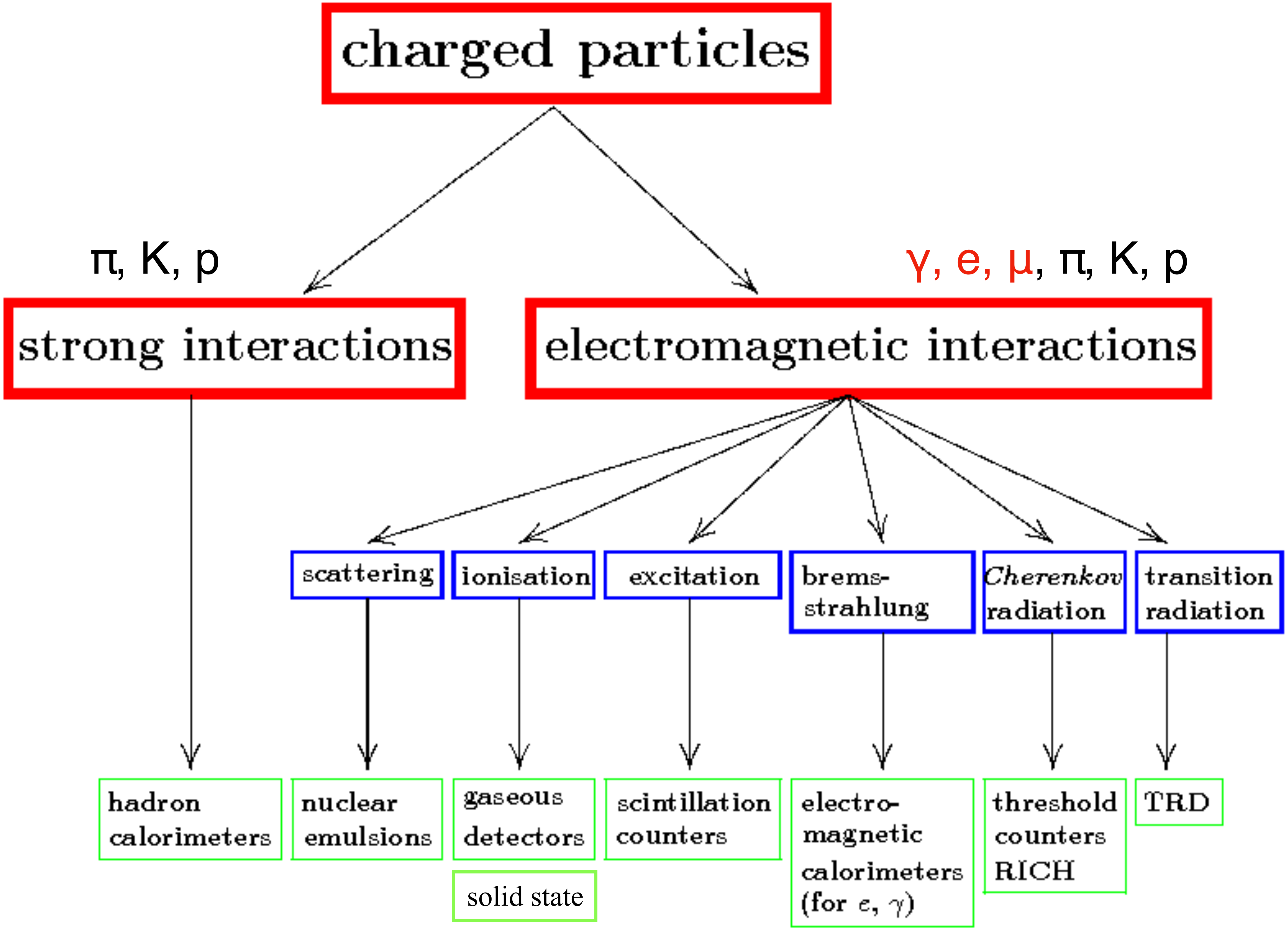
W+, W-
very massive

Z^0
very massive

Relative strength with respect to gravity

10^{40} **10^{38}** **10^{15}**

Charged Particle Interactions and Detection



charged particles

π, K, p

γ, e, μ, π, K, p

strong interactions

electromagnetic interactions

scattering

ionisation

excitation

bremsstrahlung

Cherenkov radiation

transition radiation

hadron calorimeters

nuclear emulsions

gaseous detectors

solid state

scintillation counters

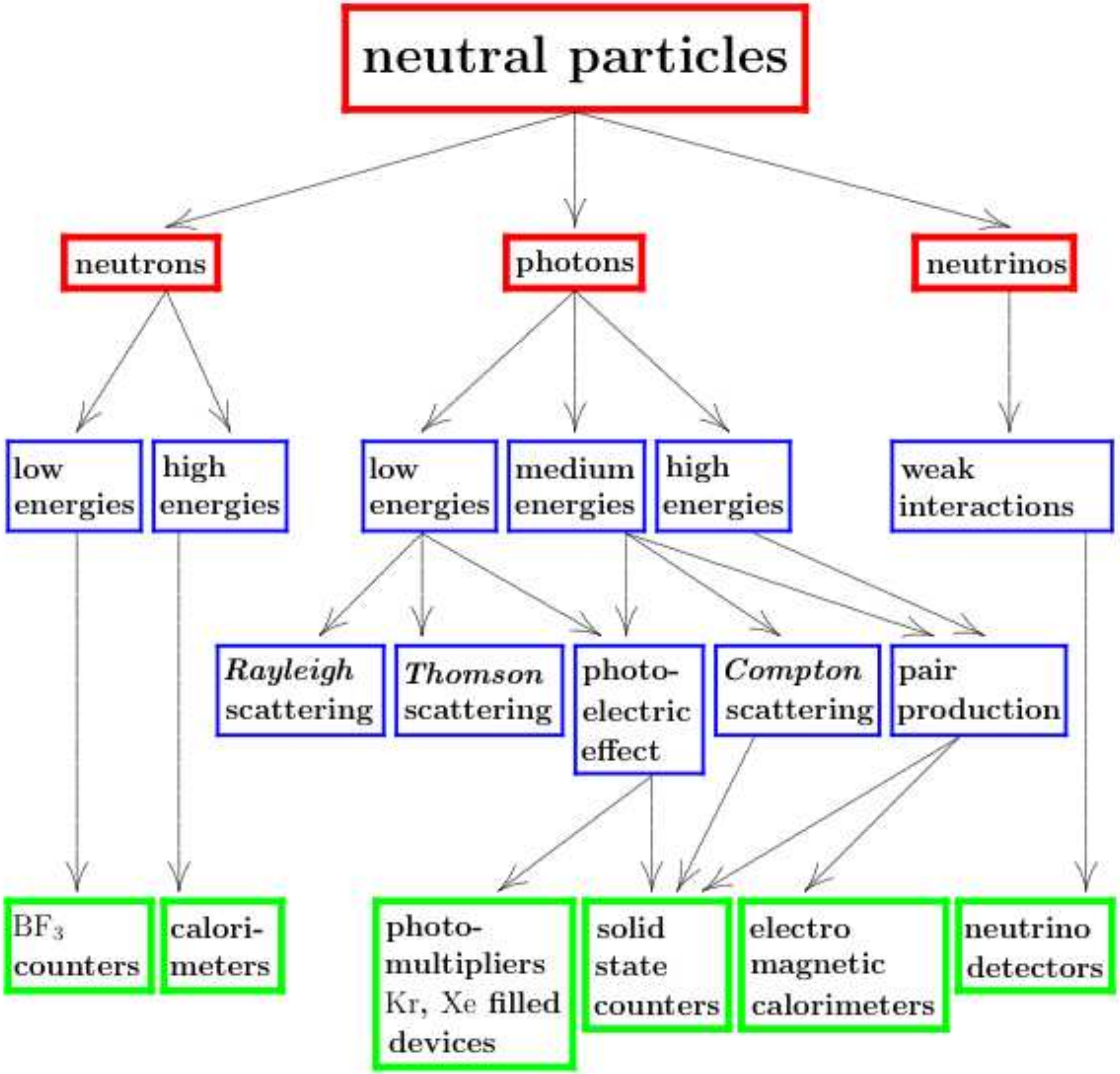
electromagnetic calorimeters (for e, γ)

threshold counters

RICH

TRD

Neutral Particle Interaction and Detection



neutral particles

neutrons

photons

neutrinos

low energies

high energies

low energies

medium energies

high energies

weak interactions

Rayleigh scattering

Thomson scattering

photo-electric effect

Compton scattering

pair production

BF_3 counters

calorimeters

photomultipliers Kr, Xe filled devices

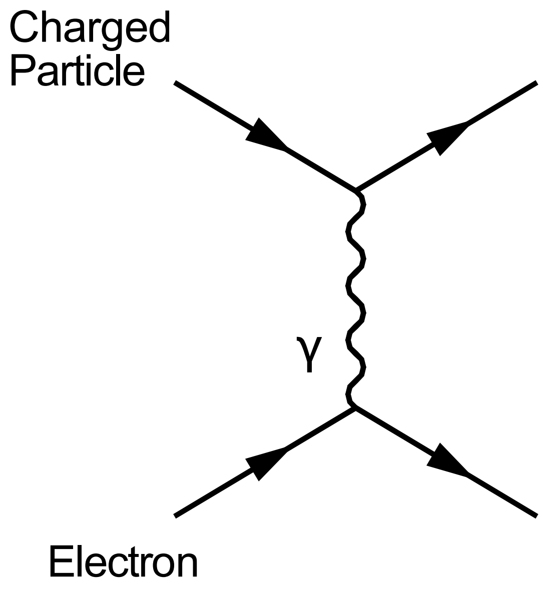
solid state counters

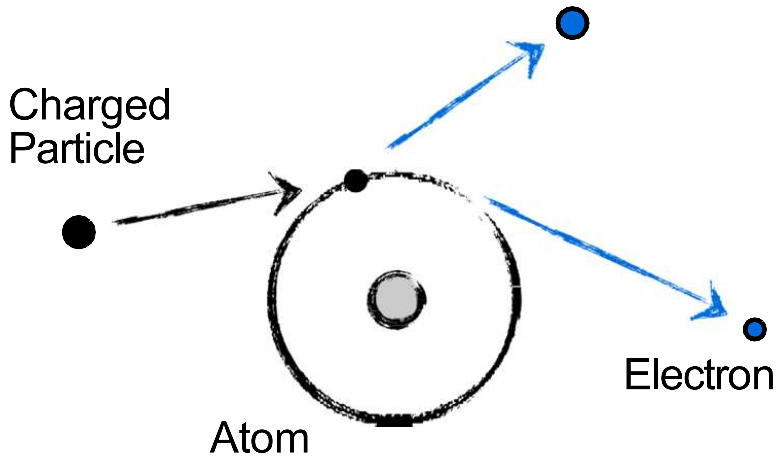
electro magnetic calorimeters

neutrino detectors

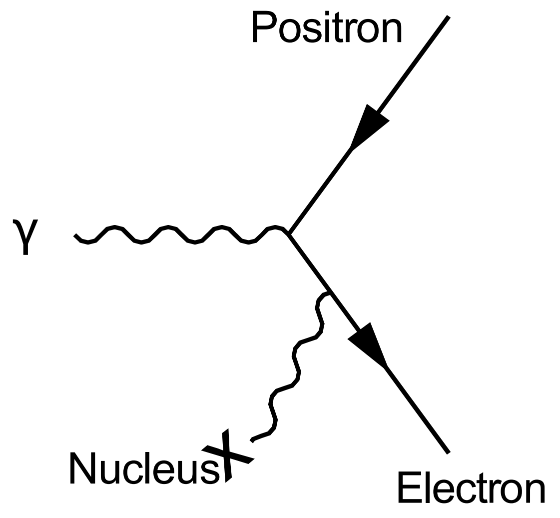
Particle Interaction with matter - examples

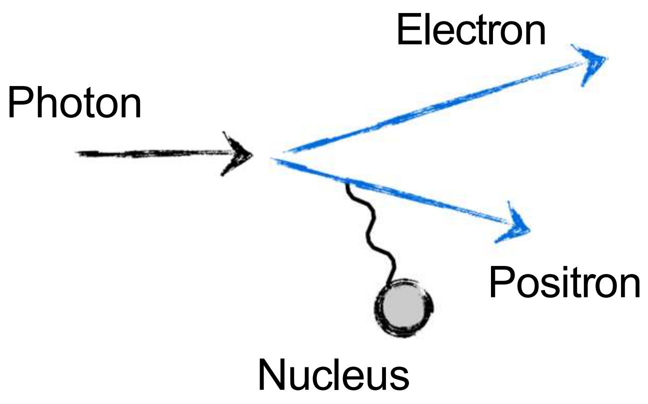
Ionization



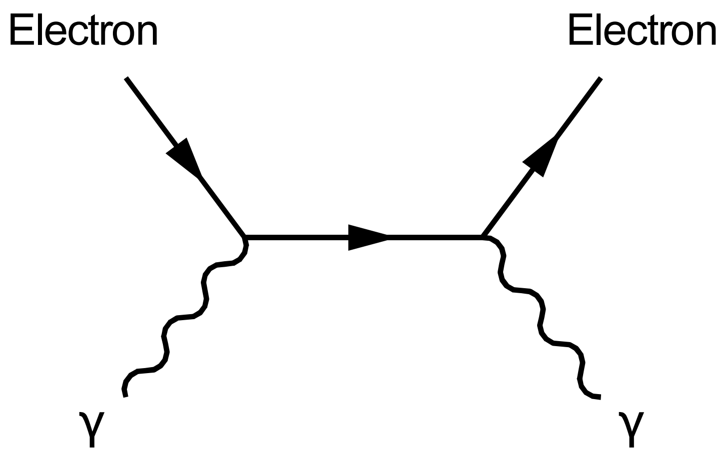


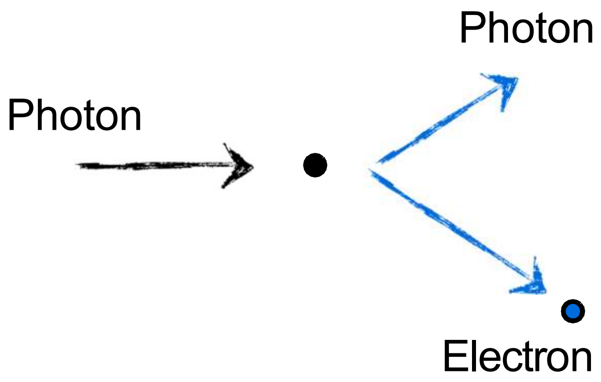
Pair Production





Compton Scattering



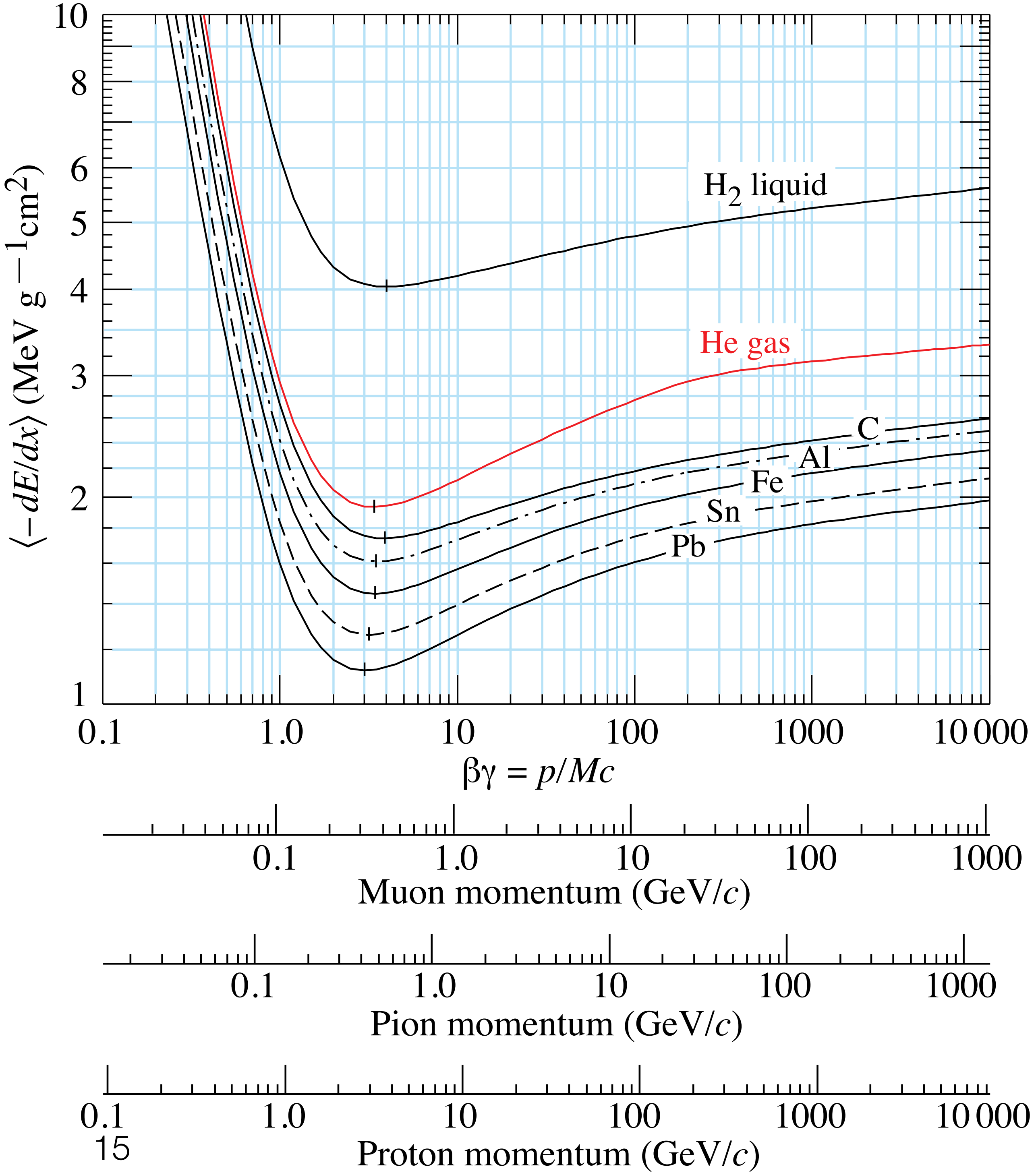


Ionization losses - Bethe-Bloch

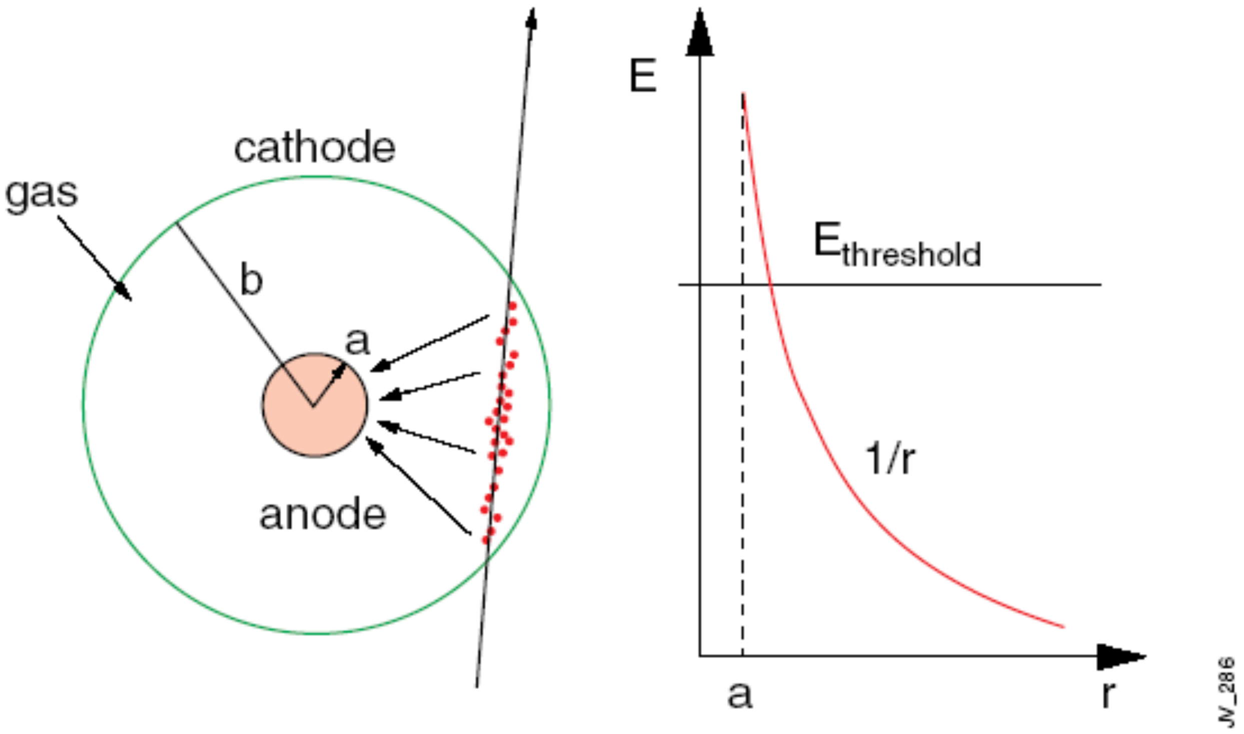
- Charged particles ionize atoms as they pass through matter

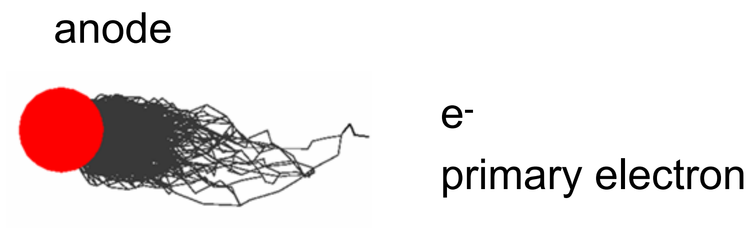
$$\frac{dE}{dx} = -4\pi N_A r_e^2 c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I^2} T^{max} - \beta^2 - \frac{\delta}{2} \right]$$ [MeV cm²/g]

- Rate of energy loss with distance depends on the momentum and particle type
  - For relativistic particles it is roughly constant at 2 [MeV cm²/g]
  - For low momentum it goes as 1/v²
  - Proportional to charge squared of the particle
  - Weakly depends on Z/A of the material



Single Wire Proportional Chamber





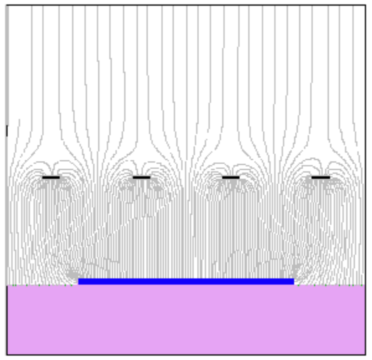
Electrons liberated by ionization drift towards the anode wire.
Electrical field close to the wire is sufficiently high for electrons (above 10 kV/cm) to gain enough energy to Ionize further → avalanche – exponential increase of number of electron ion pairs

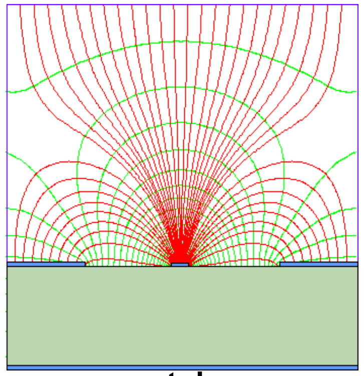
- the proportional operation mode.

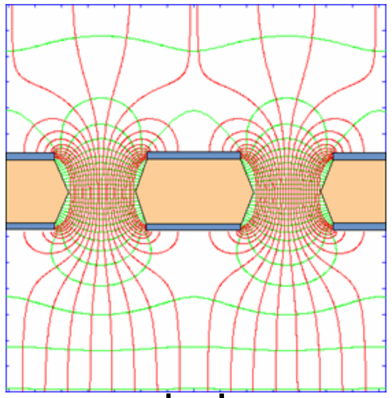
$$E(r)=\frac{CV_0}{2\pi\varepsilon_0}\cdot\frac{1}{r}$$

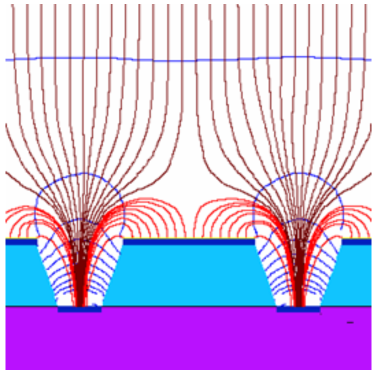
$$V(r)=\frac{CV_0}{2\pi\varepsilon_0}\cdot\ln\frac{r}{a}$$ C – capacitance/unit length

Cylindrical geometry is not the only one able to generate strong electric field:


parallel plate


strip

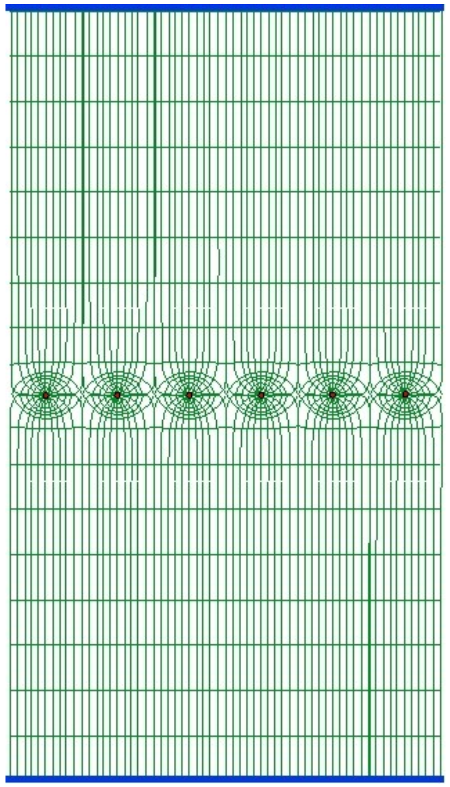

hole

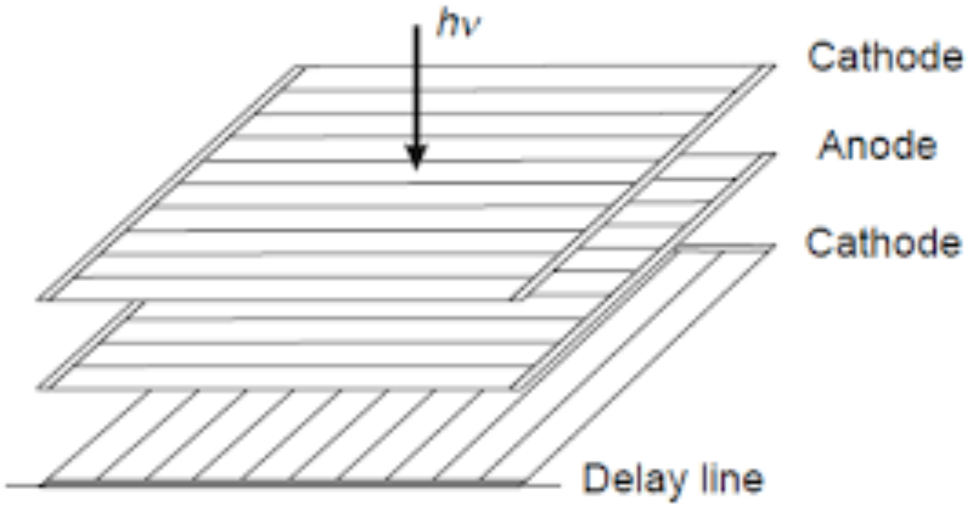

groove

Multiwire Proportional Chamber

Simple idea to multiply SWPC cell : Nobel Prize 1992

First electronic device allowing high statistics experiments !!





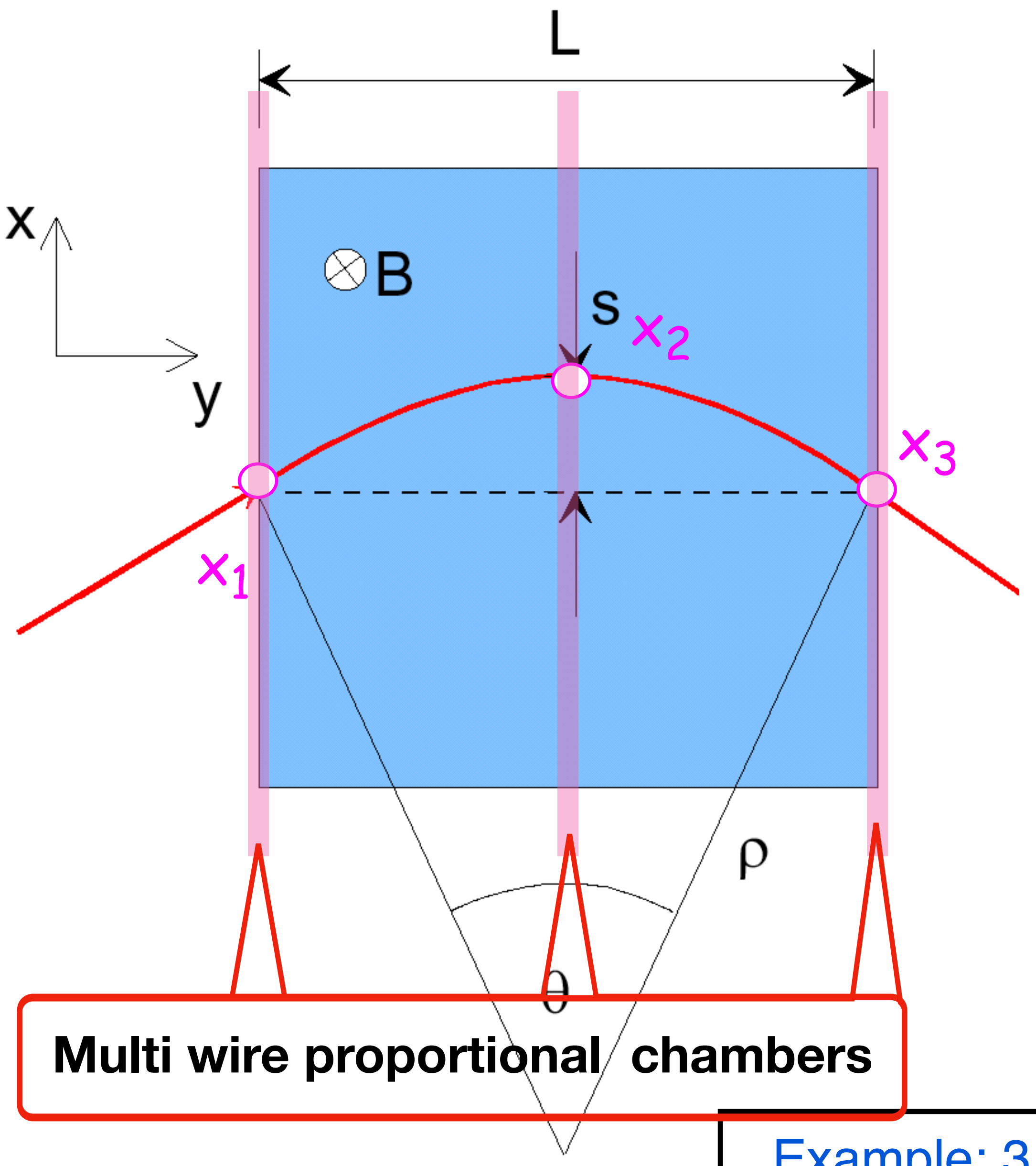
Normally digital readout :
spatial resolution limited to

$$\sigma_x \approx \frac{d}{\sqrt{12}}$$

for d = 1 mm σ_x = 300 μm

G. Charpak, F. Sauli and J.C. Santiard

Momentum Measurement in B-Fields



Multi wire proportional chambers

- Charged particles follow helix trajectory in **magnetic field B** under Lorentz force'
- The momentum (**transverse momentum p_T**) is measured from the **sagitta s**, which gives the **curvature ρ** of the track in magnetic field

Transverse momentum:

$$\boxed{p_T = qB\rho}$$

$$p_T[GeV] = 0.3\ B[T]\ \rho[m]$$

$$\frac{L/2}{\rho} = \sin\frac{\theta}{2} \approx \frac{\theta}{2}\ (\text{for small } \theta) \Rightarrow \theta \approx \frac{L}{\rho} = \frac{0.3BL}{p_T}$$

$$s = \rho(1-\cos\frac{\theta}{2}) \approx \rho\left(1-(1-\frac{1}{2}\frac{\theta^2}{4})\right) = \rho\frac{\theta^2}{8} \approx \frac{0.3BL^2}{8p_T}$$

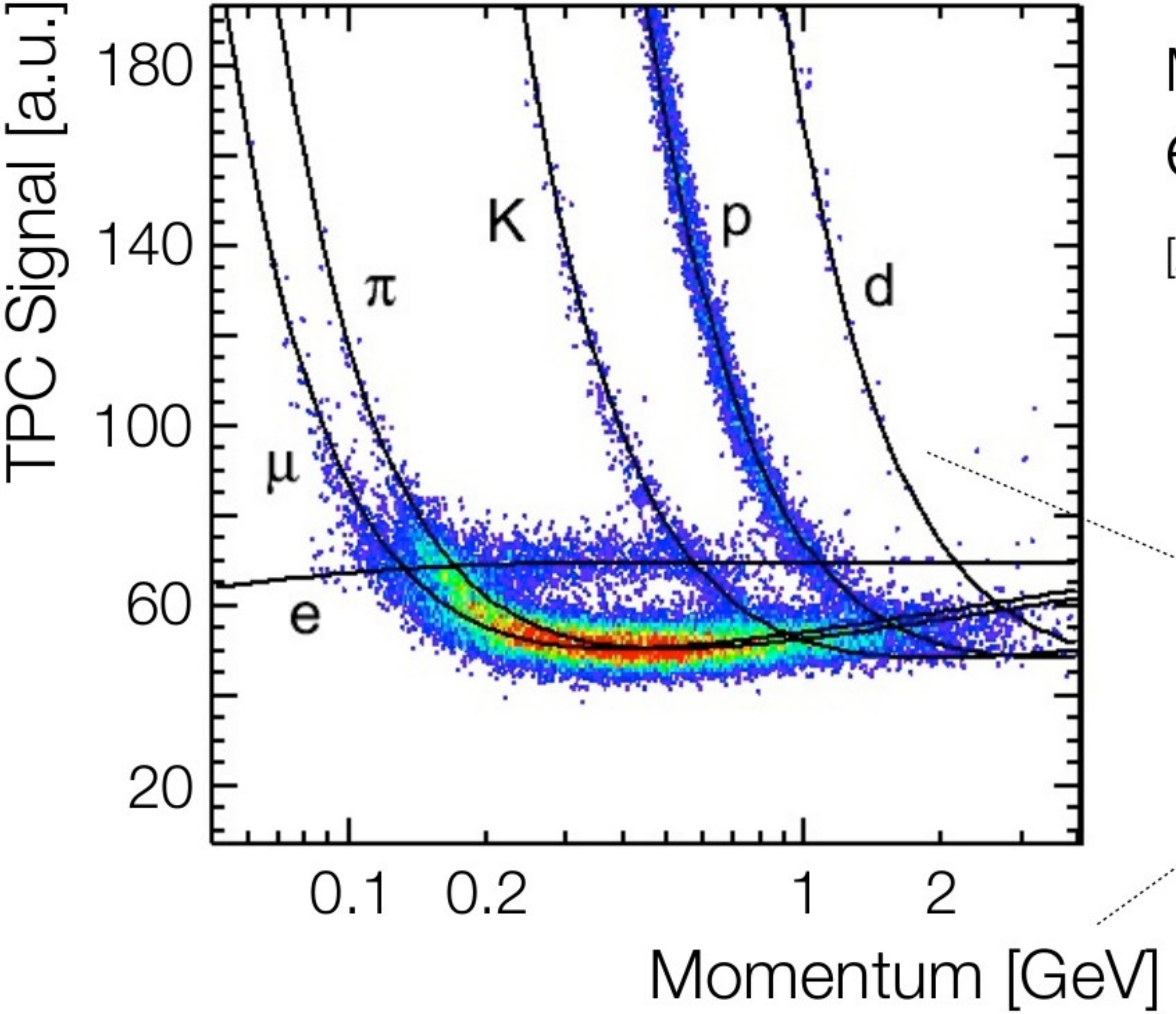
Example: 3 measurements

$$s = x_2 - (x_1+x_3)/2 \longrightarrow ds = dx_2 - dx_1/2 - dx_3/2$$

assume uncorrelated errors: $\sigma(x) \approx dx_i$

$$\sigma_s^2 = \sigma^2(x) + 2\frac{\sigma^2(x)}{4} = \frac{3}{2}\sigma^2(x)$$

Identifying particles by dE/dx



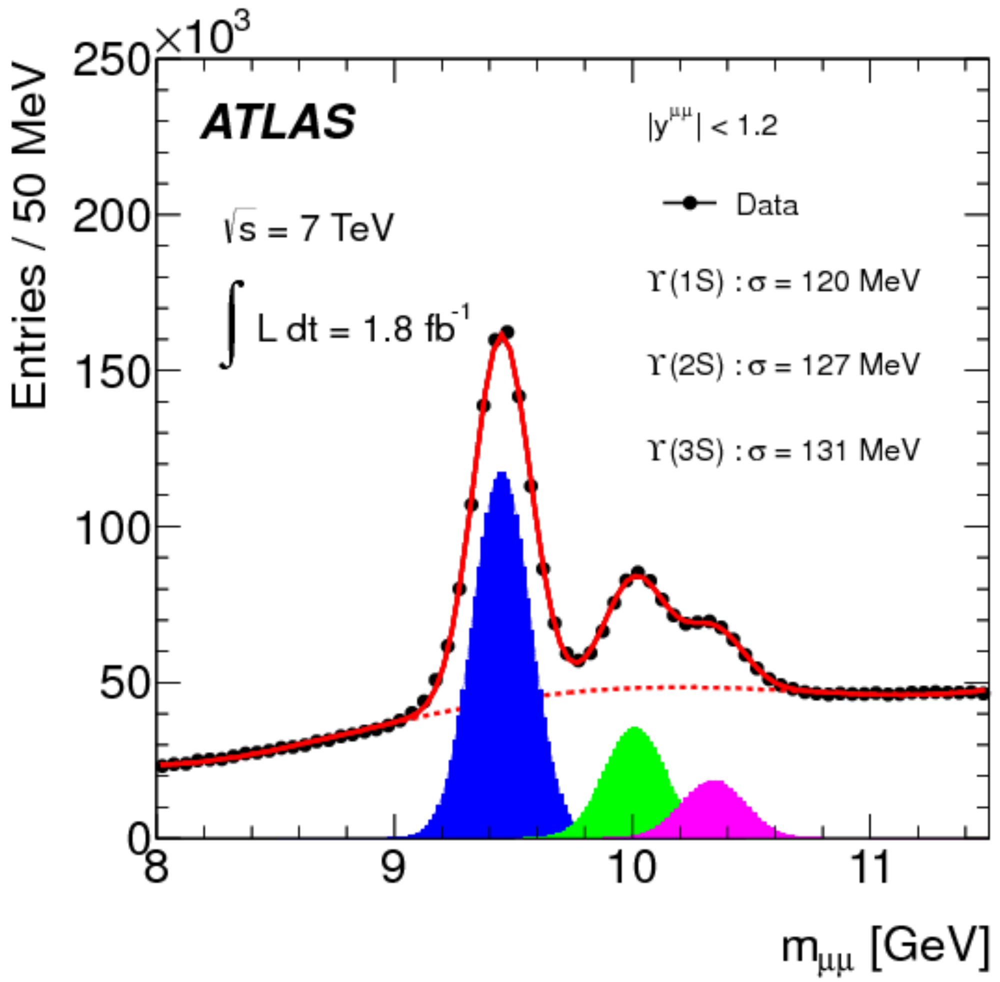
Measured
energy loss

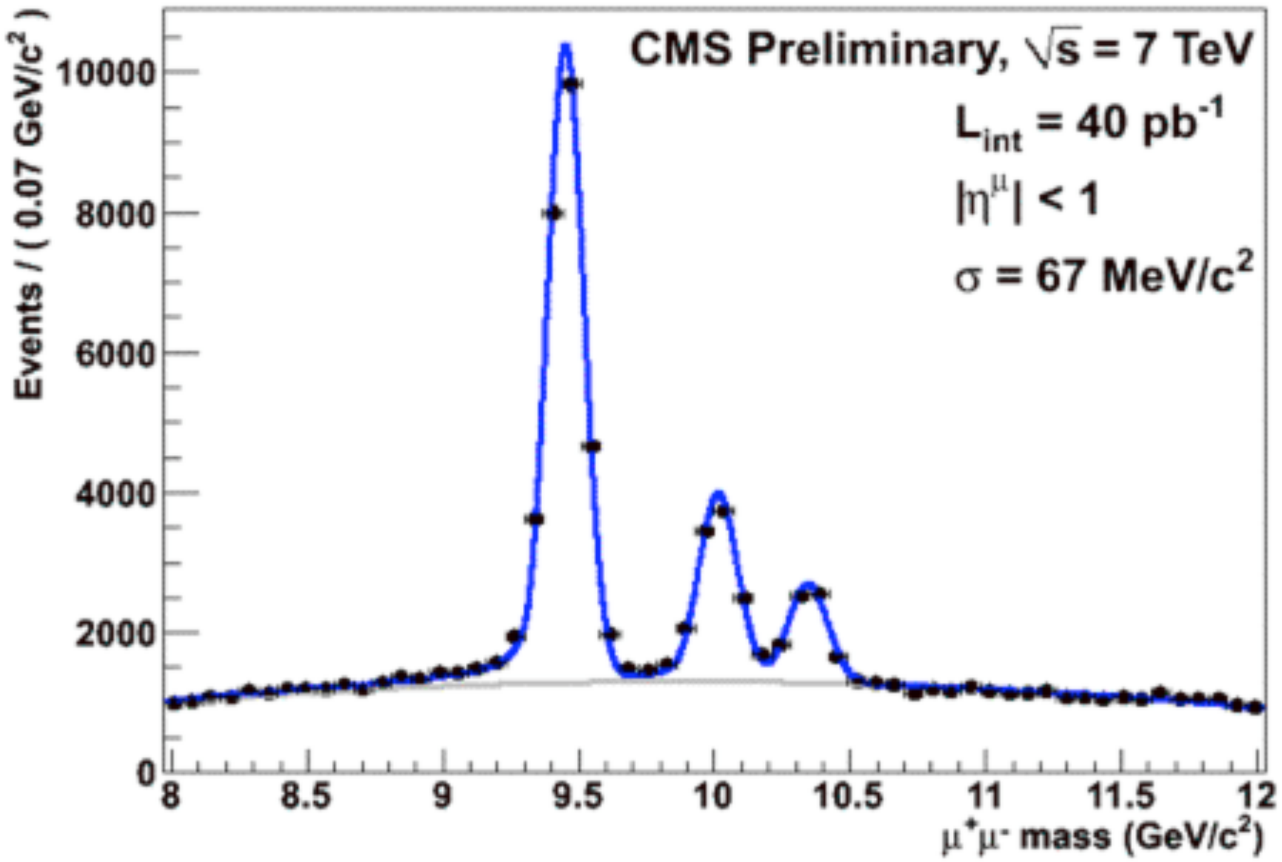
[ALICE TPC, 2009]

Bethe-Bloch

Remember:
dE/dx depends on β!

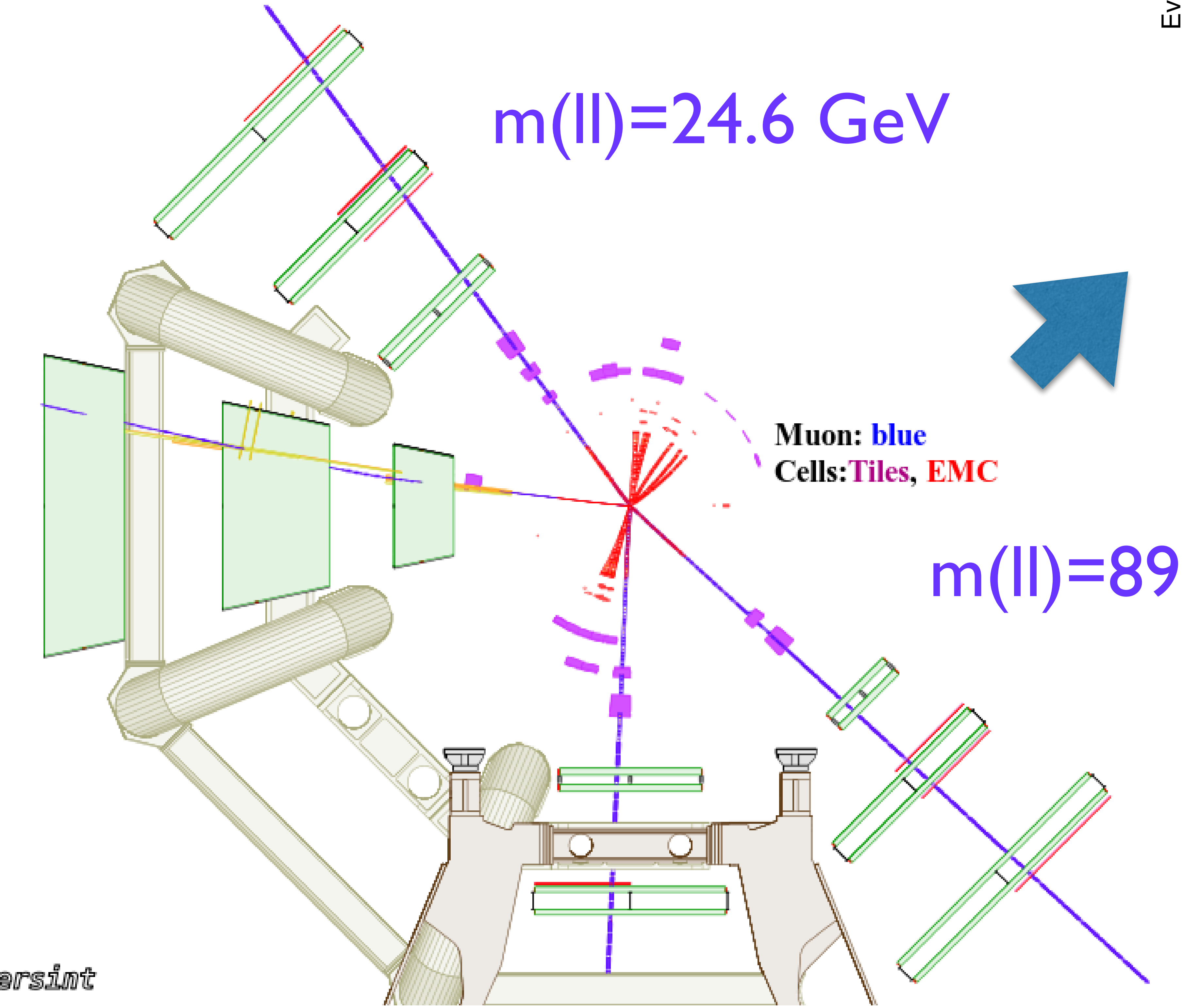
Detector Resolution





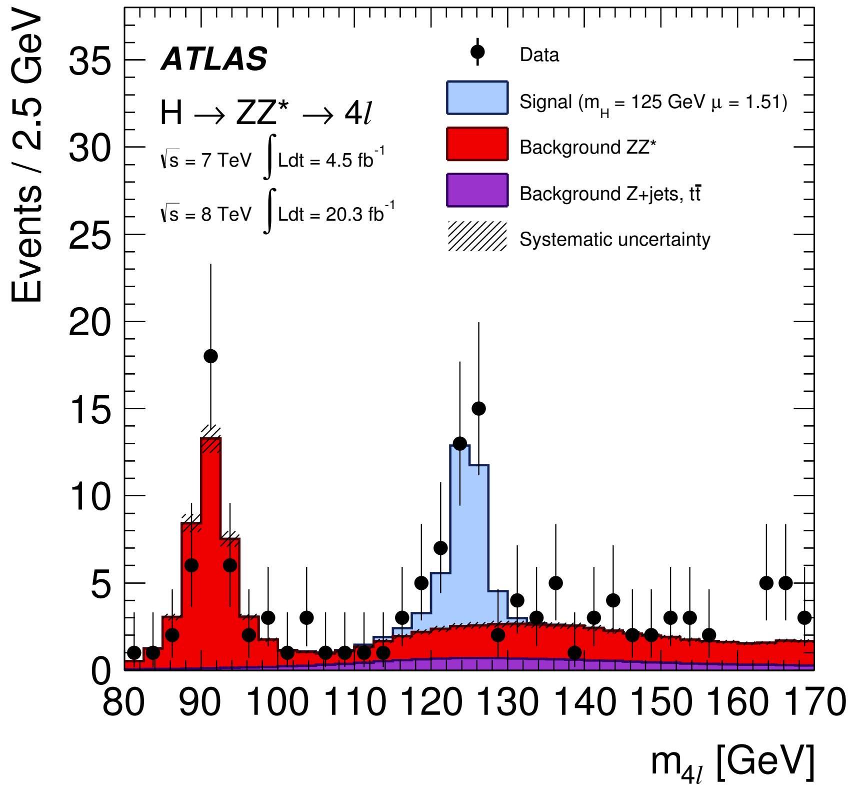
- detector resolution $S \sim 1/\sqrt{\sigma_m}$ detector with better resolution has larger probability to find signal or measure parameter more precisely, such as mass of unknown particle

Higgs to ZZ* to 4 leptons



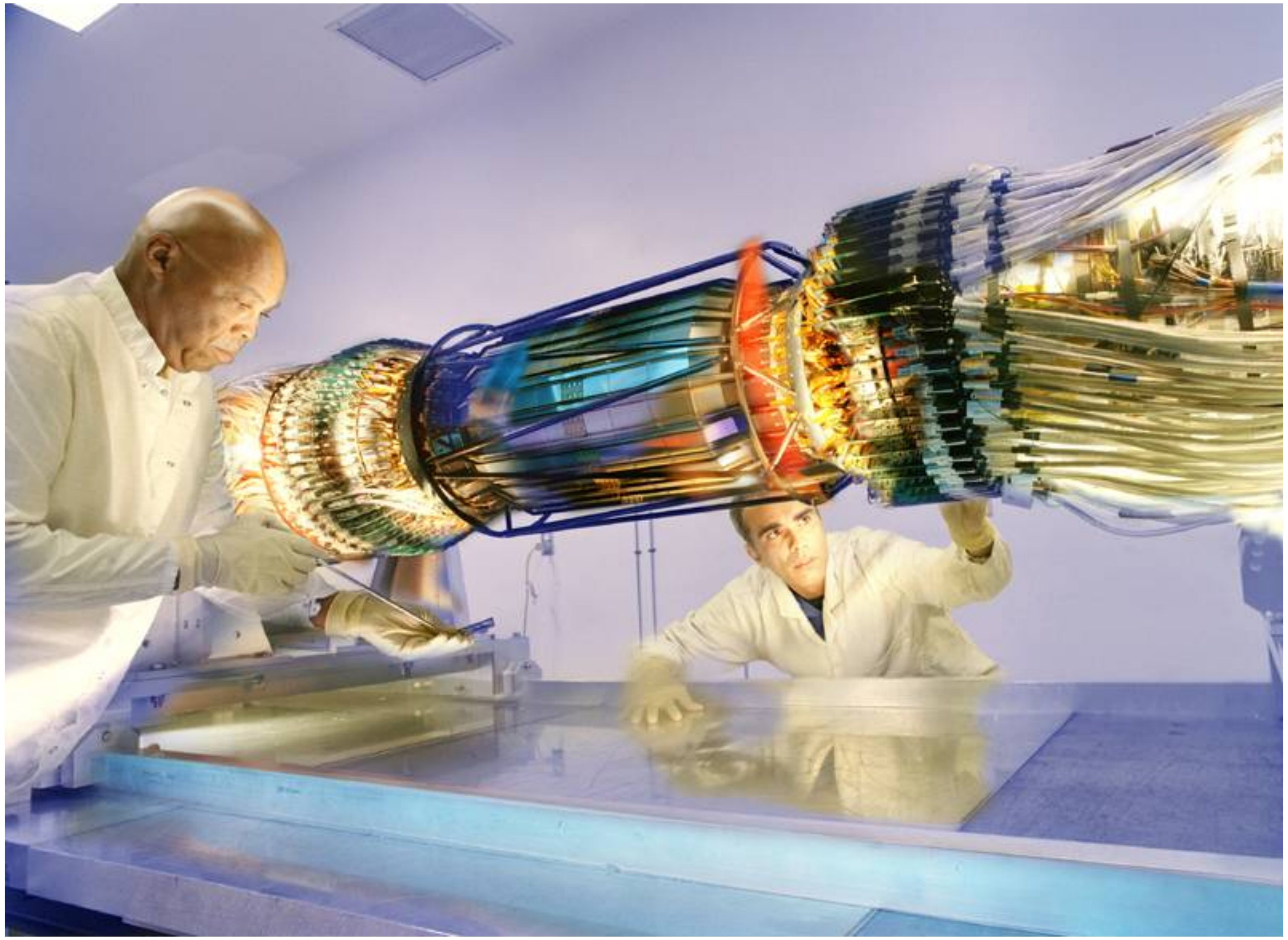
m(ll)=24.6 GeV

m(ll)=89.7 GeV

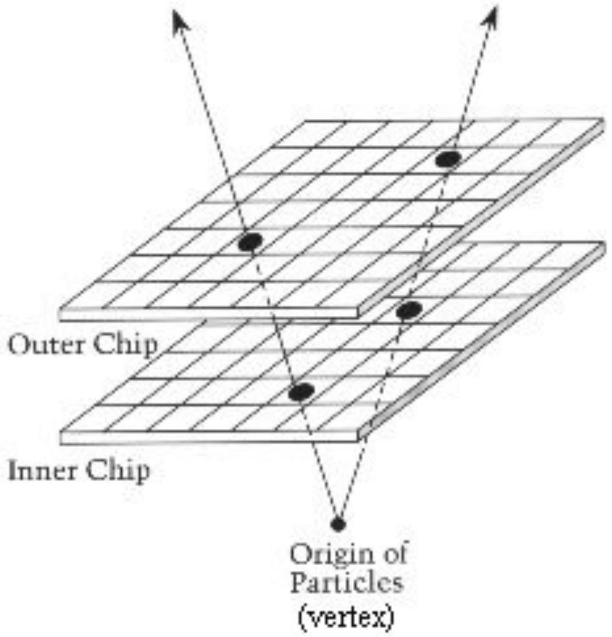


Vertex Detectors

Purpose: Ultra-high precision trackers close to interaction point to measure vertices of charged tracks



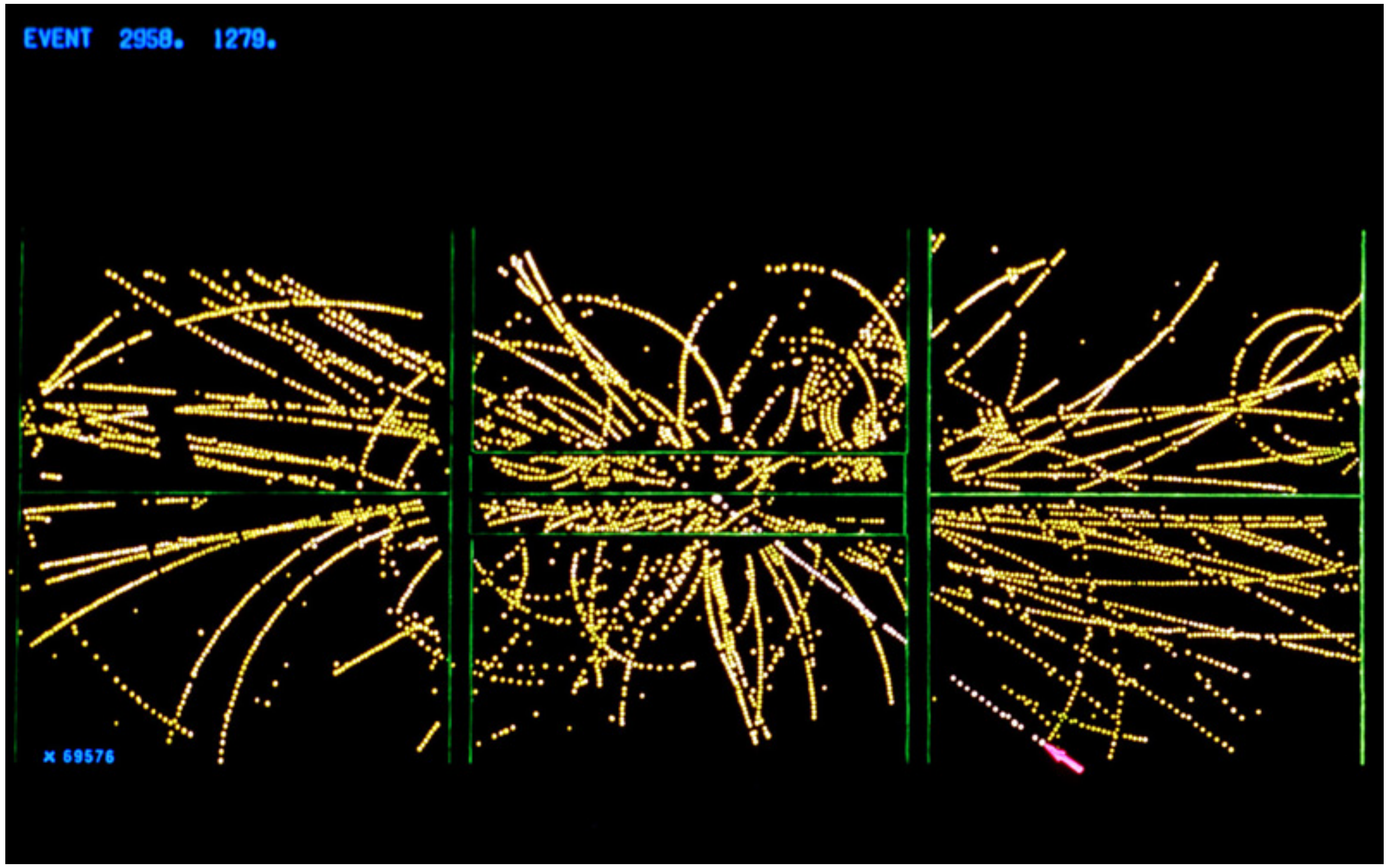
- Spatial resolution a few microns
- Low mass
- *A few layers of silicon*



Tracking Detectors

Purpose: Measure trajectories of charged particles

- Low mass
  - Reduce multiple scattering
  - Reduce shower formation
- High precision
- Multiple 2D or 3D points
- *Drift chamber, TPC, silicon...*
- Can measure momentum in magnetic field ($p = 0.3qBR$)

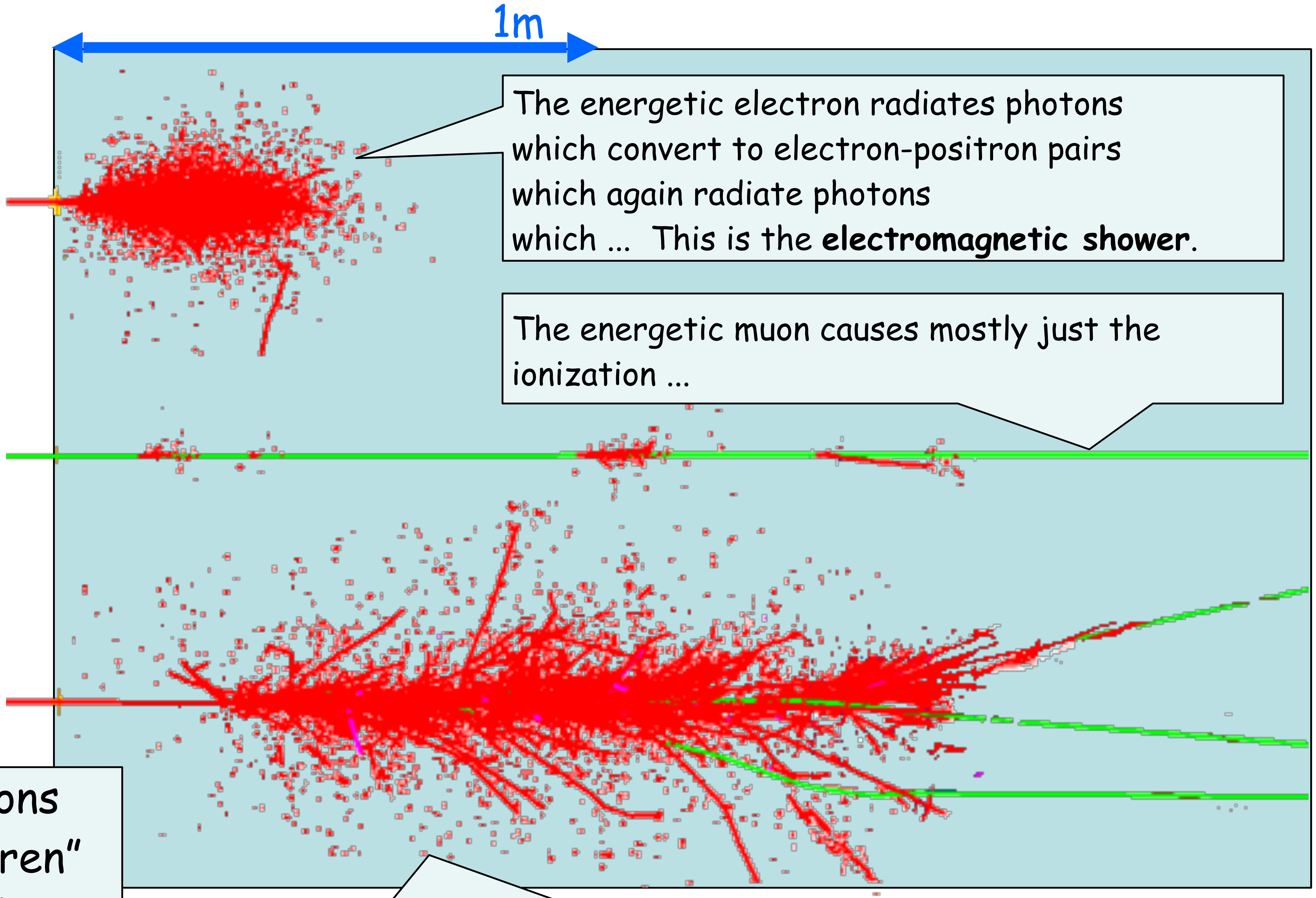


Calorimetry

General idea

- measure energy by total absorption
- also measure location
- method is destructive: particle is stopped
- quantity of detector response proportional to energy
- calorimetry works for all particles: charged and neutral
- mechanism: particle is forced to shower by the calorimeter material
- .... but in the end it is again ionization and excitation of the shower products which deposits the energy
- we distinguish electromagnetic and hadronic showers

look at interaction of different particles with the same high energy (here 300 GeV) in a big block of iron:



The energetic electron radiates photons which convert to electron-positron pairs which again radiate photons which ... This is the **electromagnetic shower**.

The energetic muon causes mostly just the ionization ...

Electrons and pions with their "children" are almost completely absorbed in the sufficiently large iron block.

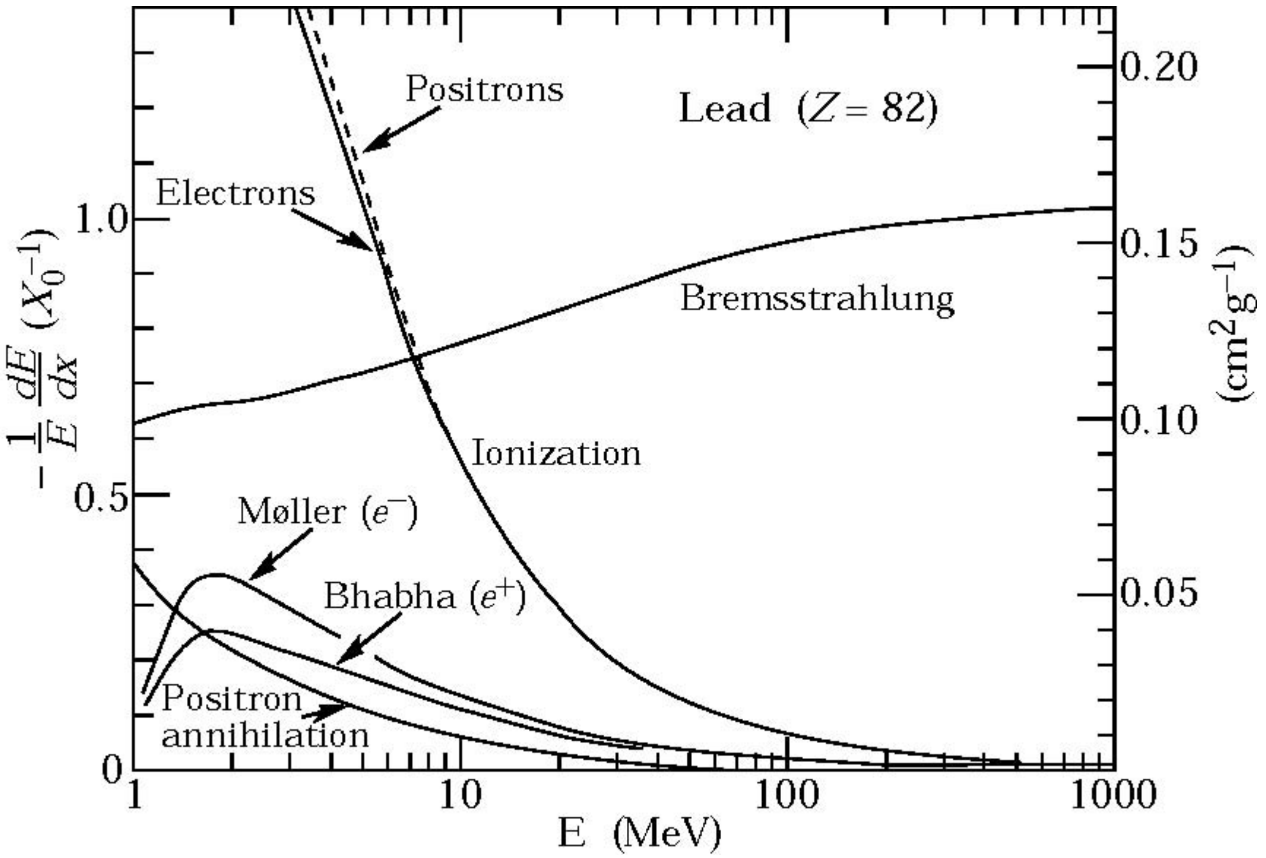
The strongly interacting pion collides with an iron nucleus, creates several new particles which interact again with iron nuclei, create some new particles ... **This is the hadronic shower.** You can also see some muons from hadronic decays.

Radiation Length for electrons and photons

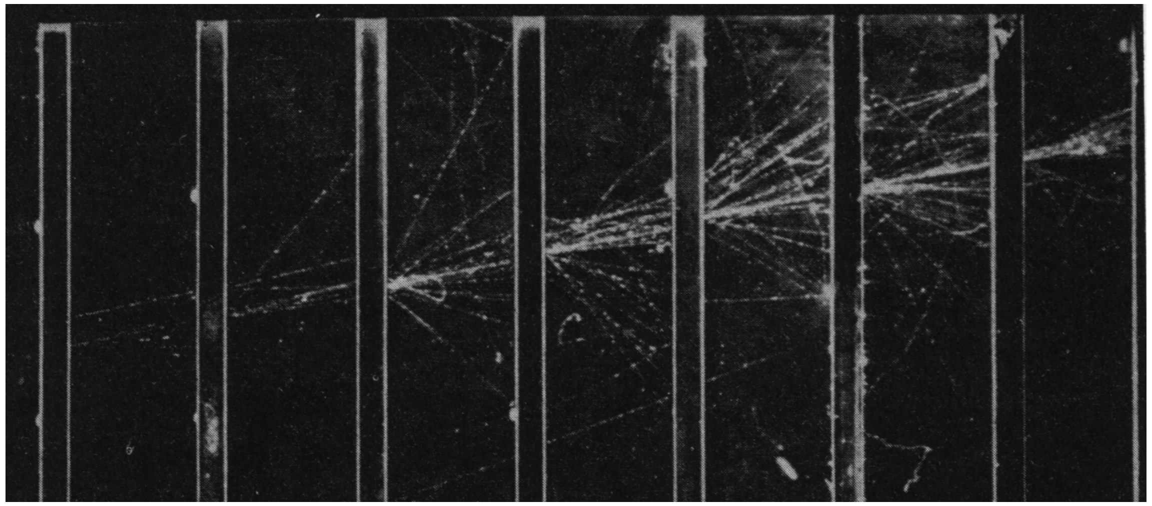
- Radiation Length X_o has 2 definitions:
  - "Mean distance over which high-energy electron loses all but 1/e of its energy by Bremsstrahlung."
  - "7/9ths of the mean free path for pair production by a high-energy photon."

$$X_0 = \frac{716.4A}{Z(Z+1)\ln(287/\sqrt{Z})} \quad (\mathrm{gcm}^{-2})$$

	X_0 (g cm^{-2})	X_0 (cm)
Air	37	30,000
Silicon	22	9.4
Lead	6.4	0.56

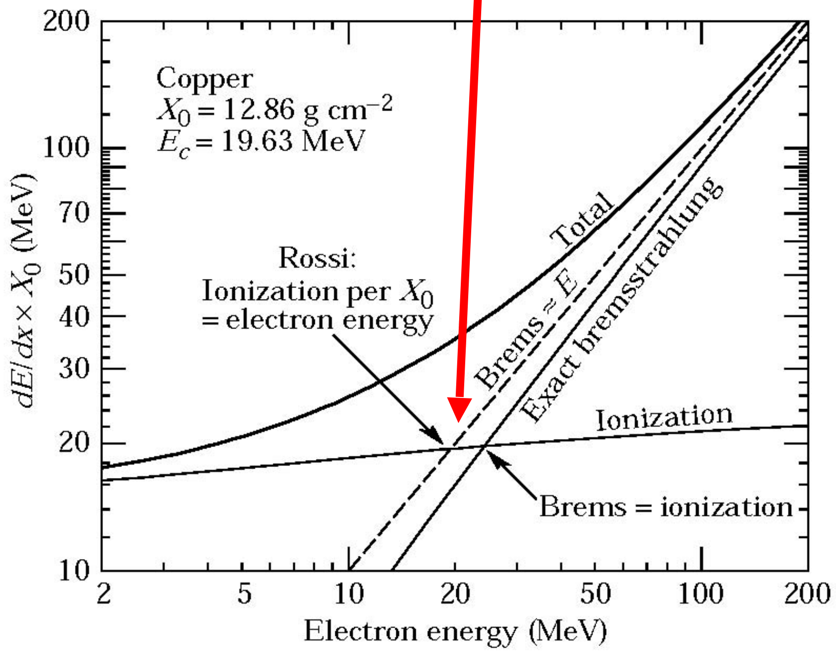


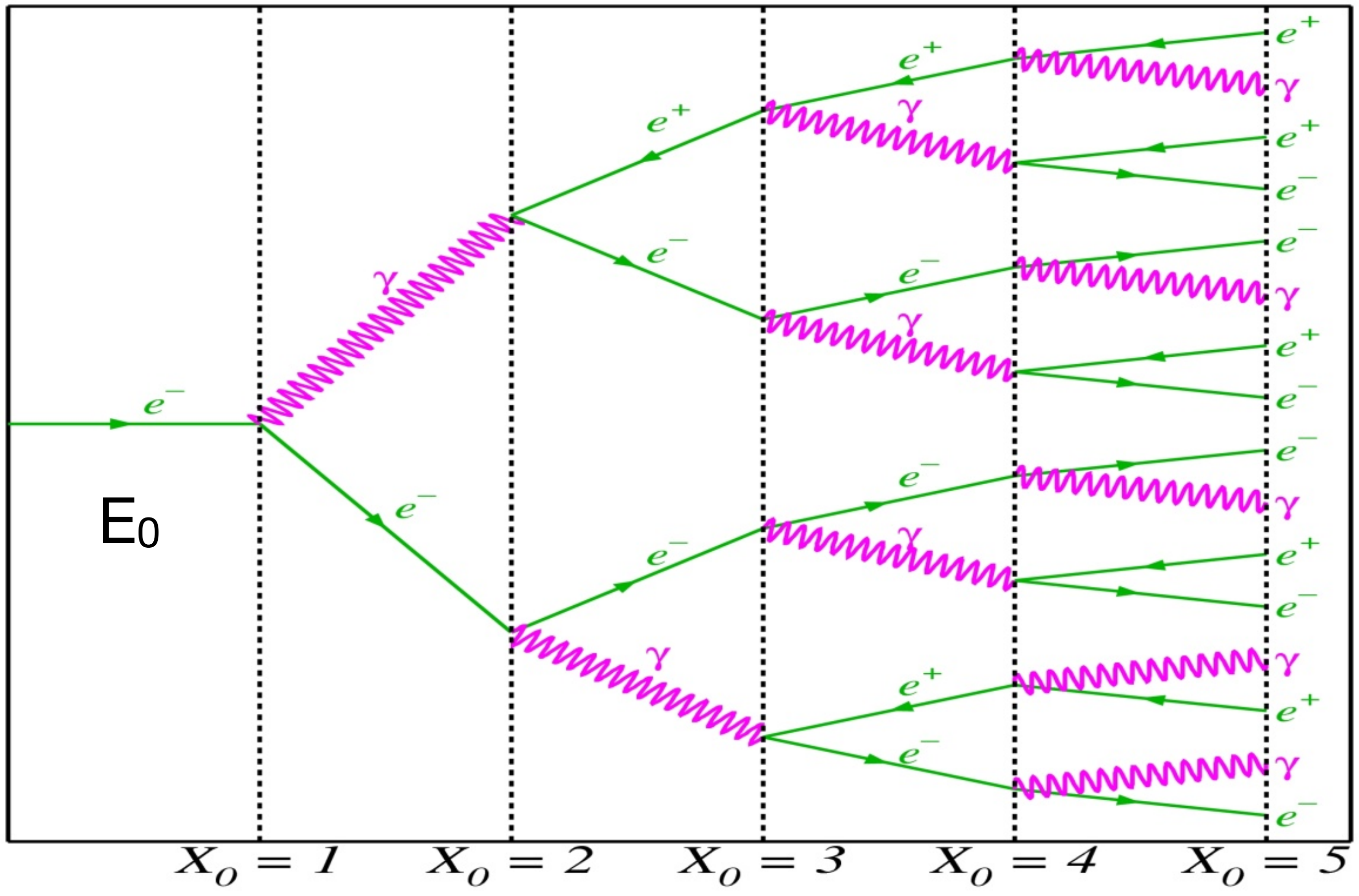
Simple Electromagnetic (EM) Shower



Electron shower in a cloud chamber with lead absorbers

E_c Critical Energy





E_0

$E_0/2$ $E_0/4$ $E_0/8$ $E_0/16$

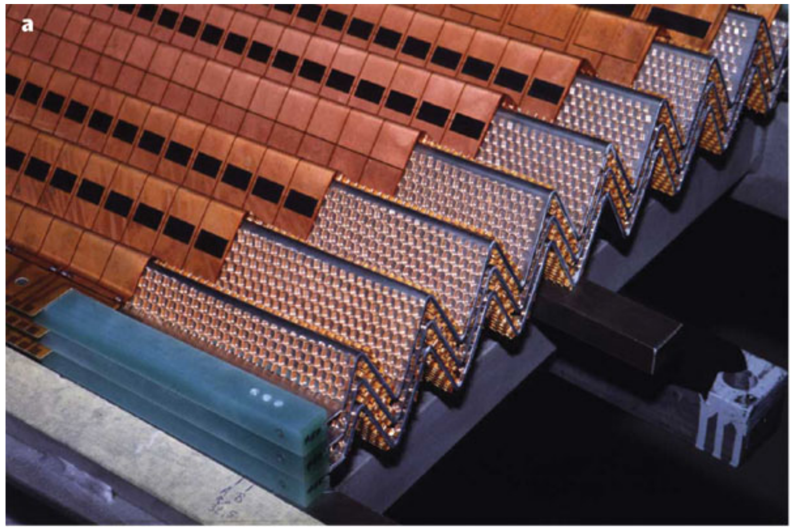
- Start with electron or photon
- Depth ~ ln(E_0)
- Most energy deposited as ionisation.

EM Calorimeter

Purpose: Identify and measure energy of electrons and photons

- Need ~ 10 X_0
  - 10 cm of lead
- Will see some energy from muons and hadrons
- Homogenous
  - *Crystal*
  - *Doped glass*
- Sampling
  - *Absorber + scintillator/MWPC/…*

ATLAS: Liquid Argon + Lead



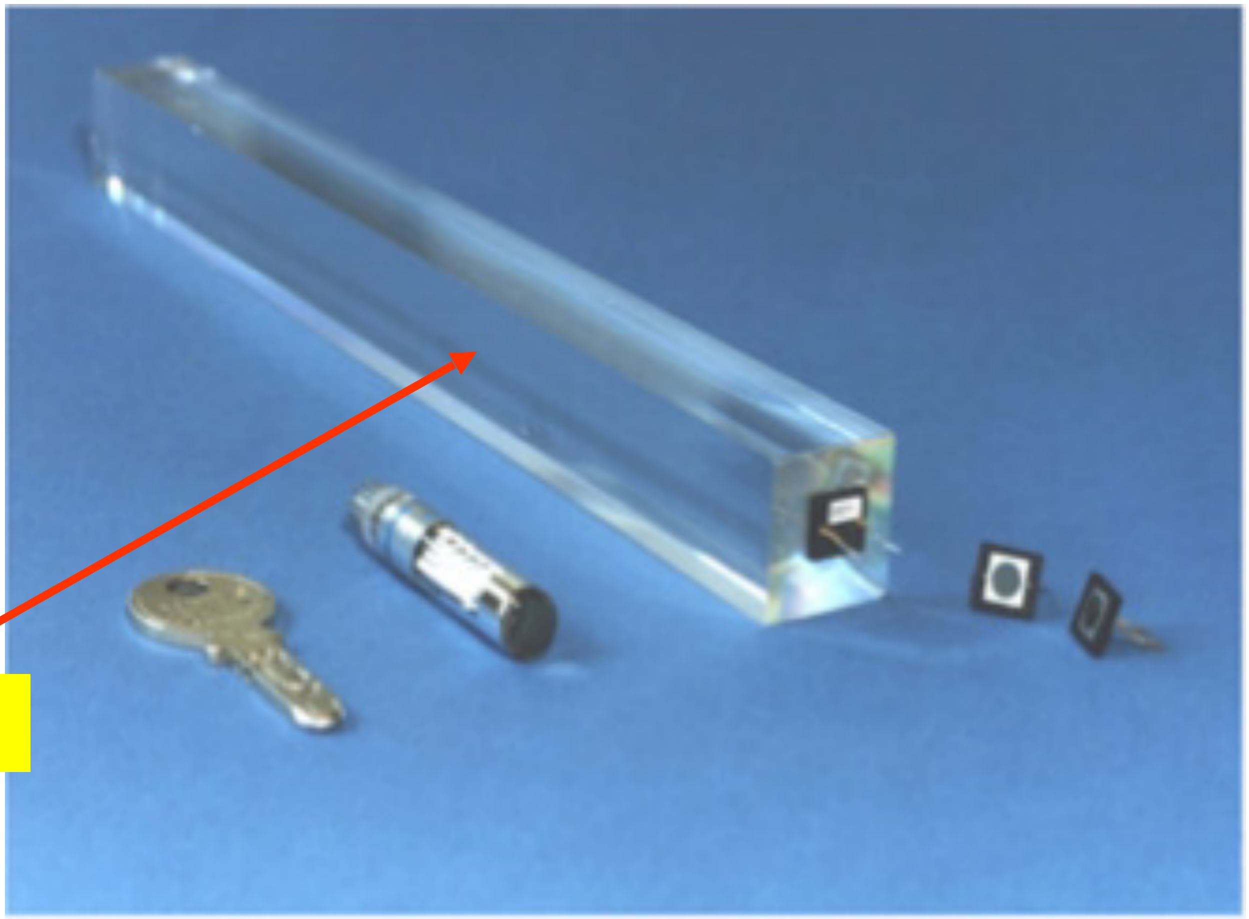
CMS: Lead-Tungstate crystal

Calorimetry - Homogeneous

In homogeneous calorimeters the functions of passive particle absorption and active signal generation and readout are combined in a single material. Such materials are almost exclusively used for electromagnetic calorimeters, e.g. crystals, composite materials (like lead glass, $PbWO_4$) or liquid noble gases.

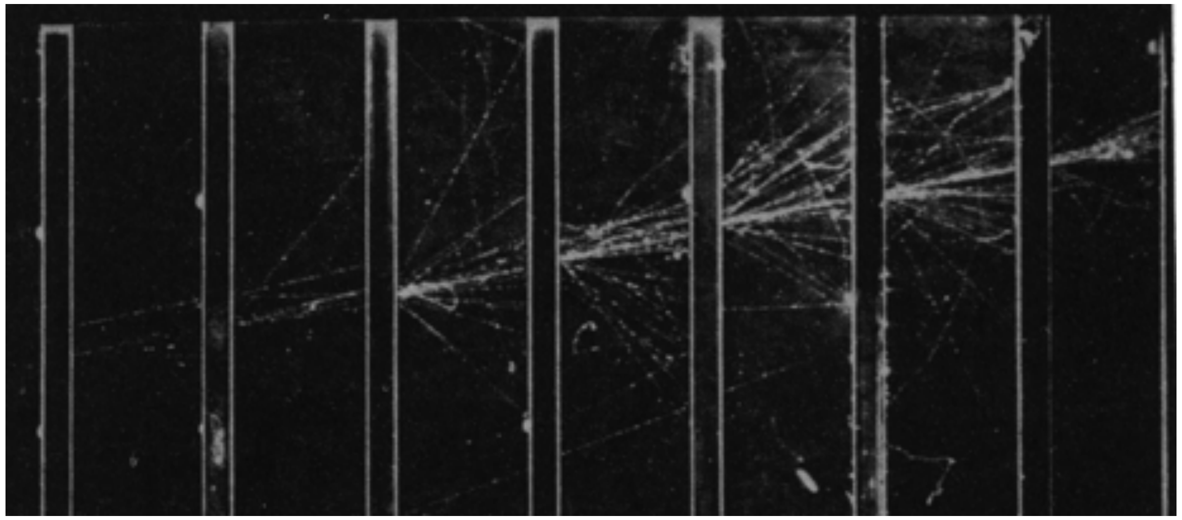
- Crystal, glass, liquid
- Acts as absorber and scintillator
- Light detected by photodetector
- E.g. $PbWO_4$

($X_0 \approx 0.9$ cm)



95% lead

Calorimetry – Sampling



Cloud chamber with lead absorbers

- In sampling calorimeters the functions of particle absorption and active signal readout are separated. This allows optimal choice of absorber materials and a certain freedom in signal treatment.
- Heterogeneous calorimeters are mostly built as sandwich counters, sheets of heavy-material absorber (e.g. lead, iron, uranium) alternating with layers of active material (e.g. liquid or solid scintillators, or proportional counters).
- Only the fraction of the shower energy absorbed in the active material is measured.
- Hadron calorimeters, needing considerable depth and width to create and absorb the shower, are necessarily of the sampling calorimeter type (see next slide).

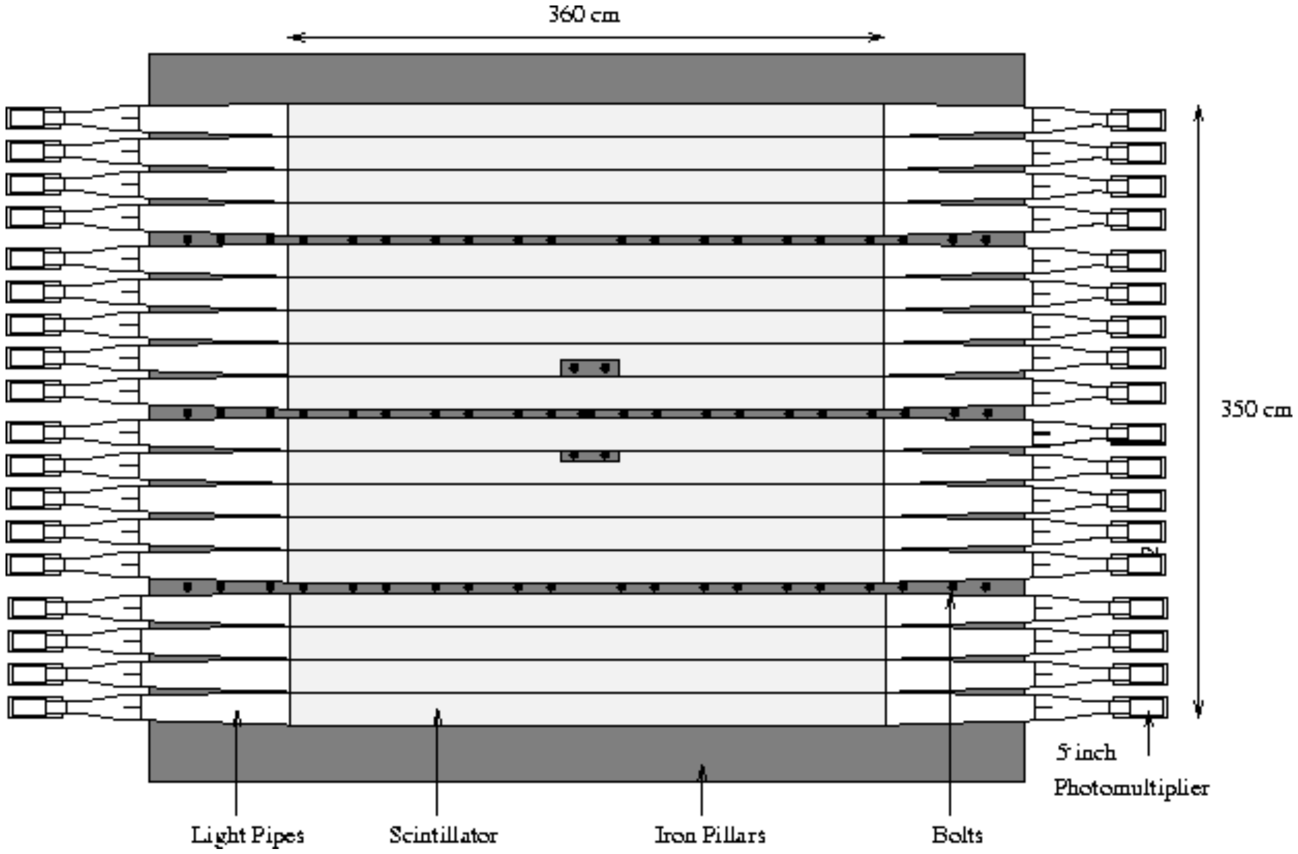
Hadronic Showers

- Nuclear interaction length >> radiation length

$$\lambda \approx 35\,\mathrm{g.cm}^{-2} A^{1/3}$$

e.g. Lead: X_0 = 0.56 cm, λ = 17 cm

- Hadron showers wider, deeper, less well understood
- Need much larger calorimeter to contain hadron shower
  - Always sampling
  - Dense metals still good as absorbers
  - Mechanical/economic considerations often important
  - Uranium, steel, brass…

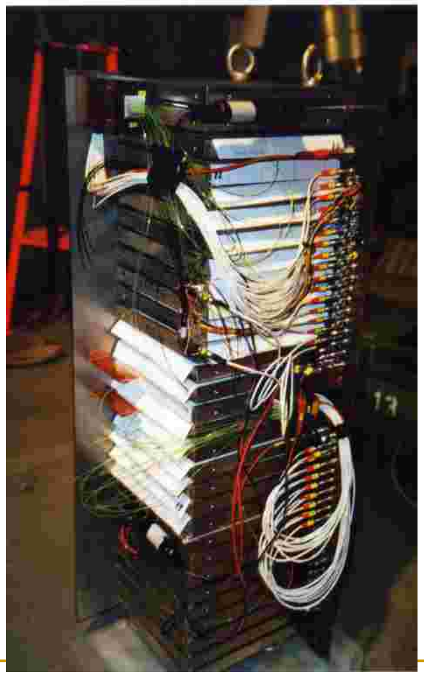


Hadronic Calorimeter from NOMAD experiment

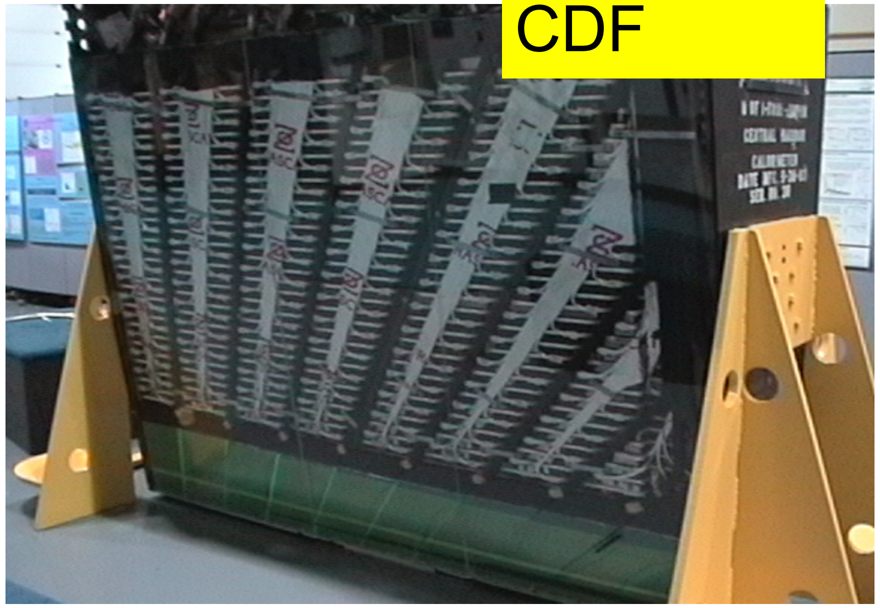
Hadron Calorimeter

Purpose: Identify and measure energy of all hadrons

- Need ~ 10 λ
  - 2 m of lead
- Both charged and neutral
- Will see some energy from muons
- Sampling
  - *Heavy, structural metal absorber*
  - *Scintillator, MWPC detector*



Hadronic Calorimeter



CDF

CMS Barrel Calorimeter

Alternating layers of steel and readout

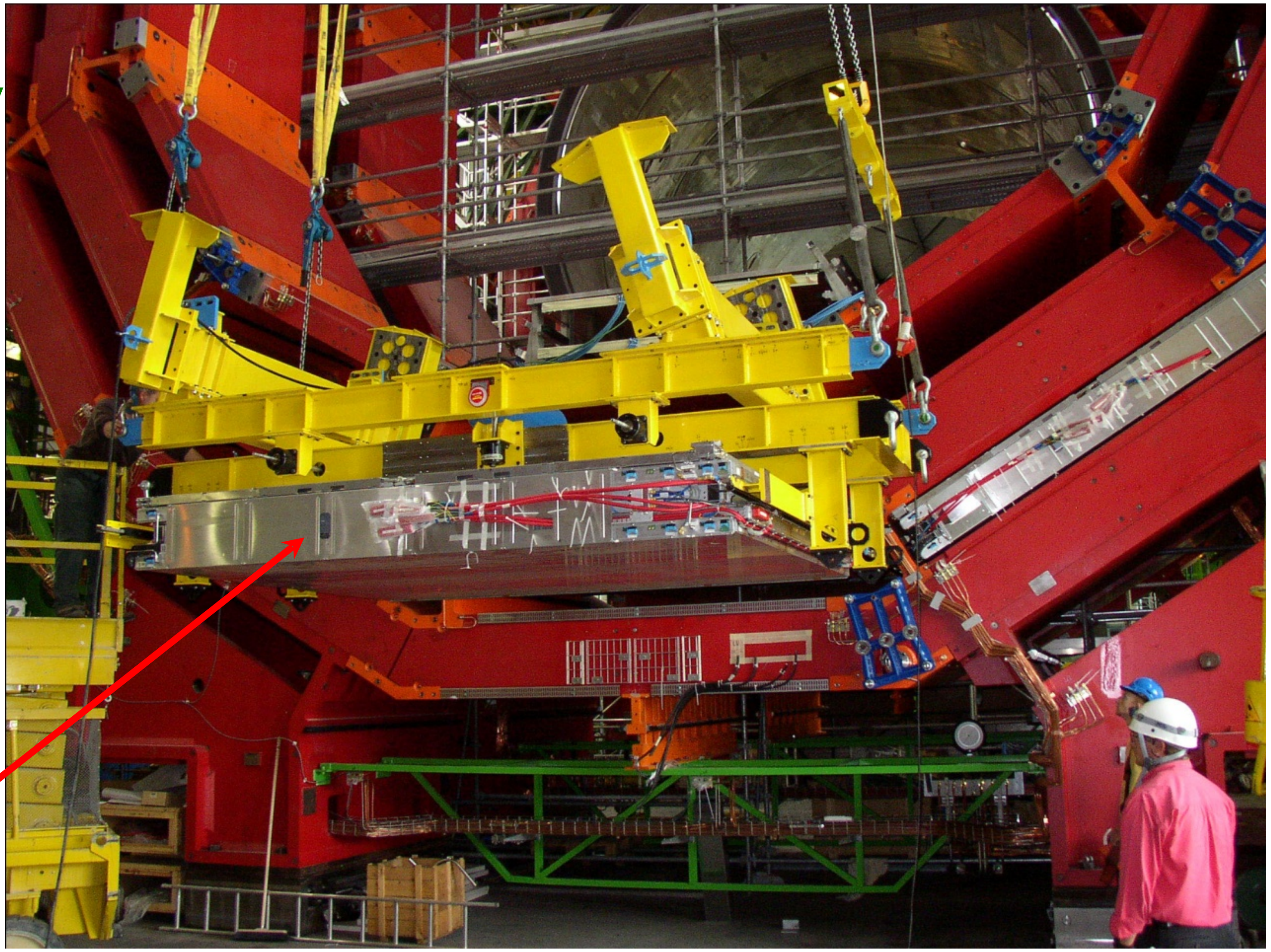
CMS Endcap Calorimeter

Muon Detectors

Purpose: Identify muons

CMS

- Muons go where other particles cannot reach:
  - No nuclear interactions
  - Critical energies >> 100 GeV
    - Always a MIP
  - Stable (τ = 2.2 μs)



A shielded detector can identify muons

"shielding" is often calorimeters or the magnet iron return yoke

Scintillator, MWPC, drift chambers…

Particle ID

Purpose: Distinguish different charged "stable" particles

- Muon, pion, kaon, proton
- Measured momentum and energy: $m^2 = E^2 - p^2$
  - Difficult at high energy $E \sim p$
- Different dE/dx in tracking detectors
  - Only for low energy β^{-2} region, no good for MIPs

Measure time-of-flight, gives β

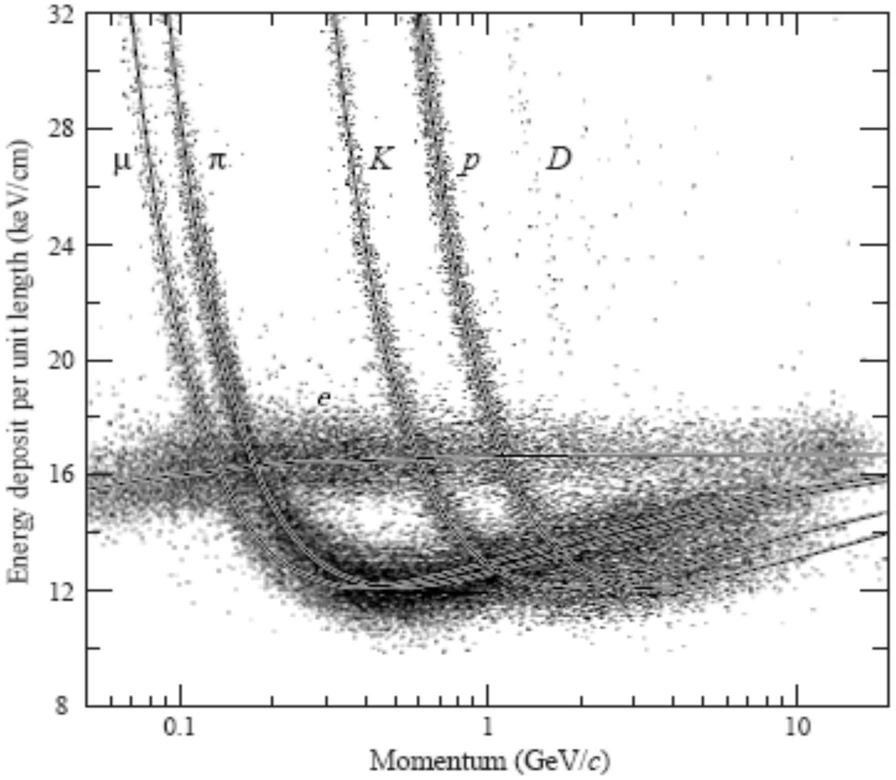
Fast scintillator

Measure β directly

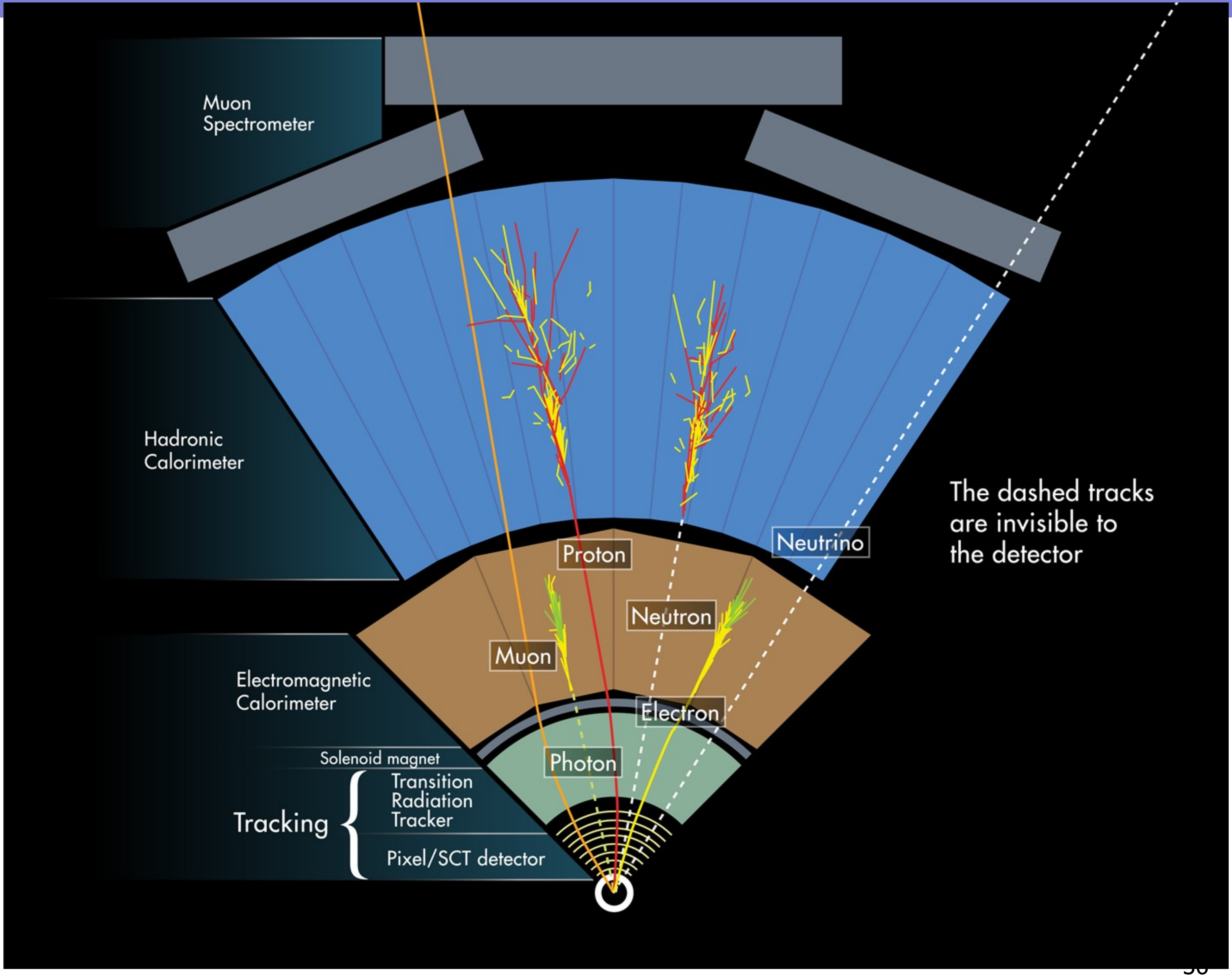
Cerenkov radiation

Measure γ directly

Transition radiation



Modern Detectors



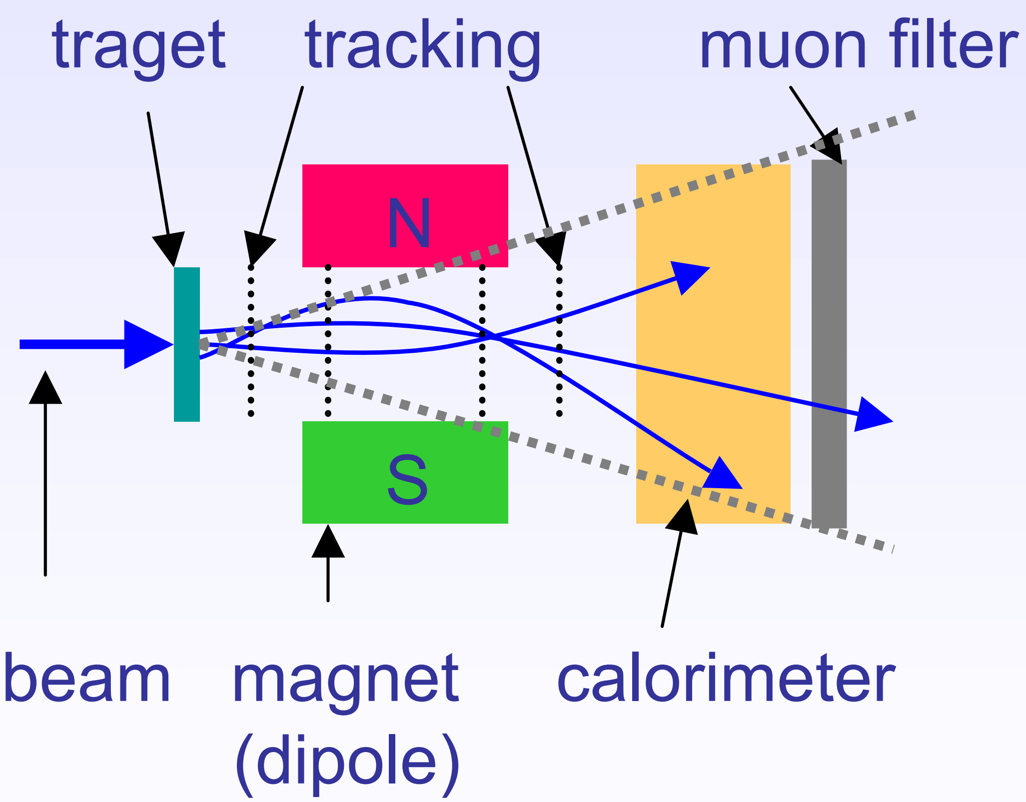
The dashed tracks are invisible to the detector

Detector Systems

Geometrical concepts

Fixed target geometry

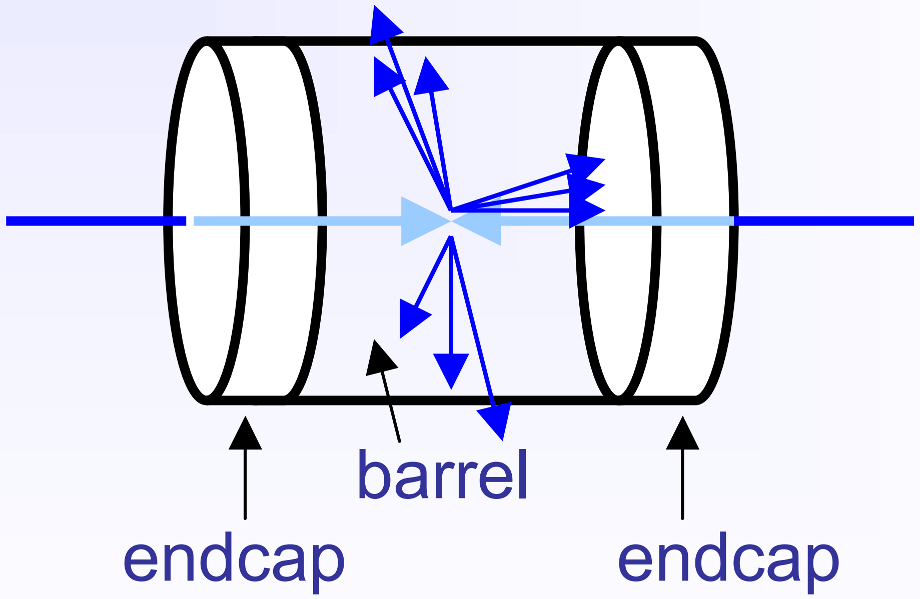
"Magnet spectrometer"



LHCb

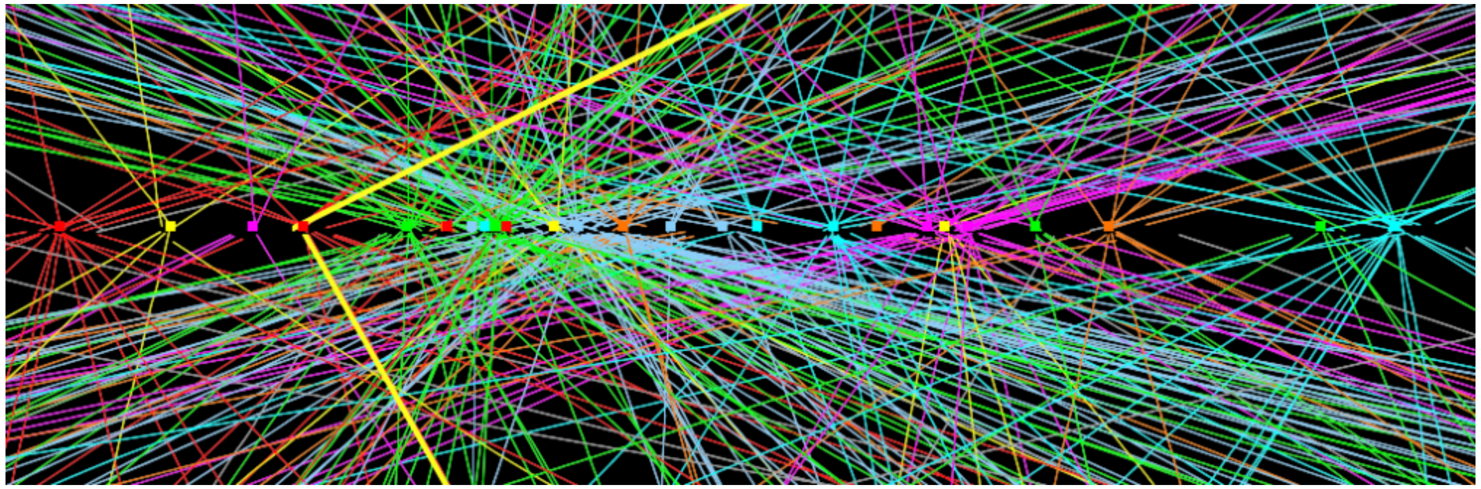
Collider Geometry

"4π multi purpose detector"

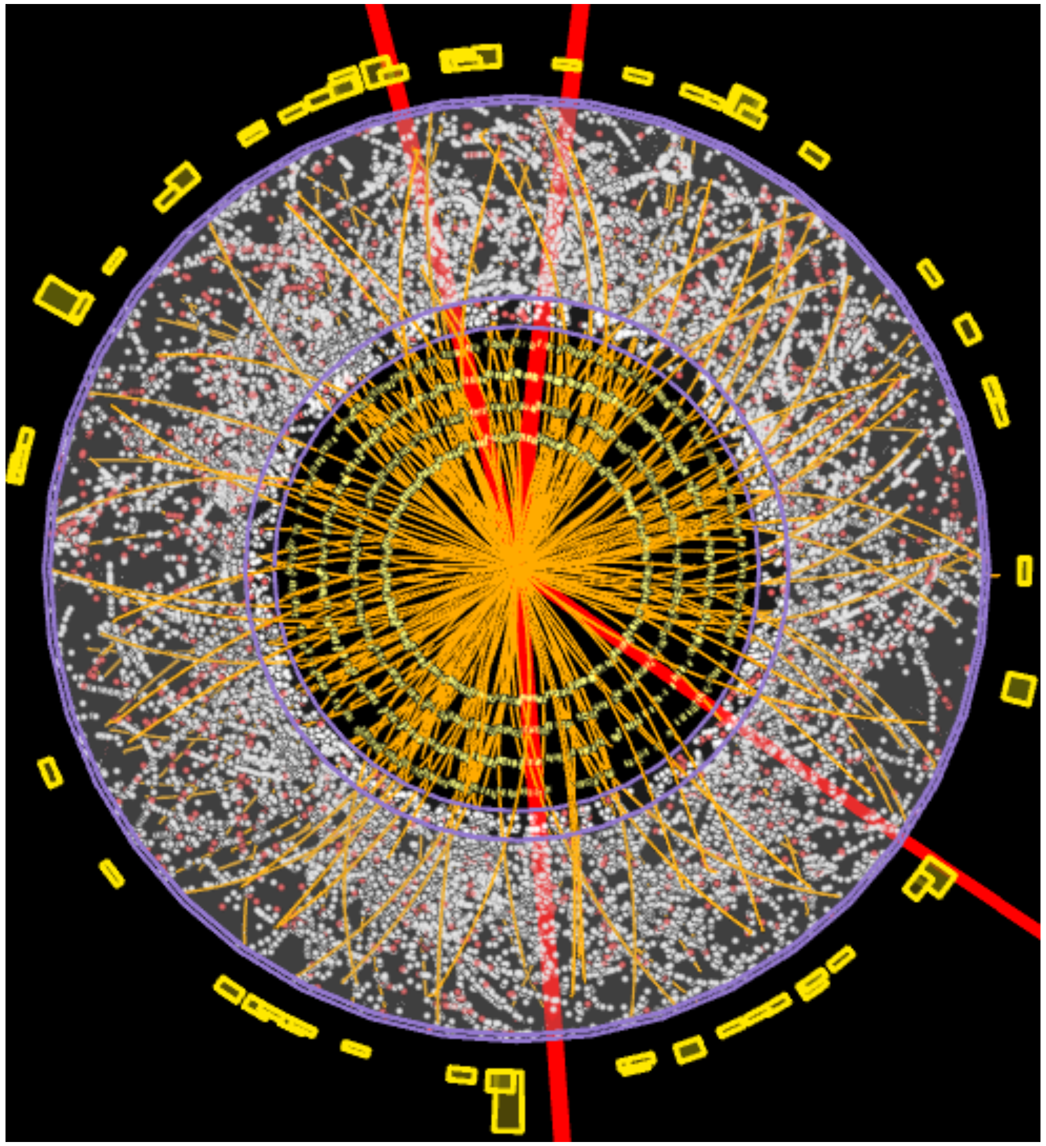


ALICE, ATLAS, CMS
LEP Experiments
Tevatron Experiments

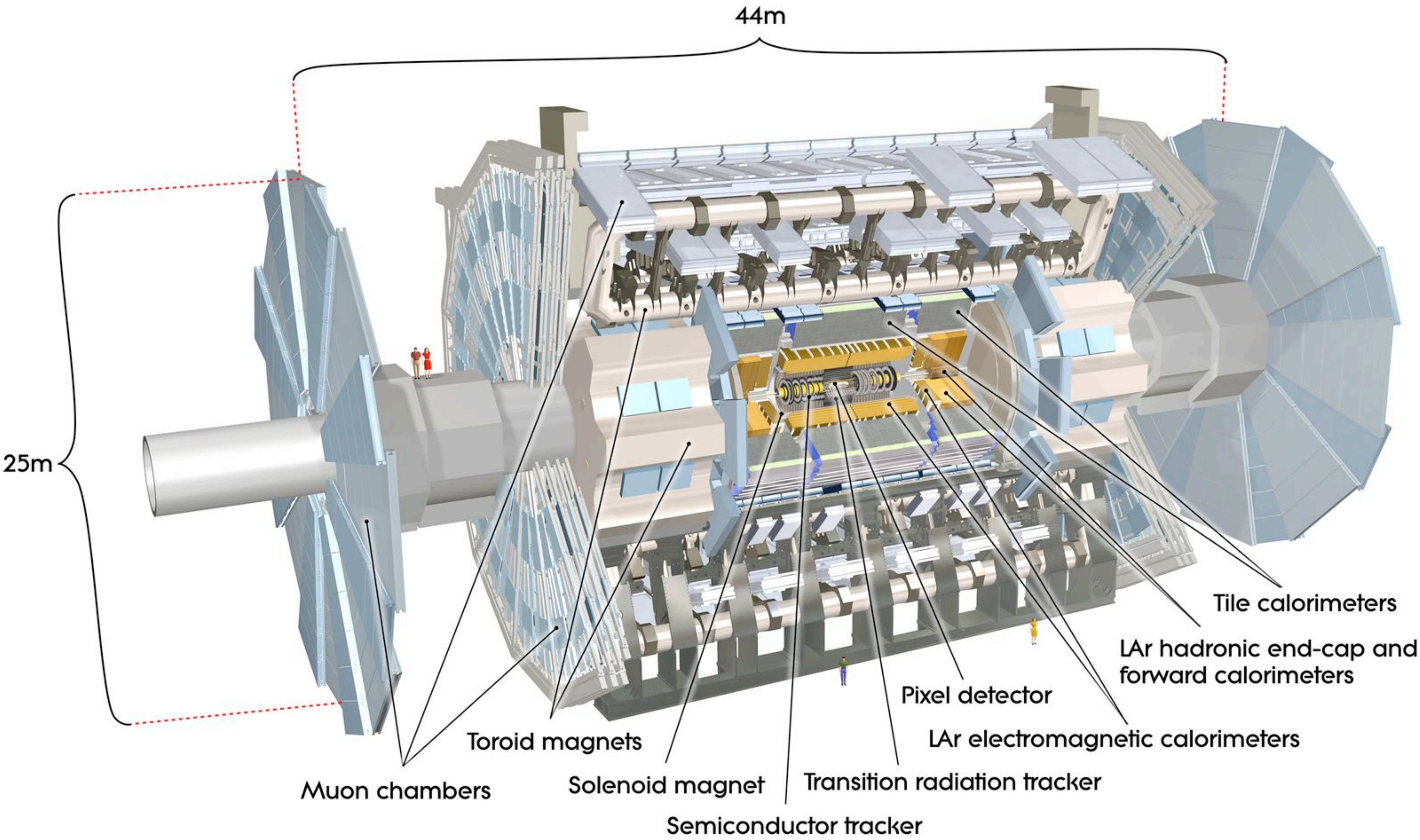
Requirements and Constraints



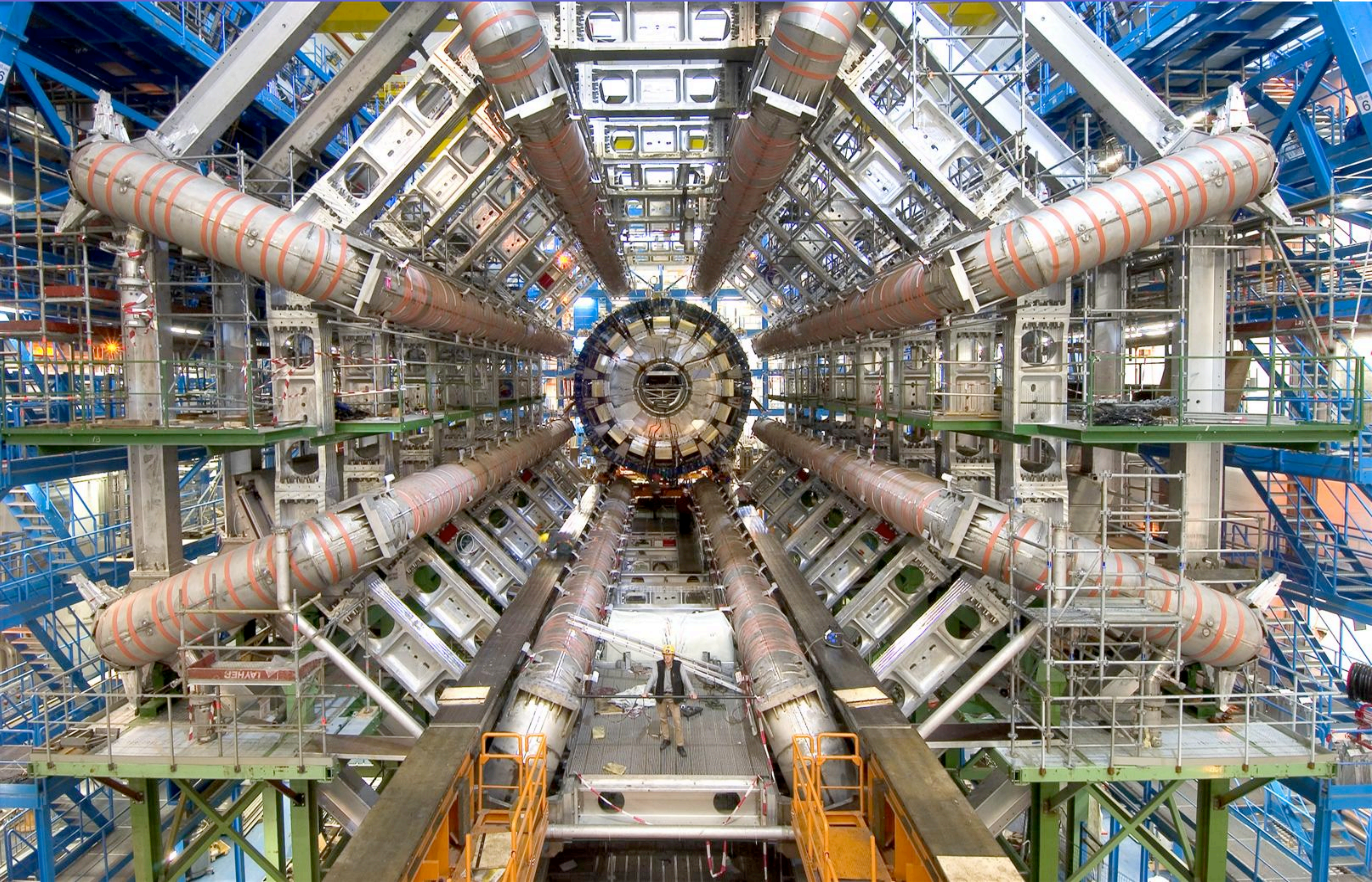
- Physics!
- Accelerator constraints
  - Fast readout
    - High frequency collision rate
  - Fine segmentation
    - High particle multiplicity in hadron colliders
    - Several interaction per bunch crossing
  - Radiation tolerance, long life time
    - High flux, damage to detectors electronics
  - Closest point to collision
    - Beam pipe size
  - Overall design
    - Magnetic field
    - Other detector systems
      - minimize material, particle distortions



ATLAS Detector



Couple Hundred Megapixel Camera



Литература

Акимов, Юрий Константинович.

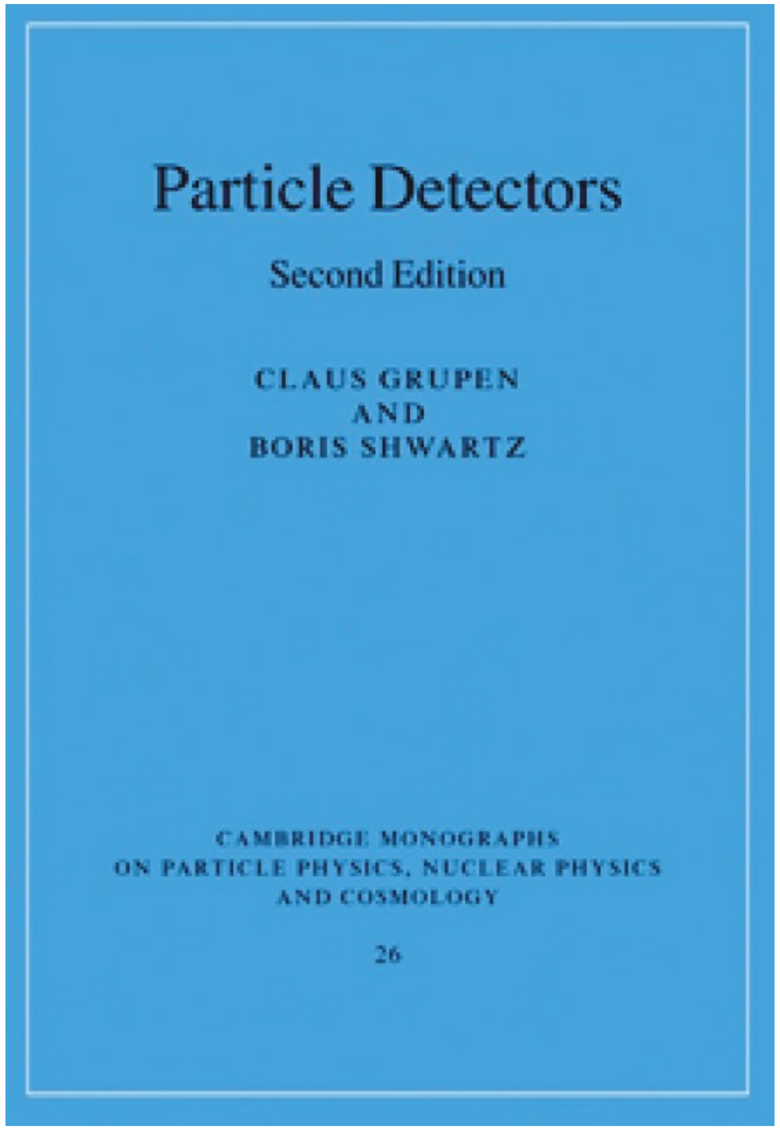
Полупроводниковые детекторы ядерных излучений / Ю. К. Акимов. - Дубна : ОИЯИ, 2009. - 277 с. : ил. ; 22 см. - (Объединенный институт ядерных исследований ; 2008-122). - Посвящ. 60-летию Лаб. ядер. проблем ОИЯИ. - Библиогр.: с. 253-277. - ISBN 978-5-9530-0213-4

Акимов, Юрий Константинович.

Газовые детекторы ядерных излучений / Ю. К. Акимов. - Дубна : ОИЯИ, 2011. - 243 с. : ил. ; 22 см. - (Объединенный институт ядерных исследований ; 2010-118). - Библиогр.: с. 219-243. - ISBN 978-5-9530-0272-1 : Посвящ. 55-летию Объед. ин-та ядер. исслед.

Акимов, Юрий Константинович.

Фотонные методы регистрации излучений / Ю. К. Акимов ; Объед. ин-т ядер. исслед. - Изд. 2-е, испр. и доп. - Дубна : ОИЯИ, 2014. - 323 с. : ил. - Библиогр.: с. 281-323. - ISBN 978-5-9530-0380-3



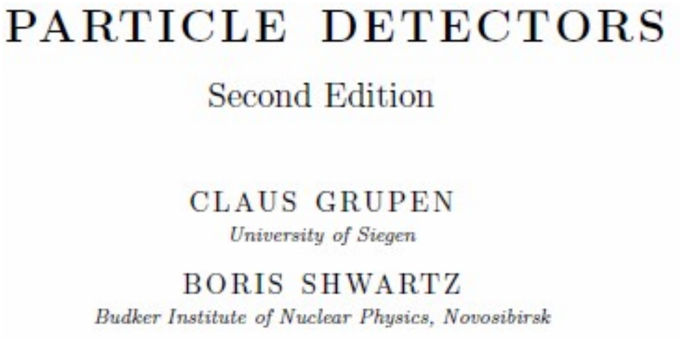
Particle Detectors

Second Edition

CLAUS GRUPEN
AND
BORIS SHWARTZ

CAMBRIDGE MONOGRAPHS
ON PARTICLE PHYSICS, NUCLEAR PHYSICS
AND COSMOLOGY

26



PARTICLE DETECTORS

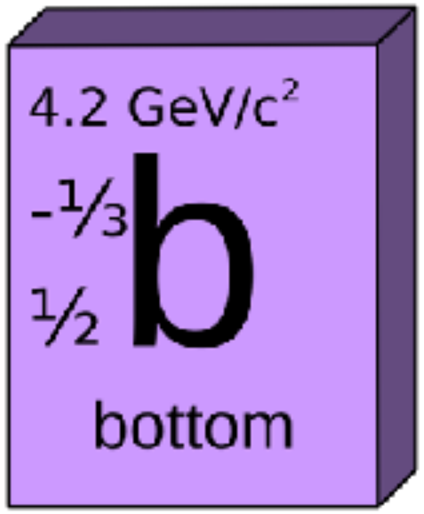
Second Edition

CLAUS GRUPEN
University of Siegen

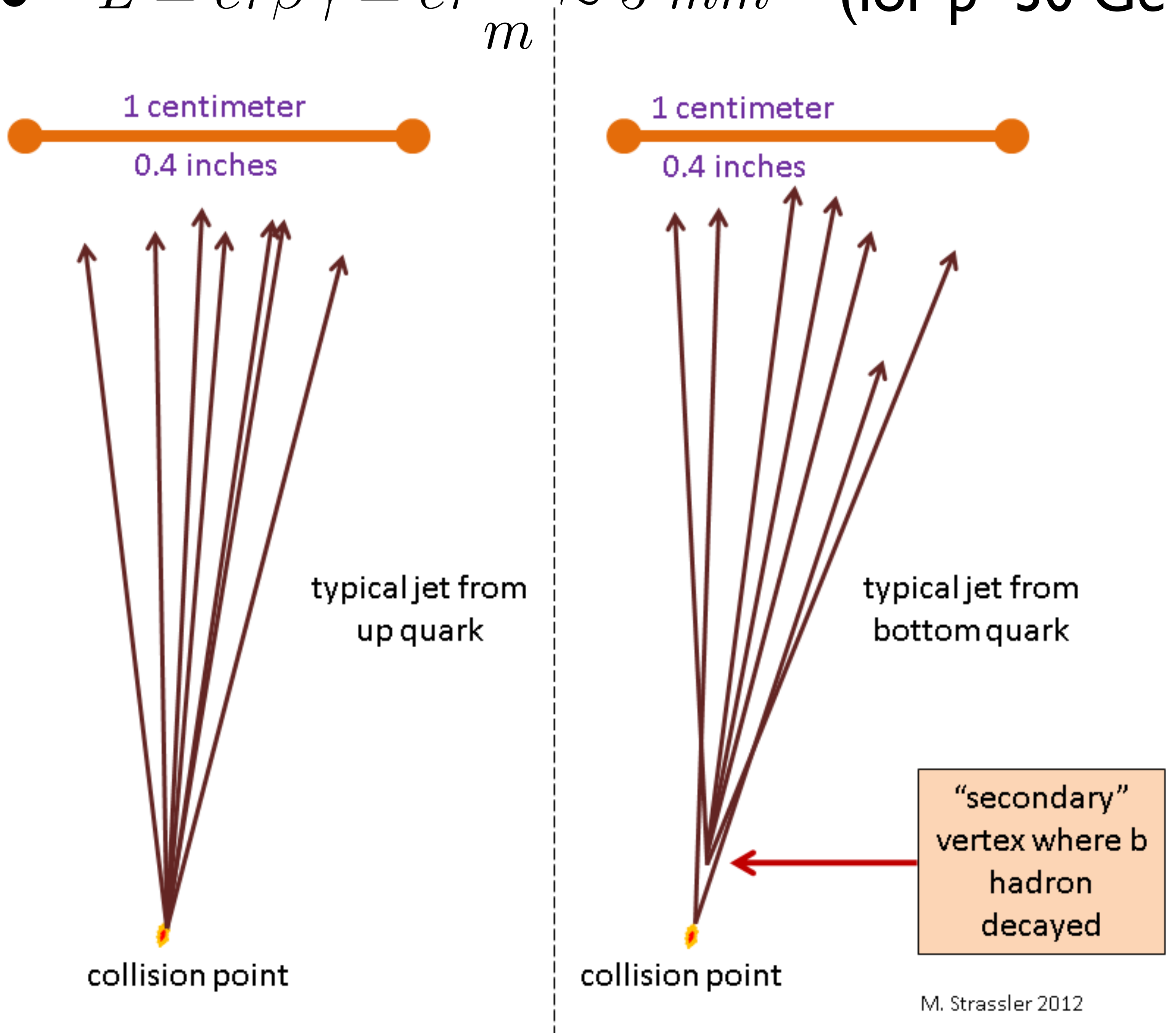
BORIS SHWARTZ
Budker Institute of Nuclear Physics, Novosibirsk

Backup

How to identify b-jets

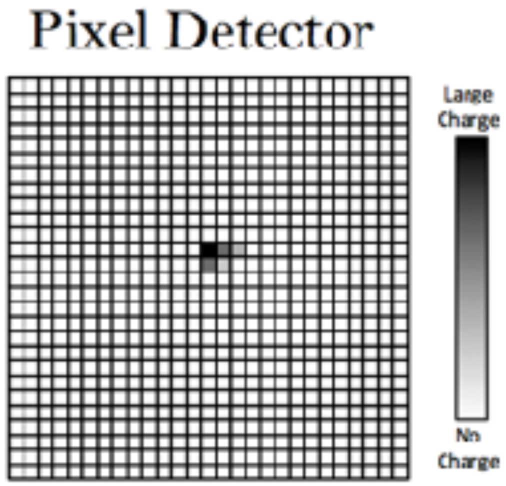


- b-quark fragments into a jet including a b-hadron
- The b-hadron flies O(10^{-12}s) before decaying
- $L = c\tau\beta\gamma = c\tau\frac{p}{m} \approx 5\ mm$ (for p~30 GeV)

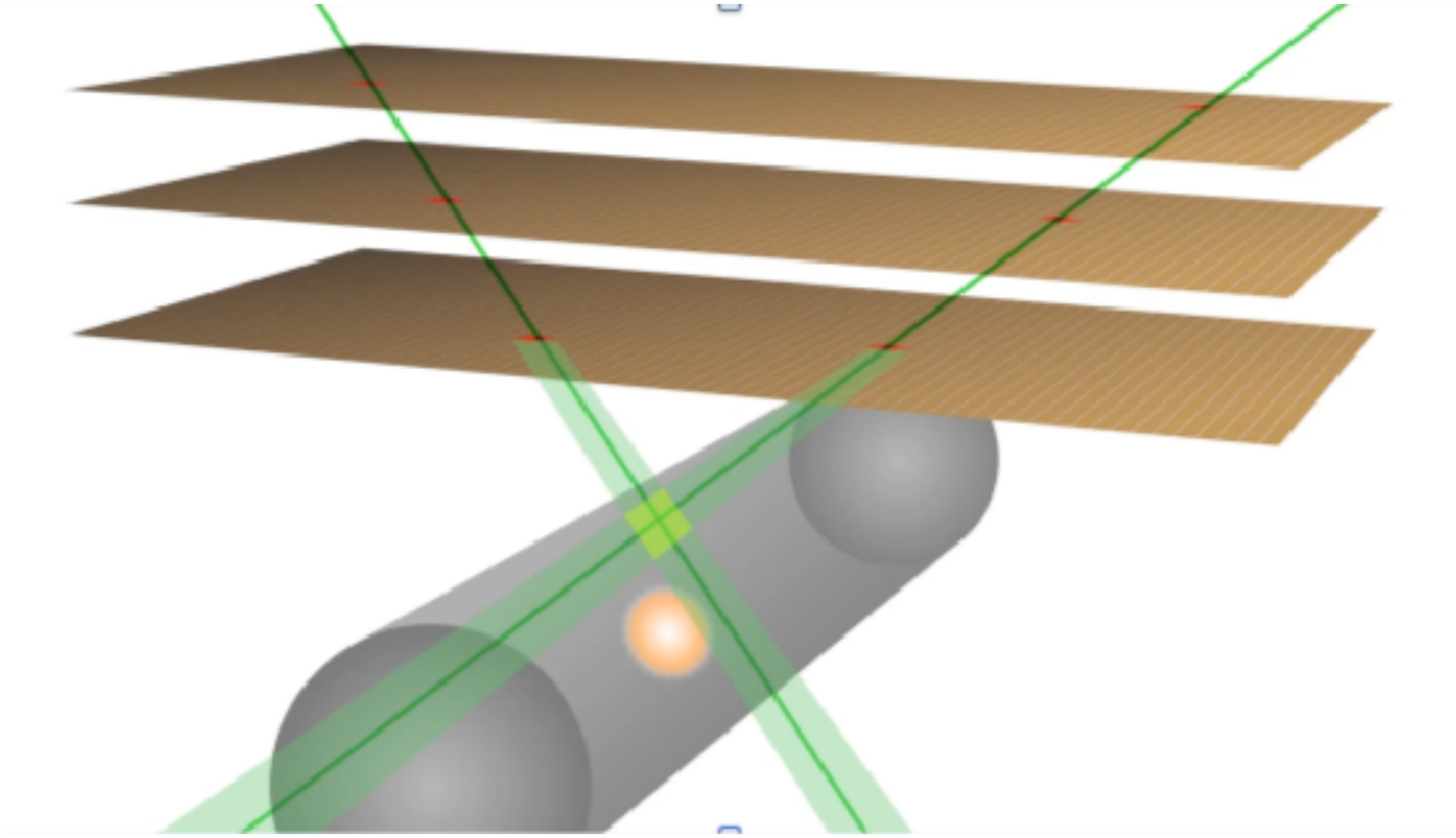


M. Strassler 2012

Basic b-jet signature

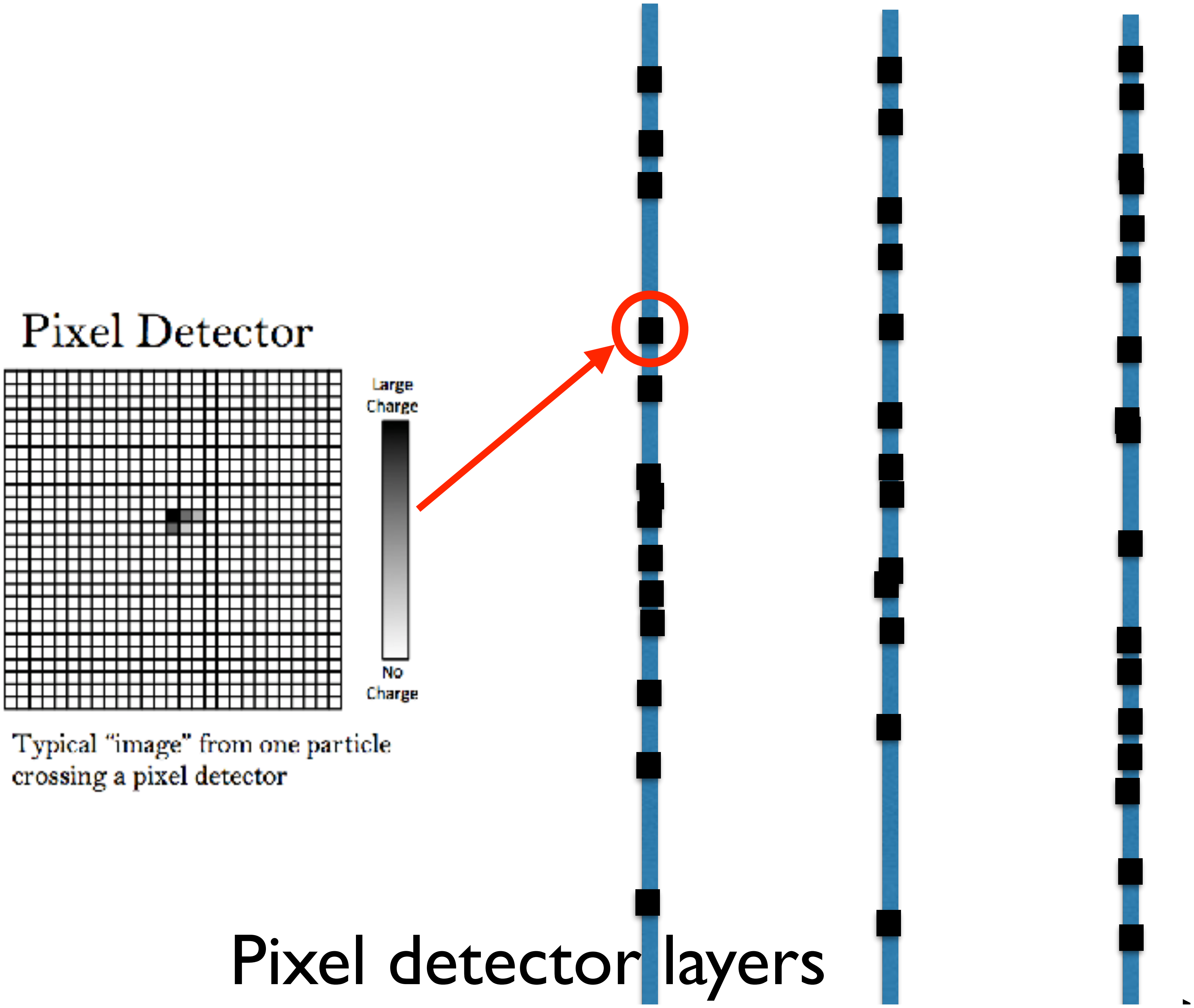


Typical "image" from one particle crossing a pixel detector



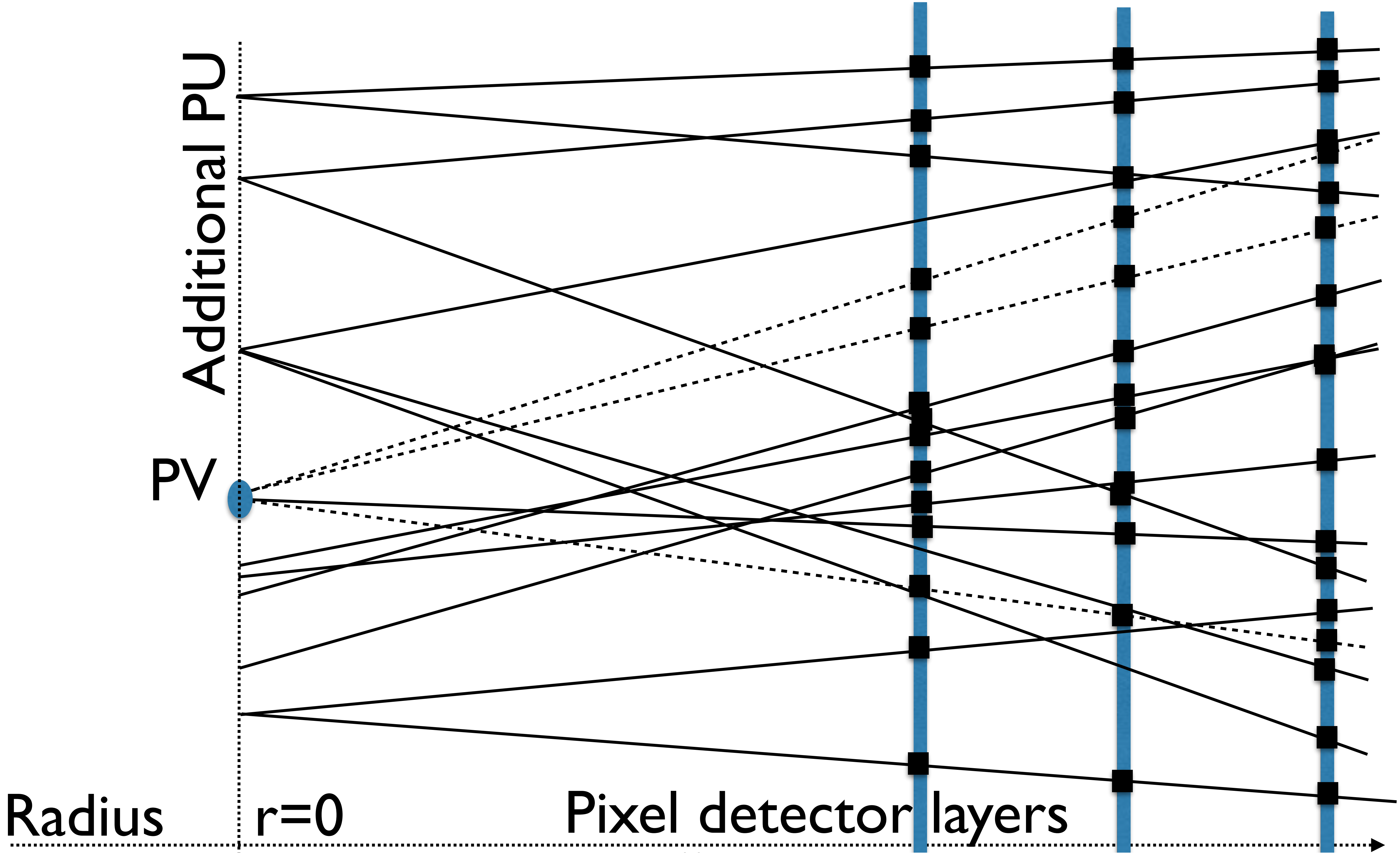
- Reconstruct clusters in pixel detector
- Reconstruct particle trajectories
- Check if tracks are compatible with originating from the primary interaction vertex
- Need to properly take extrapolation errors into account

Start from clusters…

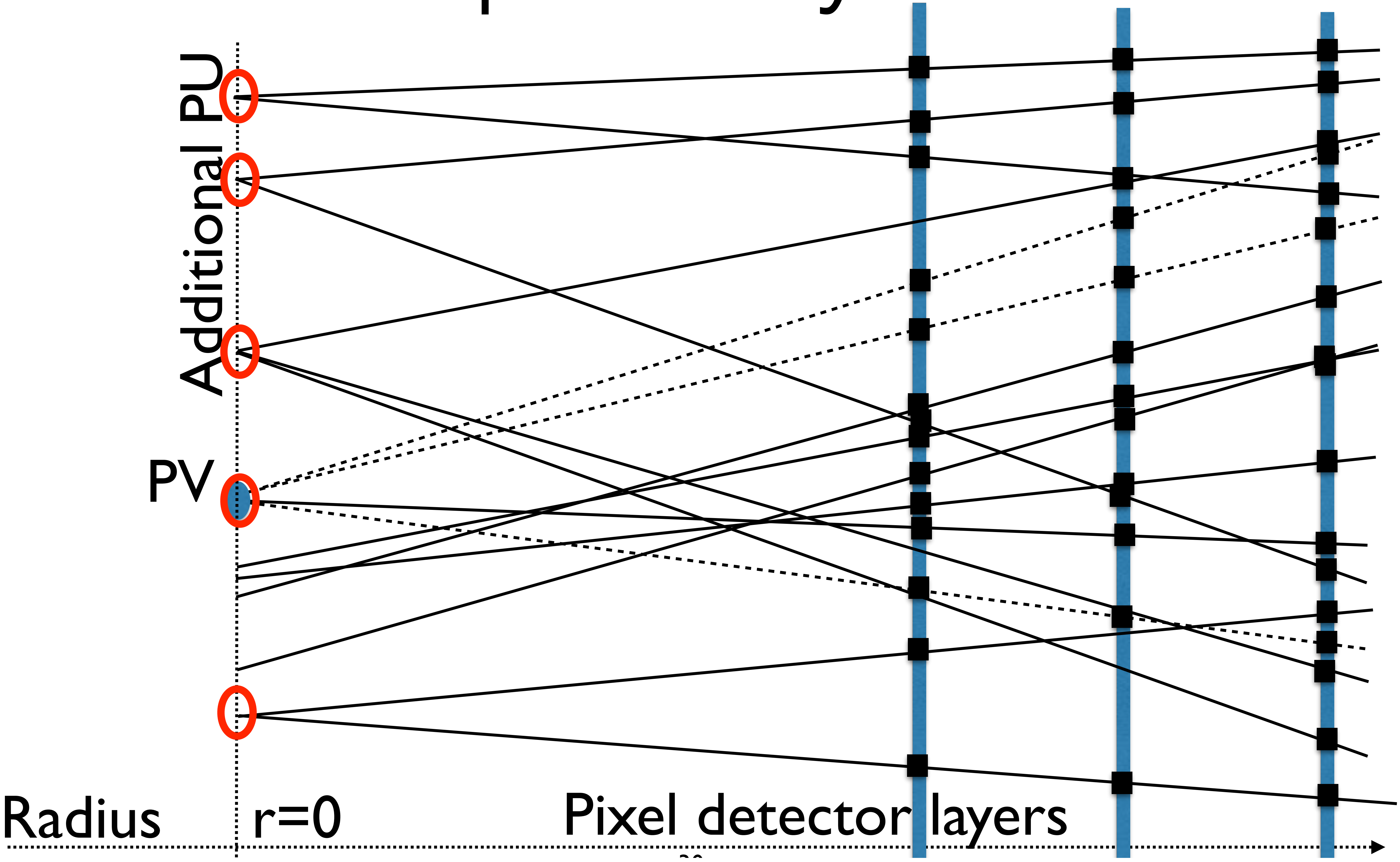


Typical "image" from one particle crossing a pixel detector

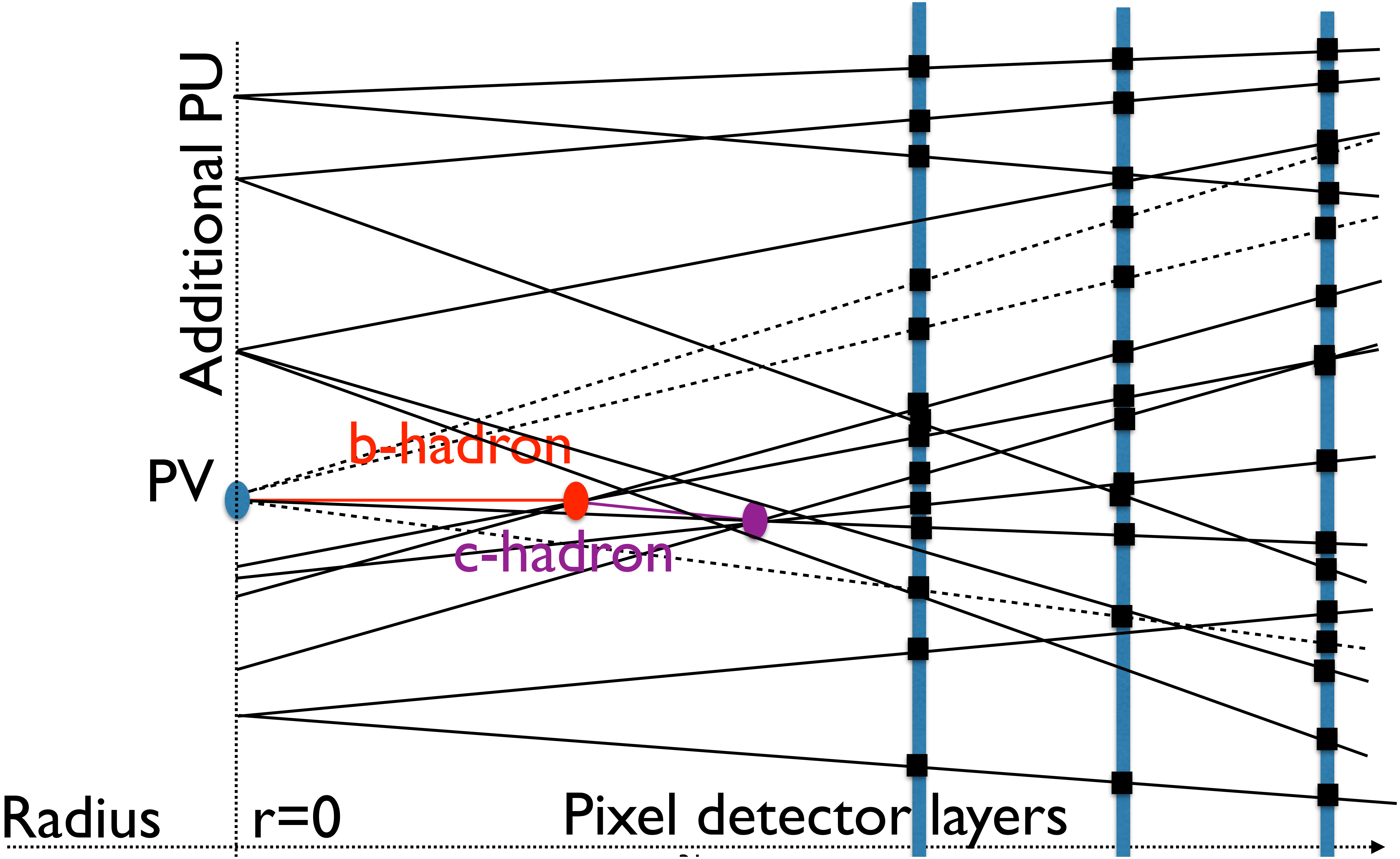
Then reconstruct tracks…



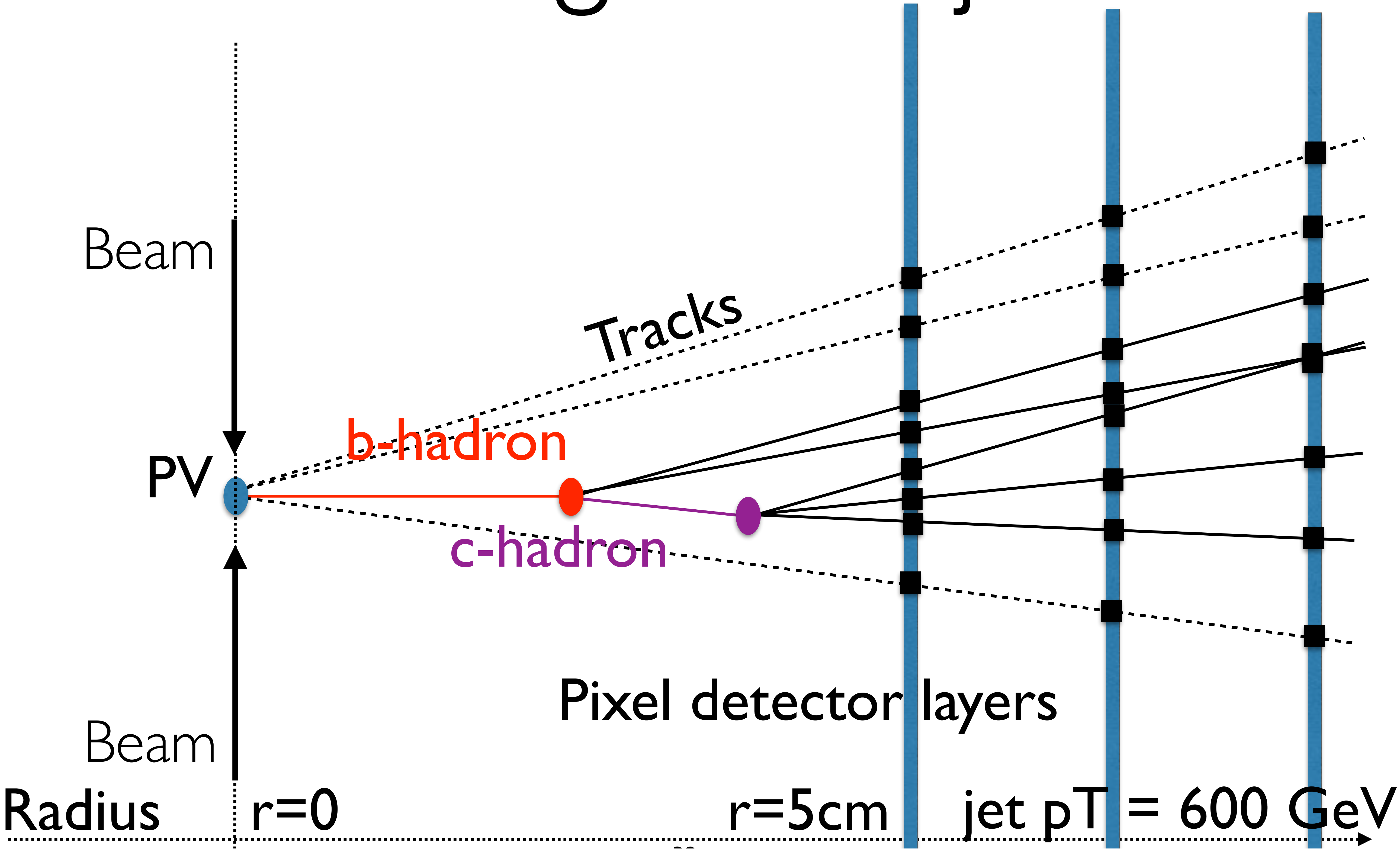
… and primary vertices



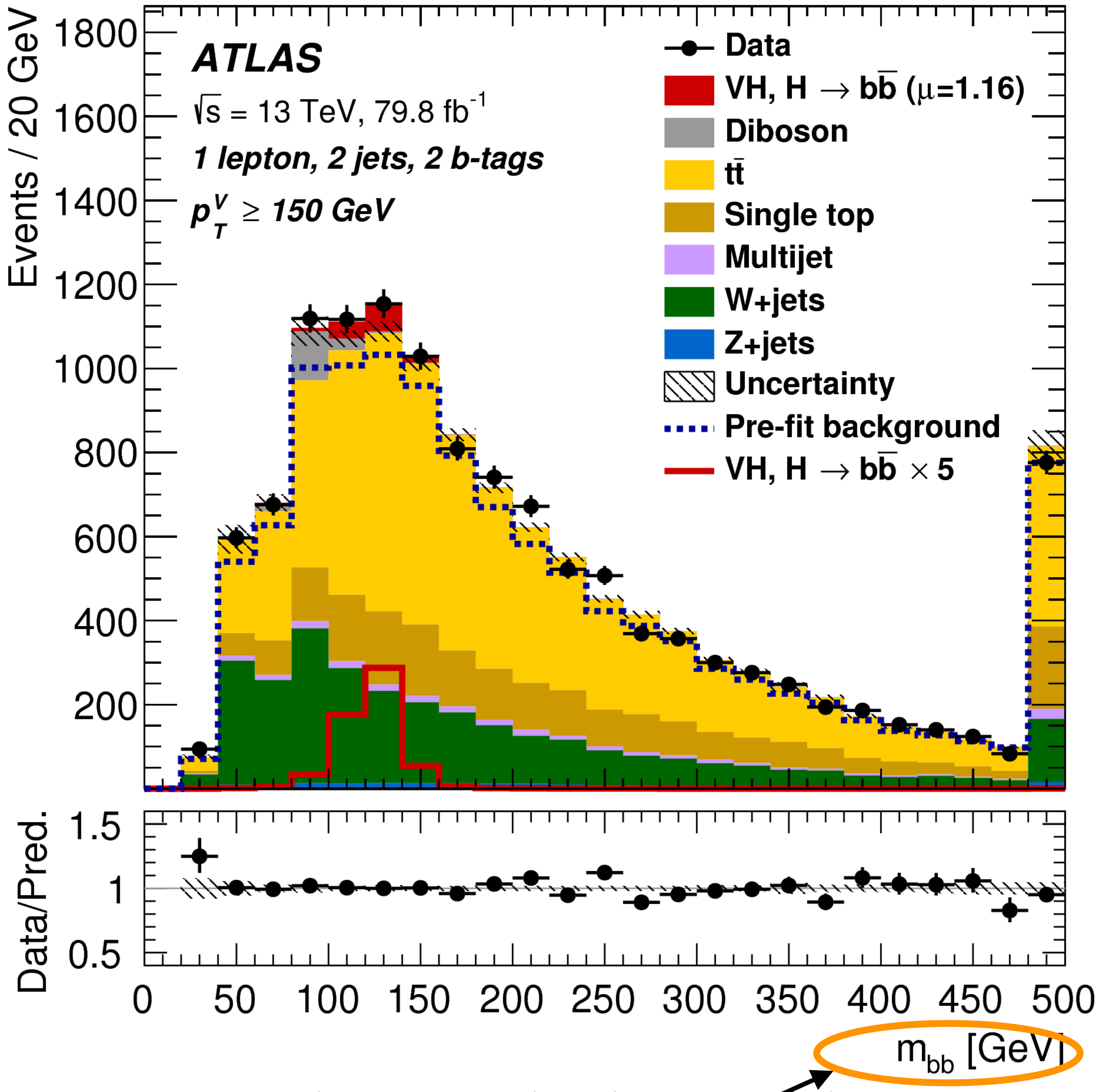
Finally identify secondary and tertiary vertices..



Isolating the b-jet…

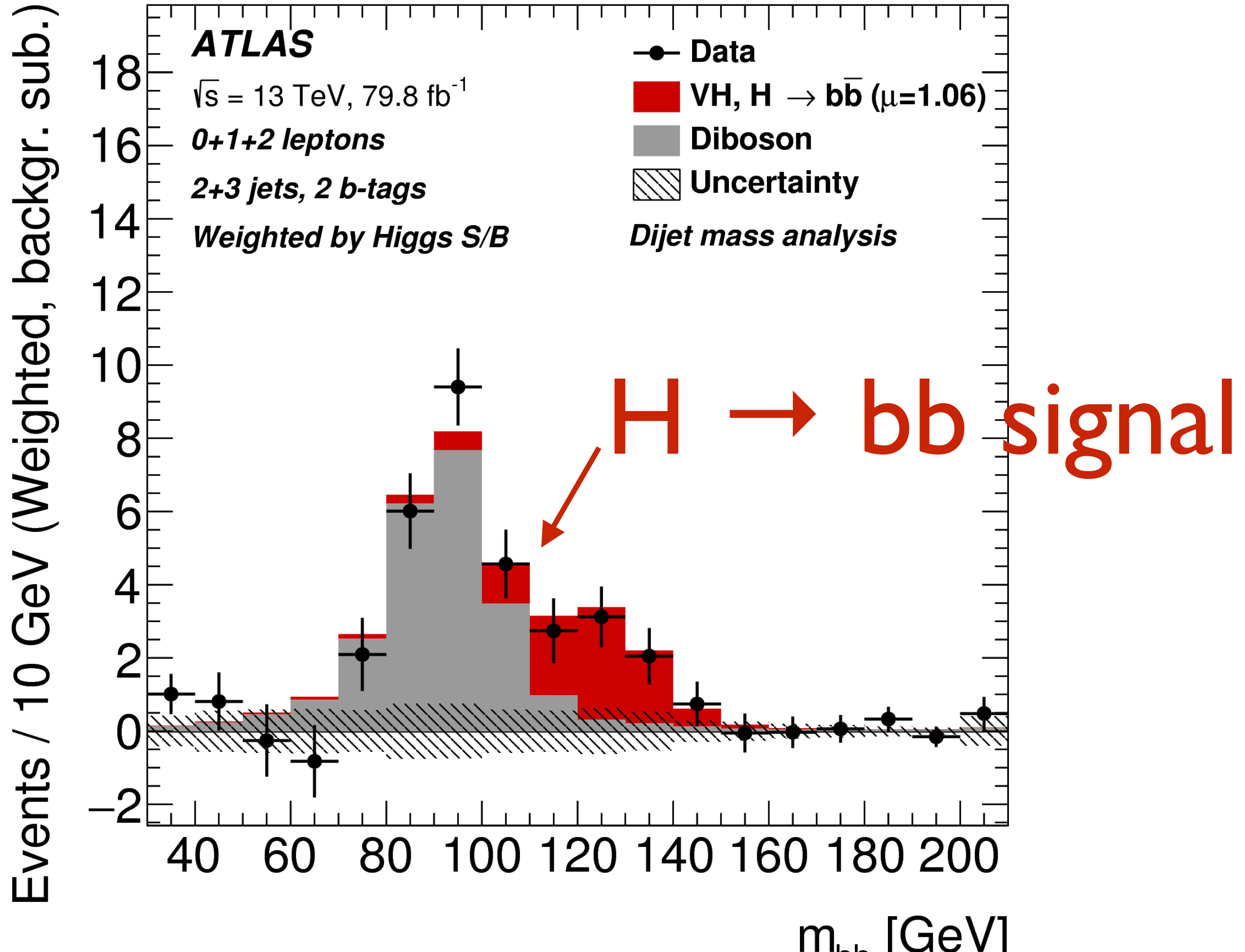


Looking for a peak...



$$m_{b\bar{b}} = (p_b + p_{\bar{b}})^{\mu}(p_b + p_{\bar{b}})_{\mu}$$

- After applying b-tagging to the two jets, backgrounds without b-jets nearly removed
- Use statistical techniques (maximum likelihood fit) to extract number of signal events
- Precisely predicting the background to subtract is the biggest challenge!



H → bb signal

- ATLAS observation of H → bb!