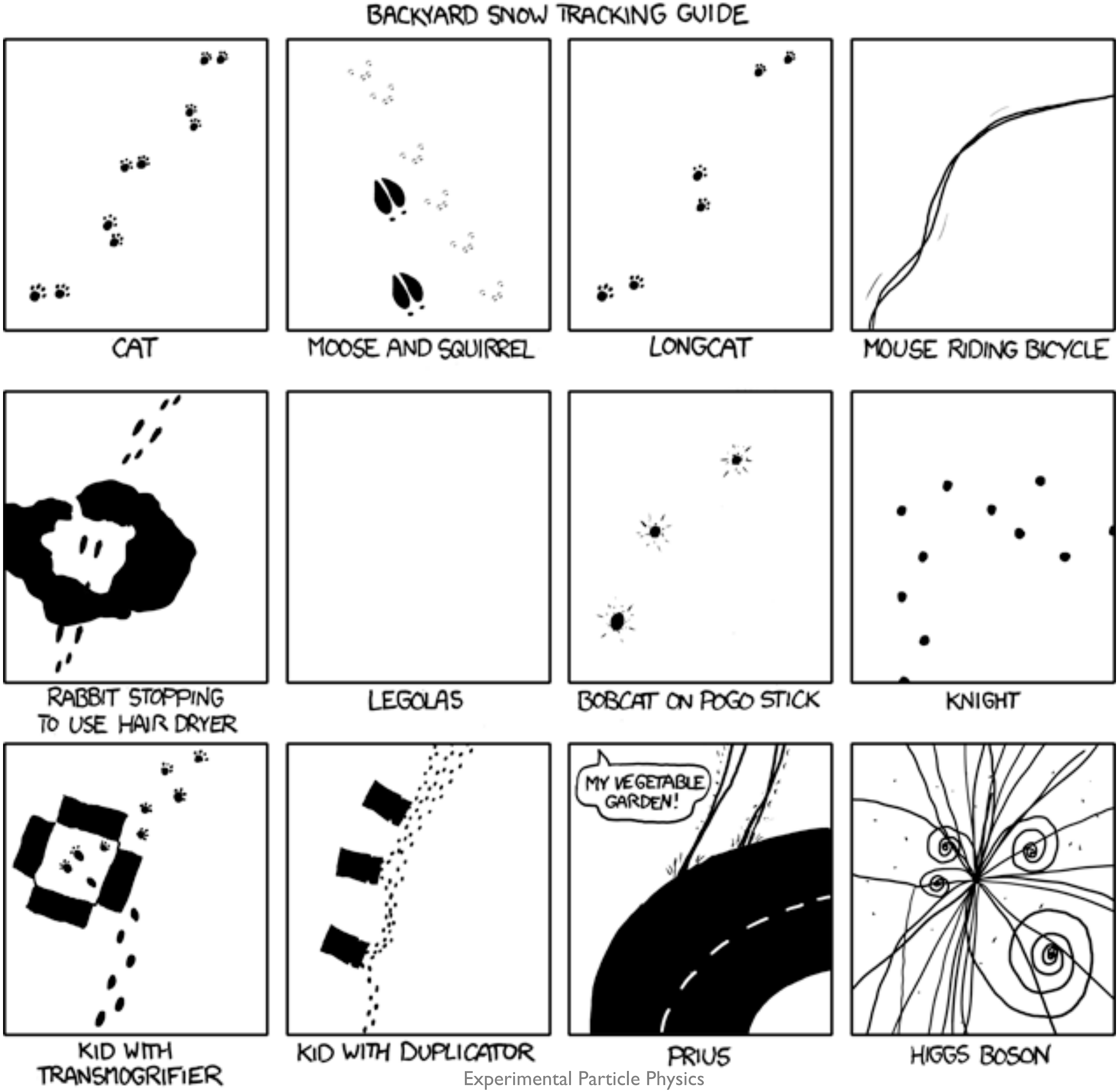
Experimental particle physics

esipap
European School of Instrumentation in Particle & Astroparticle Physics

4. systems used to identify and measure particle properties

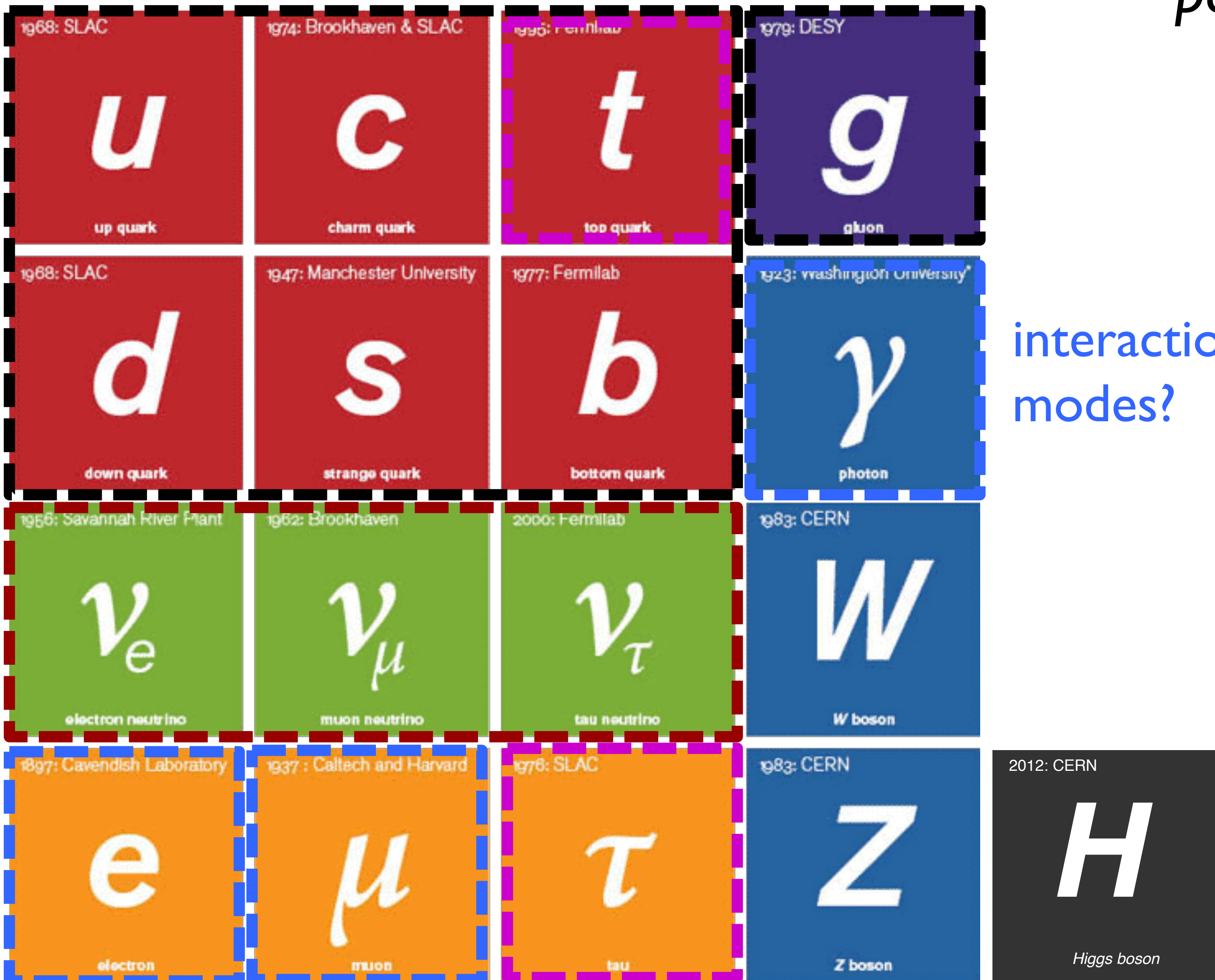


http://xkcd.com/702/

What do we want to measure?

… "stable" particles!

decays?



jets

interaction modes?

invisible

in particle detectors at accelerators

interaction modes?

decays?

Interaction mode recap…

- electrically charged
- ionization (dE/dx)
- electromagnetic shower

- electrically charged
- ionization (dE/dx)
- can emit photons
  - ✓ electromagnetic shower induced by emitted photon

- electrically neutral
- pair production
  - ✓ E > 1 MeV
- electromagnetic shower

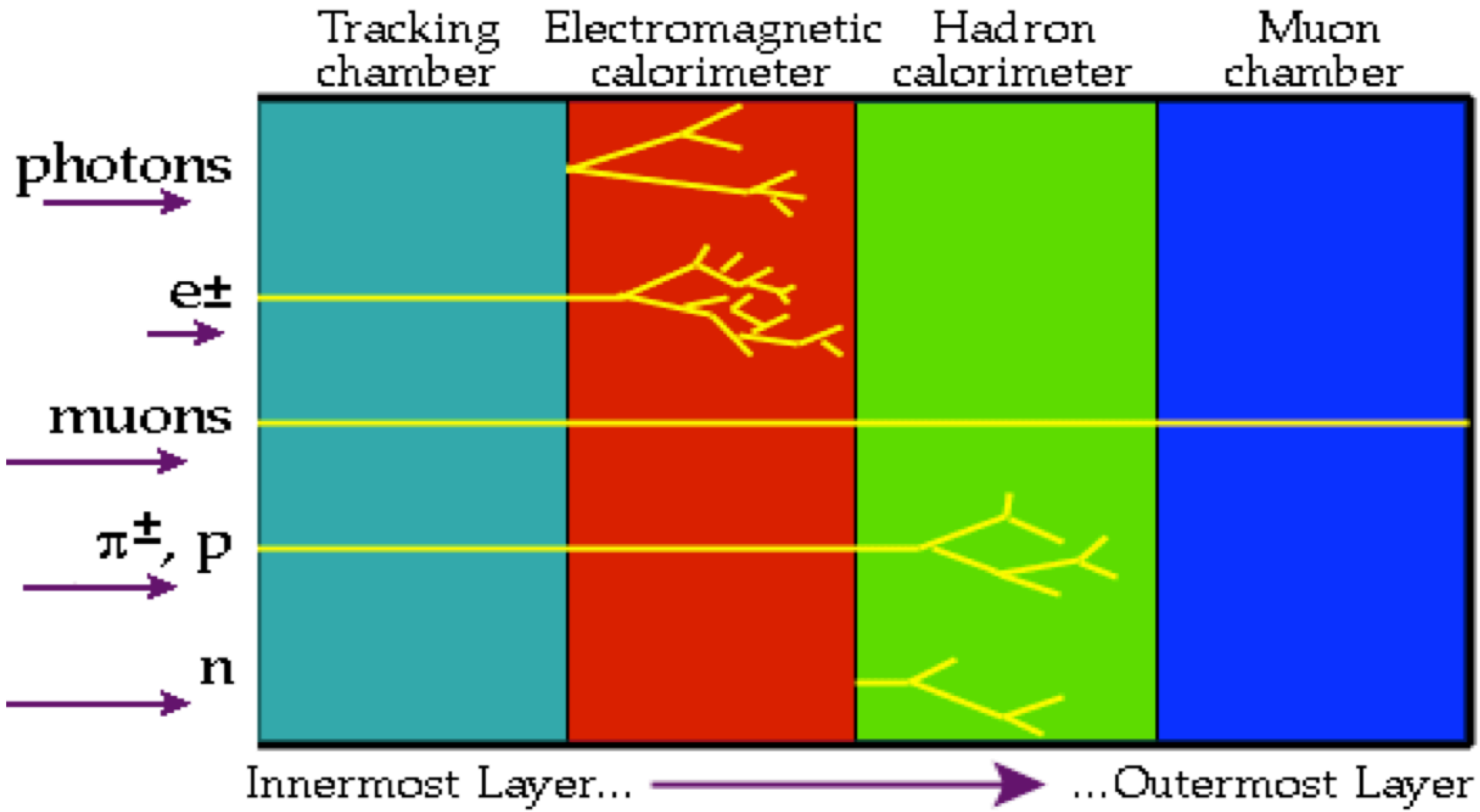
- produce hadron(s) jets via QCD hadronization process

What should a particle experiment do?

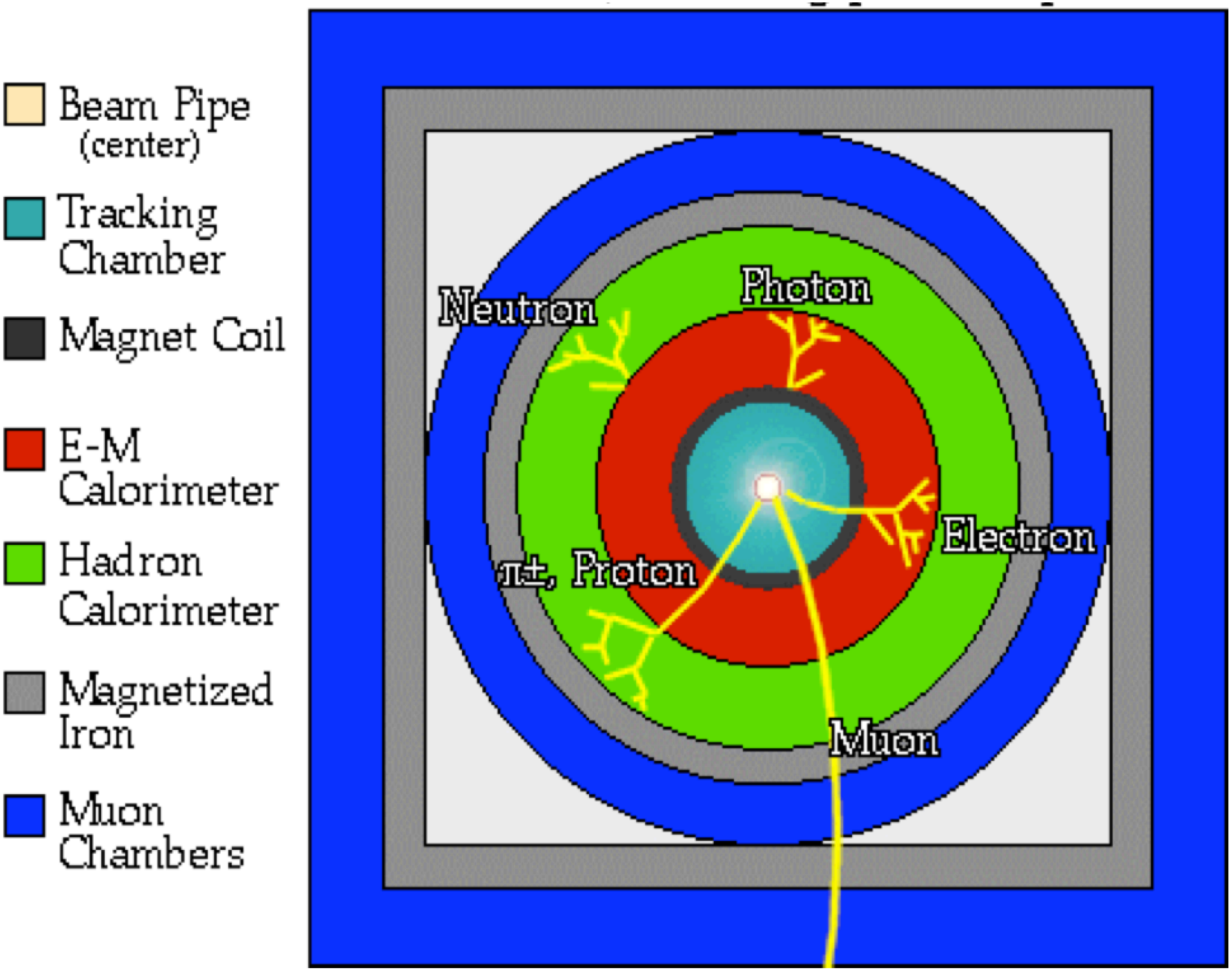
- Tracking
- Momentum and energy measurements
- Neutral particle detection
- Particle identification
- *Trigger*
- *Data acquisition*

Detector	Common uses
Scintillation counter	tracking, fast timing, triggering
Cerenkov counter	particle identification, triggering
Proportional chamber	tracking, triggering
Drift chamber	tracking, particle identification
Sampling calorimeters	neutral particle detection, triggering
Bubble chamber	vertex detector, tracking
Emulsion	high resolution vertex detection
Spark chamber	tracking
Streamer chamber	vertex detector, tracking
Transition radiation detector	high energy particle identification
Semiconductor detector	vertex detector
Flashtube hodoscope	tracking
Spark counter	high resolution timing

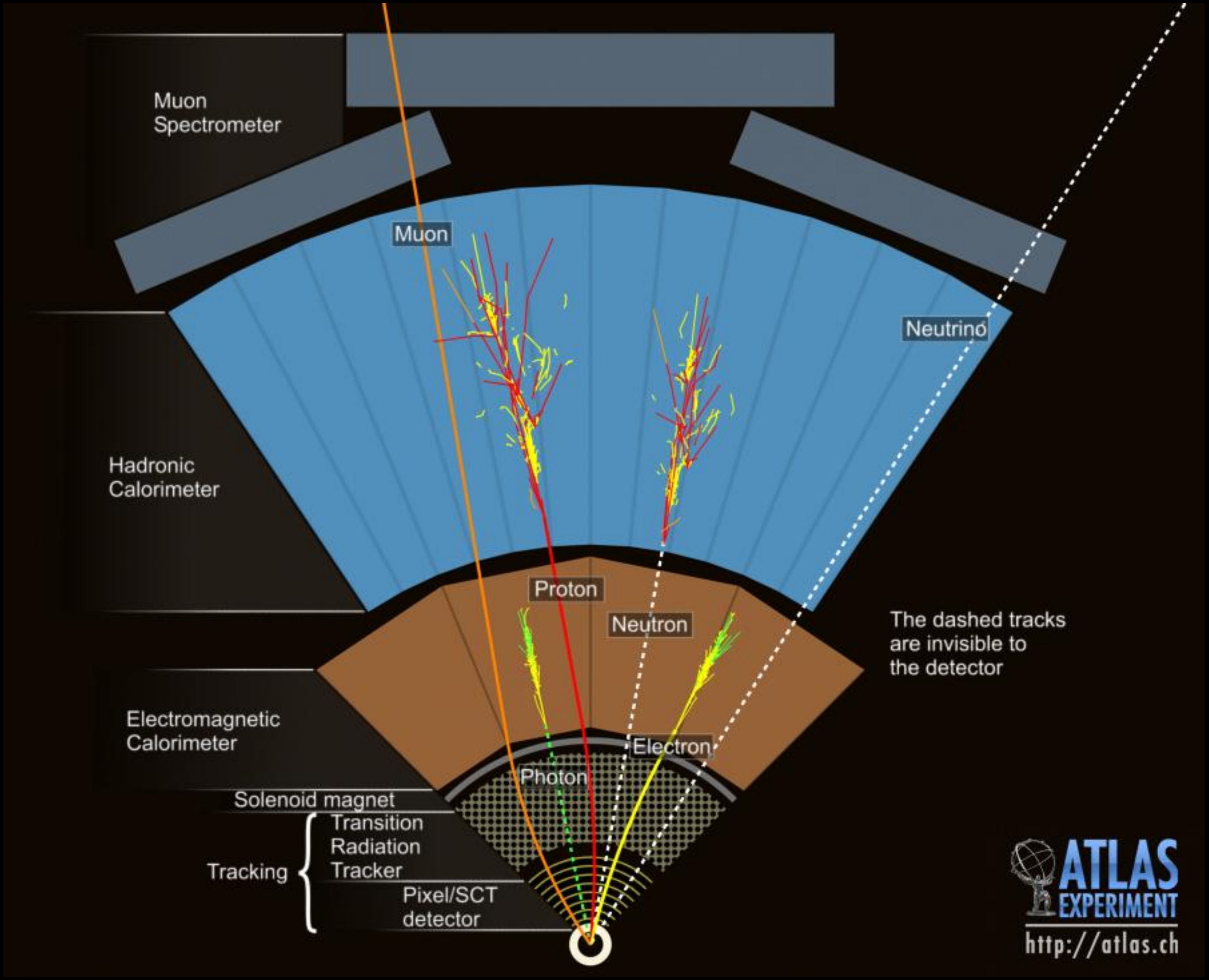
How do we "see" particles?



How do we "see" particles?

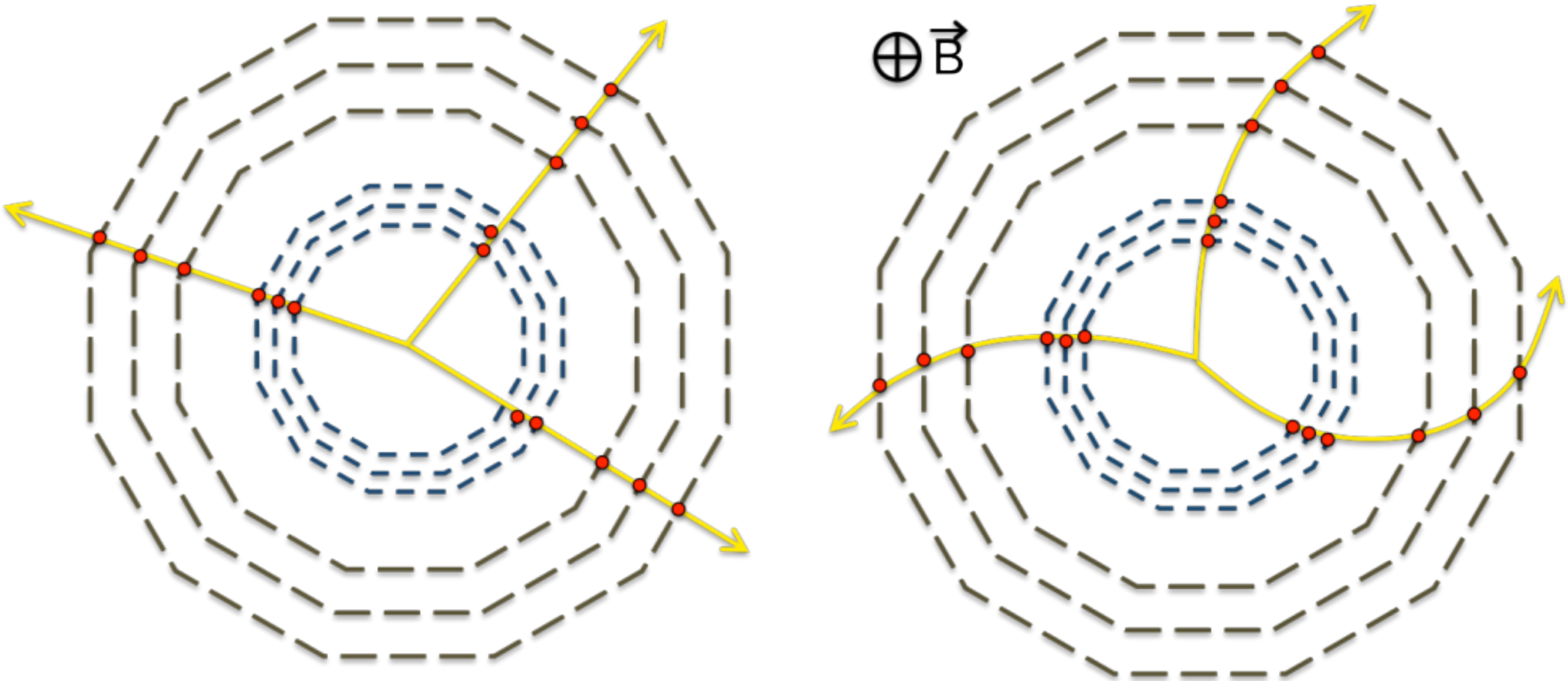


How do we "see" particles?



Magnetic spectrometer

- A system to measure (charged) particle momentum
- Tracking device + magnetic field



Magnetic spectrometer

Charged particle in magnetic field

$$\frac{d\vec{p}}{dt} = q\vec{\beta} \times \vec{B}$$

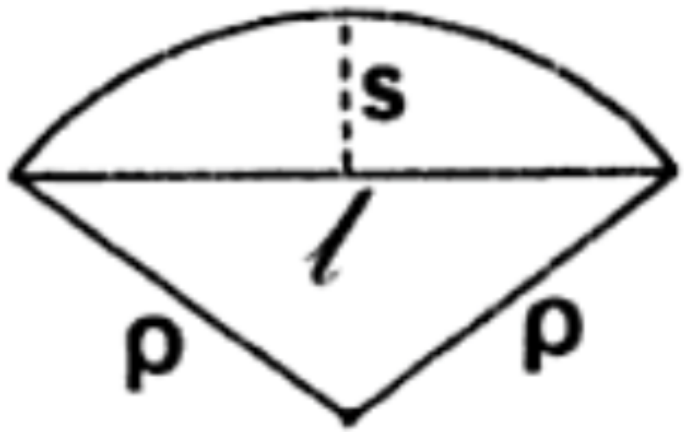
If the field is constant and we neglect presence of matter, momentum magnitude is constant with time, trajectory is helical

$$p[\mathrm{GeV}] = 0.3B[\mathrm{T}]\rho[\mathrm{m}]$$

Actual trajectory differ from exact helix because of:

- magnetic field inhomogeneity
- particle energy loss (ionization, multiple scattering)

Momentum measurement



s = sagitta

l = chord

ρ = radius

$$\underset{[\mathrm{m}]}{\rho} \simeq \frac{l^2}{8s} \qquad \underset{[\mathrm{GeV}]}{p} = 0.3\,\frac{\overset{[\mathrm{T}]\,[\mathrm{m}^2]}{Bl^2}}{\underset{[\mathrm{m}]}{8s}}$$

$$\left|\frac{\delta p}{p}\right| = \left|\frac{\delta s}{s}\right|$$

Momentum resolution due to measurement error

$$\left|\frac{\delta p}{p}\right| = \overbrace{A_N}^{\text{smaller for larger number of points}} \frac{\overbrace{\epsilon}^{\text{measurement error (RMS)}}}{\underbrace{L^2}_{\text{projected track length in magnetic field}}} \frac{p}{0.3B}$$

Momentum resolution gets worse for larger momenta

resolution is improved faster by increasing L then B

Momentum resolution

Momentum resolution due to measurement error

$$\left|\frac{\delta p}{p}\right| = \overbrace{A_N}^{\text{smaller for larger number of points}} \frac{\overbrace{\epsilon}^{\text{measurement error (RMS)}}}{\underbrace{L^2}_{\text{projected track length in magnetic field}}} \frac{p}{0.3B}$$

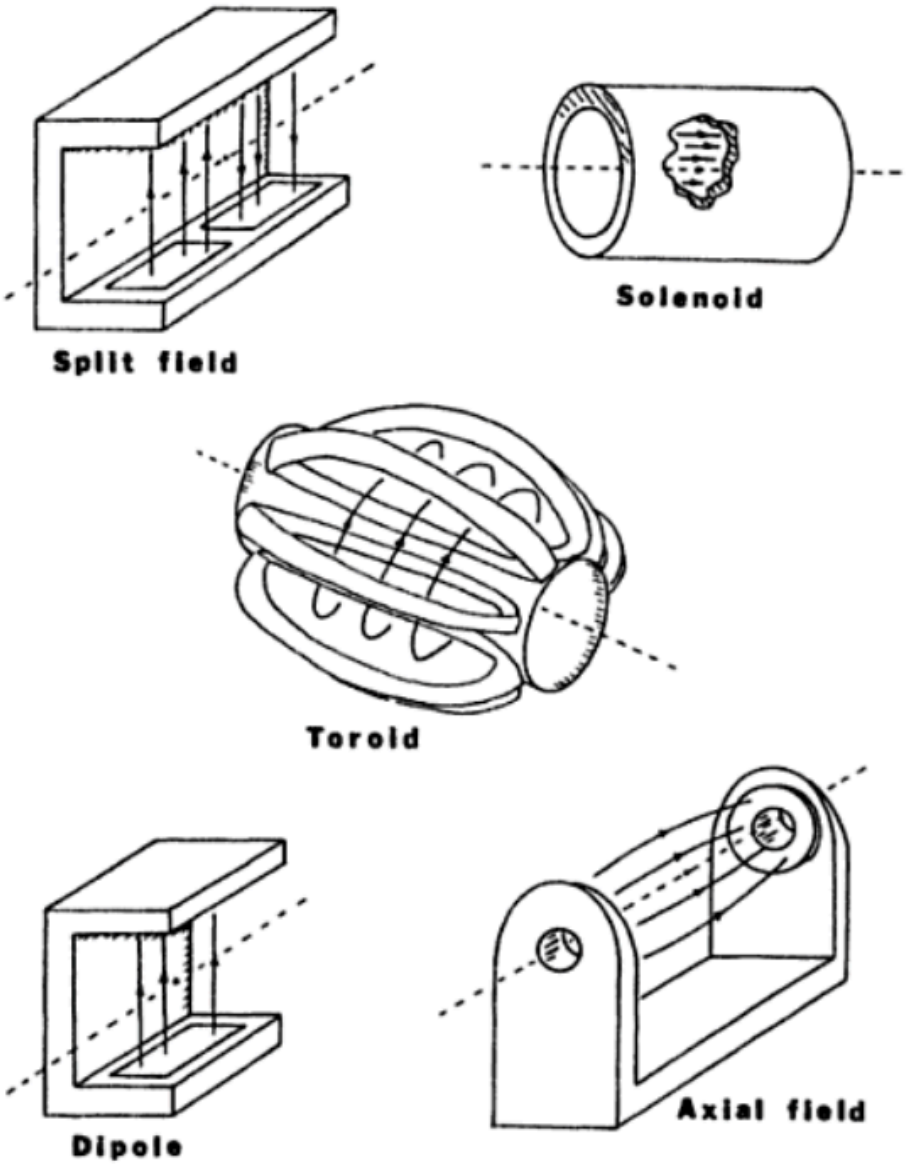
resolution is improved faster by increasing L then B

Momentum resolution gets worse for larger momenta

Momentum resolution due to multiple scattering

$$\left|\frac{\delta p}{p}\right| = \frac{p}{0.3B}\sqrt{\frac{\overbrace{\xi}^{\text{RMS of projected angle per unit thickness}}\overbrace{C_N}^{\sim 1.43}}{L}}$$

Design consideration: magnetic field (collider)



- Field…
  - ✓ should ensure good momentum resolution in region of most importance
  - ✓ Cannot be too high (low p particle would spiral)
  - ✓ Should not interfere too much with beam orbit
    - Compensate deflection with additional magnets…

Design consideration: magnetic field (collider)

	Dipole	Split field magnet	Solenoid	Axial field magnet	Toroid
Return yoke	yes	yes	yes	yes	no
Compensating magnet	yes	no	small	small	no
e^+e^- beams	no	no	yes	yes	yes
Coils before field region	no	no	no	no	yes
High p_t measurement	good	good	poor	good	poor
Forward particle measurement	good	good	poor	poor	poor

Design consideration: tracking devices

- **Inner tracker**
  - ✓ Silicon detectors (pixels, microstrips)
    - High resolution vertexing
  - ✓ Transition detector trackers
  - ✓ TPC Time Projection Chambers

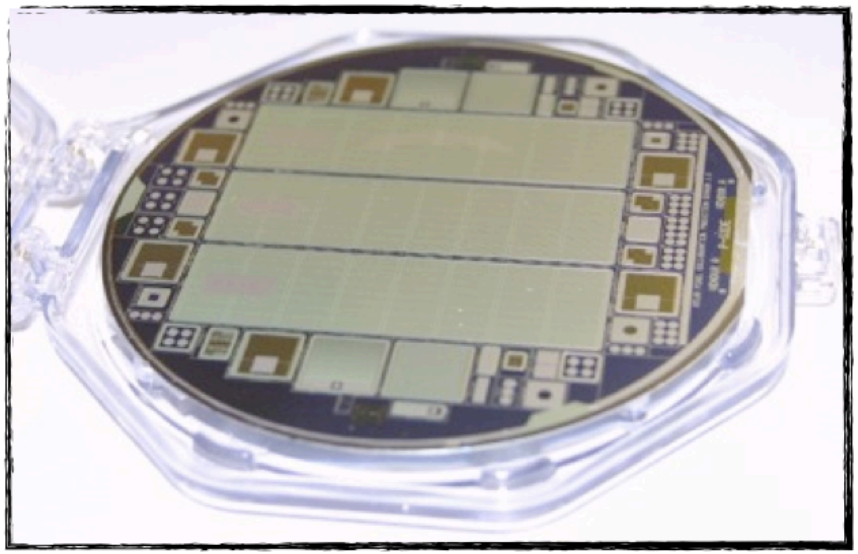
- **Muon spectrometer**
  - ✓ Drift chambers
  - ✓ MWPC (Multi Wire Proportional Chambers)
  - ✓ RPC (Resistive Place Chambers)

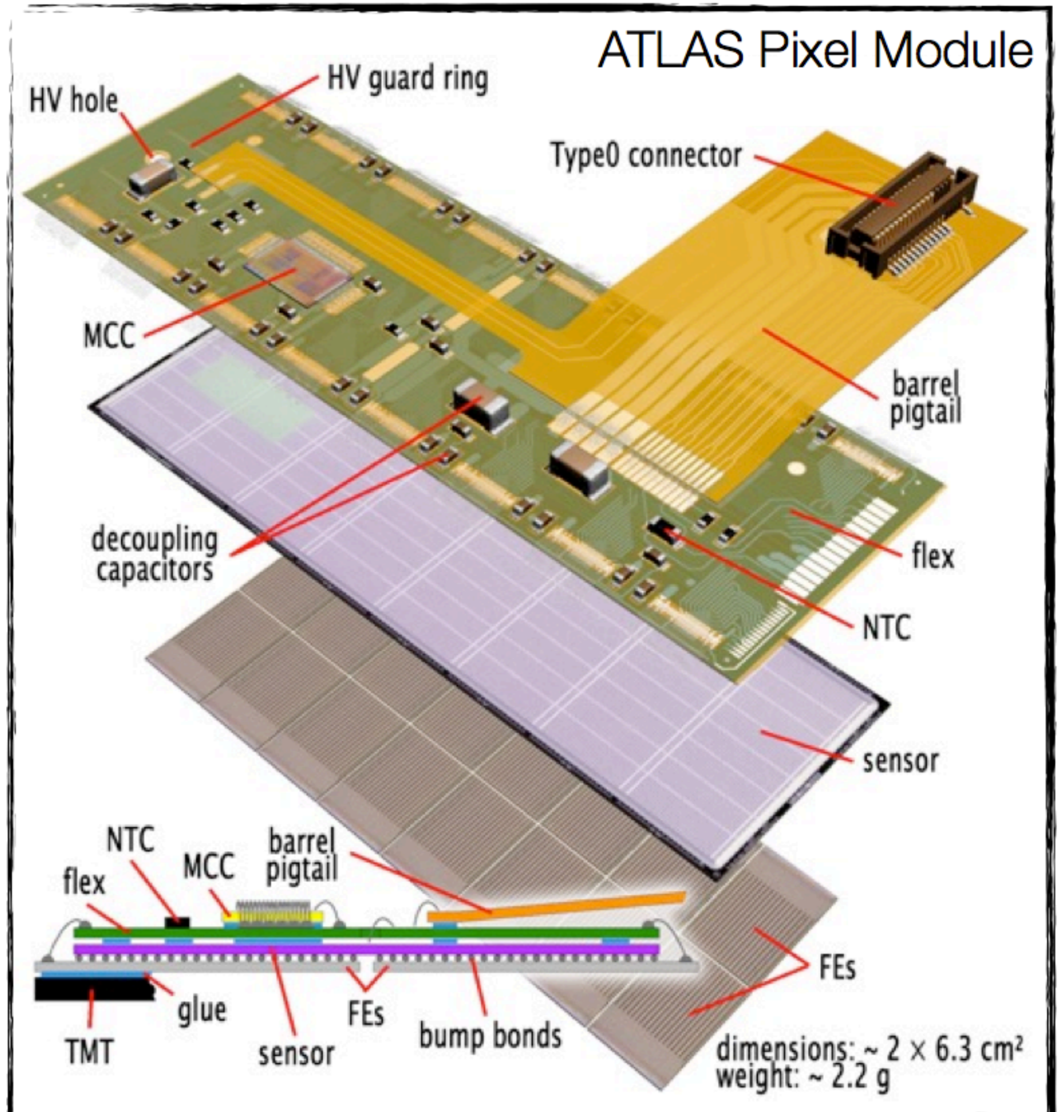
Semiconductor detectors

ATLAS
Pixel Detector

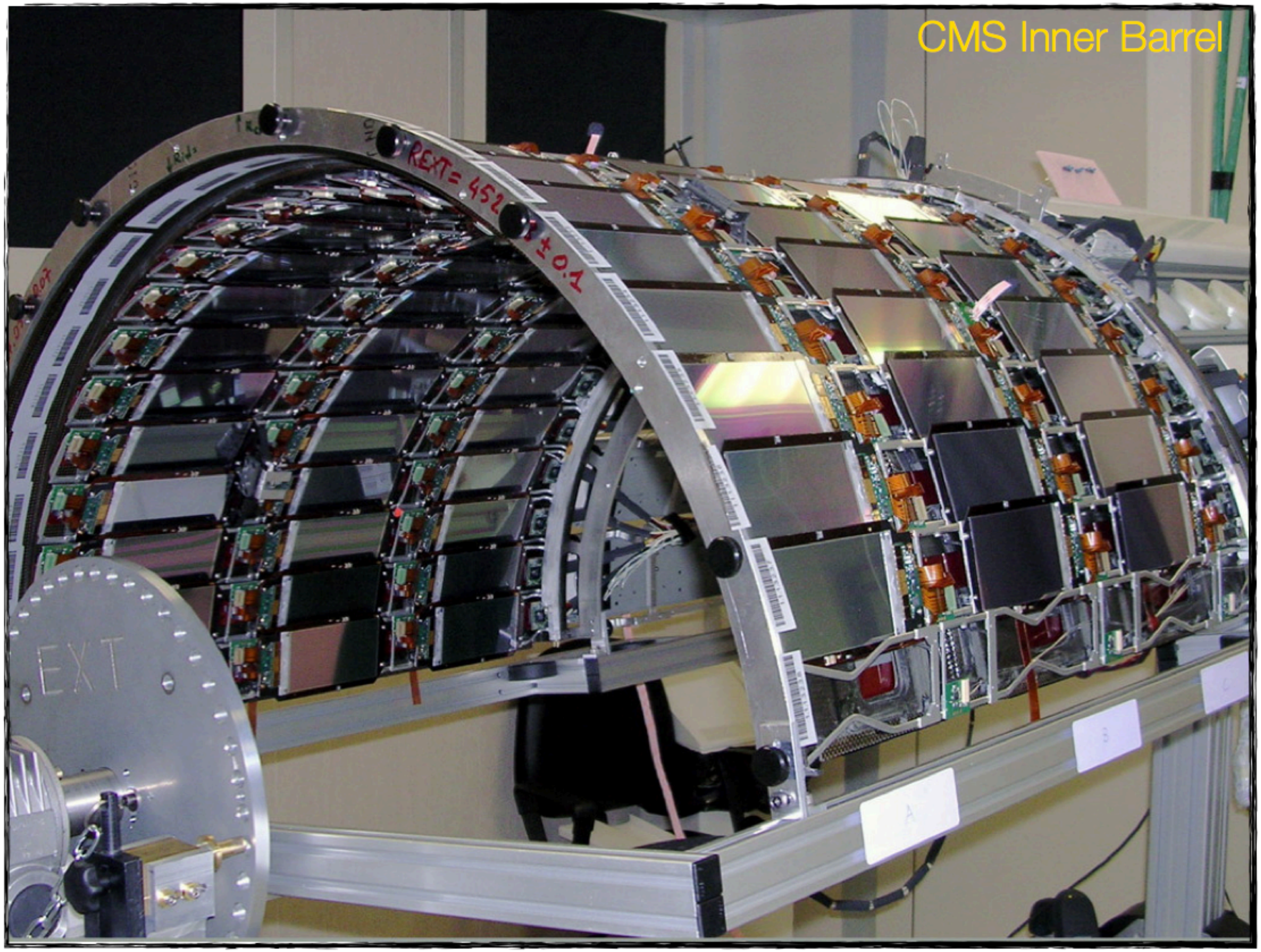
[Details]

Pixel Sensor

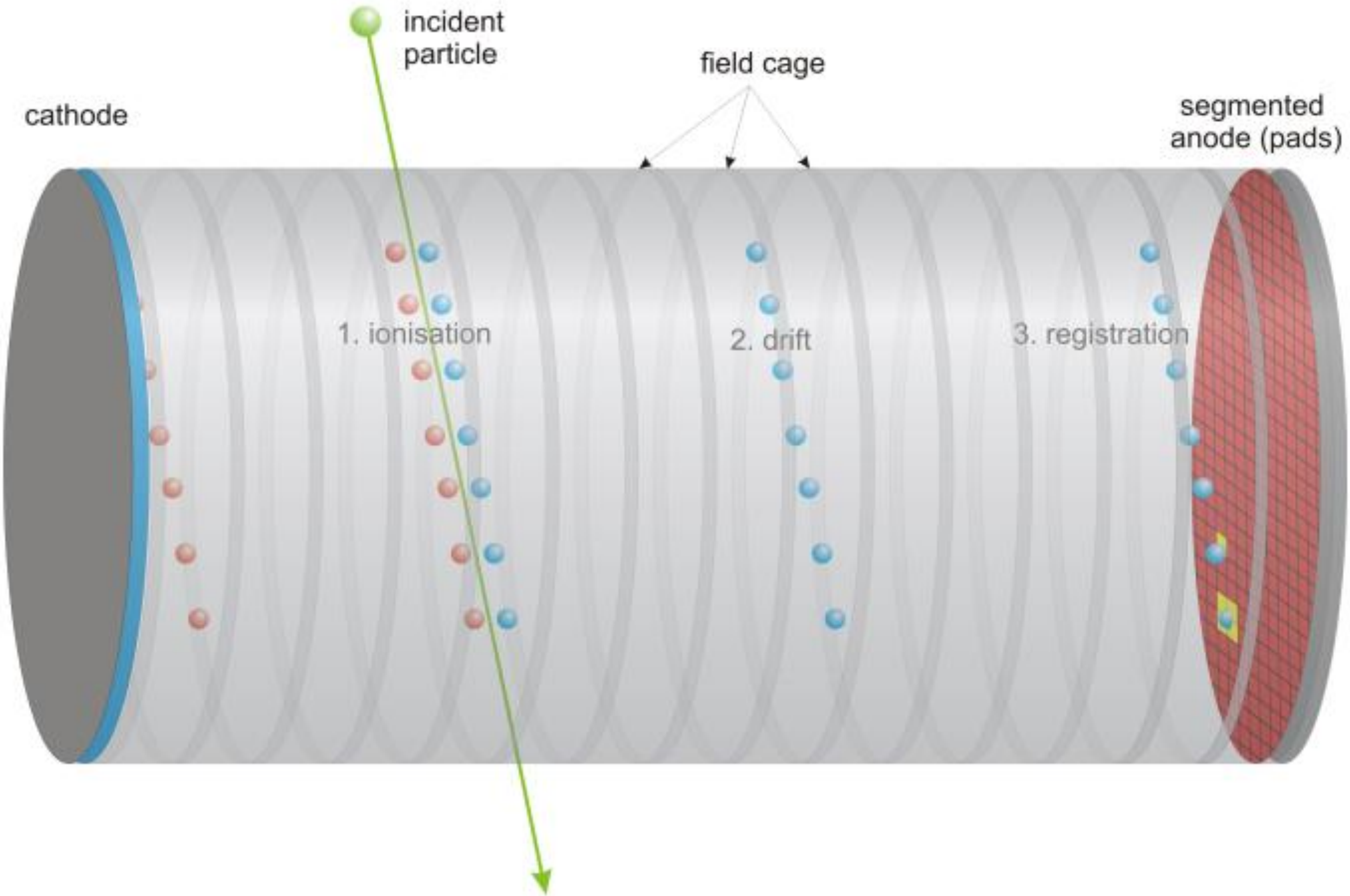




Semiconductor detectors



TPC principles of operation



ALICE TPC

ALICE TPC:

Length: 5 meter
Radius: 2.5 meter
Gas volume: 88 m^3

Total drift time: 92 μs
High voltage: 100 kV

End-cap detectors: 32 m^2
Readout pads: 557568

159 samples radially
1000 samples in time

Gas: $Ne/CO_2/N_2$ (90-10-5)
Low diffusion (cold gas)

Gain: > 10^4

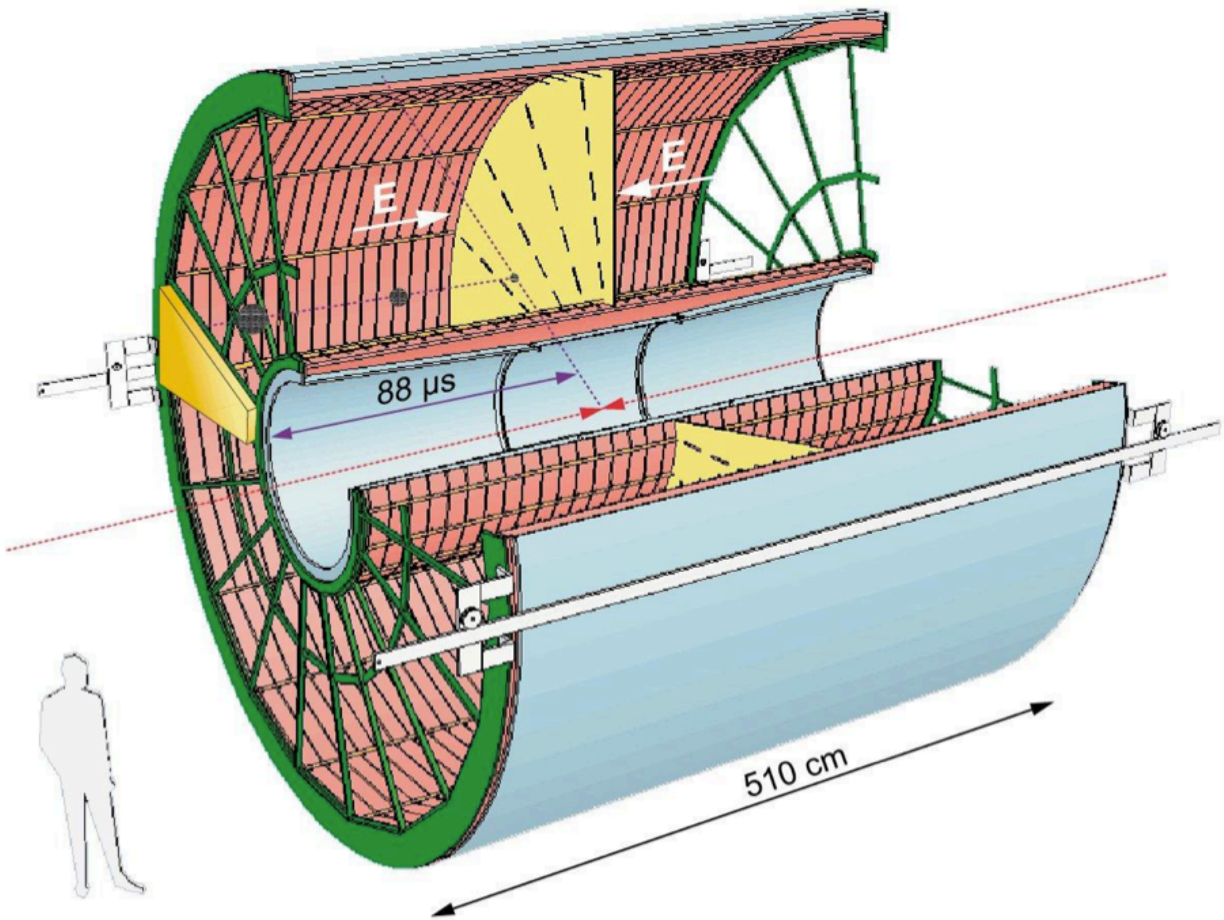
Diffusion: σ_t = 250 μm
Resolution: $\sigma \approx$ 0.2 mm

$\sigma_p/p \sim 1\%$ p; $\varepsilon \sim 97\%$
$\sigma_{dE/dx}/(dE/dx) \sim 6\%$

Magnetic field: 0.5 T

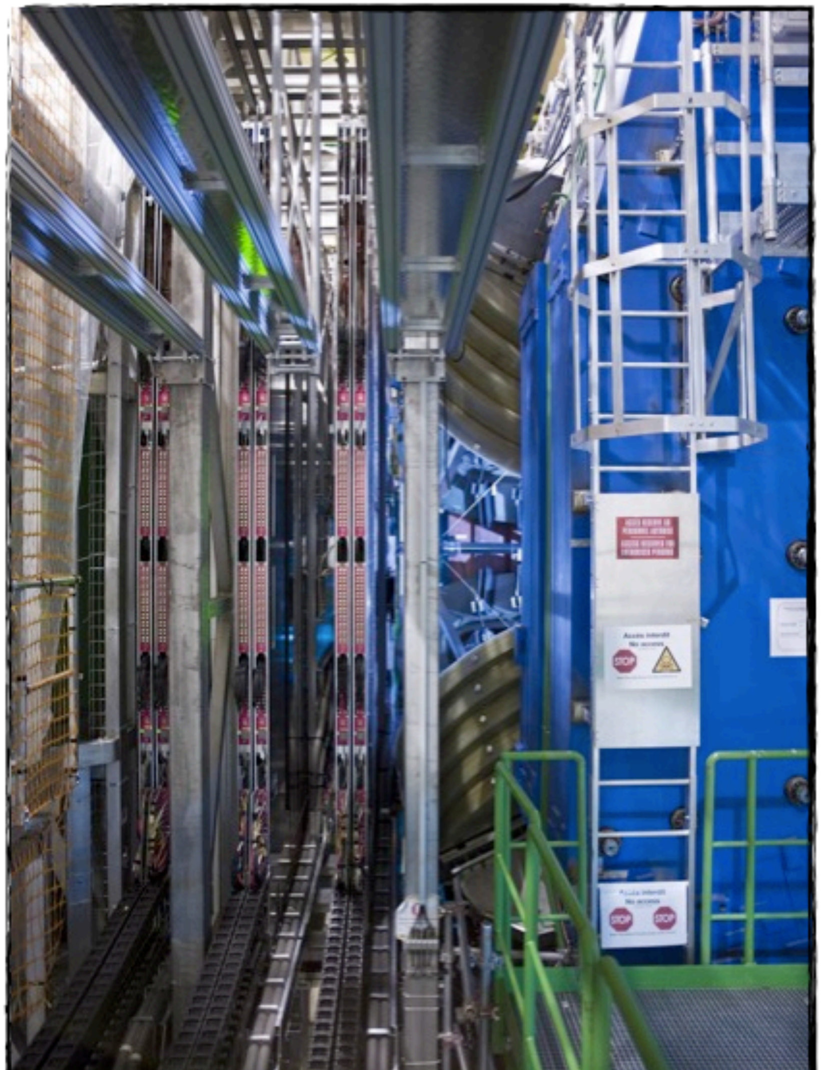
Pad size: 5x7.5 mm^2 (inner)
6x15 mm^2 (outer)

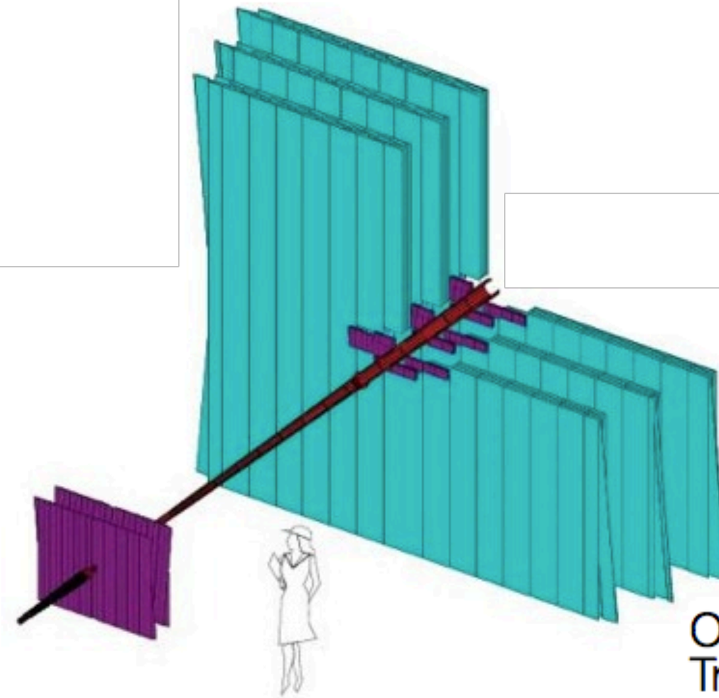
Temperature control: 0.1 K
[also resistors ...]



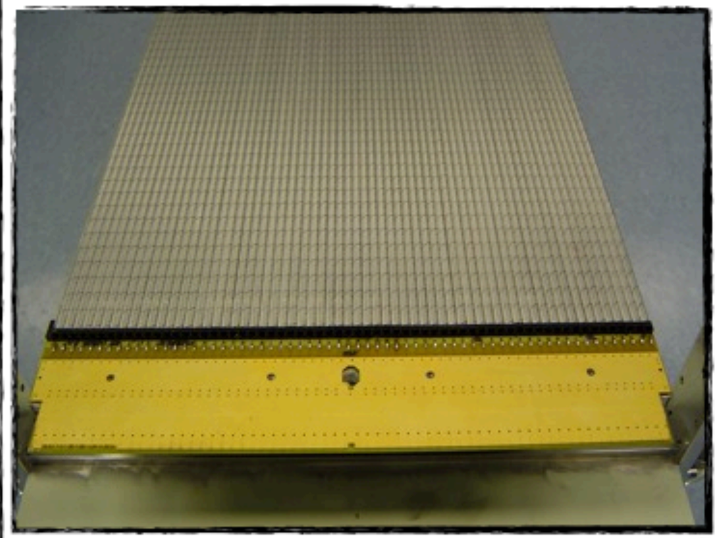
Material: Cylinder build from composite material of airline industry (X_0= ~ 3%)

LHCb outer tracker

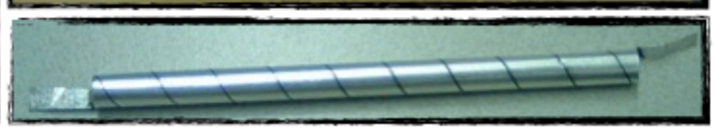




Outer
Tracker

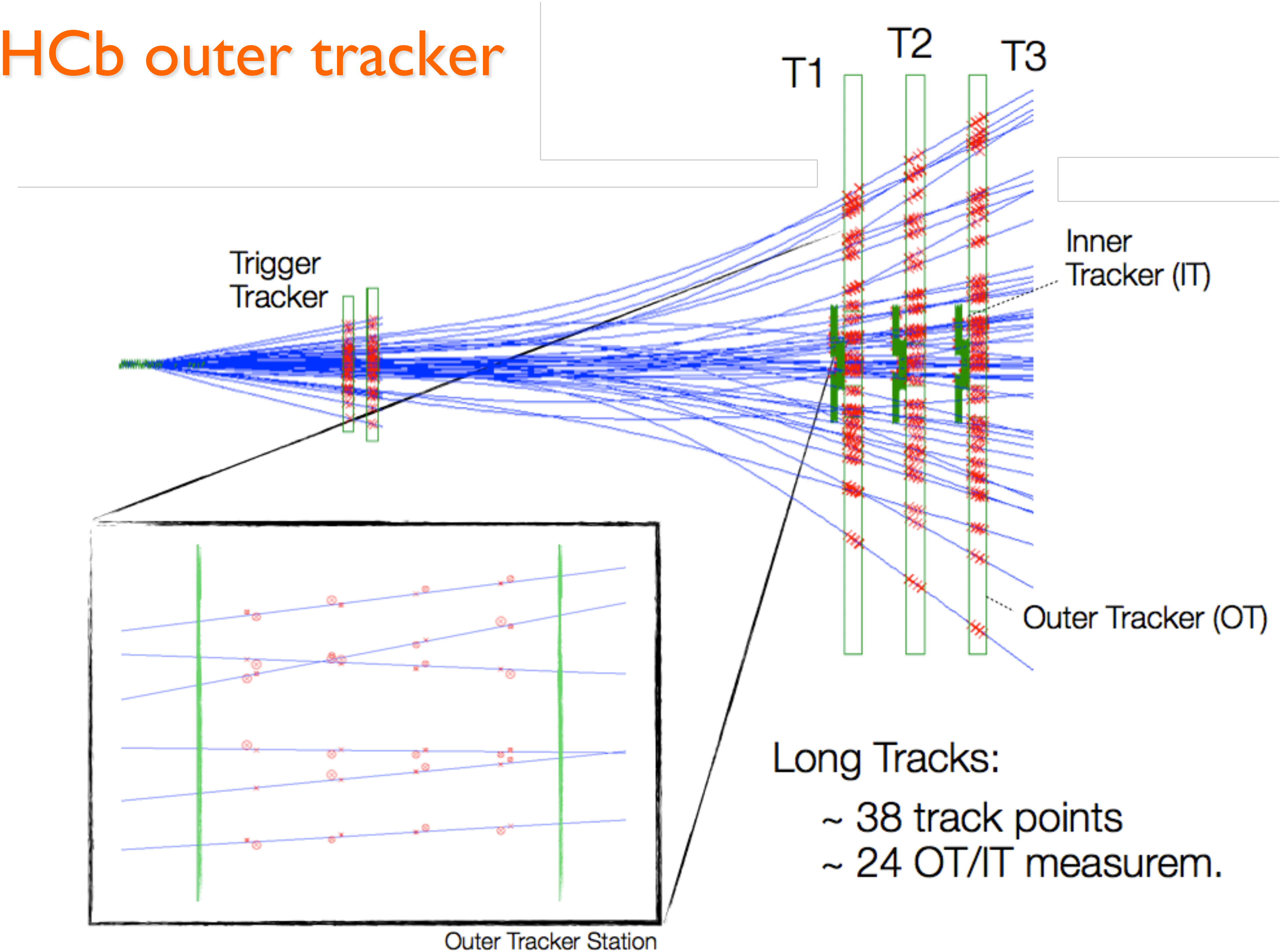


Straw Tubes
[double layers]



3 Chambers
[4 layers á 18 modules]

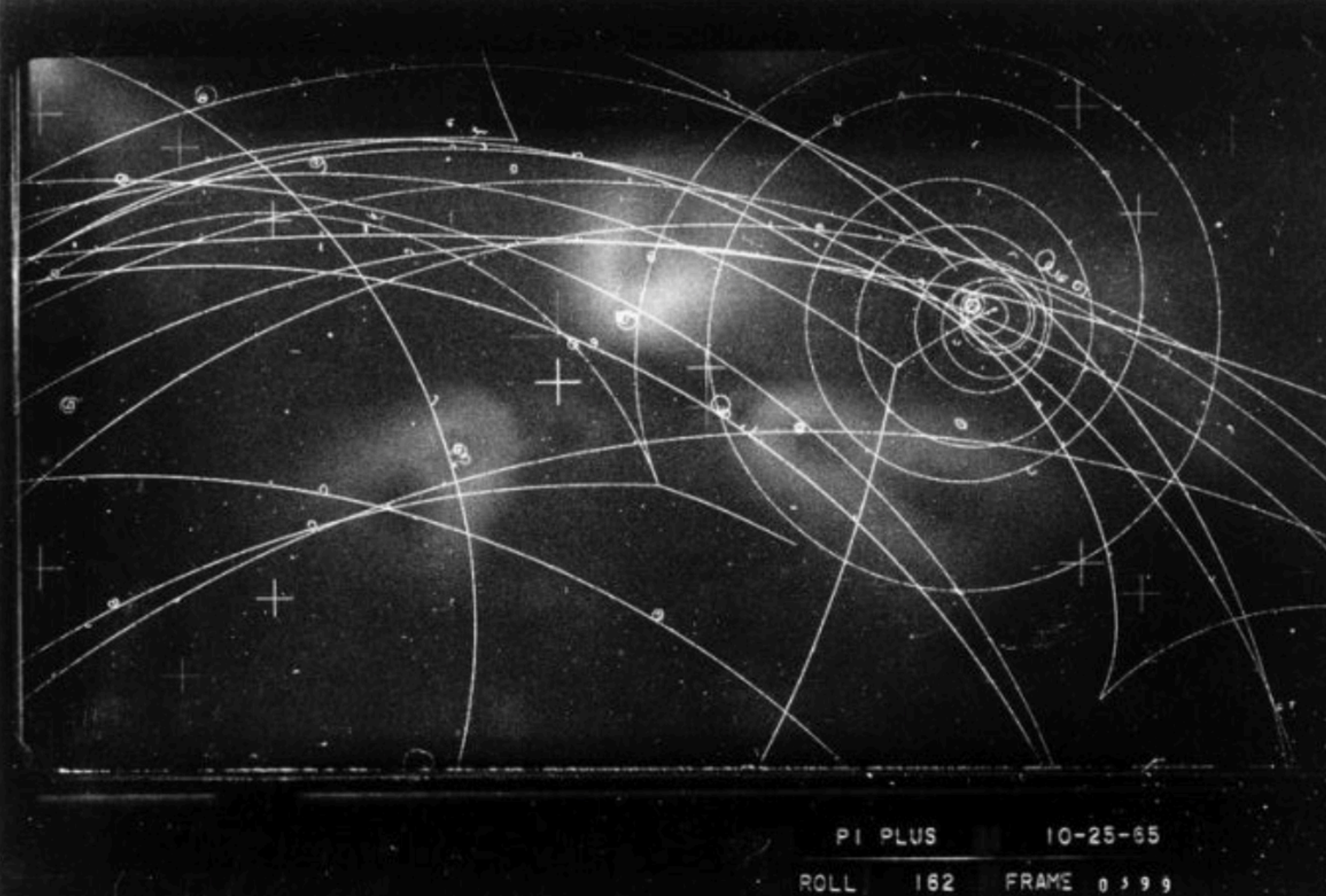
LHCb outer tracker



Long Tracks:

~ 38 track points

~ 24 OT/IT measurem.



PI PLUS
10-25-65
ROLL 162
FRAME 0399

Bubble chamber exercise

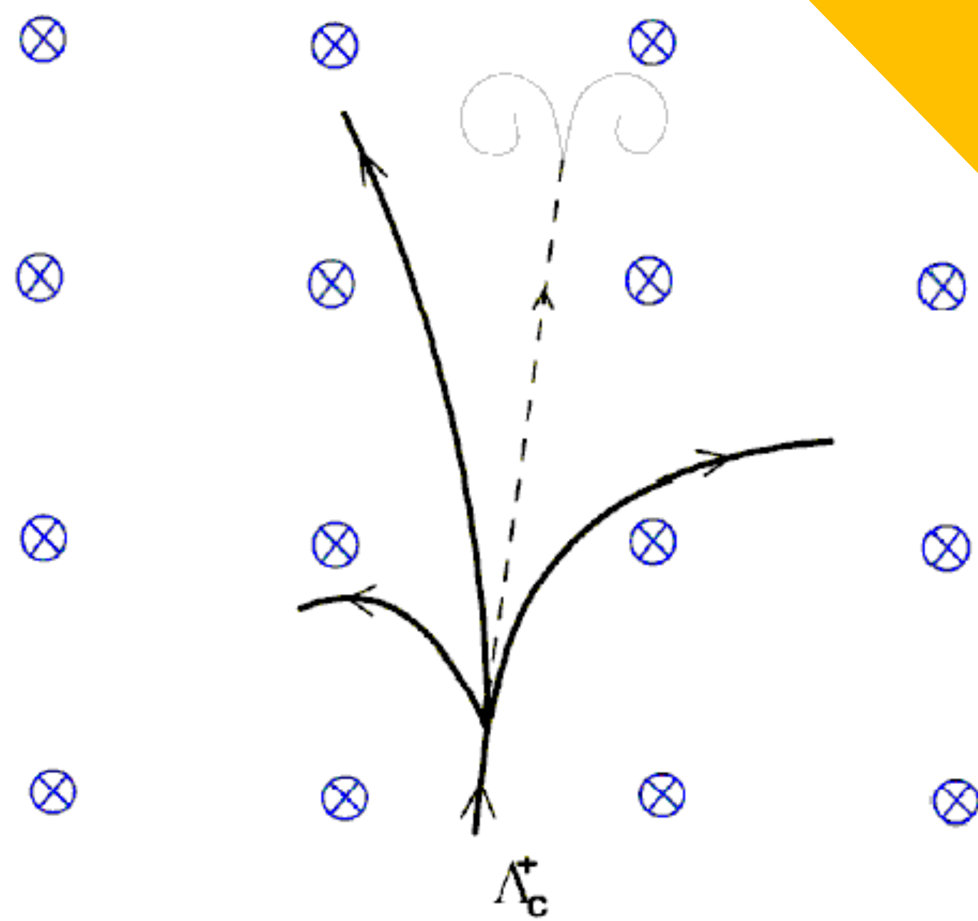
- The event shown on the right is a decay of the "charmed Lambda plus"
- Based on the properties (mass, electrical charge) of the possible resultant particles (consult the PDG site!) determine which of the four decays below this diagram represents
  - ✓ Assume the magnetic field to be **uniform**, **constant** in magnitude, and **pointing into the slide**
  - ✓ Assume all particles issued from the decay **travel at the same speed** (*speed*, not momentum), in a ***non-relativistic*** regime).

a) $\Lambda_c^+ \rightarrow \Lambda^0 \pi^+ \pi^+ \pi^-$

b) $\Lambda_c^+ \rightarrow p^+ K^- \pi^+ \pi^+ \pi^-$

c) $\Lambda_c^+ \rightarrow p^+ K^- \pi^+ \pi^0$

d) $\Lambda_c^+ \rightarrow p^+ \bar{K}^0 \pi^+ \pi^-$



Bubble chamber solution

Four particles originating from the Λ_c^+ decay are observed, 3 charged and 1 neutral (the dashed line), apparently decaying in a pair of opposite charged particles. We can therefore exclude reaction (b), otherwise we would have observed five charged tracks originating from the decay vertex.

Reactions (a), (c) and (d) all have 3 charged particles (2 positive + 1 negative) and 1 neutral particle in their final state. In order to choose the correct one we need to refer to the particle masses, that we can find in the PDG.

particle	mass [MeV]
Λ_c^+	2284
p^+	938
K^-	493
$\bar{K}^0$	497
Λ^0	1115
π^+, π^-	139
π^0	135

In the bubble chamber display, the tracks of the charged particles have different curvature. Since the magnetic field is uniform and the particles' speed is the same, a particle with larger mass will have a greater curvature radius. In fact:

$$Bqv = \frac{mv^2}{r} \longrightarrow mv = p = Bqr$$

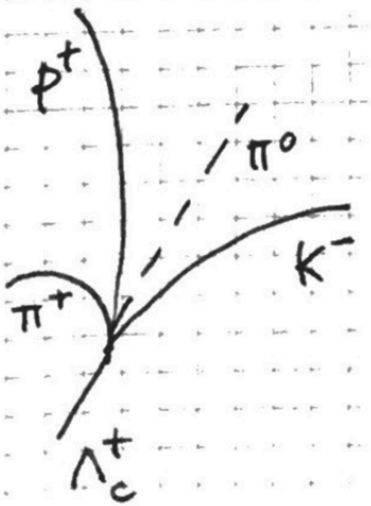
$$r = \frac{mv}{Bq} \propto m$$

Bubble chamber solution

We can therefore exclude reaction (a), since all charged particles have the same mass. For the same reason we can exclude (d), because there are two particles with the same mass in the final state (π^+, π^-).

The correct reaction is:

$$\Lambda_c^+ \rightarrow p^+ K^- \pi^+ \pi^0$$

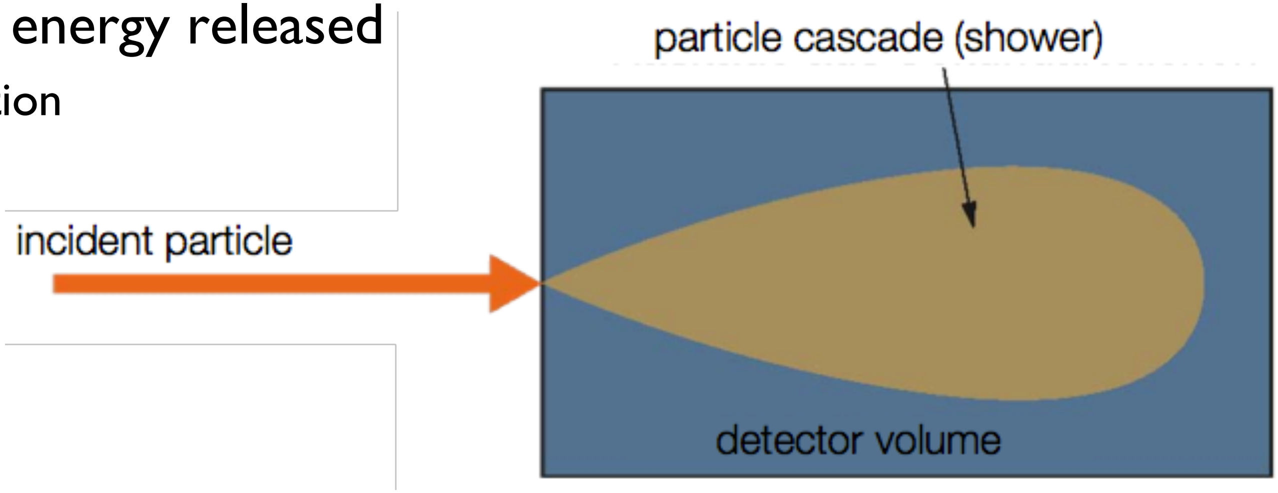


since $m_p > m_K > m_\pi$ we can assign each track to the particle according to the curvature radius.

As for the π^0, it decays as $\pi^0 \rightarrow e^+ e^- \gamma$, and the γ is not seen. Note that the momentum of the e^+e^- system is not aligned with that of the π^0!

Calorimetry

- **Detector for energy measurement via total absorption of particles**
- **Principles of operation**
  - ✓ Incoming particle initiates particle shower
    - Electromagnetic, hadronic
    - Shower properties depend on particle type and detector material
  - ✓ Energy is deposited in active regions
    - Heat, ionization, atom excitation (scintillation), Cherenkov light
    - Different calorimeters use different kind of signals
  - ✓ Signal is proportional to energy released
    - Proportionally → calibration
    - Shower containment



Calorimeters can…

- **Calorimeters can be built as 4π detectors**
  - ✓ They can detect particles over almost the full solid angle
  - ✓ Magnetic spectrometer: anisotropy due to magnetic field

$$\left(\frac{\sigma_p}{p}\right)^2 = \left(\frac{\sigma_{p_T}}{p_T}\right)^2 + \left(\frac{\sigma_\theta}{\sin\theta}\right)^2$$

- **Calorimeters are often also sensitive to particle position**
  - ✓ Important for neutral particles: no track in inner detector!
- **Calorimeters can provide fast timing signal**
  - ✓ 0.1 to 10 ns
  - ✓ They can be used for triggering!
- **Calorimeters can measure the energy of both charged and neutral particles**
  - ✓ Magnetic spectrometer: only charged particles!
- **Segmentation in depth allows particles separation**
  - ✓ e.g. separate hadrons from particles which only interact electromagnetically

Energy resolution

Calorimeter energy resolution determined by fluctuations ...

Homogeneous calorimeters:

- Shower fluctuations
- Photo-electron statistics
- Shower leakage
- Instrumental effects (noise, light attenuation, non-uniformity)

Quantum fluctuations

In addition for

Sampling calorimeters:

- Sampling fluctuations
- Landau fluctuations
- Track length fluctuations

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Quantum fluctuations	$\sim {}^{1}\!/\!\sqrt{E}$
Electronic noise	$\sim {}^{1}\!/\!E$
Shower leakage*	$\approx \mathrm{const}$
Sampling fluctuations	$\sim {}^{1}\!/\!\sqrt{E}$
Landau fluctuations	$\sim {}^{1}\!/\!\sqrt{E}$
Track length fluctuations	$\sim {}^{1}\!/\!\sqrt{E}$

* Different for longitudinal and lateral leakage ...
Complicated; small energy dependence ...

Energy resolution

Shower fluctuations:
[intrinsic resolution]

Ideal (homogeneous) calorimeter without leakage: energy resolution limited only by statistical fluctuations of the number N of shower particles ...

i.e.:

$$\frac{\sigma_E}{E} \propto \frac{\sigma_N}{N} \approx \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}} \qquad \text{with } N = \frac{E}{W}$$

$$\frac{\sigma_E}{E} \propto \sqrt{\frac{W}{E}}$$

E : energy of primary particle

W : mean energy required to produce 'signal quantum'

Examples:

Silicon detectors	:	W ≈ 3.6 eV
Gas detectors	:	W ≈ 30 eV
Plastic scintillator	:	W ≈ 100 eV

Resolution improves due to correlations between fluctuations

$$\frac{\sigma_E}{E} \propto \sqrt{\frac{FW}{E}}$$

[F: Fano factor]

Impact of shower leakage

Shower leakage:

Fluctuations due to finite size of calorimeter; shower not fully contained ...

Lateral leakage: limited influence
Longitudinal leakage: strong influence

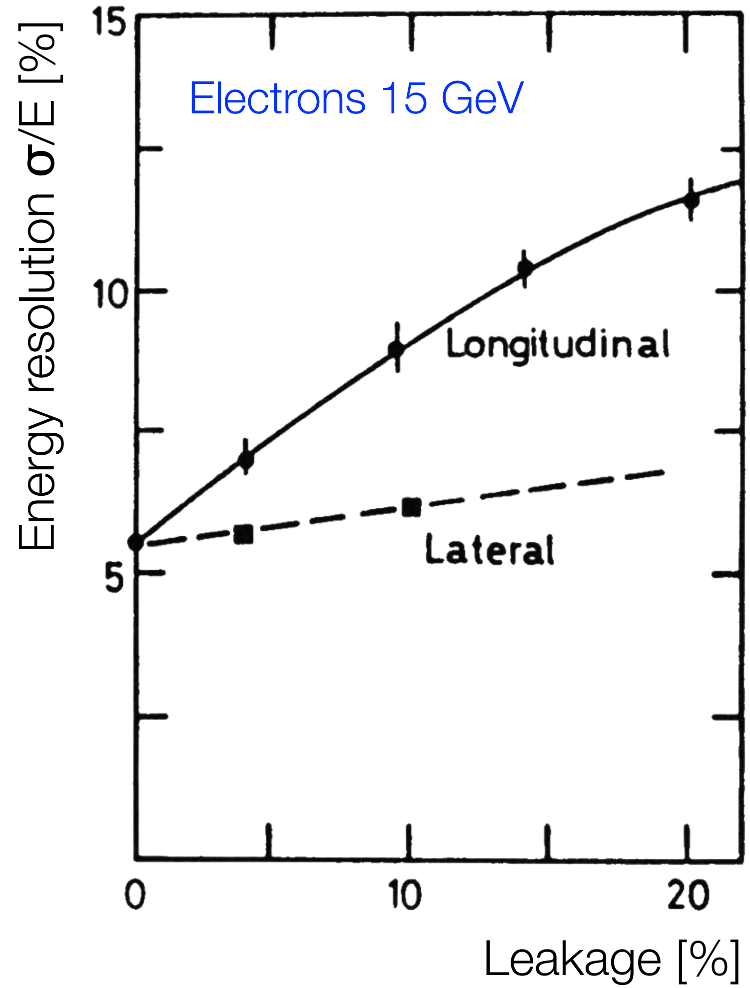
Typical expression when including leakage effects:

$$\frac{\sigma_E}{E} \propto \left(\frac{\sigma_E}{E}\right)_{f=0} \cdot \left[1 + 2f\sqrt{E}\right]$$

[f : average fraction of shower leakage]

Remark: other parameterizations exist ...

Marmor Calorimeter
[CHARM Collaboration]



Homogeneous calorimeters

★ In a homogeneous calorimeter the whole detector volume is filled by a high-density material which simultaneously serves as absorber as well as as active medium ...

Signal	Material
Scintillation light	BGO, BaF_2, CeF_3, ...
Cherenkov light	Lead Glass
Ionization signal	Liquid nobel gases (Ar, Kr, Xe)

★ Advantage: homogenous calorimeters provide optimal energy resolution

★ Disadvantage: very expensive

★ Homogenous calorimeters are exclusively used for electromagnetic calorimeter, i.e. energy measurement of electrons and photons

Sampling calorimeters

Principle:

Alternating layers of absorber and active material [sandwich calorimeter]

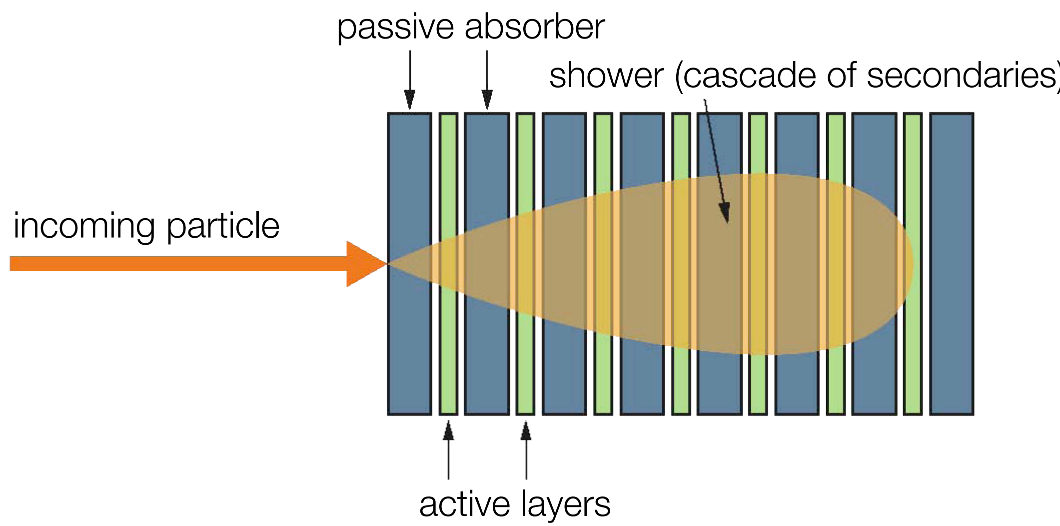
Absorber materials:
[high density]

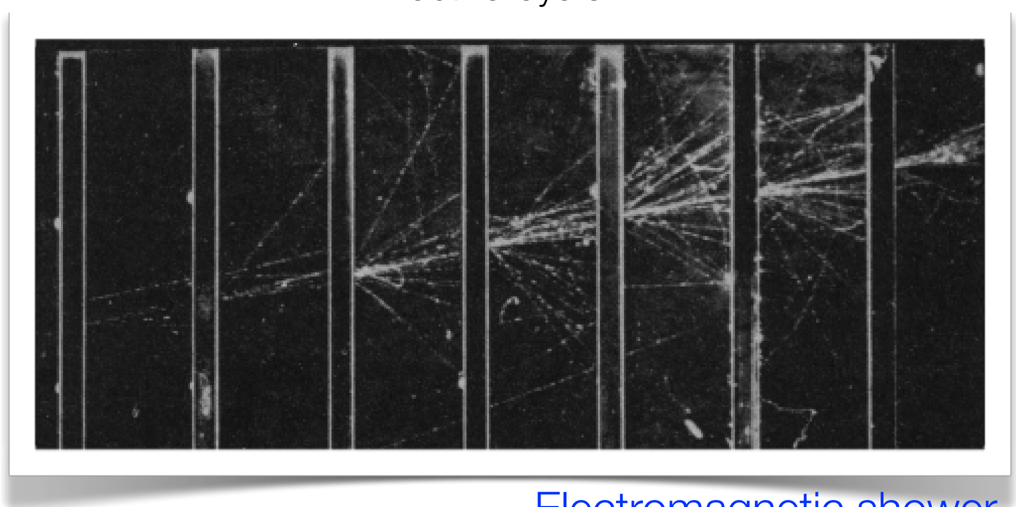
Iron (Fe)
Lead (Pb)
Uranium (U)
[For compensation ...]

Active materials:

Plastic scintillator
Silicon detectors
Liquid ionization chamber
Gas detectors

Scheme of a sandwich calorimeter





Electromagnetic shower

Sampling calorimeters

★ Advantages:

By separating passive and active layers the different layer materials can be optimally adapted to the corresponding requirements ...

By freely choosing high-density material for the absorbers one can built very compact calorimeters ...

Sampling calorimeters are simpler with more passive material and thus cheaper than homogeneous calorimeters ...

★ Disadvantages:

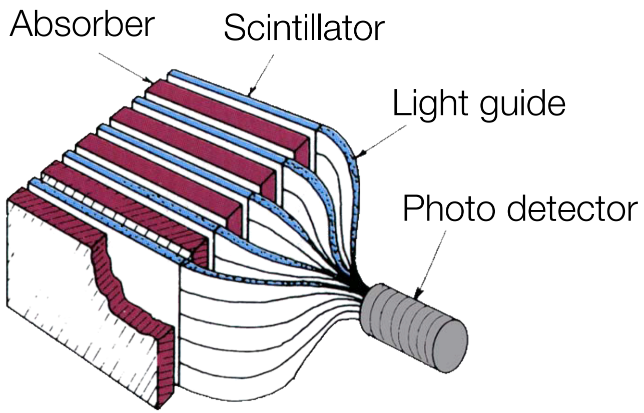
Only part of the deposited particle energy is actually detected in the active layers; typically a few percent [for gas detectors even only ~10^{-5}] ...

Due to this sampling-fluctuations typically result in a reduced energy resolution for sampling calorimeters ...

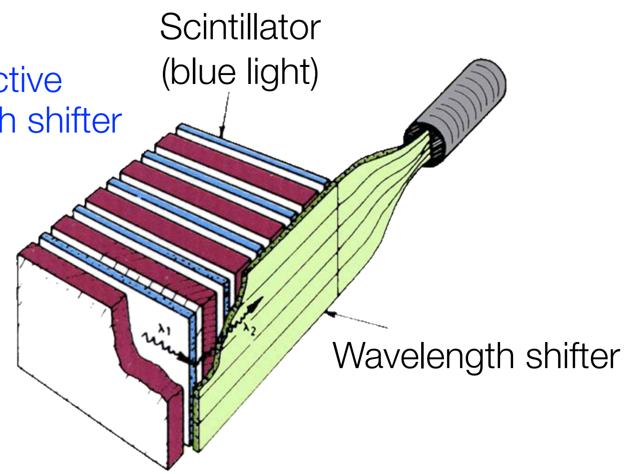
Sampling calorimeters

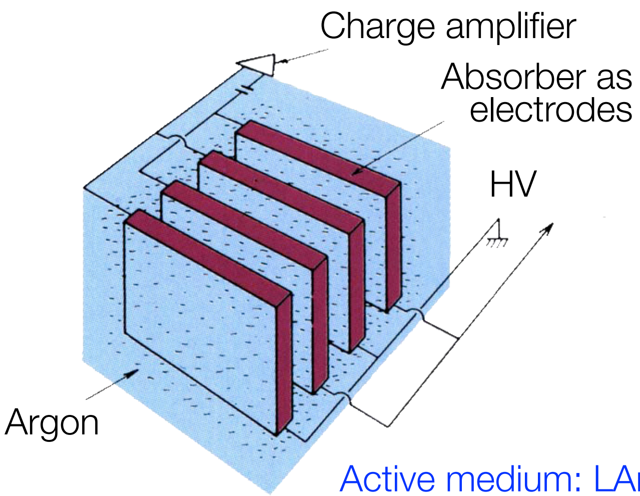
Possible setups

Scintillators as active layer;
signal readout via photo multipliers



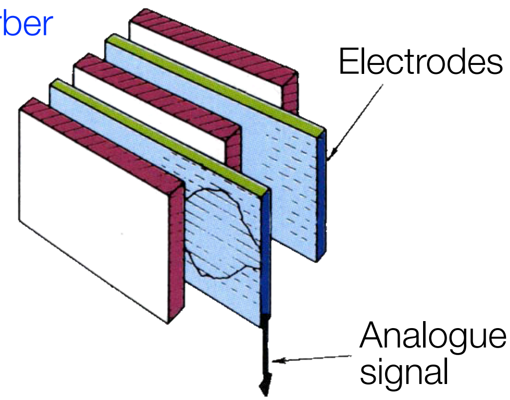
Scintillators as active layer; wave length shifter to convert light





Active medium: LAr; absorber embedded in liquid serve as electrods

Ionization chambers between absorber plates



Homogeneous vs. sampling calorimeters

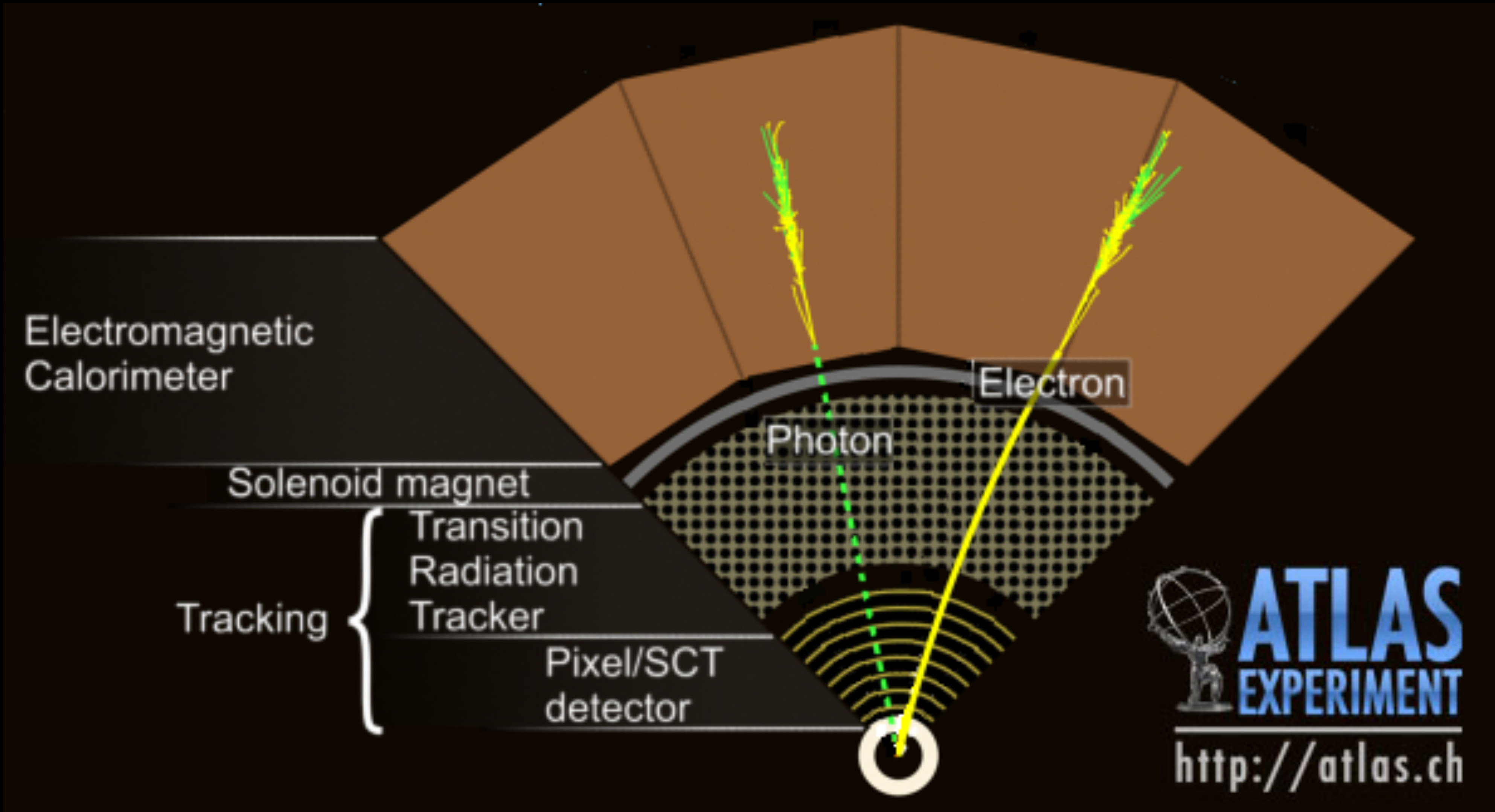
Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16\text{–}18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	$20\text{–}30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	$20\text{–}30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

Homogeneous

Sampling

Resolution of typical electromagnetic calorimeter
[E is in GeV]

Particle identification with tracker and calo



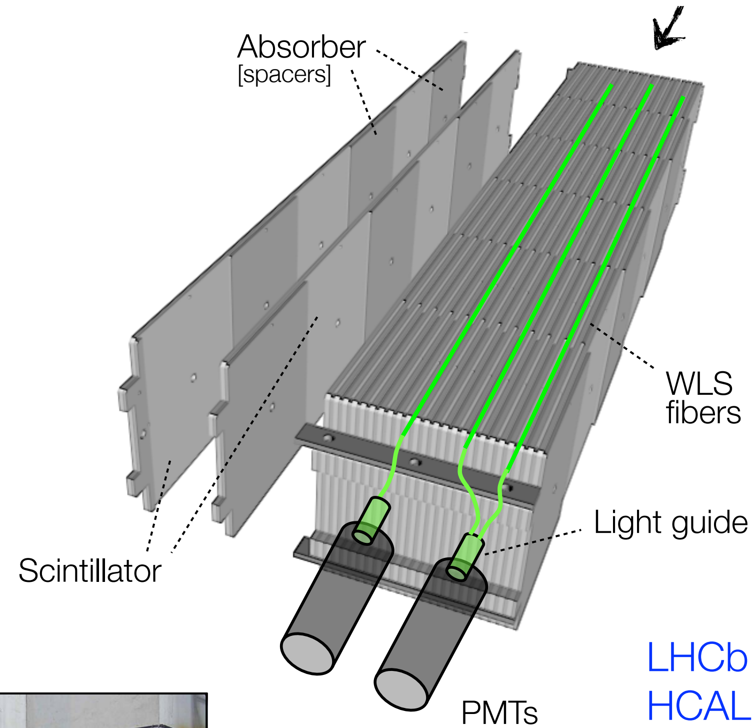
Hadronic calorimeters

Most common realization: Sampling Calorimeter

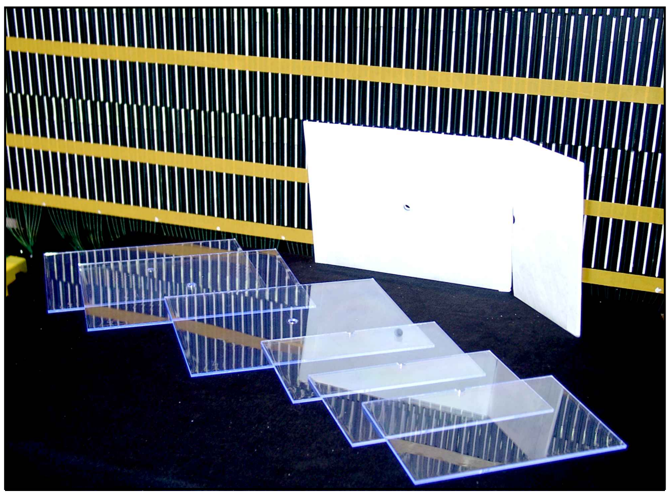
Utilization of homogenous calorimeters unnecessary (and thus too expensive) due to fluctuations of invisible shower components ...

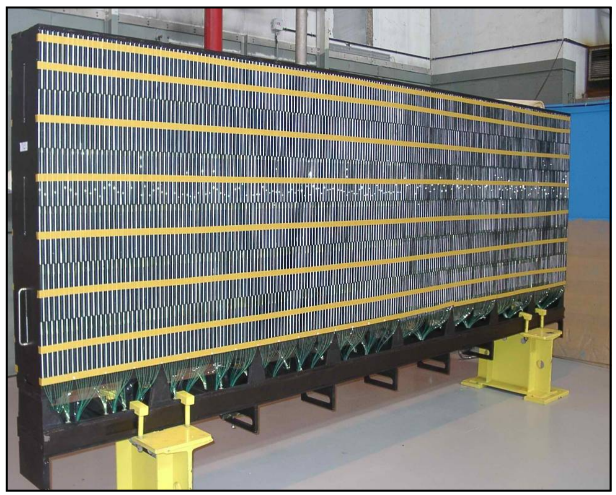
Typical absorbers : Fe, Pb, U ...
Sampling elements : Scintillators, LAr, MWPCs ...

Typical setup:
Alternating layers of active and passive material
[also: 'spaghetti' or 'shashlik' calorimeter]



LHCb
HCAL





Example:
LHCb Hadron Calorimeter

Energy resolution

Energy resolution:

e.g. inhomogeneities
shower leakage

e.g. electronic noise
sampling fraction variations

$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus B \oplus \frac{C}{E}$$

Fluctuations:

- Sampling fluctuations
- Leakage fluctuations
- Fluctuations of electromagnetic fraction
- Nuclear excitations, fission, binding energy fluctuations ...
- Heavily ionizing particles

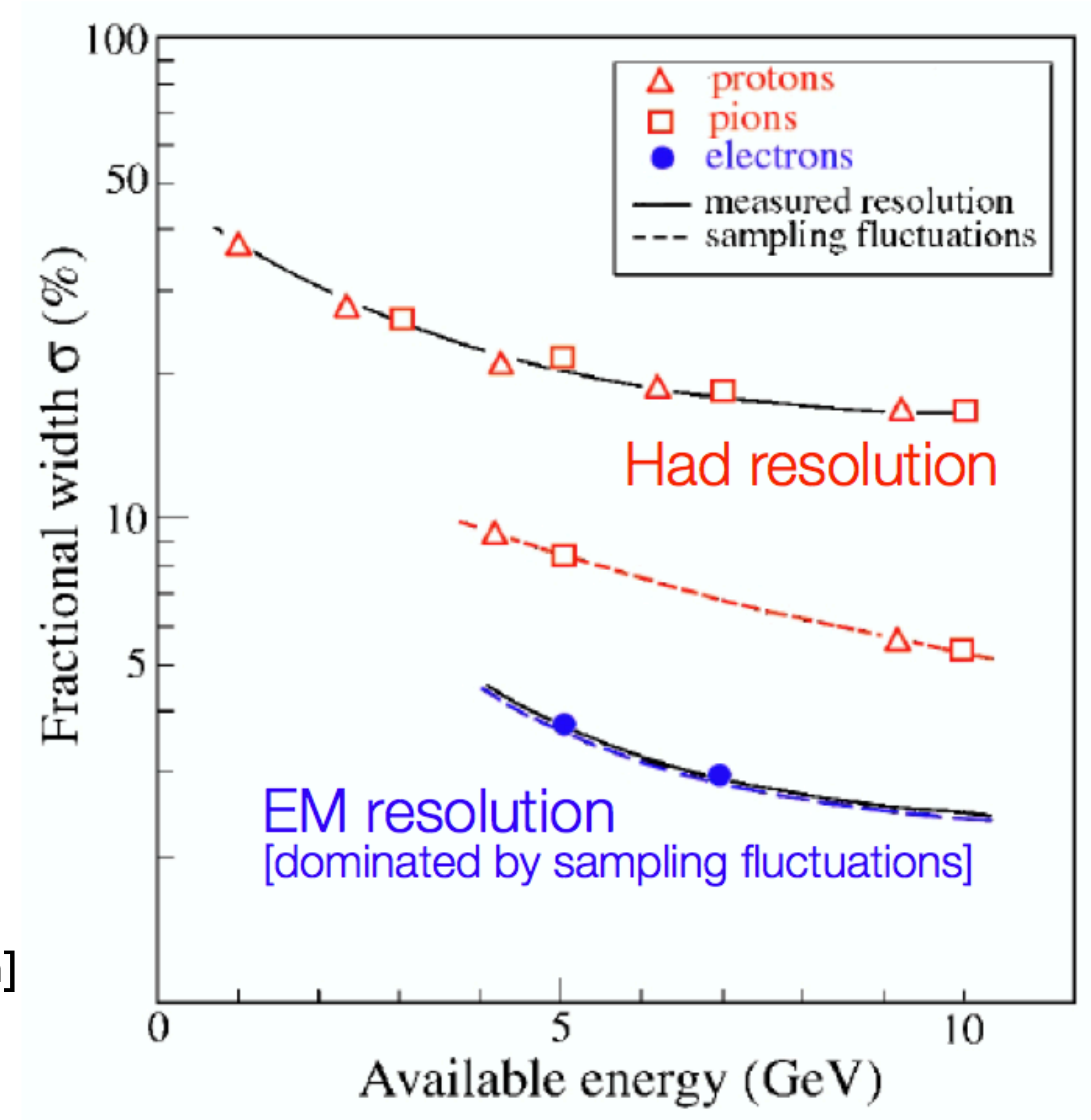
Typical:

A: 0.5 – 1.0 [Record:0.35]

B: 0.03 – 0.05

C: few %

Resolution: EM vs. HAD



[AFM Collaboration]

Sampling fluctuations only minor contribution to hadronic energy resolution

A typical HEP calorimetry system

Typical Calorimeter: two components ...

Electromagnetic (EM) +
Hadronic section (Had) ...

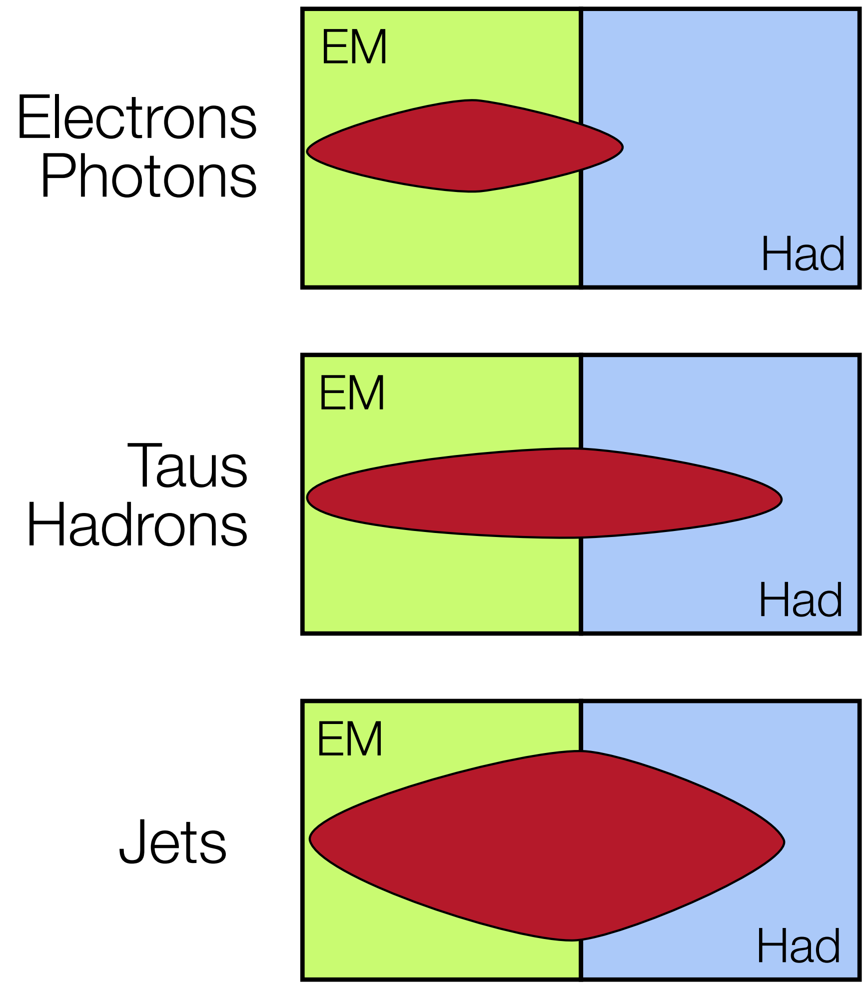
Different setups chosen for
optimal energy resolution ...

But:

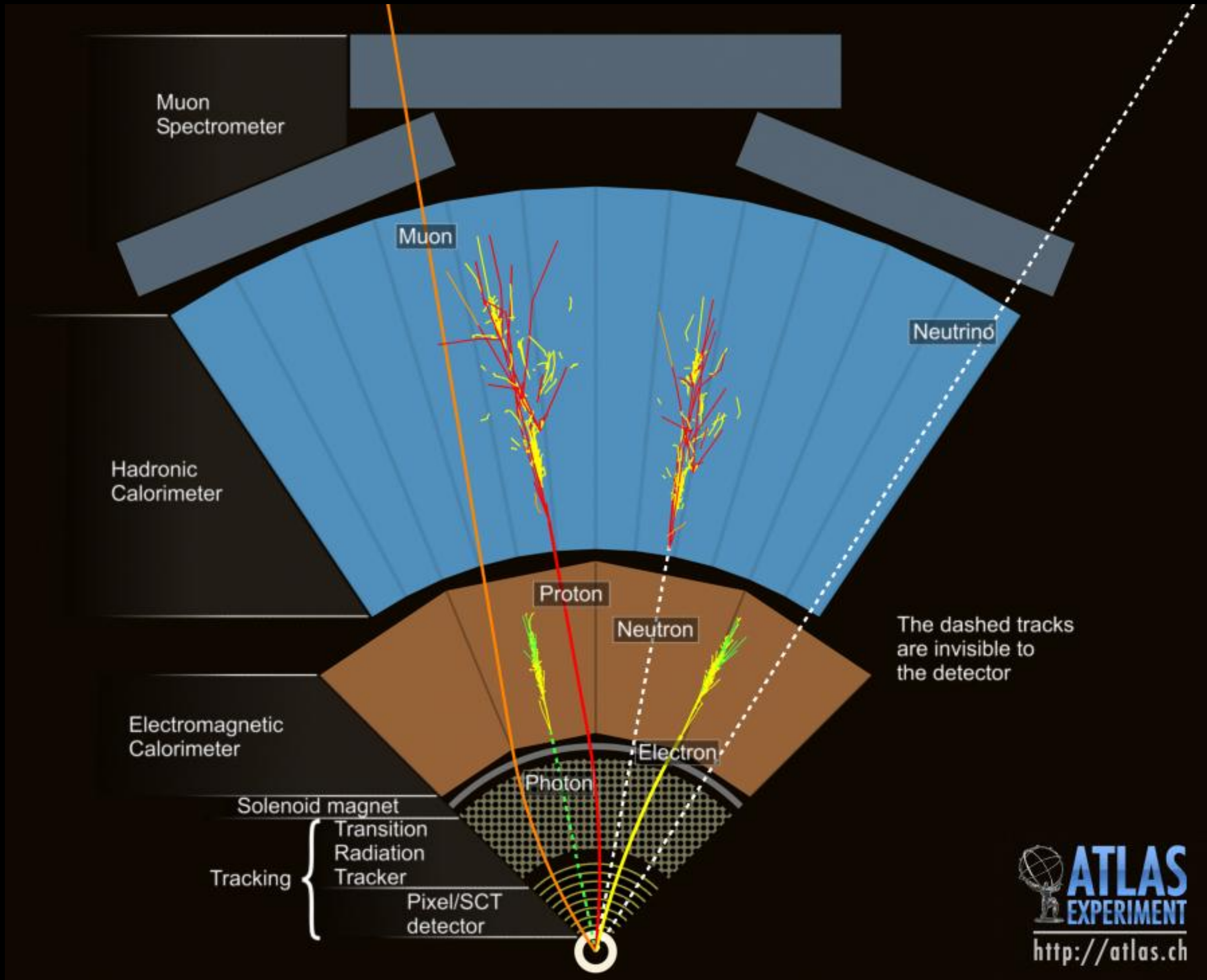
Hadronic energy measured in
both parts of calorimeter ...

Needs careful consideration of
different response ...

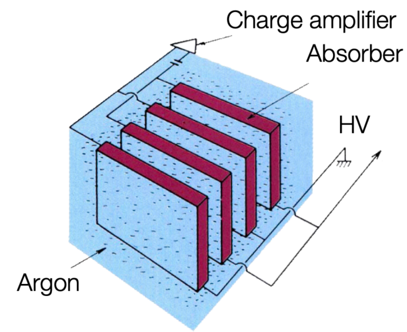
Schematic of a
typical HEP calorimeter



How do we "see" particles?



A sampling calorimeter…



A sampling electromagnetic calorimeter is composed of series of lead layers about 2 mm thick layers of lead (Pb)[1]. Between the lead layers are 2 mm wide gaps filled with liquid Argon (LAr). Lead has a $Z = 82$, $A = 206$ and a density of 11.34 g/cm^3. Liquid argon has a $Z = 18$, $A = 40$ and a density of 1.4 g/cm^3.

1. At $\eta = 0$ the depth of the ATLAS electromagnetic calorimeter is about 22 radiation lengths X_0. What would be the depth of the detector in cm if it was all made of LAr? And if it was all made of lead?

2. An electron of 5 GeV generated an electromagnetic shower in the calorimeter. Assuming that the detector was all made of LAr, at what depth would the shower reach its maximum?

3. How much energy does a minimum-ionizing-particle (mip) deposit in 22 X_0 of LAr, assuming:

$$\frac{1}{\rho_{\mathrm{LAr}}}\left(\frac{dE}{dx}\right)_{\mathrm{mip}} = 1.52\,\mathrm{MeV}/(\mathrm{g}\cdot\mathrm{cm}^{-2}) \tag{1}$$

4. How deep in cm is the *real* ATLAS electromagnetic calorimeter at $\eta = 0$, assuming a perfect succession of lead and liquid argon layers of the same thickness?

A sampling calorimeter…

I

We need to compute the radiation lenght for Pb and LAr (or search the values!). Let's use the simplified formulas

$$X_0 = 180 \frac{A}{Z} \frac{g}{cm^2}$$

(if you look on the PDG you'll find slightly different values, but the order of magnitude is correct)

$$X_0^{Pb} = \frac{206}{(82)^2} 180 \ g/cm^2 \simeq 5.5 \ g/cm^2$$

$$X_0^{LAr} = \frac{40}{(18)^2} 180 \ g/cm^2 \simeq 22.2 \ g/cm^2$$

$$x_0^{Pb} = \frac{1}{\rho_{Pb}} X_0^{Pb} = \frac{1}{11.34 \ g/cm^3} \cdot 5.5 \ g/cm^2 = 0.48 \ cm$$

$$x_0^{LAr} = \frac{1}{\rho_{LAr}} X_0^{LAr} = \frac{1}{1.4 \ g/cm^3} \cdot 22.2 \ g/cm^2 = 15.85 \ cm$$

if only LAr $\longrightarrow$ $22 X_0 \simeq 351 \ cm \simeq 3.5 \ m$

if only Pb $\longrightarrow$ $22 X_0 \simeq 10.6 \ cm$

A sampling calorimeter…

2

We need to compute (or search!) the critical energy for LAr:

$$E_c^{\text{sol./liq.}} = \frac{610\ \text{MeV}}{Z + 1.24}$$

$$E_c^{\text{LAr}} = \frac{610}{18+1.24}\ \text{MeV} \cong 31.7\ \text{MeV}$$

$$E_c^{\text{Pb}} = \frac{610}{82+1.24}\ \text{MeV} \simeq 7.3\ \text{MeV}$$ (we'll need it for point (3)…)

electrons!

$$t^{max} = \ln\left(\frac{E}{E_c}\right) - 1$$

$$= \ln\left(\frac{5\cdot 10^3\ \text{MeV}}{31\ \text{MeV}}\right) - 1 \cong 4 \quad (X/X_0)$$

$$t^{max} = 4\, x_0^{\text{LAr}} \simeq 63\ \text{cm}$$

A sampling calorimeter…

3

A mip just loose energy via ionisation, proportionally to the lenght transversed:

$$\frac{1}{\rho_{LAr}}\left(\frac{dE}{dx}\right)_{mip} = 1.52 \ \mathrm{MeV}/\mathrm{g\,cm^{-2}}$$

$$\left(\frac{dE}{dx}\right)_{mip} = 1.4 \ \mathrm{g\,cm^{-3}} \cdot 1.52 \ \mathrm{MeV}/\mathrm{g\,cm^{-2}} \simeq 2.1 \ \mathrm{MeV\,cm^{-1}}$$

$22 X_0$ of LAr are 351 cm (see point (1)):

$$\Delta E = \left(\frac{dE}{dx}\right)_{mip} \cdot \Delta l = 2.1 \ \mathrm{MeV}/\mathrm{cm} \cdot 351 \ \mathrm{cm}$$

$$\simeq 527 \ \mathrm{MeV} \quad \text{(not much!)}$$

A sampling calorimeter…

4

The 22 X_0 are equally divided between LAr and Pb, thus:

$$2\text{ mm LAr} \Rightarrow \frac{0.2\text{ cm}}{15.85\text{ cm}/X_0} = 0.012\ X_0$$

$$2\text{ mm Pb} \Rightarrow \frac{0.2\text{ cm}}{0.48\text{ cm}/X_0} = 0.41\ X_0$$

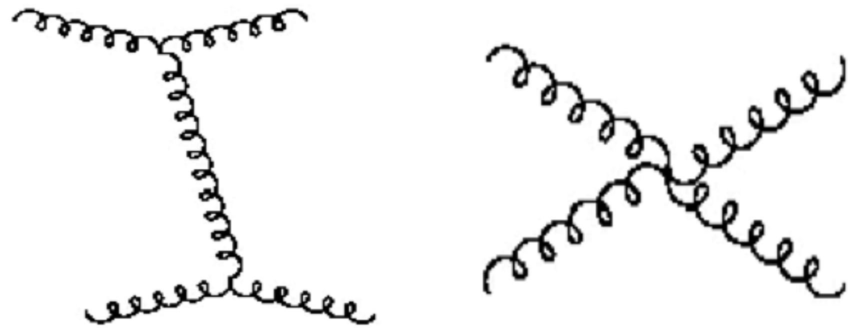
$$2\text{mm LAr} + 2\text{mm Pb} \cong 0.42\ X_0 \quad (\text{in } 4\text{ mm of detector})$$

$$22\ X_0 \Rightarrow \frac{22\ X_0}{0.42\ X_0} \cdot (4\text{ mm}) \simeq 21\text{ cm}$$

(about twice as long as when using Pb only: the LAr is almost doing nothing!)

A few words on QCD

- QCD (strong) interactions are carried out by massless spin-1 particled called gluons
  - ✓ Gluons are massless
    - Long range interaction
  - ✓ Gluons couple to color charges
  - ✓ Gluons have color themselves
    - They can couple to other gluons

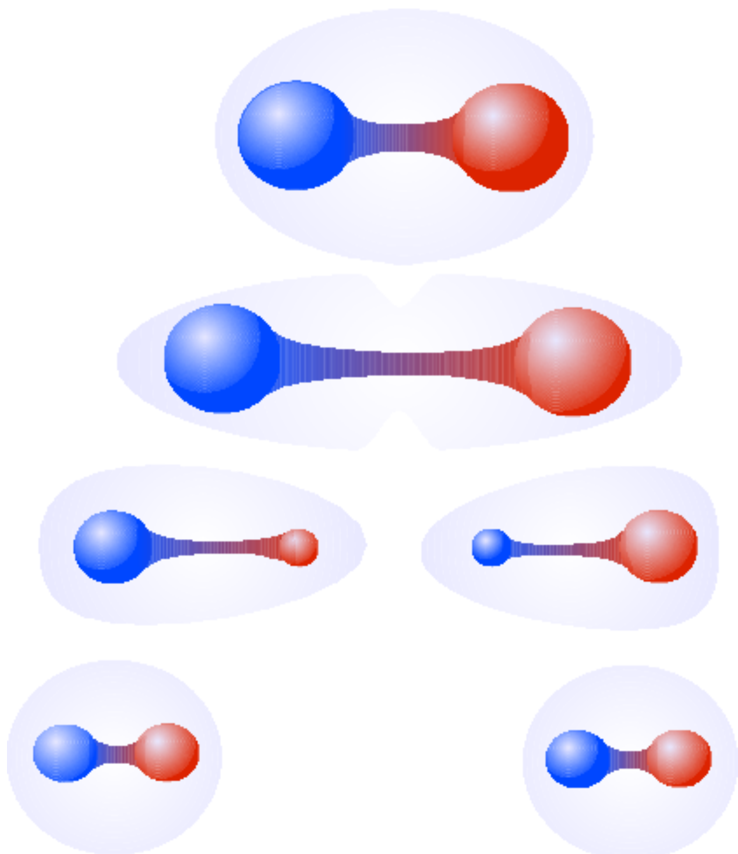


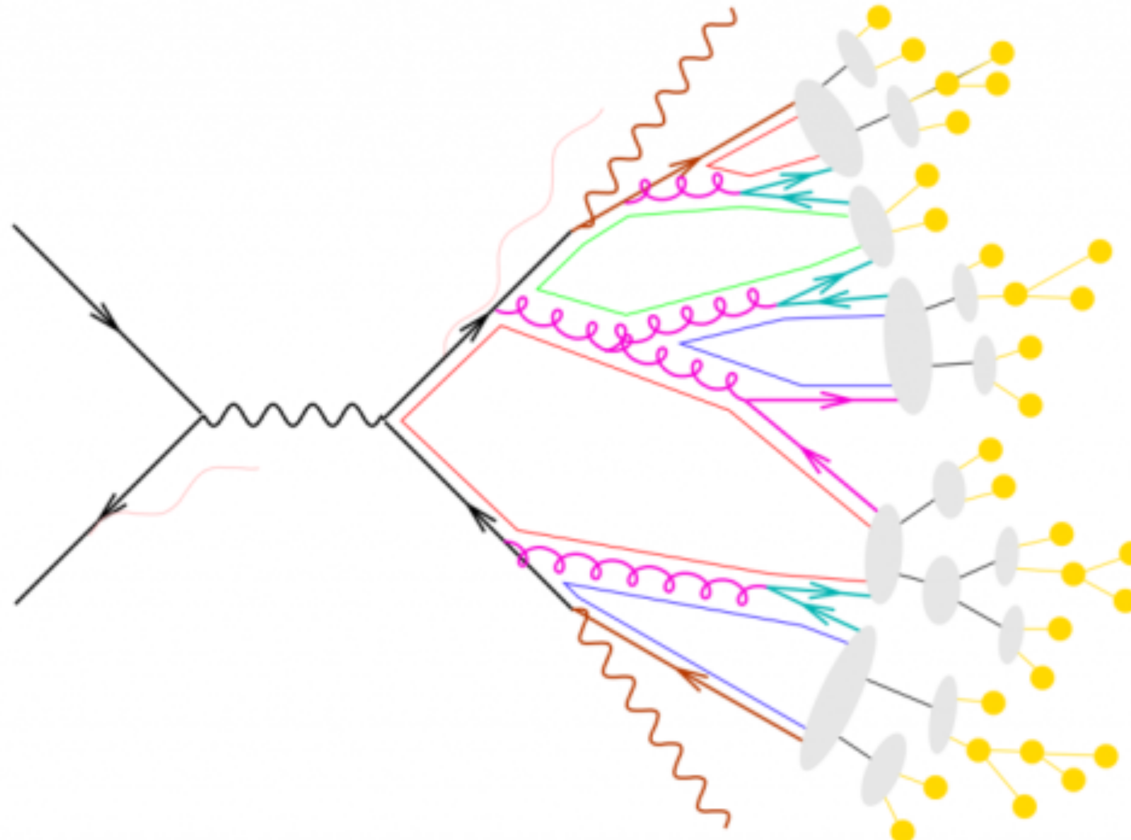
- **Principle of asymptotic freedom**
  - ✓ At short distances strong interactions are weak
    - Quarks and gluons are essentially free particles
    - Perturbative regime (can calculate!)
  - ✓ At large distances, higher-order diagrams dominate
    - Interaction is very strong
    - Perturbative regime fails, have to resort to effective models

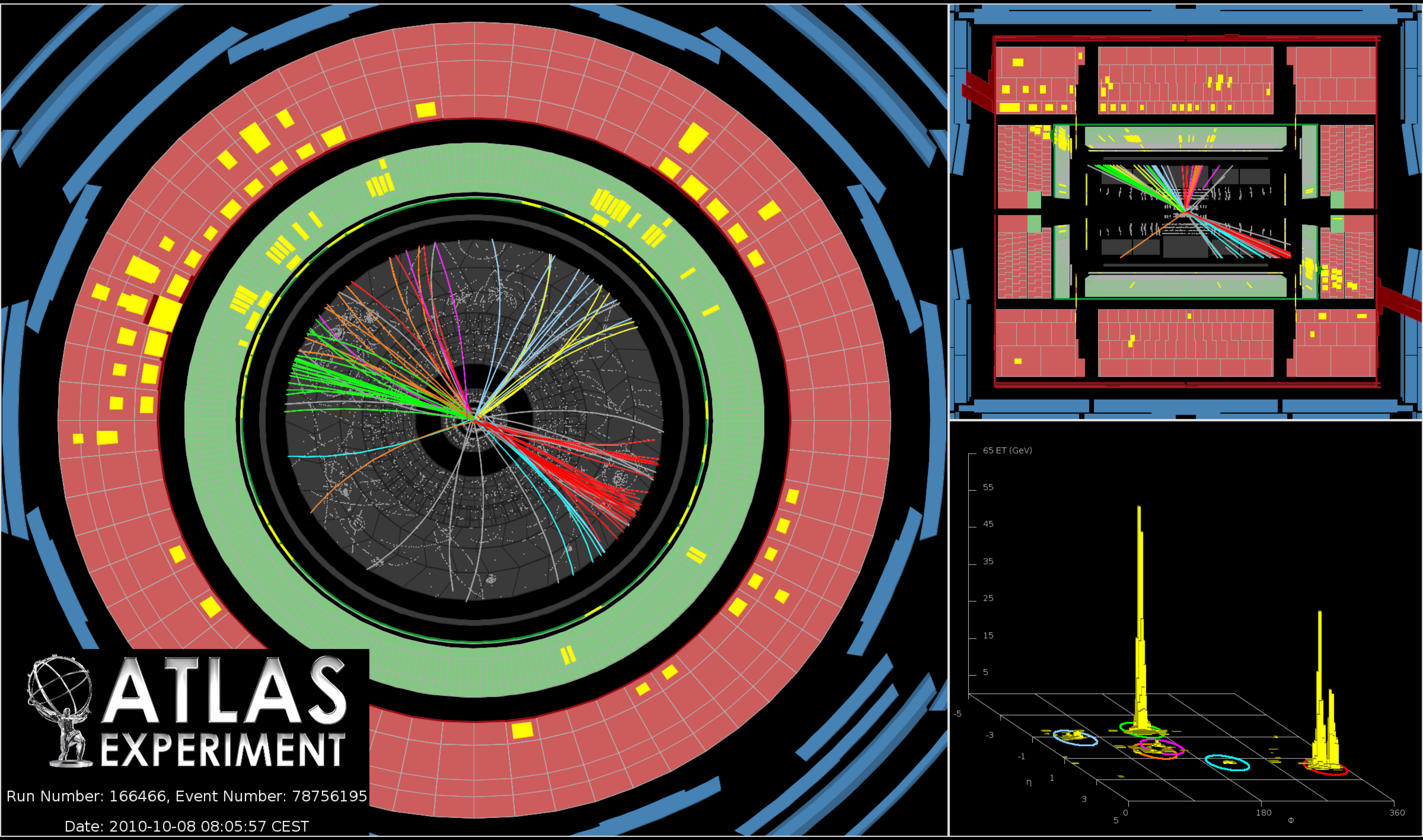
quark-quark effective potential

$$V_s = \underbrace{-\frac{4}{3}\frac{\alpha_s}{r}}_{\text{single gluon exchange}} + \underbrace{kr}_{\text{confinement}}$$

Confinement, hadronization, jets

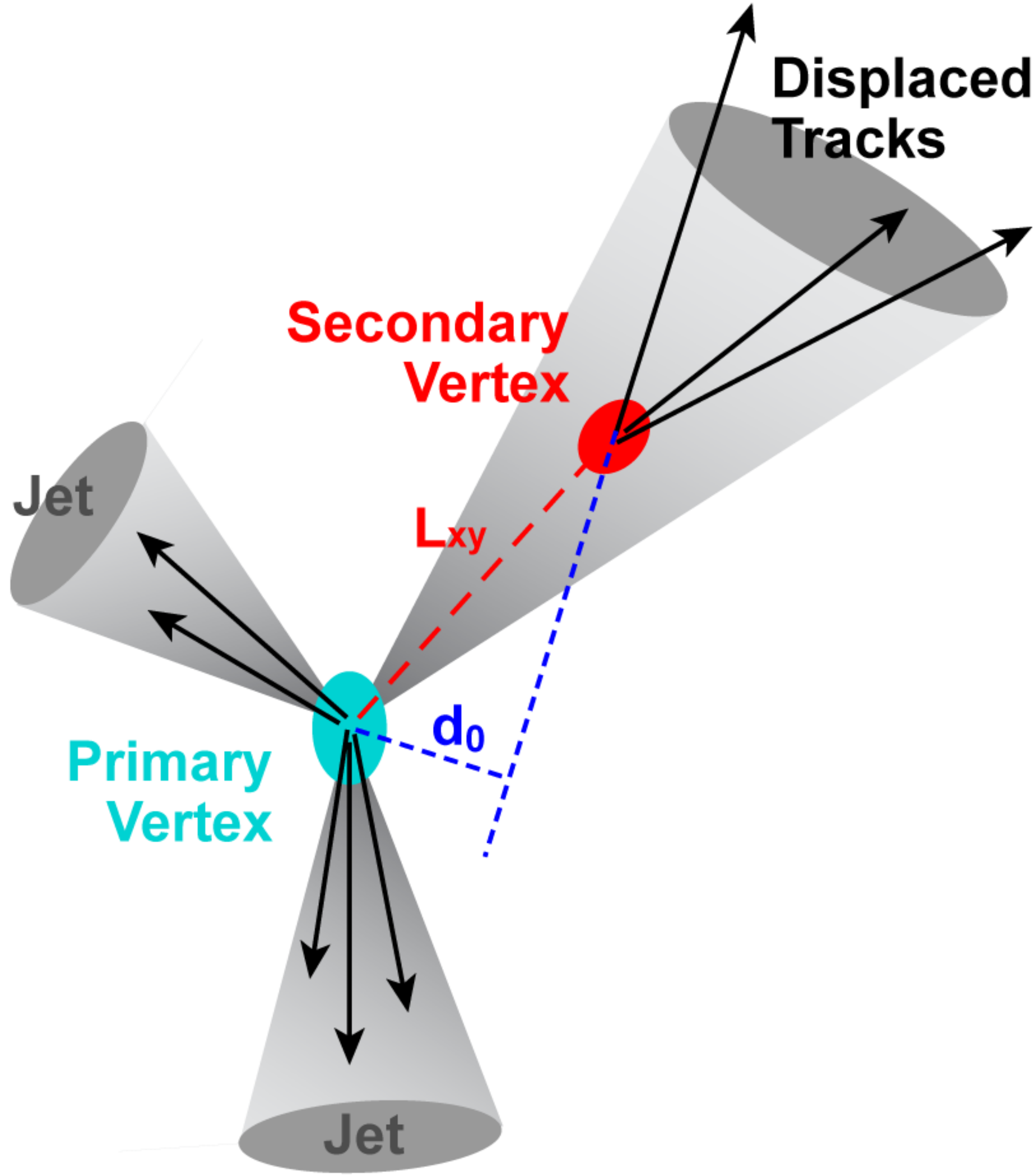





ATLAS
EXPERIMENT
Run Number: 166466, Event Number: 78756195
Date: 2010-10-08 08:05:57 CEST
65 ET (GeV)
55
45
35
25
15
5
-5
-3
-1
η
1
3
5
0
180
Φ
360

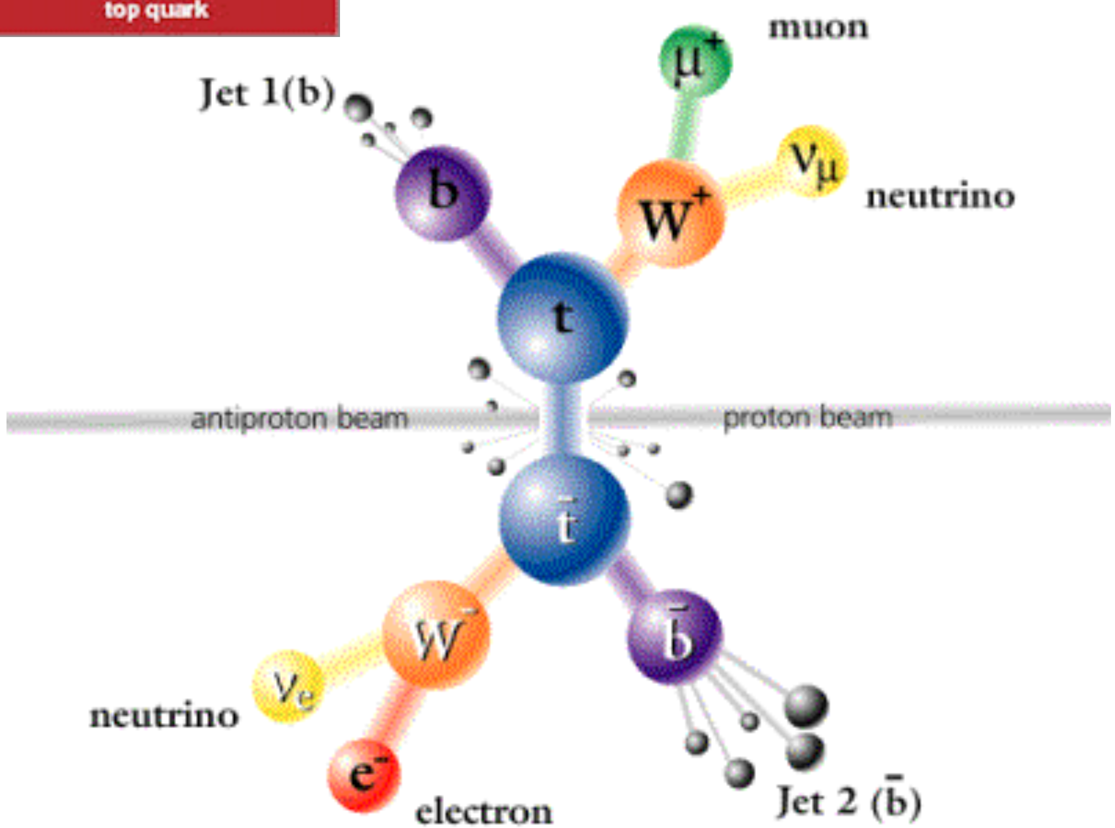
B-tagging

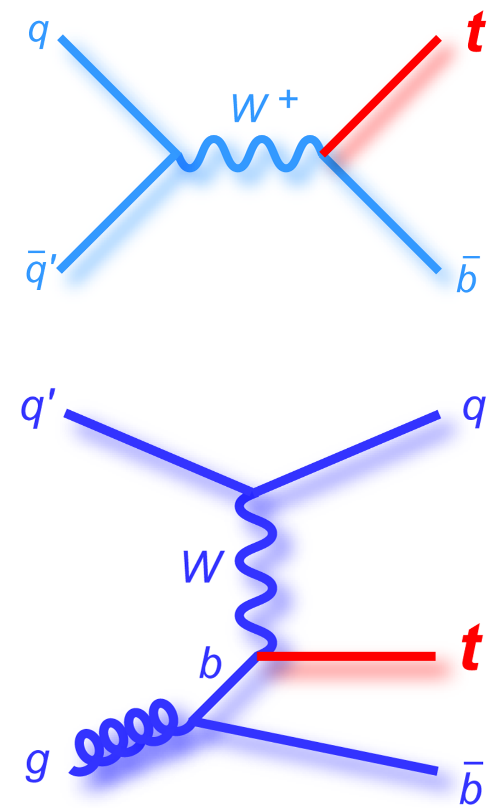
- When a b quark is produced, the associated jet will very likely contain at least one B meson or hadron
- B mesons/hadrons have relatively long lifetime
  - ✓ They will travel away form collision point before decaying
- Identifying a secondary decay vertex in a jet allow to tag its quark content
- Similar procedure for c quark…



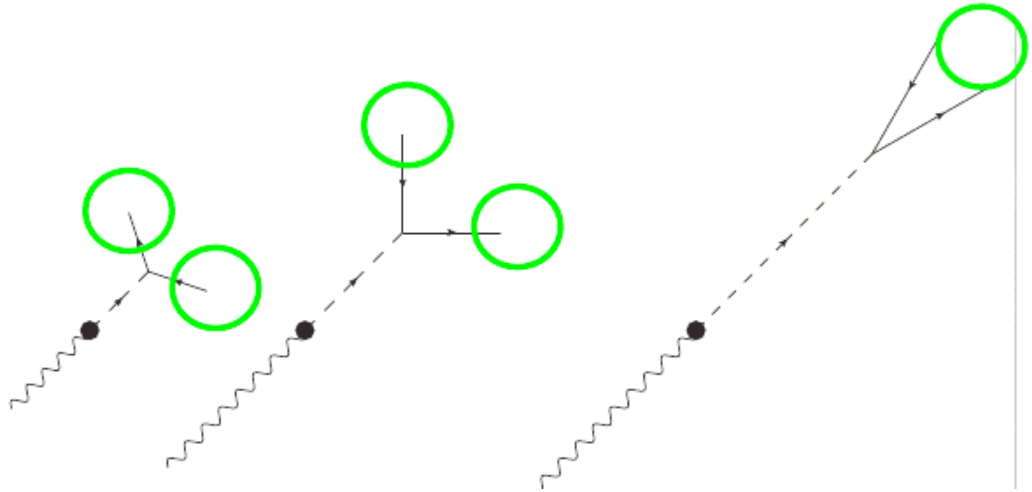
top quark

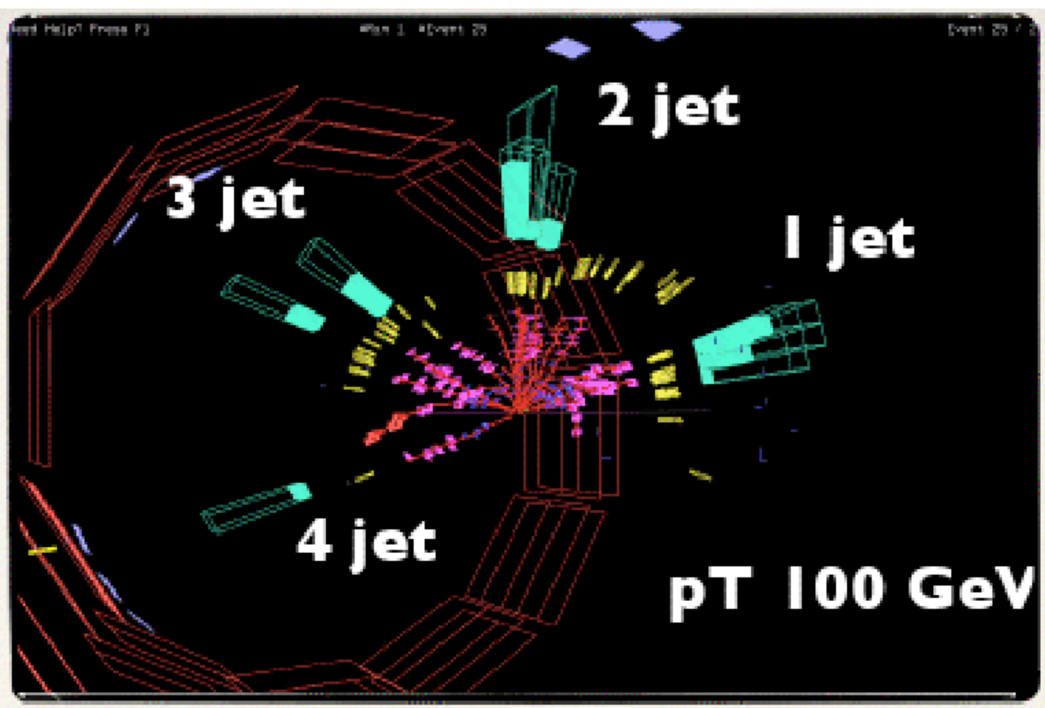
- Top quark has a mean lifetime of 5×10^{-25} s, shorter than time scale at which QCD acts: not time to hadronize!
  - ✓ It decays as $t \rightarrow Wb$
- Events with top quarks are very rich in (b) jets…





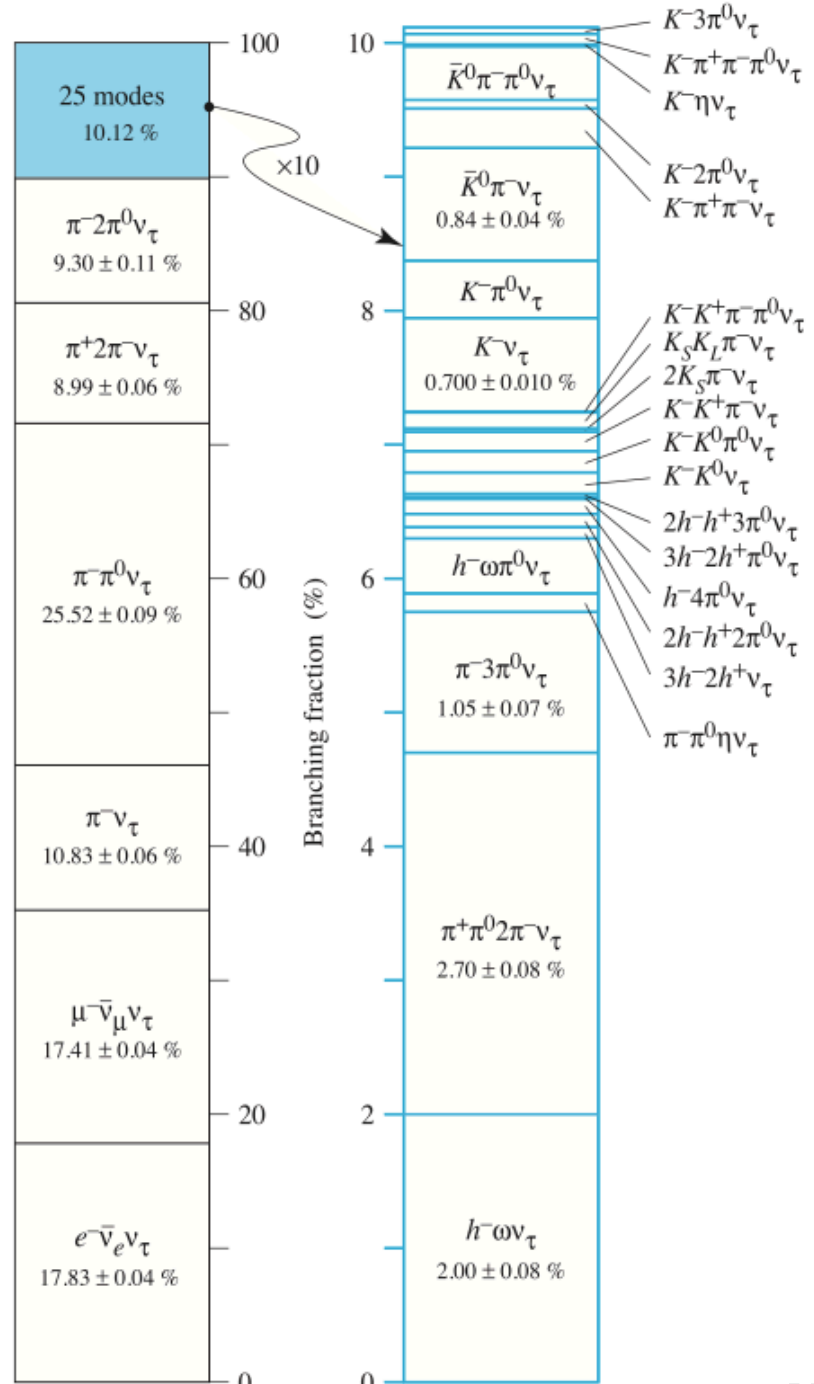
Boosted jets and jet substructure

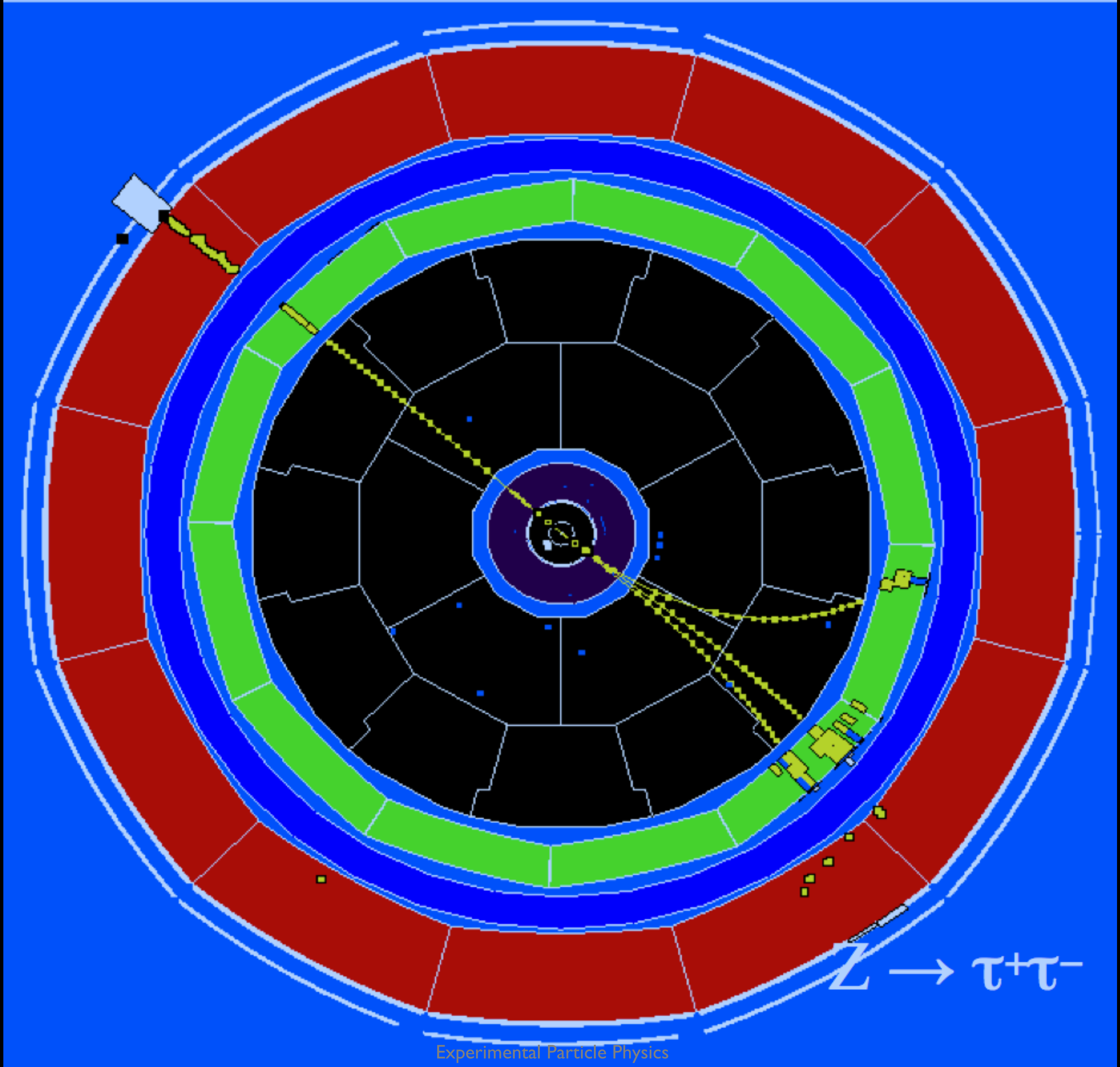




Tau

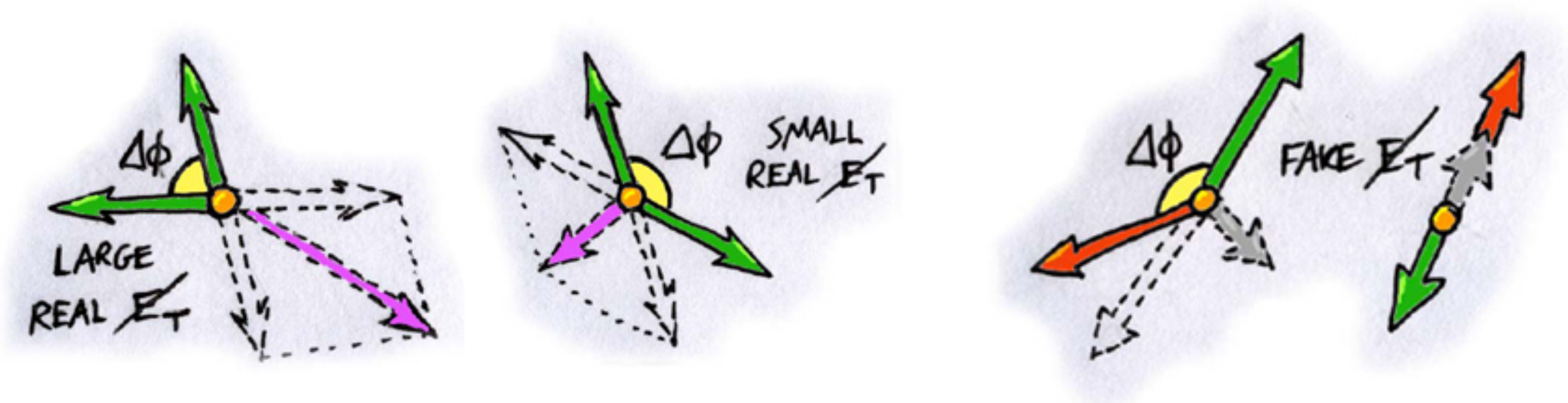
- Tau are heavy enough that they can decay in several final states
  - ✓ Several of them with hadrons
  - ✓ Sometimes neutral hadrons
- Lifetime = 0.29 ps
  - ✓ 10 GeV tau flies ~ 0.5 mm
  - ✓ Typically too short to be directly seen in the detectors
- Tau needs to be identifies by their decay products
- Accurate vertex detectors can detect that they do not come exactly from the interaction point




$Z \to \tau^+\tau^-$

Neutrino (and other invisible particles) at colliders

- Interaction length $\lambda_{int} = A / (\rho\ \sigma\ N_A)$
- Cross section $\sigma \sim 10^{-38}$ cm^2 × E [GeV]
  - ✓ This means 10 GeV neutrino can pass through more then a million km of rock
- Neutrinos are usually detected in HEP experiments through *missing (transverse) energy*



- Missing energy resolution depends on
  - ✓ Detector acceptance
  - ✓ Detector noise and resolution (e.g. calorimeters)