# Experimental particle physics

esipap...

European School of Instrumentation in Particle & Astroparticle Physics

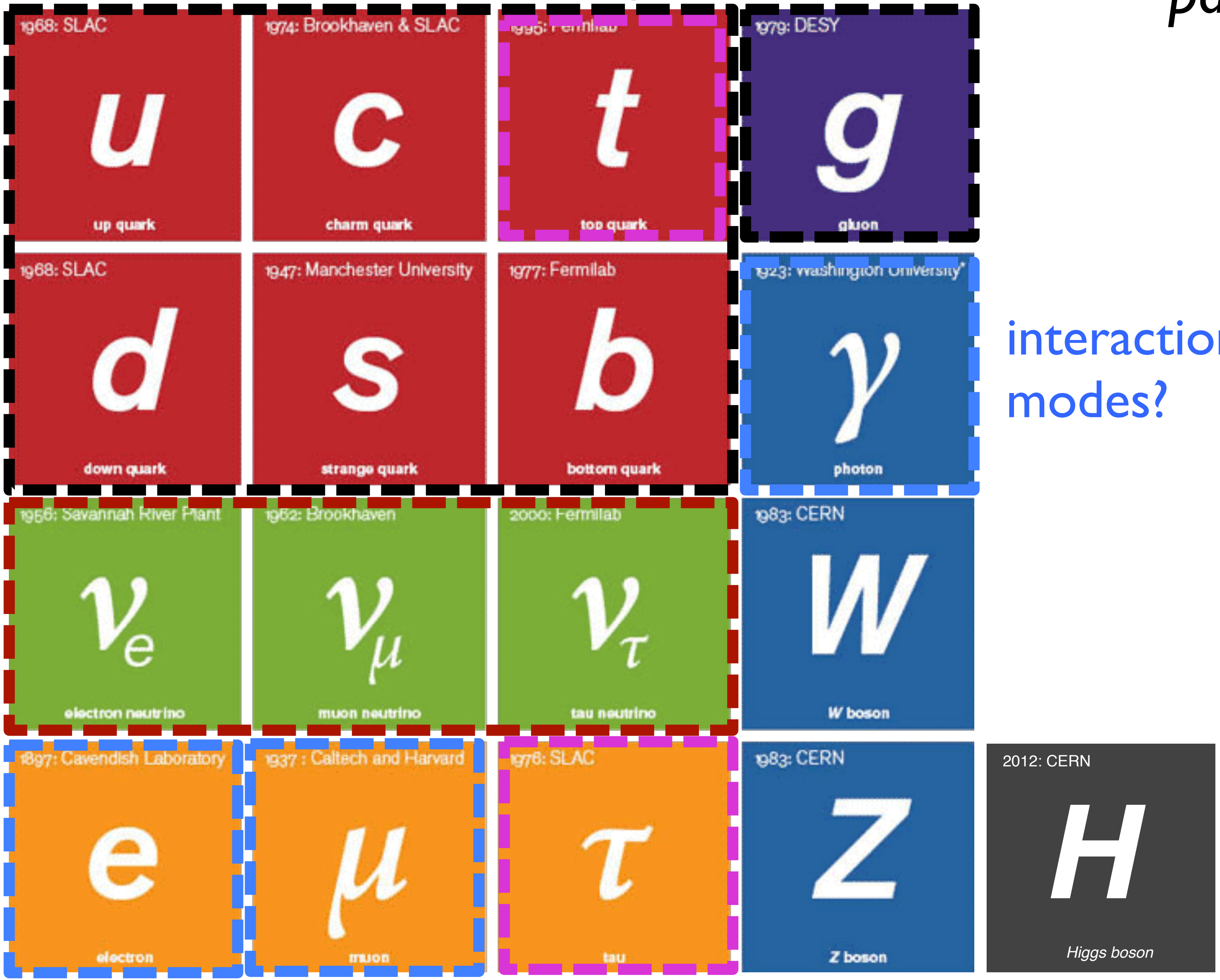
## 4.

## systems used to identify and measure particle properties

# 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

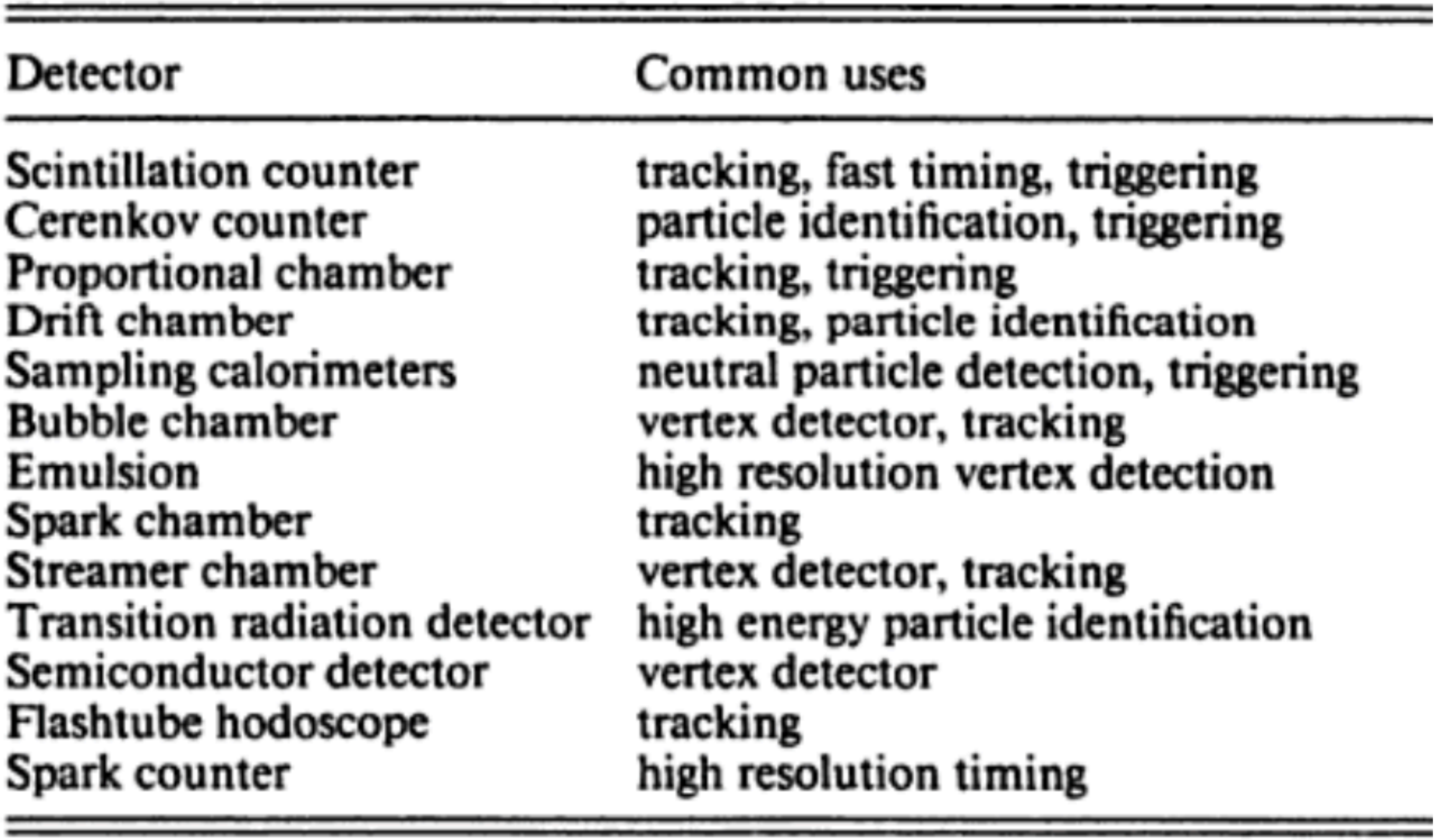
- electrically charged
- ionization (dE/dx)
- can emit photons
  - ✓ electromagnetic shower induced by emitted photon

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

- produce hadron(s) jets via QCD hadronization process

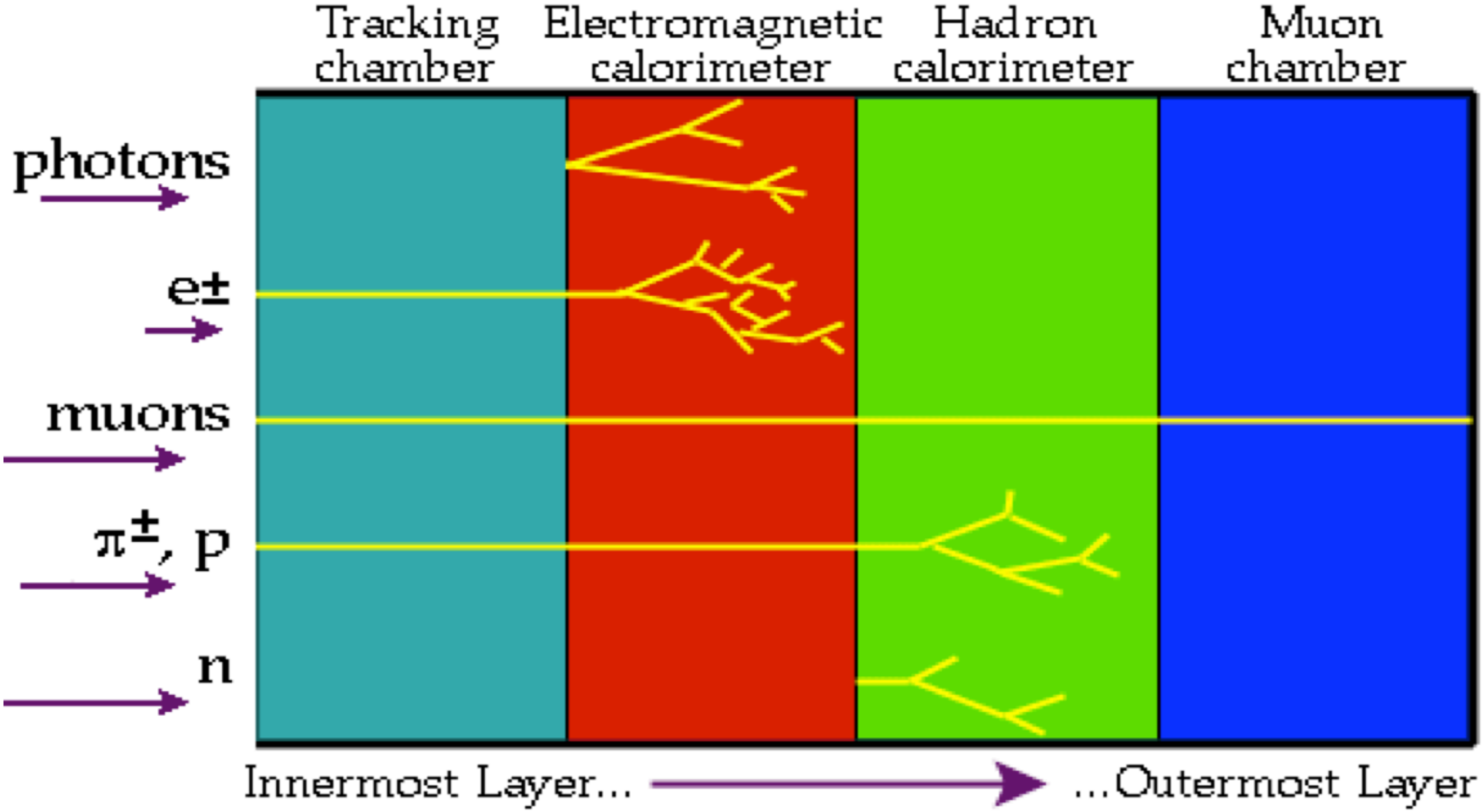
# What should a particle experiment do?

- 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?



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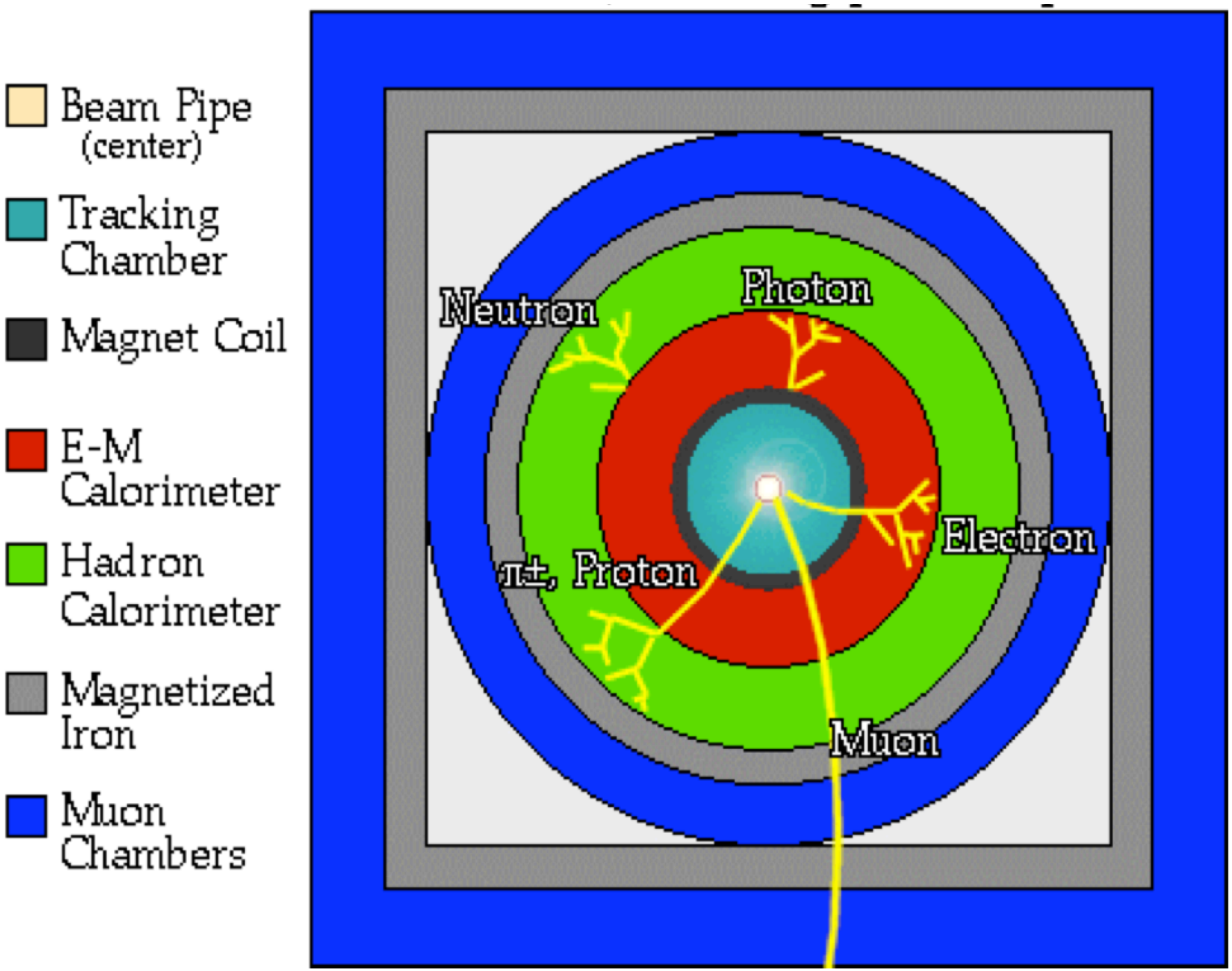
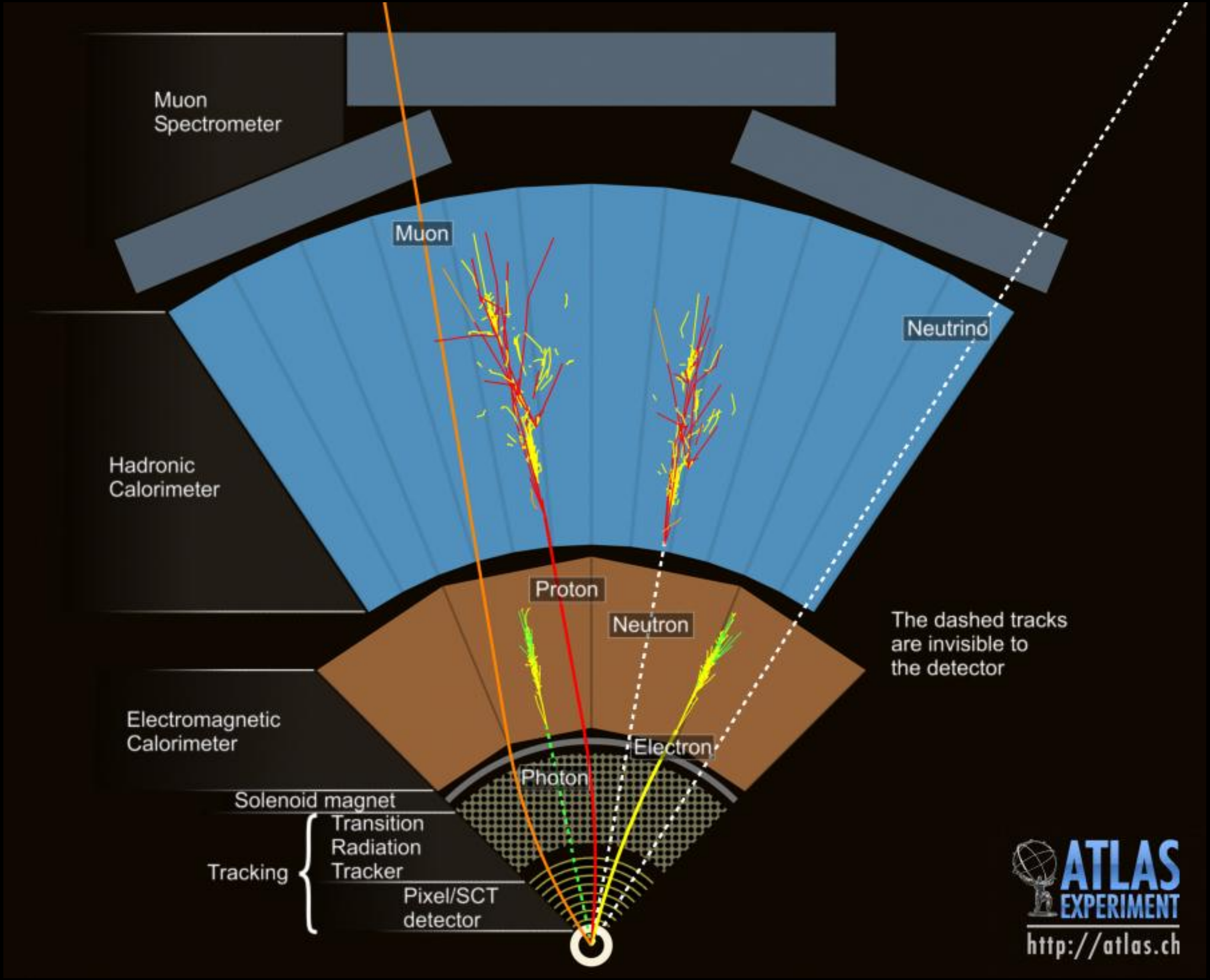


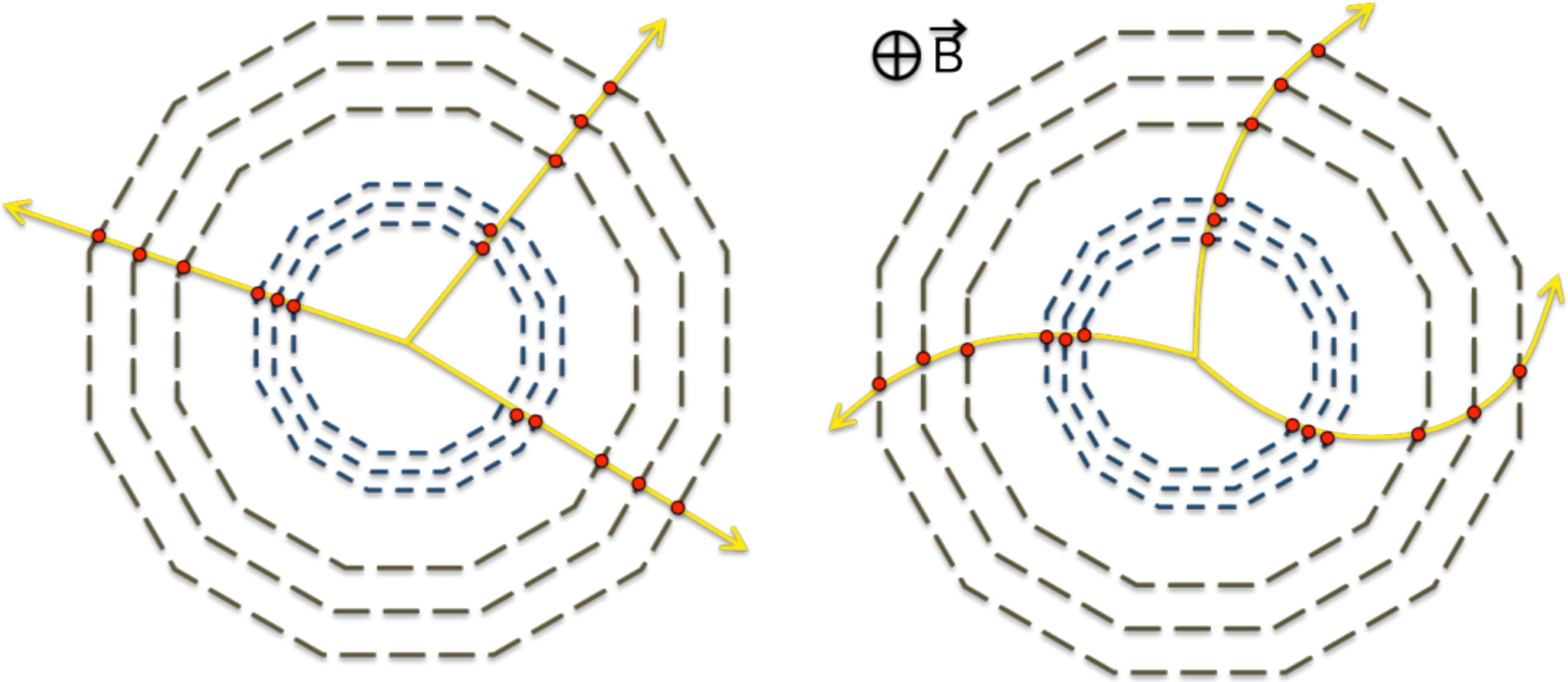
# How do we "see" particles?



The dashed tracks are invisible to the detector

# Magnetic spectrometer

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



# Magnetic spectrometer

Charged particle in magnetic field

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

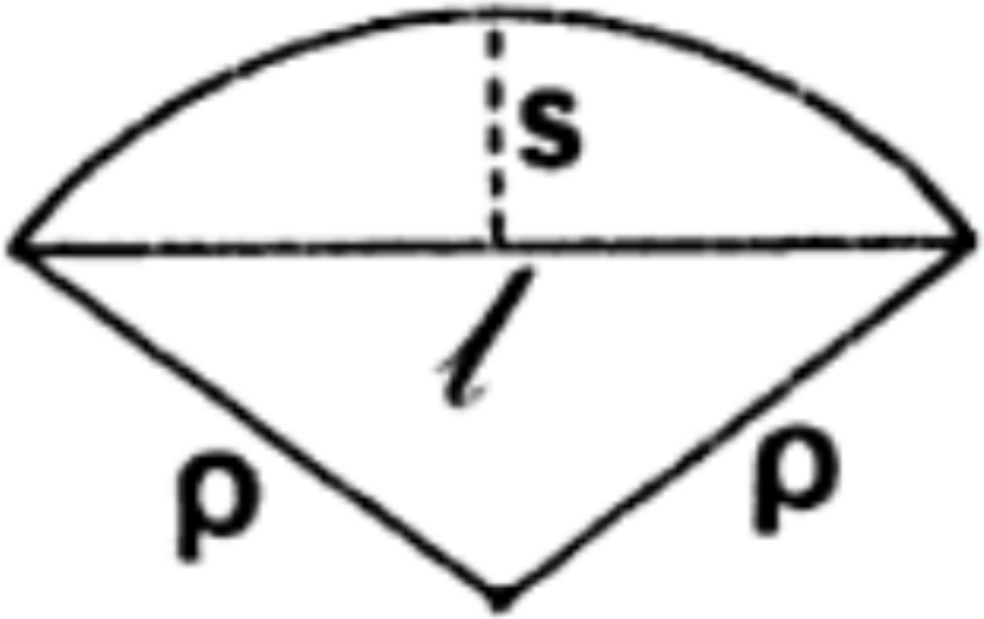
If the field is constant and we neglect presence of matter, momentum magnitude is constant with time, trajectory is helical

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

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

$$\rho \simeq \frac{l^2}{8s} \qquad p = 0.3\frac{Bl^2}{8s} \qquad \left|\frac{\delta p}{p}\right| = \left|\frac{\delta s}{s}\right|$$

# Momentum resolution

Momentum resolution due to measurement error

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

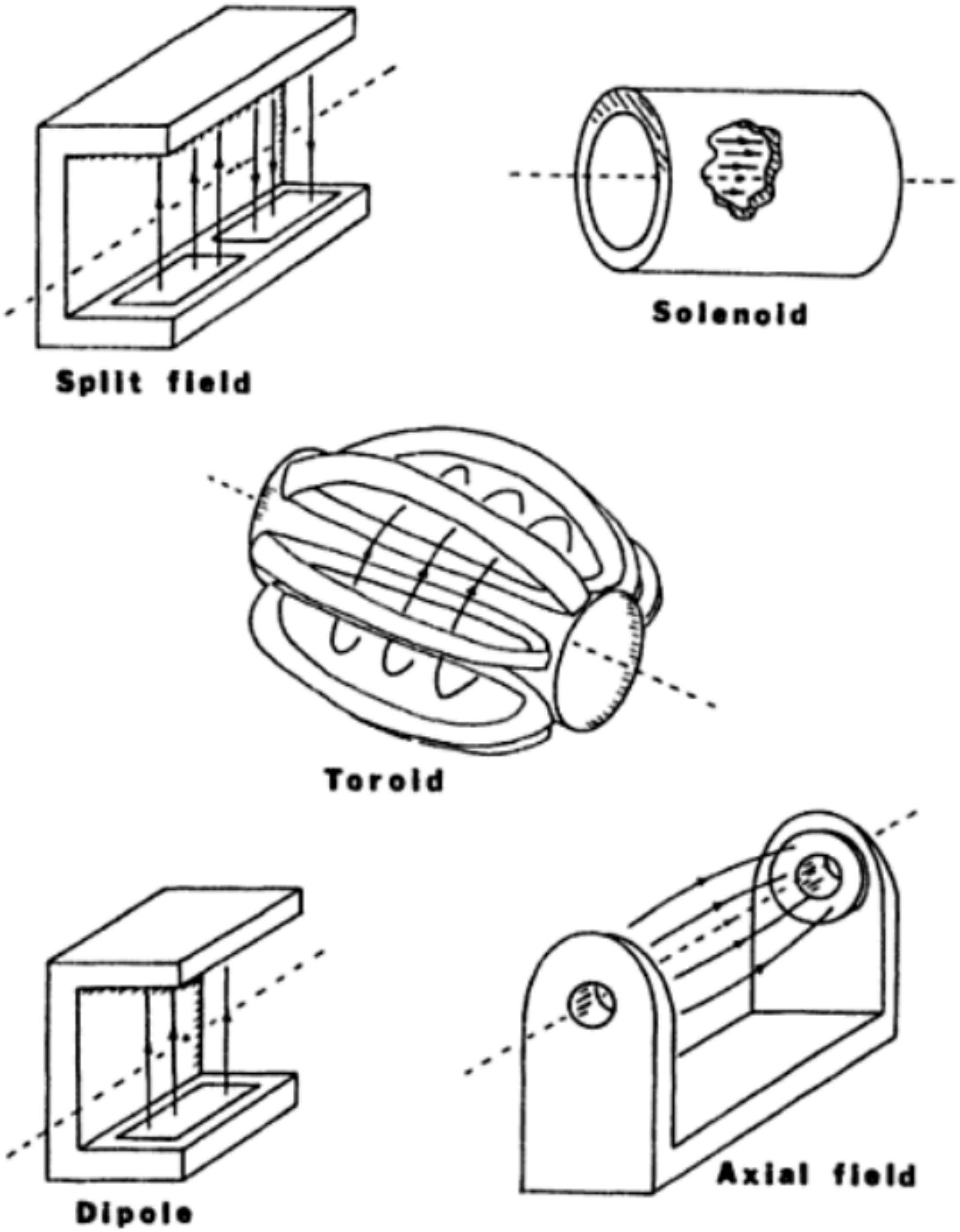
*resolution is improved faster by increasing L then B*

*Momentum resolution gets worse for larger momenta*

Momentum resolution due to multiple scattering

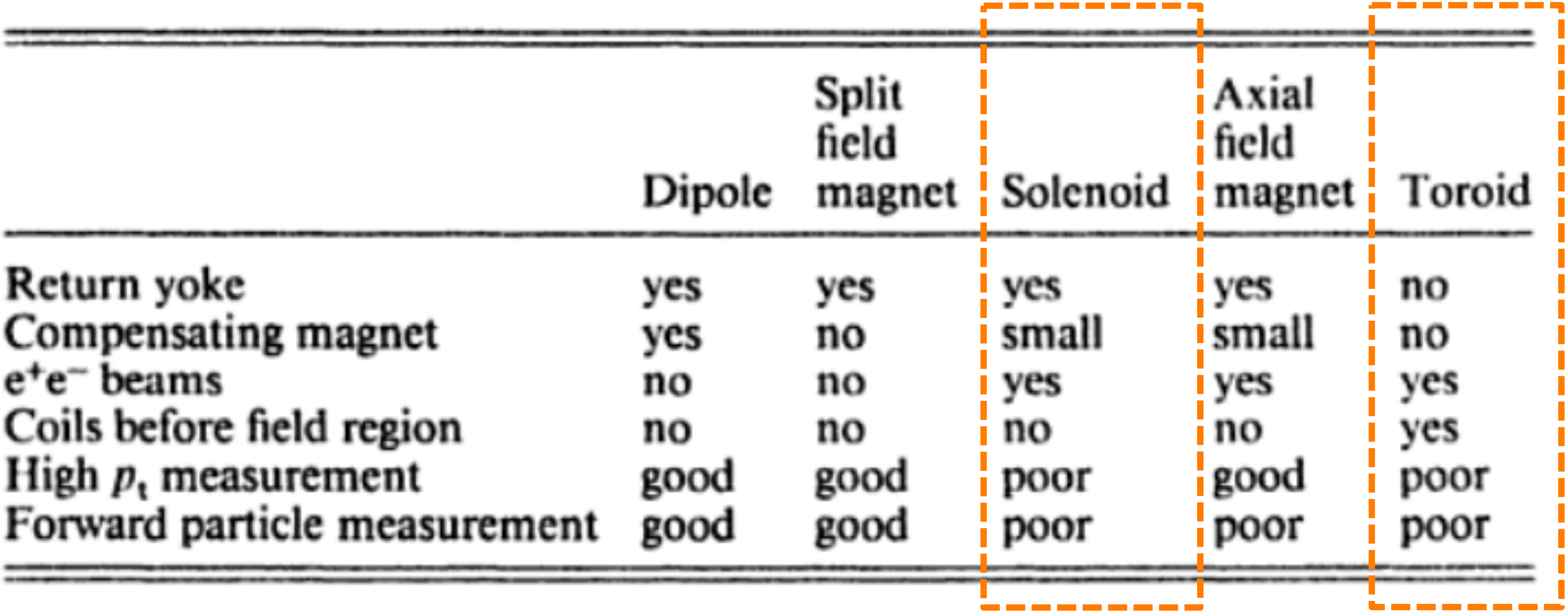
$$\left|\frac{\delta p}{p}\right| = \frac{p}{0.3B}\sqrt{\frac{\overbrace{\xi}^{\textit{RMS of projected angle per unit thickness}}\overbrace{C_N}^{\sim 1.43}}{L}}$$

# 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

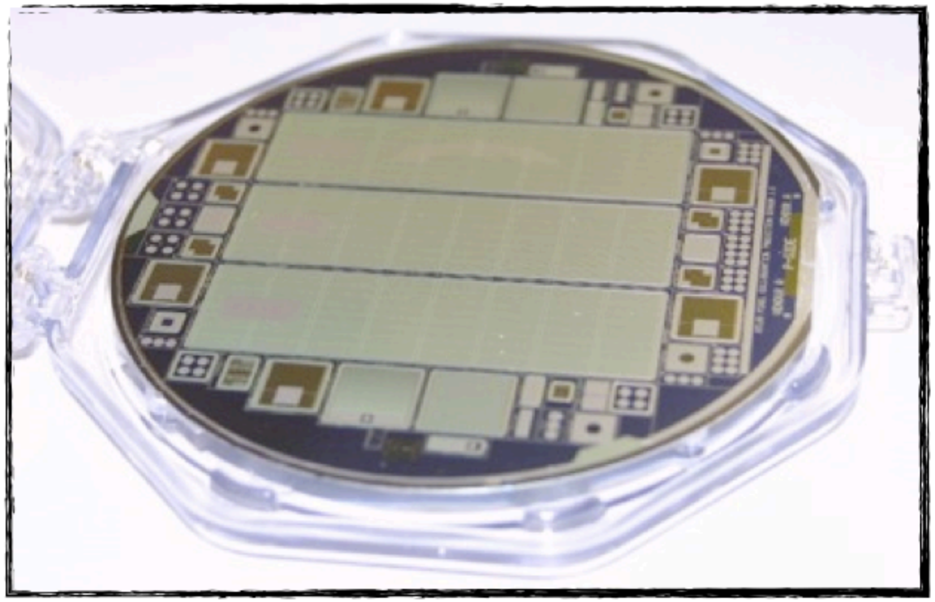
- **Muon spectrometer**
  - ✓ Drift chambers
  - ✓ MWPC (Multi Wire Proportional Chambers)
  - ✓ RPC (Resistive Place Chambers)

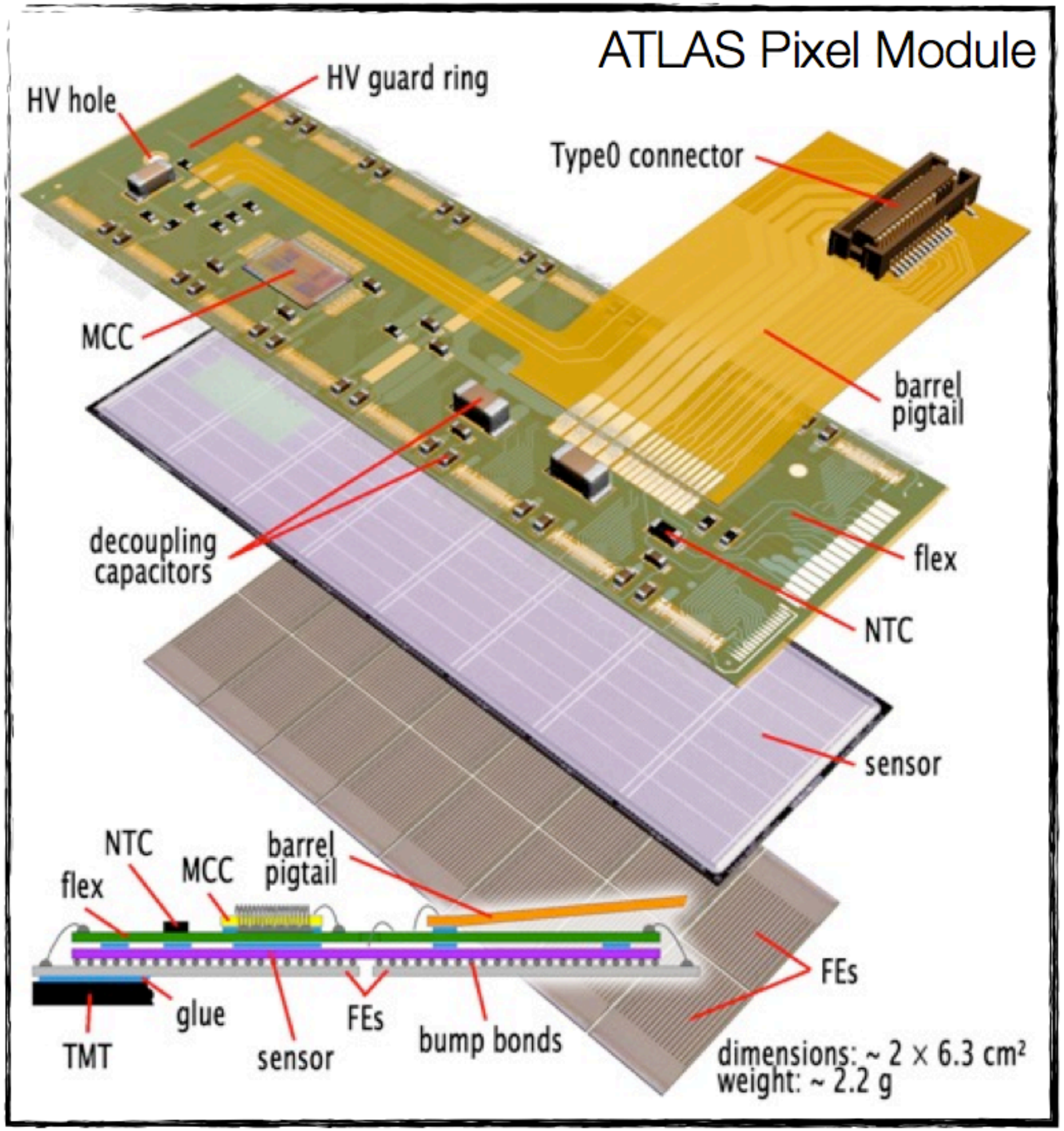
# Semiconductor detectors

ATLAS
Pixel Detector

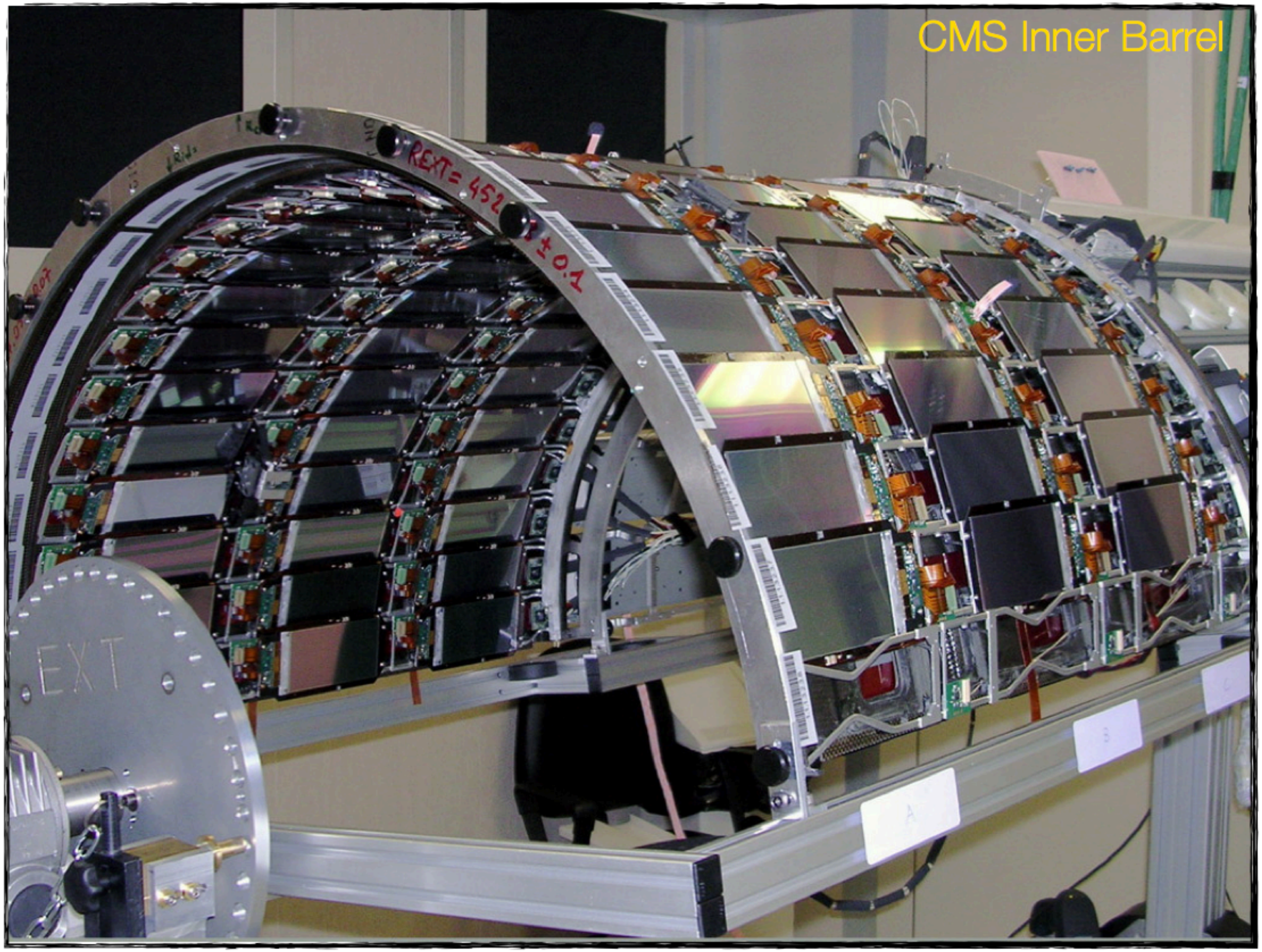
[Details]

Pixel Sensor

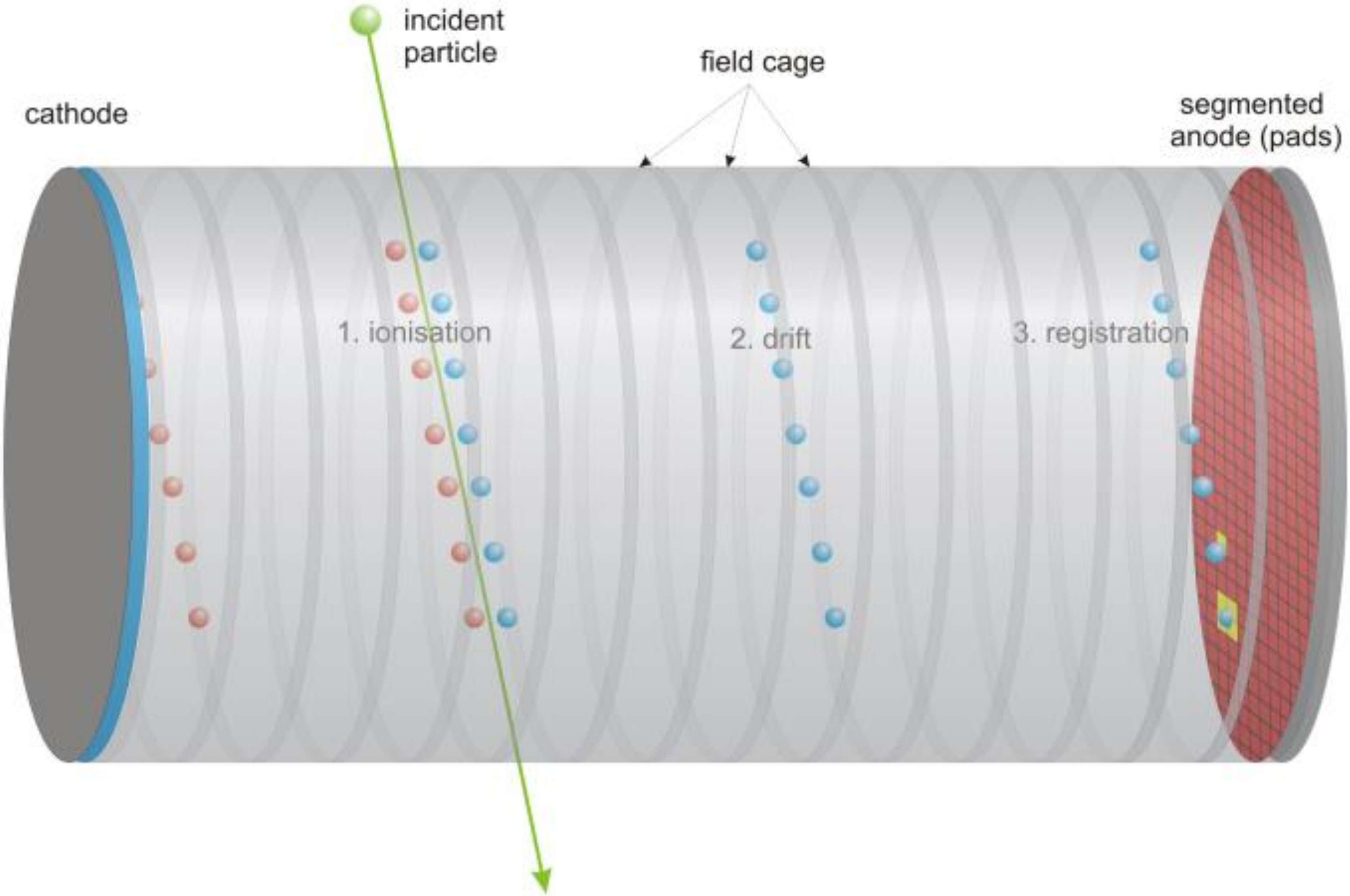




# Semiconductor detectors



# 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: > $10^4$

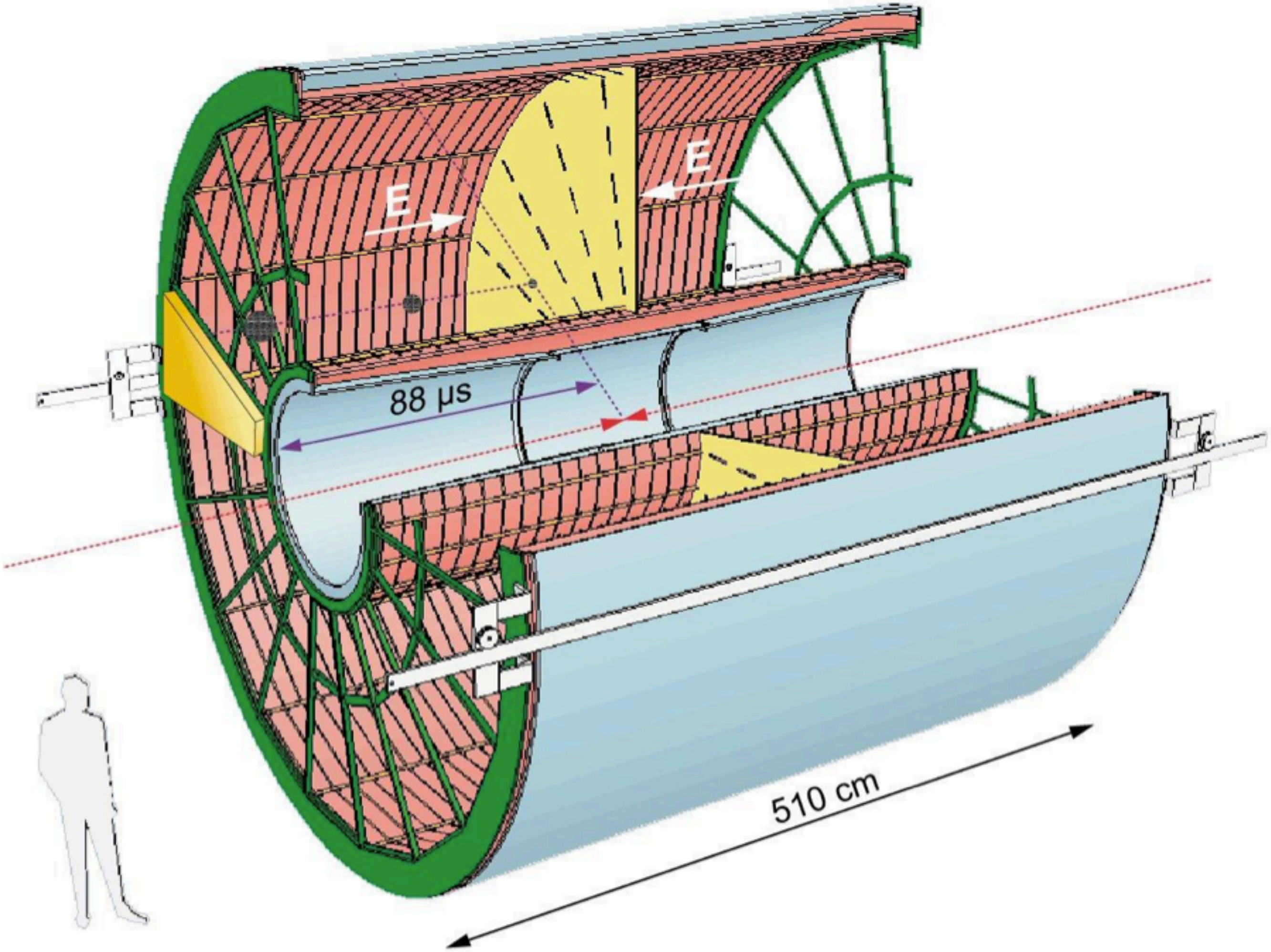
Diffusion: $\sigma_t$ = 250 μm
Resolution: $\sigma \approx$ 0.2 mm

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

Magnetic field: 0.5 T

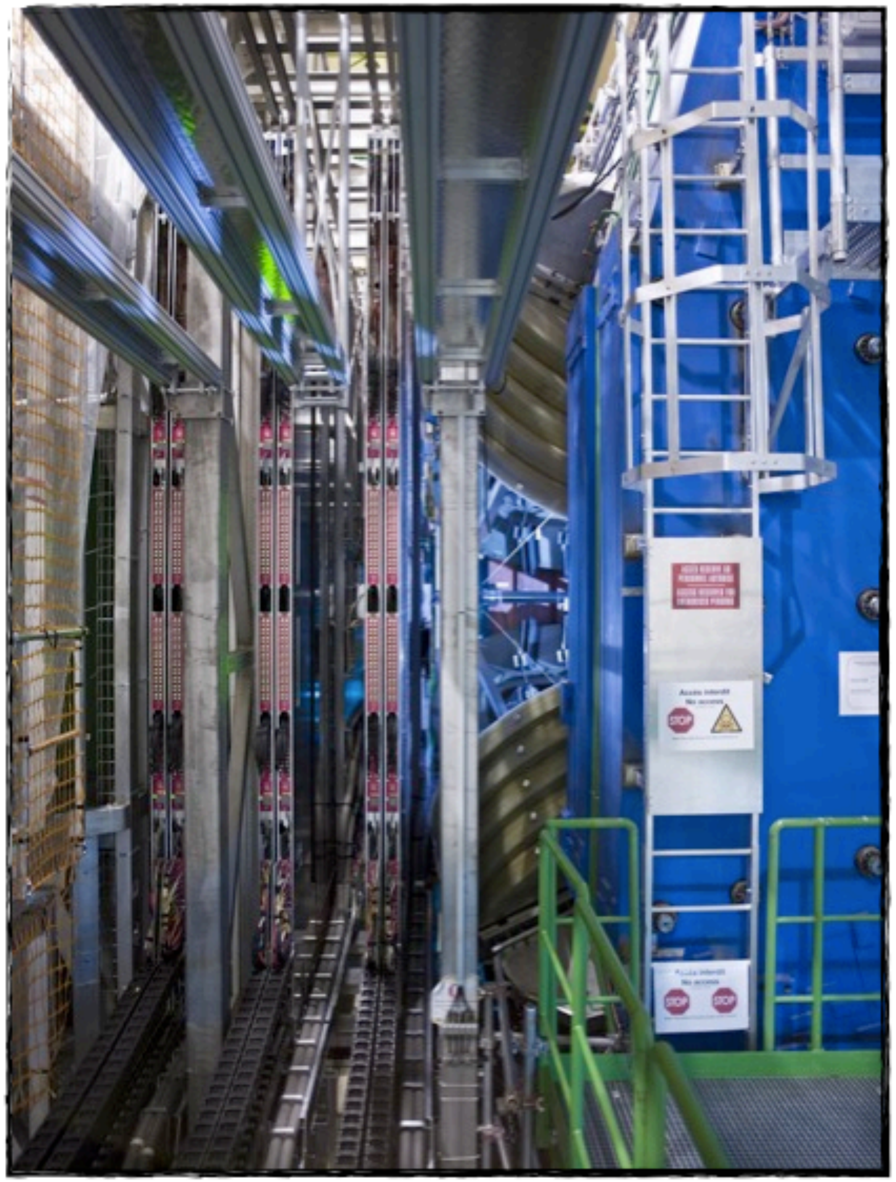
Pad size: 5x7.5 $mm^2$ (inner)
6x15 $mm^2$ (outer)

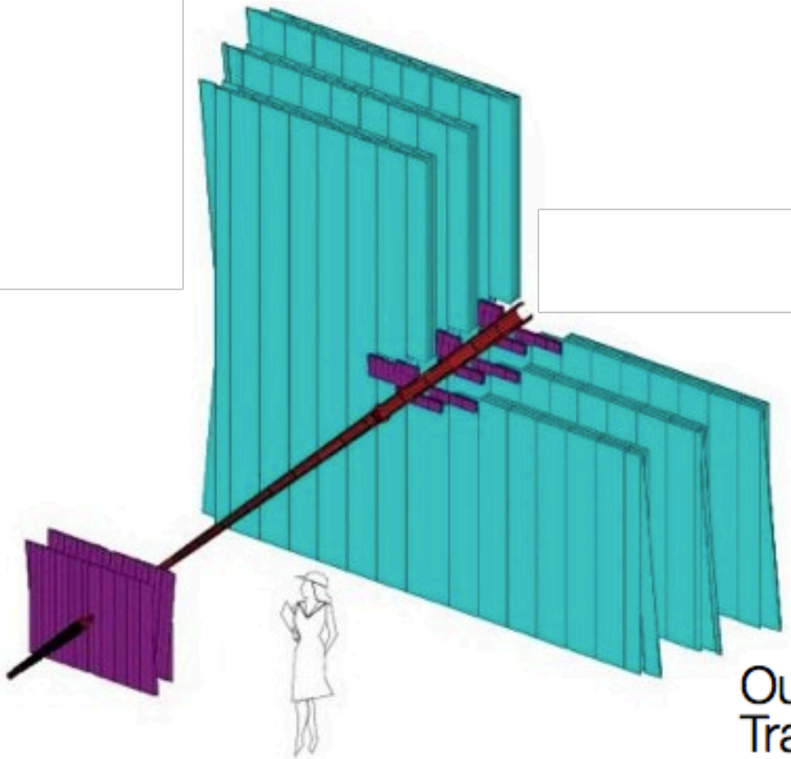
Temperature control: 0.1 K
[also resistors ...]



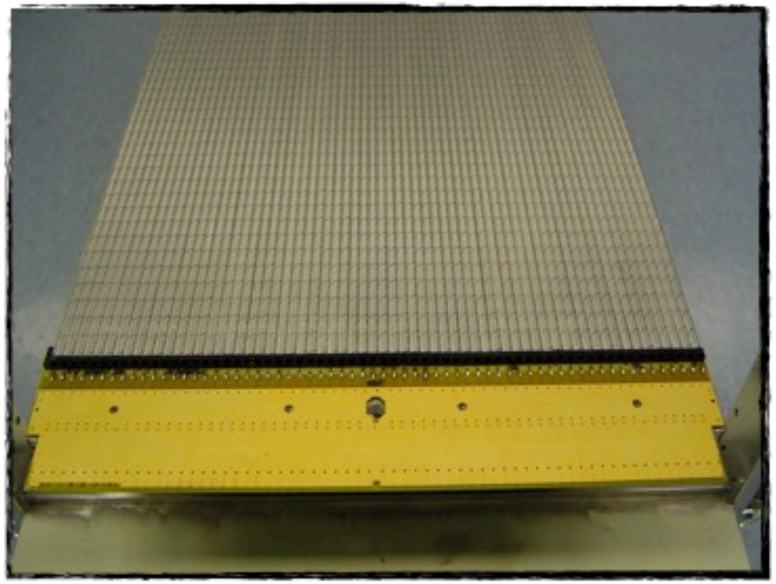
Material: Cylinder build from composite material of airline industry ($X_0$= ~ 3%)

# LHC outer tracker

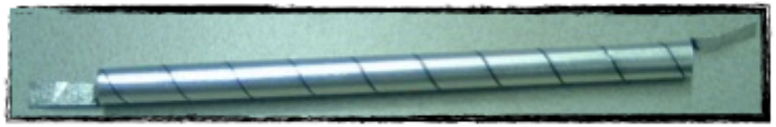




Outer Tracker

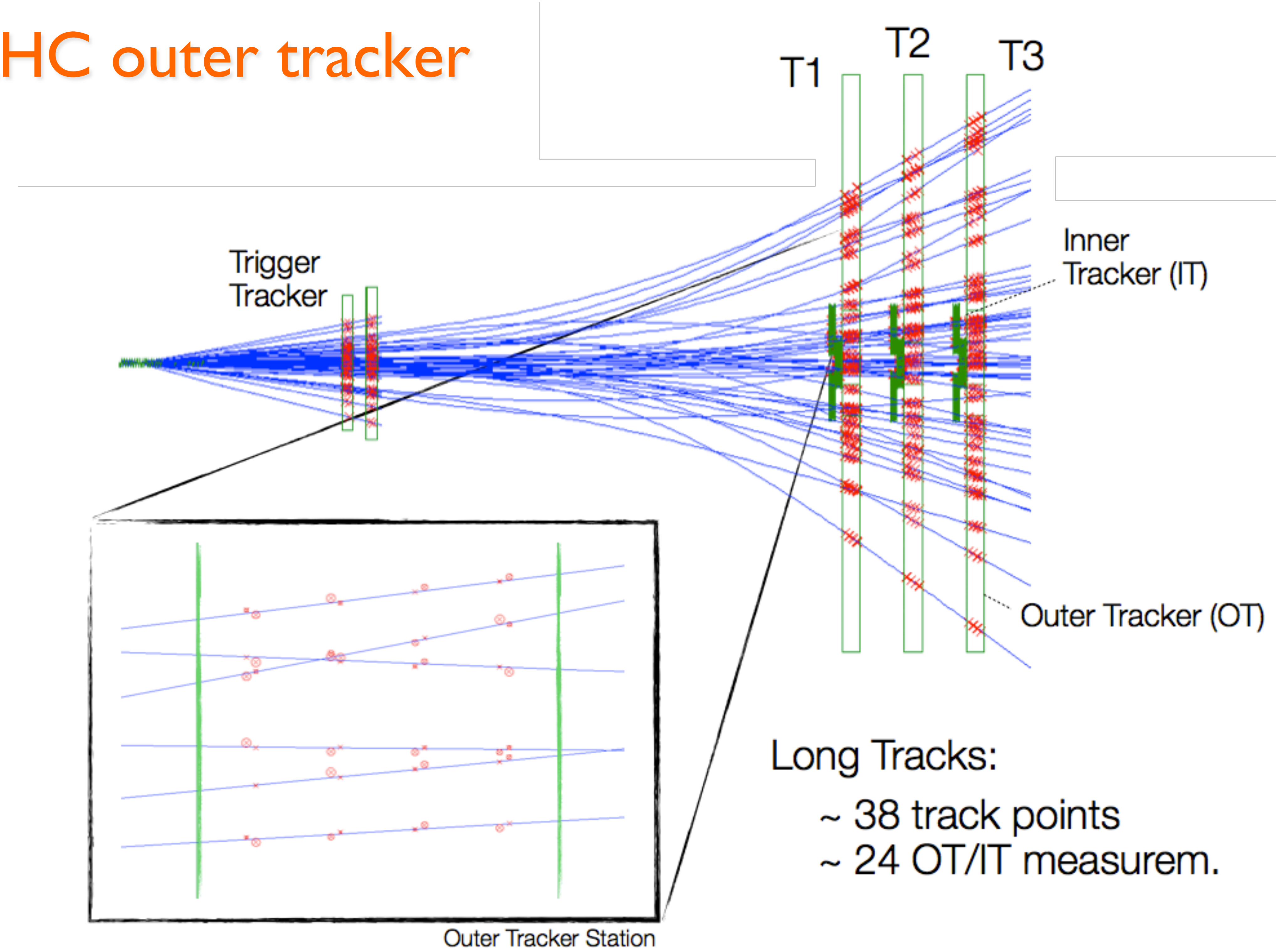


Straw Tubes
[double layers]



3 Chambers
[4 layers á 18 modules]

# LHC outer tracker

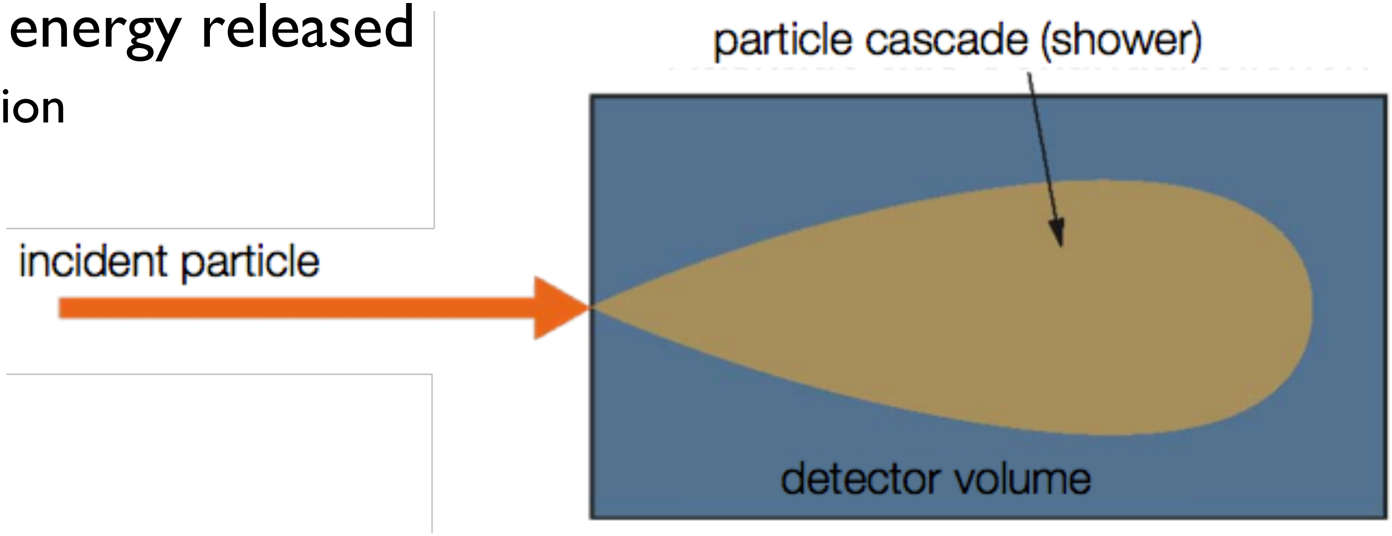


Long Tracks:

- ~ 38 track points
- ~ 24 OT/IT measurem.

# 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 4$\pi$-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

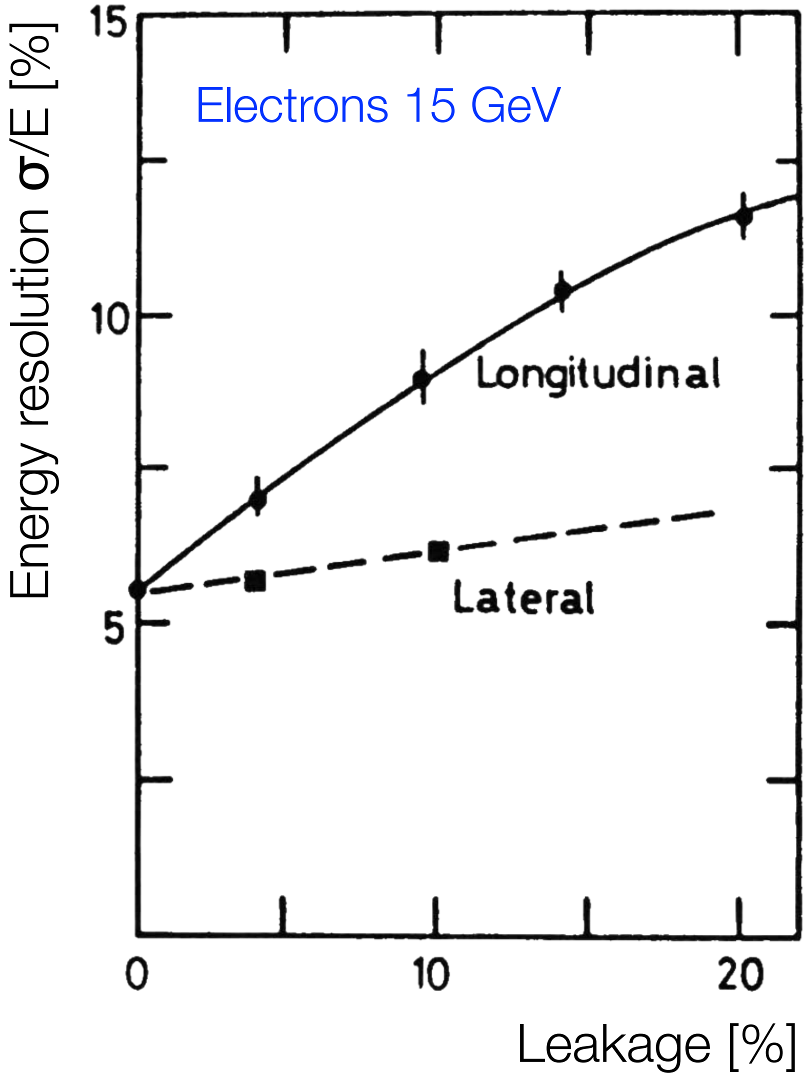
Typical expression
when including leakage effects:

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

[ $f$ : average fraction of shower leakage]

Remark: other parameterizations exist ...

Marmor Calorimeter
[CHARM Collaboration]



# Energy vs. momentum

## Energy vs. momentum measurement:

Calorimeter: $$\frac{\sigma_E}{E} \sim \frac{1}{\sqrt{E}}$$
[see below]

e.g. ATLAS:
$$\frac{\sigma_E}{E} \approx \frac{0.1}{\sqrt{E}}$$
i.e. $\sigma_E/E$ = 1% @ 100 GeV

Gas detector: $$\frac{\sigma_p}{p} \sim p$$
[see above]

e.g. ATLAS:
$$\frac{\sigma_p}{p} \approx 5 \cdot 10^{-4} \cdot p_t$$
i.e. $\sigma_p/p$ = 5% @ 100 GeV

At very high energies one has to switch to calorimeters because their resolution improves while those of a magnetic spectrometer decreases with E ...

## Shower depth:

Calorimeter: $$L \sim \ln \frac{E}{E_c}$$
[see below]

[$E_c$: critical energy]

Shower depth nearly energy independent
i.e. calorimeters can be compact ...

Compare with magnetic spectrometer: $\sigma_p/p \sim p/L^2$
Detector size has to grow quadratically to maintain resolution

# 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]

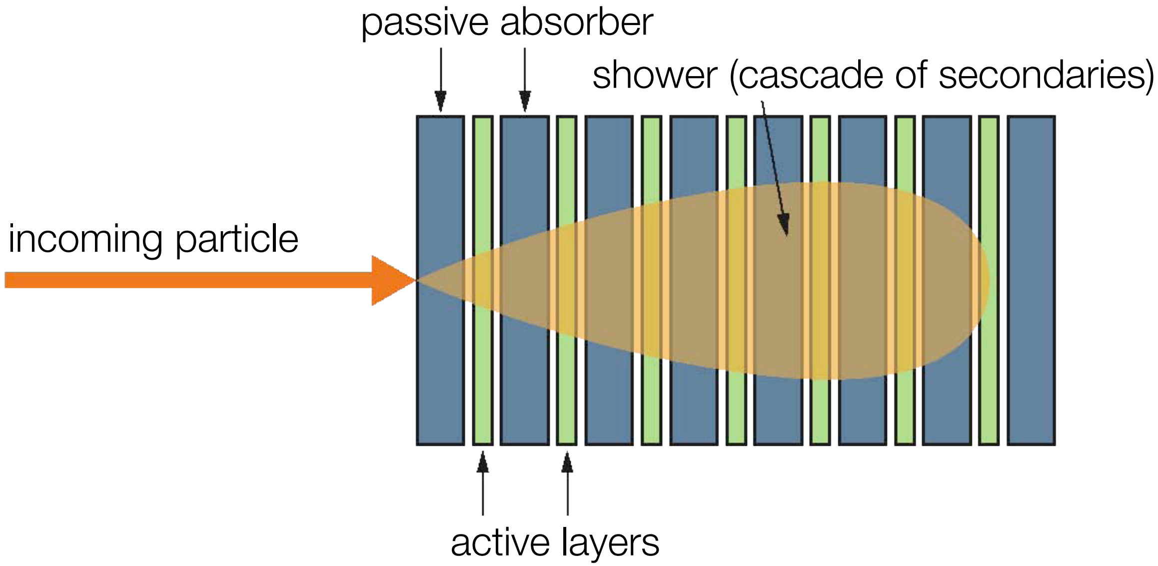
Absorber materials:
[high density]

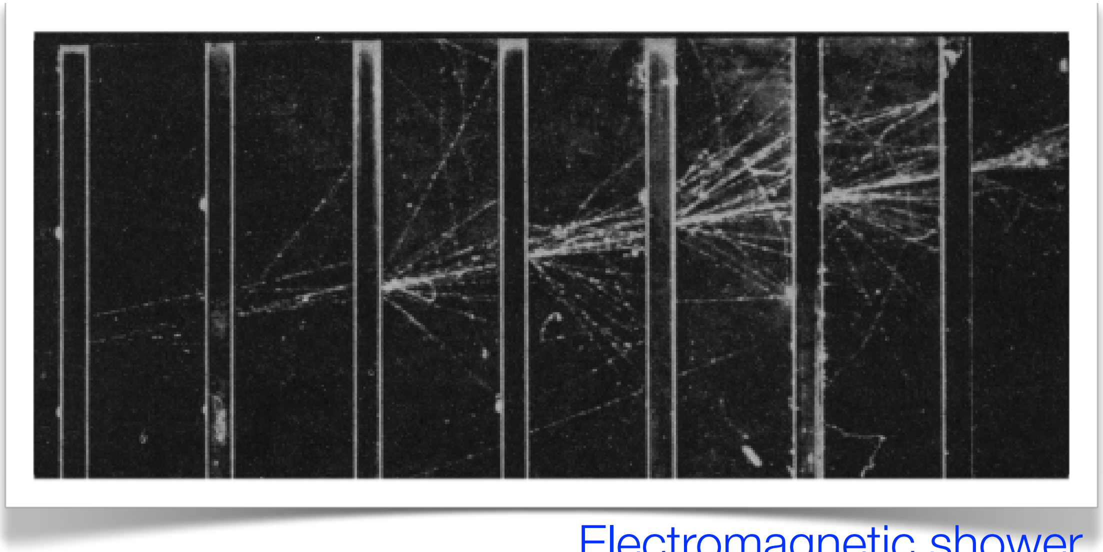
- Iron (Fe)
- Lead (Pb)
- Uranium (U)
  [For compensation ...]

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:

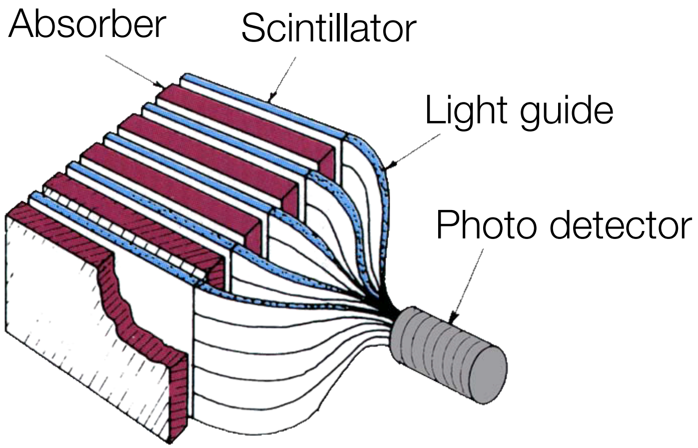
  Only part of the deposited particle energy is actually detected in the active layers; typically a few percent [for gas detectors even only ~$10^{-5}$] ...

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

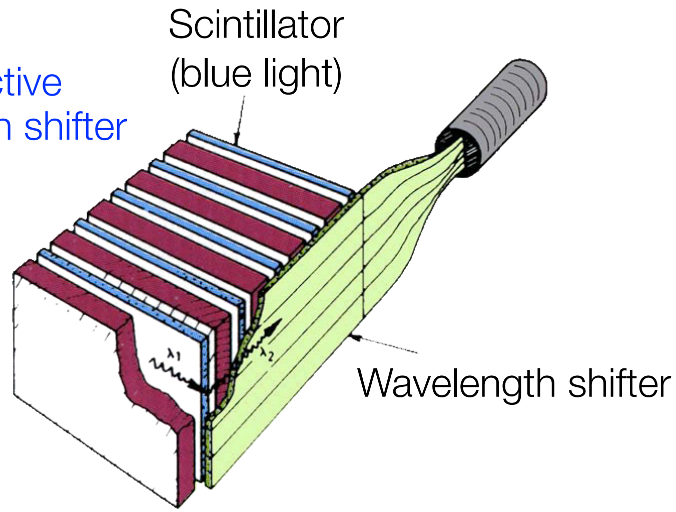
# Sampling calorimeters

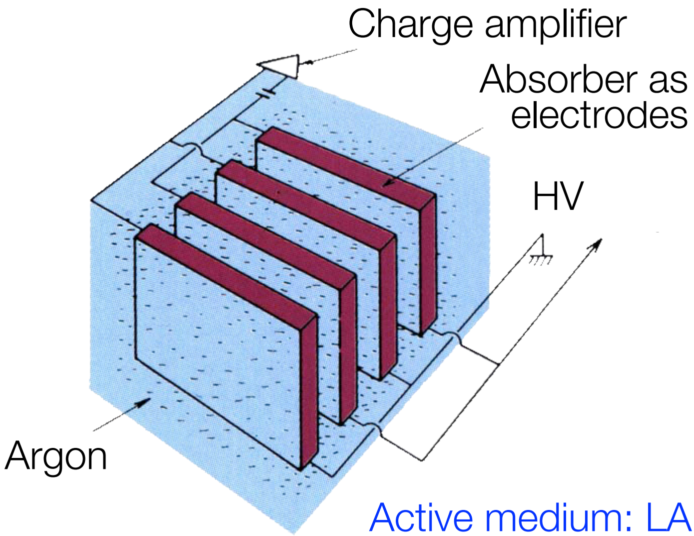
## Possible setups

Scintillators as active layer;
signal readout via photo multipliers



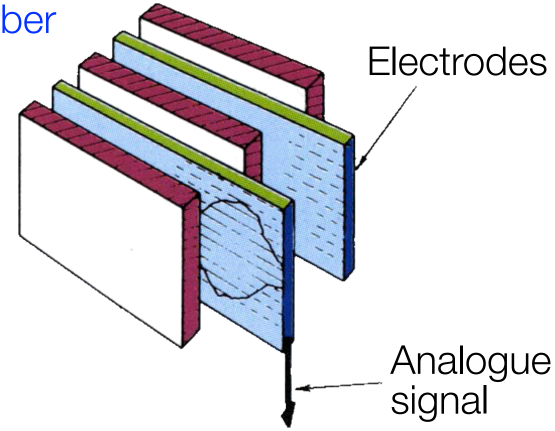
Scintillators as active
layer; wave length shifter
to convert light





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

Ionization chambers
between absorber
plates



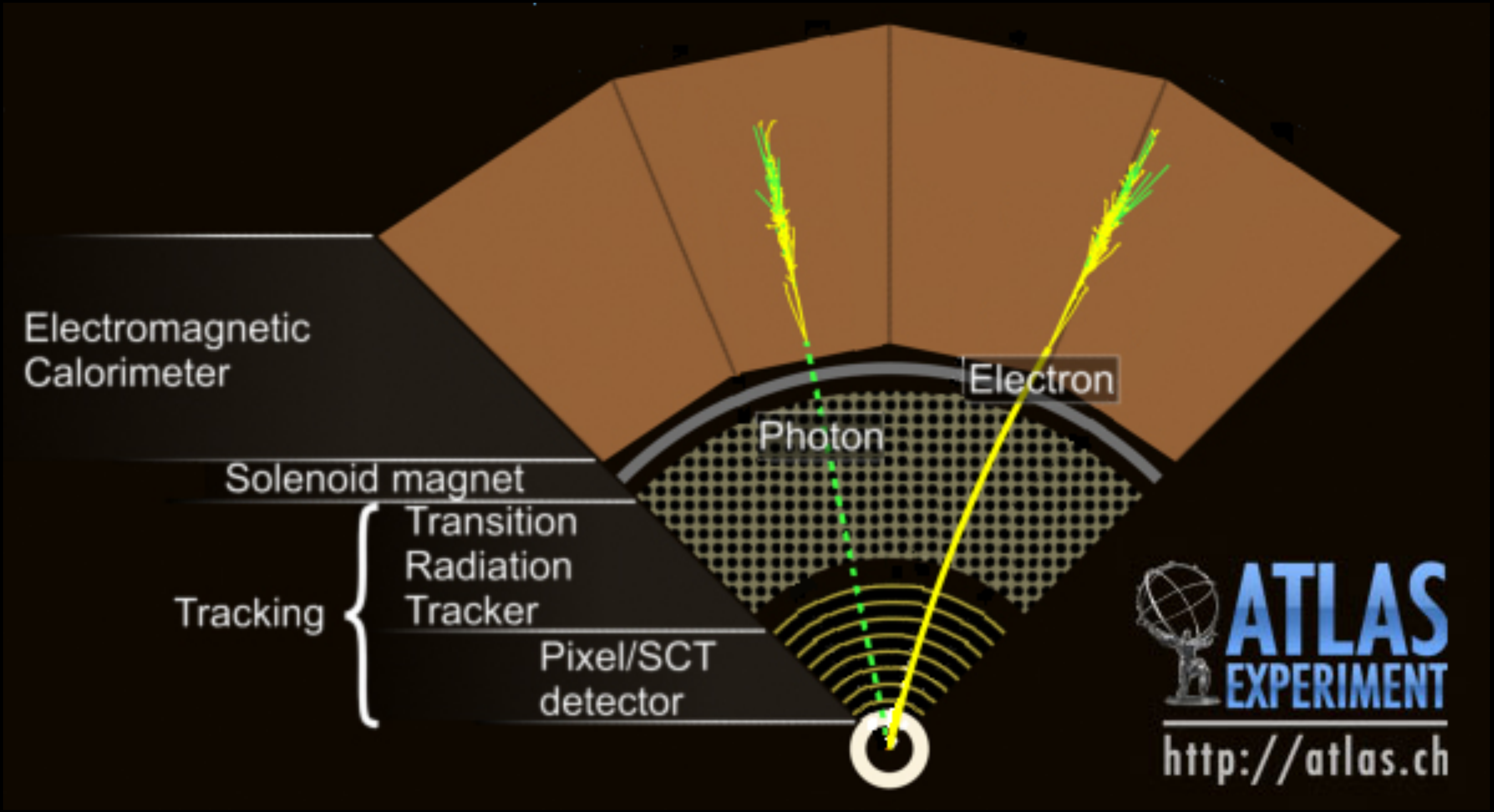
# Homogeneous vs. sampling calorimeters

| Technology (Experiment) | Depth | Energy resolution | Date | |
|---|---|---|---|---|
| NaI(Tl) (Crystal Ball) | $20X_0$ | $2.7\%/\mathrm{E}^{1/4}$ | 1983 | Homogeneous |
| $\mathrm{Bi_4Ge_3O_{12}}$ (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 | |
| $\mathrm{PbWO_4}$ (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 | Sampling |
| 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 | |

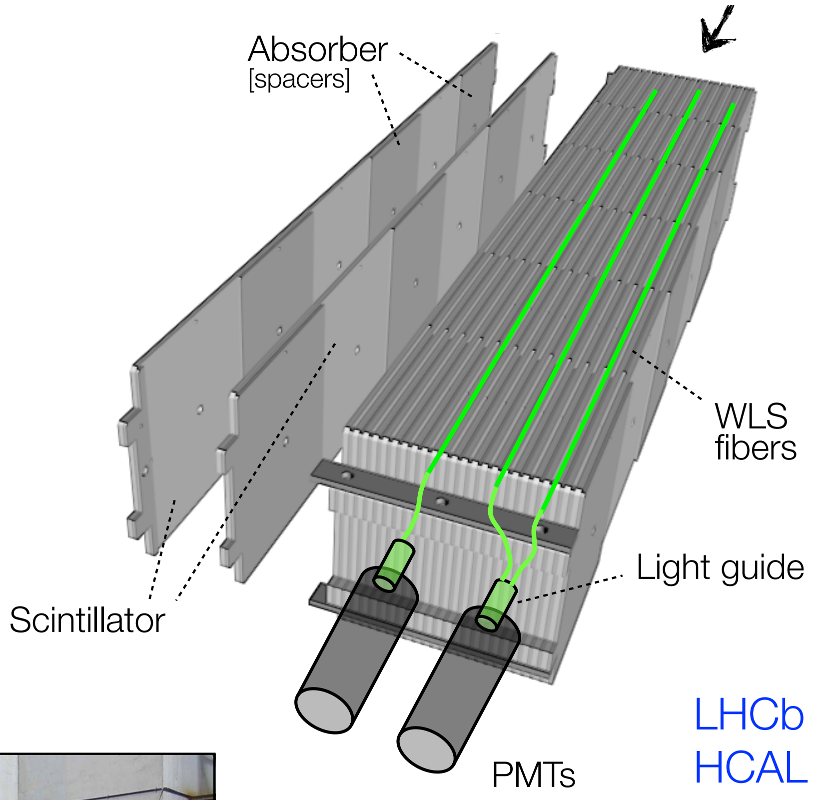
Resolution of typical electromagnetic calorimeter

[E is in GeV]

# Particle identification with tracker and calo



# Hadronic calorimeters



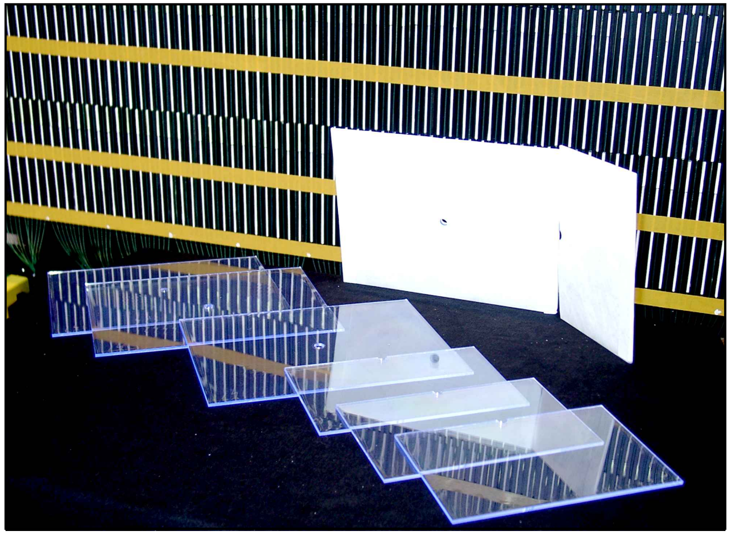
LHCb
HCAL

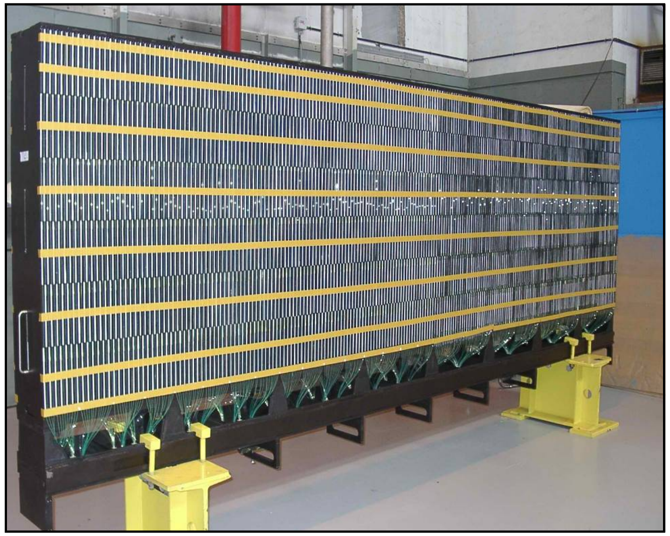
## Most common realization: Sampling Calorimeter

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]





Example:
LHCb Hadron Calorimeter

# Energy resolution

Energy resolution:

e.g. inhomogeneities
shower leakage

e.g. electronic noise
sampling fraction variations

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

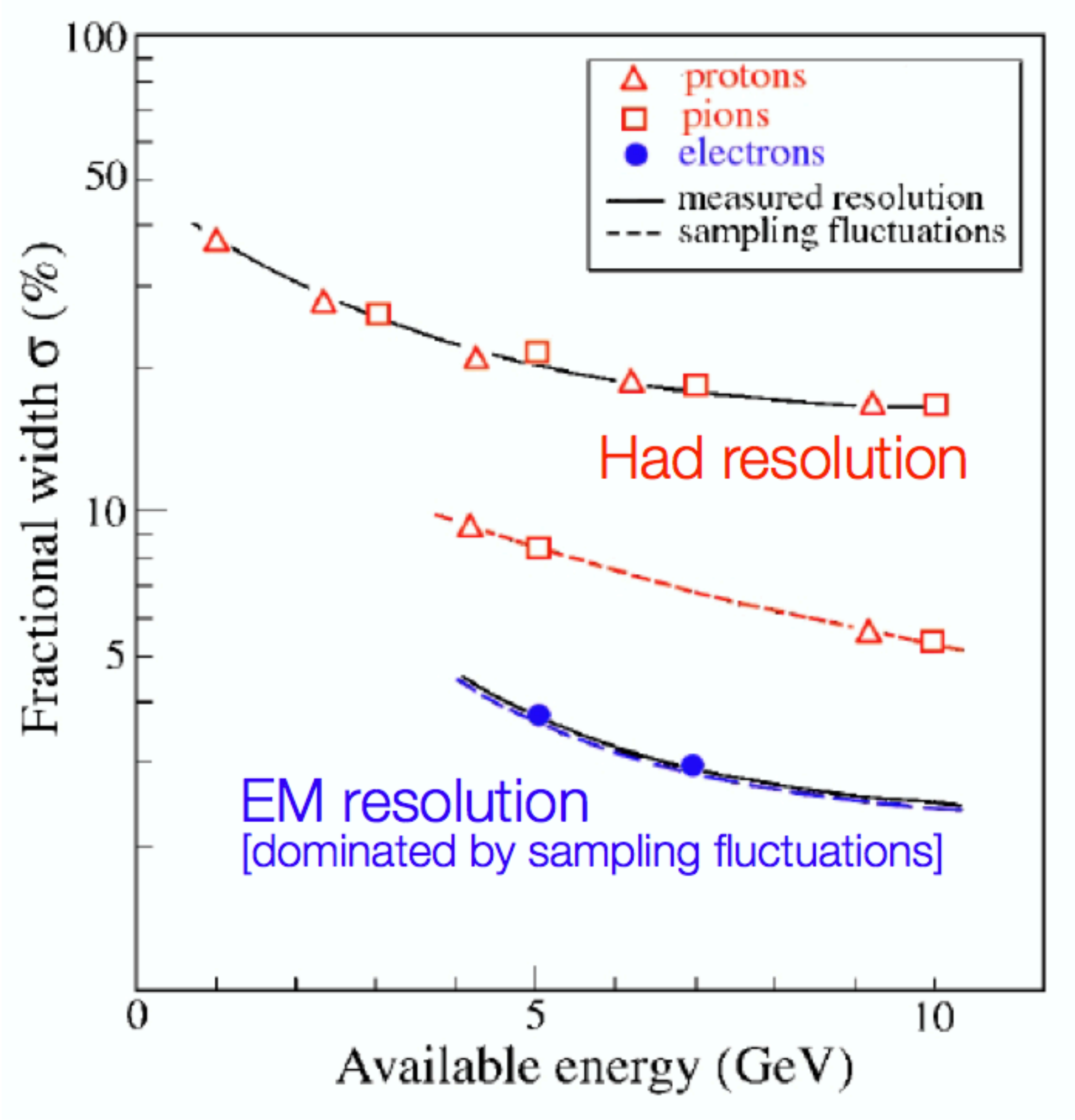
Fluctuations:

- 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) ...

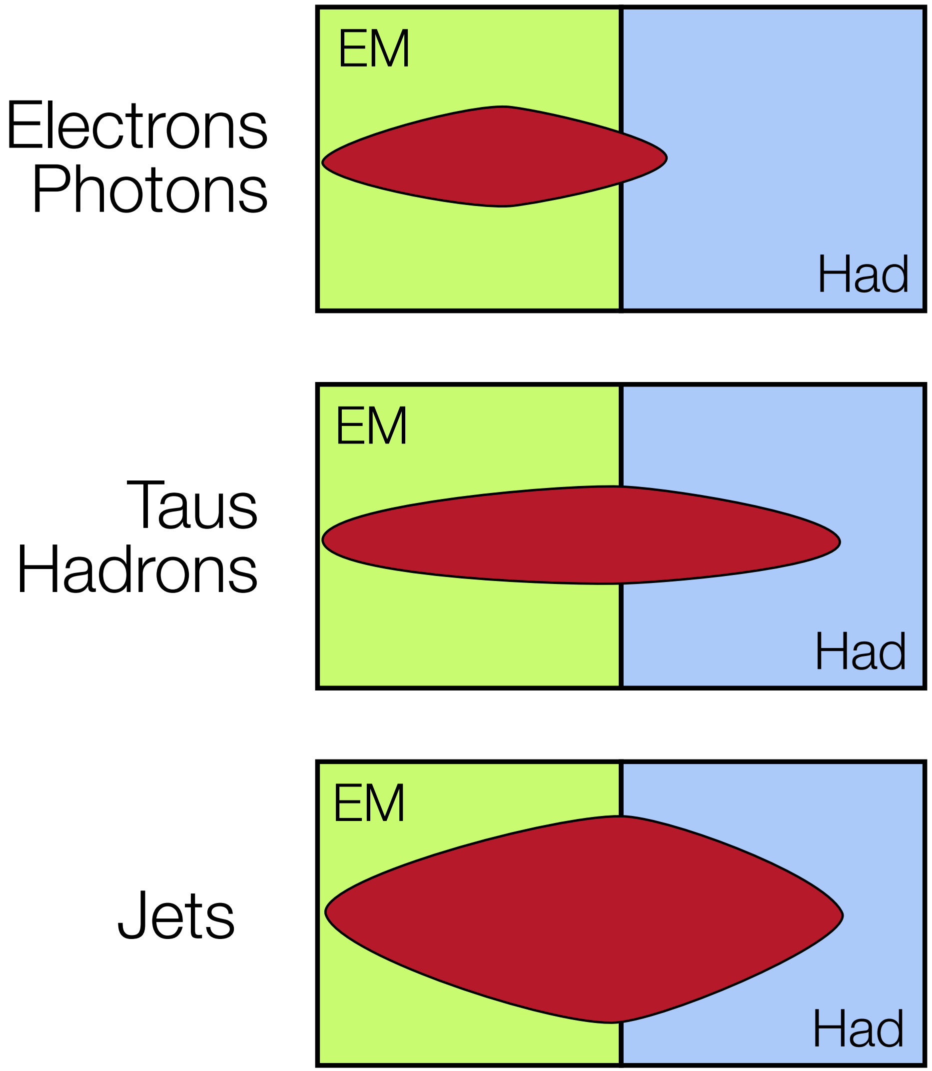
Different setups chosen for
optimal energy resolution ...

But:

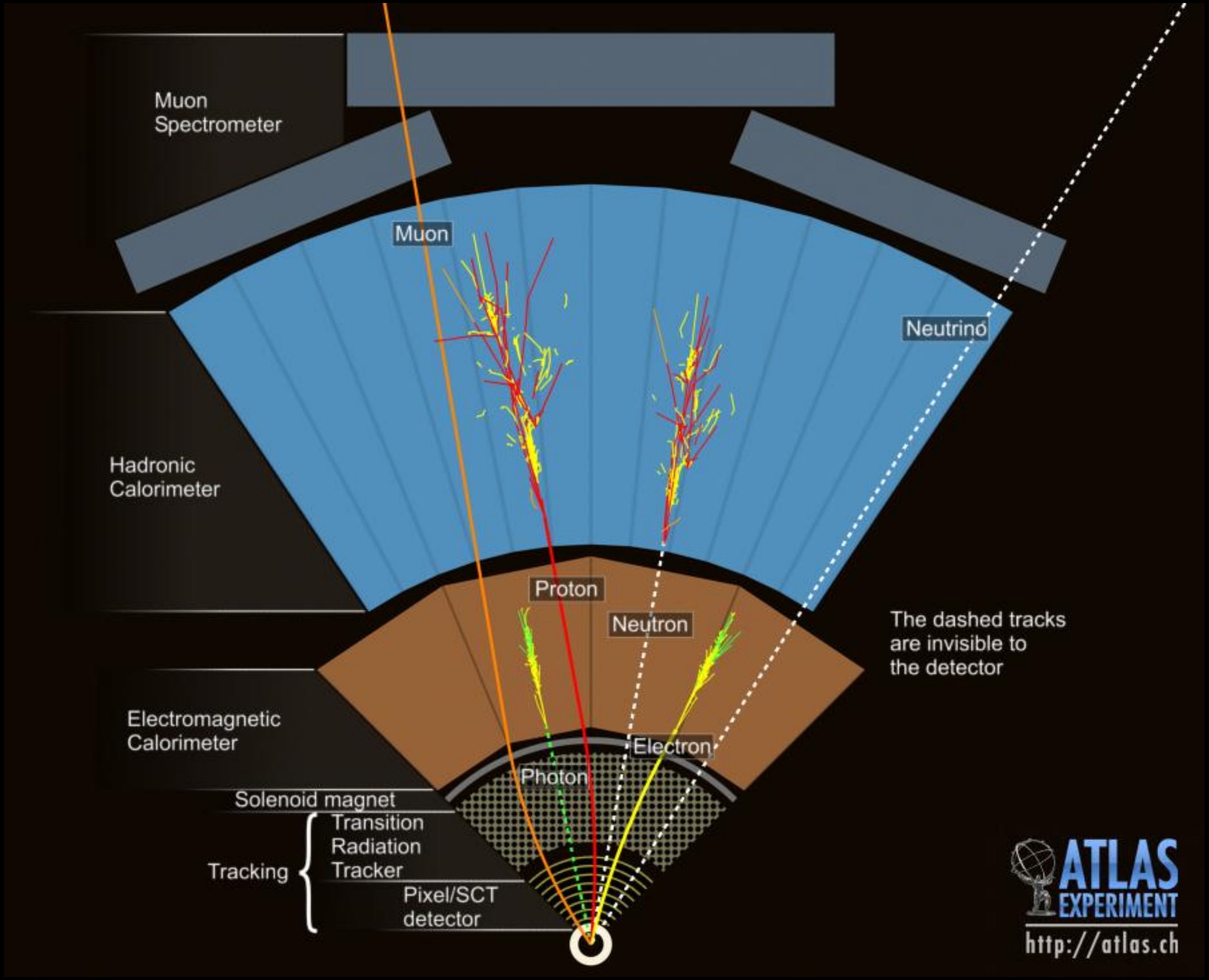
Hadronic energy measured in
both parts of calorimeter ...

Needs careful consideration of
different response ...

Schematic of a
typical HEP calorimeter

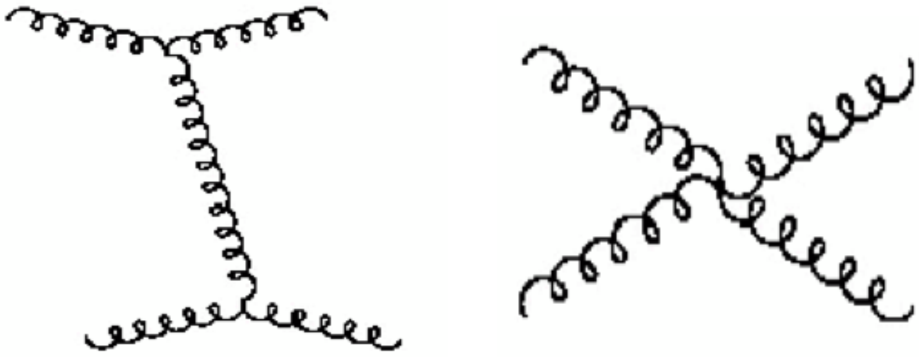


# How do we "see" particles?



# A 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

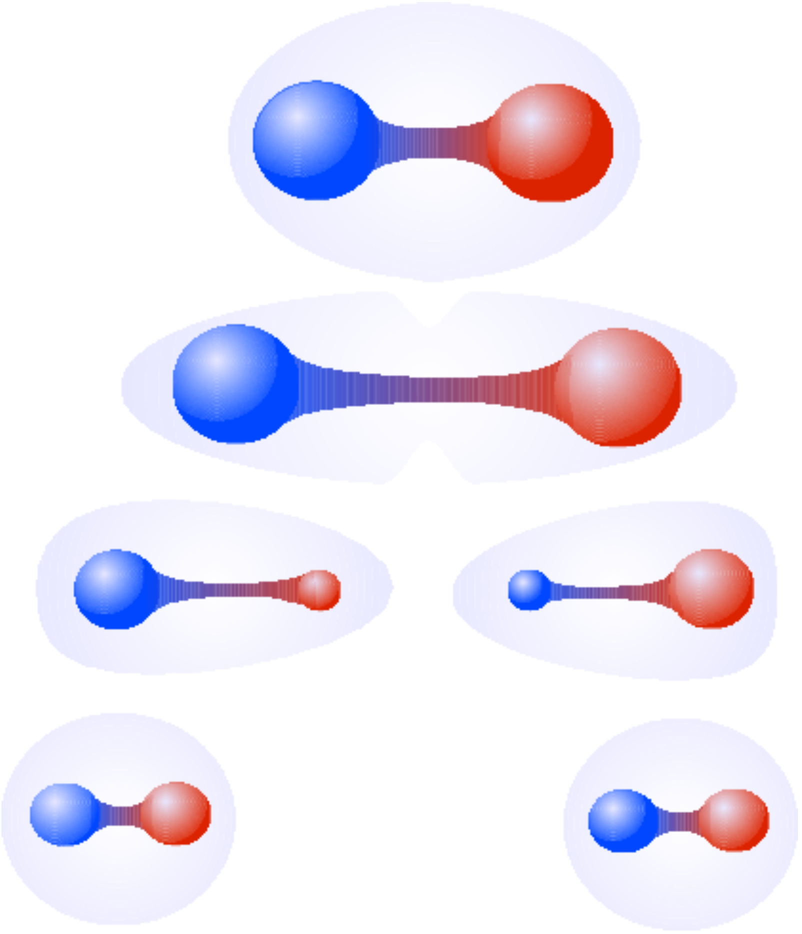


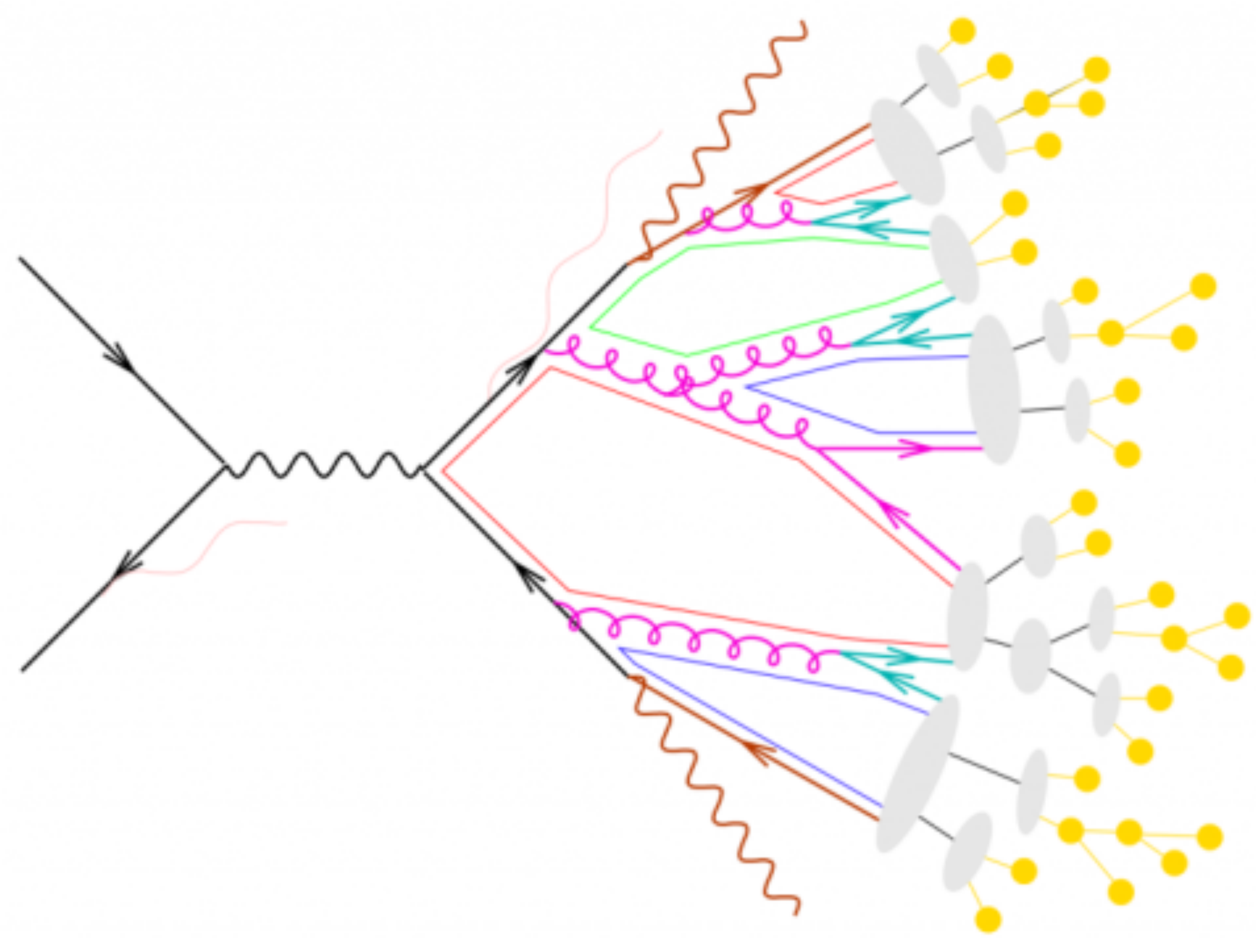
- **Principle of asymptotic freedom**
  - ✓ At short distances strong interactions are weak
    - Quarks and gluons are essentially free particles
    - Perturbative regime (can calculate!)
  - ✓ At large distances, higher-order diagrams dominate
    - Interaction is very strong
    - Perturbative regime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

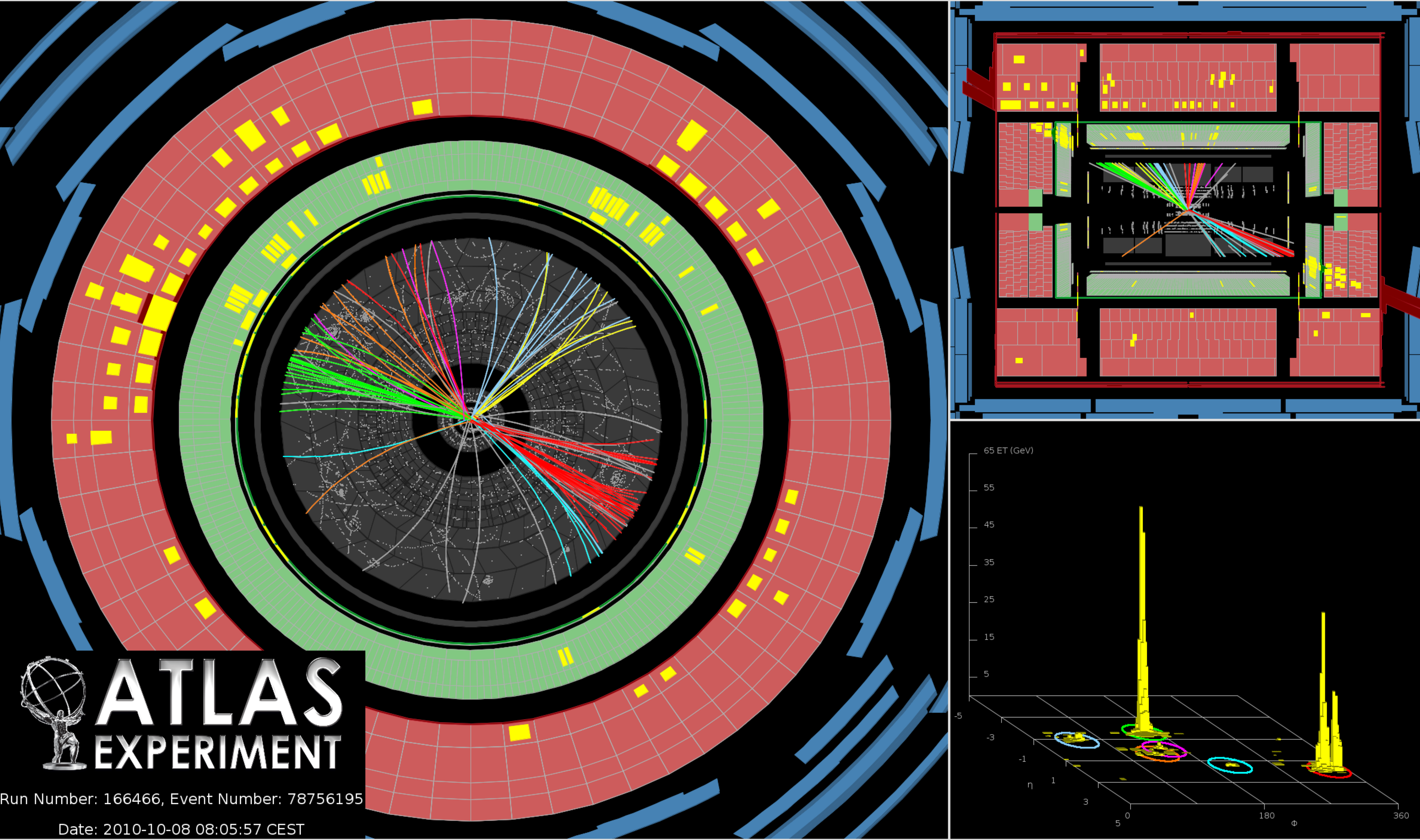
quark-quark effective potential

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

# Confinement, hadronization, jets







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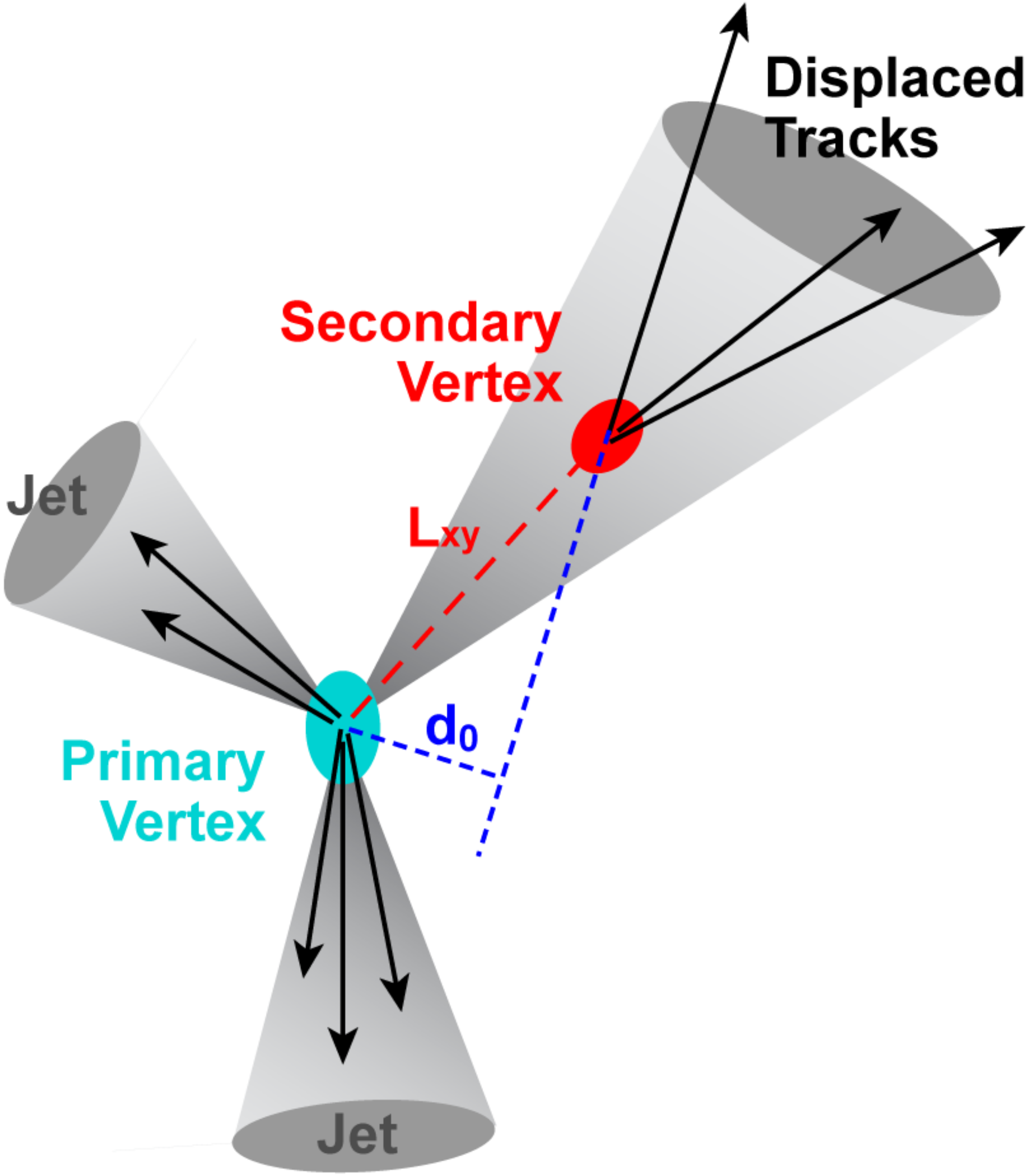
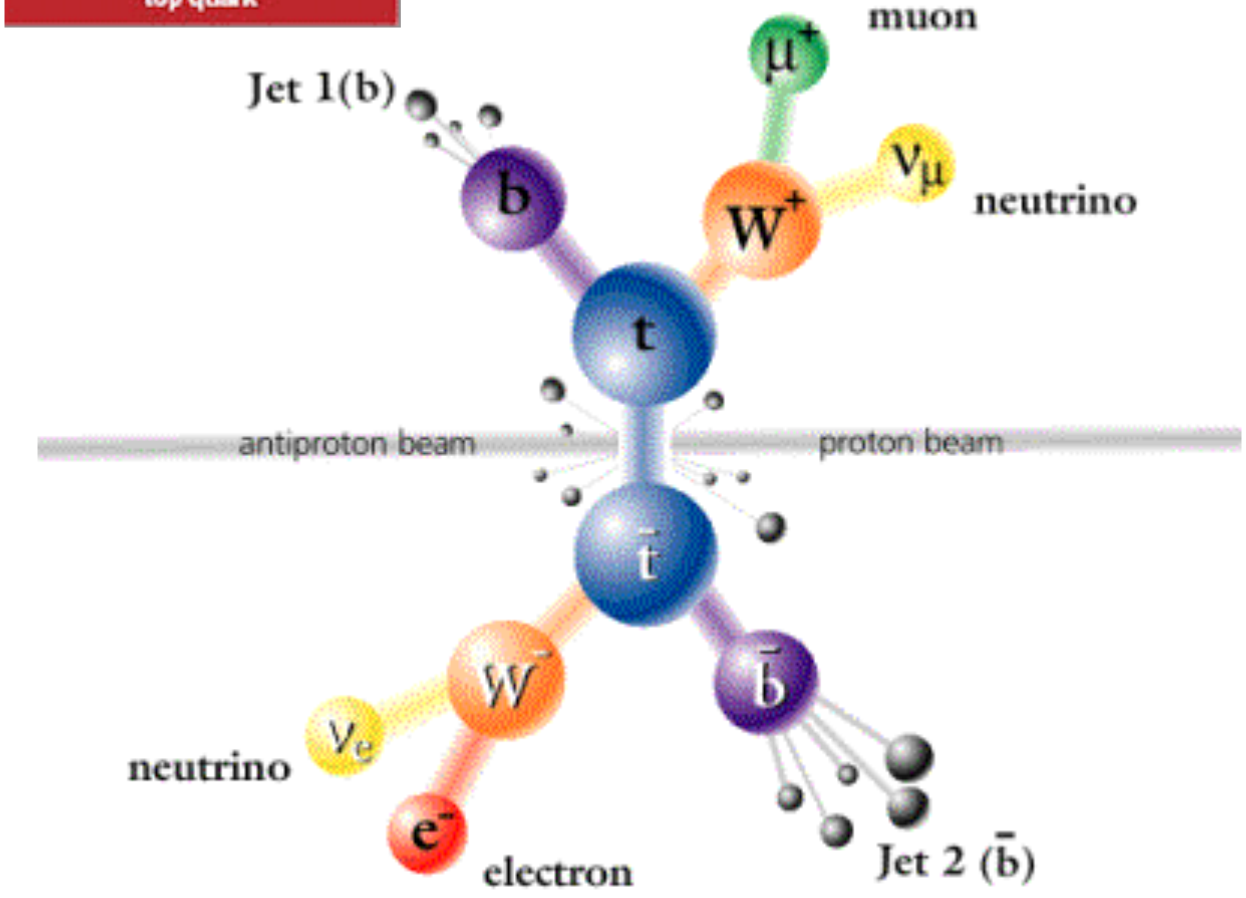
# B-tagging

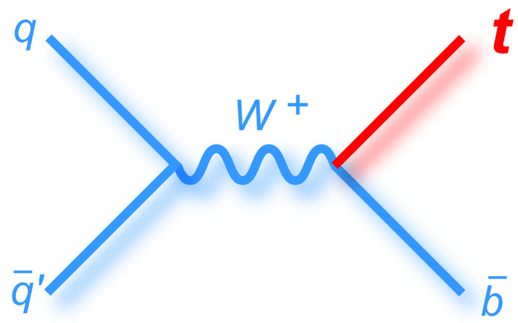
- When a b quark is produced, the associated jet will very likely contain at least one B meson or hadron
- B mesons/hadrons have relatively long lifetime
  - ✓ They will travel away form collision point before decaying
- Identifying a secondary decay vertex in a jet allow to tag its quark content
- Similar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

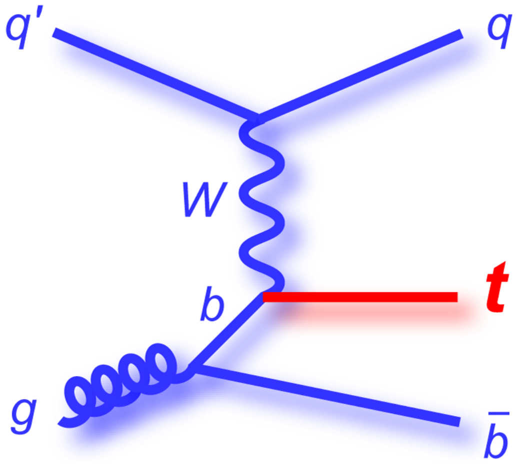


# top quark

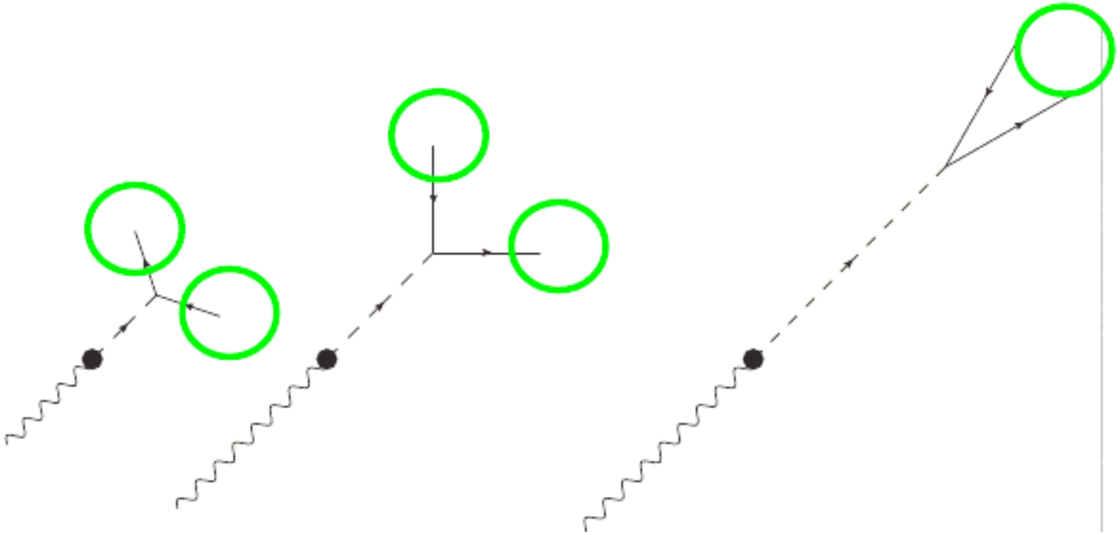
- Top quark has a mean lifetime of $5\times10^{-25}$ s, shorter than time scale at which QCD acts: not time to hadronize!
  - ✓ It decays as $t \to Wb$
- Events with top quarks are very rich in (b) jets…

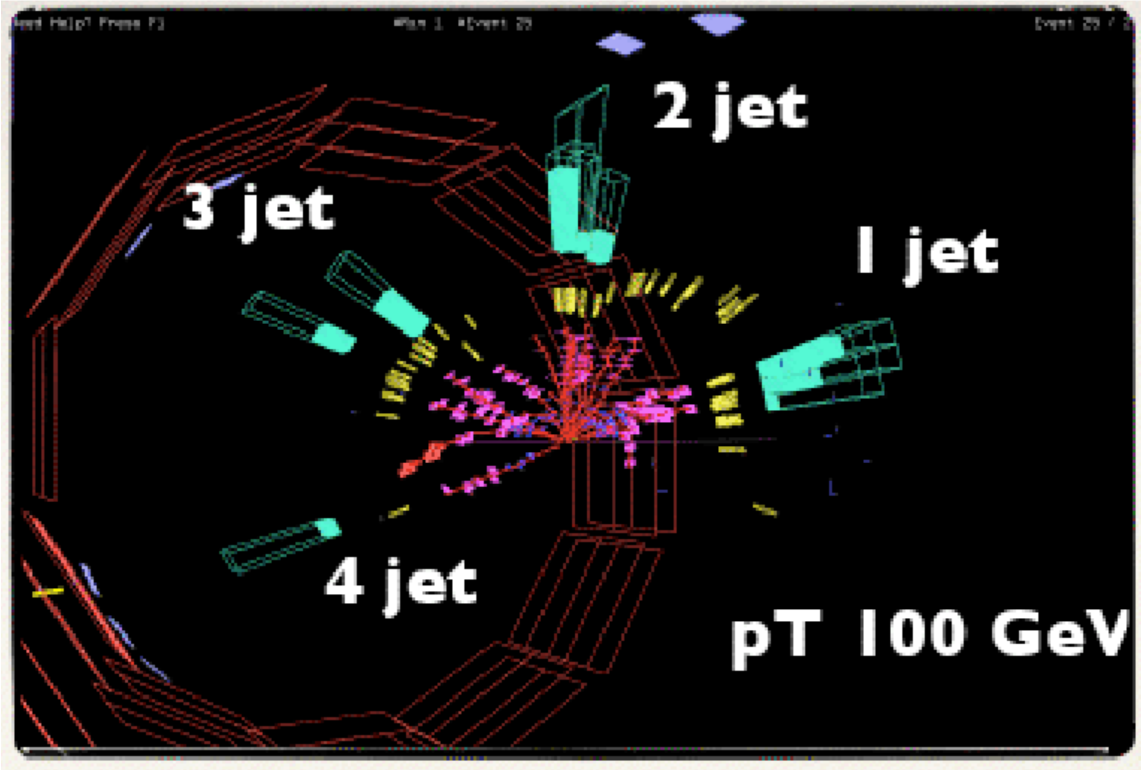


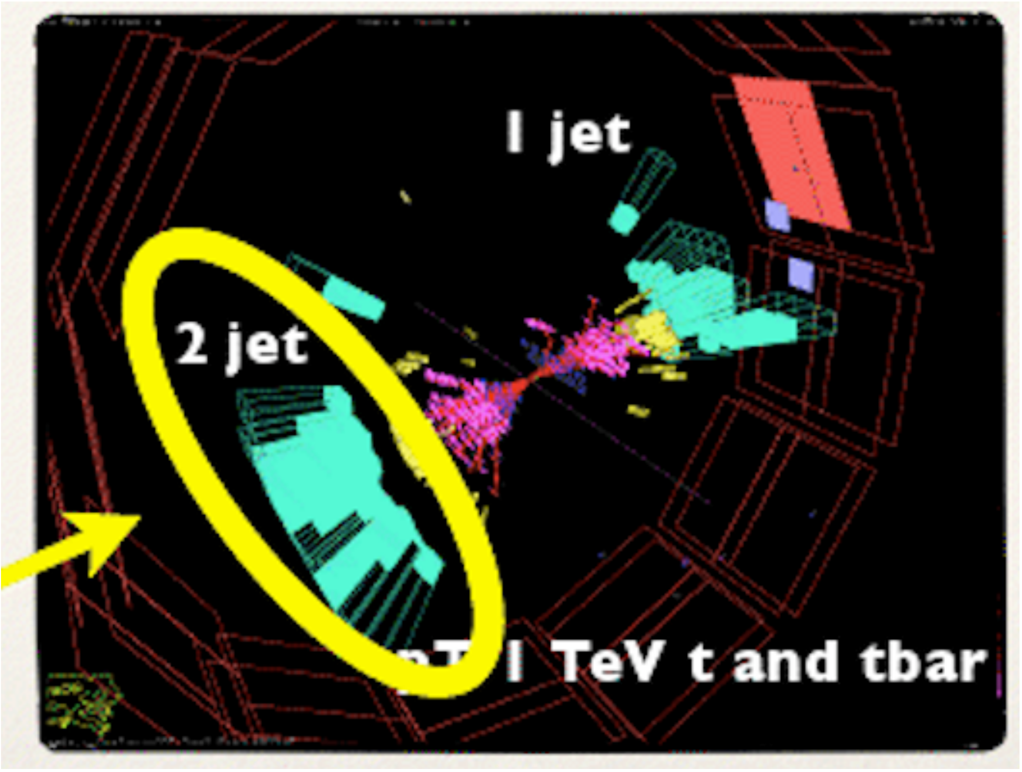




# Boosted jets and jet substructure

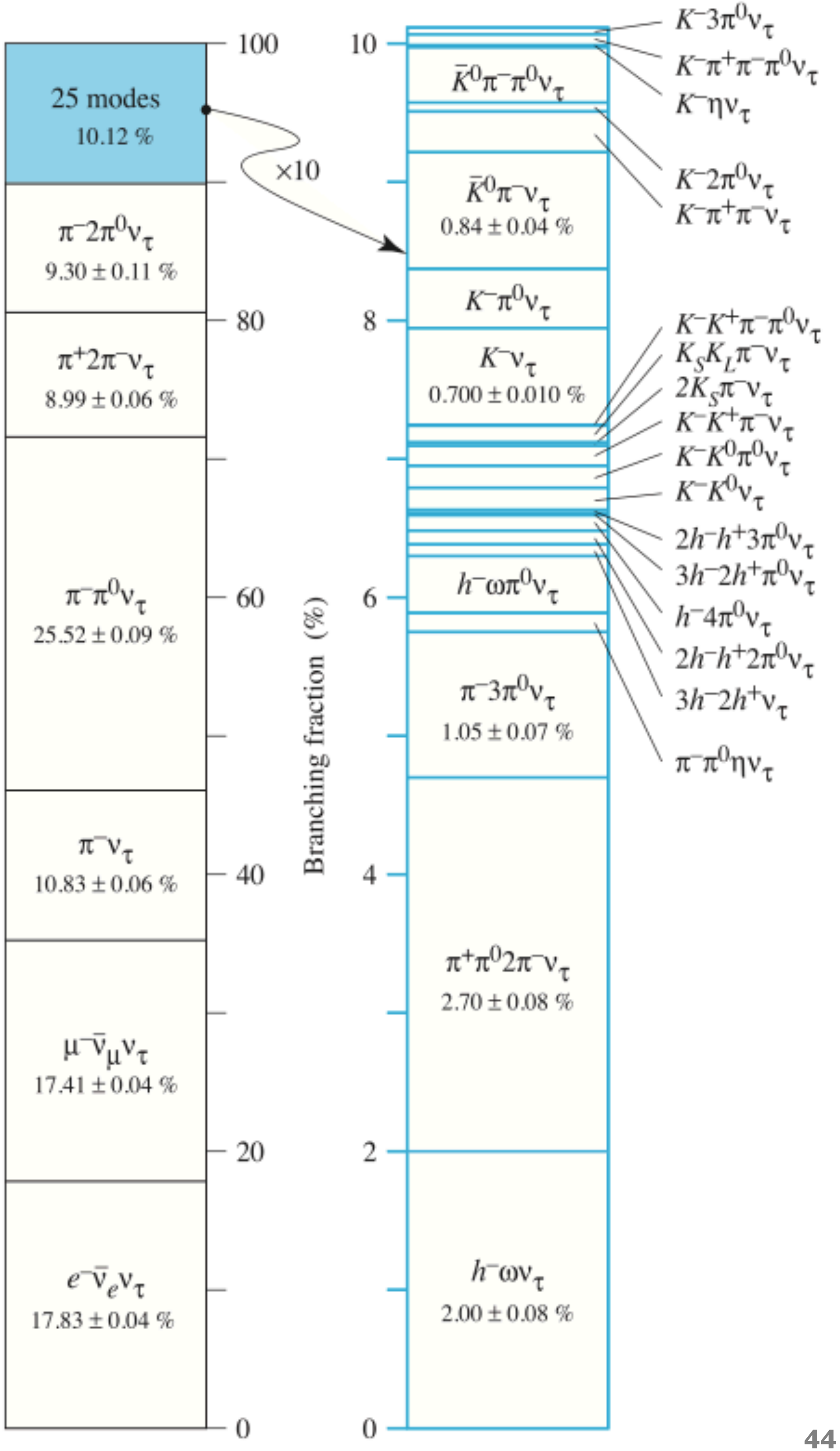


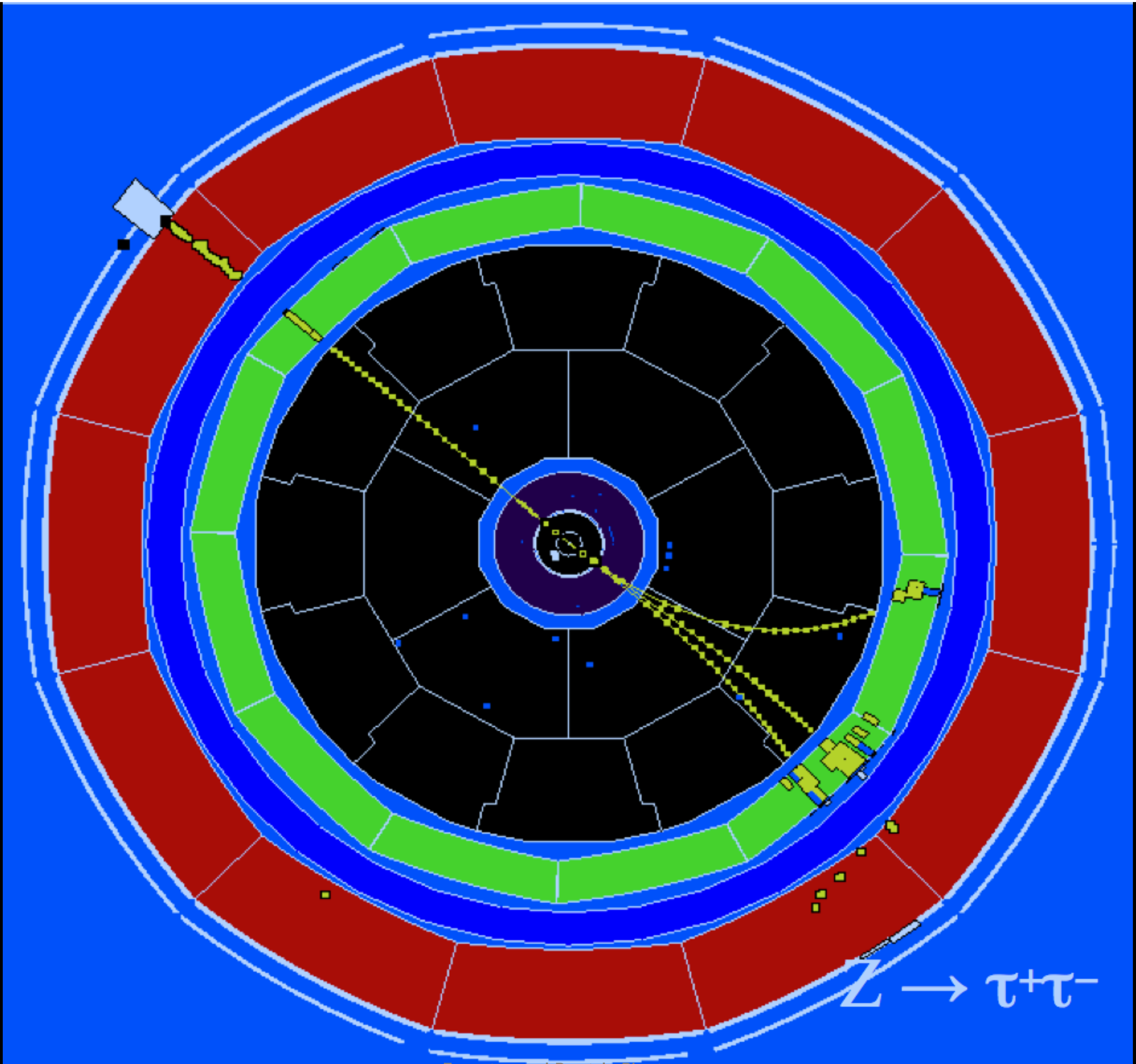




# Tau

- 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

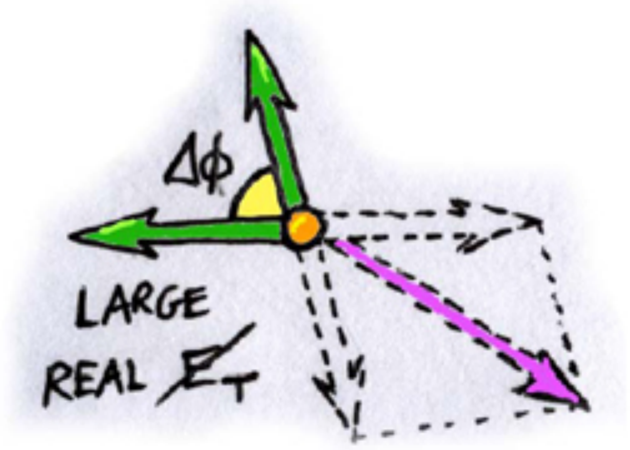


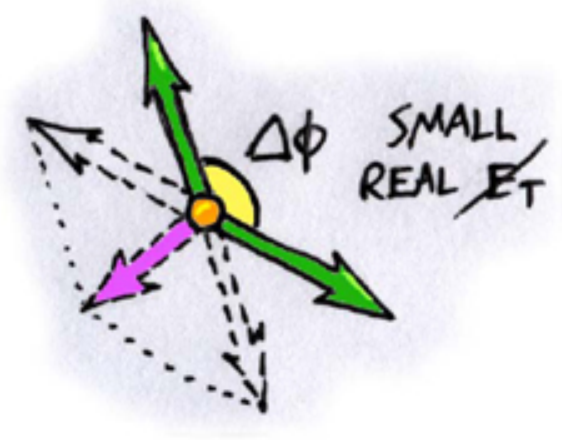


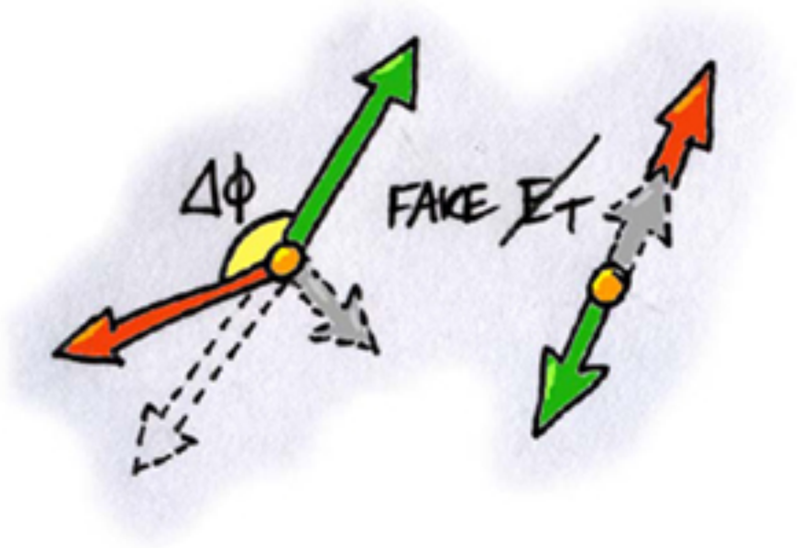
$Z \to \tau^+\tau^-$

# Neutrino (and other invisible particles) at colliders

- Interaction length $\lambda_{\text{int}} = A/(\rho\ \ \sigma\ \ N_A)$
- Cross section $\sigma \sim 10^{-38}\ \text{cm}^2 \times E$ [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)