Muon Detection

The detectors,

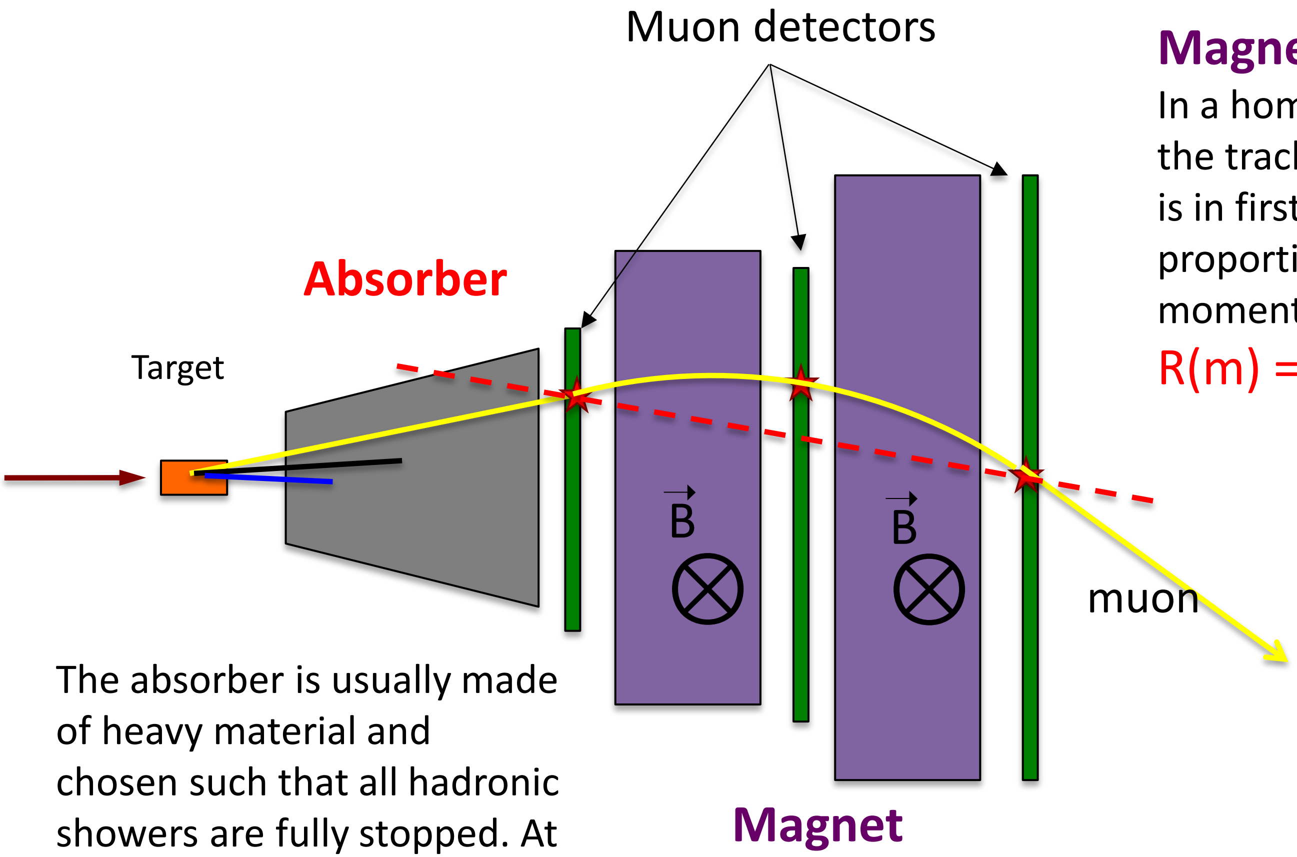
all you always wanted to know about how to build muon detectors

LECTURE 2

The muon detector design

- The design of a muon system is very simple; there are only two features that we use:
  - The high penetration capability of muons
  - The fact that they are charged and therefore curve under the influence of a magnetic field
- Which type of detectors and how they are arranged depends on the type of experiment (fixed target, collider, underground, etc.) but also on a number of other parameters.
- Let’s start by drawing a few genuine detectors and see what we have to take care off.

Genuine muon detector I



Magnet

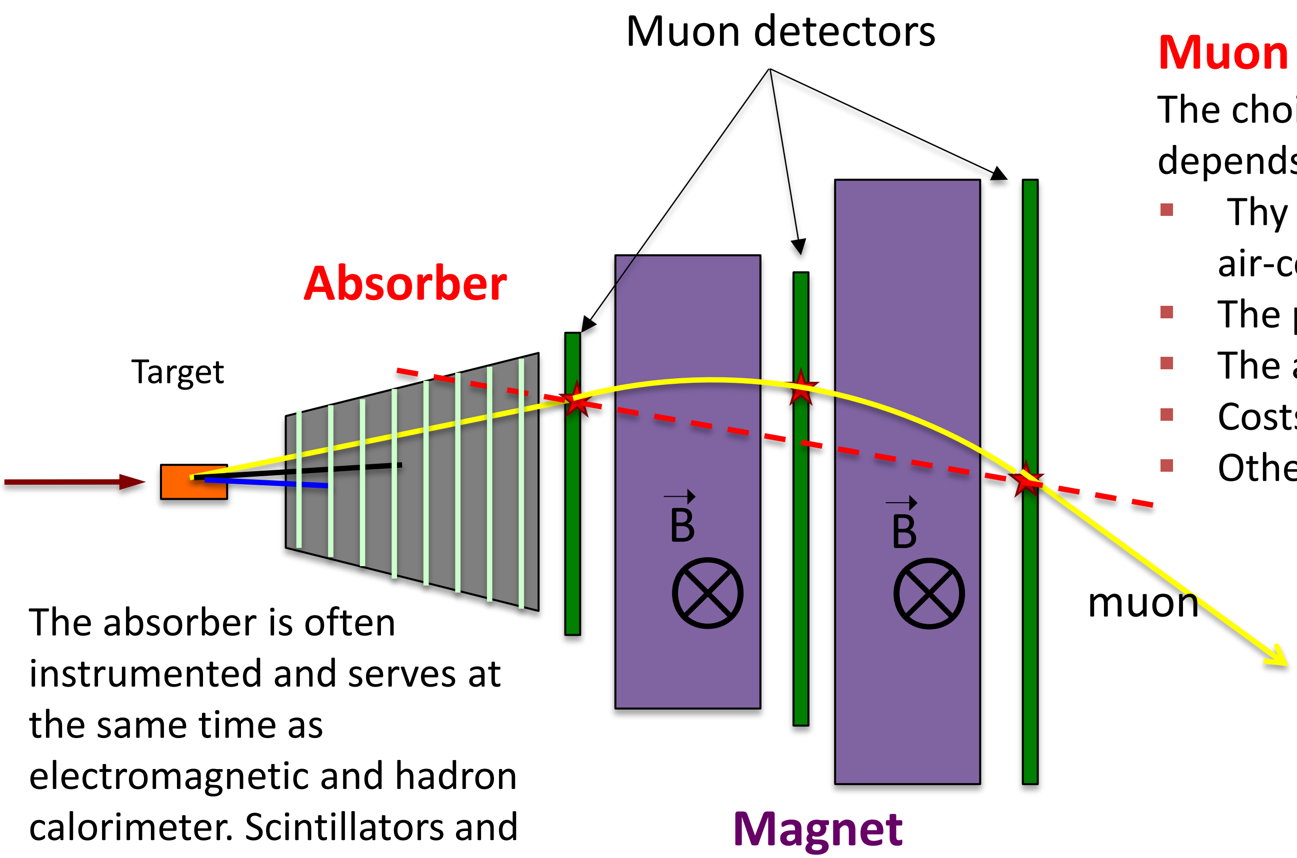
In a homogeneous magnetic field B the track curvature (bending radius R) is in first approximation directly proportional to the muon momentum

$R(m) = p(GeV)/(0.3\ B(T))$

How the magnetic field is created is in first approximation irrelevant, it can be a dipole field or a solenoidal field or a toroidal field

The absorber is usually made of heavy material and chosen such that all hadronic showers are fully stopped. At LHC energies, these are 12–15 nucl. Interaction lengths or 2–2.5 m iron.

Genuine muon detector I(b)



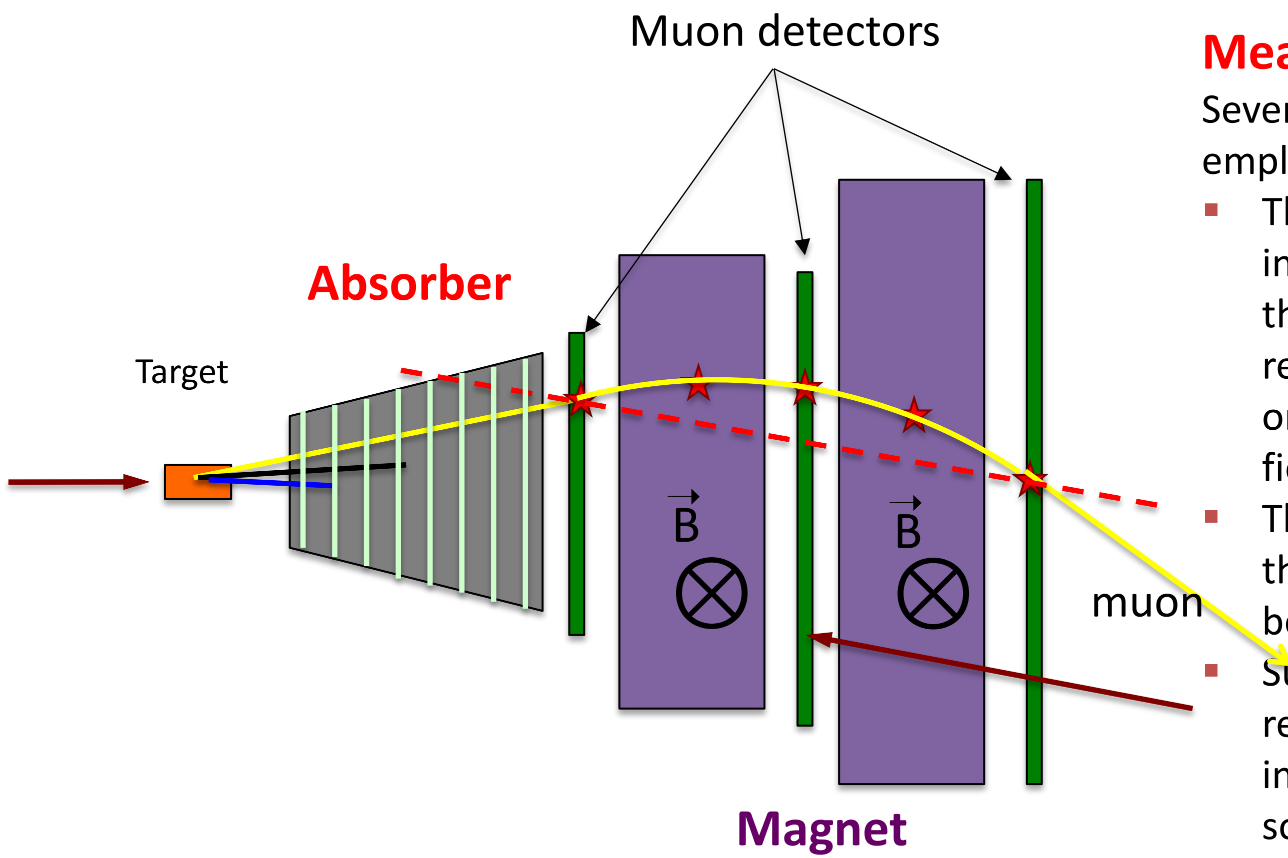
Muon detectors

The choice of the muon detectors depends on a number of parameters.

- Thy type of magnet (iron-core, air-core, …)
- The precision requirements
- The area to be covered
- Costs & maintenance
- Others ….

The absorber is often instrumented and serves at the same time as electromagnetic and hadron calorimeter. Scintillators and gaseous detectors are the most common technologies employed.

Genuine muon detector I(c)

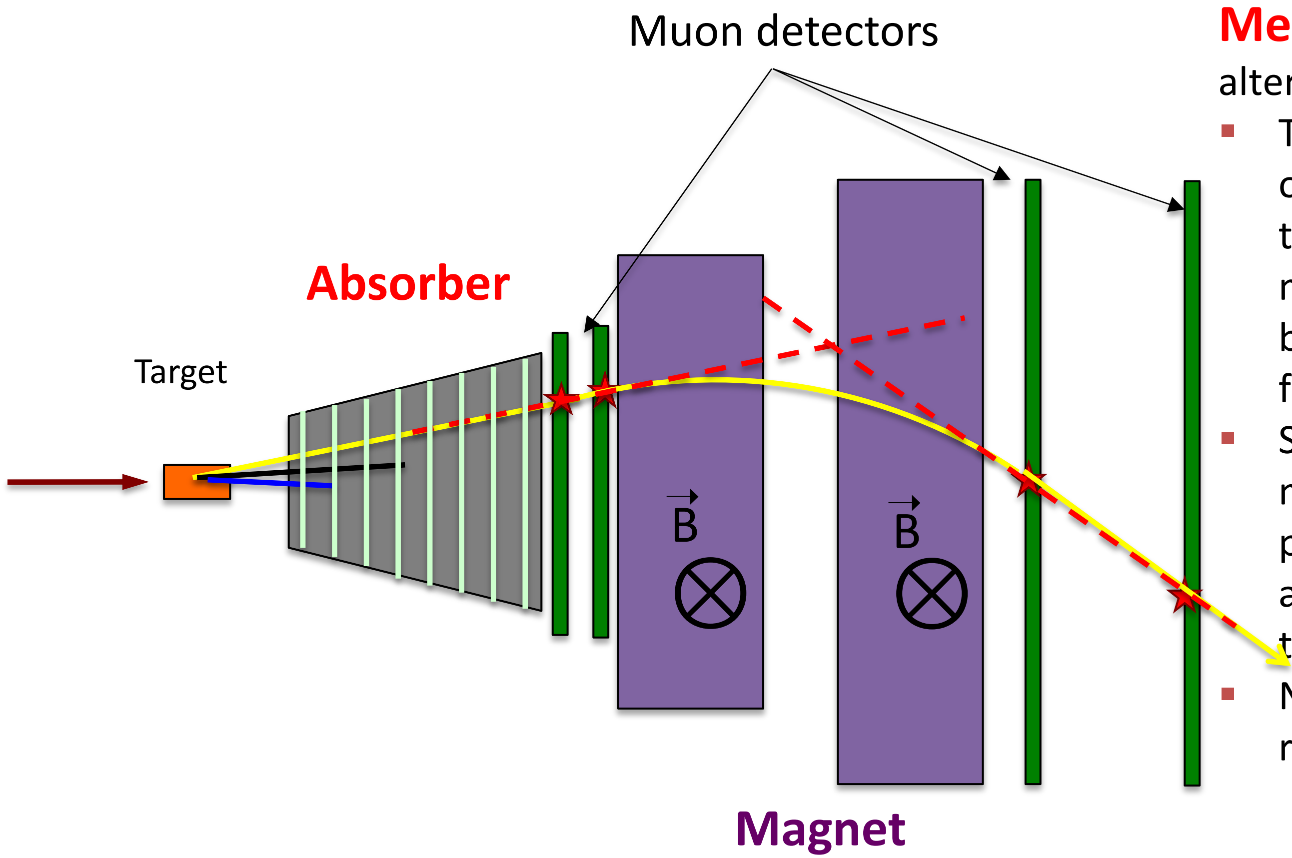


Measurement of the muon

Several configurations may be employed

- Three (or more) muon stations inside the magnetic field; one at the begin of the magnetic field region, one in the middle, and one at the end of the magnetic field (shown here).
- This allows for a measurement of the sagitta and therefore the bending radius.
- Such a configuration is ideal but requires a measurement station inside the magnetic field which sometimes is not possible.

Genuine muon detector I(d)



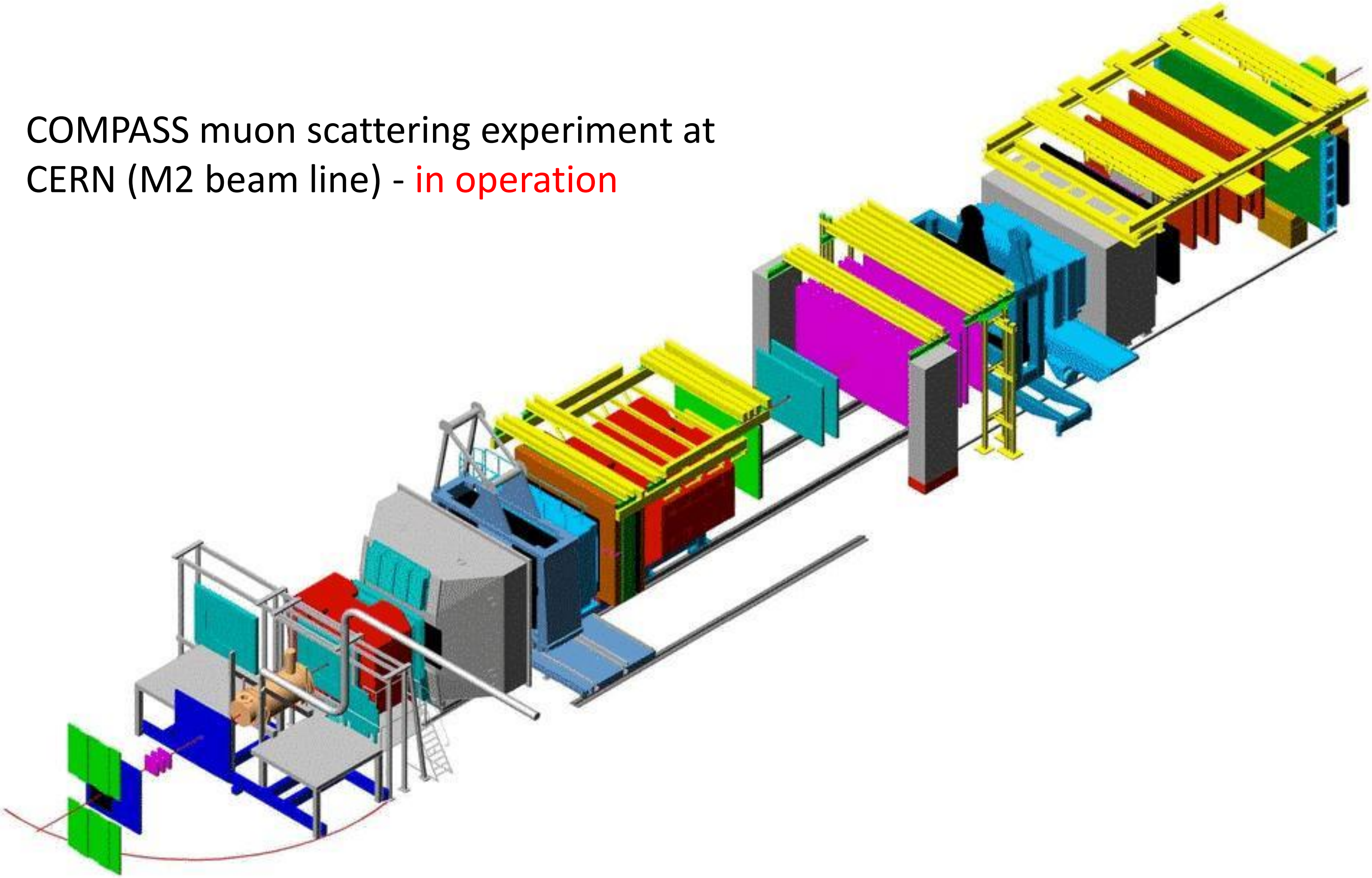
Measurement of the muon

alternative configurations

- Three (or more) muon stations outside the magnetic field; one or two before the begin of the magnetic field region and two behind the end of the magnetic field.
- Such a configuration allows for a measurement of the track position and angle before and after the magnetic field and therefore the bending radius.
- No detector inside the field is required.

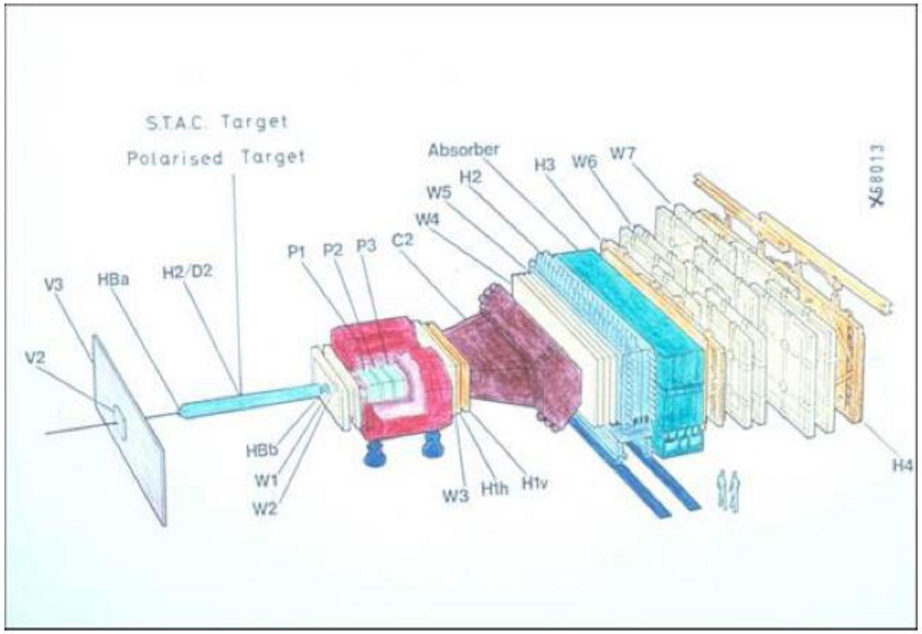
Fixed-target muon detectors I

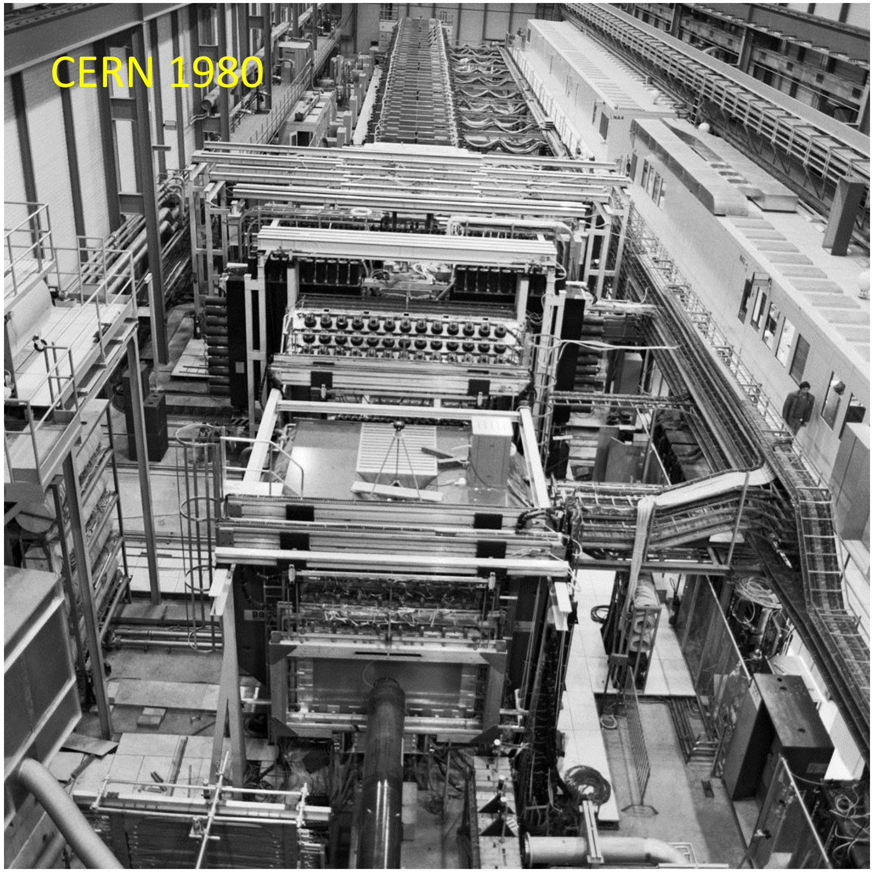
COMPASS muon scattering experiment at CERN (M2 beam line) - in operation



Fixed-target muon detectors Ib

NA2 EMC (later NMC) muon scattering experiment at CERN (M2 beam line), 1976ff



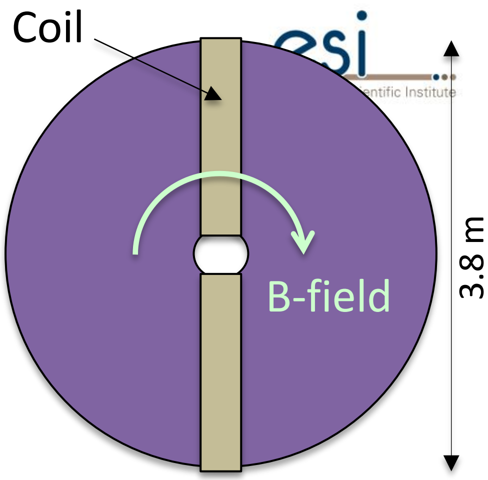


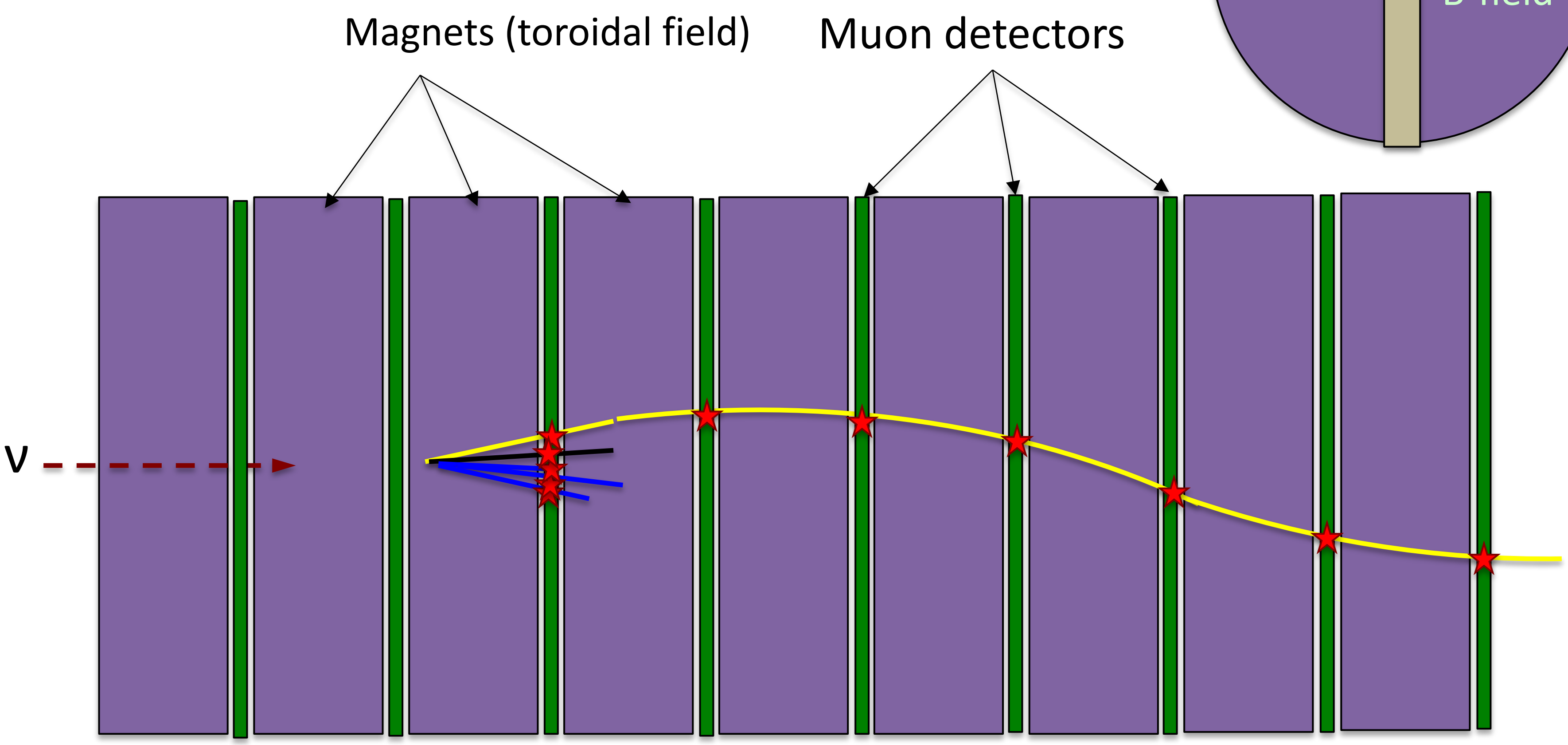
Fixed-target muon detectors II

CDHS (WA1) neutrino detector at CERN
(operational from 1976 to 1984)

1200 t Fe/scintillator modules interleaved with 21 drift chambers (y, u, v)

Genuine muon detector II

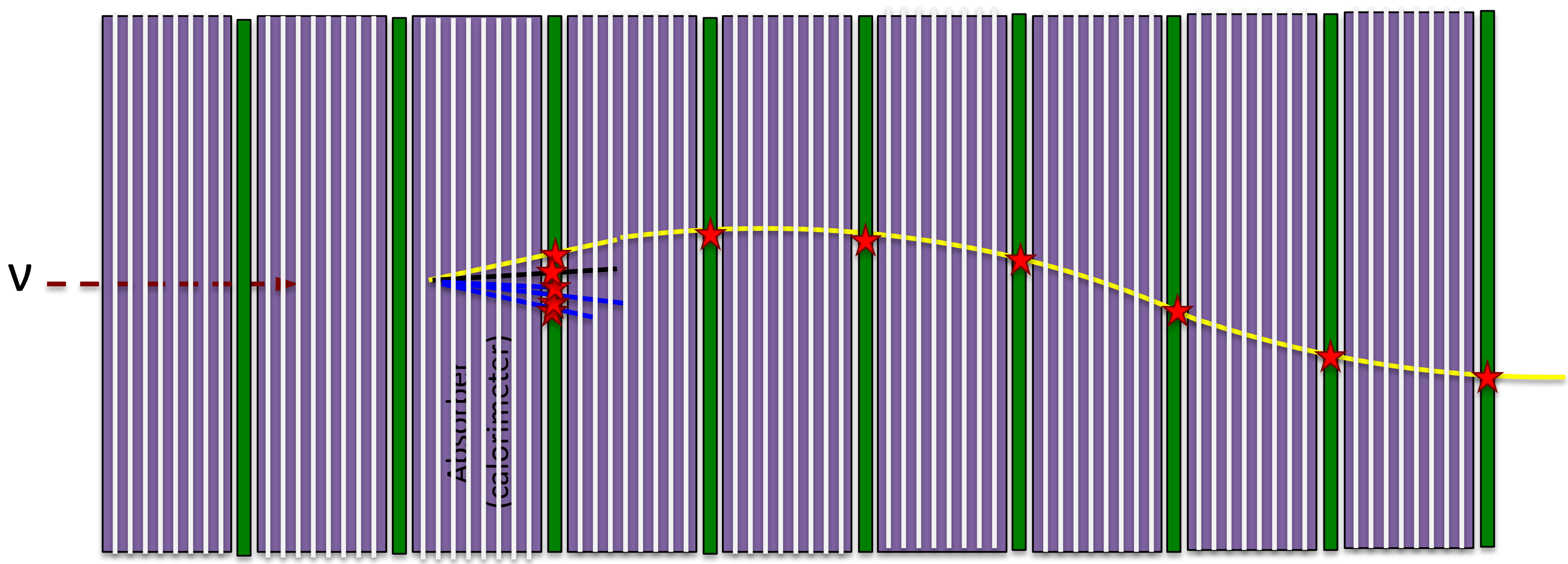




A neutrino detector

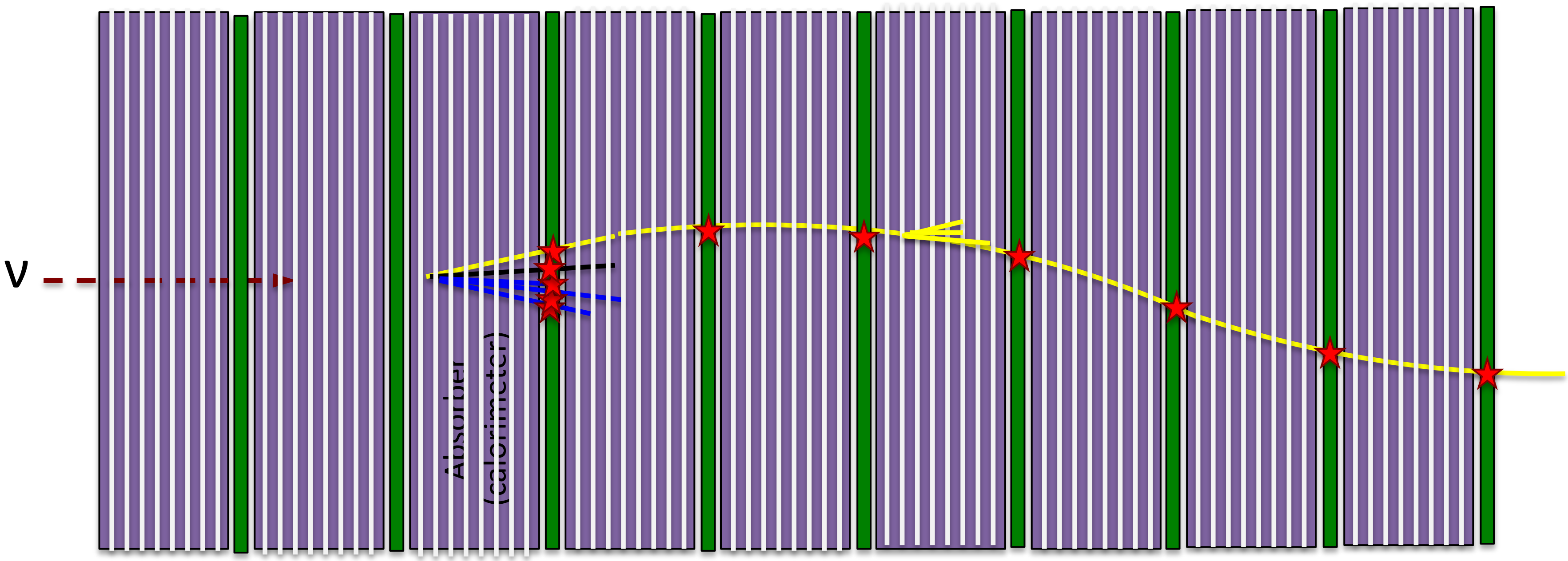
Genuine muon detector II

Absorber is instrumented with scintillators, it serves at the same time as target and also as calorimeter to measure the electromagnetic and hadronic showers



Genuine muon detector II

The instrumentation of the absorber also helps in distinguishing muons from other charged particles (pion, protons, kaons). Muons lose more or less the same energy/unit length contrary to the shower-like behaviour of the others.



In the rare events of 'catastrophic' energy losses of the muon the 'lost' energy can be measured and corrected for.

More ingredients to the detector design

- Let's have a closer look at the movement of a charged particle under the influence of a magnetic field
  - How can we determine its momentum?
  - Which are the other parameters that play a role?

Momentum measurement in a magnetic field

$p_T(\text{GeV}) = 0.3\, B(\text{T})\, R(\text{m})$ or $R = p/0.3\, B$

p_T = particle momentum (GeV)
B = magnetic field (T)
R = bending radius (m)

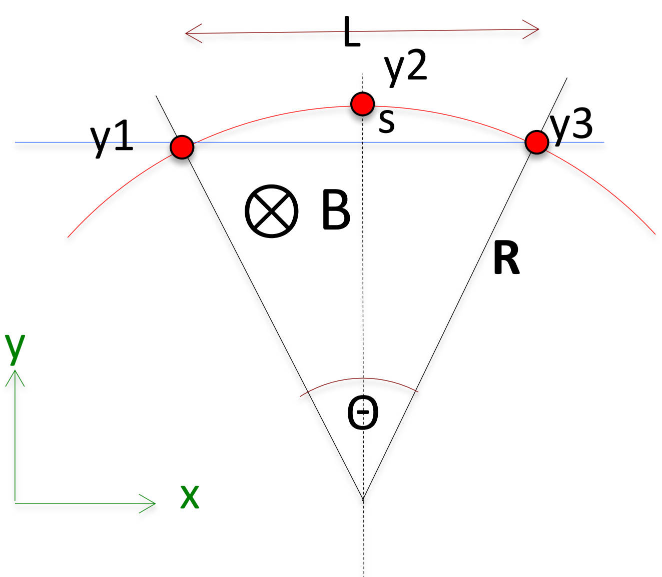
$0.5\, L/R = \sin \Theta/2 \approx \Theta/2$ (if R>>L) or
$\Theta \approx L/R$

$s = R - R \cos(\Theta/2) = R\,(1 - \cos(\Theta/2))$
for small angles: $\cos(x) \approx 1 - x^2/2$

$\Rightarrow\ s \approx R\,\Theta^2/8 \approx L^2/8\,R$

$$\Rightarrow \mathbf{s \approx 0.3\, B\, L^2/8\, p_T}$$

Bending in a homogeneous field



For three measurements (y1, y2, y3)
$s = y2 - (y1+y3)/2$
assuming the same measurement uncertainty σ_y for each point, the sagitta error becomes

$$\sigma_s = \text{sqrt}\,(3/2)\, \sigma_y$$

For a larger number ($N \geq 10$) of equidistant measurement points N, the sagitta error is given by the Glückstern formula (NIM 24 (1963) 381)

$$\sigma_s/p_T = \sigma_y\, p_T\, \text{Sqrt}(720/(N+4))/(0.3\, B\, L^2)$$

Let's apply what we have just learned

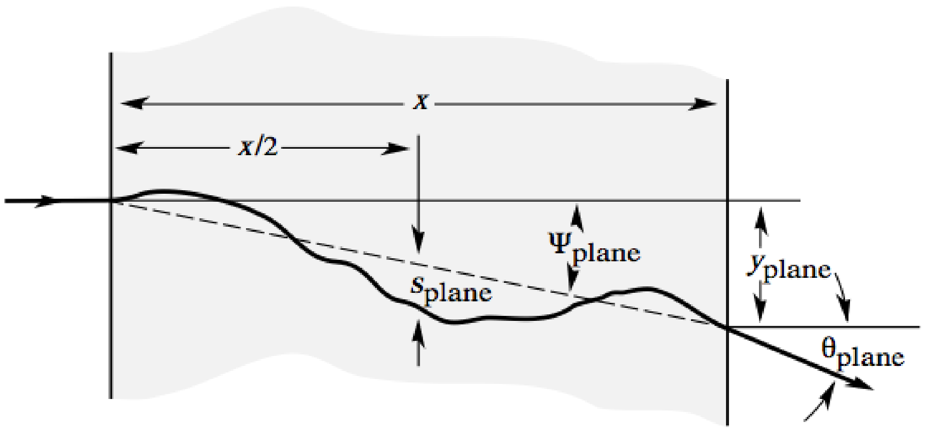
- Let's use our neutrino detector as example
  - In the CERN NBB neutrino beam ν energies of a few hundred GeV were common
  - The B-field in the iron was 1.6–1.8 T, the distance between two drift chambers was ≈1 m
- A muon of 100 GeV measured in three drift chambers (L = 2 m) has a sagitta

  $s \approx 0.3\ B\ L^2/8\ p$ or $s = 0.3 \times 1.7 \times 2^2/(8 \times 100) = 0.0025$ m
- The uncertainty on this measurement is $\sigma_s = \mathrm{sqrt}\ (3/2)\ \sigma_y$, with $\sigma_y \approx 200$ µm one gets a sagitta error of ≈250 µm or 10% of the sagitta.
- In the real experiment tracks over at least five drift chambers were required, the sagitta was, therefore, at least 10 mm. The longest measured track lengths extended over 20 drift chambers with a sagitta of almost 25 cm, 100 times larger (L^2). Applying the Gluckstern formula

  $$\sigma(p_T)/p_T = \sigma_s/p_T = \sigma_y\ p_T\ \mathrm{Sqrt}(720/(N+4))/(0.3\ B\ L^2)$$
- The relative momentum error comes out as $dp_T/p_T = 5.5 \times 10^{-4}$ for a 100 GeV muon
- Looks great! And if there was vacuum between the drift chambers that's what we would get. (Un)fortunately, there is iron and not vacuum and that spoils the resolution. We have to add a contribution to the momentum error coming from multiple scattering.

Multiple scattering

- Charged particles undergo a large number of small scattering processes when traversing matter
- They result in a change of the particle's direction (Θ) and a displacement of its position (or exit point)
- The amount of scattering is inversely proportional to the particle momentum and grows with the sqrt of the amount of material, expressed in units of its radiation length.



$\theta_0 = \theta_{plane} = 1/\sqrt{2}\ \theta_{space}$.

$= 13.6\ \mathrm{MeV}/p\ \sqrt{(x/X_0)}\ [1+0.038\ \ln(x/X_0)]$

X_0 = radiation length
x = path length
p = particle momentum

$y_{plane} = 1/\sqrt{3}\ x\ \theta_{0\$}$
$s_{plane} = ¼\ y_{plane}$

Multiple scattering error in our ν detector

- Using the parameters from our exercise
  - p = 100 GeV
  - X_0(Fe) = 1.76 cm
  - x = 1 m
- Let's calculate the scattering angle and the track displacement from one drift chamber to the next (x= 1 m)

  Θ_0 = 1.025 (1+ corr.) mrad

  = 1.025 * 1.15 mrad

  = 1.18 mrad/m

  or/and

  y_{plane}= 1/√3 x θ_0 = 0.58 * 1.18 mm/m

  = 0.68 mm/m (much larger than the single-point measurement error σ_x = 0.2 mm assumed before)
- Here we have a case where equipping the detector with extremely precise muon chambers is money thrown out of the window. Anything that measures more precisely than a few hundred µm is useless.

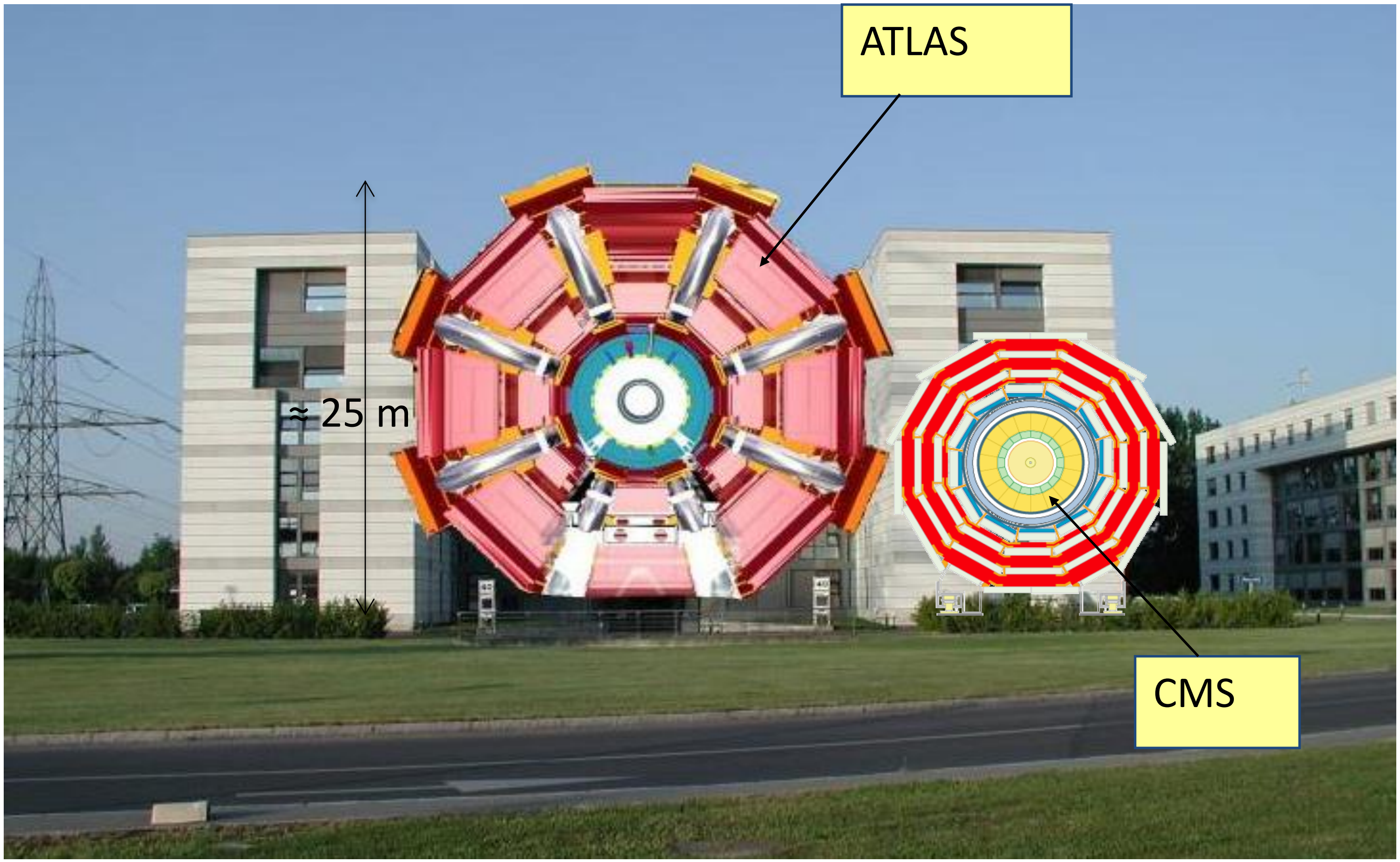
What have we learned so far on momentum measurement?

- We need a magnet – the bigger the magnetic field B, the better
- In a homogeneous field the charged particle will move on a circular track the radius of which tells us the momentum of the particle
- To fit the circle we need at least three measurement points (stations)
- For a field B and a path length L, the sagitta $s = 0.3\ B\ L^2/8\ p_T$
- The precision with which we can determine the momentum is $\sigma(p_T)/p_T = \sigma(s)/s$
- The larger p, the smaller s, the more precise the detector has to measure.
- The longer L (the distance between the first and last measurement station), the better; however, adding measurement points equally spaced does not bring a very large improvement
- Multiple scattering must be considered
  - It is often the most important error contribution. It plays a big role for low momenta particles; usually it can be ignored for very high momenta.
  - In an iron core magnet multiple scattering dominates the momentum resolution, muon detectors can be low-precision objects
  - In an air-core magnet, the detector precision and multiple scattering are the most important contributors

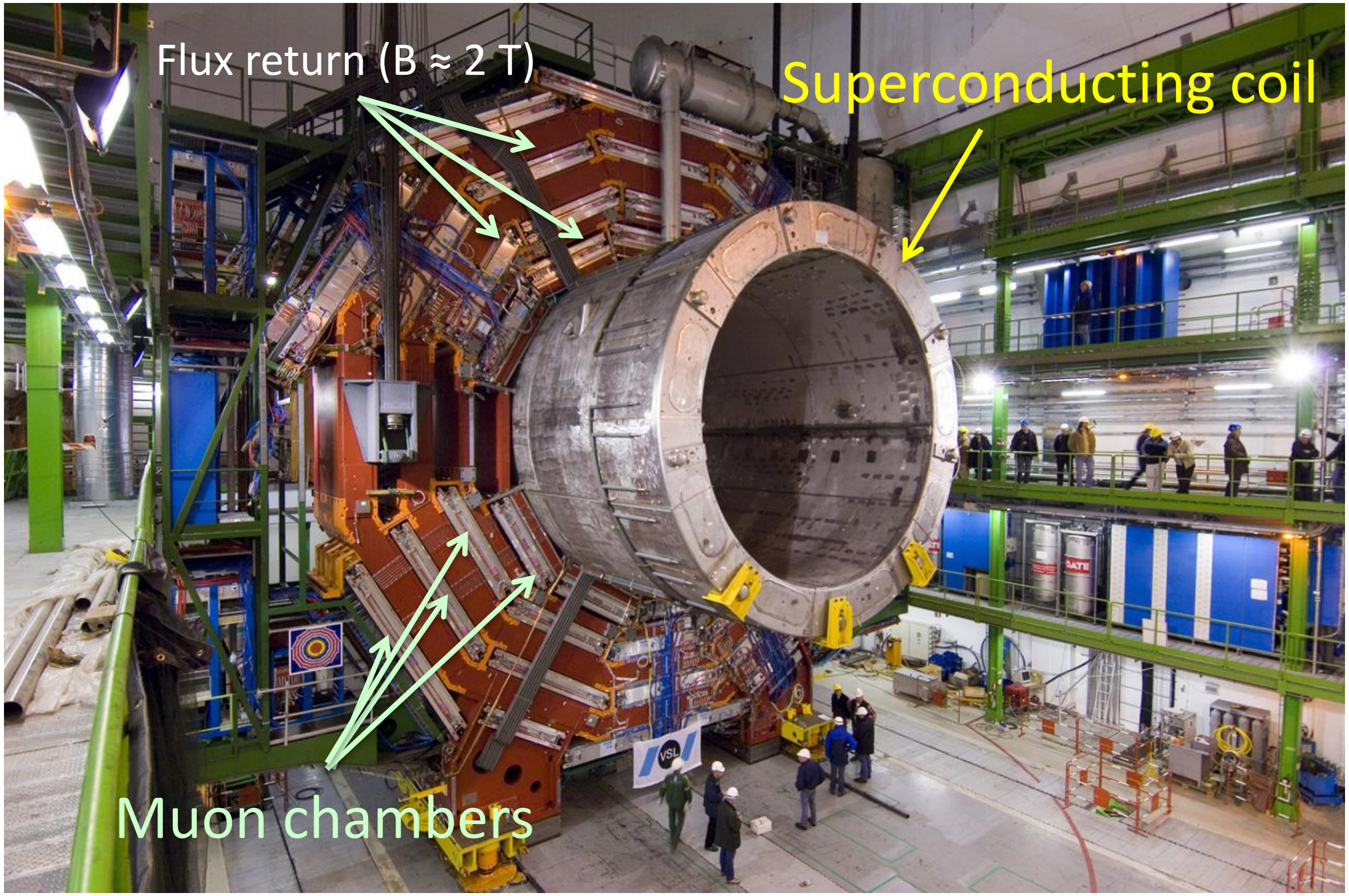
Two prominent examples ATLAS and CMS

- The two largest LHC detectors opted for two very different approaches for their muon detection systems
  - ATLAS (A Toroidal Lhc ApparatuS) chose an air-core magnet together with high-precision muon detectors leading to the largest muon system built to-date and excellent stand-alone muon performance
  - CMS (= Compact Muon System) put emphasis of measuring the muons precisely in the inner tracking system and took advantage of the field in the flux return of their large solenoidal magnet and equipped it with lower-precision muon chambers
- Both systems tried to achieve a coverage as large as possible: ATLAS up to $\eta=\pm2.7$, CMS up to $\eta=\pm2.5$.

ATLAS & CMS



CMS muon system

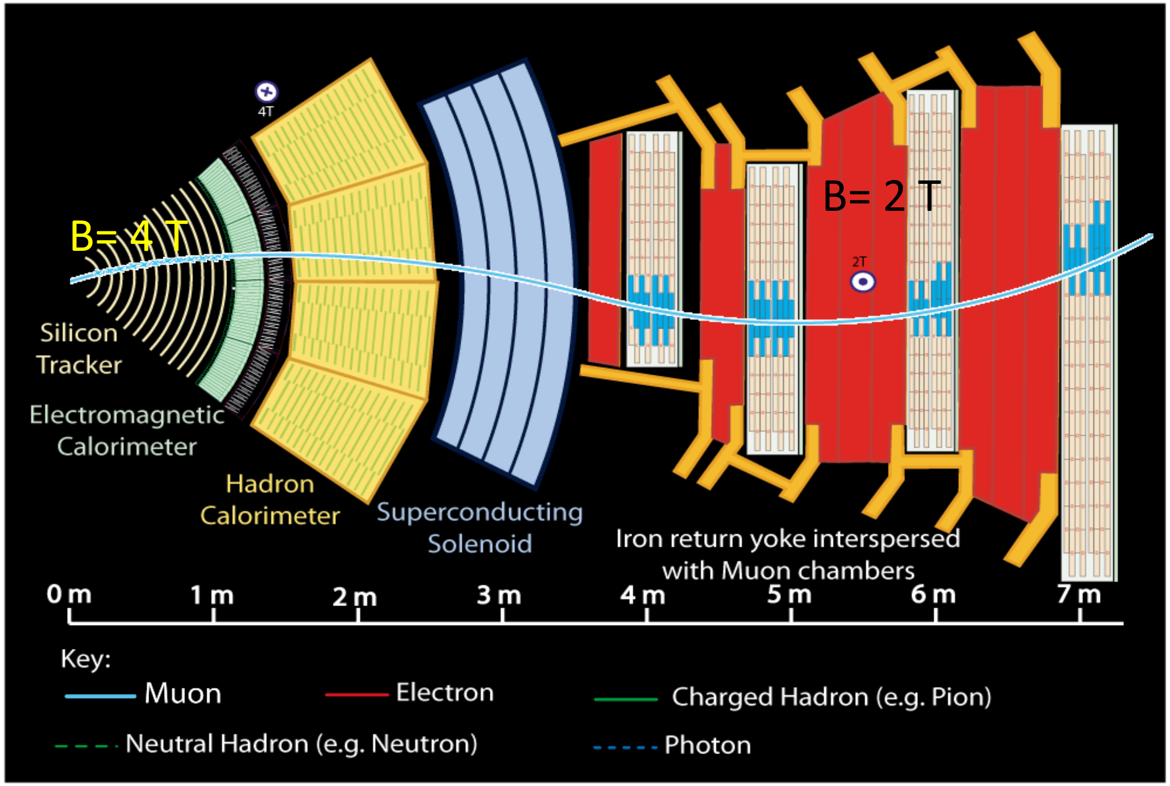


CMS muon system (schematic)

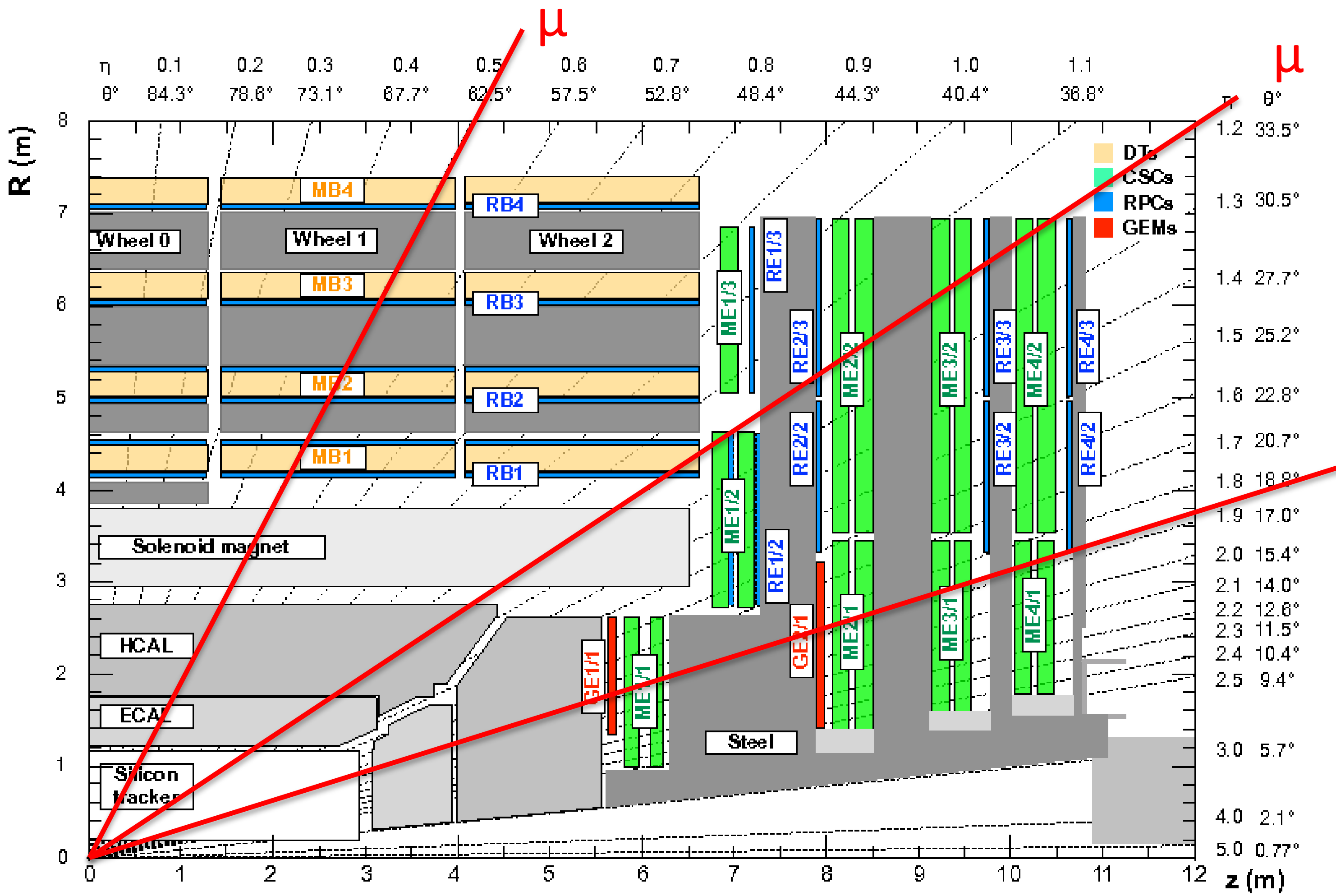
- Solenoidal field, bending in Φ, tracks in r-z are straight; field acts only on p_T
- Bending force changes as function of track angle (sinΘ)
- Muon track is measured twice

  A. Before the absorber: High field (B=4T), L=1 m. Track coordinates are measured with very good precision (Si tracker) but difficult to isolate from other tracks.

  B. After the coil, in the flux return yoke: L=3 m, B=2T (opposite direction) track coordinates are measured with moderate precision



The CMS muon system



Performance in decreases in forward direction, loss in BdL

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Muon spectrometers

TABLE 12 Main parameters of the ATLAS and CMS muon measurement systems as well as a summary of the expected combined and stand-alone performance at two typical pseudorapidity values (averaged over azimuth)

Parameter	ATLAS	CMS
Pseudorapidity coverage		
-Muon measurement	$\|\eta\| < 2.7$	$\|\eta\| < 2.4$
-Triggering	$\|\eta\| < 2.4$	$\|\eta\| < 2.1$
Dimensions (m)		
-Innermost (outermost) radius	5.0 (10.0)	3.9 (7.0)
-Innermost (outermost) disk (z-point)	7.0 (21–23)	6.0–7.0 (9–10)
Segments/superpoints per track for barrel (end caps)	3 (4)	4 (3–4)
Magnetic field B (T)	0.5	2
-Bending power (BL, in T· m) at $\|\eta\| \approx 0$	3	16
-Bending power (BL, in T· m) at $\|\eta\| \approx 2.5$	8	6
Combined (stand-alone) momentum resolution at		
-p = 10 GeV and $\eta \approx 0$	1.4% (3.9%)	0.8% (8%)
-p = 10 GeV and $\eta \approx 2$	2.4% (6.4%)	2.0% (11%)
-p = 100 GeV and $\eta \approx 0$	2.6% (3.1%)	1.2% (9%)
-p = 100 GeV and $\eta \approx 2$	2.1% (3.1%)	1.7% (18%)
-p = 1000 GeV and $\eta \approx 0$	10.4% (10.5%)	4.5% (13%)
-p = 1000 GeV and $\eta \approx 2$	4.4% (4.6%)	7.0% (35%)

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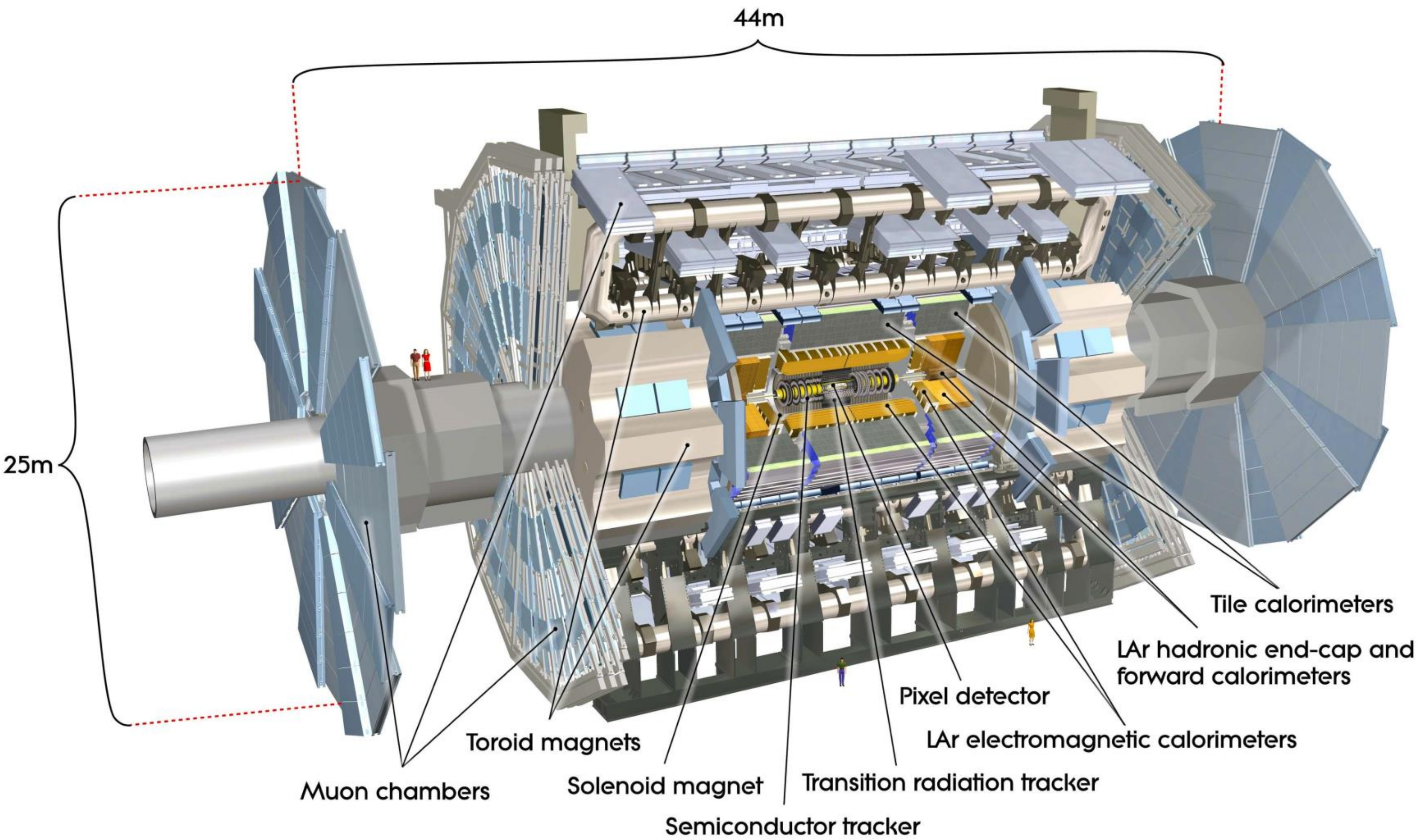
CMS measures muons extremely well in the inner tracker, much less so in the muon system

? How will the system perform at highest luminosities? Can the muons still be identified in the IDET and measured?

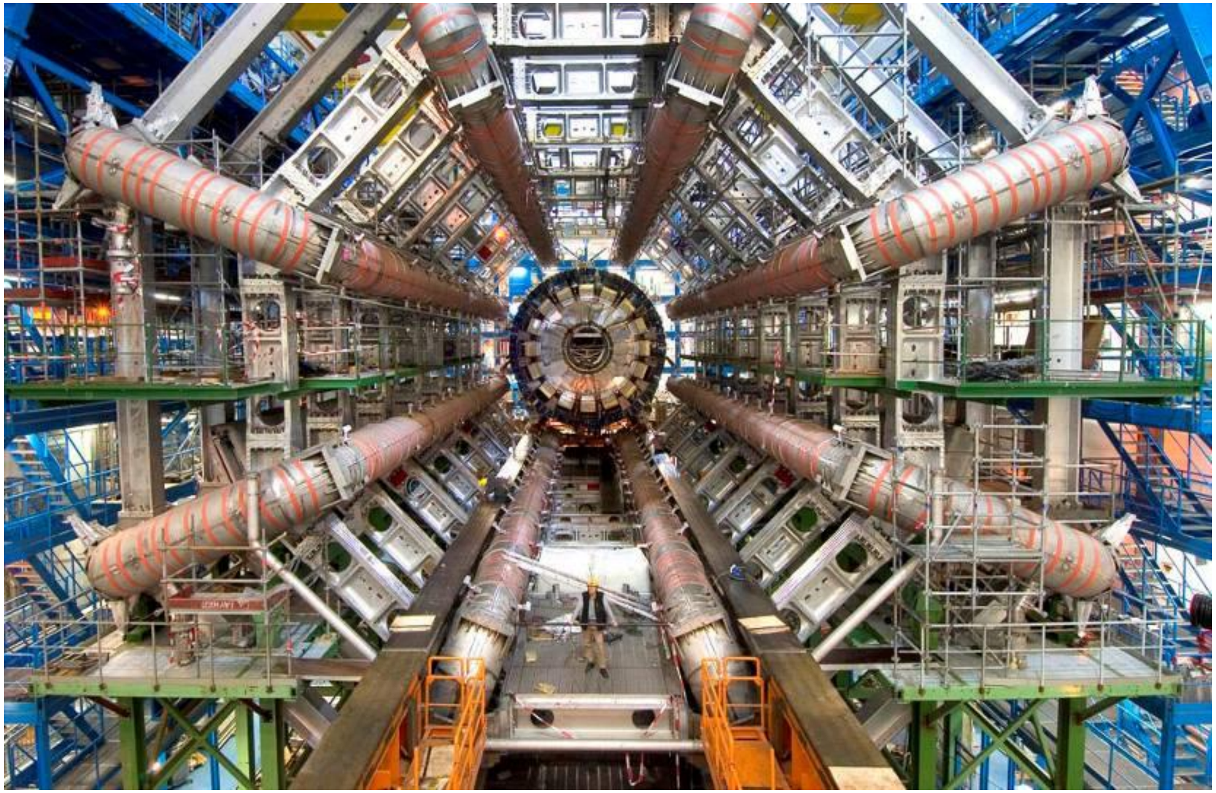
The ATLAS detector



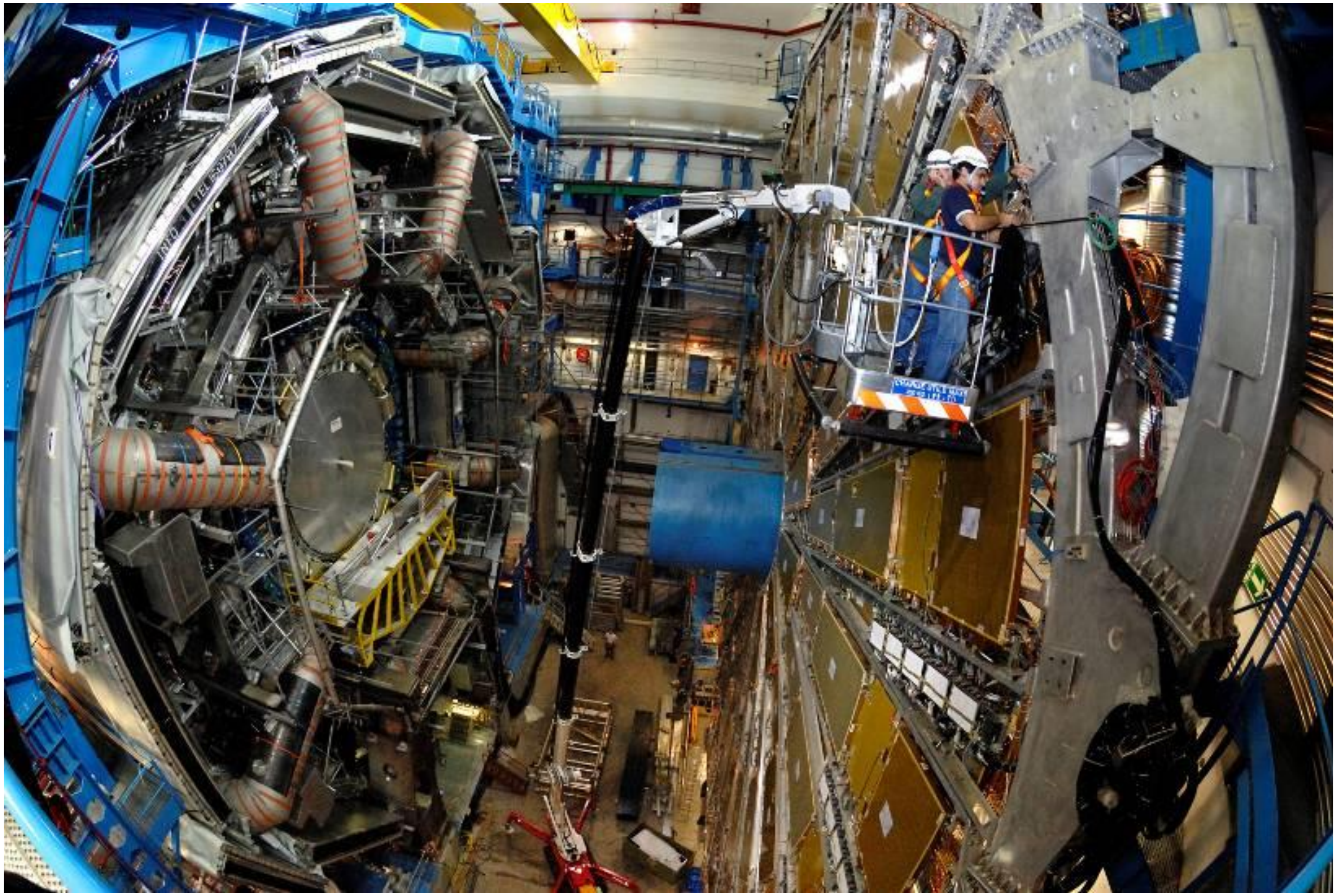
The ATLAS magnet system

- The ATLAS magnet system consists of eight superconducting barrel coils and two s.c. end-cap magnets. The latter comprise eight coils each, in a single cryostat.
- The field lines are circular (toroidal field), with B ≈ 1 T in the barrel and B ≈ 2 T in the end-caps.
- Bending force independent on track angle, magnetic field acts on p and not p_T

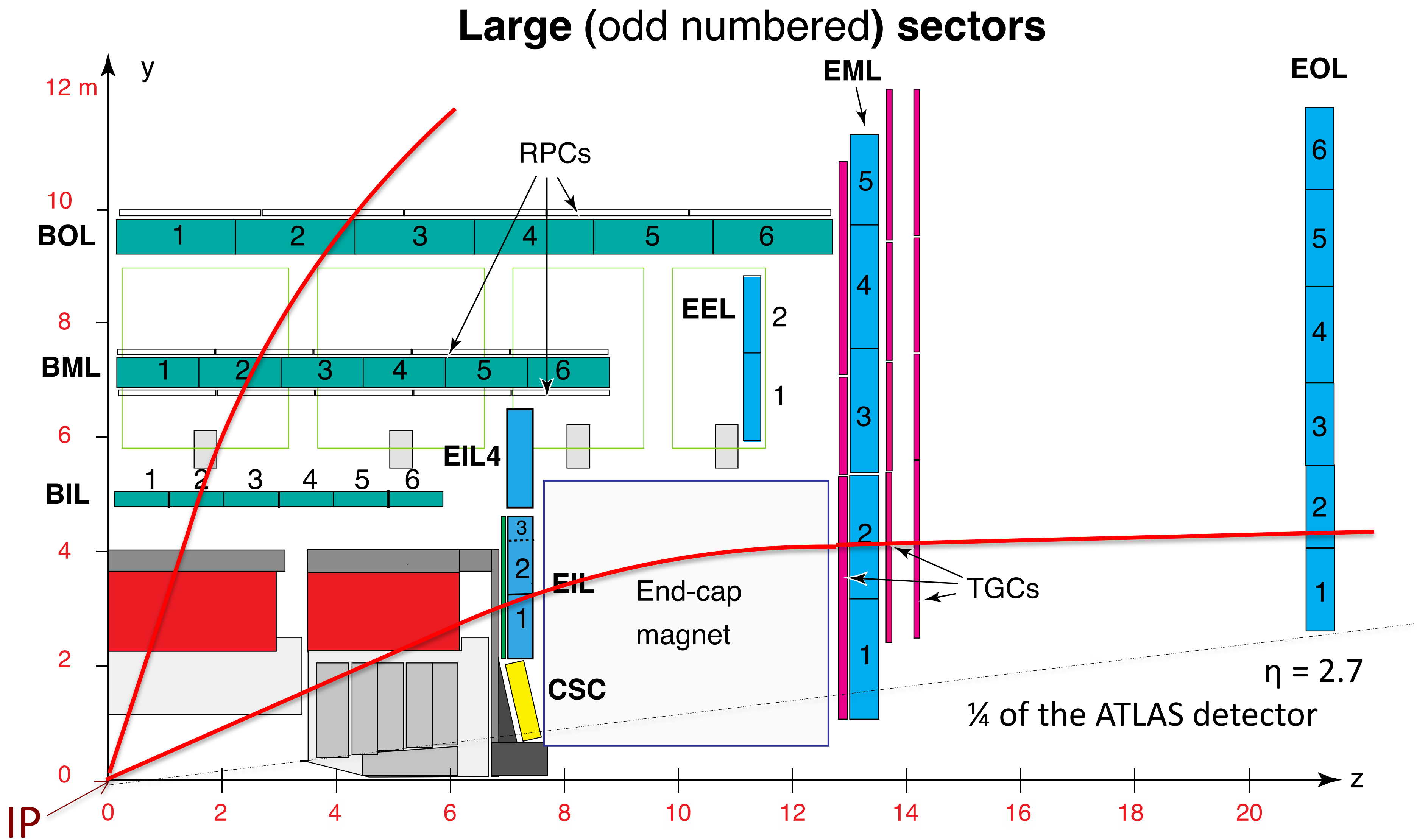
The air-core toroidal magnet



ATLAS during the installation

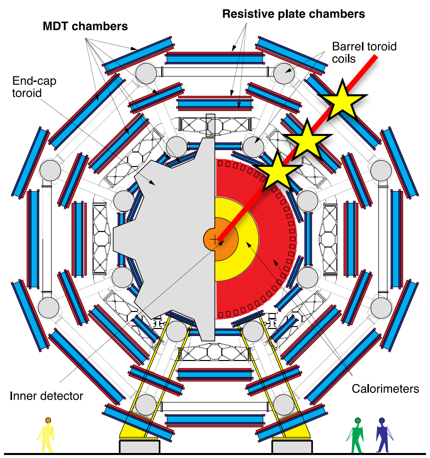


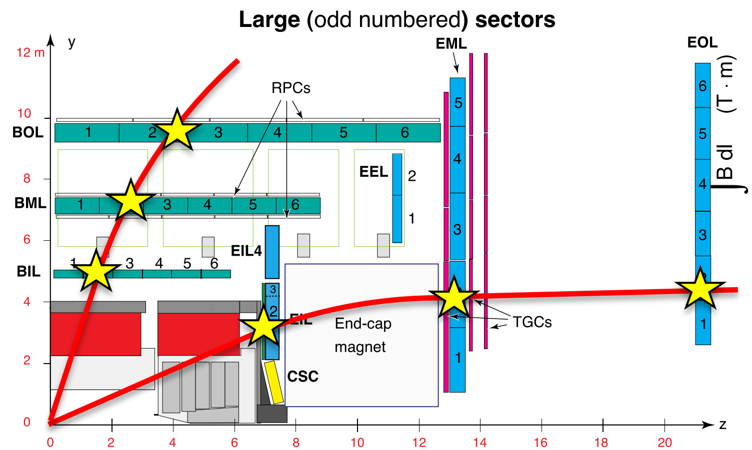
The ATLAS muon system

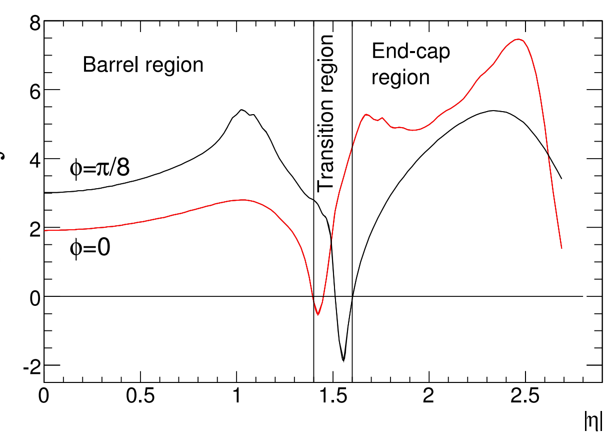


Muon measurement in ATLAS

- Muon measurement starts at r≈4.5 m after the inner tracker and 2.5 m of instrumented absorber (solenoid coil, electromagnetic and hadron calorimeters); muons are bent inside the toroidal field (B ≈ 1 – 2 T)
  - Barrel: three measurement stations measure the track sagitta, with the middle station located inside the magnetic field
  - End-cap: three measurement stations measure one point and one angle; no measurement station inside the magnetic field
- BdL increases with η, i.e., the larger p, the stronger the bending (as desired)

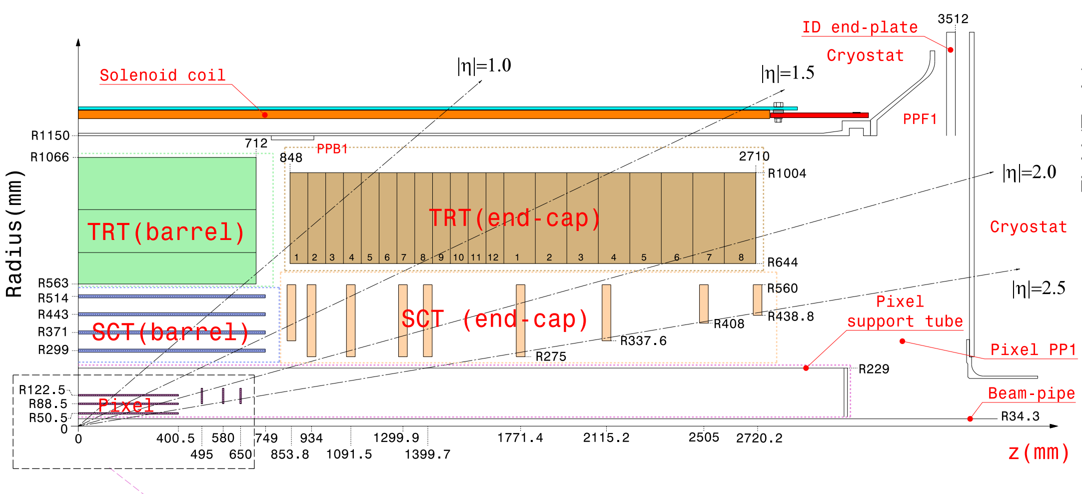


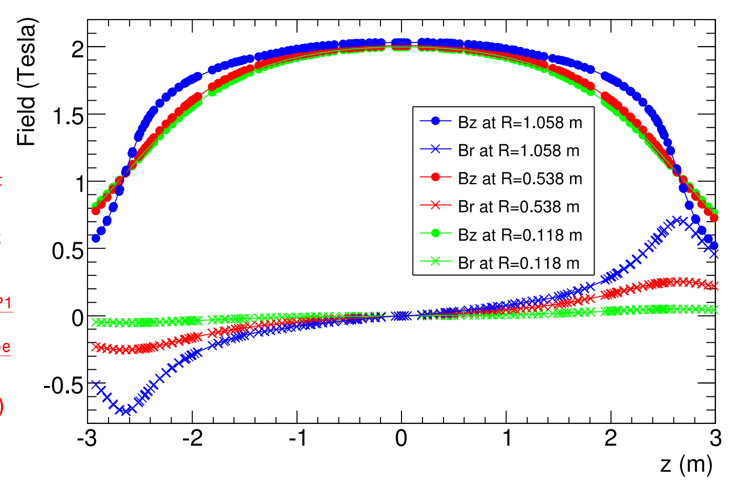




Muon measurement in ATLAS II

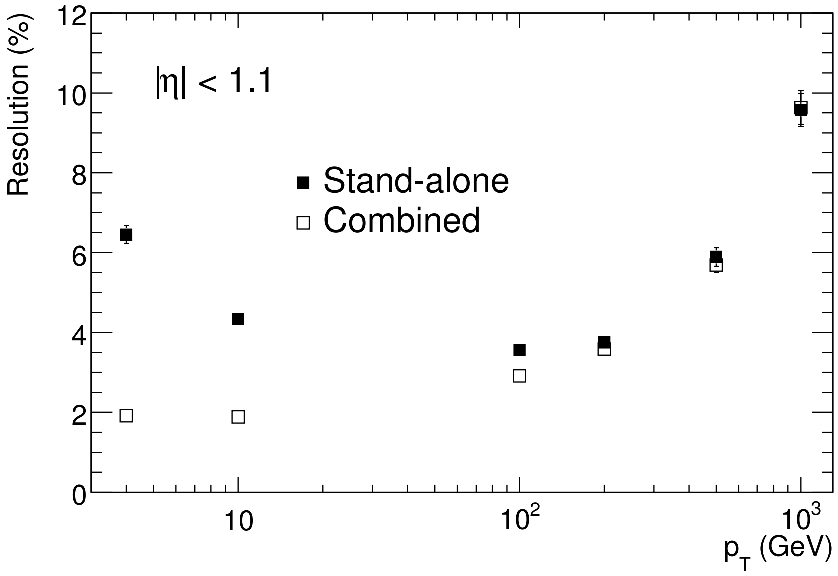
- Muons are also measured, like in CMS, in the solenoidal field of the inner tracking system
  - The inner tracking system comprises a 2 T superconducting solenoid and seven layers of Si (pixel and strip) detectors at small radius and 400k straw-tubes at large radius. The track reconstruction is completely independent of the muon system.
- In addition is the energy loss of the muons in the el and hadron calorimeters measured and used in the combined muon analysis

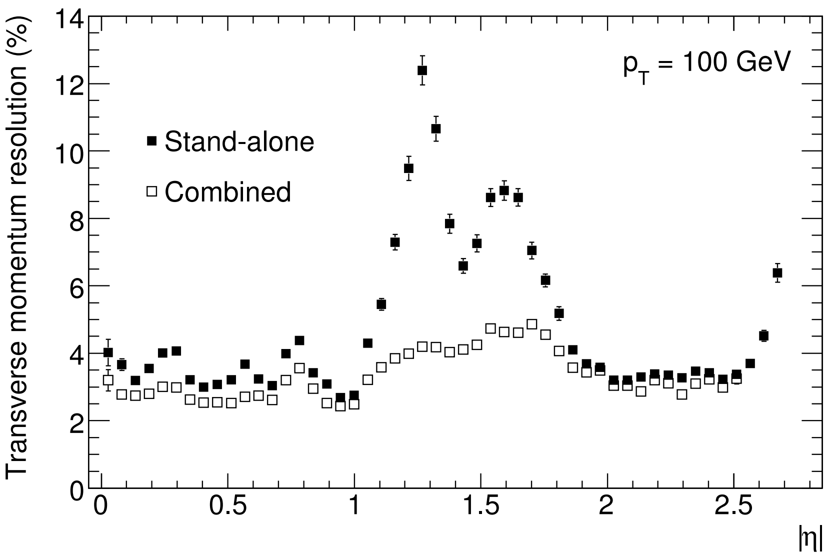




Muon measurement in ATLAS II

- Some performance plots are shown below:
- The stand-alone momentum resolution is 4% for 10 GeV muons and slowly rises to 10% for 1 TeV tracks; below 10 GeV the resolution suffers from multiple scattering (note: that muons must have an energy of 4–6 GeV to reach the muon system.
- For 100 GeV muons one reaches a momentum resolution of typically dp_T/p_T = 3–4%, with the exception of the transition region between the barrel and the end-cap
- Combining the stand-alone muon with the inner tracking system leads to a considerable improvement in the transition region and in particular for low-pT tracks where the multiple scattering error and the energy-loss fluctuations (in the calorimeter) become important.





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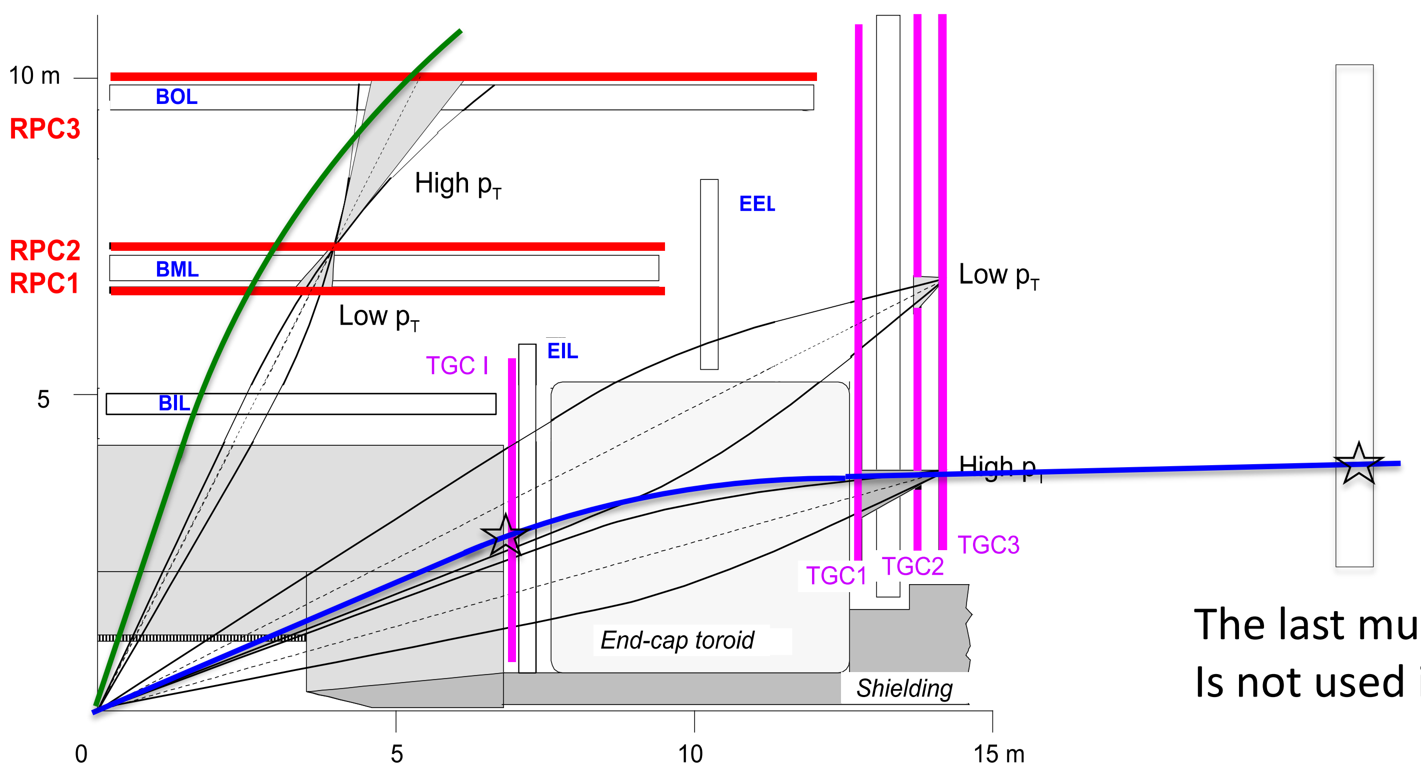
ATLAS measures muons extremely well in the muon system; the inner tracker helps in particular for low p_T tracks and in the magnetic field transition region

Muons as trigger particles in ATLAS

- Muons serve in ATLAS also in the Level-1 trigger. This requires detectors that are able to produce (and route out) a signal in less than 25 ns (LHC bunch-crossing), however, do not necessarily need to be extremely precise in the space resolution.
- ATLAS decided for a dual system with separate-function detectors for triggering and precision measurement
  - Drift tube detectors for precise tracking and RPCs (barrel) and TGCs (MWPCs) in the end-caps for triggering.
  - Only a very small region in the 1st end-cap station was equipped with Cathode Strip Chambers (CSC). Here the anticipated particle rates would have been too high for the drift tubes.



The last muon station (EO)
Is not used in the trigger !

Instrumentation

- So far we have seen a number of muon detection concepts.
- We have seen how the momentum of muons is determined.
- We have also seen that in some concepts we need very precise detectors, in others not, without having looked too much into the detectors themselves.
- This will be the subject of the 3^{rd} lecture.