The concept of Particle Detector
&
Its applications

Mohsen Khakzad

School of Particles and Accelerator (IPM)

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- What to detect?
- How to probe a particle?
- What is a detector?

- Detector applications:
  - Tracker
  - Timing Detector

Introduction

Particle properties:

- **Mass** [Unit: eV/c^2 or eV]
- **Momentum** [Unit: eV/c or eV]
- **Energy** [Unit: eV]
- **Electric charge** [Unit: e]
- **Spin, Lifetime …**

eV = 1.6×10^{-19} J

c = 299 792 458 m/c

e = $1.602176487 \times 10^{-19}$ C

Relativistic kinematics:

$$E^2 = \vec{p}^{\,2} c^2 + m^2 c^4$$

$$\beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$E = m\gamma c^2 = mc^2 + E_{\text{kin}}$$

$$\vec{p} = m\gamma\vec{\beta}c \qquad \vec{\beta} = \frac{\vec{p}c}{E}$$

Particle Identification via measurement of

e.g. $(E, \vec{p}, Q)$ or $(\vec{p}, \beta, Q)$
$(\vec{p}, m, Q)$ …

How to detect particles?

- Particle Types
  - Charged ($e^-/K^-/\pi^-$)
  - Photons (γ)
  - Electromagnetic (e^-)
  - Hadronic ($K^-/\pi^-/\mu^-$)
  - Muonic (μ^-)

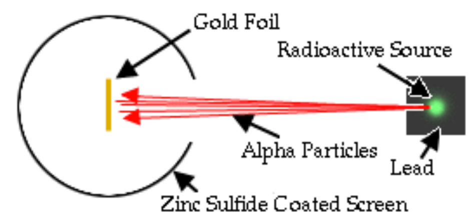
- Interaction with matter
  - Ionisation Loss
  - Radiation Loss
  - Photon Absorption
  - **Electromagnetic Showers**
  - **Hadronic Showers**
  - Cherenkov Radiation
  - Transition Radiation

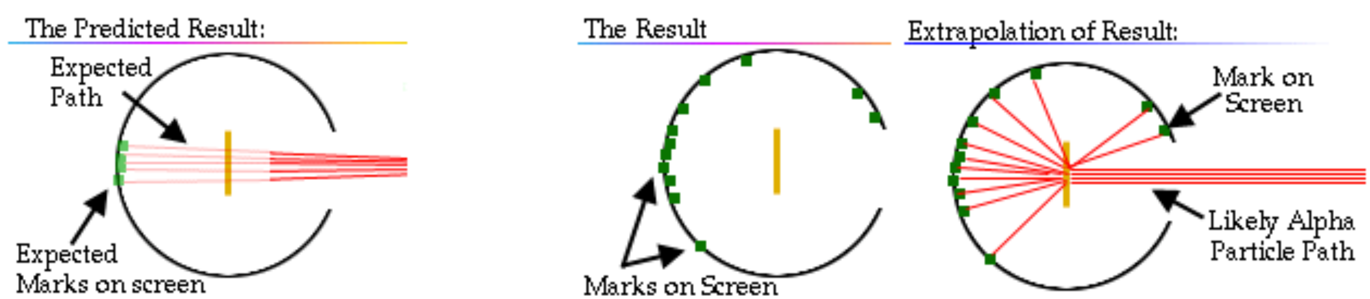
In general, we measure the energy lost as the particle passes through a medium.

Historical development (Rutherford)

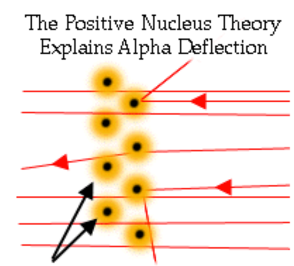
Searching for atom's structure

Beam: Alpha particle
Target: Gold atom in the foil
Detector: Zinc sulfide screen



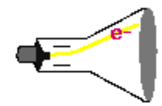


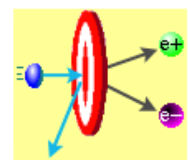
Rutherford's analysis:



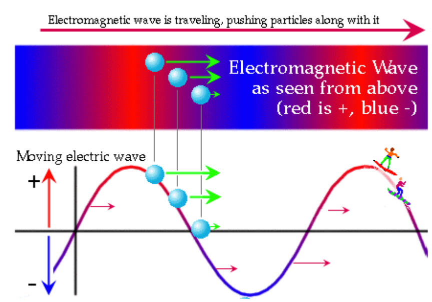
How to obtain particles?

- Produce probe particles
  - Electrons: Heating metal
  - Protons: Ionizing Hydrogen
  - Antiparticles: Hit target





- Accelerating particles

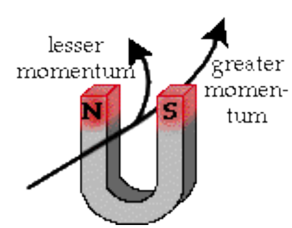


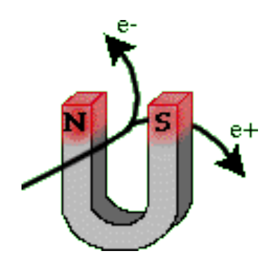
- Select and aim the particles

$$\frac{d\mathbf{p}}{dt} = \frac{q}{c}\mathbf{v} \times \mathbf{B}$$

$$p = 0.2998 B\rho \ \ \mathrm{T\text{-}m}$$

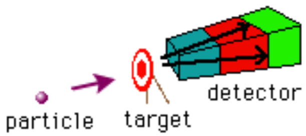
$$\rho = \text{ radius of curvature}$$



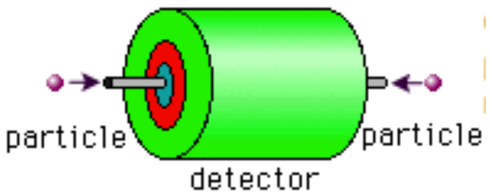


Particle Accelerators

- **Fixed target**: shoot a particle at a fixed target



- **Colliding beam**: two beams of particles cross each other

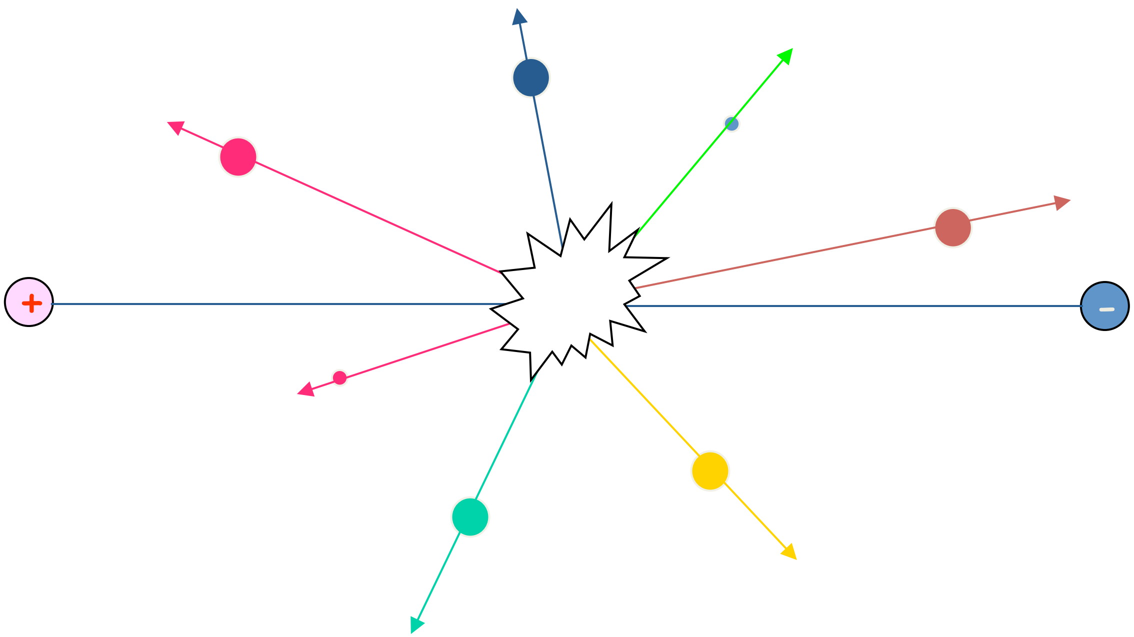


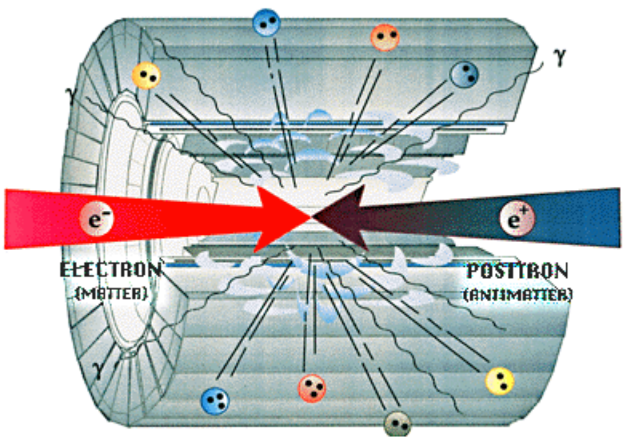
- **Linacs**: particles starts one end and comes out the other

- **Synchrotrons**: particles go around a circle

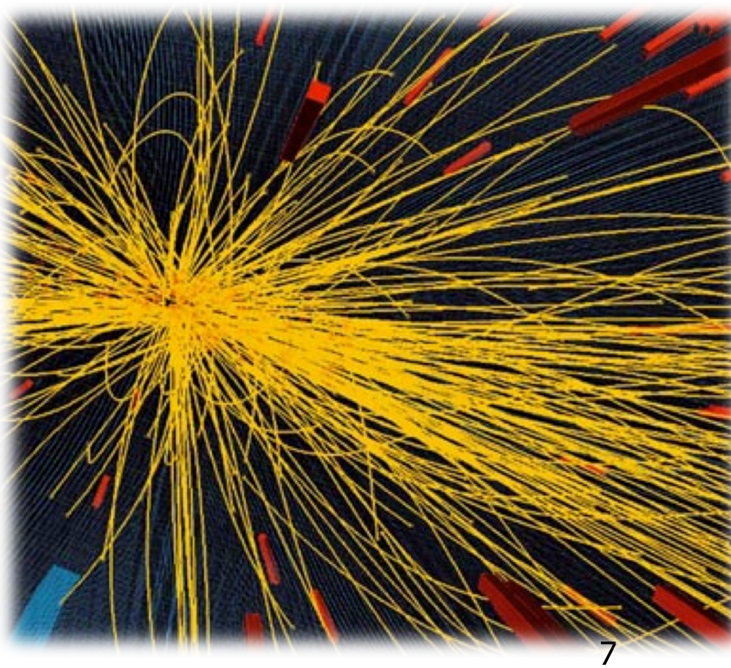
Collision

Ideally, we want to measure (E, p_x, p_y, p_z) about particles n the “collision”.





A 7 TeV proton–proton collision in CMS yielding more than 100 charged particles.



If we consider 3550 bunches: 11245 **x** 3550 = 40 millions crosses ⇒ **40 MHz**

Global Detector Systems

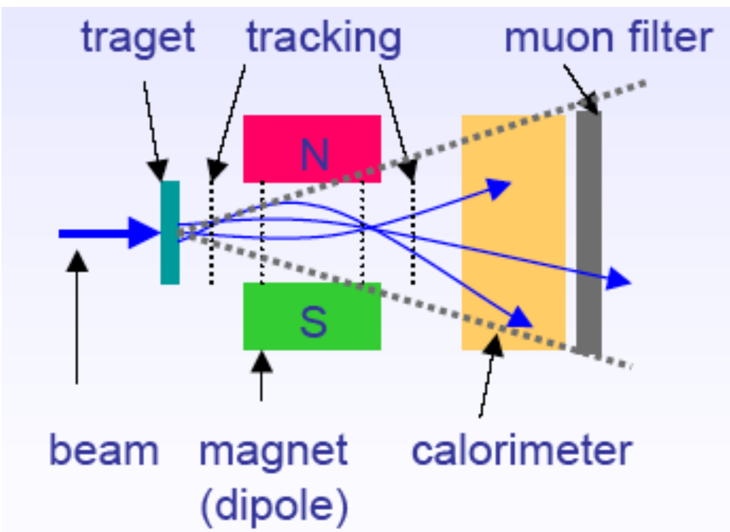
Overall Design Depends on:

- –Number of particles
- –Event topology
- –Momentum/energy
- –Particle identity

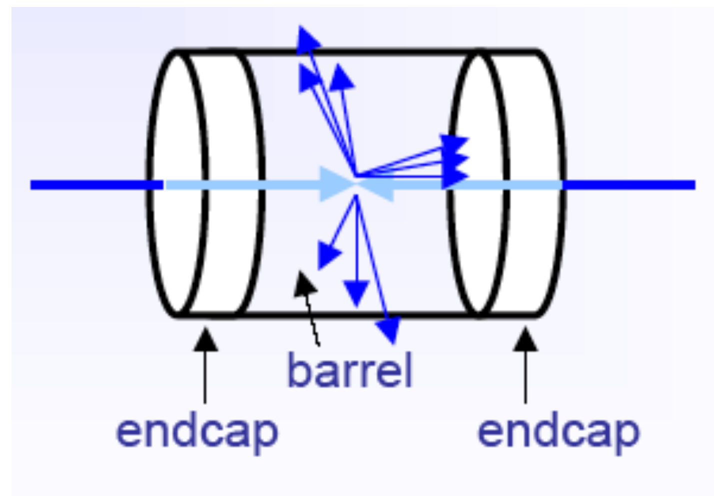
No single detector does it all…

→ Create detector systems

Fixed Target Geometry



Collider Geometry



- Limited solid angle (dΩ) coverage (forward)
- Easy access (cables, maintenance)

- "full" solid angle dΩ coverage
- Very restricted access

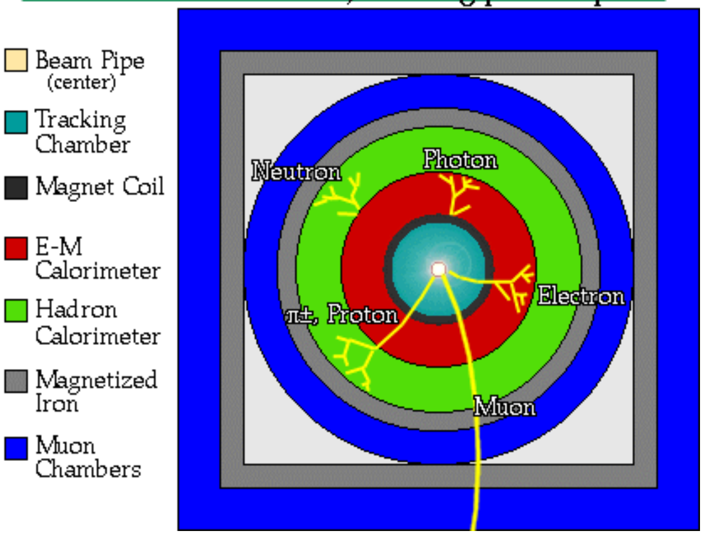
Particle Decay Signatures

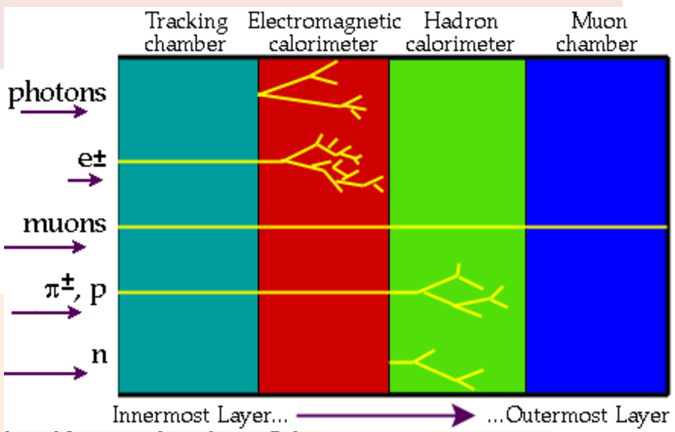
Modern detectors consist of many different pieces of equipment to measure different aspects of an event.

Particles are detected via their interaction with matter.

Many types of interactions are involved, mainly electromagnetic. In the end, always rely on ionization and excitation of matter.

A detector cross-section, showing particle paths





An “ideal” particle detector would provide…

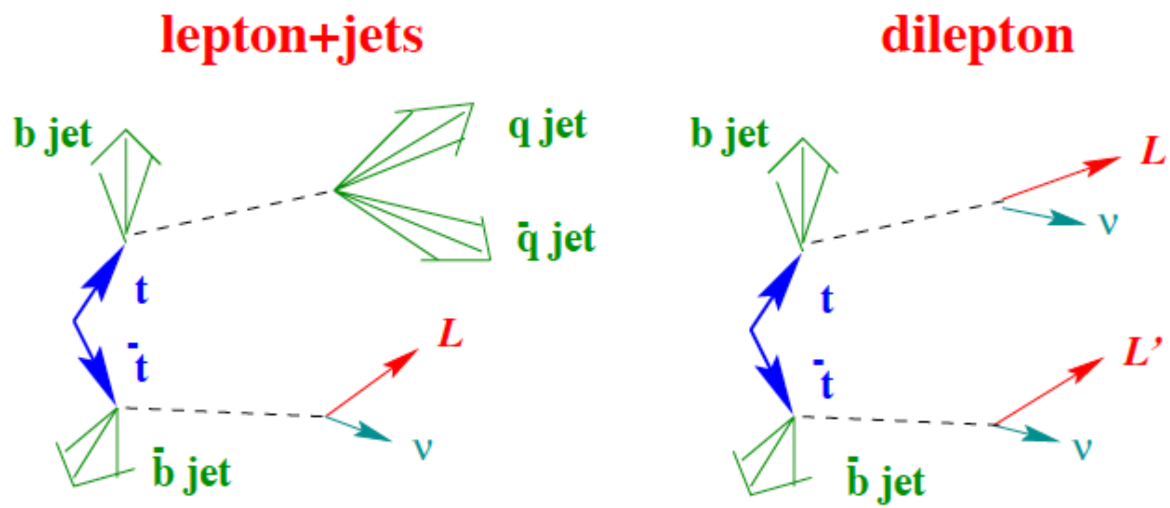
- Coverage of full solid angle, no cracks, fine segmentation (why?)
- Measurement of momentum and energy
- Detection, tracking, and identification of all particles (mass, charge)
- Fast response: no dead time (what is dead time?)

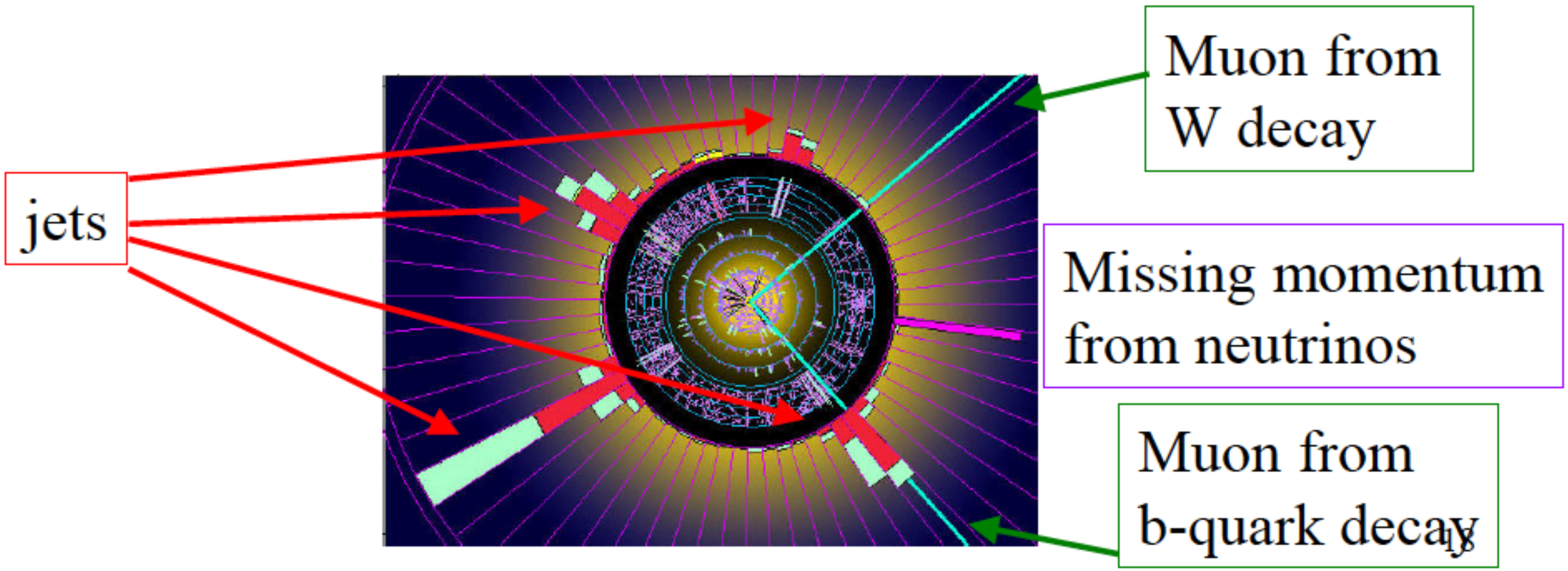
However, practical limitations: Technology, Space, Budget

Top Event

Much more complicated decays

Uses all parts of the detector





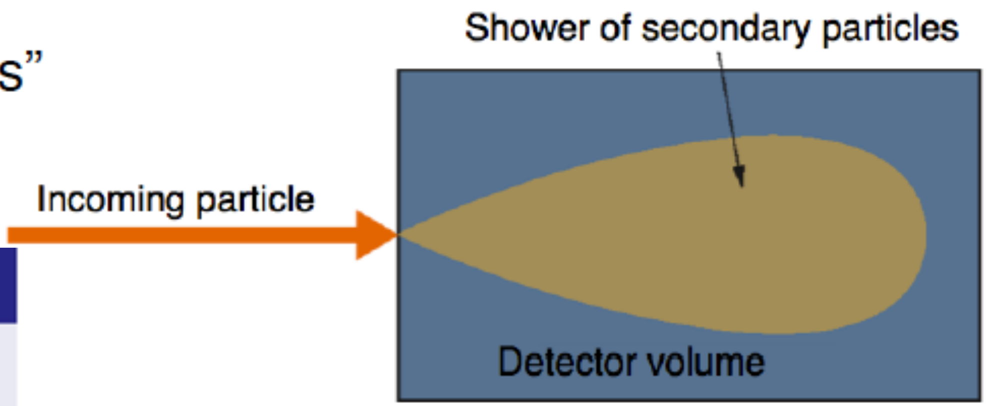
Calorimeter

★ A calorimeter is a detector which fully absorbs the particles. The signals produced are a measure for the energy of the particle.

★ The particle initiates a particle shower. Each secondary particle deposits energy and produces further particles until the full energy is absorbed.

The composition and the dimensions of these showers depend on the type and energy of the primary particle ($e^{\pm}$, photons or hadrons).

Principle of a "homogeneous" calorimeter:



energy deposition

- ionization
- excitation of atoms
- nuclear interactions
- ...

Homogeneous Calorimeter

- ★ In a homogenous calorimeter the detector material is at the same time the absorbing material and the detector.
- ★ Examples for different signal exploited:

Signal	Material
Scintillation	BGO*, BaF_2, CeF_3, $PbWO_4$
Cherenkov light	Lead glass
Ionization	Liquid noble gasses (Ar, Kr, Xe), Germanium (in nuclear physics)

* Bismuth Germanate $Bi_4Ge_3O_{12}$

- ★ Advantage: Best possible energy resolution achievable
- ★ Disadvantage: Expensive.
- ★ Homogenous calorimeters are only used as electromagnetic calorimeters (e.g. to measure energy of $e^{\pm}$ and photons).

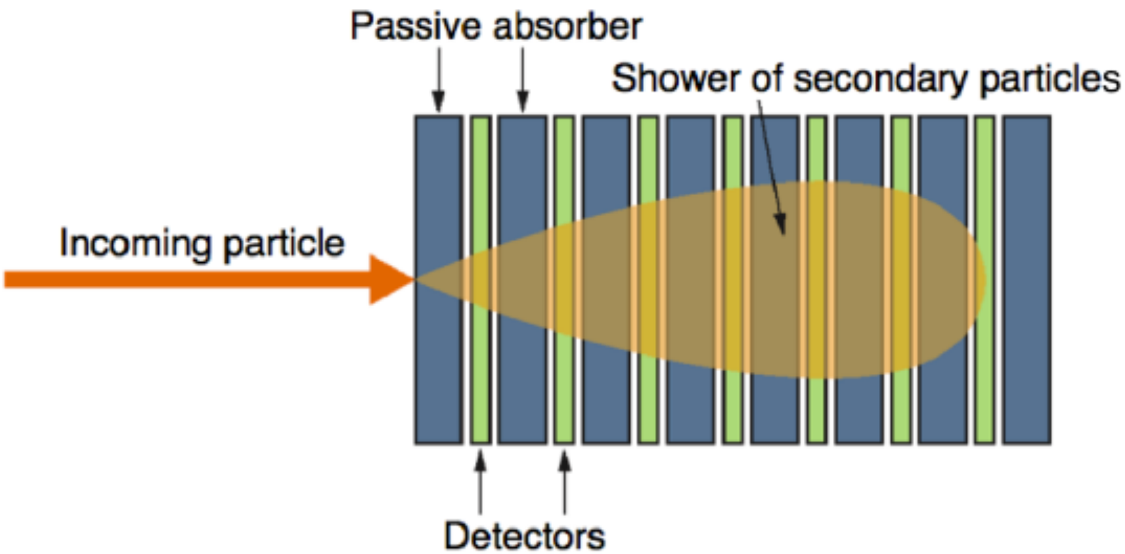
Sampling Calorimeter

- ★ A sampling calorimeter consists of alternating layers of passive absorbers and active detectors.

- ★ Typical absorbers are materials with high density, e.g.: Fe, Pb, U

- ★ Typical active detectors:
  - Plastic scintillators
  - Silicon detectors
  - Noble liquid ionization chambers
  - Gas detectors

Principle of a sampling (sandwich) calorimeter:

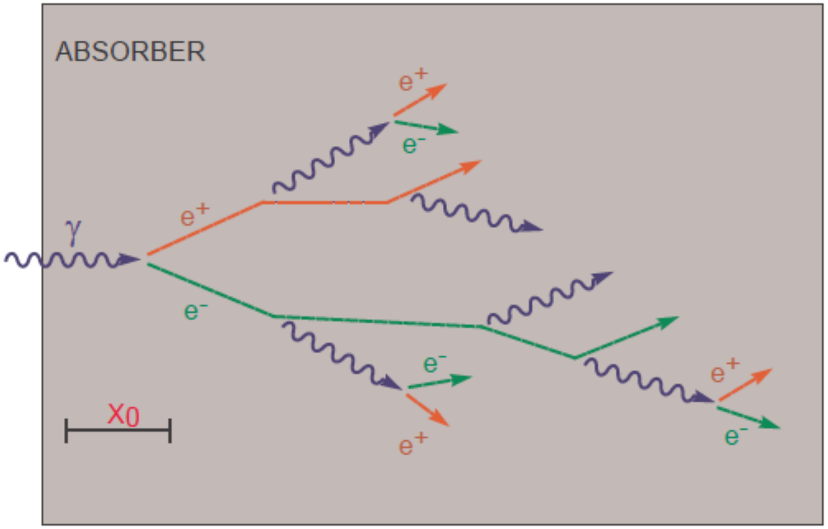


Electromagnetic Calorimeters

- Electromagnetic calorimeters measure the energy of electron, positrons and photons.
- High energy electron, positrons and photons interact via Bremsstrahlung and pair production.
  - Shower development scales with radiation length X_0
  - Energy loss is fast, e.m. calorimeter not very thick

- **E.m. calorimeters exist as homogeneous and as sampling calorimeters.**

- Particle multiplication continues until the mean particle energy equals roughly the critical energy E_c.



Hadron Calorimeters

- Hadron calorimeters measure the energy of charged and neutral hadrons
- Showers development similar to e.m. calorimeter. However, the interactions are hadronic interactions.

  - shower development scales with nuclear absorption length λ_a
  - Hadron calorimeters need not be much thicker

- **Hadron calorimeters exist only as sampling calorimeters**
- **In an experimental set-up, the e.m. calorimeter is therefore always in front of the hadron calorimeter.**

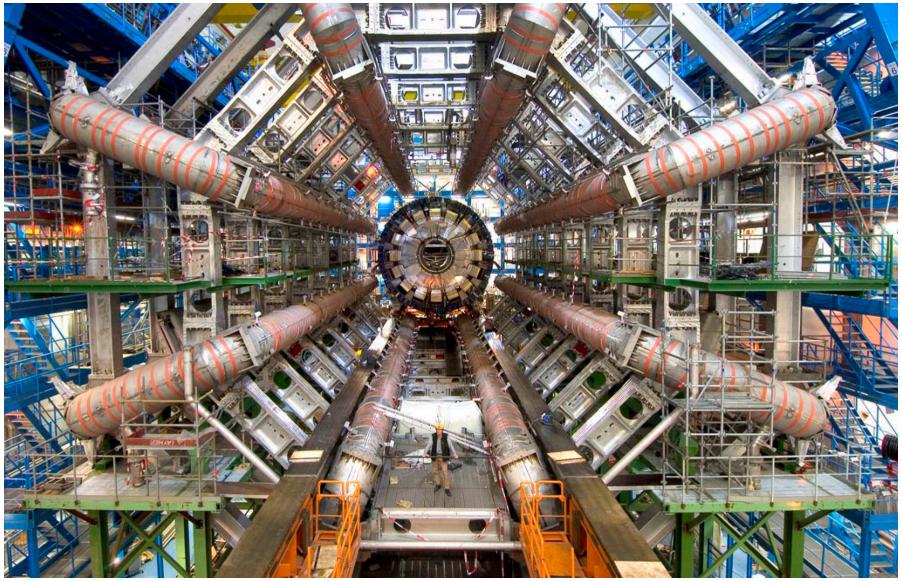
- The secondary particles produce further particles or loose energy by **ionization**, **excitation** of atoms, etc.

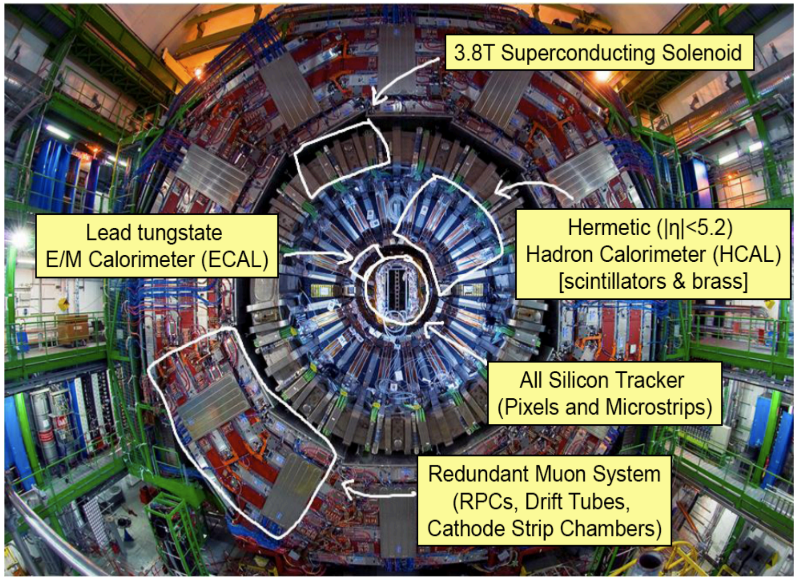
The neutral mesons decay into photons and initiate an electromagnetic shower within the hadronic shower.

Hadron Calorimeters (Examples)

Experiment	Detectors	Absorber material	*e/h*	Energie resolution (E in GeV)
UA1 C-Modul	Scintillator	Fe	≈ 1.4	$80\%/\sqrt{E}$
ZEUS	Scintillator	Pb	≈ 1.0	$34\%/\sqrt{E}$
WA78	Scintillator	U	0.8	$52\%/\sqrt{E} \oplus 2.6\%$*
D0	liquid Ar	U	1.11	$48\%/\sqrt{E} \oplus 5\%$*
H1	liquid Ar	Pb/Cu	≤ 1.025*	$45\%/\sqrt{E} \oplus 1.6\%$
CMS	Scintillator	Brass (70% Cu / 30% Zn)	$\neq 1$	$100\%/\sqrt{E} \oplus 4\%$**
ATLAS (Barrel)	Scintillator	Fe	$\neq 1$	$50\%/\sqrt{E} \oplus 3\%$**
ATLAS (Endcap)	liquid Ar	Brass	$\neq 1$	$60\%/\sqrt{E} \oplus 3\%$**

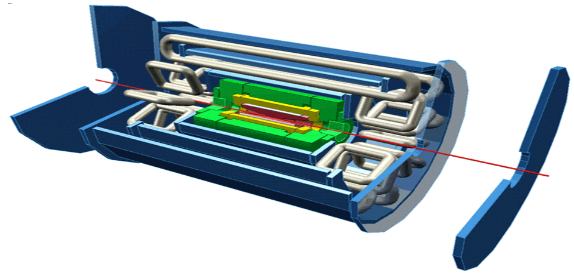
CMS and ATLAS Detectors

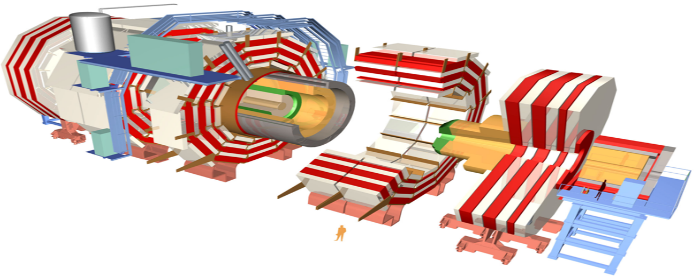


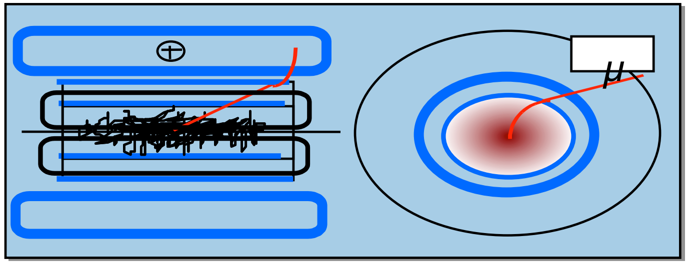


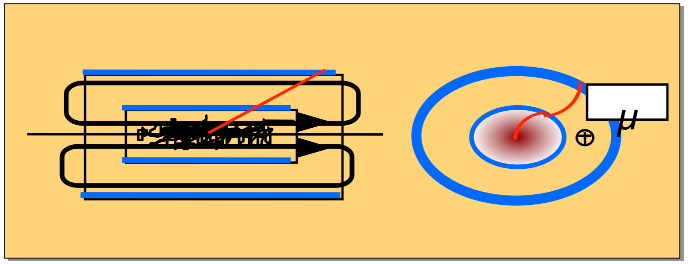
ATLAS A Toroidal LHC Apparatus

CMS Compact Muon Solenoid

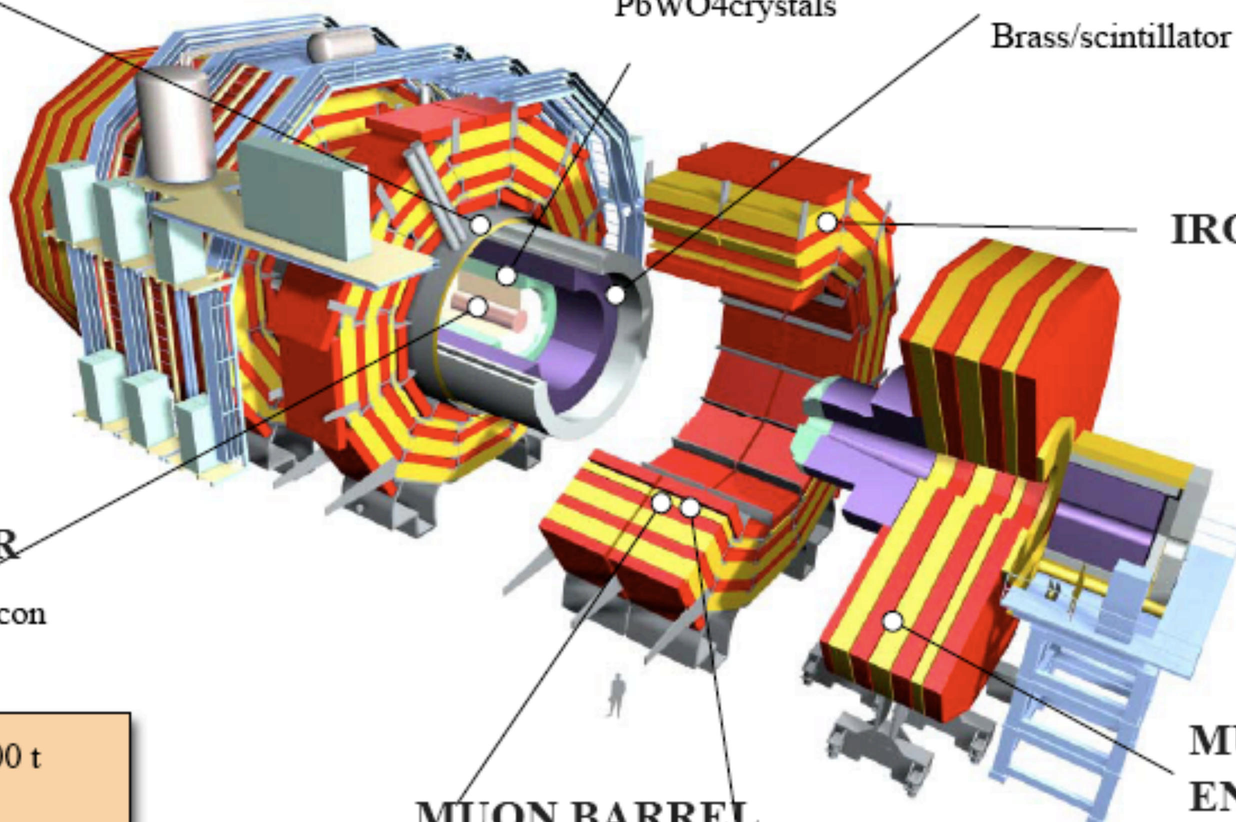








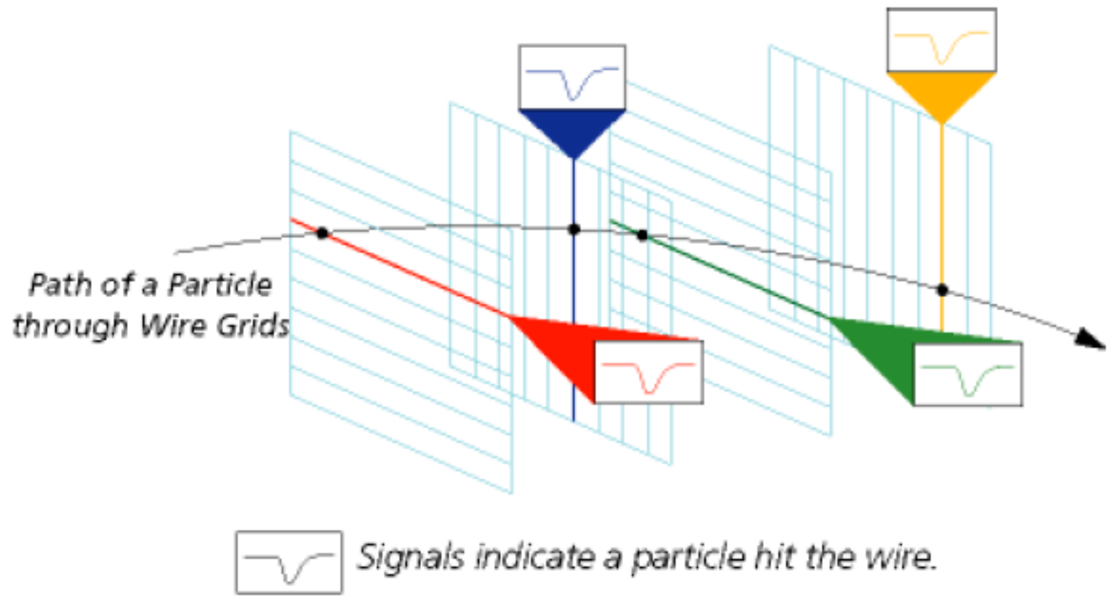
CMS (Compact Muon Solenoid)



Total weight : 12,500 t
Diameter : 15 m
Length: 21.6 m
Magnetic field : 4 Tesla

Tracking

Charged particle detectors (not necessarily “wire grids”) sensitive to ionization from passing charge particle.



Examples:

- Wire chambers (similar to Gieger counters)
- Scintillation fibers (produce light when charged particle passes through)
- Silicon detectors (produce electron-hole pairs when charge particle passes through)

Basic Idea

When we talk about "tracking," we want to do the following:

• Measure the true **path of the charged particle**, which let's us know...

• The momentum (**3-momentum**) if we know the magnetic field

• The **sign** of the charge of the particle

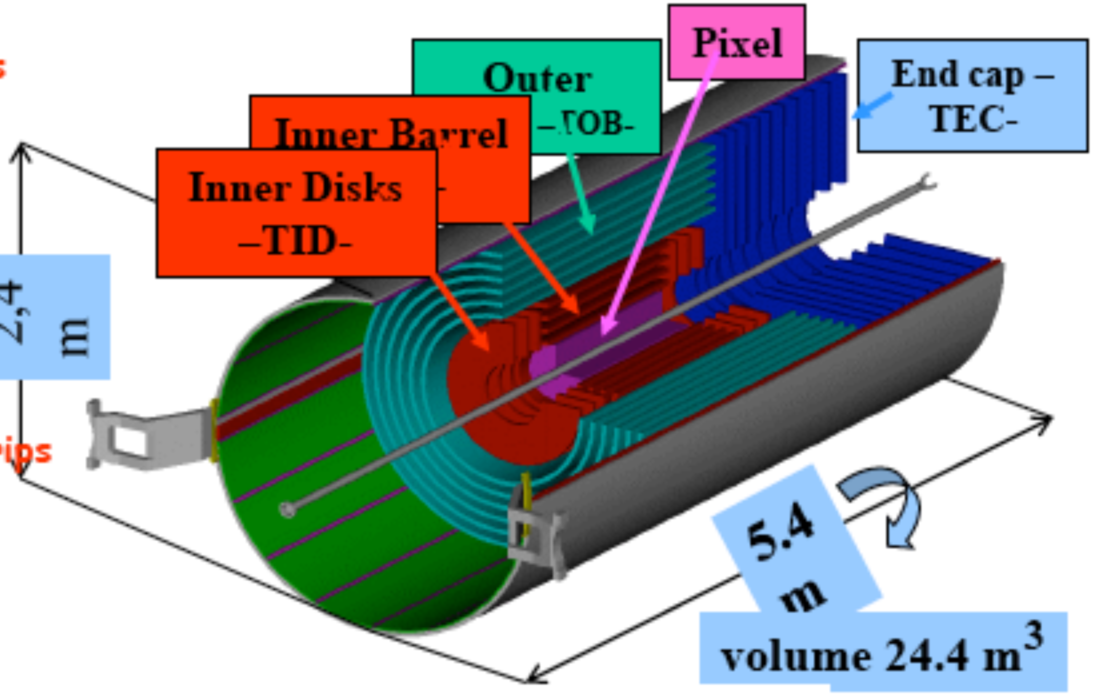
• With other constraints or assumptions, the "**origin**" in space of the particle

• Without some other detector though, we can't measure the mass independently just with a tracker

Example: Tracking in CMS

Pixel Detector

- 2 barrels, 2 disks: 40×10^6 pixels
- barrel radii: 4.1, ~10 cm
- pixel size 100×150 μm
- $\sigma_{r\phi}$= 10 μm σ_z = 10 μm

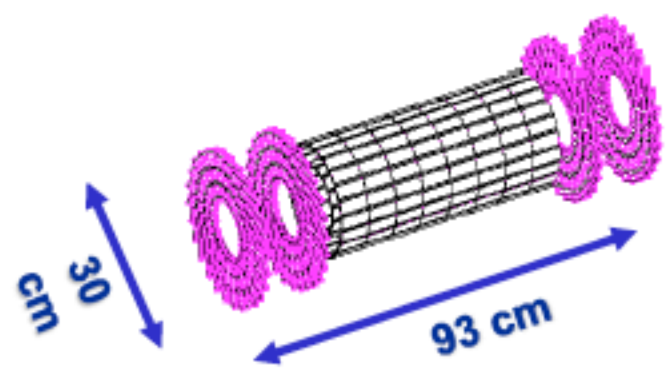


Internal Silicon Strip Tracker

- 4 barrels, many disks: 2×10^6 strips
- strip pitch 80,120 μm
- $\sigma_{r\phi}$= 20 μm σ_z = 20 μm

External Silicon Strip Tracker

- 6 barrels, many disks: 7×10^6 strips
- barrel radii: max 120 cm
- strip pitch 80, 120 μm
- $\sigma_{r\phi}$= 30 μm σ_z = 30 μm



Silicon

Why are silicon detectors such a success?

✧ **Position resolution** down to few **micron**
✧ **Readout speed**: depending on technology, **very fast**
✧ **Radiation hardness**

But:

✧ Material budget … ok …
Sensors and infrastructure rather massive compared to gasses trackers
- ➢ Use fewer layers
- ➢ Pattern recognition is more difficult

✧ Any attempt to reduce material budget makes detectors more fragile
difficult to access for repair

Advantage:
✧ Lots of commercial silicon technology to exploit!
✧ **Silicon is most widely used semiconductor in HEP**.

The CMS Tracker Upgrade: Overview

2013	**Long Shutdown 1**	• **Consolidation:** Improvement of tracker thermal insulation • New beam pipe • Installation of pixel test slice } preparation for phase-1
2014		
2015	*Data taking*	
2016		
	Technical stop	**Installation of new CMS phase-1 pixel detector**
2017	*"Phase-1"*	
2018	**LS2**	
2019	*Data taking "Phase-1" $\approx 500\ fb^{-1}$*	Exchange of innermost pixel layer after ~ $250fb^{-1}$
2020		
2021		
2022	**LS3**	**Installation of a new CMS tracker** • Phase-2 pixel detector • Phase-2 outer tracker • Track trigger
2023		
2024	*Data taking "Phase-2" $\approx 3000\ fb^{-1}$*	
↓		

Current and Future Collaborations

with CERN

R&D of the Silicon Tracker Detectors (2012 – 2014)

- In collaboration with CERN

Readout Circuits and Electronic Modules for Tracker Detectors (2013 - …)

- In collaboration with CERN

Monte Carlo simulation and construction of timing detector for Precision Proton Spectrometer (PPS)

- In collaboration with the university of Louvain

Developing CMS DQM package for the tracker upgrade in 2022

Campaign to Identify Material and Polarity

Main Goal: Identify (or confirm) technology baseline for the CMS Tracker Upgrade Phase II

Evaluate:

1. Geometry studies

2. Radiation hardness

- **Neutrons**
- **Protons**
- **Mixed**

3. Annealing behavior

Measurable:

Signal
Noise
Resolution
Breakdown
Strip / long pixel / pixel characteristics
Capacitances
Resistances
Currents
strip / long pixel / pixel isolation
Lorentz angle
TCT
Trapping time
Fields

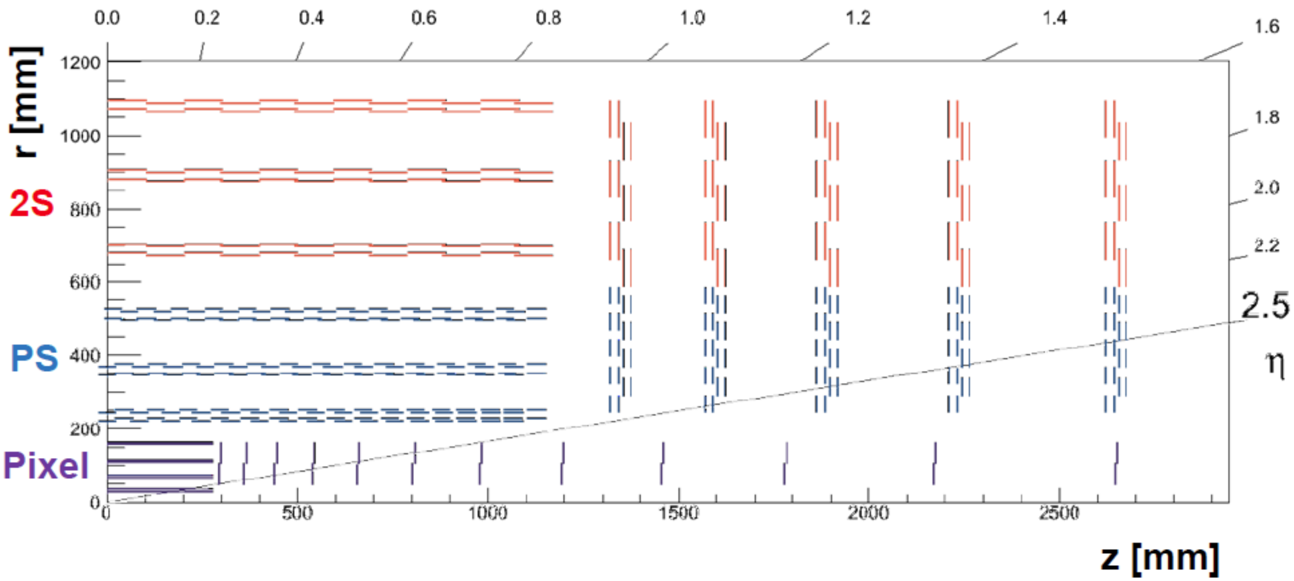
R&D on Sensors

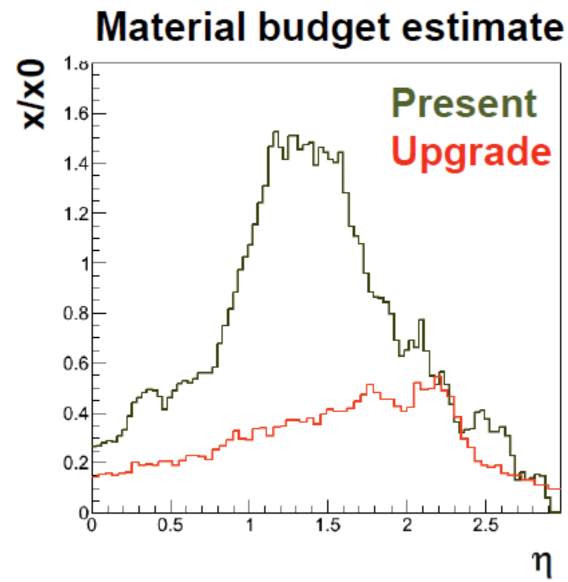
- Signal and noise were studied on sensors produced by Hamamatsu.
- Sensors were irradiated to fluences expected at radius=20&60 cm.
- n- vs. p-bulk material:
  - * n-bulk material gives a Higher signal up to $7 * 10^{14} n_{eq}/cm^2$, but at the maximum fluence tested, the p-bulk sensors measure a higher charge.
  - * Signal on n-bulk material decreases after a couple of weeks at room temperature.
  - * High noise, creating fake hits and increasing the occupancy.
- Float zone vs Magnetic Czochralski:

  Sensors made on Magnetic Czochralski material show an increased signal with annealing
- 200 microns vs. 320 microns thickness:

  For fluences up to $1 * 10^{15} n_{eq}/cm^2$, the signal is comparable for both thicknesses.
- CMS decided to use p-bulk material for the Tracker and concentrate the future work on optimizing the technology and the geometry.

Tracker Layout



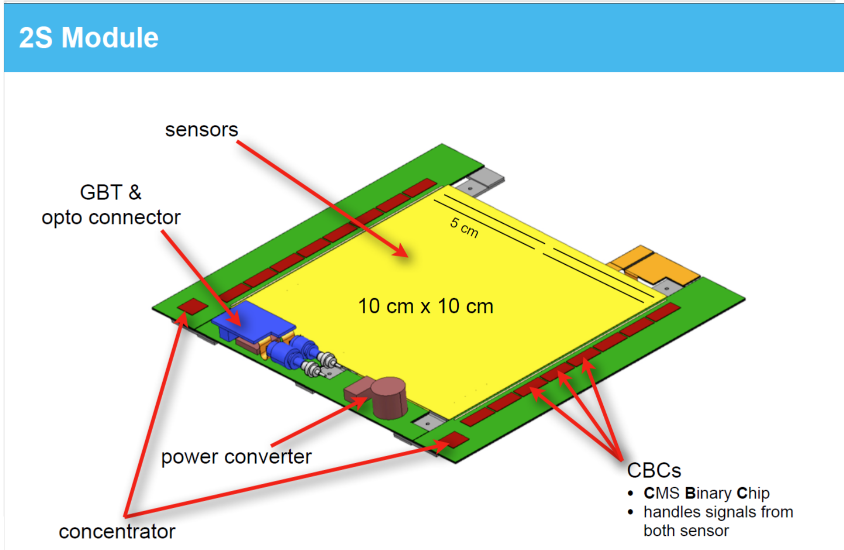


- **Baseline layout is a classical barrel + endcap layout with 5 disks**
  - Better performance at lower power, material & cost than a long barrel geometry
  - 15 348 modules, 58kW of front-end power (today: 15 148 modules, 33kW)
  - Option to extend pixel coverage to $\eta \approx 4$ is under consideration (baseline: $\eta < 2.5$)
- Two basic module types in outer tracker:
  - Modules with 2 strip sensors back-to-back ("2S p_T -modules")
  - Modules with 1 pixel and 1 strip sensor back-to-back ("PS p_T -modules")

p_T -Modules

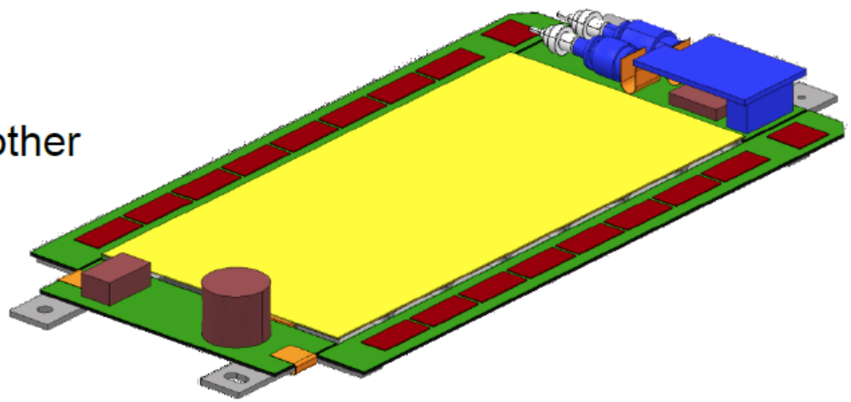
2S p_T -module

- For r > 40cm
- 2 strip sensor on top of each other
- Sensors wire-bonded to hybrid from top & bottom
- Strip dimensions: 5cm x 90µm
- 10 cm x 10 cm



PS p_T -module

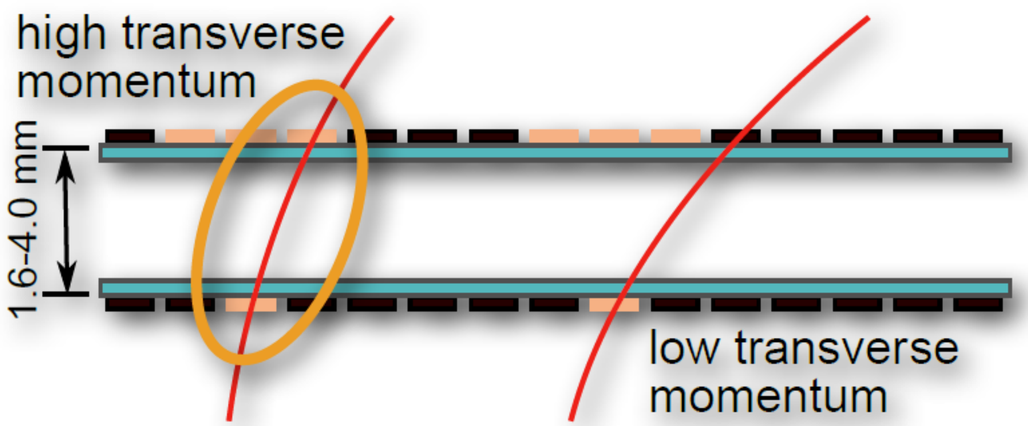
- For r > 20cm
- 1 strip sensor and 1 pixel sensor on top of each other
- Strip dimensions: 2.5cm x 100µm
- Pixel dimensions: 1.5mm x 100µm
- Provides z information
- 5 cm x 10 cm



2S p_T -module is more advanced → will concentrate on 2S p_T -module

General Module Design

- modules will have on-board pT discrimination
  - signals from two closely spaced sensors are correlated
  - exploit strong magnetic field for local pT measurement
  - local rejection of low-pT tracks to minimize data volume
- detector modules provide Level-1 and readout data at the same time
  - the whole tracker sends trigger data („stubs“) at each bunch crossing (40 MHz)
  - readout data at 100 kHz
- „stubs“ are used to form Level-1 tracks
- low power giga-bit transceiver (LP-GBT) as data link
  - currently under development
  - integrated at module level
- powering via DC-DC conversion
  - integrated at module level



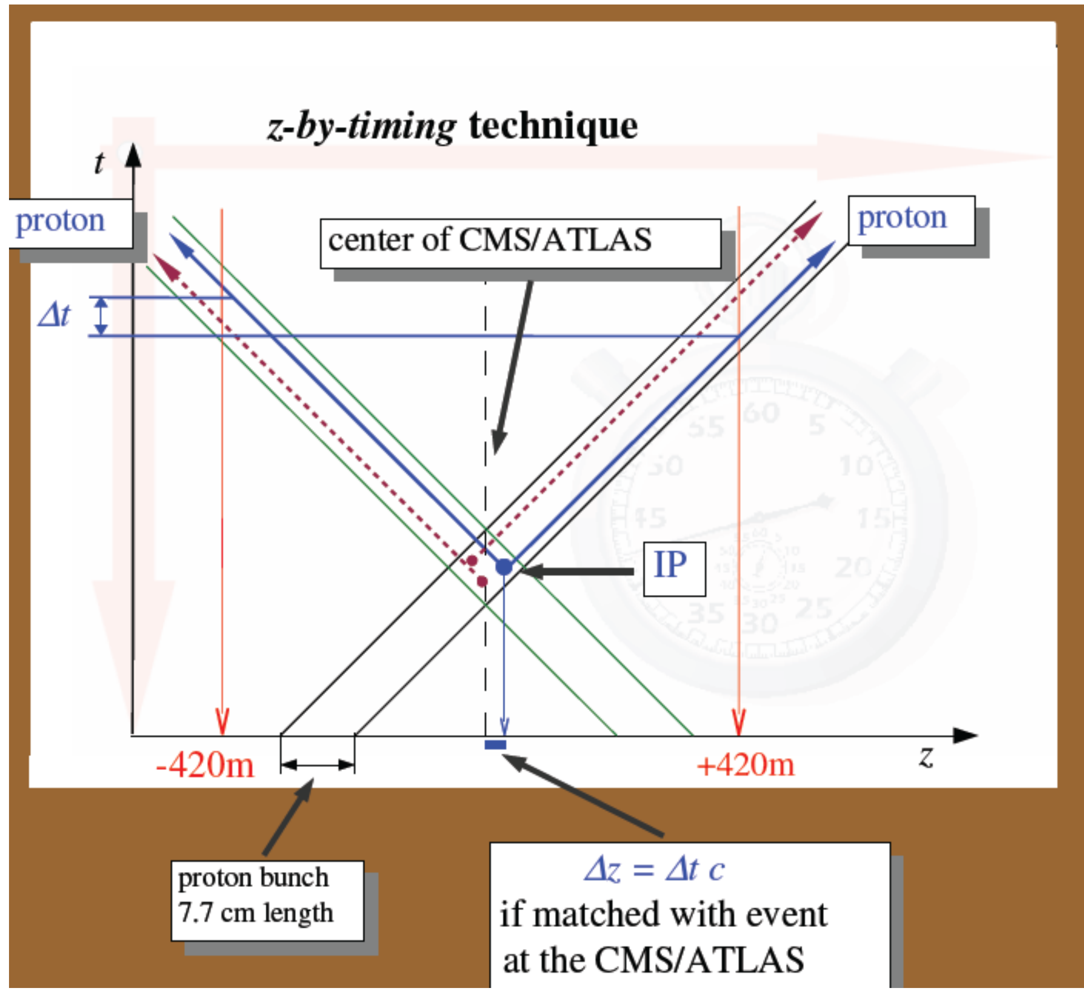
Timing Detector (GasToF)

- GasToF (Gas Time-of-Flight) detector is a Cherenkov detector
- Developed for very precise (with ~10 ps resolution) flight time measurements
- For very forward protons at the LHC

- *The* **GASTOF** *(Gas Time Of Flight) is one of proposed Cherenkov detectors*
- *Complementary of* **QUARTIC** *proposal(based on quartz radiator)*
- *Very high timing resolution (~ 10-20 ps).*
- *Such an excellent time resolution will allow for*
  - *precise measurement of the z coordinate of the event vertex for exclusive proton-proton interactions.*
- *The z-by-timing technique is based on the arrival time difference for protons detected on both sides of the interaction point (IP).*
- *A time resolution of 20 ps will give* ***4.3 mm*** *resolution in z.*
- *This z coordinate from* **GASTOF** *must match z(vertex) from the central system X measured by* CMS *or* ATLAS.

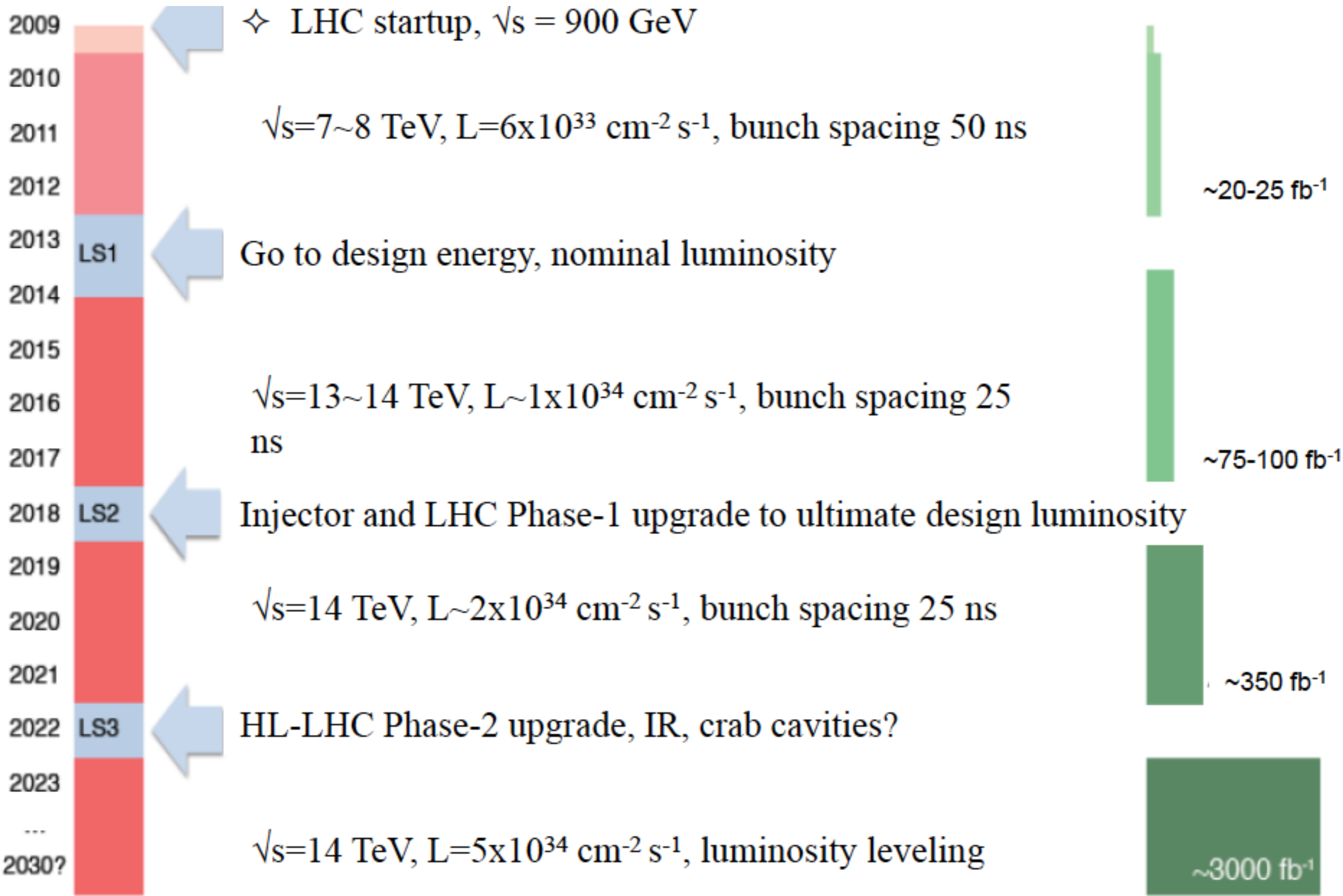
z-by-timing technique

- The z-by-timing technique is a crucial method to reduce the accidental coincidences due to event pile-up, where the two forward protons and the central system X are not coming from the same interaction.




Two GasToF detectors used for beam test

Summary: The LHC Timeline



Thank you for your attention

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Thanks to organizers!