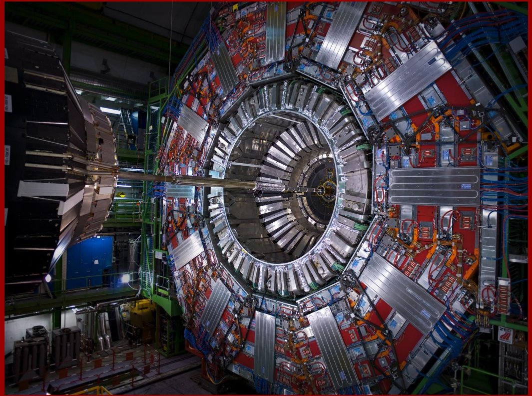
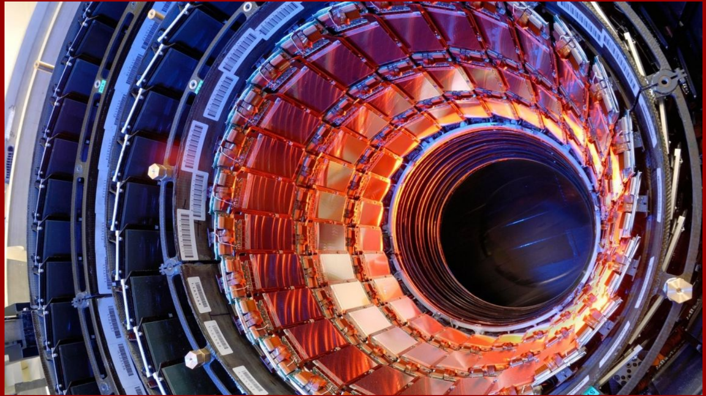




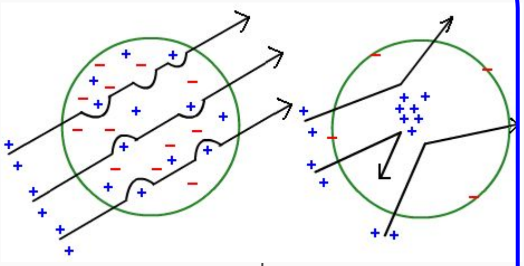
Experimental Particle Physics

Dr. Hoh Siew Yan

Knowledge Transfer Workshop
High Energy Physics@UTM
8th December 2022

Experimental Physics in a nutshell

Assumption/Hypothesis



Theoretical Model

$$\sigma(\theta) = \left(\frac{1}{4\pi\varepsilon_0}\right)^2 \frac{Z^2e^4}{M^2v^4} \times \frac{1}{\sin^4(\theta/2)}$$

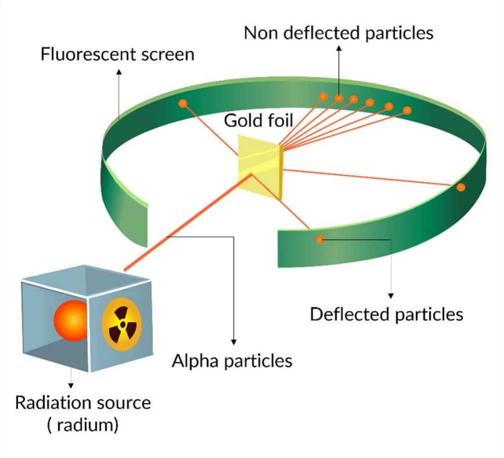
Ze = the positive charge of the target atom,

M = the mass of the α particle,

v = incident speed of the α particle,

θ = scattering angle,

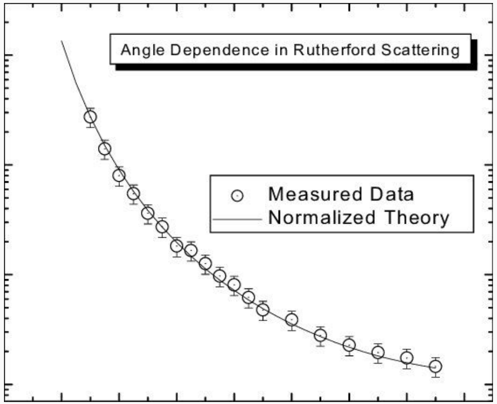
Theoretical: Physics Modeling



Optimize measurability (sensitivity) of signal over "background"

Experimental: Experimental setup

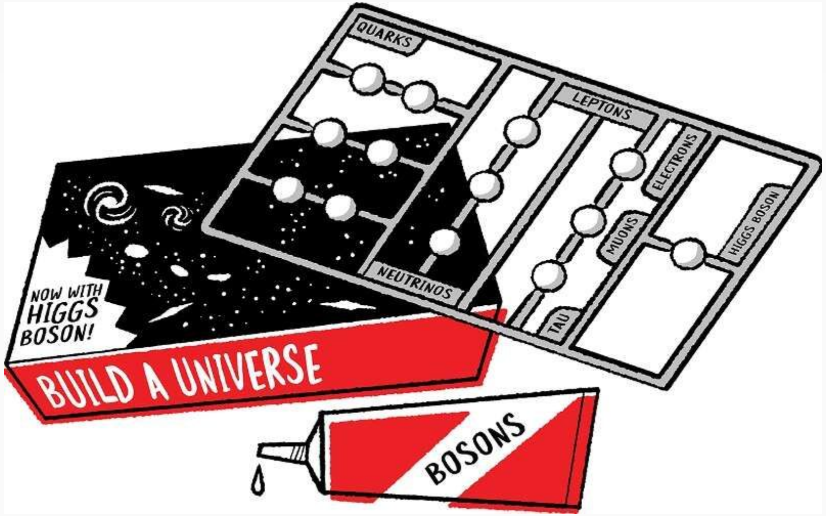
Experimental results

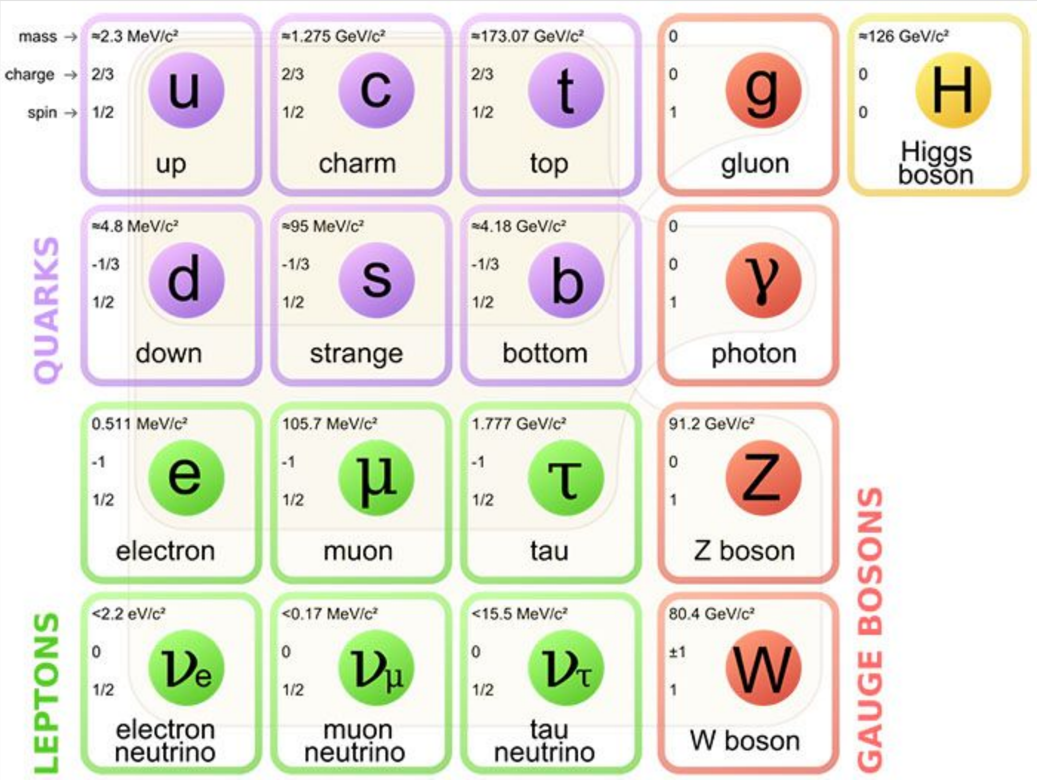


"Extract" (measure) physics from experimental results

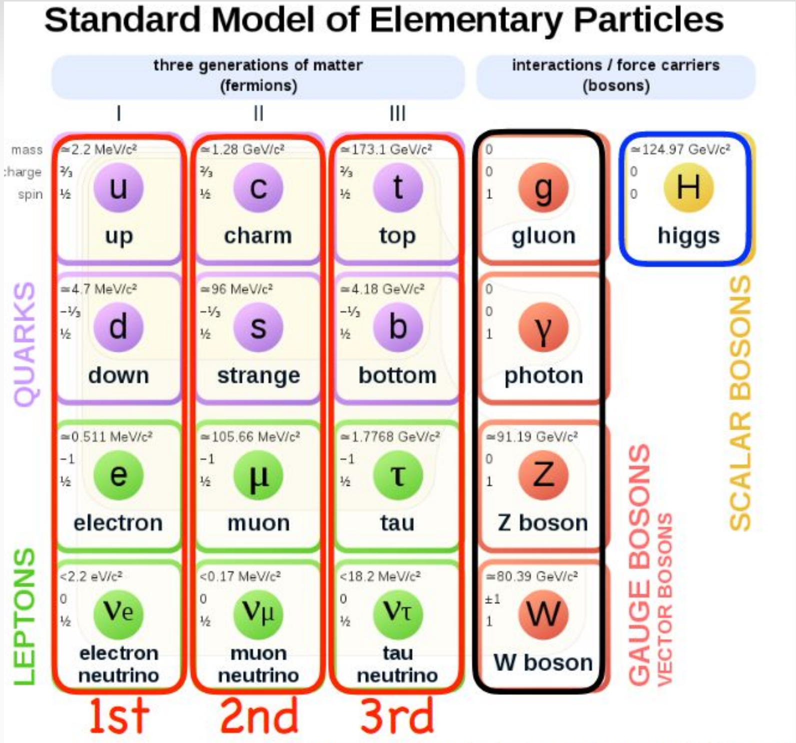
Experimental: Physics Measurement

Standard Model of Elementary Particle





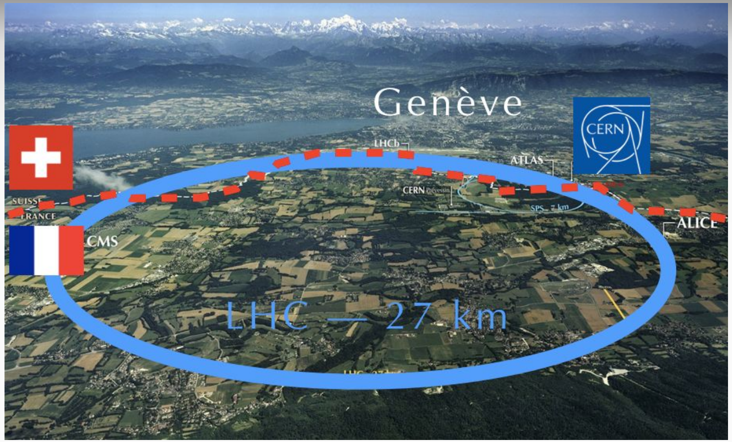
Physics Modeling

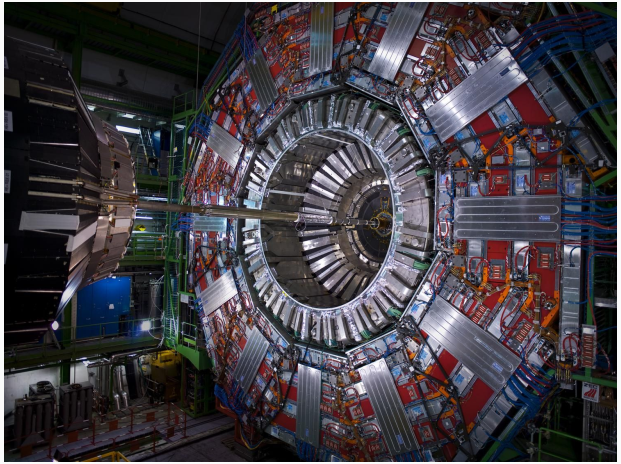


[Standard Model of Elementary Particles.svg]

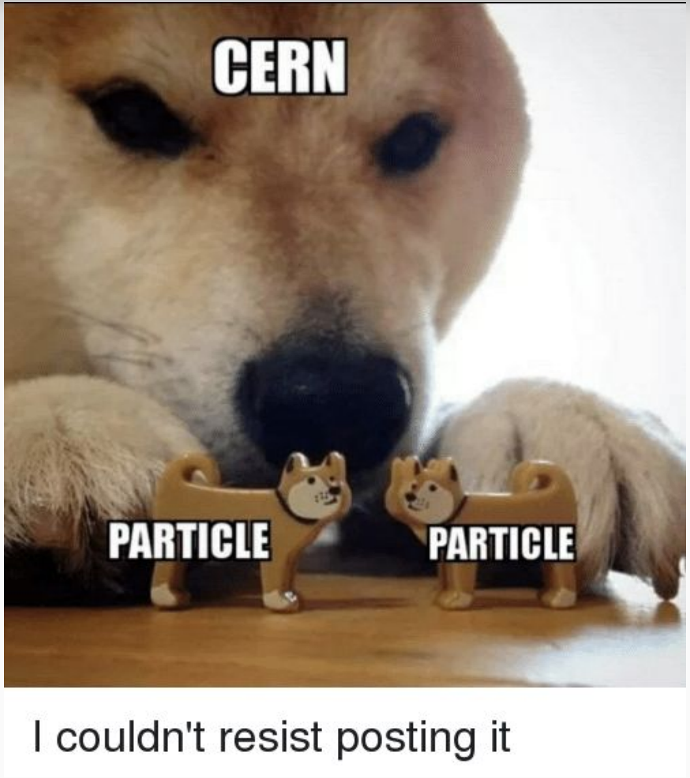
$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + h.c. \\
& + \psi_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

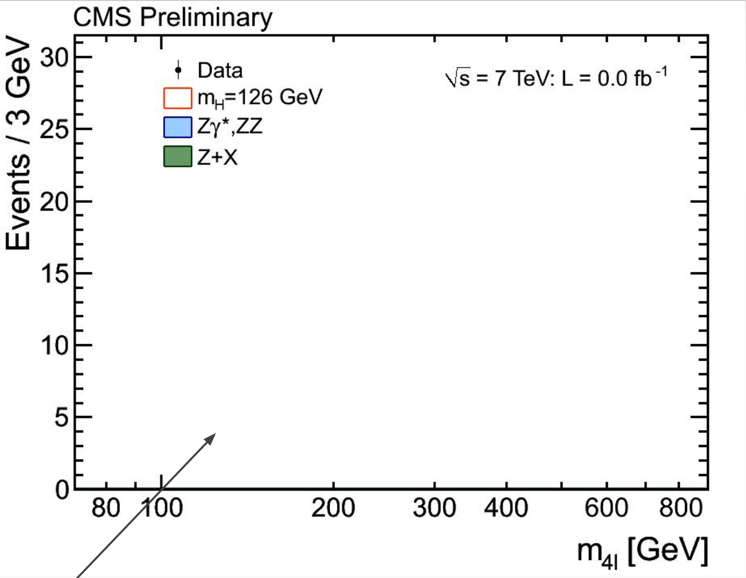
Experimental Setup





Physics Measurement





125.38 ± 0.14 GeV
@13TeV

Overview

- **Colliders and LHC**
- Detectors
- Object reconstruction
- Analysing the collision data
- Closing

Overview

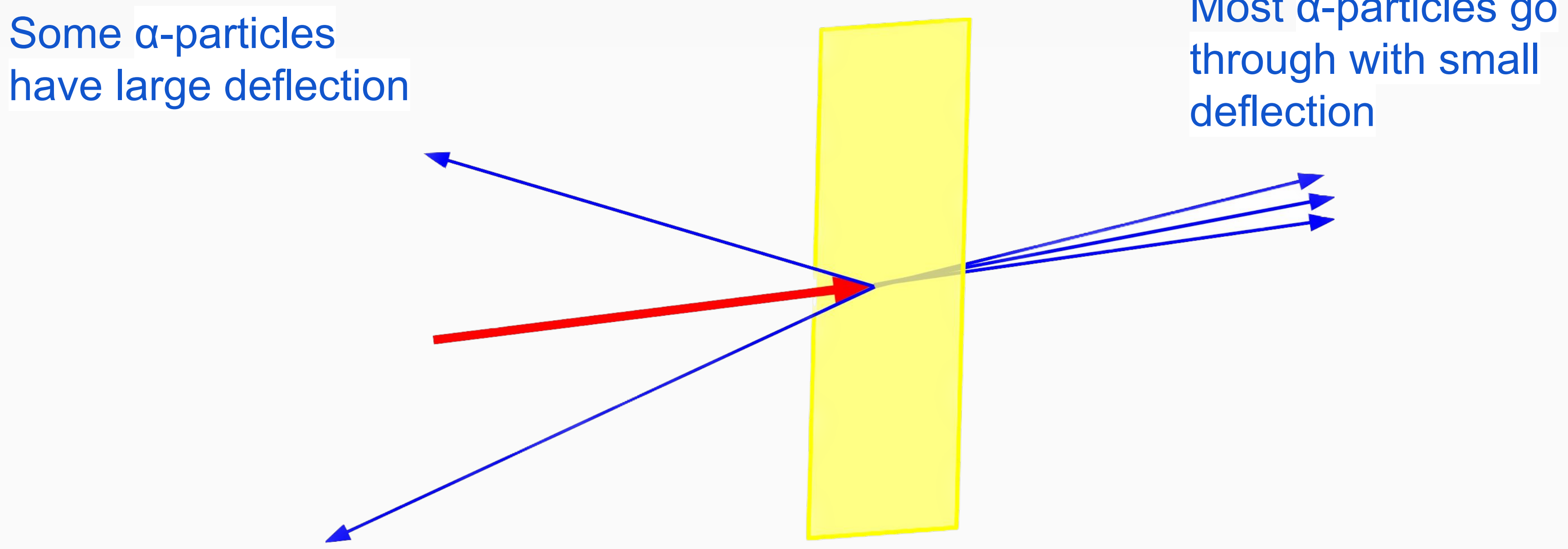
Linear/Circular

LHC, Luminosity

- **Colliders and LHC**
- Detectors
- Object reconstruction
- Analysing the collision data
- Closing

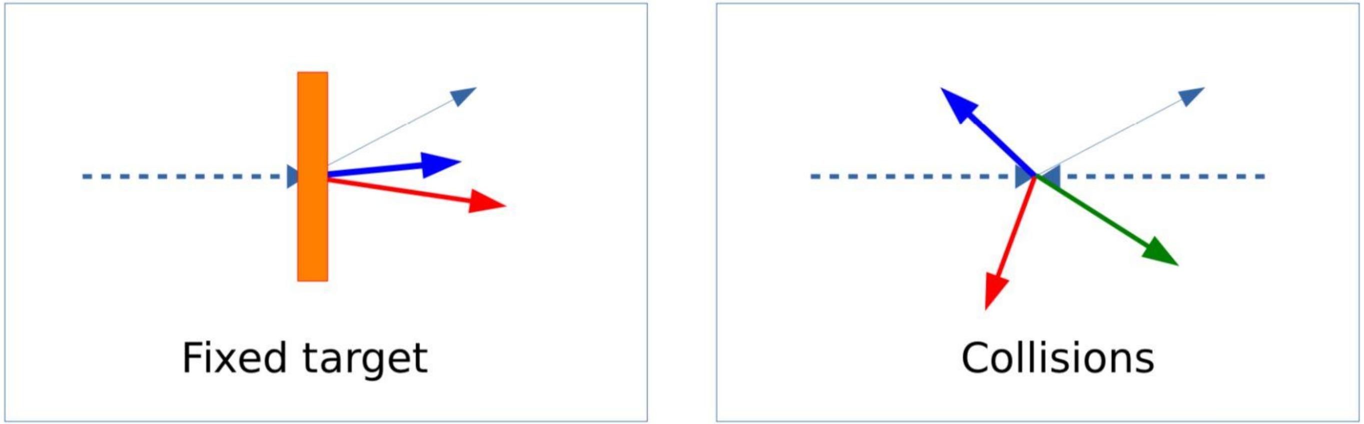
Colliders

Why collide?



Rutherford's gold foil experiment

Accelerators / Colliders



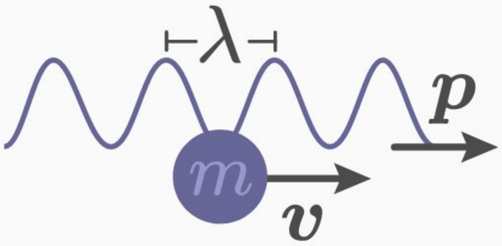
Important questions to ask:

1. Are these particles easily available?
2. Can they be manipulated readily?

Electrons and protons certainly fit the bill and almost all experiments start from them.

Why do we deal with high energy?

de-Broglie relation



$$\lambda = \frac{h}{p} = \frac{hc}{E}$$

And

$$hc = 1.24\ eV \cdot \mu m$$

- Typical energy of an α particle is 5 MeV
- So we can probe ~ 250 fm

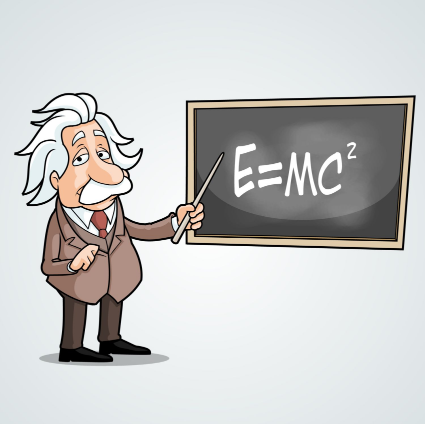
(Atom is 10 Åm, so certainly we could see inside it.)

Proton is ~ 1 fm, thus we need energy of ~ 1.24 GeV to “peek inside” a proton.

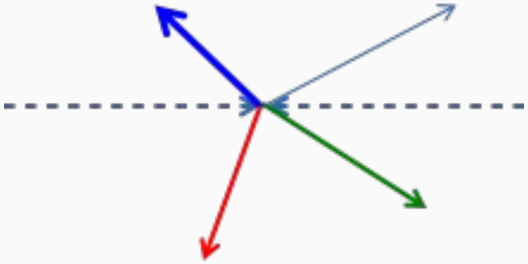
Higher energy probes smaller distance scales.

Why do we deal with high energy?

We also have



A Higgs boson has a mass of 125 GeV, to produce it we would need collisions at COM energy of at least 125 GeV



Collision

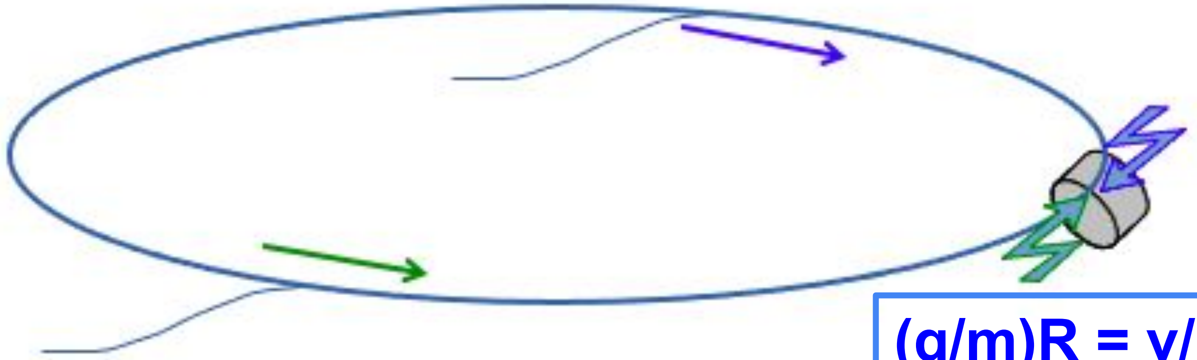
Higher energy allows us to produce higher mass particles.

Colliders

- **Linear**

Good for light particles. Eg: electrons

- **Circular**



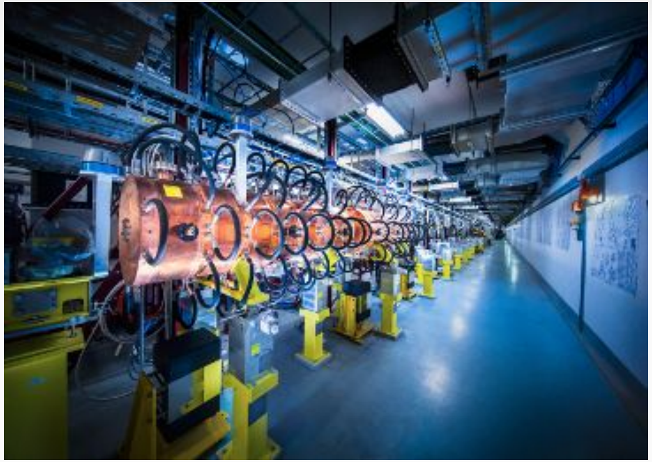
Use magnets to bend beams

$$\boxed{(q/m)R = v/B}$$

- For a fixed particle q/m is constant, for a given collider radius R is constant.
- So magnetic field B must increase with velocity v.

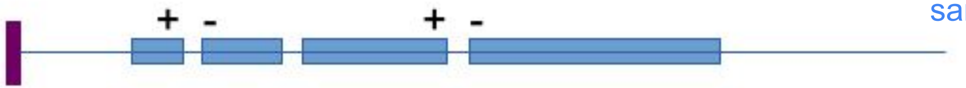
Linear Accelerators

CERN LINAC 4



- Pro:
  - No synchrotron radiation.
  - Produce reliable beam (no bending).
- Con:
  - Consists of chain of many successive gaps.
  - Particle pass the accelerator only ONCE.
  - Final energy limited by length.

Choose successive lengths such that as velocity increases, it takes same time to traverse paths (use same RF source for all kicks)



Ion source

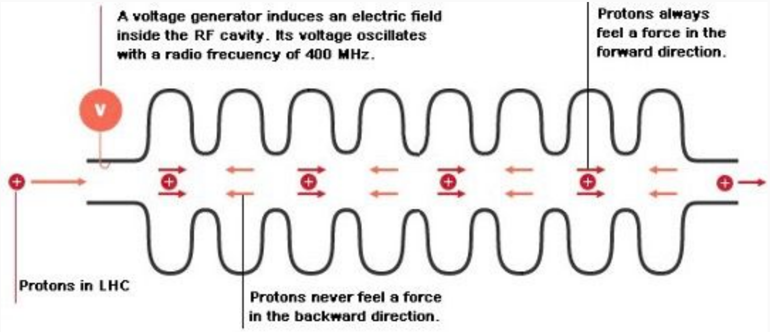
A succession of kicks

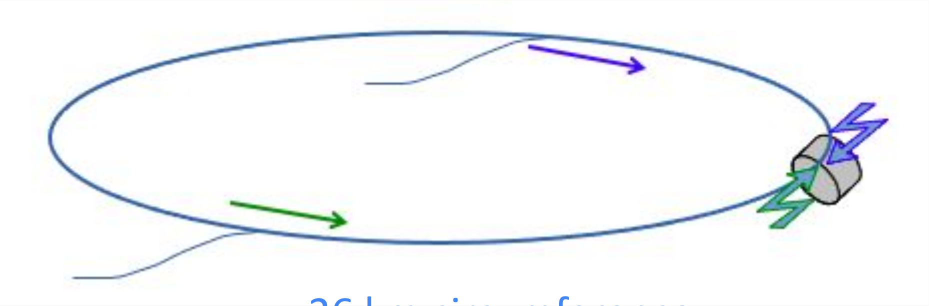
86 m acceleration length

Synchrotrons

CERN Large Hadron Collider (LHC)

- Pro:
  - Can accelerate to higher energies.
  - Can Reuse beam
  - Can have multiple collision
- Con:
  - Charged particles can radiate energies in circular motion. (Need bigger ring or heavy particles)
  - Expensive superconducting magnets (maintenance)





[26 km circumference]

Linear vs Circular

Linear Accelerator	Circular accelerator
• Easier and cheaper to build.	• Costly due to the need of huge radii to bring particles to high energy states
• Do not require large magnets.	• Large magnets are required to coerce particles into going in a circle.
• Particles travel in a straight line, each accelerating segment is used only once	• Particles can be reused as it comes around
• Used for fixed target experiment	• Used for both colliding beam and fixed target experiment.

Collider Parameters

Hadron	HERA (DESY)	TEVATRON* (Fermilab)	RHIC Brookhaven	LHC (CERN)		
Physics start date	1992	1987	2001	2009	2015	2026 (HL-LHC)
Physics end date	2007	2011	—	—		
Particles collided	ep	$p\bar{p}$	pp (polarized)	pp		
Maximum beam energy (TeV)	e: 0.030 p: 0.92	0.980	0.255 55% polarization	4.0	6.5	$\boxed{7.0}$
Max. delivered integrated luminosity per exp. (fb^{-1})	0.8	12	0.38 at 100 GeV 1.3 at 250/255 GeV	23.3 at 4.0 TeV 6.1 at 3.5 TeV	160	$\boxed{250/y}$

Running!! → RUN3

e^+e^-	CESR (Cornell)	CESR-C (Cornell)	LEP (CERN)	SLC (SLAC)
Physics start date	1979	2002	1989	1989
Physics end date	2002	2008	2000	1998
Maximum beam energy (GeV)	6	6	100 - 104.6	50
Delivered integrated luminosity per experiment (fb^{-1})	41.5	2.0	0.221 at Z peak 0.501 at 65 – 100 GeV 0.275 at >100 GeV	0.022

Heavy Ions	RHIC (Brookhaven)		LHC (CERN)			
Physics start date	2000	2012 / 2018 / 2018 / 2012 / 2004 2014 / 2002 / 2015 / 2015	2010	2012	2017	$\geq$ 2021 (high lum.)*
Physics end date	—		—			
Particles collided	Au Au	U U / Zr Zr / Ru Ru / Cu Au Cu Cu / h Au d Au / p Au / p Al	Pb Pb	p Pb	Xe Xe	Pb Pb
Max. beam energy (TeV/n)	0.1	0.1	2.51	p:6.5 Pb:2.56	2.72	2.76
$\sqrt{s_{NN}}$ (TeV)	0.2	0.2	5.02	8.16	5.44	5.5
Max. delivered int. nucleon-pair lumin. per exp. (pb^{-1})	2639 (at 100 GeV/n)	21 / 36 / 36.9 / 167 / 60 43 / 169 / 124 / 63 (all at 100 GeV/n)	77.8	194	0.05	$\approx 121/y$

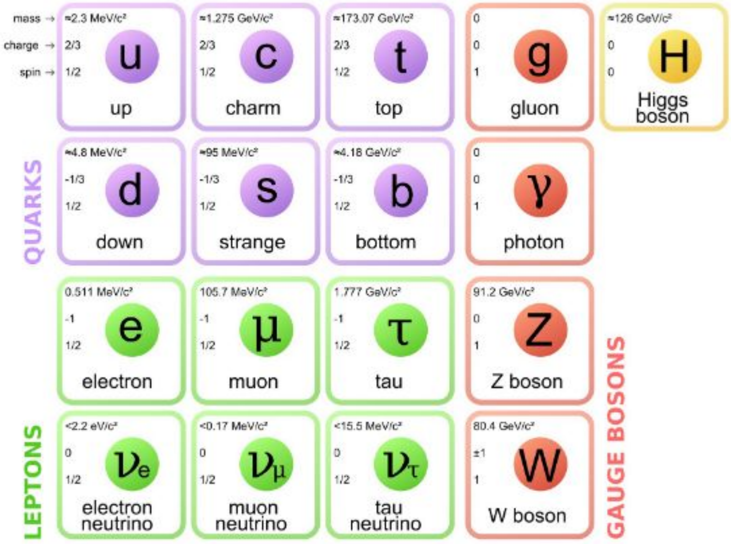
https://pdg.lbl.gov/2021/reviews/rpp2021-rev-accel-phys-colliders.pdf

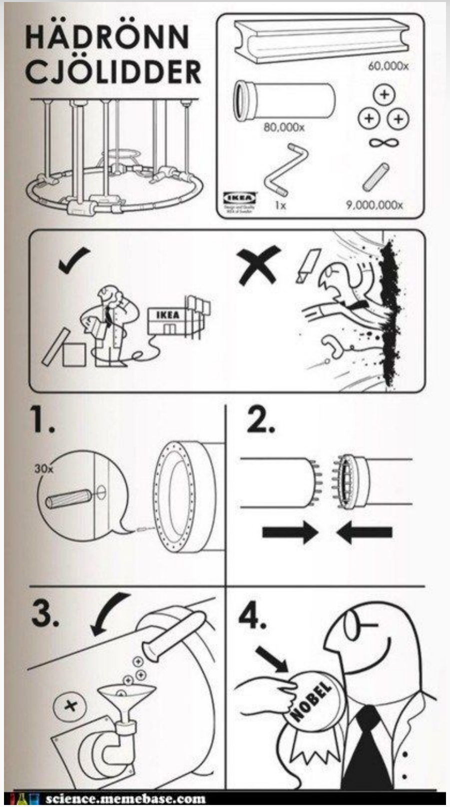
Collider as a discovery machine

Timeline of discoveries:

1897 : Electron – Cathode ray
1932 : Positron – Cloud chamber
1937 : Muon – Cloud chamber
1956 : Electron neutrino – Scintillator
1962 : Muon neutrino
1968 : u, d, s quarks – SLAC
1974 : c quark - SLAC
1975 : Tau – SLAC, LBNL
1977 : b quark – Fermilab
1979 : gluons - DESY
1983 : W and Z – UA1, UA2 (CERN)
1995 : t quark - Fermilab
2000 : Tau neutrino – DONUT collaboration

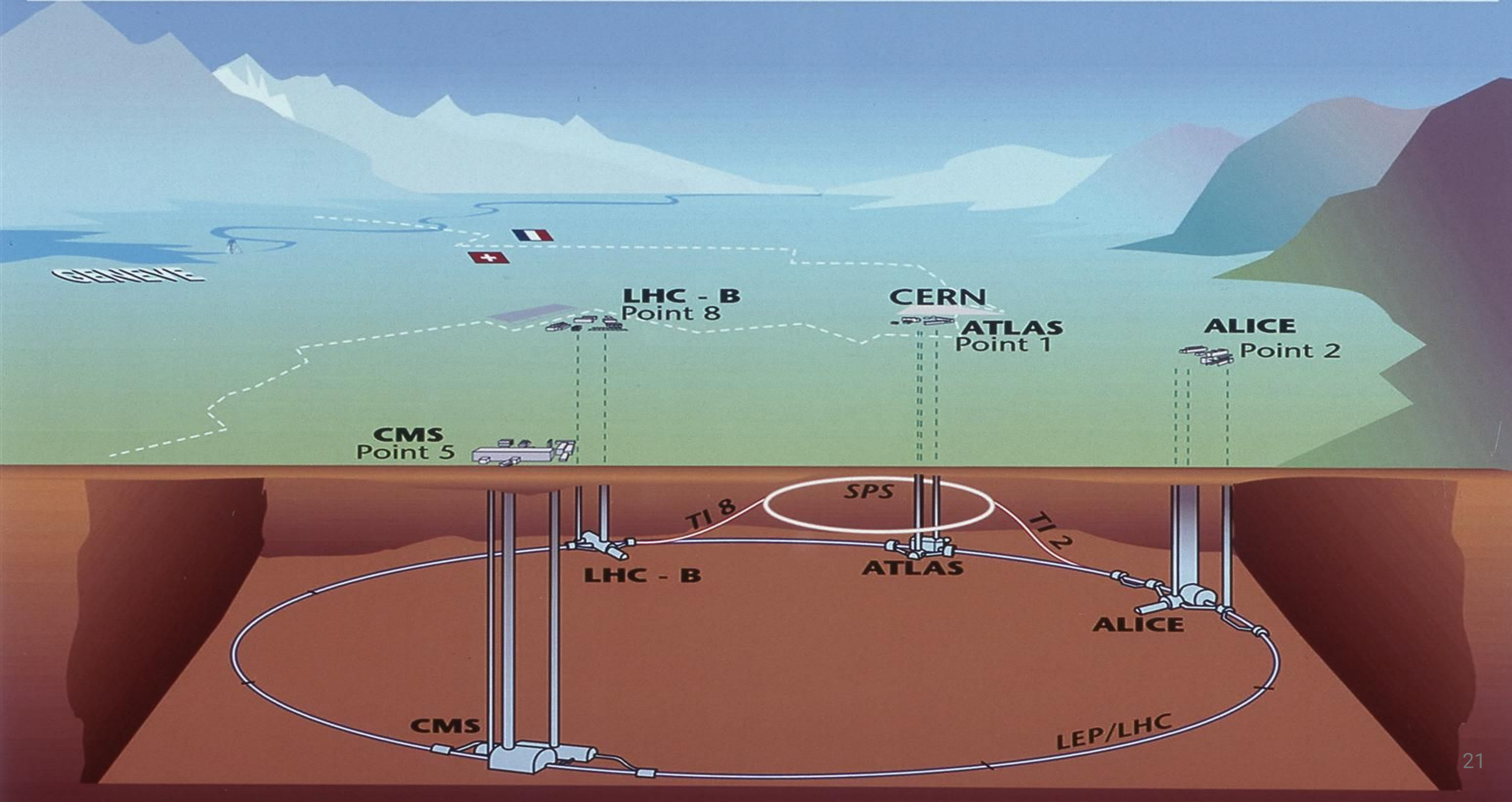
2012 : Higgs boson – LHC (CERN)





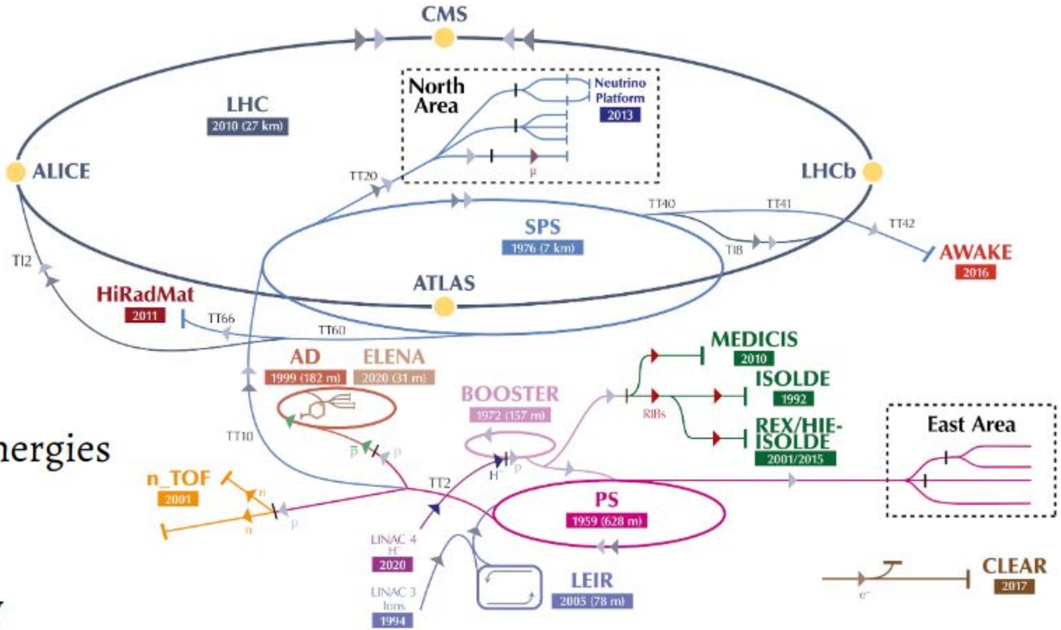
The LHC

Overall view of the LHC experiments.




LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

LHC complex



LHC operating energies

2010+2011 7 TeV

2012 8 TeV

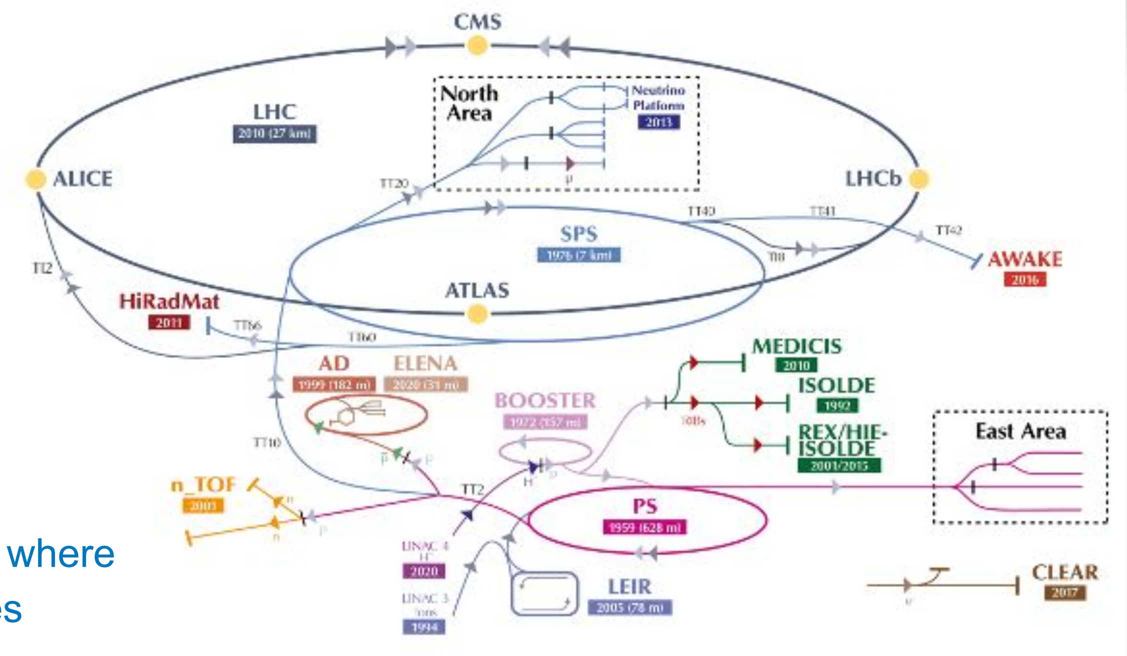
2015-2018 13 TeV

2022-.... 13.6 TeV

LINAC →	BOOSTER →	PS →	SPS →	LHC
50 MeV	1.4 GeV	26 GeV	400 GeV	7 TeV

LHC complex

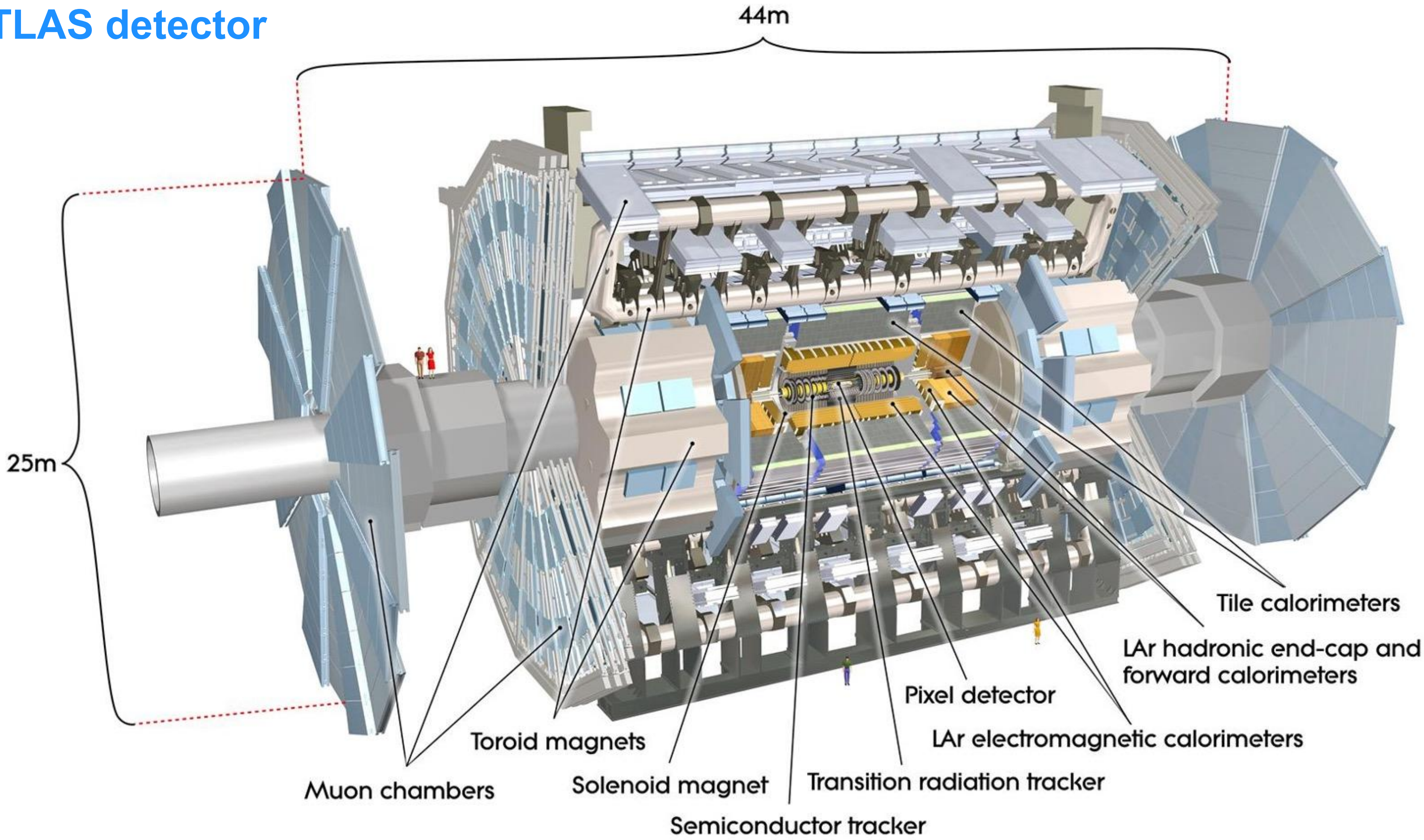
- Beam consists of proton bunches (10^{11} protons per bunch)
- There are ~2000 bunches in the beam, separated by 7.5m (25ns)
- These bunches cross each other at specific points at 40 MHz



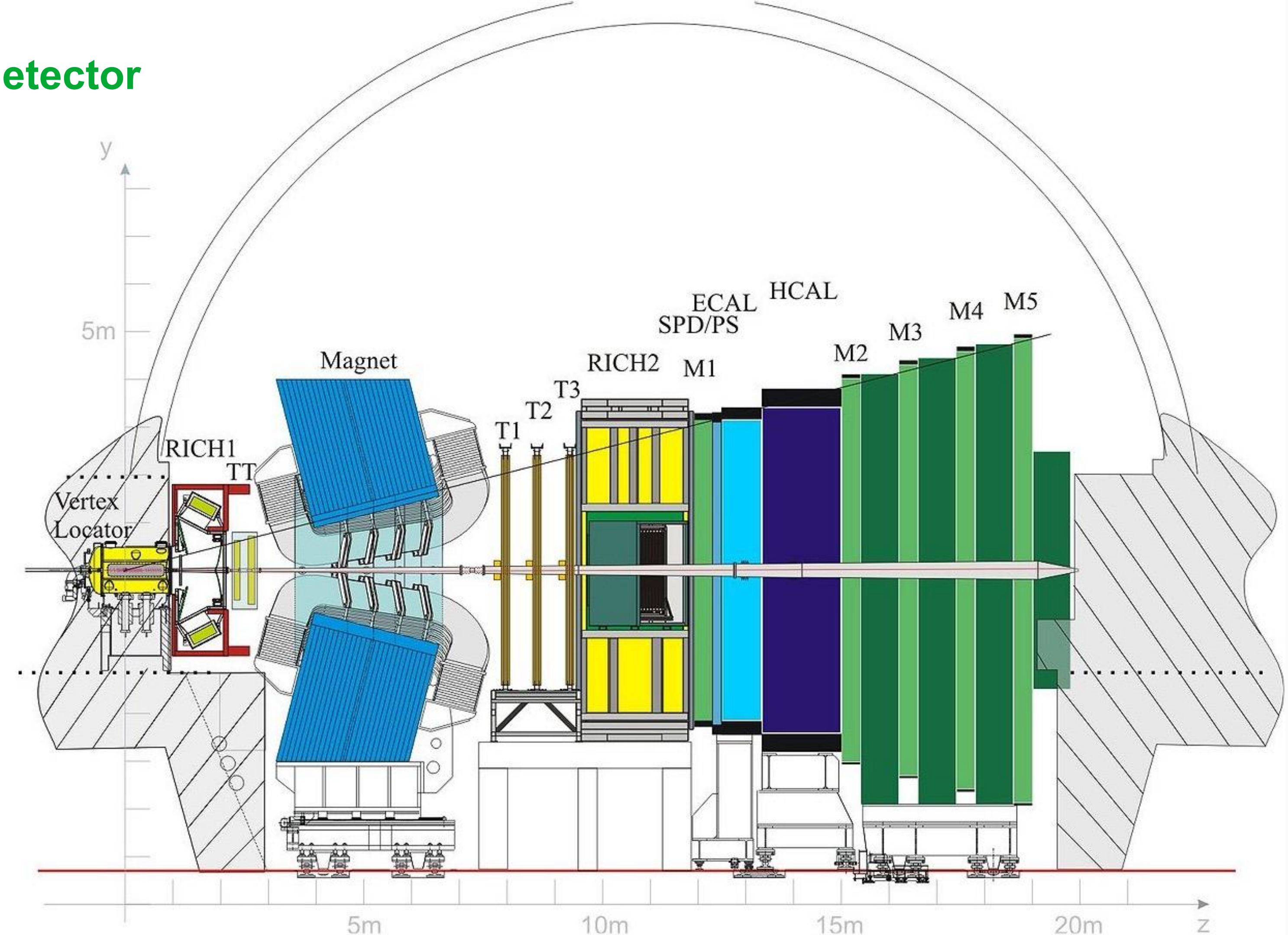
** These specific points are the detectors, where collisions happen each time a bunch crosses

∴ A collision = A bunch crossing

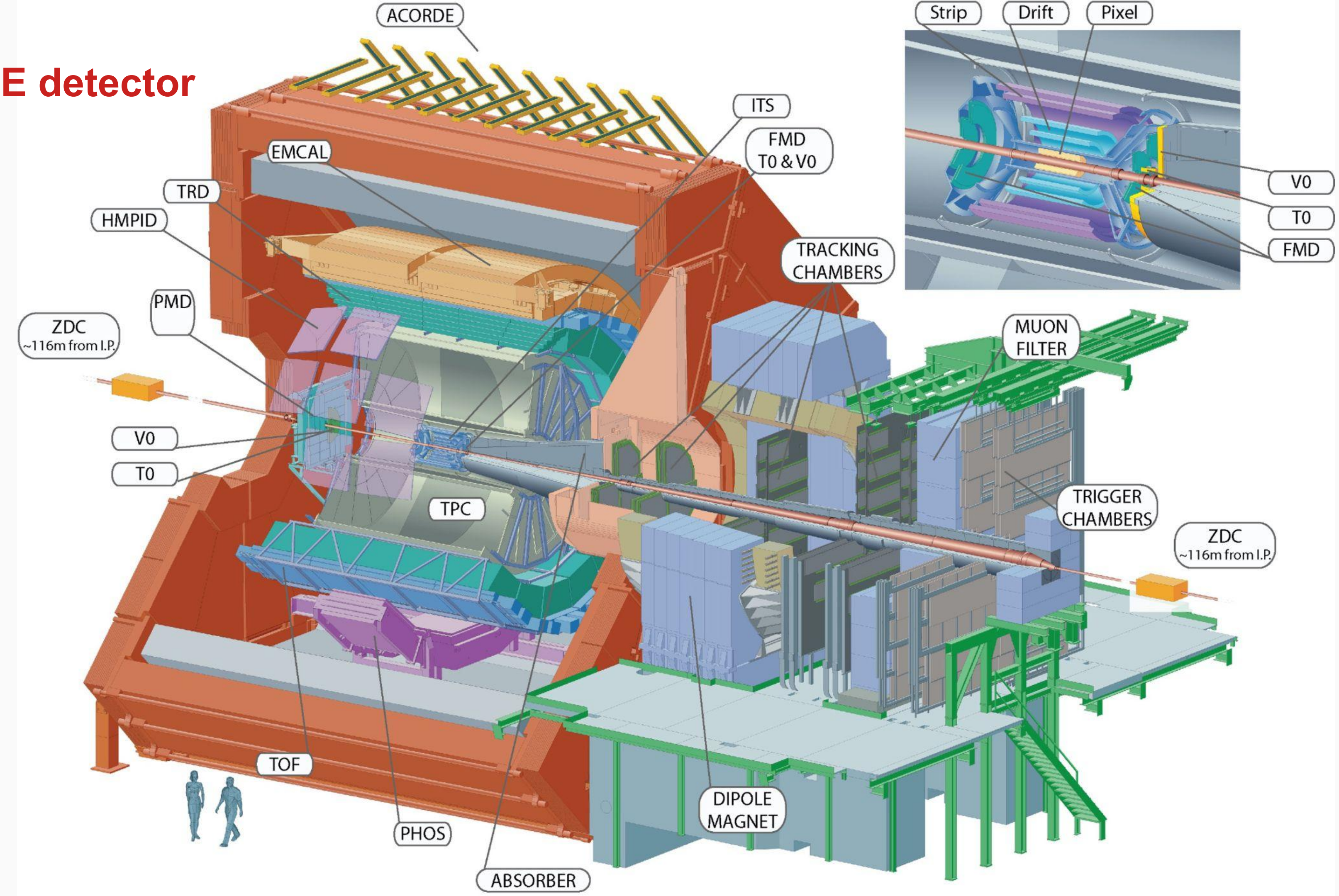
ATLAS detector

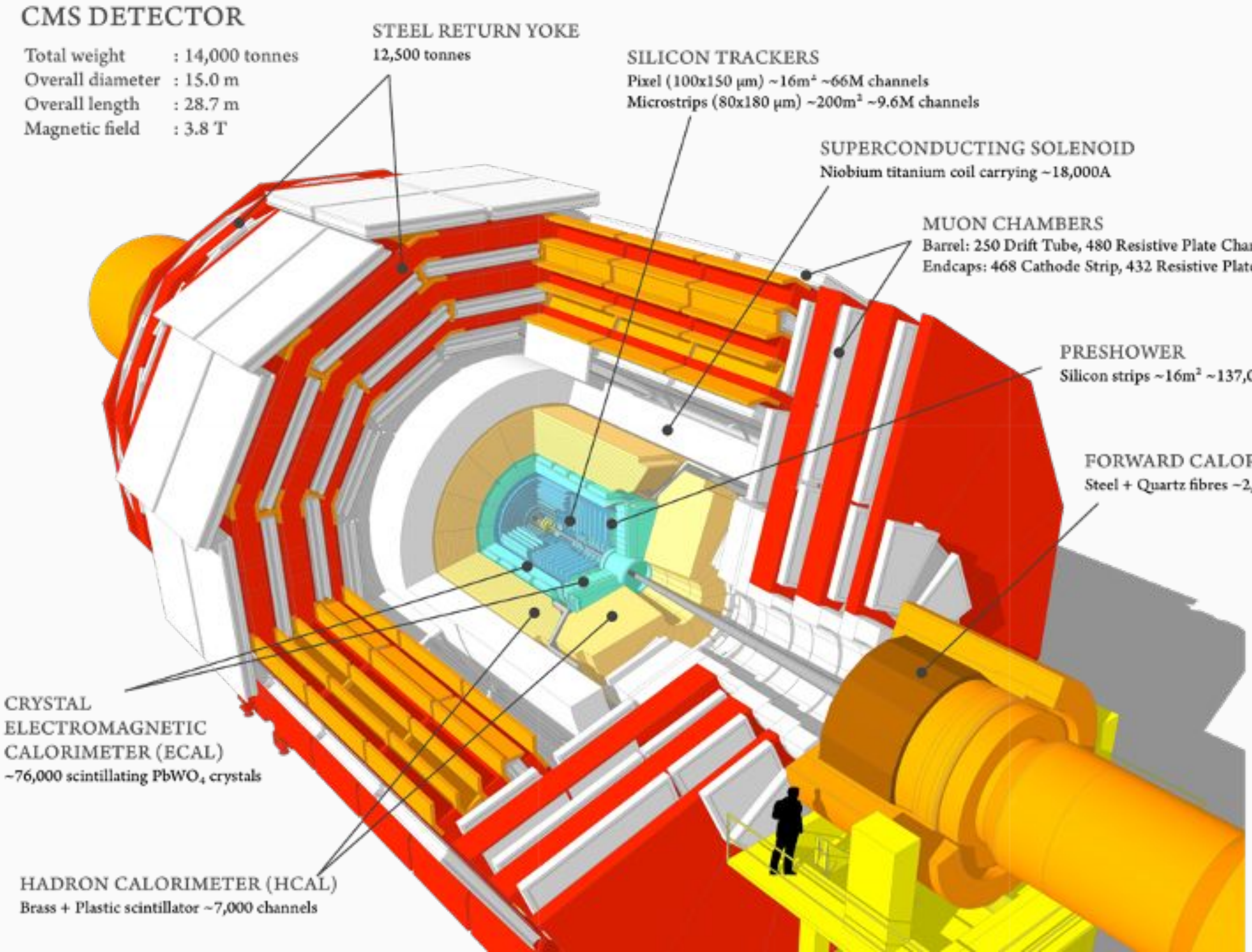


LHCb detector

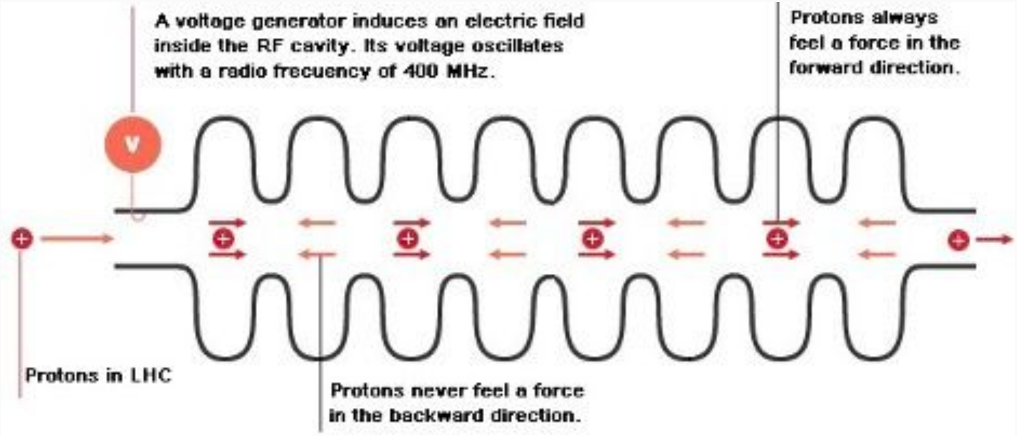


ALICE detector



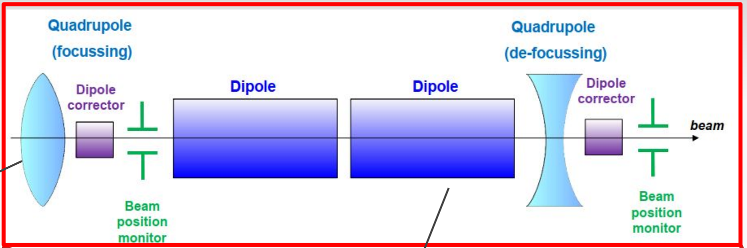

CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

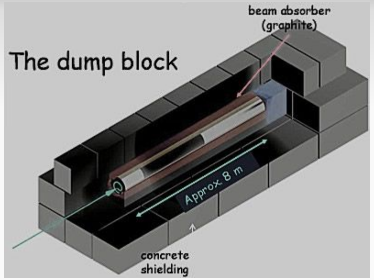
Radiofrequency (rf) cavity

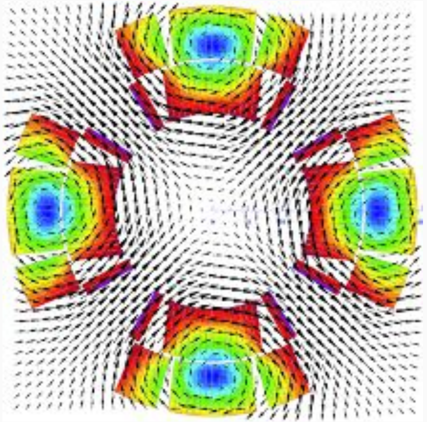


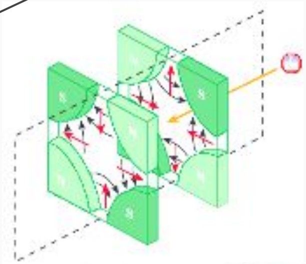
A metallic chamber containing EM field to accelerate charged particles.

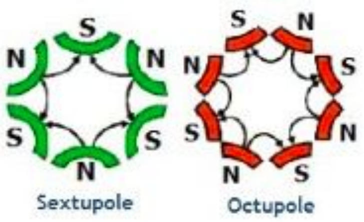
Magnets

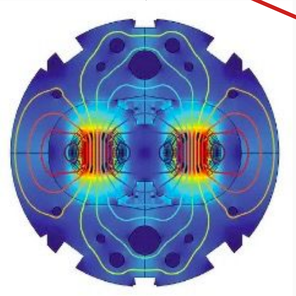


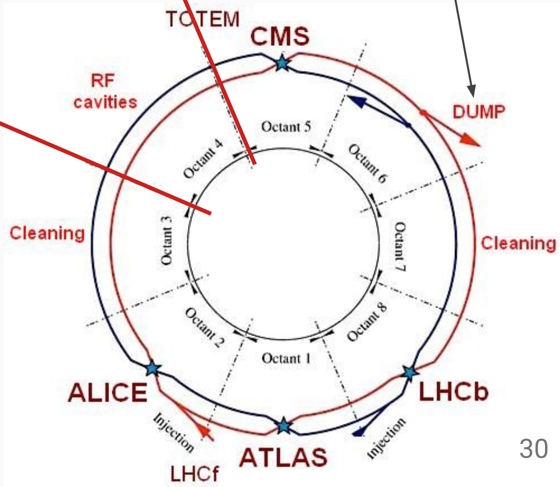










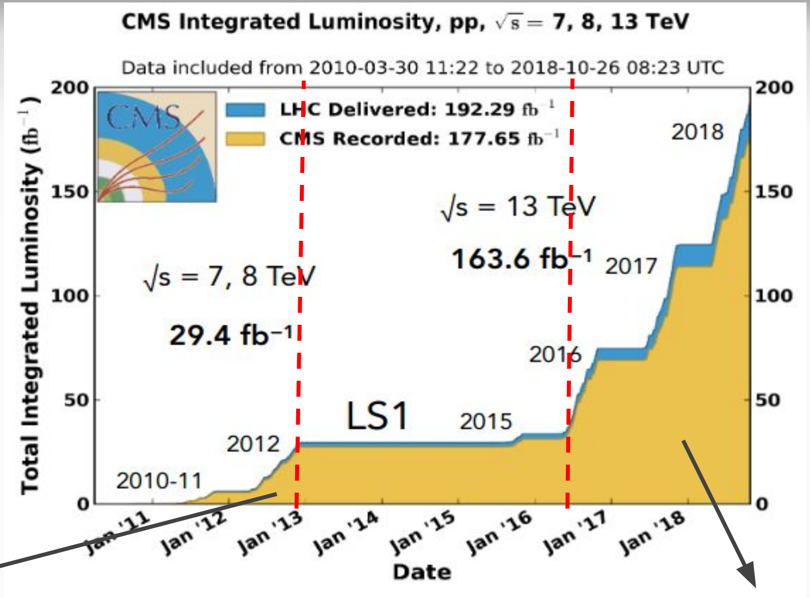


Quadrupoles and higher poles for focusing

Dipole used for bending

Integrated Luminosity, $\mathscr{L}$

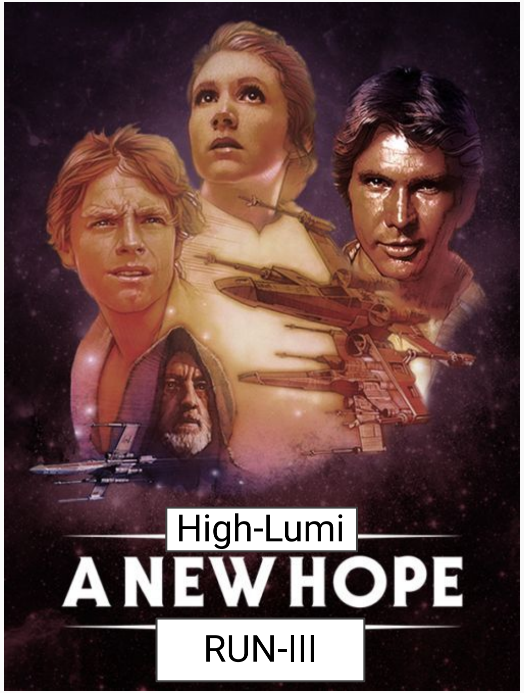
Proton-Proton Collision



Run-I Dataset

Run-II Dataset

Run-III and Beyond



$\mathscr{L}$ has dimensions of inverse area, measured in:

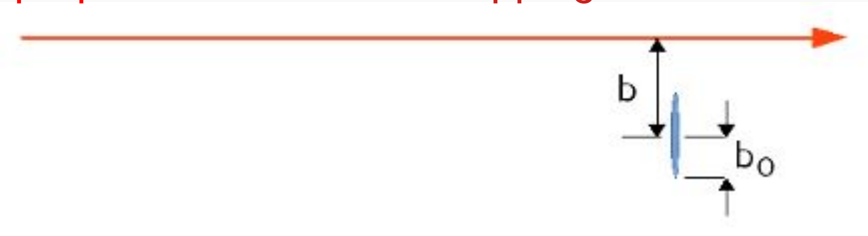
1. inverse milli-barns, mb^{-1}
2. inverse pico-barns, pb^{-1}
3. inverse femto-barns, fb^{-1}

1 barn = 10^{-28} m^2

Cross section, σ

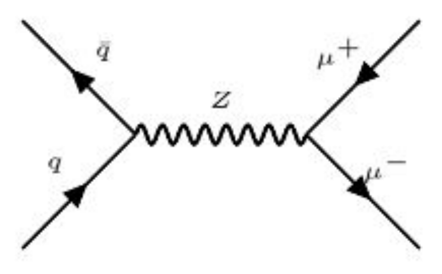
- **Classical Scattering**

- The rate at which an interaction will happen is proportional to the overlapping area between the incident particle and the target.



- **Particle Physics**

- The cross-section (denoted by σ) quantifies the rate or probability of a certain interaction taking place.
- Cross-section measured in dimension of area, ~ pb or fb.



This rate depends on the incoming particle 4-vectors, the type of interaction [which particles are interacting]

Event Counts, N

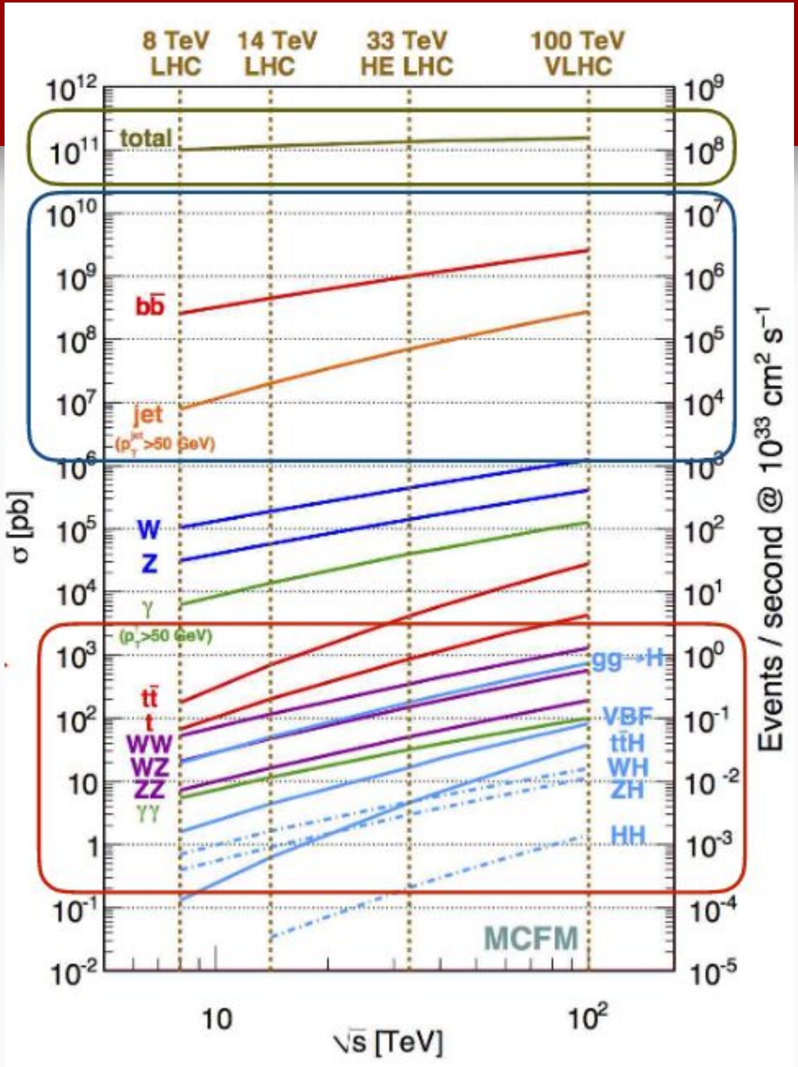
$$N = \mathcal{L}\sigma$$

N = the number of produced events for a process

$\mathcal{L}$ = integrated luminosity

σ = cross section of the process

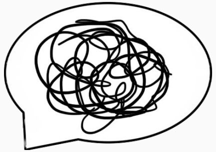
Rept.Prog.Phys.70:89,2007
arXiv:hep-ph/0611148



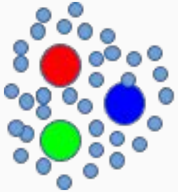
Proton-proton collisions

Expectation

Naive thought

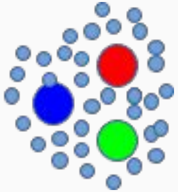



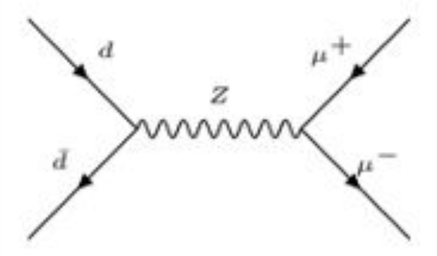
Reality



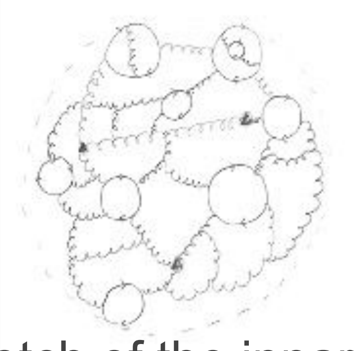
Actually

Messy... very messy.



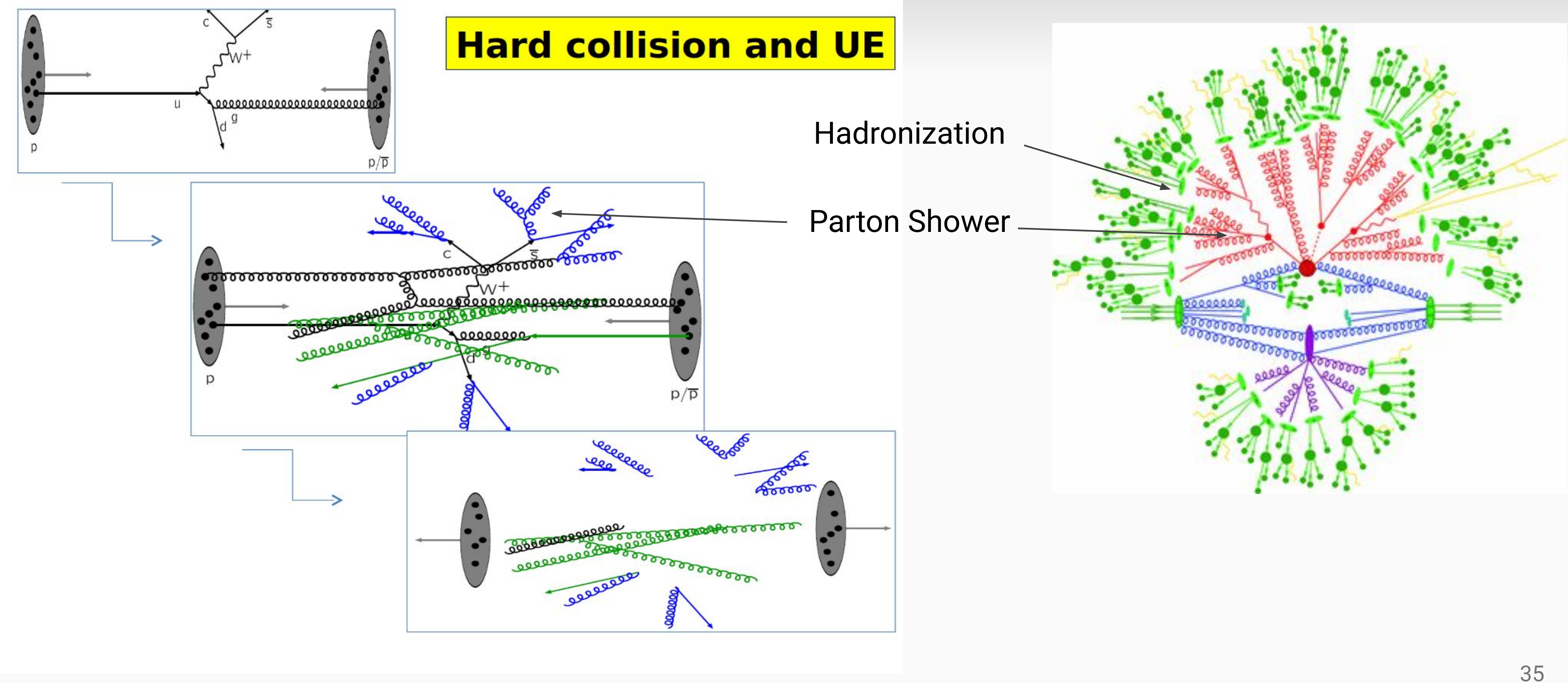


Need 4-vector (E , **p**) of incoming particle to calculate cross section

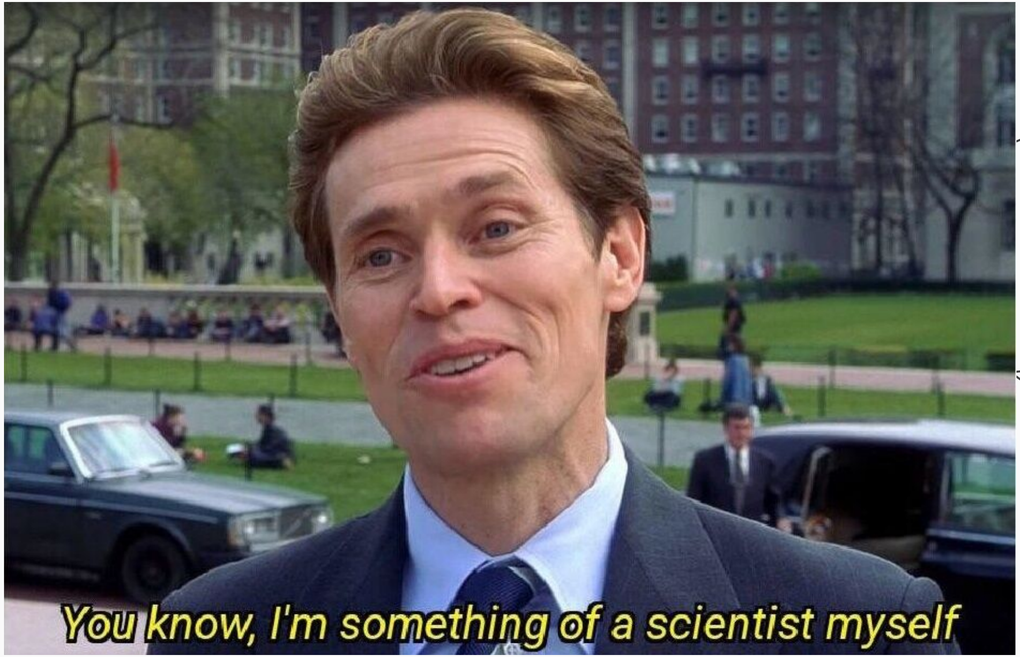


Sketch of the innards of a proton at high energy

Hadronization



Great! We are ready to go! I mean to collide protons and produce a lot of data! But…



how do we detect, observe and study the collisions data ?

Overview

- Colliders and LHC
- **Detectors**
  CMS detector, basic principles of particle detection
- Object reconstruction
- Analysing the collision data
- Closing

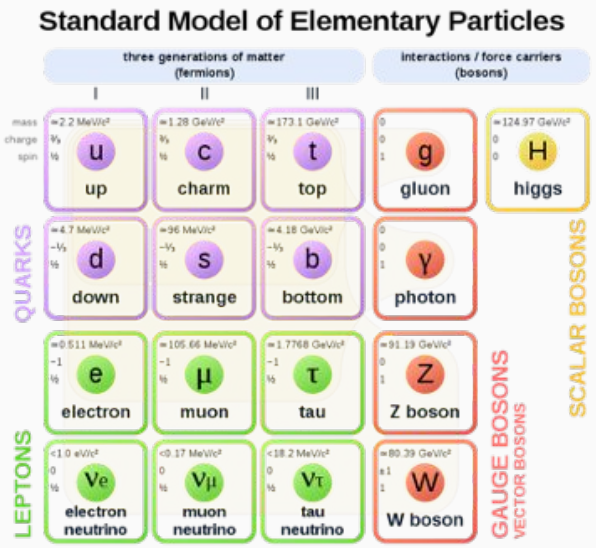
Detectors

Particle detection

- Particle can only be detected when they interact with something.
- The primary interactions of particles can be used to detect them.
  Eg: photons through EM interactions, hadrons through strong and EM interactions

Which particles can we detect?

These hadronize, producing hadrons such as pions, kaons, neutrons etc.



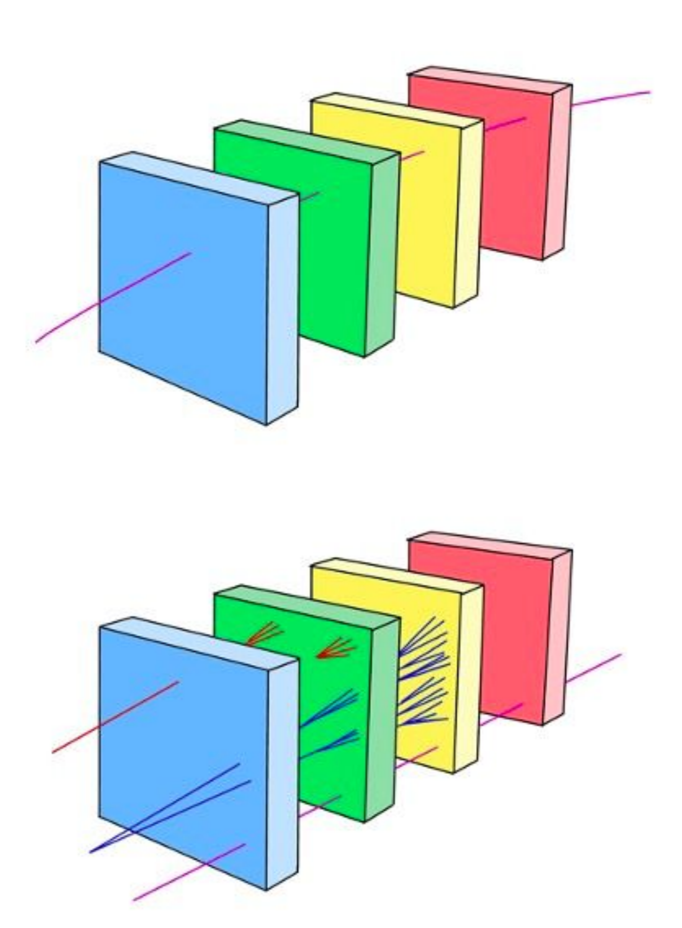
What would we like to measure?

1. The 4-vector of the particle.
2. Charge of Particle
3. If it decays, then where? Its lifetime?
4. How many particles of each kind?
5. Anything special? Did the particle interact unusually with detector?

Name	Mass	Approx. Travel distance
e	0.51 MeV	stable
γ	0	stable
μ	105 MeV	6250 m
τ	1.8 GeV	50 μm
$\pi^{\pm}$	140 MeV	56 m
n	939 MeV	10^{11} m
W	80.4 GeV	10^{-19} m
Z	91.2 GeV	10^{-19} m

Detectable particles

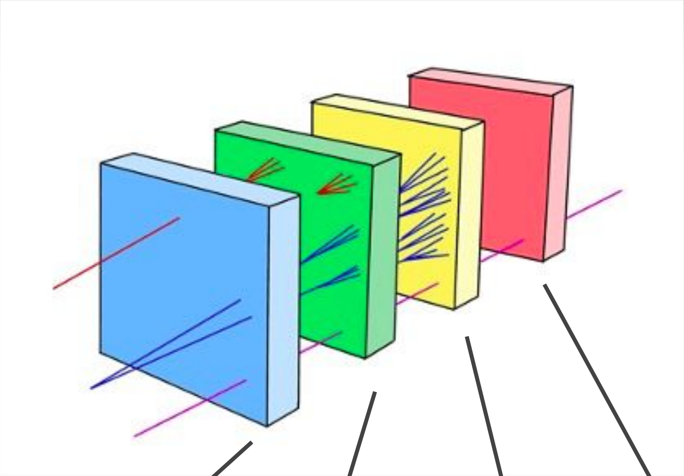
Detector

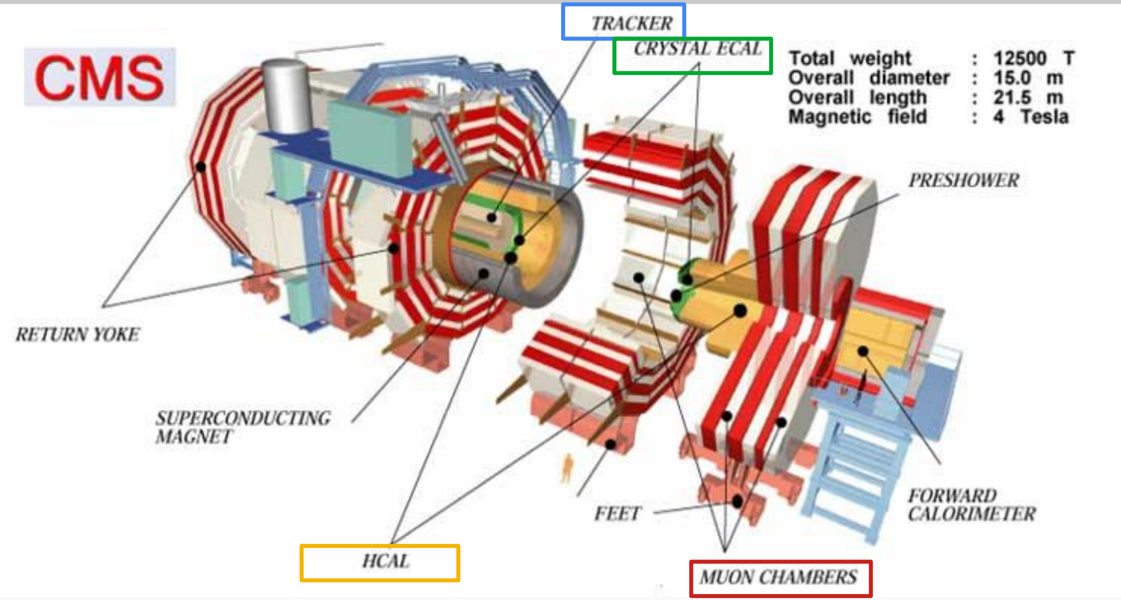


A particle produced in a collision will traverse the different sub-detectors where it will interact.

Different particles will interact differently since that is how we design the detector

Sub-Detector for CMS





Muon Chamber

Distance 14 meters

Tracker

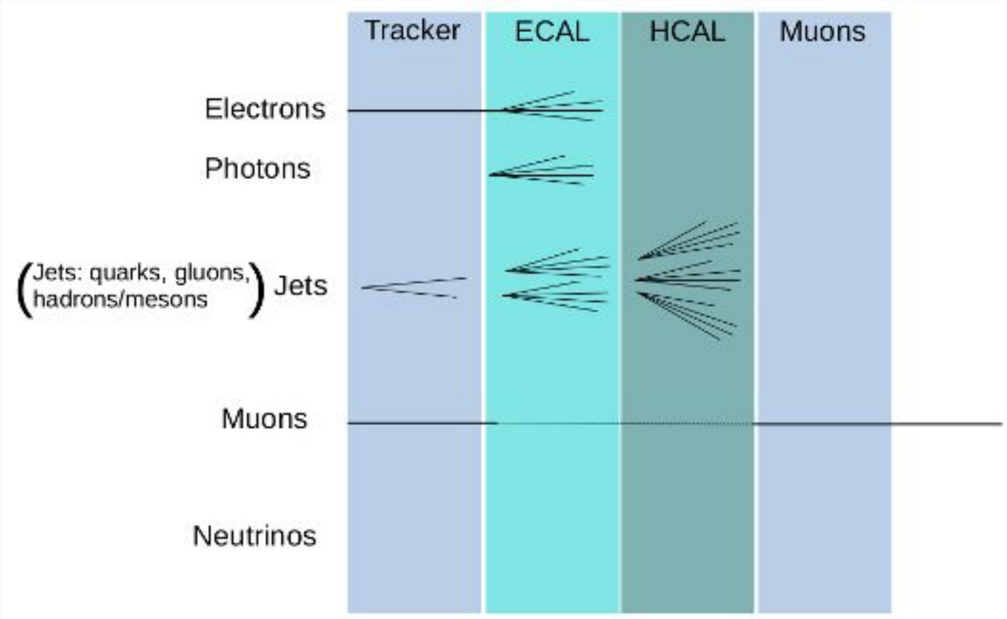
Electromagnetic Calorimetry (ECAL)

Hadronic Calorimetry (HCAL)

Building a detector

Aim:

1. To measure the 4-vectors of the particles produced in a collision.
2. To use various sub-detectors in a careful design to identify particles.



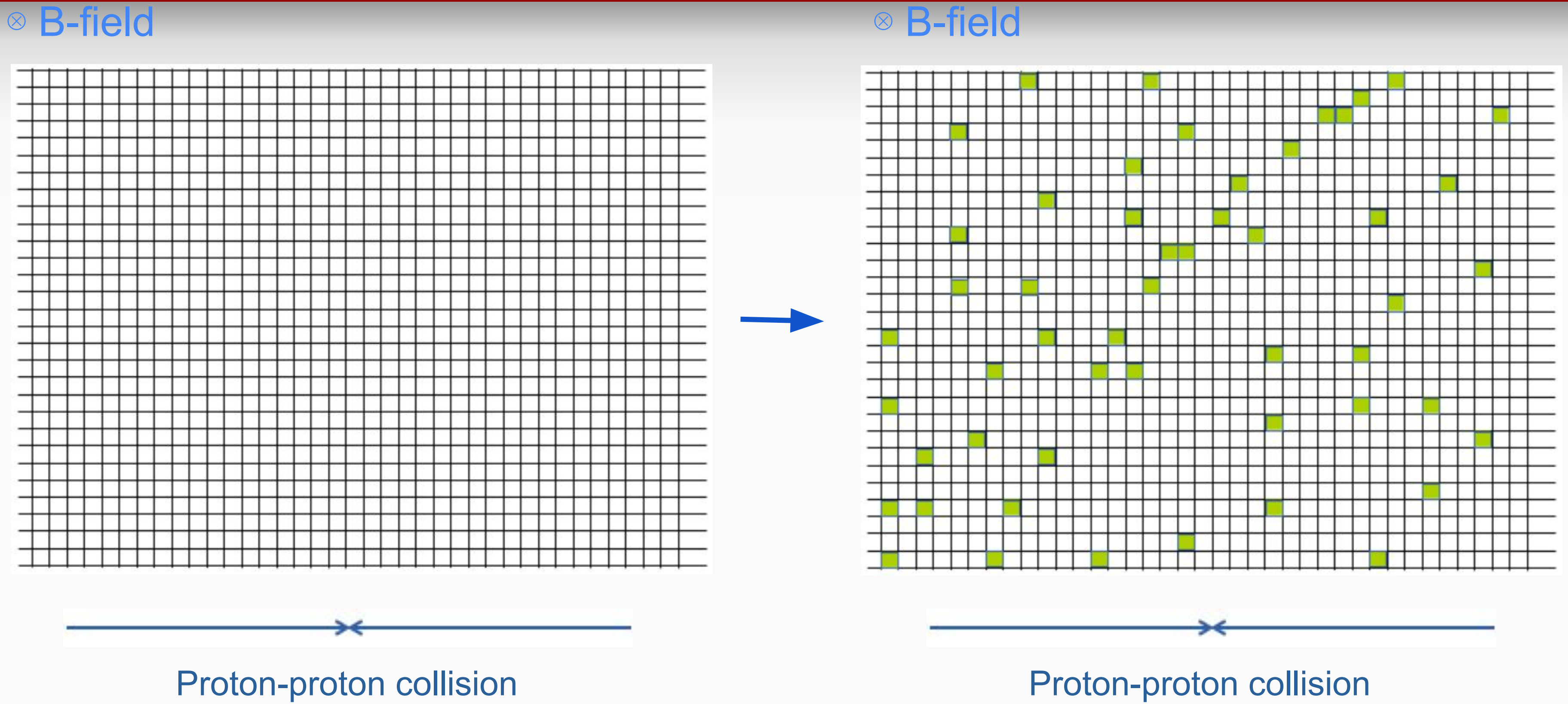
Radially outward from the collision point

Tracker: measures charge, momentum and trajectory of particle. Does not stop particle.

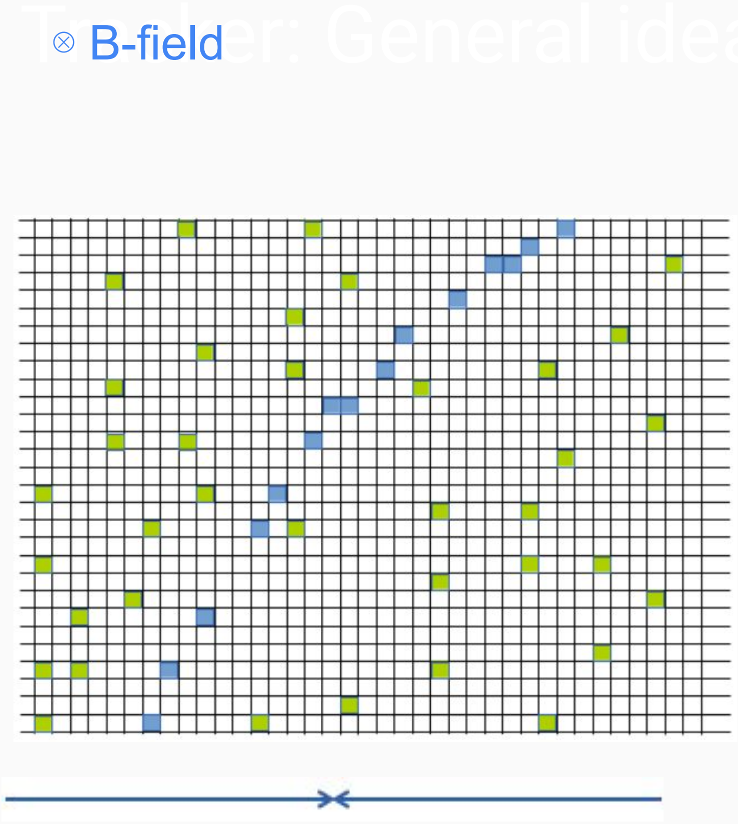
Calorimeters (CAL):
Measures complete energy of the particle (needs to stop particle completely)

Muon detector: just another tracker.

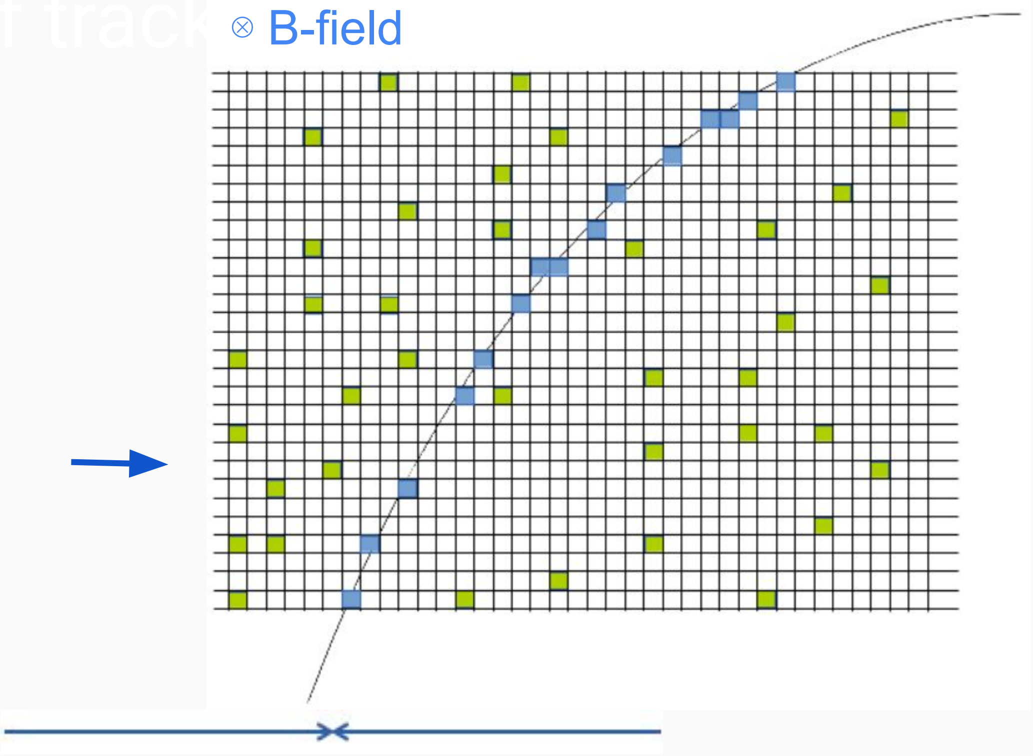
Tracker: General idea of tracking



Tracker: General idea of track



Proton-proton collision

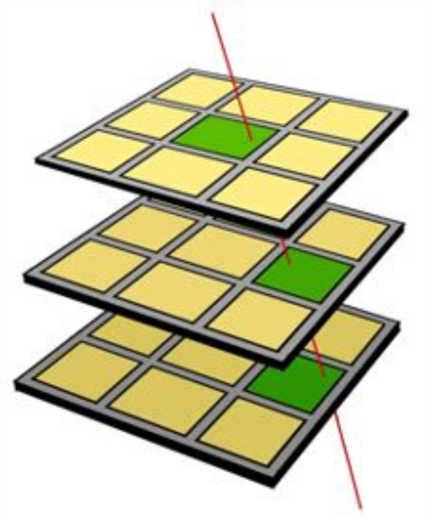


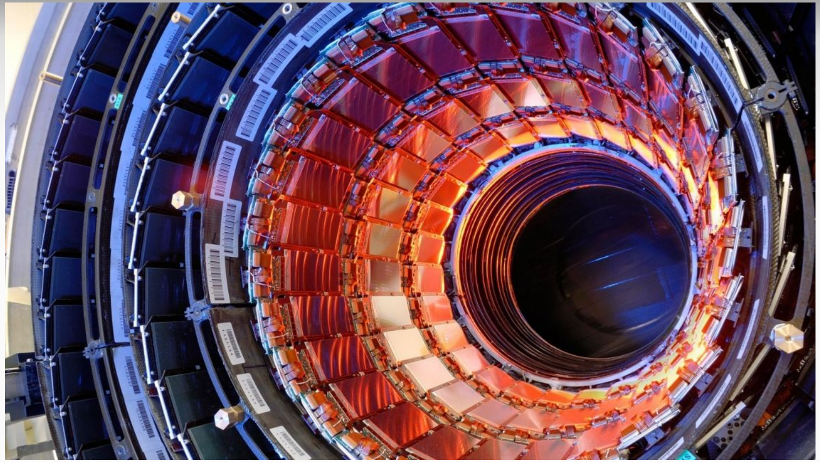
Proton-proton collision

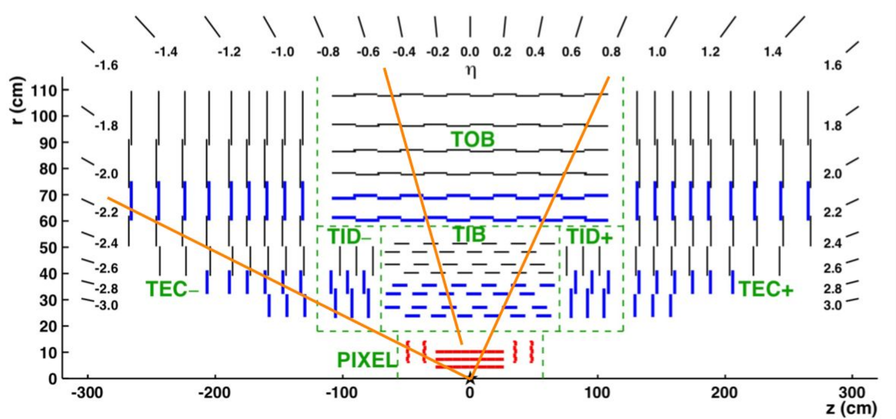
- Identifies collision point
- Measure charge
- Measure Momentum

CMS Tracking system

As a particle goes through, we can trace its path based on which pixels are lit up.



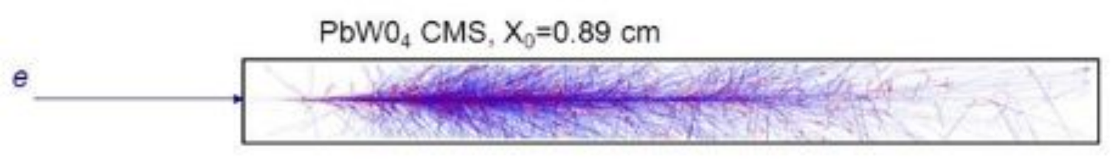




ECAL (Electromagnetic Calorimeter) :

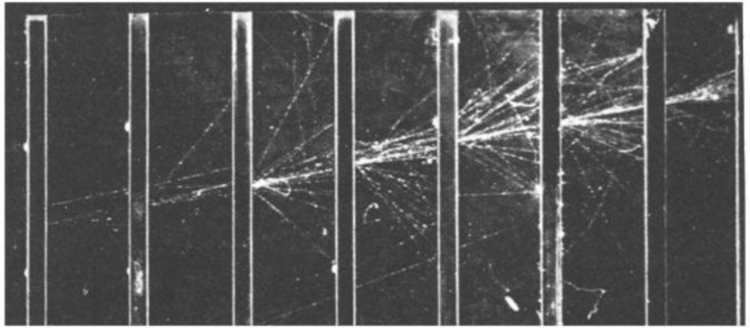
$PbWO_4$ crystals connected to photomultipliers.

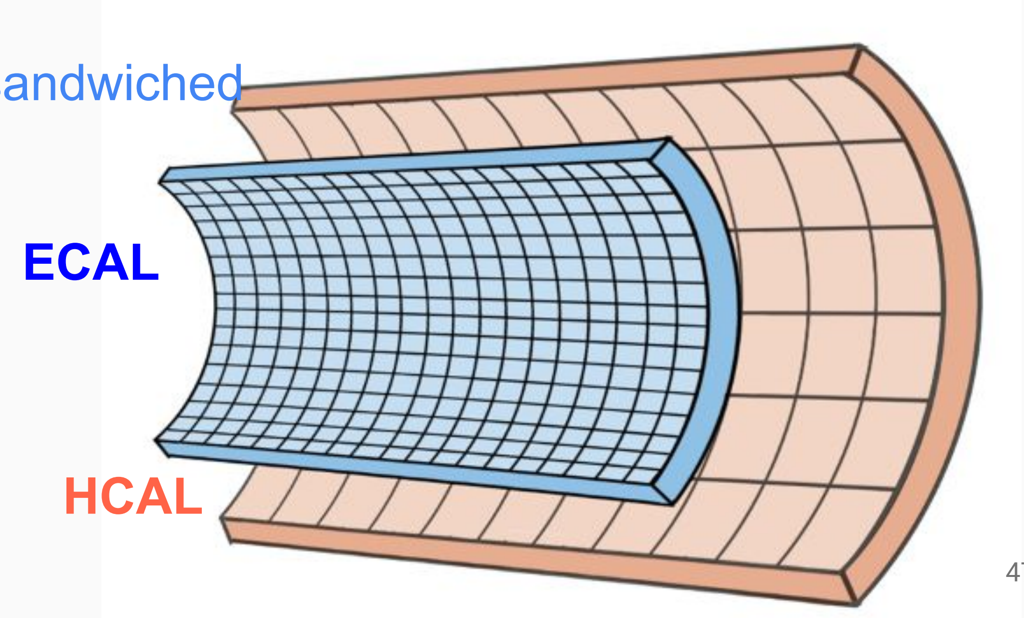
The crystal "scintillates" when electrons/photons pass through it.



HCAL (Hadronic Calorimeter) :

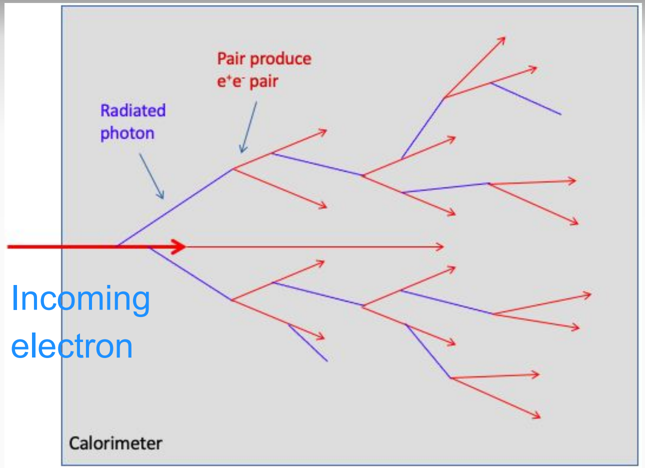
Sampling calorimeter with brass sandwiched with plastic scintillator.



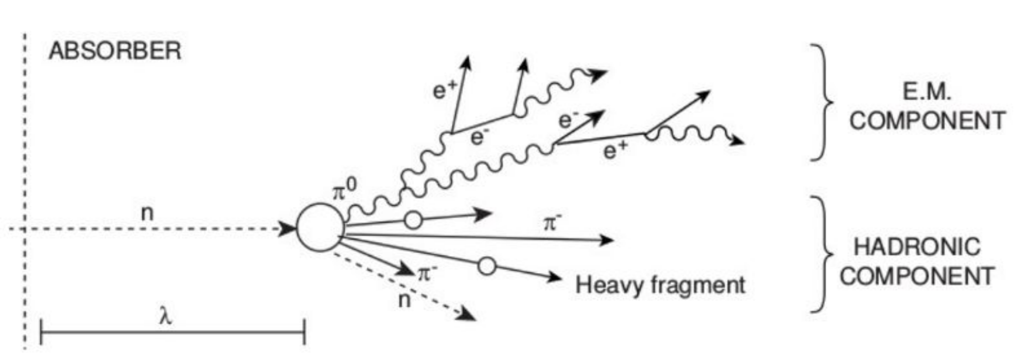


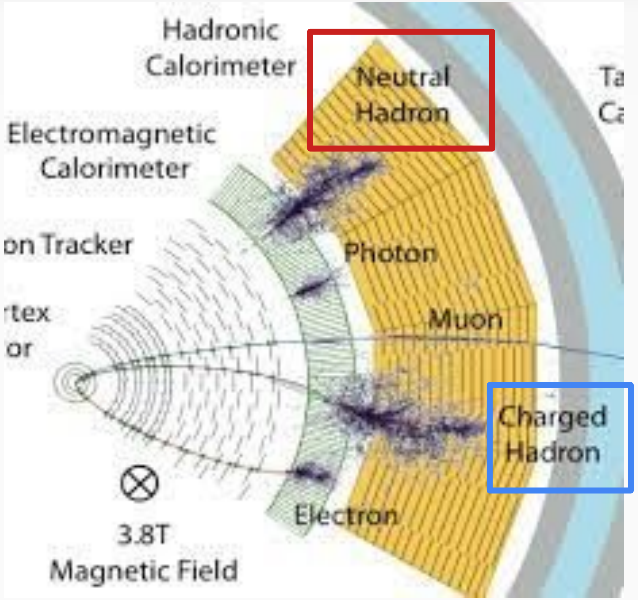
Energy measurement: Shower Profile

Electromagnetic shower

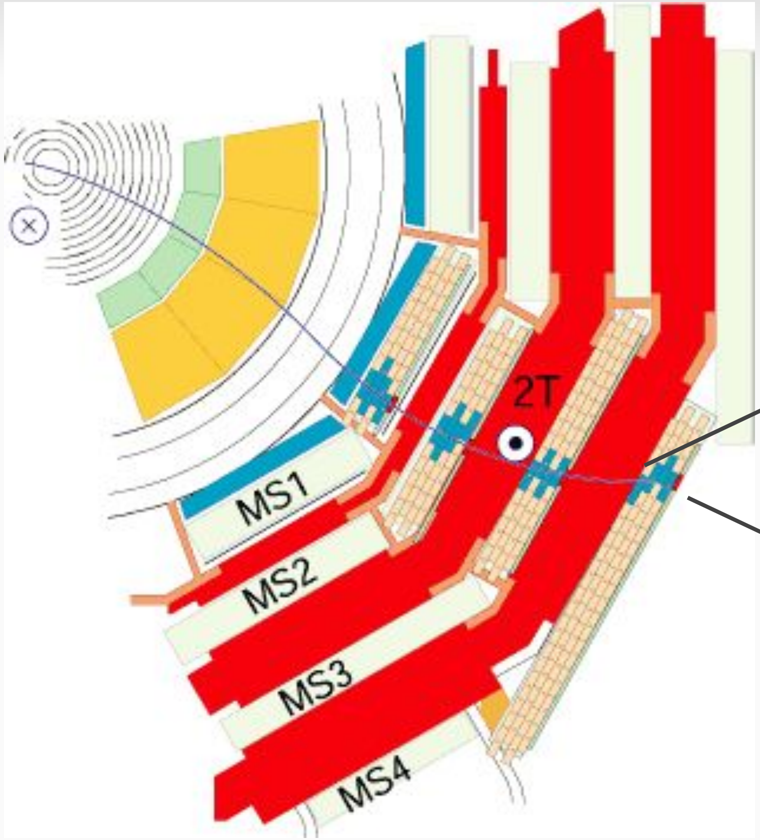


Hadronic shower

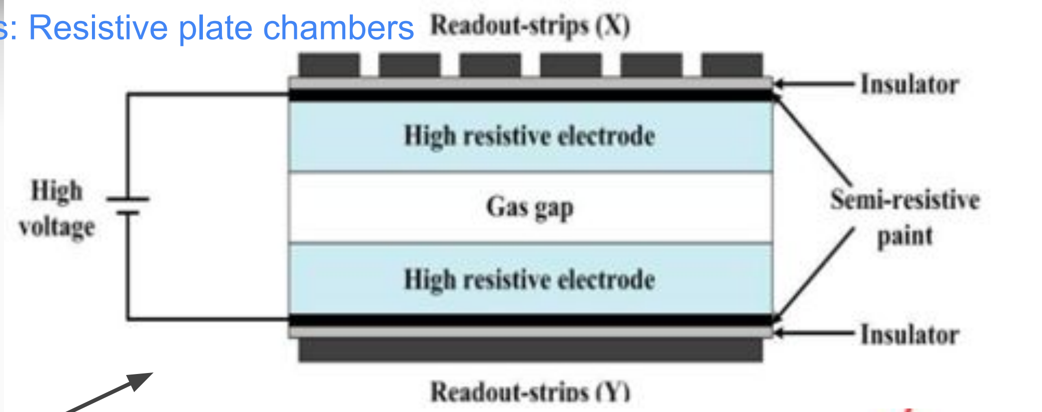




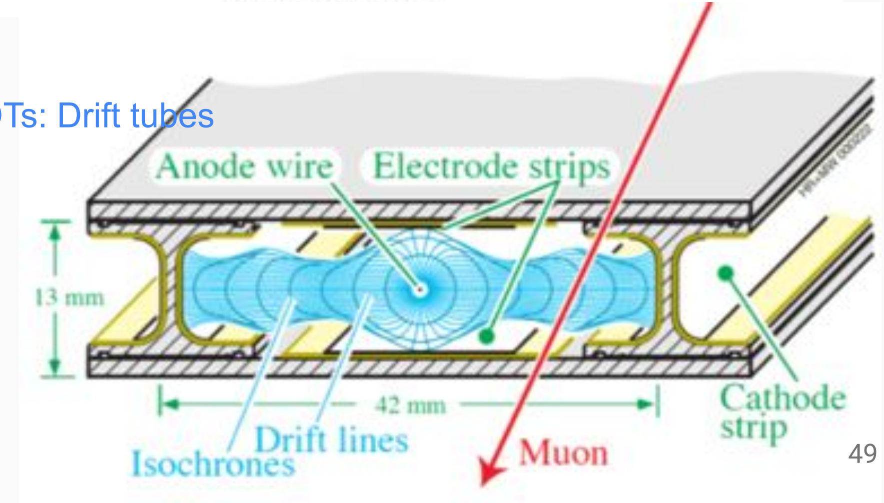
Muons Detection



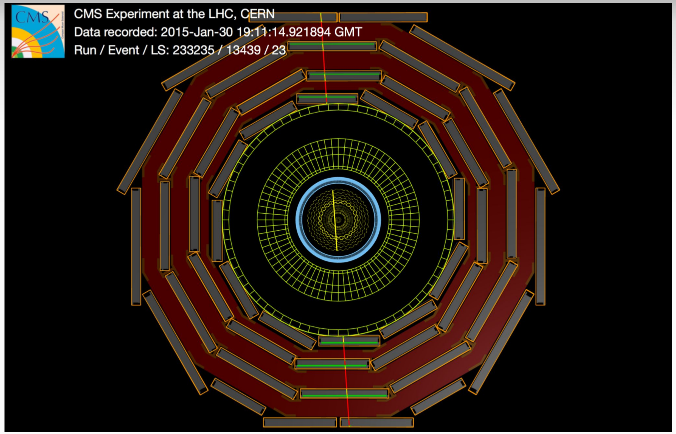
RPCs: Resistive plate chambers

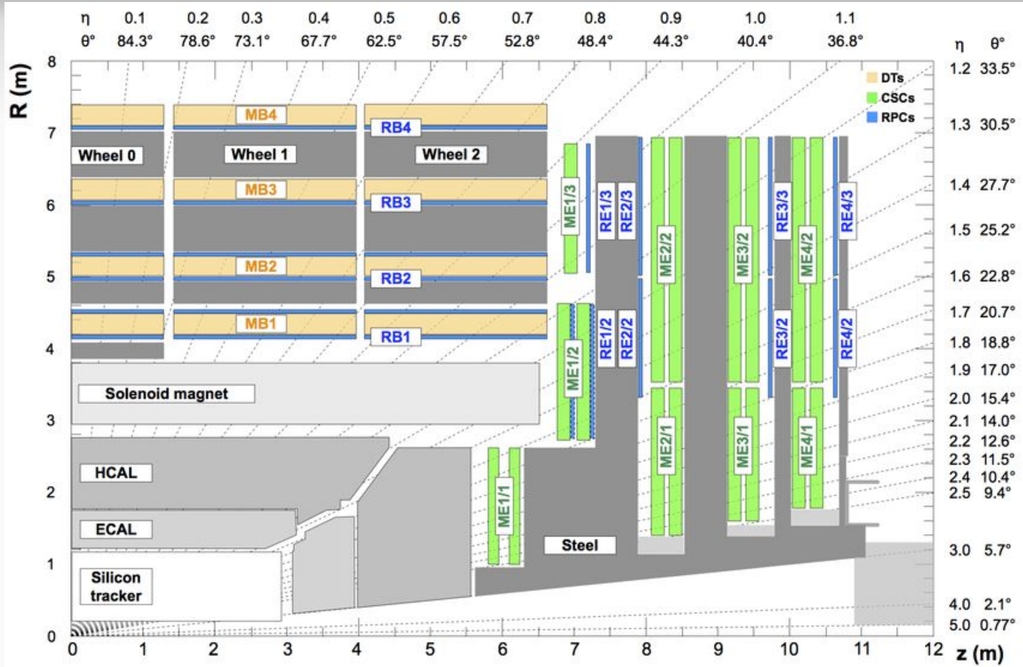


DTs: Drift tubes



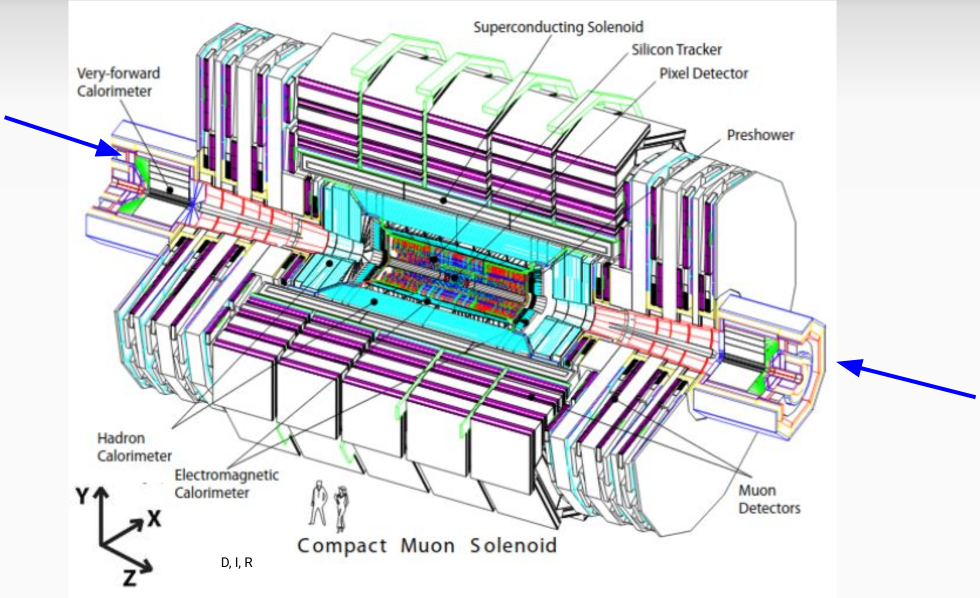
CMS Muon Detector



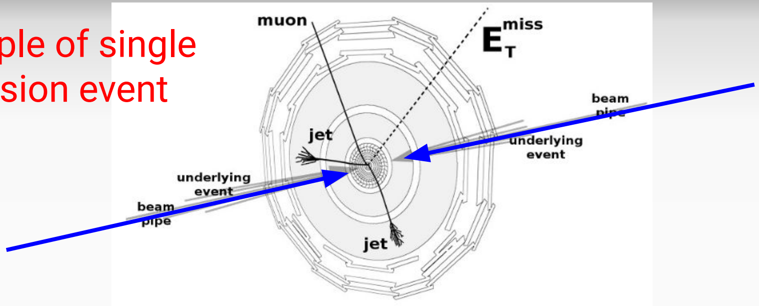


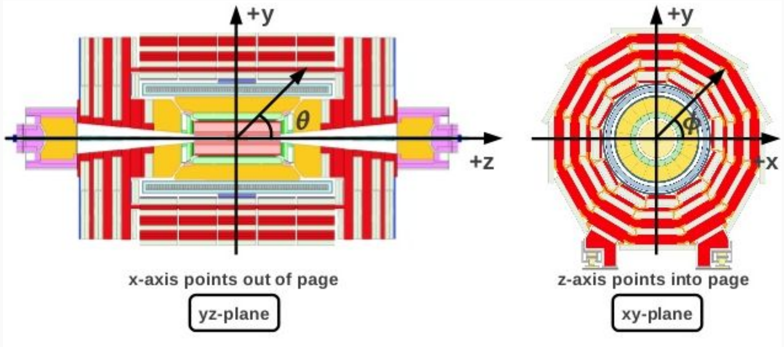
J. Instrum. 7 (2012) P10002

CMS Detector



Example of single collision event





- Basic information:
  - Multi-purpose detector
  - Length: 21.6 m
  - Diameter: 15 m
  - Weight: ~ 14,000 tons

Pseudorapidity: $\eta = -\ln\left(\tan(\theta/2)\right)$

Transverse momentum: $p_T = \sqrt{p_x^2 + p_y^2}$

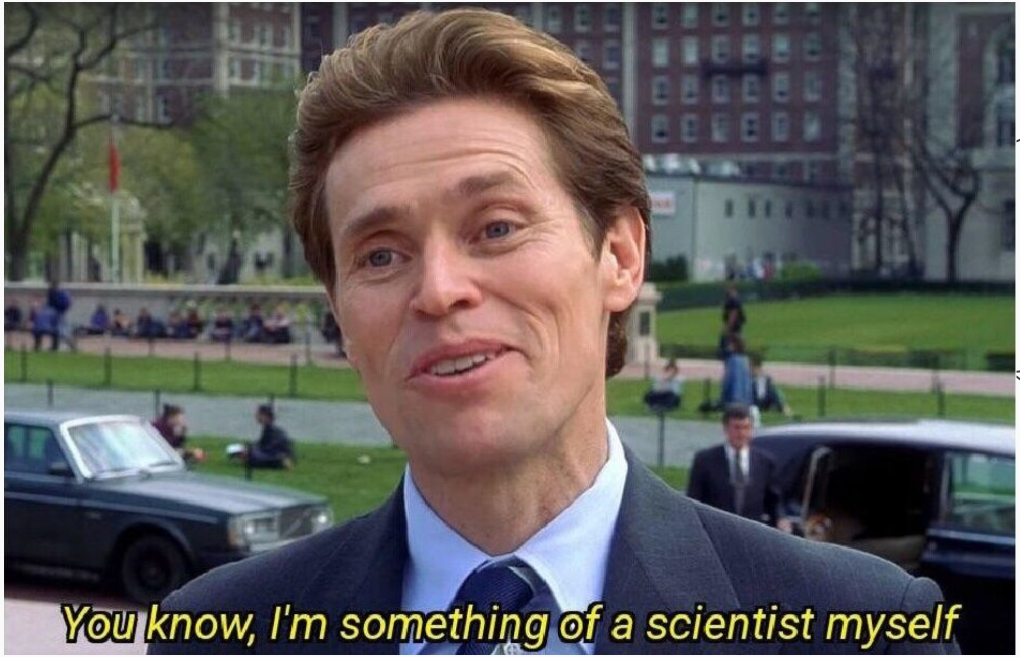
Distance between physics objects: $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

Overview

- Colliders and LHC
- Detectors
- **Object reconstruction**
- Analysing the collision data
- Closing

Electrons, photons, quarks, gauge bosons

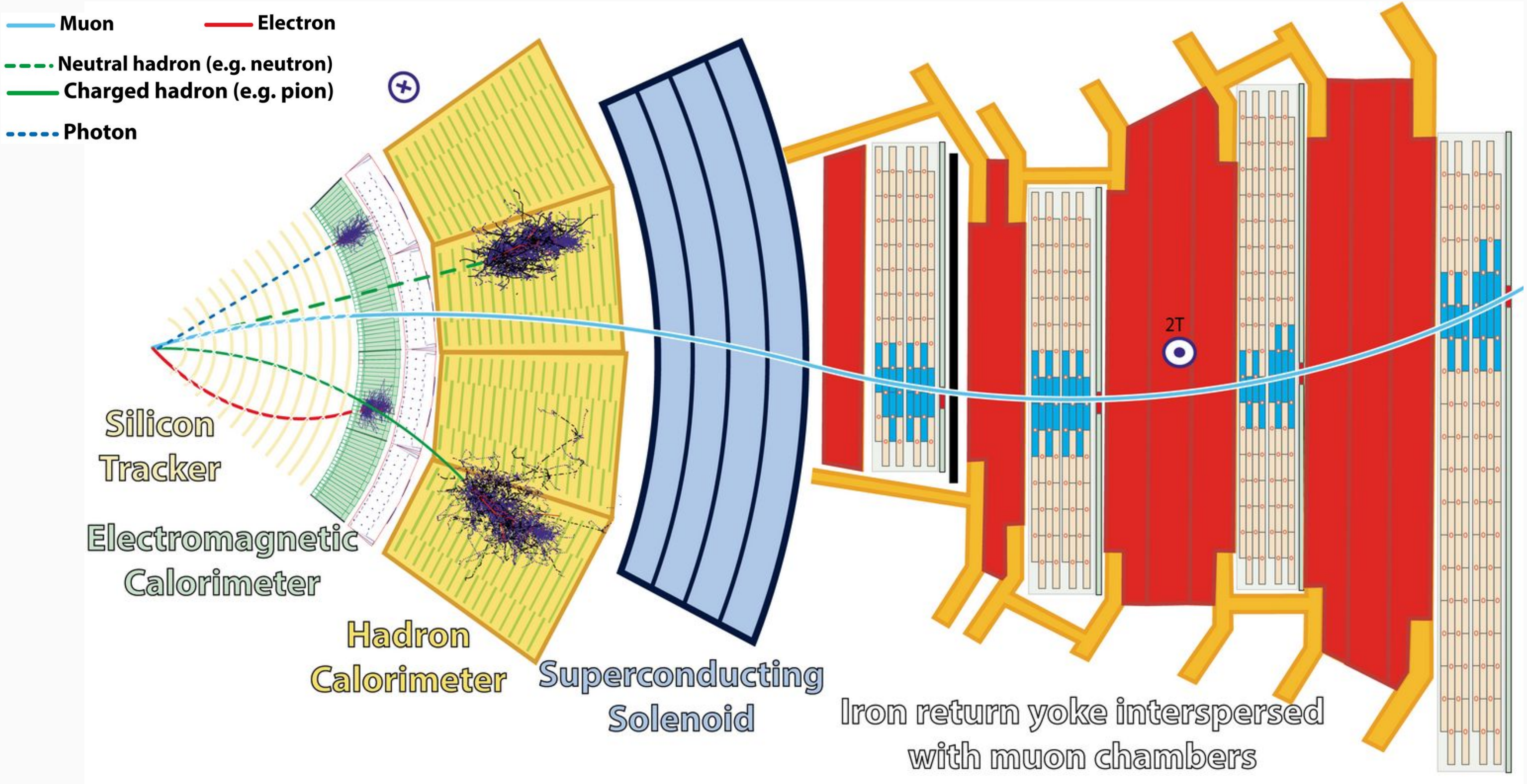
Great! We are ready to go! I mean to collide protons and produce a lot of data! To detect the particle! But...



how do we observe and study the collisions data ?

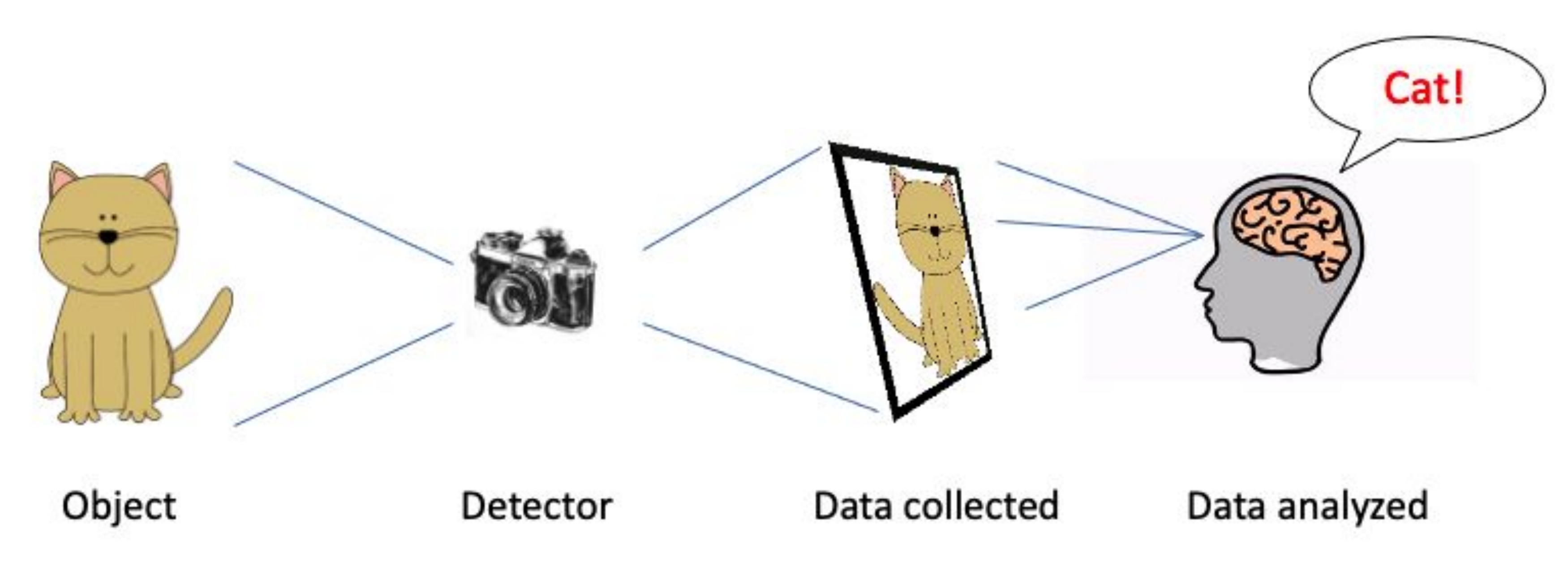
Object Reconstruction

Primary objects



This is how the detector responds to different particles passing through it.

Object Reconstruction and Identification

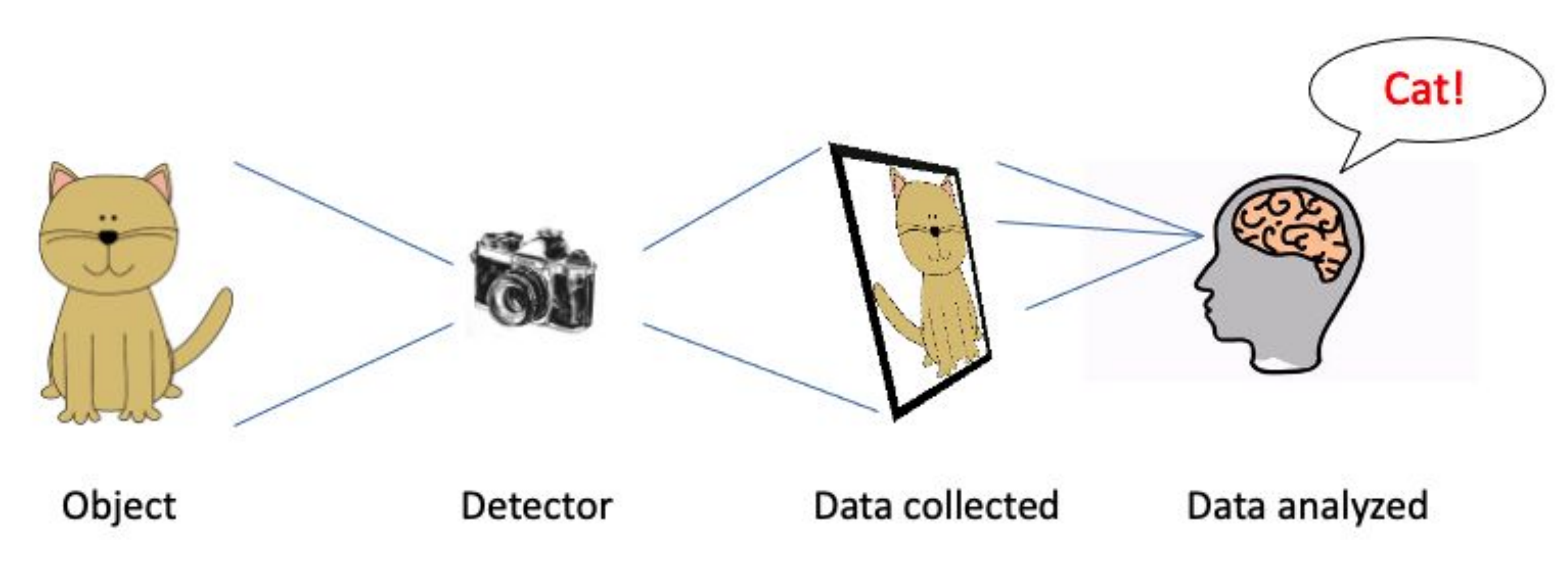


- Electron
- Photon
- Muon
- Charged Hadron
- Neutral Hadron

- Tracker + ECAL
- ECAL
- Tracker + Muon Chamber
- Tracker + ECAL + HCAL
- HCAL

- Electron
- Photon
- Muon
- Jets
- Jets

Object Reconstruction and Identification

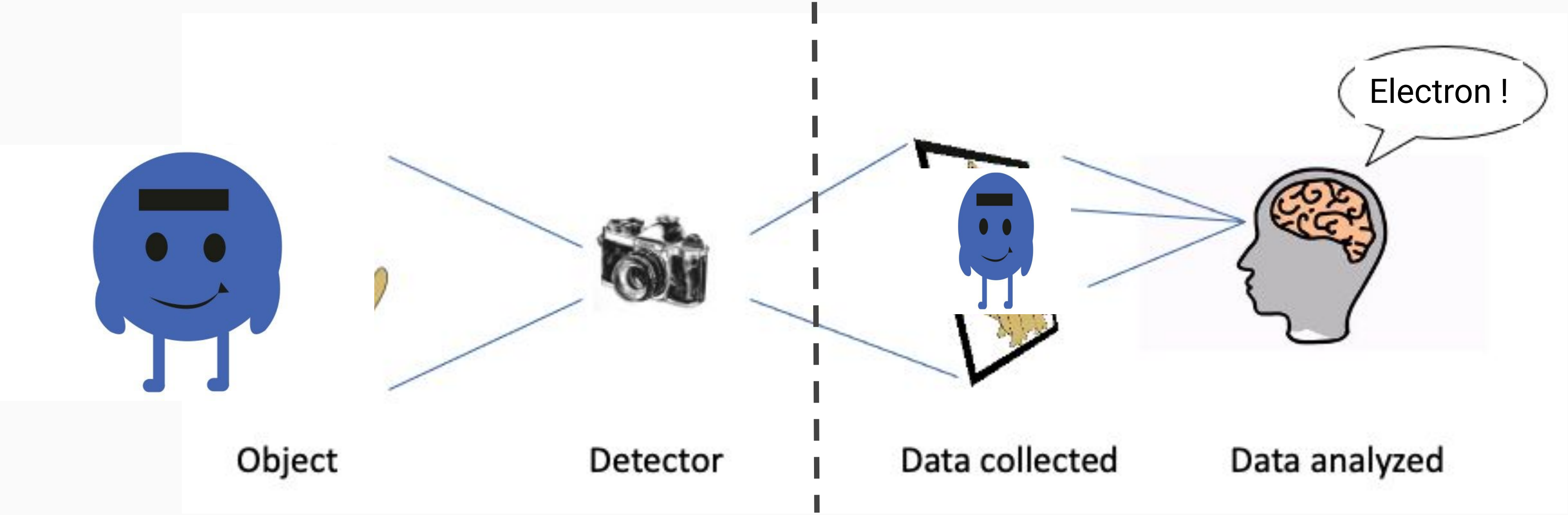


- Electron
- Photon
- Muon
- Charged Hadron
- Neutral Hadron

- Tracker + ECAL
- ECAL
- Tracker + Muon Chambers
- Tracker + ECAL + HCAL
- HCAL

- Electron
- Photon
- Muon
- Jets
- Jets

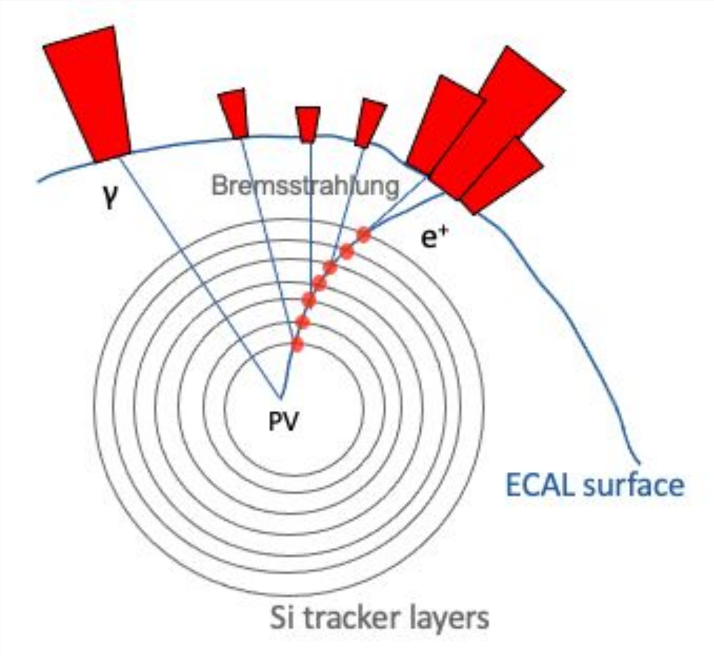
How many percent the reconstructed electron is, erm, electron?



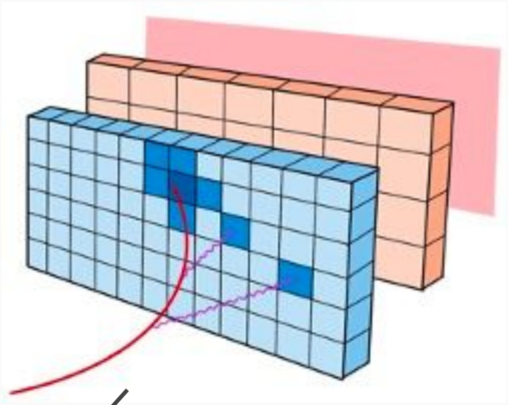
Reconstruction &
Identification

Match up tracks in the inner tracker and the ECAL.

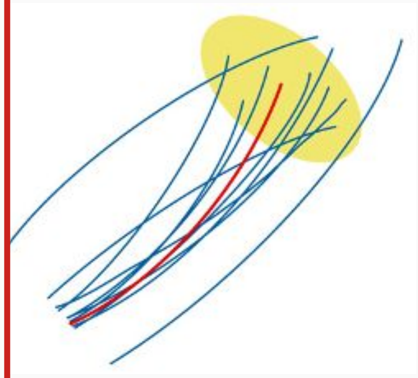
1. How good is the match? Spatially, and in momentum
2. How good are the individual tracks (inner and outer)
3. Is the calorimeter deposit low/negligible?



In practice, many photons convert to e^+e^- pair

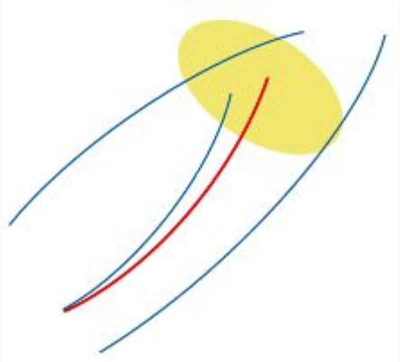


Prompt processes



Isolated

Non-Prompt processes

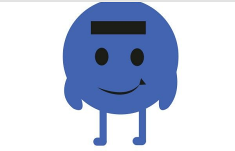


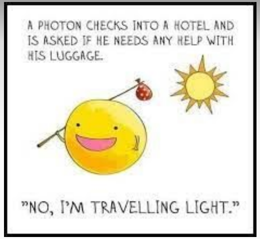
Non-isolated

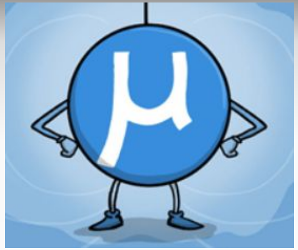
Example: Electron reconstruction and Identification

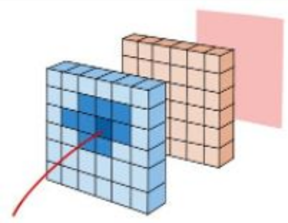
Reconstruction and Identification

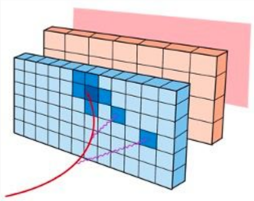
Produced particles

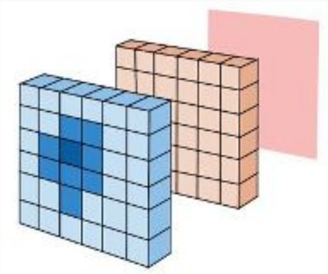


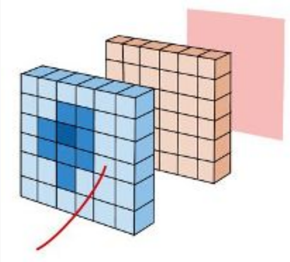


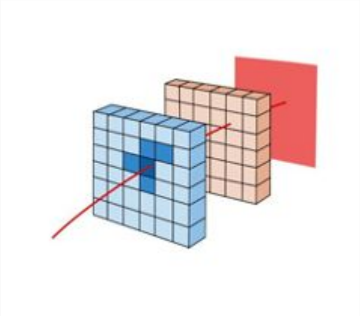




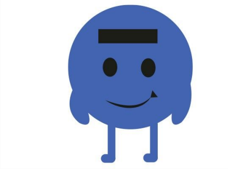


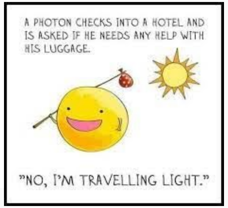


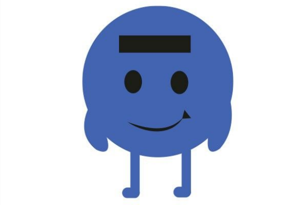


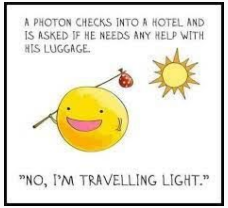


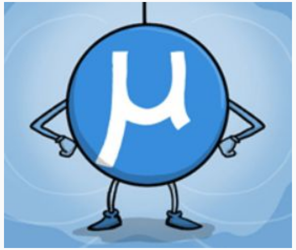
Reco & ID leptons











Isolation

Crucial for electrons, muons, photons and taus

e, μ, γ

Prompt

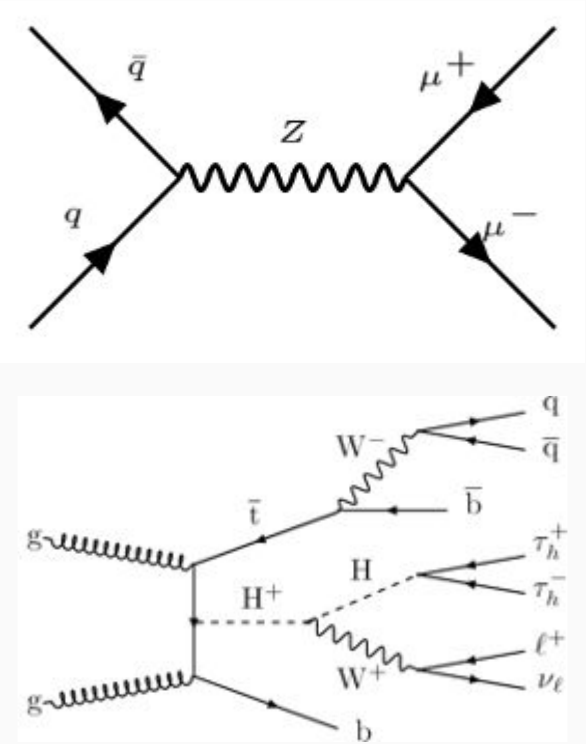
- It means the particles arise from:

1. Collision directly
2. Decay of gauge boson (W, Z)
3. Some BSM particle

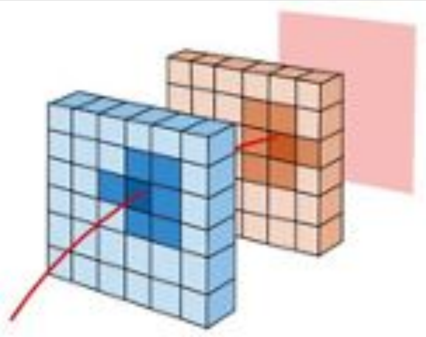
Non -Prompt

- It means everything else, typically that occur in hadron decay and are thus inside a jet.

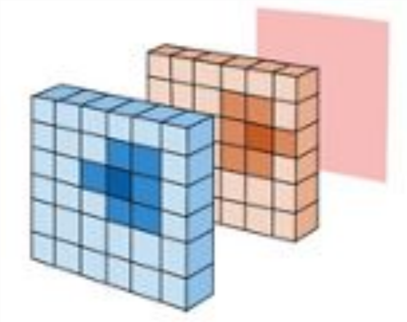
Prompt



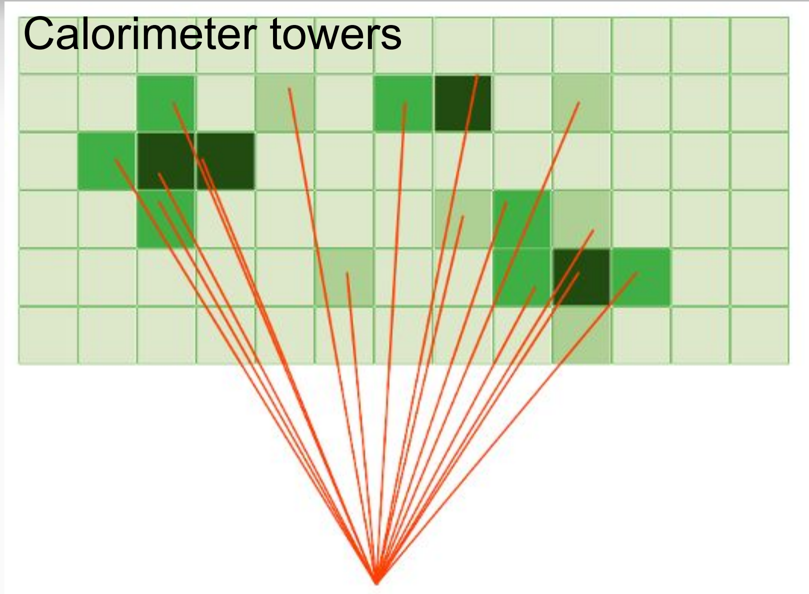
Jet Reconstruction and Identification



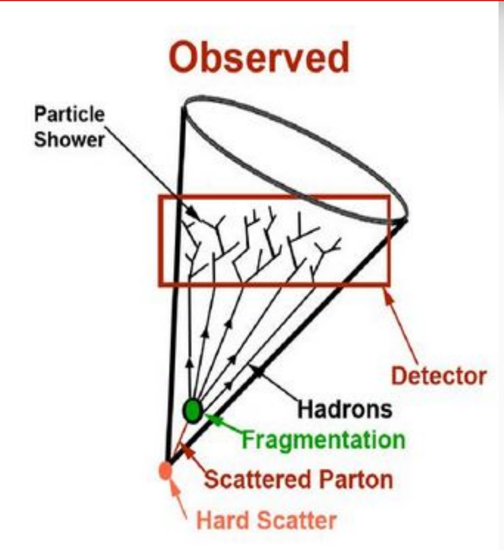
Charged hadron



Neutral hadron



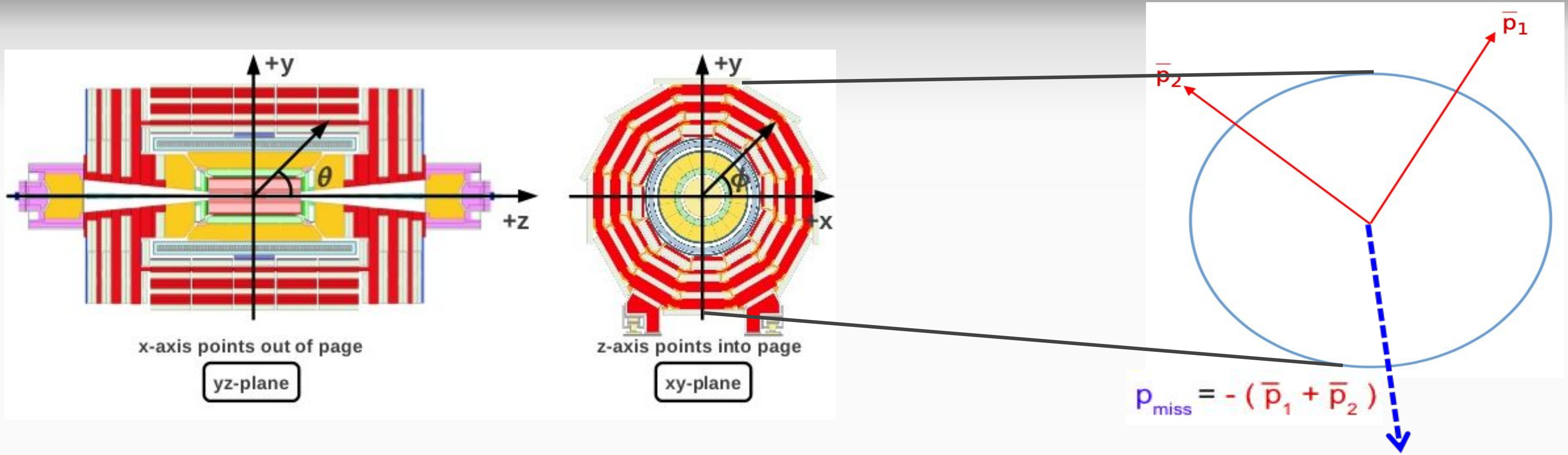
Proton-Proton Collision



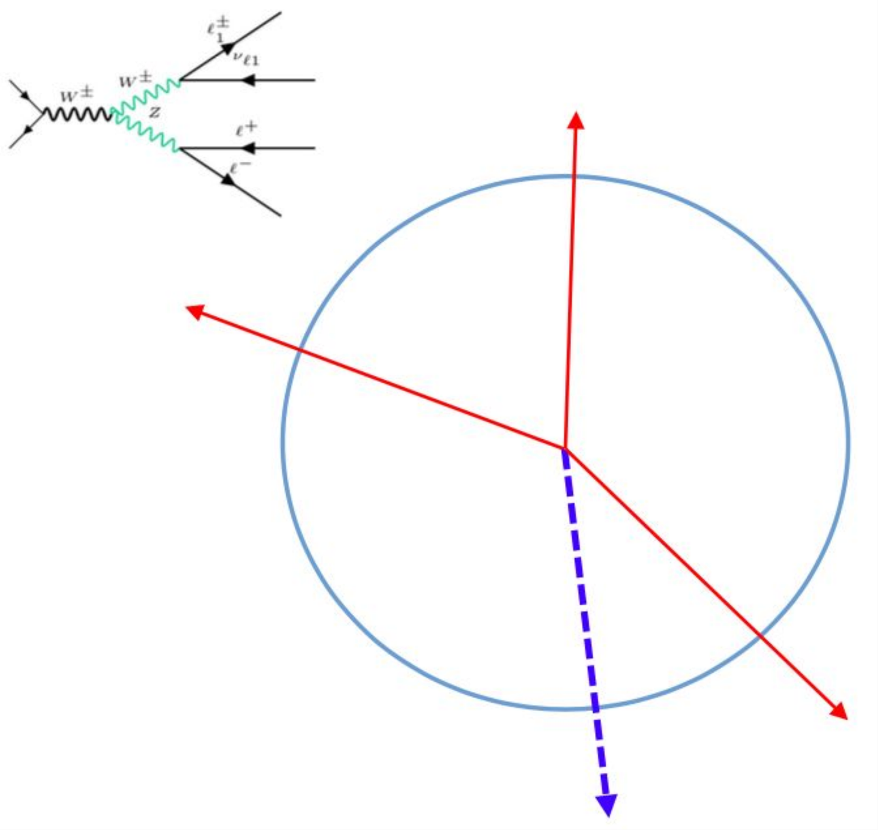
Jet

- It merges objects together, until we end up with one logical objects (i.e. a single 4-vector)

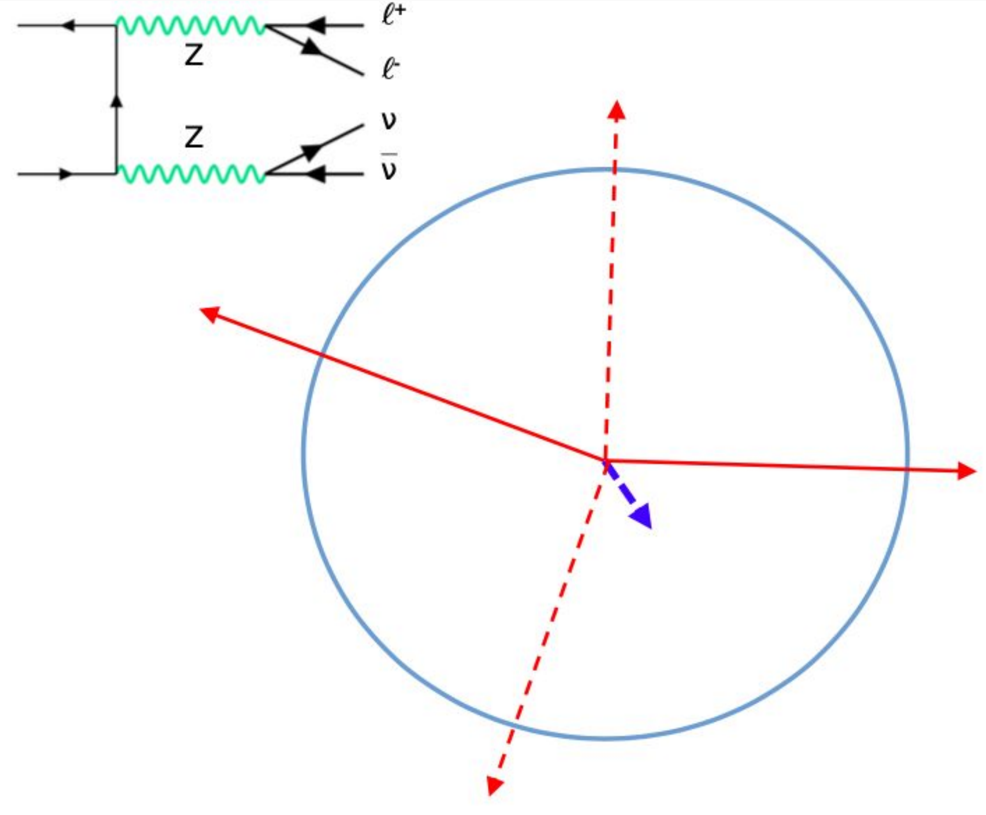
Missing Transverse Energy



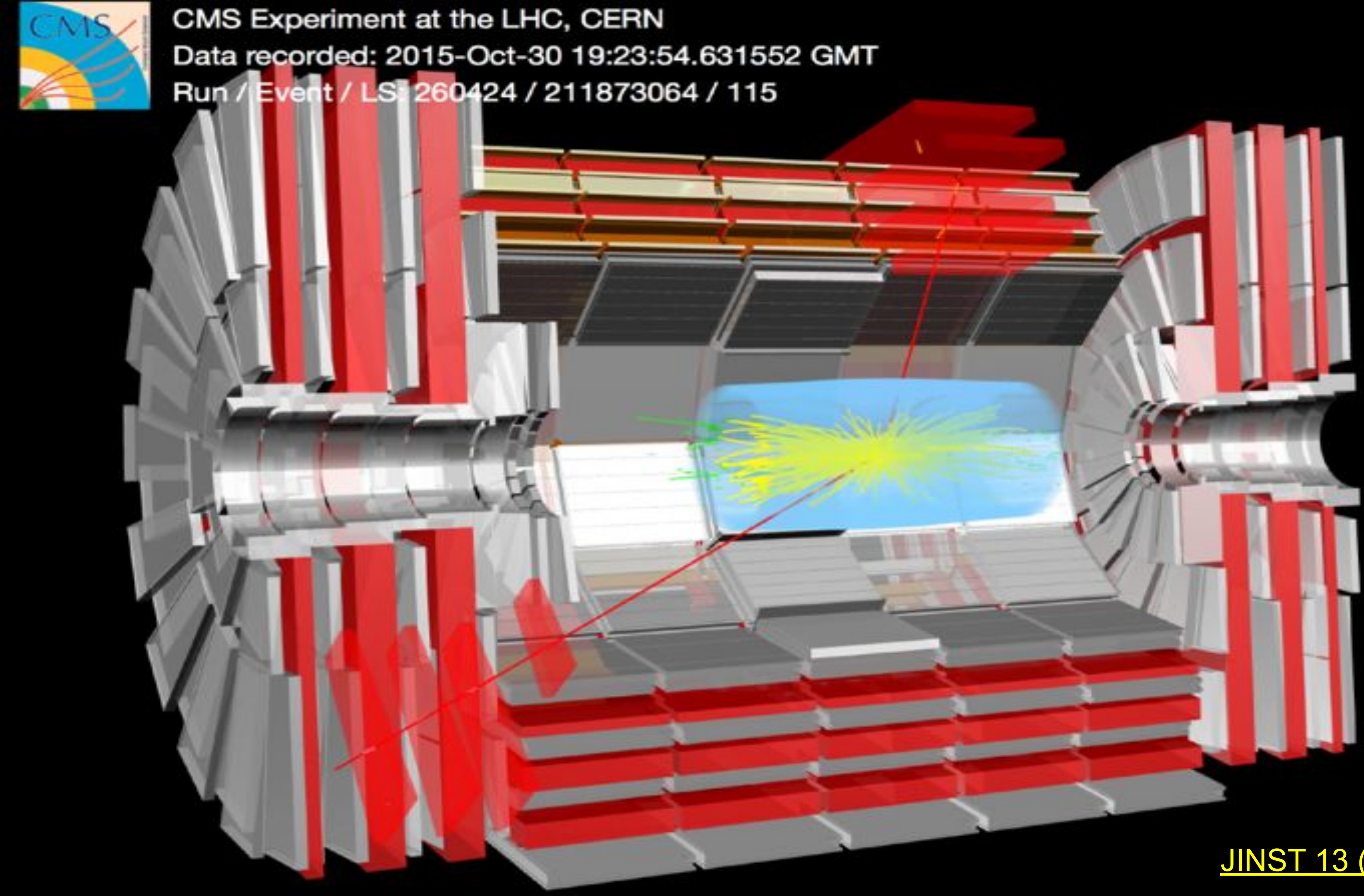
- Defined as the negative of the vector sum of transverse momentum of all observed particles.
- This means one has to understand all the observed particles well.
- Mis-measurements in measuring existing particle 4-vectors will impact missing momentum.



3 lepton + MET final state



2 leptons + MET final state



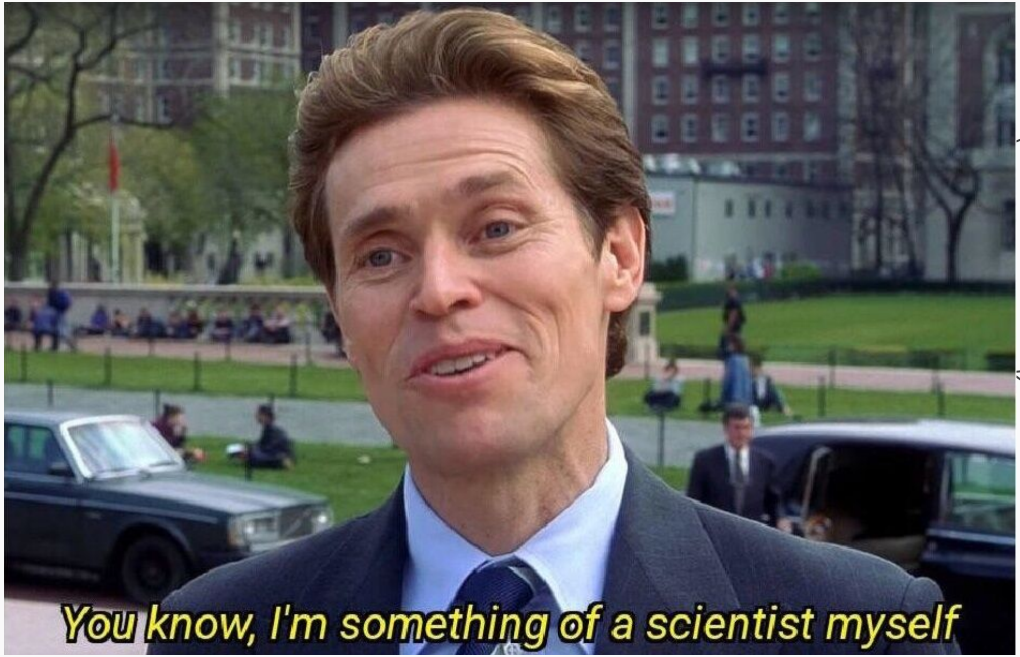
JINST 13 (2018) P06015

Overview

- Colliders and LHC
- Detectors
- Object reconstruction
- **Analysing the collision data**
- Closing

Brief walkthrough of data analysis, exp: Higgs boson discovery and measurements

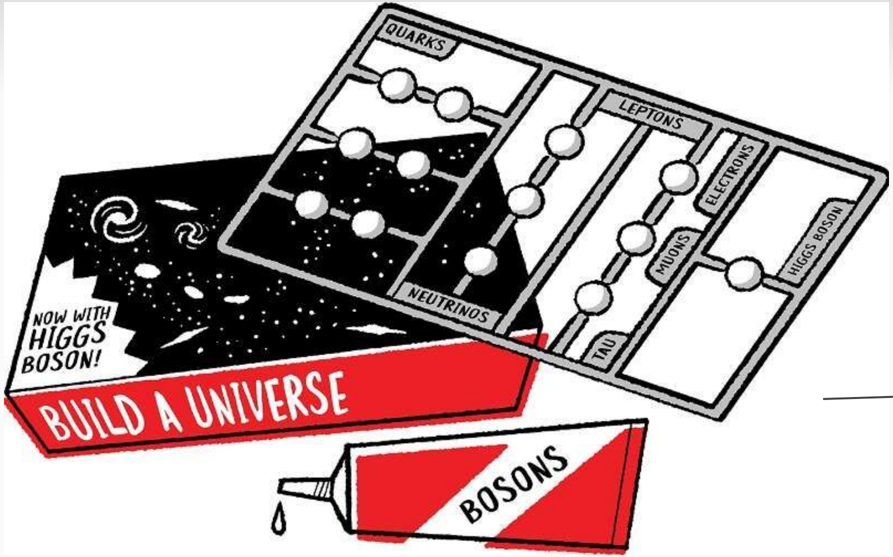
Great! We are ready to go! I mean to collide protons and produce a lot of data! To detect the particle! To observe the reconstructed particles in the detector! But...



how do we study the collisions data ?

Analyzing Collision Data

How do we study Particle Physics?



?????

We know the ingredients of the universe (effectively), how do we experimentally study or disprove them? We need to produce them!

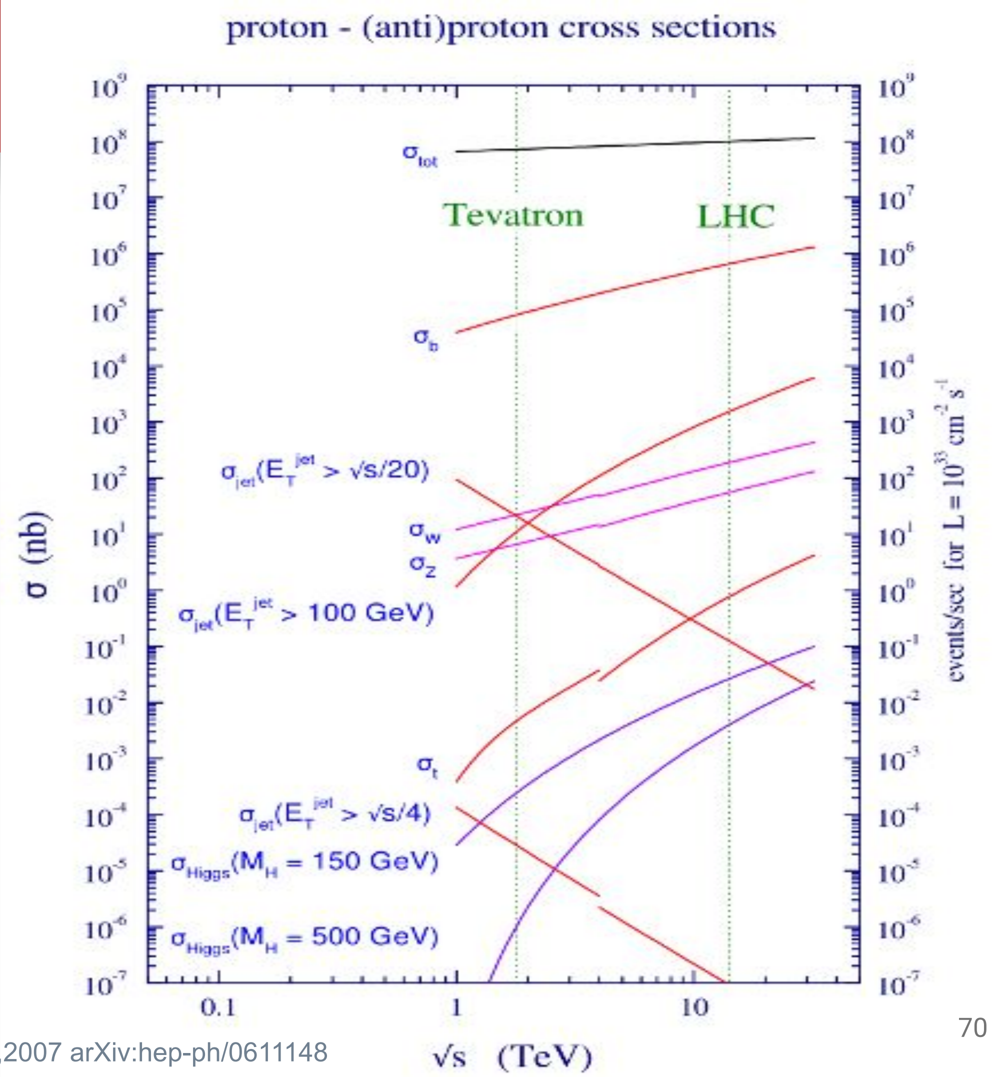
Physics = Accelerator(s) + Collider(s) + Detector(s) + Computer(s)

Triggers

$$N = \mathcal{L}\sigma$$

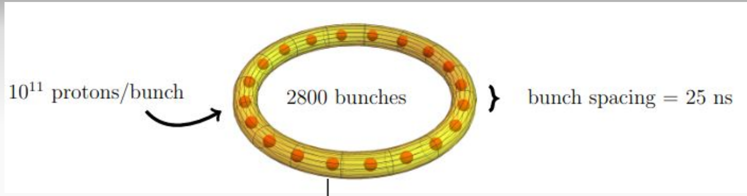
- Collisions (i.e. bunch crossings) happen at **40 MHz**
- This rate (given the event size ~1 MB) is too large for us to write everything to storage (~ 40 TB/s)
- Technology limits us to writing output at about **1 kHz**

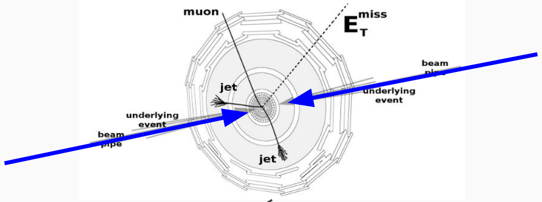
How to pick which 1000 events/s to keep out of the 40 million collisions/s ?

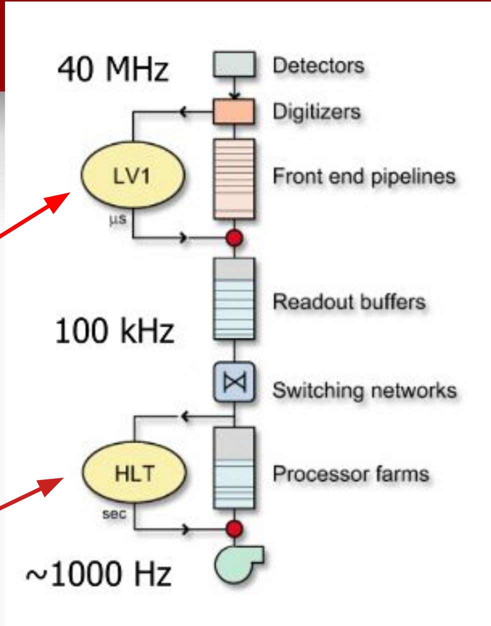


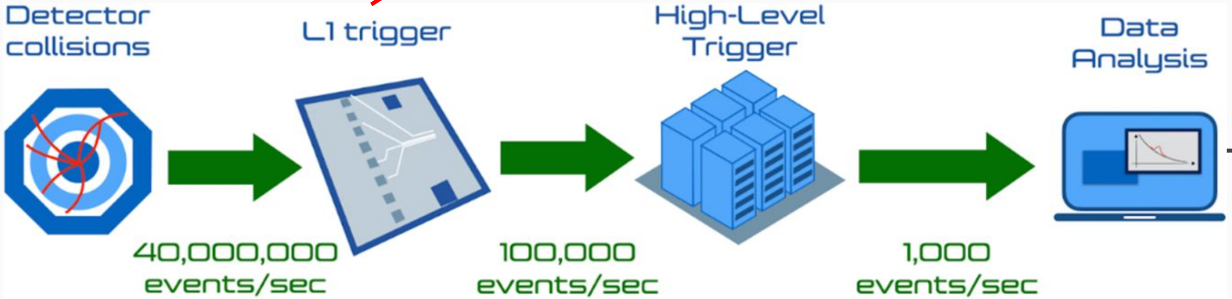
Rept.Prog.Phys.70:89,2007 arXiv:hep-ph/0611148

Data Acquisition



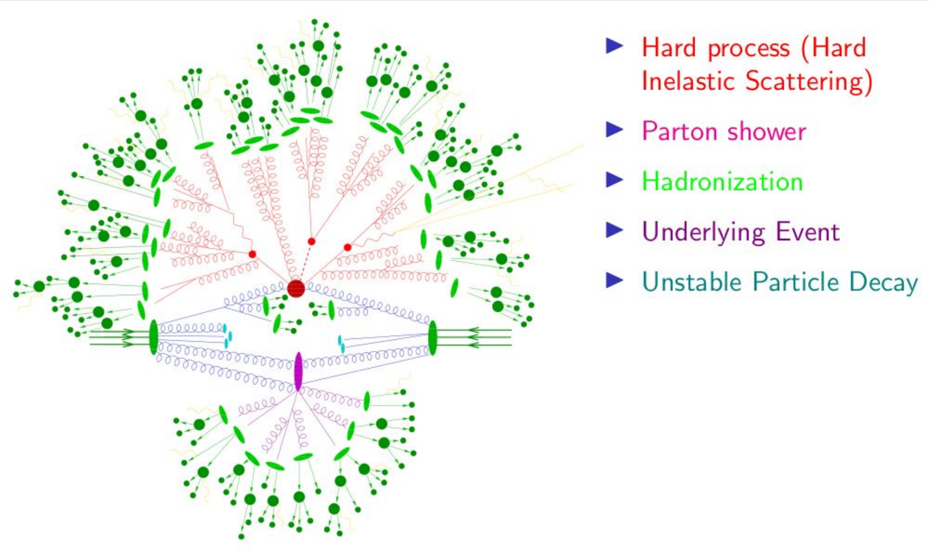


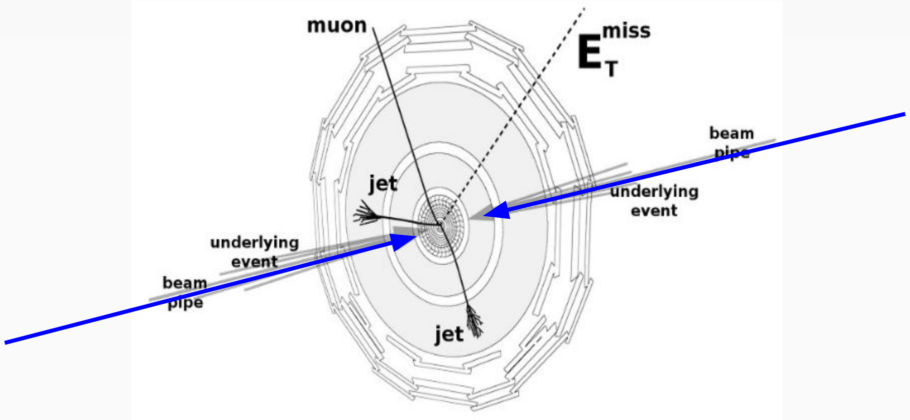




Maybe

Proton-Proton Collision





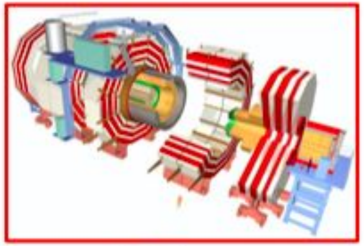
Evolution of "parton" is based on phenomenological model

What detector "see" (reconstructed)

Monte Carlo Simulation, aka Prediction

Data

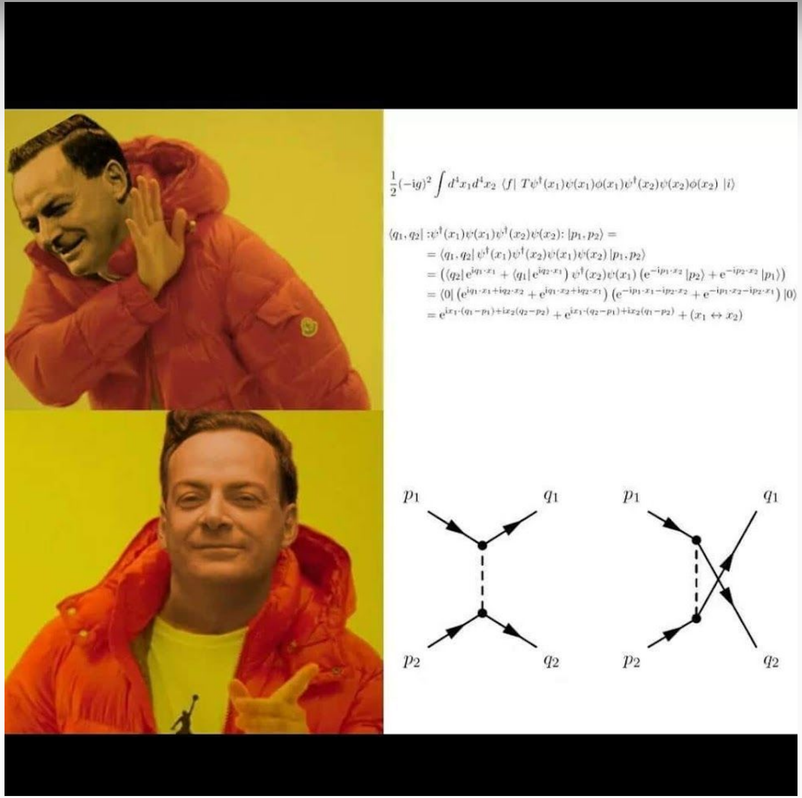
A word on ‘Monte Carlo’ samples

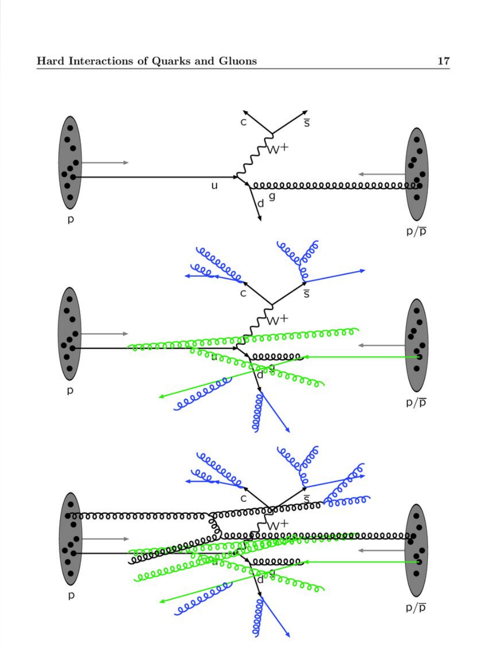


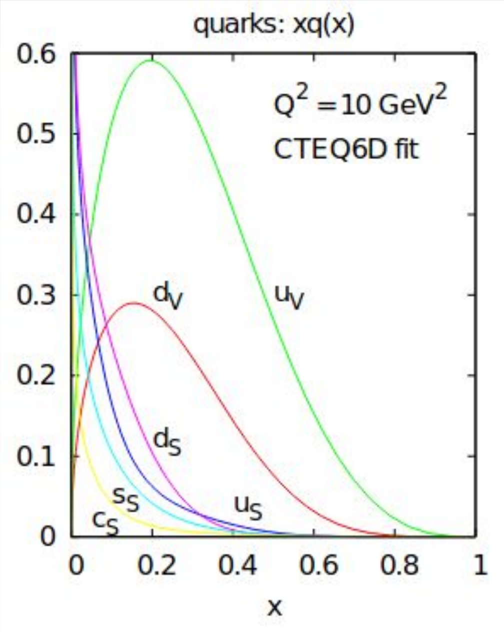
Data

Generation	For a given physics process, obtain the 4-vectors of all outgoing particles
Simulation	Simulate what happens when these outgoing particles interact with the material of the detector
Digitization	Given the material interactions, what digital signals will be generated in the detector (like actual data)
Reconstruction	Use the digital signals to reconstruct what particles were seen in the detector.

Feynman Diagrams and Parton Model





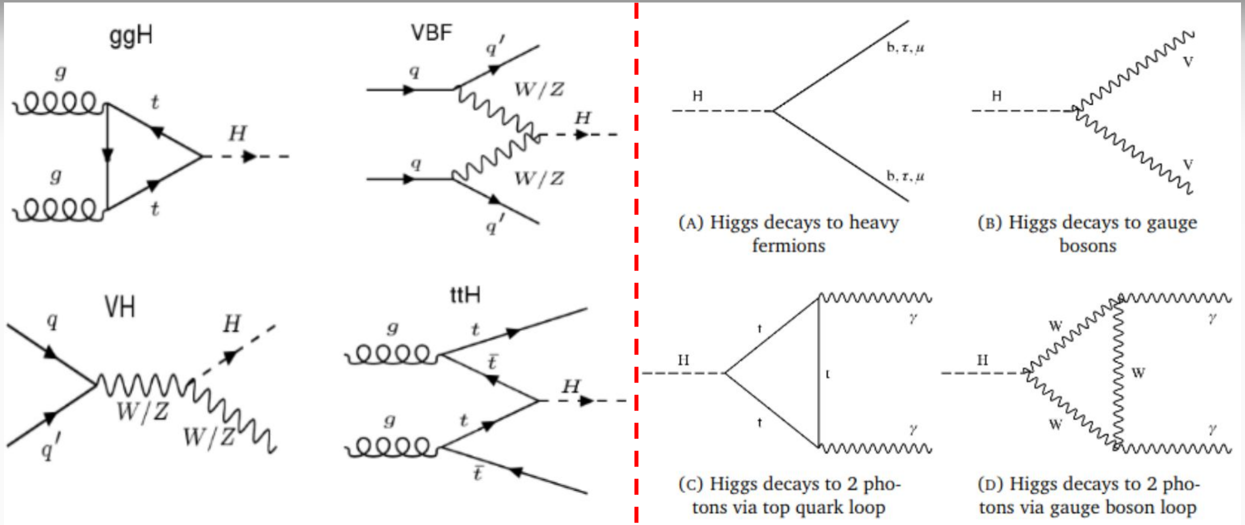


Parton distribution function (PDF) of a proton

Feynman diagram is a pictorial representation of the mathematical expressions describing the behavior and interaction of subatomic particles

The constituents of proton involve in the interaction.

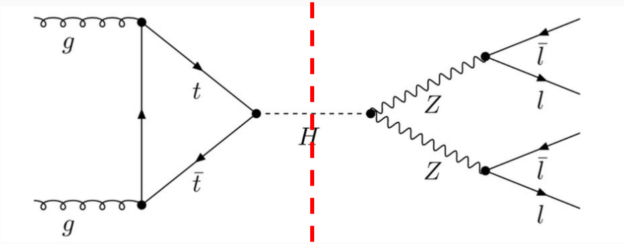
Higgs boson production and decay in LHC



Main Higgs Production

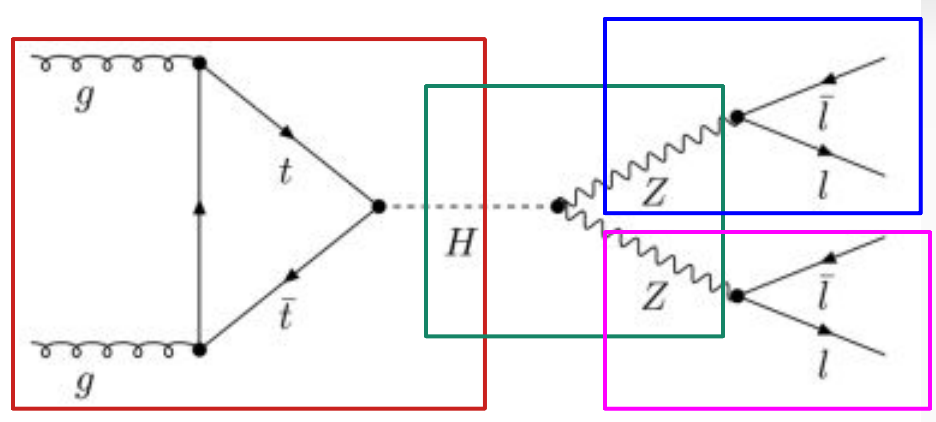
Main Decay Channel

Example:

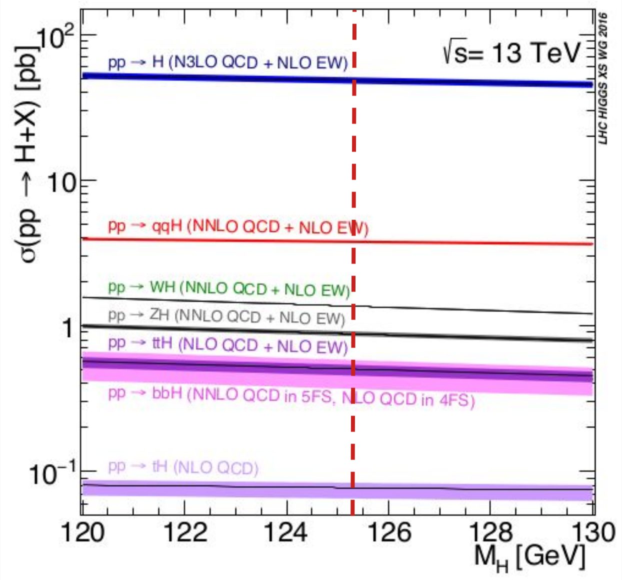


ggH Production in 4 leptons final state

Lets calculate the production rate of ggH in the final state of 4 leptons



$$\begin{aligned}\sigma(\mathrm{ggH} \to 4l) = & \ \sigma(\mathrm{ggH}) \times \mathrm{Br}(H \to ZZ) \times \mathrm{Br}(Z \to e^+e^-) \times \mathrm{Br}(Z \to e^+e^-) \\ + & \ \sigma(\mathrm{ggH}) \times \mathrm{Br}(H \to ZZ) \times \mathrm{Br}(Z \to \mu^+\mu^-) \times \mathrm{Br}(Z \to \mu^+\mu^-) \\ + & \ \sigma(\mathrm{ggH}) \times \mathrm{Br}(H \to ZZ) \times \mathrm{Br}(Z \to e^+e^-) \times \mathrm{Br}(Z \to \mu^+\mu^-) \\ + & \ \sigma(\mathrm{ggH}) \times \mathrm{Br}(H \to ZZ) \times \mathrm{Br}(Z \to \mu^+\mu^-) \times \mathrm{Br}(Z \to e^+e^-)\end{aligned}$$



M_{h} = 125.38 ± 0.14 GeV

$$
\begin{aligned}
\sigma(\text{ggH} \to 4l) = {} & \sigma(\text{ggH}) \times \text{Br}(H \to ZZ) \times \text{Br}(Z \to e^+e^-) \times \text{Br}(Z \to e^+e^-) \\
& + \sigma(\text{ggH}) \times \text{Br}(H \to ZZ) \times \text{Br}(Z \to \mu^+\mu^-) \times \text{Br}(Z \to \mu^+\mu^-) \\
& + \sigma(\text{ggH}) \times \text{Br}(H \to ZZ) \times \text{Br}(Z \to e^+e^-) \times \text{Br}(Z \to \mu^+\mu^-) \\
& + \sigma(\text{ggH}) \times \text{Br}(H \to ZZ) \times \text{Br}(Z \to \mu^+\mu^-) \times \text{Br}(Z \to e^+e^-)
\end{aligned}
$$

$$\downarrow$$

$$
\begin{aligned}
\sigma(\text{ggH} \to 4l) = {} & (44) \times (0.03) \times (0.1) \times (0.1) \\
& + (44) \times (0.03) \times (0.1) \times (0.1) \\
& + (44) \times (0.03) \times (0.1) \times (0.1) \\
& + (44) \times (0.03) \times (0.1) \times (0.1) \\
& = 0.0528pb = 52.8fb
\end{aligned}
$$

Note: 1 pico (10^{-12}) = 1000 femto (10^{-15})

$N = \mathcal{L}\sigma$

Expected Events produced:

- @7TeV, 52.8 x 5.1 ~ **270 events per second**
- @8TeV, 52.8 x 19.6 ~ **1100 events per second**
- @13TeV, 52.8 x 138 ~ **7300 events per second**

Experimental Consideration

nature

Explore content ⌄ About the journal ⌄ Publish with us ⌄

nature > articles > article

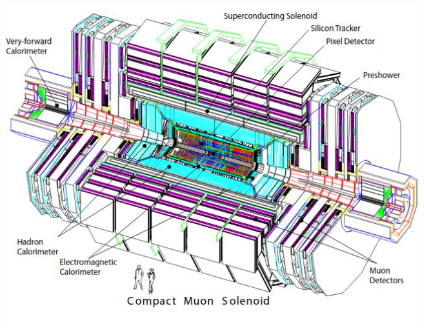
Article | Open Access | Published: 04 July 2022

A portrait of the Higgs boson by the CMS experiment ten years after the discovery

The CMS Collaboration

Nature **607**, 60–68 (2022) | Cite this article

Results!

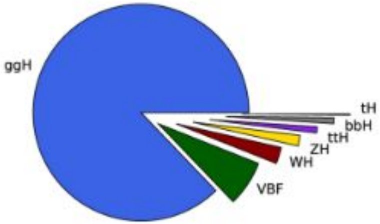


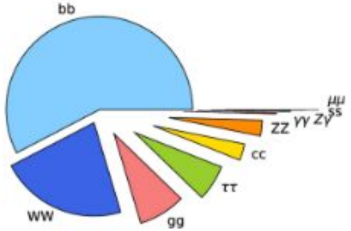
Flexing its mighty muscle!

As a guide to maximize signal sensitivity

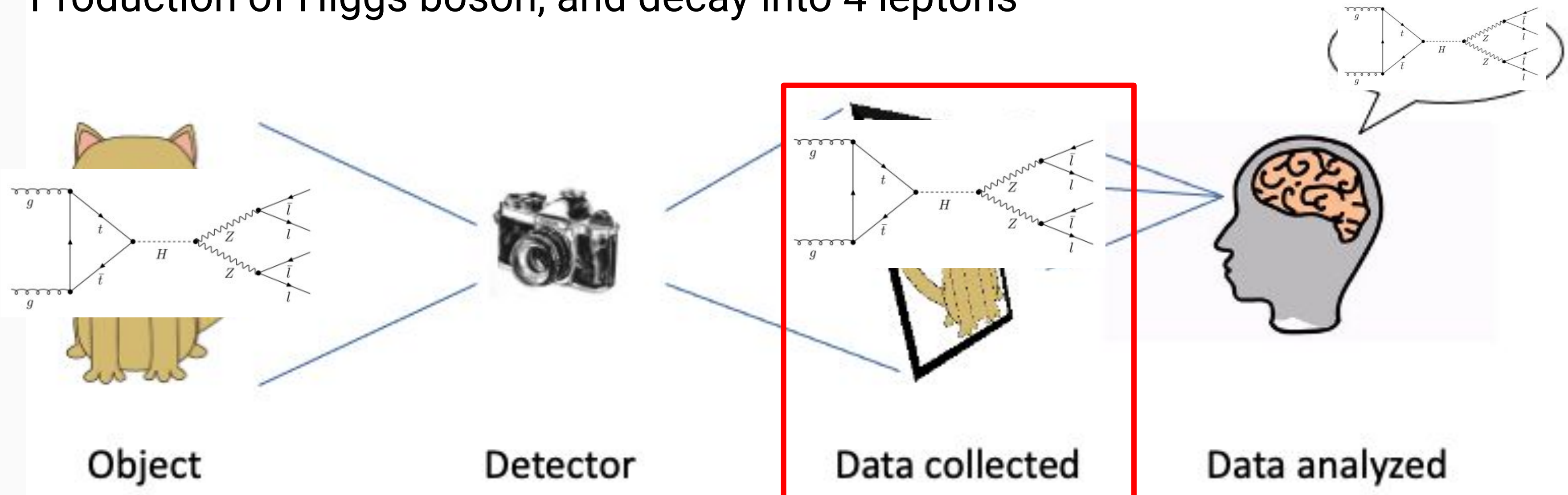
Extended Data Table 1 | The SM Higgs production cross-sections and branching fractions

Production mode	Cross section (pb)	Decay channel	Branching fraction (%)
ggH	48.31 ± 2.44	bb	57.63 ± 0.70
VBF	3.771 ± 0.807	WW	22.00 ± 0.33
WH	1.359 ± 0.028	gg	8.15 ± 0.42
ZH	0.877 ± 0.036	ττ	6.21 ± 0.09
ttH	0.503 ± 0.035	cc	2.86 ± 0.09
bbH	0.482 ± 0.097	ZZ	2.71 ± 0.04
tH	0.092 ± 0.008	γγ	0.227 ± 0.005
		Zγ	0.157 ± 0.009
		ss	0.025 ± 0.001
		μμ	0.0216 ± 0.0004





Production of Higgs boson, and decay into 4 leptons



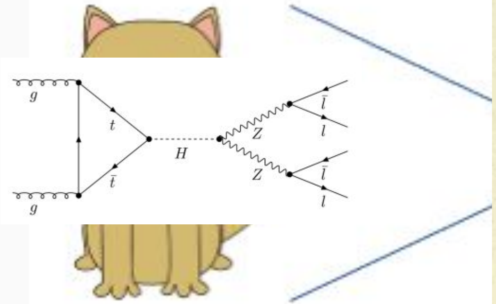
- Electrons
- Muons
- Photon
- Charged Hadrons
- Neutral Hadrons

- Tracker + ECAL
- Tracker + Muon Chambers
- ECAL
- Tracker + ECAL + HCAL
- HCAL

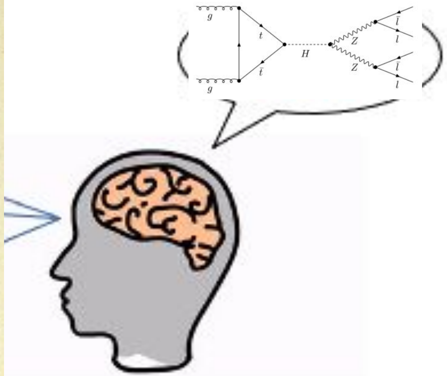
- Electrons
- Muons
- Photon
- Jets
- Jets

- Electrons 4 vector
- Muons 4 vector
- Photon 4 vector
- Jets 4 vector
- Jets 4 vector

Production of Higgs b



Object



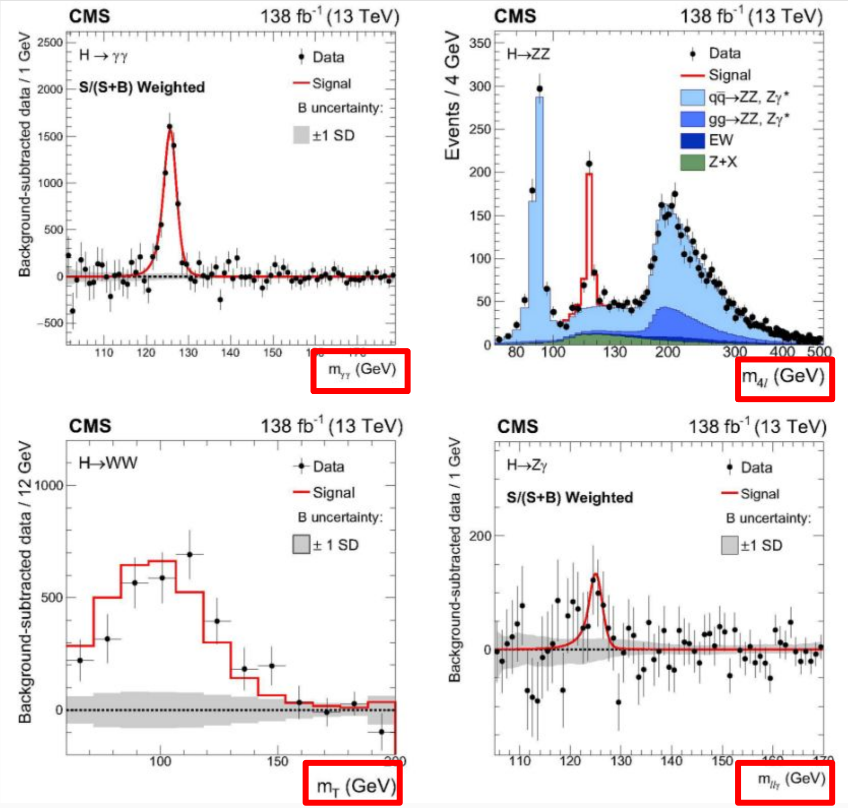
Data analyzed

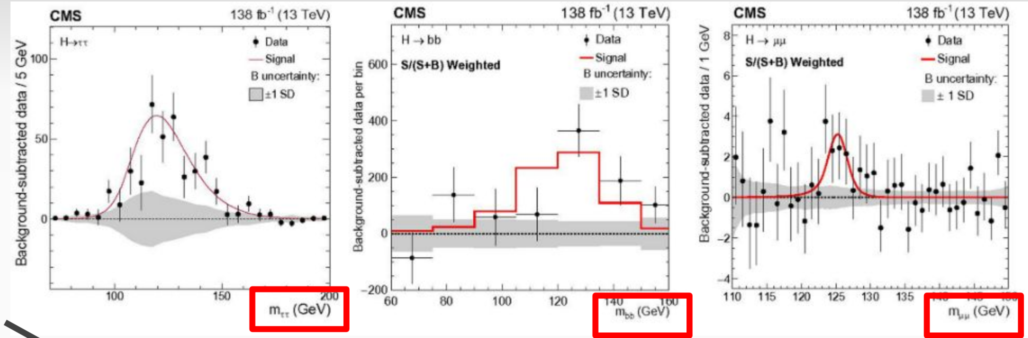
- Electrons
- Muons
- Charged Hadrons
- Neutral Hadrons

- Trac
- Trac
- Trac
- HCA

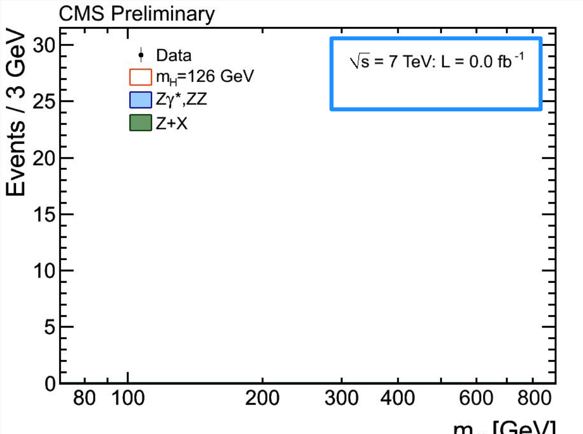
What is the acc and eff?
What is the signal significance?
How much is the false positive?
Many more…

Bump Search for Higgs boson





Legacy plot

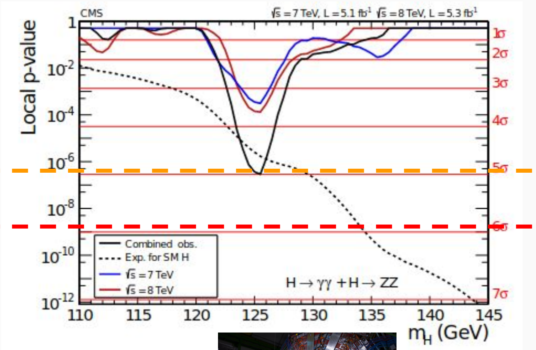


Searching for signal “bump” over background on **ALL decay channels**

M_{h} = 125.38 ± 0.14 GeV

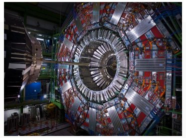
https://www.nature.com/articles/s41586-022-04892-x.pdf

Discovery Significance

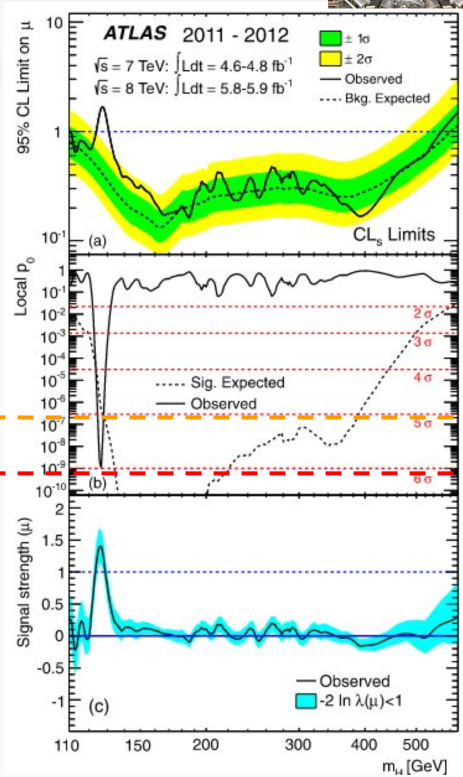


5σ mark!

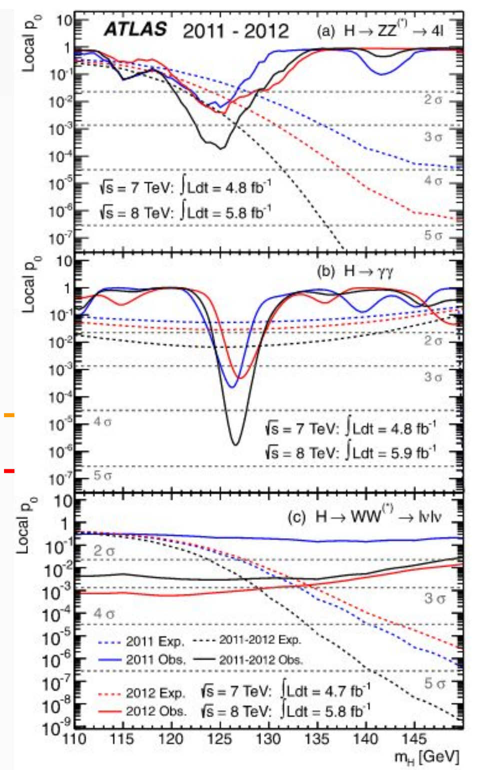
6σ mark!



Global significance



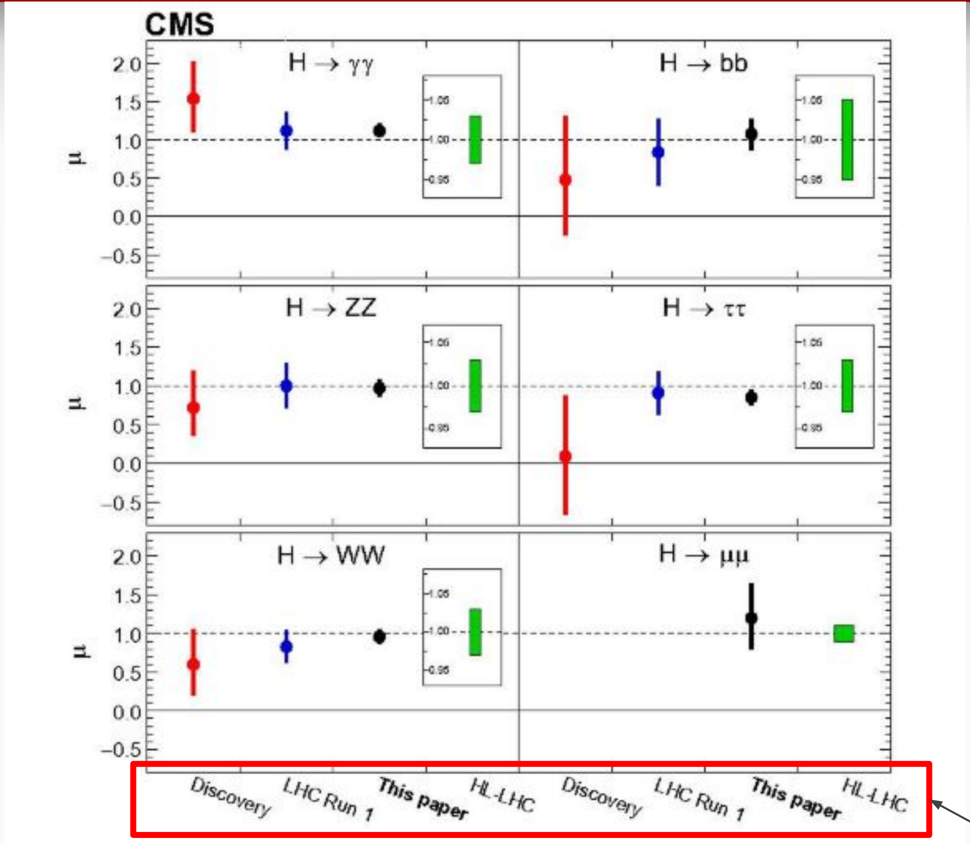
Golden Channels significance

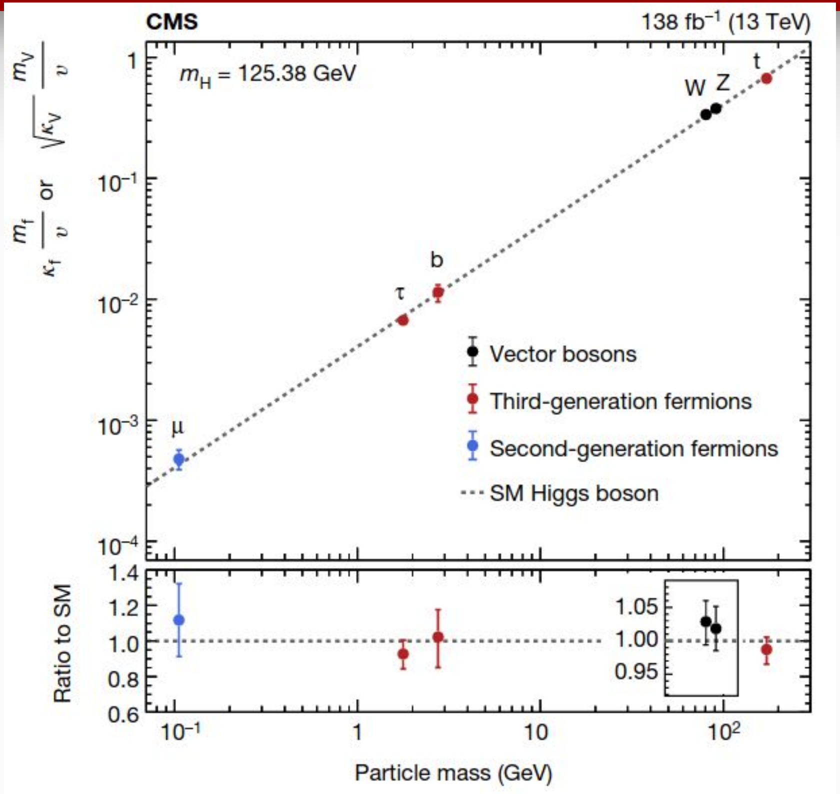


[5 sigma, whats that?]

https://www.sciencedirect.com/science/article/pii/S0370269312008581?via%3Dihub
https://www.sciencedirect.com/science/article/pii/S037026931200857X

Precision Measurement



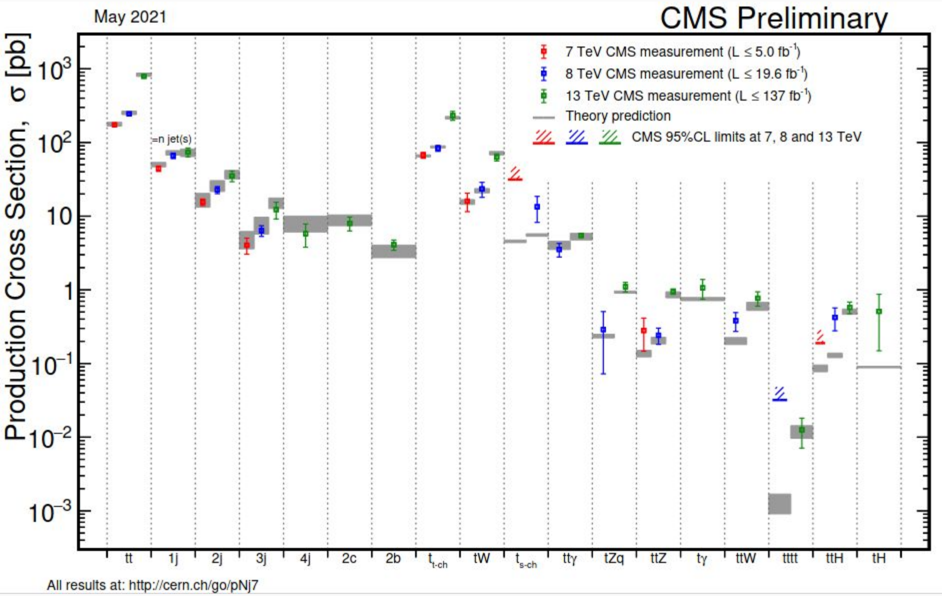


Exactly 1 decade ago!!

https://www.nature.com/articles/s41586-022-04892-x.pdf

Measurement on signal strength and yukawa coupling(s)

Diverse physics and training program at CMS experiment



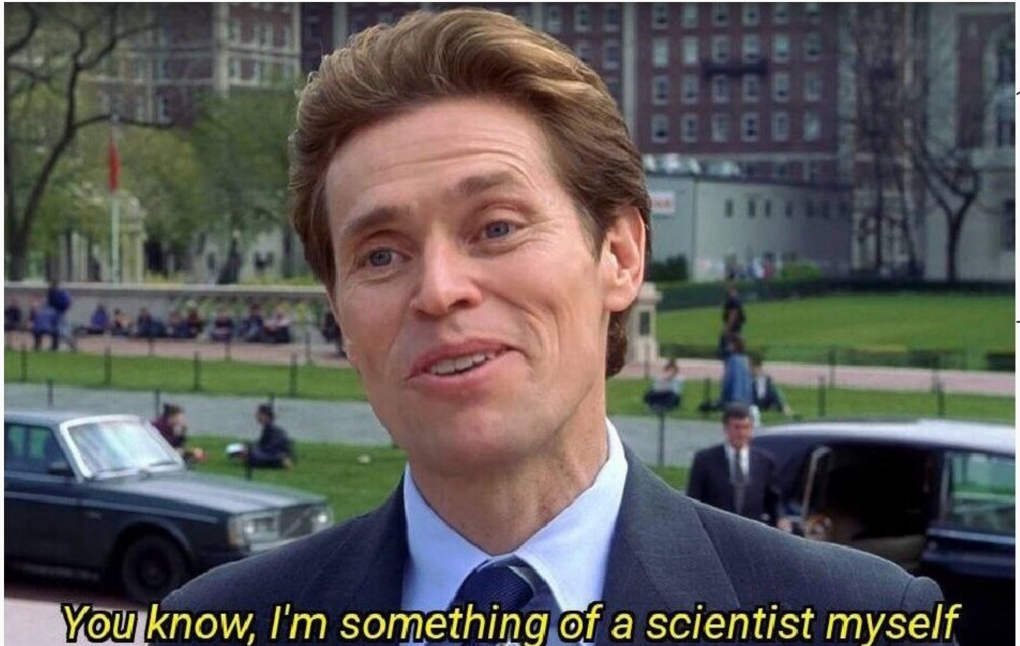
CMS is a general-purpose experiment with sub-groups producing results for many different topics including:

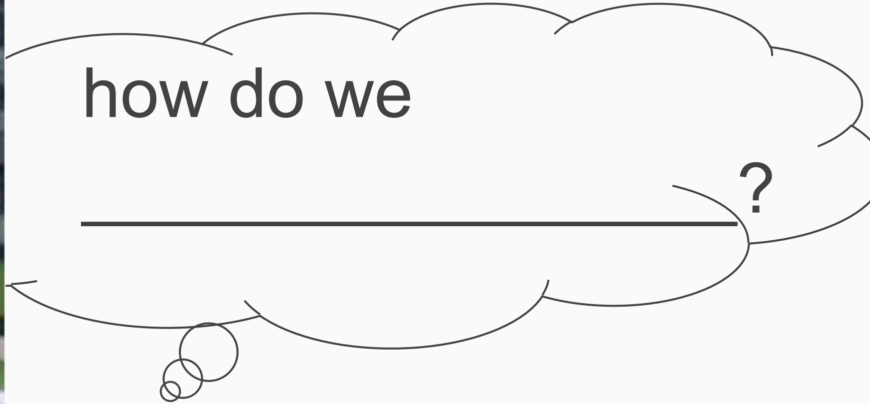
- Forward and Small-x QCD Physics
- B Physics and Quarkonia
- Standard Model Physics (Vector Bosons & Jets)
- Top Physics
- Higgs Physics
- Supersymmetry
- Exotica
- Beyond 2 Generations
- Heavy-Ion Physics

CMS public results

HSF Training

Great! We are ready to go! I mean to collide protons and produce a lot of data! To detect the particle! To observe the reconstructed particles in the detector! To study the collision data! But…

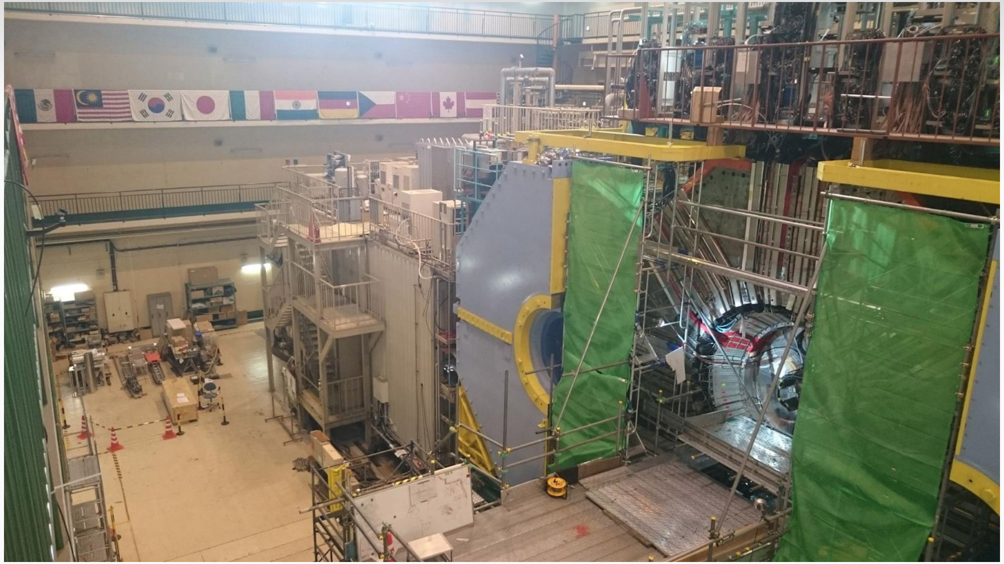


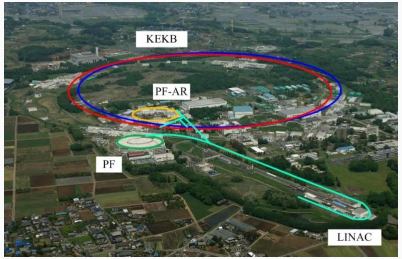


Overview

- Colliders and LHC
- Detectors
- Object reconstruction
- Analysing the collision data
- **Closing**

HEP International Collaboration





The CMS Collaboration

3103	1031	269	241	54
PHYSICISTS (1050 STUDENTS)	ENGINEERS	TECHNICIANS	INSTITUTES	COUNTRIES & REGIONS

The CMS Experiment

The Details

The CMS collaboration has around:

5494

ACTIVE PEOPLE
(PHYSICISTS, ENGINEERS, TECHNICAL, ADMINISTRATIVE, STUDENTS, ETC.)

Of these members there are about:

2053	1050	1031	978
PHD PHYSICISTS (1689 MEN, 364 WOMEN)	PHYSICS DOCTORAL STUDENTS (792 MEN, 258 WOMEN)	ENGINEERS (895 MEN, 136 WOMEN)	UNDERGRADUATES (708 MEN, 270 WOMEN)

* The above categories are, by definition, non-overlapping

** As of February 2022

Further reading

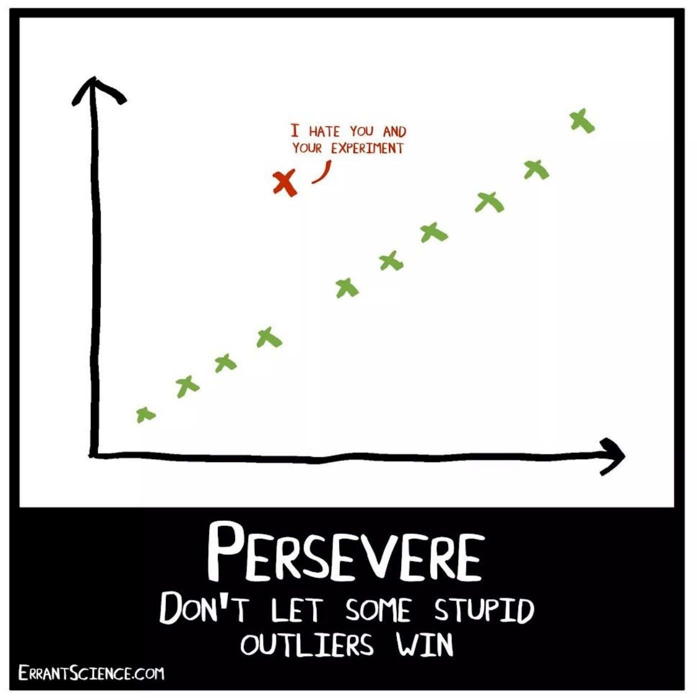
Malaysian Institution Participation in HEP

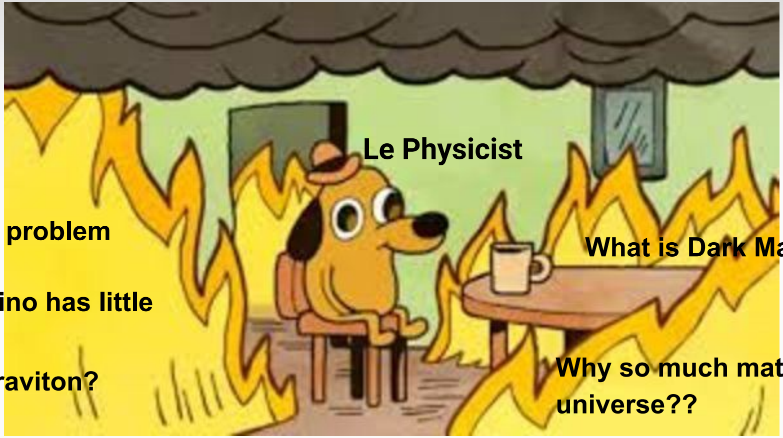
Notable mentioned

Dr. Imran yusuff
Dr. Hoh Siew Yan

As I have known of...

Closing





Le Physicist

Hierarchy problem

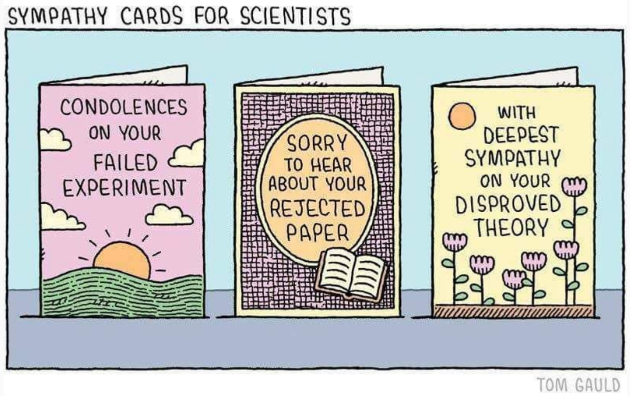
Why neutrino has little mass?

Is there a graviton?

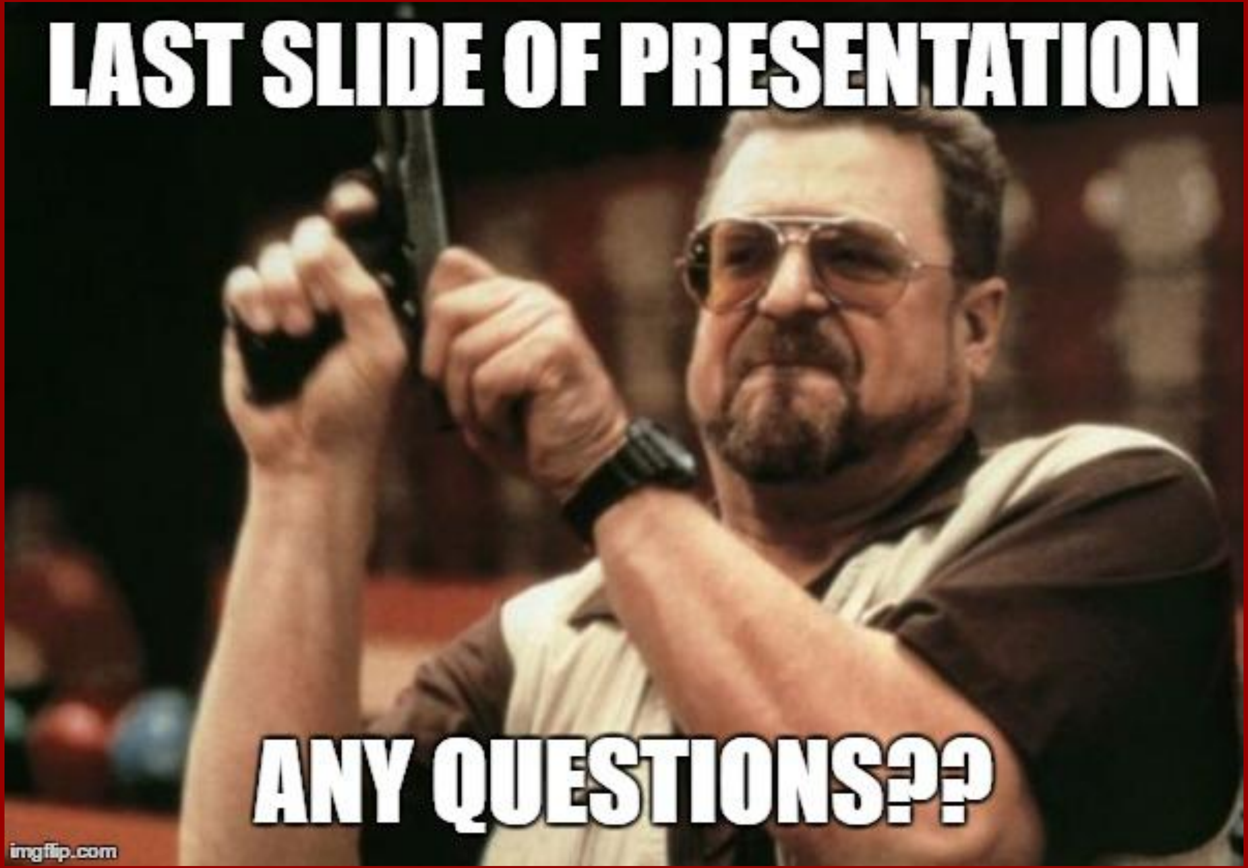
What is Dark Matter??

Why so much matter in the universe??

We LOVE OUTLINE!!! Hints of New Physics!!



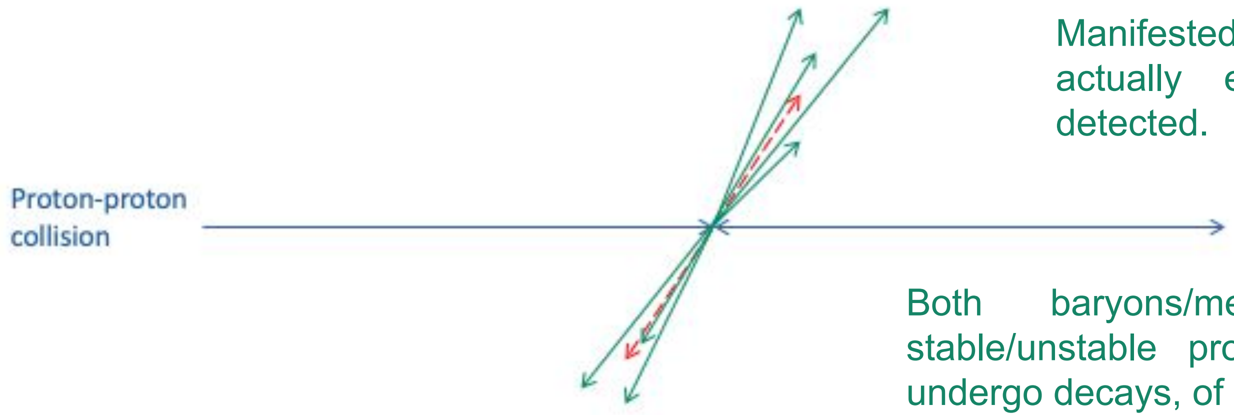
2012 gave us Higgs boson! →



Thank you for your attention!!

Backup

Jets

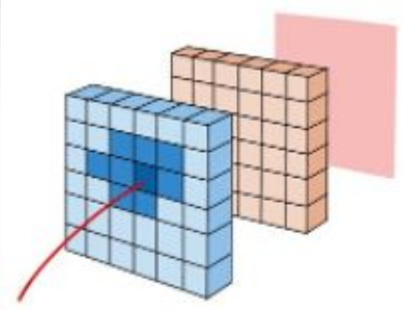


Manifested hadrons are what actually escape, and will be detected.

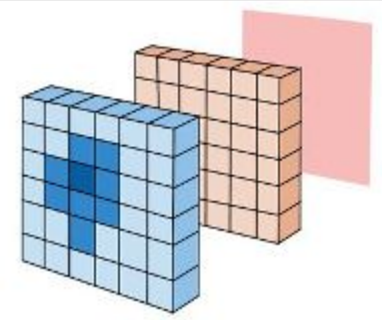
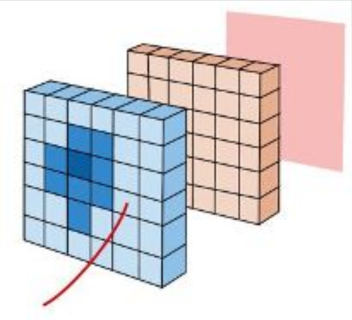
Both baryons/mesons produced, both stable/unstable produced. Unstable hadrons undergo decays, of course.
(Different ways to hadronise 'same' initial state)

- Recall that 'colored' particles produce hadrons.
- These hadrons will travel together, and we would like to combine them into a single unit, called a jet.
- We want the jet properties (4-vector) to correlate well with the properties of the initial colored particle that gave rise to the jet.

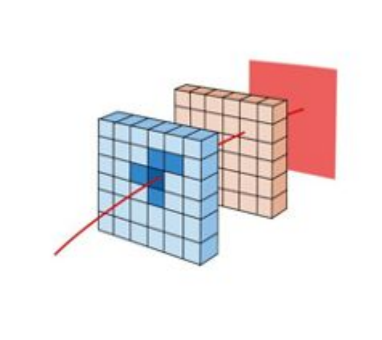
Lepton: Electron, Photon and Muon



- A track matches a calorimeter cluster
- Energy/Momentum close to 1
- Negligible HCAL deposit
- Shape of shower as expected
- Isolated

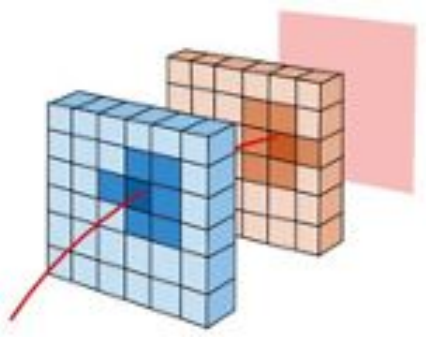



- No track matches deposit
- Energy/Momentum close to 1
- Negligible HCAL deposit
- Shape of shower as expected
- Isolated

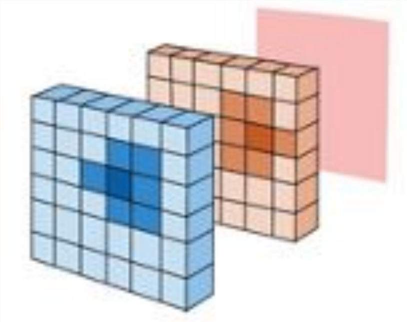


- No track matches deposit
- Energy/Momentum close to 1
- Negligible HCAL deposit
- Tranverse outermost muon chamber
- Isolated

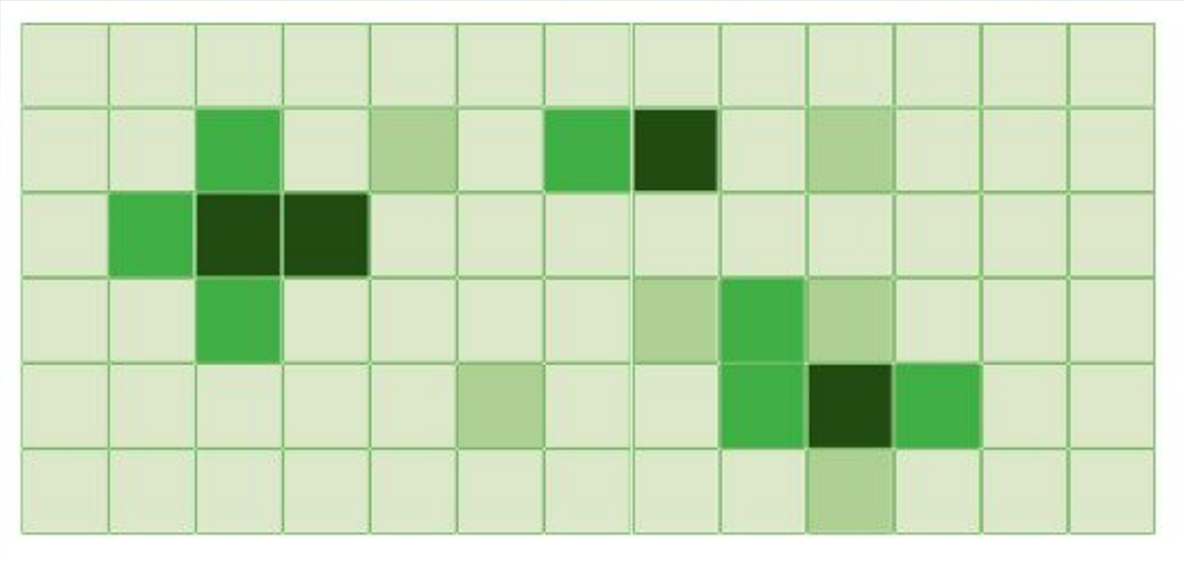
Jet clustering



Charged hadron

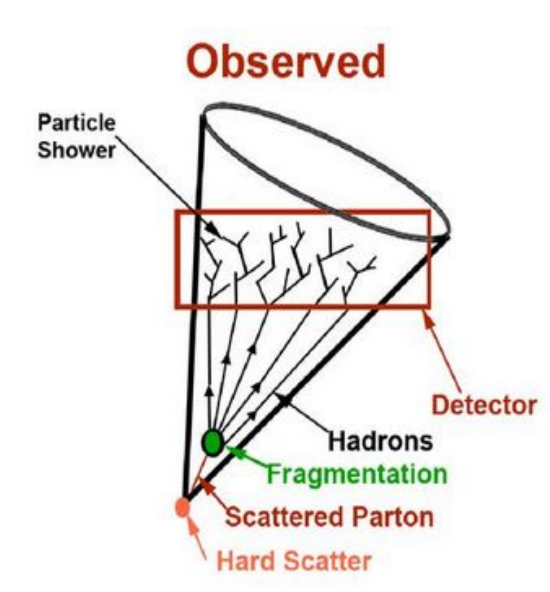


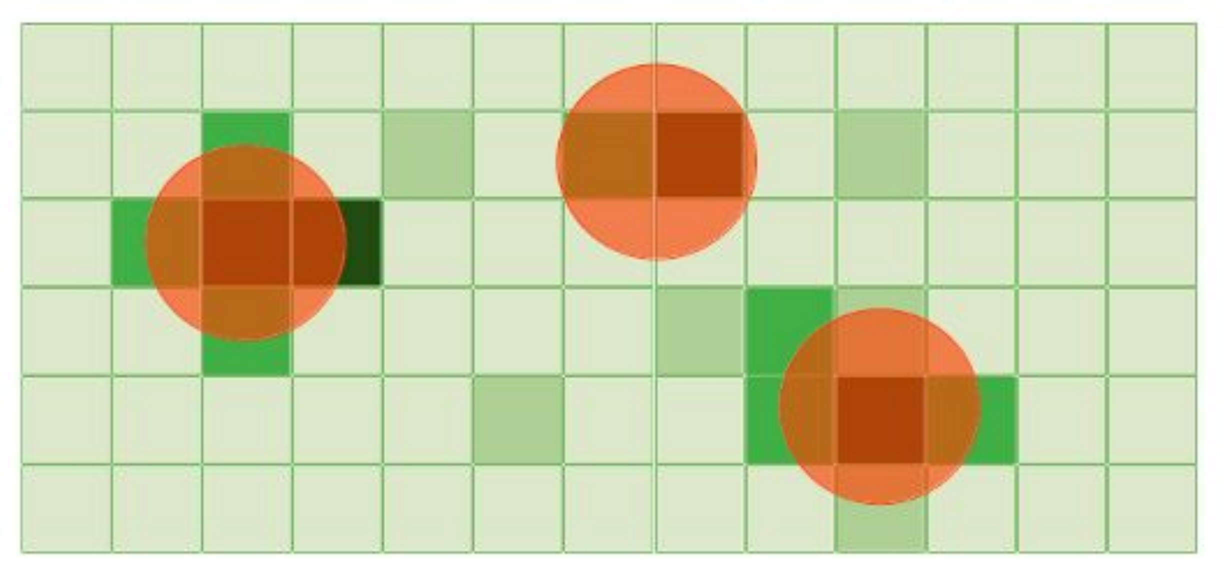
Neutral hadron



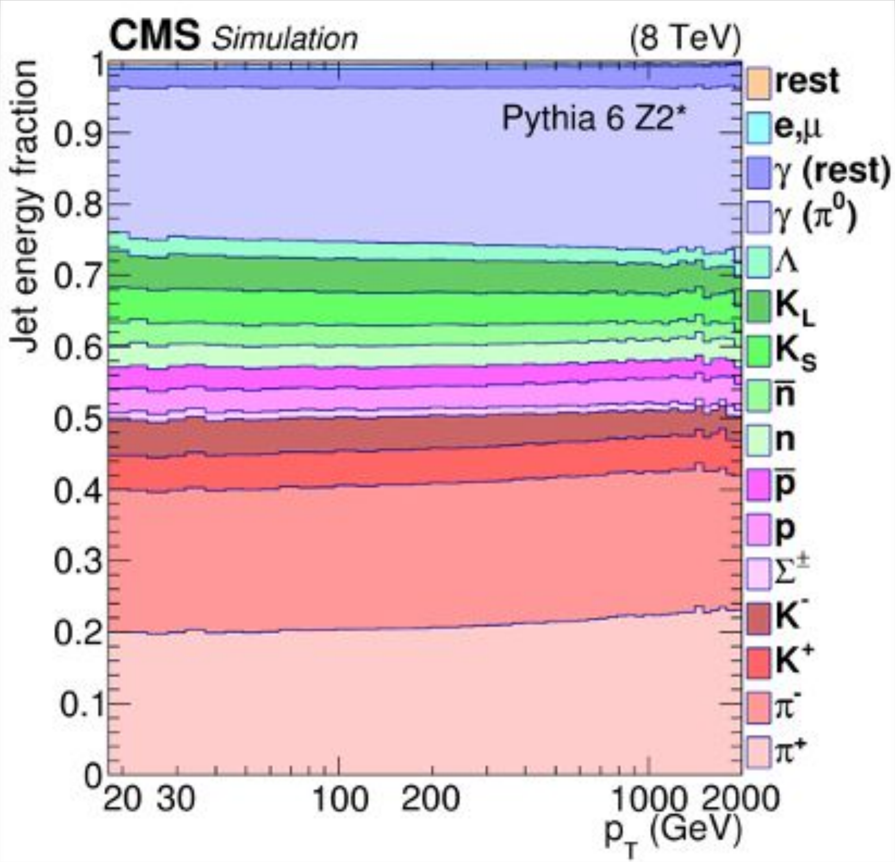
- The Jet clustering algorithm runs on the objects we give it (such as calorimeter towers).
- It merges objects together, until we end up with one logical objects (i.e. a single 4-vector)

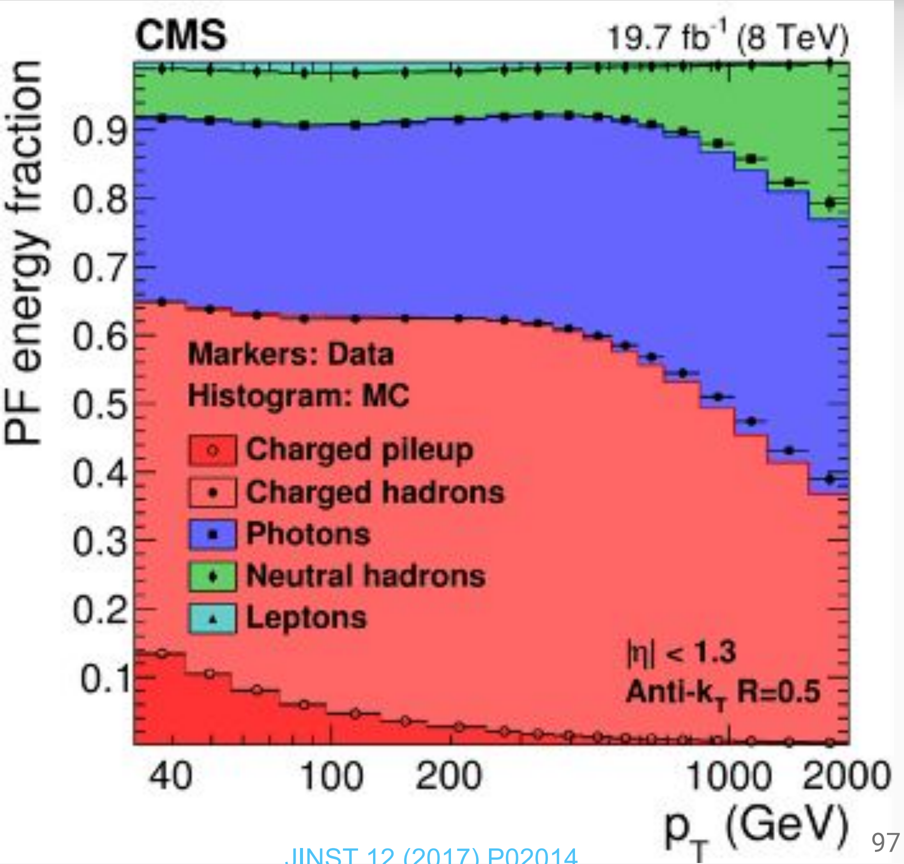
Jet clustering





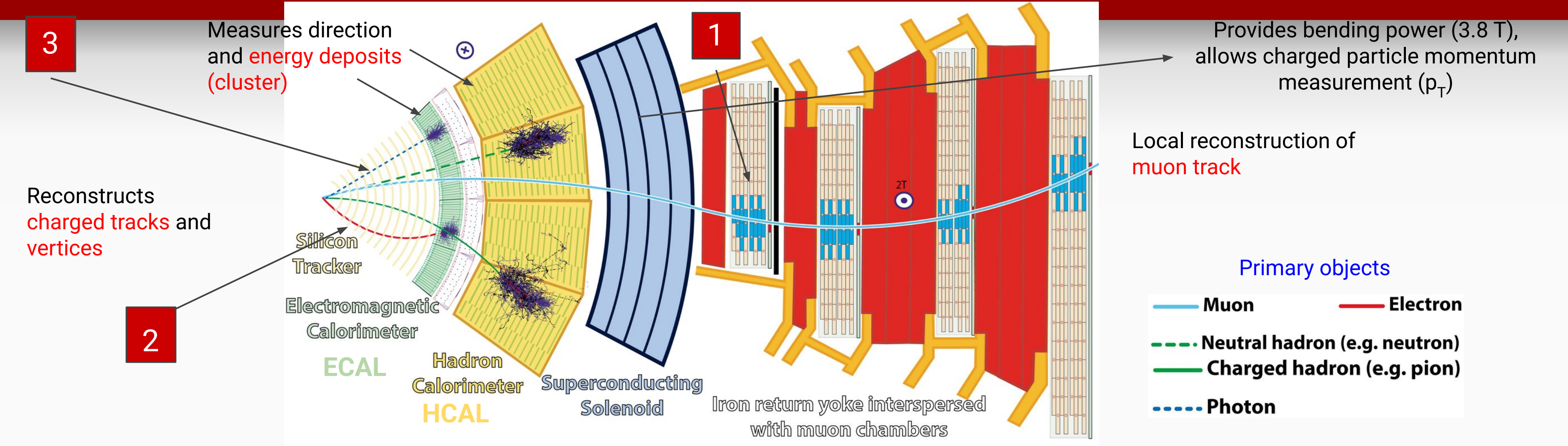
What are jets made of?





JINST 12 (2017) P02014

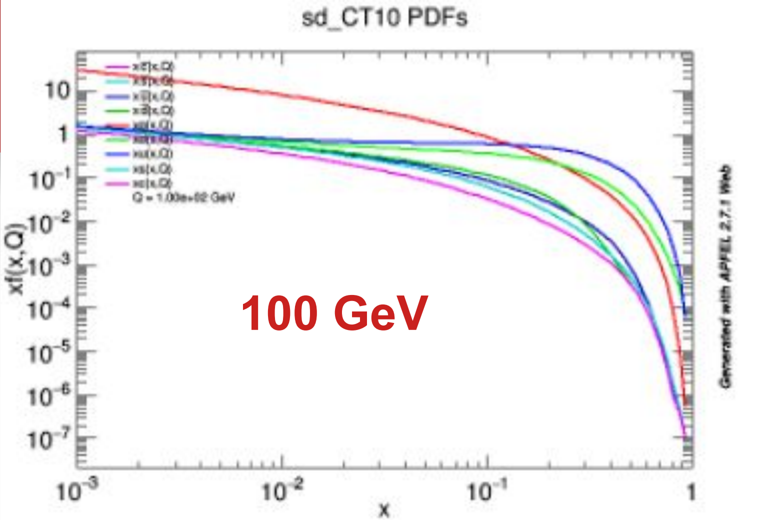
Physics Object Reconstruction

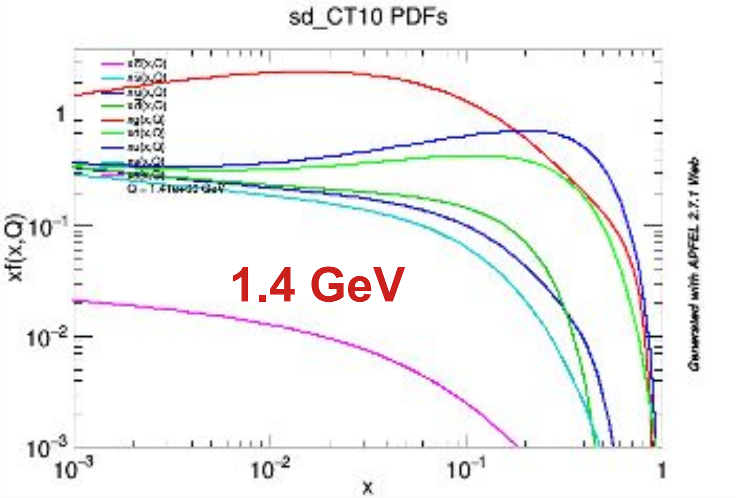


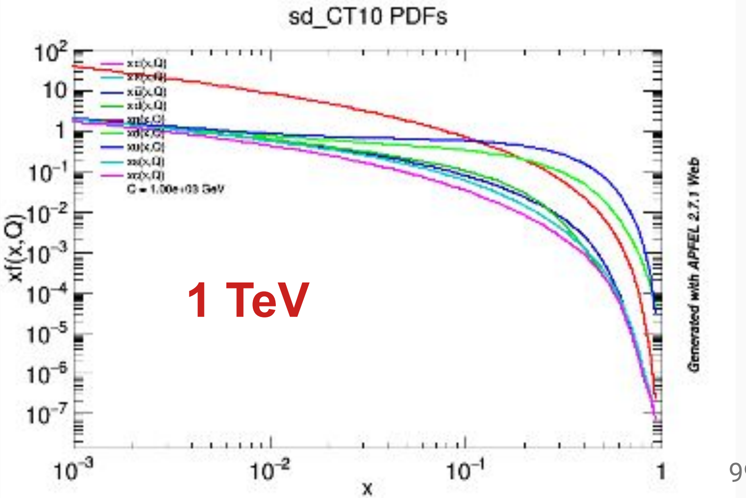
- Particle Flow (PF) algorithm uses basic elements from various sub-detectors to provide best reconstruction of the primary objects:
  1. Muon tracks are matched to tracks in inner tracker.
  2. Remaining inner tracker's tracks associated with energy deposits in ECAL (electron) and HCAL (charged hadrons).
  3. Remaining energy deposits are likely from neutral sources, ECAL (photons) and HCAL (neutral hadrons).

Parton Distribution Functions

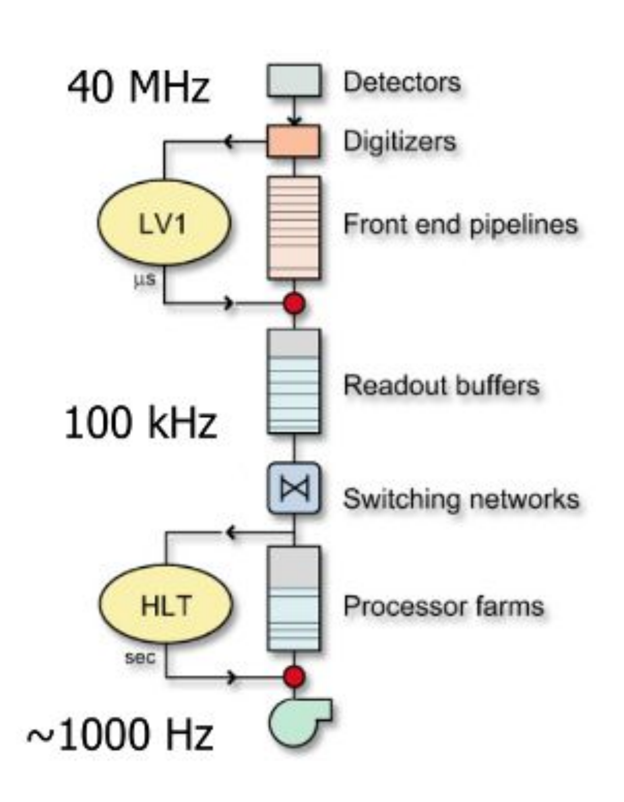
When a pair of protons interact, it could easily be gluon from one and strange quark from another. This information is quantified in parton distribution functions (PDFs).





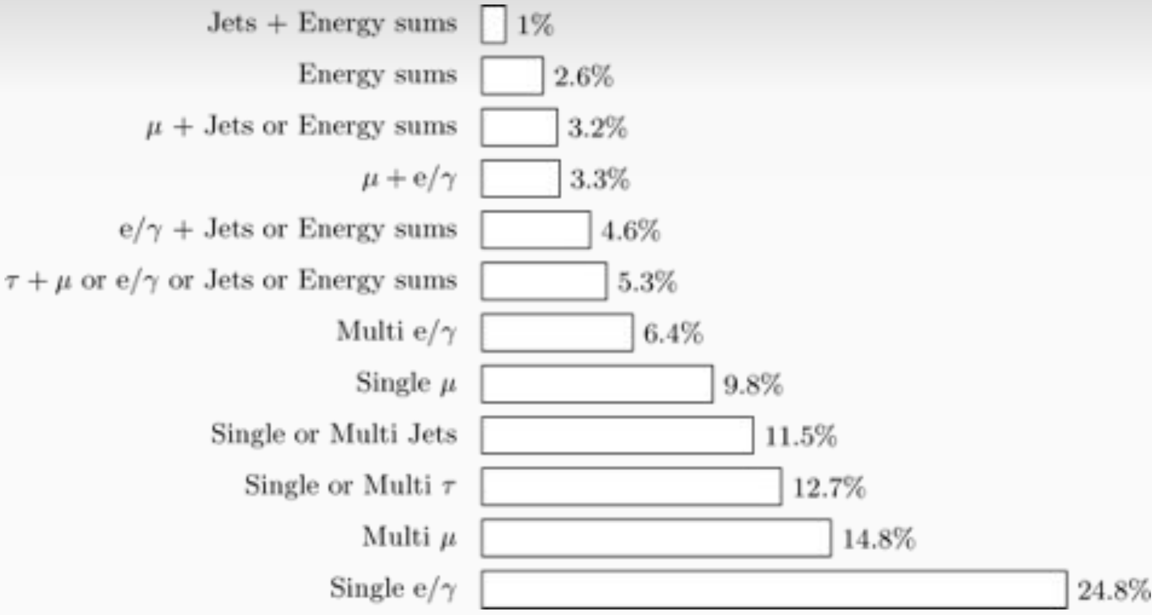


CMS trigger design



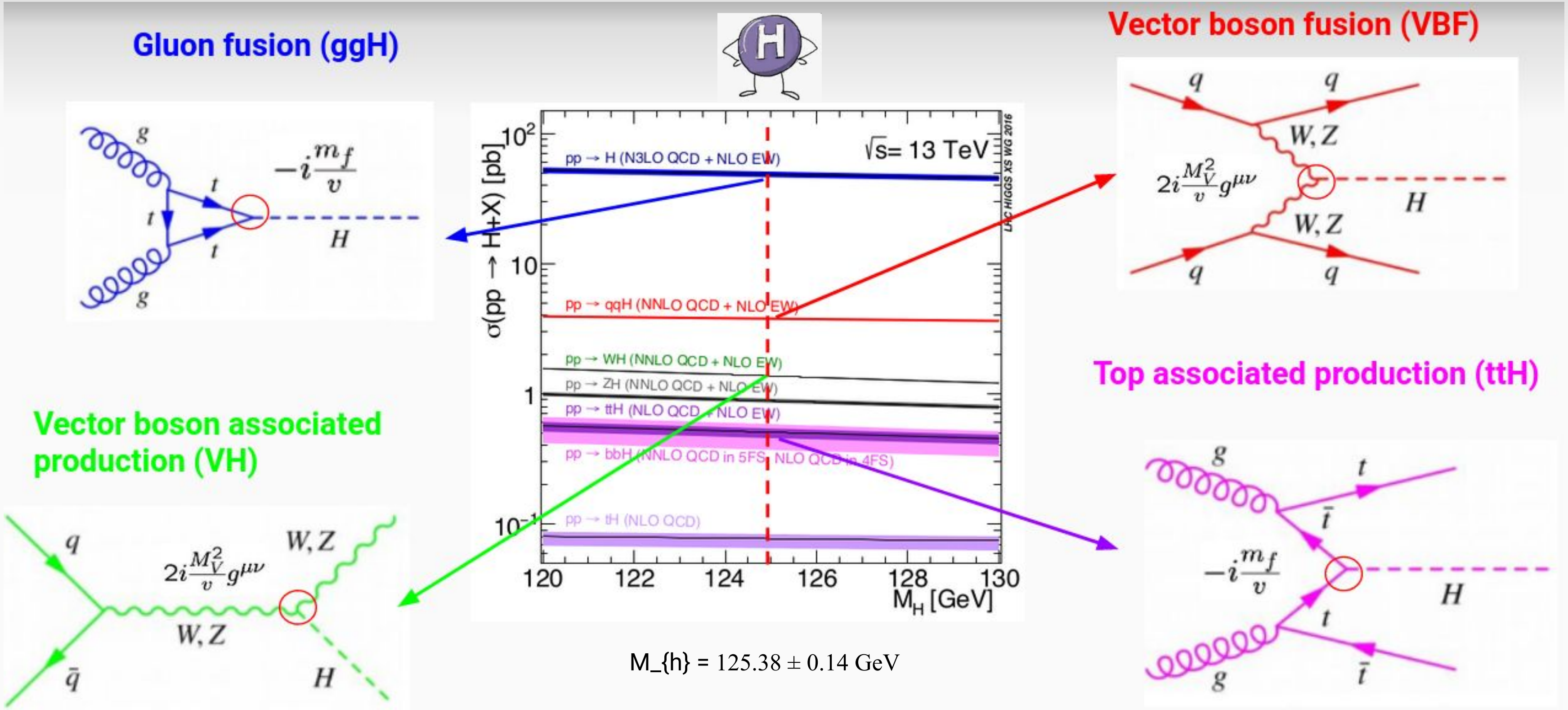
LV1 is hardware based

HLT is software based



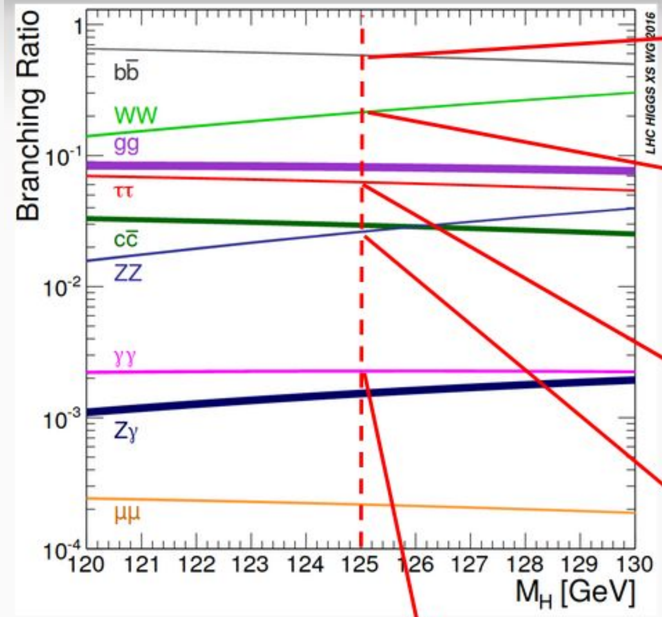
Fractions of the 100 kHz rate allocation for single and multi-object triggers and cross triggers in a typical CMS physics menu during Run 2.

Higgs Production at LHC



M_{h} = 125.38 ± 0.14 GeV

Higgs Decay at LHC



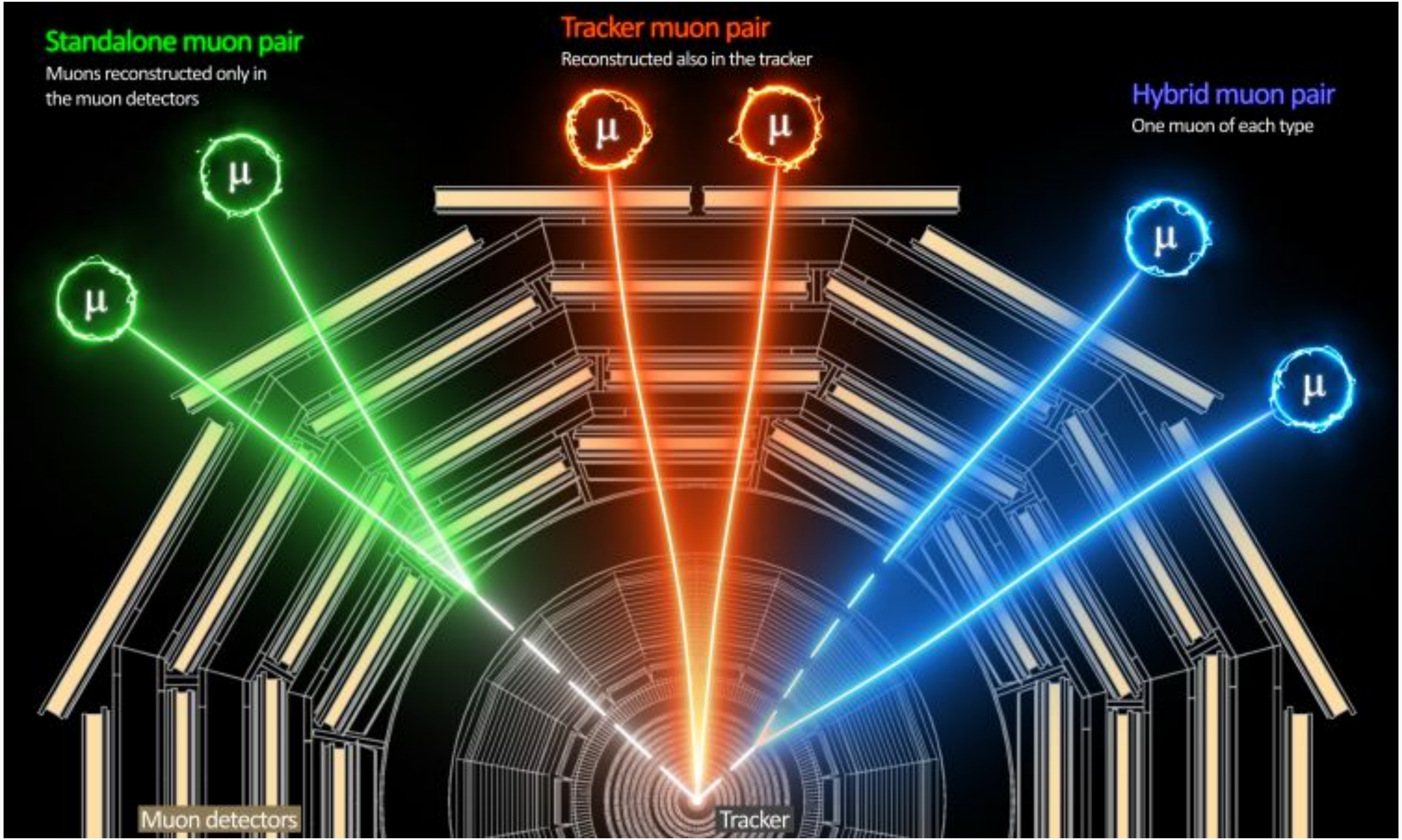
H → bb (~ 60%)
- Largest signal yield
- Large QCD background

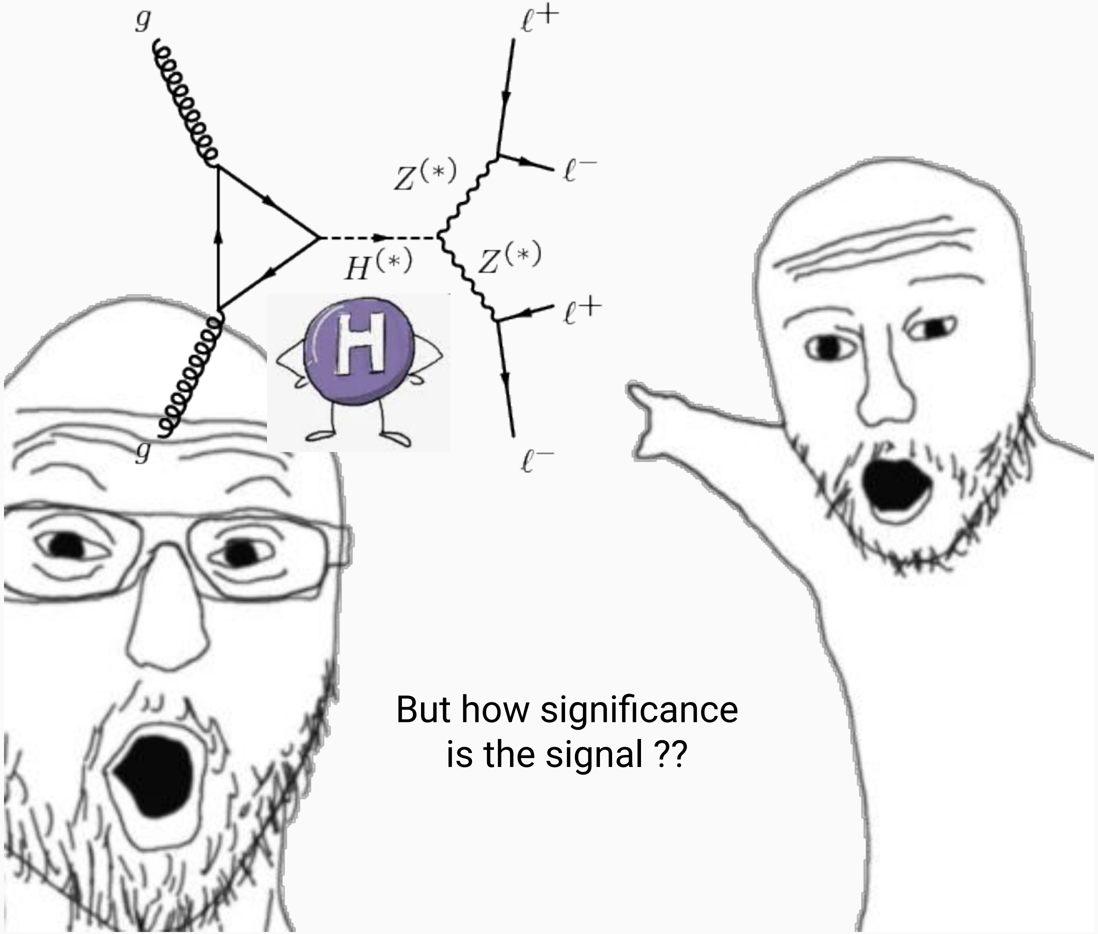
H → WW* (~ 22%)
- Large signal yield
- Clean experimental signature in WW → 2l2v final state.
- Poor Higgs mass resolution (~20%)

H → ττ (~ 6%)
- Largest leptonic decay
- Reduced background compared to H → bb

H → ZZ* (~ 3% GOLDEN]
- Small backgrounds in the 4l final state
- Good Higgs mass resolution

H → γγ (~0.1%) [GOLDEN]
- Substantial QCD backgrounds
- Good Higgs mass resolution


Standalone muon pair
Muons reconstructed only in the muon detectors
Tracker muon pair
Reconstructed also in the tracker
Hybrid muon pair
One muon of each type
μ
μ
μ
μ
μ
μ
Muon detectors
Tracker


g
g
$H^{(*)}$
$Z^{(*)}$
$Z^{(*)}$
ℓ^+
ℓ^-
ℓ^+
ℓ^-
But how significance
is the signal ??