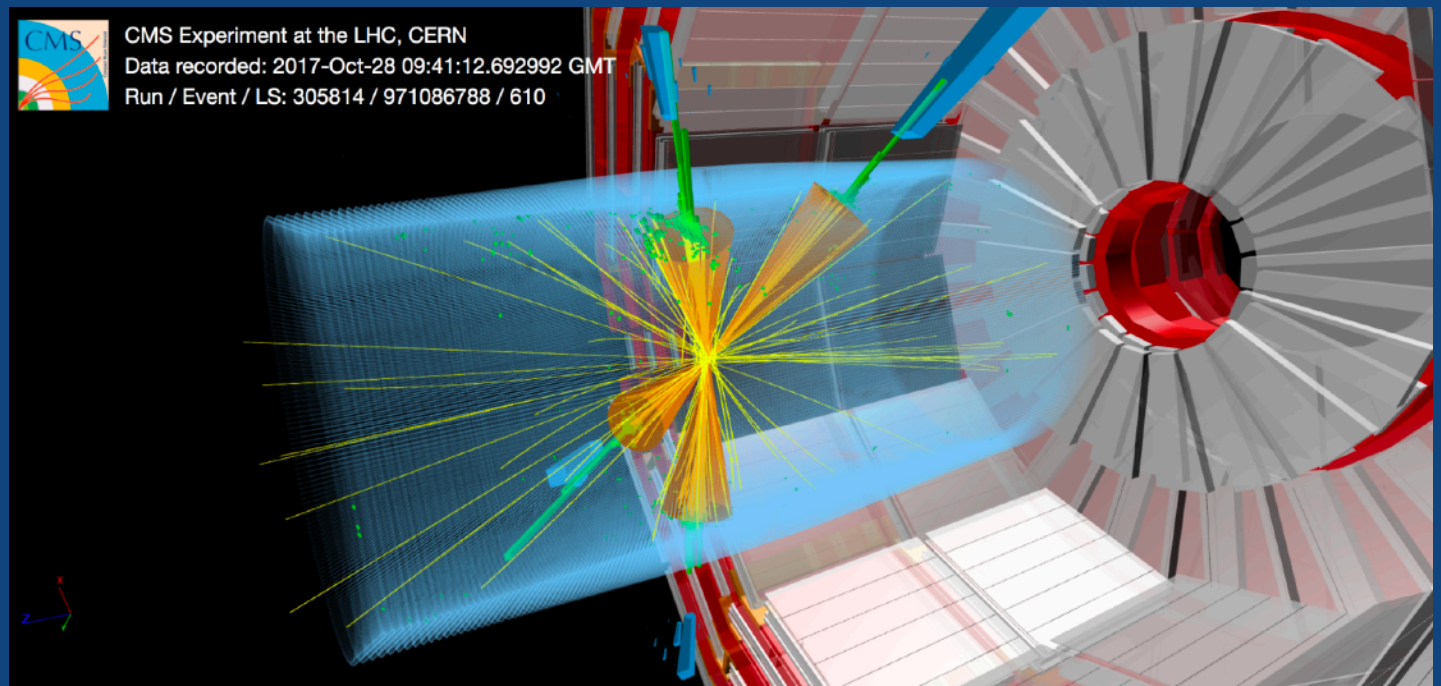
402-0703-00L

# Phenomenology of Physics Beyond the Standard Model

## Introduction - Part 1

Annapaola de Cosa adecosa@phys.ethz.ch
Michael Spira michael.spira@psi.ch



# Who are we



Annapaola de Cosa

https://decosa-group.ethz.ch/

Experimental aspects



Michael Spira

https://www.psi.ch/en/ltp-theory/people/michael-jens-spira

Theoretical concepts



Roberto Seidita

https://decosa-group.ethz.ch/

Exercises

# Course Program

What's the objective of this course? Introduce you to the quest for new physics beyond the standard model (BSM)

- 19. Feb : **Introduction** Part 1 by A. de Cosa and Part 2 by M. Spira
- 26. Feb: **Standard Model** by M. Spira
- 05. Mar: **GUT** by M. Spira
- 12. Mar: **Supersymmetry** Part 1 by M. Spira
- 19. Mar: **Supersymmetry** Part 2 by M. Spira
- 26. Mar: **SUSY Standard Model** by M. Spira
- 02. Apr: **SUSY-GUT** by M. Spira
- 09. Apr : **SUSY and SUSY Higgs Phenomenology** by M. Spira
- 16. Apr : **Sparticle Search and R-Parity Violation** by A. de Cosa
- 30. Apr : **MSSM Higgs Bosons Search** by A. de Cosa
- 07. May: **Supersymmetric Dark Matter** by M. Spira
- 14. May: **Dark Matter Searches** by A. de Cosa
- 21. May: **Experimental Strategies for BSM Searches** by A. de Cosa
- 28. May: **Hidden Valley Theory** by M. Spira and Search by A. de Cosa

# General Informations

- Lectures: Wednesday 12:45 - 14:30
- Exercises: Wednesday 14:45 - 15:30
    - 1st exercise class will take place on the **28th of February**

- Zoom connection details for remote attendance:
    - https://ethz.zoom.us/j/3257445413 (M. Spira)
    - https://ethz.zoom.us/j/4269248676 (A. de Cosa)
    - https://ethz.zoom.us/j/65507019273 (R.Seidita - exercises)

- Examination: Oral exam 20 mins

**Course schedule and course material can be found at:**
http://ihp-lx2.ethz.ch/JenseitsSM/Vorlesung.html

# Outline of this lecture (Intro Part 1)

- Why going beyond the standard model (BSM)?
  - The SM of particle physics and its limitations
- Where can we go BSM?
  - Vast landscape of theoretical models proposing new physics to address SM open questions
- How can we go BSM?
  - Particle collider experiments

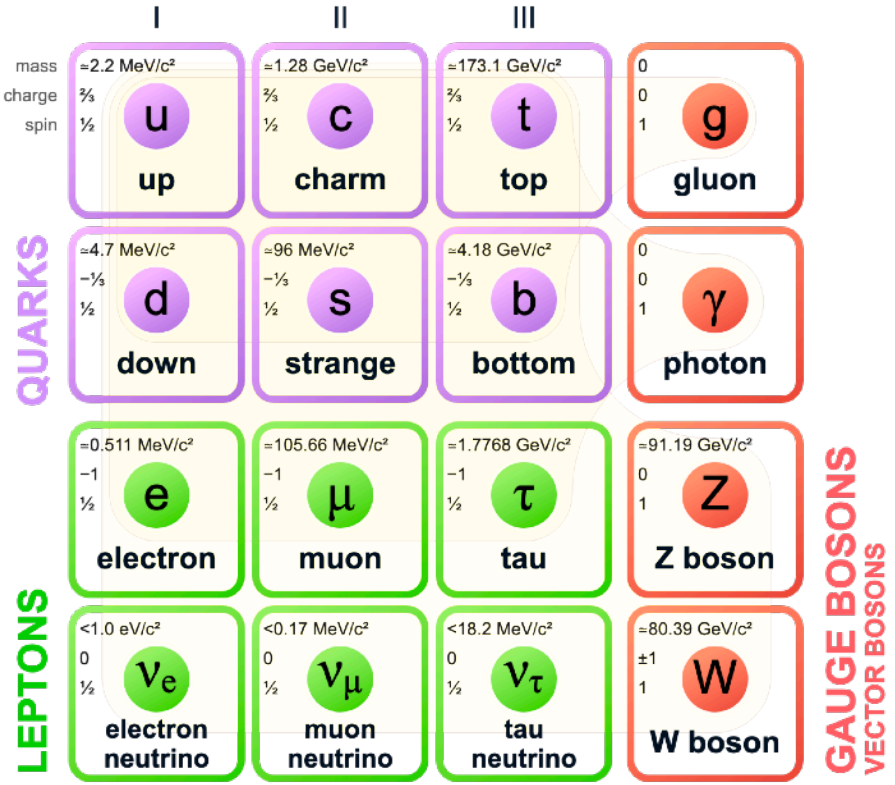
# The SM of particle physics

The SM of particle physics describes all the visible matter in the Universe and its dynamics in terms of elementary particles and fundamental interactions

12 matter fields (quarks and leptons) and corresponding anti-particles (fermions, spin=1/2)

Matter particles come in three generations with increasing masses. Why 3 families?

Gauge fields (spin 1, bosons) responsible for the interactions between particles (dynamics).

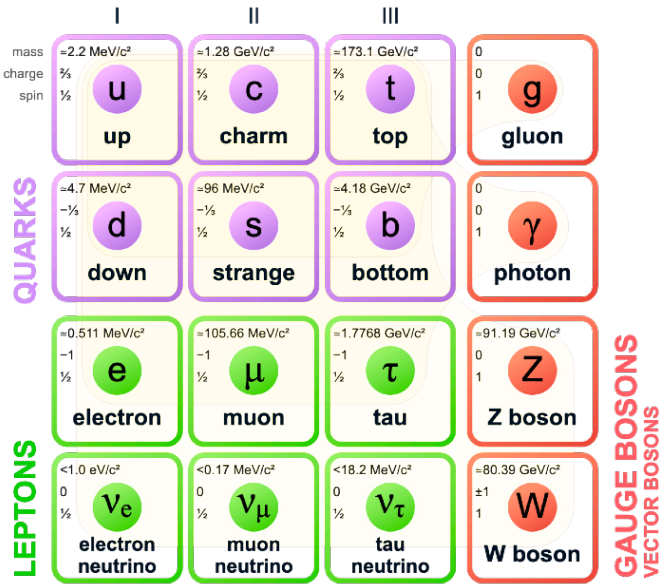


# The SM of particle physics

$$SU(3) \otimes SU(2) \otimes U(1)$$

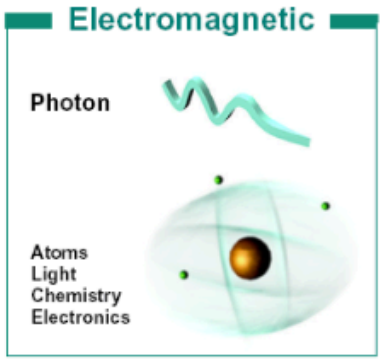
Strong interaction — Electroweak interaction

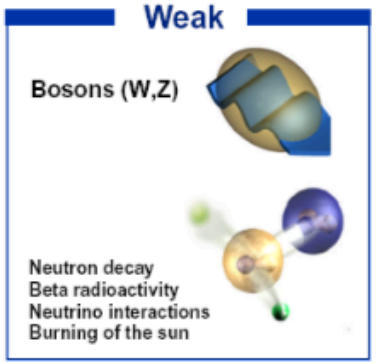
Standard Model (SM) describes the fundamental laws of the Universe in terms of only few parameters (i.e. 19+7=26)

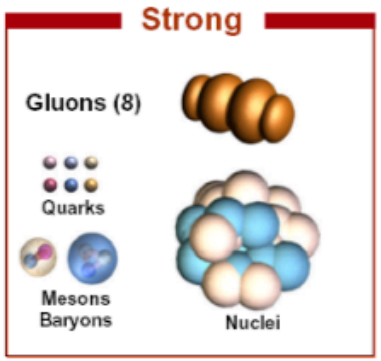


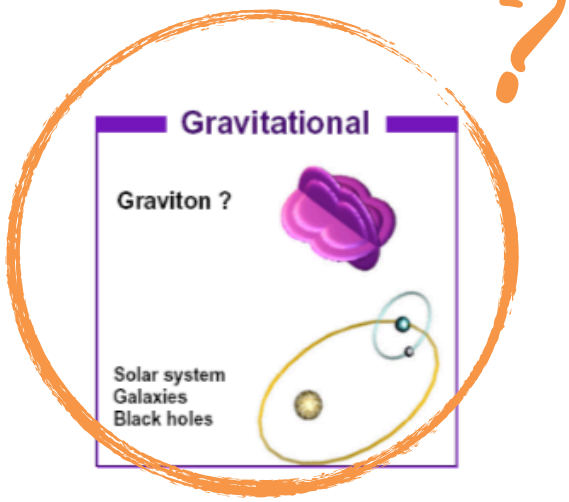

3 out of 4 interactions are described in the Standard Model of Particle Physics

What about Gravity?



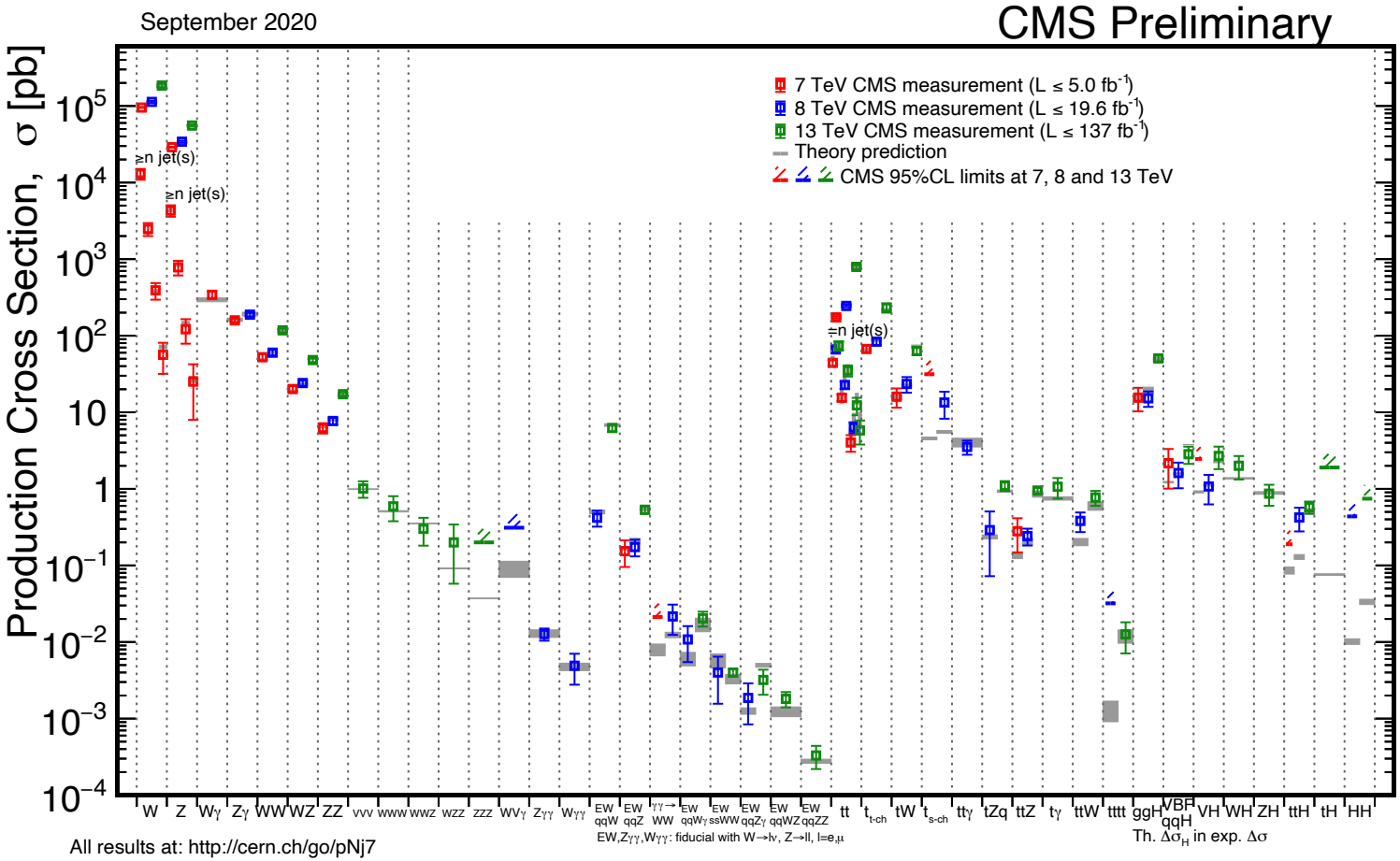



# Tests of SM predictions

## High precision measurements confirm SM predictions




SM processes spanning several orders of magnitude in cross-section

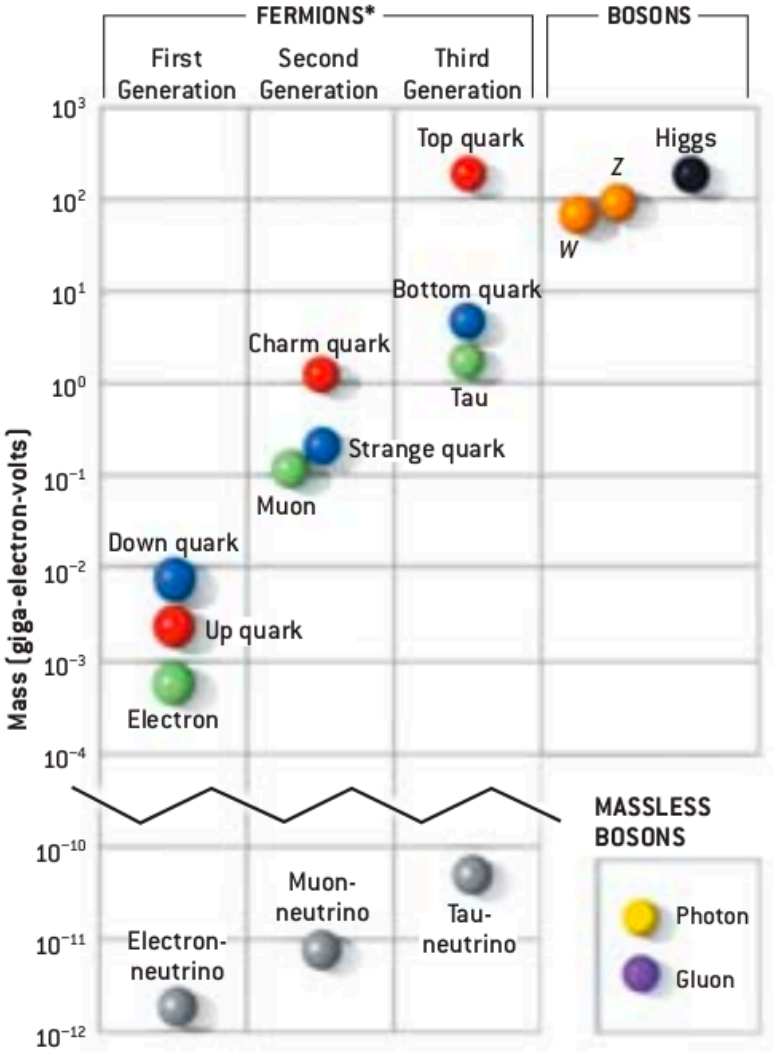
# Tests of SM predictions

High precision measurements confirm SM predictions

SM assumes all particles being intrinsically massless. Direct introduction of mass terms would ruin gauge invariance.

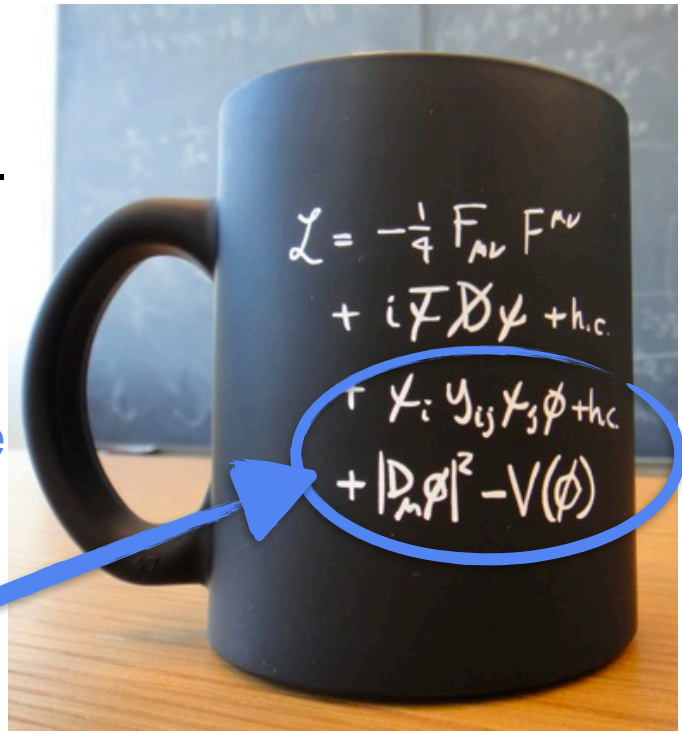
Then, how can we explain that fundamental particles have mass (with the exception of photon and gluons)?

What is the origin of particle masses? Why particle masses are so far apart?



# What about particle masses ?

A solution to the mass problem was proposed independently by Francois Englert, Robert Brout and Peter Higgs in 60'.

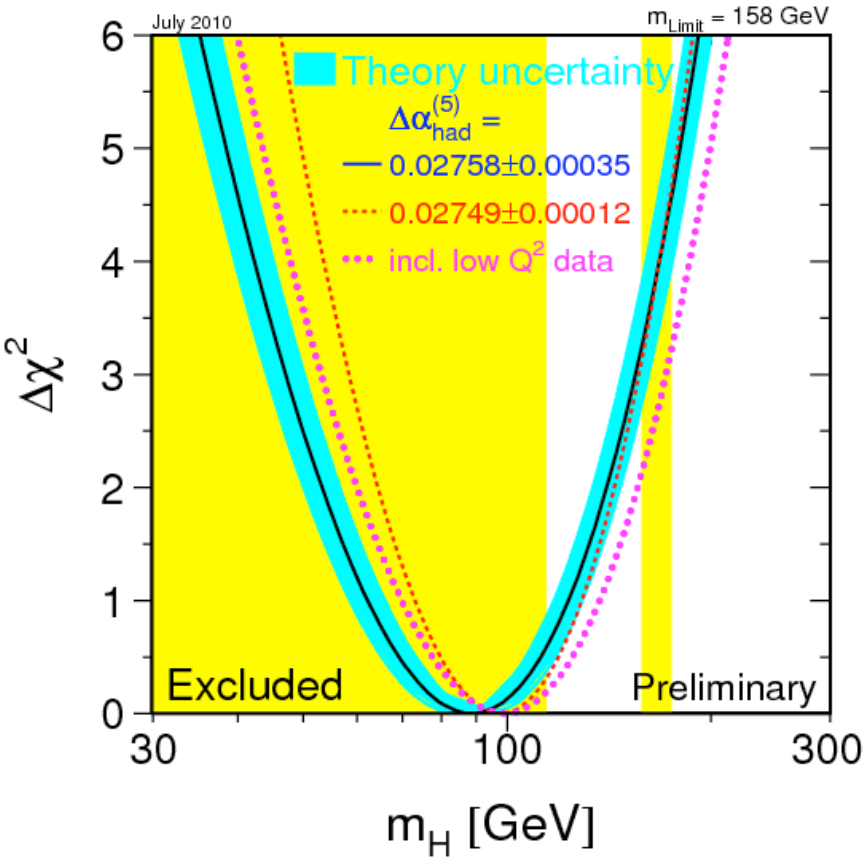



They postulated the existence of a scalar field, and hypothesised that particles acquire mass by interacting with this field, of which the Higgs boson (spin 0) is the quantum

Particle mass is proportional to the interaction strength (i.e to the couplings to the Higgs field)

# The hunt for the Higgs boson

- The hunt for the Higgs boson started with LEP accelerator and proceeded with Tevatron




https://inspirehep.net/record/880855/

Constraints from direct searches:

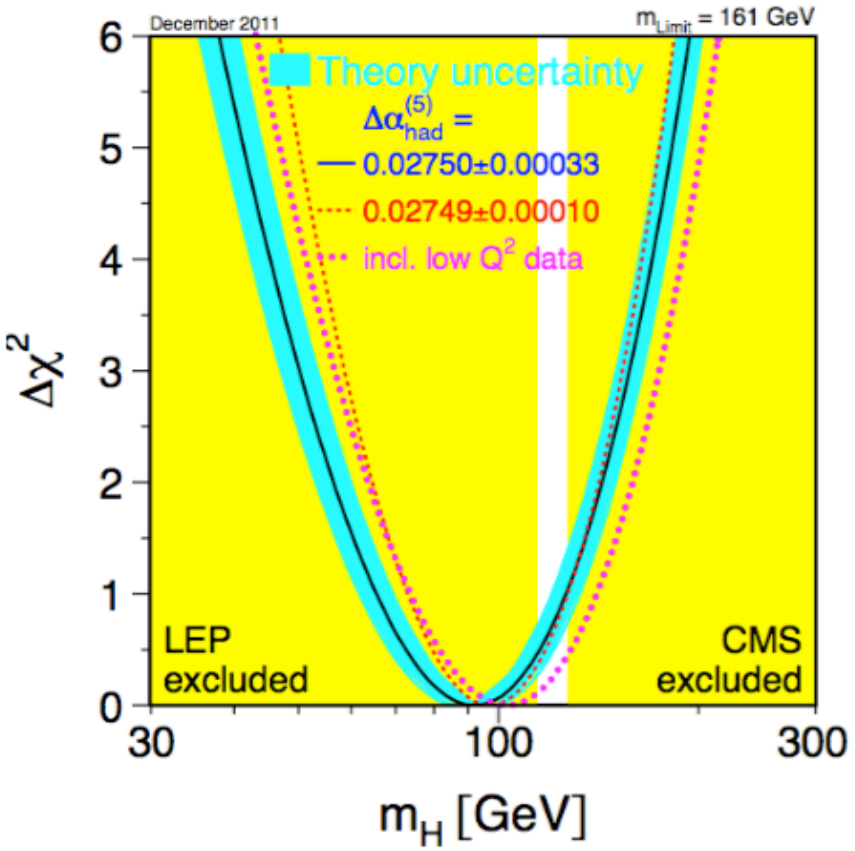
- $m_H$ > 114.4 GeV (LEP)
- $m_H$ < 158 GeV or > 175 GeV (Tevatron)

Preferred value from indirect measurements

- $m_H = 89^{+35}_{-26}$ GeV (global fit of EW precision data)

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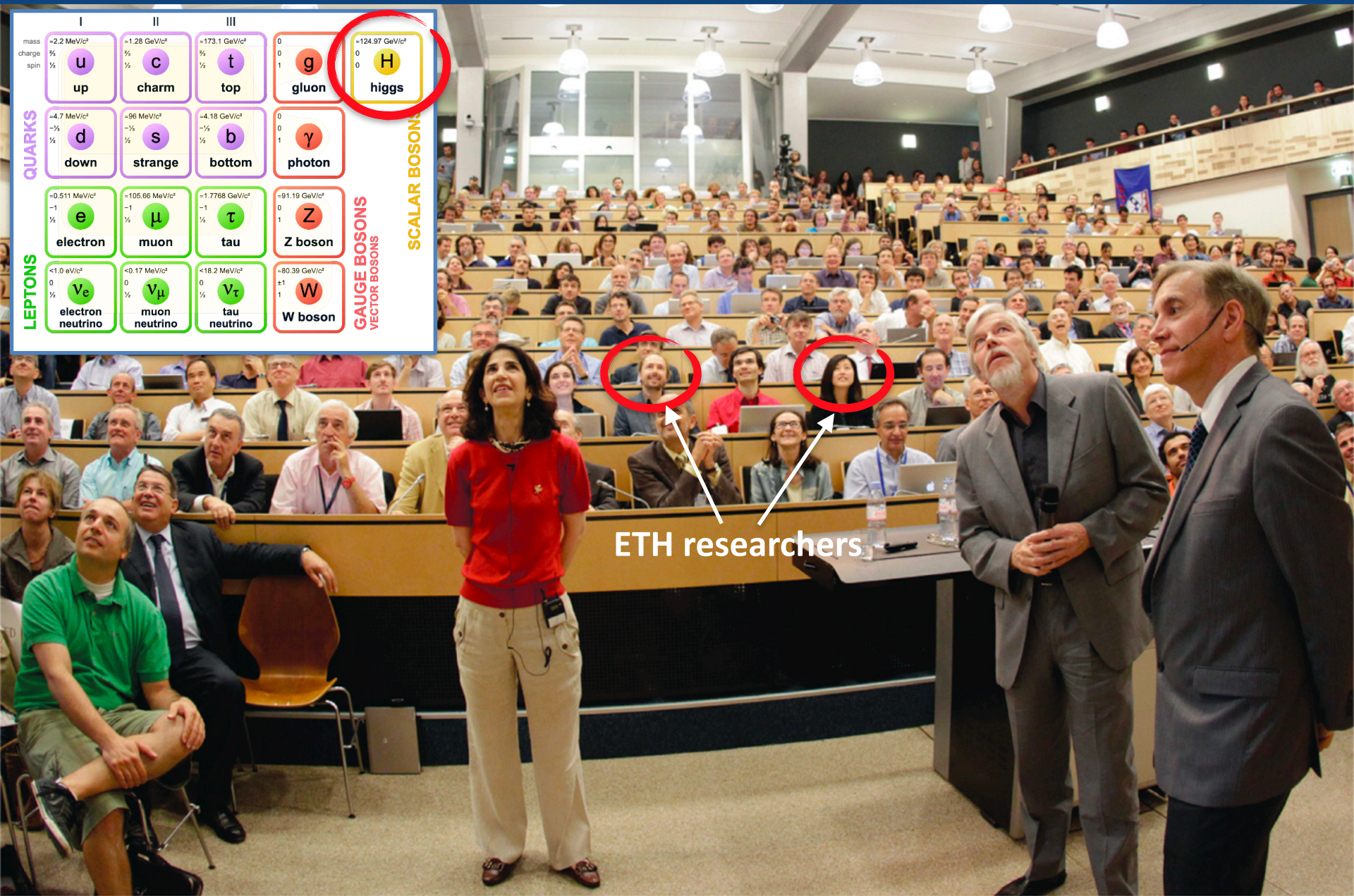
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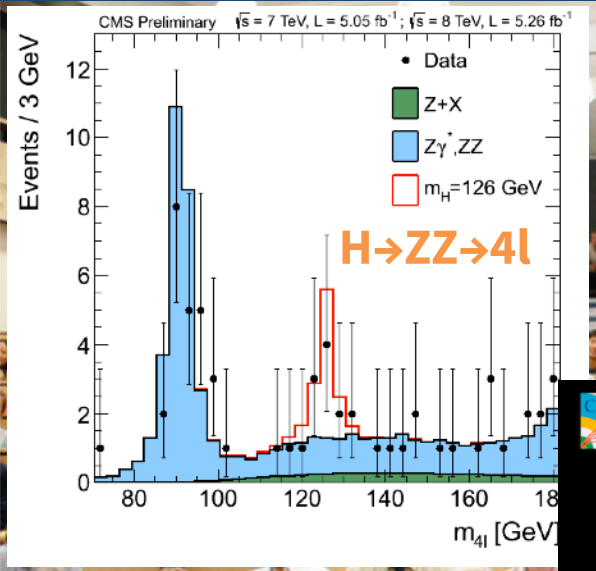
Constraints from 2011 LHC run:

- Either 115< $m_H$ < 127 GeV
- Or no light Higgs boson exists

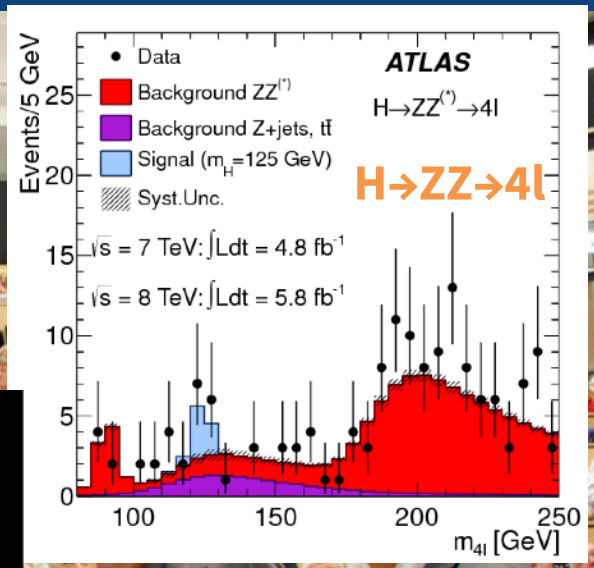
# 4th of July, 2012 - The Higgs boson discovery



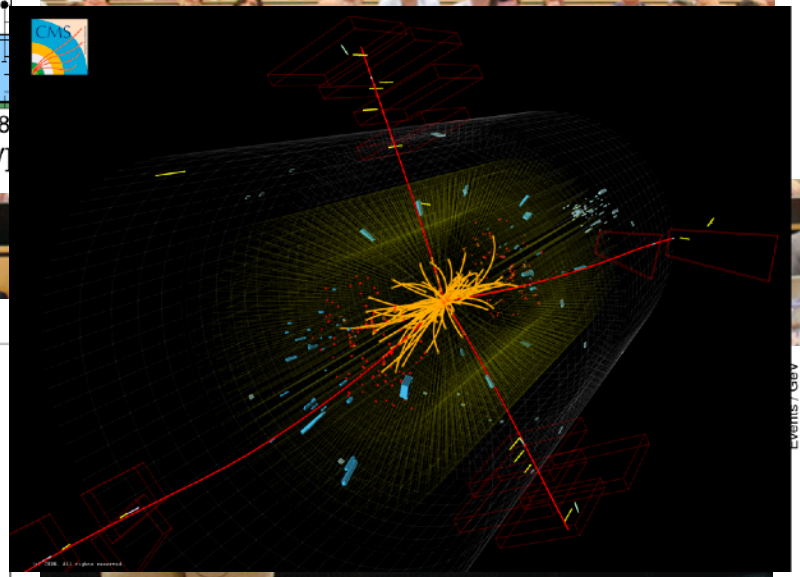
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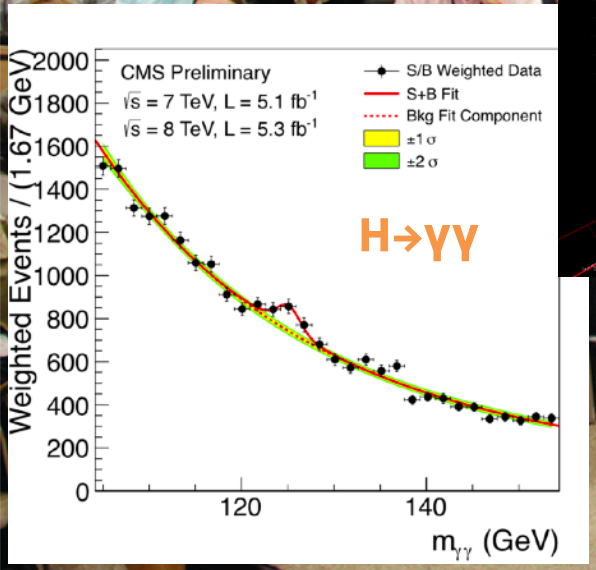

Higgs boson discovery confirmed by 2 experiments in 2 different channels

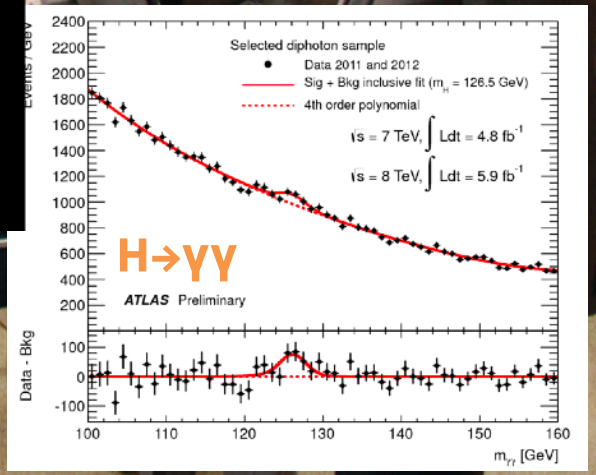




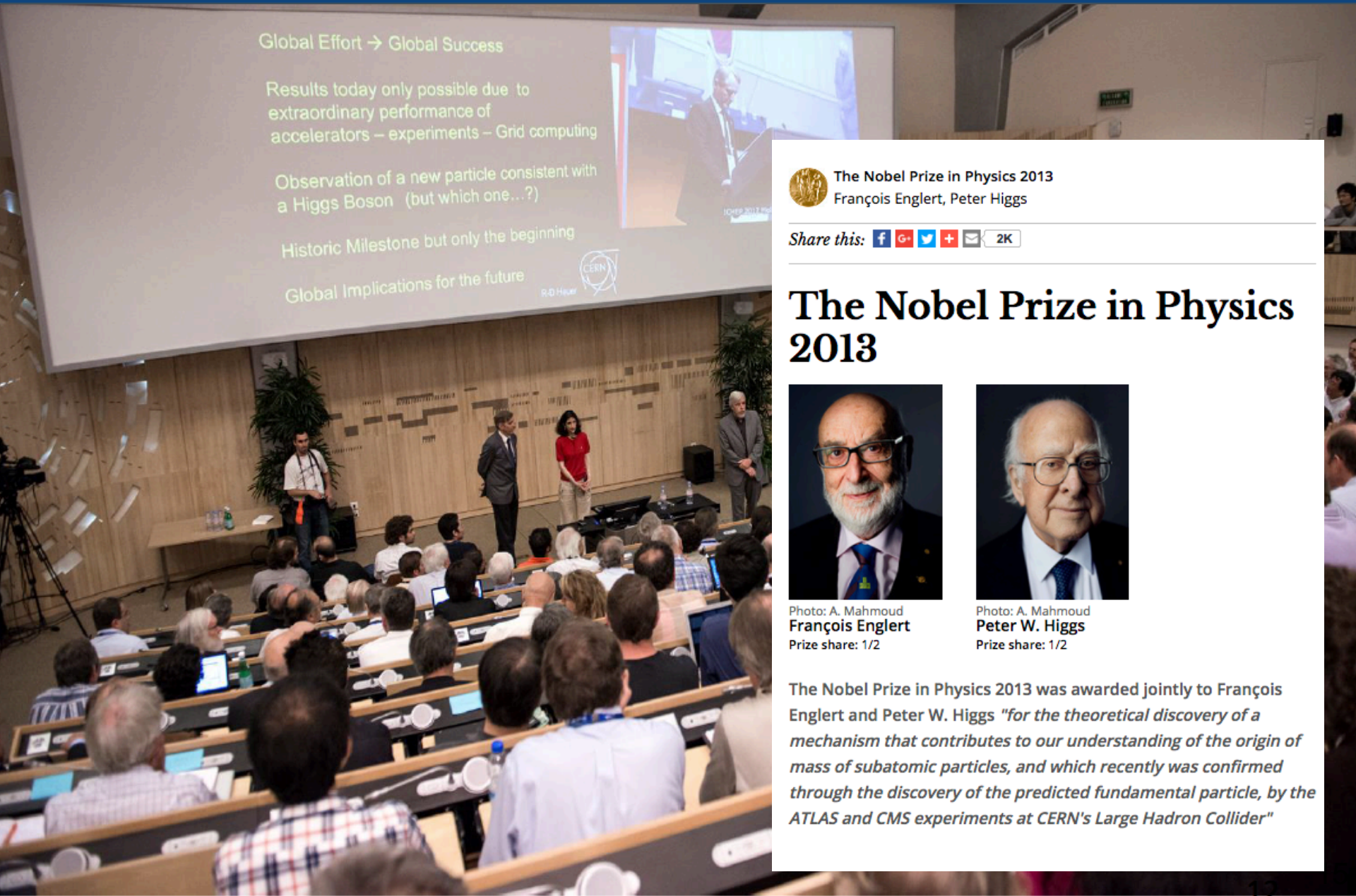







# 4th of July, 2012 - The Higgs boson discovery




The Nobel Prize in Physics 2013
François Englert, Peter Higgs

*Share this:* 2K

## The Nobel Prize in Physics 2013



Photo: A. Mahmoud
**François Englert**
Prize share: 1/2

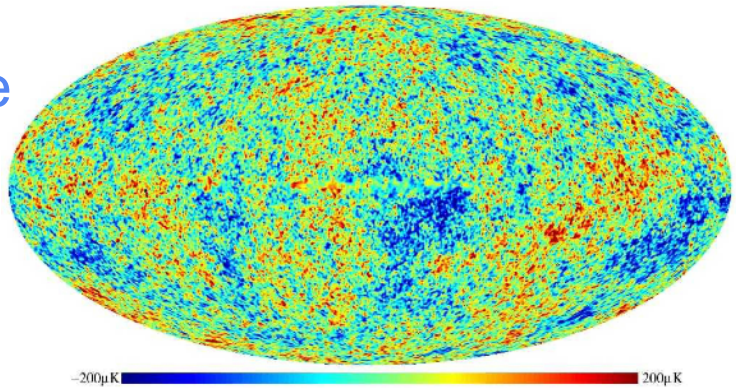


Photo: A. Mahmoud
**Peter W. Higgs**
Prize share: 1/2

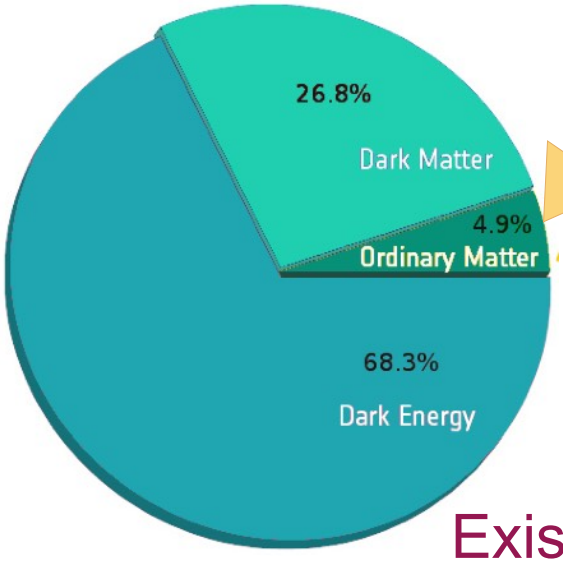
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

# Dark Matter is all around

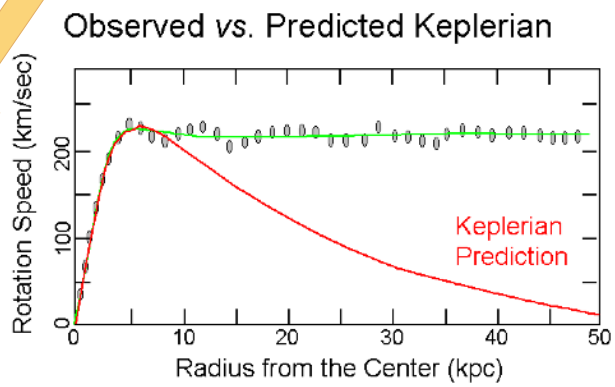
- Compelling proof of Dark Matter existence from astrophysical measurements
  - Missing mass in clusters of galaxies
  - Rotation curves of spiral galaxies
  - Gravitational lensing
- DM interacts gravitationally
  - That's almost everything we know






SM ~ 5%




What is the nature of Dark Matter?

Existence of DM is a clear evidence for new physics

# Why going beyond the SM?

There are still many open questions around SM, some of which can been answered only assuming the existence of new physics:

- Where Dark Matter come from?
- Why do we have a matter-dominated universe?
- Where neutrino masses come from?
- How is the Higgs boson mass so small?
- Can we include gravity in an extension of the SM?
- Is there a way to unify all fundamental forces?
- What is the origin of mass hierarchy among fermions?
- Why are there three families of leptons and quark?
- Why so many parameters of the Standard Model?

(Not an exhaustive list)

# How to go beyond the SM ?




A good BSM model should:

- Incorporate the SM and extend it
- Solve one or several of the SM defects
- Describe present and future experimental results

# What's there beyond SM?

## Plenty of models predicting new physics at the TeV scale




Photo courtesy: www.quantumdiaries.org

- Supersimmetry
- Grand Unified Theories
- Extended Higgs Sector
- Hidden Valleys
- Leptoquarks
- New Heavy Gauge Bosons
- Compositeness
- Extradimensions
- Technicolour
- …

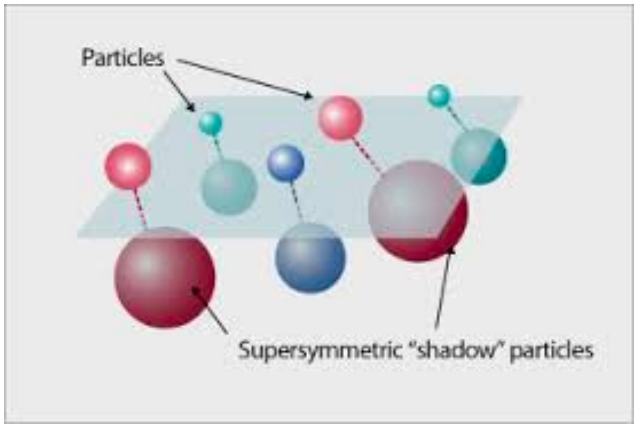
# Supersymmetry

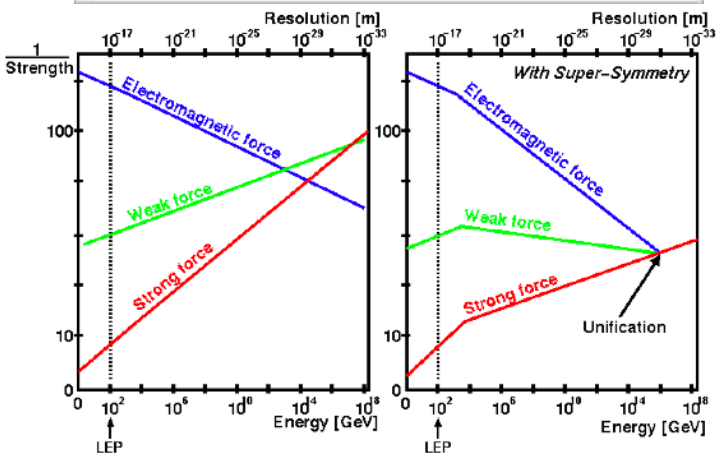
Supersymmetry: a new symmetry doubling the degrees of freedom, introducing a boson partner for each fermion and a Majorana fermionic partner for each gauge boson.

Quite naturally, SUSY is able to solve many of the SM issues at the same time:

- Solution to hierarchy problem
- Offers a good DM candidate: the lightest supersymmetric particle (LSP)
- Unification of gauge couplings
- Opening towards a theory of gravity

A selection of BSM models, including SUSY, will be covered in this course

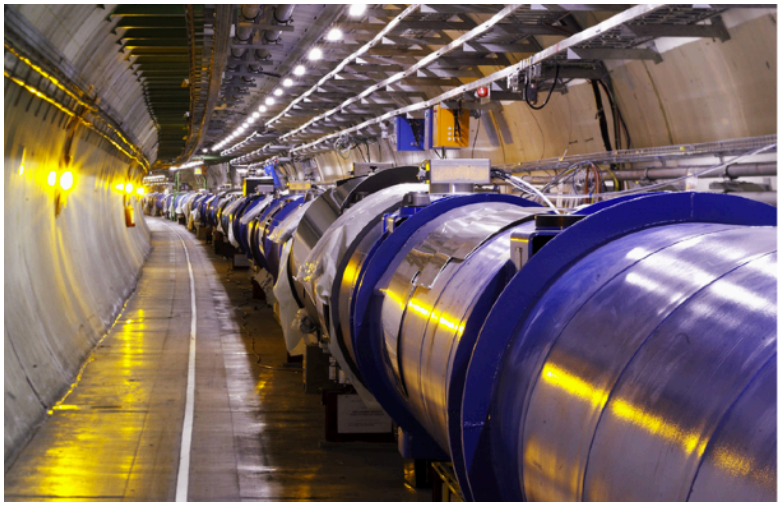


# How looking for beyond the standard Model?

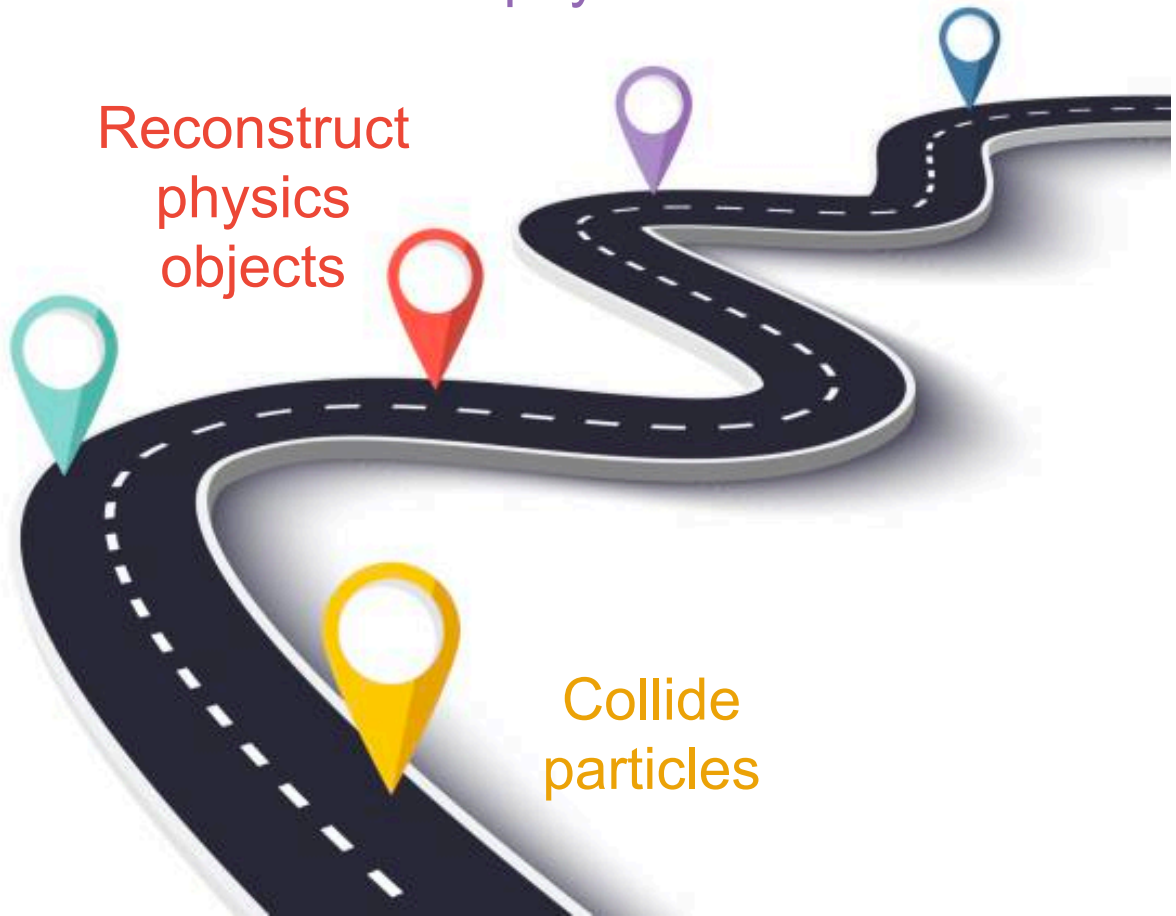
Experiments build upon accelerator machines allow to reproduce interesting SM phenomena, and possibly non-SM processes too (!), in a laboratory, pushing our exploration to the energy frontier





This course will focus on searches carried out at the Large Hadron Collider experiments, which have been designed with the primary goal to confirm the existence of the Higgs boson (✓) and to look for new physics

# Road to discovery



Collide particles

Catch collision products

Reconstruct physics objects

Calibrate against known physics

Analyse data

Results Interpretation

-

New Physics?



# Road to discovery





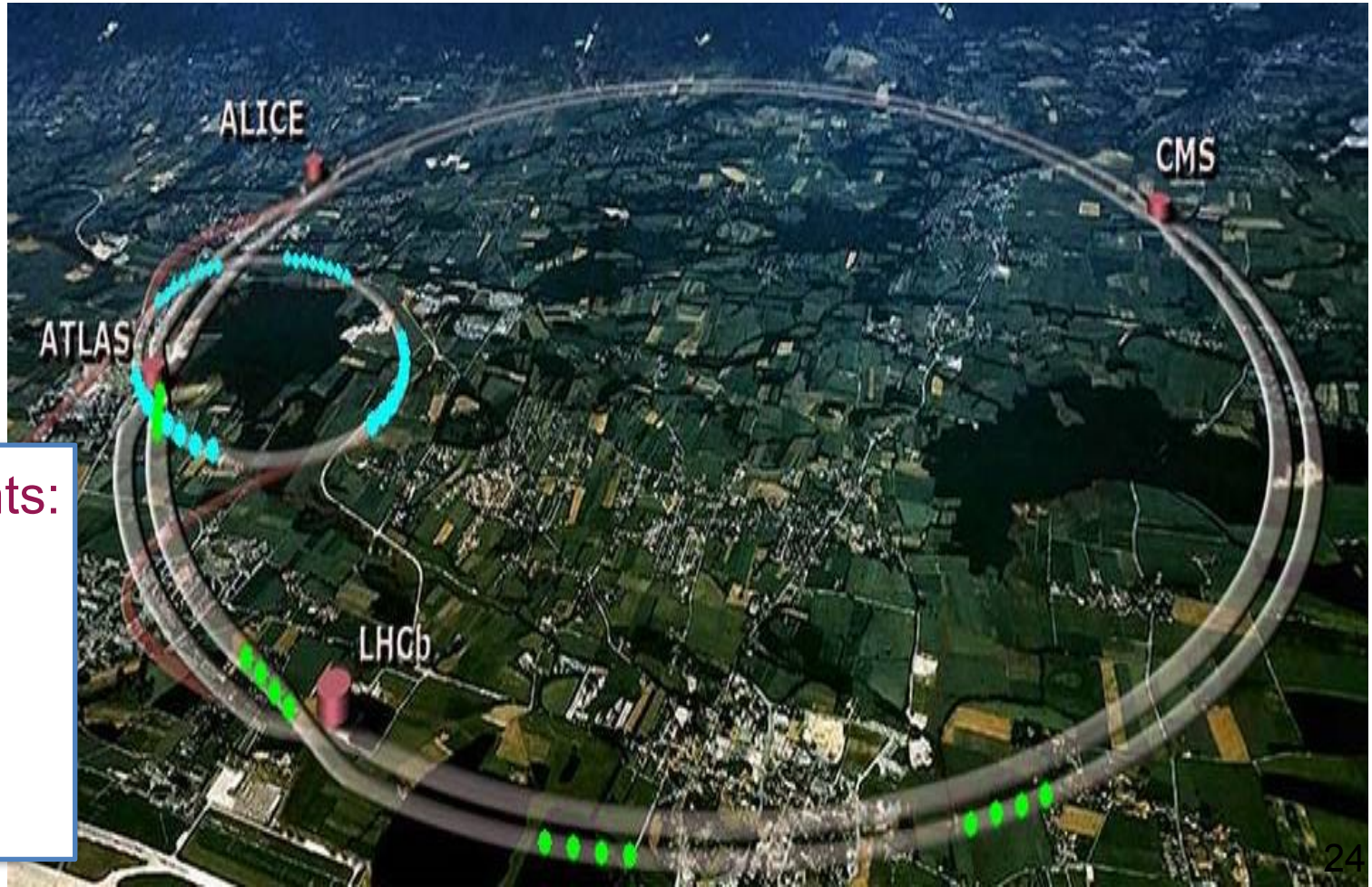
Collide particles

Build (or identify) a powerful accelerator: high energy and high luminosity

Collide particles

# Road to discovery

The Large Hadron Collider: a 27 km circumference proton-proton collider situated at CERN, on the Swiss-French border




4 experiments:

- ATLAS
- CMS
- LHCb
- ALICE

# Energy and Luminosity

- Energy constraint: one cannot produce something whose mass is larger than the centre-of-mass (CM) energy of the process

- Luminosity constraint: to detect very rare processes, very high "luminosity" (rate of pp collisions per second, per $cm^2$) is required

instantaneous luminosity [$cm^{-2}s^{-1}$]

$$N_{exp} = \sigma_{exp} \times \int \mathscr{L}(t)dt$$

cross section [barn]

integrated luminosity [$barn^{-1}$]

# Why the CERN LHC ?

- LEP accelerator at CERN couldn't go higher in center-of-mass energy because of synchrotron radiation (due to centripetal acceleration). Energy lost at each turn:

$$-\Delta E \propto \frac{1}{R}\left(\frac{E}{m}\right)^4$$

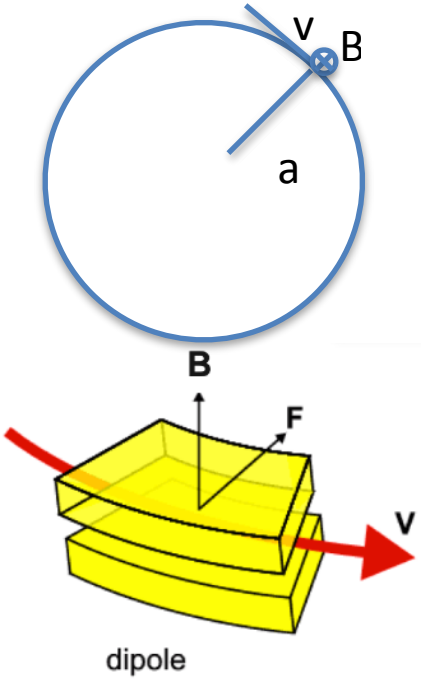
- To get higher center-of-mass energy, either larger R or larger m:

1. keep LEP tunnel and go to protons (larger m)
2. collider with larger radius R or linear collider (R=infinity)

- Decided to go for 1) Then energy of the LHC determined by LEP radius and bending power of conceivable magnets.

# LHC energy

Requiring Lorentz force (produced by the magnetic field) to keep particle within accelerator ring. Beams are deviated along the 27 km circumference by 1232 main dipoles of 15 m each, which provide a nominal magnetic field of 8.3 T




- The **Lorentz Force** can be seen as a **Centripetal Force**

$$F = q\vec{v} \times \vec{B} = \frac{mv^2}{\rho}$$

- $\rho$ is the particle's **radius of curvature** in the magnetic field

$$B\rho = \frac{mv}{q} = \frac{p}{q}$$

- $B\rho$ is the **magnetic rigidity**

$$B\rho[\mathrm{Tm}] = \frac{mv}{q} = \frac{p[\mathrm{GeV/c}]}{q} \Rightarrow B\rho = 3.3356\, p$$

- **Increasing the momentum** of a particle beam and keeping the **radius constant** requires **ramping the magnetic fields**

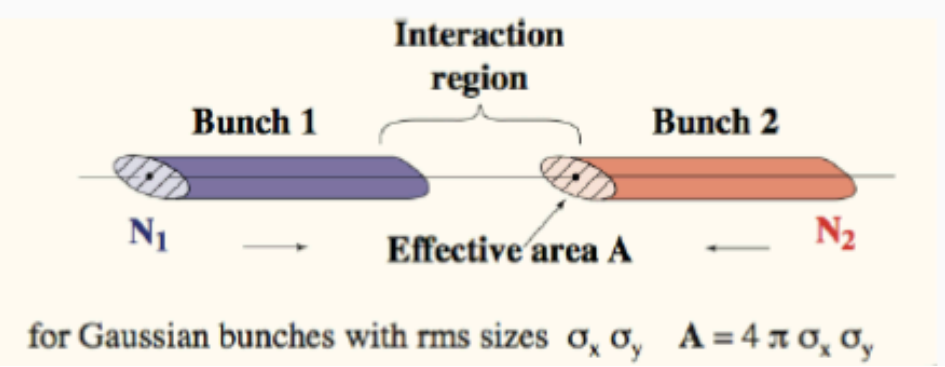
Credits to Rende Steerenberg CERNFermilab Hadron Collider Physics Summer School 2017, Lecture on Hadronic Accelerators

For nominal B field of ~ 8.3 T, rLEP = 4243 m, ρ = 2804 m (bending radius)

E (per proton) = B ρ / 3.3356 ~ 7 TeV ⇒ ECM = 14 TeV

Discovery machine: new particles up to the TeV scale

# Instantaneous luminosity




$$\mathcal{L} = \frac{f_{rev}\, n_b\, N_P^2}{4\pi\, \sigma_x\, \sigma_y} F(\theta_c, \sigma_x, \sigma_y)$$

$f_{rev}$ = frequency of the bunch revolution

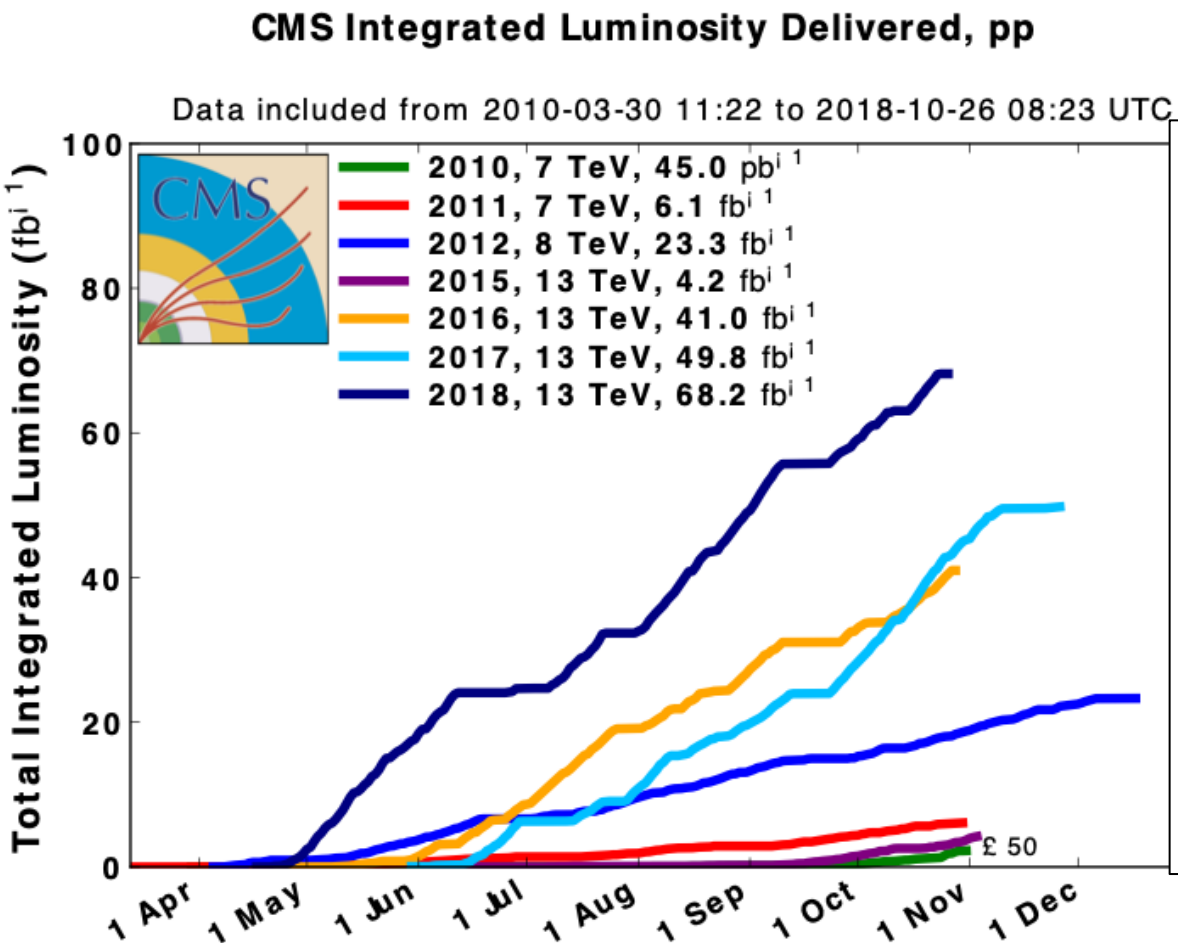
$n_b$ = number of proton bunches in the machine

$N_P$ = number of protons per bunch

$\sigma_{x,y}$ = transverse beam width

$F(\theta_c, \sigma_x, \sigma_y)$ takes into account: luminosity reduction due to crossing angle between the beams varying transverse bunch size in collision point because of bunch extension

# Energy/luminosity progression




## LHC timeline

**Run-1 (2010-2012)**

2010-2011: 6 $fb^{-1}$ at $E_{cm}$ = 7 TeV

2012: 23 $fb^{-1}$ at $E_{cm}$ = 8 TeV

**Run-2 (2015-2018)**

161 $fb^{-1}$ at $E_{cm}$ = 13 TeV

**Run-3 (2022-2024):**

exp. ~200 $fb^{-1}$ at $E_{cm}$ = 14 TeV

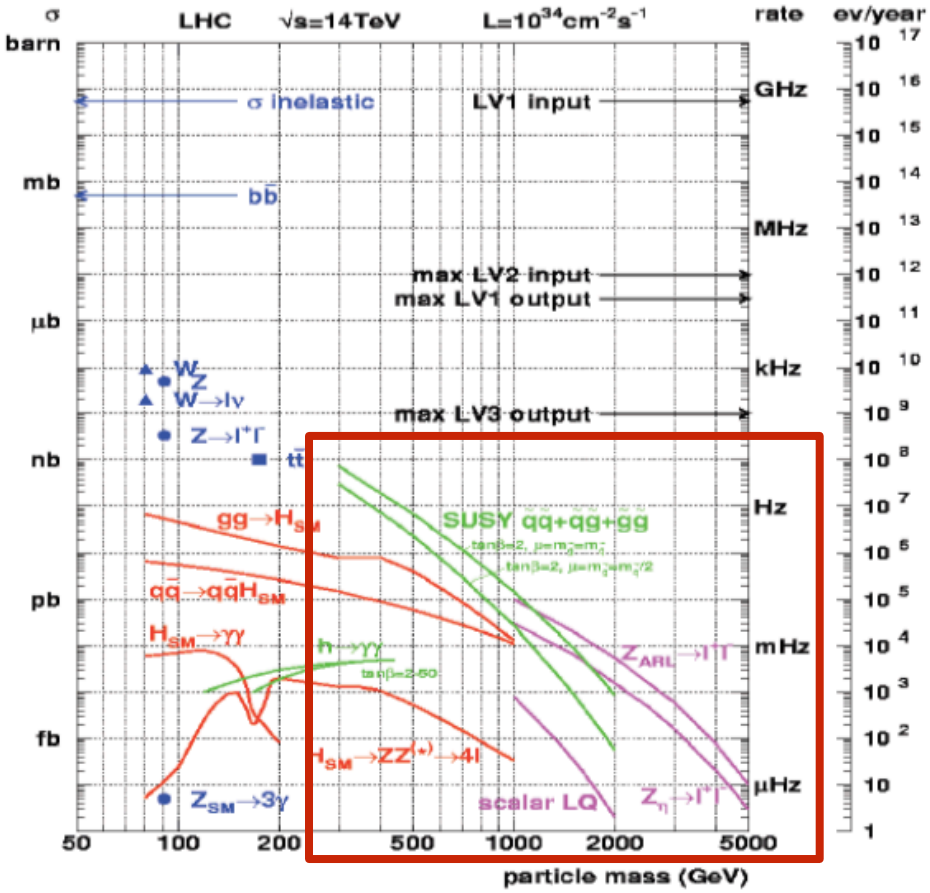
**HL-LHC (2027-2036):**

exp. ~3000 $fb^{-1}$ at $E_{cm}$ = 14 TeV

- Instantaneous luminosity: ~$2*10^{34} cm^{-2} s^{-1}$ (equivalent to 2 billions of p-p interactions per second, ~100 times higher than Tevatron, suitable for searching rare processes)

# LHC Physics rates

"Well-known" processes




New Physics!

**Expected production rate for process X:**

$$R_X^{\text{prod}} = \sigma_X \times \mathcal{L}$$

| Process | Cross section (nb) @ 14 TeV | Production rates (Hz) @ $\mathcal{L} = 10^{34}$ cm$^{-2}$s$^{-1}$ |
|---|---|---|
| inelastic | $10^8$ | $10^9$ |
| $H$ | 0.05 | 0.5 |

Many **orders of magnitude** between QCD background and primary physics channels rates

$$\frac{\sigma_{tot}}{\sigma_H} \approx 10^{11}$$

**Even if it would be feasible, saving all events at hadron collider is not useful**

**Need high energy and high luminosity to access new physics and good data filtering too!**

# Road to discovery



Catch collision products

Collide particles

Catch collision products

Build high performance detectors

# Road to discovery

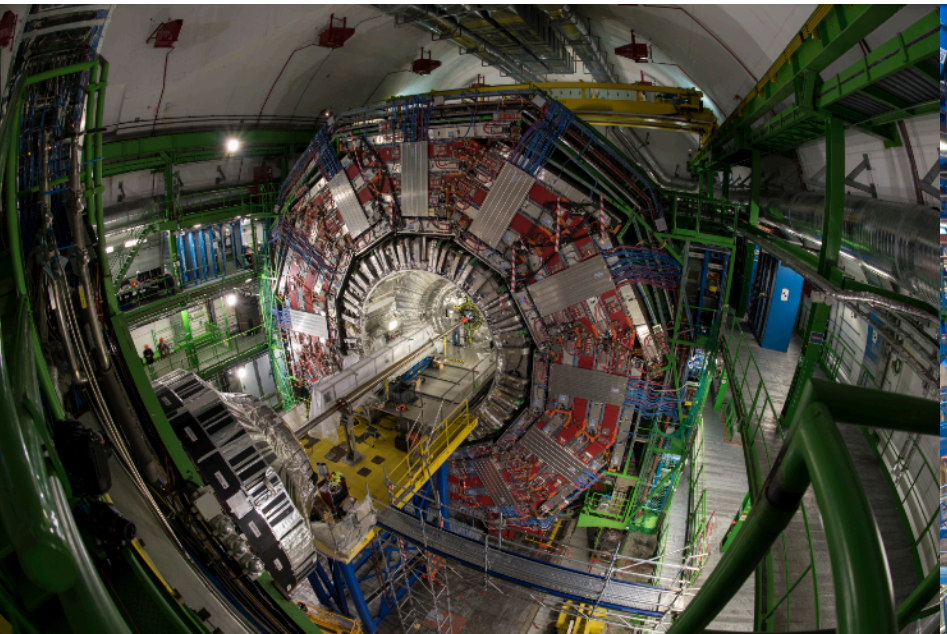
**2 multi purpose detectors @ the LHC**

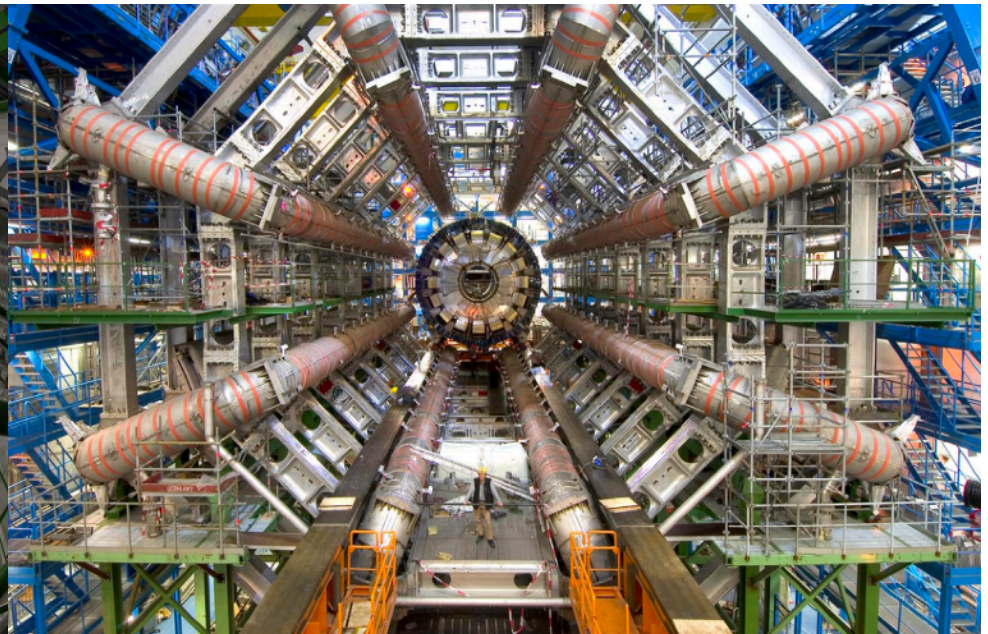
**The biggest detectors built so far**

**Have a look here: CMS collisions**

**Compact Muon Solenoid**

**A Toroidal LHC ApparatuS**





# A wide physics programme

LHC is a record machine

- Can probe **new physics at energy frontiers**: up to the TeV scale
- It's a W/Z and top factory: can provide a deeper **insight in the SM**

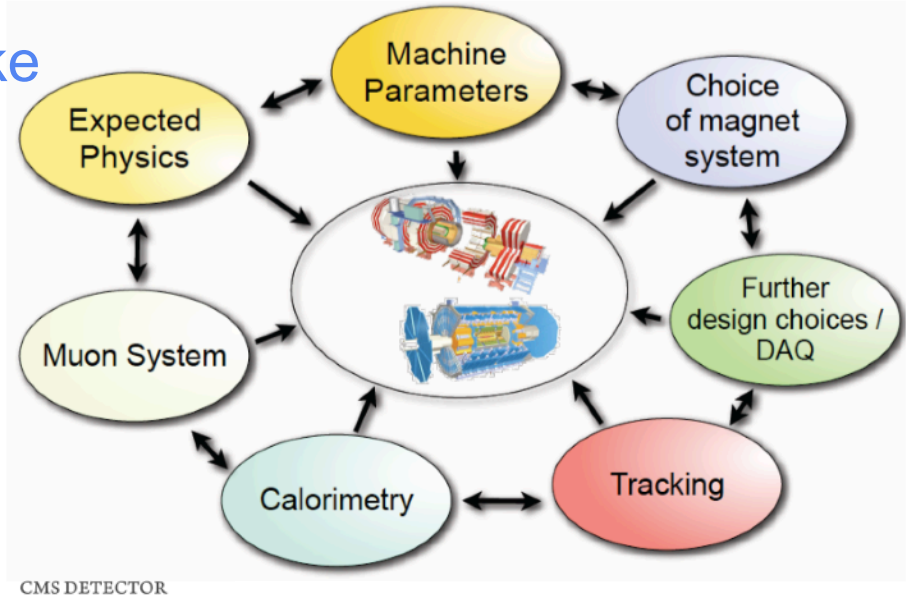
**General purpose detectors designed to cover a wide range of physics**

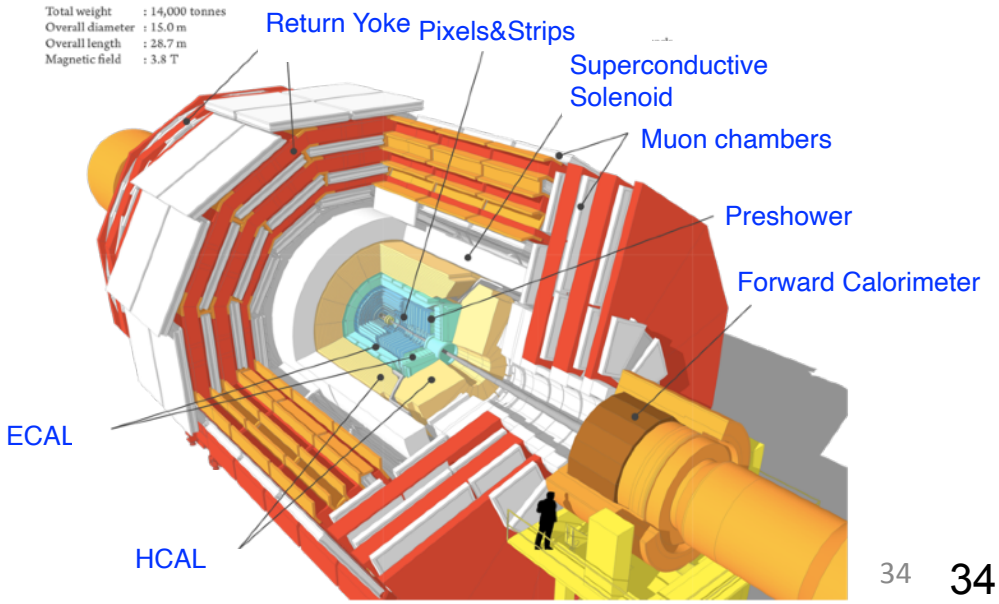
- Standard Model measurements
  - QCD jet cross sections
  - W mass measurement
  - Top quark properties: mass, couplings, decay properties
  - Search for the Higgs boson up to 1 TeV
    - study of its properties
- Search for Physics Beyond the SM
  - Search for SUSY particles, Dark Matter, extra-dimensions, heavy quarks/leptons, W'/Z', etc.
- B Physics
  - CP violation, rare decays ($B_S \rightarrow \mu\mu$)
- Heavy Ions:
  - Phase transition from hadronic matter to quark-gluon plasma

# How do we detect these particles?

To detect these particles we make them interact with the detector material

- Tracking system coupled with magnet system to measure the momentum of charged particles (electrons, muons, charged pions, kaons)
- Calorimeter system to measure energy of particles:
  - EM calorimeter
  - Hadronic calorimeter
- Muon system to identify muons and measure their momentum

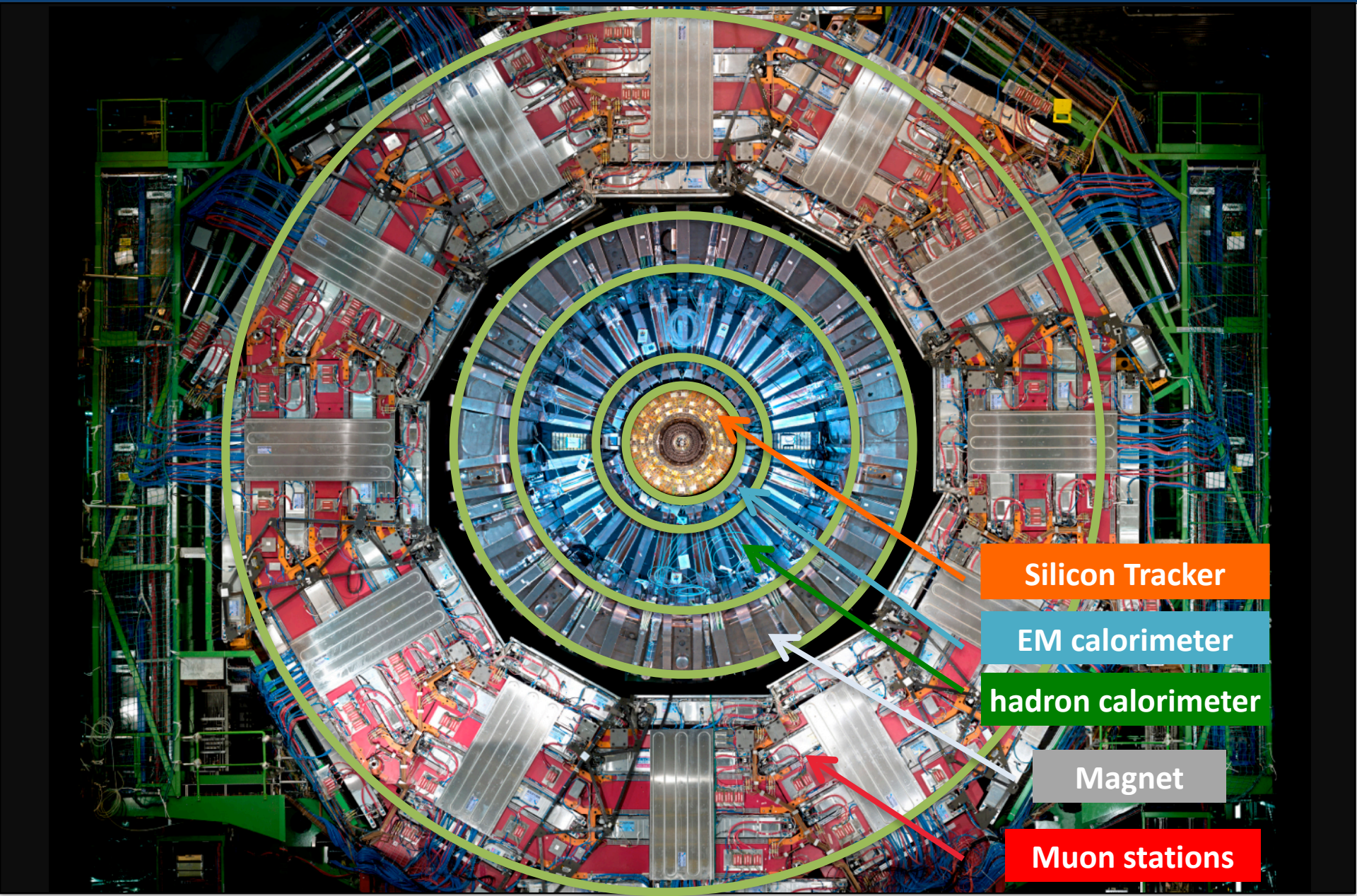




34

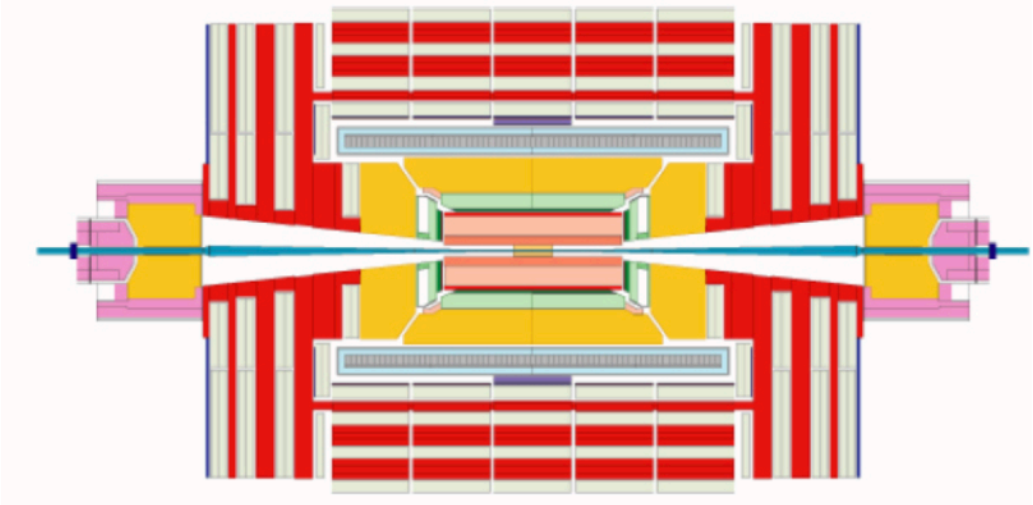
# The CMS sub-detectors



# Detector Requirements

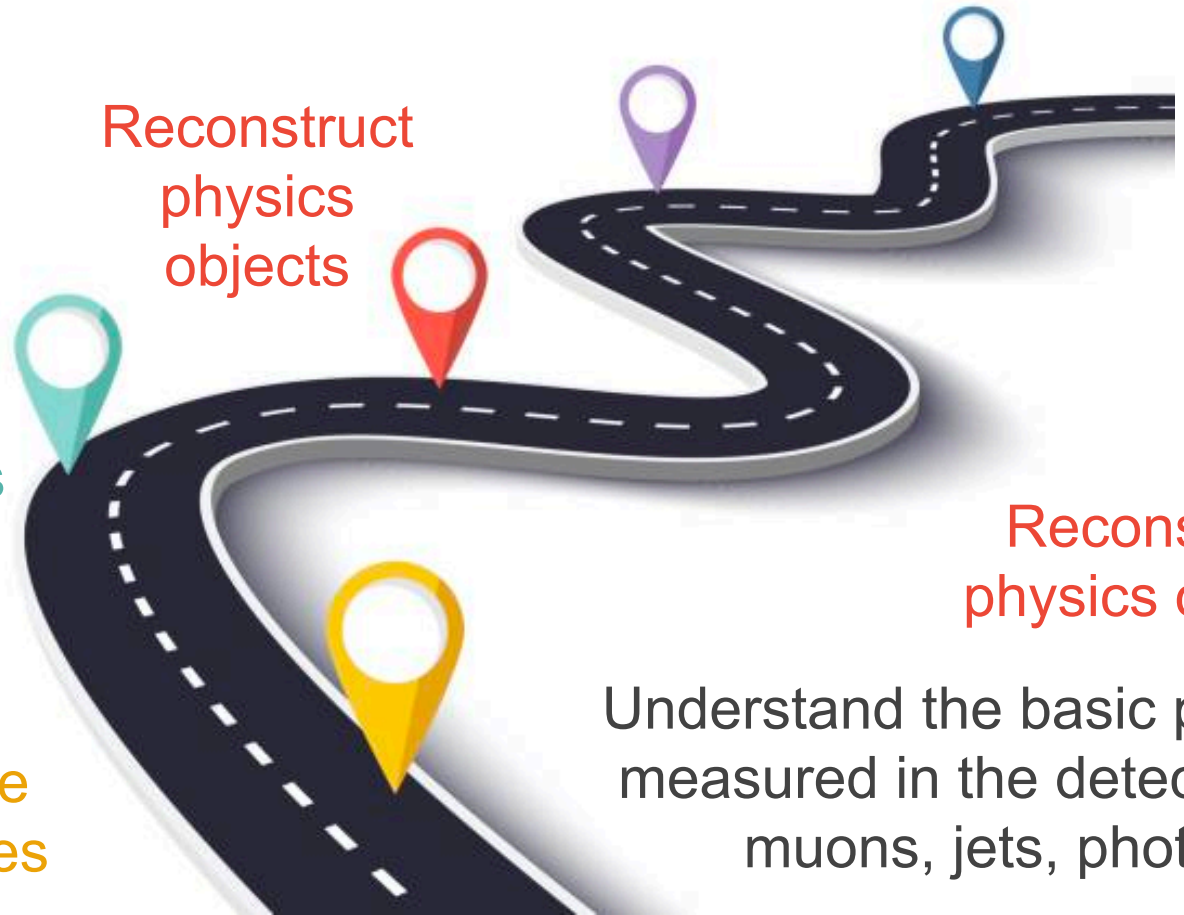
Some general requirements for general-purpose detectors at the LHC:

- Good hermeticity: most interesting physics happens at high pT (central part of the detector), but want to be able to measure also forward processes. Typical geometry:
  - barrel + end-caps



- Good resistance to extremely high doses of radiations
- High granularity for precise position, momentum, energy measurement
- Fast detectors and electronics (~25-50 ns response) to cope with LHC bunch spacing

# Road to discovery



Reconstruct physics objects

Catch collision products

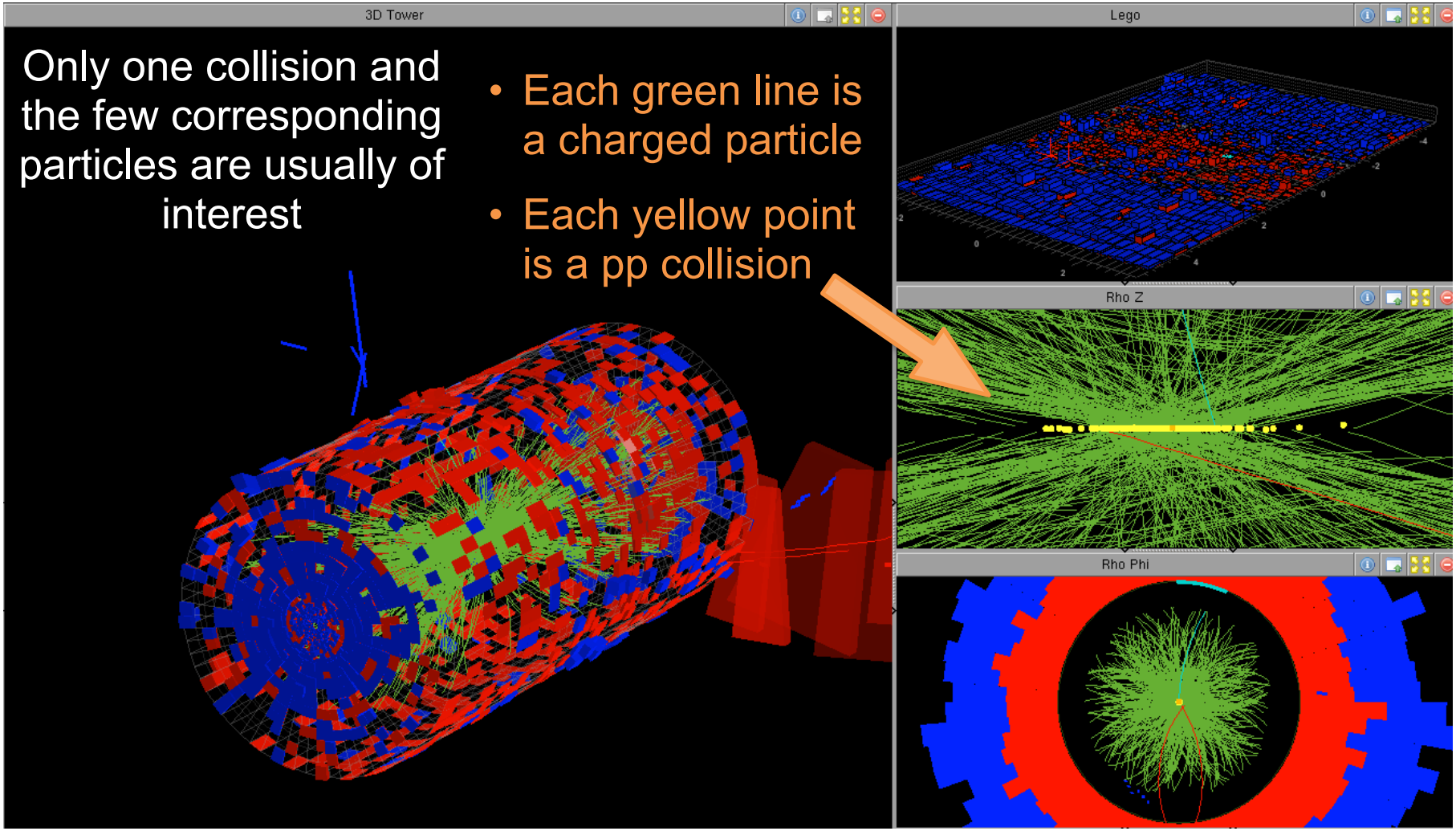
Reconstruct physics objects

Collide particles

Understand the basic physics objects measured in the detector: electrons, muons, jets, photons, etc..

# What data look like

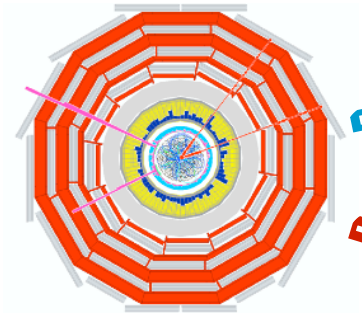
Example of real LHC data recorded by CMS: reconstructed collision with 78 primary pp collisions within the same bunch-crossing



# Data flow at LHC experiments

## Data Flow

- **Event detection + trigger selection/ simulation**
- Data reconstruction
- Data analysis



Collision Data

**40 MHz**

**Trigger**

**~100 kHz**

**DataAcQuistion and Event Filter (HLT)**

**~1 kHz**

p-p collision rate: 40 MHz
Average event size: 1.5 MB
**Full data rate: ~60 TB/s**

**CERN Storage**

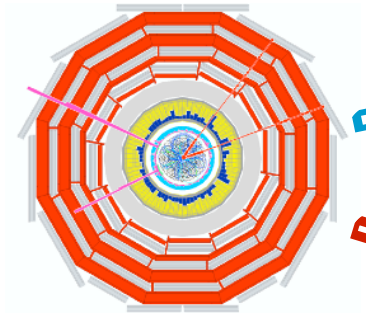
**Simulated Data**

**Simulation**

# Data flow at LHC experiments

## Data Flow

- Event detection + trigger selection/ simulation
- **Data reconstruction**
- Data analysis



Collision Data

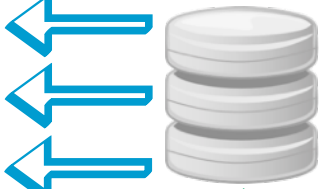
**40 MHz**

**Trigger**

~100 kHz

**DataAcQuistion and Event Filter (HLT)**

~1 kHz



CERN Storage

**Event Reconstruction**




Simulated Data

**Simulation**

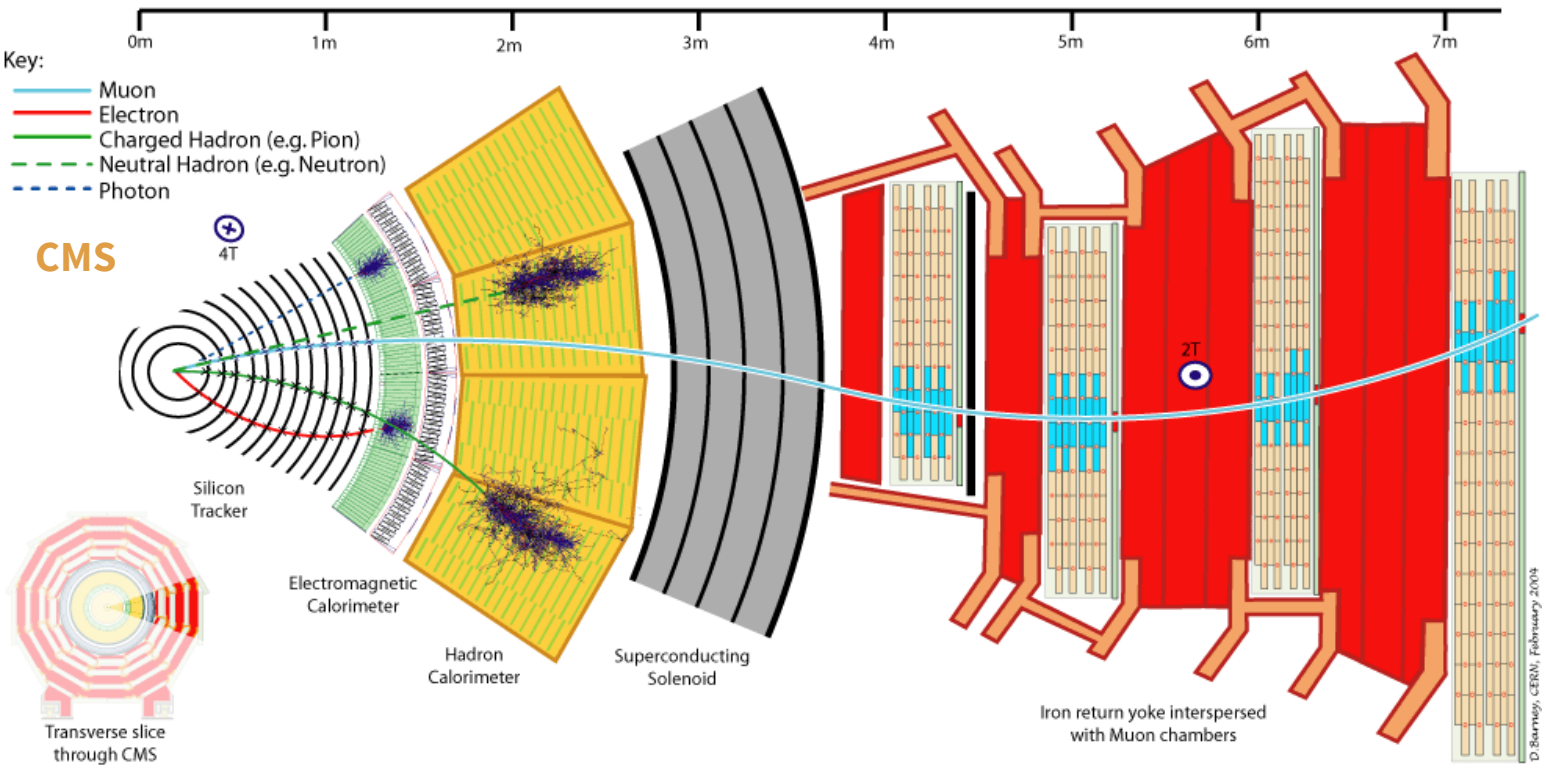
# Particle Reconstruction

High $p_T$ e,ɣ

High $p_T$ jets

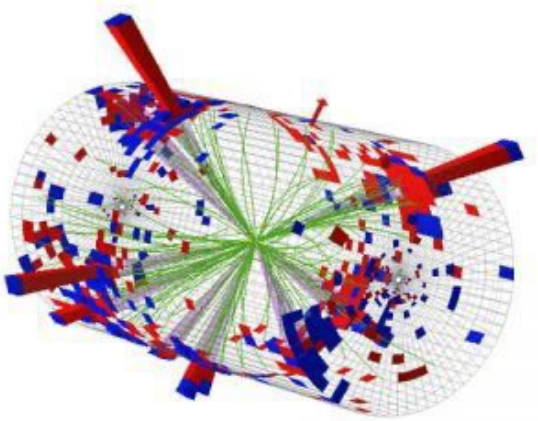
High $p_T$ μ

Global quantities
Total and Missing Transverse Energy




**Particles are identified by means of their interaction with all subdetectors.**

**Event reconstruction**



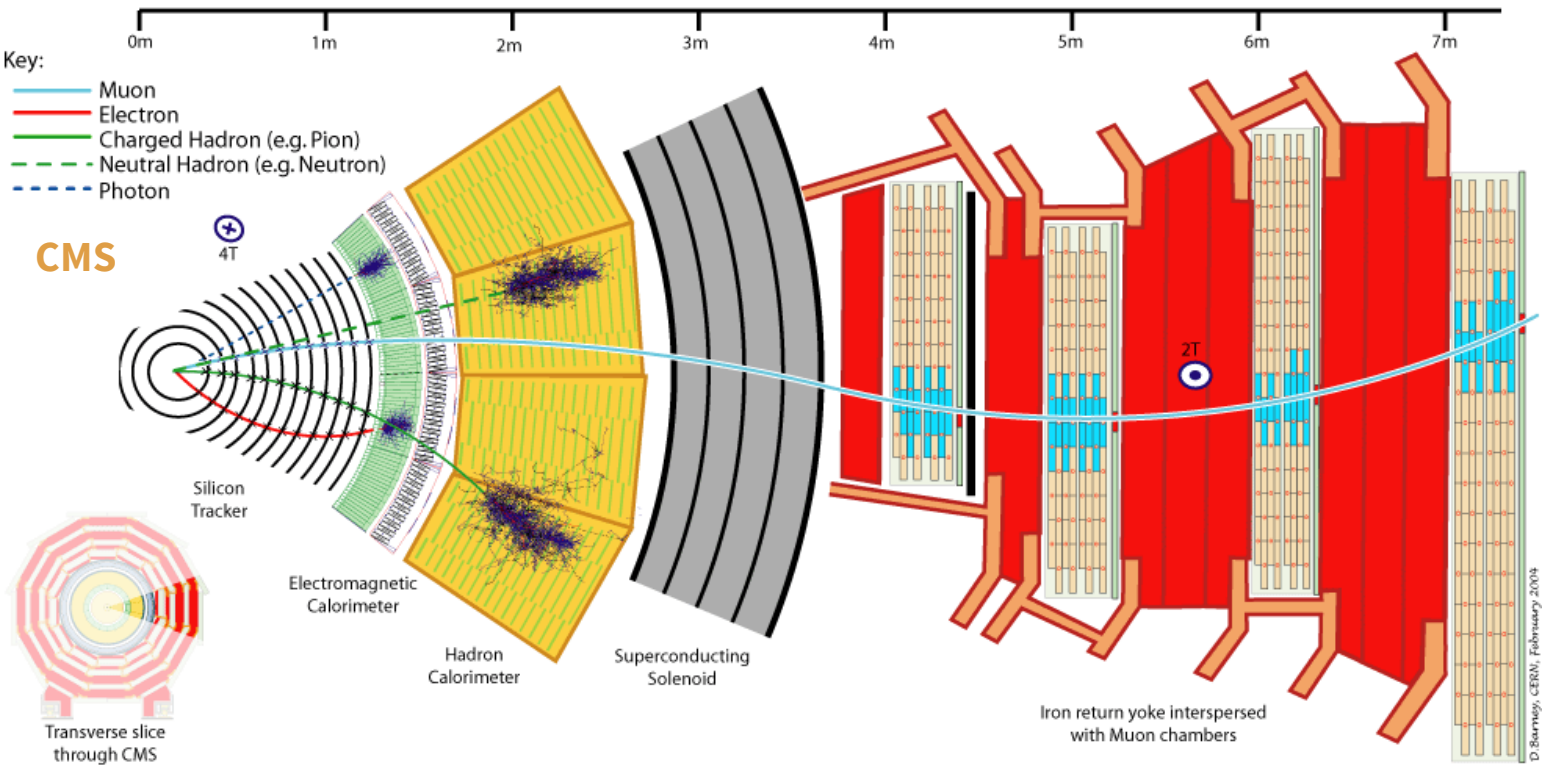
# Particle Reconstruction

High $p_T$ e,ɣ

High $p_T$ jets

High $p_T$ μ

Global quantities
Total and Missing Transverse Energy



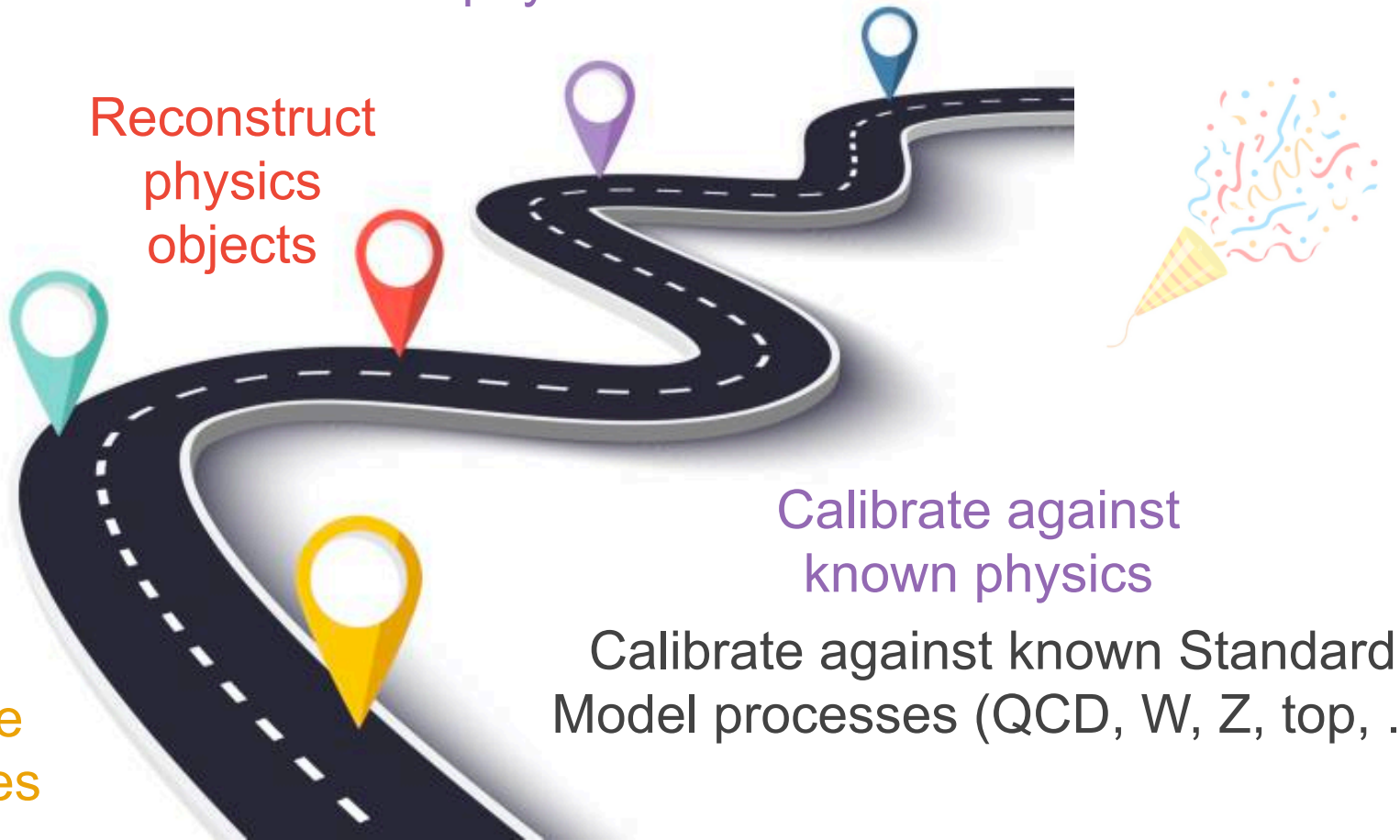

We'll see more on particle identification and reconstruction in the upcoming lectures dedicated to experimental searches for BSM physics

# Road to discovery

Calibrate against known physics

Reconstruct physics objects

Catch collision products

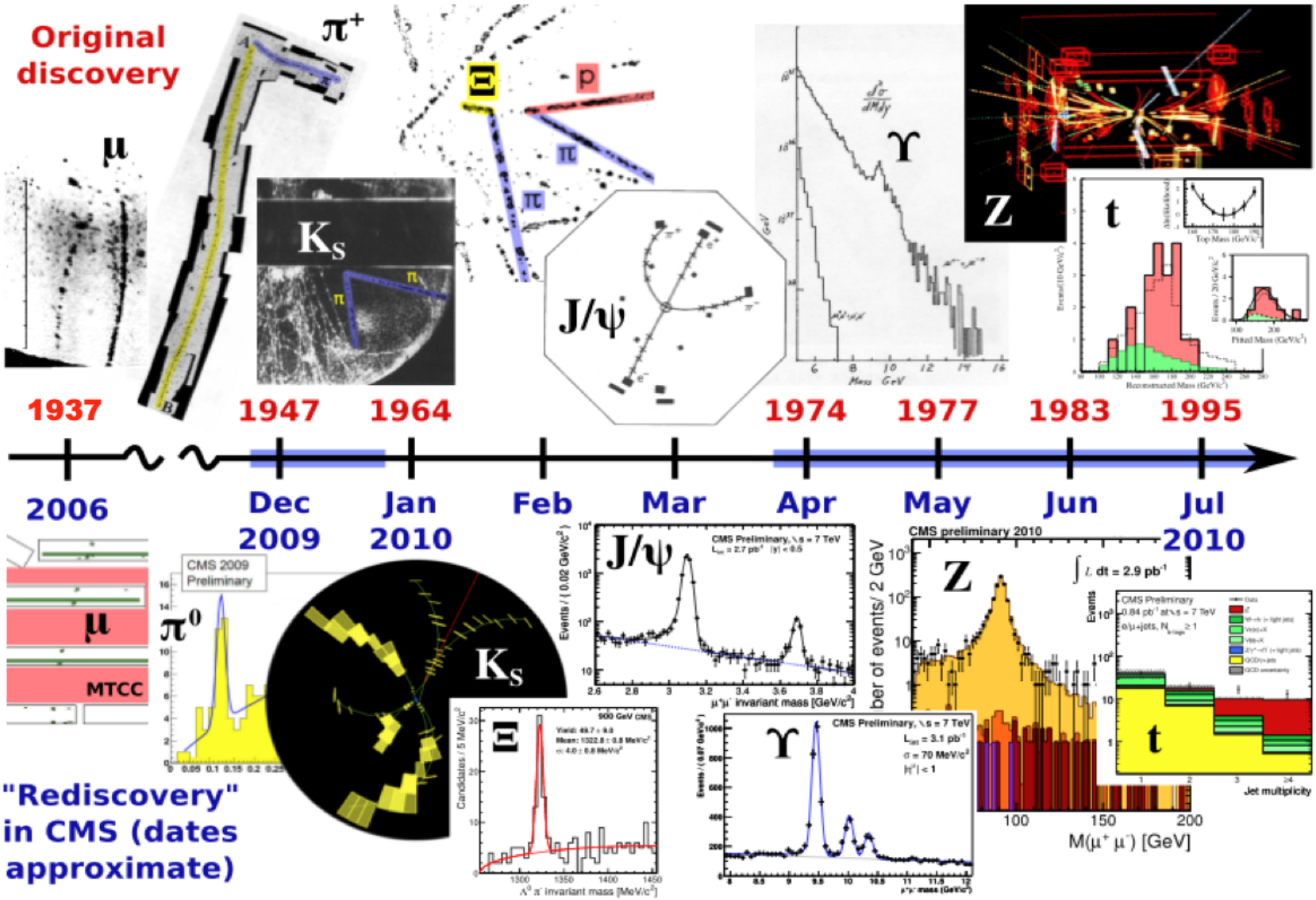


Calibrate against known physics

Calibrate against known Standard Model processes (QCD, W, Z, top, ..)

Collide particles

# 2010


Original discovery
μ
π+
Ks
Ξ
p
π
π
J/ψ
ϒ
Z
t
1937
1947
1964
1974
1977
1983
1995
2006
Dec 2009
Jan 2010
Feb
Mar
Apr
May
Jun
Jul 2010
MTCC
CMS 2009 Preliminary
π0
Ks
J/ψ
CMS Preliminary, √s = 7 TeV
μ+μ- invariant mass [GeV/c2]
CMS preliminary 2010
Z
ϒ
t
M(μ+ μ-) [GeV]
Jet multiplicity
"Rediscovery" in CMS (dates approximate)

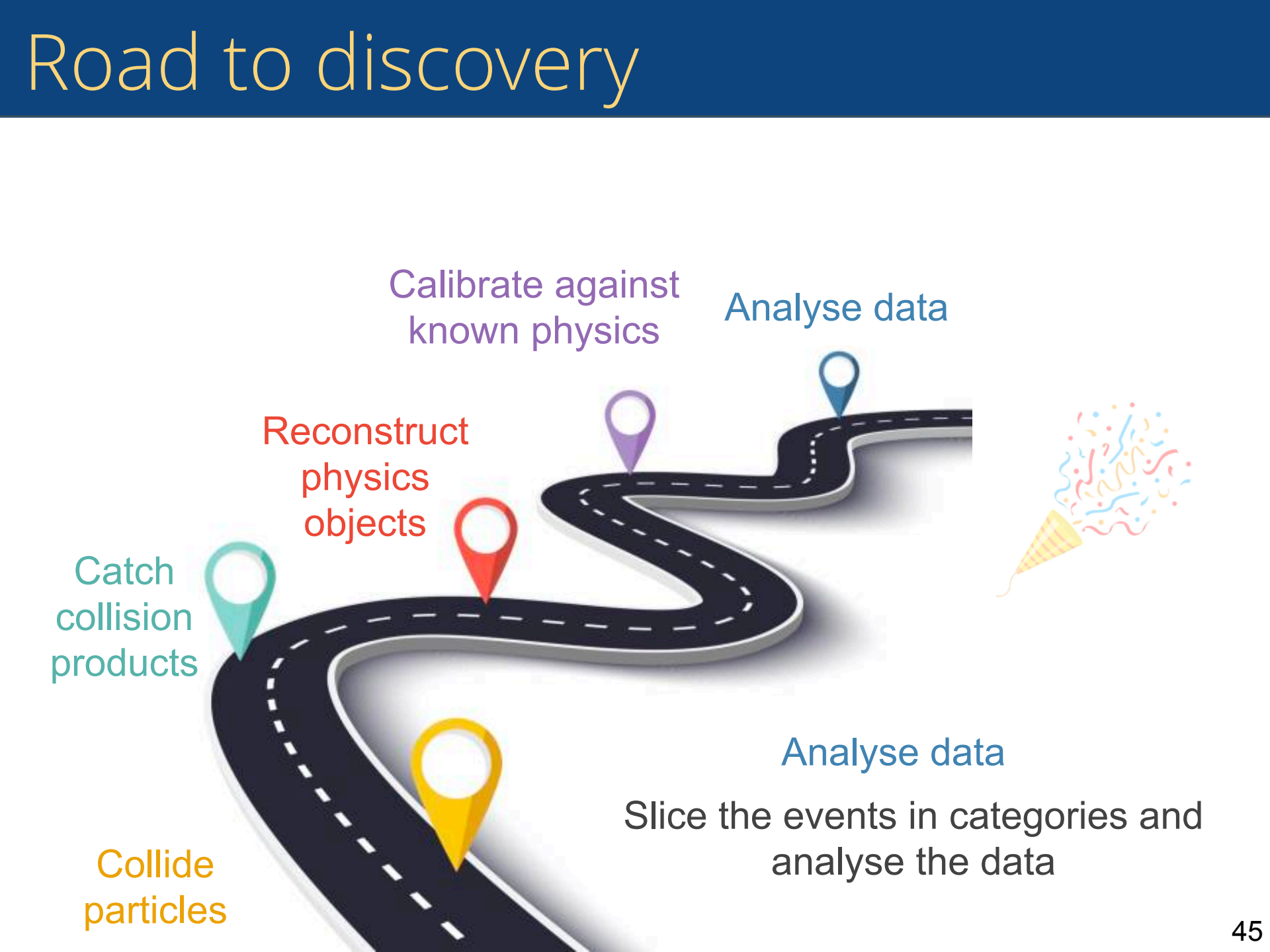
# Road to discovery

Calibrate against known physics

Analyse data

Reconstruct physics objects

Catch collision products



Analyse data

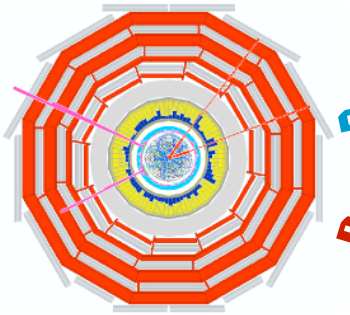
Slice the events in categories and analyse the data

Collide particles

# Data flow at LHC experiments

## Data Flow

- Event detection + trigger selection/ simulation
- Data reconstruction
- **Data analysis**



Collision Data

**40 MHz**

**Trigger**

~100 kHz

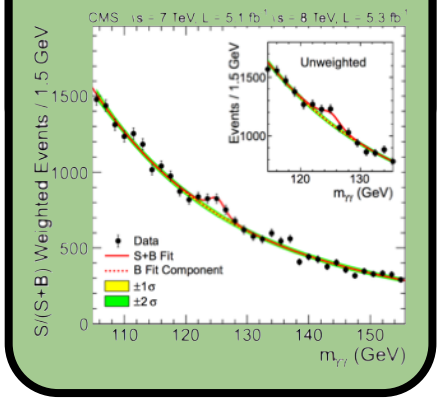
**DataAcQuistion and Event Filter (HLT)**

~1 kHz

CERN Storage

**Event Reconstruction**

**Offline analysis**




Simulated Data

**Simulation**

# Road to discovery

Results Interpretation

Calibrate against known physics

Analyse data

Reconstruct physics objects

Catch collision products

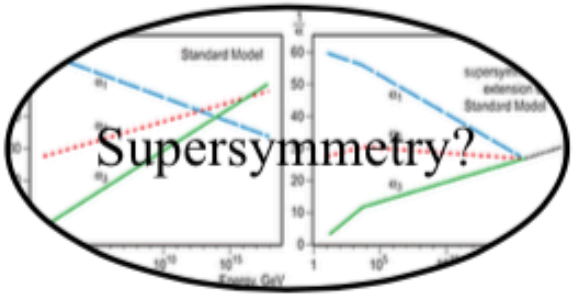


Collide particles

Results Interpretation: New Physics?

Interpret the results: measure properties, establish presence/absence of anomalies

# What will the LHC bring ?










Just the Higgs?

?

# Summary

- New physics may wait behind the corner
  - Several indications suggesting need for going beyond the SM
  - The LHC enable us to explore an uncharted territory at the energy frontier
- New physics may have high mass or manifest through very rare processes. Need
  - very high energy and luminosity machines
  - high performance detectors
  - good reconstructions and identification algorithms

What the LHC will bring? Stay tuned!

# Some interesting readings

- Overview of BSM and DM: H. Murayama's lecture at Les Houches summer school 2007, http://arxiv.org/pdf/0704.2276v1.pdf

- Introductory and accurate overview of physics at the LHC: "Physics at the LHC Run-2 and Beyond", Andreas Hoecker, Lecture notes from the 2016 European School of High-Energy Physics, https://arxiv.org/pdf/1611.07864.pdf

# Backup slides

# Radius vs Radius of Curvature

## Ex. 1: Radius versus Radius of Curvature

- LHC circumference = 26658.883 m
  - Therefore the radius r = 4242.9 m
- There are 1232 main dipoles to make 360˚
  - This means that each dipole deviates the beam by only 0.29˚
- The dipole length = 14.3 m
  - The total dipole length is thus 17617.6 m, which occupies 66.09 % of the total circumference
- The bending radius ρ is therefore
  - ρ = 0.6609 x 4242.9 m → ρ = 2804 m
- Apart from dipole magnets there are also straight sections in our collider
  - These are used to house RF cavities, diagnostics equipment, special magnets for injection, extraction etc.

Credits to Rende Steerenberg CERNFermilab Hadron Collider Physics Summer School 2017, Lecture on Hadronic Accelerators

# a needle in a hay stack

Per year, the LHC will provide about $10^{16}$ *pp* collisions.

An observation of ~ 10 events could be a discovery of new physics.

→ One has to find these 10 events among $10^{16}$ non-interesting ones!!

*Searching for a needle in a hay stack?*

- typical needle: 5 $mm^3$
- typical haystack: 50 $m^3$

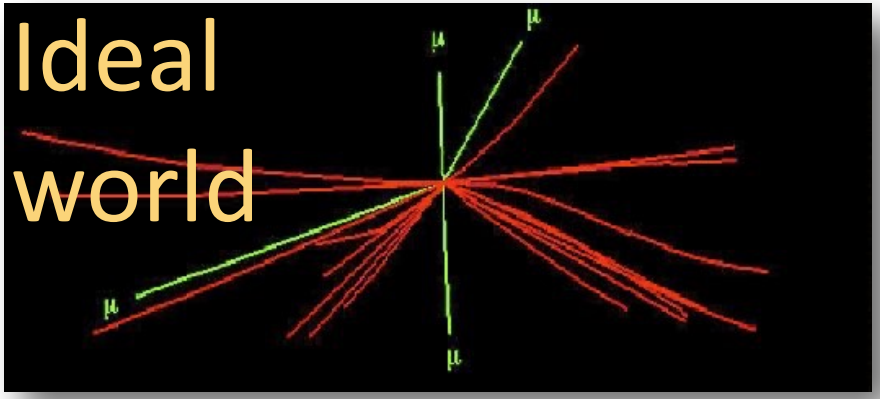
→ needle : haystack = 1 : $10^{10}$

→ Looking for new physics at the LHC is like looking for a needle in 100000 haystacks …

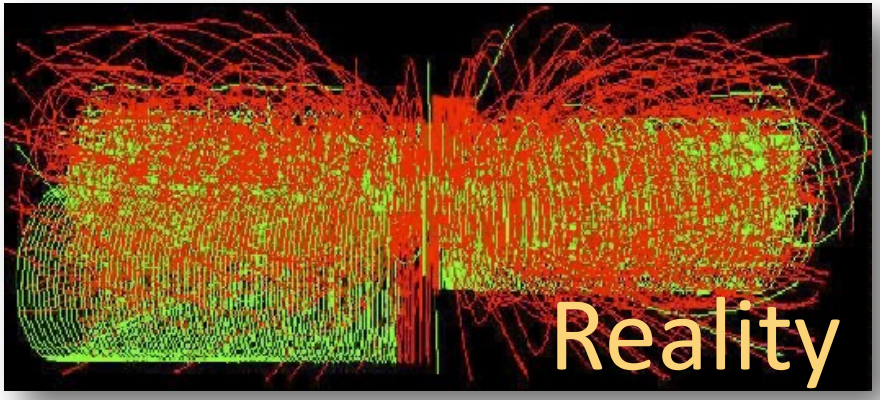
# How to identify interesting events?

Only high-$p_T$ tracks

Higgs → 4μ

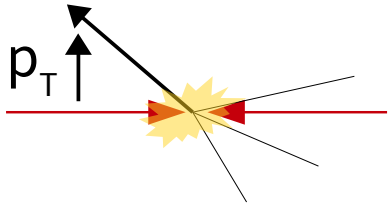



All tracks




Example: Higgs → 4μ events

- Interesting kind of events
- Key process for 2012 Higgs discovery




In practice:

- Event hidden under tons of know physics
- Exploit the physics signature to identify the underlying Higgs decay
  - 4 high-momentum μ

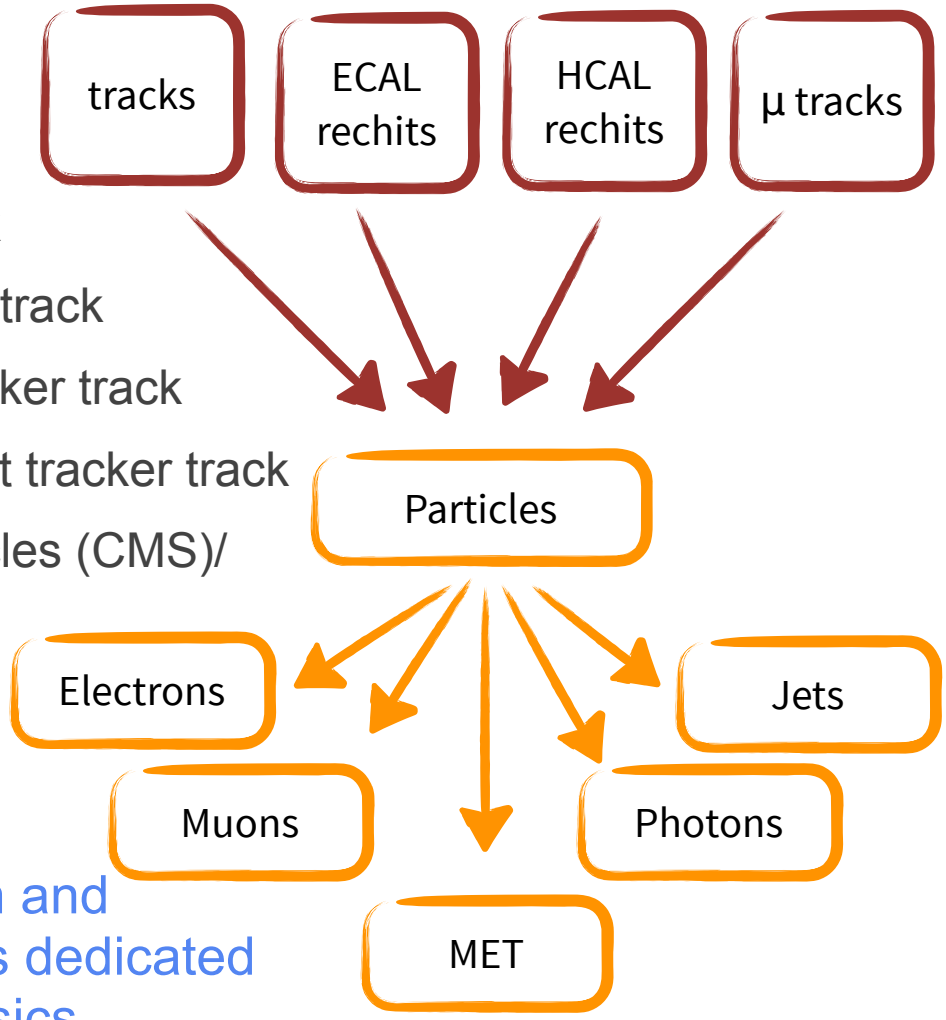
Interesting physics usually is high pT

from ISOTDAQ2017 - A.Thea

# Particle reconstruction

CMS and ATLAS reconstruction algorithms exploit information from different sub-detectors to reconstruct particles

- **muons**: tracker track + muon track
- **electrons**: ECAL cluster + tracker track
- **photons**: ECAL cluster without tracker track
- **charged hadrons**: HCAL clusters + tracker track
- **neutral hadrons**: HCAL clusters without tracker track
- **jets**: reconstructed from all other particles (CMS)/ from calorimeters(ATLAS)
- **MET:** missing transverse energy, reconstructed from all other particles

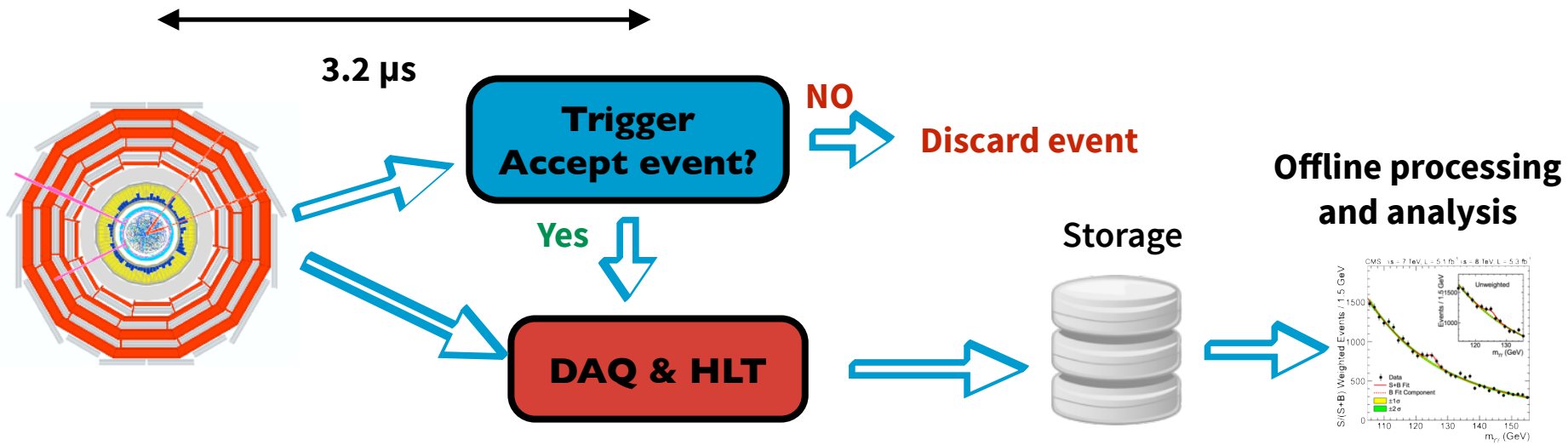



We'll see more on particle identification and reconstruction in the upcoming lectures dedicated to experimental searches for BSM physics

# Trigger

**What is the Trigger?**

- The Trigger is the system that decides online (i.e. in real time) whether to read out or discard the measurements corresponding to each observed interaction
  - If the measurement is accepted it will be stored for offline analysis




- Triggering algorithms are used to identify such events based on a “quick look” to detector data
- Reduce number of stored events to a reasonable amount

# Direct and indirect searches

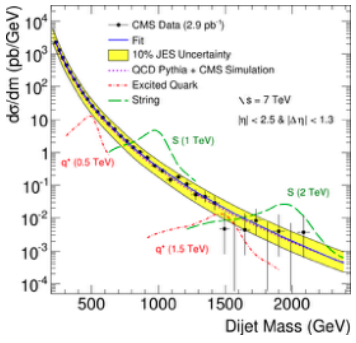
BSM physics requires new symmetries and particles. We can adopt different strategies to look for high mass states or rare processes at the LHC:

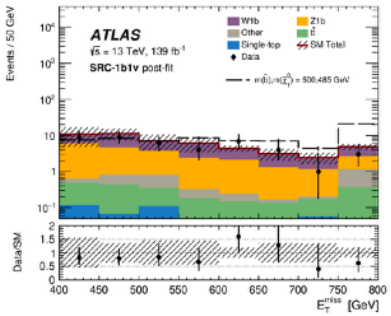
## Direct Searches

Search for decay products of new particles

Resonant states: Look for a bump over SM background

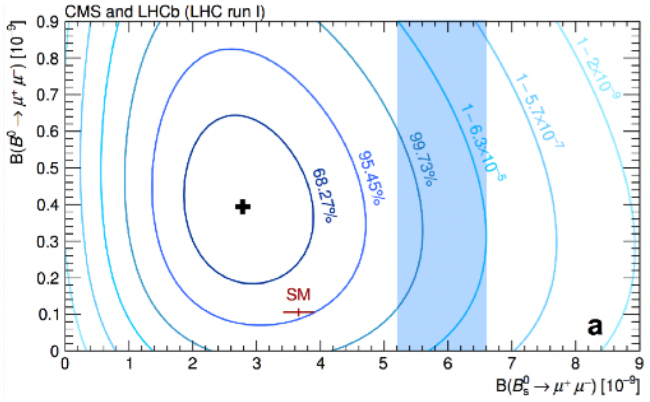
Non-resonant states: look for broad excess over SM background



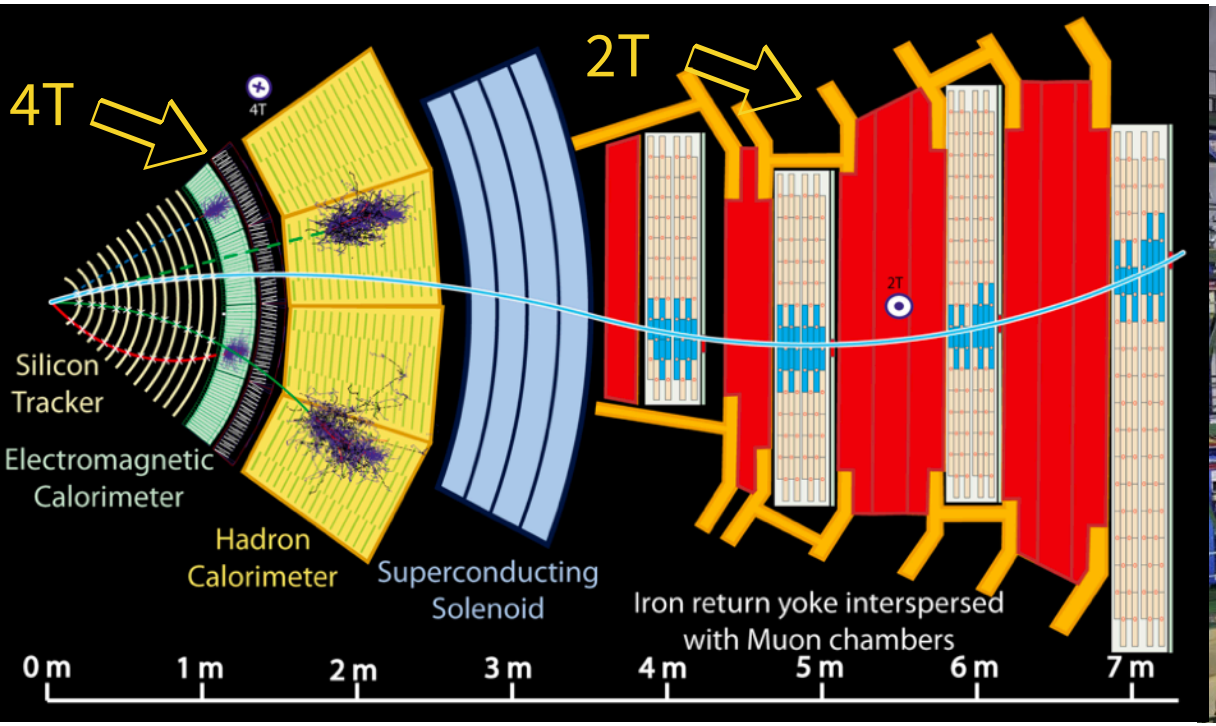

## Indirect Searches

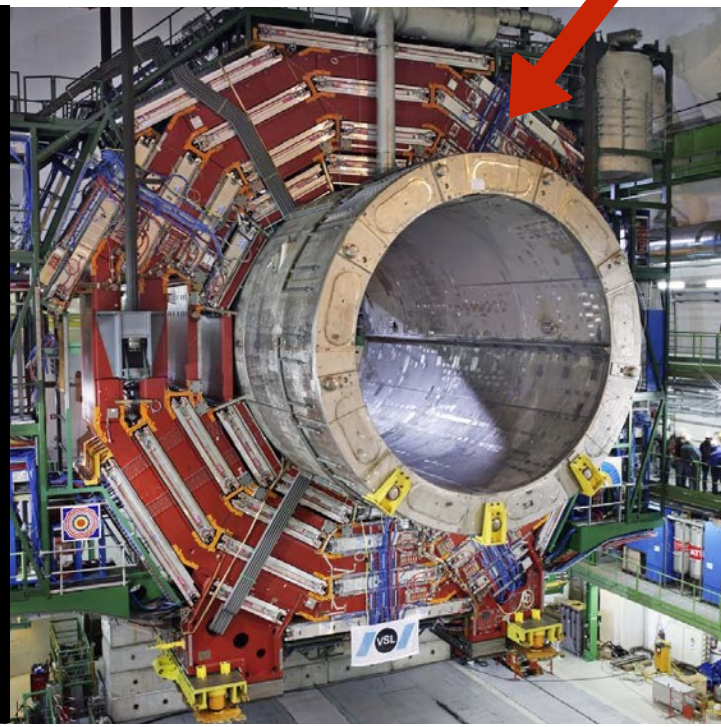
Look for deviations from SM predictions. Gives access to higher energies that those probed directly at the LCH



# Magnet

- CMS - Large radius sinusoid magnet (4 T)
  - Compact and heavy, guarantees uniform field and excellent track resolution
  - Tracker and calorimeter systems tightly fitted inside the magnet volume
  - Iron flux return ensures second momentum measurement for muons



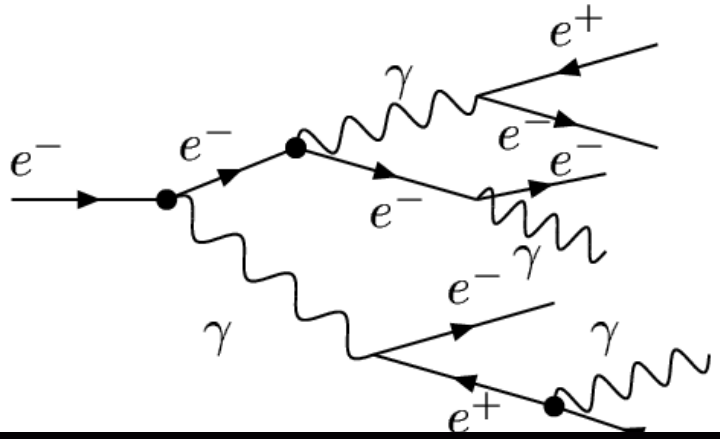



# Electromagnetic calorimeter

**Designed to catch e±/γ showers and measure their energy**

- EM showers developed from bremsstrahlung and electron pair production
- Very good resolution essential for $m_{\gamma\gamma}$ reconstruction and missing momentum reconstruction (important signatures for Higgs boson production and physics beyond SM)

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + (0.30\%)$$




1st term: Stochastic term

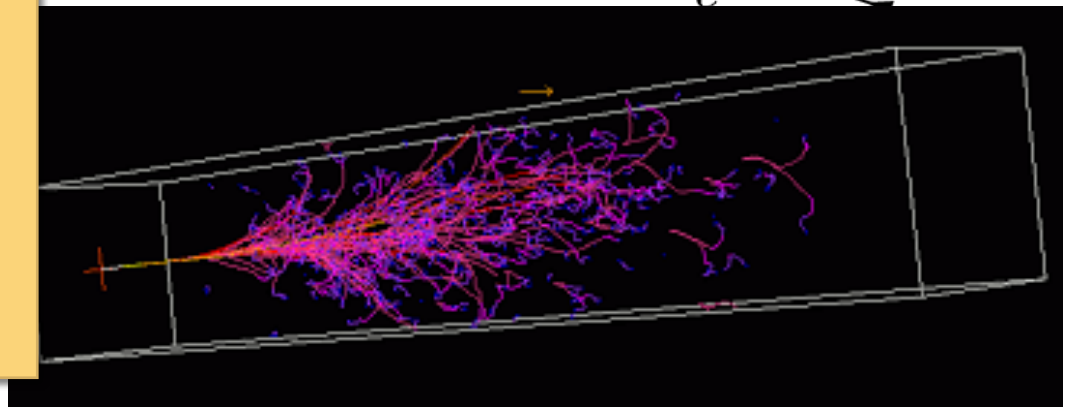
- EM fluctuation in the # of produced and collected e±

2nd term: Noise term

- Includes electronic noise and pileup

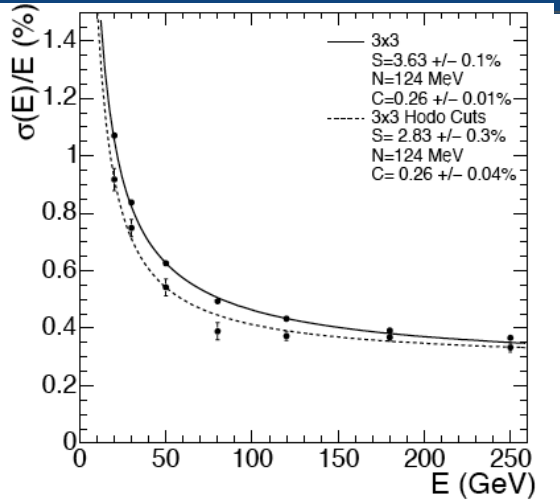
3rd term: constant term

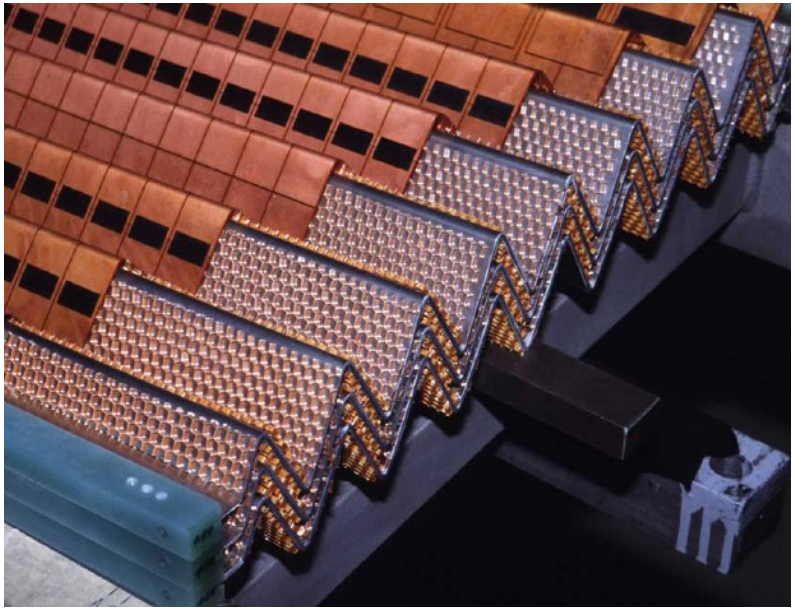
- Accounts for calibrations



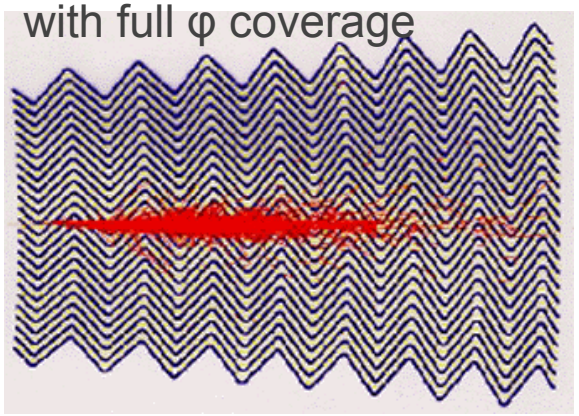
# Electromagnetic calorimeter

- CMS ECAL is a hermetic homogeneous calorimeter
  - made of $PbWO_4$ (lead tungstate) crystals
  - Light signal coming from scintillators is converted in electrical signal by avalanche photodiodes (highly resistant to radiation)



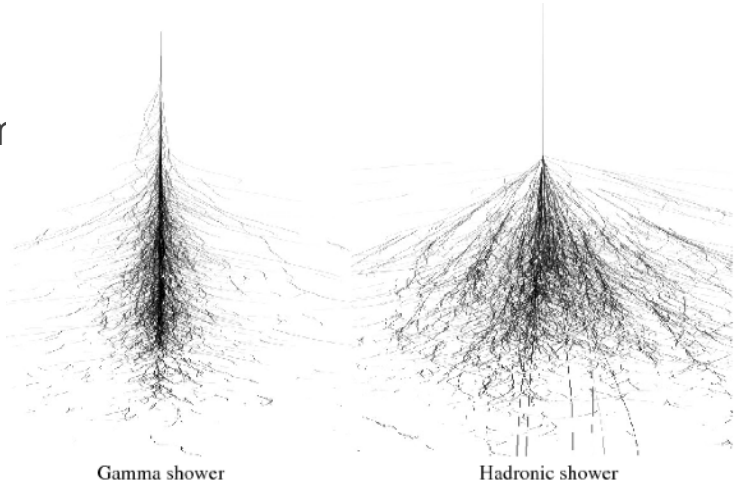



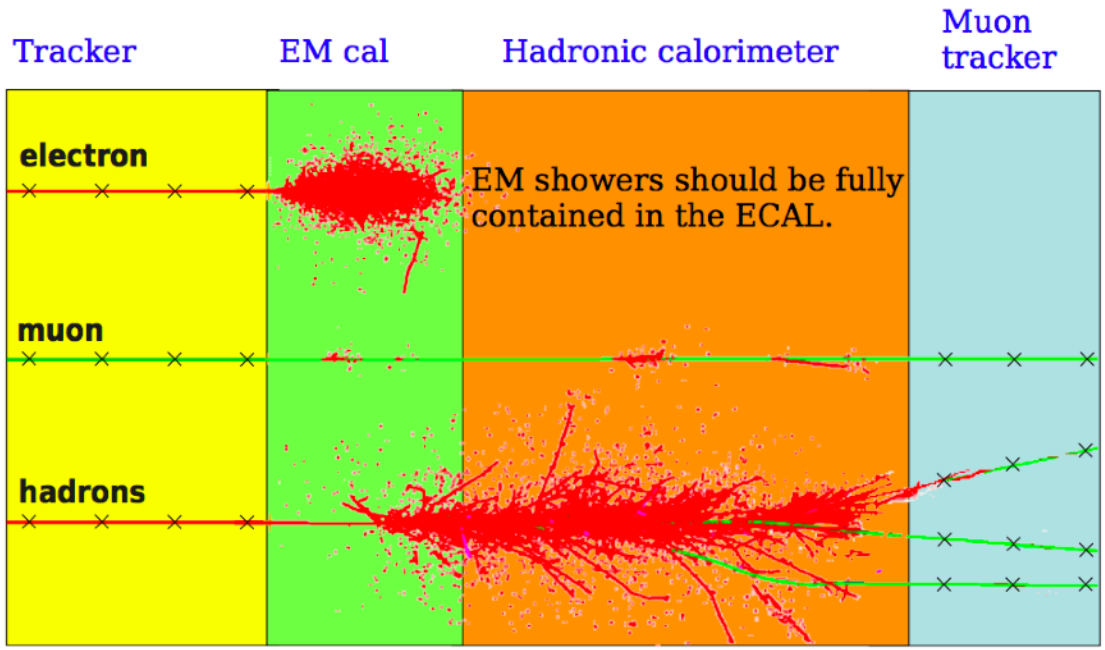
- ATLAS ECAL follows an accordion geometry
  - Sampling  Liquid Ar-Pb calorimeter
  - Very good and fast sampling with full φ coverage



# Hadron Calorimeter

- Designed to contain the hadronic shower
  - Physics behind hadronic shower different from EM sh.
    - Different longitudinal and transverse sh. evolution
  - Electrons and photons shower first and stop first
  - Poorer resolution wrt to ECAL due to large fluctuations of hadronic cascades




**H cascade should be contained within HCAL, without reaching muon tracker**

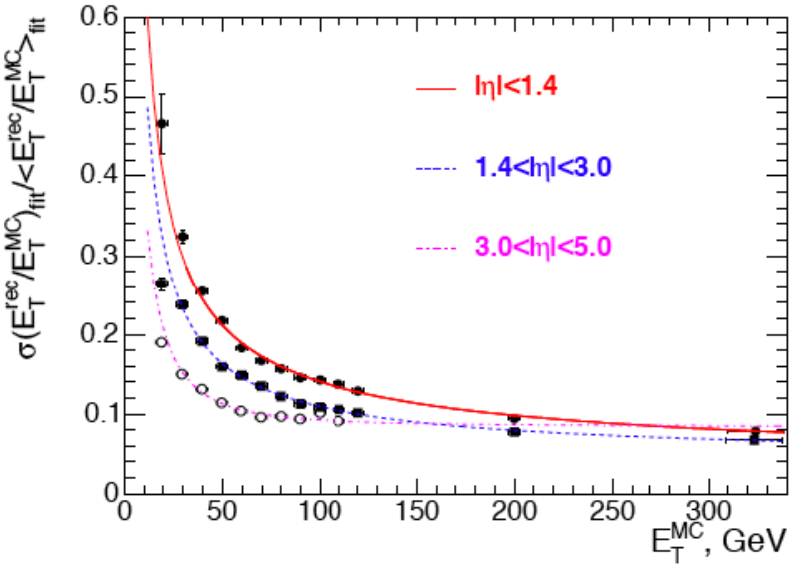
# Hadron Calorimeter

ATLAS uses **iron/copper** as absorber and **plastic scintillator/LAr** as active medium

CMS employs **plastic scintillator** and **brass**

PbWO4: 20 cm
LAr: 86 cm
Pb: 17 cm
Fe: 17 cm
Cu: 15 cm
Brass: 16 cm

**Jet transverse energy resolution**






**Brass from Russian navy shells re-used in the CMS Hadron Calorimeter**

# Muon system

$\Delta p_T/p_T \approx 1/BL^2$

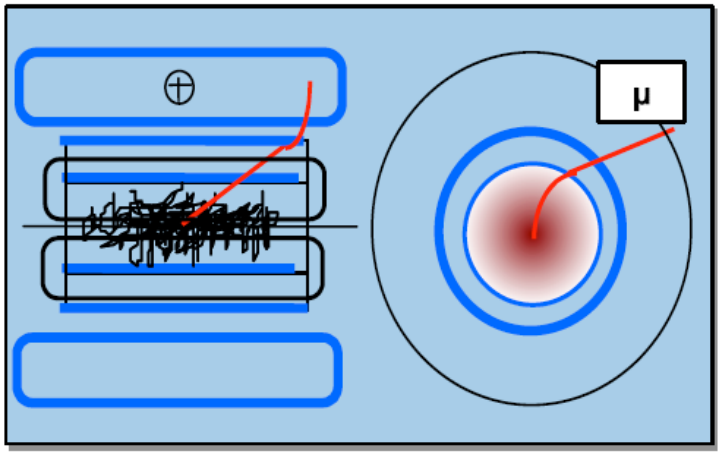
2 different approaches:

ATLAS: large L, low B

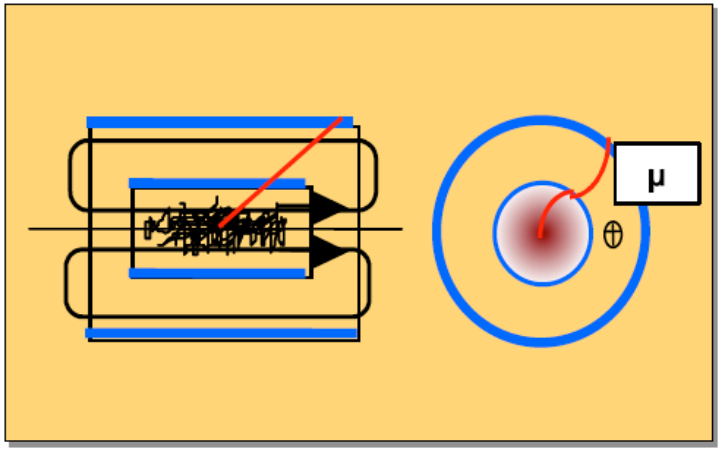
CMS: short L, high B

- Muon system must provide
  - precise muon momentum measurement
  - time measurement of bunch crossing
  - standalone trigger system involving muons
- Good resolution on a broad $p_T$ range (up to 1 TeV)
  - **~10% for $p_T$~1 TeV and ~3% for $p_T$~100 GeV**
- Fast timing resolution **≈ 2 ns**
- Large η coverage

**ATLAS**

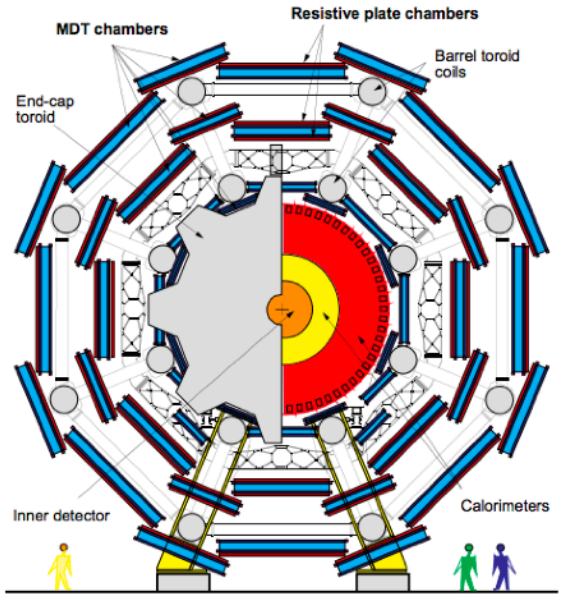



**CMS**

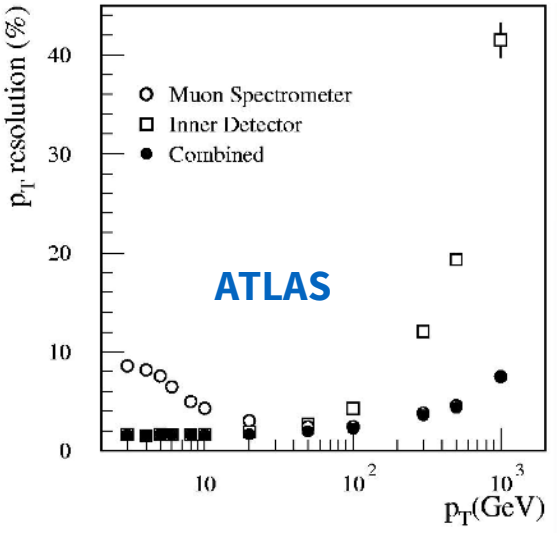


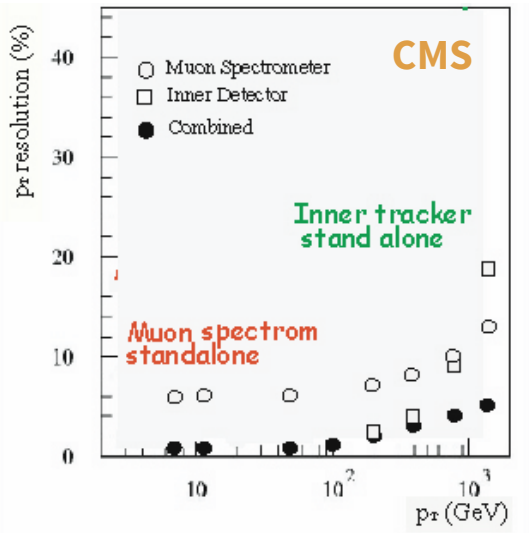
# Muon system technology

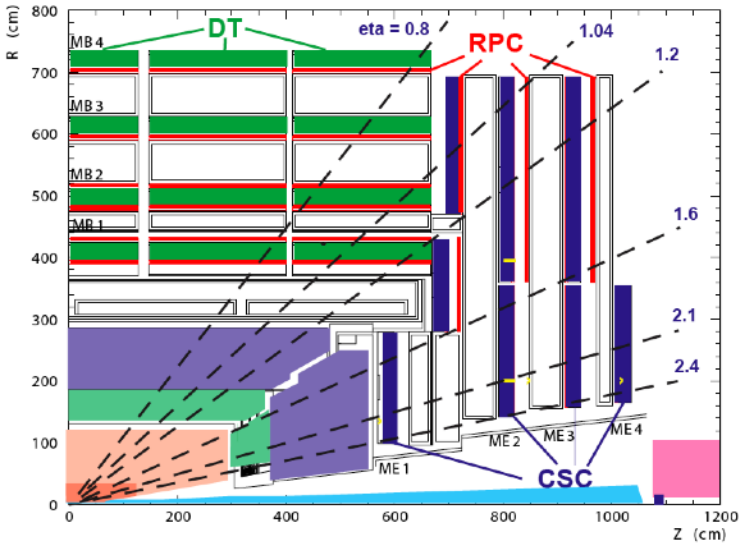
- Same technology:
  - **Drift Tubes (DT)** for precise trajectory measurement **ATLAS**
  - Completed by **Cathod Strips Chambers** (CS
    - Spatial resolution ≈ 80 µm
  - And **Resistive Plate Chambers (RPC)** for time measurements
    - Spatial resolution ≈ 1 cm




CMS



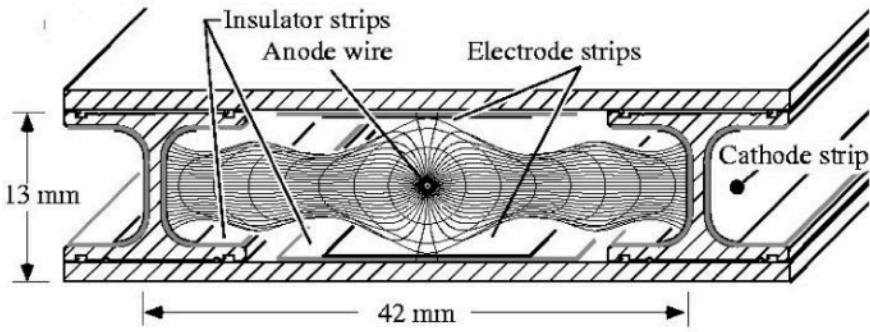



# Drift Tube chambers

**Drift cells consist of a stainless steel anode wire placed between 2 parallel aluminium layers and immersed in a gas volume**

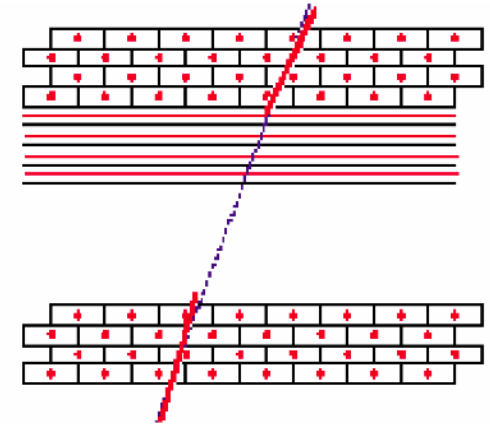
- A muon passing through will knock electrons off the atoms of gas
- The electron follows the electric field ending up at the positively-charged wires
- 3 groups of layers are placed orthogonally giving 2D measurement




**Drift time converted in a drift distance from a wire in a cell**

**(drift velocity ~ 50 µm/ns)**

**NB: R-L ambiguity per cell**



- Gas mixture (Ar/CO2 )
- 400 ns maximum drift time
- 250 µm resolution for single cell
- 100 µm resolution for chamber

# ATLAS/CMS design/performance

| | ATLAS ≡ A Toroidal LHC ApparatuS | CMS ≡ Compact Muon Solenoid |
|---|---|---|
| MAGNET (S) | Air-core toroids + solenoid in inner cavity<br>4 magnets<br>Calorimeters in field-free region | Solenoid<br>Only 1 magnet<br>Calorimeters inside field |
| TRACKER | Si pixels+ strips<br>TRT → particle identification<br>B=2T<br>$\sigma/p_T \sim 3\times10^{-4}\ p_T \oplus 0.01$ | Si pixels + strips<br>No particle identification<br>B=4T<br>$\sigma/p_T \sim 1.5\times10^{-4}\ p_T \oplus 0.005$ |
| EM CALO | Pb-liquid argon<br>$\sigma/E \sim 10\%/\sqrt{E} + 0.007$<br>longitudinal segmentation | $PbWO_4$ crystals<br>$\sigma/E \sim 3\%/\sqrt{E} + 0.003$<br>no longitudinal segm. |
| HAD CALO | Fe-scint. + Cu-liquid argon (10 λ)<br>$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$ | Brass-scint. (~7 λ +catcher)<br>$\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$ |
| MUON | Air → $\sigma/p_T \sim 2\%$(@50GeV) to 10% (@1 TeV)<br>standalone | Fe → $\sigma/p_T \sim 1\%$ (@50 GeV) to 10% (@1 TeV)<br>combining with tracker |

# Higgs production at LEP

