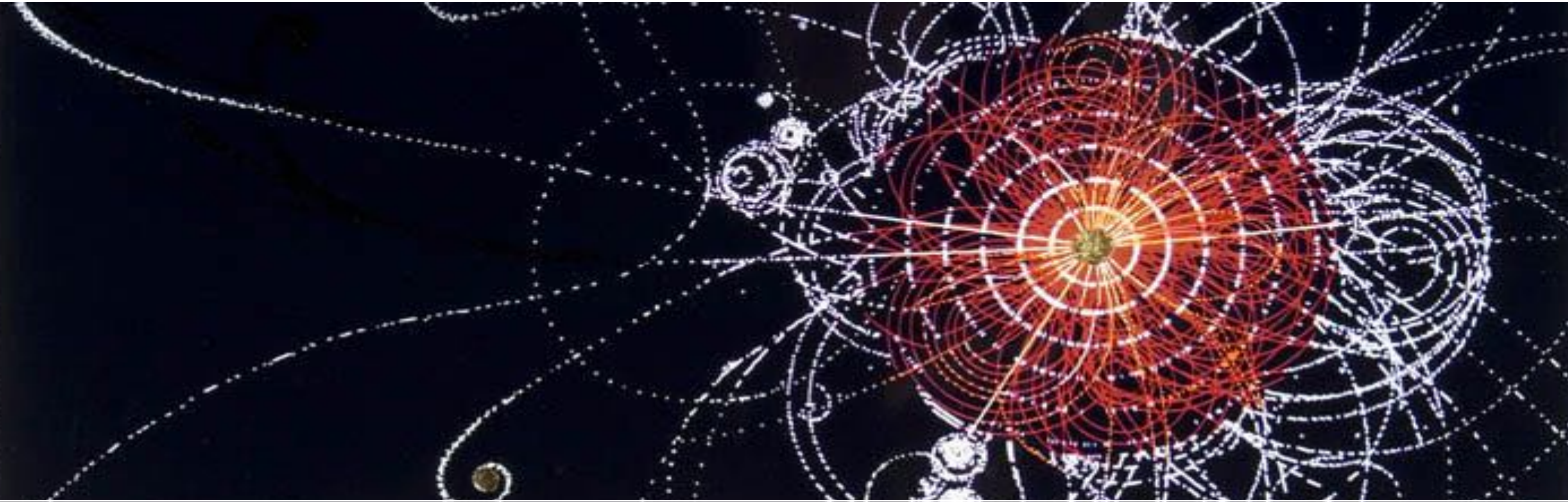
The Higgs boson discovery



Kern-und Teilchenphysik II

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4th of July, 2012 - The Higgs boson discovery

A discovery worth a Nobel Prize

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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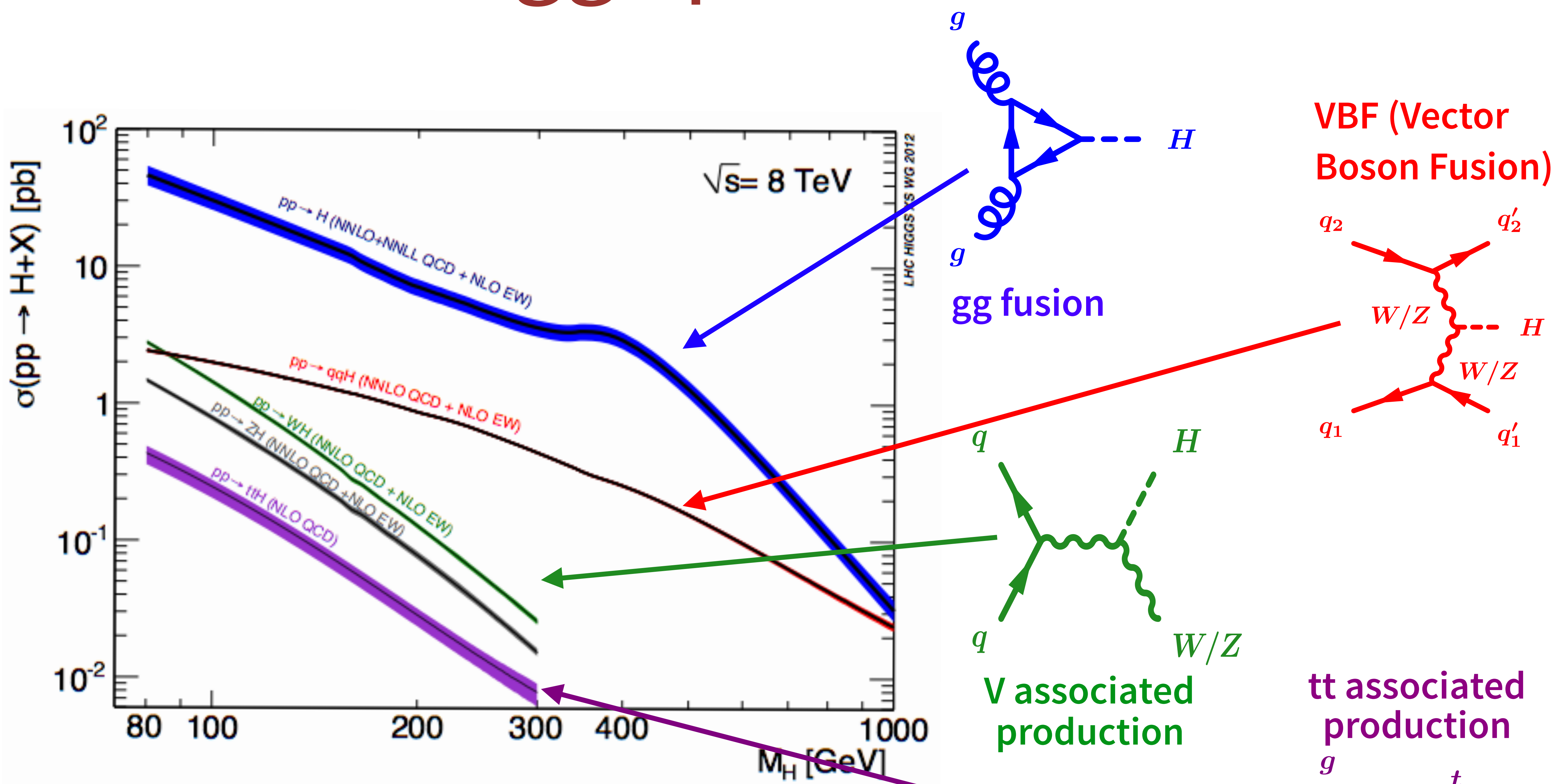
The Nobel Prize in Physics 2013

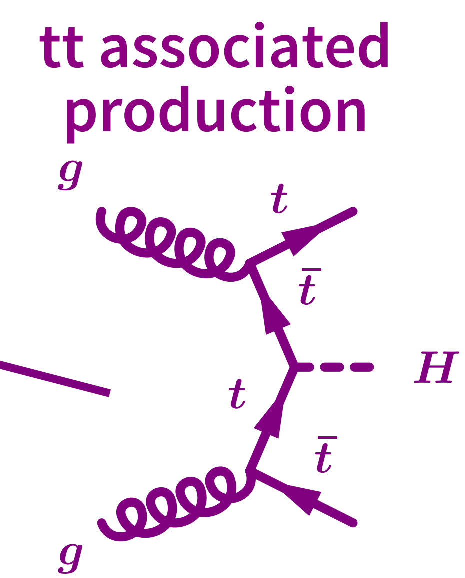
Photo: A. Mahmoud
François Englert
Prize share: 1/2

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"*

Higgs production at the LHC



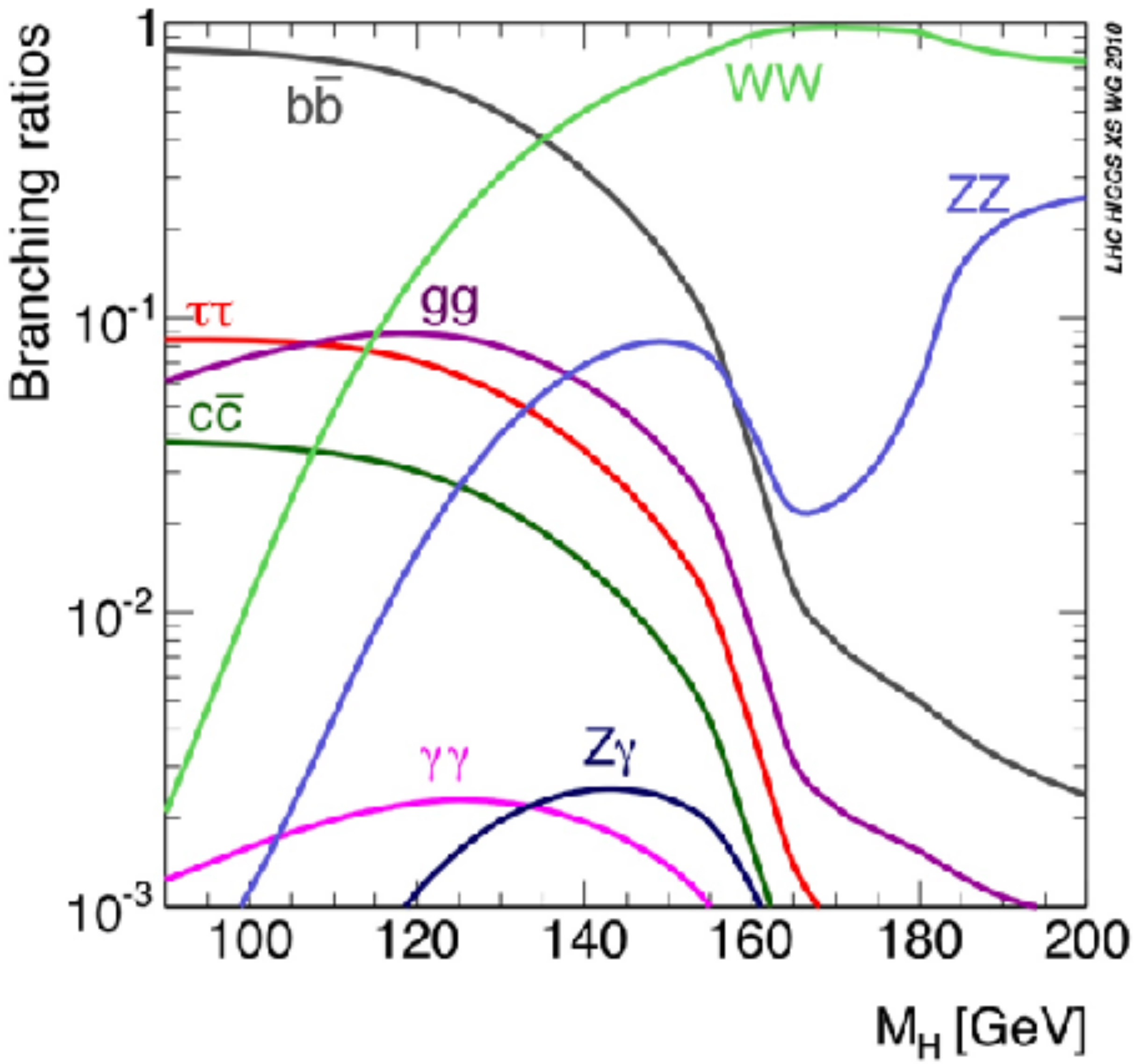


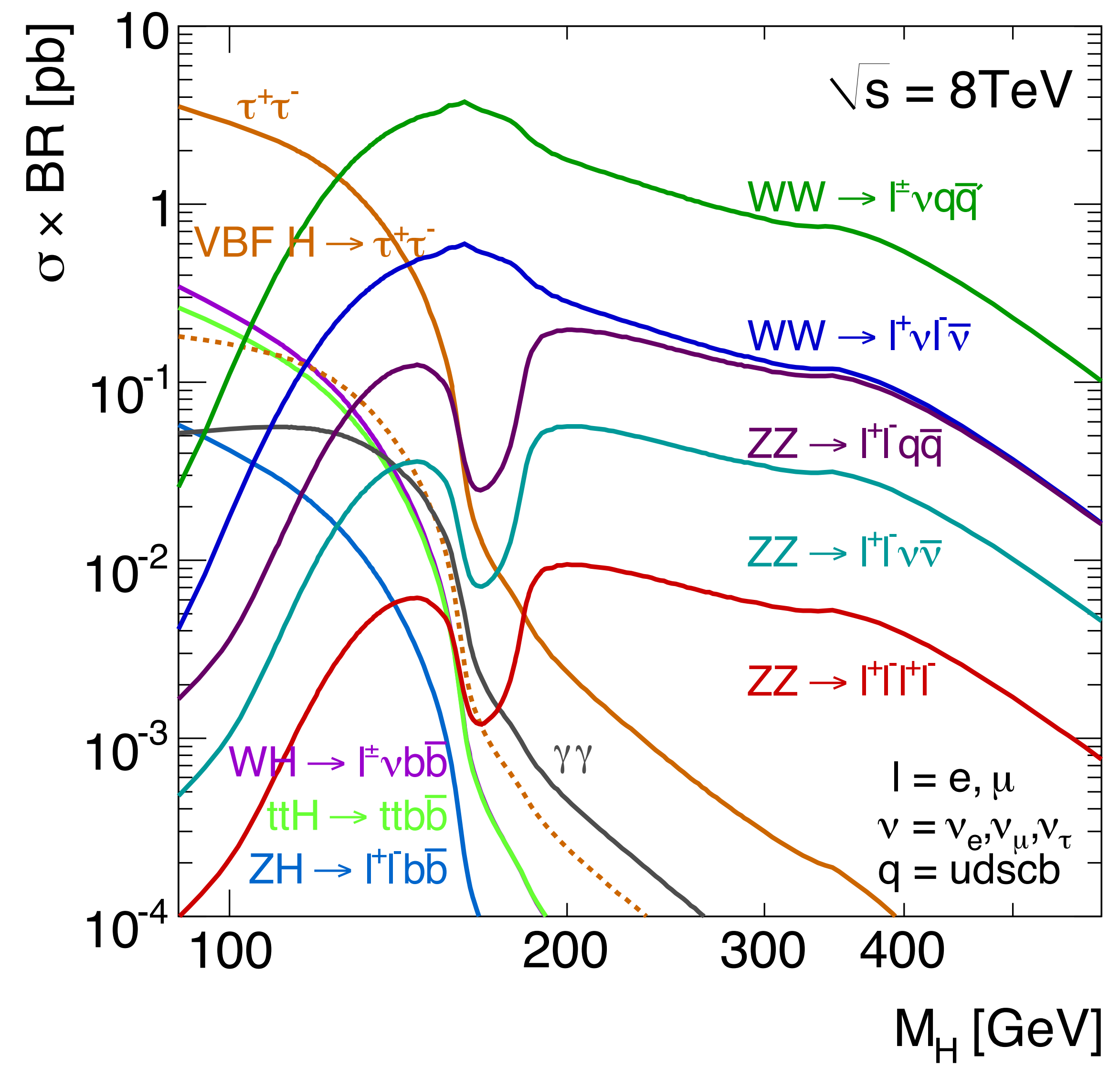
Production mechanisms:

gg fusion, VV fusion, W and Z associated production, tt associated production

Gluon fusion is the dominant production mode

Discovery channels





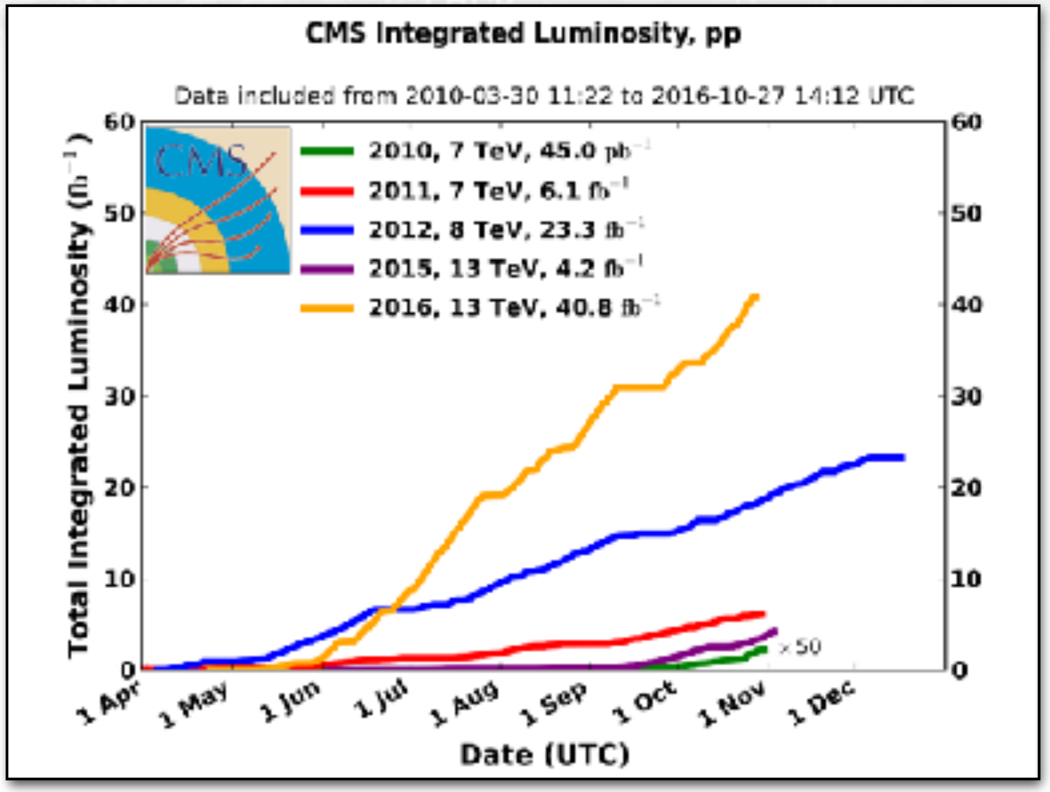
- H→bb: highest branching ratio (~58% @ 125 GeV)
  - Inclusive H→bb search not feasible due to overwhelming QCD background
- Instead H→ZZ, H→γγ has lower BR but very clean signature!

How can we trace the Higgs boson at the LHC?

The Large Hadron Collider

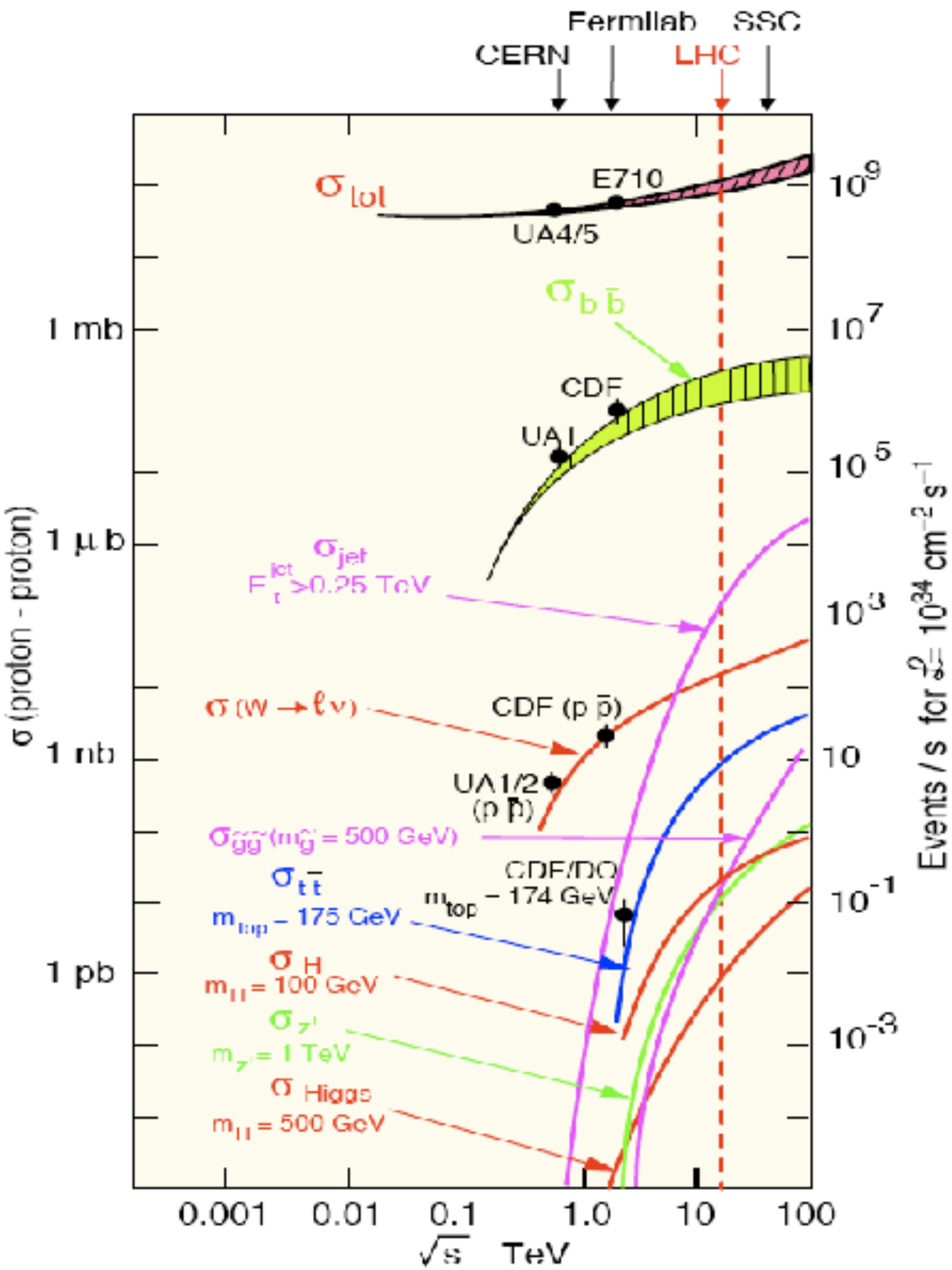
Proton-proton collider situated at CERN, on the Swiss-French border

27 km of circumference



- LHC accelerates protons at $\sqrt{s}$ = 13 TeV centre of mass energy (will reach 14 TeV, 7 times higher energy than Tevatron)
  - Discovery machine: new particles up to the TeV scale
- Collides bunch of protons every 25 ns (**40 MHz!**)
- Luminosity: ~$2*10^{-34}cm^{-2}\,s^{-1}$
- ~100 times higher than Tevatron, suitable for searching rare processes

LHC Physics rates



Expected production rate for process X:

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

Process	Cross section (nb) @ 14 TeV	Production rates (Hz) @ $\mathcal{L} = 10^{34}$ cm^{-2}s^{-1}
inelastic	10^8	10^9
$b\bar{b}$	$5{\times}10^5$	$5{\times}10^6$
$W \to \ell\nu$	15	150
$Z \to \ell\ell$	2	20
$t\bar{t}$	1	10
H	0.05	0.5

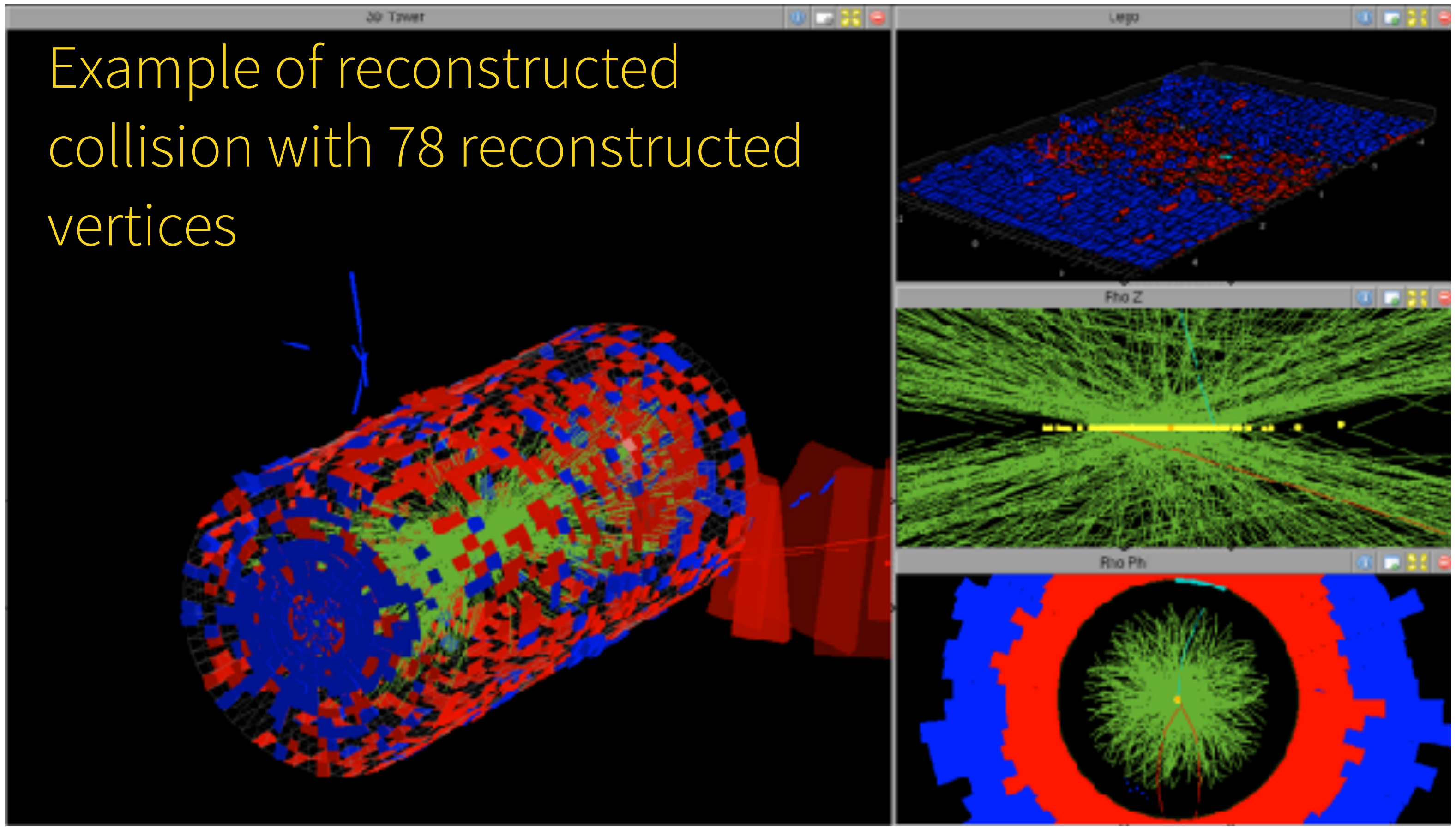
Many **orders of magnitude** between QCD background and primary physics channels rates

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

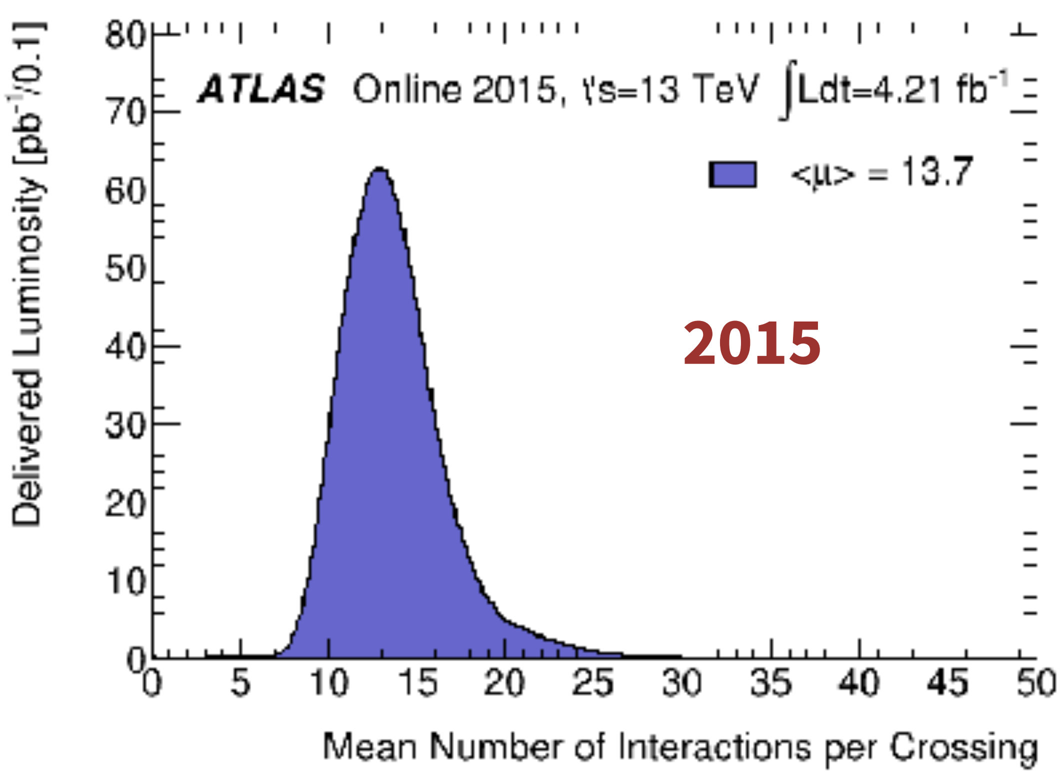
Even if it would be feasible, saving all events at hadron collider is not useful

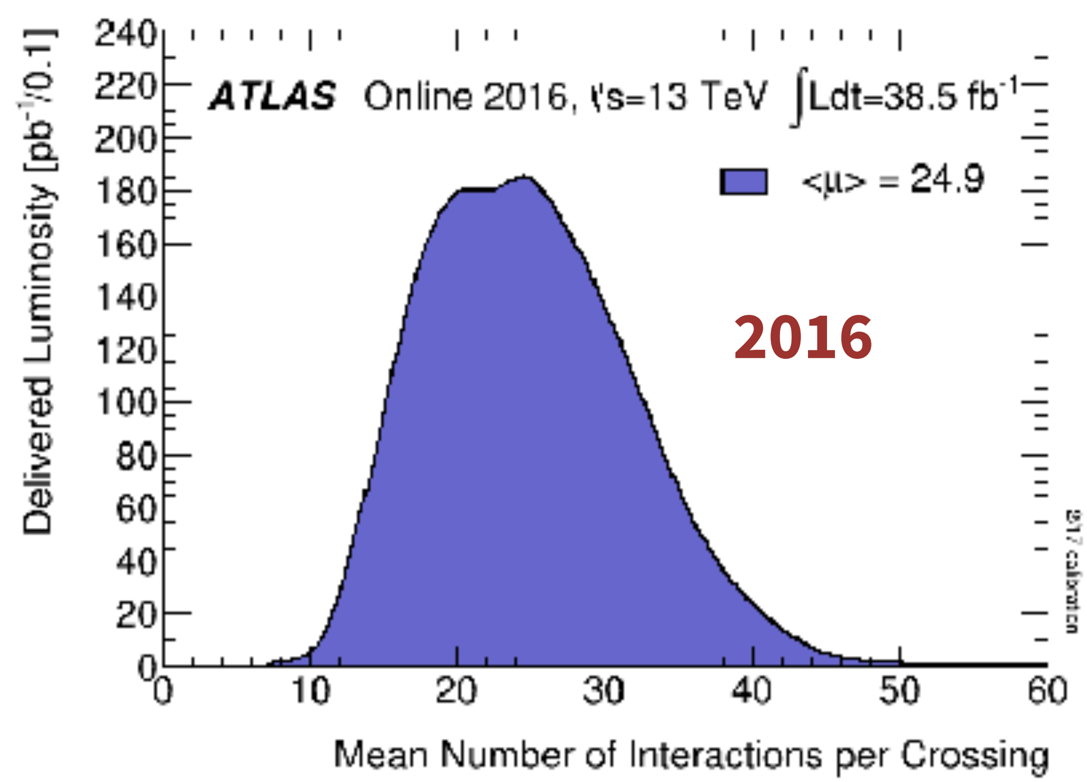
from SOTDAQ2017 - A.Thea

Pileup

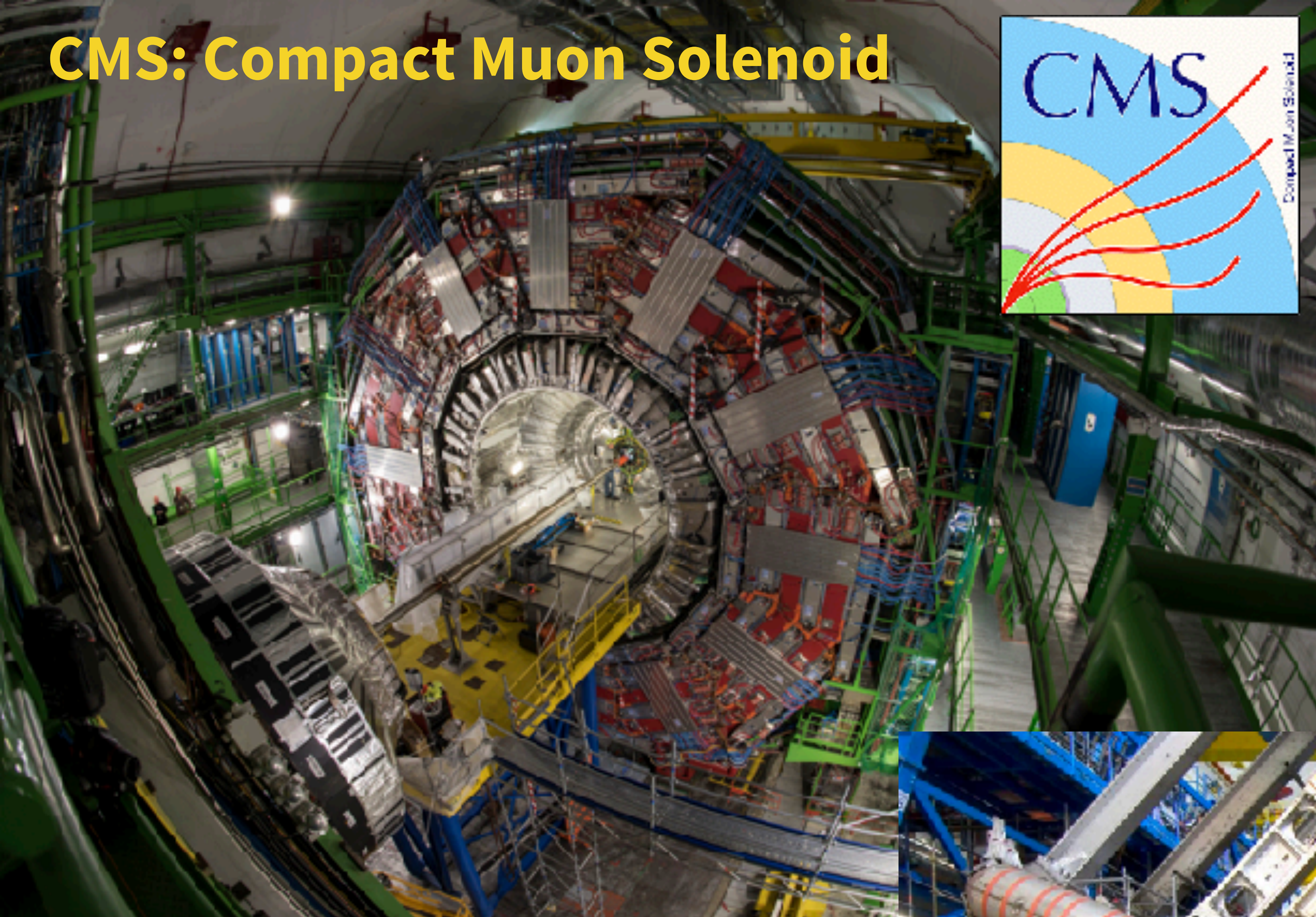


10^{19} interactions/s means ~ 25 overlapping inelastic interactions/bunch crossing **(Pileup)**

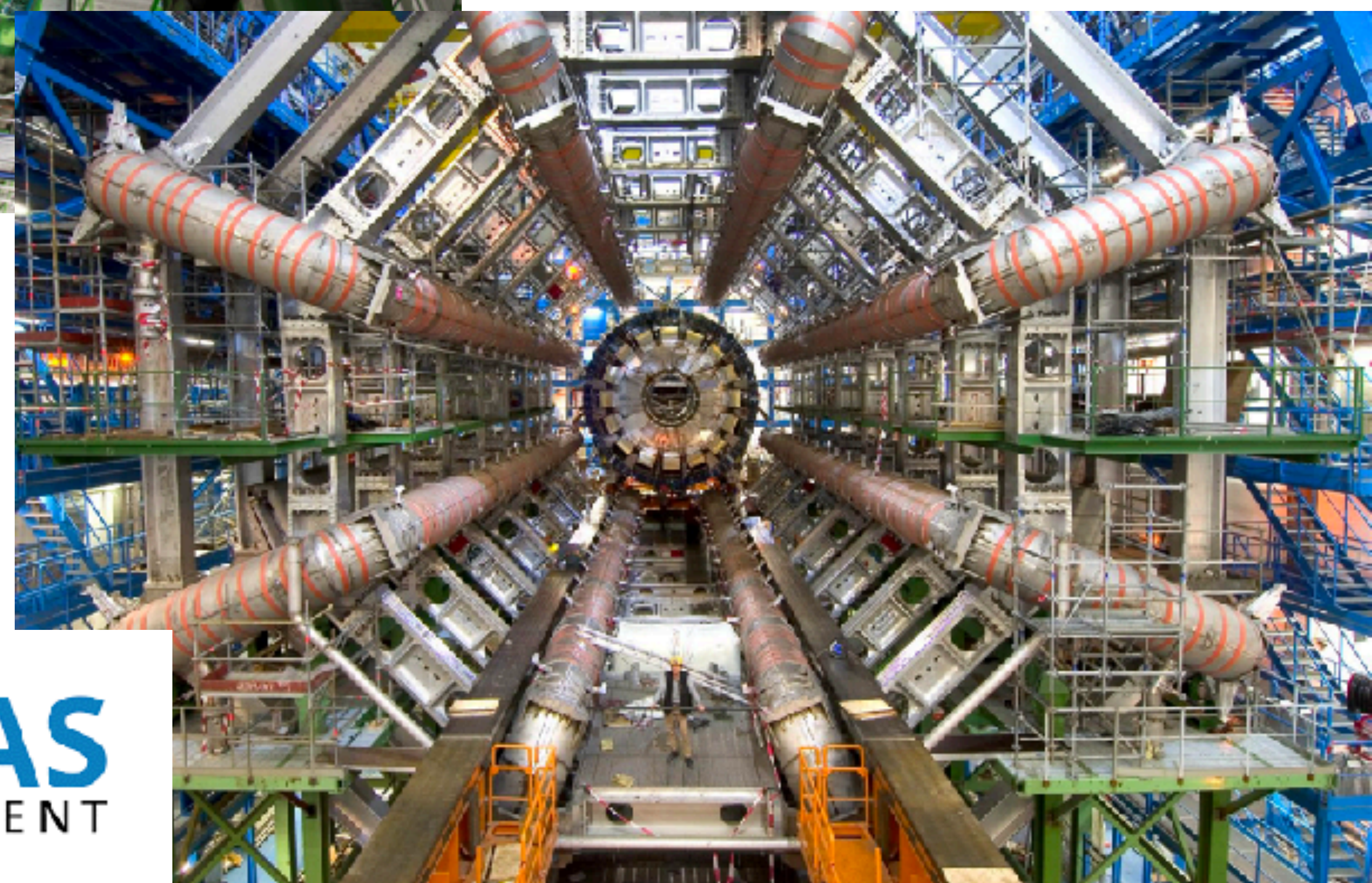




CMS & ATLAS



2 multi purpose detectors at LHC: ATLAS and CMS, the biggest detectors built so far



ATLAS: A Toroidal LHC ApparatuS

General purpose detectors : 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**

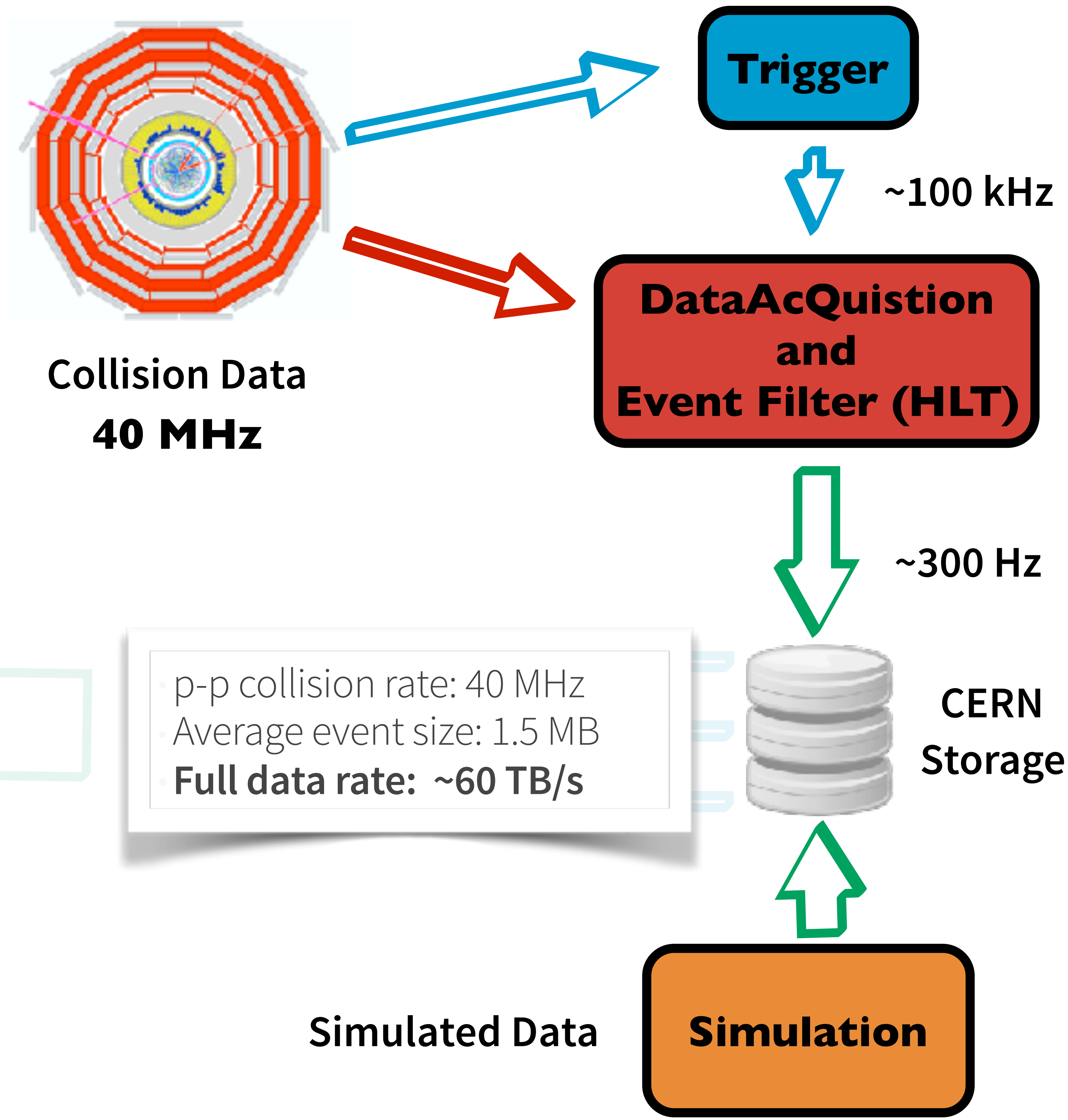
General purpose detectors designed to cover a wide range of physics

- Standard Model measurements
  - QCD jet cross sections and σ_s
  - 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 ($B_S \to \mu\mu$)
- Heavy Ions:
  - Phase transition from hadronic matter to quark-gluon plasma

Data flow at LHC experiments

Data Flow

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



Data flow at LHC experiments

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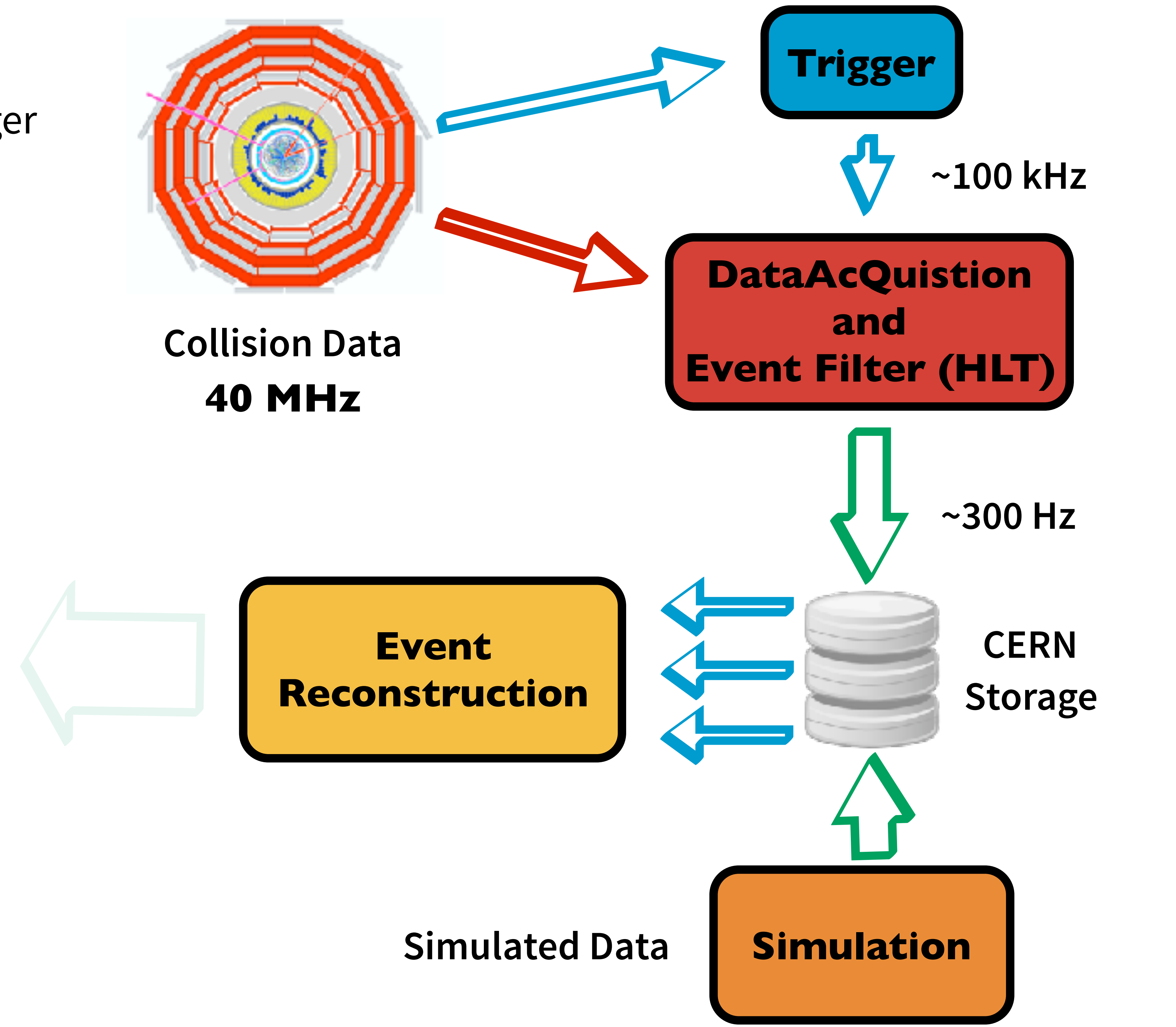

Data flow at LHC experiments

Data Flow

- Event detection + trigger selection/simulation
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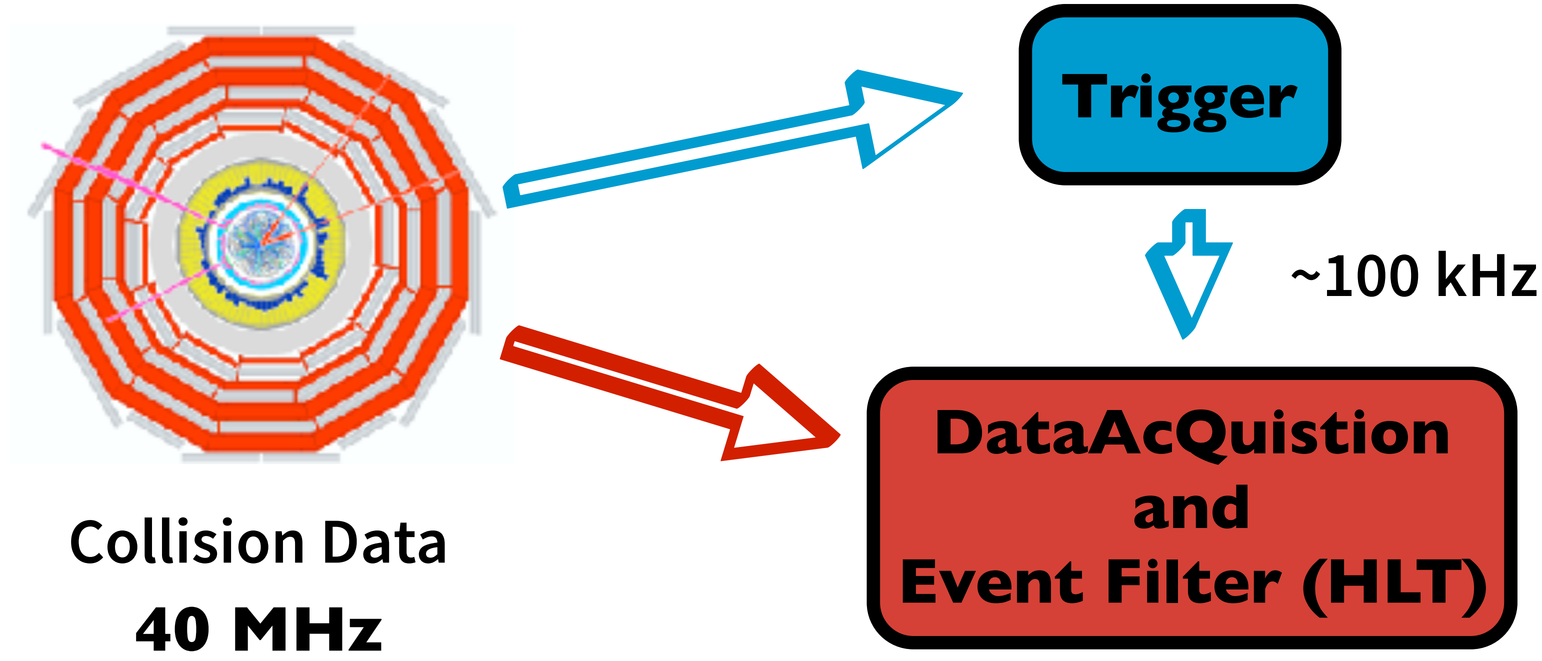
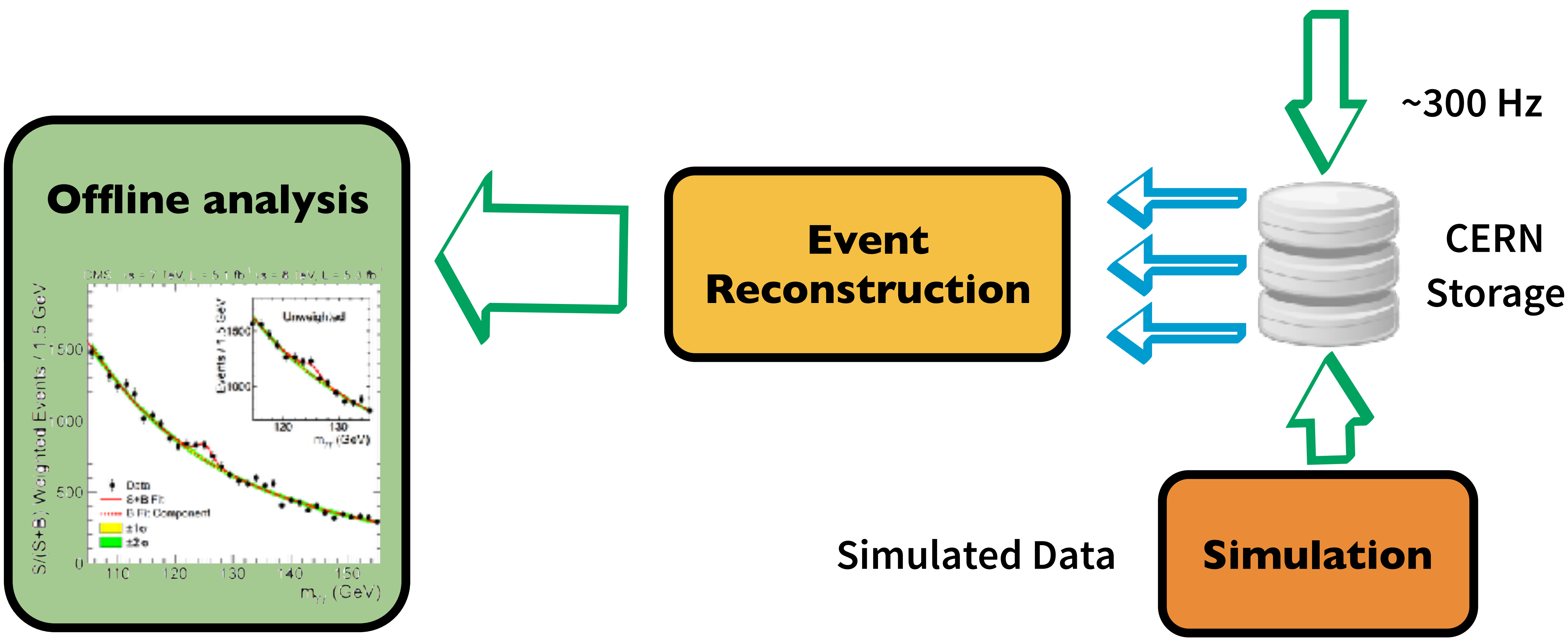
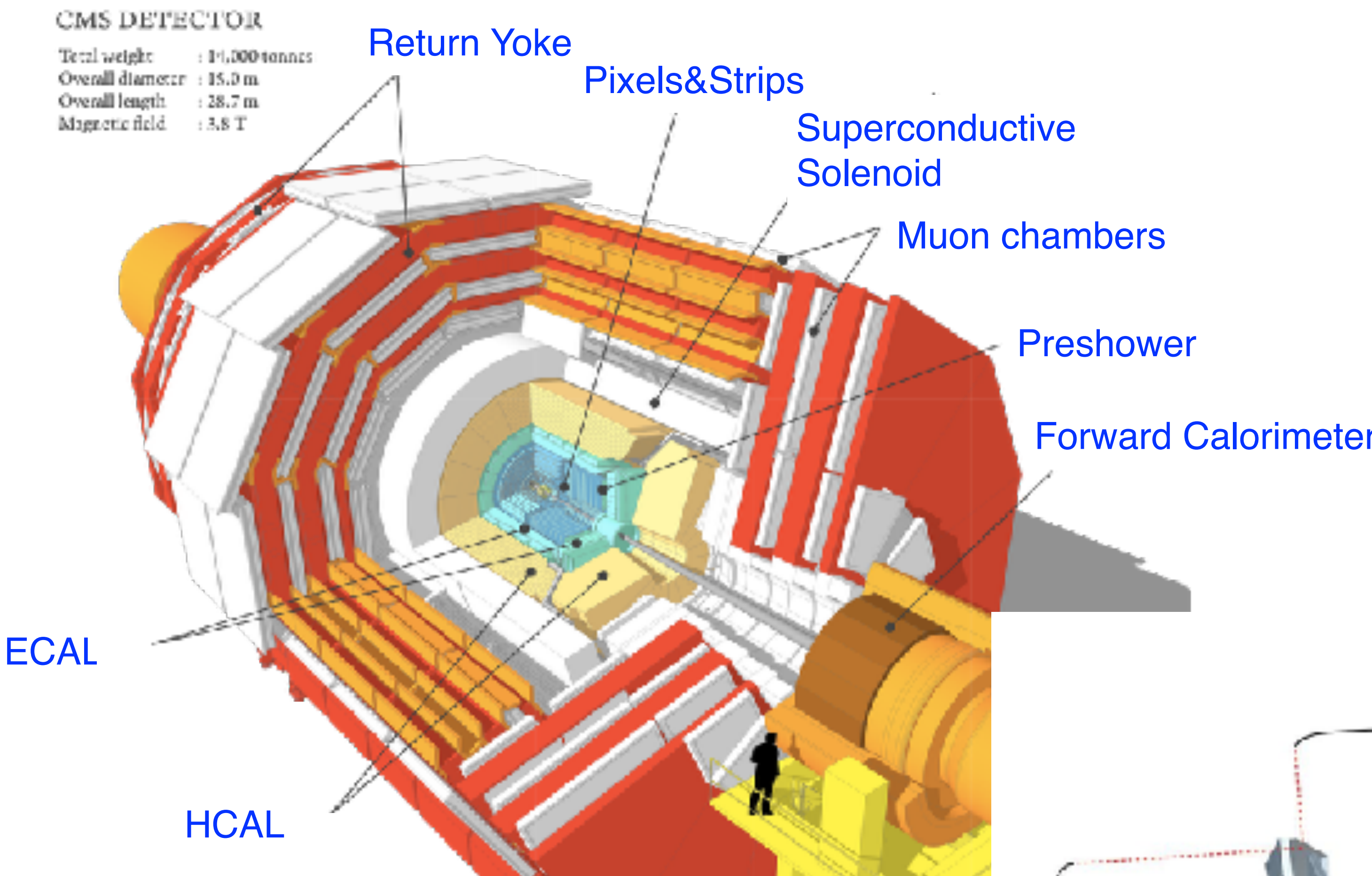




Detector

ATLAS and CMS

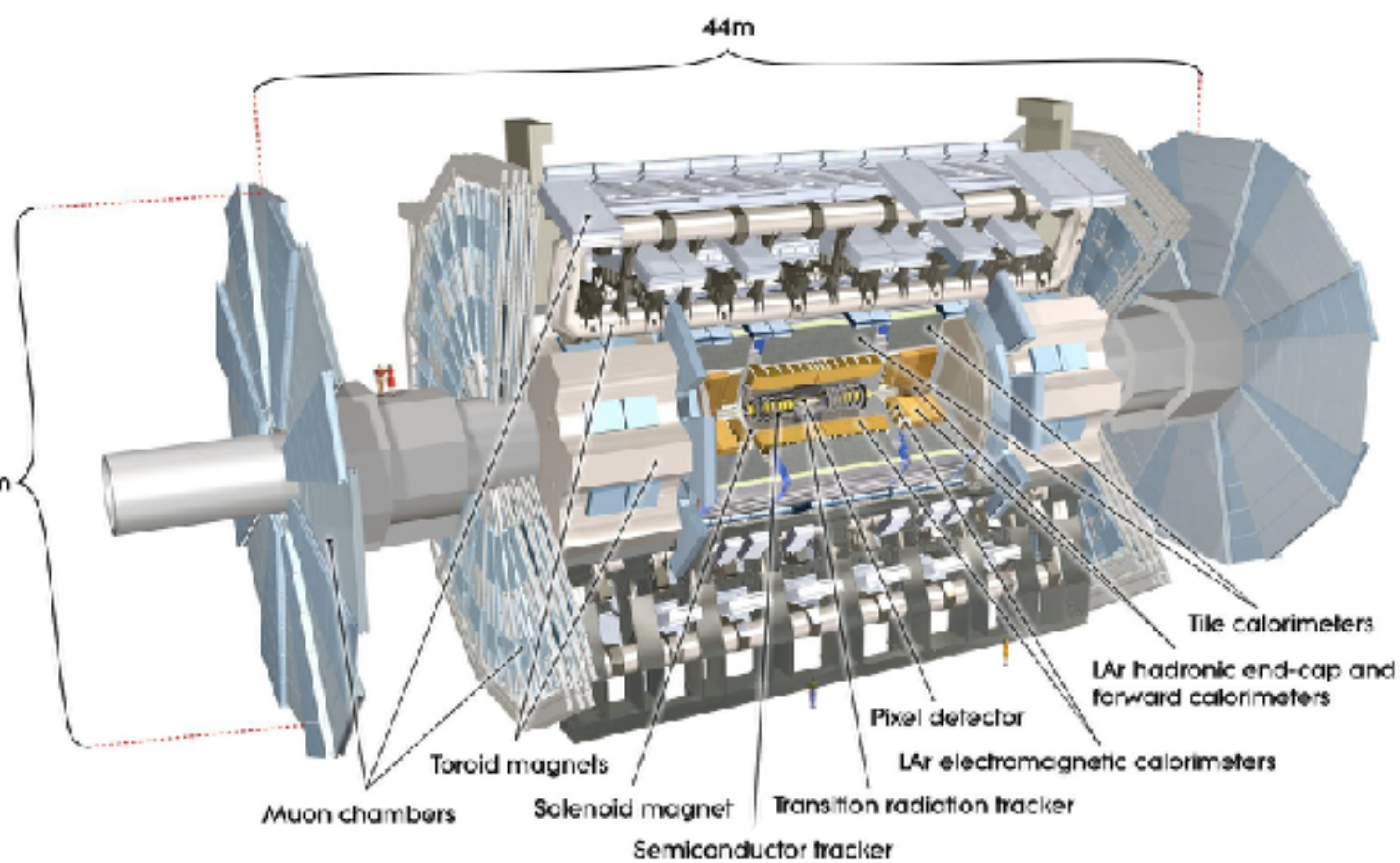


CMS

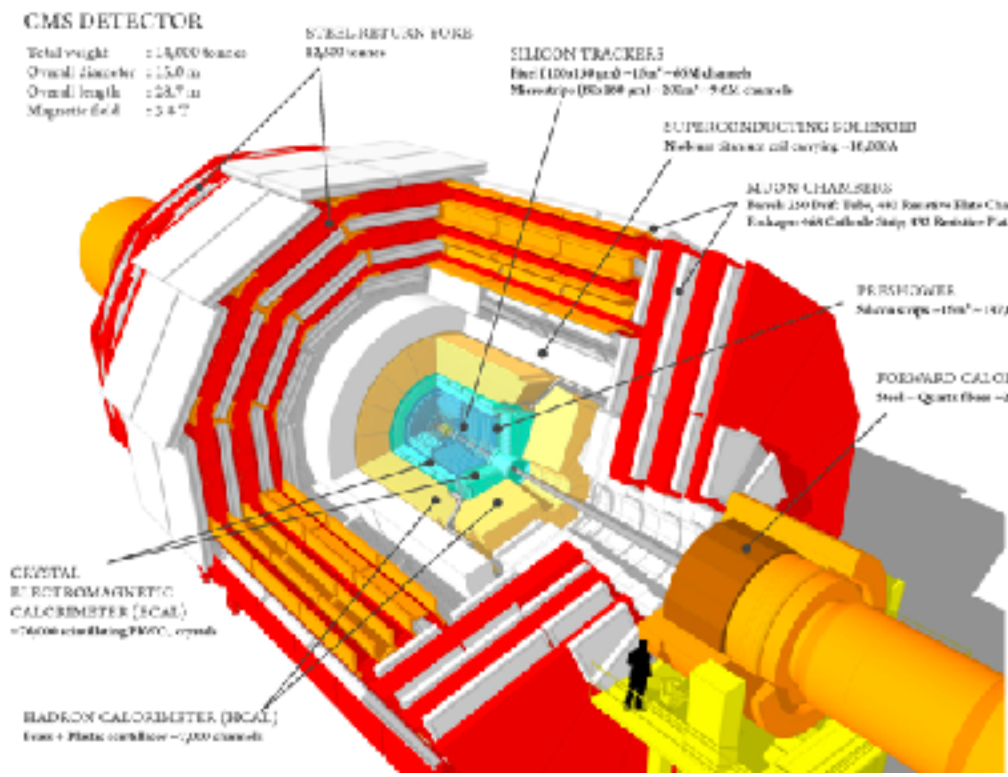
- Tracker: $\sigma(p_T)/p_T \sim 1.5 \cdot 10^{-4} p_T + 0.005$
- ECAL: $\sigma_E/E \sim 3\%/\sqrt{E\,[\mathrm{GeV}]} \oplus 0.5\%$
- HCAL: $\sigma_E/E \sim 100\%/\sqrt{E\,[\mathrm{GeV}]} \oplus 5\%$
- Trk+Mu: 1%÷10% [50 GeV-1 TeV]

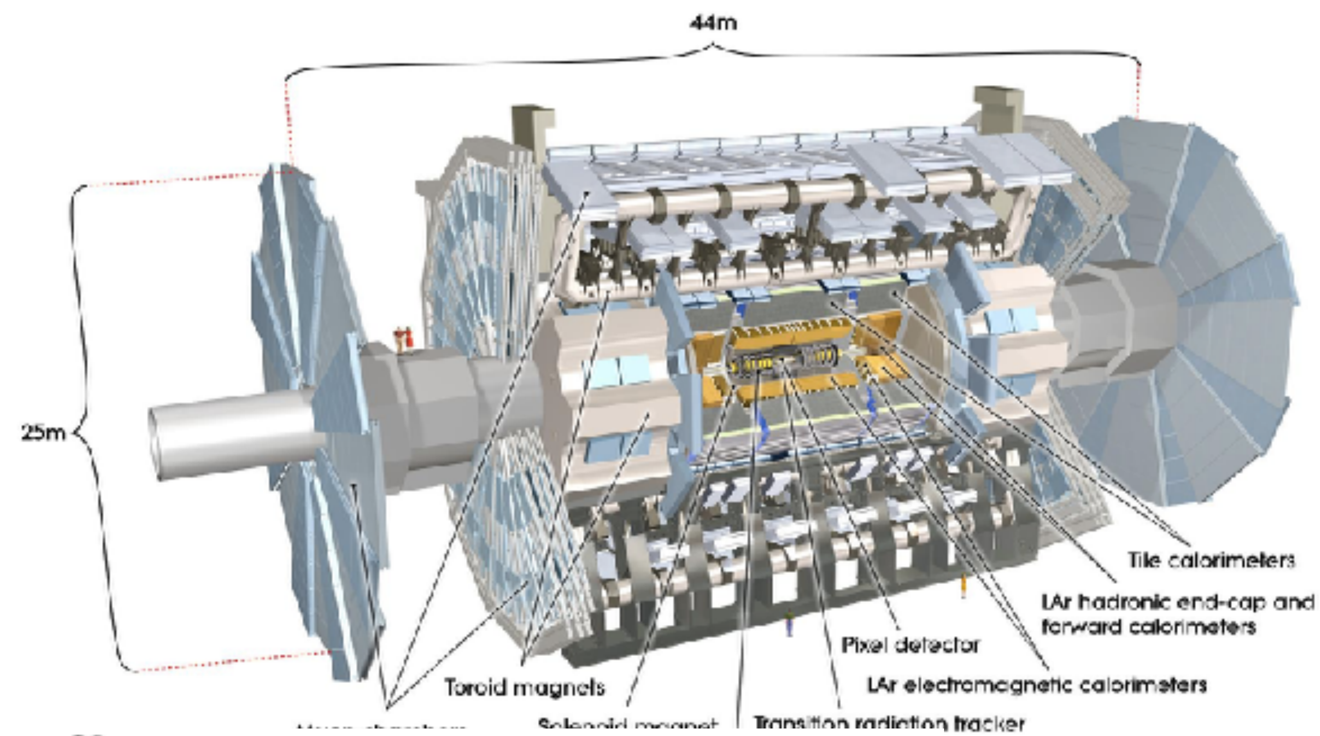
ATLAS

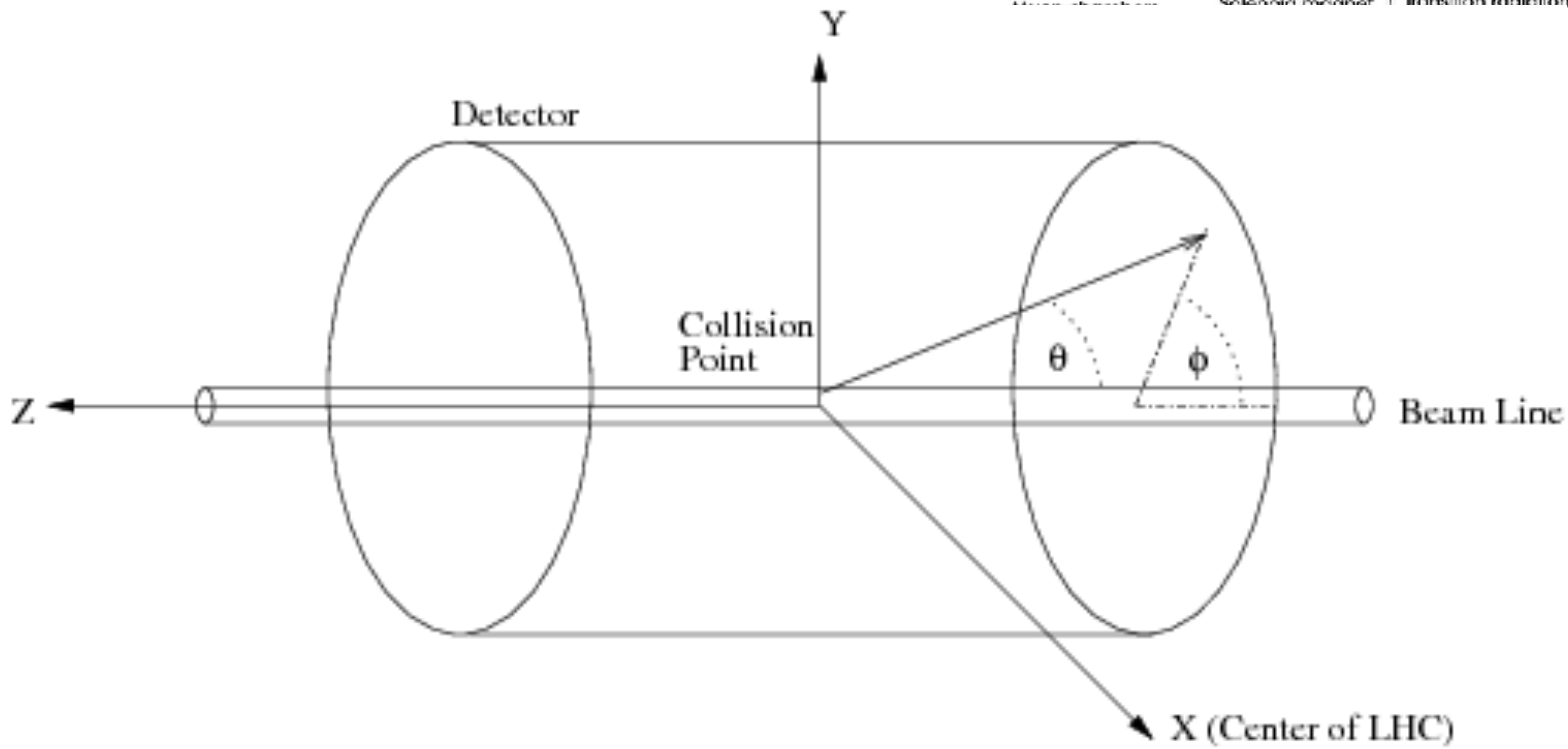
- Tracker: $\sigma(p_T)/p_T \sim 5 \cdot 10^{-4} p_T + 0.01$
- ECAL: $\sigma_E/E \sim 10\%/\sqrt{E\,[\mathrm{GeV}]} \oplus 0.7\%$
- HCAL: $\sigma_E/E \sim 50\%/\sqrt{E\,[\mathrm{GeV}]} \oplus 3\%$
- Trk+Mu: 2%÷10% [50 GeV-1 TeV]



ATLAS and CMS: Coordinate system

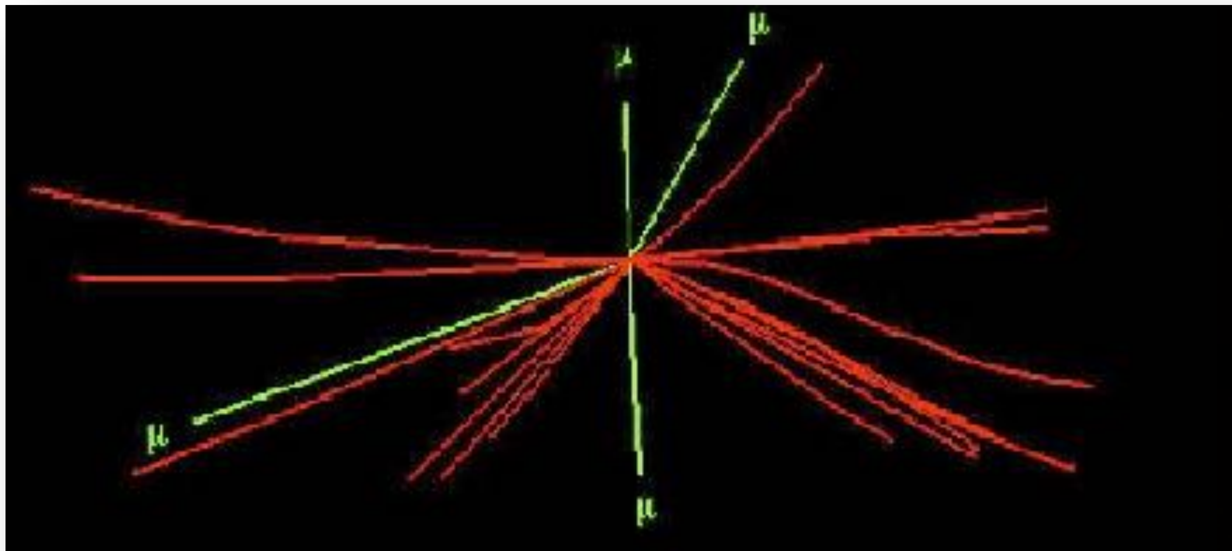






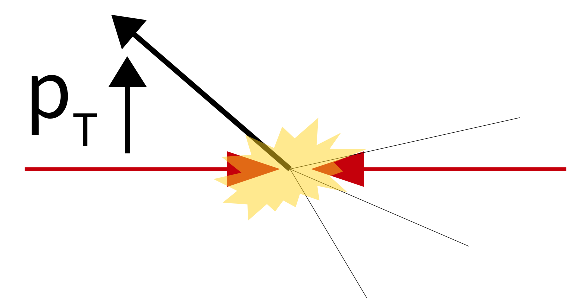
How to identify interesting events?

Only high-p_T tracks Higgs → 4μ

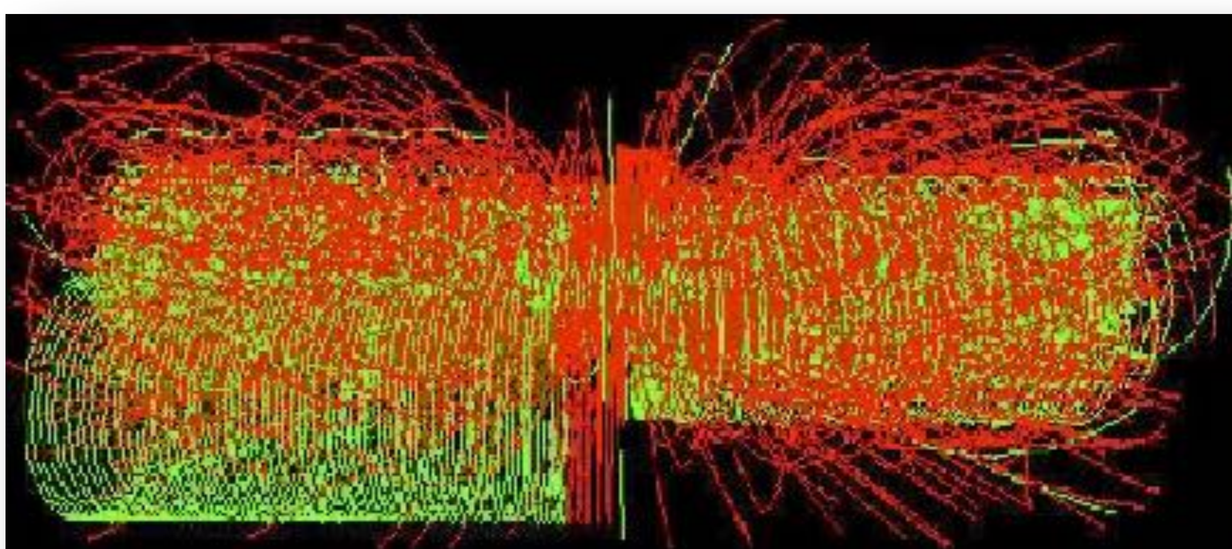


Example: Higgs → 4μ events

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



All tracks



In practice:

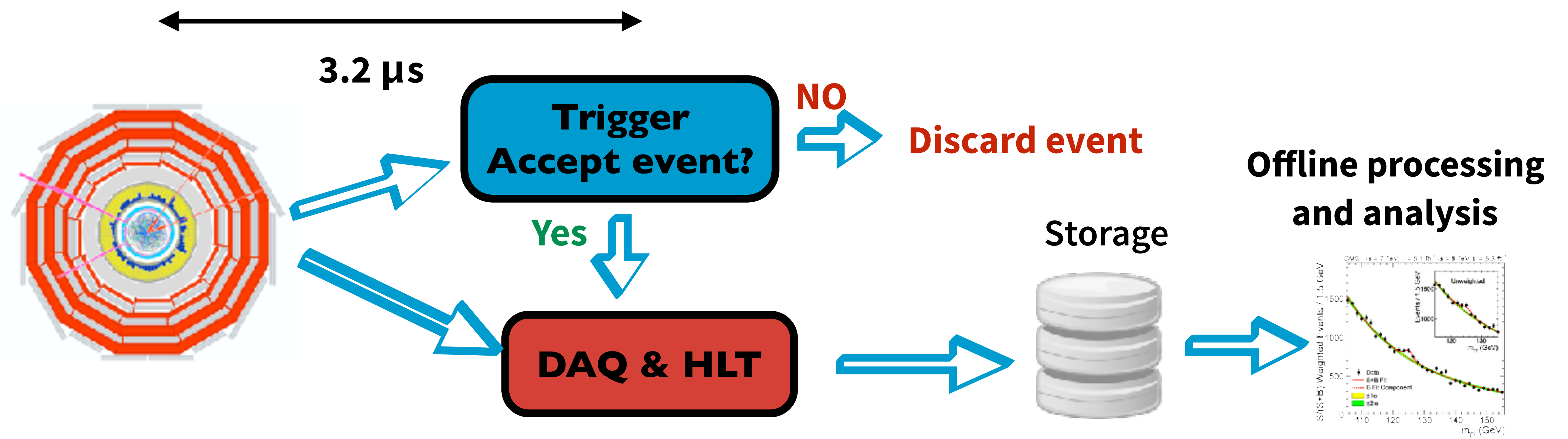
- Event hidden under tons of know physics
- Exploit the physics signature to identify the underlying Higgs decay
  - 4 high-momentum **μ**

Interesting physics usually is high pT

from ISOTDAQ2017 - A.Thea

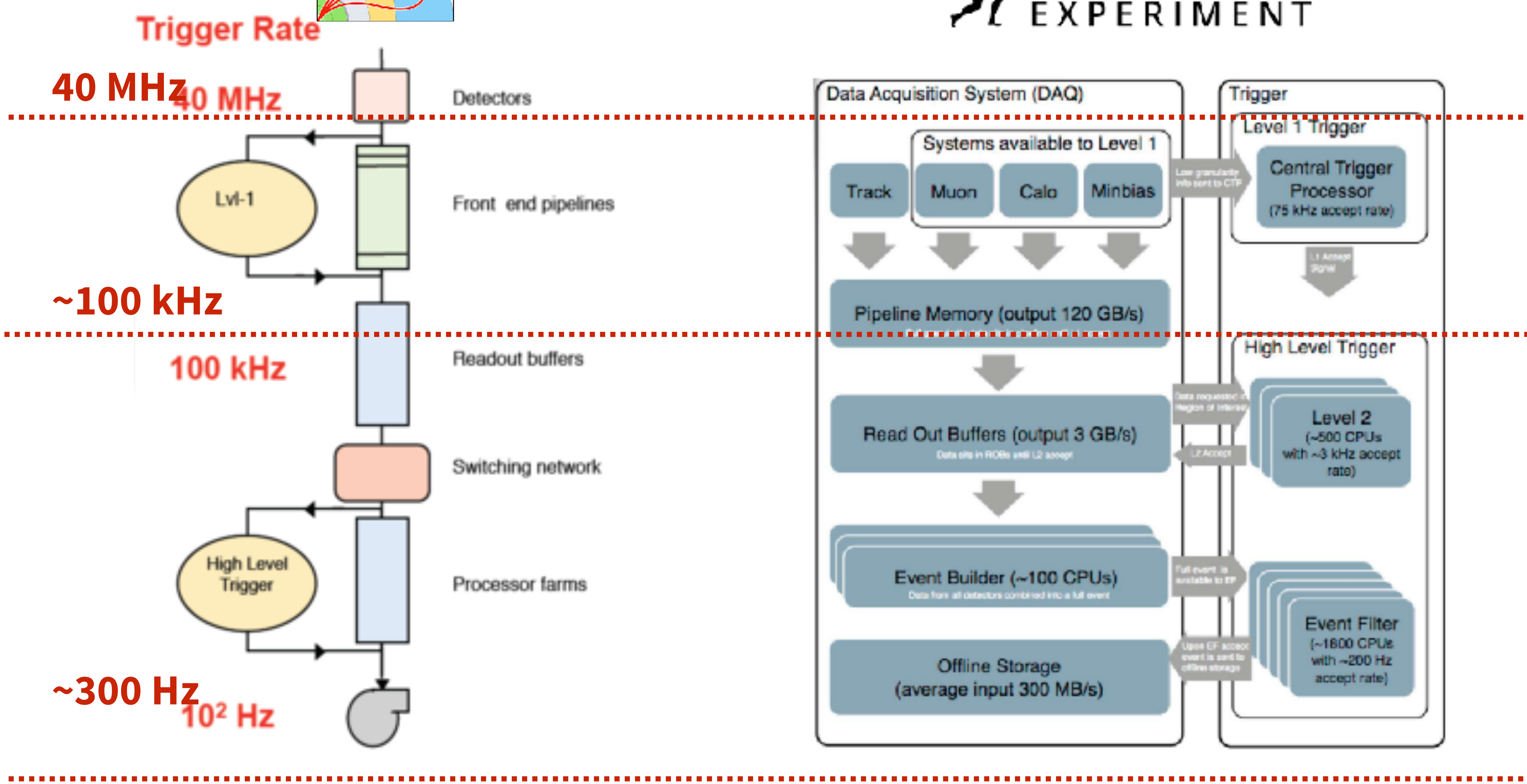
What is the Trigger?

- 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 stored for offline analysis



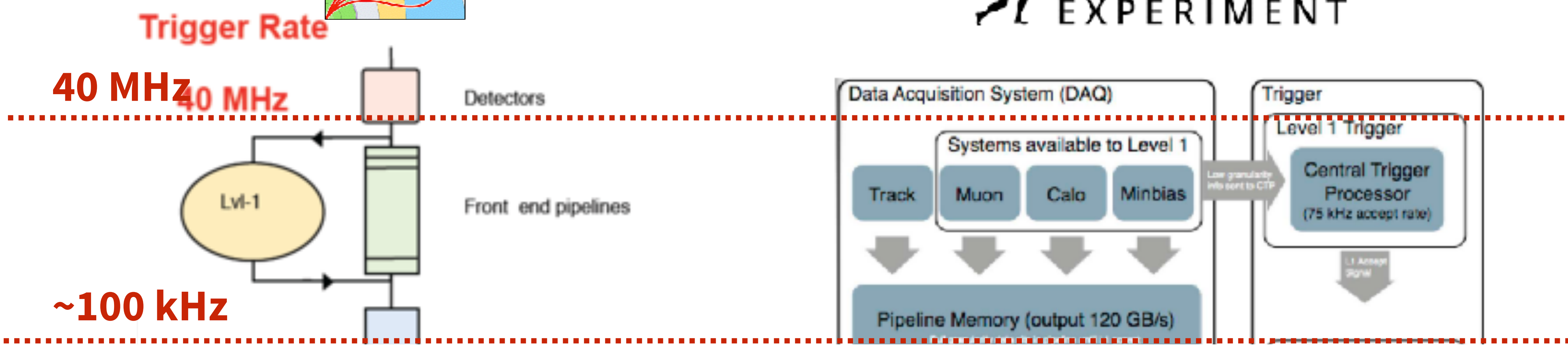
- Triggering algorithms are used to identify such events based on a “quick look” to detector data
- Reduce number of stored events to a reasonable amount

CMS and ATLAS triggers



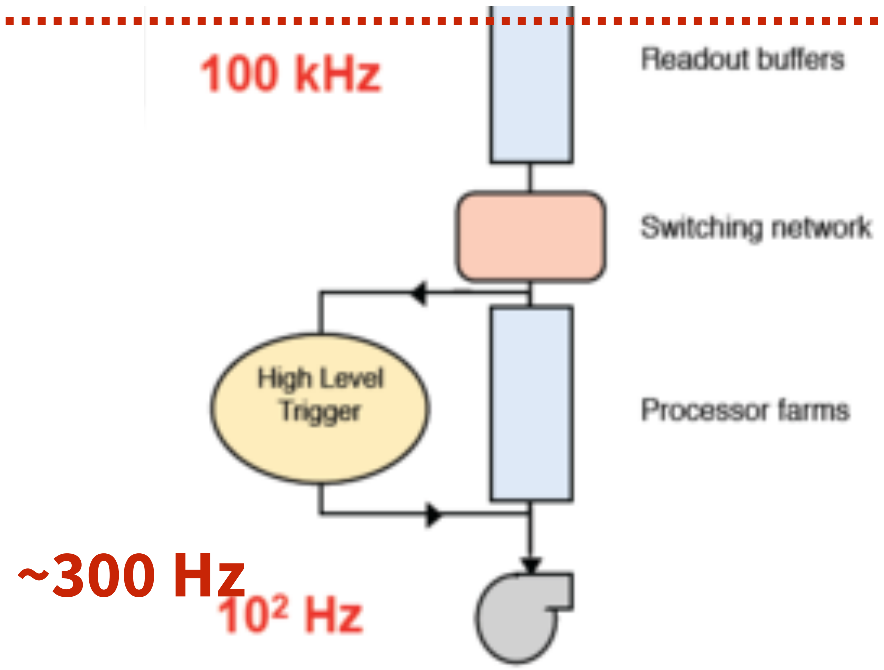
Decisions taken on the base of the presence of "triggering objects" such as electrons, photons, muons and jets, satisfying specifying requirements on E_T and p_T

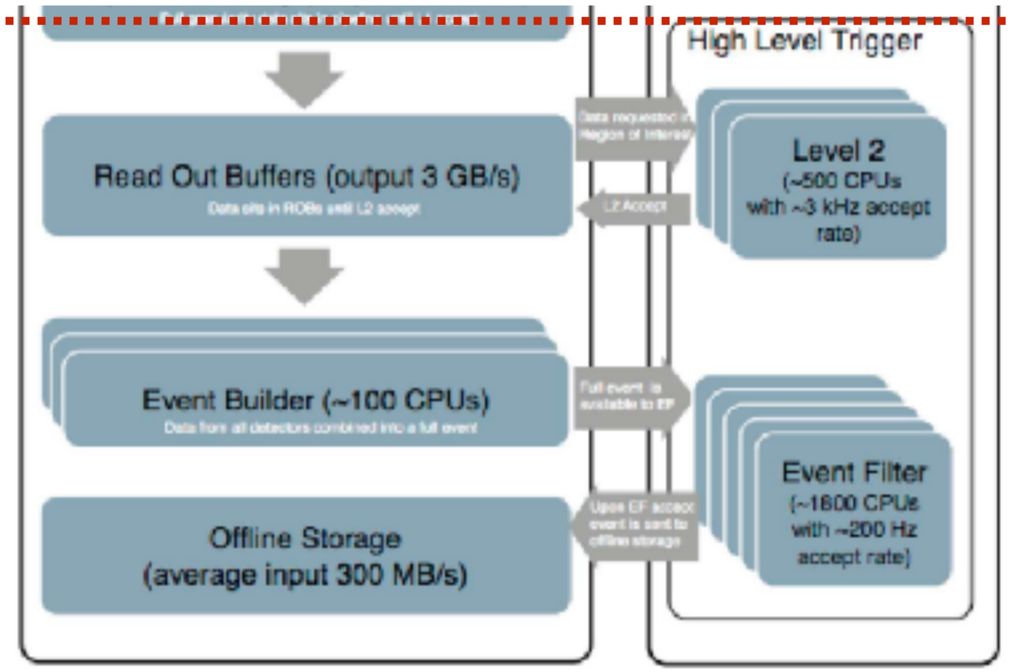
Level 1 Trigger



- Challenging goal: data reduction from 40 MHz to 100 KHz in 25 ns
- Cannot use full granularity of the detector
  - Typically based on **calorimeters and muon system**
  - Identify leptons/photons/jets candidates
  - “Global trigger” uses calorimetry energy sum and missing momentum (MET)
- Each trigger is based on a set of requirements, thresholds, e.g minimum p_T
- Different triggers can be combined to more complicated signatures, e.g dilepton, electron + MET, etc.

High Level Trigger





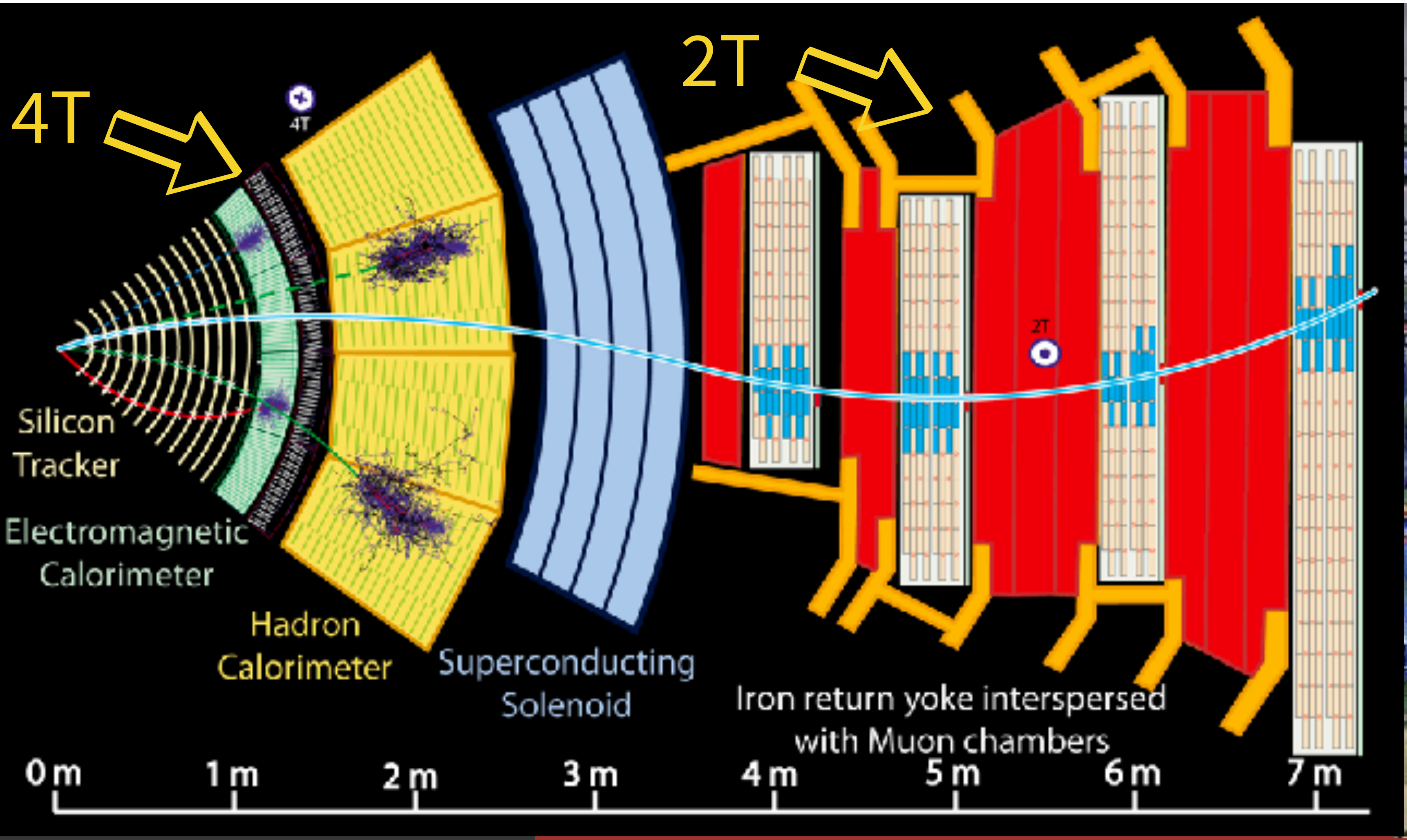
- Challenging goal: data reduction from 100 kHz to ~ 300 Hz
- Use more "sophisticated" objects
  - Typically based on **full detector data available after L1**
  - ATLAS has a 2 level HLT: Level 2 + Event Filter
    - L2 is based on info from "regions of interest", EF access full detector data

Magnet

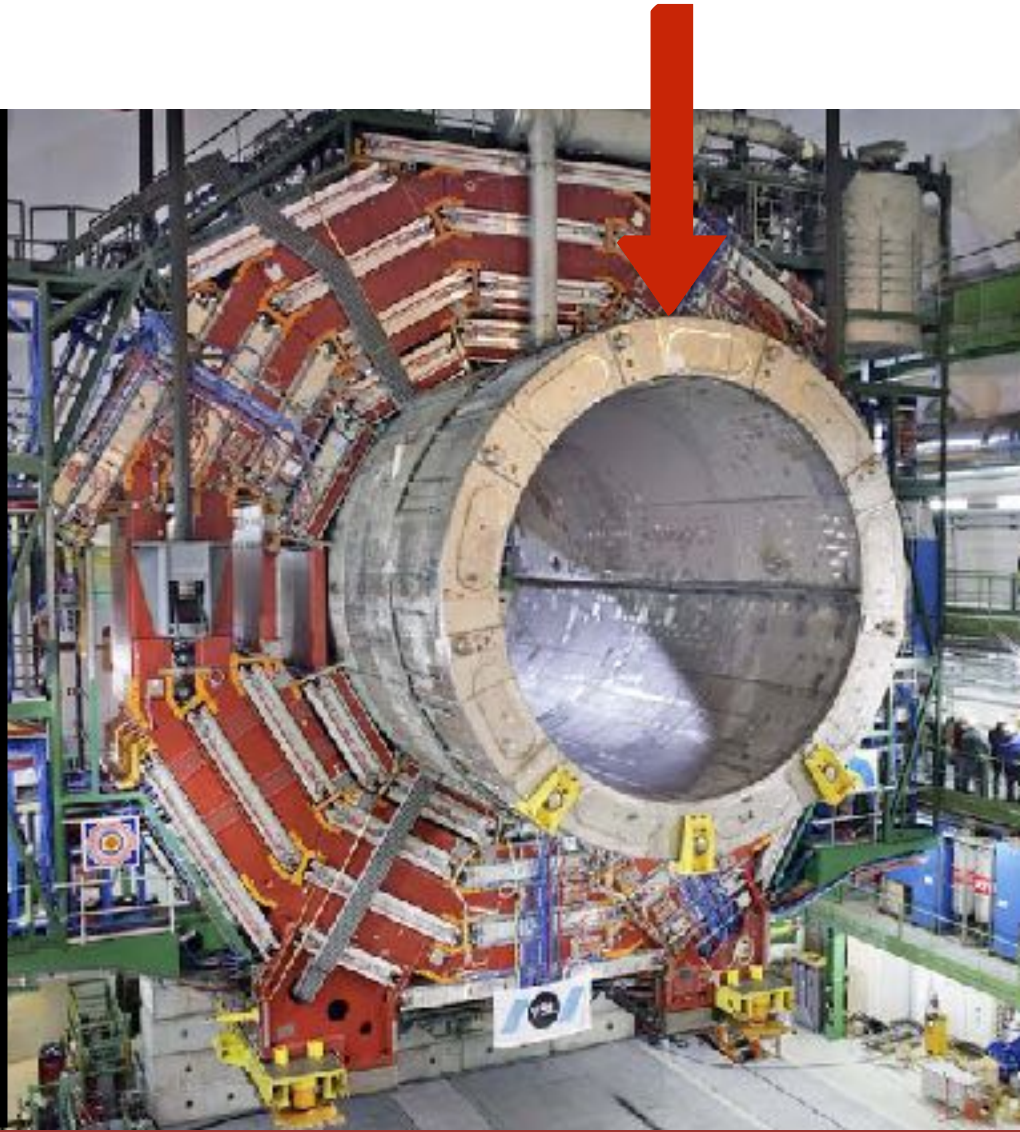
- Both experiments have implemented a specific magnet-system, designed **to measure momentum of charged particles up to ~TeV** with high resolution
- The two experiments chose different designs for their magnetic field
- **CMS - Large radius sinusoid magnet (4 T)**
- **ATLAS - Four magnet systems**

Magnet

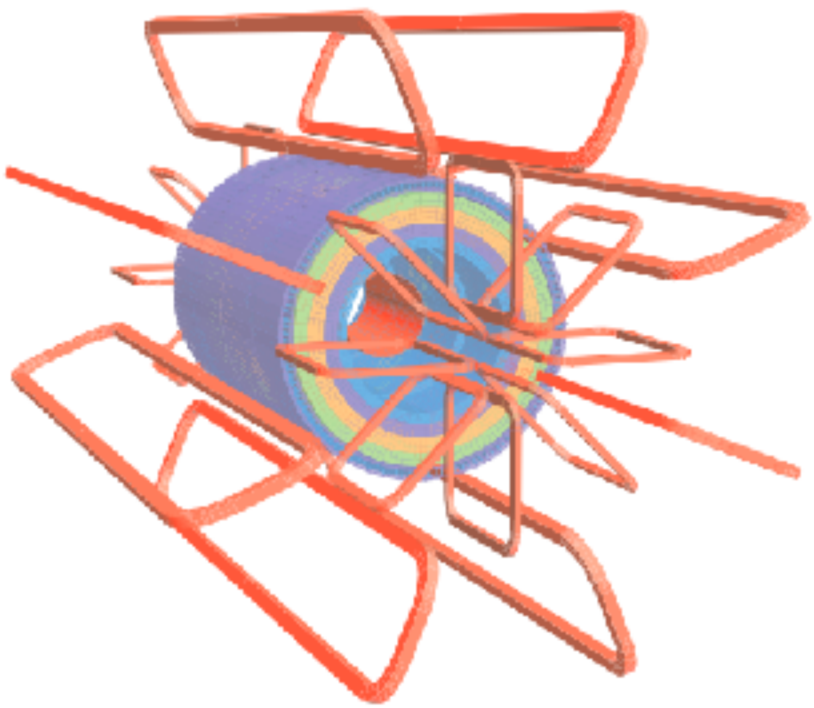
- CMS - Large radius sinusoid magnet (4 T)
  - Compact and heavy, guarantees uniform field and excellent track resolution
  - Tracker and calorimeter systems tightly fitted inside the magnet volume
  - Iron flux return ensures second momentum measurement for muons



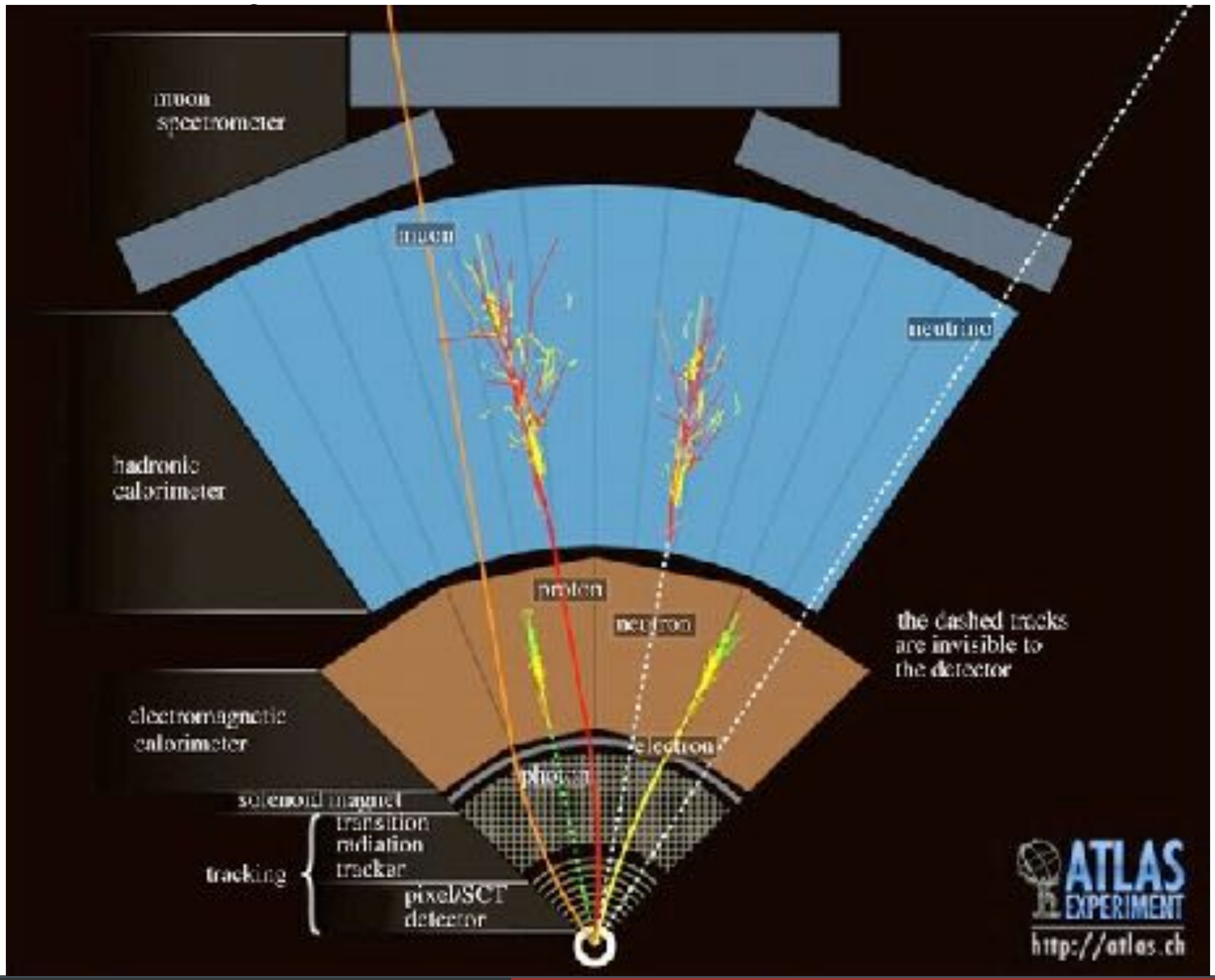
Solenoid

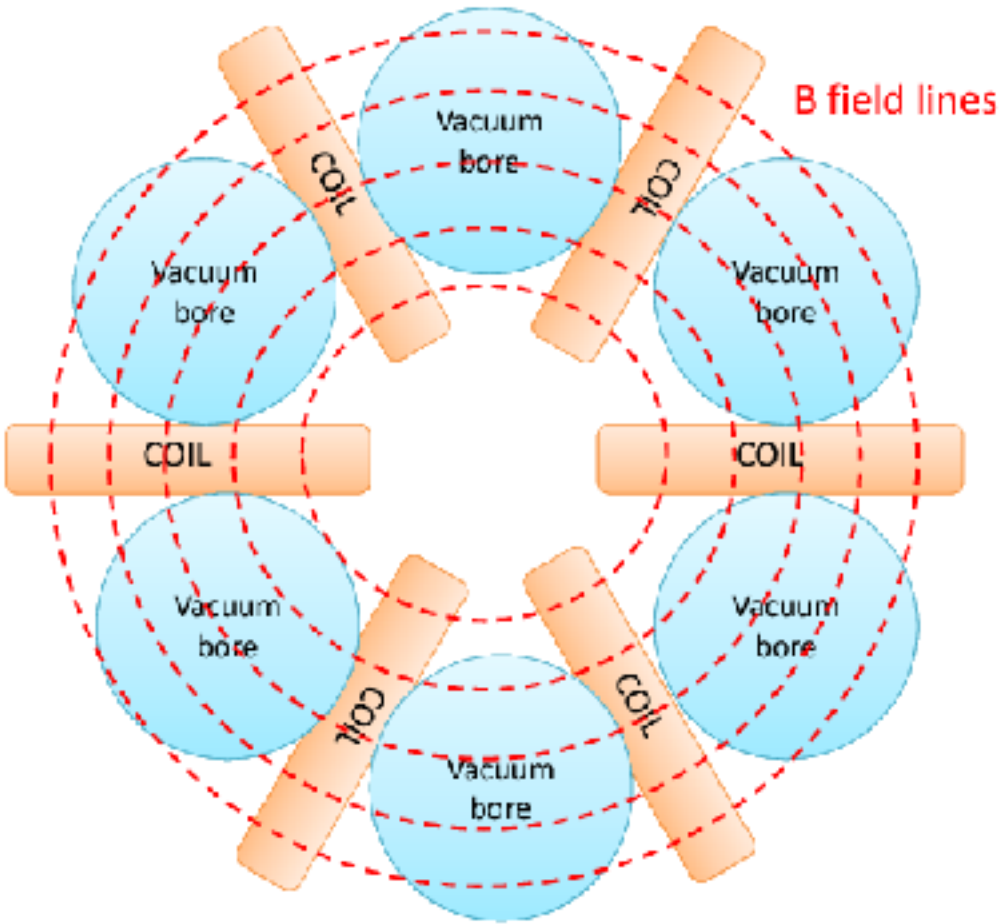


Magnet



- ATLAS - Four magnet systems
  - Small inner solenoid for tracker system (2T)
  - Three large air-core **toroid** magnets for muon spectrometer (barrel and 2 endcaps)
  - Not as compact as CMS: plenty of space to walk within the detector :) but at cost of a much more complicated field





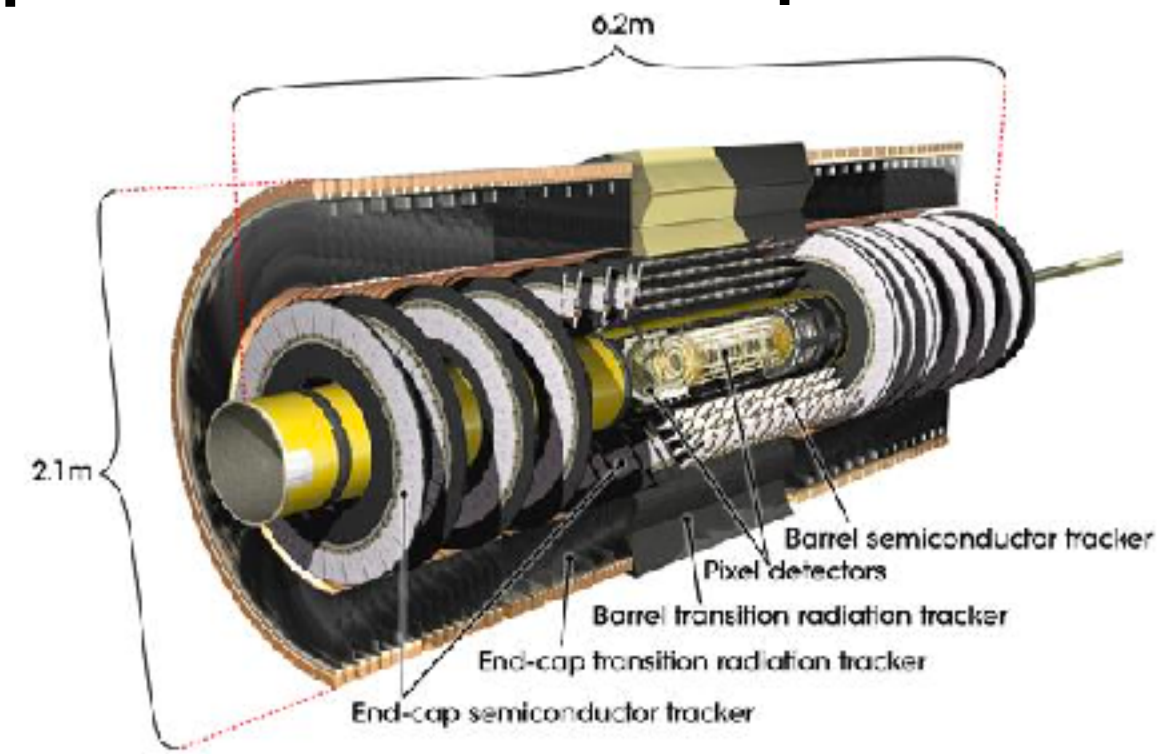
Inner traking system

Design goals of the inner tracking system

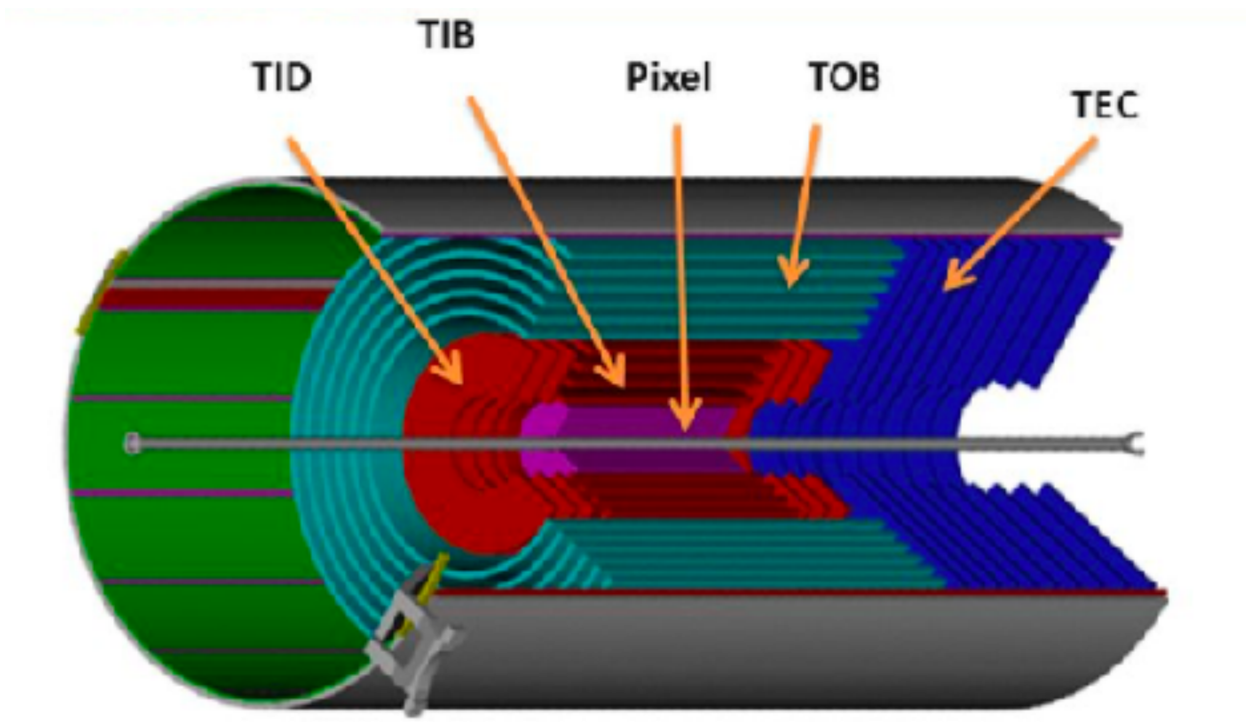
- Track ~1000 charged particles every 25 ns
  - Measure position, momentum and charge
- High track reconstruction efficiency
- Good momentum resolution (minimise multiple scattering)
- Need to be radiation resistant
- Identify particle type matching clusters in calorimeters and tracks in the muon system
- Identify long-lived particle (B hadrons, τ leptons or exotic particles)

Inner traking system

- Both ATLAS and CMS have the **inner tracker placed in the most central part** of the detector, surrounding the beam pipe
- Covers a wide angular range up to $|\eta| < 2.5$
- The tracking system is **immersed in a magnetic field** (4T for CMS and 2T for ATLAS)
  - Magnetic field is not very uniform in ATLAS

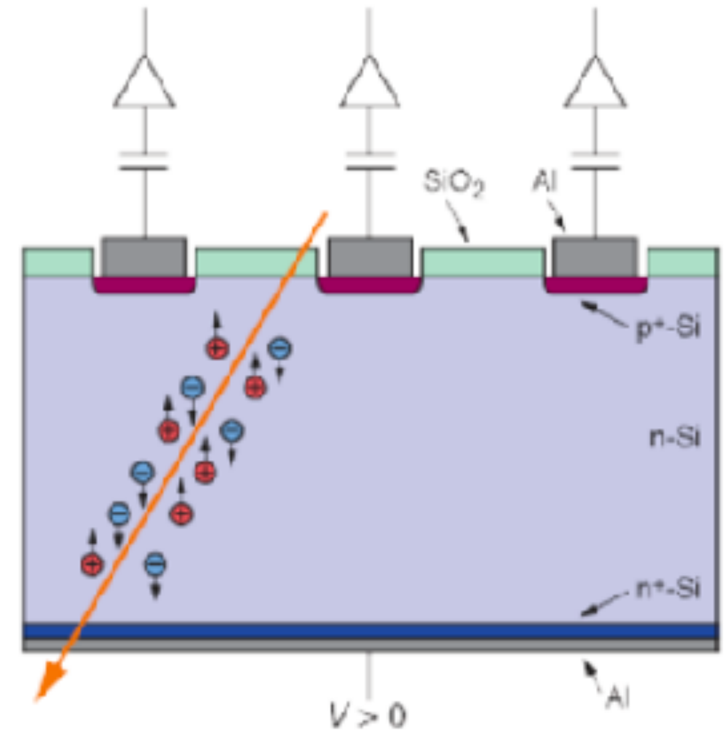


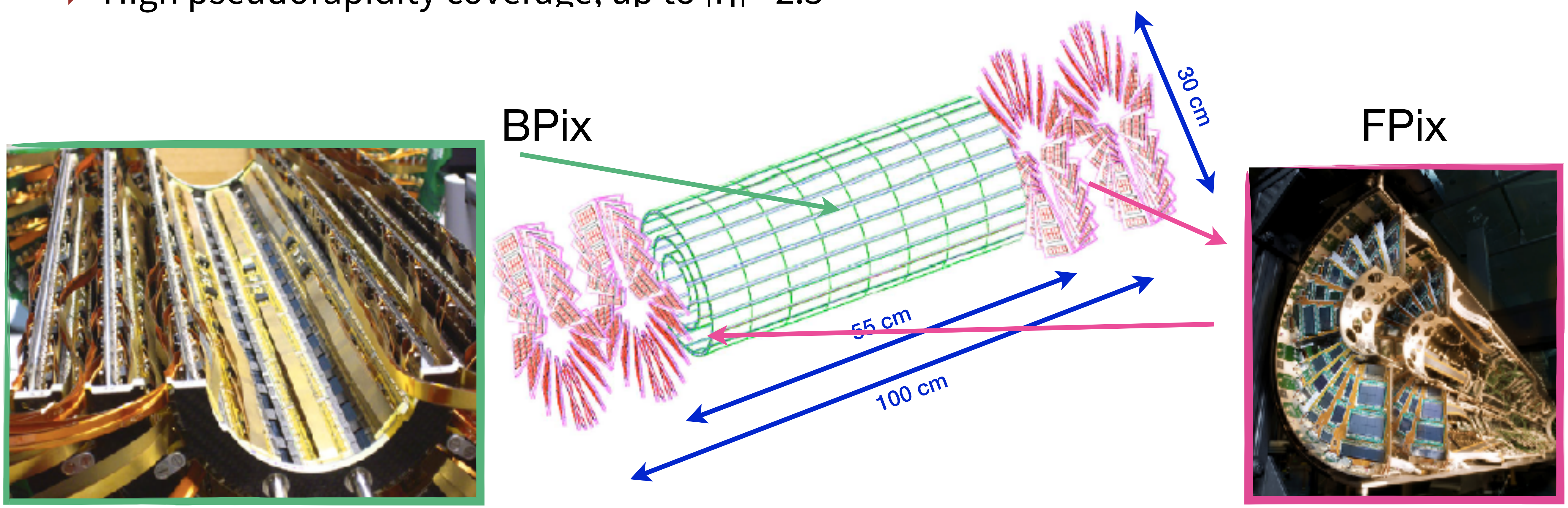
- Tracking system structure:
  - Inner silicon pixel detector
  - Outer silicon strip detector



CMS Pixel detector

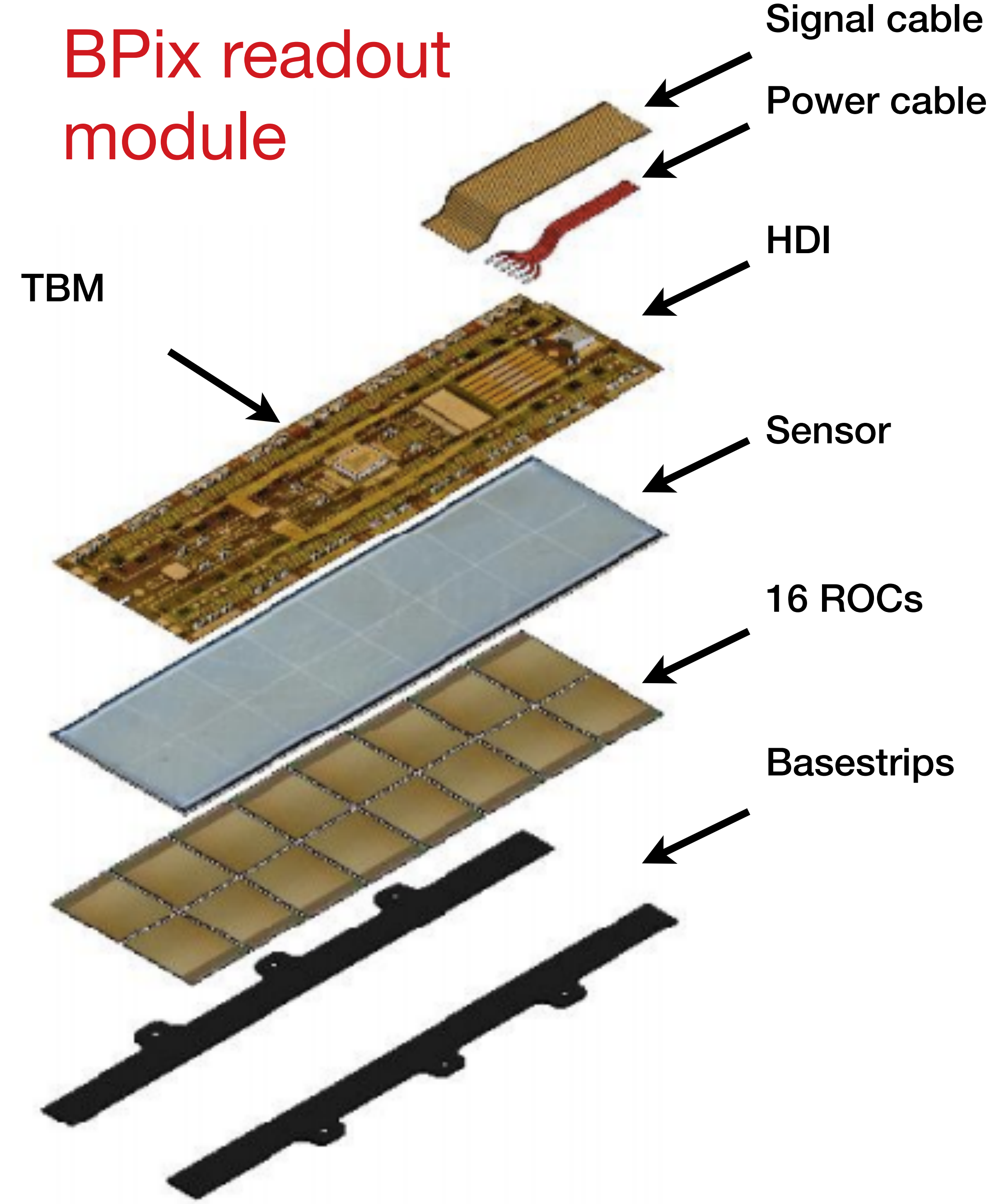
- CMS Pixel detector is a **semiconductor detector**
  - Charged particles traverse the silicon bulk generating electron-hole pairs which are collected by electrode originating the signal
- CMS has 3 Barrel pixel (BPix) layers (radii 4.3, 7.2, 11 cm) and 2 End-cap pixel disks (FPix) per side (|z| = 34.5 and 46.5 cm)
- High pseudorapidity coverage, up to $|\eta| = 2.5$



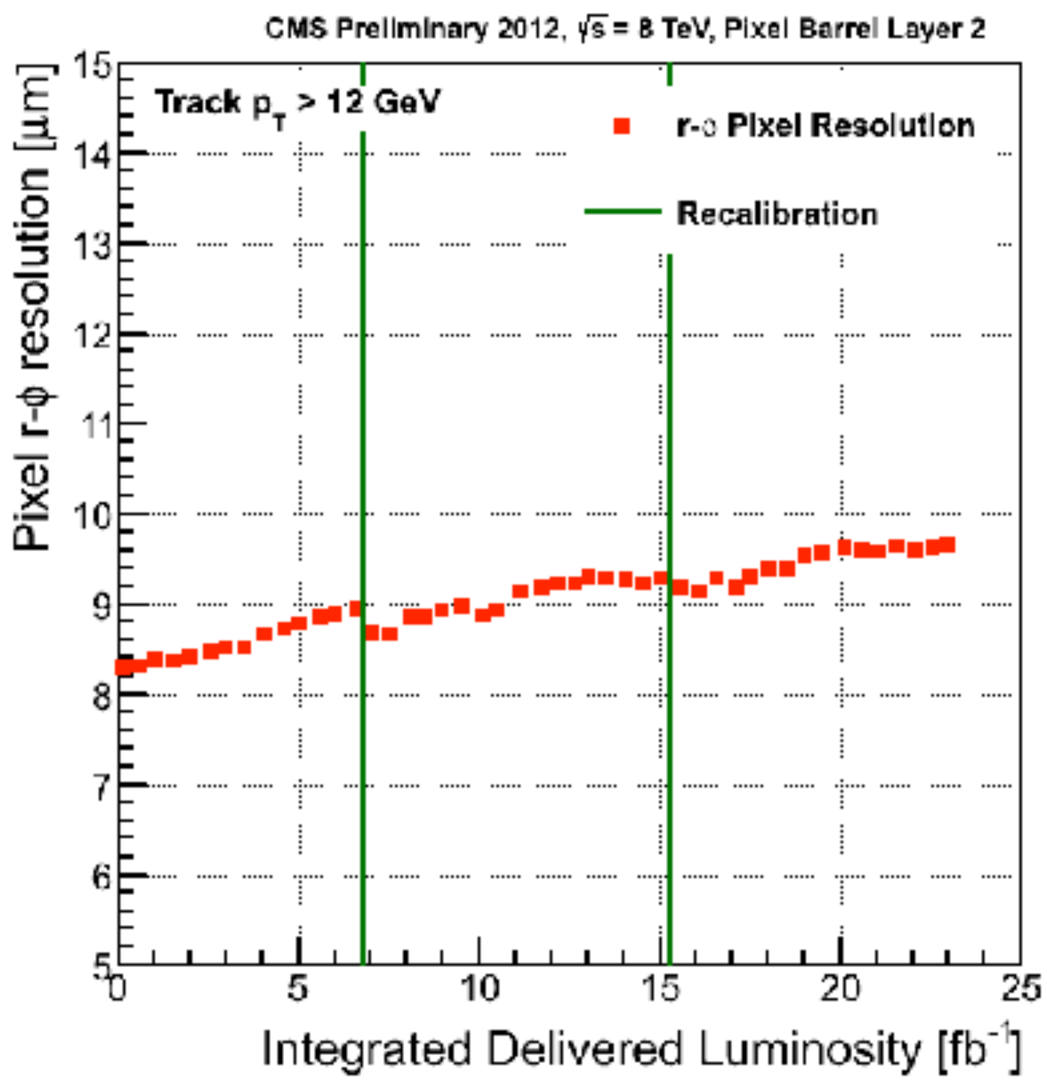


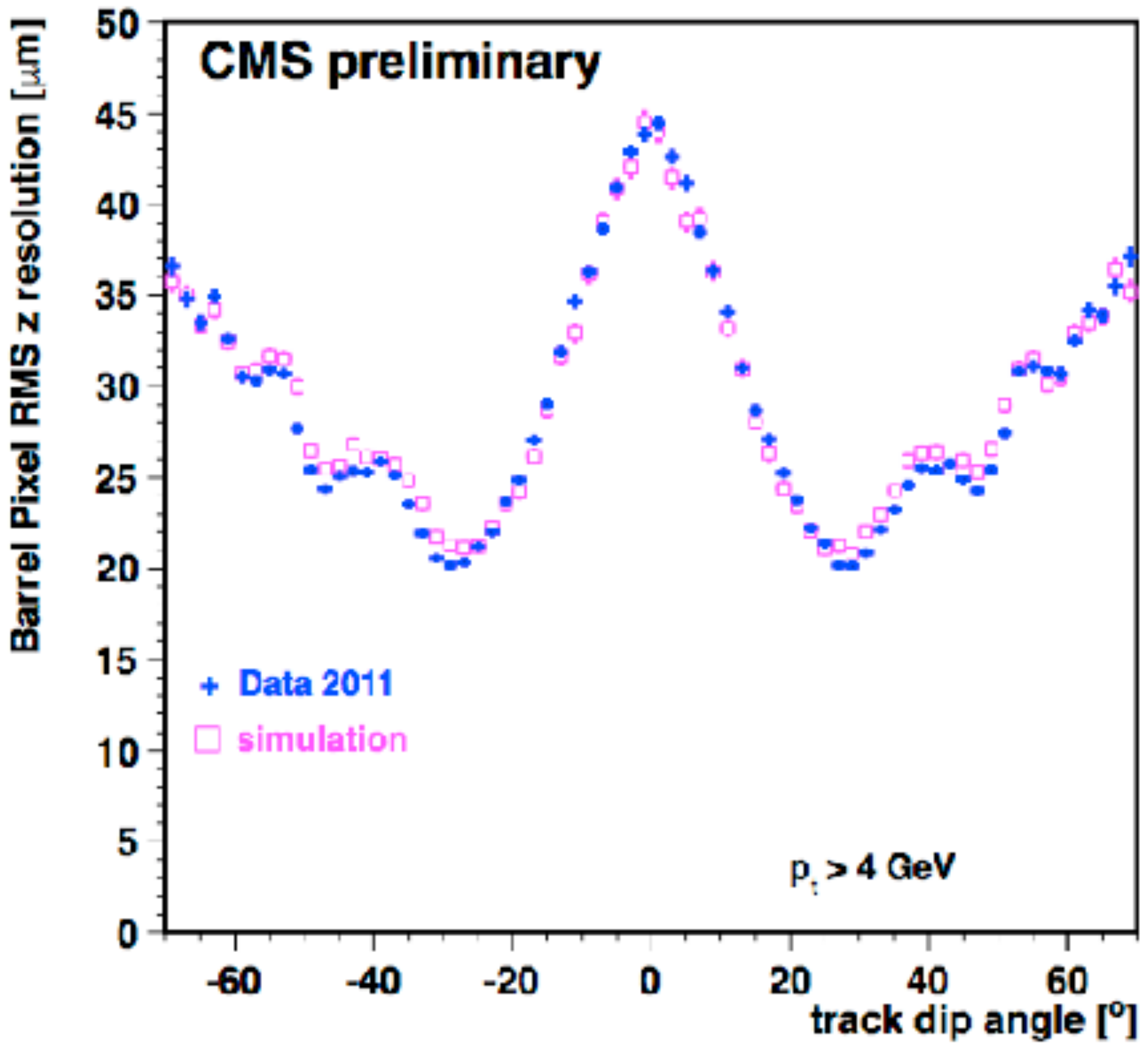
CMS Pixel detector

- 66 millions pixels
  - 100 x 150 μm
  - **Charge sharing** allow to improve spatial resolution
  - Sensor bump bonded to readout chips (ROCs)
- 1 ROC serves a 52 x 80 array of pixels
  - Read the signal generated by the passage of charged particle through the silicon
  - Noise suppression applied on ROC
  - Clock and trigger are distributed to ROCs, by the Token Bit Manager (TBM) which manages ROC controls and readout
- Signal transmission
  - The analog signal is read out by ROC and converted in optical signal to be sent to the off detector electronics for data acquisition



Pixel resolution



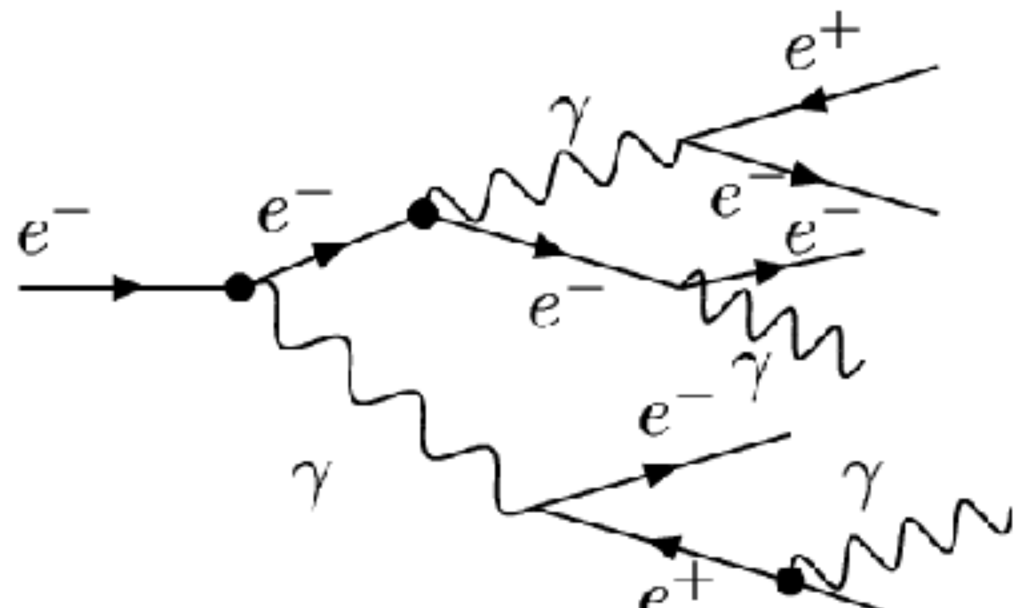


Electromagnetic calorimeter

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

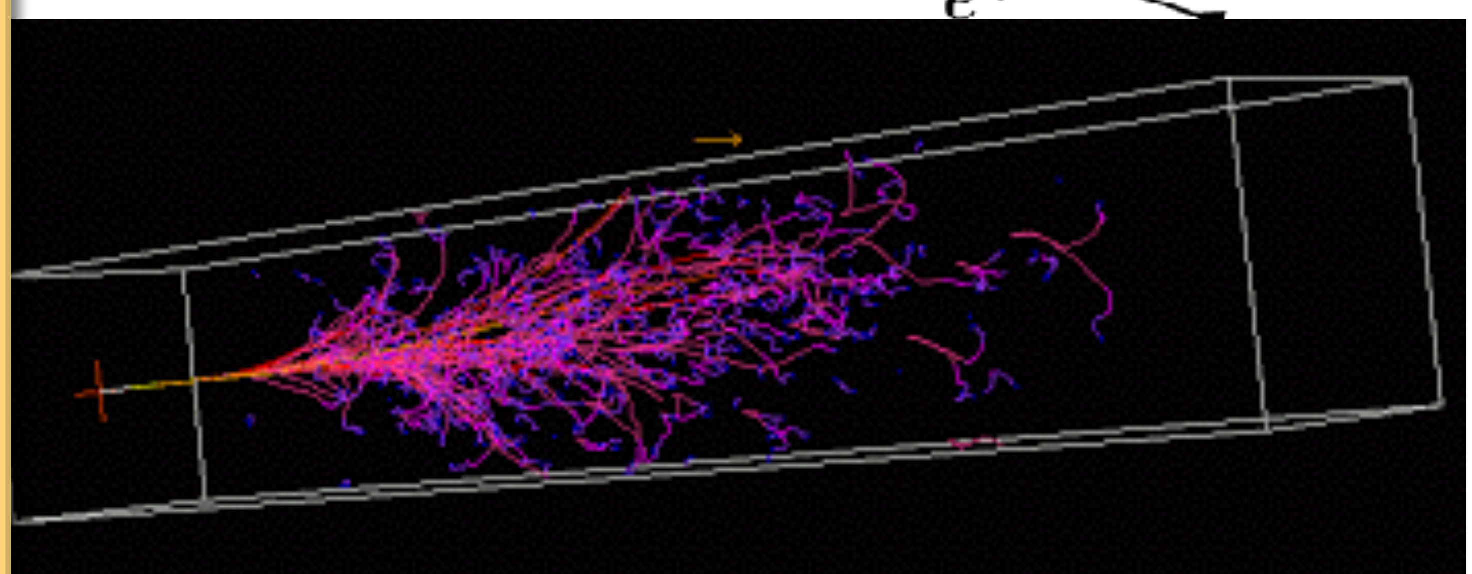
- EM fluctuation in the # of produced and collected e±

2nd term: Noise term

- Includes electronic noise and pileup

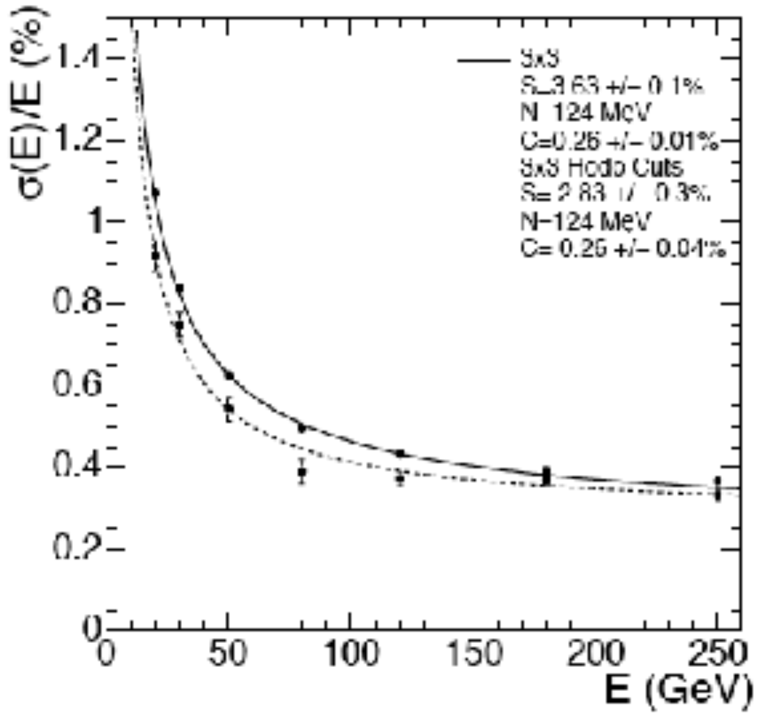
3rd term: constant term

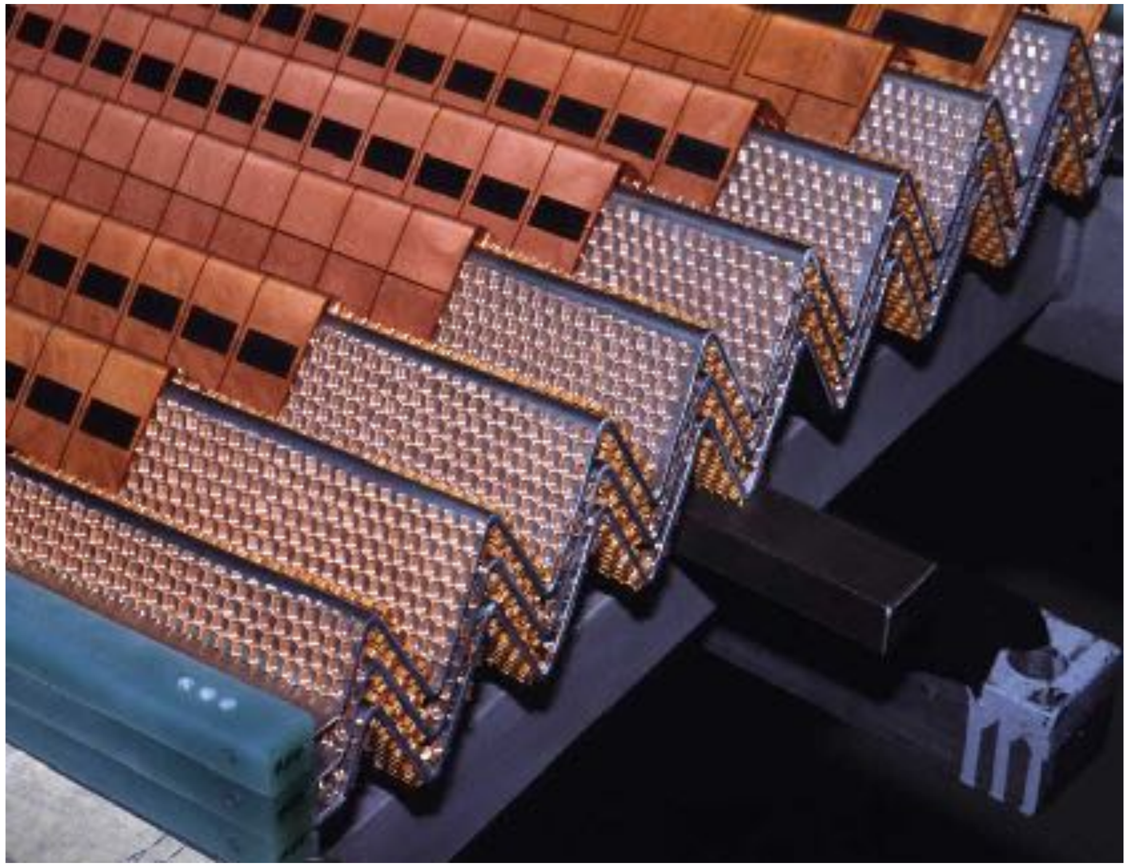
- Accounts for calibrations



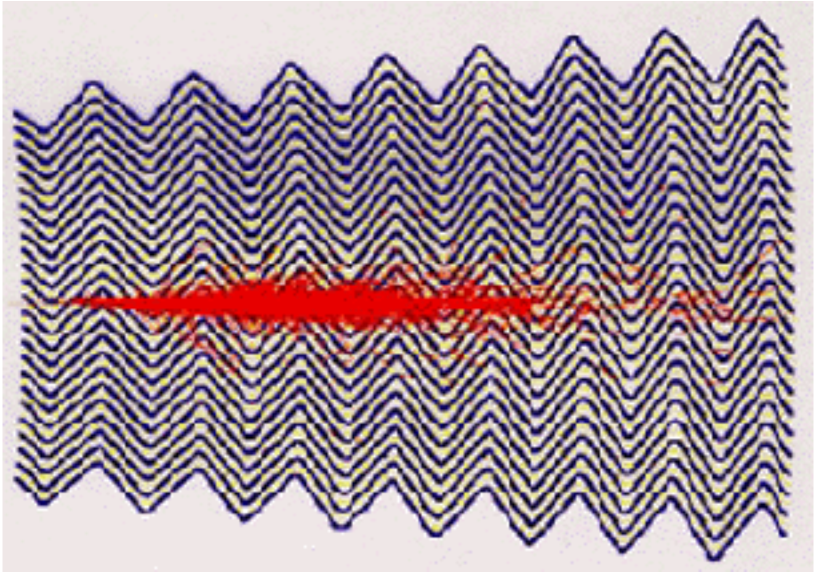
Electromagnetic calorimeter

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



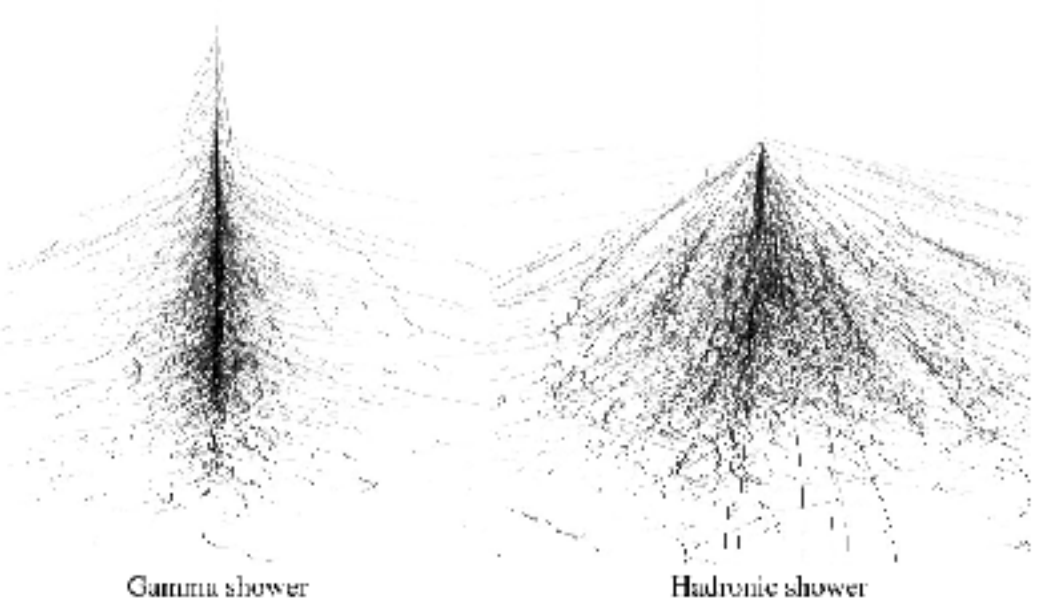


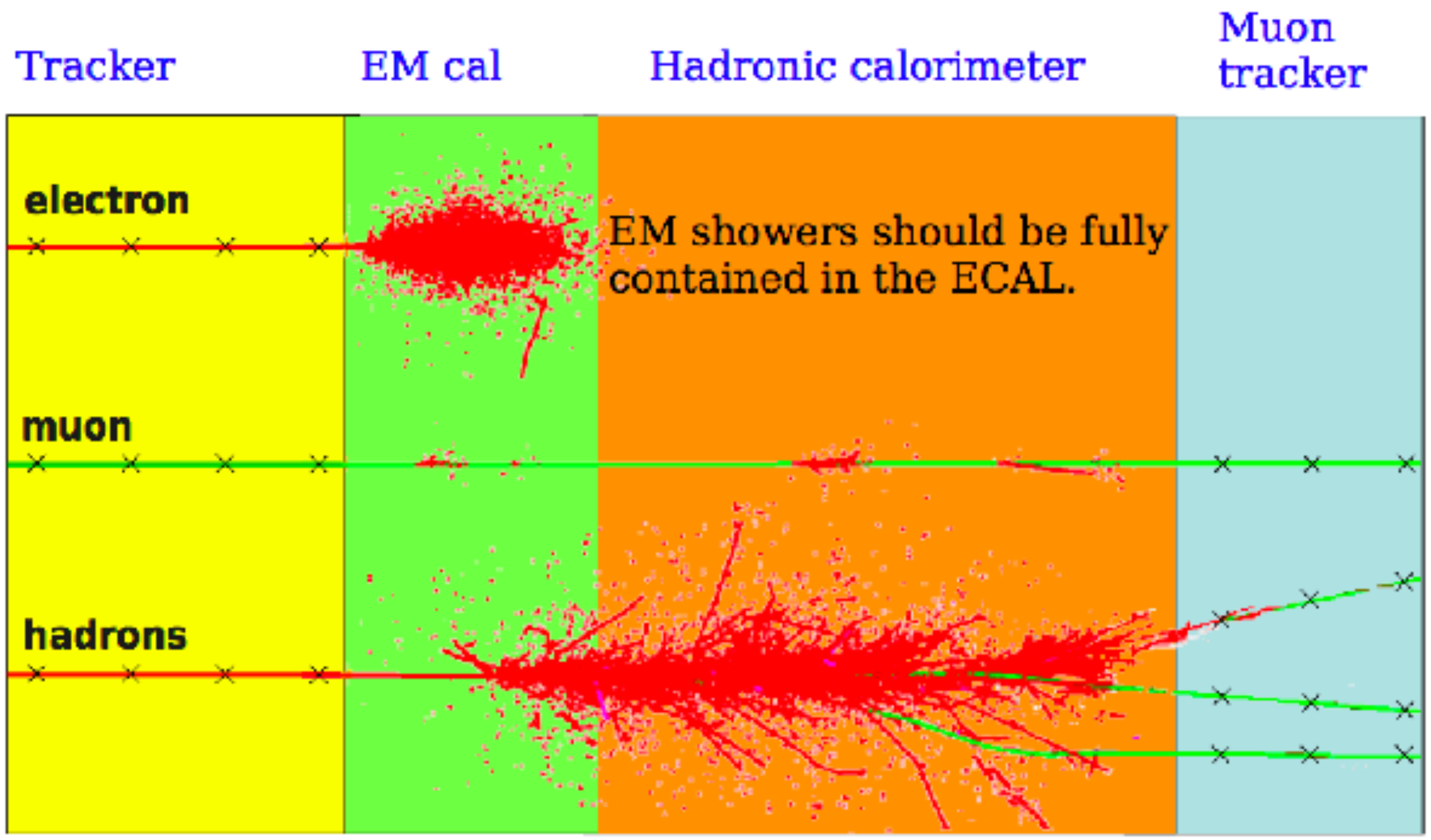
- ATLAS ECAL follows an accordion geometry
  - Sampling **Liquid Ar-Pb** calorimeter
  - Very good and fast sampling with full **φ** coverage



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

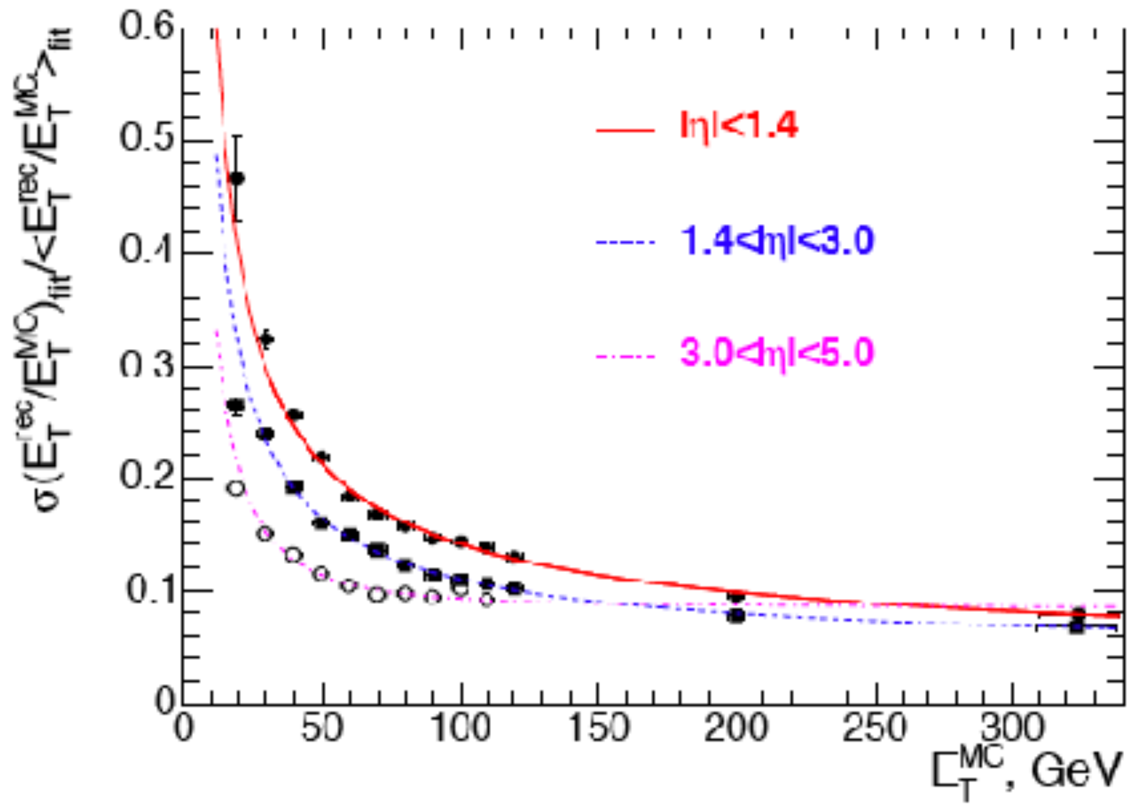
Hadron Calorimeter

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

- 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

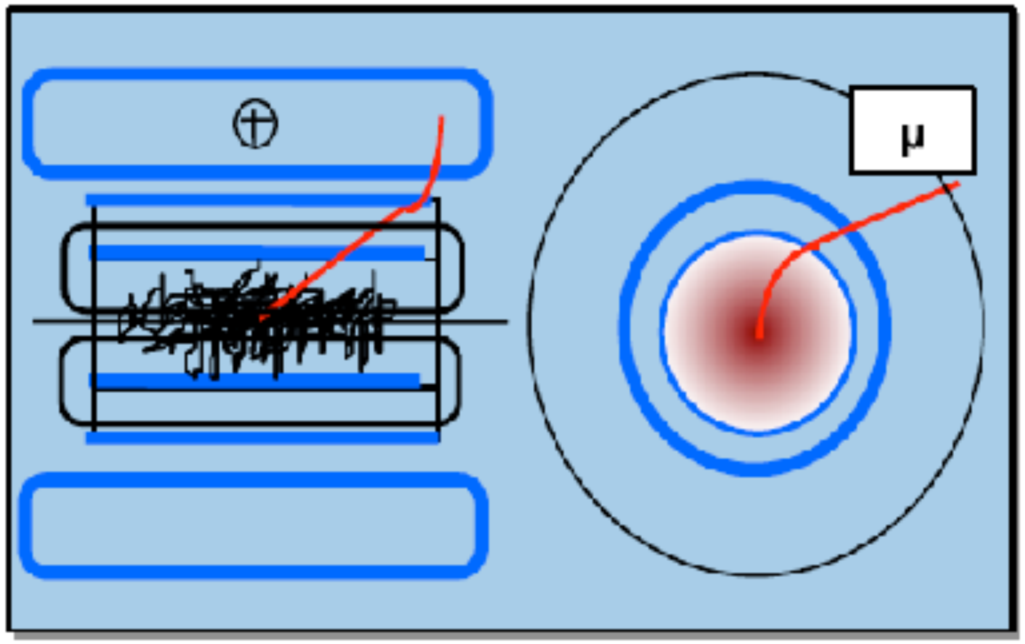
$\Delta p_T/p_T \approx 1/BL^2$

2 different approaches:

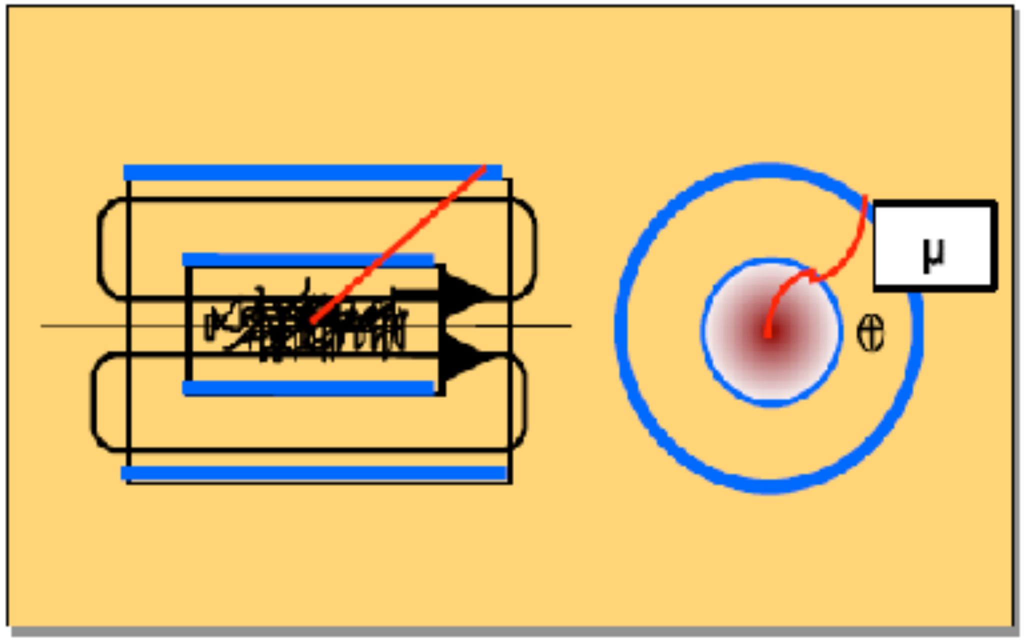
ATLAS: large L, low B

CMS: short L, high B

ATLAS



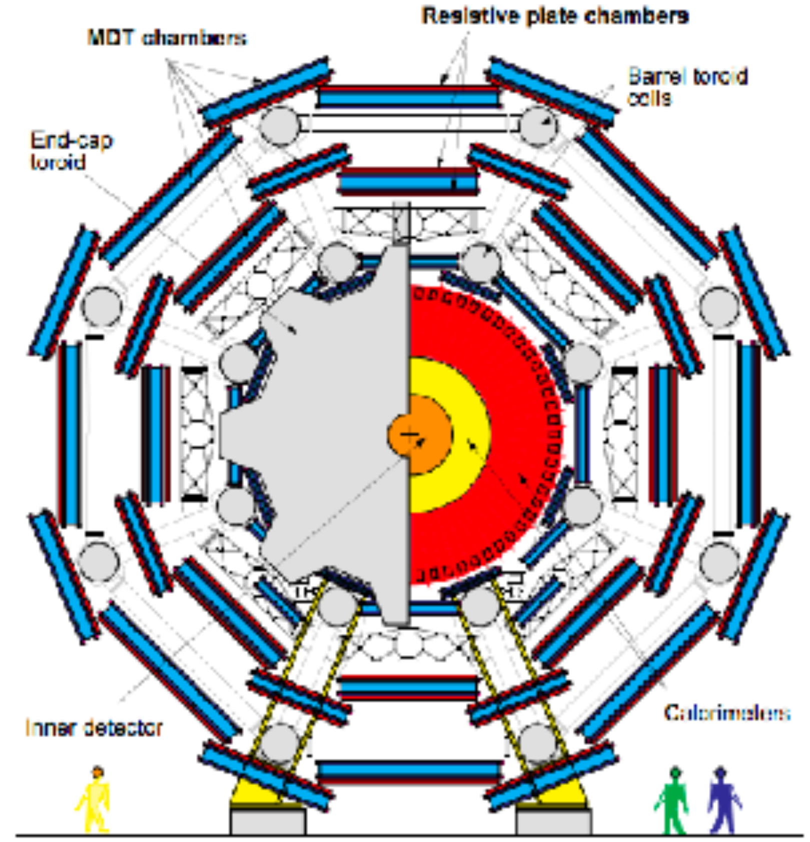
CMS



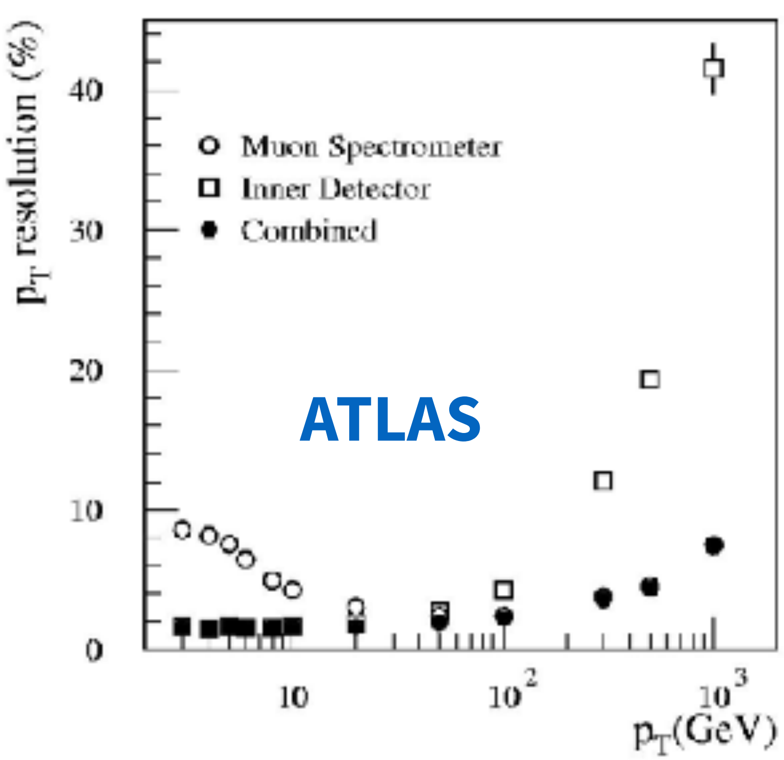
Muon system technology

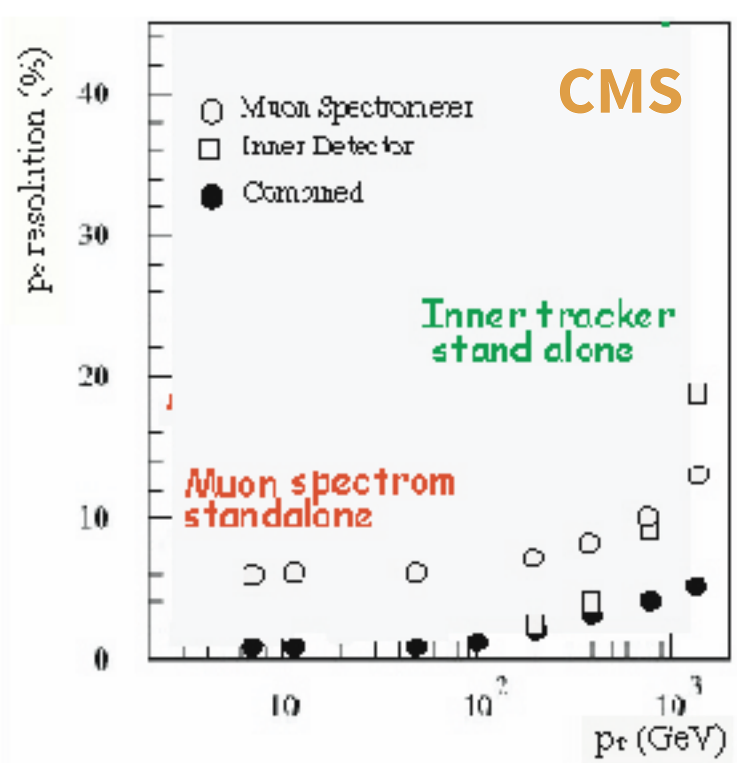
- Same technology:
  - **Drift Tubes (DT)** for precise trajectory measurement
  - Completed by **Cathod Strips Chambers** (CSC)
    - Spatial resolution ≈ 80 μm
  - And **Resistive Plate Chambers (RPC)** for time measurements

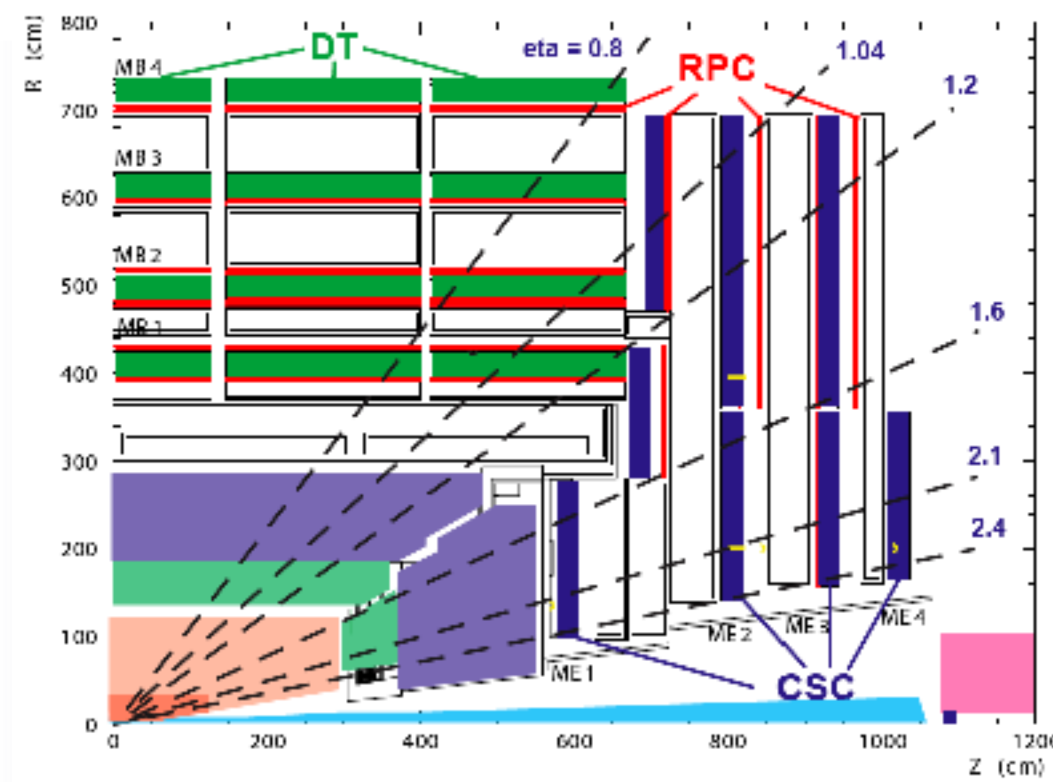
ATLAS



CMS



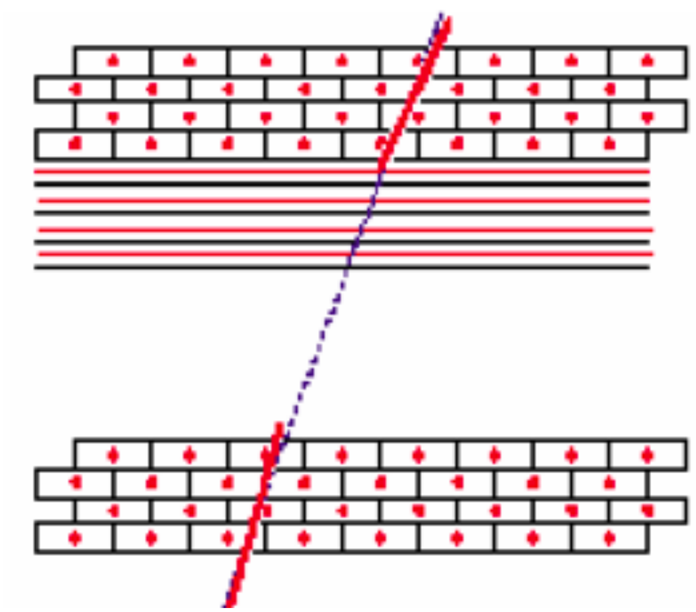


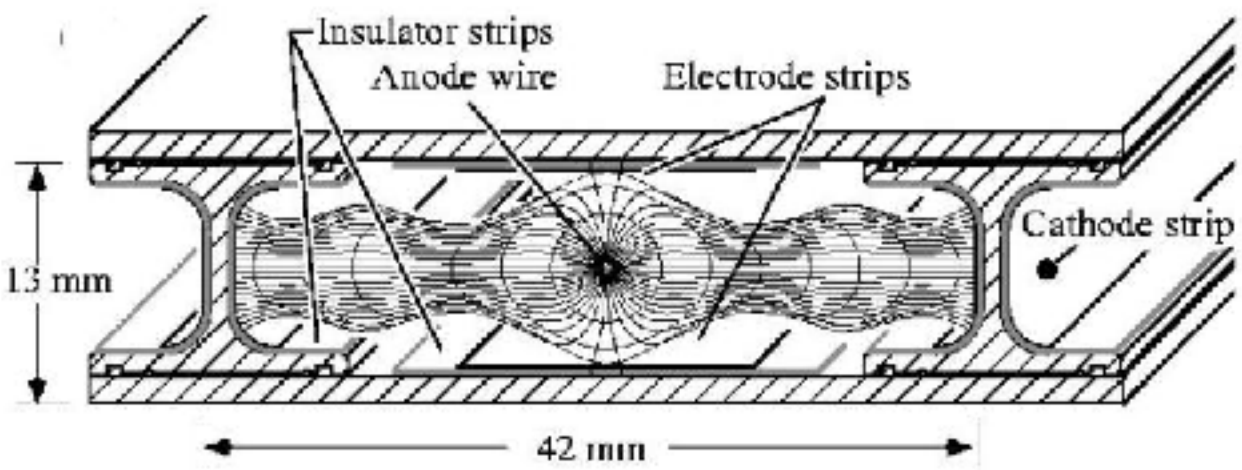


Drift Tube chambers

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

Particle Reconstruction

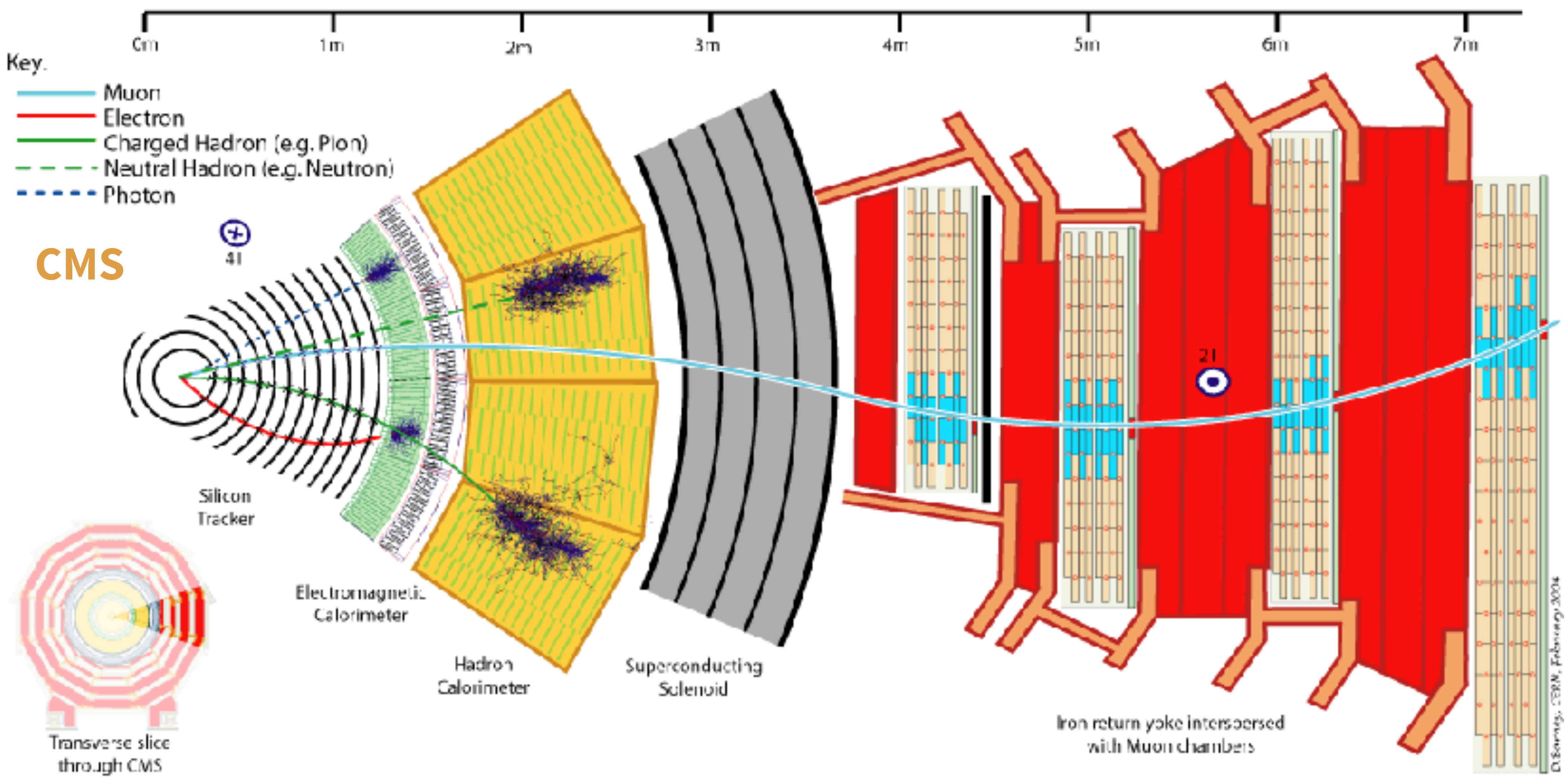
Particle Reconstruction

High p_T e,γ

p_T jets

High p_T μ

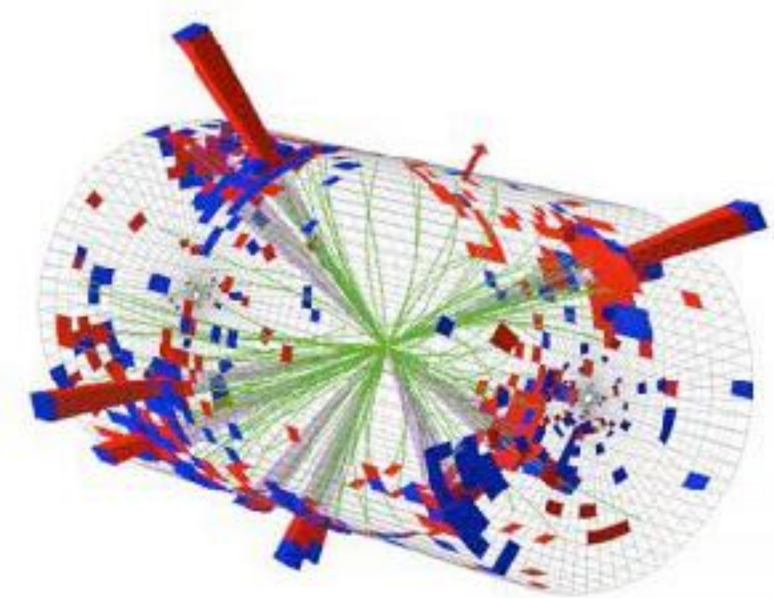
Global quantities
Total and Missing Transverse Energy



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

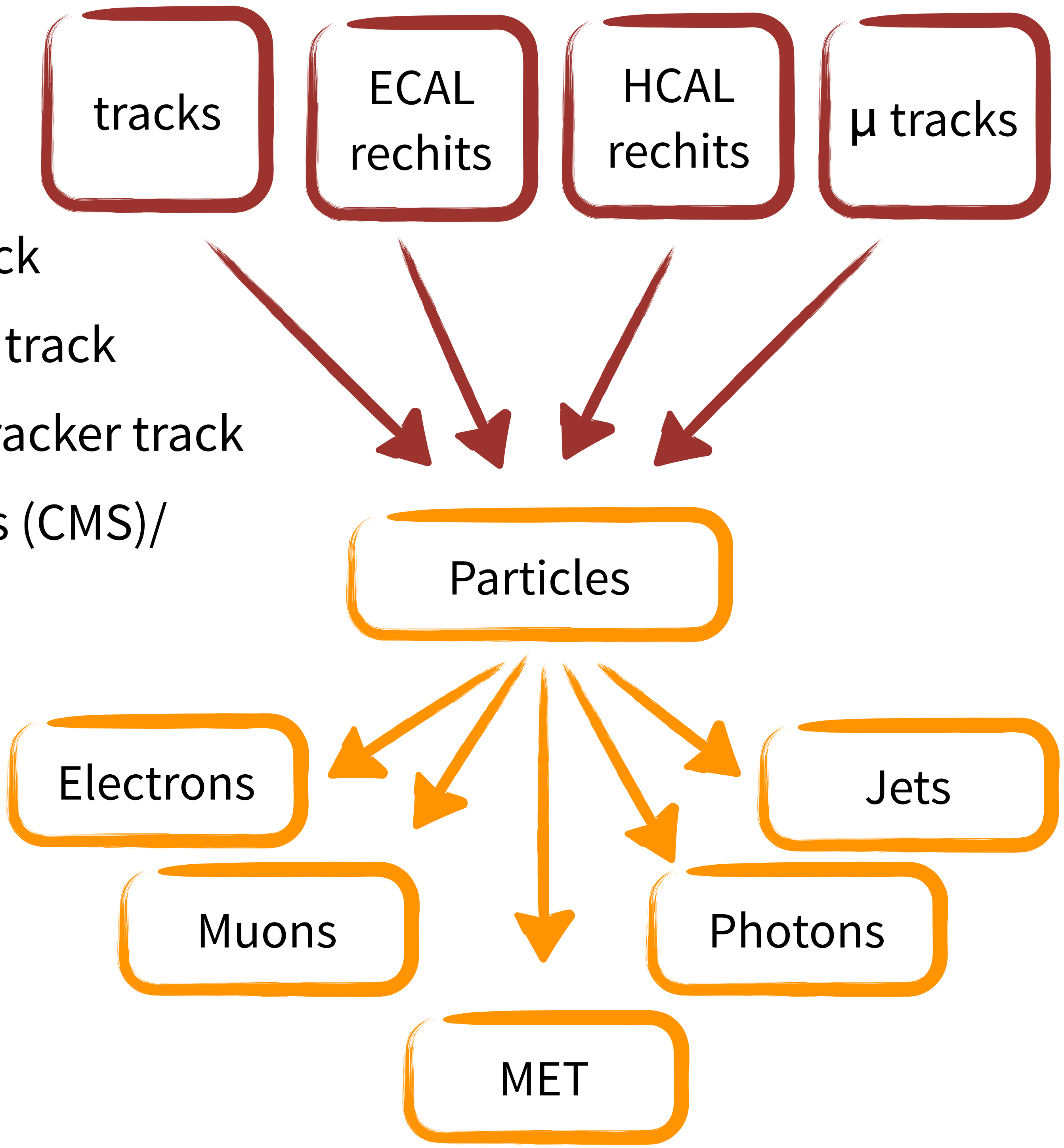
- Muons, Electrons, Photons
- Charged and Neutral Hadrons
- Jets from quark fragmentation
- Missing momentum from invisible particles (e.g neutrinos or… new physics maybe)

Event reconstruction →



Particle reconstruction

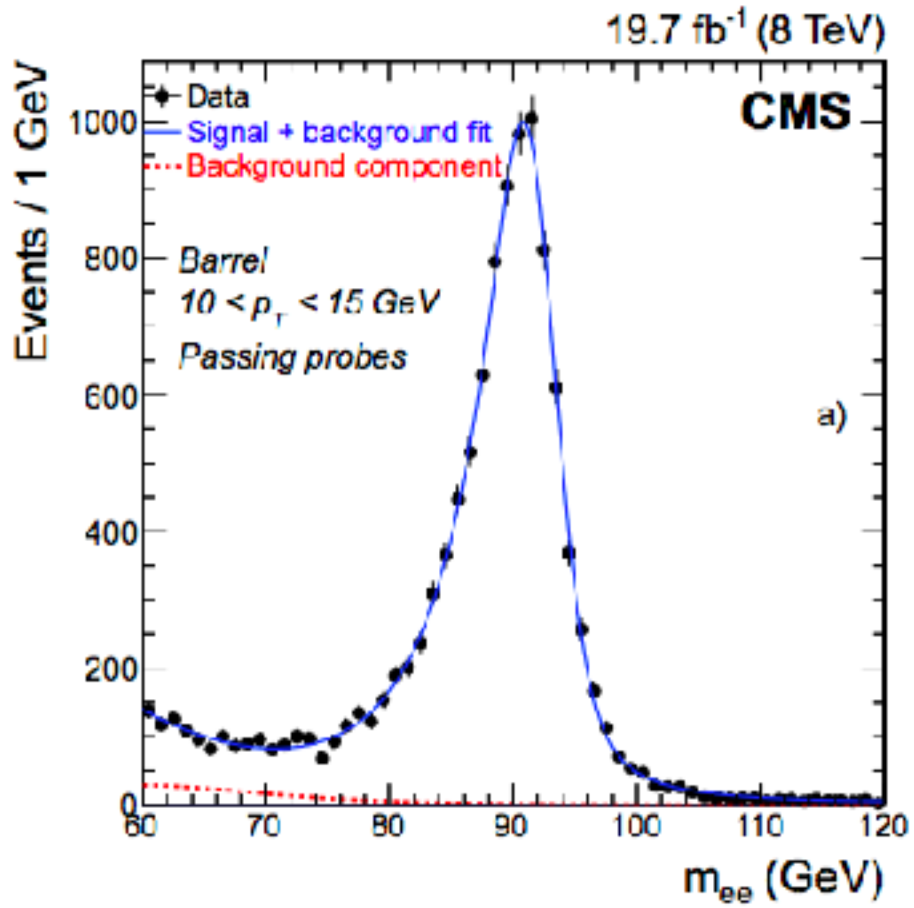
- CMS and ATLAS reconstruction algorithms exploit information from different sub-detectors to reconstruct particles
- **muons**: tracker track + muon track
- **electrons**: ECAL cluster + tracker track
- **photons**: ECAL cluster without tracker track
- **charged hadrons**: HCAL clusters + tracker track
- **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

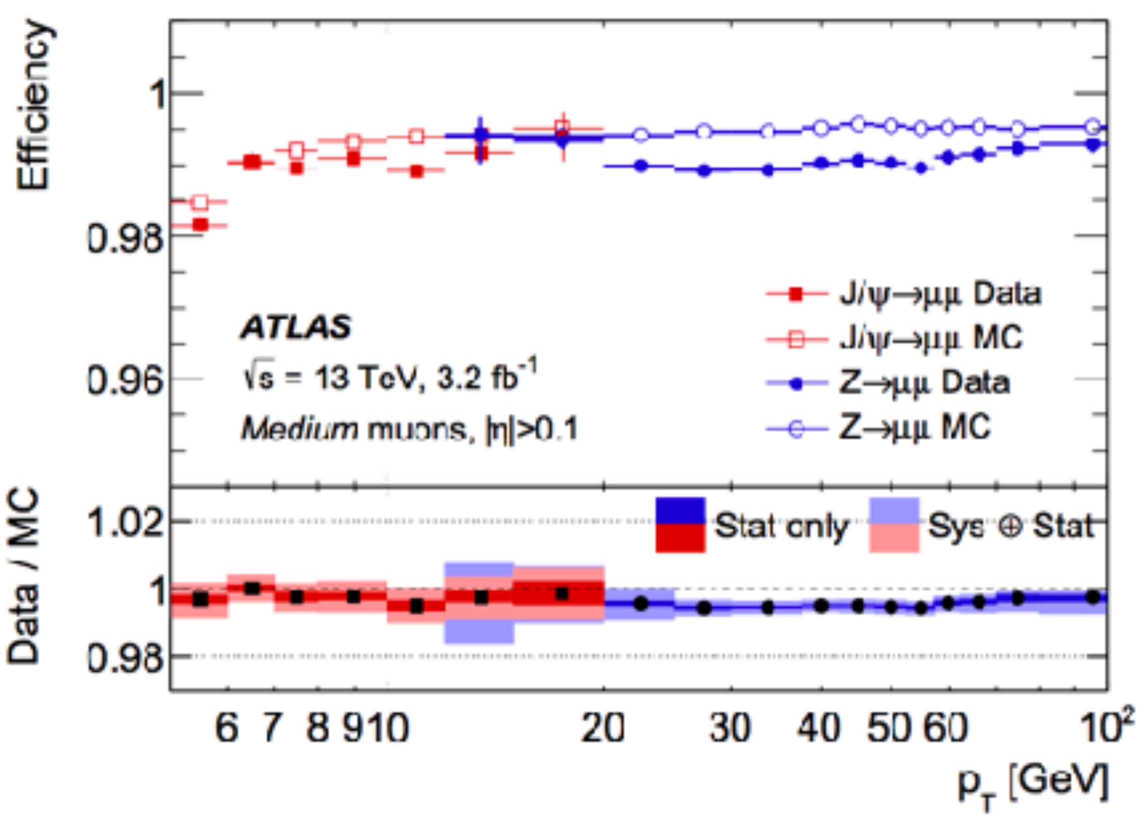


Lepton and photon reconstruction

Electrons/Photons

- Cluster reconstruction in ECAL from E deposits
  - Identification of **Superclusters**, SC(common to photons and electrons)
  - **Association of SC to tracks** in the inner tracker for e reconstruction
  - Gaussian Sum Fit (GSF) algorithm used to reconstruct electron trajectories





Muons

- Reconstructed from **position measurements in the muon spectrometer and matched to tracks** in the silicon tracker
  - Energy loss by bremsstrahlung negligible for high pT muons
  - Global fit to pair of tracks in the tracker and in the muon system to identify global muons

Lepton Isolation

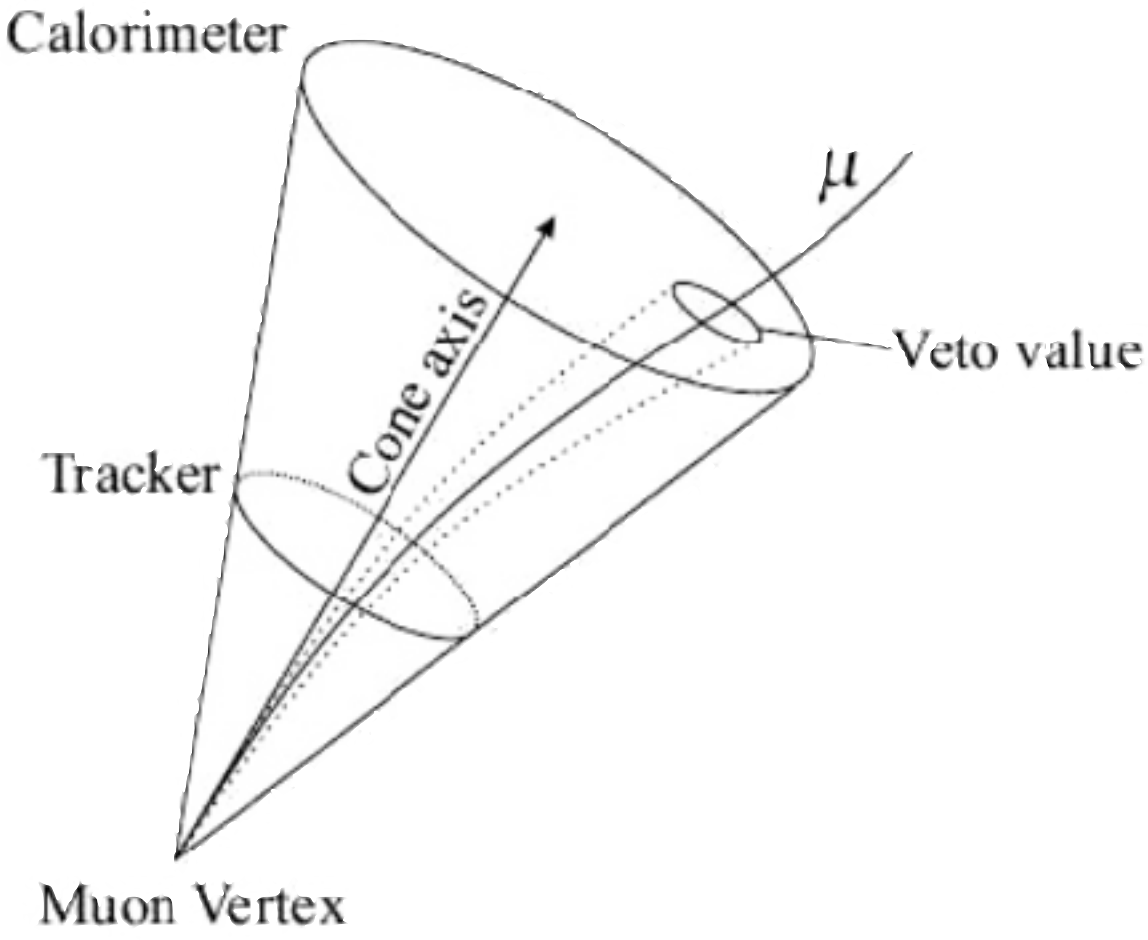
Isolation

The isolation, ***I***, is the sum of reconstructed tracks p_T and energy deposits within a cone of size ΔR around the lepton. It is used to discriminate leptons originated from boson decays from those produced in jets.

Cone Size: $\Delta R = \sqrt{(\Delta\eta^2 + \Delta\vartheta^2)}$

Isolation: $I = I_{ch} + I_{nh} + I_{ph}$ (Pile up energy deposits subtracted)

Isolated leptons: $I_\mu/p_T < 0.12$ and $I_e/p_T < 0.15$

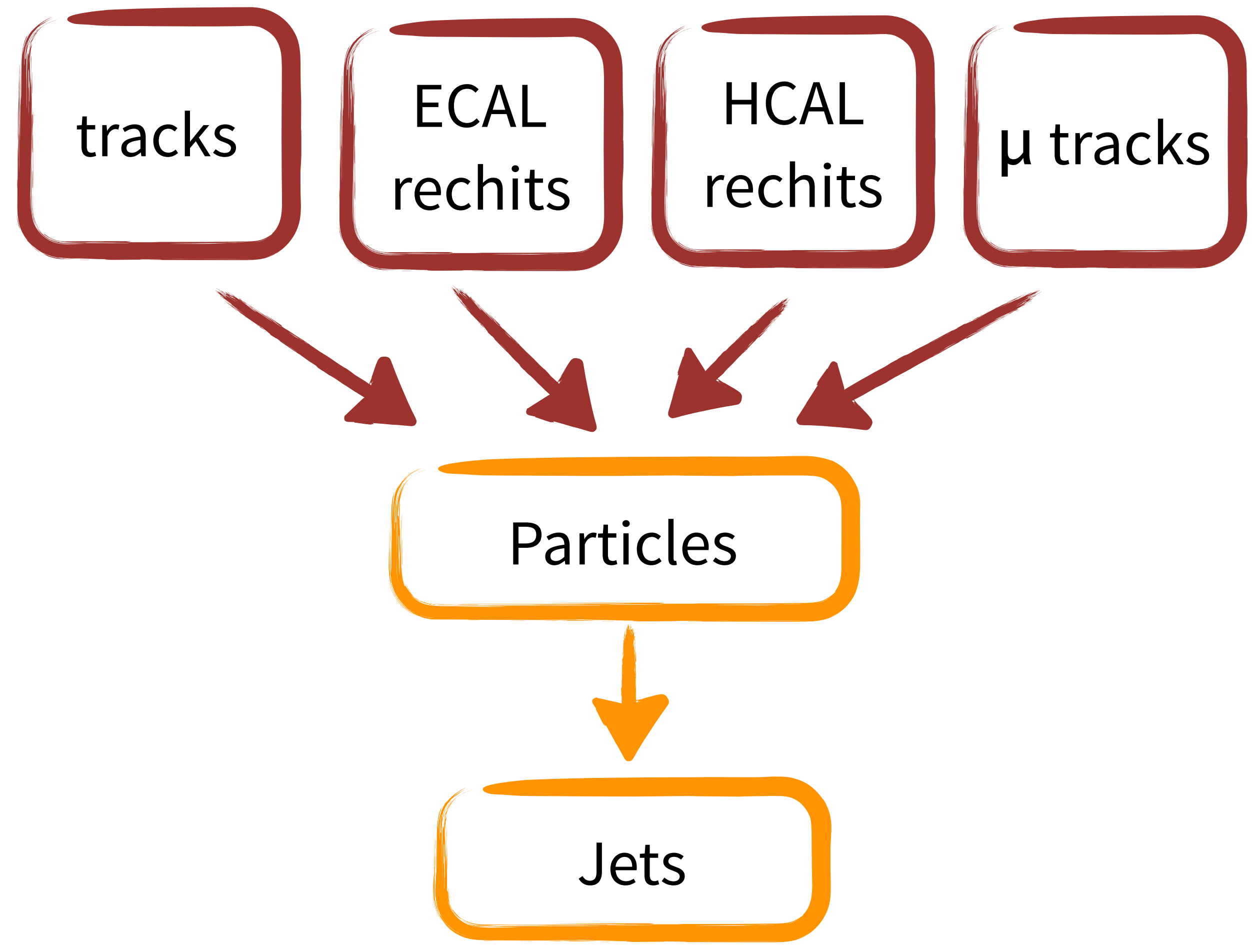


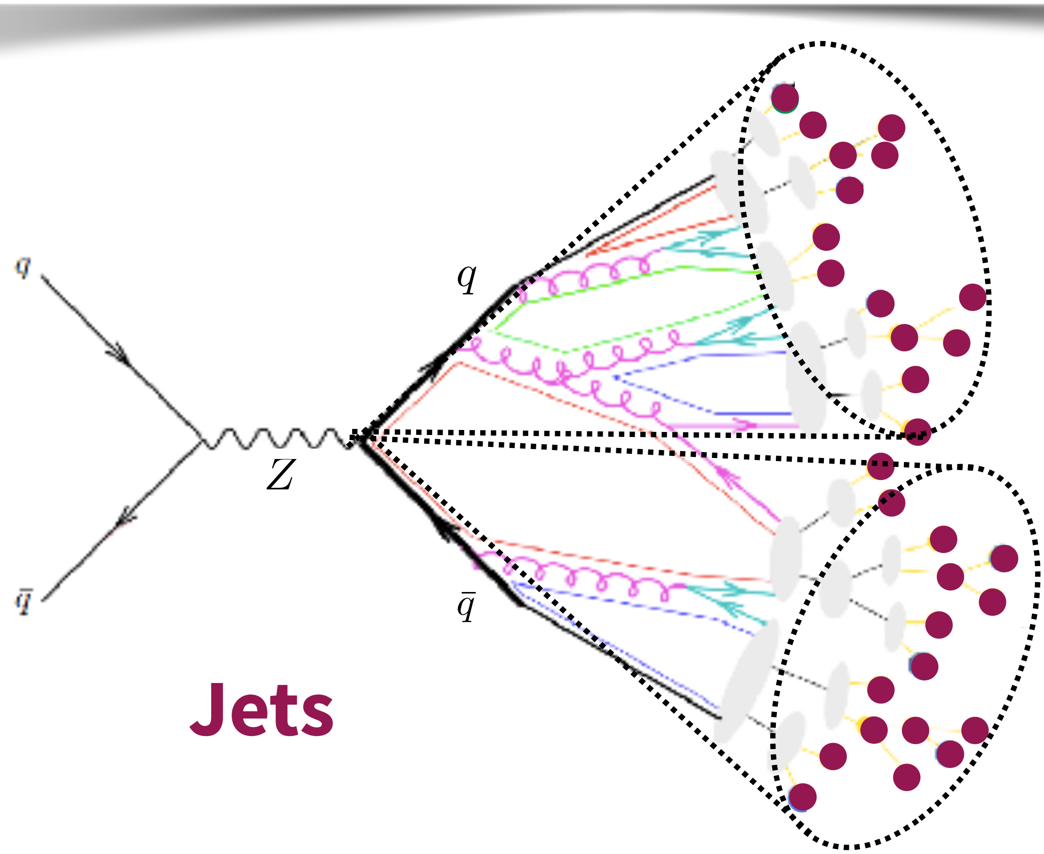
JET reconstruction

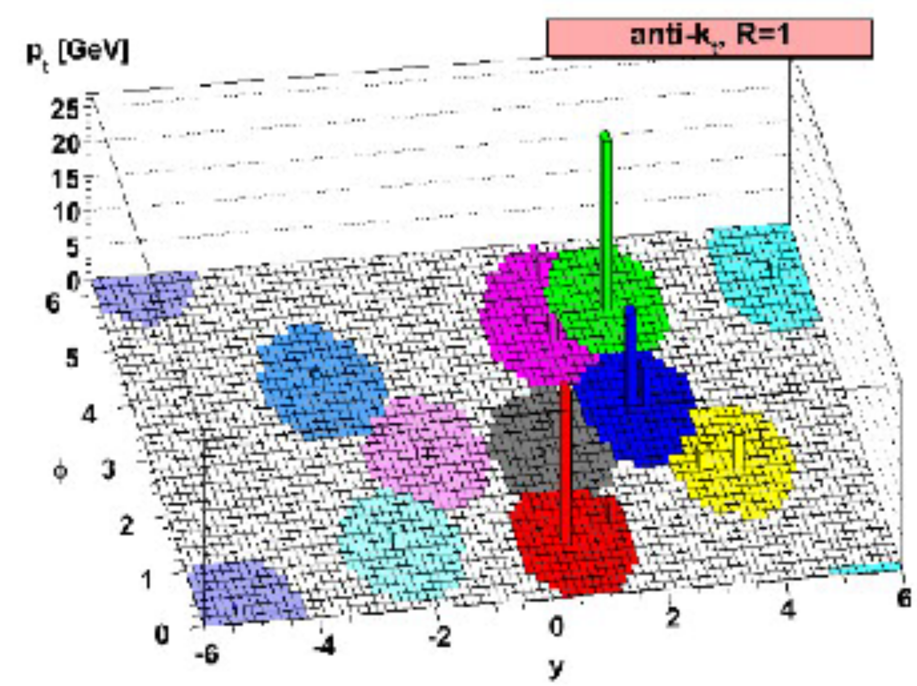
Quarks are confined by strong interaction, so they **hadronize** producing charged and neutral hadrons interacting with the detectors

These particles appeared close to each others and grouped together forming ***jets of particles***

Identified particles are clustered together based on their distance with the **anti-k_T 0.5 algorithm** (infrared safe)

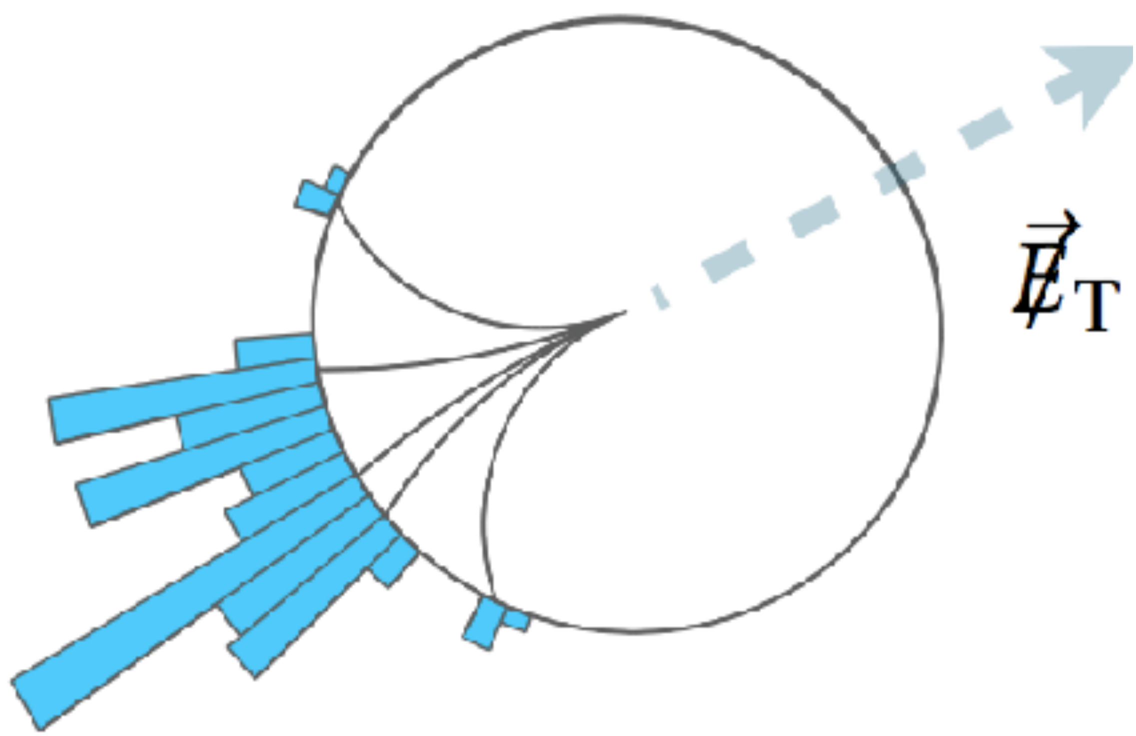




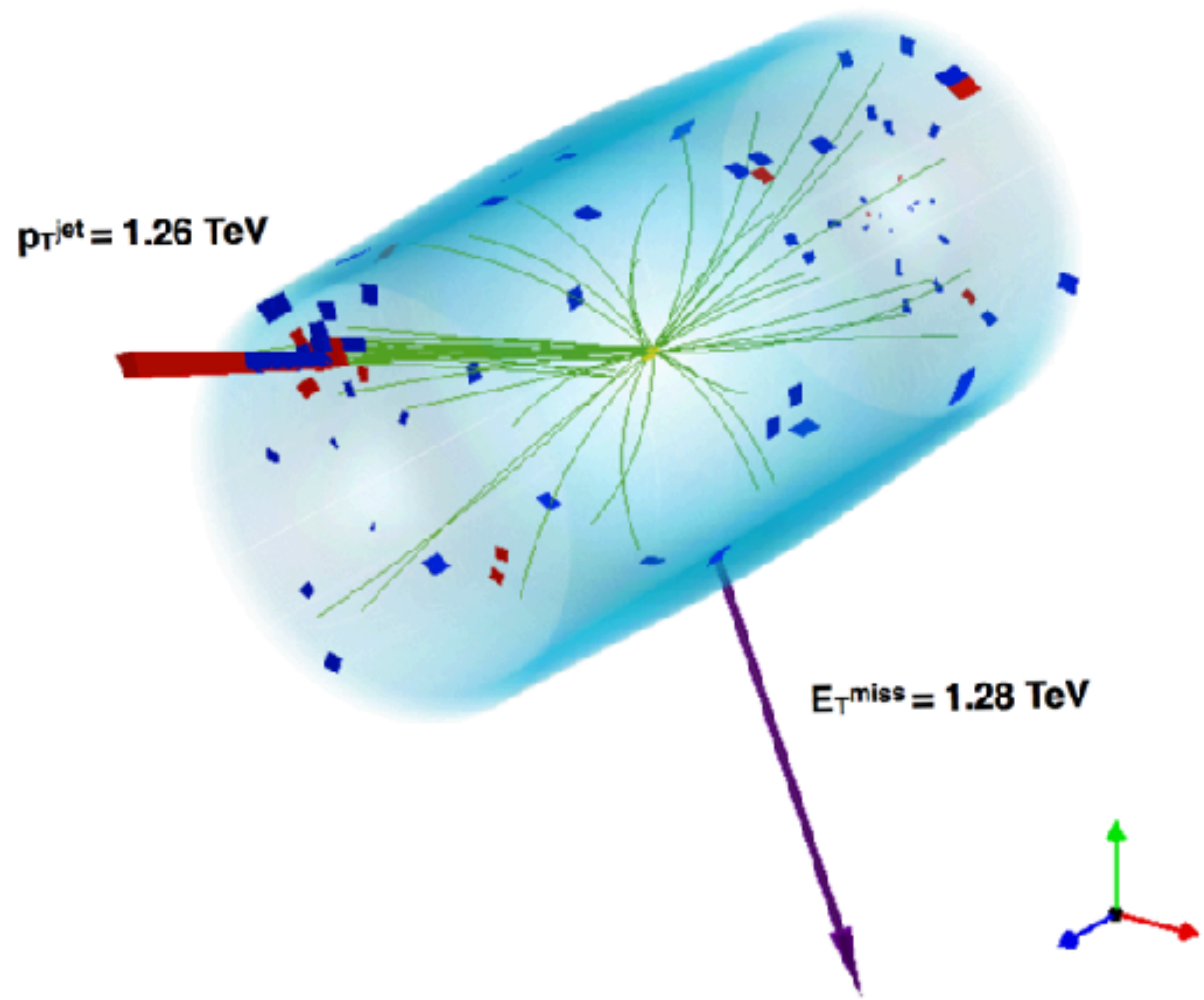


Missing energy

- Particles such as neutrinos are invisible to detectors
  - They signature is actually a ***missing signature***, identified by an energy imbalance in the plane transverse to the beams



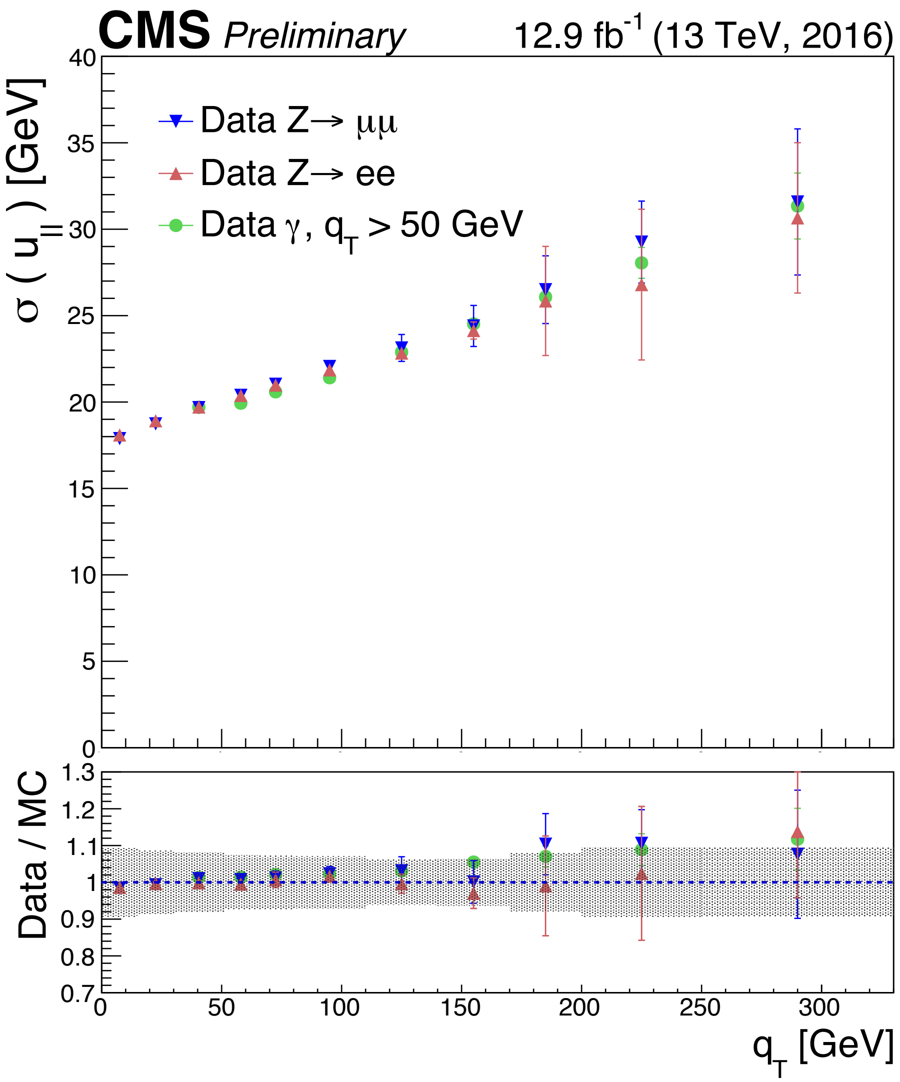
$$E_T^{miss} = -\sum_i {p_T}^i$$

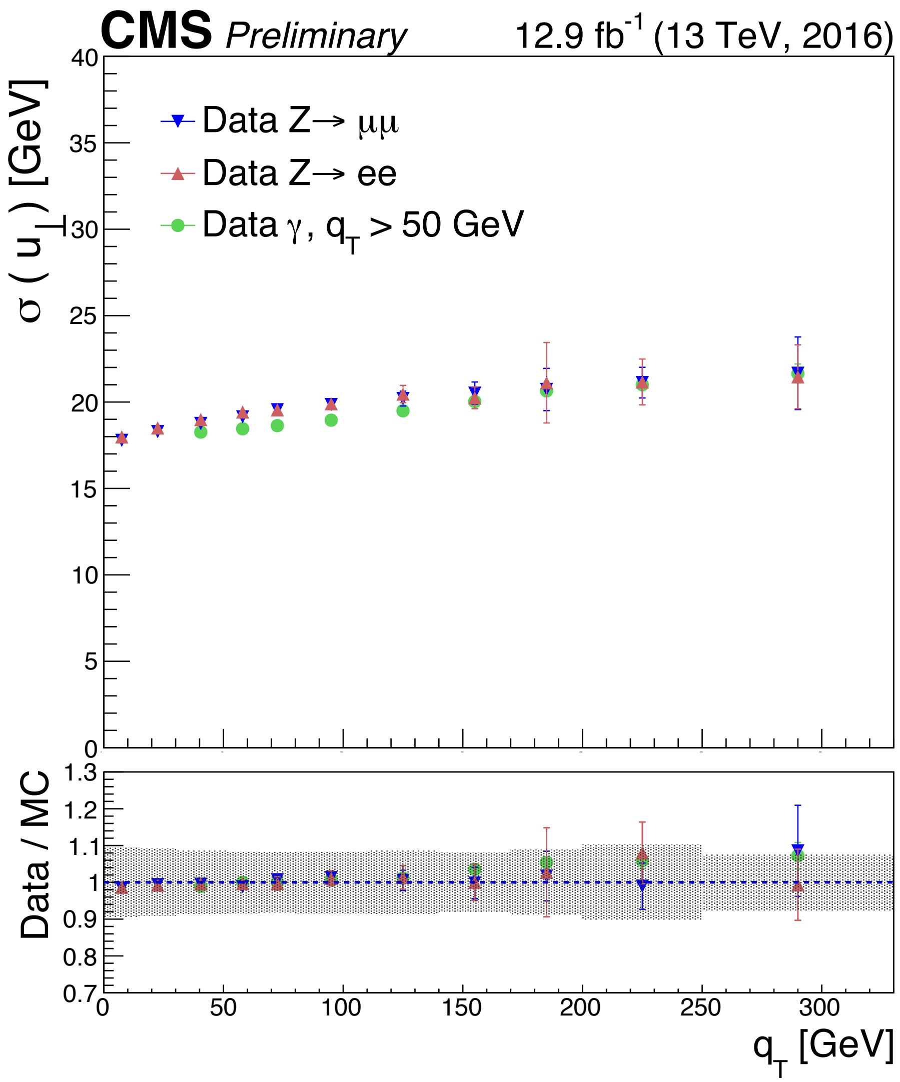


- **Missing transverse momentum** (E_T^{miss}) is defined as ***the negative sum of the transverse momenta of all reconstructed particles***

Missing Energy resolution

- Missing momentum could indicate the presence of new physics particles, such as SUSY particles or Dark Matter
- Important: high MET resolution
  - which means high precision measurement of the transverse momenta of all the other particles reconstructed in the event

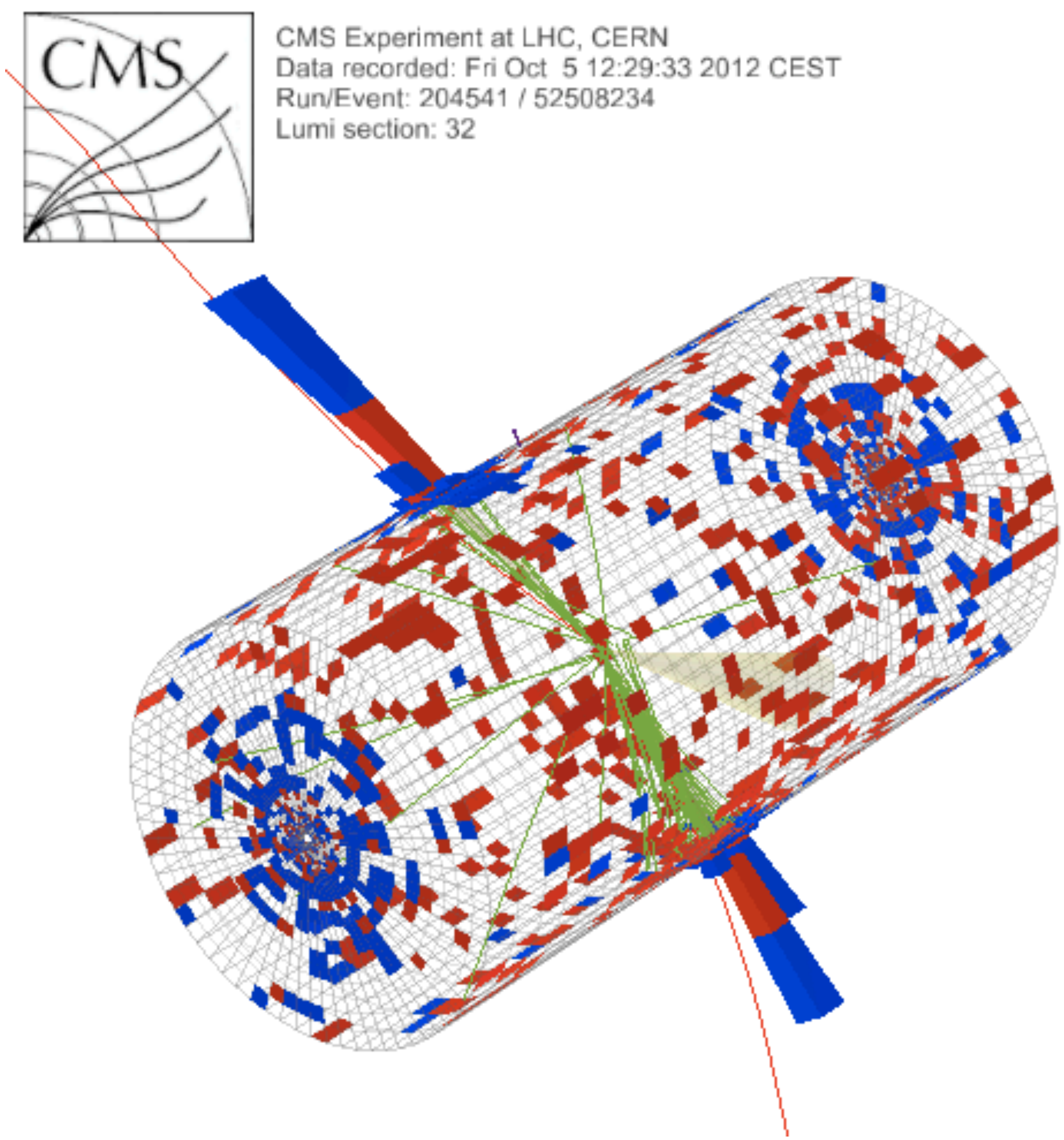


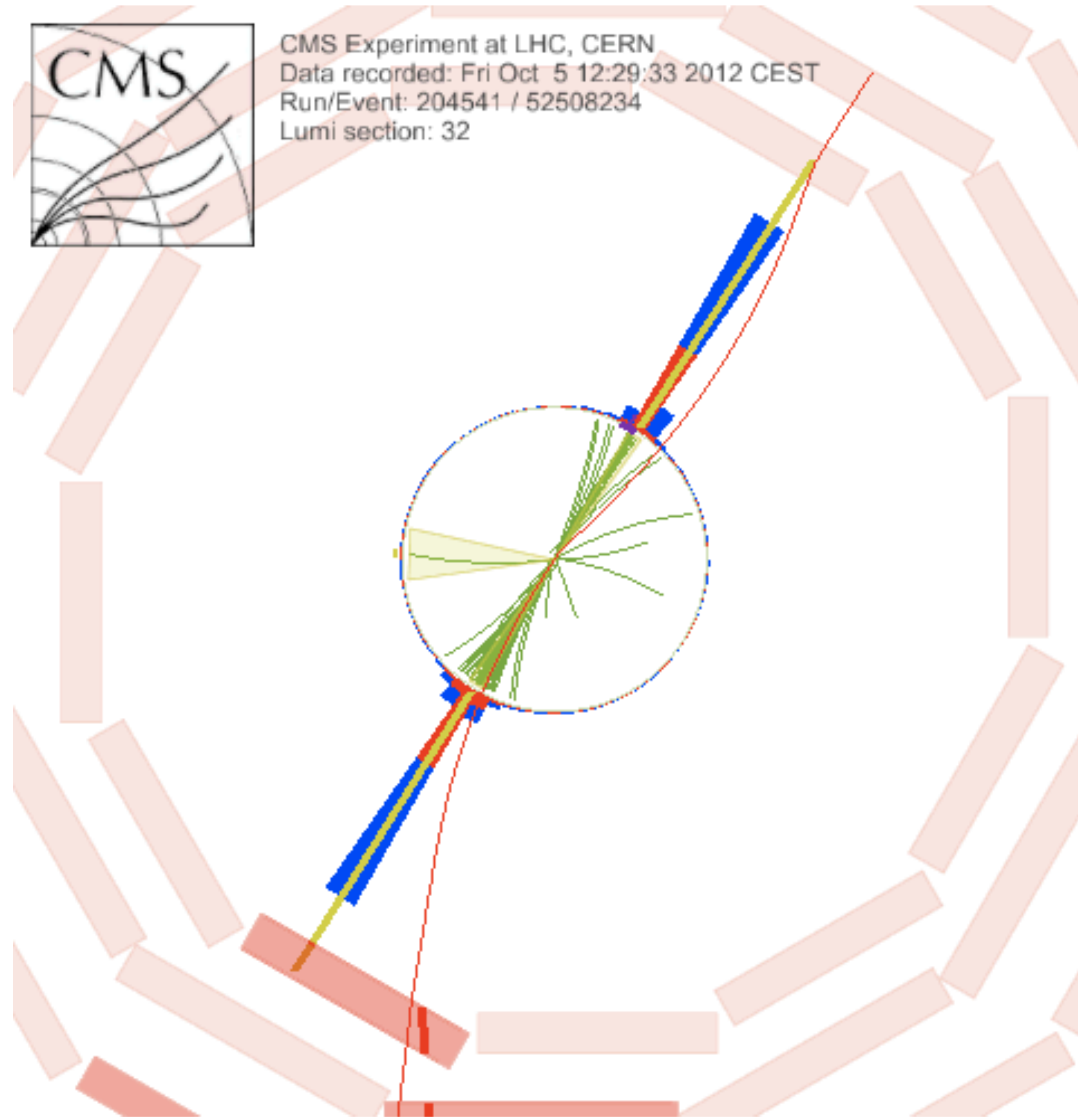


- **Fake MET** arises mostly from jet mis-reconstruction, but also from missing objects such as not reconstructed leptons or contribution from underlying event

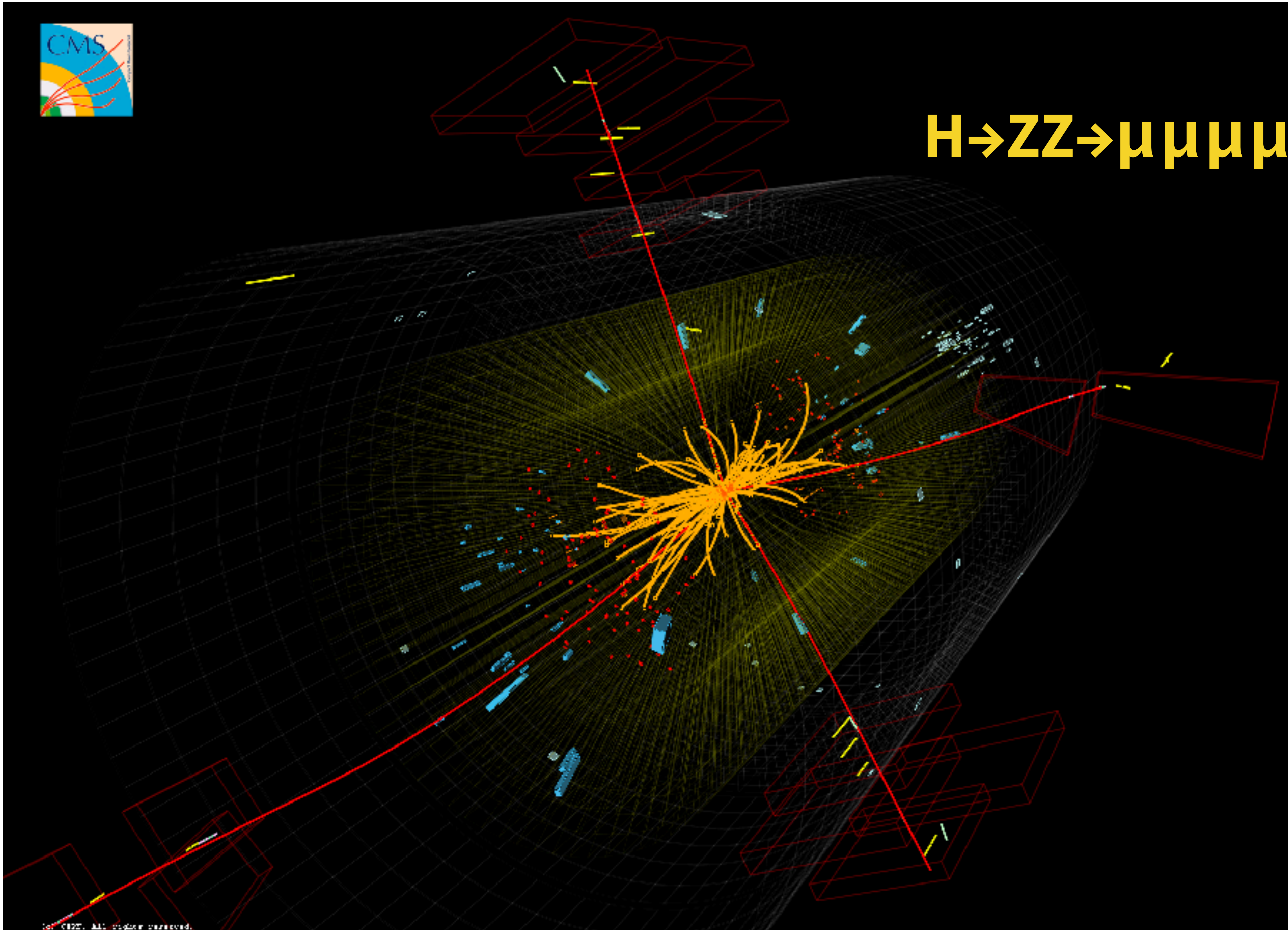
Event reconstruction

Dijet event

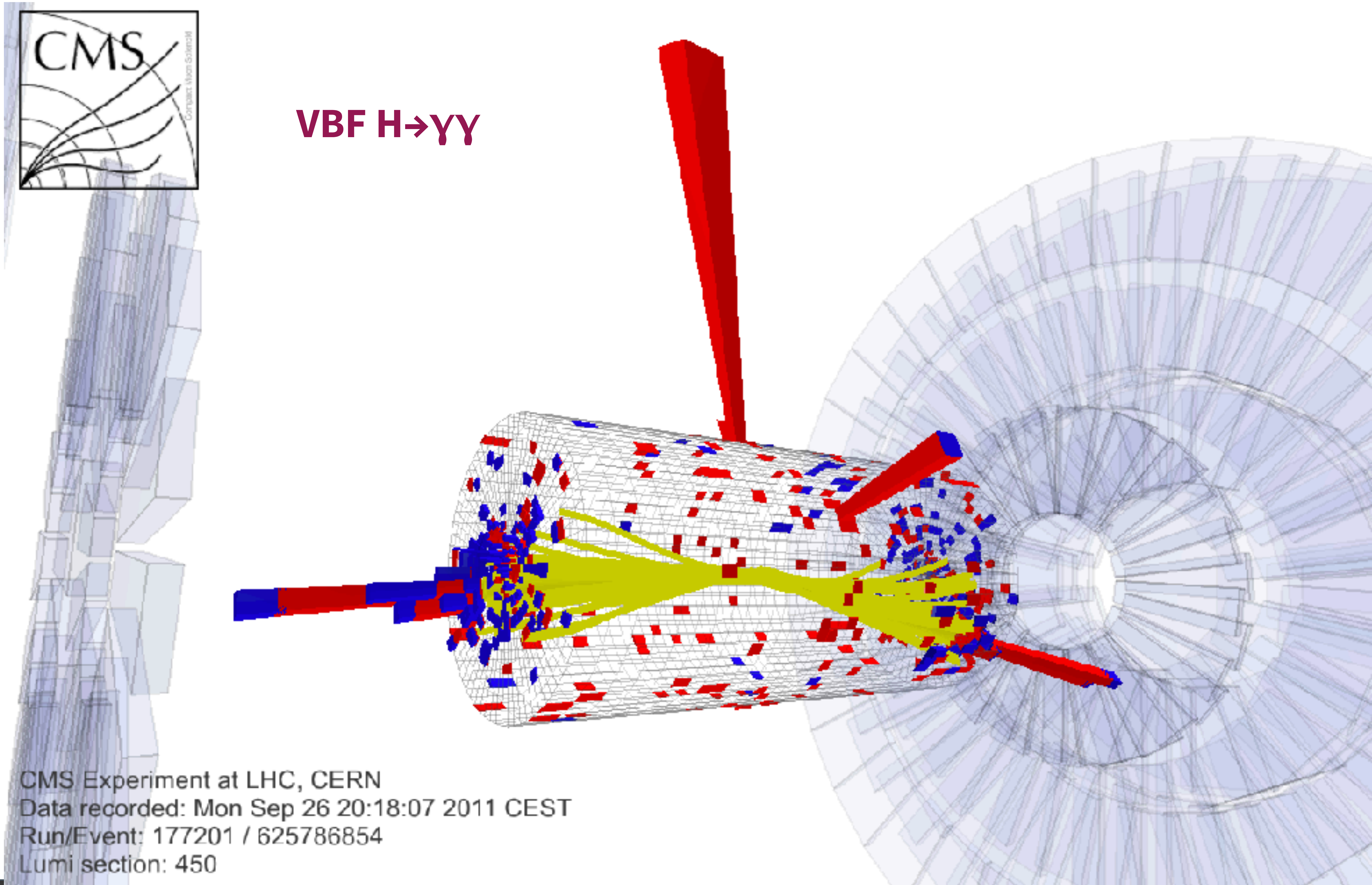




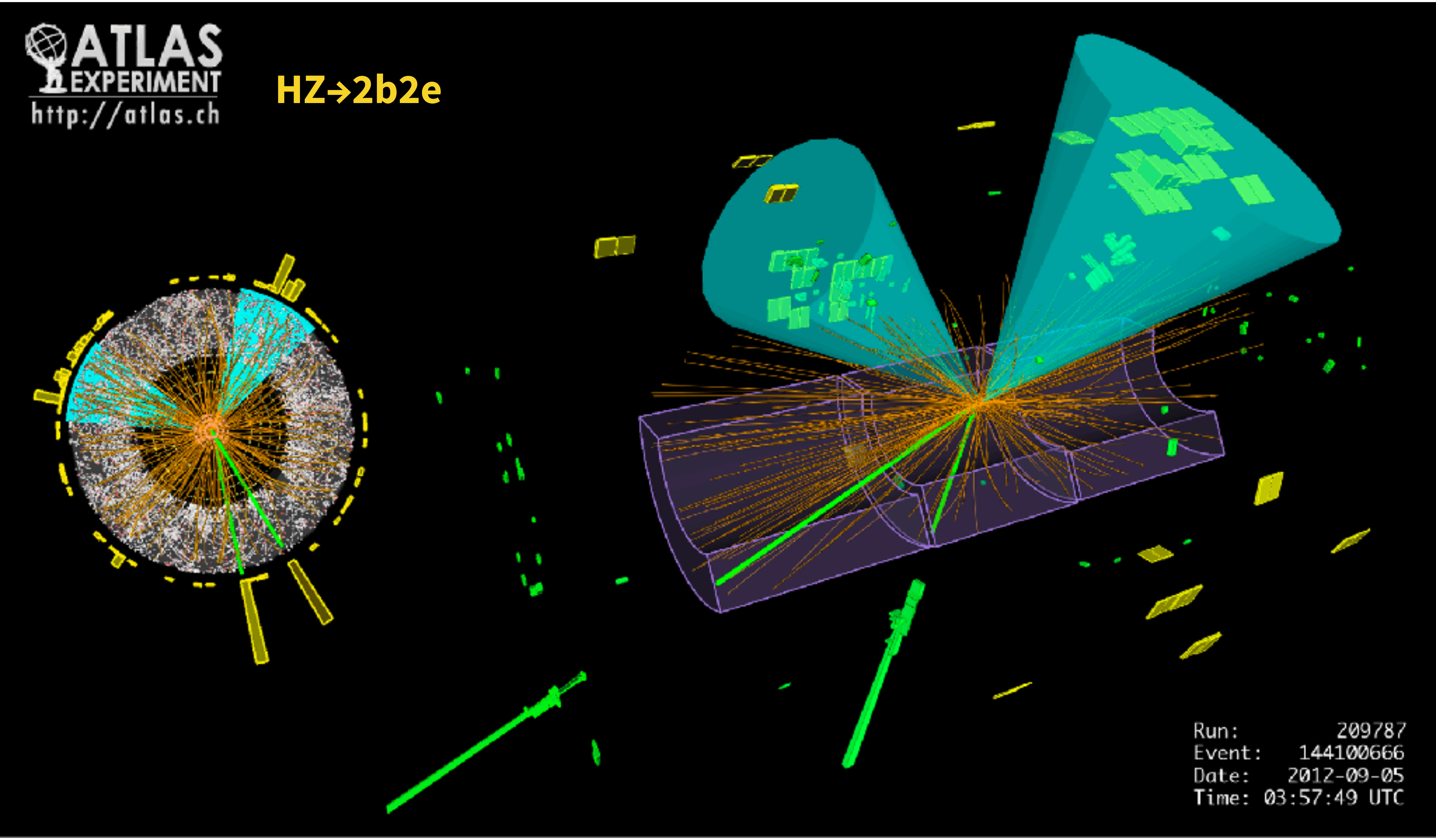
Event reconstruction



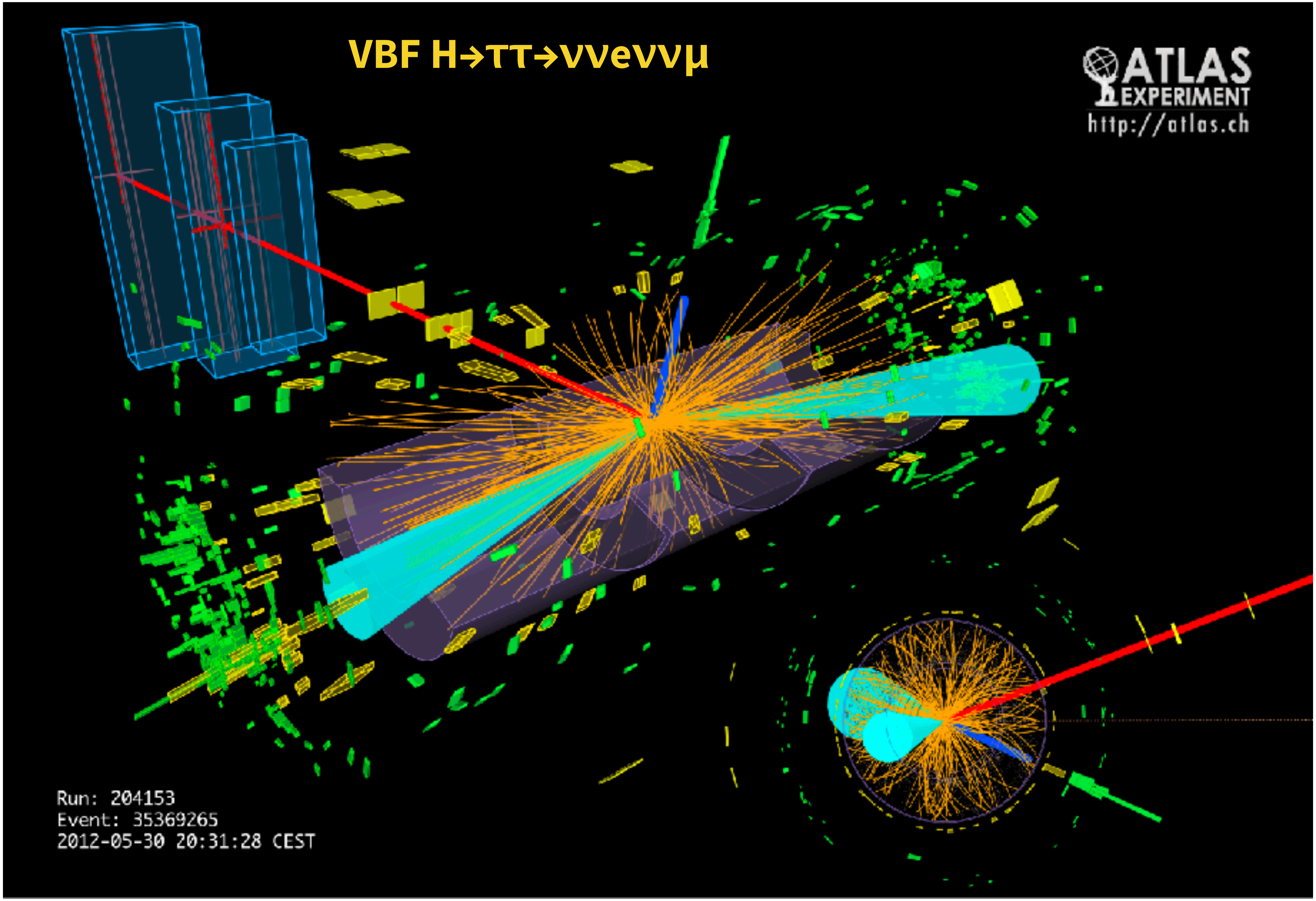
Event reconstruction



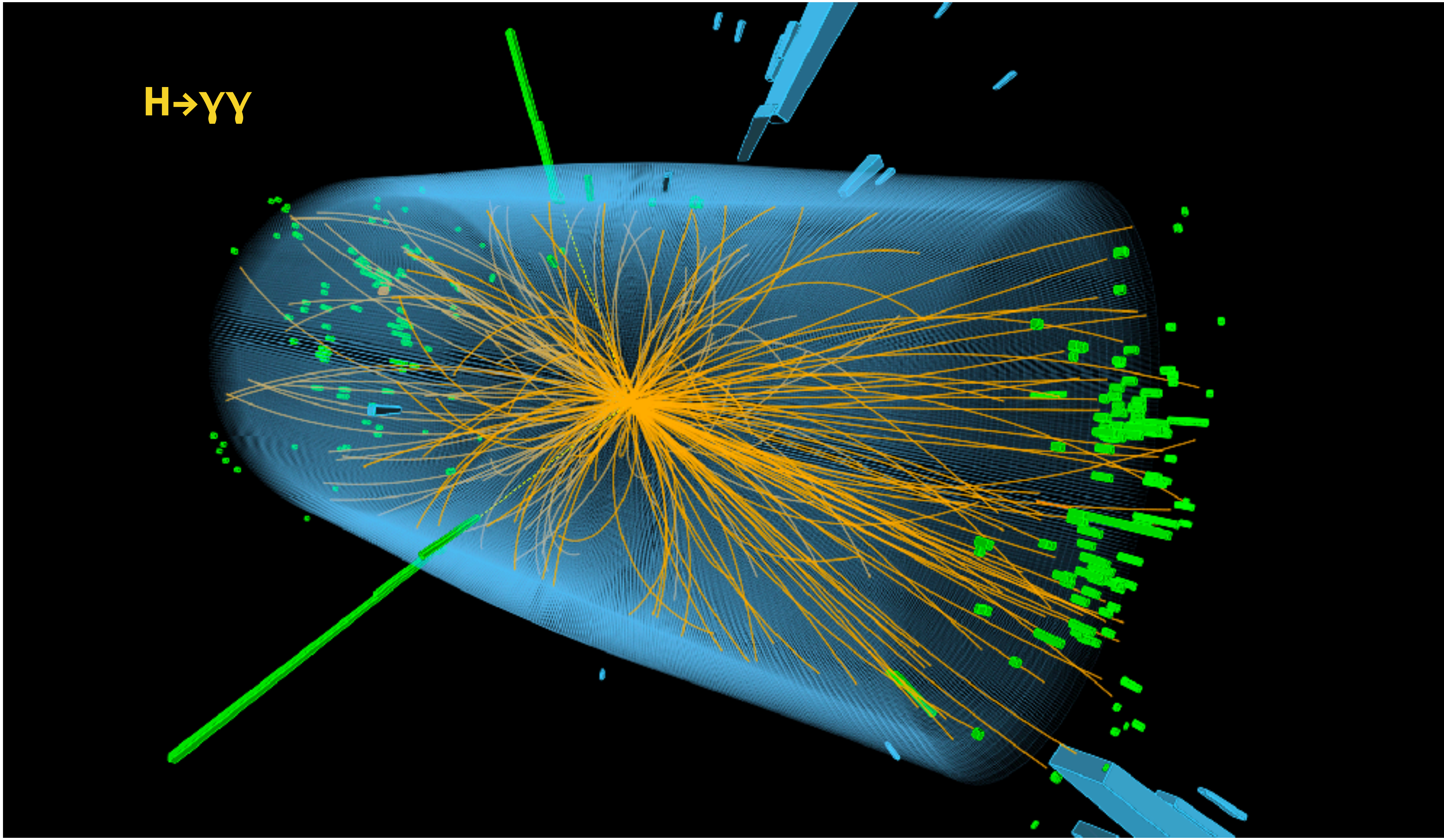
Event reconstruction



Event reconstruction



Event reconstruction



Event reconstruction