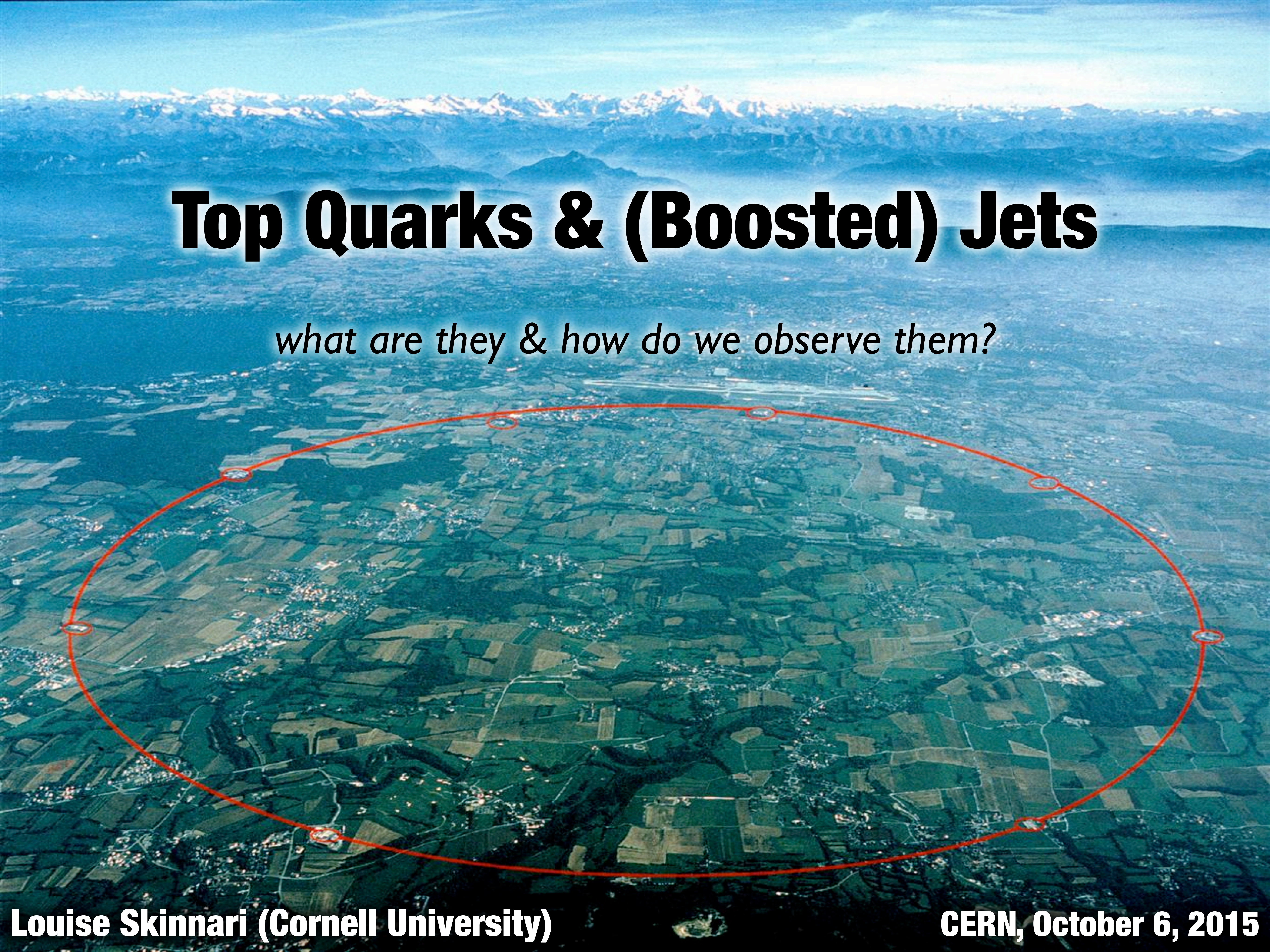
Top Quarks & (Boosted) Jets

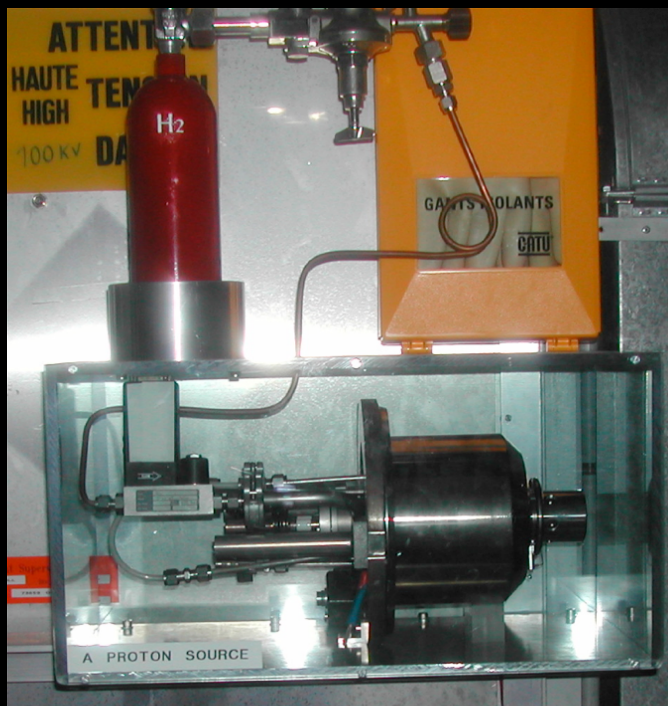
what are they & how do we observe them?

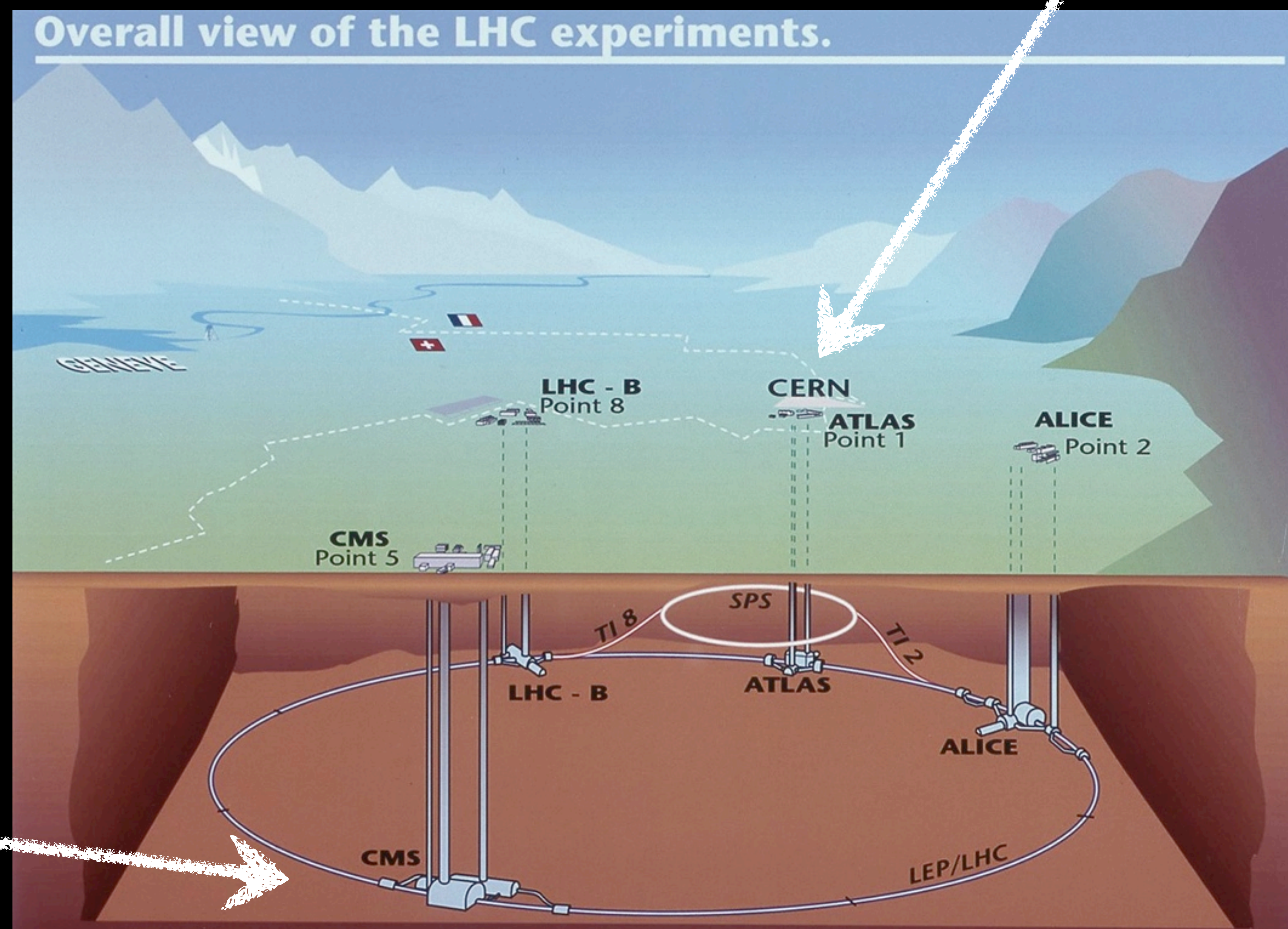


Louise Skinnari (Cornell University)

CERN, October 6, 2015

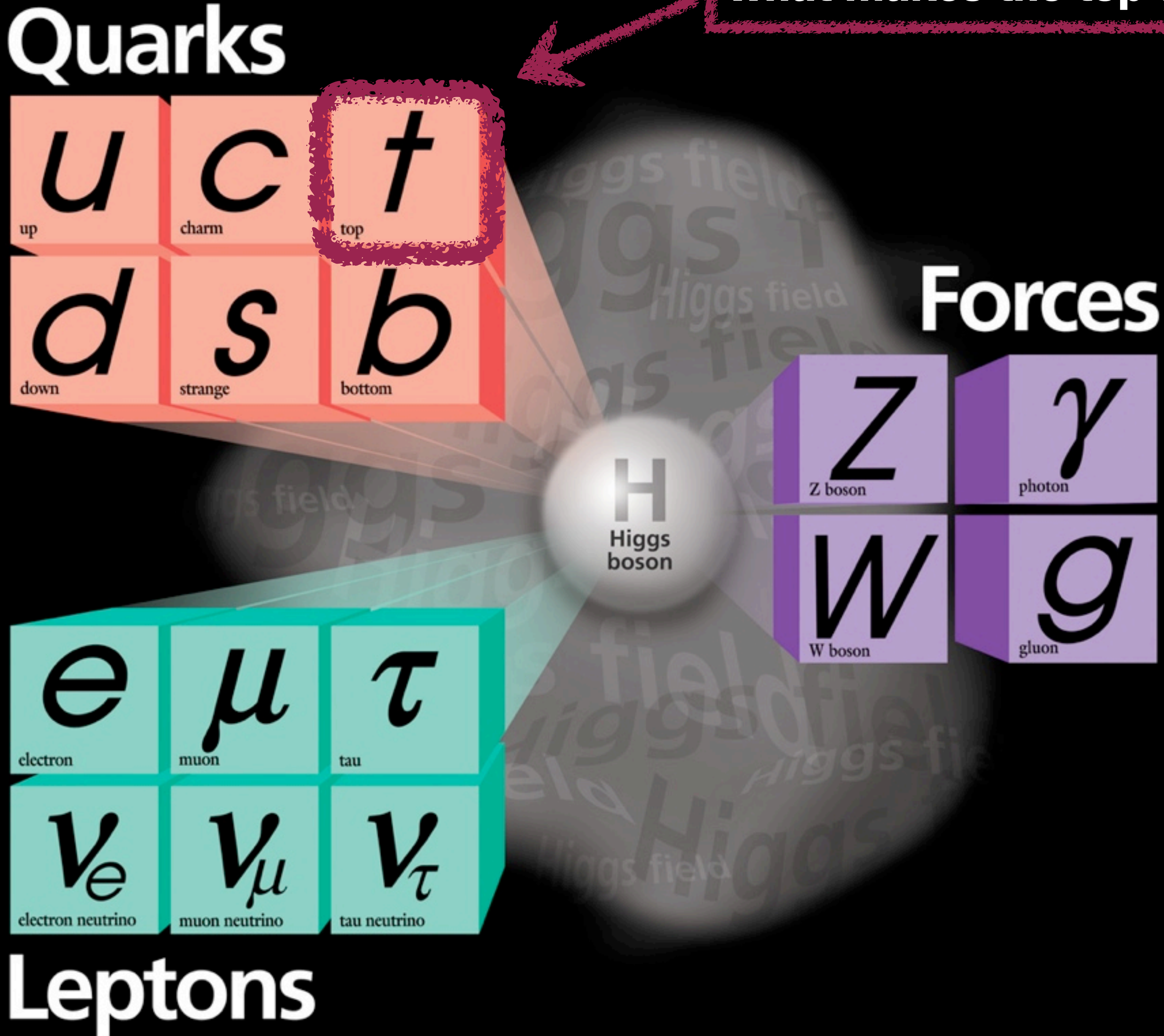
Large Hadron Collider



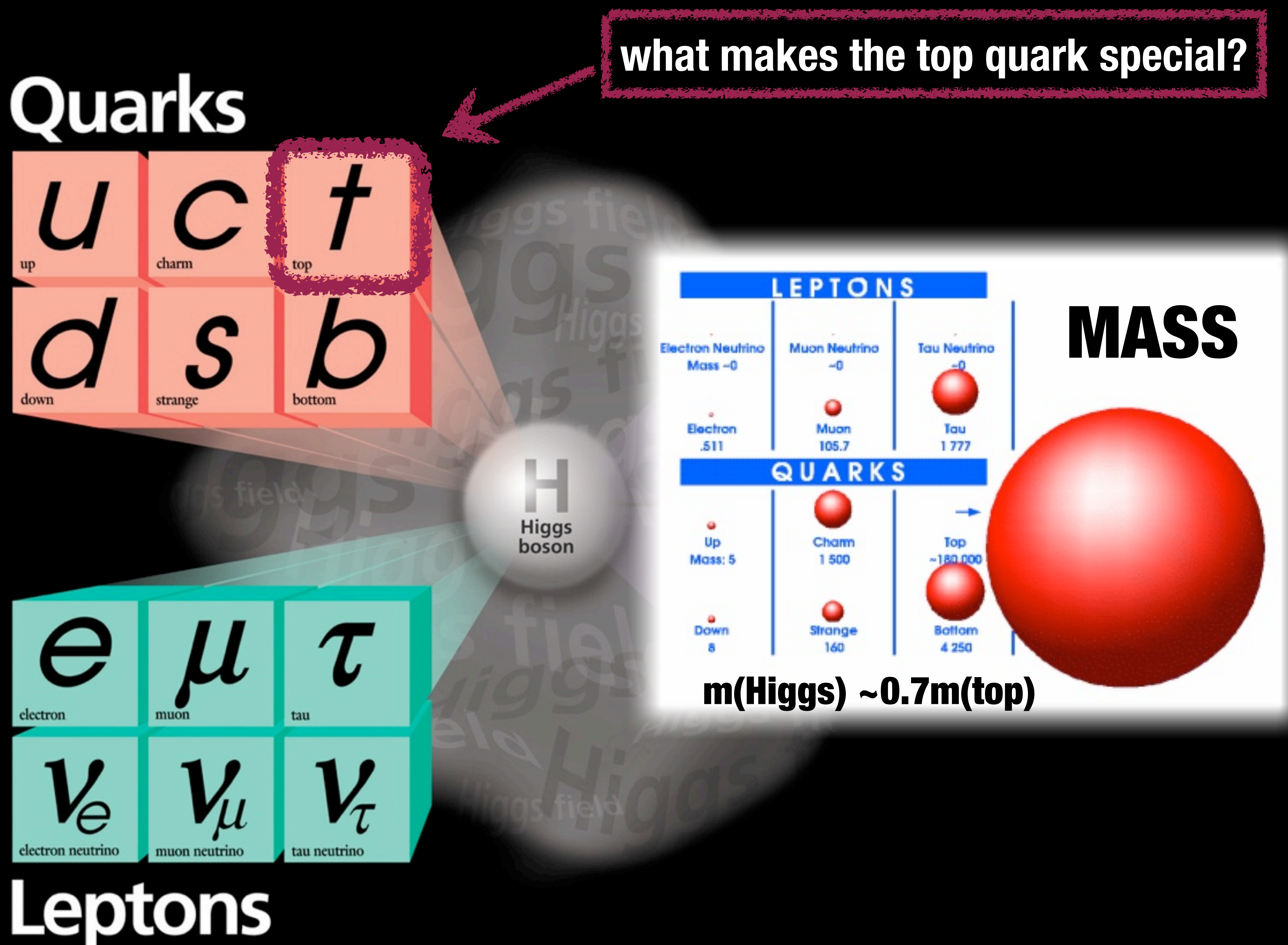


The Standard Model

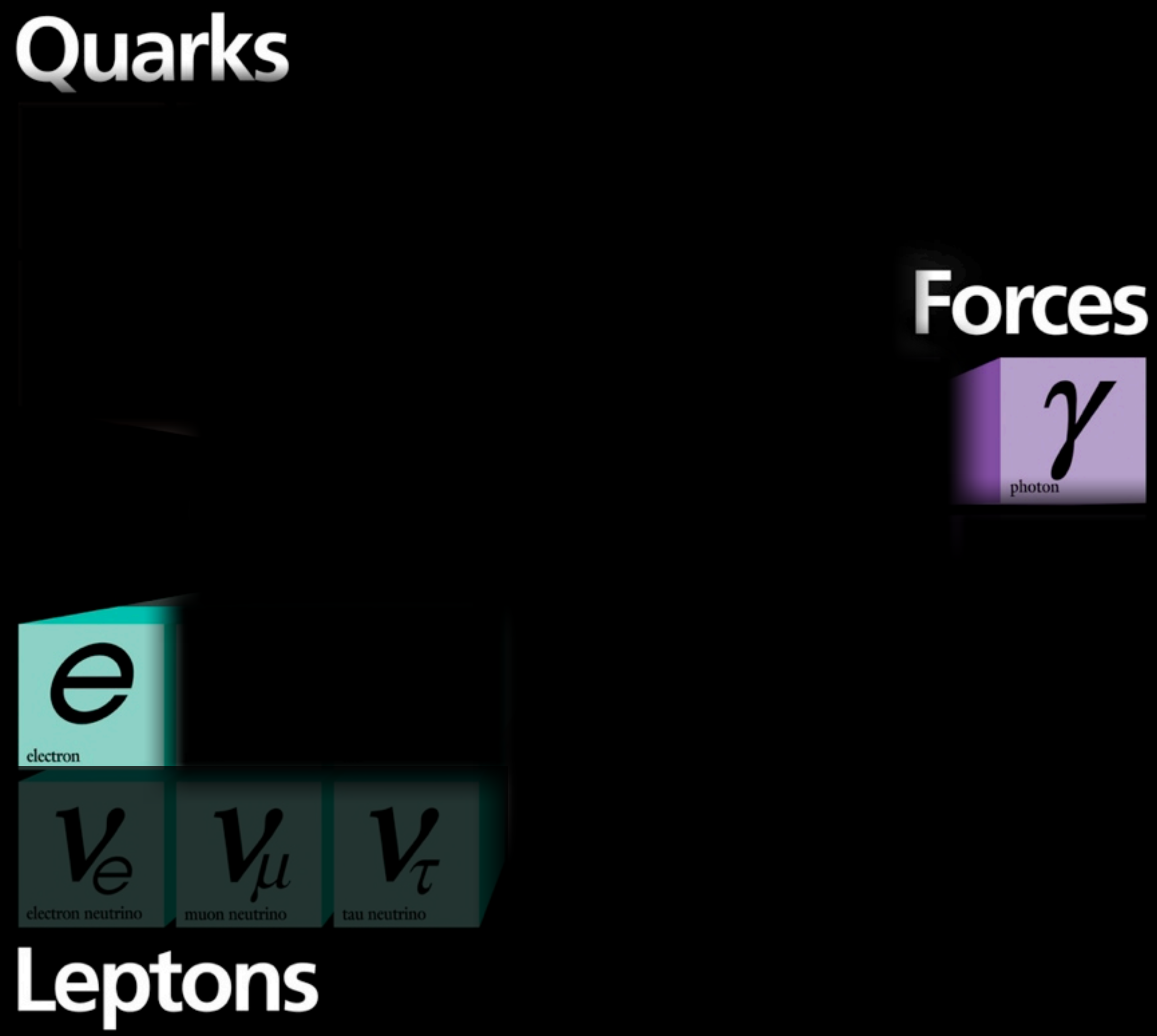
what makes the top quark special?



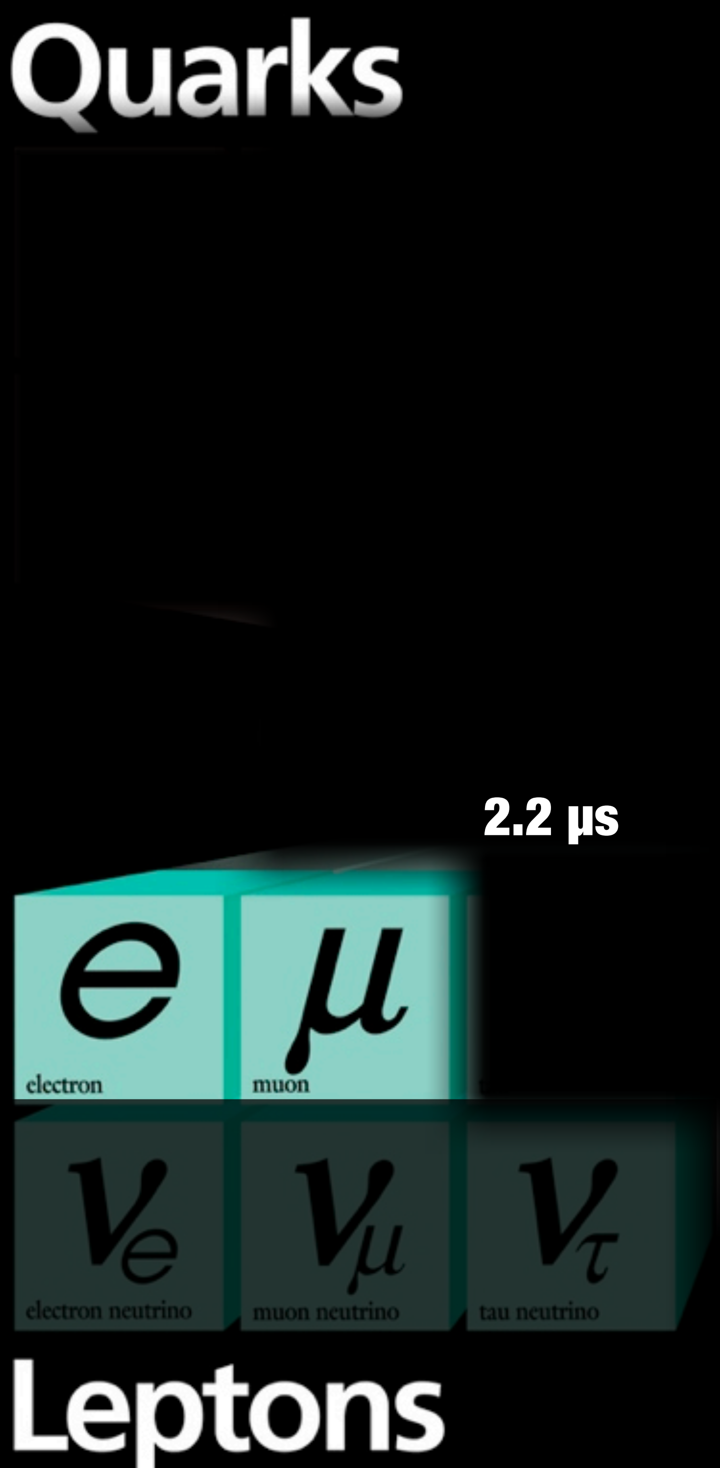
The Standard Model



Stable Particles



Stable Particles



Composite particles

Neutron 15 min

Proton ≥10^{32} years

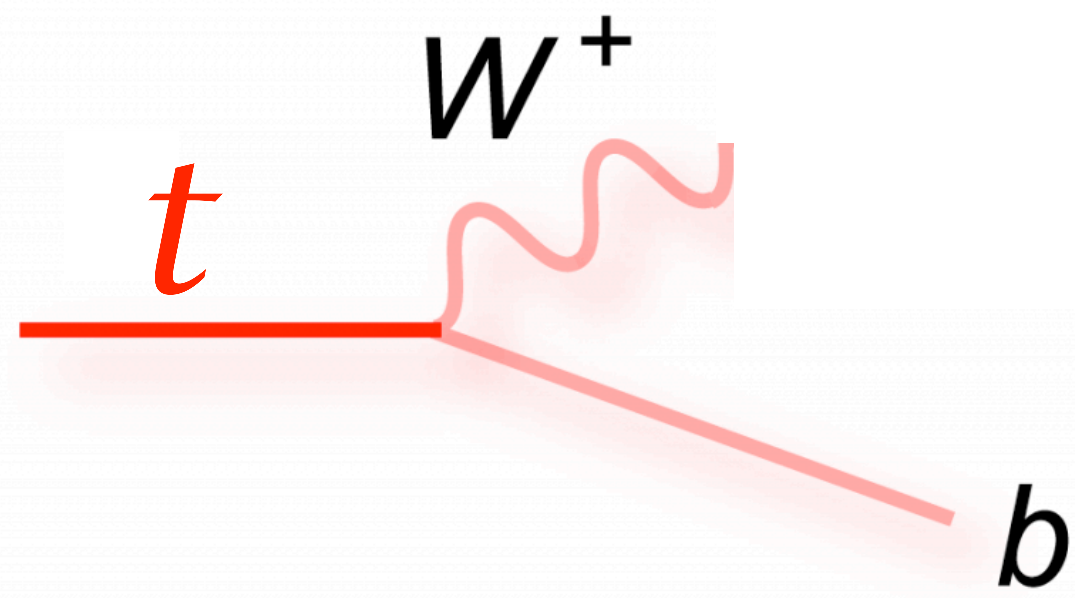
how can we then see something like a top quark?

Top Quark Decay

top quark lifetime ~10^{-25} seconds

near 100% of tops decay to W+b

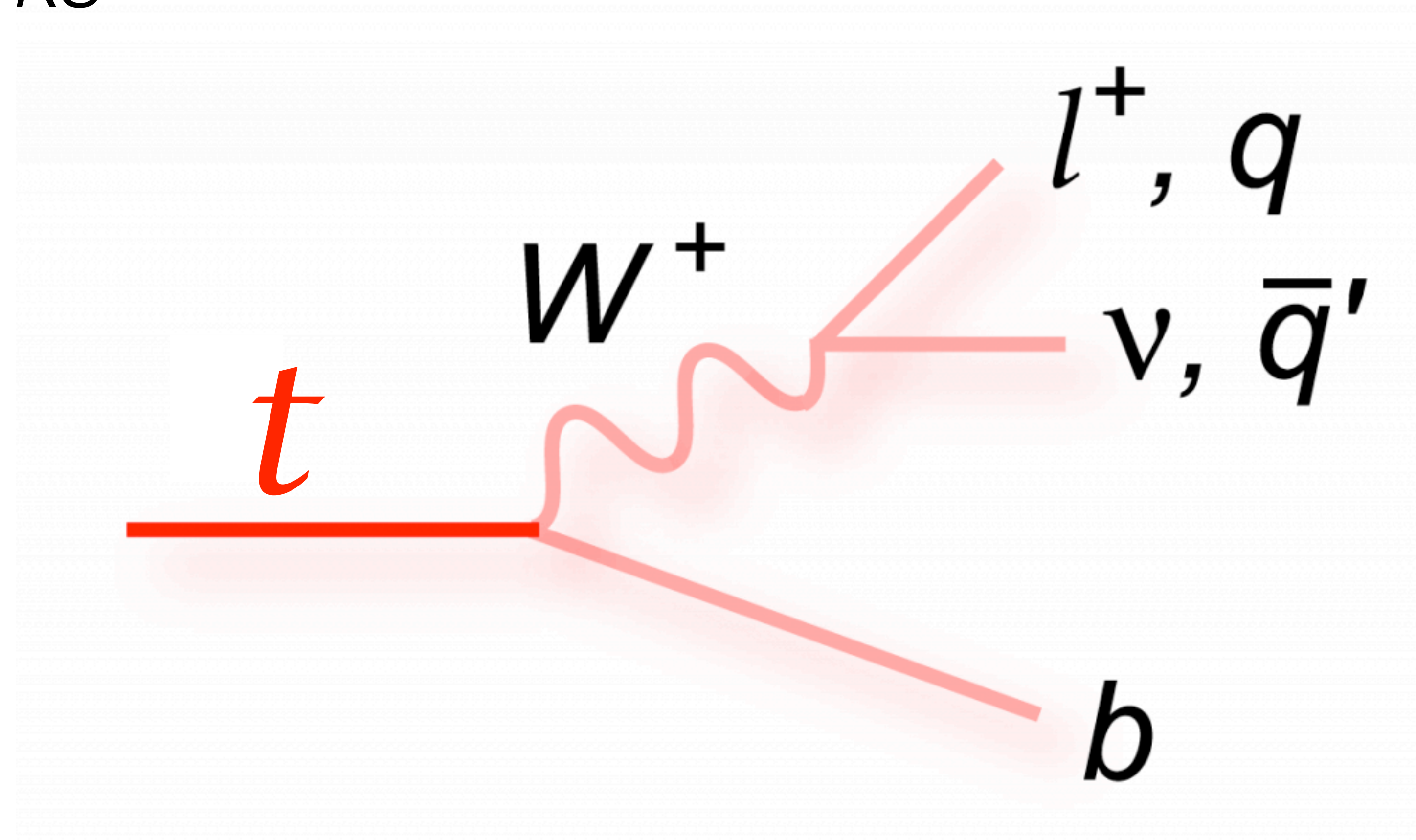
electric change = 2/3e



Top Quark Decay

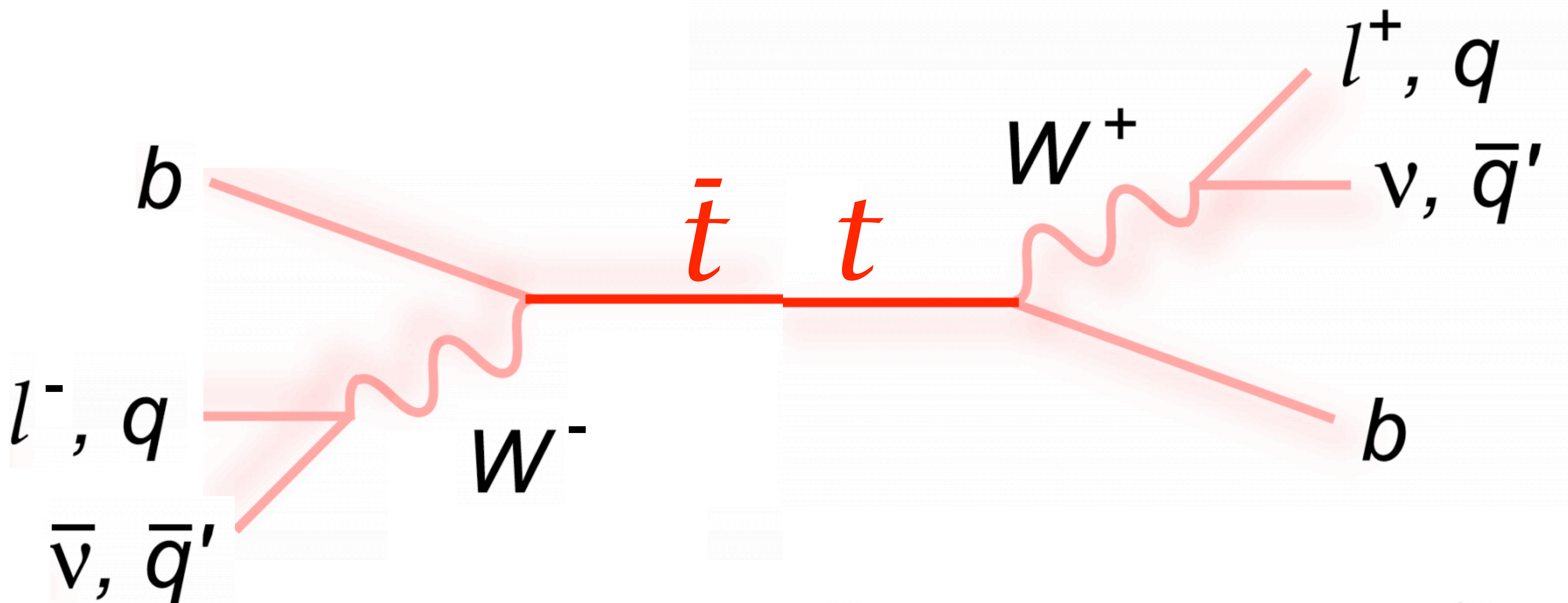
W boson lifetime ~3x10^{-25} s

W's decay to leptons/quarks

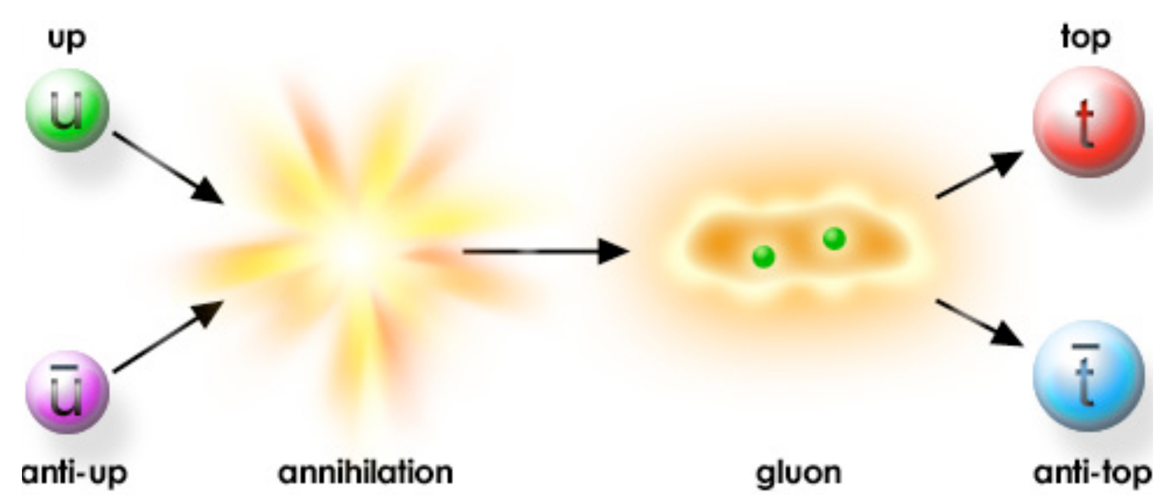


Top Quark Decay

at LHC, top quarks most often pair-produced



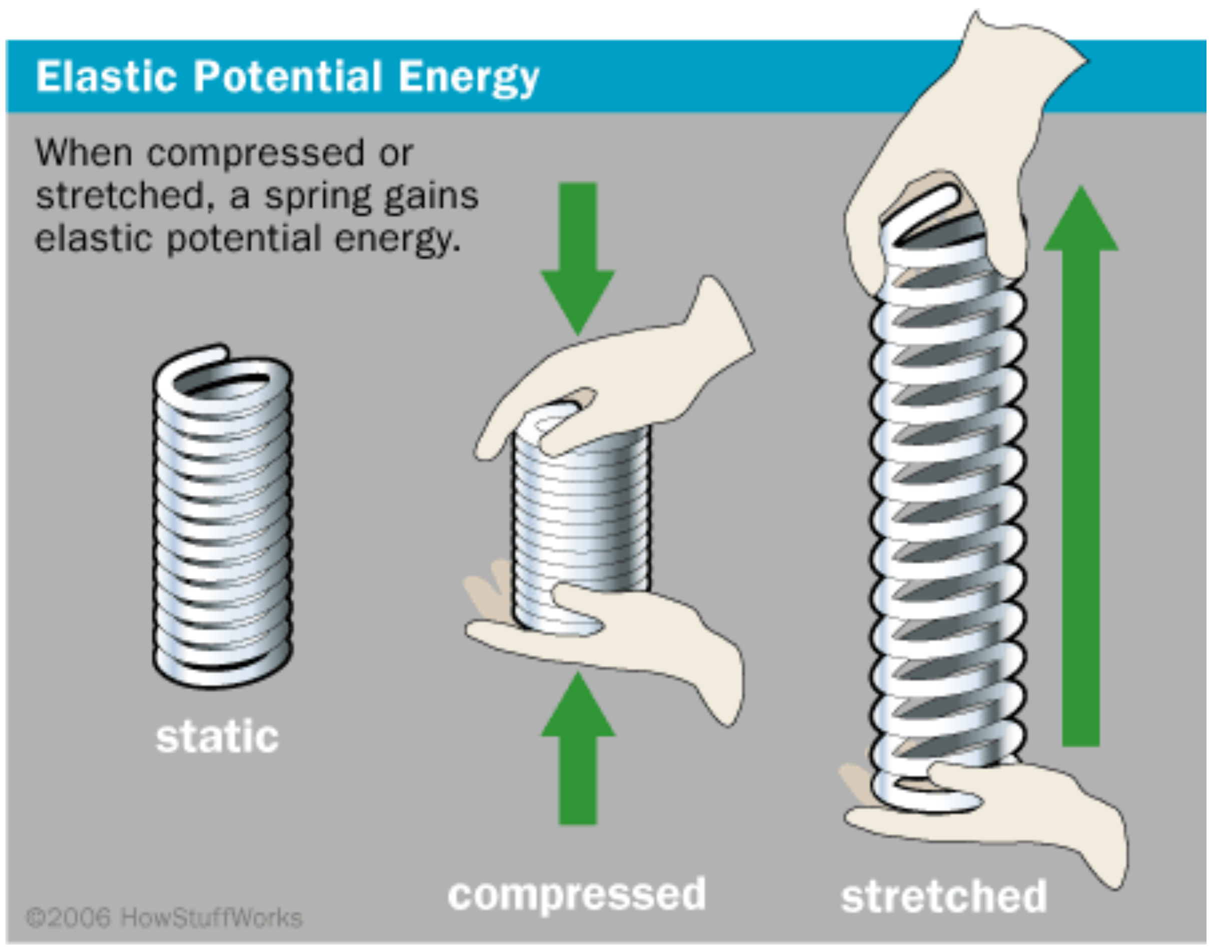
- quark-antiquark annihilation
- gluon fusion

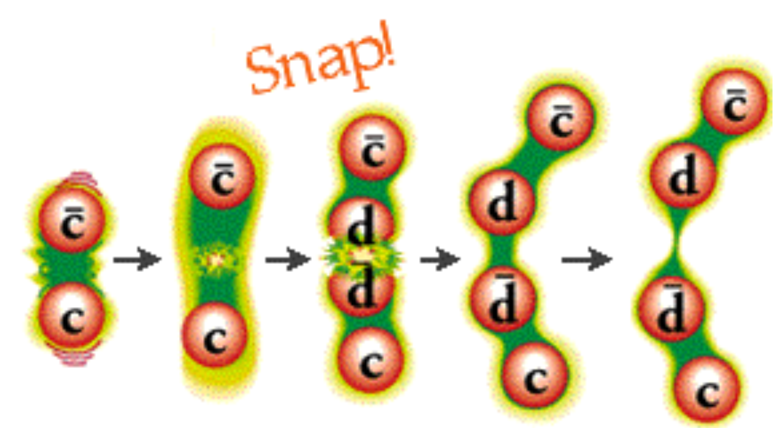


can we see a quark?

Quarks - Hadrons - Jets

- Quarks cannot exist as free particles!
  - Spring-like strong force prevents quarks from separating
  - To force quarks apart we have to add energy which in turn creates more quarks
- Hadronization - forming ***hadrons*** from quarks & gluons



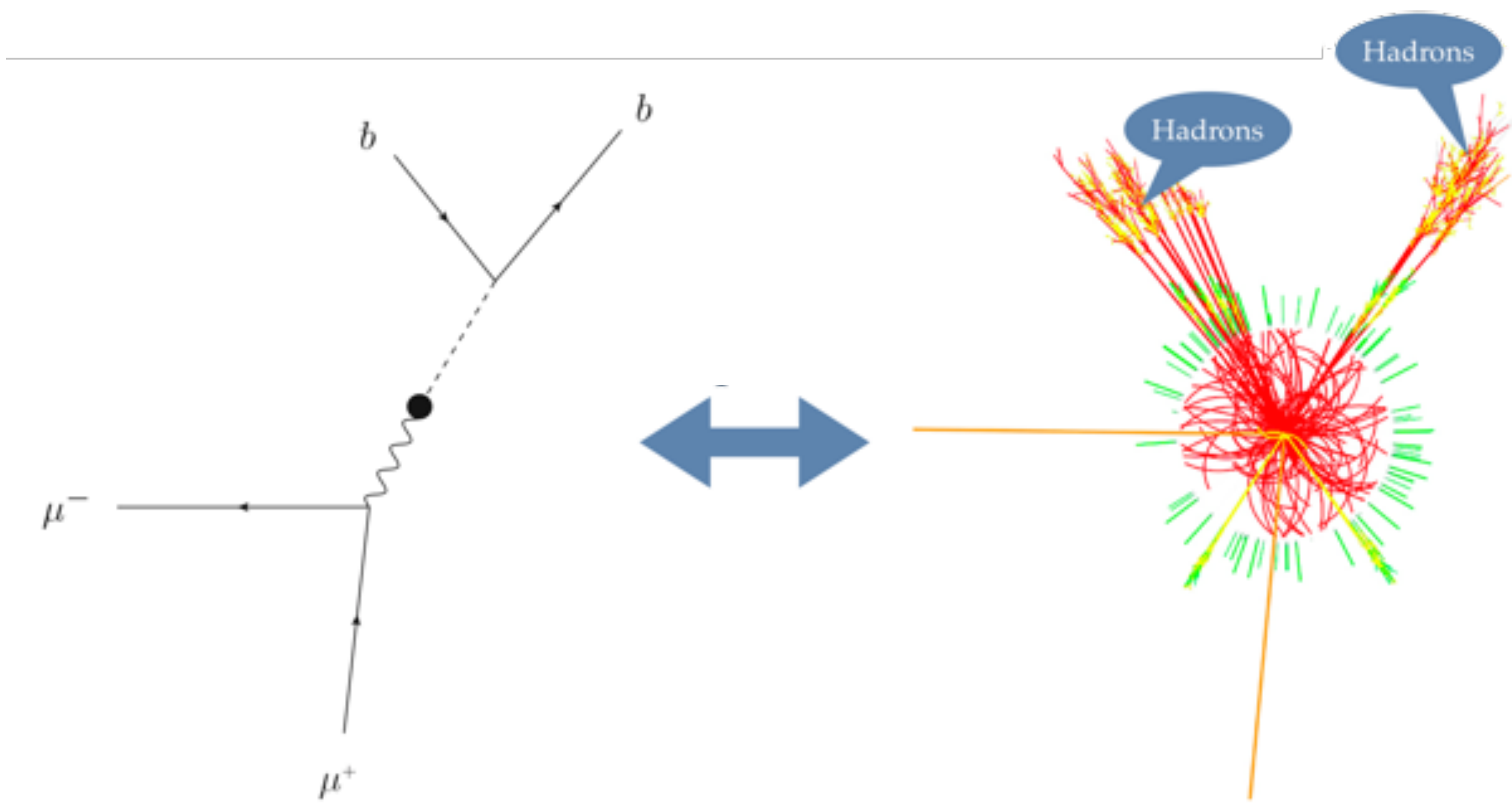


hadronization happens after ~10^{-24} s
reminder: top quark lifetime ~10^{-25} s

Quarks - Hadrons - Jets

- Hadronization result in clusters of neutral & charged particles which can be observed in the detector

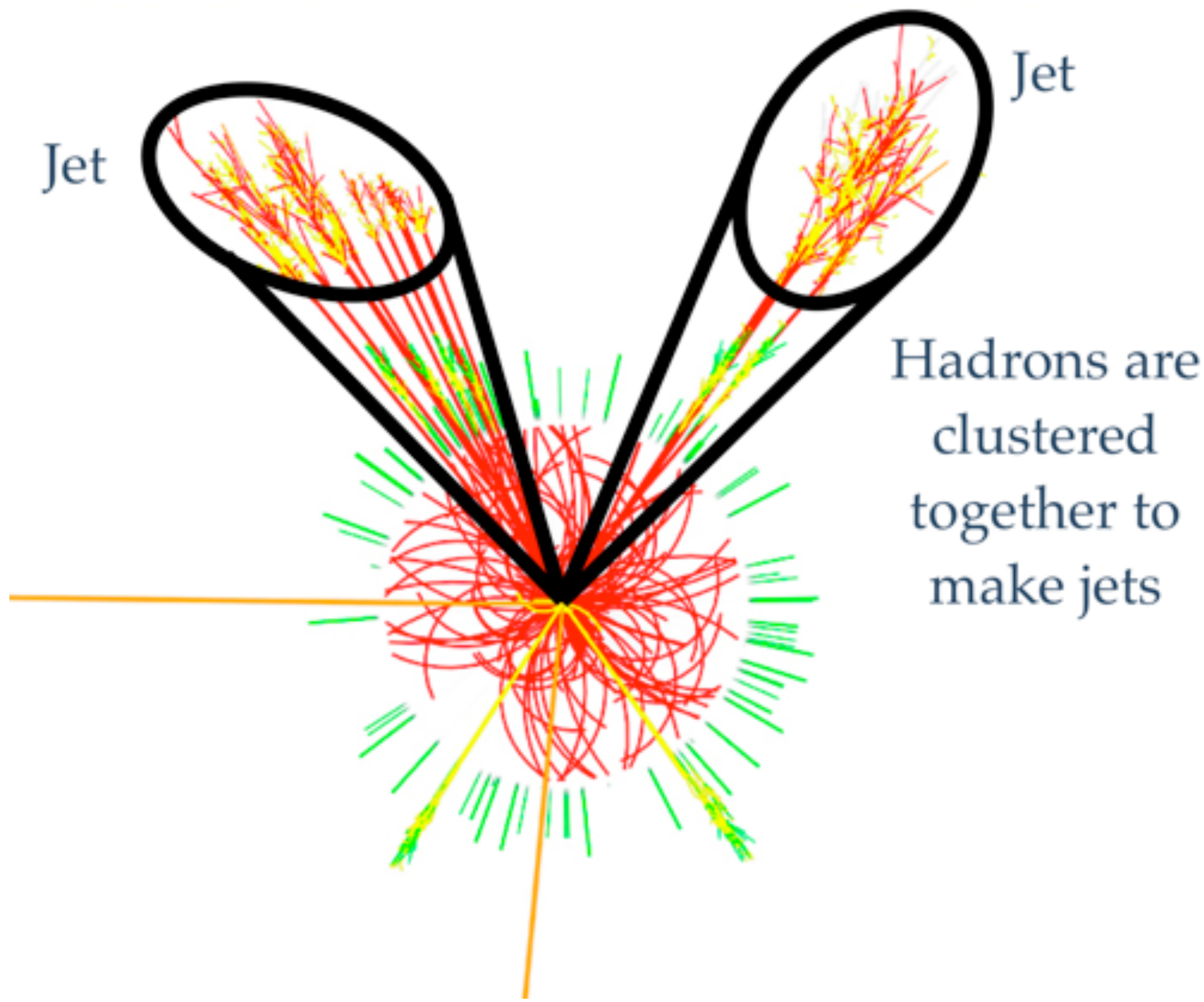
mesons: quark+antiquark
baryons: 3-quark states

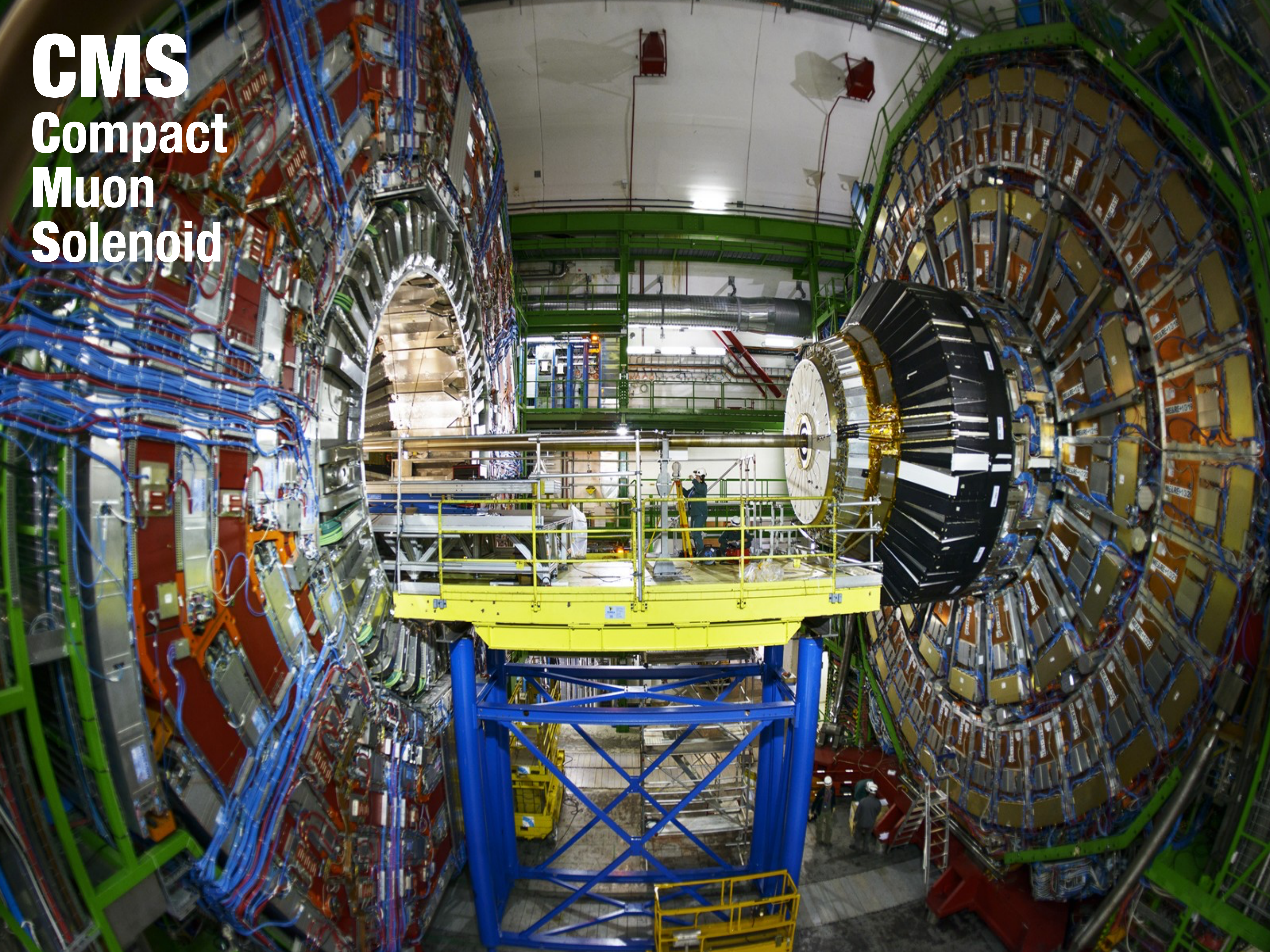


theorist view **experimentalist view**

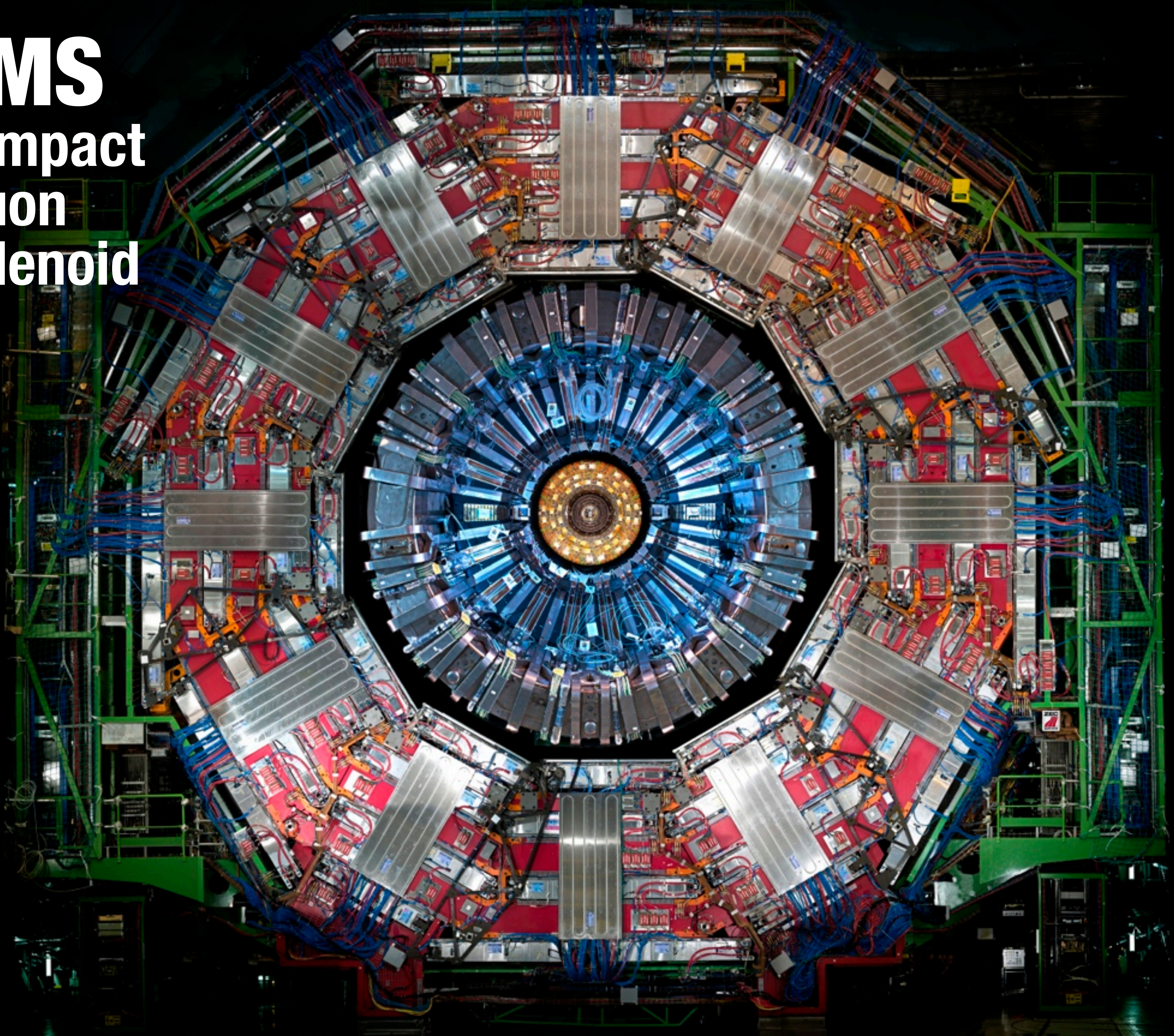
Quarks - Hadrons - Jets

- Hadronization result in clusters of neutral & charged particles which can be observed in the detector
- These clusters are called ***"jets"***

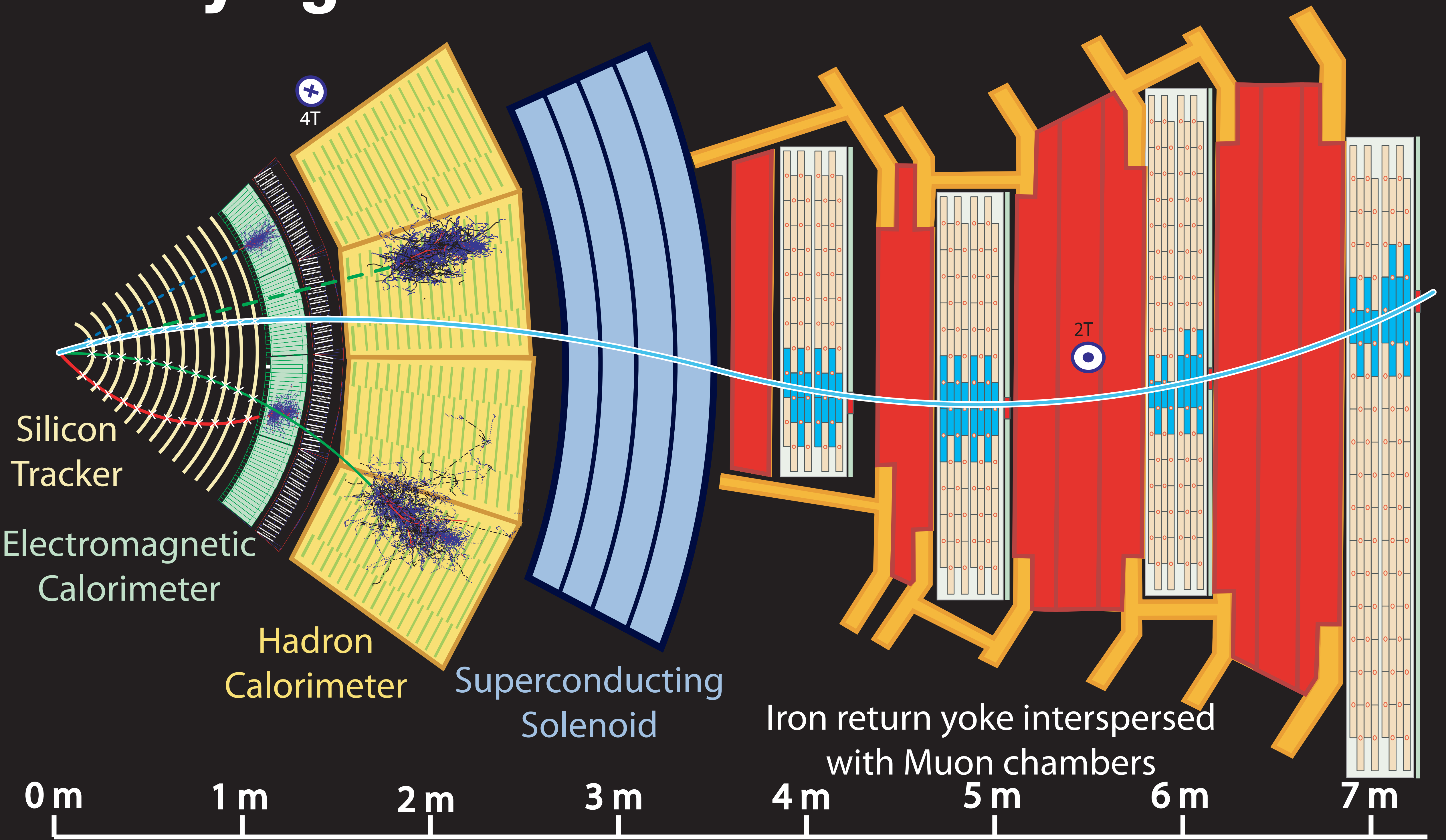



CMS
Compact
Muon
Solenoid

CMS
Compact Muon Solenoid



Identifying Particles

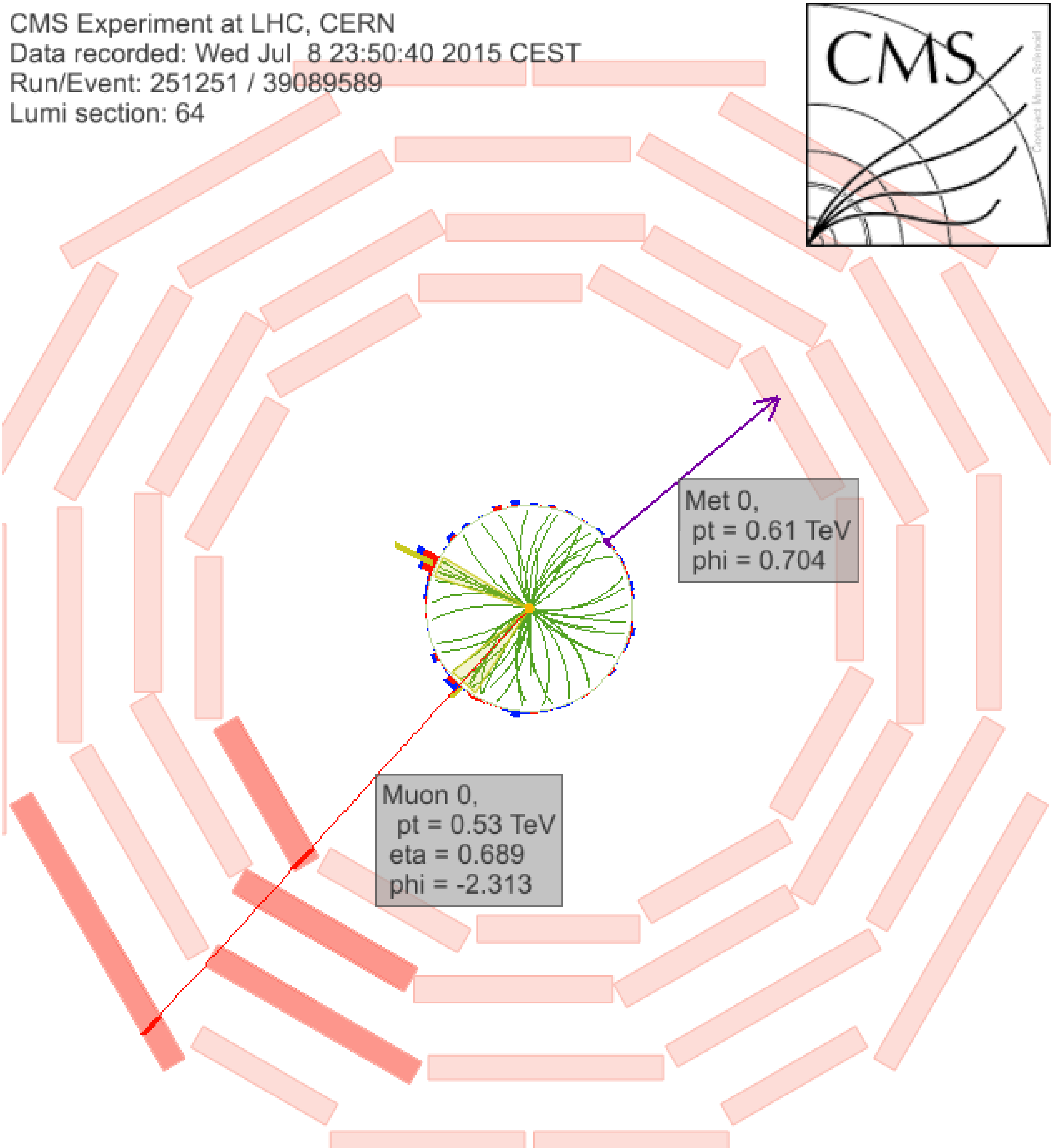


Key:

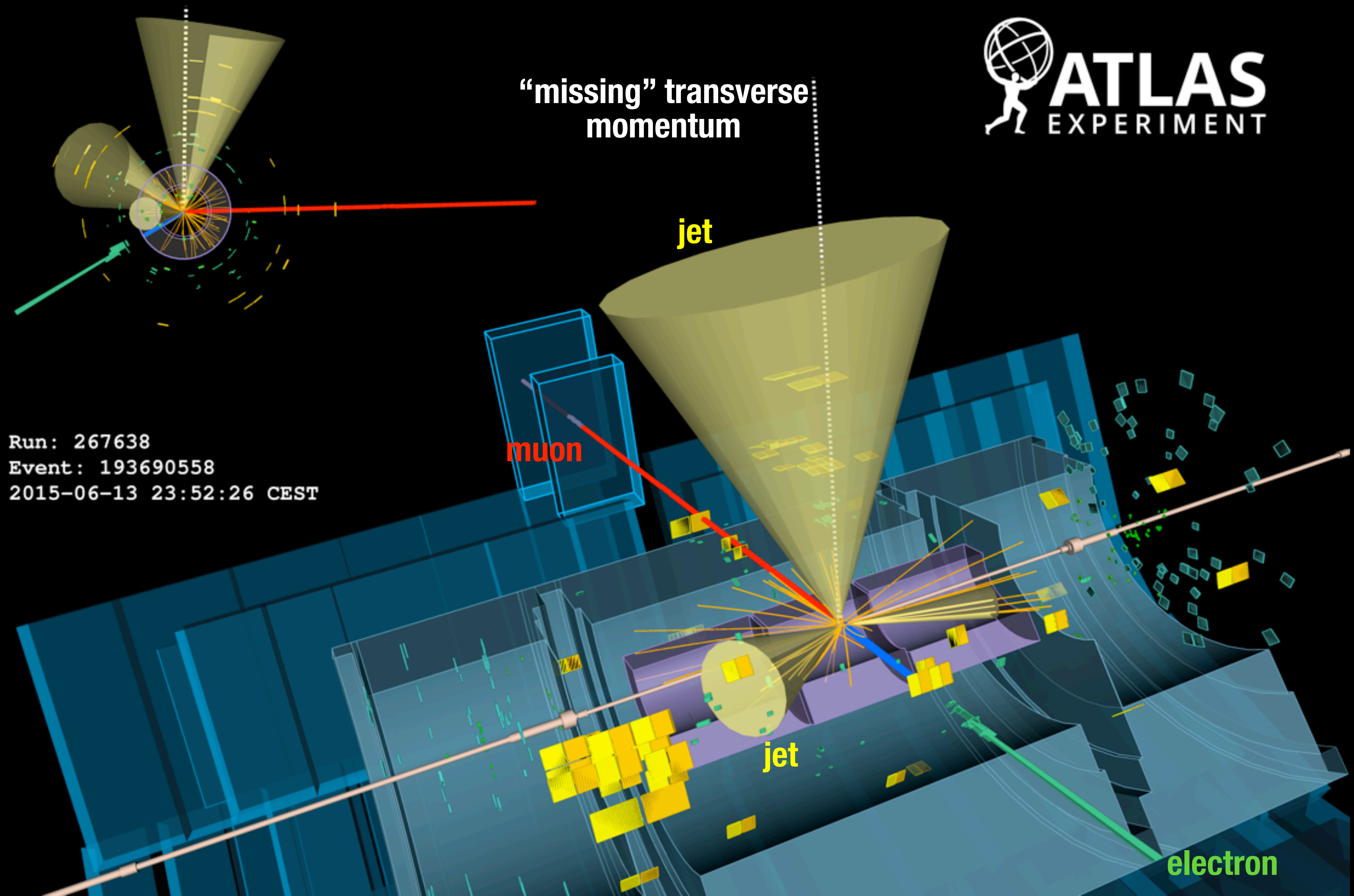
- Muon
- Electron
- Charged Hadron (e.g. Pion)
- Neutral Hadron (e.g. Neutron)
- Photon

how do we “see” a neutrino?

Momentum Conservation!



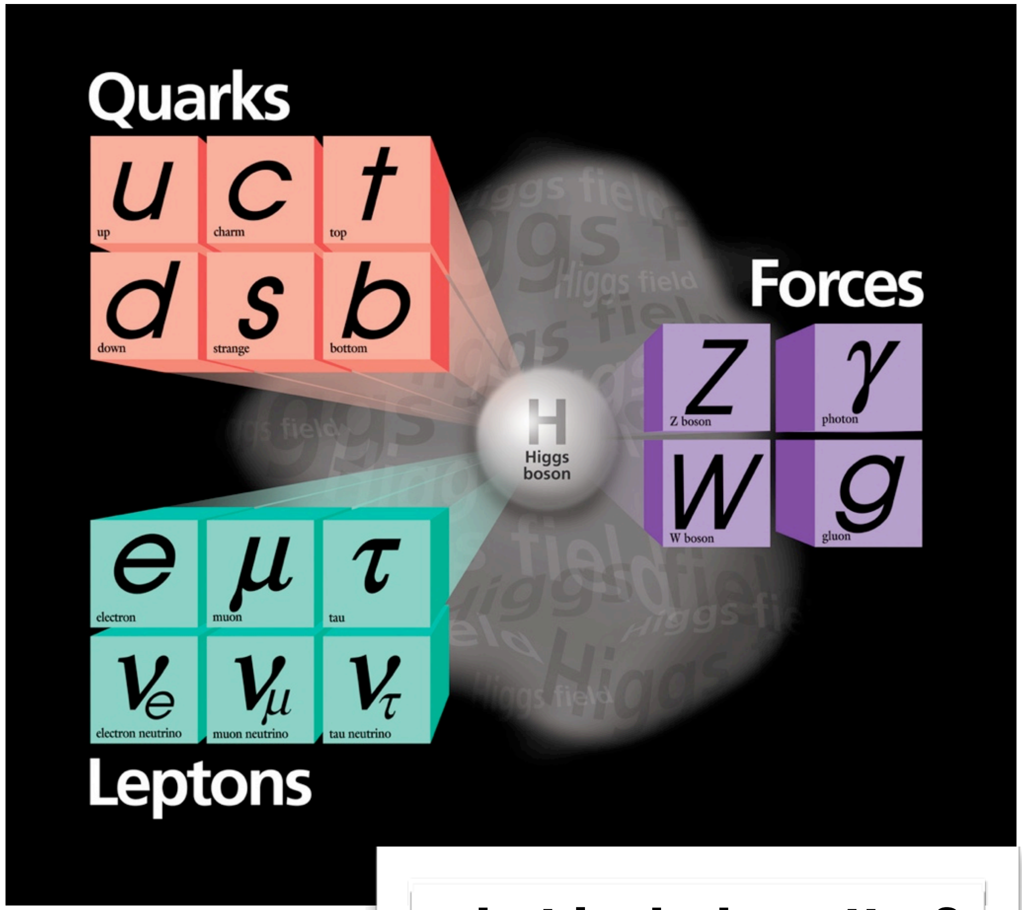
Real Top Quark Pair (...probably!)



Why Top Quarks?

- Heaviest known elementary particle
- Short-lived enough to decay before hadronizing
- Precise measurements of Standard Model properties using top quarks
- Window to “new physics” -- new exotic particles may decay preferentially to top quarks !

Is there physics beyond the SM?



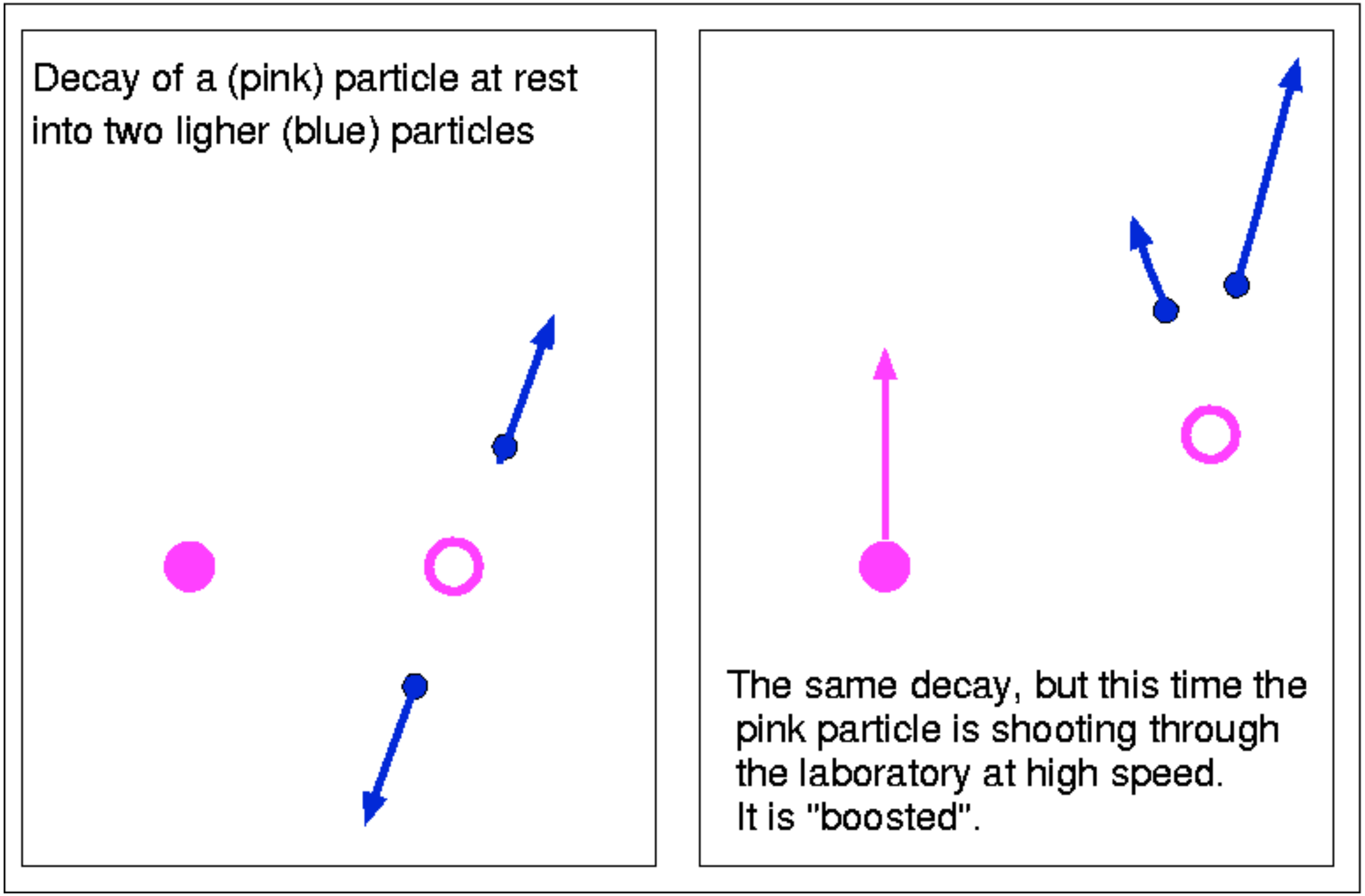
what is dark matter?

where is the anti-matter?

why are there 3 generations?

why is gravity so weak?

To make things more complicated ...
Boosted Particles

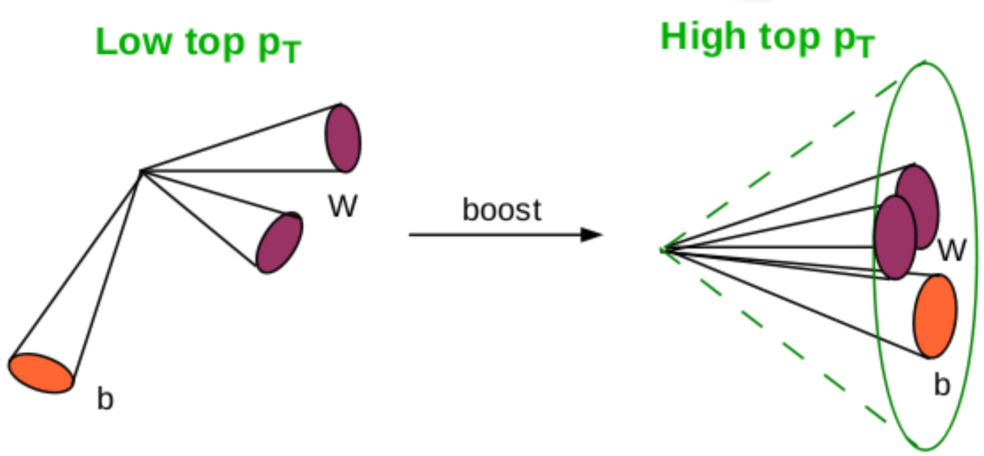


Boosted Top

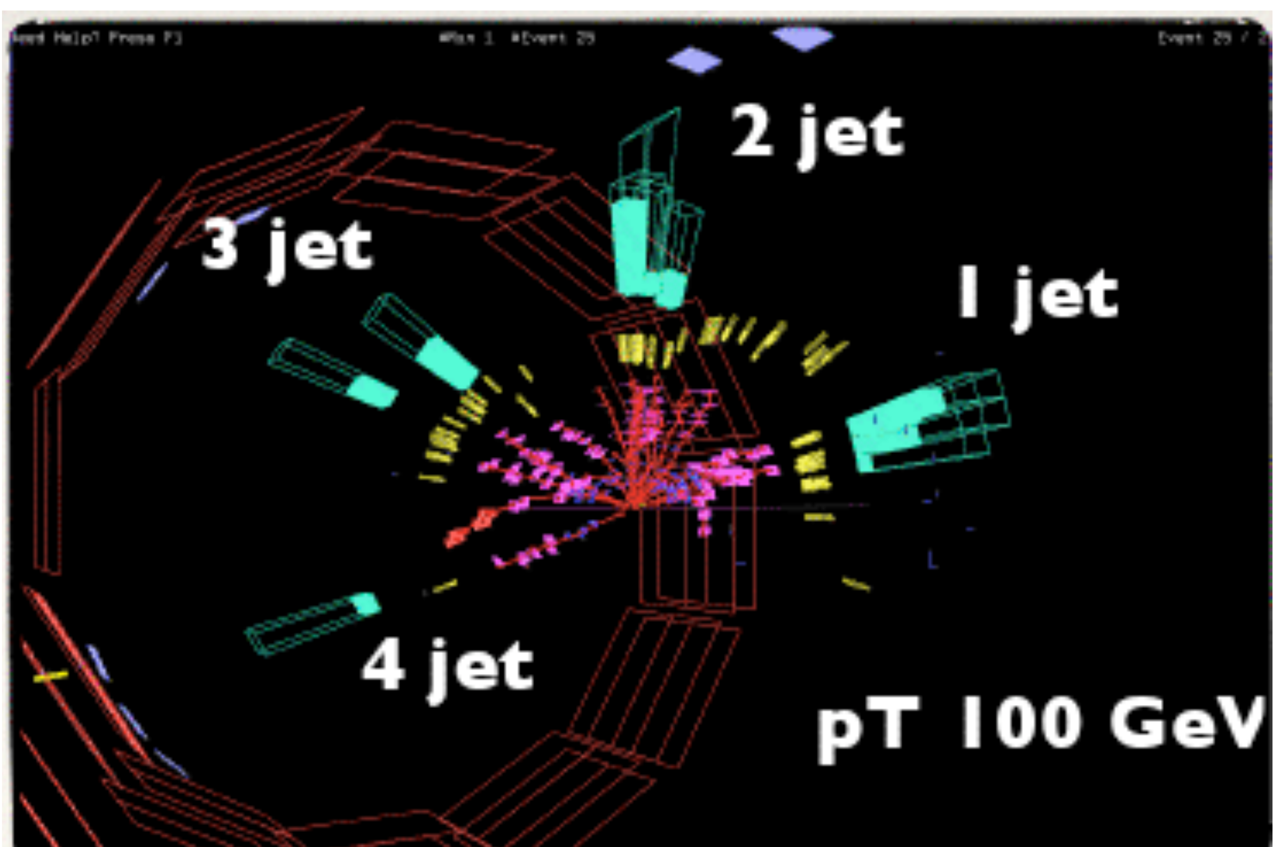
e.g. new heavy particle (Z’) decaying to two top quarks

top quarks produced with large kinetic energy

top quark in turn decays, its decay products will appear in a narrow cone

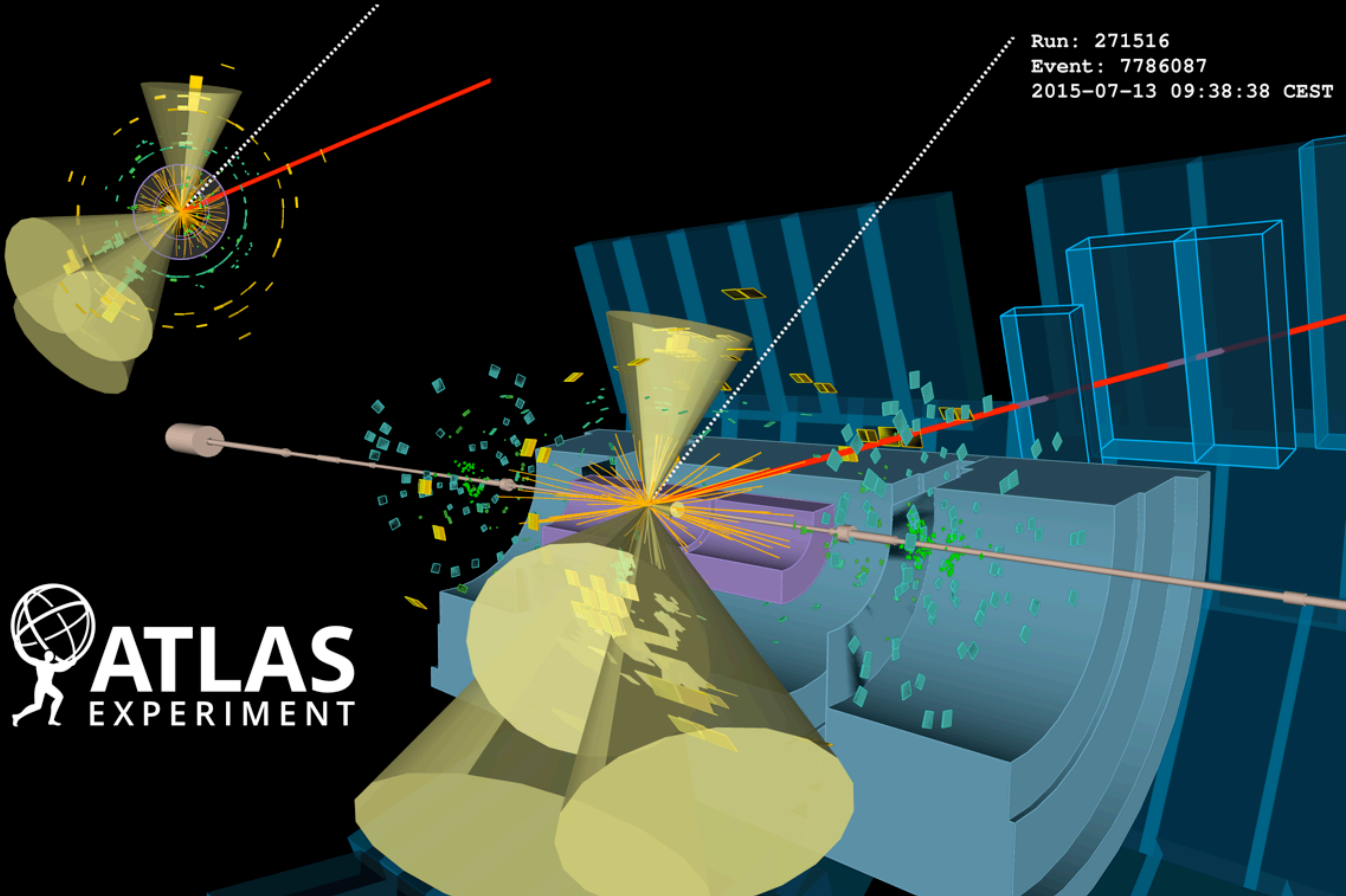


low kinetic energy

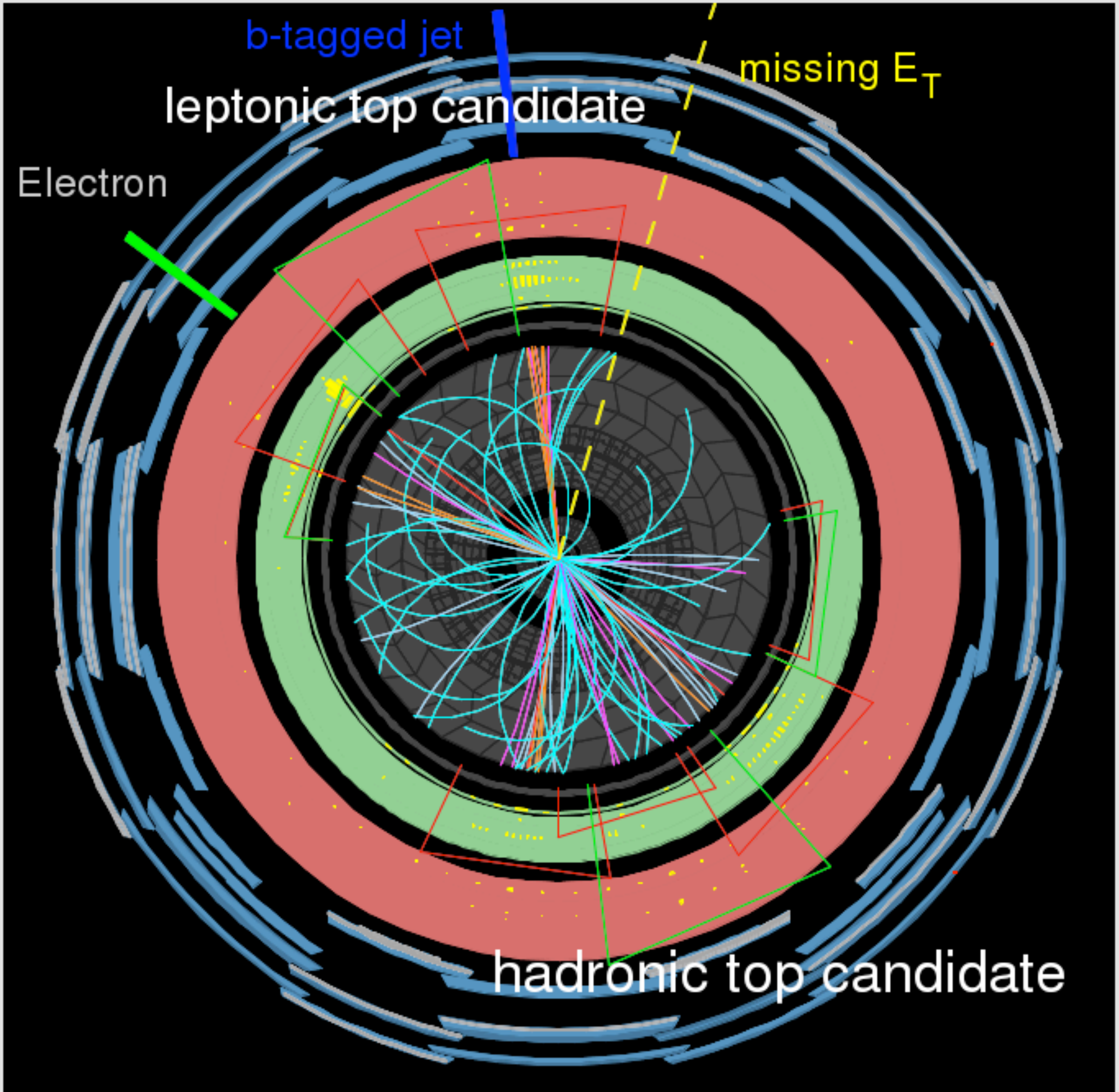


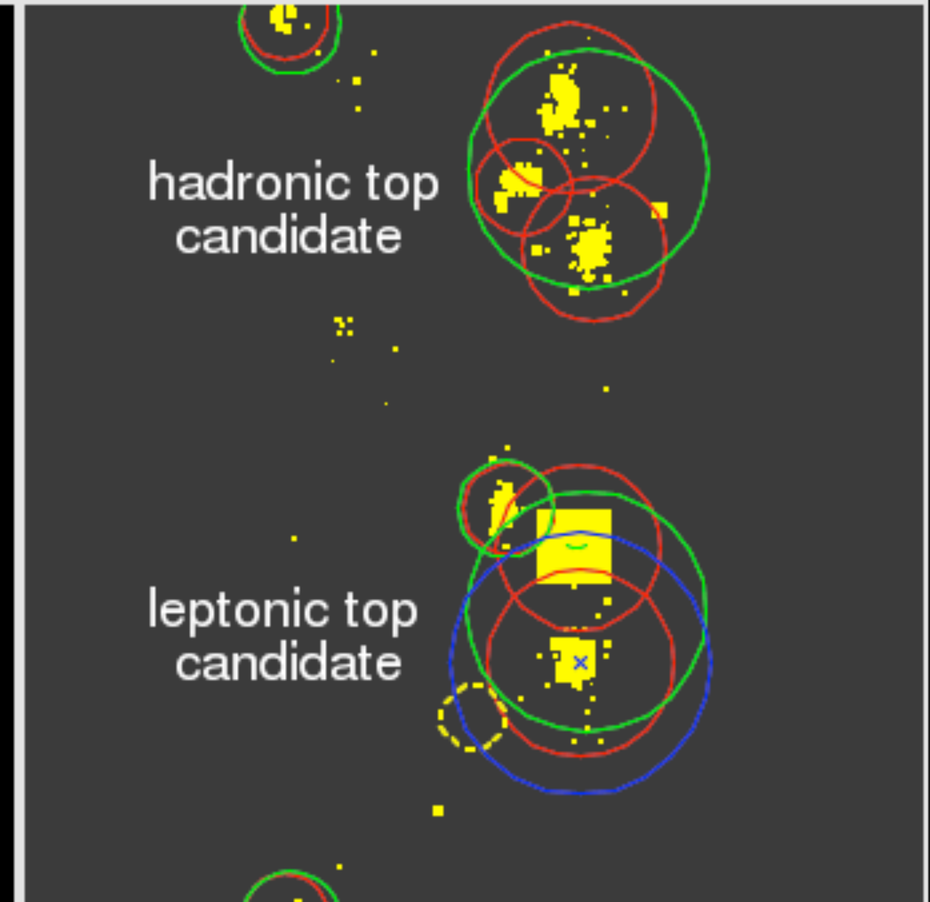
high kinetic energy

Real Boosted Top Quark Pair (...probably!)



Boosted Top - Structure Within





ATLAS EXPERIMENT

Run Number: 166658, Event Number: 34533931

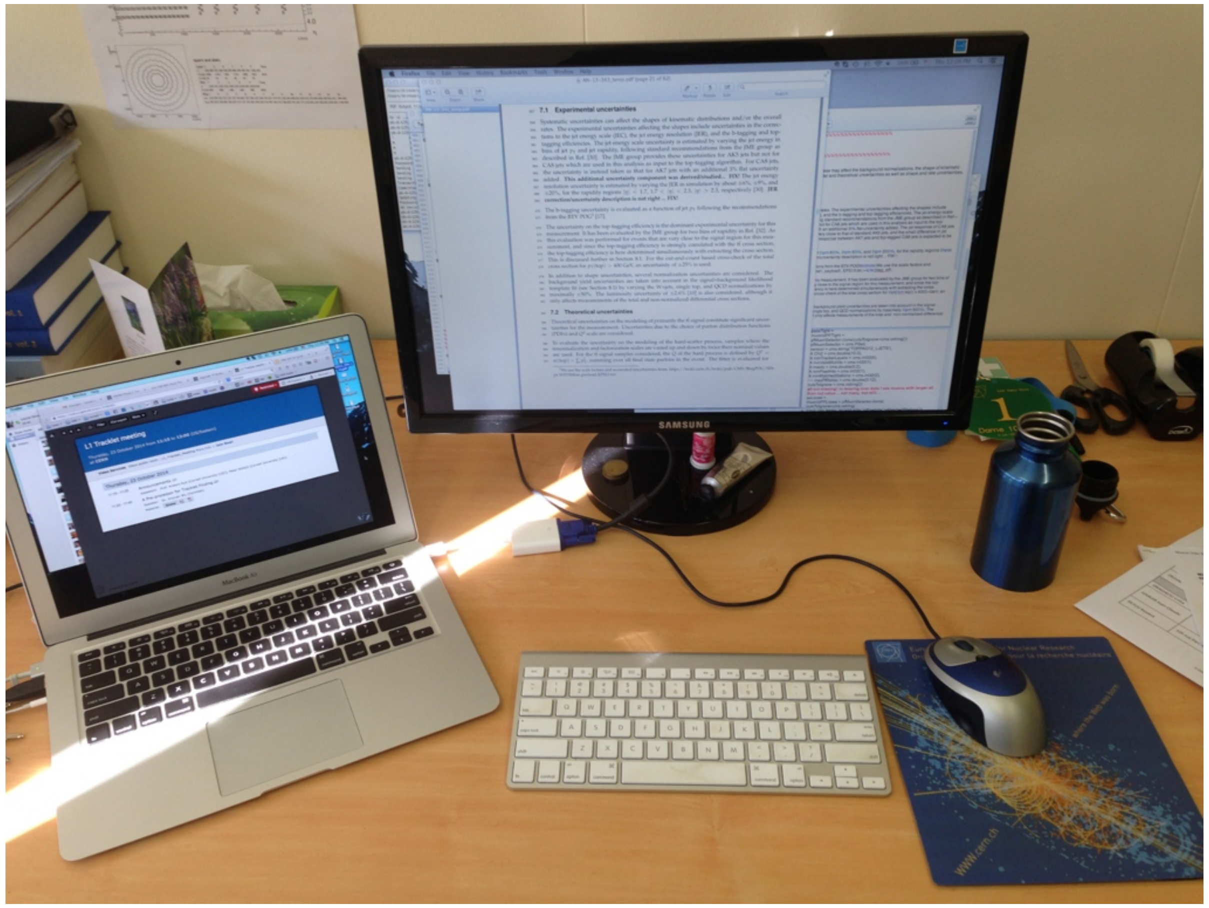
Date: 2010-10-11 23:57:42 CEST

Analyses

Use detailed simulation to predict what we should observe

Look for patterns in the data

Measure a known process vs search for unobserved phenomena



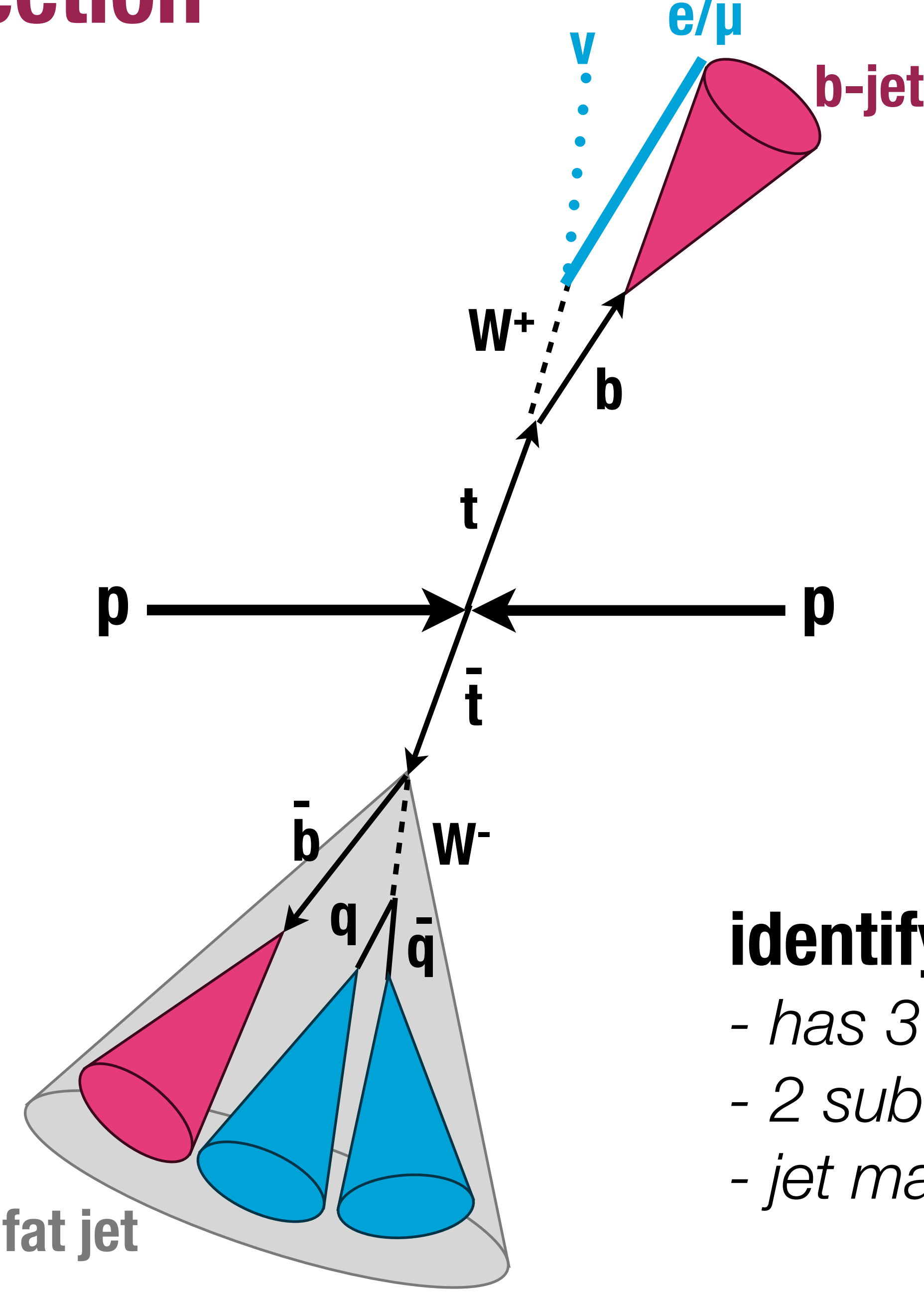
Boosted Top Measurement

Measure how often top quarks are produced with high momentum

➤ Define an event selection

one top quark decays to lepton

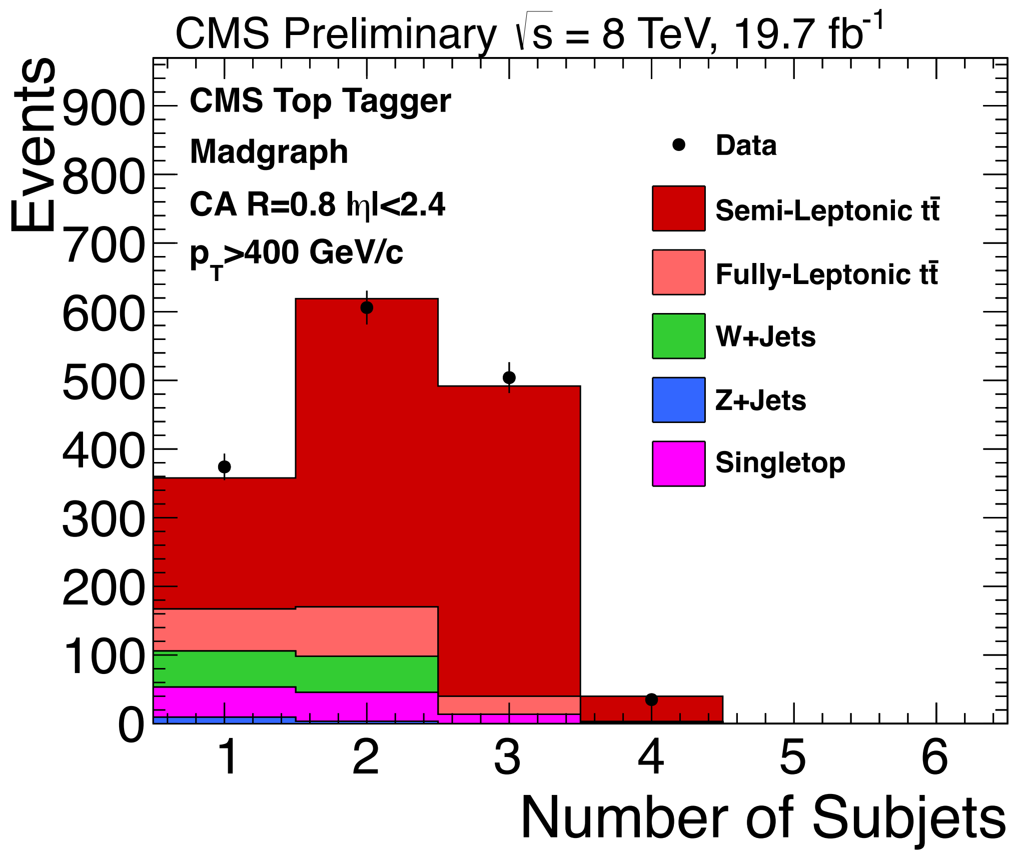
"trigger" using lepton + 2 jets



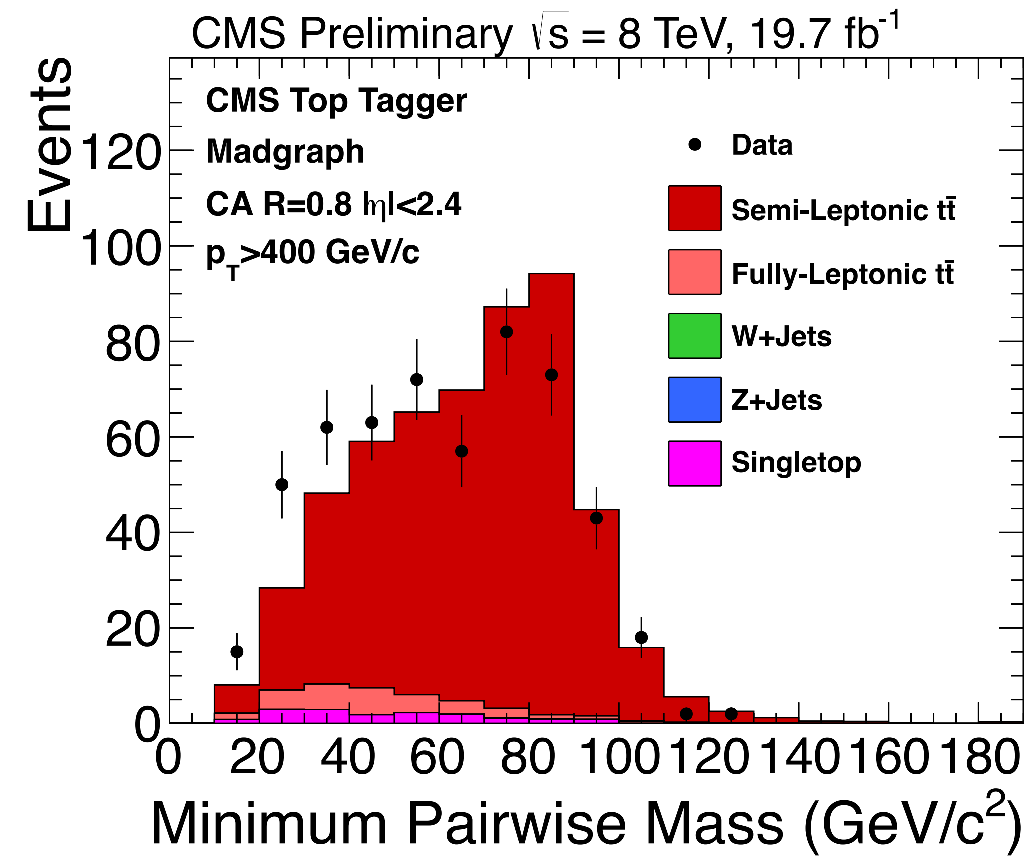
one top quark decays to quarks

identify wide jet using substructure

- *has 3 sub-jets*
- *2 sub-jets compatible with W mass*
- *jet mass compatible with top*


CMS Preliminary √s = 8 TeV, 19.7 fb-1
CMS Top Tagger
Madgraph
CA R=0.8 |η|<2.4
pT>400 GeV/c
Data
Semi-Leptonic tt̄
Fully-Leptonic tt̄
W+Jets
Z+Jets
Singletop
Events
0
100
200
300
400
500
600
700
800
900
1
2
3
4
5
6
Number of Subjets

(a)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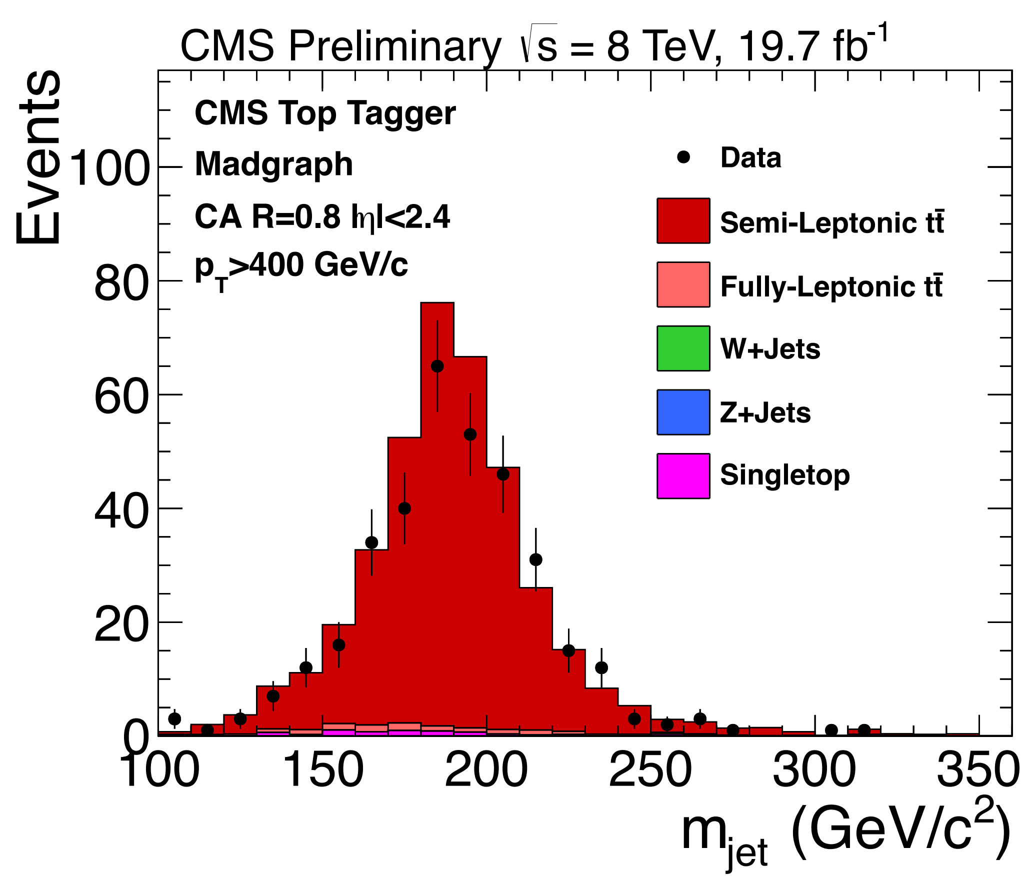
CA R=0.8 |η|<2.4
pT>400 GeV/c
Data
Semi-Leptonic tt̄
Fully-Leptonic tt̄
W+Jets
Z+Jets
Singletop
Events
0
20
40
60
80
100
120
140
160
180
Minimum Pairwise Mass (GeV/c2)

(b)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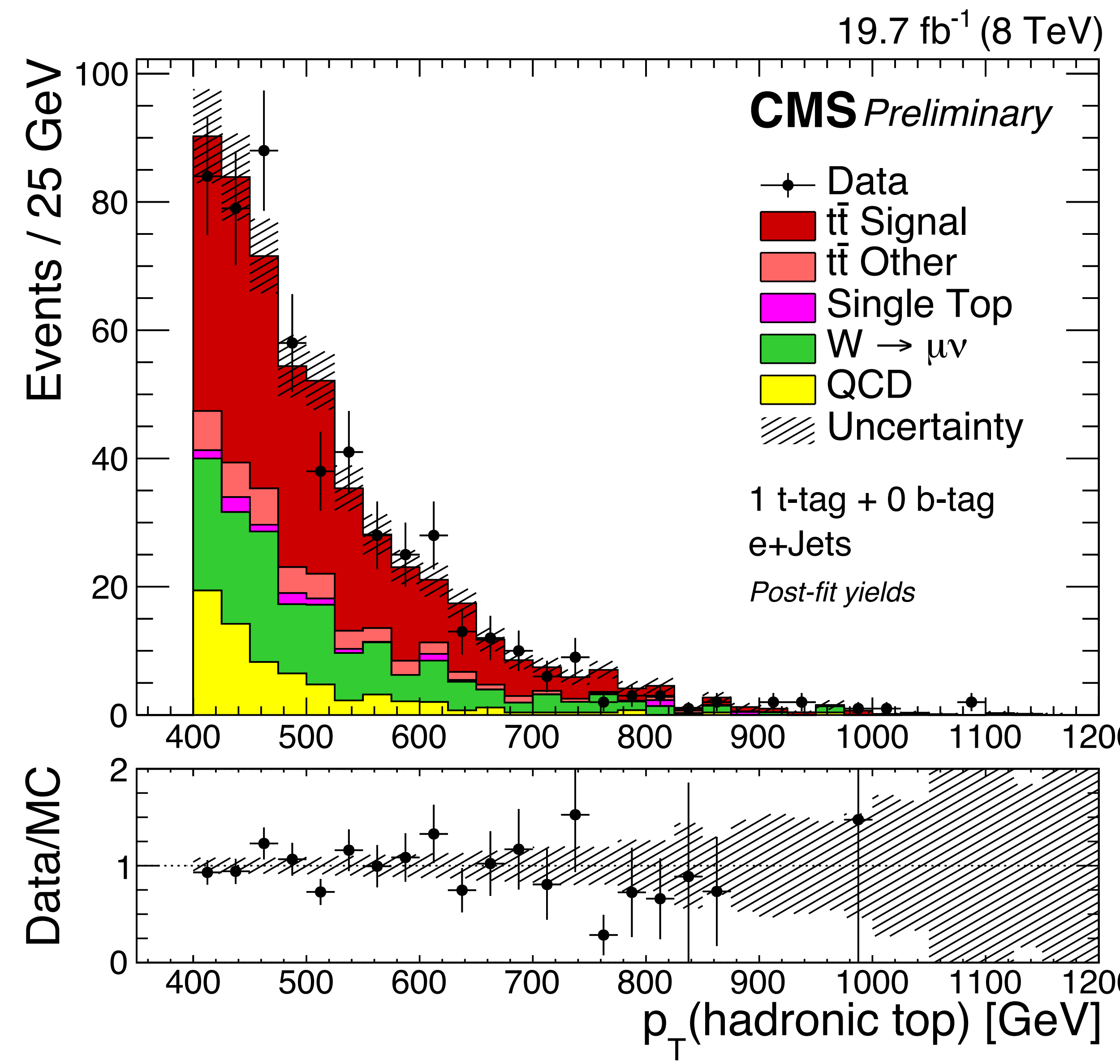
Madgraph
CA R=0.8 |η|<2.4
pT>400 GeV/c
Data
Semi-Leptonic tt̄
Fully-Leptonic tt̄
W+Jets
Z+Jets
Singletop
Events
0
20
40
60
80
100
150
200
250
300
350
mjet (GeV/c2)

Boosted Top Measurement

➤ **Estimate rate of other processes producing similar events**



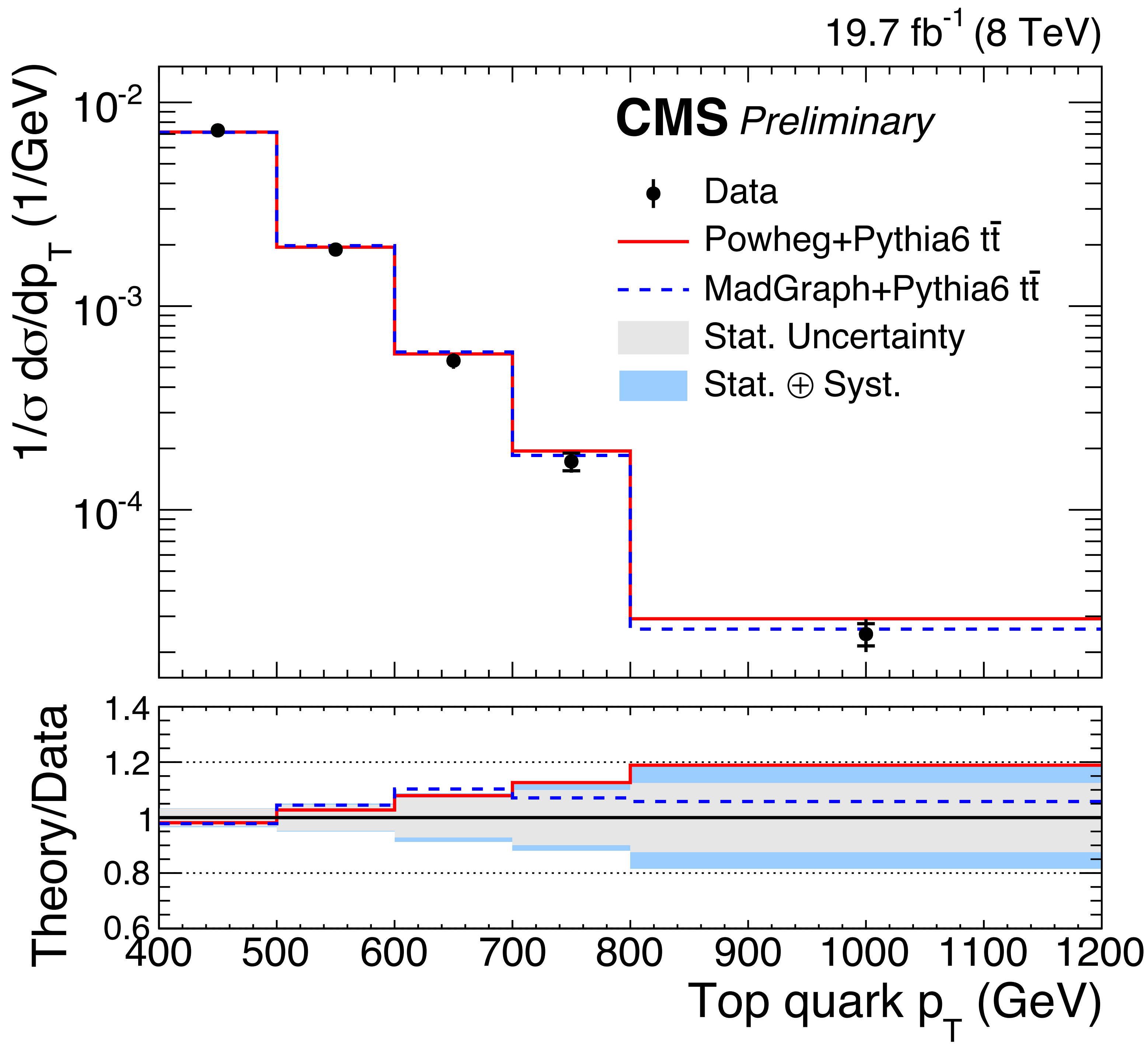
➤ **Estimate the uncertainties**

This often takes most time!

To what precision do we know the measured calorimeter energy?
How well do we know how much data we had?
...

Boosted Top Measurement

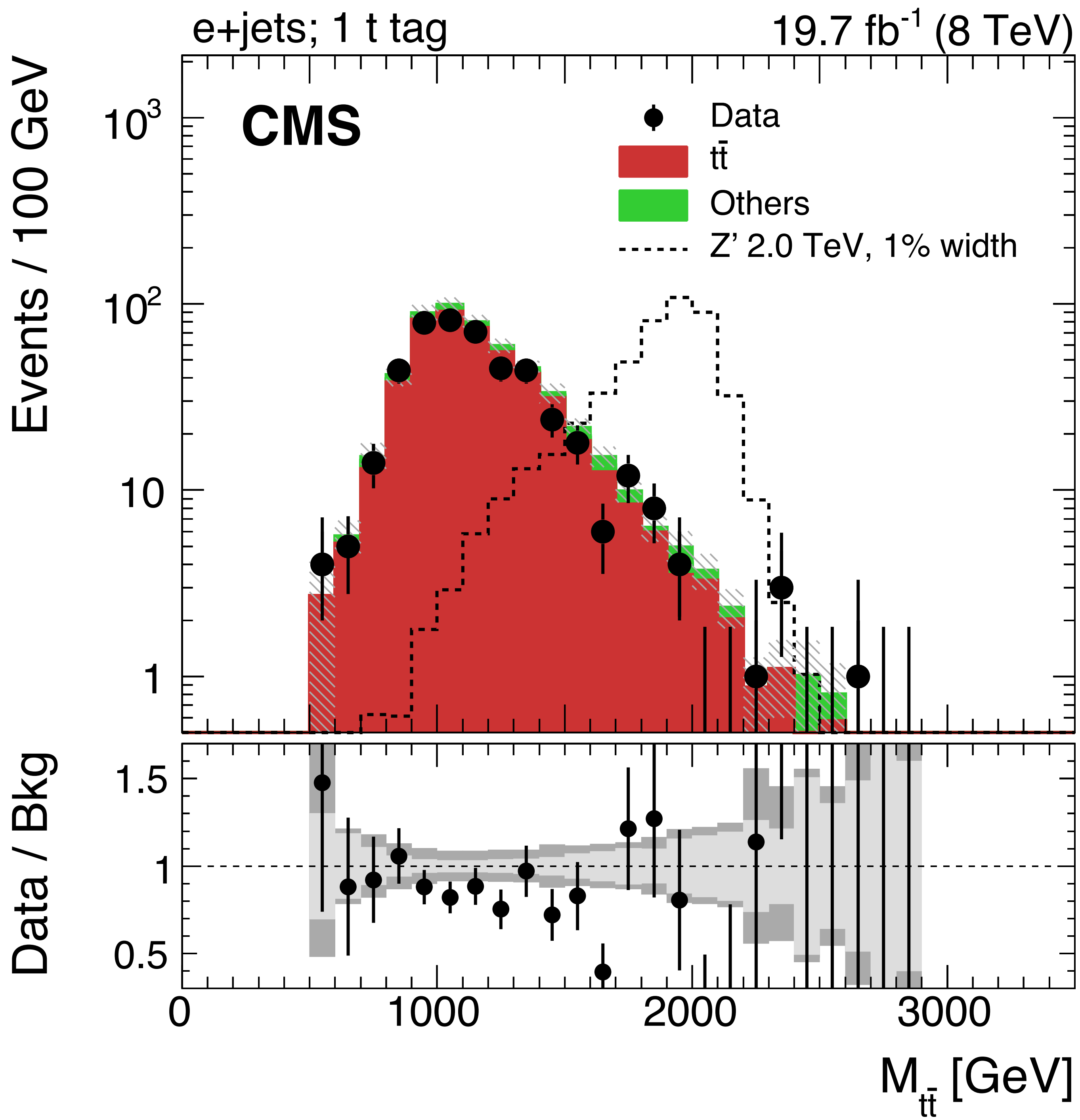
➤ **Put it all together ...**

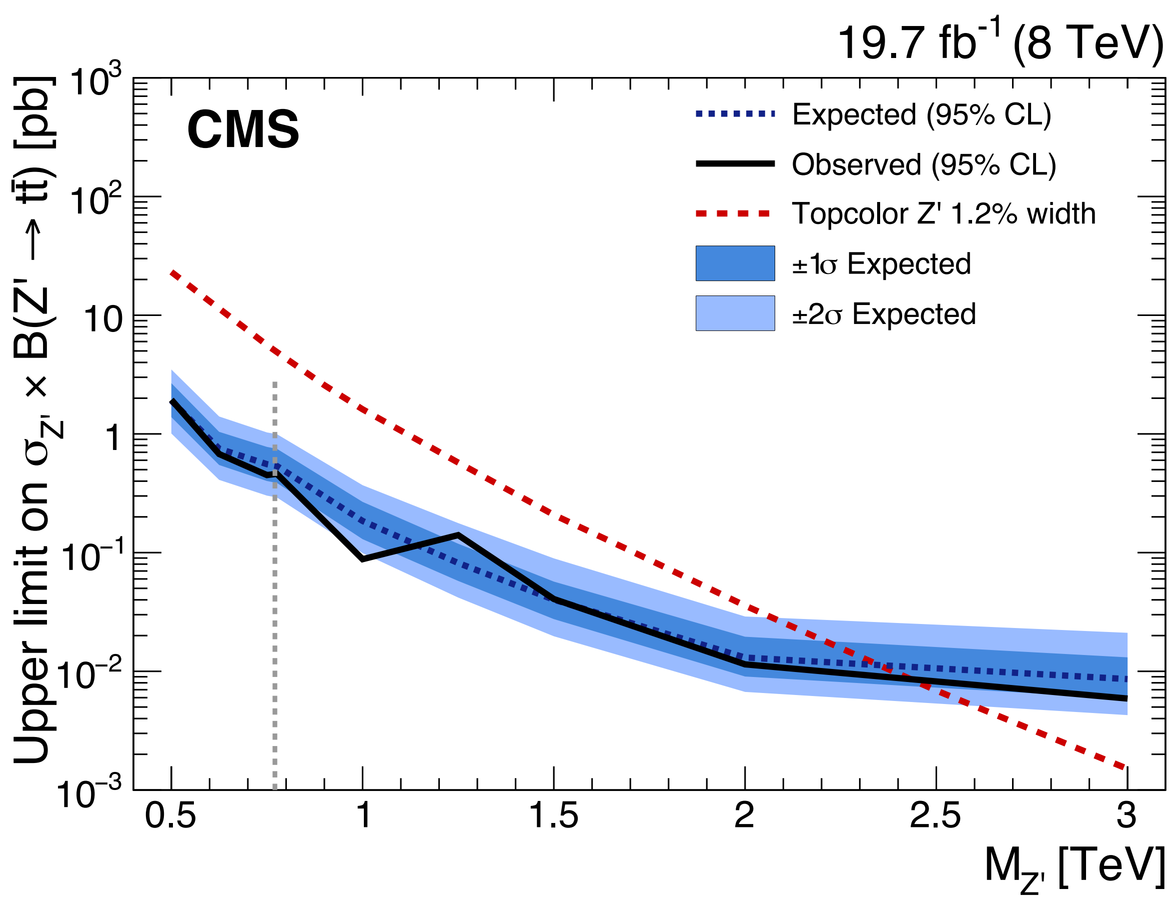


Search with Boosted Top

Many models for physics beyond the Standard Model predict new gauge bosons: Z'

"Bump-hunt" search



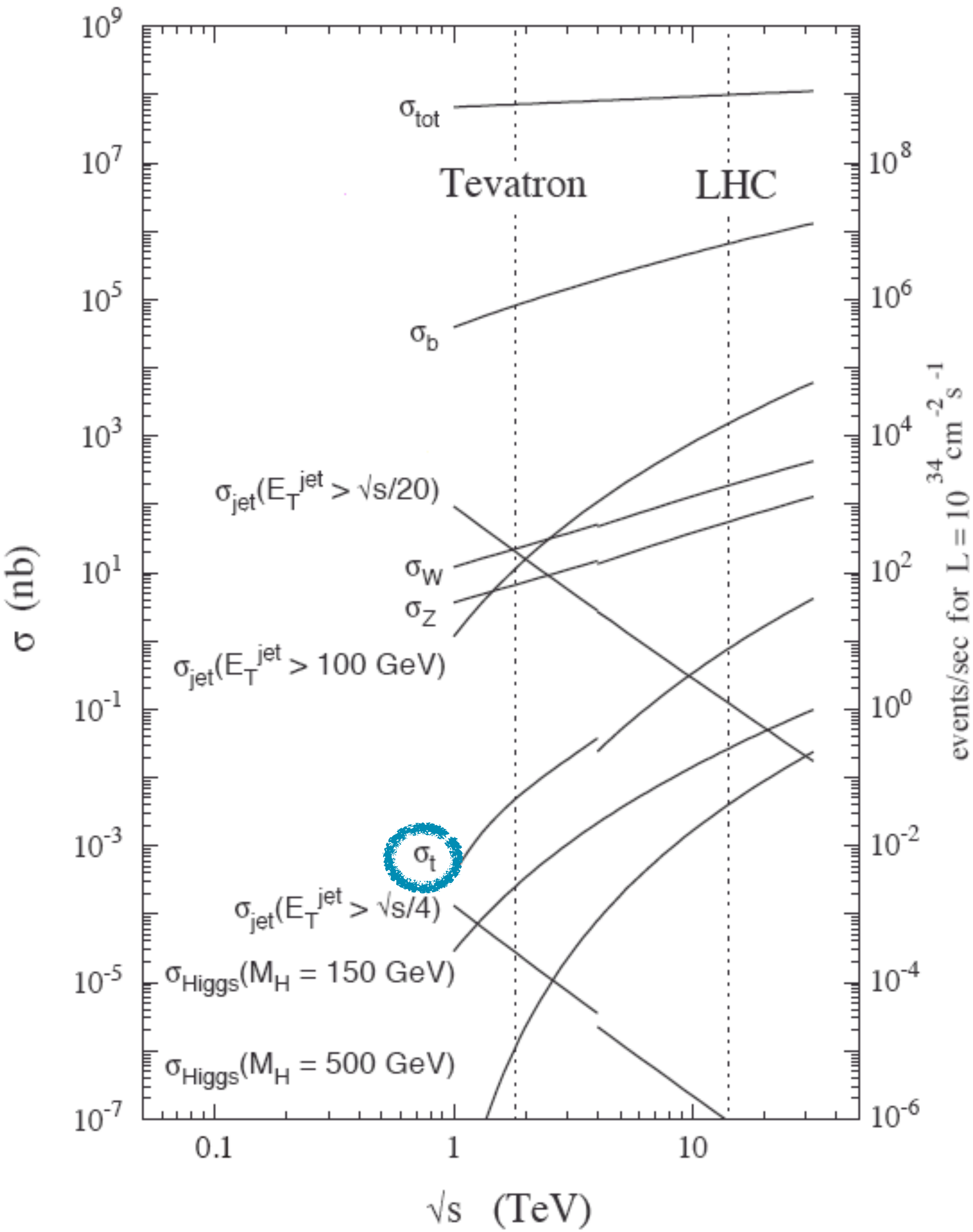


No new physics discovery (yet) !!

complications

Some Numbers

- Collisions every 0.000000025s
- Top quarks & Higgs bosons: **rare!**
- Huge amount of info produced
  - A collision event ≈ 1MB ≈ 500 page book
  - ... **40 million times / second**
- Must reduce to manageable rates ➝ **TRIGGER**



Upgrade of LHC

- *Planned upgrade of the LHC to have even higher intensities in the collisions*
- **High Luminosity LHC (2023-2025)**

$$L = fn\frac{N_1 N_2}{A}$$

where

f is the revolution frequency

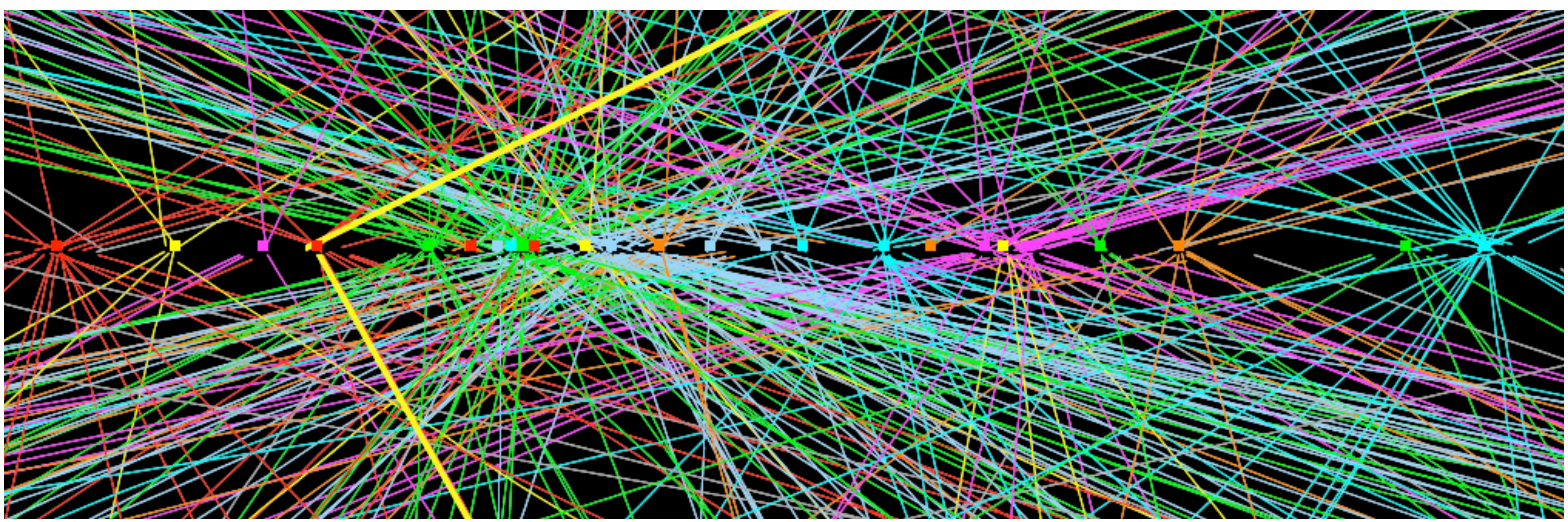
n is the number of bunches in one beam in the storage ring.

N_i is the number of particles in each bunch

A is the cross section of the beam.

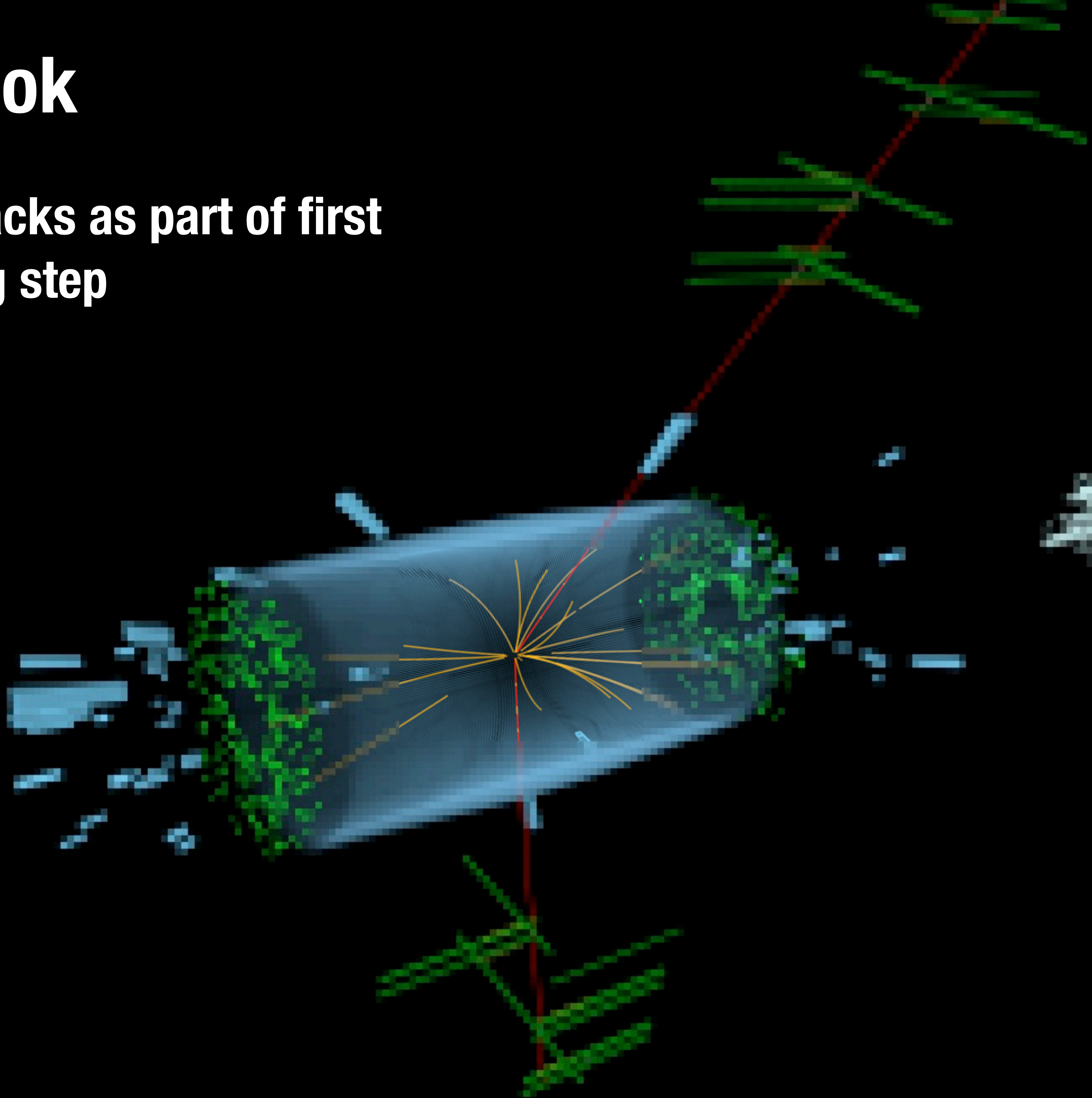
- Challenging for both accelerator & detectors, e.g. triggering

PILEUP = multiple collisions in same crossing

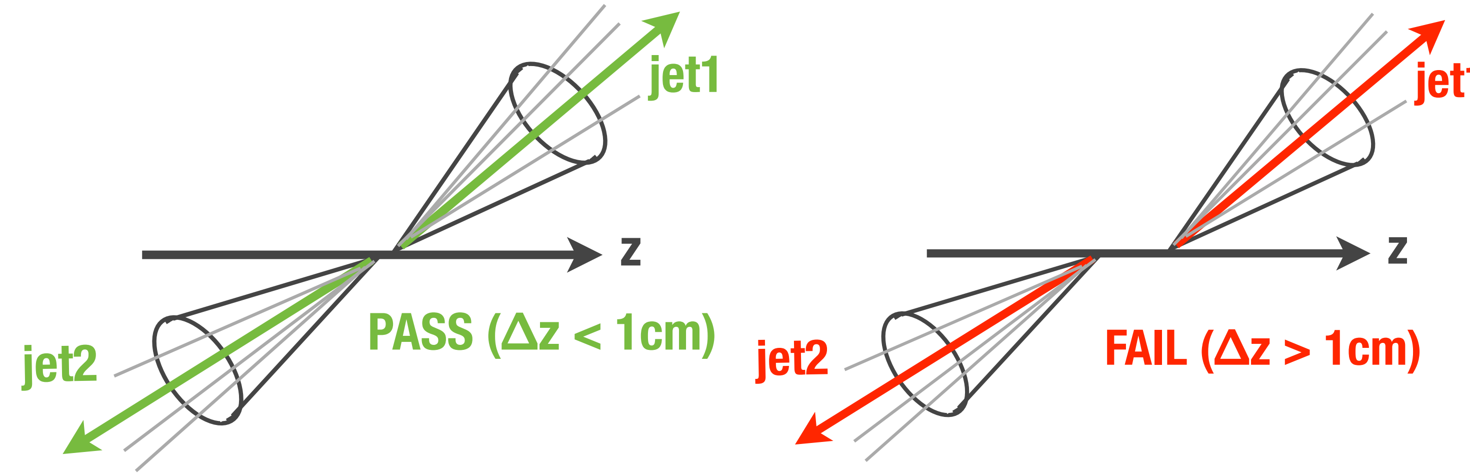


Outlook

Find tracks as part of first filtering step

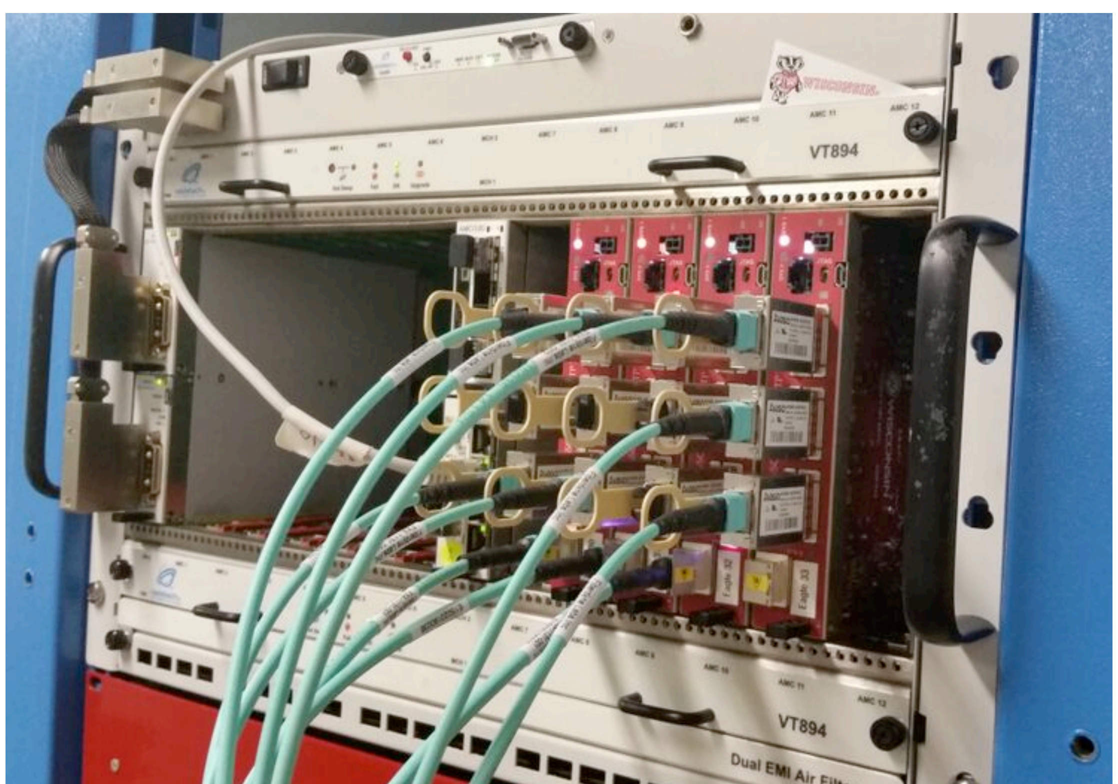


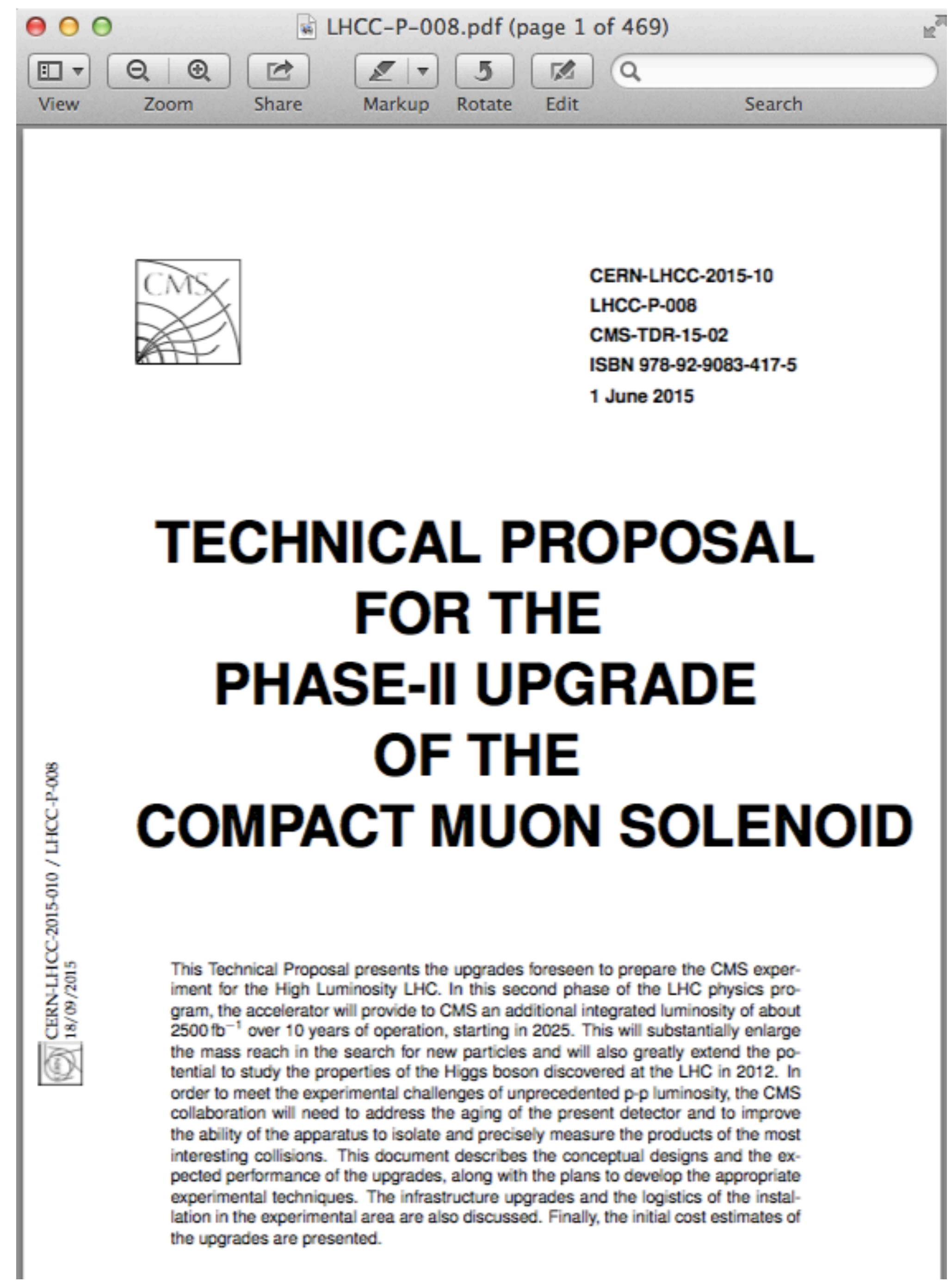
Outlook



Look inside jet cone for tracks

Use tracks to associate jets to common production point -- discard pileup events





CERN-LHCC-2015-10
LHCC-P-008
CMS-TDR-15-02
ISBN 978-92-9083-417-5
1 June 2015

TECHNICAL PROPOSAL FOR THE PHASE-II UPGRADE OF THE COMPACT MUON SOLENOID

This Technical Proposal presents the upgrades foreseen to prepare the CMS experiment for the High Luminosity LHC. In this second phase of the LHC physics program, the accelerator will provide to CMS an additional integrated luminosity of about 2500 fb^{-1} over 10 years of operation, starting in 2025. This will substantially enlarge the mass reach in the search for new particles and will also greatly extend the potential to study the properties of the Higgs boson discovered at the LHC in 2012. In order to meet the experimental challenges of unprecedented p-p luminosity, the CMS collaboration will need to address the aging of the present detector and to improve the ability of the apparatus to isolate and precisely measure the products of the most interesting collisions. This document describes the conceptual designs and the expected performance of the upgrades, along with the plans to develop the appropriate experimental techniques. The infrastructure upgrades and the logistics of the installation in the experimental area are also discussed. Finally, the initial cost estimates of the upgrades are presented.

OUTLOOK

Some resources

http://home.web.cern.ch/students-educators/summer-student-programme

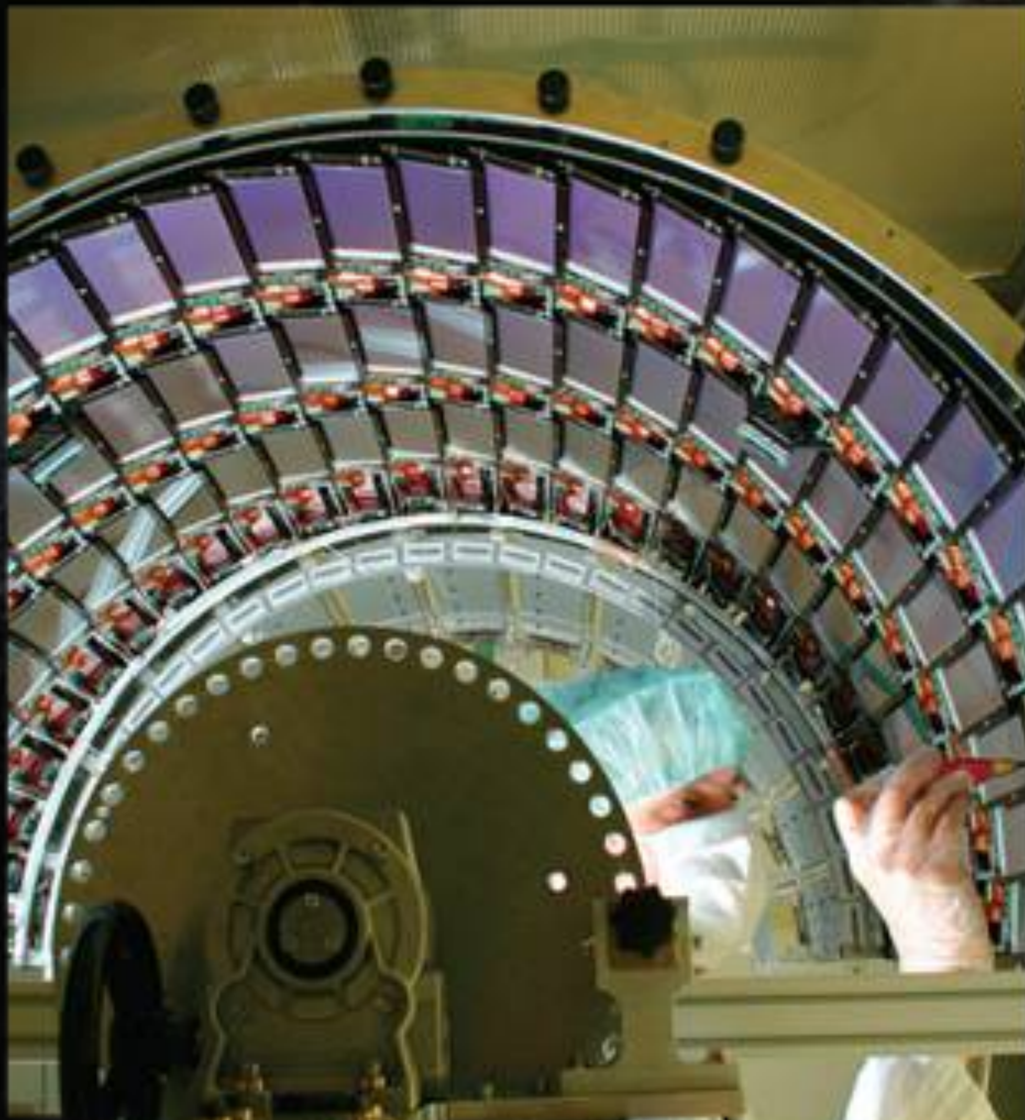
http://www.particleadventure.org

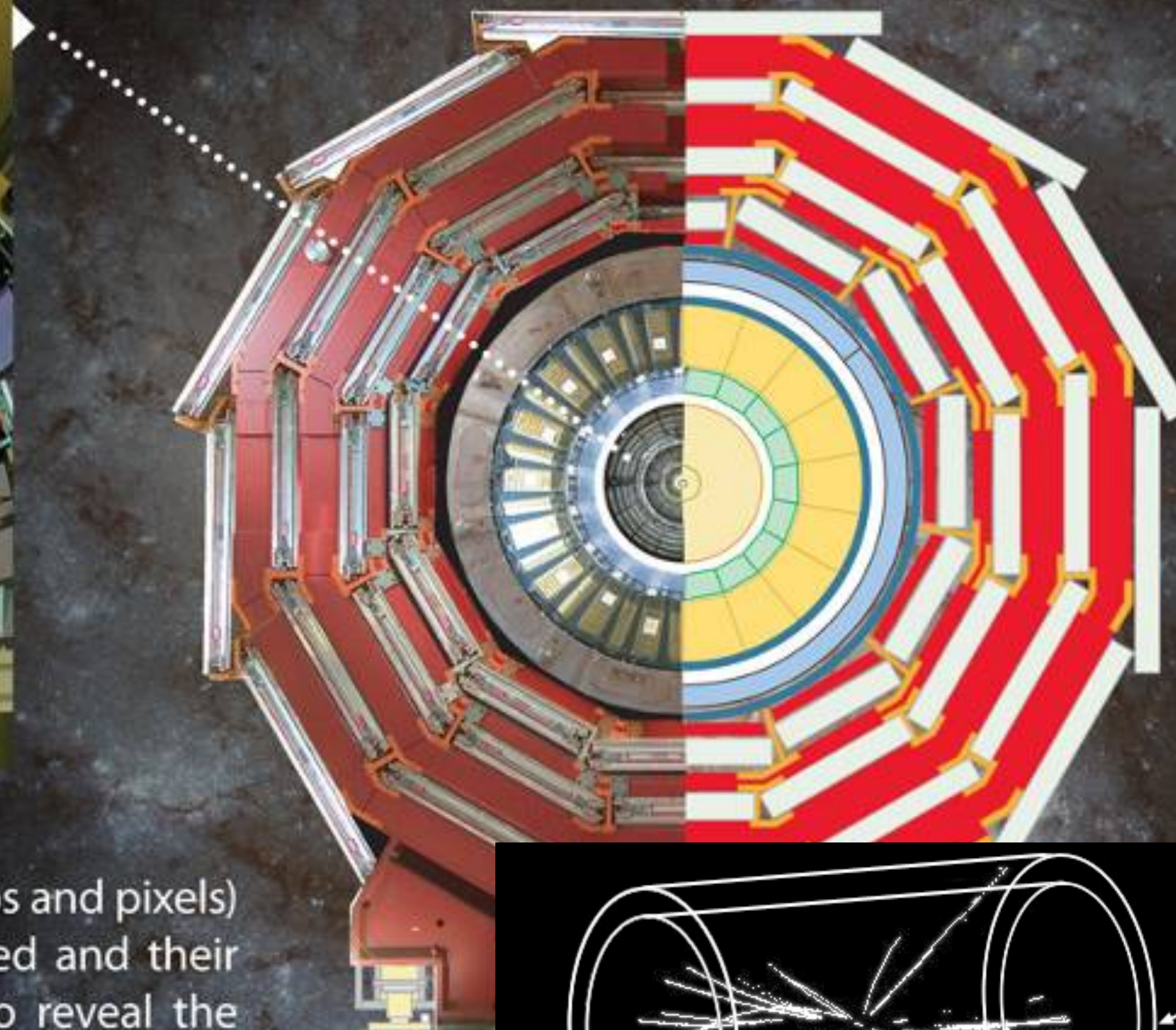
http://home.web.cern.ch/about

Enjoy the rest of your visit!


BONUS SLIDES

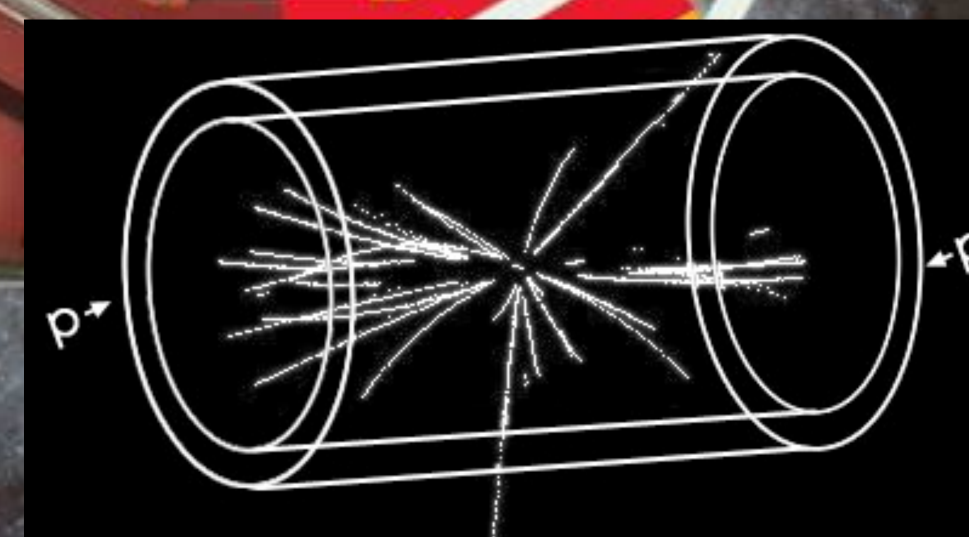
Detectors within Detector



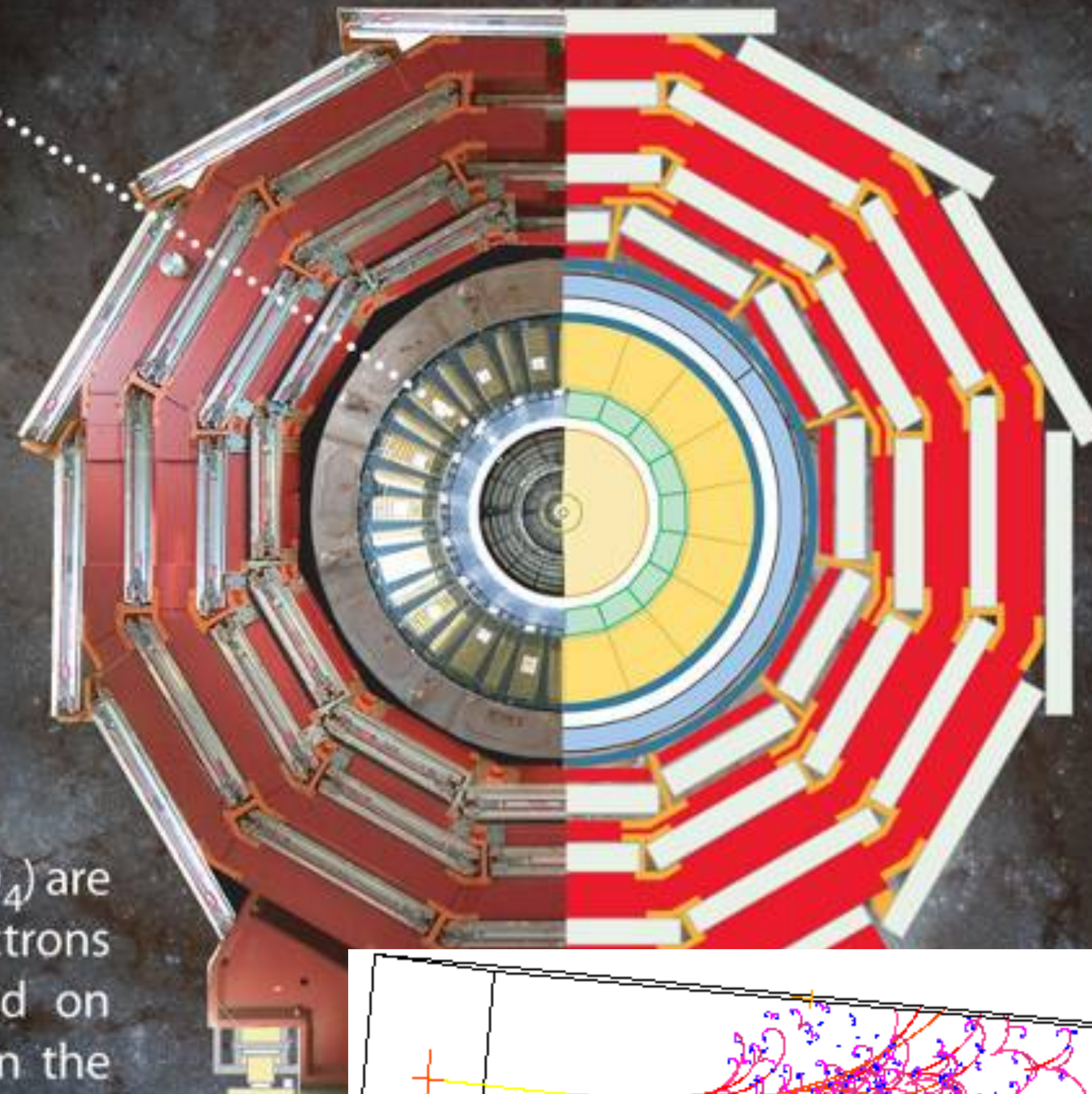


Tracker

Finely segmented silicon sensors (strips and pixels) enable charged particles to be tracked and their momenta to be measured. They also reveal the positions at which long-lived unstable particles decay.

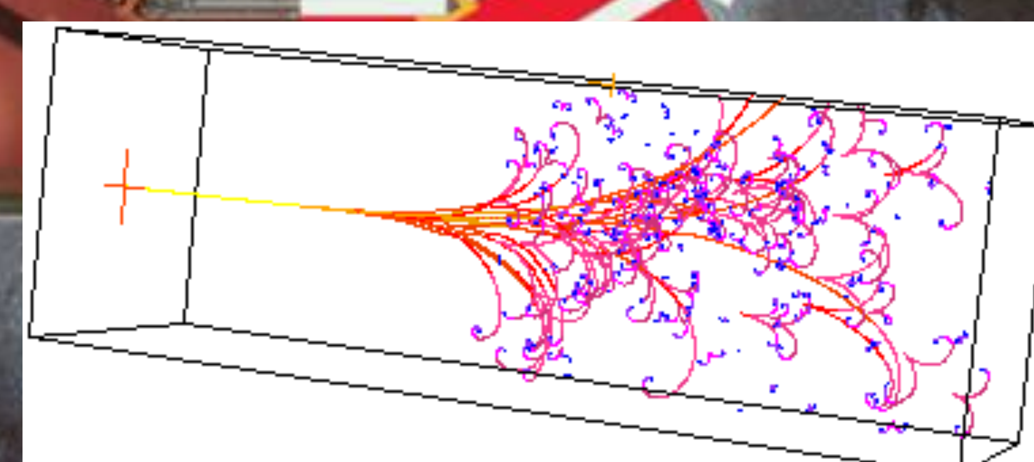


Detectors within Detector



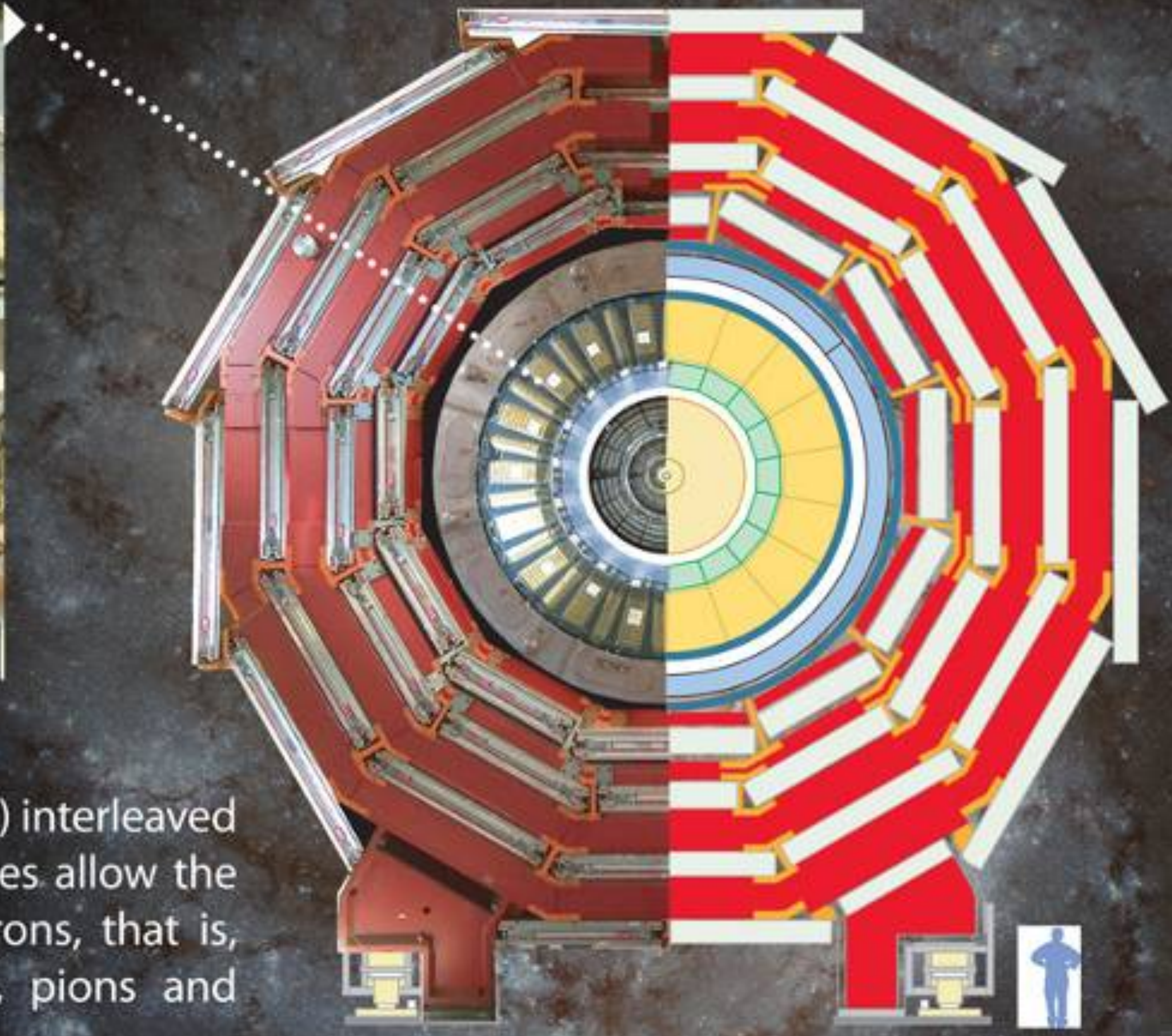
Electromagnetic Calorimeter

Nearly 80 000 crystals of lead tungstate ($PbWO_4$) are used to measure precisely the energies of electrons and photons. A 'preshower' detector, based on silicon sensors, helps particle identification in the endcaps.



EM interaction of photon/electron, cascade of secondary electrons & photons

Detectors within Detector



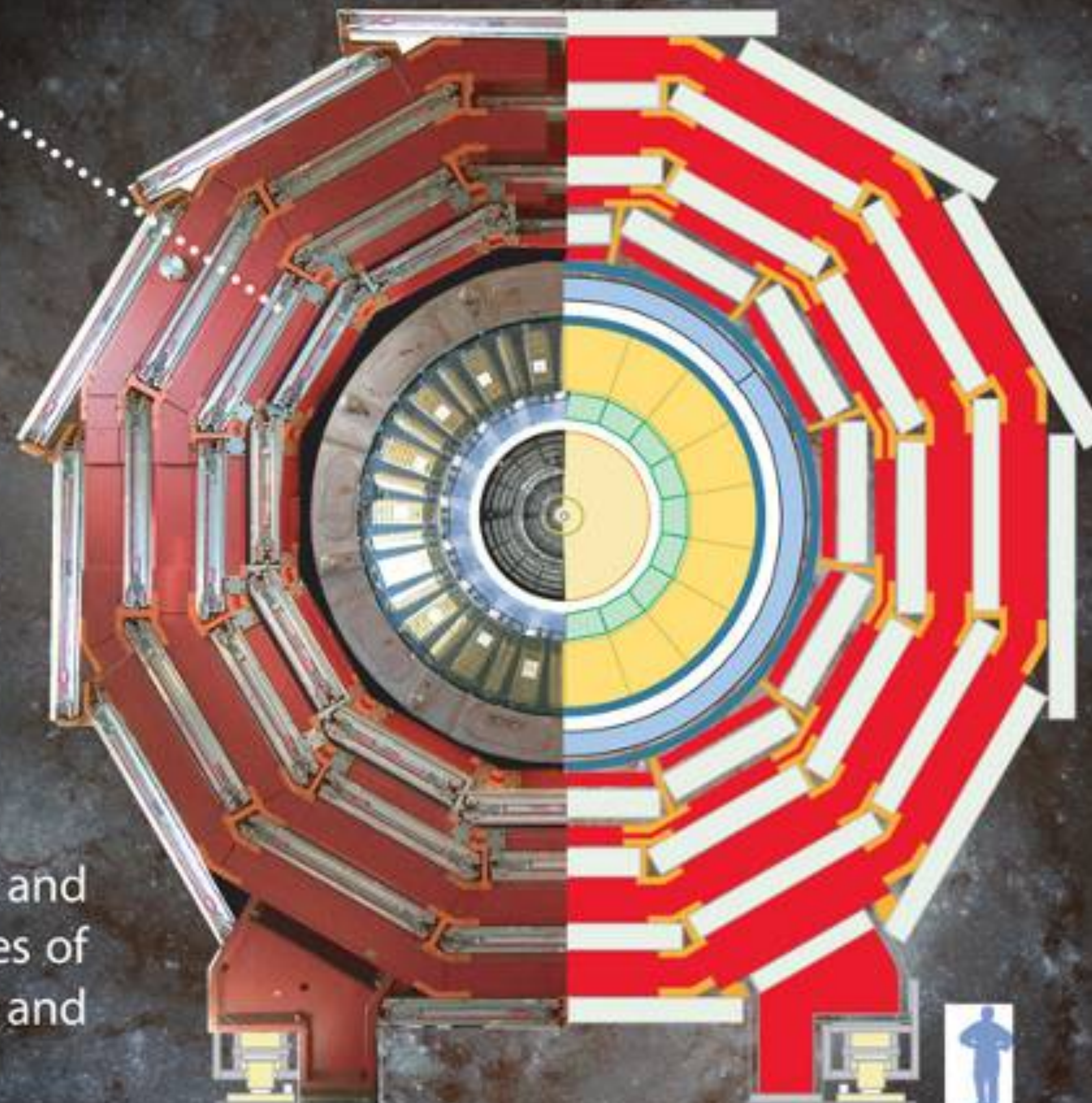
Hadron Calorimeter

Layers of dense material (brass or steel) interleaved with plastic scintillators or quartz fibres allow the determination of the energy of hadrons, that is, particles such as protons, neutrons, pions and kaons.

Detectors within Detector

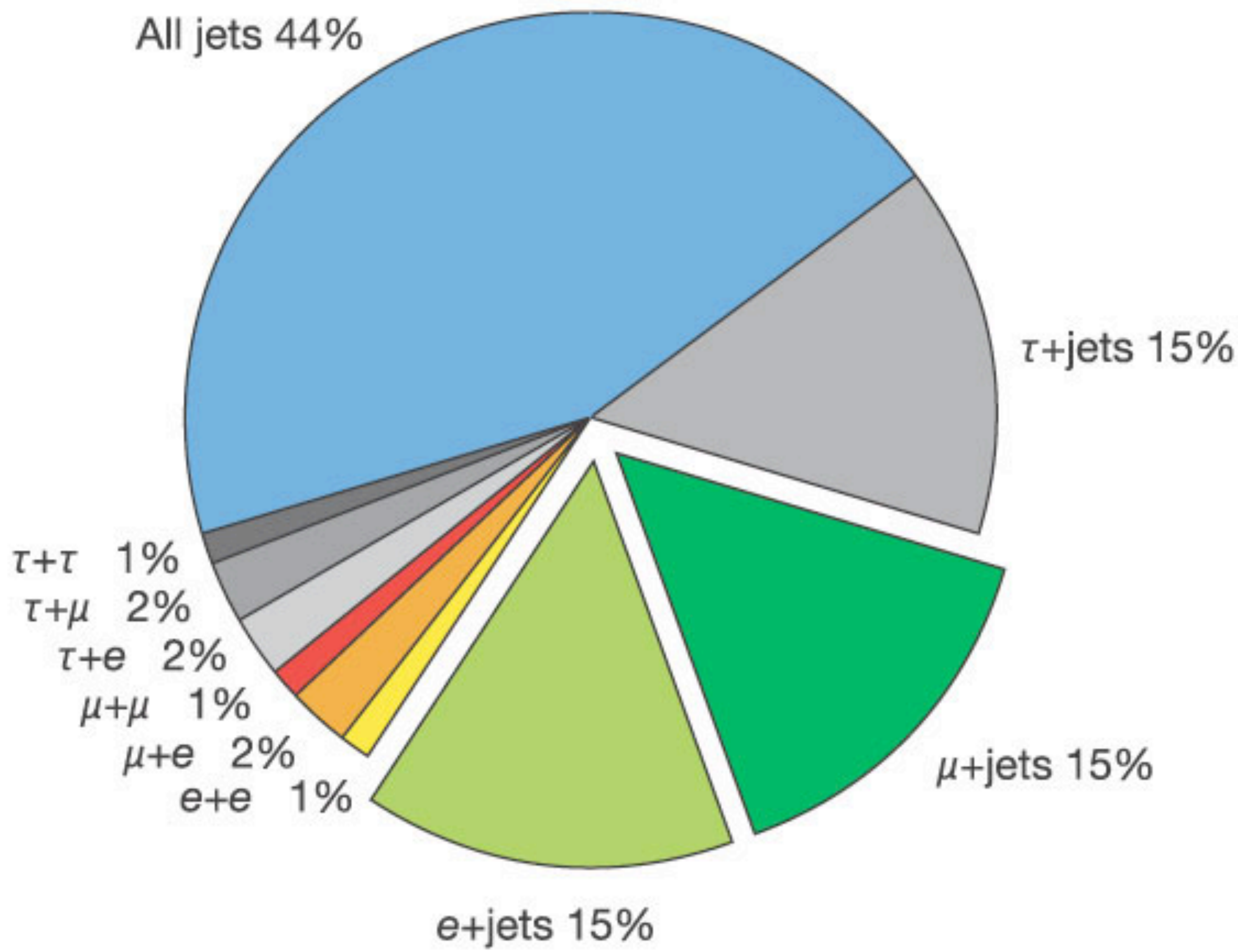
Muon Detectors

To identify muons (essentially heavy electrons) and measure their momenta, CMS uses three types of detector: drift tubes, cathode strip chambers and resistive plate chambers.

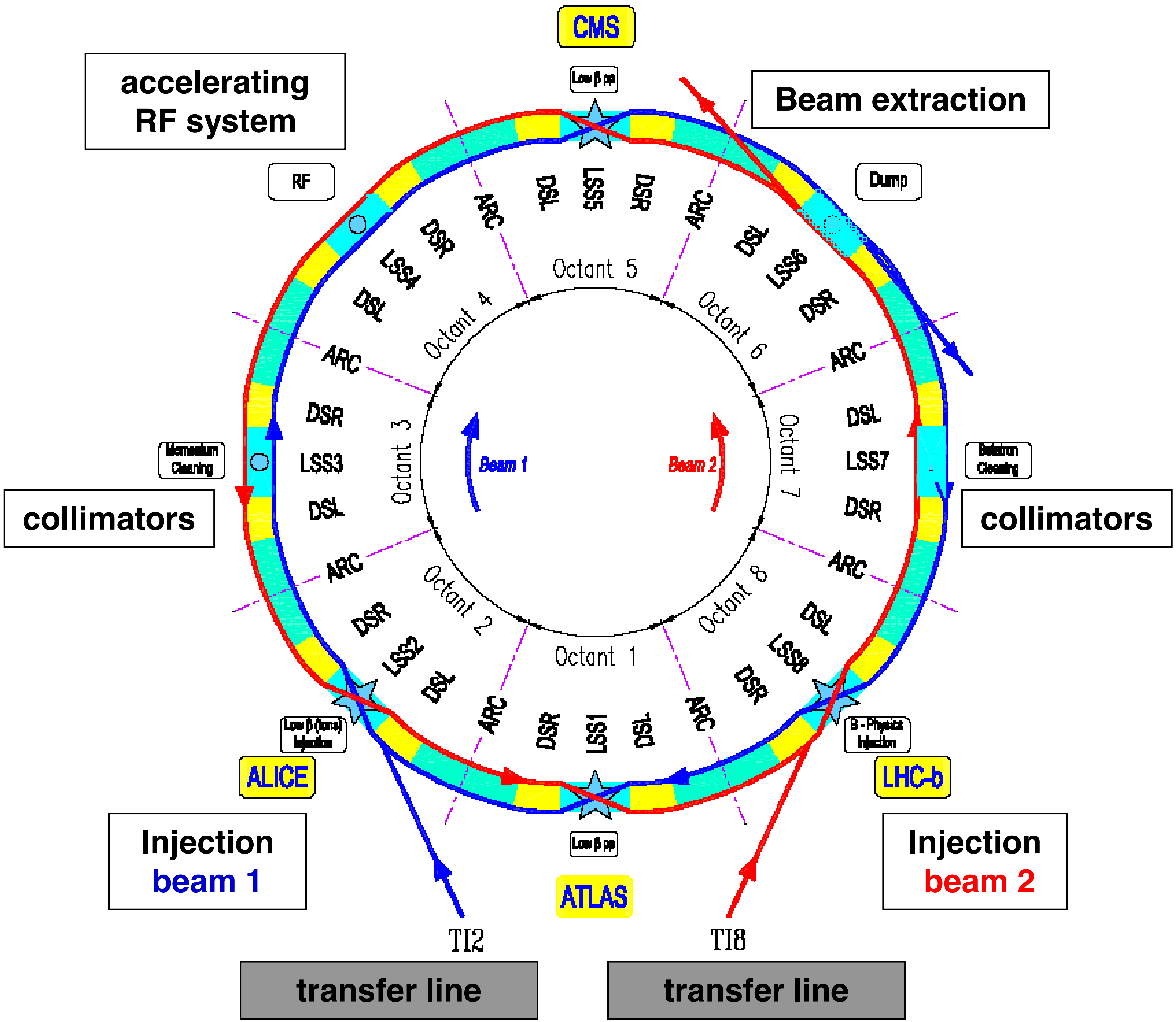


Top Quark Pair -- Detector Signature

classify depending on "final state"



LHC Beam Overview

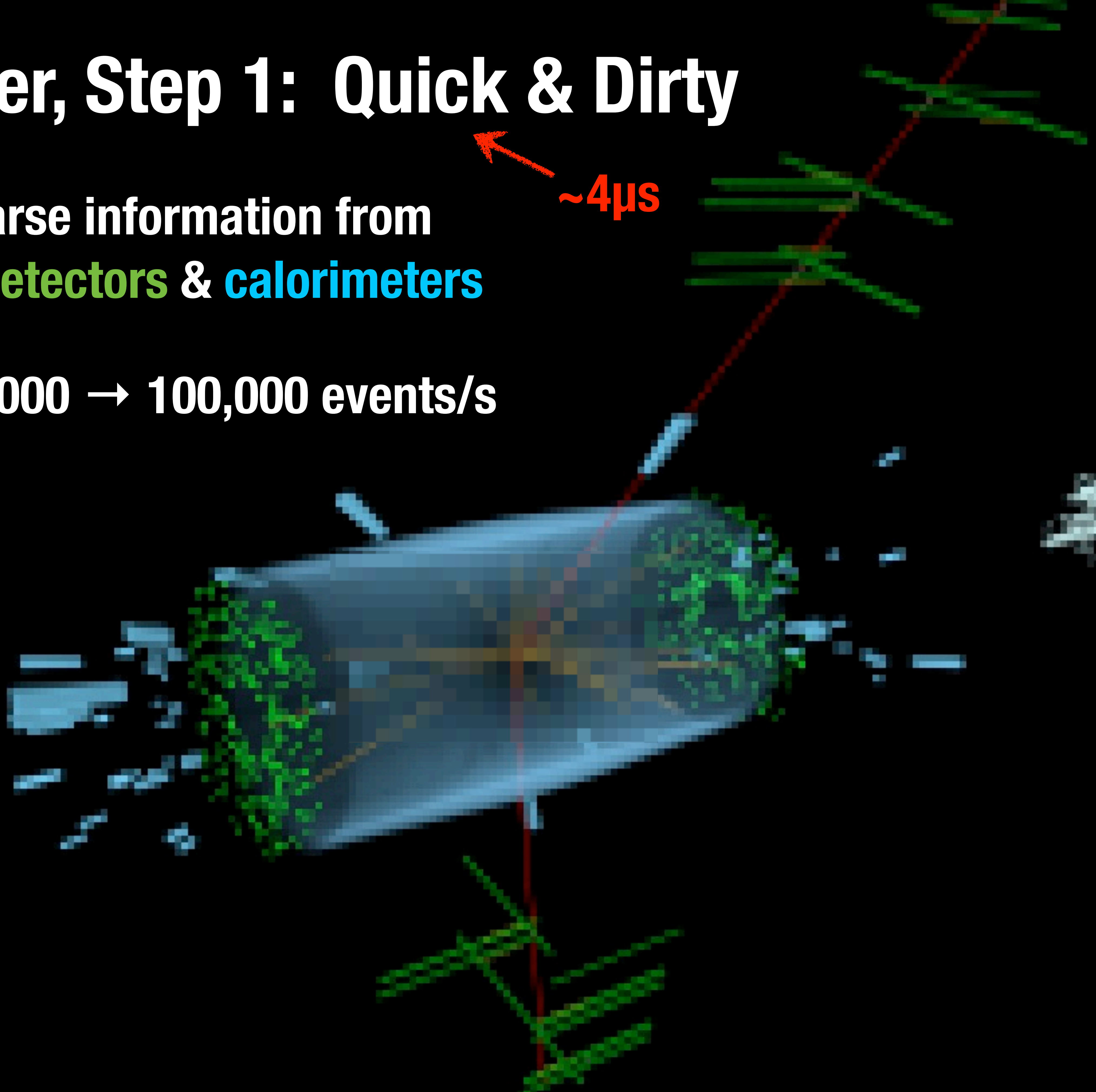


Trigger, Step 1: Quick & Dirty

~4μs

Use coarse information from
muon detectors & calorimeters

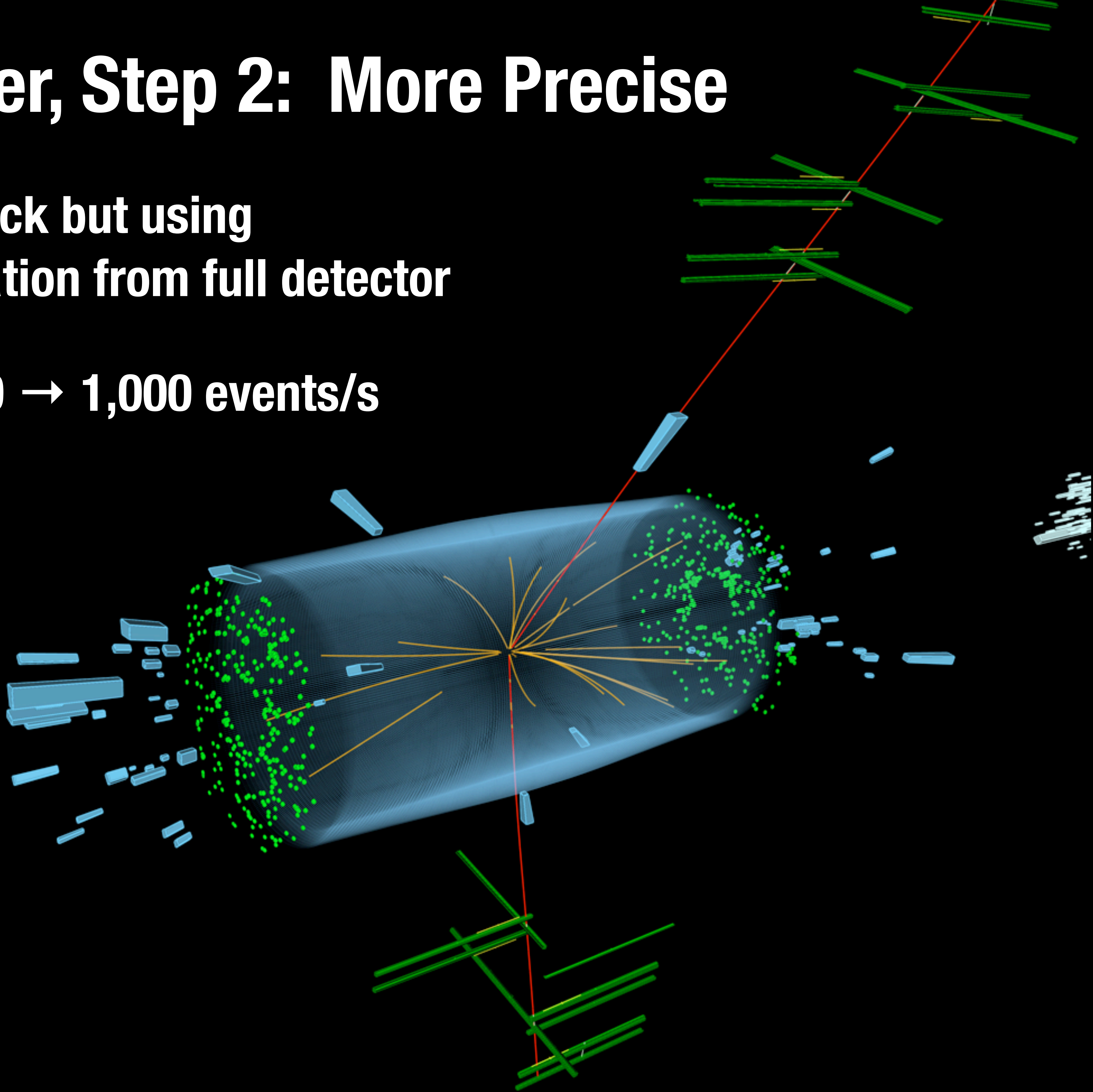
40,000,000 → 100,000 events/s



Trigger, Step 2: More Precise

Still quick but using
information from full detector

100,000 → 1,000 events/s



Triggering & Tracking

Number of muons (real & fake) produced / second
as function of transverse momentum