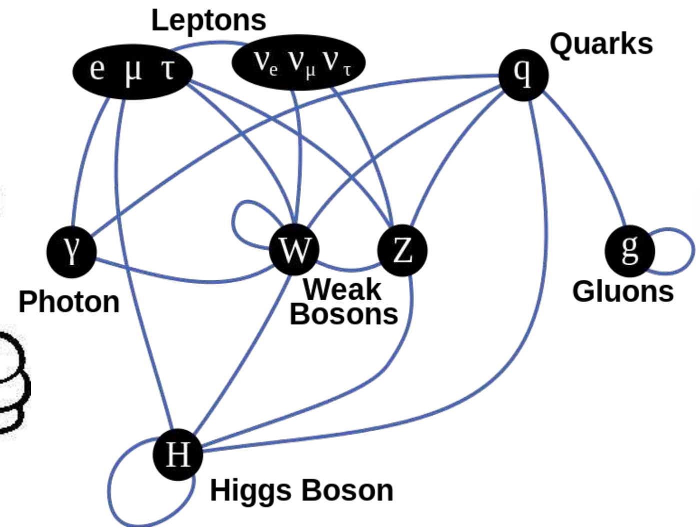
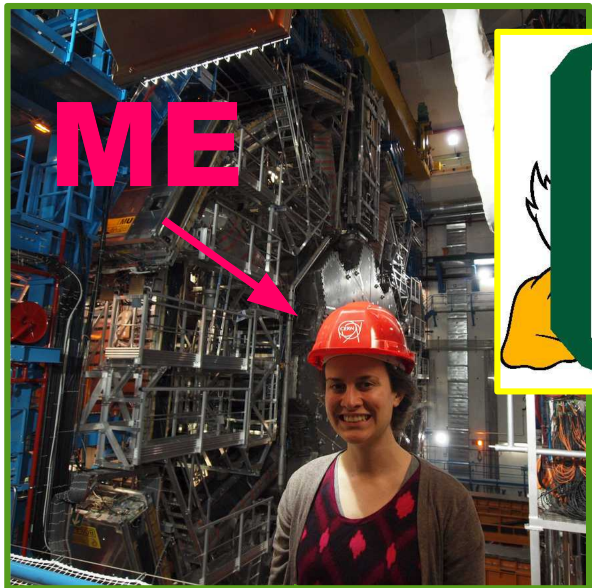
The LHC and the Higgs Boson: A Crash Course in Collider Physics



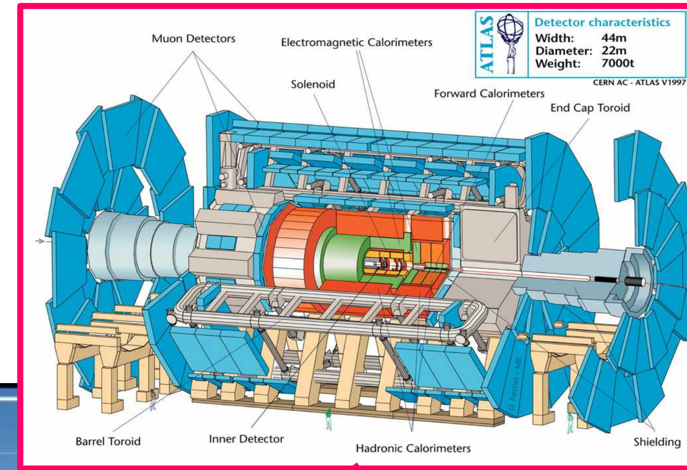
Elizabeth Brost, UO

February 26th, 2015

Hi.


ME


OREGON
© Disney


Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

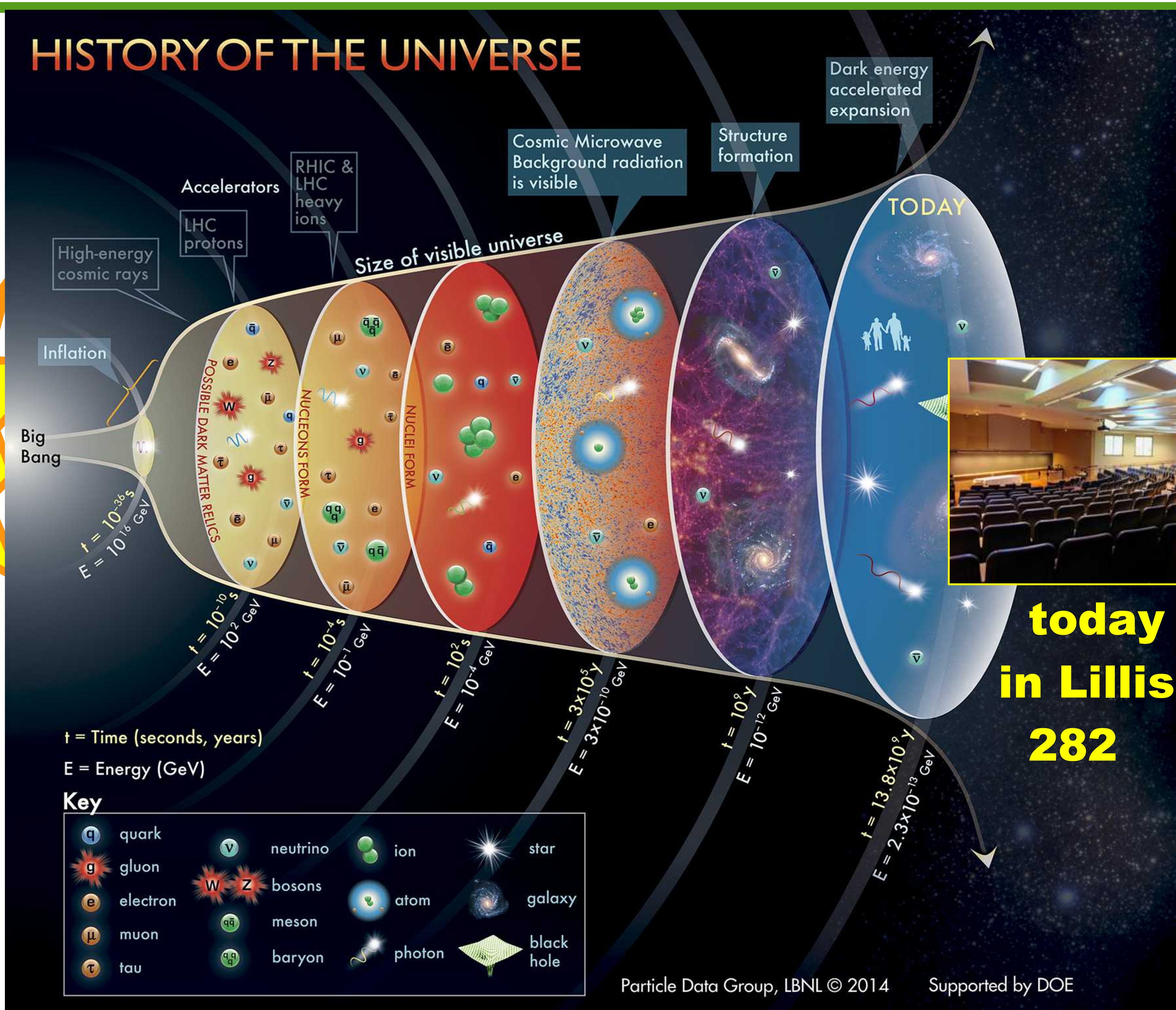

ATLAS
Collaboration

A few questions for you

Outline

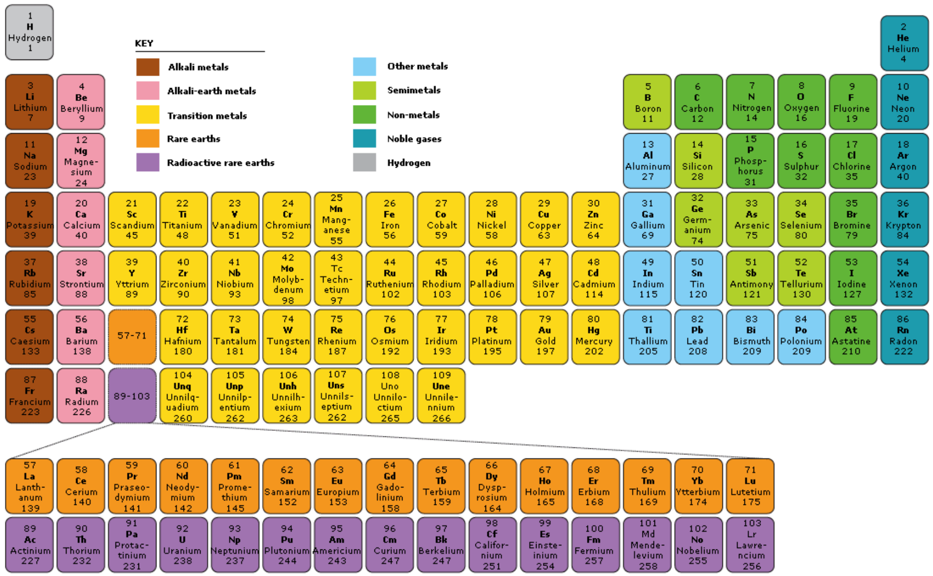
- The Big Bang
- Brief Introduction to Particle Physics
- Discovering the Higgs Boson
  - The Large Hadron Collider
  - The ATLAS Detector

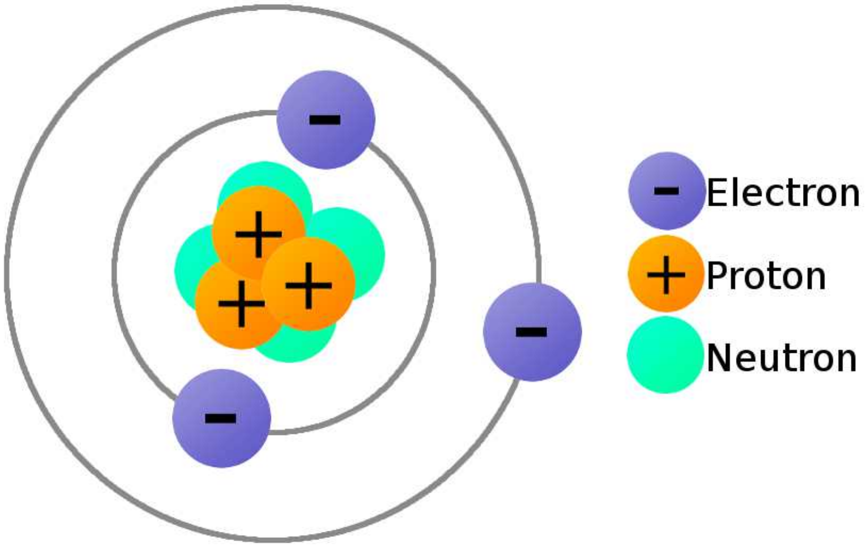
THE BIG BANG



today in Lillis 282

Matter



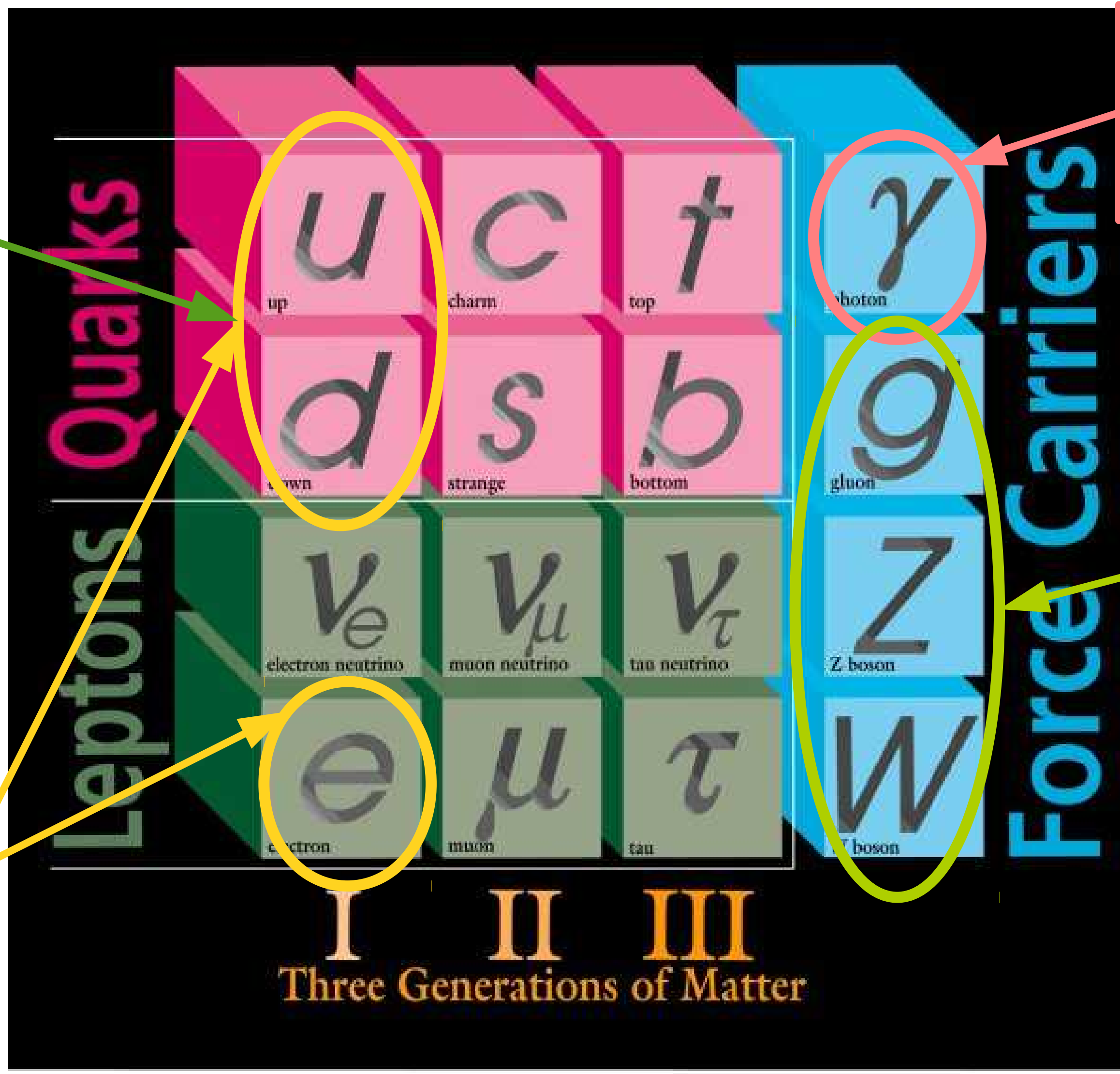


All atomic matter is made of three particles: the electron, the proton, and the neutron

The Standard Model

Make up protons and neutrons

Make up atomic matter

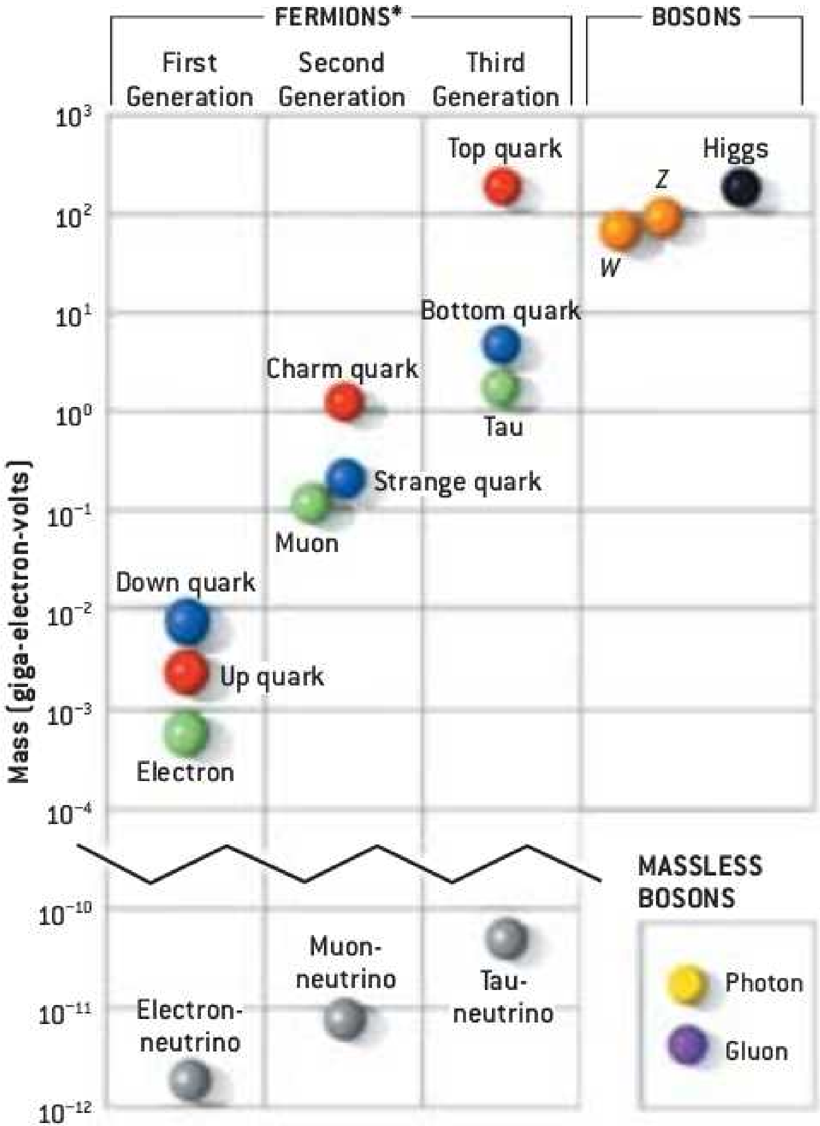


Fermilab 95-759

Electro-magnetism

Weak and strong nuclear forces

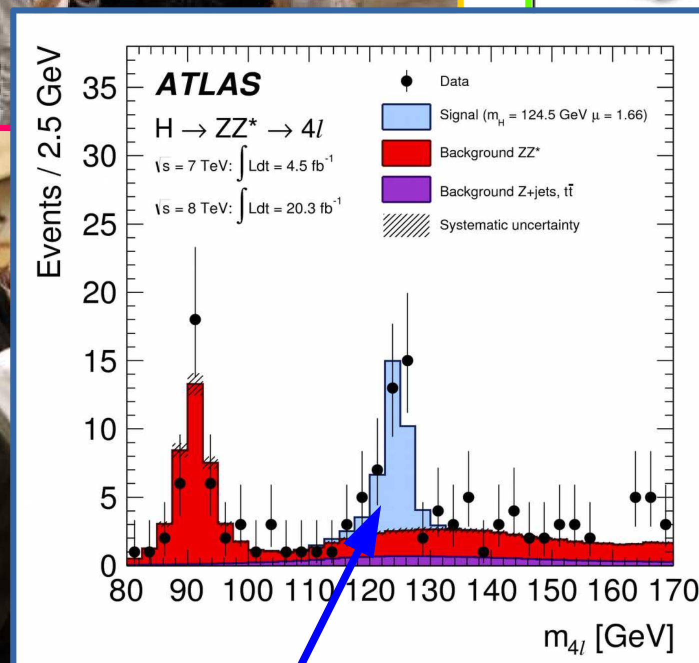
What's missing from the Standard Model?



Gordon Kane, Scientific American, May 2003

- The Standard Model is wildly successful
- But why are the masses of the **fundamental** particles so different?

A New Particle is discovered!

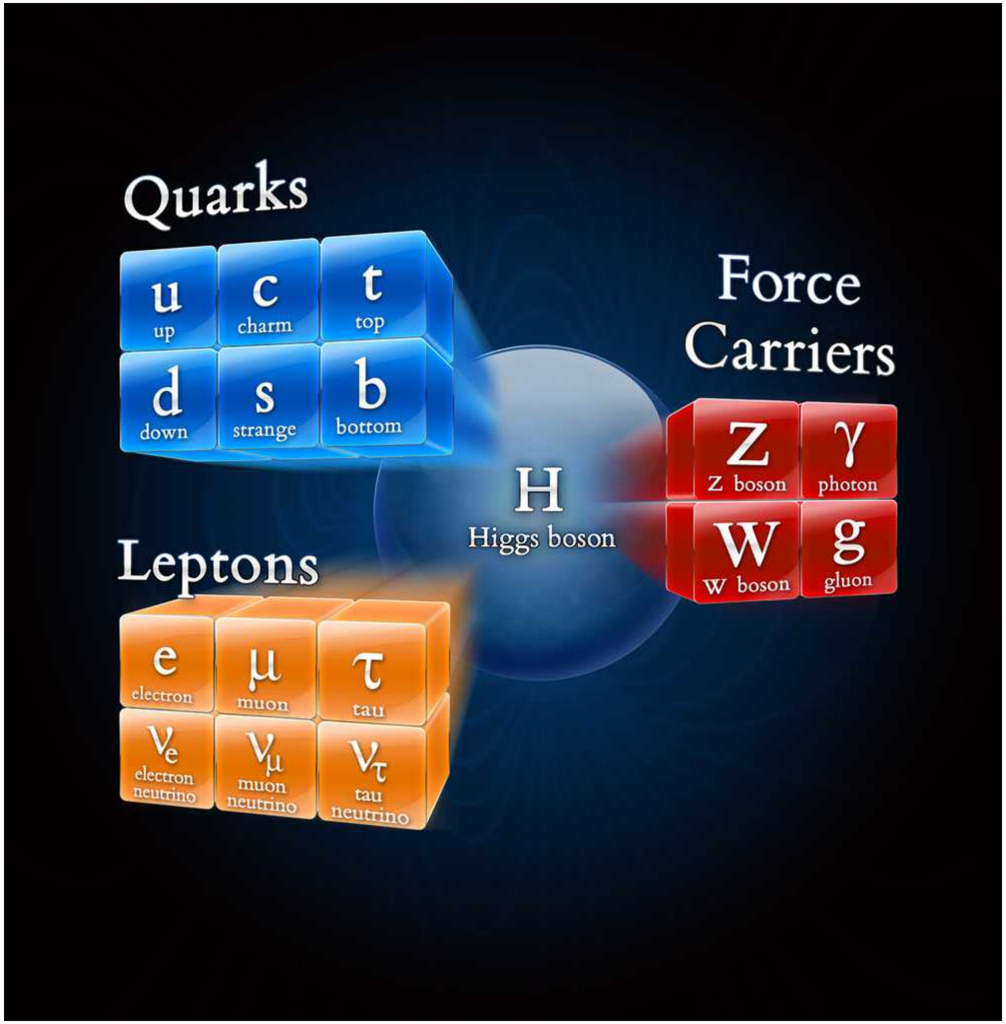


Higgs Boson

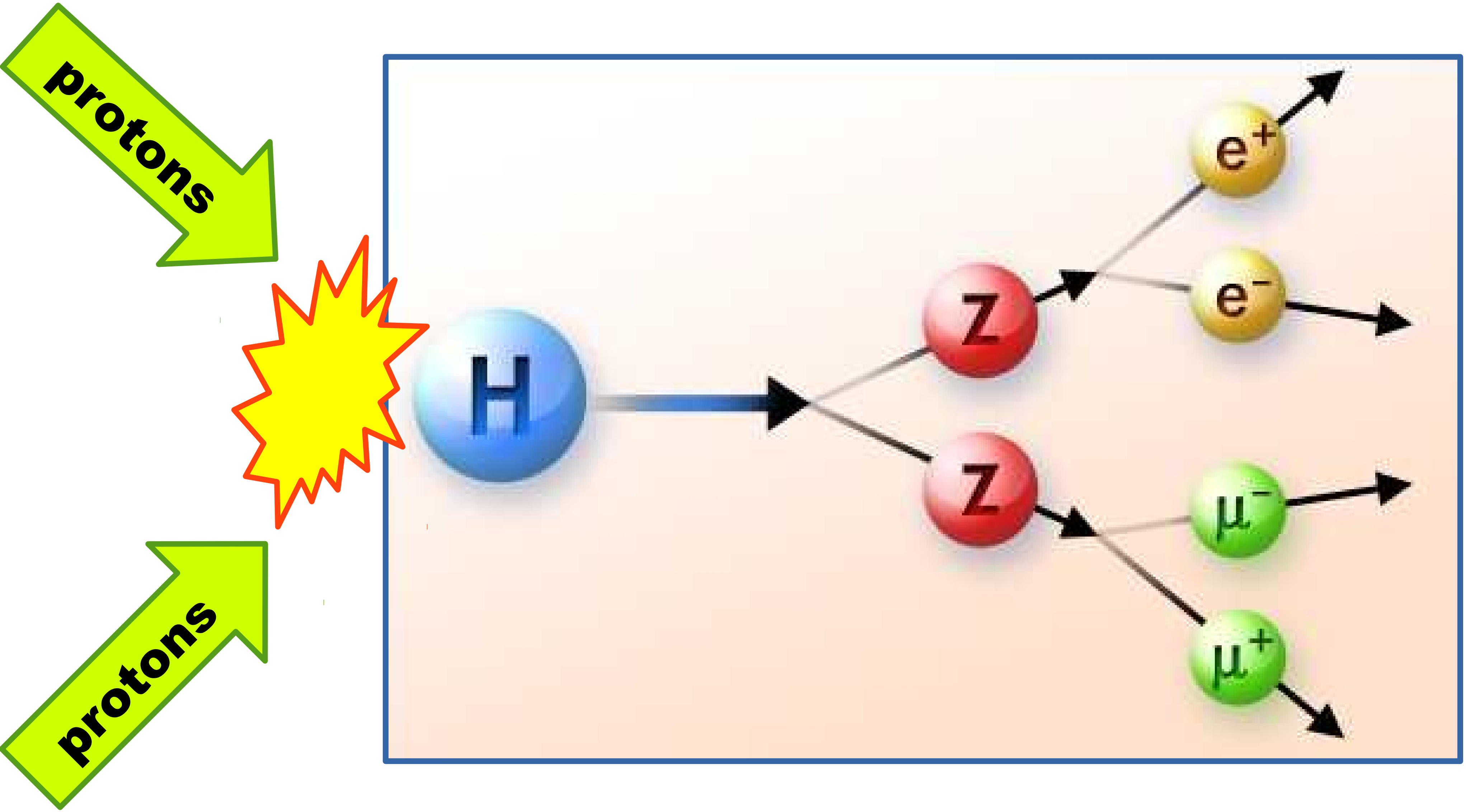
By the end of the lecture, you will understand where this plot comes from ←

The Standard Model (now)

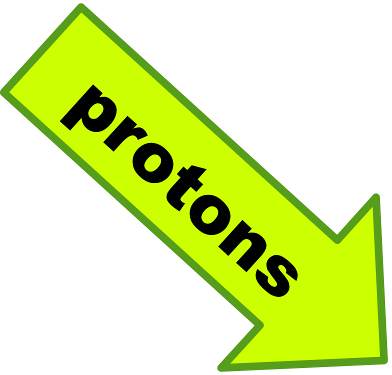
- The Higgs field fills the universe and gives mass to the fundamental particles
- The rest of this talk will discuss how we found the Higgs boson



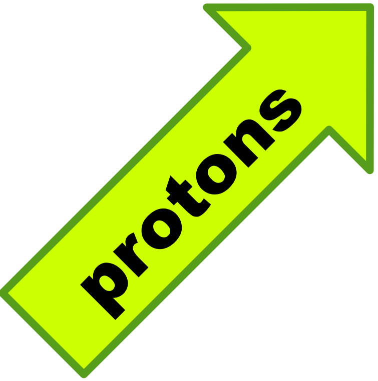
Searching for the Higgs Boson



How do we look for the Higgs?

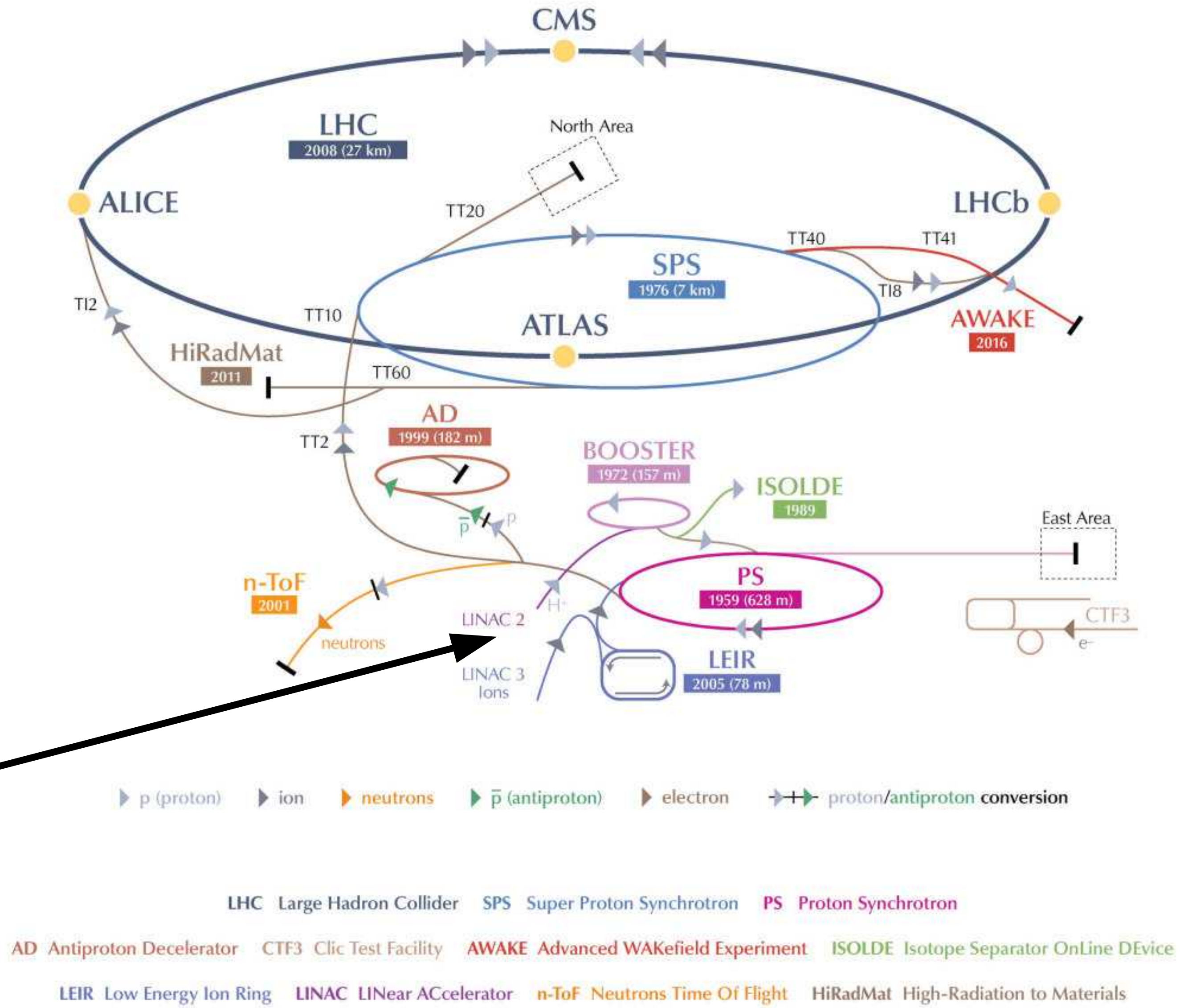


Step one: accelerate protons



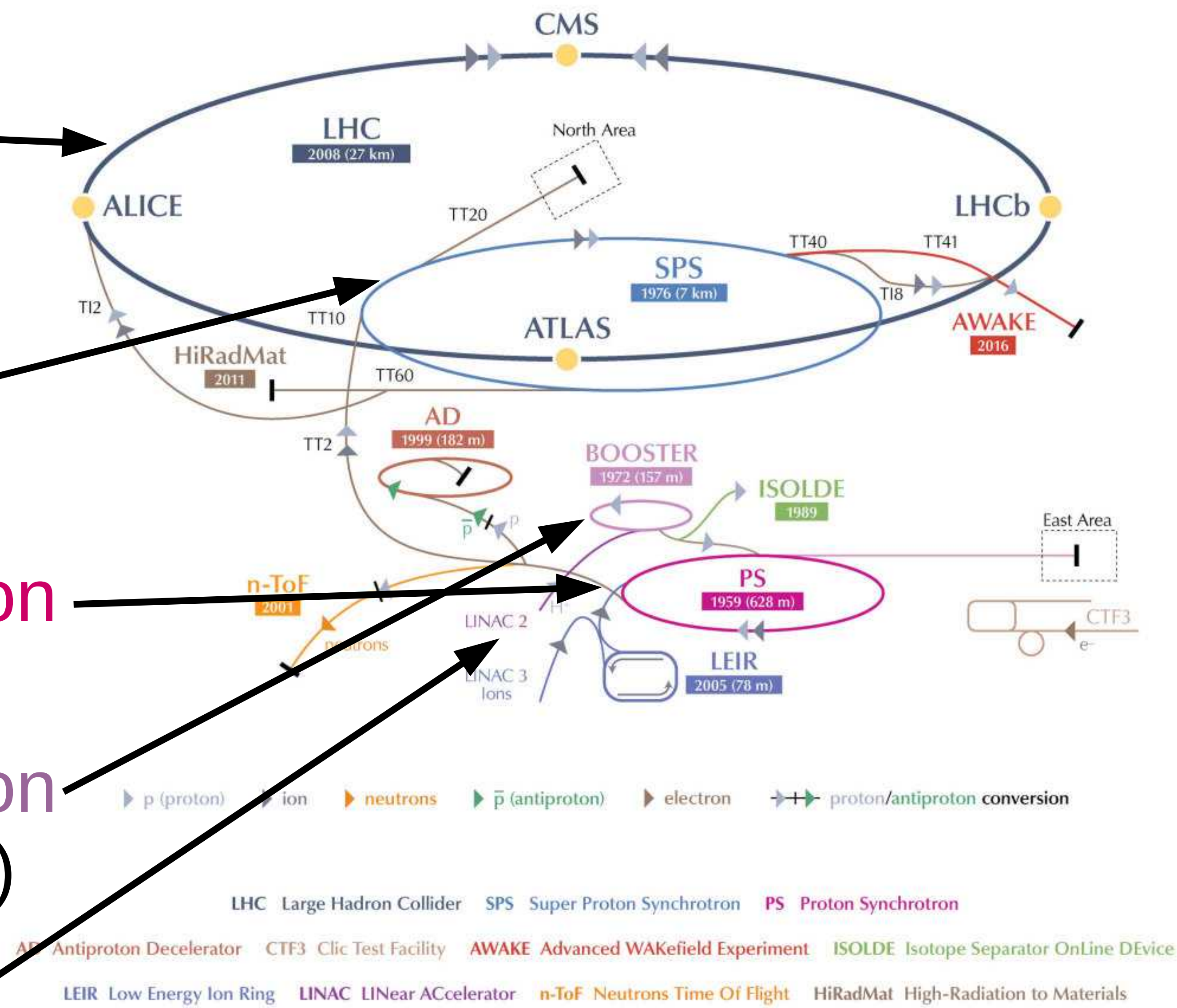
Insert Protons

All the protons that we will ever need at the LHC are contained in this bottle of hydrogen



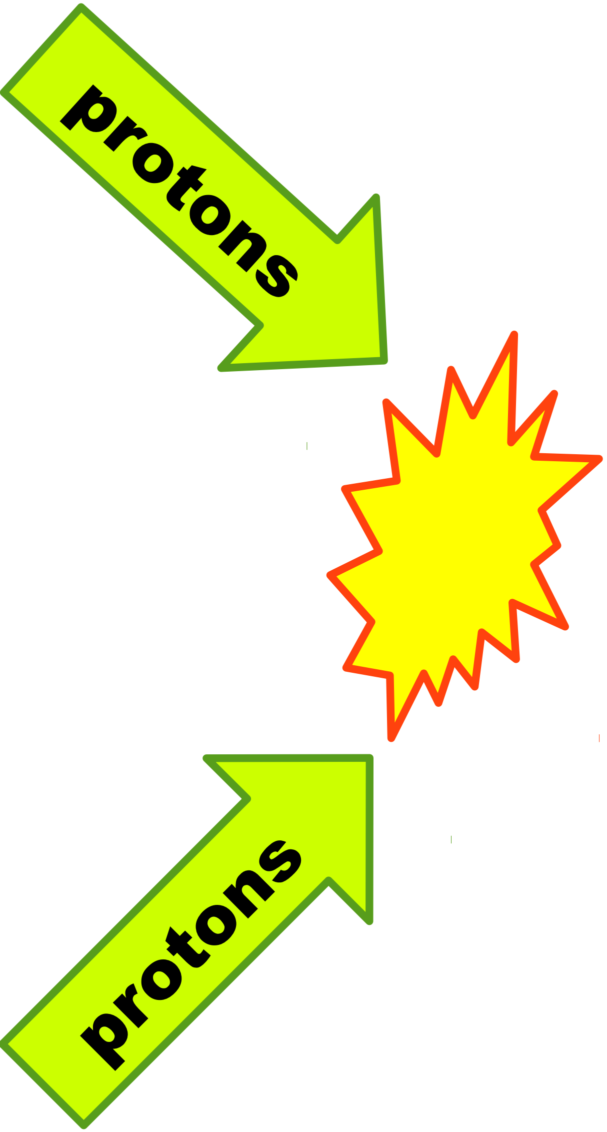
Accelerate Protons

- Large Hadron Collider (4 TeV per beam)
- Super Proton Synchrotron (450 GeV)
- Proton Synchrotron (25 GeV)
- Proton Synchrotron Booster (1.4 GeV)
- Linac 2 (50 MeV)



Accelerator Movie

How do we look for the Higgs?

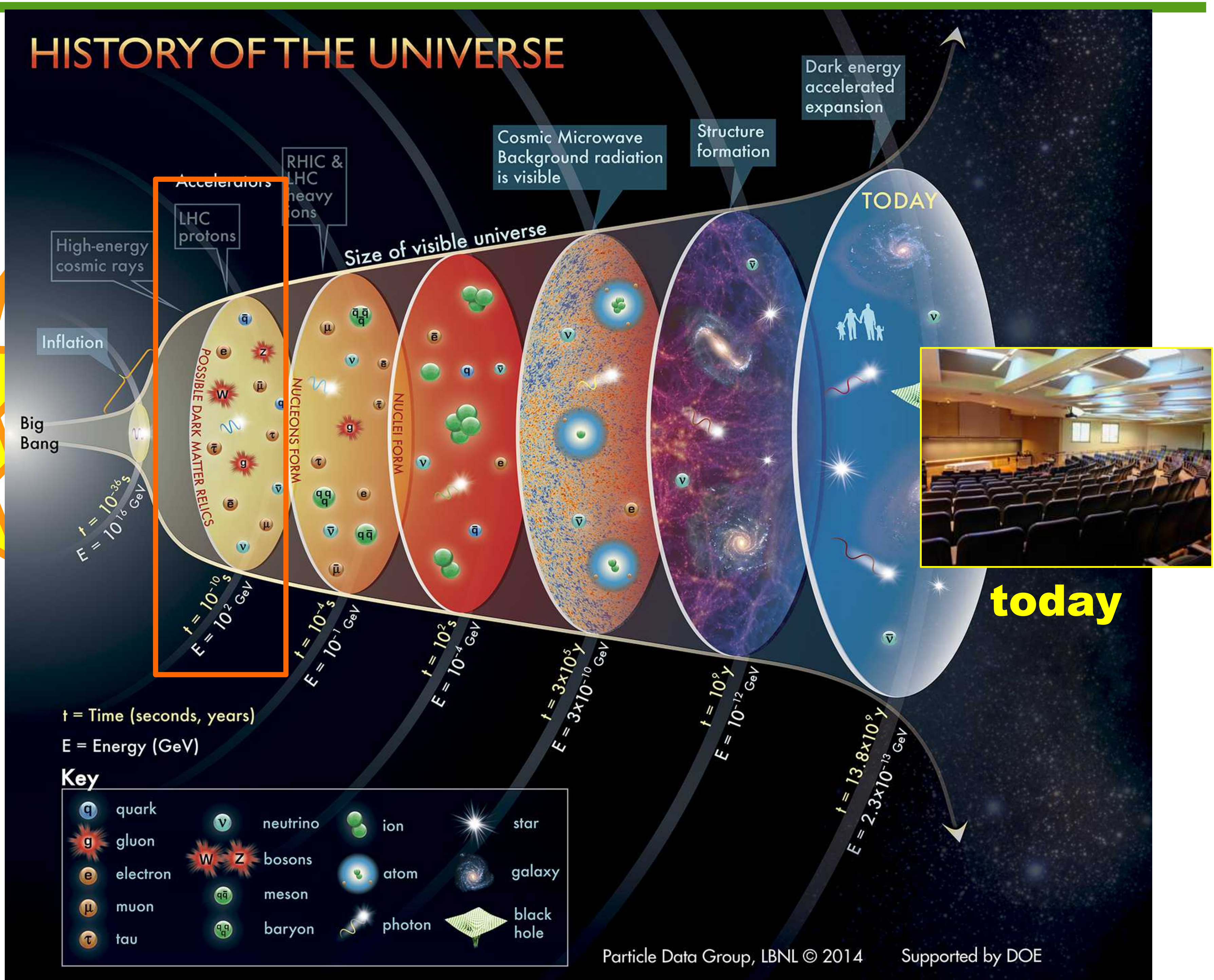


Step two: collide protons

The Large Hadron Collider

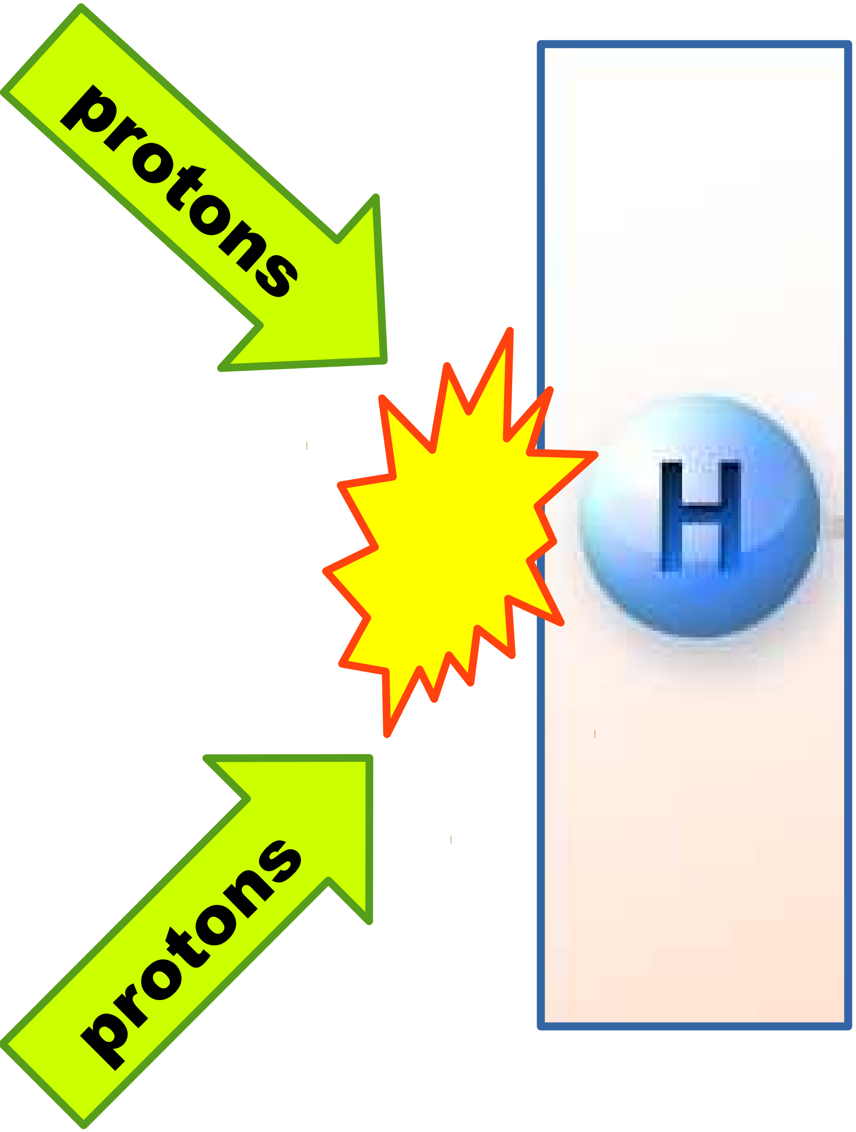
- ~27 km + 4 experiments
- Collision energy: 8 TeV
  (upgrade to 14 TeV later this year)
  - ➔ $T_{universe}$ at $t = 10^{-10}$ s

THE BIG BANG



today

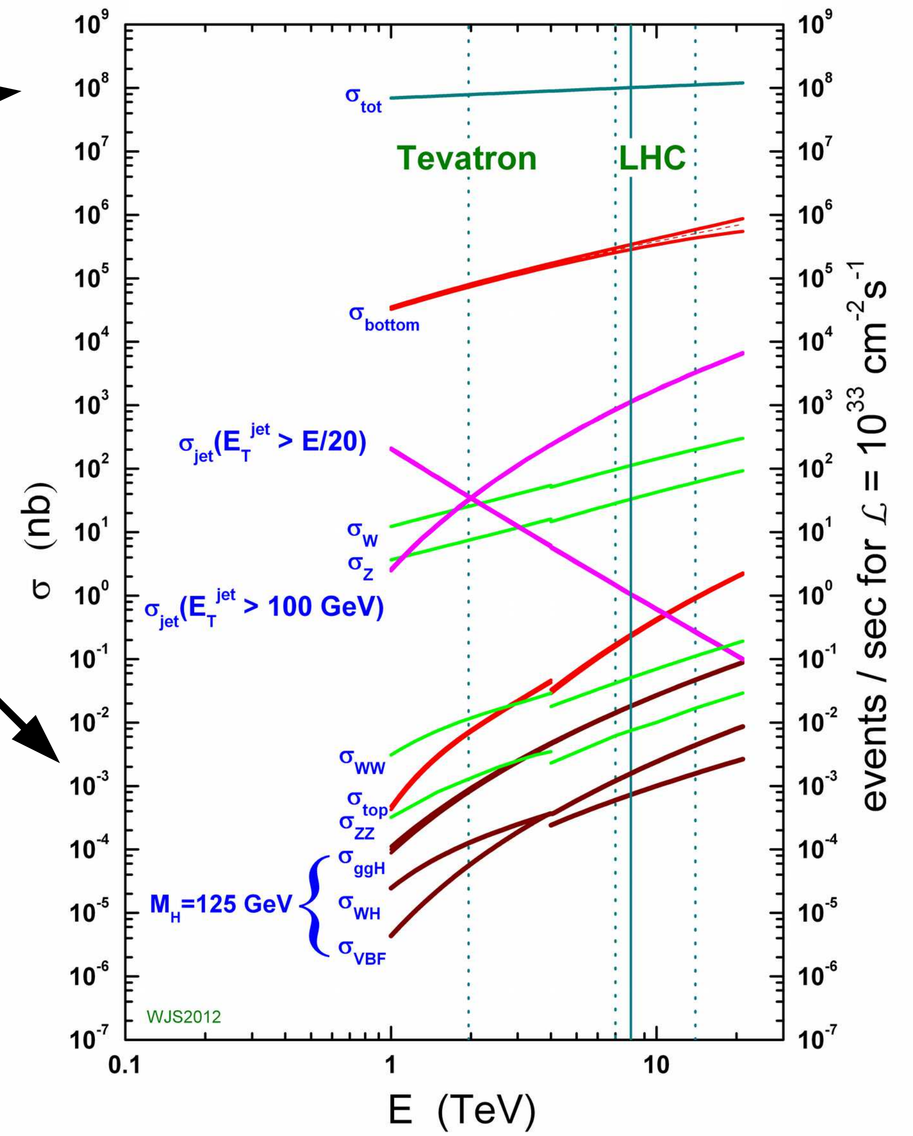
How do we look for the Higgs?



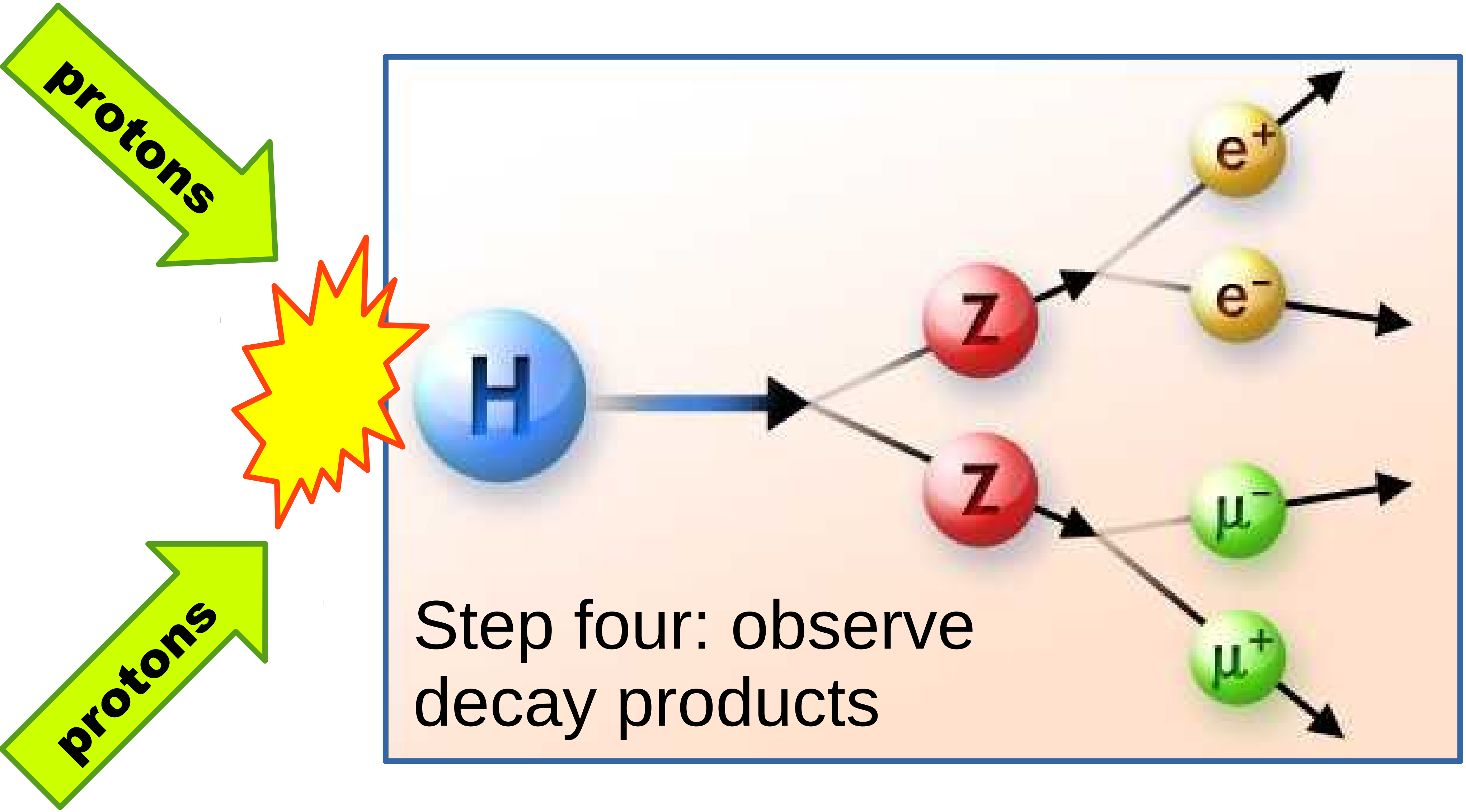
Step three: Higgs boson is produced

Collisions @ the LHC

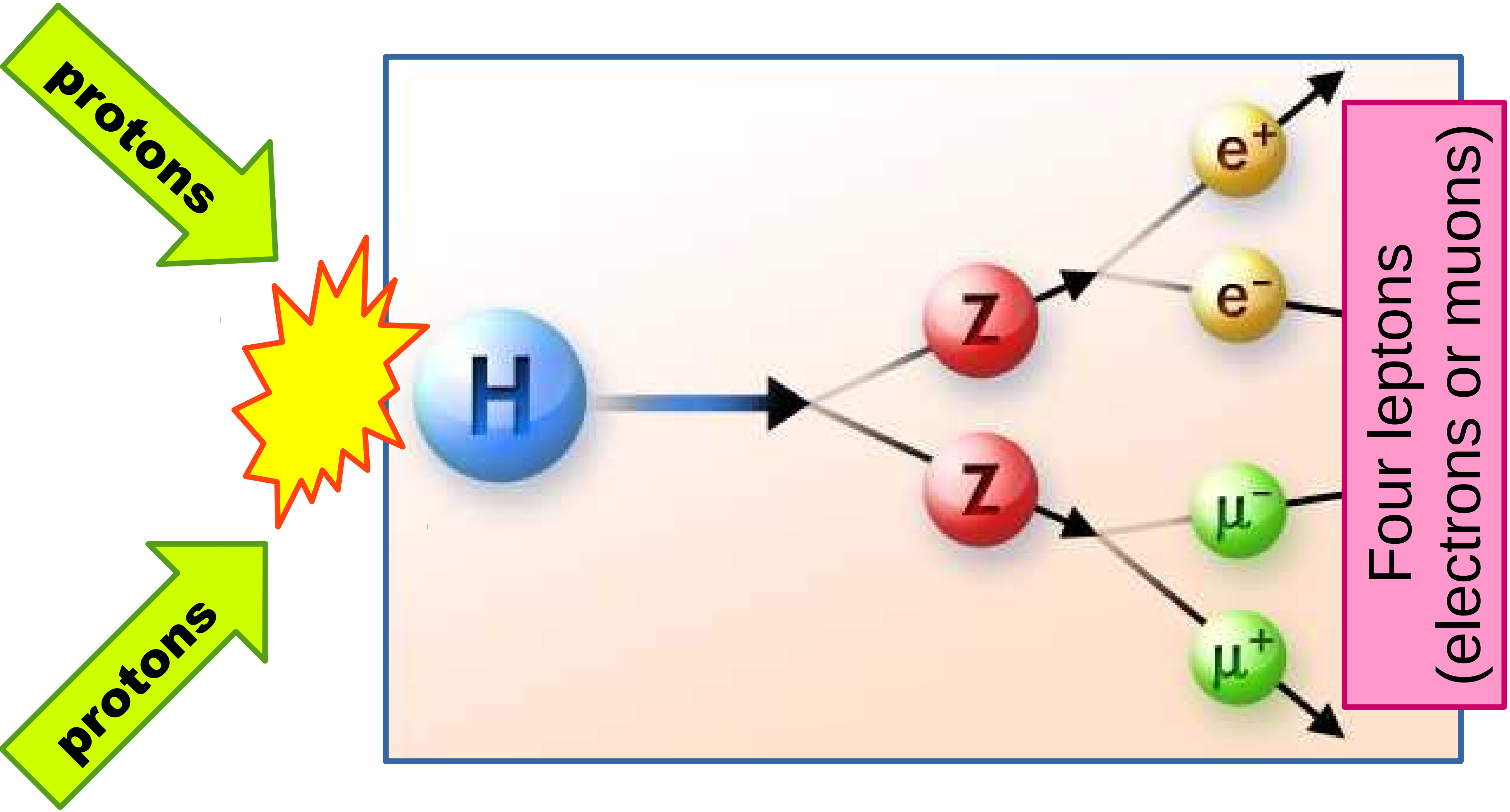
- MOST collisions are boring
- We are looking for rare processes
- How rare?
  - 300,000 Higgs events in 2012
  - But! 2,000,000,000,000,000 total events in 2012



How do we look for the Higgs?



How do we look for the Higgs?



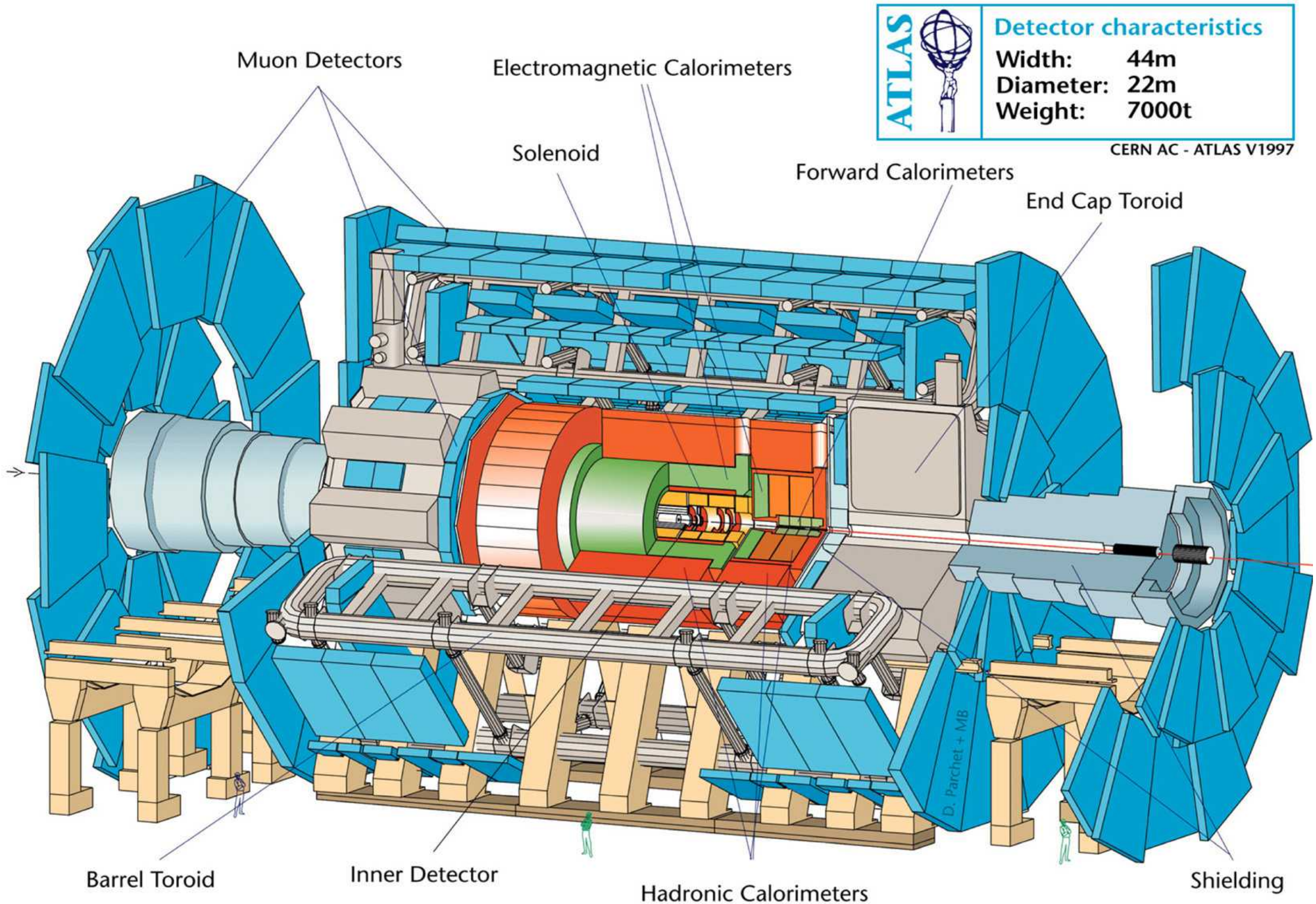
There are other decay channels, but we will focus on this one ($H \rightarrow 4\ell$)

How do we observe the leptons from the Higgs decay?

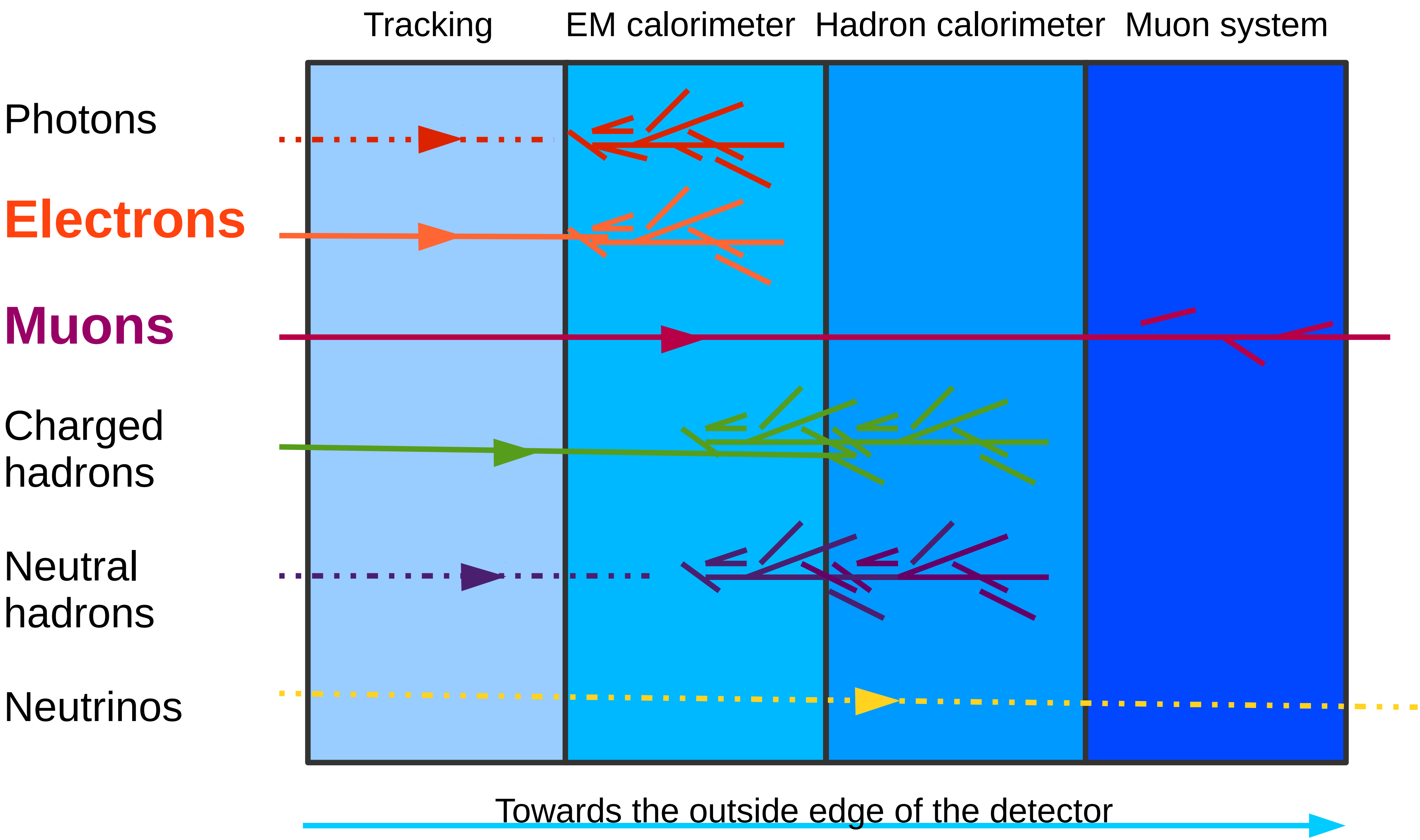
http://www.particlezoo.net/

- Use detectors to record the decay products from the process we're looking for (H → ZZ* → 4ℓ)
- Detectors ~ huge 3D digital cameras
  - ➔ picture = "event"

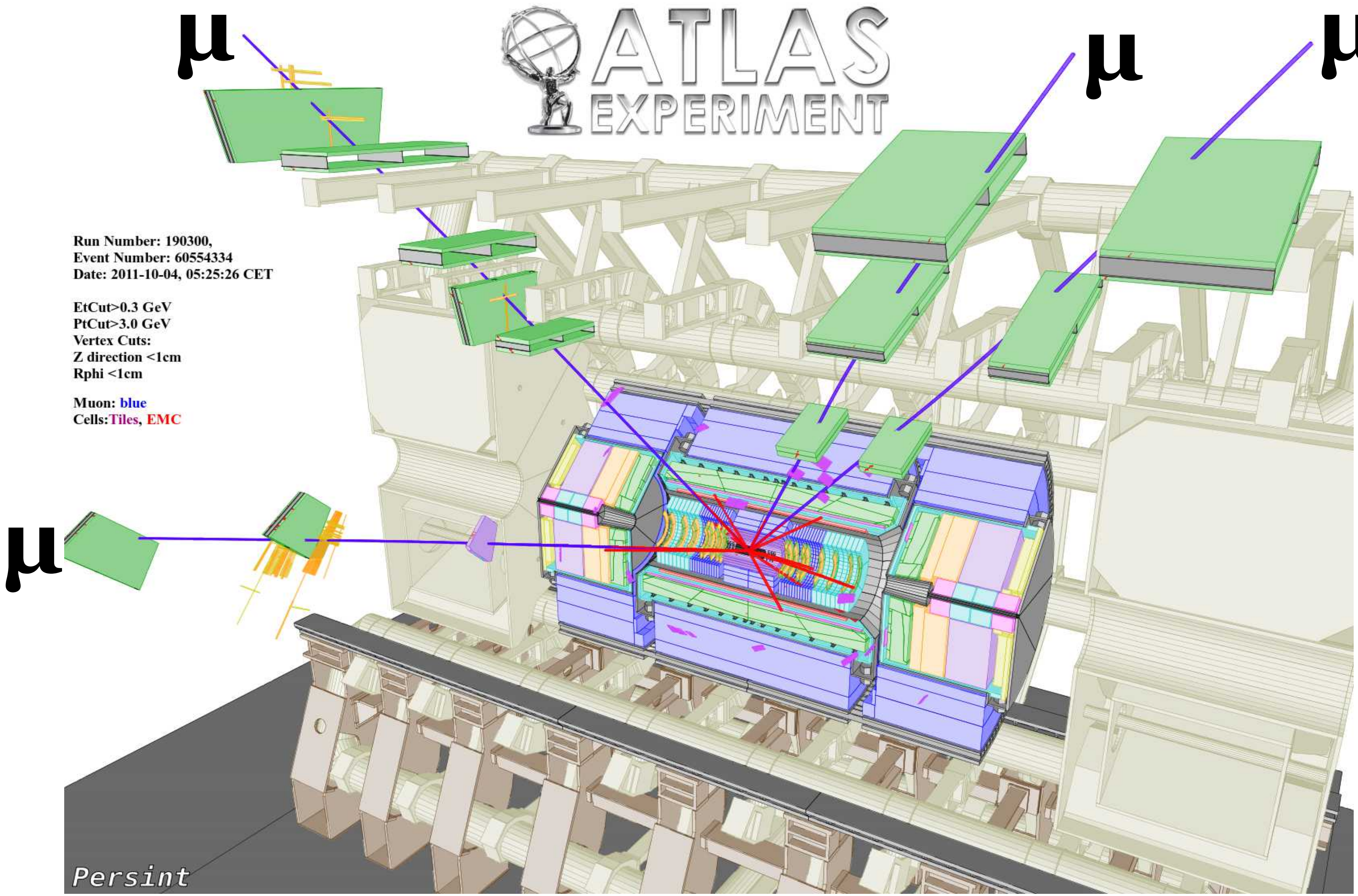
The ATLAS Detector



Particle Identification



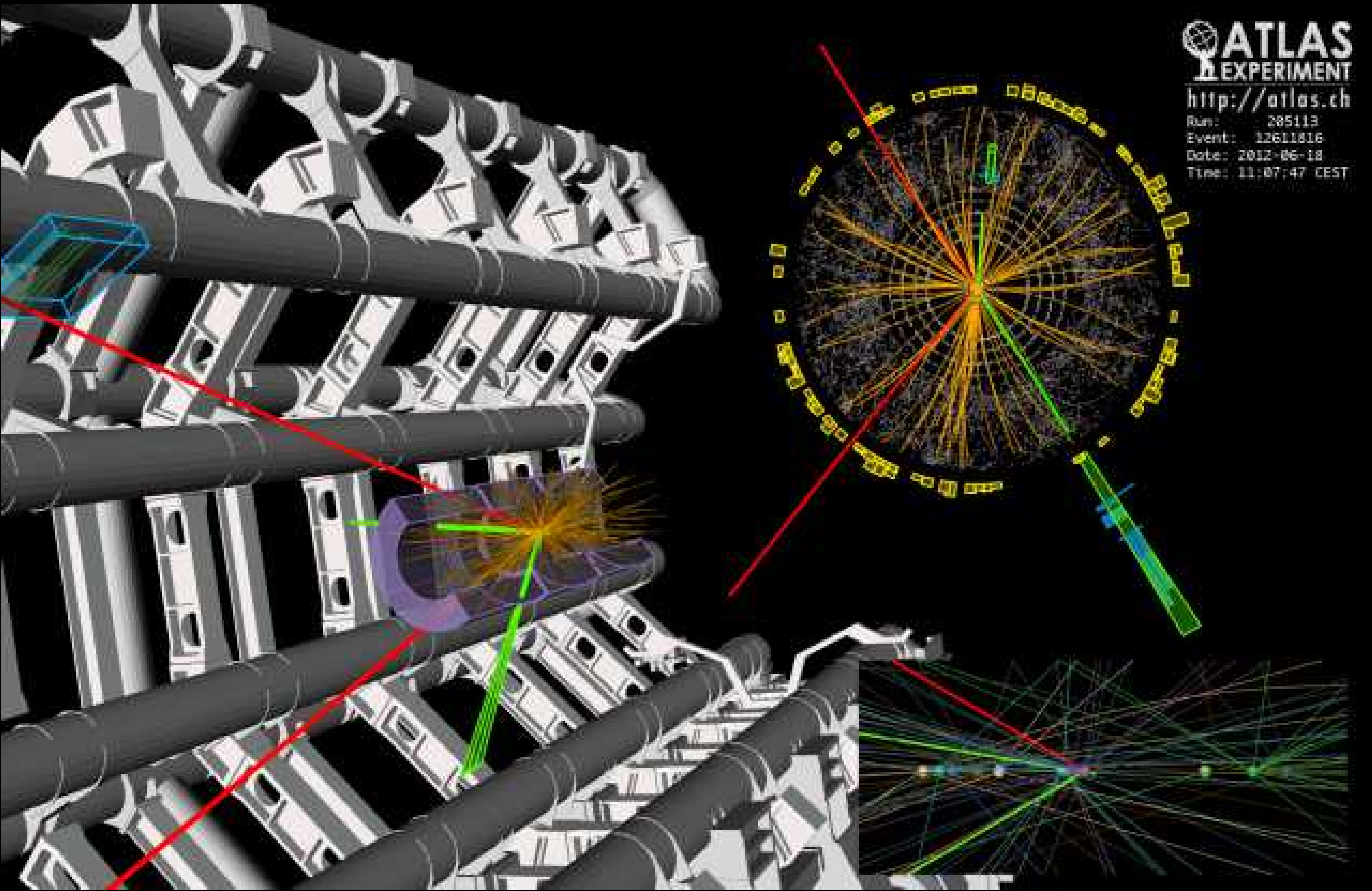
Event Display (4 muons)



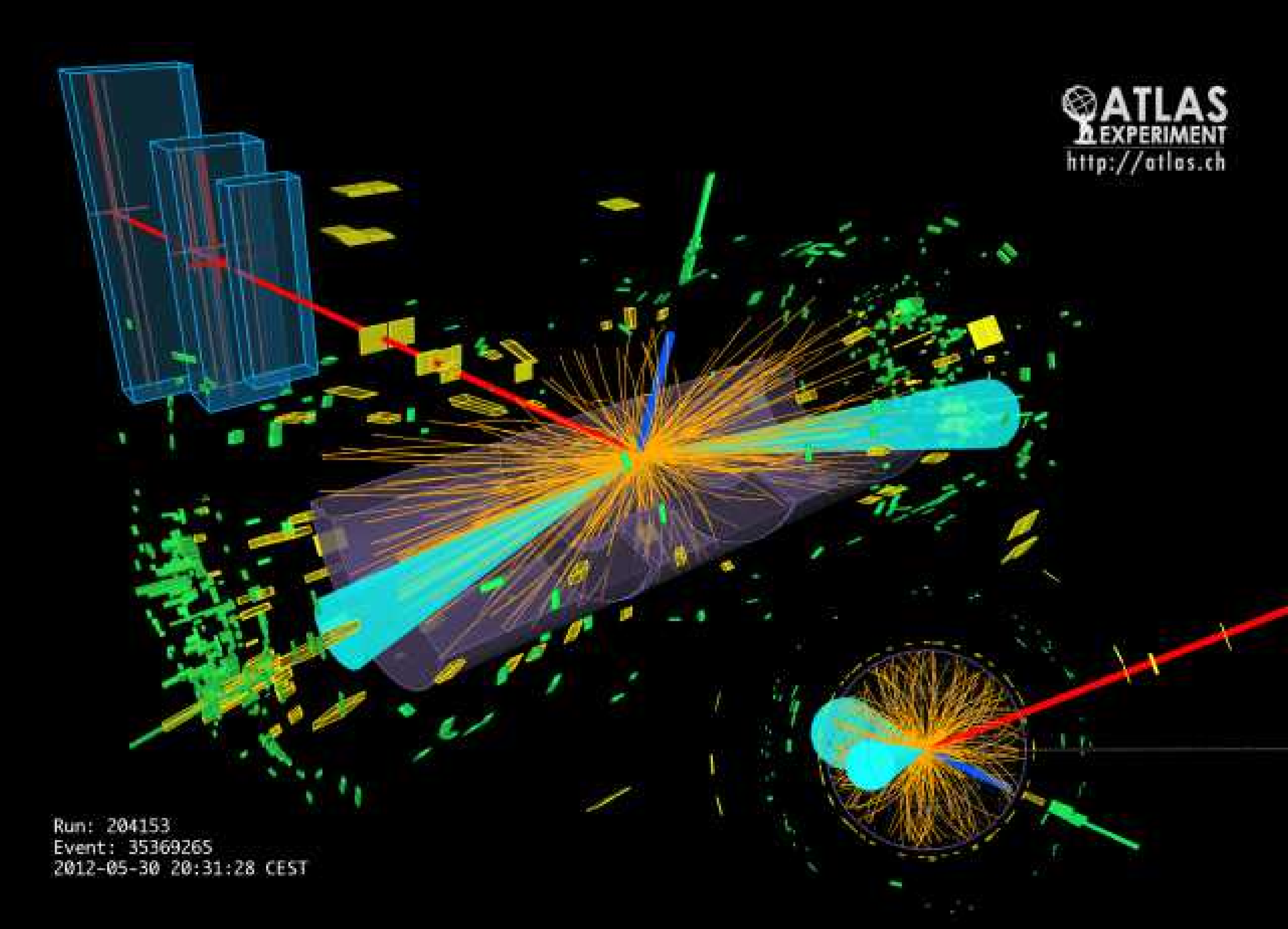
$H \to 4\ell$ event movie

Practice Identifying Higgs Events

- Remember: we're looking for four leptons
  - Two electrons and two muons
  - Four electrons
  - Four muons
- You will be timed!



https://cds.cern.ch/record/1459502



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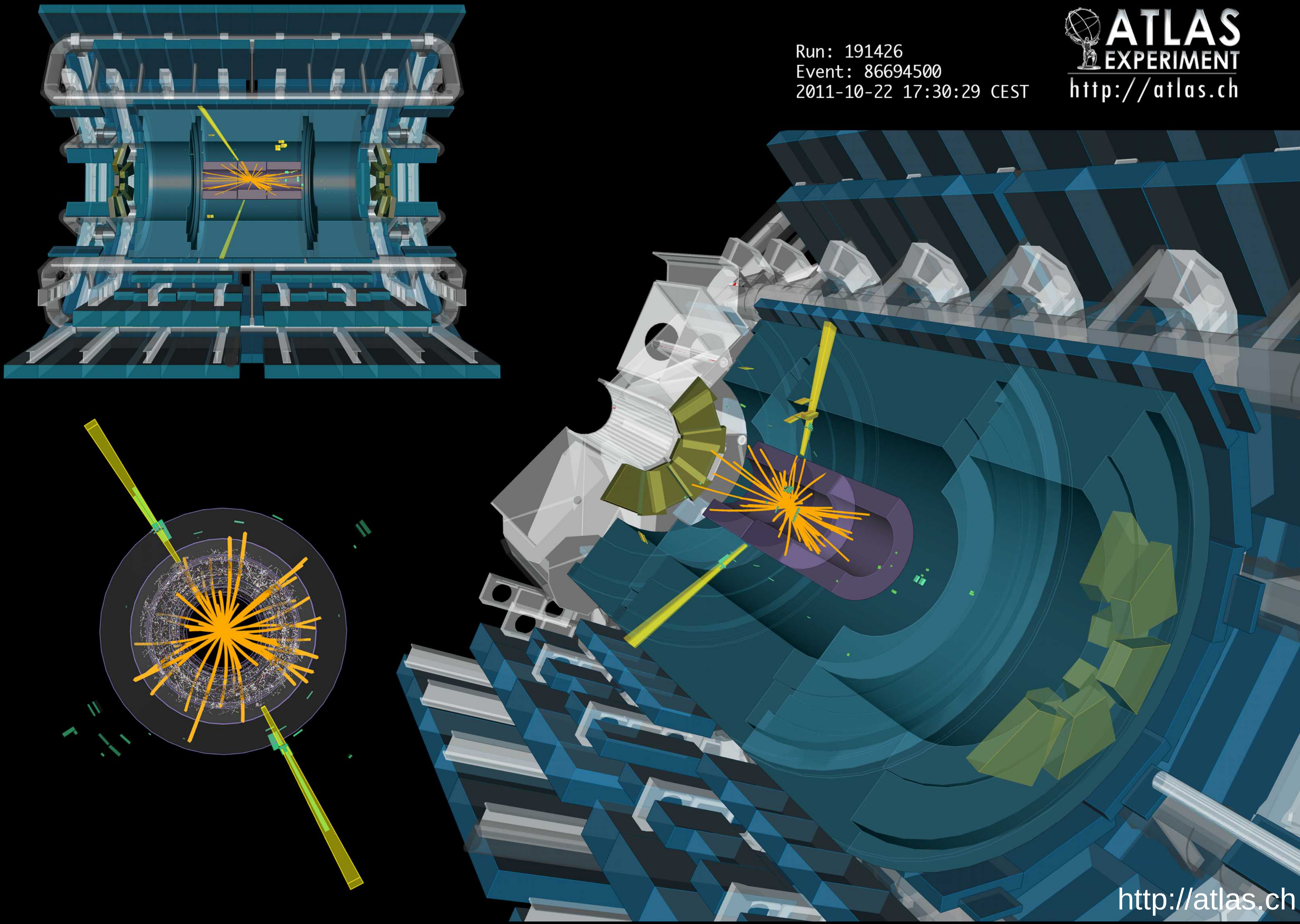
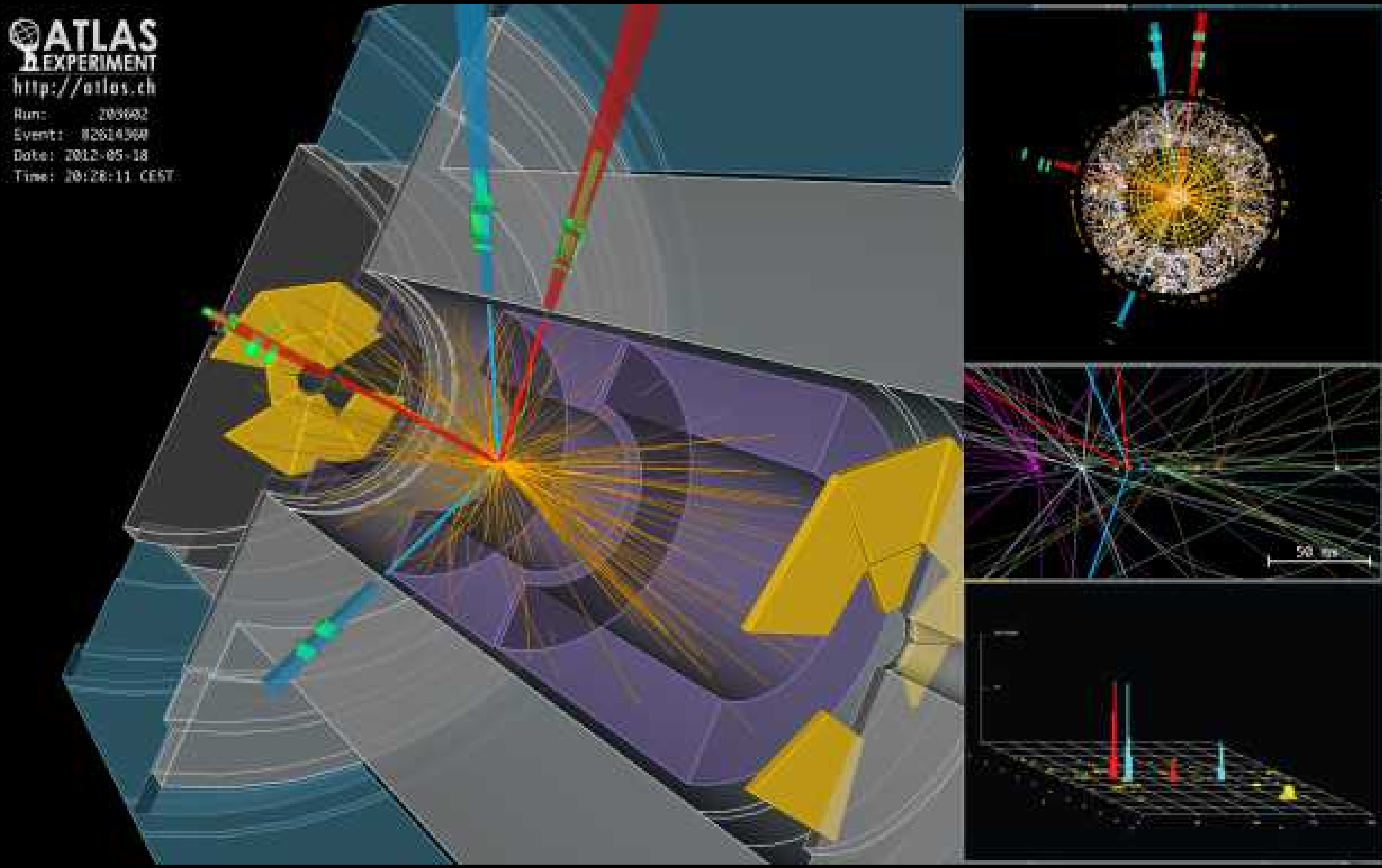


http://atlas.ch



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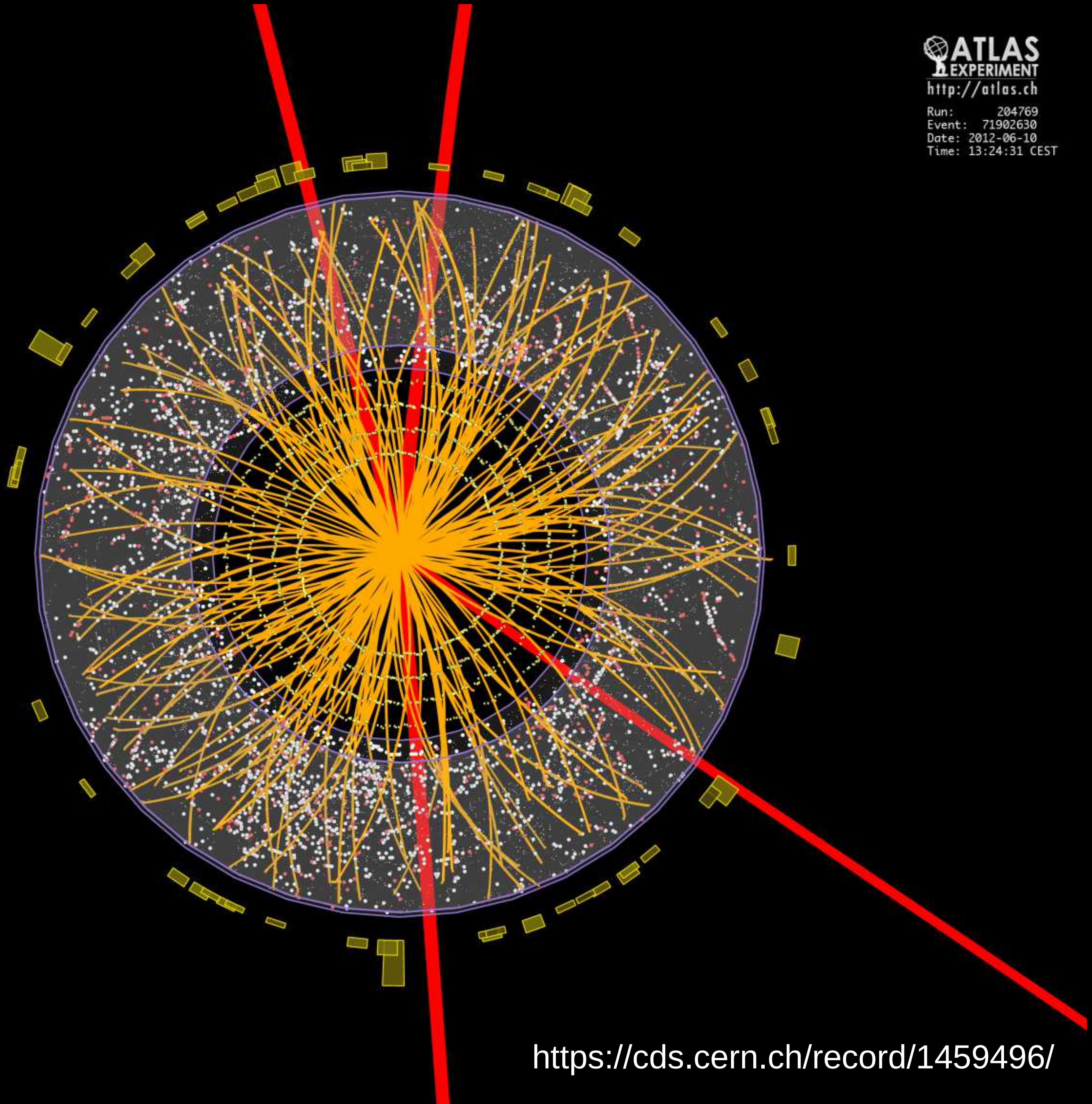

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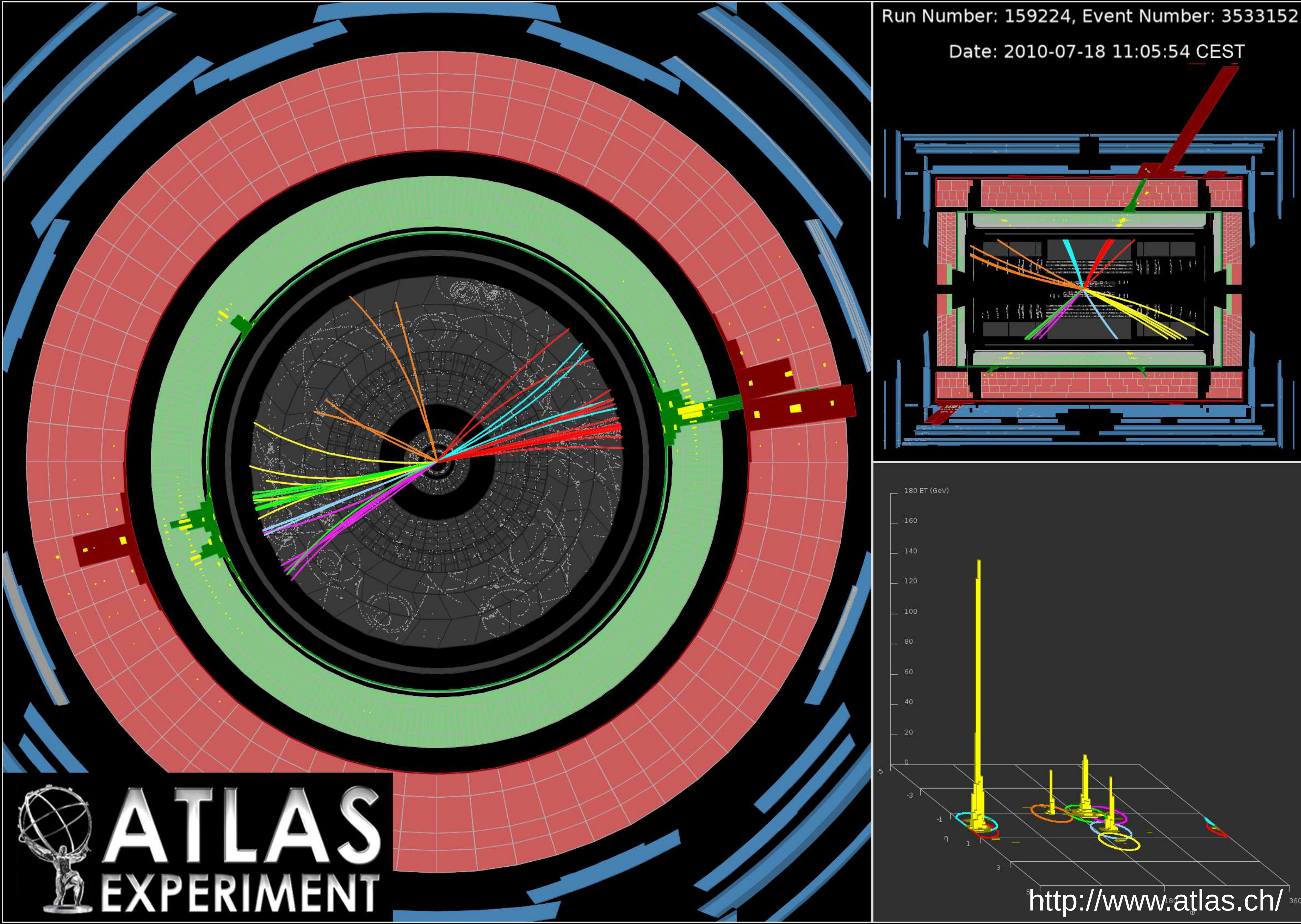
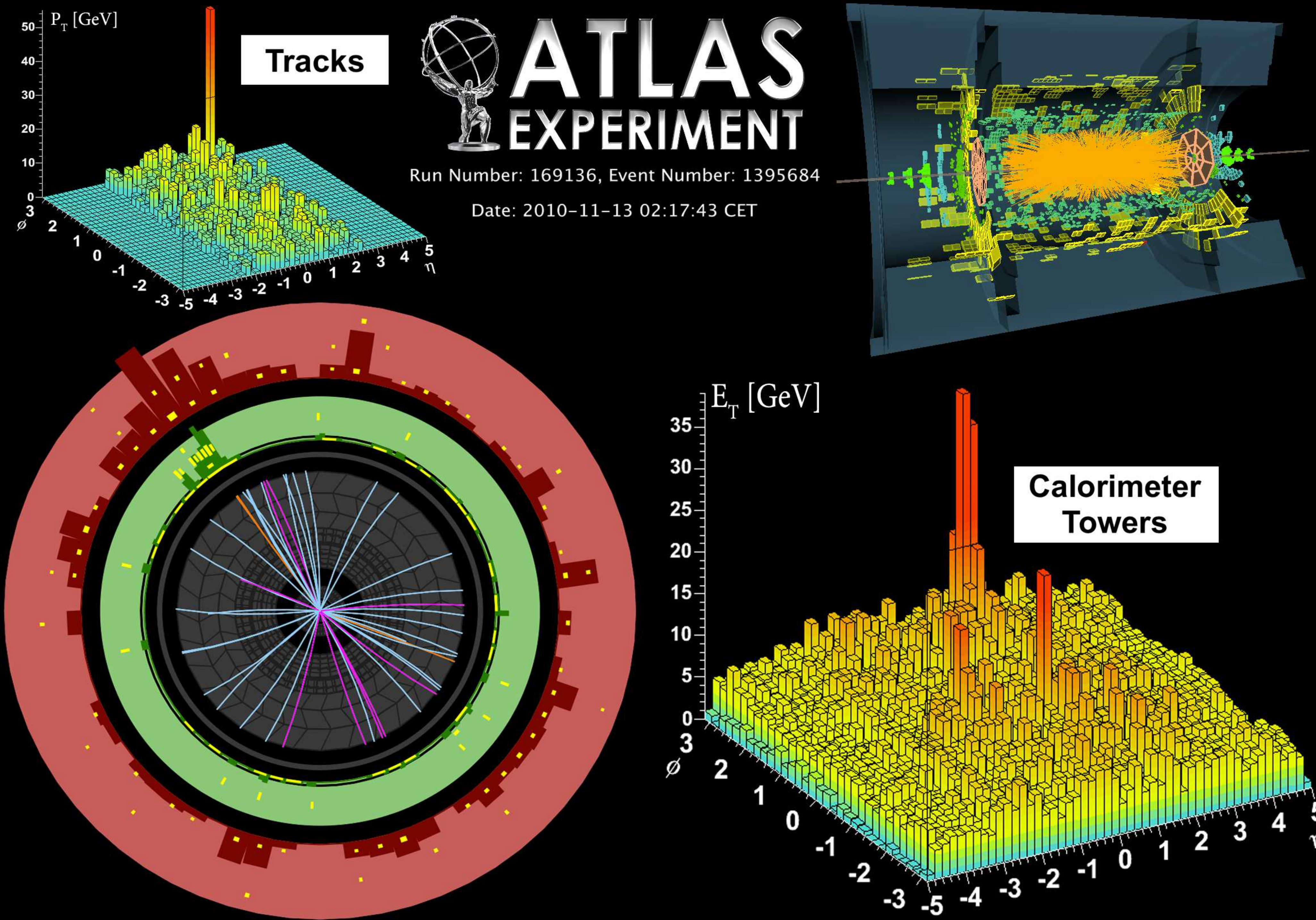
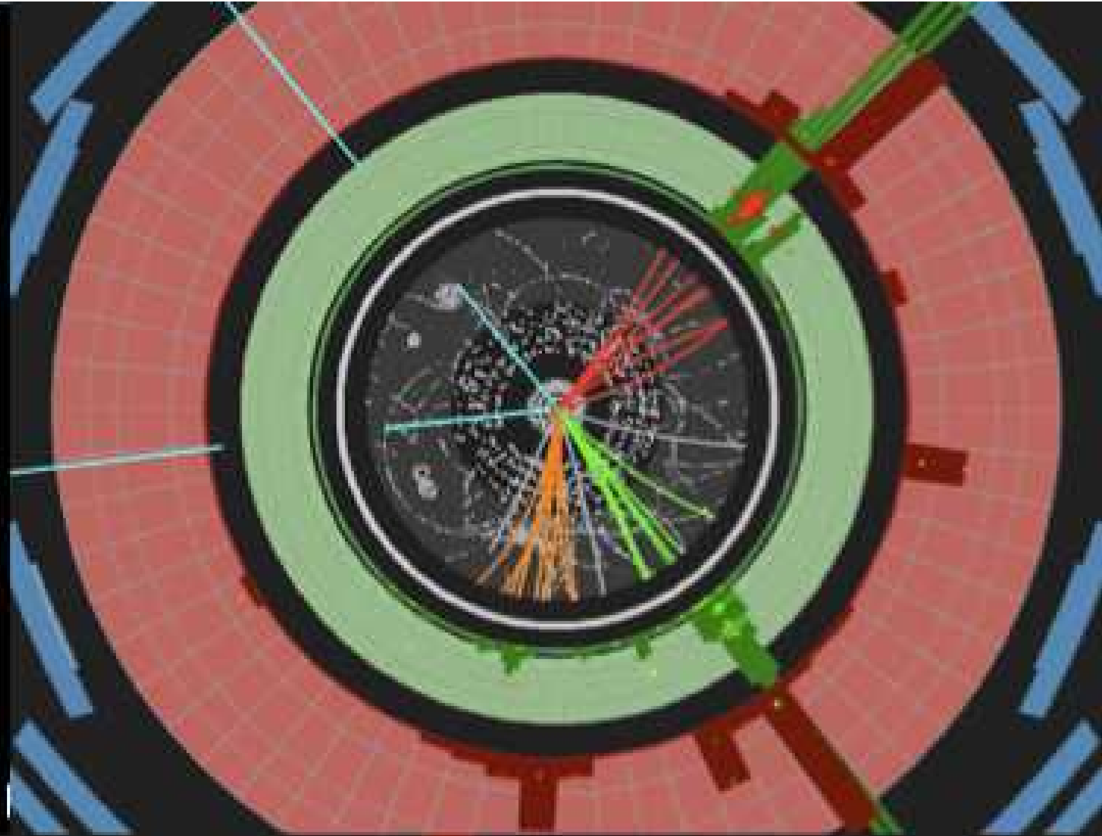

Run Number: 159224, Event Number: 3533152
Date: 2010-07-18 11:05:54 CEST
180 ET (GeV)
160
140
120
100
80
60
40
20
0
ATLAS
EXPERIMENT
http://www.atlas.ch/

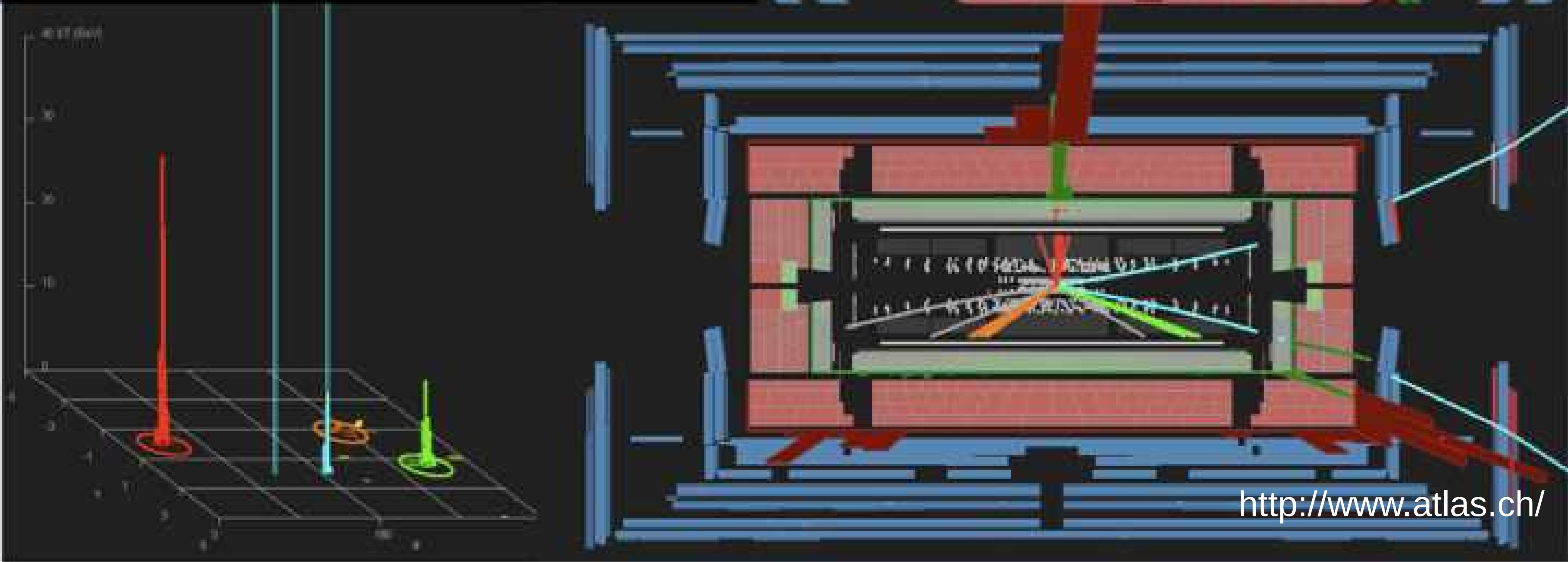


http://www.atlas.ch/

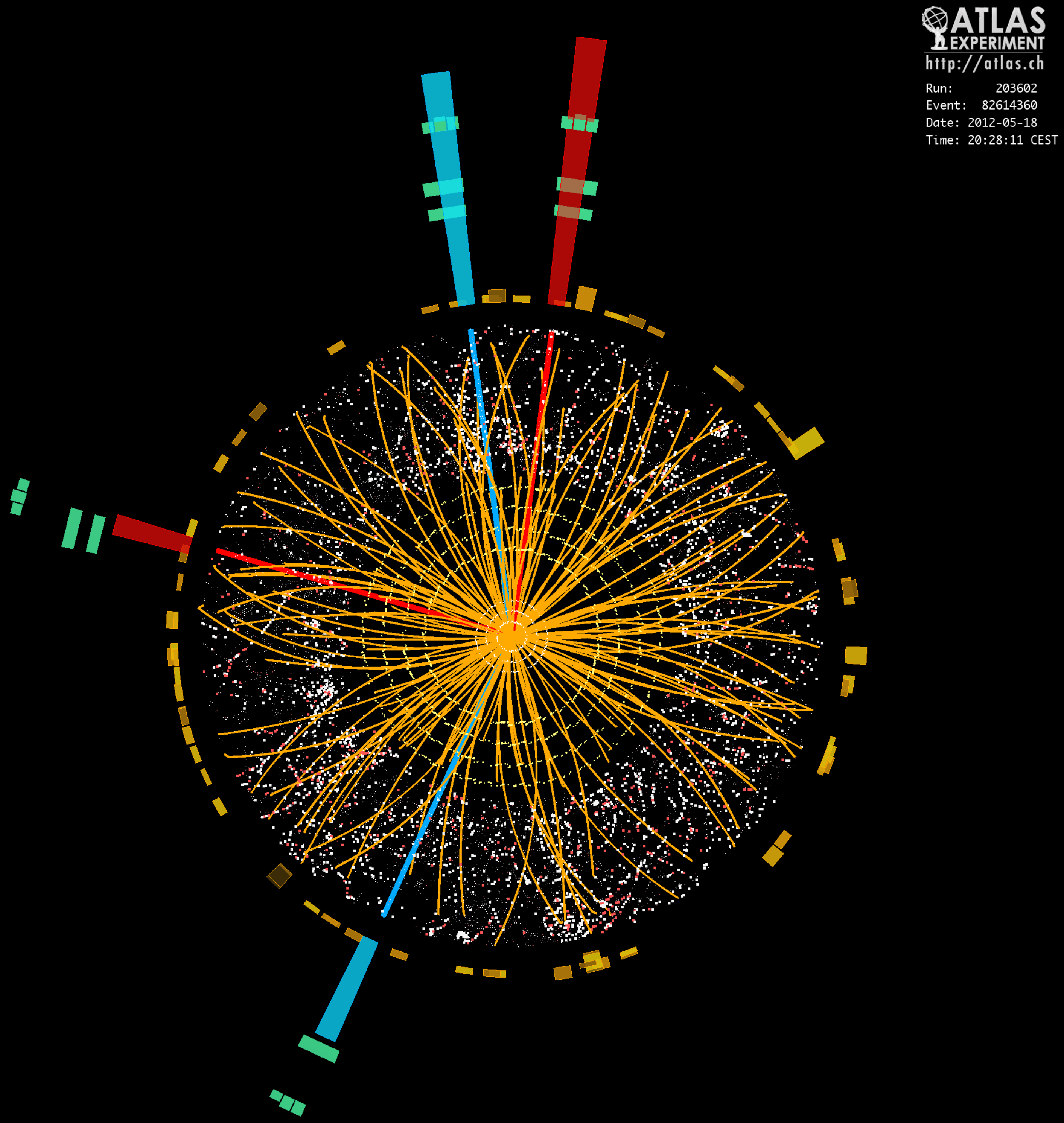
ATLAS EXPERIMENT

Run Number 158466, Event Number 4174272
Date: 2010-07-02 17:49:13 CEST





http://www.atlas.ch/



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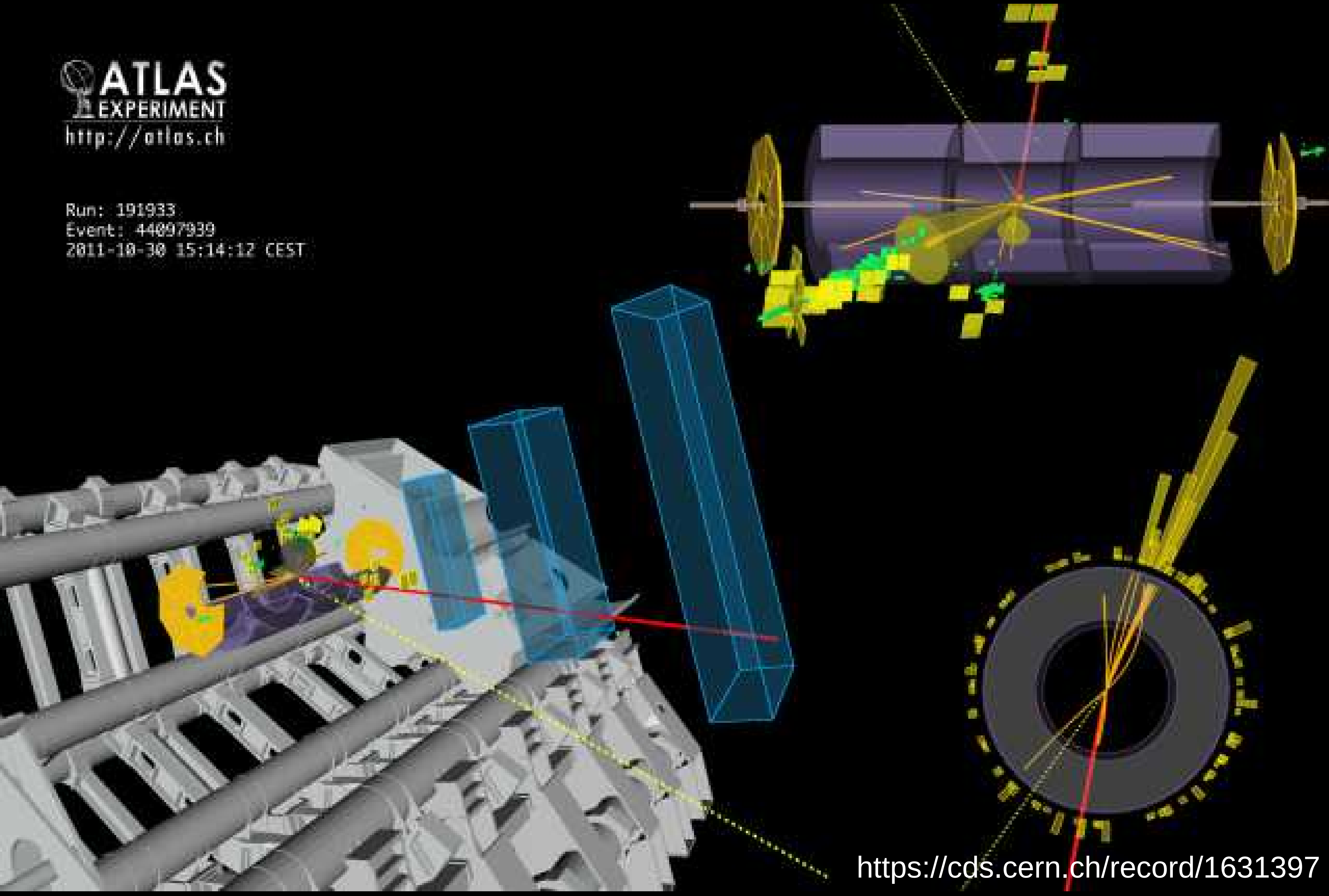


https://cds.cern.ch/record/1631397

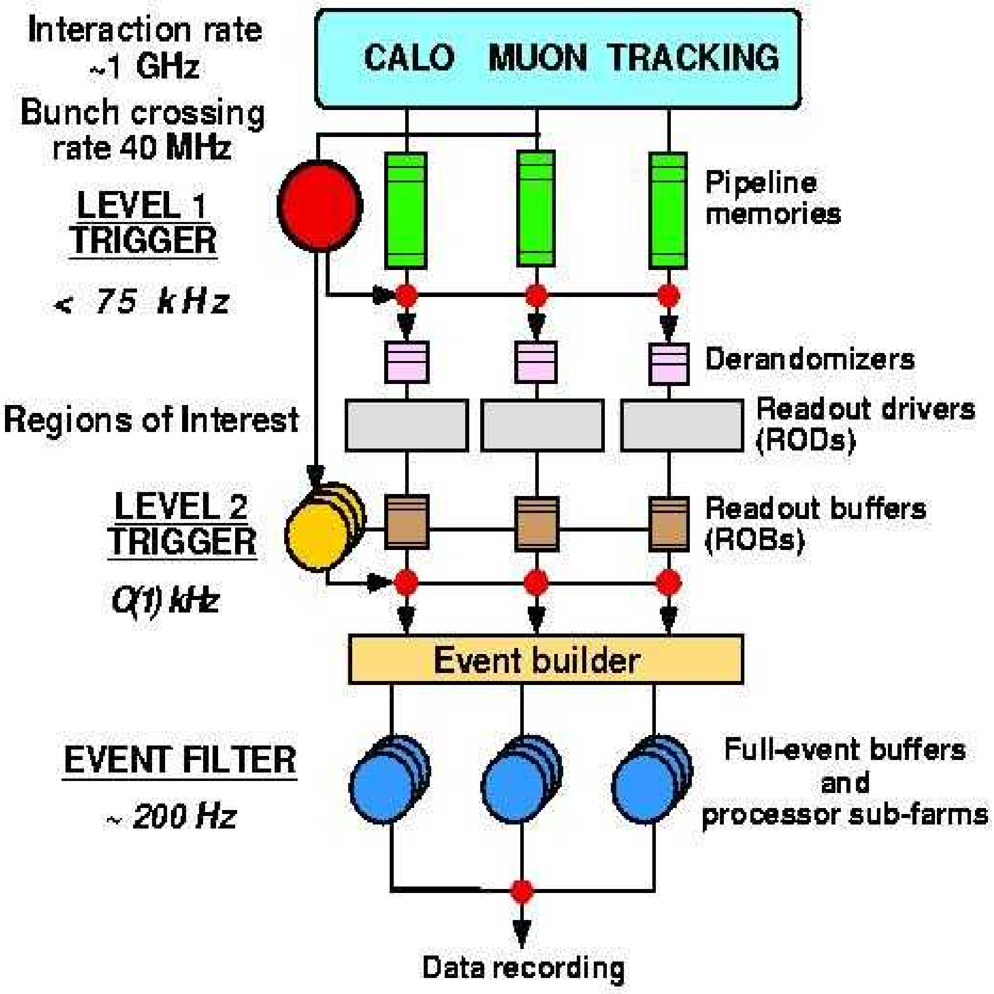
People are not good at this.

(so we don't identify collision signatures by hand.)

ATLAS Control Room on a normal day

ATLAS Control Room on an exciting day (first 7 TeV collisions)

The ATLAS Trigger System



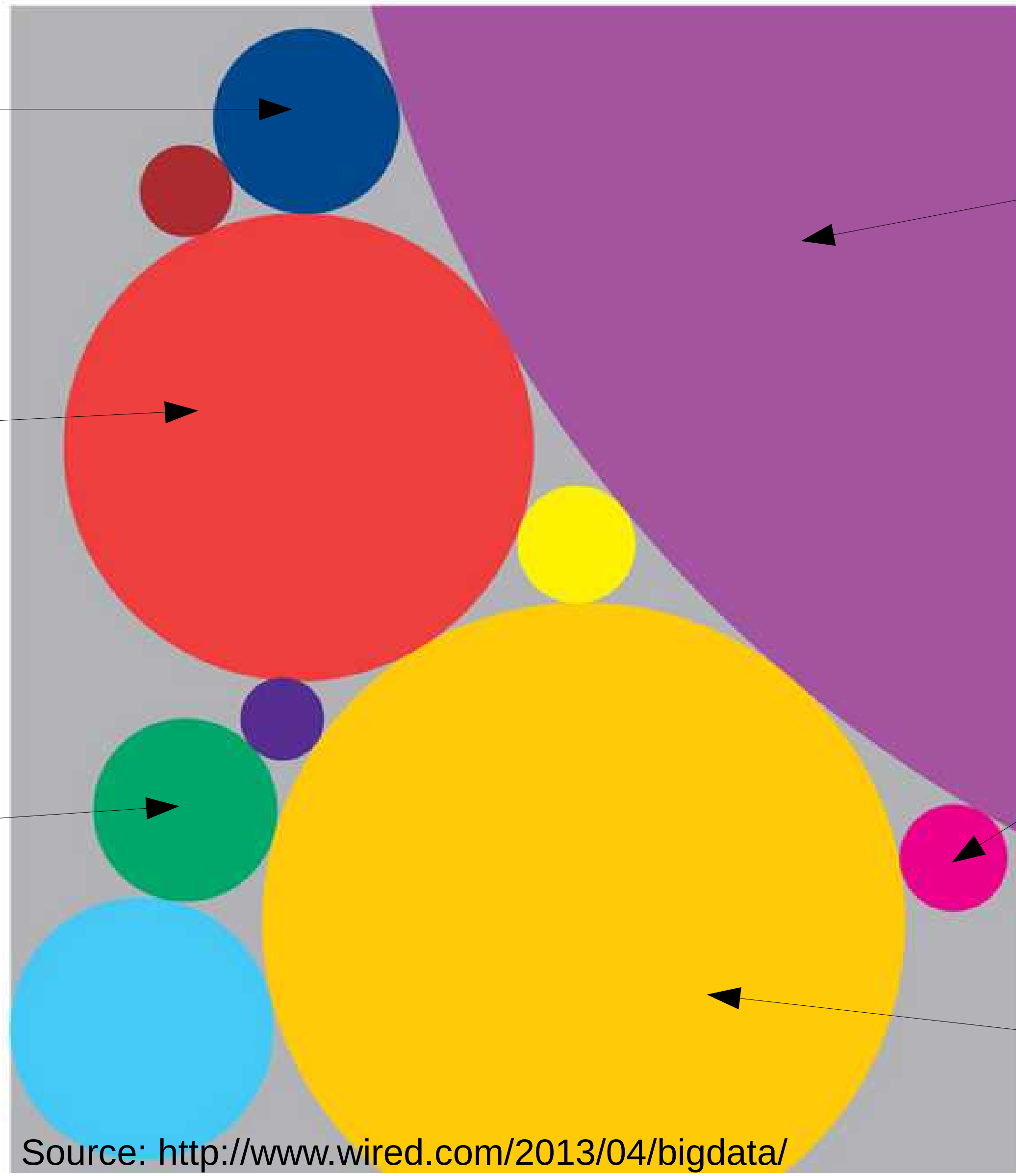
- Use event topology to save "interesting" events
- Reduce from interaction rate (~ a billion / second) to the number of events we are able to save (a few hundred / second)

“Big Data” – an aside

LHC's annual data output
(15,360 terabytes)

Google's search index

Videos uploaded to YouTube each year

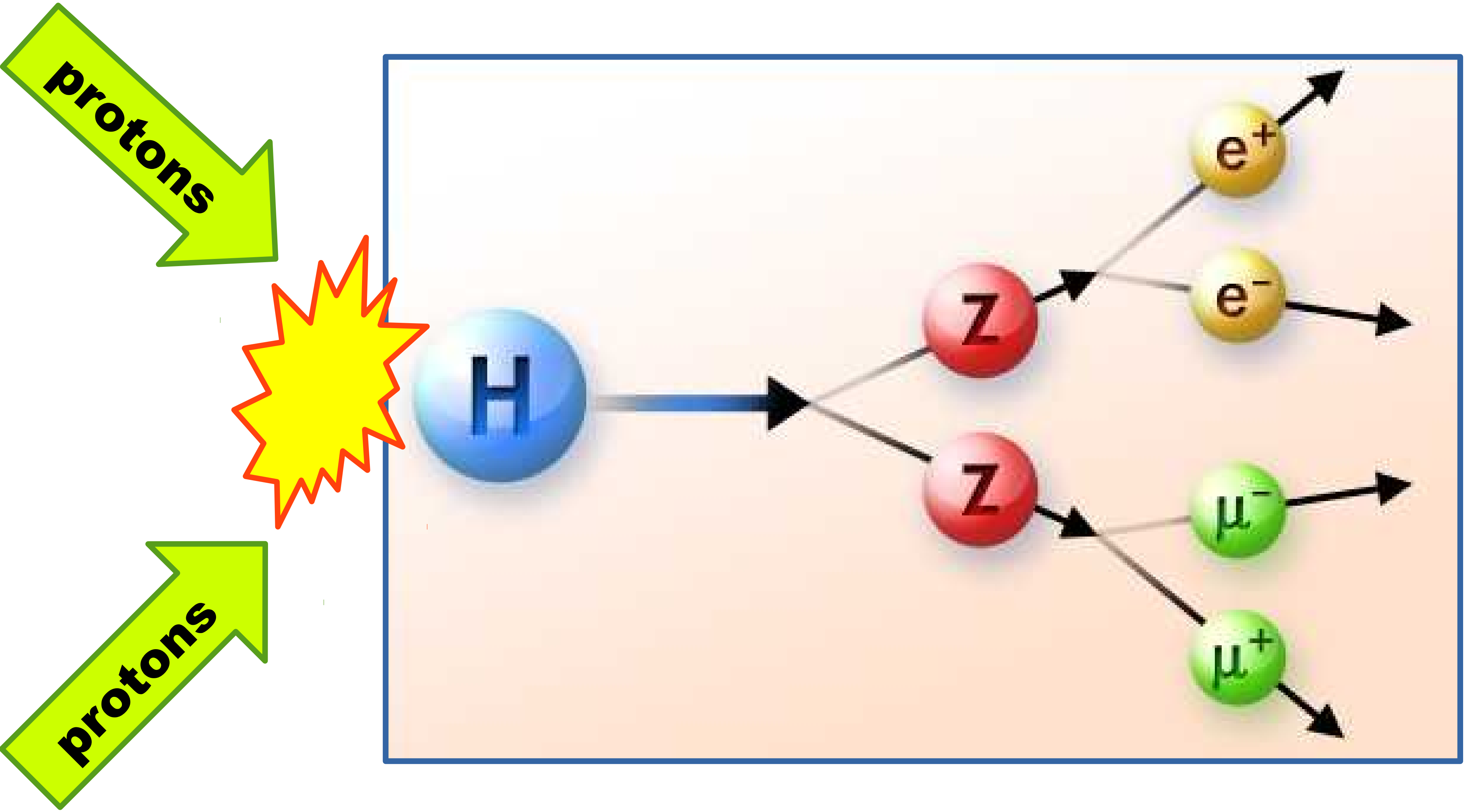


Business emails sent each year

Library of Congress' digital collection

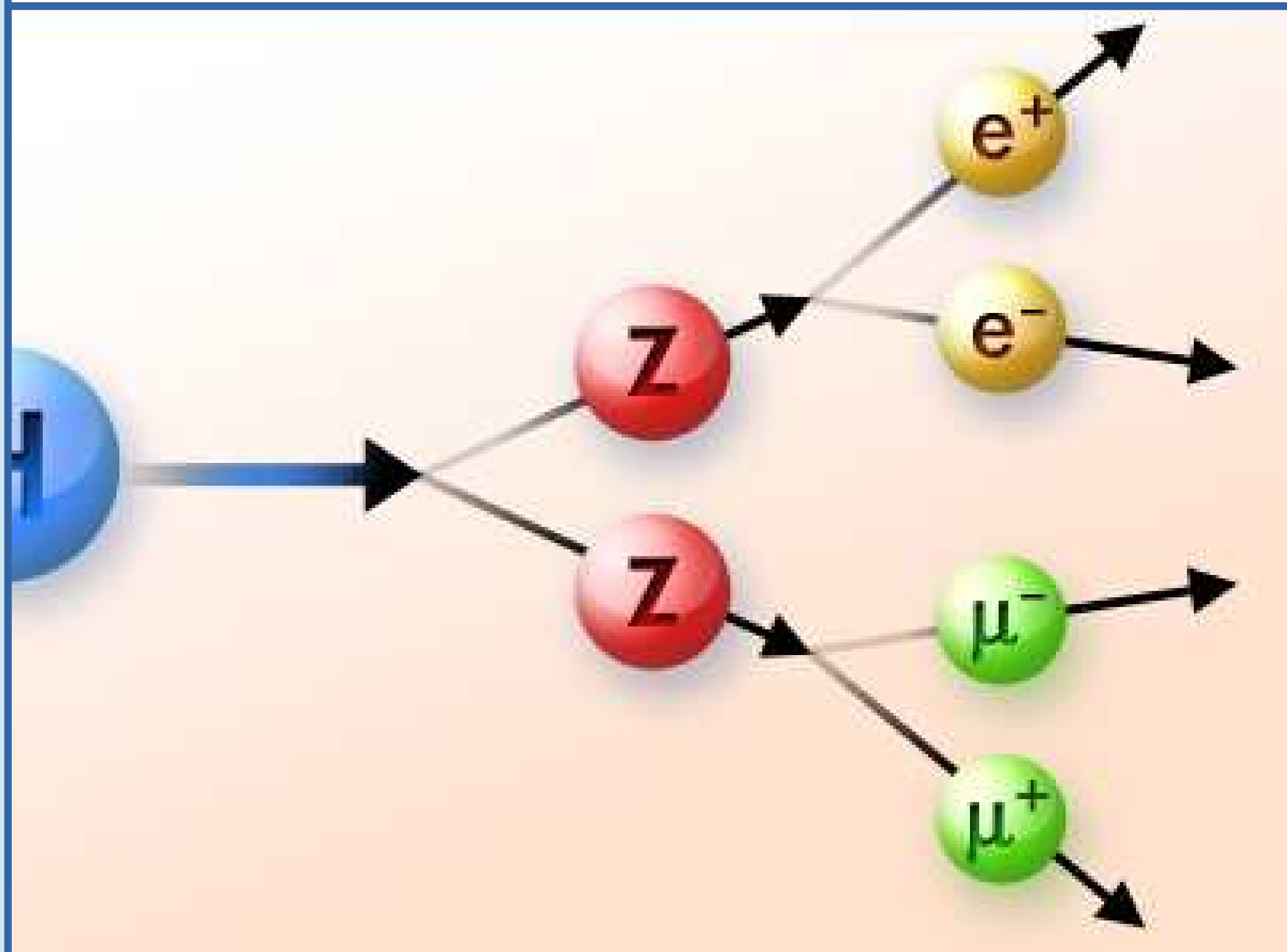
Content uploaded to Facebook each year

Now, back to the search.



Now, back to the search.

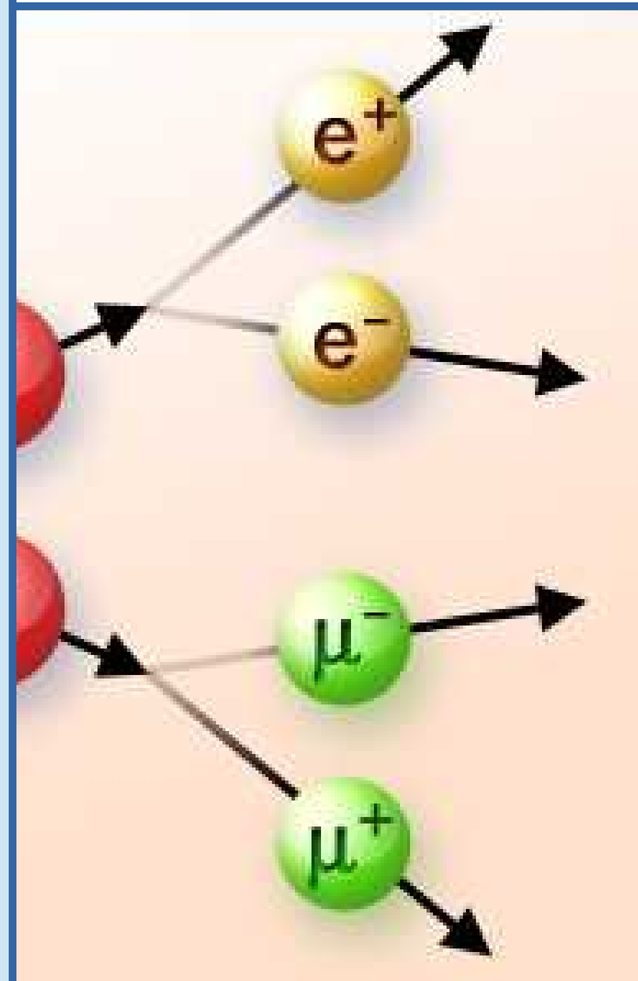
Protons: collided



Now, back to the search.

Protons: collided

Higgs boson: produced



Now, back to the search.

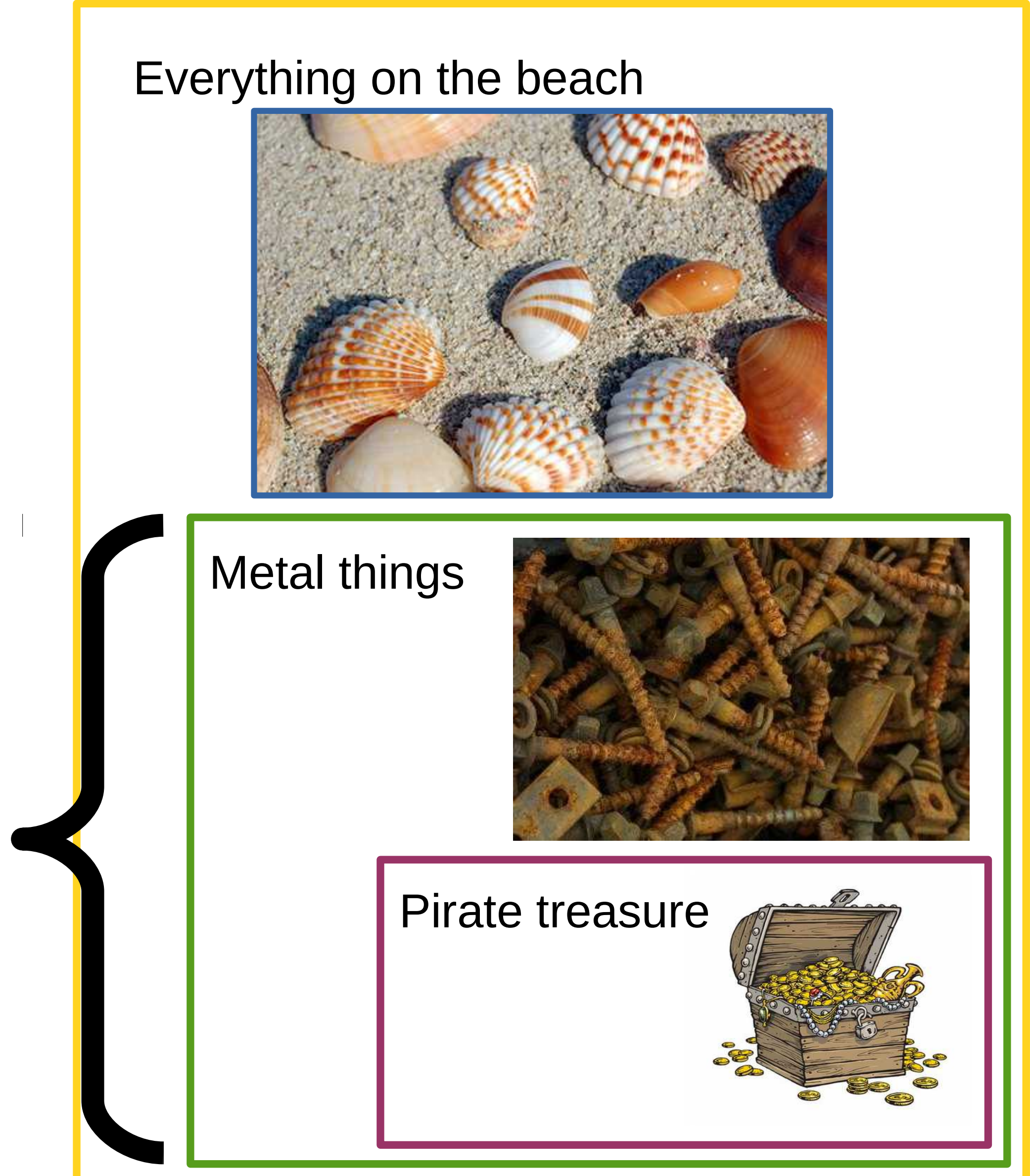
Protons:
collided

Higgs boson:
produced

4-lepton events:
collected by
ATLAS

Signal and Background: An Analogy

- Metal detector
- Search criteria:
  metal things
  - Signal = pirate treasure
  - Removes background like seashells (“reducible” background)
- Results: some treasure, some rusty metal
  - Rusty metal = “irreducible” background



Signal and Background (Higgs)

- Search criteria =

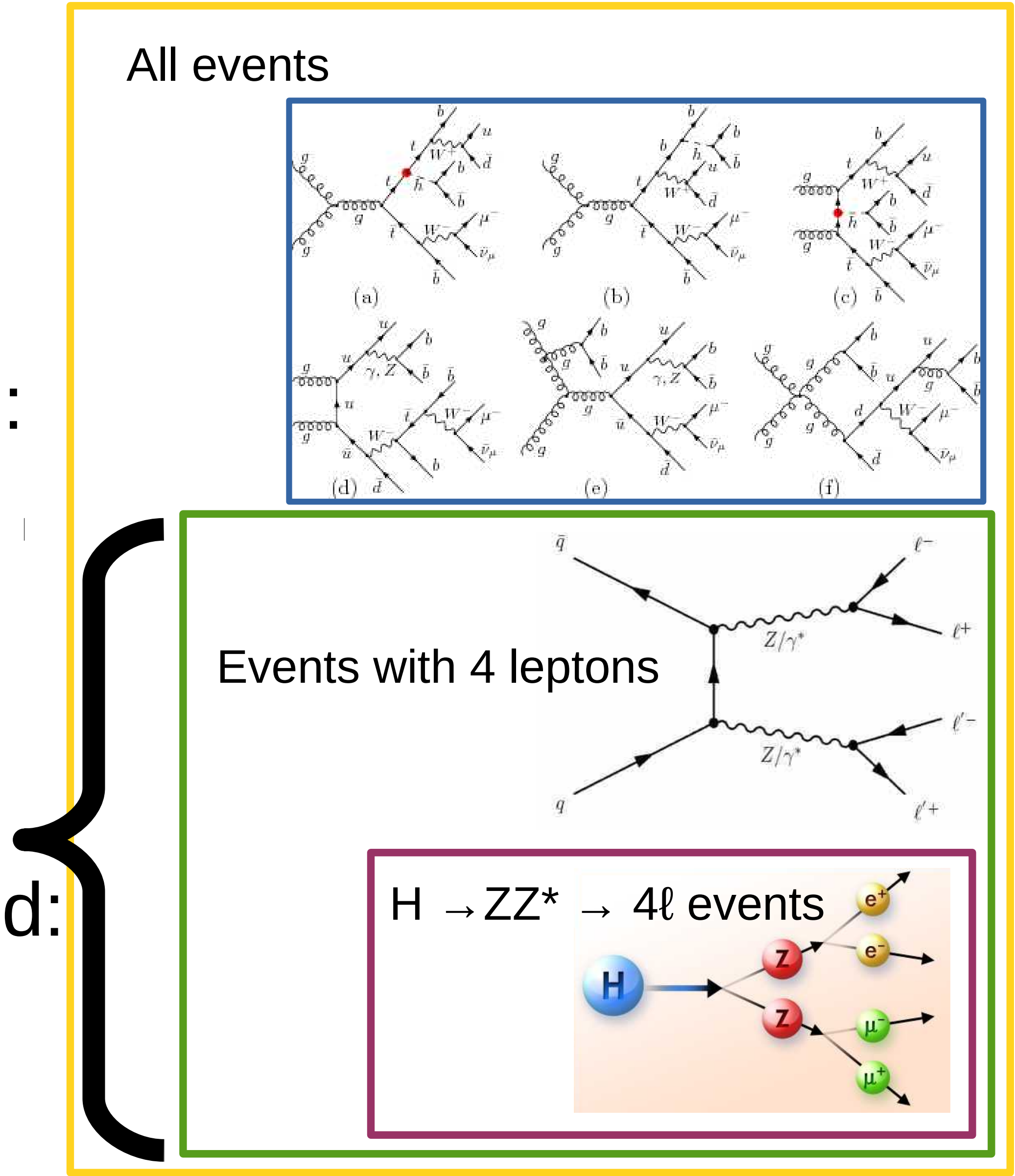
  4 leptons

  – Signal = H → ZZ* → 4ℓ

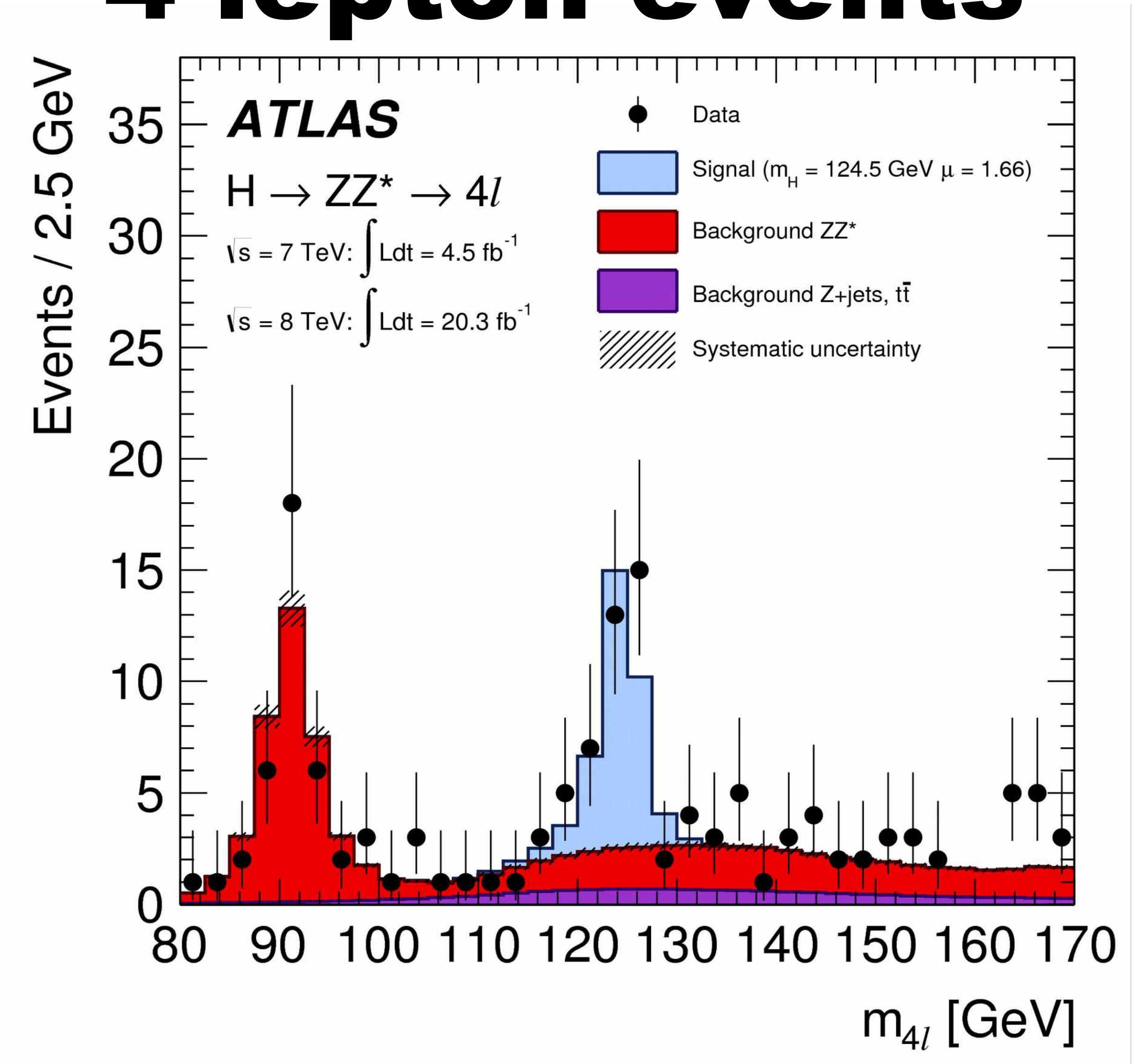
  – “reducible” background: 3-lepton events, etc.

- Results: 4-lepton events, some from Higgs decay

  – “irreducible” background: pp → ZZ → 4ℓ

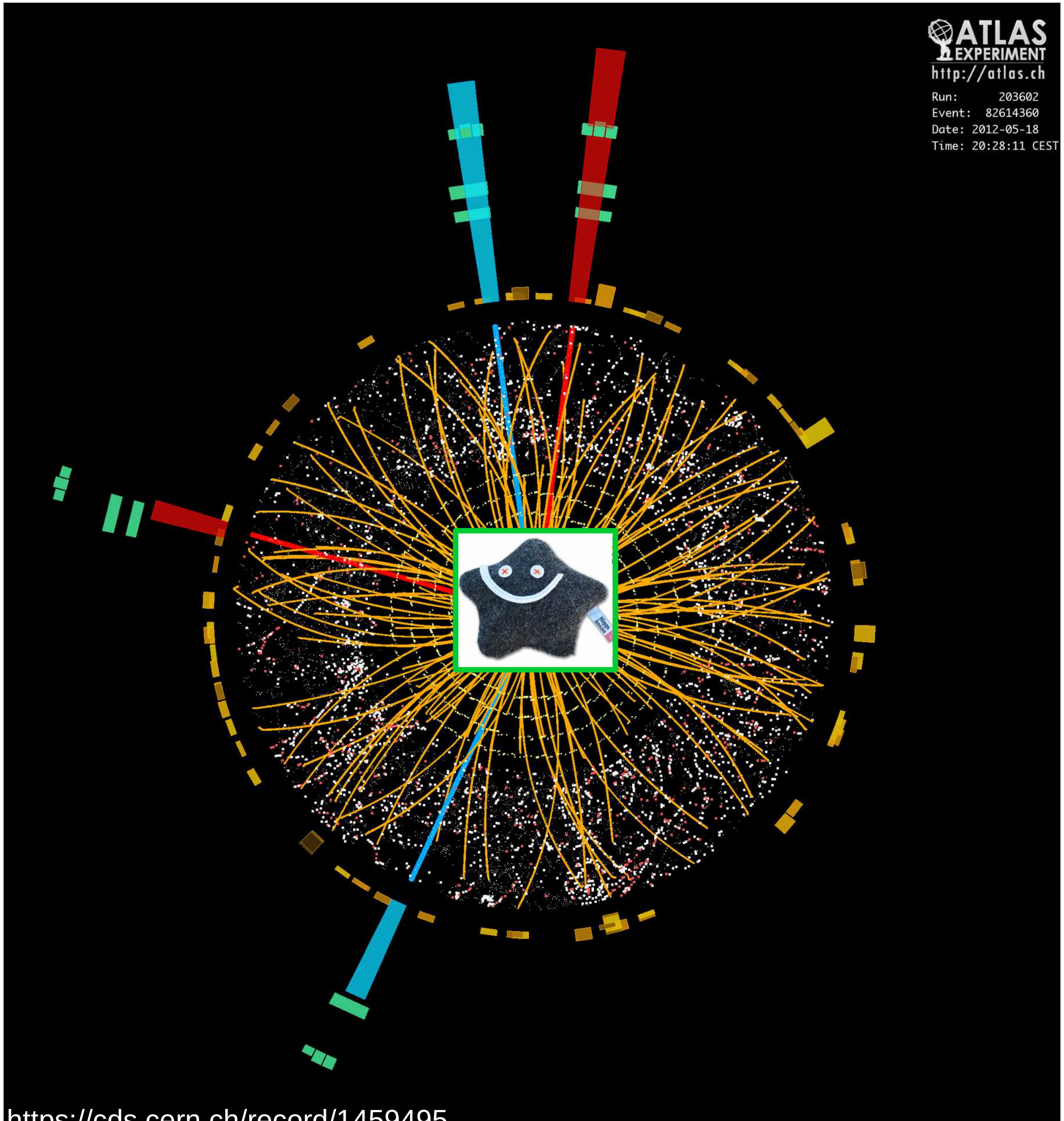


Now: plot the invariant mass of 4-lepton events



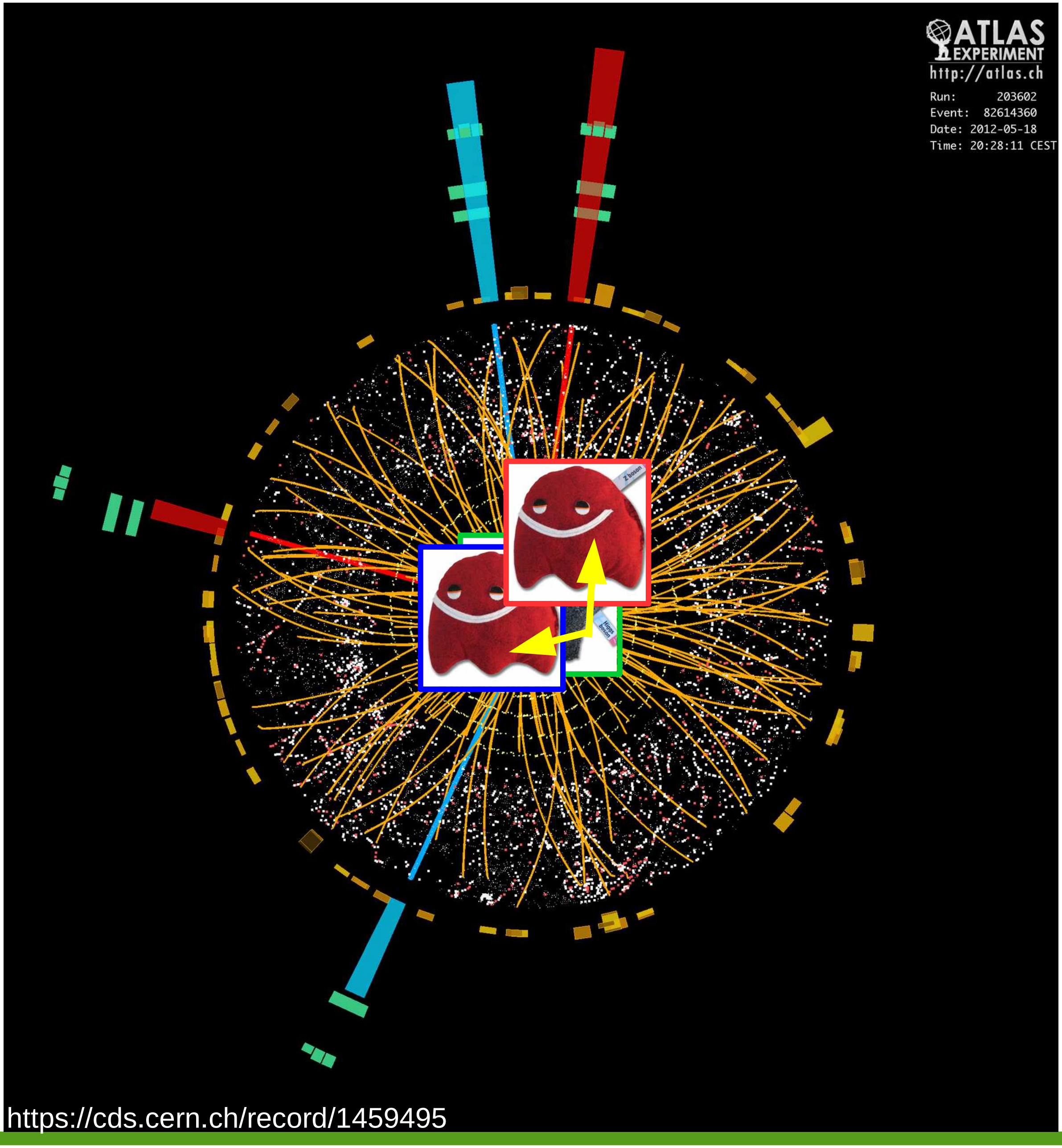
ATLAS Collaboration, Phys. Rev. D 90, 052004 (2014)

Calculate Invariant Mass

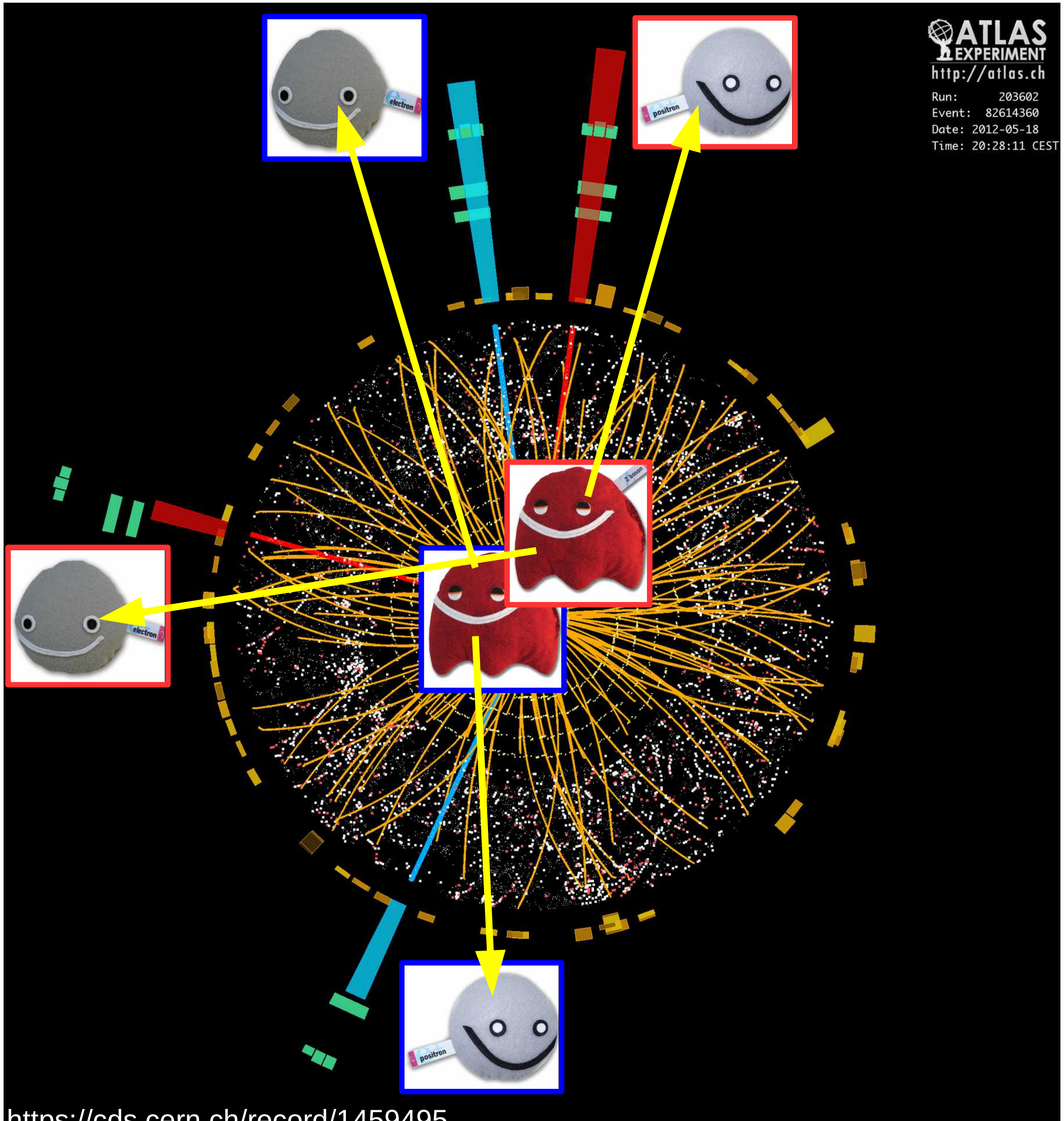


https://cds.cern.ch/record/1459495

Calculate Invariant Mass



Calculate Invariant Mass



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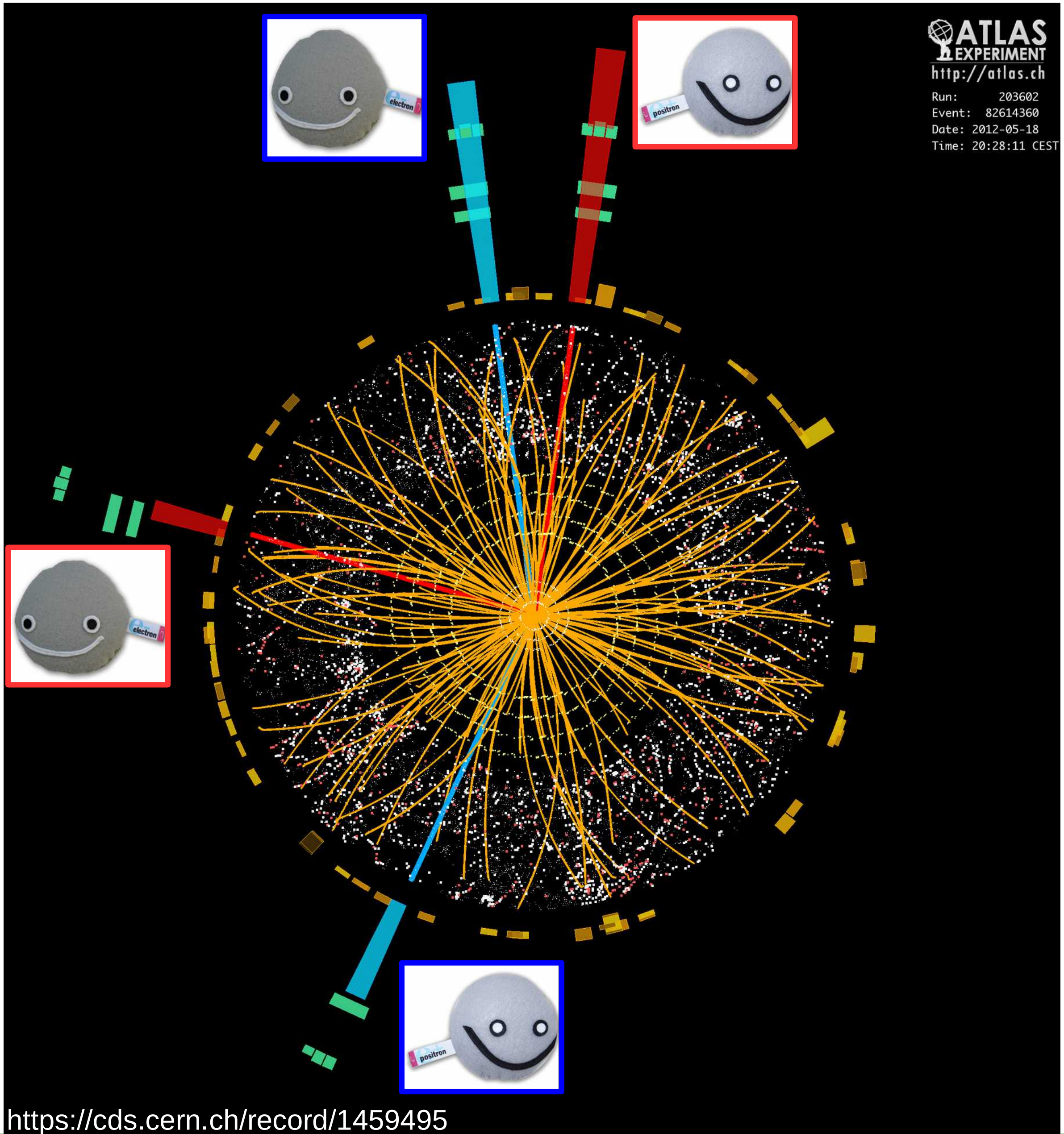

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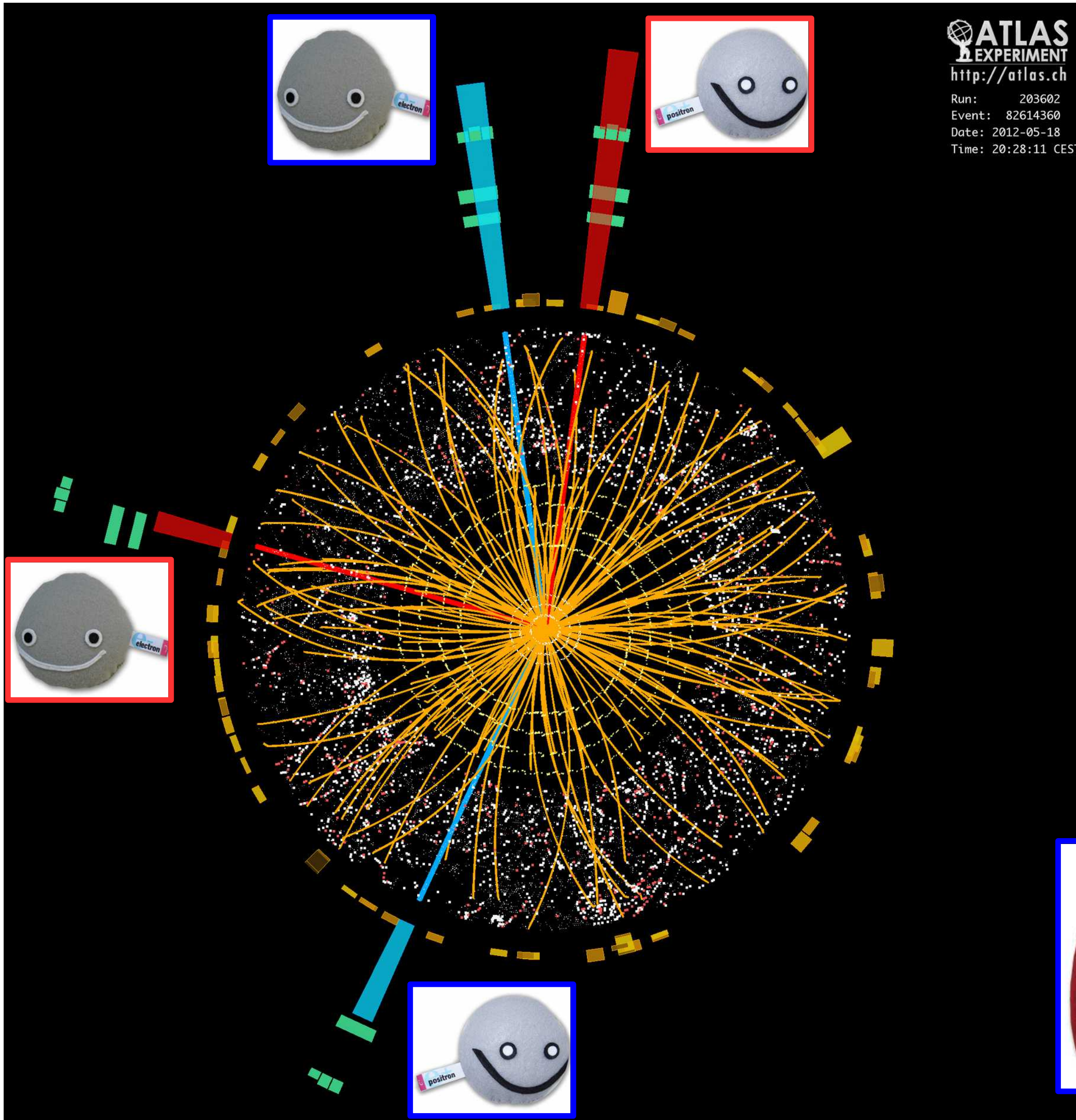
Calculate Invariant Mass



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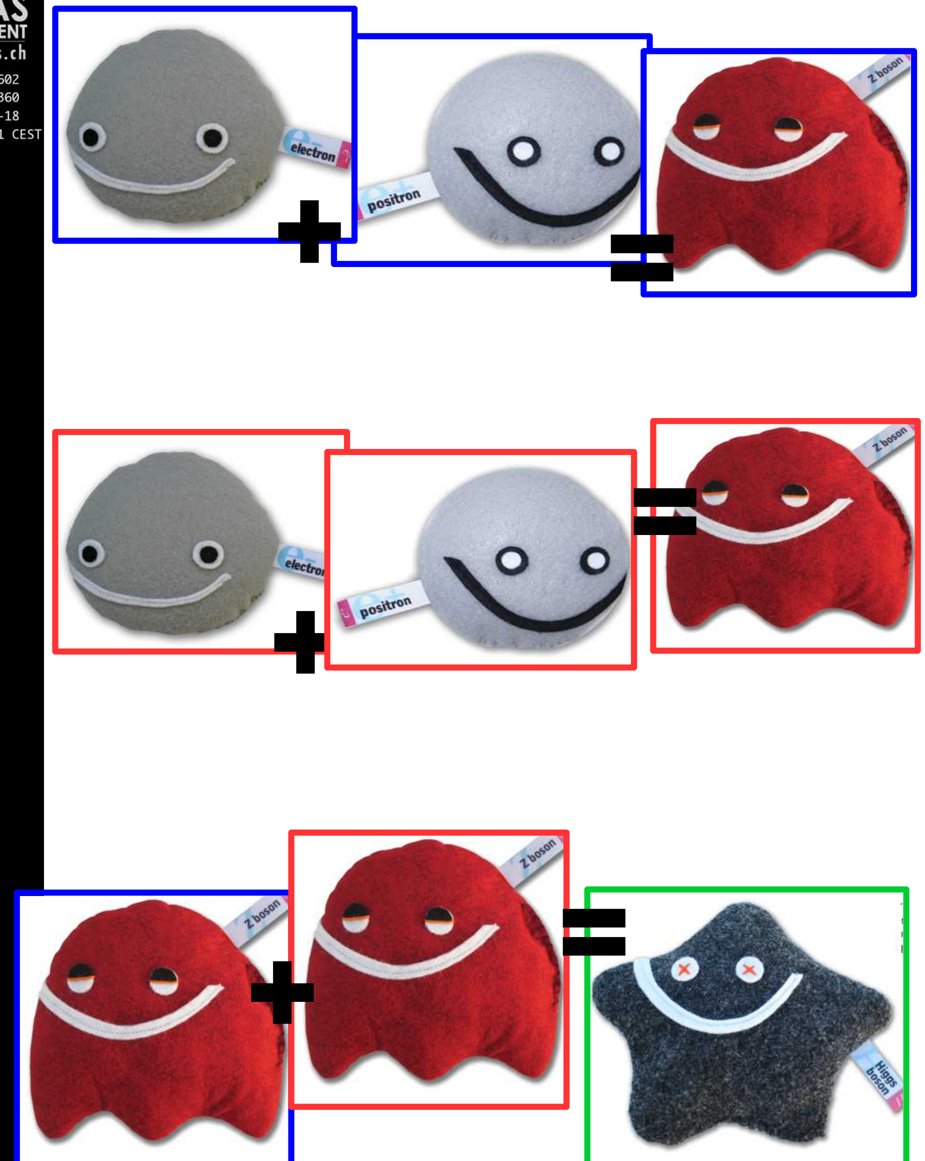
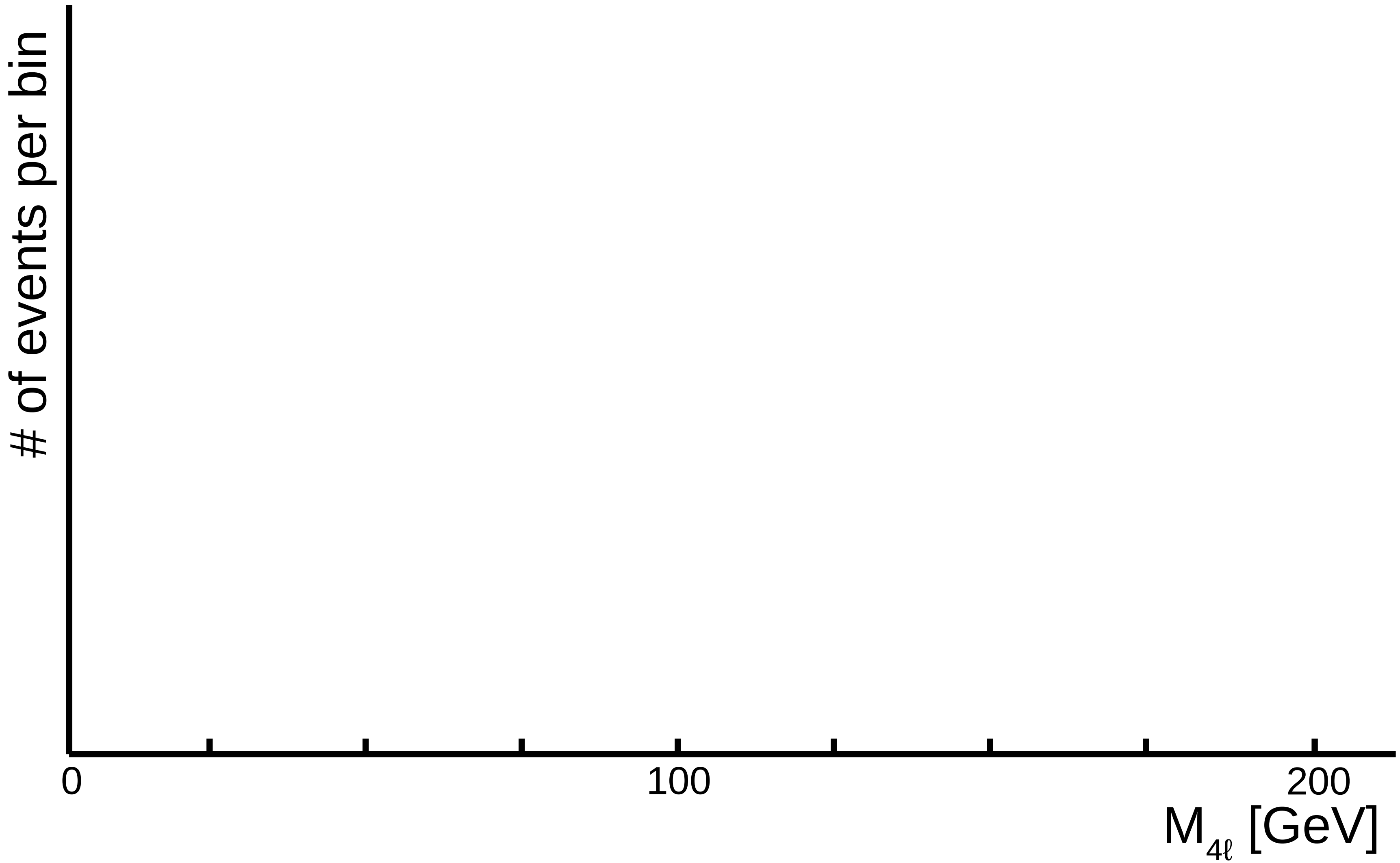


Now, we can plot the measured 4ℓ invariant mass:



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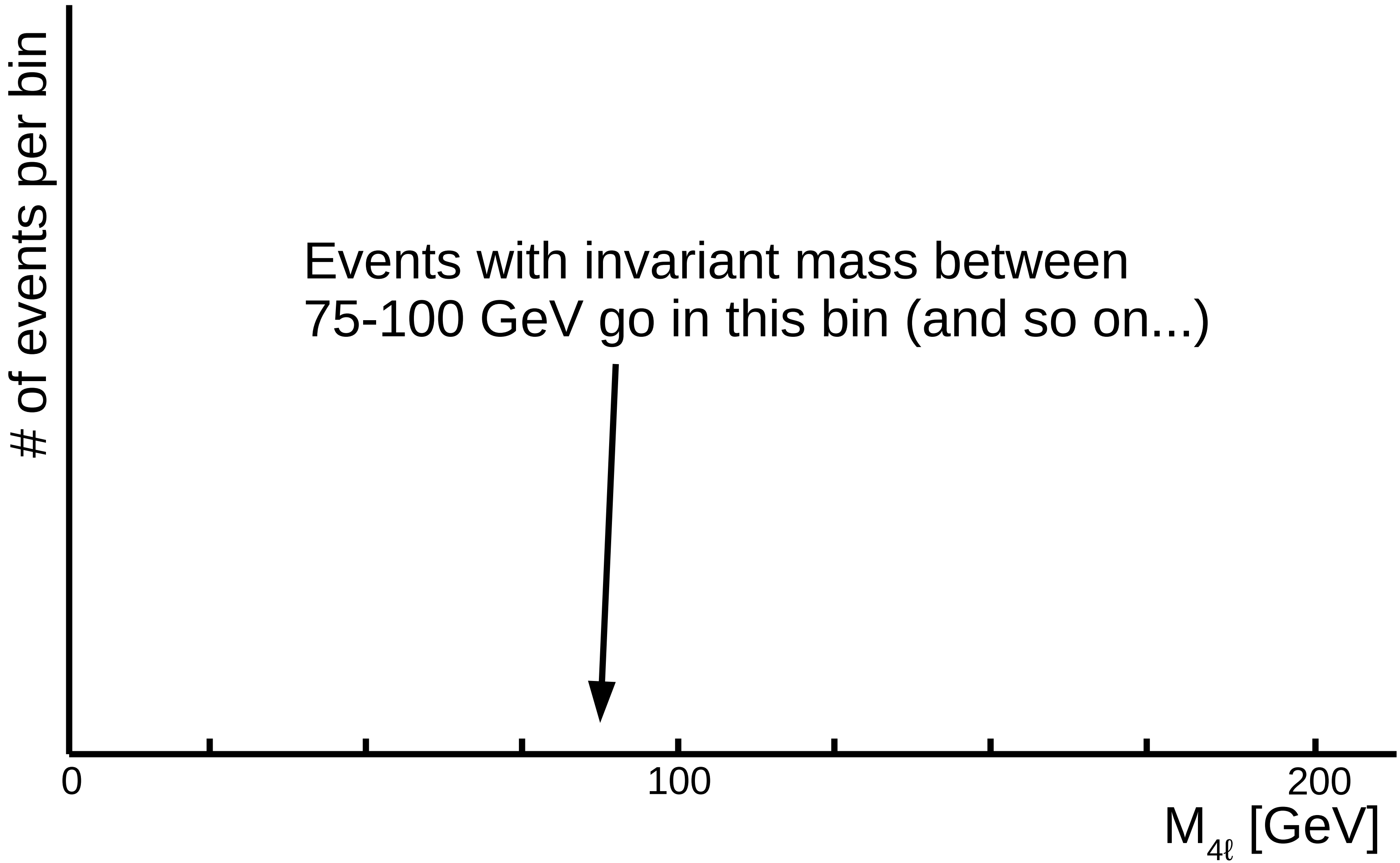

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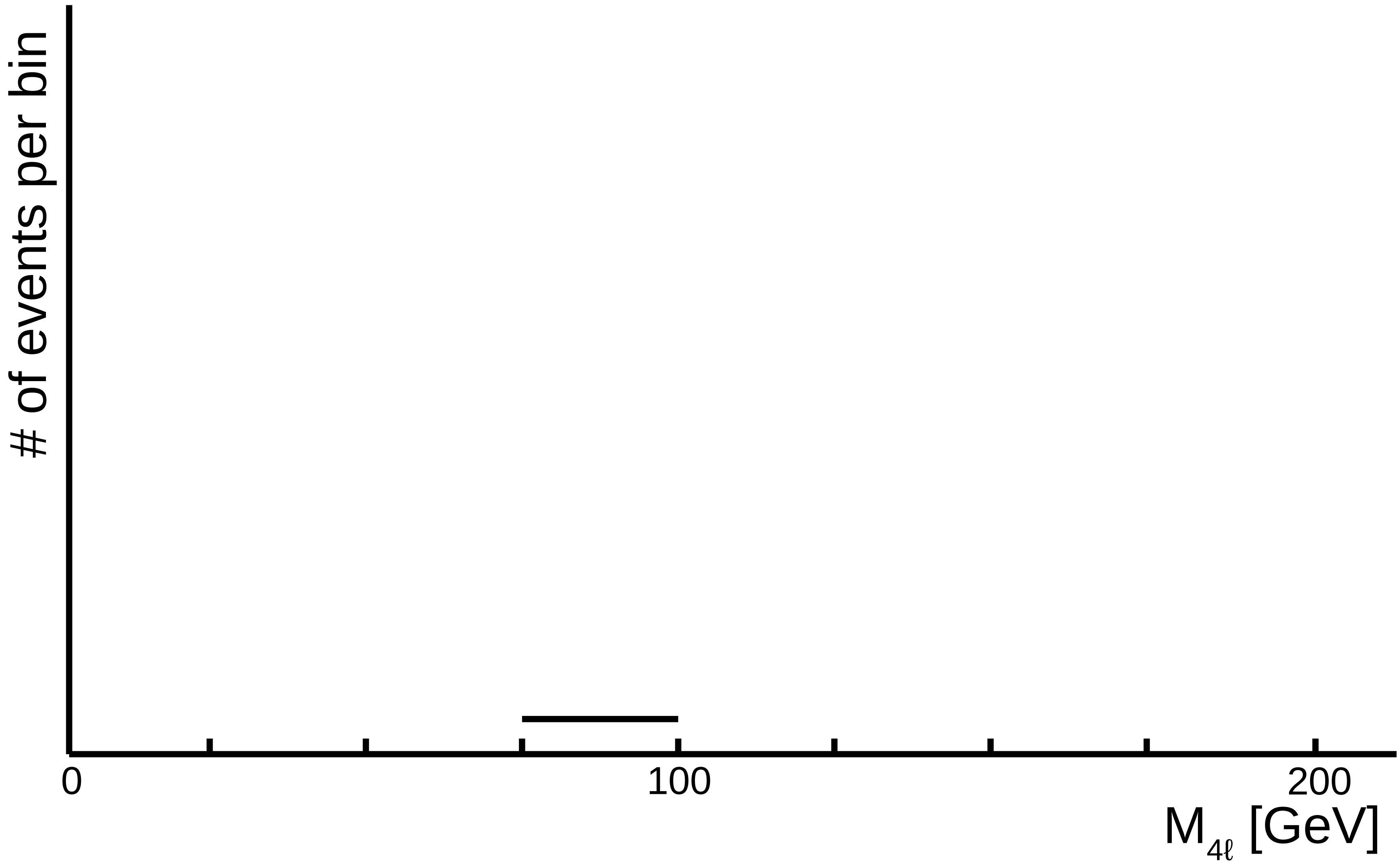

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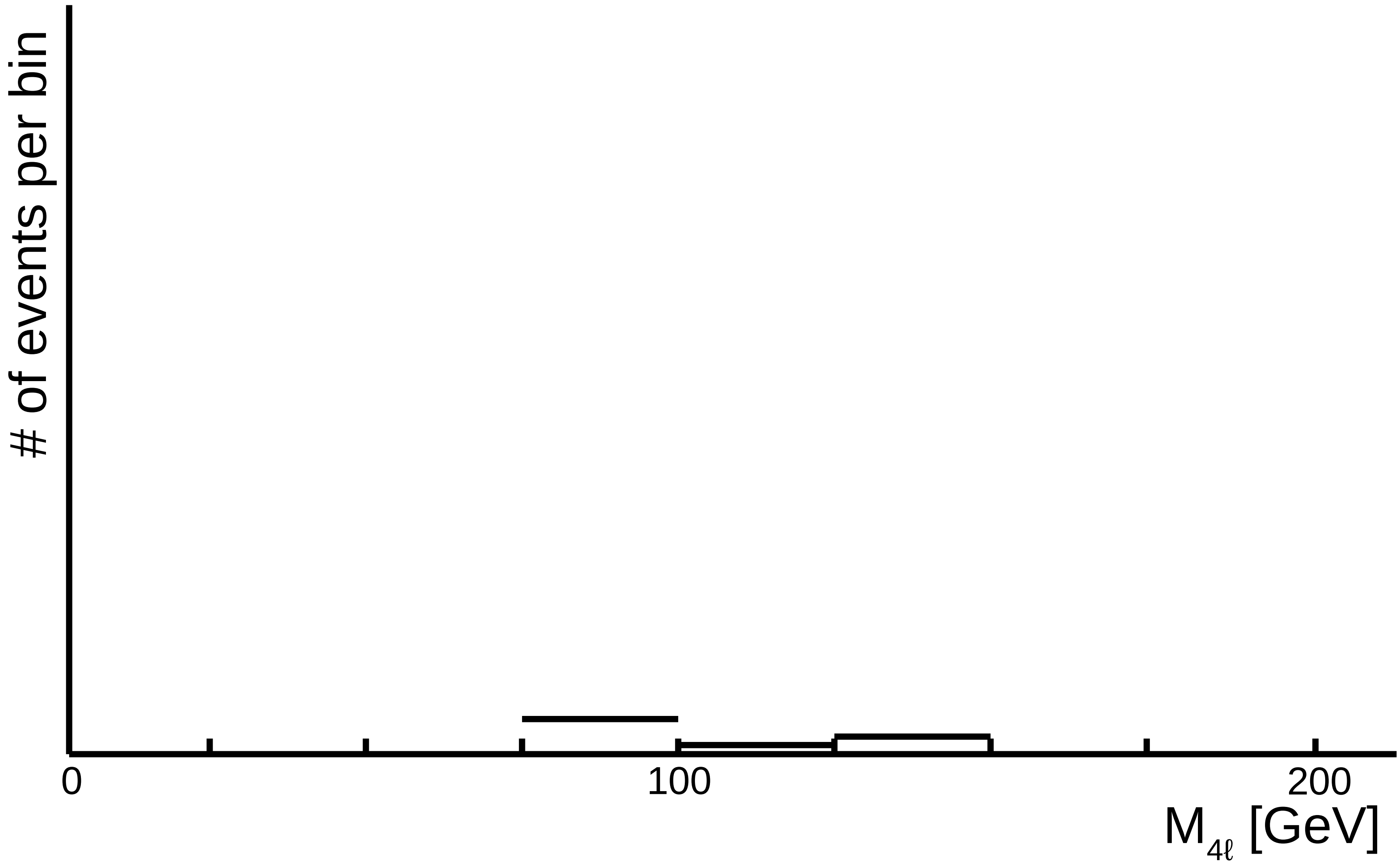

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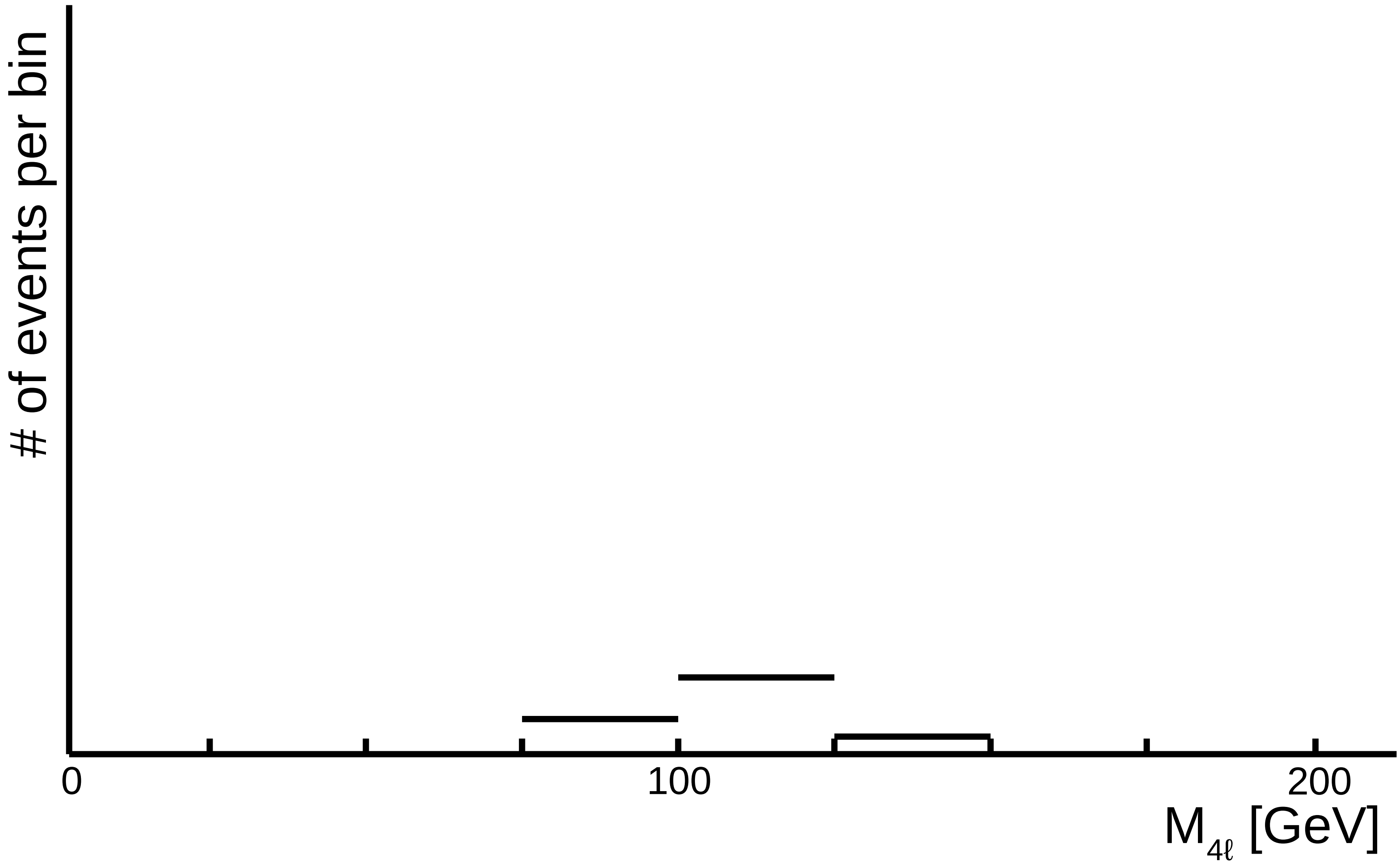

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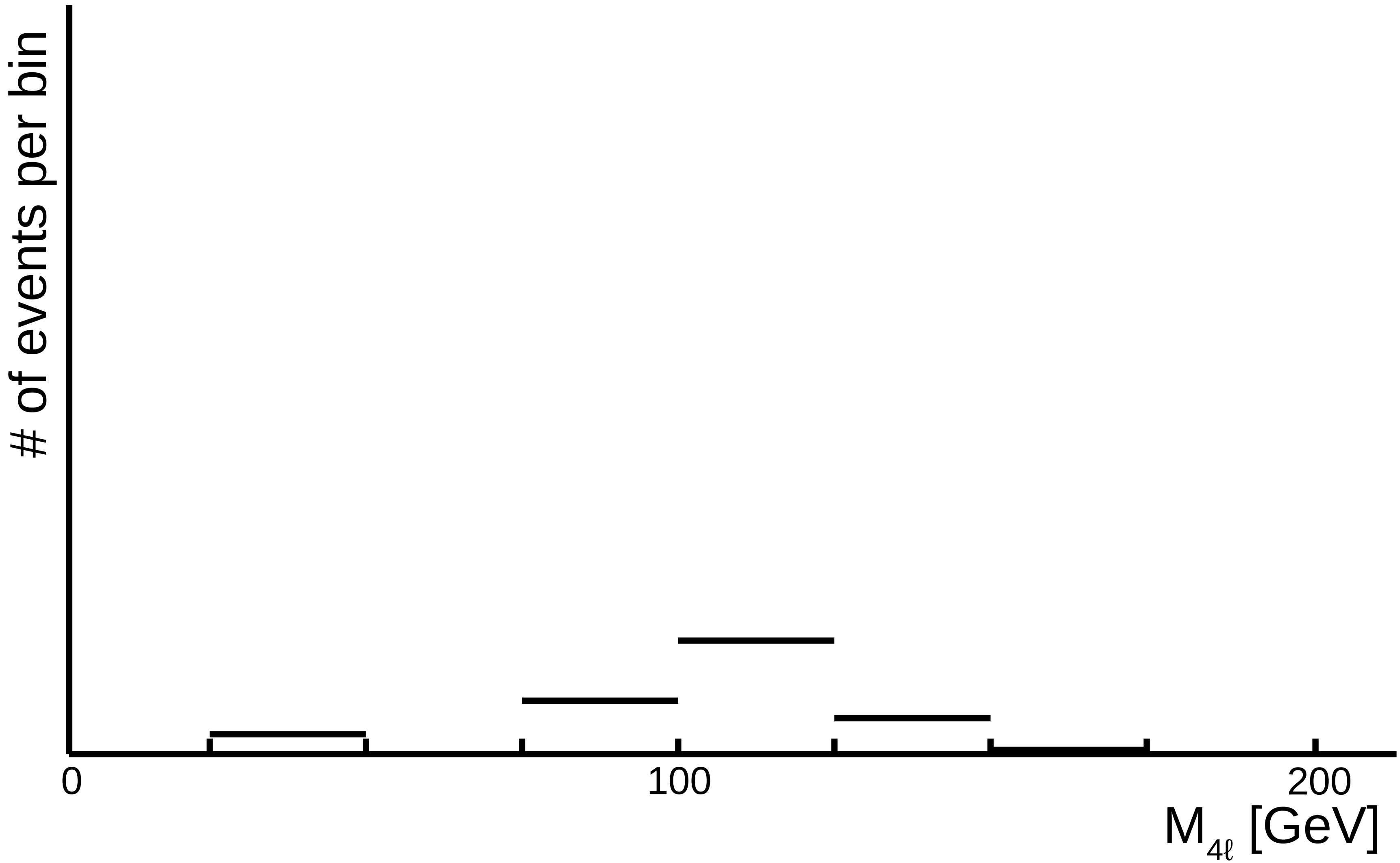

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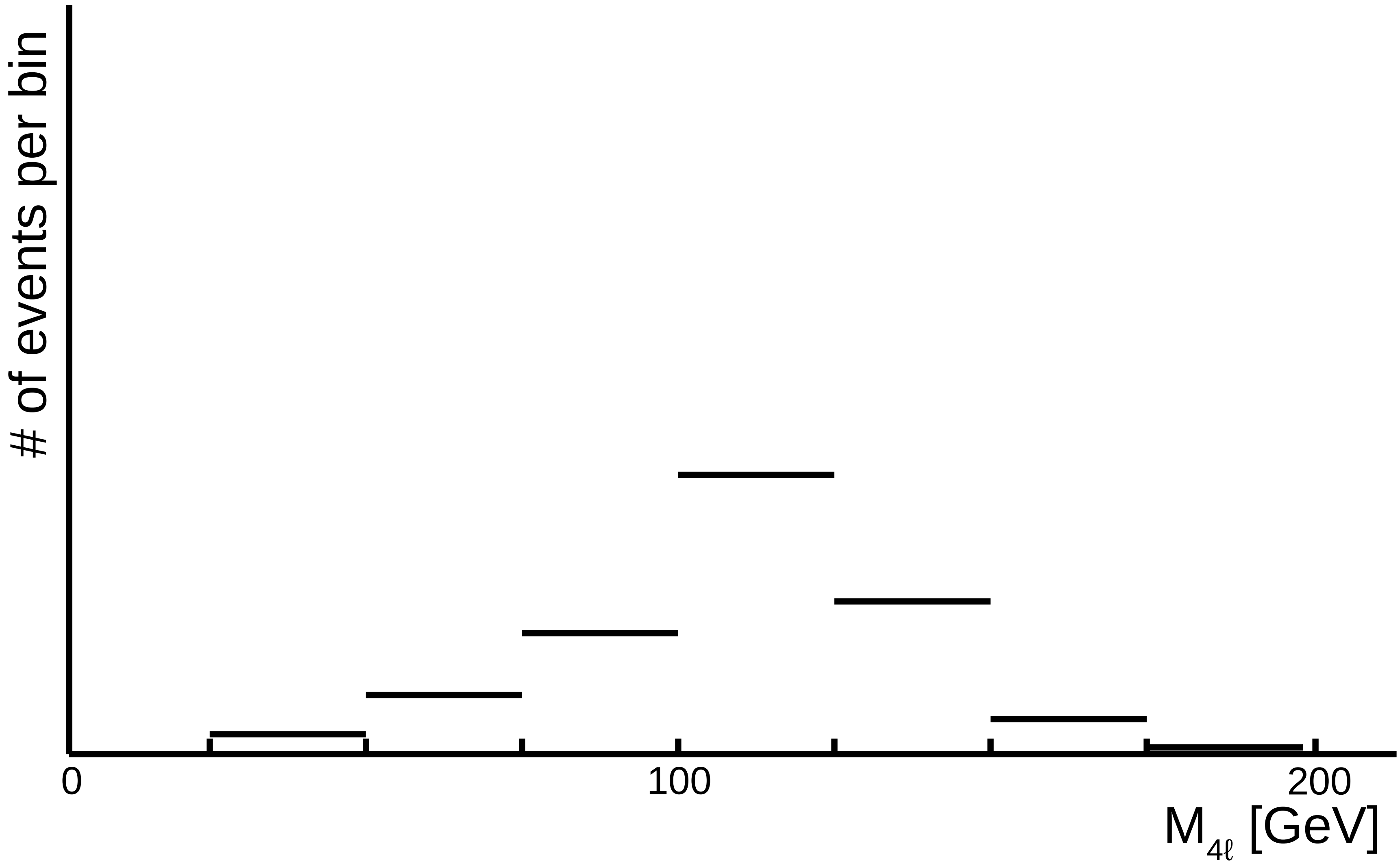

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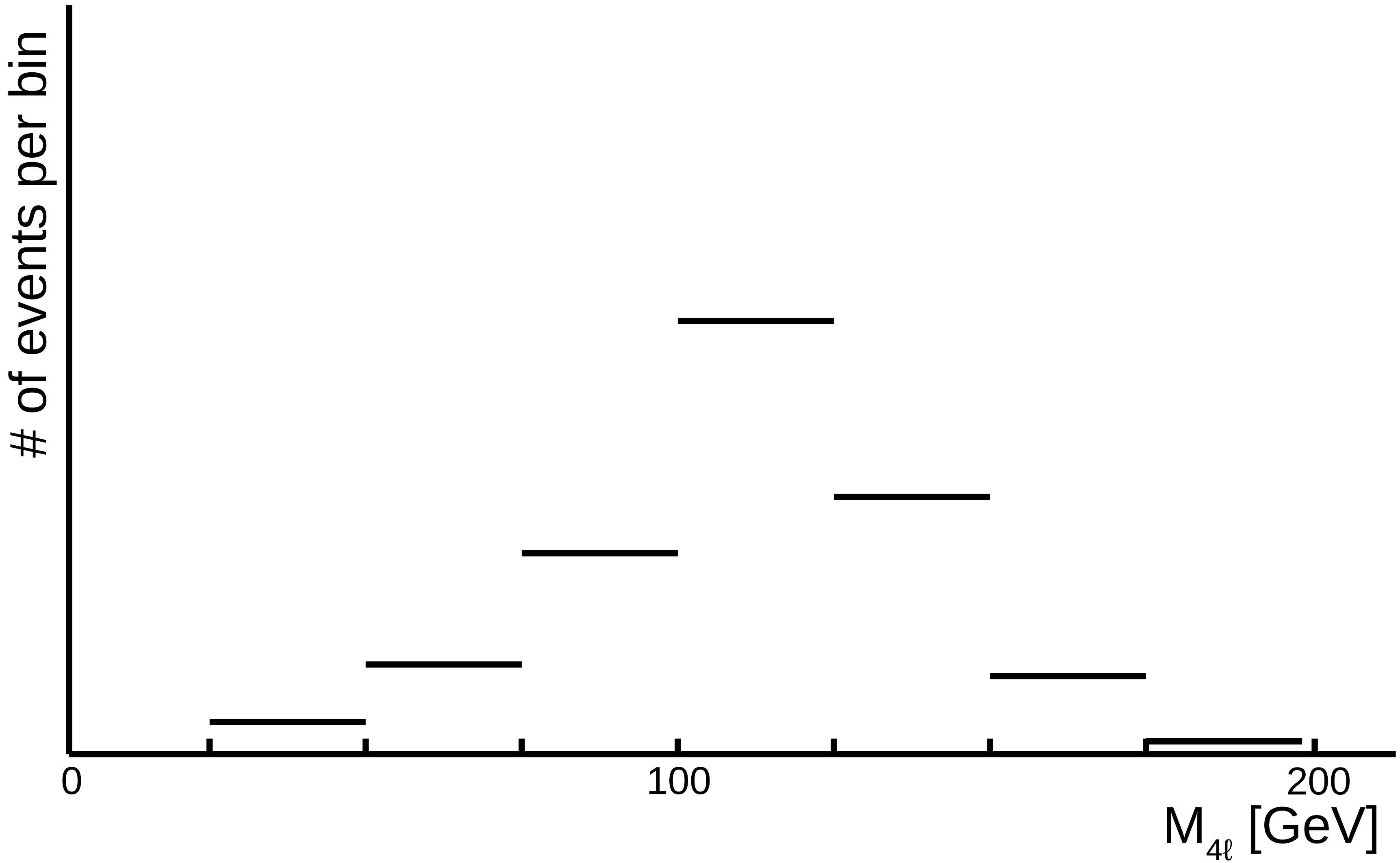
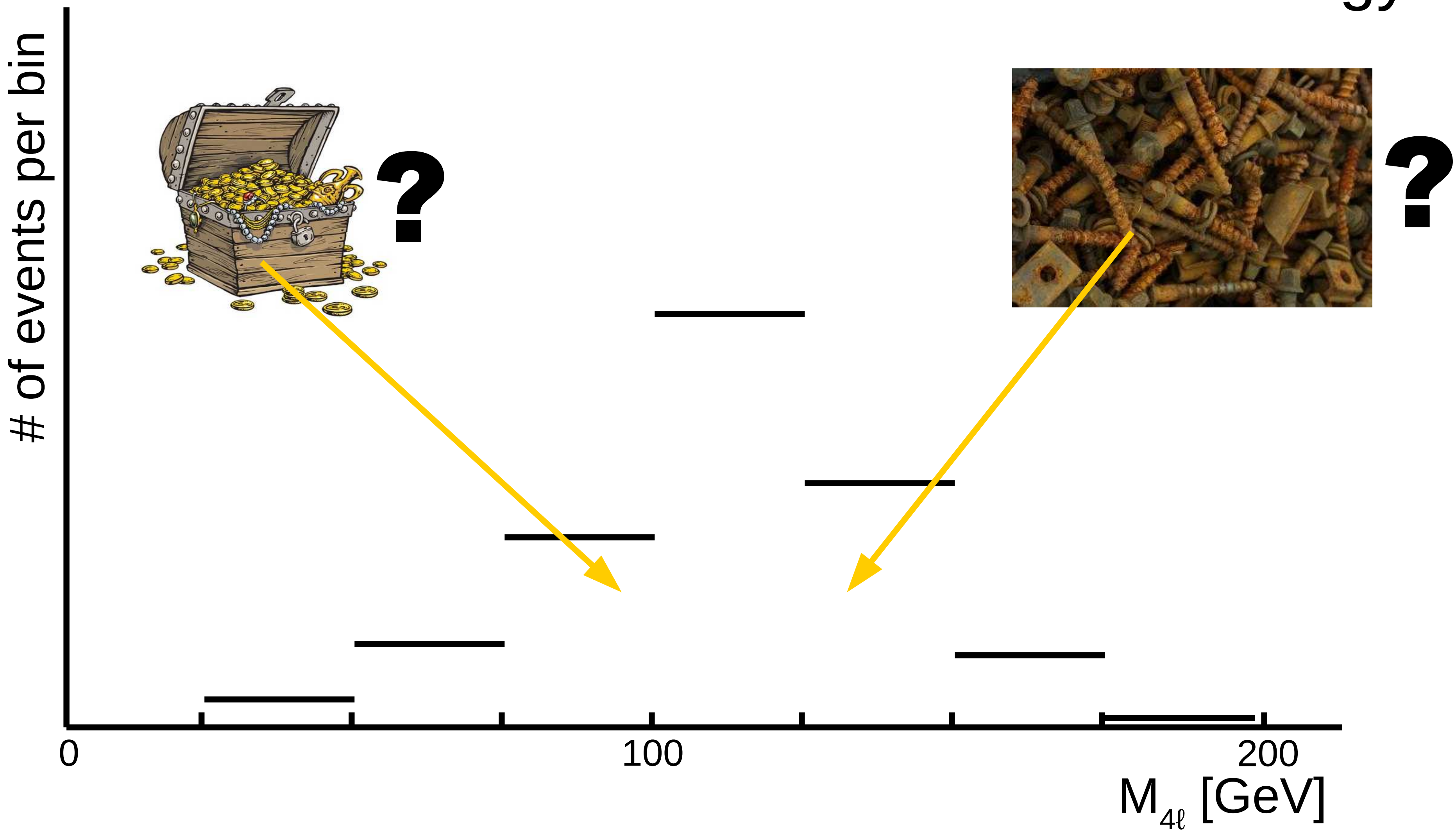
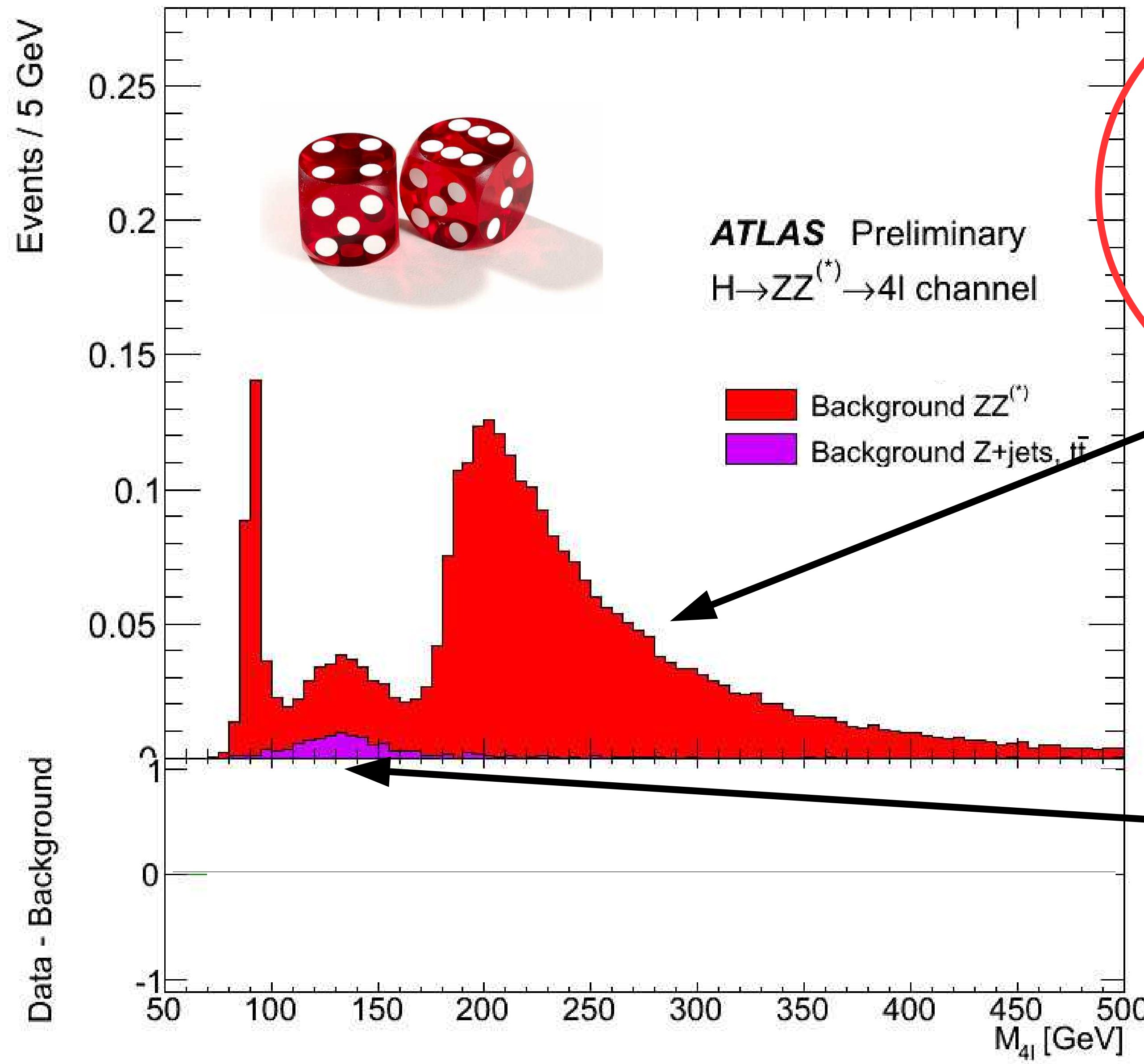


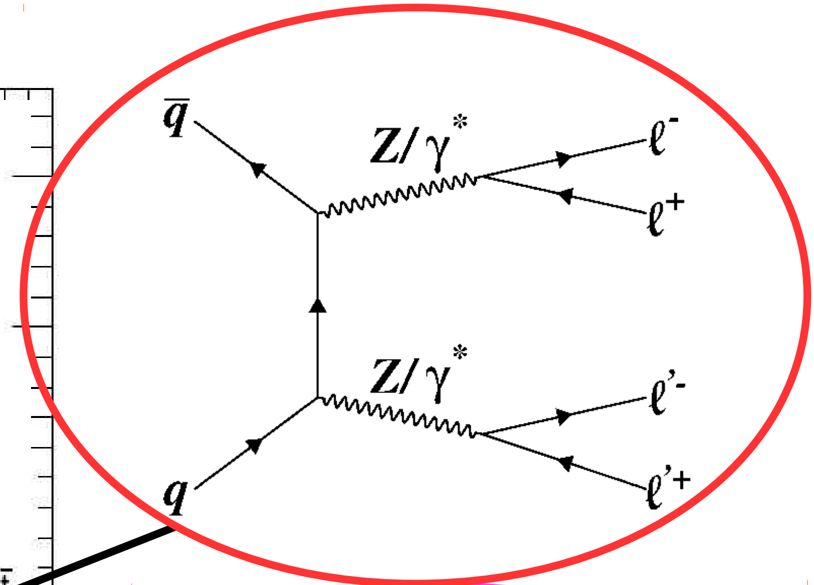
Now the question is: How many of these are Higgs events, and how many are “background”?

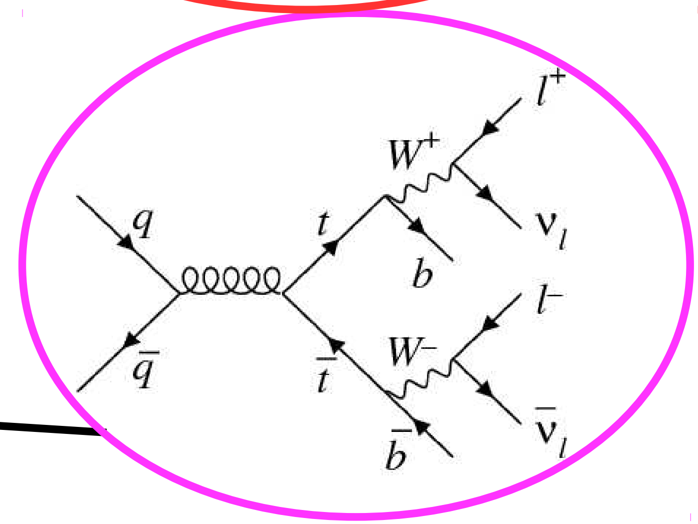
→ Recall the beach / metal detector analogy



Simulated Background Events





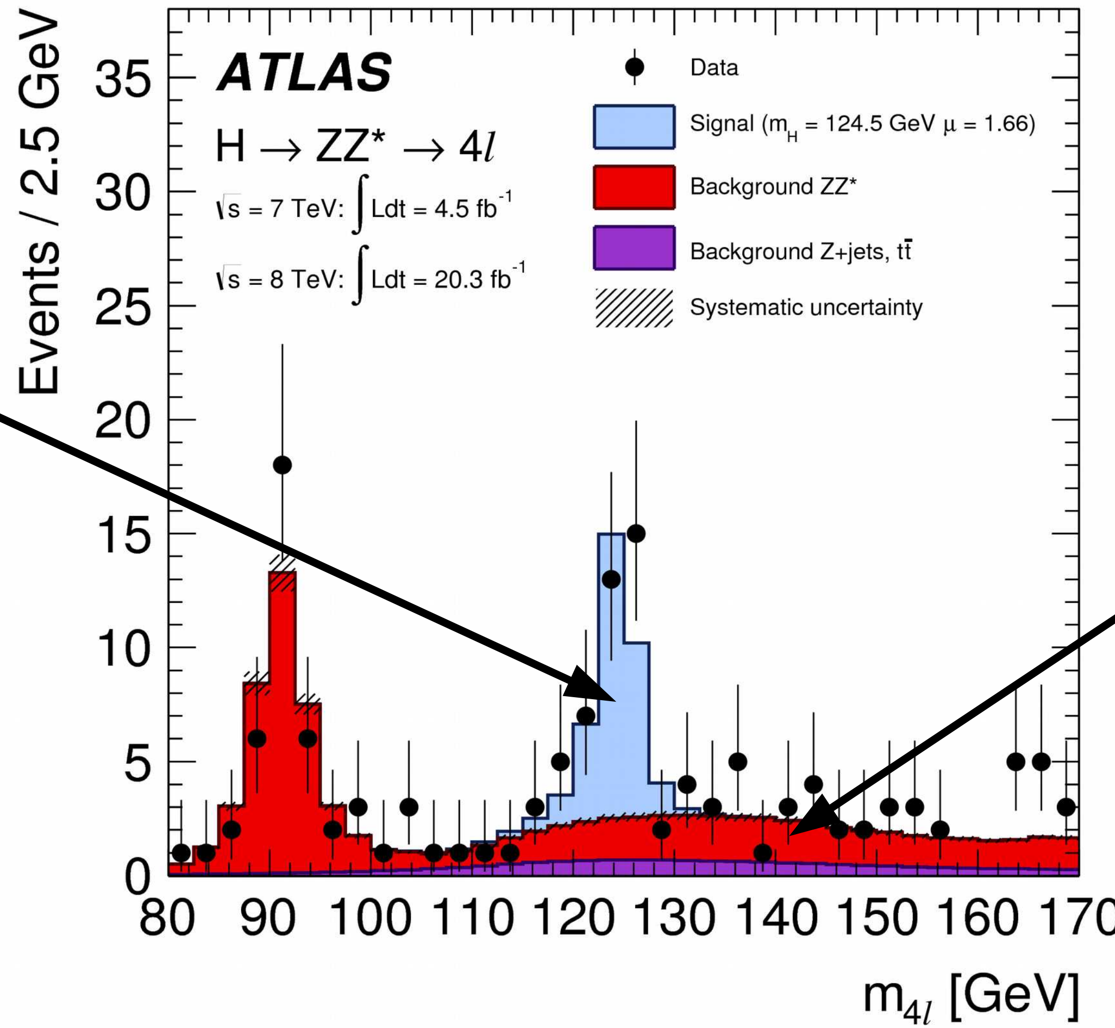


Invariant mass of 4-lepton system

Watch the ATLAS collaboration collect and analyze data

Final Result:
Higgs mass = 124.5 GeV

Signal

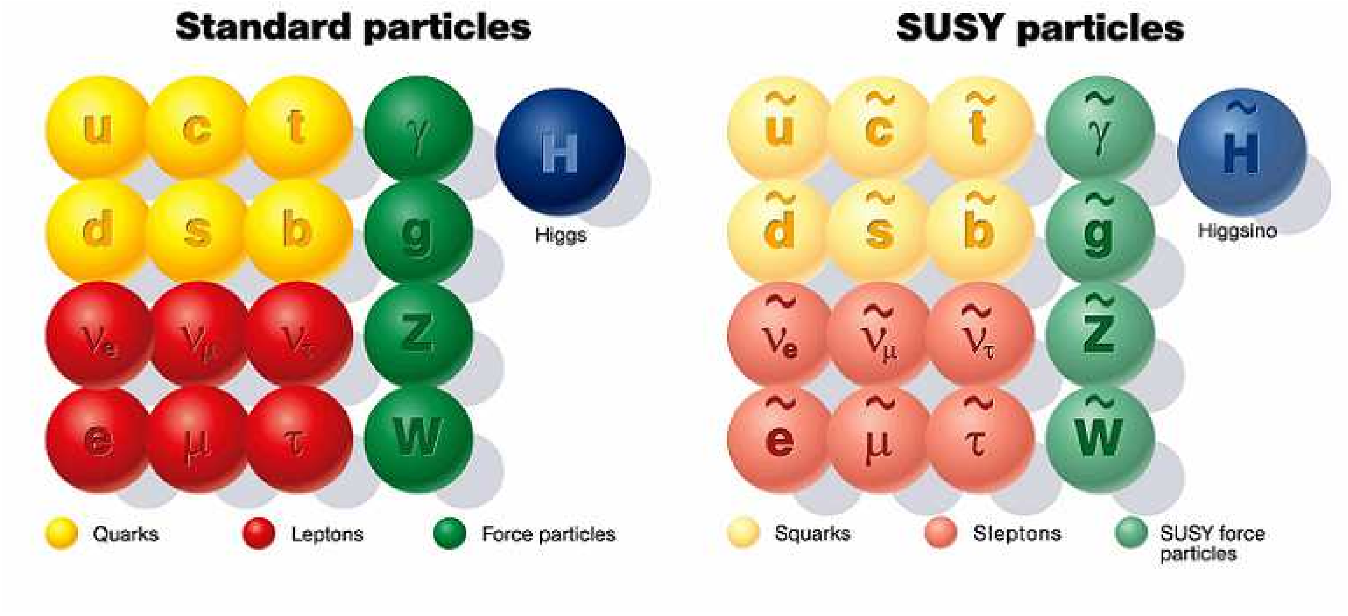


Irreducible background

ATLAS Collaboration, Phys. Rev. D 90, 052004 (2014)

The Future

- LHC turns back on this spring, at a higher energy (14 TeV)
- What will we discover next?
  - Supersymmetry? Something else?



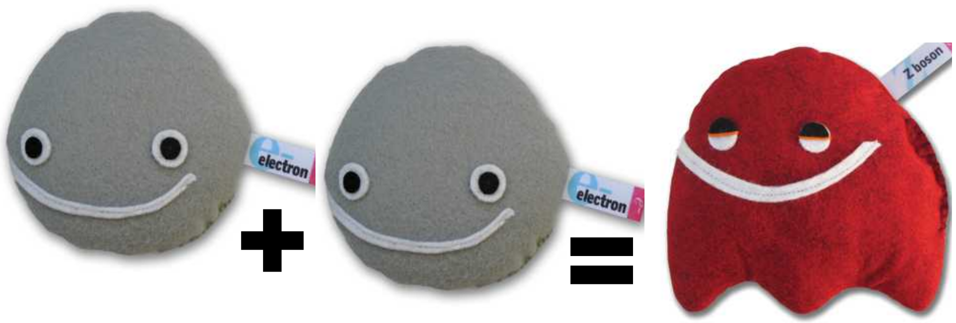
Any Questions?

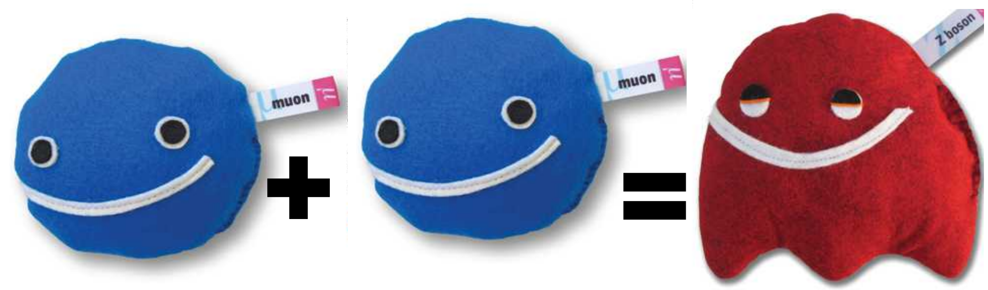
http://www.particlezoo.net/

Backup Slides

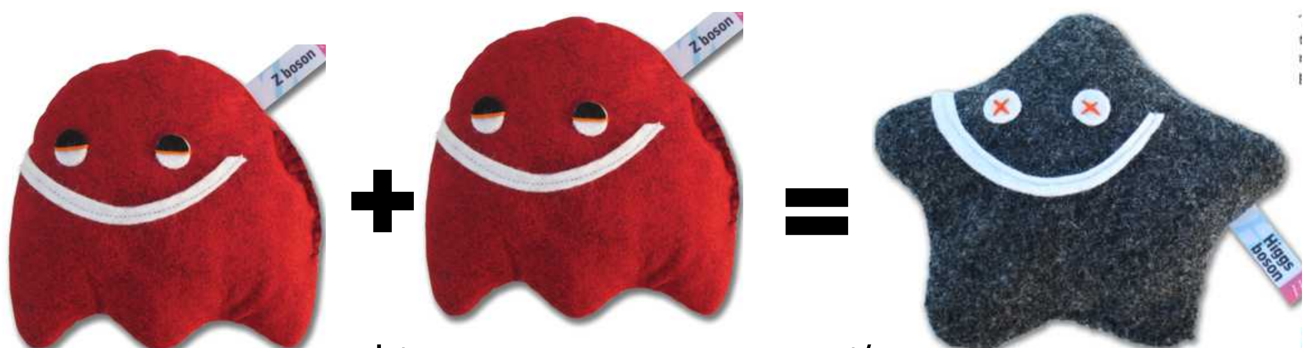
How to measure the Higgs mass

Since the leptons have very high energy compared to their mass, all you need to calculate the Z boson mass is their energy, the angle between them, and the speed of light: $M_Z = \sqrt{2E_{\ell 1}E_{\ell 2}(1-\cos\theta)} / c^2$





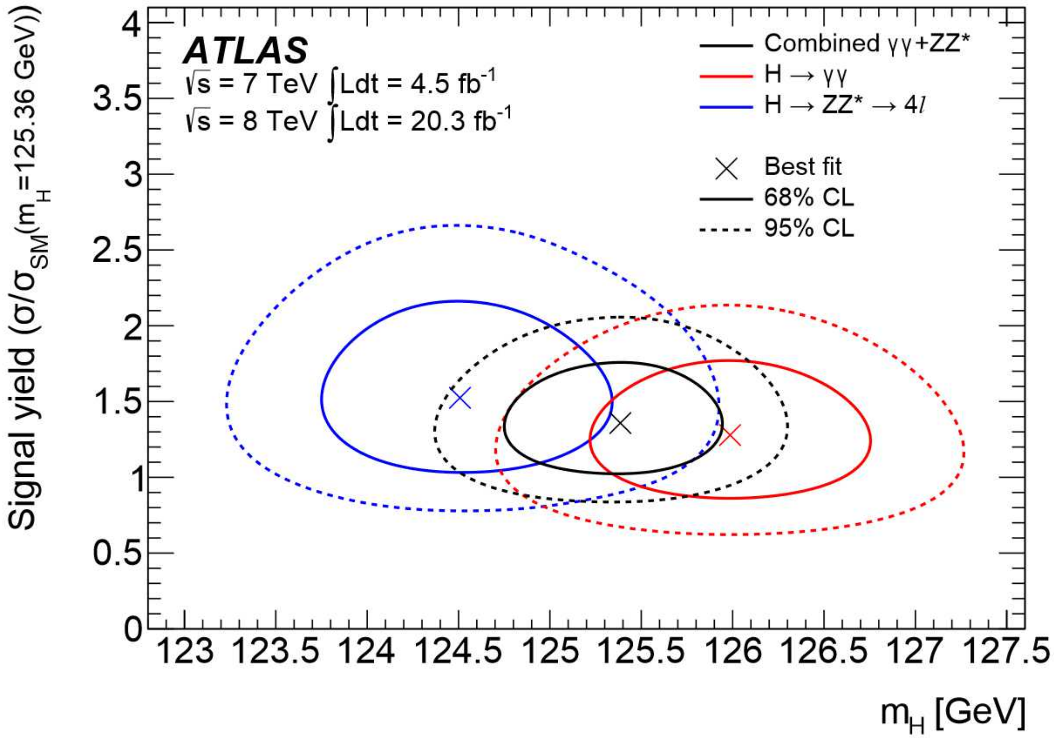
and $M_H = \sqrt{m_{Z1}^2c^4 + m_{Z2}^2c^4 + 2E_{Z1}E_{Z2}(1 - v_{Z1}v_{Z2}/c^2)\cos\theta} / c^2$



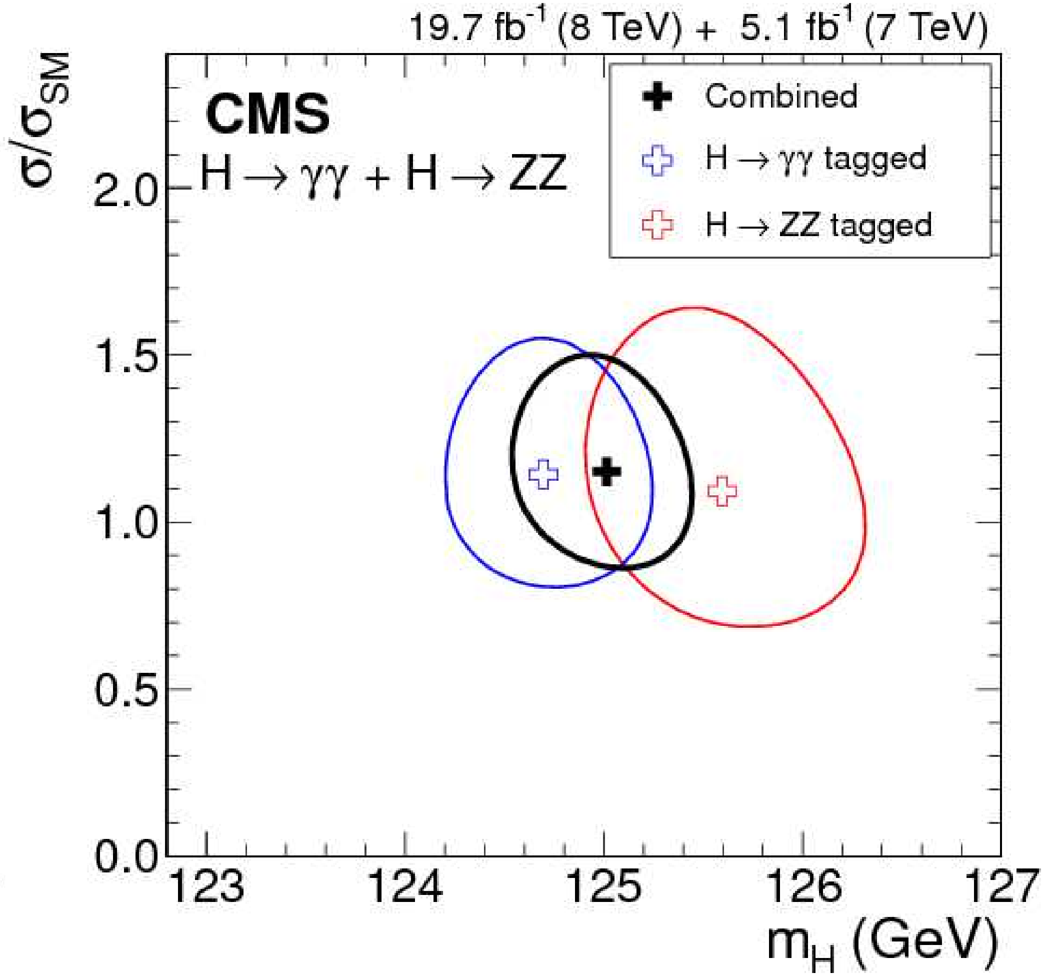
http://www.particlezoo.net/

Results

Current Higgs mass measurements from ATLAS and CMS (in 4ℓ and γγ channels)



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-12/



http://cms-higgs-results.web.cern.ch/cms-higgs-results/