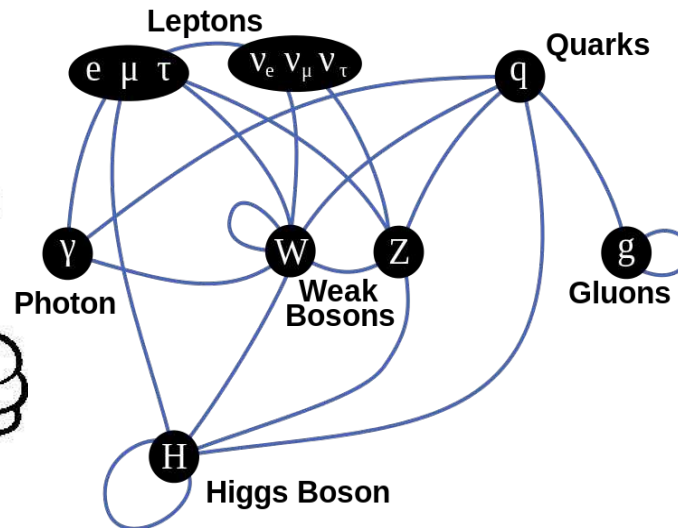
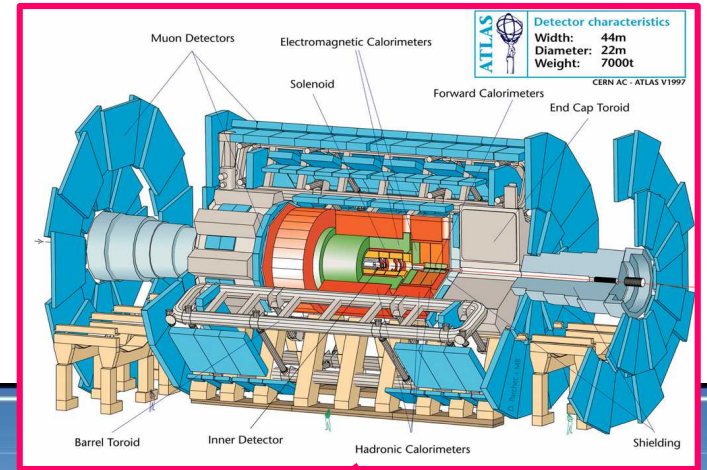
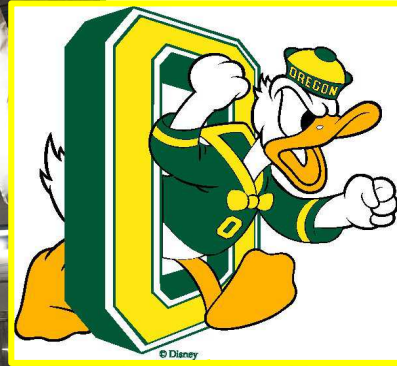
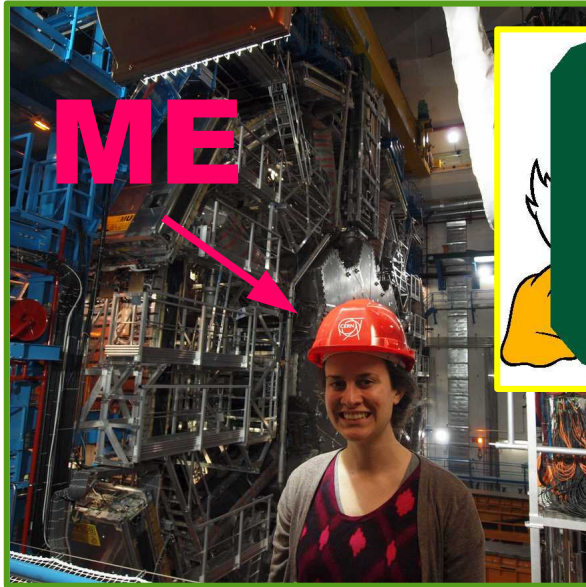


The LHC and the Higgs Boson: A Crash Course in Collider Physics



Hi.



ATLAS Collaboration



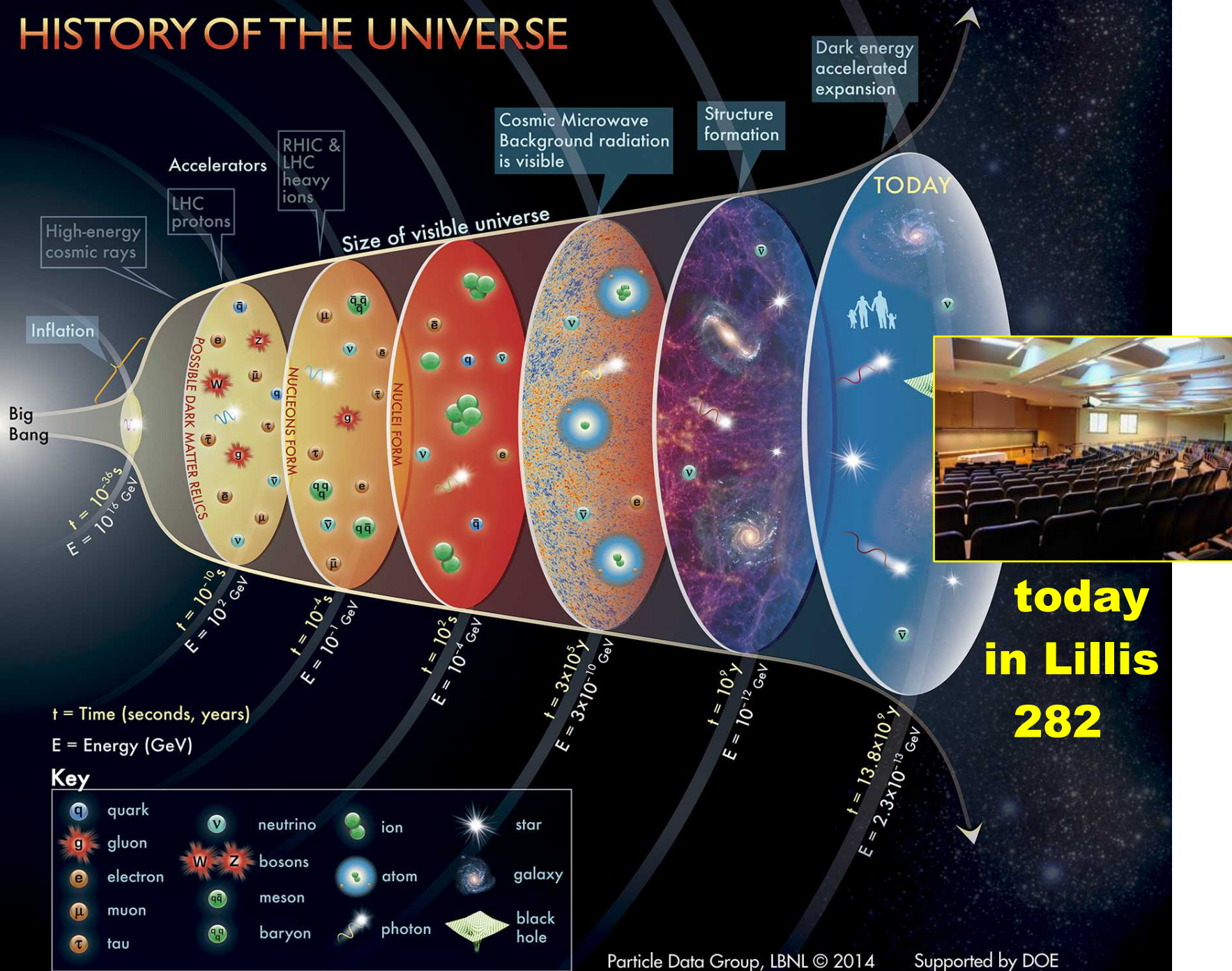
A few questions for you

Outline

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

THE BIG BANG

HISTORY OF THE UNIVERSE

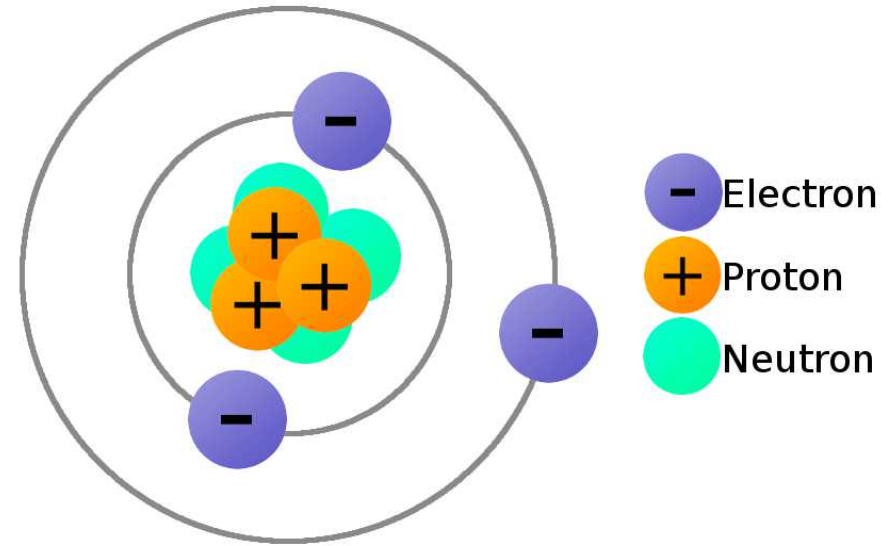


Matter

KEY

- Alkali metals
- Alkali-earth metals
- Transition metals
- Rare earths
- Radioactive rare earths
- Other metals
- Semimetals
- Non-metals
- Noble gases
- Hydrogen

1 H Hydrogen 1																	2 He Helium 4	
3 Li Lithium 7	4 Be Beryllium 9																	10 Ne Neon 20
11 Na Sodium 23	12 Mg Magnesium 24																	18 Ar Argon 40
19 K Potassium 39	20 Ca Calcium 40	21 Sc Scandium 45	22 Ti Titanium 48	23 V Vanadium 51	24 Cr Chromium 52	25 Mn Manganese 55	26 Fe Iron 56	27 Co Cobalt 59	28 Ni Nickel 58	29 Cu Copper 63	30 Zn Zinc 64	31 Ga Gallium 69	32 Ge Germanium 74	33 As Arsenic 75	34 Se Selenium 80	35 Br Bromine 79	36 Kr Krypton 84	
37 Rb Rubidium 85	38 Sr Strontium 88	39 Y Yttrium 89	40 Zr Zirconium 90	41 Nb Niobium 93	42 Mo Molybdenum 98	43 Tc Technetium 97	44 Ru Ruthenium 102	45 Rh Rhodium 103	46 Pd Palladium 106	47 Ag Silver 107	48 Cd Cadmium 114	49 In Indium 115	50 Sn Tin 120	51 Sb Antimony 121	52 Te Tellurium 130	53 I Iodine 127	54 Xe Xenon 132	
55 Cs Caesium 133	56 Ba Barium 138	57-71 Lanthanides	72 Hf Hafnium 180	73 Ta Tantalum 181	74 W Tungsten 184	75 Re Rhenium 187	76 Os Osmium 192	77 Ir Iridium 193	78 Pt Platinum 195	79 Au Gold 197	80 Hg Mercury 202	81 Tl Thallium 205	82 Pb Lead 208	83 Bi Bismuth 209	84 Po Polonium 209	85 At Astatine 210	86 Rn Radon 222	
87 Fr Francium 223	88 Ra Radium 226	89-103 Actinides	104 Unq Unnilquadium 260	105 Unp Unnilpentium 262	106 Unh Unnilhexium 263	107 Uns Unnilseptium 265	108 Uno Unniloctium 265	109 Uue Unnilennium 266										
57 La Lanthanum 139	58 Ce Cerium 140	59 Pr Praseodymium 141	60 Nd Neodymium 142	61 Pm Promethium 145	62 Sm Samarium 152	63 Eu Europium 153	64 Gd Gadolinium 153	65 Tb Terbium 159	66 Dy Dysprosium 163	67 Ho Holmium 165	68 Er Erbium 168	69 Tm Thulium 169	70 Yb Ytterbium 174	71 Lu Lutetium 175				
89 Ac Actinium 227	90 Th Thorium 232	91 Pa Protactinium 231	92 U Uranium 238	93 Np Neptunium 237	94 Pu Plutonium 244	95 Am Americium 243	96 Cm Curium 247	97 Bk Berkelium 247	98 Cf Californium 251	99 Es Einsteinium 254	100 Fm Fermium 257	101 Md Mendelevium 258	102 No Nobelium 259	103 Lr Lawrencium 260				

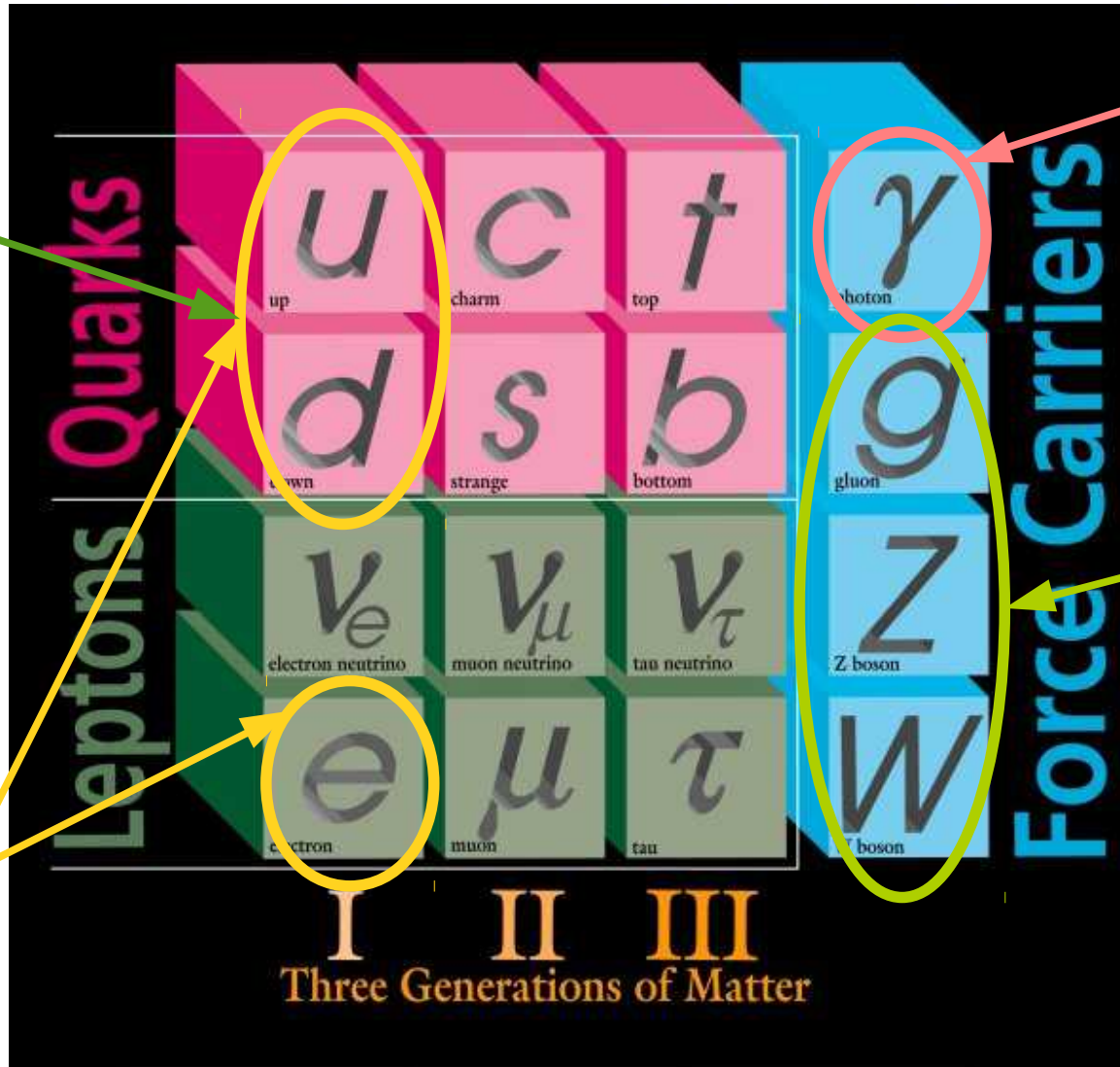


All atomic matter is made of three particles: the electron, the proton, and the neutron

The Standard Model

Make up
protons
and
neutrons

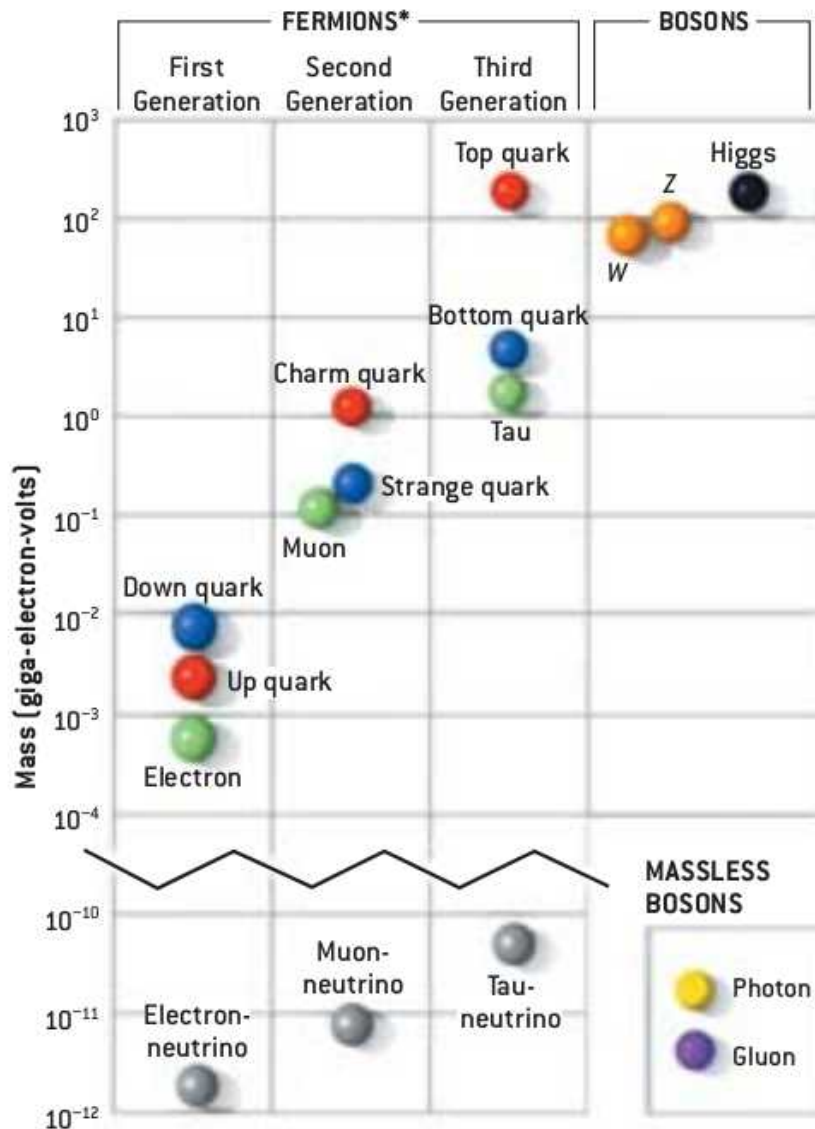
Make up
atomic
matter



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

H

The **HIGGS BOSON** is the particle of the Higgs mechanism, believed by physicists to reveal how all matter in the universe gets its mass. On July 4, 2012, the CMS and Atlas collaborations at CERN announced a 5-sigma level of certainty that the Higgs boson had been detected with a mass of around 125 GeV.

\$10.49 PLUS SHIPPING

●●●●● HEAVY
Wool felt, fleece with gravel fill for maximum mass.

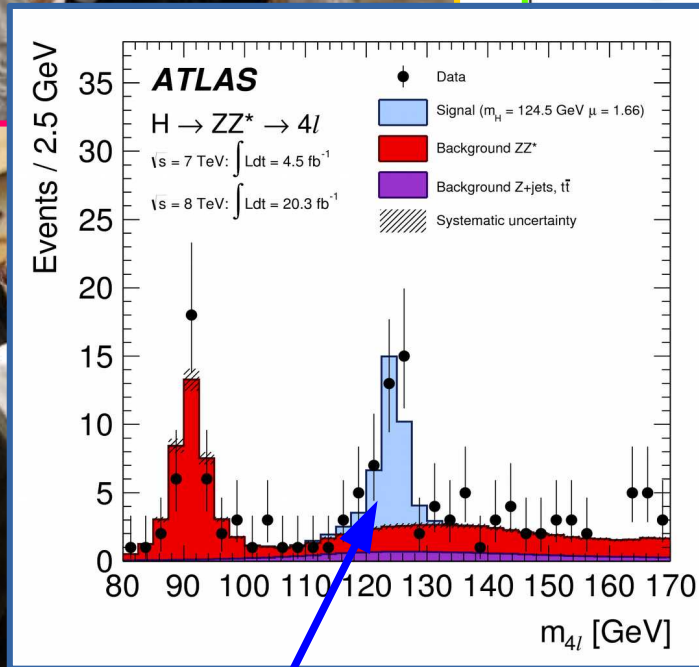
TACHYON ELECTRON UP QUARK DOWN QUARK TAU NEUTRINO MUON UP C
GLUON HIGGS BOSON NEUTRINO TACHYON ELECTRON UP QUARK DOWN
PROTON NEUTRON DOWN QUARK TAU GLUON PHOTON NEUTRINO TACHY
SON PAIR PROTON NEUTRON DOWN QUARK TAU GLU

CLEZOO

http://www.particlezoo.net/



Peter Higgs



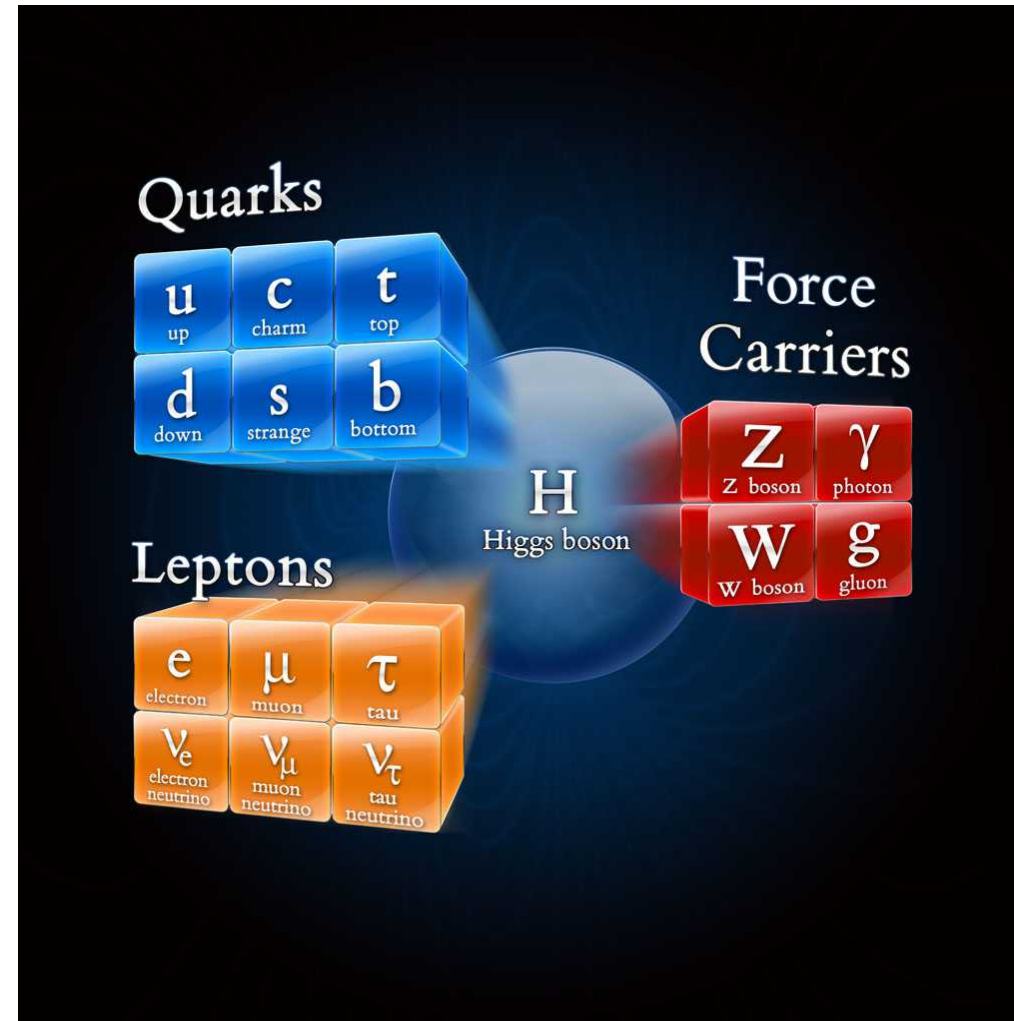
Higgs Boson

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

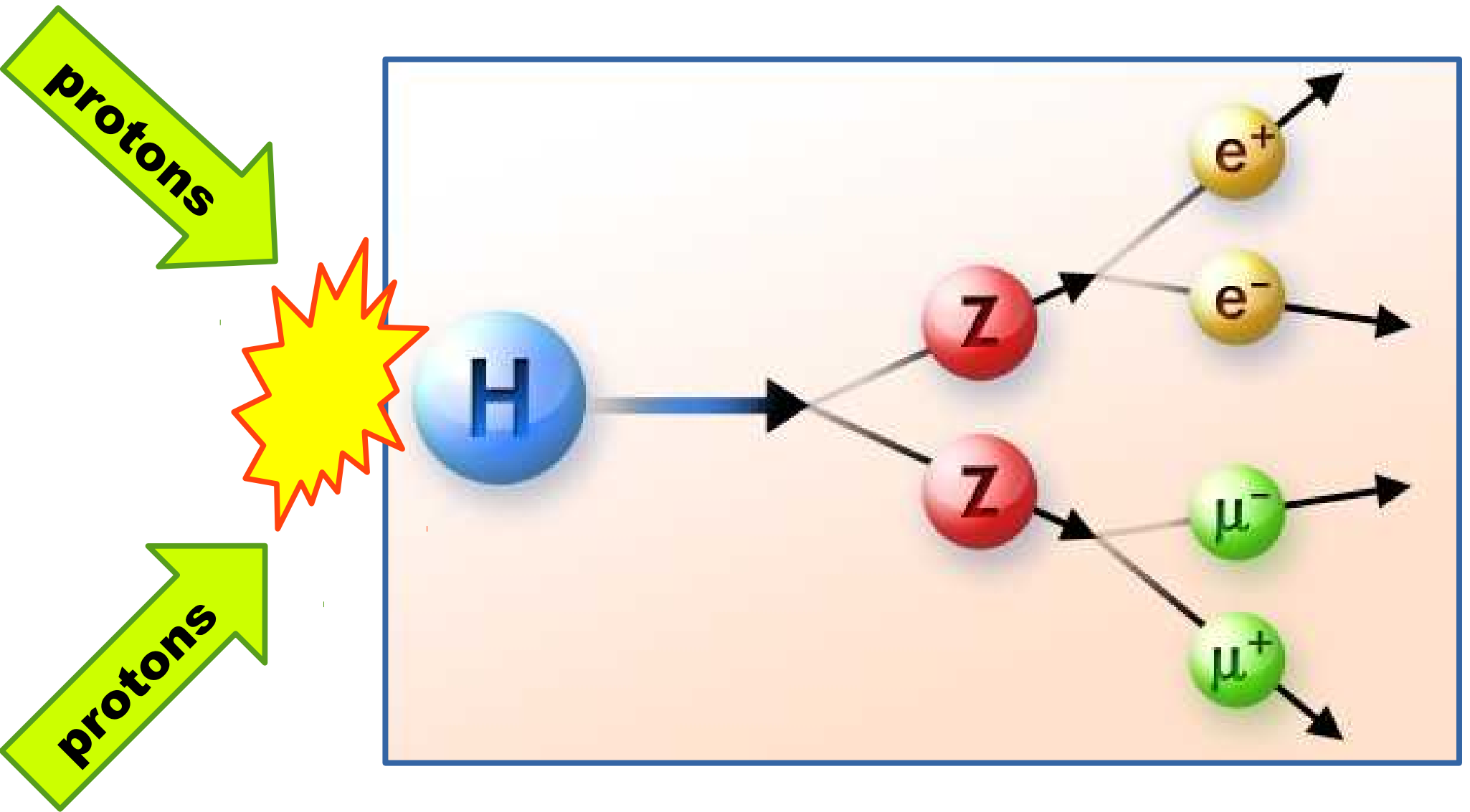
←

The Standard Model (now)

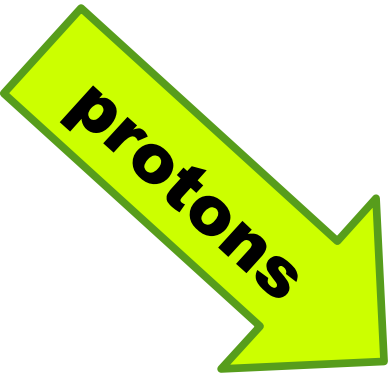
- The Higgs field fills the universe and gives mass to the fundamental particles
- The rest of this talk will discuss how we found the Higgs boson



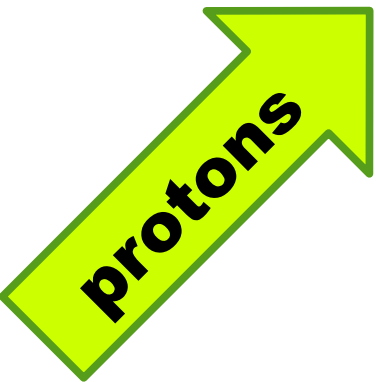
Searching for the Higgs Boson



How do we look for the Higgs?

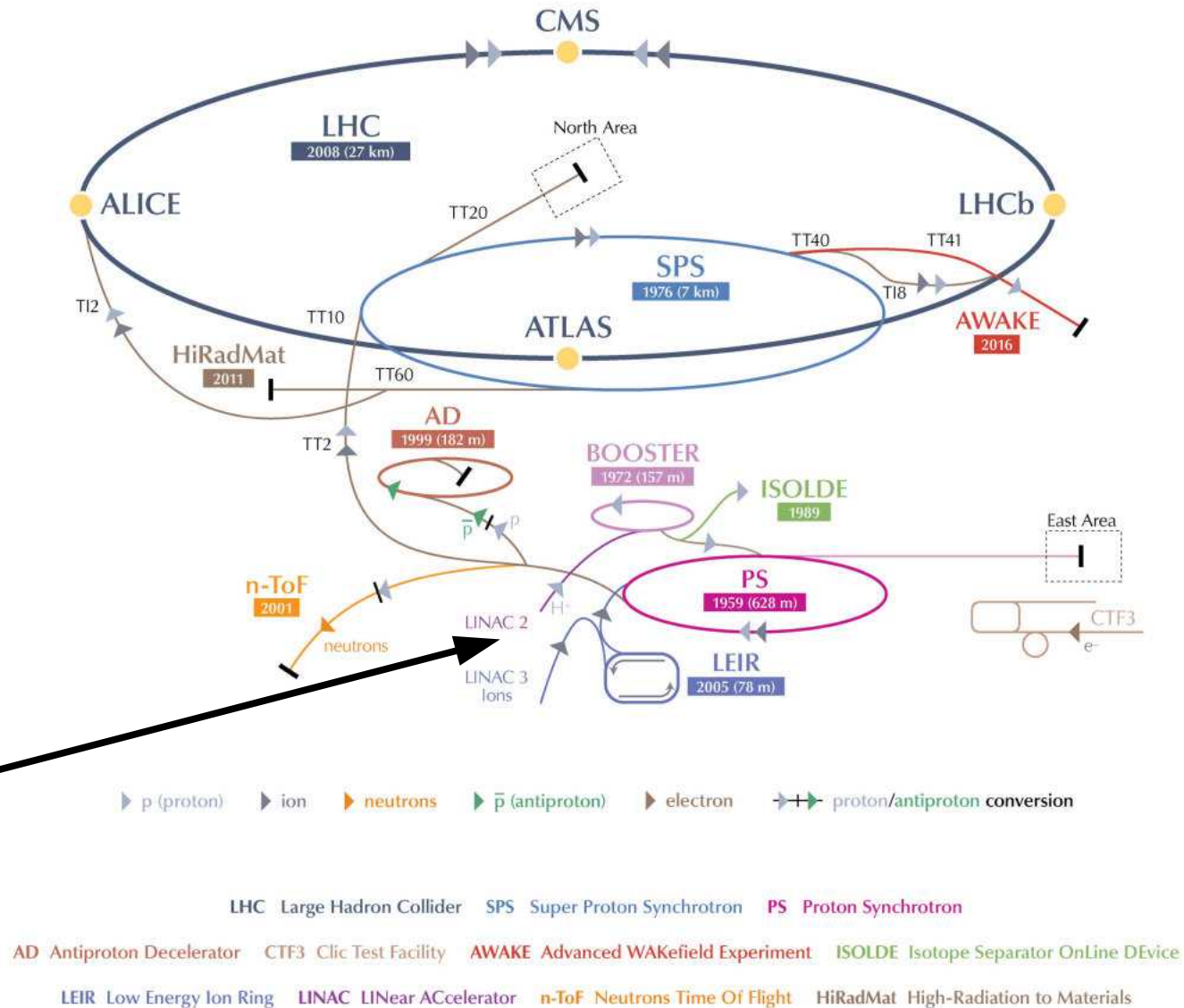


Step one: accelerate protons



Insert Protons

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



Accelerate Protons

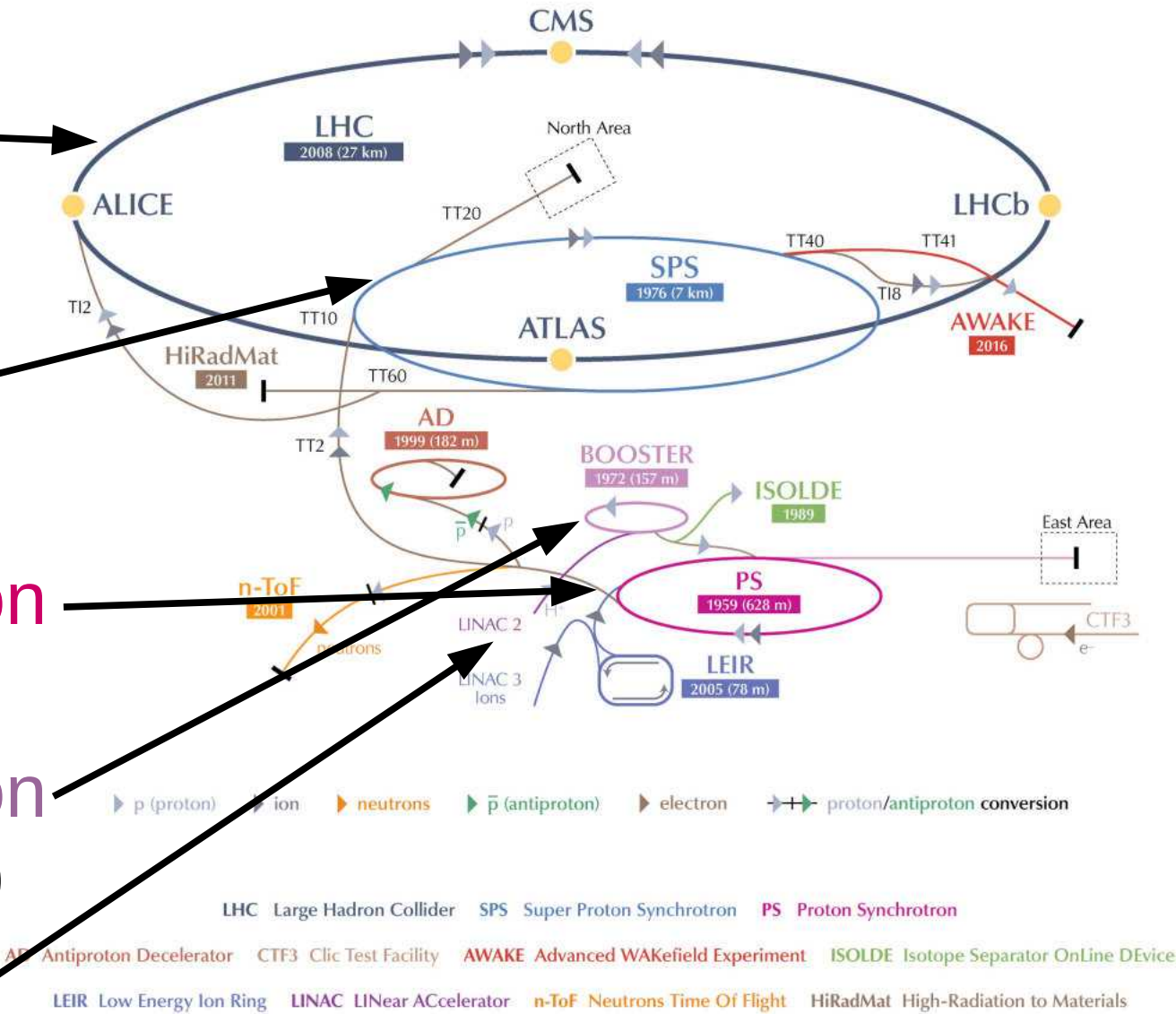
- Large Hadron Collider (4 TeV per beam)

- 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

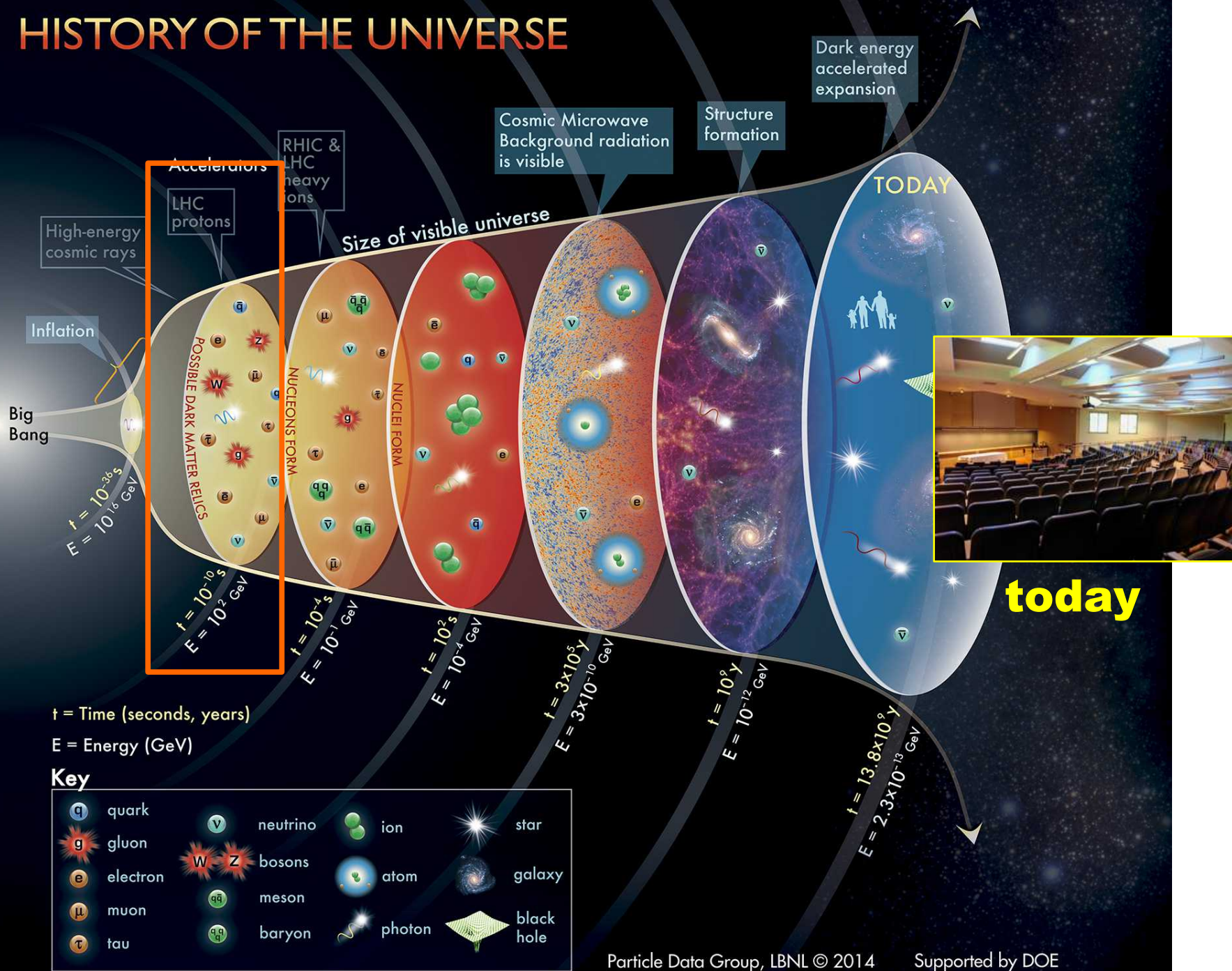
The Large Hadron Collider

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

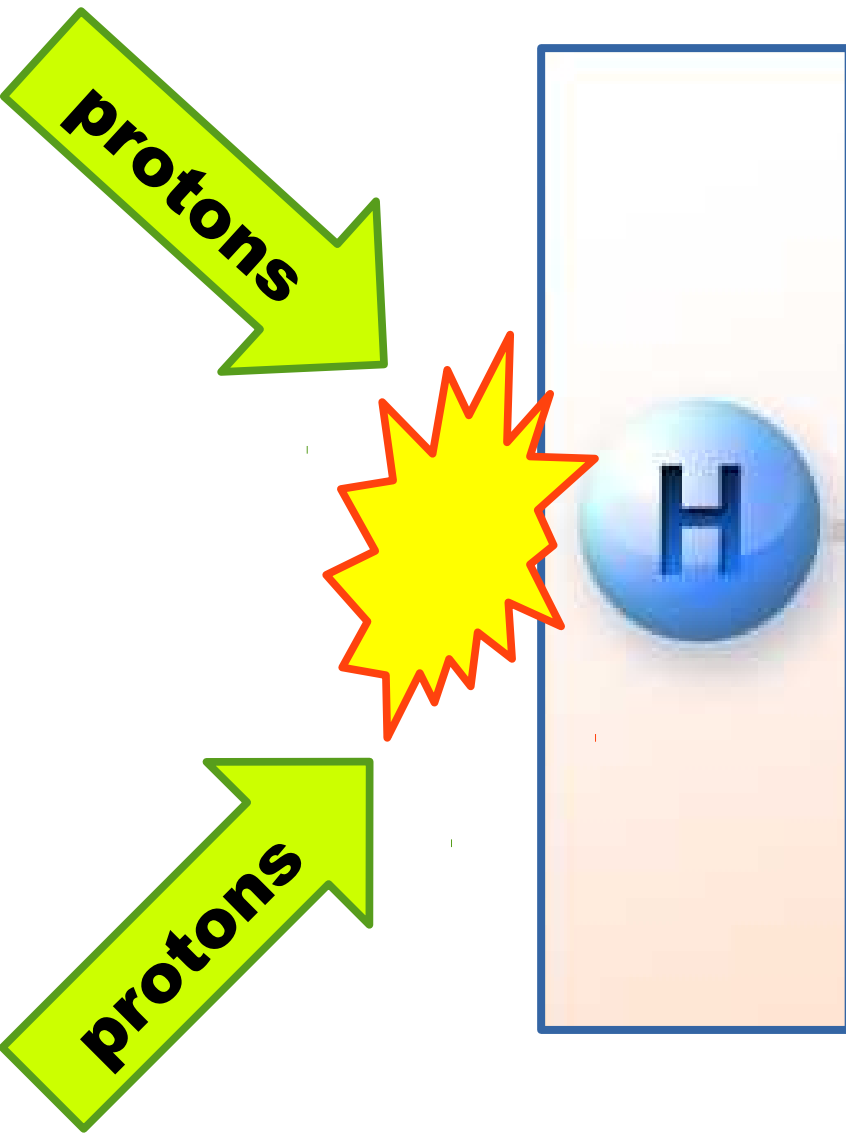


THE BIG BANG

HISTORY OF THE UNIVERSE



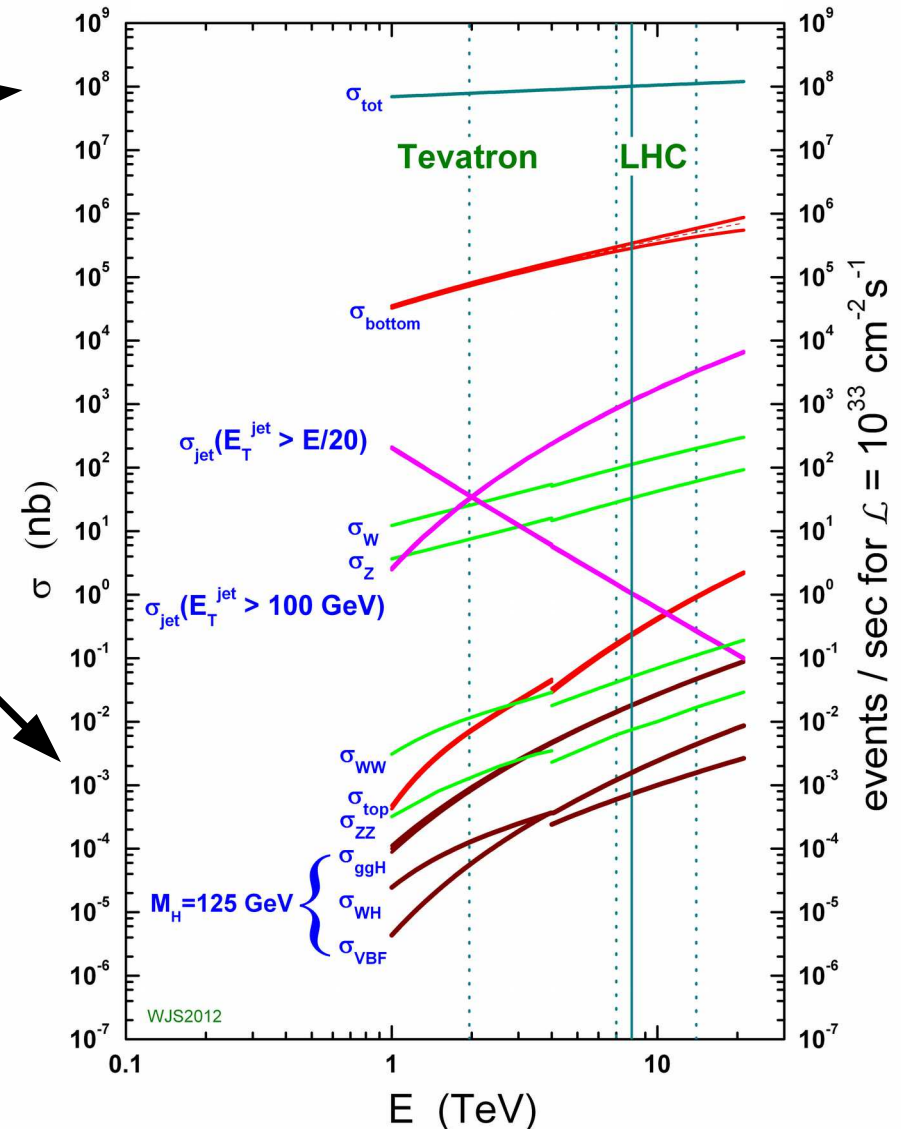
How do we look for the Higgs?



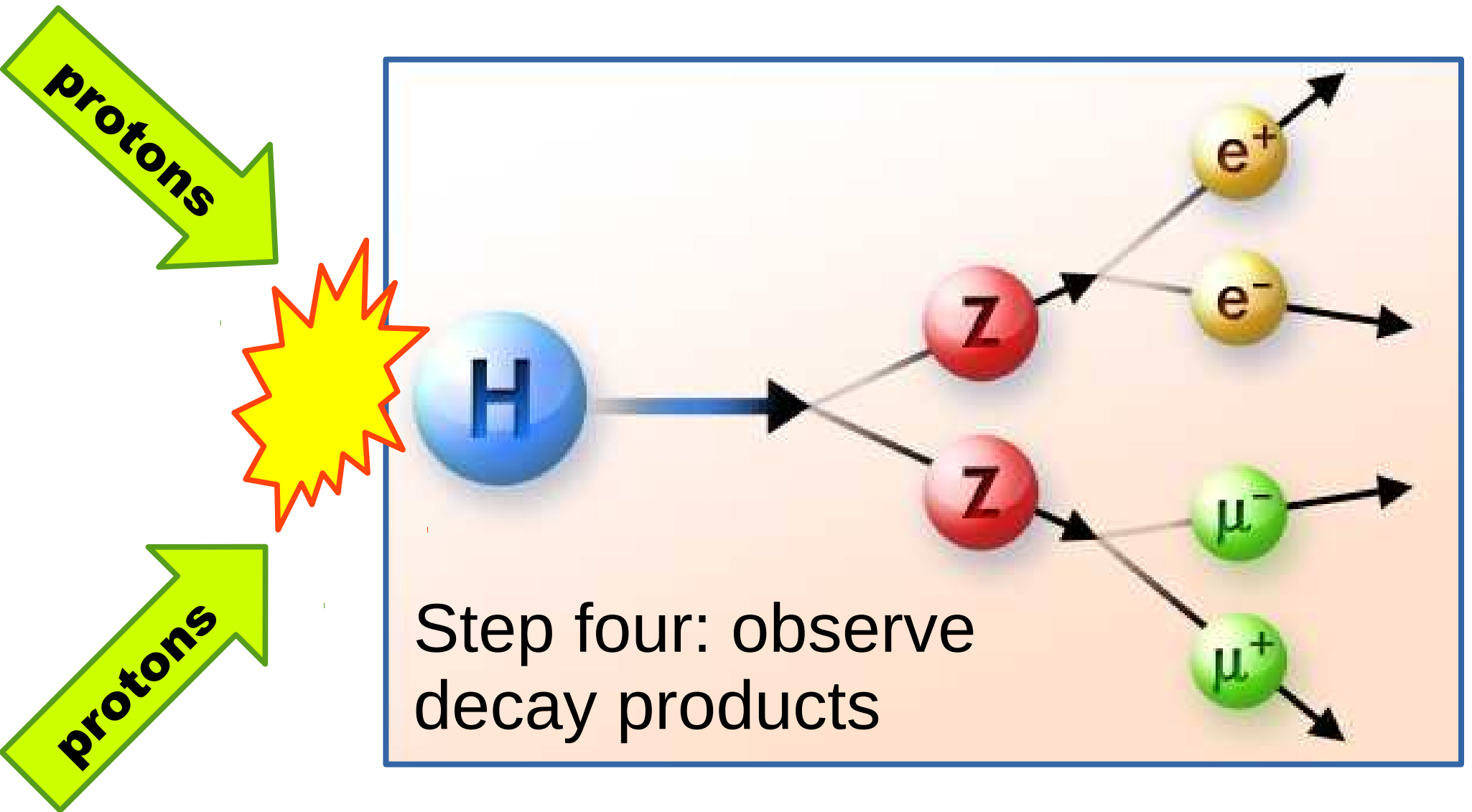
Step three: Higgs boson is produced

Collisions @ the LHC

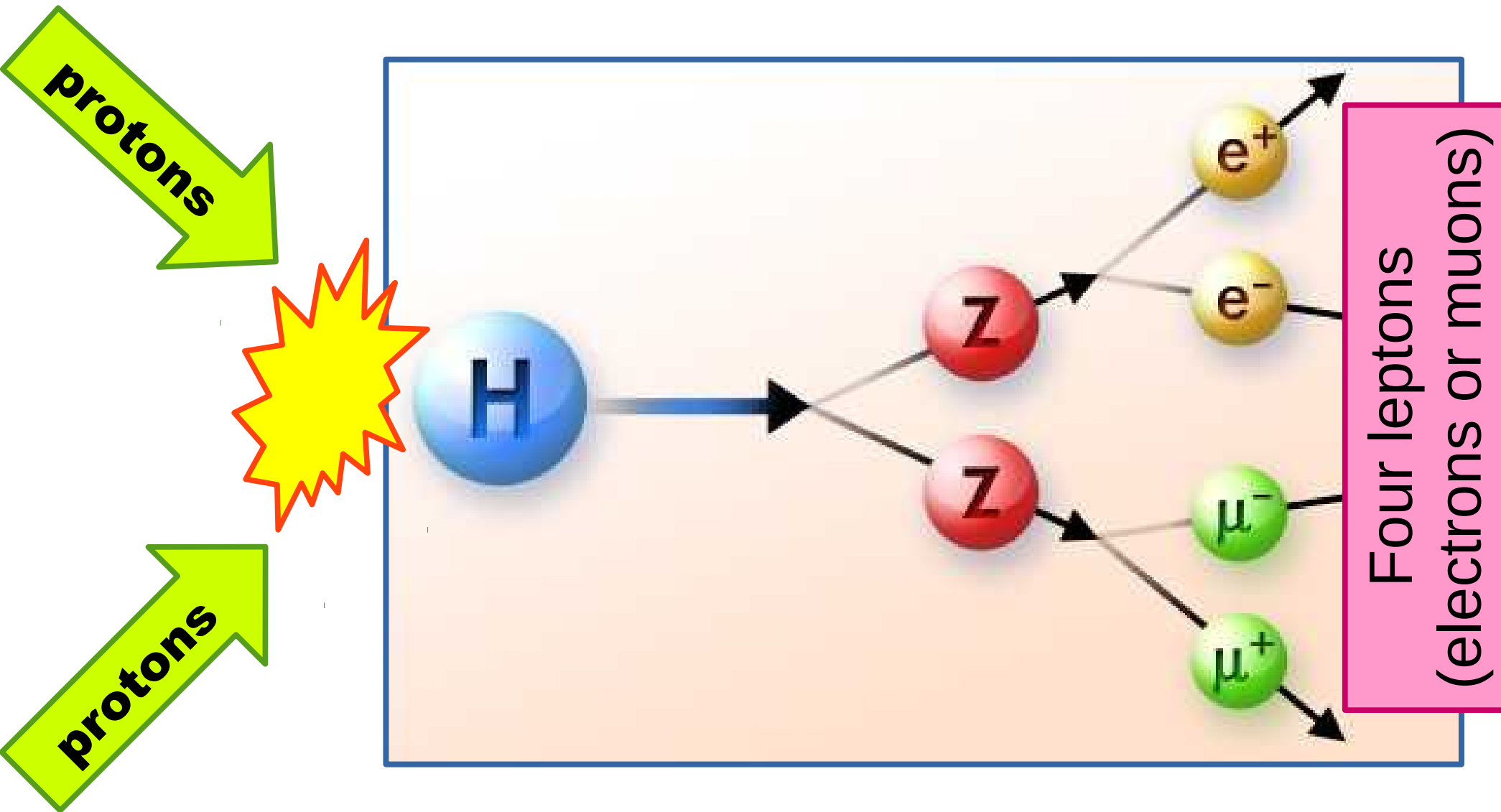
- MOST collisions are boring
- We are looking for rare processes
- How rare?
 - 300,000 Higgs events in 2012
 - But!
2,000,000,000,000,000,000 total events in 2012



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 ($H \rightarrow 4\ell$)

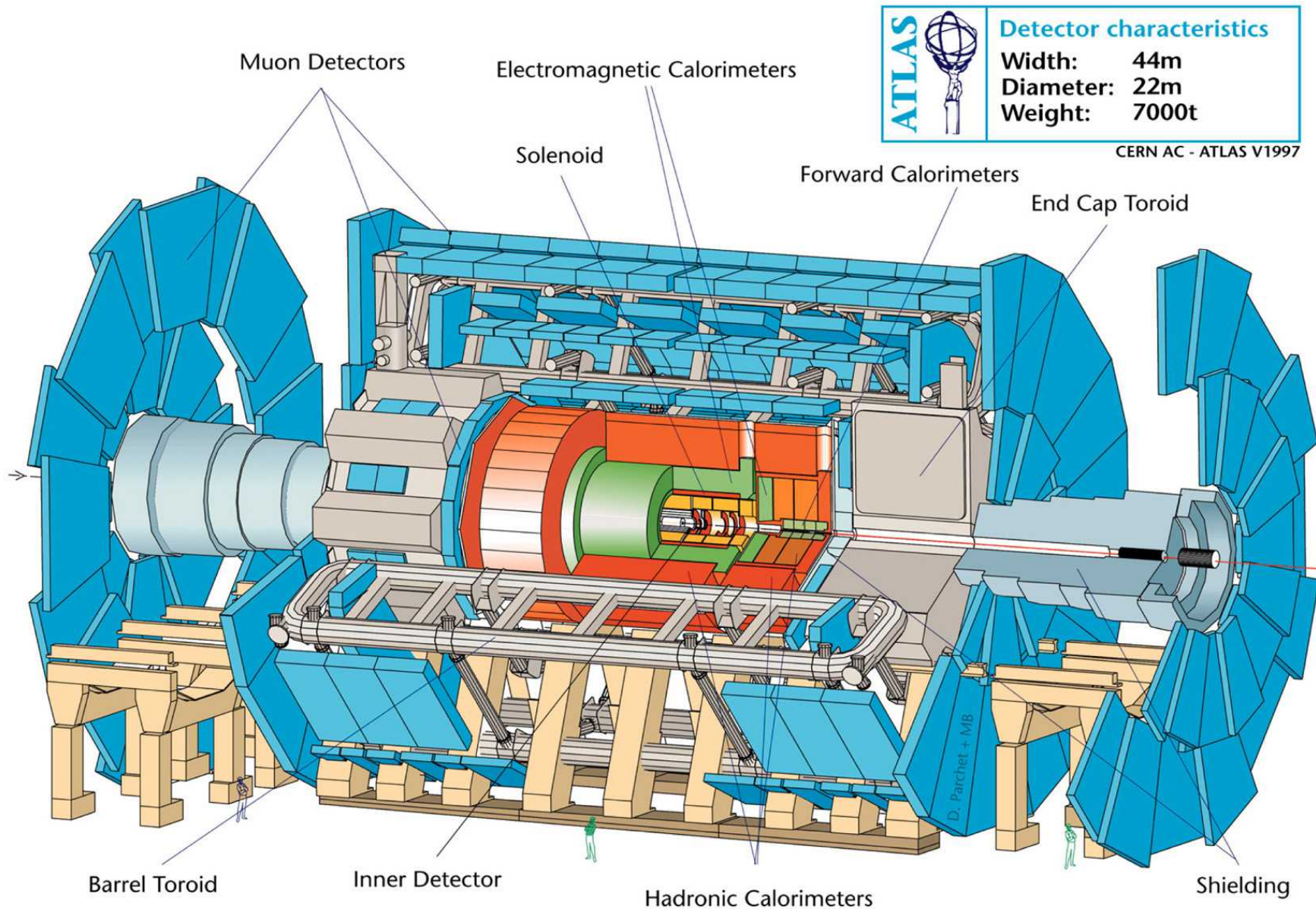
How do we observe the leptons from the Higgs decay?



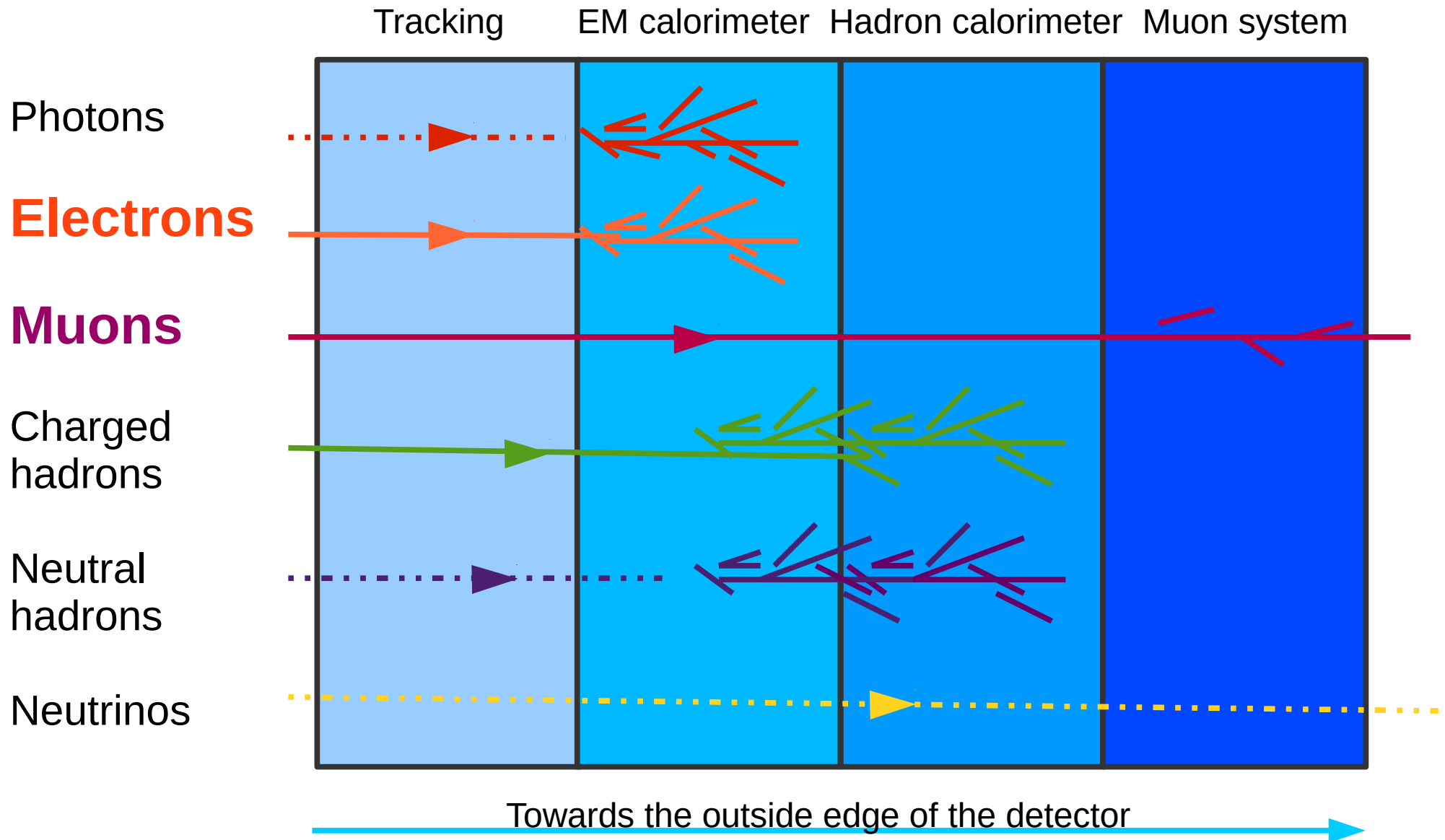
- Use detectors to record the decay products from the process we're looking for ($H \rightarrow ZZ^* \rightarrow 4\ell$)
- Detectors ~ huge 3D digital cameras
→ picture = "event"

<http://www.particlezoo.net/>

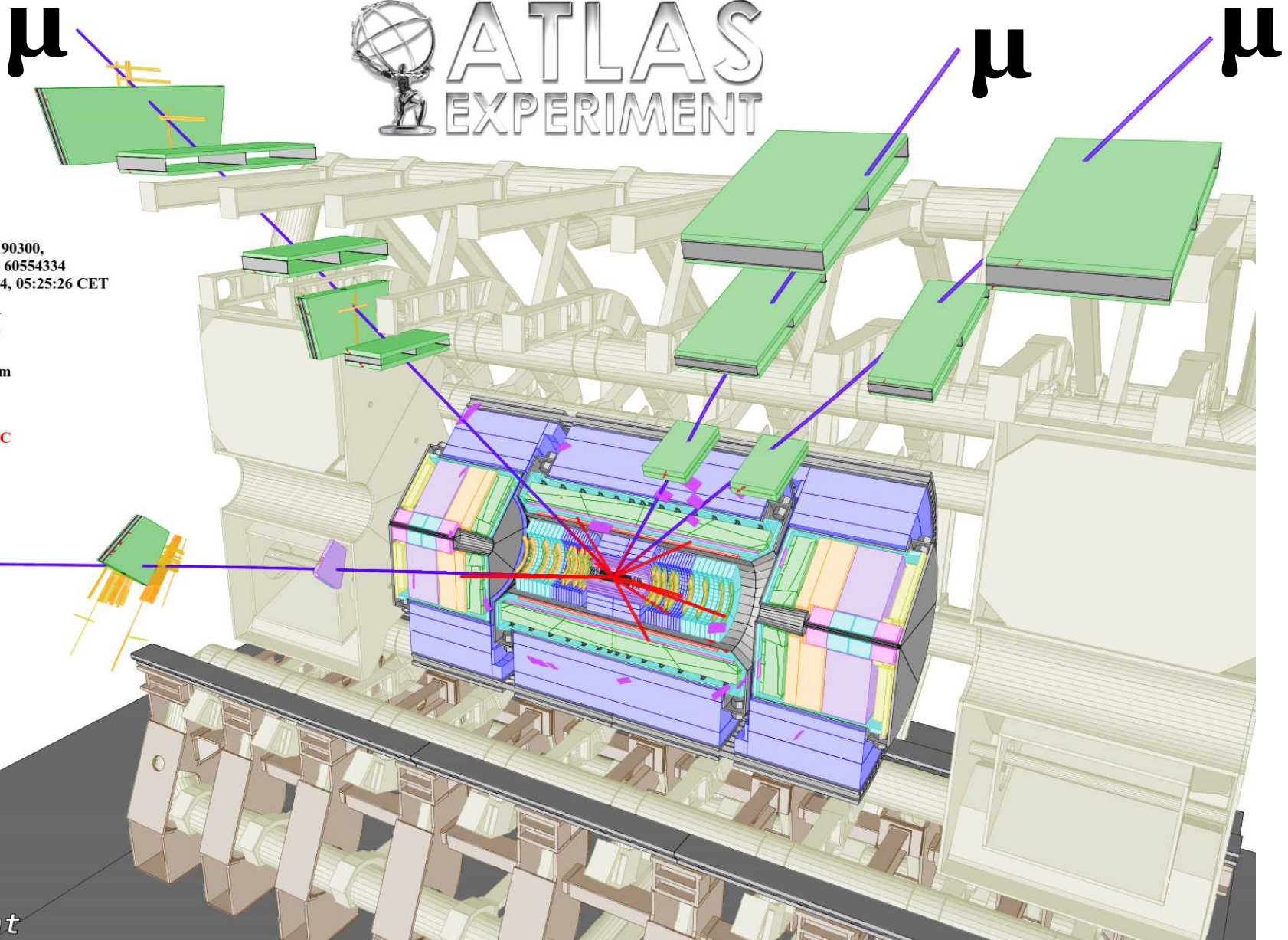
The ATLAS Detector



Particle Identification



Event Display (4 muons)



Run Number: 190300,
Event Number: 60554334
Date: 2011-10-04, 05:25:26 CET

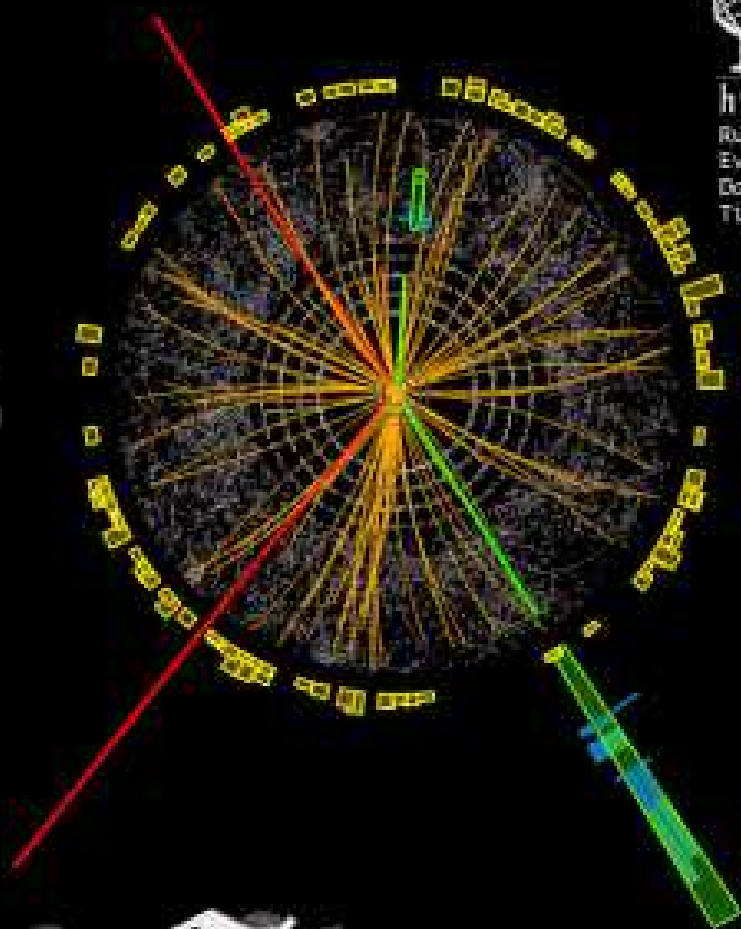
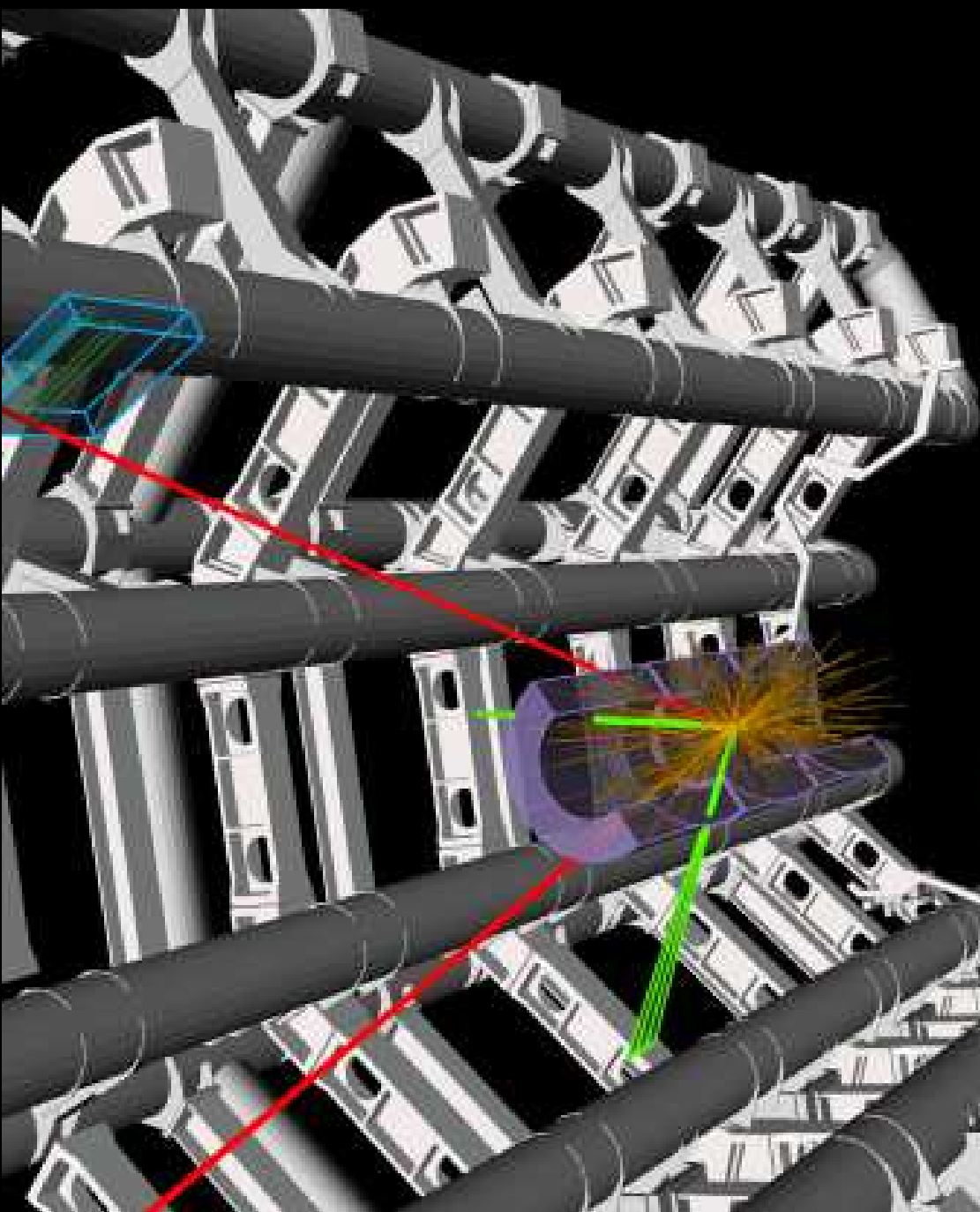
EtCut>0.3 GeV
PtCut>3.0 GeV
Vertex Cuts:
Z direction <1cm
Rphi <1cm

Muon: blue
Cells: Tiles, EMC

H \rightarrow **4** *l* **event movie**

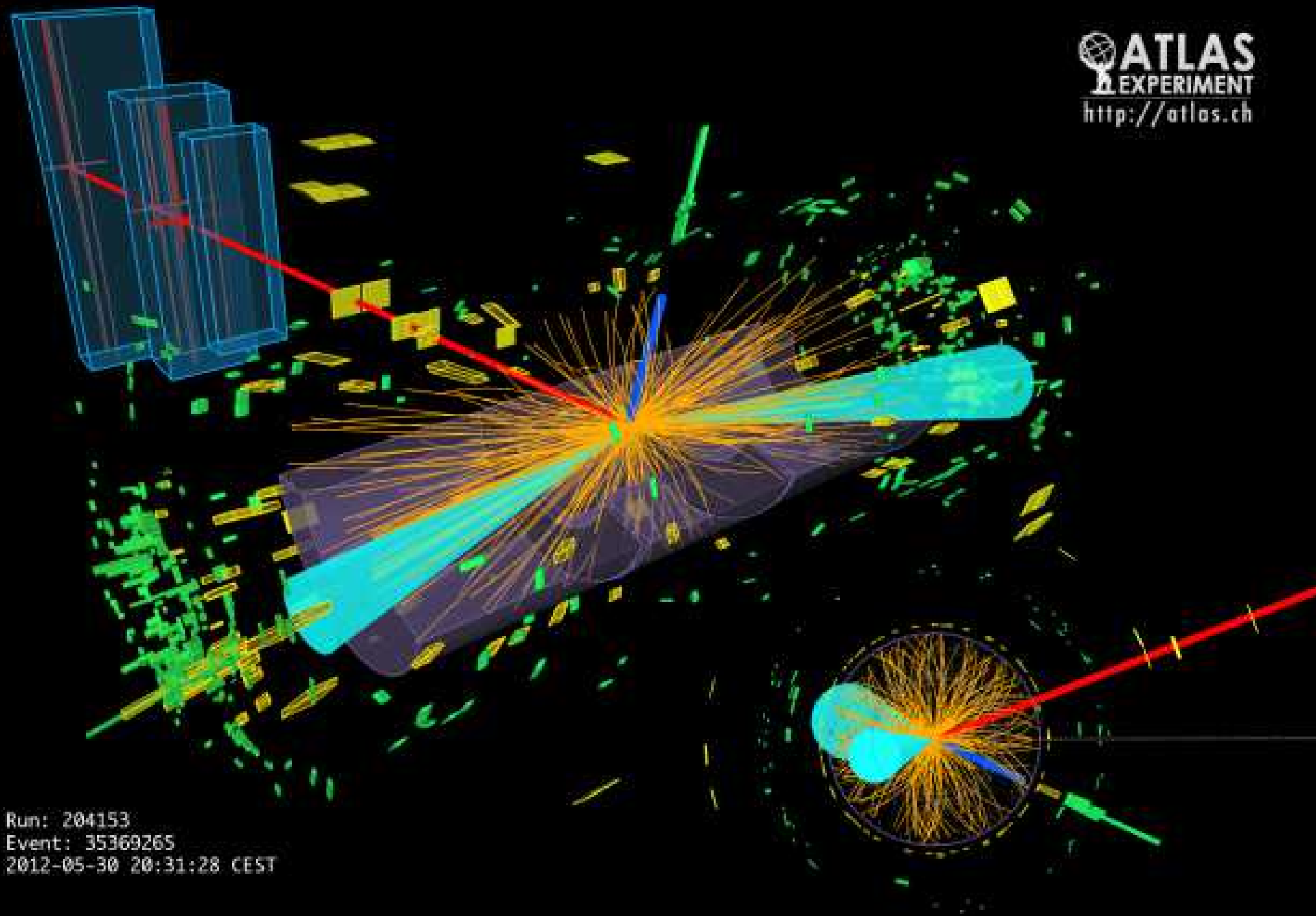
Practice Identifying Higgs Events

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

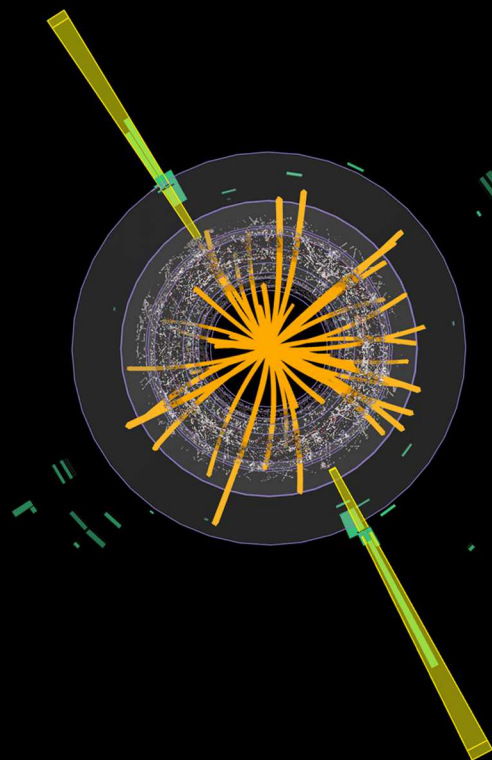
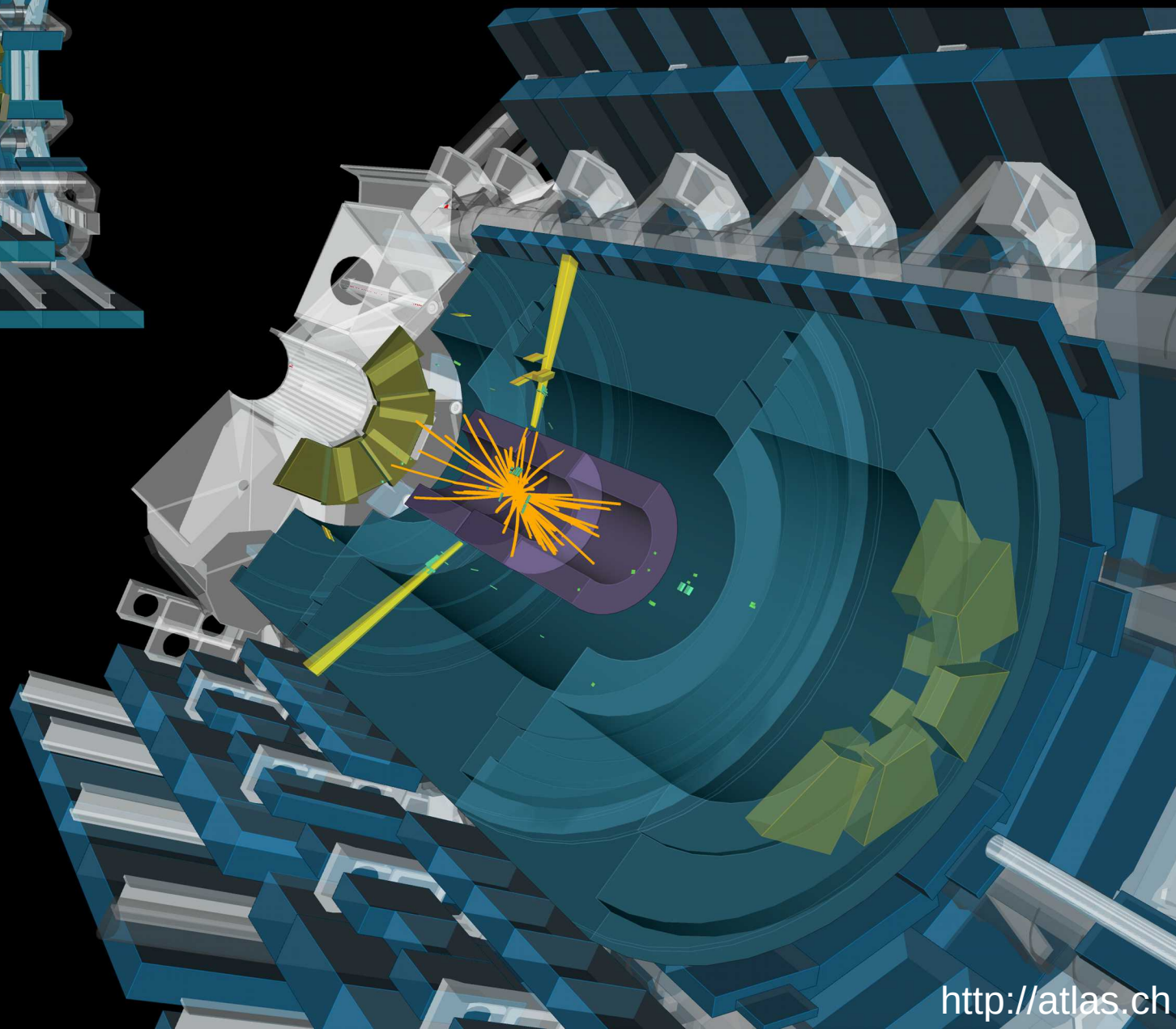
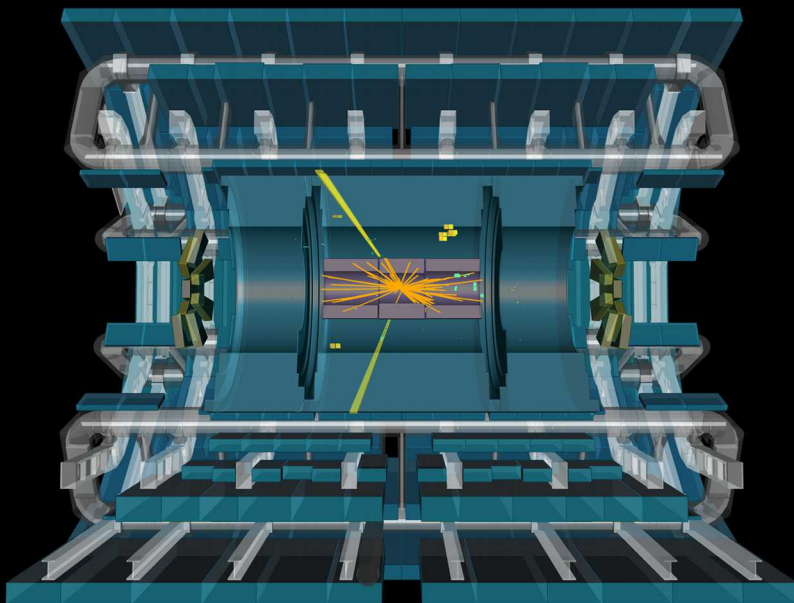


ATLAS
EXPERIMENT
<http://atlas.ch>
Run: 285113
Event: 12611816
Date: 2012-06-18
Time: 11:07:47 CEST





Run: 204153
Event: 35369265
2012-05-30 20:31:28 CEST



ATLAS
EXPERIMENT

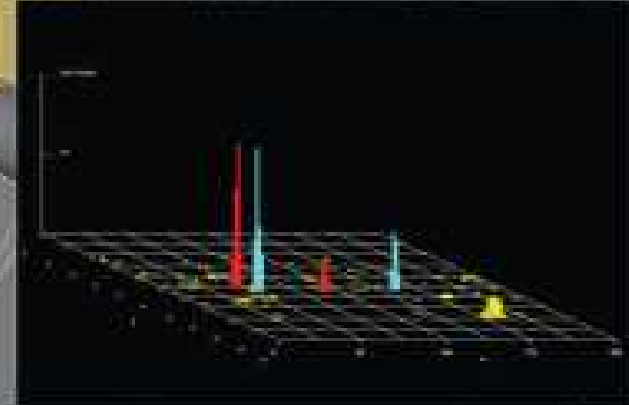
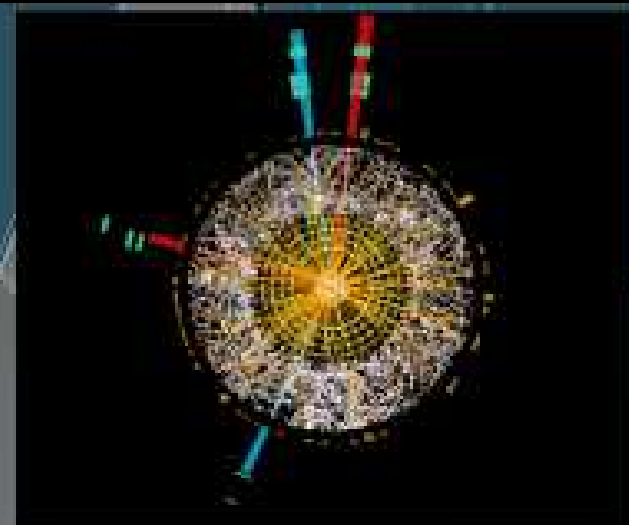
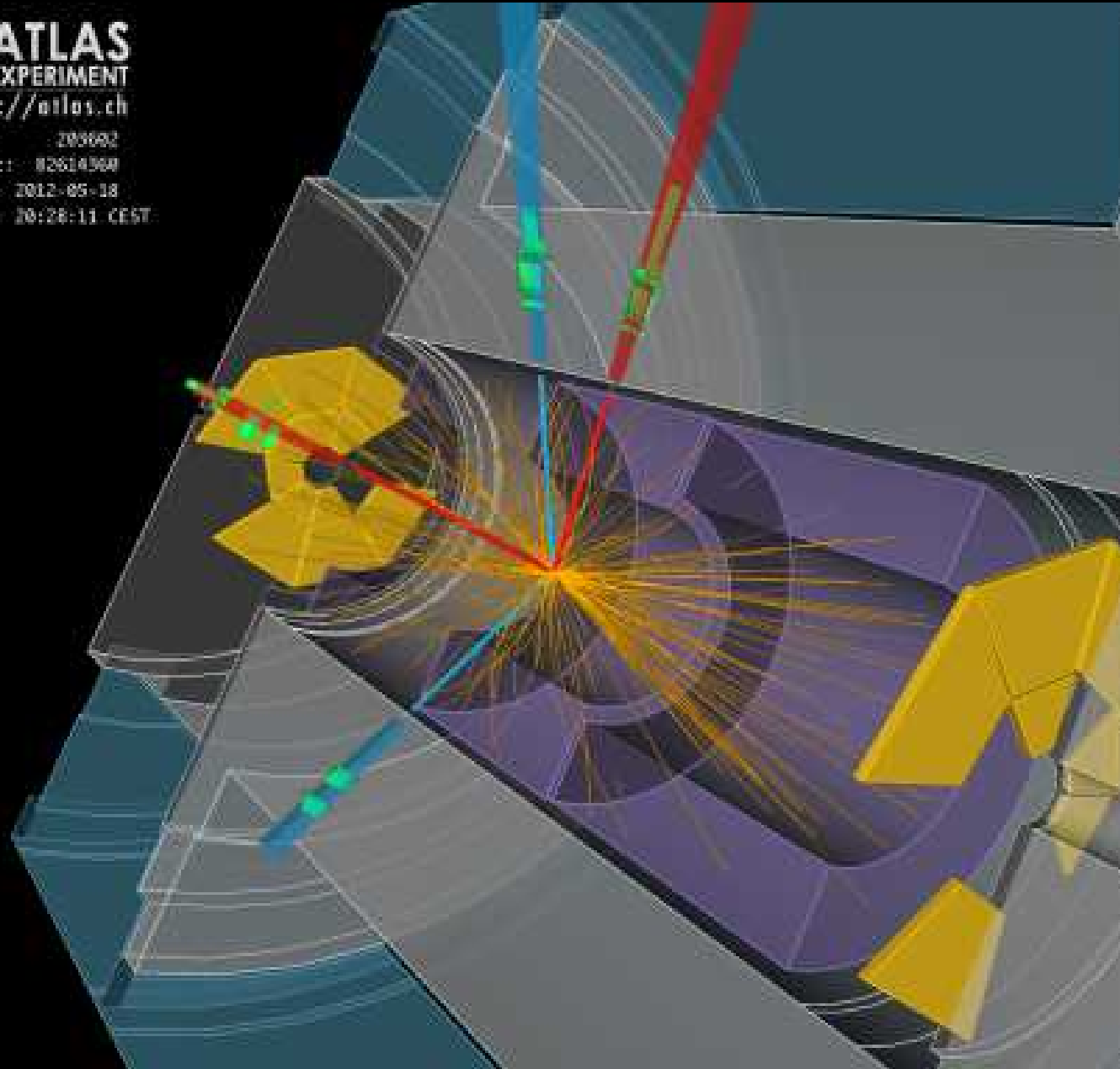
<http://atlas.ch>

Run: 203602

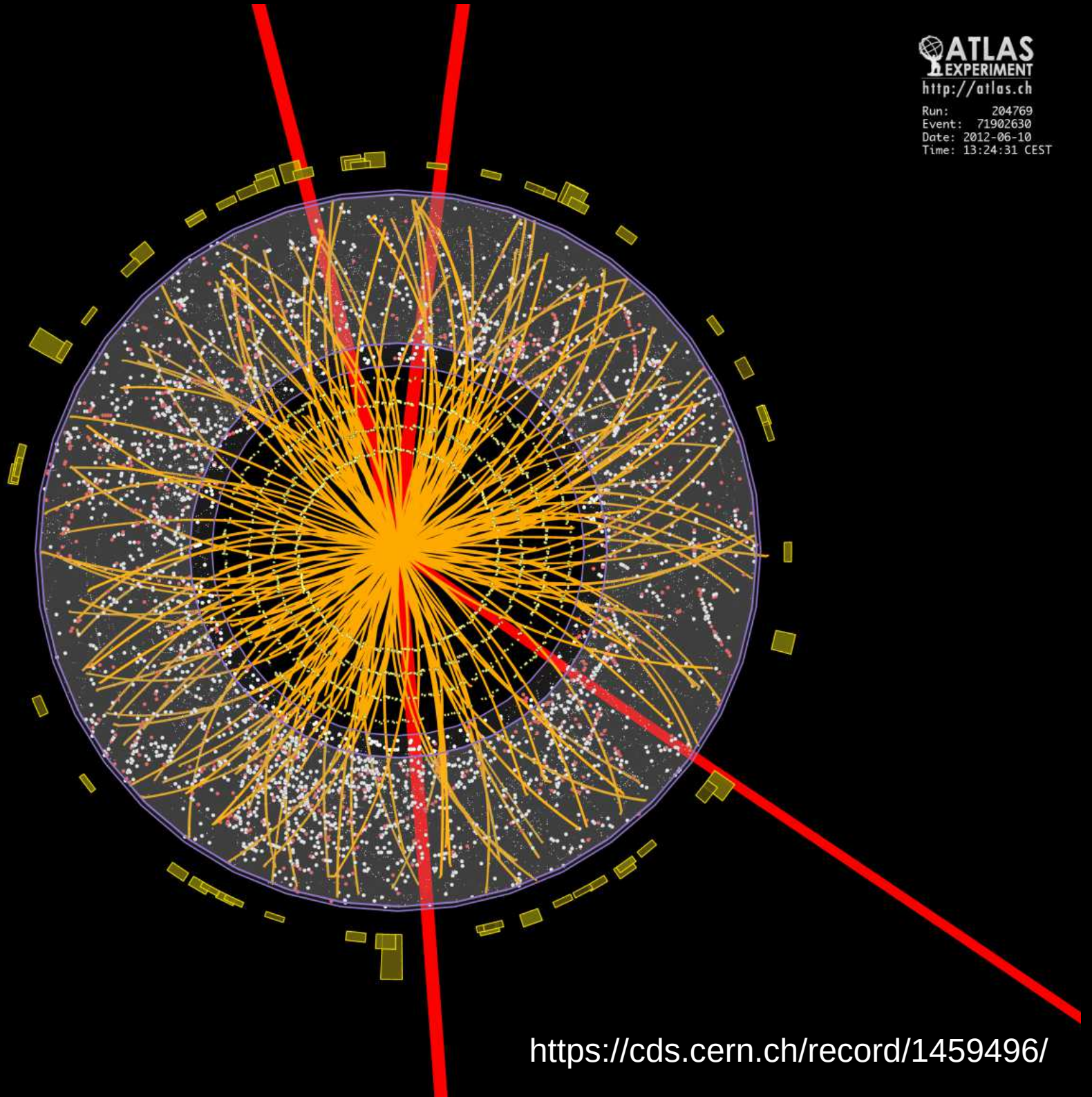
Event: 82614964

Date: 2012-05-18

Time: 20:28:11 CEST

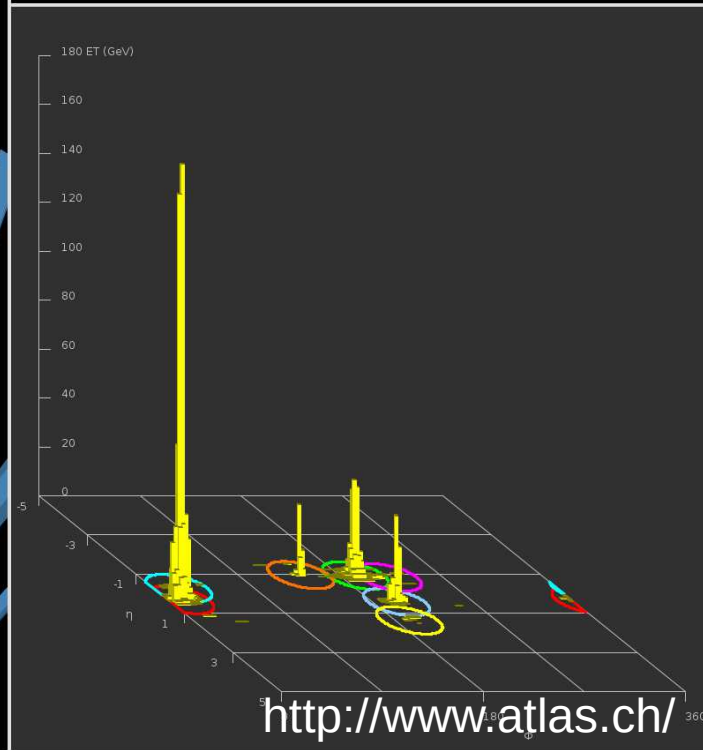
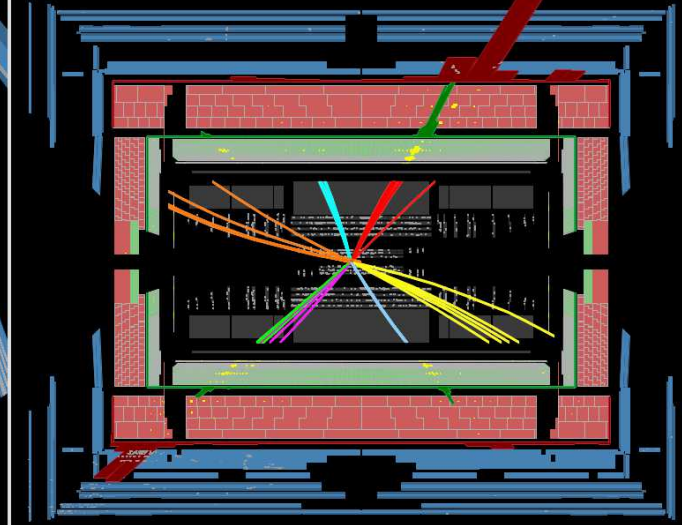
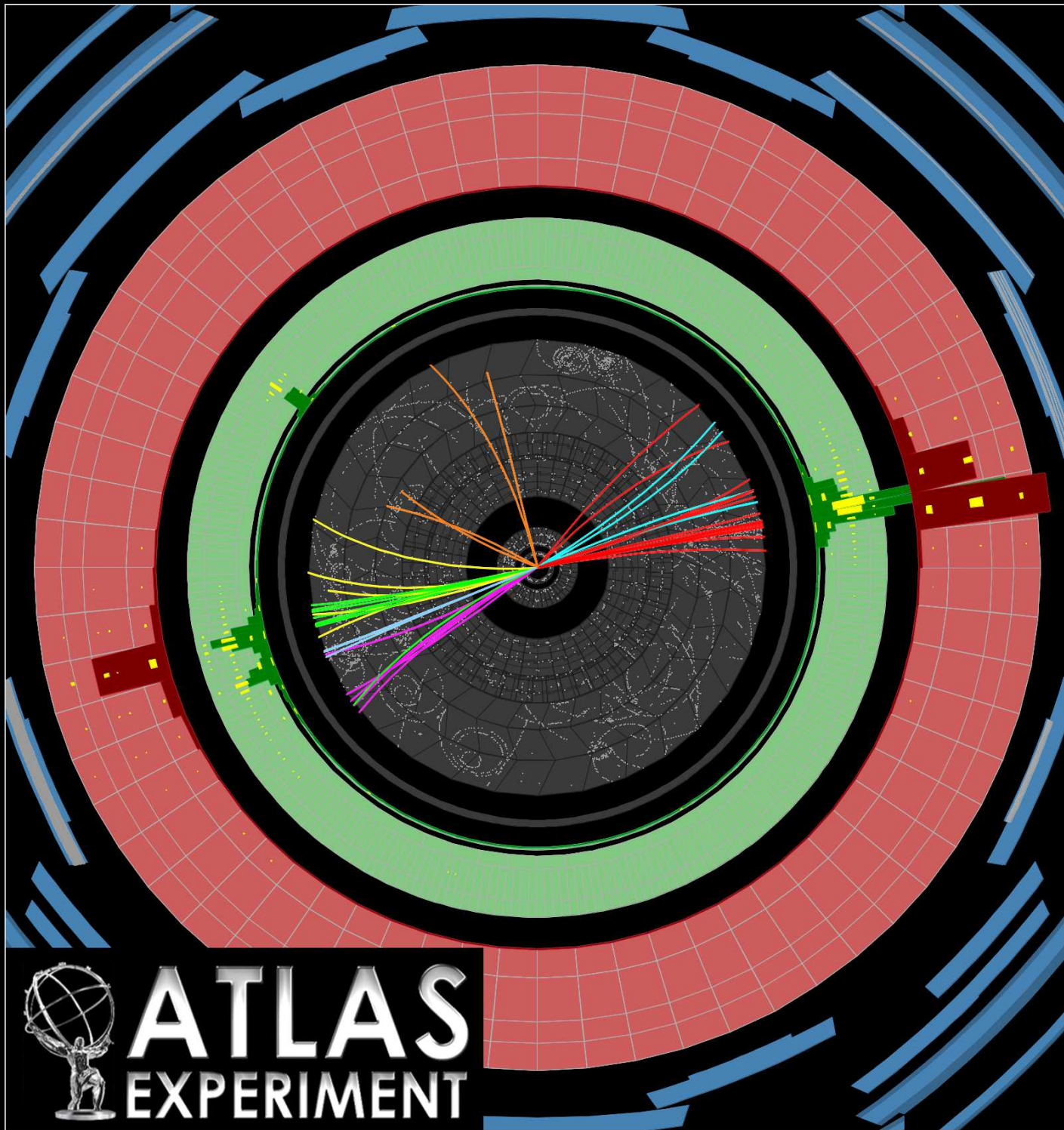


<https://cds.cern.ch/record/1459493>



Run Number: 159224, Event Number: 3533152

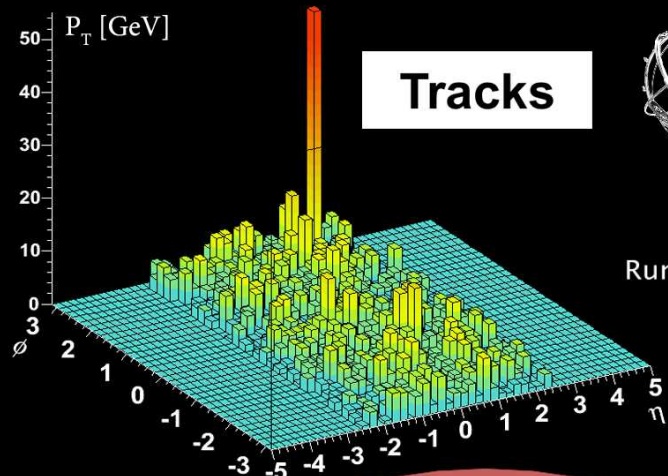
Date: 2010-07-18 11:05:54 CEST



ATLAS
EXPERIMENT

<http://www.atlas.ch/>

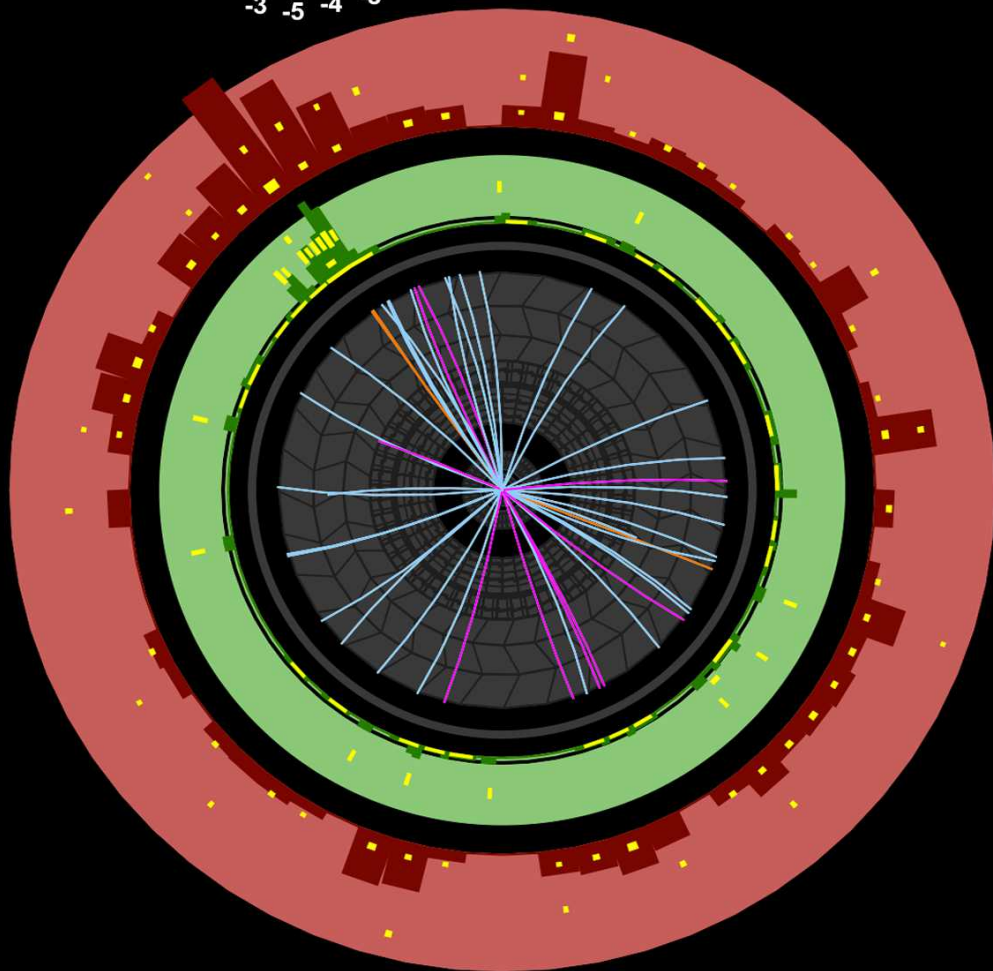
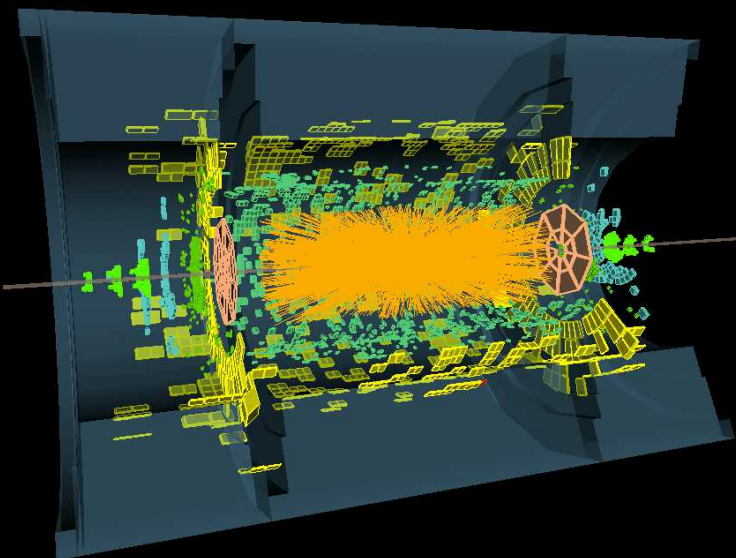
Tracks



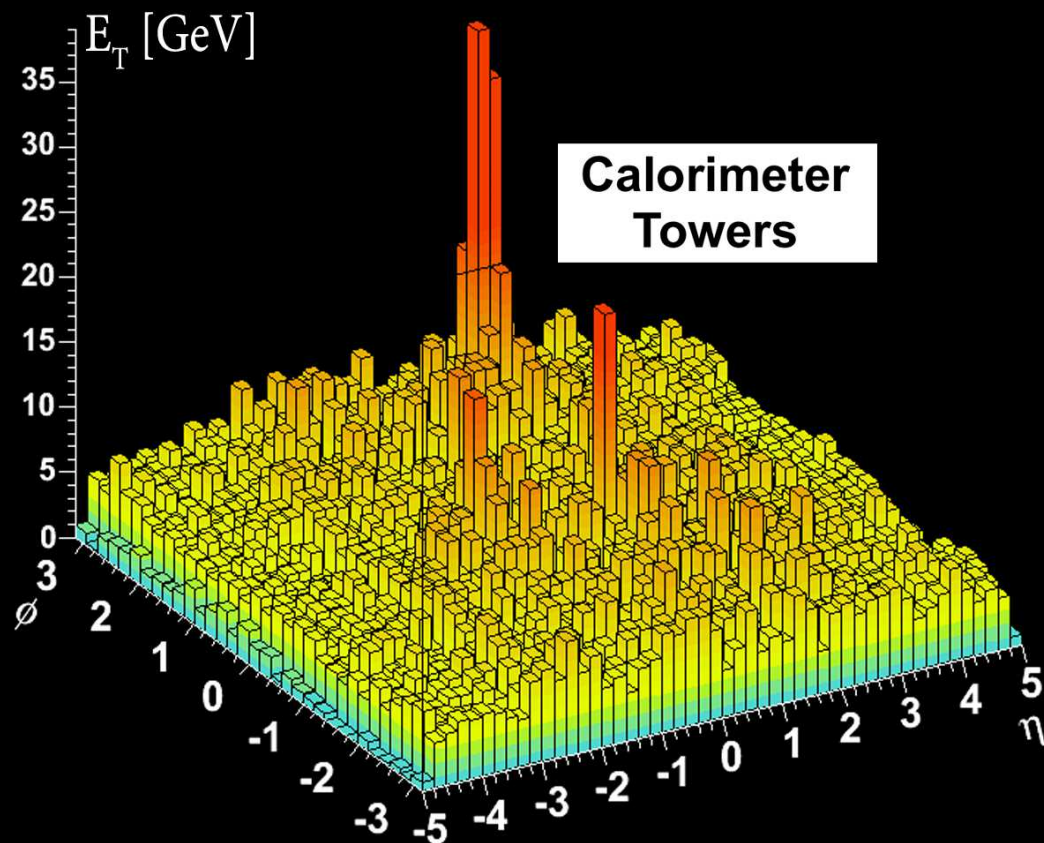
ATLAS EXPERIMENT

Run Number: 169136, Event Number: 1395684

Date: 2010-11-13 02:17:43 CET



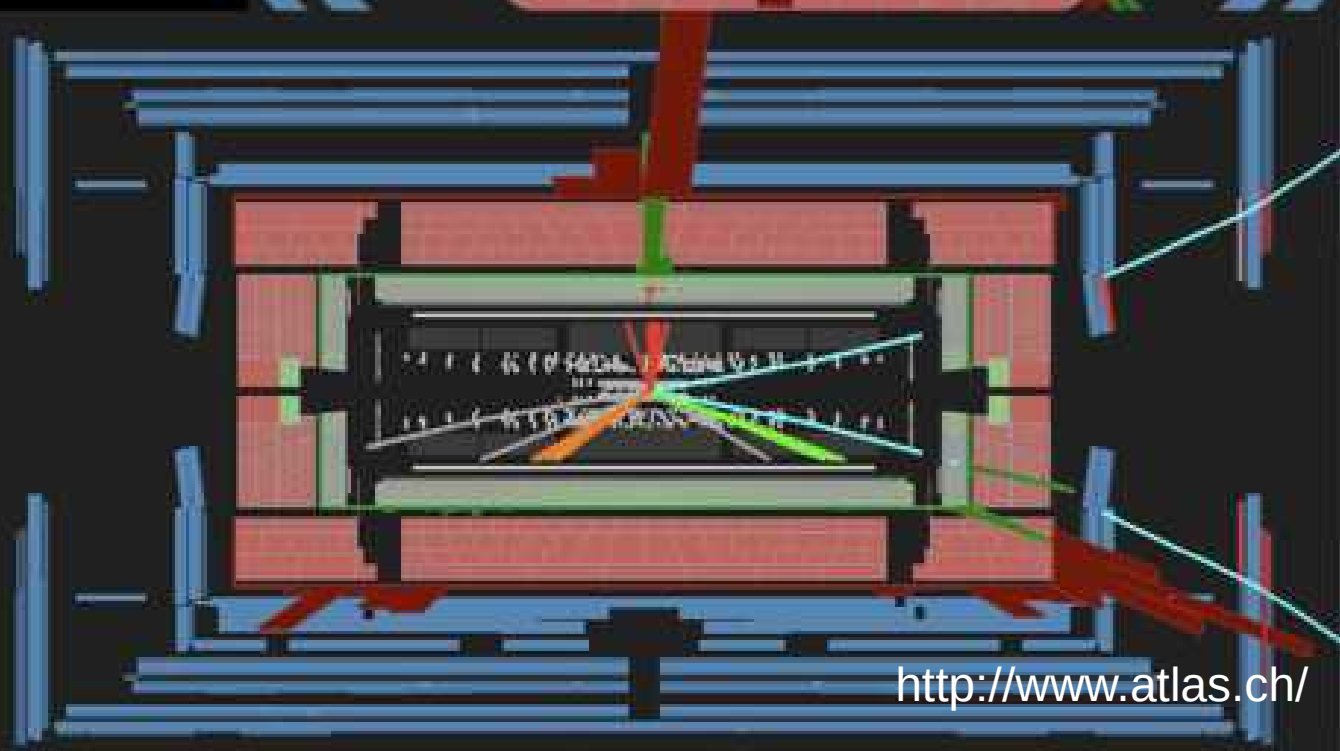
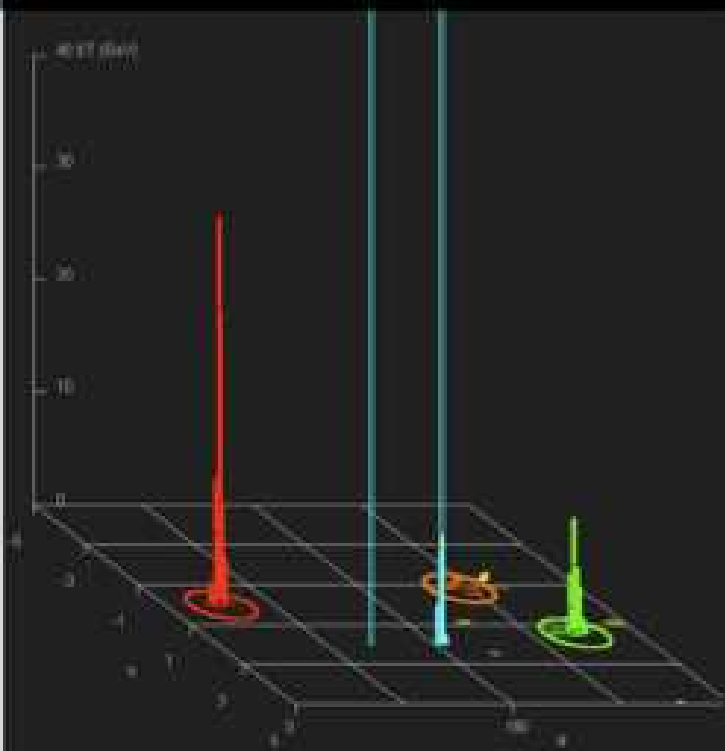
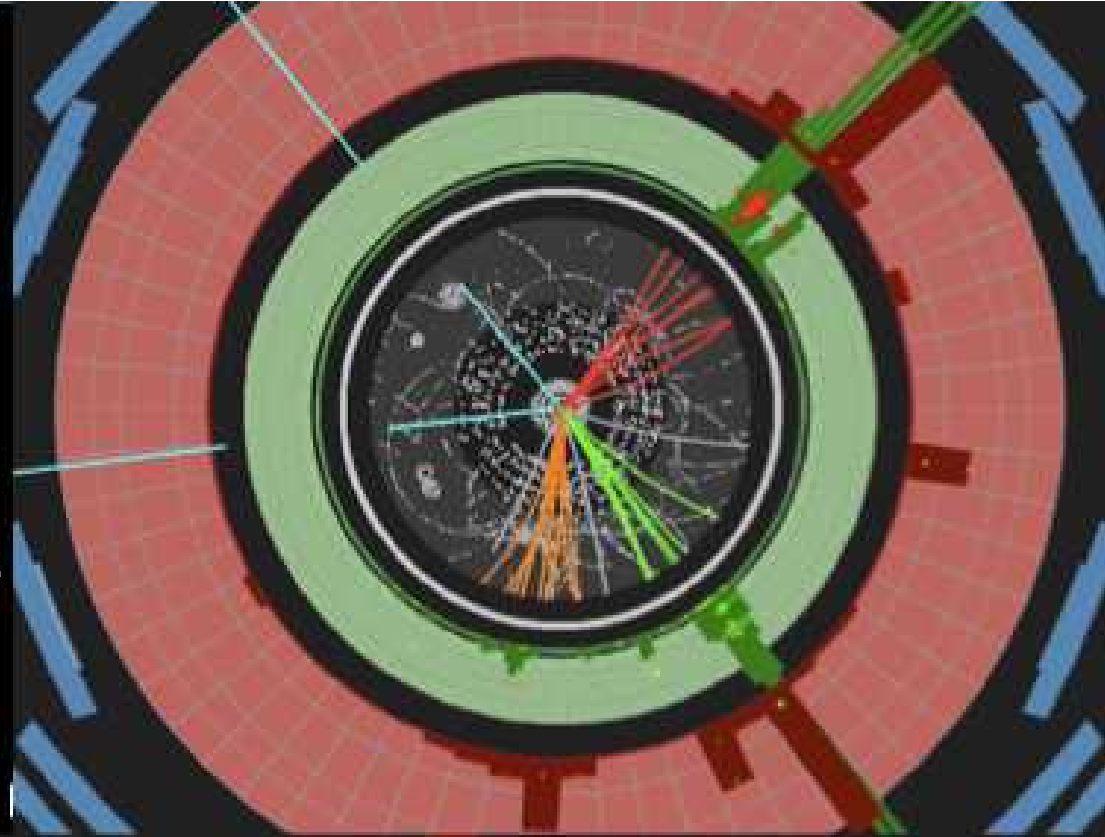
Calorimeter
Towers

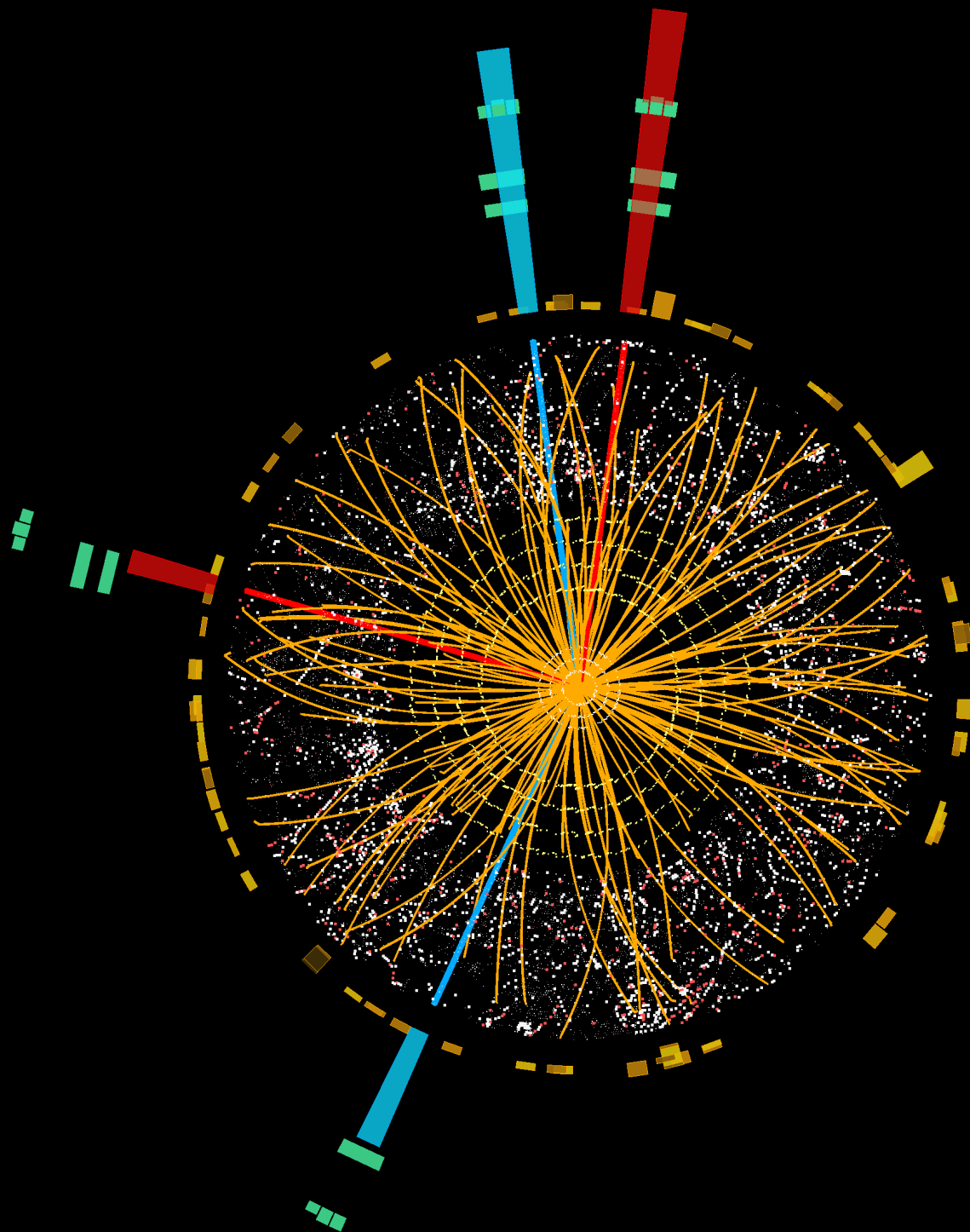




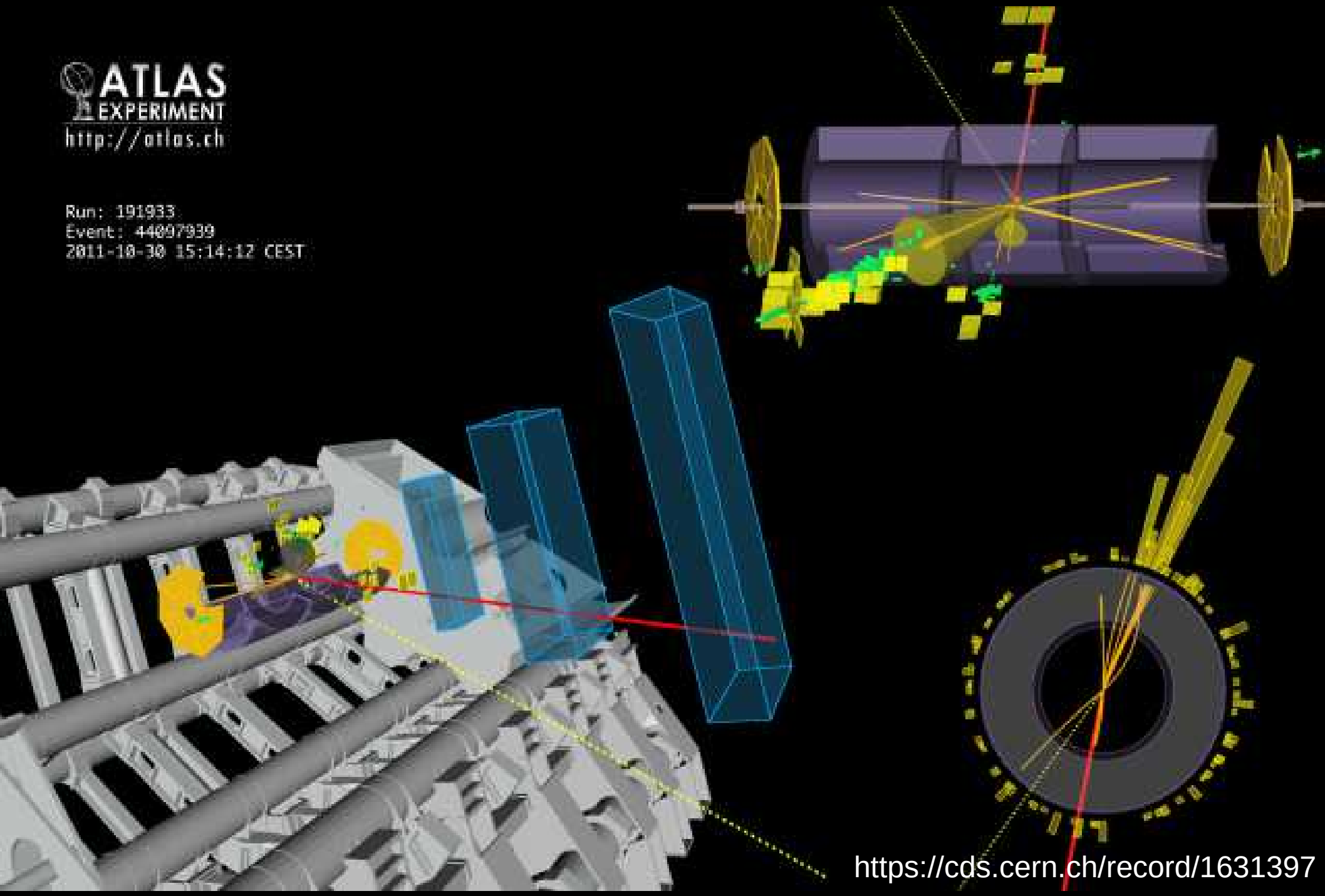
ATLAS EXPERIMENT

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





Run: 191933
Event: 44007939
2011-10-30 15:14:12 CEST



People are not good at this.

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



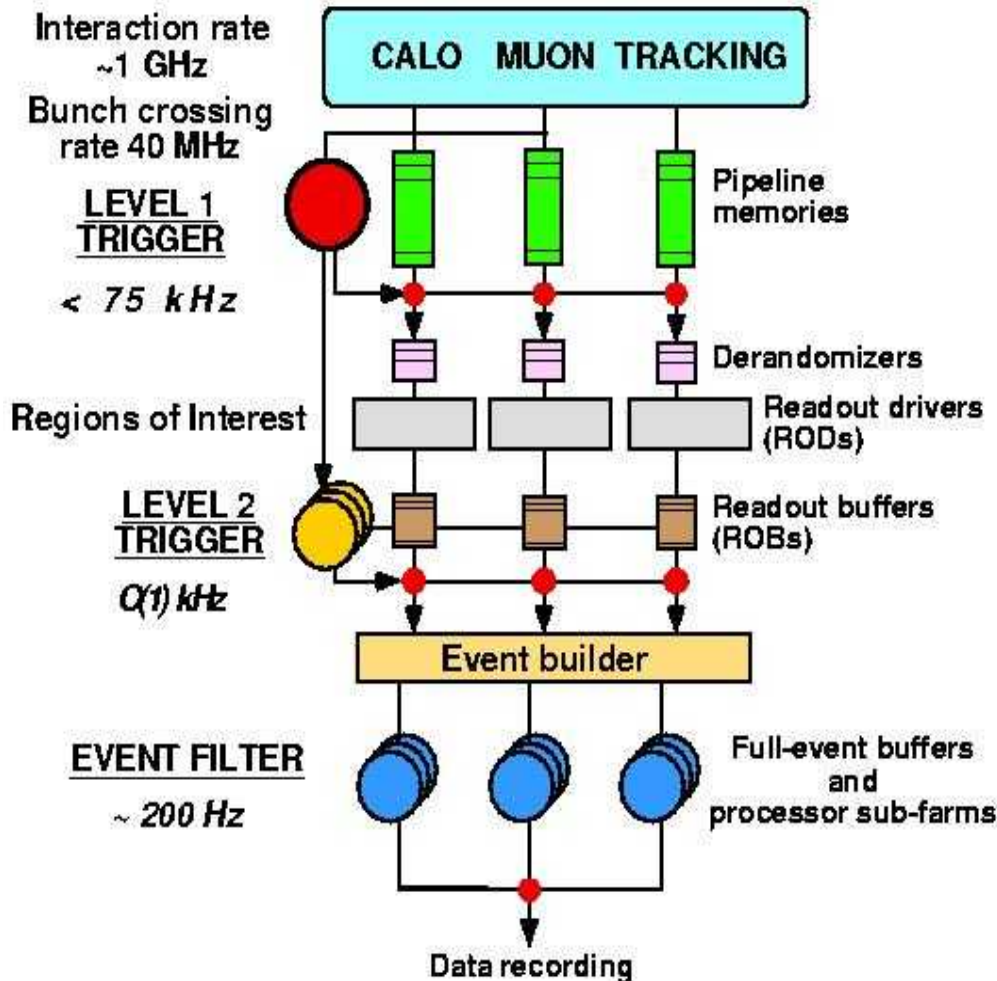
www.atlas.ch

↓ 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 (\sim 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)

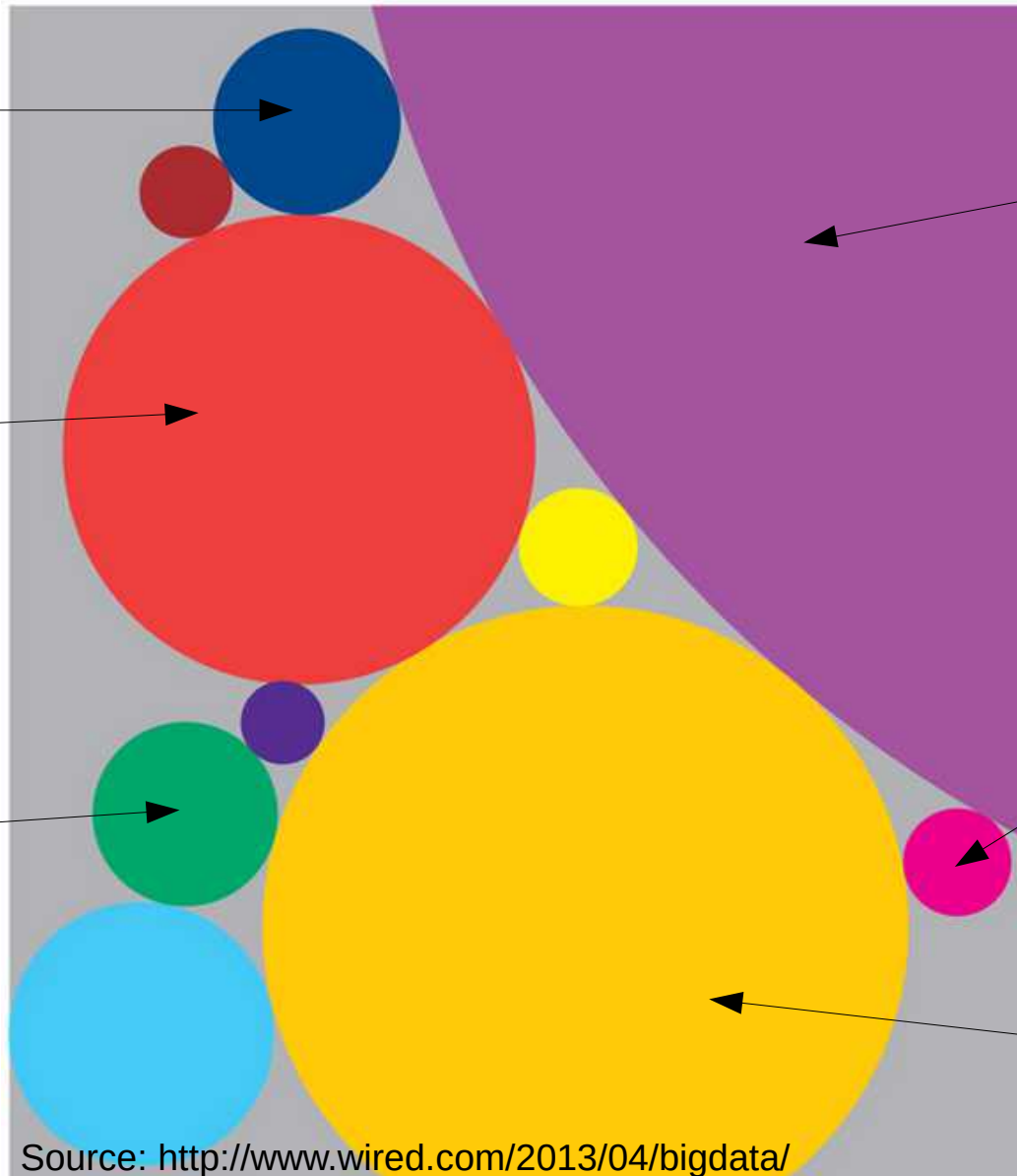
Google's search index

Videos uploaded to YouTube each year

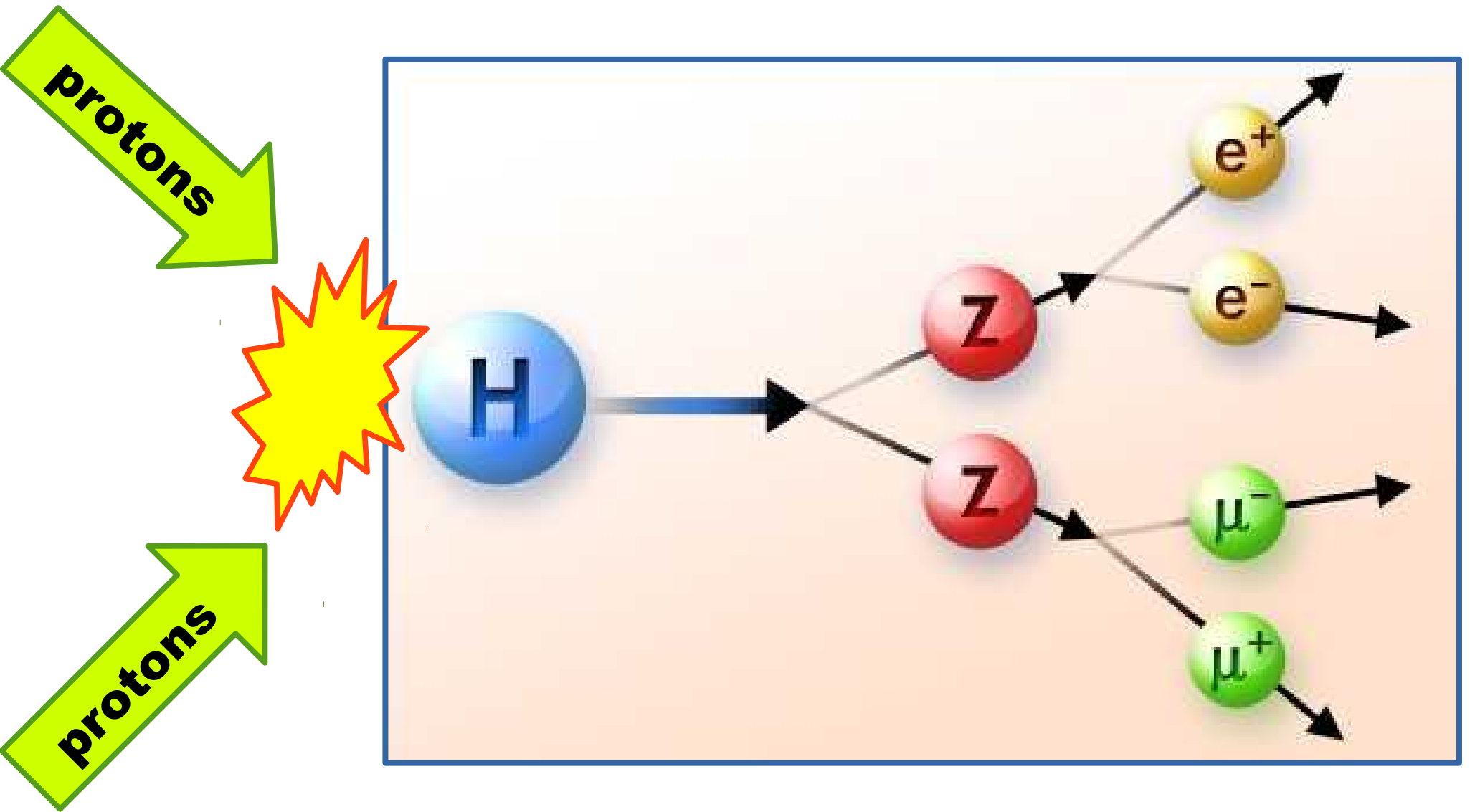
Business emails sent each year

Library of Congress' digital collection

Content uploaded to Facebook each year

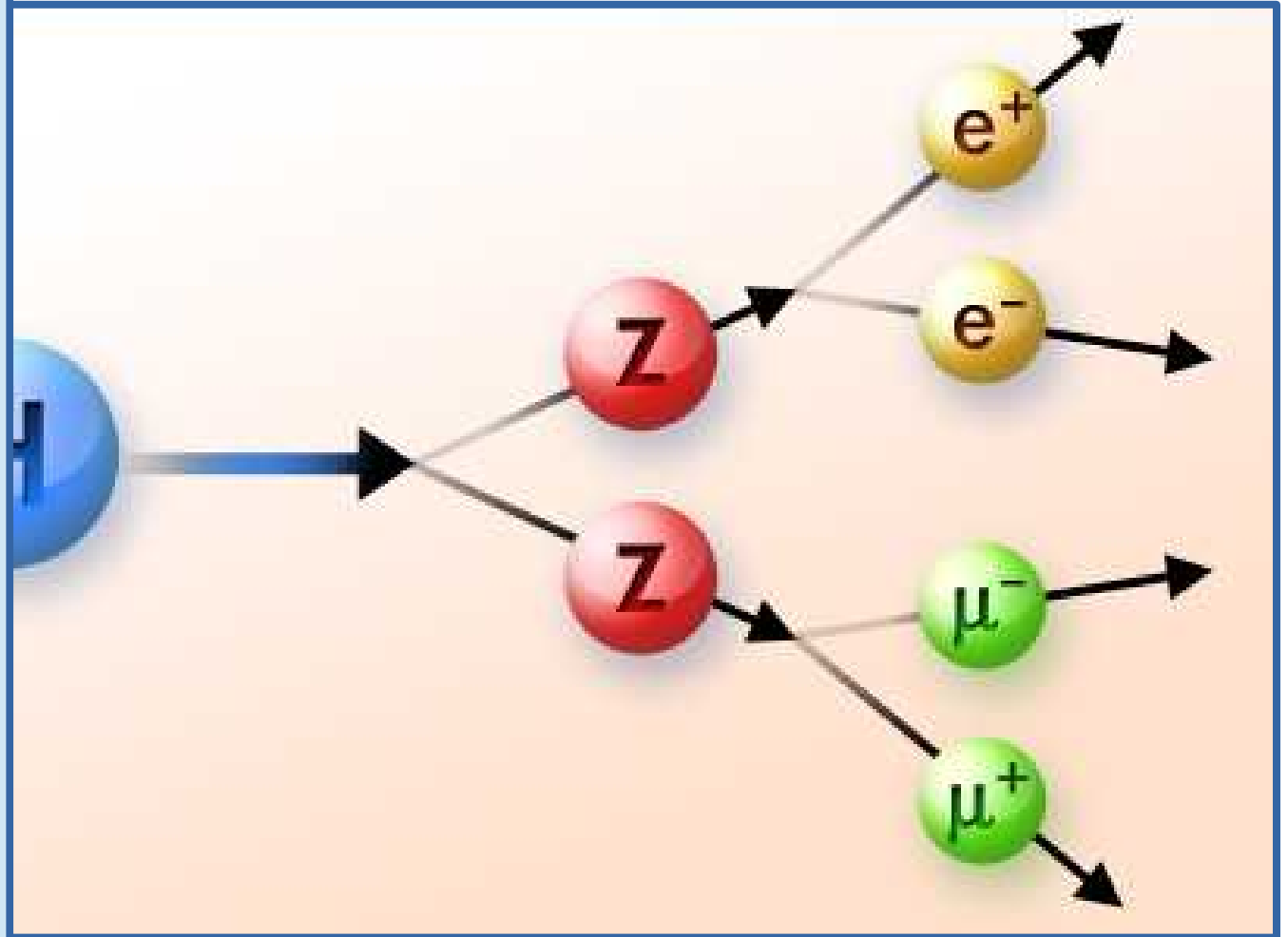


Now, back to the search.



Now, back to the search.

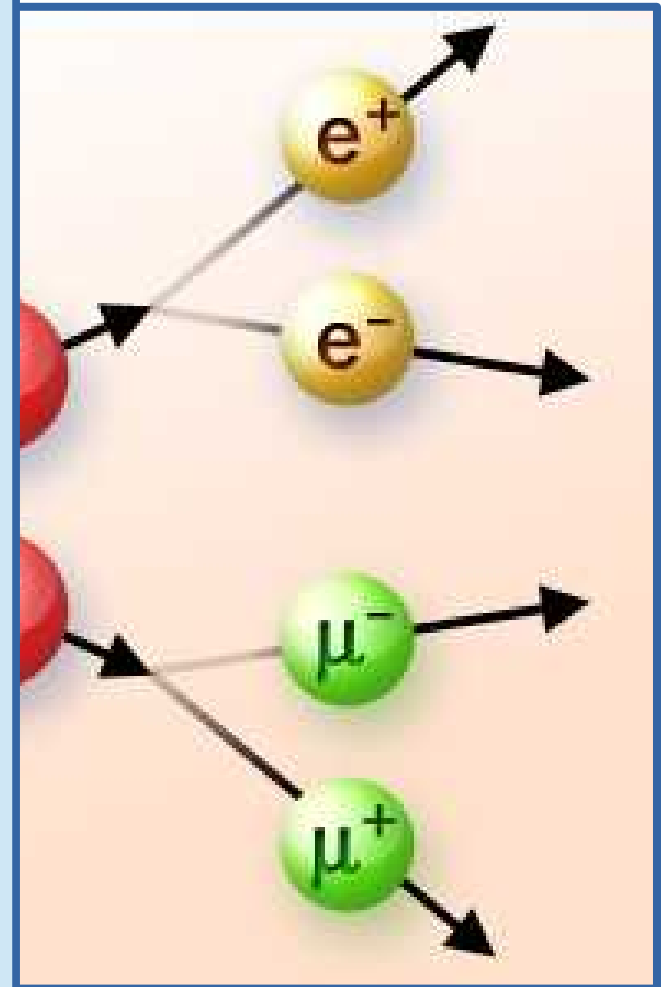
**Protons:
collided**



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

Everything on the beach



Metal things



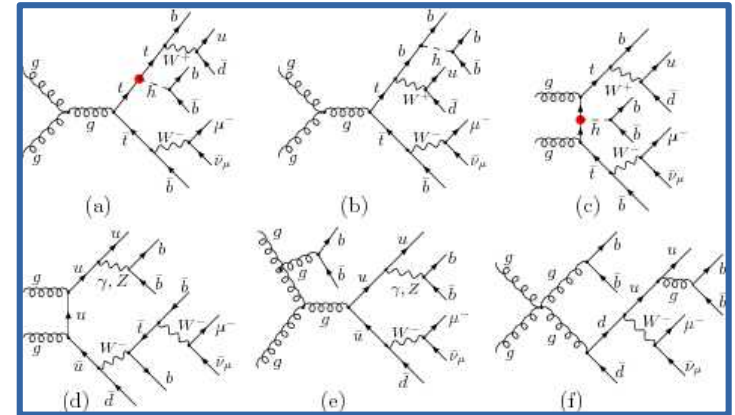
Pirate treasure



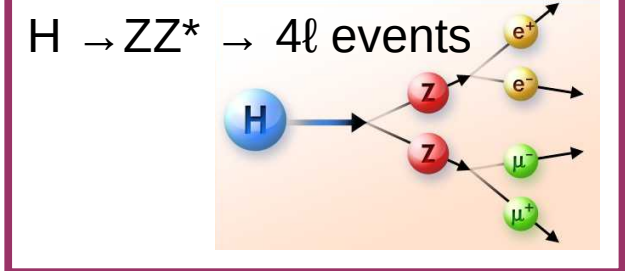
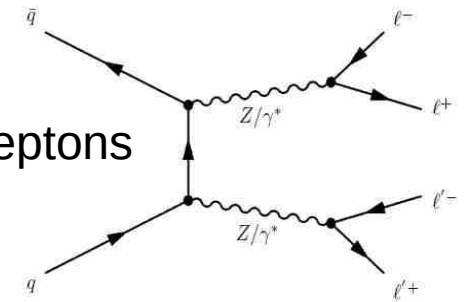
Signal and Background (Higgs)

- Search criteria =
 - 4 leptons
 - Signal = $H \rightarrow ZZ^* \rightarrow 4\ell$
 - “reducible” background: 3-lepton events, etc.
- Results: 4-lepton events, some from Higgs decay
 - “irreducible” background: $pp \rightarrow ZZ \rightarrow 4\ell$

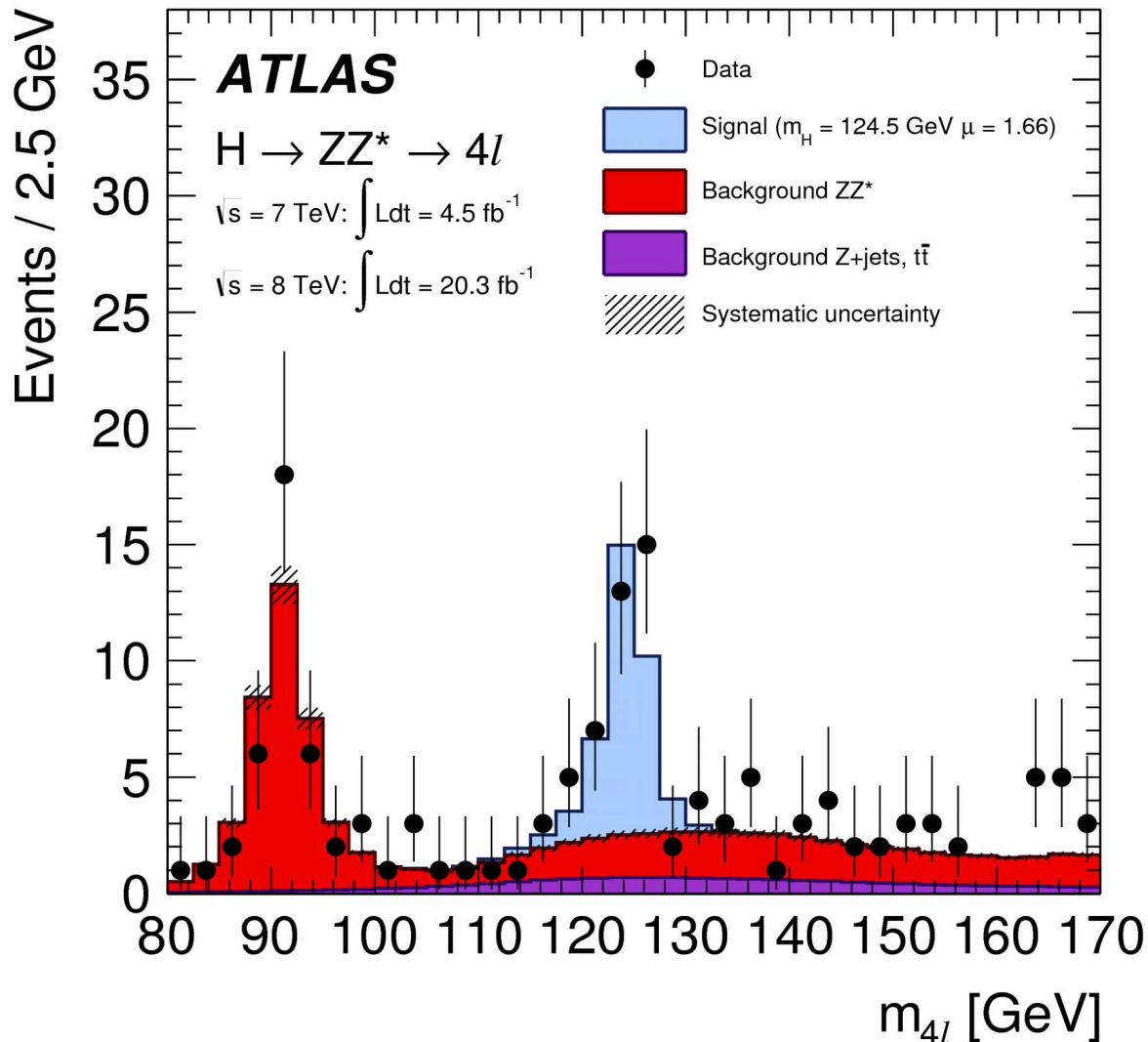
All events



Events with 4 leptons

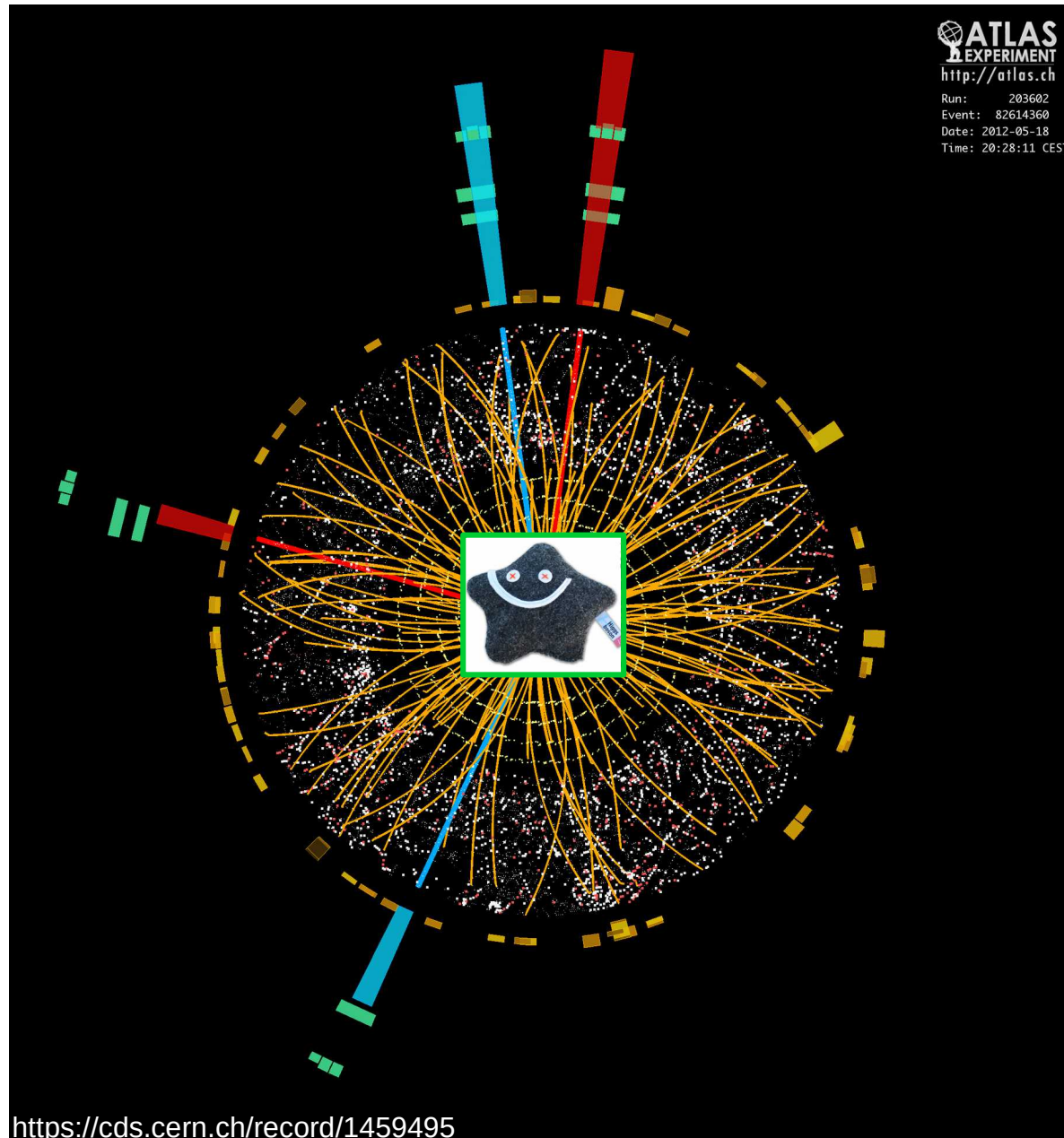


Now: plot the invariant mass of 4-lepton events

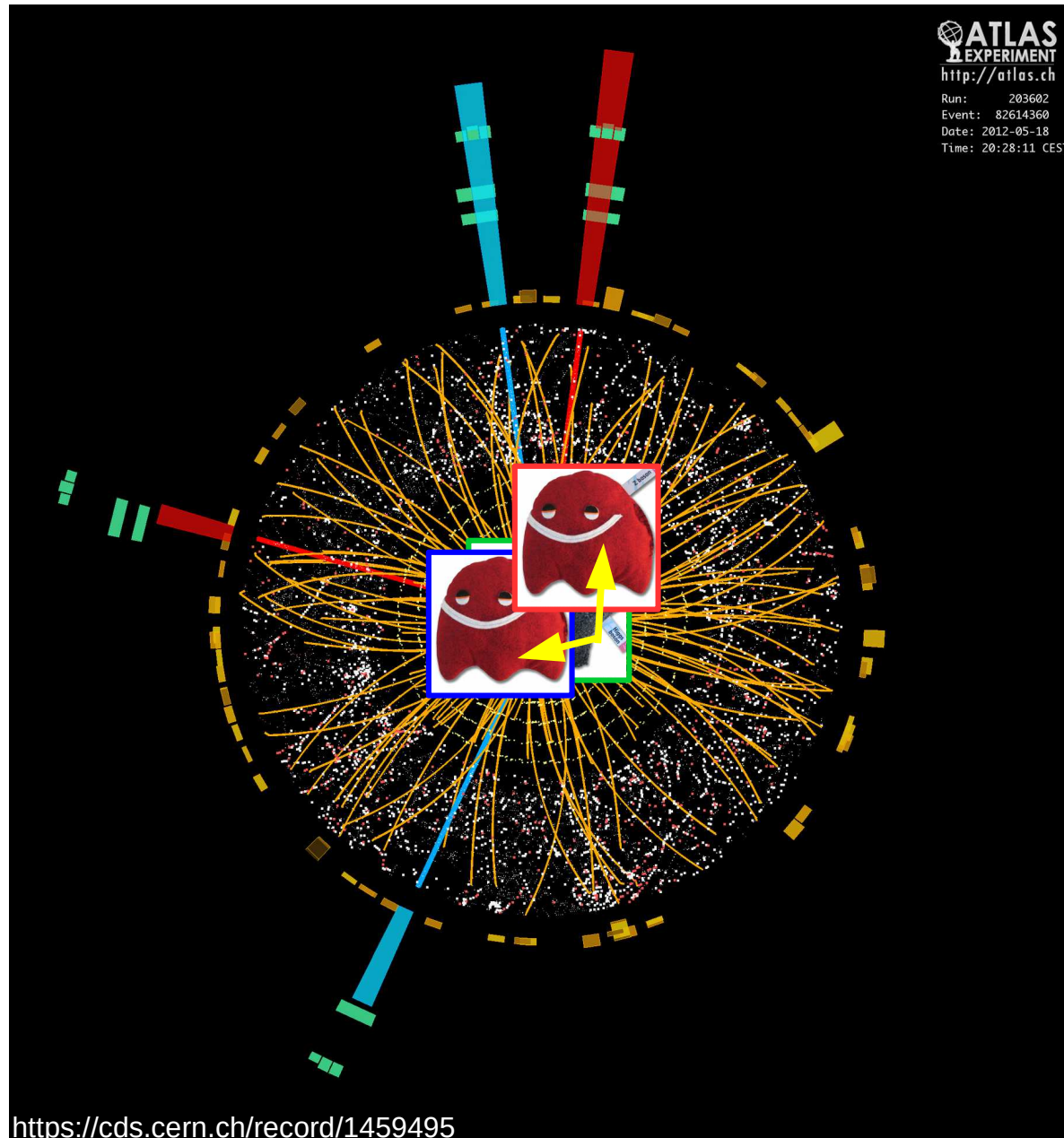


ATLAS Collaboration, Phys. Rev. D 90, 052004 (2014)

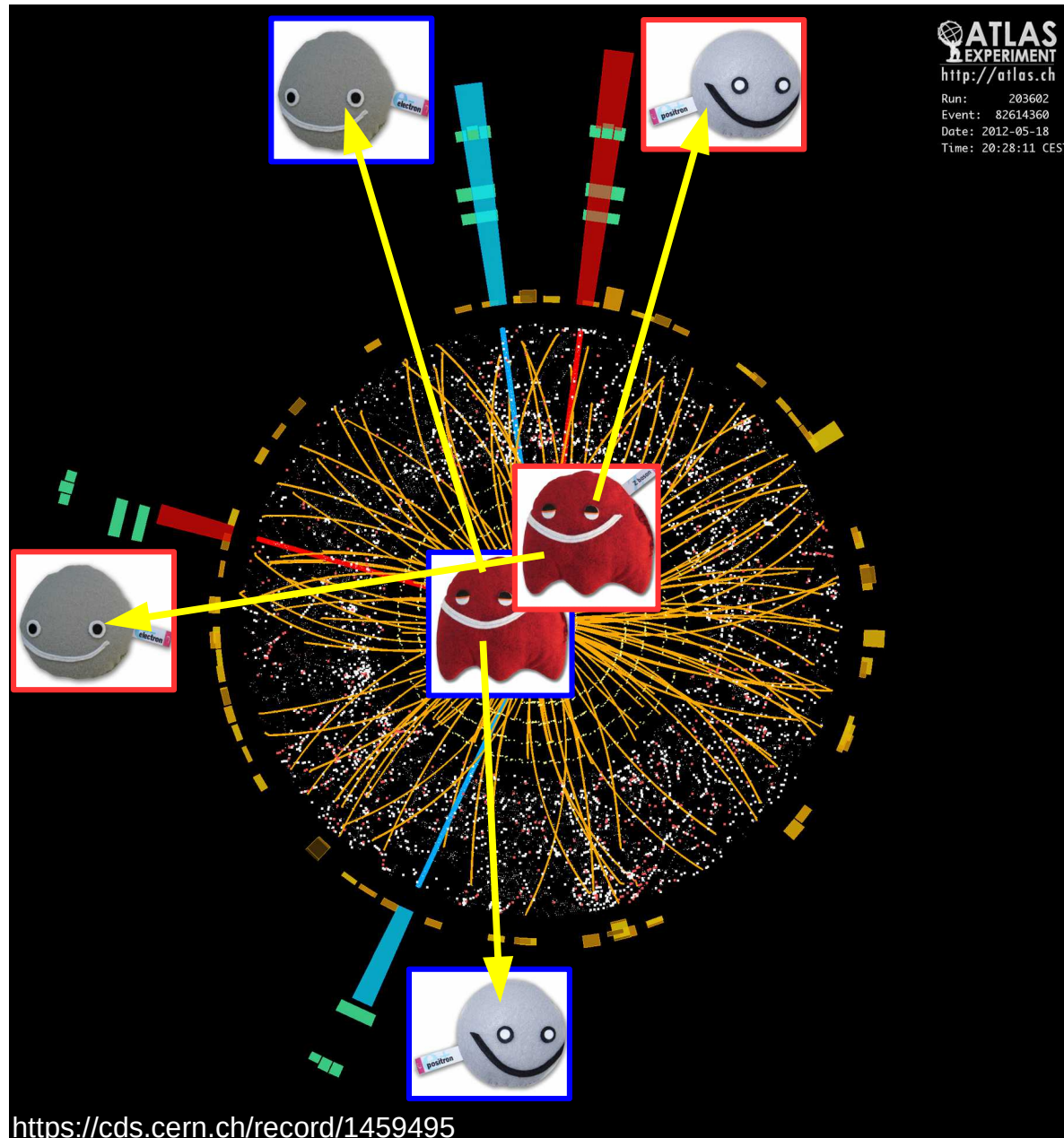
Calculate Invariant Mass



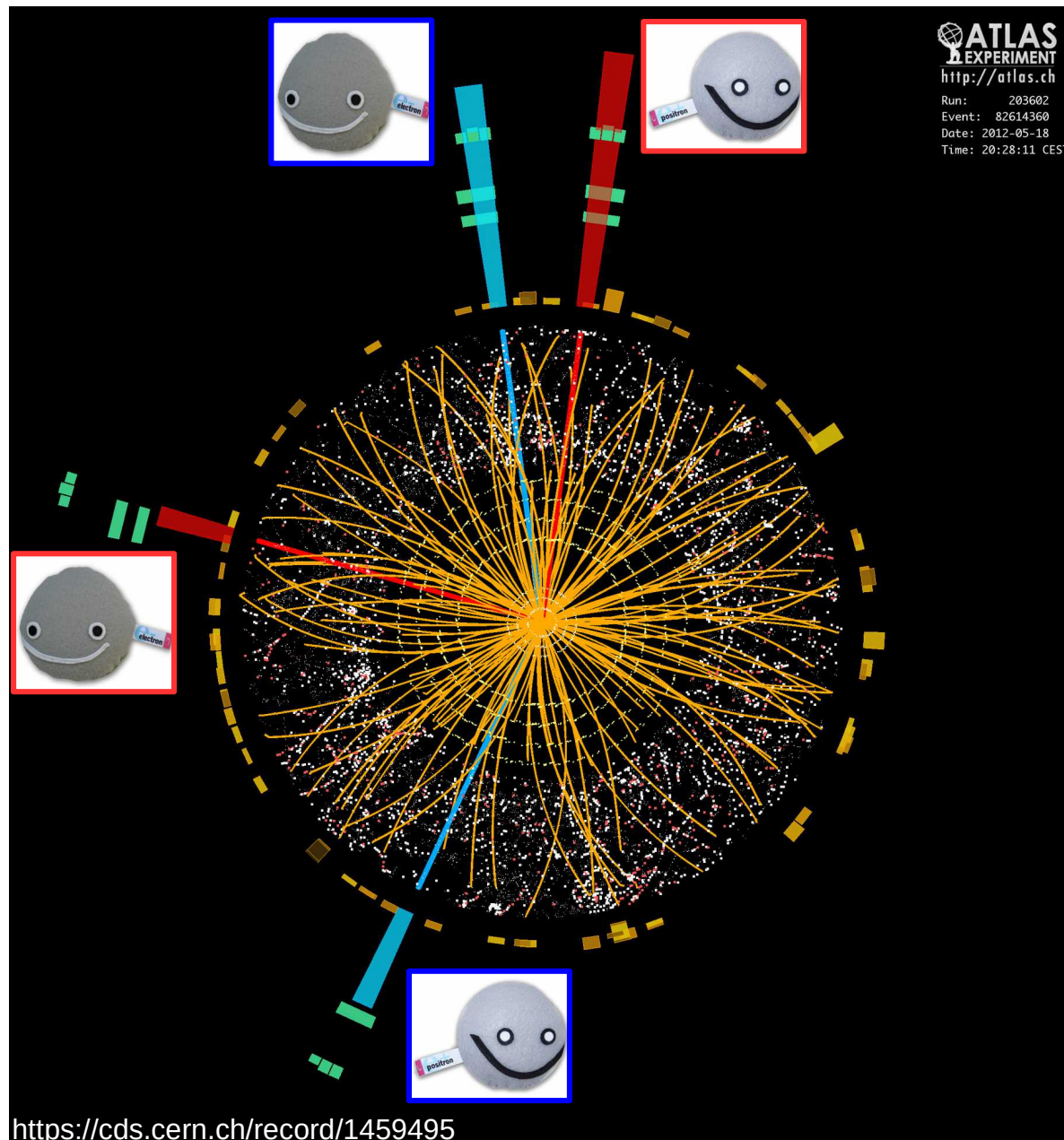
Calculate Invariant Mass



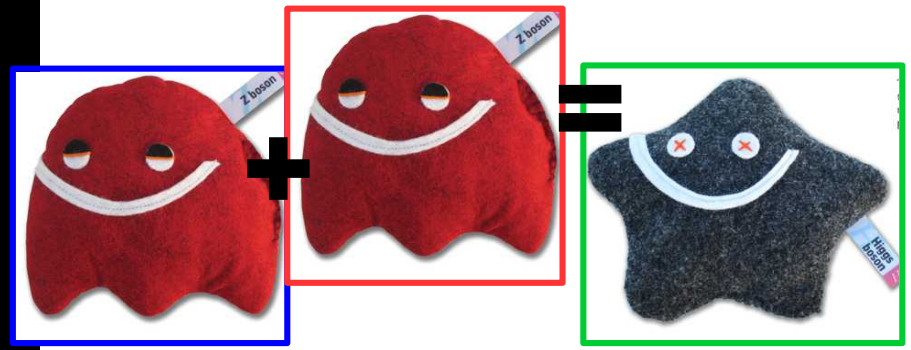
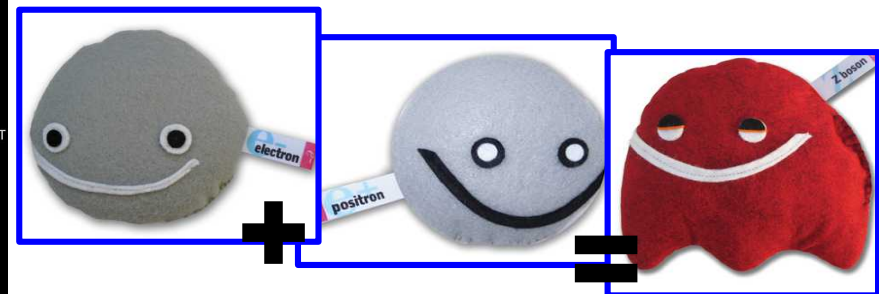
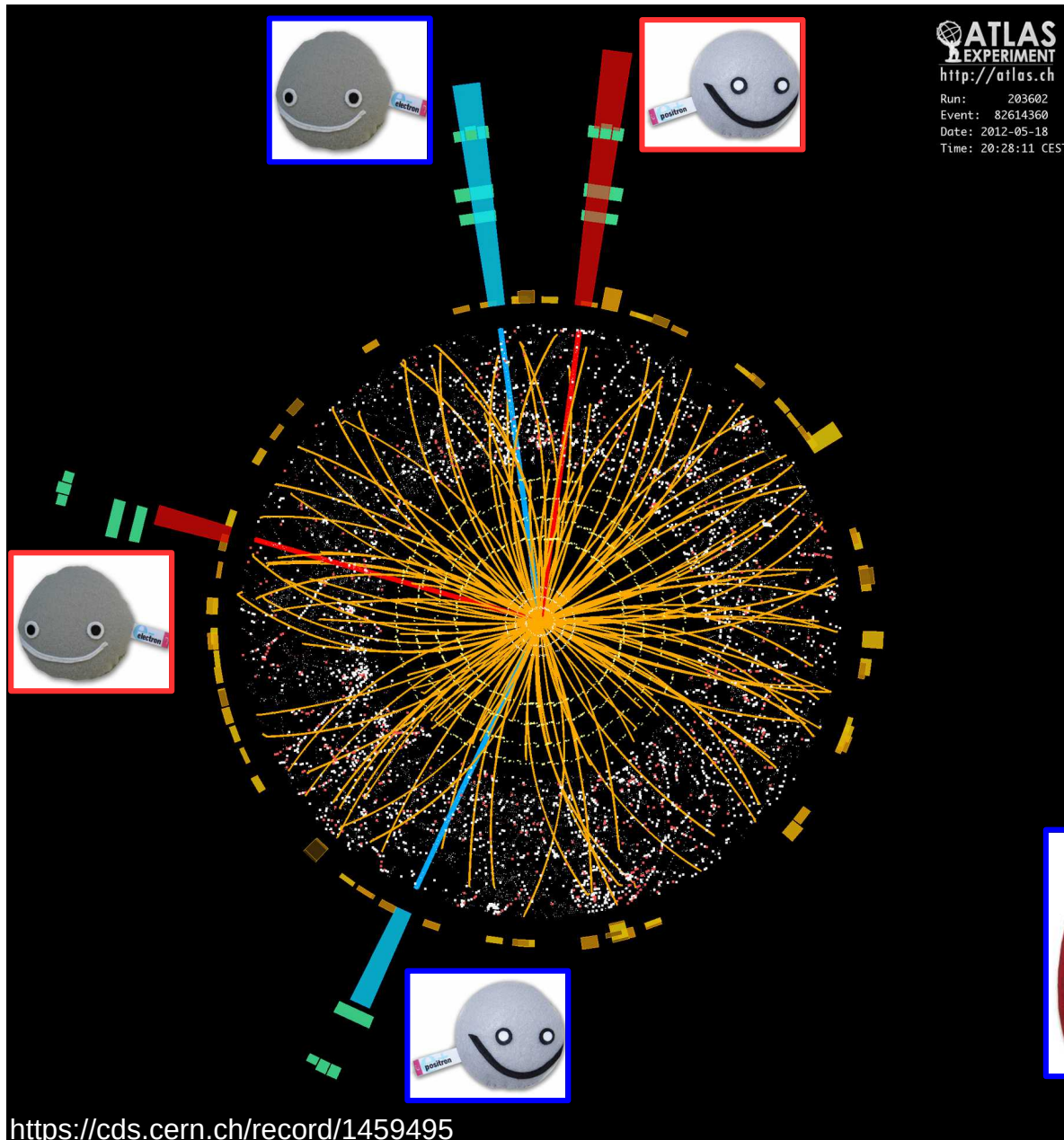
Calculate Invariant Mass



Calculate Invariant Mass

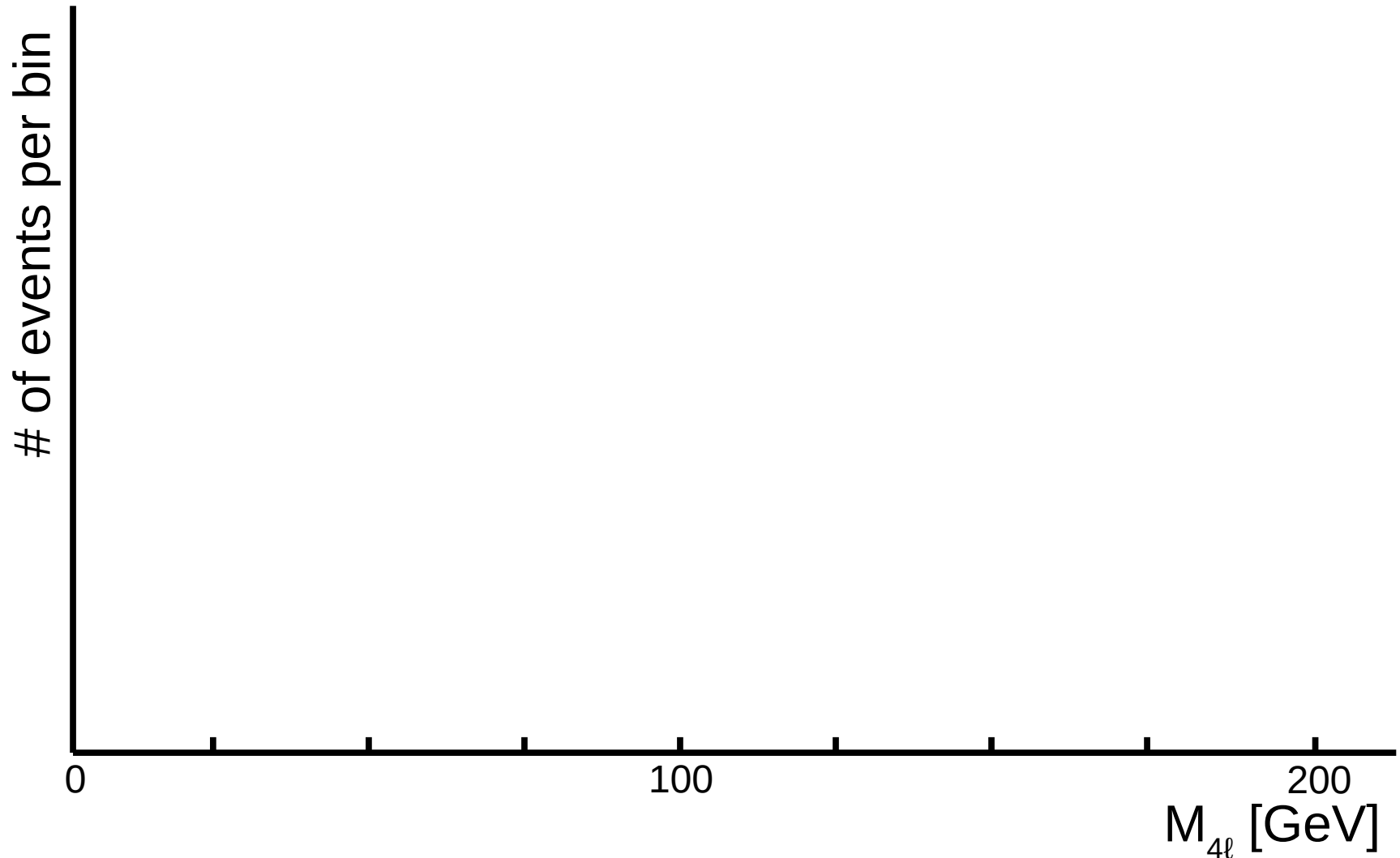


Calculate Invariant Mass

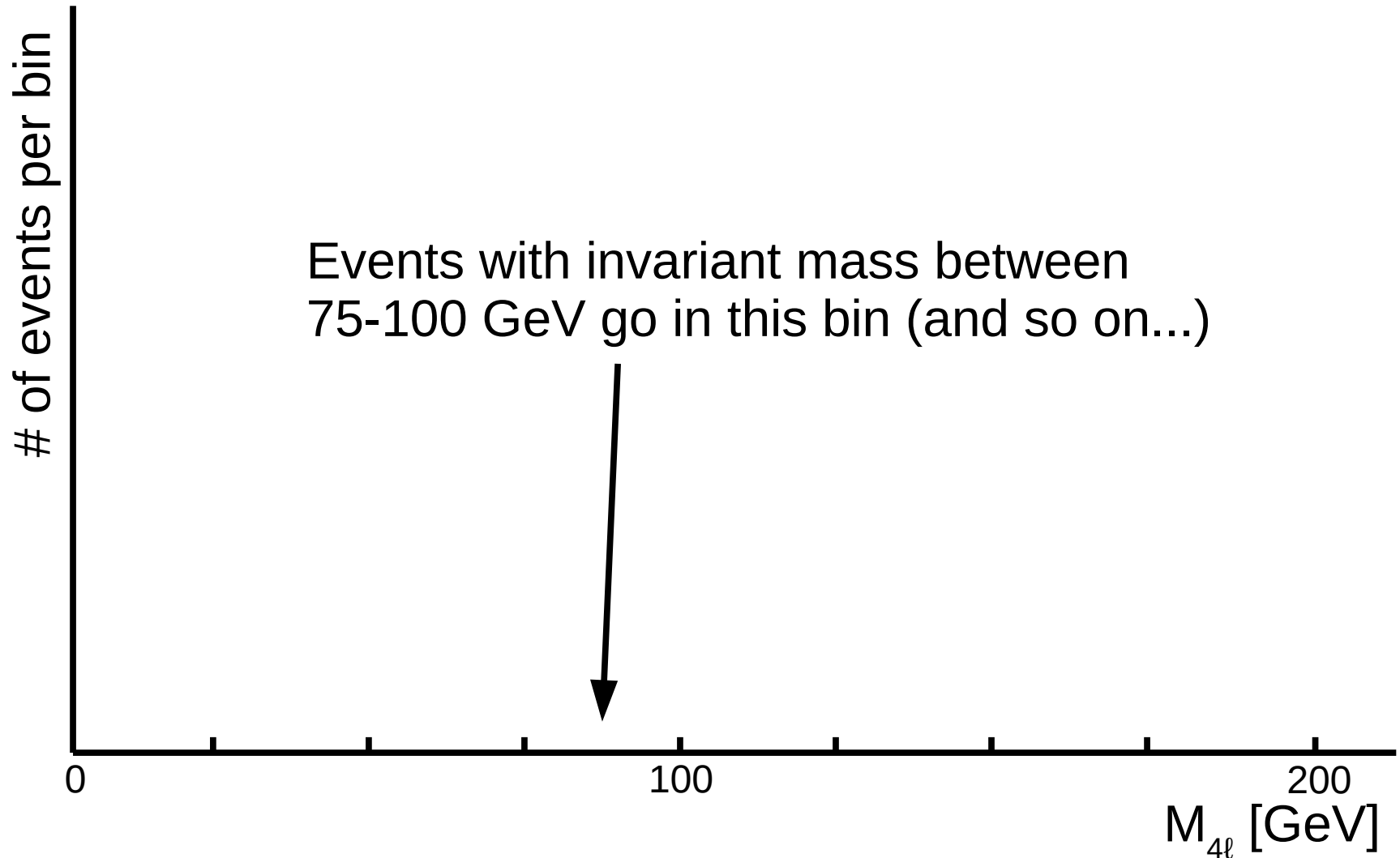


<https://cds.cern.ch/record/1459495>

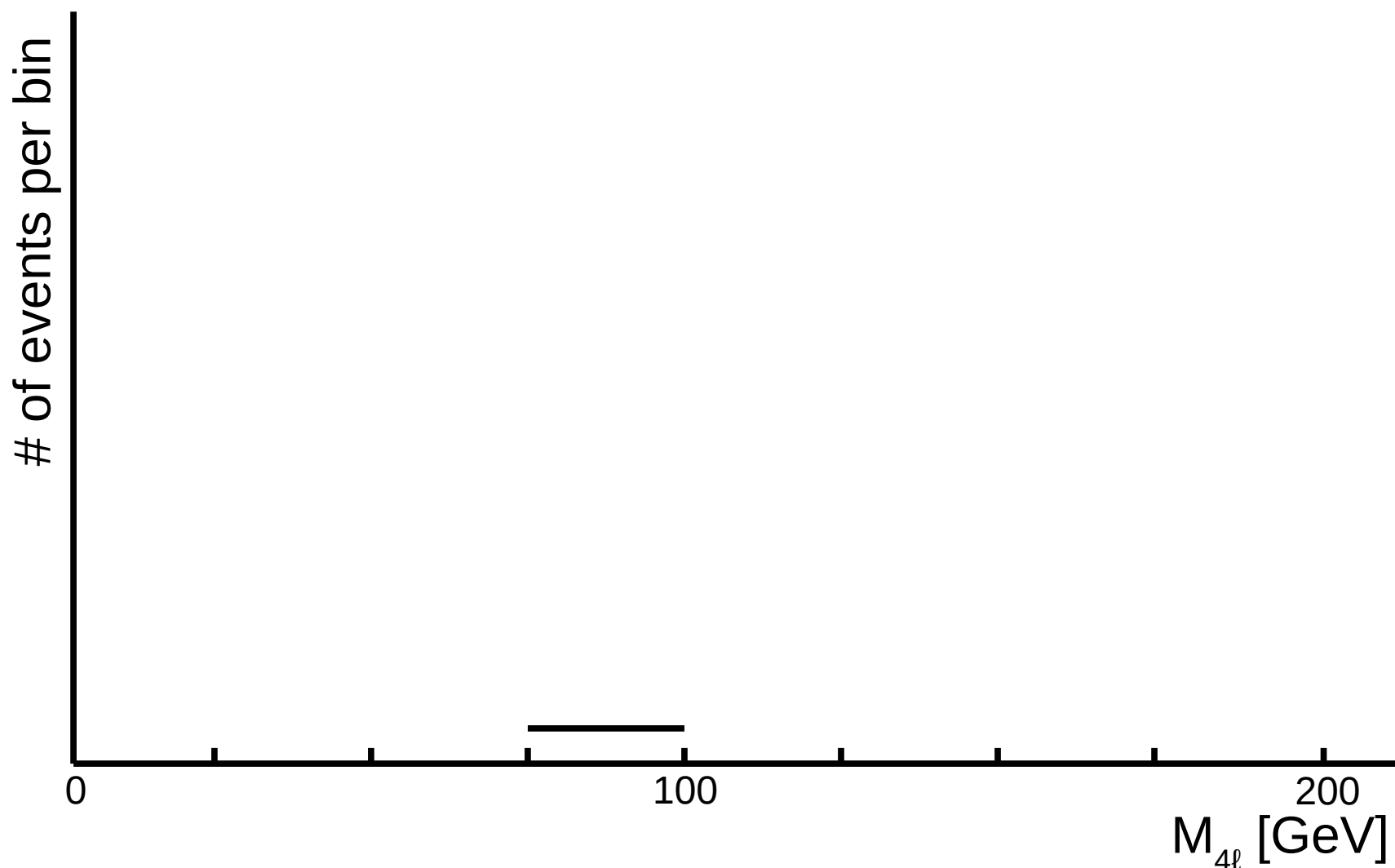
Now, we can plot the measured 4ℓ invariant mass:



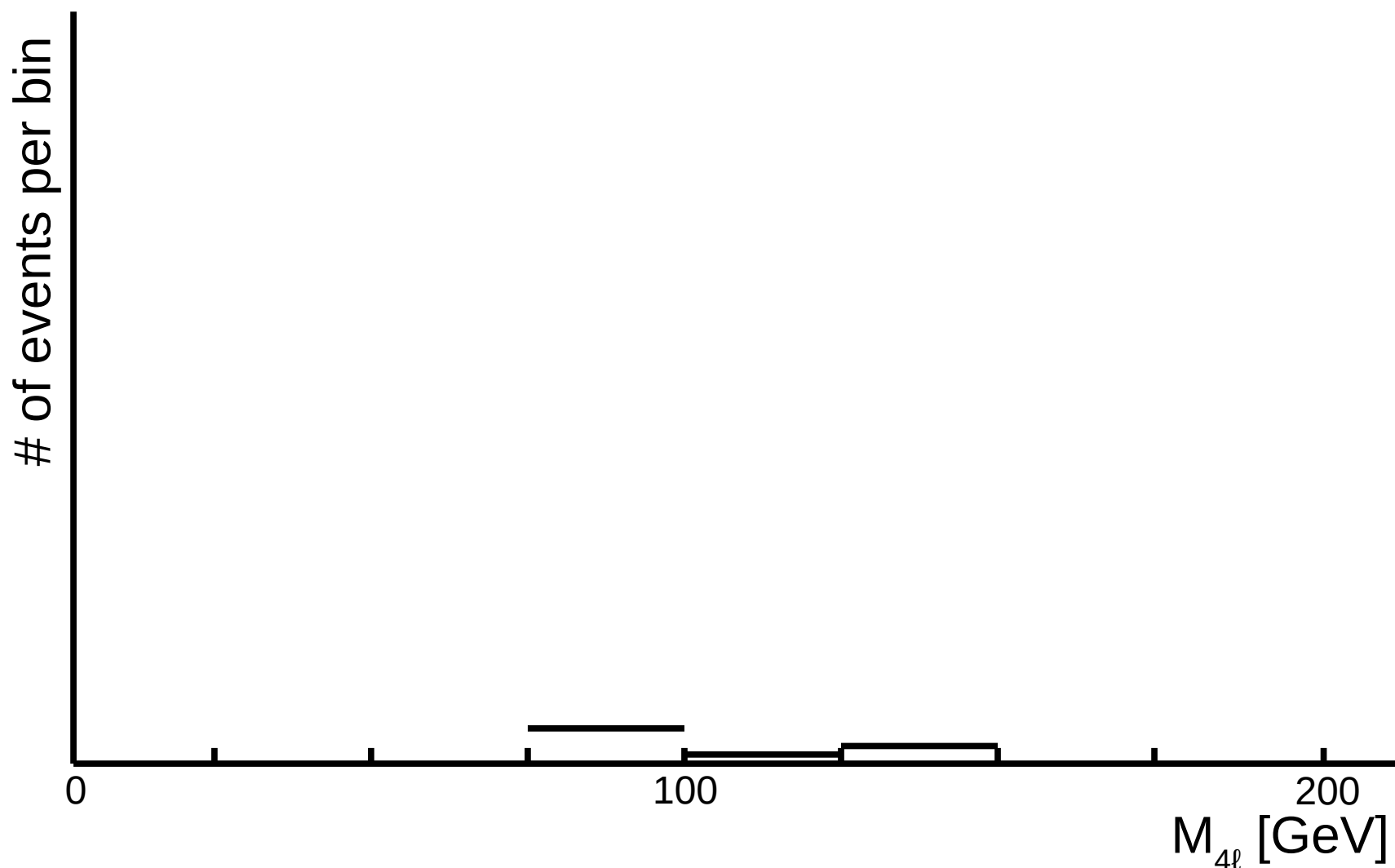
Now, we can plot the measured 4ℓ invariant mass:



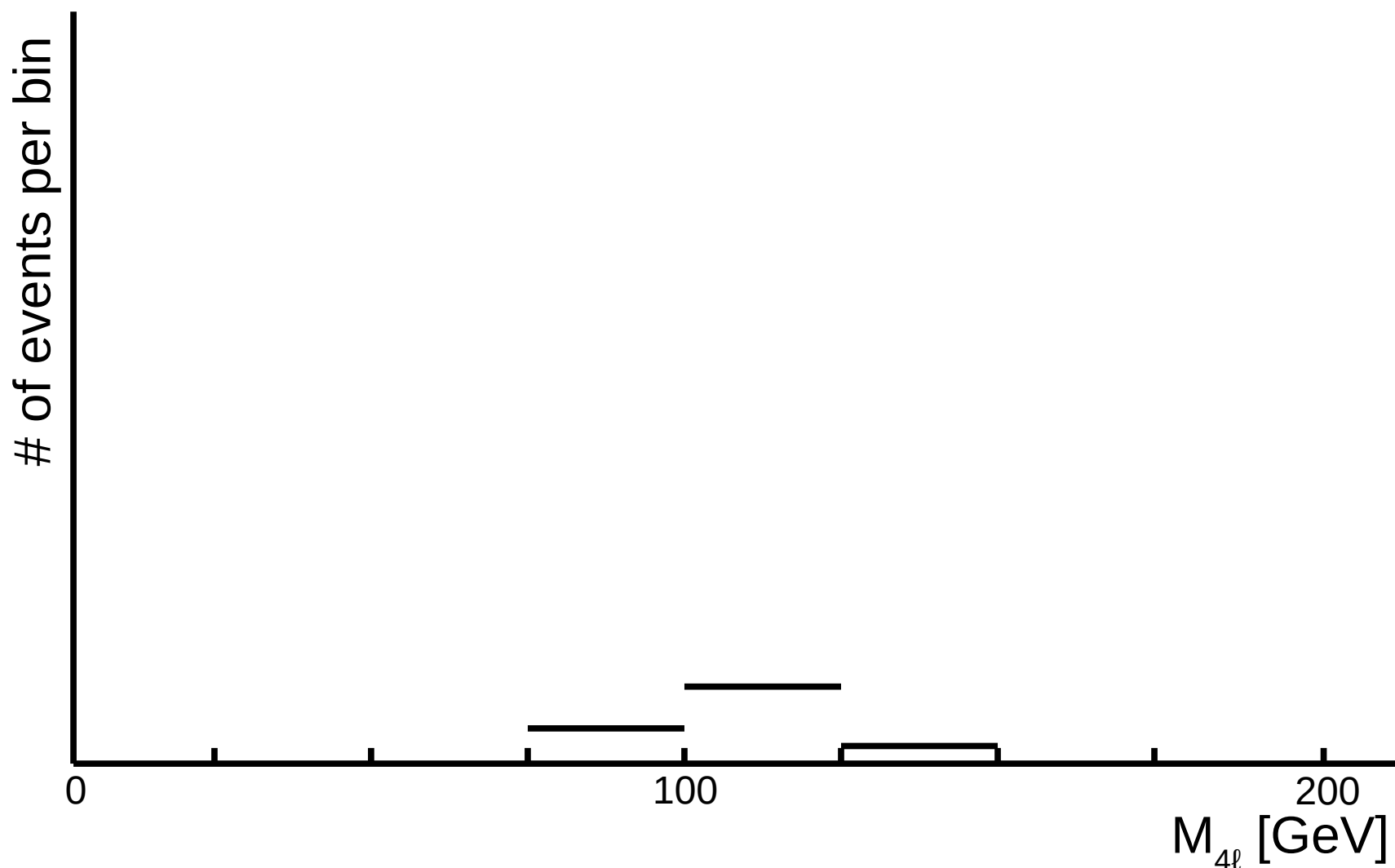
Now, we can plot the measured 4ℓ invariant mass:



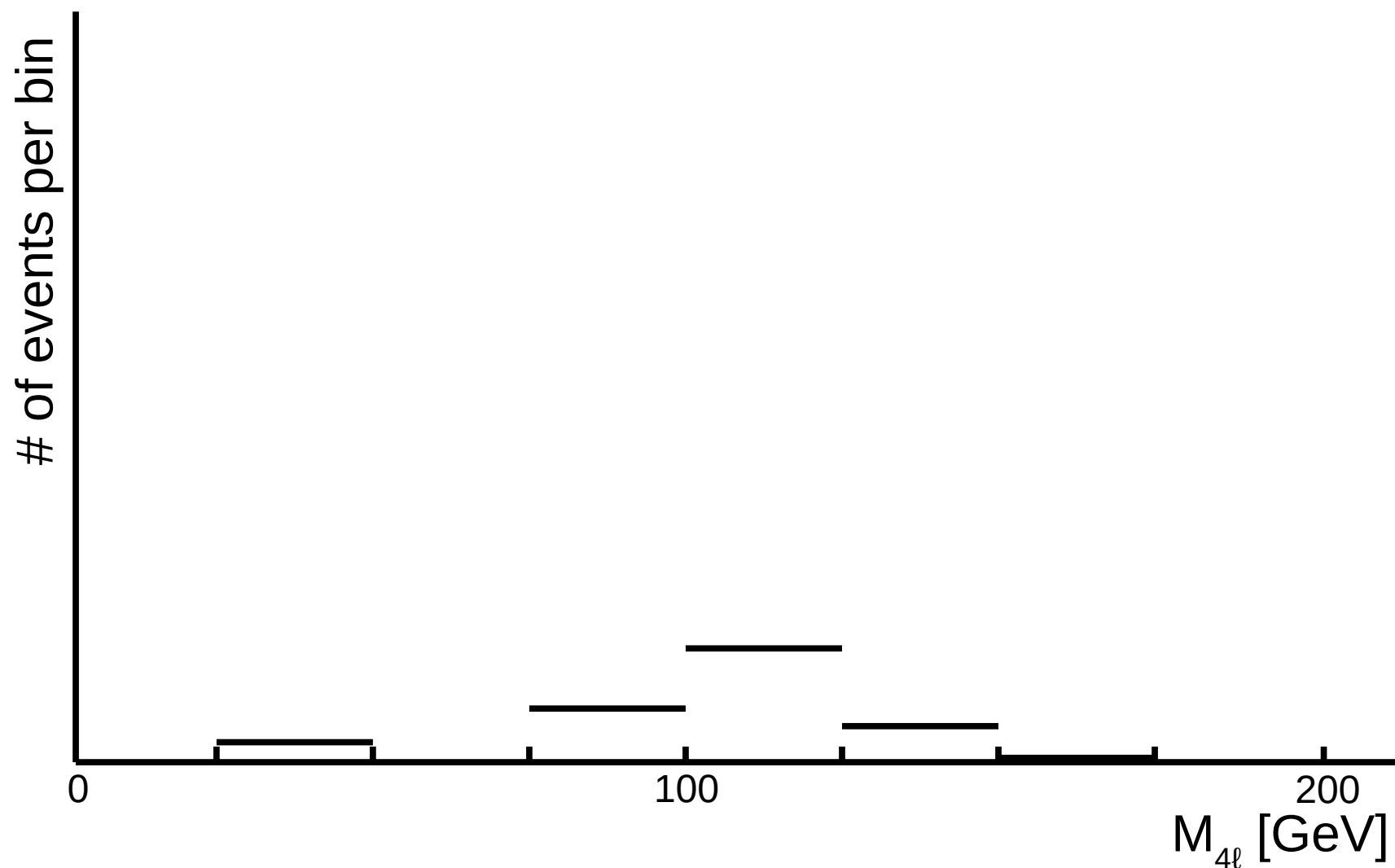
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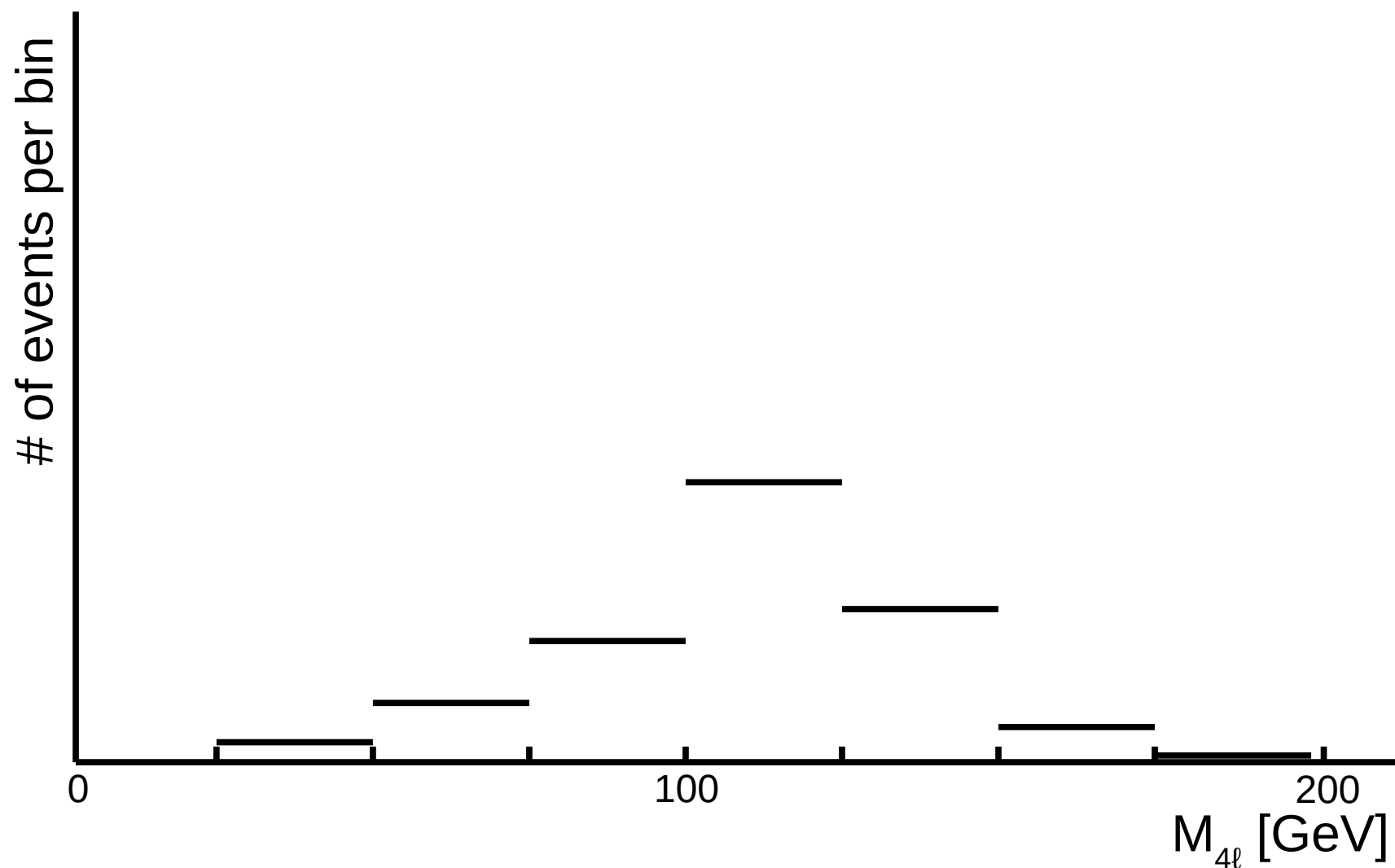
Now, we can plot the measured 4ℓ invariant mass:



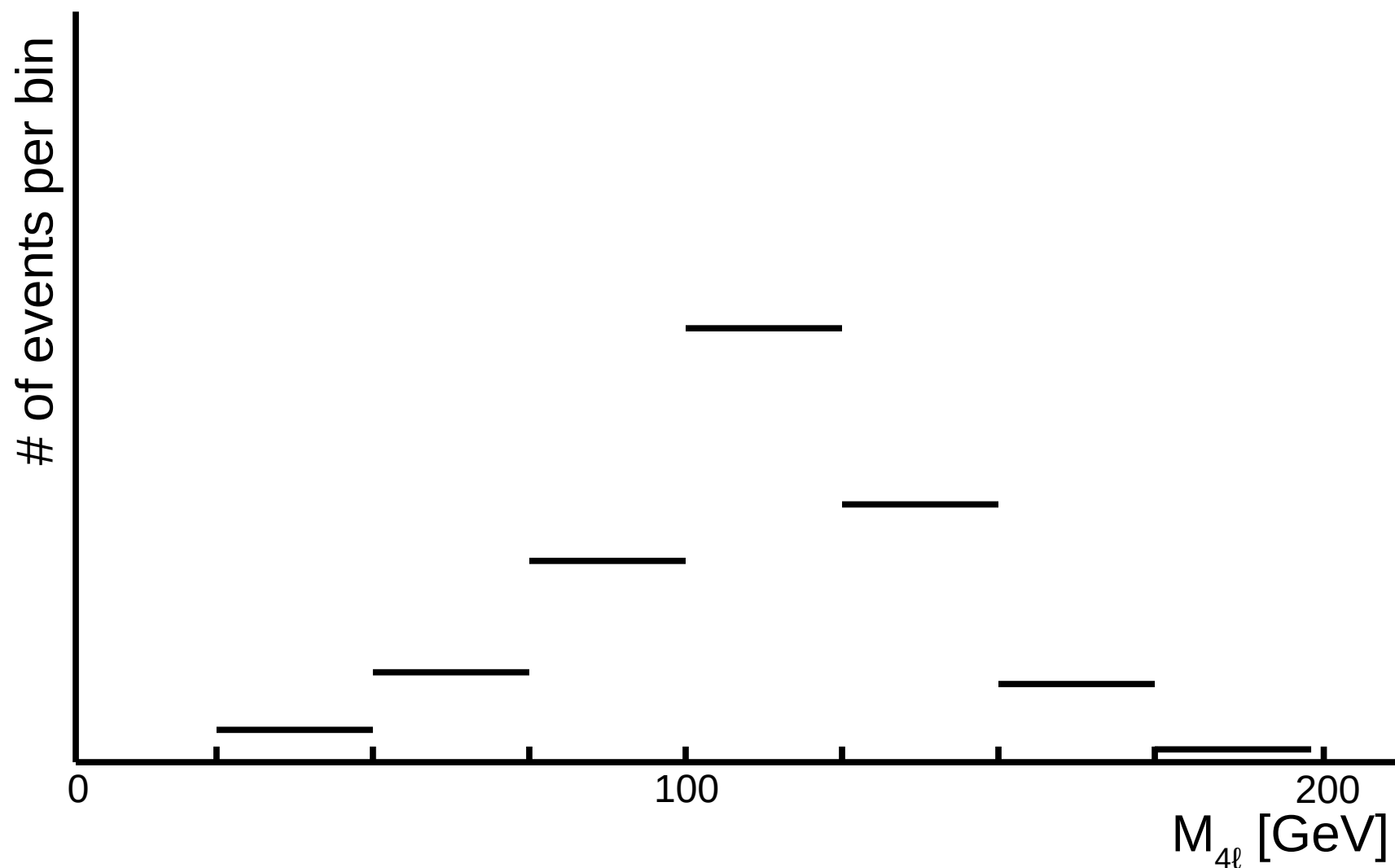
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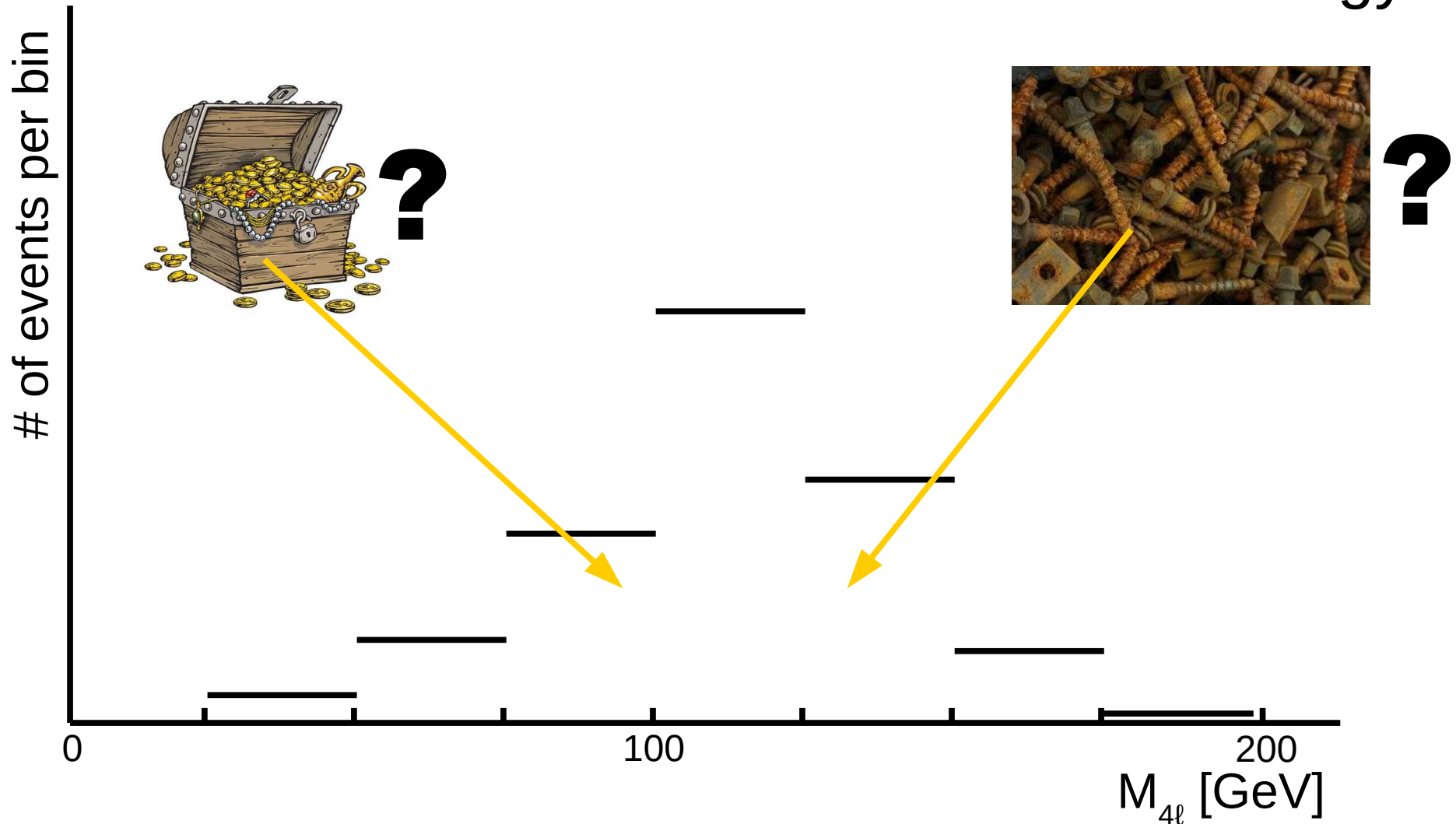


Now, we can plot the measured 4ℓ invariant mass:

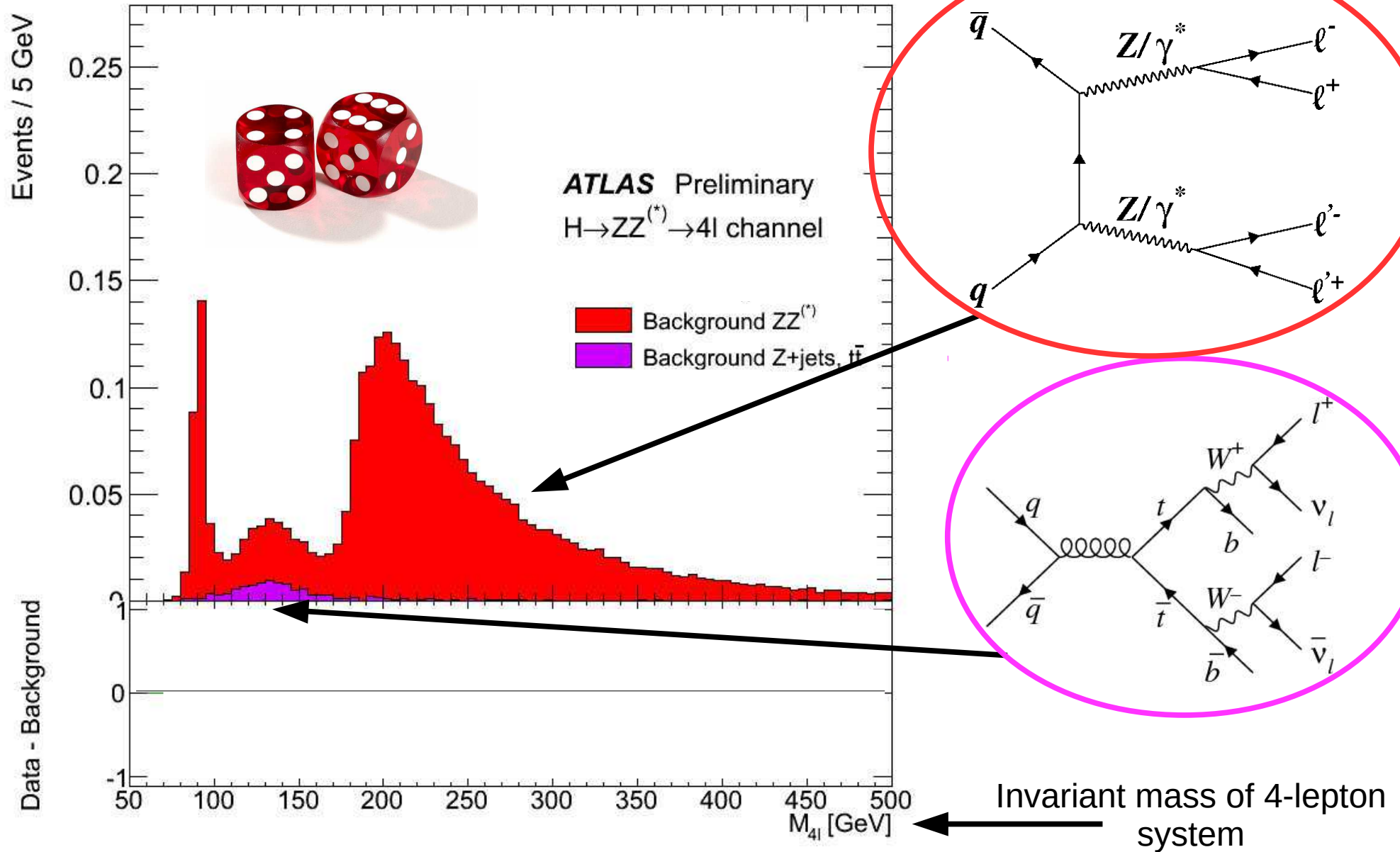


Now the question is: How many of these are Higgs events, and how many are “background”?

→ Recall the beach / metal detector analogy



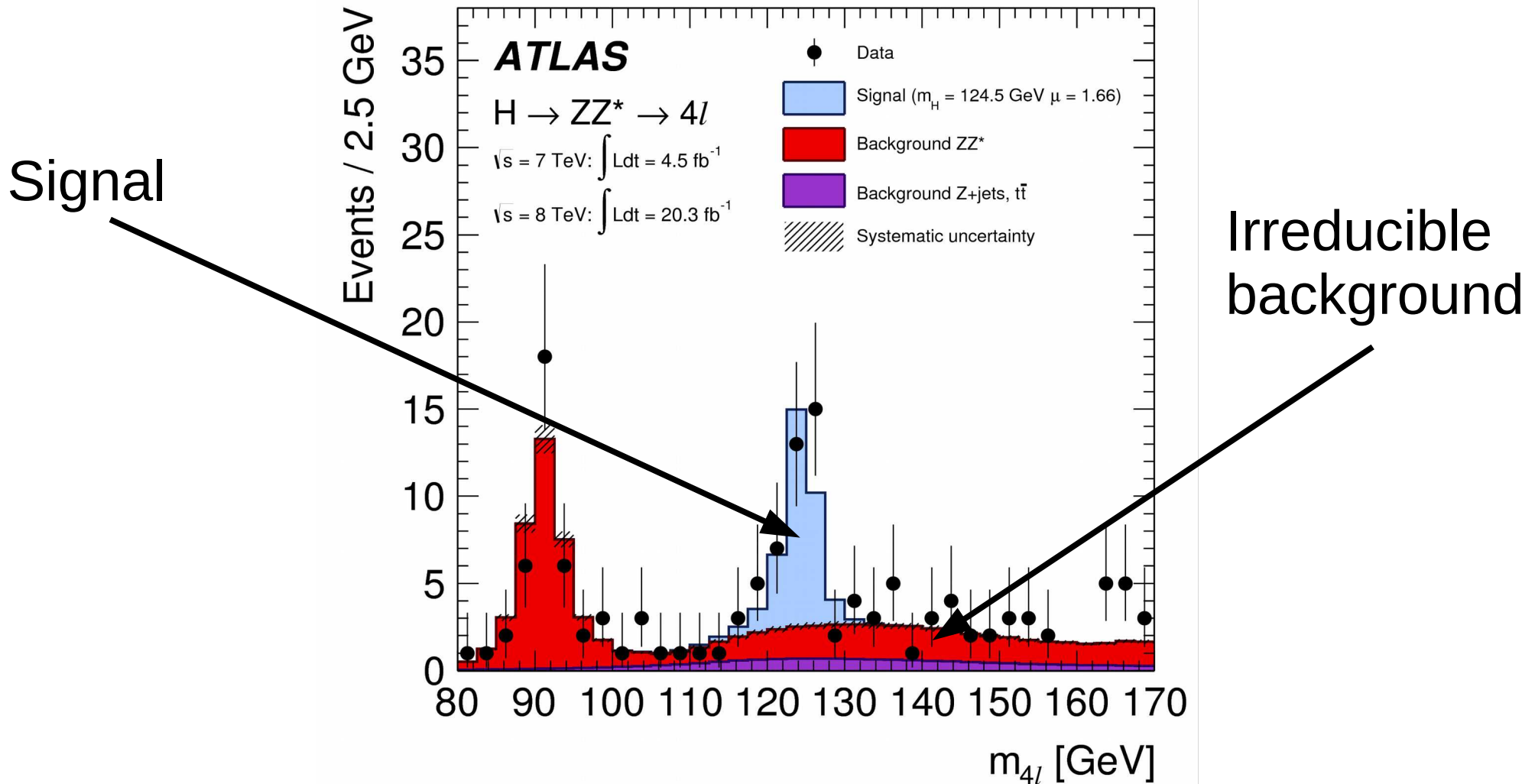
Simulated Background Events



**Watch the ATLAS collaboration
collect and analyze data**

Final Result:

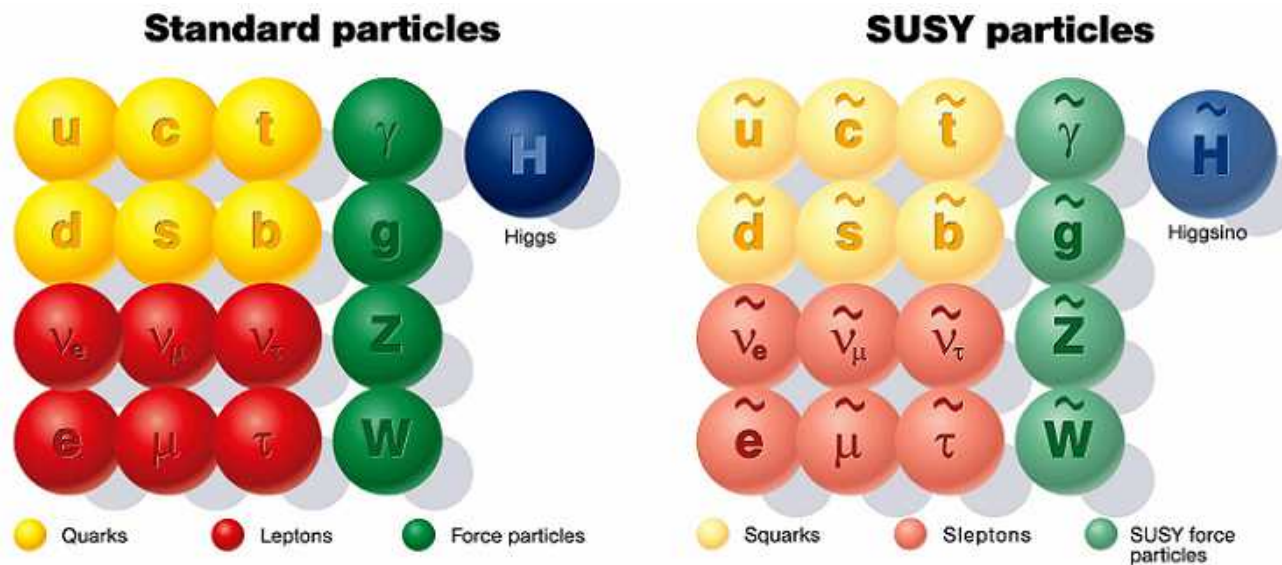
Higgs mass = 124.5 GeV



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

The Future

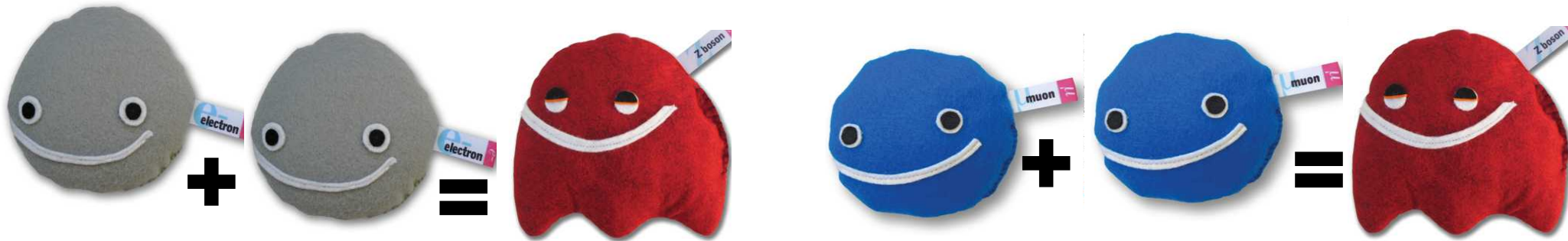
- LHC turns back on this spring, at a higher energy (14 TeV)
- What will we discover next?
 - Supersymmetry? Something else?



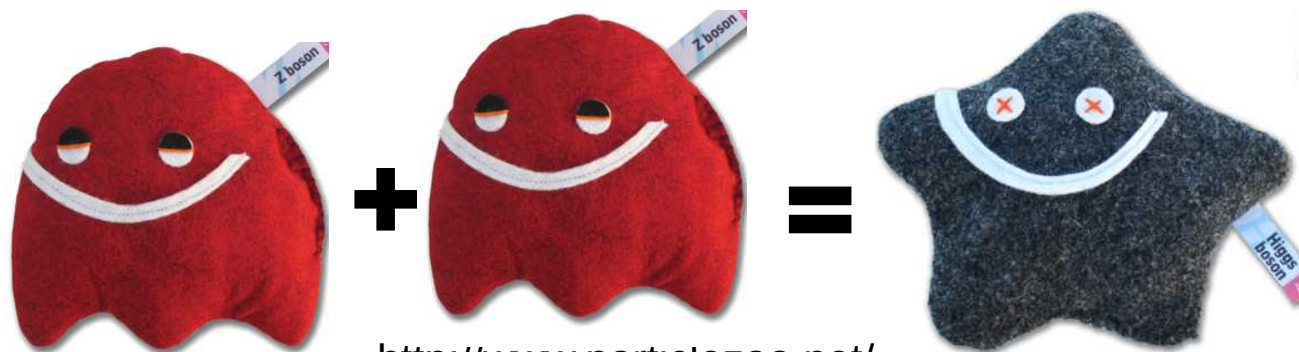
Backup Slides

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: $M_Z = \sqrt{2E_{\ell 1}E_{\ell 2}(1-\cos\theta)} / c^2$



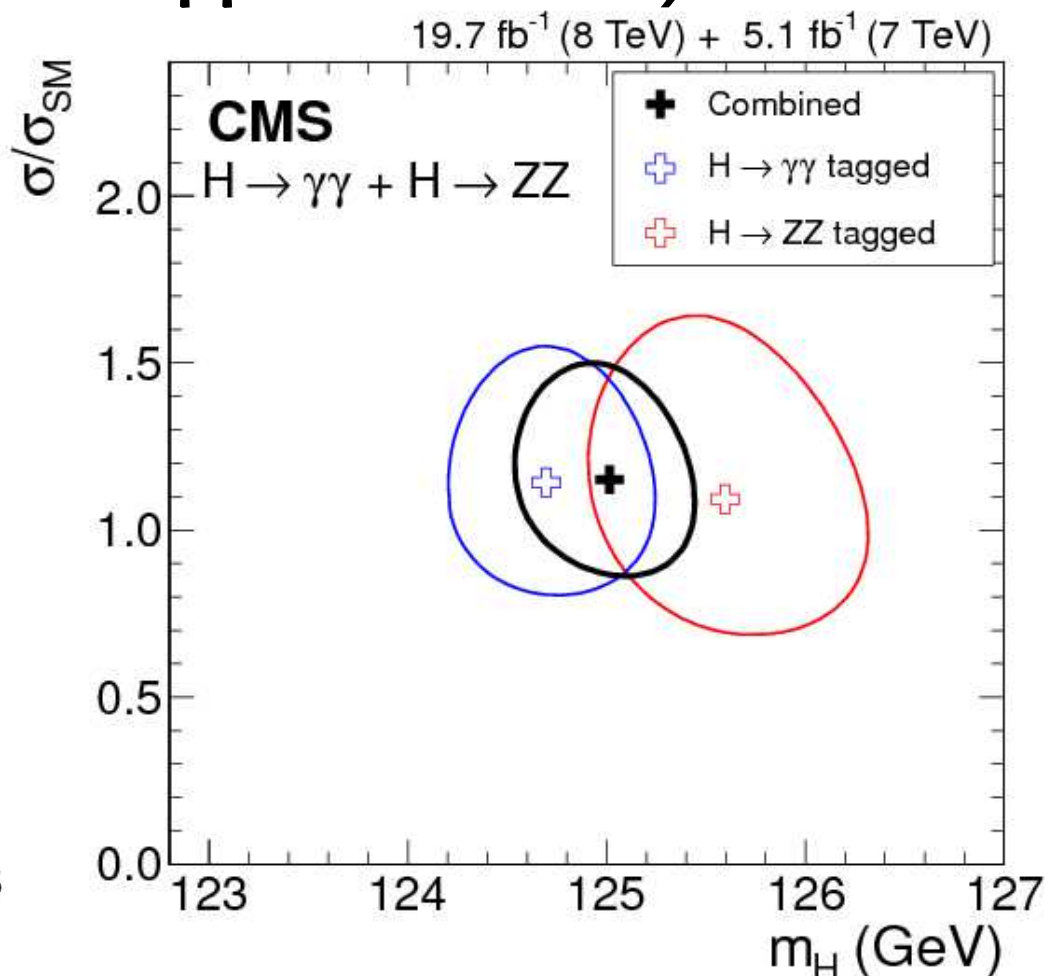
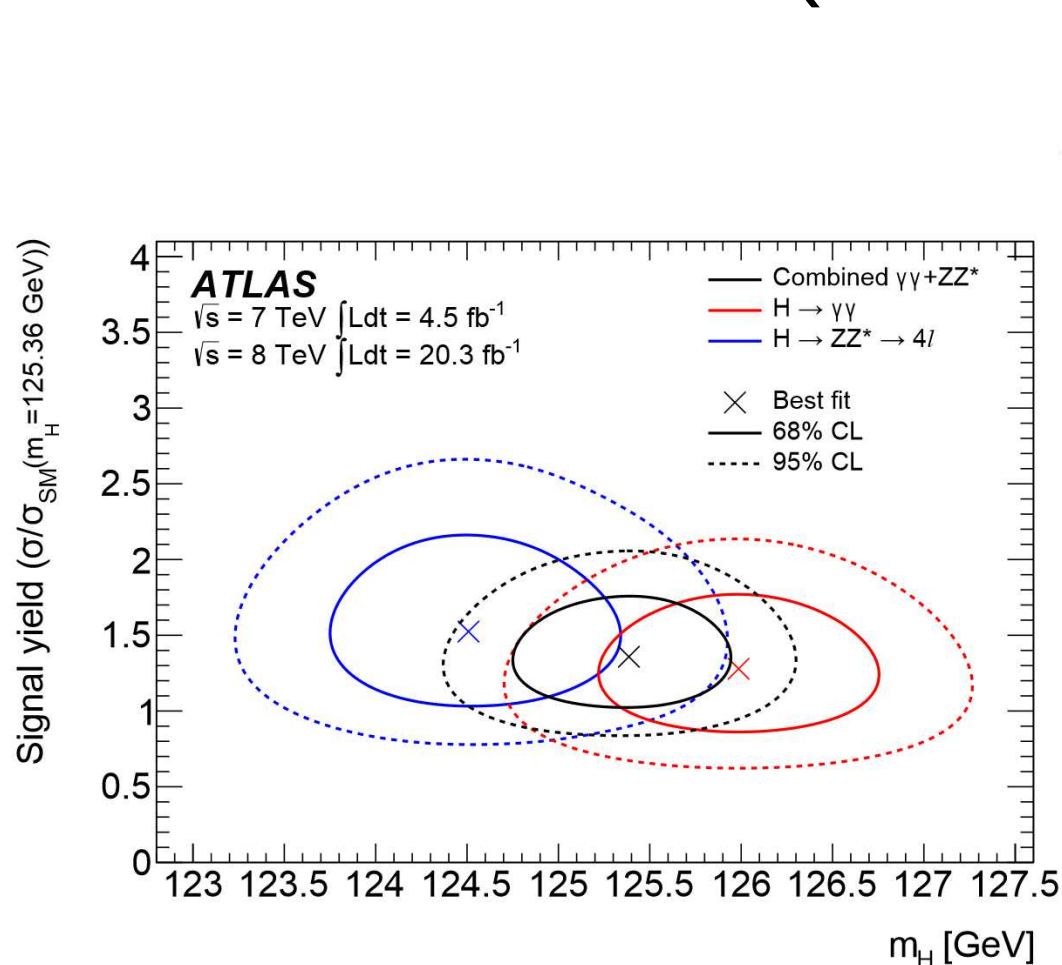
$$\text{and } M_H = \sqrt{m_{Z1}^2 c^4 + m_{Z2}^2 c^4 + 2E_{Z1}E_{Z2}(1 - v_{Z1}v_{Z2}/c^2)\cos\theta} / c^2$$



<http://www.particlezoo.net/>

Results

Current Higgs mass measurements from ATLAS and CMS (in 4ℓ and $\gamma\gamma$ channels)



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

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