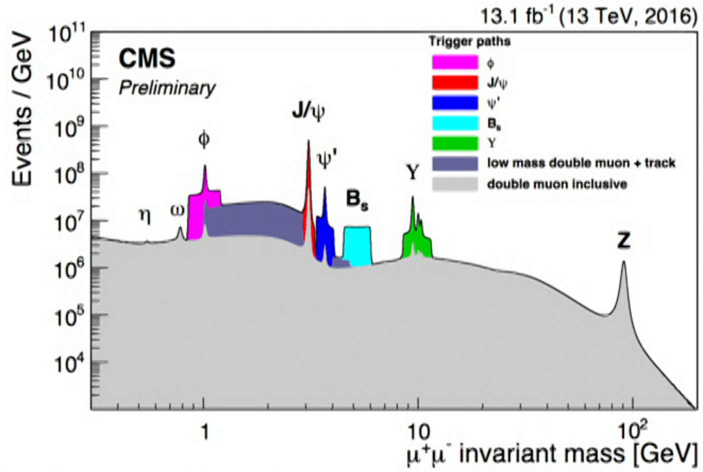
Title: Collider Experiments 3

Date: Jul 12, 2018 11:00 AM

URL: http://pirsa.org/18070032

Abstract:

Why Does This Look So Weird?



- The experiments have a *trigger* – a device that lets them select a fraction of events (around 10^{-5}) to write out
- It's not enough to write out the events you are interested in
- ***You also need to write out the events you need to understand the events you are interested in***

Oversimplified Triggering In One Slide

- Hardware-level triggering
  - Uses a subset of the detectors with a short signal formation time
  - Selects events quickly: needs to make a yes/maybe decision for every bunch crossing
    - This is 25 ns for the LHC
  - However, it can take ~1 microsecond to make a decision. It does this via *pipelining*.
    - For the LHC, 1 us means a pipeline 50 events deep
  - Rejection factor: a few hundred to a few thousand

- Software-level triggering
  - Runs on large clusters of near-commodity computers
  - Can run anything from fast algorithms to full reconstruction
  - Only analyzes the fraction of events passed by the Hardware Level, but can analyze the entire event
  - Rejection factor: also a few hundred to a few thousand (total is ~100,000)

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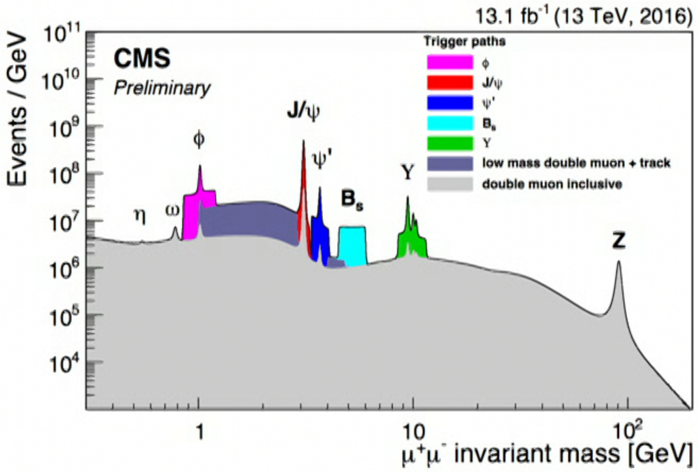

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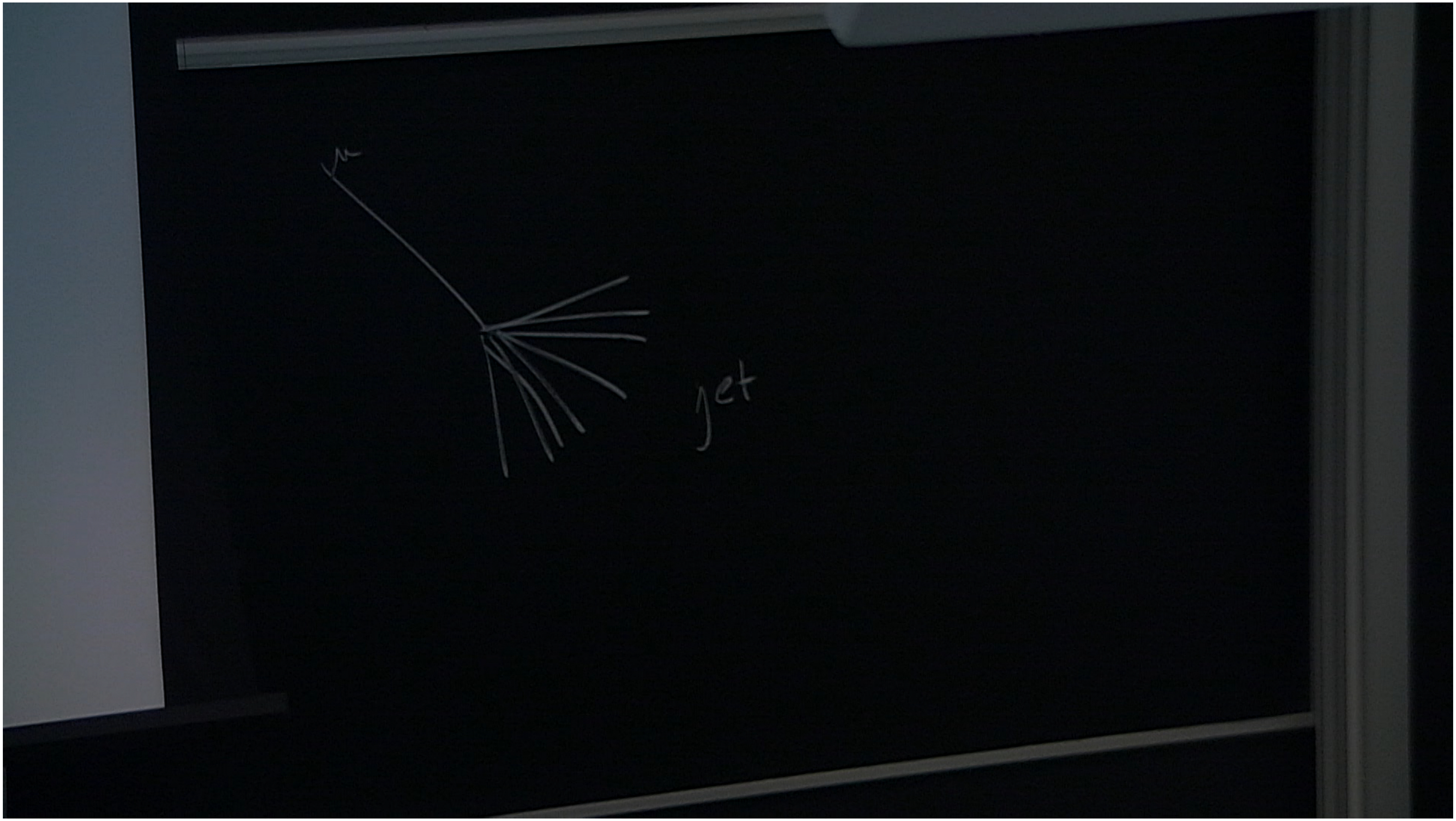
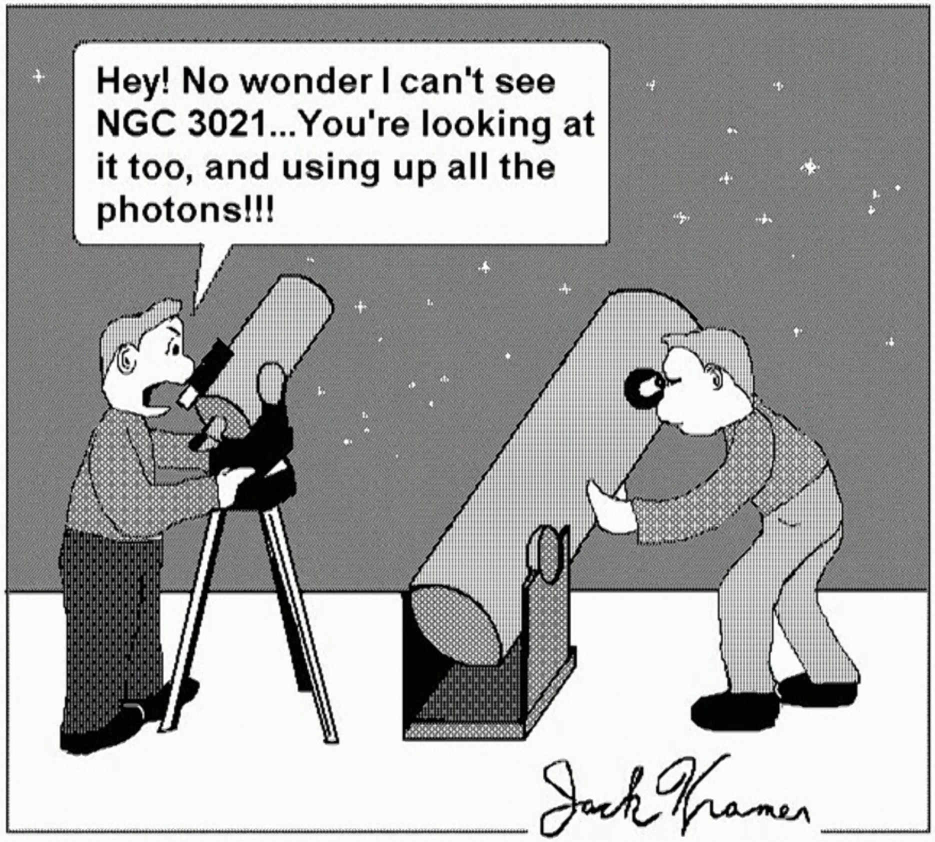
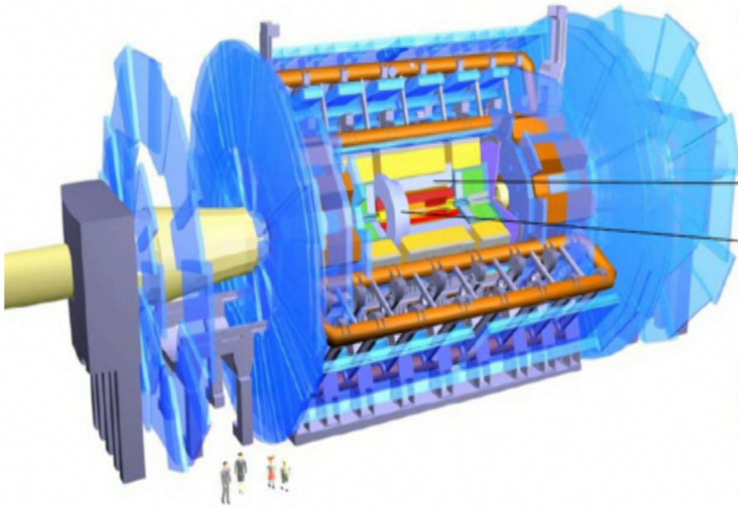
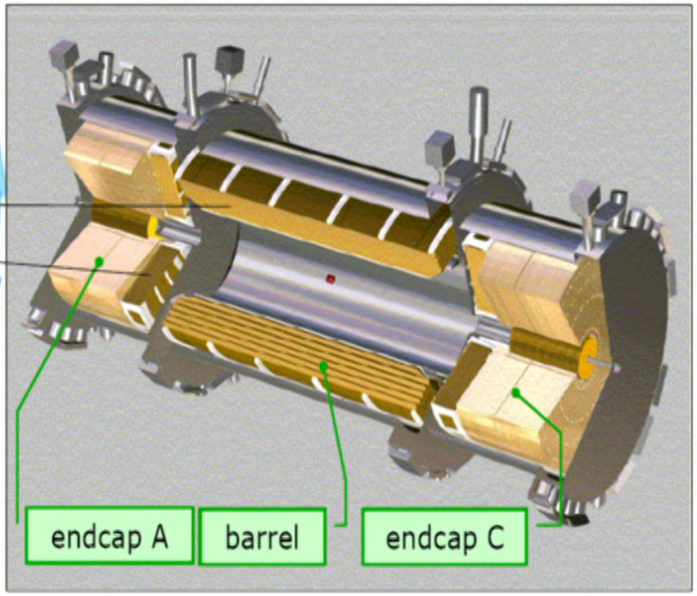

jet

Photon Detection Review



ATLAS Electromagnetic Calorimeter





Design resolution:

$$\frac{\delta E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\% \oplus \frac{0.2\,\mathrm{GeV}}{E}$$

Technology: uses lead as an absorber and liquid argon as an ionization medium. Energy deposited in the calorimeter is converted to an electrical signal.

Comparing Design Philosophies

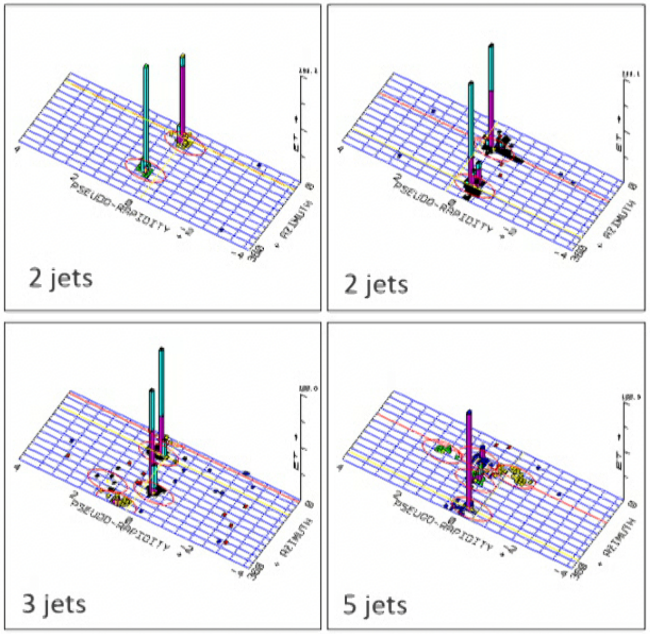
- CMS emphasizes energy resolution
  - Use PWO crystals
    - Expensive – means go to small radius to keep the detector within budget
    - Only handful of vendors worldwide
- ATLAS emphasizes background rejection
  - Able to go to larger radius: separates showers better
  - Highly segmented calorimeter allows measurement of shower development
    - One photon? Two? A hadron masquerading as a photon?
- Both calorimeters are quite thick
  - Improves resolution (showers are contained)
  - Degrades electron-hadron separation
    - ATLAS measurement of shower development is intended to compensate

Jets

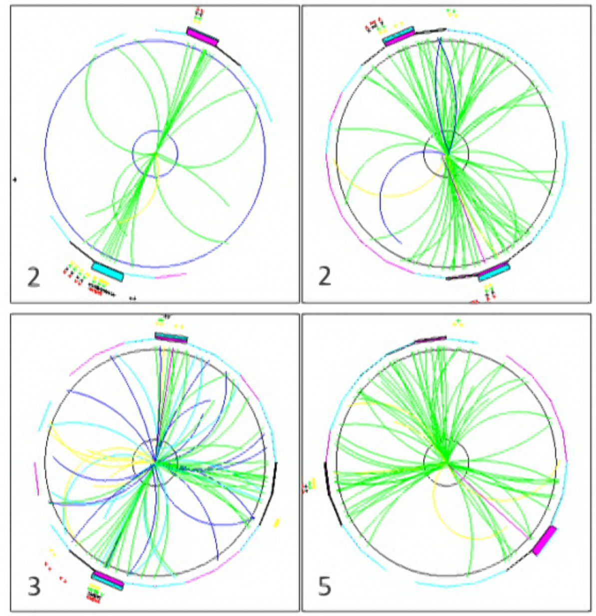
When you're a jet, you're a jet all the way...
S. Sondheim

A Two Slide Review of Jets

A “blast” of particles, all going in roughly the same direction.



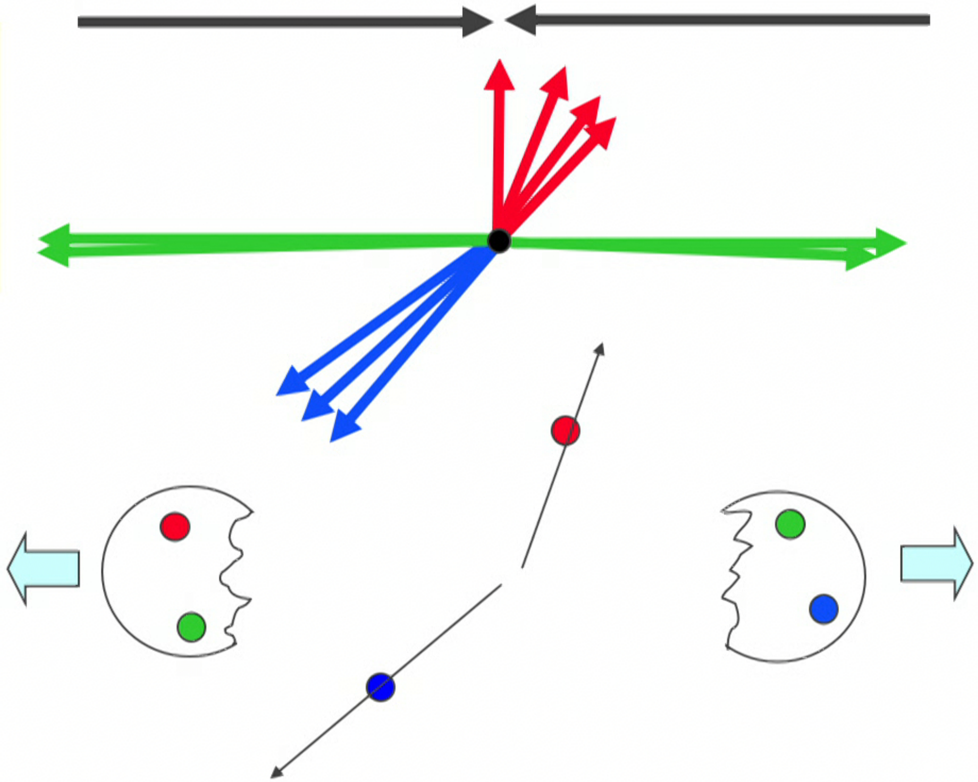
Calorimeter View



Same Events, Tracking View

The Utility of Jets

What appears to be a highly ***inelastic*** process: two protons produce two jets of other particles…
(plus two remnants that go down the beam pipe)

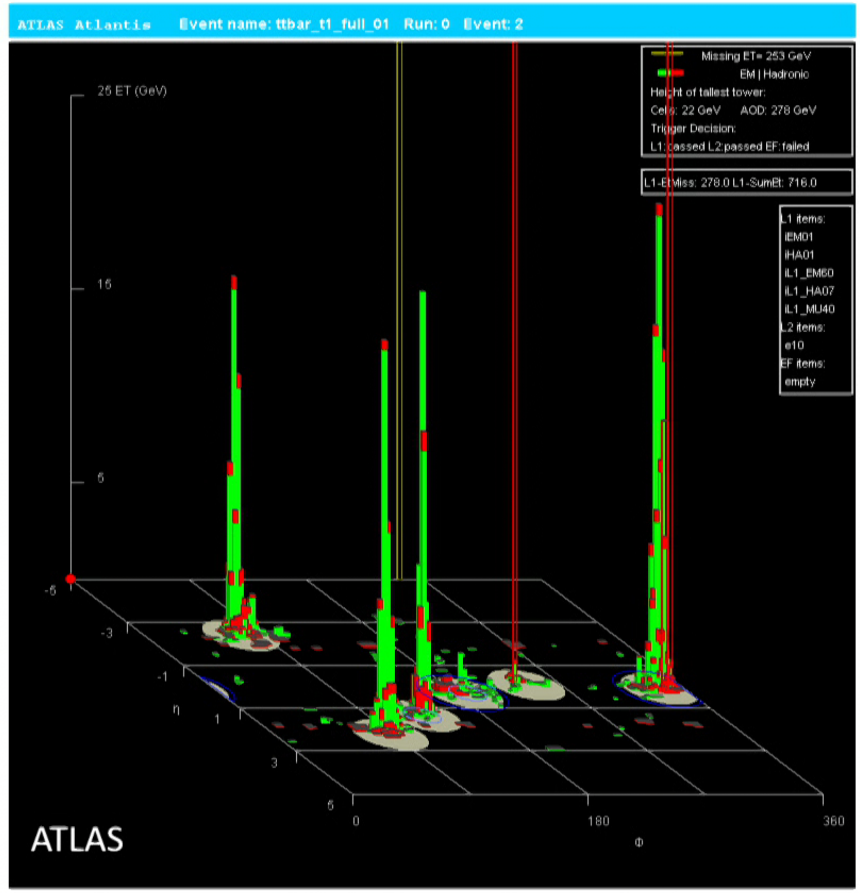


… is actually the ***elastic*** scattering of two constituents of the protons.

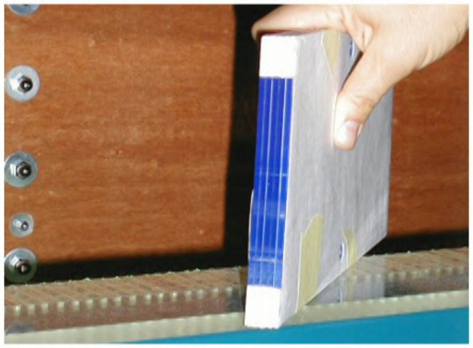
Jets are the best window we have into what the quarks are doing. Things that look very complicated when discussing individual particles simplify when talking about jets.

Measuring Jets

- Lego plot of a simulated top quark event has EM calorimeter energy in green and hadronic calorimeter energy in red.
- The prevalence of green comes from two facts:
  - Half of the particles (and ~40% of the energy) in a jet are photons from neutral meson decay
  - The LHC EM calorimeters are thick, and many hadrons begin their showers inside the electromagnetic calorimeters.

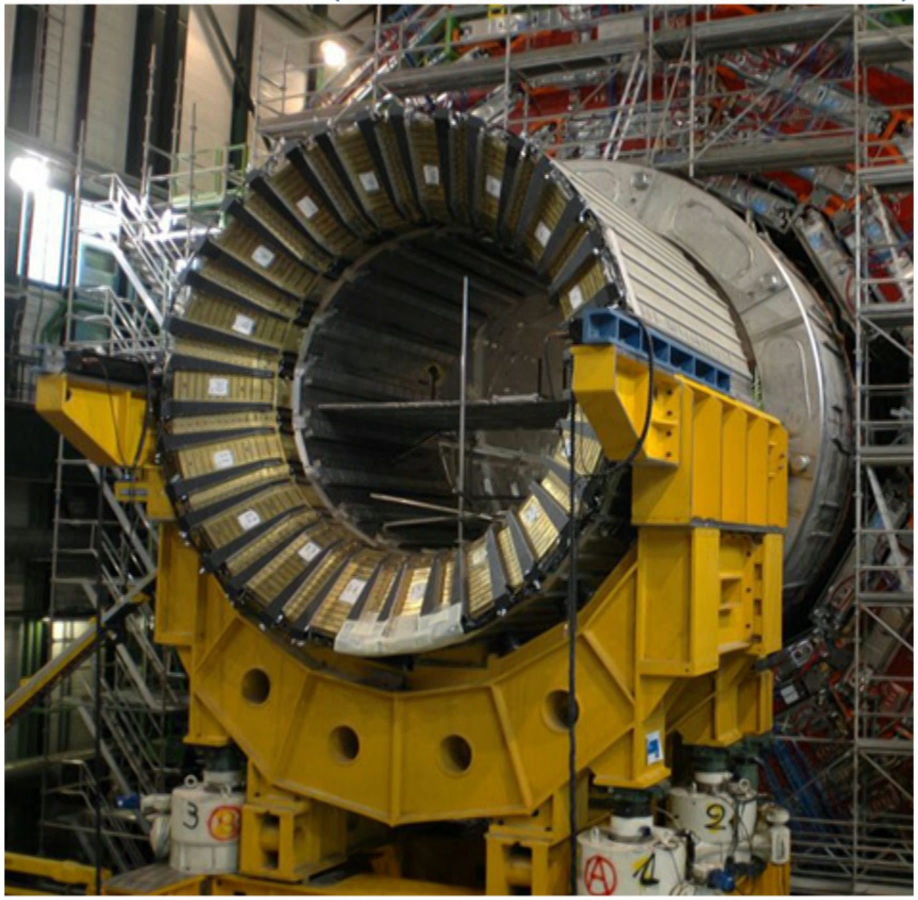


ATLAS "Tile" Hadronic Calorimeter



Uses steel as an absorber, and scintillating tiles as the active medium. Energy is converted to light.

CMS HCAL (Hadronic Calorimeter)



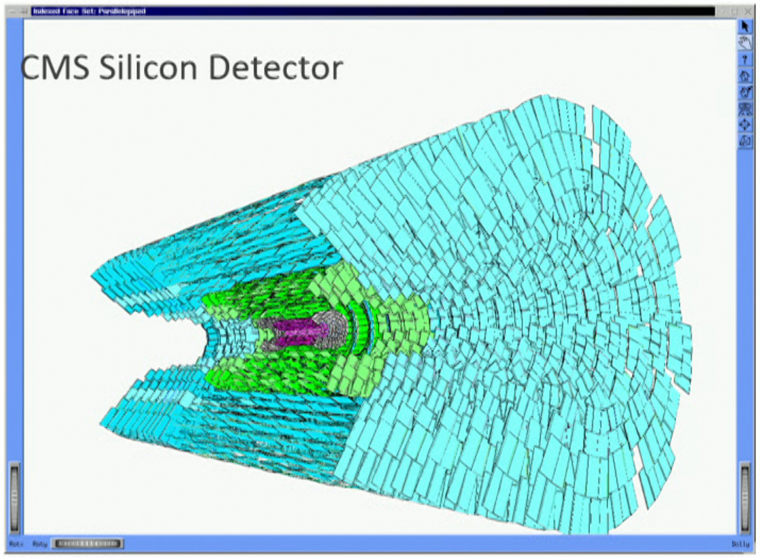
- Also a scintillating tile-based sampling calorimeter
- Technology is similar to ATLAS:
  - Absorber is brass instead of steel
  - Tile orientation is different (more conventional in CMS)
- Calorimeter is relatively thin

Comparing Design Philosophies

- CMS' calorimeter is inside their magnet
  - Additional depth is very expensive (since it requires a larger radius magnet)
  - To increase the effective thickness, it's made of a denser material (brass)
  - ATLAS is quite thick – the outer muon detector resembles the "iron ball" design.
- ATLAS would "naturally" use liquid argon for both the hadronic and electromagnetic calorimeter
  - Both D0 and H1 designed their detectors this way
  - This is also very expensive
- Both experiments have chosen to economize here
  - Slightly better performance would cost a **lot** more money

Electrons & Other Tracks

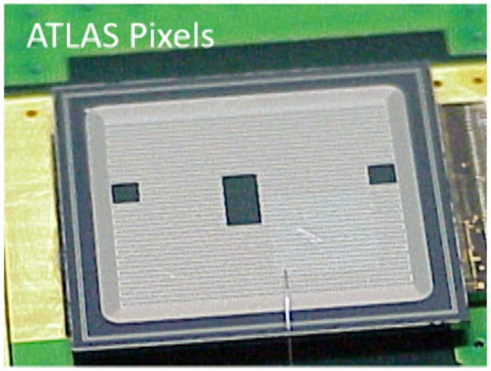
- The figure of merit for momentum measurement is BL^2. A half dozen layers of silicon close in has great impact parameter resolution – but L is tiny.
- To improve the momentum resolution, the experiments need to build out from their silicon detectors.
- CMS chose to keep going with silicon, and add another half dozen layers
  - By far, the largest silicon HEP detector ever built.

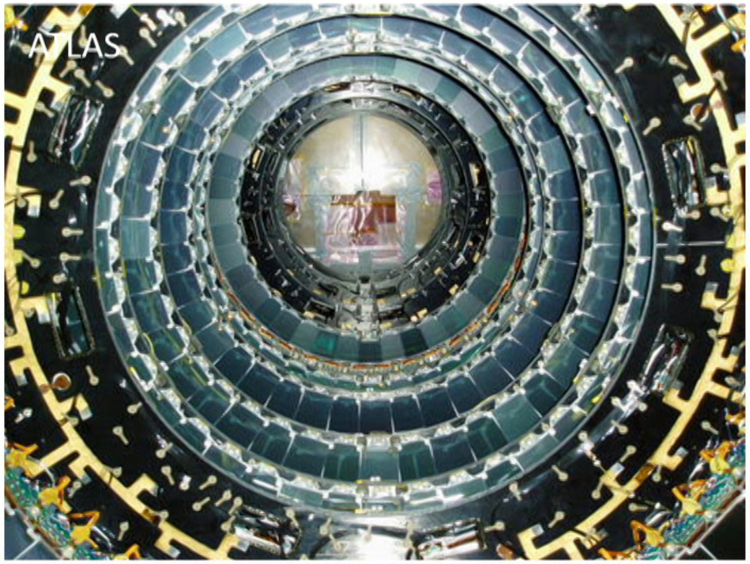


The key idea: BL^2 – relative to what?

Reminder: to tell an electron from a photon, recognize that an electron has a track (of the right momentum) in front of the cluster, and a photon has no track.

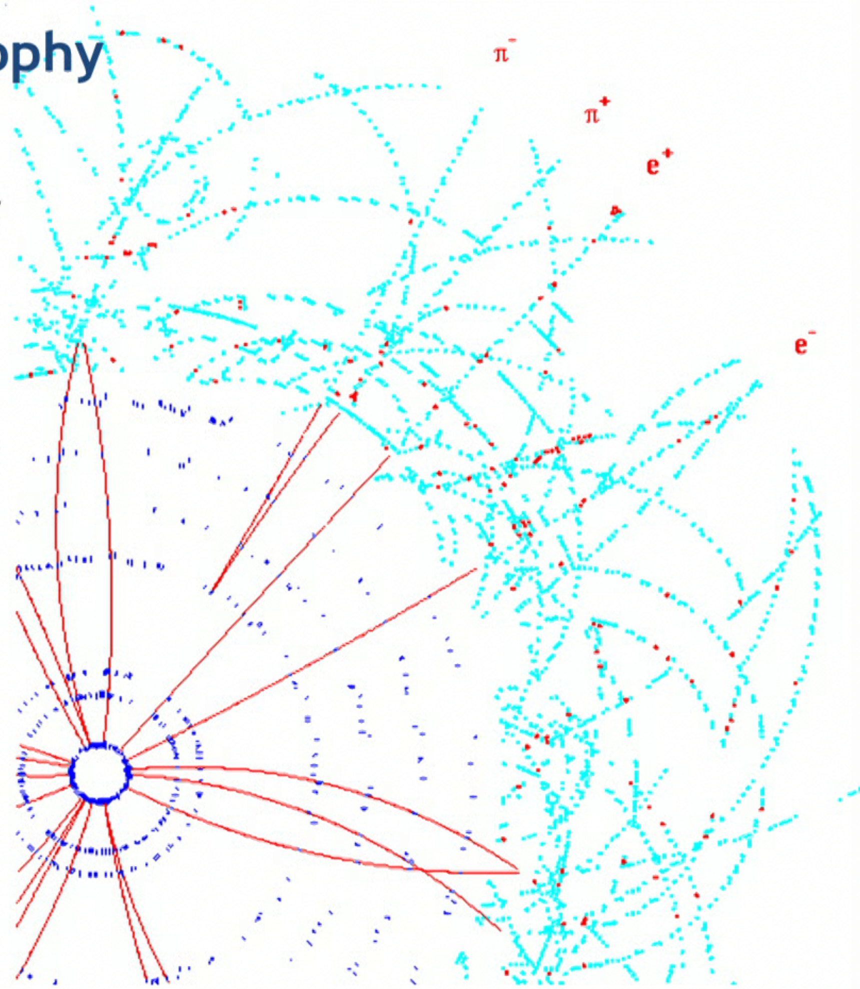
LHC Silicon Vertex Detectors



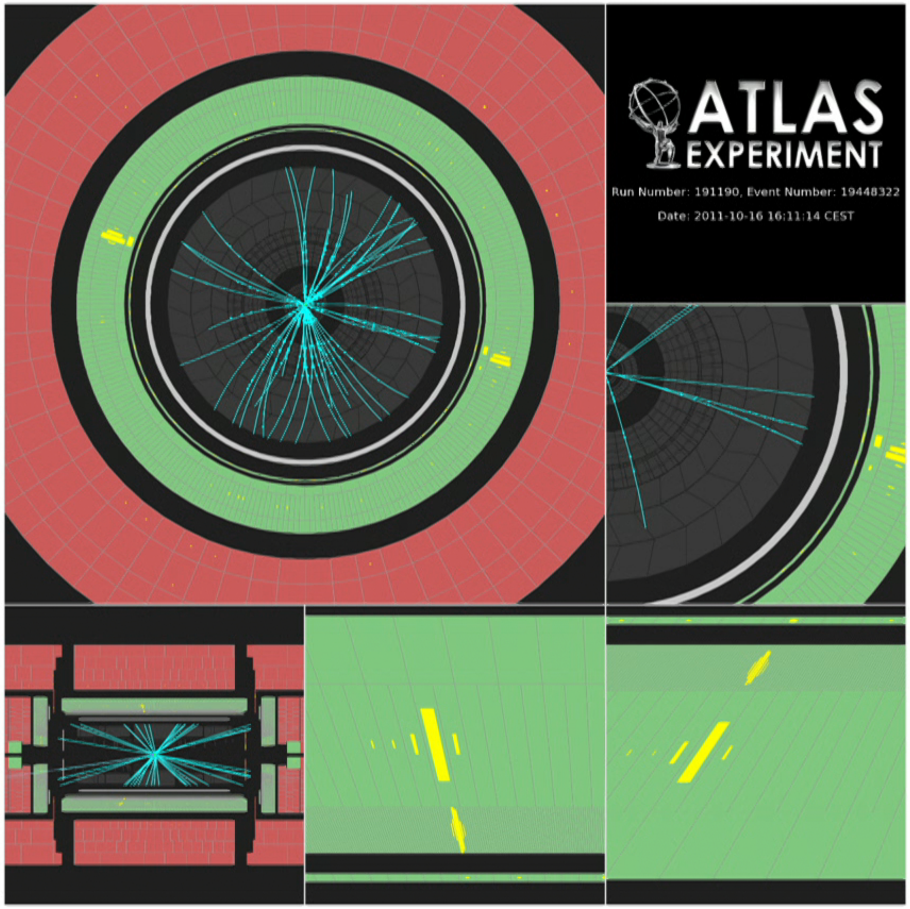


ATLAS Tracking Philosophy

- Instead of adding 6 precise points from silicon, ATLAS adds 36 "pretty good" points from a tracker based on wires inside straws.
- The detectors are designed to be sensitive to transition radiation, so can be used to aid in electron identification.
- This detector design will not work at the very highest luminosity – when that happens, ATLAS may replace with silicon.

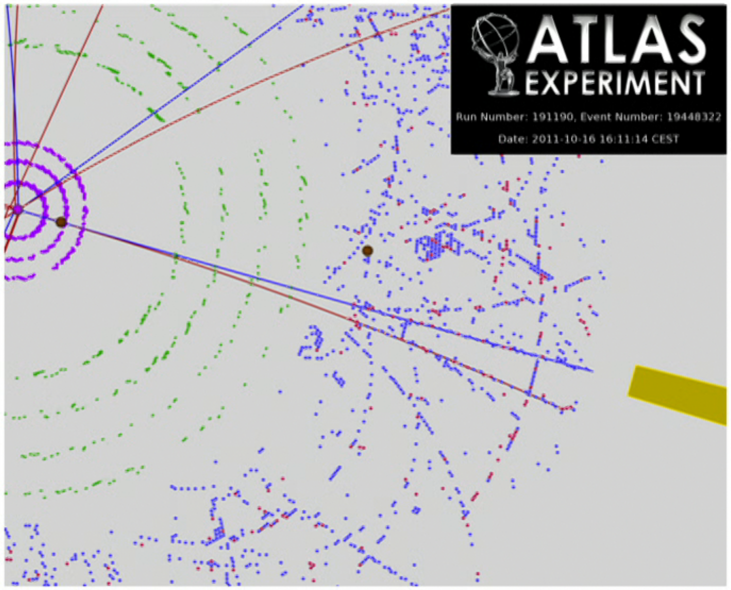


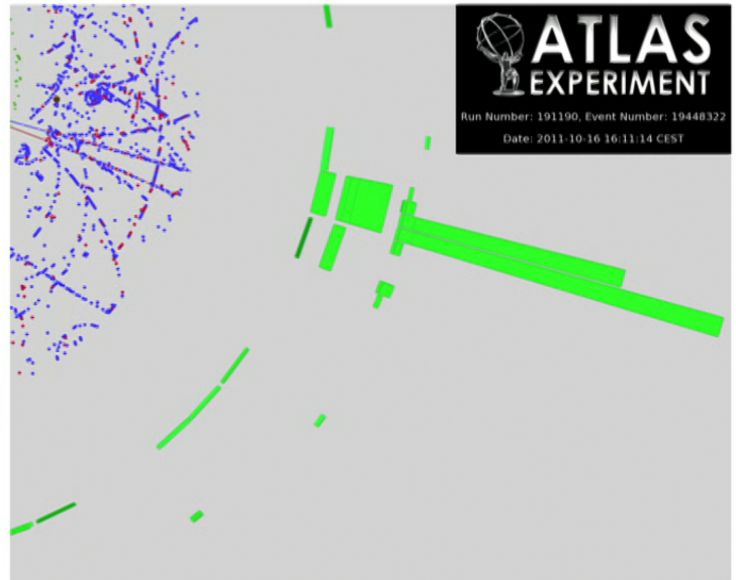
An Event We Have Seen Before



- This event has
  - One central unconverted photon
  - One central converted photon
  - A low pTt (6.5 GeV)
- This places it in Category 5

The Conversion in More Detail

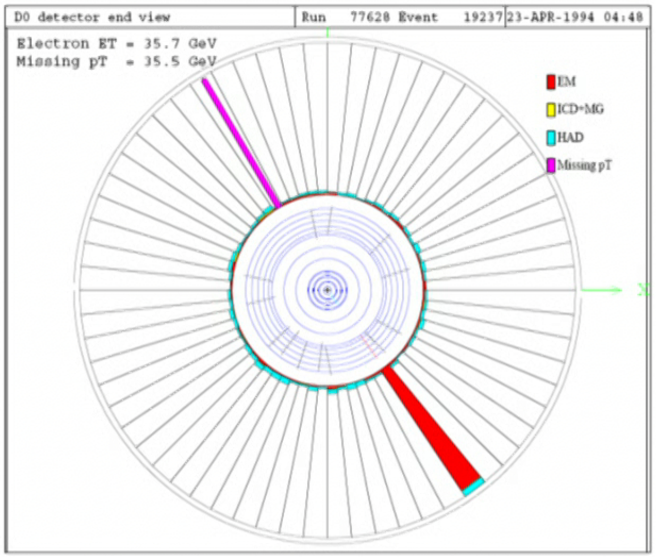




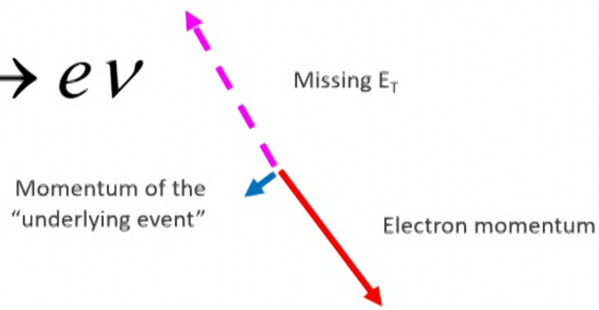
The tracks from $\gamma \rightarrow e^+e^-$ are clear and distinct. Red hits are high threshold TRT hits and confirm that these are in fact electrons.

The shape of the EM cluster in the calorimeter is consistent with two electrons very near each other.

Missing Transverse Energy



$$W \to e\nu$$



- We know momentum is conserved.
- An apparent imbalance of momentum can be due to an escaping neutrino
  - Calculated by adding up all the other momenta and reversing the sign
- We work only in the *xy* (transverse) plane
  - Many particles escape unmeasured down the beampipe (this will be important later)

Pink is the New Black

...and neutralinos are the new neutrinos.

- In Supersymmetry, every fermion has a boson that's its partner and vice versa
  - The spin-1 photon's partner is the spin-½ photino
- The lightest supersymmetric particle is stable

$$\tilde{\gamma} \not\to \bar{\nu}\nu$$ (violates conservation of angular momentum)

$$\tilde{\gamma} \not\to e^{+}e^{-}\nu$$ (violates conservation of lepton number)

$$\tilde{\gamma} \not\to \bar{n}nn$$ (violates conservation of baryon number)

- This is called "R parity conservation" and it keeps your supersymmetric theory from violating experimental limits, such as that for proton decay
  - It leads to a common signature in SUSY models: particles that exit your detector without interacting, leading to missing momentum

Footnotes:
1. The g, Z and H all have partners, and these partners have the same quantum numbers, so they mix.
2. There are ways to contrive an R-parity violating theory that evades experimental bounds

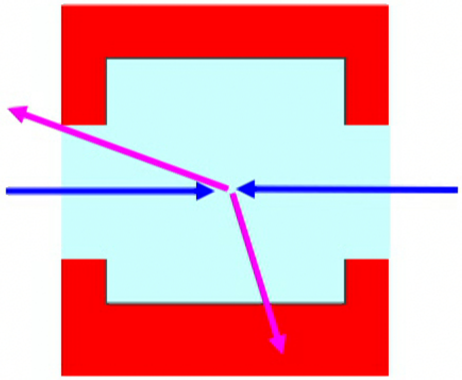
Variations on a Theme

- More exotic: theories with extra dimensions can also have missing E_T signatures
  - The entire standard model is replicated (so-called Kaluza-Klein modes)
    - The “KK graviton” is one candidate for a particle that gives large missing E_T.
    - Depending on the model, you might get more.
- Even more exotic: theories with names like “Hidden Valleys” and “Shadow Matter”.

The point is not whether these particular theories are right or wrong. The point is that Missing E_T is a common signature present in multiple models, so it should be looked for.

Hermiticity

- A fancy way of saying "holes are bad"
- Particles escape down holes and cracks, and generate missing E_T
  - "Real missing E_T, because it truly is missing
  - "Fake missing E_T" in the sense that it wasn't what you were looking for
    - Difference between an undetected and an undetectable particle
- Holes, gaps and cracks are necessary
  - Minimum of two holes (for the beam)
  - Cables need to come out somewhere
  - Cooling and cryogens need to go in
    - If they go in, they have to come out



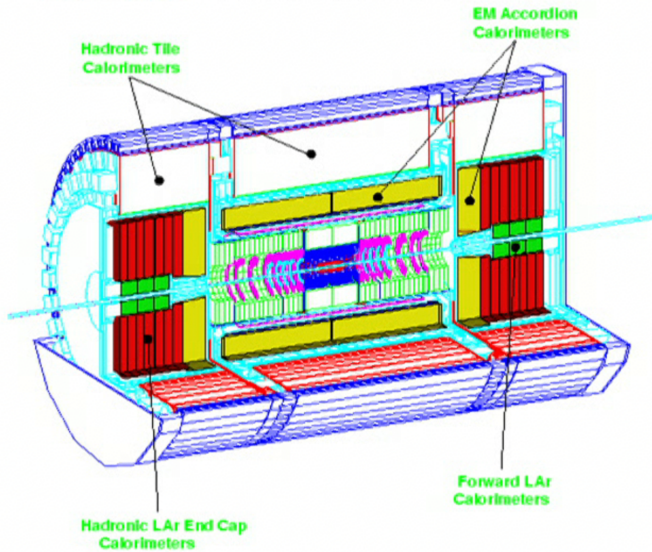
Why Are Detectors as Long As They Are?

- Why not make detectors longer and longer and longer?
  - Resource limitations
    - Making it twice as big costs twice as much money
    - ...and takes twice as many people
    - ...or takes twice as long
- Relativistic kinematics affects the design of a detector
  - Heavy objects are produced almost at rest
    - Their decay products populate all 4π of solid angle
    - What matters is **solid angle**
  - Light objects are produced uniformly across **rapidity**
    - In principle, argues for a long detector
    - But if the mass is low, the cross-section is high, and you're making a lot of them – one unit of rapidity is as good as any other
  - In either case, there's a natural point where it's no longer cost effective to keep going forward

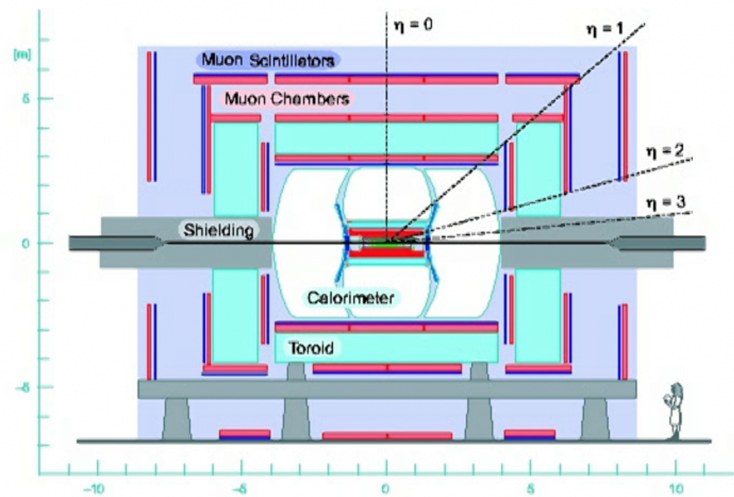
I wish someone had told me this sooner.

Why are LHC experiments a little longer than Tevatron experiments?

ATLAS Calorimetry (Geant)



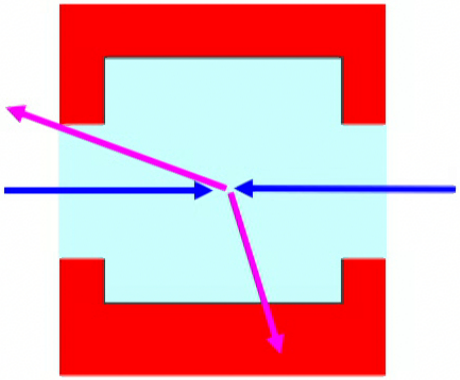
D0 detector

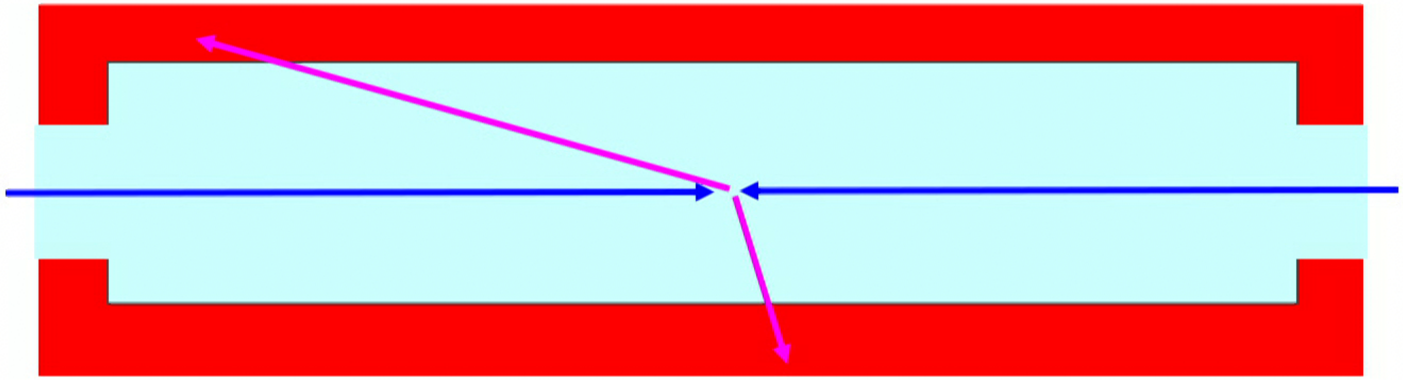


- One reason is for Missing E_T performance (long is good)
- Another reason is from kinematics
  - Quark-antiquark collisions at the LHC are asymmetric.
  - Even for light objects, extra coverage doesn't hurt you – it just costs $

Improving Missing ET

- To keep particles from escaping, one can:
  - Make the holes smaller
    - There's a limit to this
  - Make the detector longer
    - The hole is the same size, but subtends a smaller angle





Mismeasured Jets

- One way to generate fake missing ET is to mismeasure an object in the event.
- Jets are the usual suspects:
  - There are a lot of them
  - There are several things that can go wrong:
    - Plain old mismeasurement
    - Particles down cracks
    - Particles in dead regions of the detector
      - Undercorrection and overcorrection are both possible
    - Particles in the jet decaying with a leading neutrino
    - And so on…

With apologies to Spinal Tap

These all sound unlikely.

That's because they **are** unlikely.

The reason that this is important is…

Triggering!

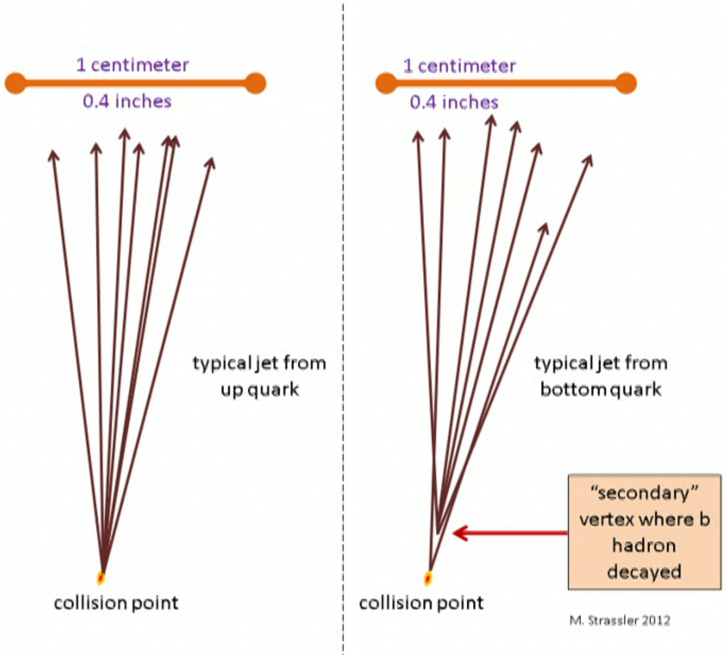
- Jets are everywhere!
- A few percent of events contain a jet
- Maybe one in a million can fake your signal…but you might make millions of jets per signal event

- The Three Laws of Triggering
  - 1. You cannot analyze an event you didn't trigger on – and there are no do-overs!
  - 2. If you aren't going to analyze an event, it doesn't help to trigger on it
  - 3. If you are going to cut an event, cut it as early in the chain as you can.

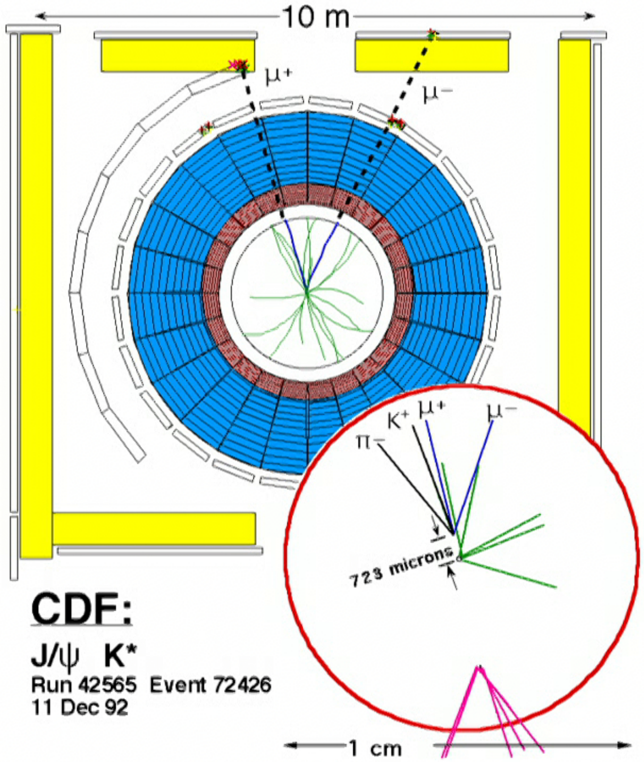
Putting it All Together

- These are the building blocks
- Take an electron and missing energy (neutrino) and you have a W (candidate)
- Take two W's and two jets (maybe with b-tagging) and you have two top quarks
- Take a muon and a jet and you have a leptoquark (candidate) and so on…
- What is b-tagging? (If there is time, watch the blackboard – taus too)

B-tagging

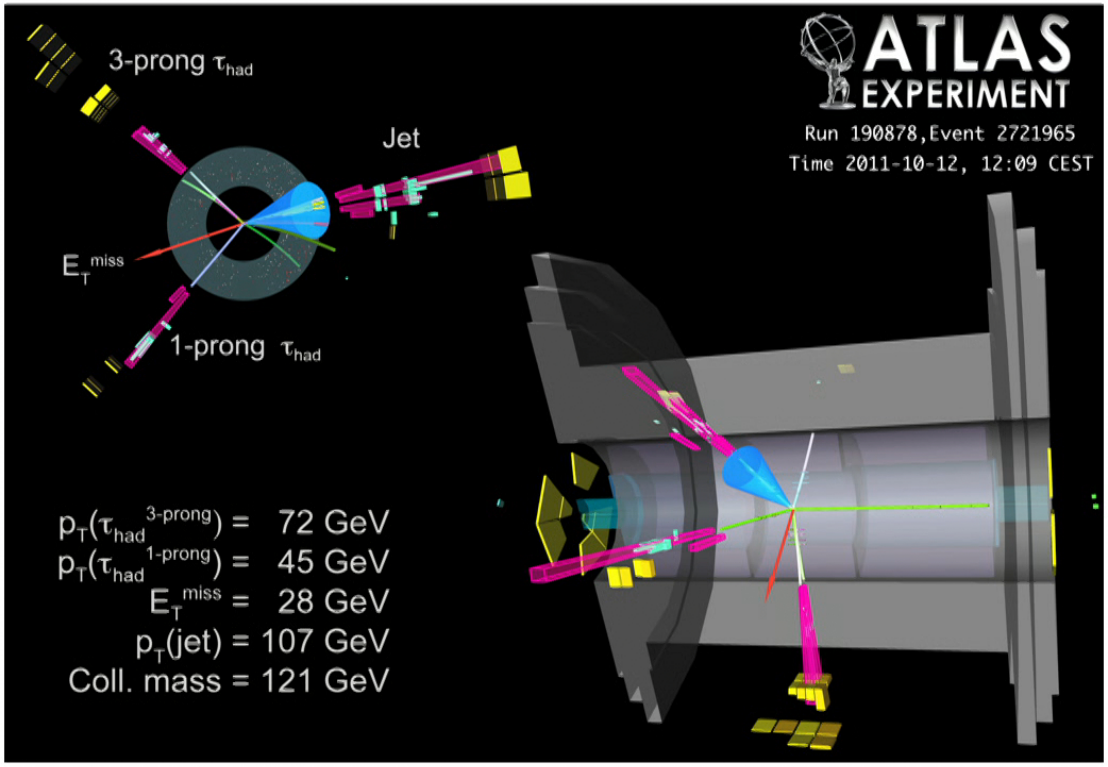


1 centimeter
0.4 inches
typical jet from up quark
collision point
1 centimeter
0.4 inches
typical jet from bottom quark
"secondary" vertex where b hadron decayed
collision point
M. Strassler 2012

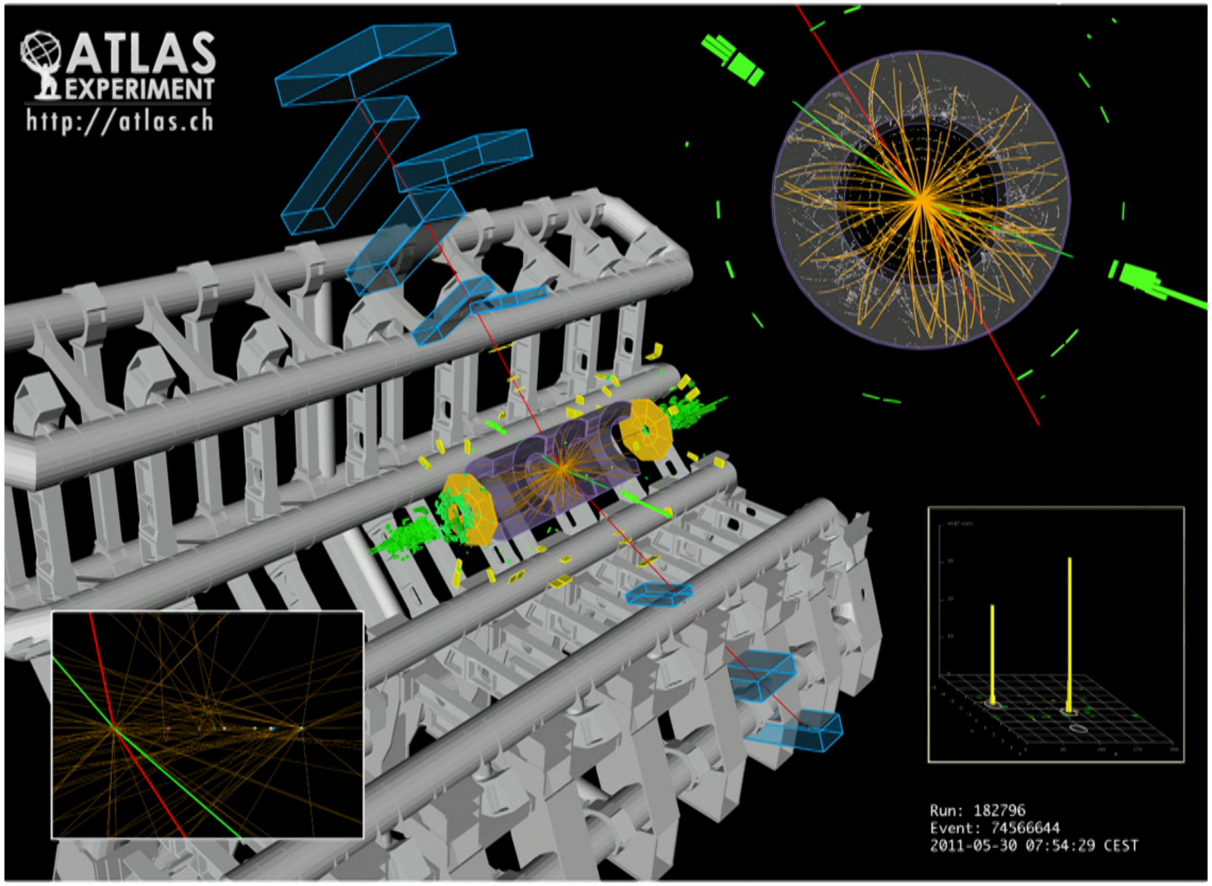


10 m
μ+
μ−
K+ μ+
π−
μ−
723 microns
CDF:
J/ψ K*
Run 42565 Event 72426
11 Dec 92
1 cm

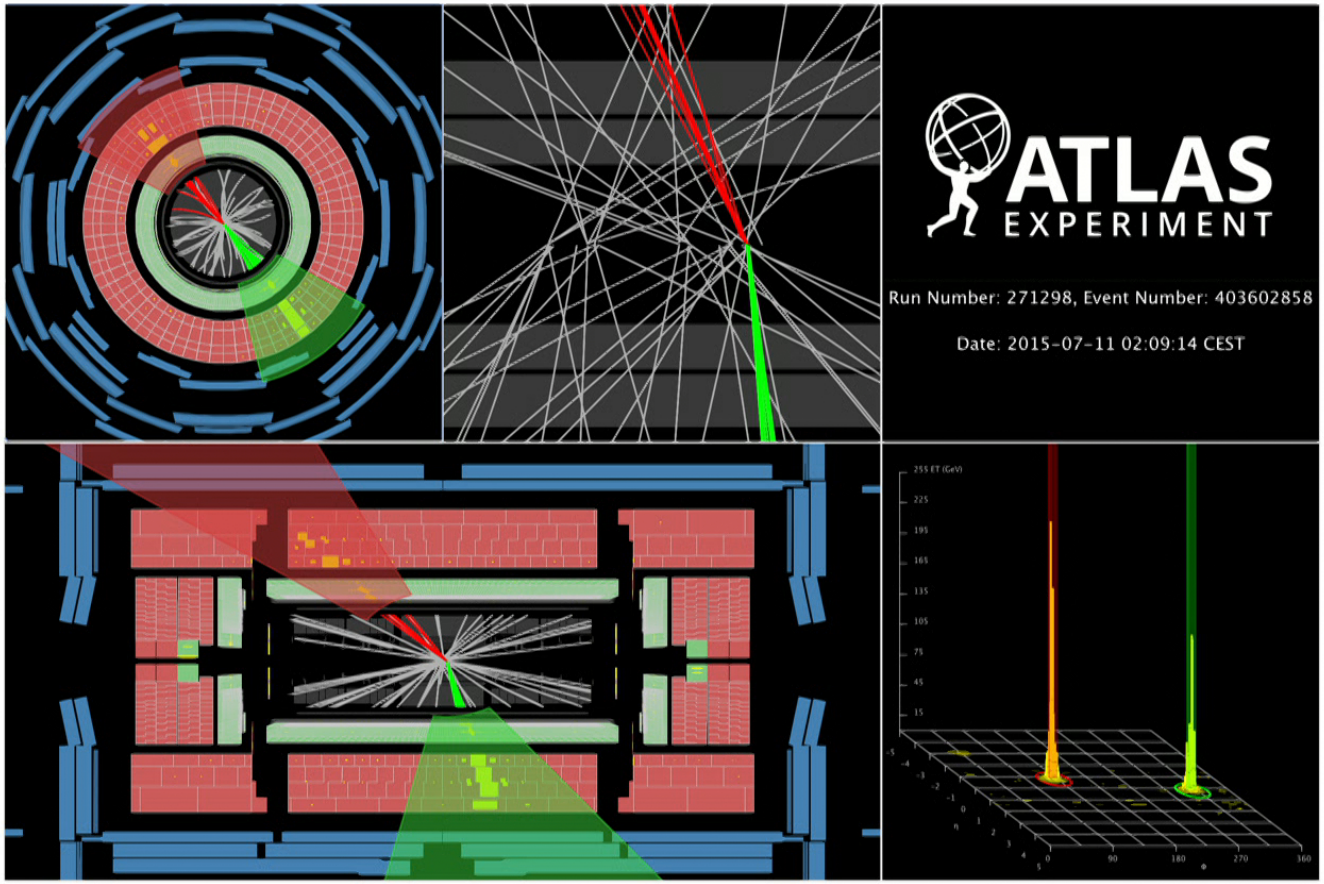
H → ττ


3-prong τ_{had}
Jet
E_T^{miss}
1-prong τ_{had}
ATLAS EXPERIMENT
Run 190878,Event 2721965
Time 2011-10-12, 12:09 CEST
$p_T(\tau_{had}^{3\text{-prong}})$ = 72 GeV
$p_T(\tau_{had}^{1\text{-prong}})$ = 45 GeV
E_T^{miss} = 28 GeV
p_T(jet) = 107 GeV
Coll. mass = 121 GeV

H → ZZ* → μμee


ATLAS
EXPERIMENT
http://atlas.ch
Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST

A More Useful Dijet Event Display



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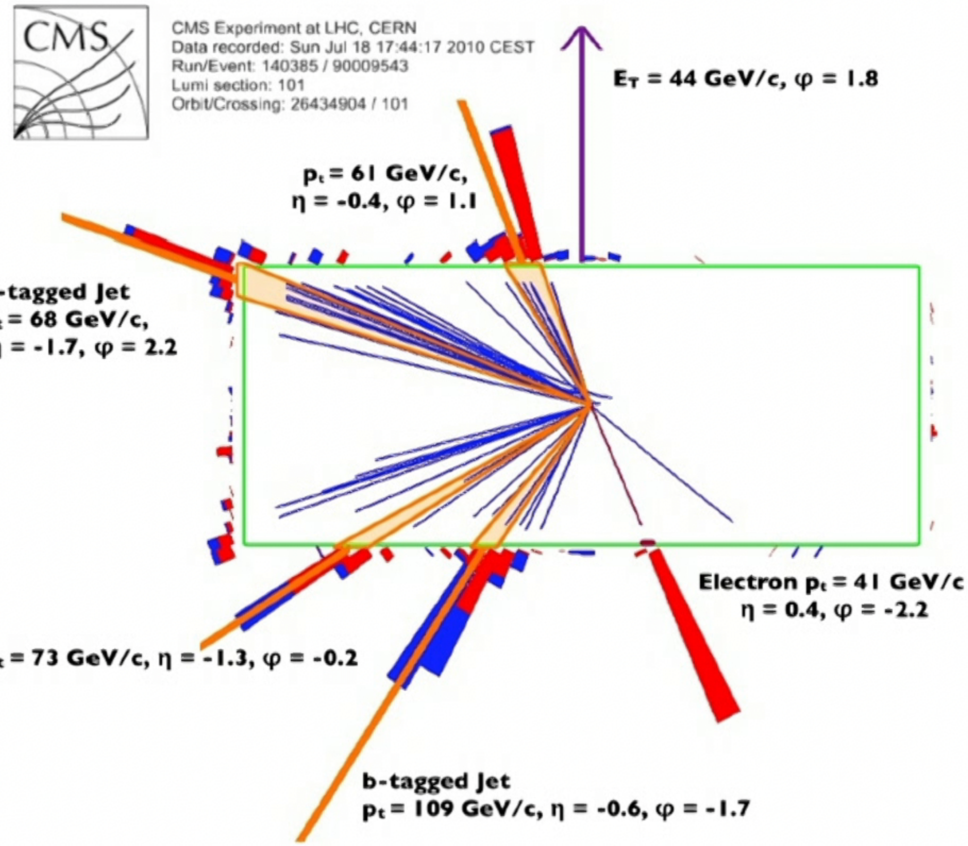
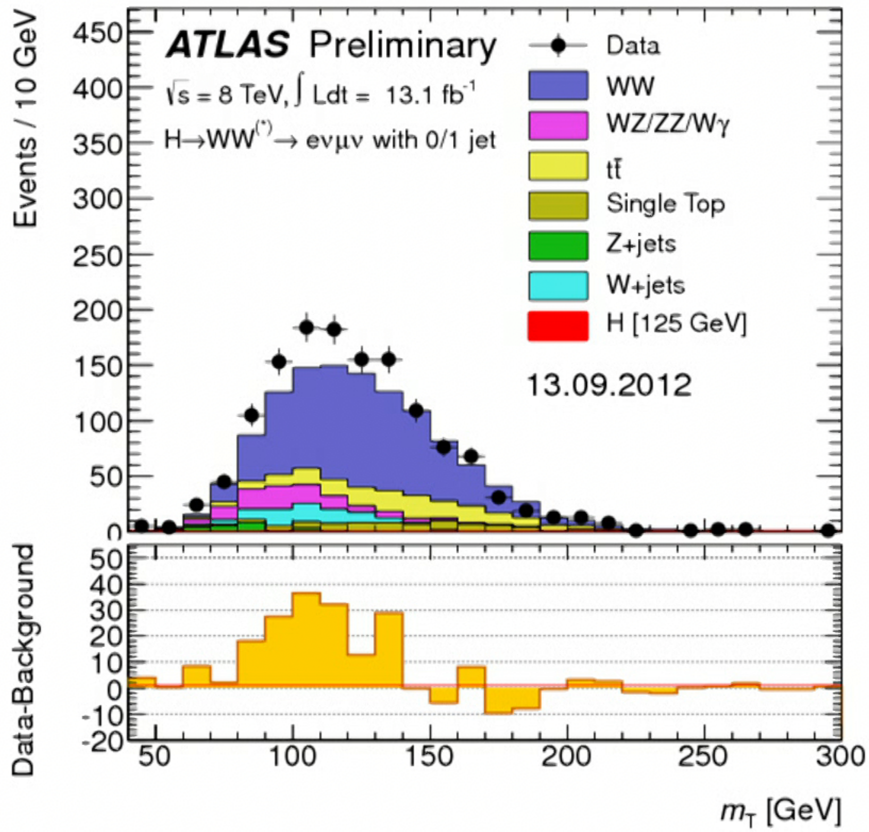
Top-antitop pair

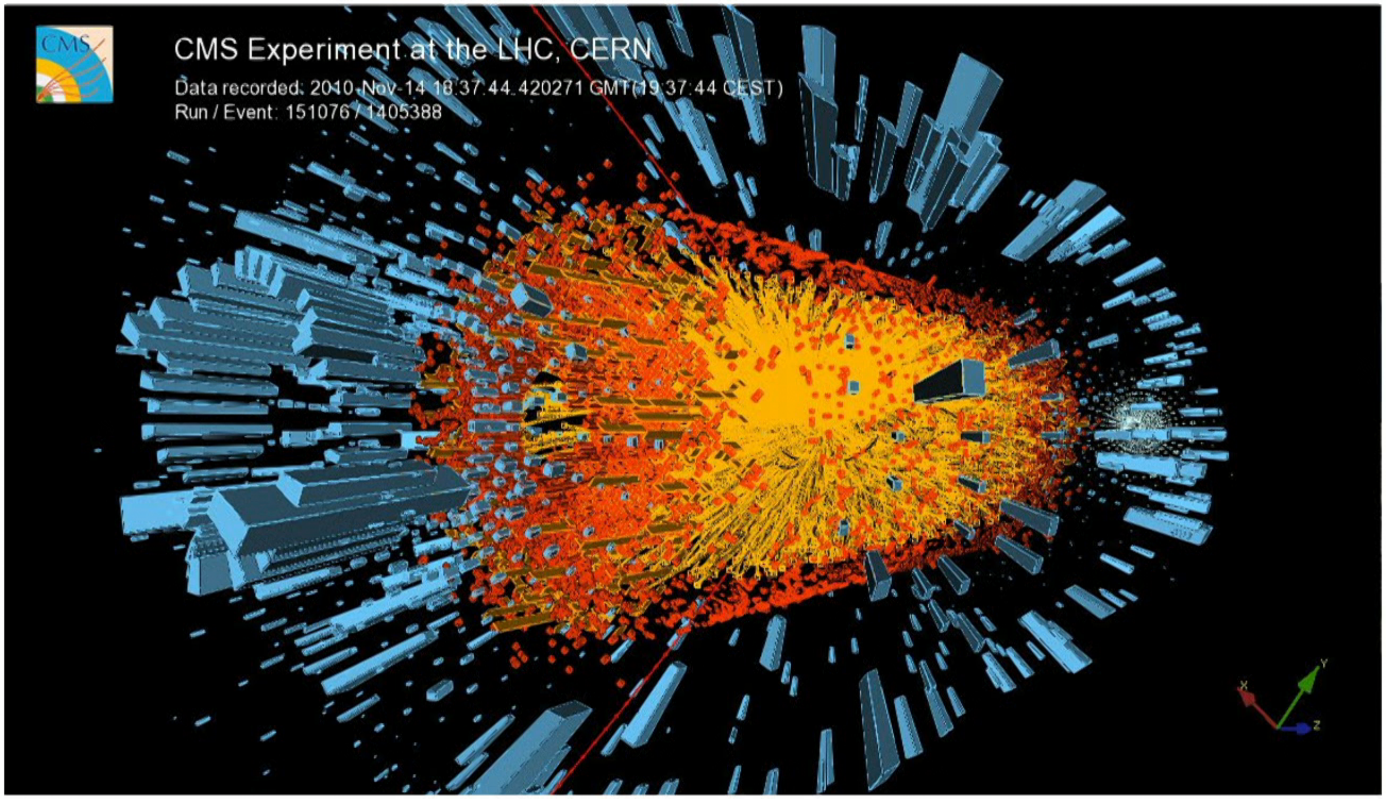


Higgs to WW



ATLAS Preliminary
$\sqrt{s}$ = 8 TeV, $\int$ Ldt = 13.1 fb^{-1}
H→WW$^{(*)}$→ eνμν with 0/1 jet
Data
WW
WZ/ZZ/Wγ
$t\bar{t}$
Single Top
Z+jets
W+jets
H [125 GeV]
13.09.2012
Events / 10 GeV
Data-Background
m_T [GeV]

A Heavy Ion (Pb-Pb) Collision



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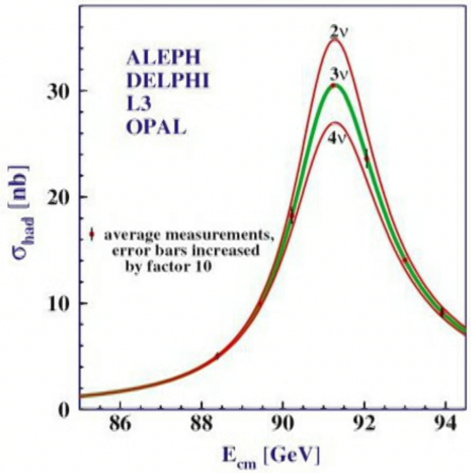
Synchrotron Radiation

$$P \sim \frac{E^4}{m^4 r^2}$$

- Charged particles in a circular orbit radiate
- Electrons radiate way more than protons
  - At LEP, these are very hard x-rays
  - At LHC (same tunnel), it's in the near UV
  - At LEP continual acceleration is necessary to replenish the energy lost to synchrotron radiation
- A little more energy and you get a lot more radiation
  - LEP lost 3 GeV per turn (vs. 7 keV for LHC)
- Going to a bigger tunnel doesn't really help
- Electricity is expensive, so less beam helps – but then we lose in luminosity
- This is why LHC has 70x the energy of LEP

LEP, Neutrinos and Non-Neutrinos



- By scanning the energy, we could (and did) map out the width of the Z boson
- By looking at the events, one can map out each partial width of the Z
- What's left over – the invisible width – could be neutrinos. If so, how many generations are there?
  - N = 2.984 ± 0.0008