Life, the Universe, and Electroweak Symmetry Breaking

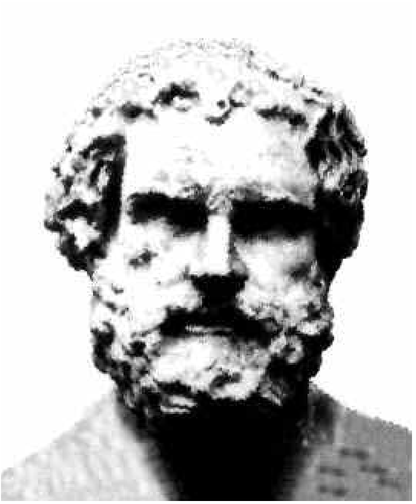
Andrew Askew
Florida State University

Outline

- What is this about?
- How does one do this?
- What has one learned?
- What WILL one learn?

The Questions that drive us…

- For thousands of years, we've been asking the questions:
  - What is matter made of?
  - How does it work?



- Democritus of Adbera ~ 460BC – 370 BC

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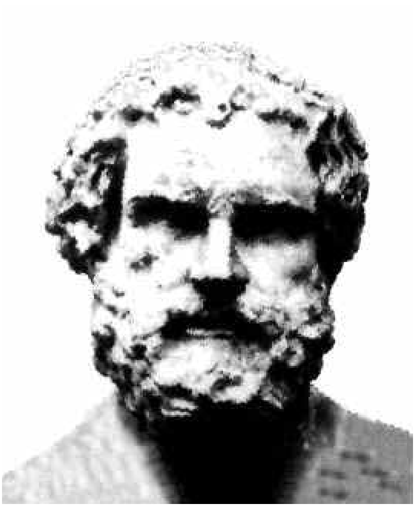

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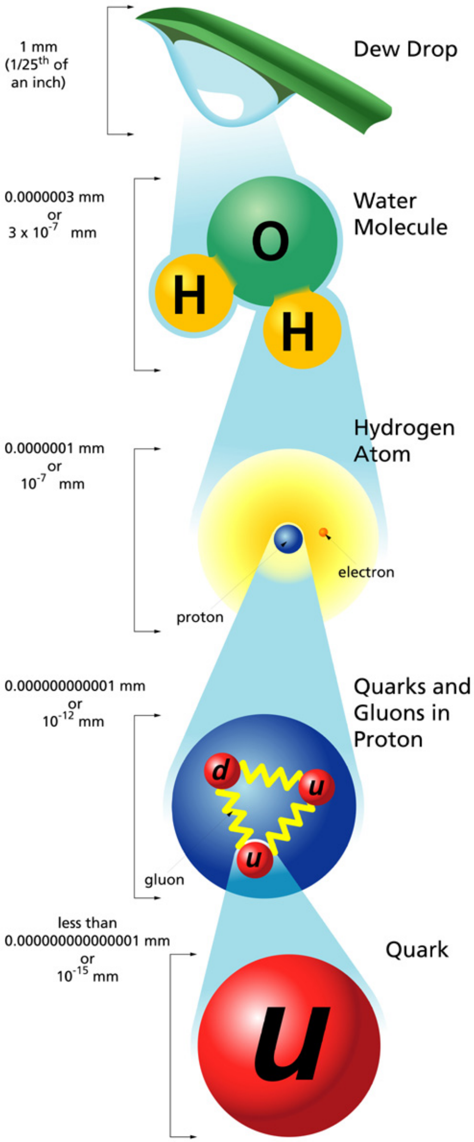
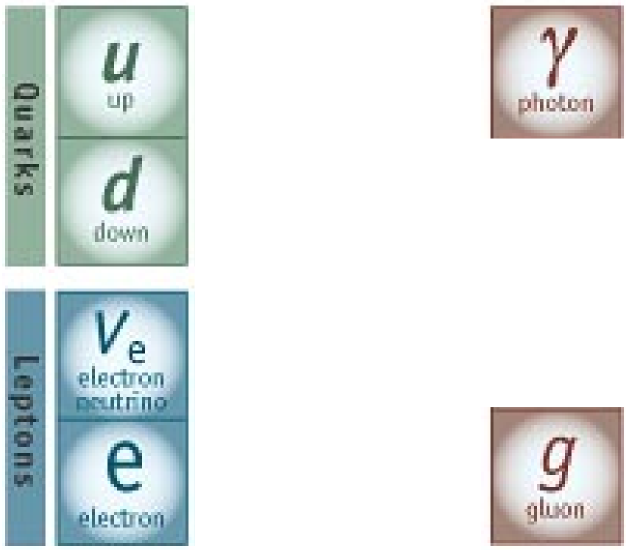
Time passes, things get more complicated.



Our 'atoms'



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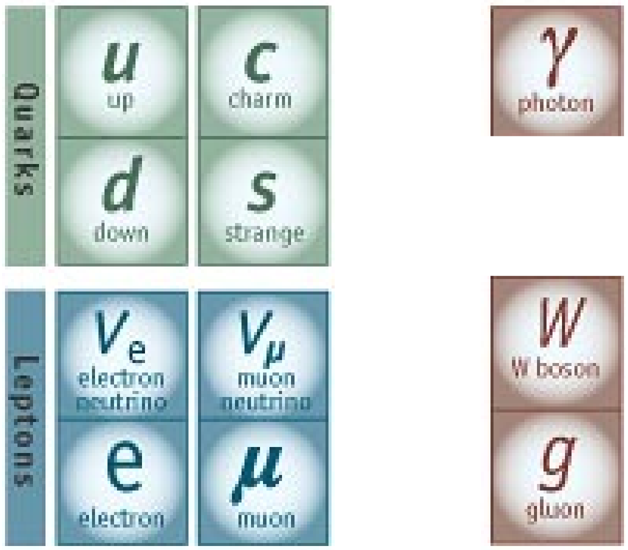

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- And if we look more closely, we reveal more.

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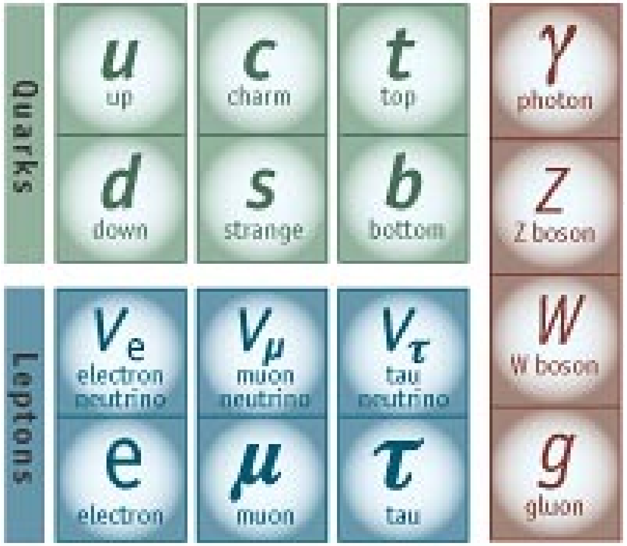
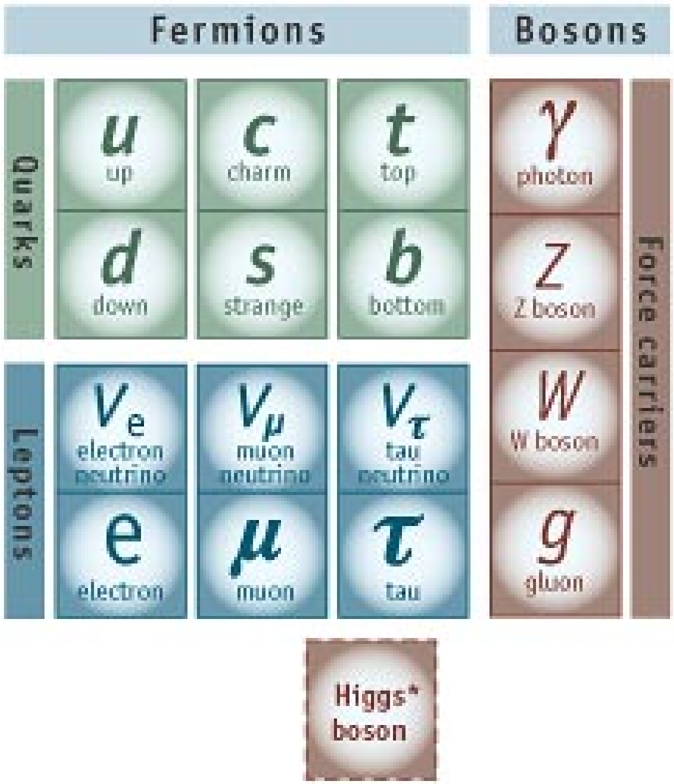


- So upon closer examination, we have a different set of atoms.
- And if we look more closely, we reveal more.
- And still more.

Thus far…

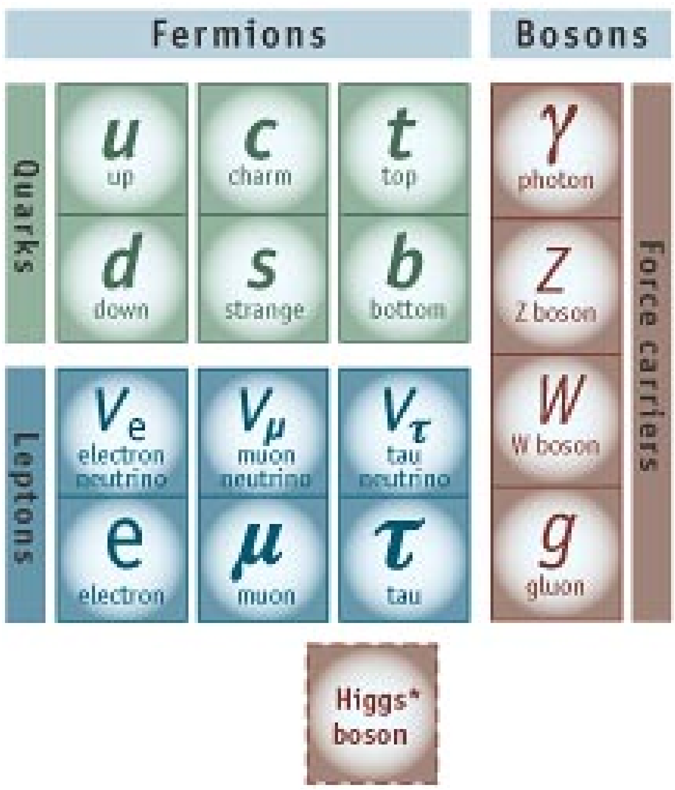
- The Standard Model: An enormous success.



  - Provides an understanding of what nucleons, atoms, stars, you and me are made of.
  - Describes how all of matter's constituents interact with one other.

Or…not.

- The Standard Model: An enormous failure



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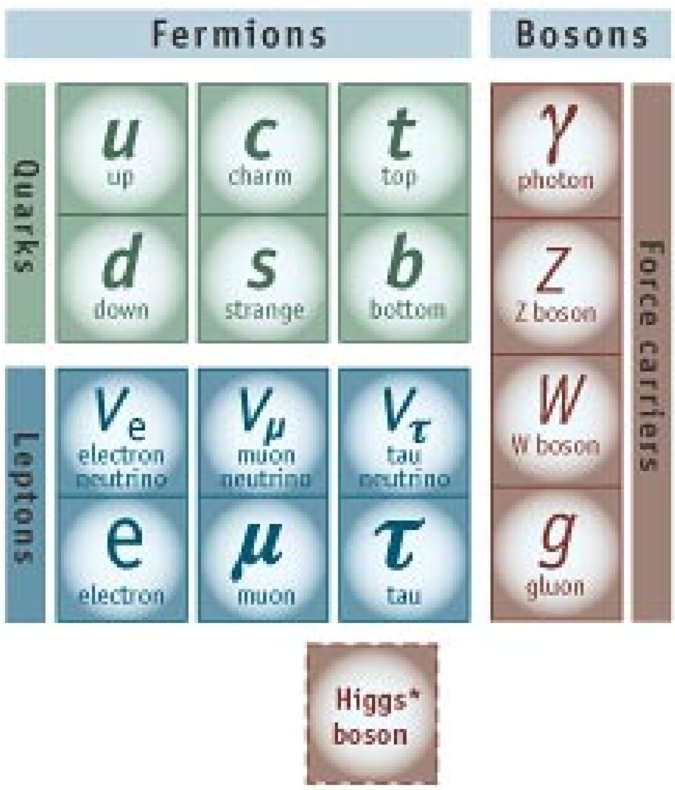

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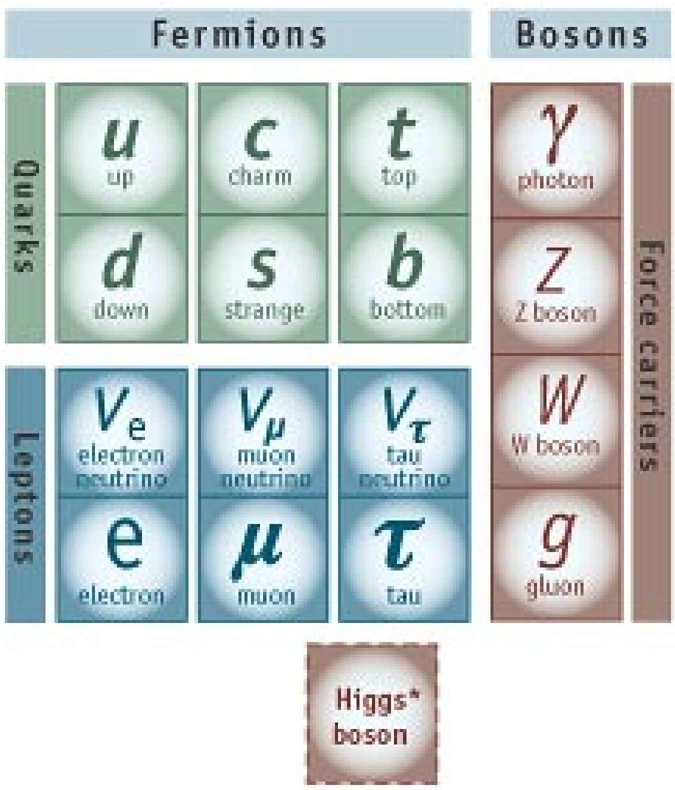

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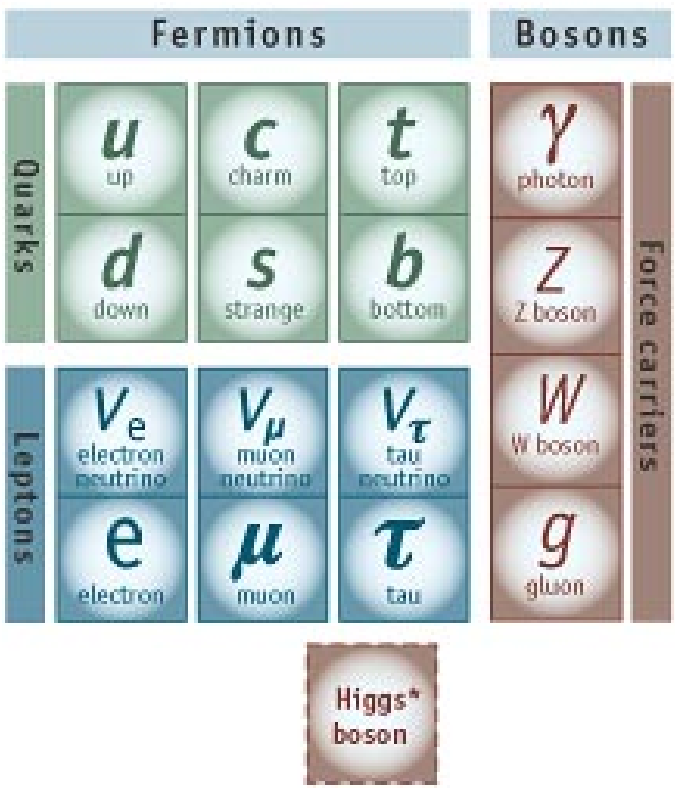

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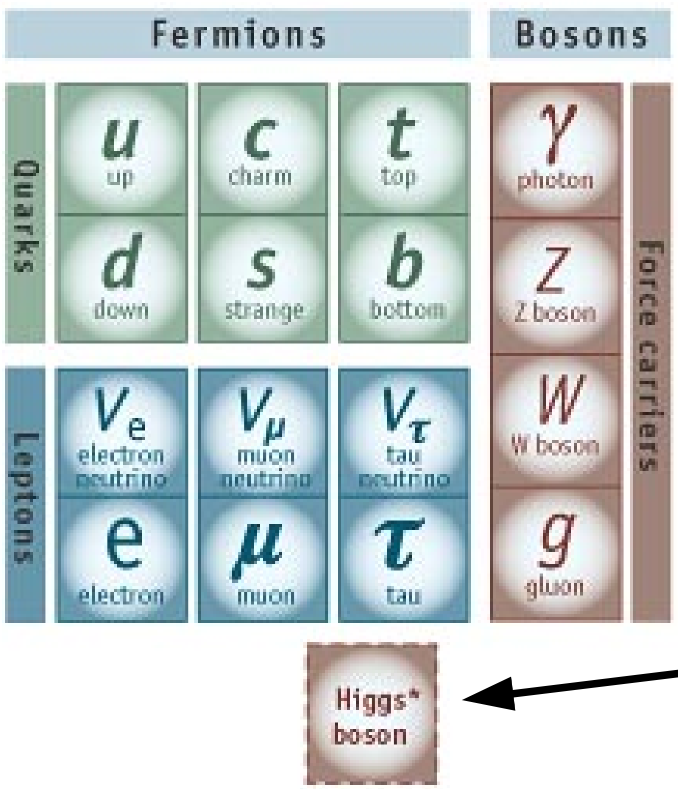

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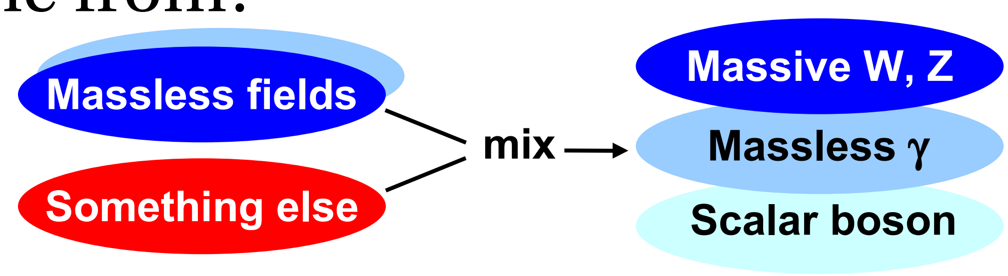
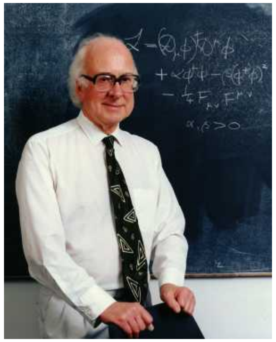
- The SM cannot explain the matter anti-matter asymmetry.
- The SM cannot incorporate gravity with Electromagnetic, Weak and Strong interactions.
- Dark matter and Dark energy?
- The Higgs itself is in some sense an add-on.
  - Needed "something" to give masses to the W and Z.

You know. The "God particle"?

- What's this about a Higgs?
  - Photons and W/Z bosons interact with (couple to) particles with the same strength:
    - Electroweak unification.
- Yet while the universe (and this room) is filled with photons, the W and Z are massive and mediate a weak force.
- Where does this mass (the symmetry breaking) come from?





The "Higgs Mechanism"

But what if…

- What if there is no Higgs?

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There is no spoon.

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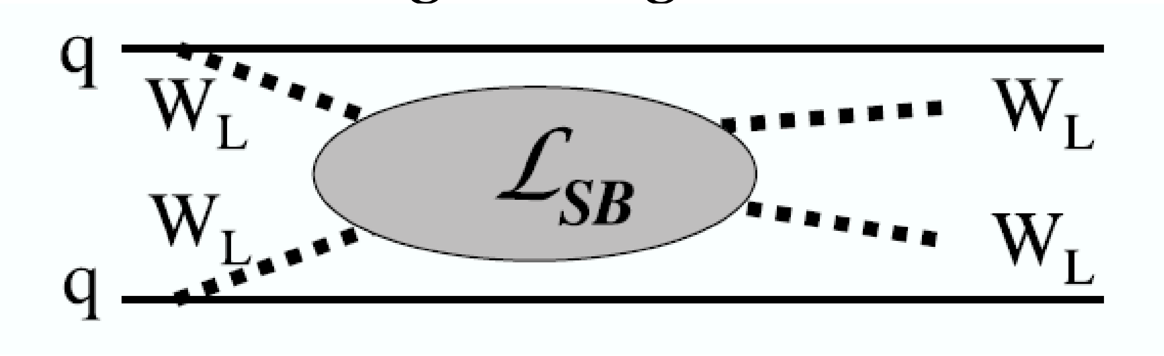

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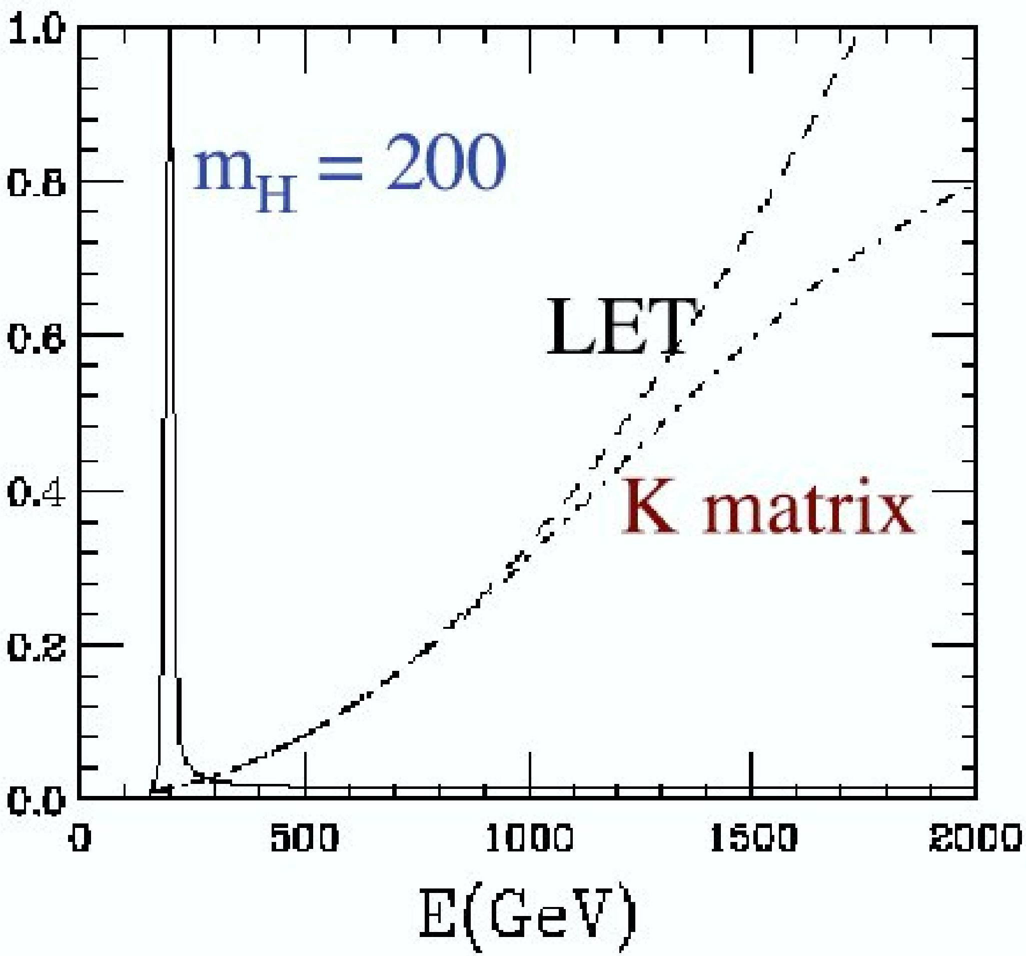
- Something has to handle this electroweak symmetry breaking (real problem if not).
  - Either there's a Higgs and the interaction of the weak bosons stay weak at all energies.
  - OR there isn't one and the Weak interaction has to become STRONG at high energies (~1 TeV).
- Therefore, studying the coupling of the electroweak bosons can tell us more about if there's a Higgs, or maybe...if there isn't.

But what if…

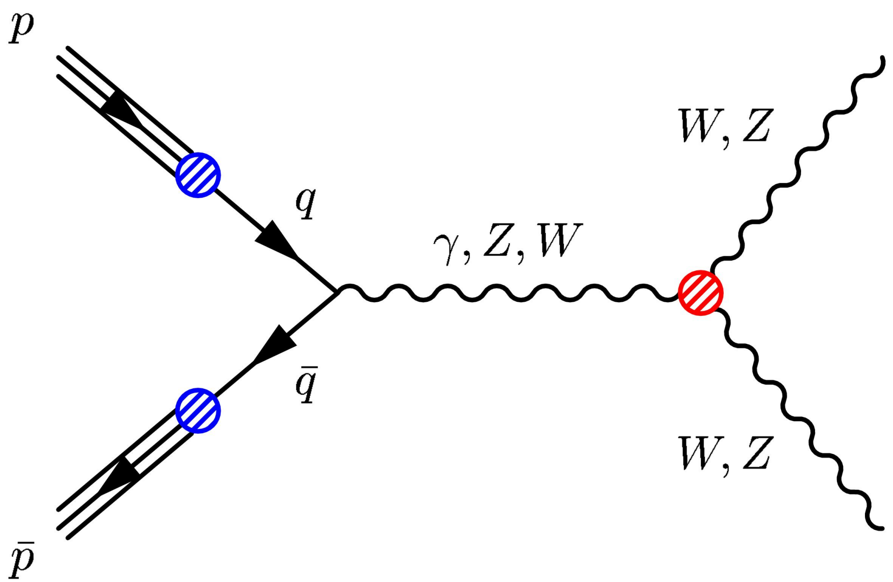


There is no spoon. Warped space?

- The "no-lose" theorem: At 1 TeV
  - EITHER we observe the Higgs
  - OR we'll see the strength of the weak interaction increase.

So what does one look for?

- Try to find pairs of bosons produced at the same time.



- We're studying weak forces, on small scales (high energies). How do you do that?

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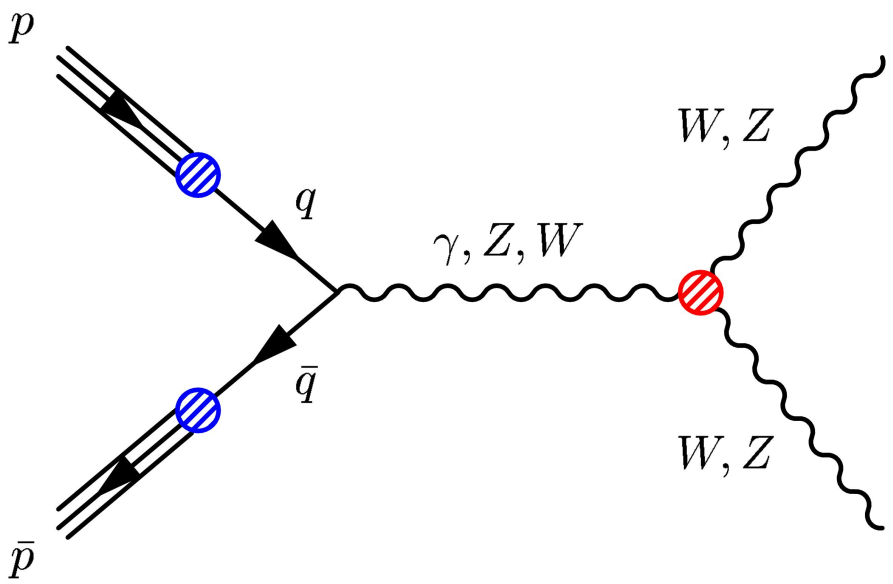
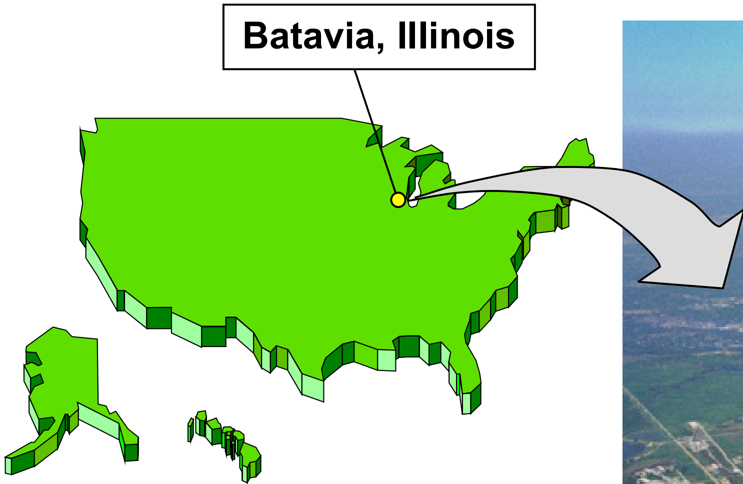
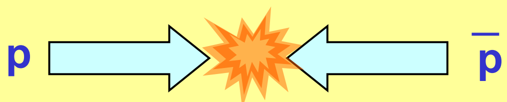


- We're studying weak forces, on small scales (high energies). How do you do that?
- You get a BIIIIGGGGGG microscope.

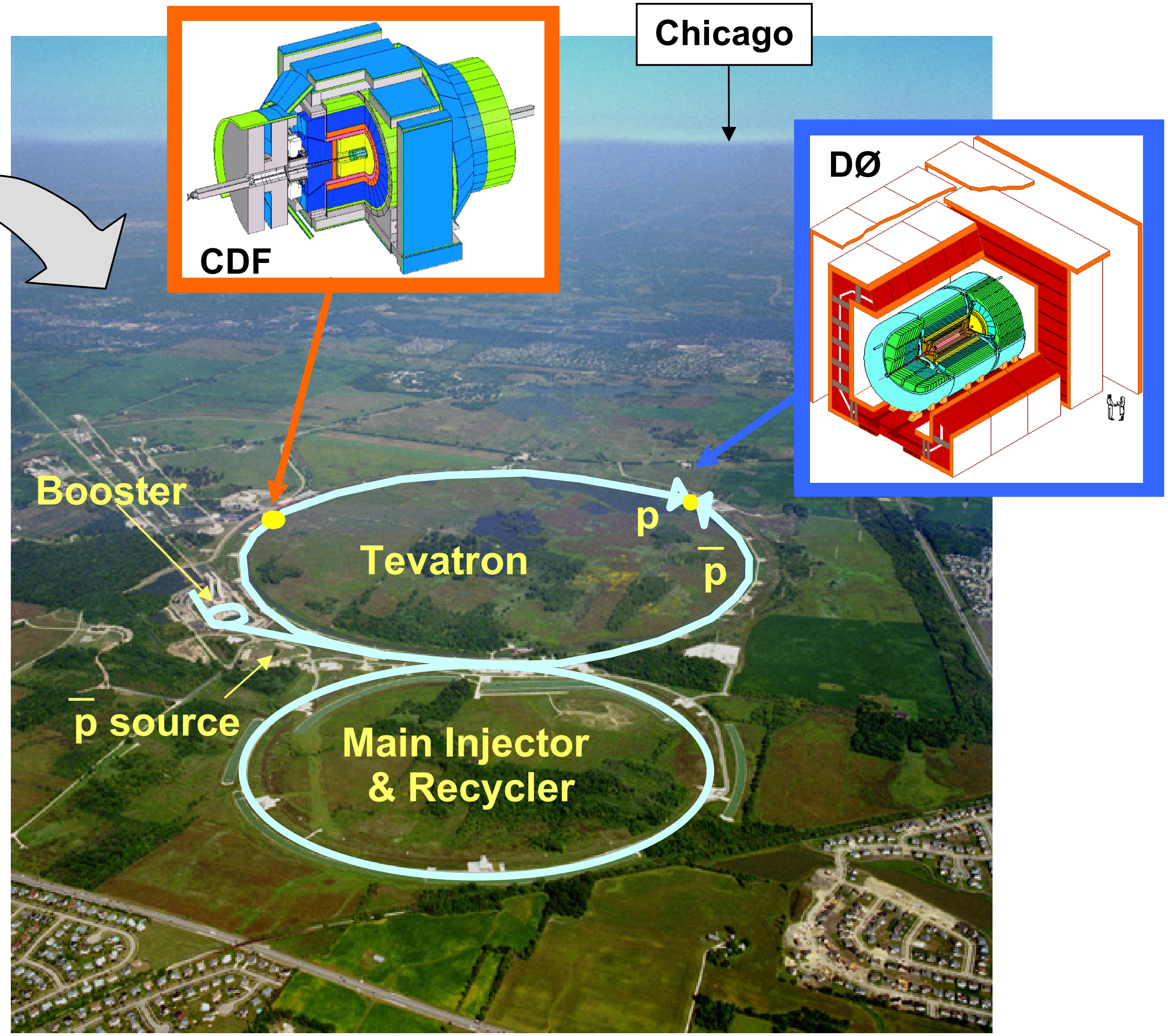
Currently the biggest microscope:



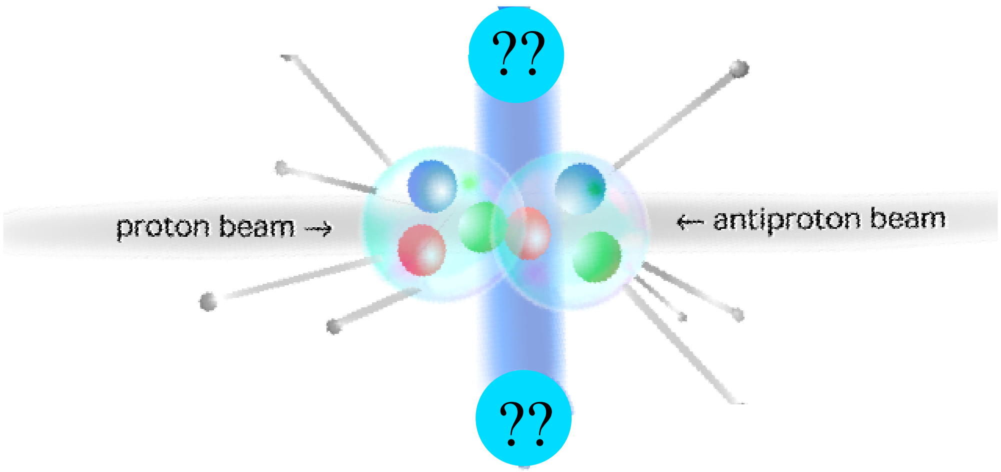


$\sqrt{s} = 1.96$ TeV
$\Delta t = 396$ ns

Run I 1992-96
Run II 2001-09



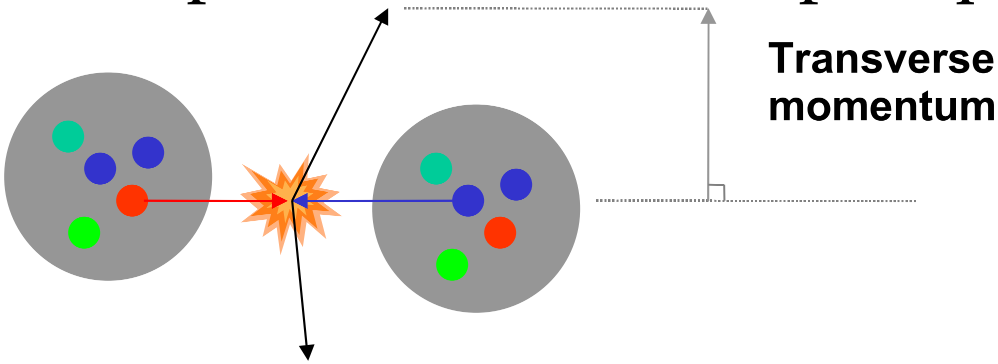
The point being thus:



- By using a collider, we become able to study all the different particles in the universe, even though the vast majority of matter is made up of only a few. Including the massive bosons.
- And then we can investigate how they interact.

Proton-Antiproton Collisions:

- A messy business: these aren't point particles, protons and antiprotons are made up of quarks and gluons.



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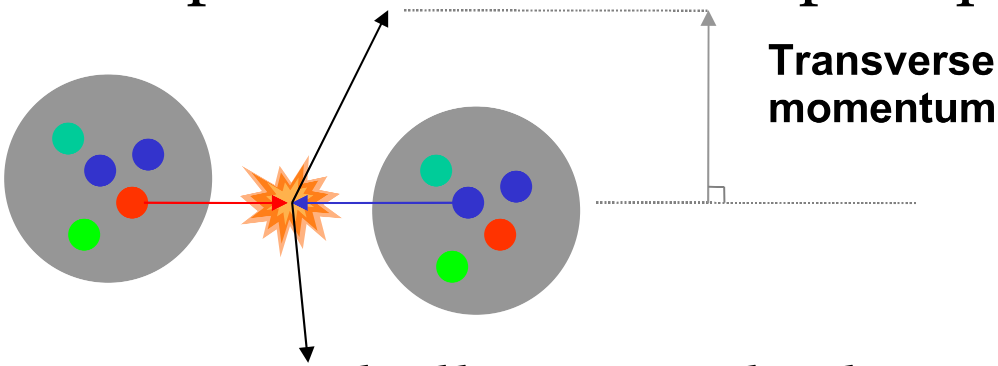

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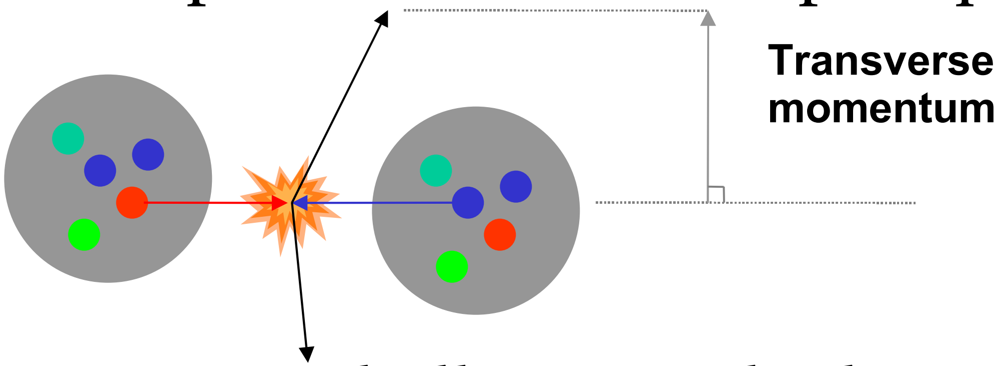

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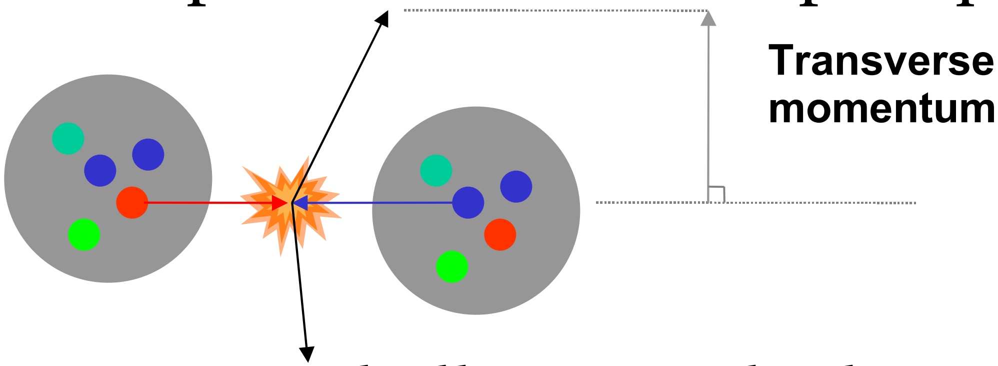

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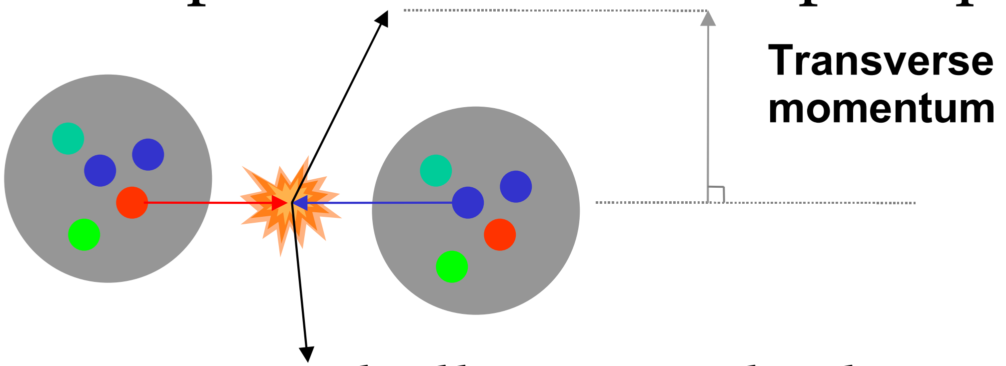

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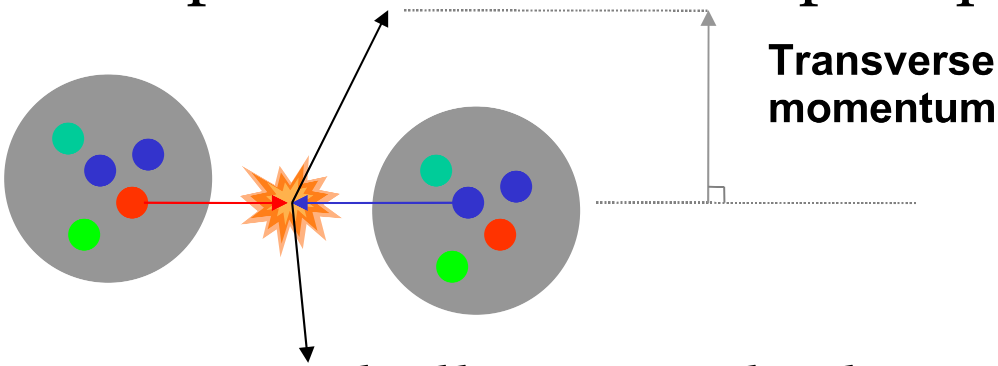
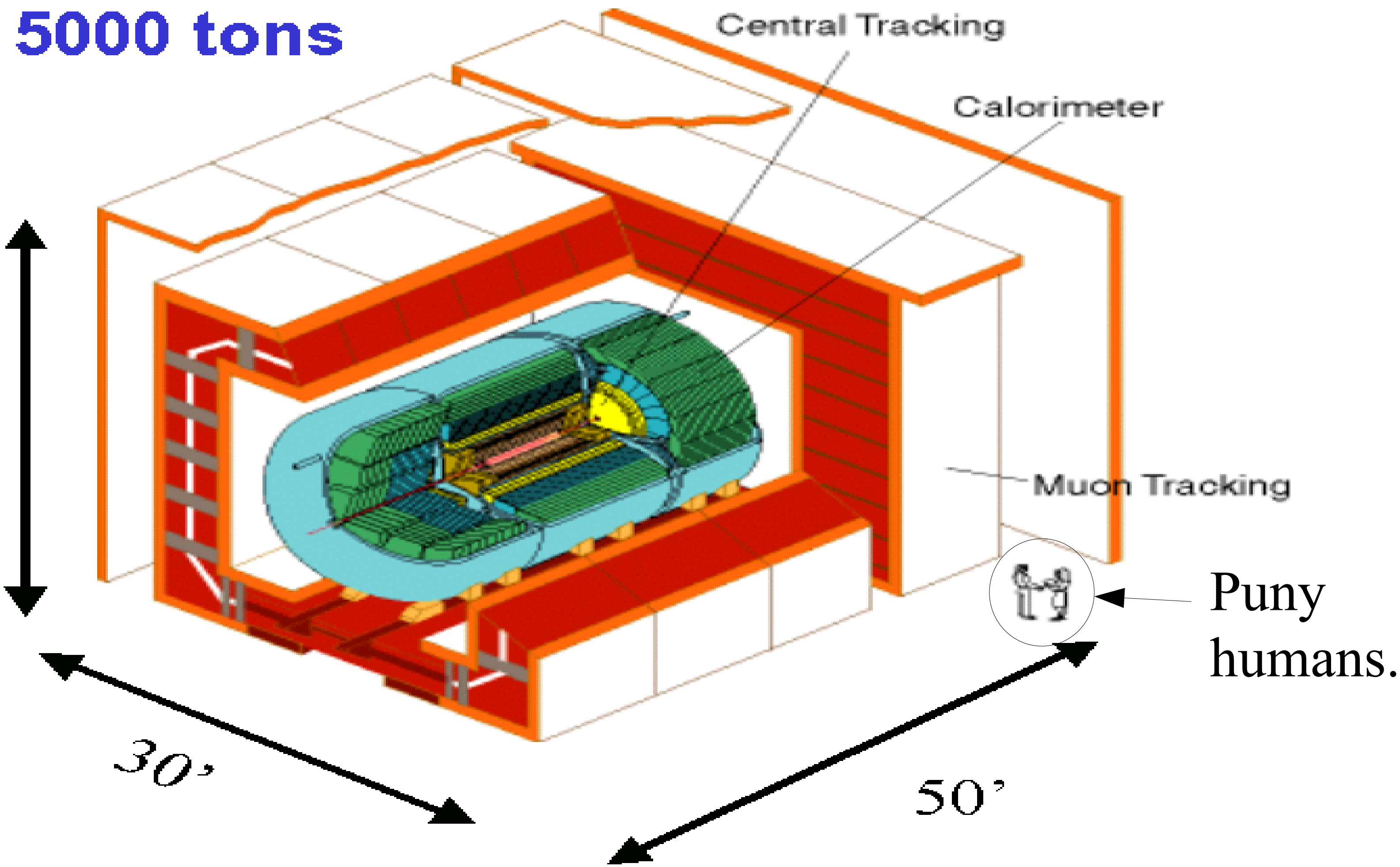


- How messy? Imagine a balloon in which one places three billiard balls. Then fill the remaining space with Jello. Now make a second one of these.
- Now smash them together as hard as you can. Messy.
- Go ahead, try it at home!
  - This is sorta silly, but I have a point: collisions are highly active, and don't all occur at the same energy.

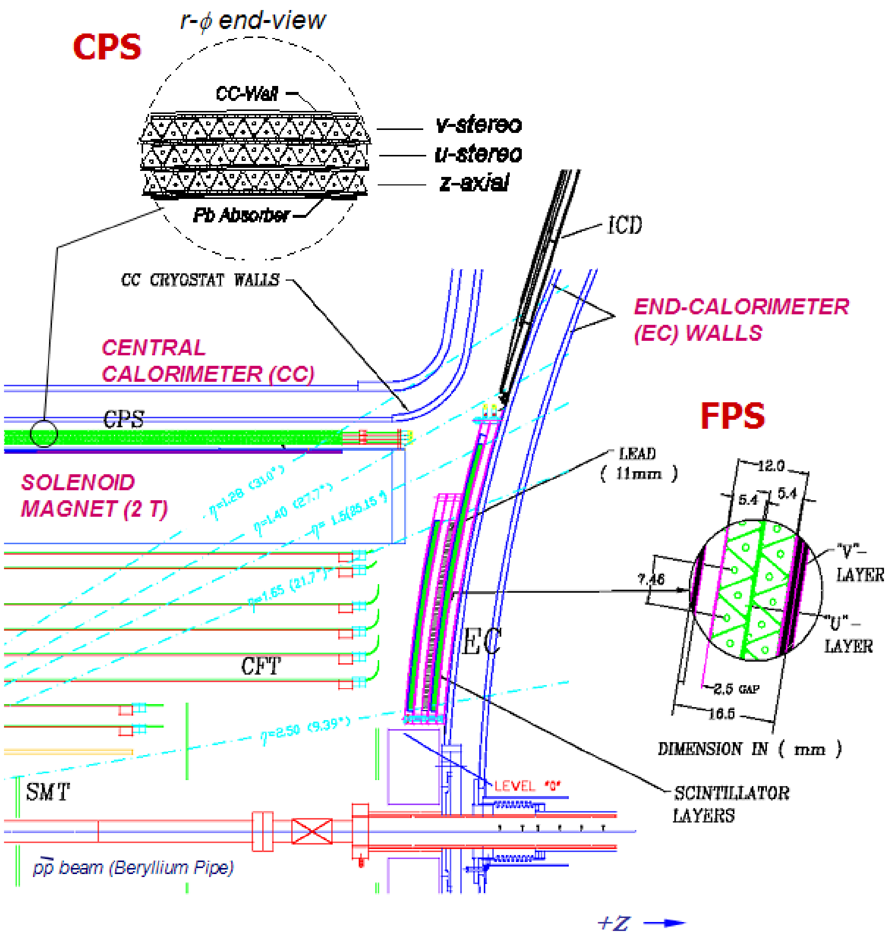
The Mess

- Most of what happens at a hadron collider is pure quantum chromodynamics (QCD).
  - This is interesting in its own right, but not what we're looking to study here!
- There are SO many of these types of interactions, that we always have to explore the possibility that our most interesting events are actually just QCD masquerading as our physics!
- If only there were some device we could exploit...

The D0 Detector

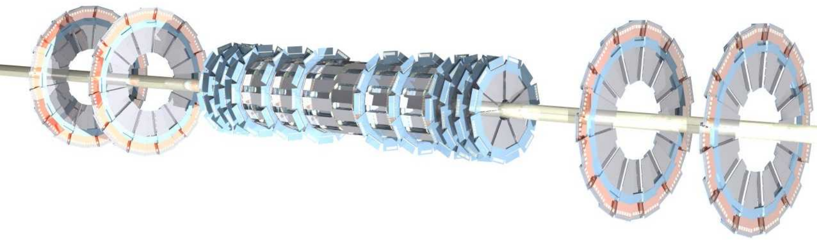


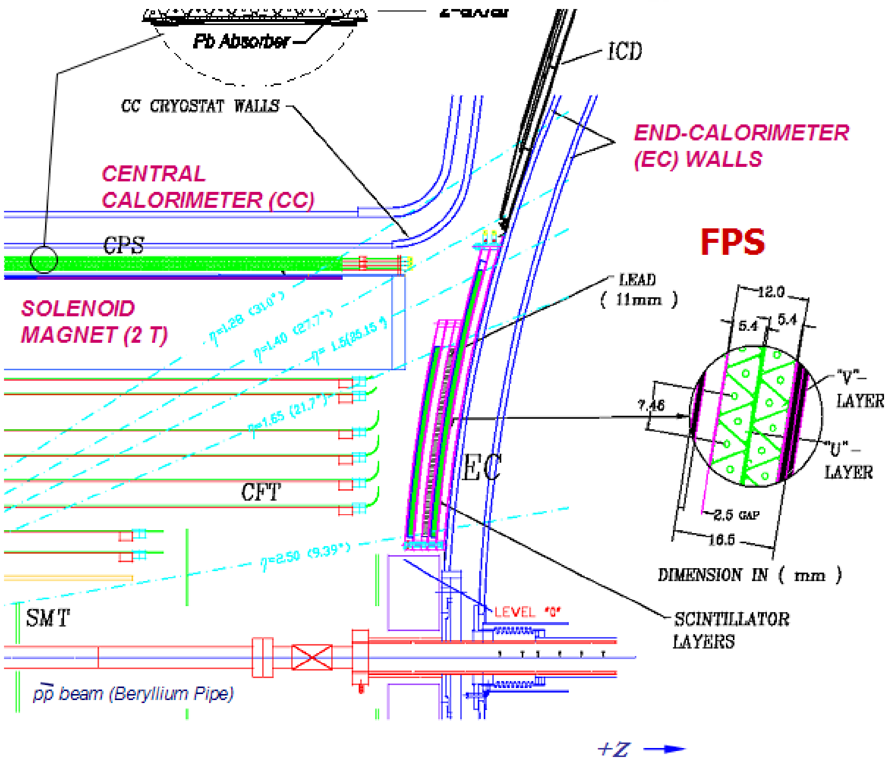
Central Tracking



- Silicon Tracker
- Fiber Tracker
- 2T solenoid
- Detect charged particles and measure their momentum.
- Preshower Detectors

Central Tracking





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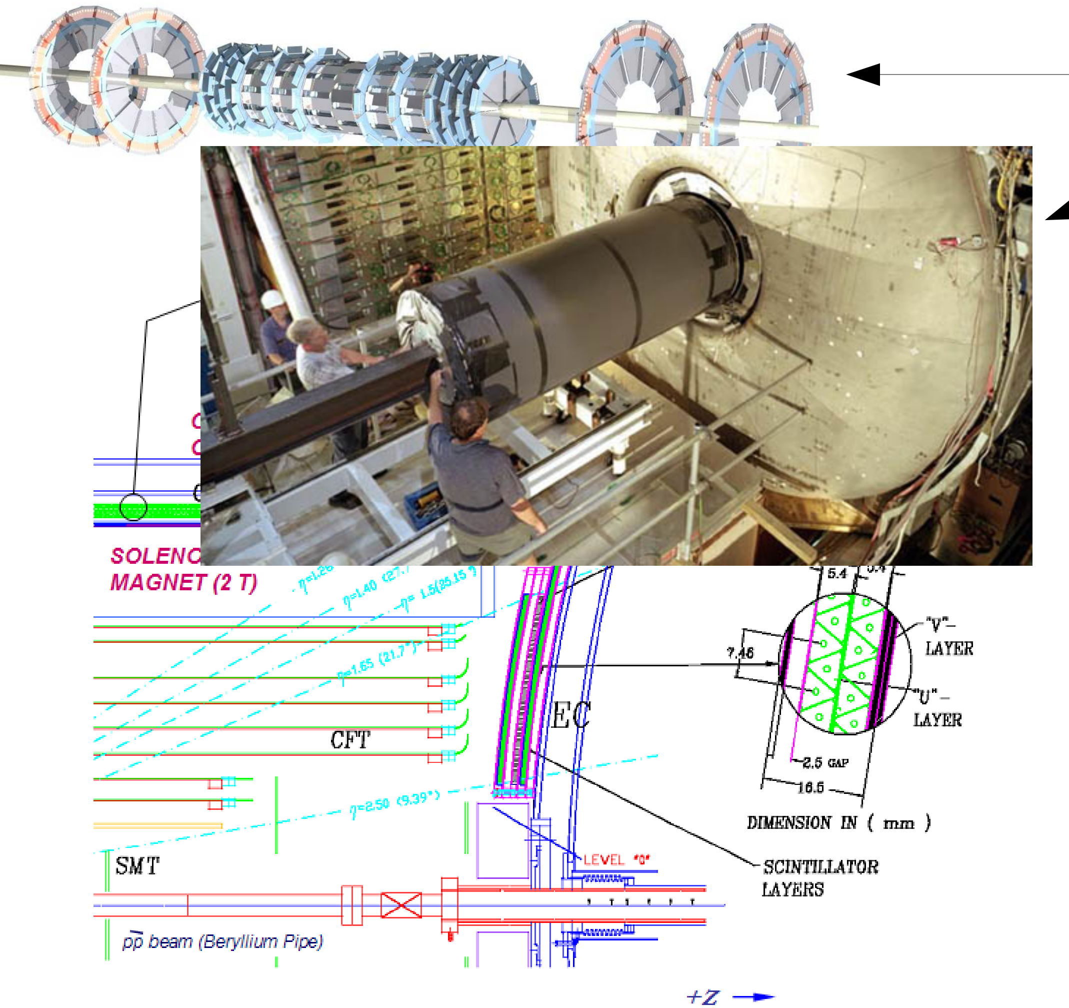

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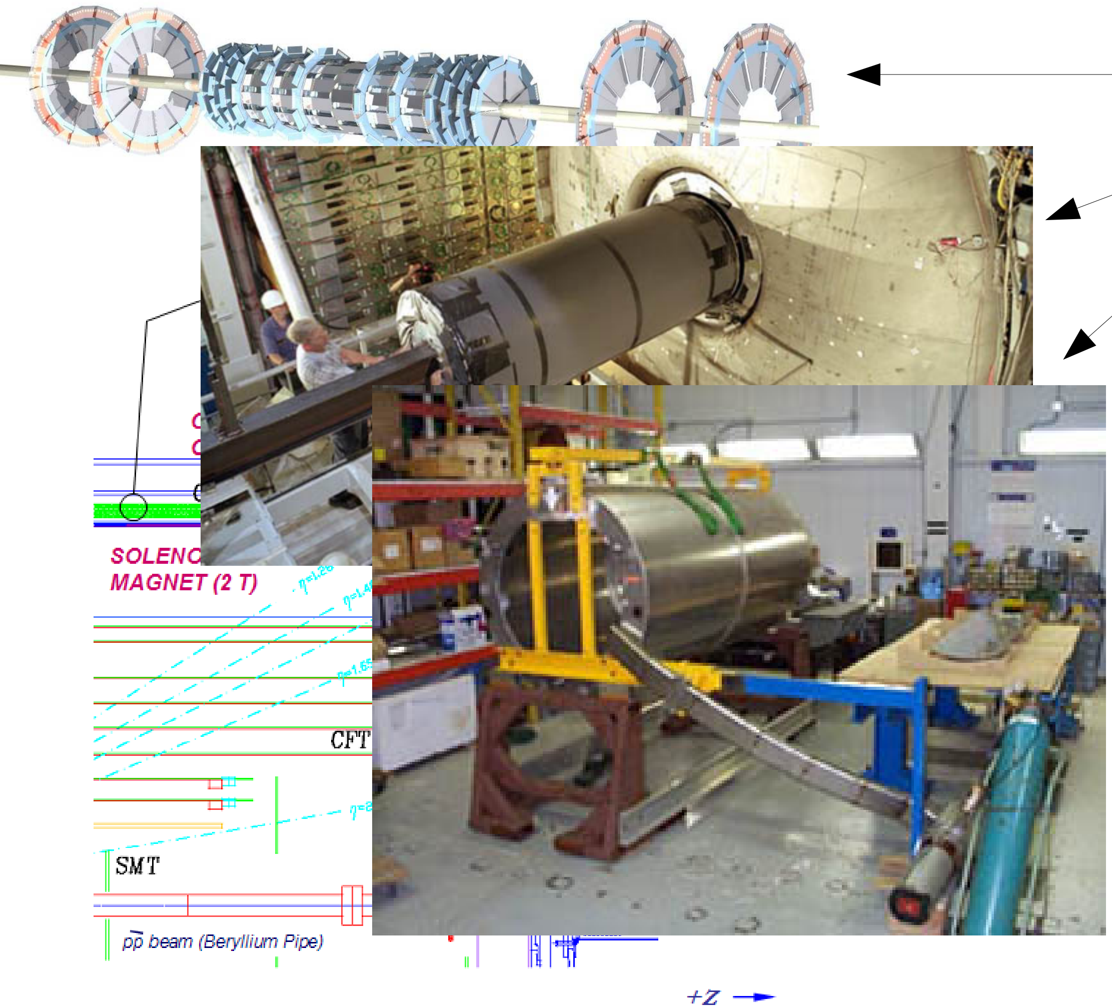

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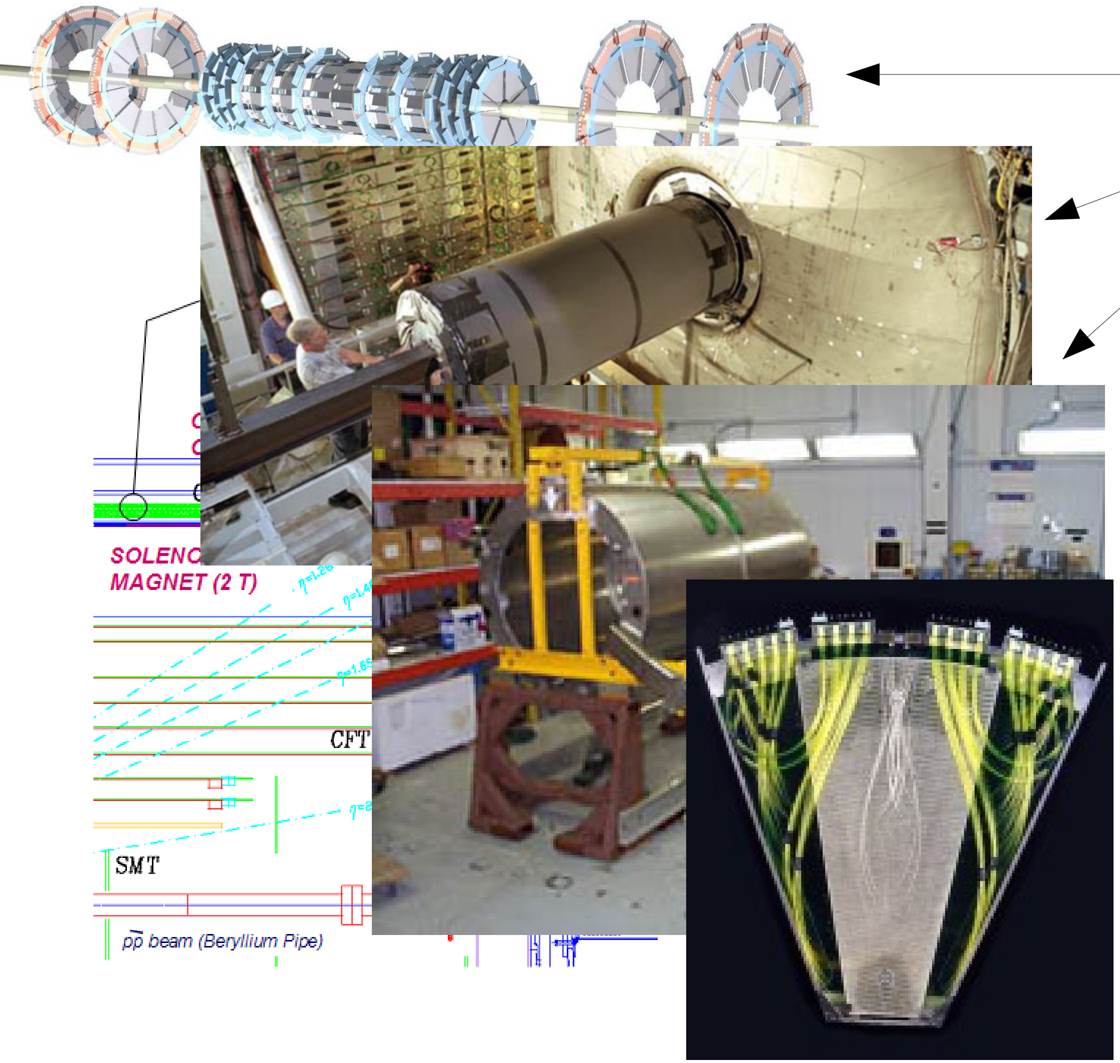

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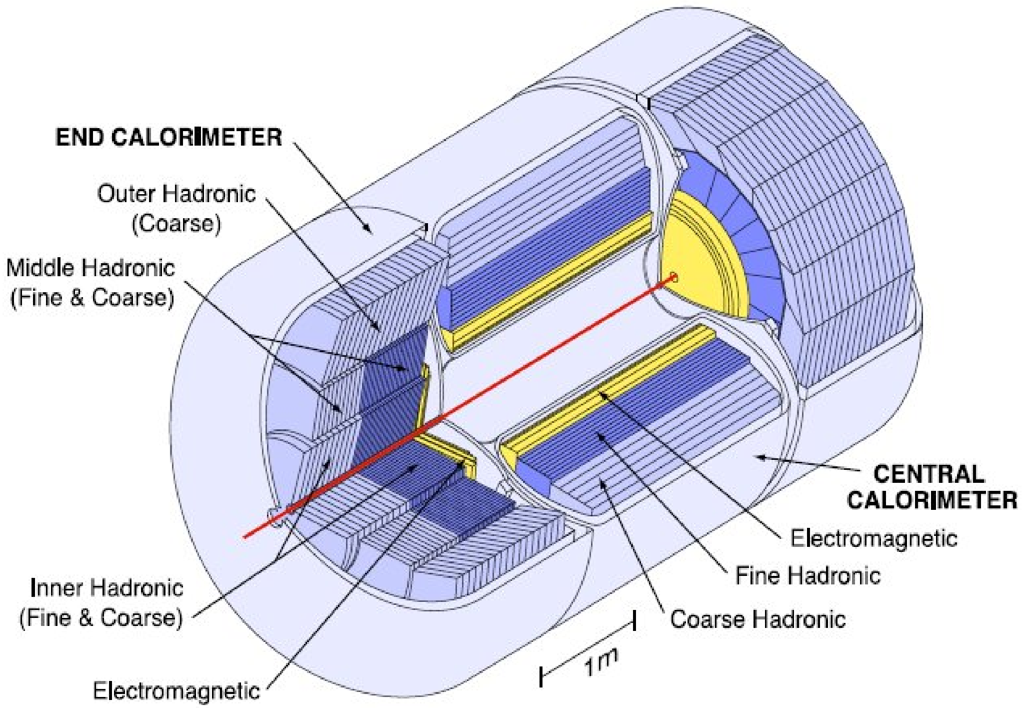
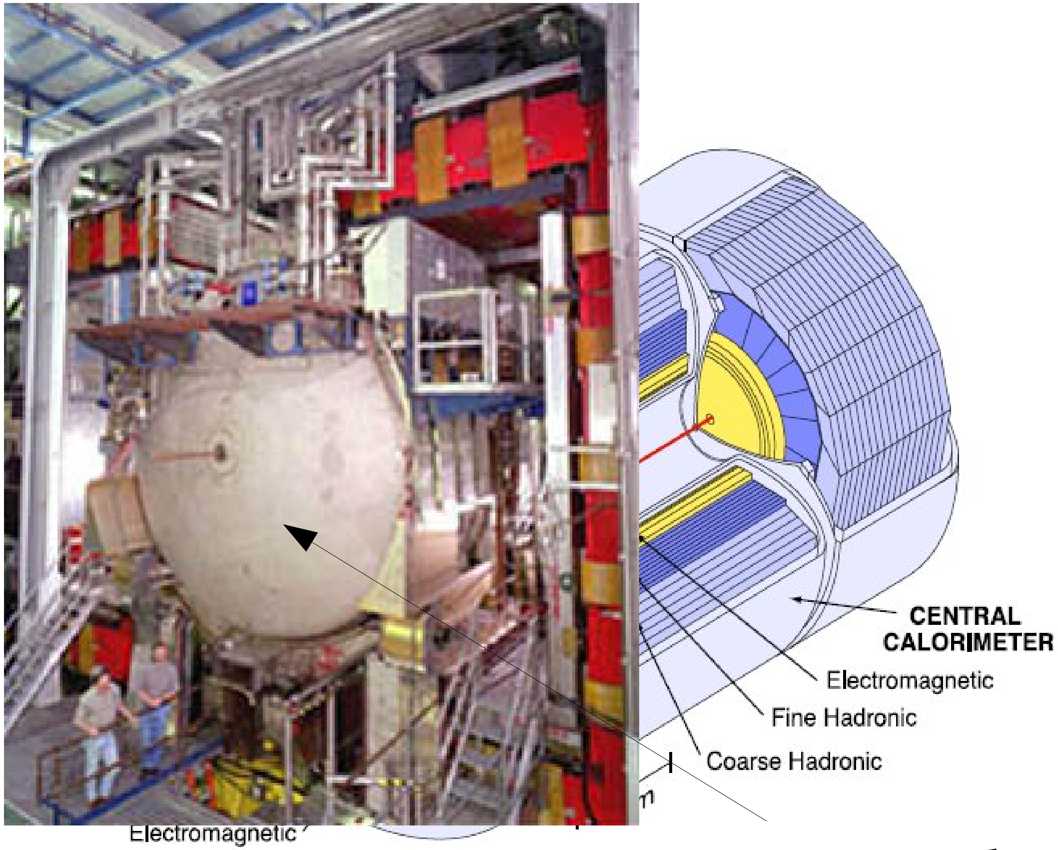
Calorimetry



- LAr/U calorimeter.
- Important note: Very good coverage, very few particles can escape detection.

Calorimetry



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Central Calorimeter

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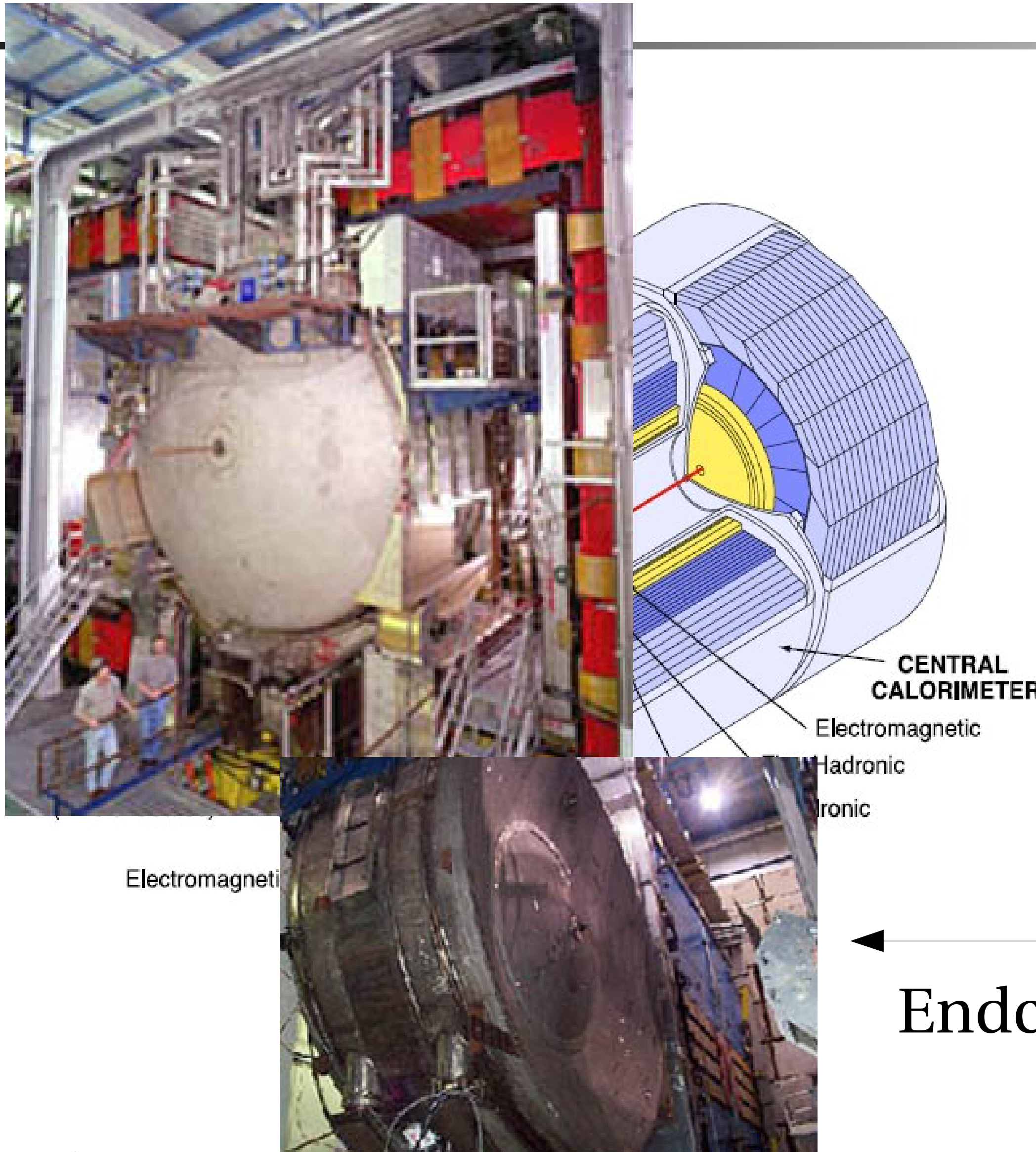

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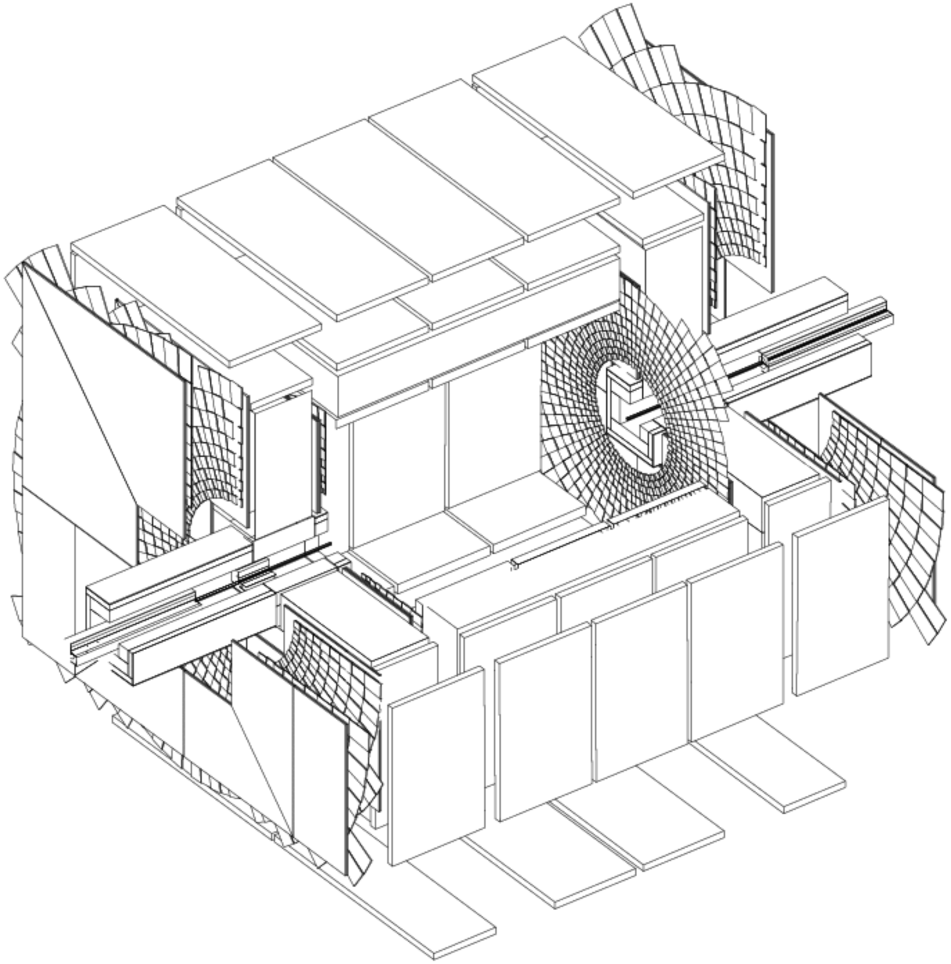
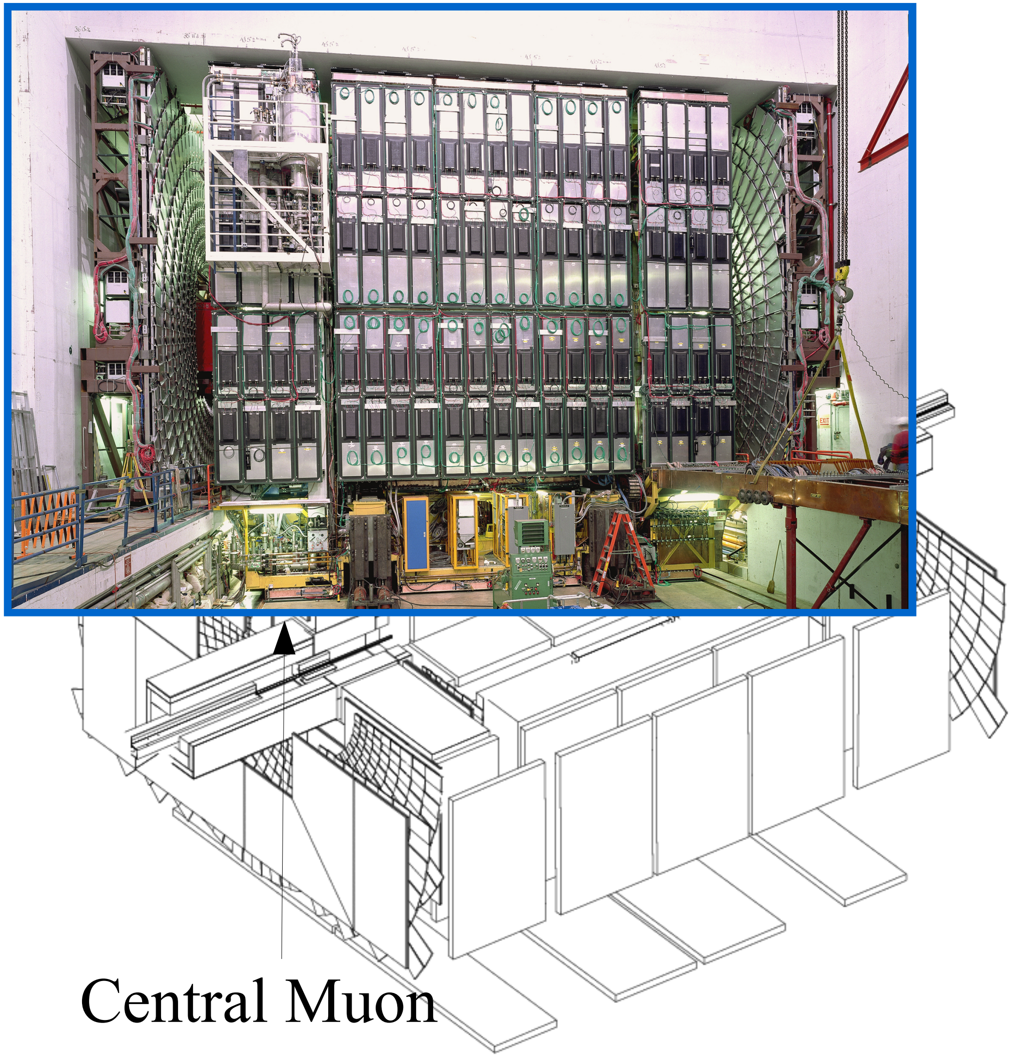
Endcap calorimeter

Muon Detectors



- Outermost detector.
  - Muons will mainly not interact with the rest of the detector.
- Basically a separate tracking system for just these particles as they leave, complete with a separate magnet.

Muon Detectors



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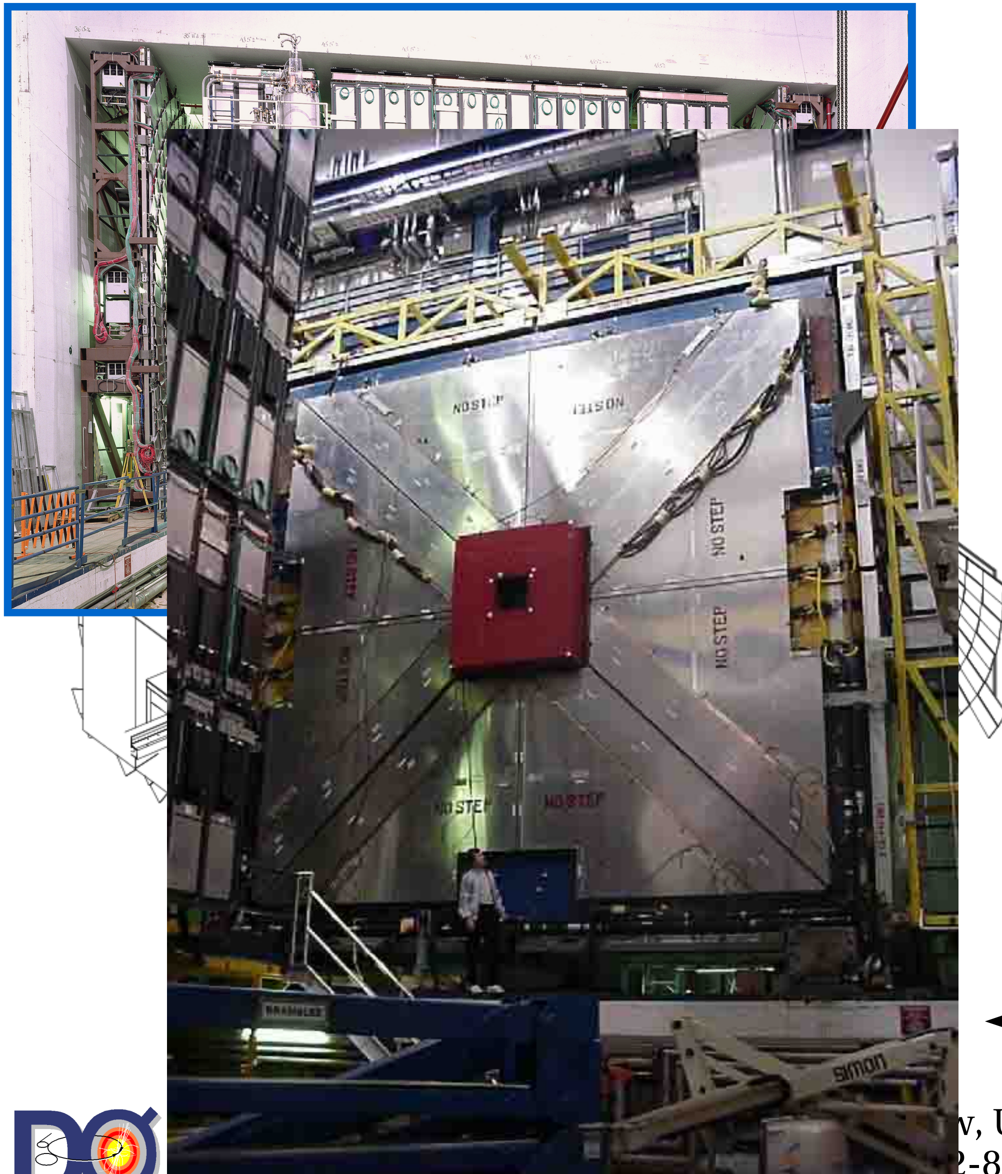

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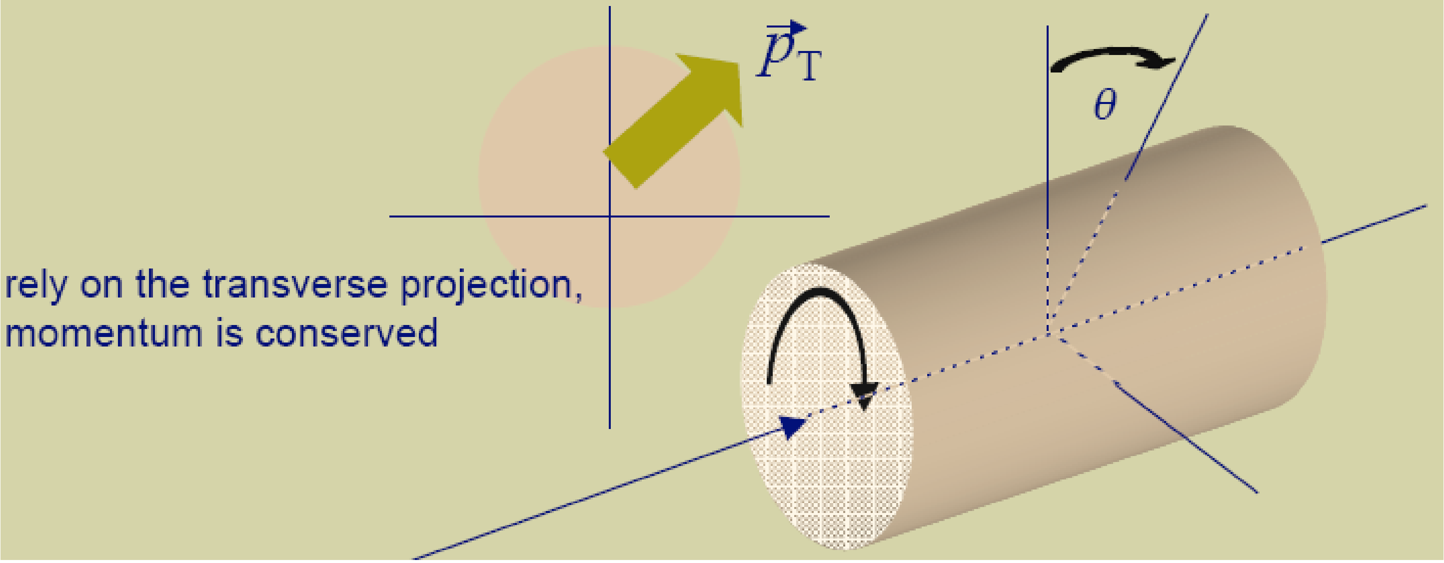
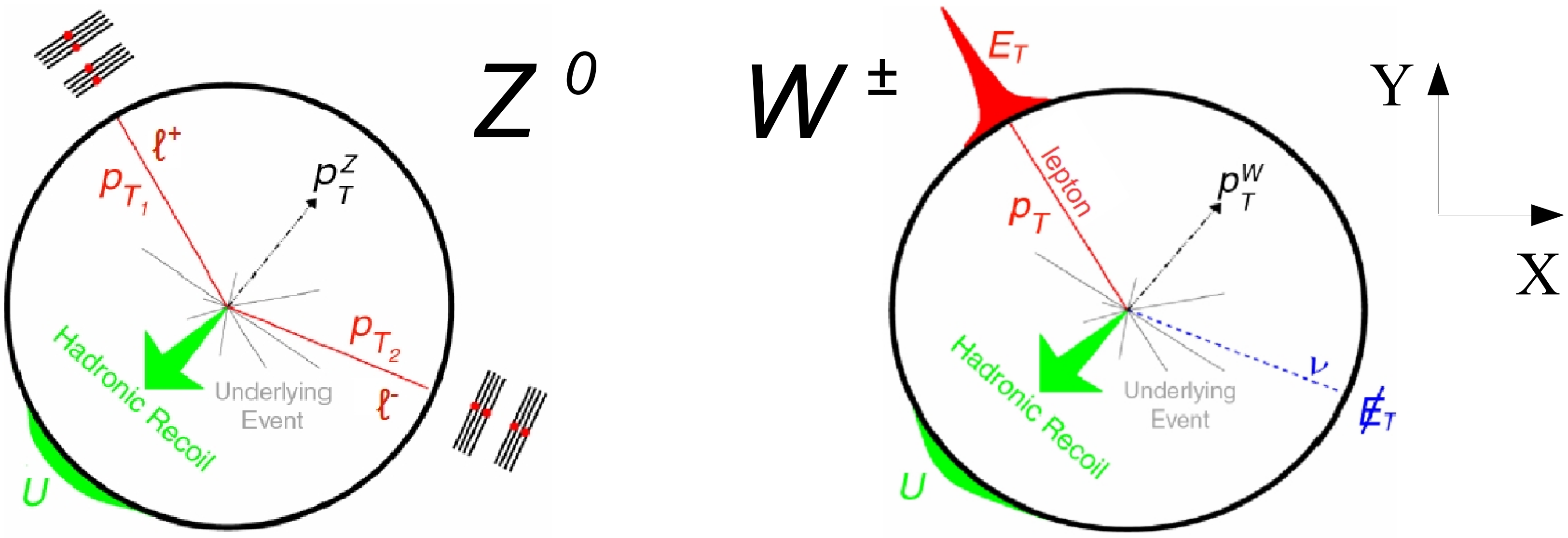
Forward muon

A Quick Word About E and E_T



- Since:
  - A.) Many particles can escape down the beamline.
  - B.) Collision may be unbalanced in Z (different momentum fractions).
- The TRANSVERSE Energy (E_T) is typically used as opposed to the TOTAL energy E.

The cleanest bits of the mess:

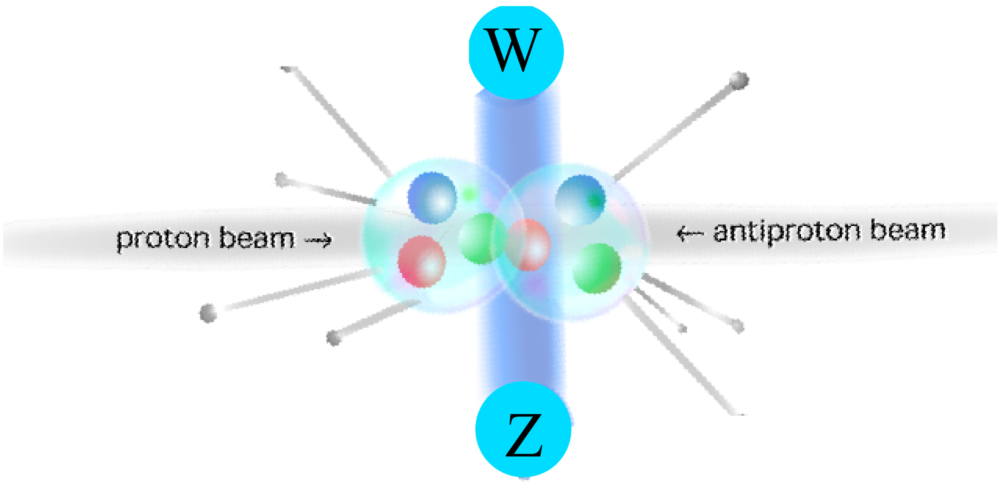


- Decays that involve electrons and muons are among the cleanest signals, since they have very distinctive patterns.
- Looking for pairs of bosons:
  Clean + Clean = Extra Clean

To Recap:

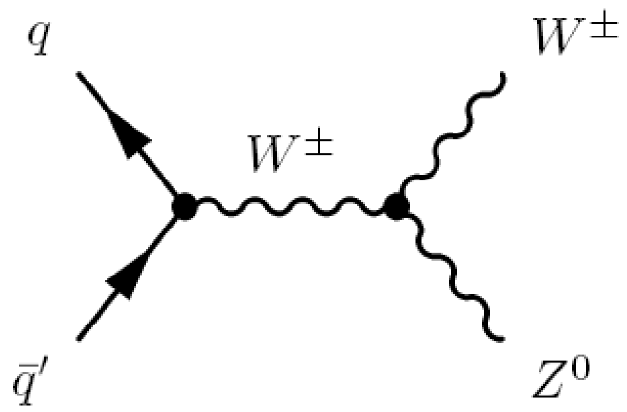
- We have the tools (Tevatron), and a detector (D0), now we just need something to look for.
  - Look for pairs of bosons: WZ, WW, Wγ.
  - All actually occur in SM.
  - All have the vertex of interest in common.
  - Remember what I said earlier: If the weak force starts acting strong, then we should see more of these interactions with higher energy.
    - Ergo: Higher energy bosons

WZ



WZ

- Very interesting:
  - Just probes the coupling of the two massive gauge bosons to each other.
  - Very small rate of production, since we require both bosons to decay to leptons.
    - At the time we first measured it, this was THE smallest cross section ever measured at a hadron collider.



WZ

- Very interesting:
  - …the
  - …re
  - …ron

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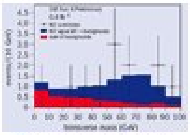
Sep 7, 2006

D0 finds evidence for WZ pair production

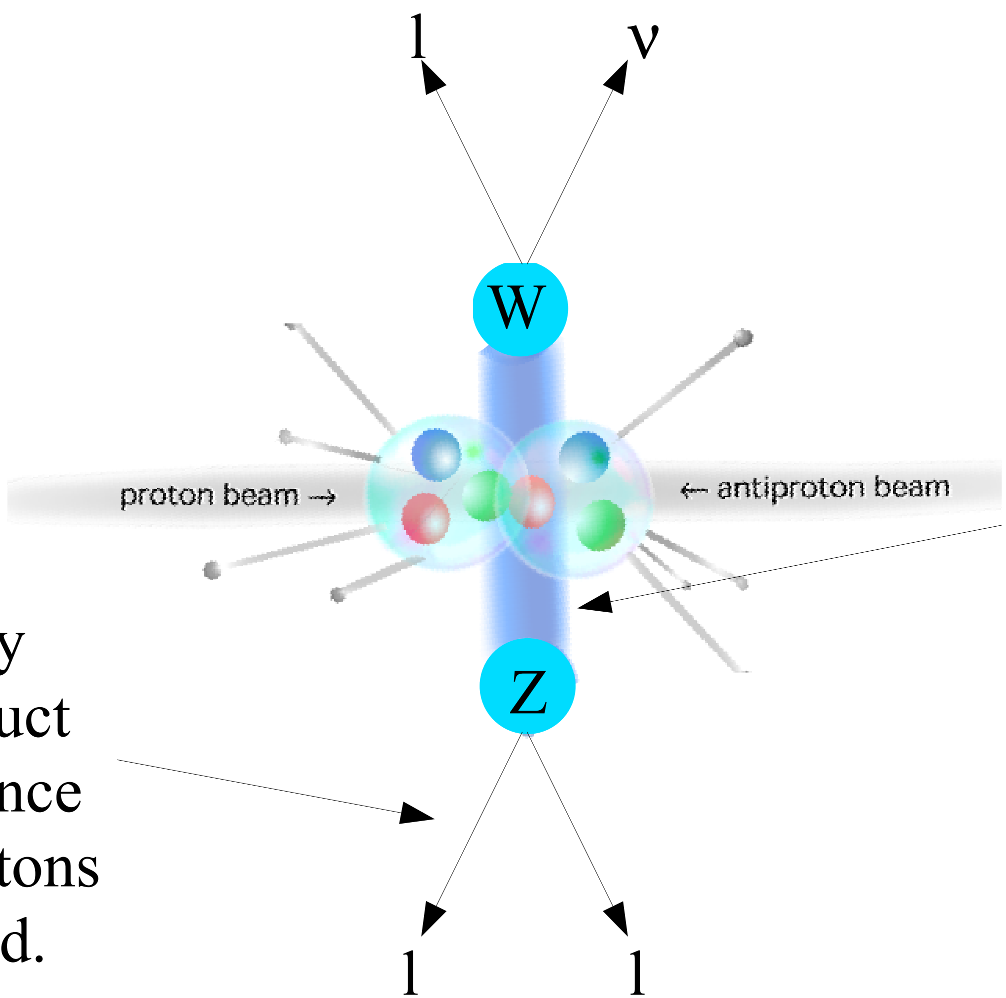
The D0 Collaboration at Fermilab has announced the first measurement of the cross-section for WZ pair production in proton-antiproton collisions. The cross-section times branching ratio for the process is the smallest ever measured at a hadron collider. The data for this result were taken from more than 1 fb^{-1} of total collision data at the Tevatron, and a sample of 1.5 thousand million events.



Transverse mass

Making this measurement requires events in which both the W and Z boson decay to leptons, but while such events provide the cleanest signature of WZ events, they constitute only 1.4% of all WZ decays. D0 found 12 events, each containing three charged leptons with high transverse momentum together with missing transverse energy (indicating an undetected neutrino), with an expected background of 3.6±0.2 events. The probability that the

WZ

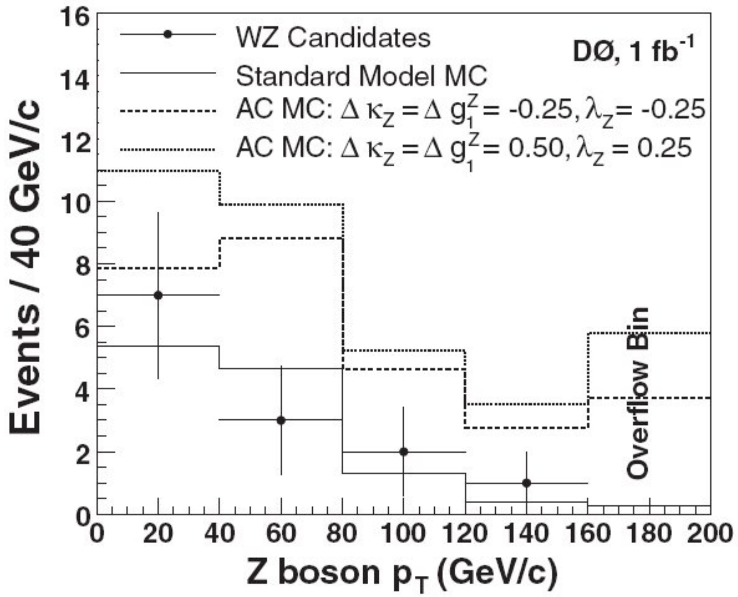


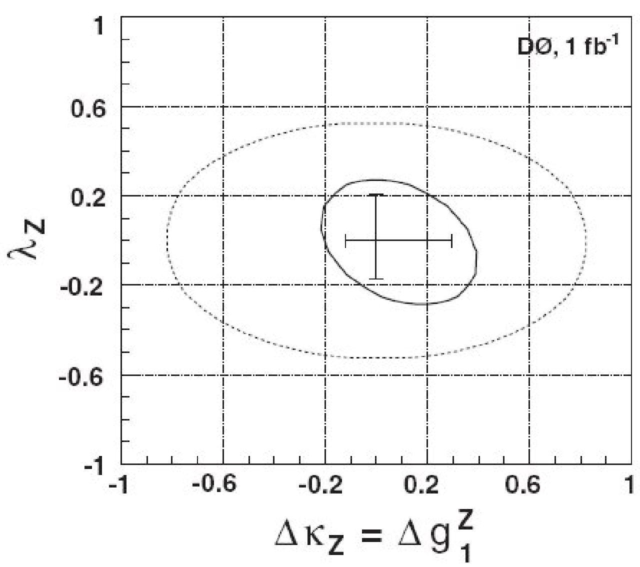
Stronger couplings, more energetic Z produced.

Can fully reconstruct the Z, since both leptons measured.

WZ

- This is still not very many events.
- 13 candidates out of … 1.5 billion on tape.

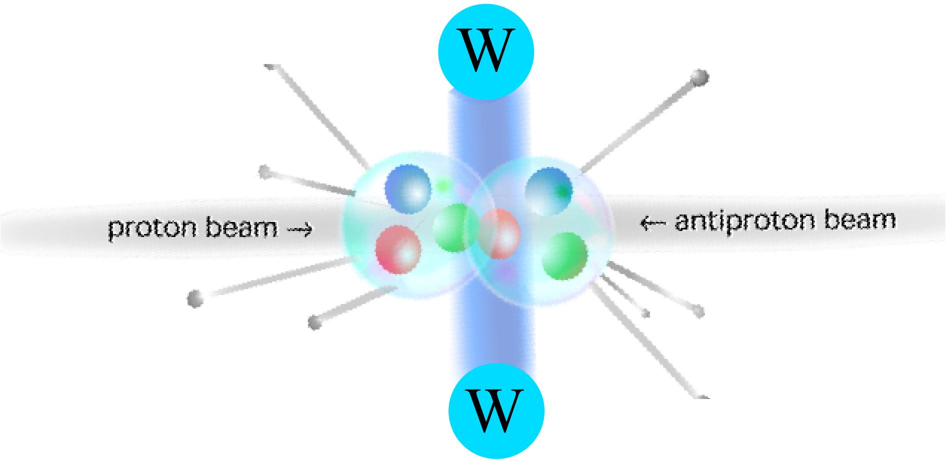




- Contour of coupling limits.

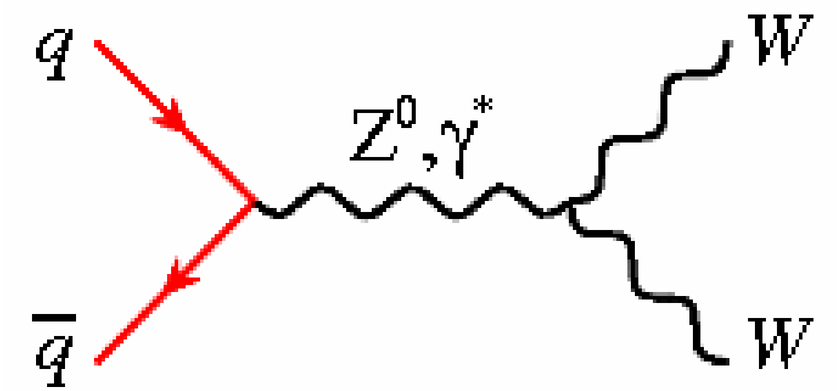
<--------

WW

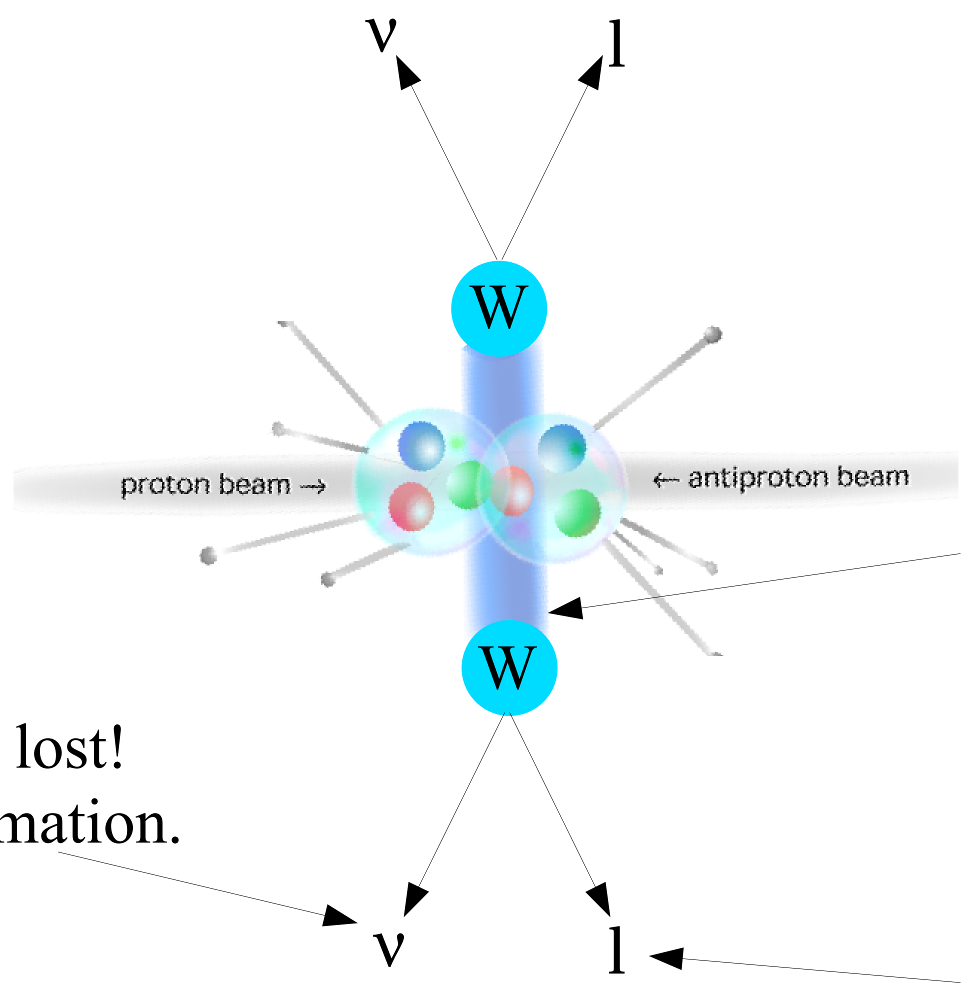


WW

- WW production is a very hot topic (one of the preferred channels for certain Higgs masses).
- Also contains the coupling of the W to the photon AND the Z.



WW

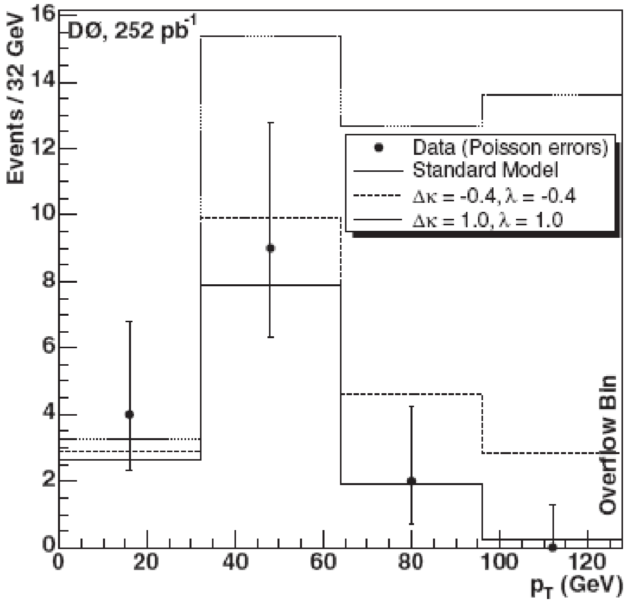


Increased coupling strength, more energetic W

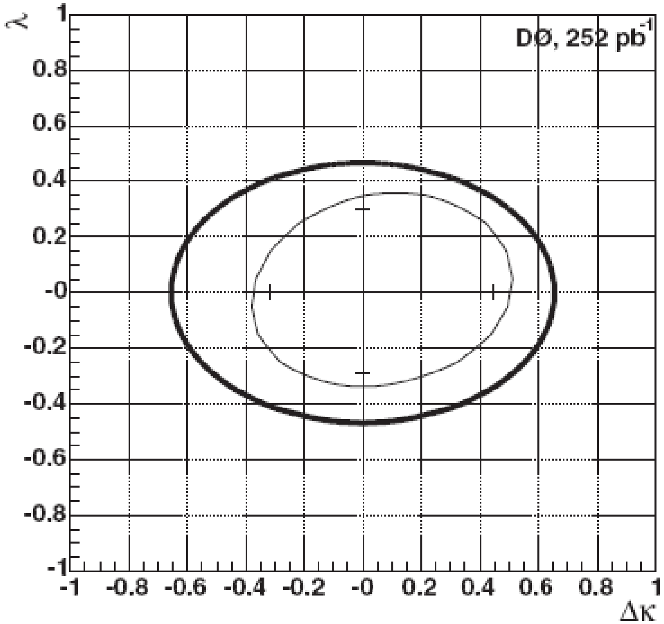
Neutrino lost! No information.

Correlated to W energy.

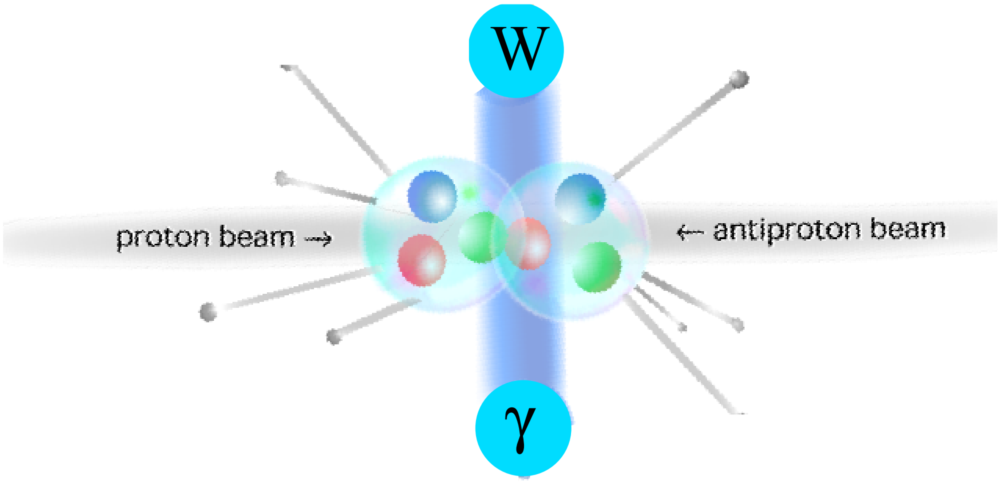
WW AC Result



- <---Lepton transverse energy. For large couplings (meaning STRONGER weak force), would be more at high E_T.
- Limits couplings could take on from our data --->



Wγ

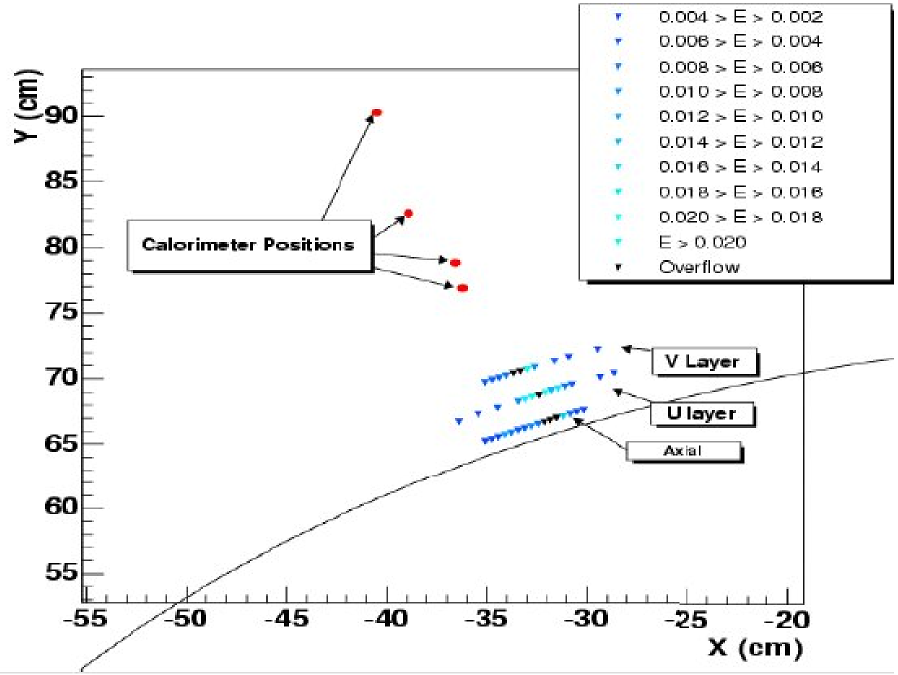


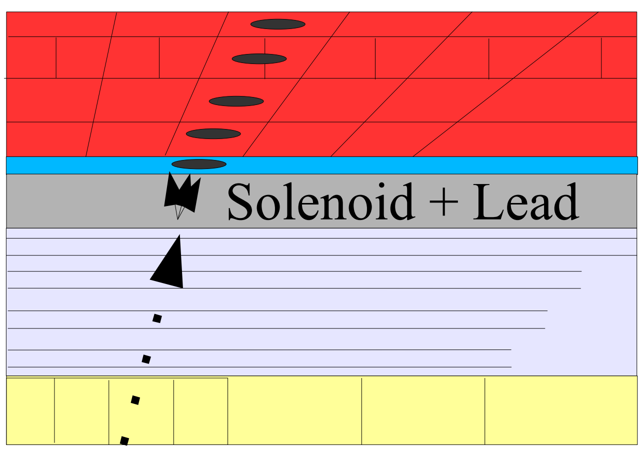
There wasn't a mention of...γ?

- Photons: If an electron is a splash in the calorimeter with a matched track, then a photon should be the same, just without a track, right?
- Not so easy: Plenty of things go 'splash' in the calorimeter, very few of them are actually photons.
- No samples of events to study them either!
  - For e and μ, I have mentioned that the Z may be used. No real equivalent for photons.
- Must be inventive!

Damn the torpedoes!

- Preshowers are effectively more calorimetry, can give more rejection.

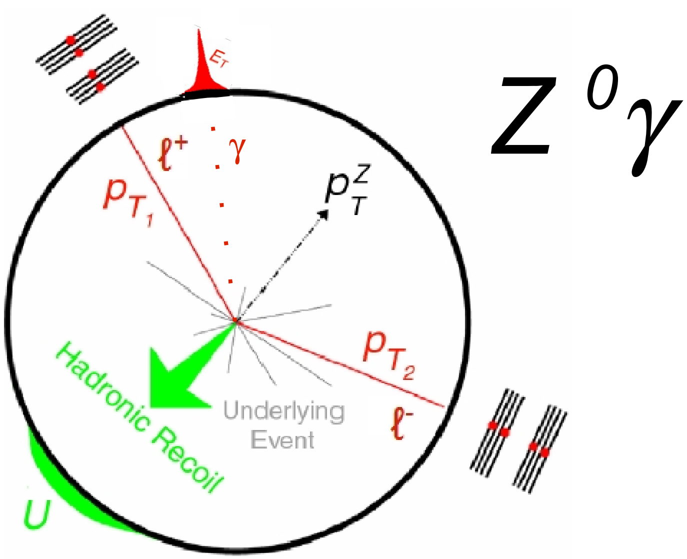


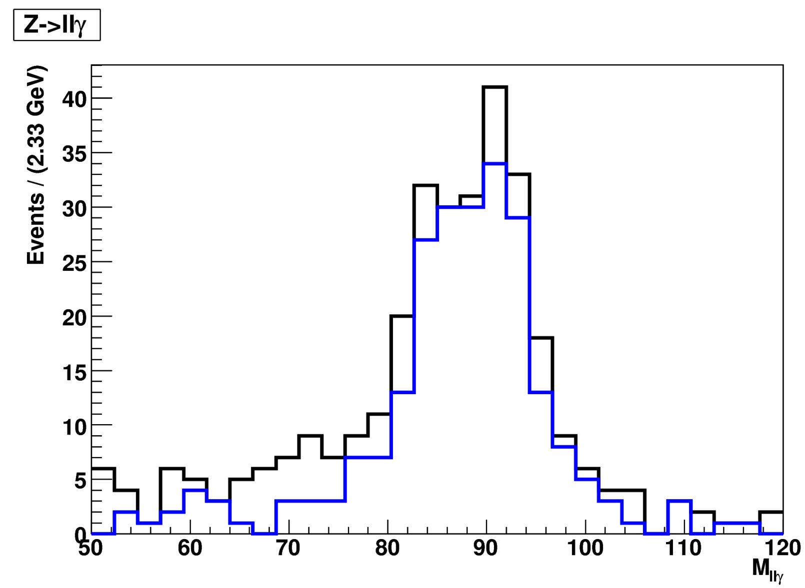


- Since there's several layers of calorimeter, we can “point” photons back to their origin.

The same…only different.

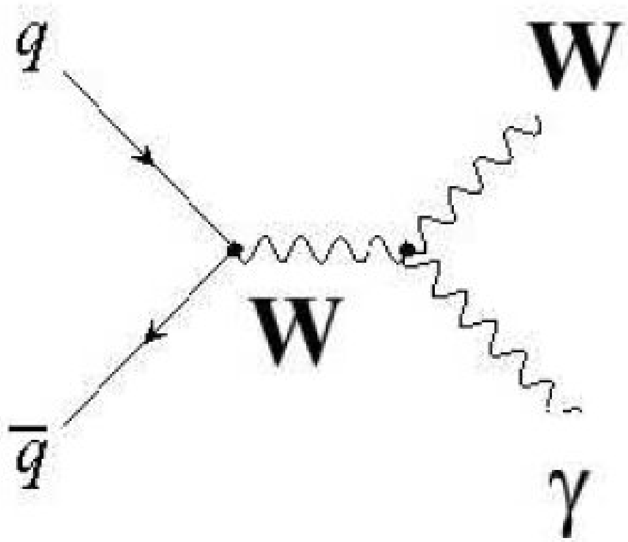
- One can use Z->ll to study leptons and test how well the algorithms work.
- Similarly, one may use Zγ->llγ to get a picture of how well the photon algorithms work.



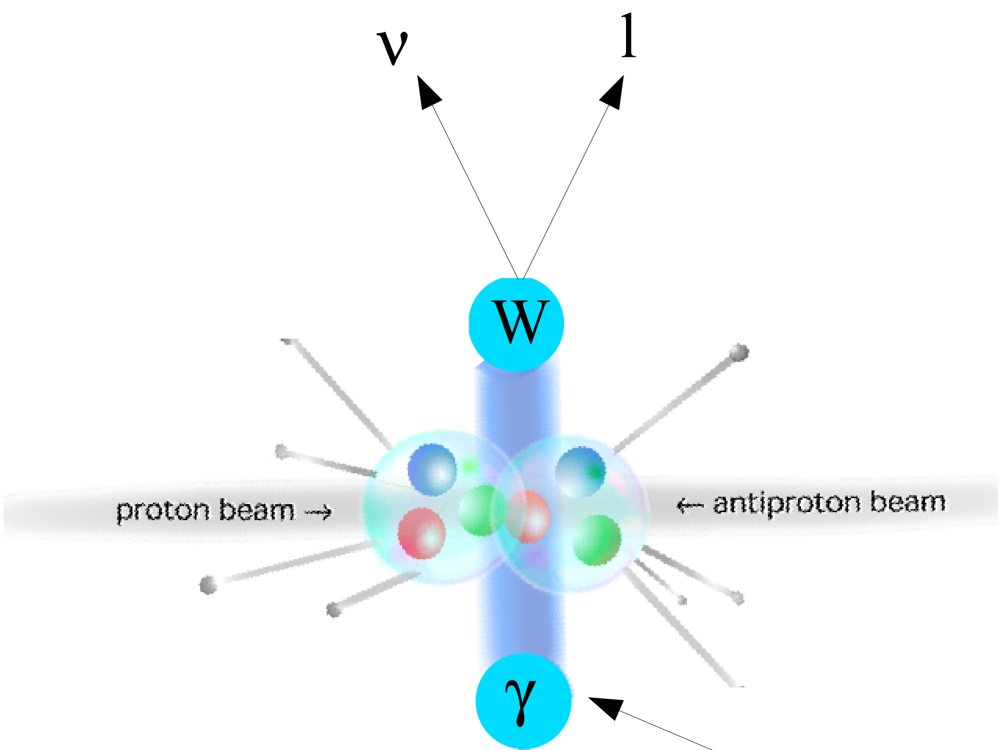


Wγ

- Like WZ, Wγ production only probes the W boson coupling to the photon.
- Unlike WZ, this has both a much larger production rate. The caveat being that one has to understand photon reconstruction.



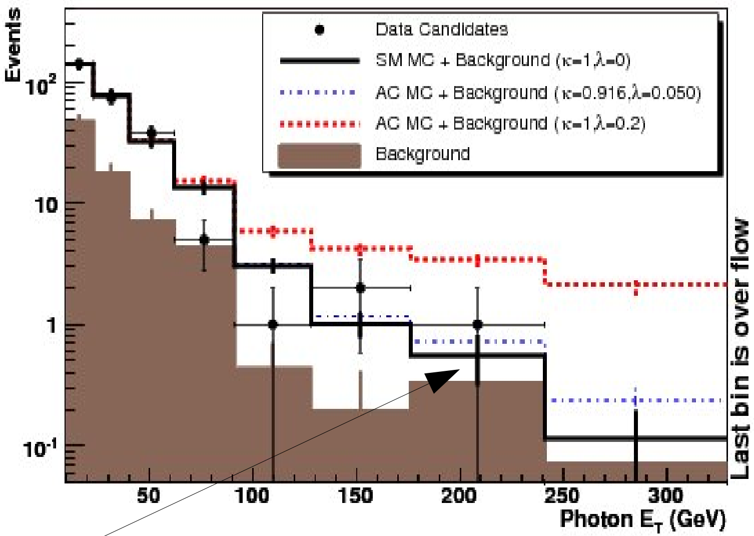
Wγ



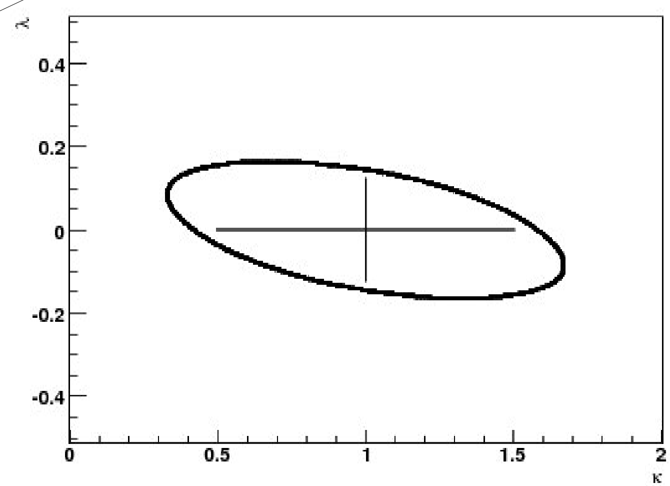
Stable, energy directly measured!

Wγ

- In good agreement with SM expectation.
- In fact, you'll note that this contour curve is quite a bit tighter than the others.



Photons in excess of 200 GeV!



Interference?

- In this particular case, we can do more than simply look at the boson transverse energy.
- There's a set of three diagrams which interfere, and the interference is BROKEN if the couplings are misbehaving.
- Think of this as interferometry: there's more than intensity to study, there's also the angular distribution.

Interference?

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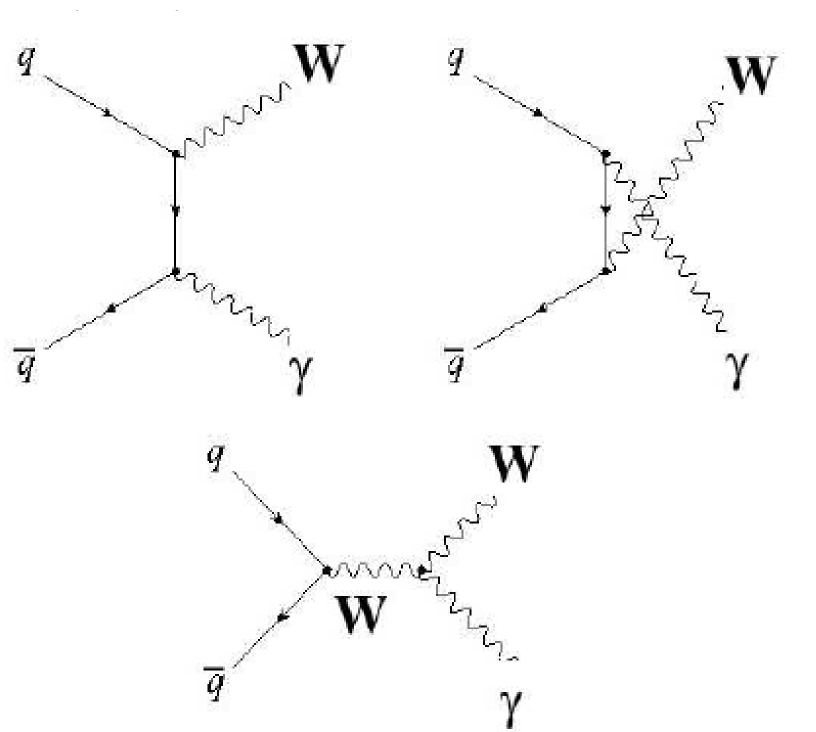
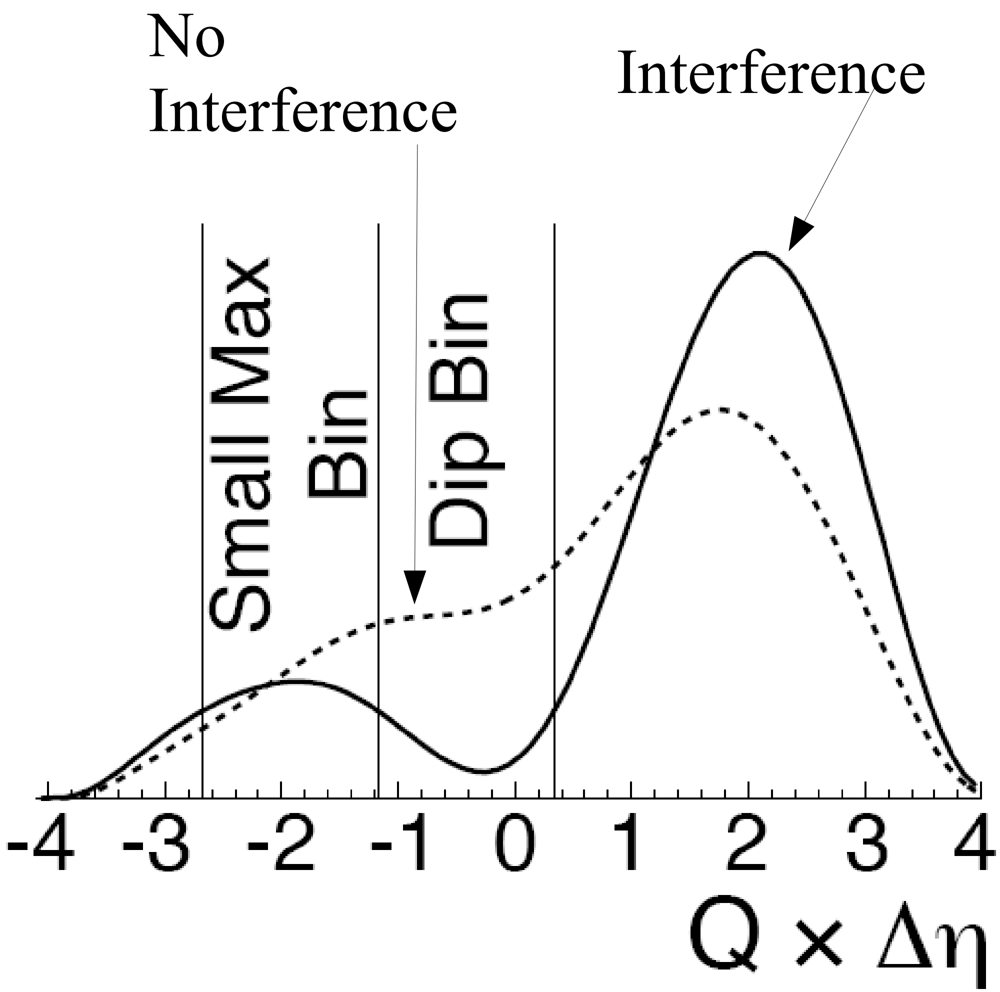
- There's a se ... interfere, and the inte ... couplings are misbeha
- Think of thi ... s more than intensi ... e angular distribution

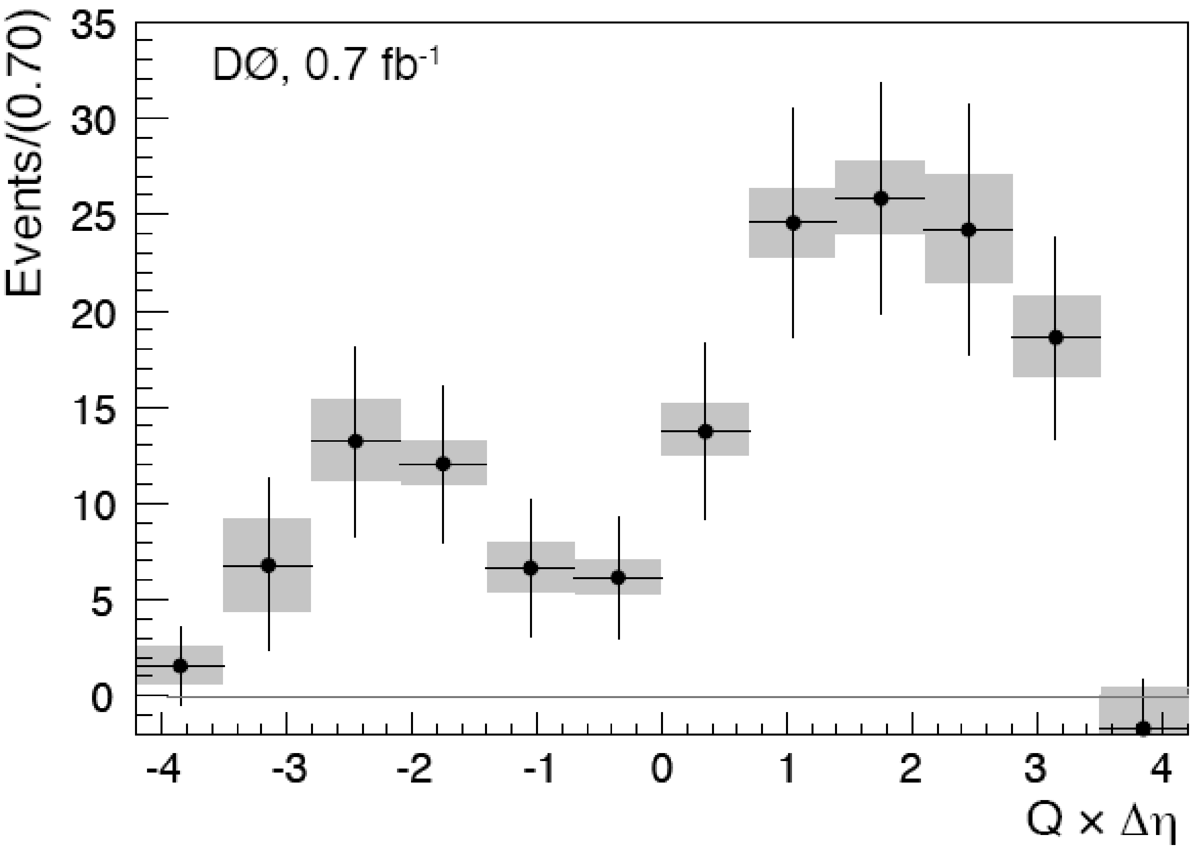


What's our distribution?



- Basically looking at an angular difference between the photon and lepton.
- Nice graceful dip if there is interference.
- Big lump if not.

Our actual measured distribution:



- Simply a beautiful test, disjoint from the photon E_T shown previously.
- Also: first measurement of this distribution.

So what's next?

- The Tevatron continues to tick along.
- Slowly, with more statistics, we begin to sample more events that have higher and higher collision energy.

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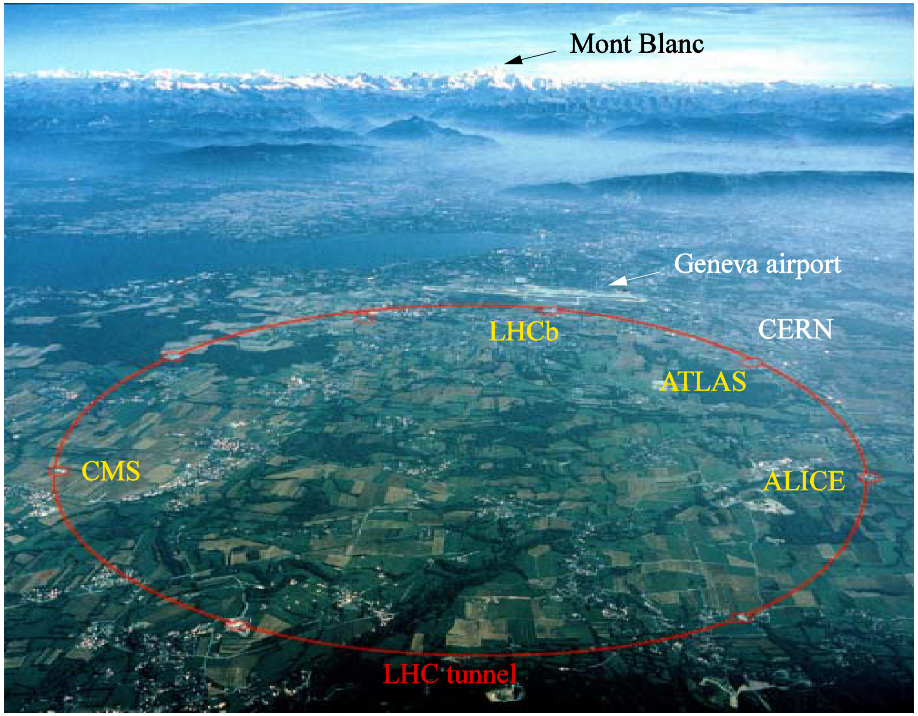
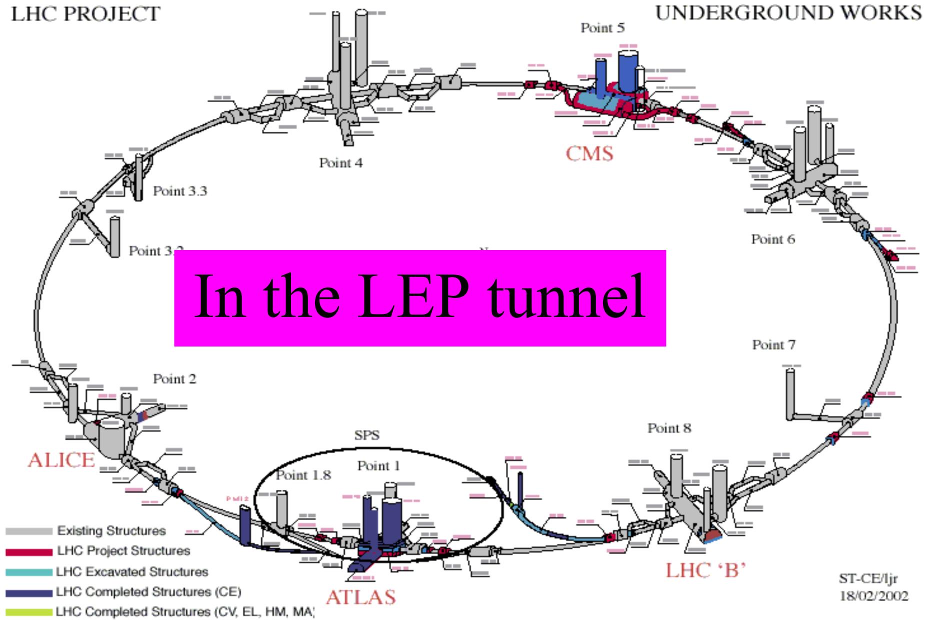
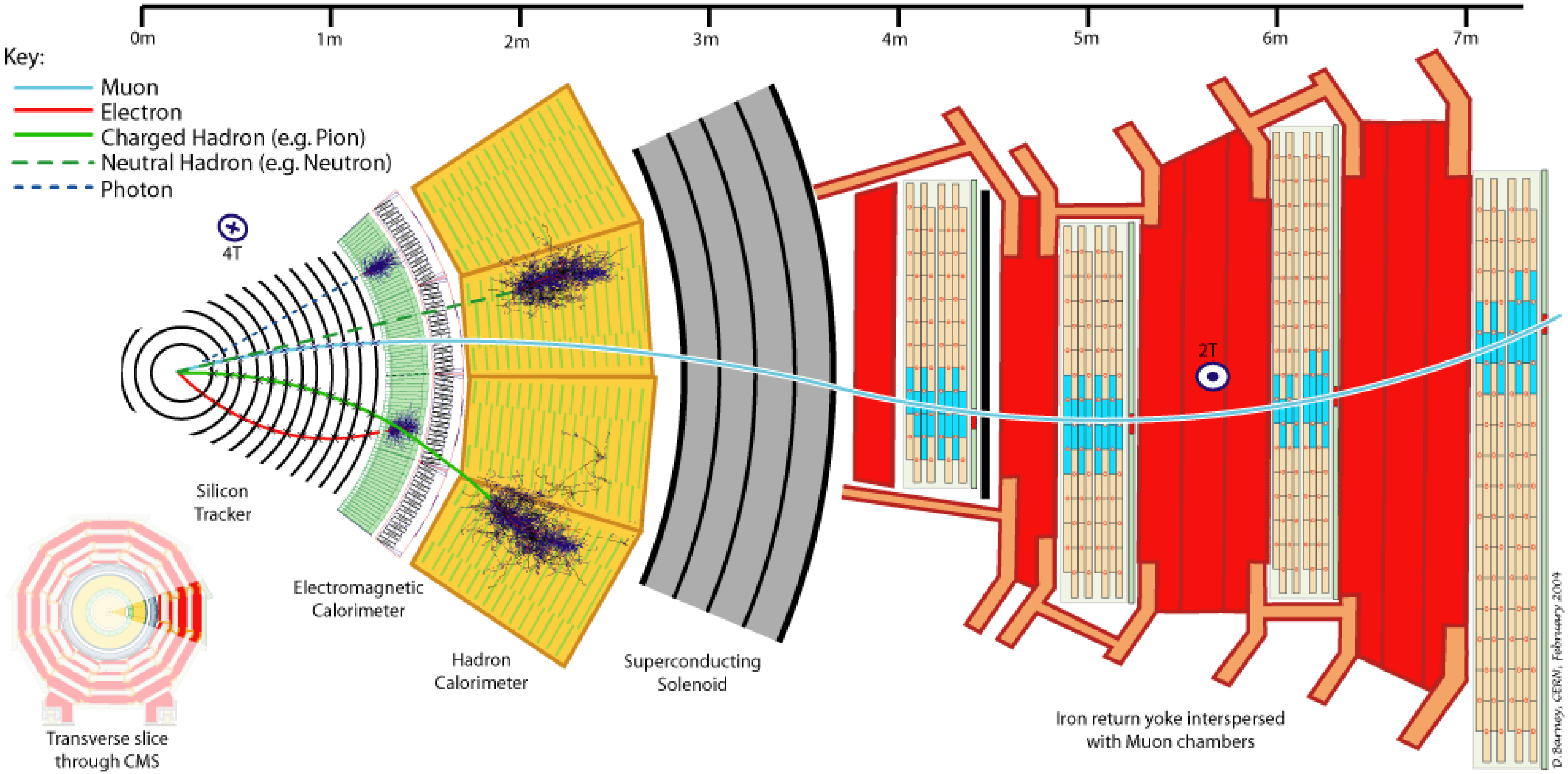
A bigger boat.



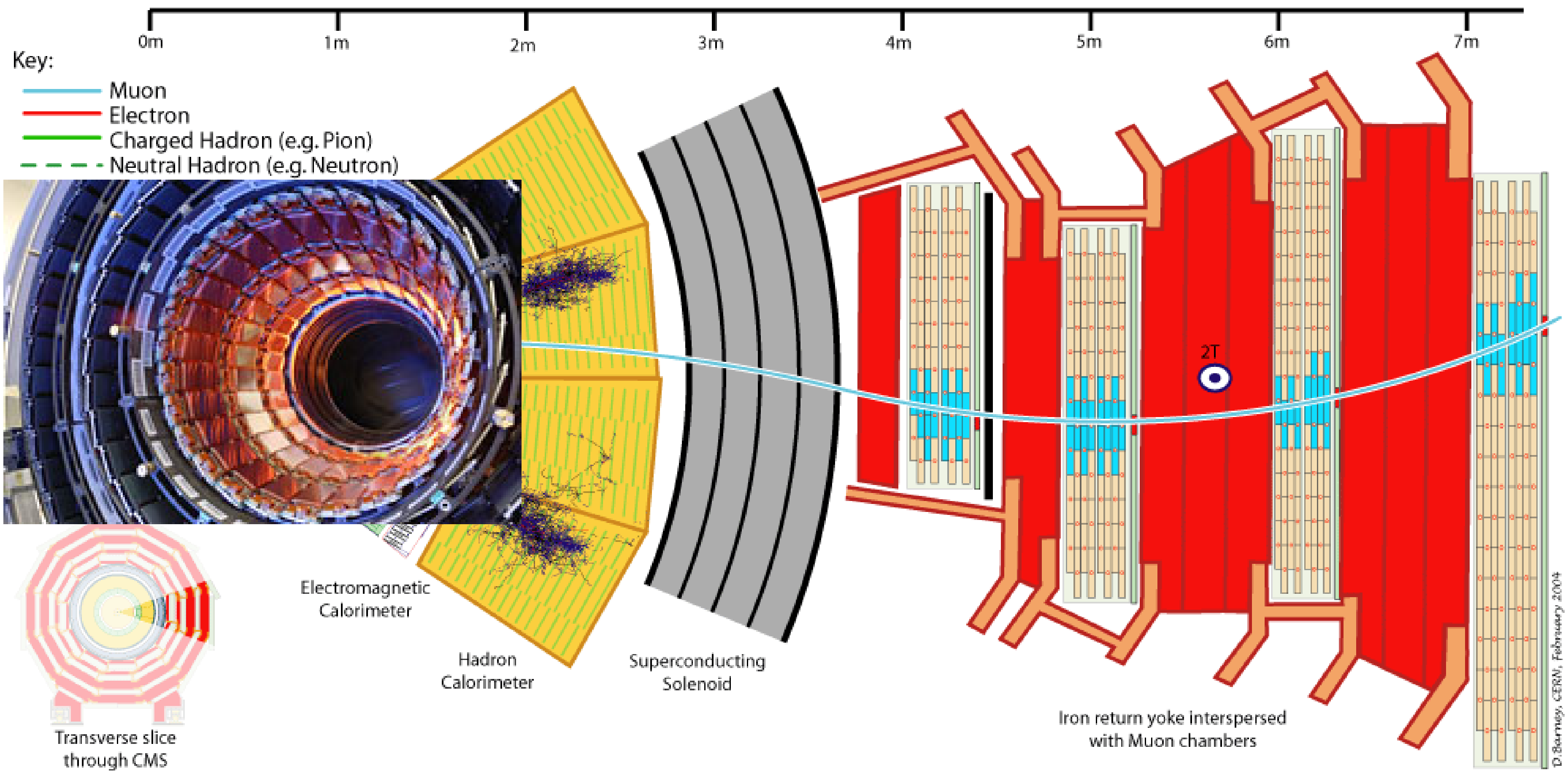


- pp $\sqrt{s}$ =14 TeV
- crossing rate 40 MHz (25 ns)
- circumference of 27 km (16.8 miles)

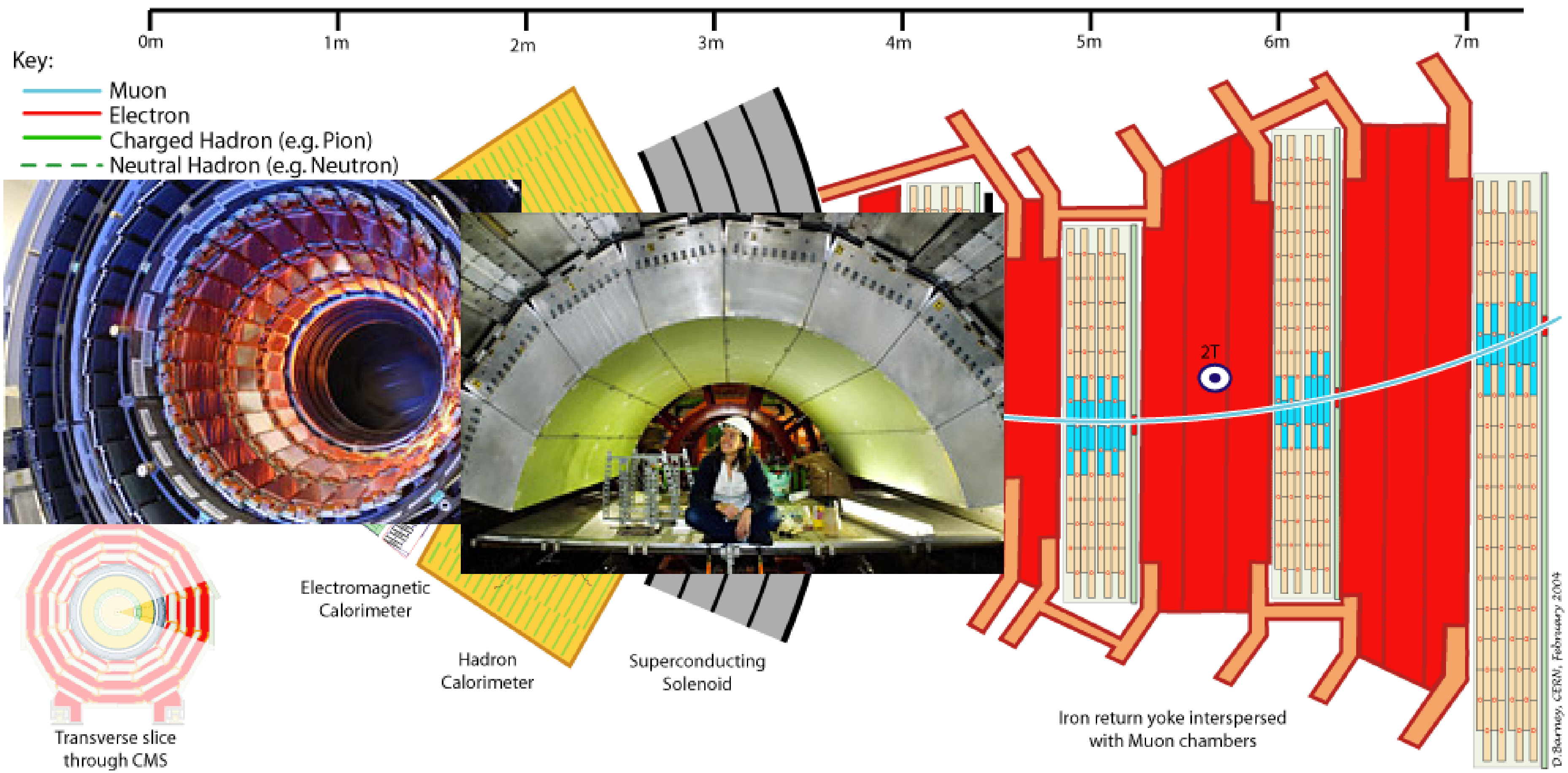
CMS detector



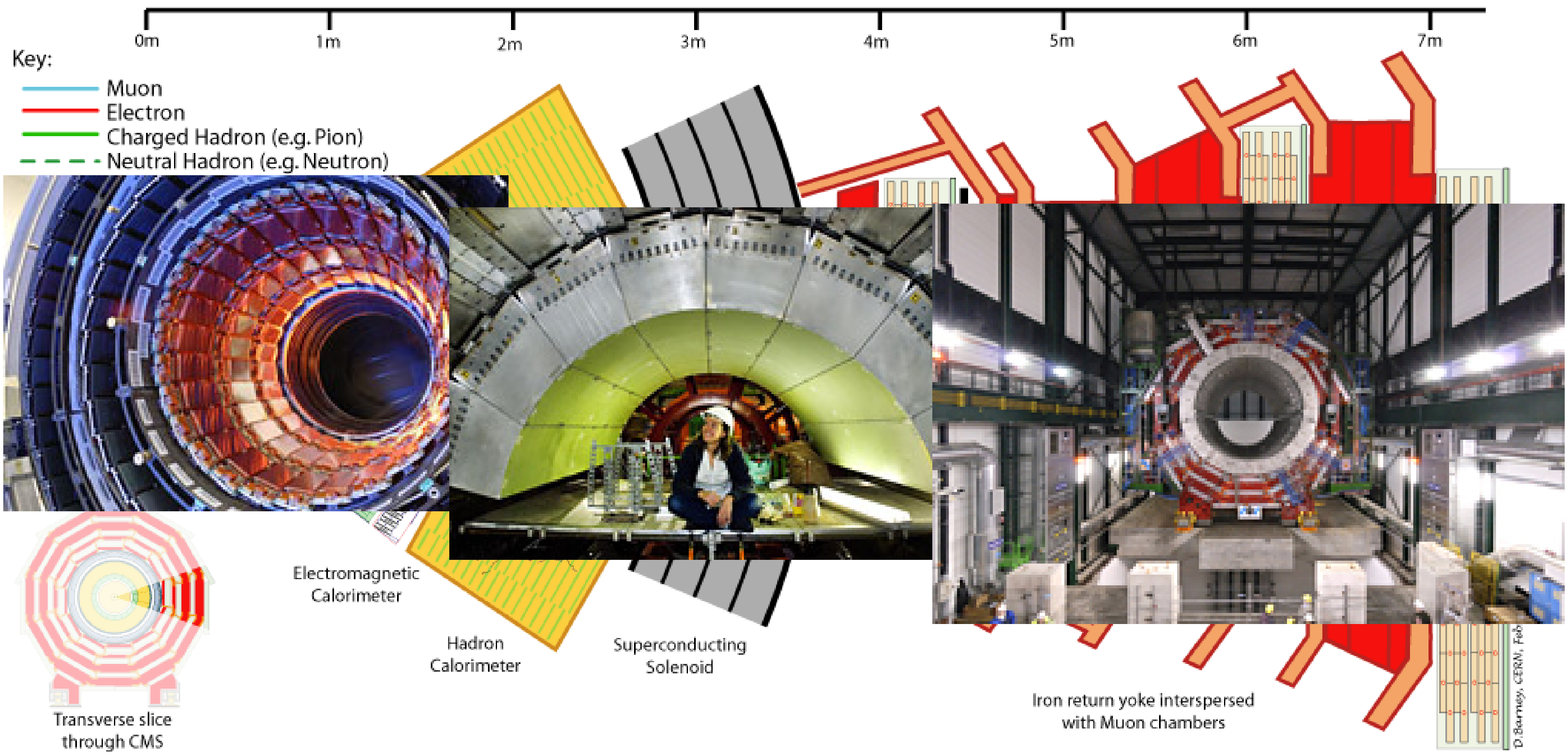
CMS detector



CMS detector



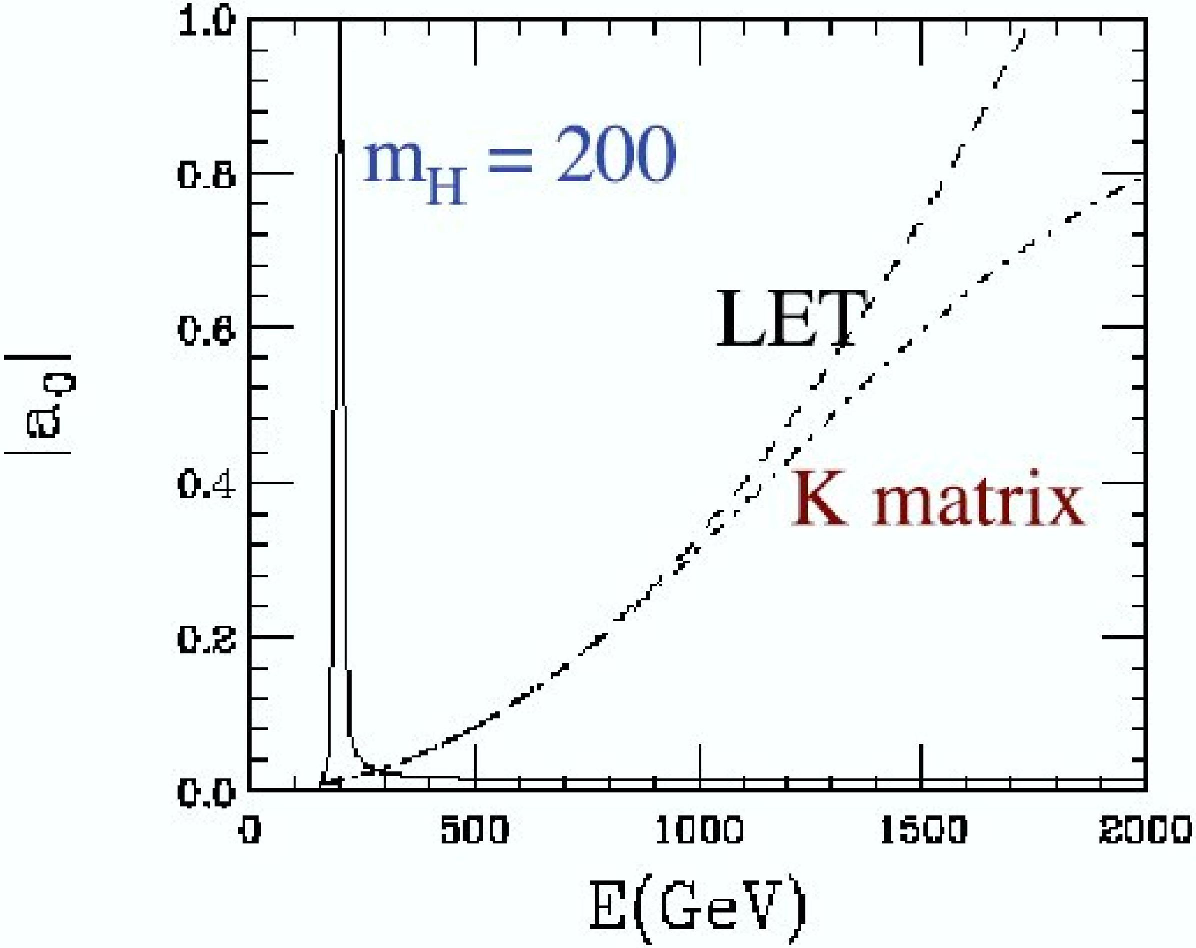
CMS detector



Moving forward.

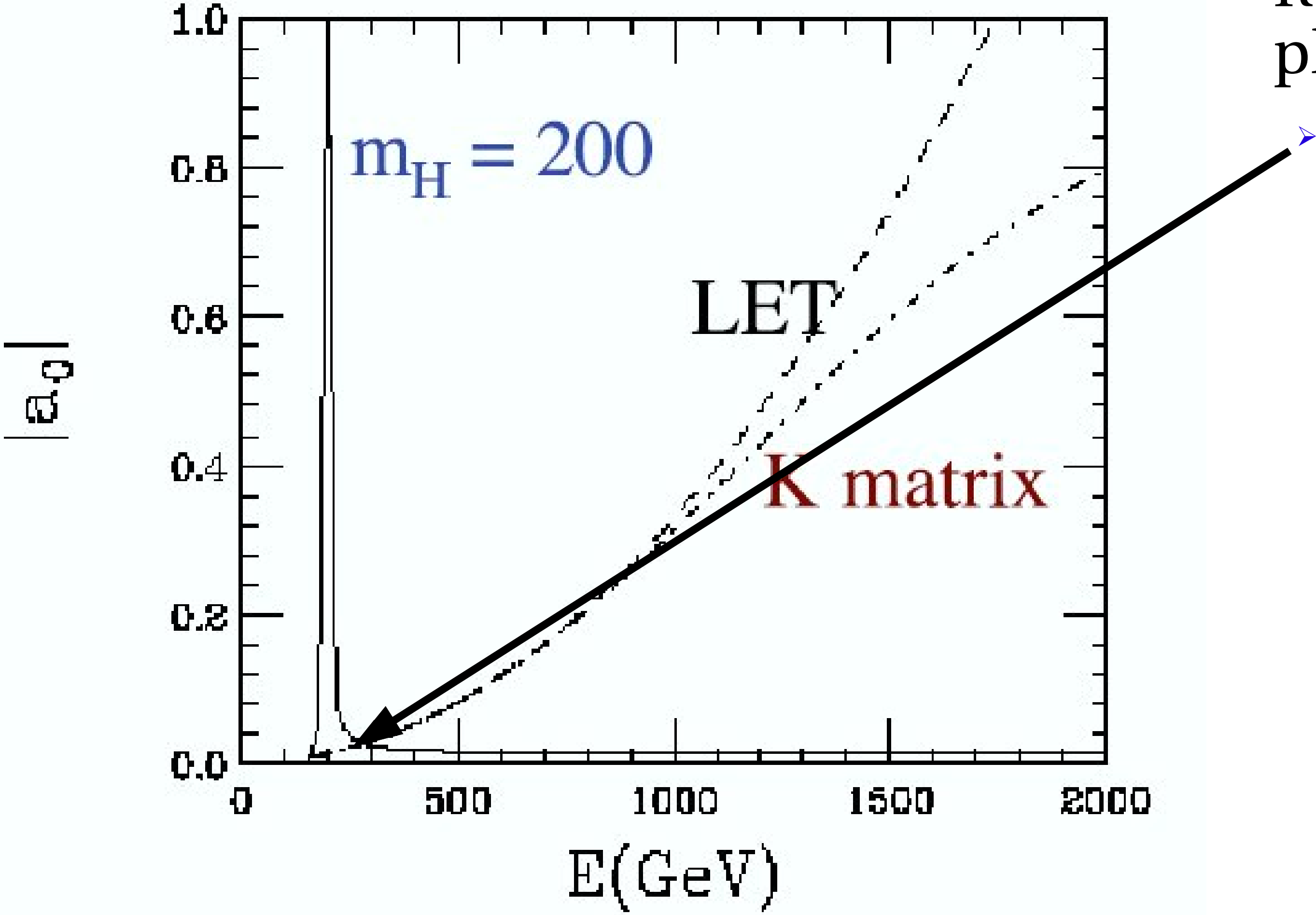
- The Tevatron operates at a collision energy of 2 TeV.
  - Which means the actual collisions, since each beam's energy is spread over the different quarks, is much lower.
  - While there is still sensitivity, difference would have to be large.

Moving forward.



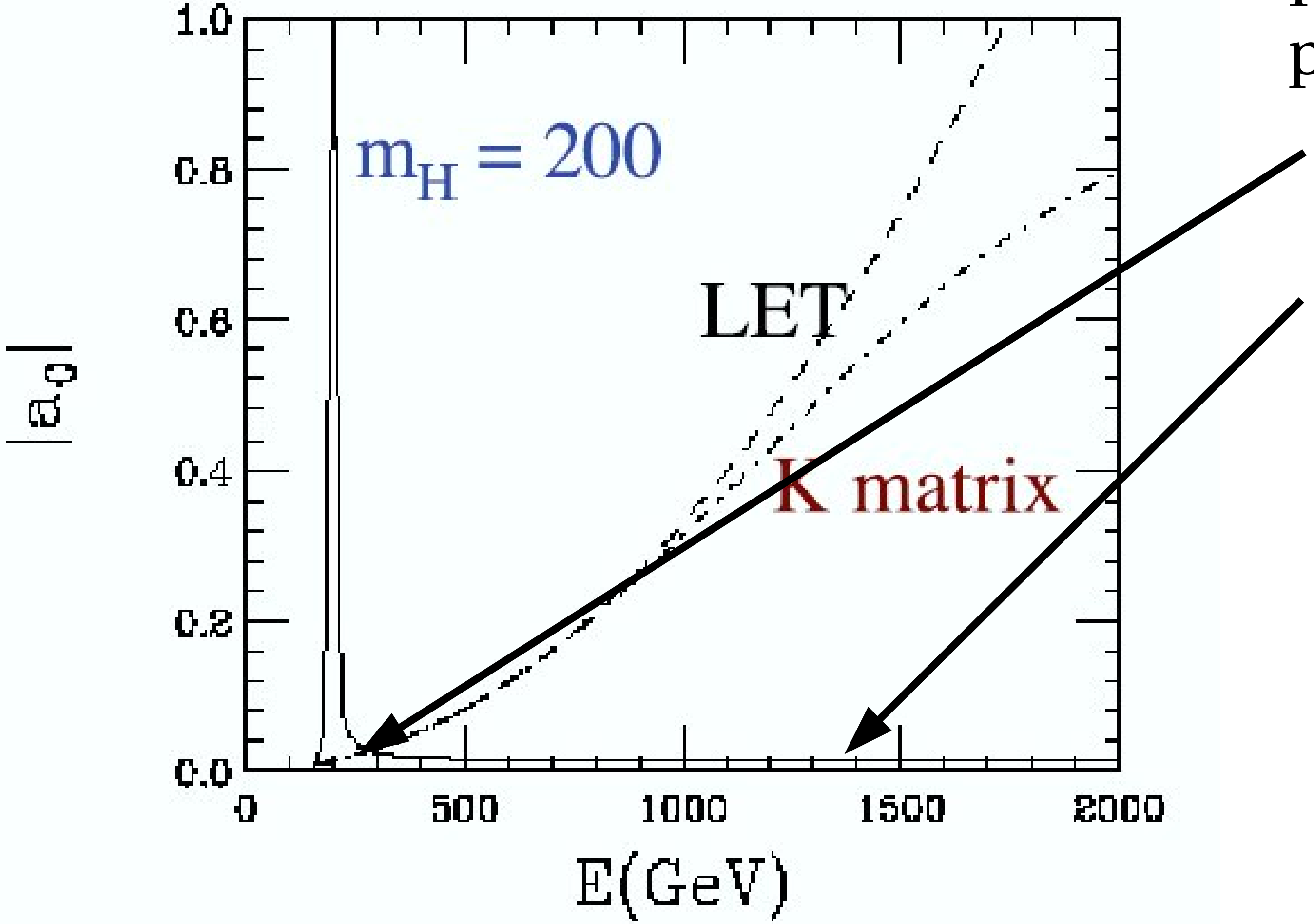
- Remember this plot?

Moving forward.



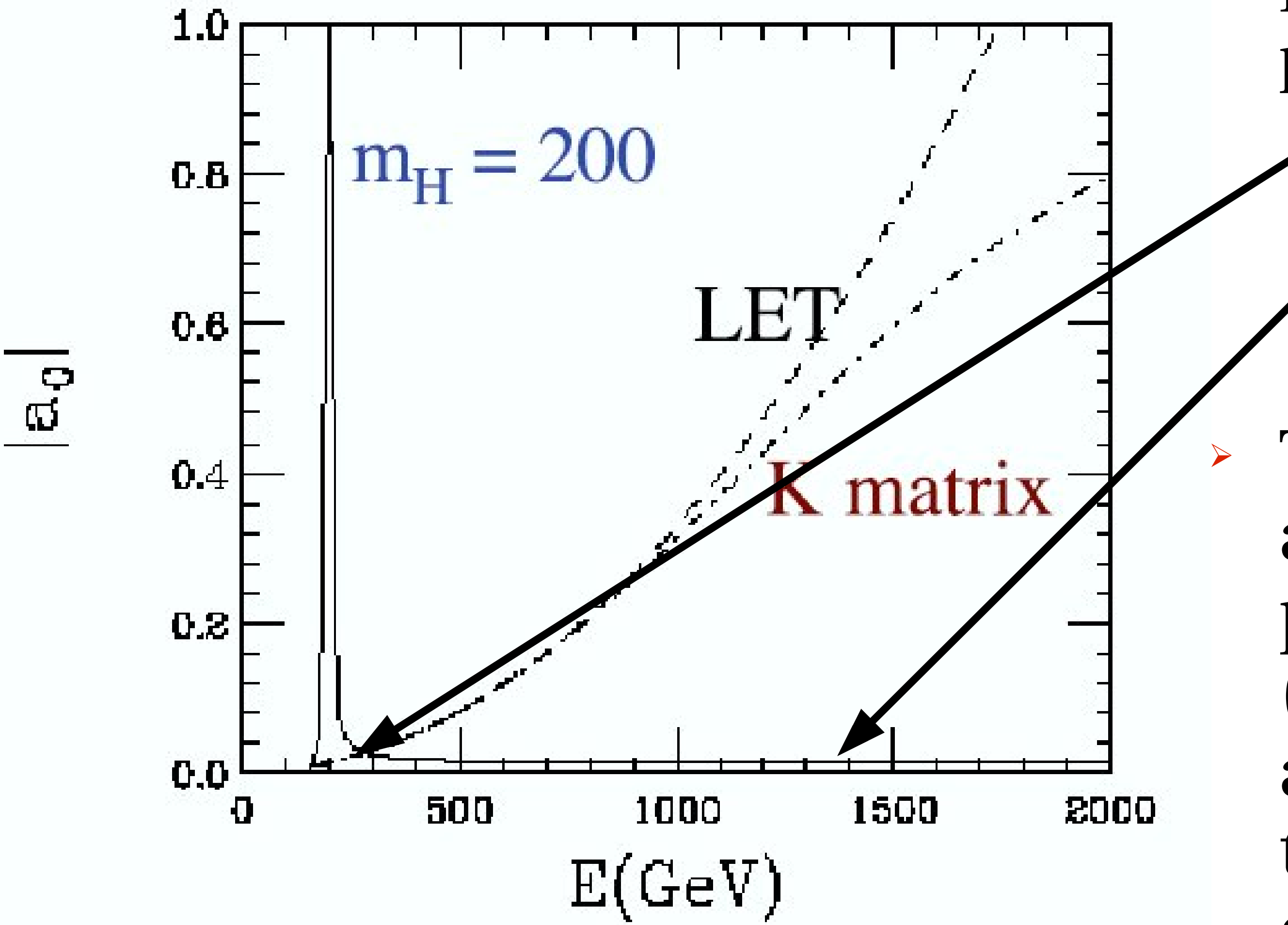
- Remember this plot?
  - Tevatron sensitive here.

Moving forward.



- Remember this plot?
  - Tevatron sensitive here.
  - LHC starts out at around here.

Moving forward.



- Remember this plot?
  - Tevatron sensitive here.
  - LHC starts out at around here.
- To this add that at LHC one produces WW (and others) at around 10 times the rate of Tevatron.

Moving forward.

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  - Which means the actual collisions, since each beam's energy is spread over the different quarks, is much lower.
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  - However as a training ground for LHC...
    - Messy environments, poorly simulated backgrounds (QCD). Data based estimates required.
    - Novel algorithms for background rejection.
    - Detector performance requires *in situ* measurements.
  - Sounds pretty familiar!

Moving forward.

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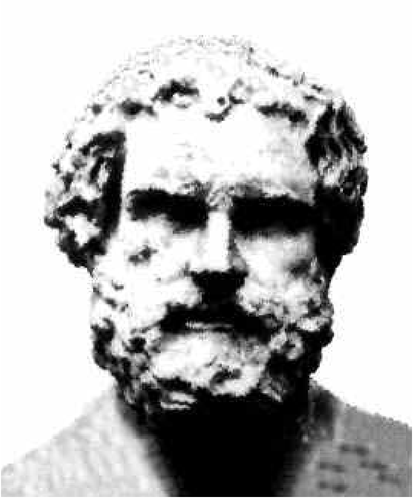
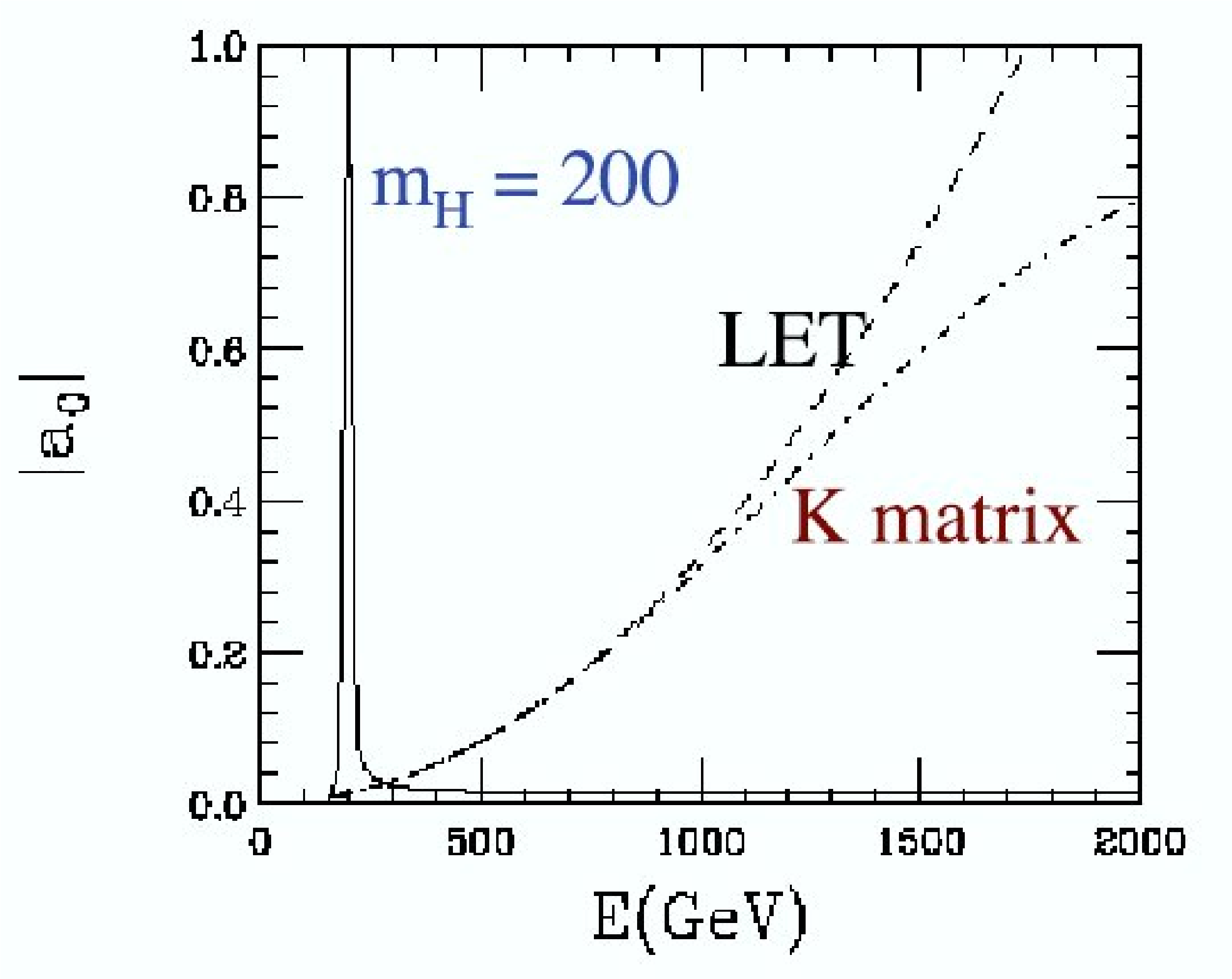
  - Which means the actual collisions, since each beam's energy is spread over the different quarks, is much lower.
  - While there is still SOME sensitivity, difference would have to be large.
  - However as a training ground for LHC...
- Nothing like doing physics, to learn how to do physics!

In Summary

- The Tevatron gives us an opportunity to:
  - Study production of pairs of bosons.
  - Probe the nature of electroweak symmetry breaking.
  - Learn how to cope in a difficult physics environment. Best training for LHC.
- We'll keep on asking the questions!



BACKUPS



$m_H = 200$
LET
K matrix
$|a_0|$
E(GeV)
0
500
1000
1500
2000
0.0
0.2
0.4
0.6
0.8
1.0

Yeah, it is big...