Discovery of the Higgs Boson

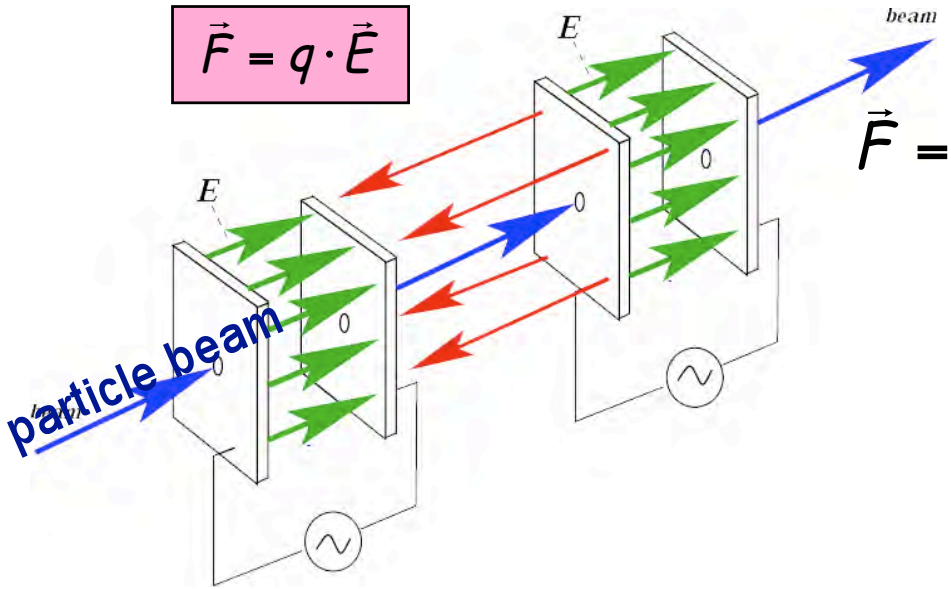
Part 1: Theory (Heather Logan)

Part 2: Experiment (Thomas Koffas)

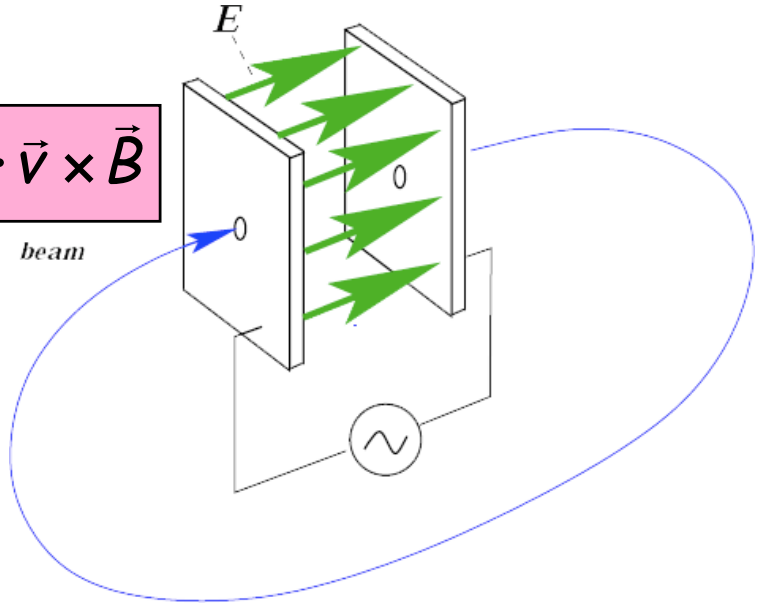
- The LHC
- Particle Detectors
- Signal Extraction
- The Higgs Discovery
- Outlook

Acceleration in an electrical field

$$\vec{F} = q \cdot \vec{E}$$



$$\vec{F} = q \cdot \vec{E} + q \cdot \vec{v} \times \vec{B}$$



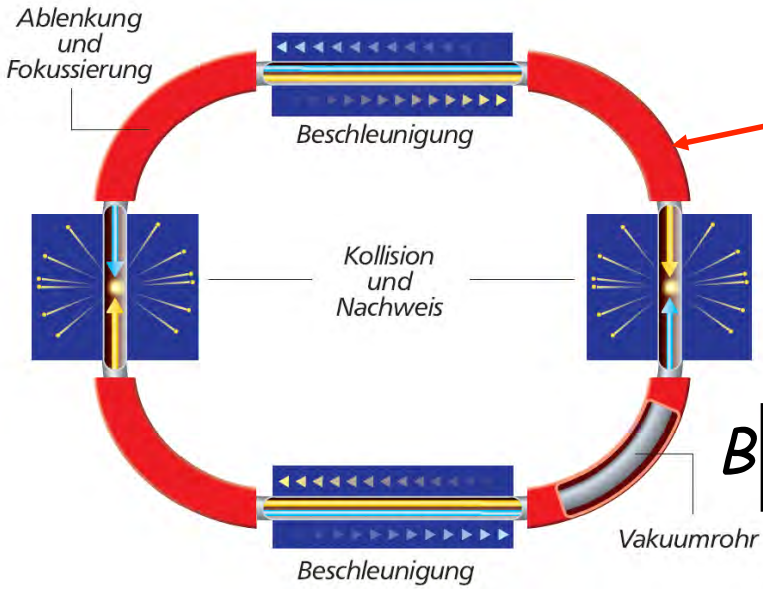
Accelerators use a time-varying electric field

- For high energies one needs a long collider ✗

Circular accelerators use the same accelerating unit many times…

- Allows to reach higher energies ✓
- The beam can be stored ✓
- Needs magnets to keep particle on track ✗
- Energy is lost due to synchrotron radiation ✗

Could be useful by itself...



$$B[Tesla] = \frac{P[GeV]}{0.3 \cdot \rho[m]}$$

Canadian Light Source
Centre canadien de rayonnement synchrotron

Particle physicists' unit for "everything" the electronvolt (eV)

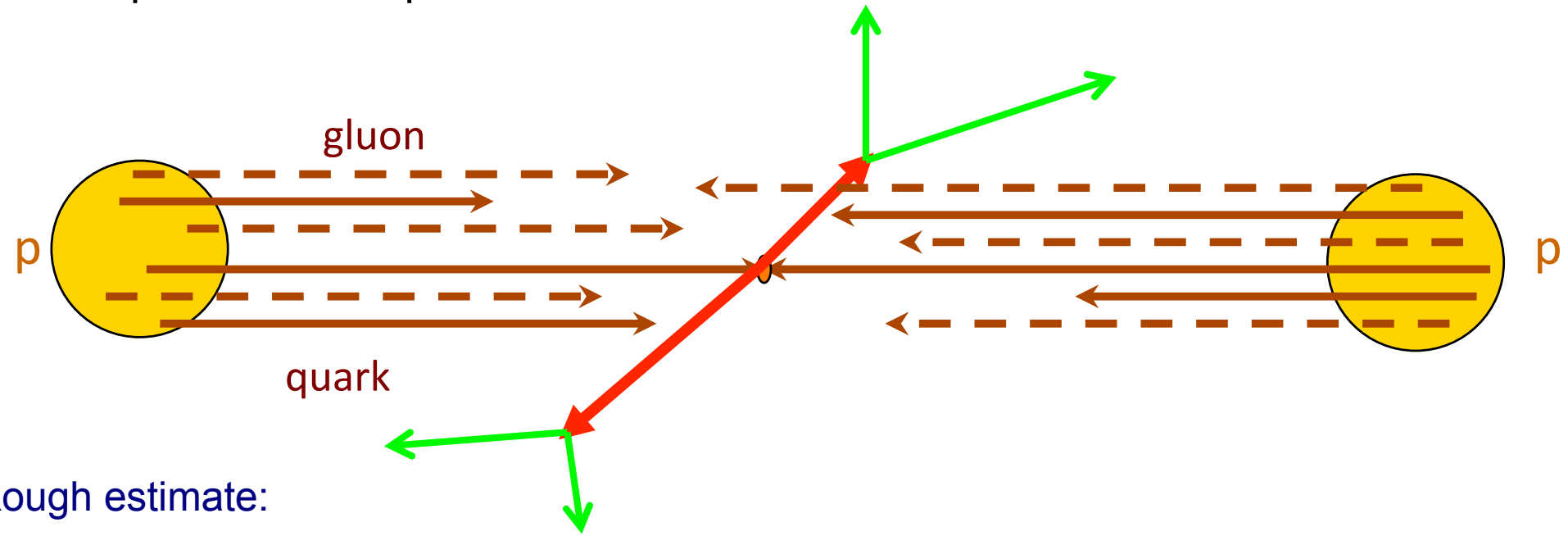
- **An electronvolt is the energy a particle with a charge equivalent to the electron charge (e.g. an electron or a proton) gains when accelerated in an electric field of 1 V**

52	GeV (Giga eV)	mass of the iron atom
1	GeV	mass of the proton
0.5	MeV (Mega eV)	mass of the electron
0.025	eV	temperature in this room
2.3×10^{-13}	eV	temperature in the universe today

Which Energy is Needed?

- To search for the Higgs boson (and potentially other new heavier particles):

  → production of particles with a few TeV needed



Rough estimate:

- In a collision, one of the constituents of the proton (~3 quarks+3 gluons) collides

  → To produce a new particle with m > 1 TeV: $E_{constituent} > 0.5$ TeV

  → Proton needs at least 6×0.5 TeV = 3 TeV of energy

In practice gluons/quarks do not share energy equally so eventually the proton needs at least 5TeV of energy

Choice for our experiments: a discovery (p) machine
= LHC (Large Hadron Collider) with 7 TeV beam energy

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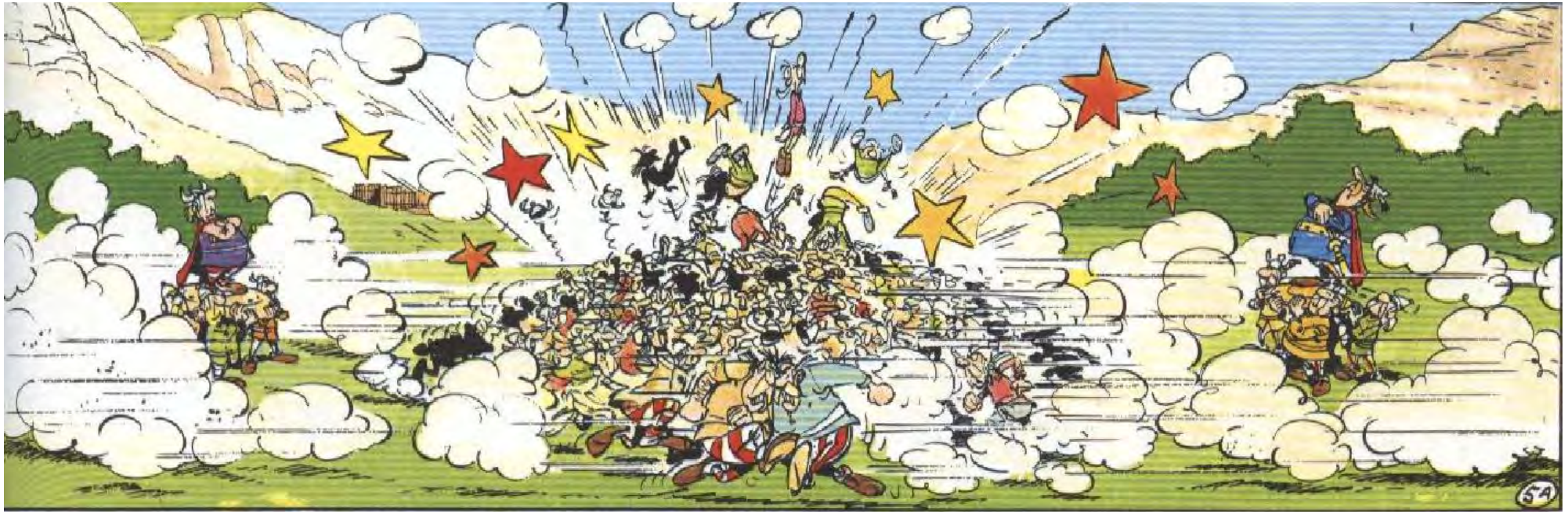

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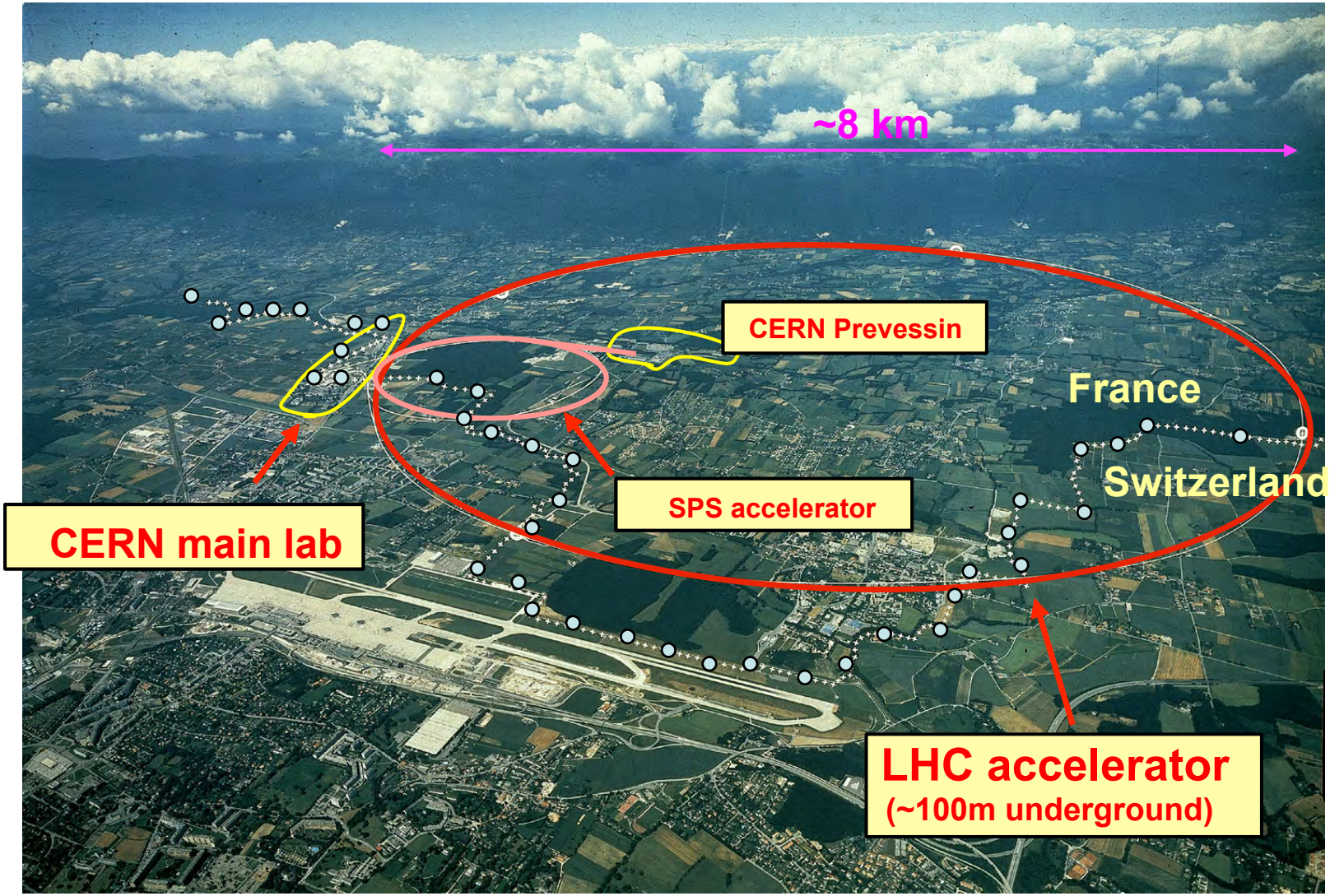
Large Hadron Collider at CERN



The LHC Project: “start” 28 years ago…

1984: First ideas on LHC (2x5...9 TeV) and SSC(=Superconducting Super Collider, 2x20 TeV), construction of LEP(= Large Electron-Positron Collider) tunnel starts;

1988: SSC approved (Waxahachie, Texas);

1989: First collisions in LEP and SLC, R&D for LHC starts;

1993: SSC construction stopped

1994: LHC approved (Start in 2005)

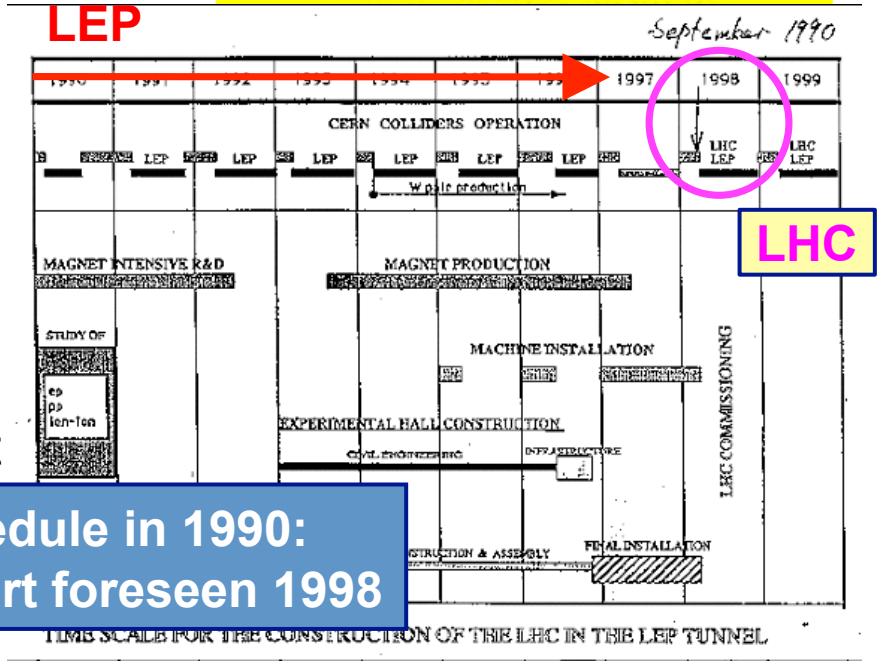
1995: Discovery of the top Quarks at Fermilab /USA, approval of the LHC experiments ATLAS and CMS

2000: End of LEP operation, no Higgs, no SUSY...

2008: September, first LHC operation; accident

2009: November, LHC begins normal operations.

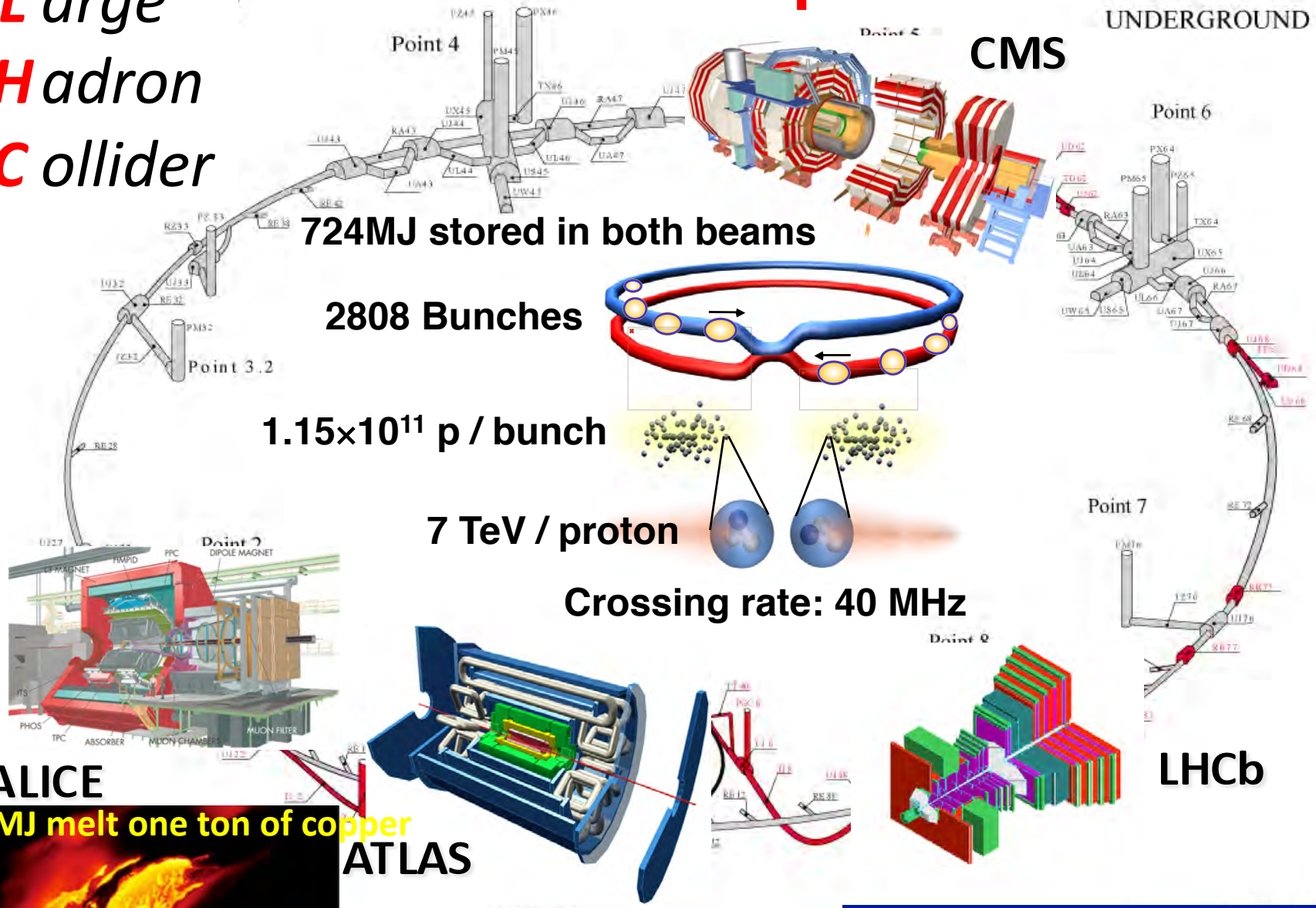
First idea (1984)
LHC and LEP together in one tunnel!



Schedule in 1990:
LHC start foreseen 1998

The Four LHC Experiments

L arge
H adron
C ollider



protons are moving at
99.999999% of the speed of light

Key parameter: magnetic field of (beam-bending) dipoles

$$p\,(\text{TeV}) = 0.3\,B(\text{T})\,R(\text{km})$$

For p = 7 TeV and R = 4.3 km

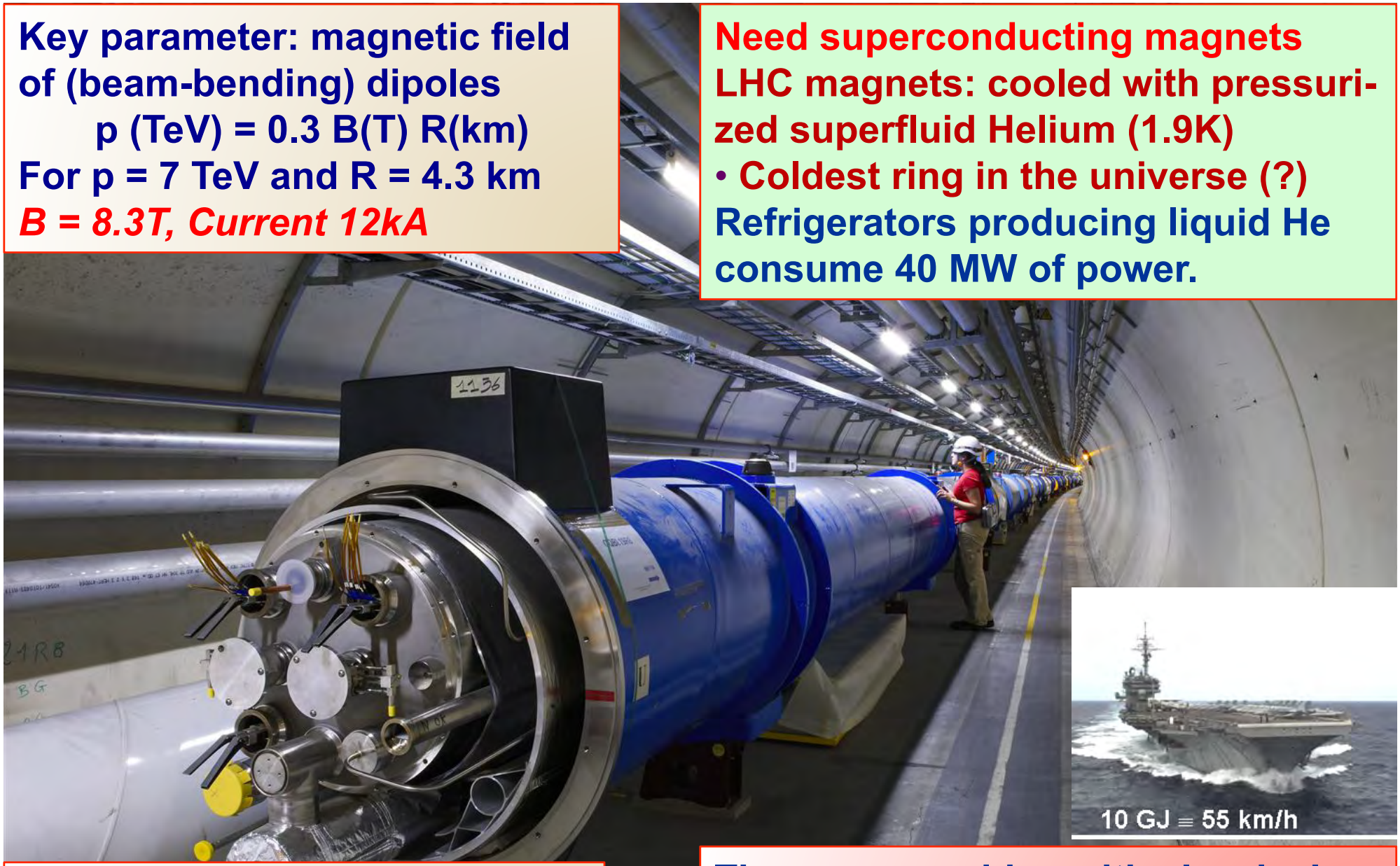
B = 8.3T, Current 12kA

Need superconducting magnets

LHC magnets: cooled with pressurized superfluid Helium (1.9K)

- **Coldest ring in the universe (?)**

Refrigerators producing liquid He consume 40 MW of power.



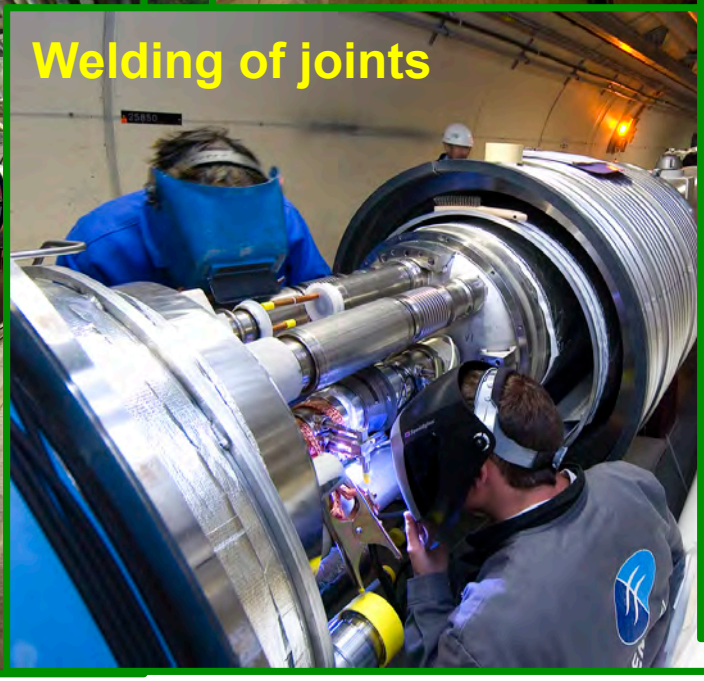
1232 high-tech SC dipole magnets

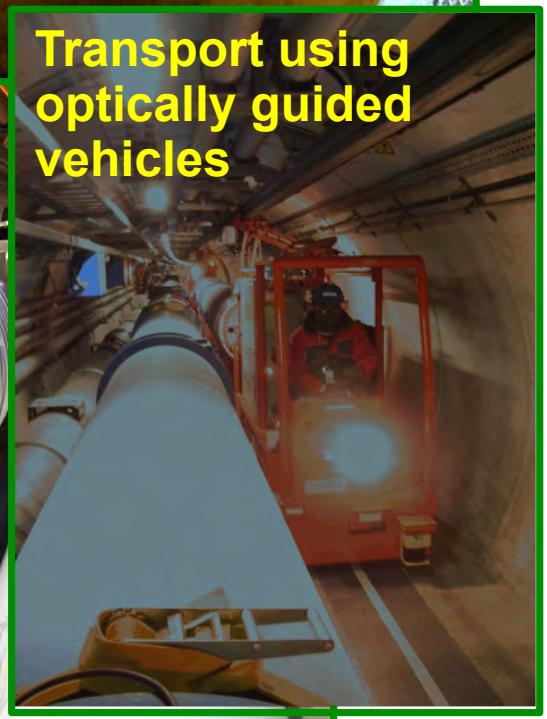
Stored energy:	**11.3GJ**
Dipole weight:	**34 tons**
Nb-Ti SC cable:	**7600 km**

The same machine with classical electromagnets would have:

- **Circumference: 100 km**
- **Power consumption: 1000 MW**

Magnet installation





Beam Energy at the LHC

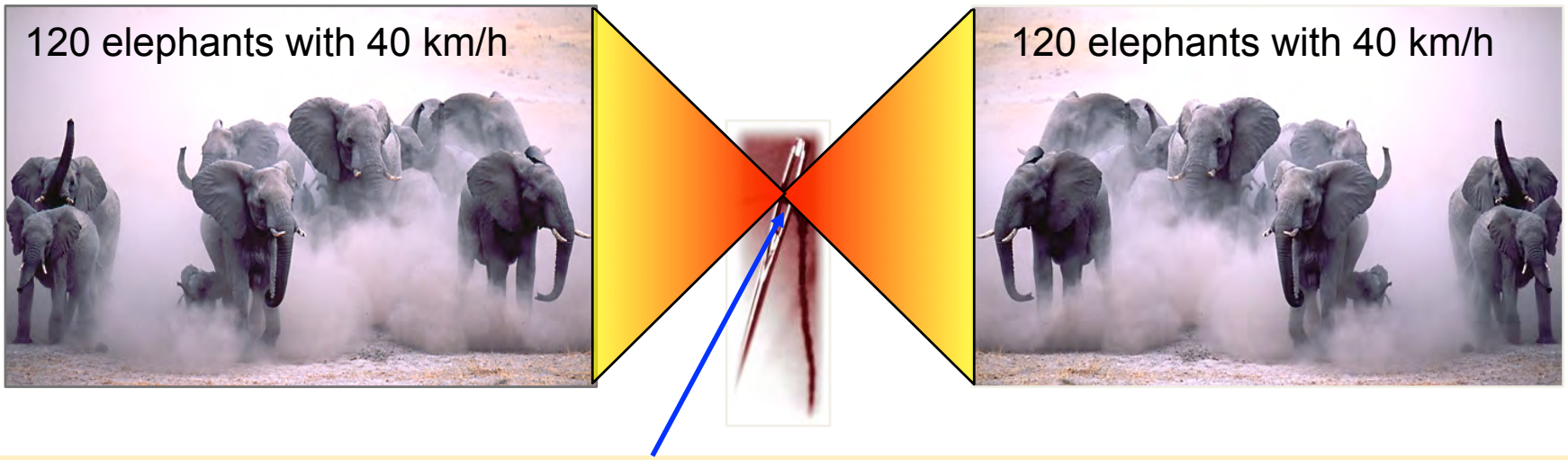
Energy of a single proton corresponds to a flying mosquito (1 μJ)

=

2808 “wagons” with 10^{11} protons, each of 7 TeV energy

➡ 360 MJ stored energy in each beam

Corresponds to collision of 2×120 elephants



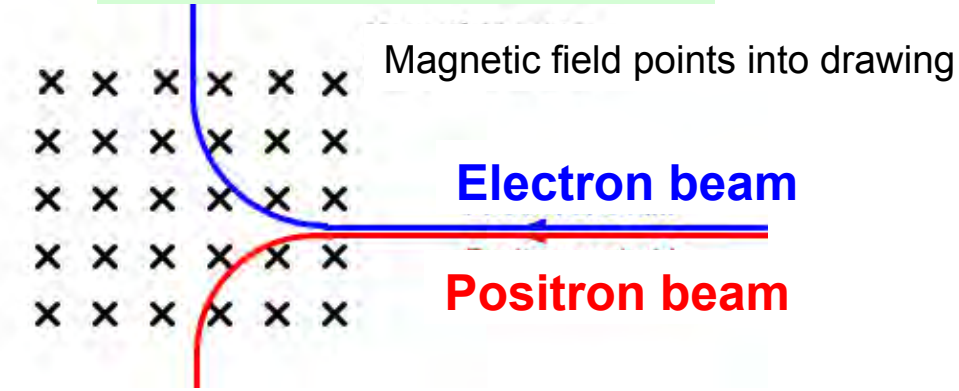
Needle head: diameter 0.3 mm. The proton beams at collision point are ~20 times smaller: diameter 16 μm

Particle Physics Detector Concepts

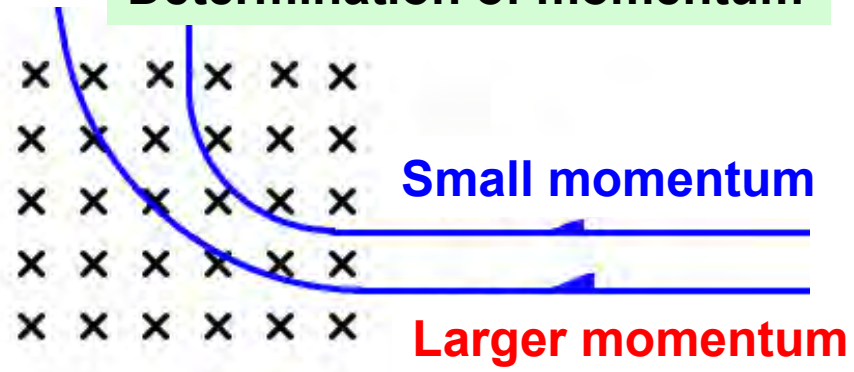
Determine the basic characteristics of a particle, charge and momentum:

Detectors are placed in a magnet

Determination of charge



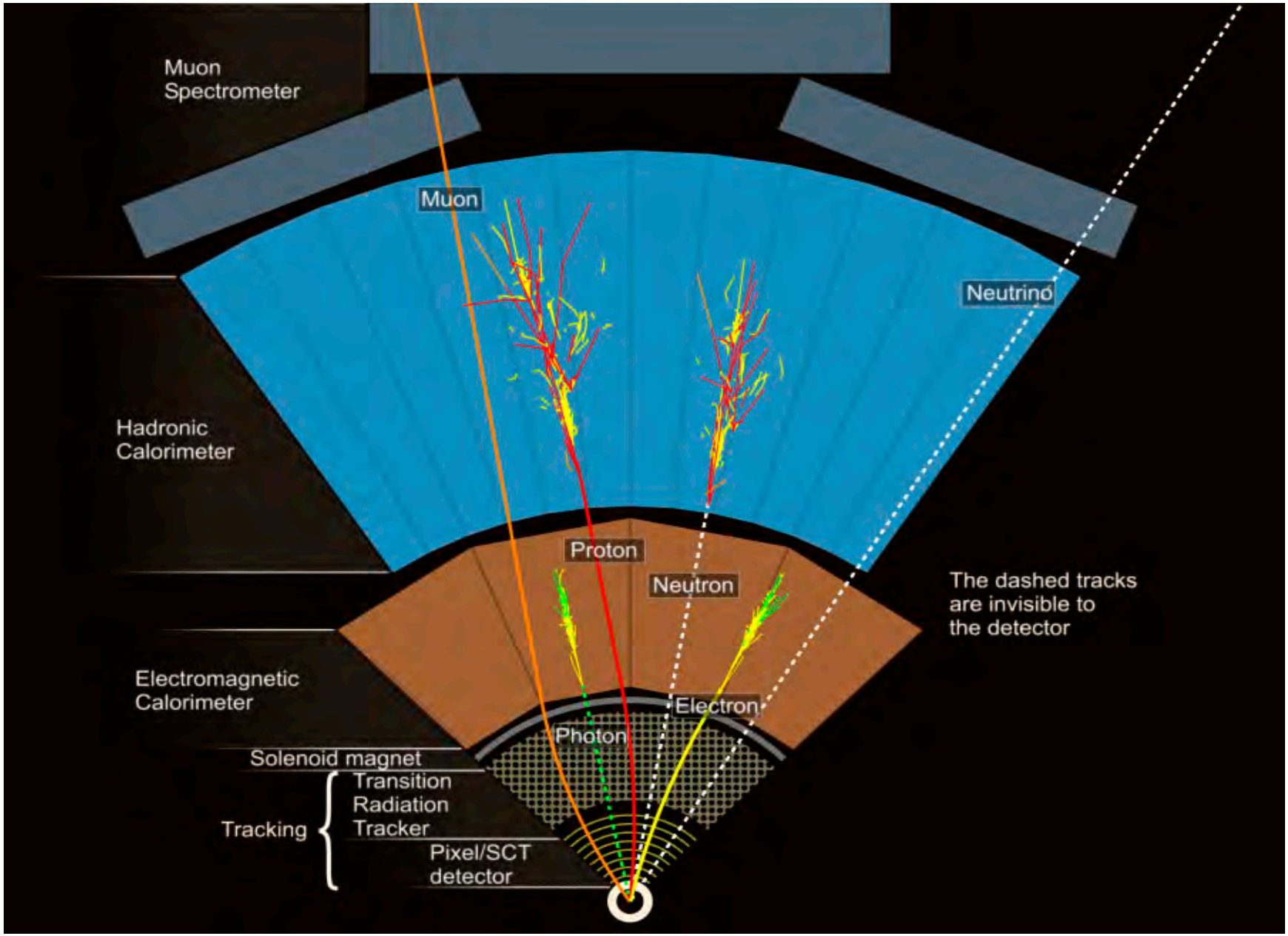
Determination of momentum



The perfect detector…

- **...should reconstruct any interaction of any type with 100% efficiency and unlimited resolution**
- **Reality: restricted efficiency and limited resolution**
  - → not all particles are detected
  - → some leave the detector without any trace (neutrinos)
  - → some escape through non-sensitive detector areas (holes, cracks, etc.)

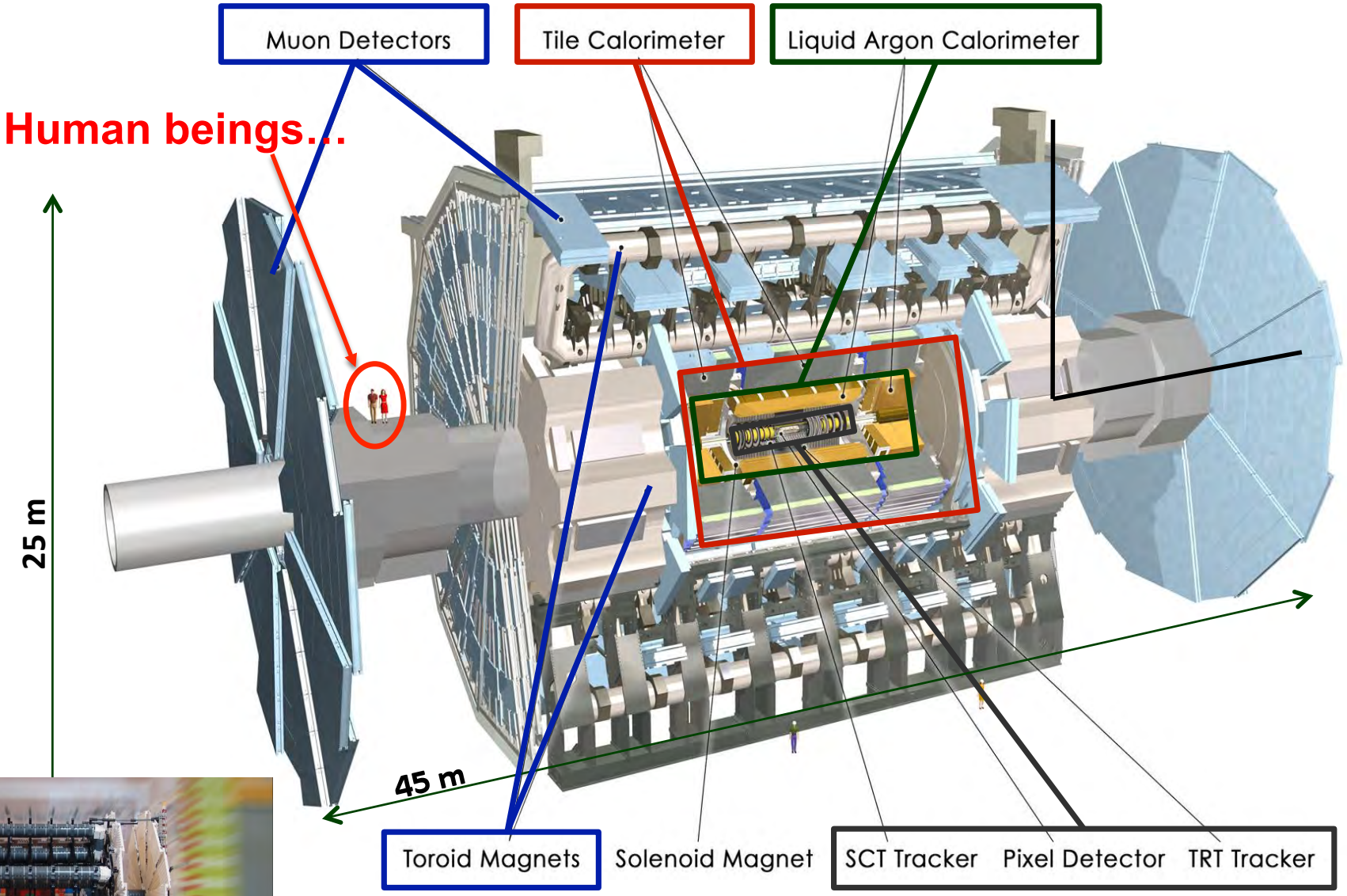
Detector Layers- Different "Camera" Types for Different Particles

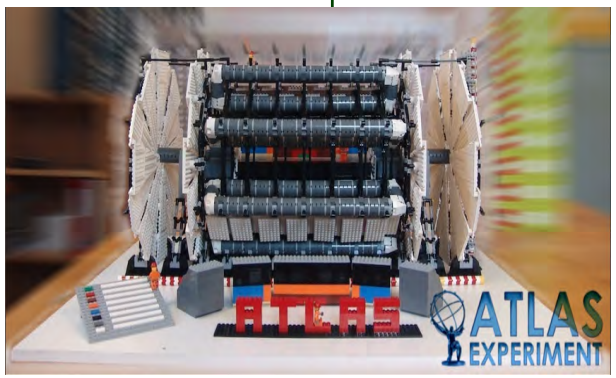


Perspective: Operation of an LHC Detector

- Analogy: 3D digital camera with 100 Mpix
- 40 million pictures per sec (which correspond to the happenings during the first ~1/10 of a billionth of a second after the Big Bang)
  - Information: 10,000 encyclopedias per second
- First selection of photographs: 100,000 / sec
  - Each is up to ~ 1MB
- Gets analyzed on a process farm with ~ 50000 CPU cores
- Every second, store the best 200-300 of these pictures
- ~ 10 million GB/year (3 million DVDs/year)
- Good camera allows one to see details
  - When taking many pictures “rare” events can be studied

A Toroidal LHC ApparatuS

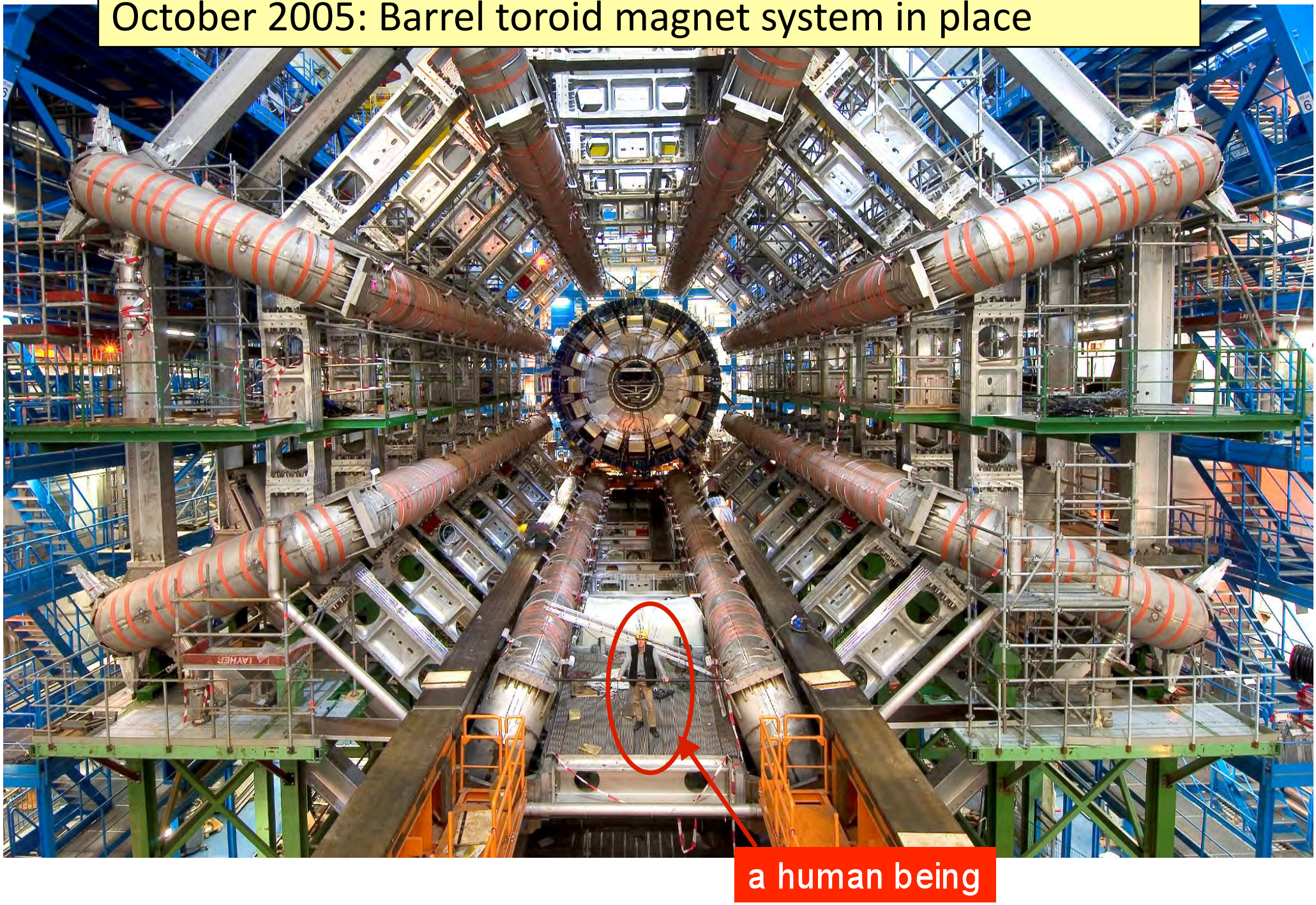




7,000 tons…


ATLAS cavern (-100 m) in June 2003

October 2005: Barrel toroid magnet system in place

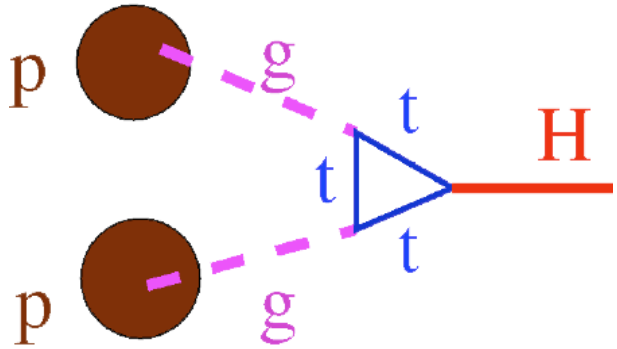


June 2008: installation completed → closure of the LHC beam pipe inside the ATLAS cavern

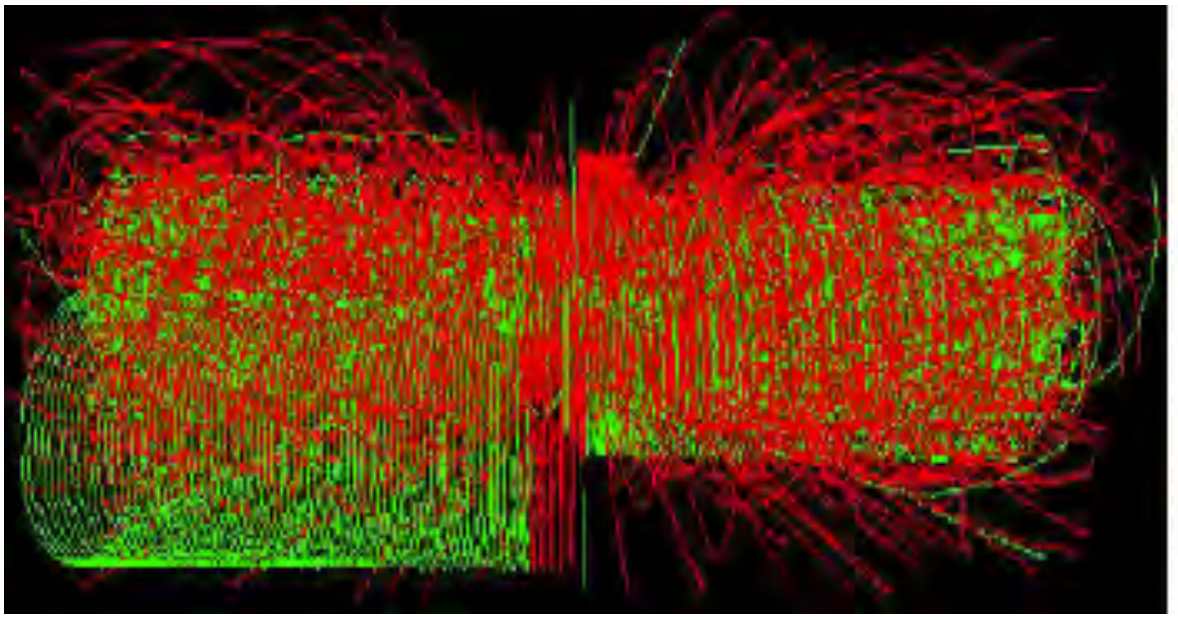
Higgs Production at the LHC

- **Possible production process:**

~90% of the times

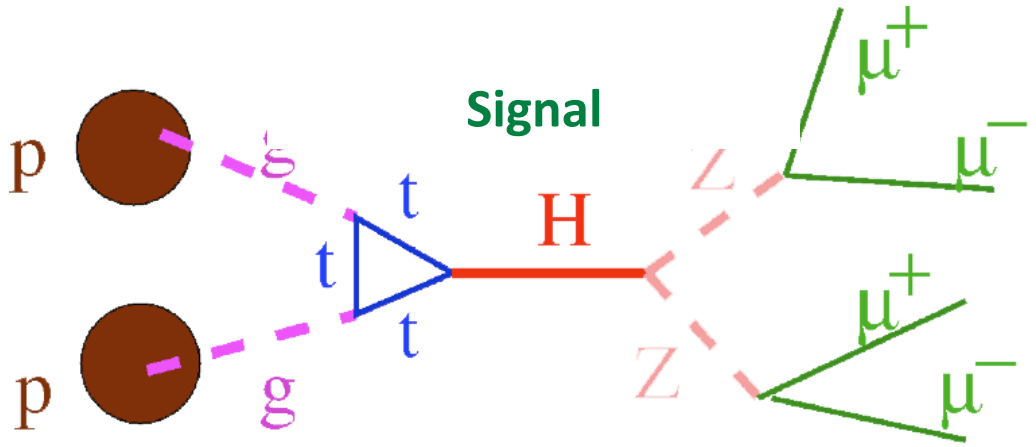


- **Higgs is an inherently unstable particle and decays promptly**
  - **Can only observe the stable products in the end…**
- **This could be quite a mess!**



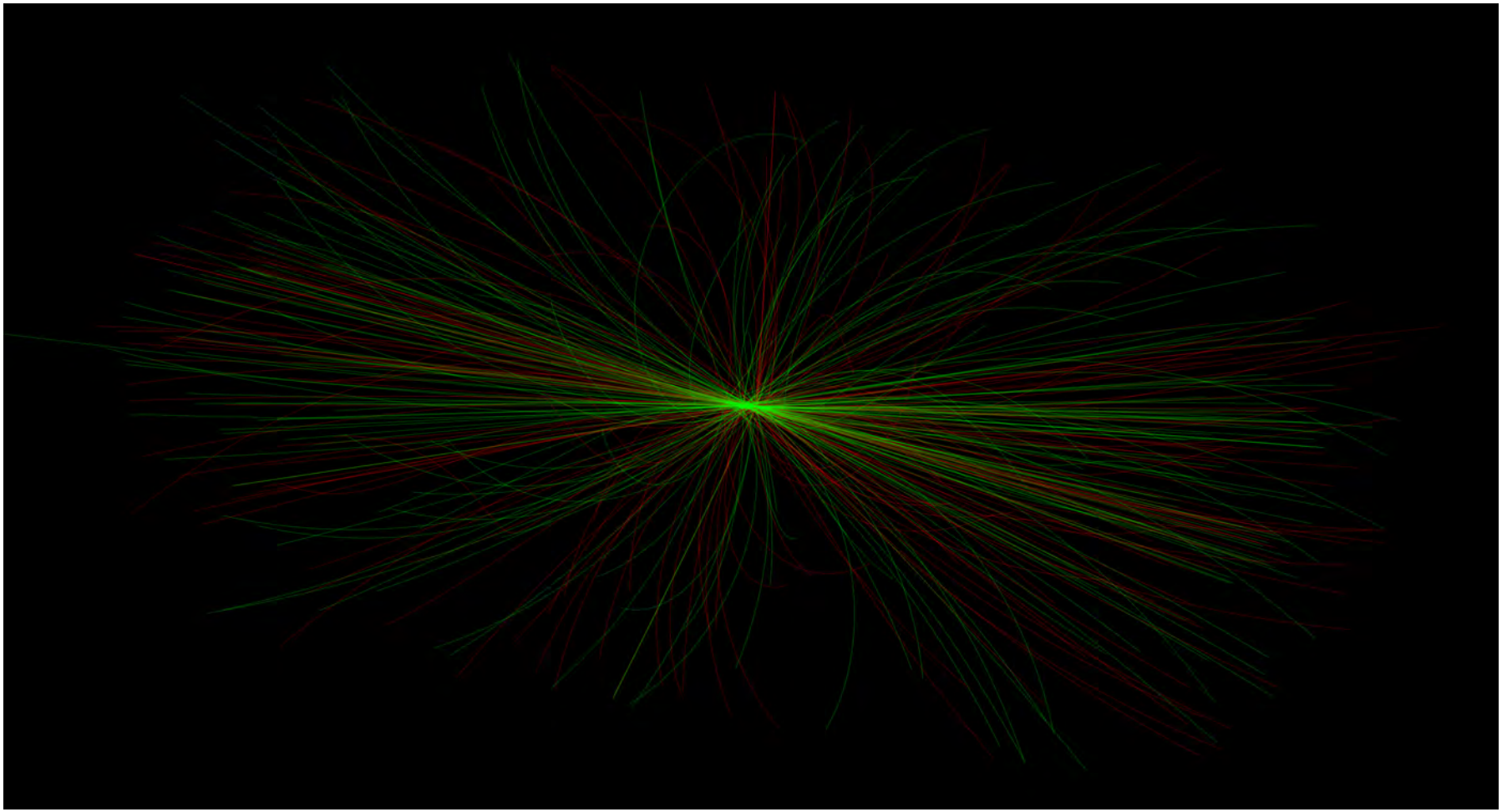
Searching for a Needle in a Haystack: The Higgs Search at the LHC

- One way we expect the Higgs to be produced and to decay (Signal):



- … how to find "photos" of this process?

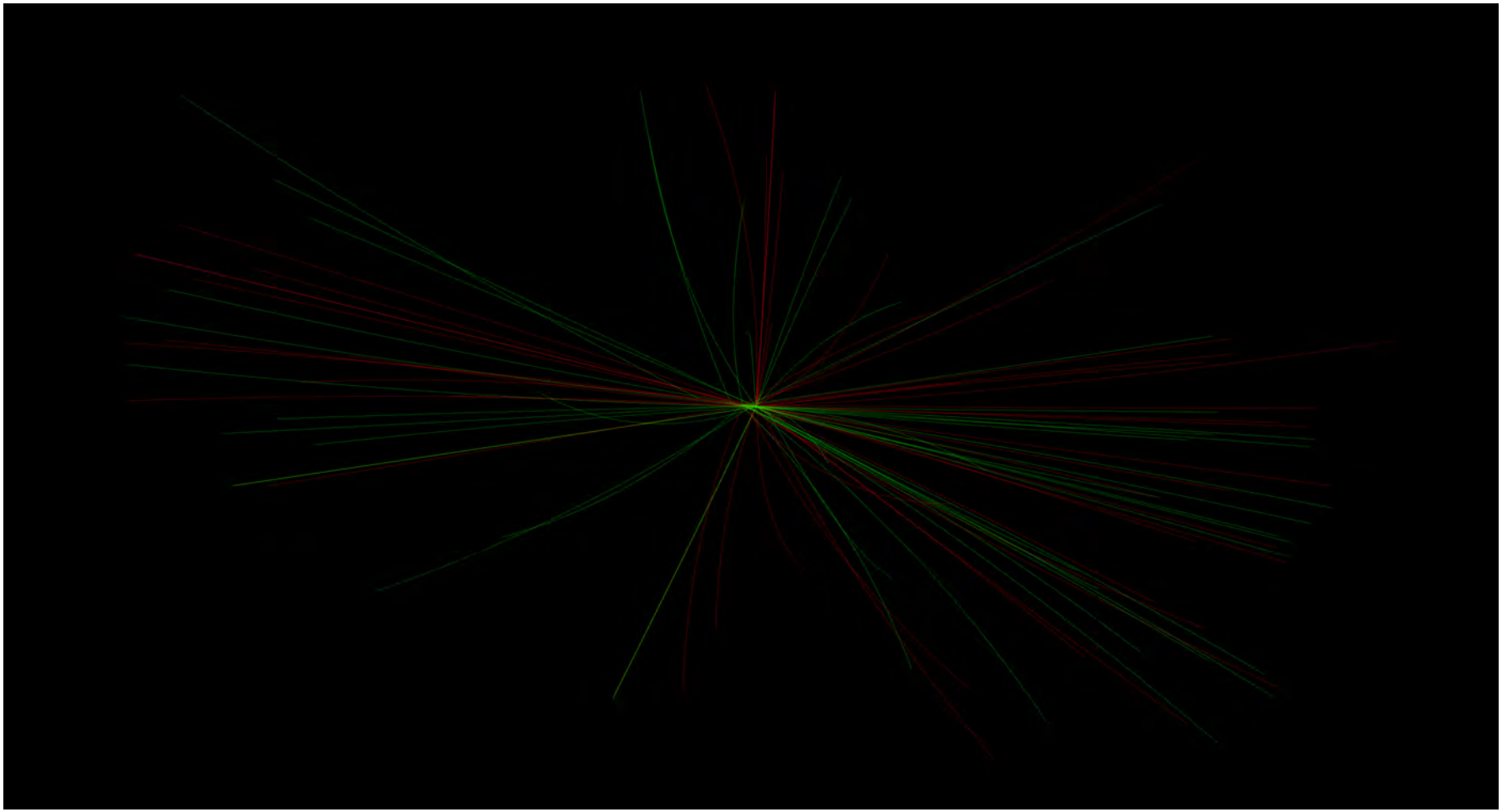
Simulated Event, tracks only



Positive charged particle
Negative charged particle

Track momentum > 200MeV

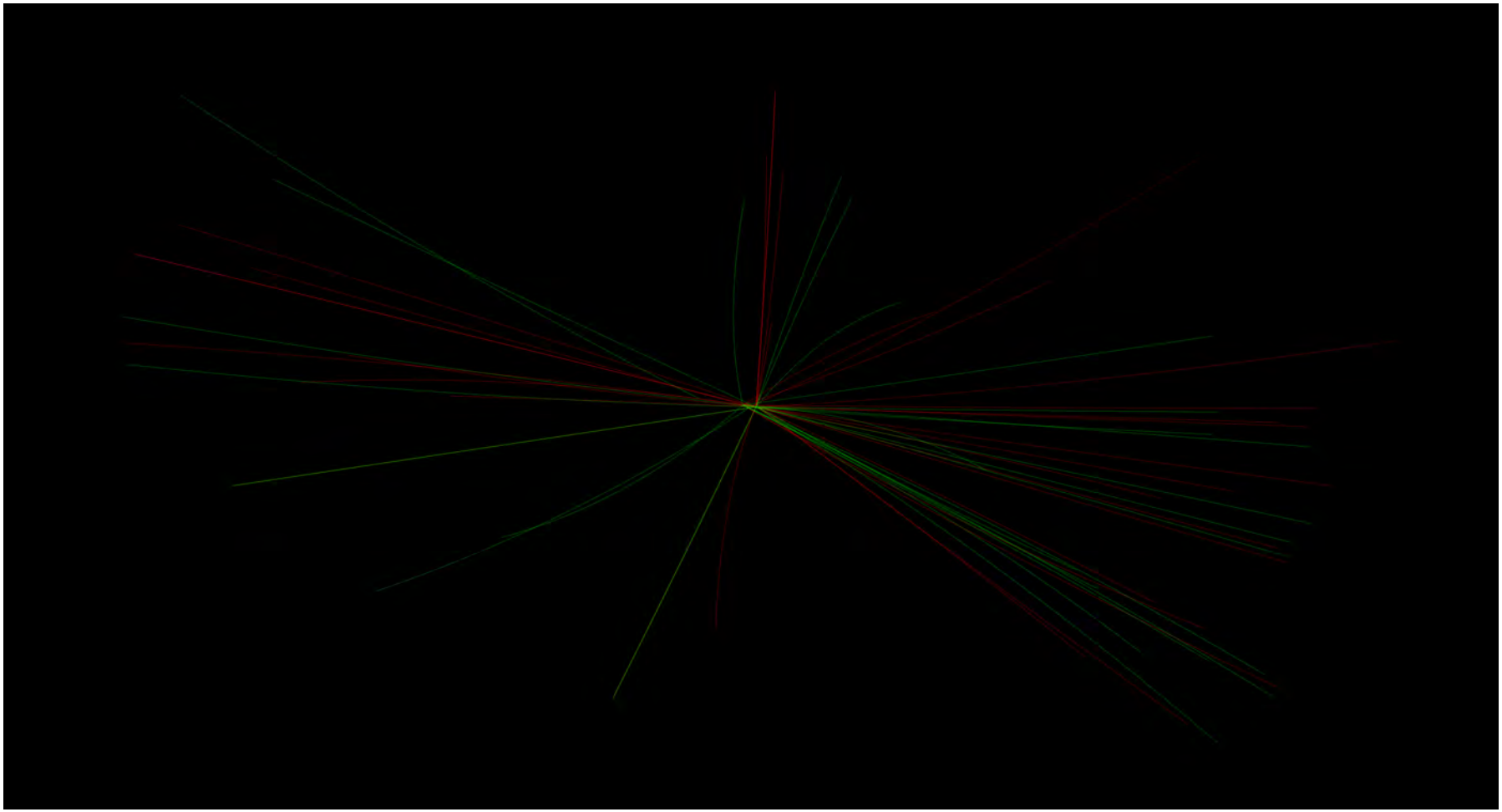
Simulated Event, tracks only



Positive charged particle
Negative charged particle

Track momentum > 1 GeV

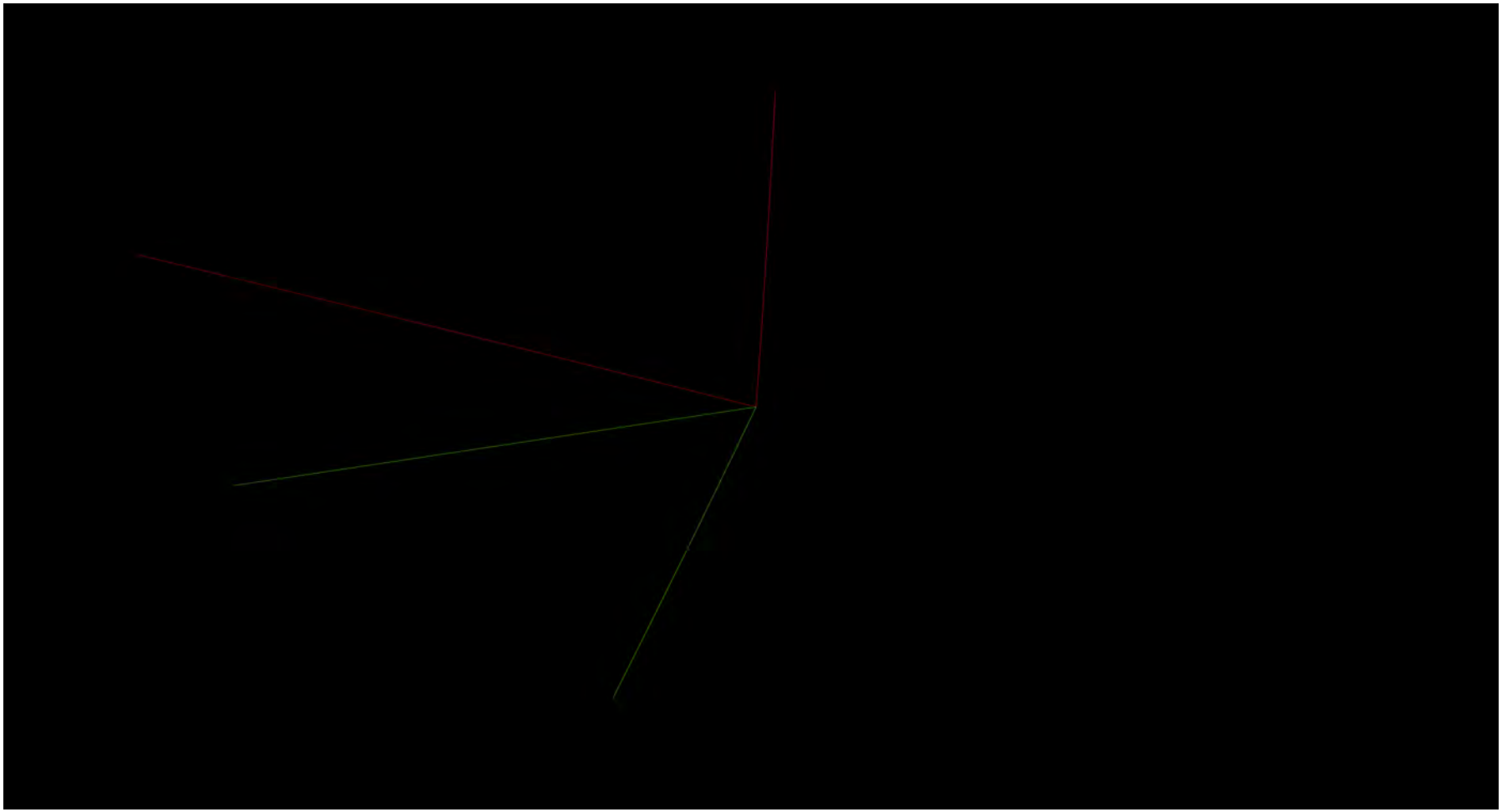
Simulated Event, tracks only



Positive charged particle
Negative charged particle

Track momentum > 3 GeV

Simulated Event, tracks only



Positive charged particle
Negative charged particle

Track momentum > 10 GeV

Searching for a Needle in a Haystack: The Higgs Search at the LHC

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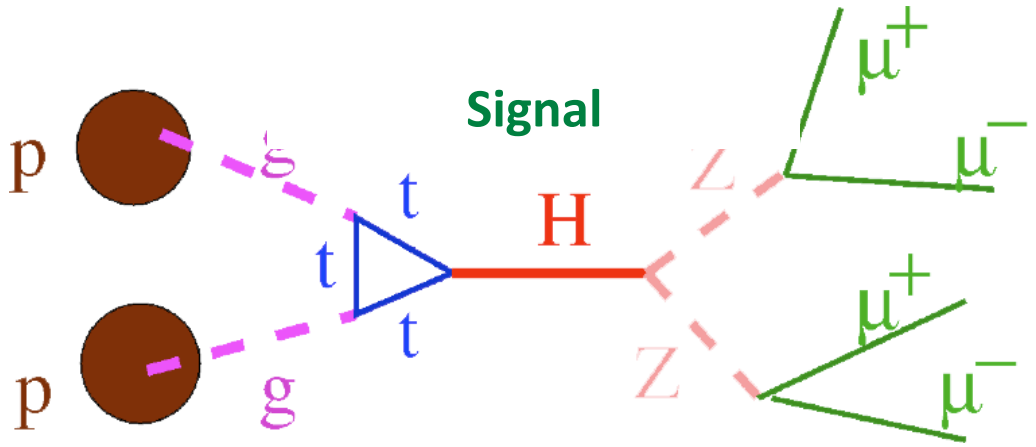
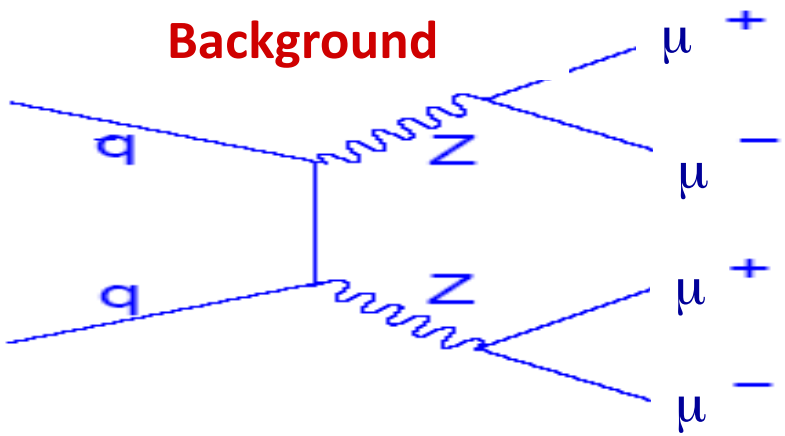
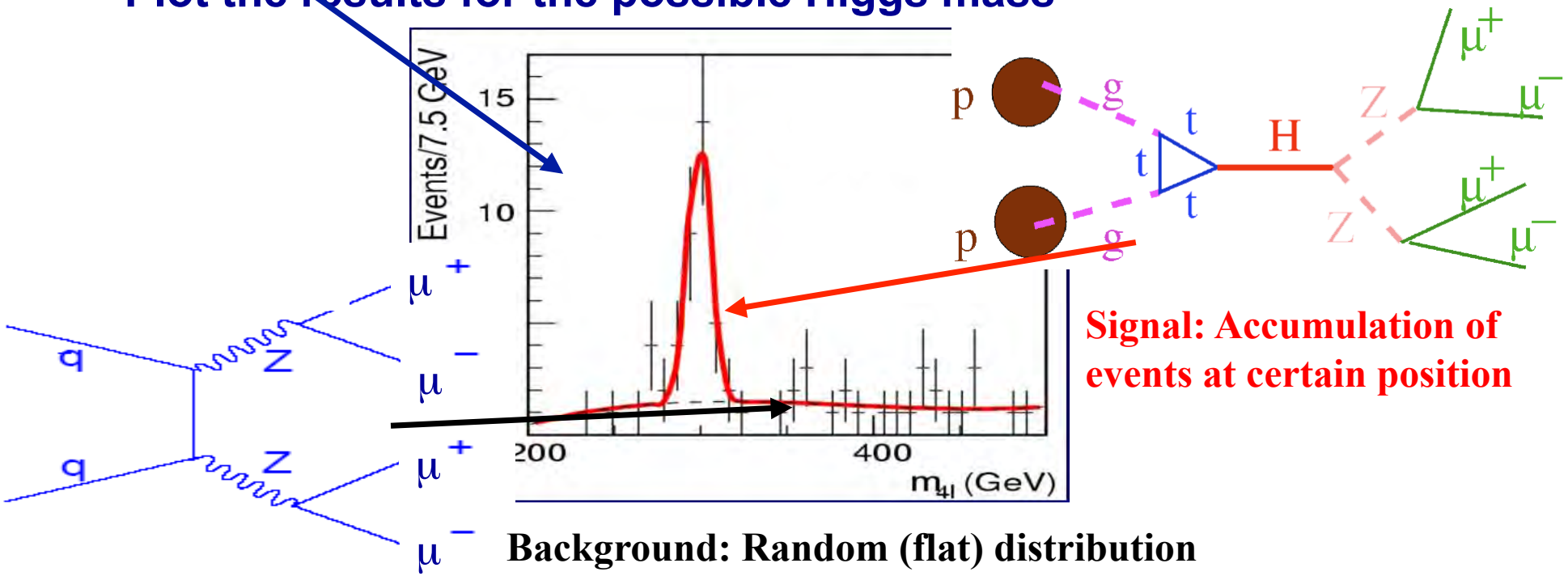


- **…but 4 muons could be also produced by the following process (background)**



Searching for a Needle in a Haystack: The Higgs Search at the LHC

- **Trick: "combine" one positive charged track and one negative charge track and calculate the momentum and energy of the "mother" particle, the Z**
  - Using momentum conservation, energy conservation
- **"combine" the 2 Z particles and calculate mass of the "mother" particle, possibly the Higgs**
- **Plot the results for the possible Higgs mass**



Signal: Accumulation of events at certain position

Background: Random (flat) distribution

Searching for a Needle in a Haystack: The Higgs Search at the LHC

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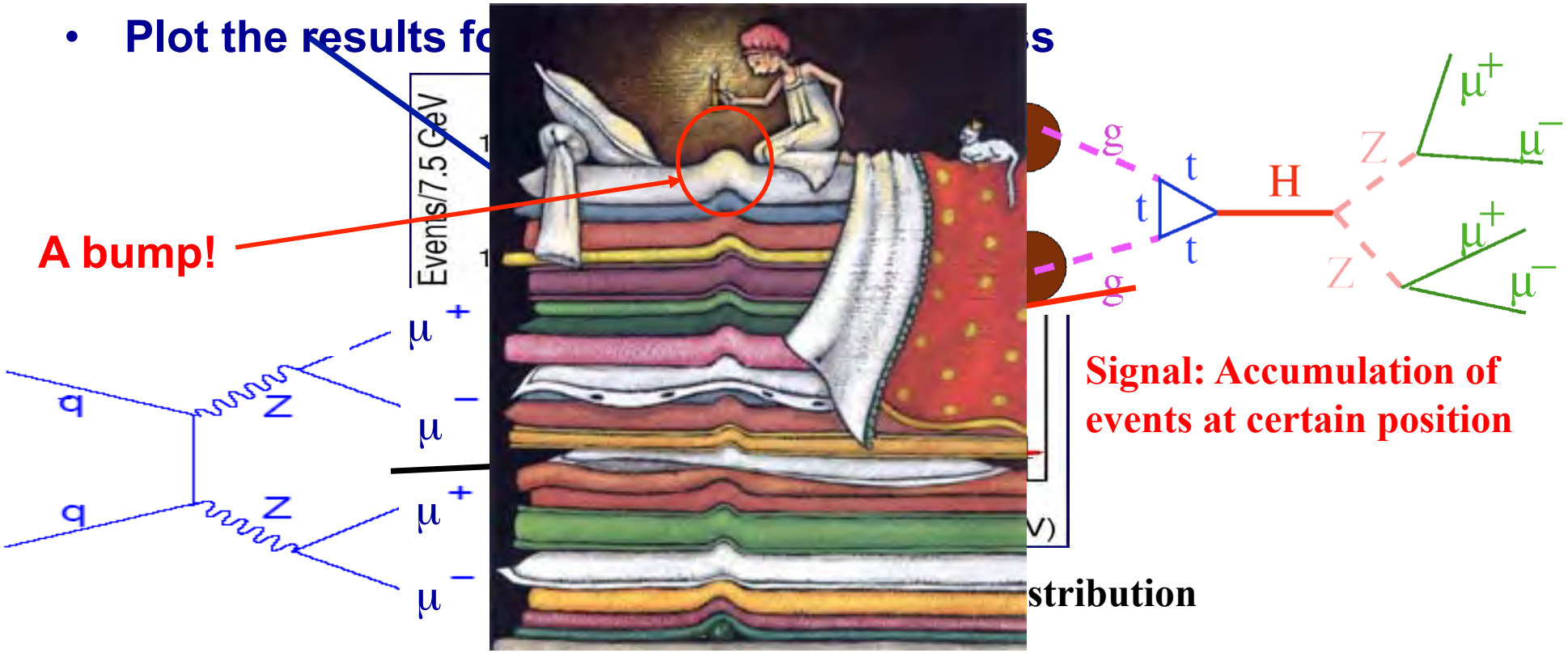
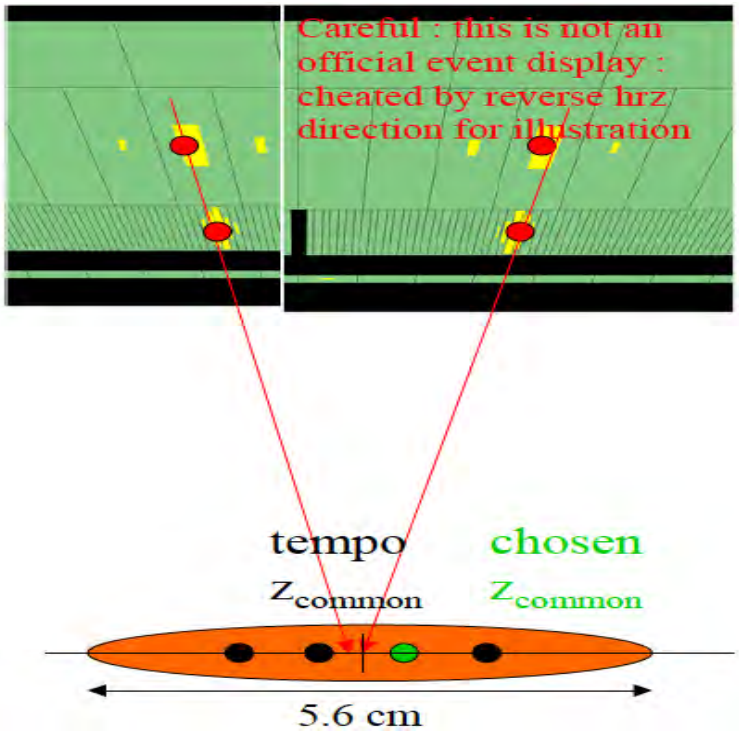


Bump Hunting for Dummies: Searching for the Higgs at the LHC

- Look for potential Higgs final decay products that can be fully reconstructed:
  - Good candidates are: leptons (electrons, muons) or photons
- If leptons pair them to create a Z-particle; then pair two Z-particles to create a Higgs
  - Use energy and momentum conservation…
- If photons, pair two of them that are pointing to a common origin

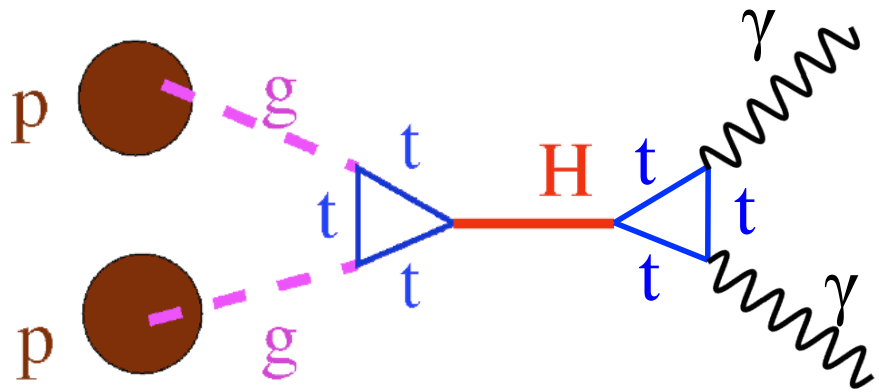


Congratulations!
You have created a resonance!

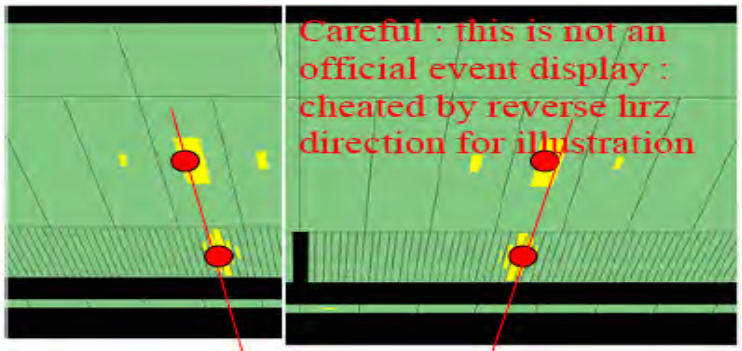
Carleton UNIVERSITY had been hunting bumps like that for quite some time…

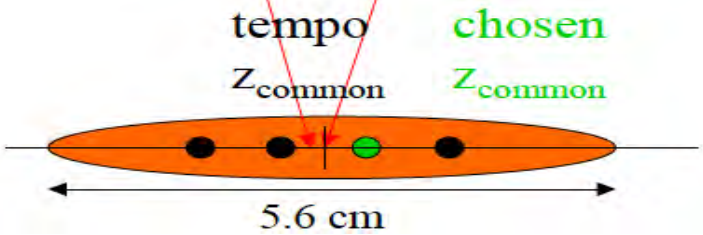
Alone in Canada it was actually looking for the ones that made the difference…

The Higgs Decaying into Two Photons

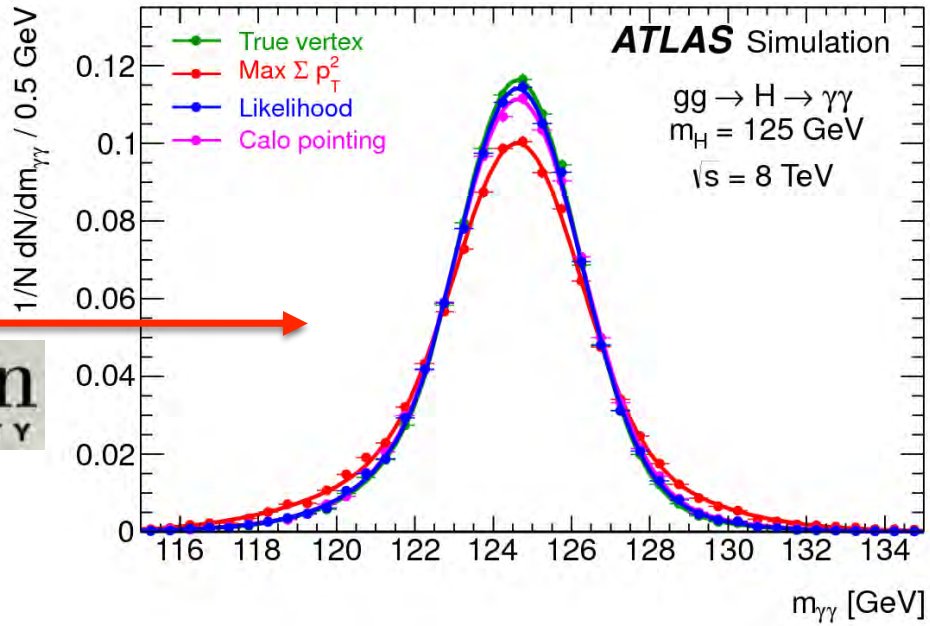


The ideal scenario in a perfect world…





Carleton UNIVERSITY



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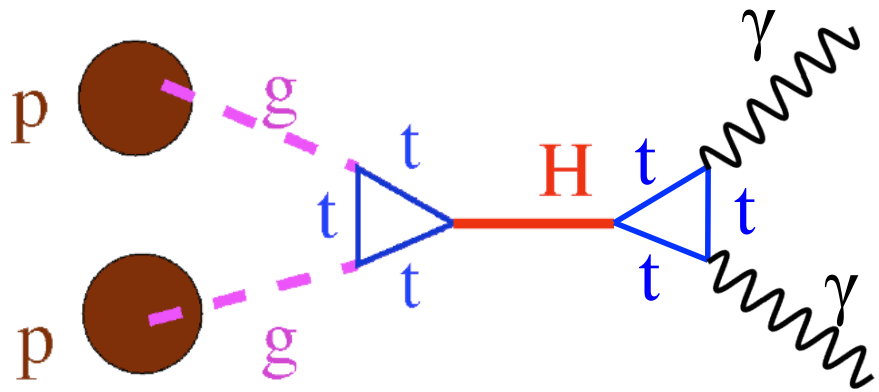
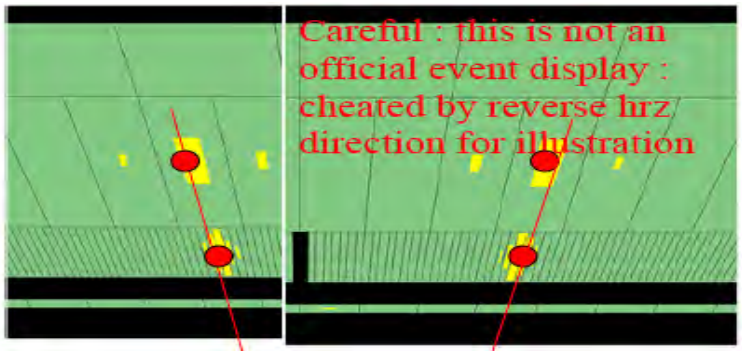
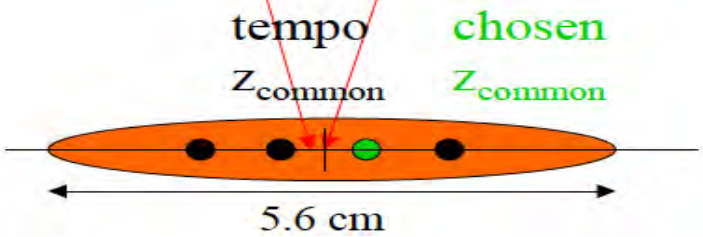


Reality in a not so perfect world…





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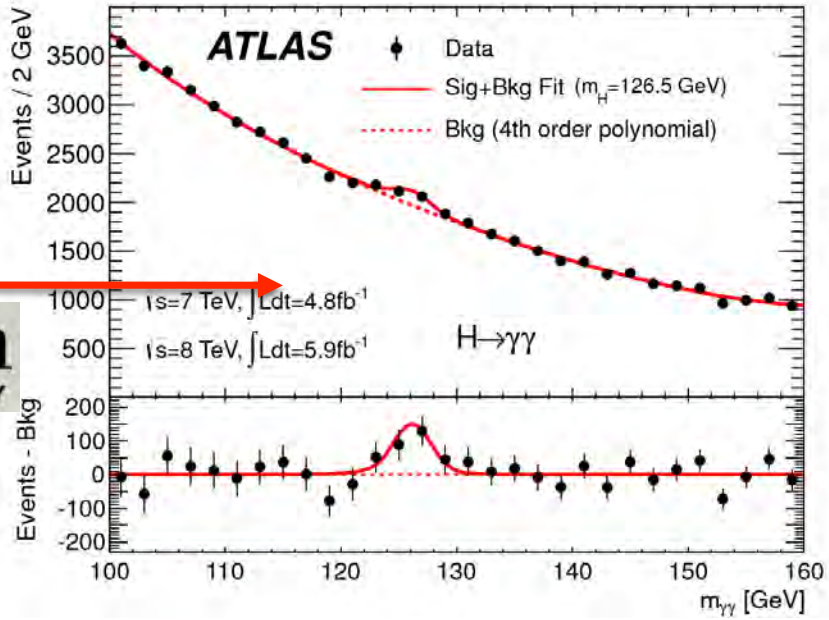
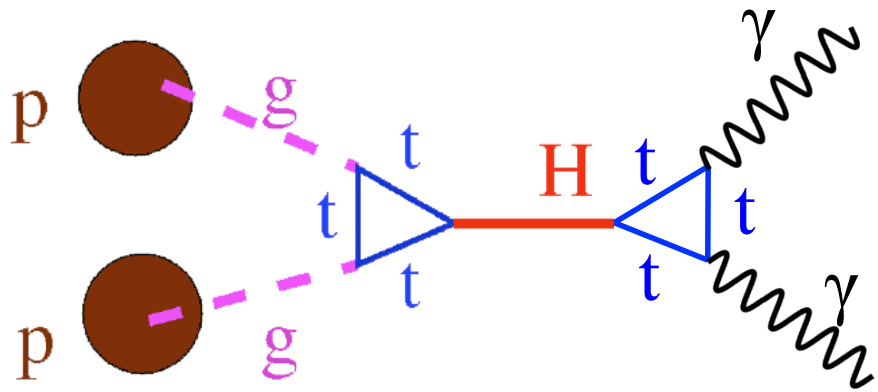


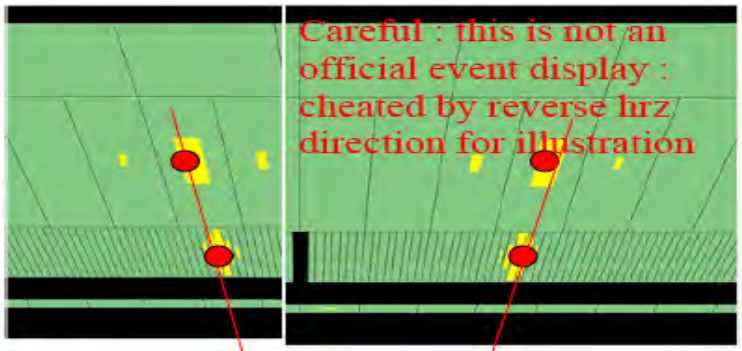
The Higgs Decaying into Two Photons

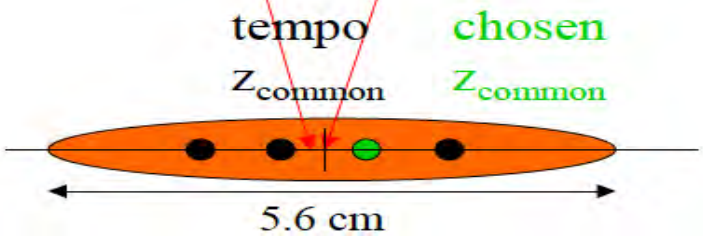


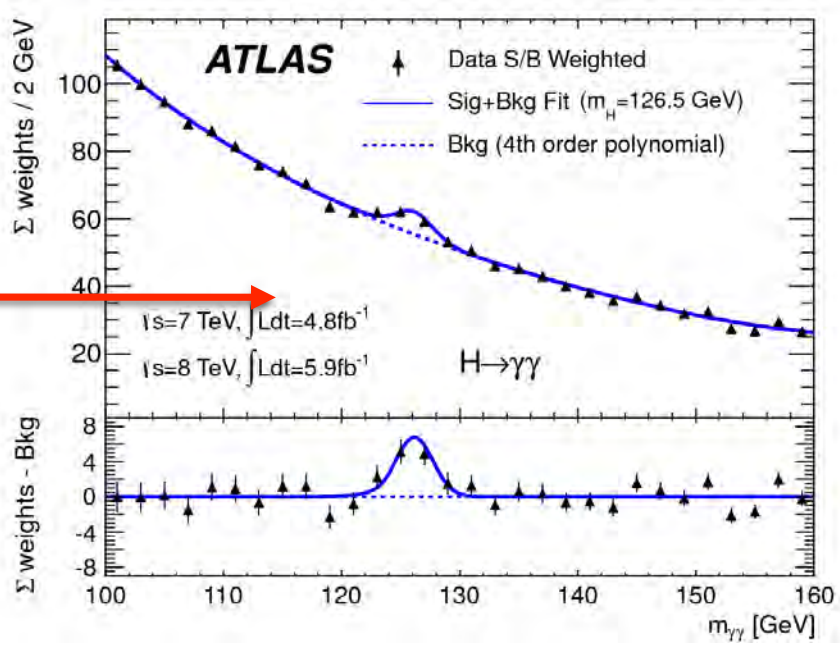
Categorization or photon profiling:

weigh more the good and the beautiful

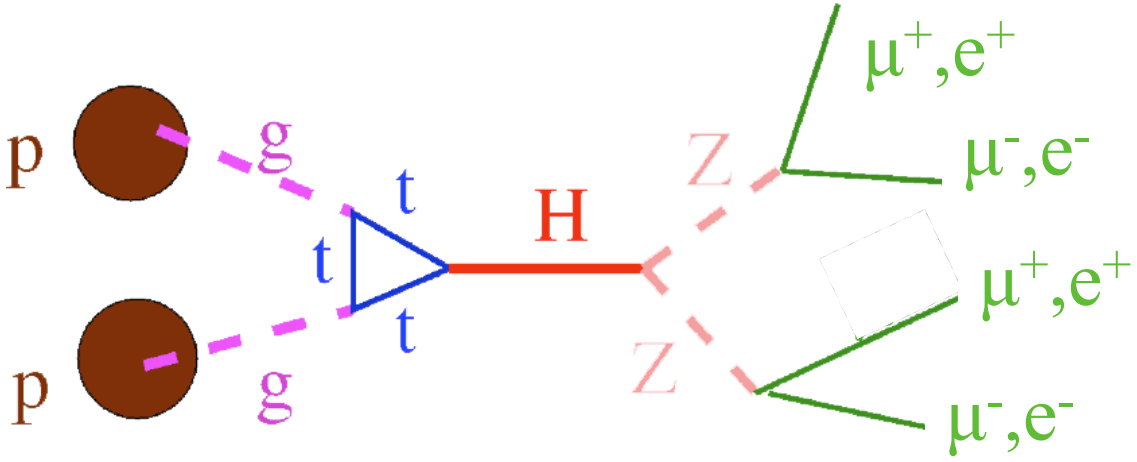
originally a Carleton UNIVERSITY **idea**







The Higgs Decaying into Four Leptons

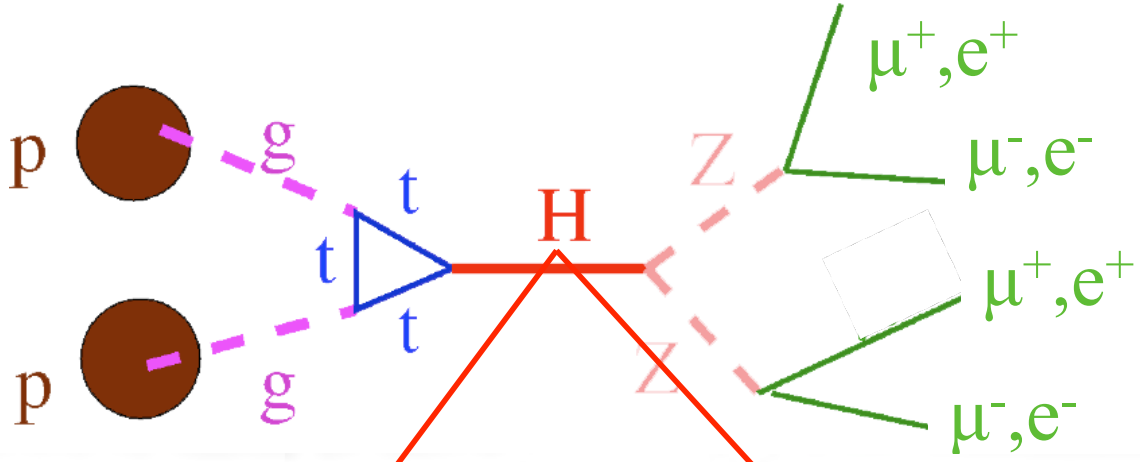


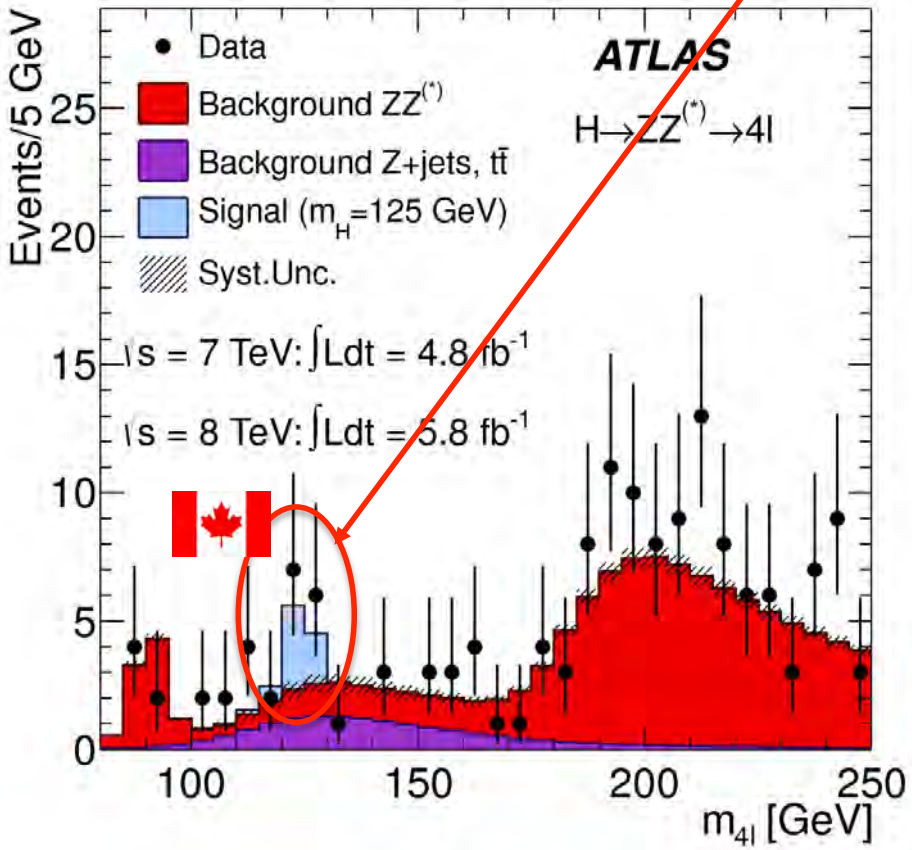
- **At least one of the four produced leptons has rather low energy ("soft"):**
  - A particularly problematic situation for the ATLAS detector
- **Carleton UNIVERSITY spearheaded the effort to improve the reconstruction of the electrons**

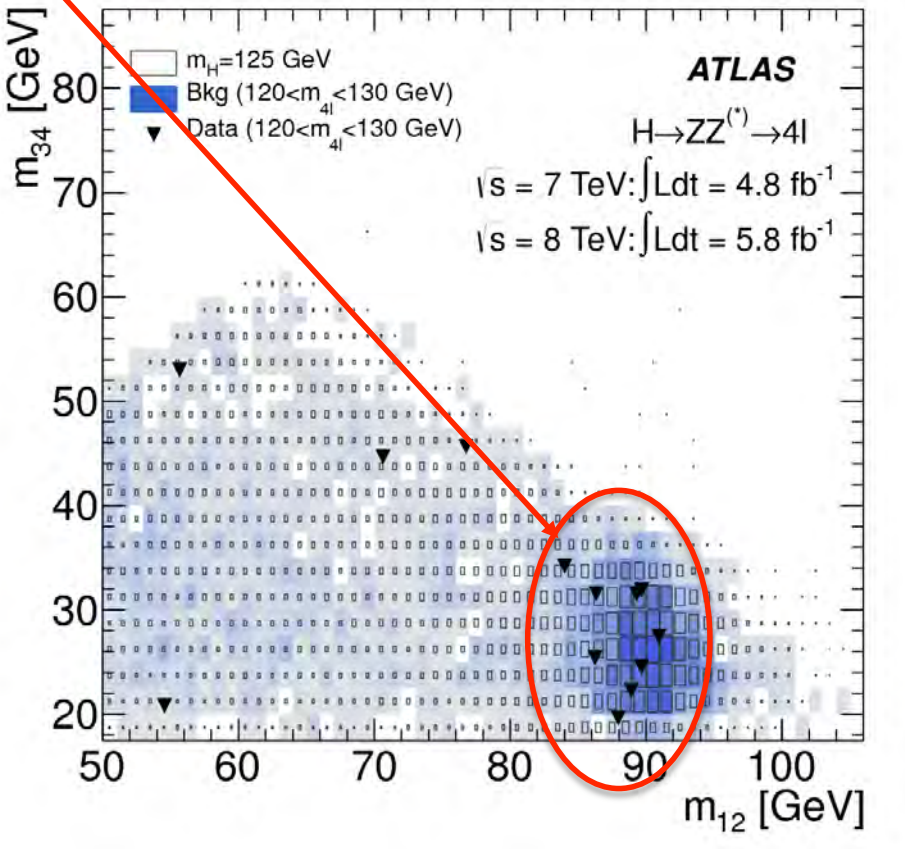
~1/3 of the useful events observed have been due to this

THE MOST SPECTACULAR ACHIEVEMENT OF THE ATLAS HIGGS SEARCH

The Higgs Decaying into Four Leptons





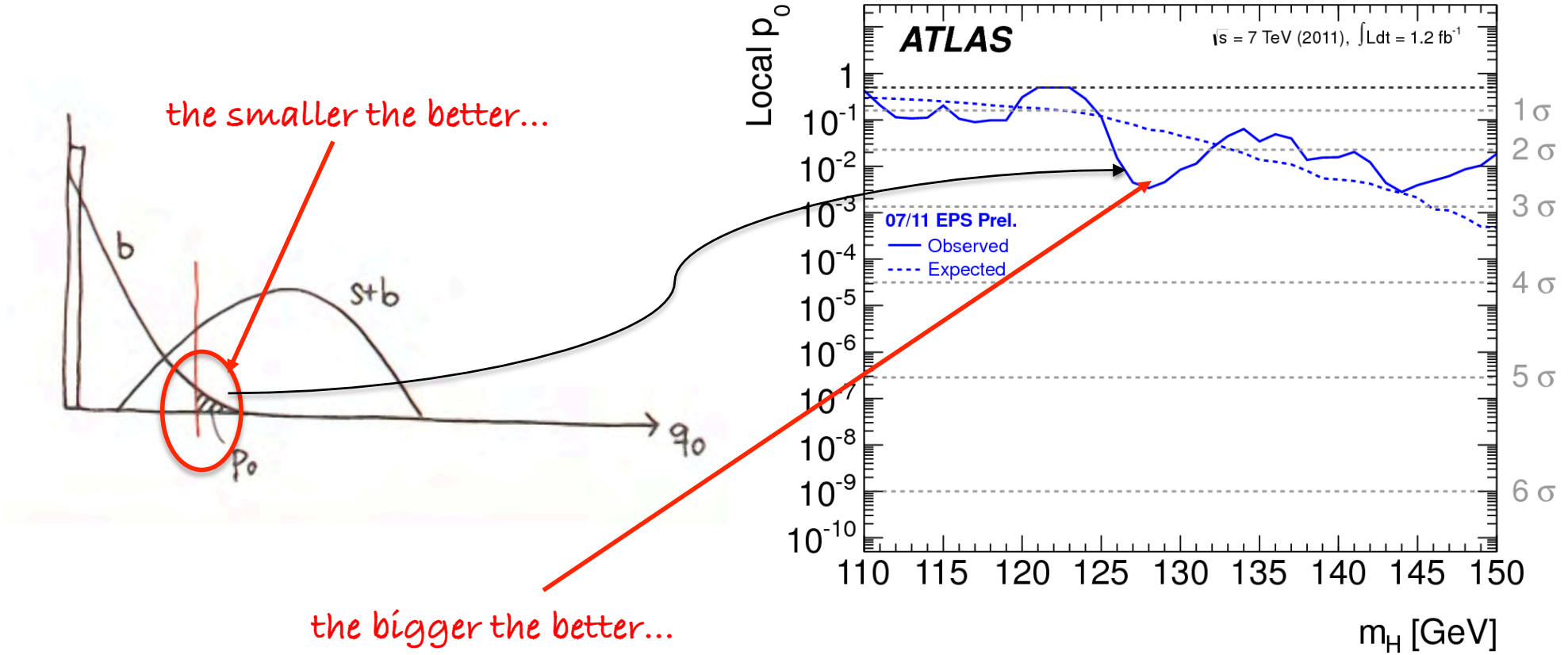


Observation of a Higgs-like Boson

Each of the two Higgs-decay channel searches provide clear evidence for the existence of a "bump"

Join them and one can increase the sensitivity

become more "princess-like" or become more "significant"



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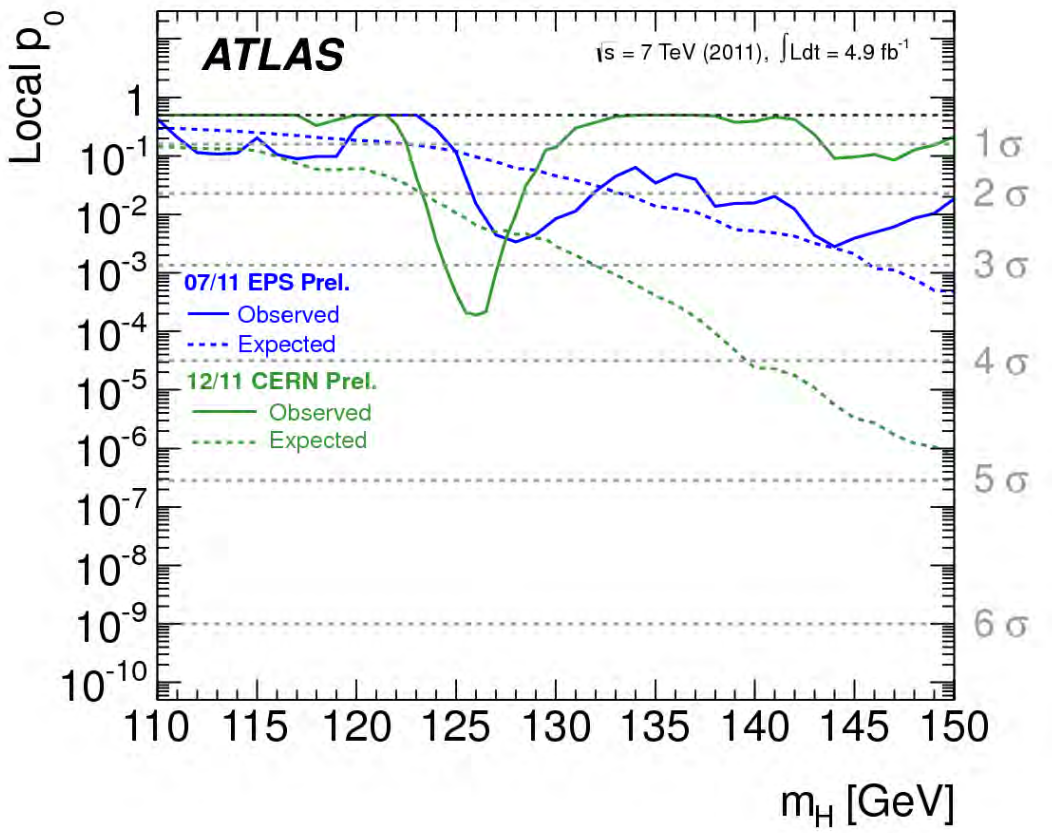

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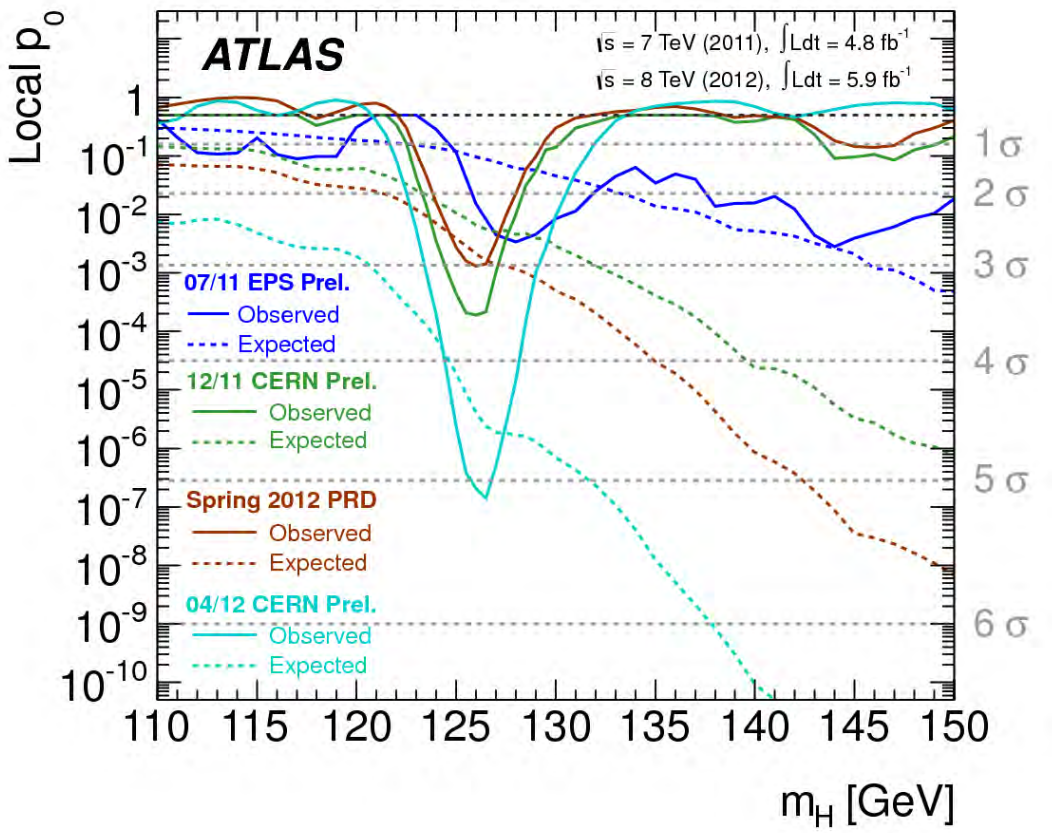

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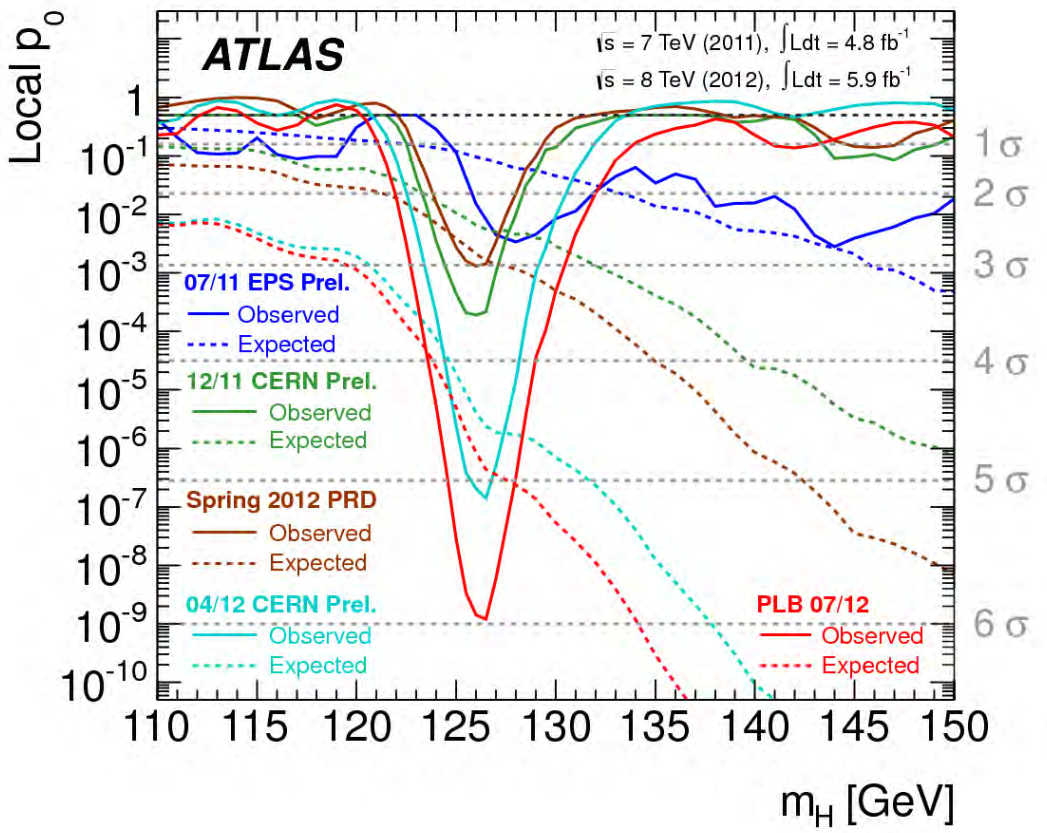
to 5.9 σ!




The Sydney Morning Herald
Die Presse
Happy Higgs Day
„Es geht darum, die Welt zu verstehen"

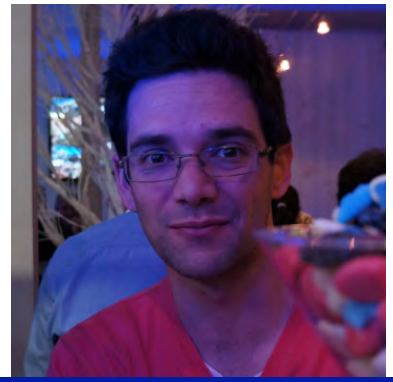
The Human Face of a Discovery

Dr. F. Tarrade, Carleton
Higgs Note editor, Higgs Mass Measurement Leader

Dr. J-F Marchand, Carleton
Higgs Signal Extraction Leader, Higgs Mass Measurement Leader

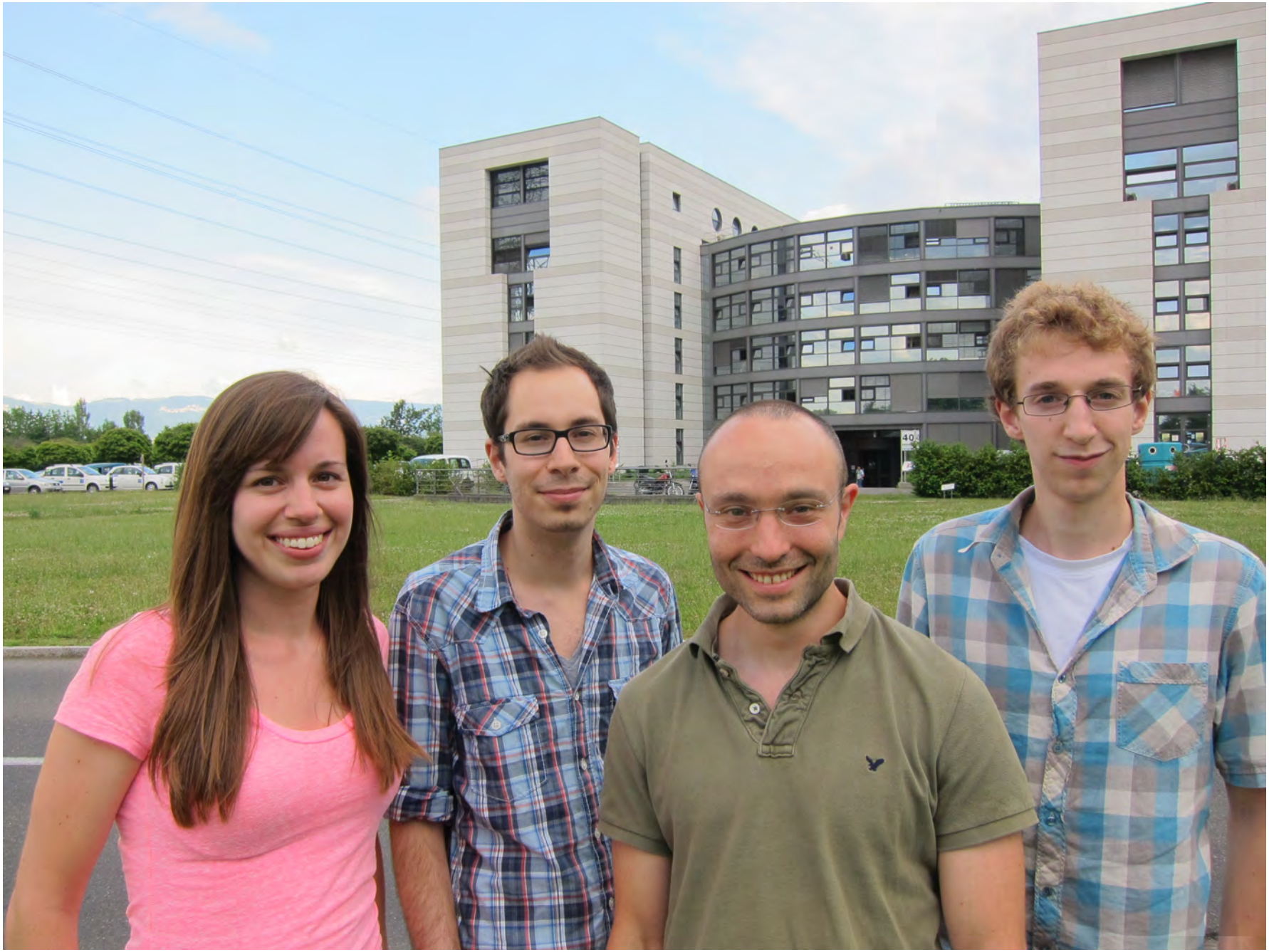
Dr. C. Anastopoulos, CERN
Higgs Note Editor
Higgs Analysis Sub-convener

Dr. K. Tackmann, DESY
Higgs Note Editor
Higgs Analysis Sub-convener



Dr. A. Morley, CERN
Track Reconstruction Leader

Carleton Celebrity Students



Where we stand…

- **Discovery of a new boson consistent with the SM Higgs boson**
  - ~6σ significance using the data till July 2012
- **Need to measure now in detail the properties of this new boson**
  - Is it really what we think that it is?
  - What more information can we extract about the SM?

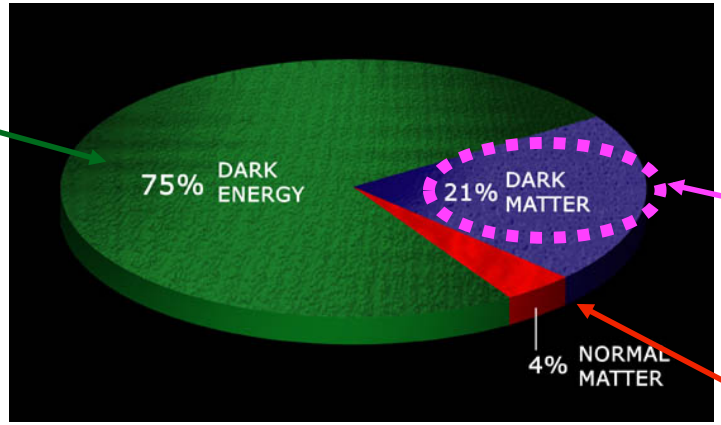
Can it provide clues for very important open issues?

Dark Matter and Supersymmetry

Darth Vader

© Rocky Kolb

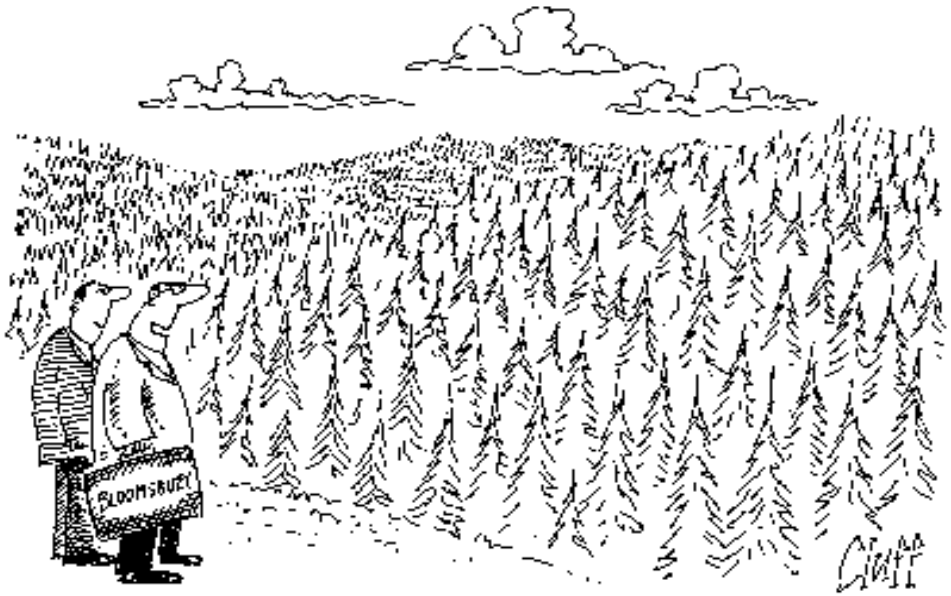
Composition of the universe



In our universe there must be about 5 times more Dark Matter than known matter!!!

Dark Matter

matter



"One day, all of these will be supersymmetric phenomenology papers."

There is an extension of the Standard Model which could explain Dark Matter
⇒ Supersymmetry (short: **SUSY**)

- Very popular, more than 7000 publications since 1990

What we already know that does not fit in the picture…

…is the **neutrinos!** The mystery particles of the universe

Nobody had predicted that they **have mass**…

Can we measure it?

Perhaps…

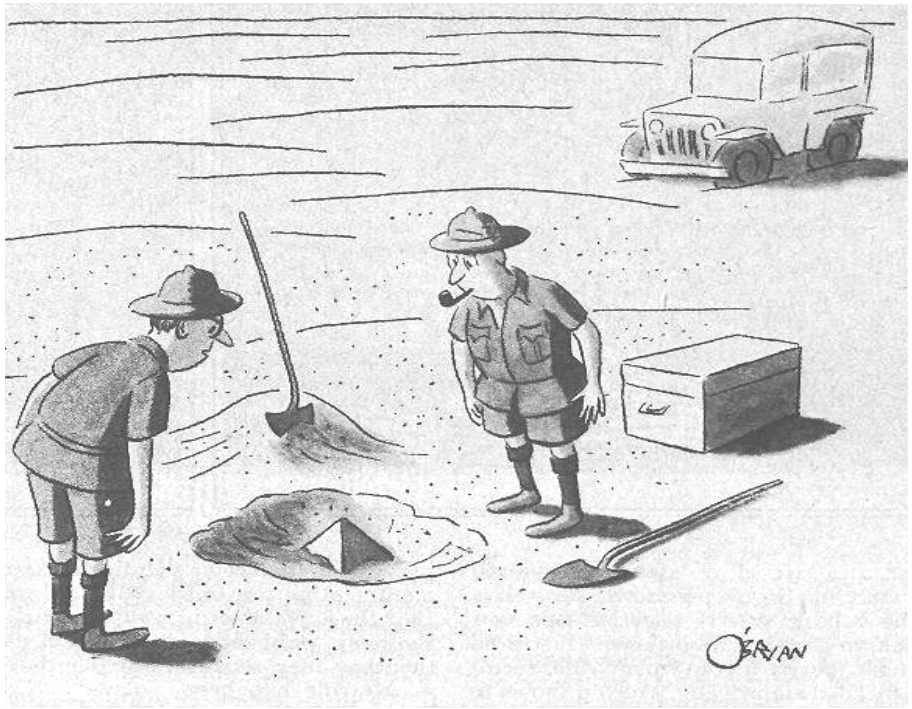
Carleton UNIVERSITY

is already working in that direction

More exciting news may be coming in the future from your local physics department

Conclusion

Last winter I used to show this…



"This could be the discovery of the century. Depending, of course, on how far down it goes."

If this is what I think it is, we've got a lot of work ahead of us..

This is more appropriate now…