Exploring Nature's Fundamental Forces and Particles with the **Large Hadron Collider**

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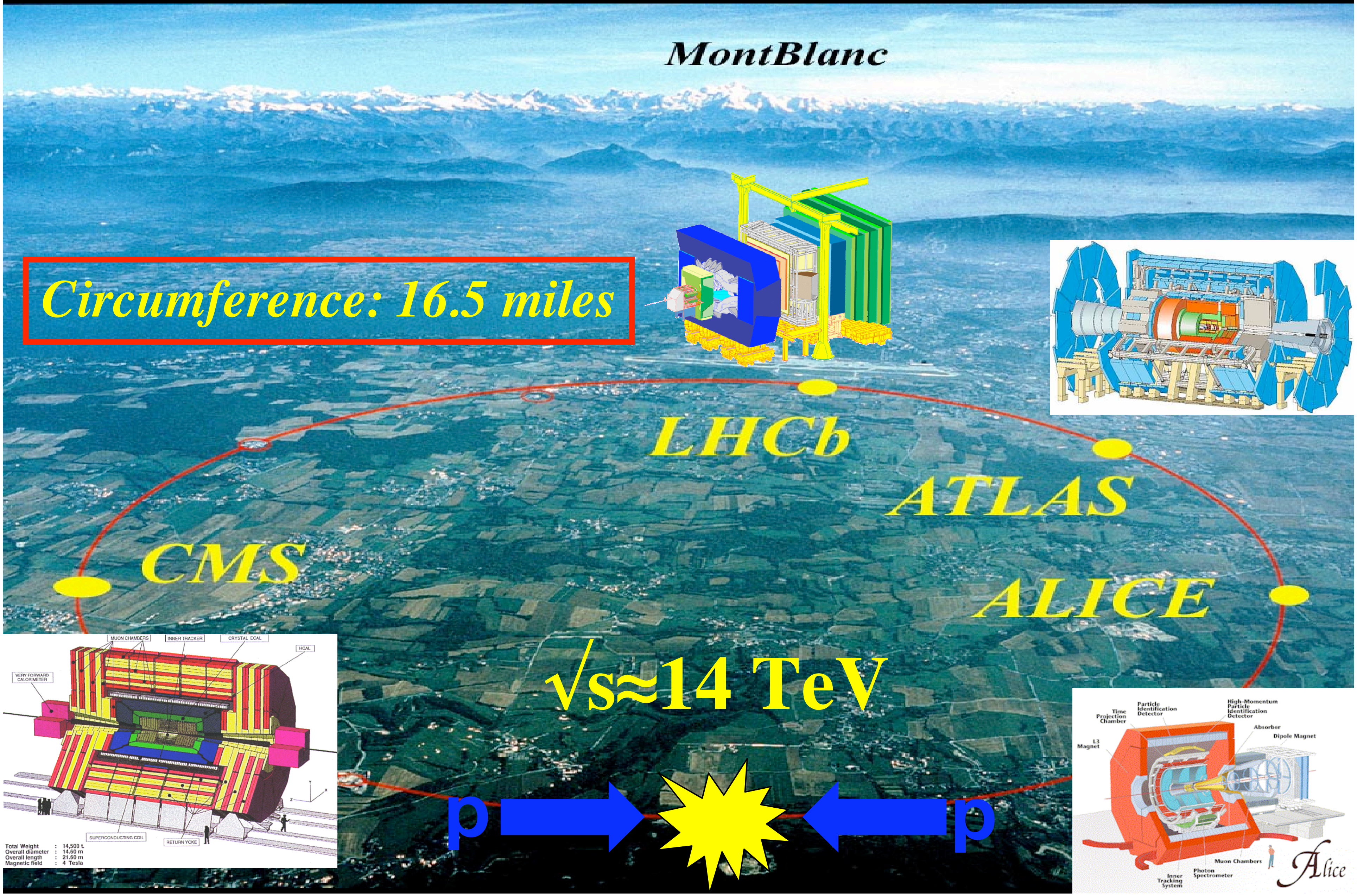
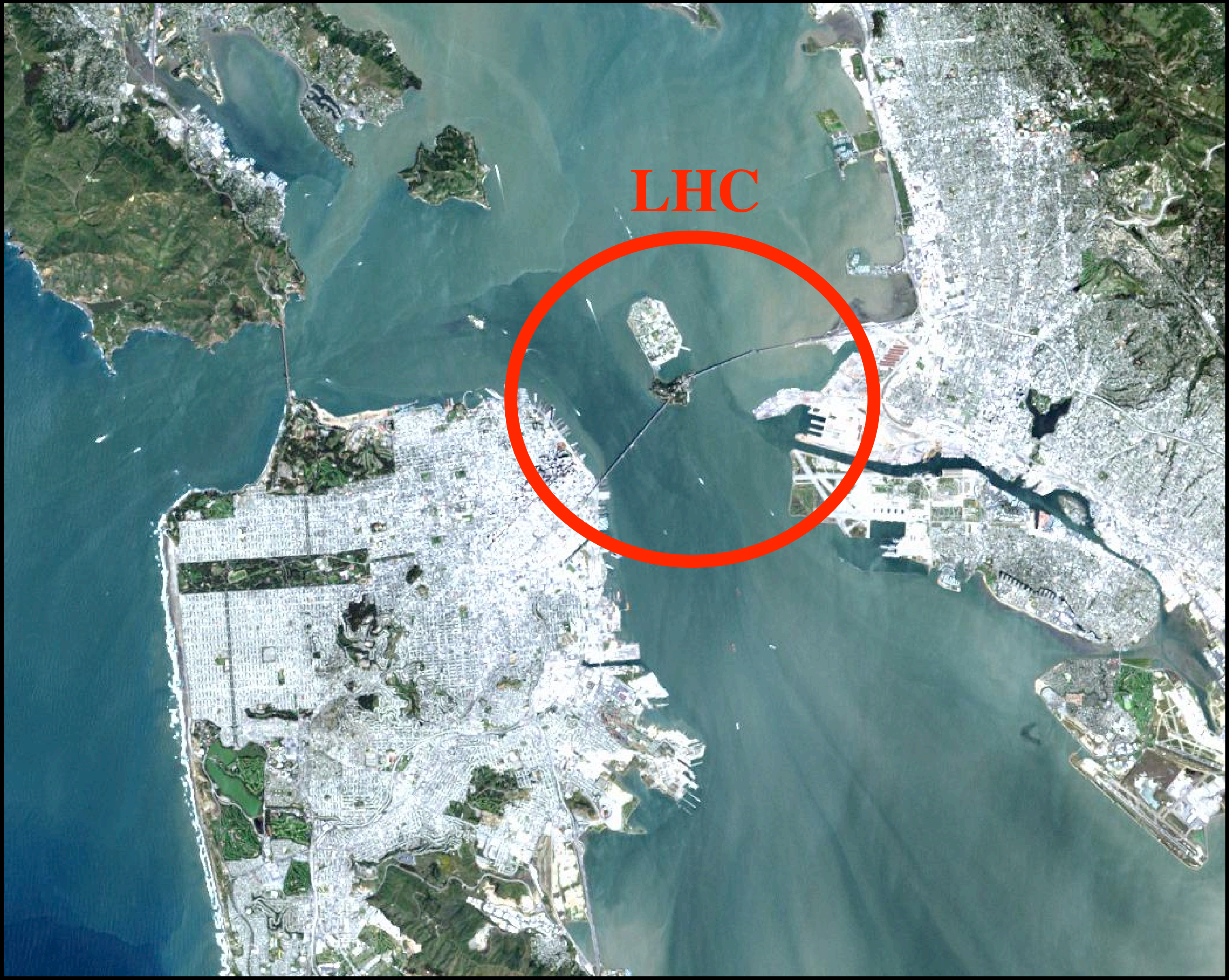
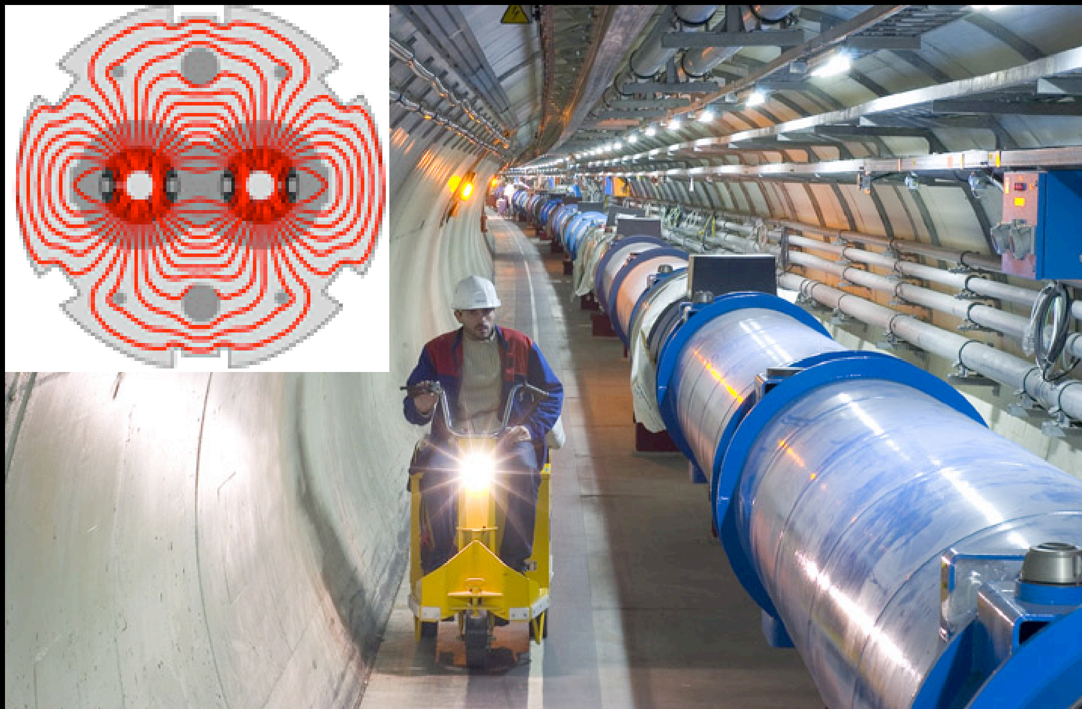
The Large Hadron Collider (LHC)



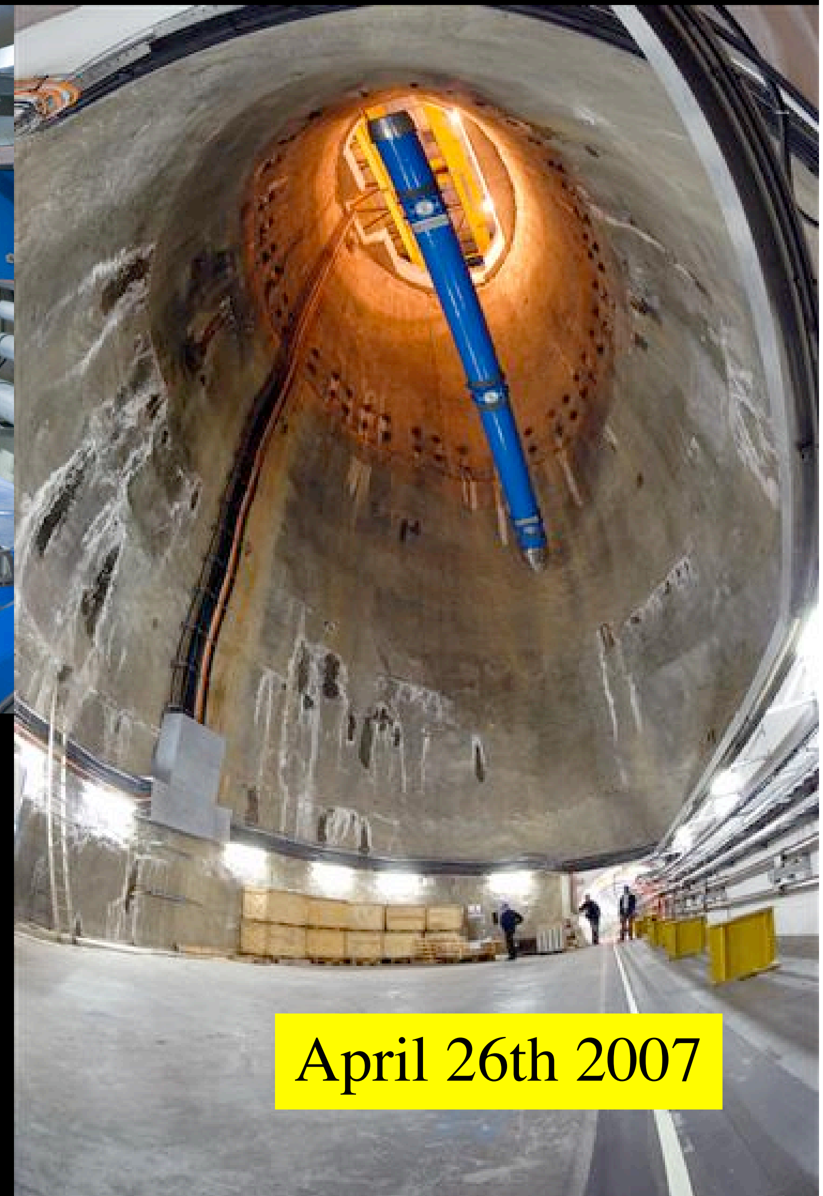
LHC in the Bay



LHC Accelerator



- 30,000 tons of 8.4T dipole magnets
- Cooled to 1.9K with 90 tons of liquid helium
- Energy of beam = 362 MJ
  - Kinetic energy of 15 ton truck at 500 mph



Luminosity

- Single most important quantity
  - Drives our ability to detect new processes

$$L = \frac{f_{rev}\, n_{bunch}\, N_p^{\,2}}{A}$$

revolving frequency: f_{rev}=11254/s
#bunches: n_{bunch}=2835
#protons / bunch: $N_p = 10^{11}$
Area of beams: A~40 μm

  - Rate of physics processes per unit time directly related:

$$N_{obs} = \int L dt \cdot \varepsilon \cdot \sigma$$

Cross section σ: Given by Nature (theorists)

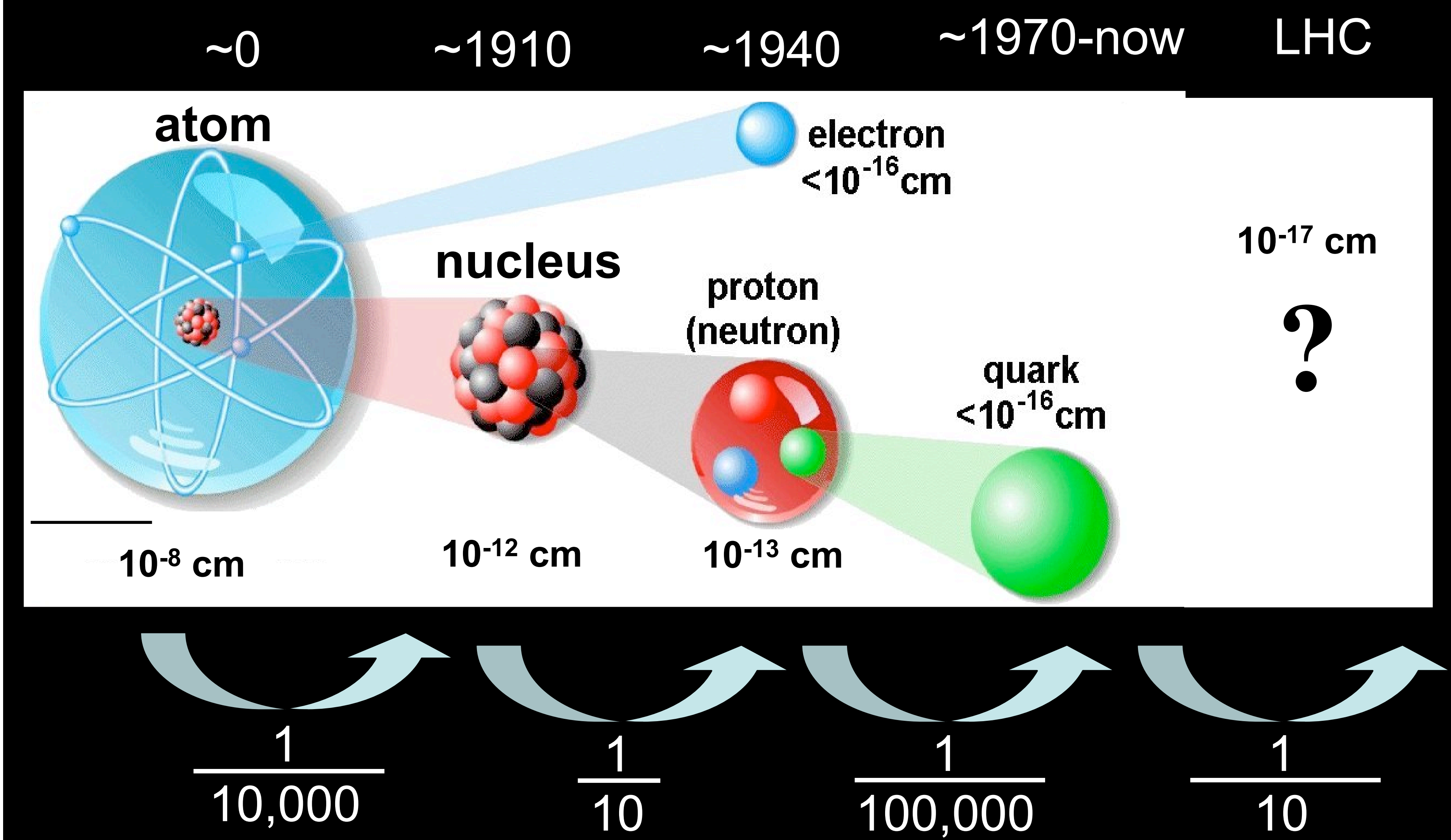
Efficiency: optimized by experimentalist

Ability to find something depends on N_{obs}

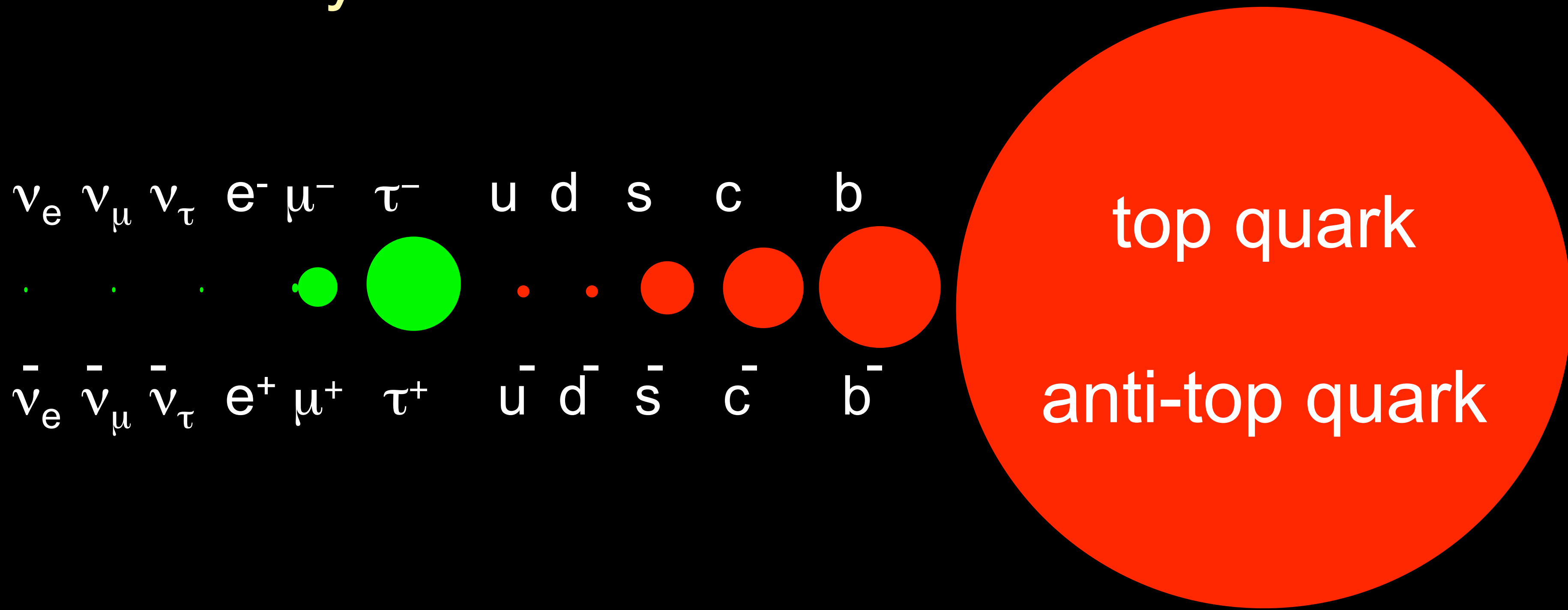
What Do We Hope to find at LHC?

- Answers to very fundamental and simple questions:
  - Why do electrons have mass?
    - Possible answer: The Higgs boson
  - Why is gravity so weak?
    - Possible answer: supersymmetric particles
- NB: This planet (and we!) would not exist if it was otherwise

We learned a lot in the last century



Elementary Particles: Matter



(Mass proportional to area shown but all sizes still < 10^{-19} m)

Why are there so many leptons and quarks?
And, why do they all have different masses?

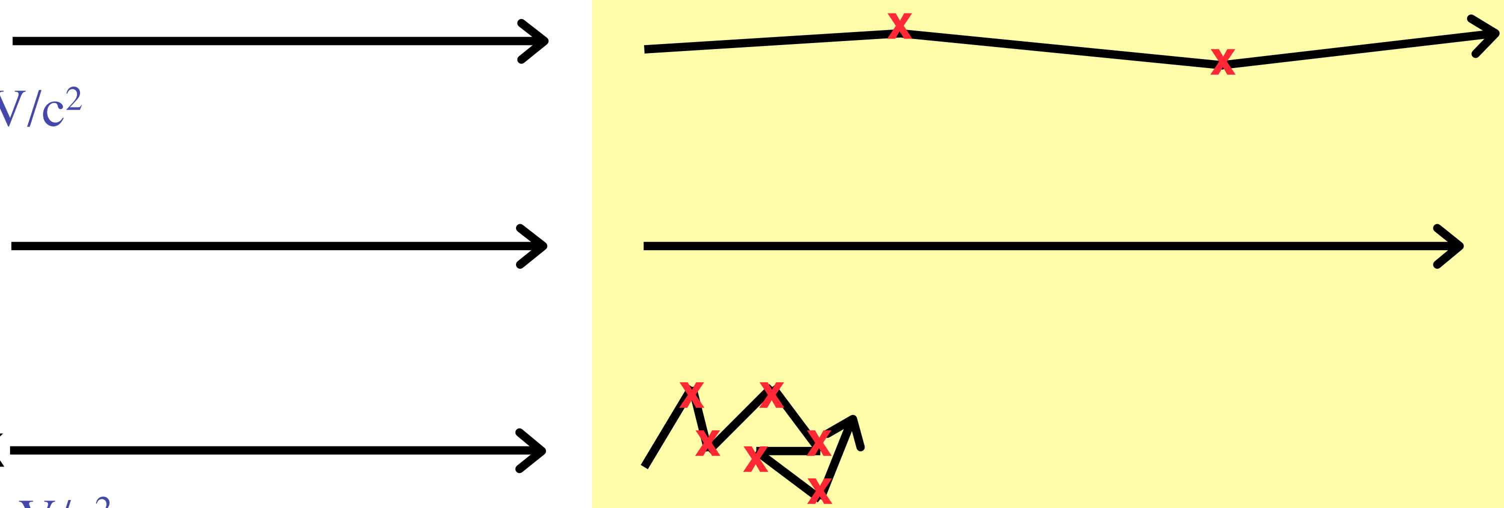
Origin of Mass

Nothing in the universe	Something in the universe

Electron
$m=5.11\ 10^5\ eV/c^2$

Photon
$m=0$

Top Quark
$m=1.72\ 10^{11}\ eV/c^2$

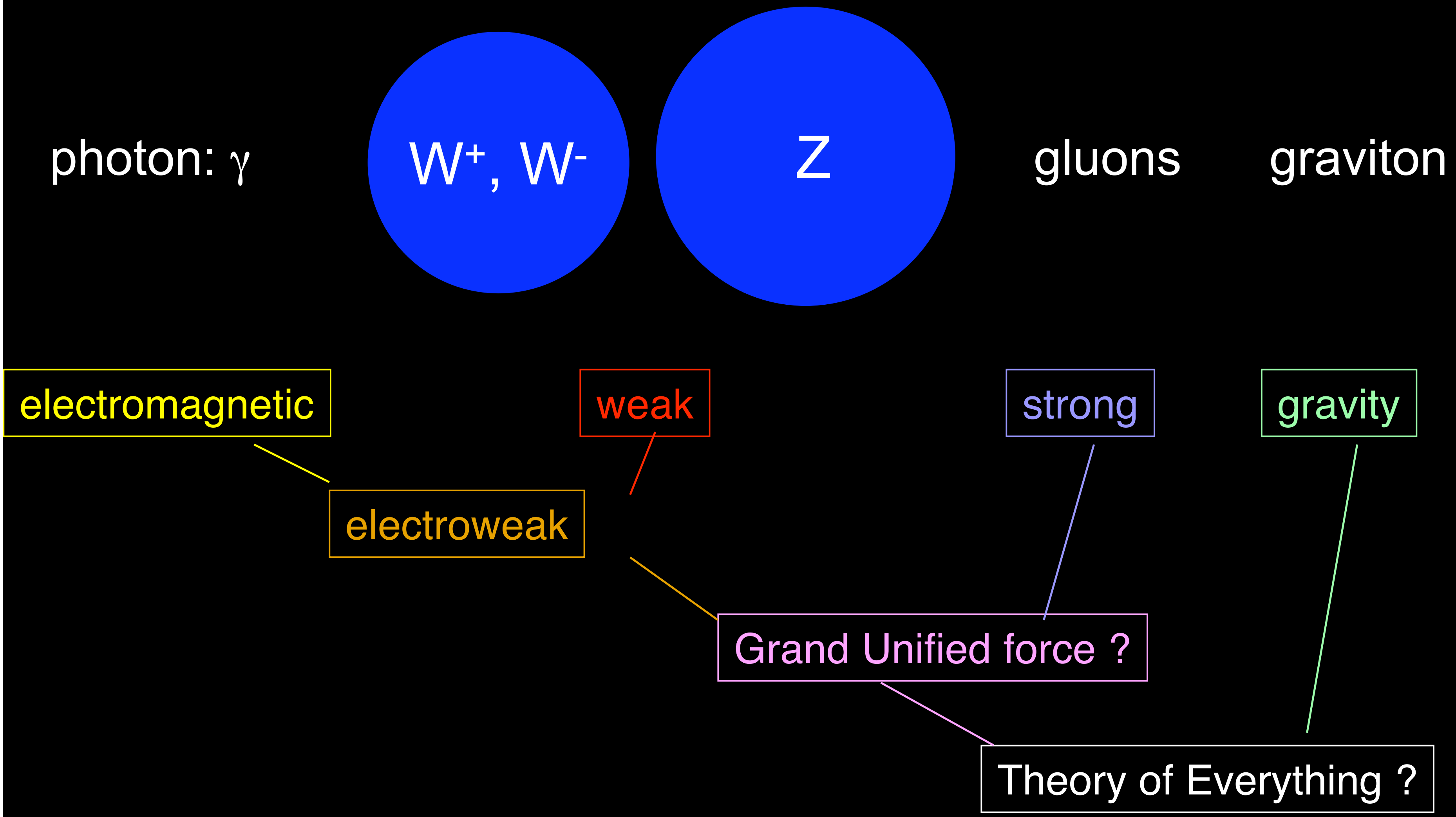


Higgs Particles interact with other particles the stronger the heavier they are:

- distance ~10^{-17} cm => will be found at LHC!

Why is Gravity so weak compared to the other forces?

Elementary Particles: Force Carriers

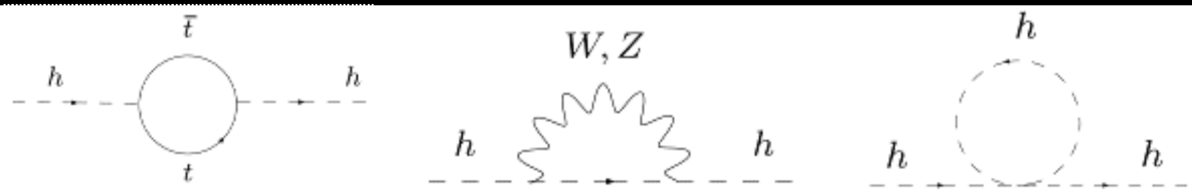


The "finetuning problem"

- Why is gravity is so much weaker than the weak force?
  - Newton: G_N=6.67 x 10^{-11} m^3kg/s^2 ~10^{-38} GeV^{-2}
  - Fermi: G_F=1.17 x 10^{-5} GeV^{-2}
- Or why is the W boson mass so small?
  - Weak scale: M_W ~$1/M_{weak}=1/\sqrt{G_F}$ = $3x10^2$ GeV
  - Natural scale: $M_{Planck}=1/\sqrt{G_N}$~10^{19} GeV

⇒"Finetuning" required to make W boson mass small

Finetuning Problem

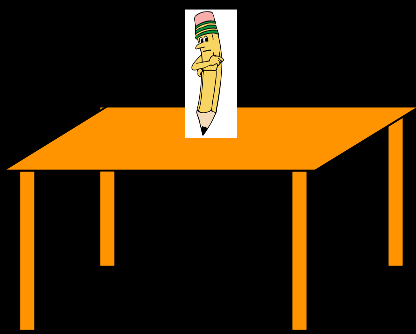


$$m^2_H \approx (200\ \mathrm{GeV})^2 = m^2_H{}^{tree} + \delta\, m^2_H{}^{top} + \delta\, m^2_H{}^{gauge} + \delta\, m^2_H{}^{higgs}$$

- Free parameter $m^2_H{}^{tree}$ “finetuned” to cancel huge corrections dm so that

  200 GeV=1000000000000000200 GeV-1000000000000000000 GeV

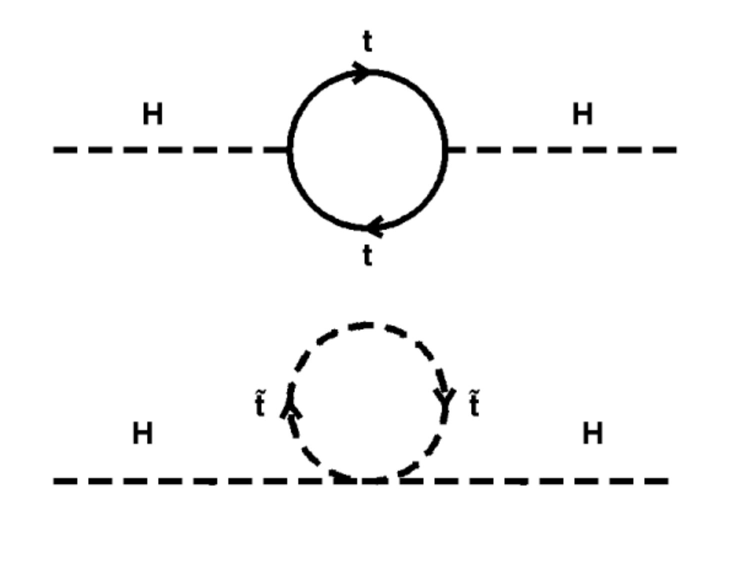
- Isn’t that Crazy!?!
  - Some unknown ad-hoc parameter introduced with superb precision
    - We were very lucky it worked out like this!
  - Like finding a pen on a table like this



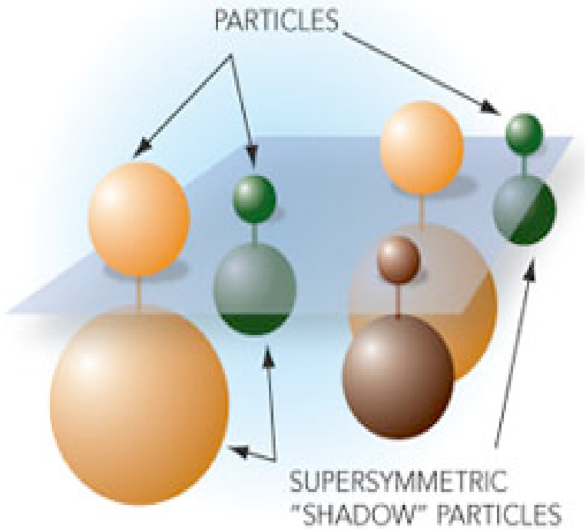
Seems wrong somehow

Solving the finetuning problem

- Add new particles
  - New loops cancel old loops!
    - Size of loops naturally the same
  - No hugely tuned ad-hoc parameter needed
- "Supersymmetric" particles
  - Each standard model particle has a partner, e.g.:
    - Electron => Selectron
    - Quark => Squark
    - Photon => Photino
    - W boson => Wino



Superpartners!



Already happened in History!

- Might also seem crazy to have another set of particles introduced to solve aesthetic problem
- Analogy in electromagnetism:
  - Free electron has Coulomb field: $\Delta E_{\mathrm{Coulomb}} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_e}.$
  - Mass receives corrections due to Coulomb field:
    - $(m_e c^2)_{obs} = (m_e c^2)_{bare} + \Delta E_{\mathrm{Coulomb}}.$
    - With $r_e < 10^{-17}$ cm: $0.000511 = (-3.141082 + 3.141593)\ \mathrm{GeV}.$
  - Solution: the positron!

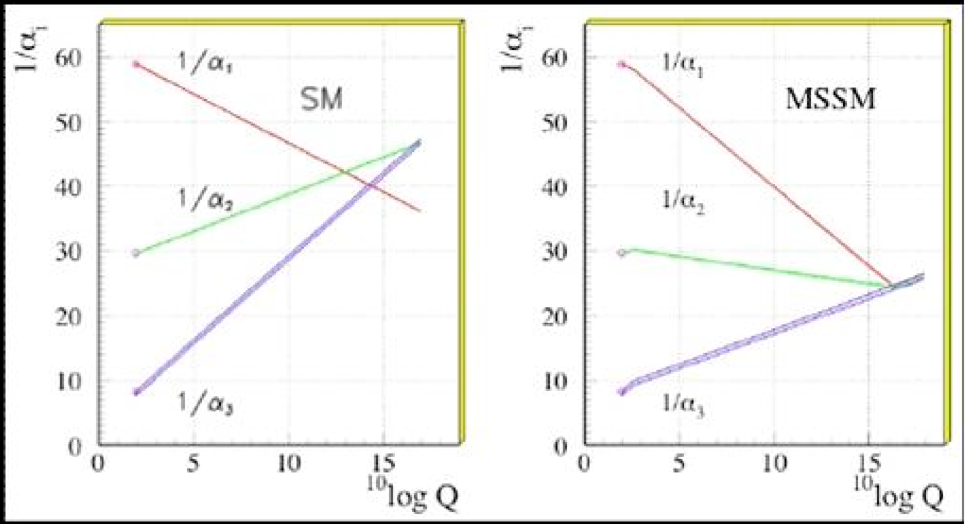
$$\Delta E = \Delta E_{\mathrm{Coulomb}} + \Delta E_{\mathrm{pair}} = \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e}\ .$$

<<1

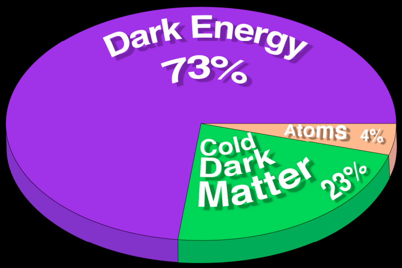
Problem was not as bad as today's but it resulted in new particle species: anti-particles

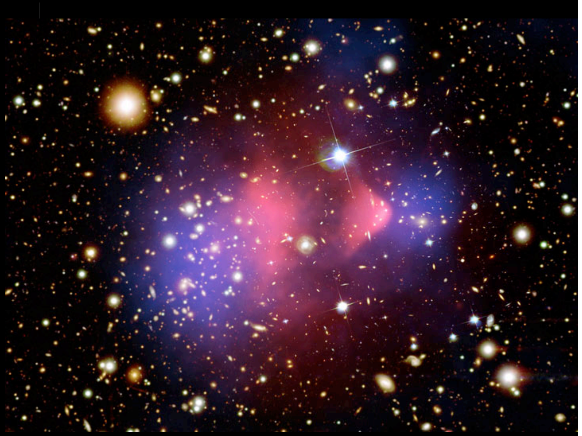
More virtues of Supersymmetry (SUSY)

- Electromagnetic, strong and weak force unify!
  - Miss unification in SM (barely)
  - Exactly unify in SUSY!



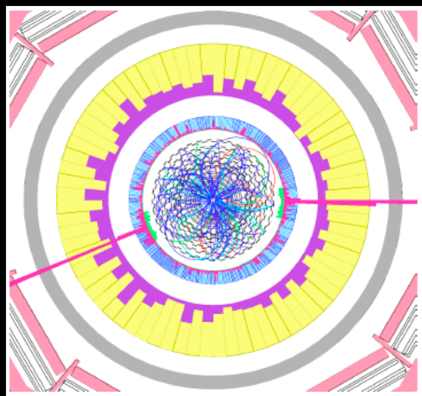
- Includes candidate for dark matter with 0.1-1 TeV mass
  - Cosmology data point to such a particle
  - May contribute most of the Dark Matter in Universe
    - 5 times more than ordinary matter



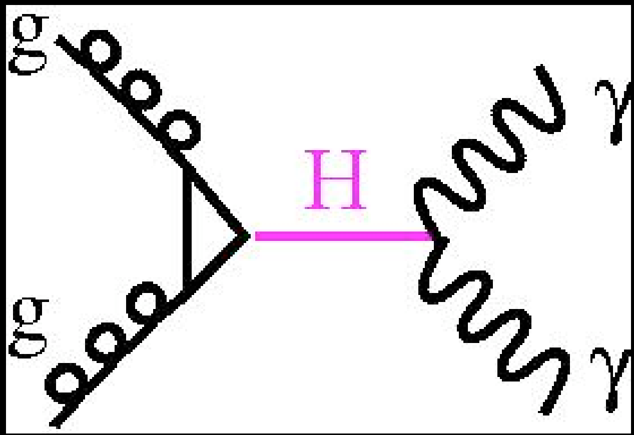


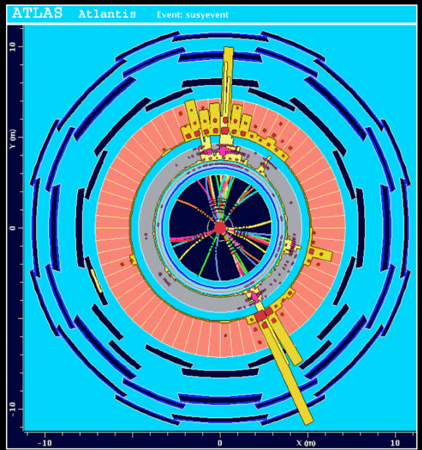
If SUSY particles are solution to hierarchy problem they will be found at the LHC

The Experimental Challenge

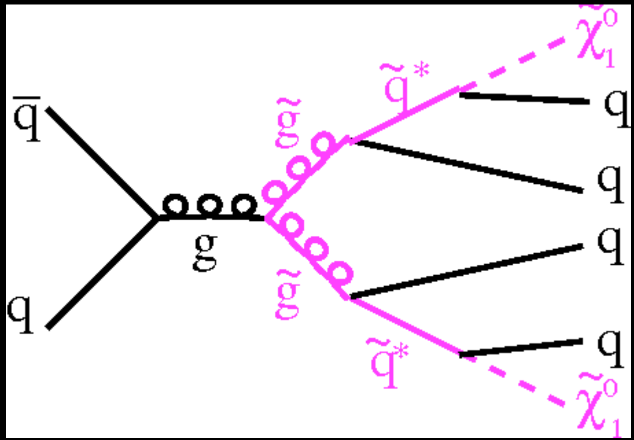


Higgs





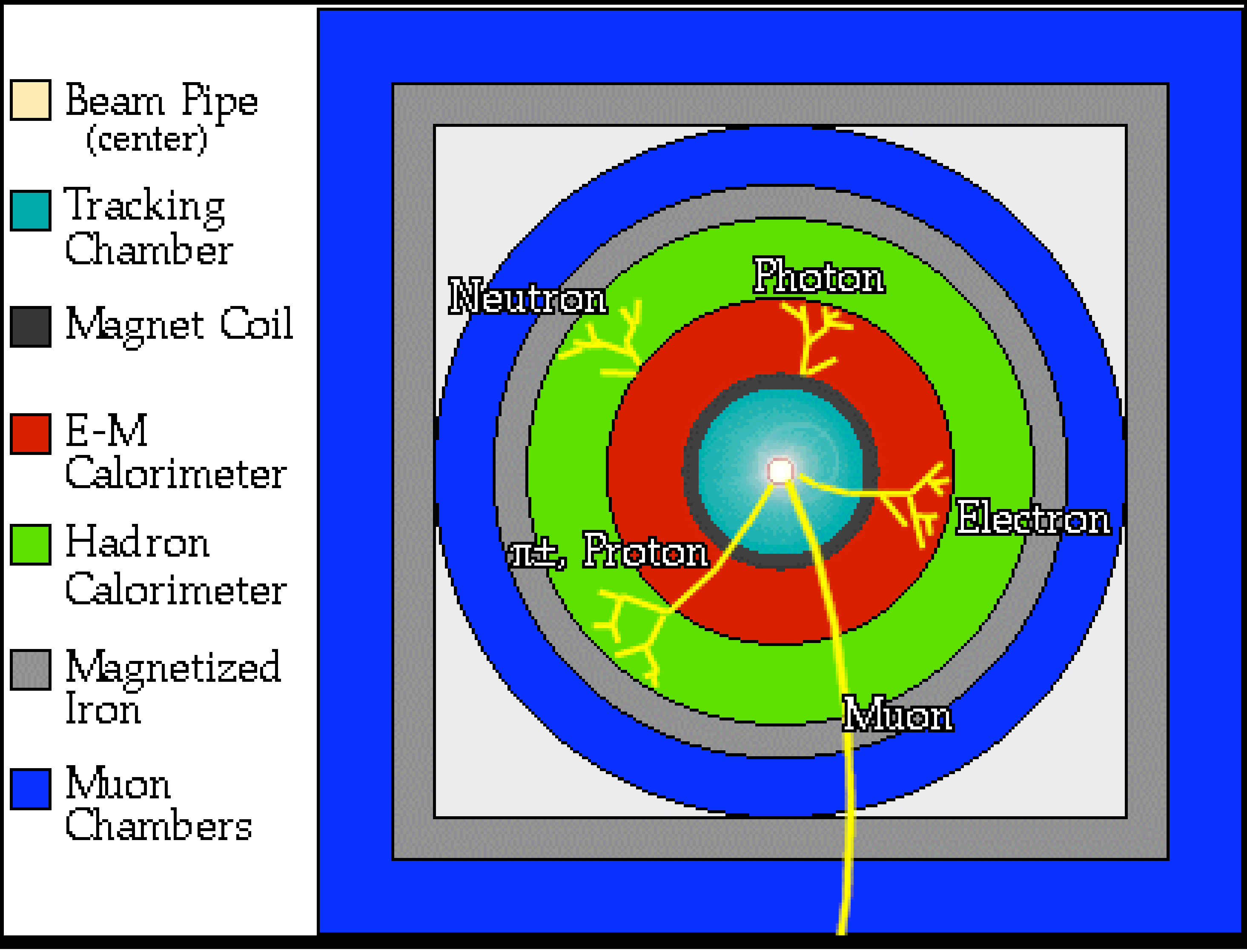
Supersymmetry



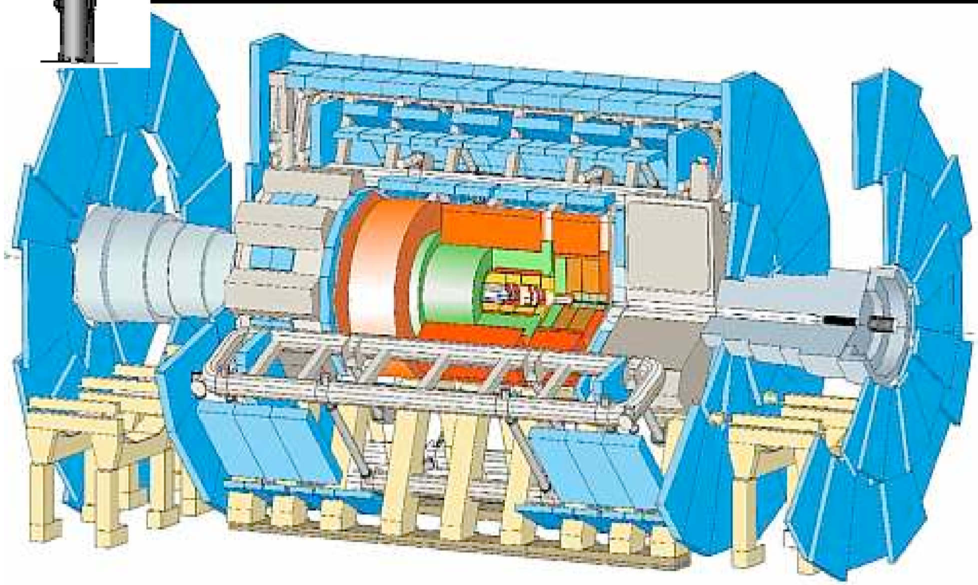
- Measured hits in detector
- => use hits to reconstruct particle paths and energies
- => estimate background processes
- => understand the underlying physics

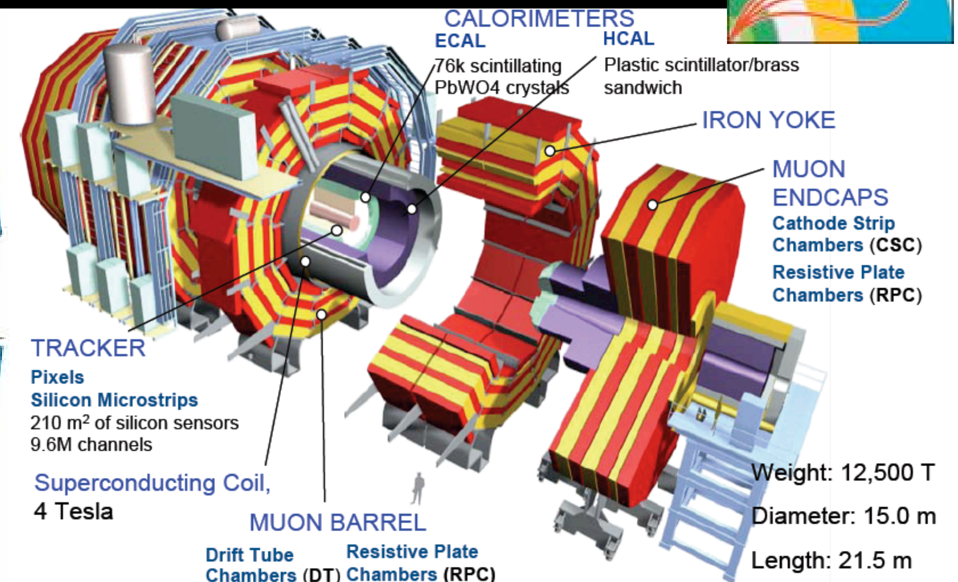
Particle Identification

- Detector designed to separate electrons, photons, muons, neutral and charged hadrons



ATLAS and CMS Detectors





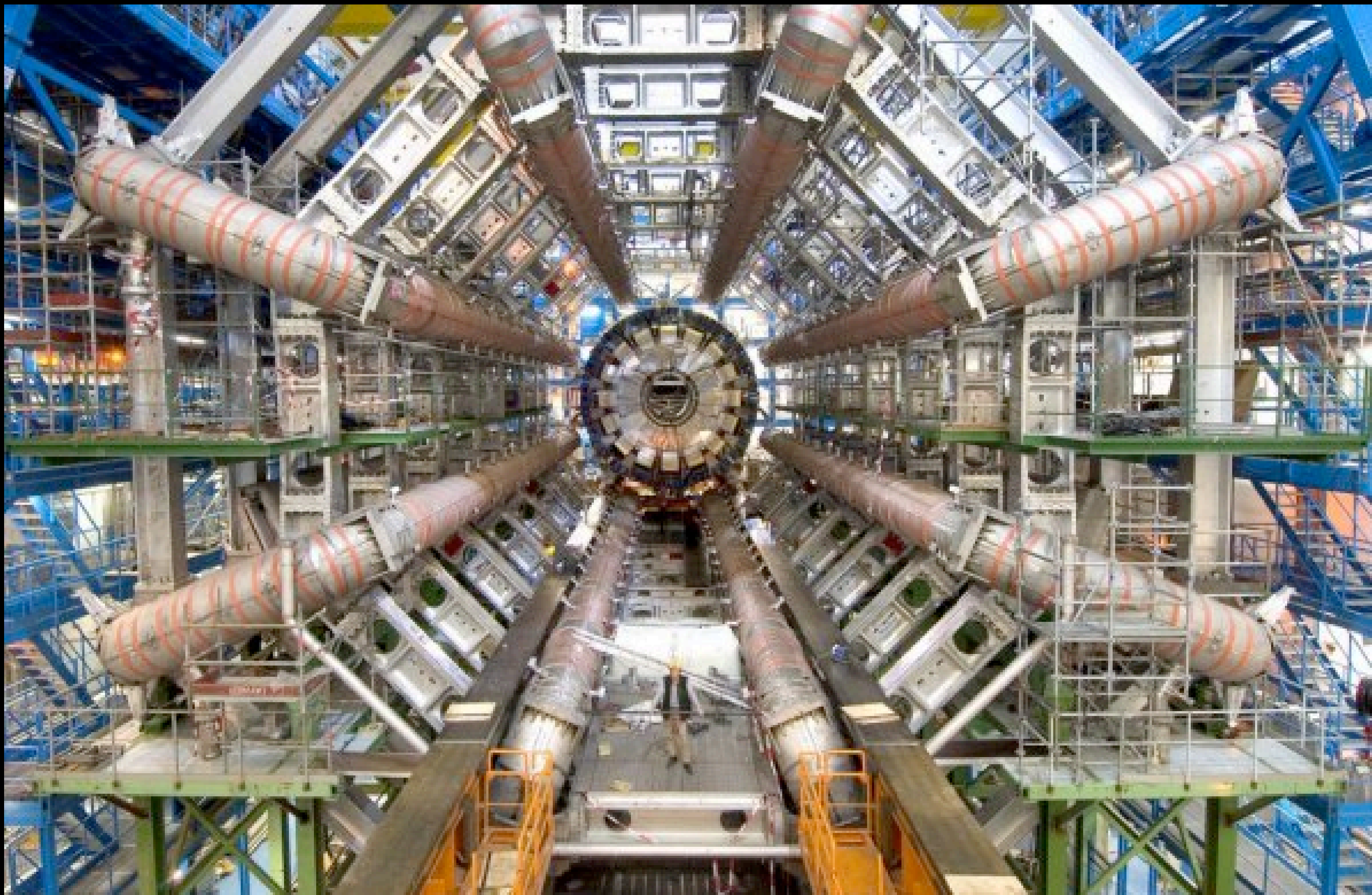
	Weight (tons)	Length (m)	Height (m)
ATLAS	7,000	42	22
CMS	12,500	21	15

ATLAS and CMS in Berlin

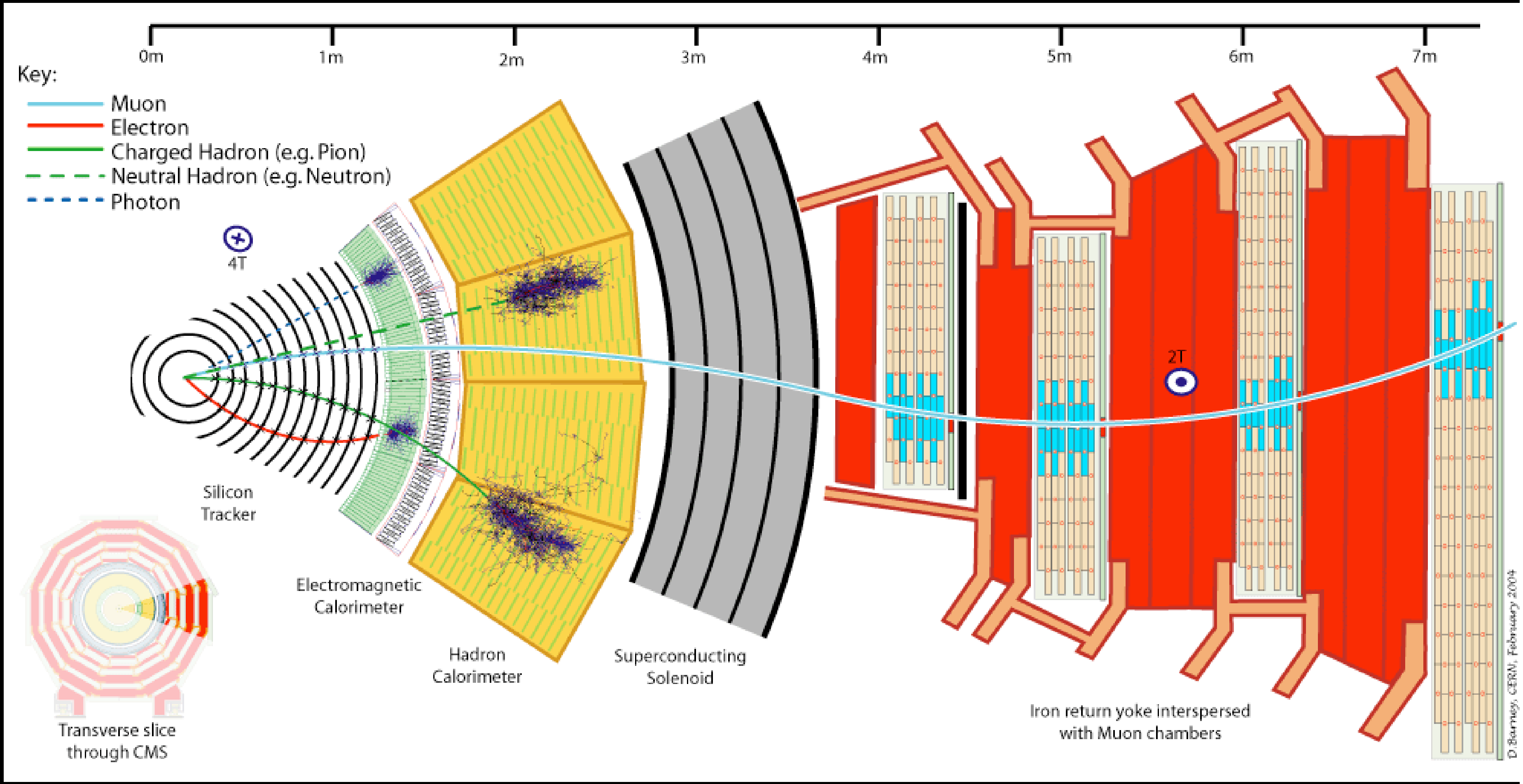
Detector Mass in Perspective

CMS is 30% heavier than the Eiffel tower

ATLAS Detector in Construction (2005)



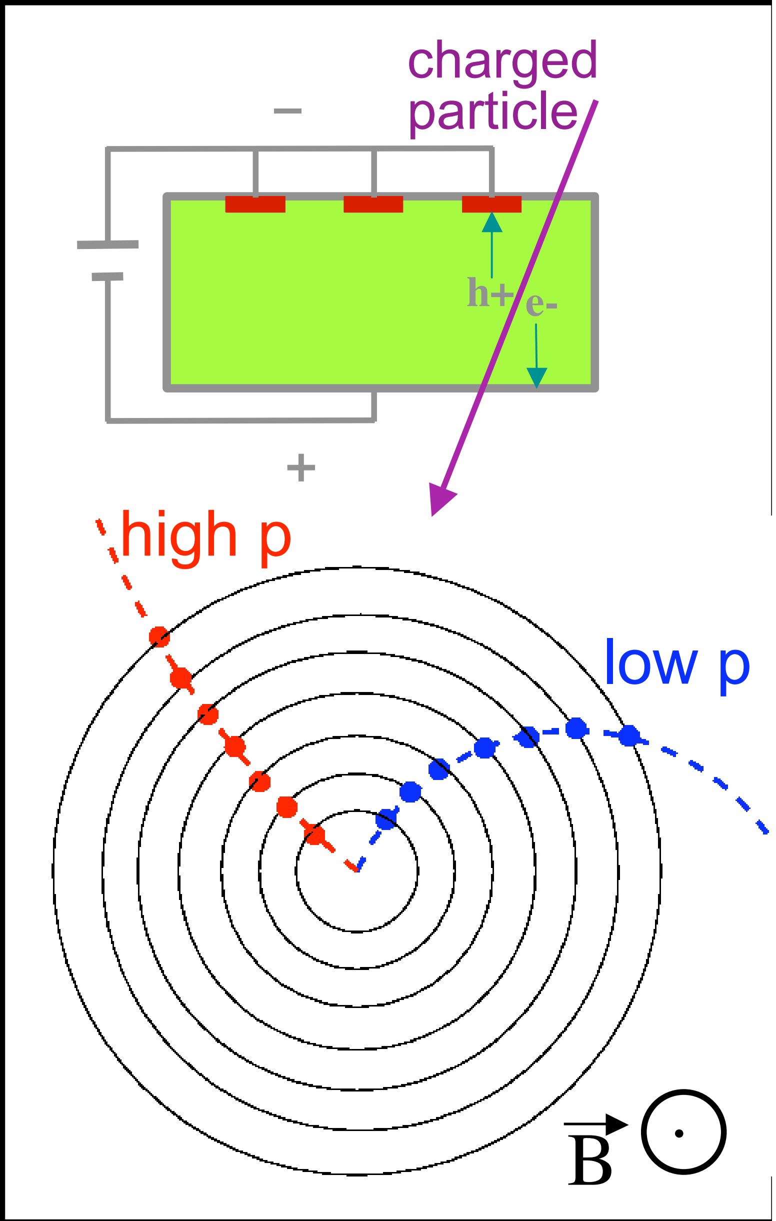
Detailed Layout



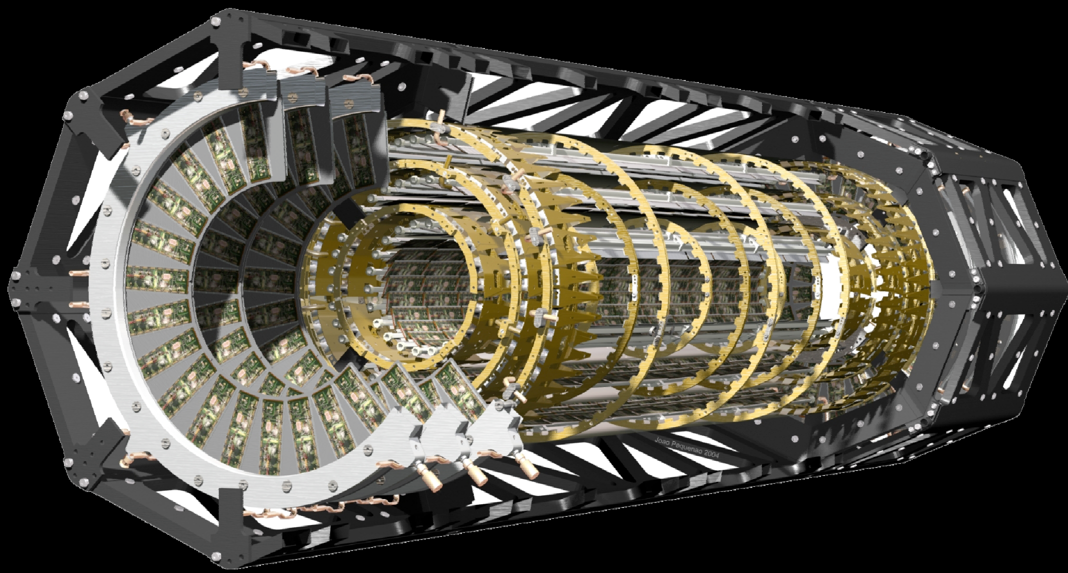
- About 100 million separate readout channels
  - 3000 km of cables

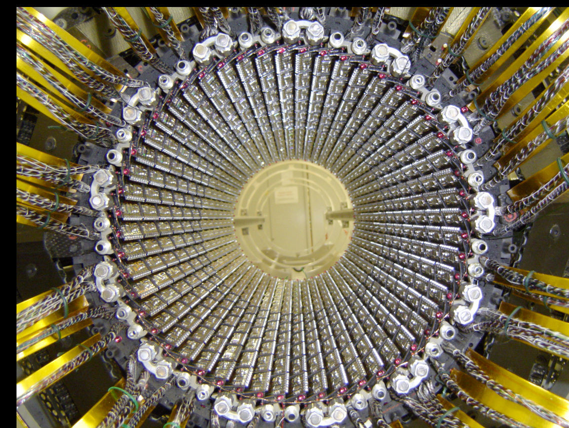
Silicon Tracking Detectors

- Charged particle traverses silicon sensor (semi-conductor)
  - Sets free charge carriers
    - Drift to electrodes
    - Measured charge gets collected at electrodes
  - Thus we find out position of particle
    - Resolution typically 15 μm
- Detector placed inside magnetic field:
  - Lorentz force: $\mathbf{F}_L \sim q\, \mathbf{v} \times \mathbf{B}$
- Hits along trajectory are fit to form a track
  - deviation from straight line proportional to momentum (**p~v**)
  - Direction of curvature tells us the electric charge



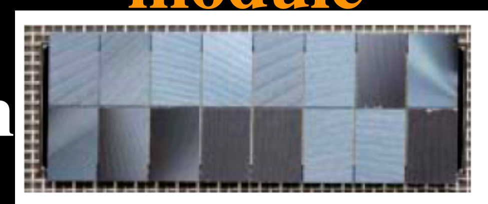
The ATLAS Pixel Detector

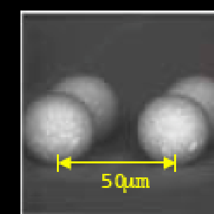




module

2 cm

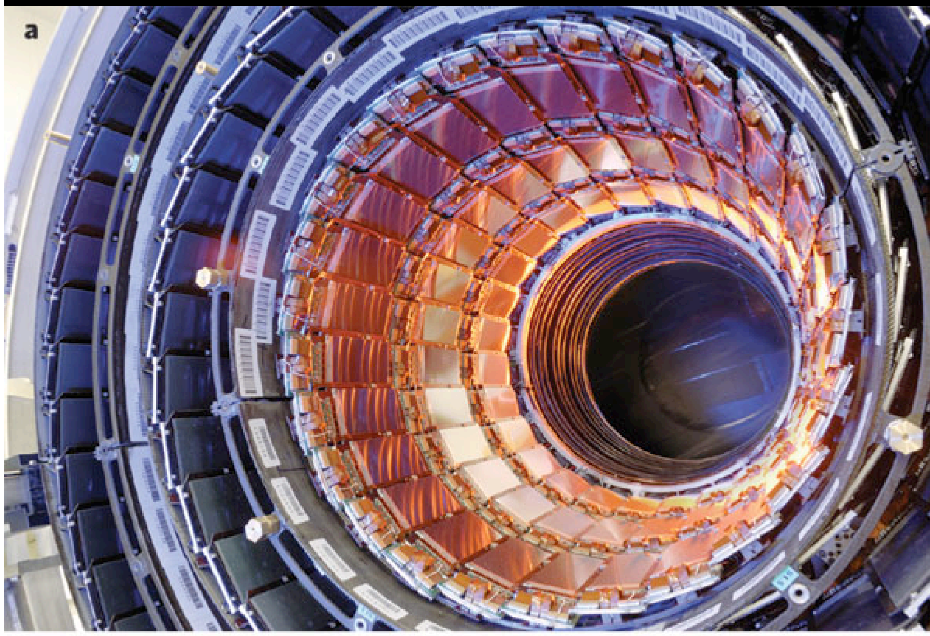


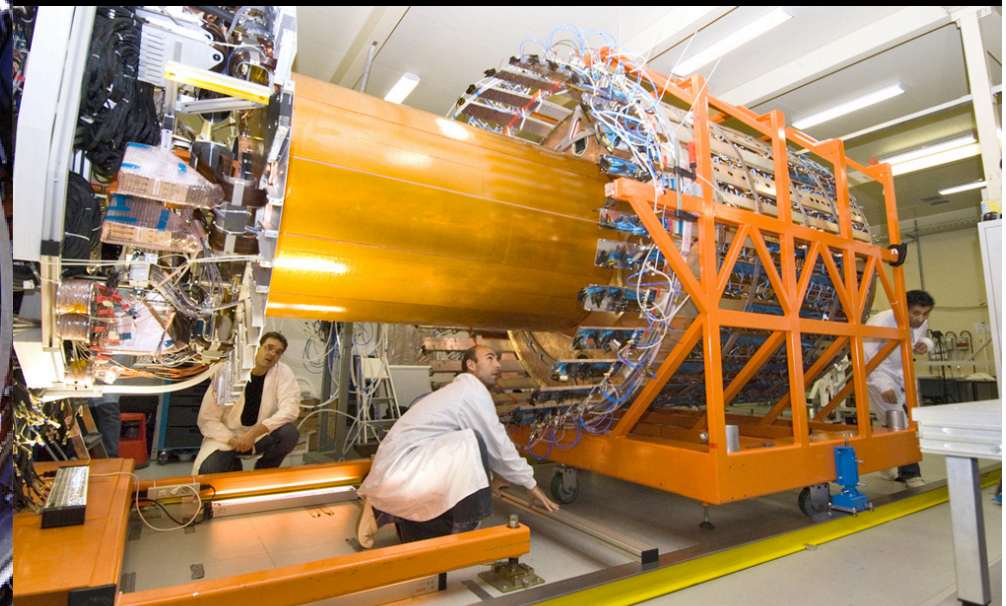


6 cm

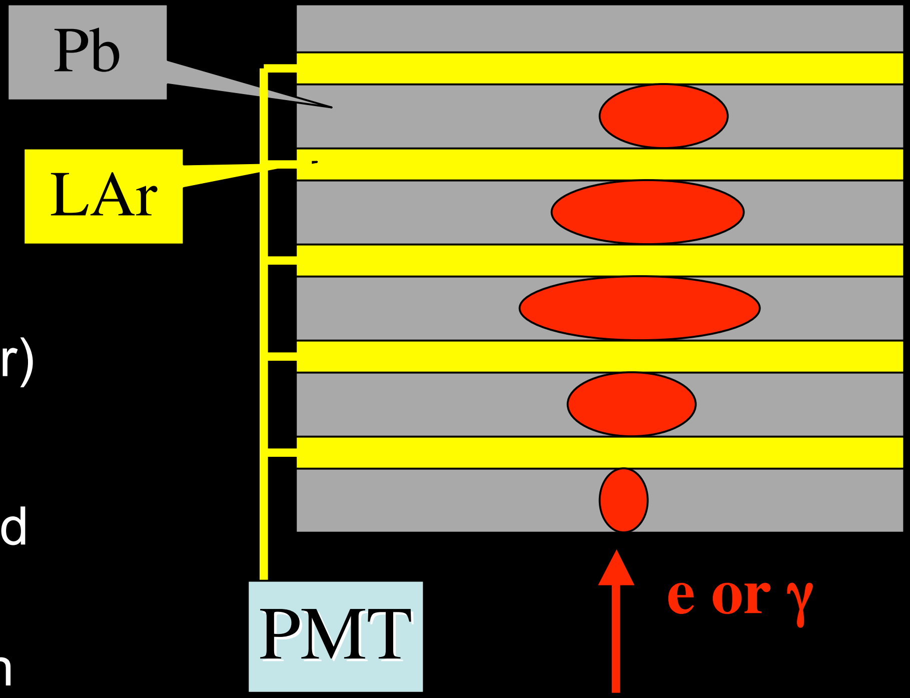
- Cylinder: L=1.4 m , R=12.25 cm
- 80,000,000 individual pixels arranged in modules:
  - 16 chips per module, 2880 pixels per chip => 46080 pixels/module
  - Distance between pixels: 50 µm (“pitch”)
- Designed and built mostly in the United States (Berkeley)

Tracking Detectors

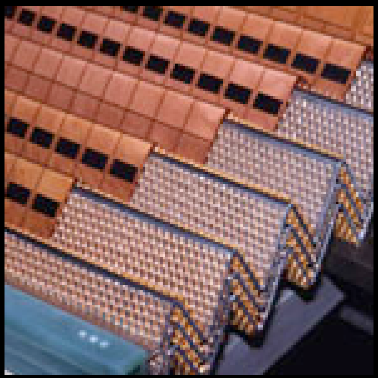




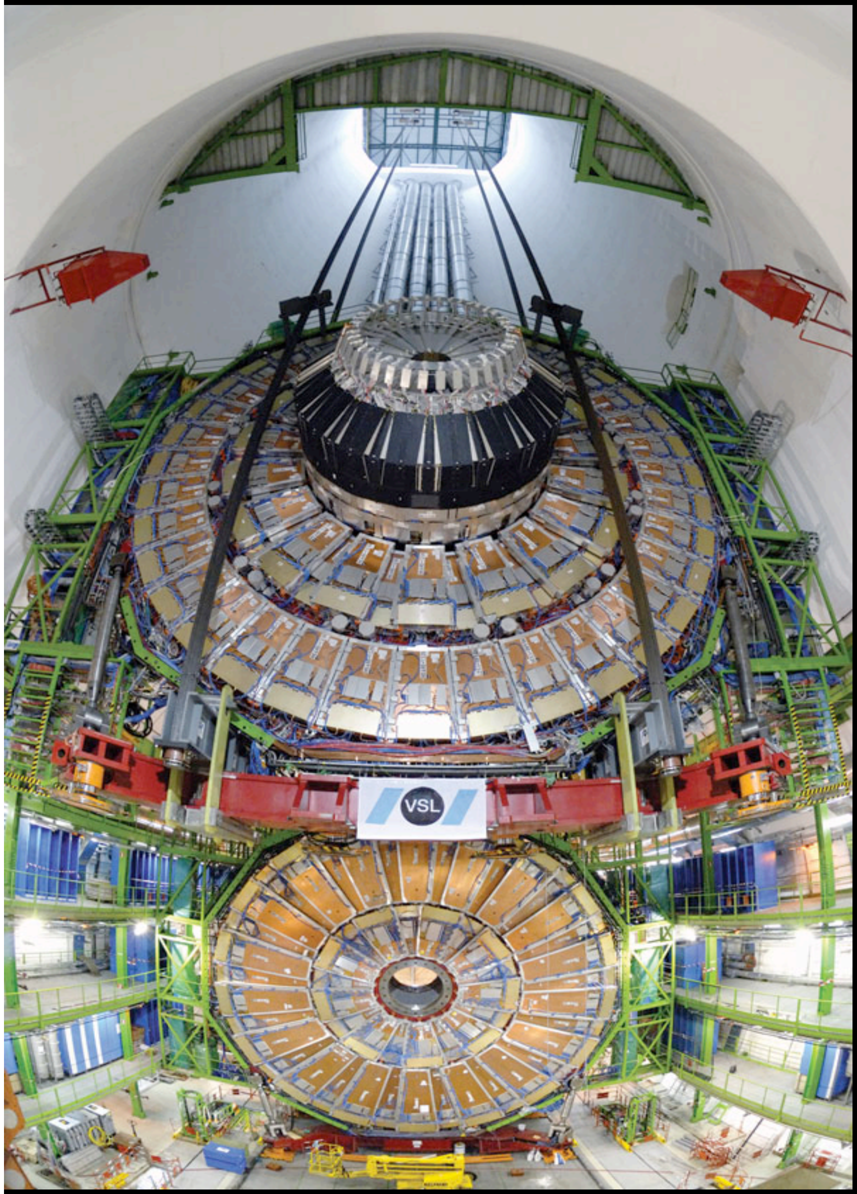
Electromagnetic Calorimeter

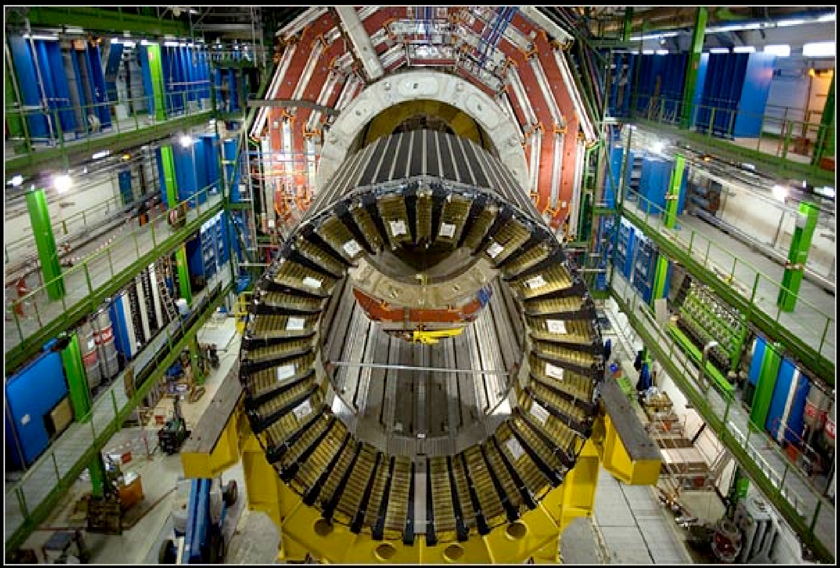


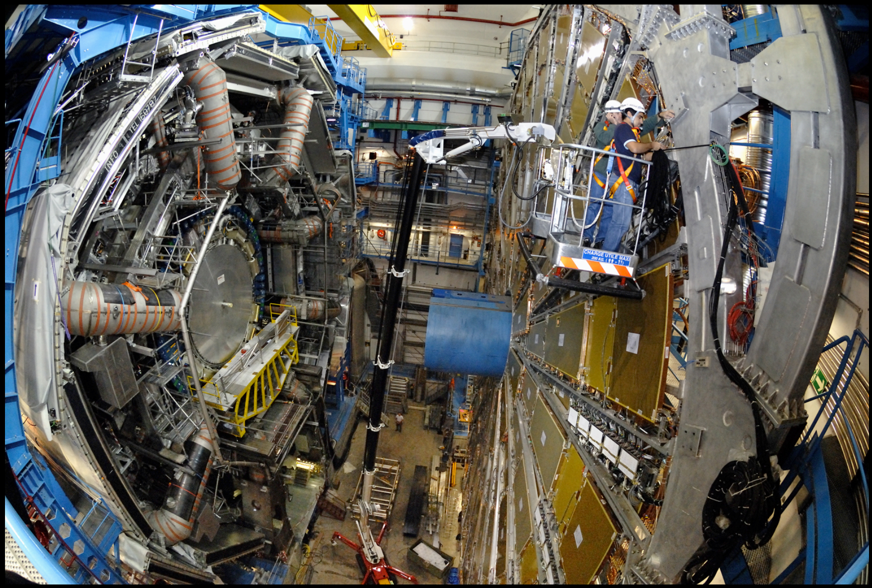
- Sandwich structure:
  - Absorber material: lead (Pb)
  - Active material: Liquid Argon (LAr)
- Energy measurement:
  - Electromagnetic shower produced through interactions with lead
  - Photons collected in Liquid Argon
  - N(photons)$\propto$ energy of particle
  - Photomultiplier tube (“PMT”)
    - Amplification of signal => readout
- Position measurement:
  - High spatial granularity => position known



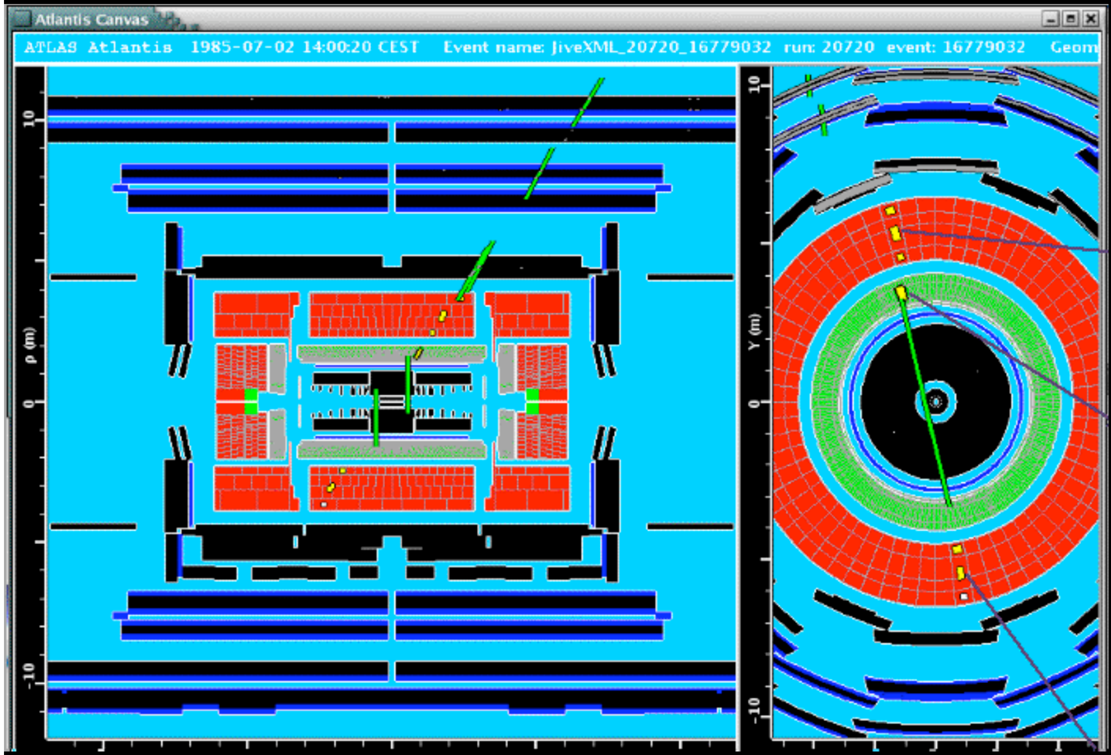
Muon Systems and Calorimeters

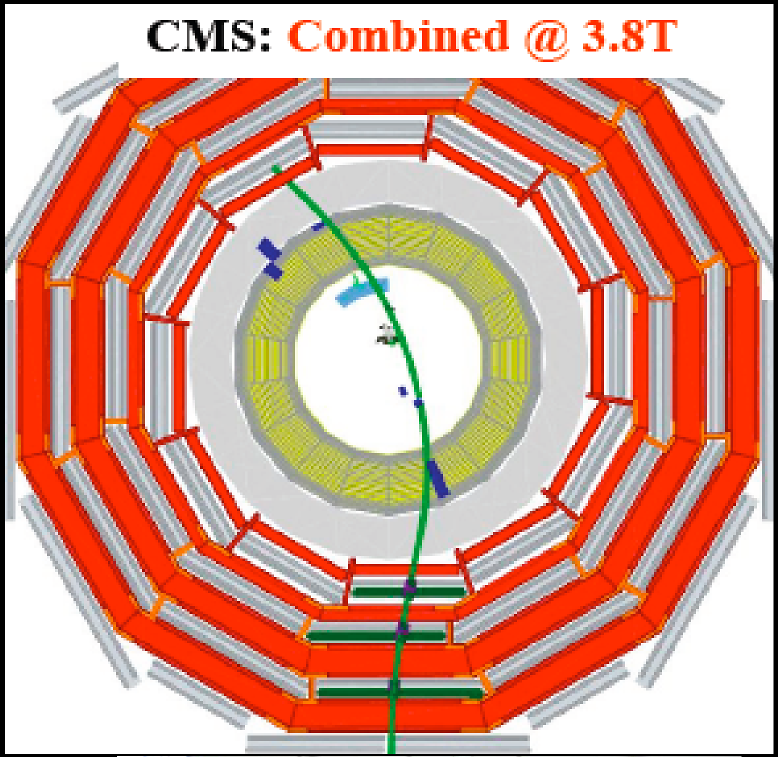






Cosmic Muon Data





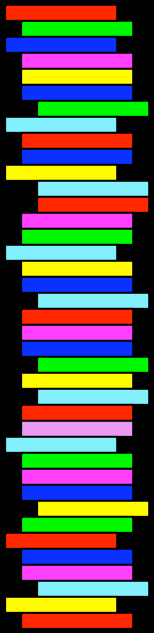
Experiments are currently preparing for LHC data taking - analysis of cosmic muon data

2000 Physicists from all over the World

(including 400 PhD students)
+ many technician and engineers

Enormous Data Volumes

- **Pushing the computing limits!**
  - 1 second of LHC data: 1000 GigaBytes
    - **10,000 sets of the Encyclopedia Britannica**
  - 1 year of of LHC data: 10,000,000 GB
    - **25 km tower of CD's (~2 x earth diameter)**
  - 10 years of LHC data:
    - **All the words spoken by humankind since its appearance on earth**

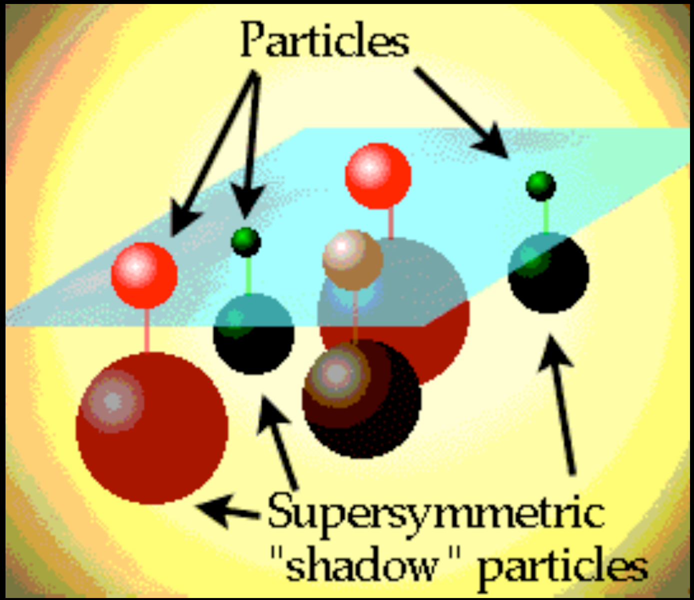


- **Solution: the "Grid"**
  - Global distribution of CPU power
    - More than 100 CPU farms worldwide share computing power

Some Example Analyses

Finding the Higgs boson:
-with photons
-with Z-bosons

Finding a Supersymmetric World



Rates of Processes

- Everything happens probabilistically

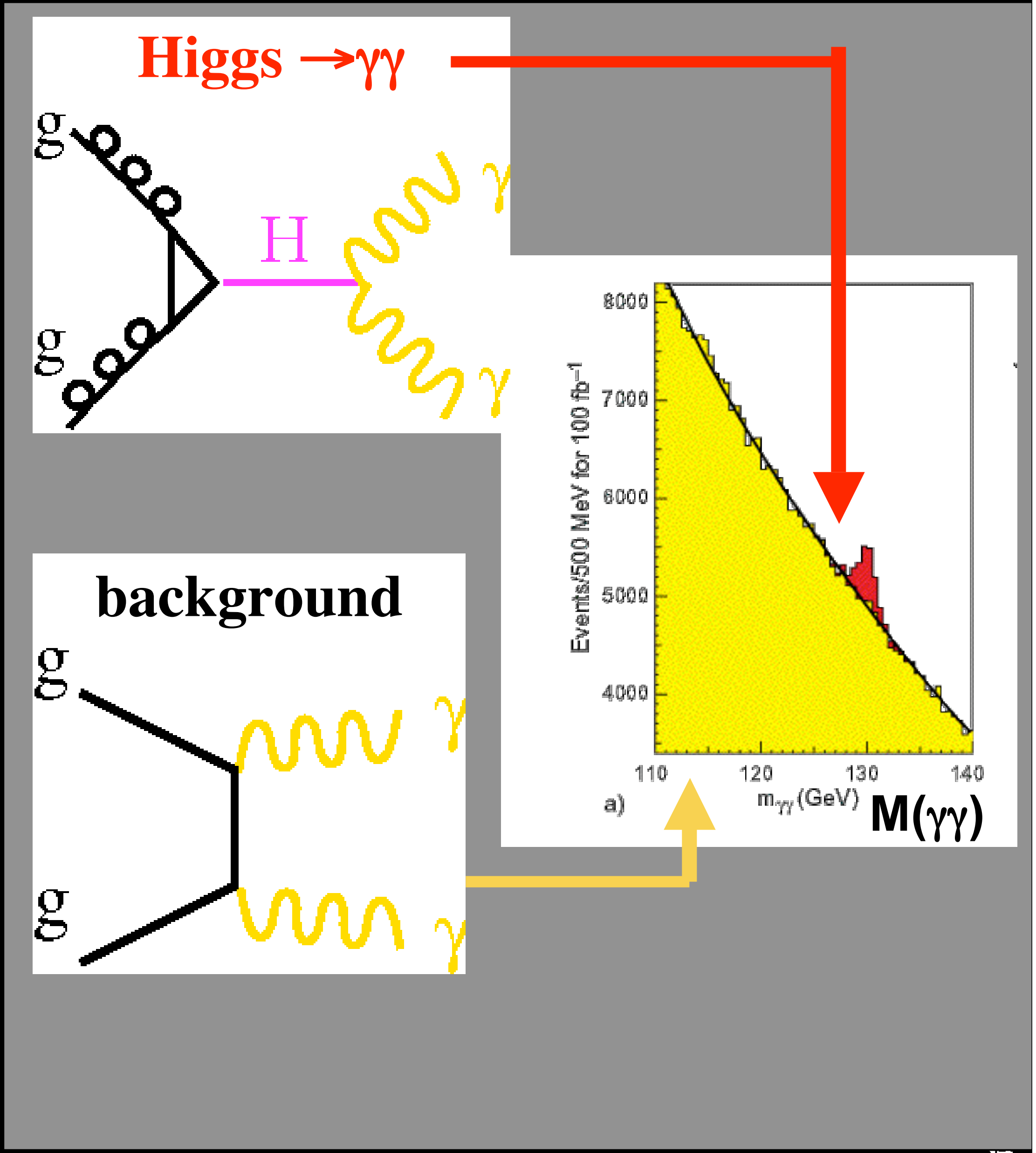
Process	Rate
any	600 million / sec
$W \rightarrow e\nu$	10 / sec
Top quark	1 / sec
SUSY	<1 / min
$H \rightarrow \gamma\gamma$	8 / day

- And competing “background processes” that can be large
  - Key experimental work is to suppress/reduce and understand them

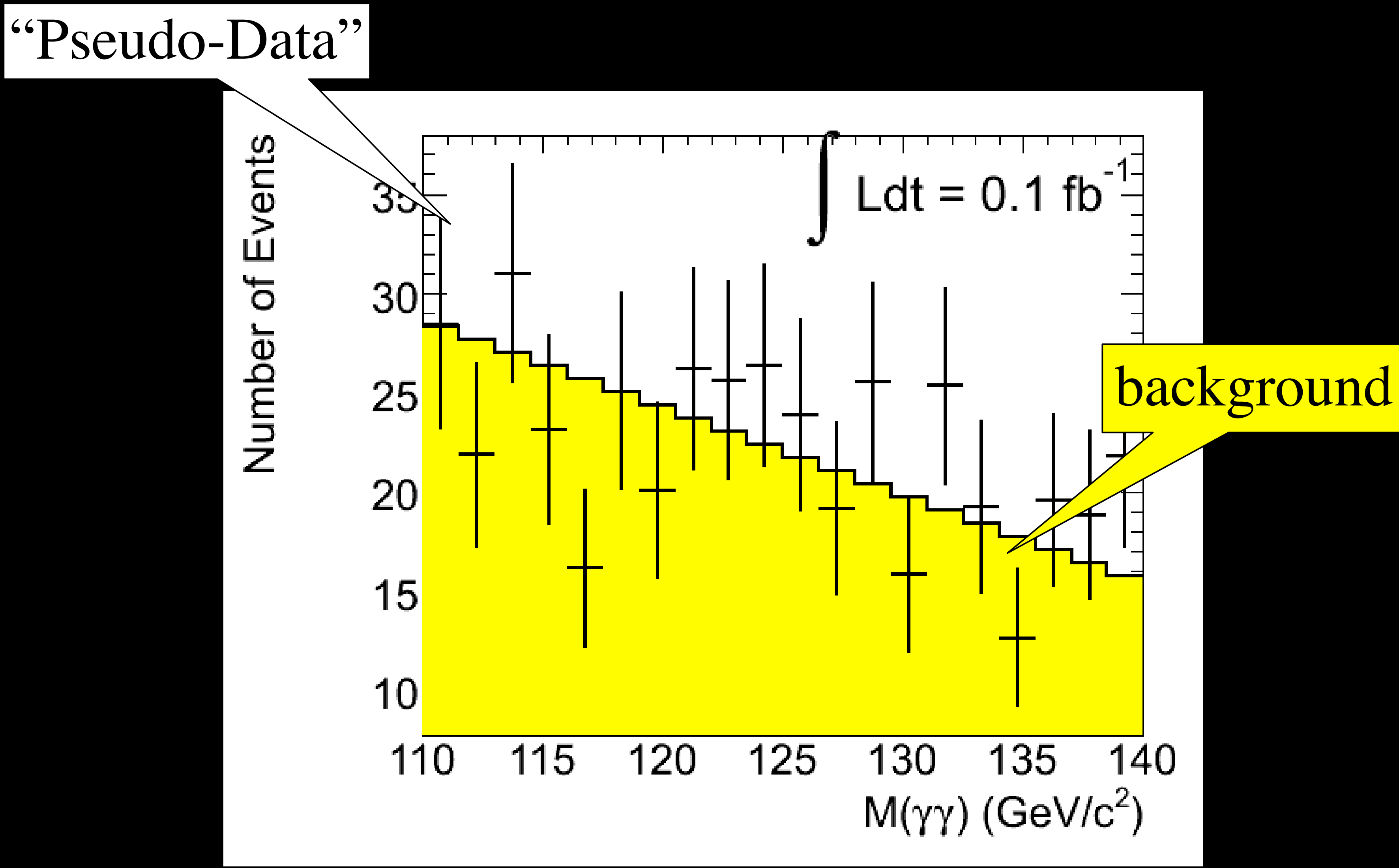
Finding the Higgs Boson (with photons)

- Find 2 high energy photons
  - If M(H)<130 GeV/c^2
- Separate signal from backgrounds
  - Backgrounds can look exactly the same
  - but for γ's from Higgs:

$$M(H)=M(\gamma\gamma)=\sqrt{[(E_1+E_2)^2-(p_1+p_2)^2]}$$

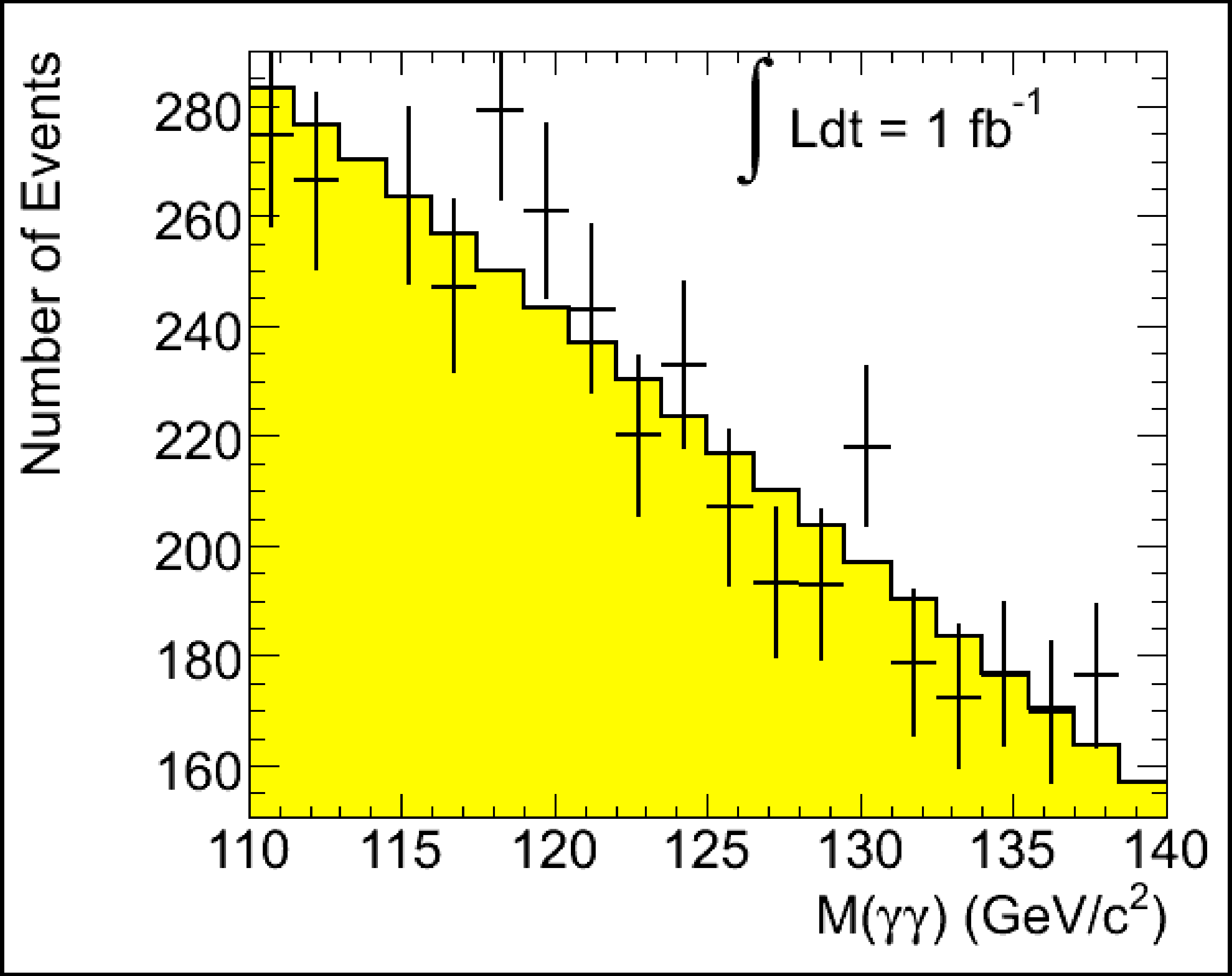


It will emerge with time



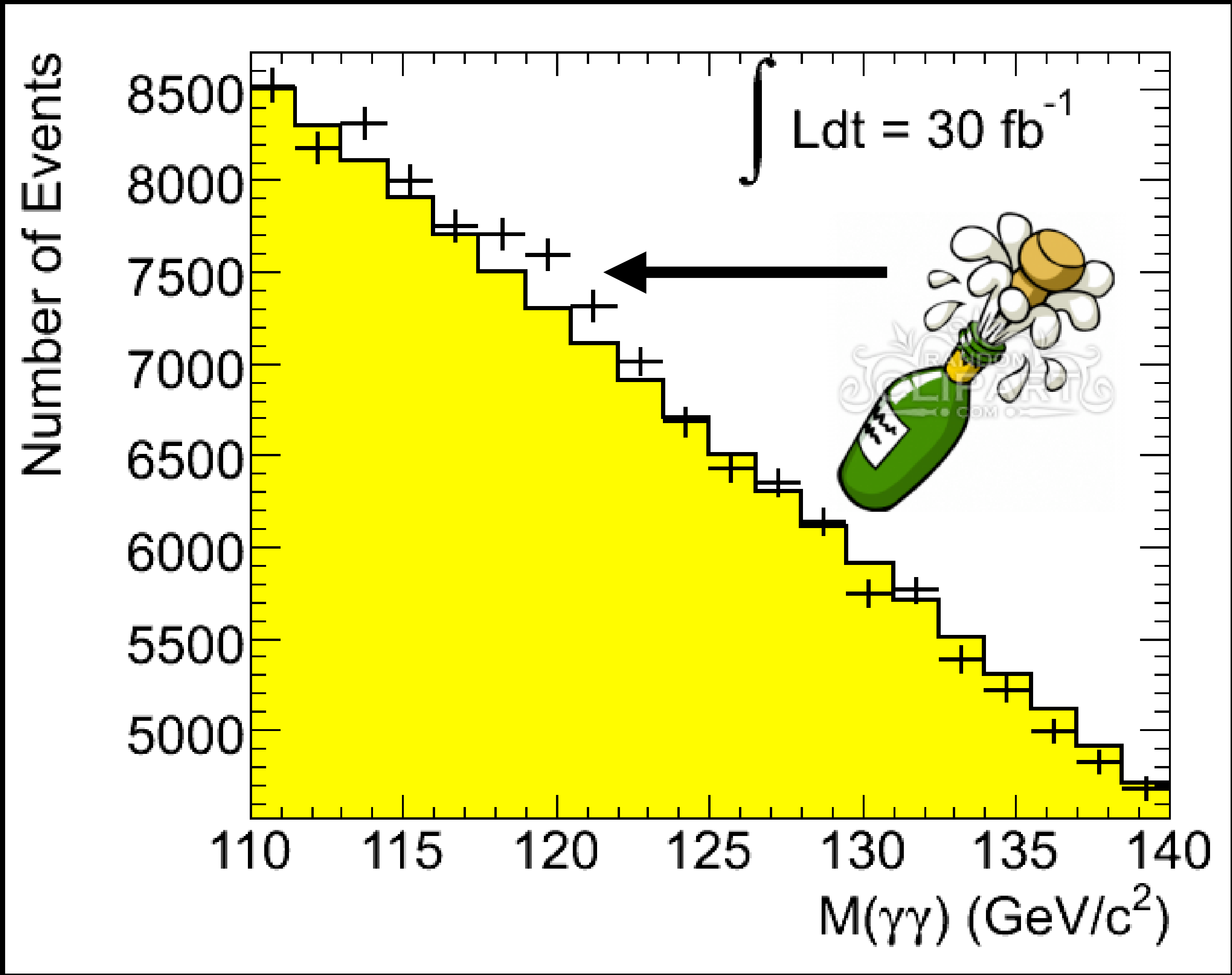
$\int Ldt = 0.1\ fb^{-1}$: $N_{Higgs} \approx 2$ (year: 2008/2009)

It will emerge with time



$\int Ldt = 1\ fb^{-1}$: $N_{Higgs} \approx 25$ (year: 2009)

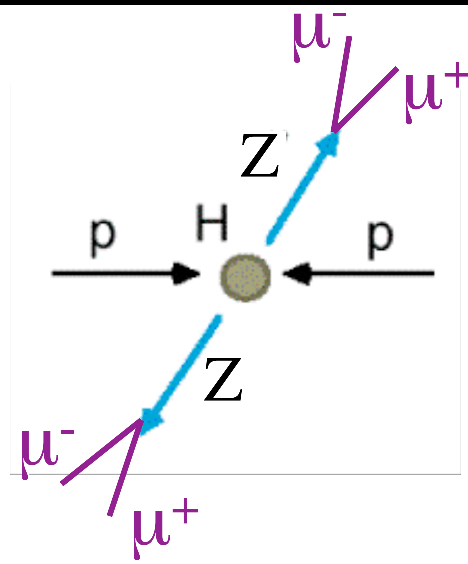
There it is!



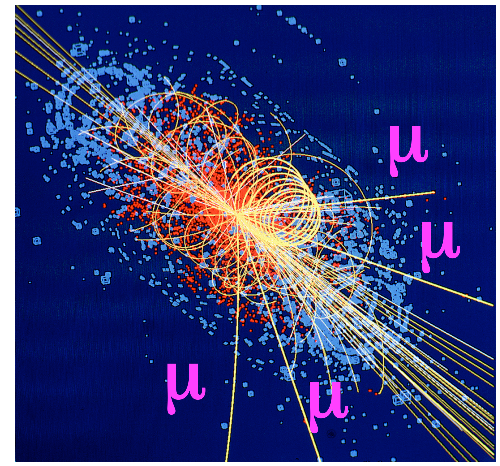
$\int Ldt = 30\ fb^{-1}$: $N_{Higgs} \approx 750$ (year: 2011/2012?)

Finding the Higgs Boson (with Z's)

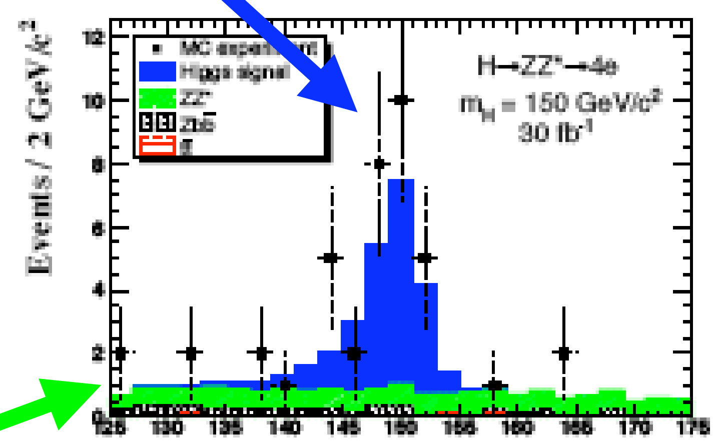
- Find 4 high energy muons or electrons
  - If M(H)>130 GeV/c^2
- Separate signal from backgrounds
  - Again calculating the invariant mass
  - Backgrounds much smaller than in diphoton case:
    - Easier!



simulated event



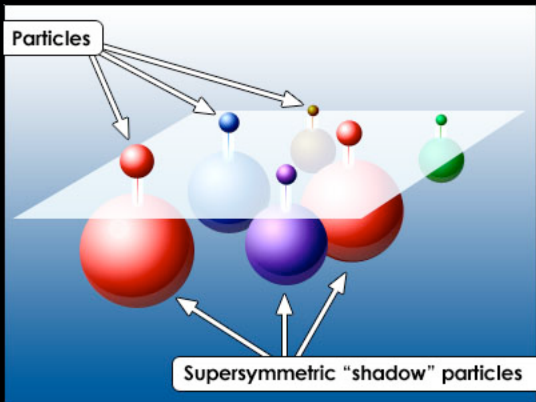
Higgs signal

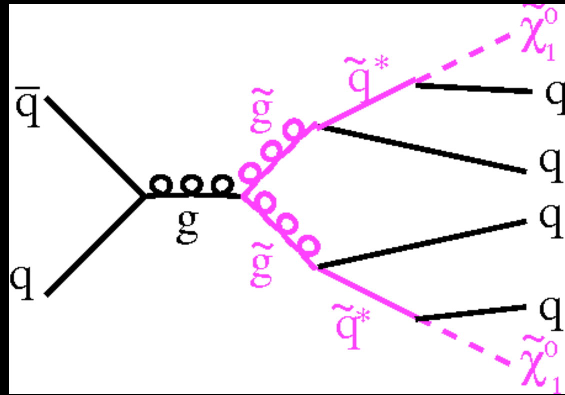


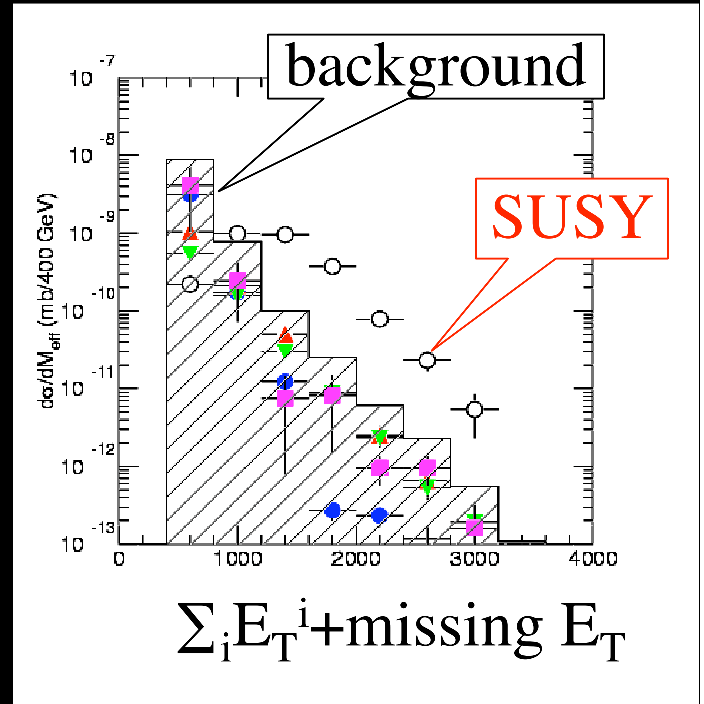
Background

M(eeee)

Finding a Supersymmetric World





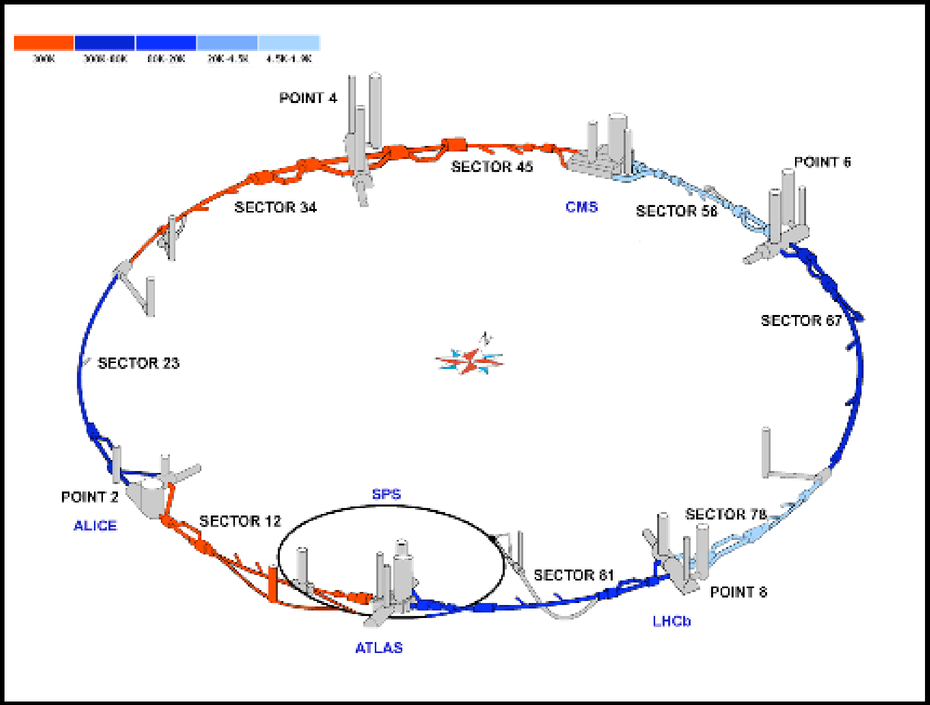


- **Supersymmetric particles decay into ordinary particles:**
  - Measure decay products
  - Dark matter particle ($\tilde{\chi}_1^0$) escapes detector unseen:
    - Momentum balance tell us presence of dark matter particles ("missing E_T")
- **Search strategy:**
  - Search for many high energy particles plus large missing E_T

Might find the missing Dark Matter in the Universe

Many Other Possibilities…

When ? LHC Schedule



- Accelerator currently cooling down to 1.9 K
- 1st beams in June 2008
- 1st collisions in August/September (at ~10 TeV)
- 1st physics results hopefully next year
- 1st discoveries in 2009/2010?

Conclusions

- The LHC will finally probe the "TeV scale" ($r = 10^{-17}$ cm)
  - Known to be special since 1934
- After a 15 year design and construction phase the LHC experiments are taking data!
  - Cosmic muons now, pp collisions later this year
- Biggest experiments ever built
  - >2000 physicists per experiment work towards a common goal
- LHC will definitely answer some (and hopefully many) fundamental questions
  - Within the next 2-5 years we'll know a lot more

Further Information

- CERN: http://public.web.cern.ch
- Particle Physics: http://particleadventure.org
- Experiments:
  - ATLAS: http://www.atlas.ch
  - CMS: http://cmsinfo.cern.ch/outreach/

  (including many movies)