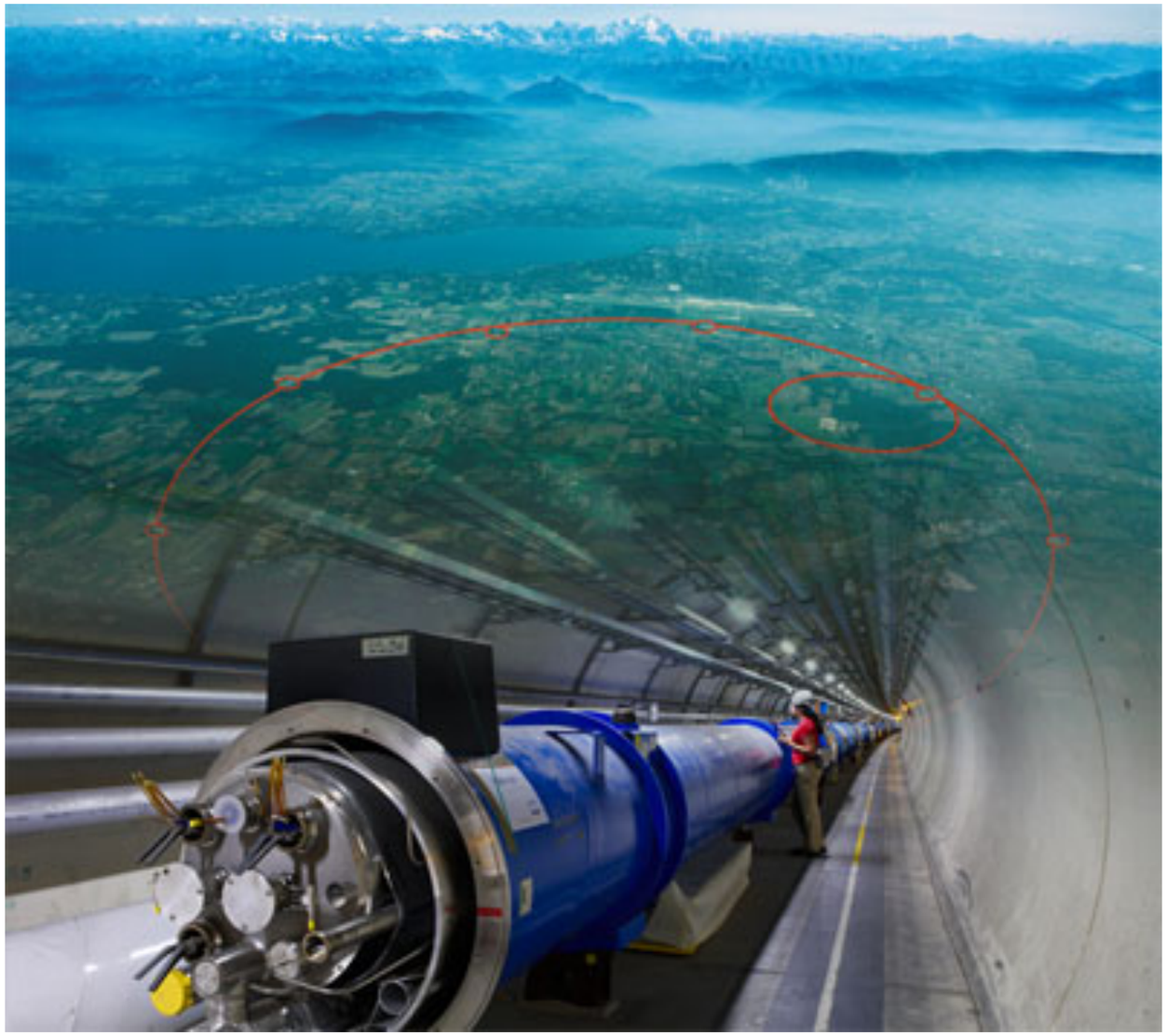
The Elementary Particle Physics Frontier: First Results from the Large Hadron Collider



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Rutgers University

NJAAPT Annual Meeting
March 19, 2011

Outline

Particle Physics

- The Standard Model
- Issues with the Standard Model
- The Higgs Mechanism
- Supersymmetry

The LHC

- Need for Higher Energies
- The CMS Detector

Search for Extra Dimensions

- First Results
- Strong gravity
- Black hole production

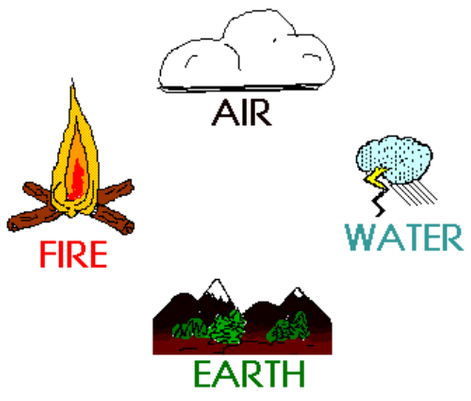
Elementary Particle Physics

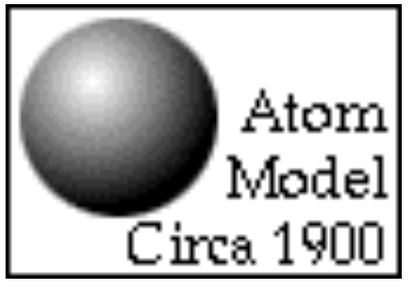
What are the building blocks of nature?

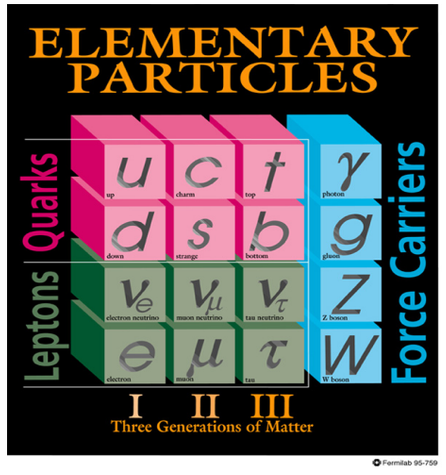
What is the world made of?

What holds it together?

Fundamental Particles







The Standard Model

Major advance in the 1970's

Mathematically consistent theory of the fundamental particles and their interactions

Ingredients:
- Fermion matter particles
- Gauge interactions
- Gauge Bosons

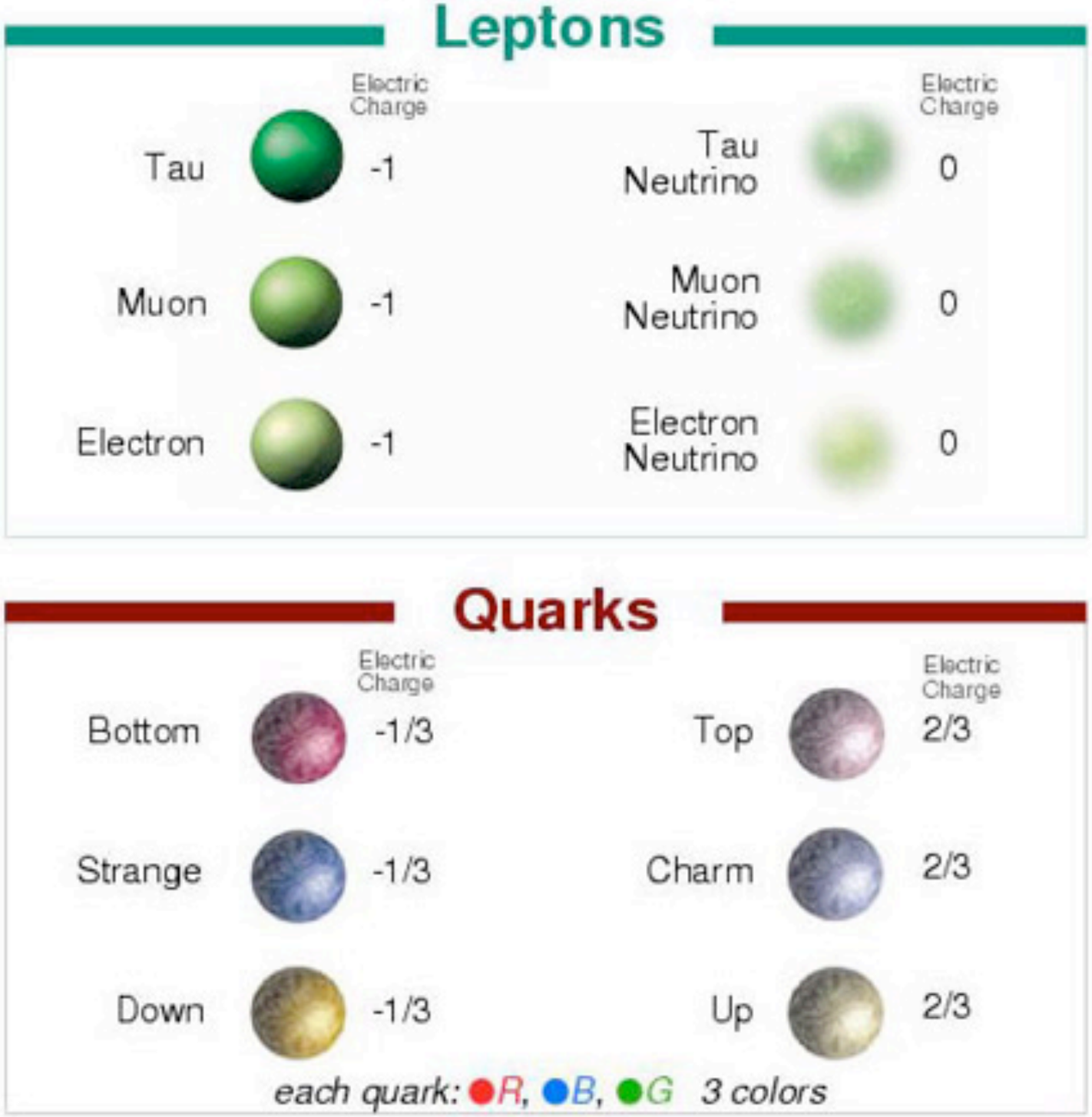
Explains all physics down to $\approx 10^{-18}$ m !

Matter Particles

Twelve point-like Fundamental Fermions (spin -1/2) particles

and anti-particles

Wide range of masses (arbitrary parameters)



Fundamental Interactions

Electromagnetism (QED)

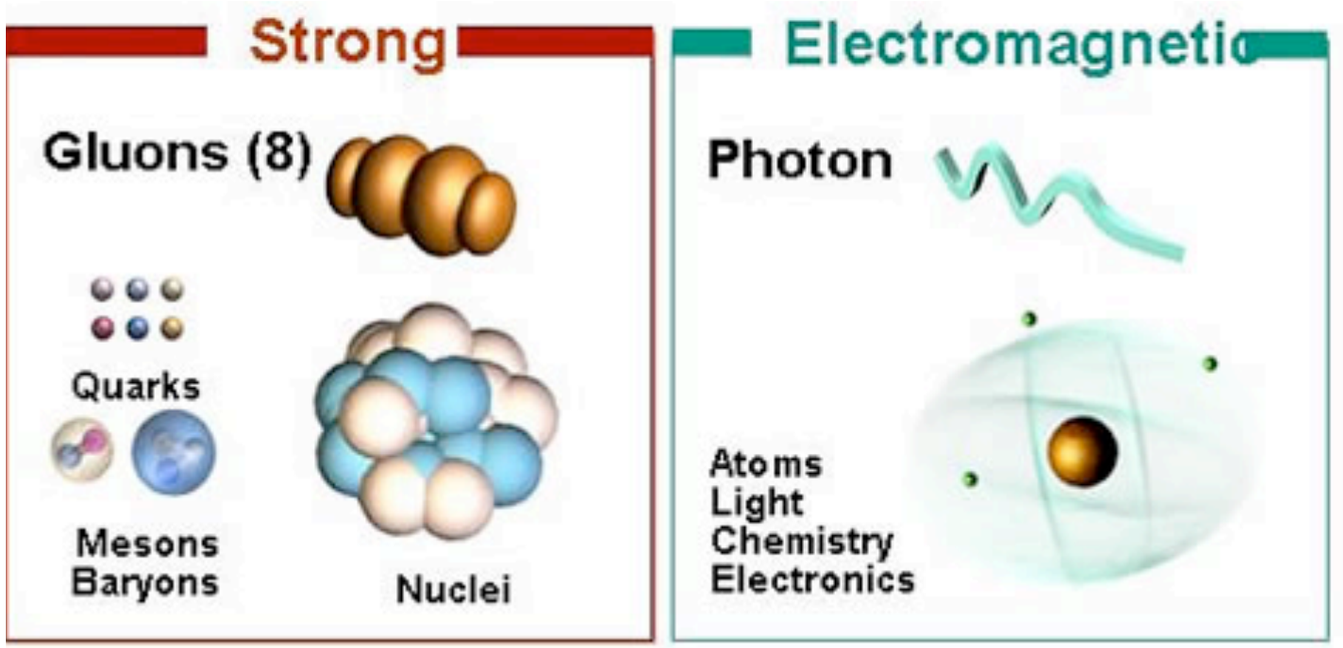
- atomic physics
- chemistry
- biology

Strong (QCD)

- binding of quarks (protons, neutrons, ….)
- nuclear physics

Weak

- neutrino interaction
- heavy quark/lepton decay
- fusion (solar energy)

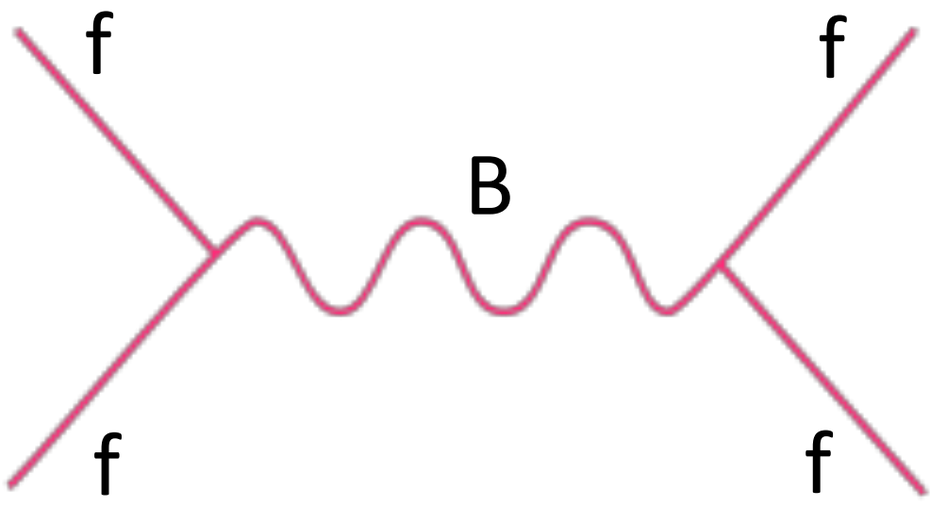


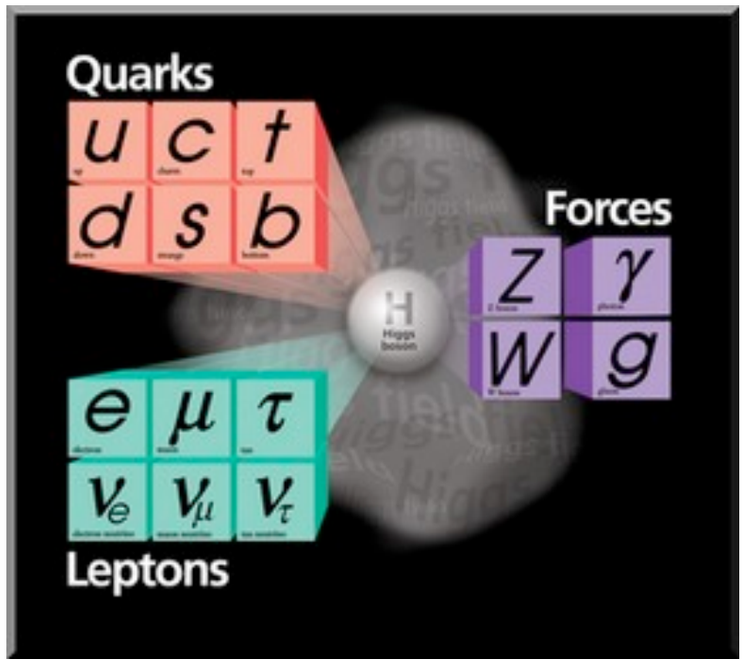
SM has nothing to Say about gravity

- Too weak for experiments
- no quantum theory of gravity

Gauge Forces

All three interactions due to exchange of gauge (spin-1) Bosons





Interaction	Fermions	Gauge Boson	Charges
QED	e, μ, τ, quarks	photon	electrical charge (-)
QCD	quarks	gluons	color charge (r, g, b)
Weak	all	W^+, W^-, Z	isocharge (up, down)

Local Gauge Symmetry

In order for the theory to make sense
(not give infinities that can't be removed)
it must be locally gauge symmetric

The gauge Bosons
(photon, gluons, W, Z)
must be massless

Spontaneous Symmetry Breaking

The underlying theory is symmetric

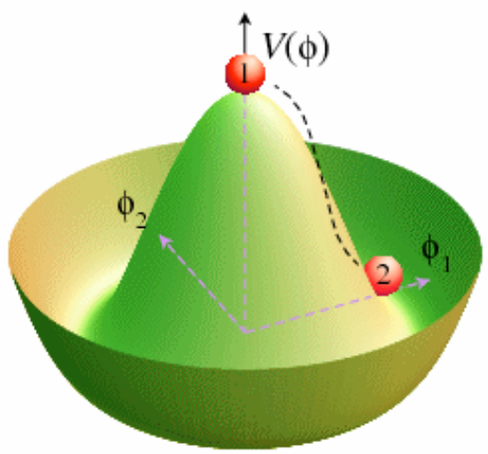
The symmetry in broken by the solution.

Example: Trajectory of ball in Newtonian physics

The solution (the universe) breaks the symmetry by choosing one of the (many) solutions

complex scalar field

actually a Mexican sombrero potential



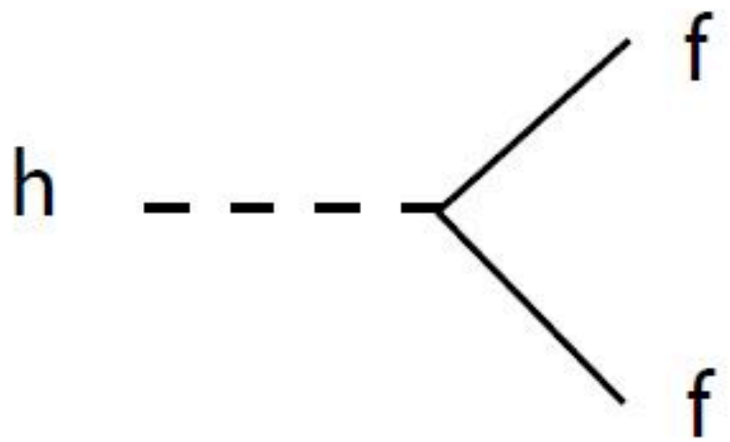
Source of Particle Mass

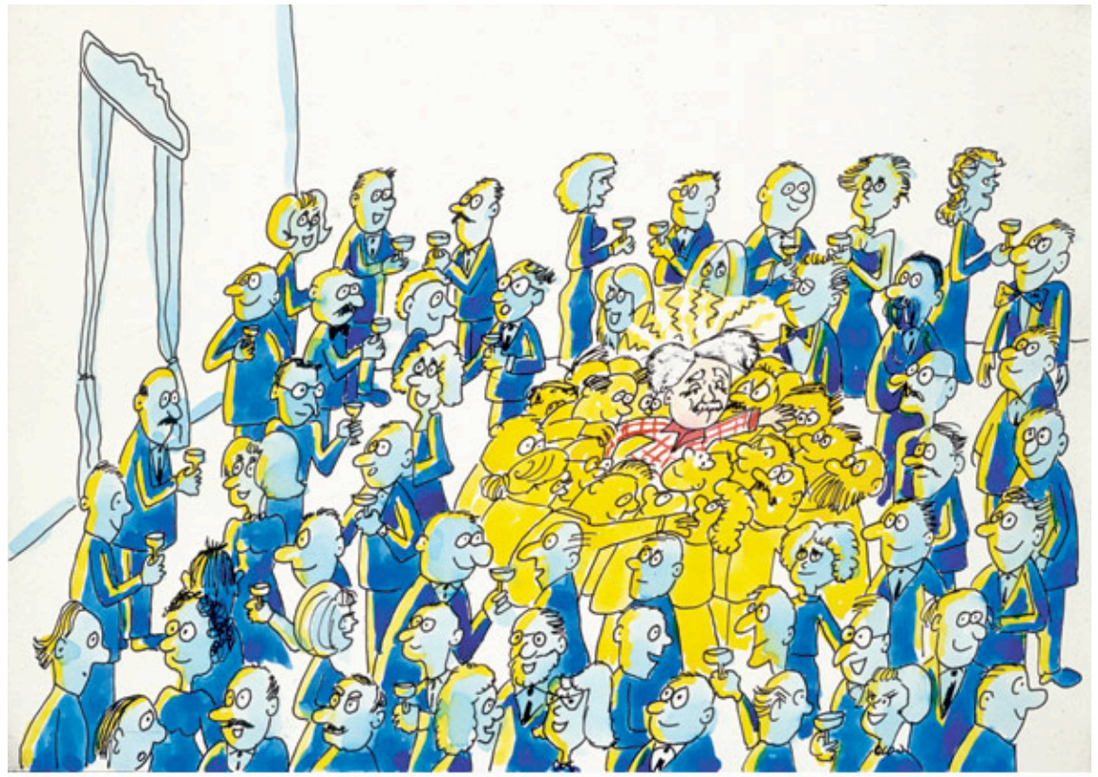
According to the Standard Model all mass is due to the Higgs mechanism

The W and Z boson get mass by "eating" the Higgs field

Higgs field gives the extra degree of Freedom (longitudinal polarization) Needed for a massive spin-1 particle

Fermions get mass by interacting with the vacuum Higgs field





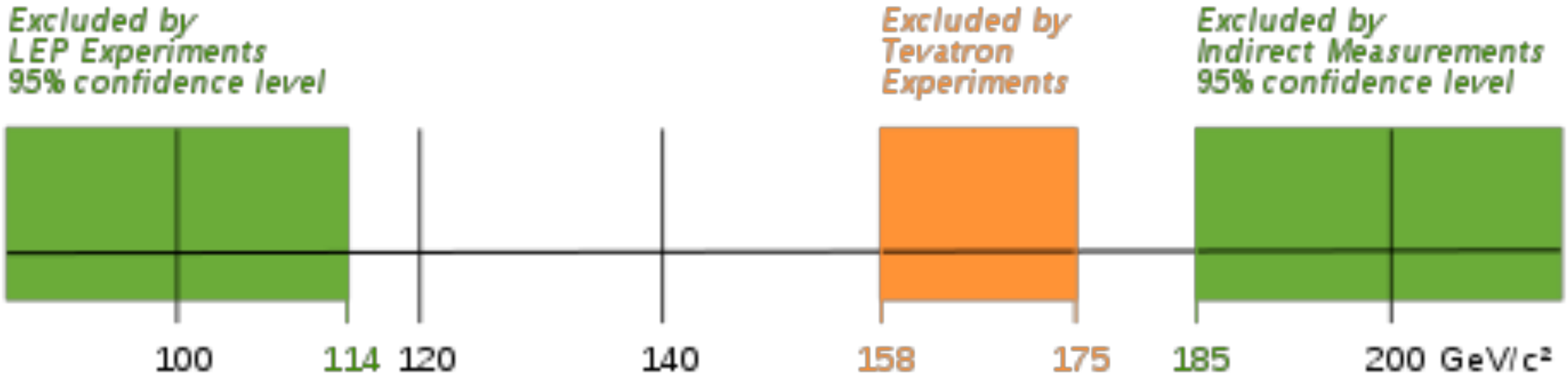
Higgs Boson

Quanta of excitation of the Higgs field

→ physical Higgs scalar (spin-0) particle

Higgs mass not directly predicted by theory

Experimentally we are closing in

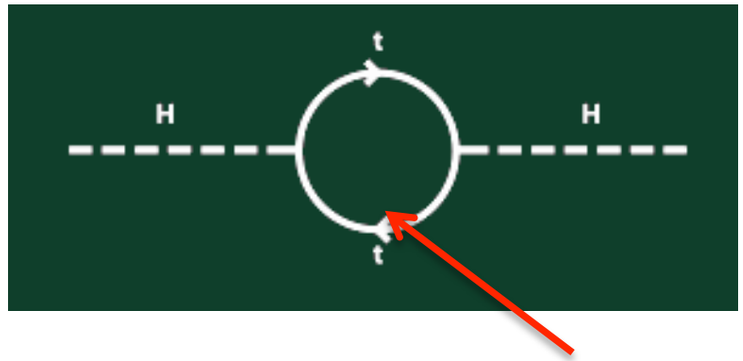


The LHC should soon fill in the gaps

Naturalness Problem

Problem with mass of fundamental scalar

Modifications to mass term due to Fermion loops are quadratically divergent



$$M_H^2 = M_0^2 + \frac{g_f}{8\pi^2}\Lambda^2$$

momentum of loop ranges up to cutoff Λ

Λ Is the energy scale where theory fails

Presumably the Planck scale where quantum gravity effects become important

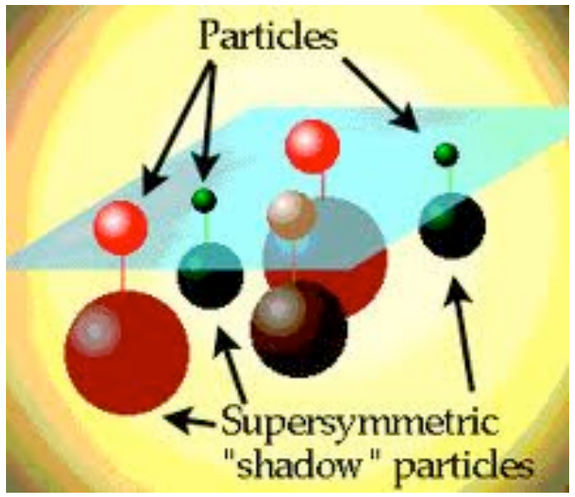
$10^{19}\ \mathrm{GeV/c^2}$

$\Rightarrow$ Higgs mass is 17 orders of magnitude smaller than its natural mass

A New Symmetry

Supersymmetry

For every particle there is a superparticle

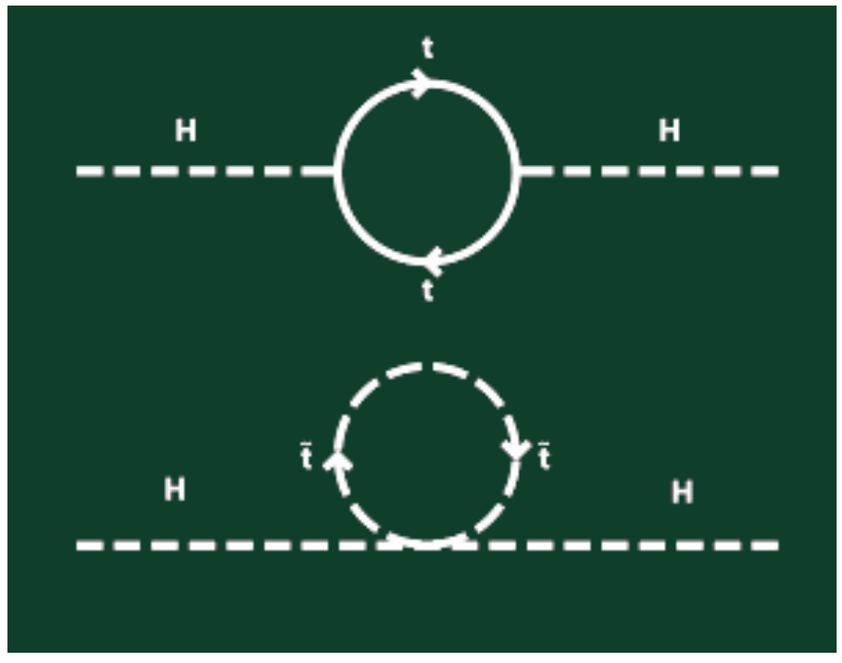


fermion $\leftrightarrow$ super boson

boson $\leftrightarrow$ super fermion

fermion and boson loops contribute to mass term with opposite signs.

They cancel



Supersymmetry is Broken

None of the super particles have been seenWhy?

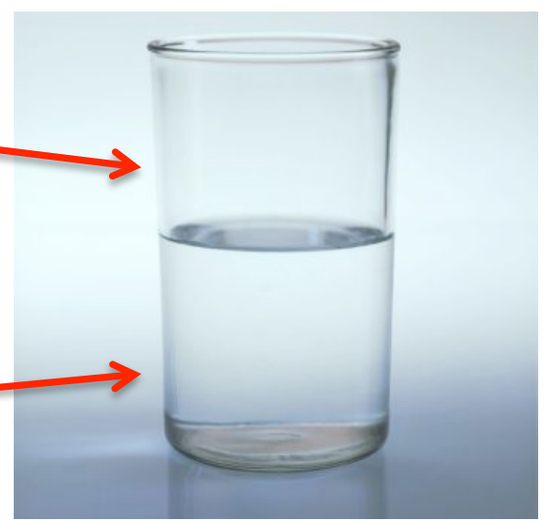
Maybe masses are too large to have been produced

Supersymmetry is broken

Masses can't be much larger than a few TeV or solution of naturalness problem will be ruined

We haven't seen a single one of the super particles

We've seen one half (the particle half) of supersymmetry



Heisenberg Uncertainty

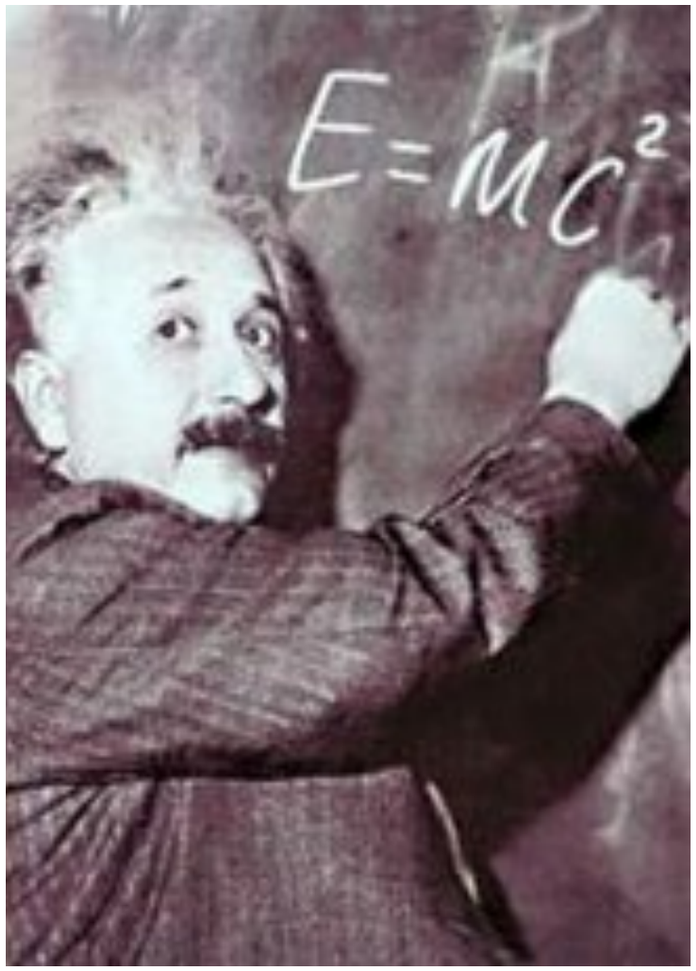
$$p = \hbar/\lambda$$

$$\Delta x \Delta p \geq \hbar/2$$

the more finely you want to probe something

the harder you have to kick it

Mass Energy



$$E = mc^2$$

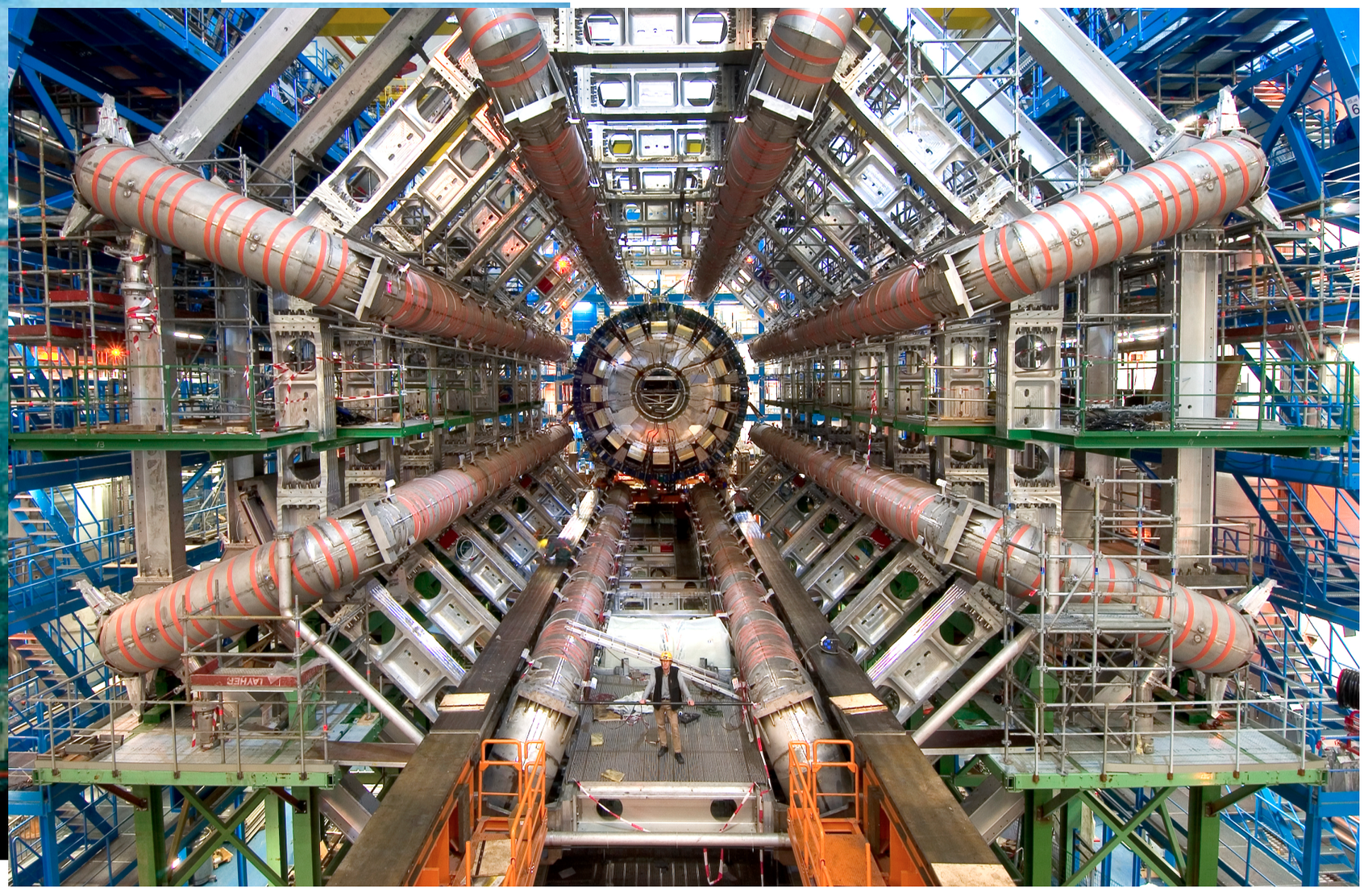
Mass is energy

to produce particles with large mass
need large collision energy

The Tools

The Large Hadron Collider

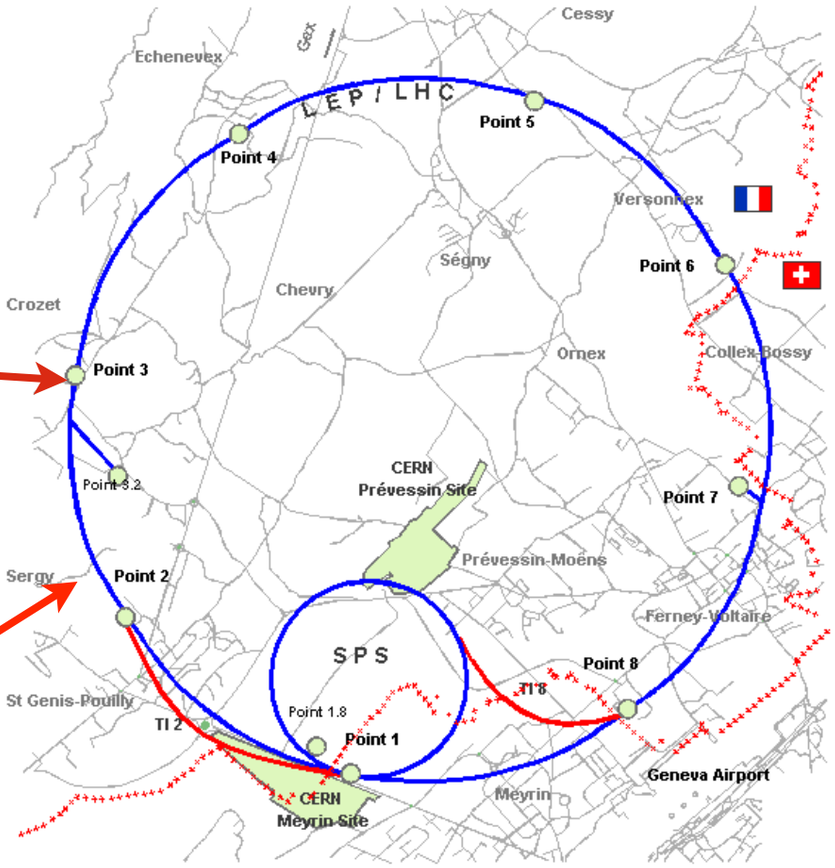
The ATLAS Detector



Why Such Big Tools

RF cavity

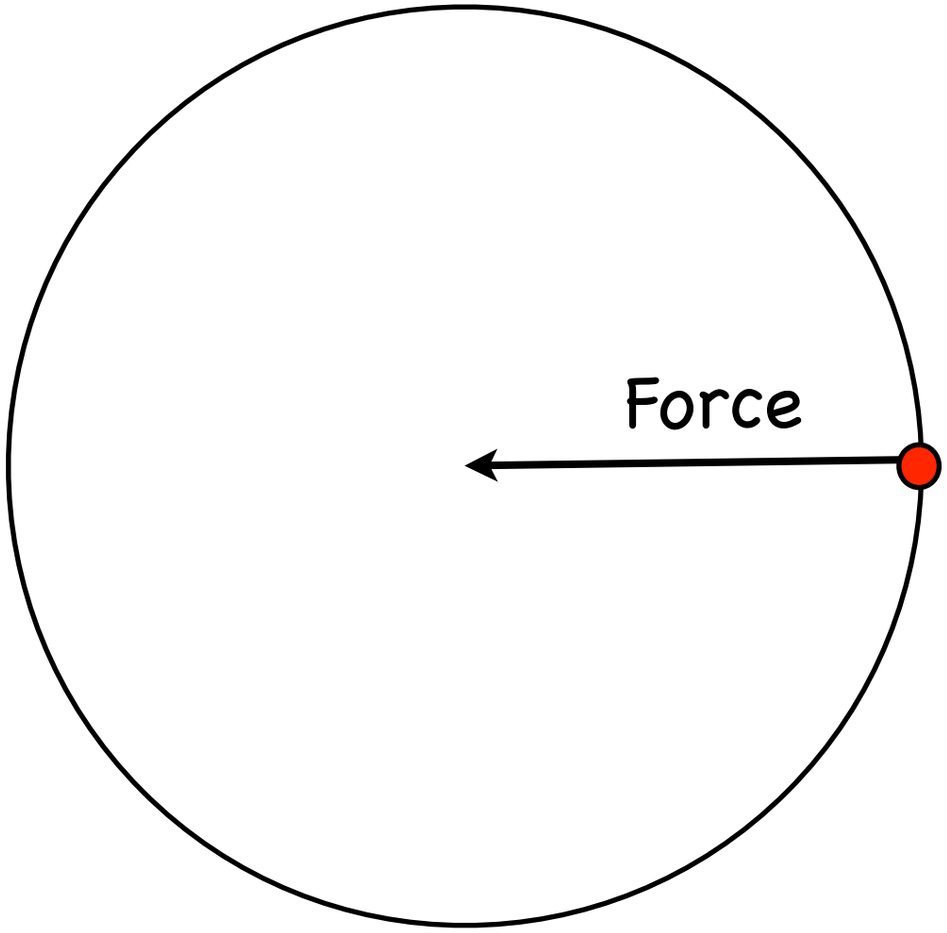
dipole magnets



Bend particles in circle

Accelerate them a bit every time around

Centripetal Force



Charged particle in magnetic field

$$F_{mag} = qvB$$

Centripetal force

$$F_{cent} = mv^2/R$$

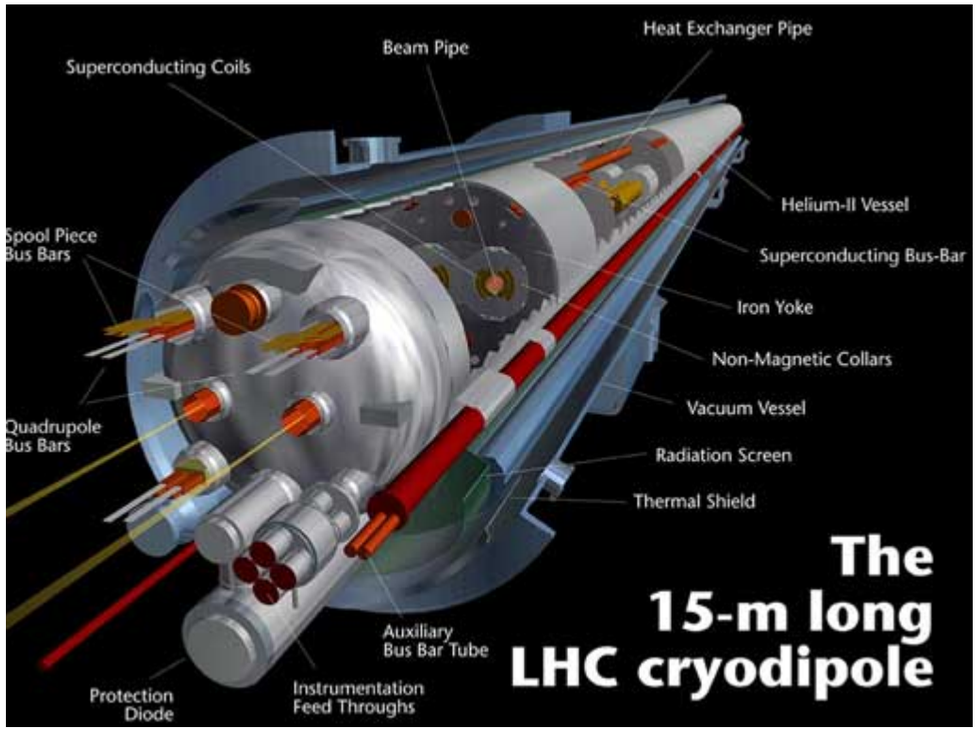
$$mv^2/R = qvB$$

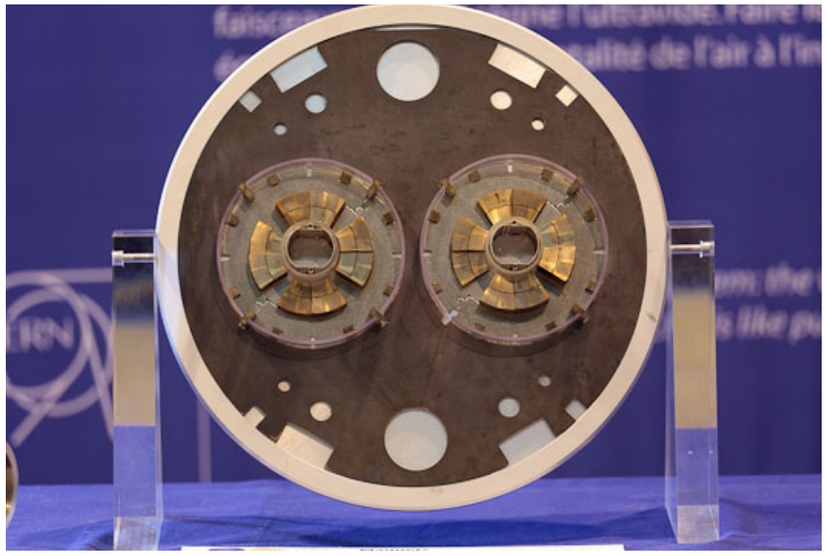
$$R = mv/qB = p/qB$$

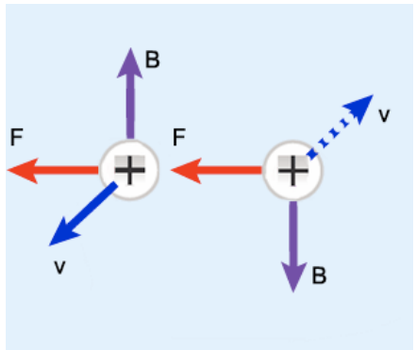
at relativistic velocities
energy is proportional to p

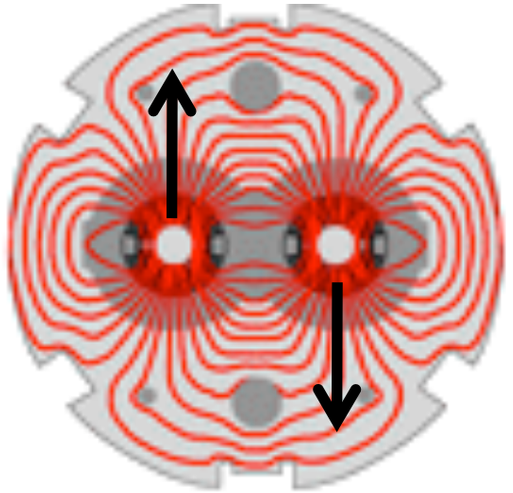
$$E = pc \quad \Rightarrow \quad R \propto E$$

LHC Dipole Magnets





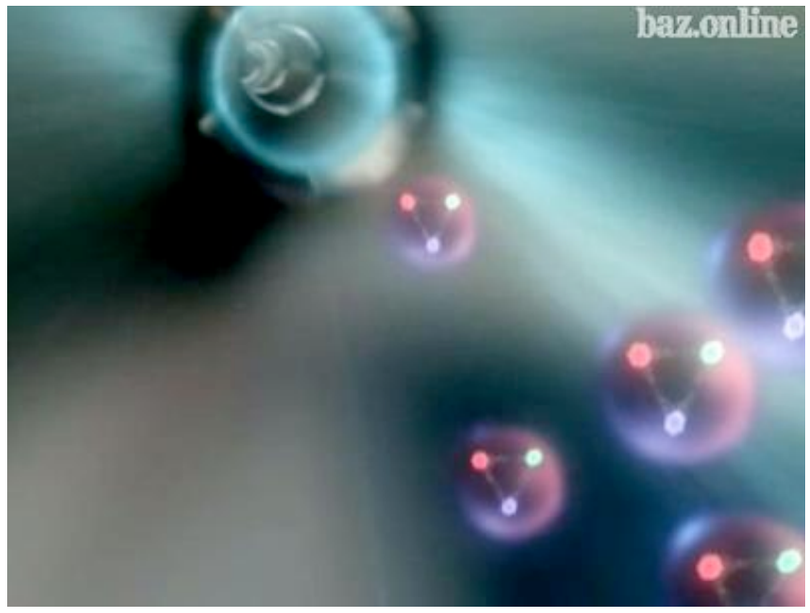




- 1232, 15-m long, 35 tons
- 8.4 T (for 7 TeV beam)
- 11,700 Amps
- 1.9° K

Energy in LHC Beam

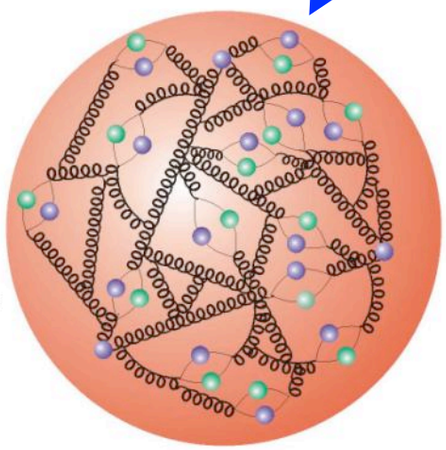
10^{14} 7 TeV protons



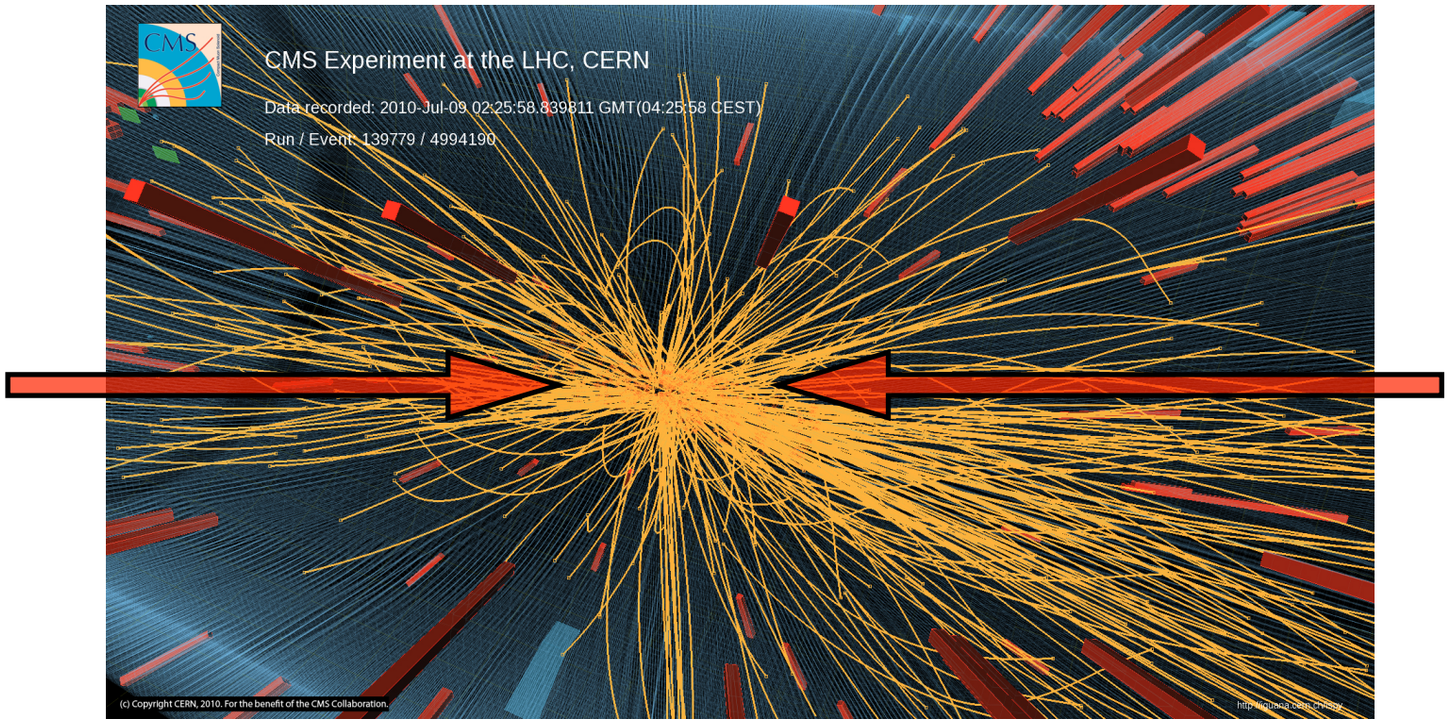
- Energy stored in in LHC beam is about 362 MJ (design)
  - How much energy is this?
    - The two LHC beams together could melt nearly one ton of copper.
    - Equivalent to 77.4 kg of TNT
    - Energy of an aircraft carrier traveling 11.7 knots
    - Equivalent to a person in a Subaru driving at 1700 km/h.

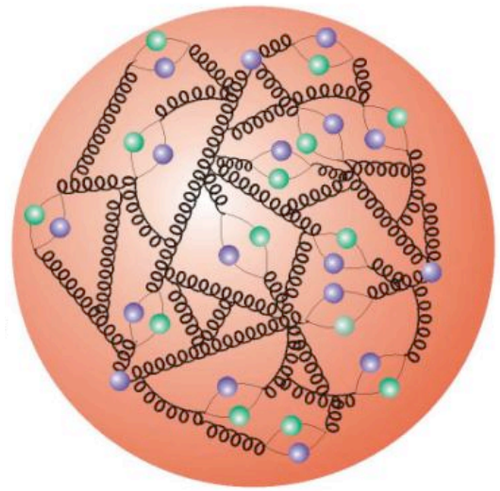
14 TeV Proton Collisions

Bag of quarks and gluons



proton



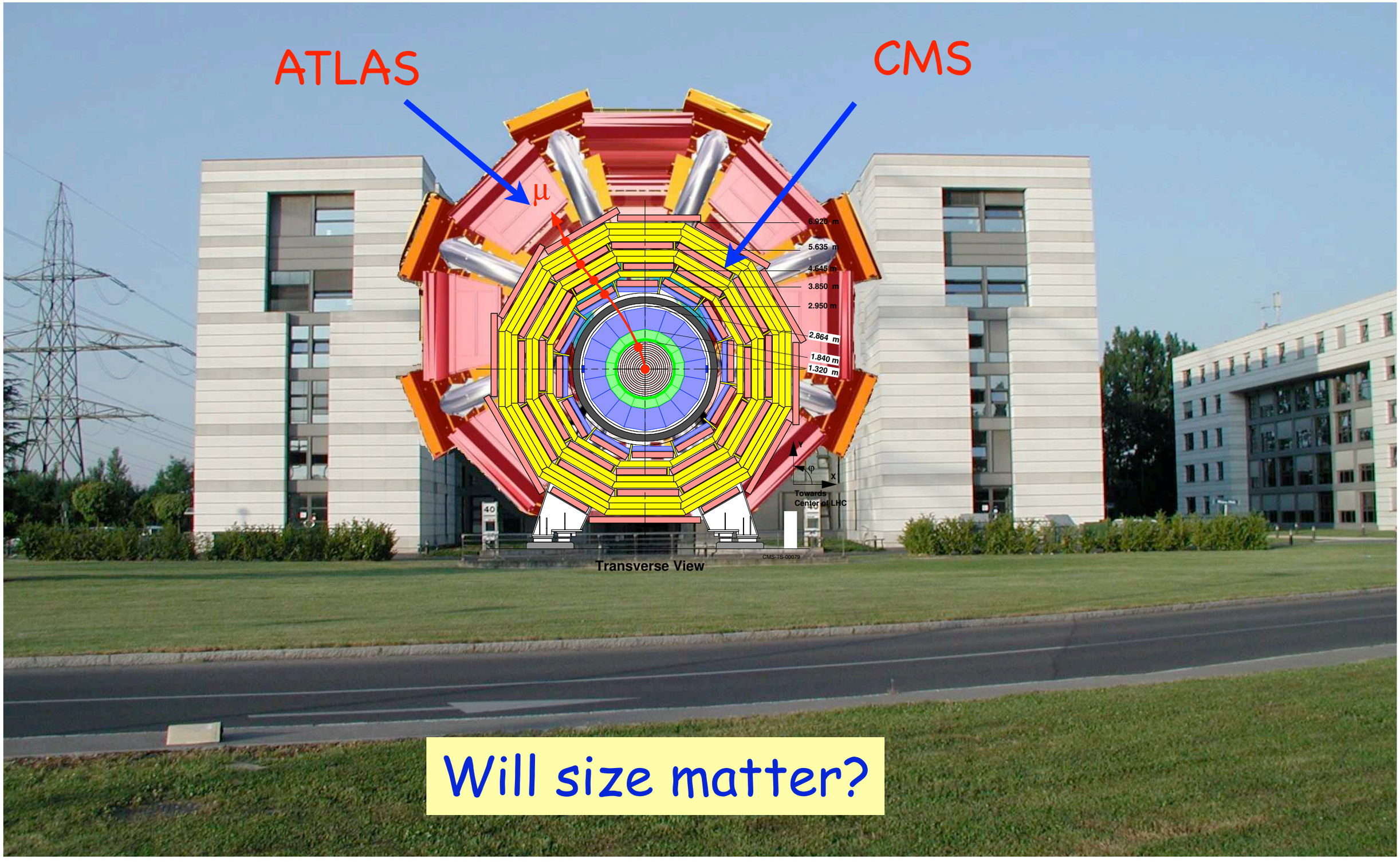


proton

How do we sort this out

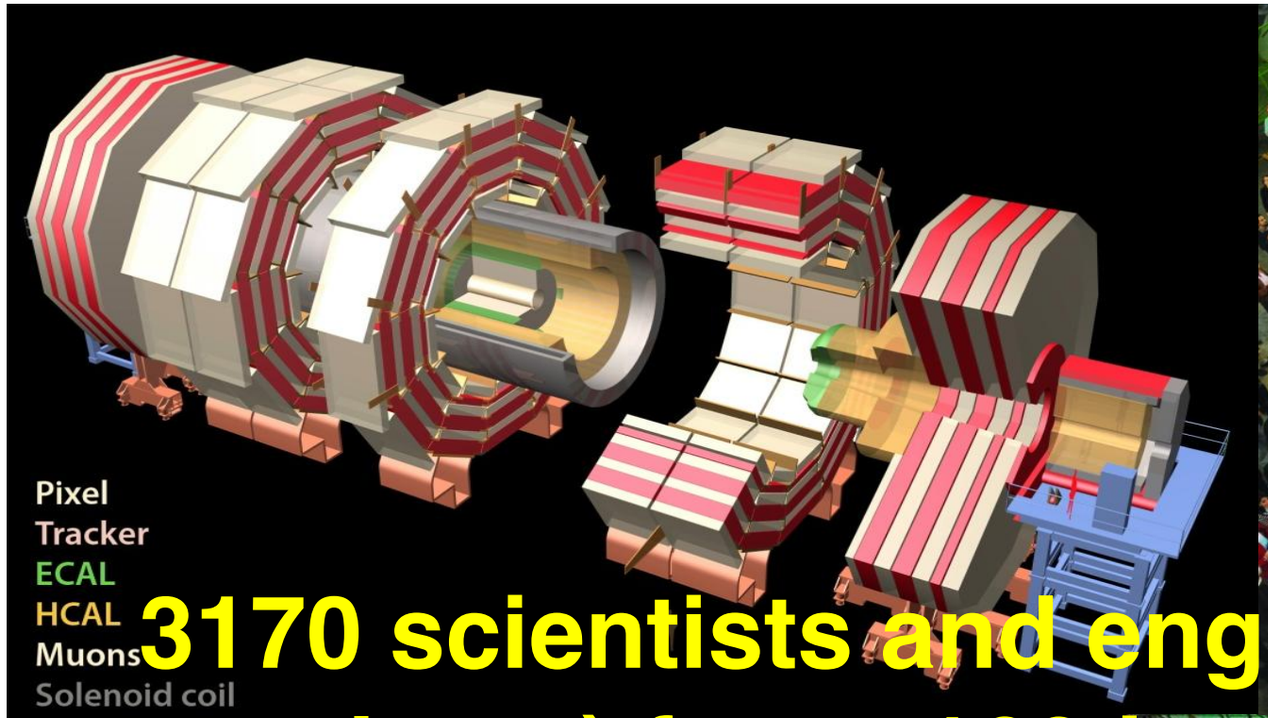
Only 1 in 10 billion collisions are really of interest

B~~i~~g Huge Detectors

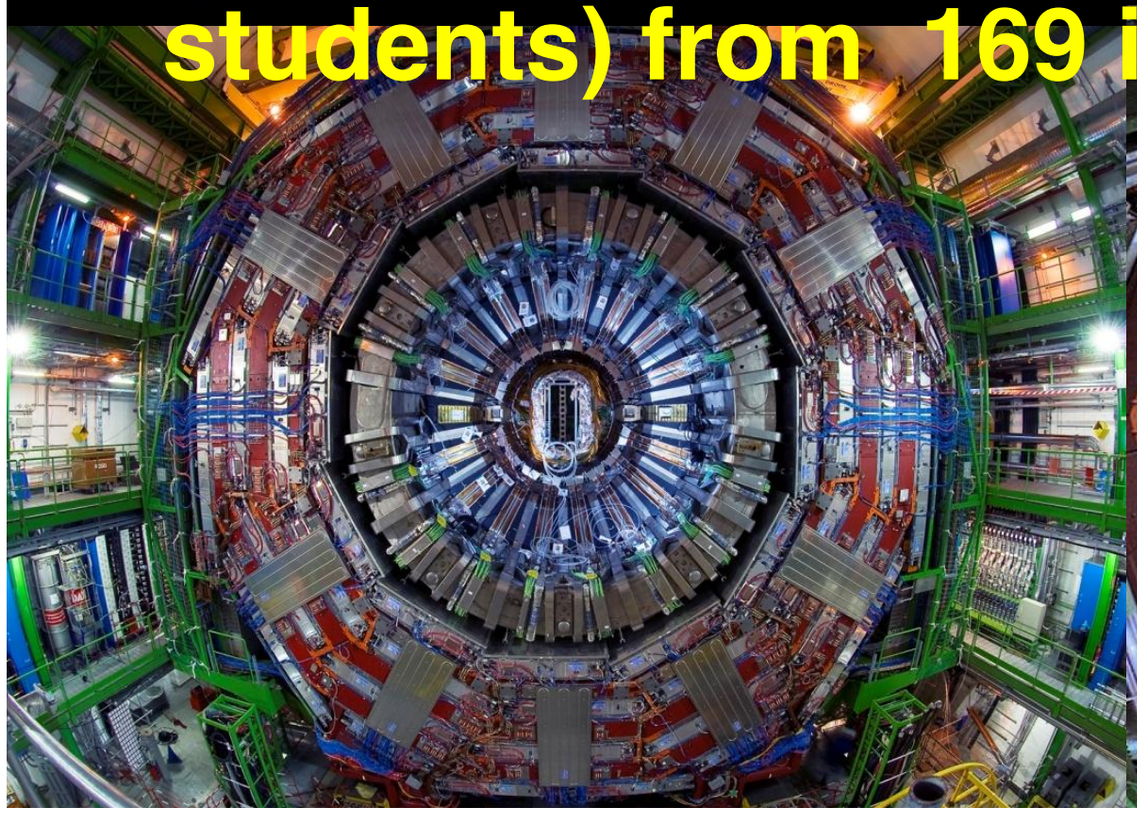


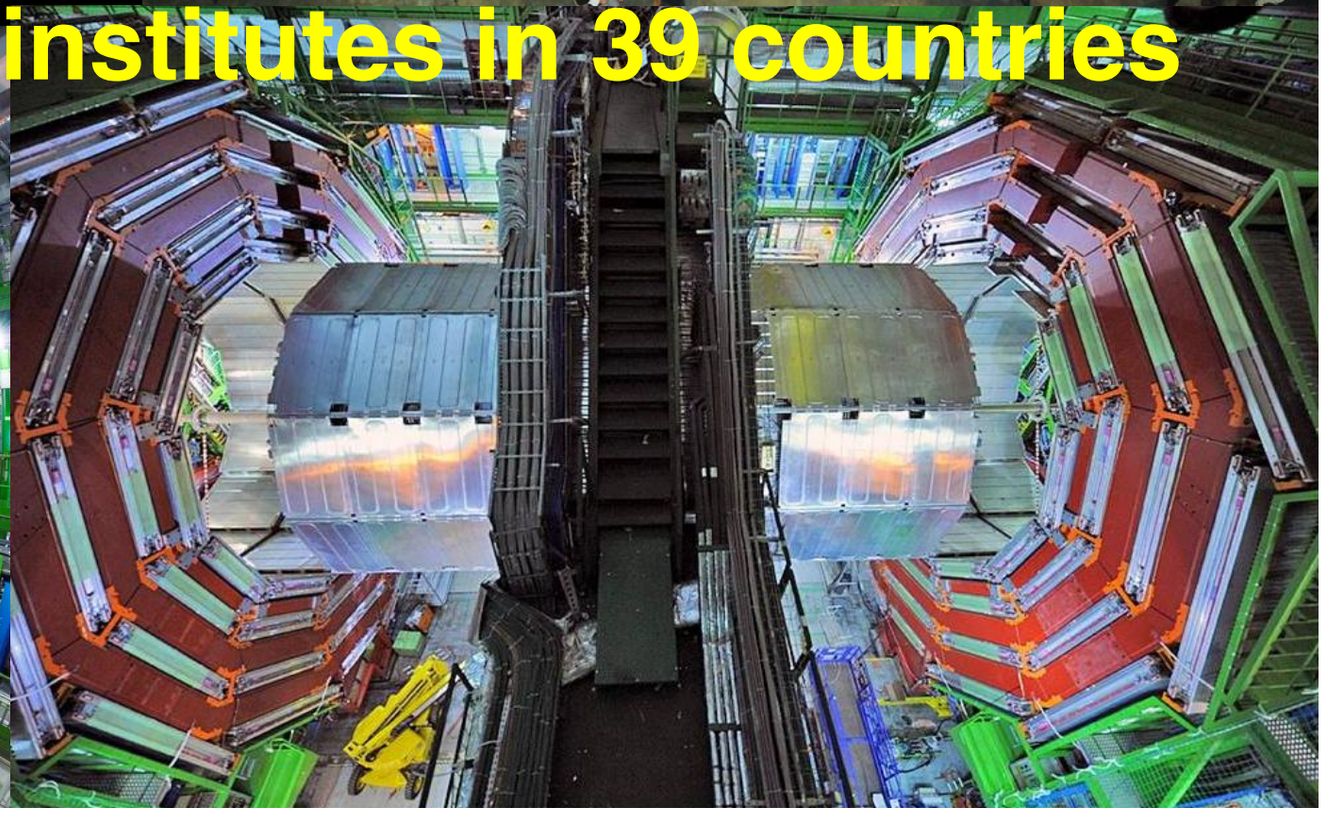
Will size matter?

Compact Muon Solenoid



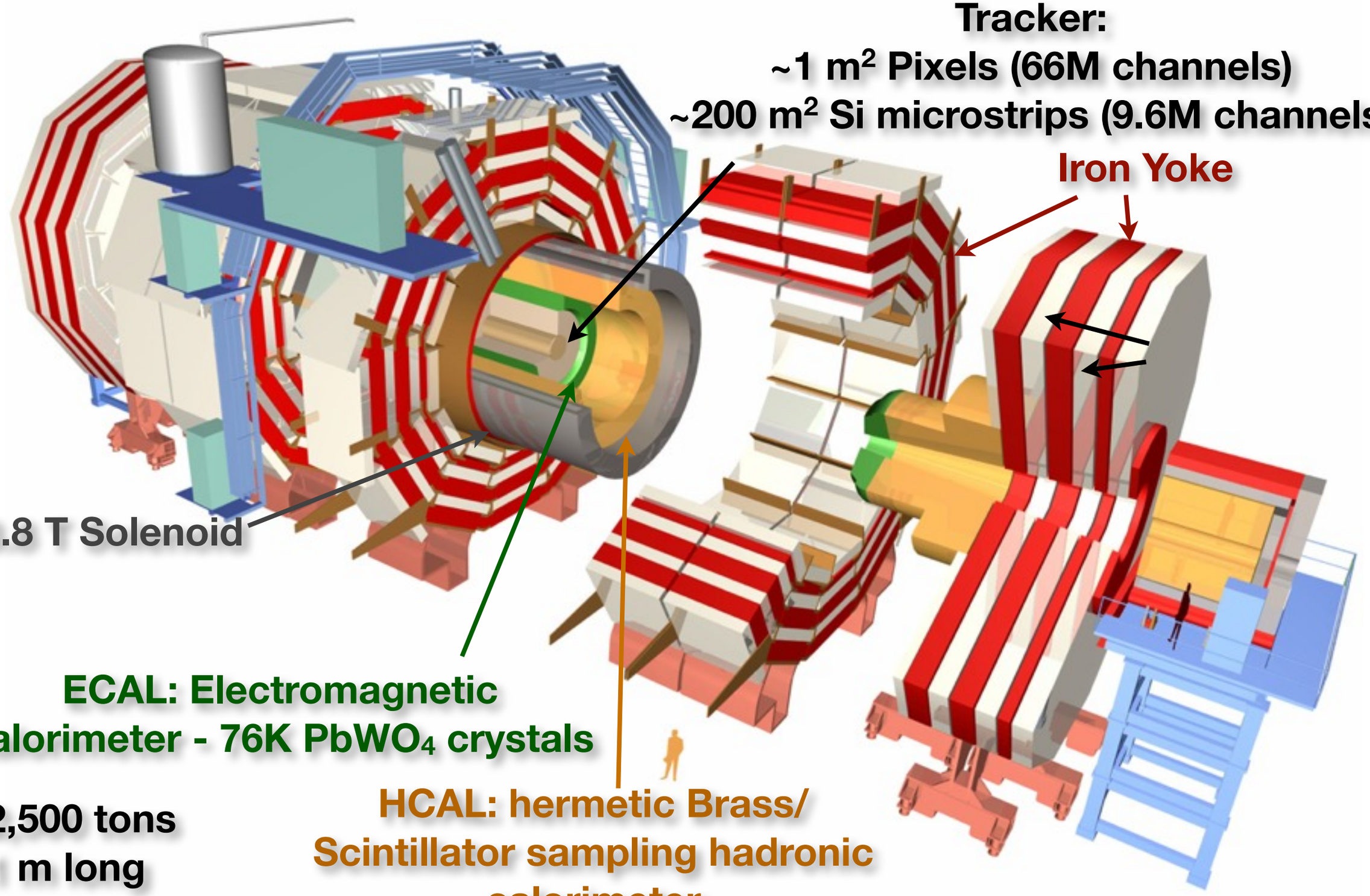
3170 scientists and engineers (including ~800 students) from 169 institutes in 39 countries





Anatomy of a Detector

A Slice of the CMS Detector

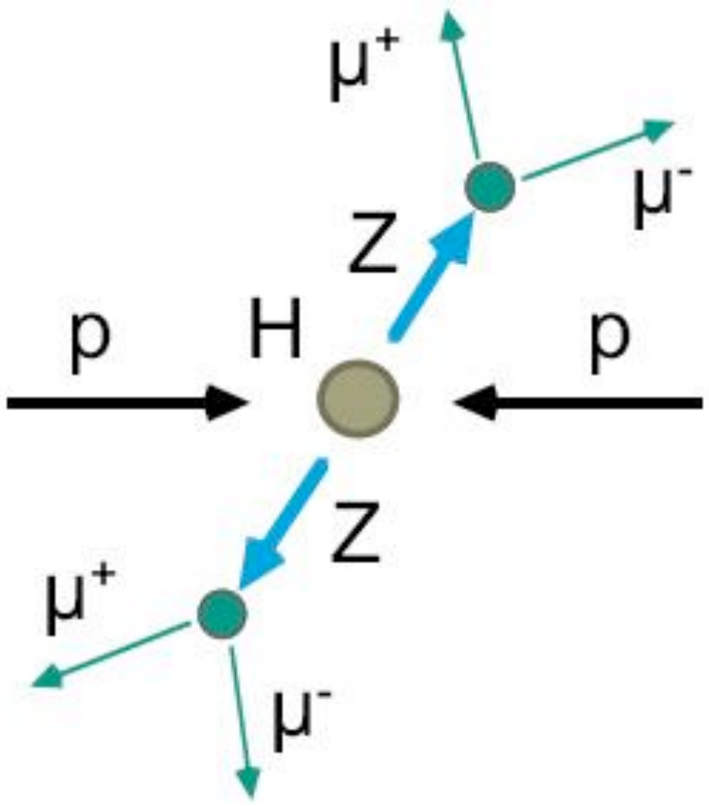


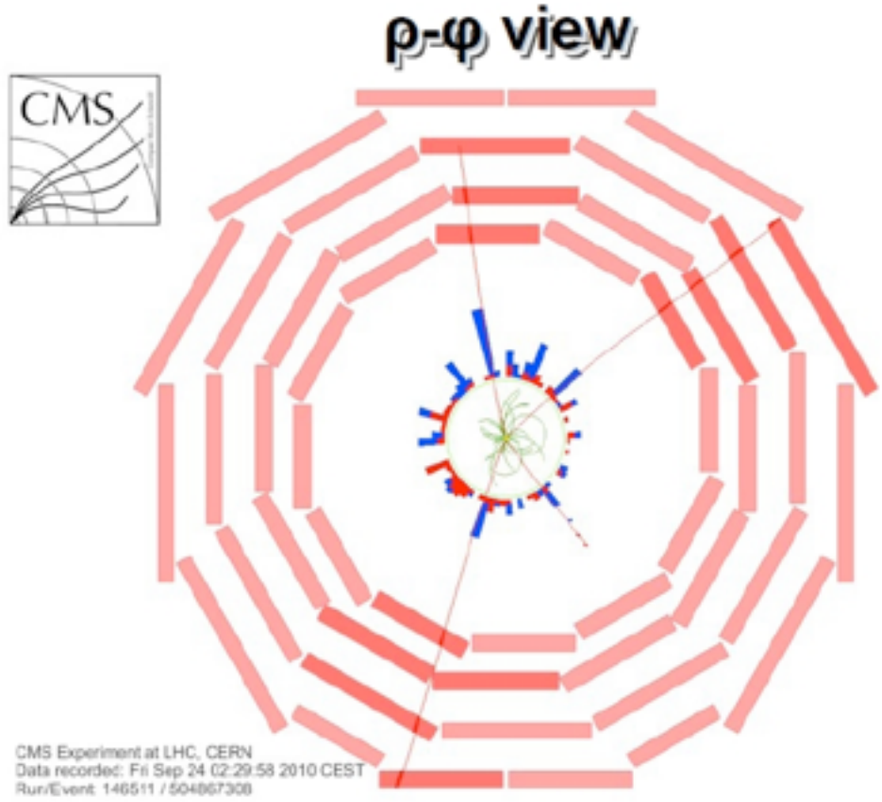
The Program of Particle Physics

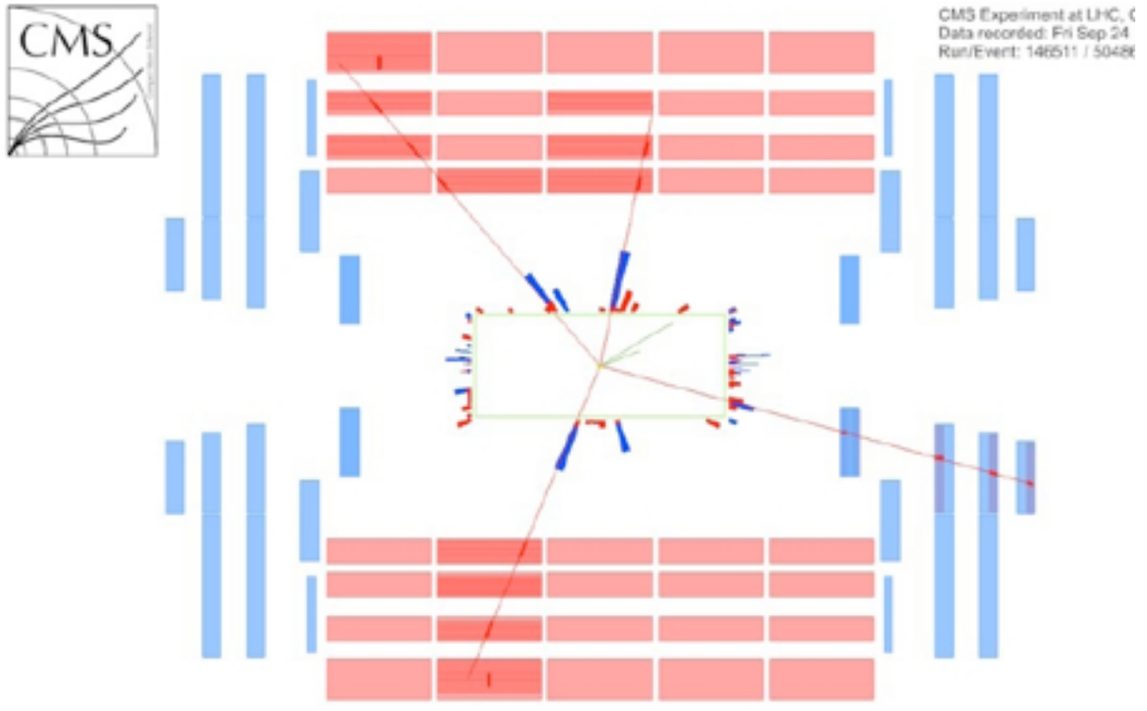
- Discover the Higgs Boson
- Discover Supersymmetric Particles

This is what the LHC is designed for.
You should be hearing a lot about these soon.

Higgs to Four Muons Event







Only a few percent probability when it was discovered (Sept.) that it was just background

Now consistent with the data we have

Gravity

Why is gravity so weak?

probably the most important question in particle physics

$$F \sim \frac{1}{r^2}$$

Gravity become "strong" at a Planck scale of 10^{19} GeV

→ $R = 10^{-35}$ m

This is 18 orders of magnitude from the weak scale of 100 GeV. Why?

Extra Dimensions

Answer: Maybe there are extra "large" dimensions. Gravity lives in these other dimensions while other forces only live in three dimensions

String theory → 7 extra dimension

assumed to be size of Planck scale

10^{-35} m

But maybe not

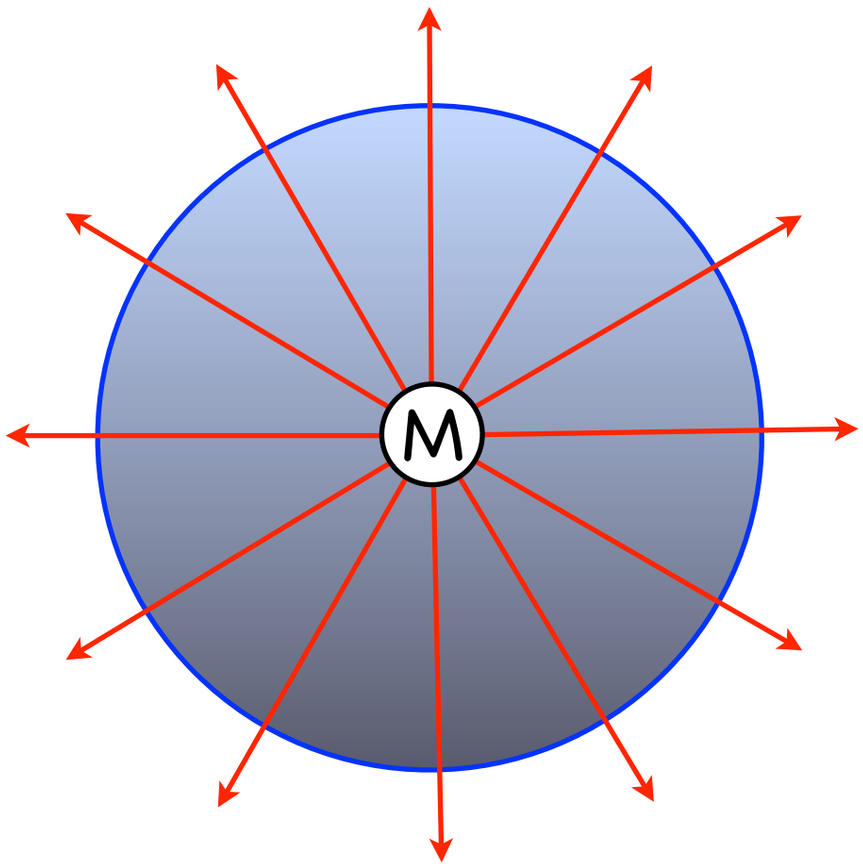
Cavendish Experiment

$$F \sim \frac{1}{r^2}$$

Only confirmed down to about 0.1 mm

below that we don't know

Gauss's Law



gravity proportional to density of force lines on surface

$F \sim 1/r^2$ for 3 dimensions

$F \sim 1/r$ for 2 dimensions

$F \sim 1/r^{n-1}$ for n dimensions

If there is a "large" extra dimension gravity will go as

$$F \sim 1/r^3$$

at distances smaller than the size of the extra dimension

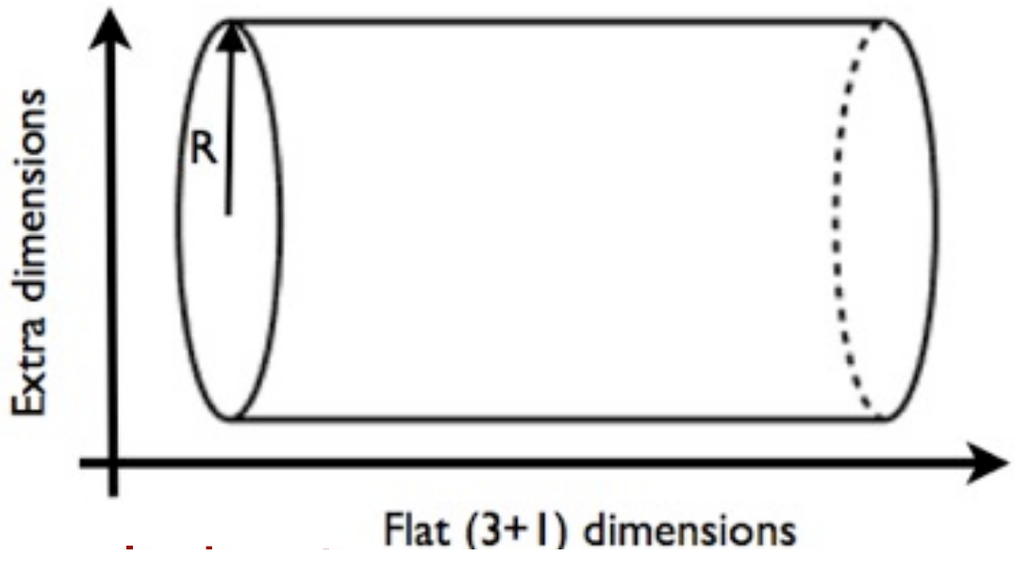
Gravity will get strong faster

May see strong gravity at the LHC

What is the LHC Sensitive to?

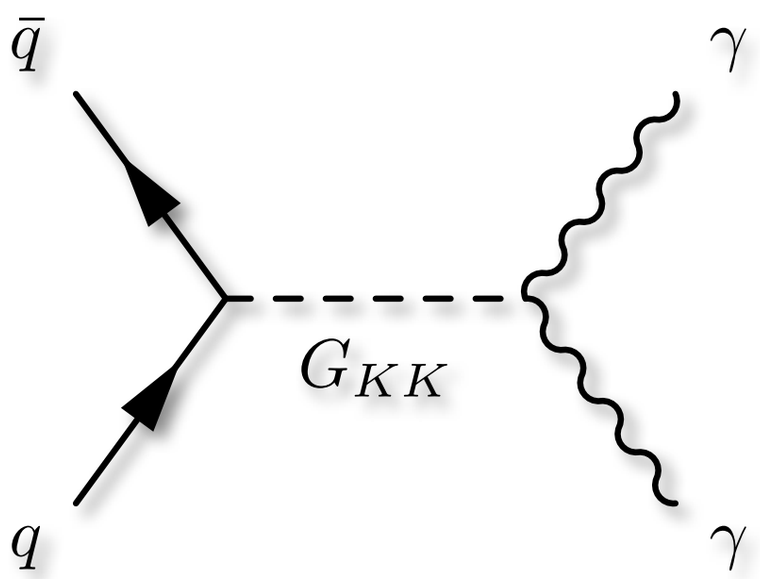
Number of extra dimensions	Minimum size for strong gravity at 1 TeV	
1	6×10^{12} m	ruled out!
2	0.6 mm	probably ruled out
3	3 nm	OK!
.	.	
.	.	
.	.	
7	2 fm	

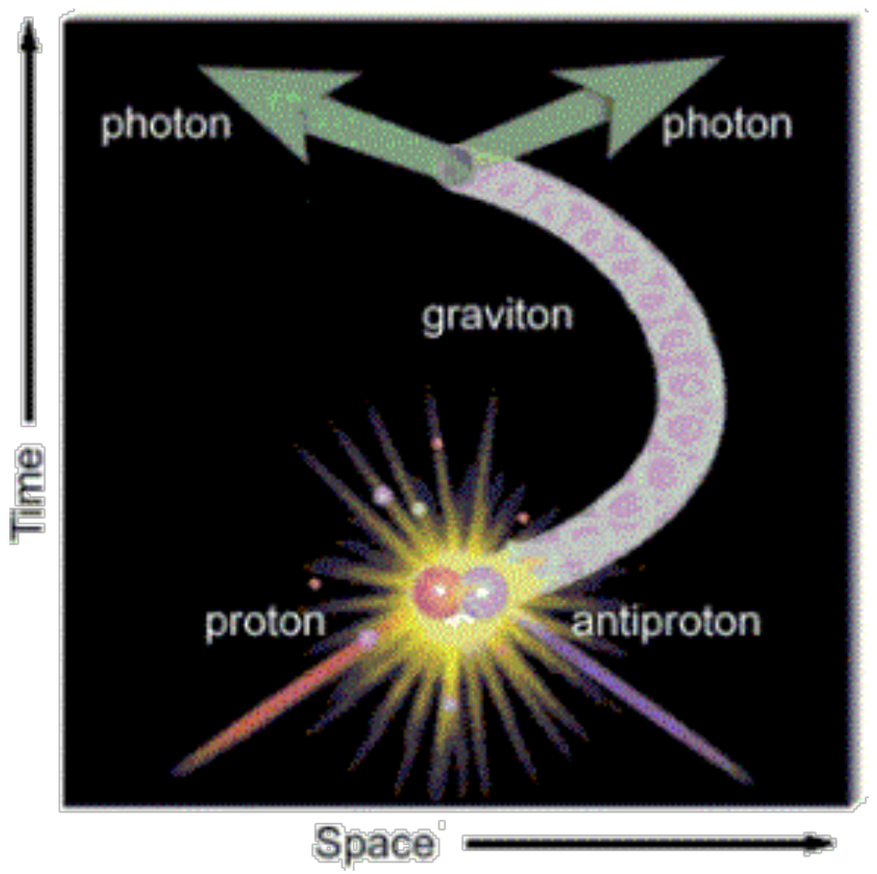
Knocking Gravitons Out of the Brane



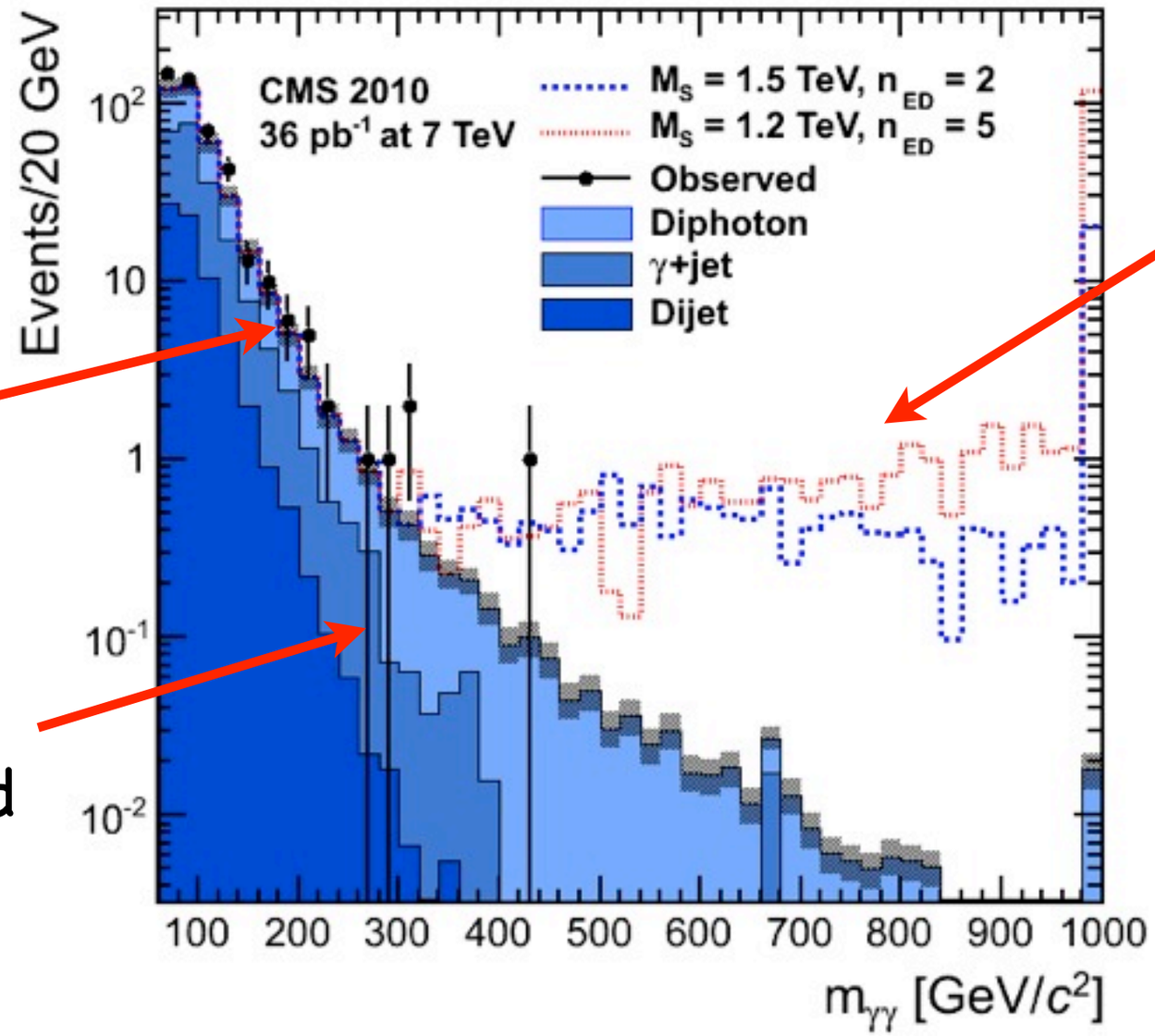
Knock gravitons out of the brane into the bulk

that then come back and decay to photons





Look for High Mass Photon Pairs



signal expectation

good agreement

SM background

No excess events seen

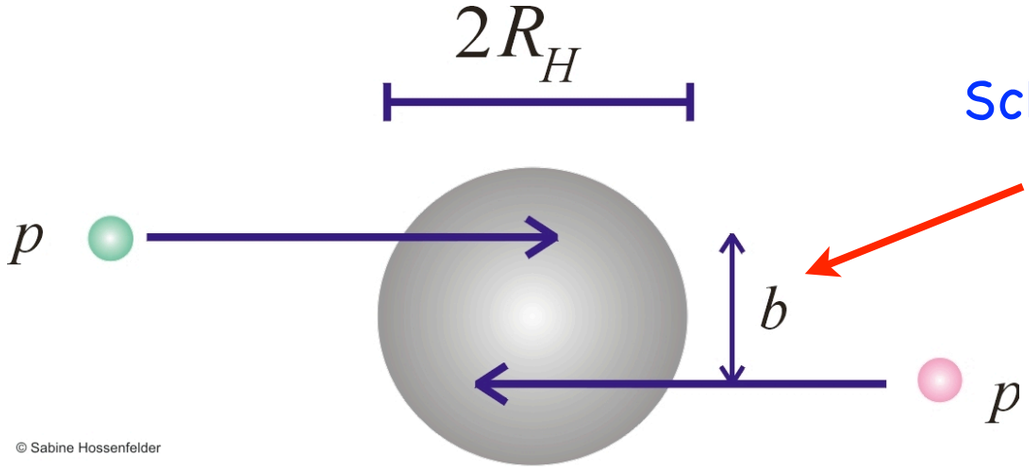
$M_{\gamma\gamma} > 500$ GeV/c²

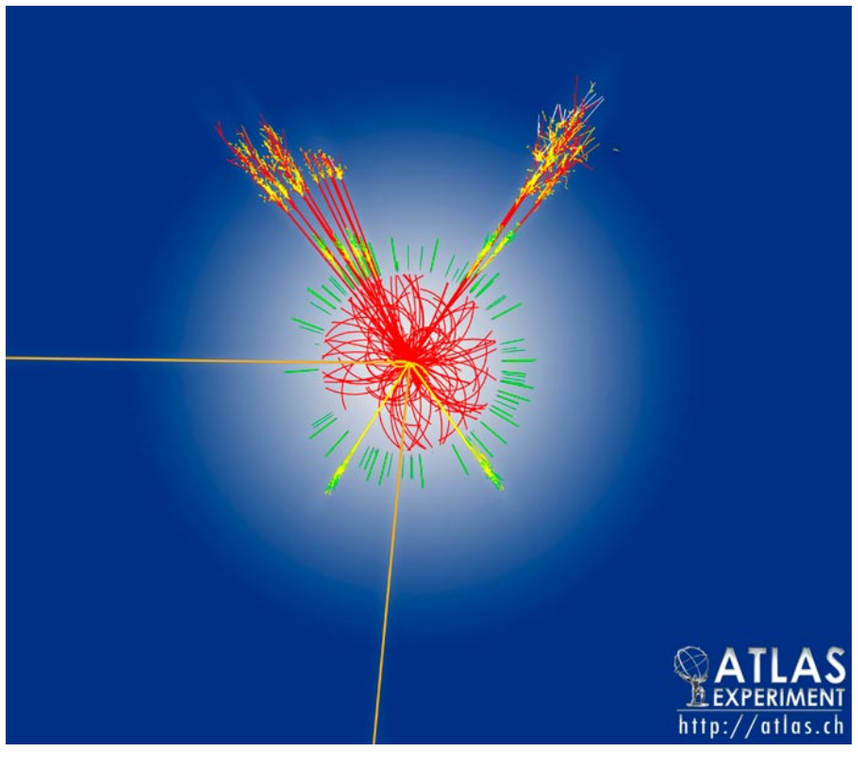
$M_S > 1.5$ TeV/c² for $n_{ED} = 7$

$M_S > 2.3$ TeV/c² for $n_{ED} = 3$

Black Hole Production

If gravity strong collisions may pack enough energy (mass) into a volume with radius less than Schwarzschild radius to create black hole





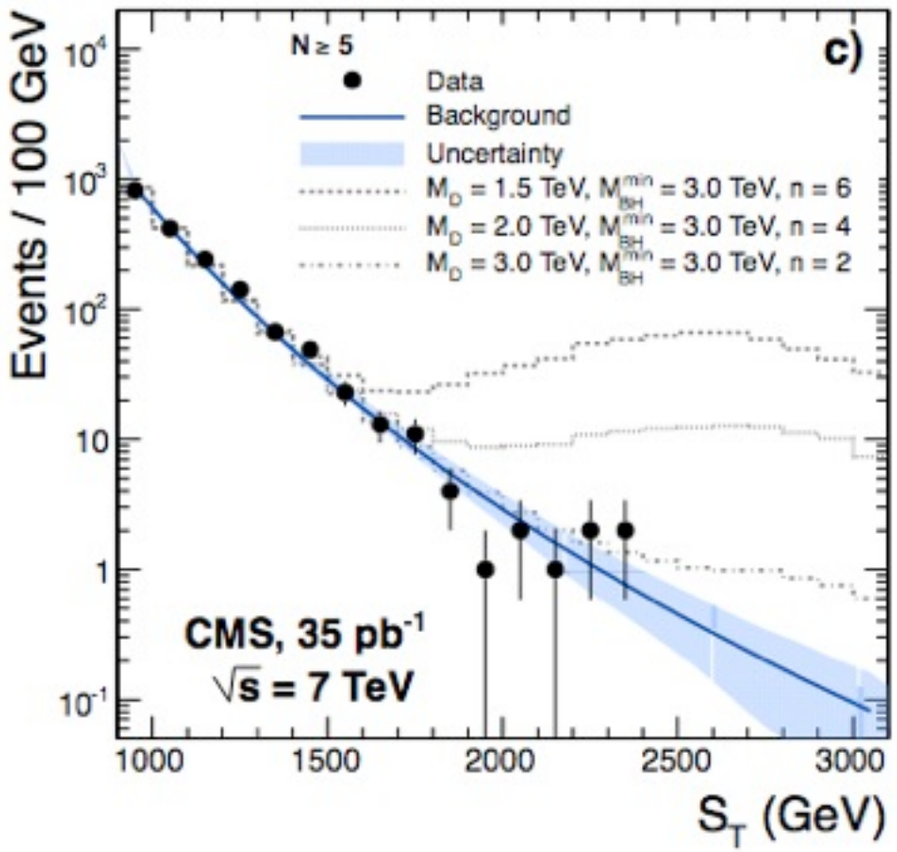
These would evaporate immediately 10^{-26} s by Hawking radiation

Black Hole Limits

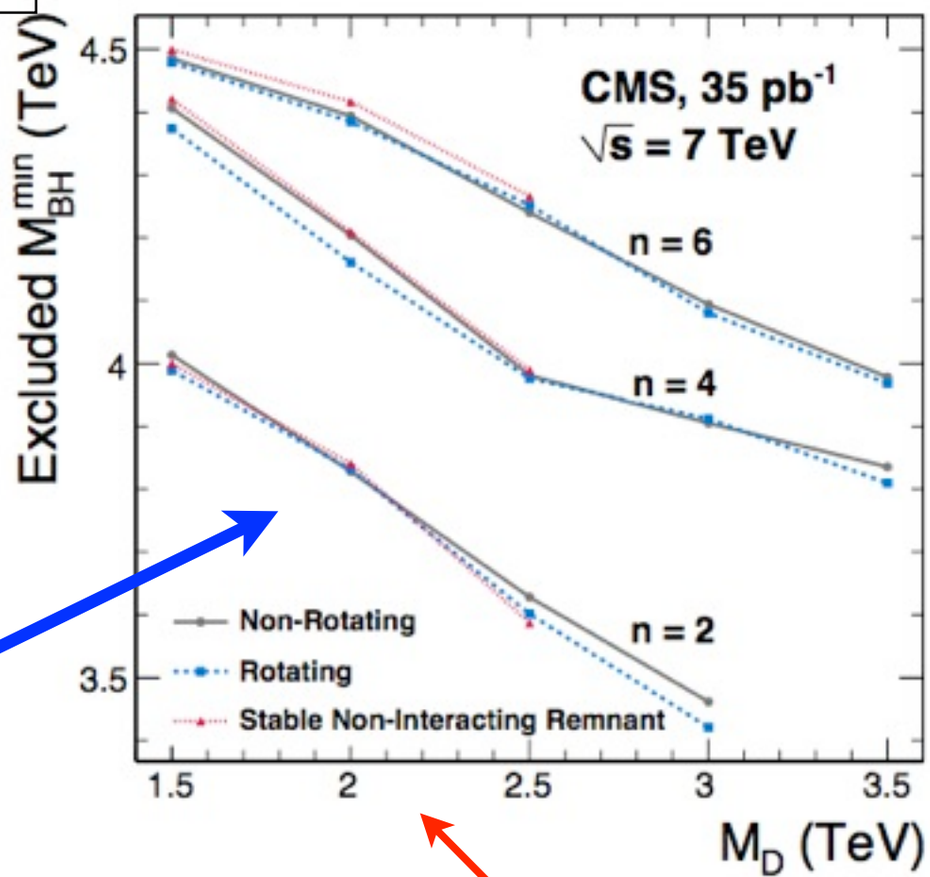
Black holes decay to a lot of particles

Sum up (transverse) momentum in the event

$$S_T = \sum p_T$$



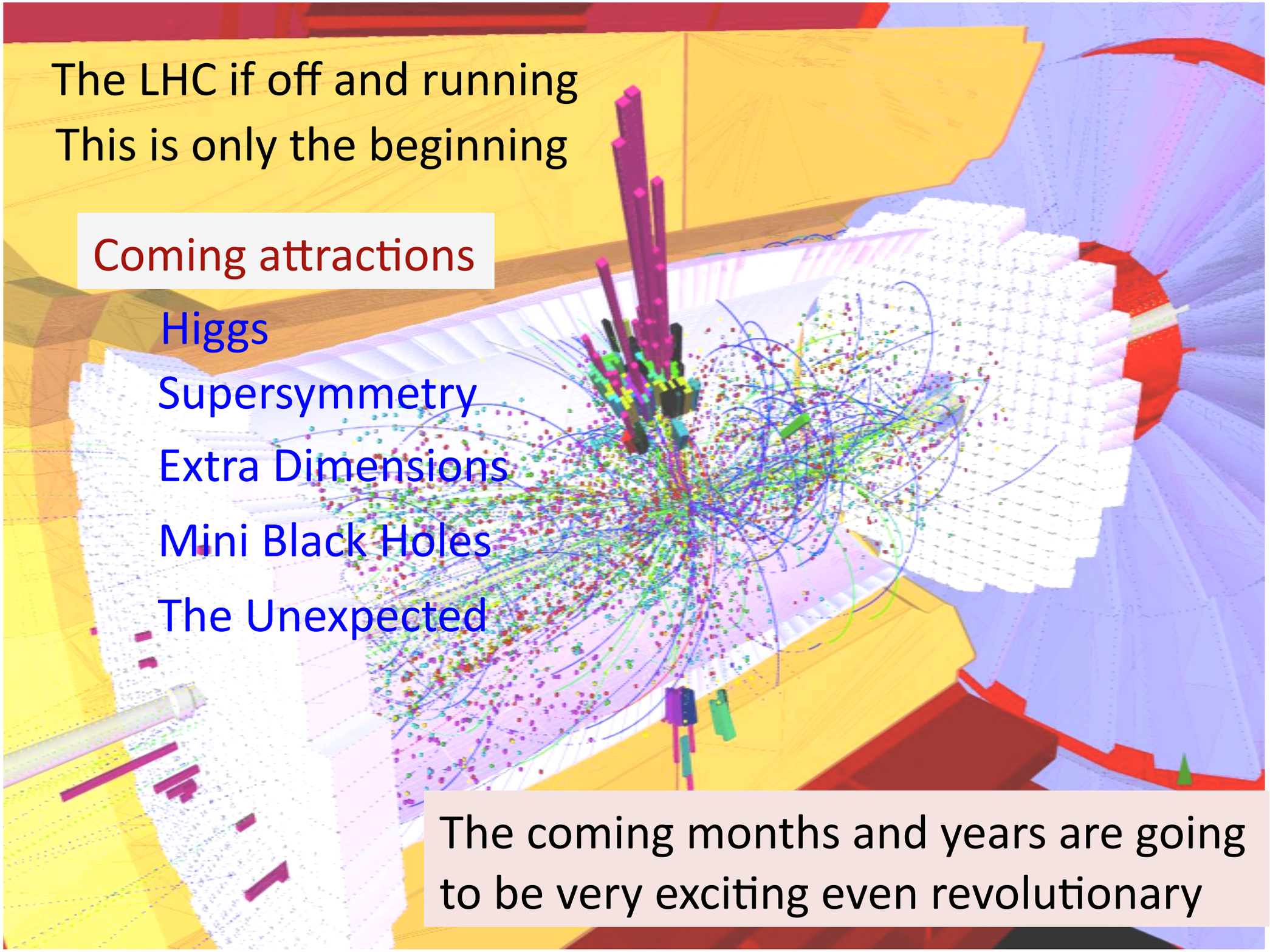
black hole mass



regions below curves are excluded

energy scale of extra dimension

Conclusion



The LHC if off and running

This is only the beginning

Coming attractions

- Higgs
- Supersymmetry
- Extra Dimensions
- Mini Black Holes
- The Unexpected

The coming months and years are going to be very exciting even revolutionary