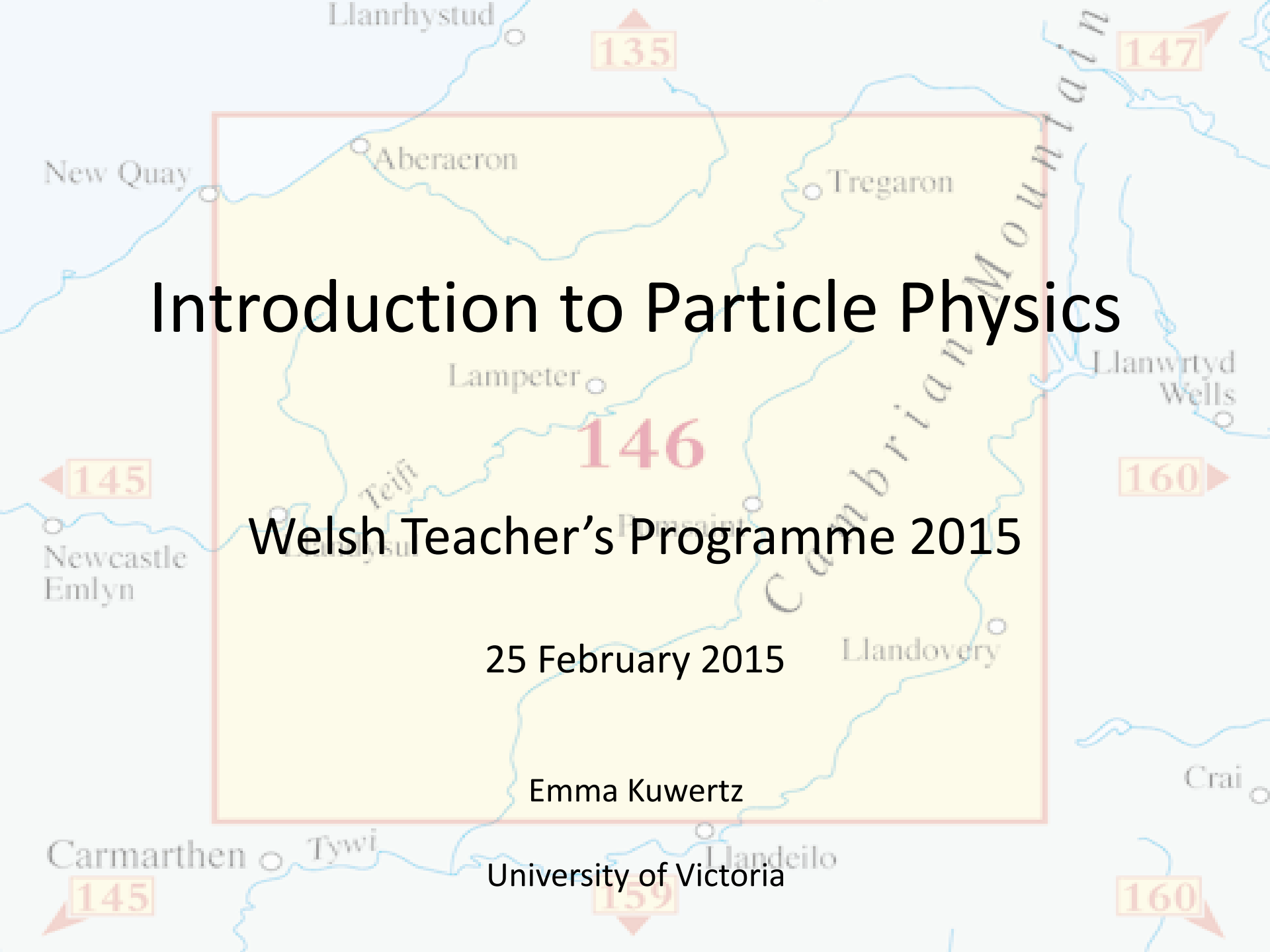


Introduction to Particle Physics

Welsh Teacher's Programme 2015

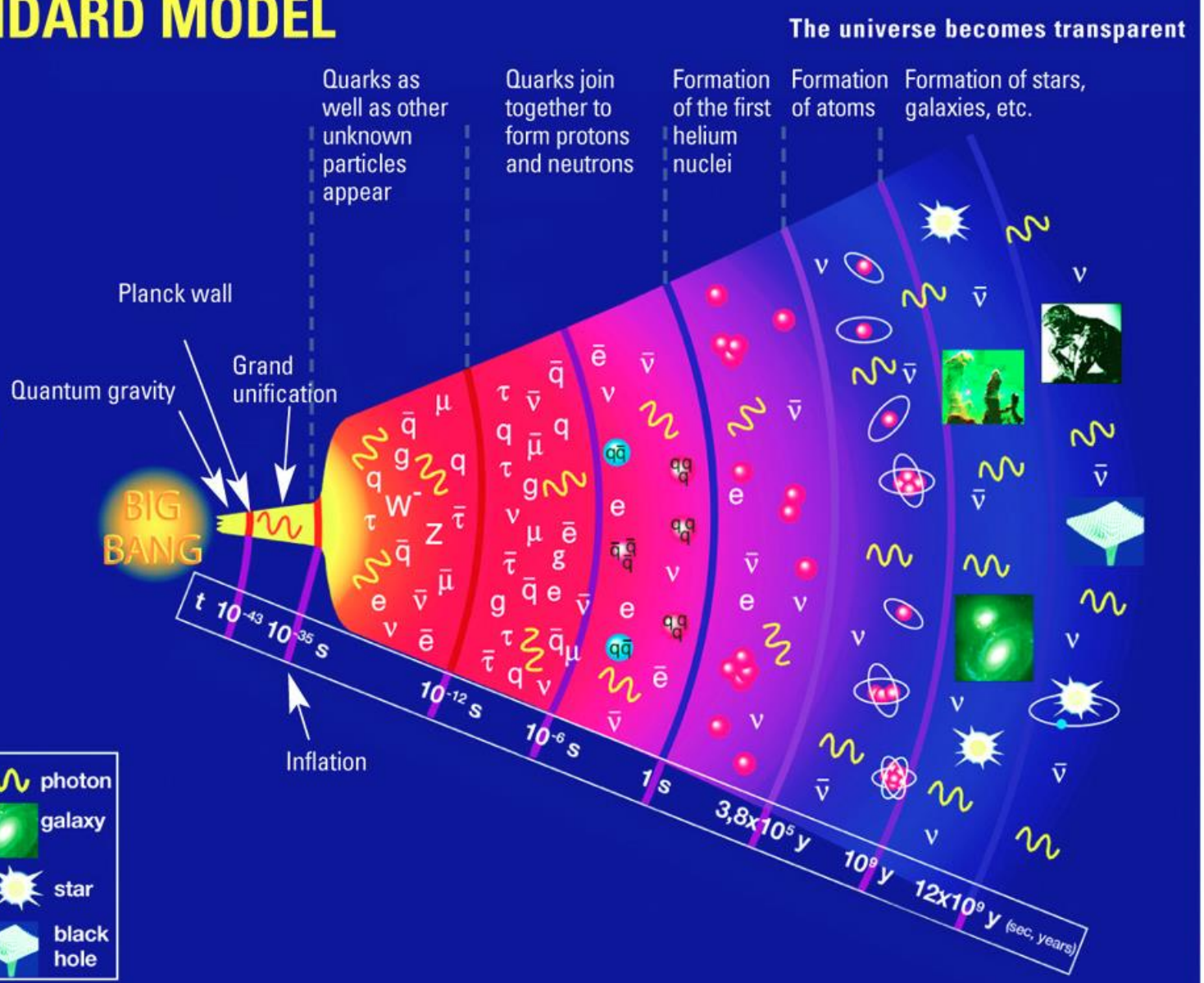
25 February 2015

Emma Kuwertz

University of Victoria

THE UNIVERSE ACCORDING TO THE STANDARD MODEL

Since the Big Bang, the primordial universe has gone through a number of stages, during which particles, and then atoms and light gradually emerged, followed by the formation of stars and galaxies.
This is the story as told by the "standard model" theory used today.



Captions			
q quark	W, Z bosons	photon	
g gluon	qq meson	galaxy	
e electron	qqq baryons	star	
μ muon τ tau	ions	black hole	
ν neutrino	atom		

young, hot, energetic → old, cool, less energetic

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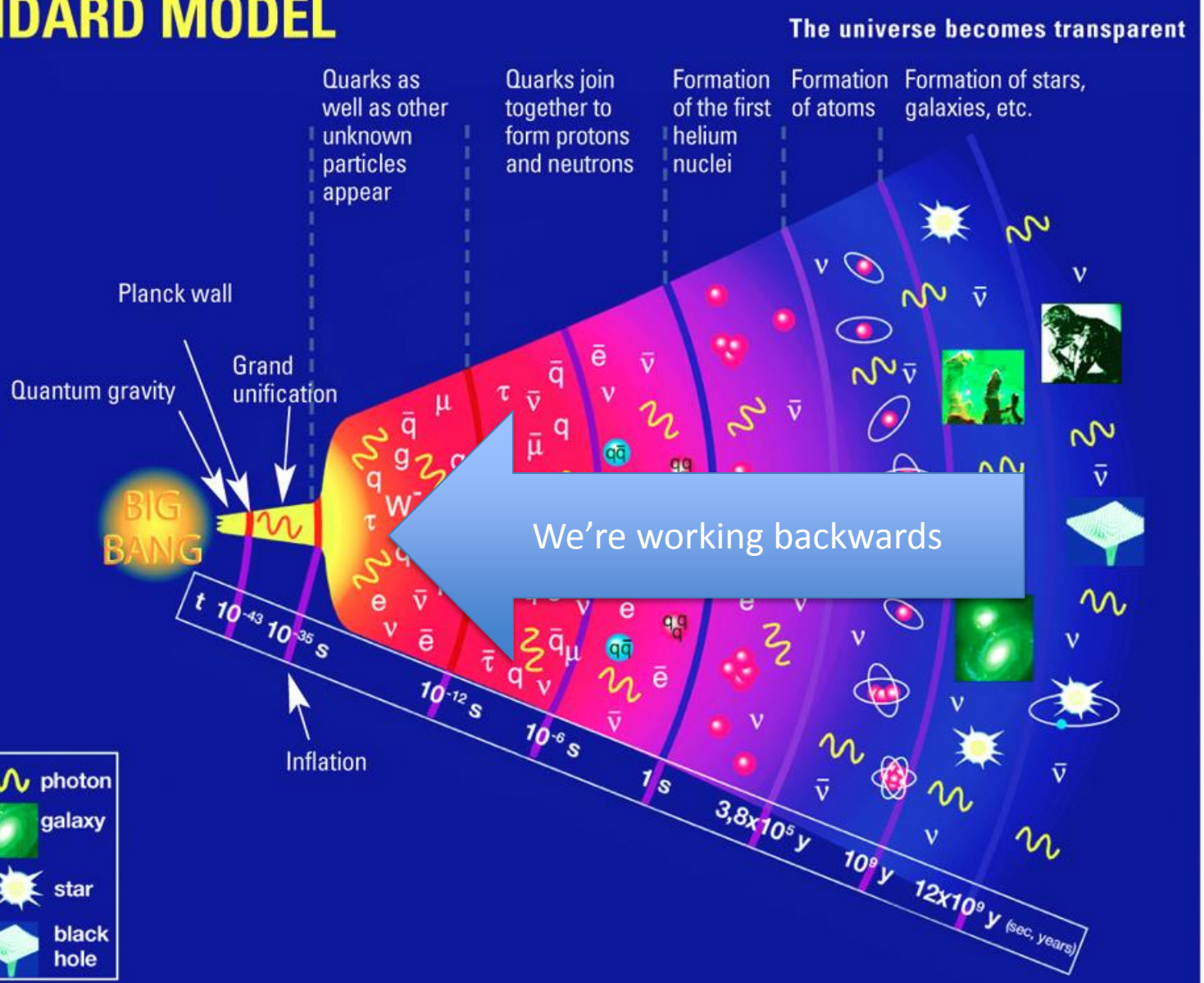

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What is the universe made of?

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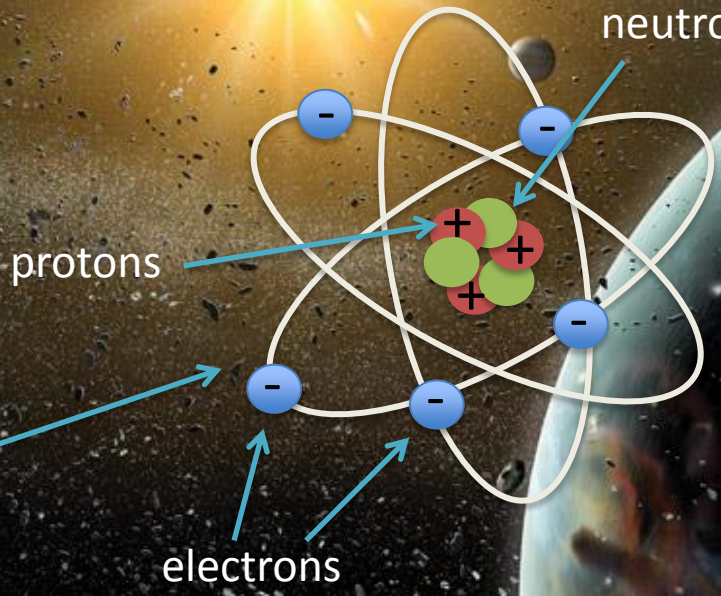
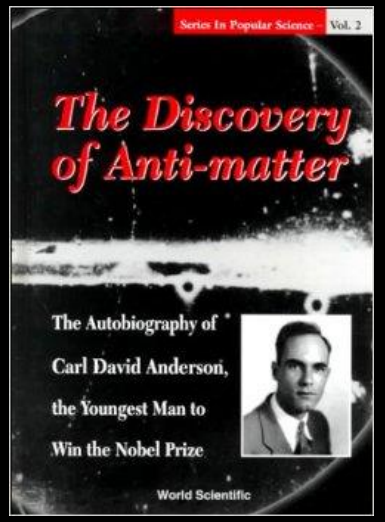


Antimatter

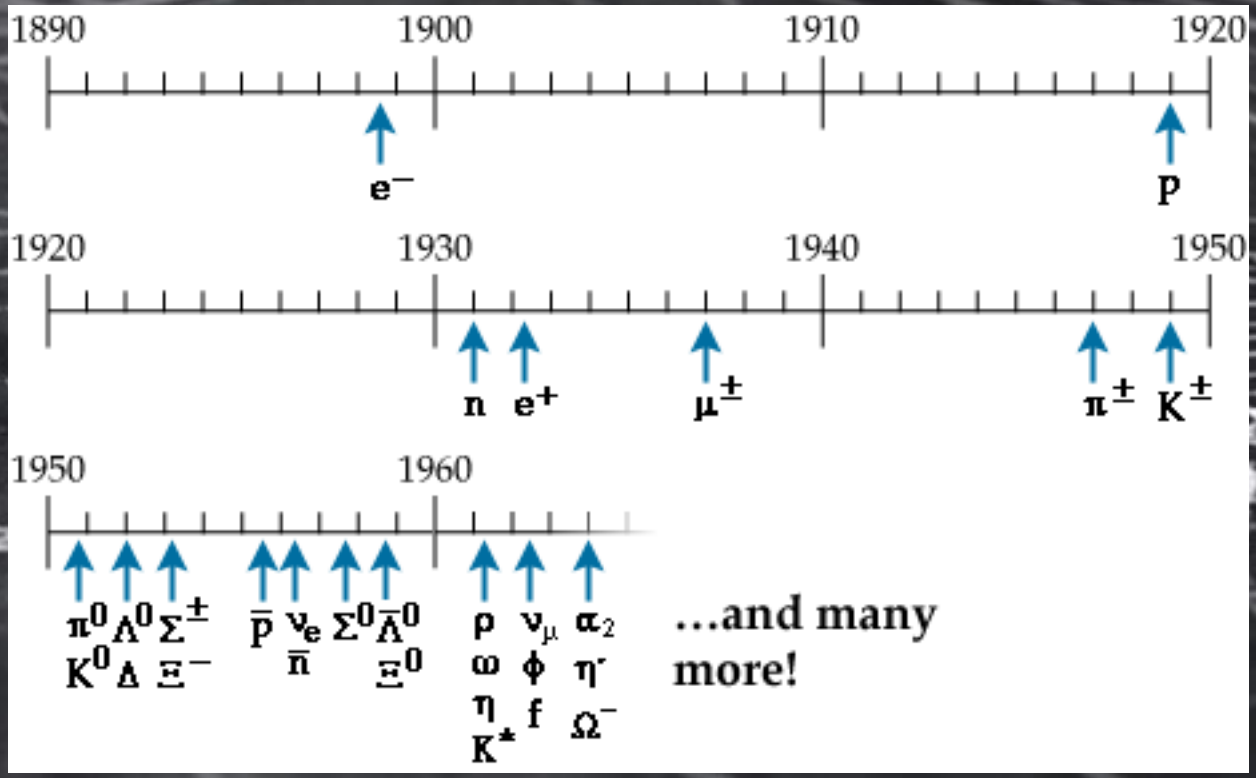
1928: Dirac predicted existence of antimatter.



1932: antielectrons (positrons) discovered by Carl D. Anderson (Nobel prize 1936)

1995: antihydrogen consisting of antiprotons and positrons produced at CERN

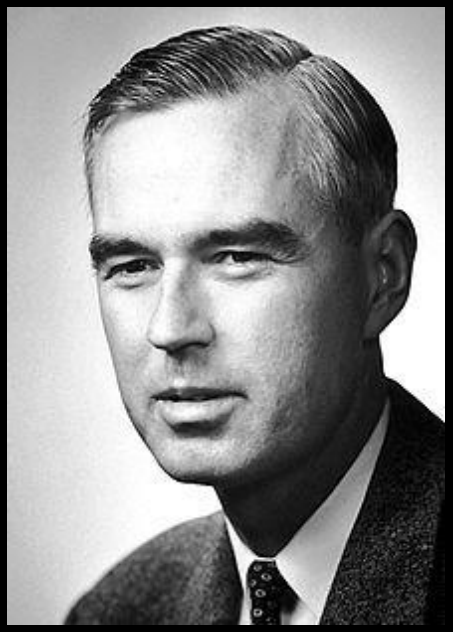
Particles discoveries take off…



Chaos!

The finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a 10,000 dollar fine.

(Willis Lamb)

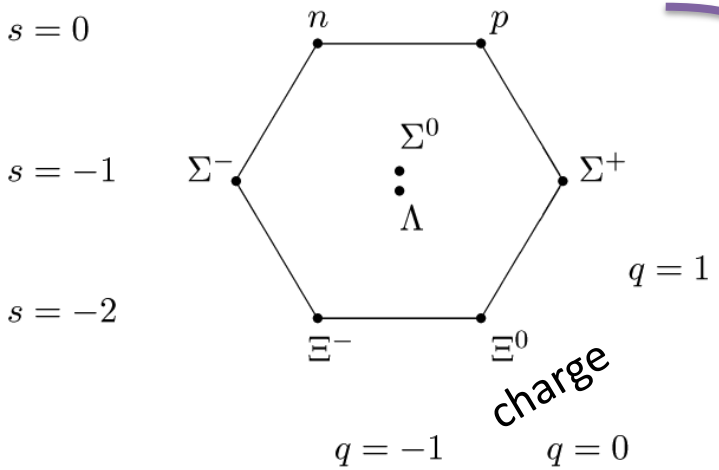


Had I foreseen this, I would have gone into botany.

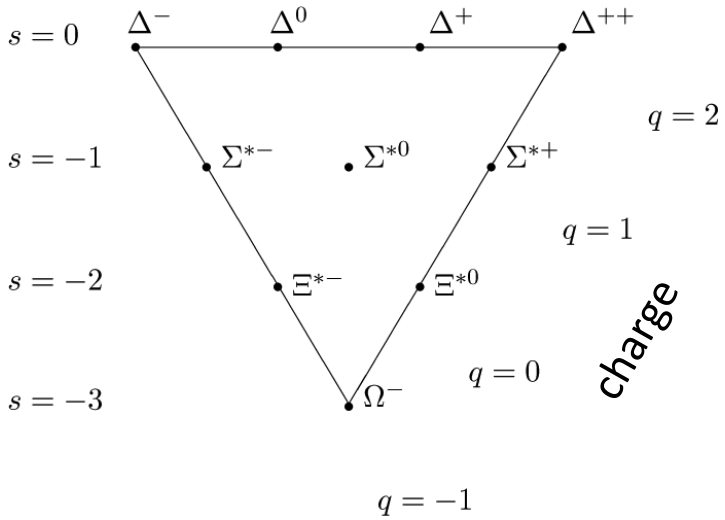
(Wolfgang Pauli)

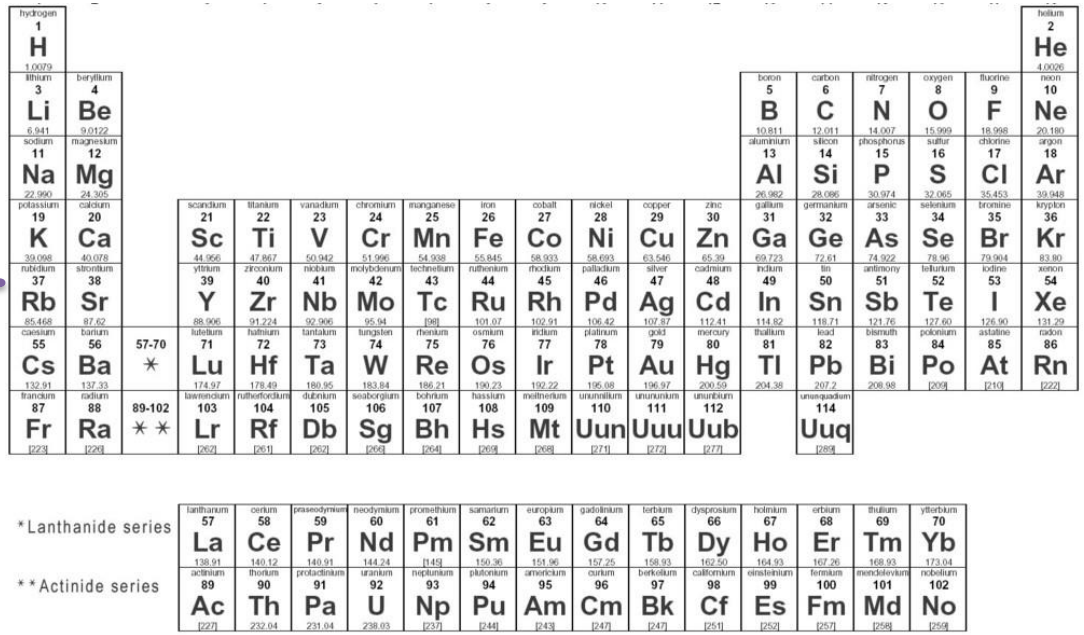
A periodic table of particles?

spin



strangeness





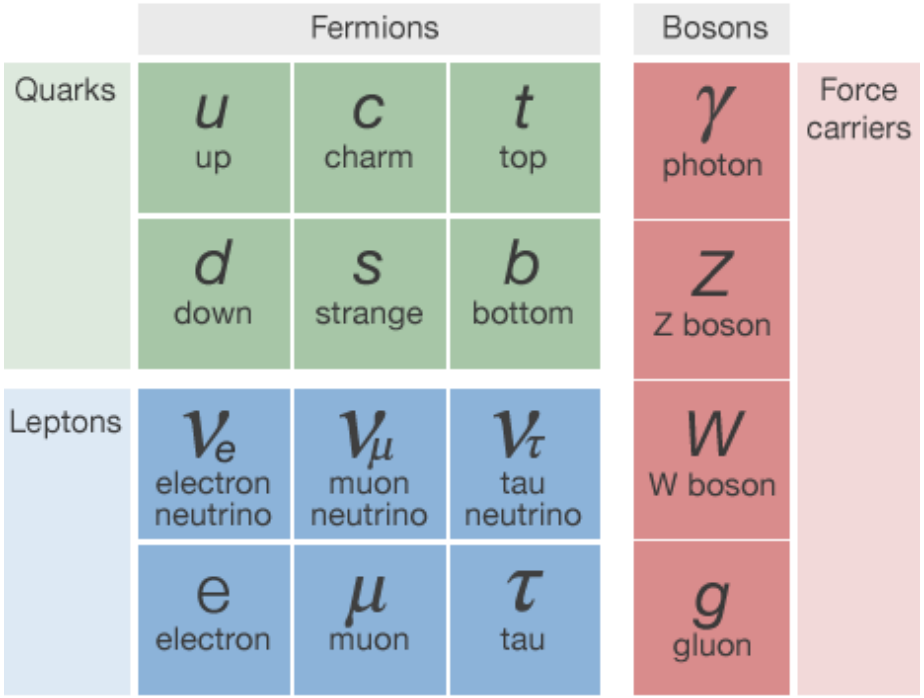
The Standard Model

q = +3/2

q = -1/2

Charge neutral

q = -1



Spin ½

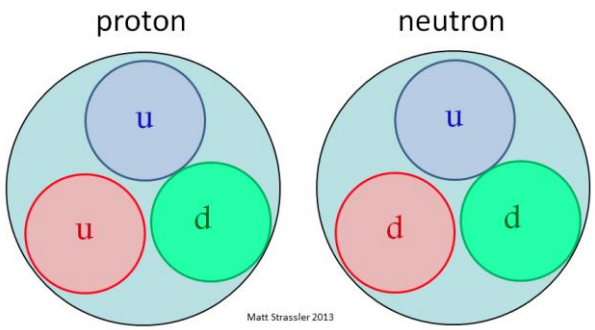
Spin 1

Fermion mass

Matter

These are what protons and neutrons are made of

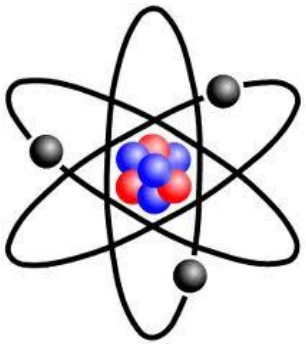
	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	

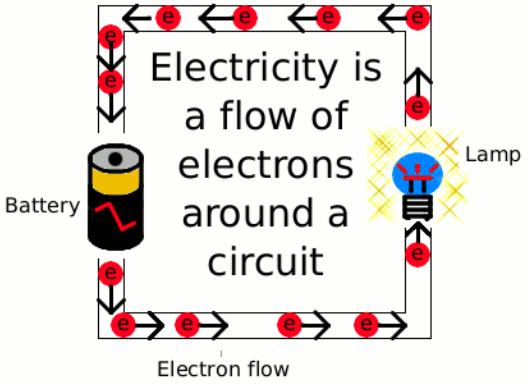


Matter

	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	

These form a cloud around atomic nucleii

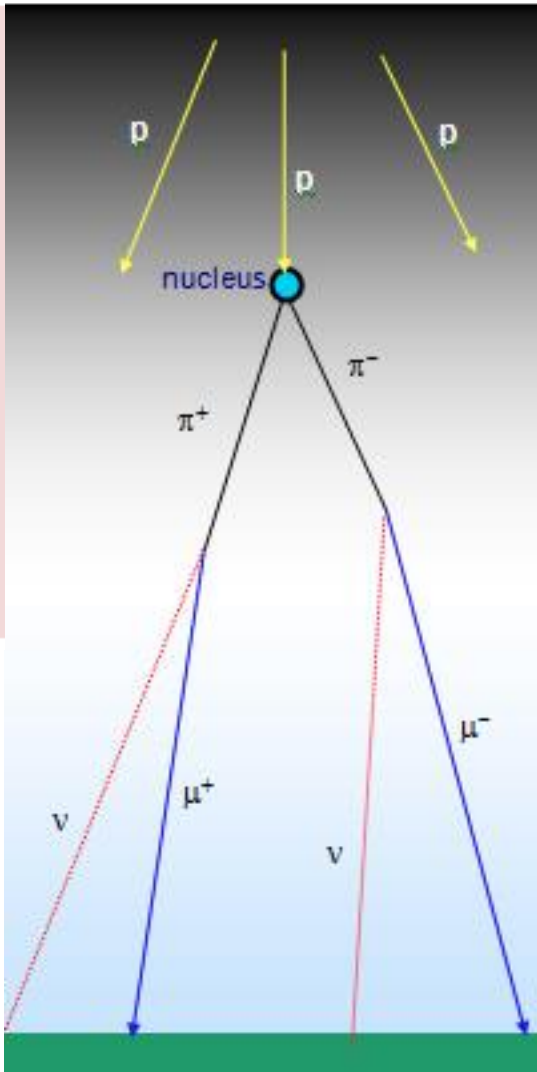




Matter

	Fermions			Bosons	Force carriers
Quarks	u up	c charm	t top	γ photon	
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	

Produced by cosmic rays

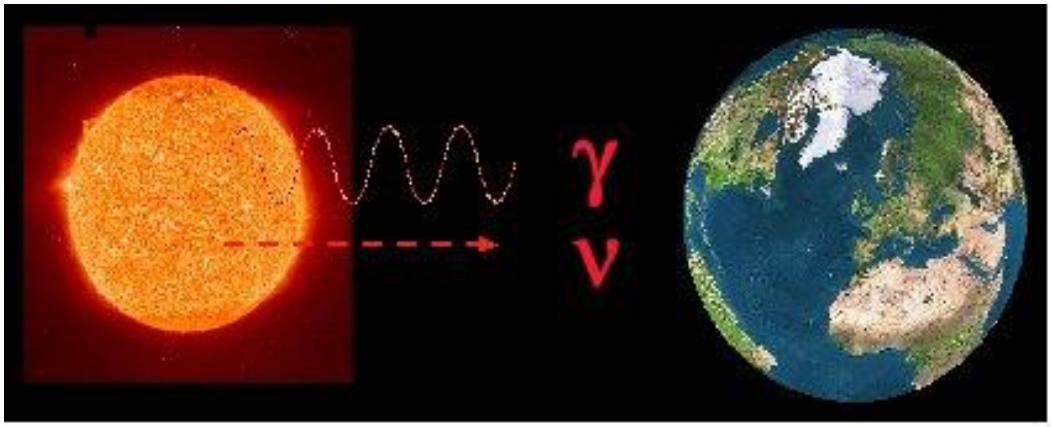


A few hundred of these pass through your body every second

Matter

	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	

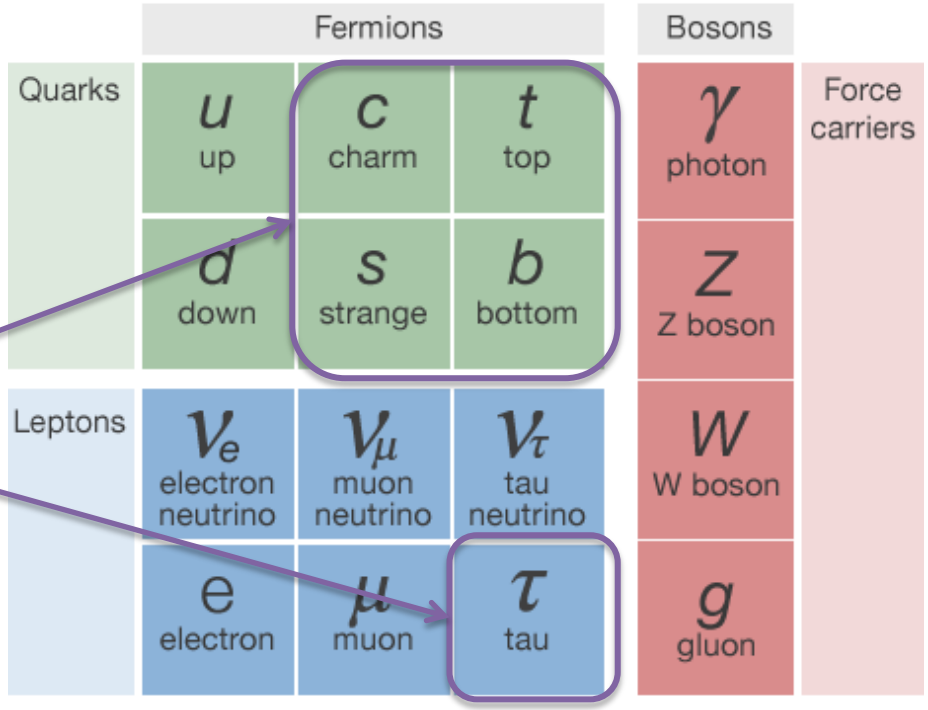
These come from nuclear reactions in the sun, radioactive decays, etc.



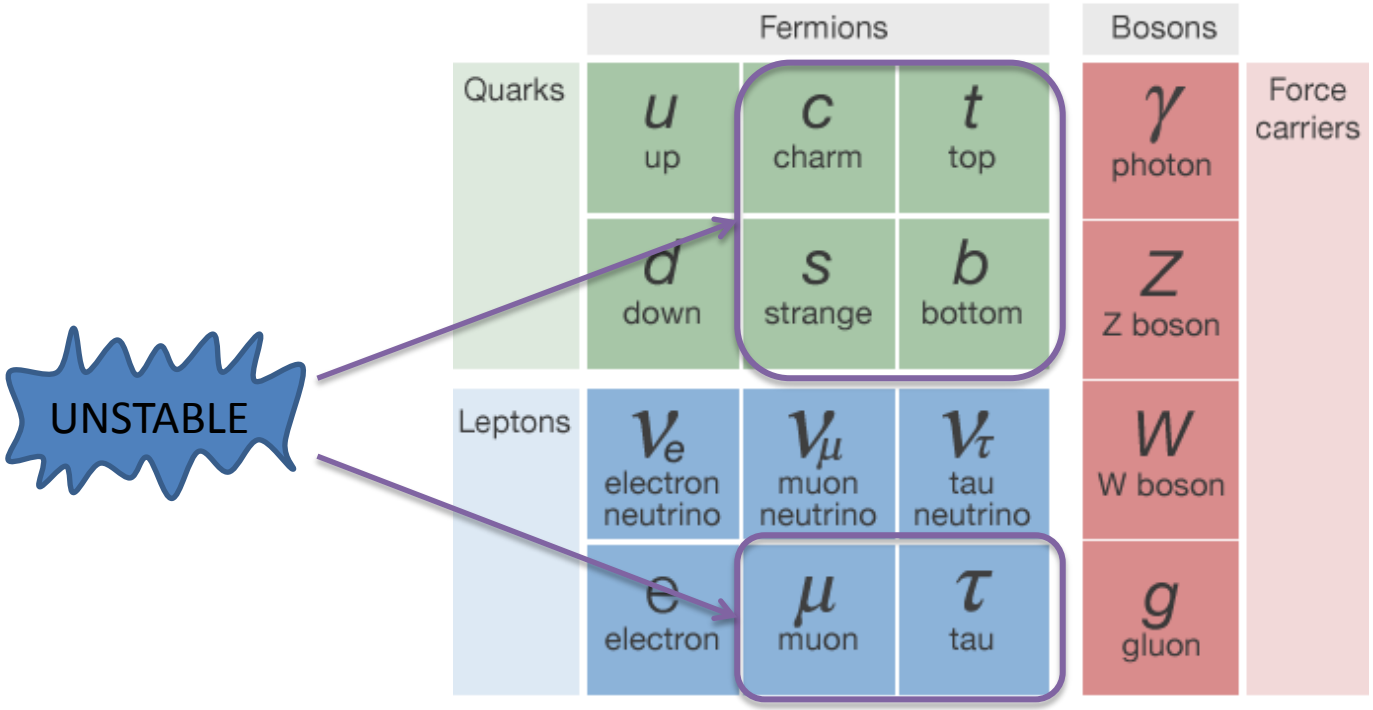
A few billion of these pass through your body every second

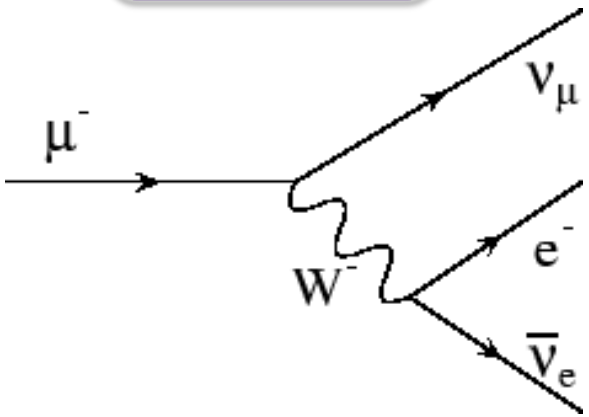
Matter

Unless you're really into particle physics you may not have heard of these guys



Matter

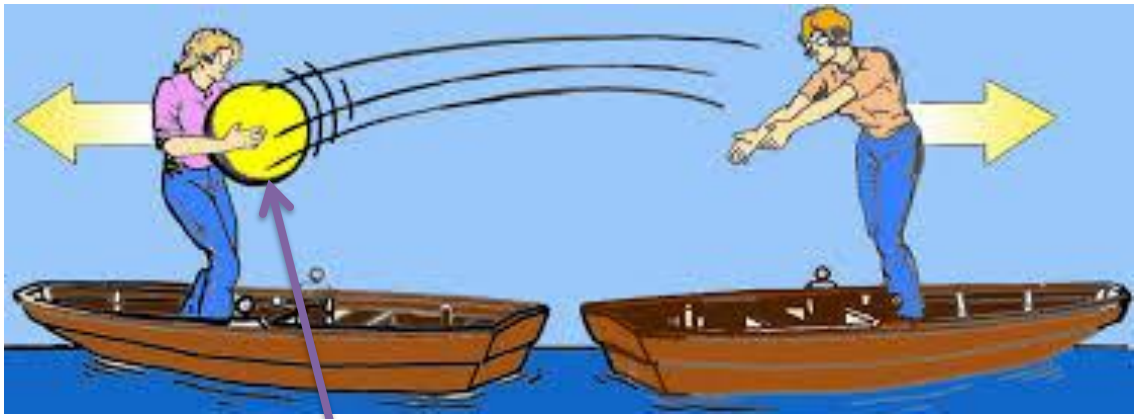

Fermions
Bosons
Quarks
Leptons
Force carriers
u up
c charm
t top
γ photon
d down
s strange
b bottom
Z Z boson
νe electron neutrino
νμ muon neutrino
ντ tau neutrino
W W boson
e electron
μ muon
τ tau
g gluon
UNSTABLE

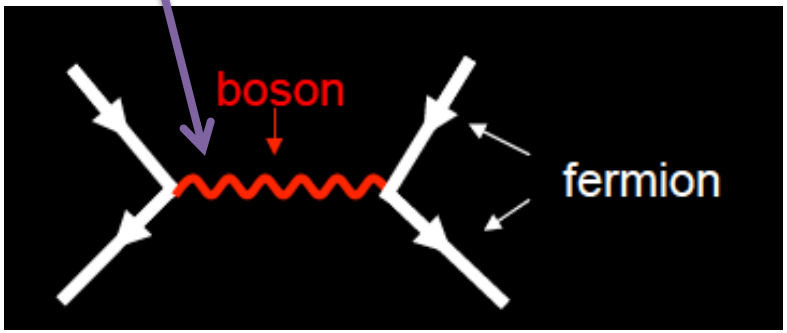

μ-
νμ
W-
e-
ν̄e

Forces

Person A and person B exchanging a ball

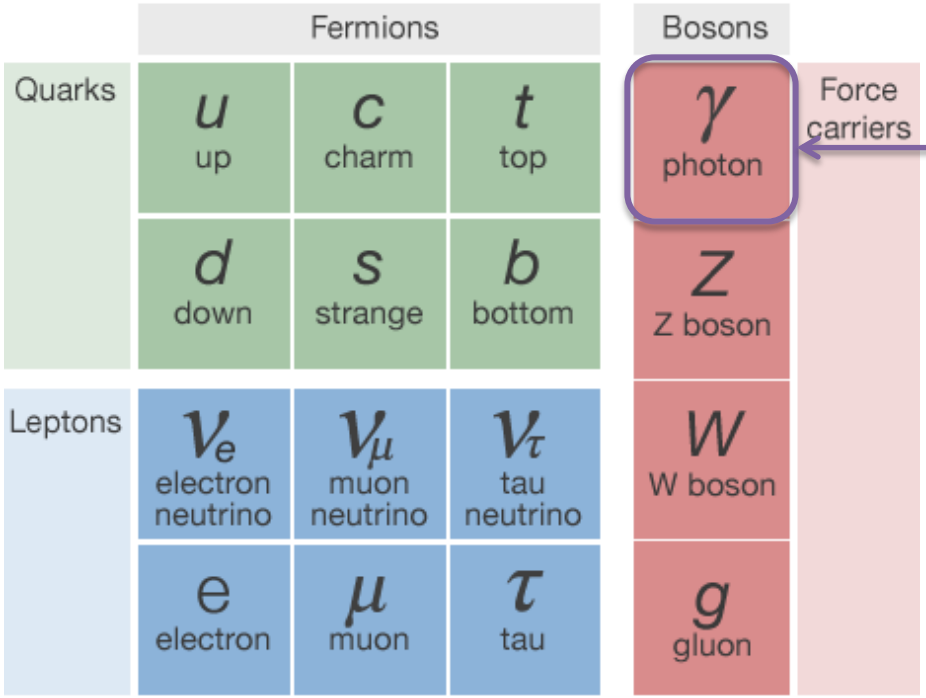
A B





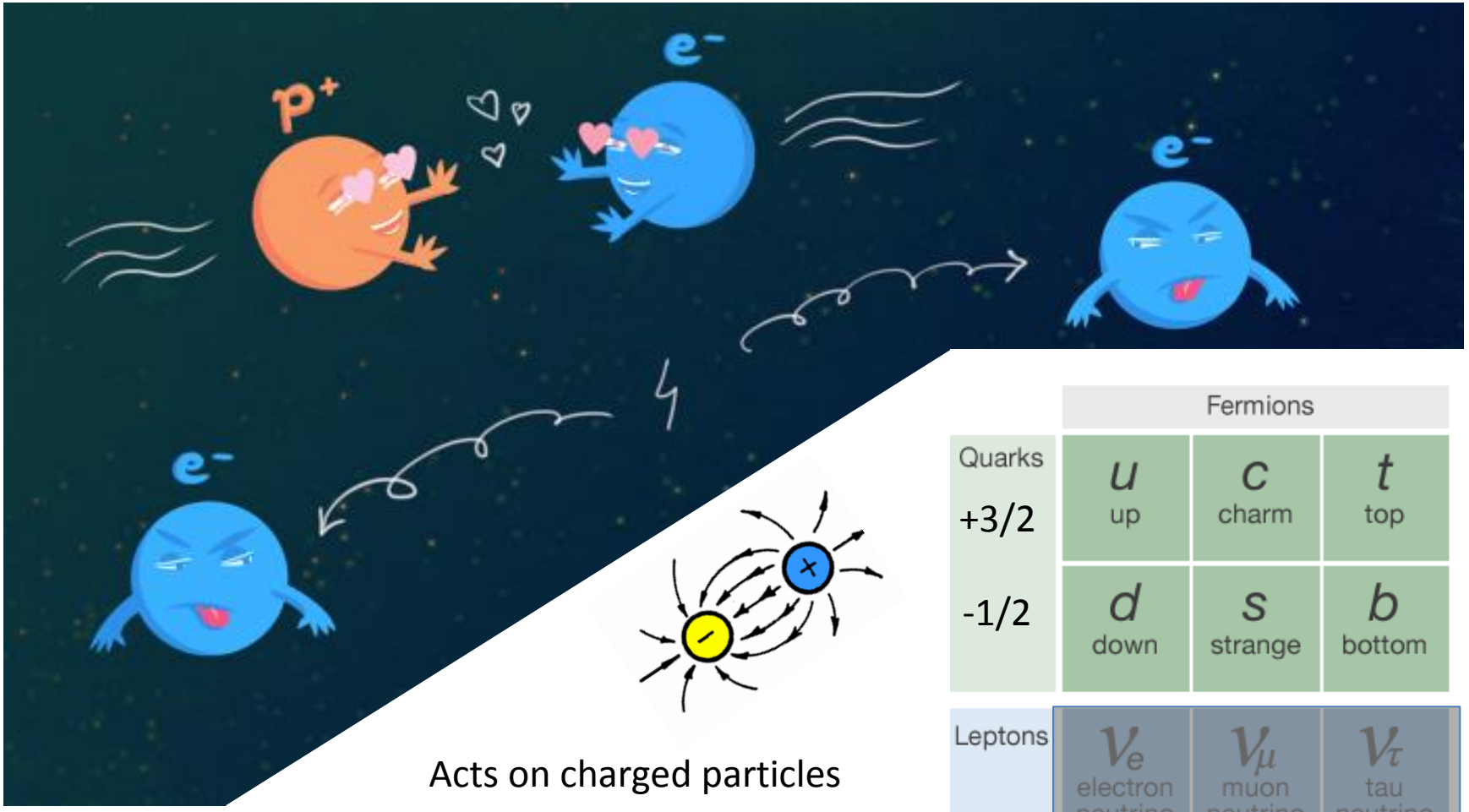
Fermions exchanging a boson

EM force



These keep electrons in place around the nucleii

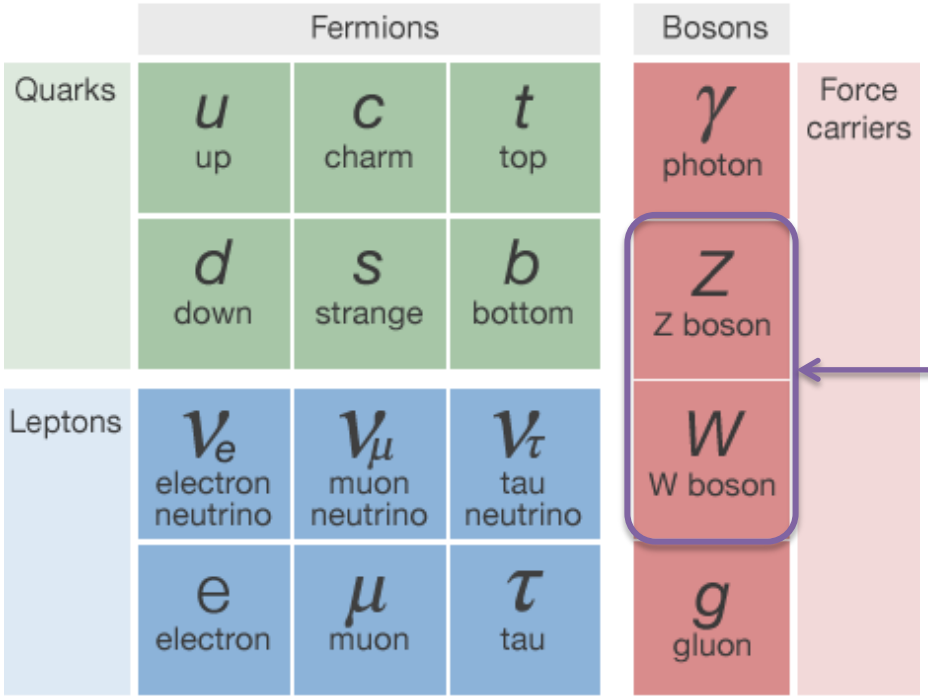
EM force



Acts on charged particles

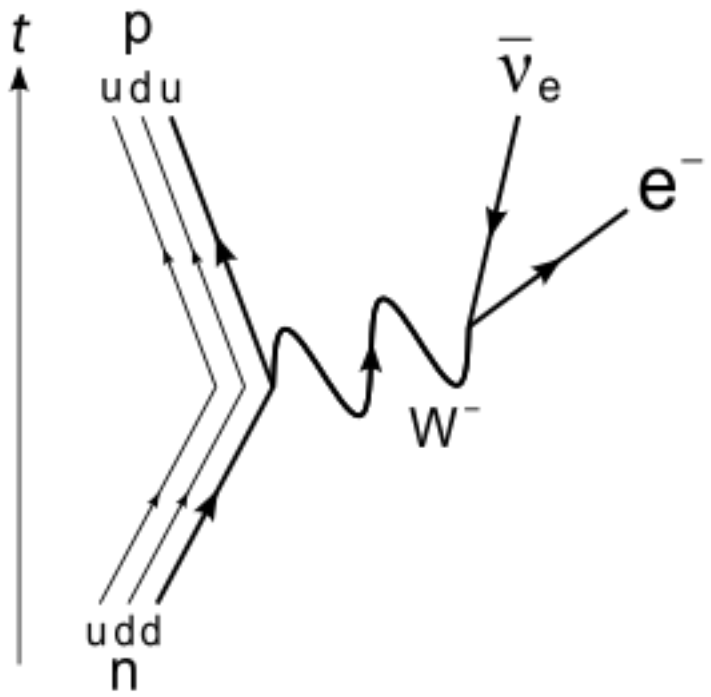
	Fermions		
Quarks			
+3/2	u up	c charm	t top
-1/2	d down	s strange	b bottom
Leptons			
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
+1	e electron	μ muon	τ tau

Weak force



These are responsible for beta decay

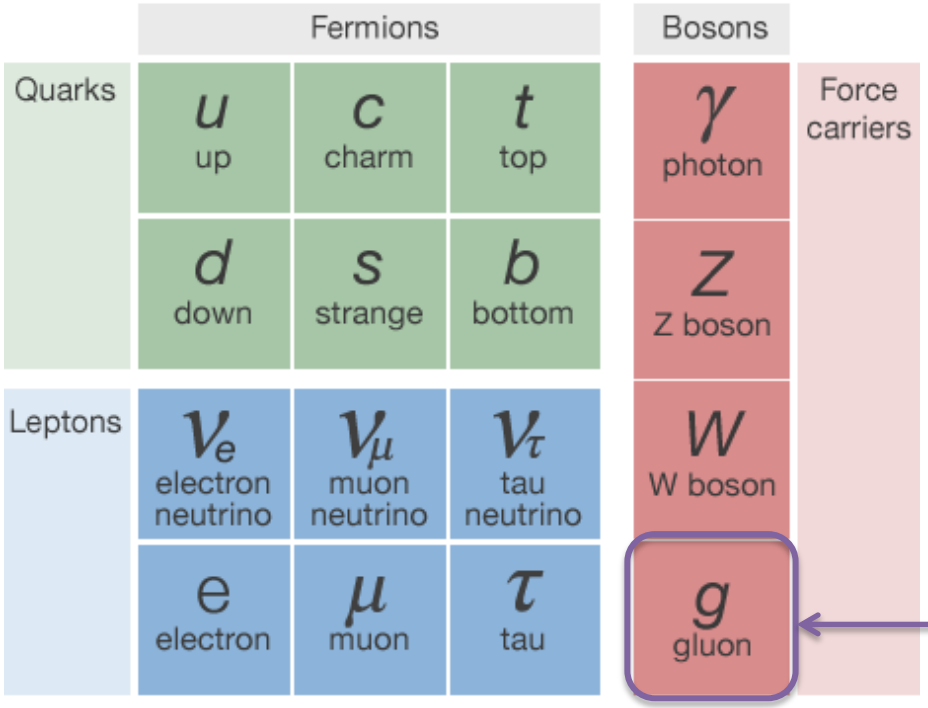
Weak force



Acts on all the matter particles
Mediated by massive bosons

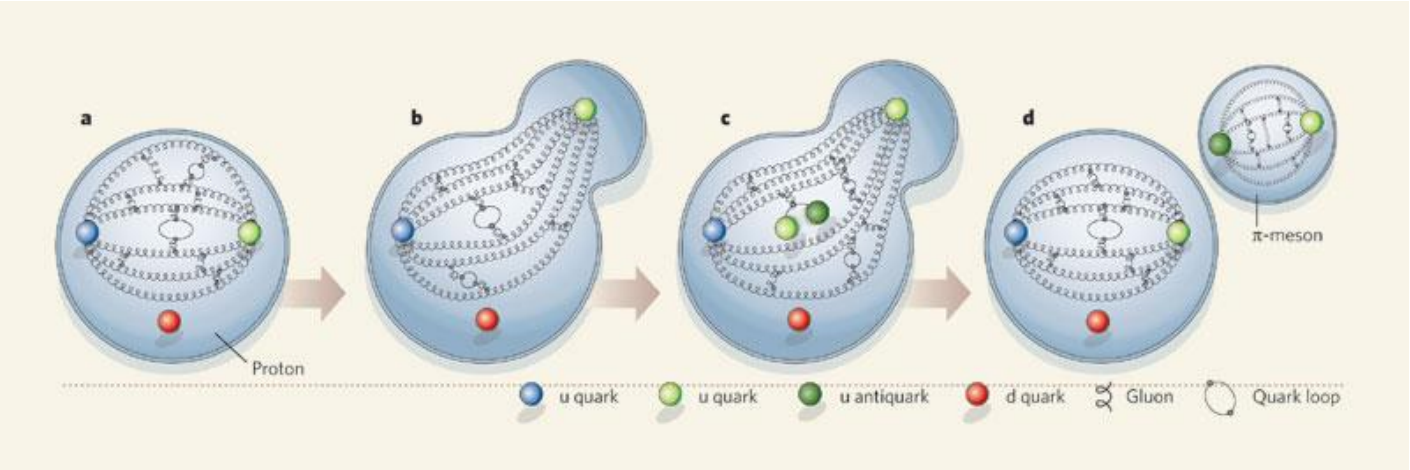
	Fermions		
Quarks	*u* up	*c* charm	*t* top
	d down	*s* strange	*b* bottom
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
	e electron	μ muon	τ tau

Strong force



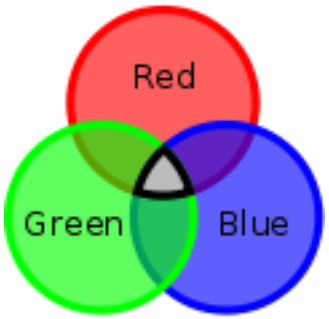
These glue the quarks together inside the protons and neutrons

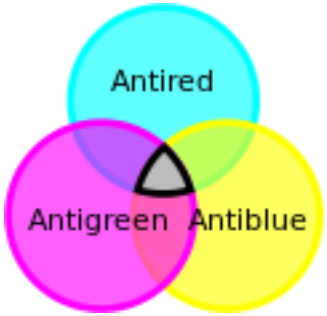
Strong force



Baryons: qqq
Mesons: q anti-q

Acts on particles with colour charge

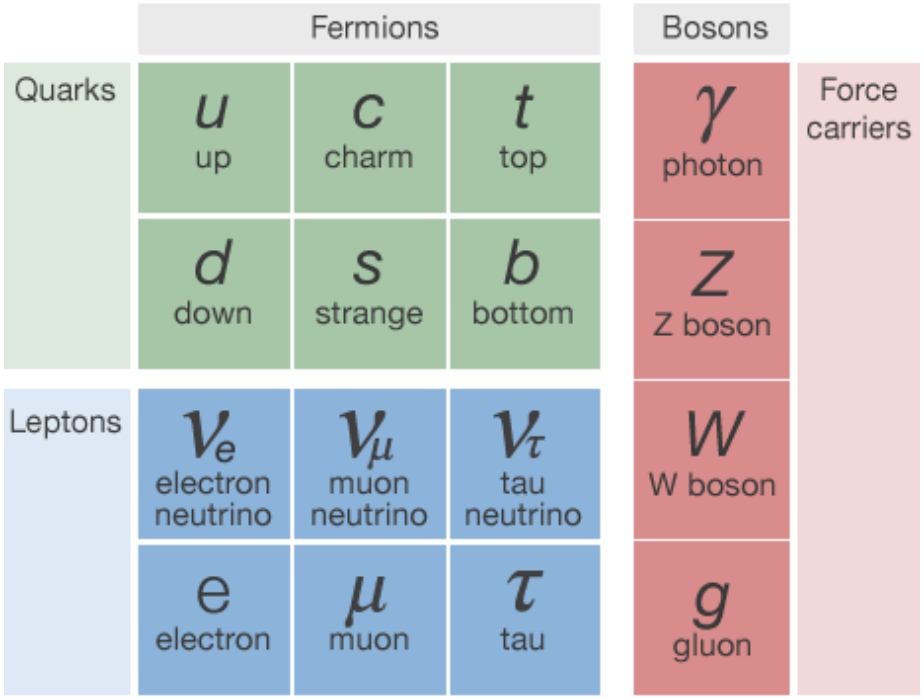




	Fermions		
Quarks	u up	c charm	t top
	d down	s strange	b bottom
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
	e electron	μ muon	τ tau

Gravitational force

?



?

Graviton?

Force strength: “couplings”

EM force between 2 electrons:

$$F = \frac{e^2}{4\pi\epsilon_0 r^2}$$

$$\alpha = \frac{e^2}{4\pi\epsilon_0}\frac{1}{\hbar c}$$

$$F = \frac{\alpha}{r^2}$$

Strong	$\alpha_s \sim 1$
Electromagnetic	$\alpha_{EM} \sim 1/137$
Weak	$\alpha_W \sim 10^{-6}$
Gravitational	$\alpha_g \sim 10^{-39}$

Coupling constant quantifies force strength

Note: couplings are energy dependent!

Force strength: “couplings”

Strong	$\alpha_s \sim 1$
Electromagnetic	$\alpha_{EM} \sim 1/137$
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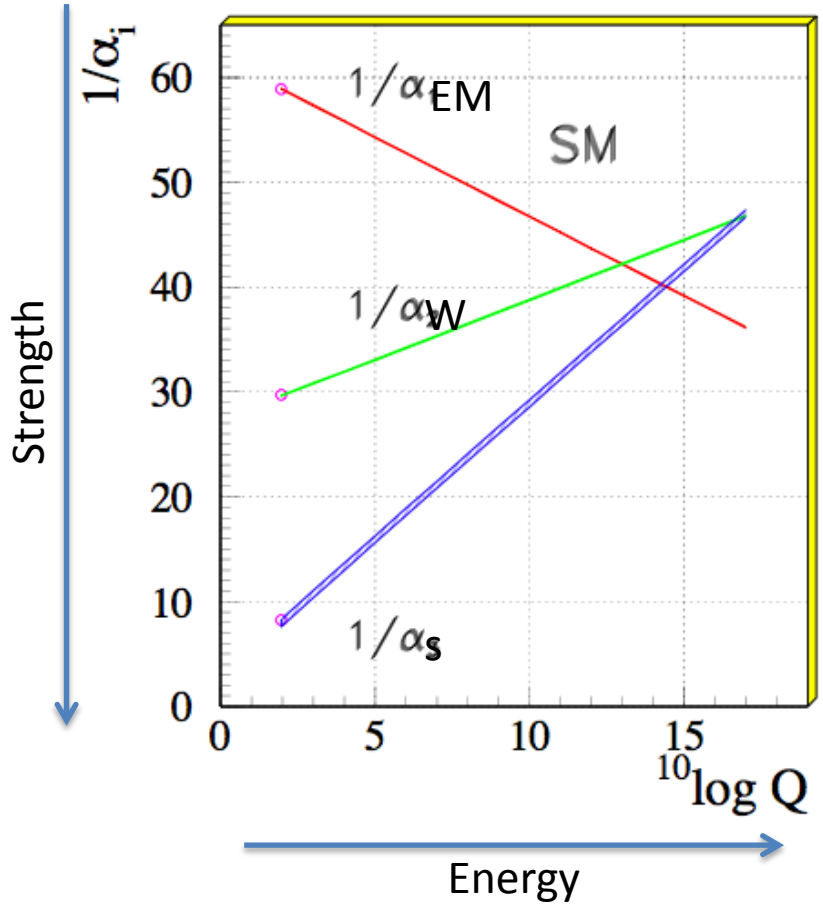
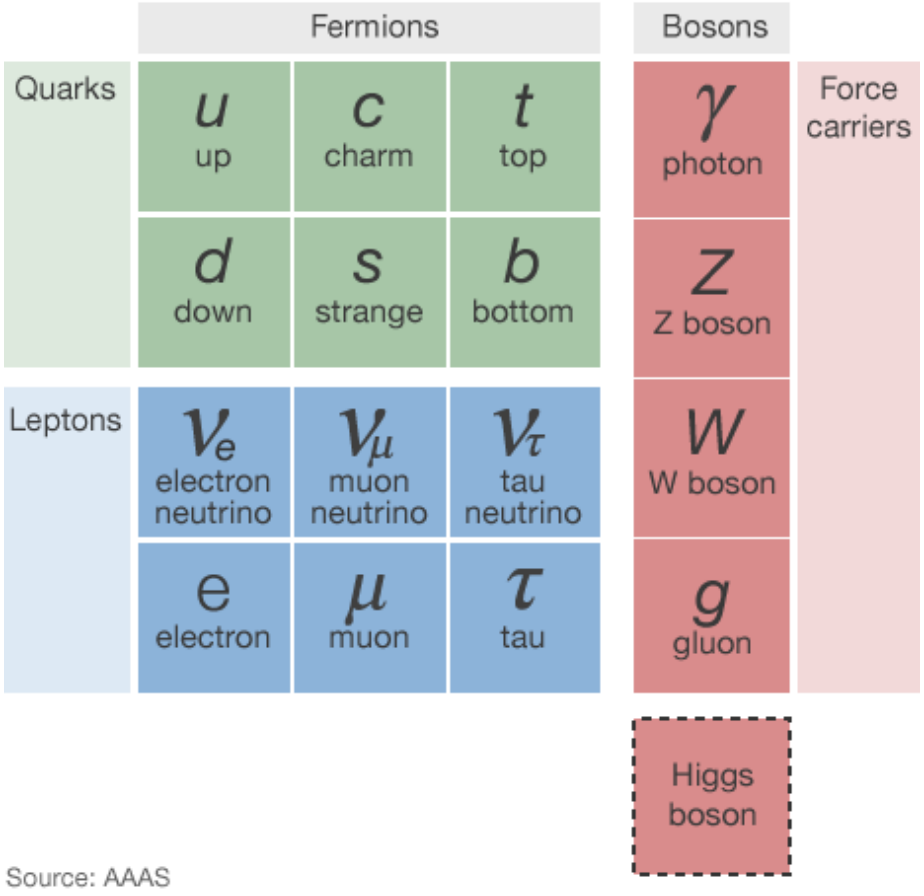
Gravitational	$\alpha_g \sim 10^{-39}$



Note: couplings are energy dependent!

A missing piece



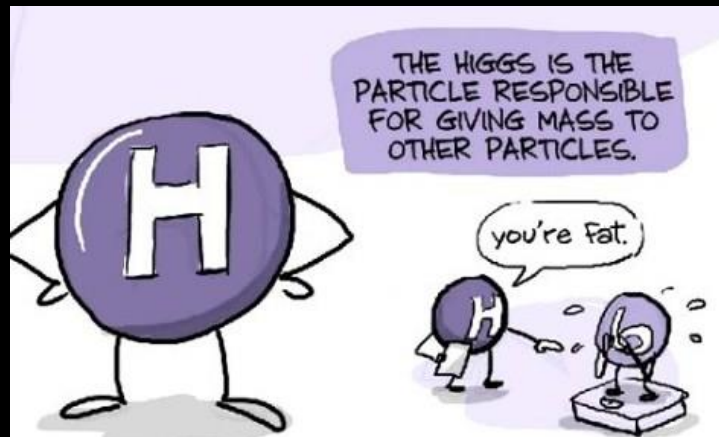
BOSONS

force carriers
spin = 0, 1, 2, ...

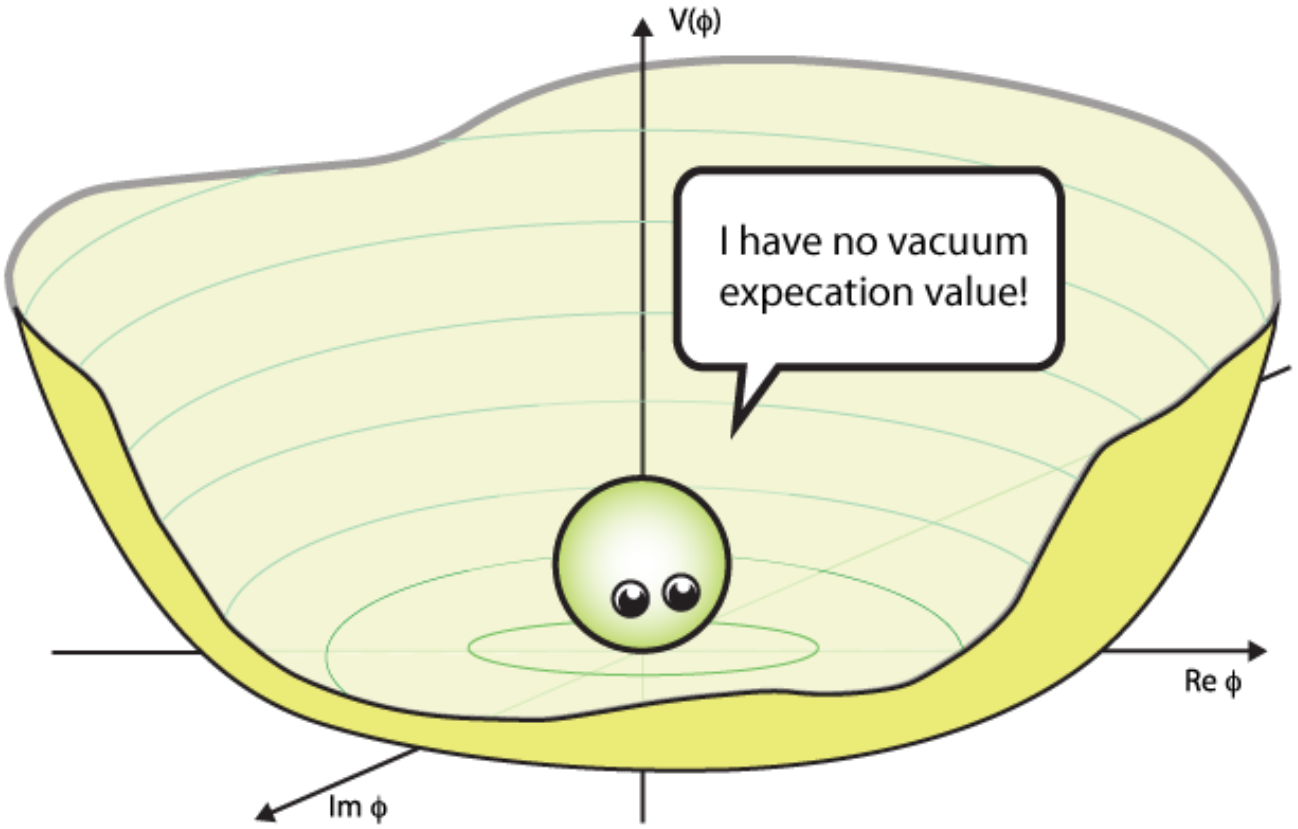
Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Massive bosons?
Requires a new potential in the Standard Model!



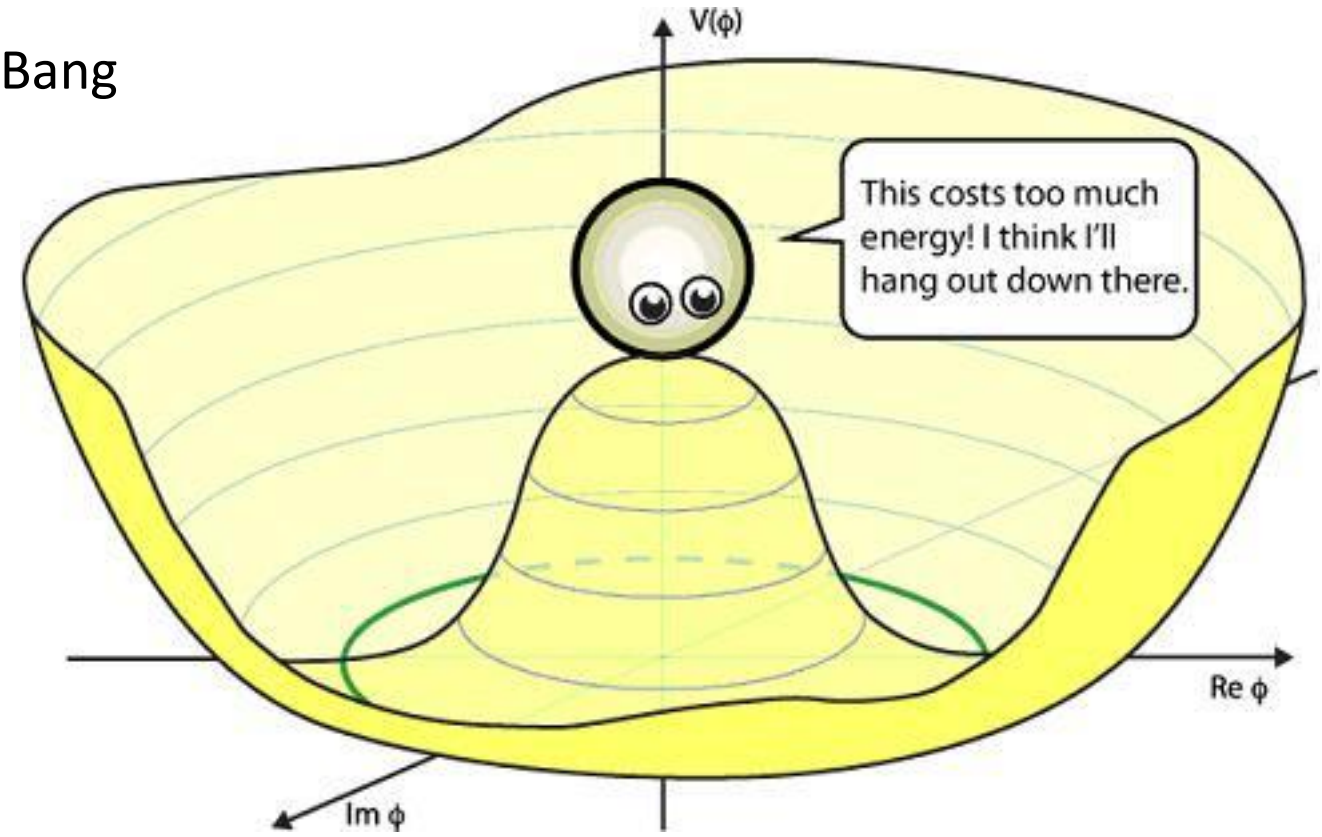
Higgs boson



http://www.quantumdiaries.org/2011/11/21/why-do-we-expect-a-higgs-boson-part-i-electroweak-symmetry-breaking/

Higgs boson

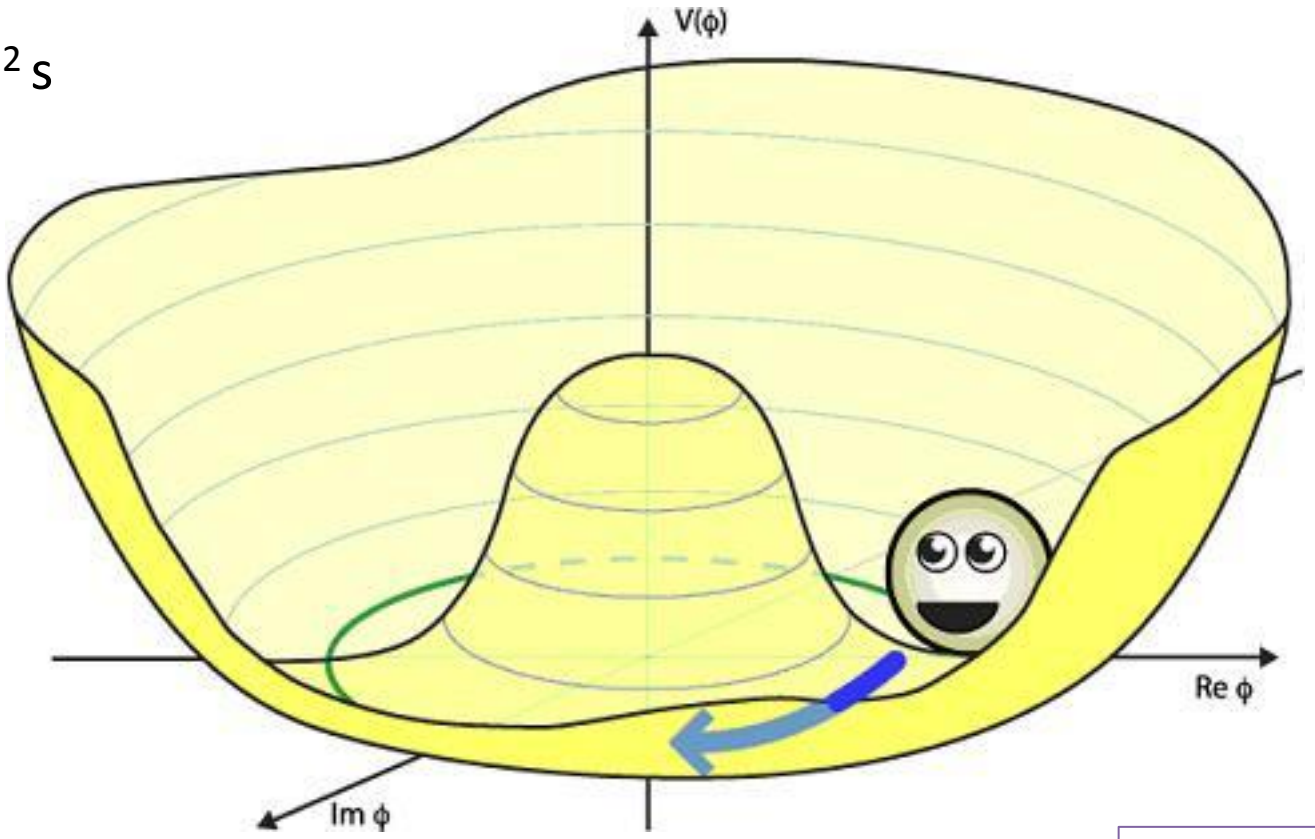
t = Big Bang



Massless bosons

Higgs boson

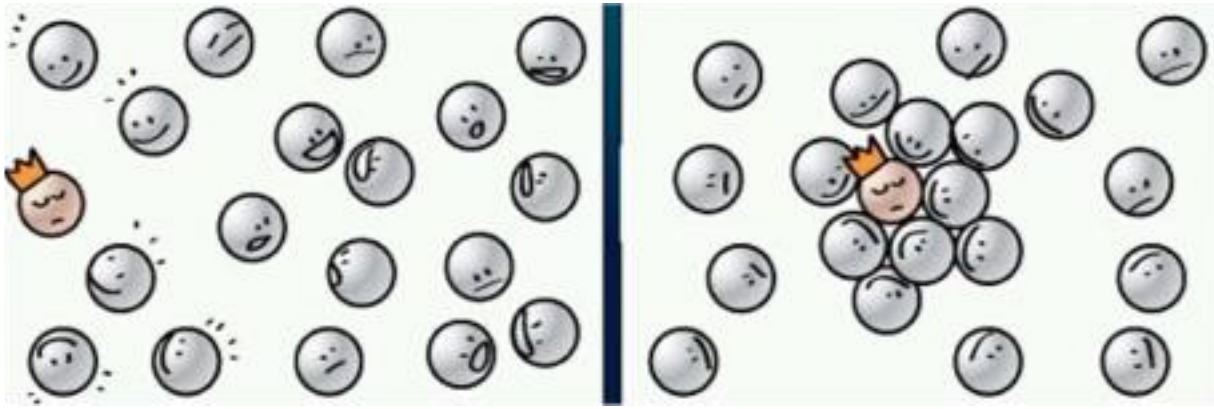
$t \sim 10^{-12}$ s



Spontaneous symmetry breaking → massive bosons

Four new degrees of freedom:
Z^0, W^+, W^-, h^0

Higgs field pervades all space and couples to particles to give them mass



Experimental triumph for SM

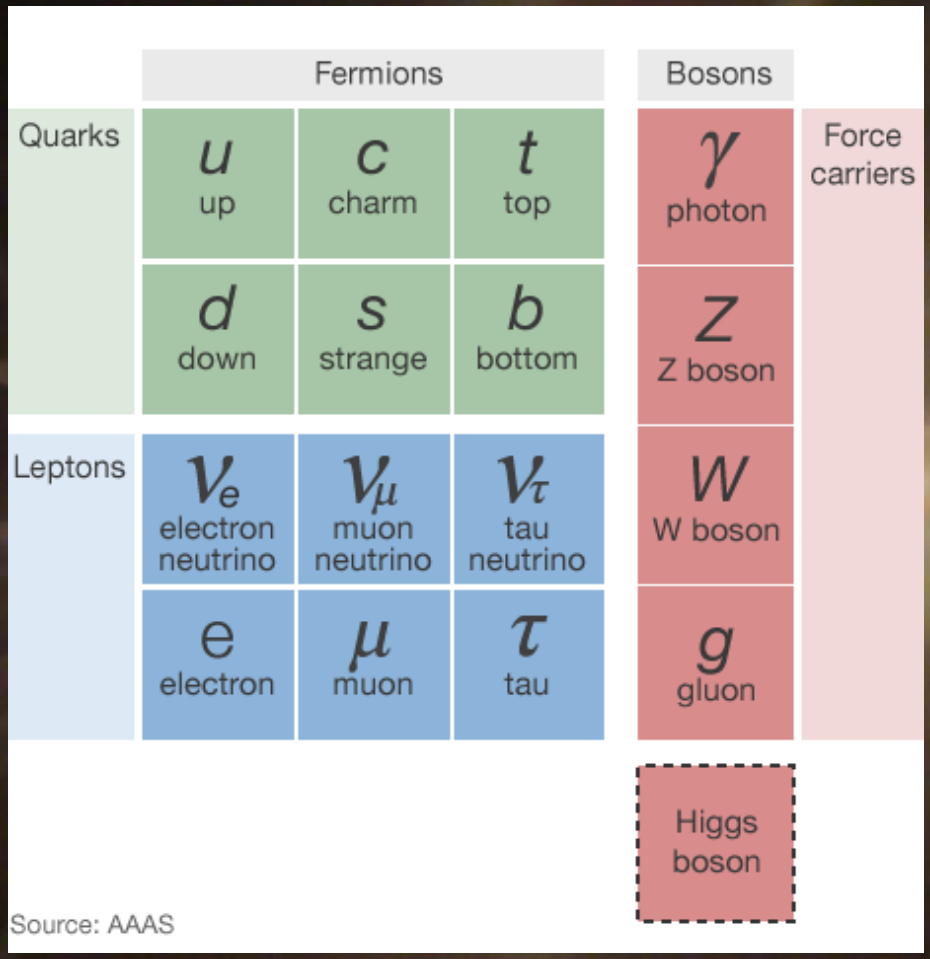
Looks like the Higgs boson has been found at last!

Brout, Englert
and Higgs rock.

The Standard
Model rocks.

CERN rocks.

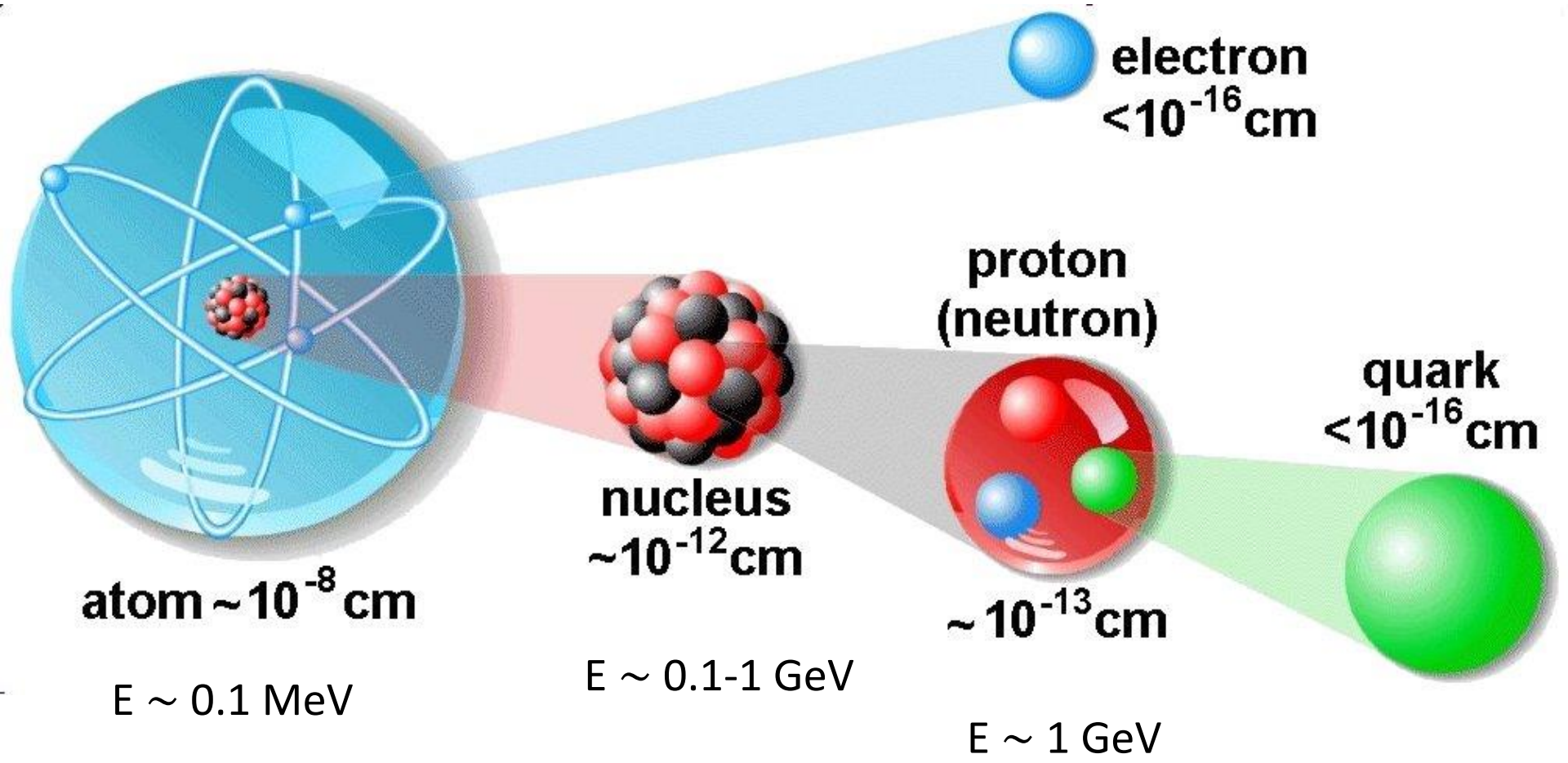
The Standard Model



How do we explore such small scales?

High energies to probe small distances: $E = hc/\lambda$

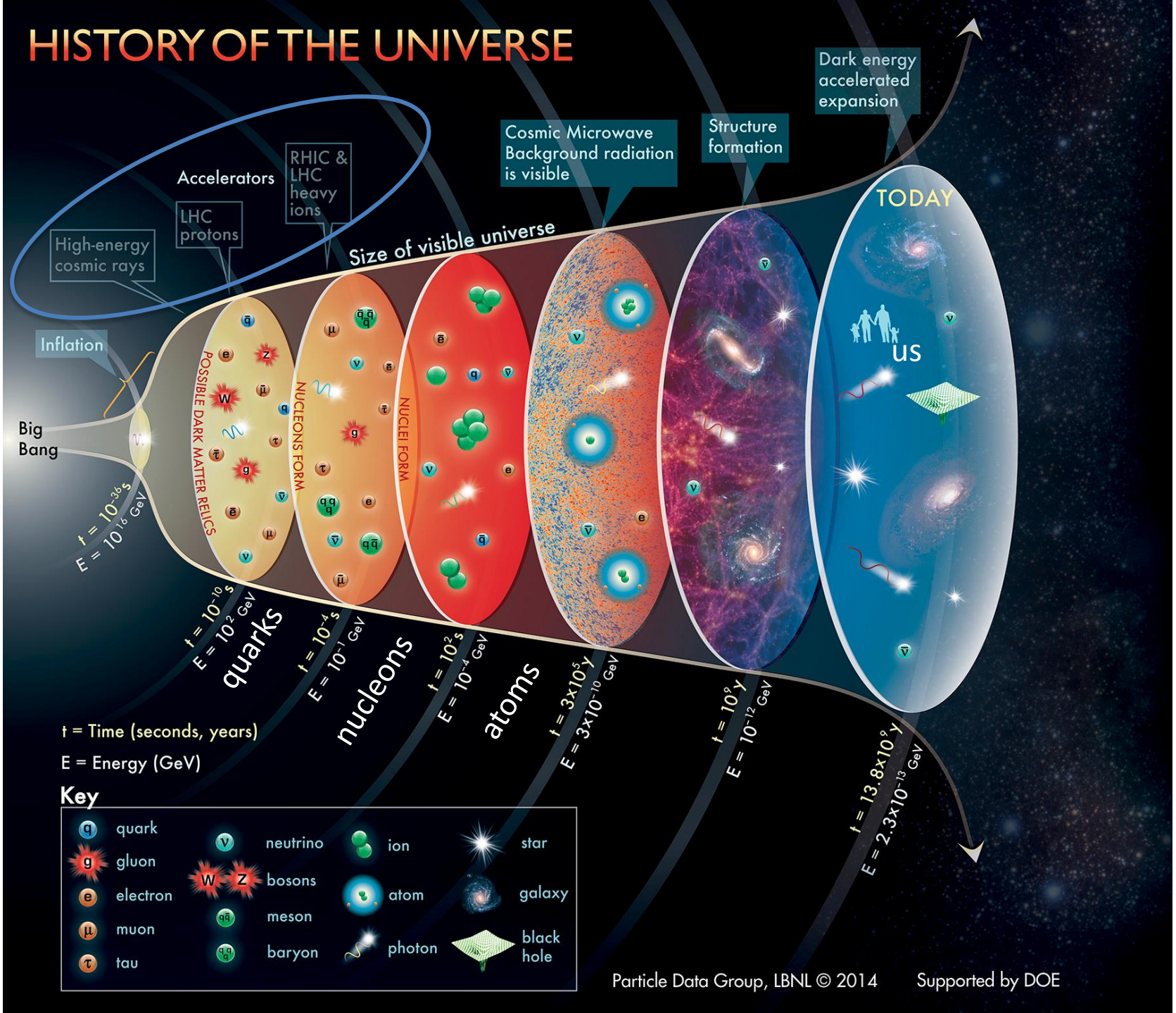
E ~ 1 TeV



E ~ 0.1 MeV

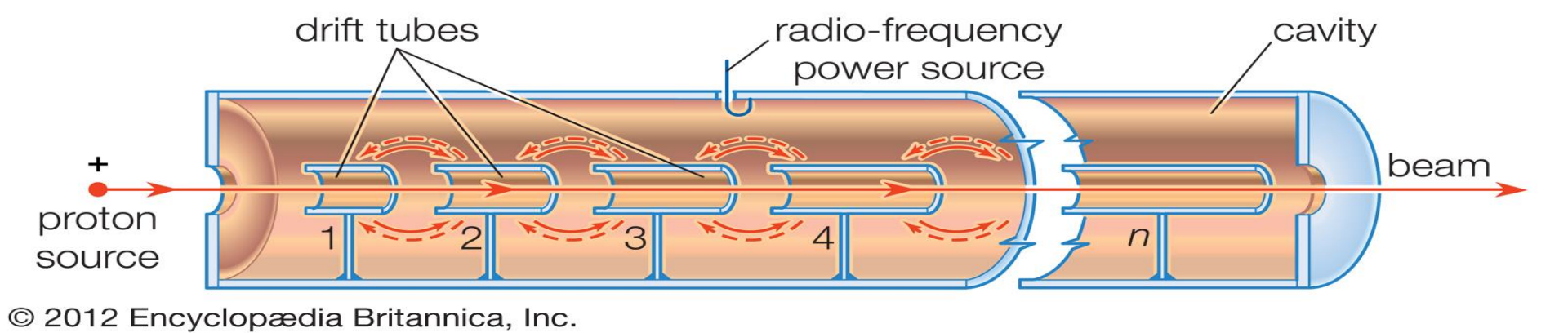
E ~ 0.1-1 GeV

E ~ 1 GeV


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
TODAY
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
Inflation
Big Bang
us
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
quarks
t = 10^-4 s
E = 10^-1 GeV
nucleons
t = 10^2 s
E = 10^-4 GeV
atoms
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE

Particle accelerators

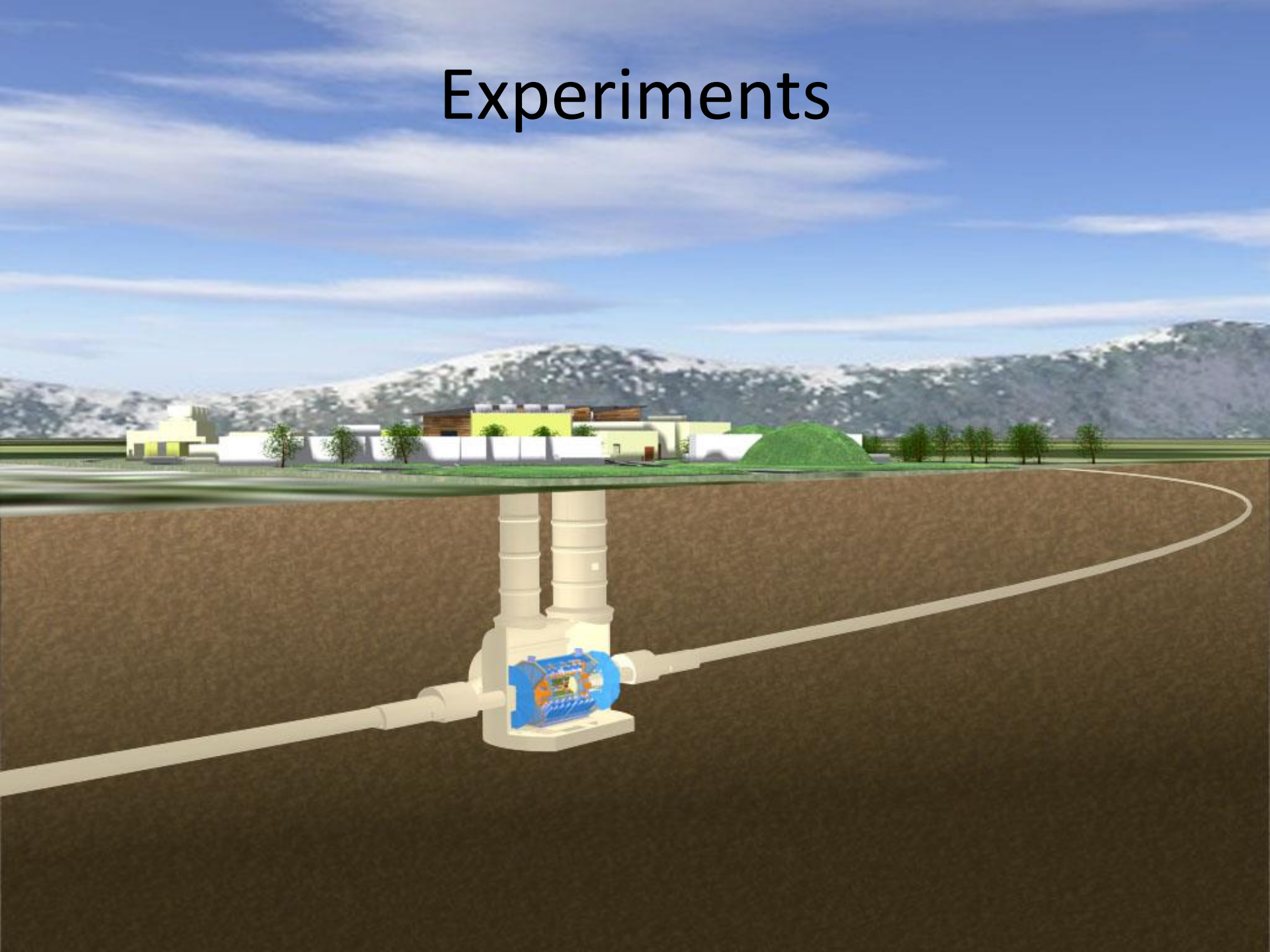
$$E_{cm} = \sqrt{\sum_i E_i^2 - \sum_i p_i^2} \qquad E = mc^2$$



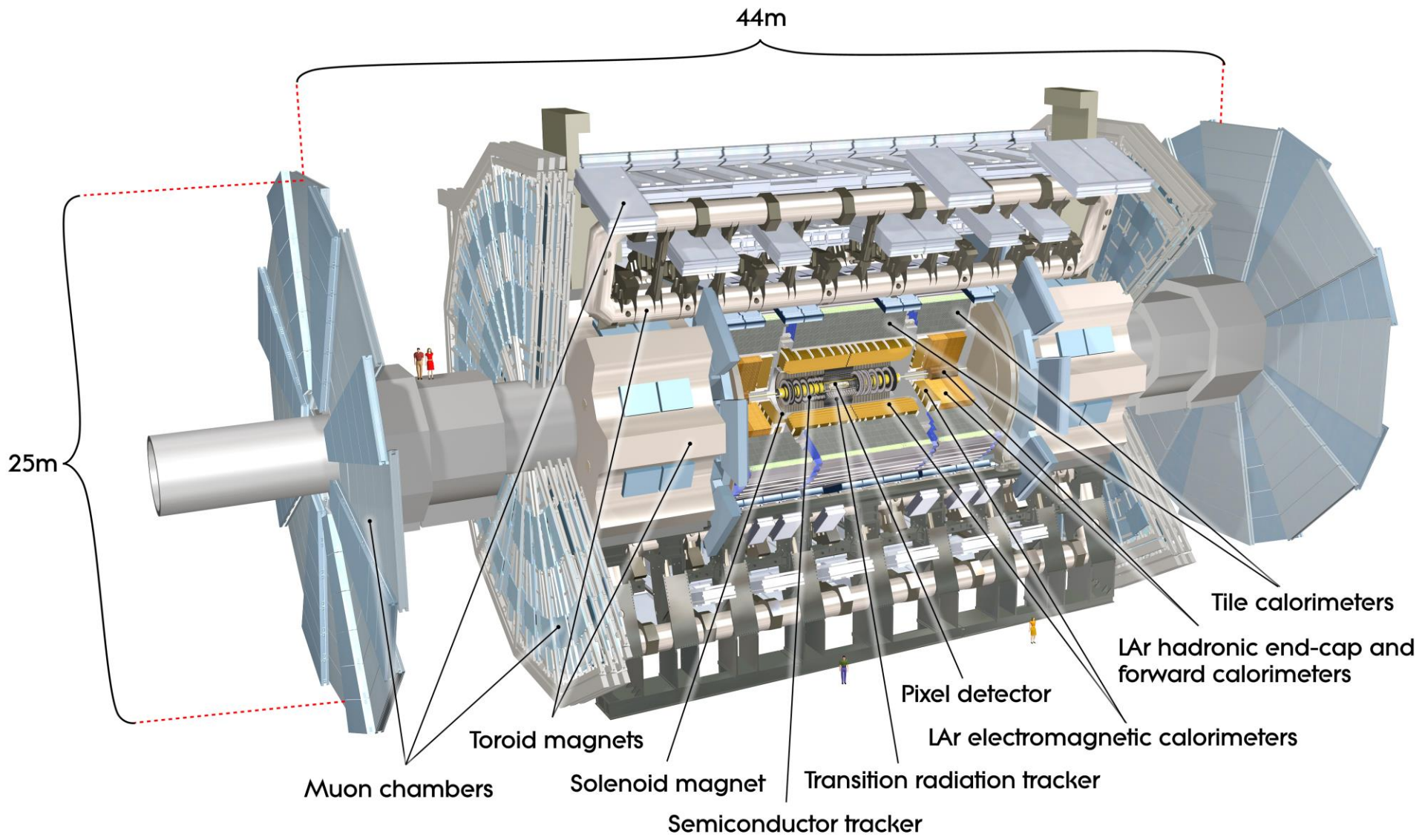
Large Hadron Collider

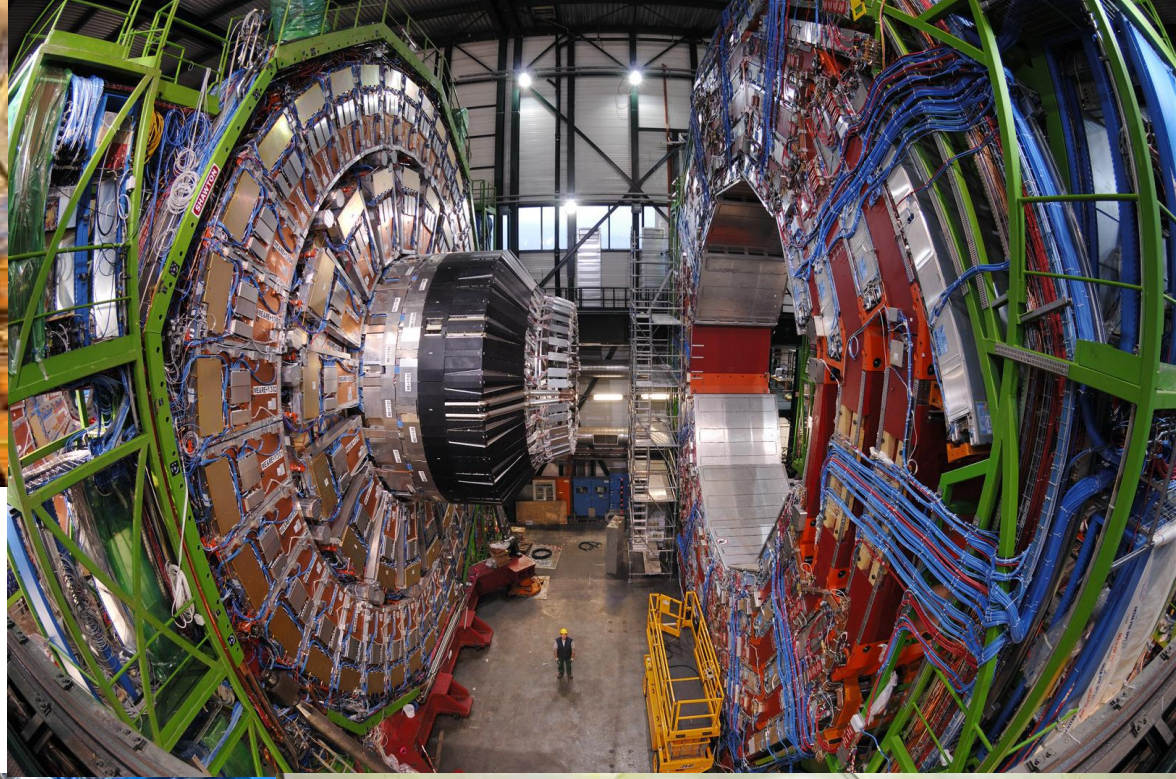
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
ALICE
CMS
LHC 27 km

Experiments

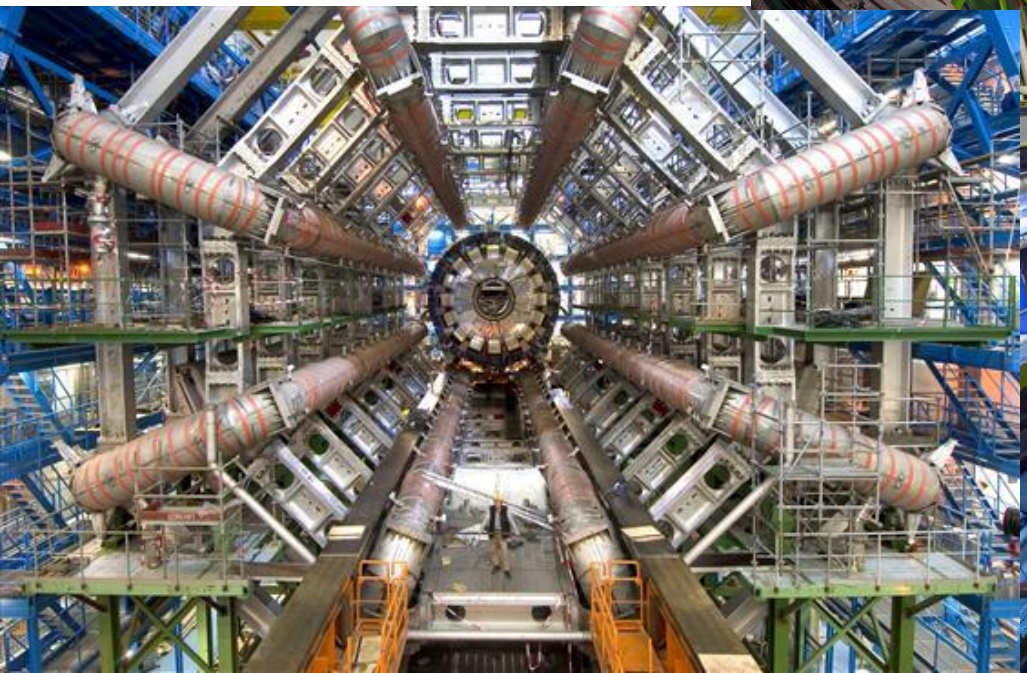


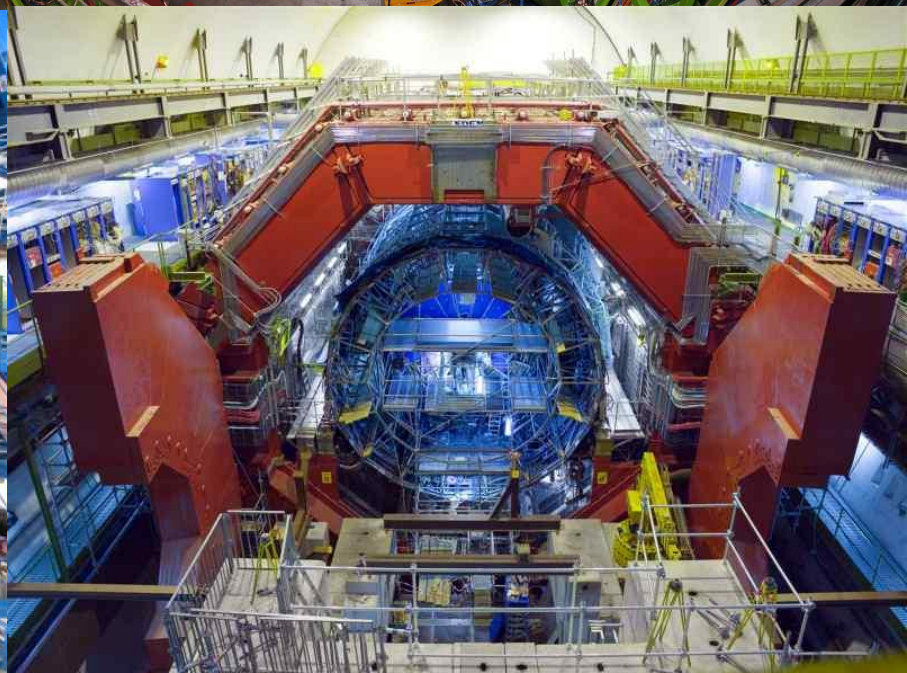
Experiments





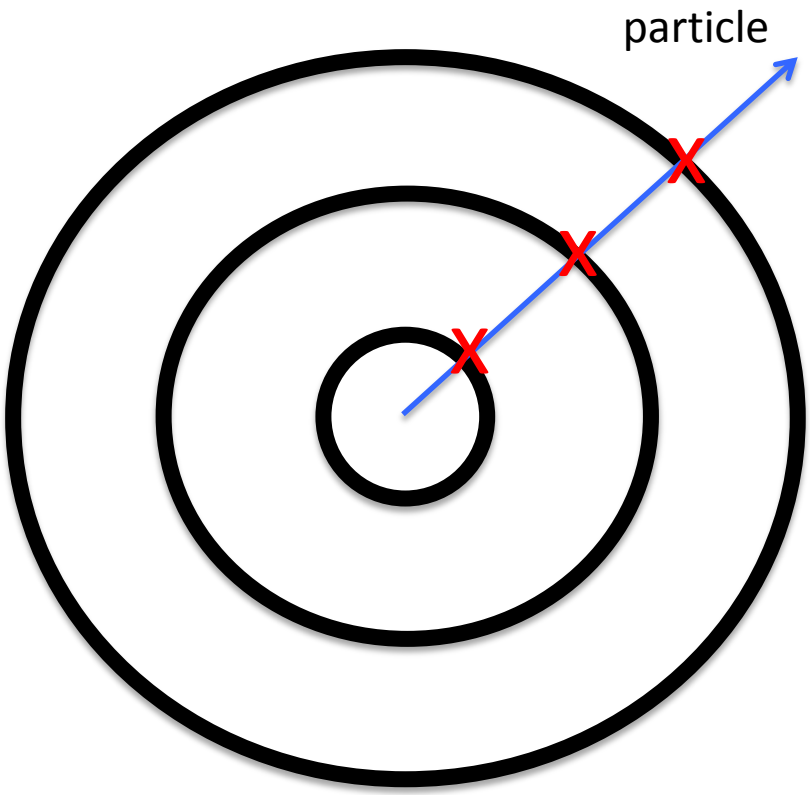
Four LHC experiments

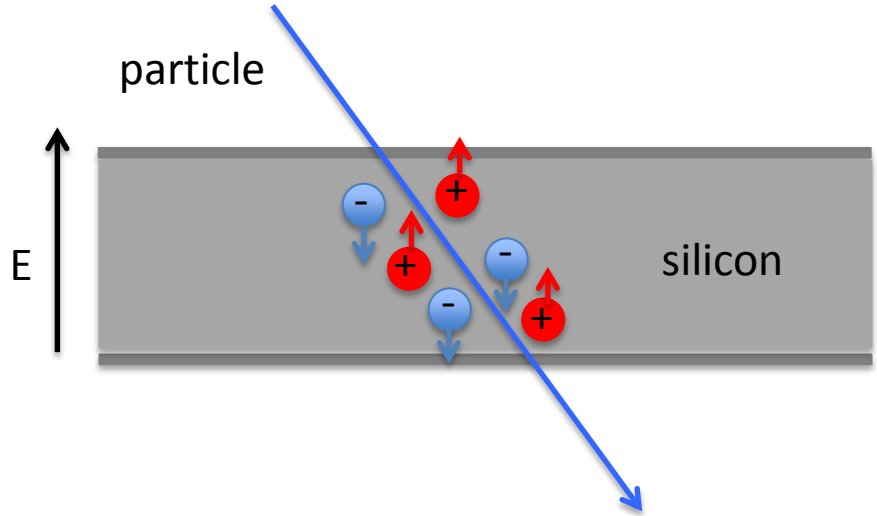




Particle detection

Measure the **position** of a particle



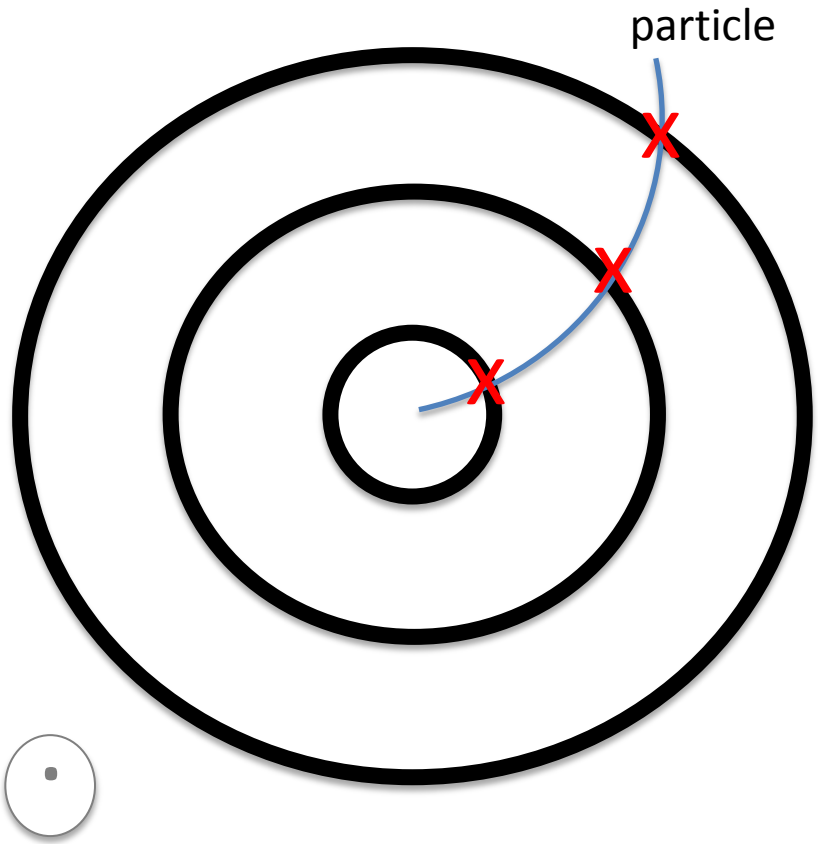


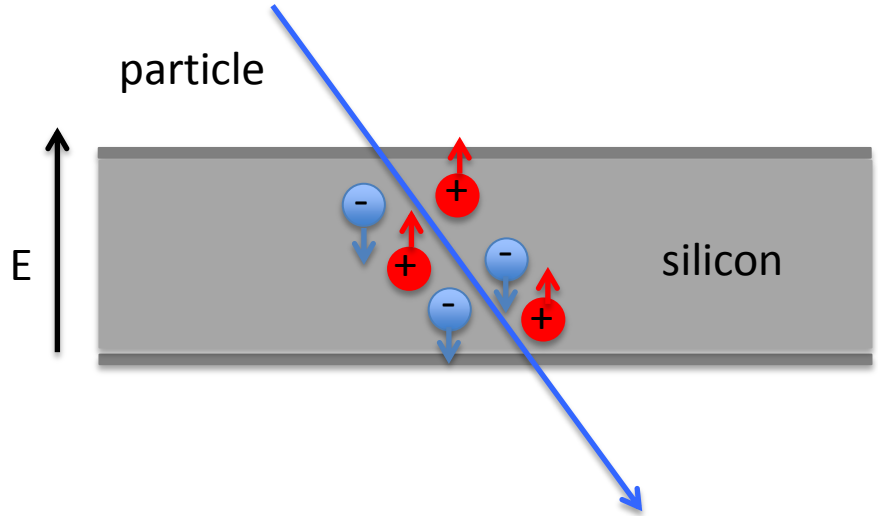
Particle detection

p = 0.3 Br

p = momentum
B = field strength
r = radius of curvature

Measure the **position** of a particle
Measure the **momentum** of a particle





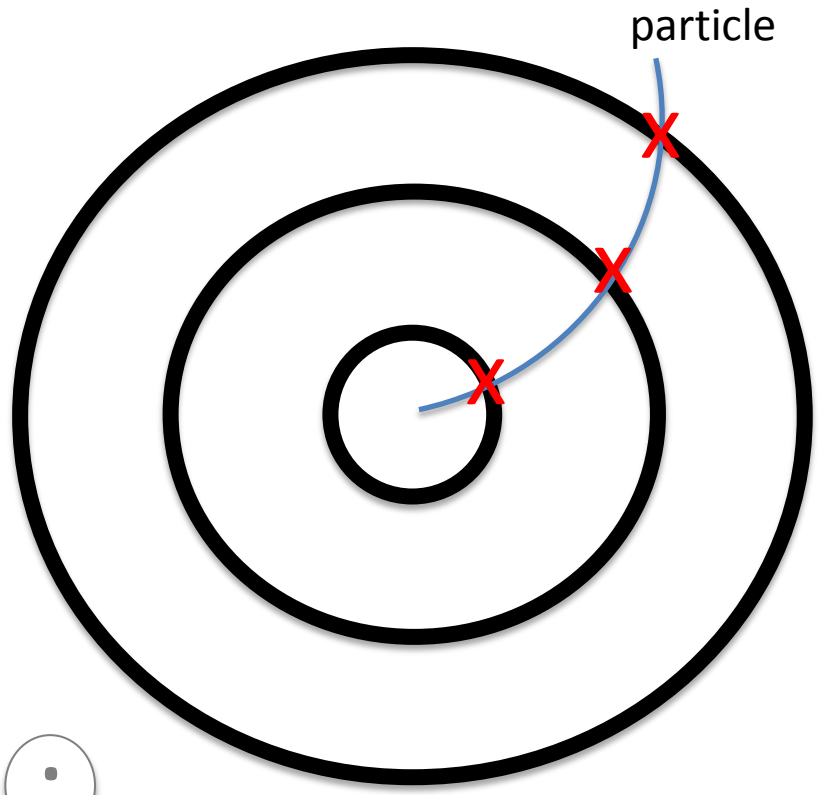
B-field

ATLAS solenoid: 5.8m long, 1.23m inner radius

Particle detection

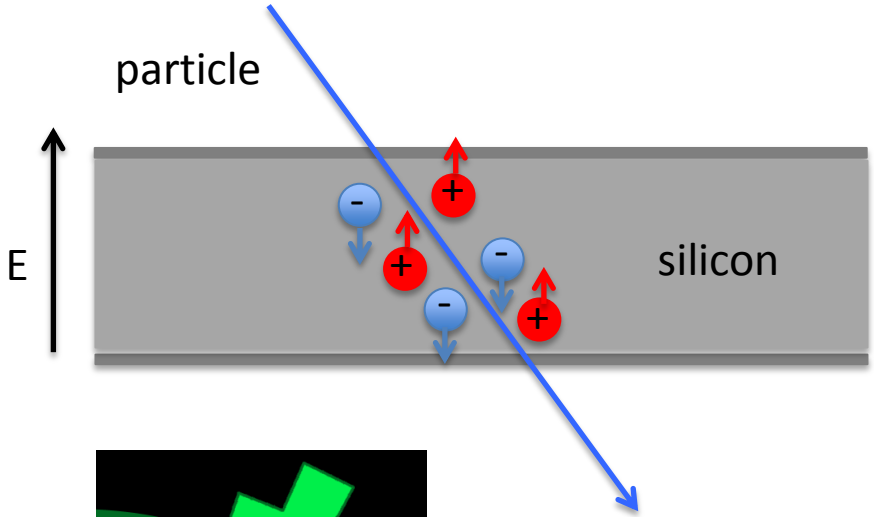
p = 0.3 Br

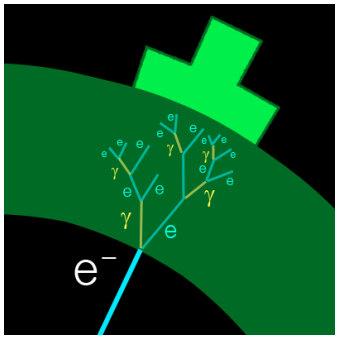
p = momentum
B = field strength
r = radius of curvature



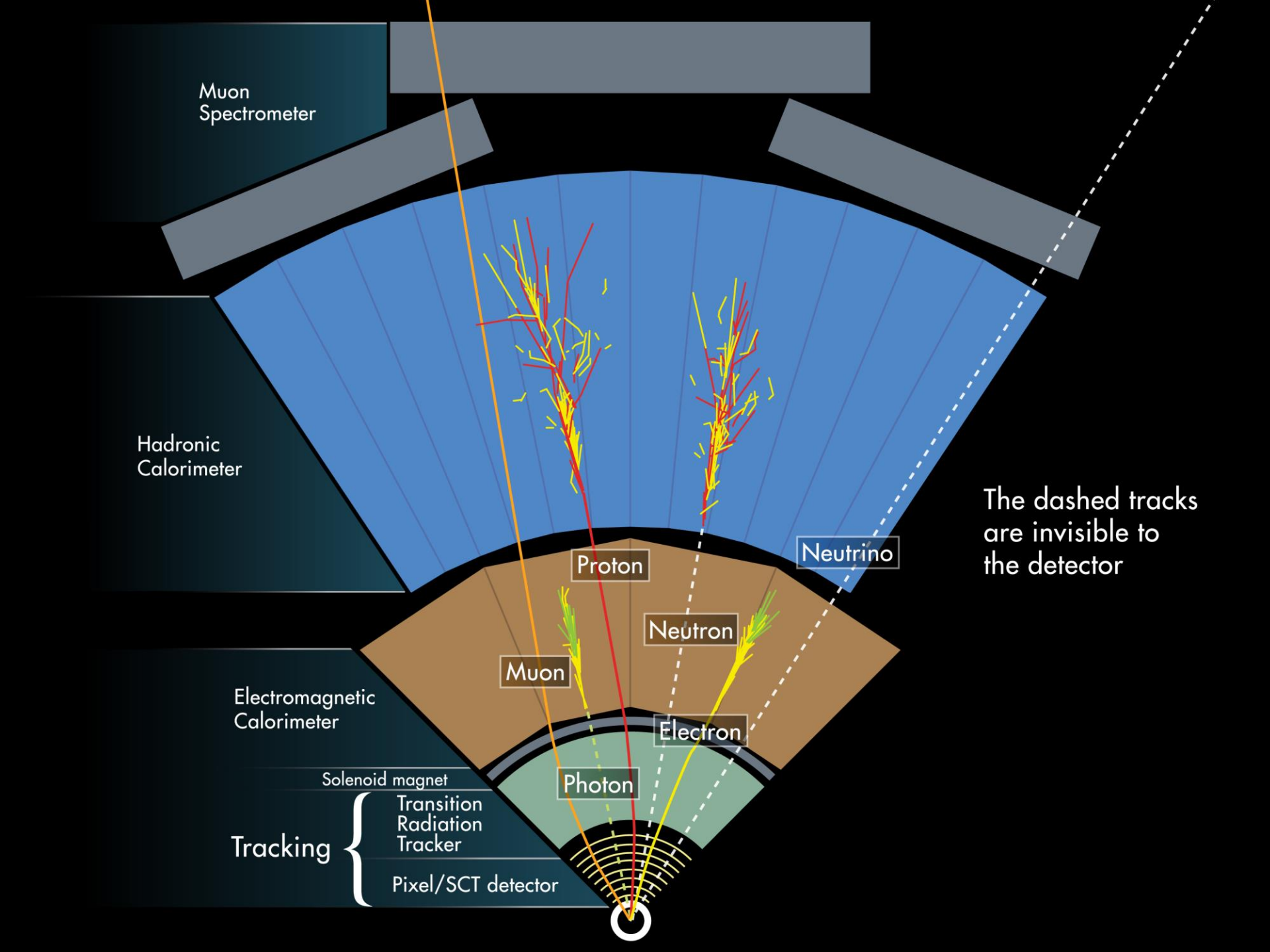
B-field (2 T for ATLAS)

Measure the **position** of a particle
Measure the **momentum** of a particle
Measure the **energy** of a particle

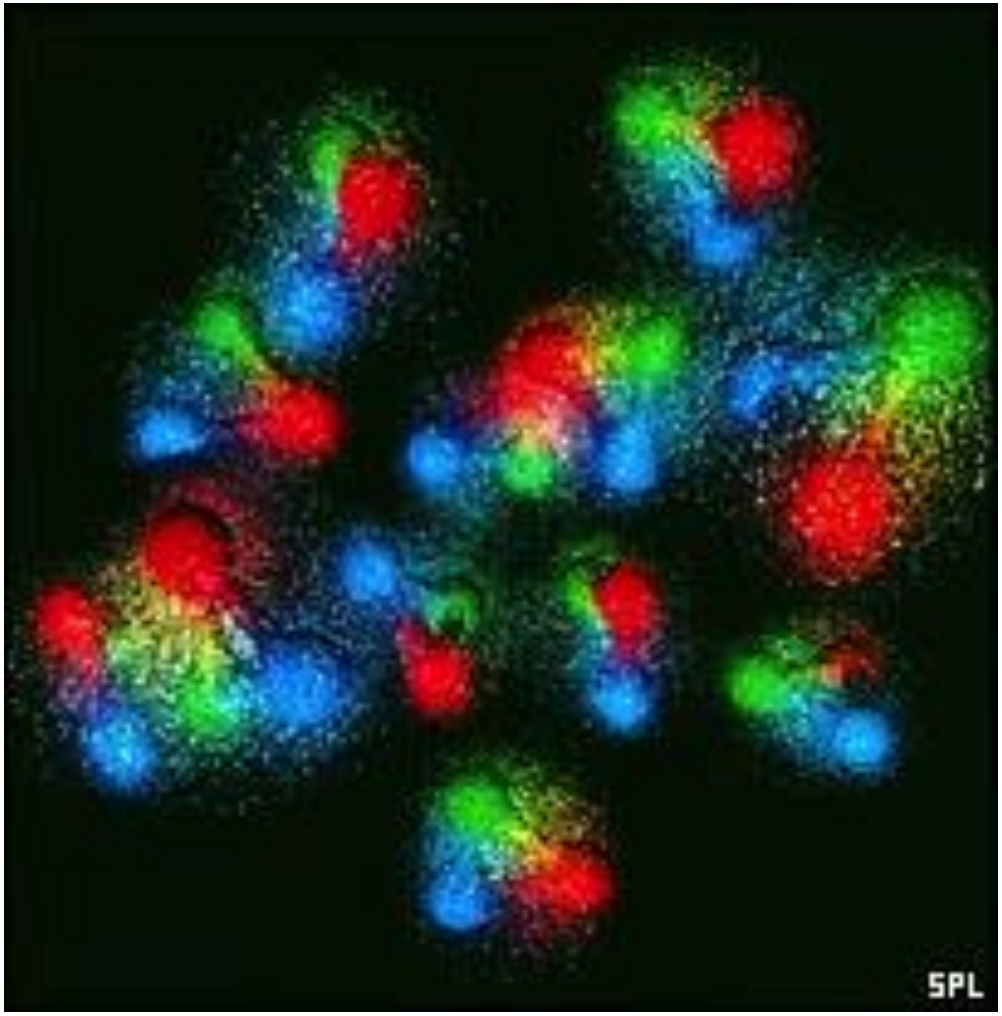




EM shower

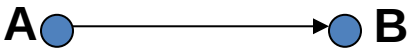

Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT detector
Proton
Neutron
Muon
Electron
Photon
Neutrino
The dashed tracks
are invisible to
the detector

Entering the quantum world…



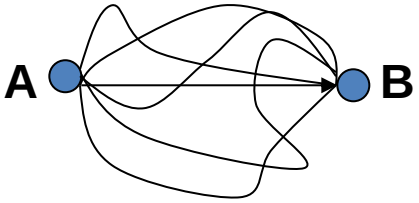
Carbon-12 nucleus

Classical View

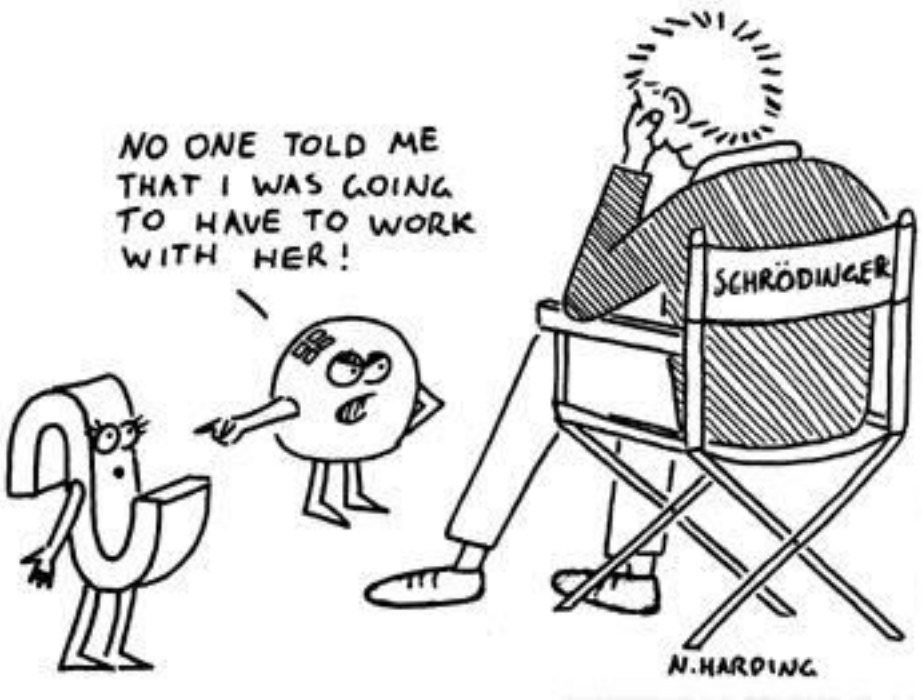


Any particle traveling from A to B takes a direct path

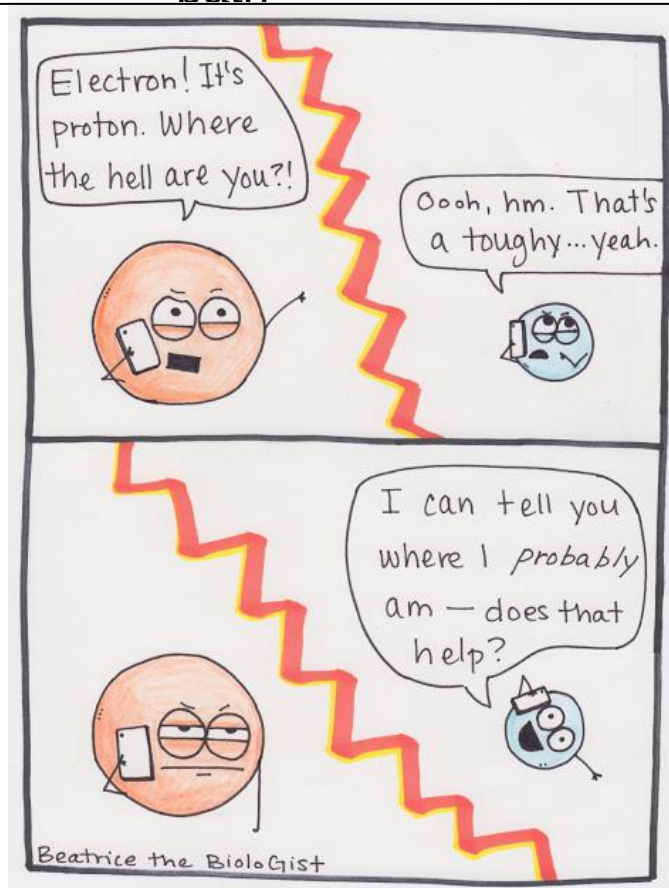
Quantum View



Any particle traveling from A to B takes *every possible* path

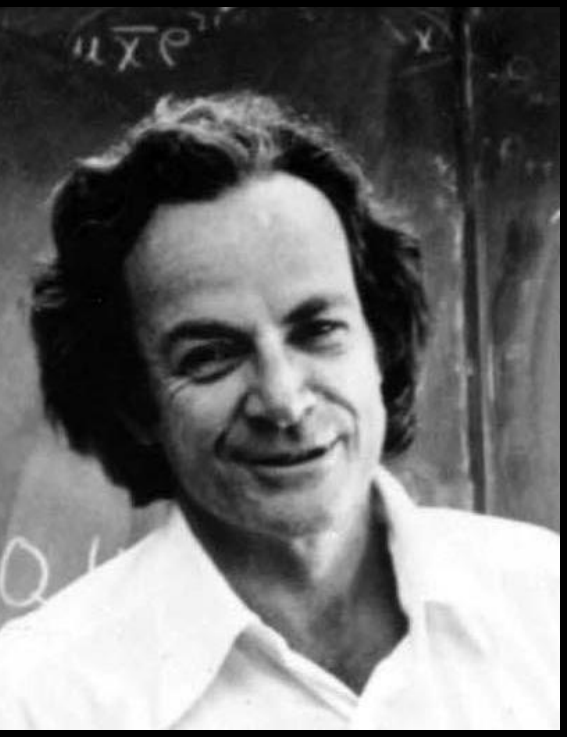


Wave particle duality



If quantum mechanics hasn't profoundly shocked you, you haven't understood it yet.

(Niels Bohr)

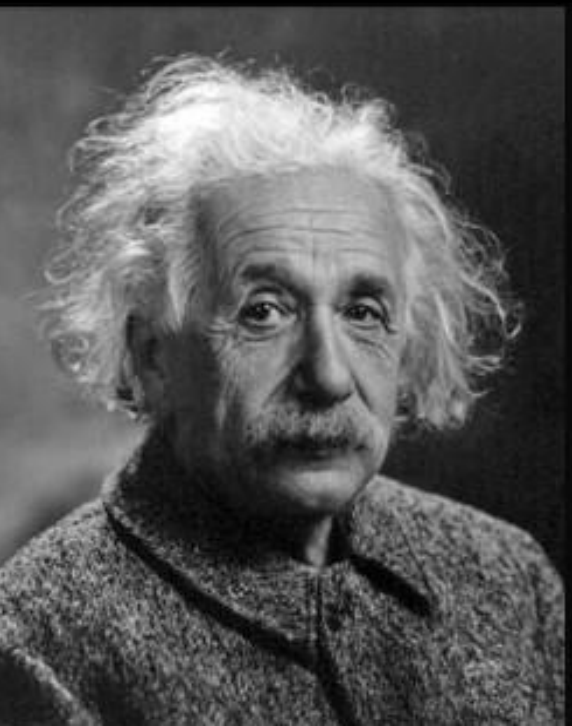


Anyone who claims to understand quantum theory is either lying or crazy.

(Richard Feynman)

If quantum mechanics hasn't profoundly shocked you, you haven't understood it yet.

(Niels Bohr)

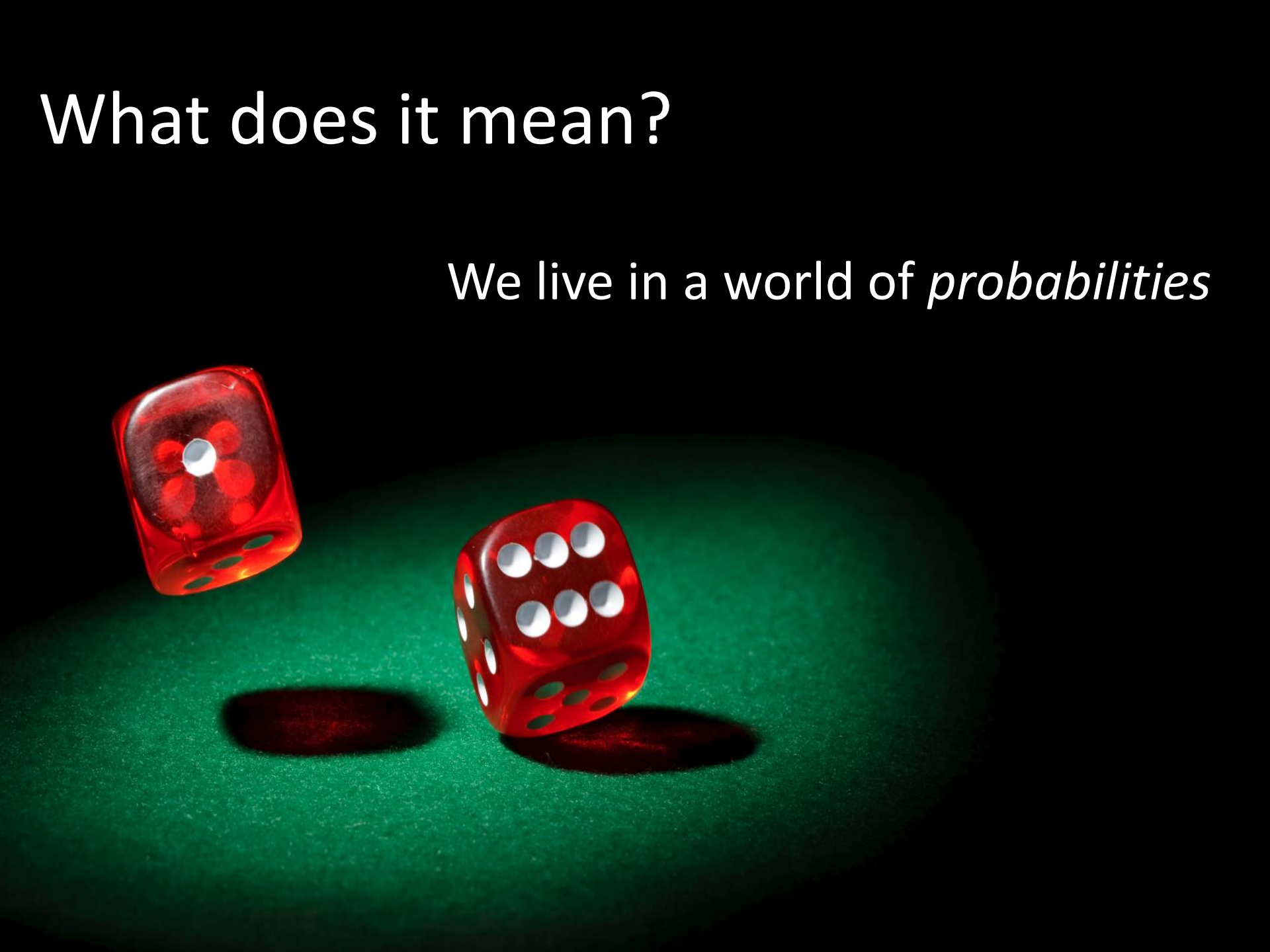


Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing. The theory says a lot, but does not really bring us any closer to the secret of the old one. I, at any rate, am convinced that He does not throw dice.

(Albert Einstein)

What does it mean?

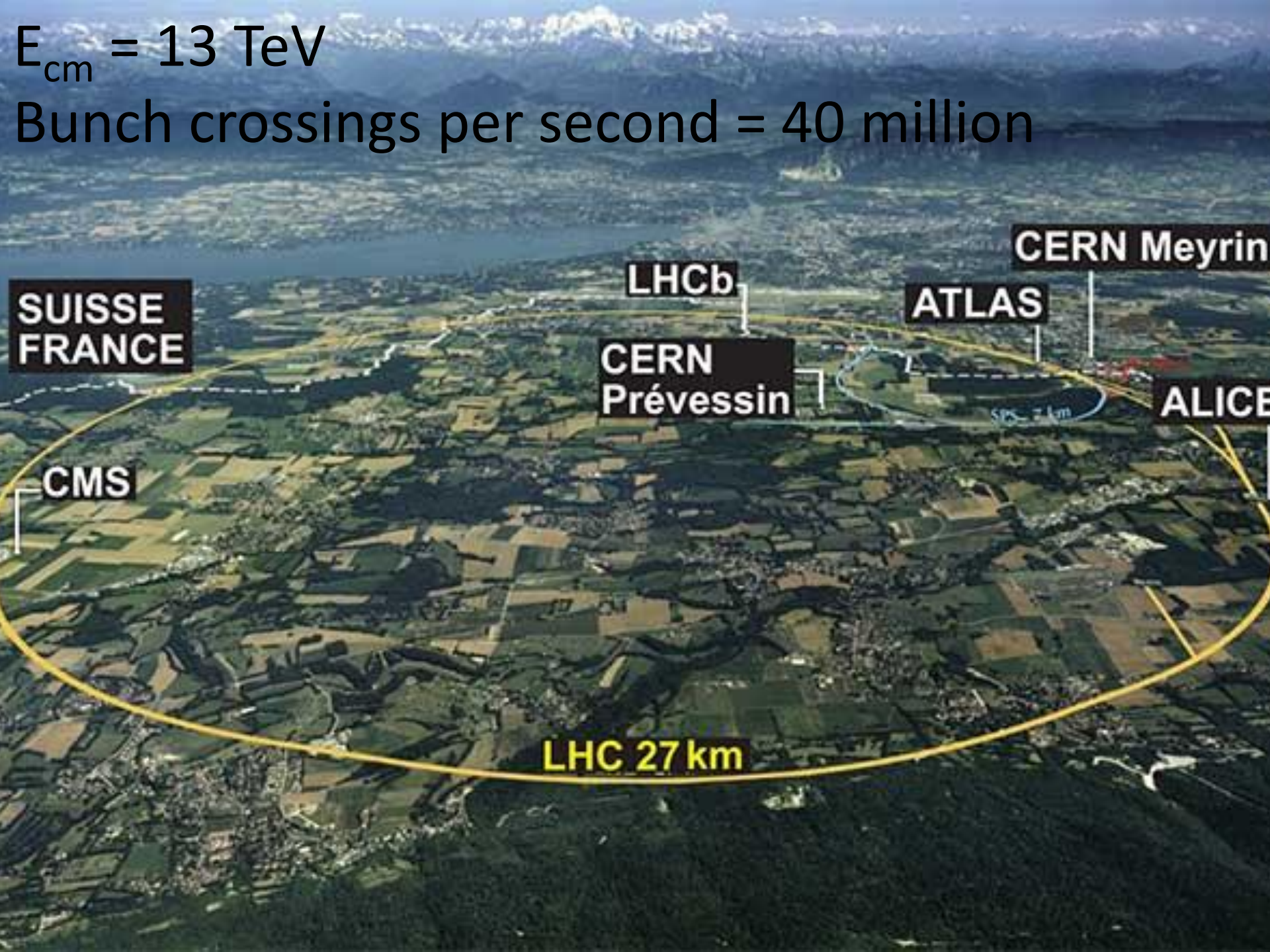
We live in a world of *probabilities*

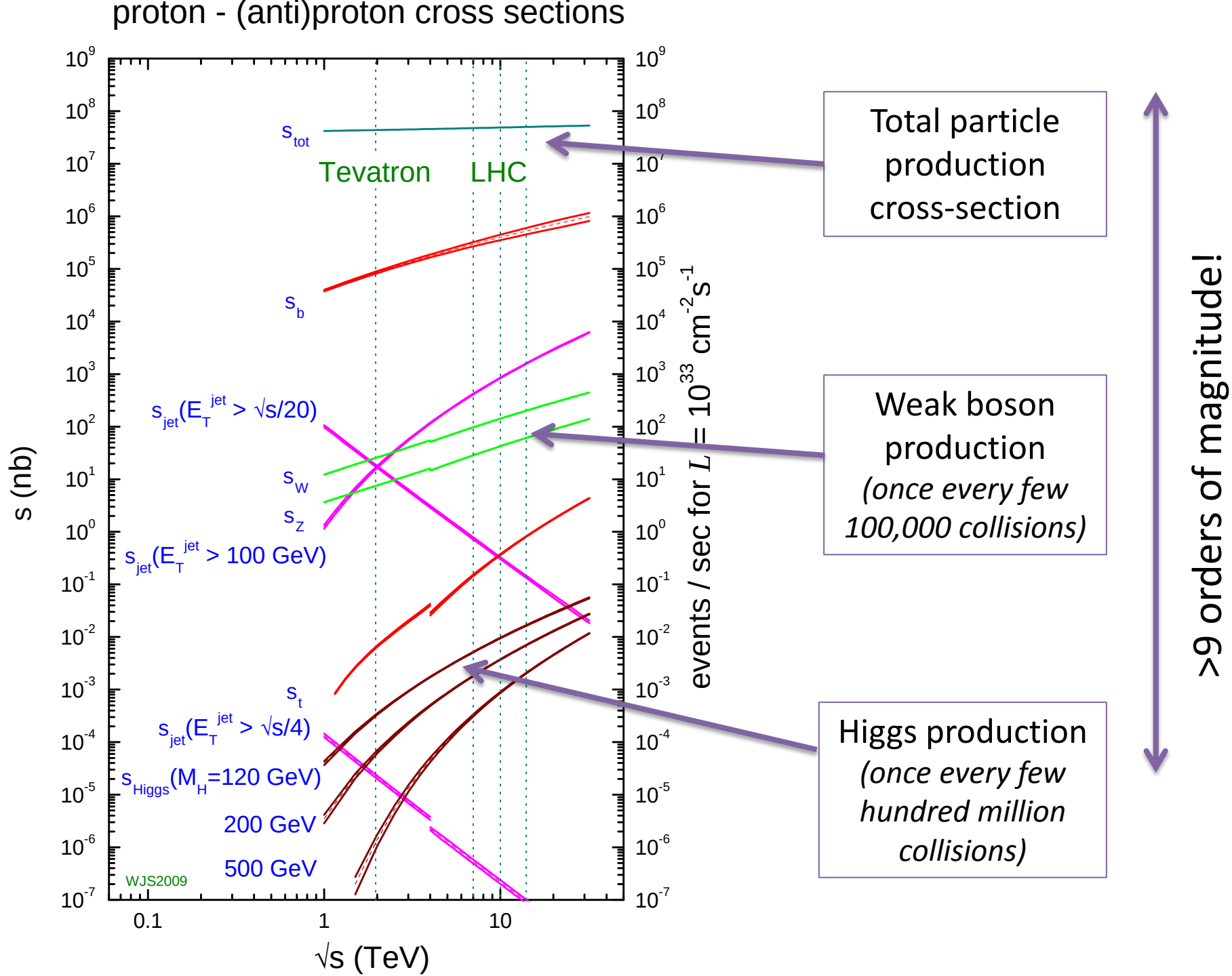



AL
BOHR

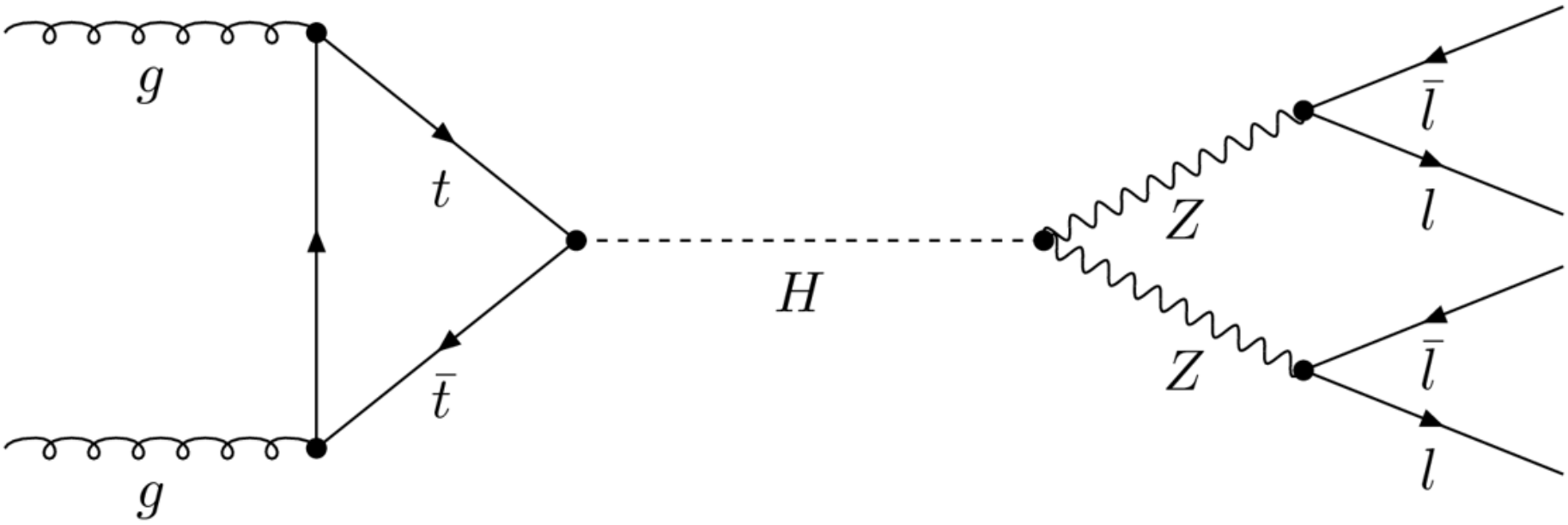
E_{cm} = 13 TeV

Bunch crossings per second = 40 million

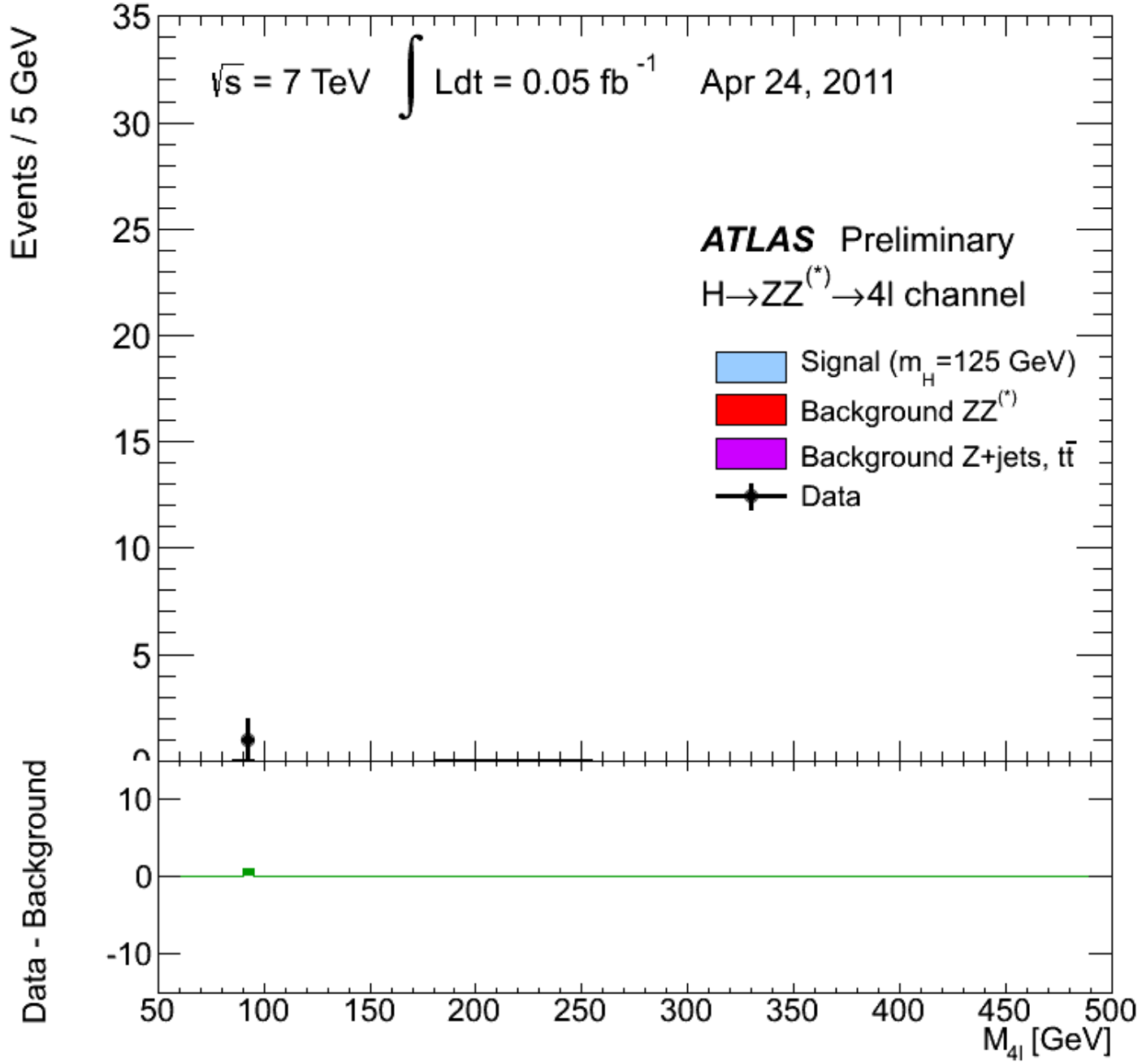


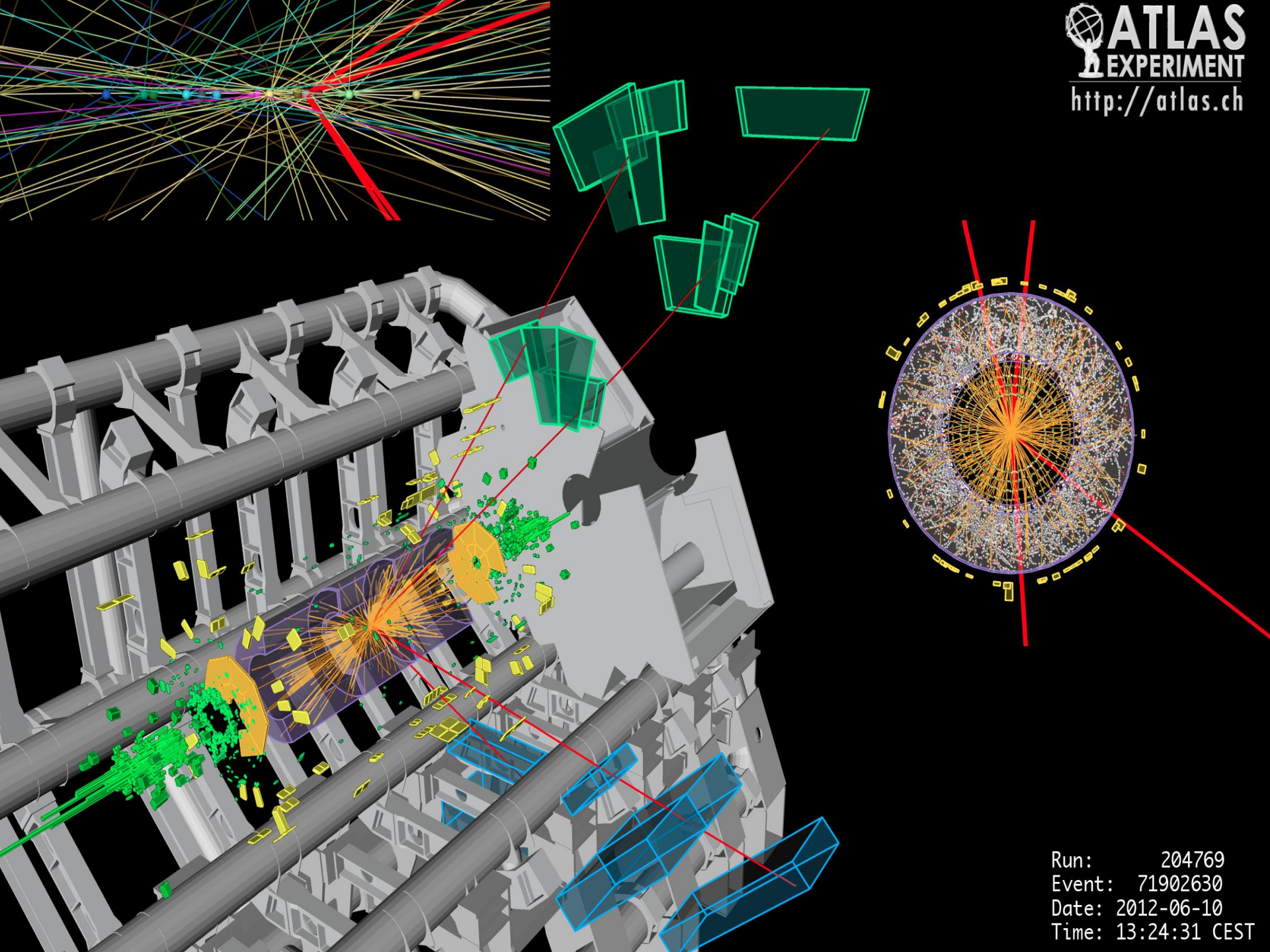

proton - (anti)proton cross sections
s (nb)
events / sec for L = 10^33 cm^-2 s^-1
√s (TeV)
Tevatron
LHC
s_tot
s_b
s_jet(E_T^jet > √s/20)
s_W
s_Z
s_jet(E_T^jet > 100 GeV)
s_t
s_jet(E_T^jet > √s/4)
s_Higgs(M_H=120 GeV)
200 GeV
500 GeV
WJS2009
Total particle production cross-section
Weak boson production (once every few 100,000 collisions)
Higgs production (once every few hundred million collisions)
>9 orders of magnitude!

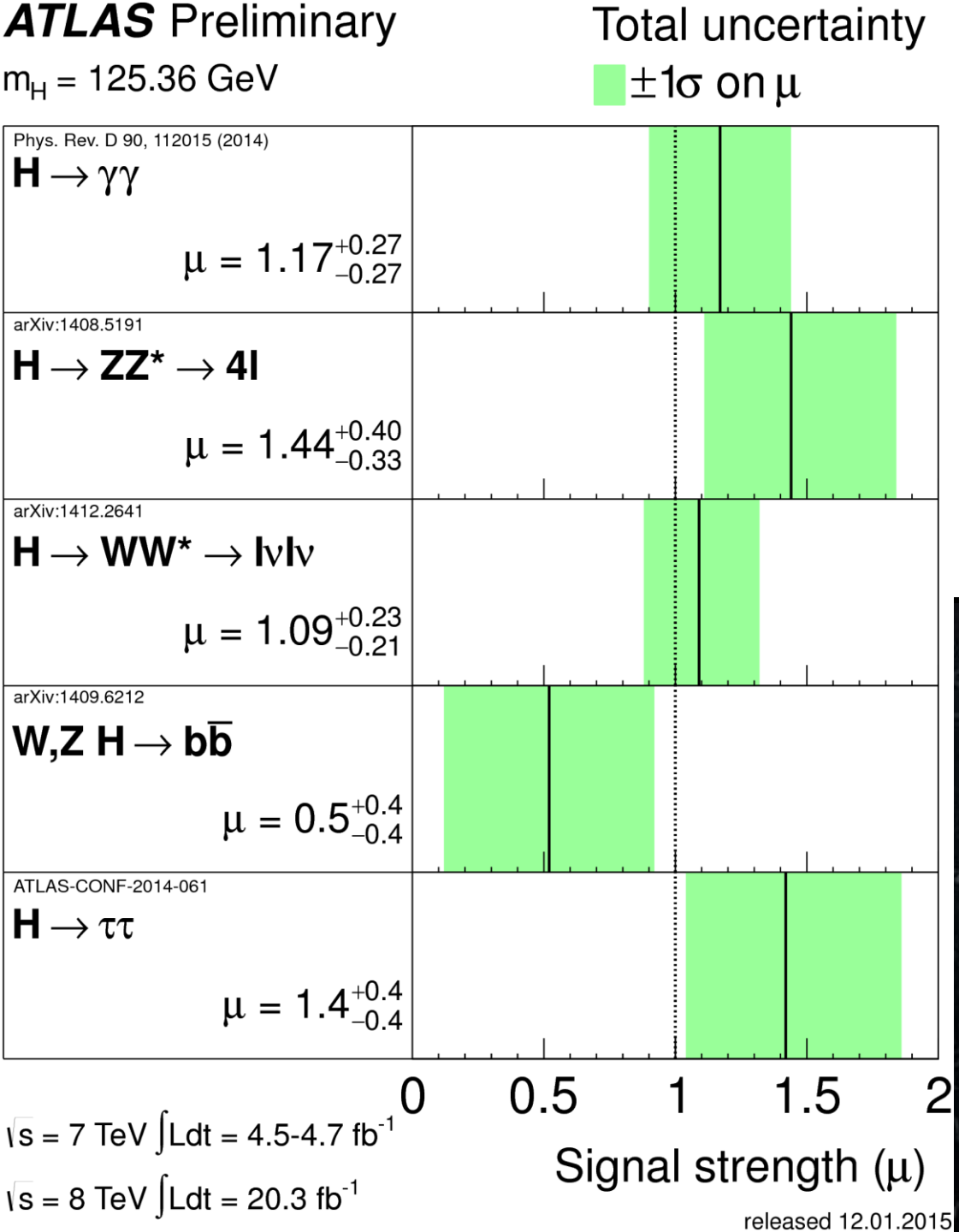
Example: Higgs → ZZ



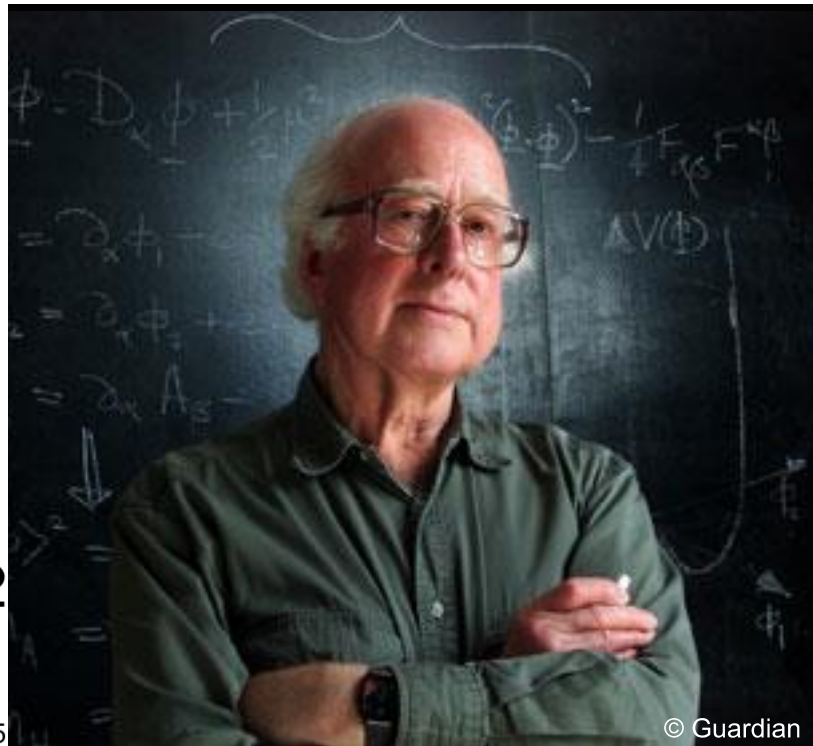
Tag the leptons
Predict the background from Standard Model ZZ production


√s = 7 TeV ∫ Ldt = 0.05 fb -1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m H =125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M4l [GeV]
35
30
25
20
15
10
5
10
0
-10
50
100
150
200
250
300
350
400
450
500


ATLAS
EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

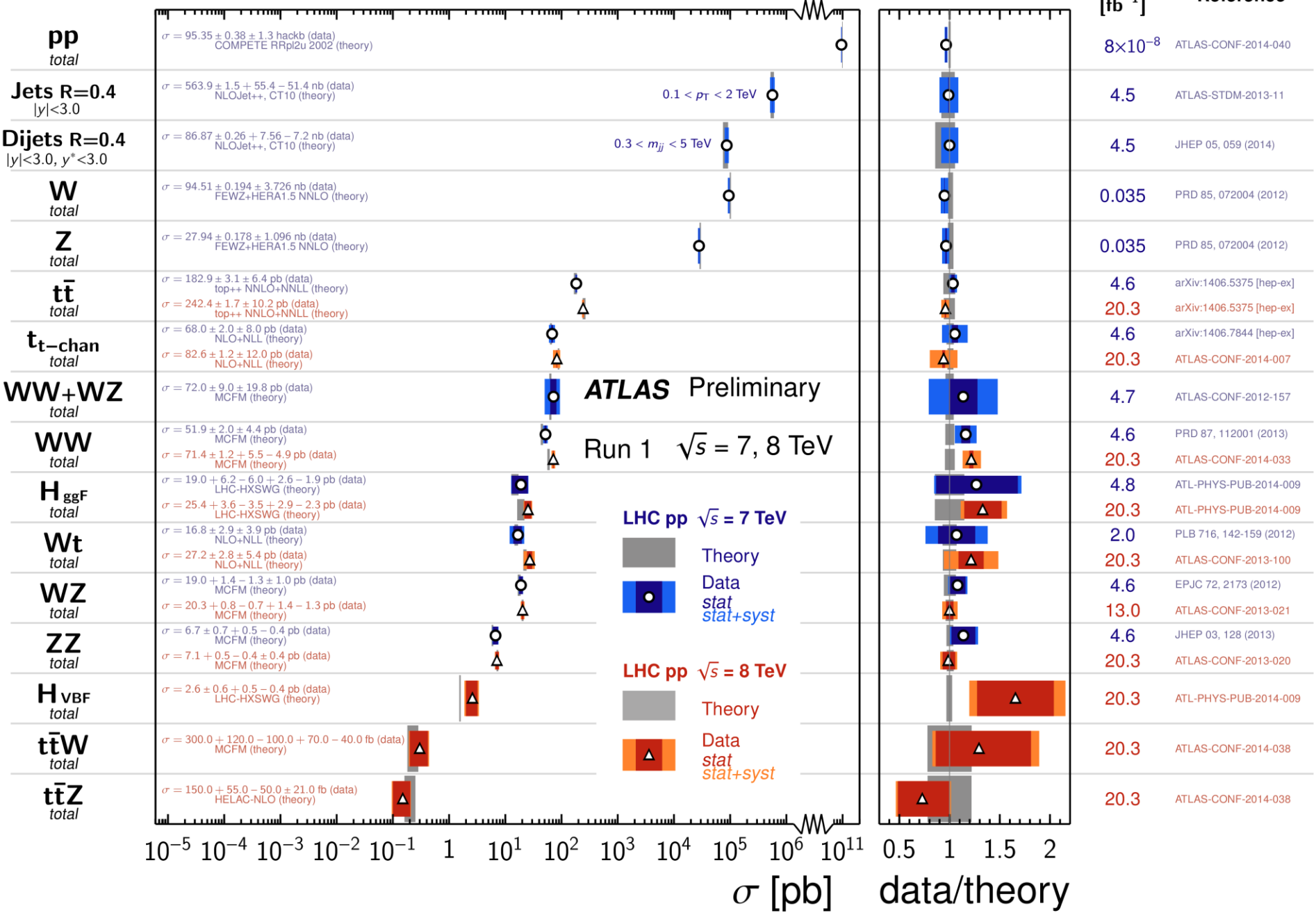


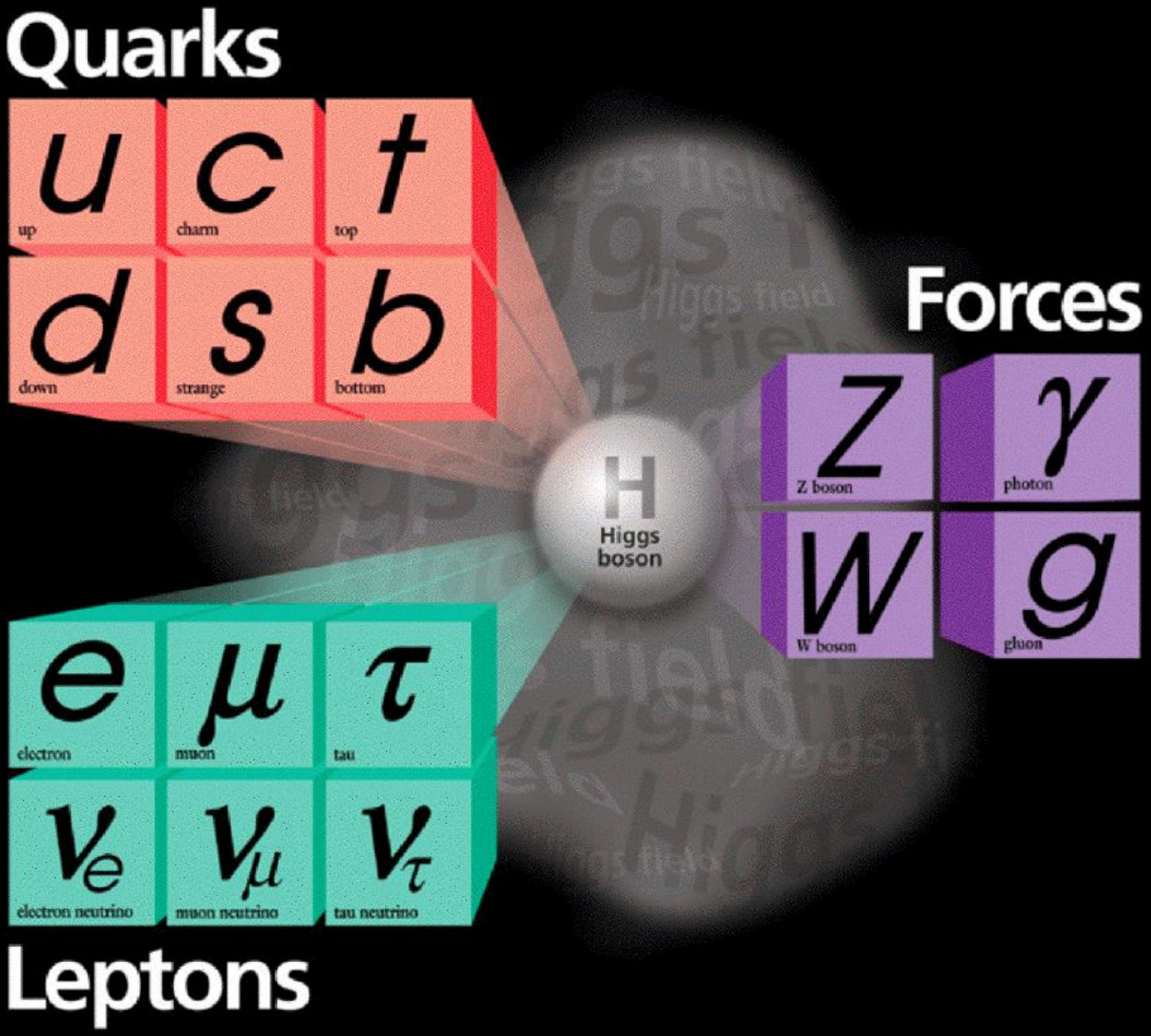
So far observations compatible with Standard Model Higgs boson



Standard Model Total Production Cross Section Measurements

Status: July 2014

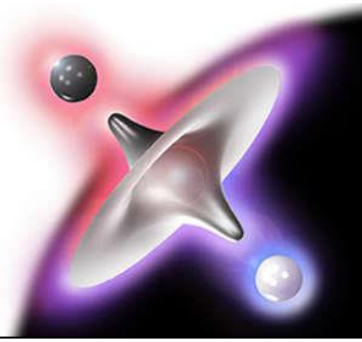




What else are we after?

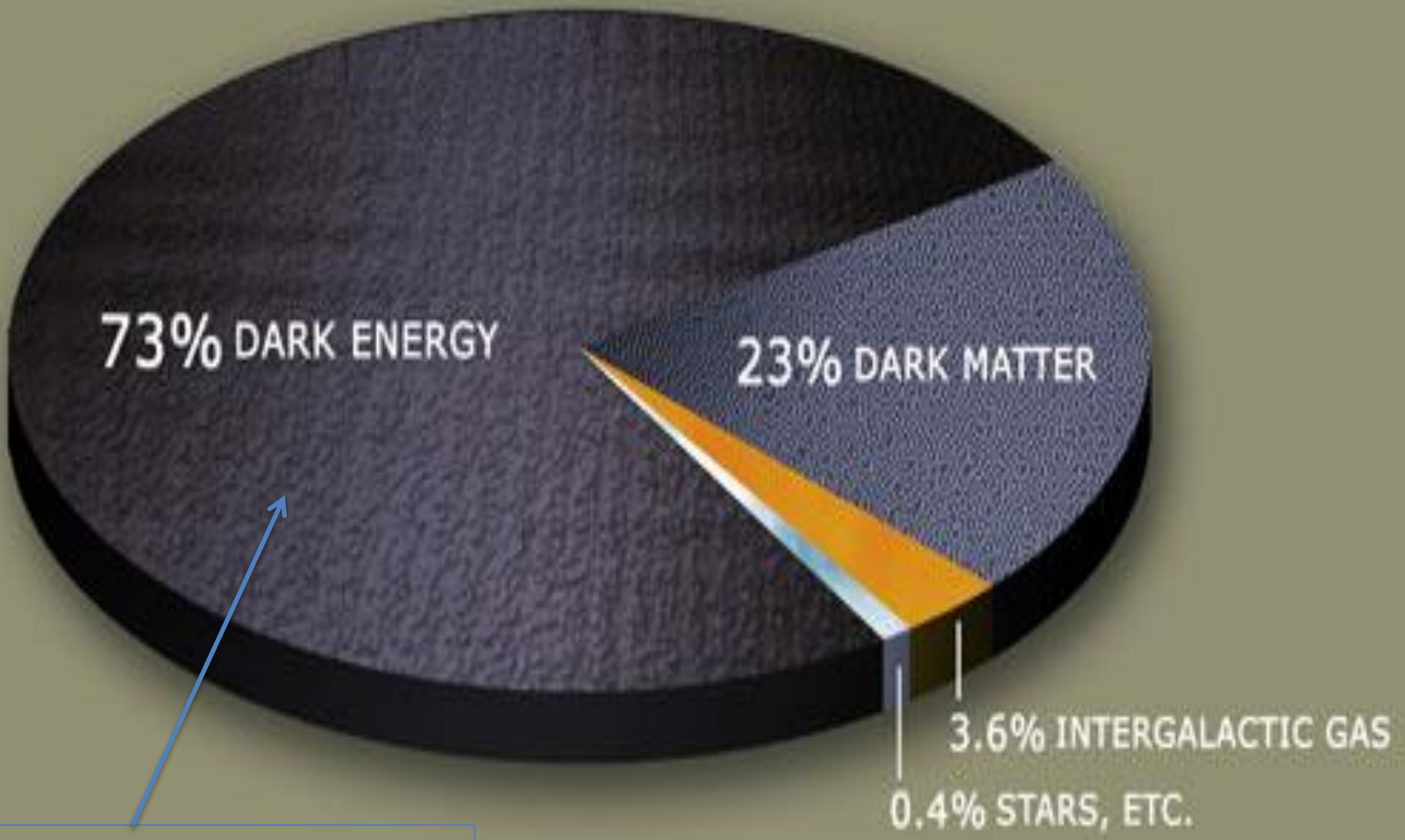
Antimatter -- matter asymmetry

In the beginning matter and anti-matter in equal parts (why not?)



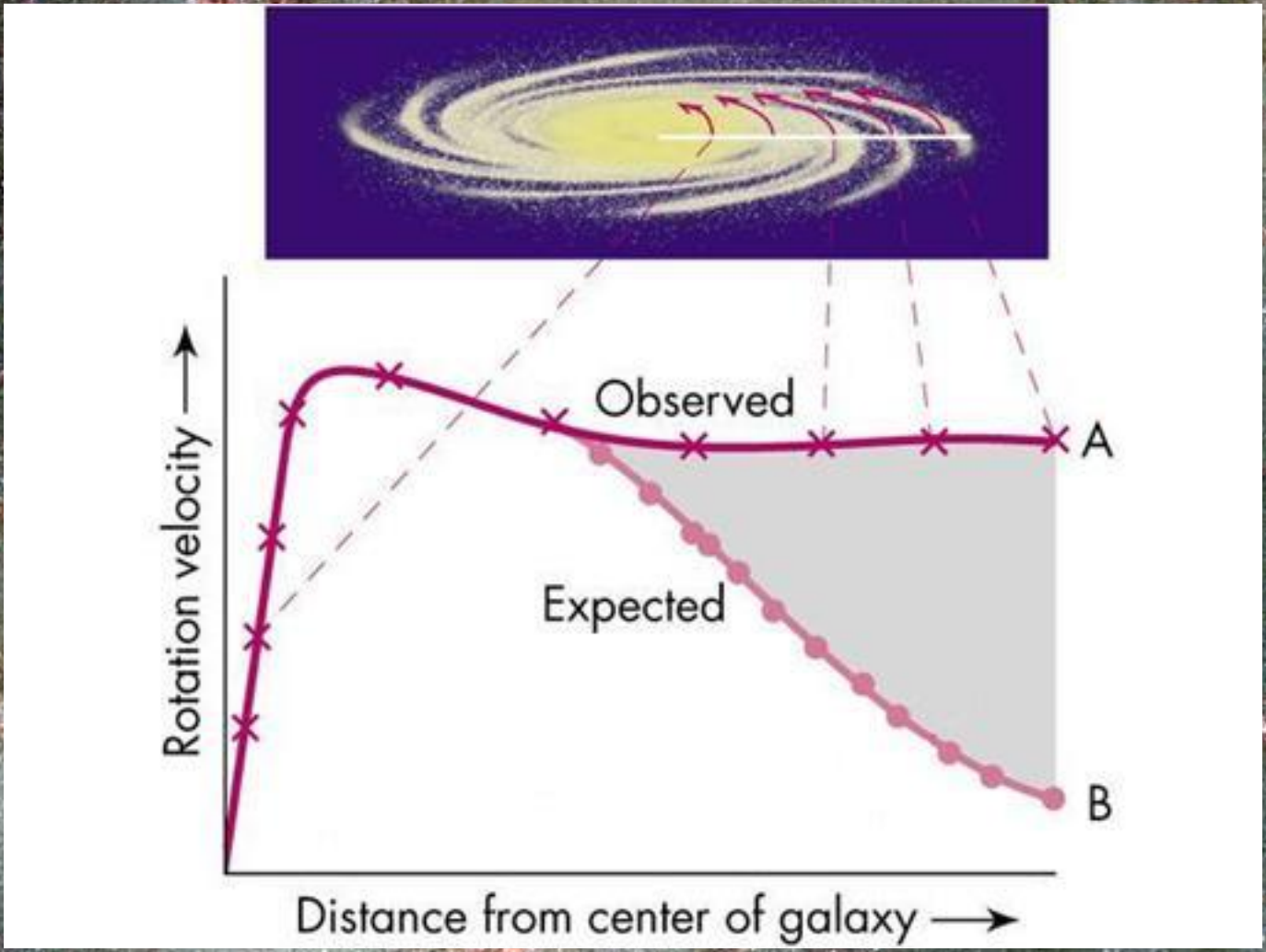
But the universe is made of *matter*

Well… some of it at least

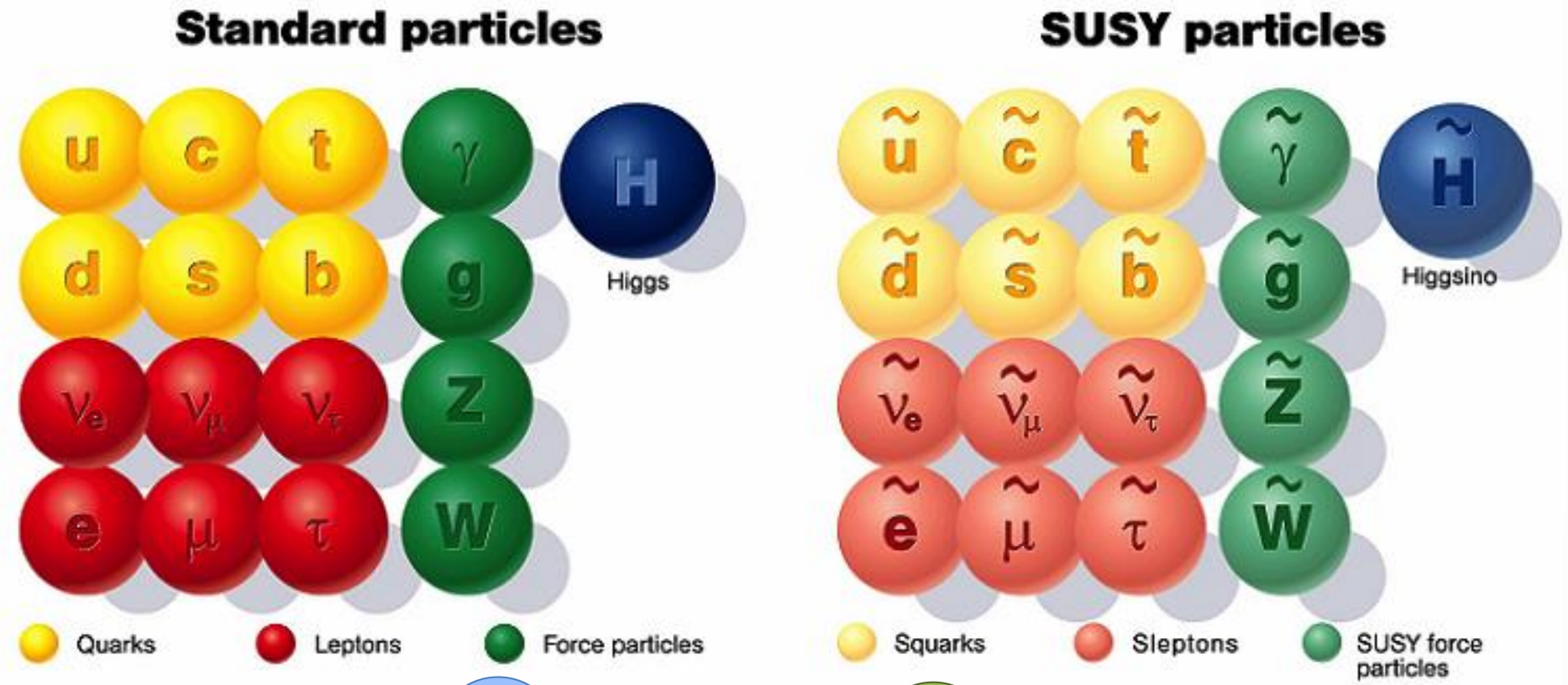


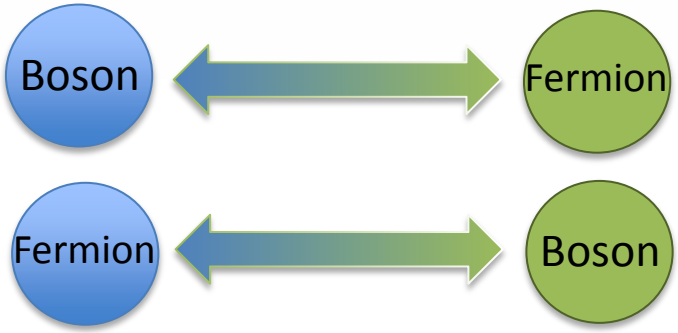
Leaving this stuff for the cosmologists

Dark Matter

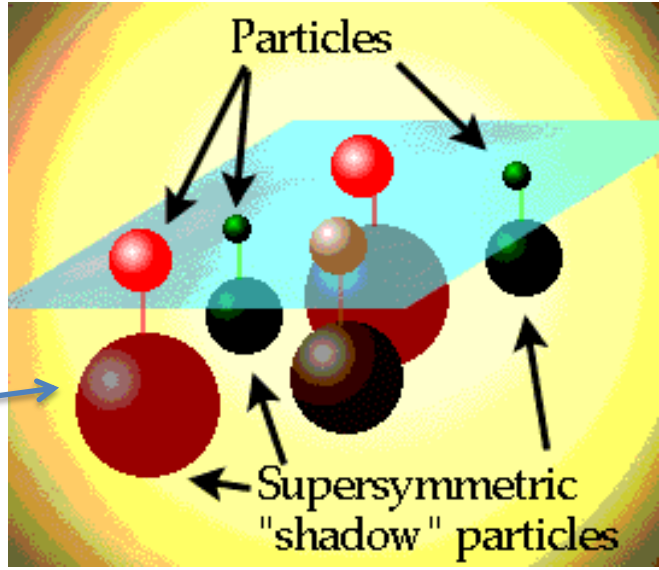

Observed
A
Expected
B
Rotation velocity
Distance from center of galaxy

New physics?

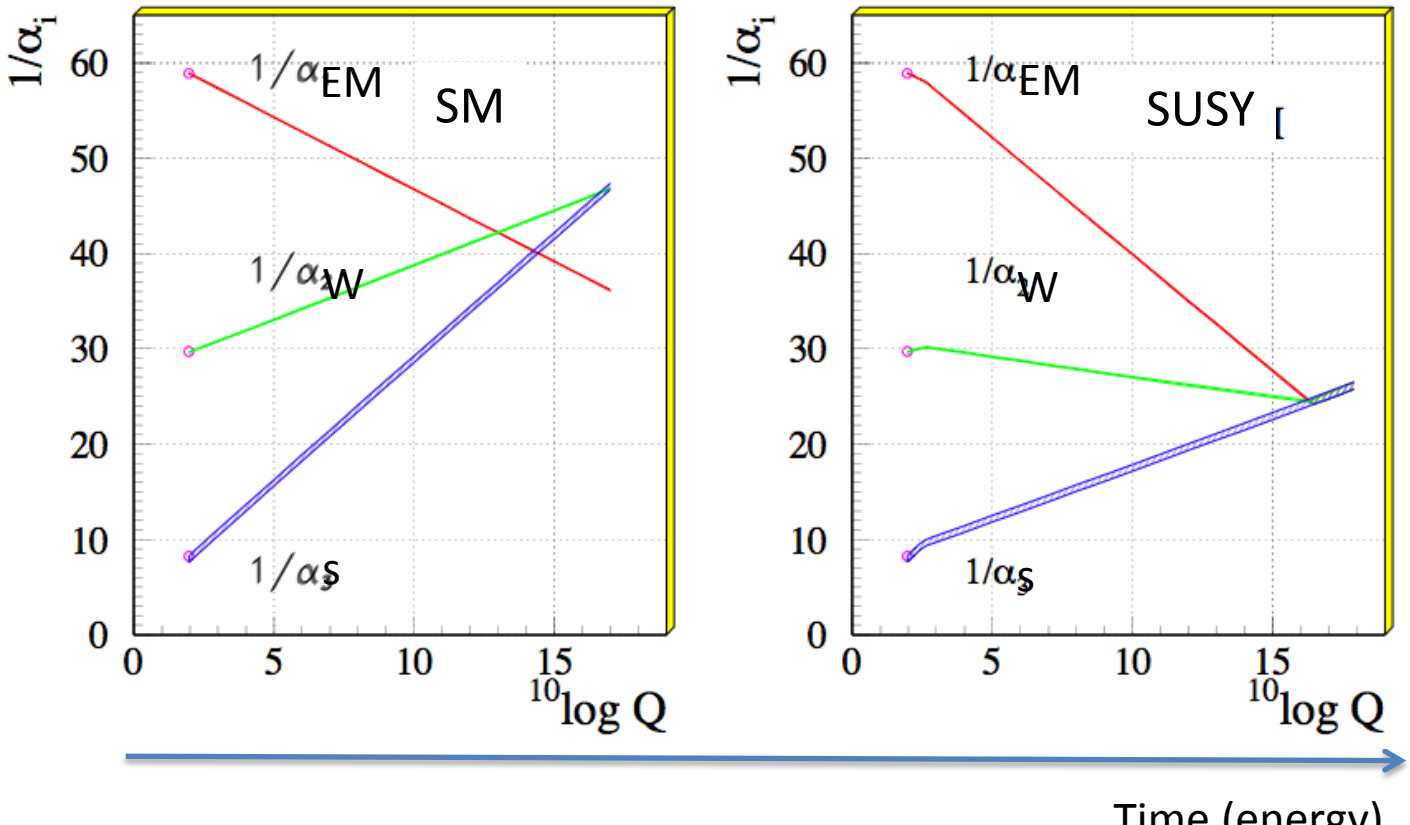

Standard particles
u
c
t
γ
H
Higgs
d
s
b
g
νe
νμ
ντ
Z
e
μ
τ
W
Quarks
Leptons
Force particles
SUSY particles
ũ
c̃
t̃
γ̃
H̃
Higgsino
d̃
s̃
b̃
g̃
ν̃e
ν̃μ
ν̃τ
Z̃
ẽ
μ̃
τ̃
W̃
Squarks
Sleptons
SUSY force particles


Boson
Fermion
Fermion
Boson

Why do we like Supersymmetry (SUSY)?



Dark matter candidates?



Unification of forces at high energies

bosonic TC
composite Higgs
TC-TC
hypercolor
supercolor
techni-GIM
extended TC
pseudo NGB
NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
effective susy
susy
NNMSSM
NMSSM
MSSM +νR
ununified SM
axigluon
sterile ν
heavy Majorana ν
6th gen
5th gen
4th gen
lepto quark
vector-like family
fractionally charged
milli-charged
mono-pole
Z'ψ
Z'χ
WR
Z'SM
Z'η
X
Y
S, T, U
shadow matter
mirror symmetry
triplet Higgs
doubly charged Higgs
Type I
Type II
general 2HDSM
spontaneous CP
superweak
milli-weak
Weinberg's 3HD
Majoron
axion
saxion
axino
familon
NGB
worm-hole
Extra dim
quintessence
k-essence
Λ
composite W, Z
g, ℓ
contact int.
N=2
N=4
N=8
string
hetero tic
matrix M
IIB
IIA
F
I