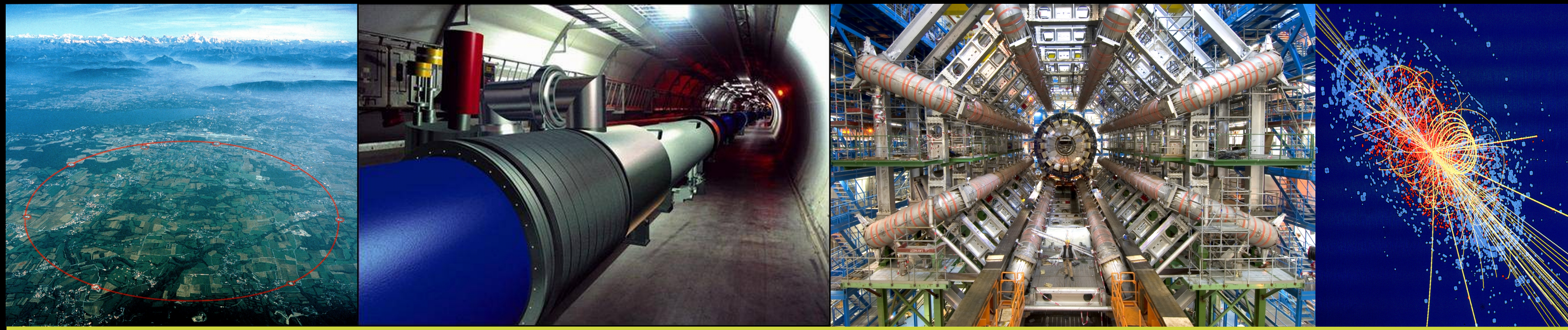
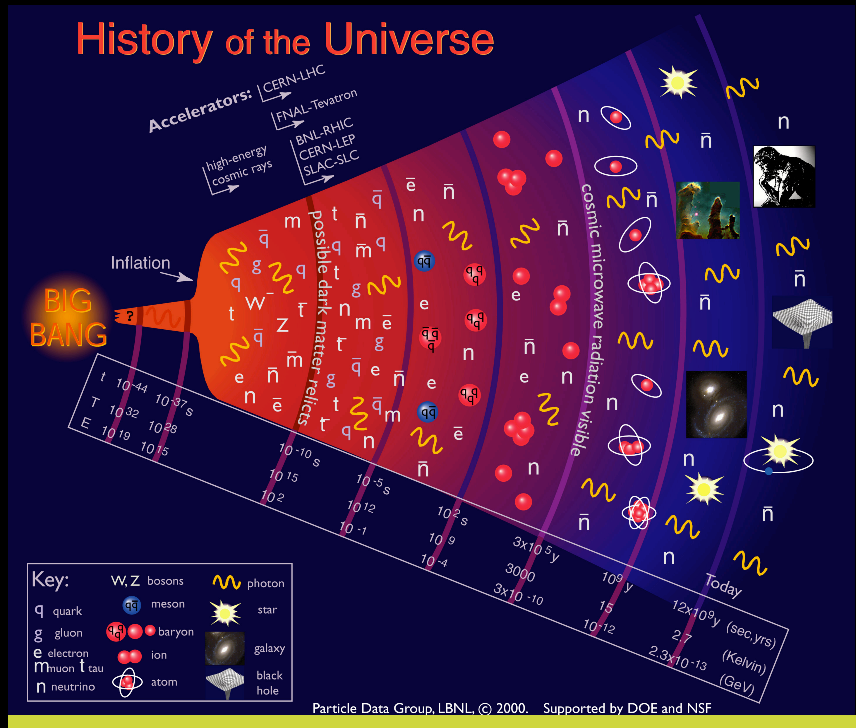


Introduction to particle physics

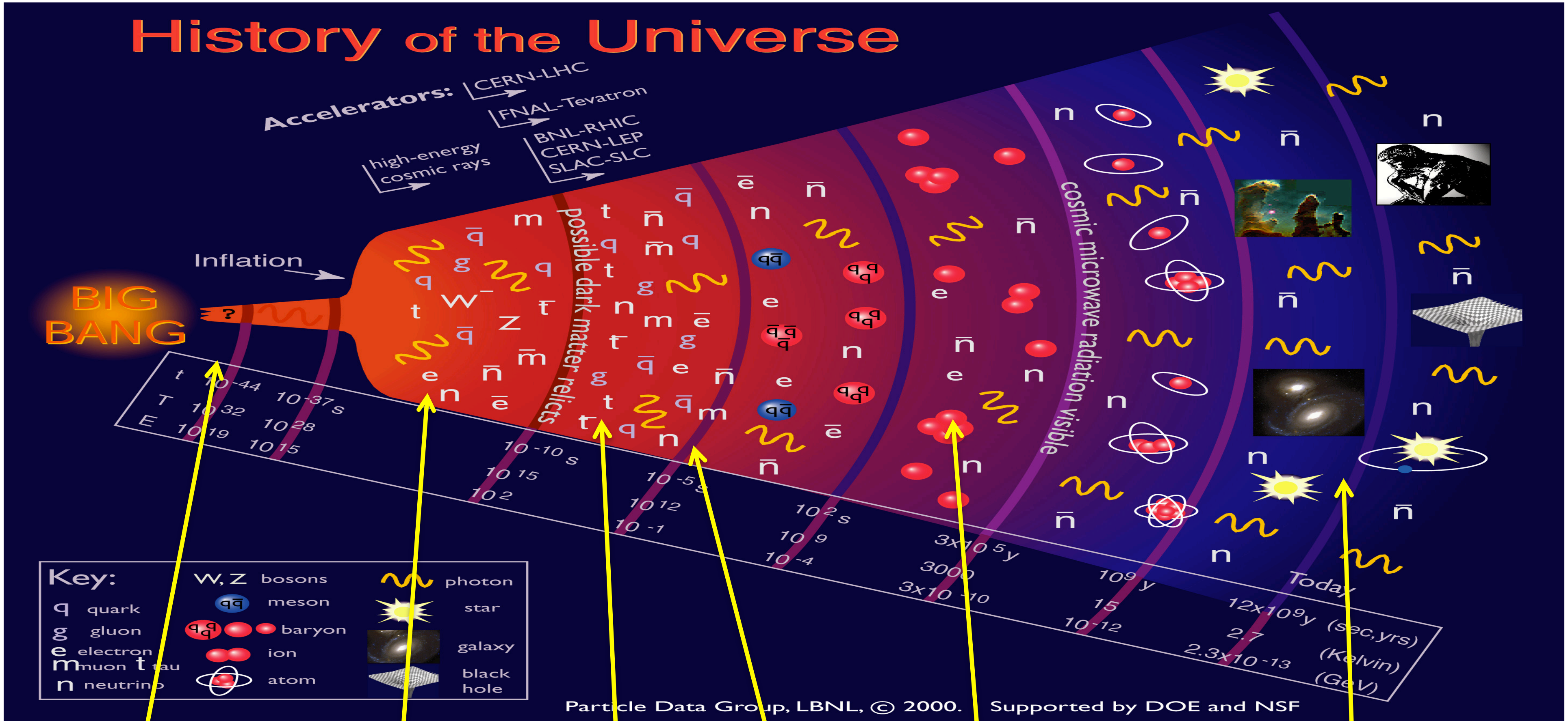
Tara Shears, University of Liverpool

BIG BANG


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
Today
(sec,yrs)
(Kelvin)
(GeV)
Key:
W, Z bosons
photon
quark
meson
star
gluon
baryon
electron
ion
galaxy
muon
tau
neutrino
atom
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

> > >

NOW



Cosmology

LHC

Nuclear physics

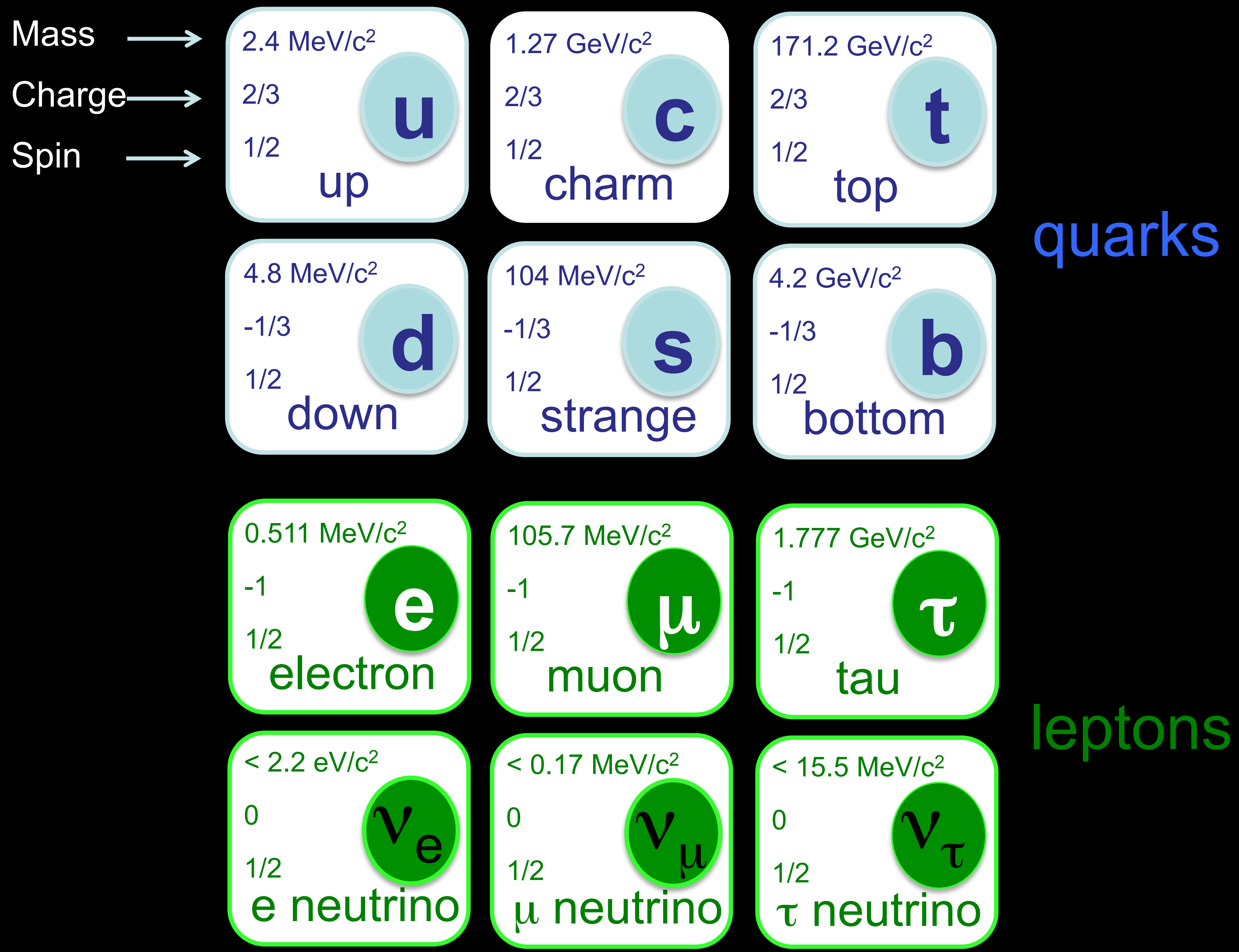
Cosmic rays

Quark/gluon plasma

Astrophysics

u	c	t	e	μ	τ
d	s	b	ν_e	ν_μ	ν_τ
quarks			leptons		

Particle Physics 8/7


Mass
Charge
Spin
2.4 MeV/c²
2/3
1/2
u
up
1.27 GeV/c²
2/3
1/2
c
charm
171.2 GeV/c²
2/3
1/2
t
top
4.8 MeV/c²
-1/3
1/2
d
down
104 MeV/c²
-1/3
1/2
s
strange
4.2 GeV/c²
-1/3
1/2
b
bottom
quarks
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
< 2.2 eV/c²
0
1/2
νe
e neutrino
< 0.17 MeV/c²
0
1/2
νμ
μ neutrino
< 15.5 MeV/c²
0
1/2
ντ
τ neutrino
leptons

And … antimatter

Classical equation of motion:
Linear.

$$E = 0.5mv^2$$

Einstein's equation of motion:
Quadratic.

$$E^2 = p^2c^2 + m^2c^4$$

Interpretation: every fermion has an antimatter version.

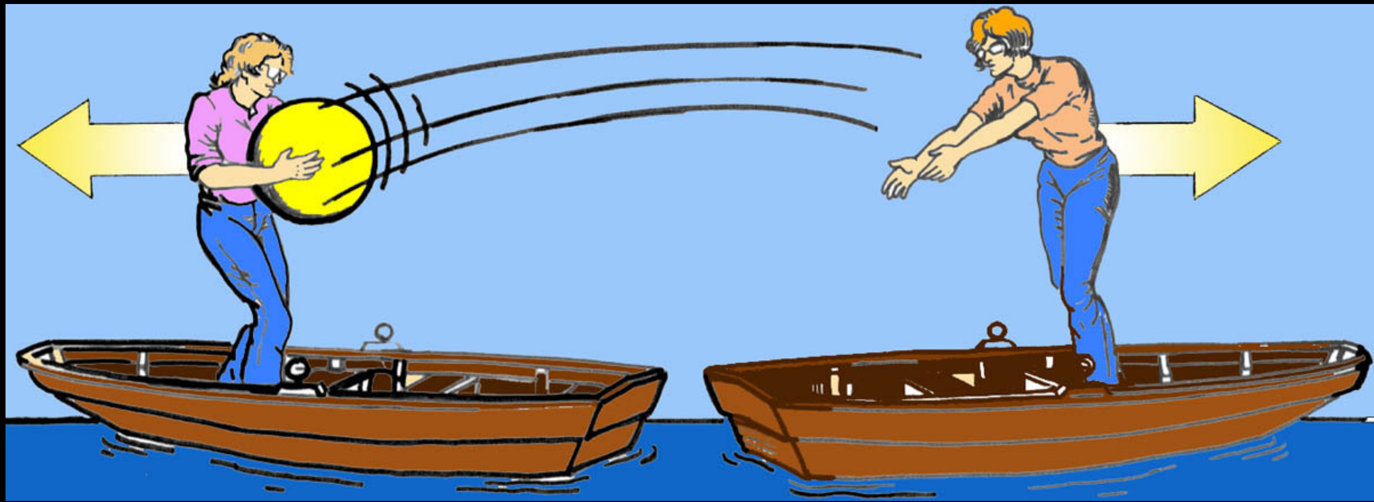
Same mass, opposite charge

eg. antiquark $\bar{q}$, antimuon μ^+, antineutrino $\bar{\nu}$

Antimatter 14/7

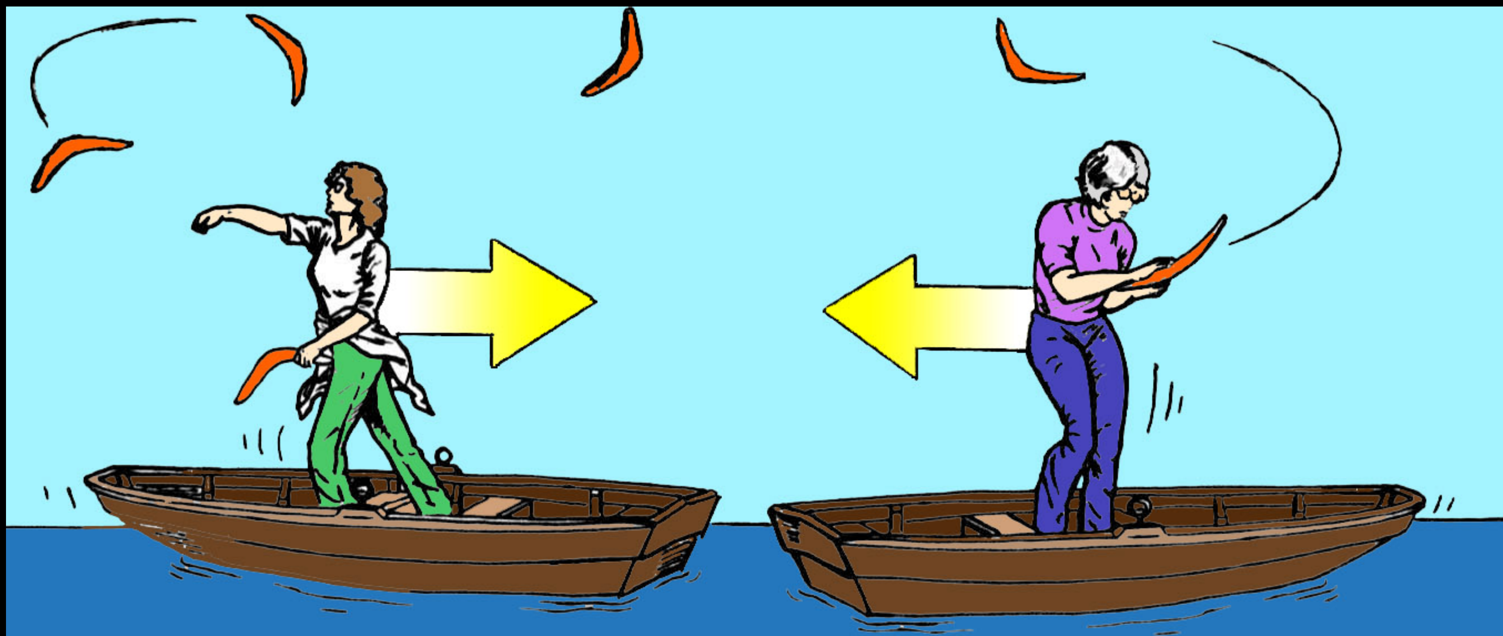
Matter is held together by forces;

– mediated by force carrying particles (bosons; spin 1)



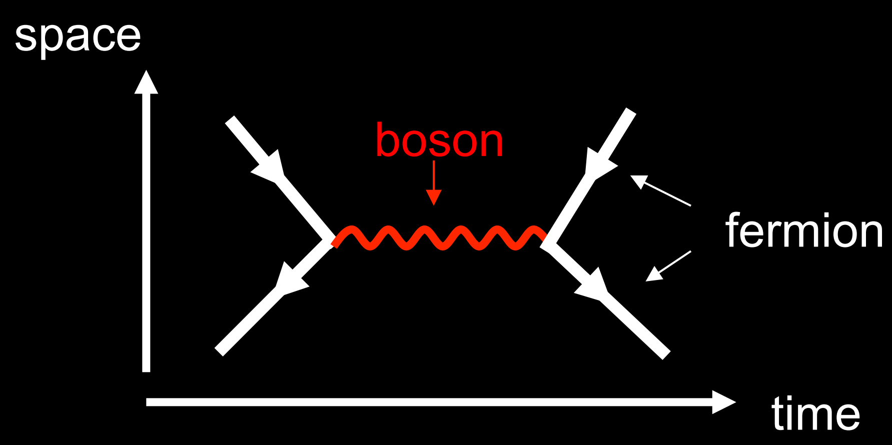
Matter is held together by forces;

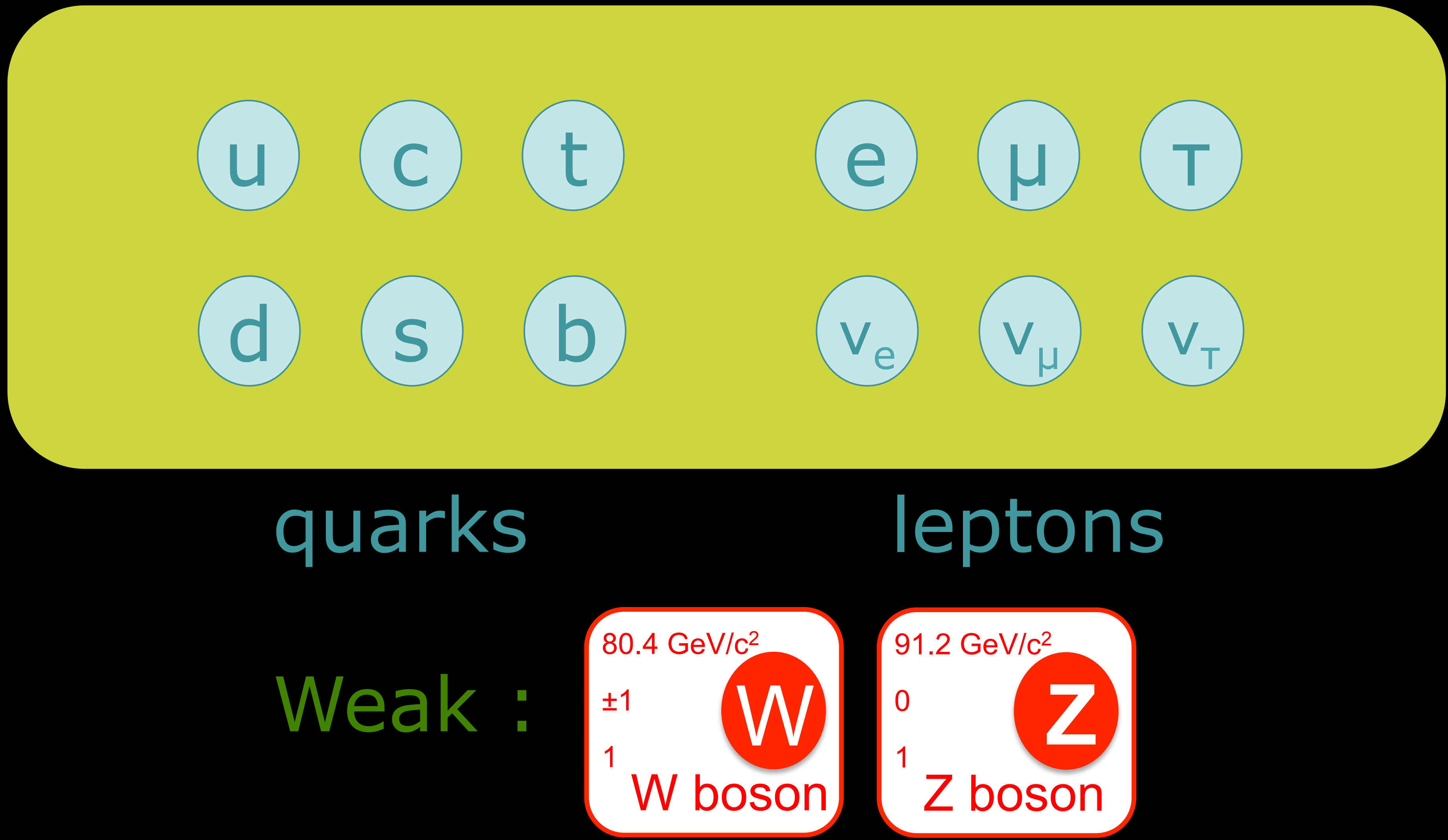
– mediated by force carrying particles (bosons; spin 1)

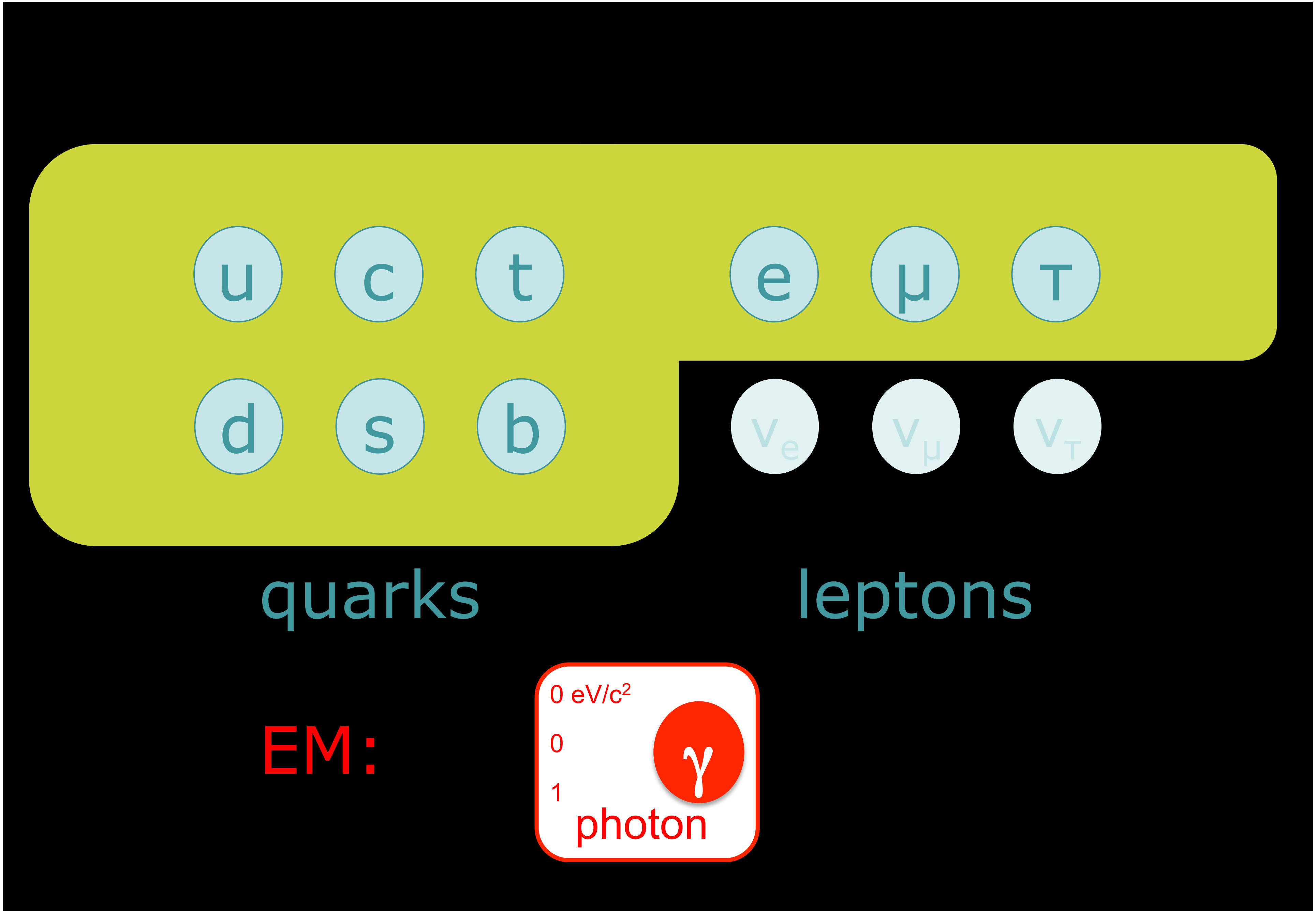


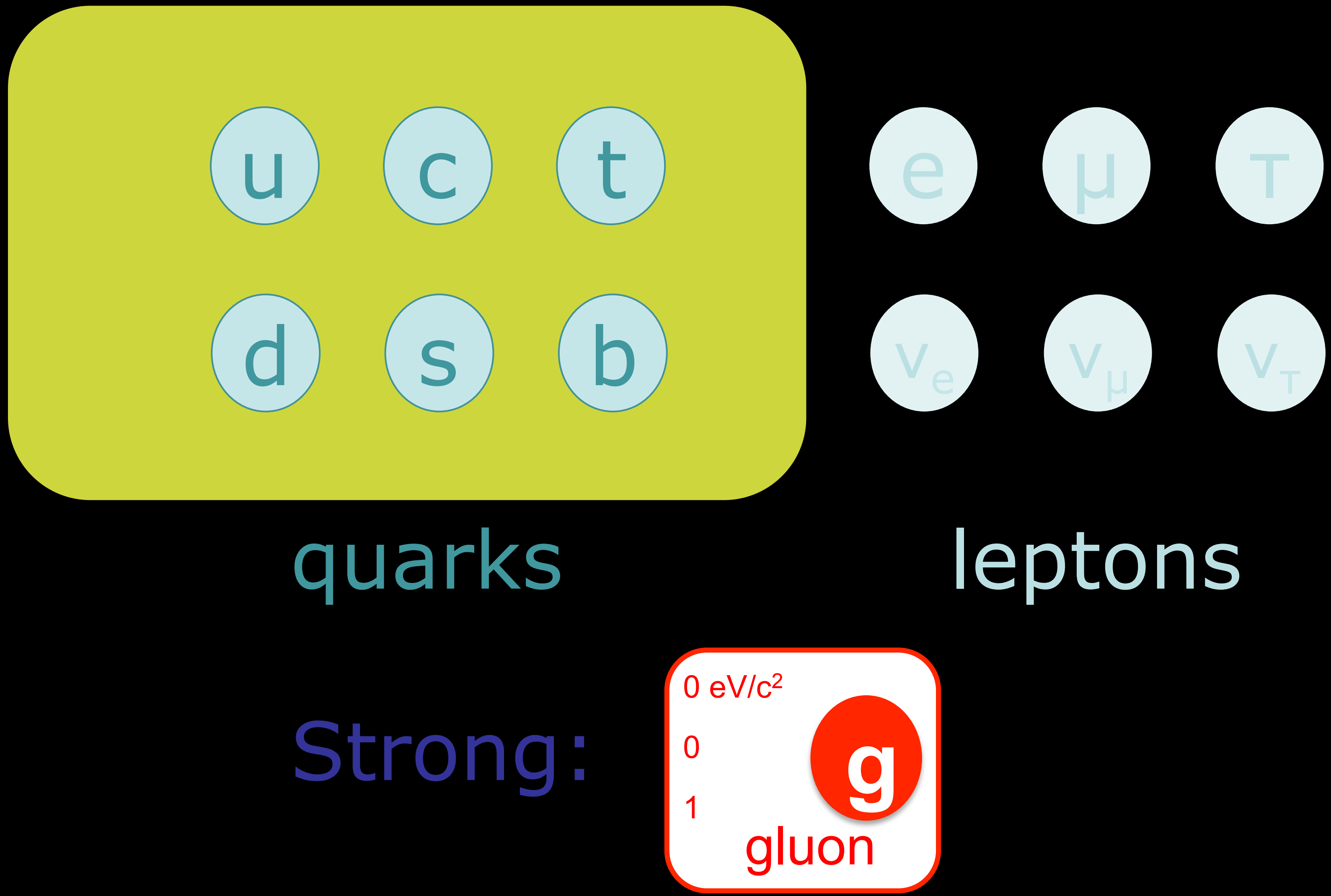
Aside: Feynman diagrams

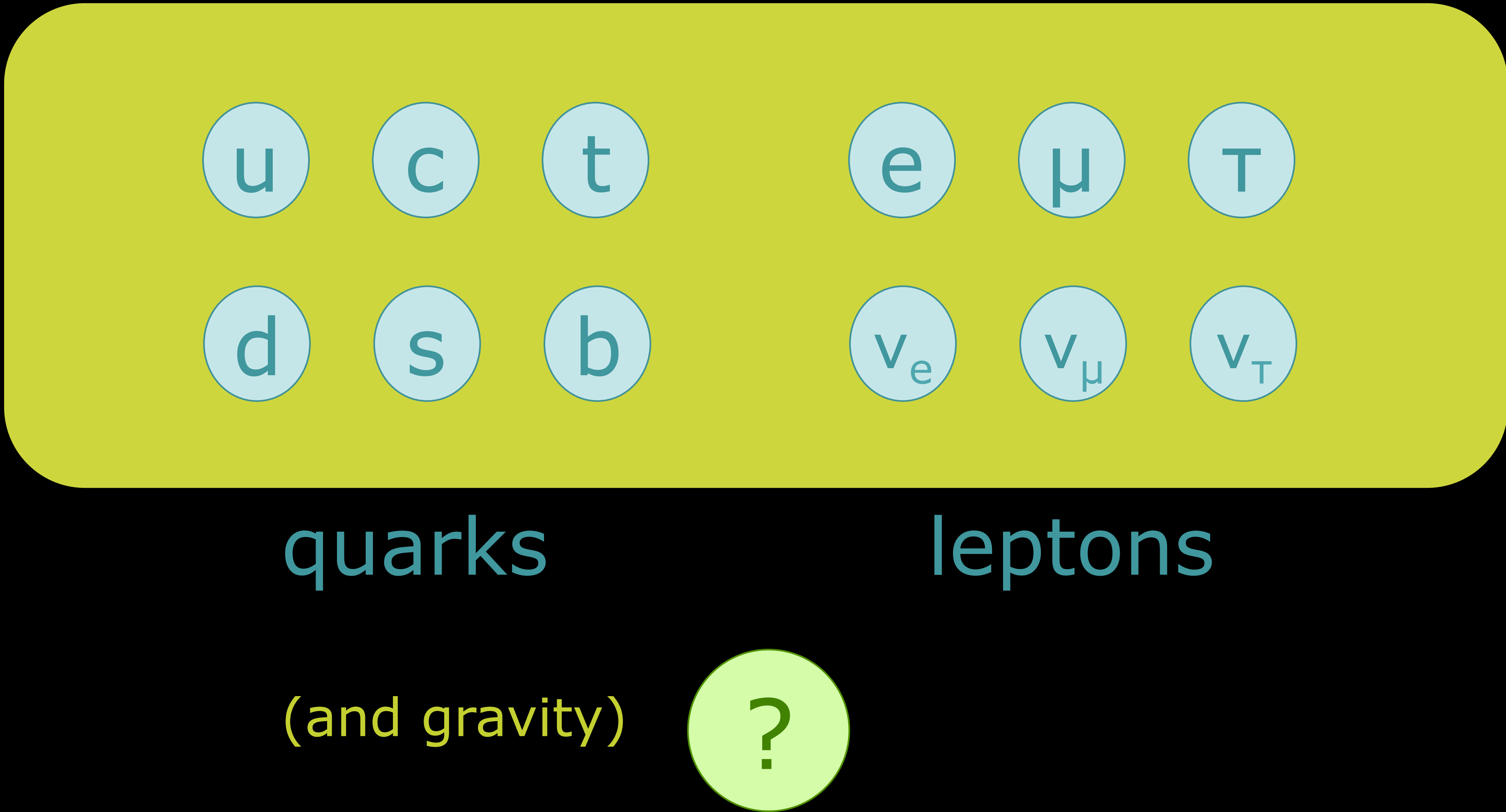
"tree" level
Lowest order




u c t
d s b
e μ τ
ν_e ν_μ ν_τ
quarks
leptons
Weak :
80.4 GeV/c²
±1
1
W
W boson
91.2 GeV/c²
0
1
Z
Z boson


u
c
t
e
μ
τ
d
s
b
ν_e
ν_μ
ν_τ
quarks
leptons
EM:
0 eV/c²
0
1
γ
photon


u
c
t
d
s
b
e
μ
τ
ν_e
ν_μ
ν_τ
quarks
leptons
Strong:
0 eV/c²
0
1
g
gluon


u
c
t
e
μ
τ
d
s
b
ν_e
ν_μ
ν_τ
quarks
leptons
(and gravity)
?

Force Strengths:

Quantified by "**coupling constants**" α

eg. EM force: $$F = \frac{q_1 q_2}{4\pi\varepsilon_0 r^2}$$

Define: $$\alpha = \frac{q_1 q_2}{4\pi\varepsilon_0 \hbar c} = \frac{g^2}{4\pi}$$

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

Force Strengths:

Quantified by "**coupling constants**"

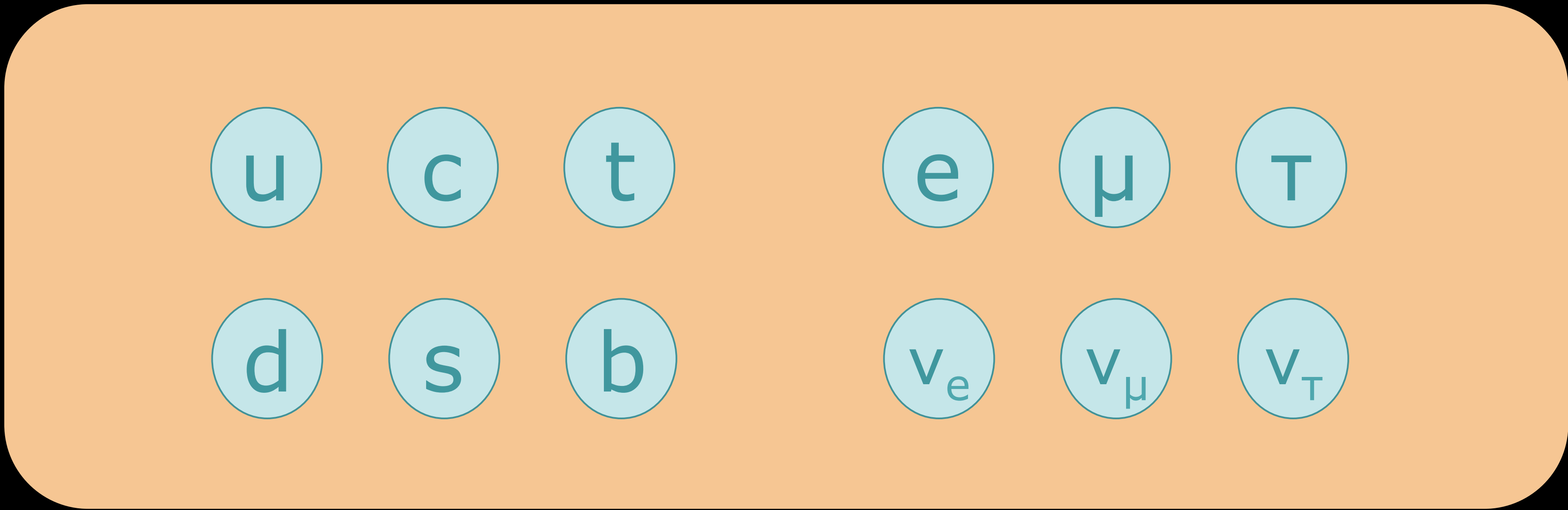
Strong: $\alpha_s \sim 1$

Electromagnetic: $\alpha_{em} \sim 1/137$

Weak: $\alpha_W \sim 10^{-6}$

Gravity: $\alpha_g \sim 10^{-40}$

(note: low energy/large distance scale values.
Coupling strength changes with energy)



quarks

leptons

Mass:

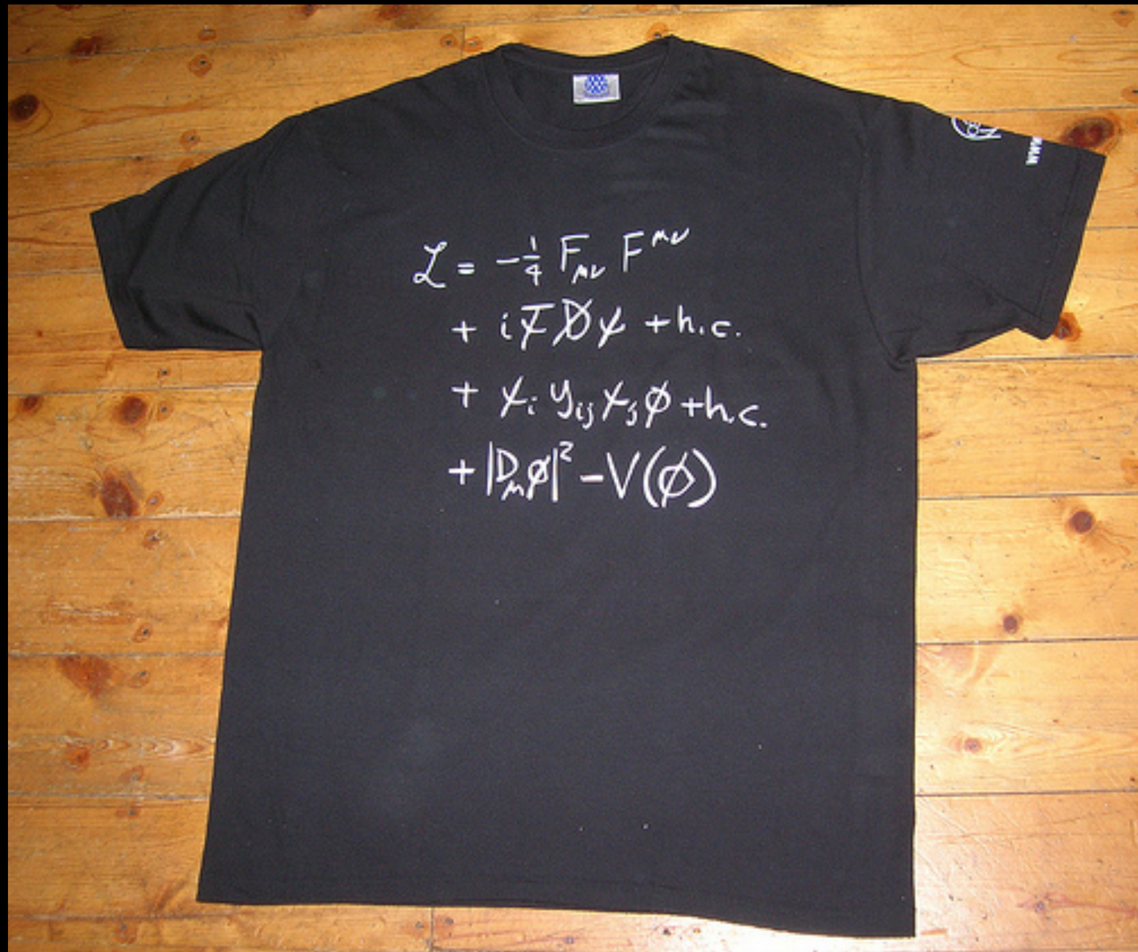
Higgs

Higgs 16/7

[redacted]

Standard Model

Matter
Forces
Higgs



Similarities, differences:

EM force	**Weak force**	**Strong force**
Electric charge (1)	Weak charge (2)	Colour charge (3)
Massless photon	Massive $W^{\pm}$,Z	8 massless gluons
Coupling g	Coupling g_W	Coupling g_s

Value unknown/ not predicted

Similarities, differences:

EM force	**Weak force**	**Strong force**
Electric charge (1)	Weak charge (2)	Colour charge (3)
Massless photon	Massive $W^{\pm}$,Z	8 massless gluons
Coupling g	Coupling g_W	Coupling g_s

Higgs

Value unknown/ not predicted

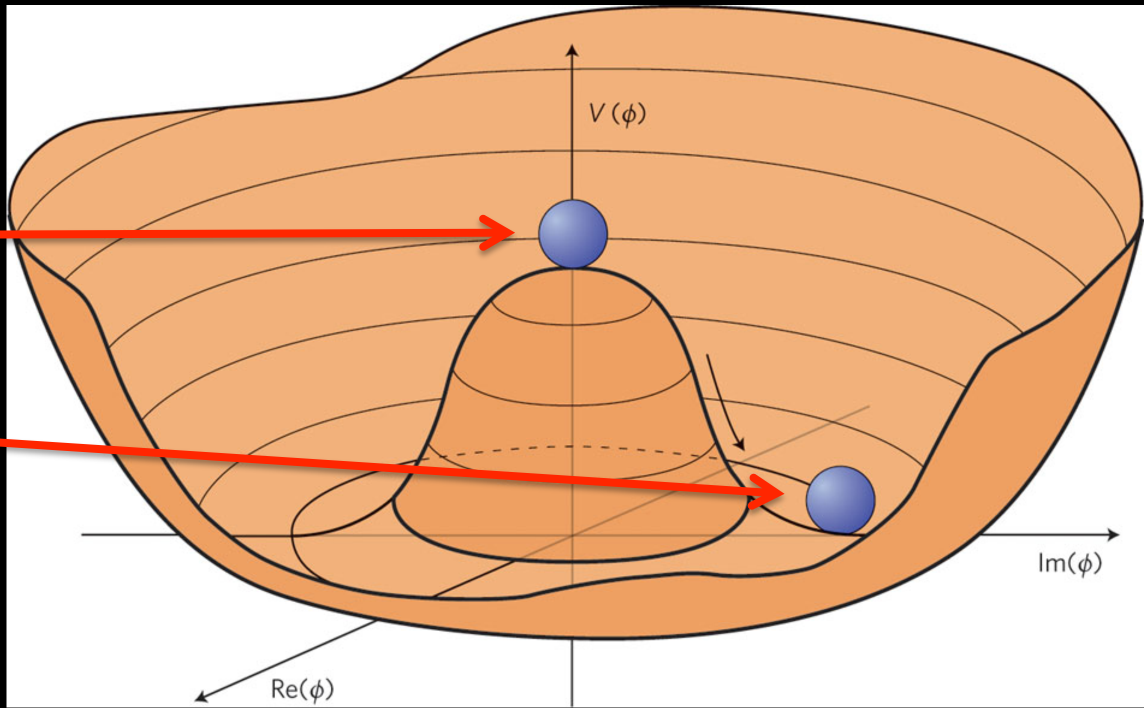
Introduce Higgs field:

Complex doublet (1d case shown here to get idea)

Potential energy $V(\phi) = -0.5\mu^2|\phi|^2 + \lambda|\phi|^4$

Big Bang
Massless bosons

Shortly (~10^{-12} s) after
Spontaneous symmetry breaking
Bosons acquire mass
(nb. fermions too)



Higgs

Introduce Higgs field :

Couples to particles to give mass (amount ~ coupling strength)

Complex doublet has 4 free parameters

3 absorbed into W+, W-, Z boson mass

W+, W-, Z, γ mixtures of original weak, em massless bosons.

1 manifested as a massive Higgs boson (m_H)

(note: Higgs field gives mass to fermions by a different mechanism)

Higgs

Introduce Higgs field :

After symmetry breaking, Higgs sector properties are:

- spinless Higgs boson (m_H)
- vacuum expectation value (mean field value) (v)

Consequences:

Weak and electromagnetic forces connected

Massive Z is mixture of massless em + weak bosons

Mw, Mz and weak, em couplings related:

$\tan \theta_W = g_W / g$

$M_W = M_Z \cos \theta_W$

Similarities / differences within Standard Model

EM force	**Weak force**	**Strong force**
Electric charge (1)	Weak charge (2)	Colour charge (3)
Massless photon	Massive $W^{\pm}$,Z	8 massless gluons
Coupling g	Coupling g_W	Coupling g_s

Value unknown/ not predicted

Similarities / differences within Standard Model

EM force

Abelian

Only charged particles couple

Weak force

Non-abelian

Only left handed particles couple

quark mixing (3 generations, CP)

Neutrino mixing (3 generations, CP)

Strong force

Non-abelian

Only quarks couple

Similarities / differences within Standard Model

Running couplings

EM force

Abelian

Only charged particles couple

Weak force

Non-abelian

Only left handed particles couple

quark mixing (3 generations, CP)

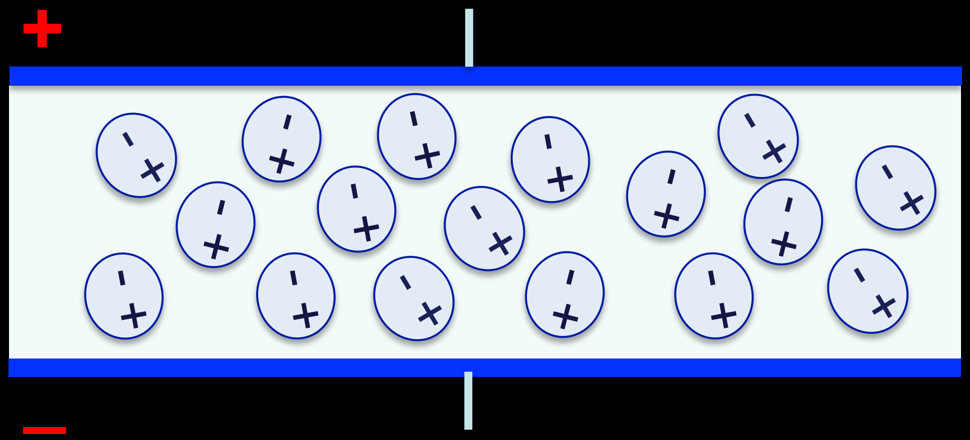
Neutrino mixing (3 generations, CP)

Strong force

Non-abelian

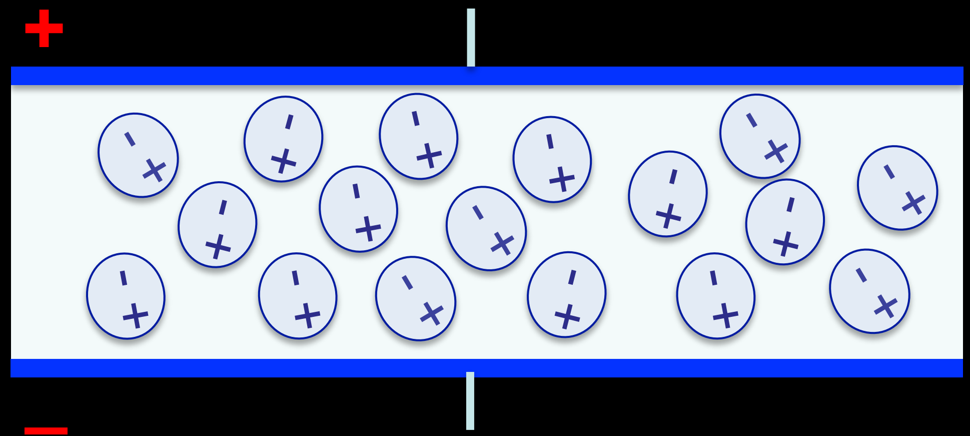
Only quarks couple

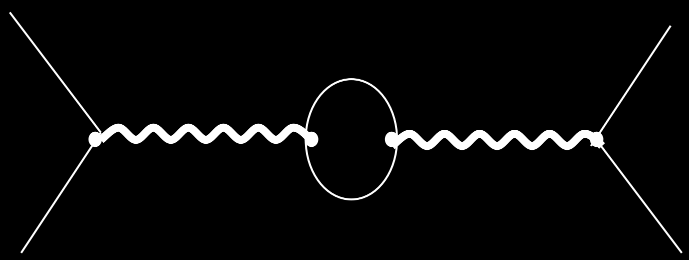
Running couplings



Parallel plate capacitor
Dielectric reduces apparent charge on plates (polarisation)
Screening of charge.

EM force



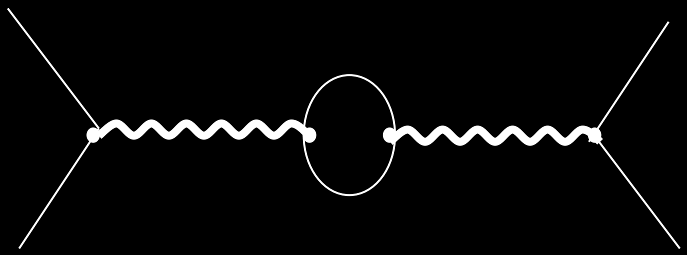


Charge screened by **vacuum polarisation**;

High E ⇒smaller distances ⇒see more charge

EM force strength increases with E

QCD, Weak force

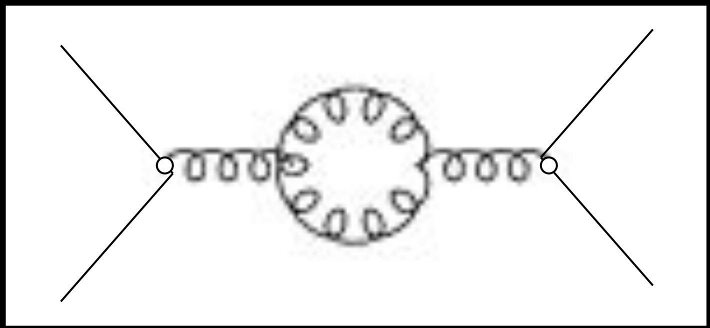


Charge screened by **vacuum polarisation**;

High E ⇒smaller distances ⇒see more charge

Force strength increases with E

+



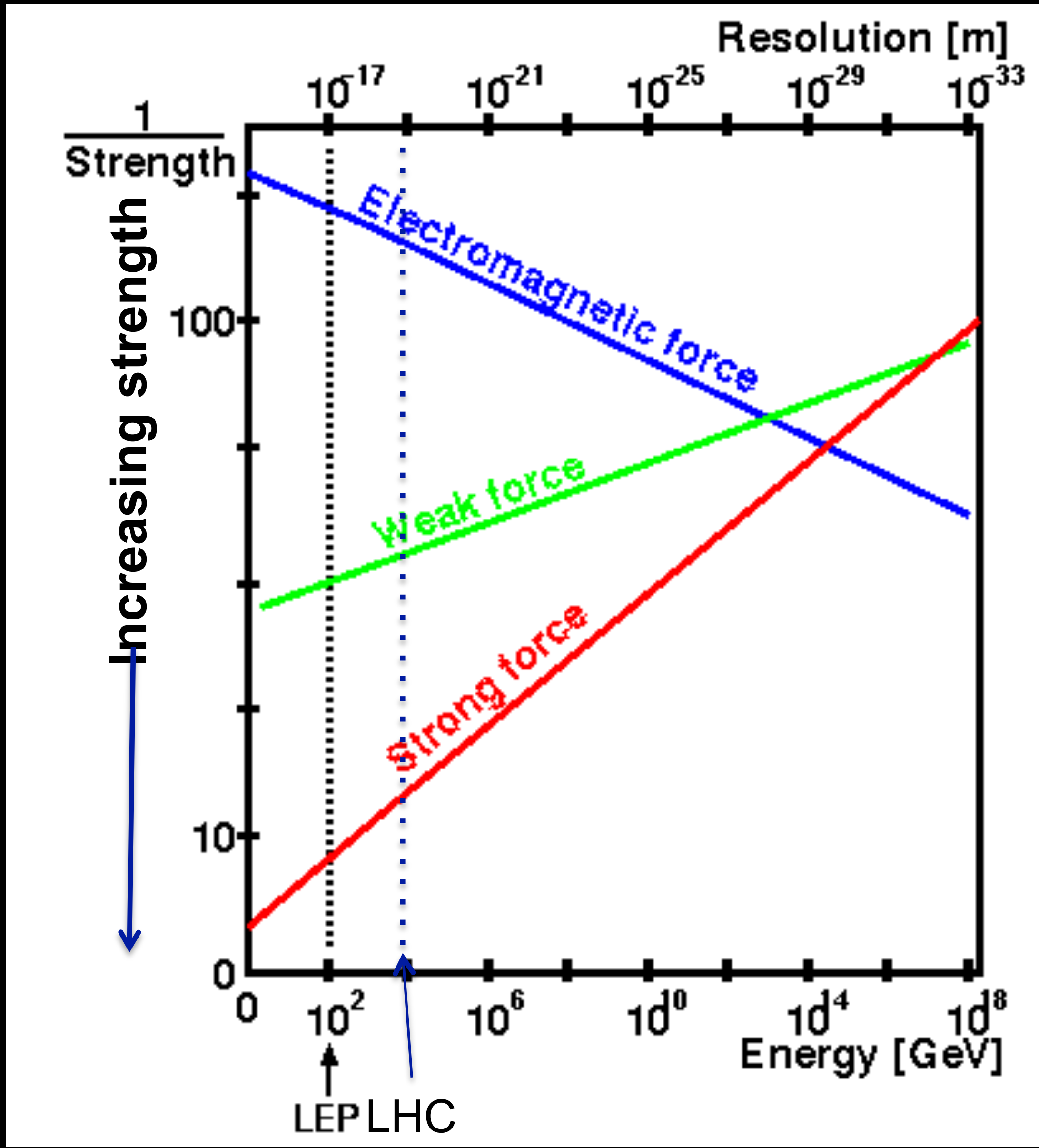
Non-abelian forces (weak, strong) also include these “extra” charge loops

Higher E =>smaller distances => see less charge

Net effect: **force strength decreases with E**

Note:
1/force strength plotted.

1/em falls with E.
1/weak rises with E.
1/strong rises with E.



Implications: QCD

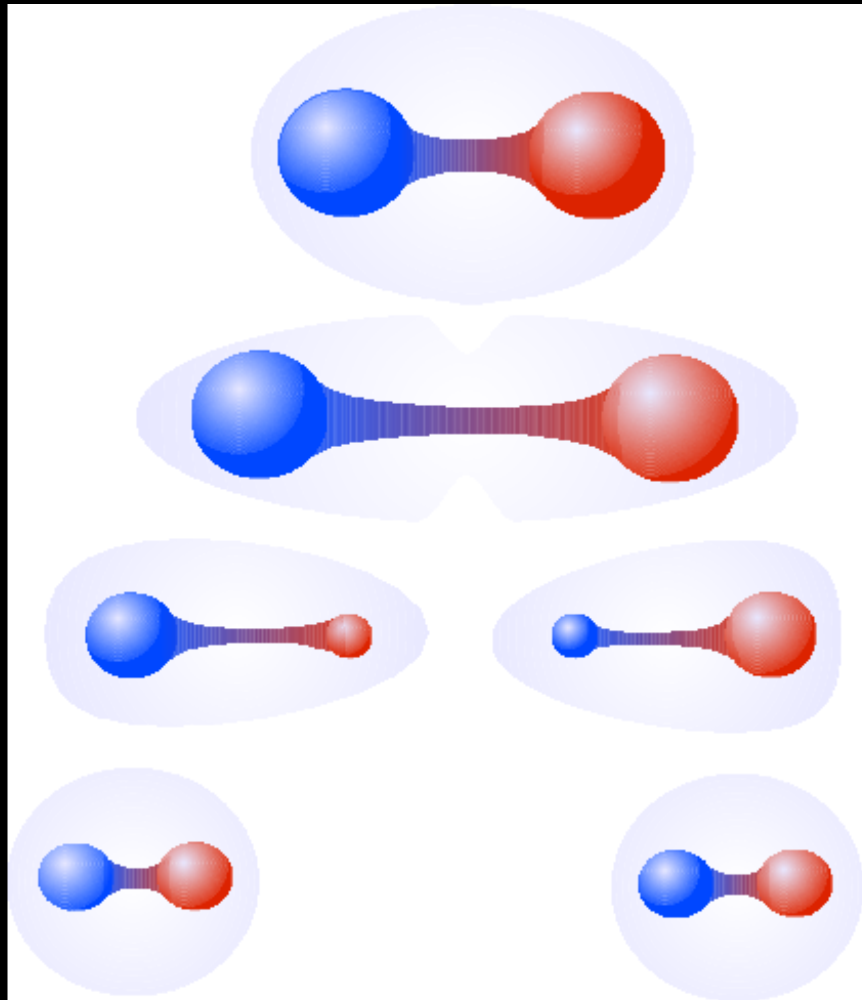
Force grows with distance.

Confinement

- No free quarks
- Colourless hadrons
  - Baryons (3 q)
  - Mesons (q anti-q)
  - Tetraquarks? (2q 2anti-q)
  - ?

Hadronisation

- jets



Similarities / differences within Standard Model

EM force

Abelian

Only charged particles couple

Weak force

Non-abelian

Only left handed particles couple

quark mixing (3 generations, CP)

Neutrino mixing (3 generations, CP)

Strong force

Non-abelian

Only quarks couple

Standard Model fixed up to include experimental observations.

=> Better predictive power.

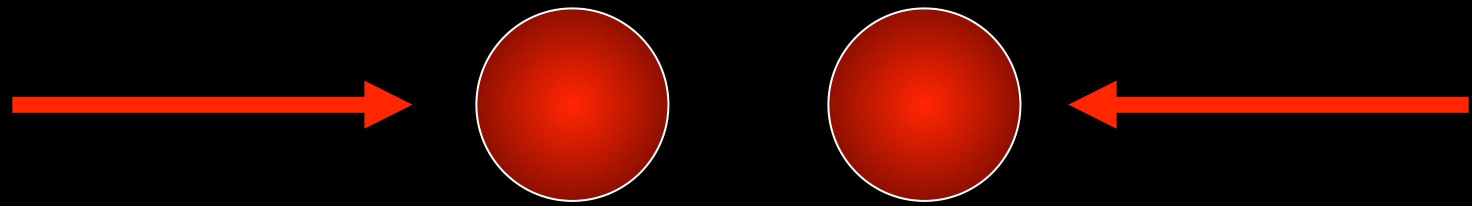
Very successful.

How do we know/test this?

Experiment

1) Source of fundamental particles

Particle accelerator: beams of charged particles, accelerated by em force

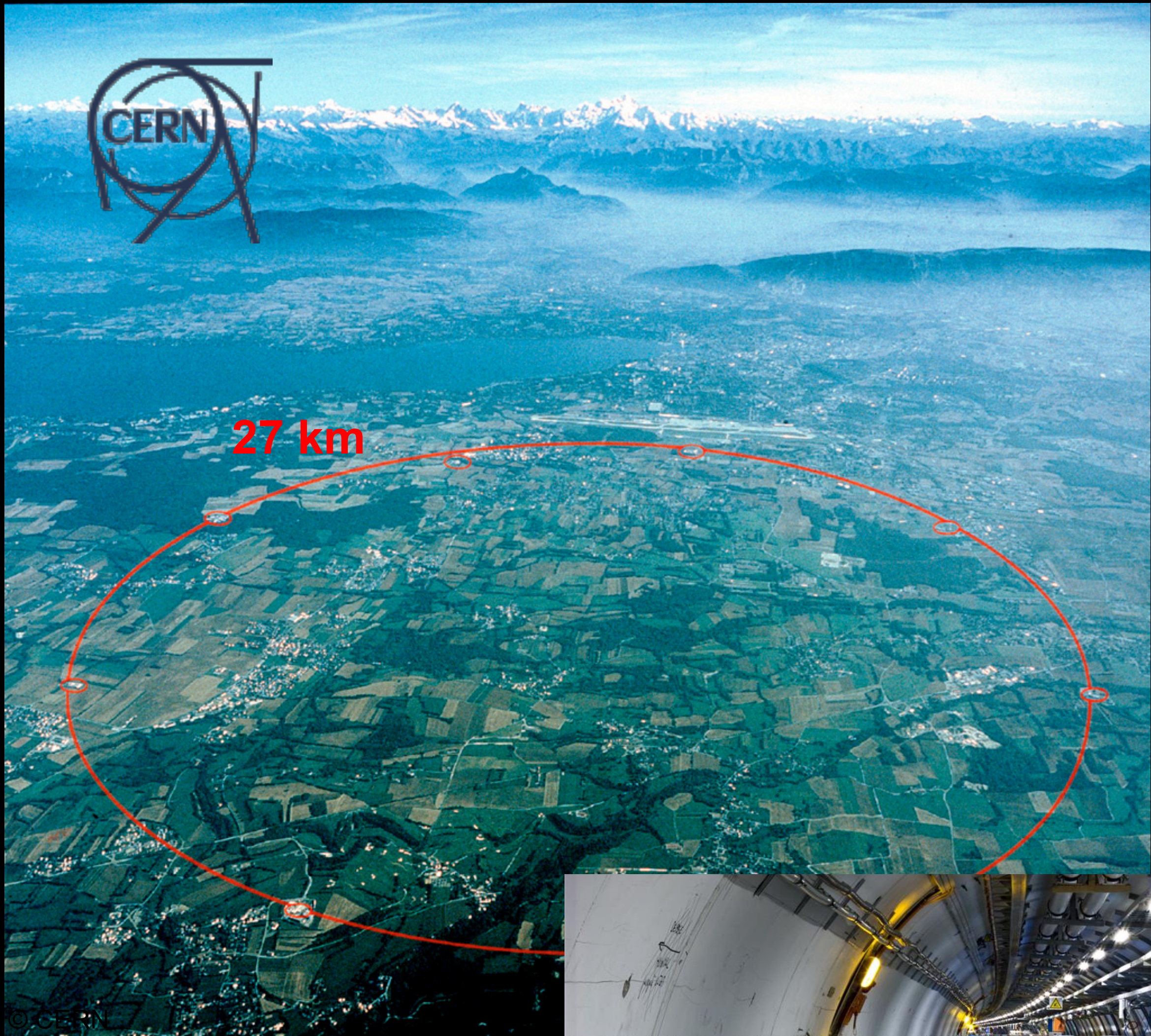


$$\sqrt{s} = \sqrt{\left(\sum_i E_i^2 - \sum_i p_i^2\right)}$$

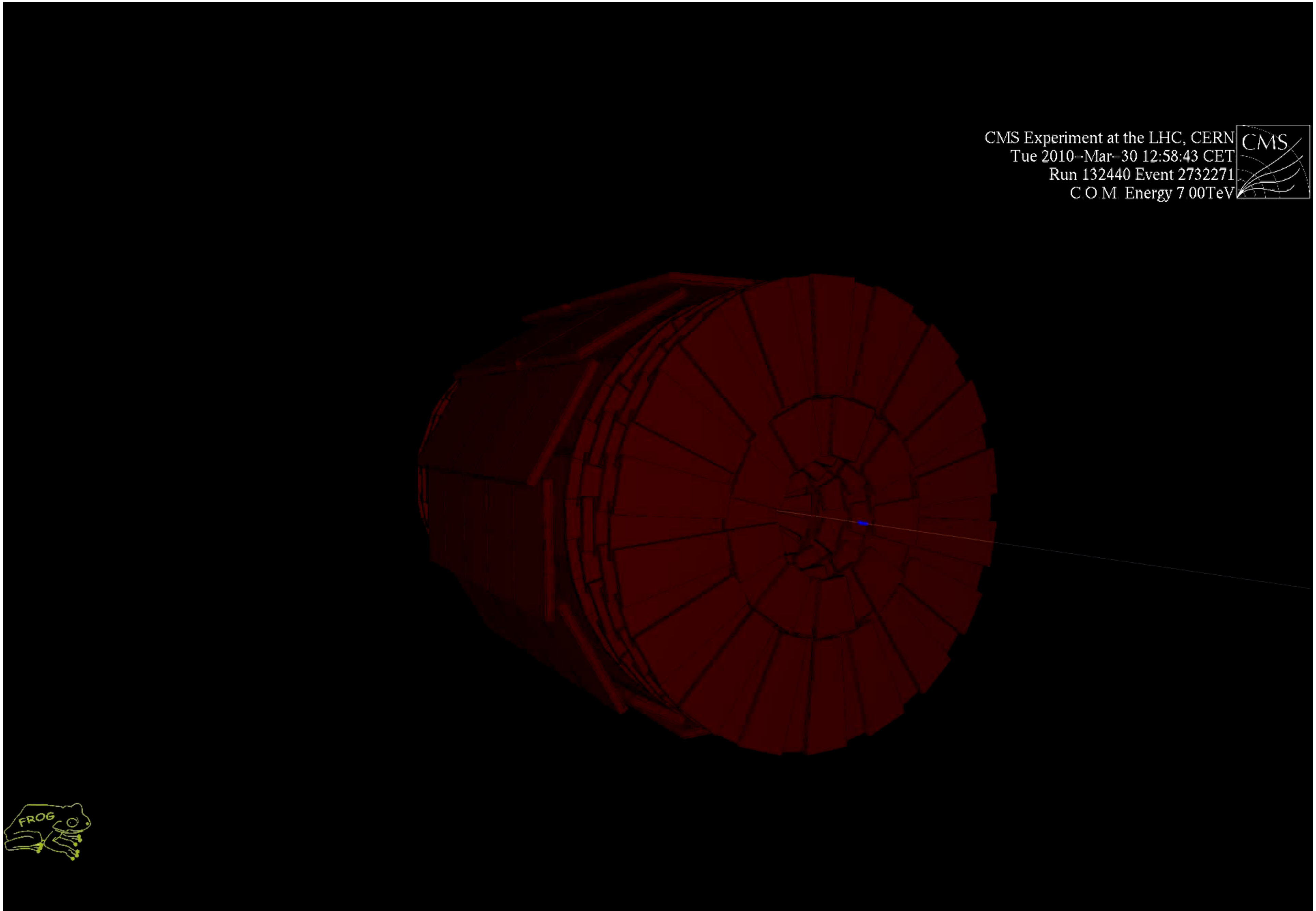
$$E = mc^2$$

(also cosmic rays, neutrinos from nuclear reactors…)

Accelerators 9/7



LHC:
High energy (√s=14 TeV)
Circular
Proton beams
Up to 10^8 collisions/s


CMS Experiment at the LHC, CERN
Tue 2010-Mar-30 12:58:43 CET
Run 132440 Event 2732271
C.O.M. Energy 7.00TeV
FROG

2) Record fundamental particles

Particles lose energy travelling through material

- Ionisation
- Radiation
- Interaction

Read out and record particle energy deposits

- Locate
- Reconstruct **(px, py, pz, m)**
- Identify

Detectors 10/7

(px,py,pz,m)

↑

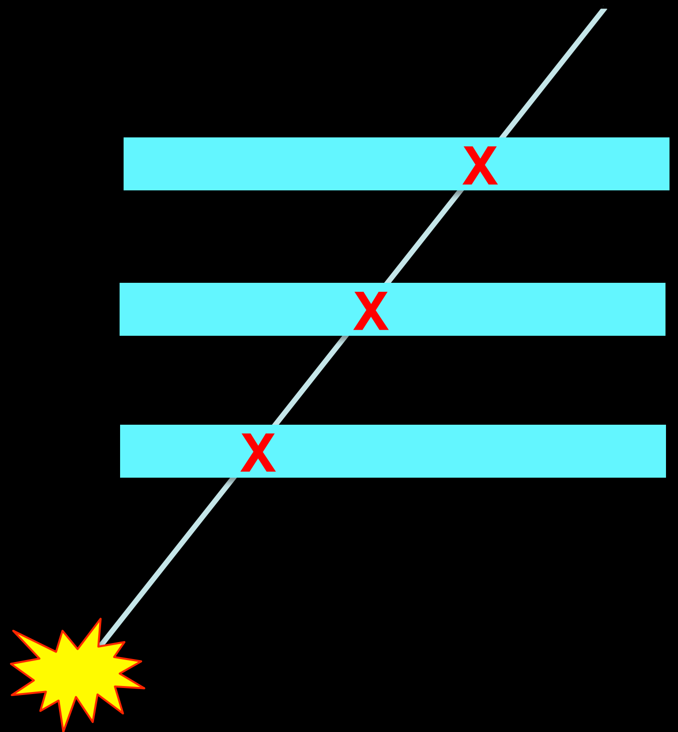
(x,y,z)

Reconstruct path

Reconstruct momentum

Measure energy

Identify type



Tracking detectors

Charged particles

Location:

- Ionisation (gas)
- e/hole (silicon)

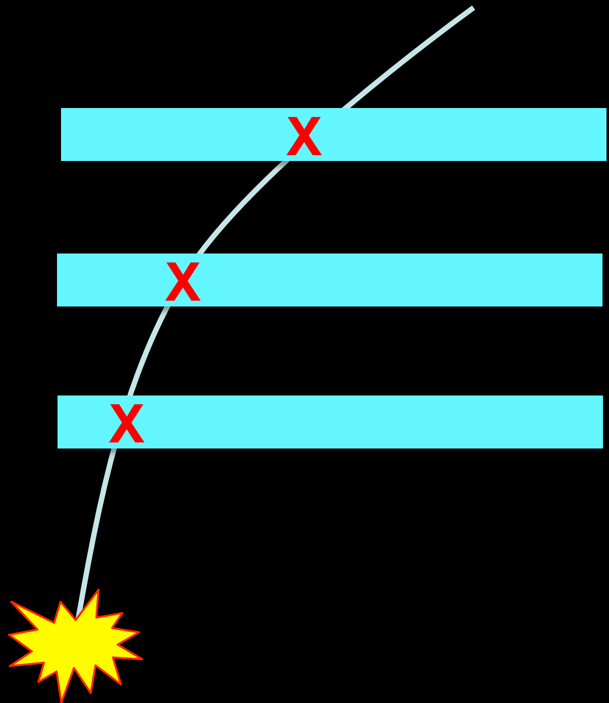
(**px,py,pz**,m)

Reconstruct path

Reconstruct momentum

Measure energy

Identify type



Magnetic field
Relate track curvature, B to p.

$$p = 0.3Br$$

Tara Shears, University of Liverpool

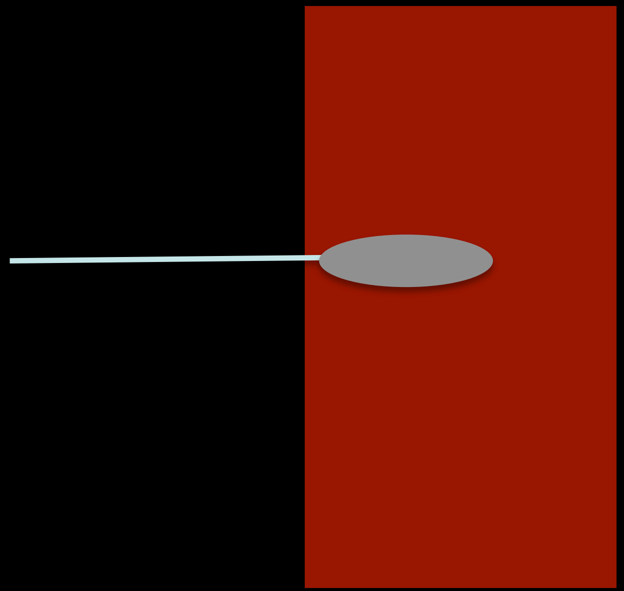
(px,py,pz,**m**)

Reconstruct path

Reconstruct momentum

Measure energy

Identify type



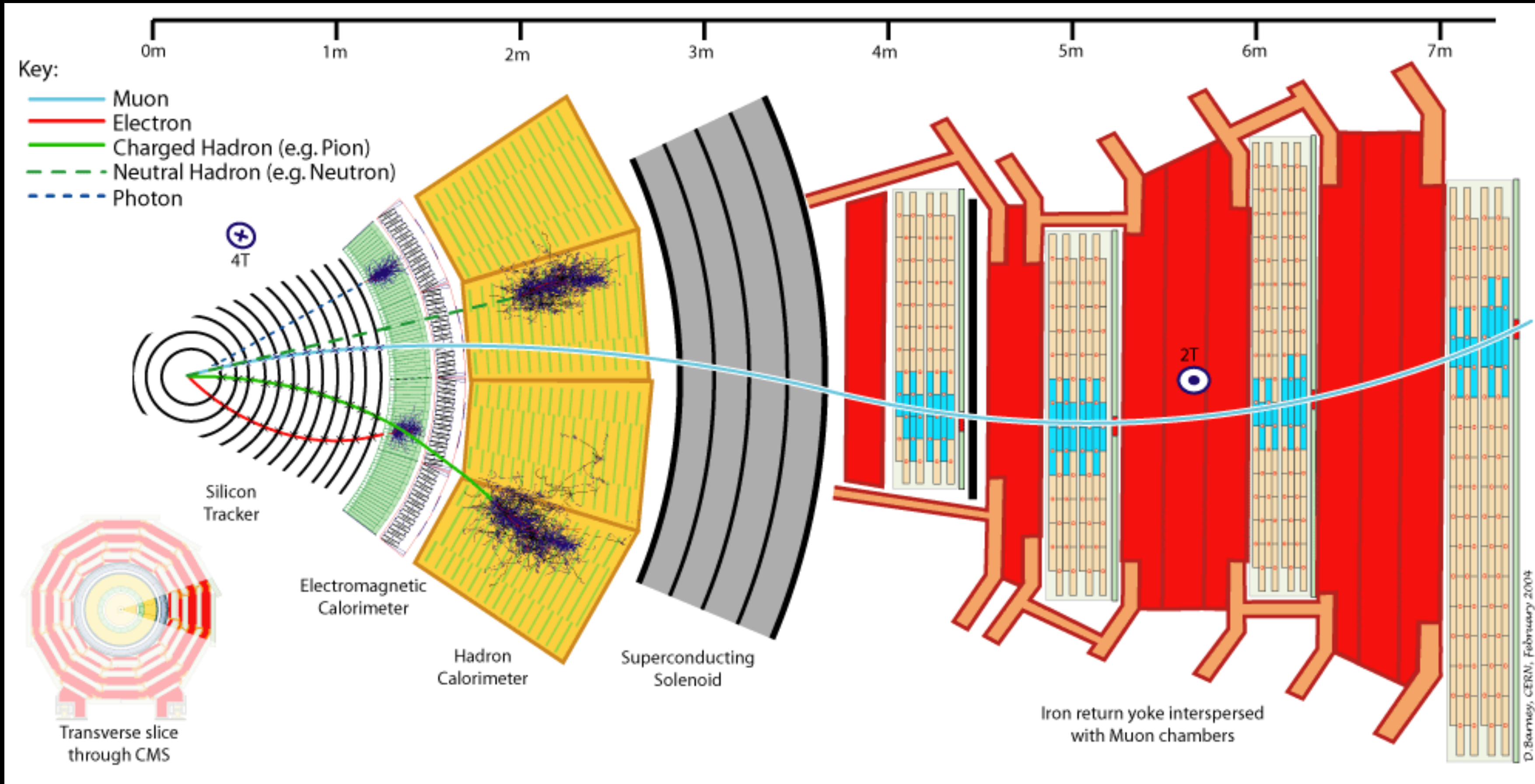
Calorimeters

Charged + neutral particles

Two types:

- Electromagnetic
- Hadronic

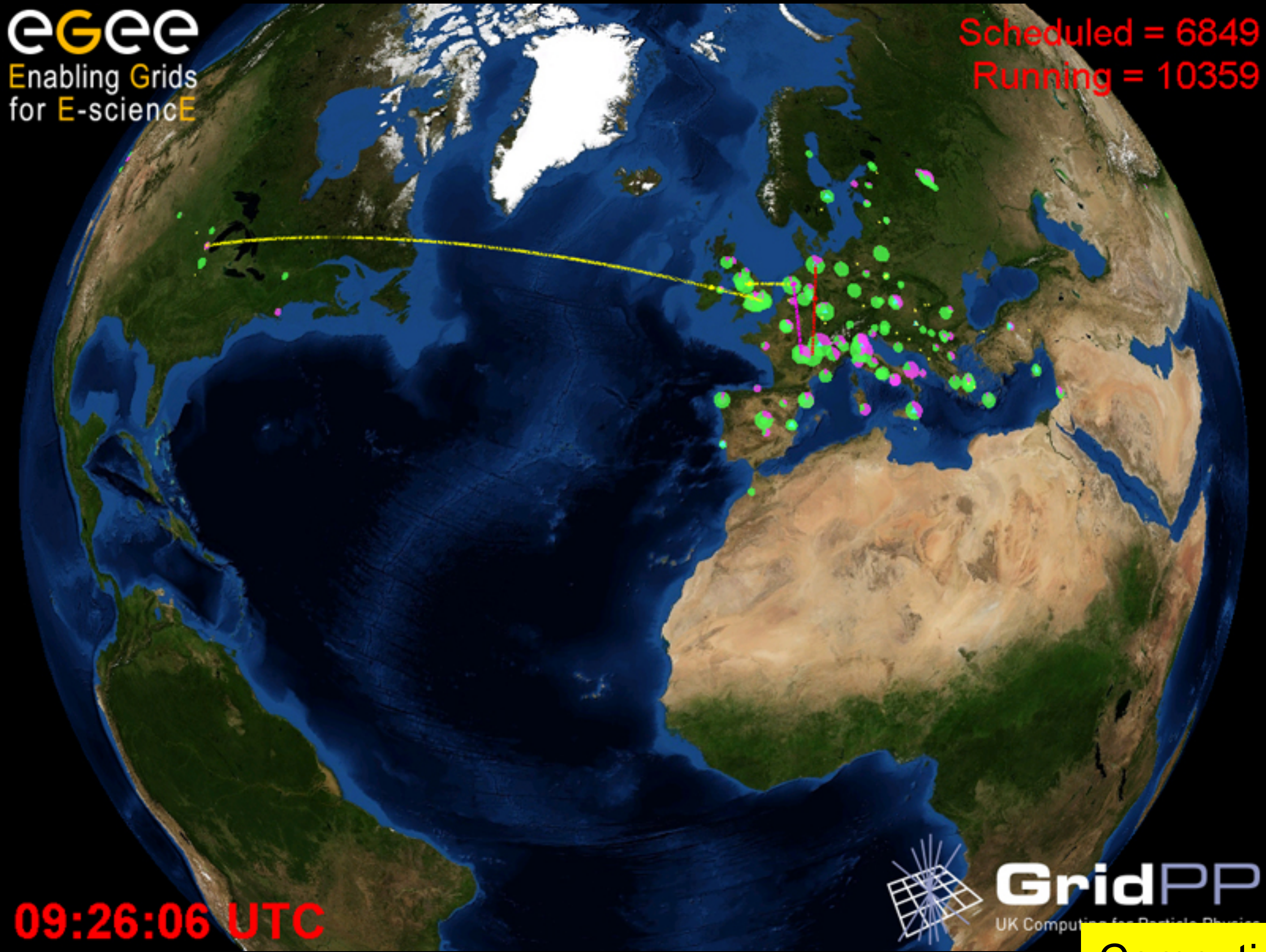
Absorb + measure energy



Identify particles by characteristic signatures in experiment

Add computers: calculate particle paths and energies

Add theory: infer what fundamental process happened

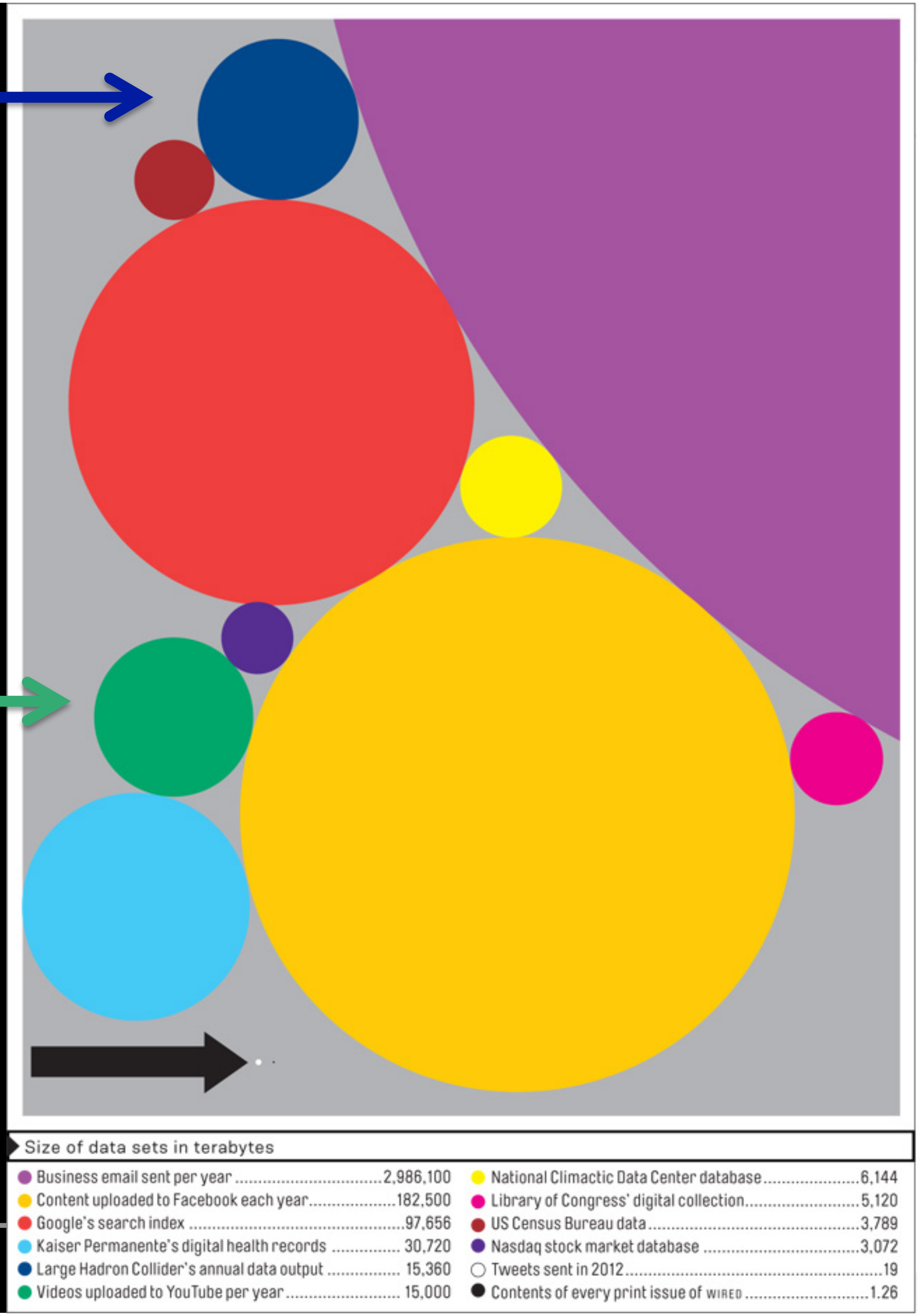


Computing 15/7

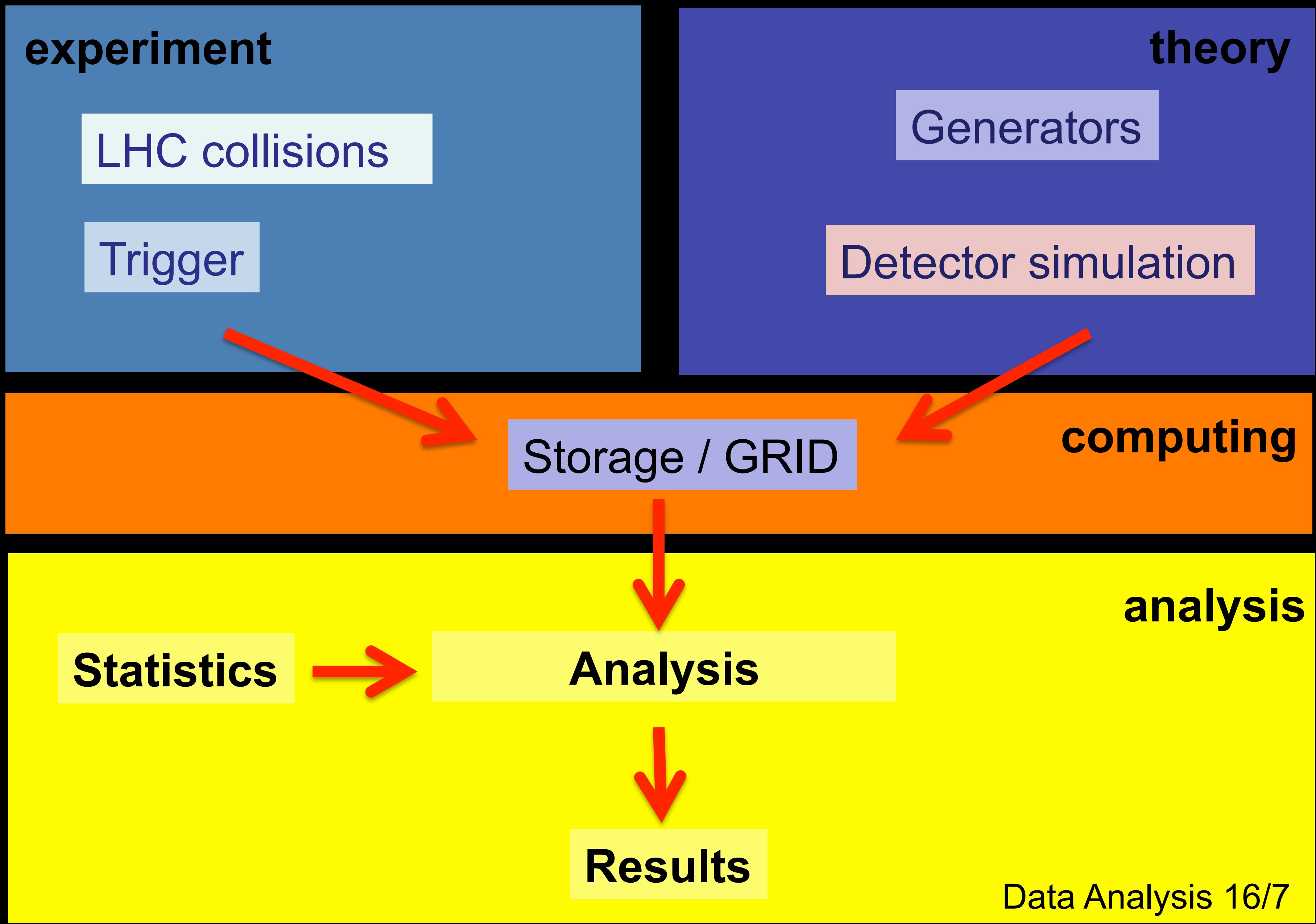
Big data …

LHC
15 360 TB/yr

Videos uploaded to YouTube
15 000 TB/yr



(http://www.wired.com/2013/04/bigdata/)


experiment
LHC collisions
Trigger
theory
Generators
Detector simulation
computing
Storage / GRID
analysis
Statistics
Analysis
Results
Data Analysis 16/7

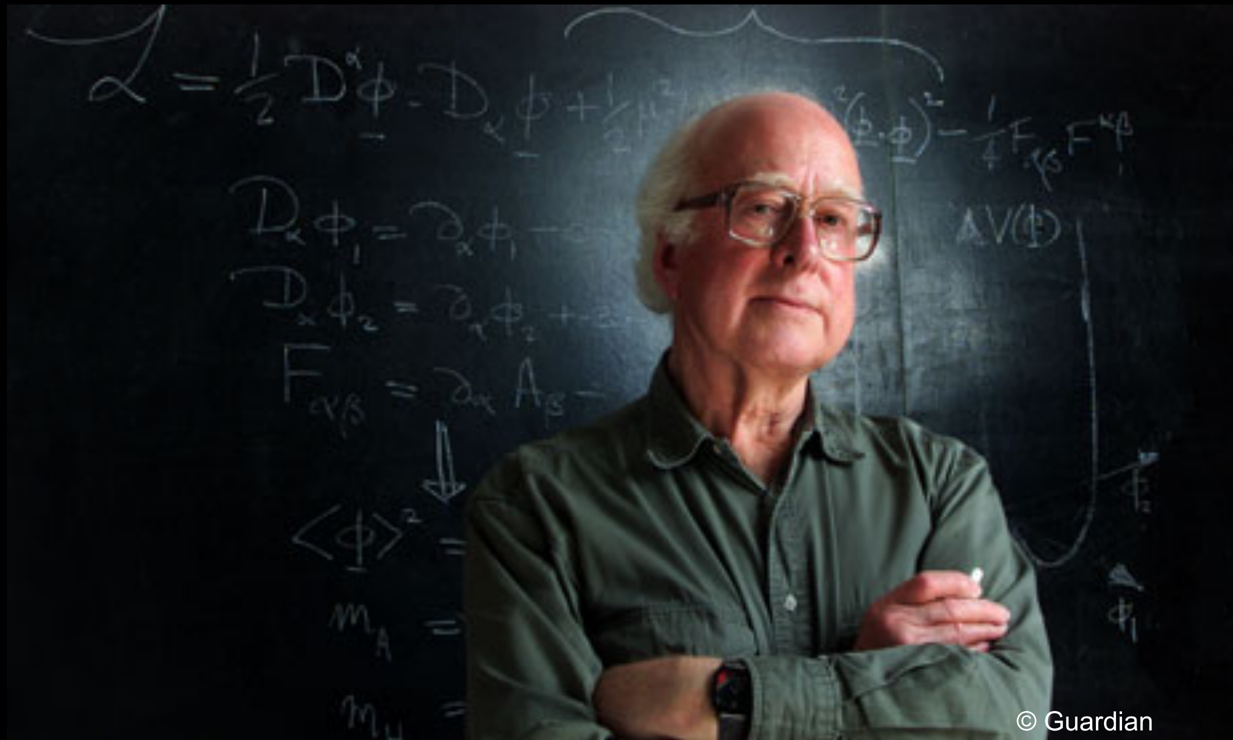
LHC Physics 16/7

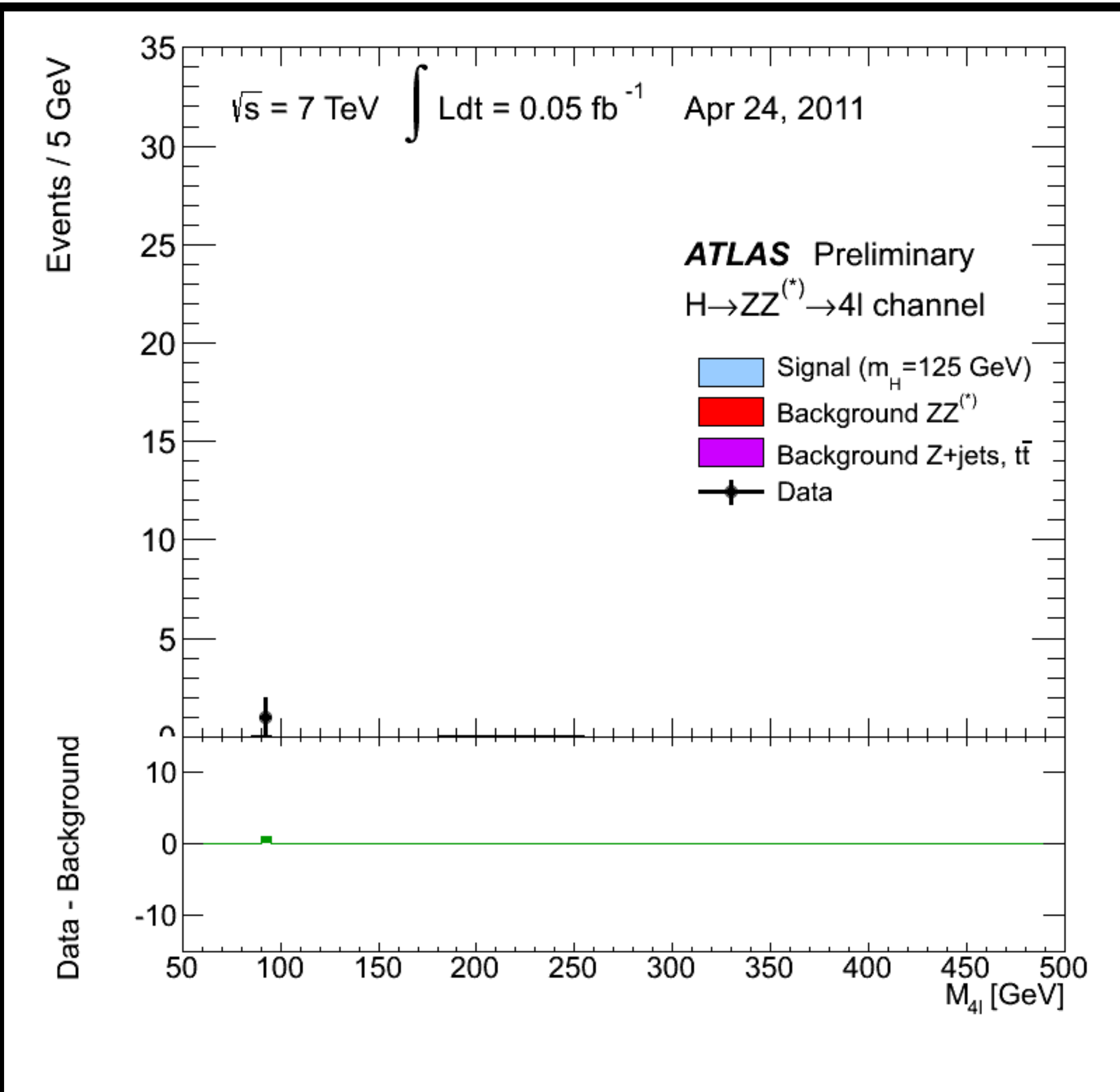
nice …

BUT

Unknowns

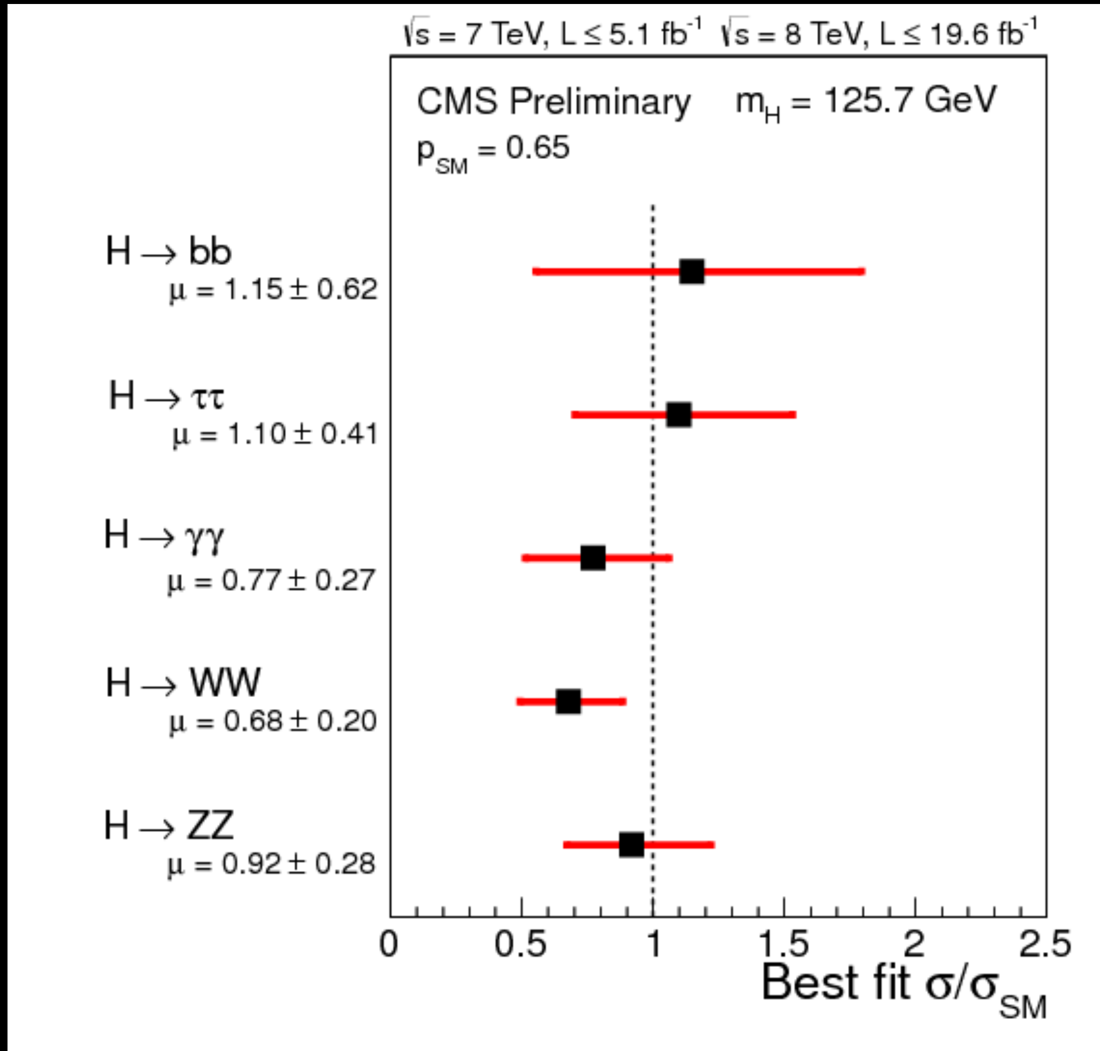
(0)
is the theory correct ?





Events / 5 GeV
√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, $t\bar{t}$
Data
Data - Background
M_{4l} [GeV]

A Higgs?
The Higgs?



> 3,000 papers since the start of 2012…..

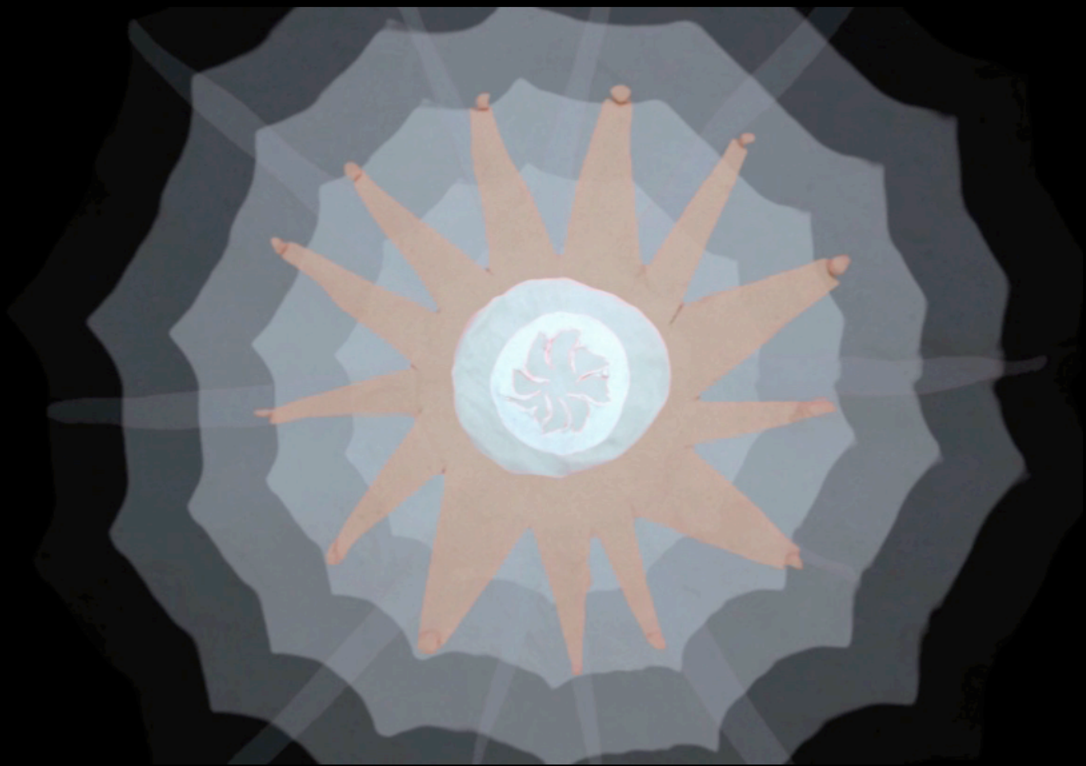
(1)

antimatter

Big Bang:
equal amounts of matter and antimatter created

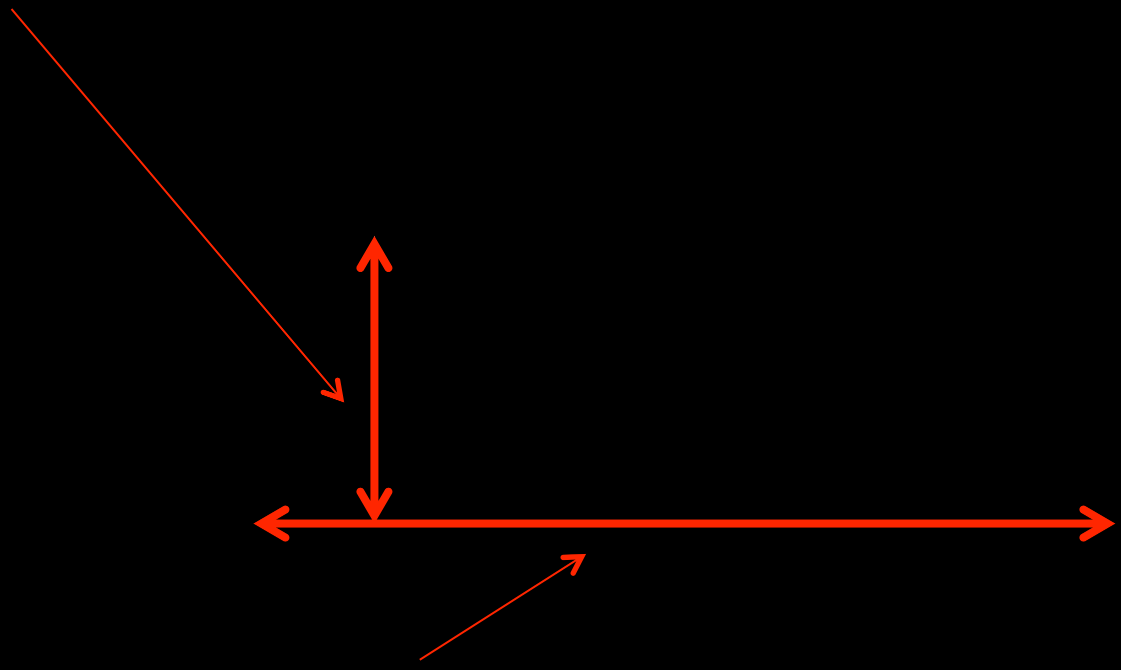
Now:
we (matter) exist

Why?

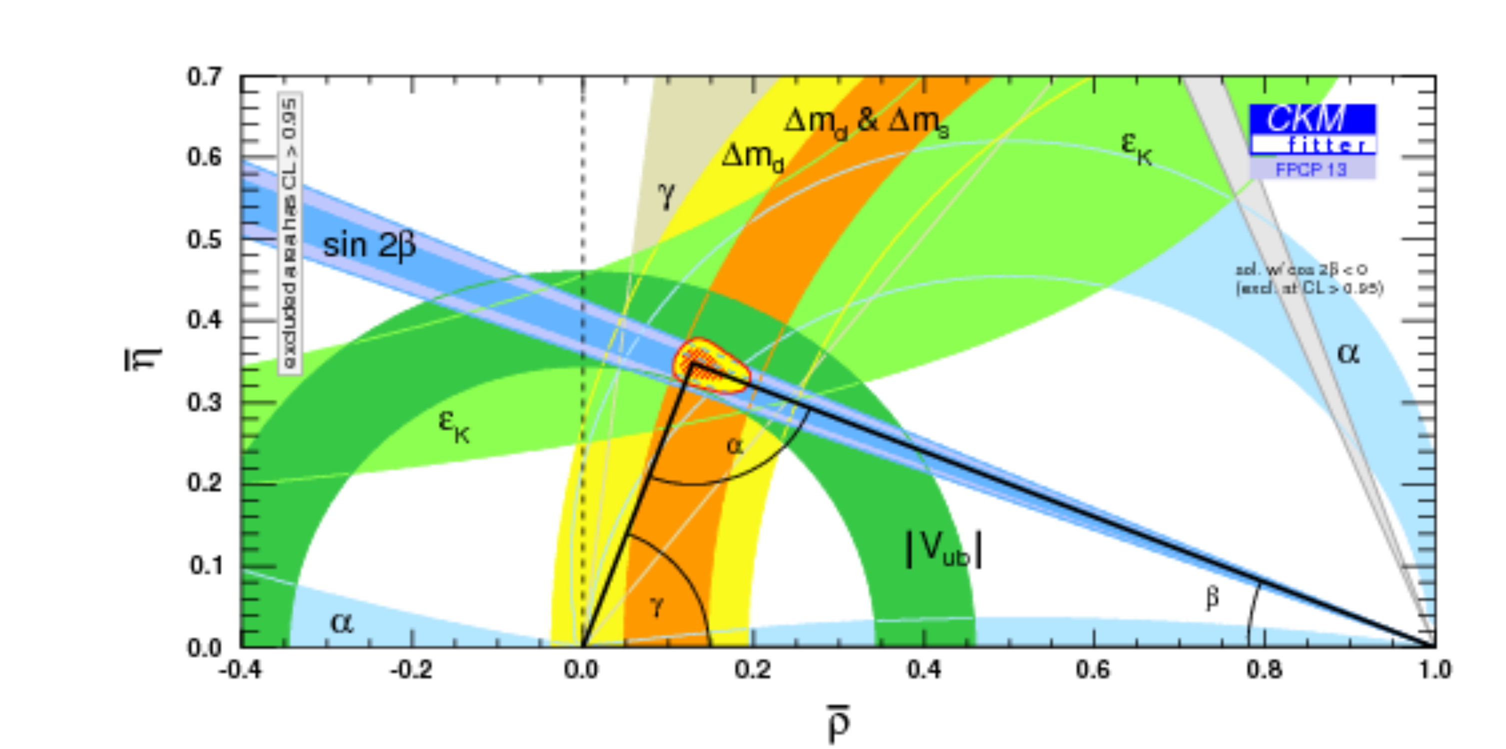


4 numbers

Measure of matter / antimatter difference



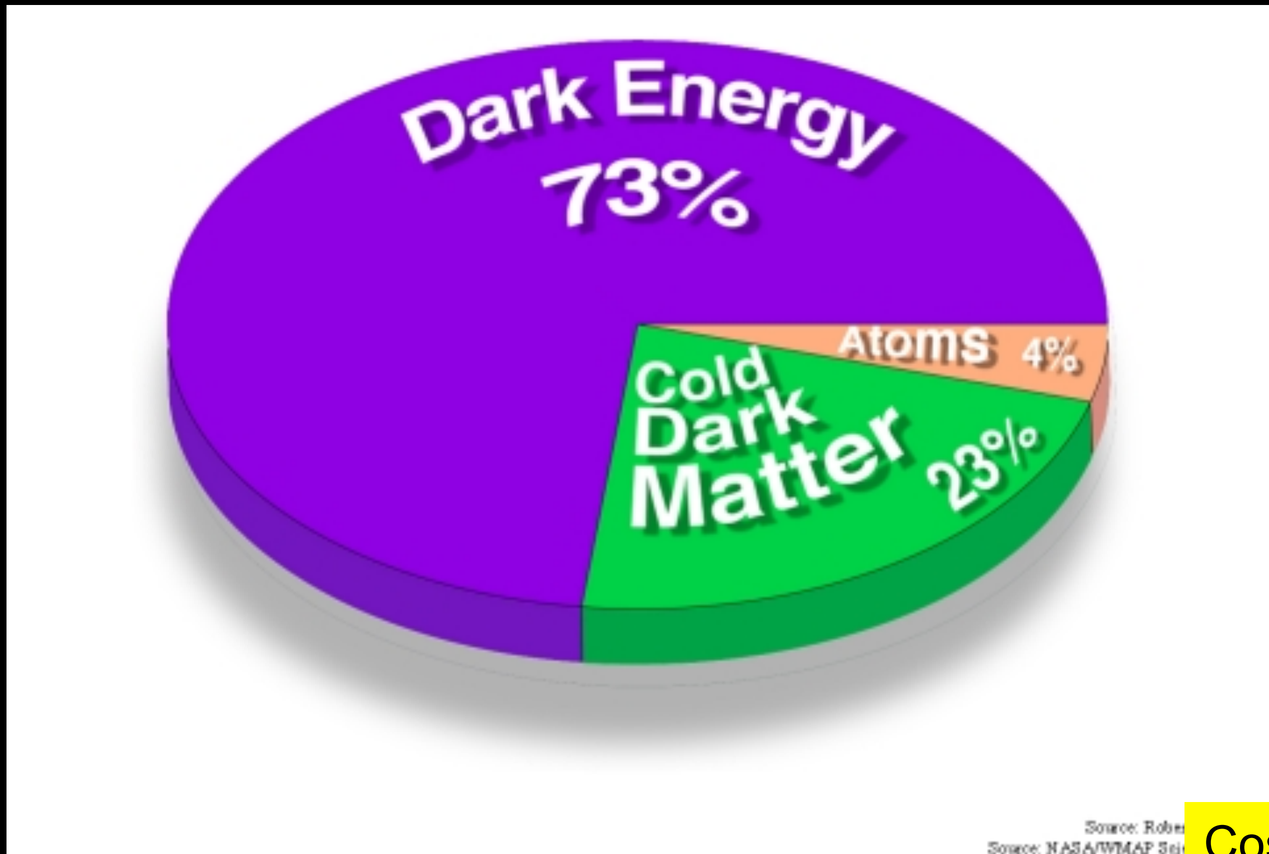
Measure of quark behaviour under the weak force



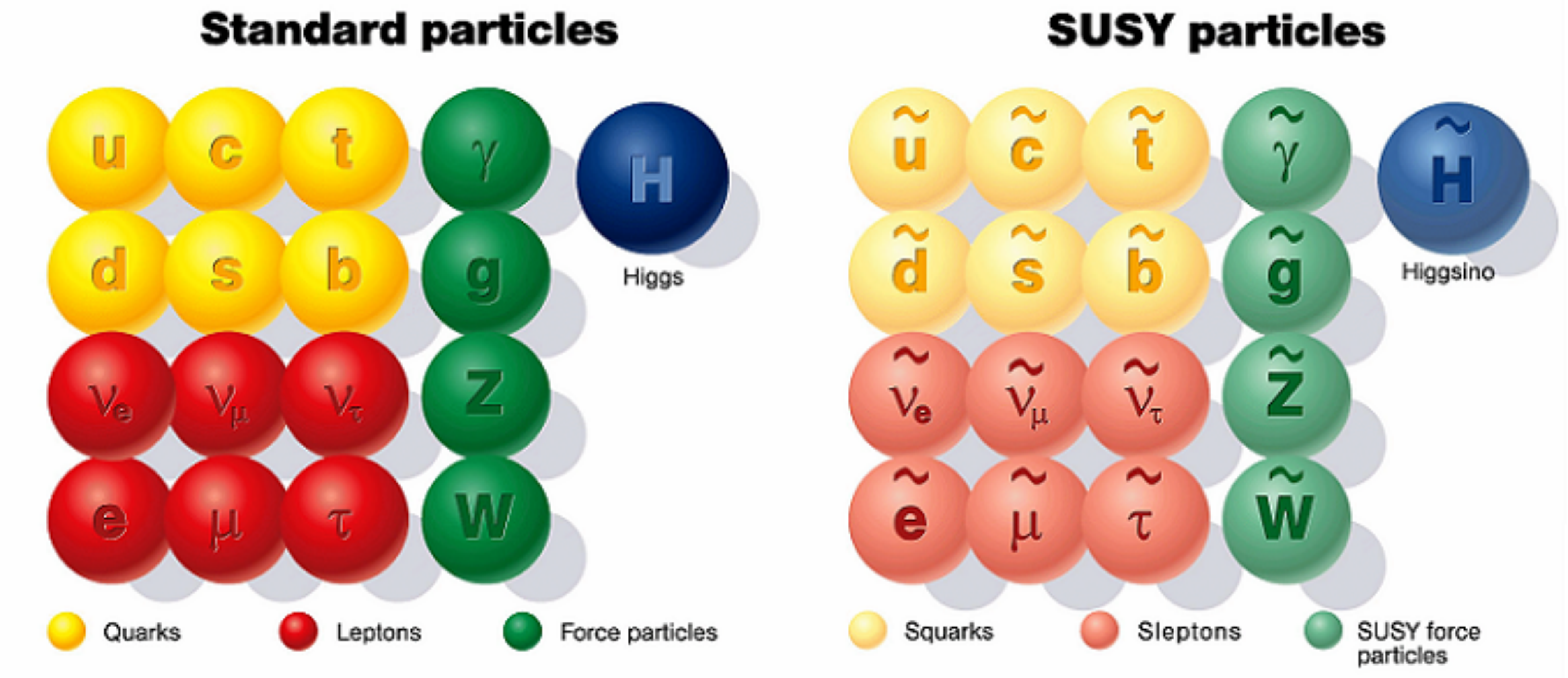
CKM fitter
FPCP 13
excluded area has CL > 0.95
sin 2β
γ
Δm_d
Δm_d & Δm_s
ε_K
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
α
ε_K
α
|V_ub|
γ
α
β
η̄
ρ̄
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0

?

(2)
and the other 96% ?

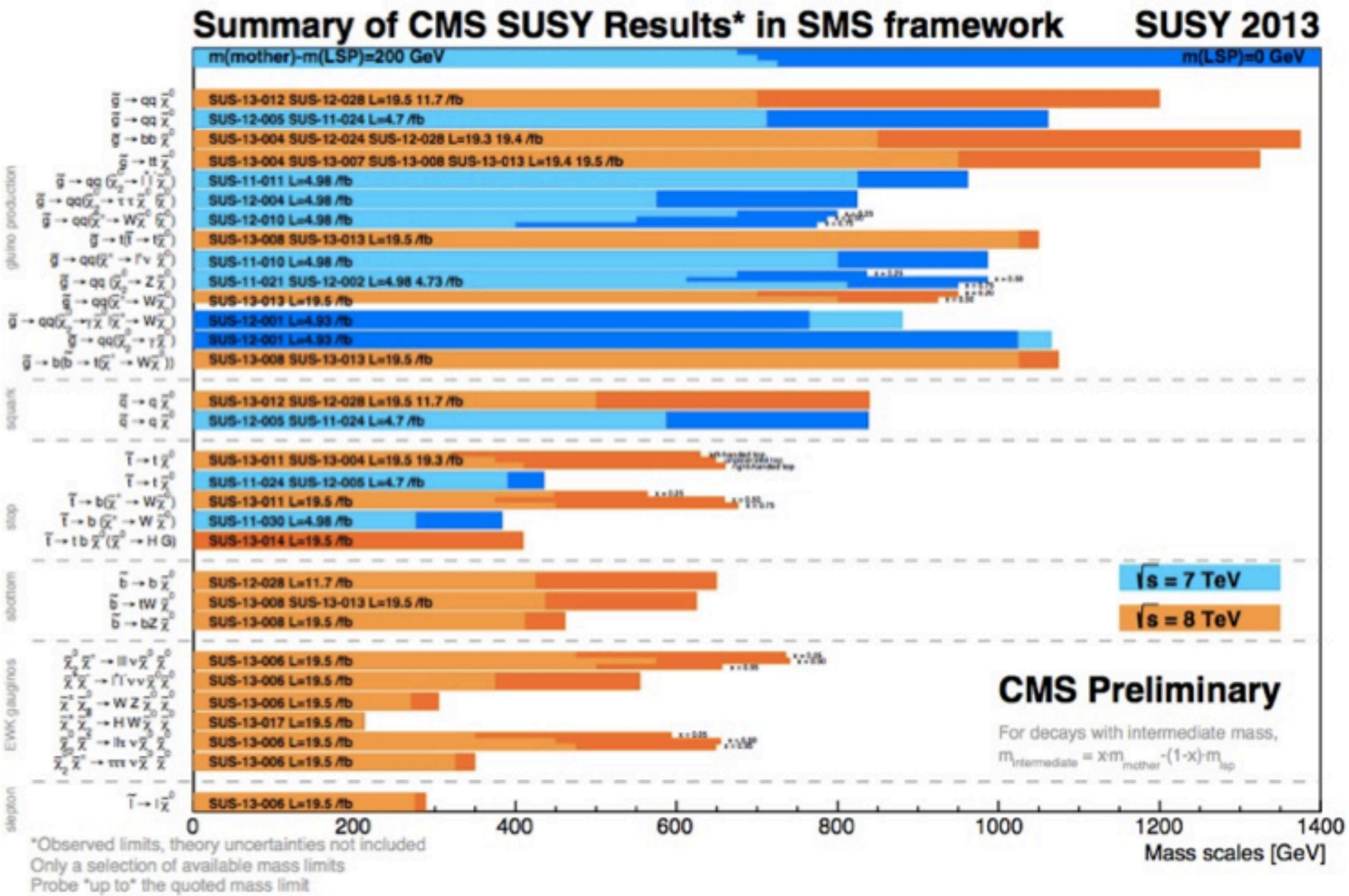


Cosmology 16/7



Beyond Standard Model 15/7

The "we did not find SUSY" Plot



Markus Klute

11

?

Many questions….

How many dimensions?

What is mass?

What about gravity?

4 forces?

12 matter particles?

Where did all the antimatter go?

Mini black holes?

What about the other 96% of the universe …..

2015

?

2015

watch this space