Introduction to particle physics

CERN summer student lectures 2013

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What particle physics describes

What we know (and what we don't)

The Standard Model; matter; forces.

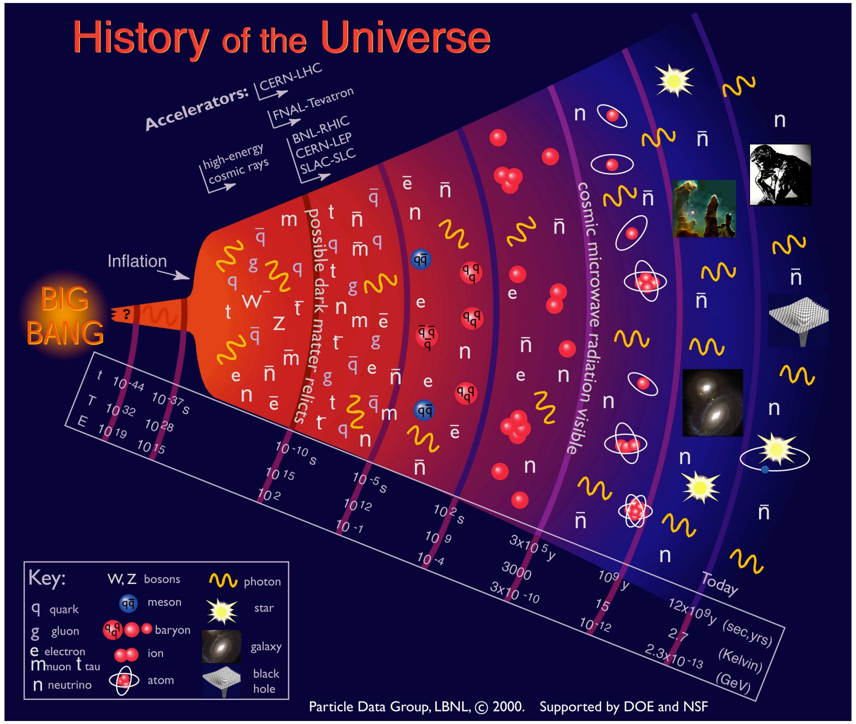
Experiments; performing research

Outstanding questions and mysteries …

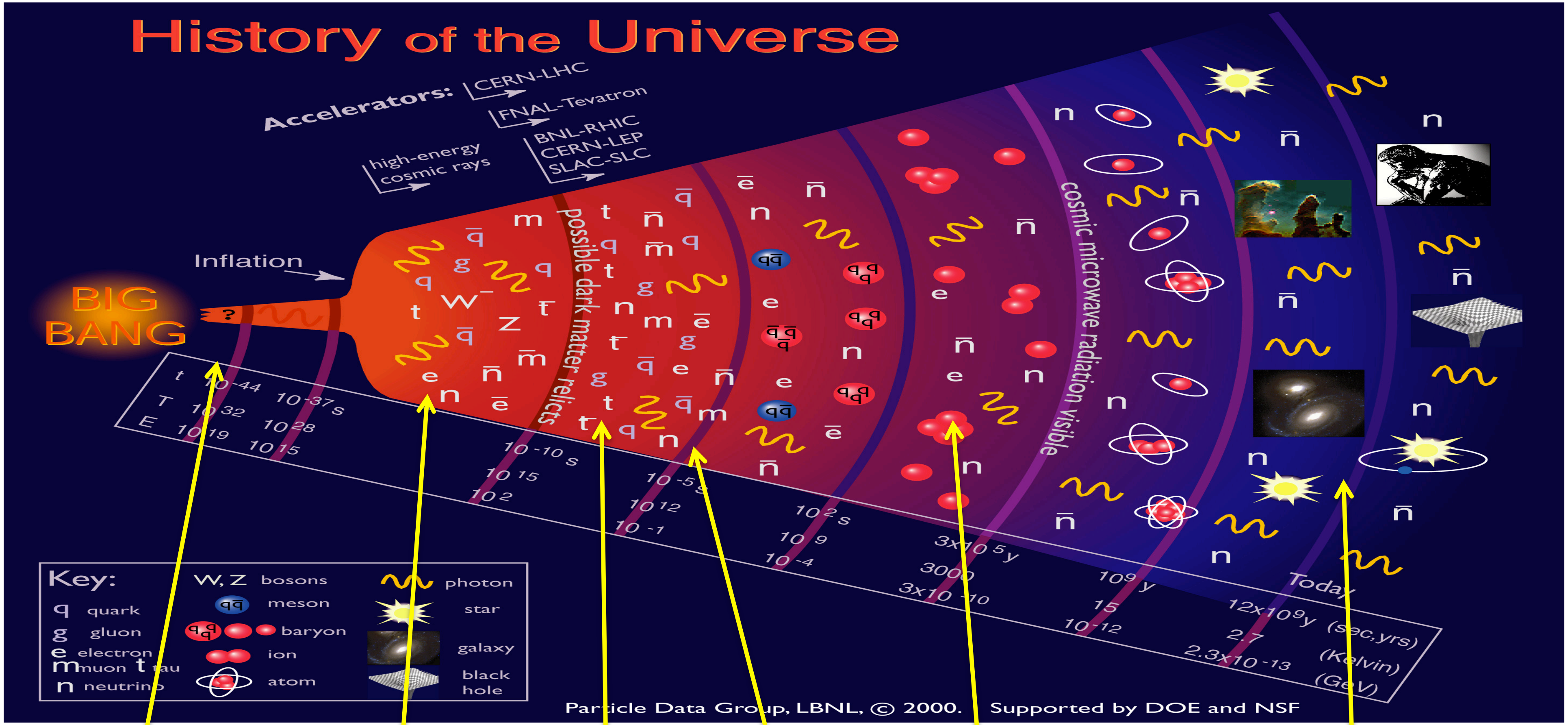
…… in the next two hours!

The universe

BIG BANG



NOW



Cosmology
1/8/13

LHC

Nuclear physics
17/7/13

Cosmic rays

Astrophysics

Quark/gluon plasma
Heavy ions 23/7/13

Plus ....
Antimatter 6/8/13
Astroparticle physics 6/8/13

aside: units

Our scale	
Length	**m**
Mass	**kg**
Time	**s**
Energy	**$kg\ m^2\ s^{-2}$**

Particle Physics	
Length	**fm**
Mass	**eV/c^2**
Time	**s**
Energy	**eV**

Convert

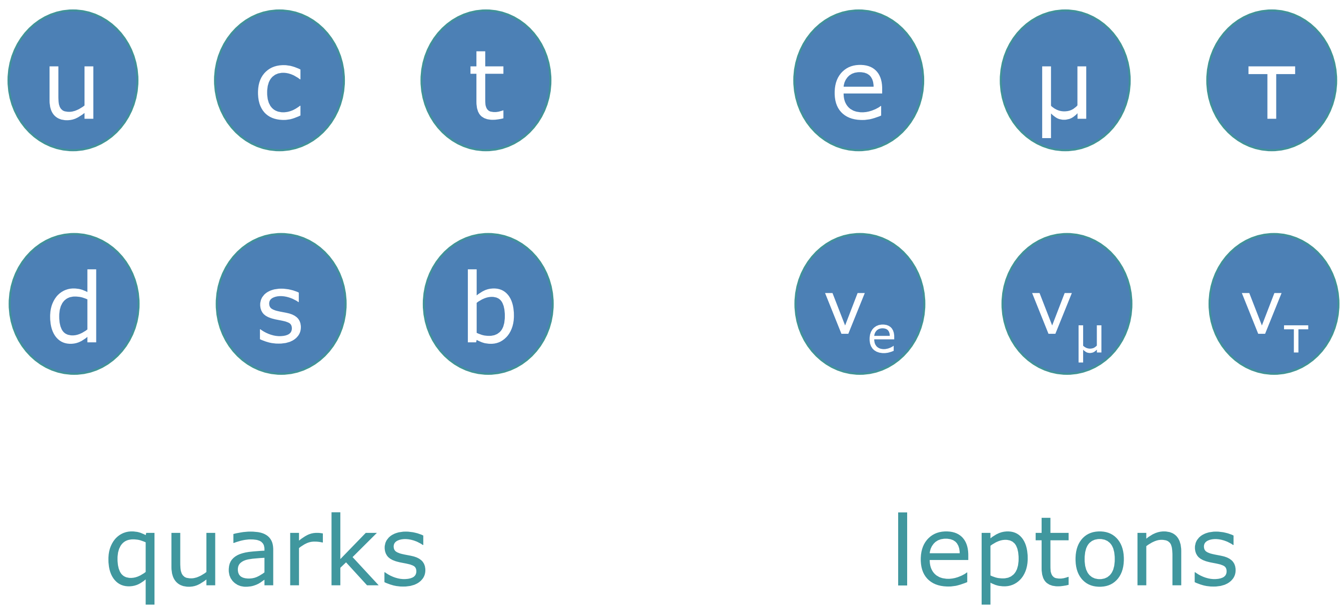
1 eV = 1.6×10^{-19} J

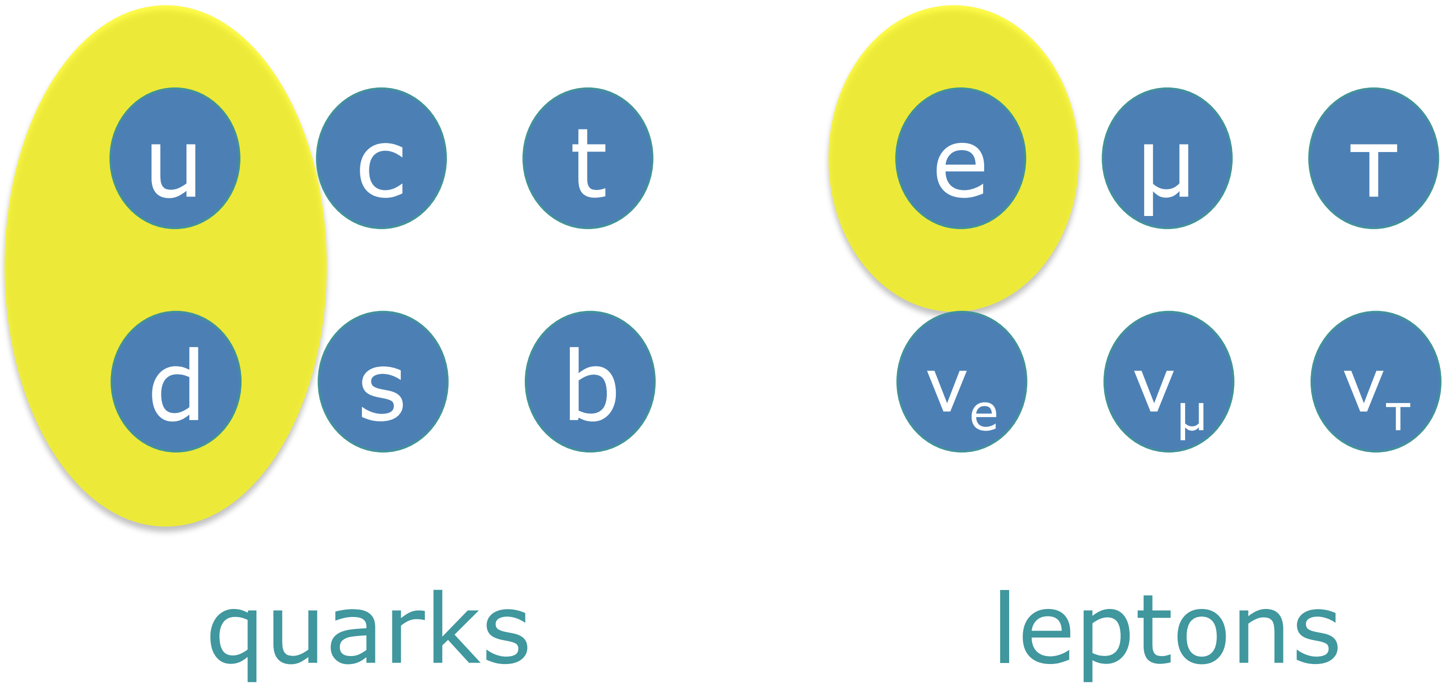
1 GeV = 10^9 eV

1 TeV = 10^3 GeV

1 fm = 10^{-15} m

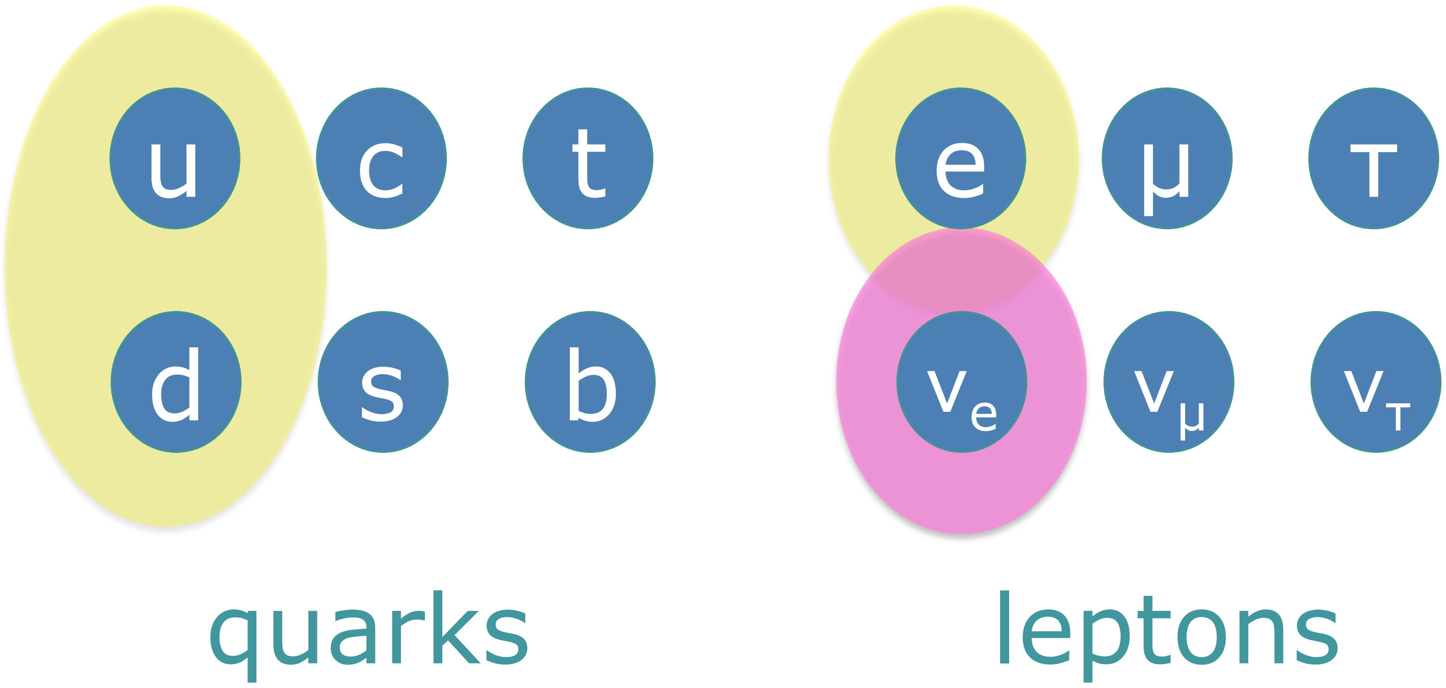
Note: often set c = 1….


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

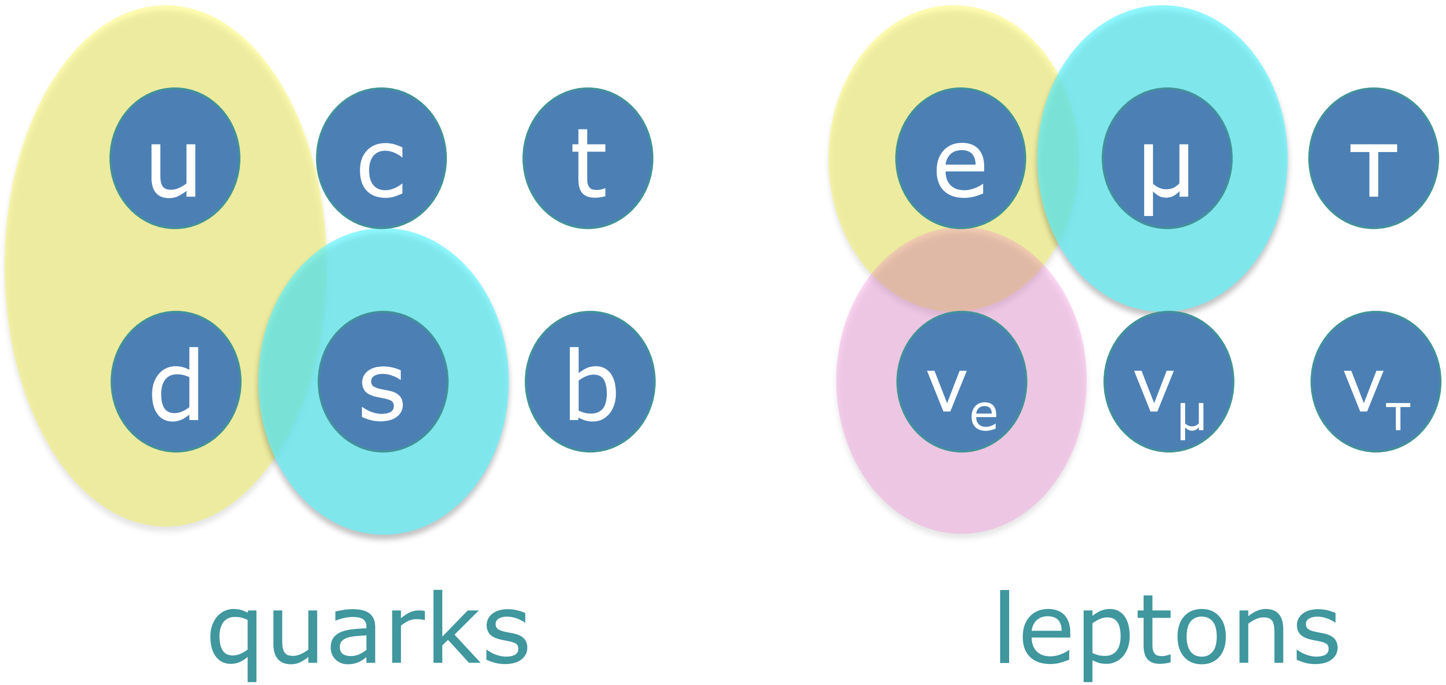


u,d proposed 1960s, discovered ~1968

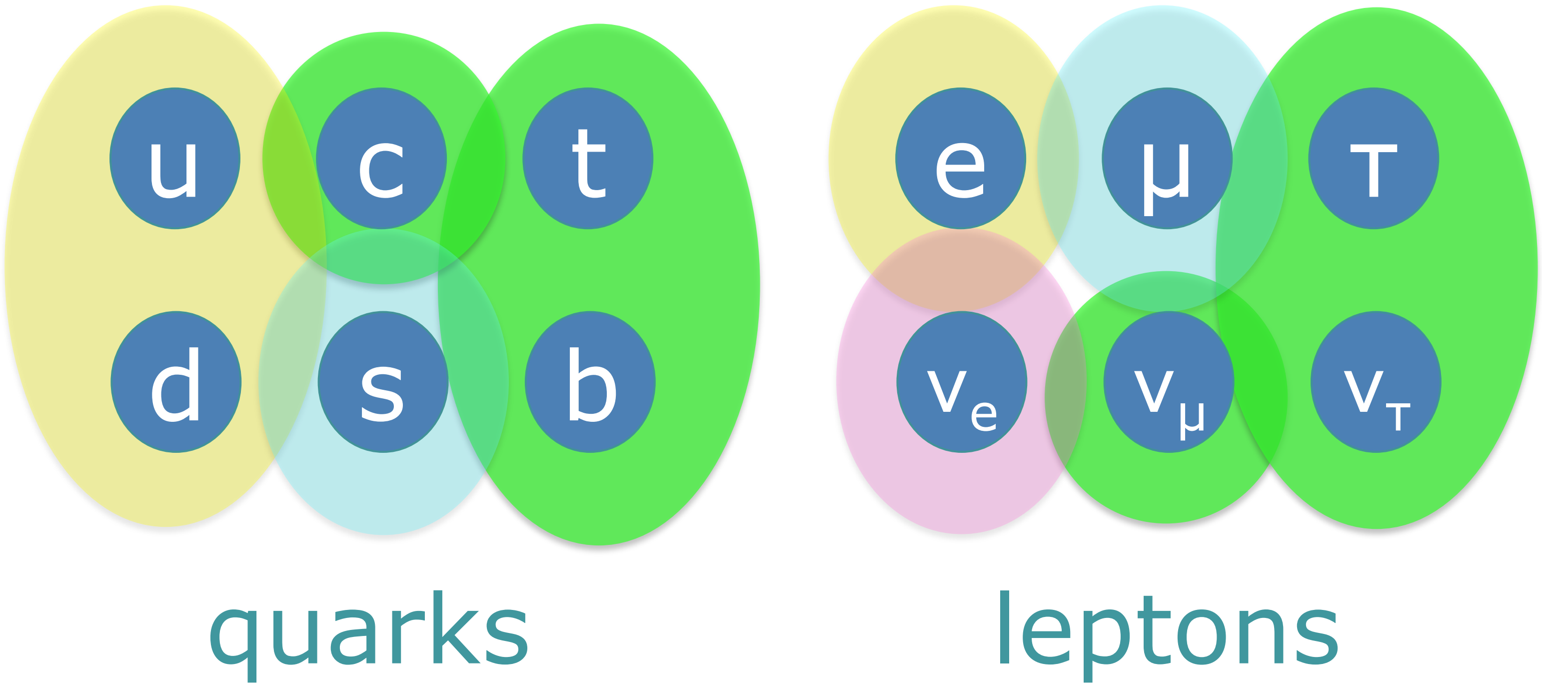
e discovered 1897



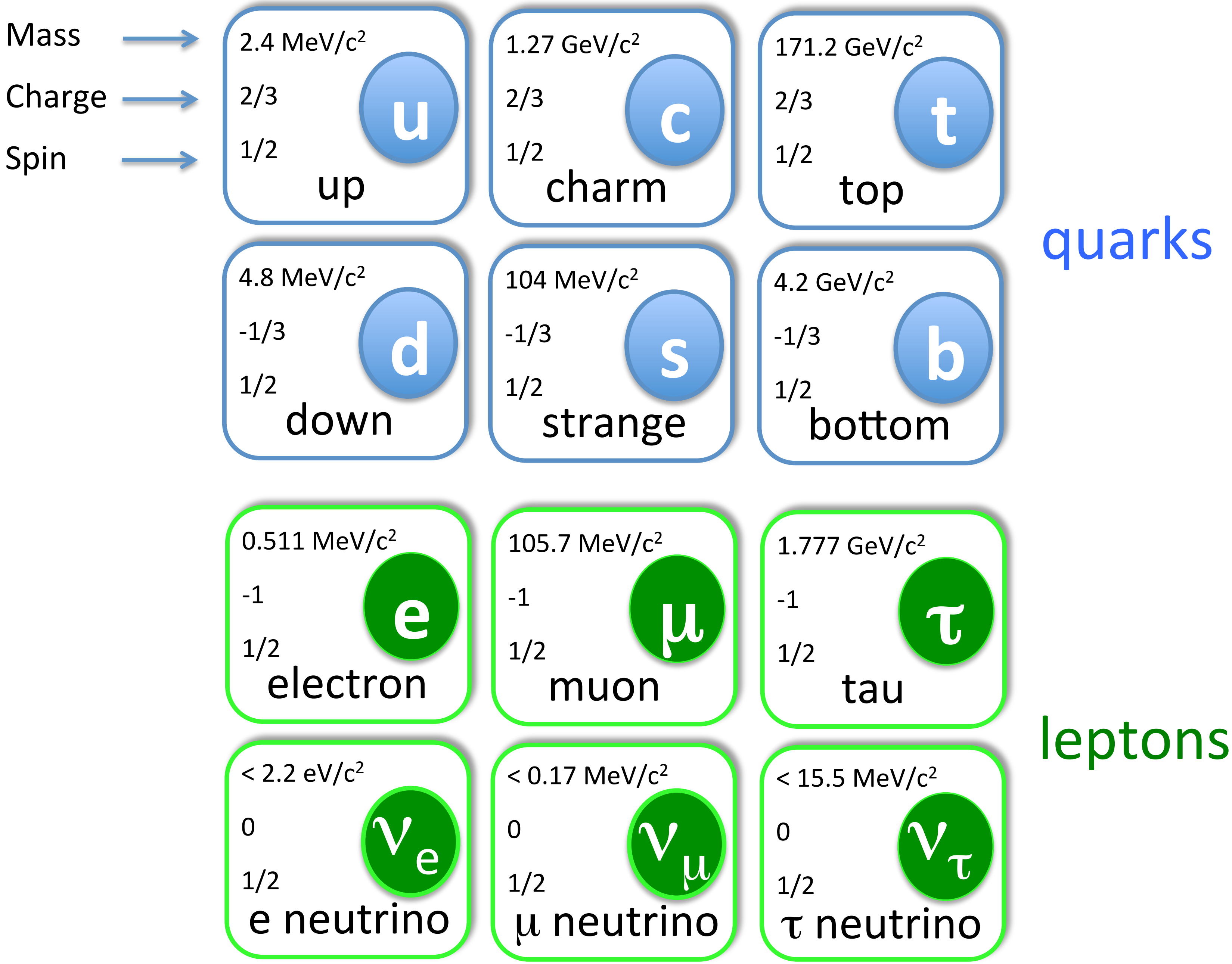
Radioactive decay (inferred 1930s, seen 1956)



Cosmic ray experiments (1930s, 1940s)



Collider experiments (1960s -)


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

Antimatter

Einstein's equation of motion*: $$E^2 = p^2c^2 + m^2c^4$$

Two energy solutions for the same mass;

- Matter
- Antimatter

Every fermion has an antimatter version.

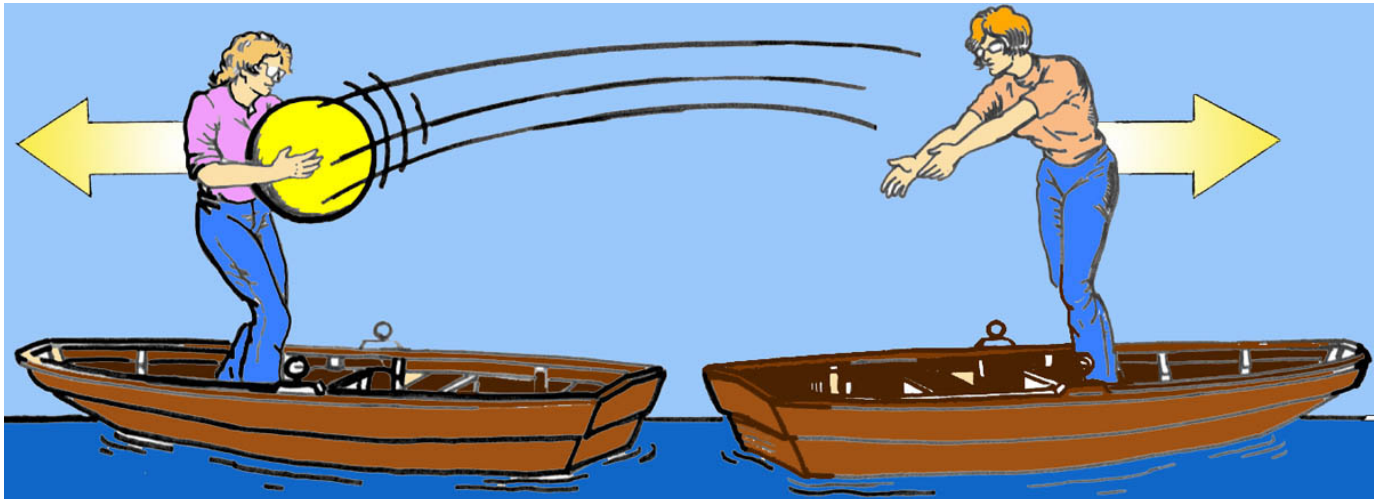
Same mass, opposite charge

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

*(and others, more famously Dirac)

Matter is held together by forces;

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



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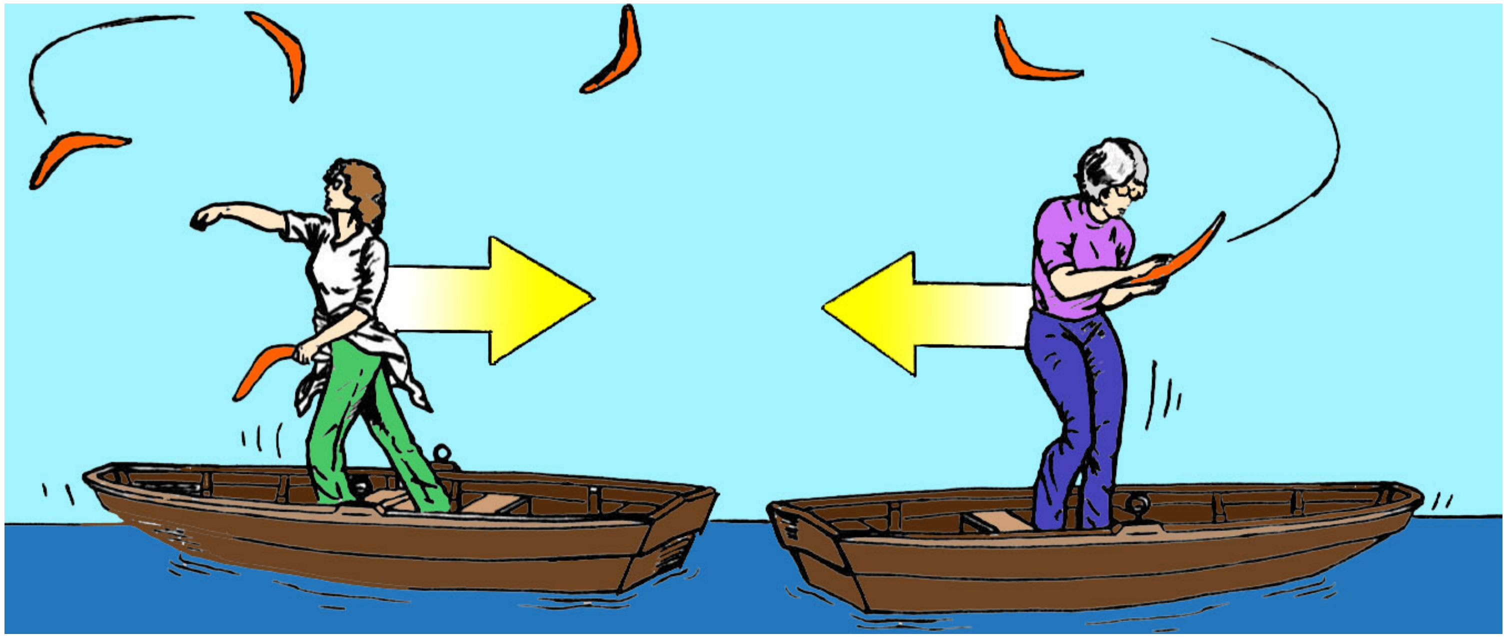
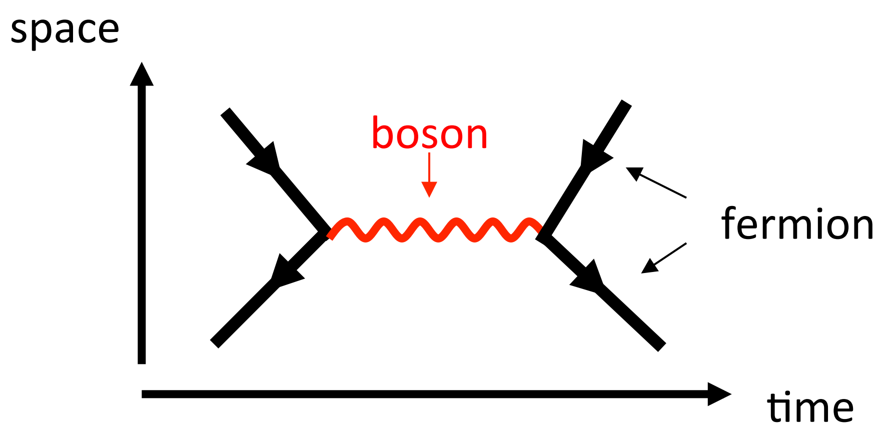


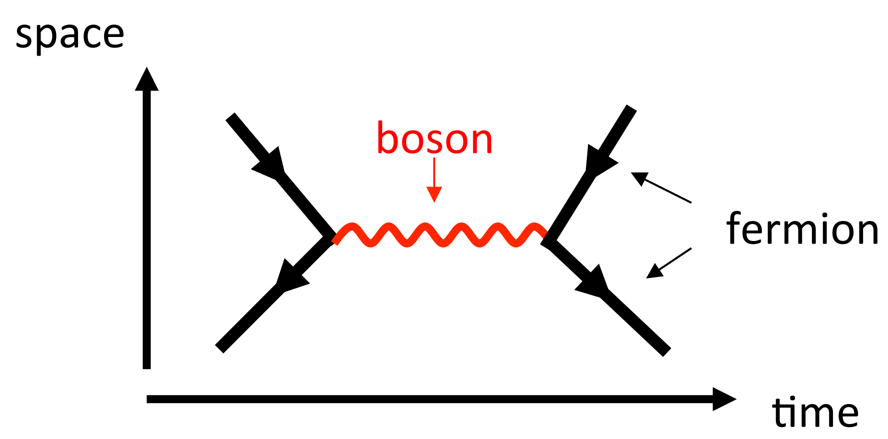
Feynman diagrams

"tree" level
Lowest order

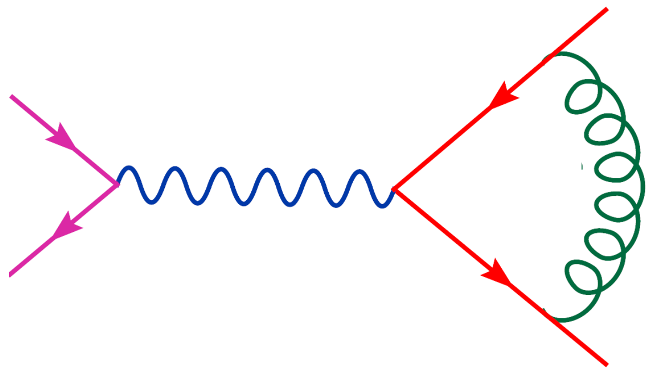


Feynman diagrams

"tree" level
Lowest order

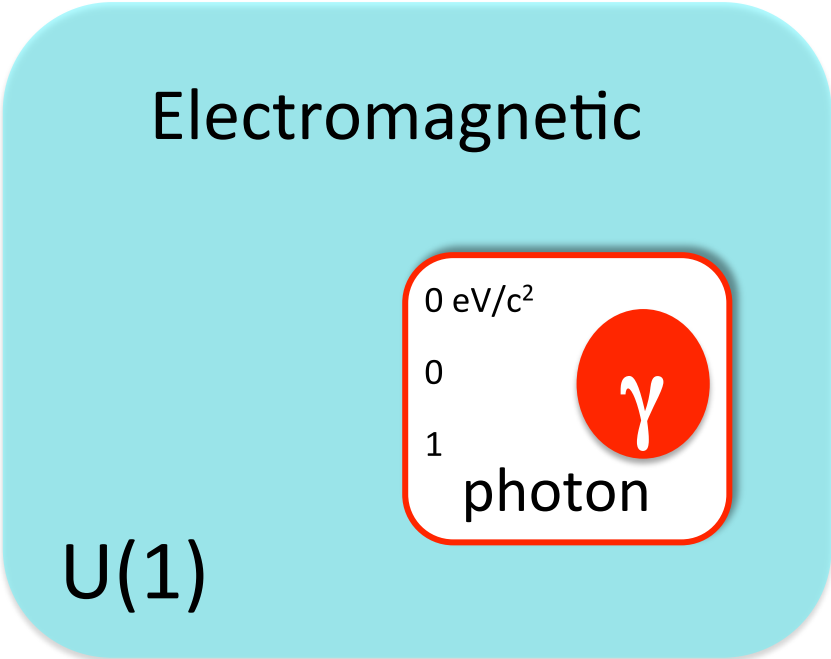


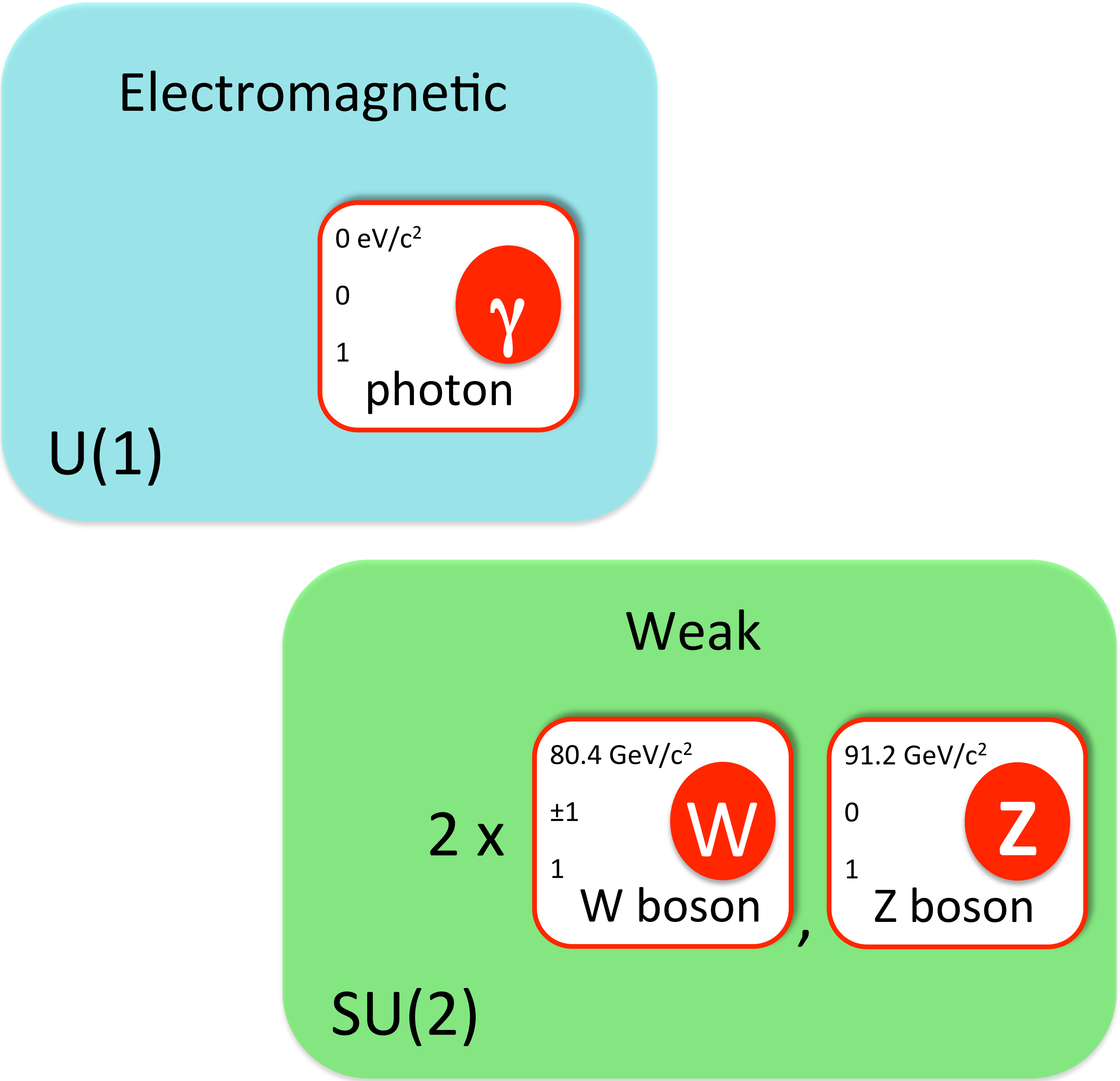
Higher orders possible
Loops

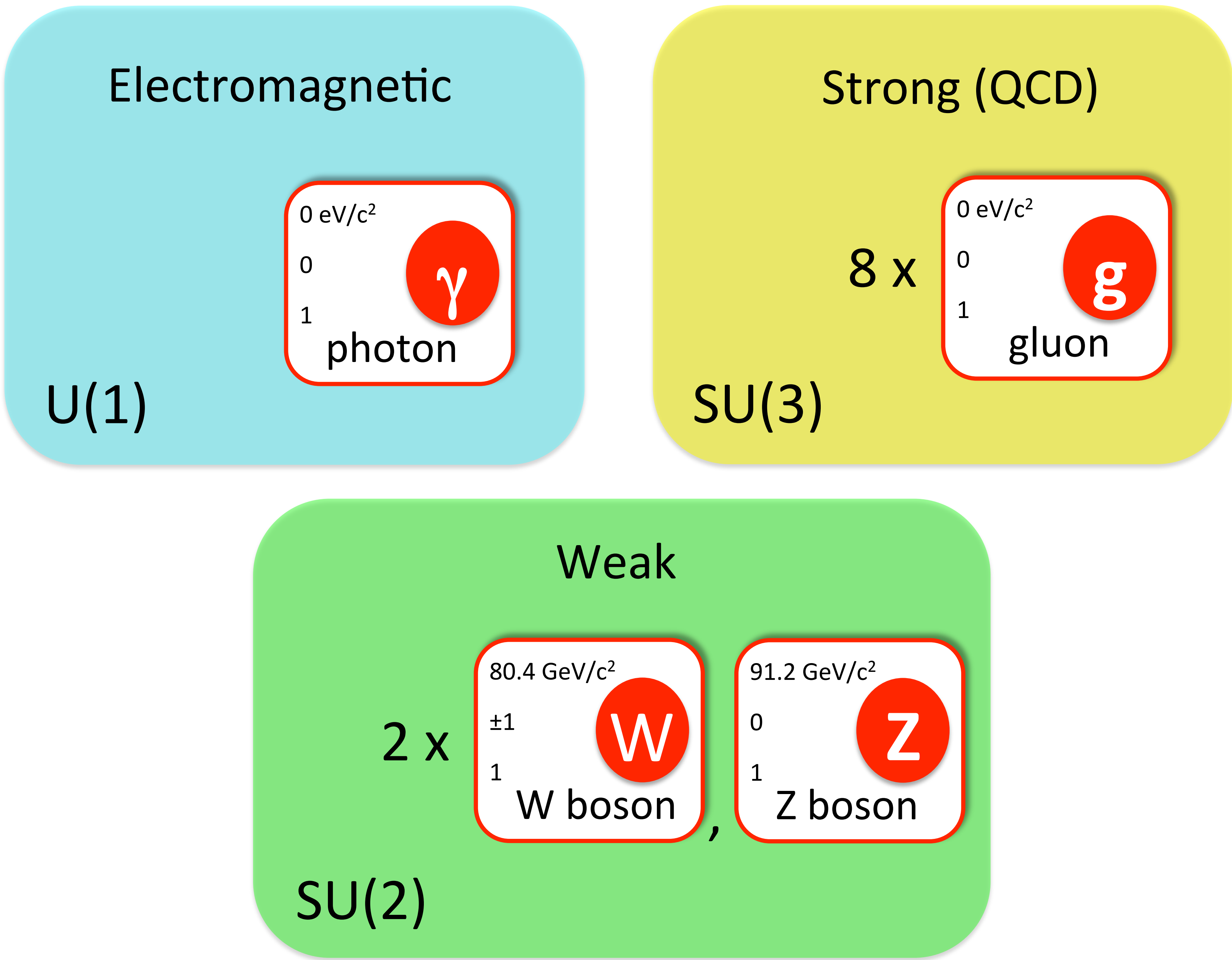


Matter is held together by forces;

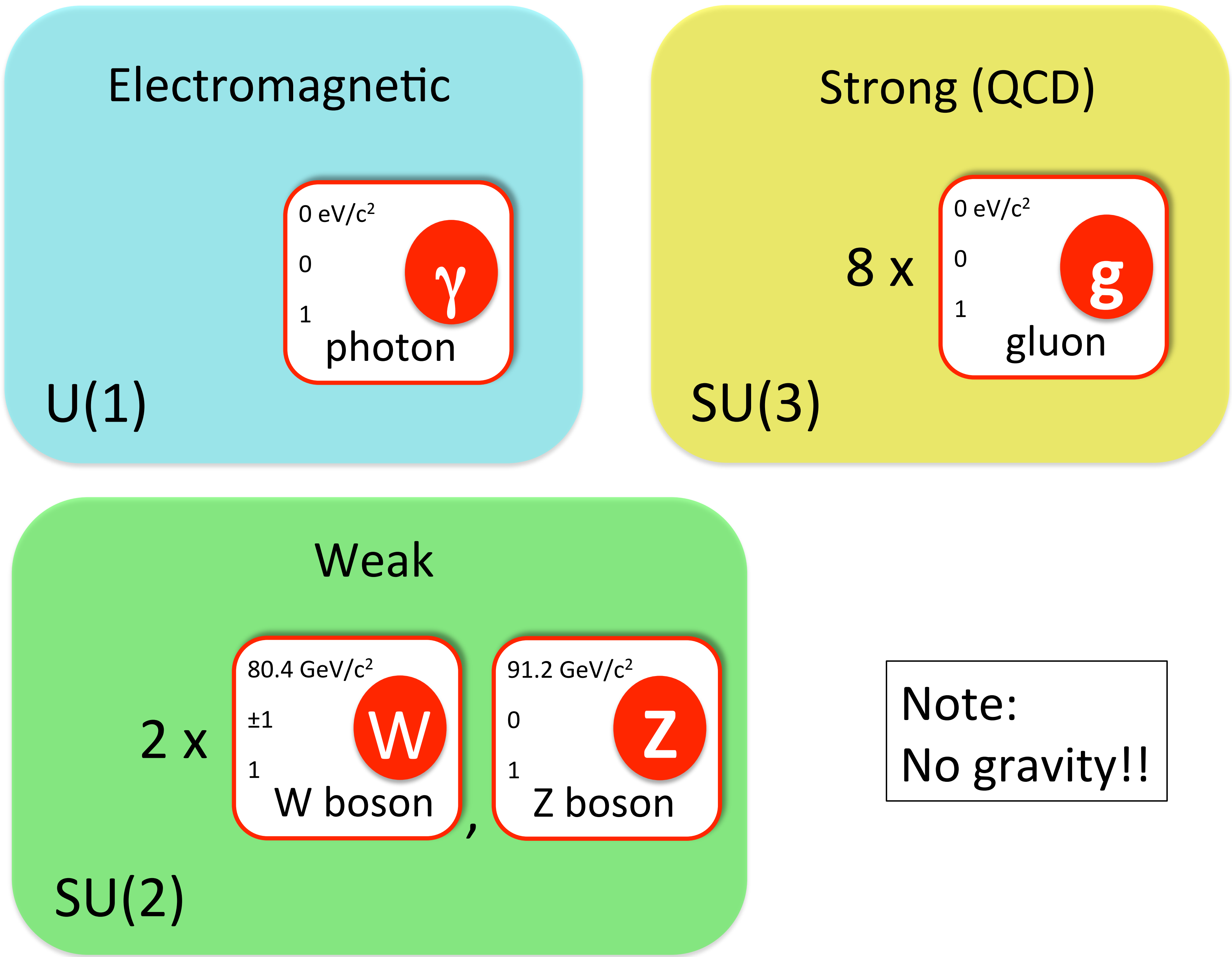
- mediated by force carrying particles (bosons; spin 1)
- **3 forces considered in particle physics**


Electromagnetic
0 eV/c²
0
1
γ
photon
U(1)


Electromagnetic
0 eV/c²
0
1
γ
photon
U(1)
Weak
2 x
80.4 GeV/c²
±1
1
W
W boson
,
91.2 GeV/c²
0
1
Z
Z boson
SU(2)



Electromagnetic
0 eV/c²
0
1
γ
photon
U(1)
Strong (QCD)
8 x
0 eV/c²
0
1
g
gluon
SU(3)
Weak
2 x
80.4 GeV/c²
±1
1
W
W boson
,
91.2 GeV/c²
0
1
Z
Z boson
SU(2)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SU(3)
Weak
2 x
80.4 GeV/c²
±1
1
W
W boson
,
91.2 GeV/c²
0
1
Z
Z boson
SU(2)
Note:
No gravity!!

EM force	**Weak force**	**Strong force**
Electric charge (1)	Weak charge (2)	Colour charge (3)

Value unknown/
not predicted

EM force

Electric charge (1)

Massless photon

Weak force

Weak charge (2)

Massive $W^{\pm}$,Z

Strong force

Colour charge (3)

8 massless gluons

Value unknown/
not predicted

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

EM force

Abelian

Weak force

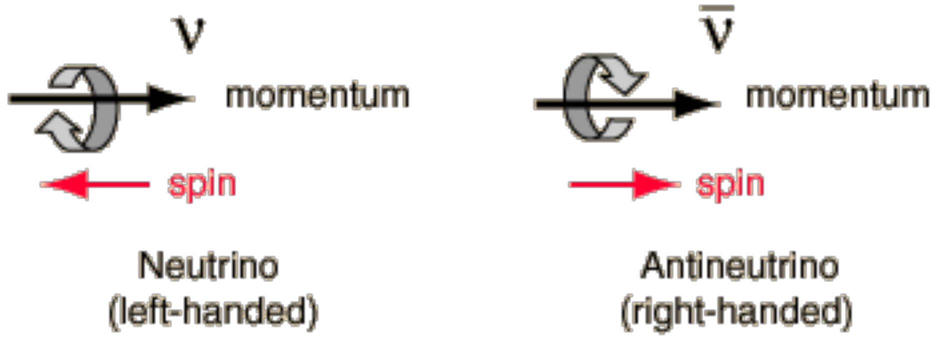
Non-abelian

Strong force

Non-abelian

Value unknown/
not predicted

Flavour and CPV 1/8/13
Neutrino physics 22/7/13



EM force

Abelian

Only charged particles couple

Weak force

Non-abelian

Only left handed particles couple

Strong force

Non-abelian

Only quarks couple

Value unknown/
not predicted

Flavour and CPV 1/8/13
Neutrino physics 22/7/13

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

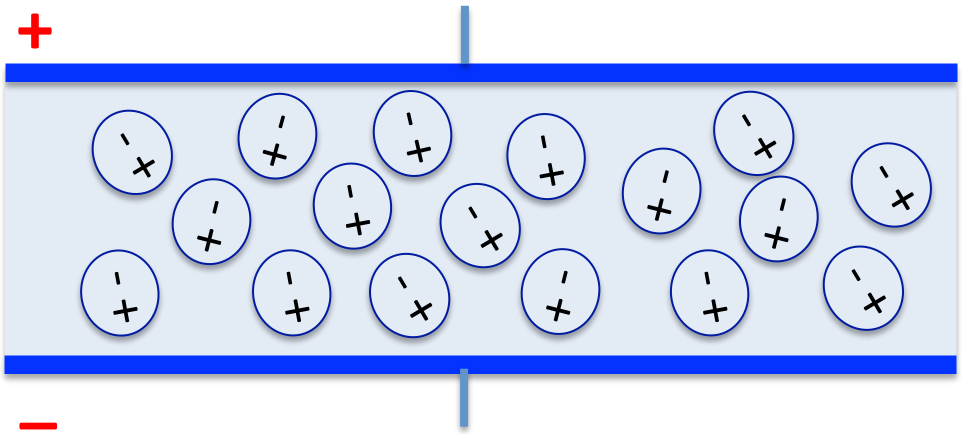
Non-abelian

Only quarks couple

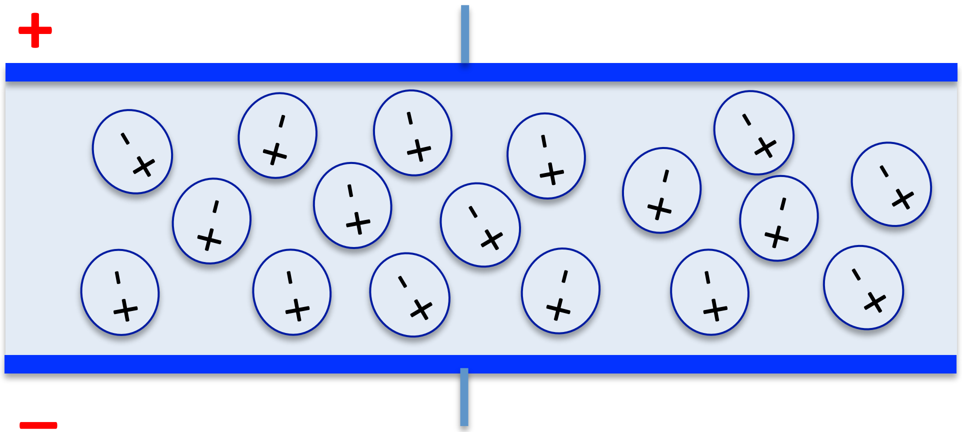
Value unknown/ not predicted

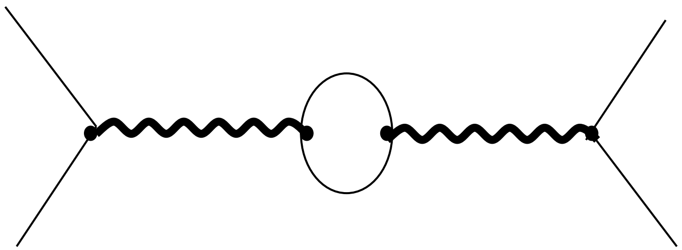
Flavour and CPV 1/8/13
Neutrino physics 22/7/13

Running couplings



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



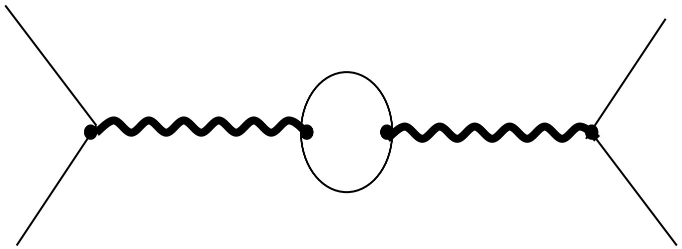


Screening of charge by **vacuum polarisation**;

High E ⇒smaller distances ⇒see more charge

Coupling increases with E

Non-Abelian effects

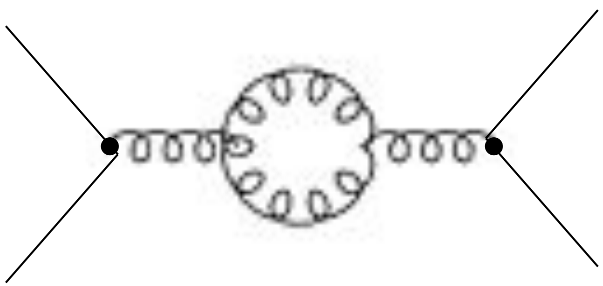


Screening of charge by vacuum polarisation;

High E ⇒smaller distances ⇒see more charge

Coupling increases with E

+

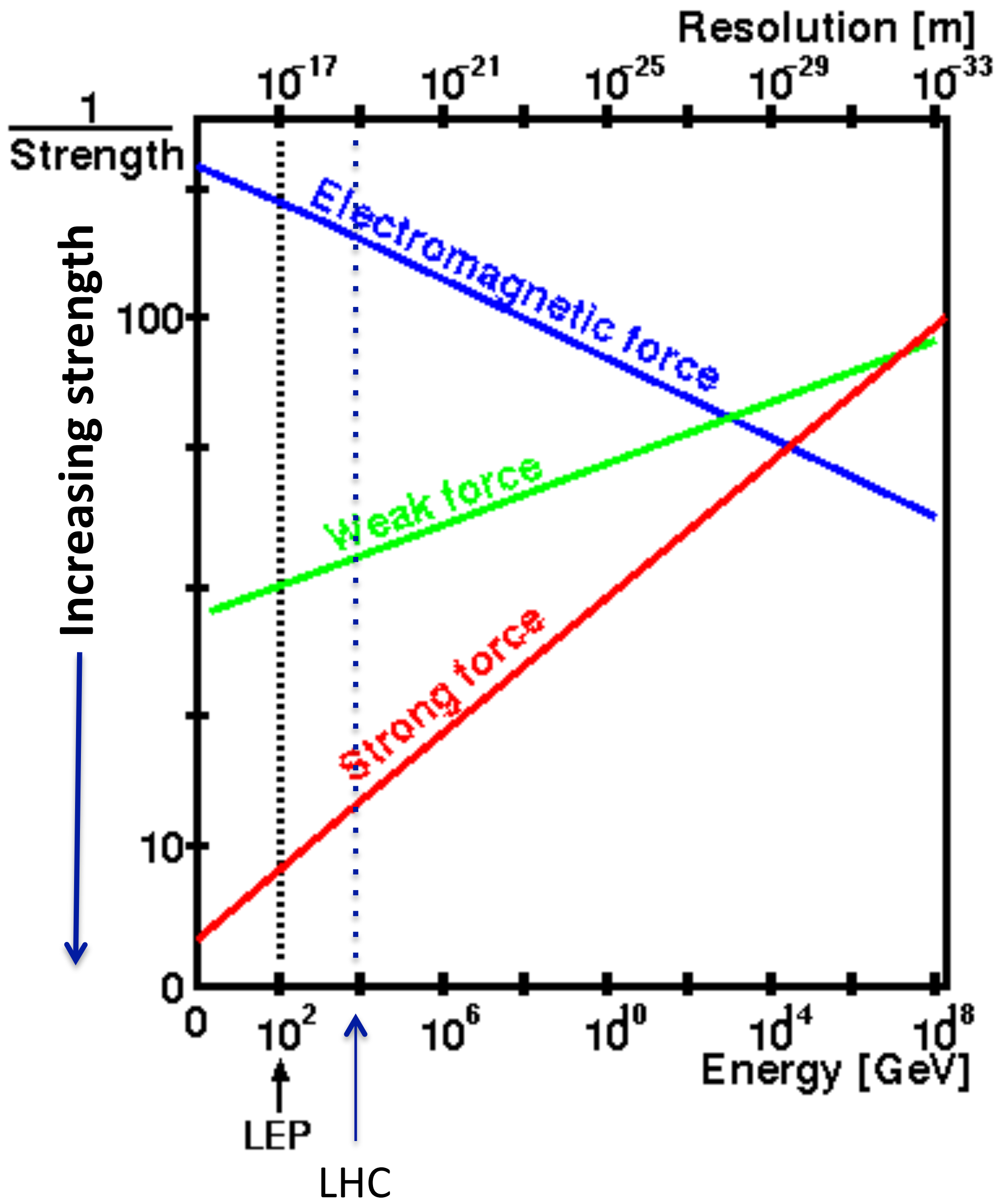


Non-abelian forces also include these "extra" charge loops

Net effect: **coupling decreases with E**

Note:
1/coupling plotted.

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



QCD

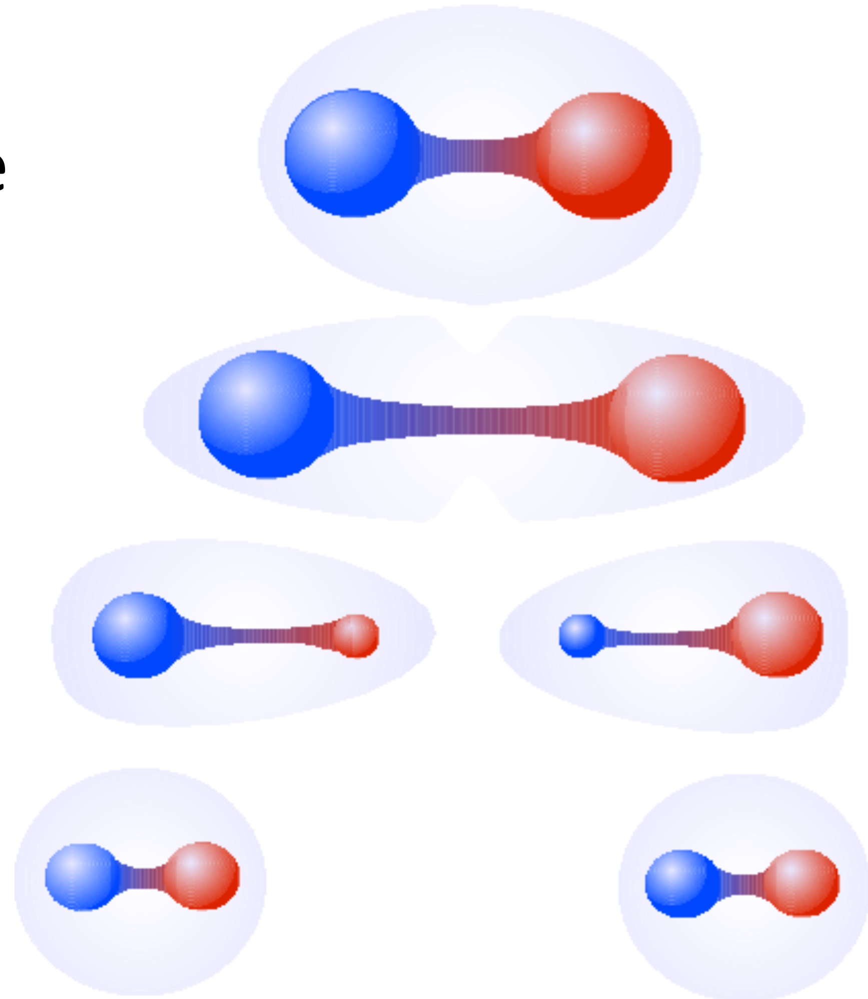
Force grows with distance

Confinement

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

Hadronisation

- jets



Quantum Electrodynamics: QED

Quantum Chromodynamics: QCD

Quantum Electrodynamics: QED

Electric charge → Atoms → Molecules

Quantum Chromodynamics: QCD

Colour charge → Baryons → Nucleus

Quantum Electrodynamics: QED

Electric charge → Atoms → Molecules

Interaction of electric charges and photons

Quantum Chromodynamics: QCD

Colour charge → Baryons → Nucleus

Interaction of colour charges and gluons

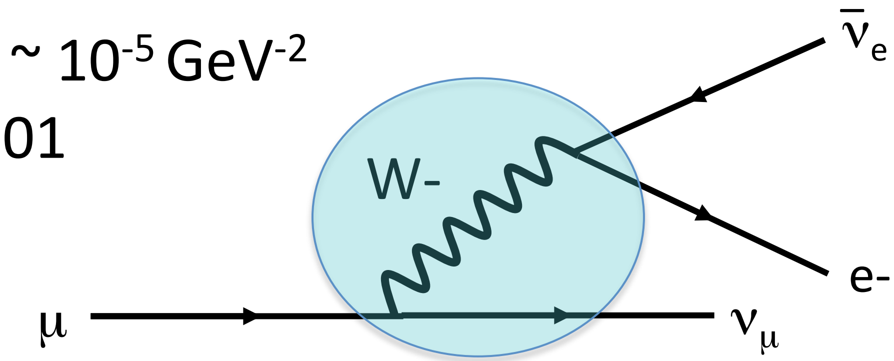
Different forces, but **similar** (mathematical) structure/behaviour

Weak force vs. EM, QCD?

Muon decay:

Strength of weak force ~ G_F ~ 10^{-5} GeV^{-2}

cf. strength of em force ~ 0.01



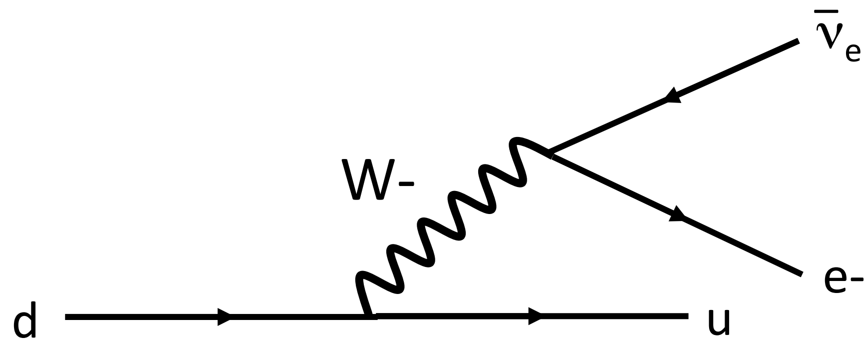
W boson **massive**

Factor involved in boson exchange ~ $1/(E^2+M^2)$ (hence units)

Strength of weak force = em force if M~ 30 GeV   (M_W~80 GeV)

Weak force vs. EM, QCD?

W couples to:
Upper and lower members of a fermion generation.



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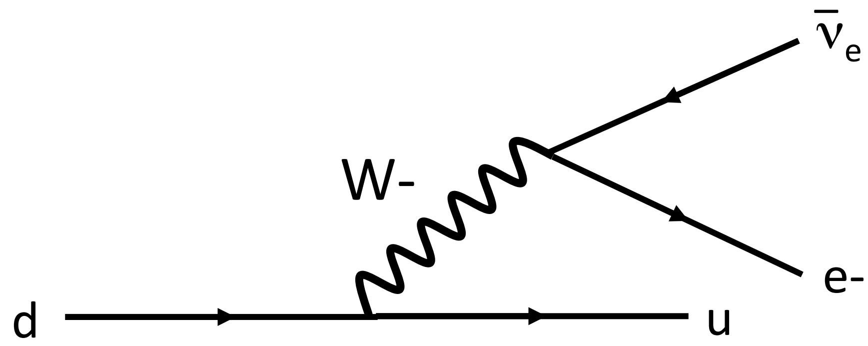
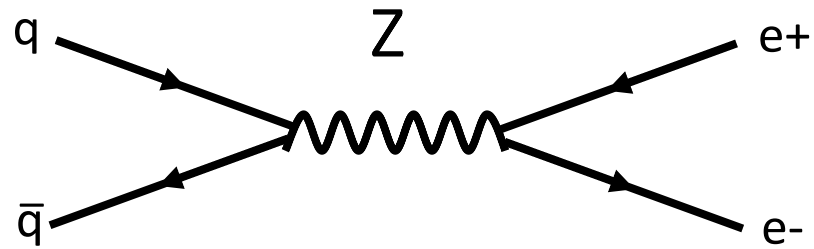


Z couples to:
Matter and antimatter versions of a fermion.



Weak force vs. EM, QCD?

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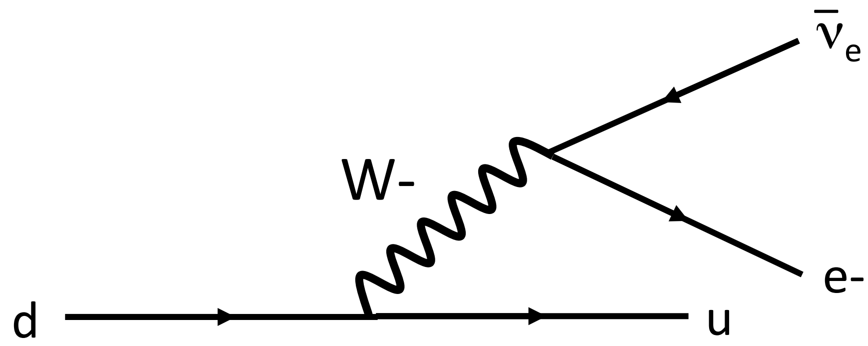

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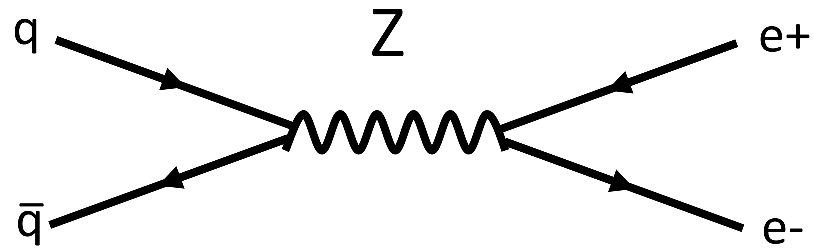


W, Z massive (unlike QCD/em).

Higgs

Bosons are **massless** in theory (local gauge invariance*)

Introduce Higgs field (value of Higgs potential v):

- Couples to particles to give mass (amount ~ coupling strength)
- Introduces spinless Higgs boson (m_H)

* See your Standard Model course.

Higgs

Bosons are **massless** in theory (local gauge invariance*)

Introduce Higgs field (value of Higgs potential v):

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

Introduces spinless Higgs boson (m_H)

Consequences:

Unifies weak and electromagnetic forces

Massive Z is mixture of massless em + weak bosons

Relates Mw, Mz and weak, electromagnetic couplings:

$\tan \theta_W = g_W / g$

$M_W = M_Z \cos \theta_W$

* See your Standard Model course.

July 4th 2012

126 GeV/c^2

0

0

H

Higgs

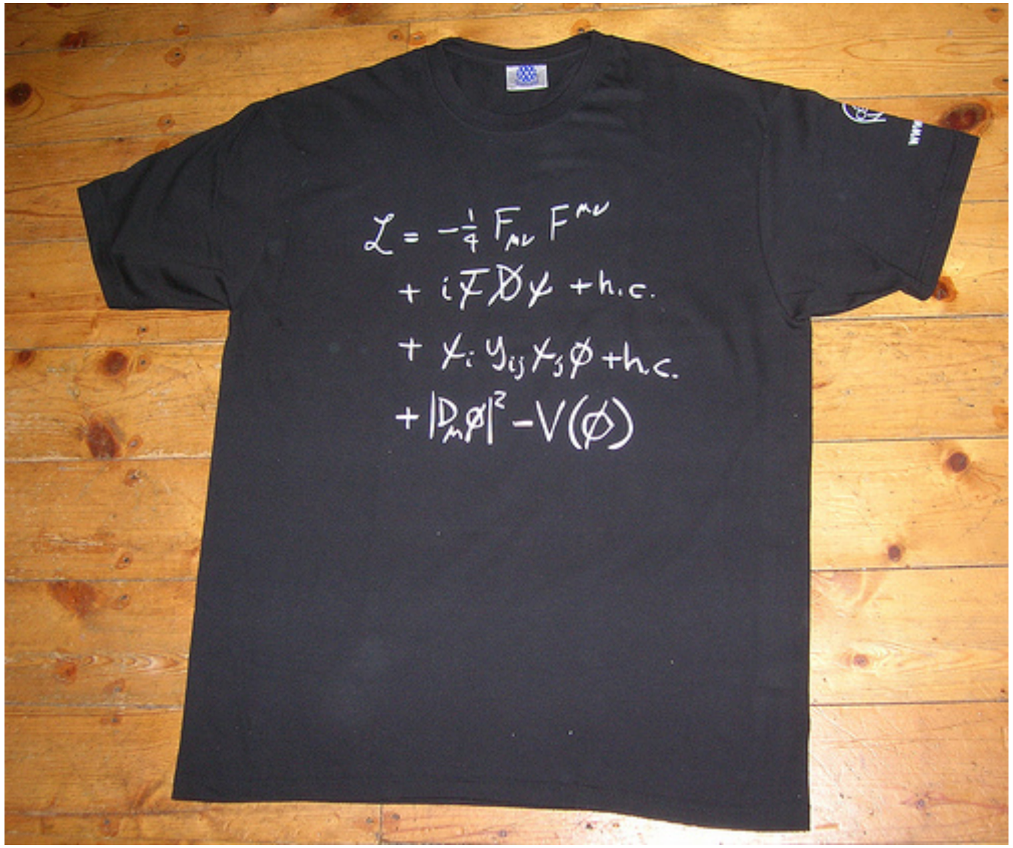
364 days later .. you are here

Standard Model

Standard Model (SM)

Quantum field theory based on lagrangians

We use the SM to predict experimental observations



Standard Model 4/7/13
HEP theory concepts 11/7/13
SM physics LHC 25/7/13

Successes

Consistent with experiment

No deviations seen

Predictions (eg Higgs) proven

Holes

Incomplete (eg. no gravity)

Few explanations

Many ad-hoc additions to fit experimental data

Successes

Consistent with experiment

No deviations seen

Predictions (eg Higgs) proven

Holes

Incomplete (eg. no gravity)

Few explanations

Many ad-hoc additions to fit experimental data

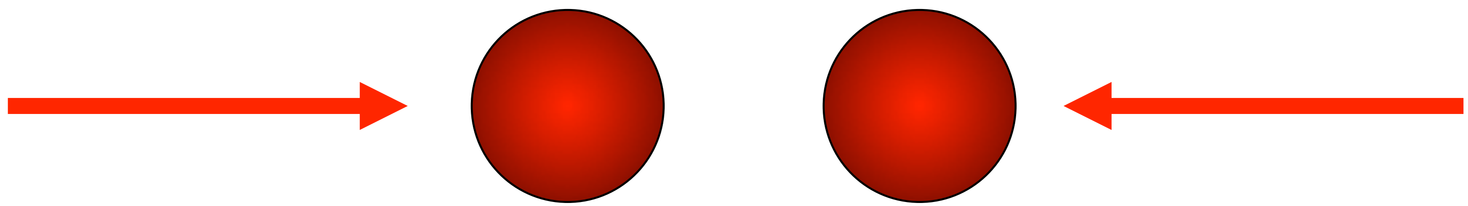
Need to find a breakdown to move forward.

Need experiments.

Experiments.

Particle accelerators

Beams of charged particles accelerated by electromagnetic force*.



Centre of mass energy: $\sqrt{s} = \sqrt{\left(\sum_i E_i^2 - \sum_i p_i^2 \right)}$

* Note: also used as sources; cosmic rays, neutrinos from nuclear reactors.

Linear

No bremsstrahlung

Long (for high energy)

"one shot" accelerator

Circular

Bremsstrahlung

Strong magnets needed to maintain circular beam path

Long beam lifetime; many revolutions, many collisions.

Protons vs. electrons

Accelerators 4/7/13
Medical physics 30/7/13

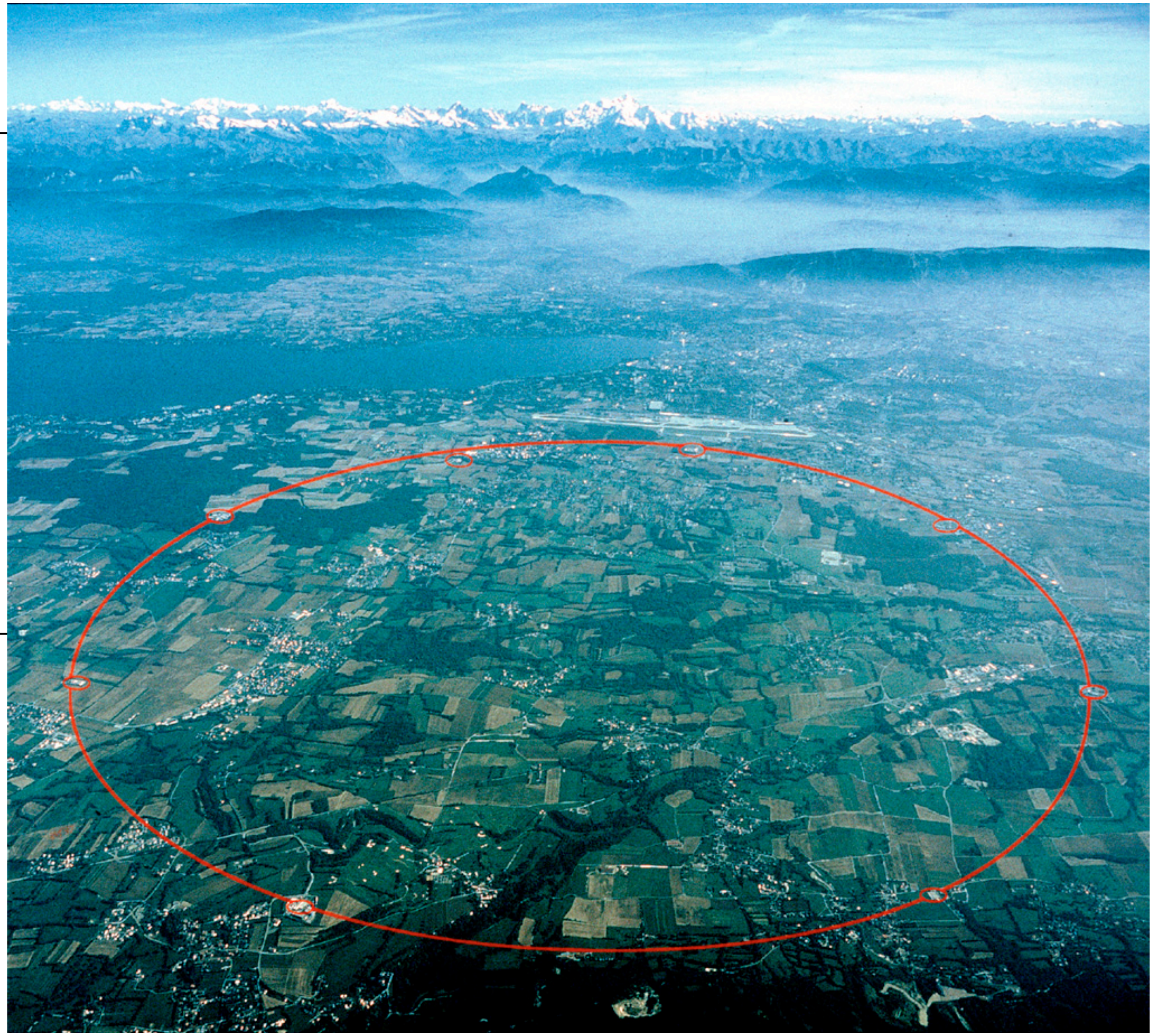
LHC:

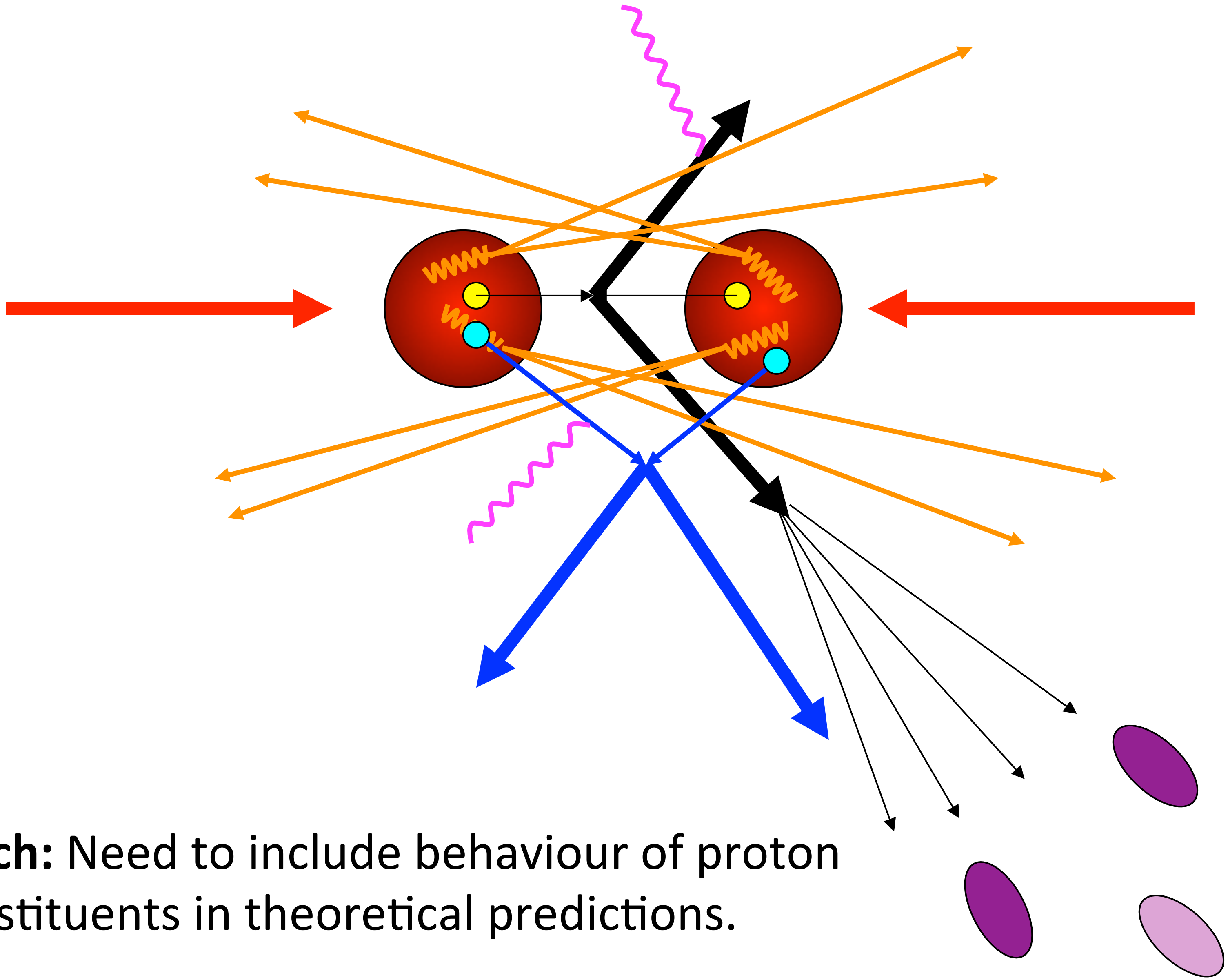
High energy ($\sqrt{s}$=14 TeV)

Circular

Proton beams

Up to 10^8 collisions/s





Catch: Need to include behaviour of proton constituents in theoretical predictions.

Particle detectors

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

↑

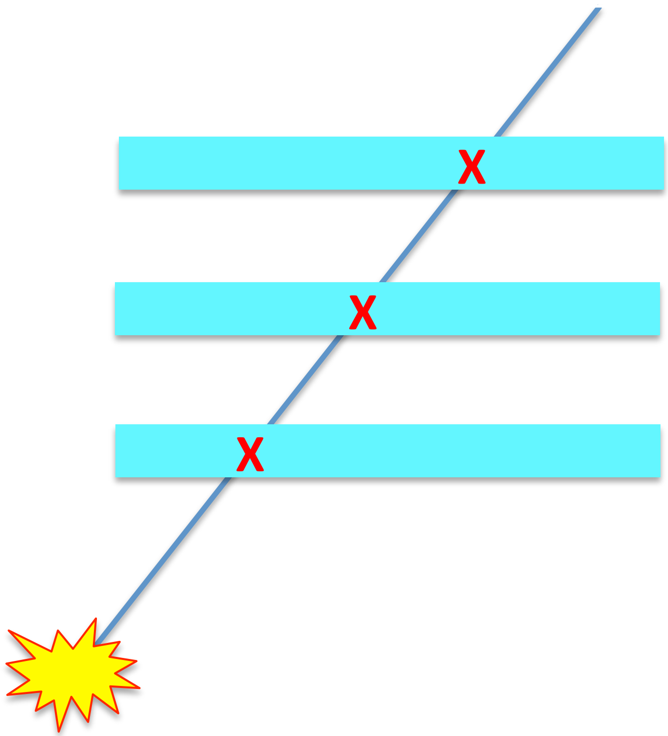
(x,y,z)

Reconstruct path

Reconstruct momentum

Measure energy

Identify type



Tracking detectors
Charged particles
Location:
 Ionisation (gas)
 e/hole (silicon)

Detectors 10/7/13
Electronics/TDAQ 11/7/13

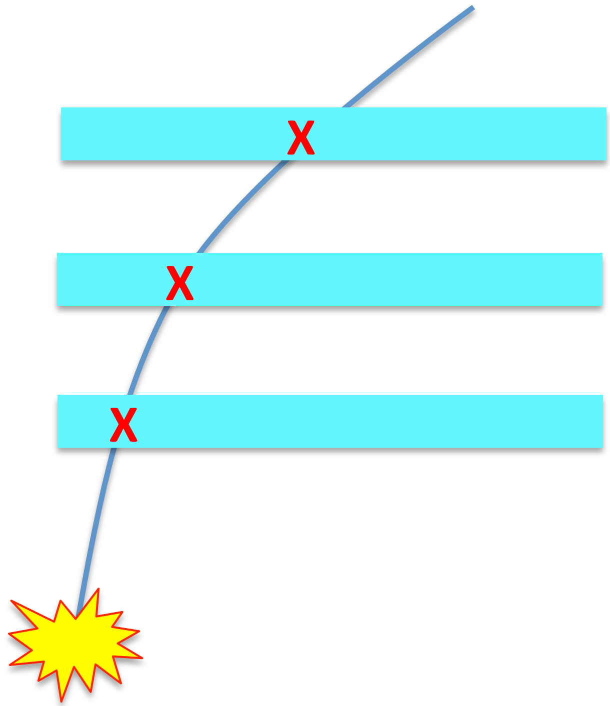
(**px,py,pz**,m)

Reconstruct path

Reconstruct momentum

Measure energy

Identify type



Magnetic field
Relate track curvature, B to p.

$$p = 0.3Br$$

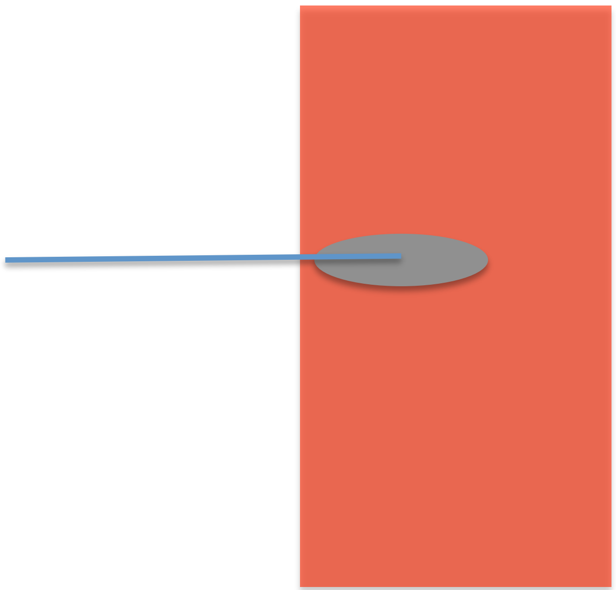
(px,py,pz,**m**)

Reconstruct path

Reconstruct momentum

Measure energy

Identify type



Calorimeters

Charged + neutral particles

Two types:

- Electromagnetic
- Hadronic

Absorb + measure energy

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

Reconstruct path

Reconstruct momentum

Measure energy

Identify type

Location of absorption:

Calorimeters

Muon chambers

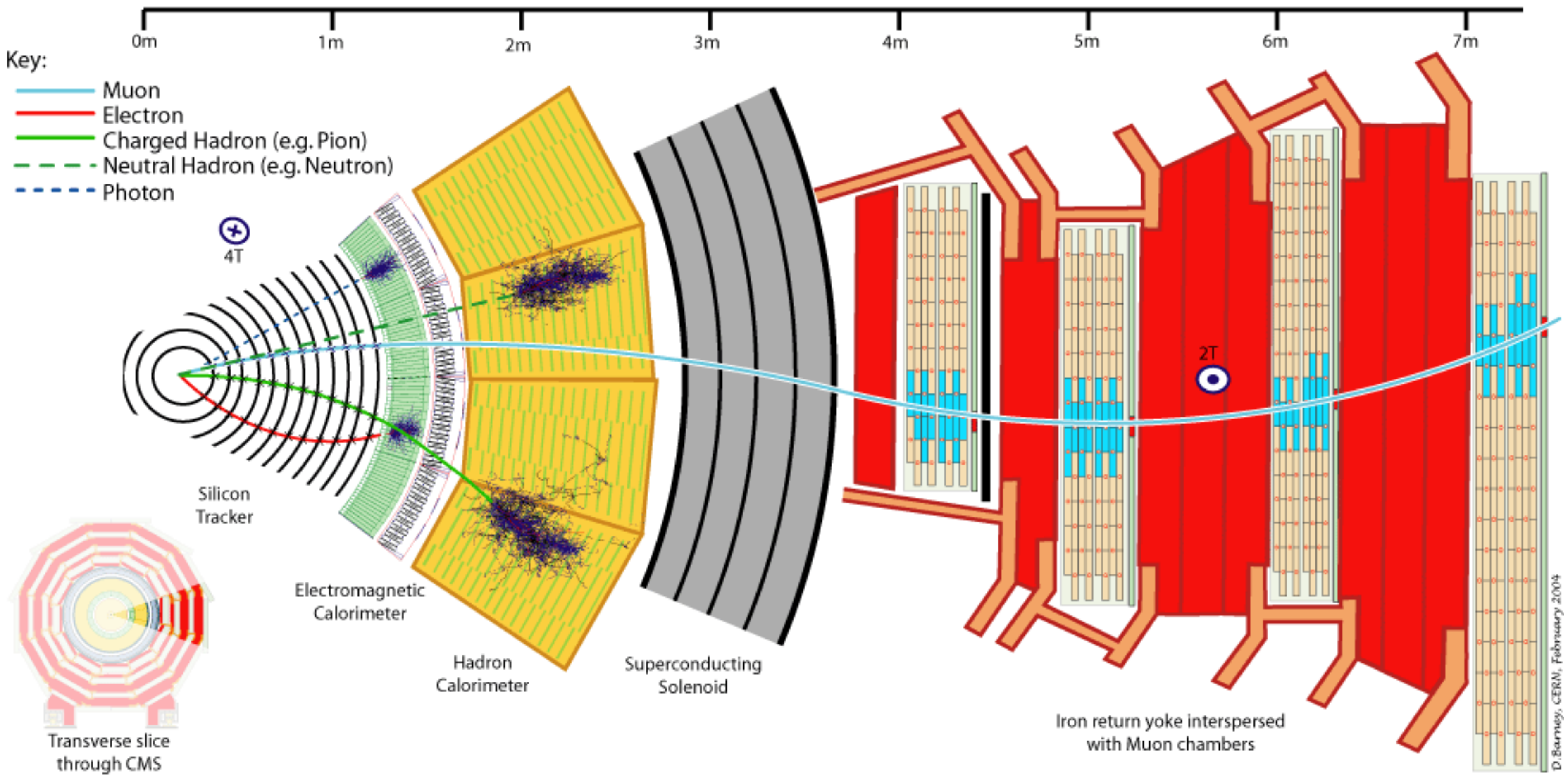
Cerenkov detectors (**v**)

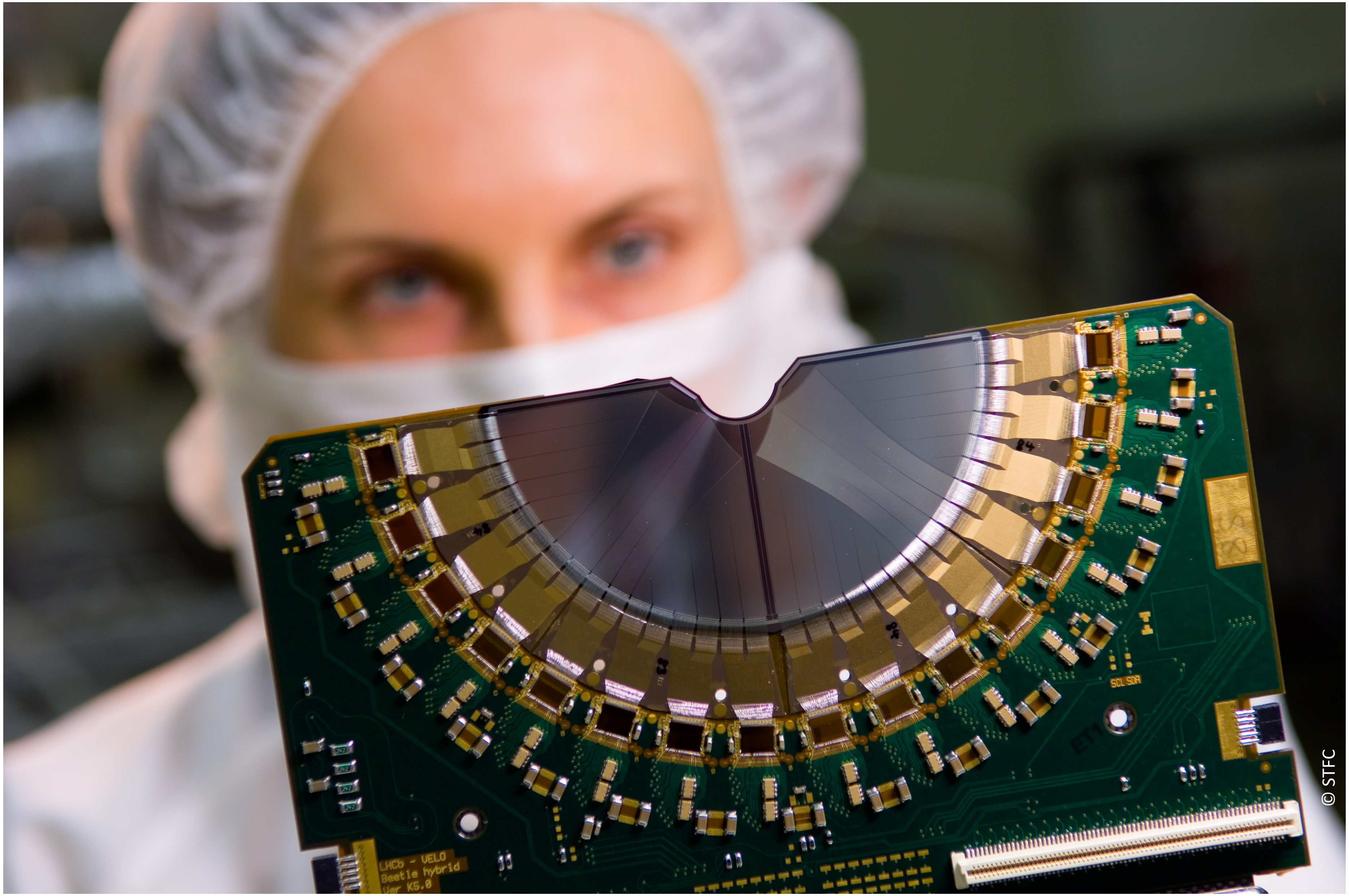
Add momentum -> m

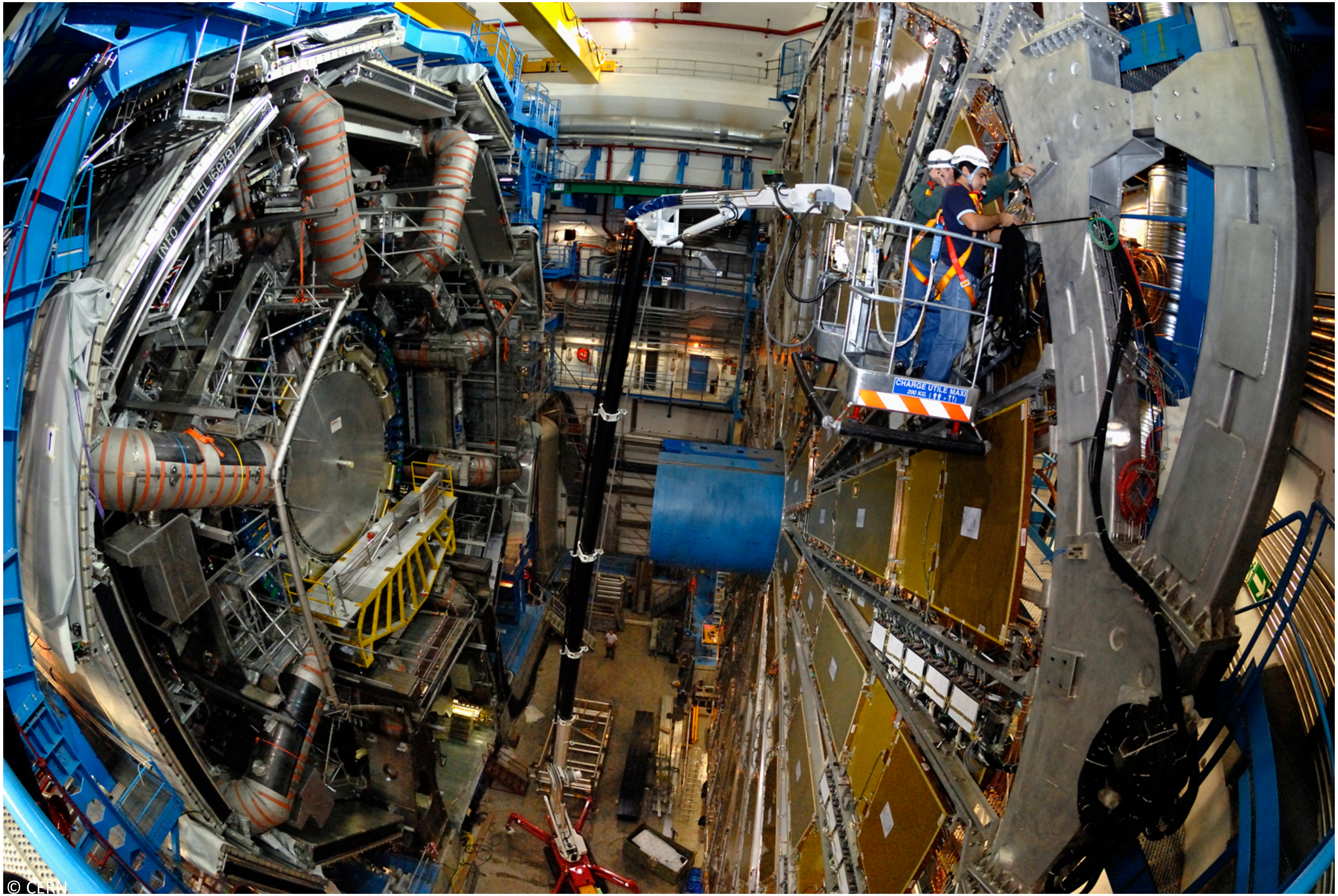
Transition radiation (γ)

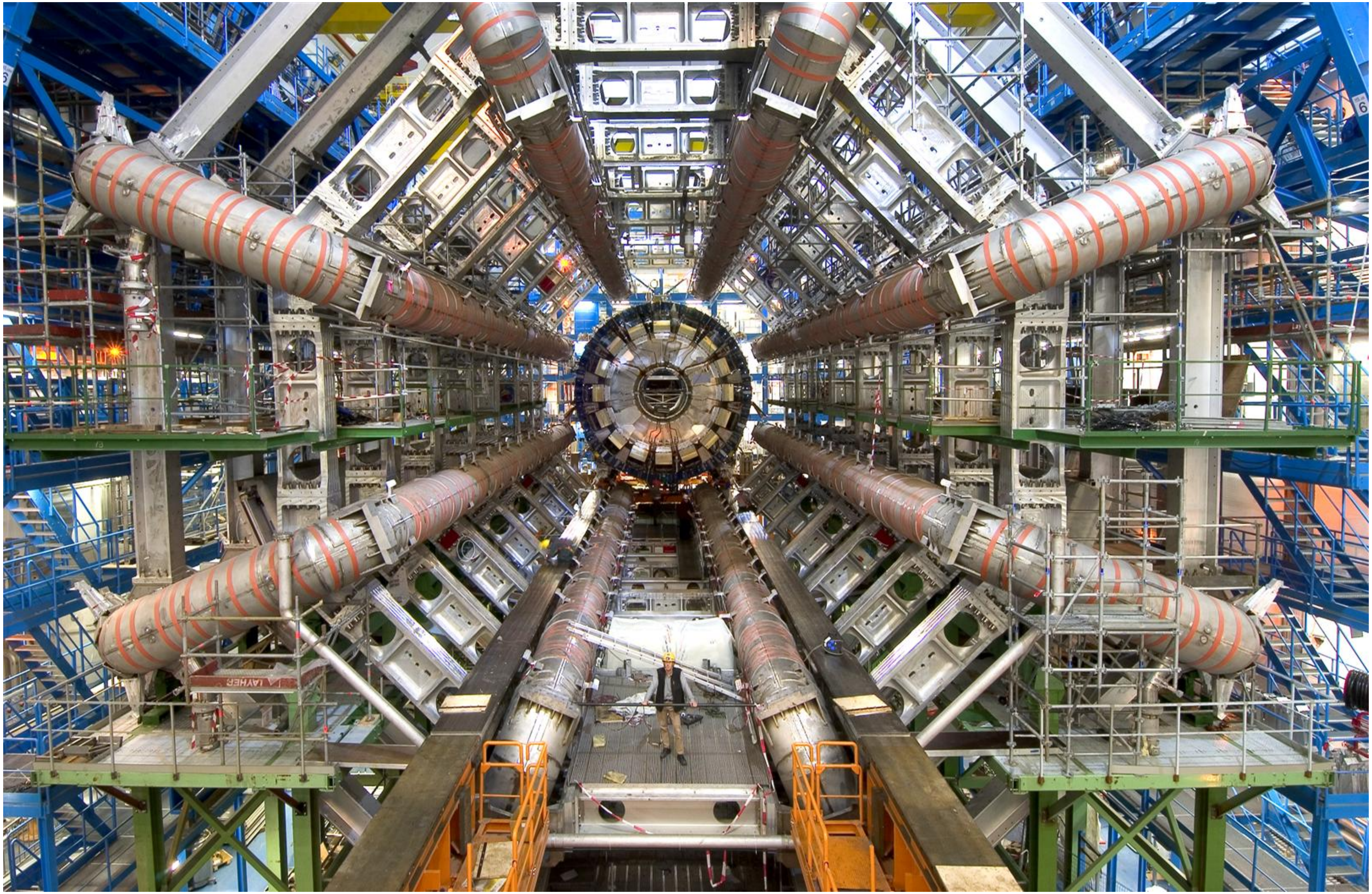
Add energy -> m

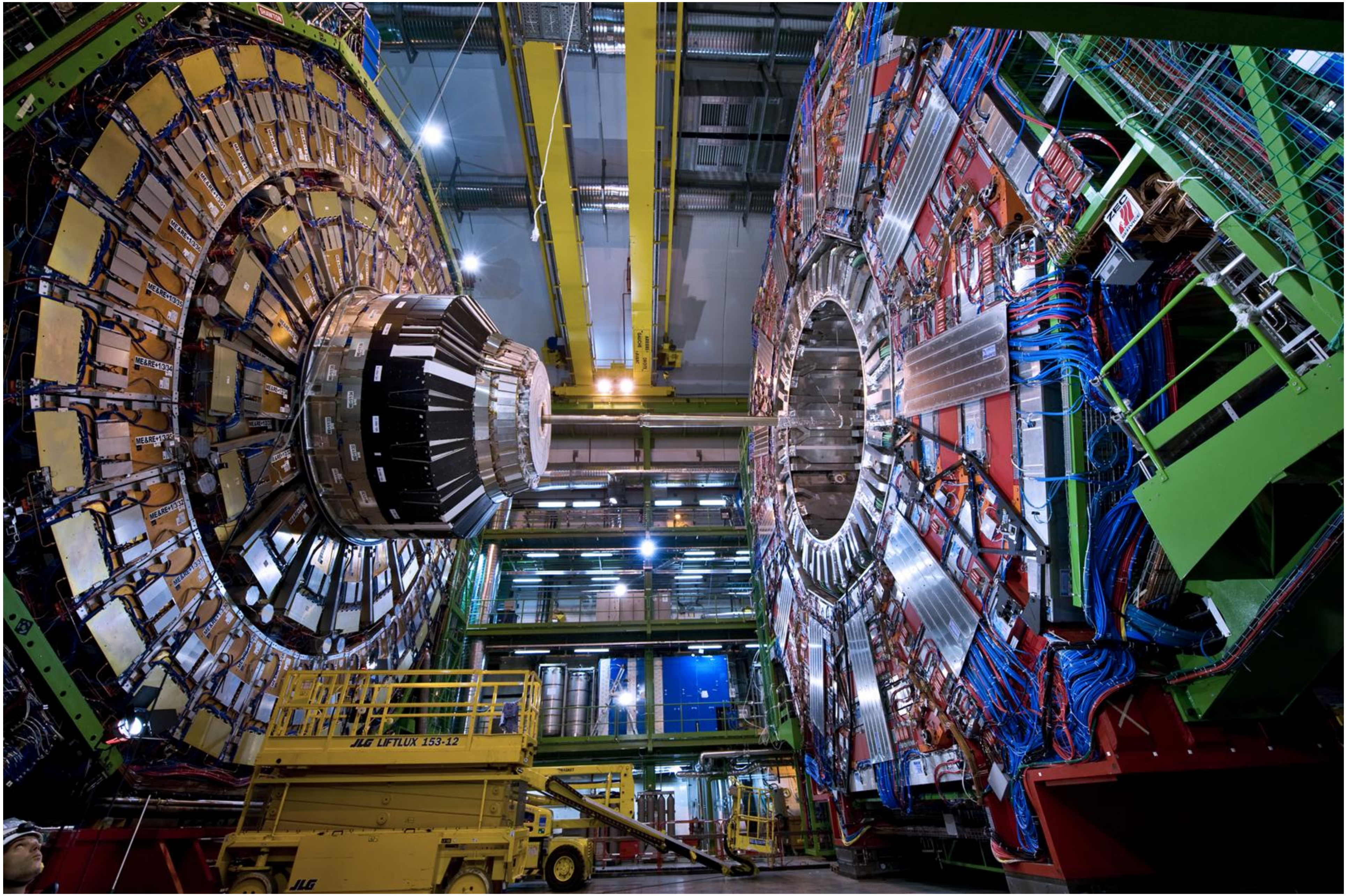
Time-of-flight (comparative m)

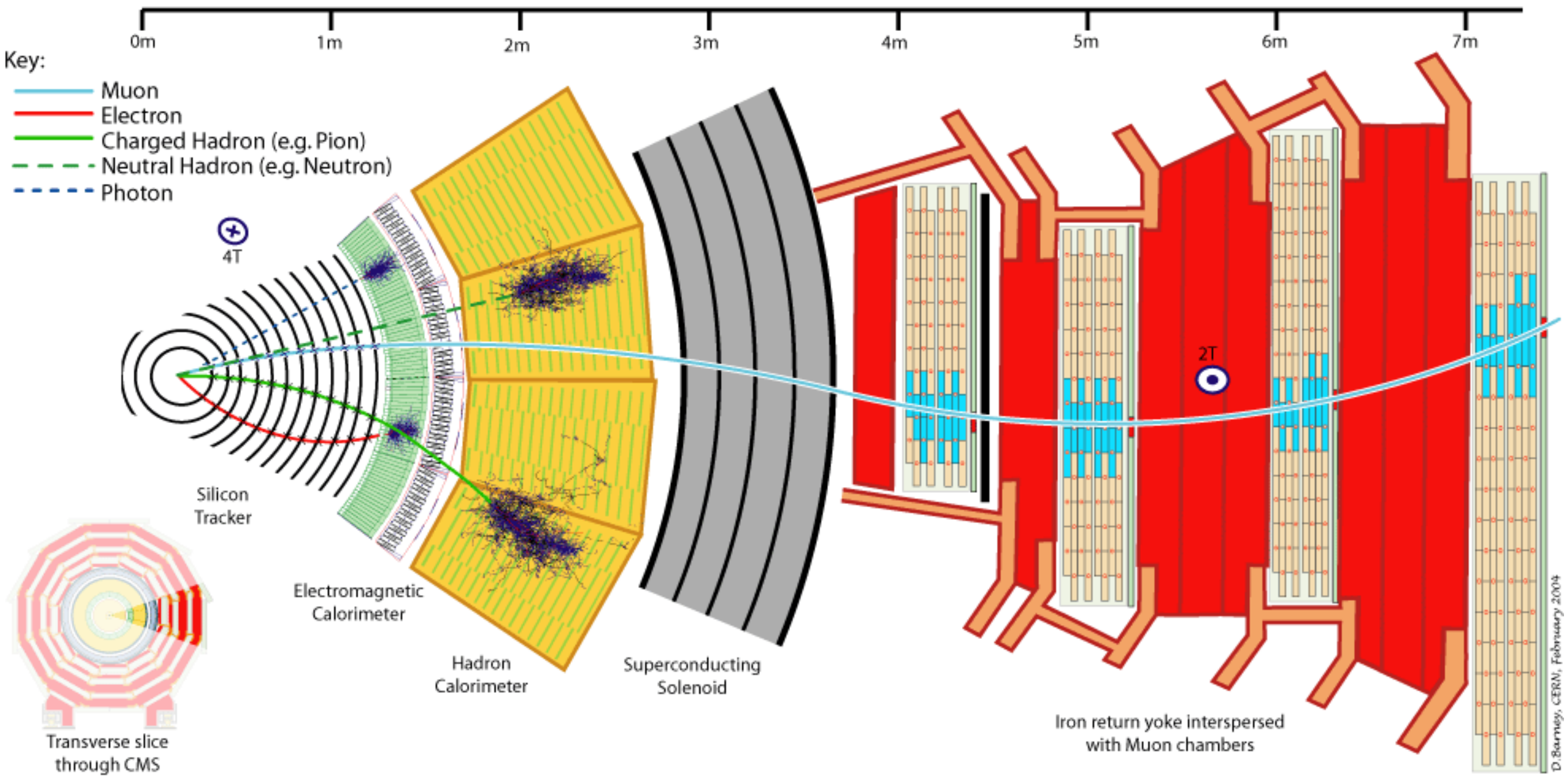

0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004


LHCb - VELO
Beetle hybrid
Ver K5.0
SCL SDA


CHARGE UTILE MAXI
200 KG.
© CERN



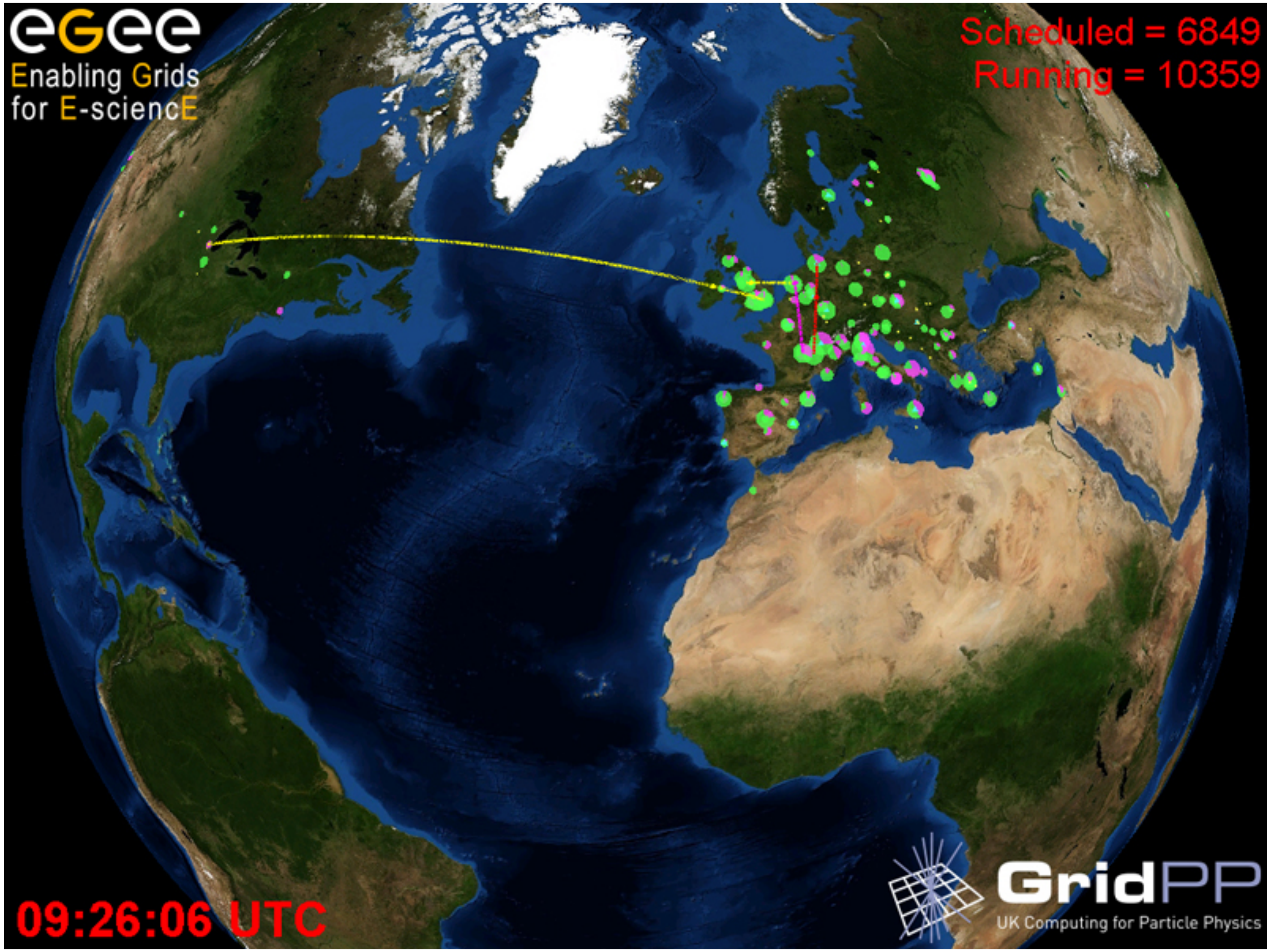

JLG LIFTLUX 153-12

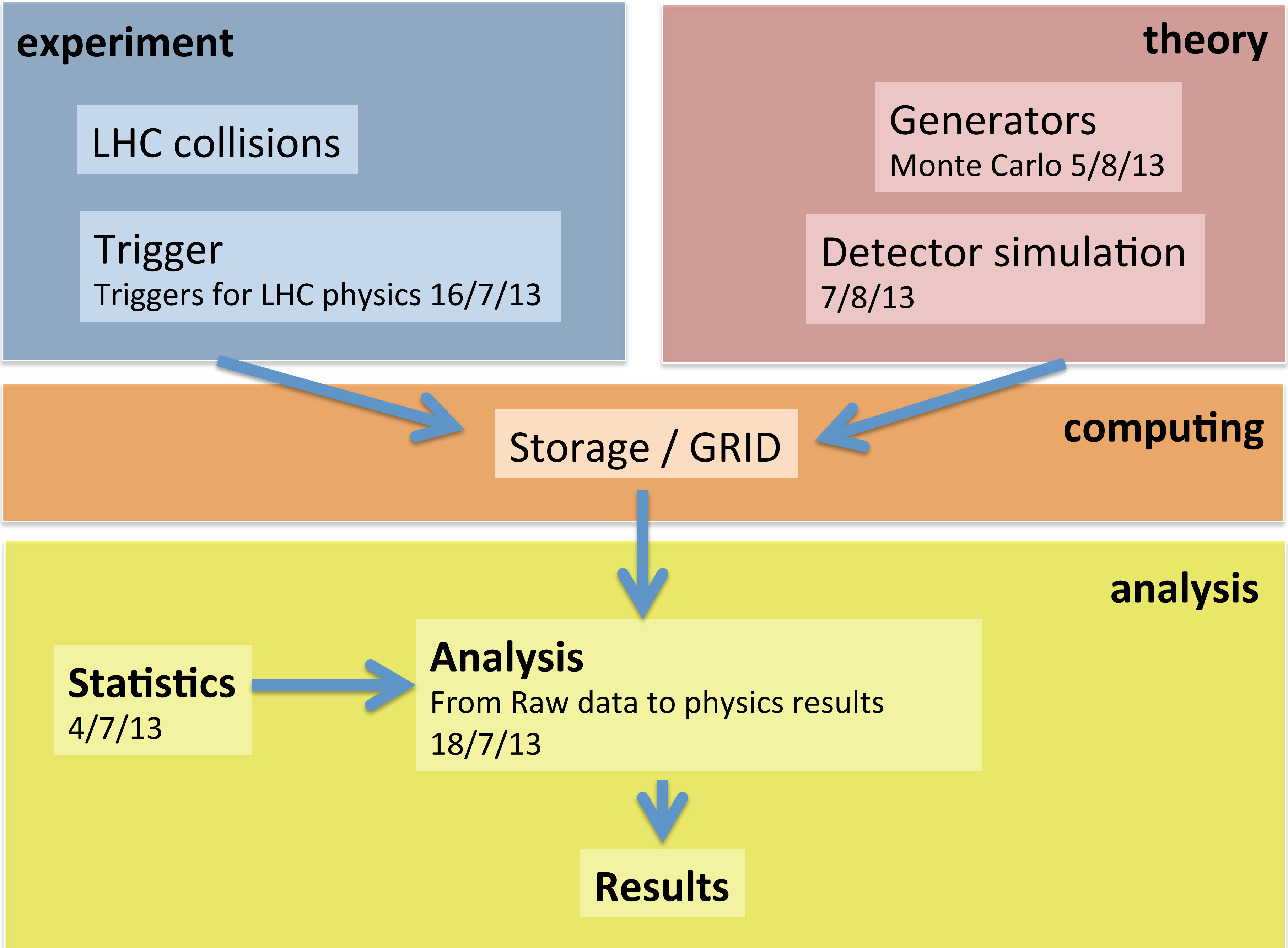


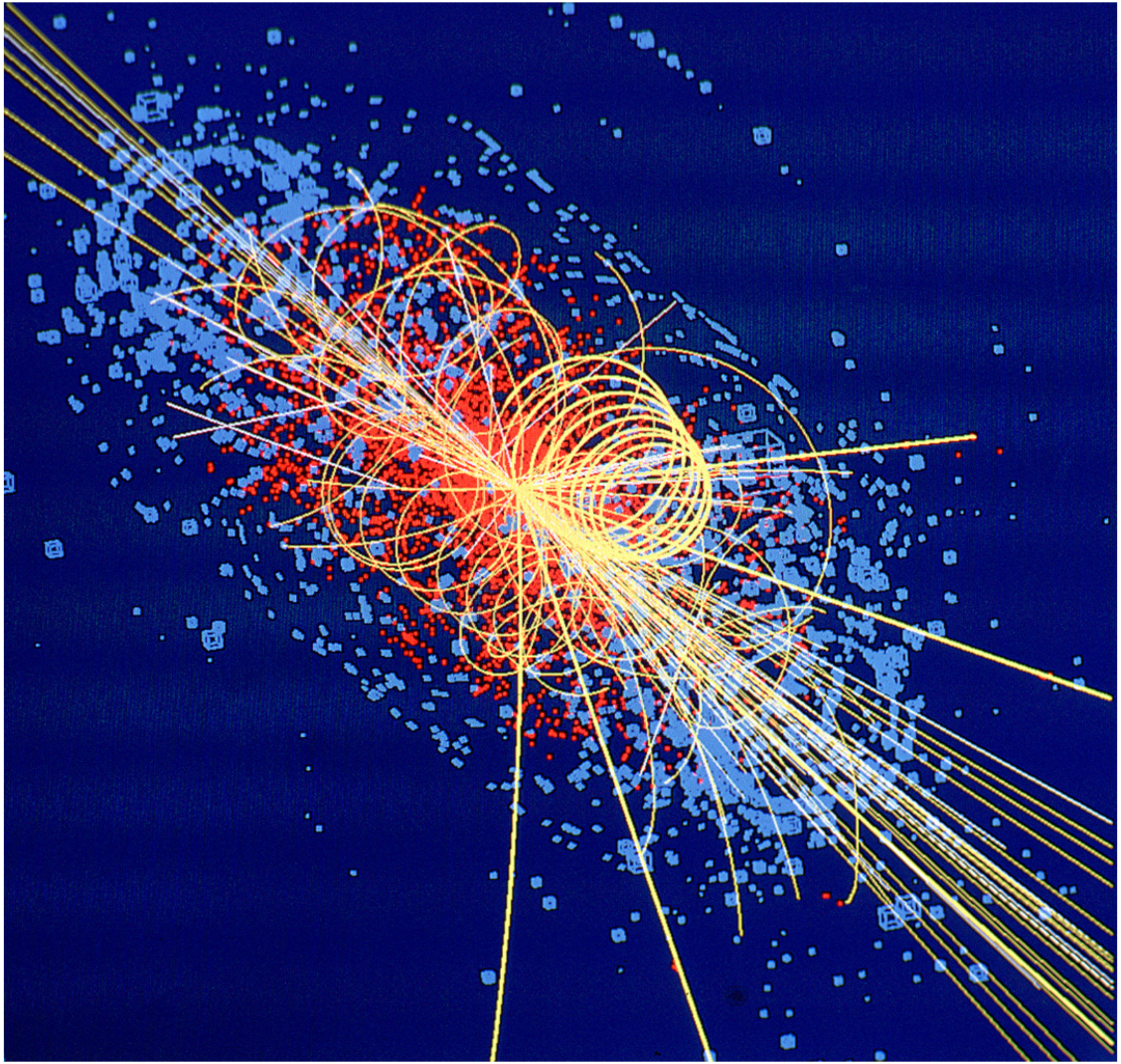
Identify particles by characteristic signatures in experiment

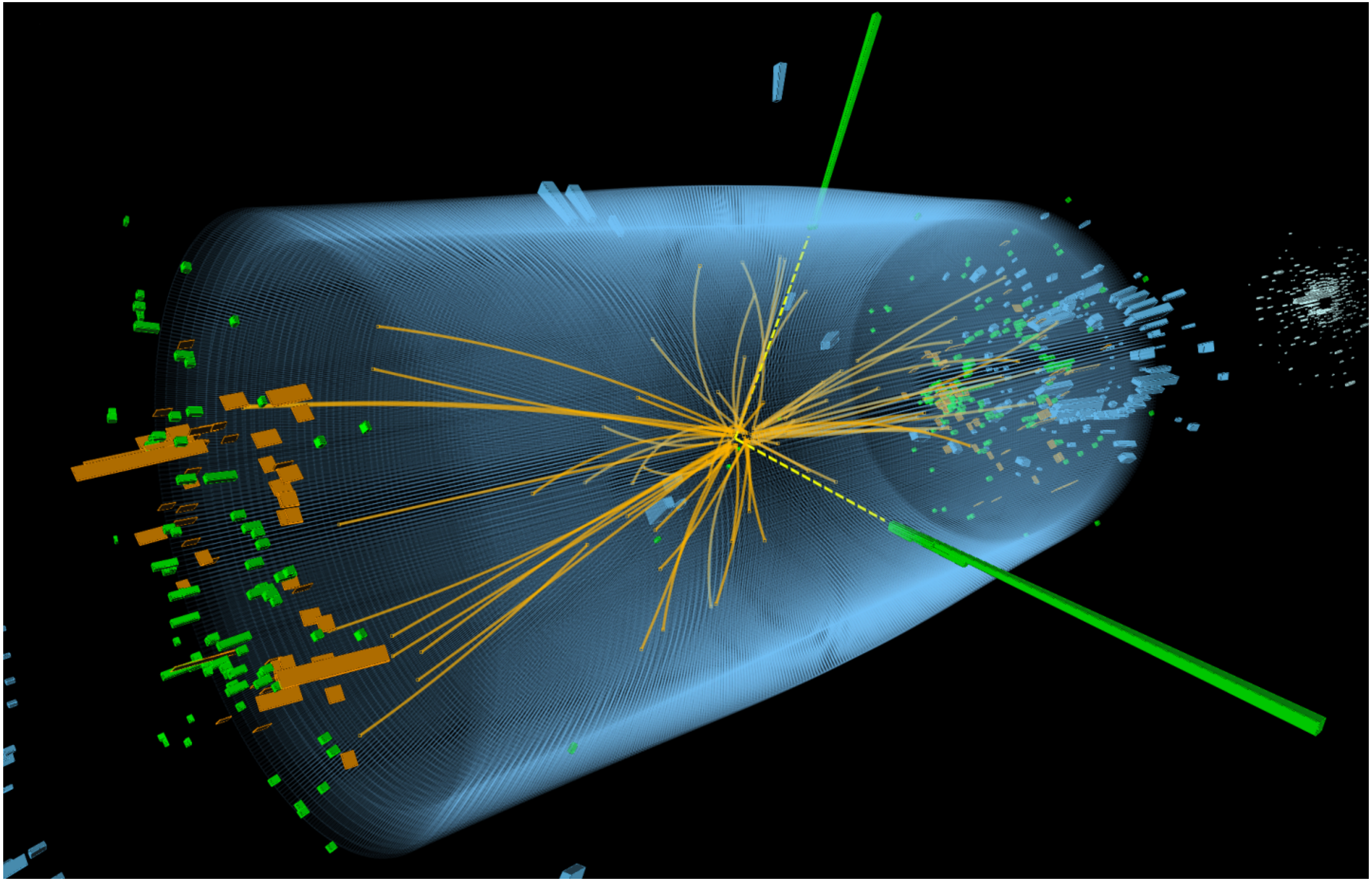
Add computers: calculate particle paths and energies

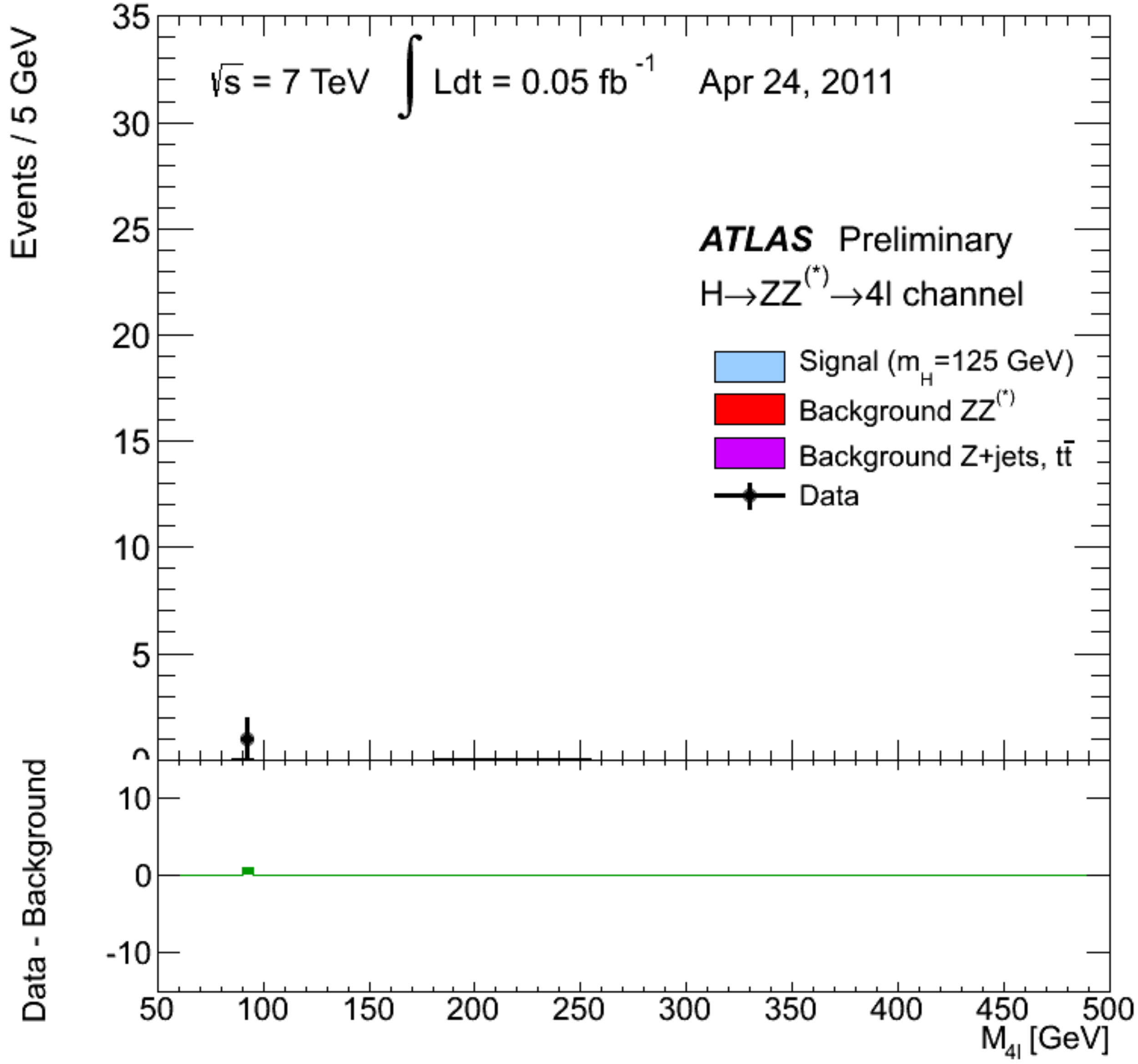
Add theory: infer what fundamental process happened


egee
Enabling Grids
for E-sciencE
Scheduled = 6849
Running = 10359
GridPP
UK Computing for Particle Physics
09:26:06 UTC


experiment
LHC collisions
Trigger
Triggers for LHC physics 16/7/13
theory
Generators
Monte Carlo 5/8/13
Detector simulation
7/8/13
computing
Storage / GRID
analysis
Statistics
4/7/13
Analysis
From Raw data to physics results
18/7/13
Results







√s = 7 TeV ∫ Ldt = 0.05 fb -1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M4l [GeV]

Future facilities

Too many open questions to stop here.

- New neutrino facility?
- New high energy machine?
- New linear collider?

Physics at future colliders 24/7/13
Future colliders technologies 25/7/13
LHC upgrade 29/7/13

The known unknowns

- Gravity
- Antimatter
- Dark matter, dark energy
- A unified theory
- + unknown unknowns…..

Gravity

Can't describe it in SM

Can include it in string theory – not very testable

Large extra dimensions could be observed at LHC (no sign so far…)

?

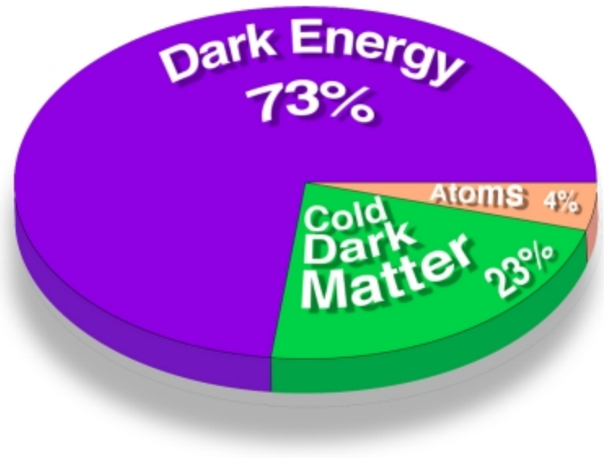
CP violation

Consistent picture in SM but insufficient to explain matter – antimatter asymmetry of the universe

? Answer lies in new physics?

?

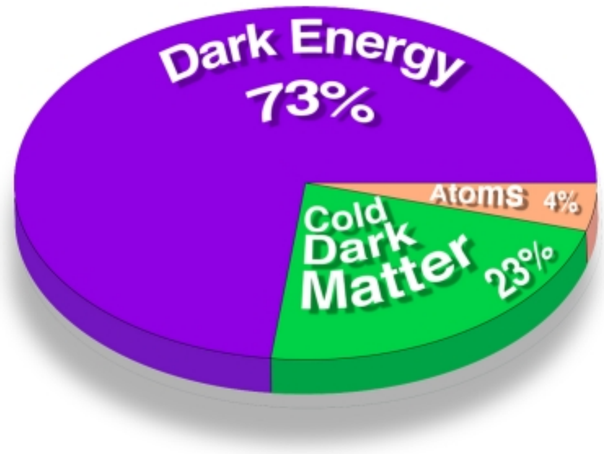
Antimatter 6/8/13
Flavour and CPV 1/8/13



Source: Robert Kirshner
Source: NASA/WMAP Science Team

SM with electroweak and strong interactions only describes 4% of the universe

Beyond the Standard Model 16/7/13
Search for beyond SM physics at hadron colliders 29/7/13



Source: Robert Kirshner
Source: NASA/WMAP Science Team

SM with electroweak and strong interactions only describes 4% of the universe

Dark energy:

?

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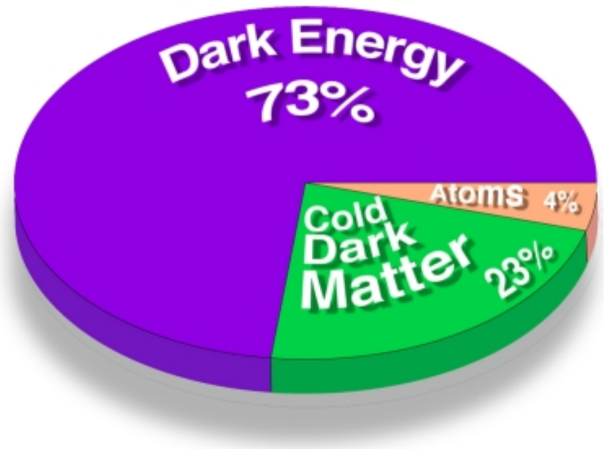

SM with electroweak and strong interactions only describes 4% of the universe

Source: Robert Kirshner
Source: NASA/WMAP Science Team

Dark energy:

?

Dark matter?

Try Supersymmetry (SUSY).

Lightest supersymmetric particle is a dark matter candidate (massive and unobservable)

Beyond the Standard Model 16/7/13
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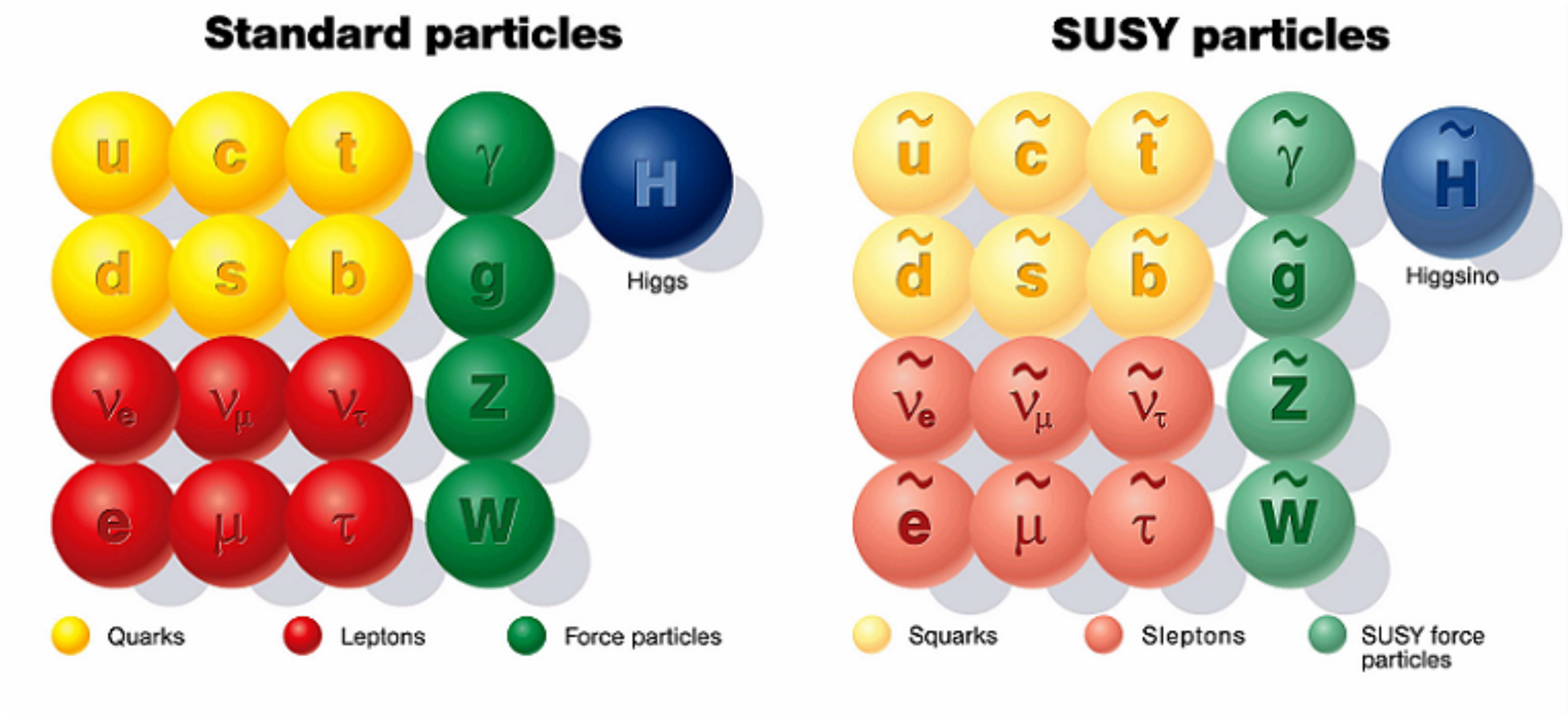
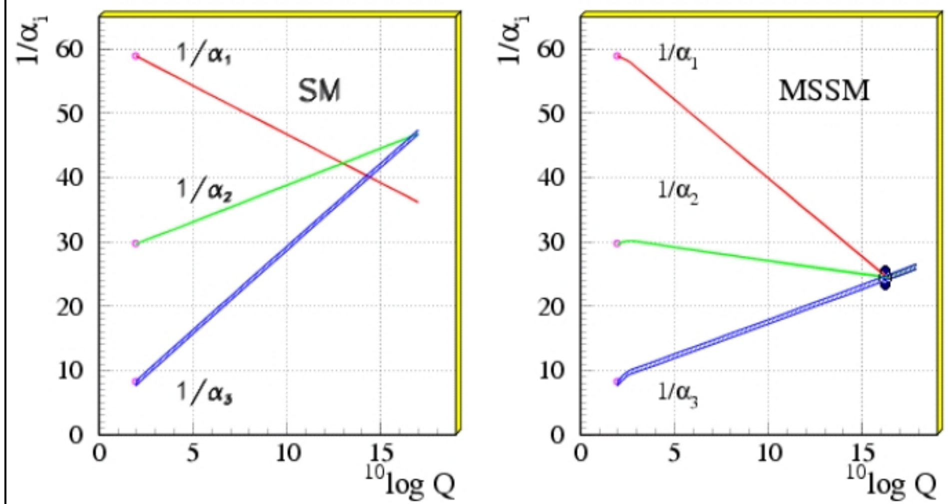

Standard particles
SUSY particles
u c t γ
d s b g
Z
W
H
Higgs
Higgsino
Quarks
Leptons
Force particles
Squarks
Sleptons
SUSY force particles

Why 3 forces? 3 generations?

What if there is 1 force, which fractured at high energy to give what we see today?

Forces "run" with energy ….. and don't agree at high energy

New Physics (eg. SUSY) can modify their evolution to join up → unification?



Particles – why so many ingredients of matter?

Why are their masses so different?

Conclusions

Particle physics describes the smallest structures in the universe

Theory: the Standard Model

- Works fabulously well
- Frustrating

Many big mysteries to solve.