The Particle World: an introduction to particle physics

CERN summer student lectures 2015

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What particle physics describes

What we know (and what we don't)

The Standard Model: matter; forces; Higgs.

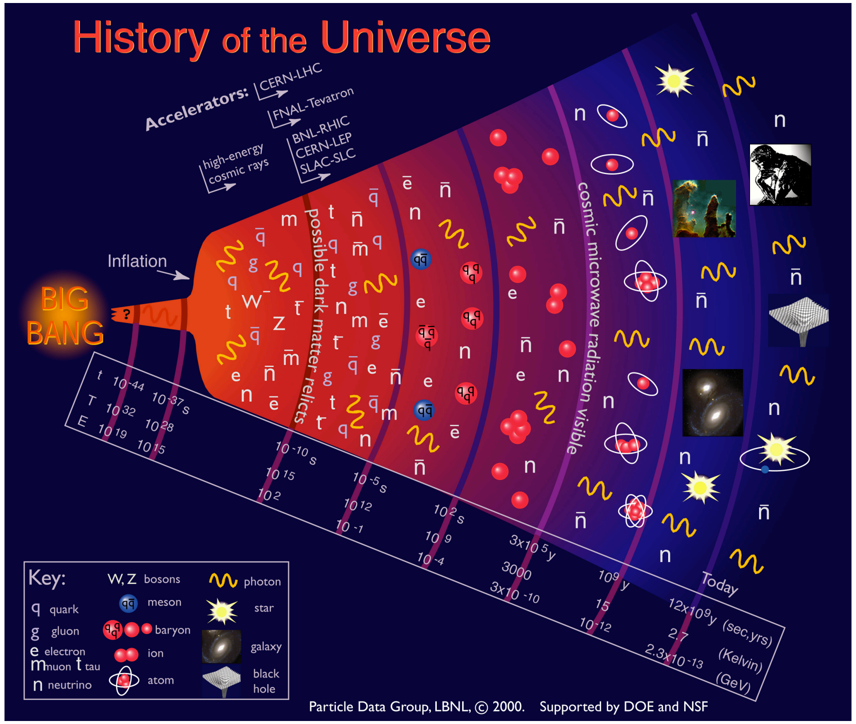
Experiments; performing research

Outstanding questions and mysteries …

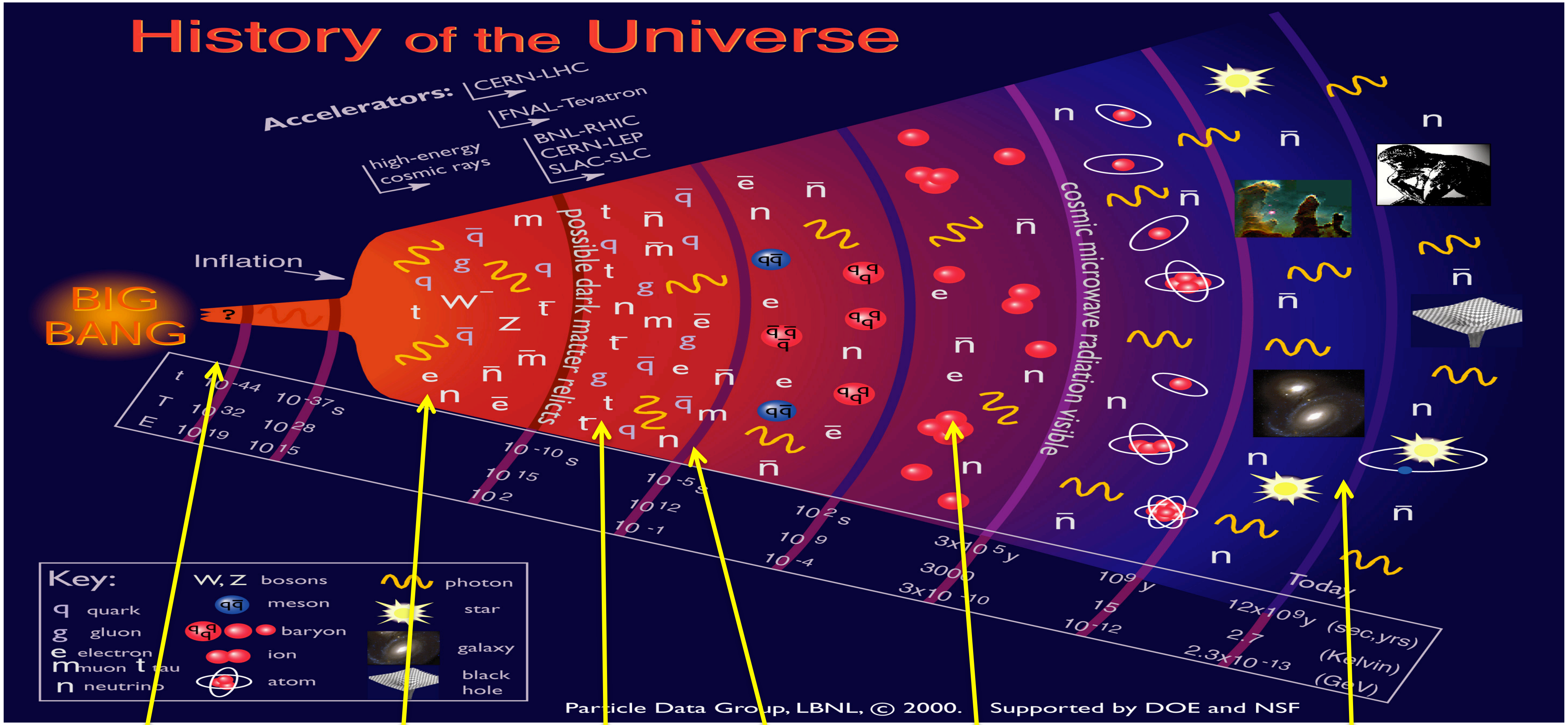
…… in the next three hours!

The universe

BIG BANG



NOW



Cosmology
23/7/15

Cosmic rays

LHC

Quark/gluon plasma
Heavy ions 22/7/15

Nuclear physics
8/7/15

Astrophysics

Plus ….
Antimatter 4/8/15
Astroparticle physics 4/8/15

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

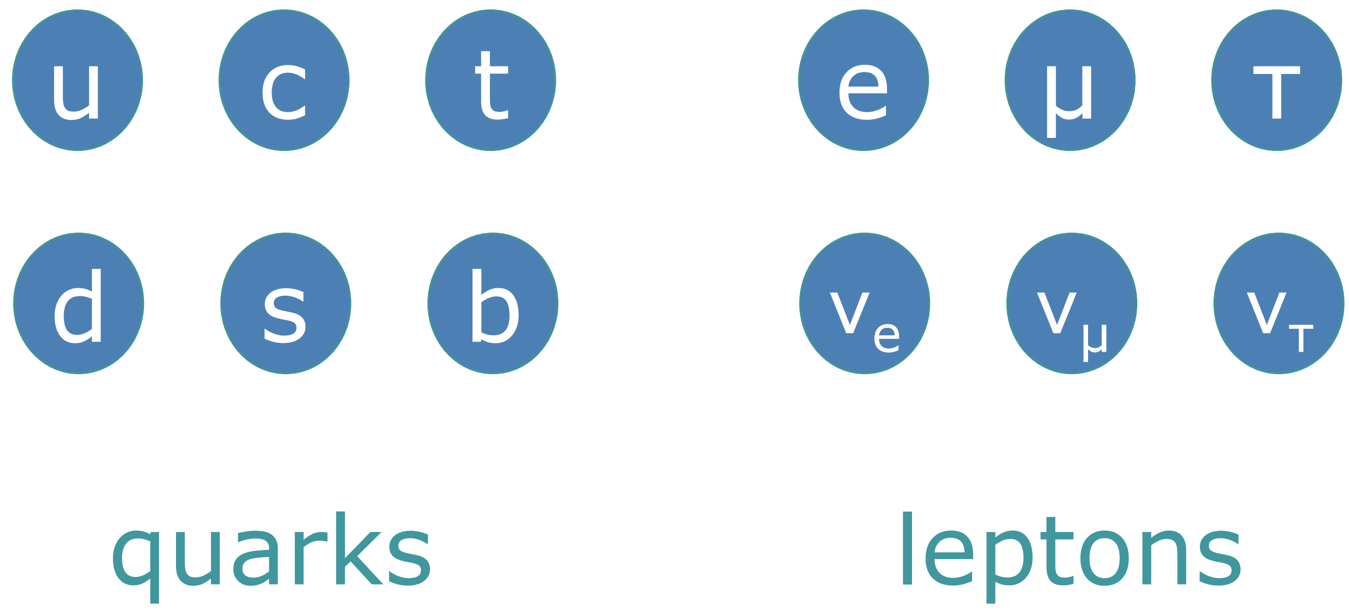
1 eV = 1.6 x 10^{-19} J

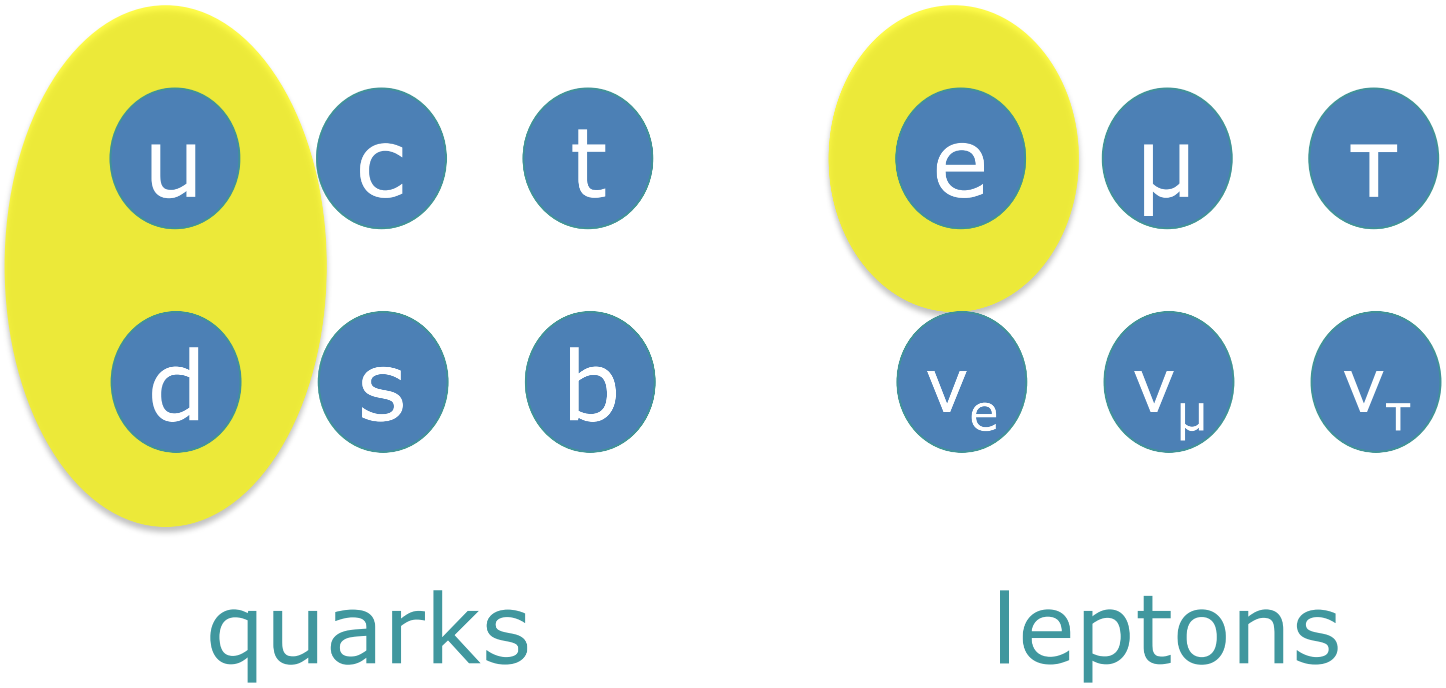
1 GeV = 10^9 eV

1 TeV = 10^3 GeV

1 fm = 10^{-15} m

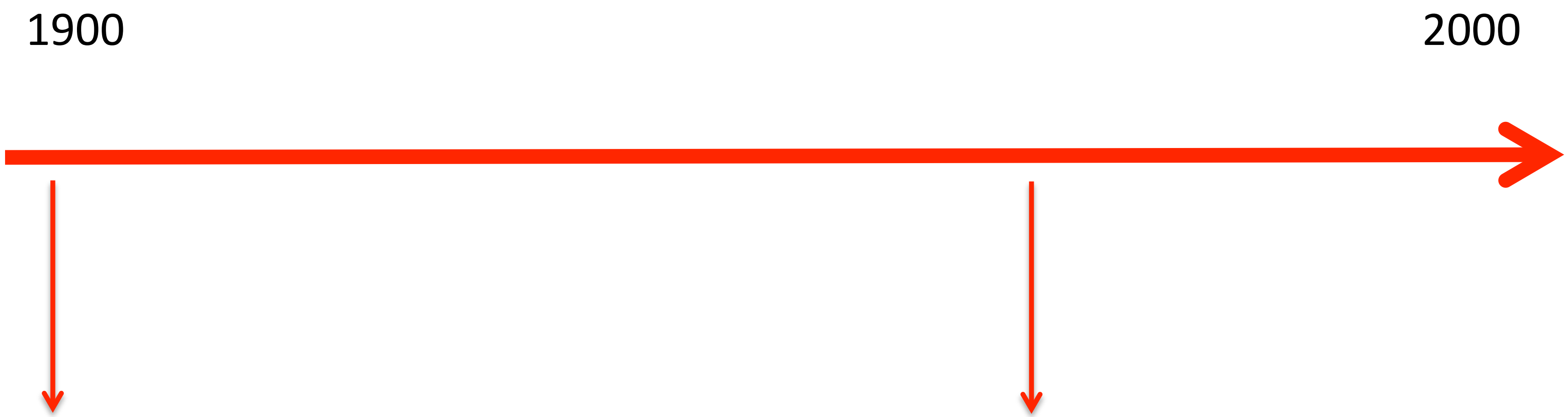
Note: often set $\hbar = c = 1$


u
c
t
d
s
b
e
μ
τ
νe
νμ
ντ
quarks
leptons



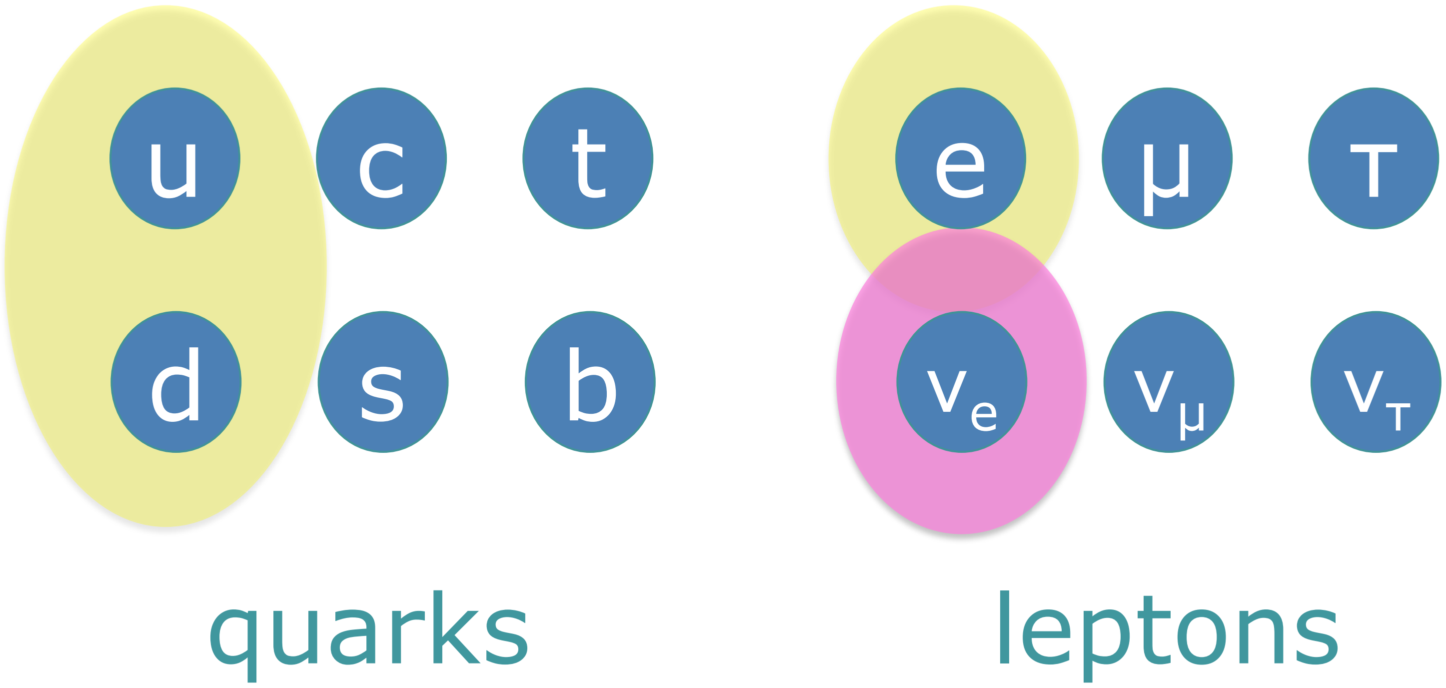
u,d proposed 1960s, discovered ~1968

e discovered 1897

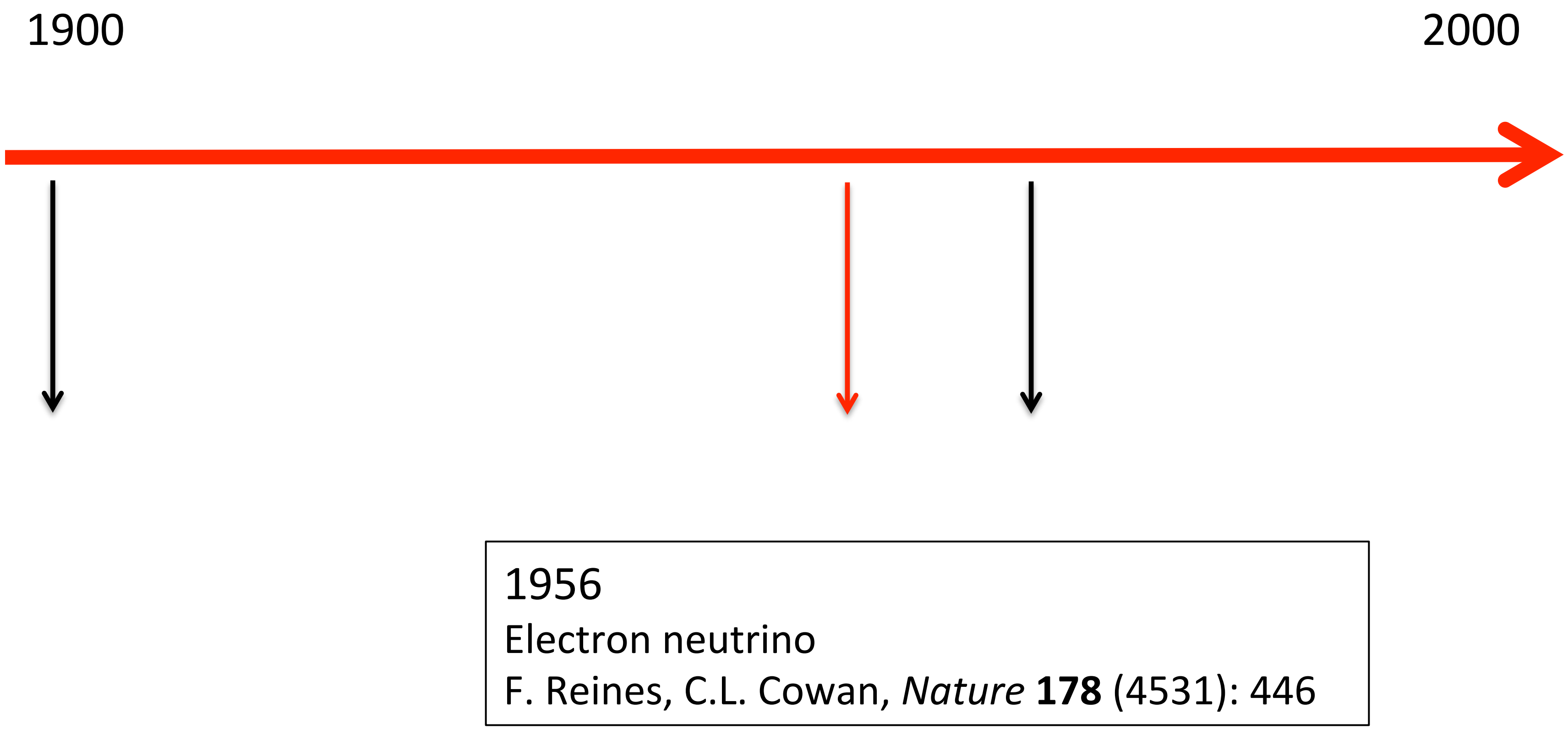


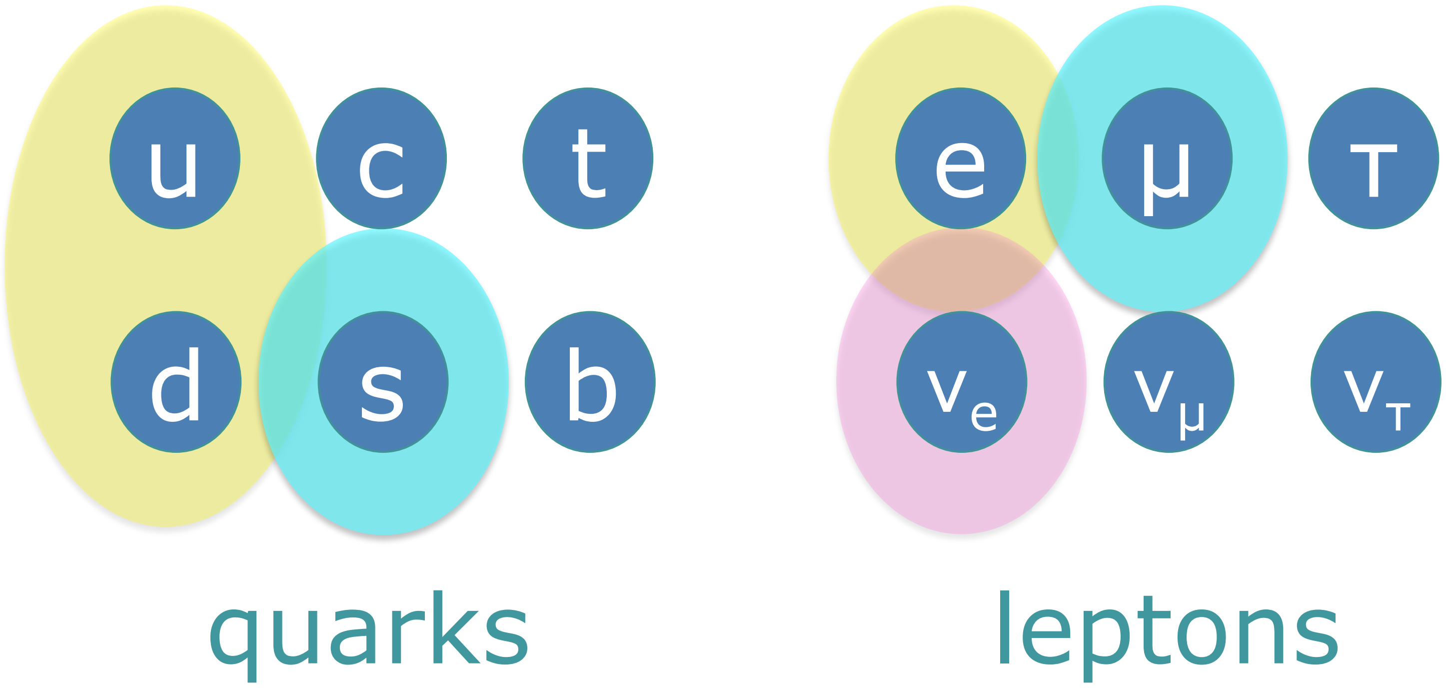
1897
Electron
J.J. Thomson, *Philosophical magazine* **44**:293

1969
up, down, strange quarks
E.D. Bloom *et al. Physical Review Letters* **23** (16): 930
J. M. Breidenbach *et al. Physical Review Letters* **23** (16): 235

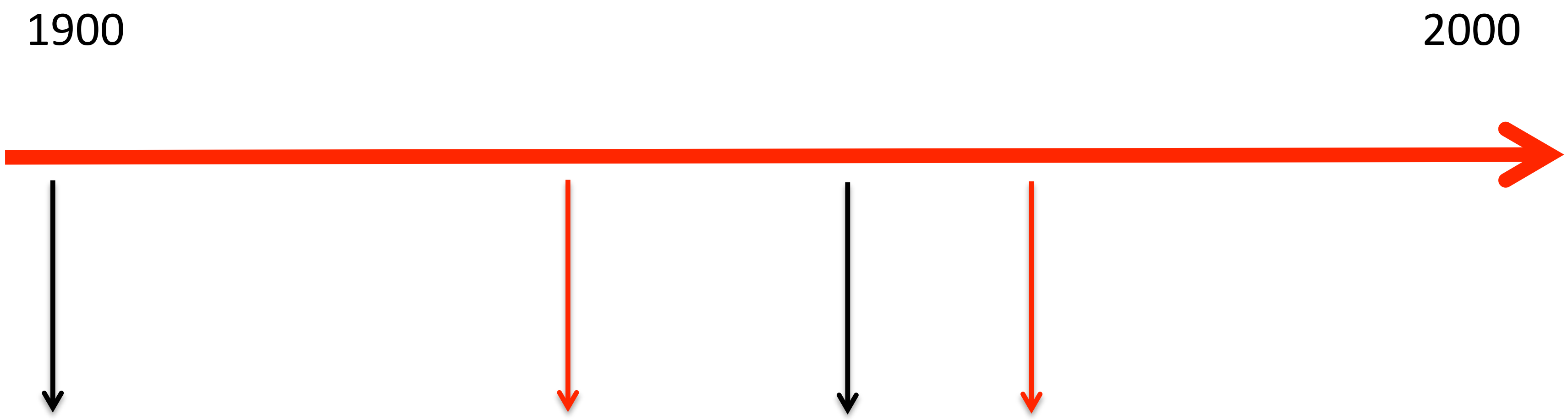


Radioactive decay (inferred 1930s, seen 1956)


1900
2000
1956
Electron neutrino
F. Reines, C.L. Cowan, *Nature* **178** (4531): 446

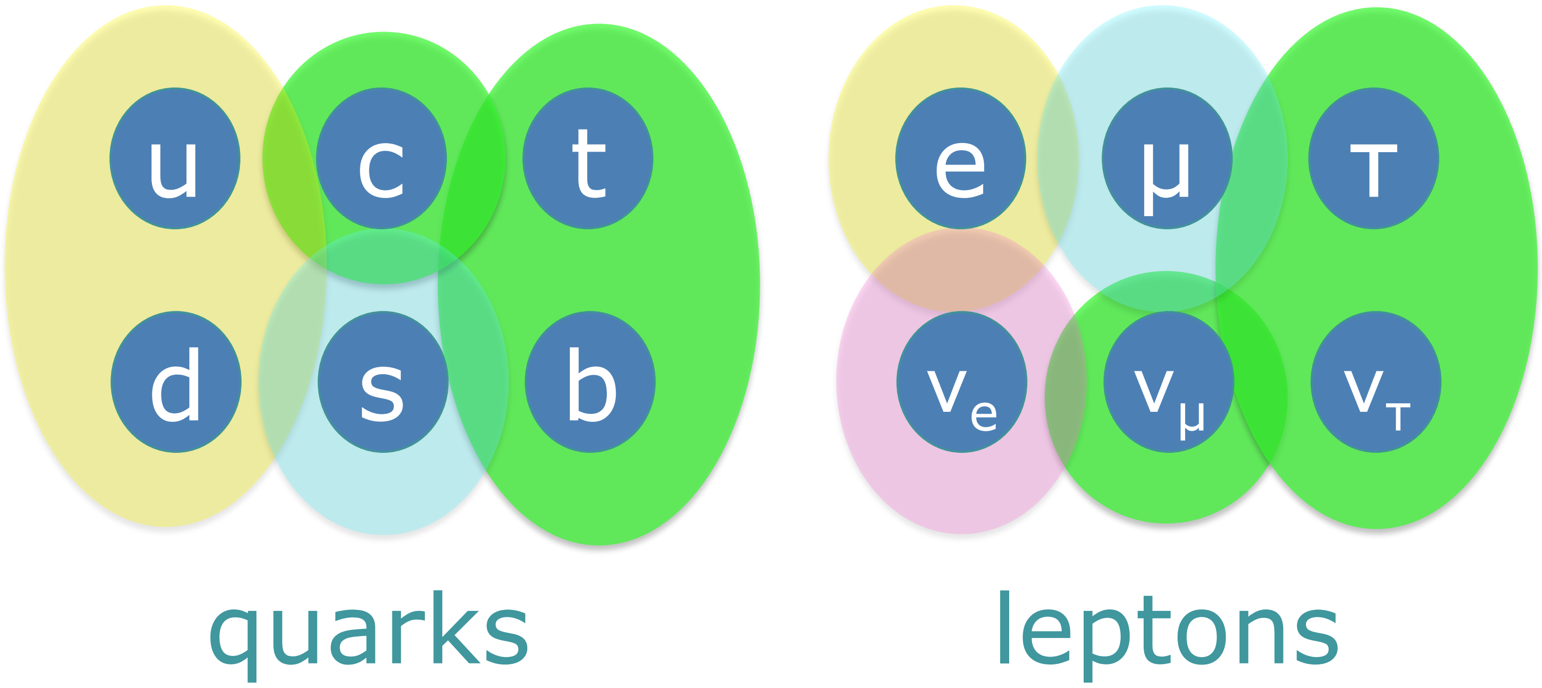


Cosmic ray experiments (1930s, 1940s)

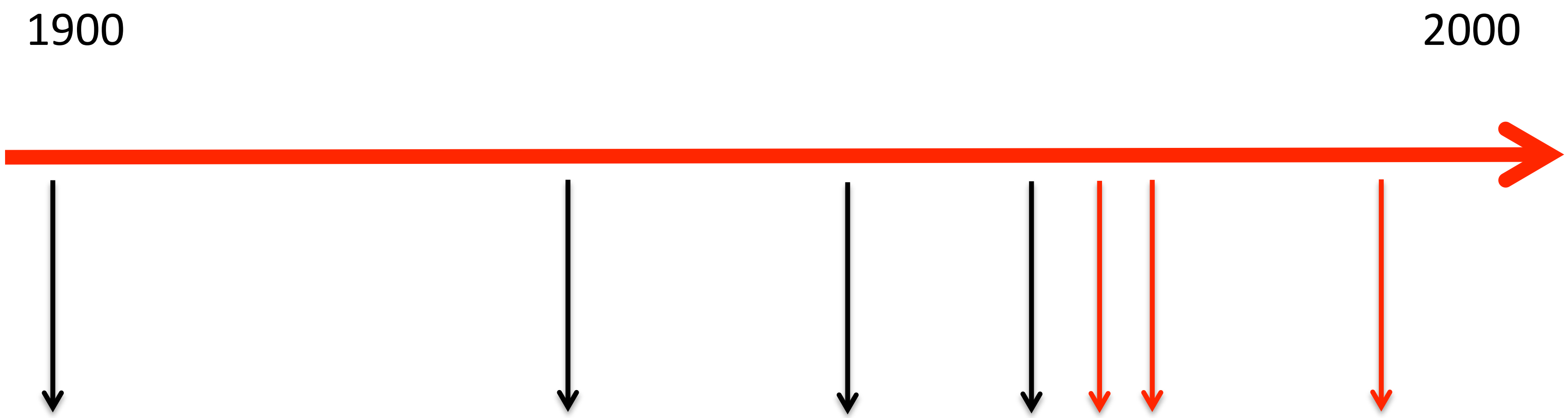


1937
Muon
S.H. Neddermeyer, C.D. Anderson,
Physical Review **51** (10): 884

1969
up, down, strange quarks
E.D. Bloom *et al. Physical Review Letters* **23** (16): 930
J. M. Breidenbach *et al. Physical Review Letters* **23** (16): 235



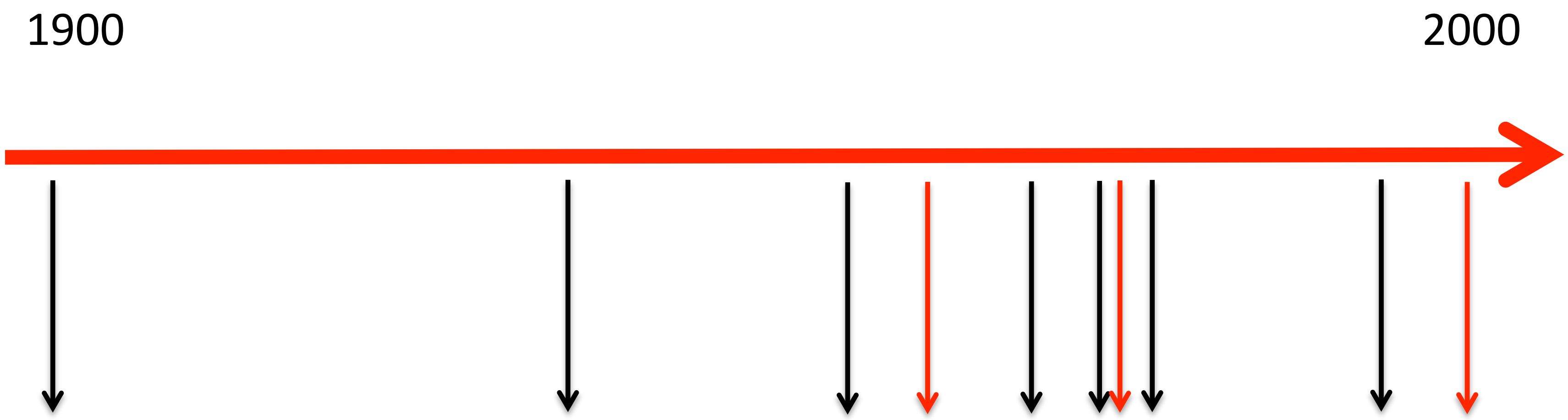
Collider experiments (1960s -)



1974
Charm quarks
J.J. Aubert *et al.* *Physical Review Letters* **33** (23): 1404
J.-E. Augustin *et al.* *Physical Review Letters* **33** (23): 1406

1977
Bottom quarks
S.W. Herb *et al.* *Physical Review Letters* **39** (5): 252.

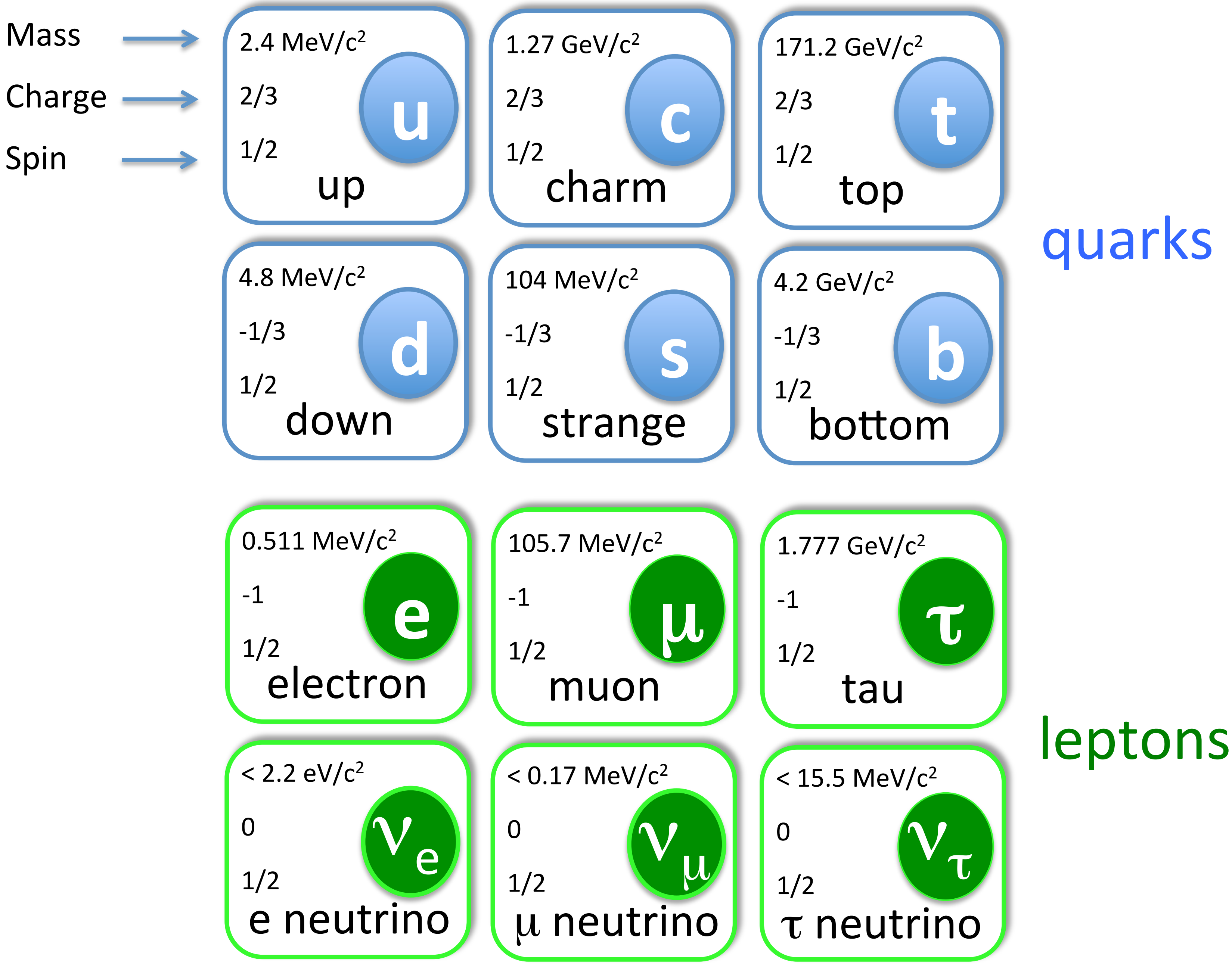
1995
Top quarks
F. Abe *et al.* (CDF collaboration) *Physical Review Letters* **74** (14): 2626–2631.
S. Arabuchi *et al.* (D0 collaboration) *Physical Review Letters* **74** (14): 2632–2637.



1962
Muon neutrino
G. Danby *et al*. *Physical Review Letters* **9** (1):36

1975
Tau lepton
M.L. Perl *et al. Physical Review Letters* **35** (22): 1489.

2000
Tau neutrino
K. Kodama *et al.* (DONUT Collaboration),
Physics Letters B **504** (3): 218.


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
quarks
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
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
leptons
< 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

And … 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.

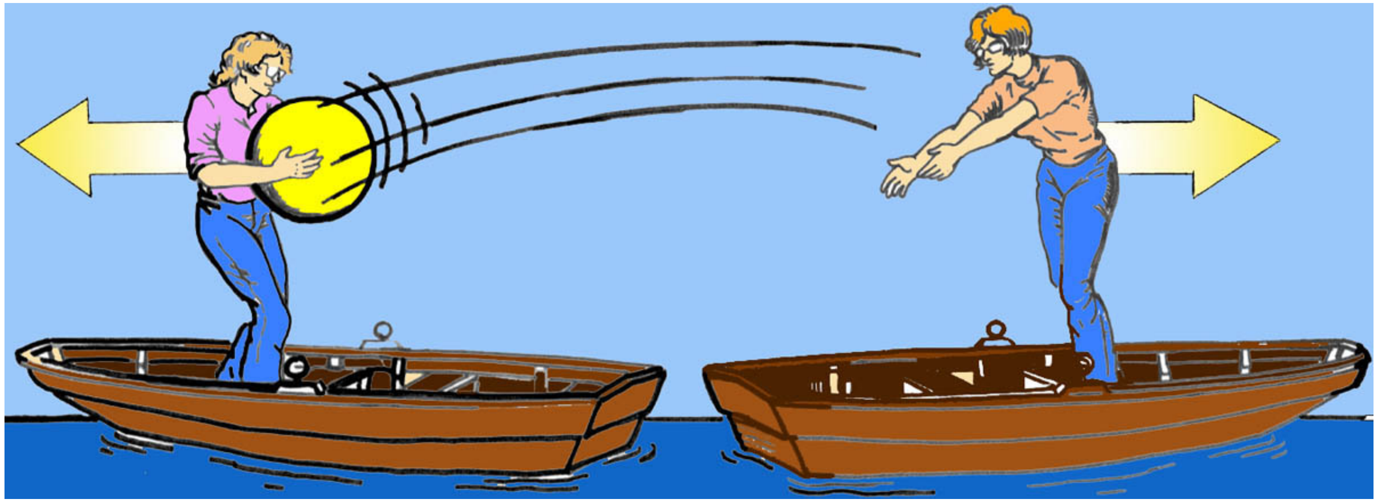
Same mass, opposite charge

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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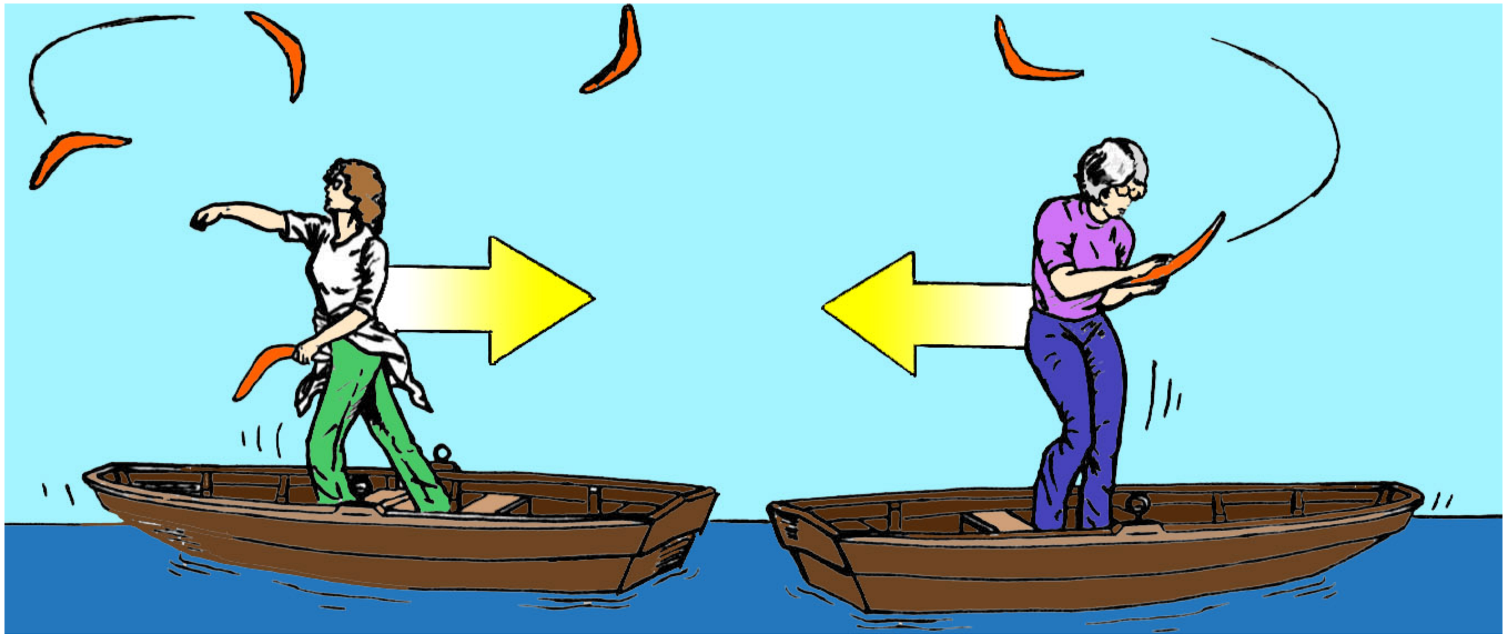
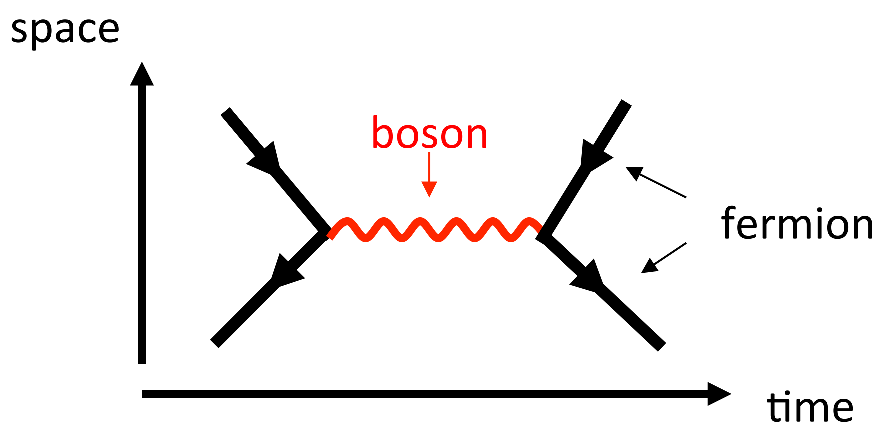


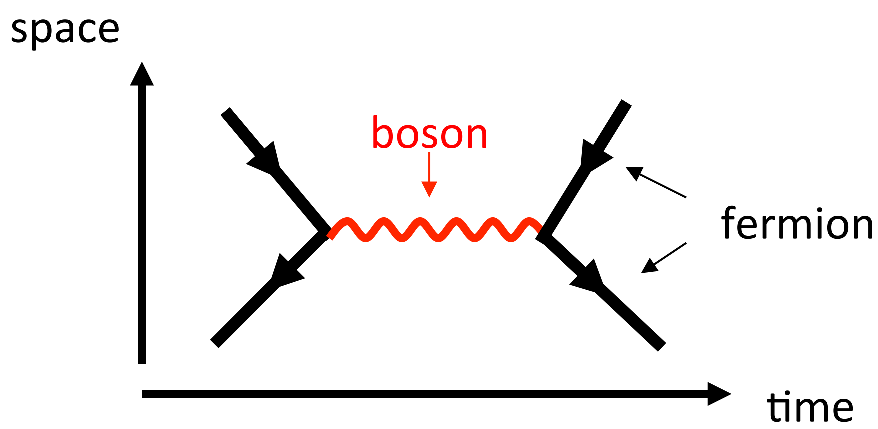
Aside: Feynman diagrams

“tree” level
Lowest order

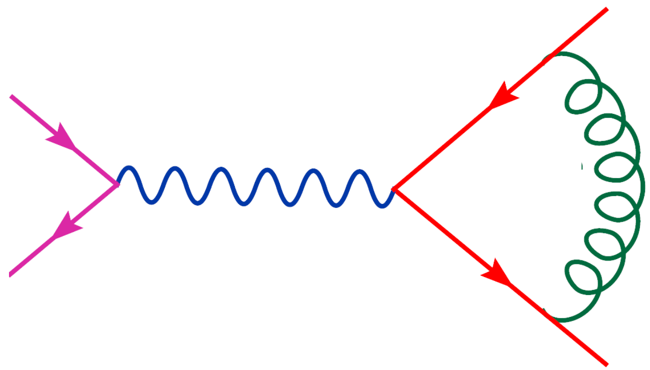


Aside: Feynman diagrams

“tree” level
Lowest order

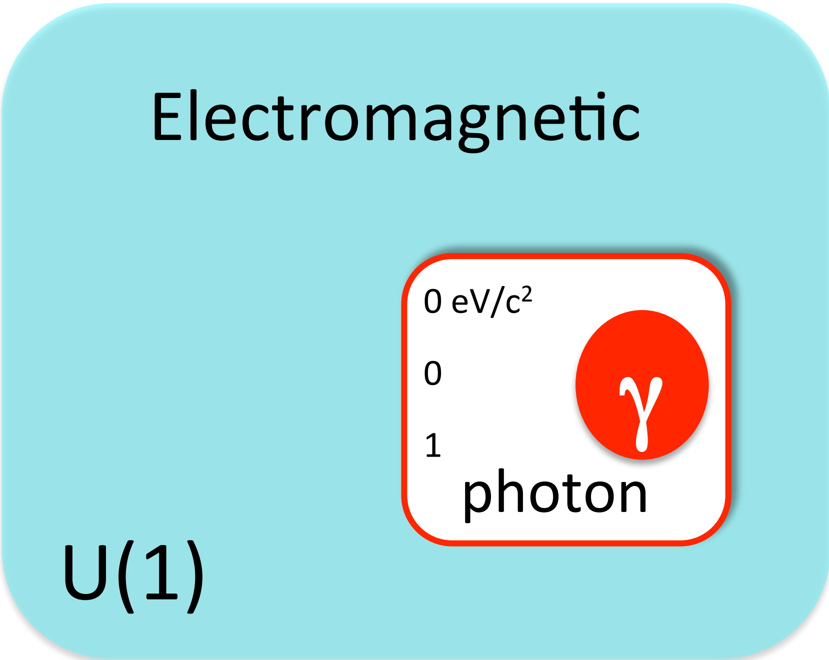


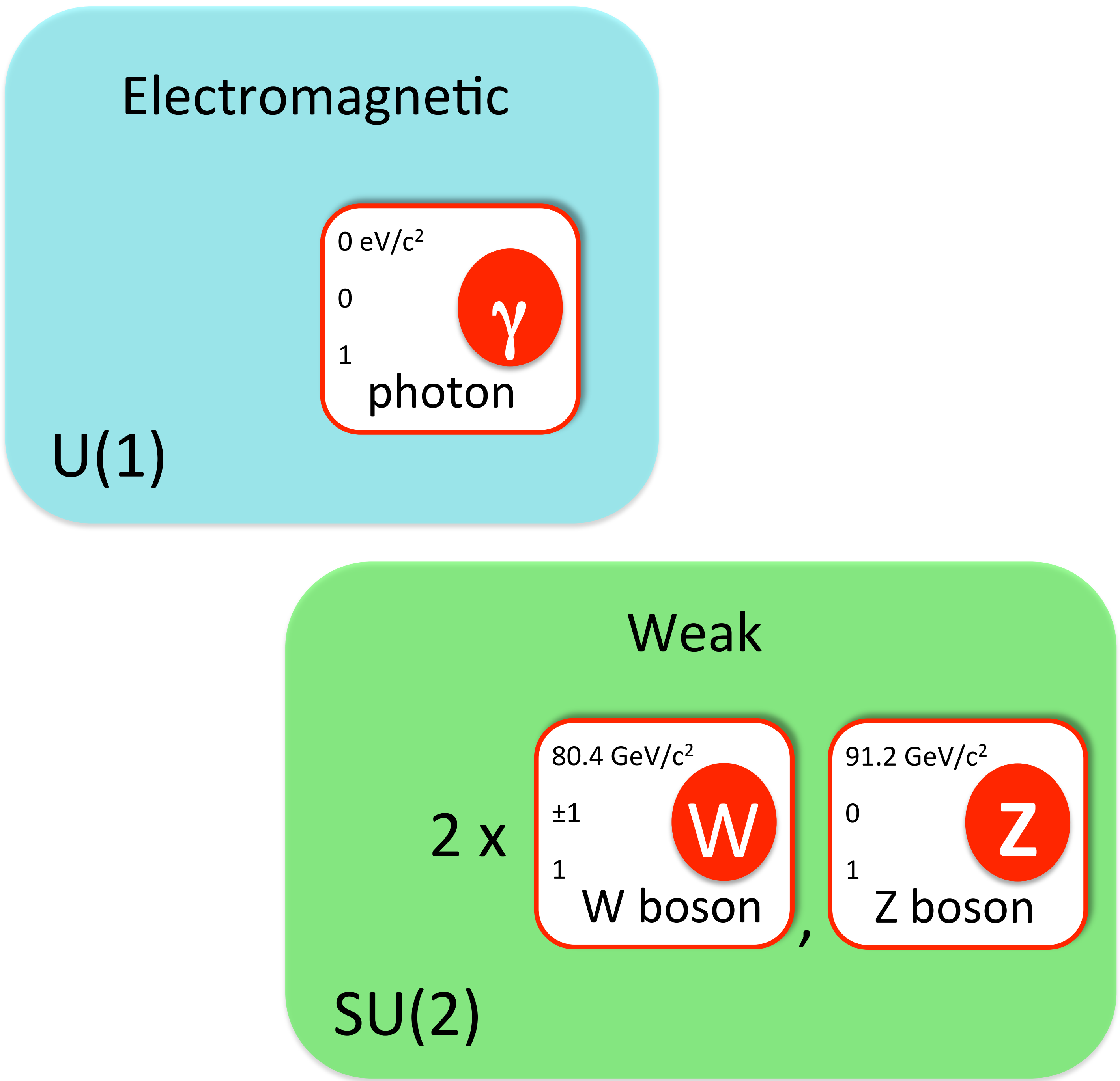
Higher orders possible
Loops



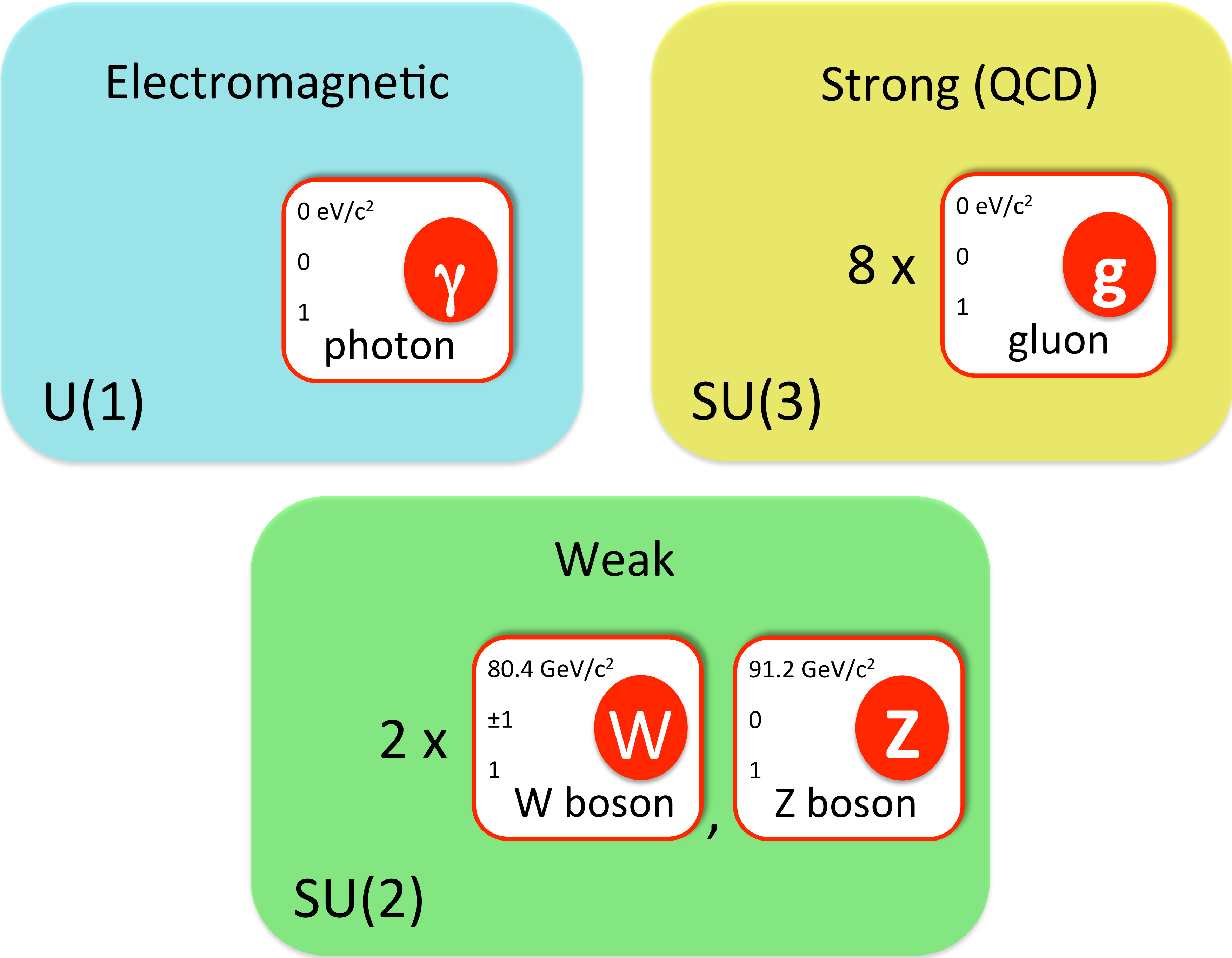
Matter is held together by forces;

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

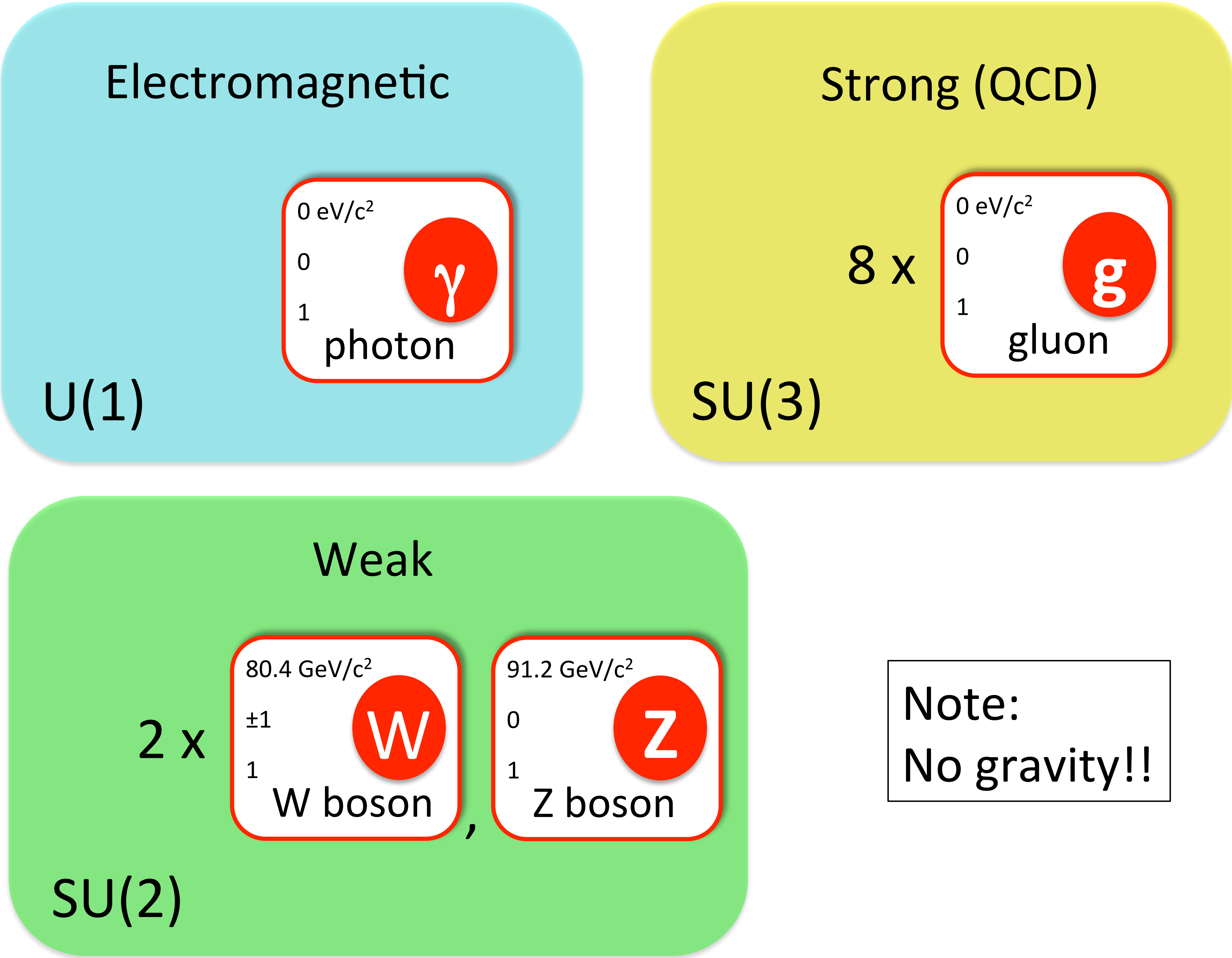

Electromagnetic
0 eV/c²
0
1
γ
photon
U(1)



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)



Note:
No gravity!!

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

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

Value unknown/
not predicted

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Coupling g	Coupling g_W	Coupling g_s

Value unknown/
not predicted

EM force

Abelian

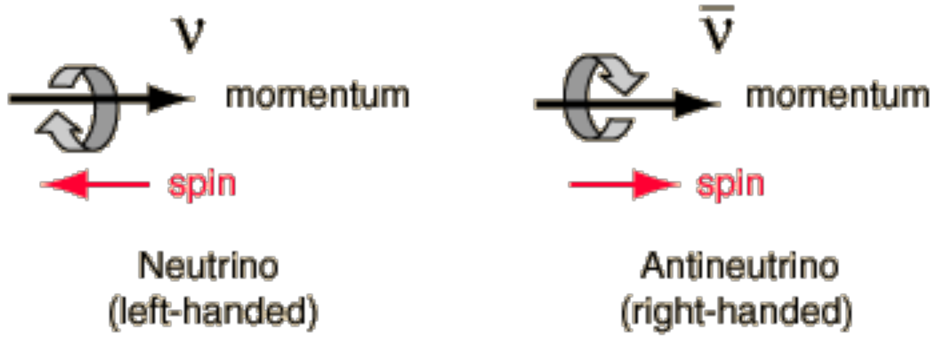
Weak force

Non-abelian

Strong force

Non-abelian

Value unknown/
not predicted



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

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quark mixing (3 generations, CP)

Neutrino mixing (3 generations, CP)

Strong force

Non-abelian

Only quarks couple

Value unknown/ not predicted

Flavour and CPV 14/7/15
Neutrino physics 15/7/15

Where do the differences come from?

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

Value unknown/
not predicted

Massive gauge bosons are a problem

Standard Model equations have a very particular form.

- (local) gauge invariance* imposed
- satisfied if we derive equations treating matter and forces together, and if **bosons are massless**.

Massive gauge bosons require a gauge-invariant fix-up to our theory.

=> Higgs mechanism

* See your Standard Model course.

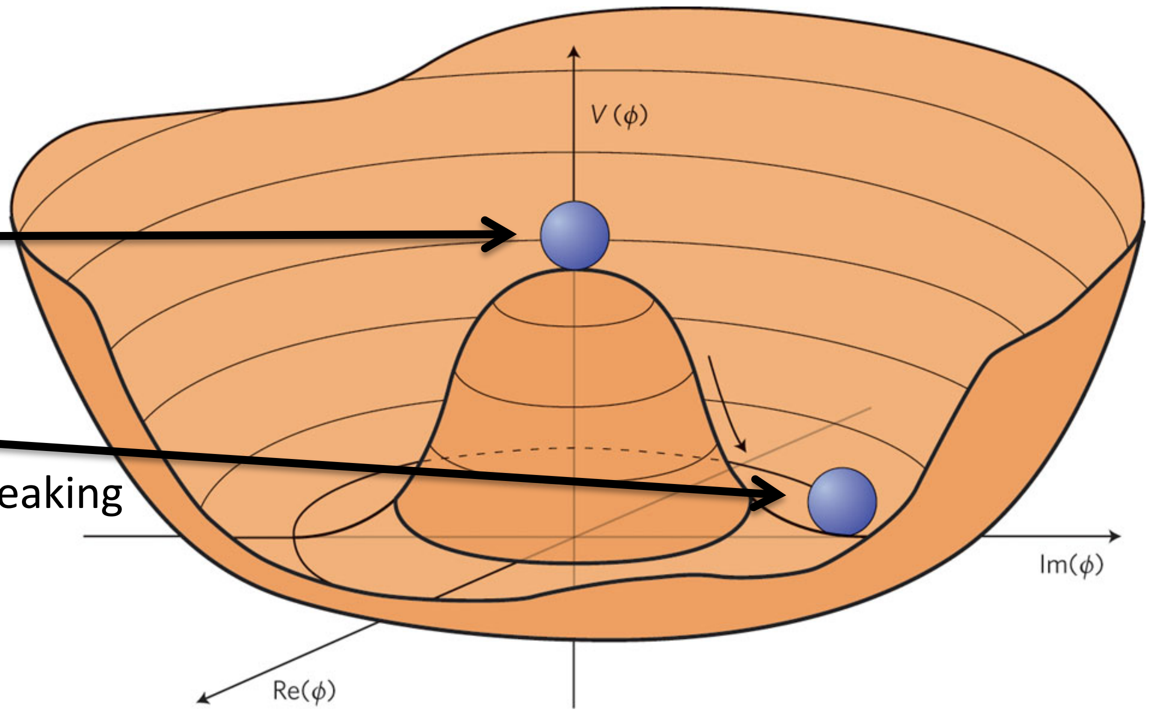
Higgs

Introduce Higgs field:

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

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

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)

[redacted]

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 admixtures 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 :

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 admixtures 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)

Yukawa coupling; yet to be fully tested.

- No deep explanation; motivated by simplicity.

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

Relates Mw, Mz and weak, electromagnetic couplings:

$\tan \theta_W = g_W / g$

$M_W = M_Z \cos \theta_W$

July 4th 2012

126 GeV/c^2

0

0

H

Higgs


The Economist
In praise of charter schools
Britain's banking scandal spreads
Volkswagen overtakes the rest
A power struggle at the Vatican
When Lonesome George met Nora
JULY 7TH–13TH 2012
Economist.com
A giant leap for science
Finding the Higgs boson

~3 years later .. you are here

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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

Force Strengths:

Quantified by "**coupling constants**" $\alpha = \dfrac{g^2}{4\pi}$

Strong: $\alpha_s \sim 1$

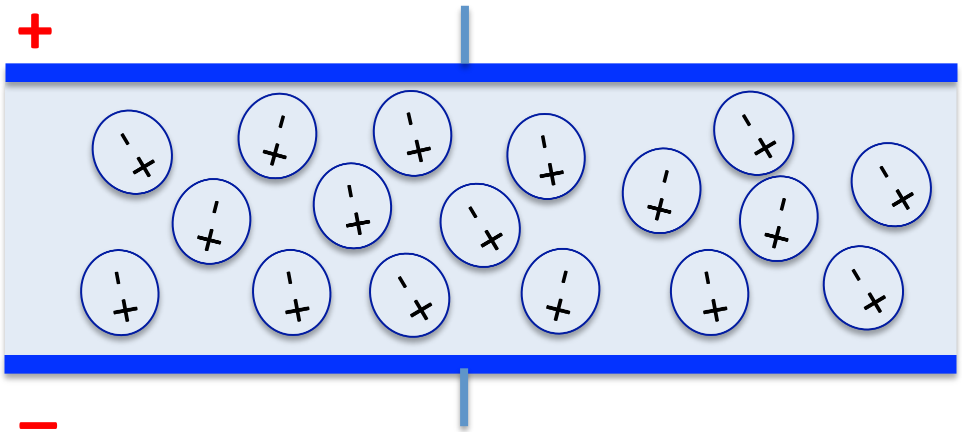
Electromagnetic: $\alpha_{em} \sim 1/137$

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

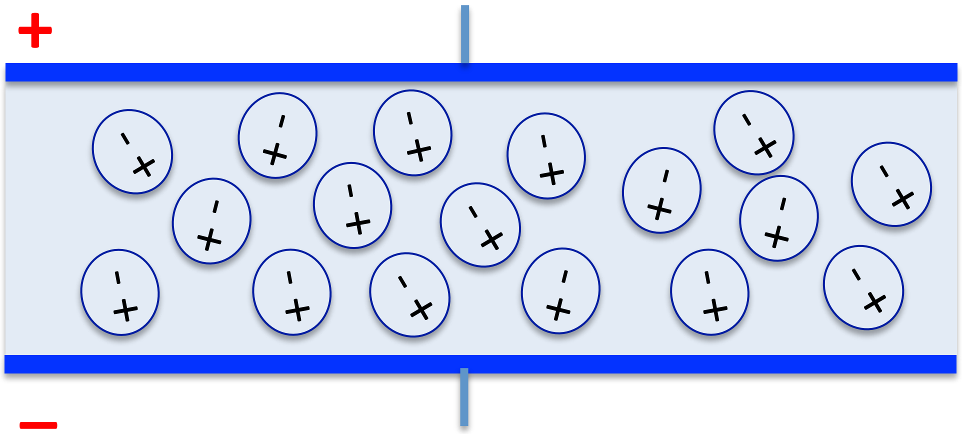
Gravity: $\alpha_g \sim 10^{-40}$

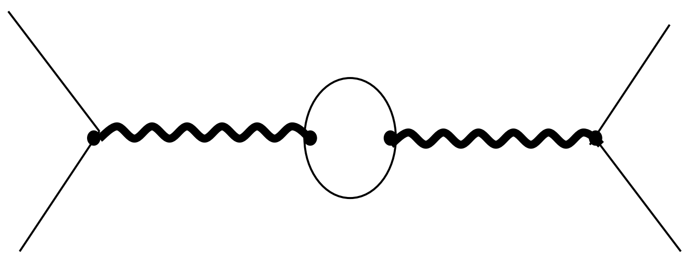
(note: low energy/large distance scale values. Coupling strength changes with energy)

Running couplings



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



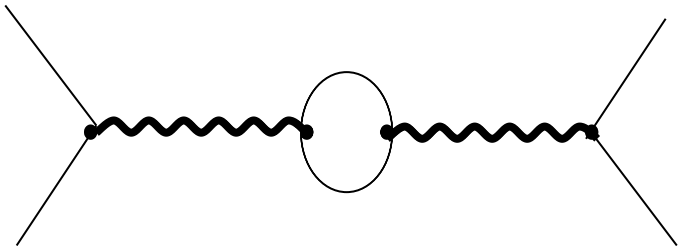


Screening of charge by **vacuum polarisation**;

High E ⇒smaller distances ⇒see more charge

Coupling increases with E

Non-Abelian effects



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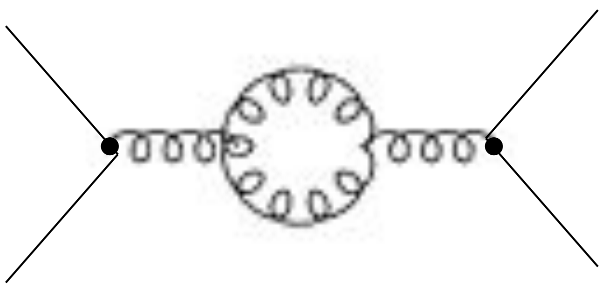


Non-abelian forces also include these “extra” charge loops

Net effect: **coupling decreases with E**

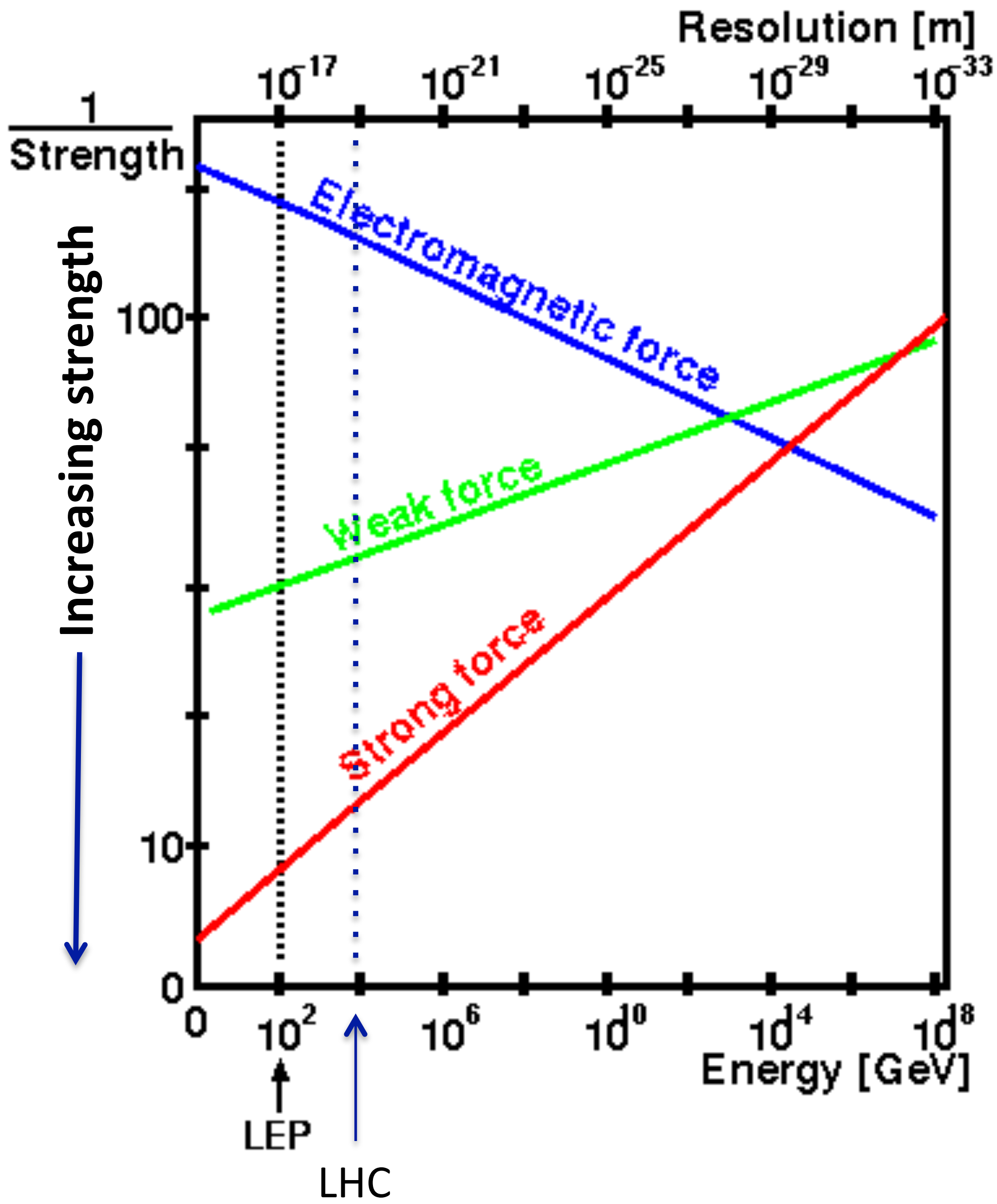
Note:

1/coupling plotted.

1/em falls with E.

1/weak rises with E.

1/strong rises with E.



Implications: QCD

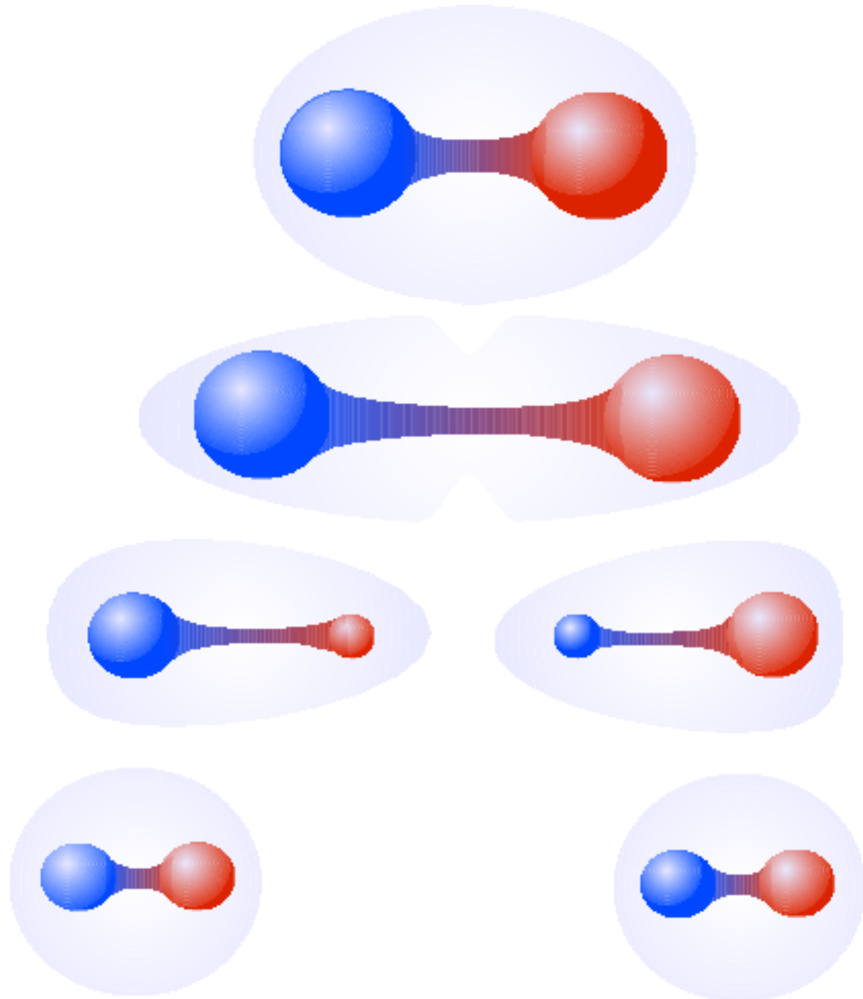
Force grows with distance.

Confinement

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

Hadronisation

- jets



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

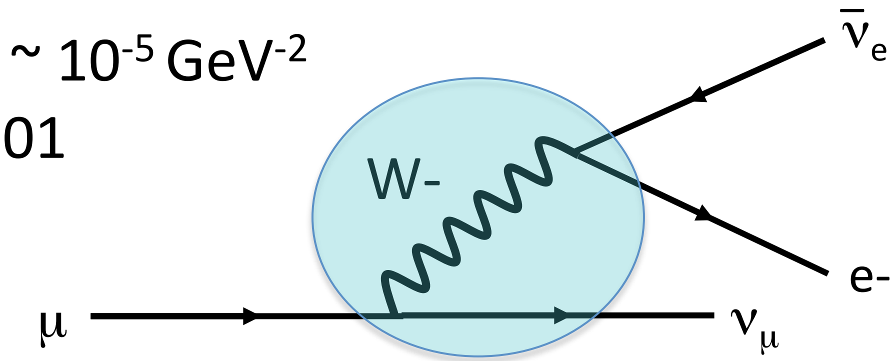
Different forces, but **similar** (mathematical) structure/behaviour

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)

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

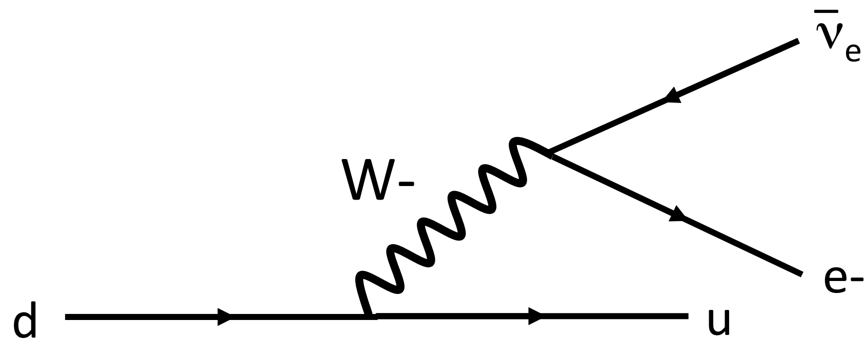
Non-abelian

Only quarks couple

Value unknown/ not predicted

Weak force vs. EM, QCD?

W couples to:
Upper and lower members of a fermion generation.
L- (R-) handed (anti)particles



(observed, not predicted behaviour)

Weak force vs. EM, QCD?

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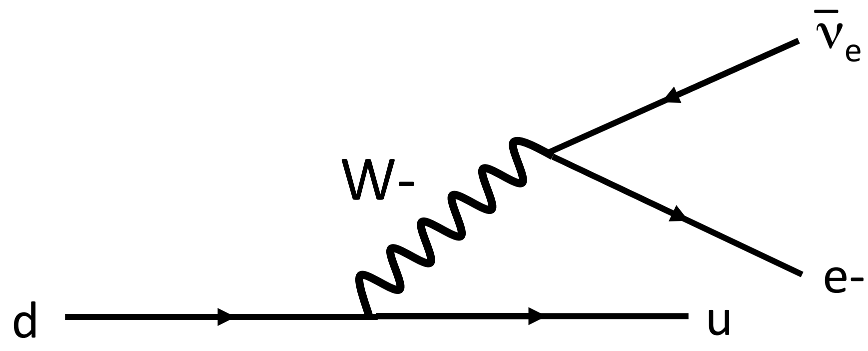
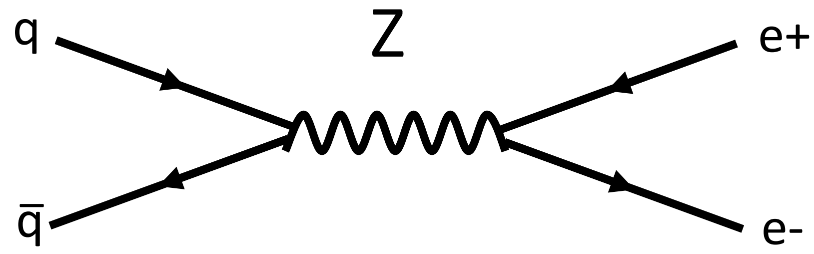


Z couples to:
Matter and antimatter versions of a fermion.
Complicated mix of L-, R- particles.



"vector, axial couplings"; Higgs mechanism.

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Neutrino mixing (3 generations, CP)

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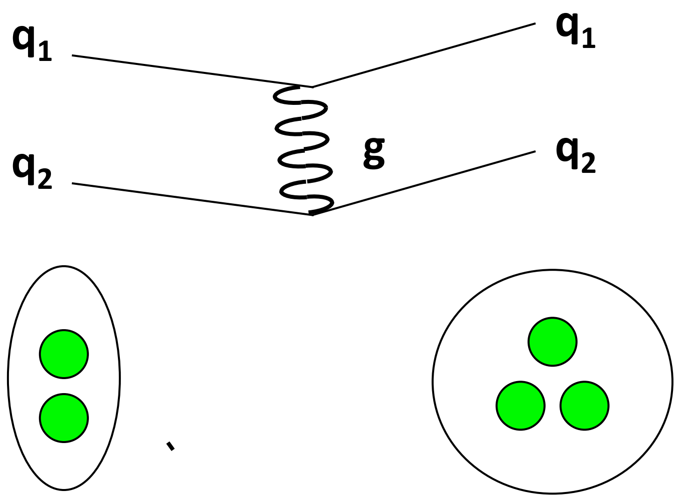
Flavour and CPV 29/7/14
Neutrino physics 21/7/14

Weak vs. mass quark eigenstates

Mass eigenstates of quarks form hadrons



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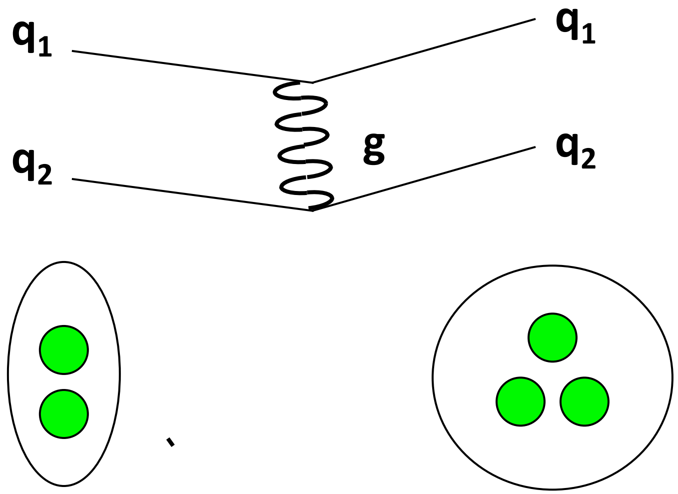
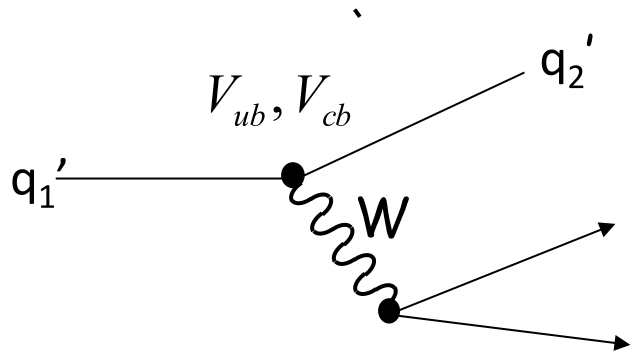


W couples to weak quark
eigenstates q'

q' admixture of q and vice versa



Quark mixing

$$\begin{pmatrix} d_W \\ s_W \\ b_W \end{pmatrix} = \begin{pmatrix} & & \\ & & \\ & & \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Weak, mass eigenstates related by mixing matrix in SM (CKM matrix)

Mixing matrix is unitary (inverse = complex conjugate)

CKM matrix

CKM matrix (1973 – before charm! Predicted 3rd generation)

Elements describe every weak quark transition

SM does not predict existence of or values for matrix elements (couplings of W to quarks).

Input by experimental data

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CP violation

C = charge operator
P = parity operator

CP operation changes particle q to antiparticle $\bar{q}$ (and vice versa)
CP **violation** if q→$\bar{q}$' rate different to $\bar{q}$'→q ie. $V_{qq'} \neq V_{qq'}^{*}$

CP violation observed in weak decays.

Note:

- **SM does not predict** CP violation.
- **SM does not explain** CP violation.
- CP violation **must be added** to SM.

CP violation

- Need 3 generations of quarks to introduce CP violation into theory

$$\begin{pmatrix} d_W \\ s_W \\ b_W \end{pmatrix} = \begin{pmatrix} \quad & \quad & \quad \\ \quad & \quad & \quad \\ \quad & \quad & \quad \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Mixing matrix is 3x3.

Unitarity constraints $\Rightarrow$ 4 independent parameters

3 angles quantify mixing between (1,3) (2,3) (1,2) generations, **1 complex phase** (mechanism for introducing CP)

Aside: neutrino CP violation, mixing

- Similar framework adopted for neutrinos (MNS matrix). Weak (ν_e, ν_μ, ν_τ) related to mass eigenstates (ν_1 etc):

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} & & \\ & & \\ & & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3 angles quantify mixing between (1,3) (2,3) (1,2) generations, **1 complex phase** (mechanism for introducing CP)

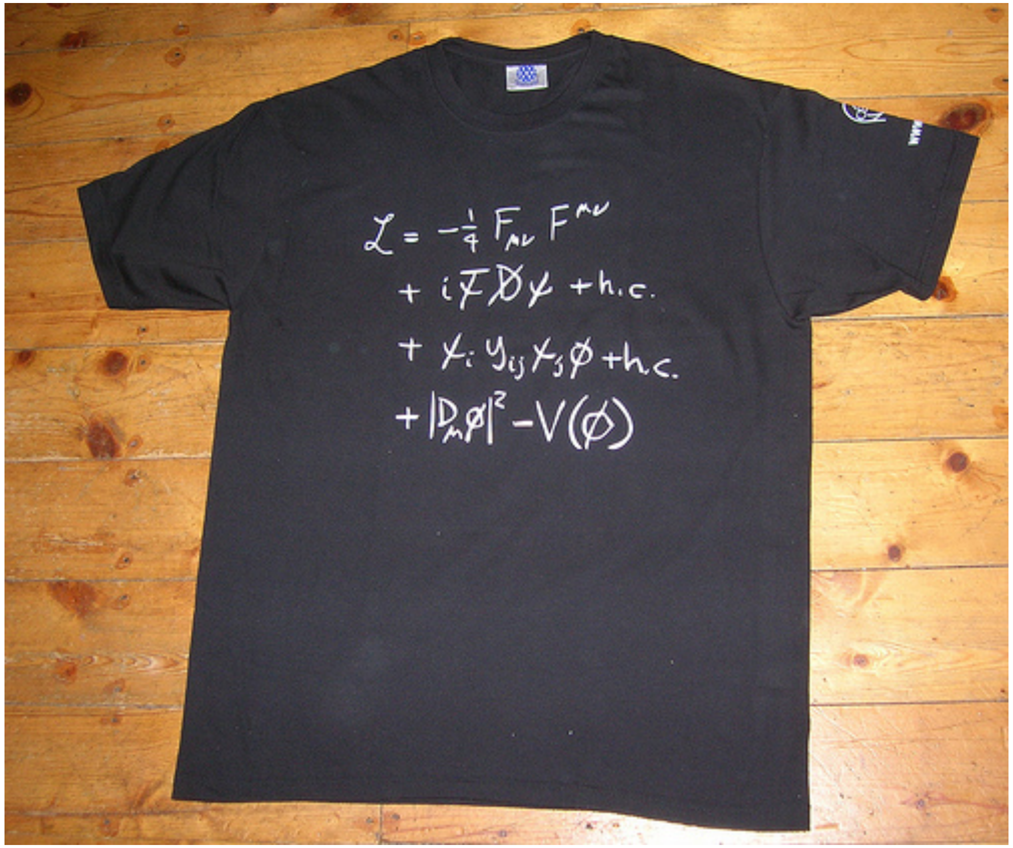
Note: parameters investigated in dedicated neutrino experiments

Standard Model

Standard Model (SM)

Quantum field theory based on lagrangians

We use the SM to predict experimental observations



Standard Model 2/7/15
HEP theory concepts 1/7/15
SM physics LHC 20/7/15

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

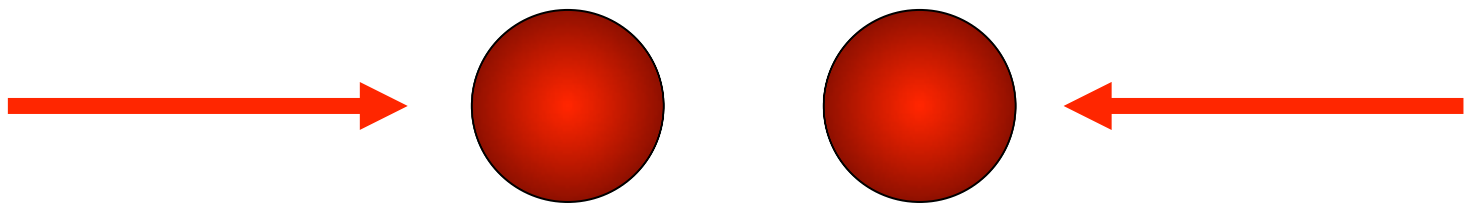
Need to find a breakdown to move forward.

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 2/7/15, 5/8/15
Medical physics 28/7/15

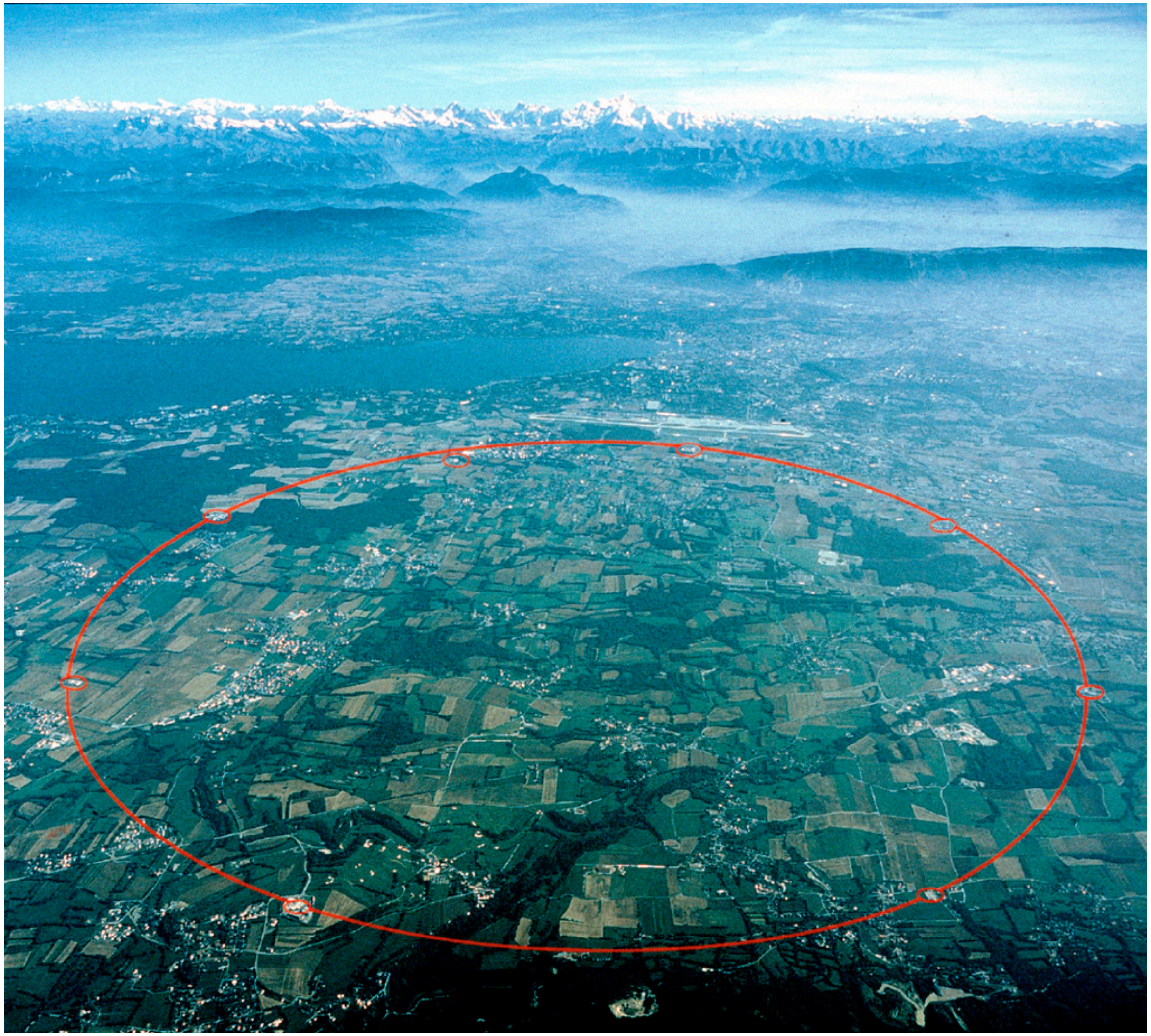
LHC:

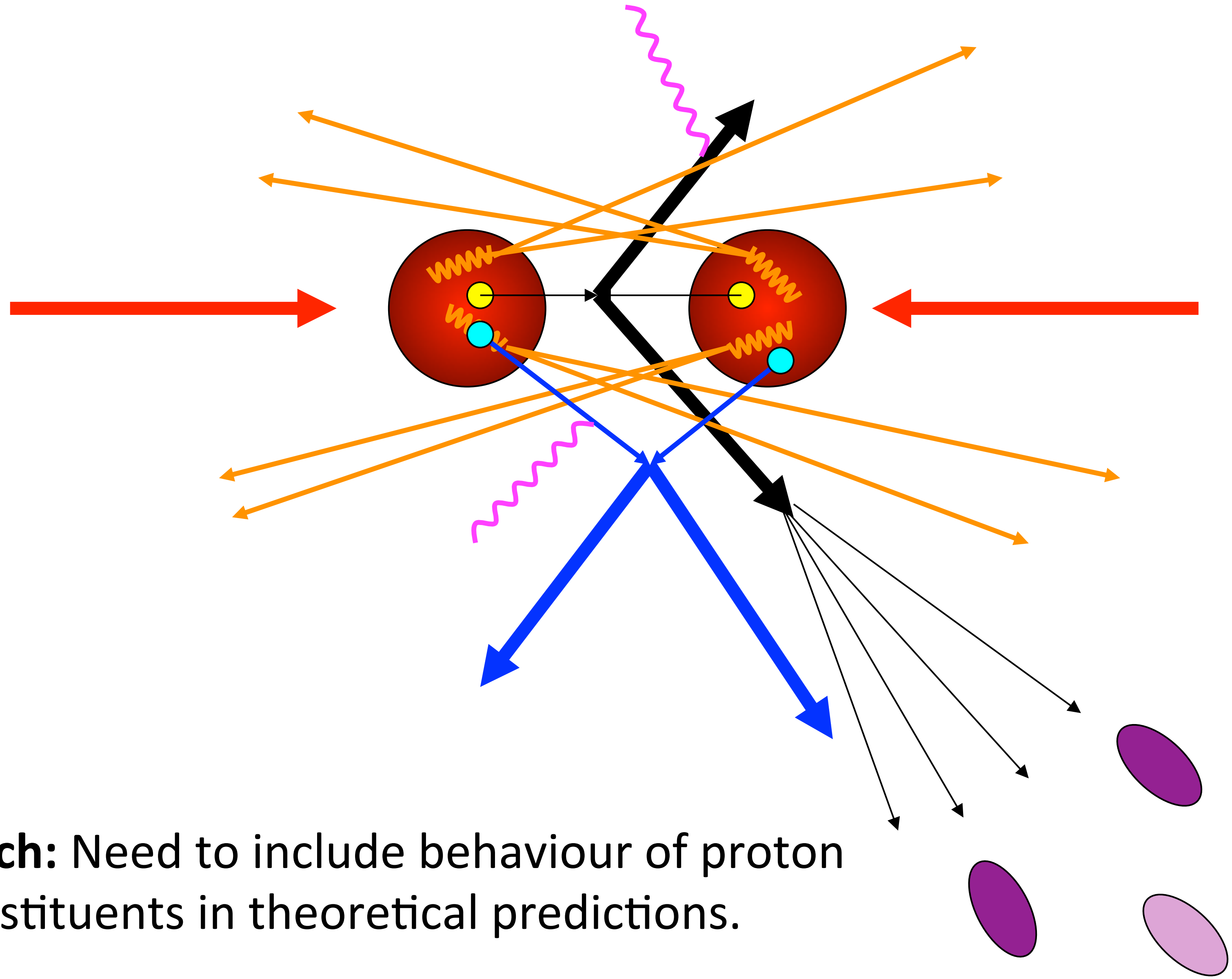
High energy ($\sqrt{s}$=14 TeV)

Circular

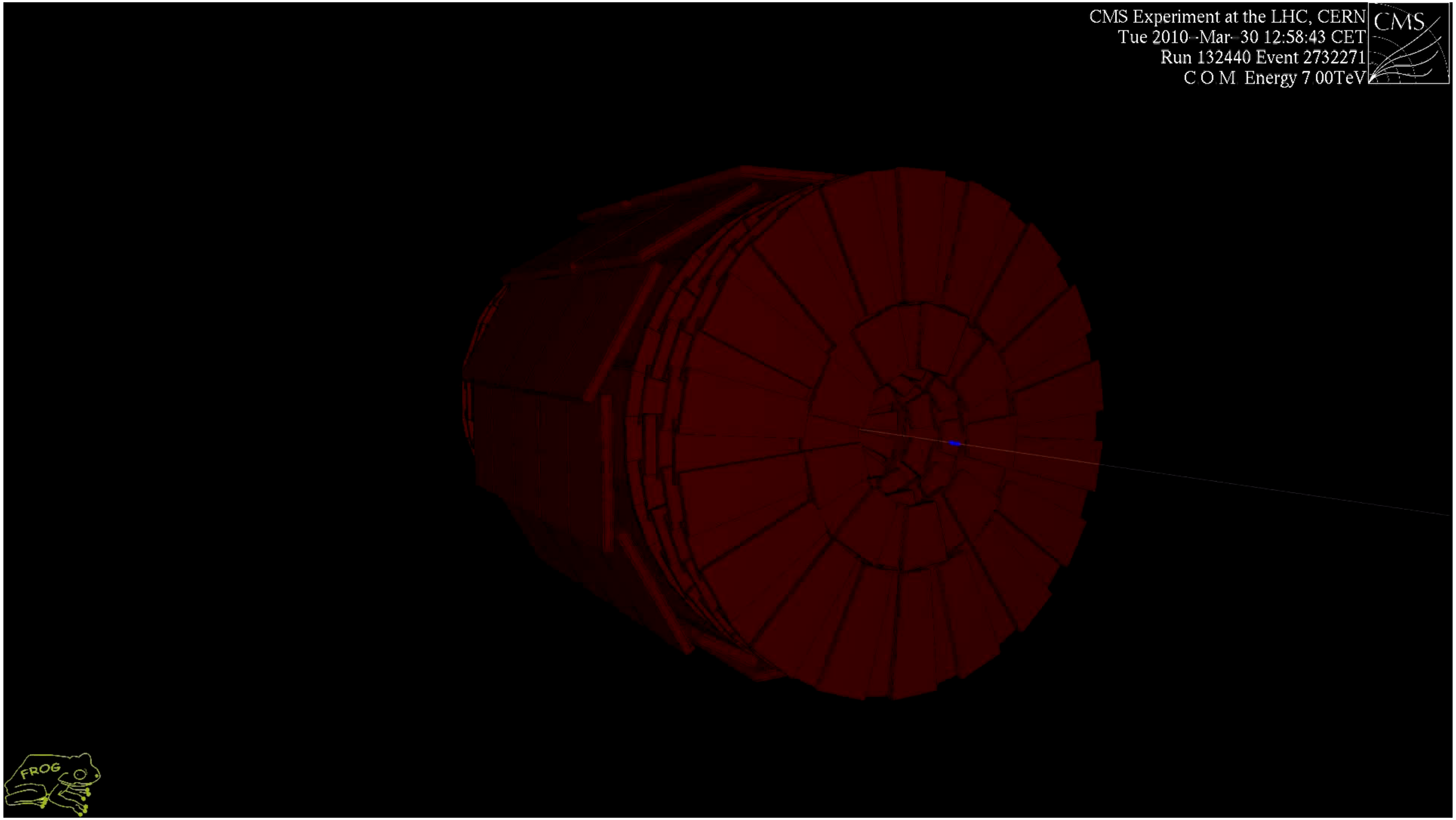
Proton beams

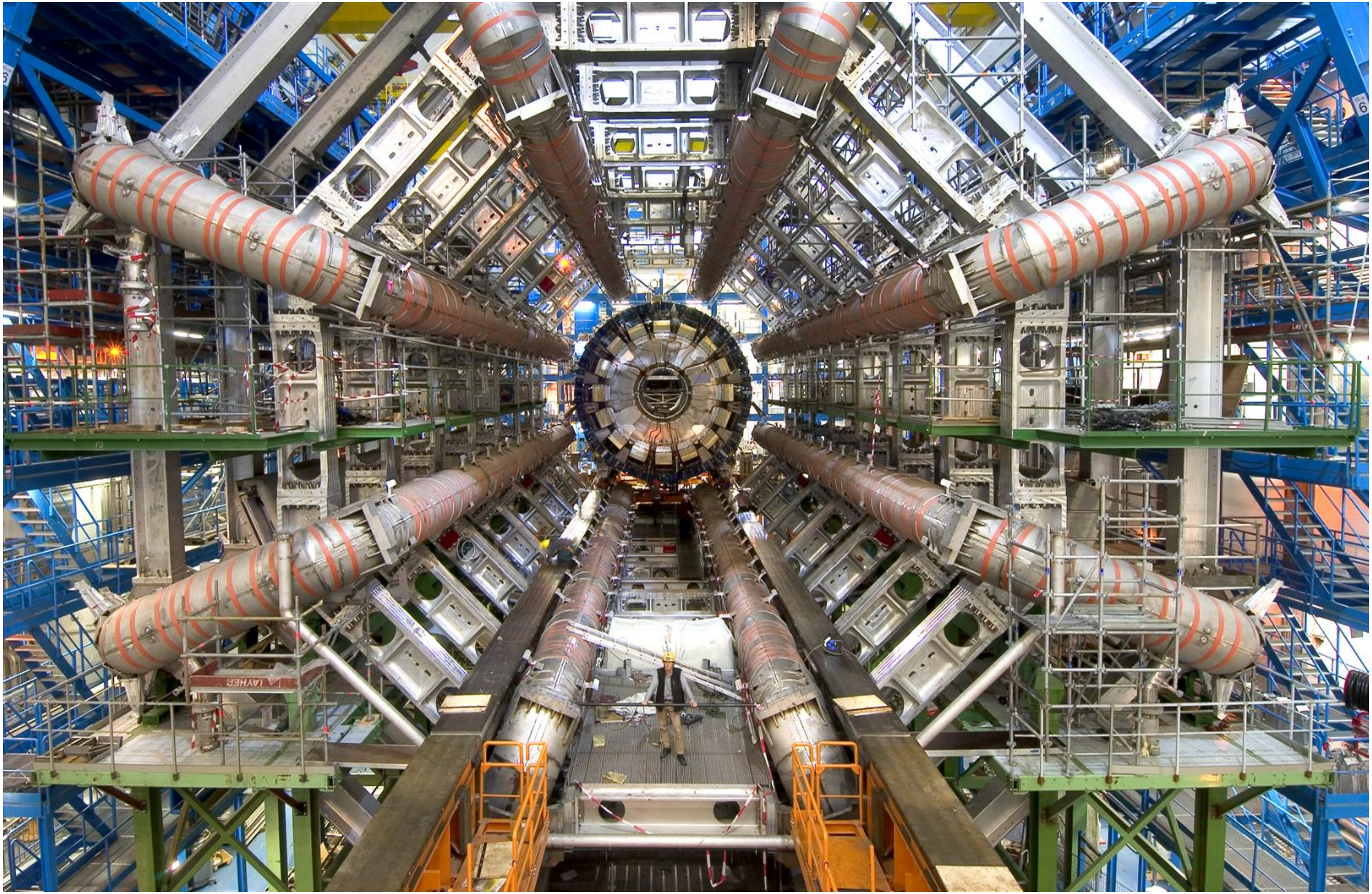
Up to 10^8 collisions/s

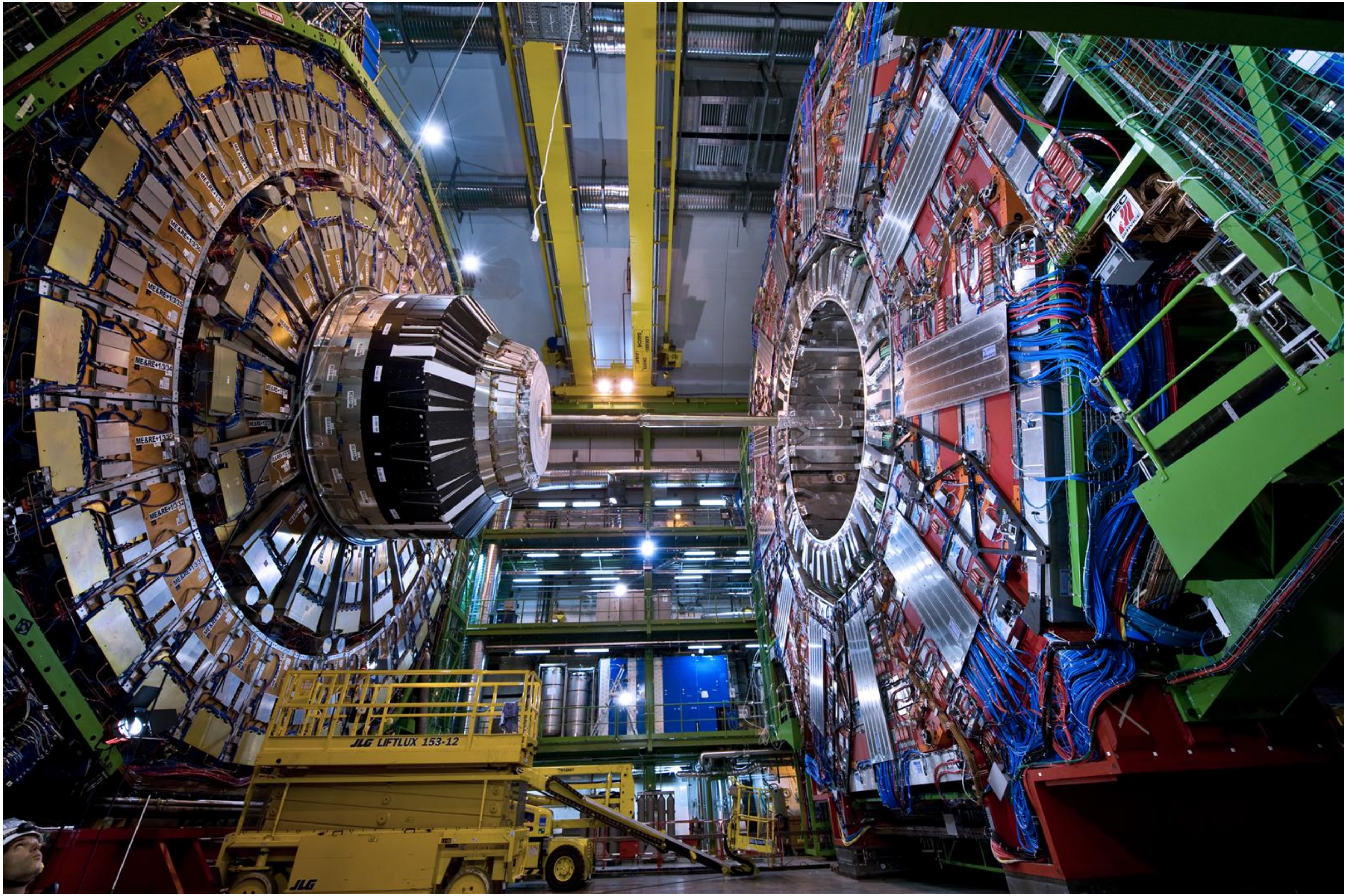




Catch: Need to include behaviour of proton constituents in theoretical predictions.


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




JLG LIFTLUX 153-12
JLG

(and ALICE, LHCb, Moedal, LHCf, TOTEM….)

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

↑

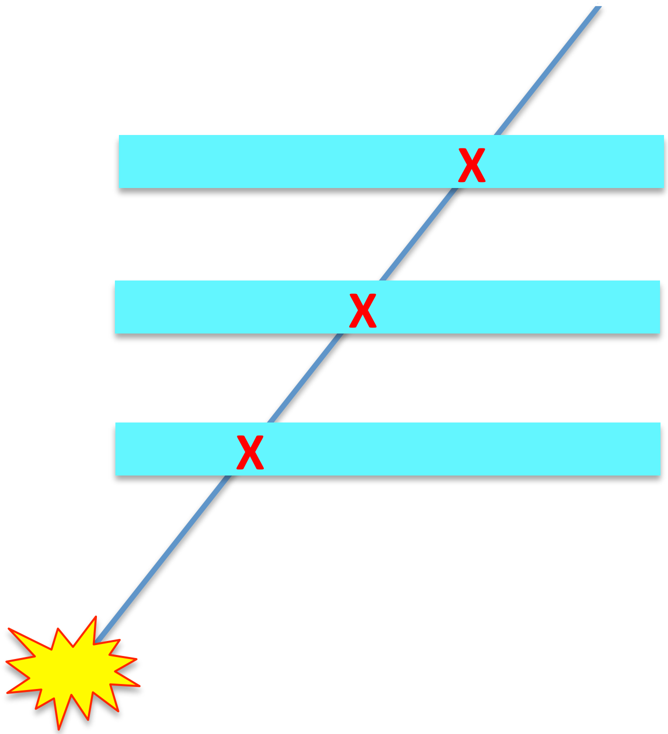
(x,y,z)

Reconstruct path

Reconstruct momentum

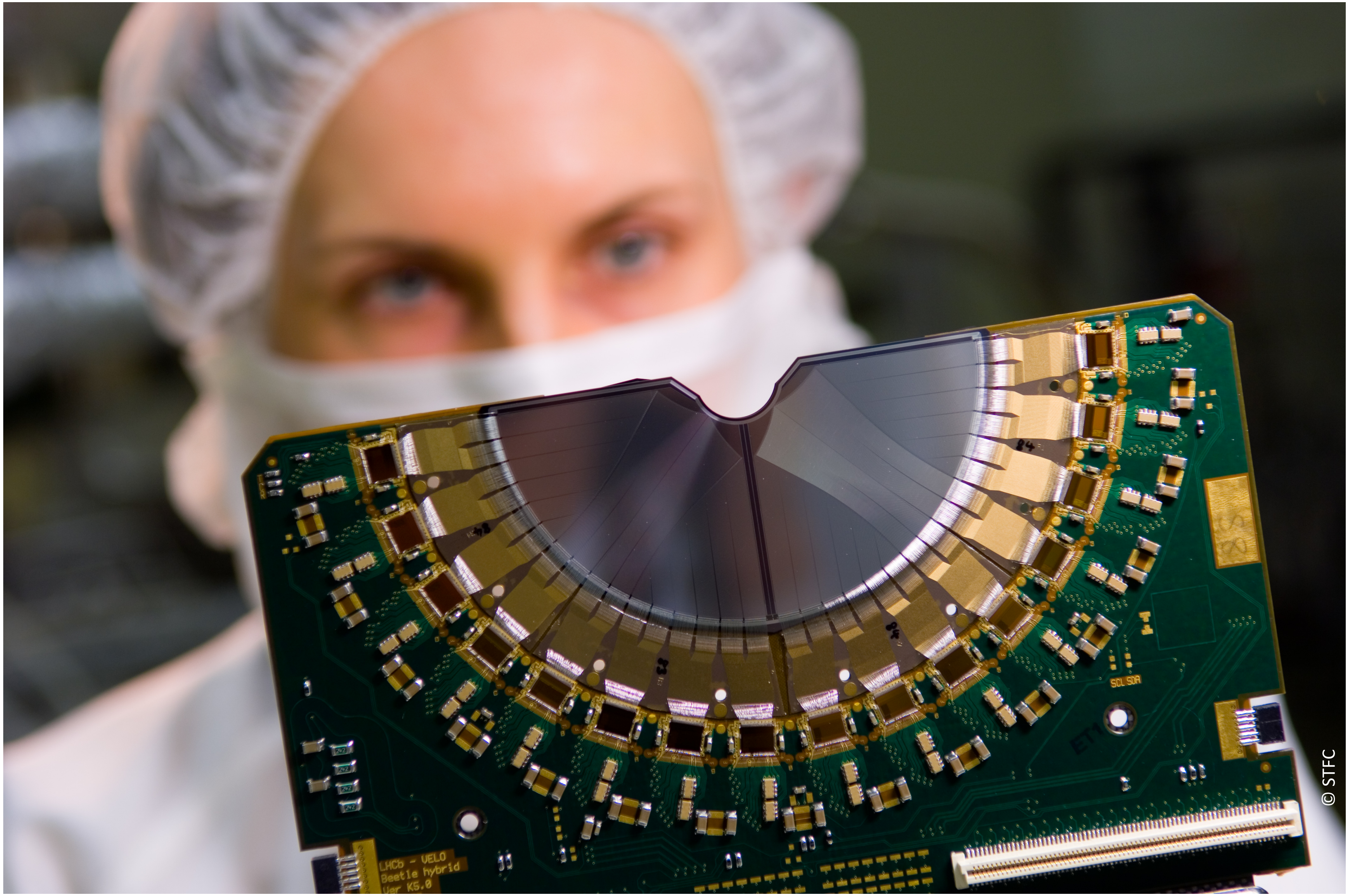
Measure energy

Identify type



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

Detectors 9/7/15
Electronics/TDAQ 13/7/15


LHCb - VELO
Beetle hybrid
Ver K5.0

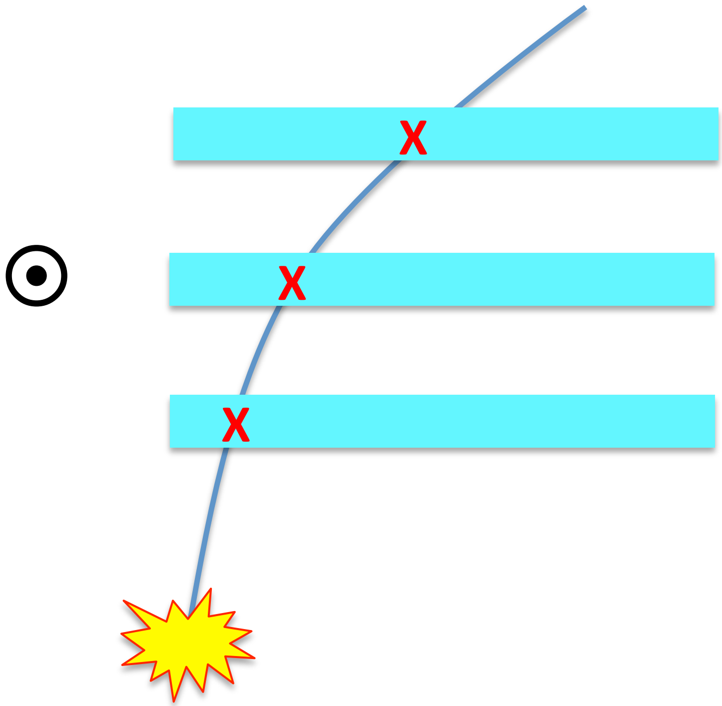
(**px,py,pz**,m)

Reconstruct path

Reconstruct momentum

Measure energy

Identify type



Magnetic field

Relate track curvature, B to p.

$$p = 0.3Br$$

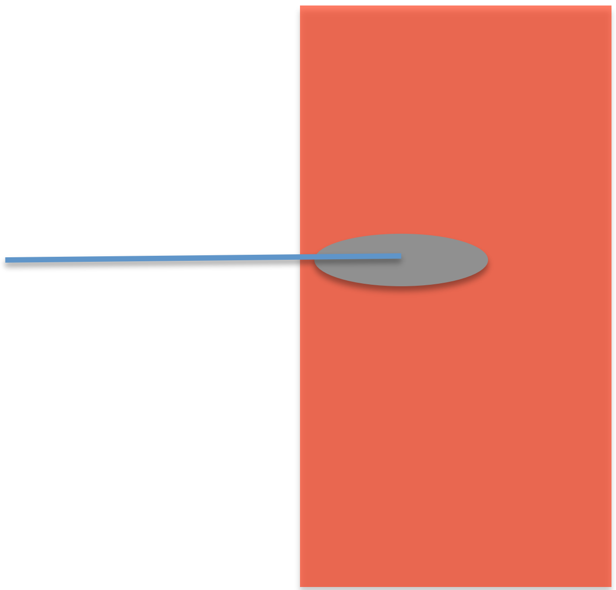
(px,py,pz,**m**)

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

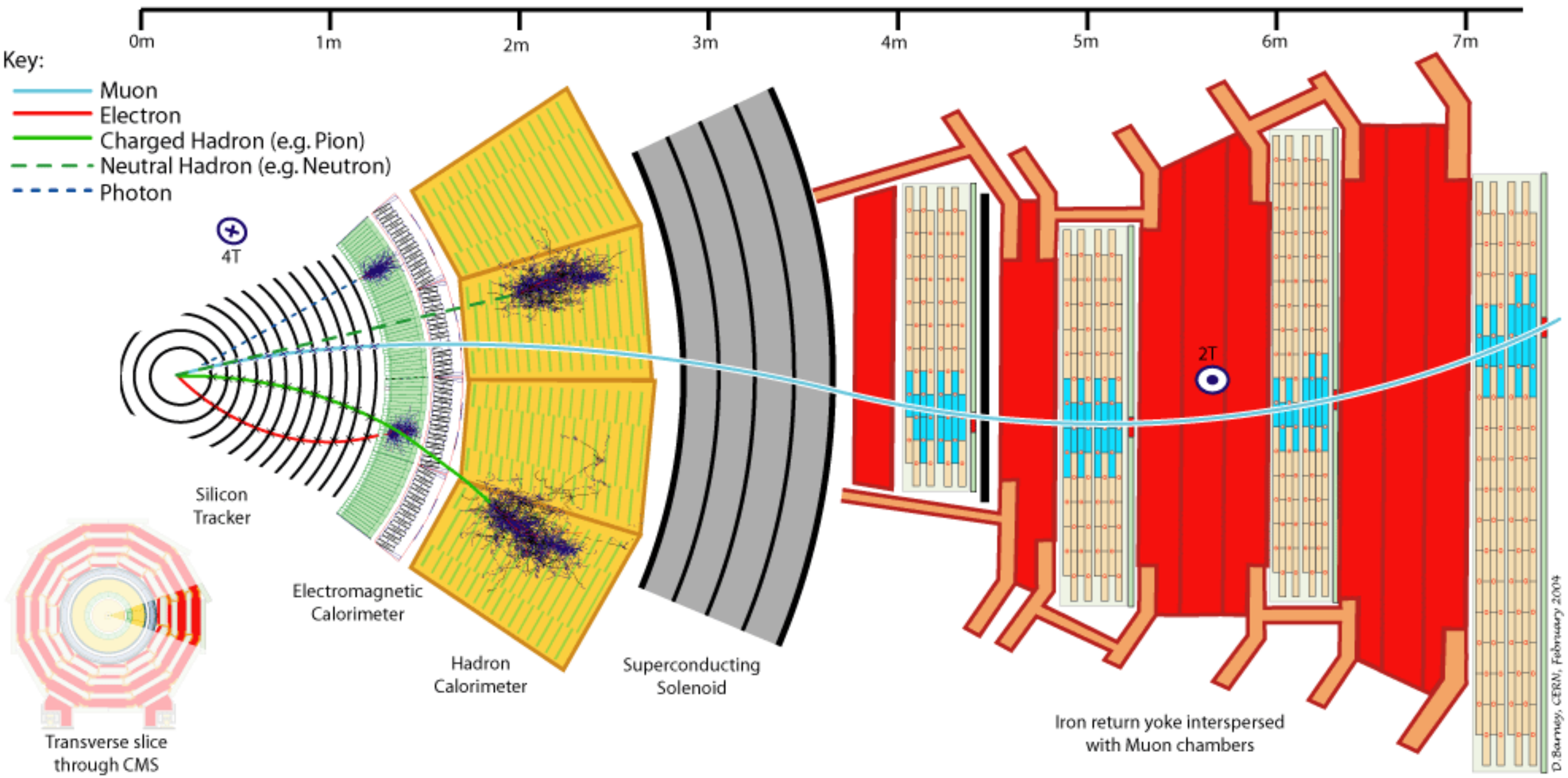
Cerenkov detectors (**v**)

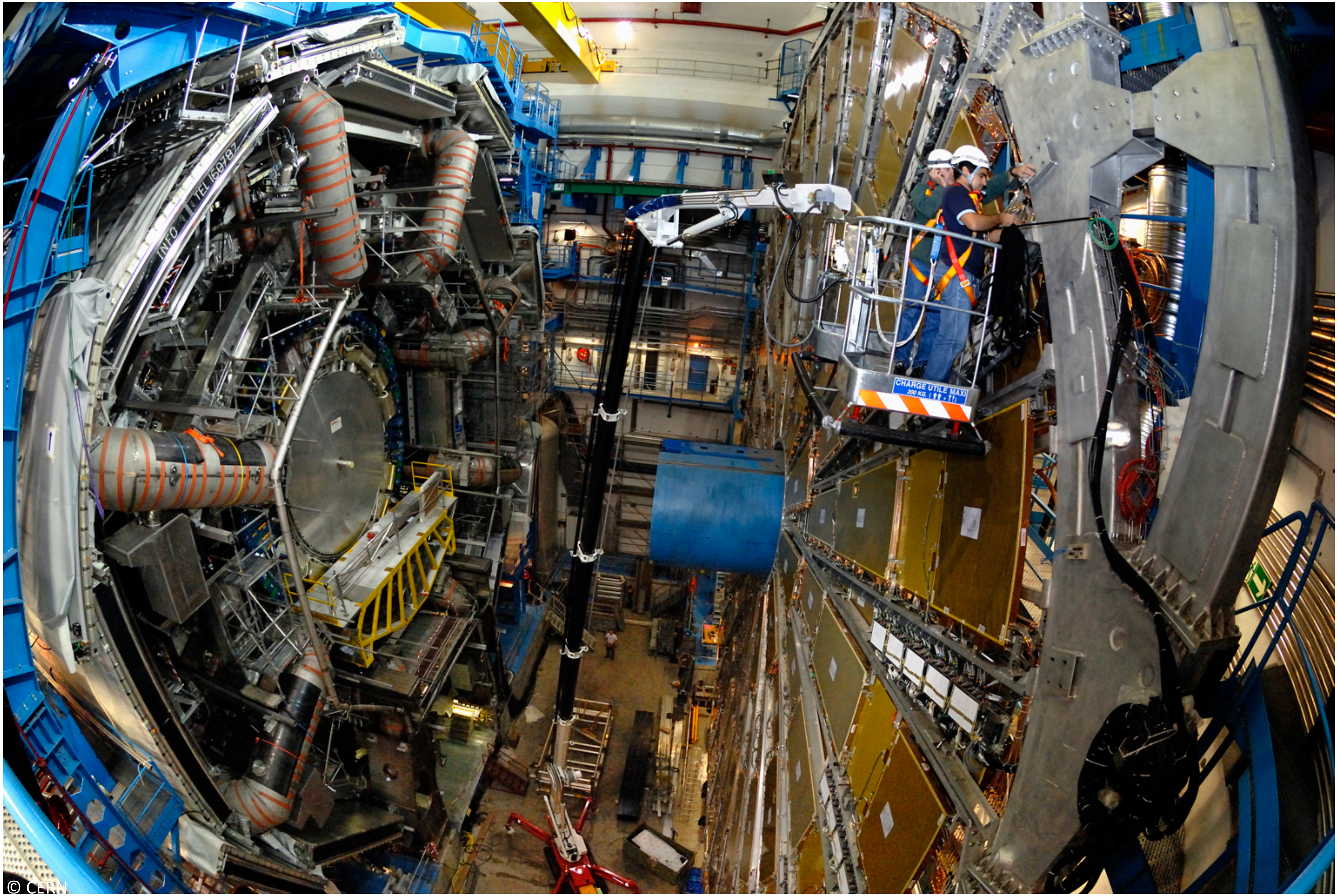
Add momentum -> m

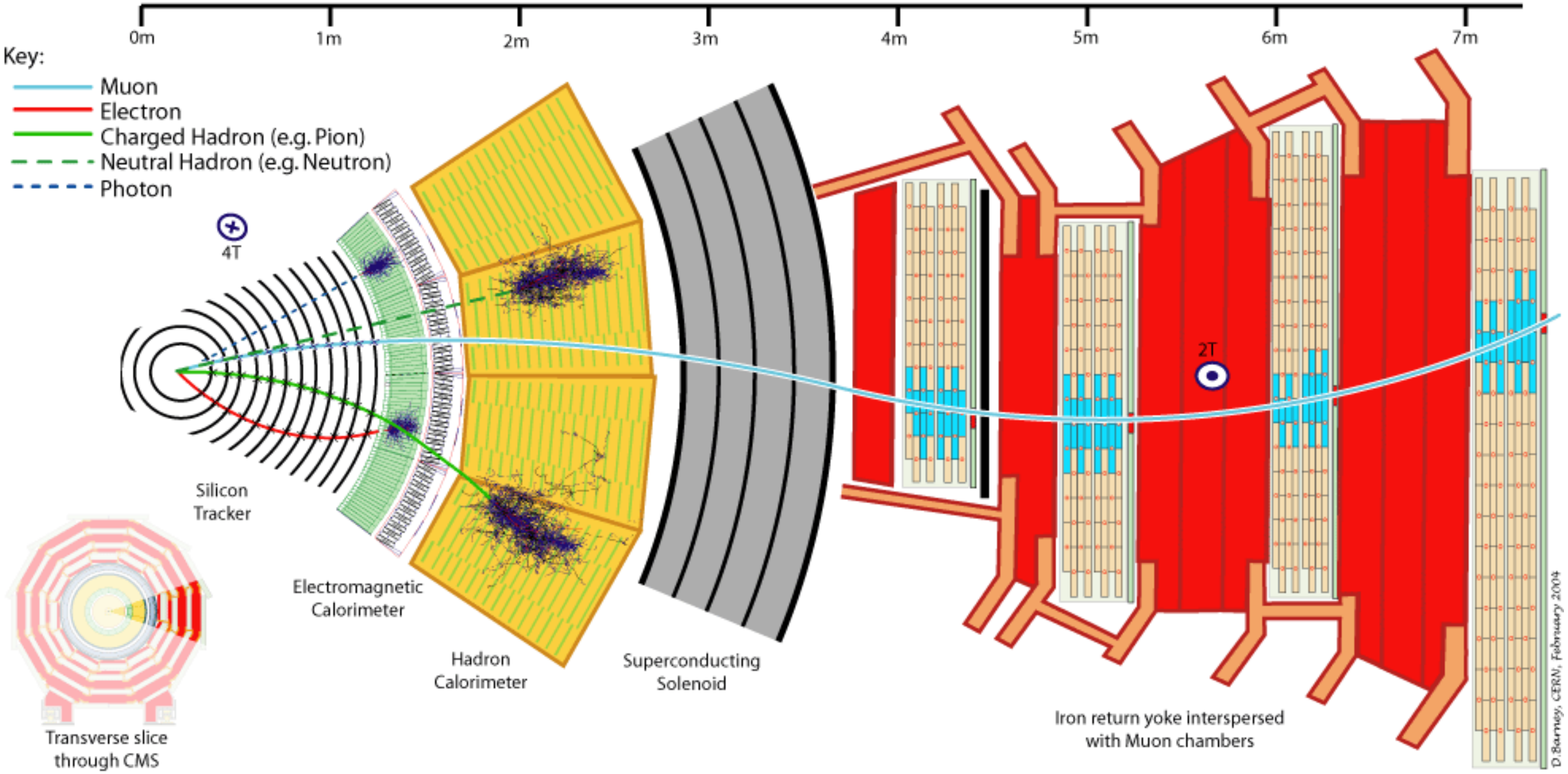
Transition radiation (γ)

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

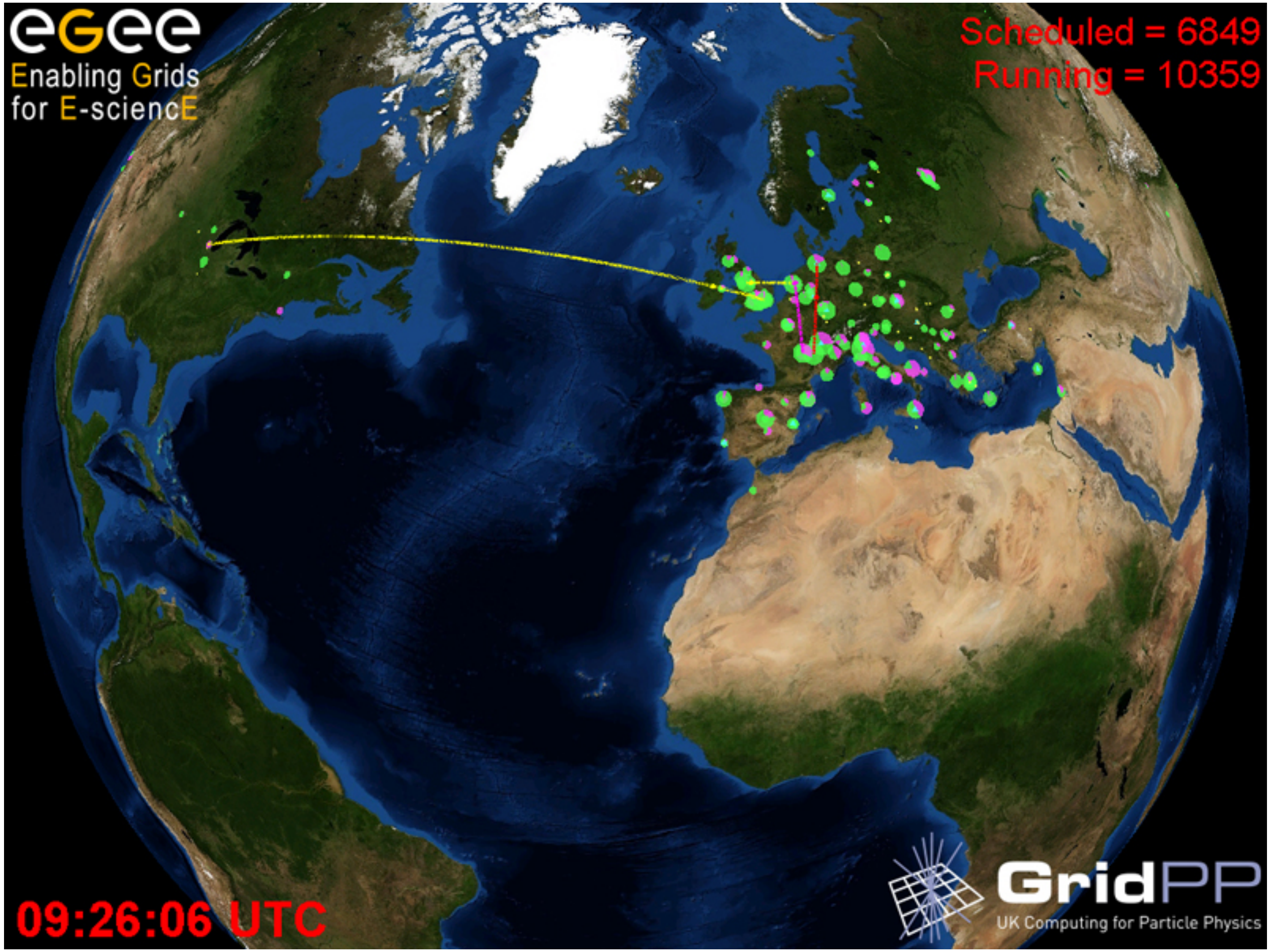

CHARGE UTILE MAXI
200 KG.



Identify particles by characteristic signatures in experiment

Add computers: calculate particle paths and energies

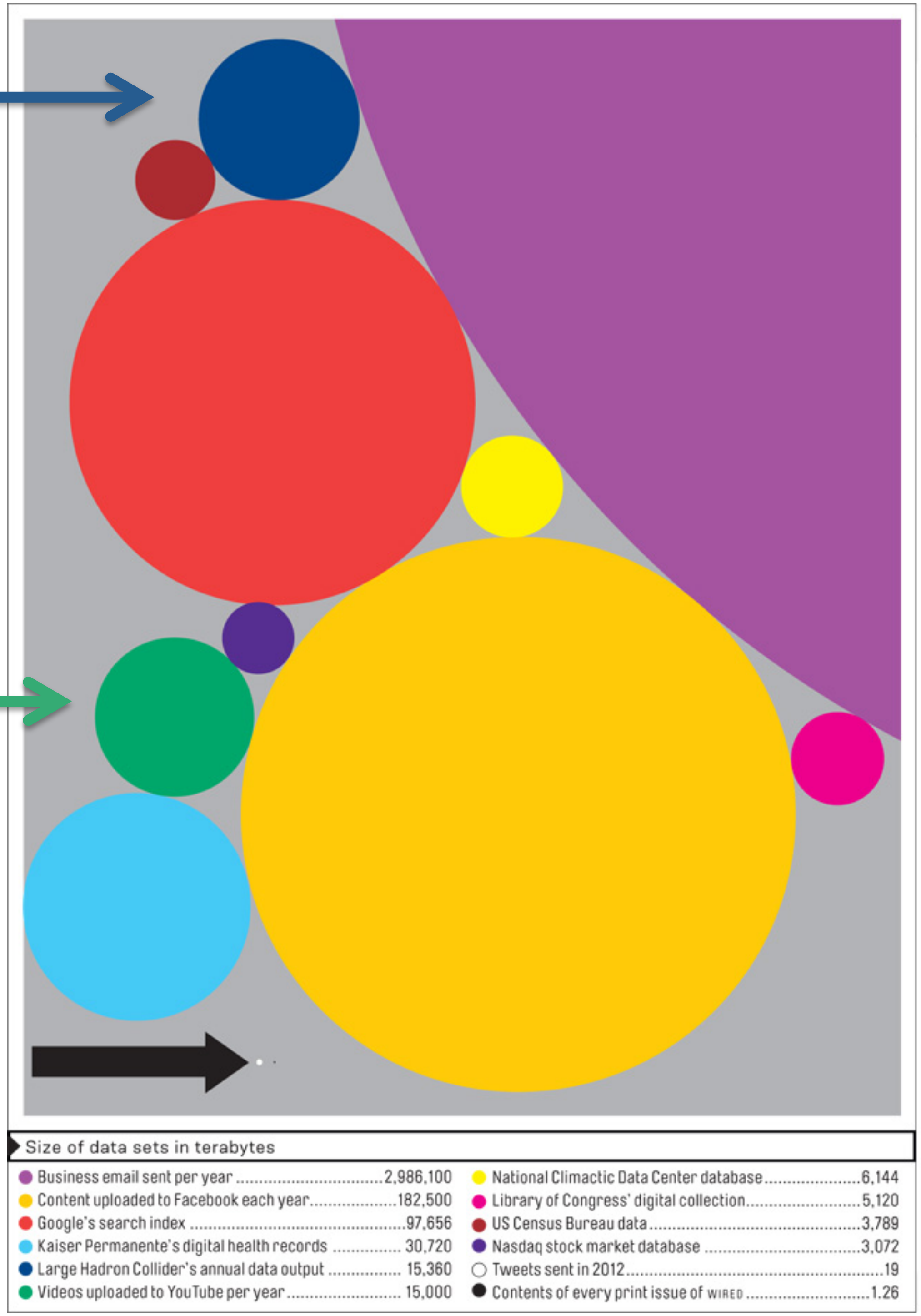
Add theory: infer what fundamental process happened


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

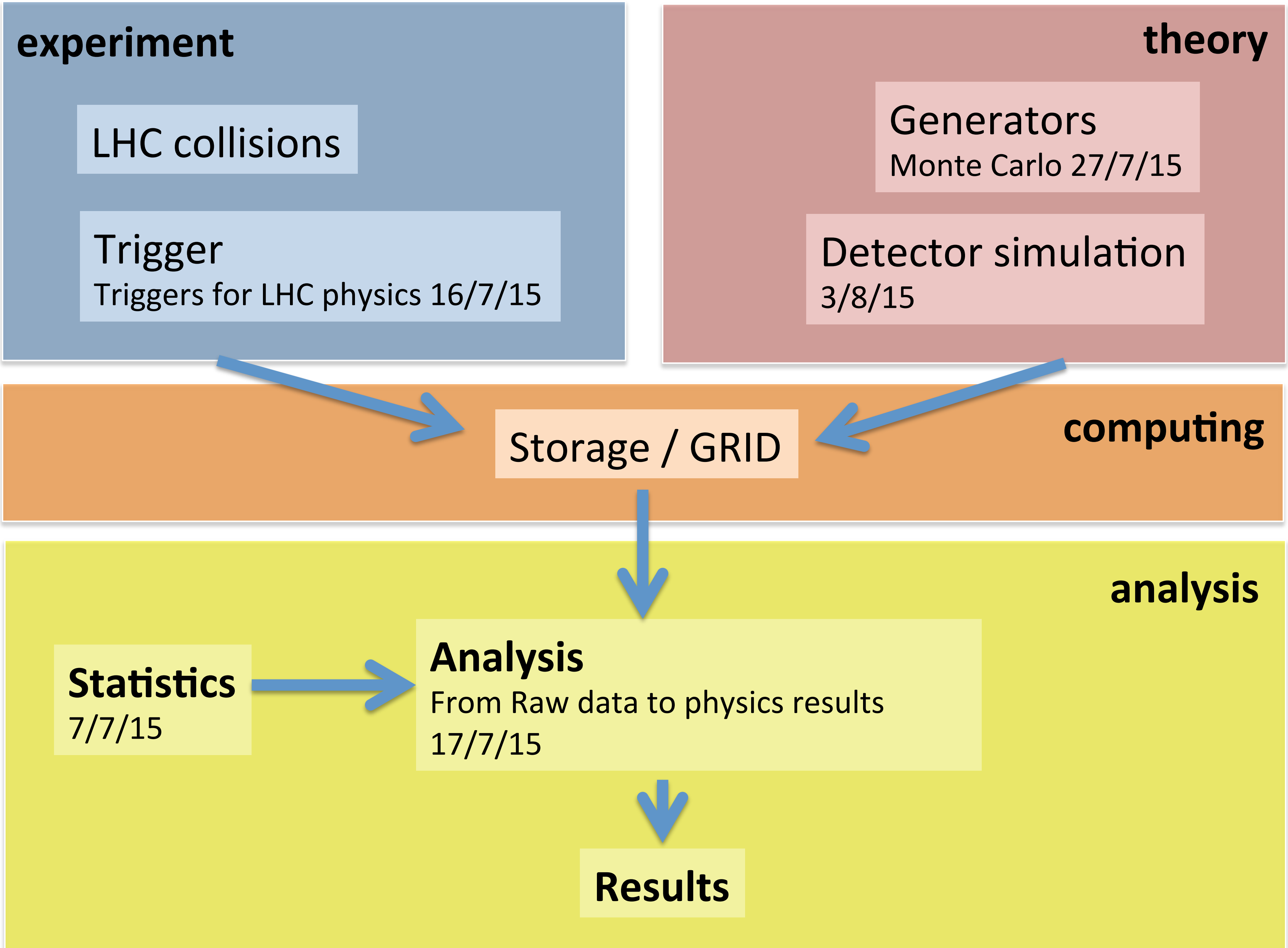
LHC
15 360 TB/yr

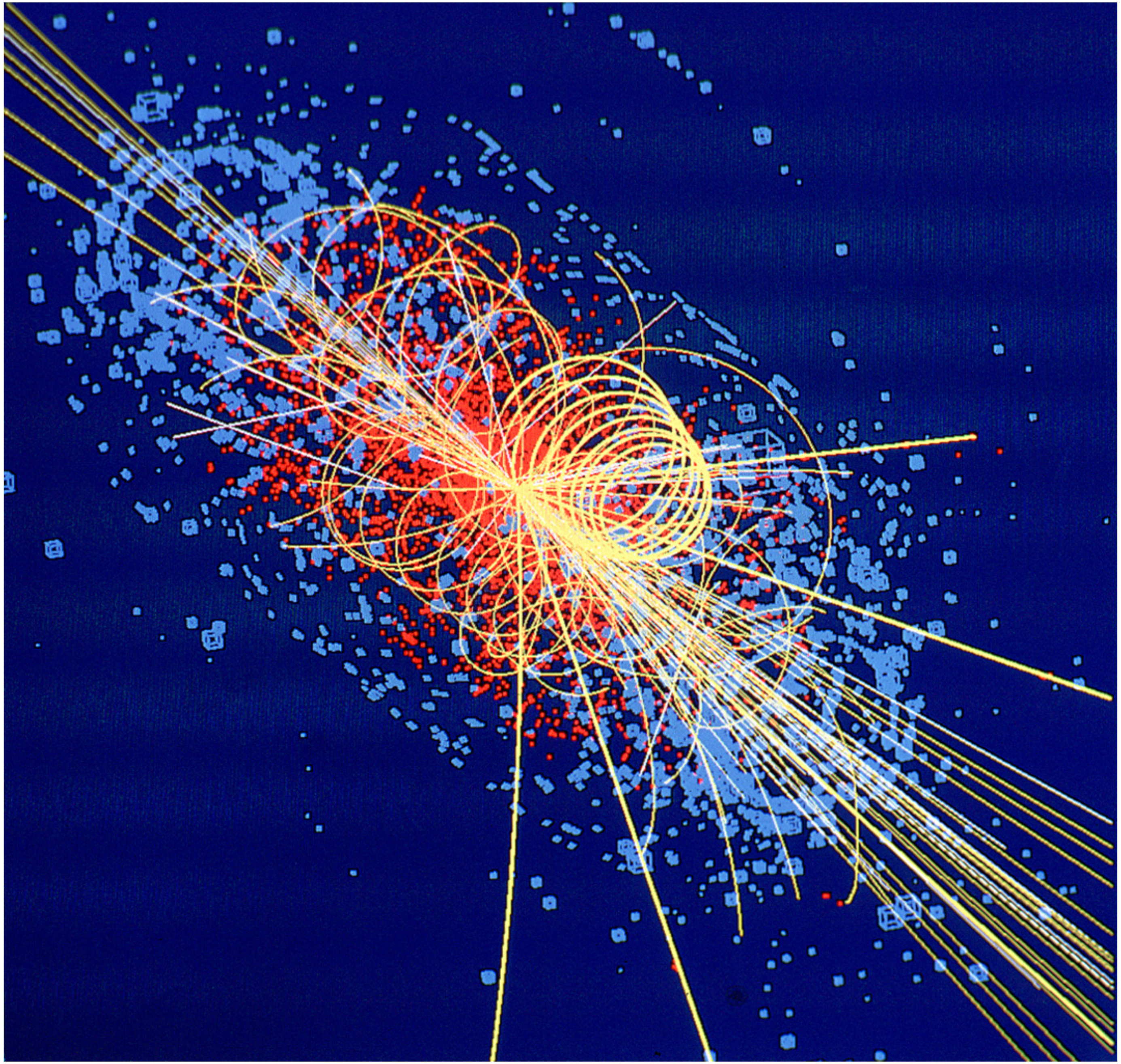
Big data ....

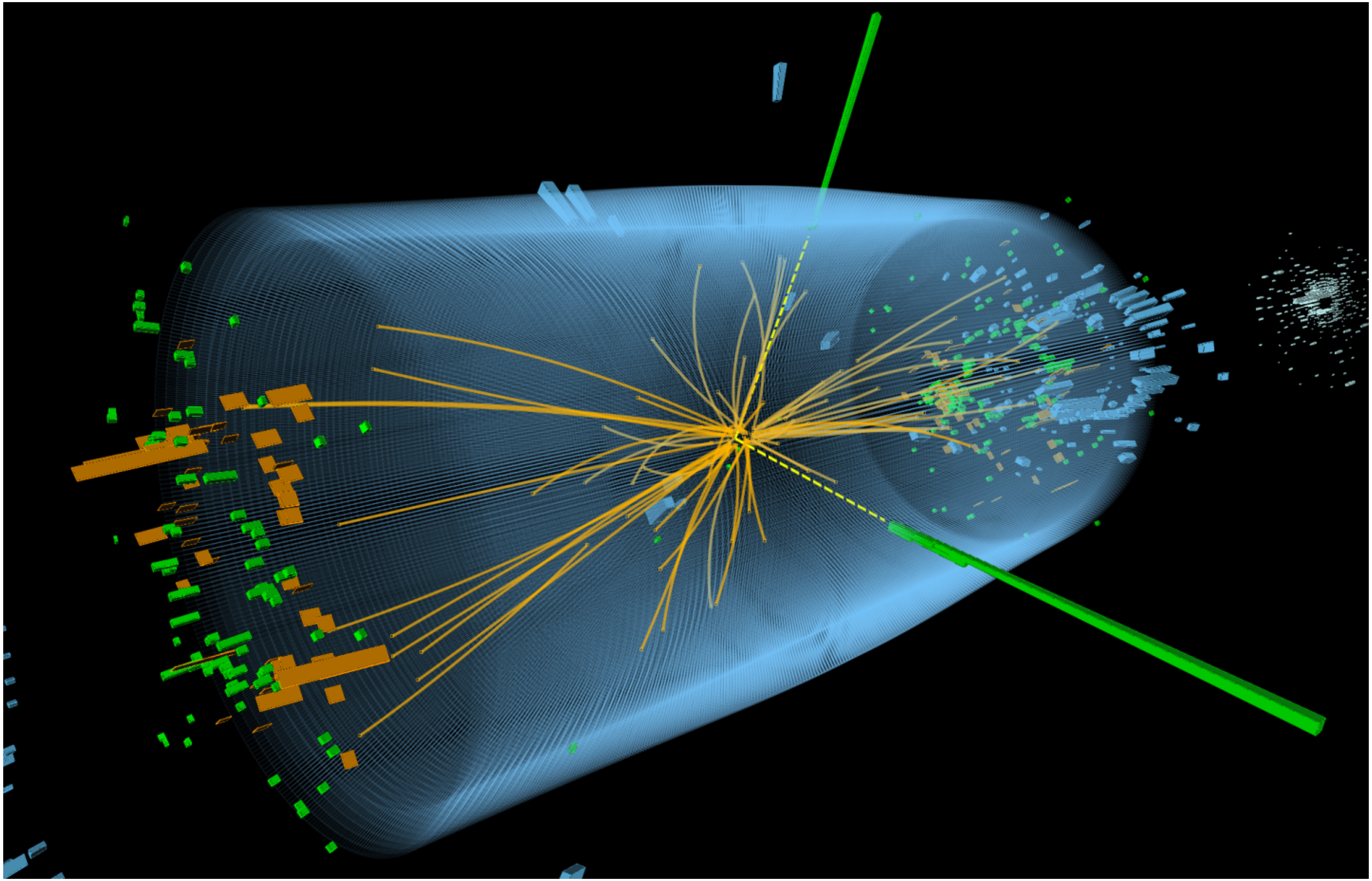
Videos uploaded to YouTube
15 000 TB/yr



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


experiment
LHC collisions
Trigger
Triggers for LHC physics 16/7/15
theory
Generators
Monte Carlo 27/7/15
Detector simulation
3/8/15
computing
Storage / GRID
analysis
Statistics
7/7/15
Analysis
From Raw data to physics results
17/7/15
Results





Future facilities

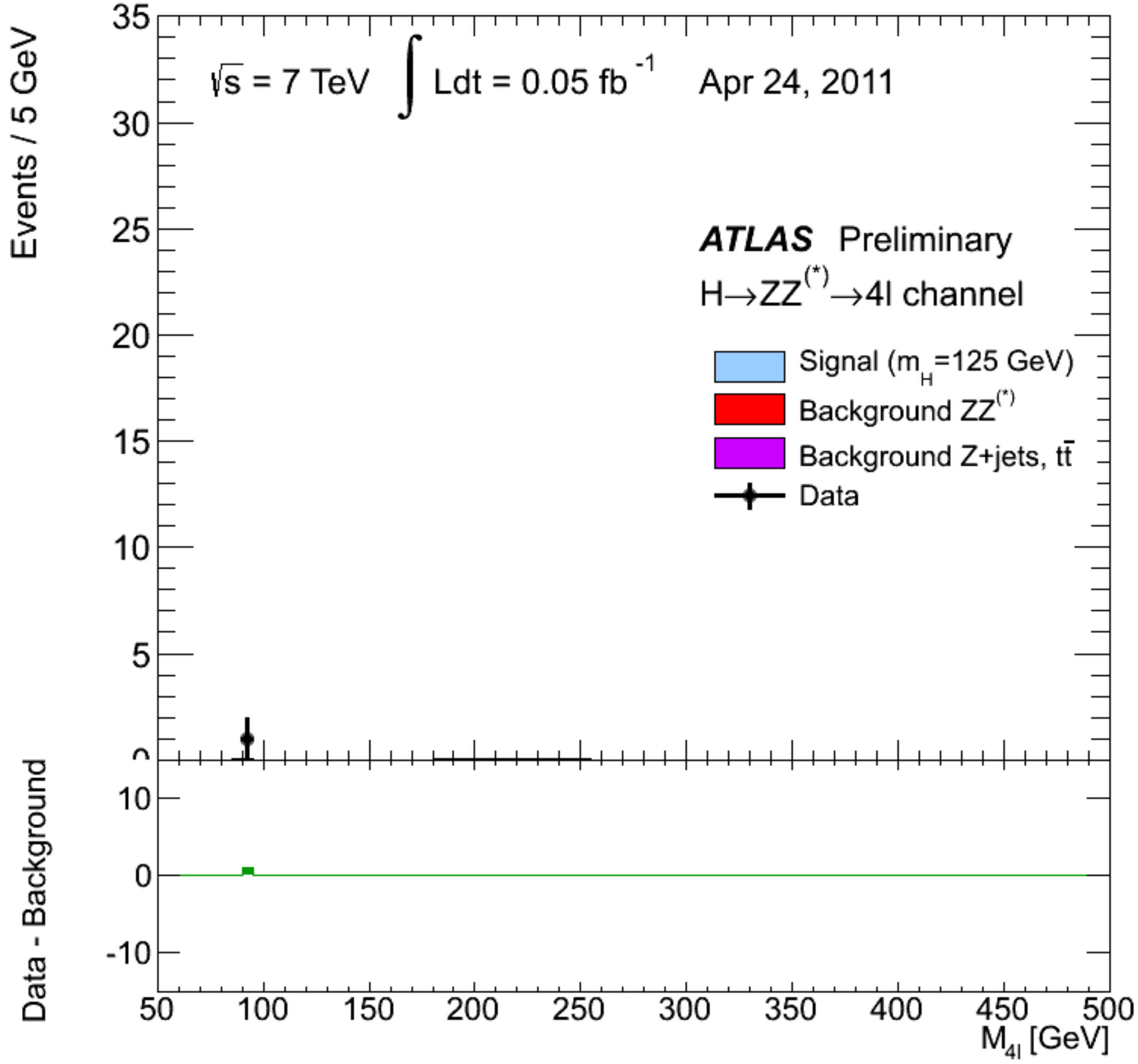
Too many open questions to stop here.

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

Physics at future colliders 29/7/15
Future colliders technologies 29/7/15
LHC upgrade 3/8/15

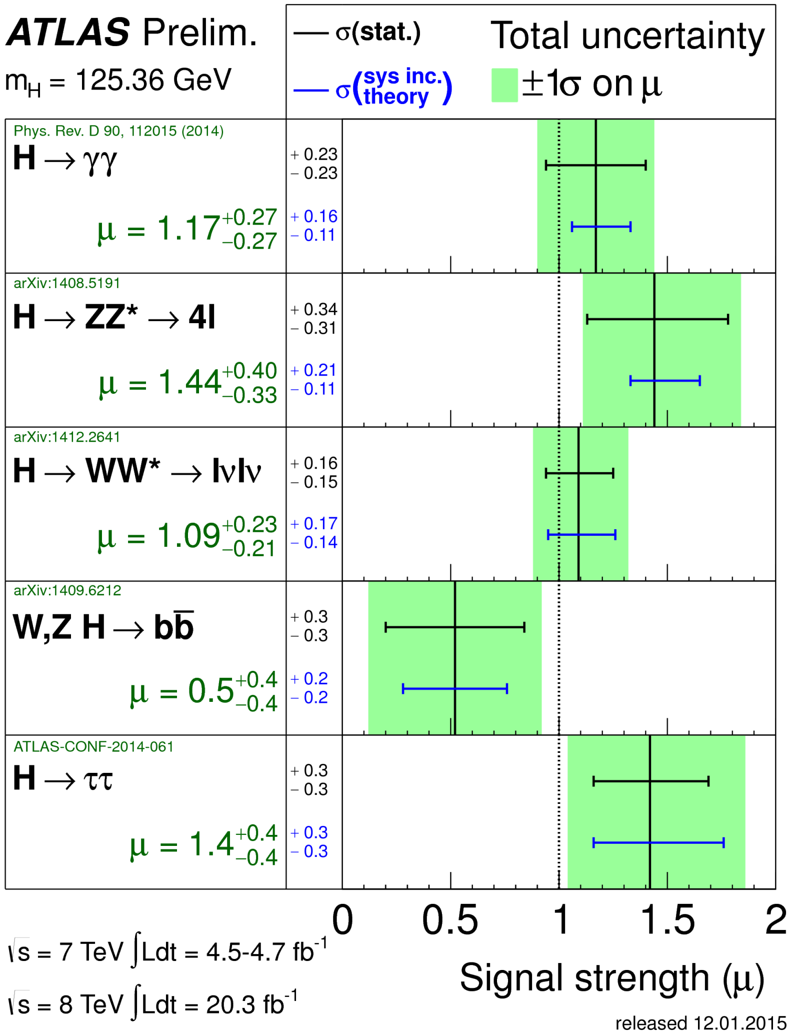
The known unknowns

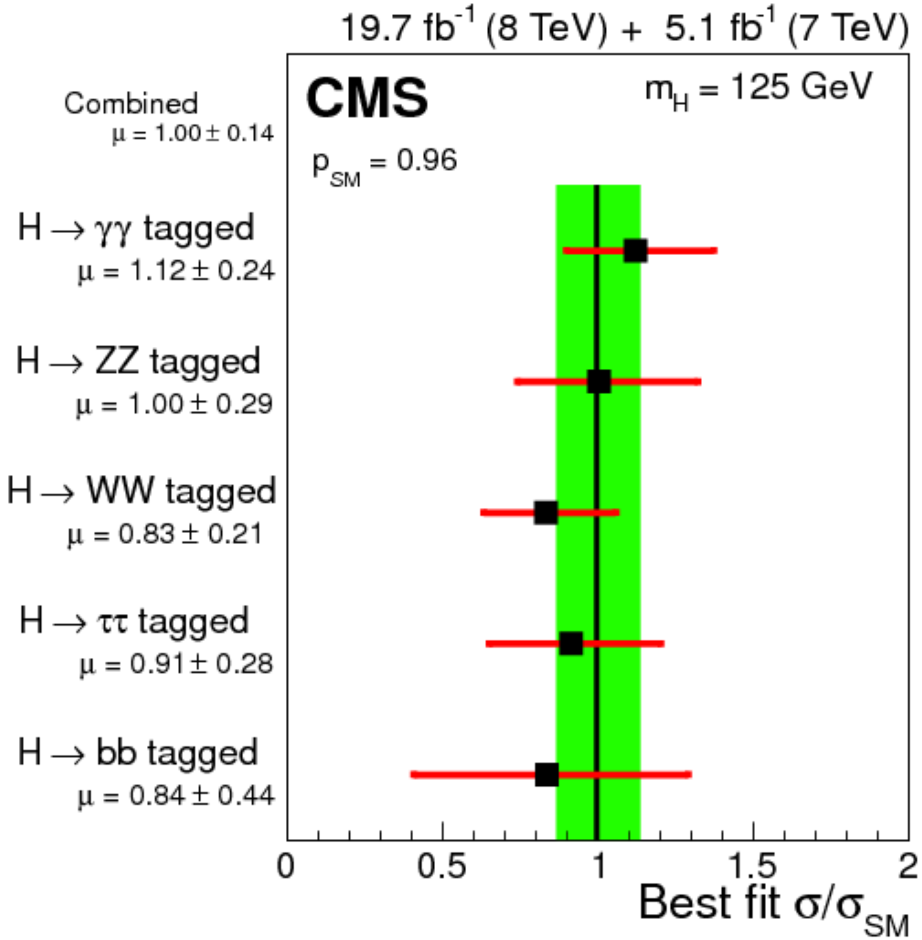
- Higgs
- Gravity
- Antimatter
- Dark matter, dark energy
- A unified theory
- + unknown unknowns…..



√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]
35
30
25
20
15
10
5
0
10
0
-10
50
100
150
200
250
300
350
400
450
500

A Higgs? The Higgs?





> 3,700 papers since the start of 2012…..

Gravity

Can't describe it in SM

Can include it in string theory – not very testable (yet)

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

?

CP violation

Consistent picture in SM but can we explain matter – antimatter asymmetry of the universe?

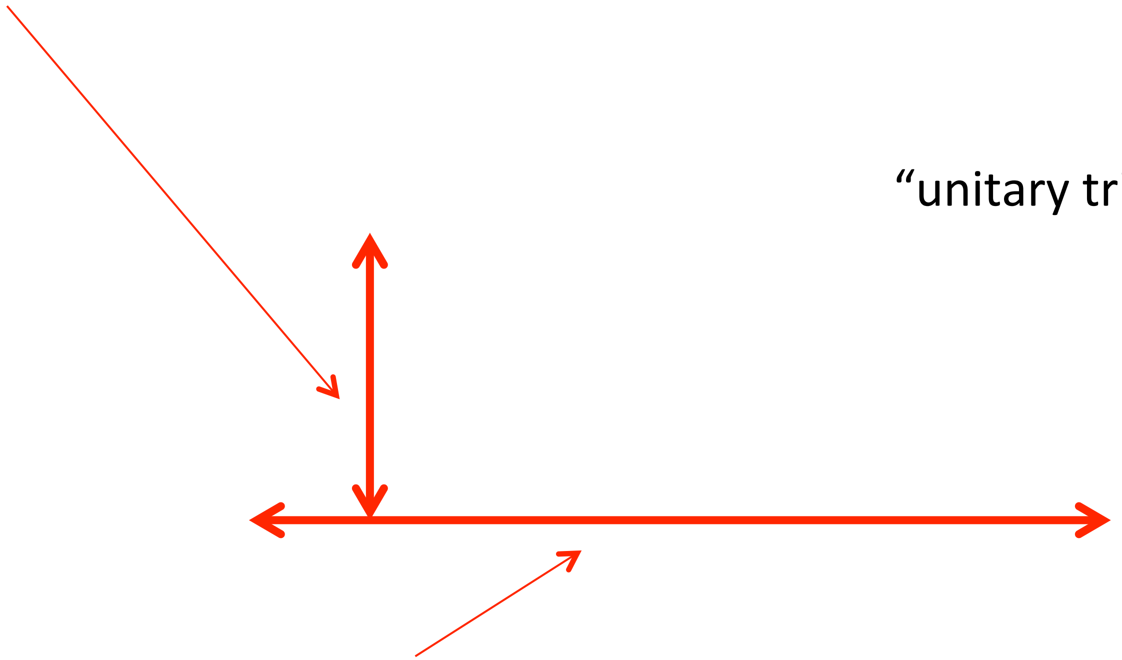
Does the answer lie in new physics?

?

Antimatter 4/8/15
Flavour and CPV 14/7/15

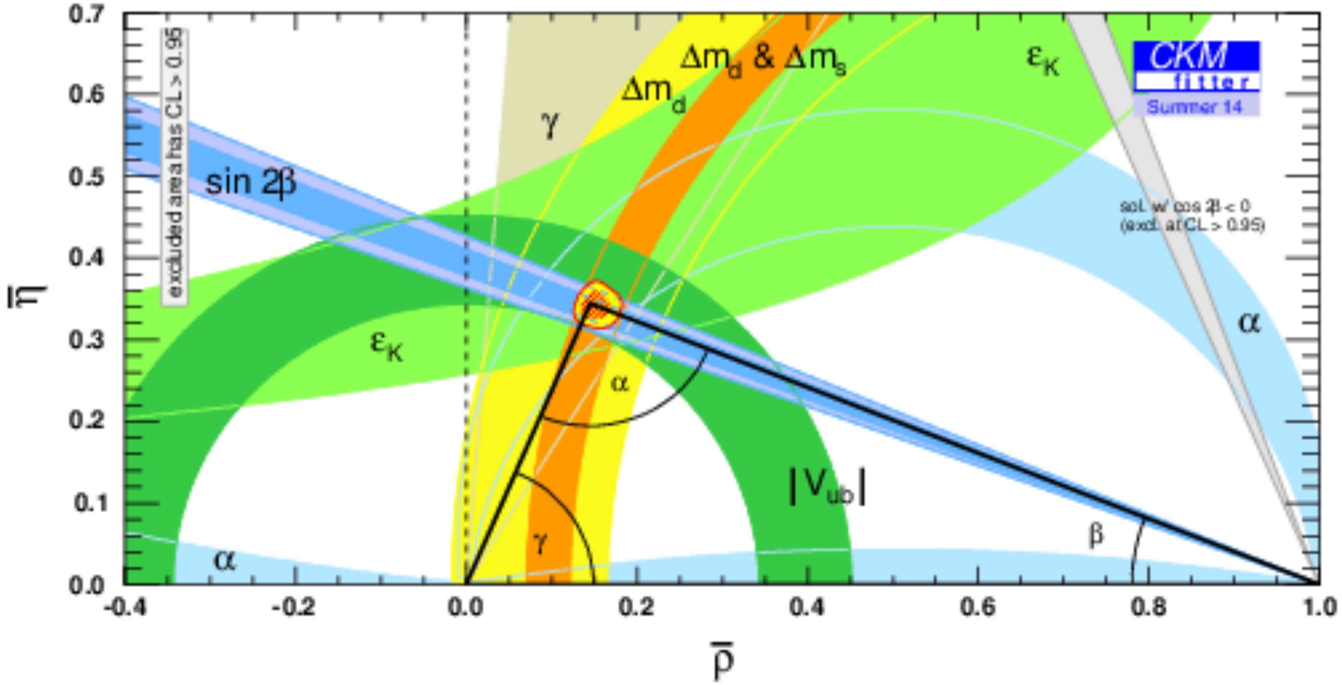
SM: 4 numbers

Measure of matter / antimatter difference (1)



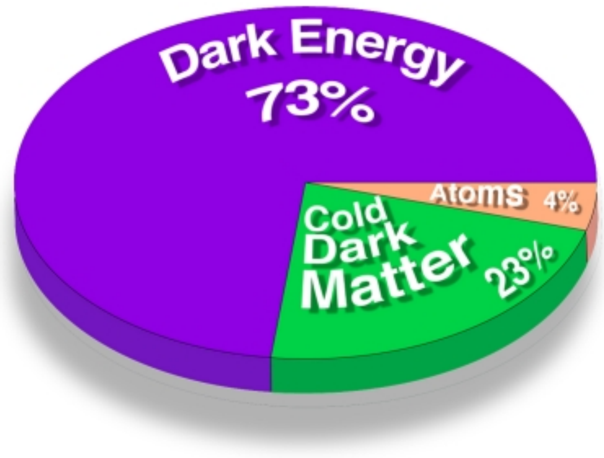
“unitary triangle”

Measure of quark behaviour under the weak force (3)



Measurements + SM consistent, but **much, much too small.**

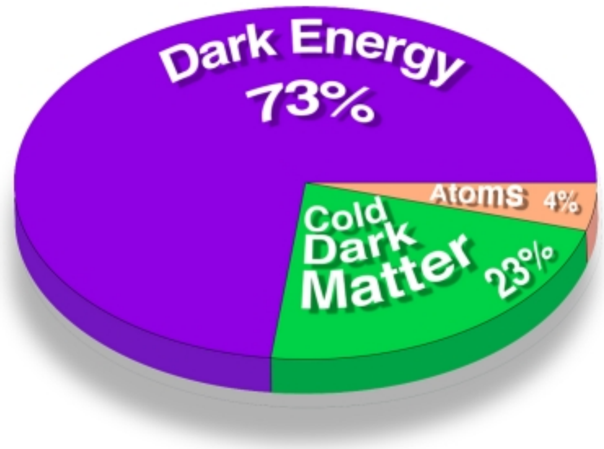
Dark stuff?



Source: Robert Kirshner
Source: NASA/WMAP Science Team

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

Beyond the Standard Model 20/7/15
Search for beyond SM physics at hadron colliders 27/7/15



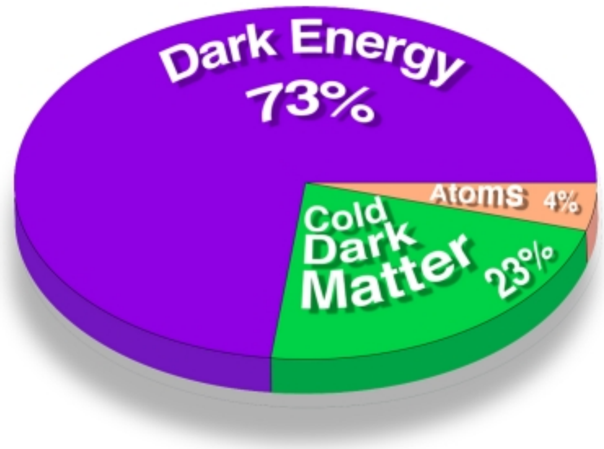
Source: Robert Kirshner
Source: NASA/WMAP Science Team

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

Dark energy:

?

Beyond the Standard Model 20/7/15
Search for beyond SM physics at hadron colliders 27/7/15



Source: Robert Kirshner
Source: NASA/WMAP Science Team

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

Dark energy:

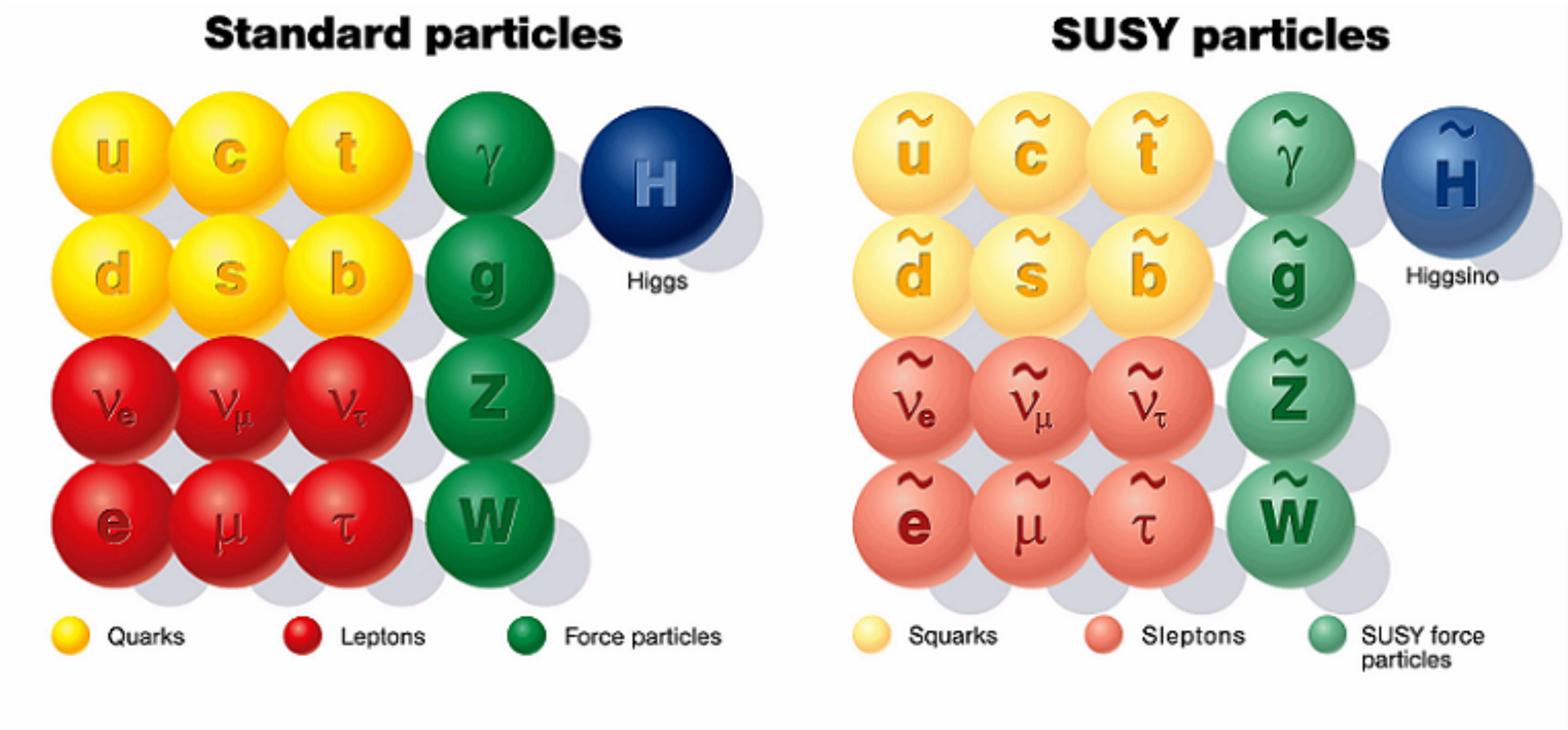
?

Dark matter?

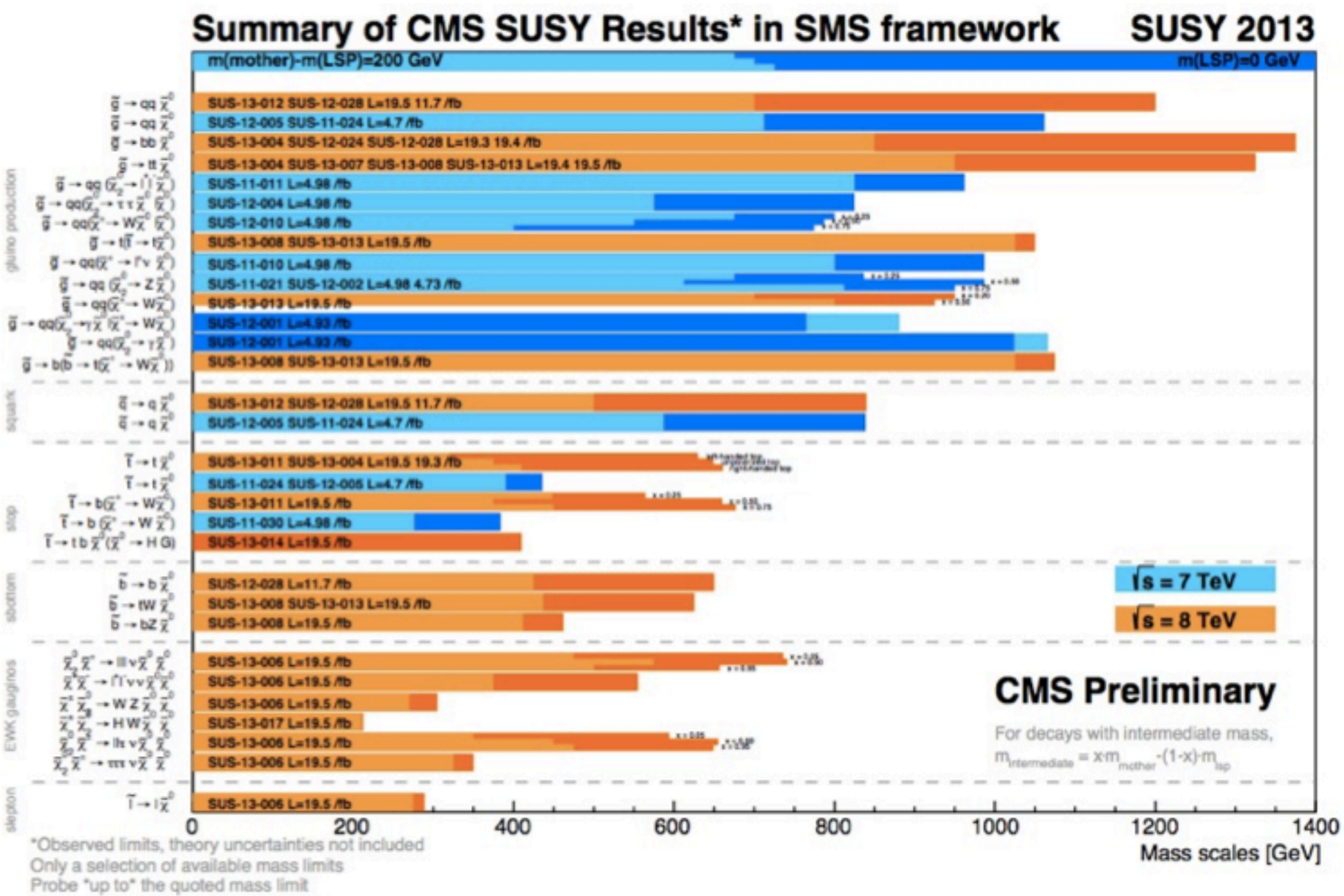
Try Supersymmetry (SUSY).

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

Beyond the Standard Model 20/7/15
Search for beyond SM physics at hadron colliders 27/7/15


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

The “we did not find SUSY” Plot

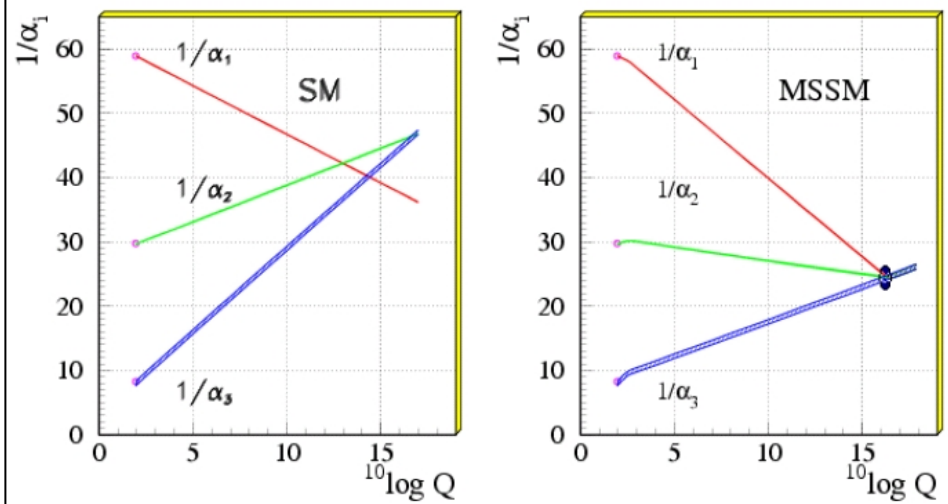


Why 3 forces? 3 generations?

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
- Is fabulously frustrating

Many big mysteries to solve.