Introduction to Particle Physics

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16th February 2016

What is particle physics?

"The study of fundamental particles and their properties"

- Collins dictionary

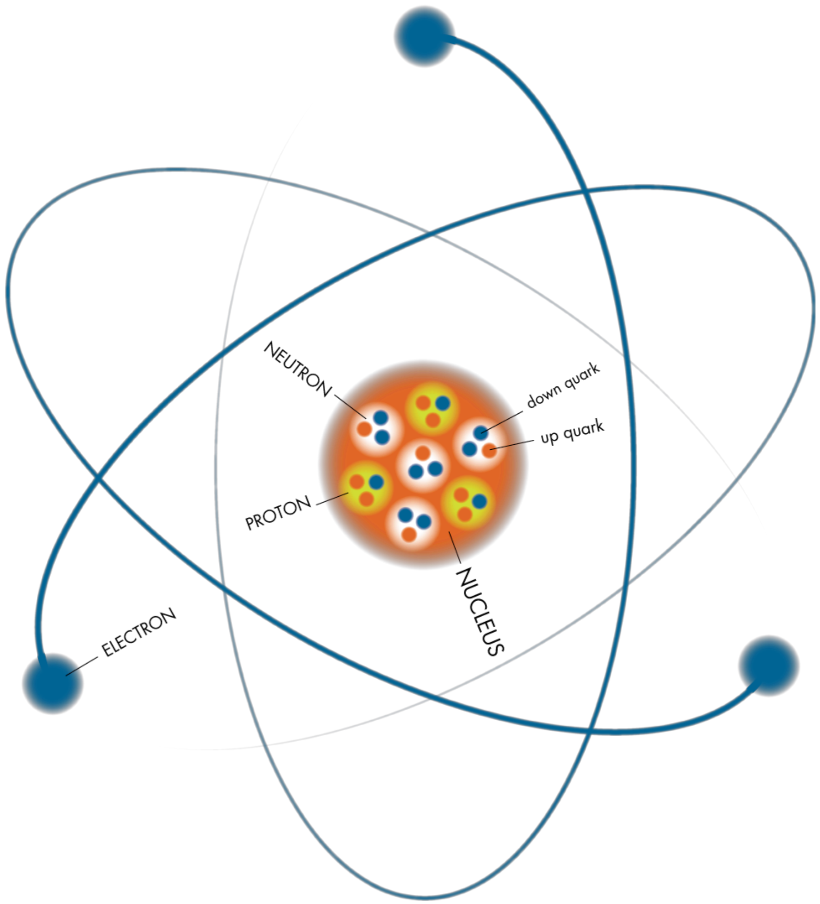
- What are fundamental particles?
  - Democritus (460 – 370 BC): Ancient Greek Philosopher
  - Everything is made up of atoms (atomos – "that cannot be divided")

- And now …?

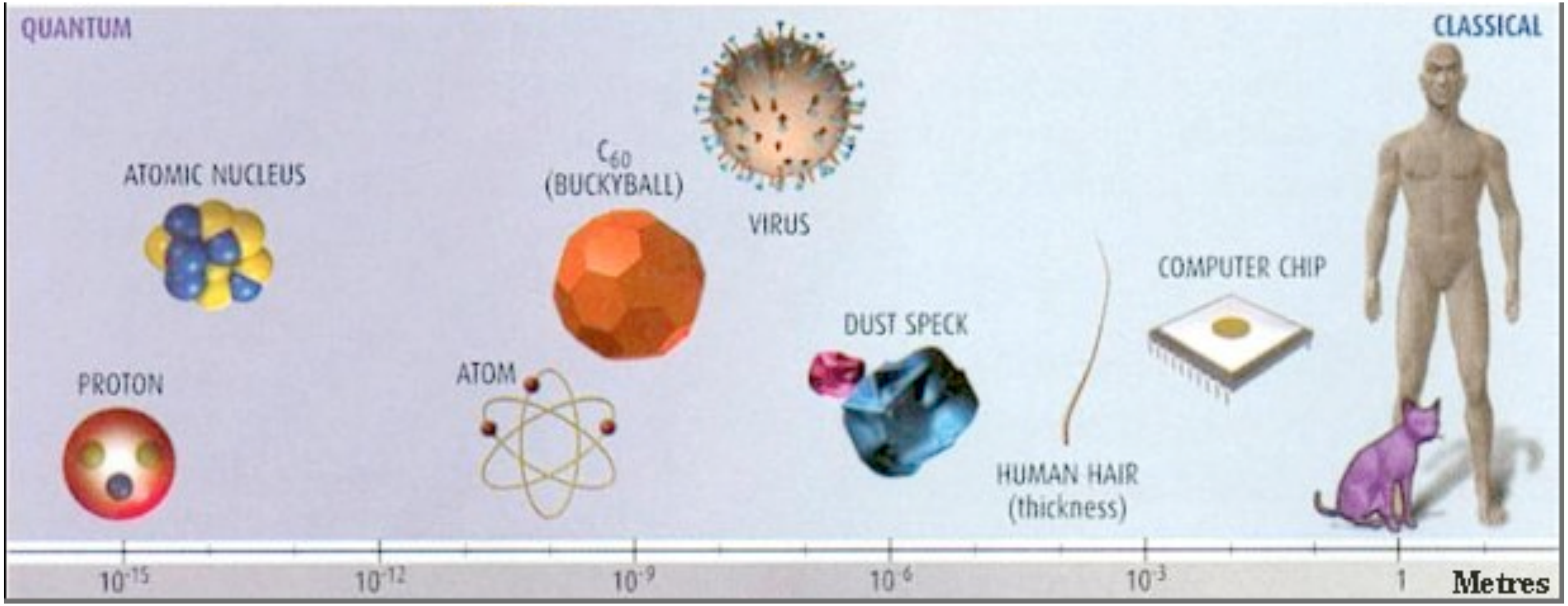
The atom

- The atom is not fundamental
  - A dense nucleus
  - Cloud of orbiting electrons
- The nucleus contains protons and neutrons
  - Made up of quarks
- As far as we know, quarks and electrons are fundamental

Courtesy of University of Birmingham

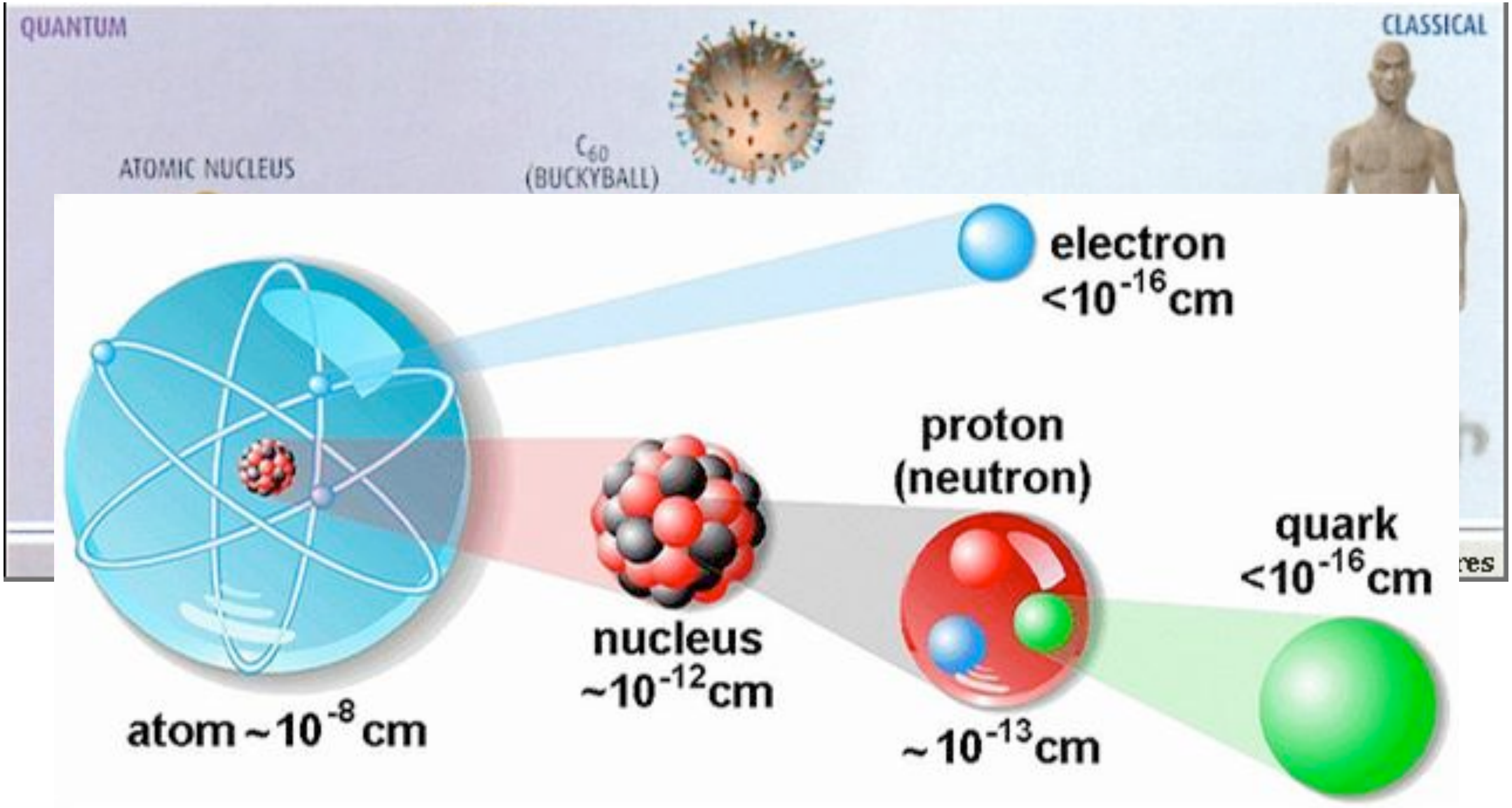


The scale of things



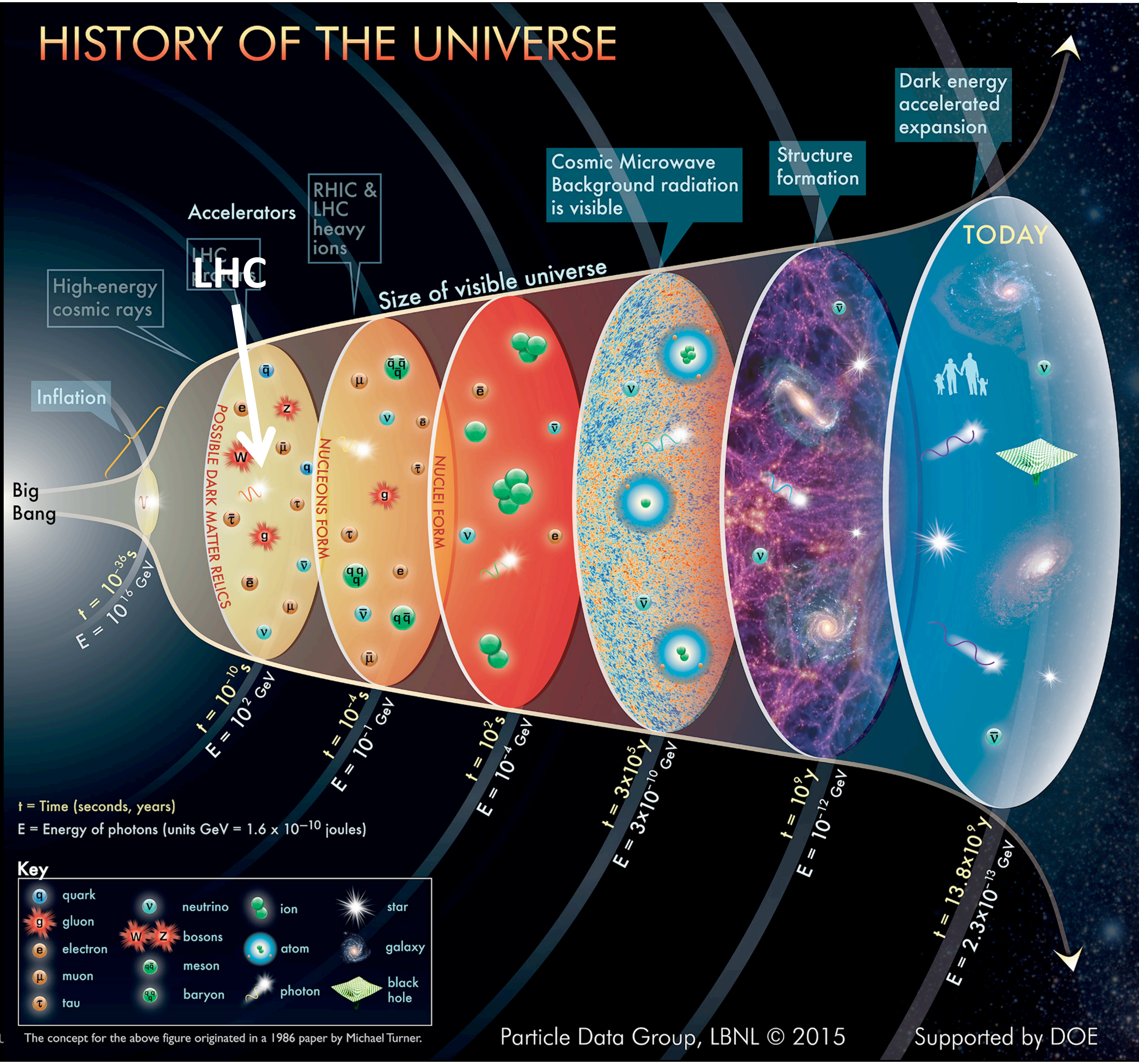
Interactive version: http://htwins.net/scale2/

The scale of things

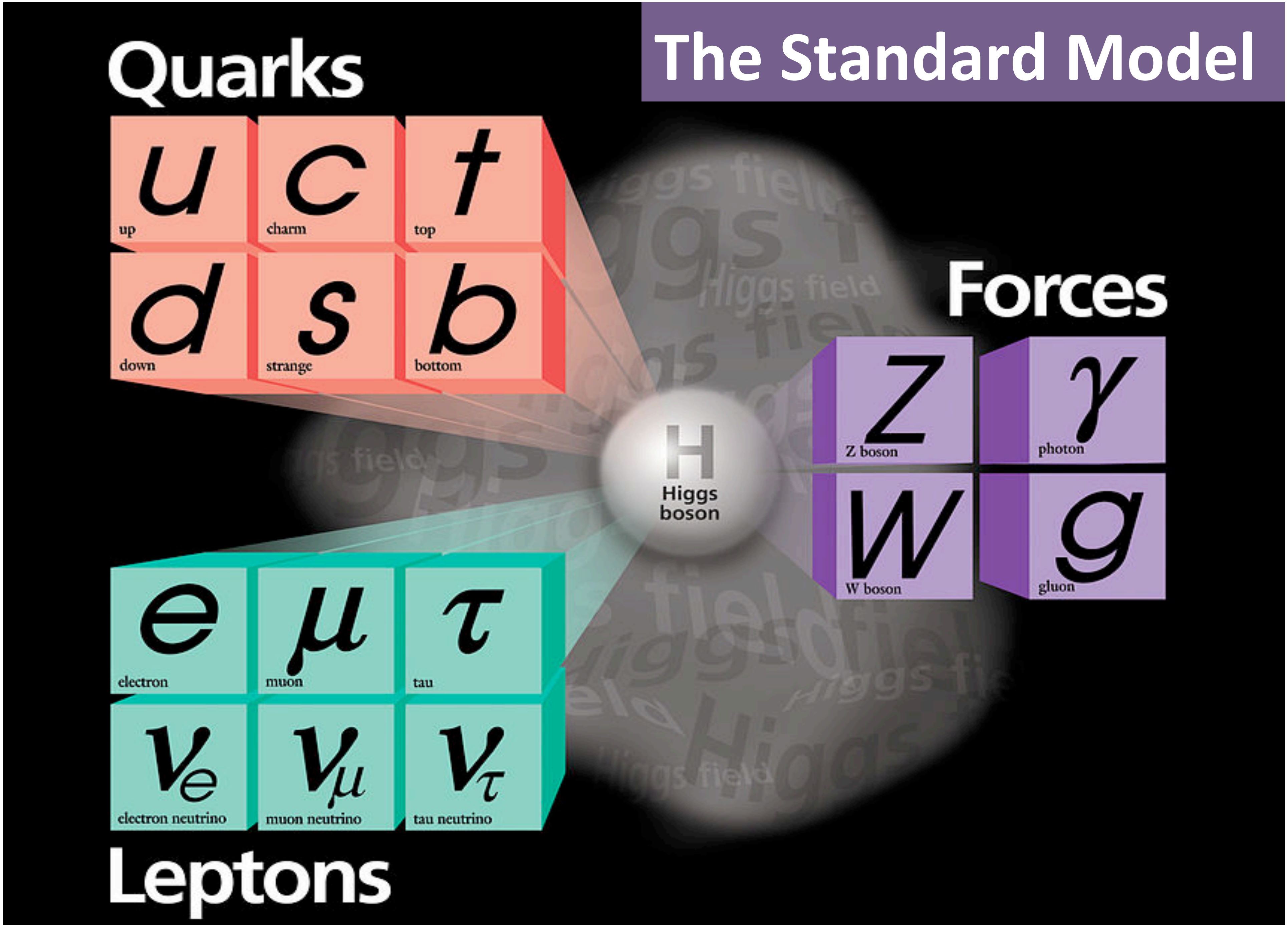


10^{-16} = 0.0000000000000001 cm

Brunel University London



The Standard Model



The Standard Model

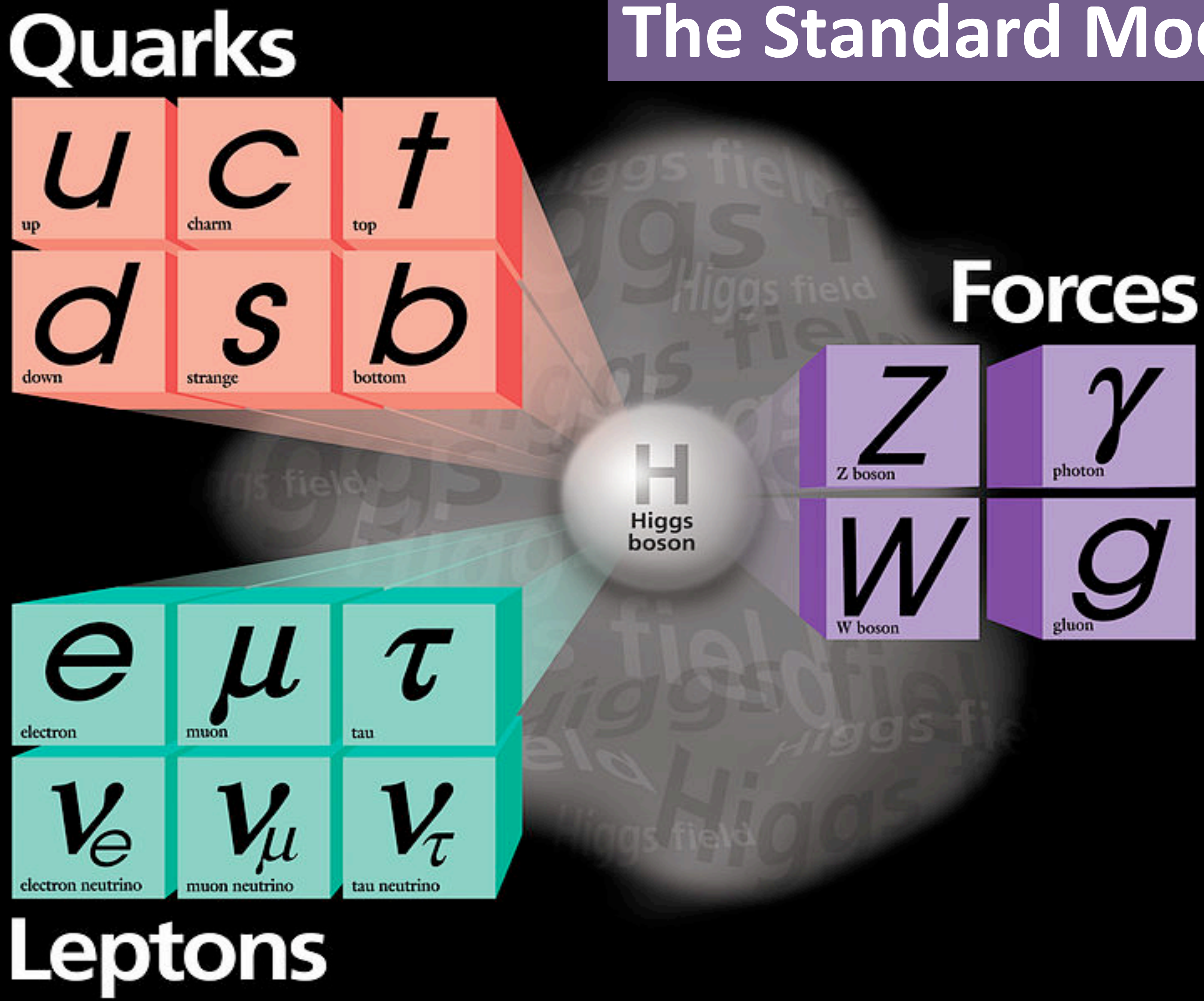
Required to build atoms

Produced in cosmic rays

Produced in radioactive decays

The particles required to build all visible matter

The Standard Model



Anti-matter

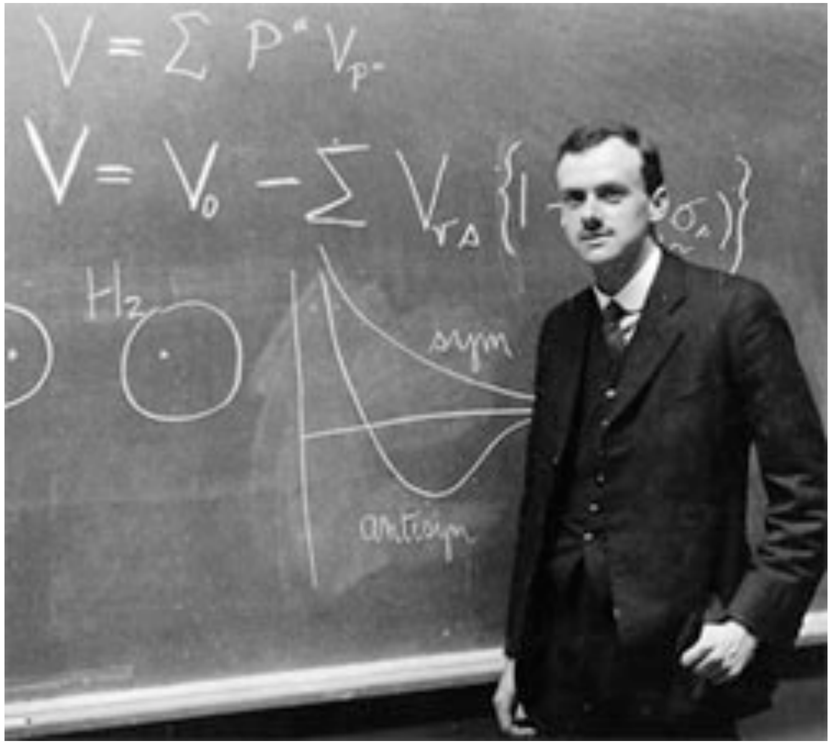
- The classical equation of motion:

$$E = \frac{1}{2}mv^2$$

- Equation of motion based on Einstein's theory of relativity:

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

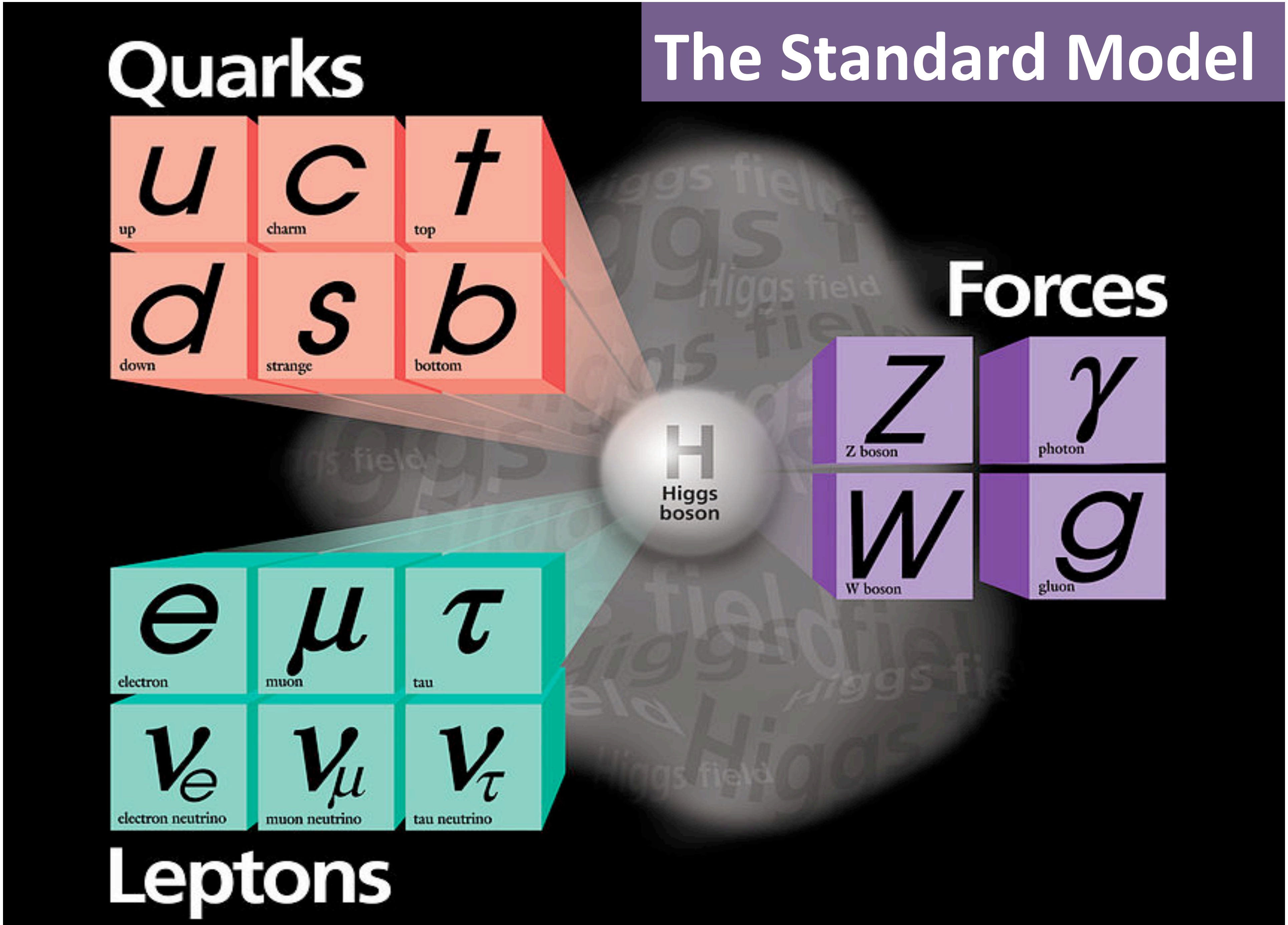
  - Quadratic ➔ two solutions
    - **Anti-matter**



Paul Dirac – predicted the existence of the positron in 1928: antielectron

- Anti-particles: Same mass, opposite charge (+ other quantum numbers)

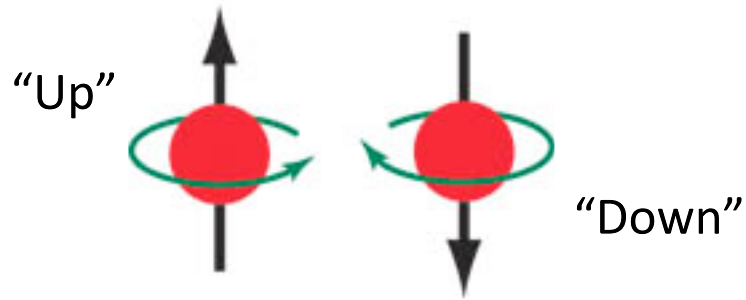
The Standard Model



Spin

- Attempts in the 1920s to measure the magnetic field generated by electrons orbiting atomic nuclei showed
  - Electrons act as if they are spinning rapidly
  - Produce a tiny magnetic field ("magnetic moment") as a result

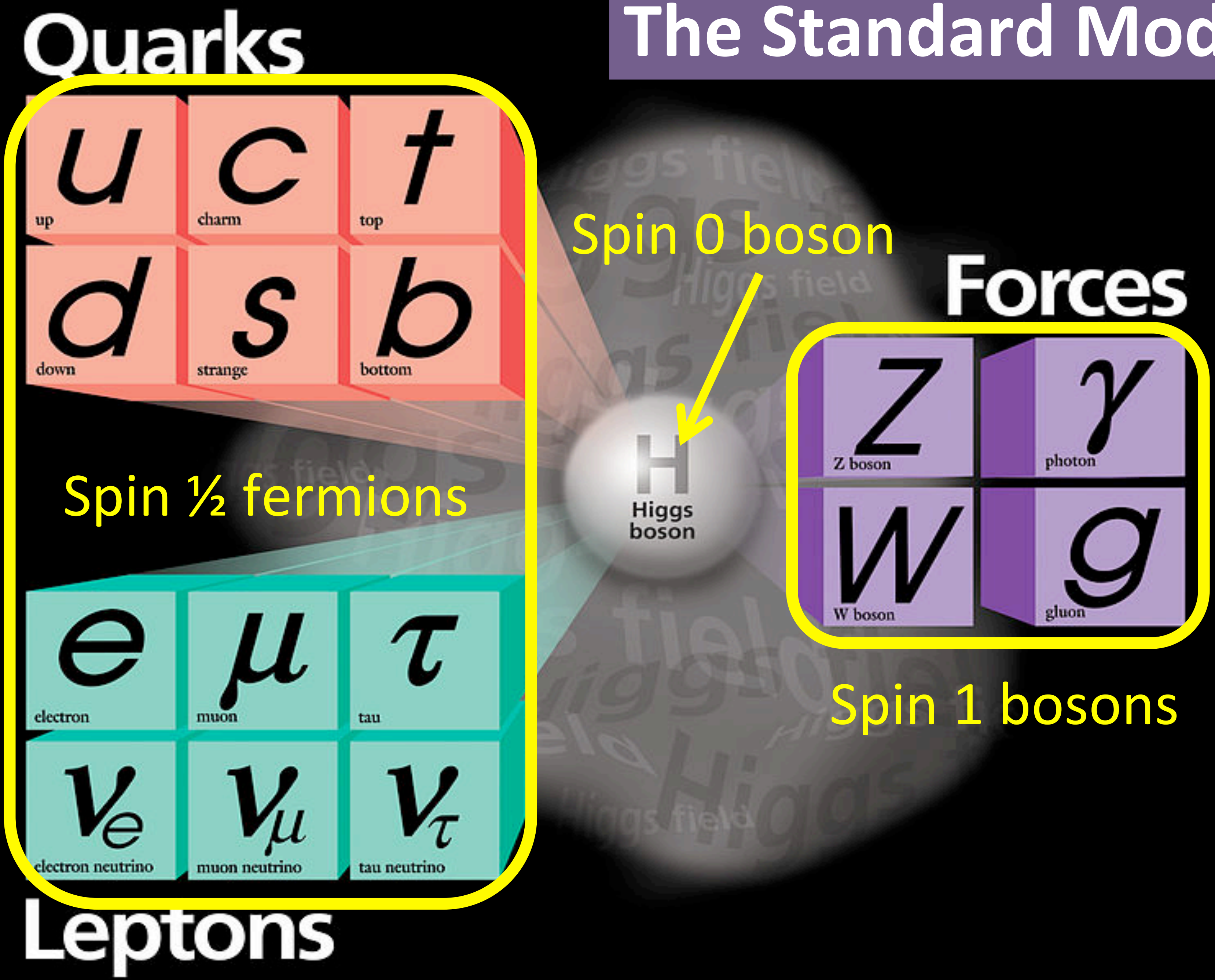
- **This became known as spin**



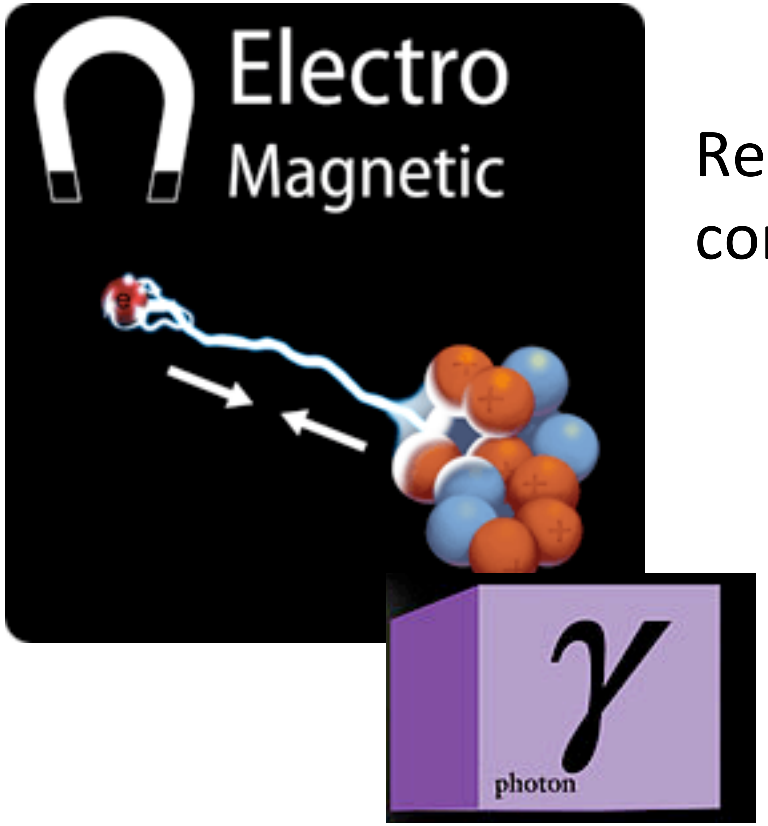
- Then we add the Quantum Mechanics and it gets really weird
  - Size of magnetic moment is much bigger than expected
  - Only discrete values of spin are allowed

- But it is important – influences chemistry and solid-state physics

The Standard Model



The fundamental forces

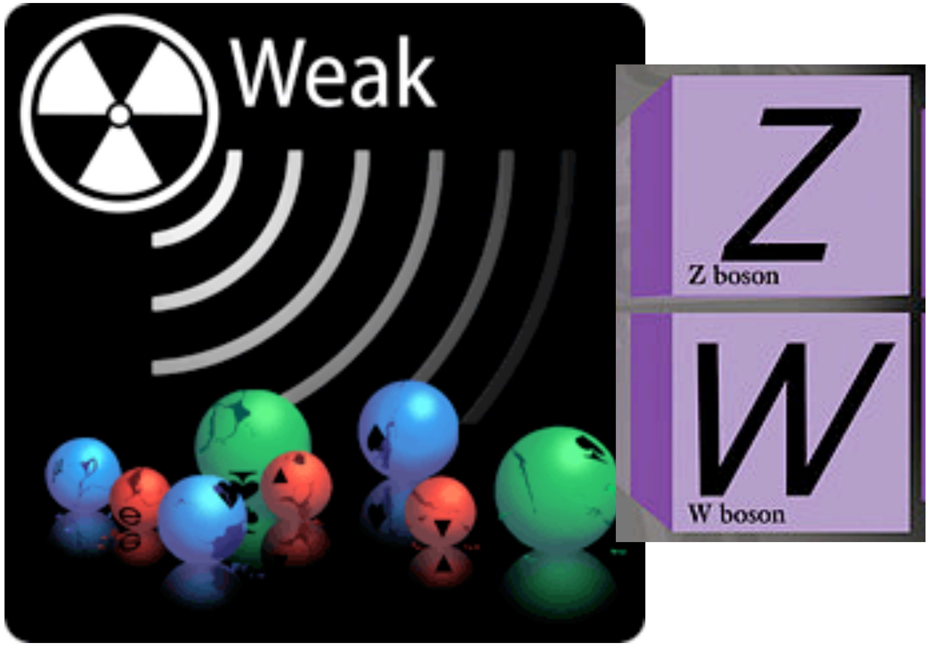


Required to construct atoms

Experienced by all particles with non-zero electric charge
➔Quarks and leptons

Experienced by all particles with “colour charge”
➔ Quarks

The fundamental forces



Required for radioactivity

Experienced by all particles with "weak charge"
➔ Quarks and leptons

Matter particles experience forces through the exchange of the "force carriers" or *mediators*

Interaction Strength

- The relative strength of each force quantified by the coupling constants

- An example: The electromagnetic force

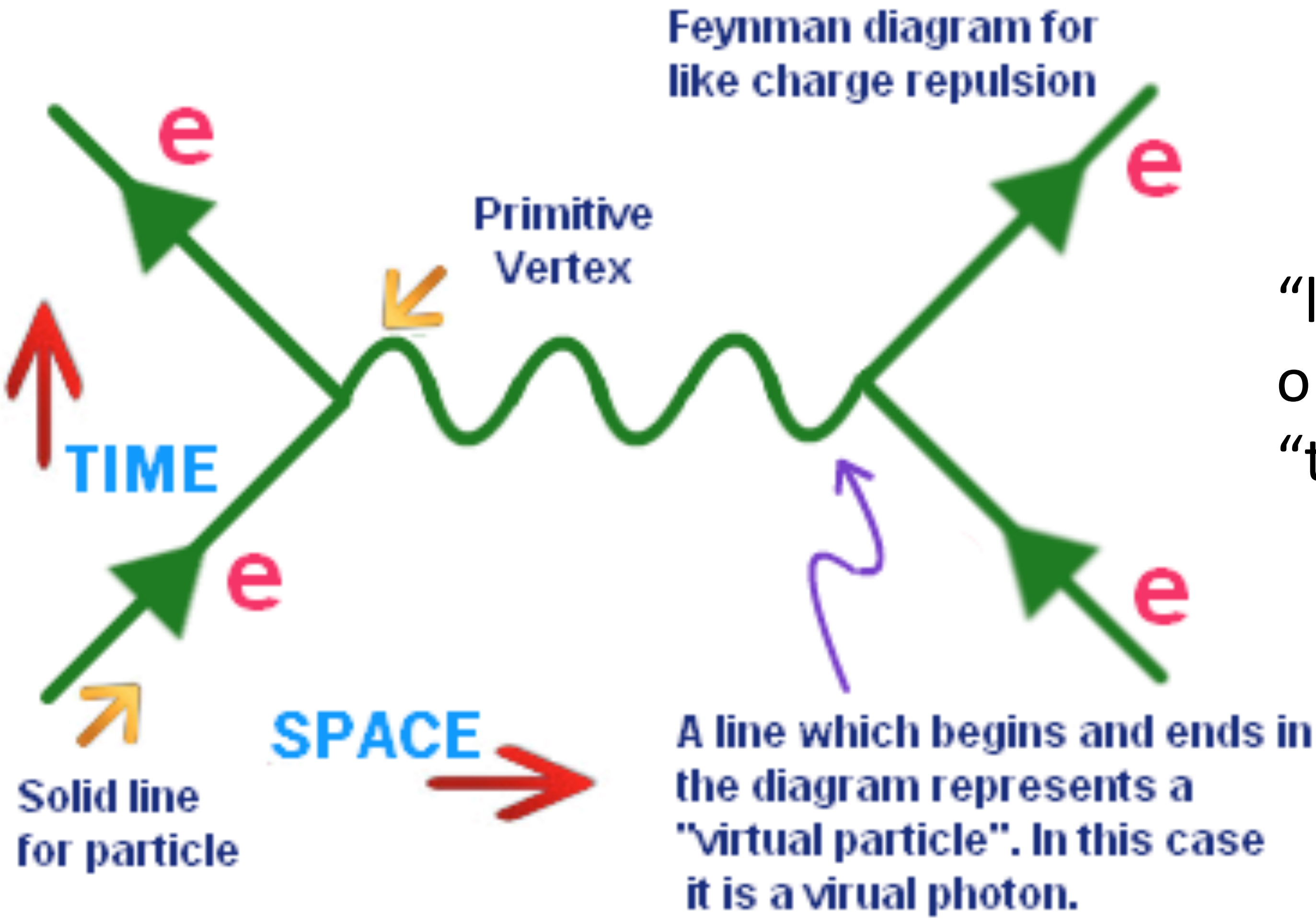
$$F = \frac{q_1 q_2}{4\pi\varepsilon_0 r^2}$$

$$\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c}$$

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

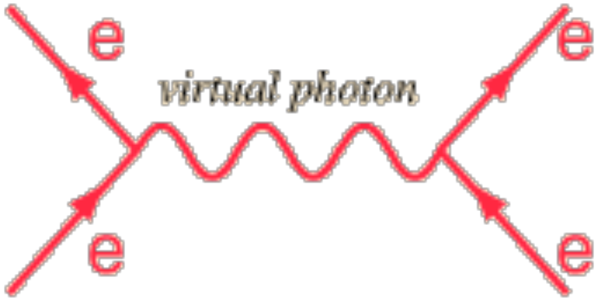
Coupling Constants		
Strong	α_S	1
Electromagnetic	α	1/137
Weak	α_W	10^{-6}
Gravity	α_g	10^{-39}

Feynman Diagrams

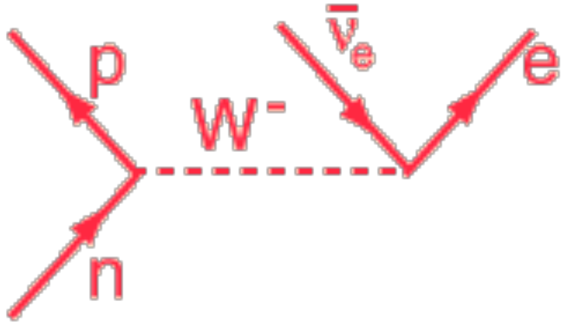


"lowest order"
or
"tree level"

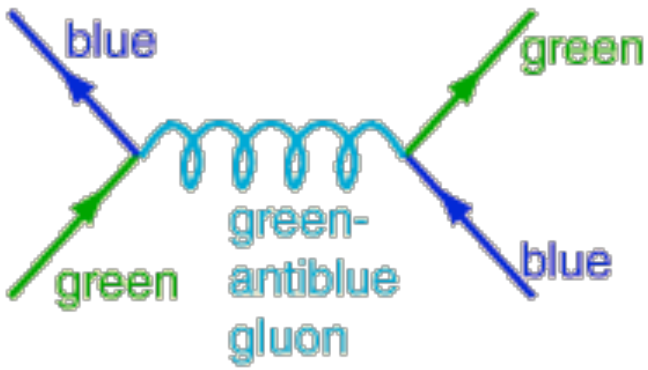
Feynman Diagrams



Electromagnetic



Weak

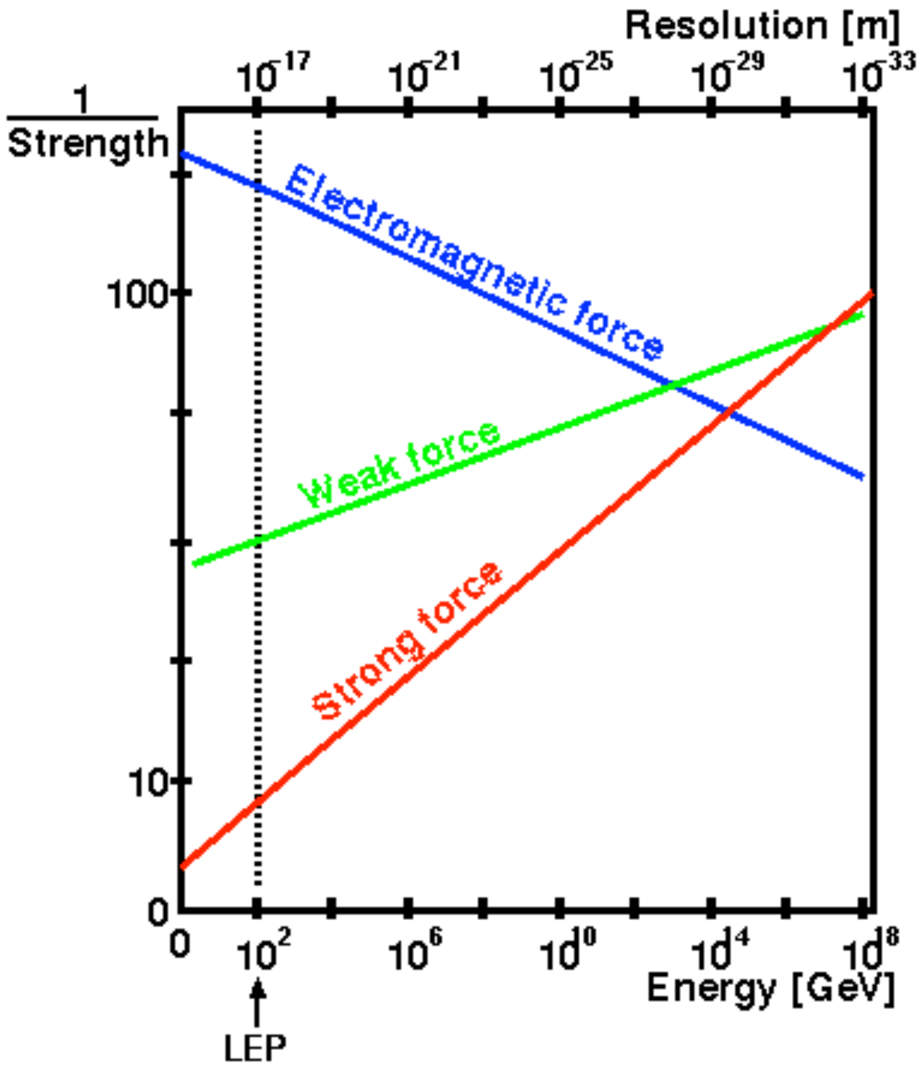


between quarks

Strong Interaction

Coupling Constants revisited

- Coupling "constant" – the interaction strength varies with energy(distance)

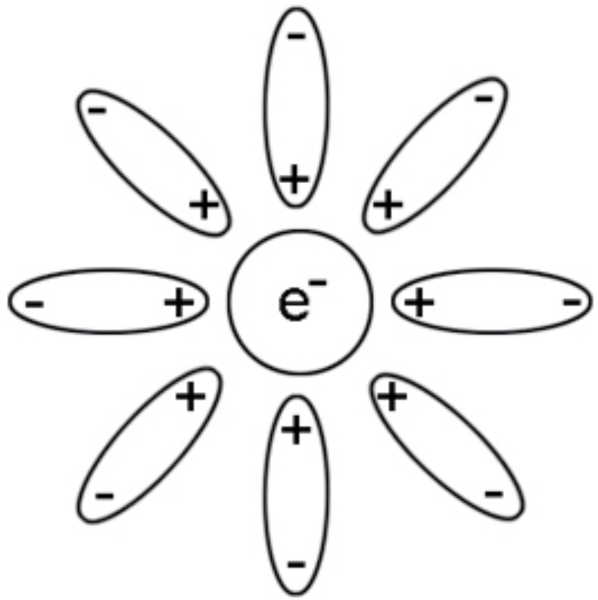


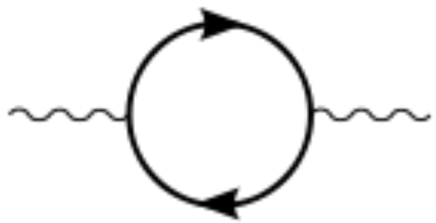
- Known as ***the running couplings***

- Where does this behaviour come from?

Running of α_{EM}

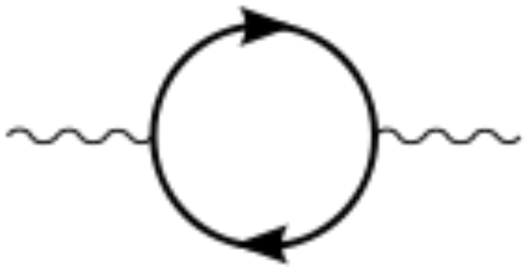
- Consider an electron in a dielectric medium
- Dielectric reduces apparent charge of the electron (polarisation)
  - Known as charge screening





- Charge screened by **vacuum polarisation**
- High E ⇒ smaller distances ⇒ “see” more charge
- **EM force strength increases with E**

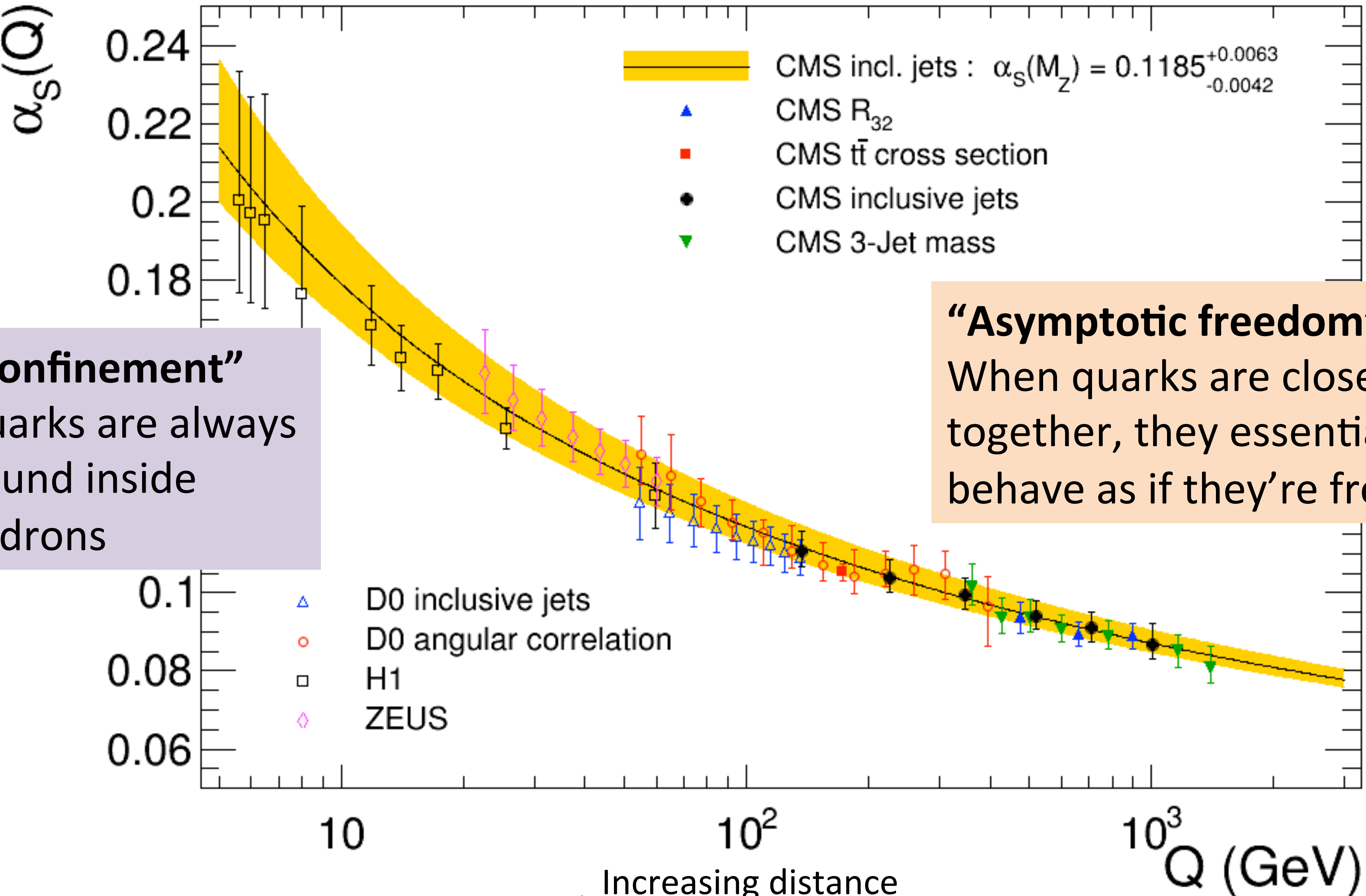
Coupling Constants: Strong & Weak Forces



- Charge screened by **vacuum polarisation**
- **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**

The Strong Coupling Constant



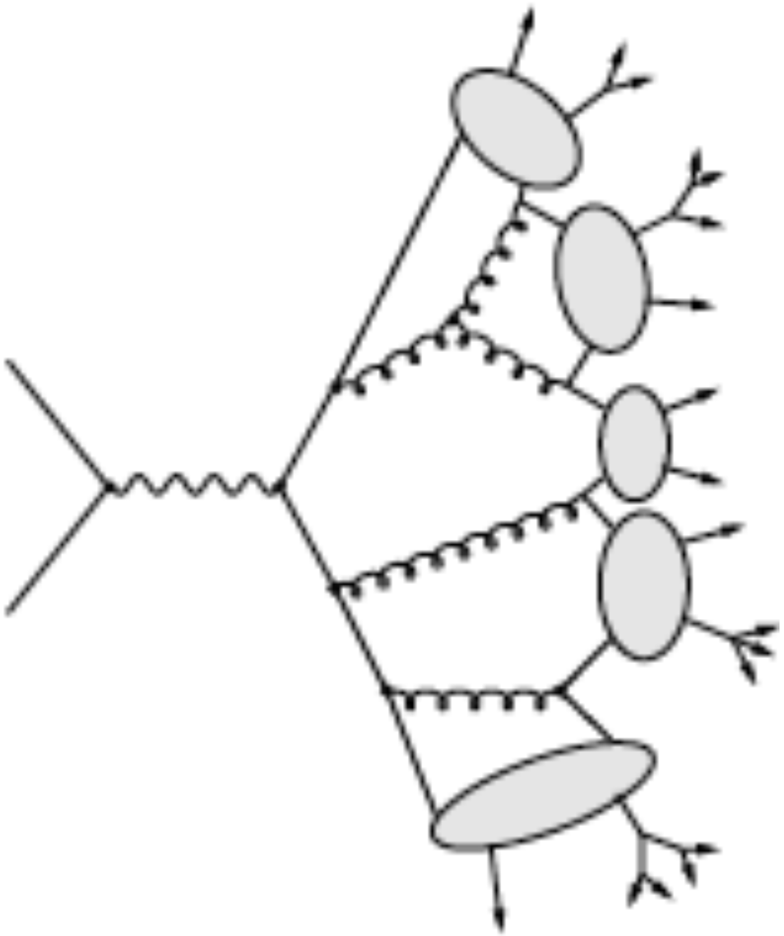
"Confinement"
Quarks are always bound inside hadrons

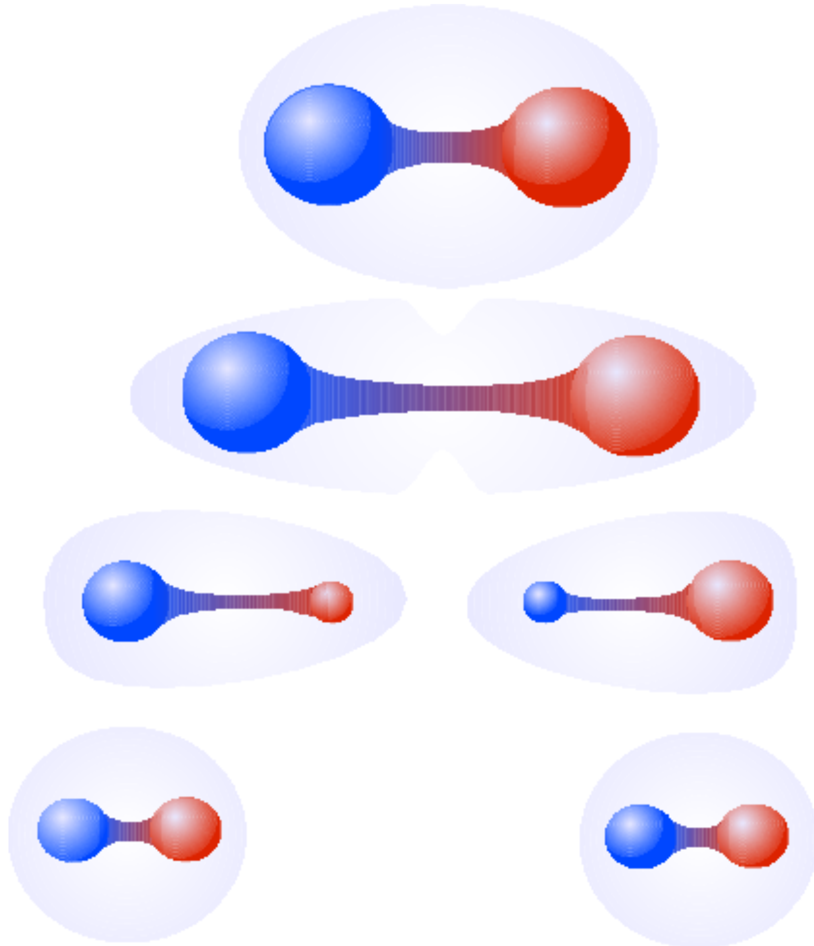
"Asymptotic freedom"
When quarks are close together, they essentially behave as if they're free

Increasing distance

Implications for the Strong Force

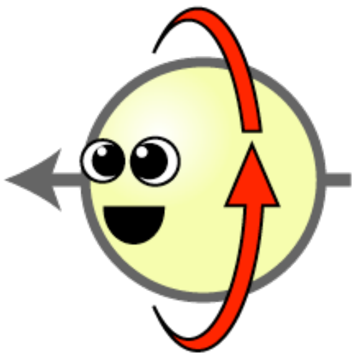
- Confinement leads to ***hadronisation***
  - Quarks and gluons produced in interactions combine to form hadrons



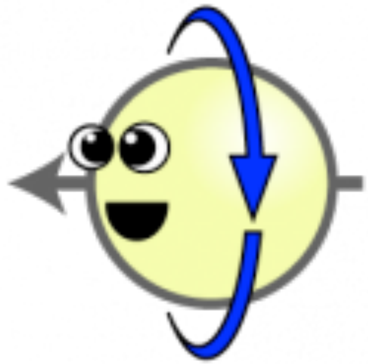


Helicity and Parity

- ***Helicity*** or the "handedness" of a particle is based on its spin relative to the direction of motion:



Right-handed



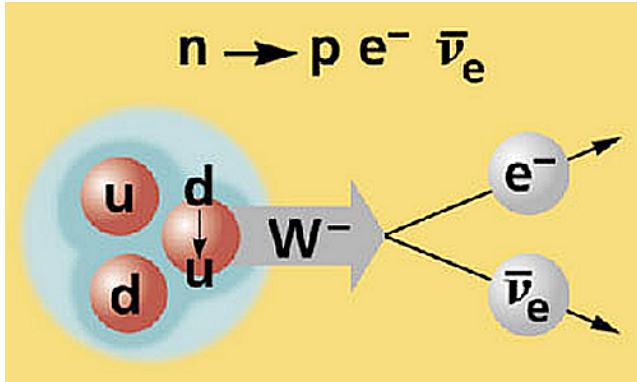
Left-handed

- ***Parity*** is an operation that switches right-handed particles for left-handed ones and vice versa
  - Creates a mirror image

Weak interactions

- Parity is conserved in Strong and EM interactions
  - Parity violation observed in weak interactions

- Quarks change flavour in weak interactions:



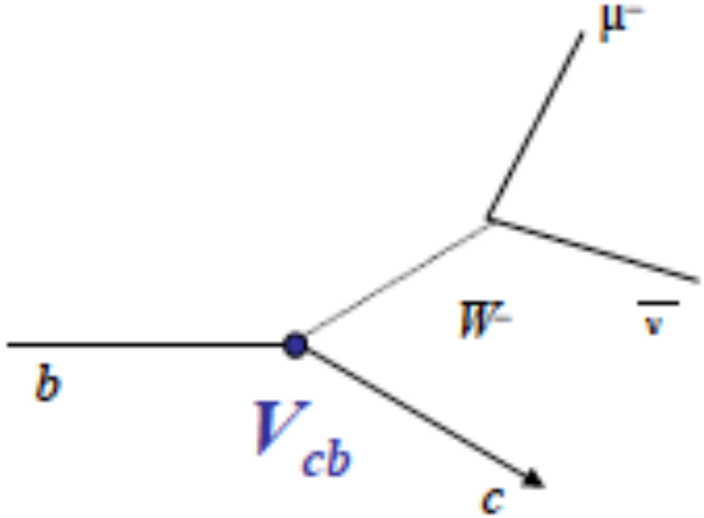
- Explain this using the Cabibbo-Kobayashi-Maskawa mechanism:

Mass states $$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$ Flavour states

The CKM Matrix

➢ What does the CKM Matrix mean?

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



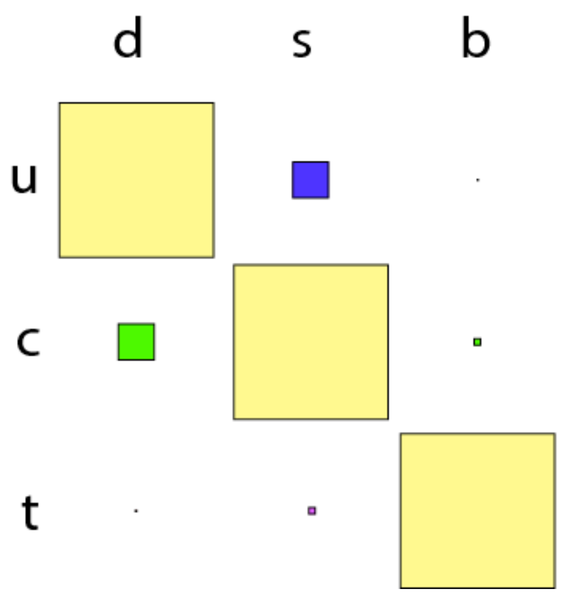
➢ Each element describes the probability of a transition from one quark flavour to another

➢ CKM matrix is a unitary matrix

  ➢ $VV^{-1} = VV^{\dagger} = I_3$

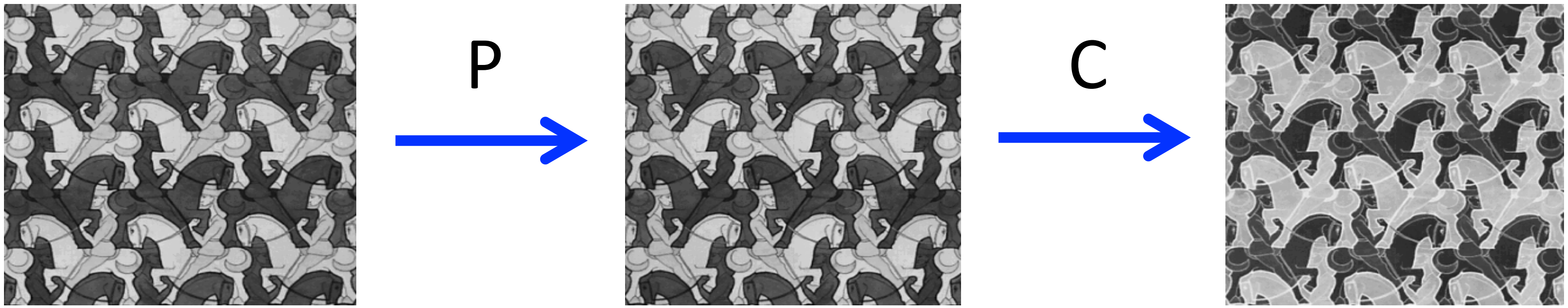
$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

$$V_{td}V_{ud}^{*} + V_{ts}V_{us}^{*} + V_{tb}V_{ub}^{*} = 0$$



Charge-Parity Conservation?

- Observed that both parity and "charge conjugation" (particles ←→ anti-particles) were violated in weak interactions
- Physicists therefore looked to the combined CP operation to restore symmetry



CP violation

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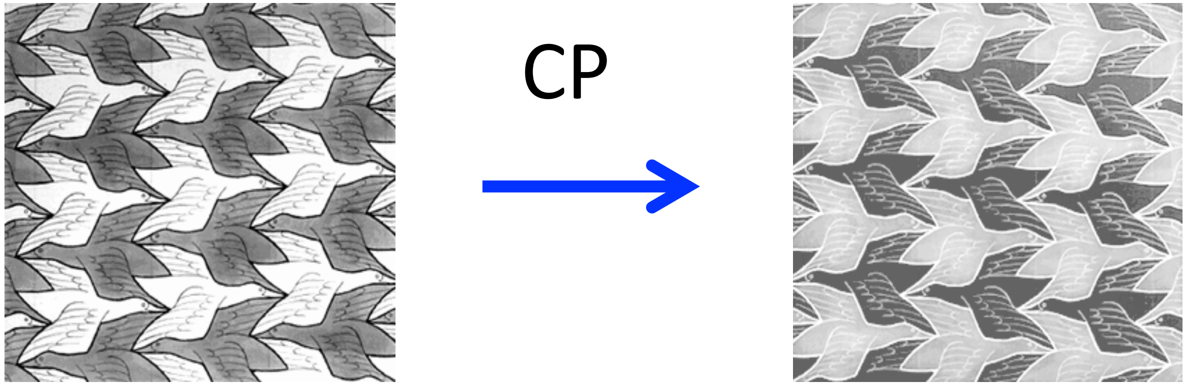


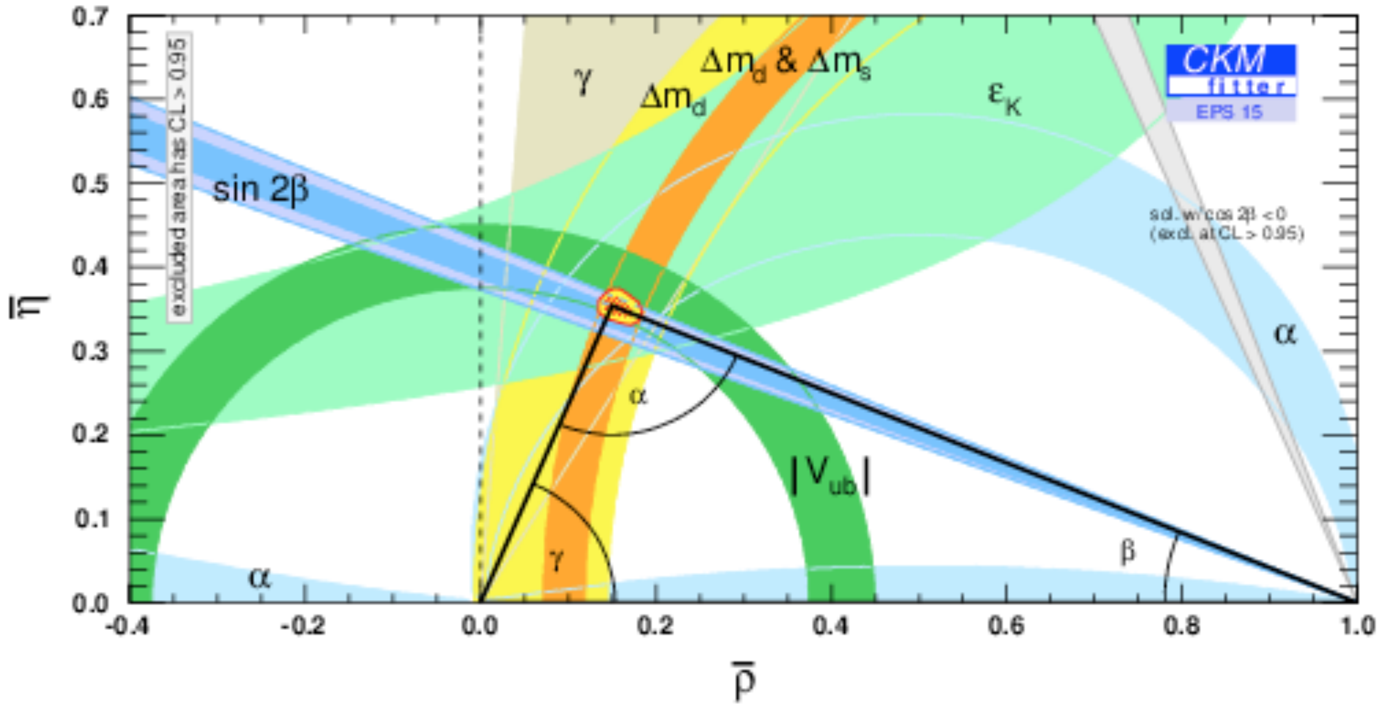
- CP was shown to be violated by studying neutral Kaons
  - K^0 is its own anti-particle ➔ "mixing"
- Mass states give us a K^0 with a short lifetime and another with a long lifetime

CP violation

- This is interesting, but why is it important?
- Matter-Antimatter Asymmetry
  - The Big Bang produced equal amounts of matter and antimatter
  - Today, the Universe is matter dominated
  - **What happened?**
- Need processes in which matter and antimatter behave differently to account for this:
  - **CP violation**
- The amount of CP violation so far observed is insufficient to explain the asymmetry
- The Standard Model accommodates CPV, but does not have a natural explanation for it …

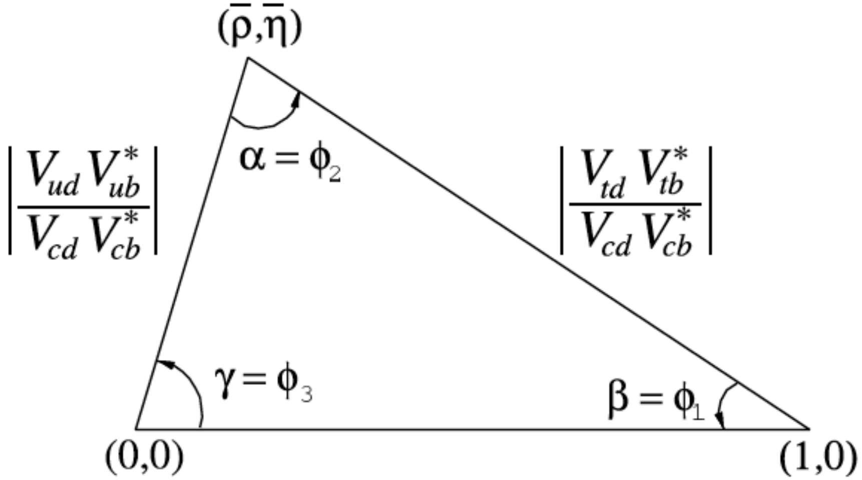
CP violation

- Use the CKM matrix to study CP violation



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

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



Electroweak unification

- $W^{\pm}$ boson has electric charge => suggests a connection between the Weak and Electromagnetic forces

- In the 1960s Glashow, Weinberg and Salam demonstrated that these forces are actually one single ***Electroweak force***
  - Won the 1979 Nobel Prize for Physics
  - W and Z bosons were experimentally observed in 1983 at CERN

- But … How can one force accommodate both a massless mediator (the photon) and two massive mediators (the W and Z bosons)?

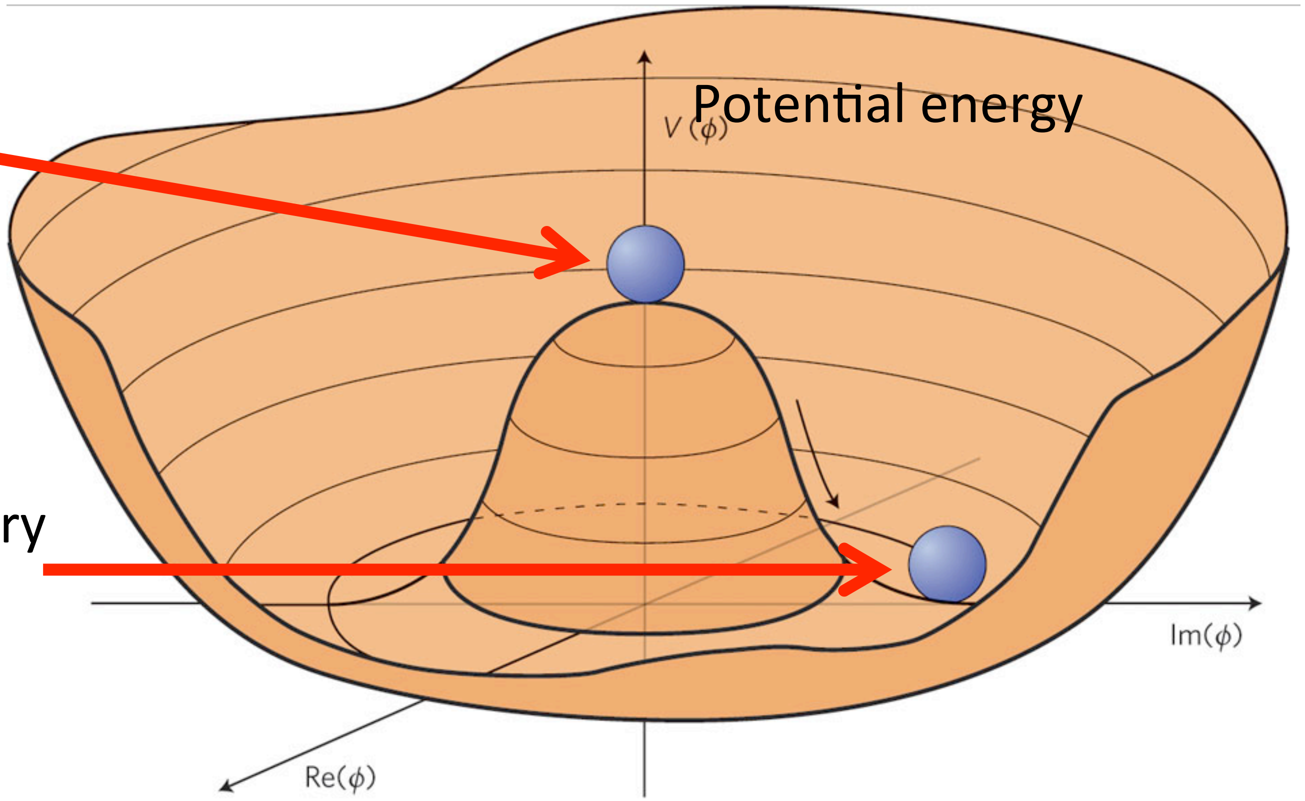
Electroweak Symmetry Breaking

- Theoretical framework for the entire Standard Model requires that "gauge symmetry" is preserved
  - This requires all particles to have zero mass
  - Clearly this is not true in reality!

- We need to break this symmetry without messing up the rest of the Standard Model
  - This is where the Higgs Mechanism comes in

The Higgs Mechanism

- Introduces a Higgs field:



At the Big Bang
Massless bosons

Shortly after (10^{-12}s)
spontaneous symmetry
breaking occurs
Massive bosons

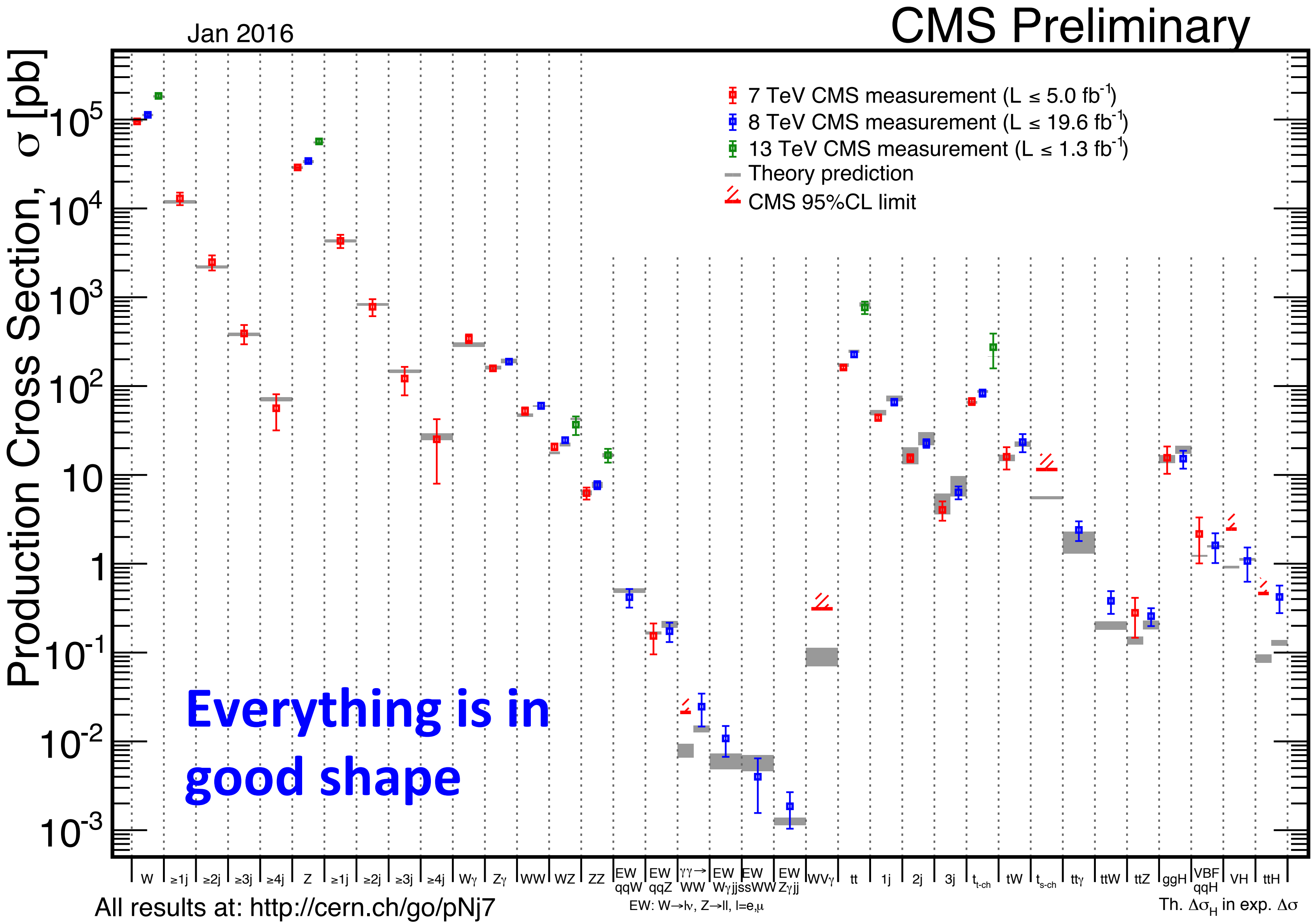
- Particles (fermions and bosons) gain mass from interaction with the field
- Higgs boson is a by-product of the existence of the Higgs field

The Standard Model

- The Standard Model is very successful
  - Very accurate predictions that have been experimentally verified

- How do we test the Standard Model?
  - Through experiment

The Standard Model



The Standard Model

- The Standard Model is very successful
  - Very accurate predictions that have been experimentally verified

- How do we test the Standard Model?
  - Through experiment

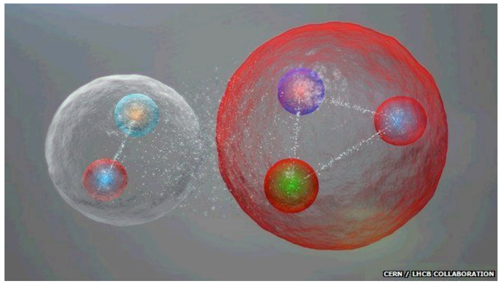
- How do we conduct an analysis of collisions provided by the LHC?
  - Use Higgs boson analysis as an example

What can we detect?

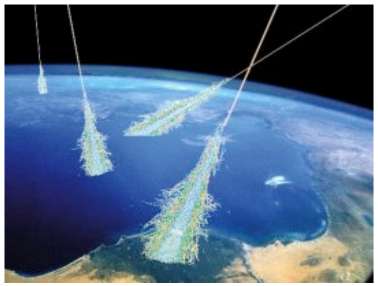
- A typical general purpose detector can identify the following:

- Charged particles
  - Anything with an electric charge
- Electrons & photons
  - Collectively known as “electromagnetic particles”

- Anything made of quarks
  - Collectively known as “hadronic particles”

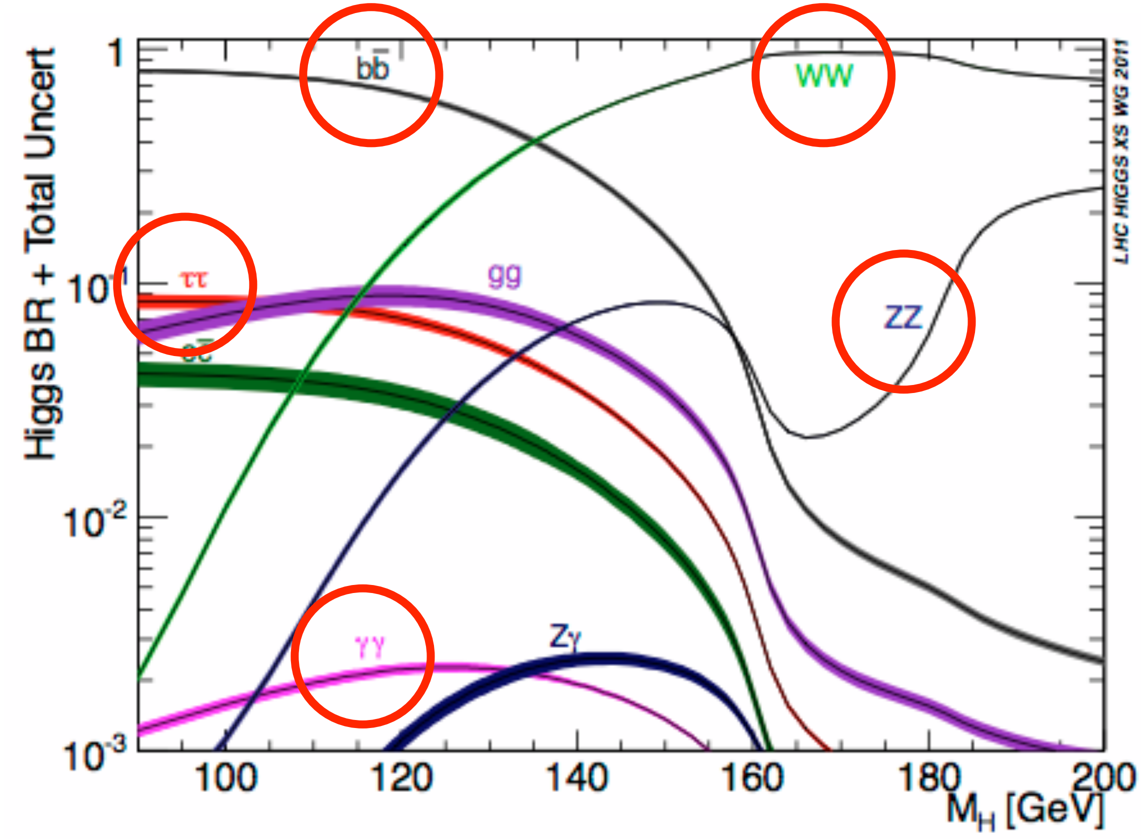


- Muons



Higgs Hunting

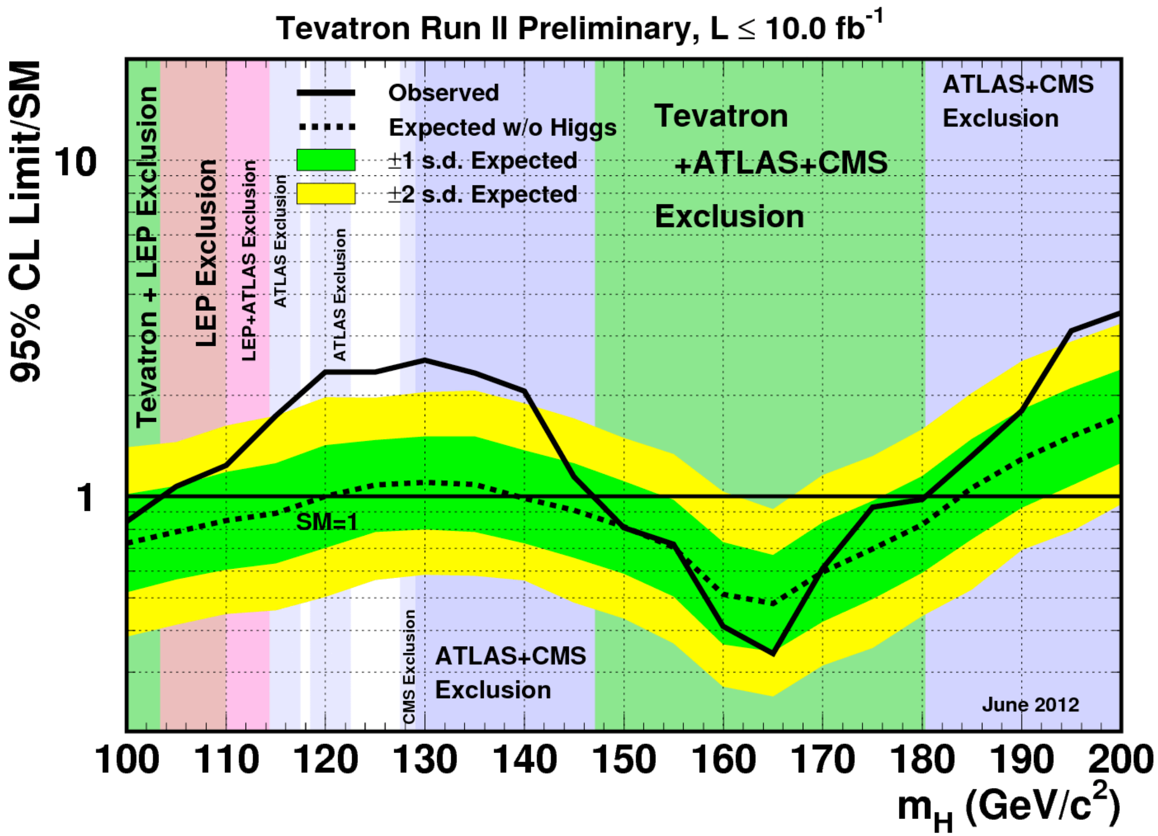
- The Higgs mechanism does not predict what the mass of the Higgs boson should be …
- So how do you find a Higgs if you don't know where to look?



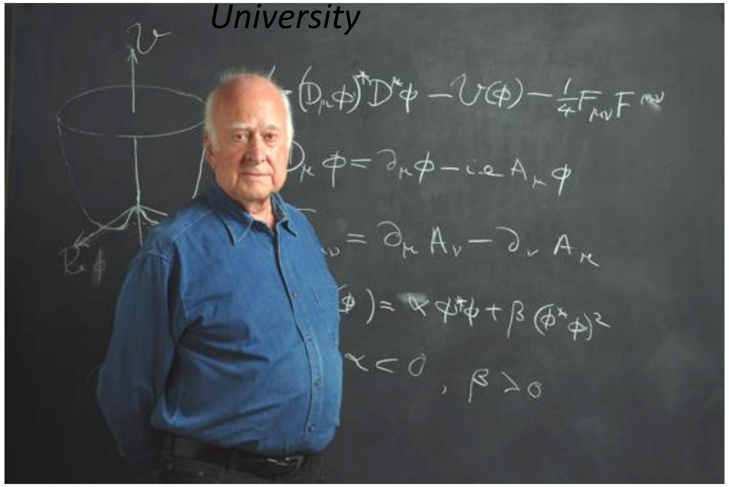
- Look for signatures in the data that could be produced by the Higgs and compare them to what is expected from the SM without the Higgs
  - Excess number of events in data ➔ something new …

Finding the Higgs Boson

- Using these techniques, many experiments have looked for the Higgs …



Courtesy of Edinburgh University

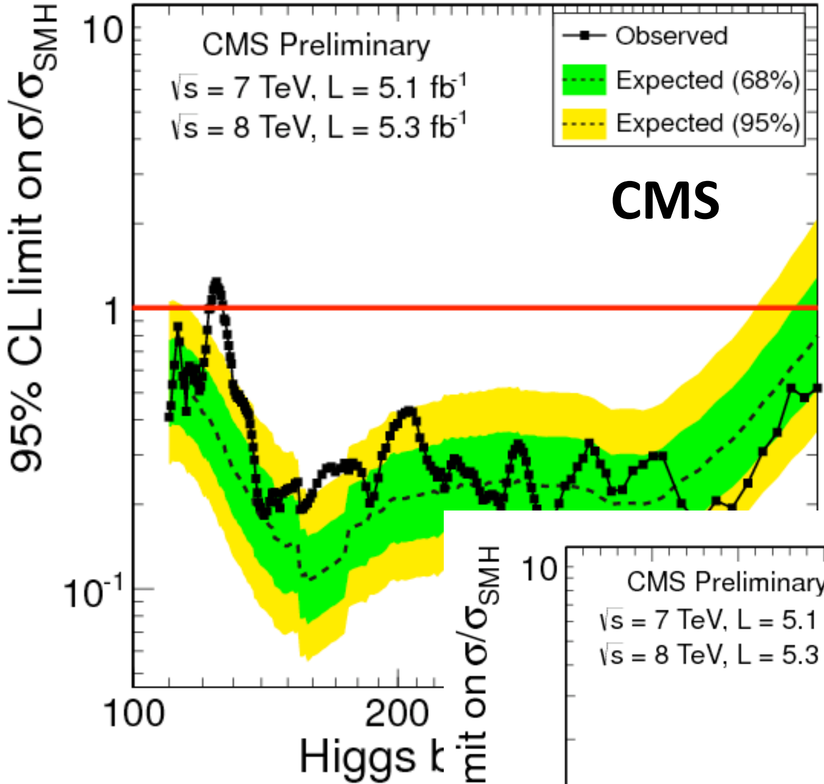


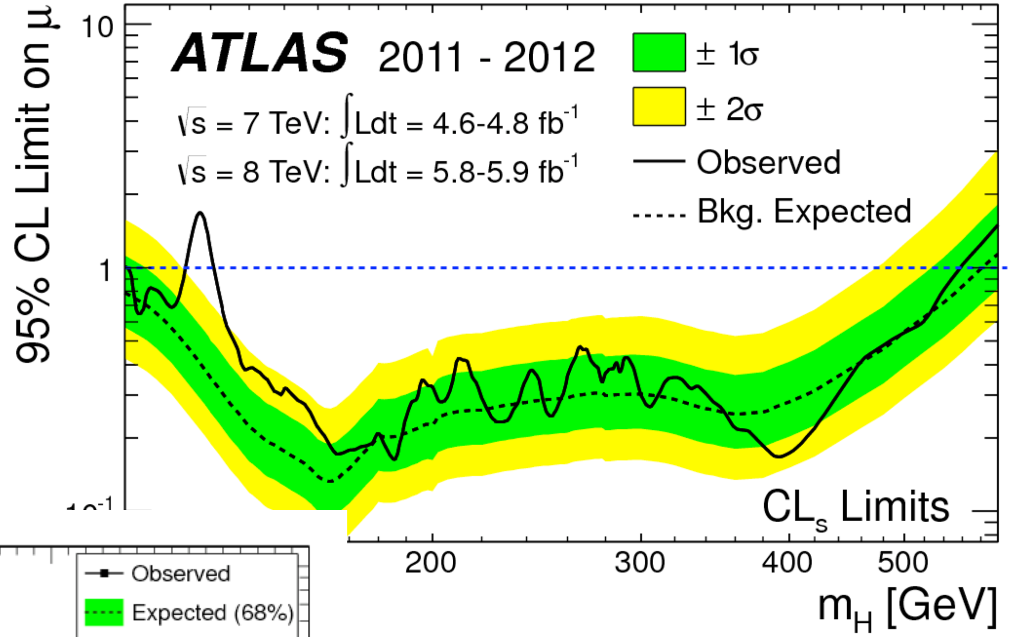
Prior to July 2012, the most concrete sighting of the Higgs …

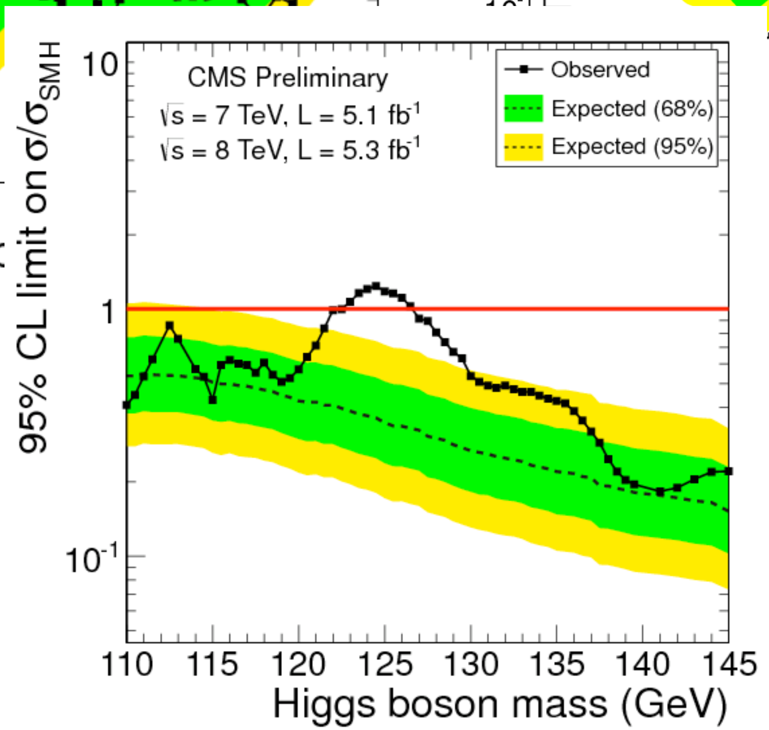
← The state of play in June 2012

And then one month later?

Observation of a new boson





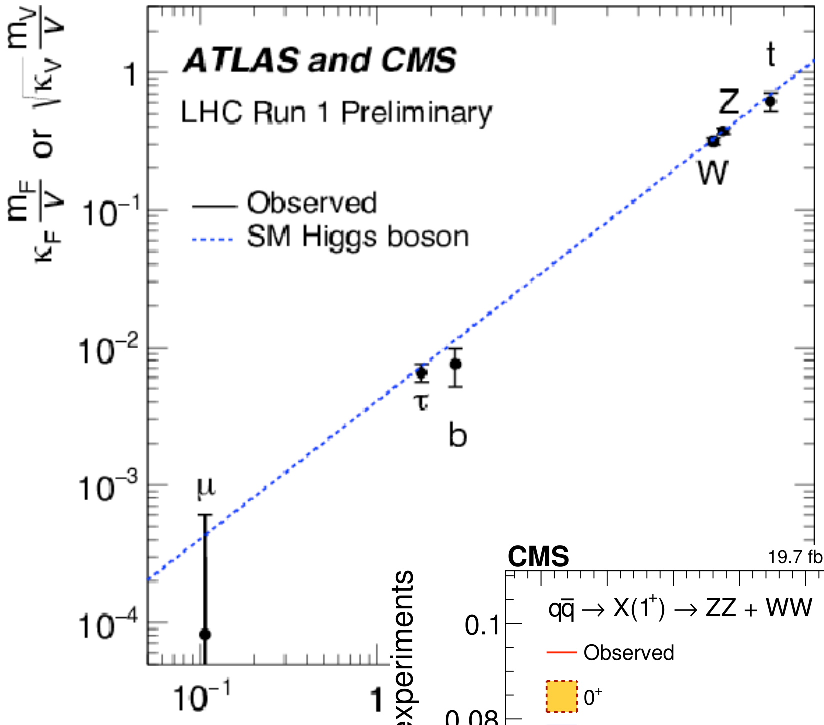


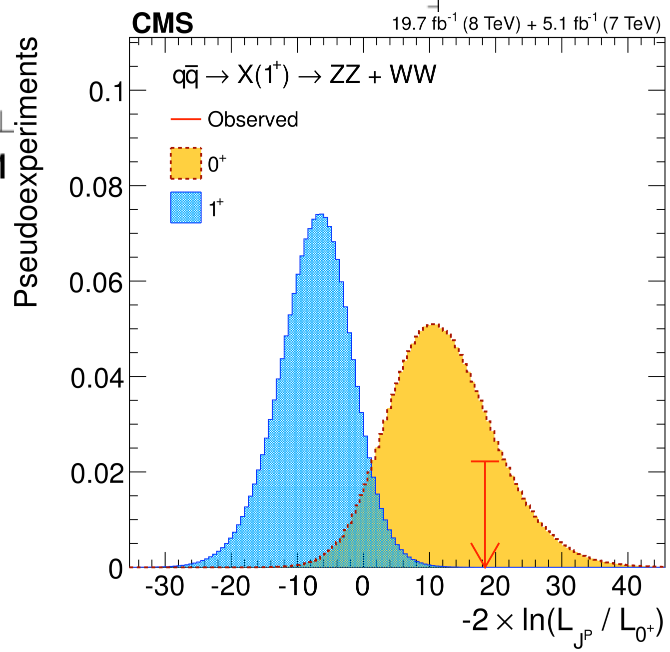
On 4th July 2012 the CMS and ATLAS Collaborations announced the observation of a new "Higgs-like" boson

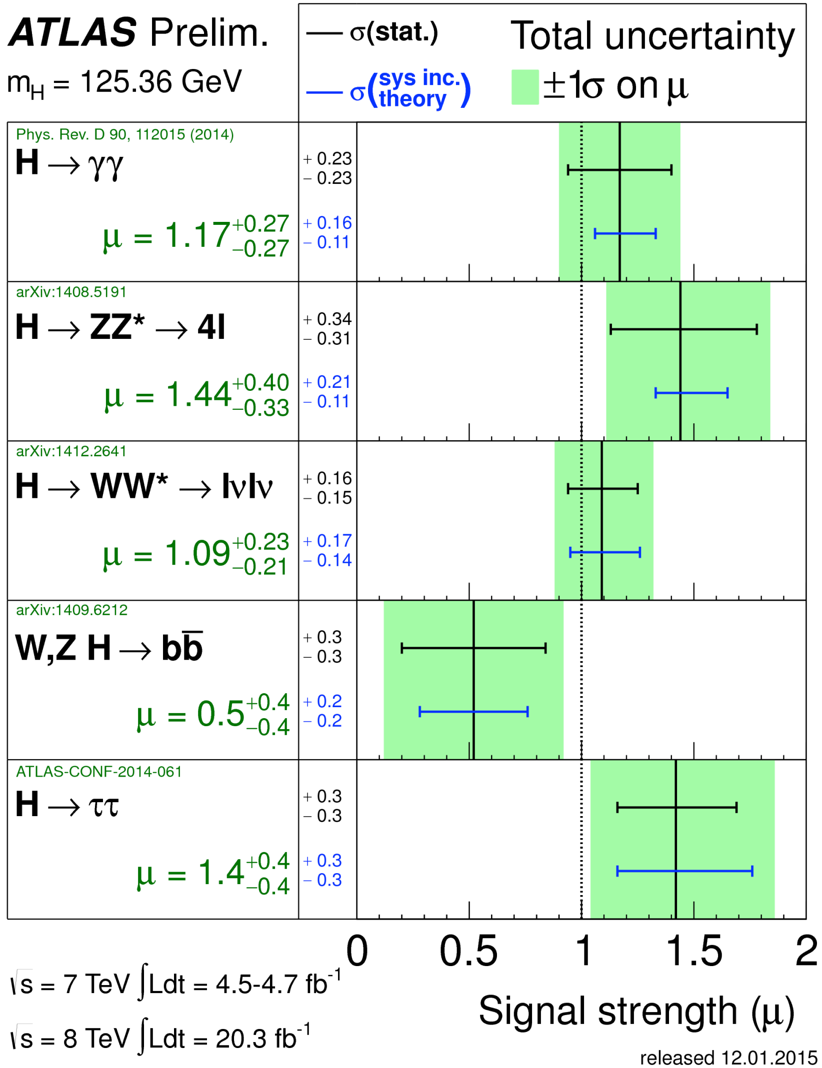
Why "Higgs-like"?

- What is it that we found?
  - A boson with spin ≠ 1 and mass approximately 125 GeV
  - Appears to decay as expected for the SM Higgs boson
- But that is all we knew in July 2012!
- There is more than one model that predicts the existence of the Higgs
- There are other models that can explain the masses of fundamental particles (and predict the existence of new bosons)
  - But they do not use the Higgs mechanism
- So what do we know now?

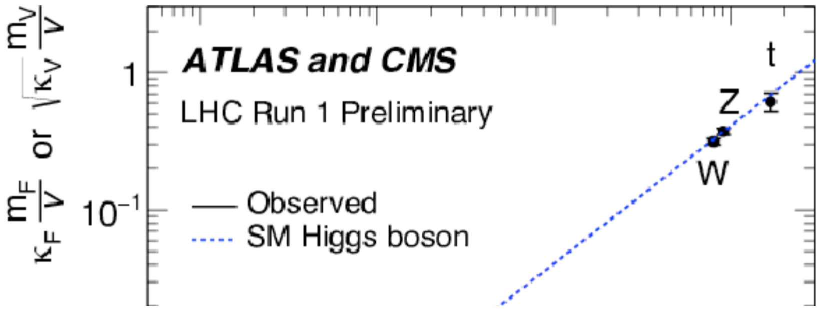
And now …?

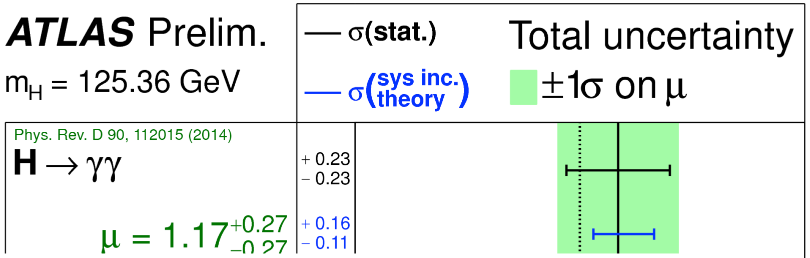

ATLAS and CMS
LHC Run 1 Preliminary
Observed
SM Higgs boson
t
Z
W
τ
b
μ
κF mF/V or √κV mV/V
1
10^-1
10^-2
10^-3
10^-4
10^-1
1


CMS
19.7 fb^-1 (8 TeV) + 5.1 fb^-1 (7 TeV)
qq̄ → X(1^+) → ZZ + WW
Observed
0^+
1^+
Pseudoexperiments
0.1
0.08
0.06
0.04
0.02
0
-30
-20
-10
0
10
20
30
40
-2 × ln(L_J^P / L_0^+)


ATLAS Prelim.
m_H = 125.36 GeV
σ(stat.)
σ(sys inc. theory)
Total uncertainty
±1σ on μ
Phys. Rev. D 90, 112015 (2014)
H → γγ
μ = 1.17 +0.27 −0.27
+ 0.23
− 0.23
+ 0.16
− 0.11
arXiv:1408.5191
H → ZZ* → 4l
μ = 1.44 +0.40 −0.33
+ 0.34
− 0.31
+ 0.21
− 0.11
arXiv:1412.2641
H → WW* → lνlν
μ = 1.09 +0.23 −0.21
+ 0.16
− 0.15
+ 0.17
− 0.14
arXiv:1409.6212
W,Z H → bb̄
μ = 0.5 +0.4 −0.4
+ 0.3
− 0.3
+ 0.2
− 0.2
ATLAS-CONF-2014-061
H → ττ
μ = 1.4 +0.4 −0.4
+ 0.3
− 0.3
+ 0.3
− 0.3
0
0.5
1
1.5
2
√s = 7 TeV ∫Ldt = 4.5-4.7 fb^-1
√s = 8 TeV ∫Ldt = 20.3 fb^-1
Signal strength (μ)
released 12.01.2015

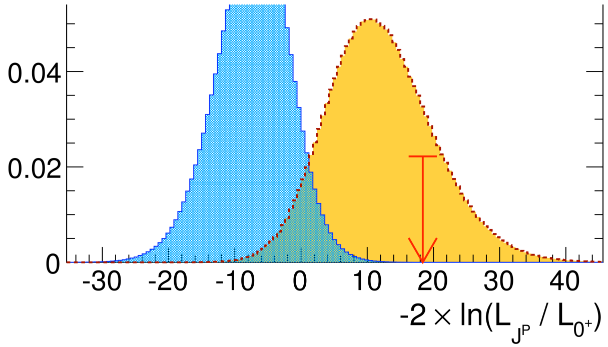
And now …?

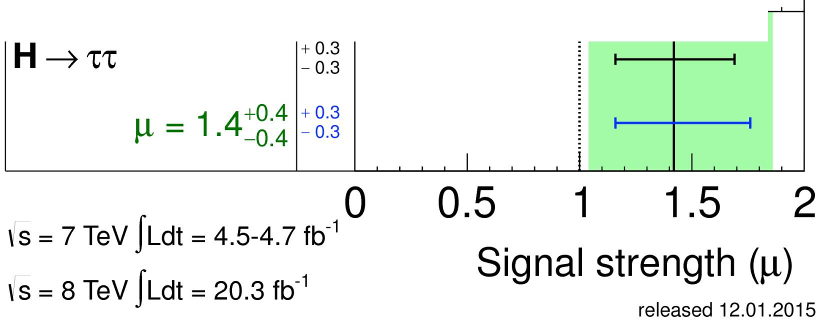




Everything is consistent with the properties of a Higgs boson

We are now willing to call it "a" Higgs boson





Why “a” Higgs boson?

- We know this can’t be the end of the story

- Higgs mechanism was added to the Standard Model “by hand”
  - We’d like a theory that naturally includes it

- There are also problems with the mass of the Higgs …

The mass of the Higgs boson

- The problem is known as the Hierarchy problem
  - Quantum corrections mean that the Higgs should be much heavier than ~125 GeV

- Consider putting an ice cube somewhere hot
  - If we'd put it in the oven, we'd be really surprised if it hadn't melted after 10 mins
  - Highly improbable
- We expected the Higgs to have a similar mass to the W and Z, which it does
  - But the theory says this is highly improbably
- **How can we explain this?**

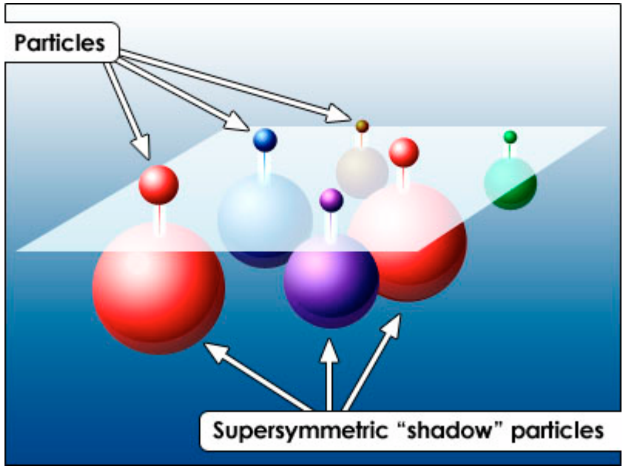
Beyond the Standard Model

- In order to explain the Higgs mass, we need to go beyond the Standard Model

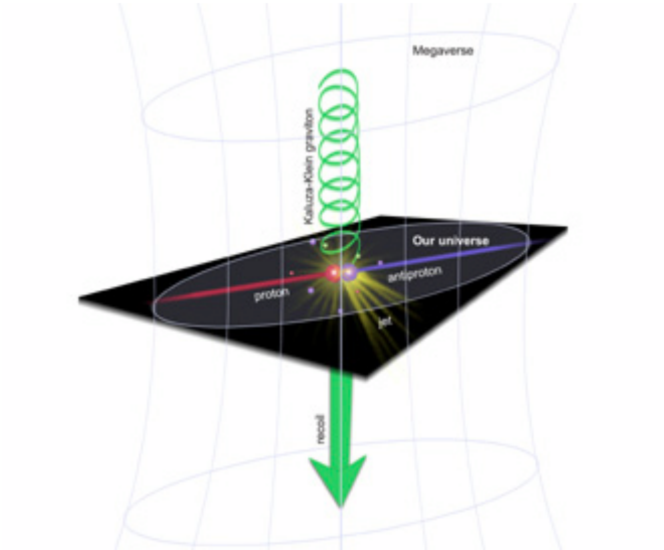
- We also need to answer some other basic questions like:

    - Why are there only four forces ?
    - Why is there a matter-antimatter asymmetry ?
    - What are dark matter and energy ?
    - Why are there only three generations ?
    - …

Beyond the SM: The contenders

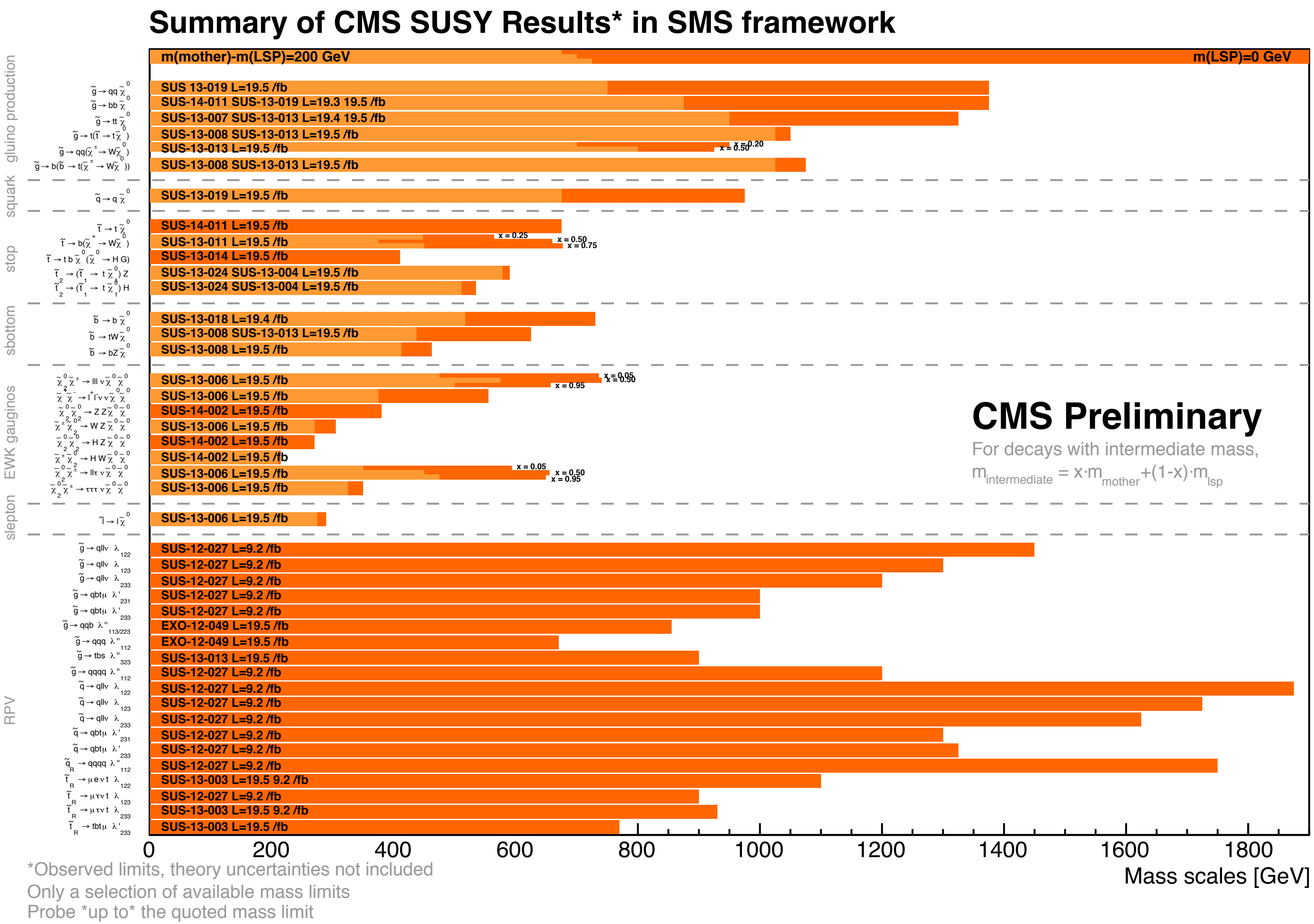


- Supersymmetry
  - Includes 5 Higgs bosons
  - Unifies forces at very high energies
  - Provides a candidate for dark matter
  - Solution for the “hierarchy problem”



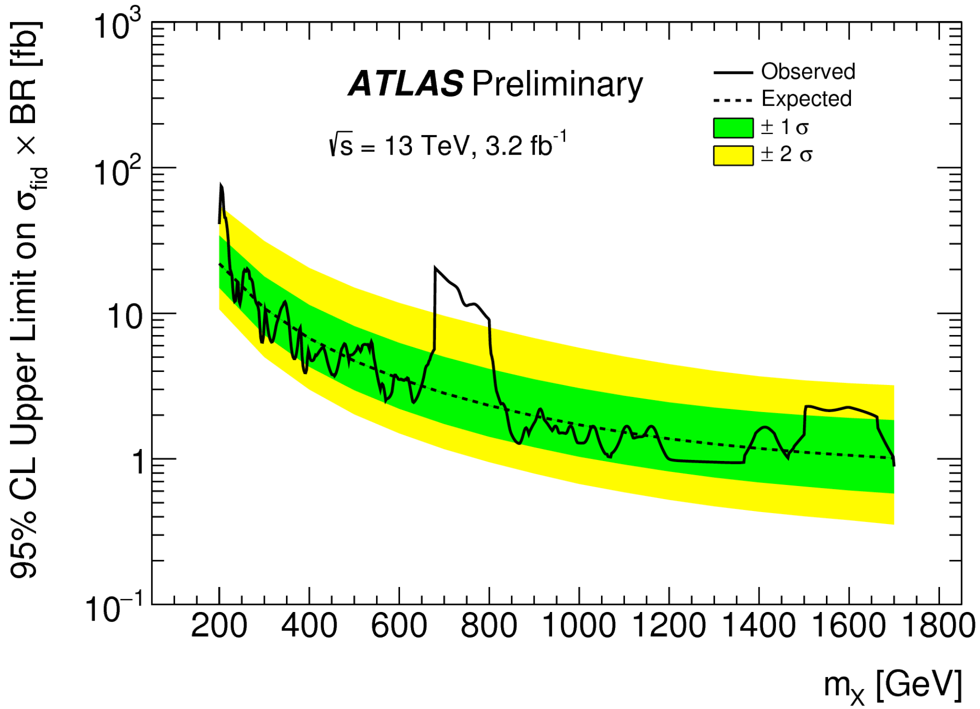
- Extra dimensions
  - Framework for including gravity in the SM
  - Solution to the “hierarchy problem”
- Technicolour, Little Higgs, Hidden valley models, …

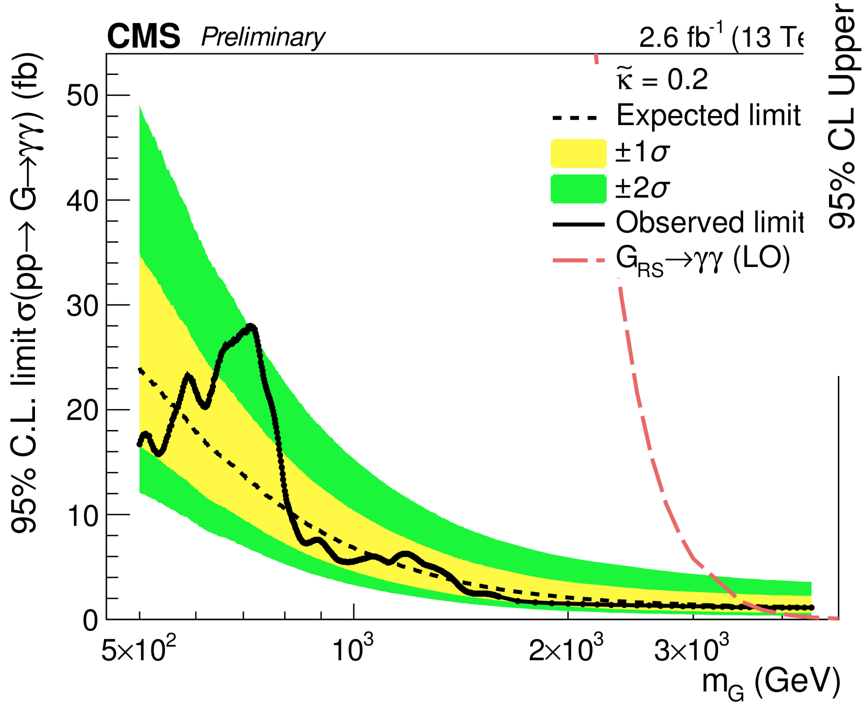
Supersymmetry



LHC Run 2

- Re-start of running in 2015: First look at data at centre-of-mass energy of 13 TeV
- Many new results
- One caused some interest:
- Diphoton resonance search





- 3.6σ excess in ATLAS data
- 2.6σ excess in CMS data
- Combines to ~4σ
- Interesting, but we need more data

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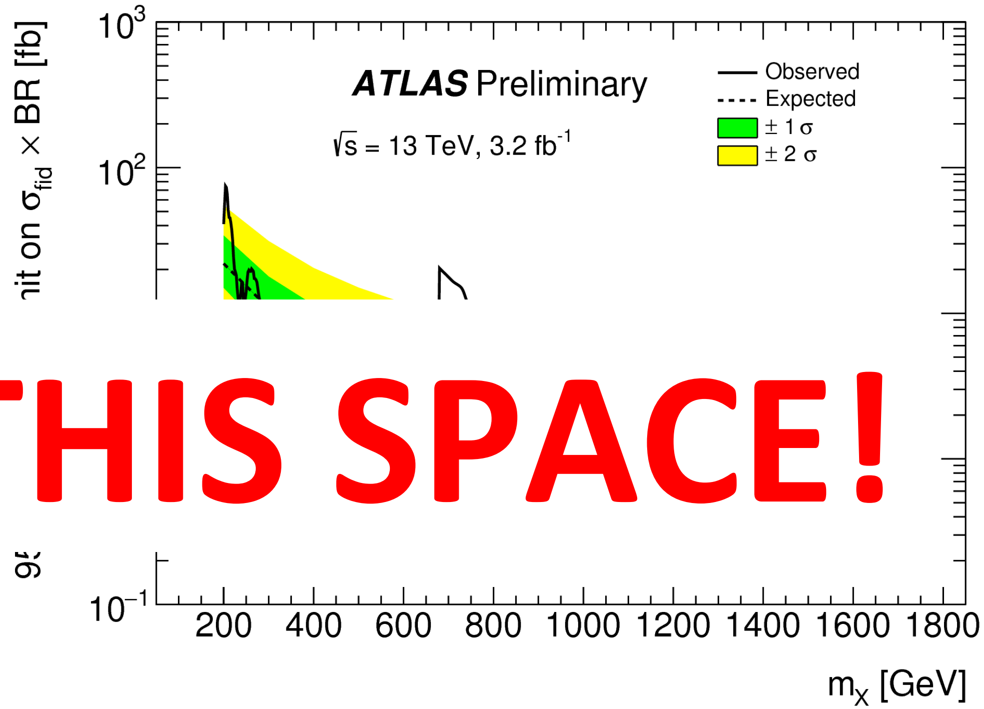
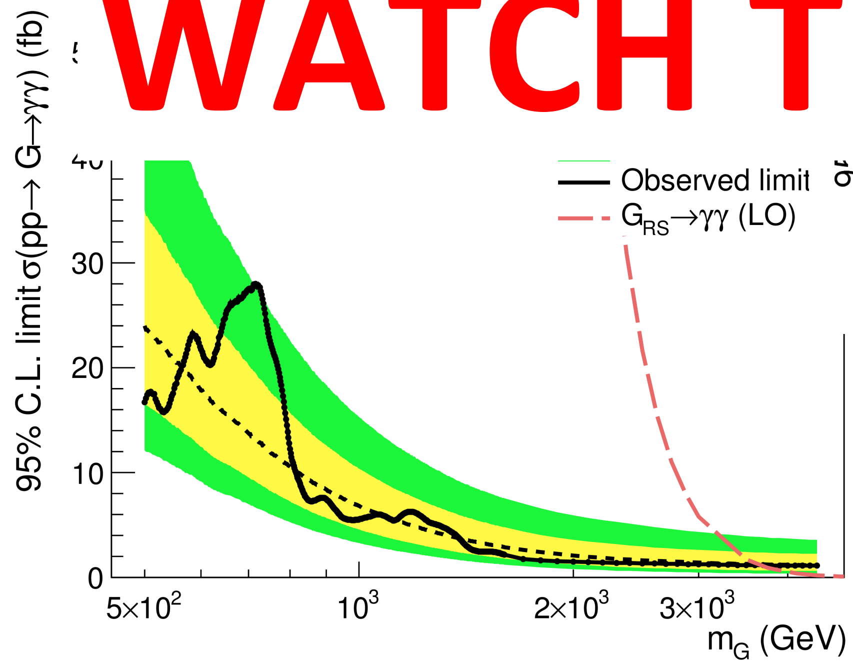


WATCH THIS SPACE!



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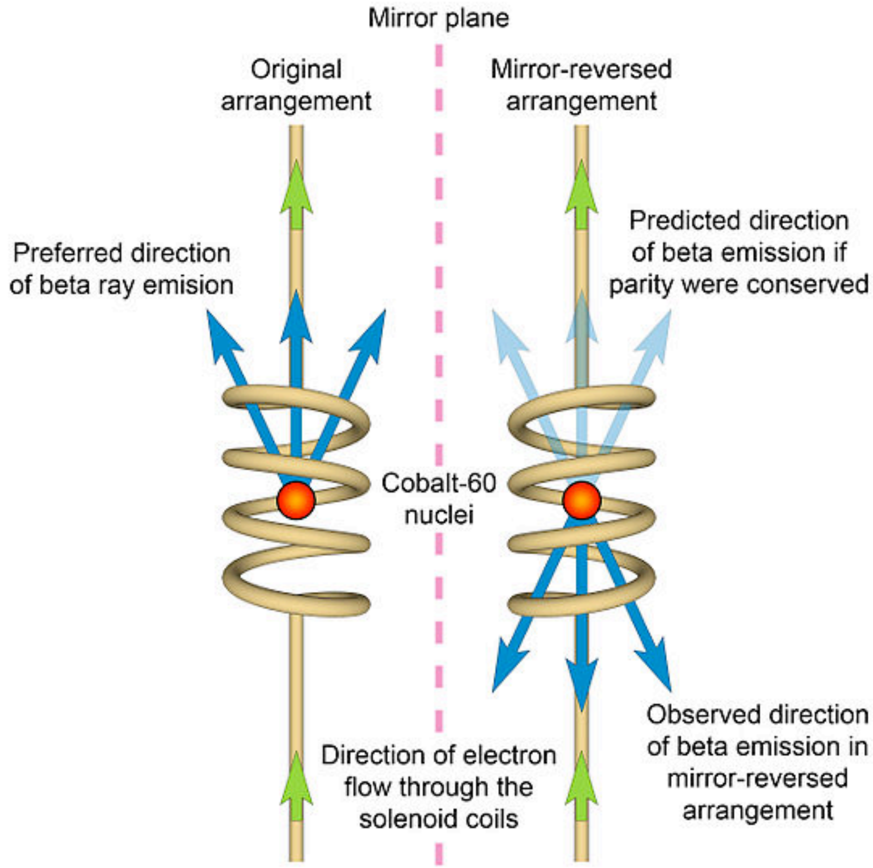
Brunel University London

Additional Material

Parity Violation

- Parity conserved in EM and Strong interactions
- In 1956 Lee and Yang proposed that parity should be violated in weak interactions
- Experimentally confirmed in 1957 by Wu et al.
- Study beta decay of Co^{60}
- If parity conserved, expect to see equal amounts of e- in each direction



Coverage around the world

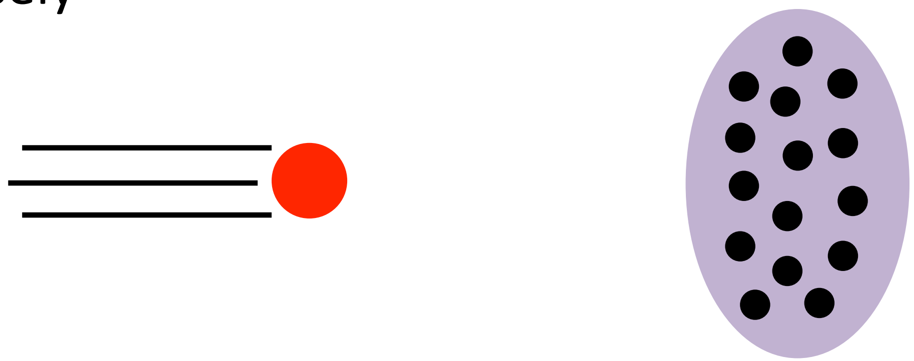
- Approximately 0.5 Million people watched the seminar live
- More than 1 Billion people saw highlights of the seminar

Twitter trends on 4th July 2012

What is a "cross section"?

- The probability that two particles will collide and react in a certain way

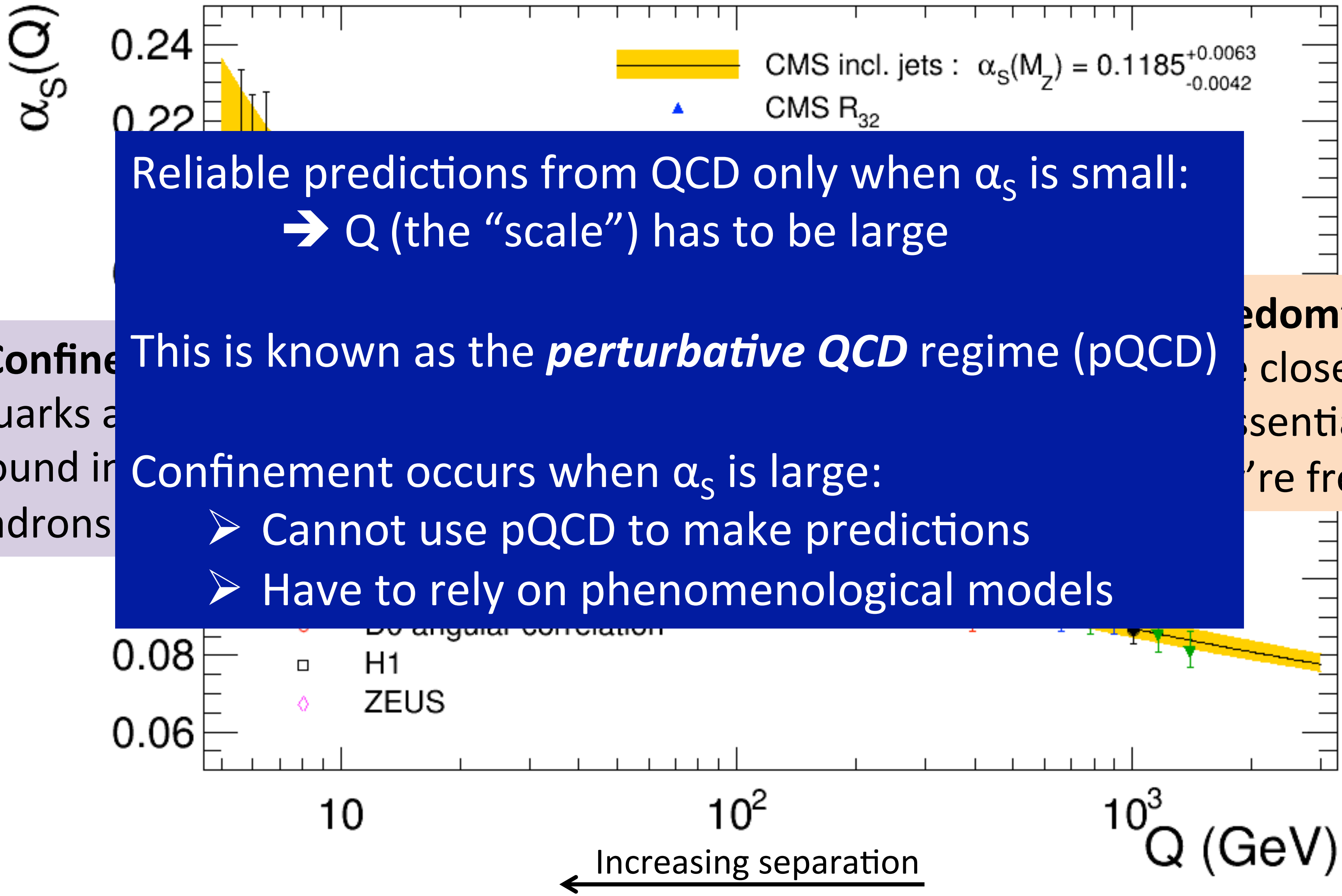
- Why do we call this a cross section?
  - Originally thought of particles as tiny, indestructible balls
  - Fundamental particles so small, impossible to aim them at each other precisely



Collision probability = ratio of area of projectiles to total area of the cloud

Subsequently realized the analogy isn't the right one, but the name stuck

Making predictions using QCD



Reliable predictions from QCD only when α_S is small:

➔ Q (the "scale") has to be large

This is known as the ***perturbative QCD*** regime (pQCD)

Confinement occurs when α_S is large:

- Cannot use pQCD to make predictions
- Have to rely on phenomenological models

"Confine

Quarks a
bound ir
hadrons

edom"

close
sentially
're free