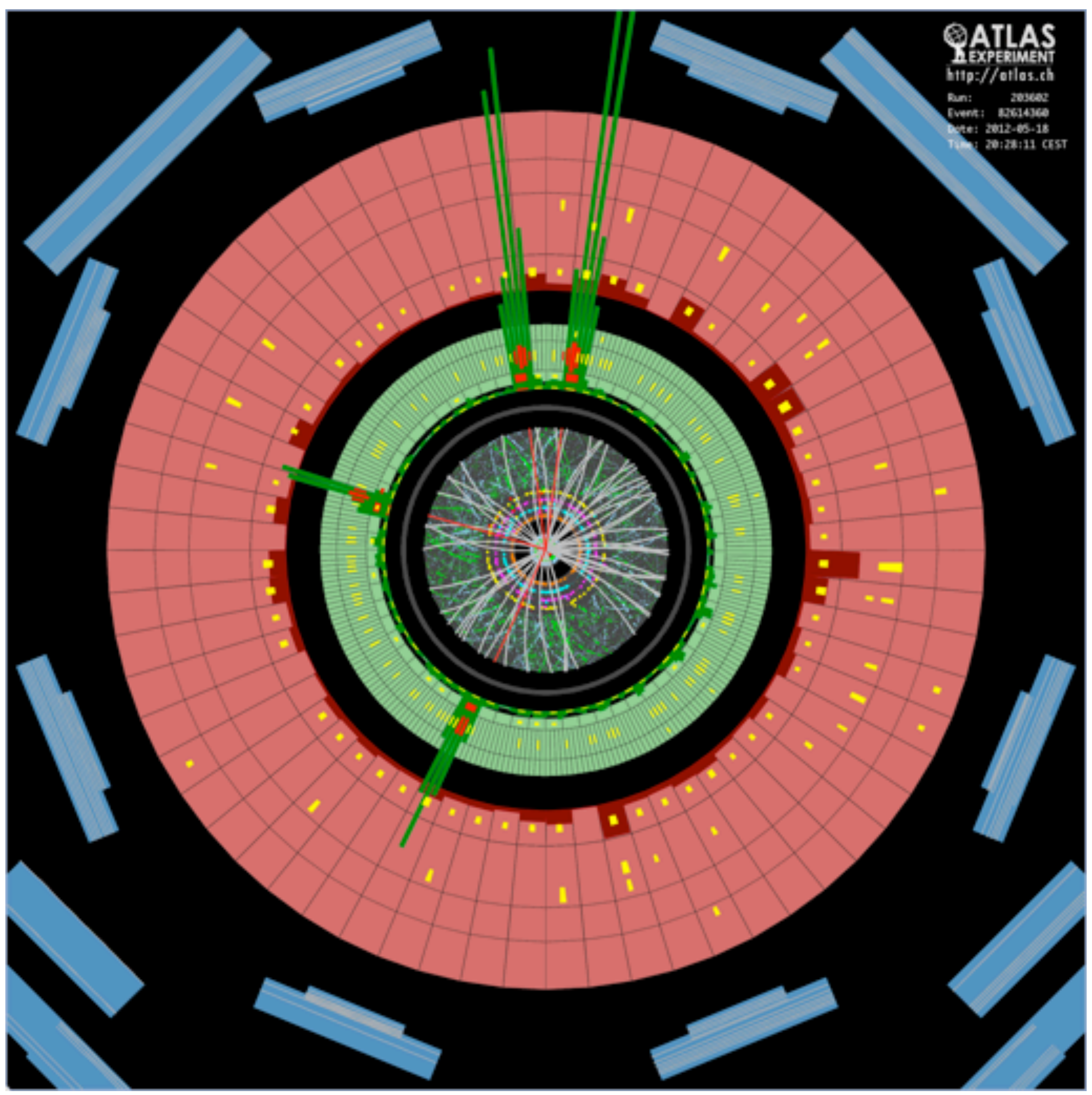
Particle Physics

Dr Victoria Martin, Spring Semester 2013
Lecture 1: The Mysteries of Particle Physics,
or “Why should I take this course?”



Contents:

- Review of the Standard Model
  - ➡ What we know
  - ➡ What we don’t know
- Highlights from 2012 particle physics
  - ➡ What we know now that we didn’t know this time last year

Course Organisation

Teaching weeks: 14 January - 15 February; 25 February - 5 April

ILW: 18 - 22 February (no lectures)

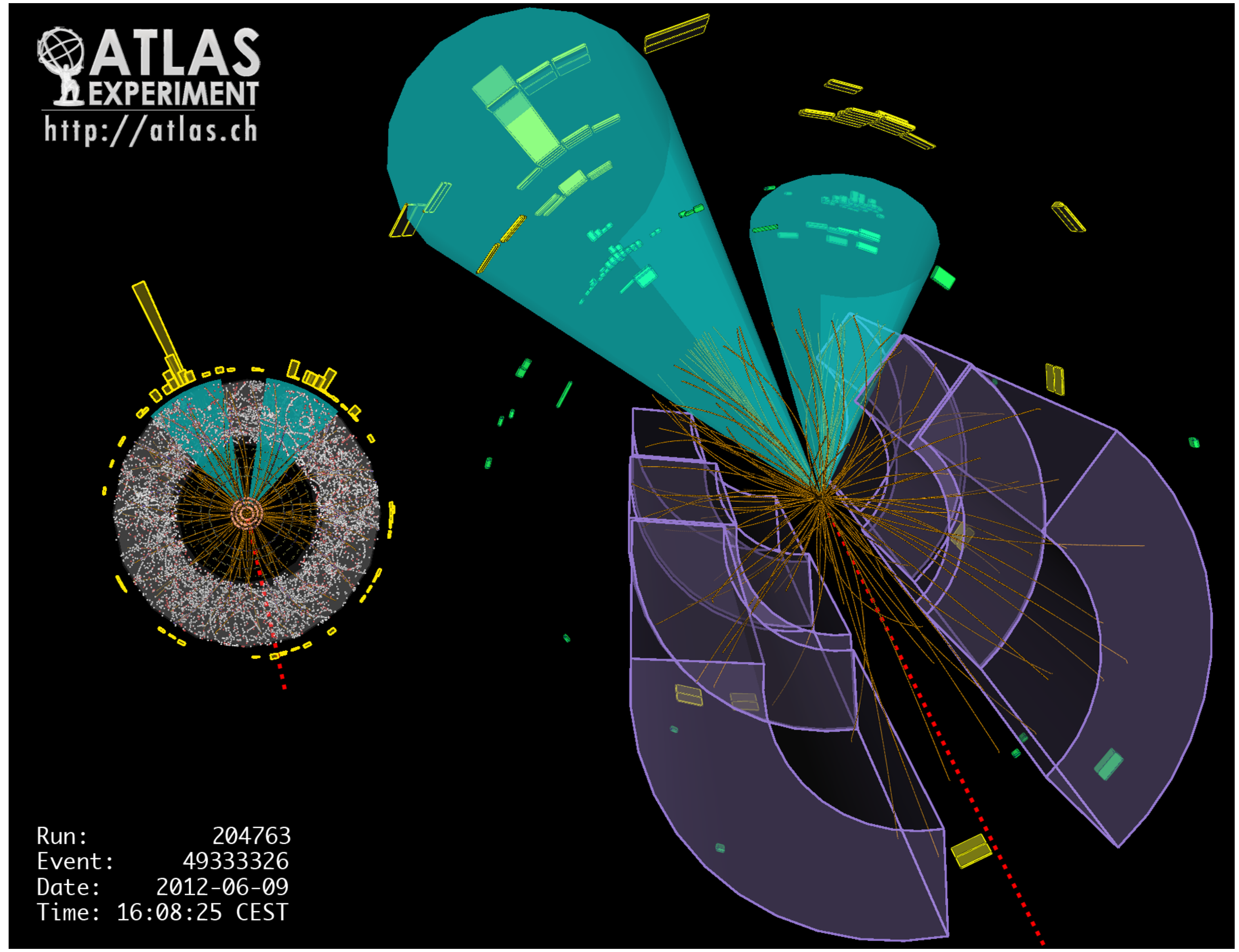
Particle Physics course:

- **18 Lectures**: Tuesday, Friday 12:10-13:00 (JCMB 5215)
  - No PP lectures: 10 Feb, 6 April
  - Two themes: **Particles & interactions of the Standard Model, Current topics in particle physics**
- **Tutorials**: Monday 3-5 in 5326
- I'll try to recommend reading for the course from *Introduction to Elementary Particle Physics* by David Griffiths. (7 copies in Darwin Library)

- Printed notes and problem sheets handed out periodically and available on the web.
- Lecture slides (and eventually solution sheets) will only be available on the web.

Me

- Dr Victoria Martin, JCMB 5419
- I work on the ATLAS experiment at the Large Hadron Collider at CERN.
- I currently lead the University of Edinburgh ATLAS team of ~20 PhD students, postdoctoral researchers and academics



- I also have an interest in future colliders e.g. a high energy $e+e-$ collider
- Personal interest: looking for the decay of the Higgs boson into quarks, *e.g.* $H \rightarrow b\bar{b}$

References & Websites

- Course website: http://www2.ph.ed.ac.uk/~vjm/Lectures/SH_IM_Particle_Physics_2013.html

Introductory textbooks

- D.Griffiths – *Introduction to Elementary Particles* (Wiley 2008)
- C. Tully - *Elementary Particle Physics in a Nutshell* (Princeton 2011)
- B.R.Martin & G.Shaw – Particle Physics (Wiley 1997)
- D.H.Perkins – Introduction to High Energy Physics (CUP 2000)

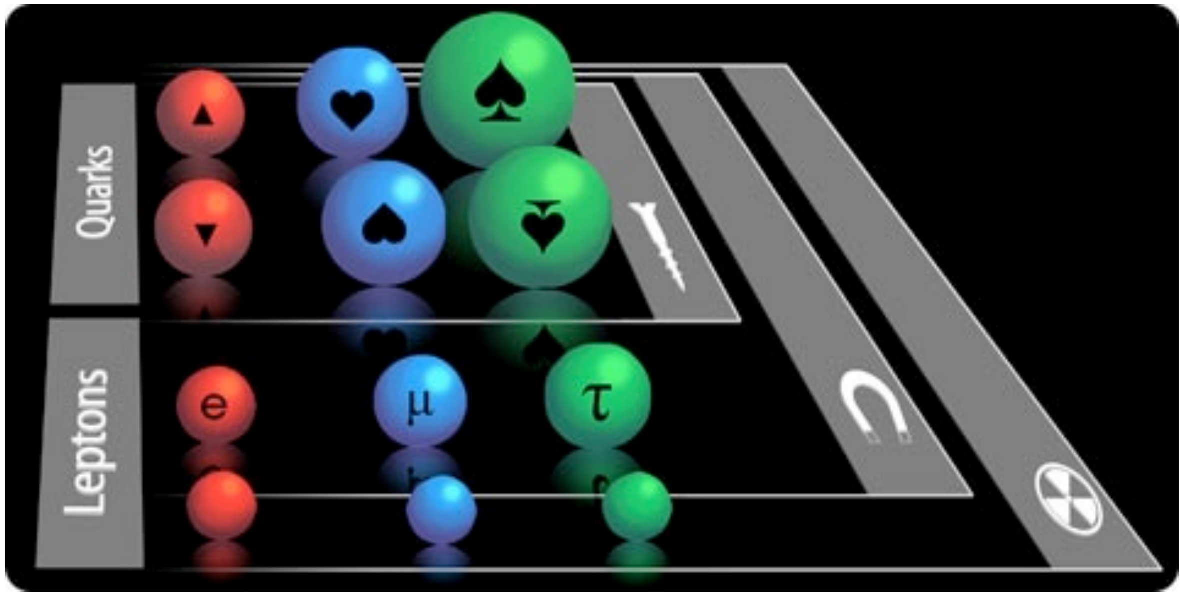
More advanced textbooks

- F.Halzen & A.D.Martin – Quarks & Leptons (Wiley 1984)
- A.Seiden – Particle Physics: A Comprehensive Introduction (Addison-Wesley 2005)
- I.J.R.Aitchison & A.J.G.Hey – Gauge Theories in Particle Physics (Hilger 1989)

Useful websites

- ✧ CERN/LHC http://public.web.cern.ch/public
- ✧ Particle Data Group (PDG) http://pdg.lbl.gov

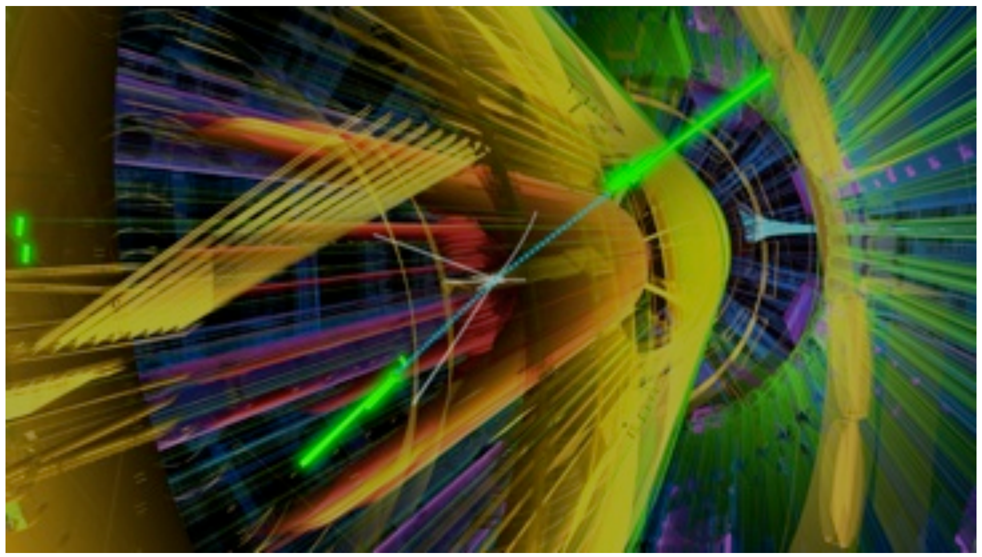
Particles & Interactions of the Standard Model

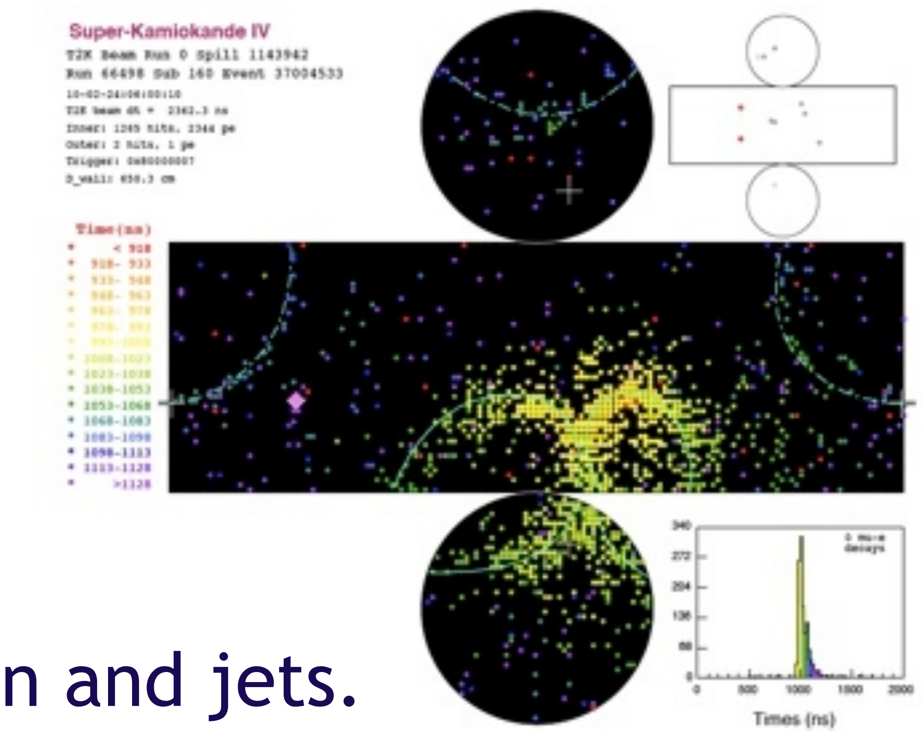


1. Introduction: *The Mysteries of the Standard Model*
2. Forces, feynman diagrams, scattering.
3. Dirac equation & spinors.
4. Electromagnetic interactions: Quantum Electrodynamics (QED).
5. Weak Interactions, Weak decays & Neutrino scattering.
6. Deep inelastic scattering, the parton model & parton density functions.
7. Strong interactions: Quantum Chromodynamics (QCD) and Gluons.
8. Quark model of hadrons. Isospin and Strangeness. Heavy quarks.

Current Topics in Particle Physics

Content to be finalised, but probably including...



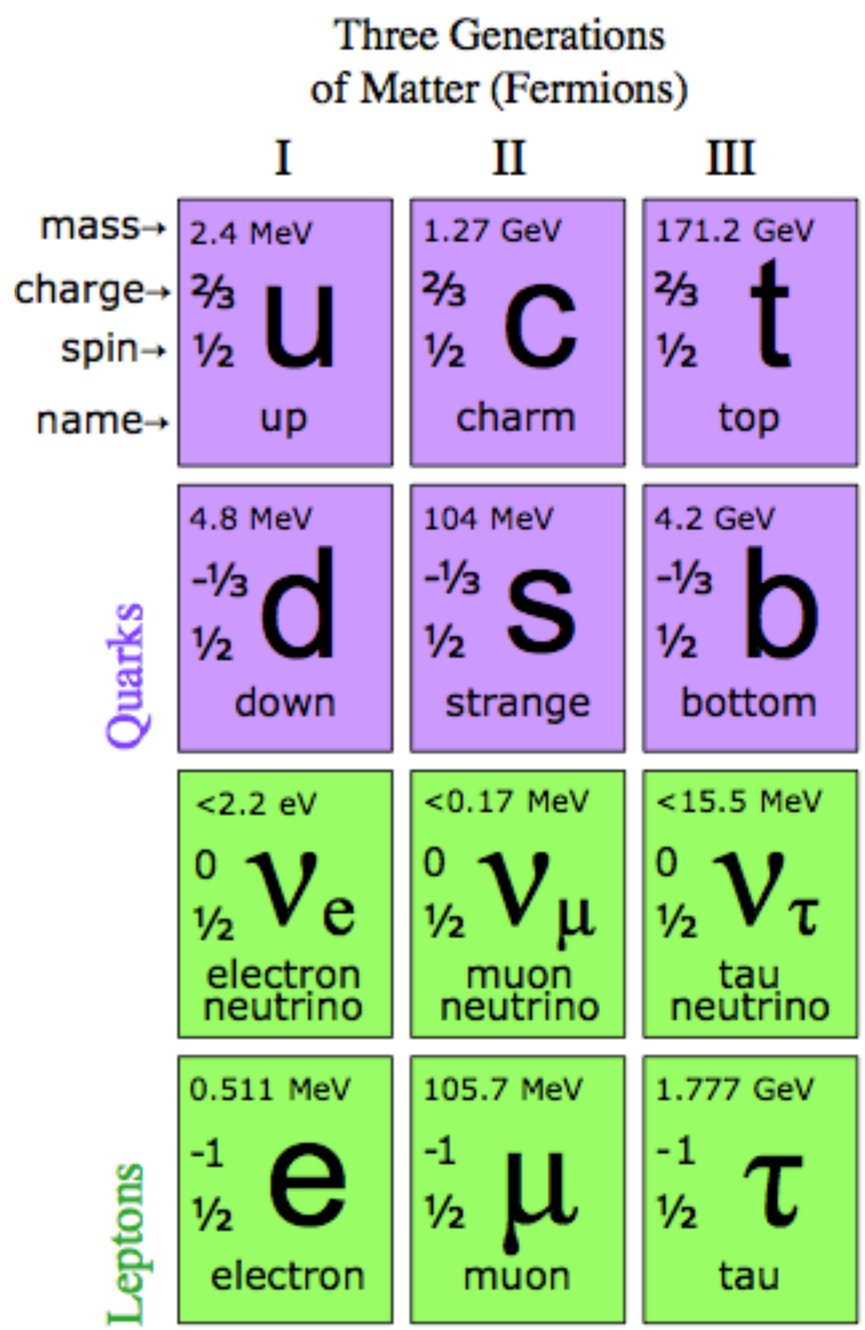


10. Hadron production at Colliders, Fragmentation and jets.
11. Weak decays of hadrons. CKM matrix.
12. Symmetries. Parity. Charge conjugation. Time reversal. CP and CPT.
13. Mixing and CP violation in K and B meson decays.
14. Neutrino oscillations. MNS matrix. Neutrino masses.
15. Electroweak Theory. W and Z boson masses.
16. Spontaneous symmetry breaking and the Higgs boson.
17. Beyond the Standard Model. Supersymmetry. Grand unification.
18. Recent physics results at the LHC.

Standard Model Matter Particles

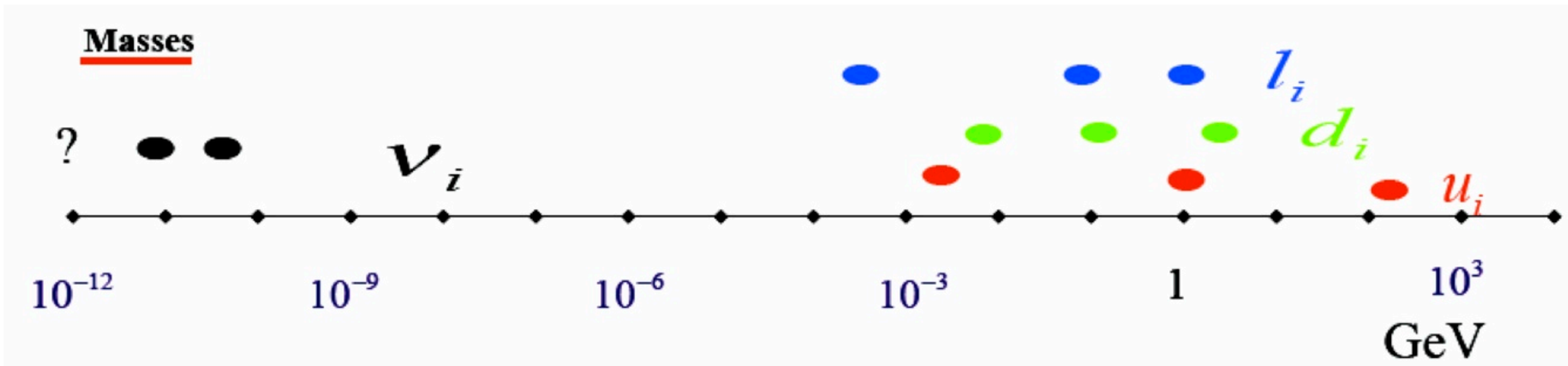
- Matter particles are observed to be $s=½$ fermions.
- Two distinct types: **quarks** and **leptons**.
- Grouped into three, successively heavier, generations.
- Four key quantum numbers: charge (Q), isospin (I_Z), baryon number (B), lepton number (L)

Q Charge	I_Z Isospin	B Baryon Number	L Lepton Number
+2/3 e	+1/2	+1/3	0
-1/3 e	-1/2	+1/3	0
0	+1/2	0	+1
-1 e	-1/2	0	+1



Mysteries of the Fermion Masses

- Masses are well measured (apart from the very low mass ν_i) but the hierarchy not understood:



- Logarithmic scale covers 15 orders of magnitude!

- Charged leptons (ℓ_i=e,μ,τ), up-type quarks ($\mathbf{u}_i$ = **u,c,t**) and down-type quarks ($\mathbf{d}_i$=**d,s,b**) quarks have similar masses but the patterns are not identical

- Absolute scale of neutrino (ν_i) masses is unknown apart from upper bound on $\mathbf{m}(\nu_e) <$ **2eV**
- Only two independent ν_i mass differences are known:

$$\Delta m_{12}^2 = (7.5\pm0.2) \text{ x } 10^{-5} \text{ eV}^2,\ \Delta m_{23}^2 = (2.32^{+0.12}_{-0.08}) \text{ x } 10^{-3} \text{ eV}^2$$

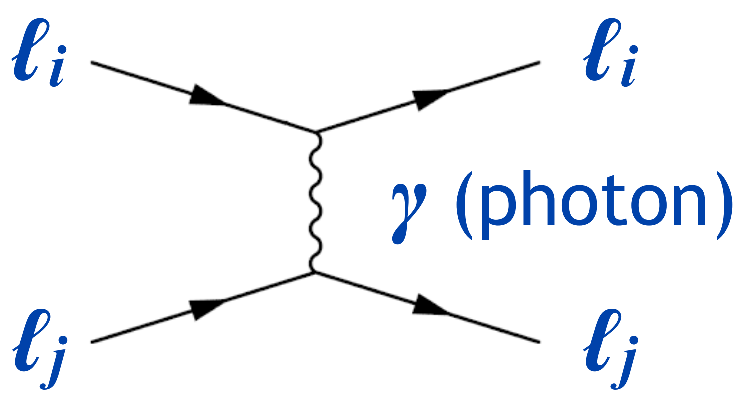
Standard Model Forces

- Four interactions observed in nature: electromagnetic, strong, weak and gravity.
- The Standard Model describes interactions due to electromagnetic, strong, weak.
- Interactions between the fermions are transmitted by "force carrying" gauge bosons with ***S=1***.
- Each force couples to a property of the fermions.
- The structure of the interactions of each force are described mathematically by a symmetry group (more on this later)

Interaction	Coupling Strength	Couples To	Gauge Bosons	Charge e	Mass GeV/c^2
Strong	$\alpha_s \approx 1$	colour-charge	Gluons (g)	0	0
Electromagnetic	$\alpha = 1/137$	electric charge	Photon (γ)	0	0
Weak	$G_F = 1 \times 10^{-5}$	weak hyercharge	$W^{\pm}$	± 1	80.385 ± 0.015
			Z^0	0	91.1876 ± 0.0021
Gravity	0.53×10^{-38}	mass	Graviton	0	0

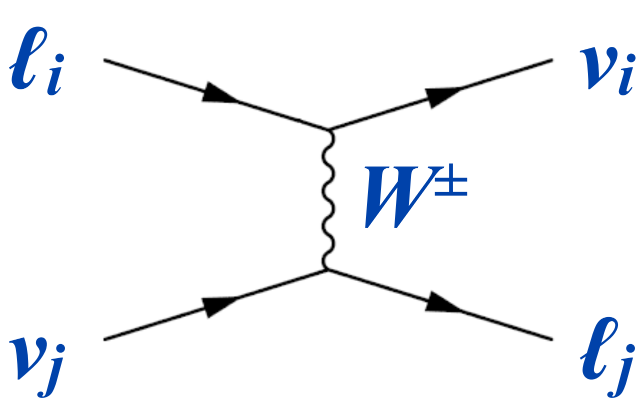
Interactions of the Leptons

Electromagnetic

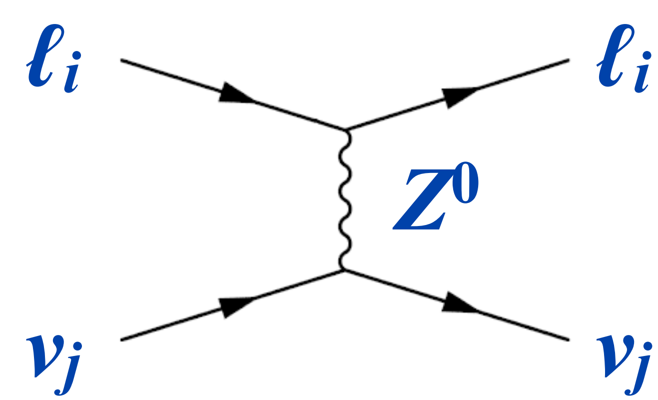


No strong interactions!

Weak (charged)



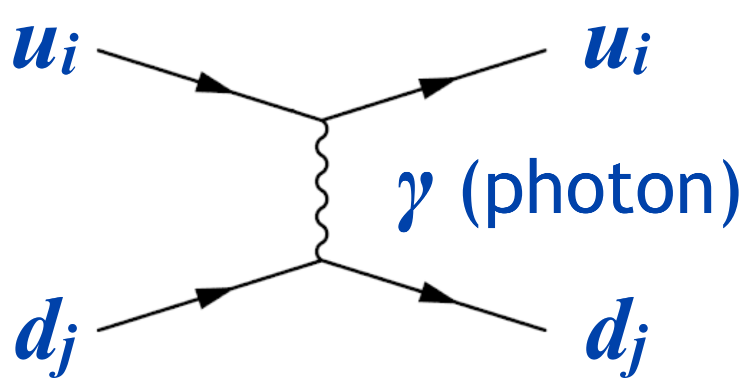
Weak (neutral)



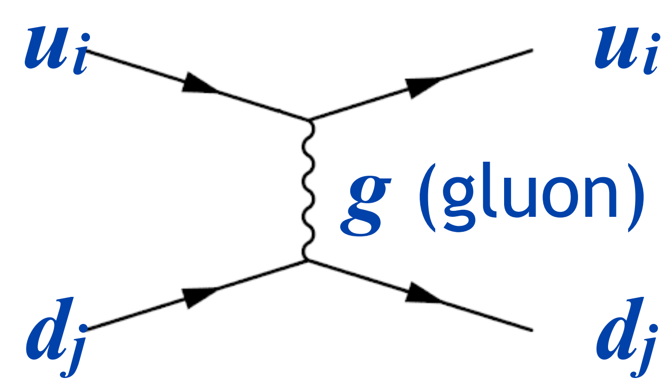
- Leptons interact due to all the electromagnetic and weak forces.
  - All charged leptons ($\ell_i = e, \mu, \tau$) have the same couplings (lepton universality)
  - Only W-boson interactions can cause the leptons to change flavour (from charged to neutral)

Interactions of the Quarks

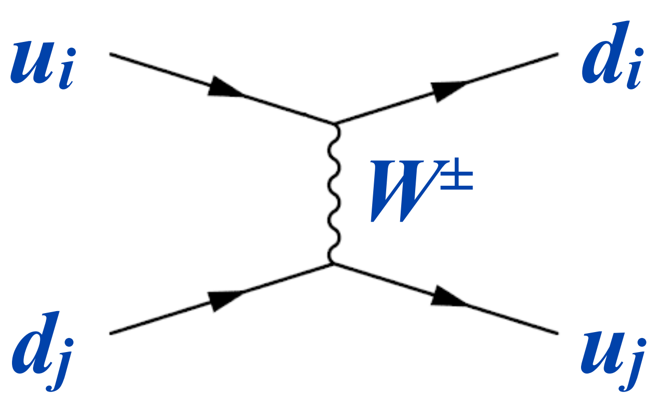
Electromagnetic



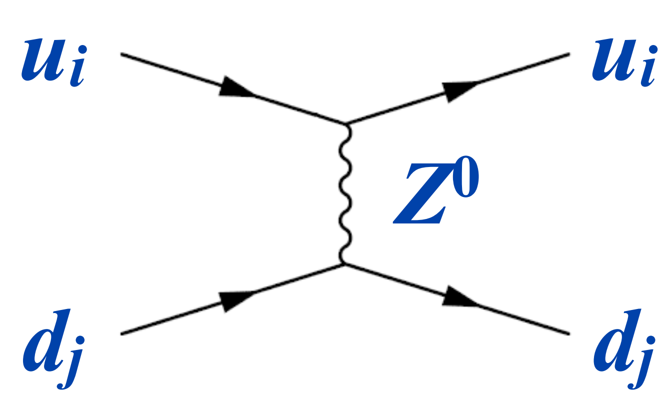
Strong



Weak (charged)



Weak (neutral)



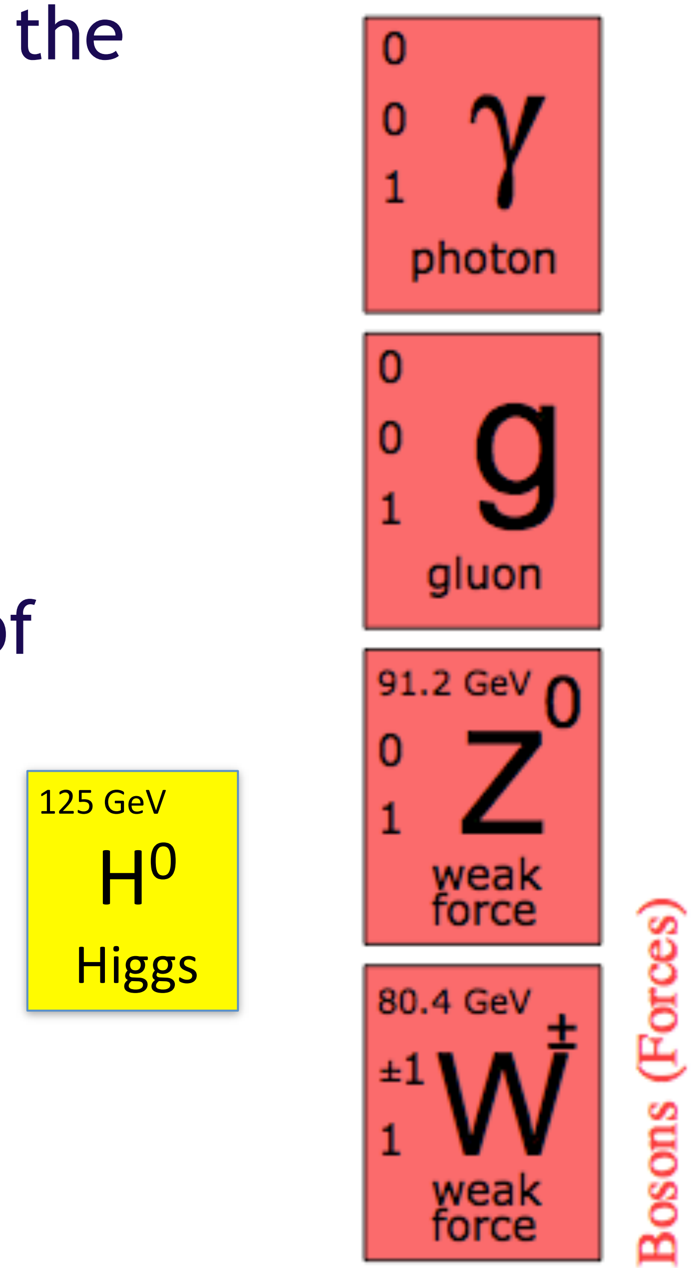
- Quarks interact due to all the forces.
  - All flavours have the same strong force coupling
  - Only W-boson interactions can cause the quarks to change flavour (from up-type to down-type).

Mysteries of the Fermions

- Are the fermions really point-like objects ($r_e < 10^{-20}$m)?
- Why are there exactly twelve (or 24) elementary fermions?
- Why are there three "generations" with different "flavours"?
- Why do quarks have strong interactions with three "colour charges"?
- Why do weak interactions change quark flavour, but not lepton flavour?
- Why do neutrinos have flavour oscillations?
- Why more matter than anti-matter (baryon asymmetry)?

Mysteries of the Bosons

- Electromagnetic and weak interactions are unified at the Electroweak scale (**246 GeV**)
  - ➡ Is there a “grand unified” scale where the strong interaction is also included?
- What is the mechanism that breaks electroweak symmetry, and how does it explain the large masses of the W and Z bosons?
- Are there extra Higgs bosons?
- What are the couplings of Higgs boson(s)?
- How do we include gravity?



Quark Mixing

- Quark flavours are observed to change in W-boson interactions

- Described in the Standard Model with the Cabibbo–Kobayashi–Maskawa quark mixing matrix

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

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97428 \pm 0.00015 & 0.2253 \pm 0.0007 & 0.00347^{+0.00016}_{-0.00012} \\ 0.2252 \pm 0.0007 & 0.97345^{+0.00015}_{-0.00016} & 0.0410^{+0.0011}_{-0.0007} \\ 0.00862^{+0.00026}_{-0.00020} & 0.0403^{+0.0011}_{-0.0007} & 0.999152^{+0.000030}_{-0.000045} \end{bmatrix}.$$

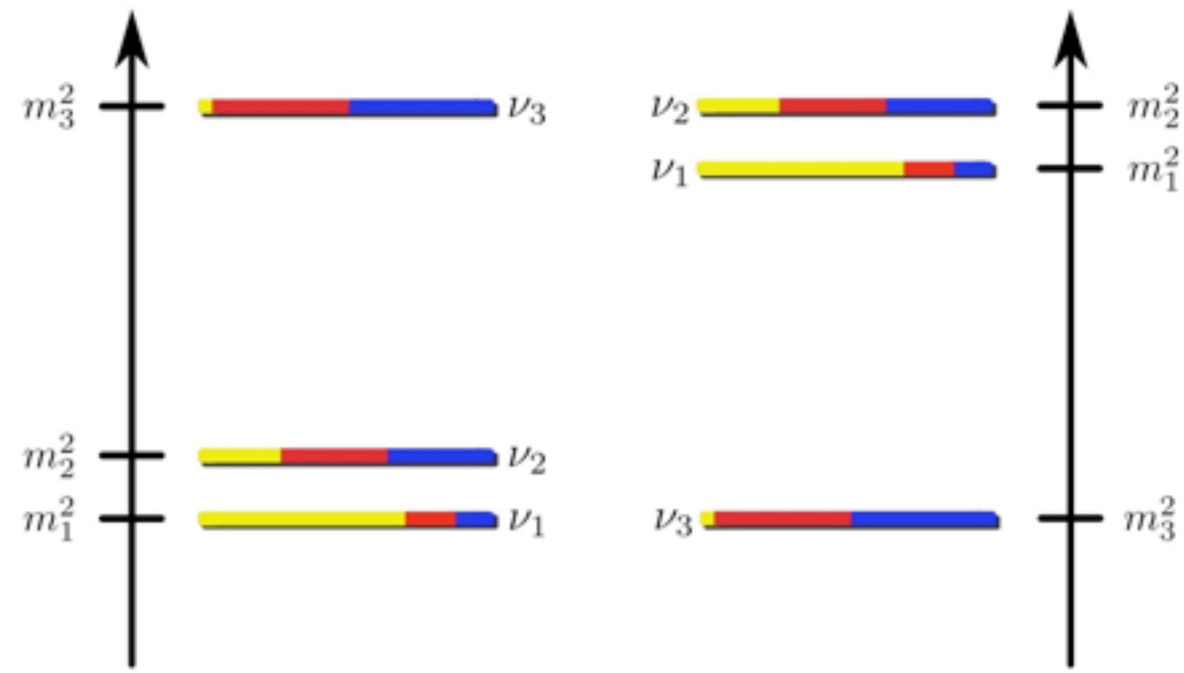
- The parameters of this matrix are experimentally measured, but why this structure!?

reference: Wikipedia http://en.wikipedia.org/wiki/Cabibbo-Kobayashi-Maskawa_matrix

Neutrino Mixing

- Neutrinos are also observed to change flavour e.g. muon neutrinos produced in the atmosphere from cosmic rays $\nu_\mu \rightarrow \nu_\tau$
- Implies neutrinos have mass. The mass eignenstates of the neutrinos are a mixture of ν_e, ν_μ and ν_τ. Two possible solutions for current measurements:

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



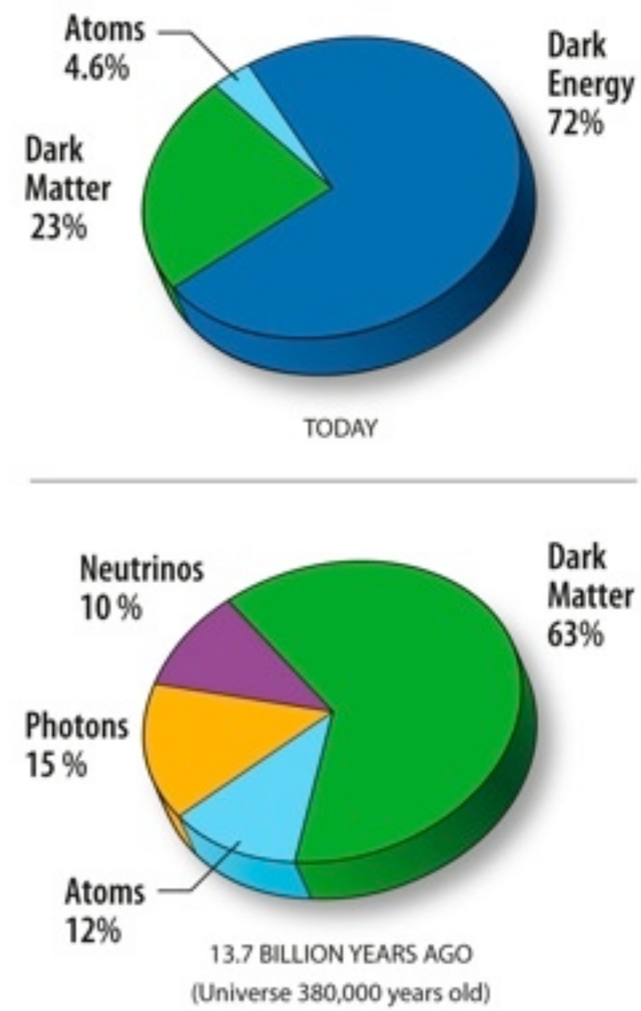
$$\mathrm{U_{NH}} = \begin{bmatrix} 0.822 & 0.547 & -0.150+0.0381i \\ -0.356+0.0198i & 0.704+0.0131i & 0.614 \\ 0.442+0.0248i & -0.452+0.0166i & 0.774 \end{bmatrix} \quad \mathrm{U_{IH}} = \begin{bmatrix} 0.822 & 0.547 & -0.150+0.0429i \\ -0.354+0.0224i & 0.701+0.0149i & 0.618 \\ 0.444+0.0278i & -0.456+0.0186i & 0.770 \end{bmatrix}.$$

- Mixing fractions are experimentally measured. Why this pattern!?
- Neutrinos masses don't really fit into the Standard Model, they imply other particles/interactions we haven't observed yet.

reference: Wikipedia http://en.wikipedia.org/wiki/Pontecorvo-Maki-Nakagawa-Sakata_matrix

The Dark Side

- Only 4.6% of the current universe is normal matter (baryons + electrons = atoms)



- To account for rotation curves of galaxies, gravitational lensing and large scale structure need:

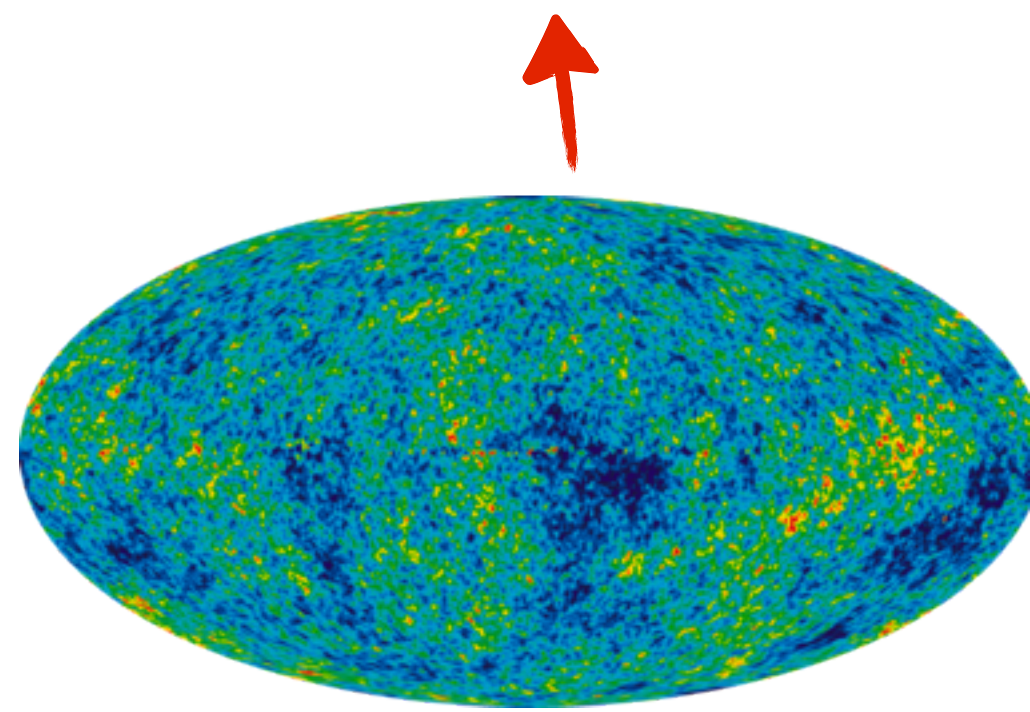
  23.3% "Dark Matter"

  Must be weakly interactive massive particles (not yet discovered) candidates are provided by a "supersymmetric" extension to the Standard Model

- To account for acceleration of expansion of the universe need:

  72.1% "Dark Energy"

  May be described by a cosmological constant Λ



Could particle physics describe either dark matter or dark energy?

Beyond the Standard Model

Many models proposed to explain some mysteries in the Standard Model, *e.g.*

★ **Supersymmetry (SUSY):** every SM particle has a supersymmetry partner:

- ➡ $S=0$ squarks and sleptons
- ➡ $S=\frac{1}{2}$ neutralinos, charginos, higgsinos
- ➡ automatically introduces extra Higgs bosons

We are searching for these new particles directly at the LHC. Neutralinos may be candidates for dark matter.

★ **Grand unified theories** merge strong & electroweak interaction at 10^{11} to 10^{16} GeV

- ➡ Proton decay? Lifetime >10^{29} to 10^{33} years (depending on model)

Search for evidence of proton decay

★ **Additional Heavy neutrino(s)** at GUT scale can explain neutrino oscillations and light neutrino masses.

★ **Extra dimension where only gravity interacts**

- ➡ Mini black holes, new resonances

Searches at the LHC.

Particle Physics in 2012

The two big results of the year were:

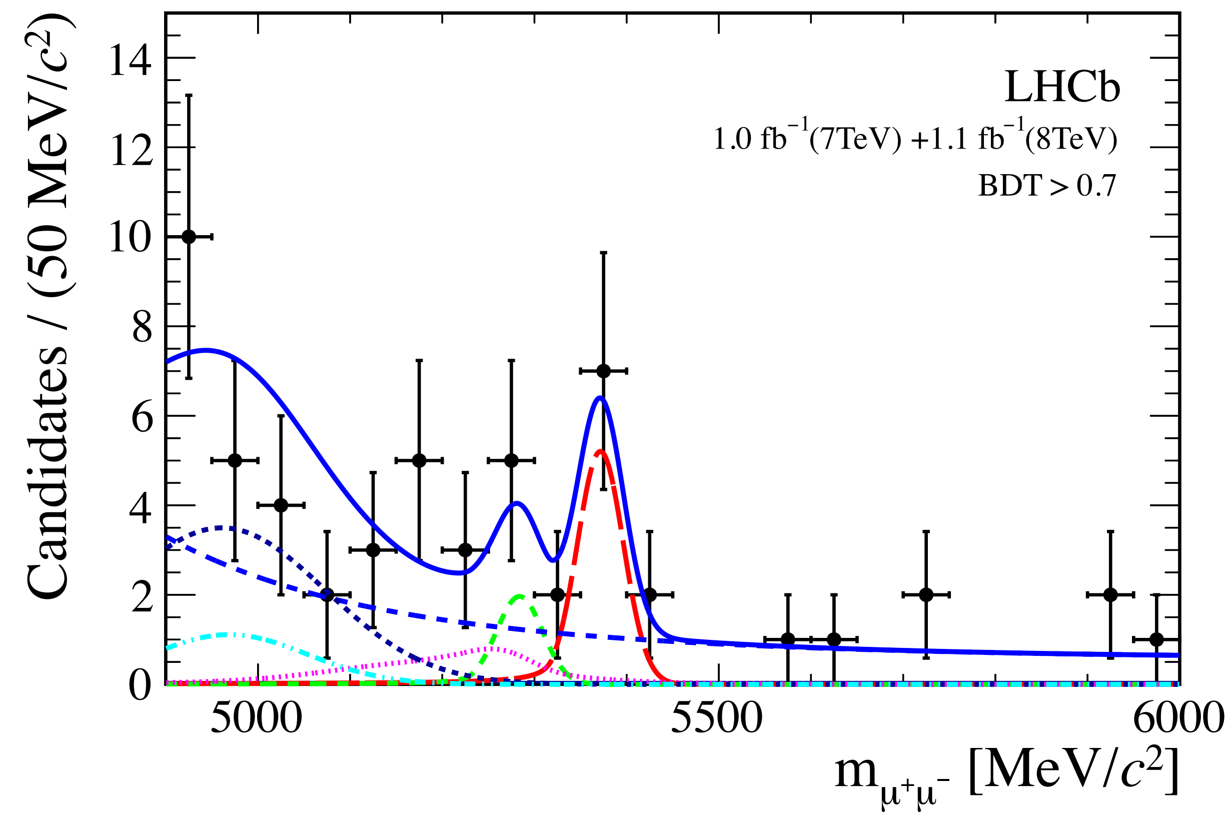
★Discovery of a new boson, very probably the Higgs boson!

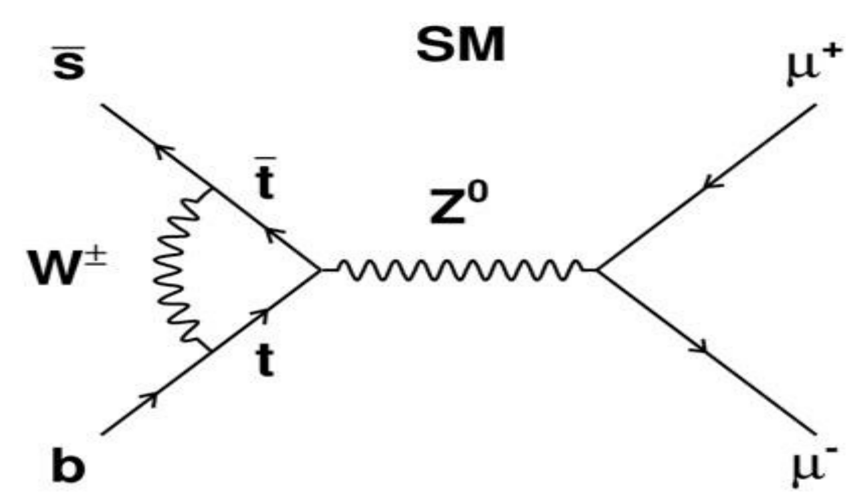
★A first measurement of $\boldsymbol{B_S \to \mu^+ \mu^-}$

★A measurement of neutrino mixing angle $\mathbf{\sin \theta_{13}}$

Observation of $B_S \to \mu^+\mu^-$

- By LHCb experiment at CERN
- Measured Branching Ratio is **$BR(B_S \to \mu^+\mu^-) = (3.2 \pm^{1.5}{}_{1.2}) \times 10^{-9}$**
- Compatible with the prediction of the Standard Model
- Better measurements could limit the contributions from non-Standard Model processes

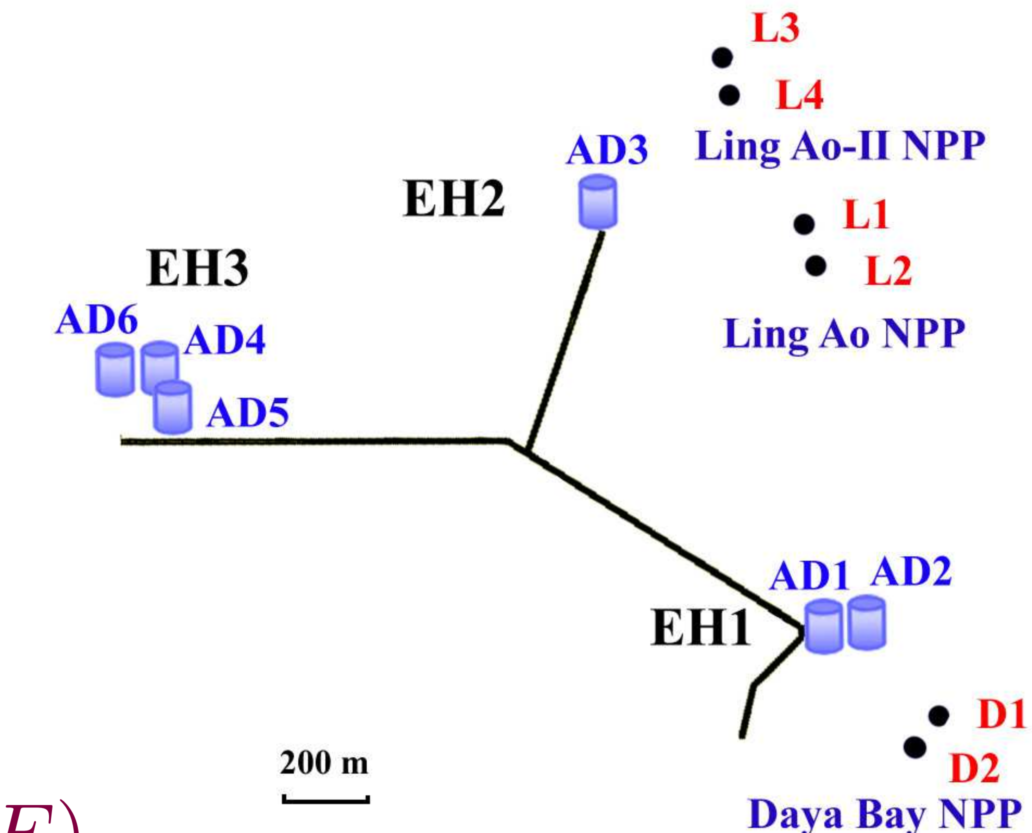




reference: http://arxiv.org/abs/1211.2674

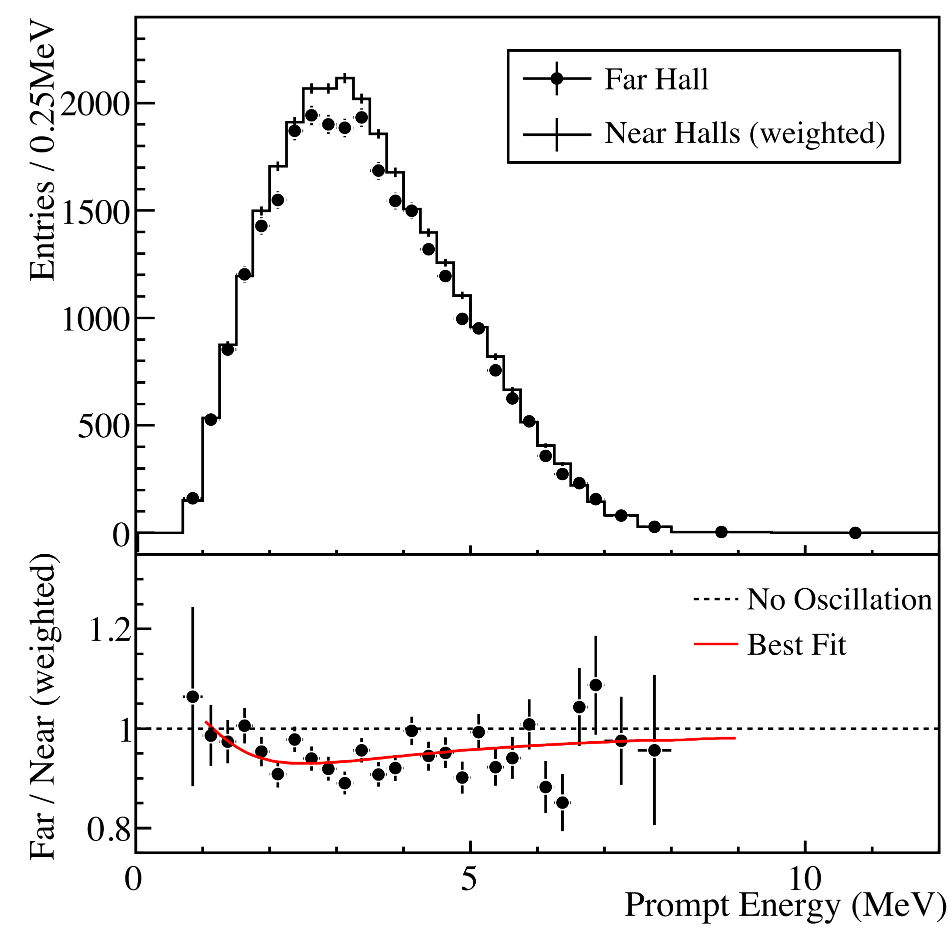
Electron Neutrino Disappearance

- Day Bay experiment in South China
- Sensitive to electron anti-neutrinos ($\bar{\nu}_e$) from six nuclear reactors (**D**, **L**) detected by six detectors (**AD**).
- Look at difference between detection rates between near (**EH1, EH2**) and far (**EH3**) detectors.



$$P_{\text{survival}} \approxeq 1 - \sin^2 2\theta_{13} \sin^2(1.267 \Delta m^2_{31} L/E)$$

- $\Delta m_{31}{}^2 = 2.23 \pm {}^{0.12}{}_{0.08}$ **meV²** measured from the atmospheric reactions
- E is the energy of $\bar{\nu}_e$ in **MeV**
- L is the distance of between detectors in metres.
- Measurement is $\sin^2\theta_{13} = 0.0089 \pm 0.0011$



reference: http://arxiv.org/abs/1210.6327

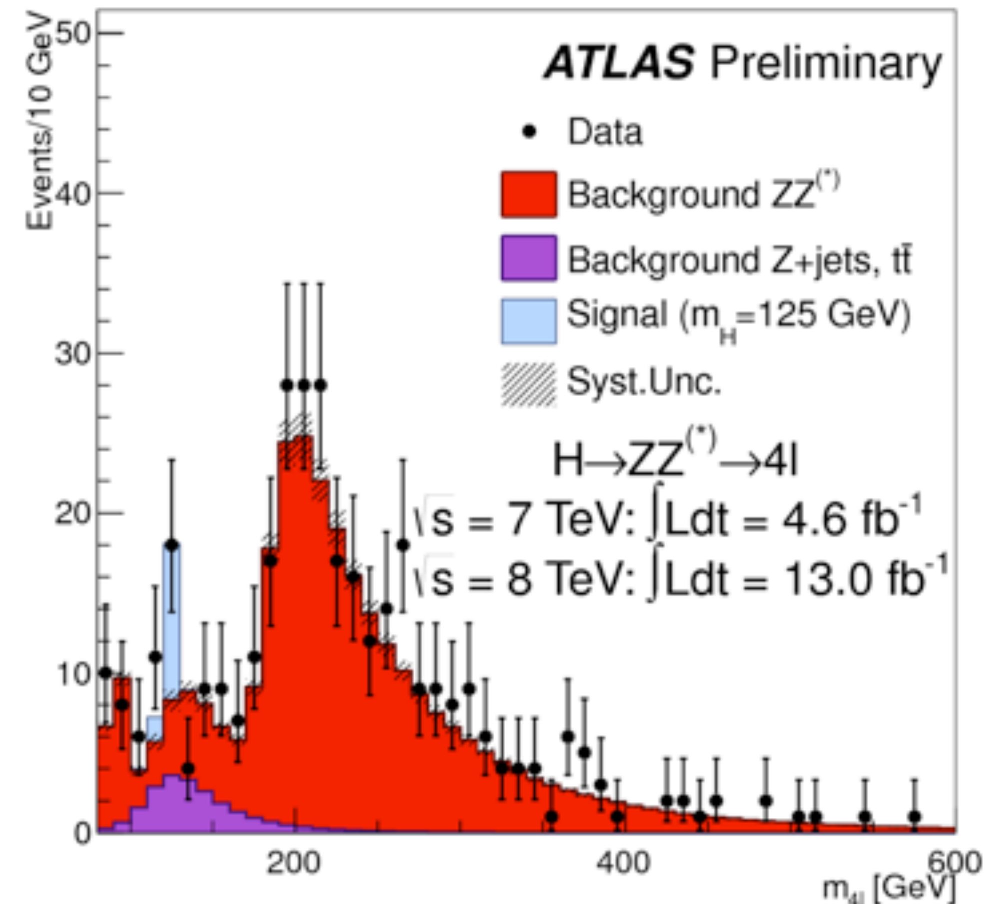
Discovery of the Higgs Boson

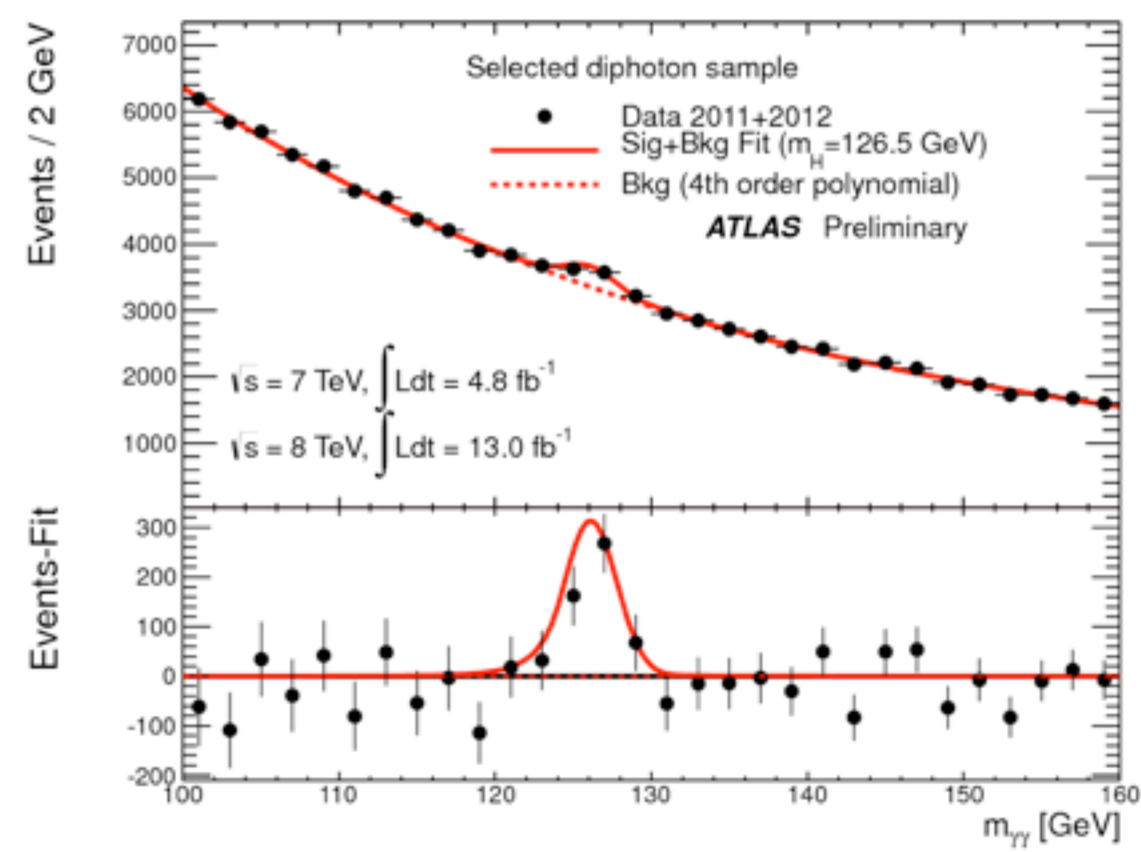
- ATLAS and CMS experiments at CERN

- "Bumps" observed in invariant mass at $\mathbf{m \approx 125\ GeV}$ in:
  - ➡ $\gamma\gamma$
  - ➡ $\ell^+\ell^-\ell^+\ell^-$ ($\ell=\{e,\mu\}$)

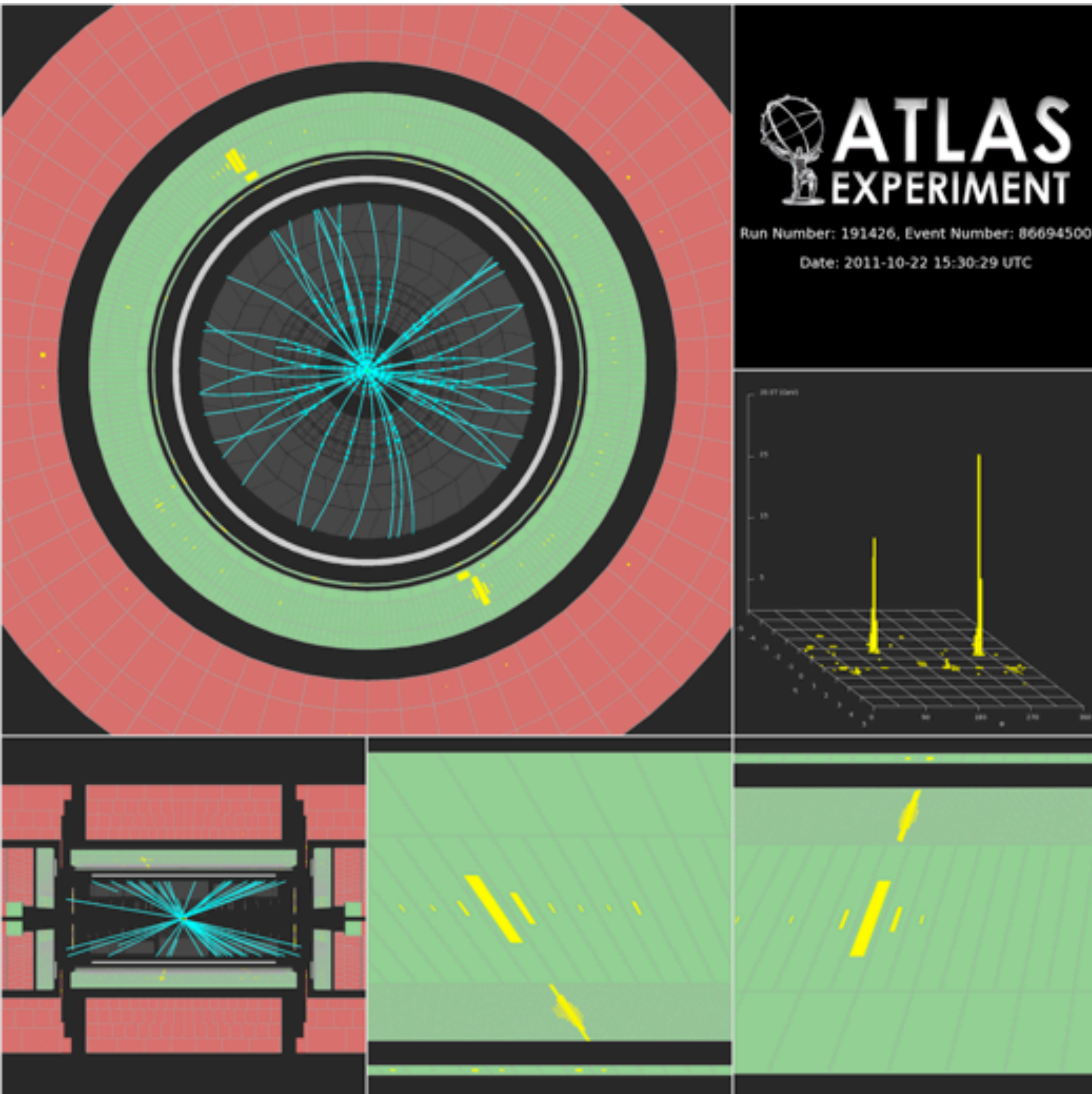
- Consistent with $H\to\gamma\gamma$ and $H\to ZZ\to 4\ell$ production

- Statistical significance of the excess is now 7 σ from ATLAS alone!



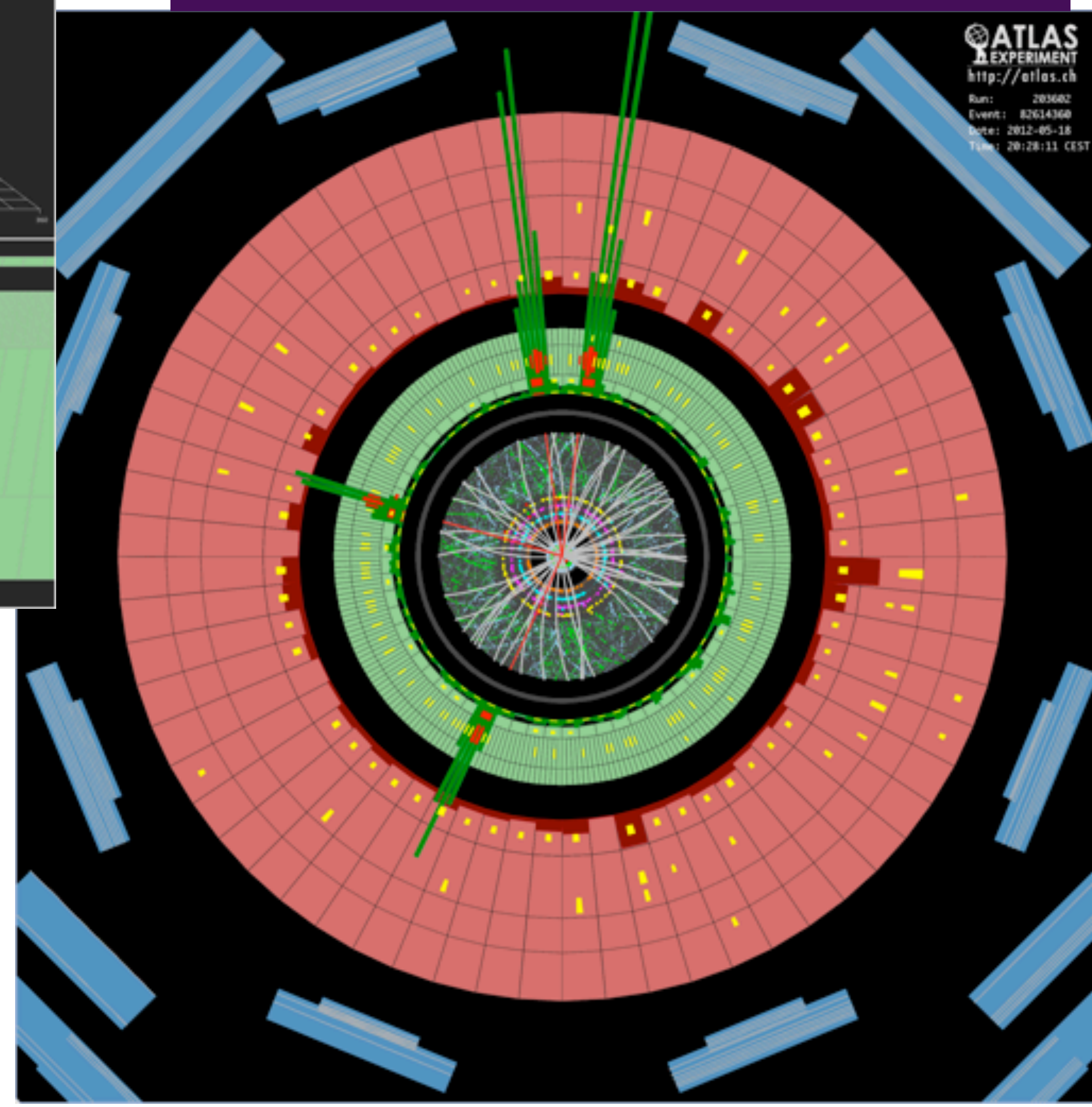


References: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-170/, ATLAS-CONF-2012-169/, ATLAS-CONF-2012-168/



$H \rightarrow \gamma\gamma$ candidate event

$H \rightarrow ZZ \rightarrow 4e$ candidate event



December 2012

- Fabiola Gianotti is named Time magzine Person of the Year 2012, runner up

- Higgs boson is particle of year 2012.

- Professor Higgs awarded Membership of the Order of the Companions of Honour by Queen Elizabeth II

- Alan Walker is awarded an MBE for services to science engagement and science education in Scotland.

http://www.ph.ed.ac.uk/news/new-years-honours-2013-08-01-13

Prof Higgs visits ATLAS

Summary & Reading List

- Summary: the Standard Model is our current model for particle physics. But it doesn't explain all observations.

- Experiments are underway to try to make precise measurements and search for new phenomena.

- Key point from today: learn/review the Standard Model particles and forces.

Highly suggested reading:

- Today's lecture: Griffiths 1.1 -1.5
- Friday's Lecture: Griffiths chapter 2