UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

Recreating the Big Bang:
Higgs Bosons, Birmingham & the LHC

Prof Paul Newman
Particle Physics Group Leader

University Open Day
June 2018

Late 19th Century: Atoms as nature's basic building blocks

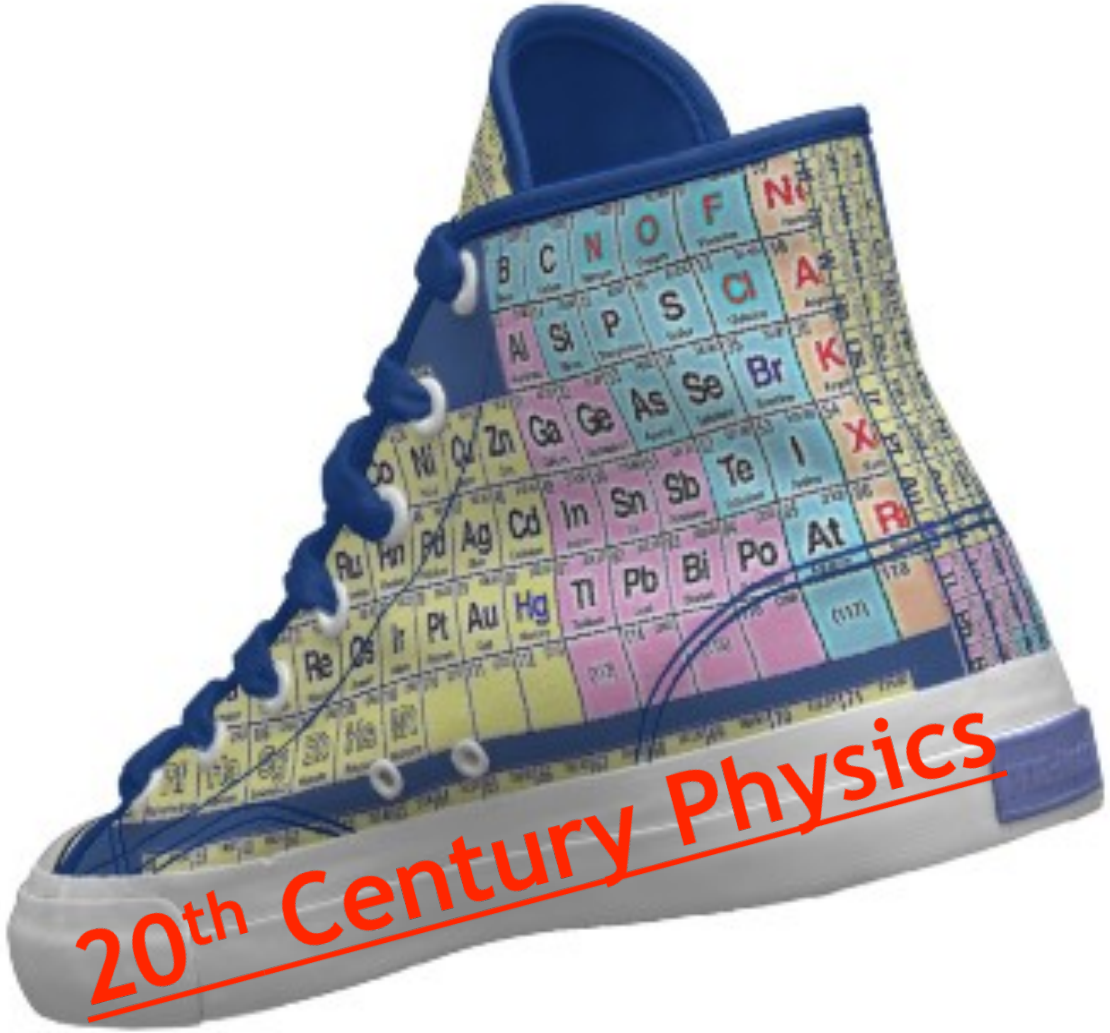
1 H Hydrogen 1.00794																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989770	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosphorus 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57 La Lanthanum 138.9055	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89 Ac Actinium (227)	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 Ds Darmstadtium (269)	111 Rg Roentgenium (272)	112 Cn Copernicium (277)	113	114				

58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
90 Th Thorium 232.0381	91 Pa Protactinium 231.03588	92 U Uranium 238.0289	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

"There is nothing new to be discovered in physics now,
All that remains is more and more precise measurement."

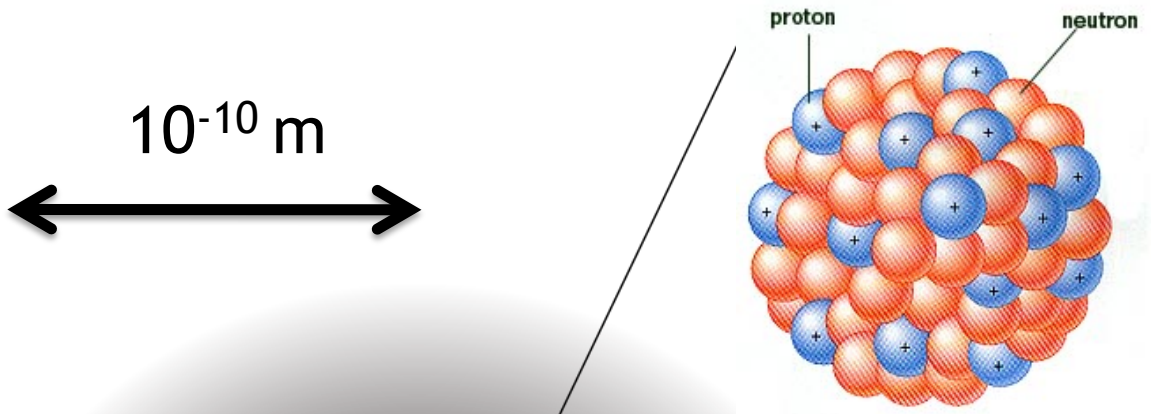
Lord Kelvin, 1900

Late 19th Century: Atoms as nature's basic building blocks



A much deeper (and simpler) structure has been revealed in collisions of very high energy particles at accelerators

A Modern Picture of the Atom



10^{-10} m

10^{-14} … 10^{-15} m

Nucleus

… a marble in a football stadium …

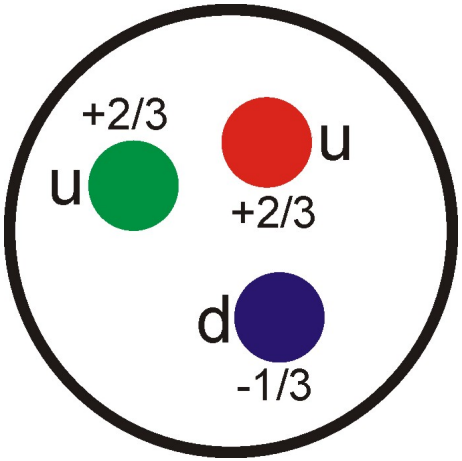
Cloud of orbiting electrons

To probe even deeper inside the protons and neutrons, we hit them with very high energy particles …

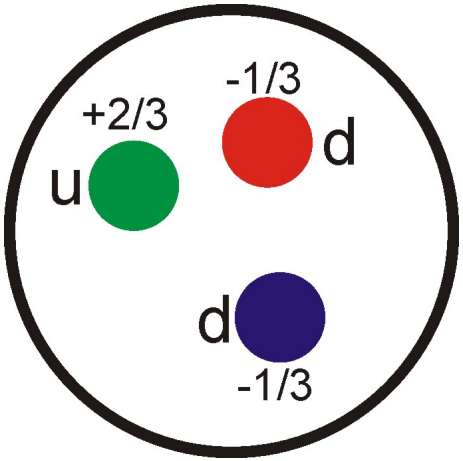
The Modern Picture of Protons and Neutrons

In 1969, an experiment using a 2-mile long electron accelerator showed that protons have structure → "quarks"

- Protons and neutrons made from Up (u) and Down (d) quarks.
- u-quarks have +2/3 of electron charge, d-quarks have -1/3



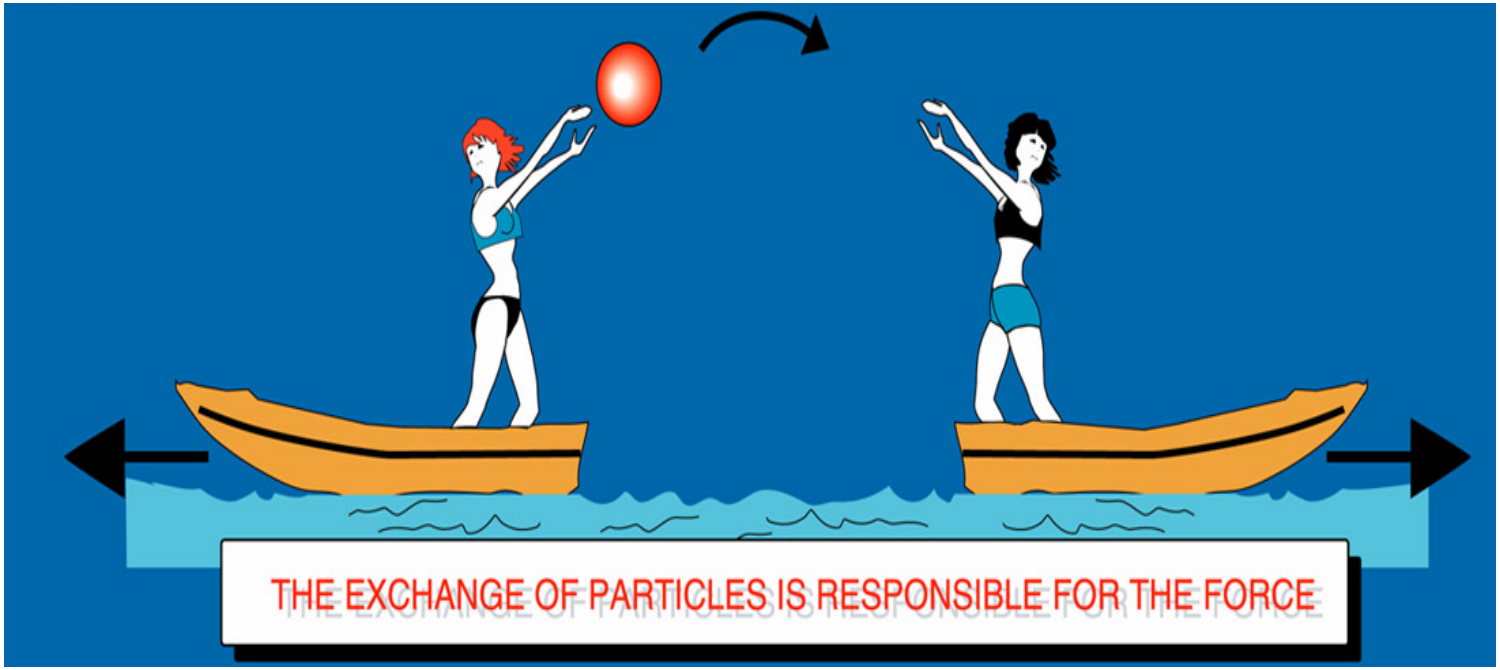
Proton

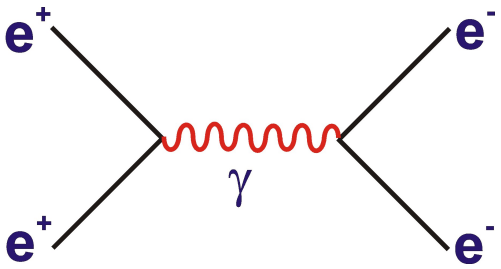


Neutron

The Particle Physics view of Forces

Microscopic view: forces caused by more particles being exchanged between the electrons and quarks





e.g. Electric & magnetic forces are caused by exchange of photons (particles of light)

Radioactive β decay is caused by exchange of heavier particles called W and Z bosons

W and Z boson discovery, 1983

CERN-EP/83-13
21 January 1983

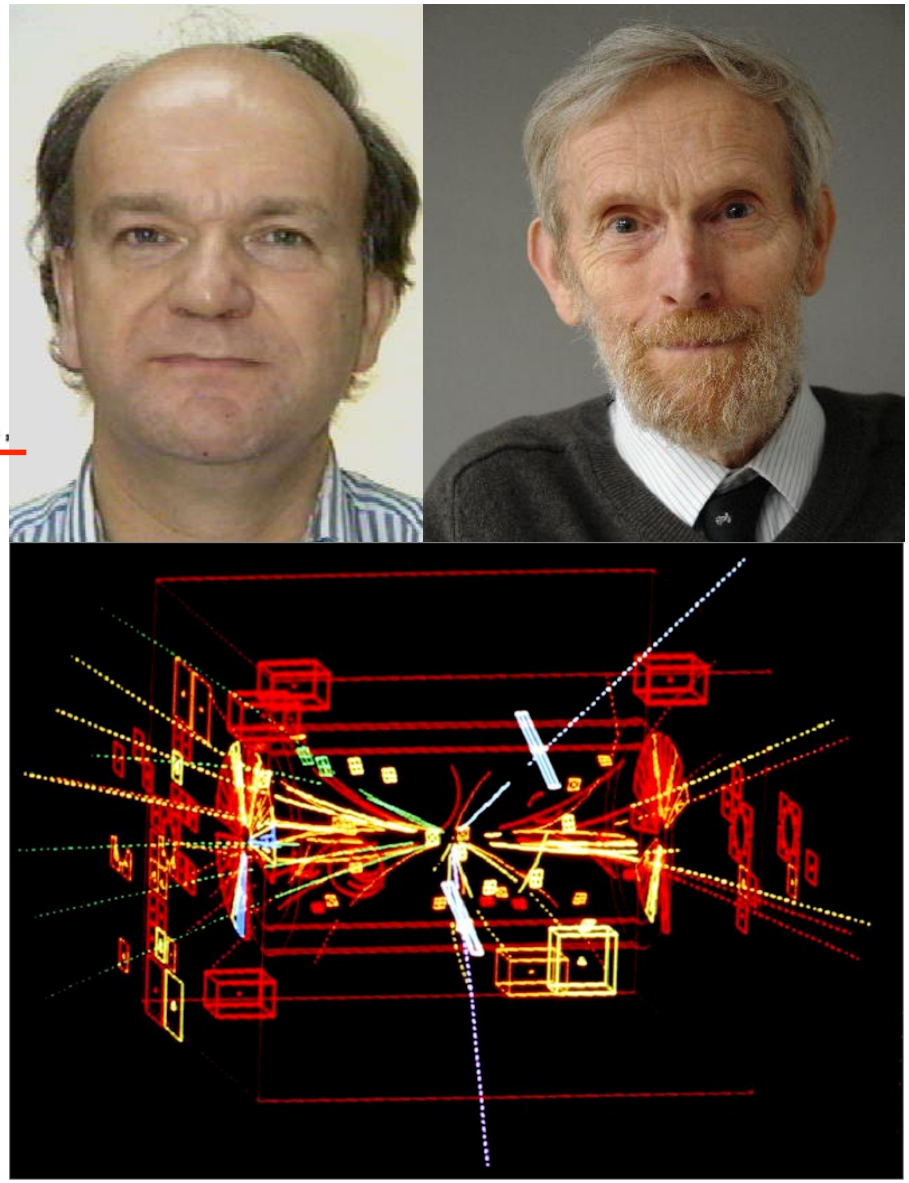
C2 Hpl

EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland

Aachen[1]-Annecy (LAPP)[2]-Birmingham[3]-CERN[4]-Helsinki[5]-Queen Mary College, London[6]-Paris (Coll. de France)[7]-Riverside[8]-Roma[9]-Rutherford Appleton Lab.[10]-Saclay (CEN)[11] Vienna[12] Collaboration

G. Arnison[10], A. Astbury[10], B. Aubert[2], C. Bacci[9], G. Bauer**, A. Bézaguet[4], R. Böck[4], T.J.V. Bowcock[6], M. Calvetti[9], T. Carroll[4], P. Catz[2], P. Cennini[4], S. Centro[4], F. Ceradini[9], S. Cittolin[4], D. Cline**, C. Cochet[11], J. Colas[2], M. Corden[3], D. Dallman[4], M. DeBeer[11], M. Della Negra[2], M. Demoulin[4], D. Denegri[11], A. Di Ciaccio[9], D. DiBitonto[4], L. Dobrzynski[7], J.D. Dowell[3], M. Edwards[3], K. Eggert[1], E. Eisenhandler[6], N. Ellis[4], P. Erhard[1], H. Faissner[1], G. Fontaine[7], R. Frey[8], R. Frühwirth[12], J. Garvey[3], S. Geer[7], C. Ghesquière[7], P. Ghez[2], K.L. Giboni[1], W.R. Gibson[6], Y. Giraud-Héraud[7], A. Givernaud[11], A. Gonidec[2], G. Grayer[10], P. Gutierrez[8], T. Hansl-Kozanecka[1], W.J. Haynes[10], L.O. Hertzberger*, C. Hodges[8], D. Hoffmann[1], H. Hoffmann[4], D.J. Holthuizen*, R.J. Homer[3], A. Honma[6], W. Jank[4], G. Jorat[4], P.I.P. Kalmus[6], V. Karimäki[5], R. Keeler[6], I. Kenyon[3], A. Kernan[8], R. Kinnunen[5], H. Kowalski[4], W. Kozanecki[8], D. Kryn[4], F. Lacava[9], J.-P. Laugier[11], J.-P. Lees[2], H. Lehmann[1], K. Leuchs[1], A. Lévêque[11], D. Linglin[2], E. Locci[11], M. Loret[11], J.-J. Malosse[11], T. Markiewicz[4], G. Maurin[4], T. McMahon[3], J.-P. Mendiburu[7], M.-N. Minard[2], M. Moricca[9], H. Muirhead[4], F. Muller[4], A.K. Nandi[10], L. Naumann[4], A. Norton[4], A. Orkin-Lecourtois[7], L. Paoluzi[9], G. Petrucci[4], G. Piano Mortari[9], M. Pimiä[5], A. Placci[4], E. Radermacher[1], J. Ransdell[8], H. Reithler[1], J.-P. Revol[4], J. Rich[11], M. Rijssenbeek[4], C. Roberts[10], J. Rohlf[4], P. Rossi[4], C. Rubbia[4], B. Sadoulet[4], G. Sajot[6], G. Salvi[6], G. Salvini[9], J. Sass[11], J. Saudraix[11], A. Savoy-Navarro[11], D. Schinzel[4], W. Scott[10], T.P. Shah[10], M. Spiro[11], J. Strauss[12], K. Sumorok[3], F. Szoncso[12], D. Smith[8], C. Tao[4], G. Thompson[6], J. Timmer[4], E. Tscheslog[1], J. Tuominiemi[5], S. Van der Meer[4], J.-P. Vialle[4], J. Vrana[7], V. Vuillemin[4], H.D. Wahl[12], P. Watkins[3], J. Wilson[3], G.Y. Xie[4], M. Yvert[2], E. Zurfluh[4]



→ The present day …


North Sea
Denmark
Lithuania
United Kingdom
Isle of Man
Ireland
Poland
Netherlands
Germany
Belgium
Luxembourg
Czechia
Slovakia
Hungary
Austria
Switzerland
Slovenia
France
Croatia
Bosnia and Herzegovina
Montenegro
Bay of Biscay
Monaco
Italy


Geneva

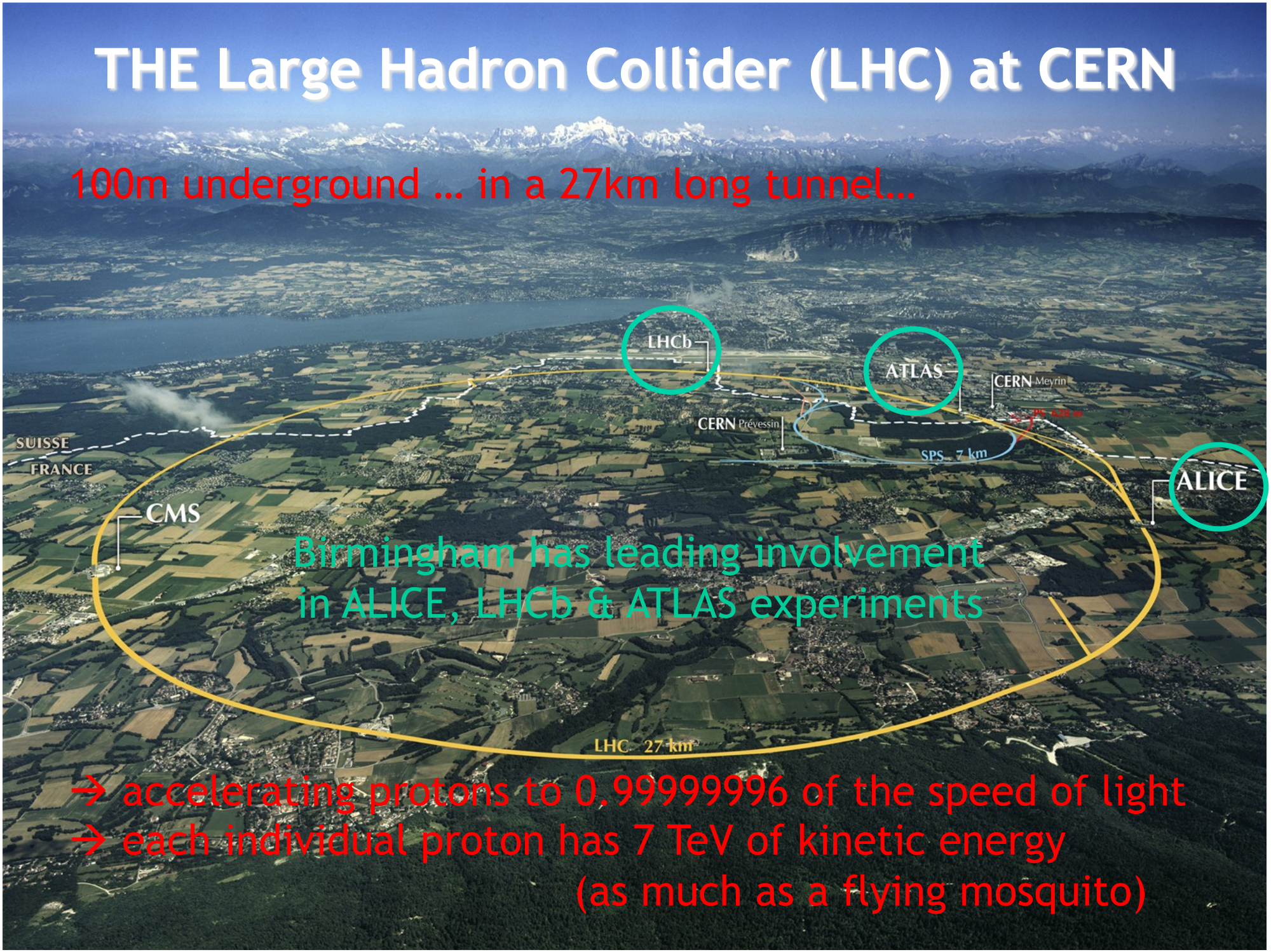
Birmingham Undergraduate visit to CERN

March 2017

… the world's biggest physics laboratory

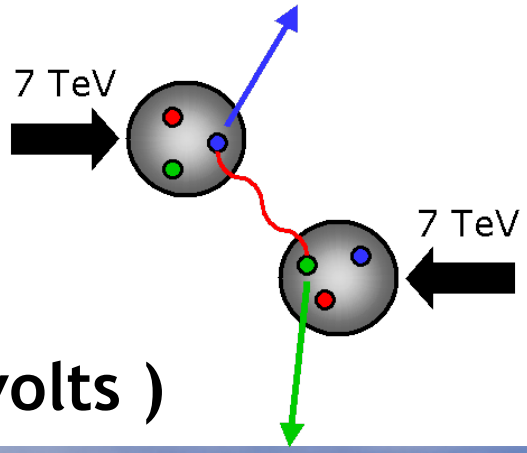
CERN

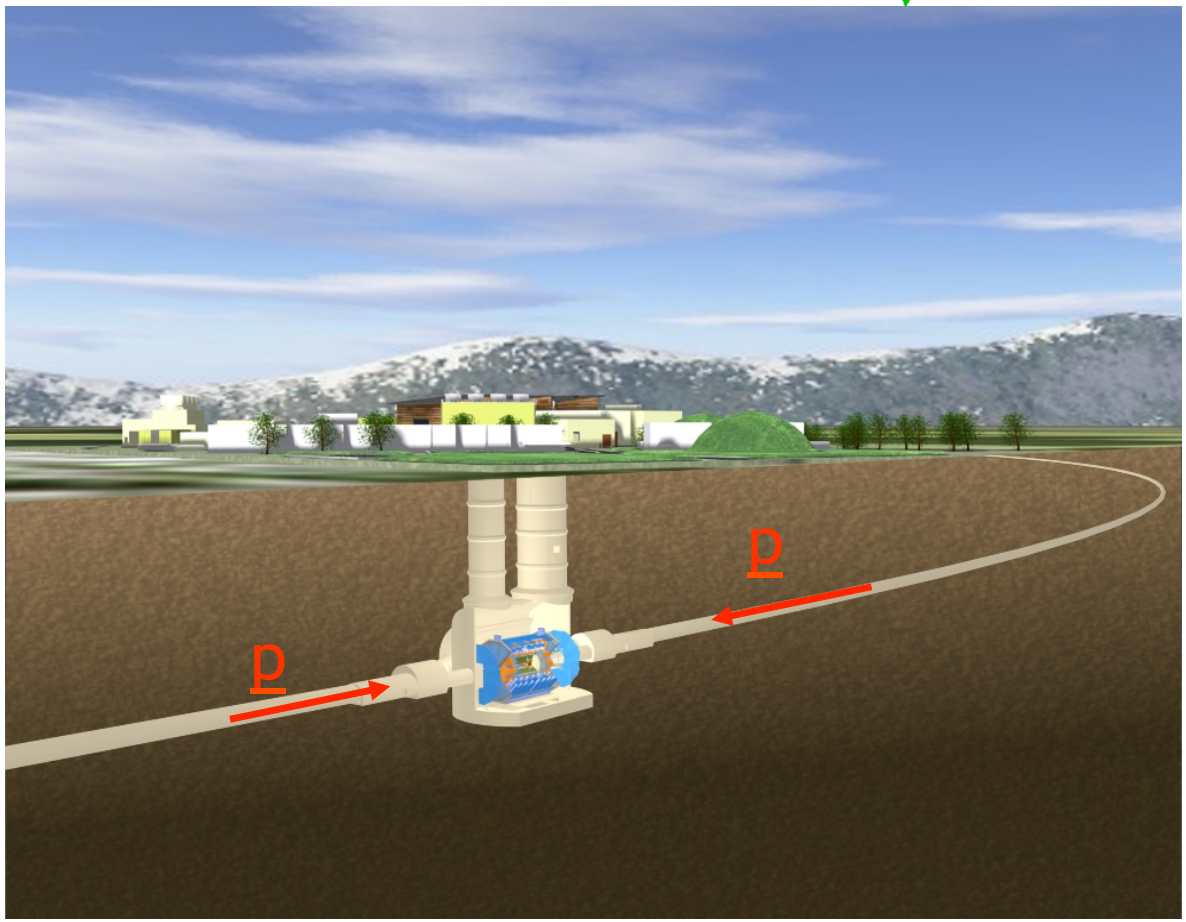
THE Large Hadron Collider (LHC) at CERN



The LHC Beams

Colliding protons each with about the energy of a flying mosquito (7 trillion electron-volts)

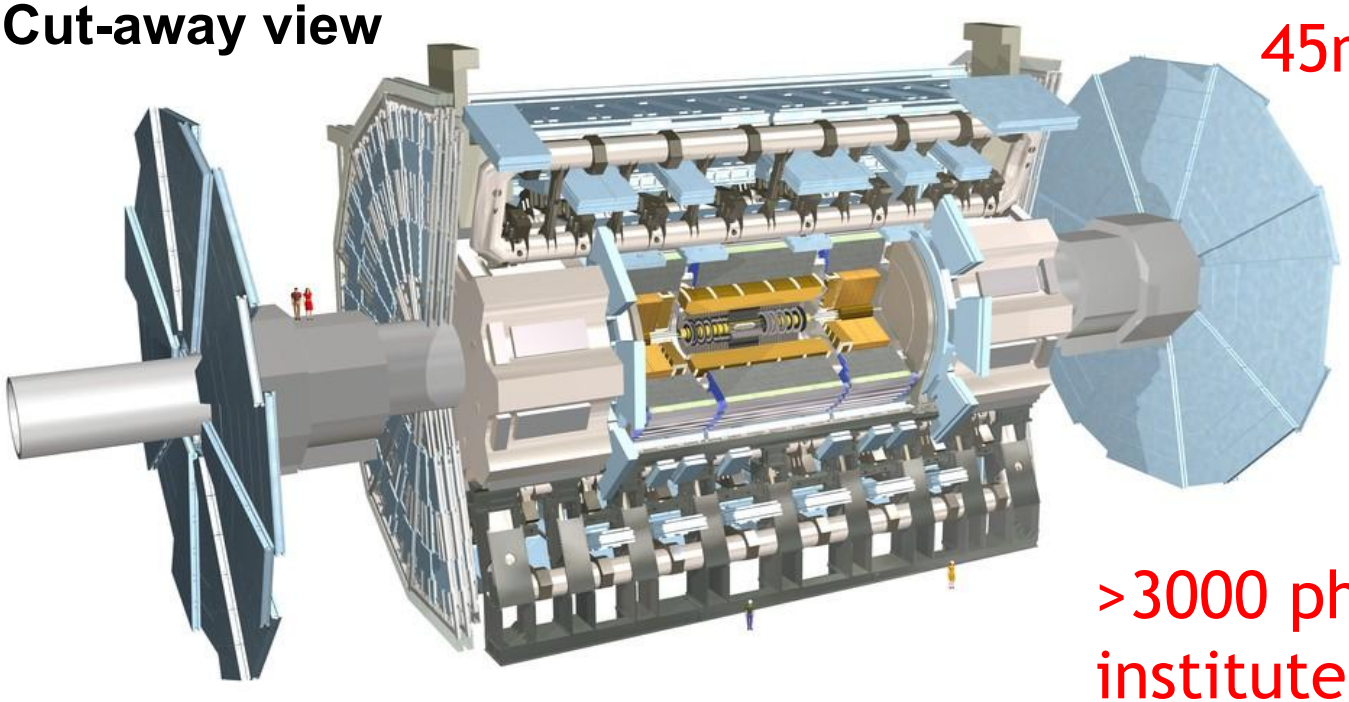




- Each proton goes round ring 11,000 times per second.
- 10^{11} protons per bunch, with 40 million bunch crossings per second
- About 20 collisions in every bunch crossing.
- Total stored energy of 300 MJ … equivalent to a family car at 1000 mph

Detecting the Results of the Collisions: ATLAS

Cut-away view

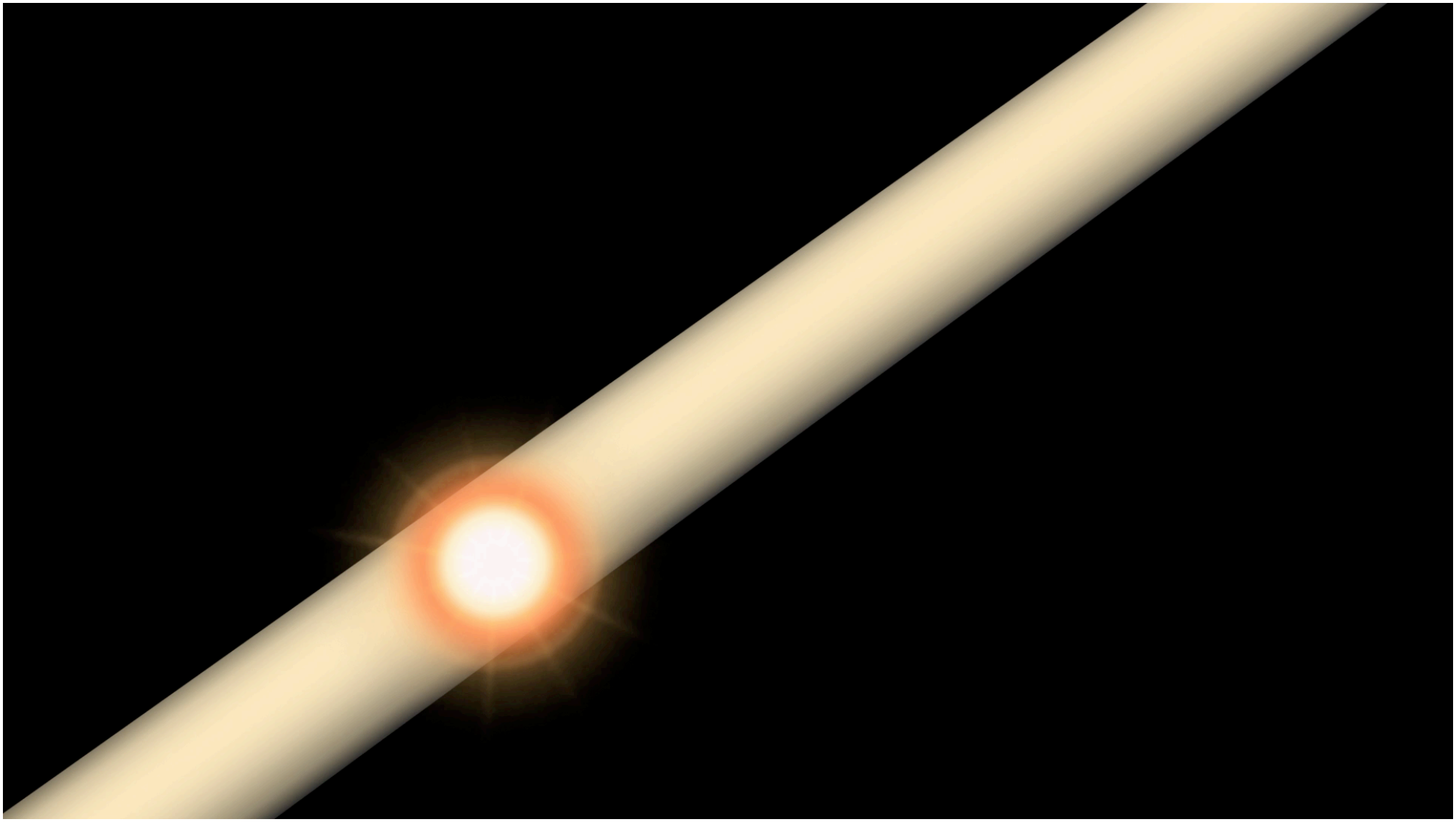


45m x 25m x 25m

>3000 physicists from 174 institutes in 38 countries

Prof Dave Charlton, Birmingham University

ATLAS Spokesperson 2013-2017



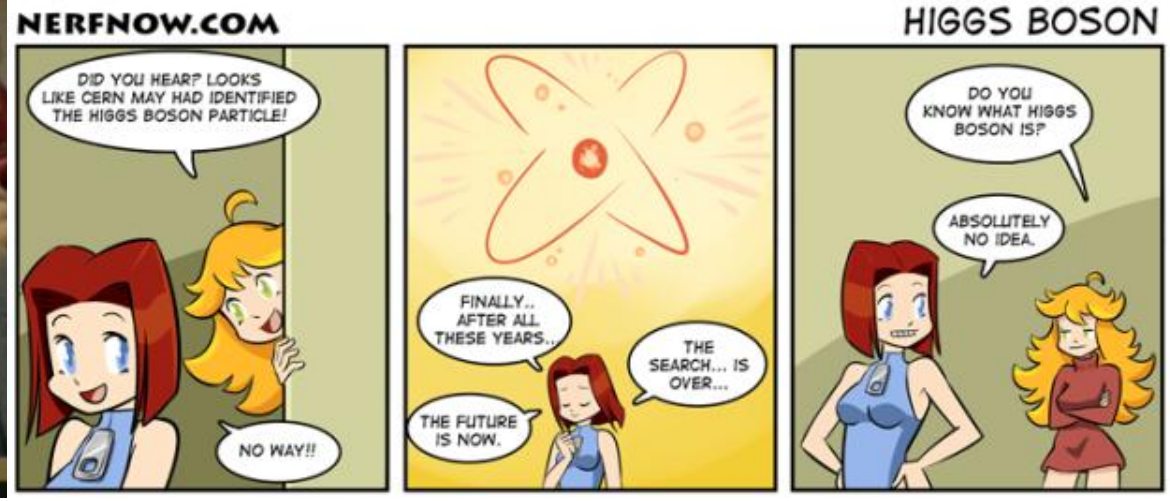
What has the LHC Discovered?...

8 October 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert and Peter Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"



Physics Letters B 716 (2012) 1–29

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration

G. Aad [48], T. Abajyan [21], B. Abbott [111], J. Abdallah [12], S. Abdel Khalek [115], A.A. Abdelalim [49], O. Abdinov [11], R. Aben [105], B. Abi [112], M. Abolins [88], O.S. AbouZeid [158], H. Abramowicz [153], H. Abreu [136], B.S. Acharya [164a,164b], L. Adamczyk [38], D.L. Adams [25], T.N. Addy [56], J. Adelman [176], S. Adomeit [98], P. Adragna [75], T. Adye [129], S. Aefsky [23], J.A. Aguilar-Saavedra [124b,a], M. Agustoni [17], M. Aharrouche [81], S.P. Ahlen [22], F. Ahles [48], A. Ahmad [148], M. Ahsan [41], G. Aielli [133a,133b], T. Akdogan [19a], T.P.A. Åkesson [79], G. Akimoto [155], A.V. Akimov [94], M.S. Alam [2], M.A. Alam [76], J. Albert [169], S. Albrand [55], M. Aleksa [30], I.N. Aleksandrov [64], F. Alessandria [89a], C. Alexa [26a], G. Alexander [153], G. Alexandre [49], T. Alexopoulos [10], M. Alhroob [164a,164c], M. Aliev [16], G. Alimonti [89a], J. Alison [120], B.M.M. Allbrooke [18], P.P. Allport [73], S.E. Allwood-Spiers [53], J. Almond [82], A. Aloisio [102a,102b], R. Alon [172], A. Alonso [79], F. Alonso [70], A. Altheimer [35], B. Alvarez Gonzalez [88], M.G. Alviggi [102a,102b], K. Amako [65], C. Amelung [23], V.V. Ammosov [128,*], S.P. Amor Dos Santos [124a], A. Amorim [124a,b], N. Amram [153], C. Anastopoulos [30], L.S. Ancu [17], N. Andari [115], T. Andeen [35], C.F. Anders [58b], G. Anders [58a], K.J. Anderson [31], A. Andreazza [89a,89b], V. Andrei [58a], M.-L. Andrieux [55], X.S. Anduaga [70], S. Angelidakis [9], P. Anger [44], A. Angerami [35], F. Anghinolfi [30], A. Anisenkov [107], N. Anjos [124a], A. Annovi [47], A. Antonaki [9], M. Antonelli [47], A. Antonov [96], J. Antos [144b], F. Anulli [132a], M. Aoki [101], S. Aoun [83], L. Aperio Bella [5], R. Apolle [118,c], G. Arabidze [88], I. Aracena [143], Y. Arai [65], A.T.H. Arce [45], S. Arfaoui [148], J.-F. Arguin [93], E. Arik [19a,*], M. Arik [19a], A.J. Armbruster [87], O. Arnaez [81], V. Arnal [80], C. Arnault [115], A. Artamonov [95], G. Artoni [132a,132b], D. Arutinov [21], S. Asai [155], S. Ask [28], B. Åsman [146a,146b], L. Asquith [6], K. Assamagan [25], A. Astbury [169], M. Atkinson [165], B. Aubert [5], E. Auge [115], K. Augsten [127], M. Aurousseau [145a], G. Avolio [163], R. Avramidou [10], D. Axen [168], G. Azuelos [93,d], Y. Azuma [155], M.A. Baak [30], G. Baccaglioni [89a], C. Bacci [134a,134b], A.M. Bach [15], H. Bachacou [136], K. Bachas [30], M. Backes [49], M. Backhaus [21], J. Backus Mayes [143], E. Badescu [26a], P. Bagnaia [132a,132b], S. Bahinipati [3], Y. Bai [33a], D.C. Bailey [158], T. Bain [158], J.T. Baines [129], O.K. Baker [176], M.D. Baker [25], S. Baker [77], P. Balek [126], E. Banas [39], P. Banerjee [93], Sw. Banerjee [173], D. Banfi [30], A. Bangert [150], V. Bansal [169], H.S. Bansil [18], L. Barak [172], S.P. Baranov [94], A. Barbaro Galtieri [15], T. Barber [48], E.L. Barberio [86], D. Barberis [50a,50b], M. Barbero [21], D.Y. Bardin [64], T. Barillari [99], M. Barisonzi [175], T. Barklow [143], N. Barlow [28], B.M. Barnett [129], R.M. Barnett [15], A. Baroncelli [134a], G. Barone [49], A.J. Barr [118], F. Barreiro [80], J. Barreiro Guimarães da Costa [57], P. Barrillon [115], R. Bartoldus [143], A.E. Barton [71], V. Bartsch [149], A. Basye [165], R.L. Bates [53], L. Batkova [144a], J.R. Batley [28], A. Battaglia [17], M. Battistin [30], F. Bauer [136], H.S. Bawa [143,e], S. Beale [98], T. Beau [78], P.H. Beauchemin [161], R. Beccherle [50a], P. Bechtle [21], H.P. Beck [17], A.K. Becker [175], S. Becker [98], M. Beckingham [138], K.H. Becks [175], A.J. Beddall [19c], A. Beddall [19c], S. Bedikian [176], V.A. Bednyakov [64], C.P. Bee [83], L.J. Beemster [105], M. Begel [25], S. Behar Harpaz [152], P.K. Behera [62], M. Beimforde [99],

How discoveries change:

Higgs bosons, 2012

C. Belanger-Champagne[85], P.J. Bell[49], W.H. Bell[49], G. Bella[153], L. Bellagamba[20a], M. Bellomo[30], A. Belloni[57], O. Beloborodova[107,f], K. Belotskiy[96], O. Beltramello[30], O. Benary[153], D. Benchekroun[135a], K. Bendtz[146a,146b], N. Benekos[165], Y. Benhammou[153], E. Benhar Noccioli[49], J.A. Benitez Garcia[159b], D.P. Benjamin[45], M. Benoit[115], J.R. Bensinger[23], K. Benslama[130], S. Bentvelsen[105], D. Berge[30], E. Bergeaas Kuutmann[42], N. Berger[5], F. Berghaus[169], E. Berglund[105], J. Beringer[15], P. Bernat[77], R. Bernhard[48], C. Bernius[25], F.U. Bernlochner[169], T. Berry[76], C. Bertella[83], A. Bertin[20a,20b], F. Bertolucci[122a,122b], M.I. Besana[89a,89b], G.J. Besjes[104], N. Besson[136], S. Bethke[99], W. Bhimji[46], R.M. Bianchi[30], M. Bianco[72a,72b], O. Biebel[98], S.P. Bieniek[77], K. Bierwagen[54], J. Biesiada[15], M. Biglietti[134a], H. Bilokon[47], M. Bindi[20a,20b], S. Binet[115], A. Bingul[19c], C. Bini[132a,132b], C. Biscarat[178], B. Bittner[99], K.M. Black[22], R.E. Blair[6], J.-B. Blanchard[136], G. Blanchot[30], T. Blazek[144a], I. Bloch[42], C. Blocker[23], J. Blocki[39], A. Blondel[49], W. Blum[81], U. Blumenschein[54], G.J. Bobbink[105], V.B. Bobrovnikov[107], S.S. Bocchetta[79], A. Bocci[45], C.R. Boddy[118], M. Boehler[48], J. Boek[175], N. Boelaert[36], J.A. Bogaerts[30], A. Bogdanchikov[107], A. Bogouch[90,*], C. Bohm[146a], J. Bohm[125], V. Boisvert[76], T. Bold[38], V. Boldea[26a], N.M. Bolnet[136], M. Bomben[78], M. Bona[75], M. Boonekamp[136], S. Bordoni[78], C. Borer[17], A. Borisov[128], G. Borissov[71], I. Borjanovic[13a], M. Borri[82], S. Borroni[87], V. Bortolotto[134a,134b], K. Bos[105], D. Boscherini[20a], M. Bosman[12], H. Boterenbrood[105], J. Bouchami[93], J. Boudreau[123], E.V. Bouhova-Thacker[71], D. Boumediene[34], C. Bourdarios[115], N. Bousson[83], A. Boveia[31], J. Boyd[30], I.R. Boyko[64], I. Bozovic-Jelisavcic[13b], J. Bracinik[18], P. Branchini[134a], G.W. Brandenburg[57], A. Brandt[8], G. Brandt[118], O. Brandt[54], U. Bratzler[156], B. Brau[84], J.E. Brau[114], H.M. Braun[175,*], S.F. Brazzale[164a,164c], B. Brelier[158], J. Bremer[30], K. Brendlinger[120], R. Brenner[166], S. Bressler[172], D. Britton[53], F.M. Brochu[28], I. Brock[21], R. Brock[88], F. Broggi[89a], C. Bromberg[88], J. Bronner[99], G. Brooijmans[35], T. Brooks[76], W.K. Brooks[32b], G. Brown[82], H. Brown[8], P.A. Bruckman de Renstrom[39], D. Bruncko[144b], R. Bruneliere[48], S. Brunet[60], A. Bruni[20a], G. Bruni[20a], M. Bruschi[20a], T. Buanes[14], Q. Buat[55], F. Bucci[49], J. Buchanan[118], P. Buchholz[141], R.M. Buckingham[118], A.G. Buckley[46], S.I. Buda[26a], I.A. Budagov[64], B. Budick[108], V. Büscher[81], L. Bugge[117], O. Bulekov[96], A.C. Bundock[73], M. Bunse[43], T. Buran[117], H. Burckhart[30], S. Burdin[73], T. Burgess[14], S. Burke[129], E. Busato[34], P. Bussey[53], C.P. Buszello[166], B. Butler[143], J.M. Butler[22], C.M. Buttar[53], J.M. Butterworth[77], W. 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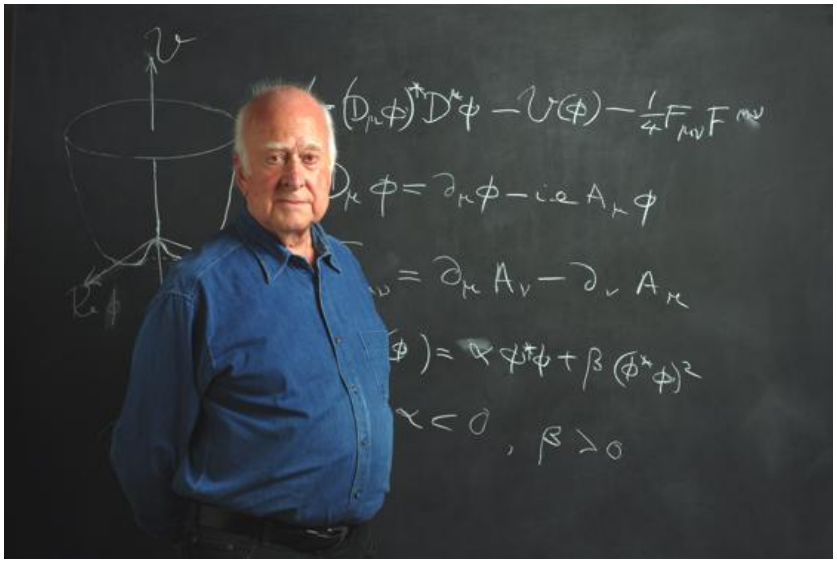
K. Yamamoto [63], S. Yamamoto [155], T. Yamamura [155], T. Yamanaka [155], T. Yamazaki [155], Y. Yamazaki [66], Z. Yan [22], H. Yang [87], H. Yang [173], U.K. Yang [82], Y. Yang [109], Z. Yang [146a,146b], S. Yanush [91], L. Yao [33a], Y. Yao [15], Y. Yasu [65], G.V. Ybeles Smit [130], J. Ye [40], S. Ye [25], M. Yilmaz [4c], R. Yoosoofmiya [123], K. Yorita [171], R. Yoshida [6], K. Yoshihara [155], C. Young [143], C.J. Young [118], S. Youssef [22], D. Yu [25], J. Yu [8], J. Yu [112], L. Yuan [66], A. Yurkewicz [106], M. Byszewski [30], B. Zabinski [39], R. Zaidan [62], A.M. Zaitsev [128], Z. Zajacova [30], L. Zanello [132a,132b], D. Zanzi [99], A. Zaytsev [25], C. Zeitnitz [175], M. Zeman [125], A. Zemla [39], C. Zendler [21], O. Zenin [128], T. Ženiš [144a], Z. Zinonos [122a,122b], D. Zerwas [115], G. Zevi della Porta [57], D. Zhang [33b,ak], H. Zhang [88], J. Zhang [6], X. Zhang [33d], Z. Zhang [115], L. Zhao [108], Z. Zhao [33b], A. Zhemchugov [64], J. Zhong [118], B. Zhou [87], N. Zhou [163], Y. Zhou [151], C.G. Zhu [33d], H. Zhu [42], J. Zhu [87], Y. Zhu [33b], X. Zhuang [98], V. Zhuravlov [99], D. Zieminska [60], N.I. Zimin [64], R. Zimmermann [21], S. Zimmermann [48], M. Ziolkowski [141], R. Zitoun [5], L. Živković [35], V.V. Zmouchko [128,*], G. Zobernig [173], A. Zoccoli [20a,20b], M. zur Nedden [16], V. Zutshi [106], L. Zwalinski [30]

The Higgs Mechanism

For over half a century, we have had an incredibly successful theory of all known particles and forces

… except that it predicts all particles are massless!



Peter Higgs and others proposed a `Higgs field' present throughout the entire universe

… grabbing hold of passing particles with mass

… slowing them down compared with massless particles like photons

The Higgs field is weird! Unlike force fields such as gravity:

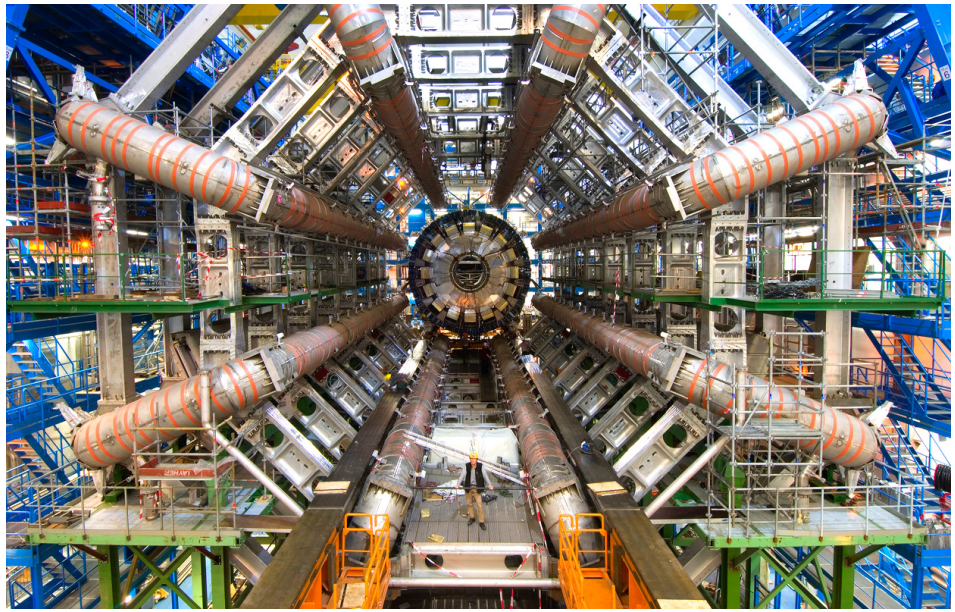
→ No preferred direction

→ No need for a source … equally strong in vacuum of inter-galactic space as it is in this room …

How to Prove the Higgs theory?

Another prediction of Higgs theory … there should be a new particle … a Higgs boson

Very very hard to produce … 1 in every 10 billion collisions at the LHC



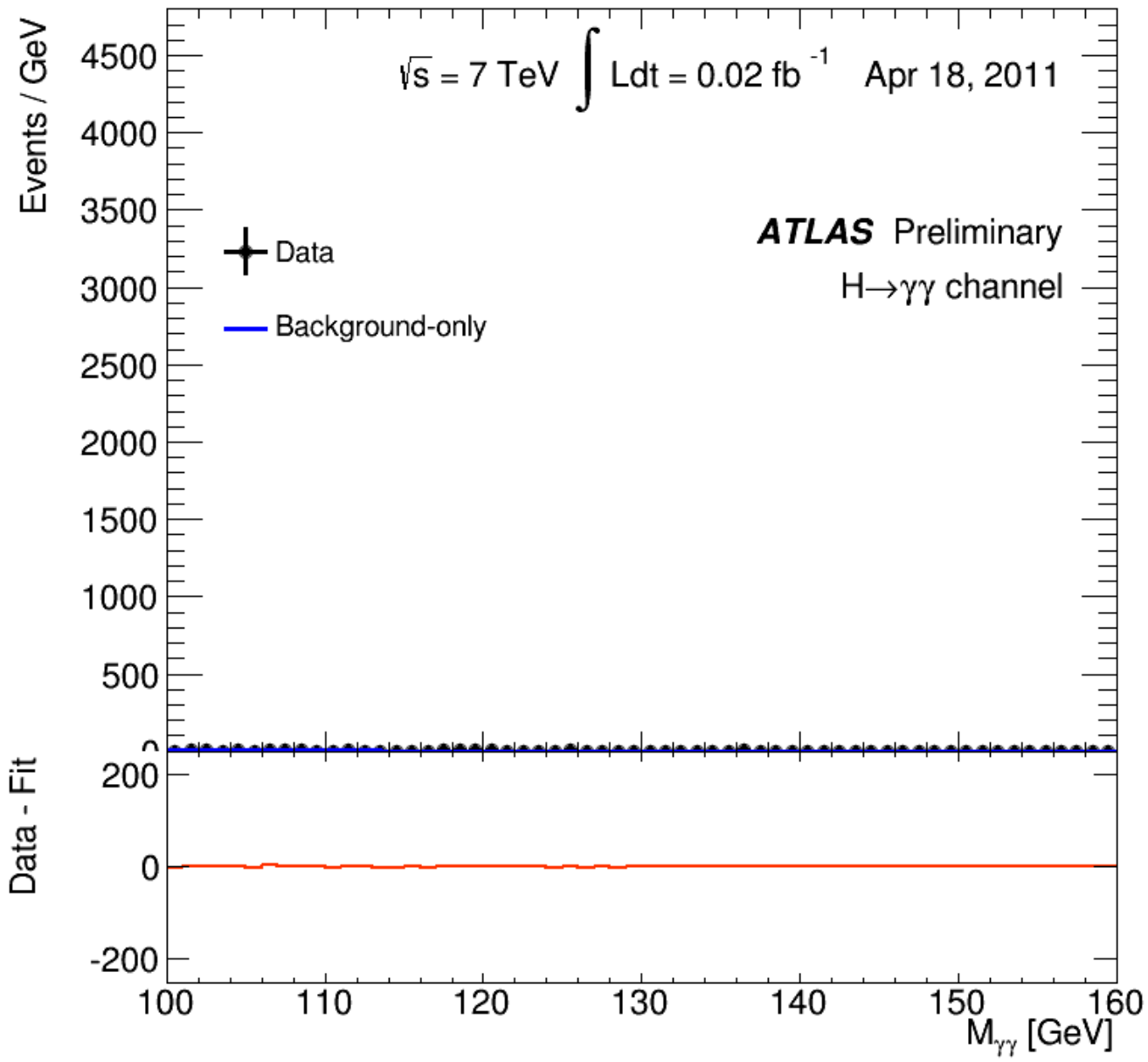
Searching for the Higgs Boson

~~It's like looking for a needle in a haystack~~

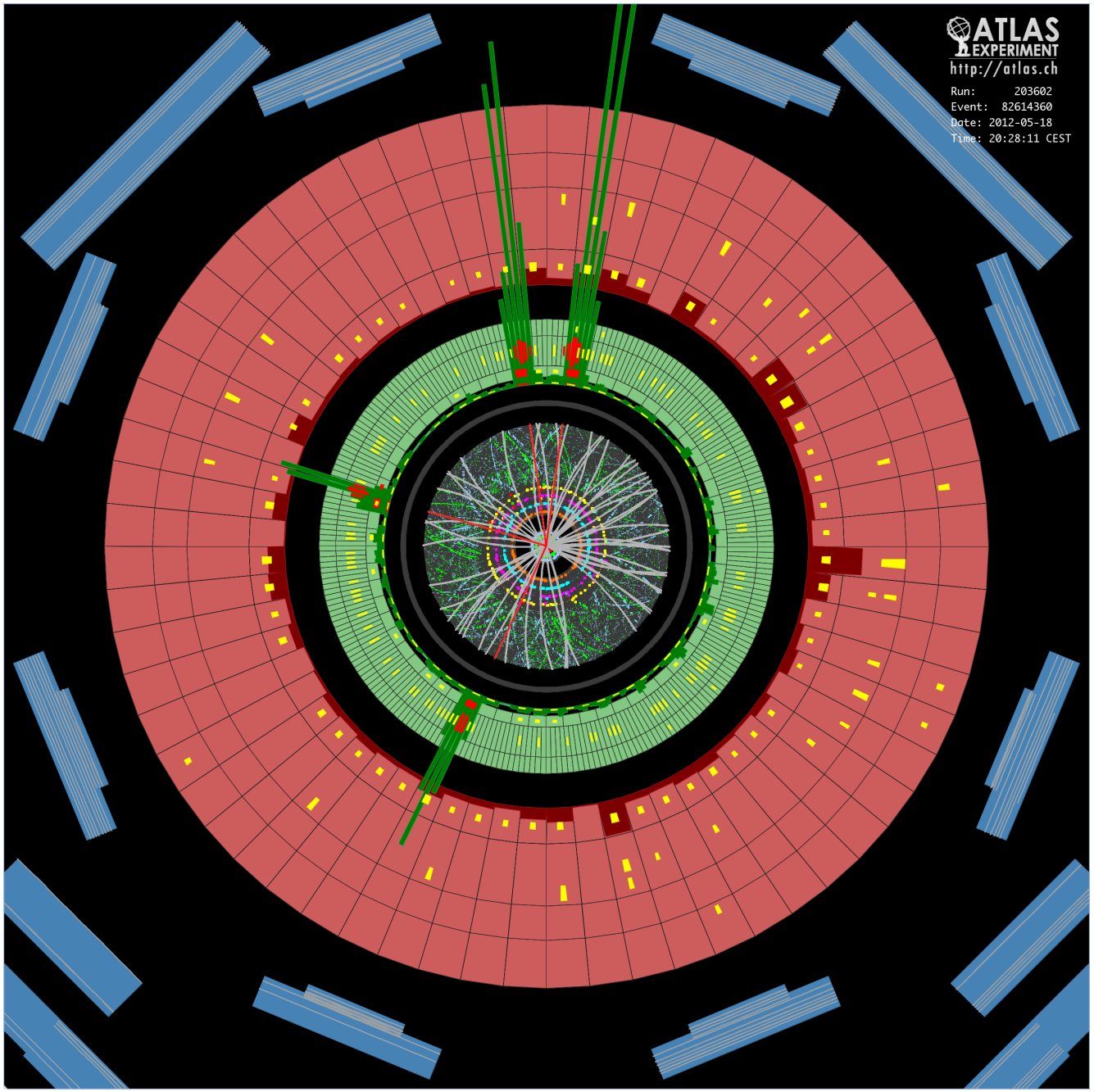
~~It's like looking for a needle in 10000 haystacks~~

It's like looking for a piece of hay in 10000 haystacks

Looking for Higgs decaying to 2 photons



Spotlight on Birmingham contributions …



Higgs candidate decaying to four electrons via ZZ

…

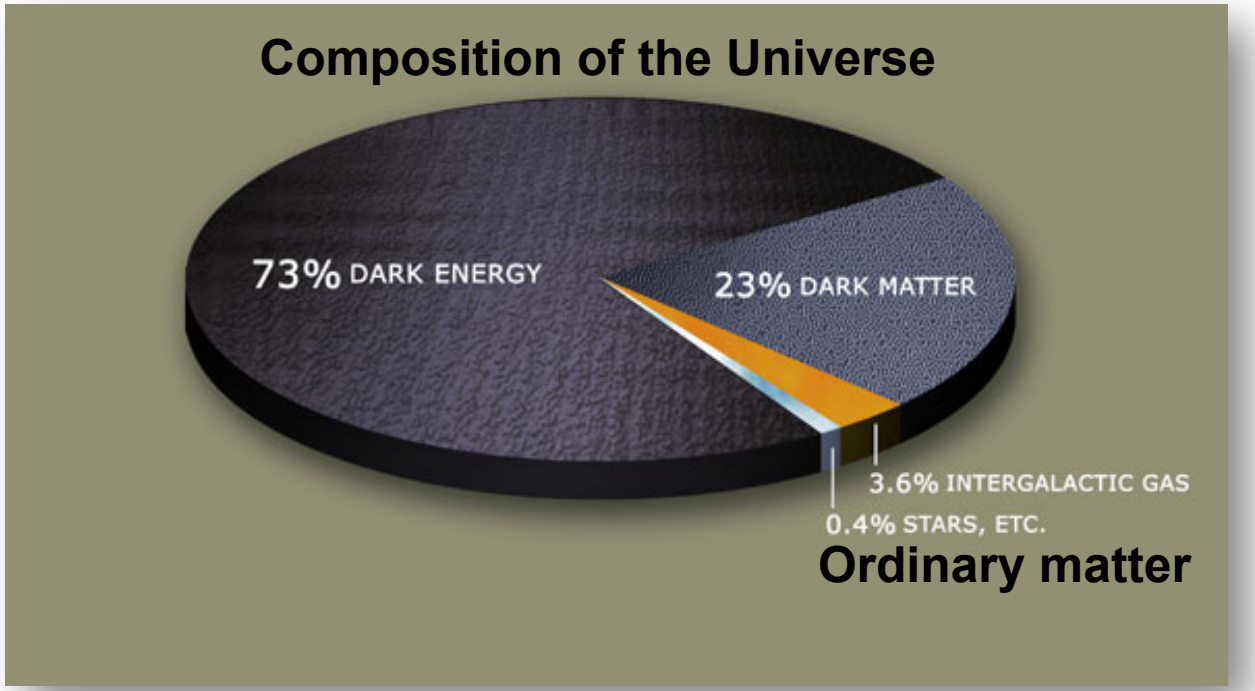
Birmingham-led analysis

Triggered using electronics produced by Birmingham

shown using our ATLANTIS event display

What Next at the LHC?... One Possibility

Looking at our Universe we see much more than ordinary matter (or antimatter)



The dark side of the universe…

If dark matter is made up of unknown elementary particles, they could be discovered at the LHC… we are searching hard!

The Future?

- Early days … Higgs discovered with 1% of total planned collisions at half the design beam energy

- LHC collecting data 2015-2018 with energy doubled

- The LHC is scheduled to run for another 20 years …

  - Will we see a deeper structure to the quarks?
  - Will we see Dark Matter, Supersymmetry, Extra Dimensions?
  - Will we see something completely unexpected!

… WATCH THIS SPACE!!!

Lots more information on the LHC and how it relates to our undergraduate degree programmes downstairs in Y1 Lab …