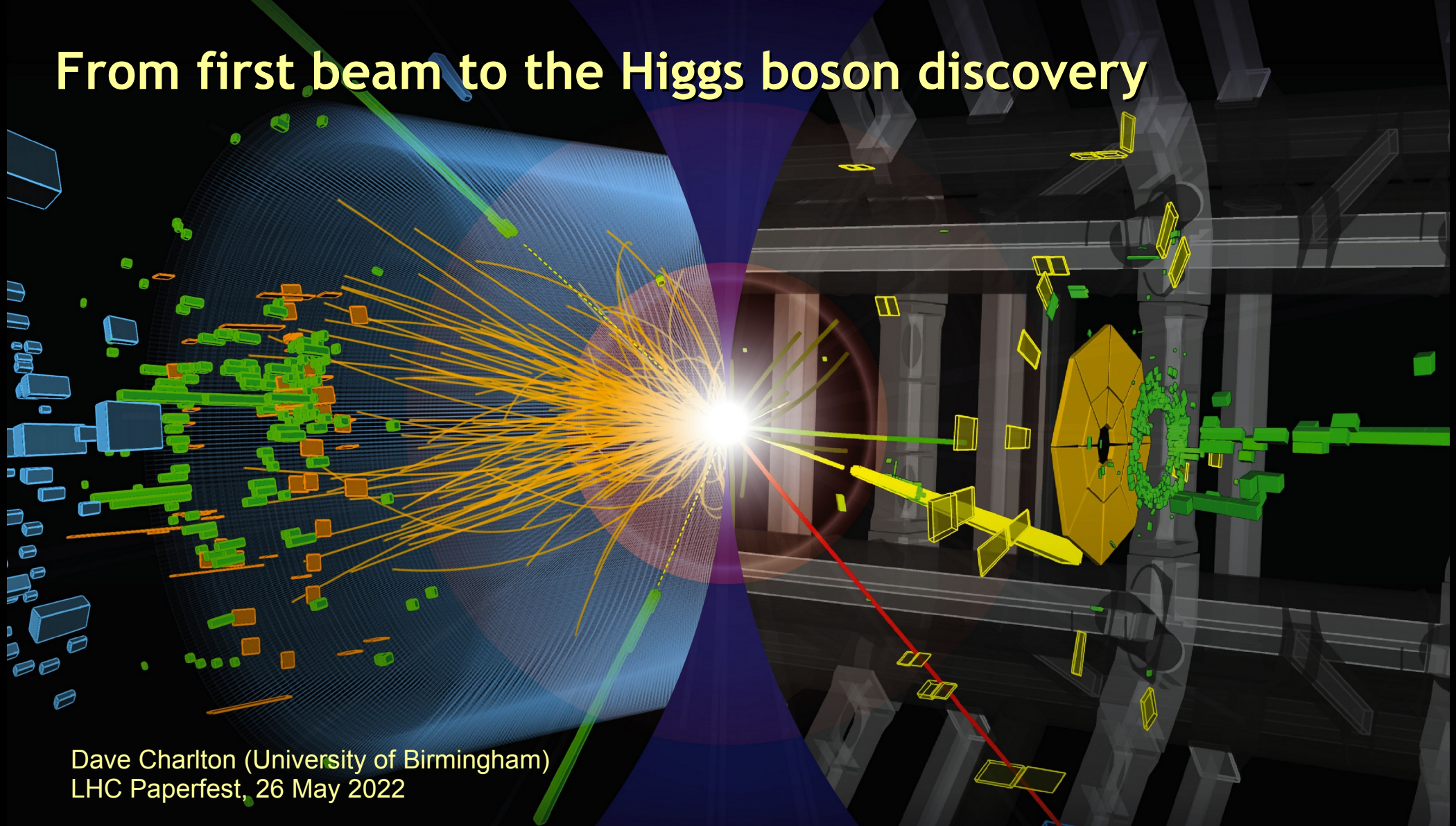
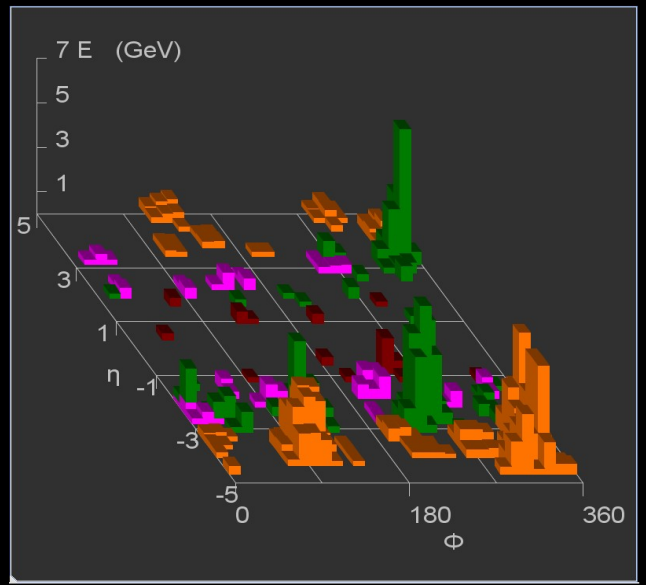
From first beam to the Higgs boson discovery



Dave Charlton (University of Birmingham)
LHC Paperfest, 26 May 2022

20 Nov 2009

Candidate Collision Event



ATLAS EXPERIMENT

2009-11-23 14:22 CET

Run 140541, Event 171897

http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

First physics paper from LHC collisions

Eur. Phys. J. C (2010) 65: 111–125
DOI 10.1140/epjc/s10052-009-1227-4

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

28 Nov 2009

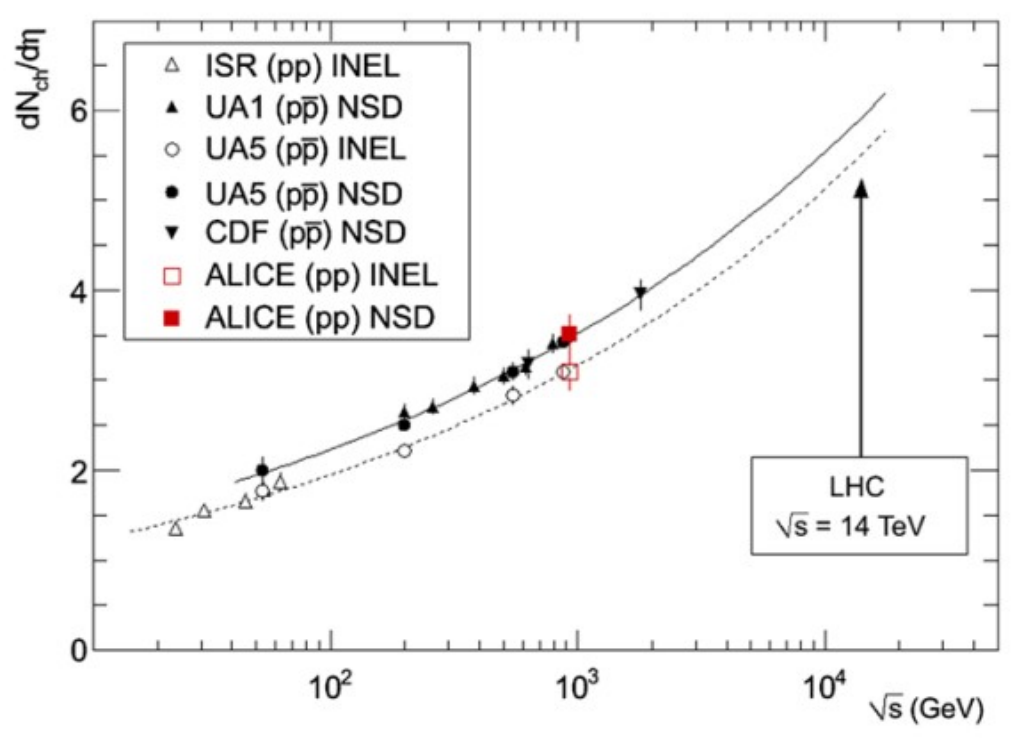
First proton–proton collisions at the LHC as observed with the ALICE detector: measurement of the charged-particle pseudorapidity density at $\sqrt{s} = 900$ GeV

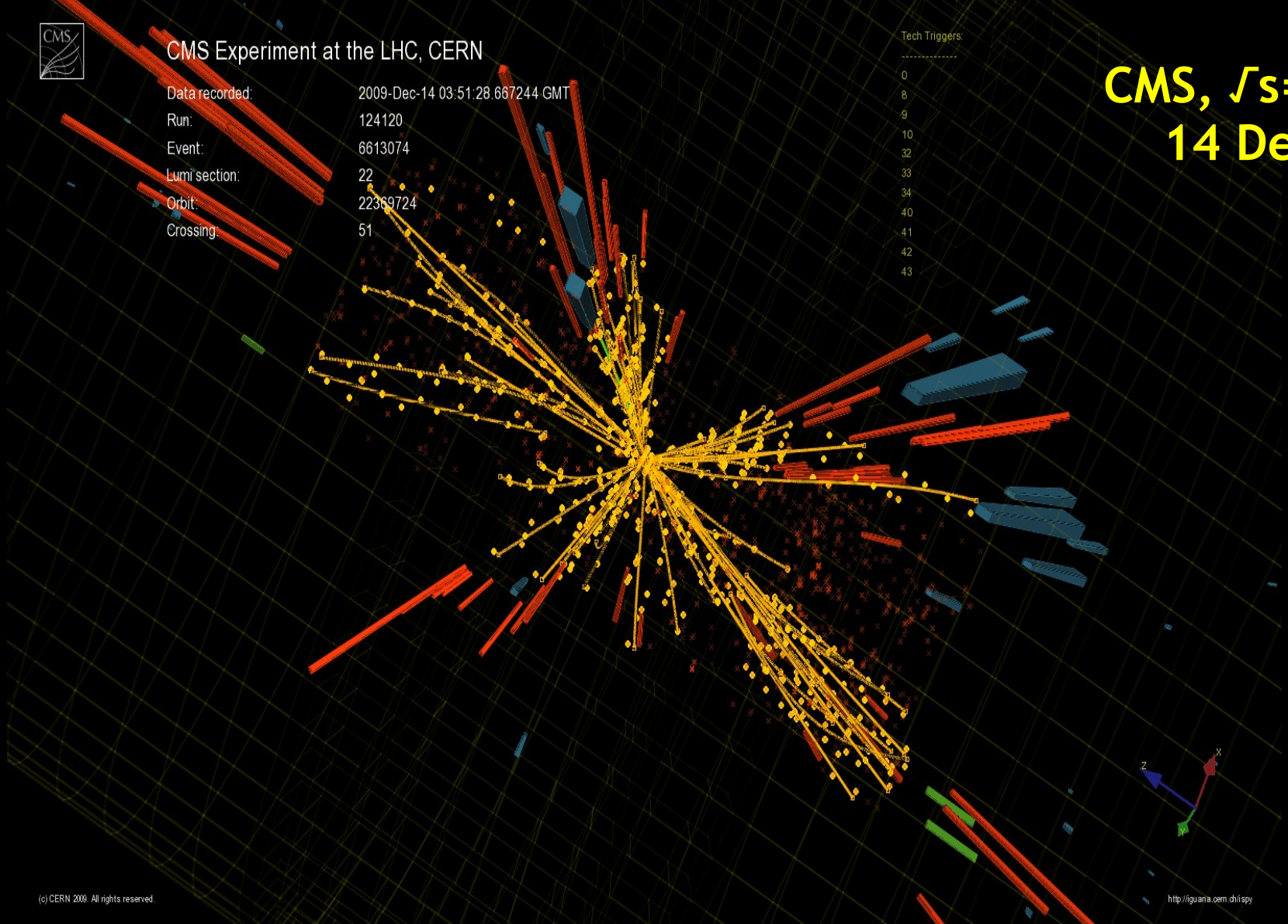
The ALICE Collaboration

K. Aamodt[78], N. Abel[43], U. Abeysekara[30], A. Abrahantes Quintana[42], A. Acero[63], D. Adamová[86], M.M. Aggarwal[25],

...just five days after the first collisions

First measurement of proton-proton collisions at the LHC





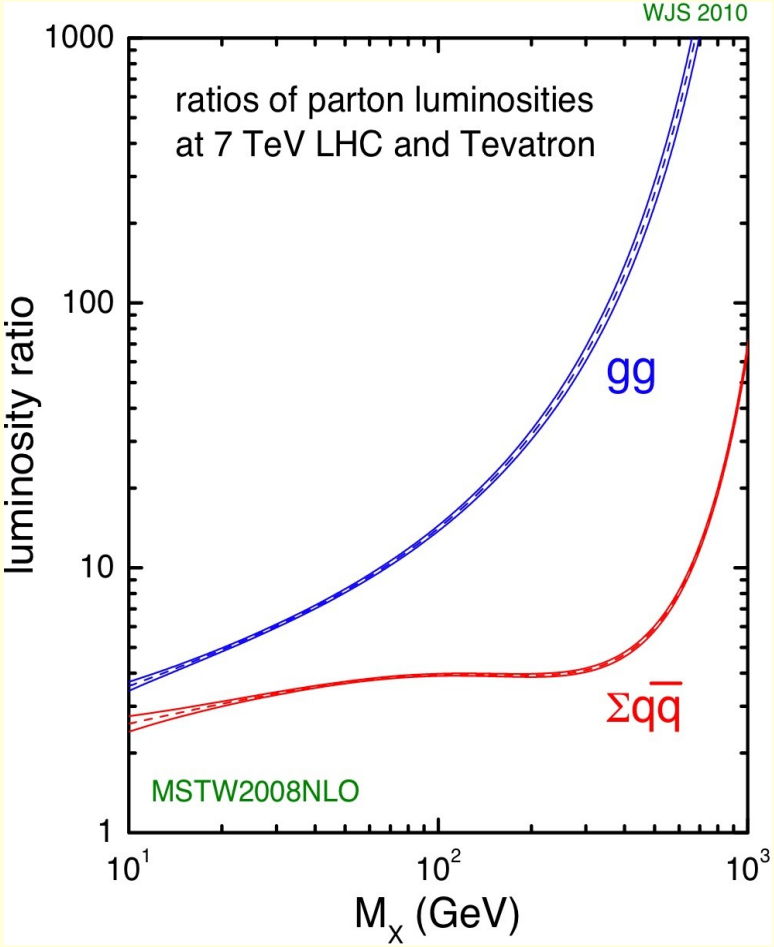
CMS, $\sqrt{s}$=2.36 TeV
14 Dec 2009

2010: Collisions at 7 TeV

Addressing the dual requirements

- Higher collision energy *("√s")*
- Greater number of collisions *(integrated luminosity)*

Big increase in flux of gluons and quarks compared to previous accelerator (Tevatron)

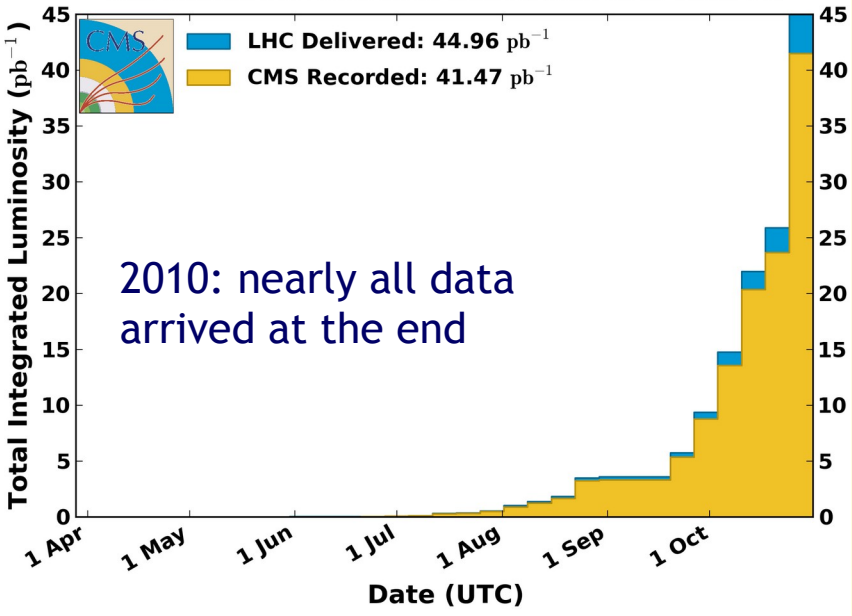


Mass of object to be produced

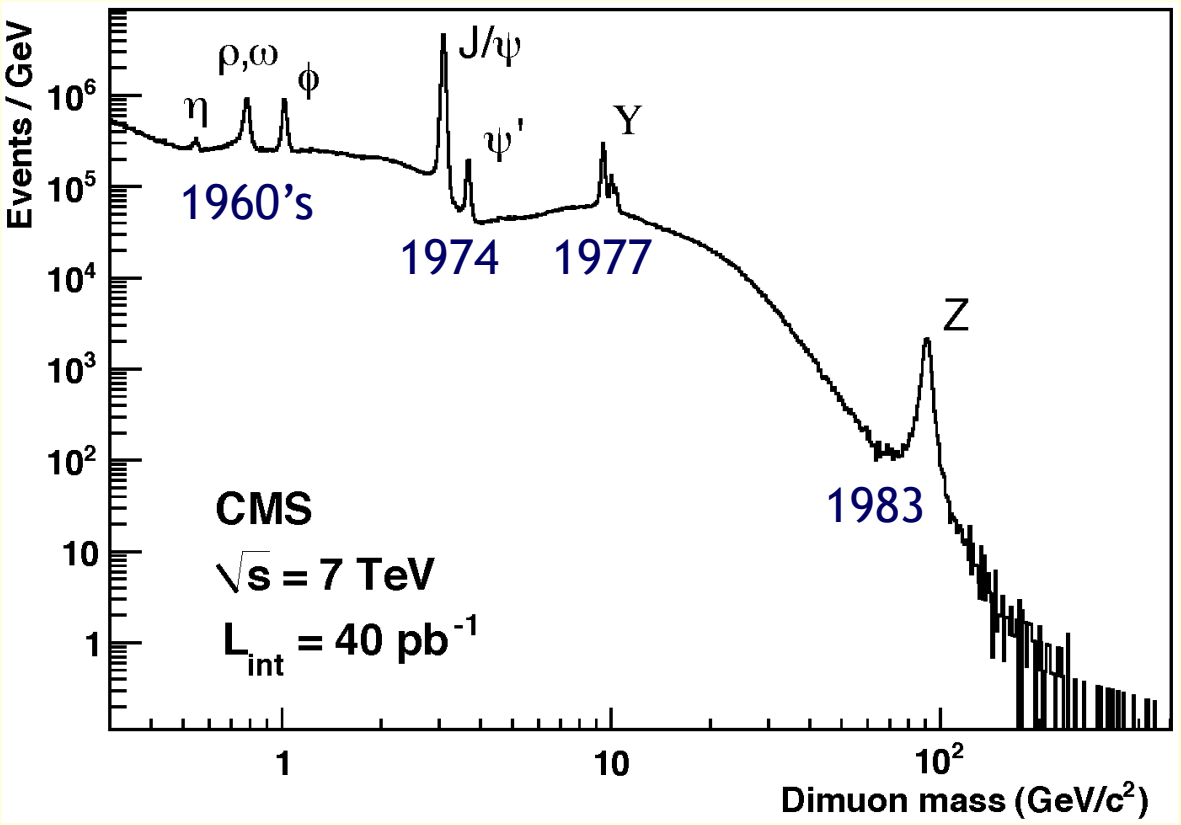
2010: Collisions at 7 TeV

Addressing the dual requirements

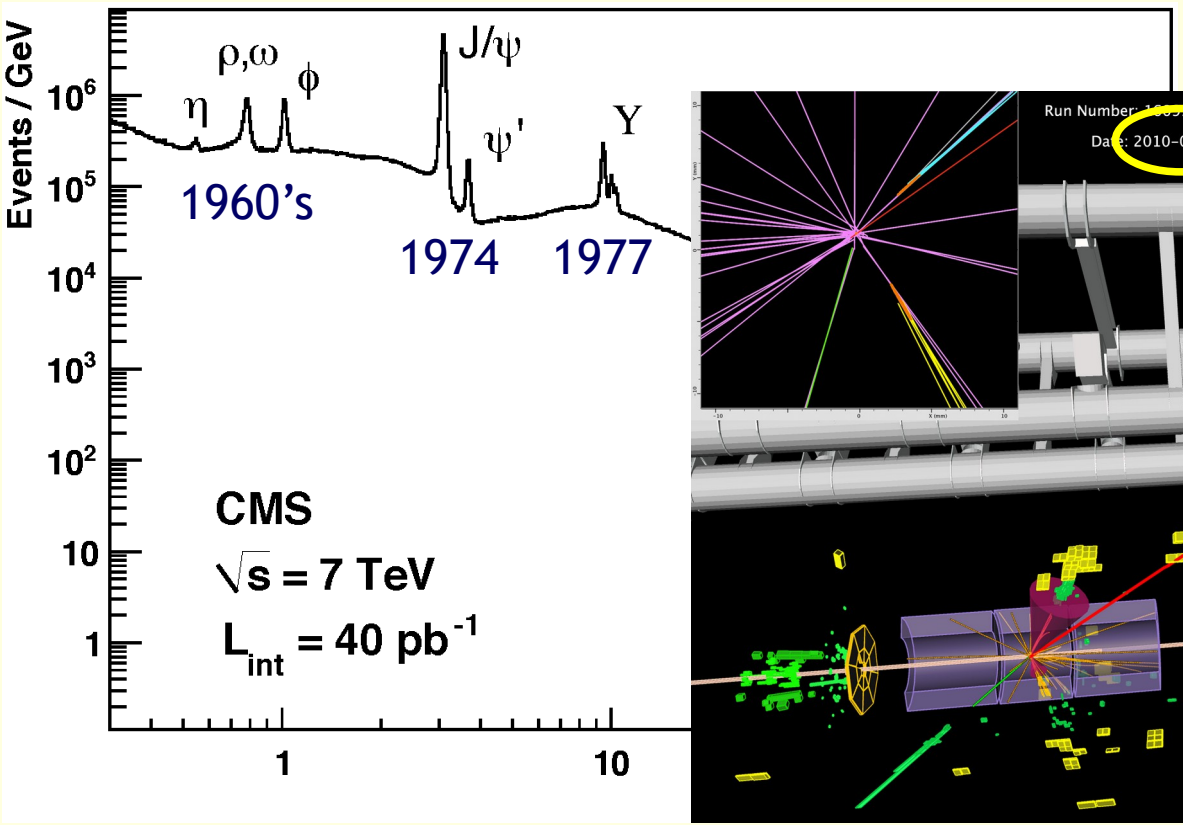
- Higher collision energy *("√s")*
- Greater number of collisions *(integrated luminosity)*



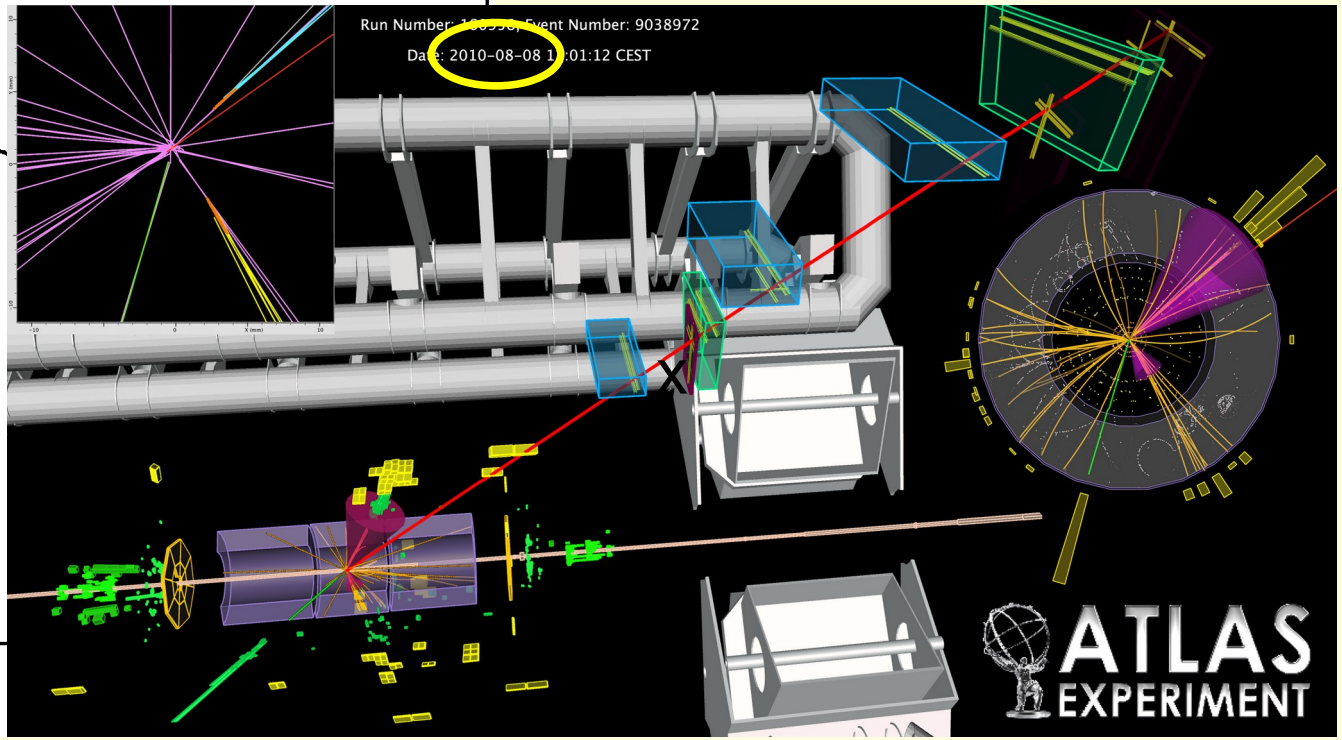
Re-establishing the known particles



Re-establishing the known particles



top quarks (1995)



Physics Letters B 694 (2010) 209–216

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Measurement of $\sigma(pp \to b\bar{b}X)$ at $\sqrt{s} = 7$ TeV in the forward region ☆

LHCb Collaboration

ARTICLE INFO

Article history:
Received 14 September 2010

ABSTRACT

Decays of b hadrons into final states containing a D^0 meson and a muon are used to measure the $b\bar{b}$ production cross-section in proton–proton collisions at a centre-of-mass energy of 7 TeV at the LHC.

Physics Letters B 695 (2011) 424–443

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

First measurement of the cross section for top-quark pair production in proton–proton collisions at $\sqrt{s} = 7$ TeV ☆

CMS Collaboration

CERN, Switzerland

ARTICLE INFO

Article history:
Received 30 October 2010

ABSTRACT

The first measurement of the cross section for top-quark pair production in pp collisions at the Large Hadron Collider at center-of-mass energy $\sqrt{s} = 7$ TeV has been performed using a data sample

JHEP

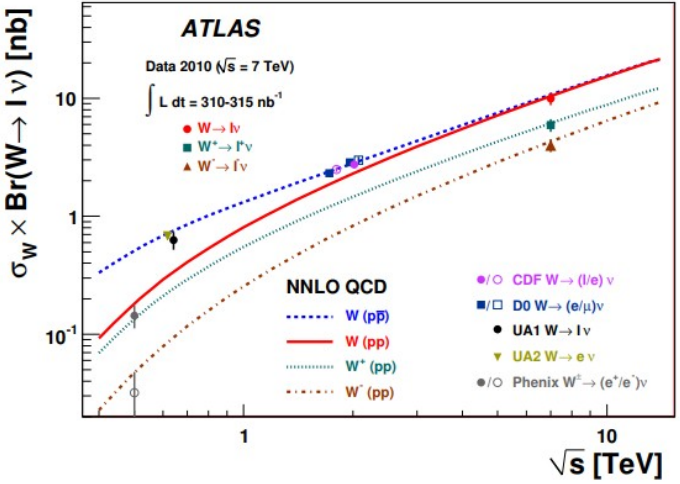
PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: October 13, 2010
ACCEPTED: November 24, 2010
PUBLISHED: December 14, 2010

Measurement of the $W \to \ell\nu$ and $Z/\gamma^* \to \ell\ell$ production cross sections in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

The ATLAS Collaboration[1]

ABSTRACT: First measurements of the $W \to \ell\nu$ and $Z/\gamma^* \to \ell\ell$ ($\ell = e, \mu$) production cross sections in proton-proton collisions at $\sqrt{s} = 7$ TeV are presented using data recorded



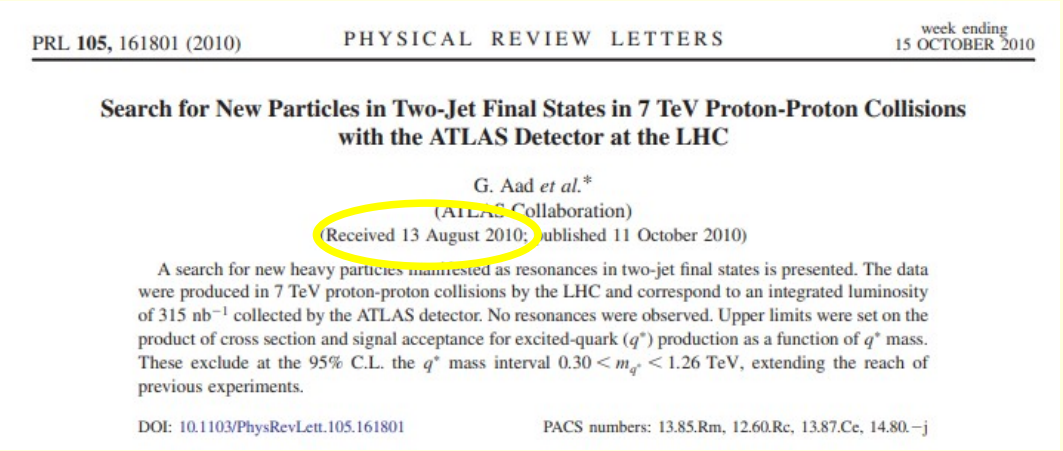
Searching for new processes

Particles or interactions which are too high mass, or too weakly coupled, to have been seen before

Every step in energy and luminosity gives us more reach

Broad types of search

- topological searches looking for new/anomalous event signatures
- model-driven searches (e.g. supersymmetry: SUSY)
- and many in-between (e.g. some dark matter searches)



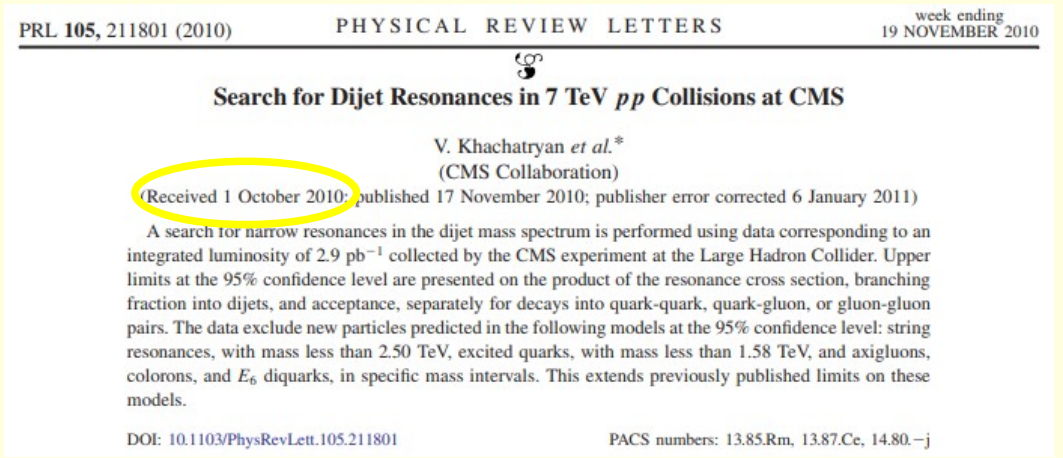
PRL 105, 161801 (2010) PHYSICAL REVIEW LETTERS week ending 15 OCTOBER 2010

Search for New Particles in Two-Jet Final States in 7 TeV Proton-Proton Collisions with the ATLAS Detector at the LHC

G. Aad *et al.**
(ATLAS Collaboration)
(Received 13 August 2010; published 11 October 2010)

A search for new heavy particles manifested as resonances in two-jet final states is presented. The data were produced in 7 TeV proton-proton collisions by the LHC and correspond to an integrated luminosity of 315 nb^{-1} collected by the ATLAS detector. No resonances were observed. Upper limits were set on the product of cross section and signal acceptance for excited-quark (q^*) production as a function of q^* mass. These exclude at the 95% C.L. the q^* mass interval $0.30 < m_{q^*} < 1.26$ TeV, extending the reach of previous experiments.

DOI: 10.1103/PhysRevLett.105.161801 PACS numbers: 13.85.Rm, 12.60.Rc, 13.87.Ce, 14.80.−j



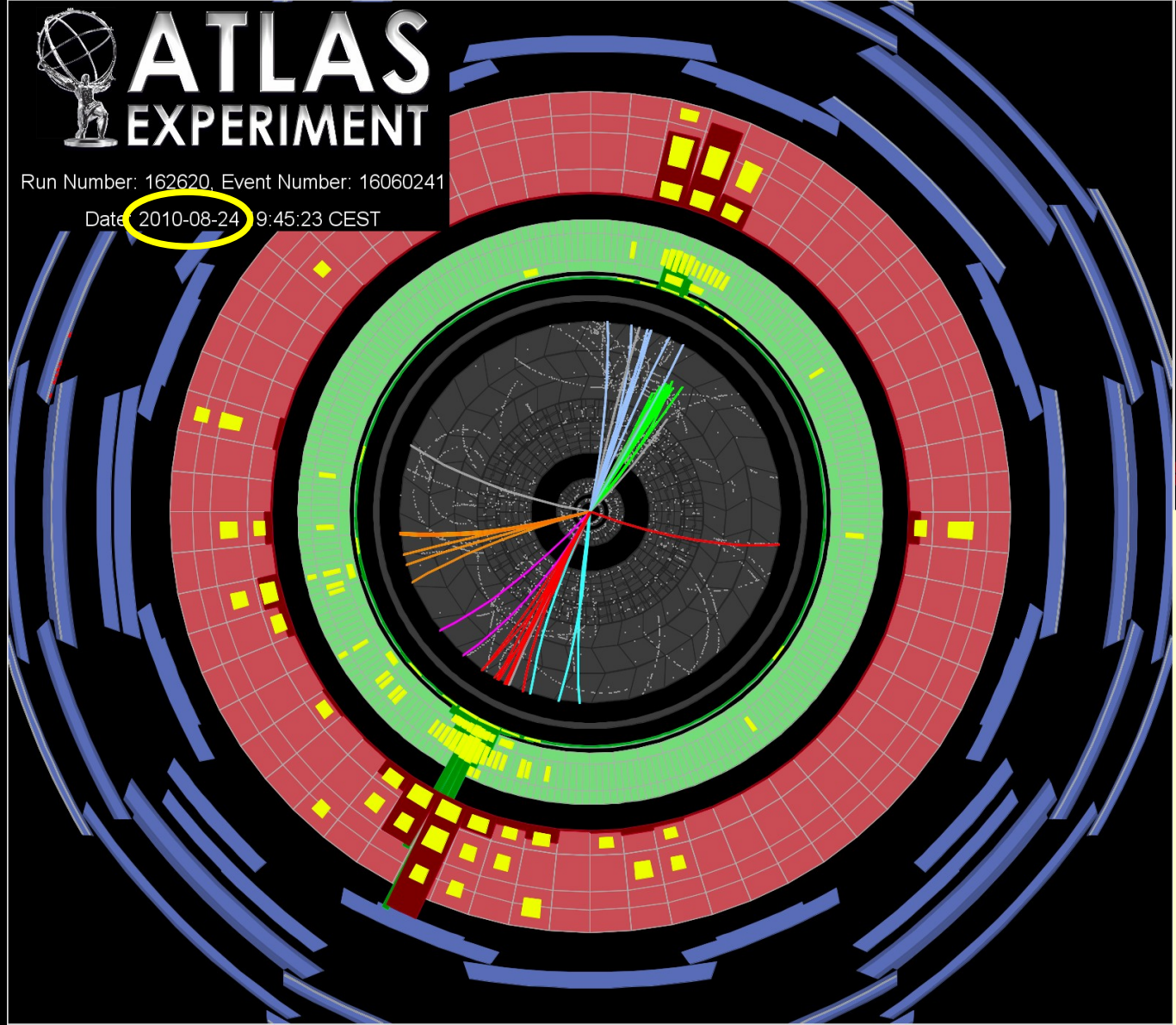
PRL 105, 211801 (2010) PHYSICAL REVIEW LETTERS week ending 19 NOVEMBER 2010

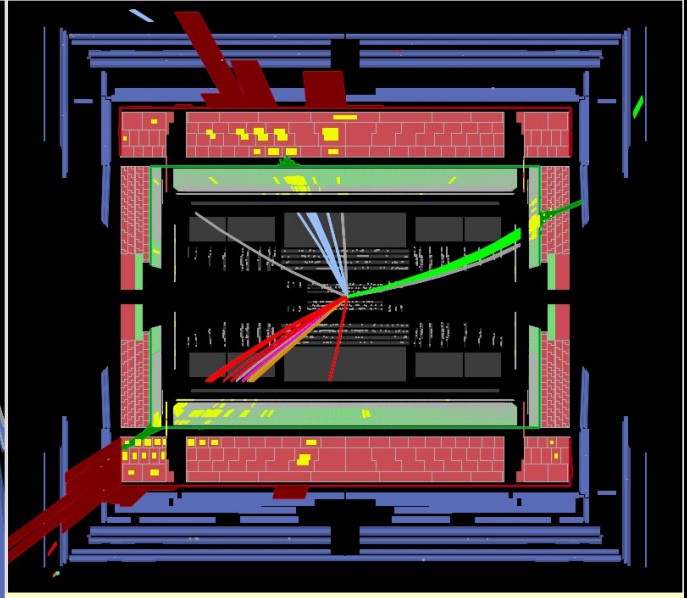
Search for Dijet Resonances in 7 TeV *pp* Collisions at CMS

V. Khachatryan *et al.**
(CMS Collaboration)
(Received 1 October 2010; published 17 November 2010; publisher error corrected 6 January 2011)

A search for narrow resonances in the dijet mass spectrum is performed using data corresponding to an integrated luminosity of 2.9 pb^{-1} collected by the CMS experiment at the Large Hadron Collider. Upper limits at the 95% confidence level are presented on the product of the resonance cross section, branching fraction into dijets, and acceptance, separately for decays into quark-quark, quark-gluon, or gluon-gluon pairs. The data exclude new particles predicted in the following models at the 95% confidence level: string resonances, with mass less than 2.50 TeV, excited quarks, with mass less than 1.58 TeV, and axigluons, colorons, and E_6 diquarks, in specific mass intervals. This extends previously published limits on these models.

DOI: 10.1103/PhysRevLett.105.211801 PACS numbers: 13.85.Rm, 13.87.Ce, 14.80.−j



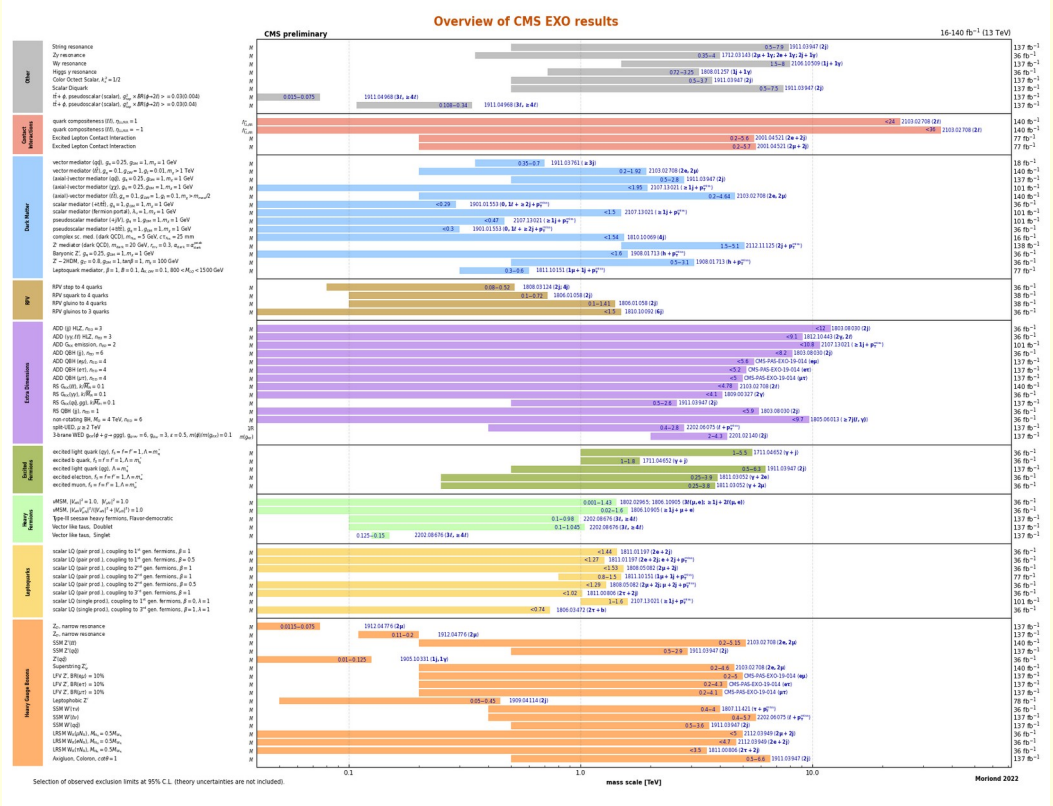


Two very high energy jets of hadrons in this event, plus a third lower energy jet

The two jets together have a mass of 3.1 TeV

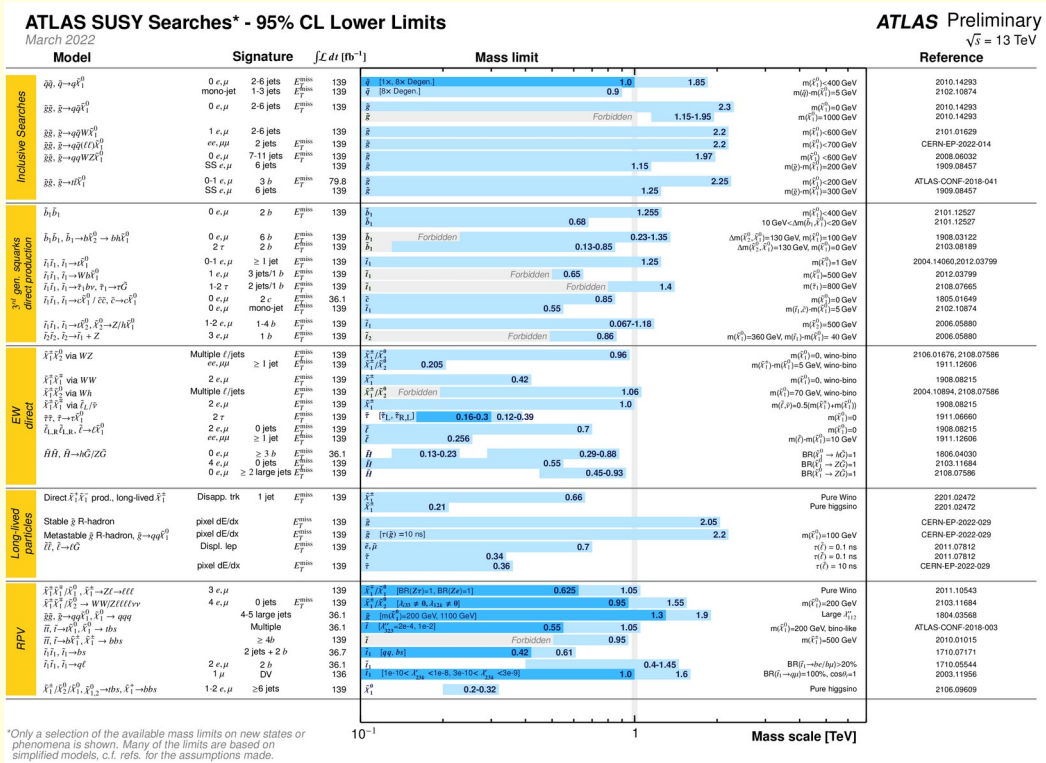
No previous collider could get close to these energies

A fraction of the model constraints from searches (2022)



Today, around 800 different search papers from ATLAS and CMS

Aiming to leave no stone unturned…



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

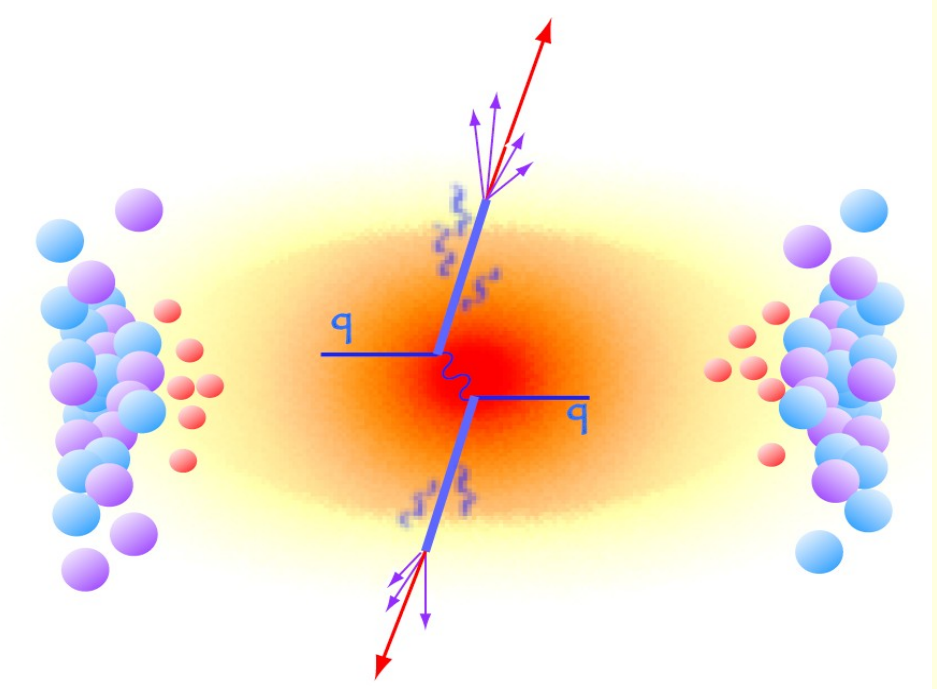
Observation of jet quenching

LHC also collides lead (Pb) nuclei

- Forms a region of hot dense matter – quark-gluon plasma

First LHC Pb+Pb collisions in 2010: saw immediately the new phenomenon of "jet quenching"

- High-energy quark or gluon travelling far through the hot dense matter loses energy
- "One-sided" jet events



While not "conventional" Beyond-the-Standard Model new physics, this was a new physical phenomenon

Observation of j

LHC also collides lead (Pb) nuclei

- Forms a region of hot dense matter – quark-gluon plasma

First LHC Pb+Pb collisions in 2010: saw immediately the new phenomenon of “jet quenching”

- High-energy quark or gluon travelling far through the hot dense matter loses energy
- “One-sided” jet events

PRL 105, 252303 (2010) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS Detector at the LHC

G. Aad *et al.**
(ATLAS Collaboration)

(Received 25 November 2010; published 13 December 2010)

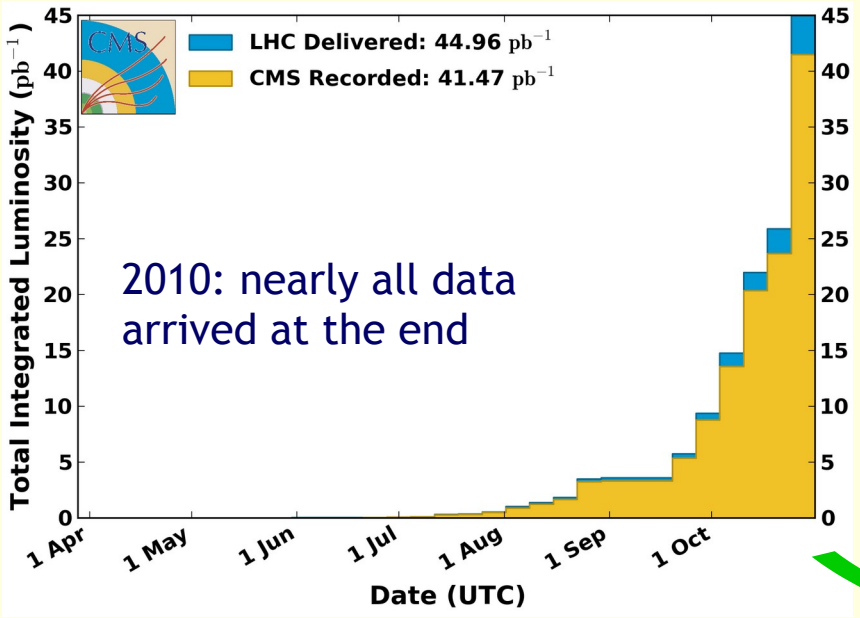
By using the ATLAS detector, observations have been made of a centrality-dependent dijet asymmetry in the collisions of lead ions at the Large Hadron Collider. In a sample of lead-lead events with a per-nucleon center of mass energy of 2.76 TeV, selected with a minimum bias trigger, jets are reconstructed in fine-grained, longitudinally segmented electromagnetic and hadronic calorimeters. The transverse energies of dijets in opposite hemispheres are observed to become systematically more unbalanced with increasing event centrality leading to a large number of events which contain highly asymmetric dijets. This is the first observation of an enhancement of events with such large dijet asymmetries, not observed in proton-proton collisions, which may point to an interpretation in terms of strong jet energy loss in a hot, dense medium.

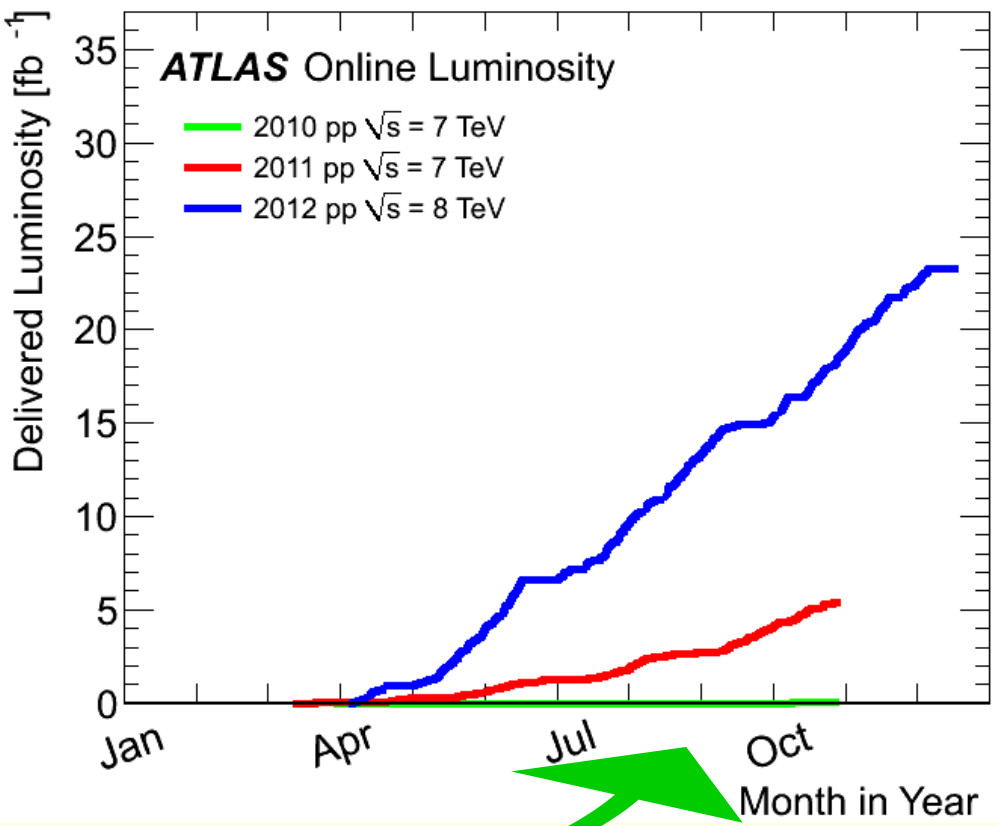
DOI: 10.1103/PhysRevLett.105.252303 PACS numbers: 25.75.Bh

2010 to 2012: Collisions at 7, 8 TeV

Addressing the dual requirements

- Higher collision energy *("√s")*
- Greater number of collisions *(integrated luminosity)*





End 2011: the first new particle of many

A new excited particle state of bottomonium, the $\chi_b(3P)$, was found via a distinctive decay mode – an new hadron state

PRL 108, 152001 (2012) PHYSICAL REVIEW LETTERS week ending 13 APRIL 2012

Observation of a New χ_b State in Radiative Transitions to $\Upsilon(1S)$ and $\Upsilon(2S)$ at ATLAS

G. Aad *et al.**
(ATLAS Collaboration)

(Received 21 December 2011; revised manuscript received 18 February 2012; published 9 April 2012)

The $\chi_b(nP)$ quarkonium states are produced in proton-proton collisions at the Large Hadron Collider at $\sqrt{s} = 7$ TeV and recorded by the ATLAS detector. Using a data sample corresponding to an integrated luminosity of 4.4 fb^{-1}, these states are reconstructed through their radiative decays to $\Upsilon(1S, 2S)$ with $\Upsilon \to \mu^+\mu^-$. In addition to the mass peaks corresponding to the decay modes $\chi_b(1P, 2P) \to \Upsilon(1S)\gamma$, a new structure centered at a mass of 10.530 ± 0.005(stat) ± 0.009(syst) GeV is also observed, in both the $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ decay modes. This structure is interpreted as the $\chi_b(3P)$ system.

DOI: 10.1103/PhysRevLett.108.152001 PACS numbers: 14.40.Pq, 12.38.−t, 13.20.Gd, 14.65.Fy

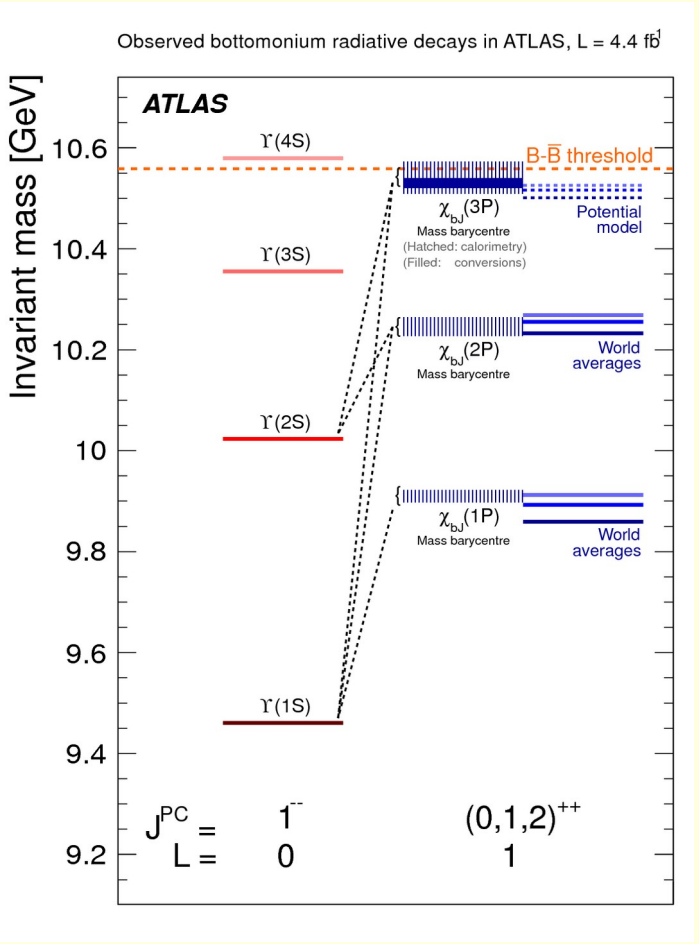
Measurements of the properties of heavy quark-antiquark bound states, or quarkonia, provide a unique insight into the

liquid-argon calorimeters for both electromagnetic and hadronic measurements. The muon spectrometer surrounds

LHC reports discovery of its first new particle

By Jonathan Amos
Science correspondent, BBC News

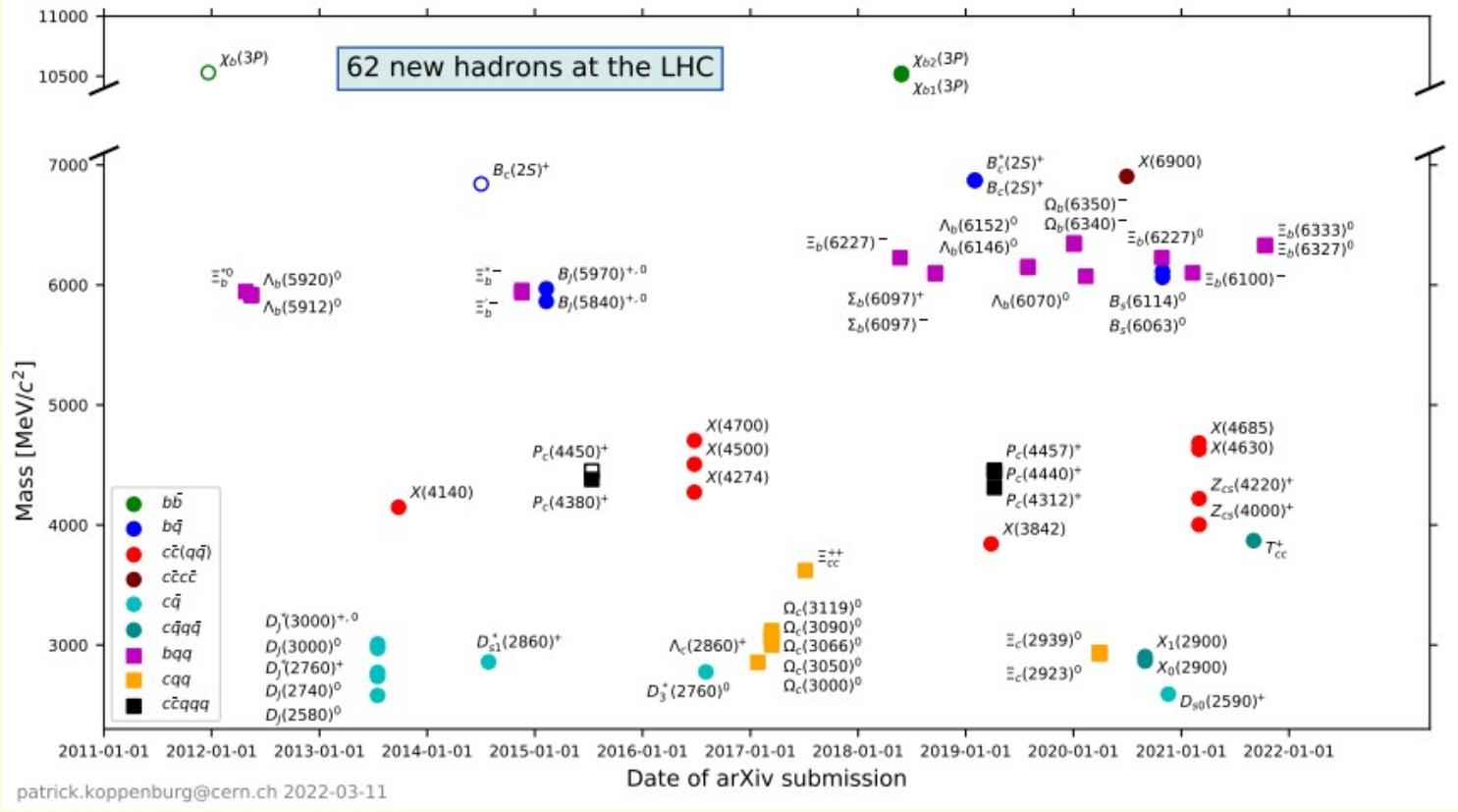
22 December 2011



End 2011: the first new particle of many

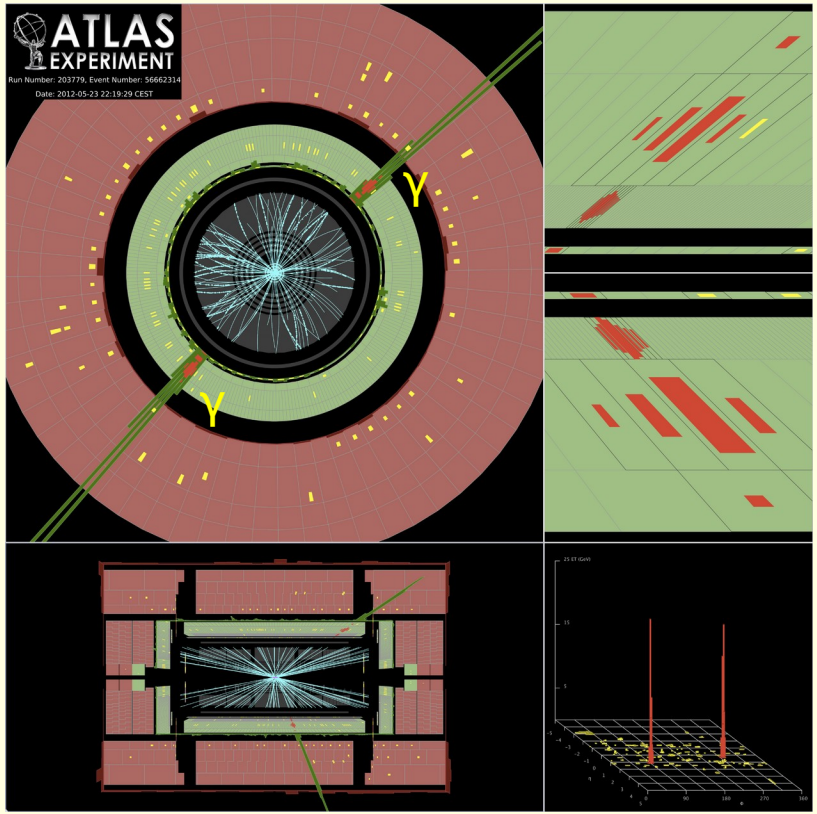
Many more *new hadrons* discovered since then – a speciality particularly of LHCb

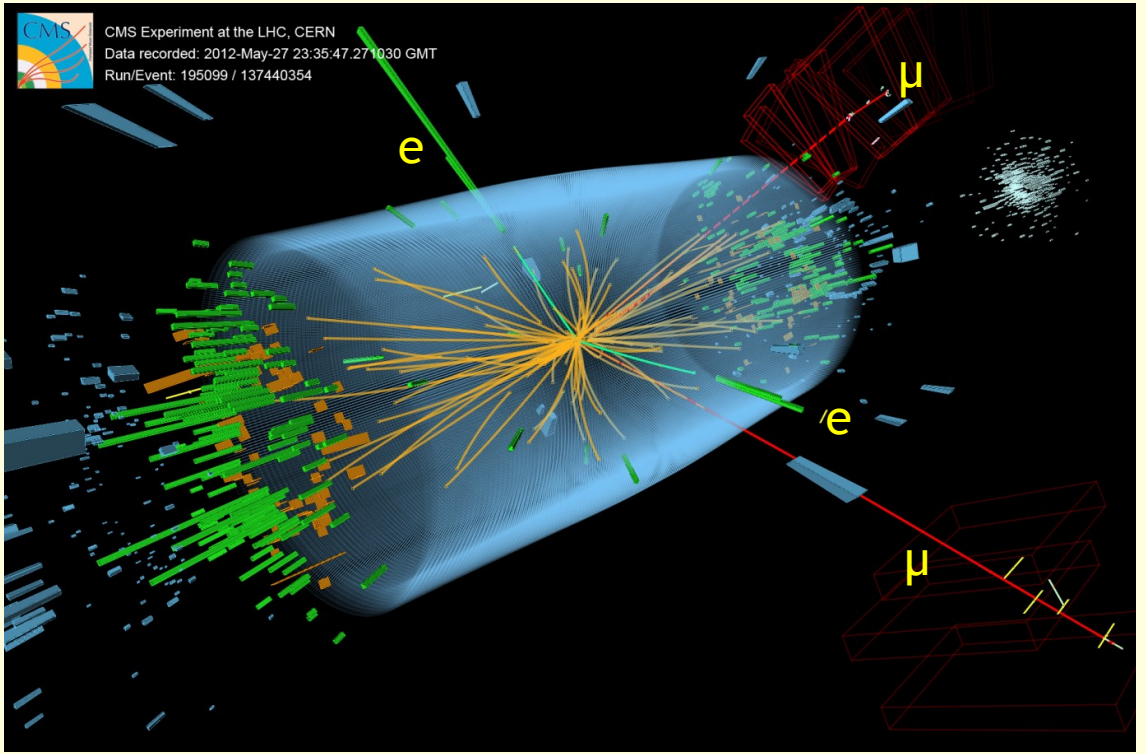
LHCb measures a vast range of properties of hadrons containing b and c quarks



The big one: Higgs boson *search*

The two key channels for discovery: H→γγ and H→4ℓ (ℓ=e/μ)
Both allow to reconstruct the ***mass*** of a putative object decaying to either state





H search papers with 2011 data

Selected for a Viewpoint in *Physics*
PRL **108,** 111803 (2012) PHYSICAL REVIEW LETTERS week ending 16 MARCH 2012

Search for the Standard Model Higgs Boson in the Diphoton Decay Channel with 4.9 fb^{-1} of pp Collision Data at $\sqrt{s} = 7$ TeV with ATLAS

G. Aad *et al.**
(ATLAS Collaboration)
(Received 7 February 2012; published 13 March 2012)

A search for the standard model Higgs boson is performed in the diphoton decay channel. The data used correspond to an integrated luminosity of 4.9 fb^{-1} collected with the ATLAS detector at the Large Hadron

Physics Letters B 710 (2012) 383–402
Contents lists available at SciVerse ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

Search for the Standard Model Higgs boson in the decay channel $H \to ZZ^{(*)} \to 4\ell$ with 4.8 fb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV with ATLAS ☆

ATLAS Collaboration *

ARTICLE INFO
Article history:
Received 7 February 2012

ABSTRACT
This Letter presents a search for the Standard Model Higgs boson in the decay channel $H \to ZZ^{(*)} \to \ell^+\ell^-\ell'^+\ell'^-$, where $\ell, \ell' = e$ or μ, using proton–proton collisions at $\sqrt{s} = 7$ TeV recorded with the ATLAS

Physics Letters B 710 (2012) 403–425
Contents lists available at SciVerse ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

Search for the standard model Higgs boson decaying into two photons in pp collisions at $\sqrt{s} = 7$ TeV ☆

CMS Collaboration *
CERN, Switzerland

ARTICLE INFO
Article history:
Received 7 February 2012

ABSTRACT
A search for a Higgs boson decaying into two photons is described. The analysis is performed using a dataset recorded by the CMS experiment at the LHC from pp collisions at a center-of-mass energy of

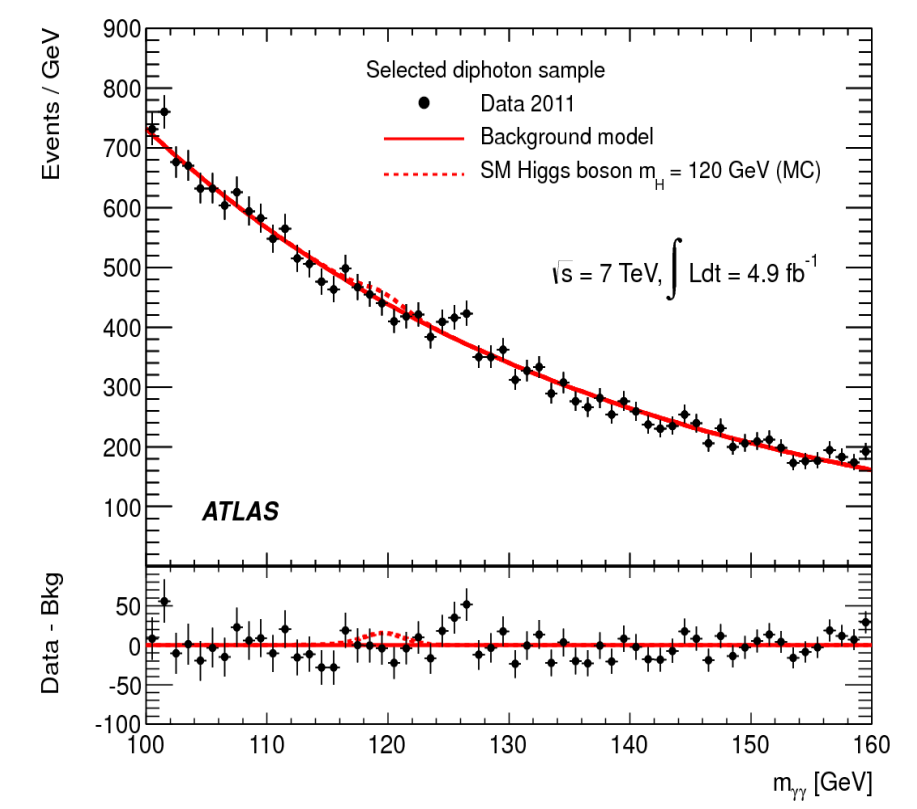
Selected for a Viewpoint in *Physics*
PRL **108,** 111804 (2012) PHYSICAL REVIEW LETTERS week ending 16 MARCH 2012

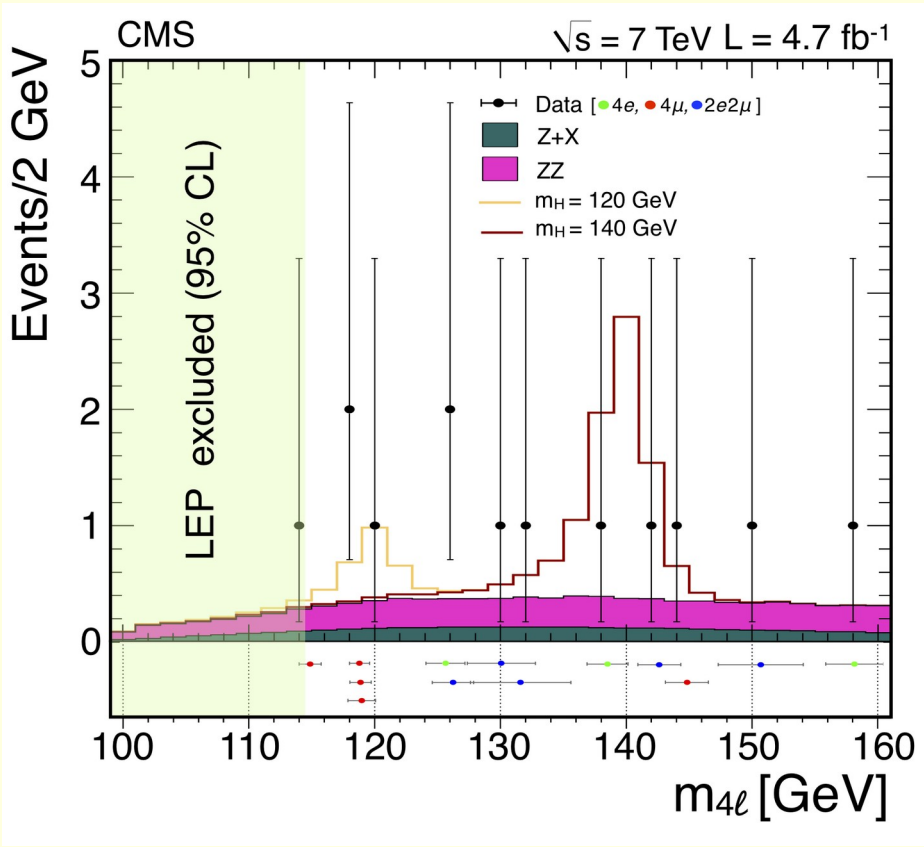
Search for the Standard Model Higgs Boson in the Decay Channel $H \to ZZ \to 4l$ in pp Collisions at $\sqrt{s} = 7$ TeV

S. Chatrchyan *et al.**
(CMS Collaboration)
(Received 9 February 2012; published 13 March 2012)

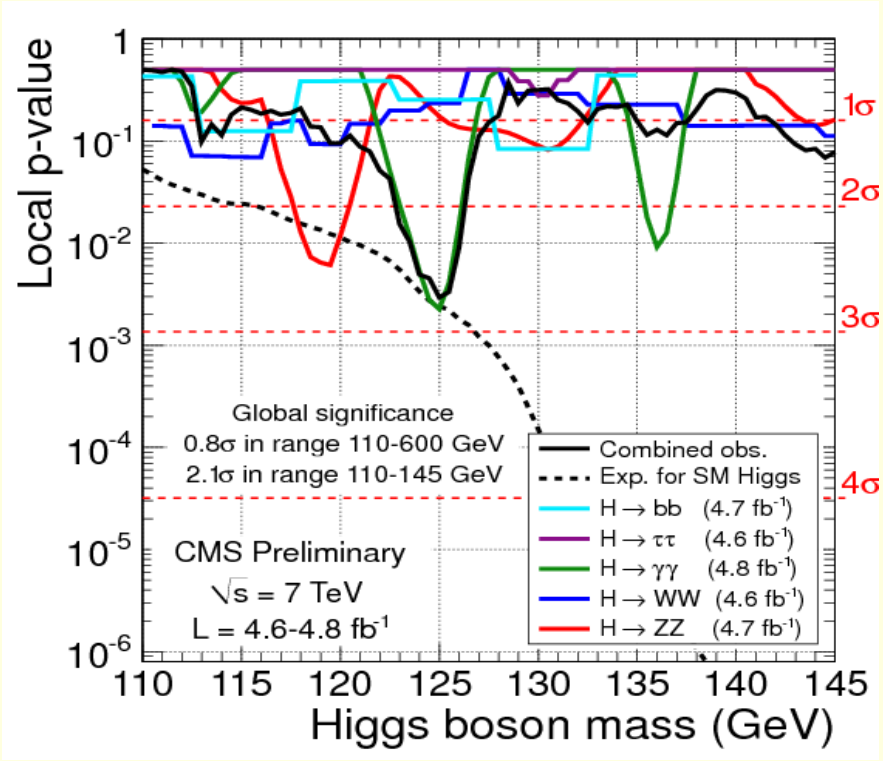
A search for a Higgs boson in the four-lepton decay channel $H \to ZZ$, with each Z boson decaying to an electron or muon pair, is reported. The search covers Higgs boson mass hypotheses in the range of

December 2011 - "Intriguing hints"

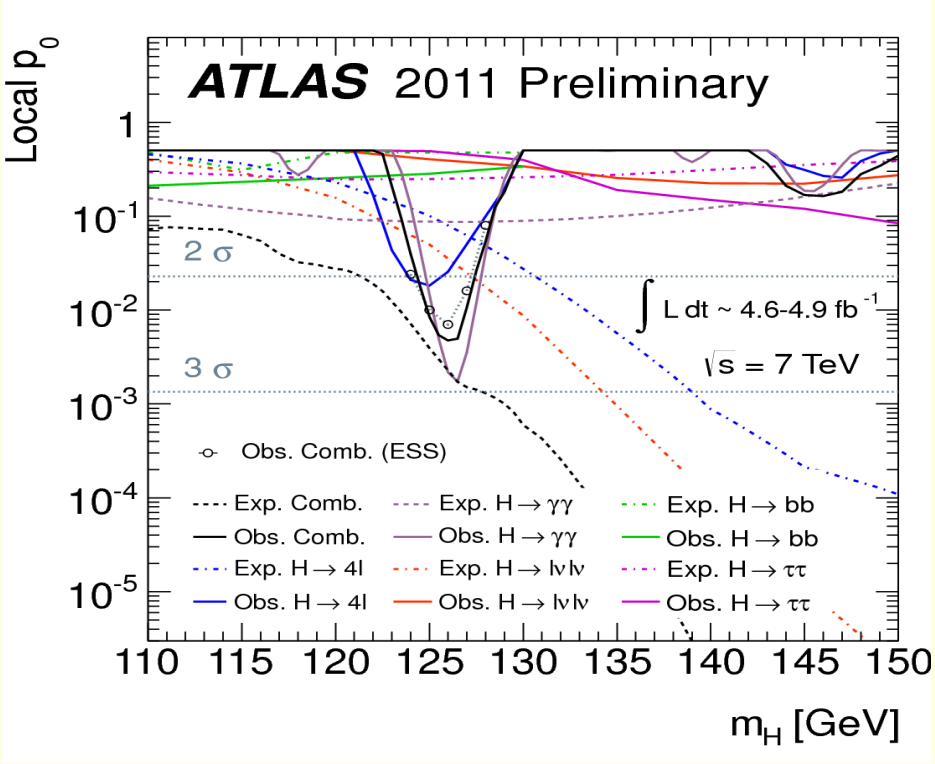




December 2011 - "Intriguing hints"

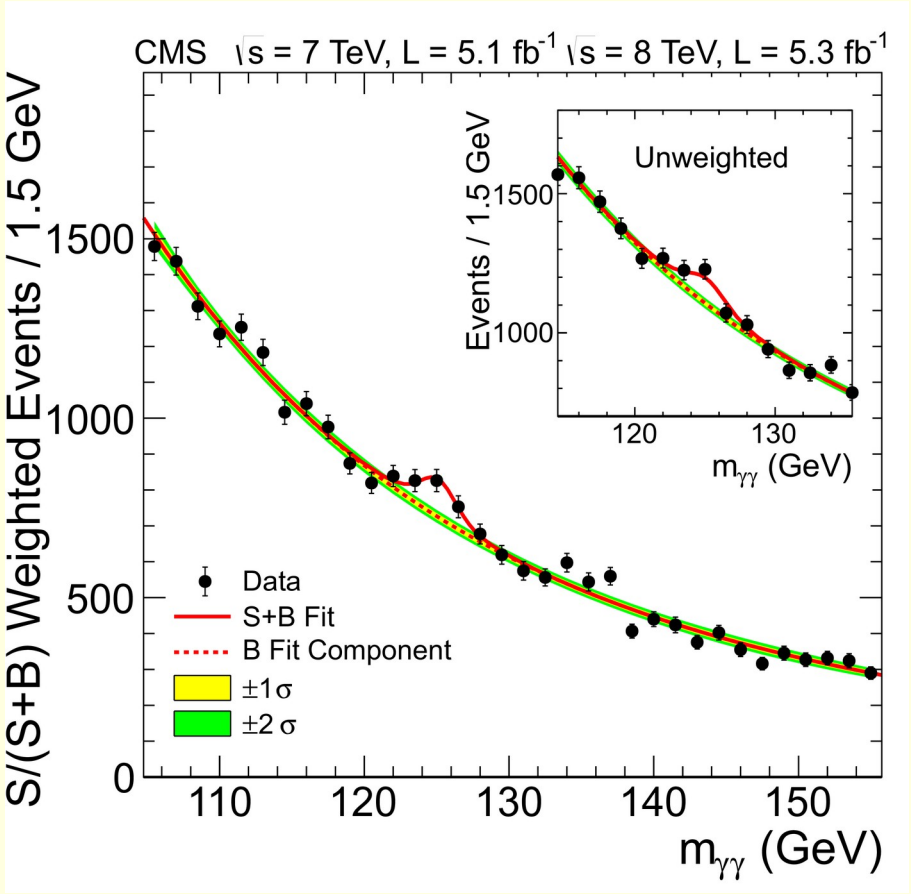


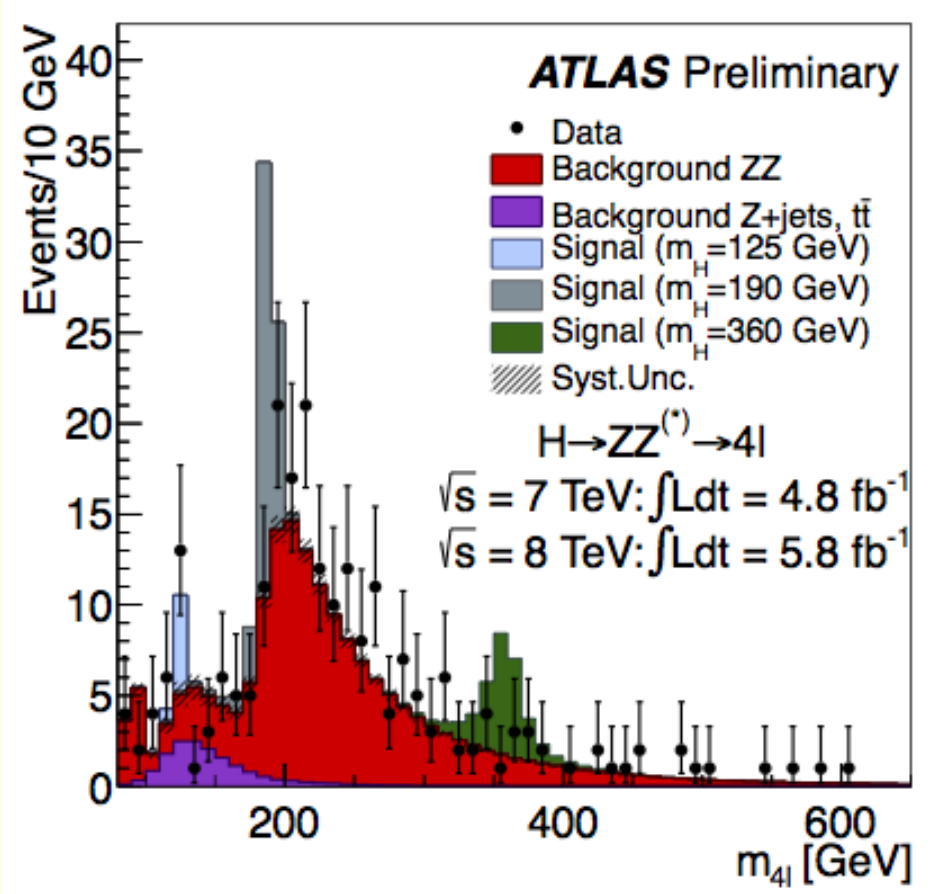
Minimum p-value at 125 GeV
Local significance 2.8σ
Global significance ~0.8-2.1σ



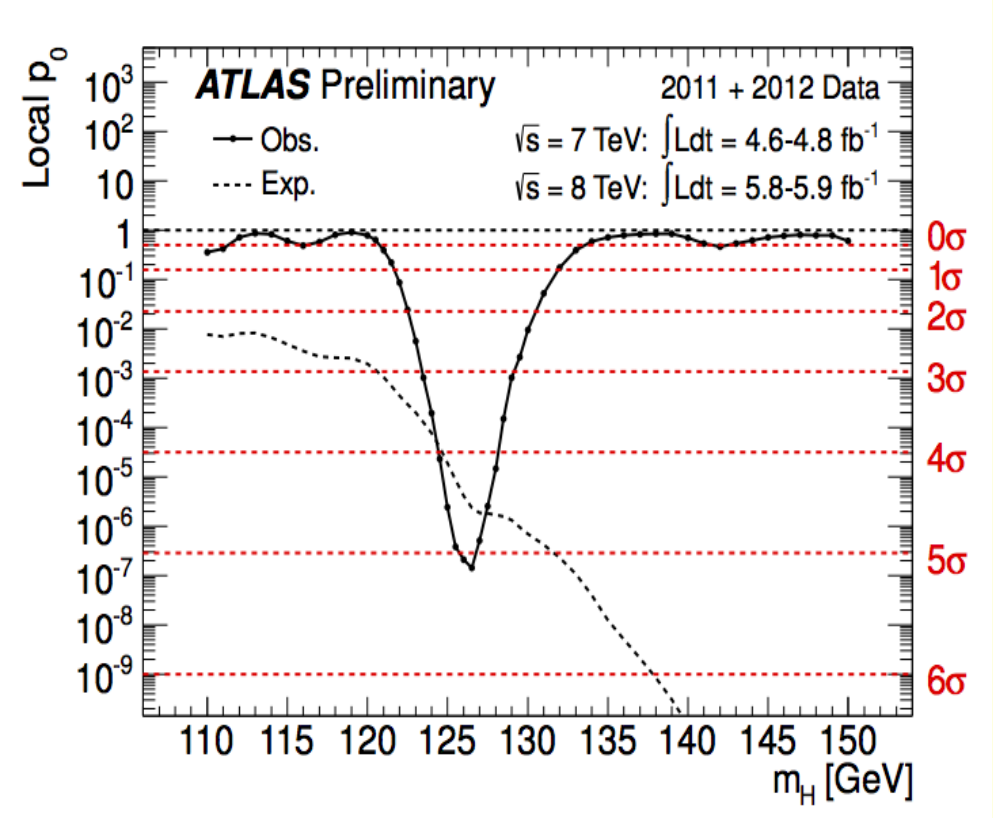
Minimum p-value at 126 GeV
Local significance 2.5σ
Estimated global significance *~0.5σ-1.6σ*

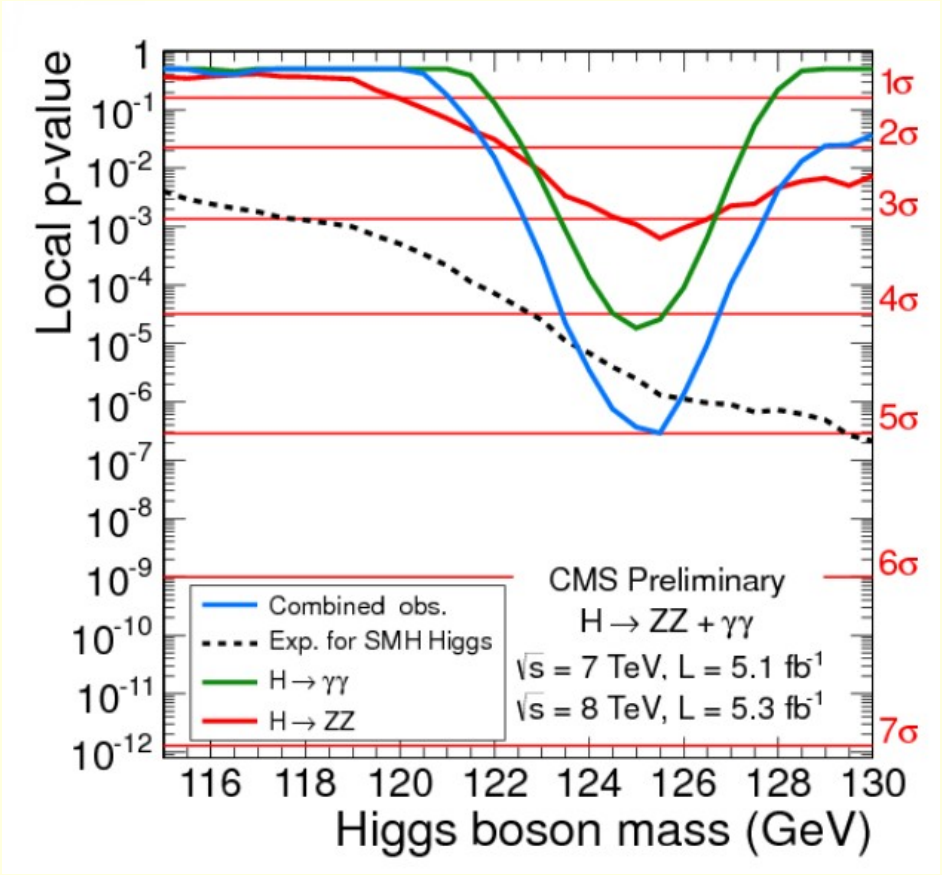
"Opening the box" in 2012





"Opening the box" in 2012






Combined results: the excess
ATLAS Preliminary
Obs.
Exp.
√s = 7 TeV: ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 5.8-5.9 fb⁻¹
2011 + 2012 Data
Expected from SM Higgs at given m_H
m_H [GeV]
Local Significance
5σ
Maximum excess observed at
m_H = 126.5 GeV
Local significance (including energy-scale systematics)
5.0 σ
Probability of background up-fluctuation
3 x 10⁻⁷
Expected from SM Higgs m_H=126.5
4.6 σ
Global significance: 4.1-4.3 σ (for LEE over 110-600 or 110-150 GeV)
RESERVED

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 *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

ARTICLE INFO

Article history:
Received 31 July 2012
Received in revised form 8 August 2012
Accepted 11 August 2012
Available online 14 August 2012
Editor: W.-D. Schlatter

ABSTRACT

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

Physics Letters B

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Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

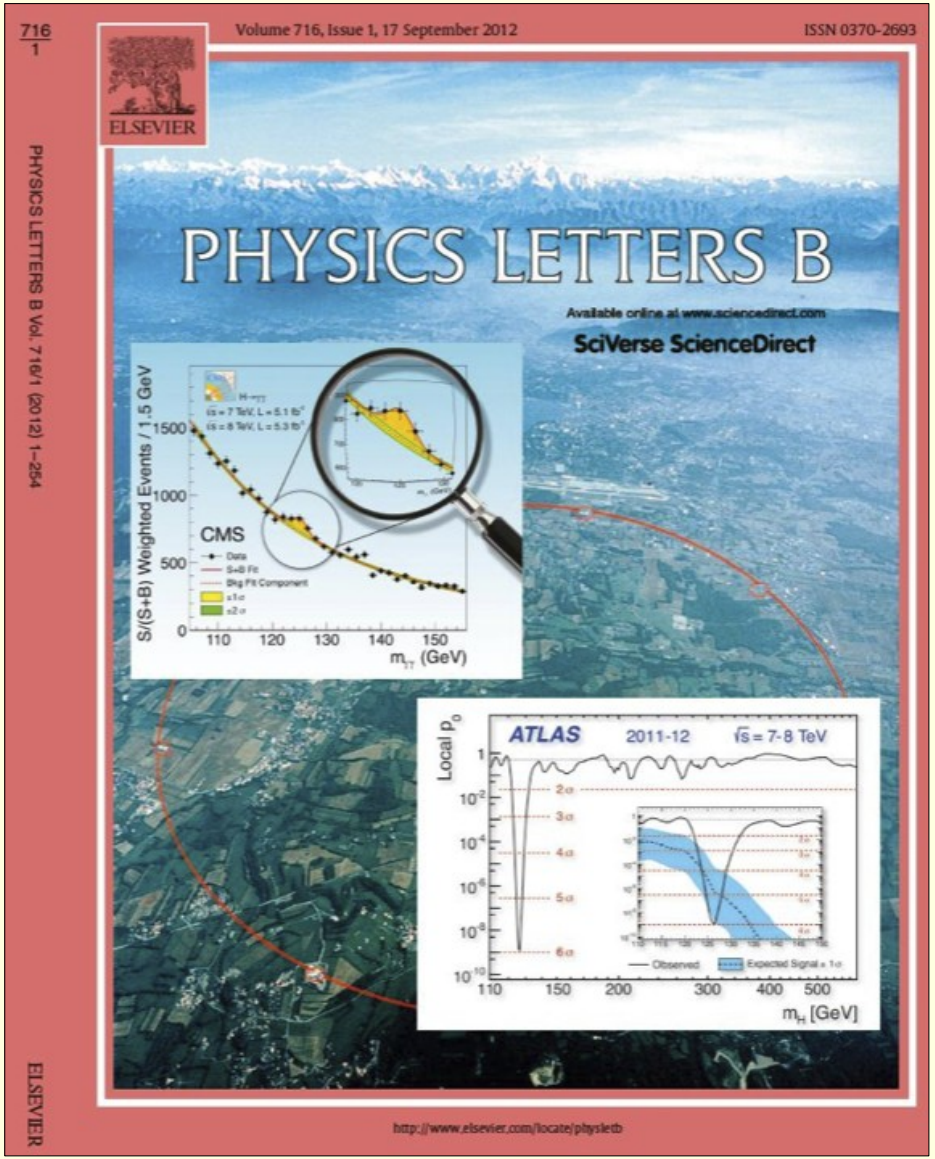
ARTICLE INFO

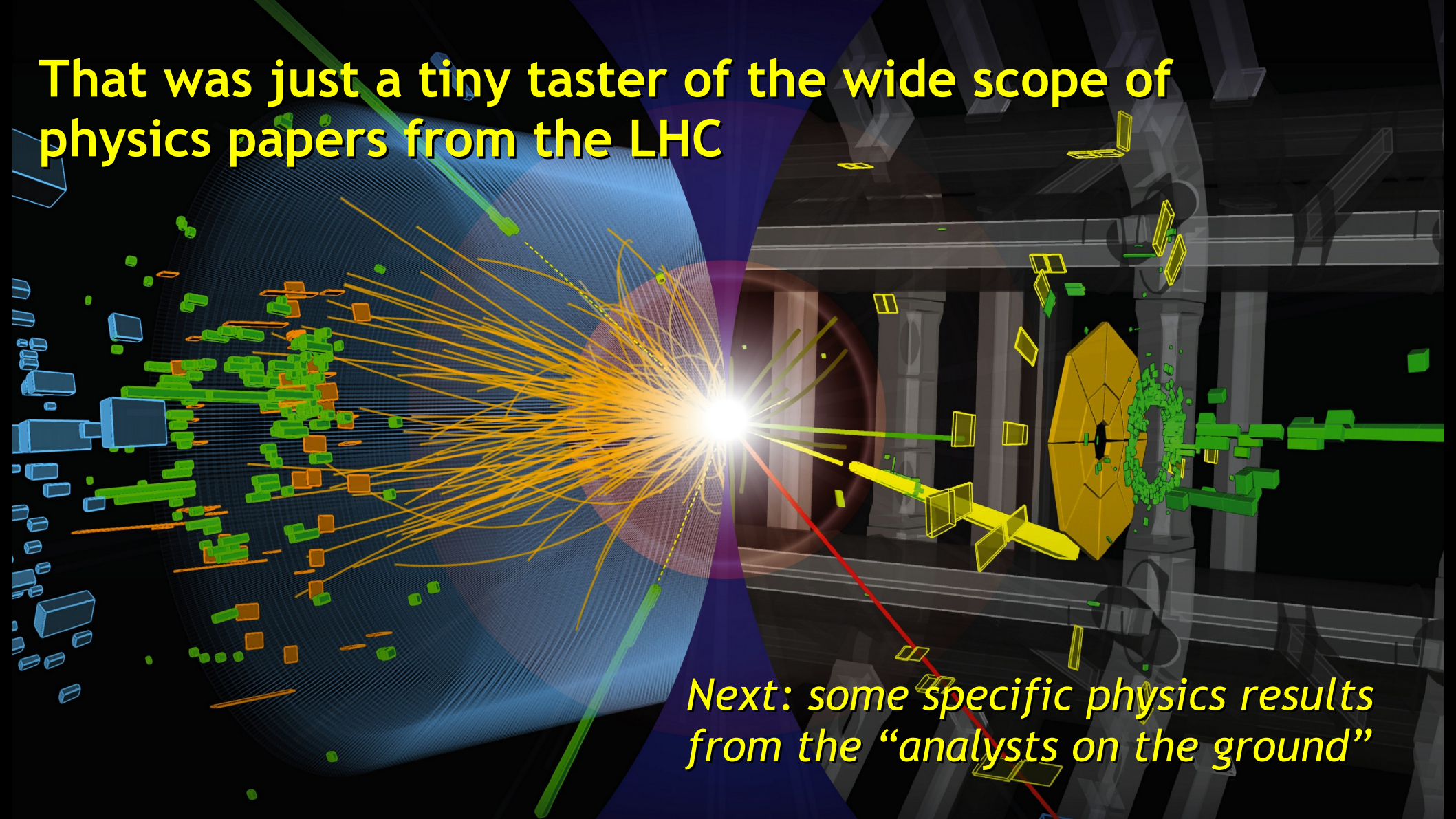
Article history:
Received 31 July 2012
Received in revised form 9 August 2012
Accepted 11 August 2012
Available online 18 August 2012
Editor: W.-D. Schlatter

Keywords:
CMS
Physics
Higgs

ABSTRACT

Results are presented from searches for the standard model Higgs boson in proton–proton collisions at $\sqrt{s} = 7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, and $b\bar{b}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of 125.3 ± 0.4(stat.) ± 0.5(syst.) GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.




That was just a tiny taster of the wide scope of physics papers from the LHC
Next: some specific physics results from the "analysts on the ground"