The Research Council of Norway

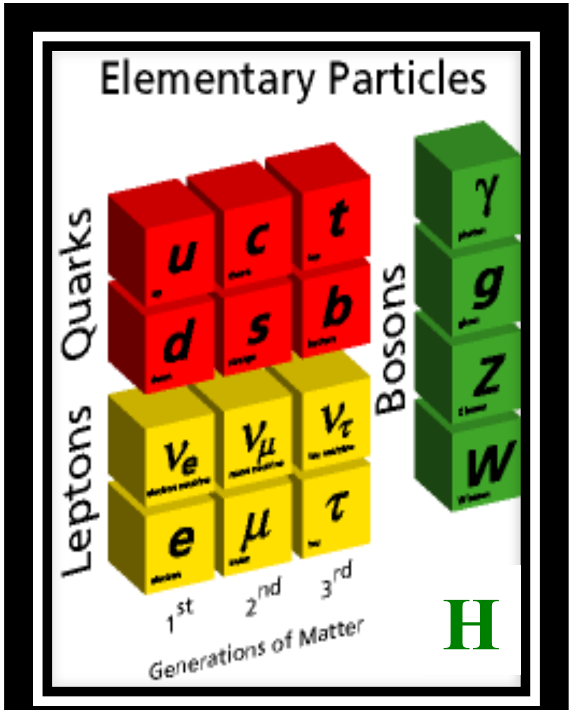
UiO : University of Oslo

ATLAS Experiment

A trip through some ATLAS achievements
&
Student opportunities

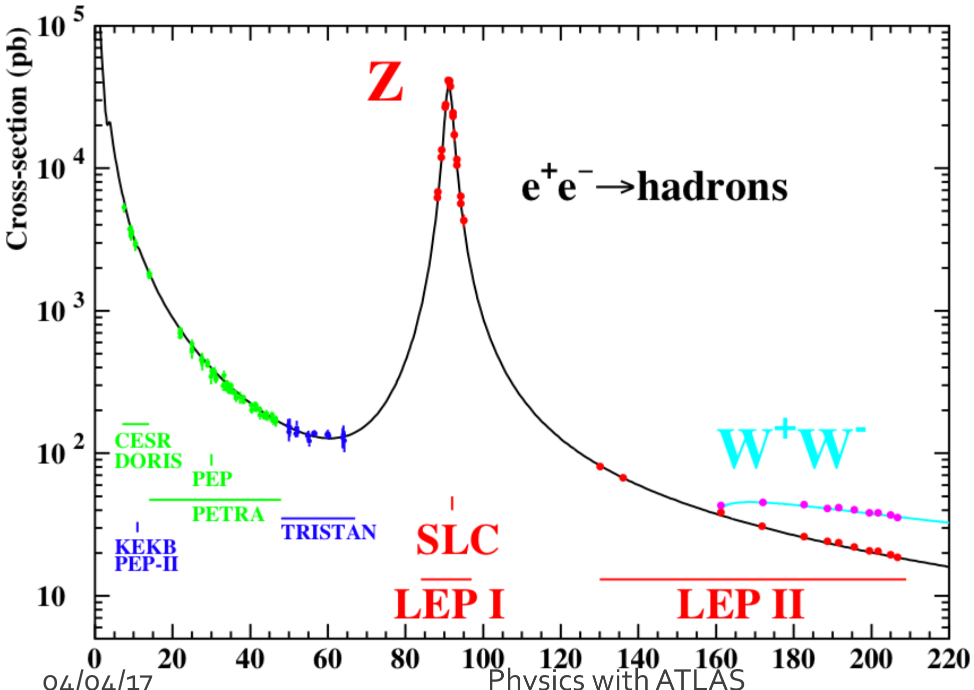
PHYSICS OF THE EARLY UNIVERSE

04.04.2017



- All forces in nature obey a form of symmetry.
  - Gauge-symmetry
- The Standard Model (SM) describes interactions between elementary particles grouped in 3 families of quarks and leptons

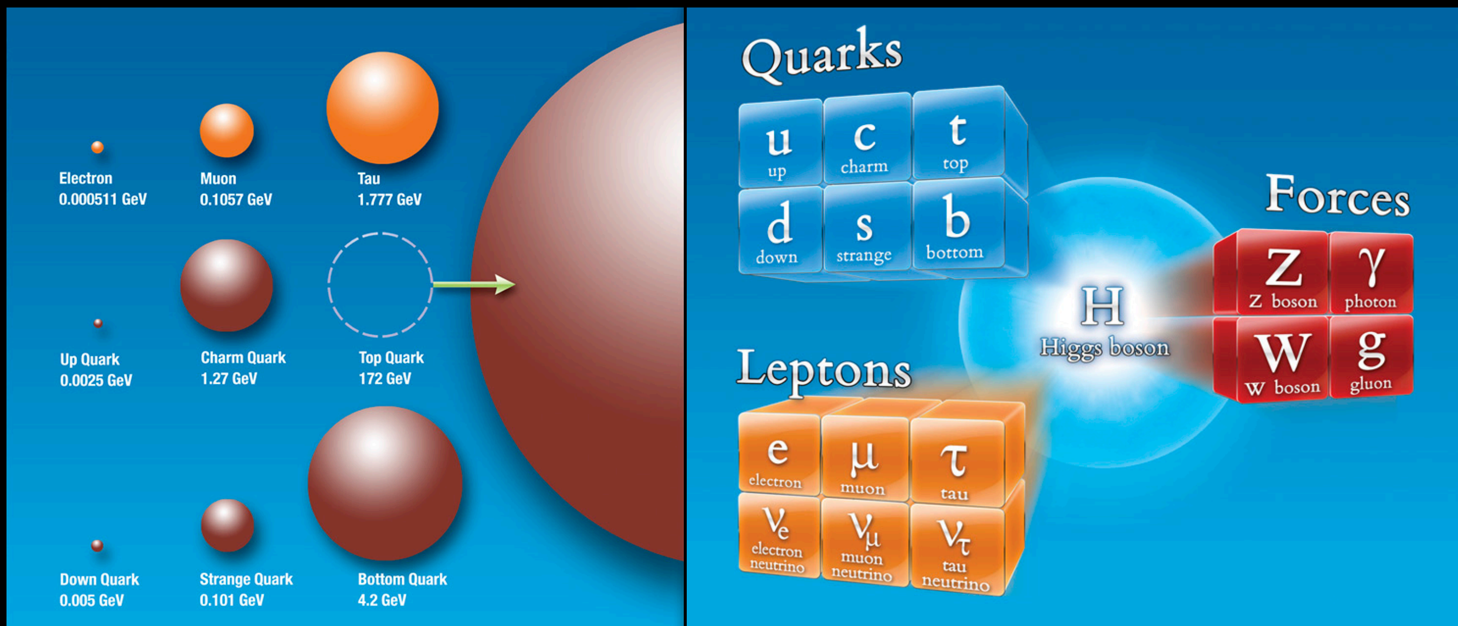
- The Standard Model
  - unifies Electromagnetism (long range, macroscopic, photon has no mass) and Weak force (short range, microscopic, W and Z are heavy) ...at high energies
  - describes (almost) all current particle physics data



- The Electroweak symmetry must be broken at low energies in order to give the weak bosons (W,Z), as well as all matter particles, masses.
- A scalar field requiring a new particle, the Higgs Boson ...

The Standard Theory of Particles and Forces

- Forces are dictated by (gauge) symmetries
  - Fermions in 3! = $SU(3)_C*[SU(2)_L*U(1)_Y]$ → QCD + Electroweak ("=" QED + Weak)



- Symmetries of laws do not necessarily lead to symmetries of outcomes
  - Electroweak symmetry spontaneously broken – Brout Englert Higgs mechanism
  - BEH "hides" EW symmetry, gives masses to weak gauge bosons and "approves" fermion masses, predicts couplings of particles to Higgs, and more
- Higgs boson mass is not predicted by the SM
- → Must be measured!

Origin of mass

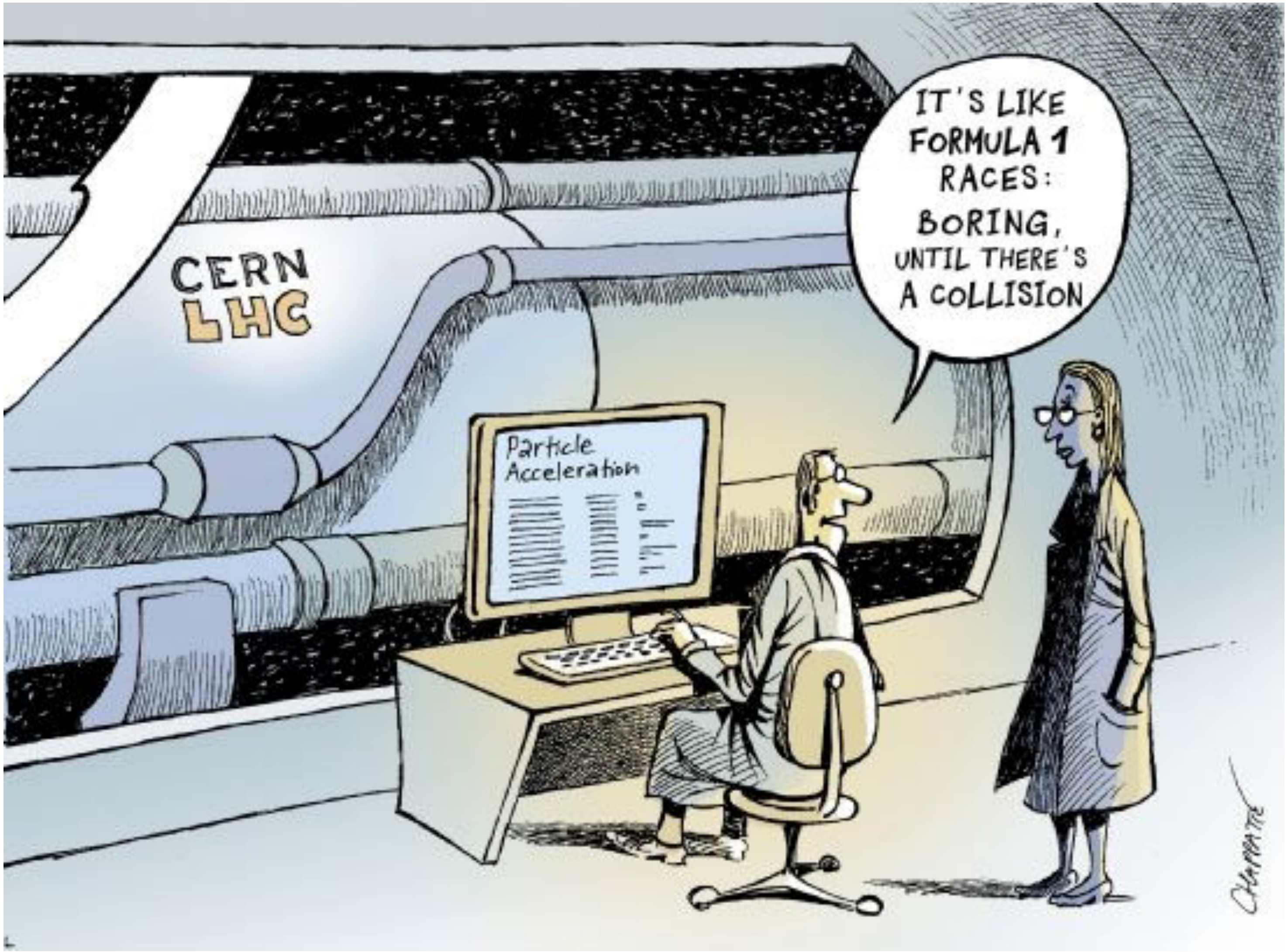
http://www.atlas.ch/multimedia/4-muon-event.html#origin-of-mass

LHC Physics

- Particle collisions at LHC
  - proton + proton
    - Study Standard Model, including Higgs, in new energy domain
    - Search for new physics capable of explaining various mysteries
    - Be ready for surprises
  - LHC collides also heavy ions: pb-pb and p-pb
    - High energies and high densities
    - New state of matter, quark-gluon plasma, ...

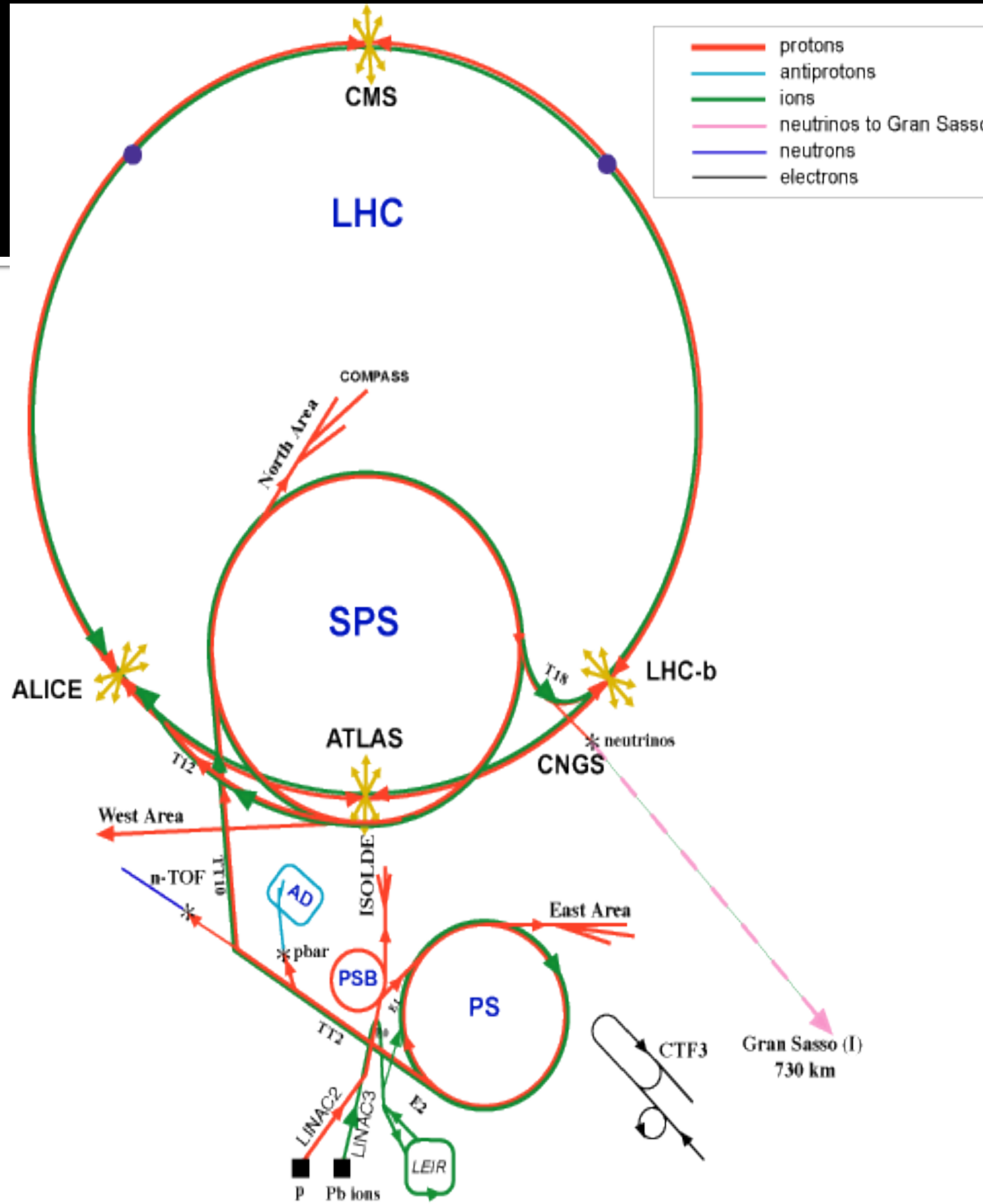
$$N_{\text{Physics}} = \sigma_{\text{Physics}} \left(\int \mathcal{L} dt \right)_{\text{Beams}}$$

- Sensitivity to rare phenomena
  - with small cross sections
  - depends on the luminosity

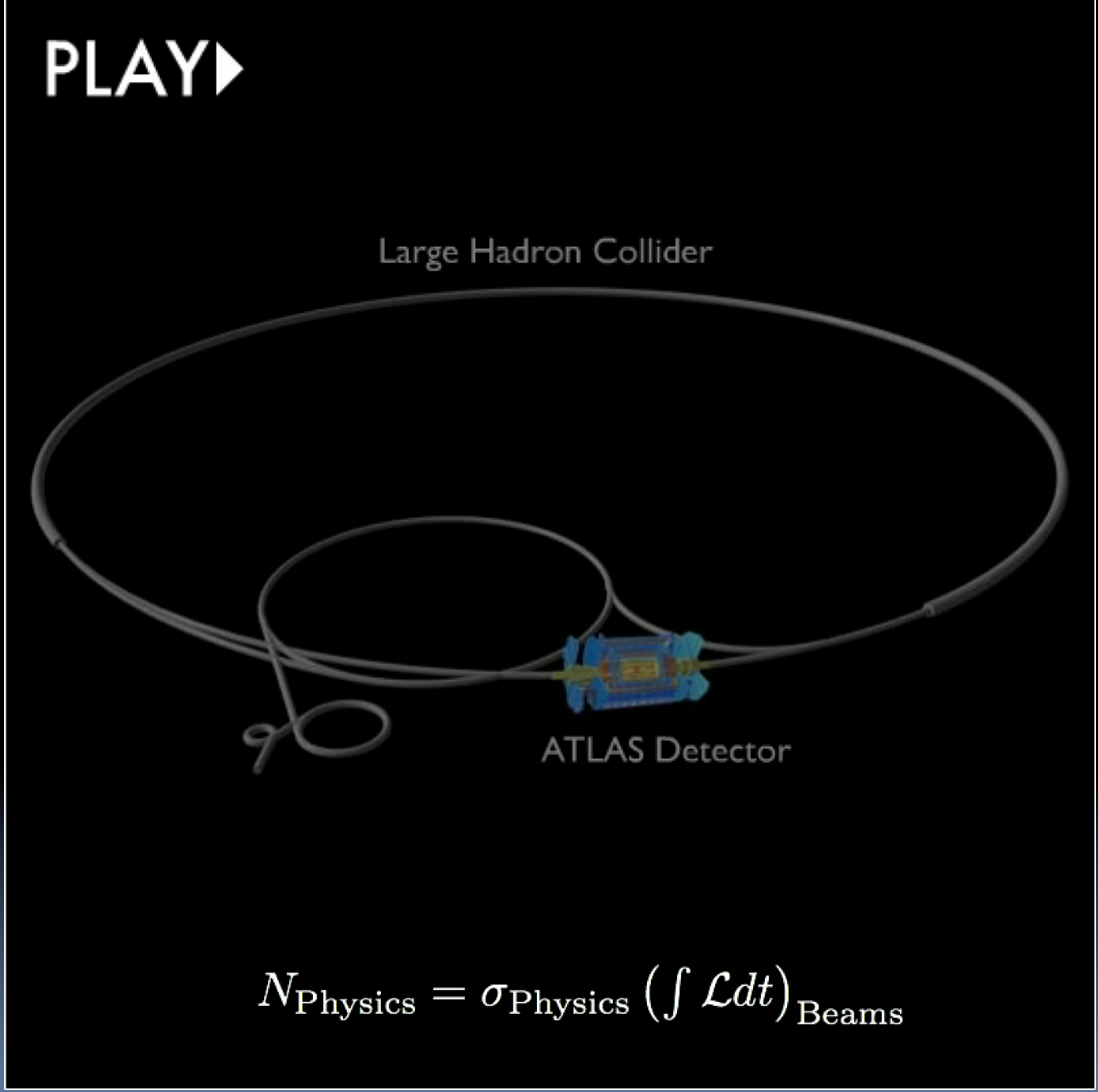

CERN
LHC
Particle Acceleration
IT'S LIKE FORMULA 1 RACES: BORING, UNTIL THERE'S A COLLISION

Accelerator complex

- Collisions with different particles lead to complementary information:
  - pN,
  - e^+e^-, ep
  - pp, ppbar,
  - pb pb,
  - νN, νe^-, μN,
- Previous accelerators as pre-accelerators
- Collider vs Fixed Target experiments
  - Collider: LHC pp and PbPb collisions
  - Fixed Target: neutrino beam sent from CERN to Gran Sasso in Italy 730 km away



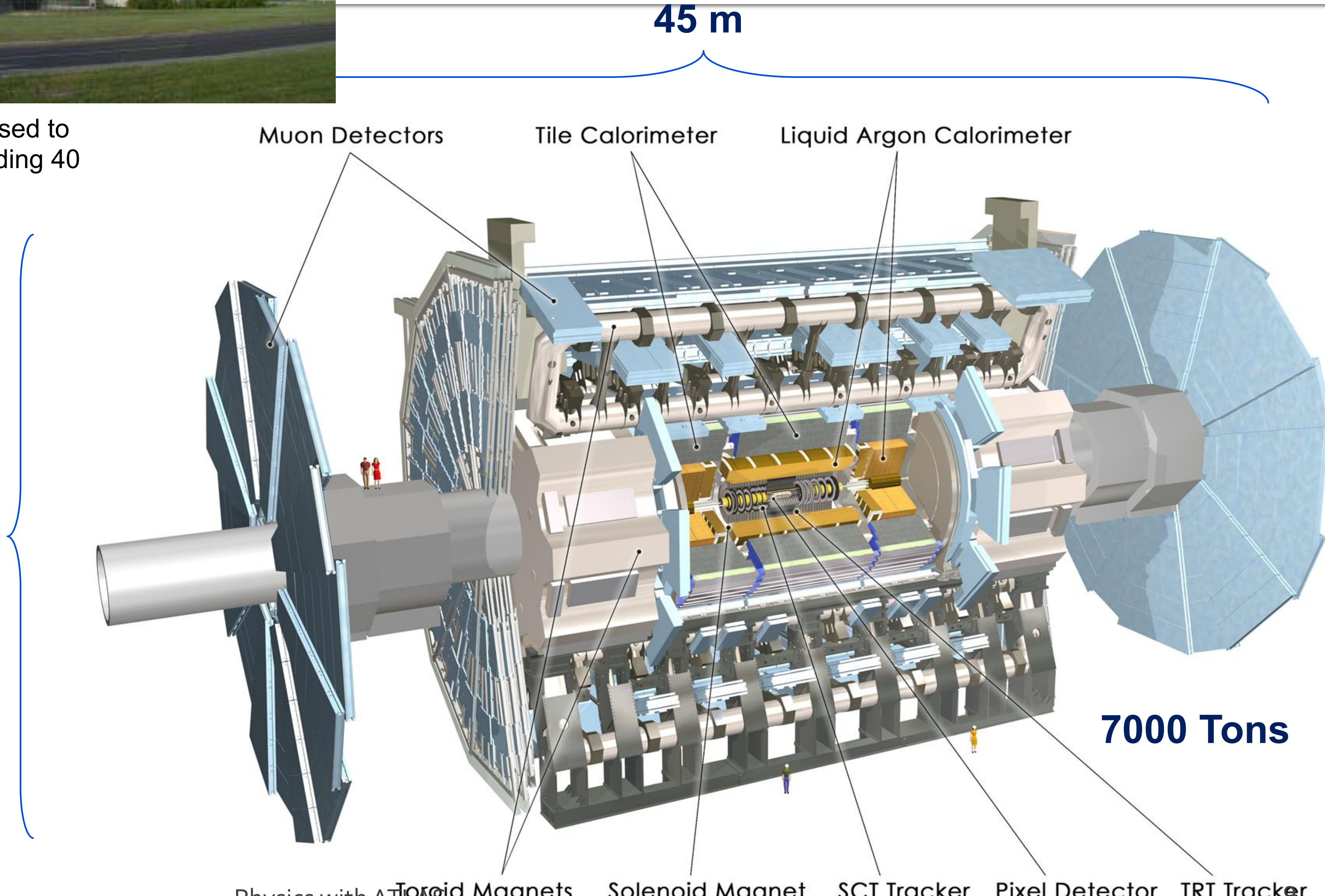
- Particle collisions at LHC
  - Simulated proton + proton → black hole candidate
  - LHC collides also heavy ions: pb-pb and p-pb



- Sensitivity to rare phenomena – with small cross sections – depends on the luminosity

ATLAS
Multipurpose Detector

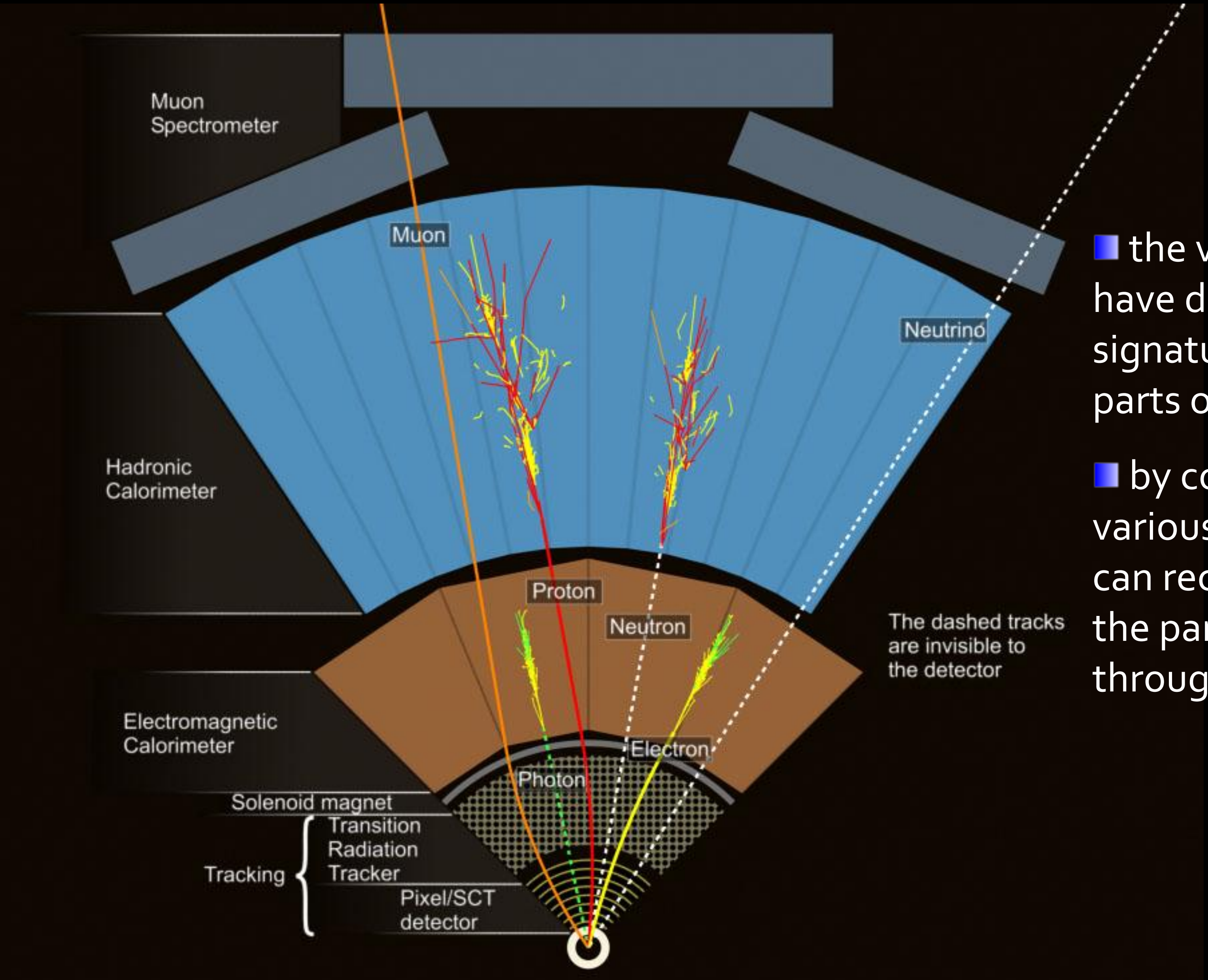
ATLAS superimposed to the 5 floors of building 40



Let's build ATLAS in ~ 1 minute … or 3 or 5

http://www.atlas.ch/multimedia/4-muon-event.html#atlas-built-1-minute

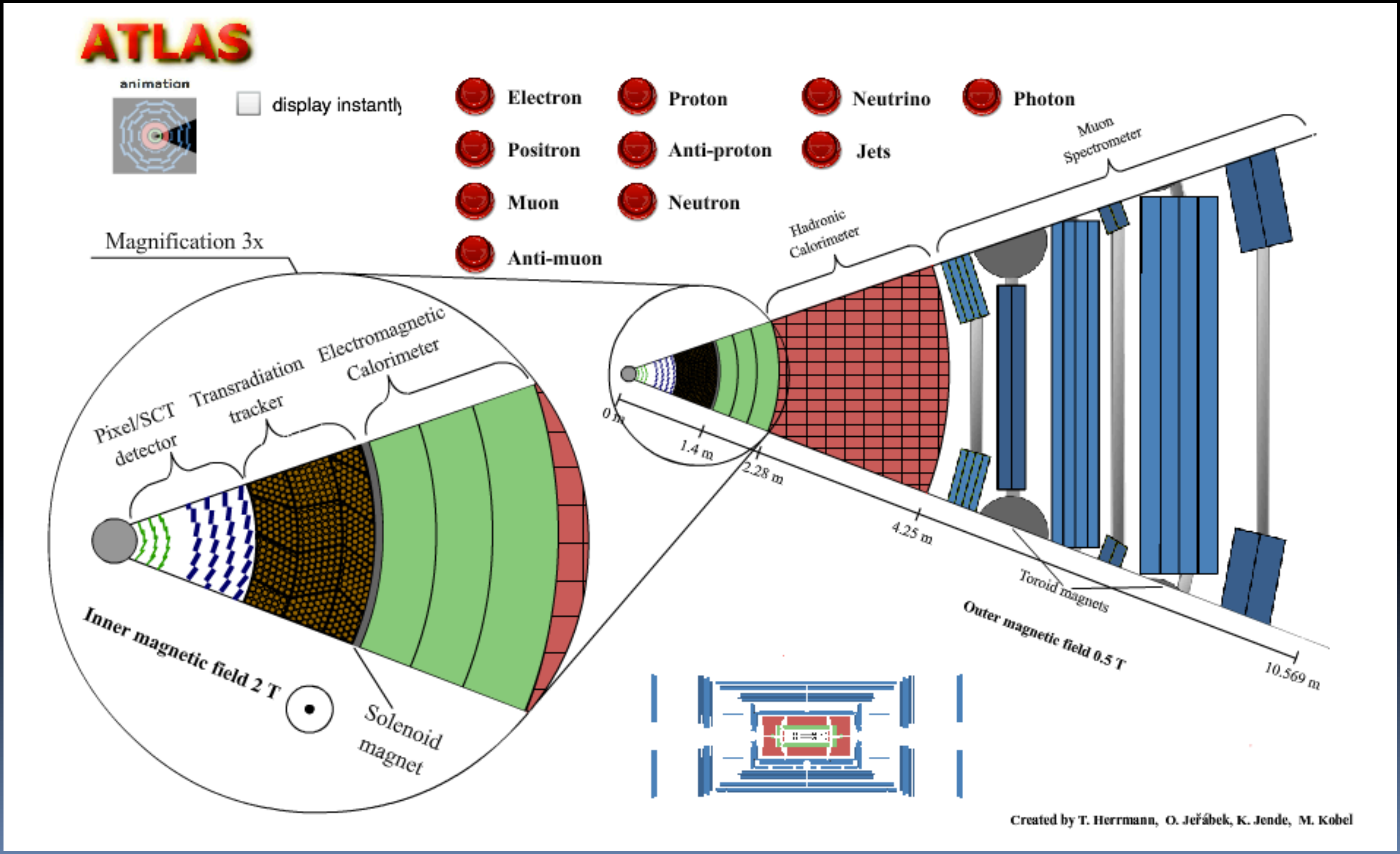
Particle detection



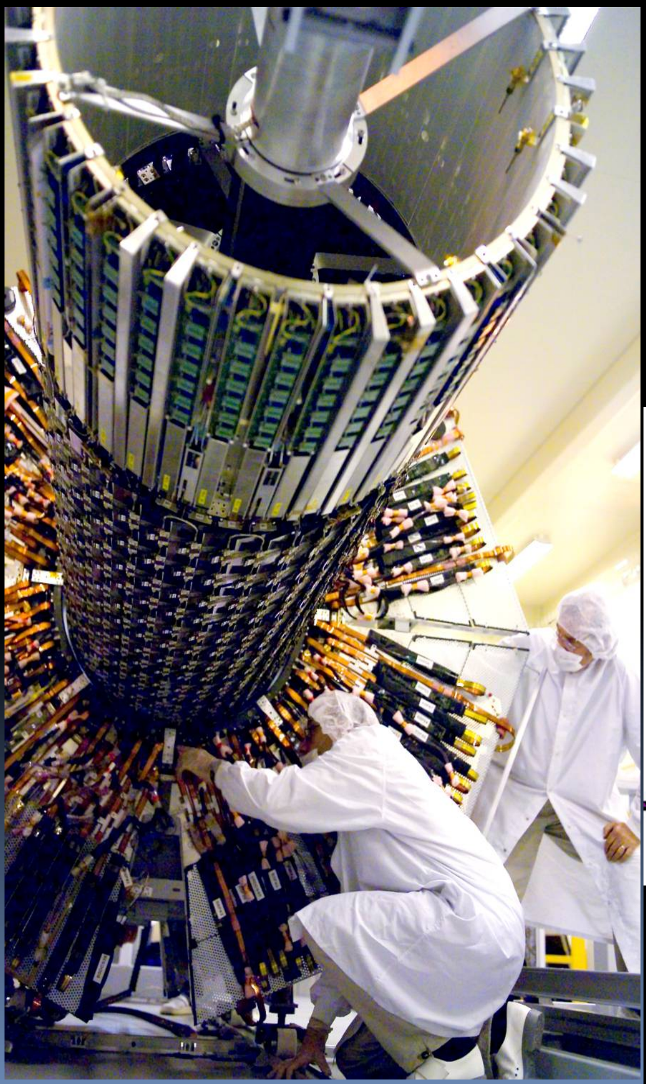
- the various particles have different signatures in different parts of the detector
- by combining the various signatures, we can reconstruct how the particle moved through the detector

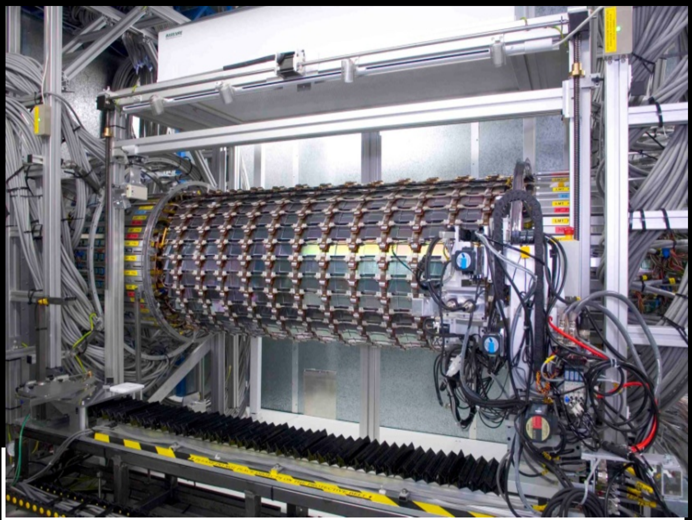
Particle identification

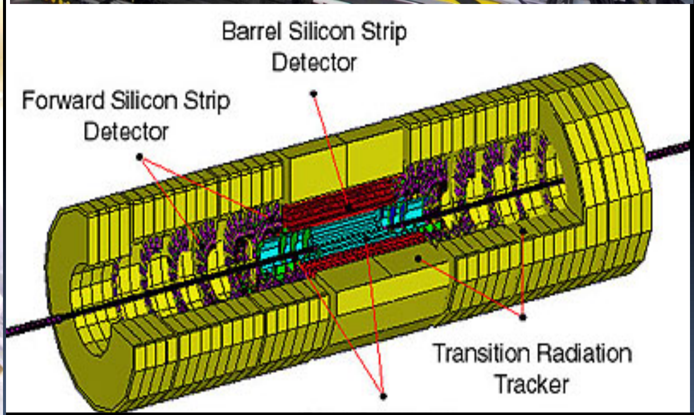
http://www.atlas.ch/multimedia/4-muon-event.html#episode-2 http://atlas.physicsmasterclasses.org/en/zpath_playwithatlas.htm



One of the Norwegian contributions to ATLAS: “Semi Conductor Tracker” (SCT) – Oslo, Bergen, Uppsala made 320 silicon-modules ~ 15% of ATLAS needs



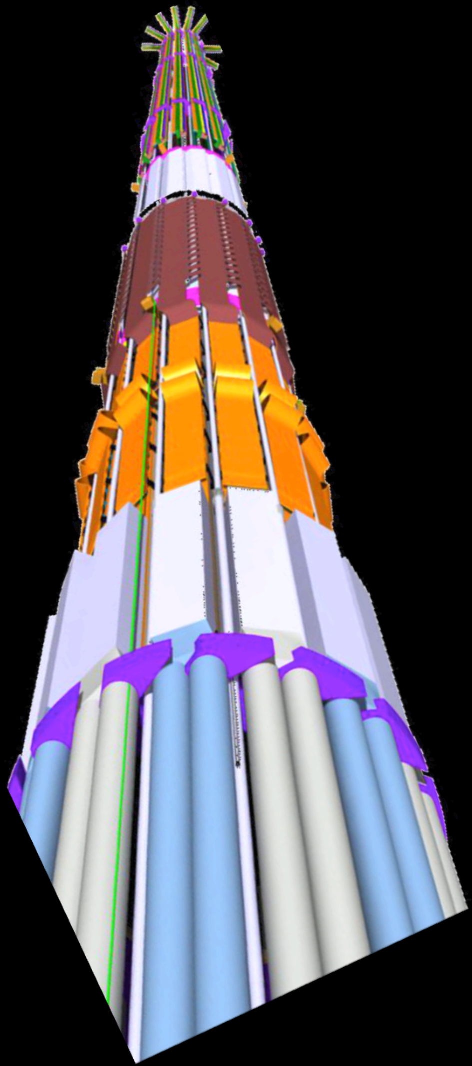




ATLAS upgrade

→ Insertable pixel B-Layer

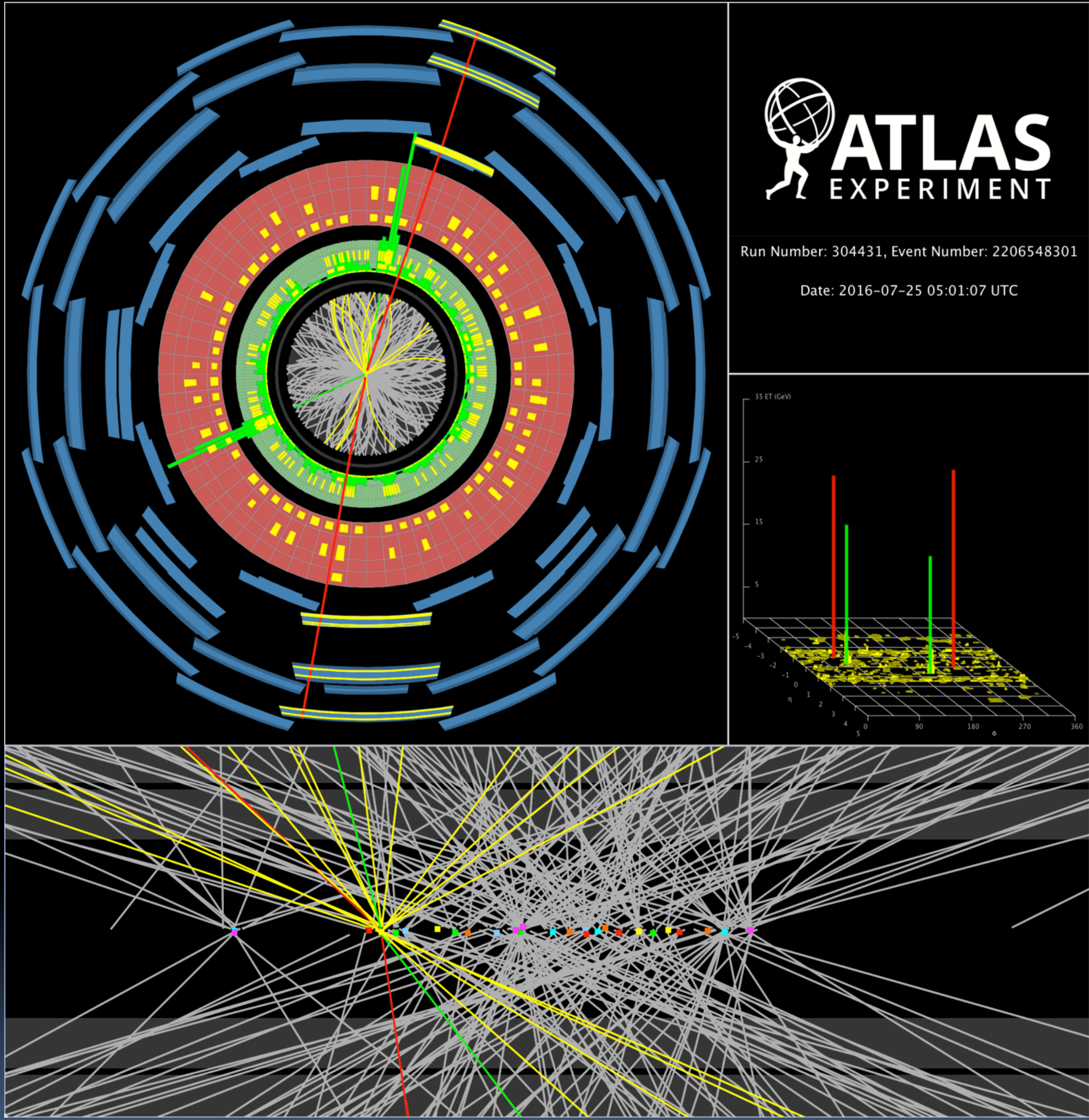
→ 3D-Pixel R&D



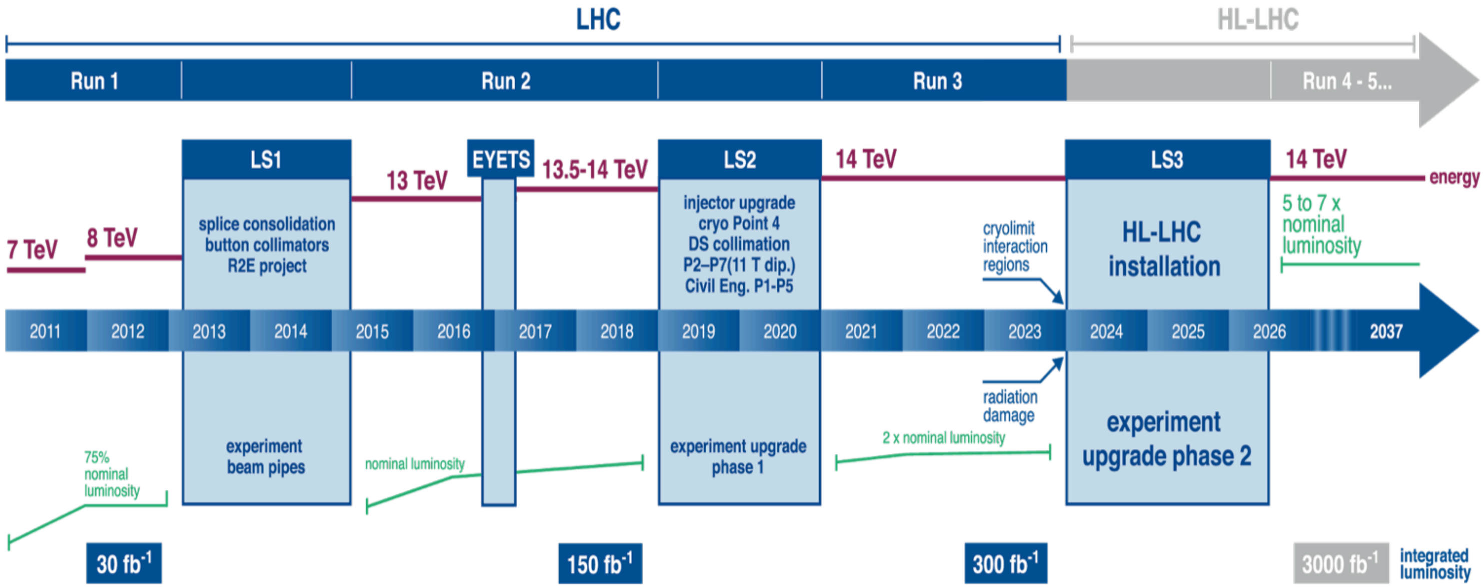
Tough conditions with many interactions per beam crossing

- ATLAS detector functioned well despite recording many interactions per collision
  - Due to increase in luminosity

- Display event Higgs → μμee
  - 4-lepton invariant mass 119 GeV
  - Additional 25 interactions - primary vertices

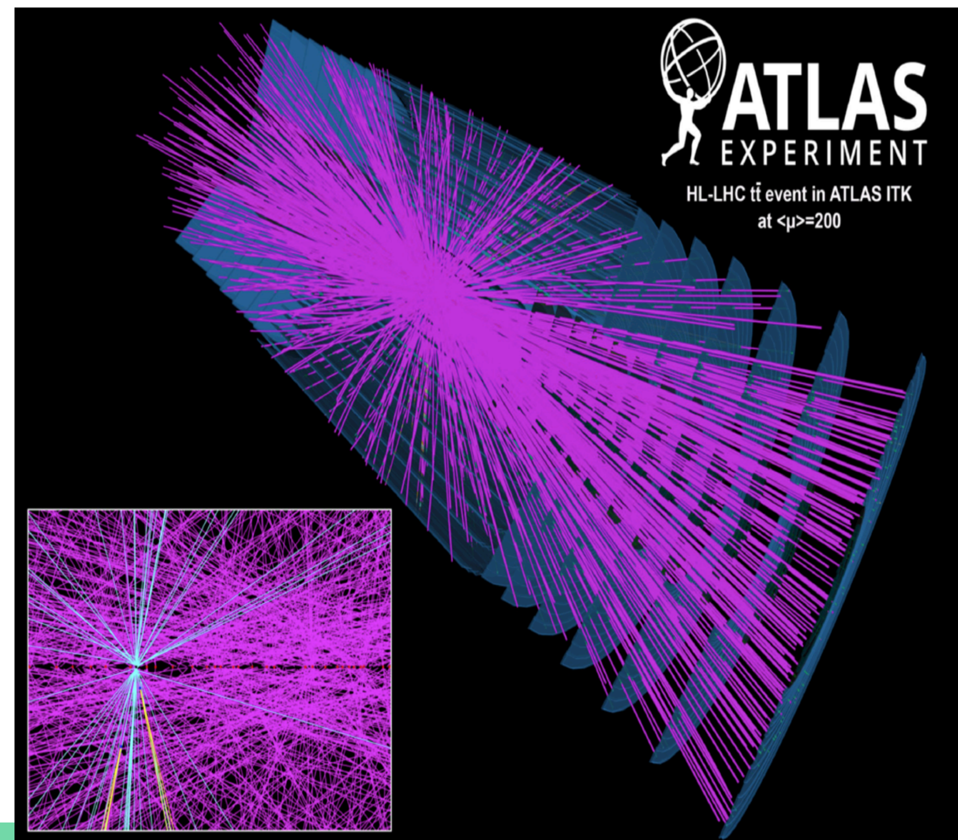


ATLAS & LHC Upgrade plans



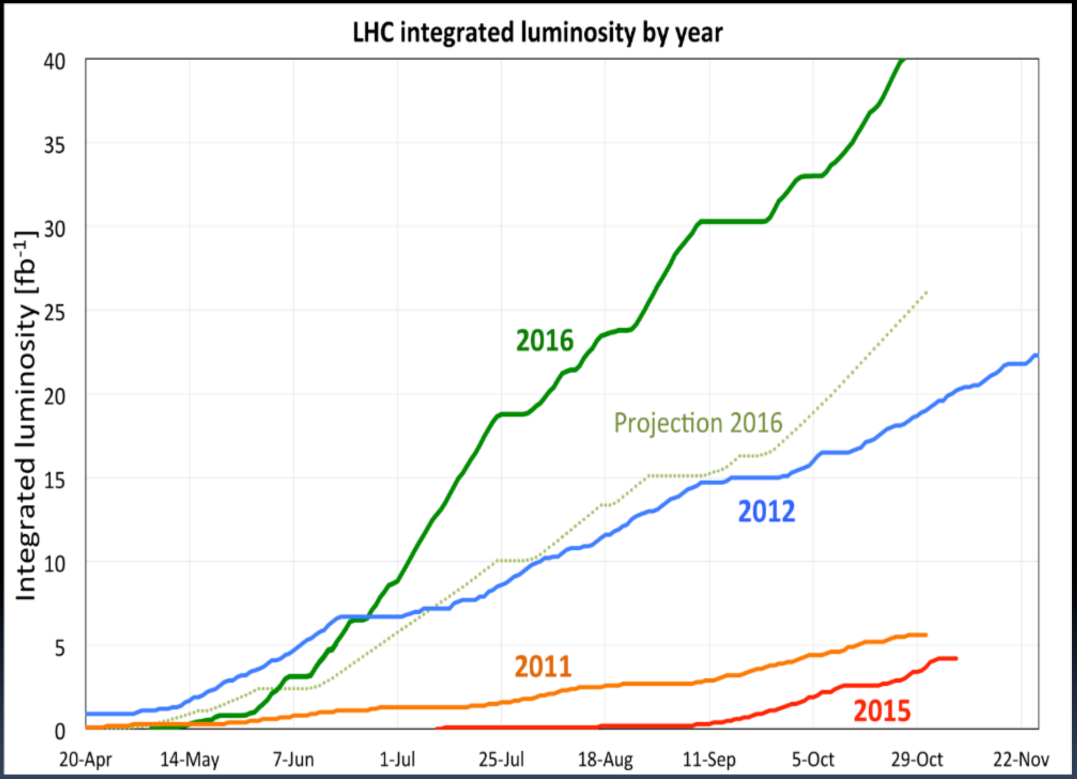
- All Silicon Inner Tracker – Itk - Strips + Pixels

- Simulated top-antitop event in the new silicon ITk tracker at a mean pile-up of 200



LHC and ATLAS performance

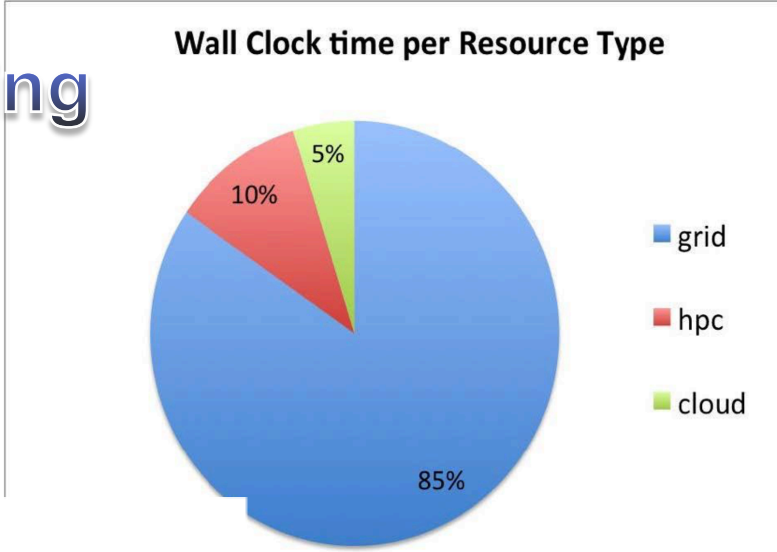
- Excellent LHC performance 16>12>11>15>10
  - Max luminosityin 2016 already 1.37 times the design value
  - 2010: 0.05 fb^{-1} at 7TeV
  - 2011: 5.6 fb^{-1} at 7TeV
  - 2012: 23 fb^{-1} at 8TeV
  - 2015: 3.x fb^{-1} at 13TeV
  - 2016: 33.x fb^{-1} at 13TeV

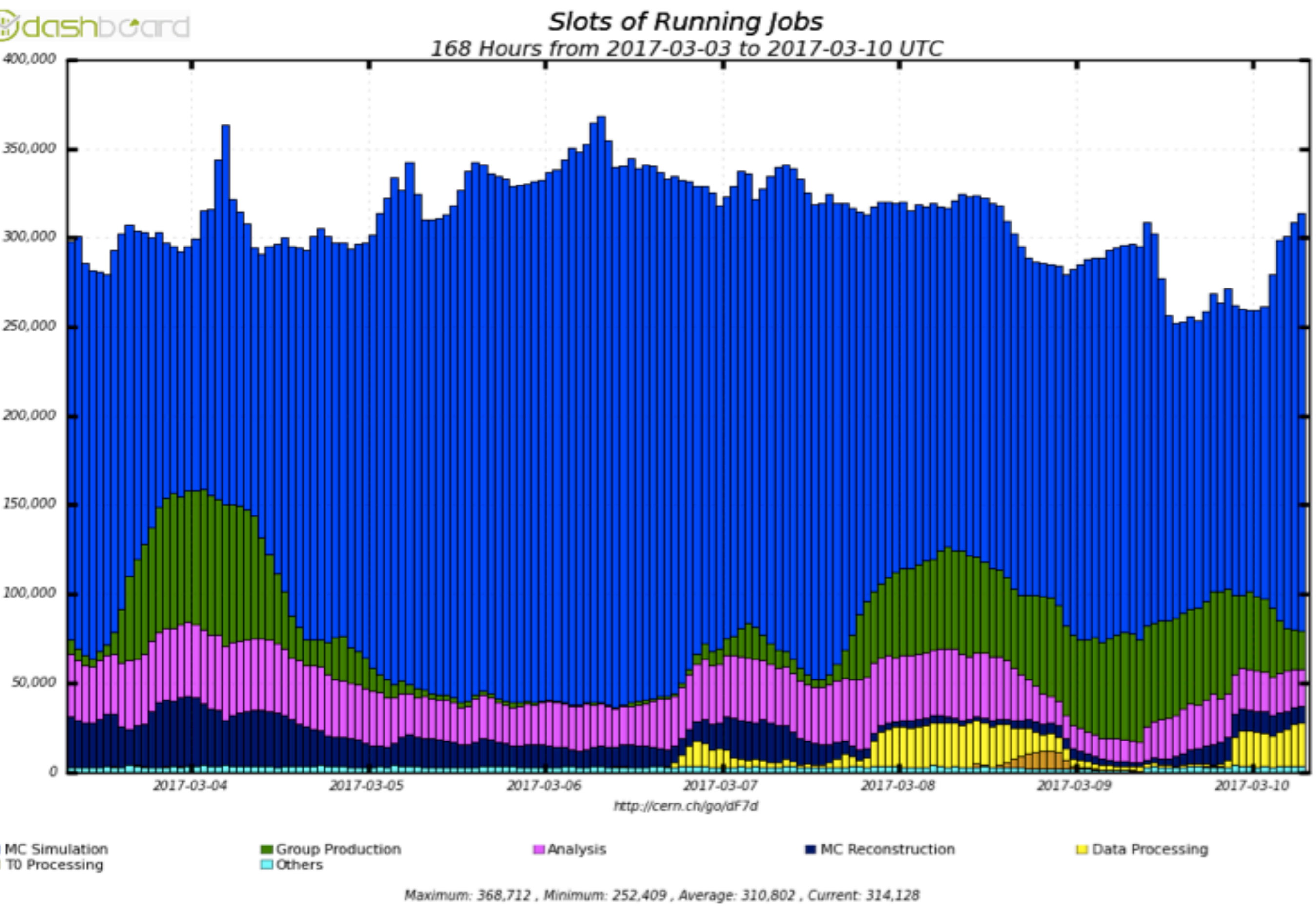


- Excellent detector performance
  - ATLAS recorded 92% of luminosity delivered by LHC at 13 TeV

Software & Distributed computing

- ❖ Outstanding contributions to Software & Computing

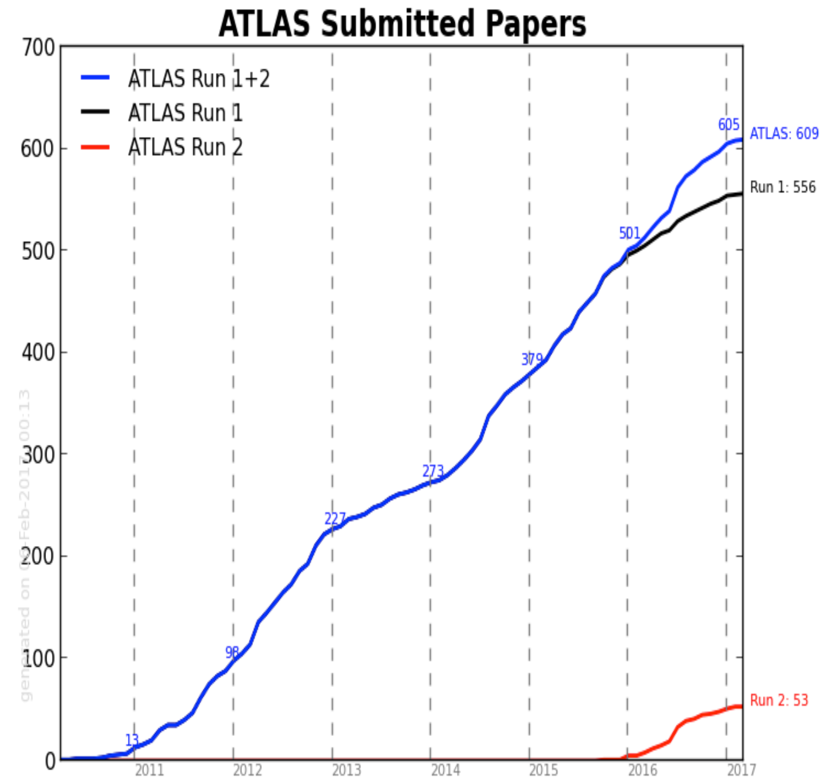


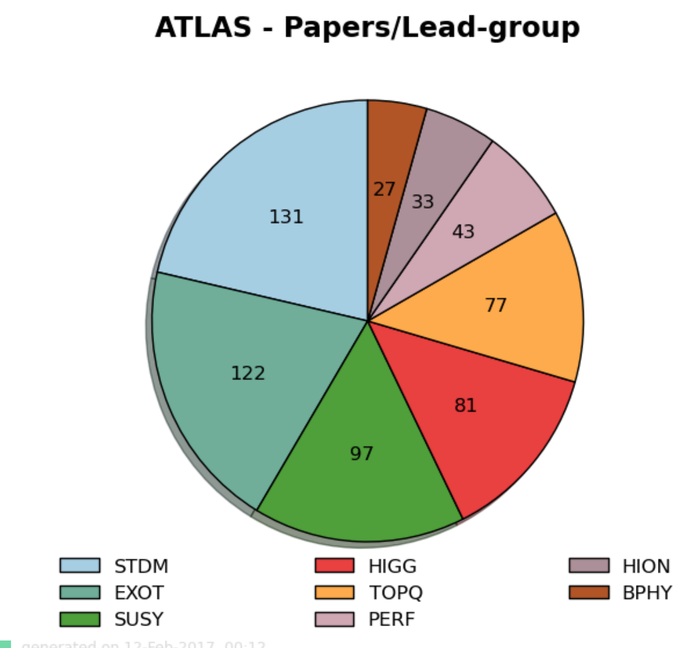


- ❖ 100's of PetaBytes of data stored
- ❖ Concurrent ATLAS jobs on the WLCG 2016 - 2017 routinely exceeded 300 000 dominated by simulations
  - ➢ ~10% running on NorduGrid ARC-enabled opportunistic resources

Publications

- Physics publications cover extensive searches at 7, 8, 13 TeV, for
  - new physics phenomena (Supersymmetry, DM, exotics)
  - measurements of SM processes (Higgs boson and Bottom quark)
  - By the end of 2016 ATLAS has produced about 600 publications in refereed journals





eeμμ event in p-p collisions

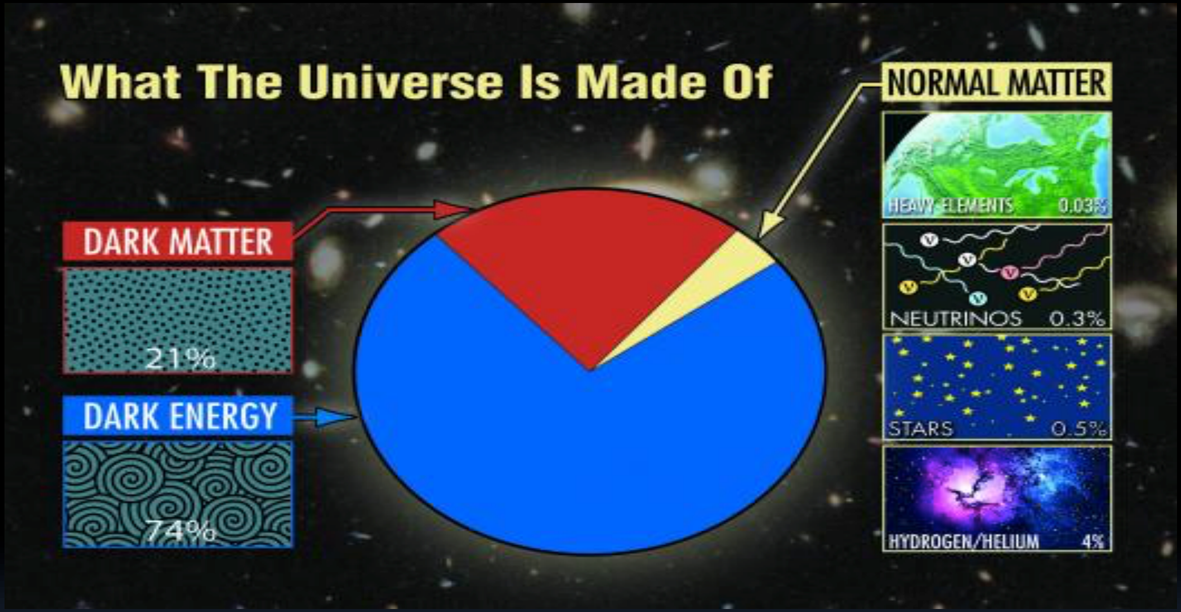
http://www.atlas.ch/multimedia/4-muon-event.html#2-electron-2-muon-event

Heavy Ion Collision

http://www.atlas.ch/multimedia/4-muon-event.html#heavy-ion-event

Introduction

- Two of the greatest mysteries in physics today
  - nature of dark matter
  - behavior of the gravitational force at the microscopic scale
- Physics of the very early Universe

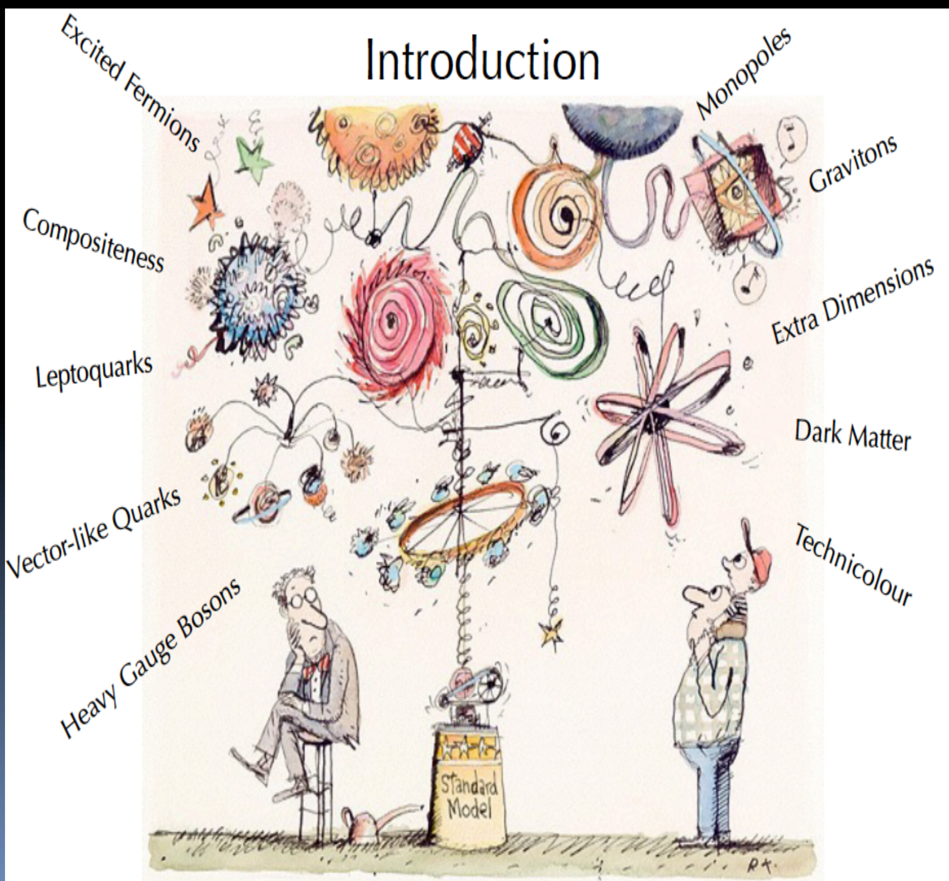


- What can we do with the 5% we think we know about the Universe?
  - Experiment and find out about the remaining 95%
  - Build a "microscope"
- What is exotic enough?
  - Broad and intense research program Beyond the Standard Model & SUSY

Exotic phenomena, LHC, ATLAS …

"NotYetThoughtOfs"

- Many theories Beyond the Standard Model (BSM) predict new phenomena which give rise to narrow resonances or broad non-resonant deviations from the SM
  - Including …



Proton-proton Collisions

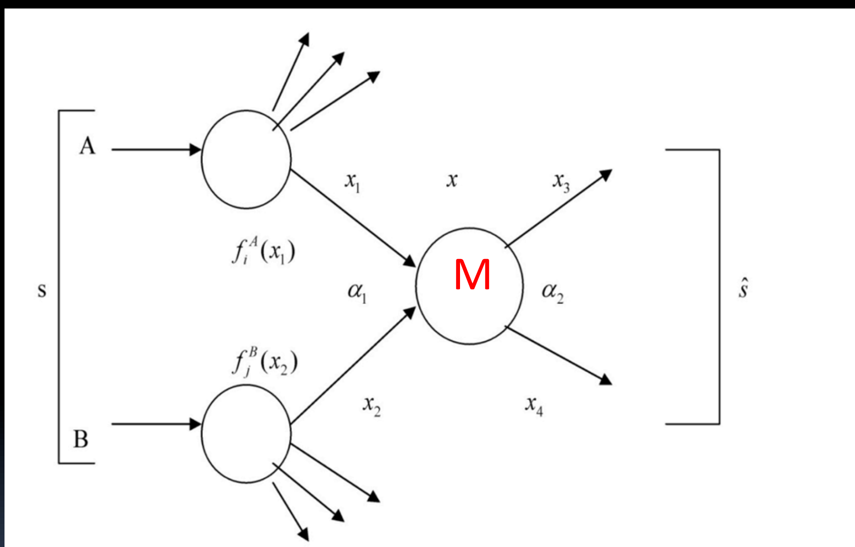
- Higher <x> values mean higher masses M
  - 13 TeV: LHC is top-quark factory
  - M>5TeV accessible …

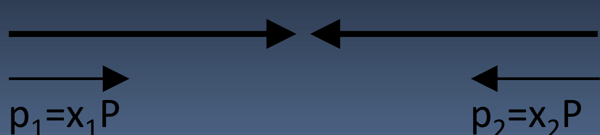
$$\langle x \rangle = \frac{M}{\sqrt{s}}$$

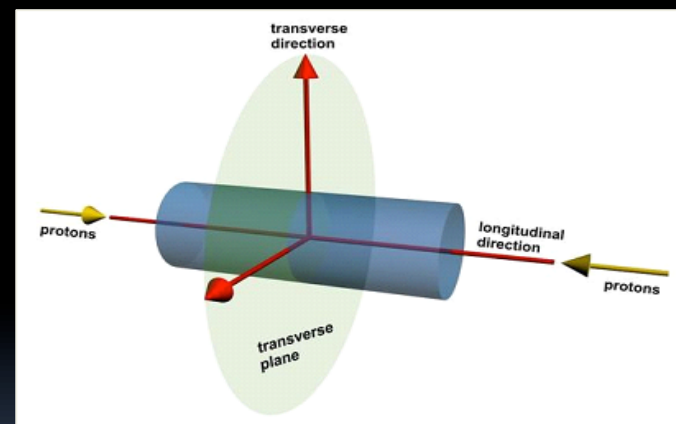
$$M = 2m_t \Rightarrow \langle x \rangle \approx 0.027$$

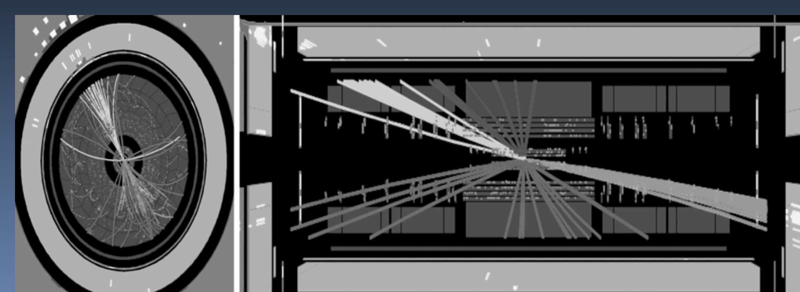
$$M = 5TeV \Rightarrow \langle x \rangle \approx 0.38$$

- Quarks & gluons taking part in collision carry fraction ***x*** of proton momentum



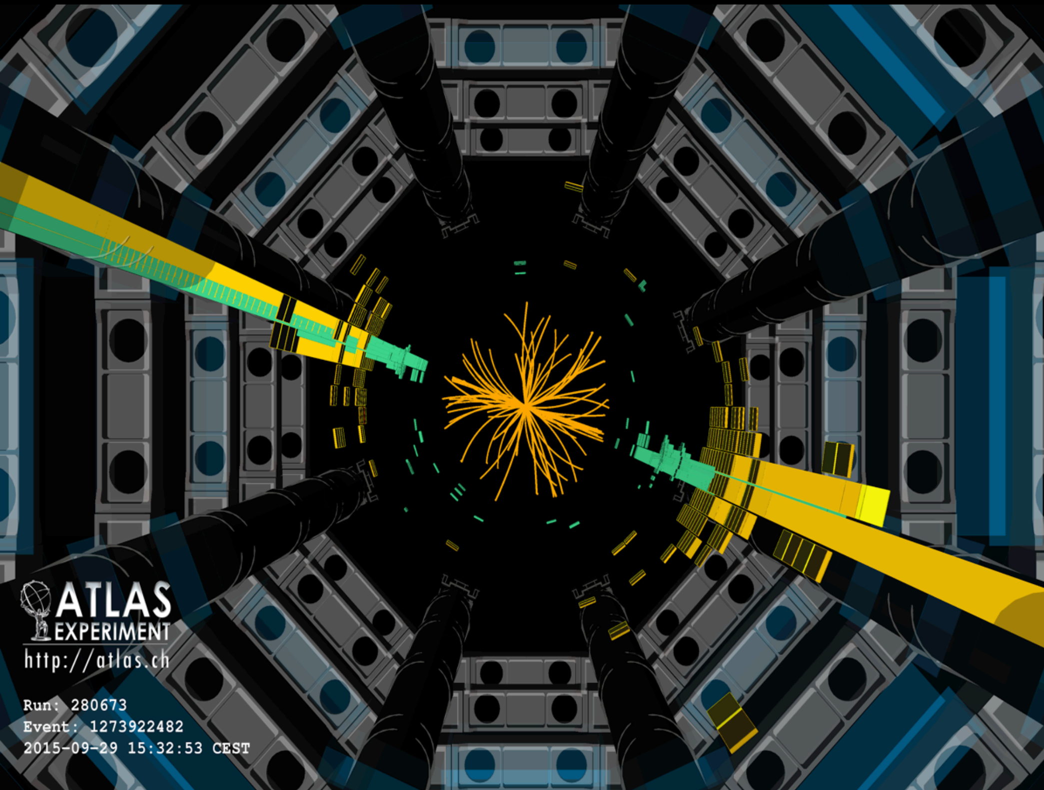






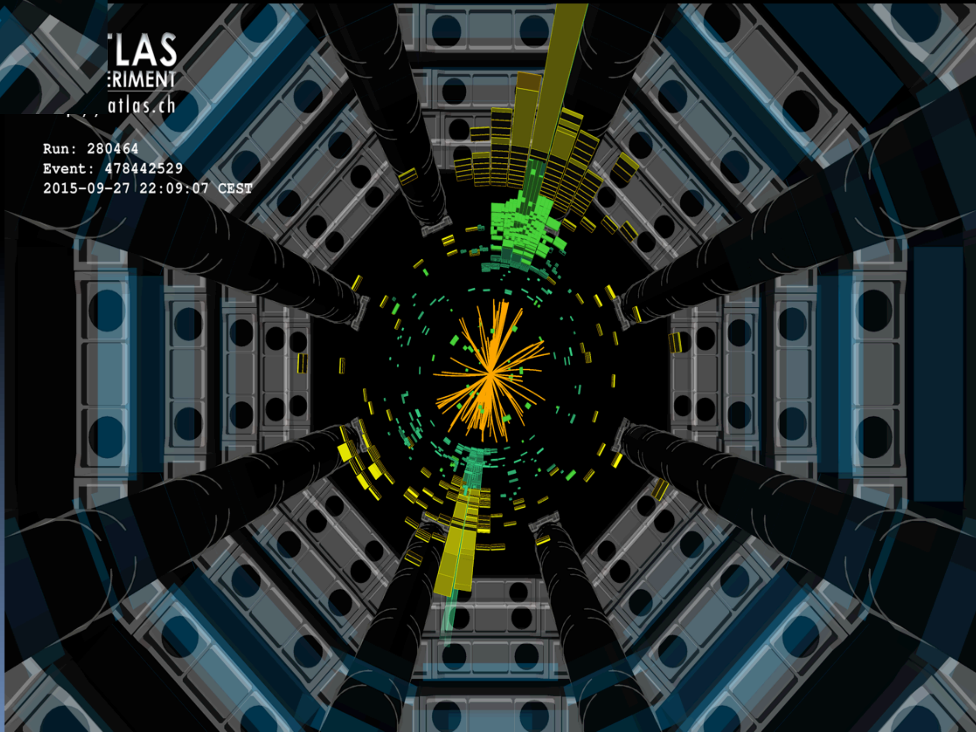
High-mass dijet events

m_{jj}: 7.9 TeV

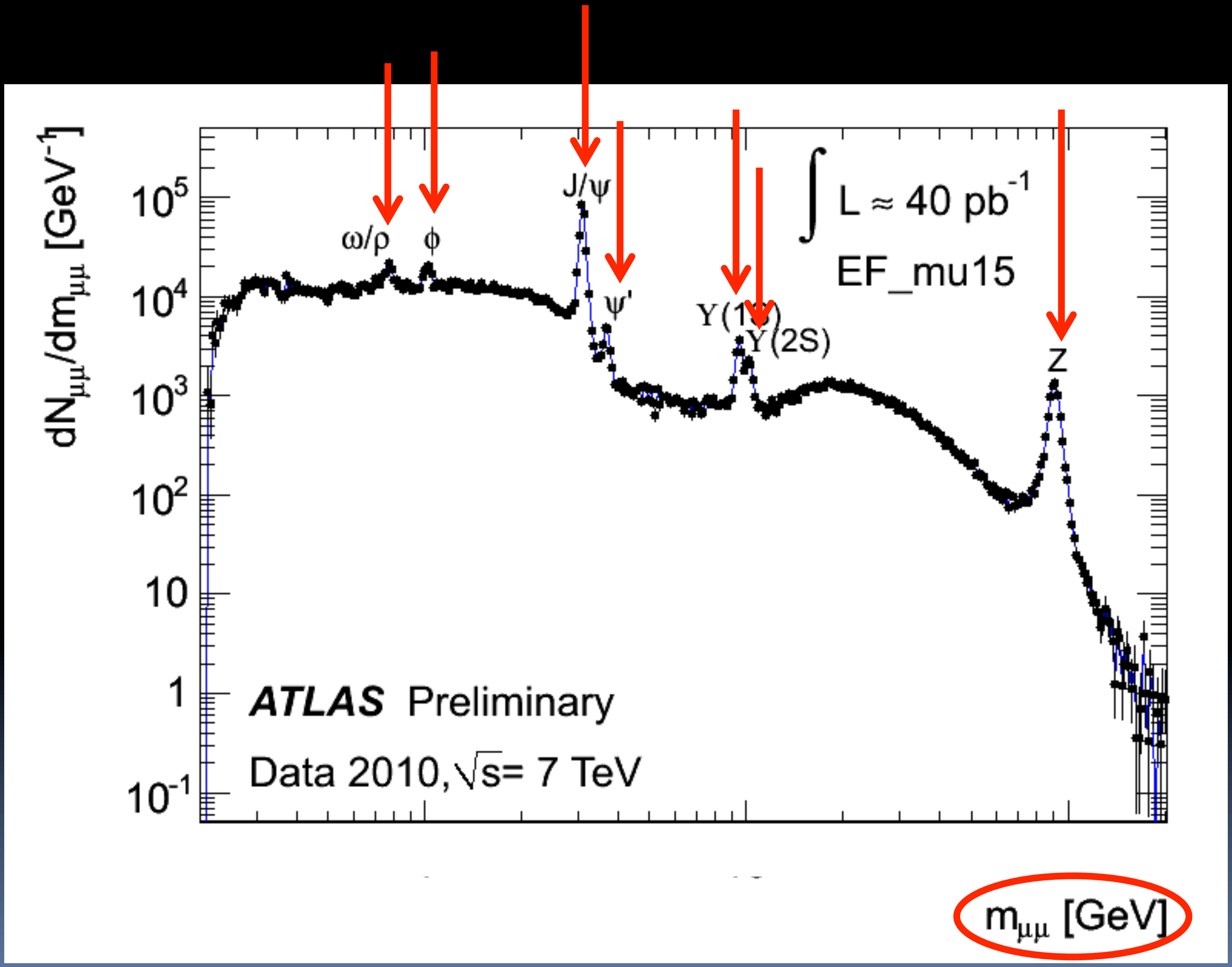


Back-to-back in transverse plane (no p_T)

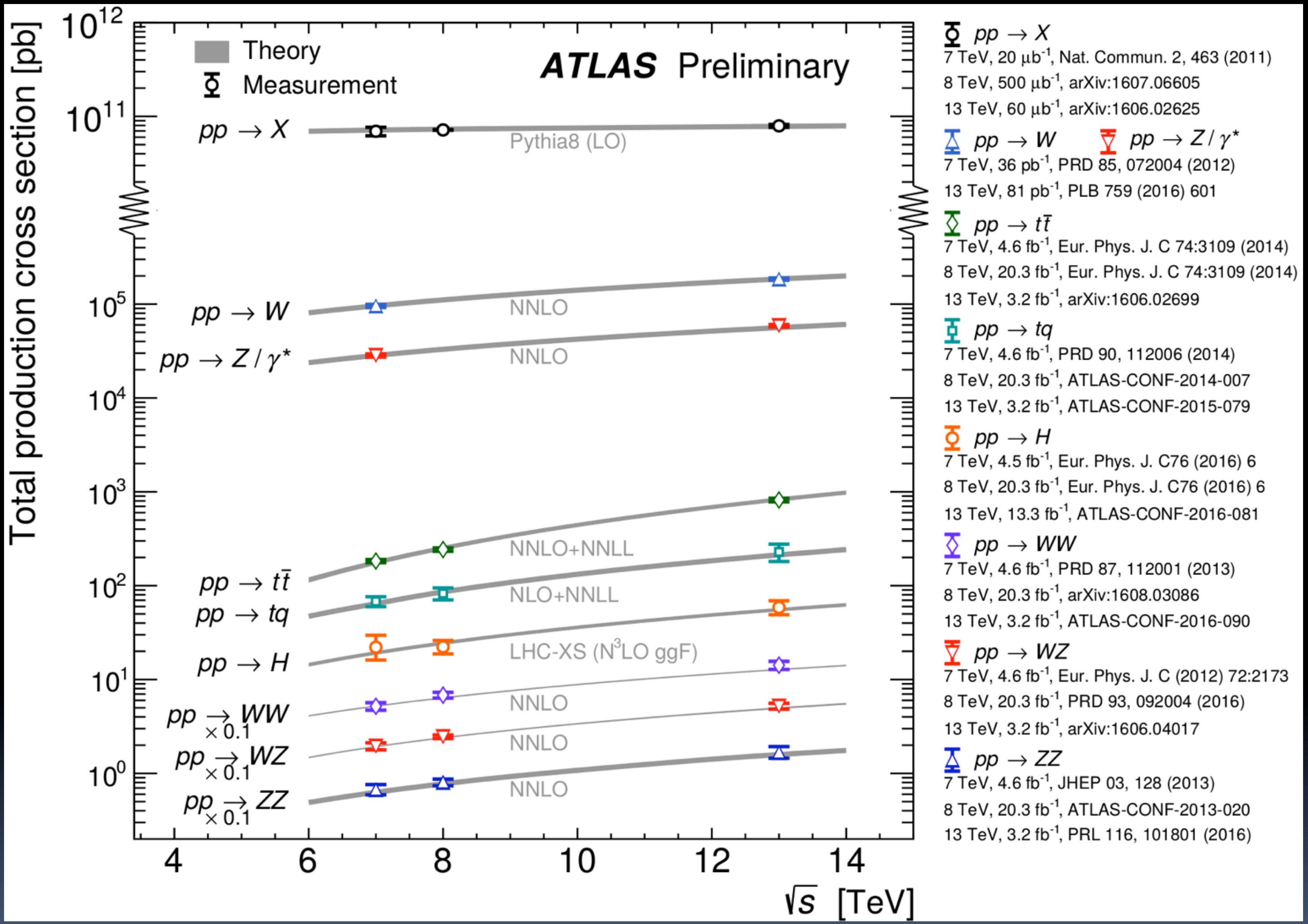
Boost in the longitudinal view (net momentum of colliding partons along beam axis)



Everything in place?



SM Cross section measurements: 7, 8, 13 TeV

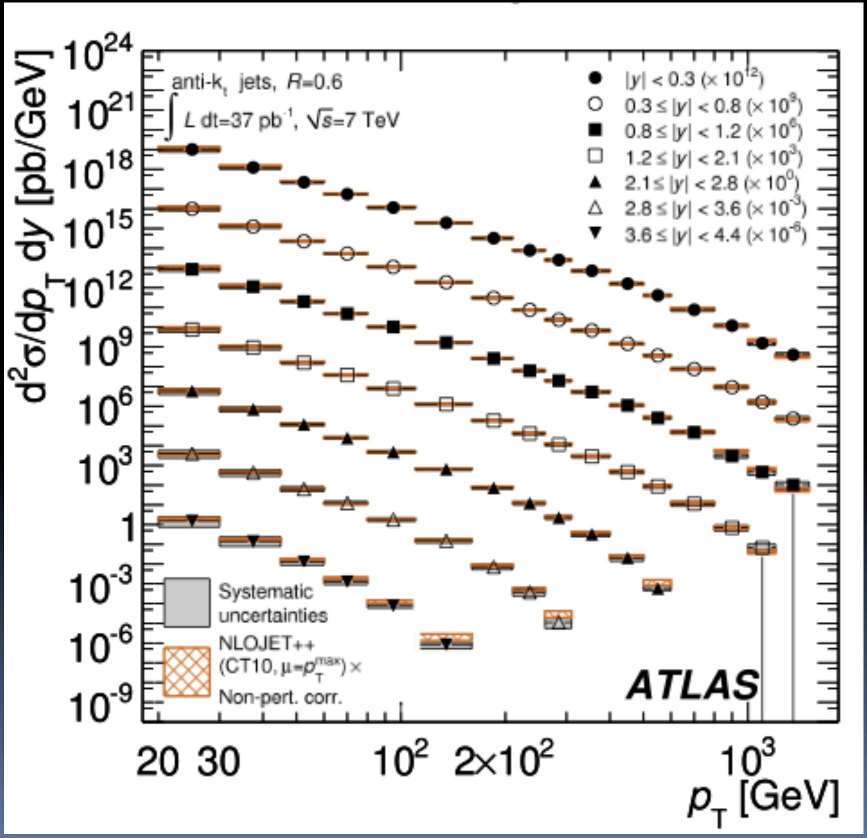


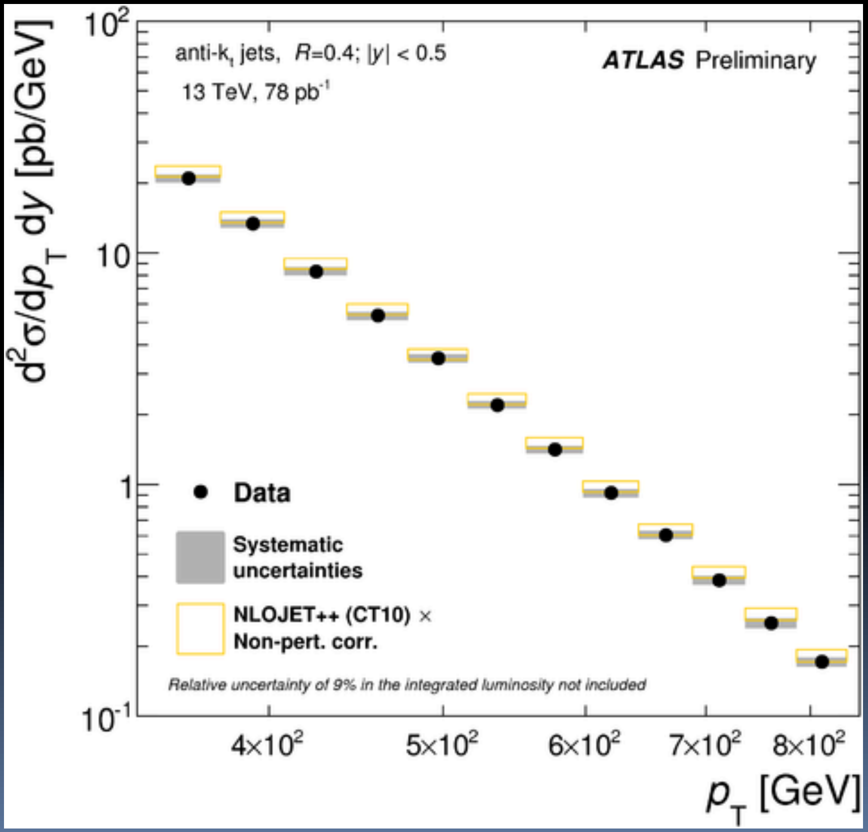
- Impressive agreement data - theory Next-Next -Leading-Log (NNLL)
- LHC surpassed (or does as well as) Tevatron and LEP in many precision measurements …

- Before New Physics shows up ?
  - ➢ Control Standard Model processes, especially (but not only) QCD!

Quantum ChromoDynamics - Jets

- Inclusive Jet cross sections
  - QCD works well and fits data over 10+ orders of magnitude – impressive!
  - 7 TeV - 13 TeV

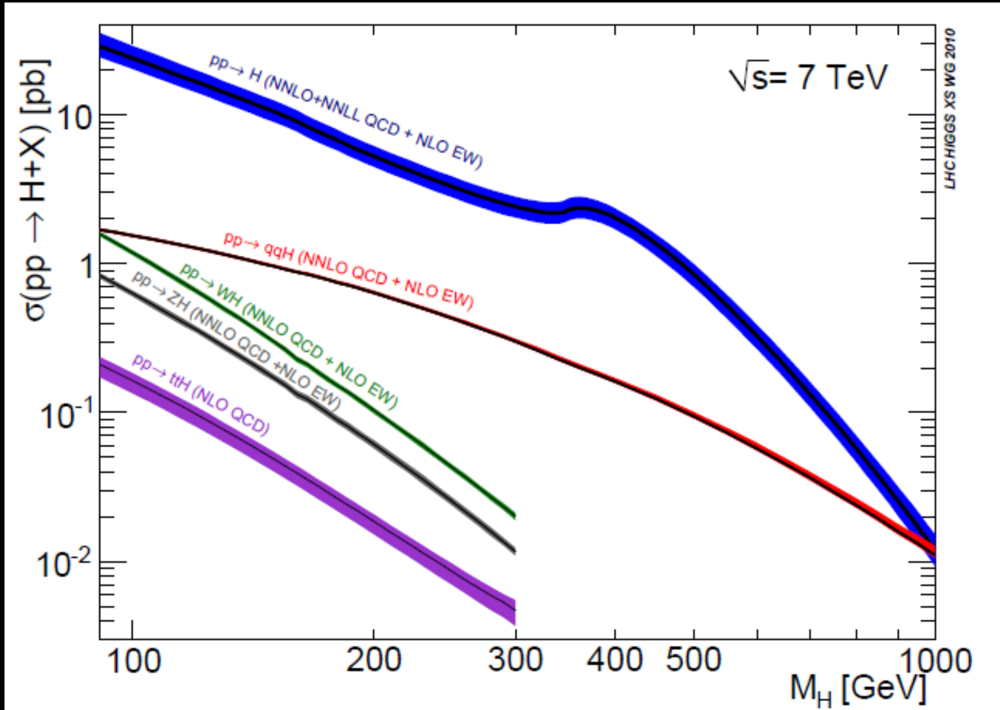


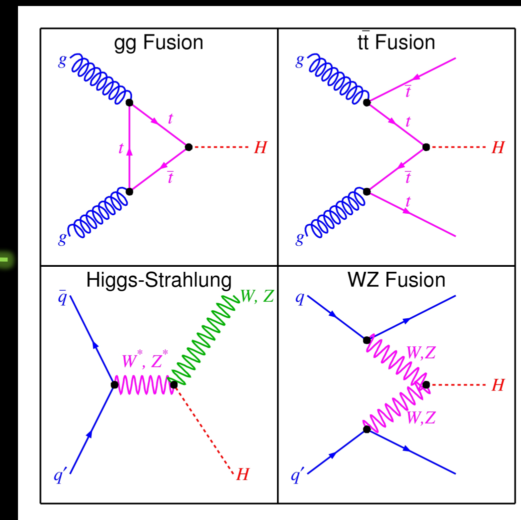


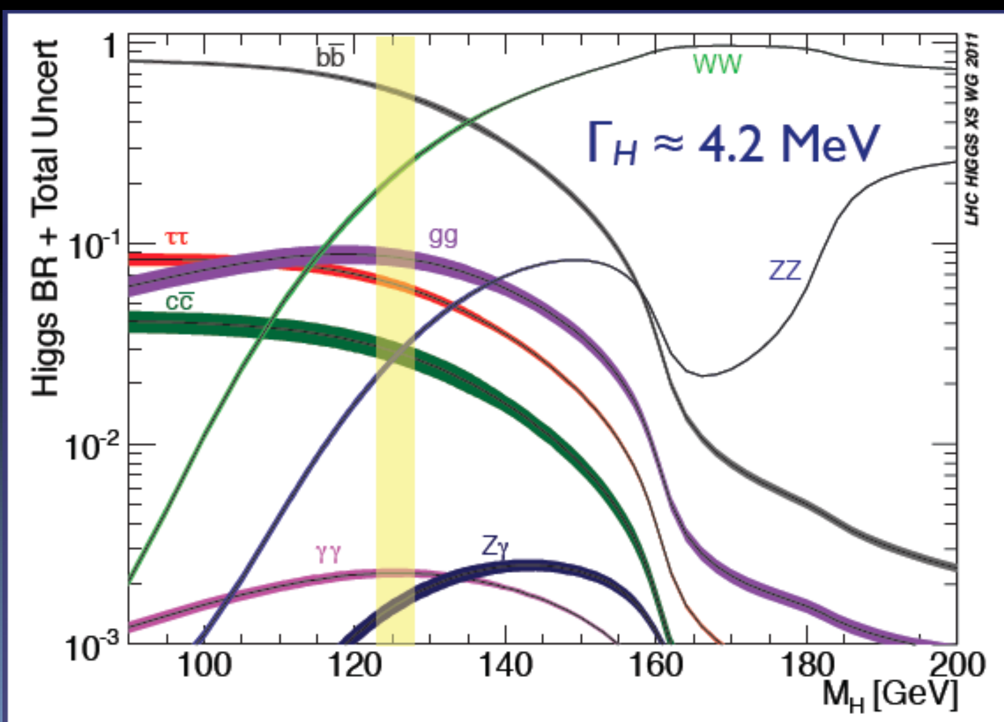
Why LHC

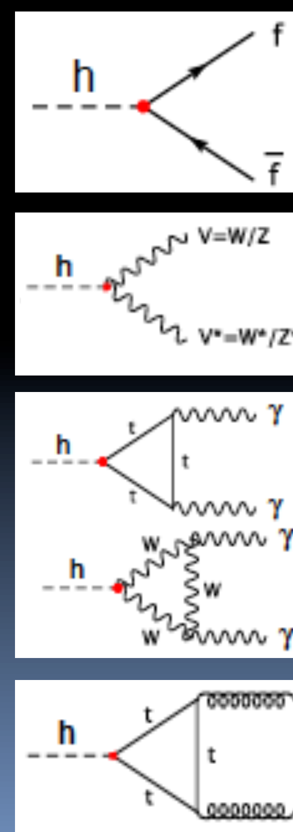
- Several accelerators / colliders built to discover (among others) the Higgs particle
- LHC was planned not to miss the Higgs

Higgs production and decay at LHC



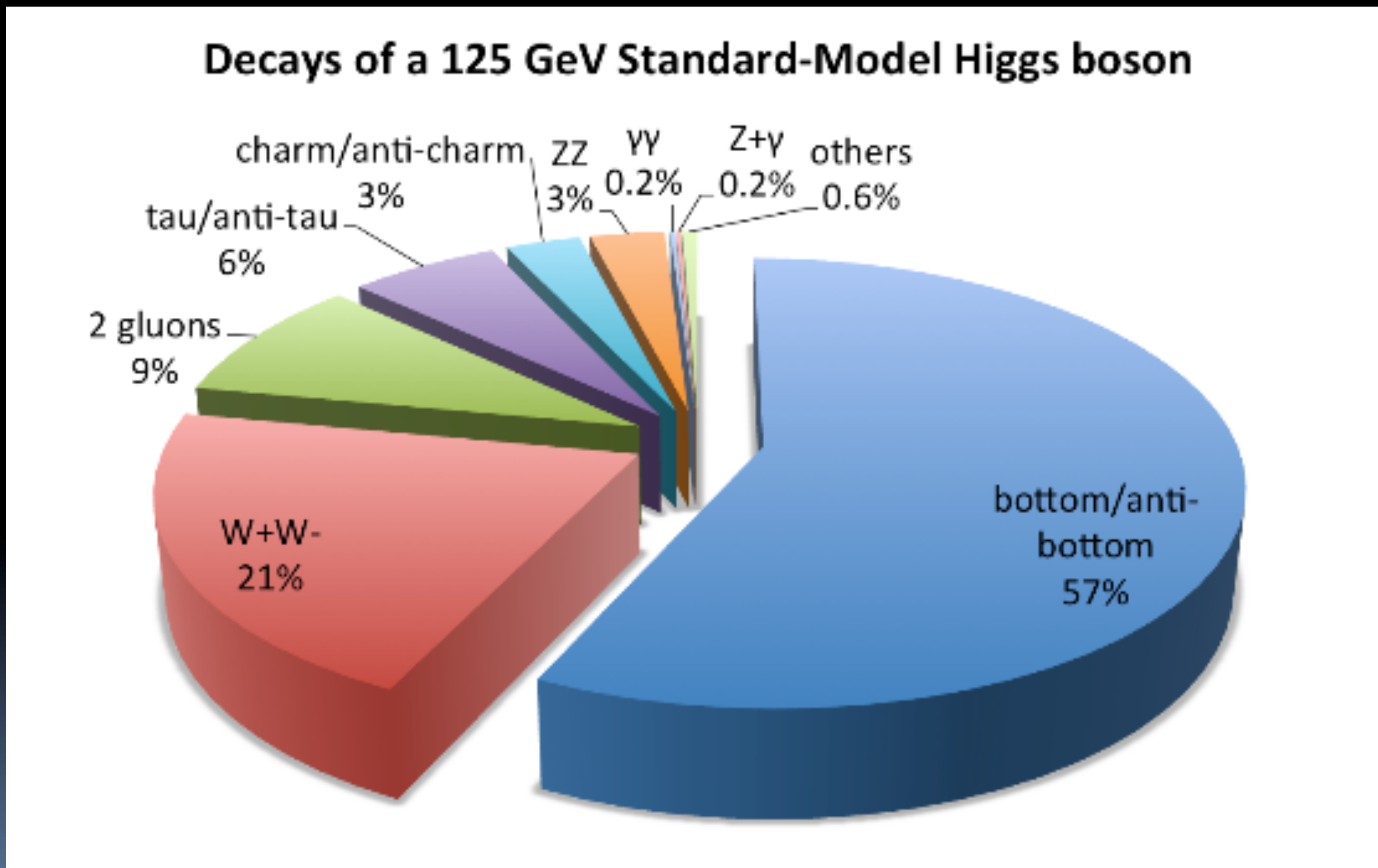




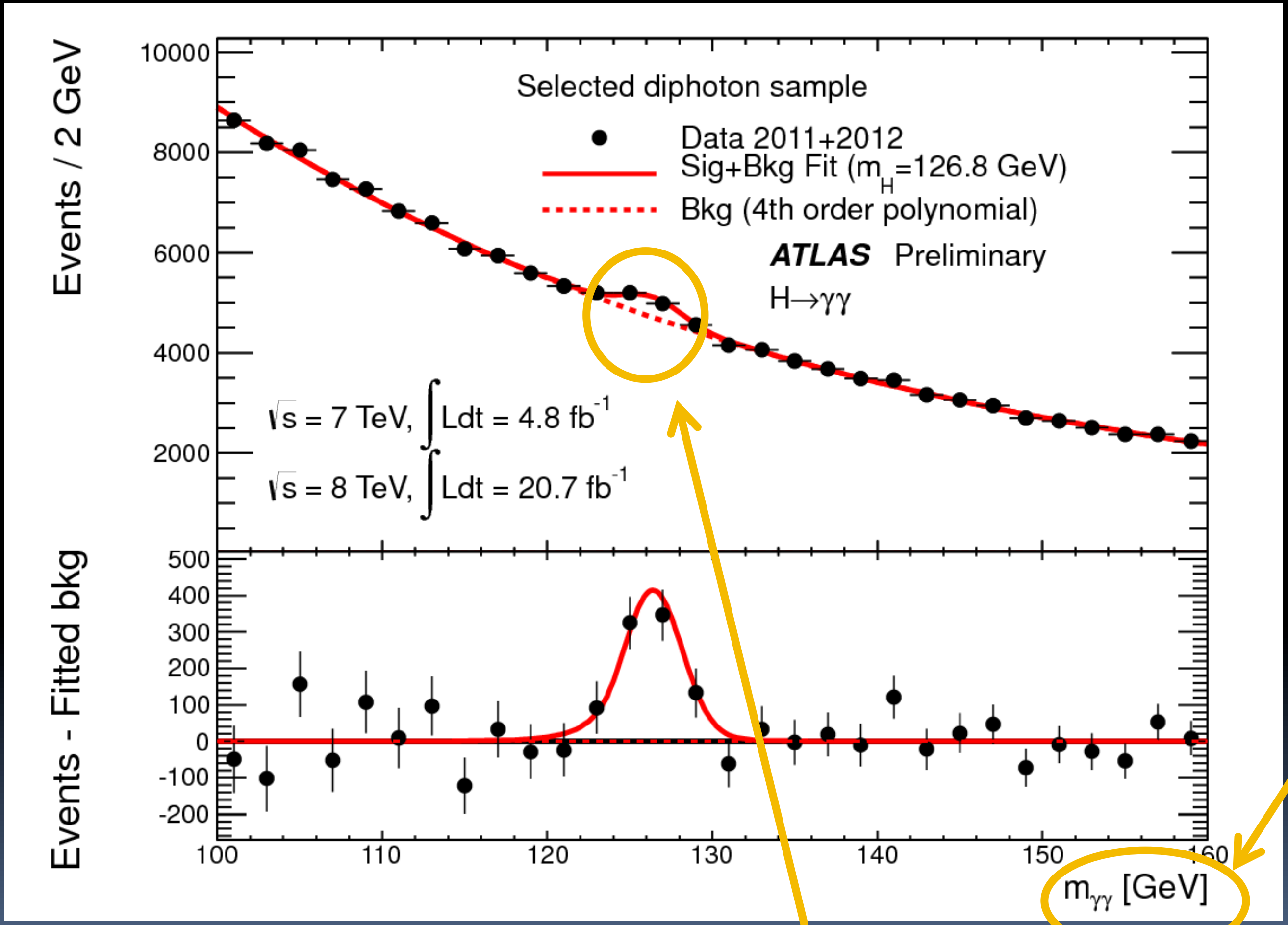


- 125 GeV … a rather good compromise
- 4/5 production processes
- ≥5 decay channels

The 125 GeV Higgs cake …



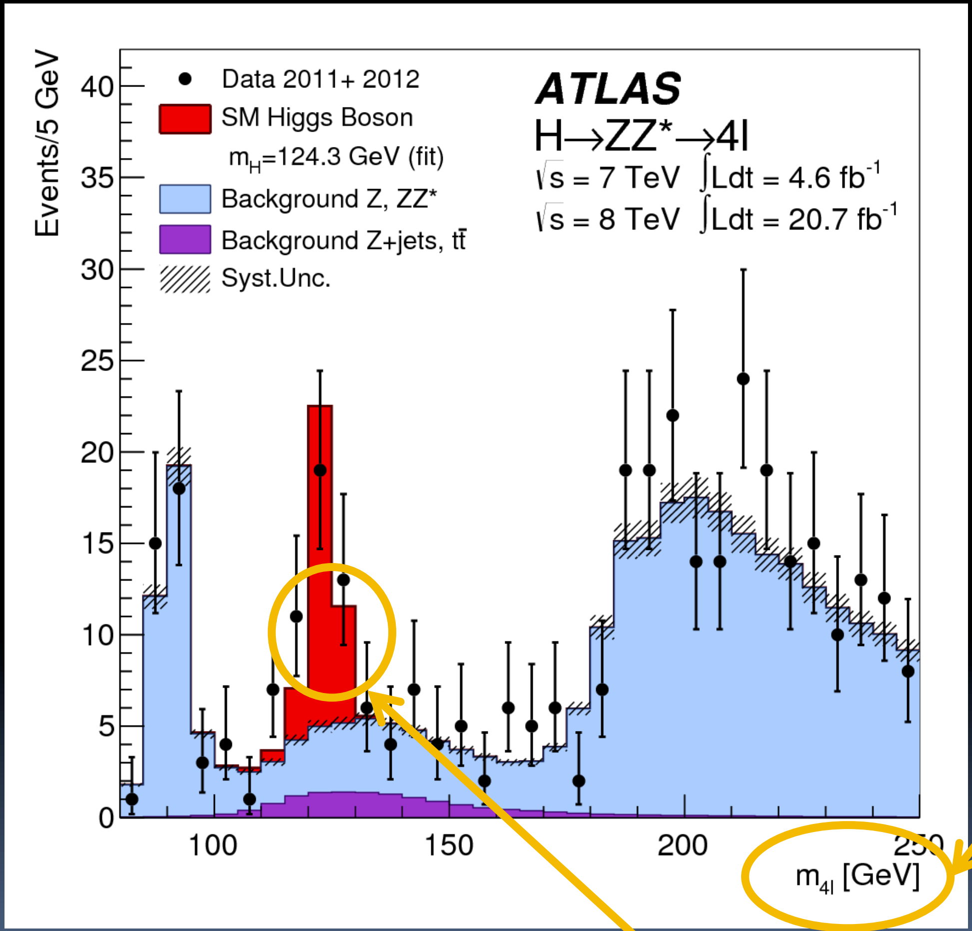
Anything new?



Invariant mass of photons

Higgs particle at 126 GeV!

Anything new?

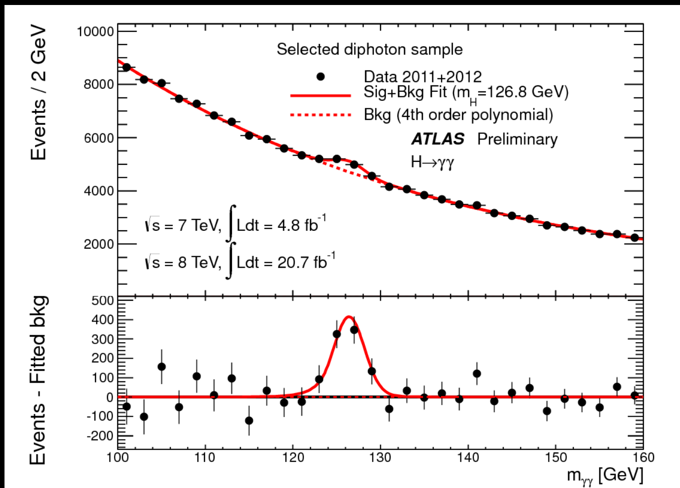


Invariant mass of 4 leptons

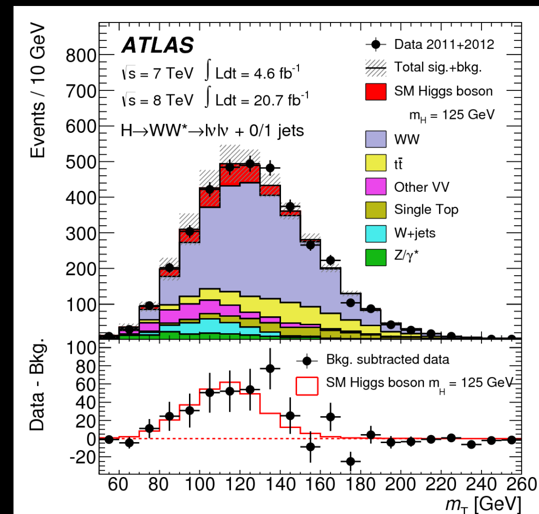
Higgs particle at 125 GeV

Higgs discovery?

H→γγ

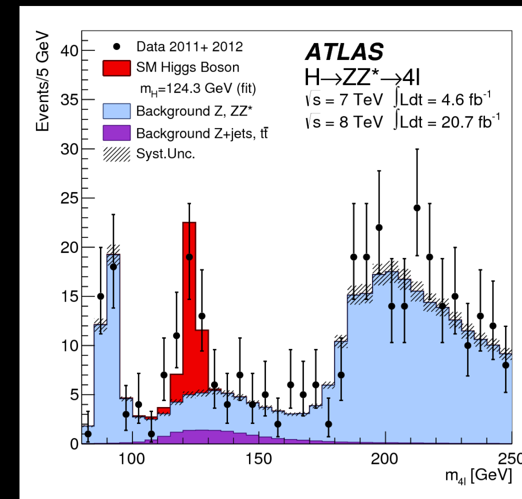


H→WW*→lνlν

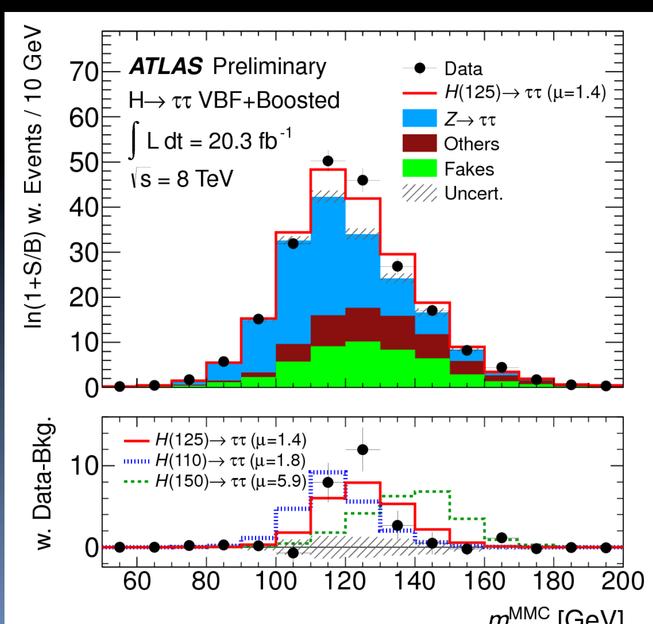


$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{P}_{\mathrm{T}}^{\ell\ell} + \mathbf{P}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

H→ZZ*→llll

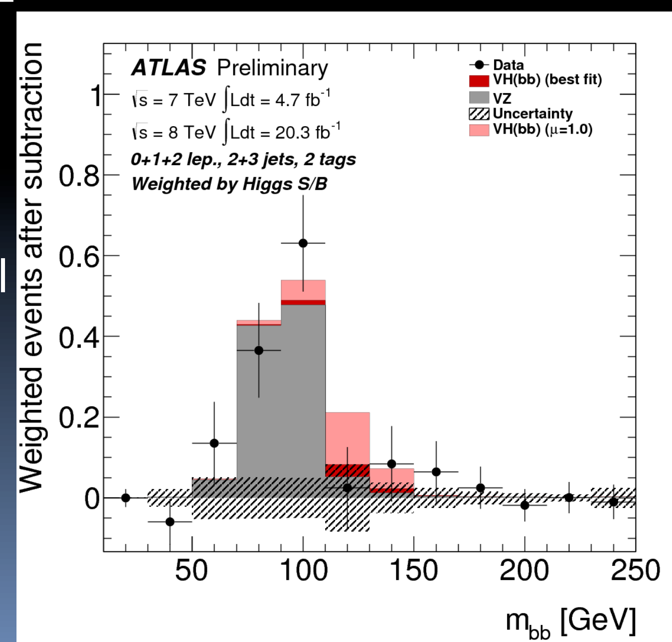


H→ττ



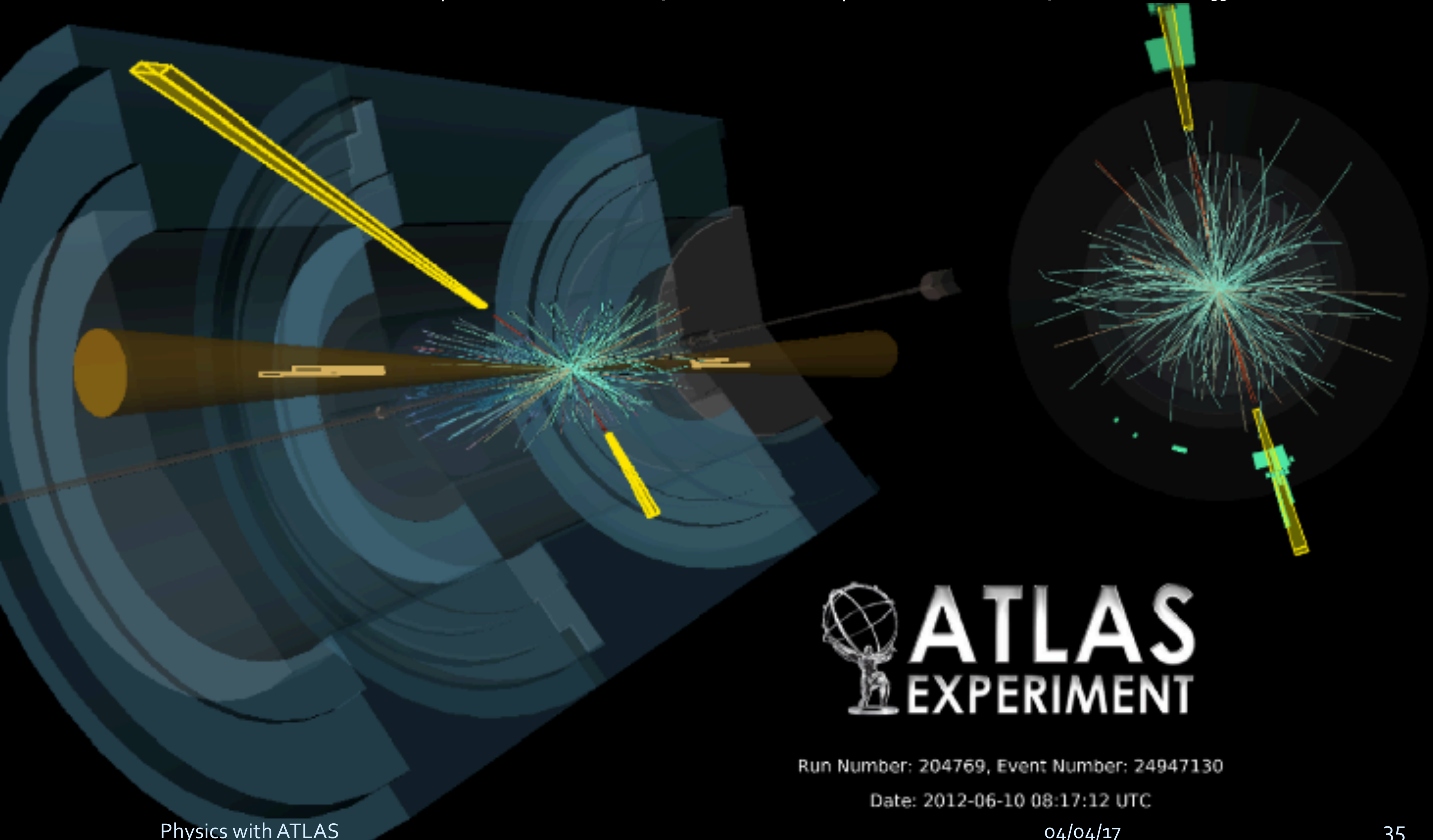
- Fermions
- Tau evidence > 4σ
- Bottom decays still need be confirmed

H→bb

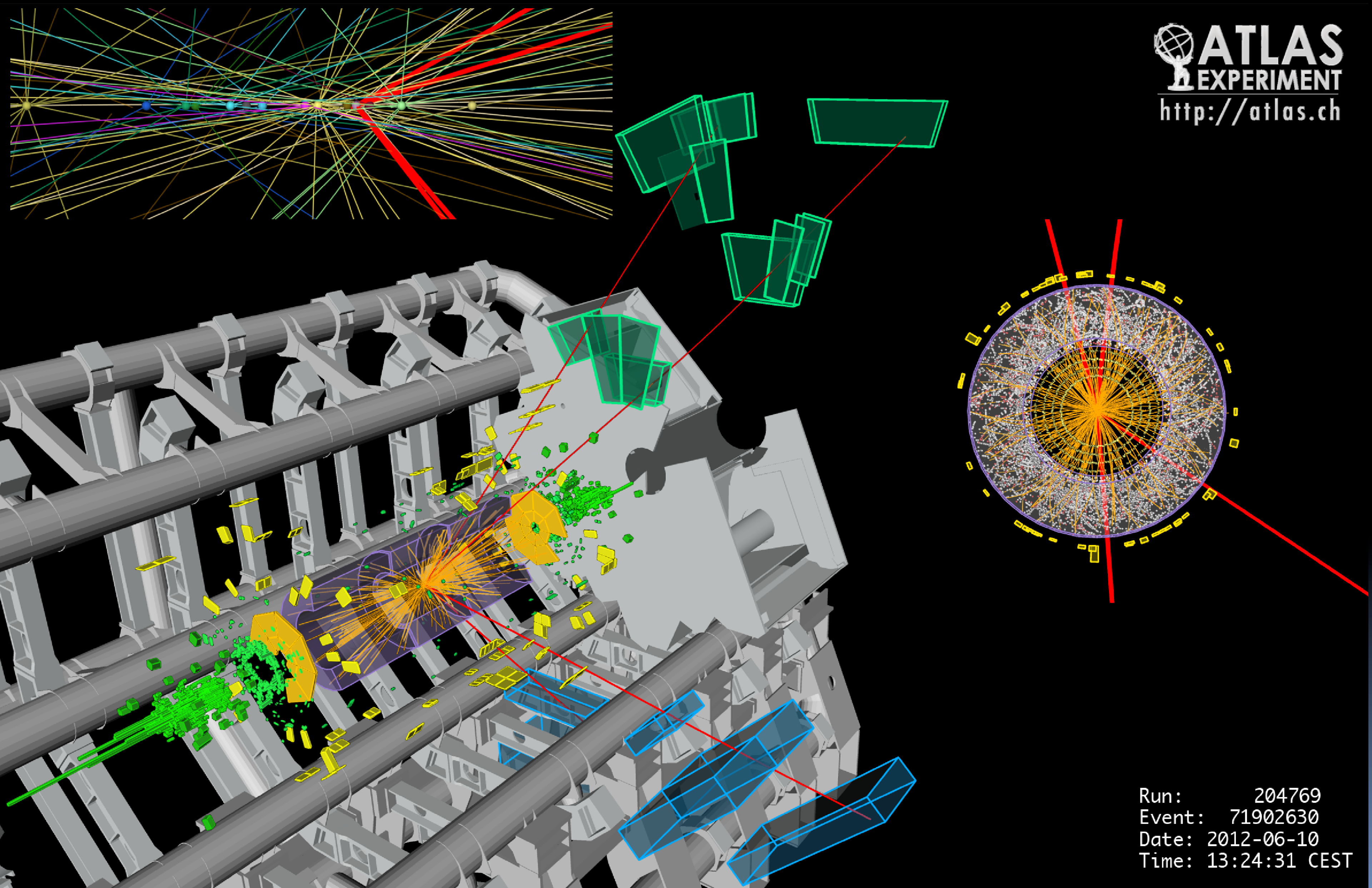


H→γγ

Vector Boson Fusion candidate at $\sqrt{s}$=8TeV
2 converted photons and two high-mass jets
- Photons: (E_T = 80.1 GeV, η = 1.01); (E_T = 36.2 GeV and η = −0.17)
- Measured di-photon mass = 126.9 GeV
- Jets: (E_T = 121.6 GeV, η = -2.90); (E_T = 82.8 GeV, η = 2.72) ; Mjj=1.67 TeV

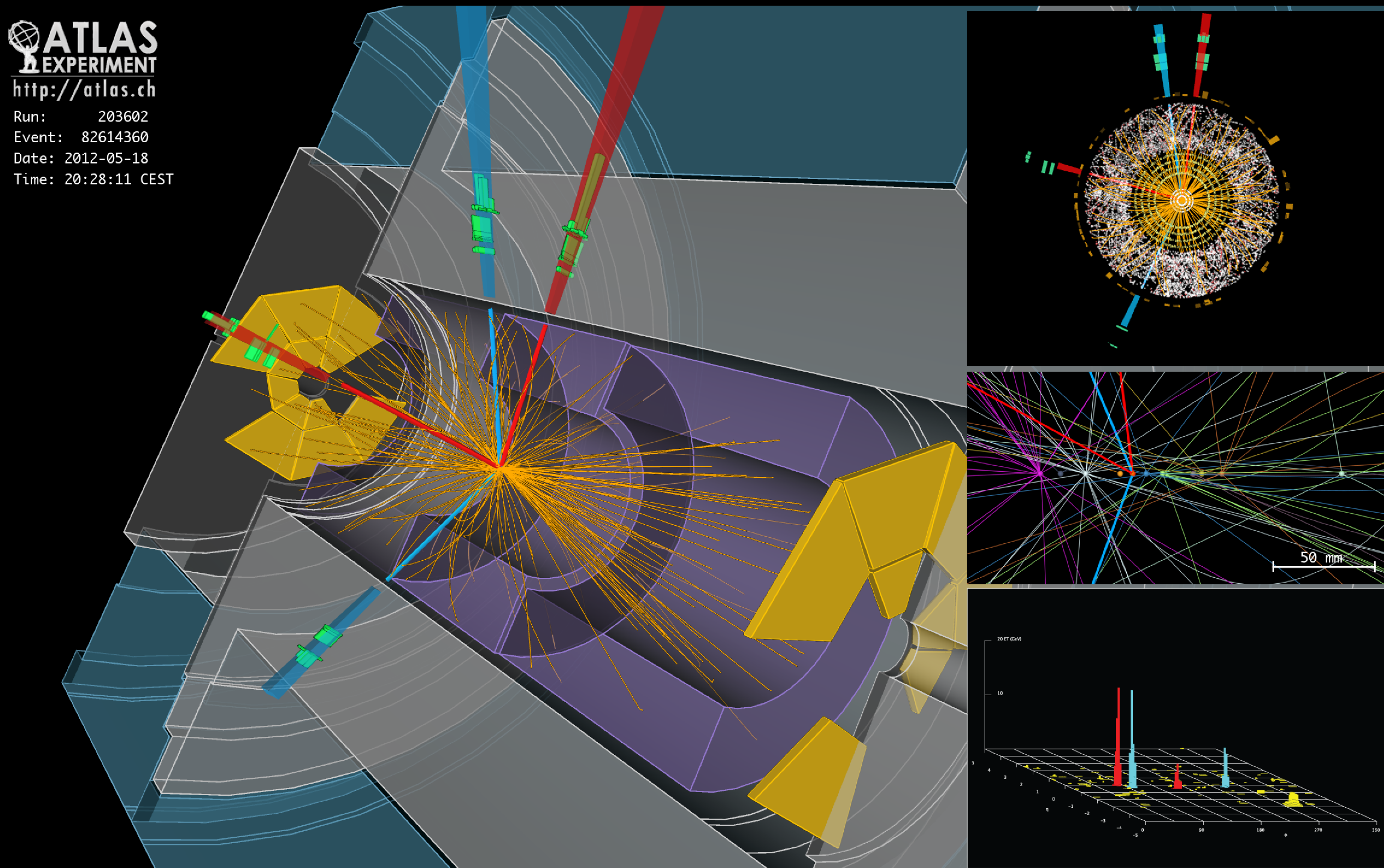


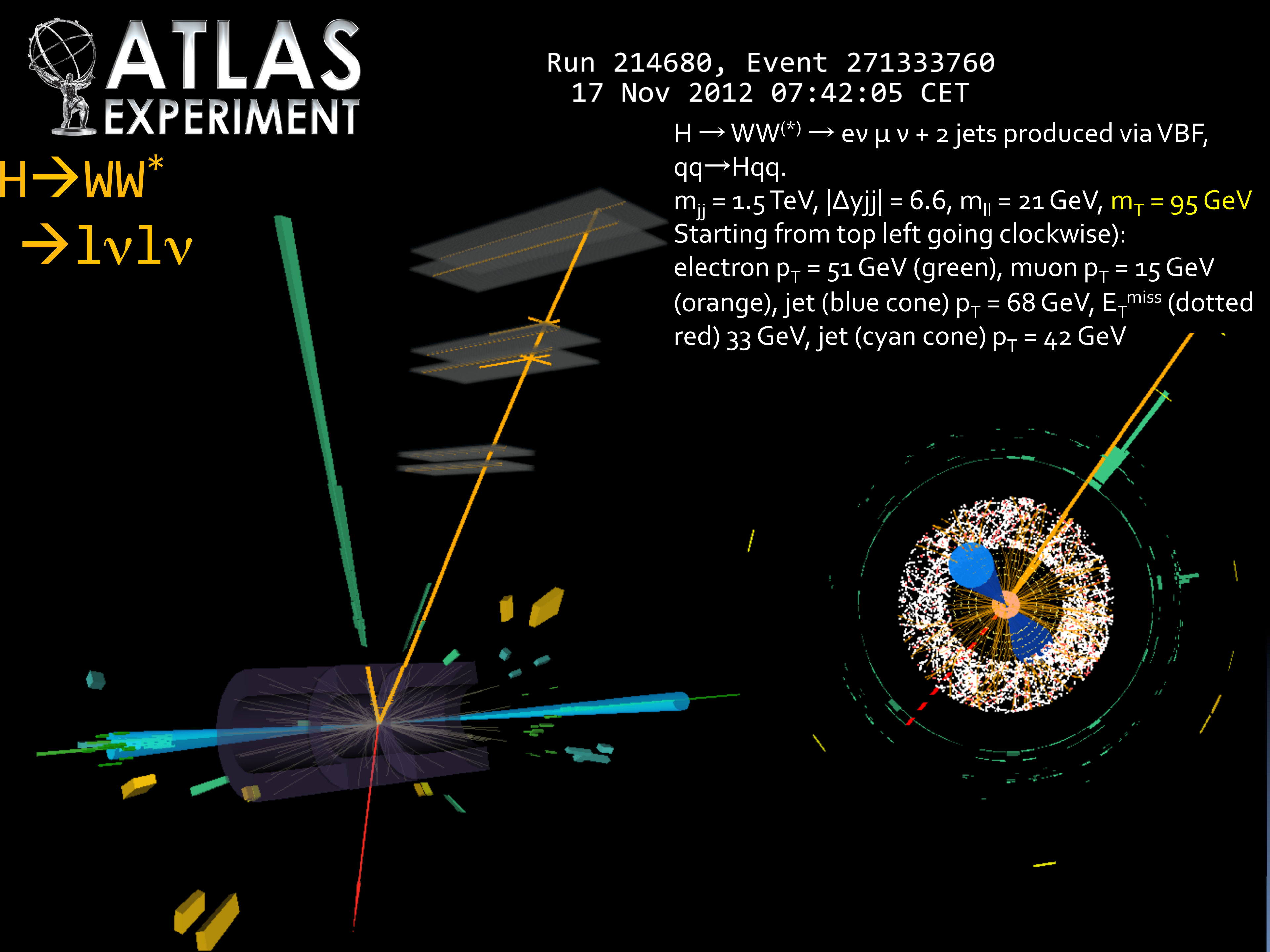
$H \rightarrow ZZ^* \rightarrow \mu^+\mu^-\mu^+\mu^-$ m_4=127.4 GeV. m_{12}=86.6 GeV, m_{34}=31.6 GeV



$H \rightarrow ZZ^{*} \rightarrow e^{+}e^{-}e^{+}e^{-}$

m_4=124.6 GeV. m_{12}=70.6 GeV, m_{34}=44.7 GeV

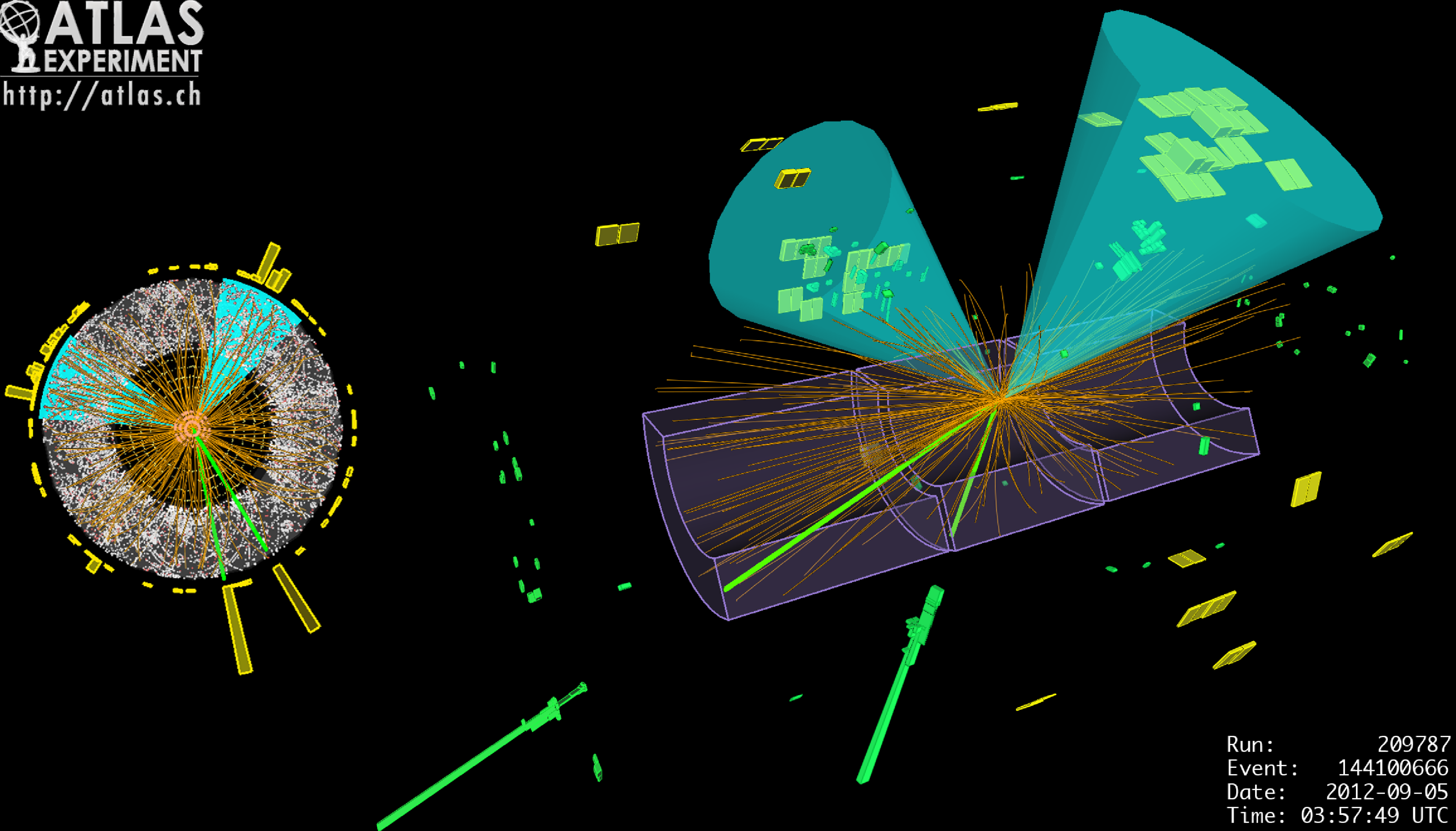


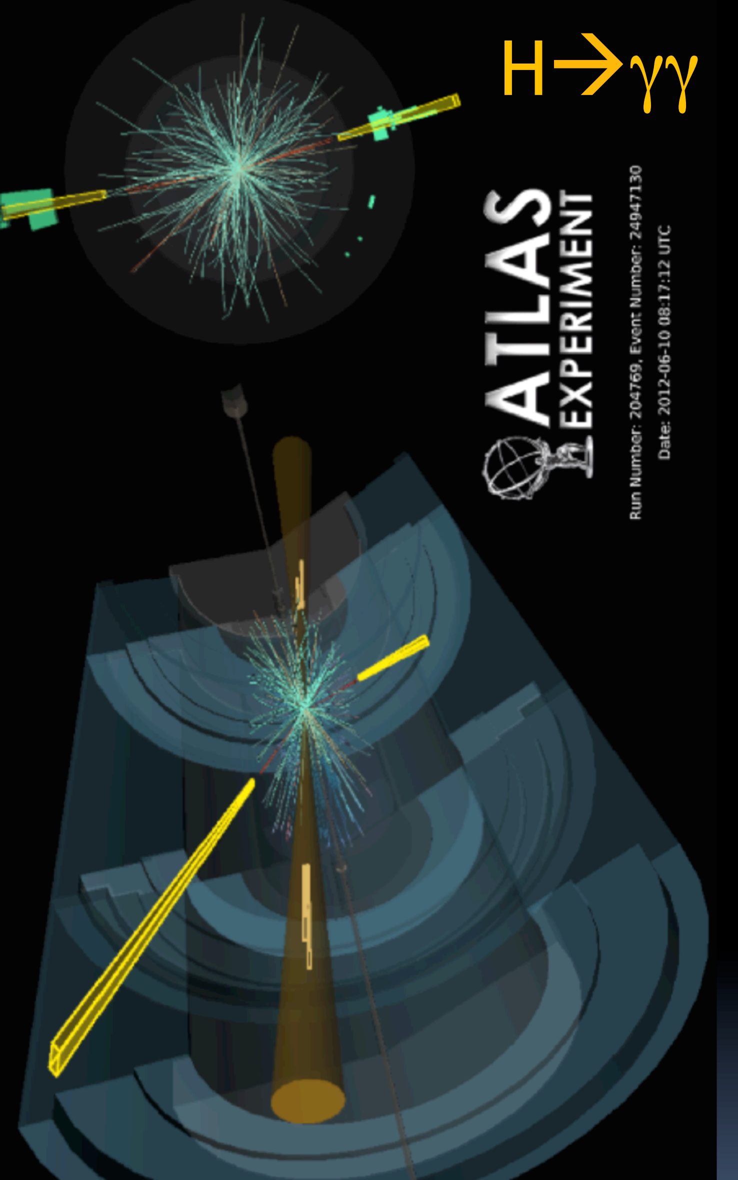

ATLAS EXPERIMENT
Run 214680, Event 271333760
17 Nov 2012 07:42:05 CET
H→WW*
→lνlν
H ⟶ WW(*) ⟶ eν μ ν + 2 jets produced via VBF, qq⟶Hqq.
mjj = 1.5 TeV, |Δyjj| = 6.6, mll = 21 GeV, mT = 95 GeV
Starting from top left going clockwise):
electron pT = 51 GeV (green), muon pT = 15 GeV (orange), jet (blue cone) pT = 68 GeV, ET miss (dotted red) 33 GeV, jet (cyan cone) pT = 42 GeV

H→b-bbar candidate

- 2 identified b-jets (p_T=70 GeV, p_T=65 GeV, m_{bb}=122 GeV)
- 2 electrons (p_T=63 GeV, p_T=54 GeV).

ATLAS EXPERIMENT
http://atlas.ch




H→γγ
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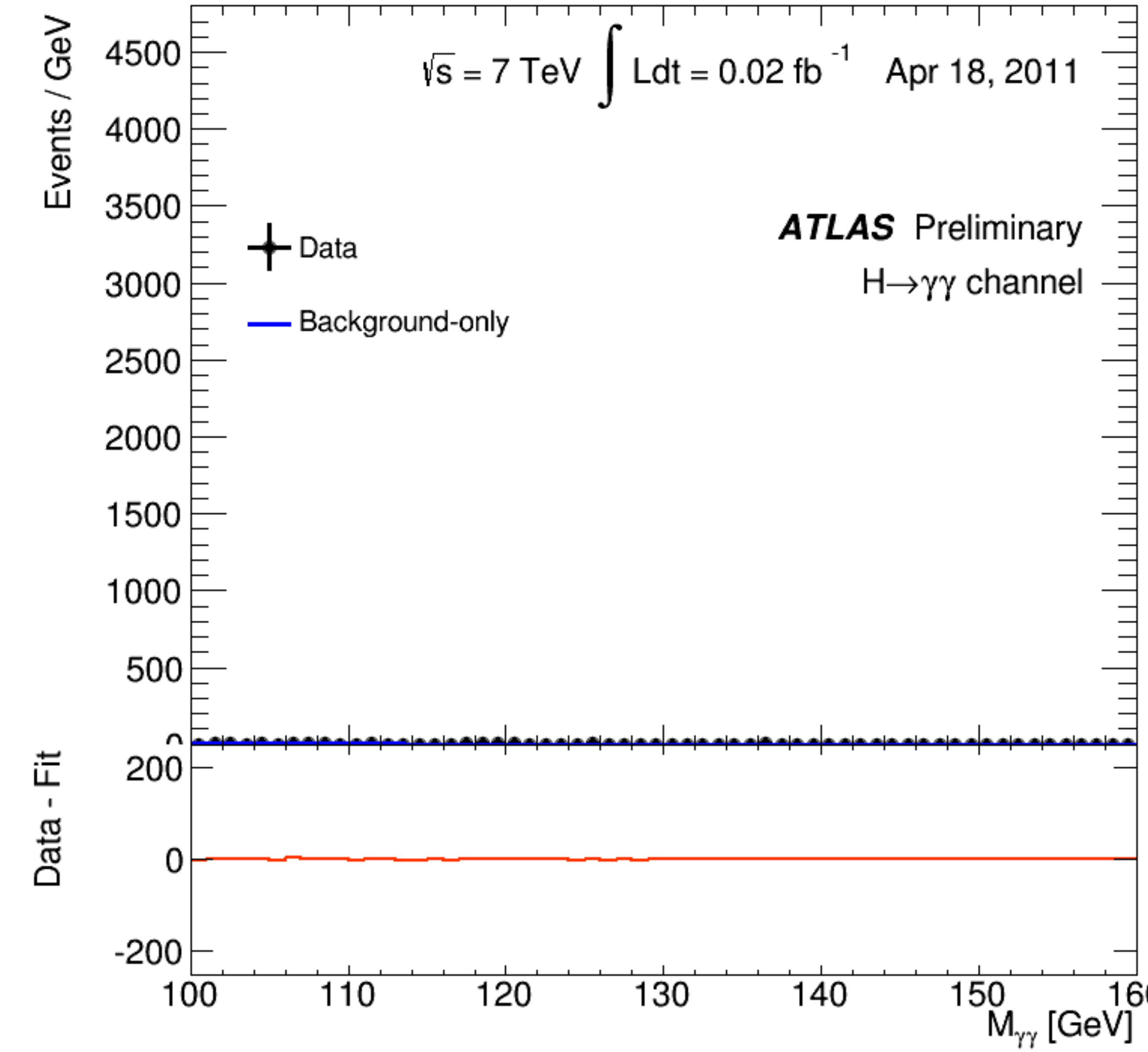
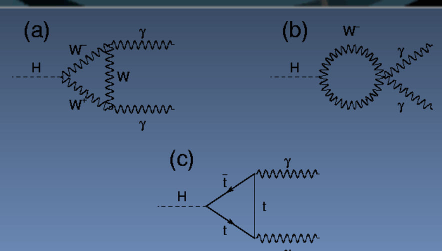
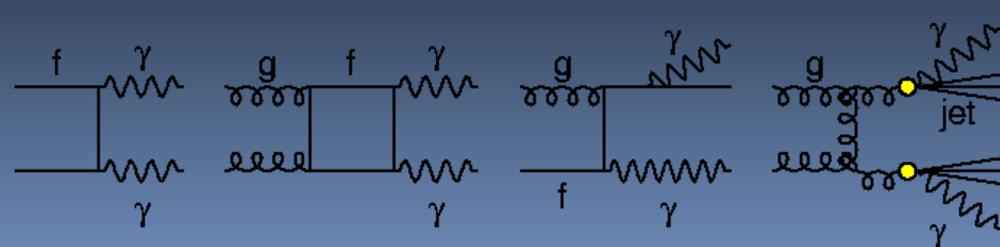
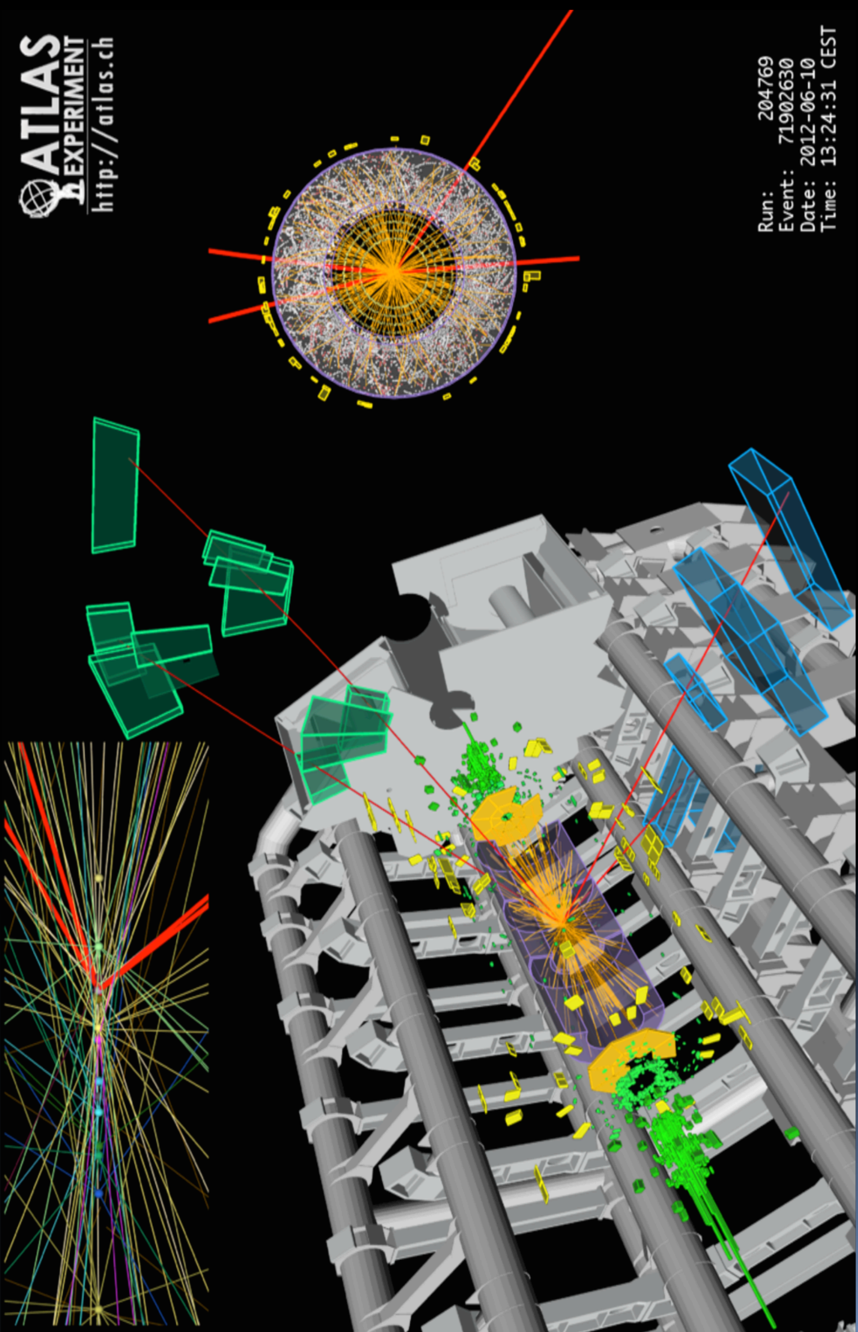
Date: 2012-06-10 08:17:12 UTC

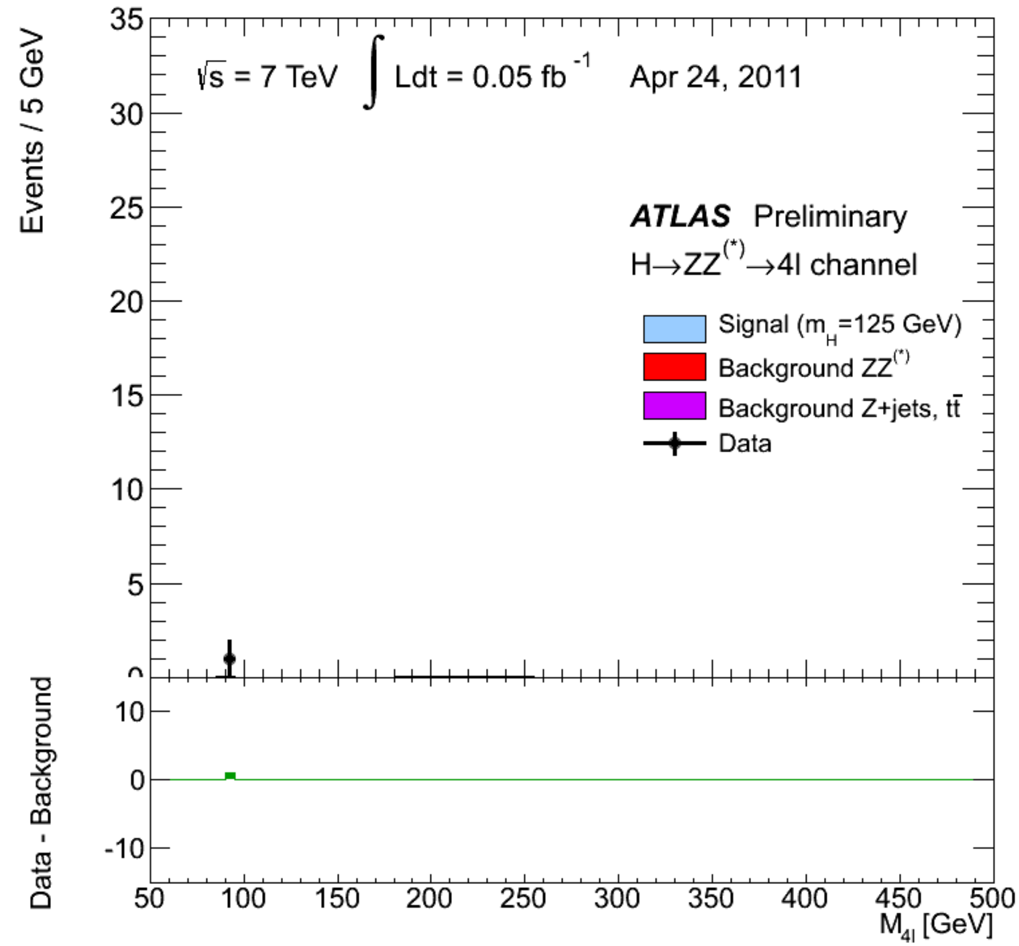

√s = 7 TeV ∫ Ldt = 0.02 fb^{-1} Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
Data - Fit
$M_{\gamma\gamma}$ [GeV]
4500
4000
3500
3000
2500
2000
1500
1000
500
200
0
-200
100
110
120
130
140
150
160


(a)
(b)
(c)


f
g
γ
jet

$H \rightarrow ZZ^* \rightarrow l^+l^-l^+l^-$

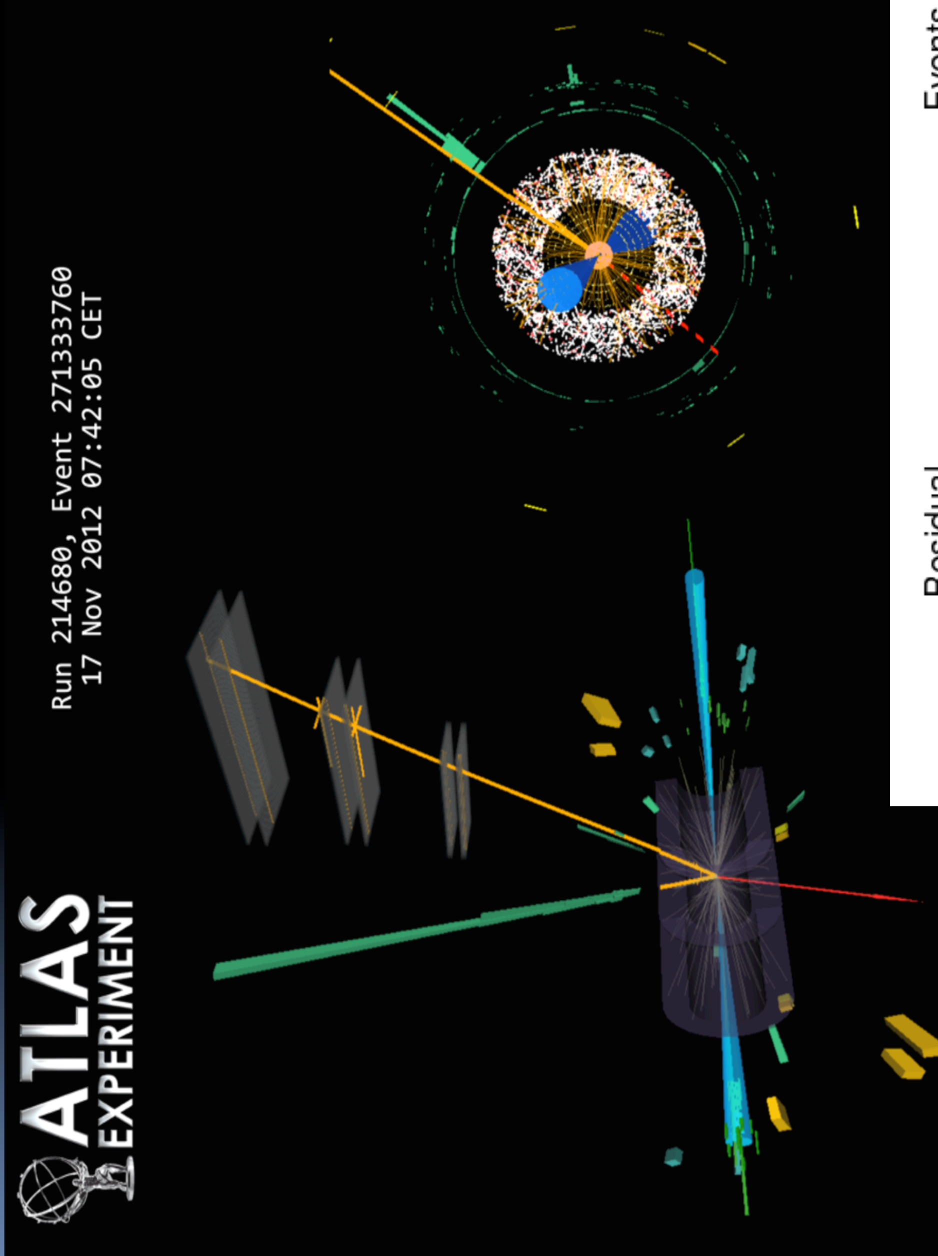


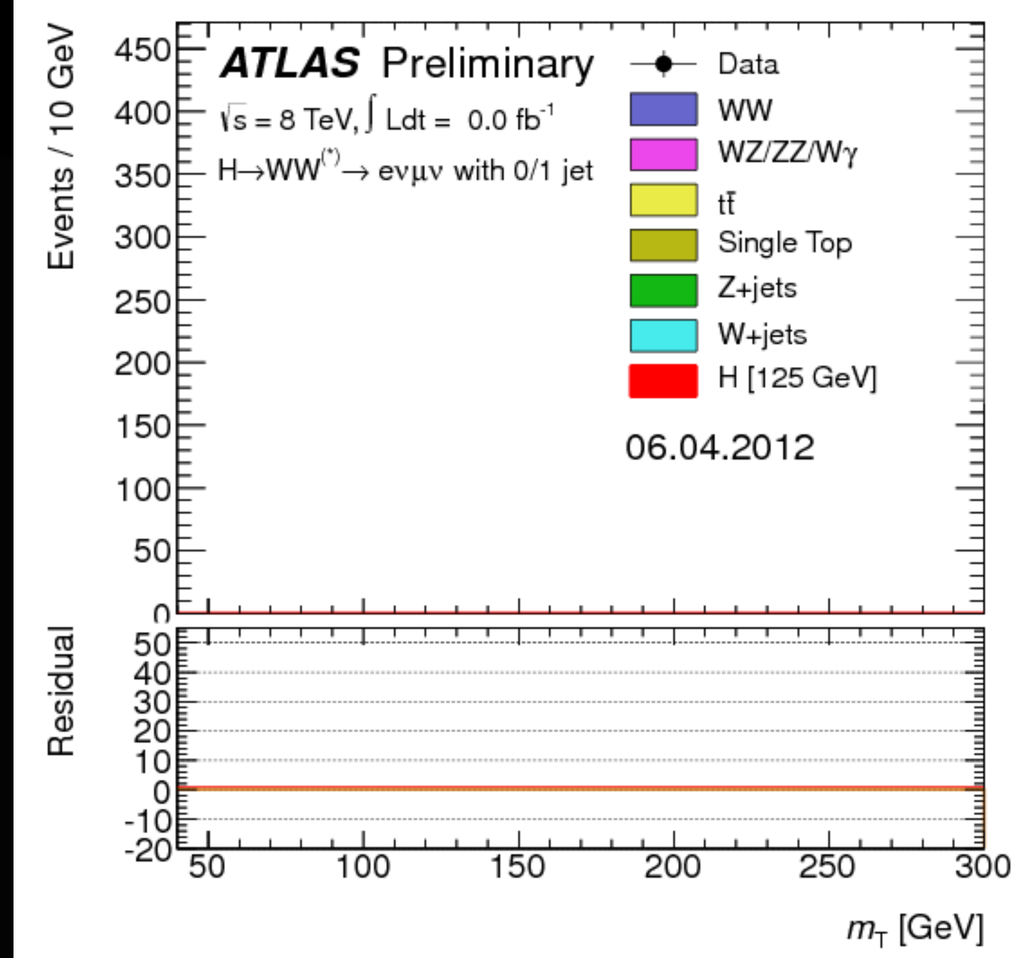


Understanding of “background” is important

- Most of which is due to important physics at the heart of the gauge structure / symmetry of electroweak interaction
- Higgs showed up between 2 relatively busy regions!

$H \to WW^* \to l\nu l\nu$





$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{P}_{\mathrm{T}}^{\ell\ell} + \mathbf{P}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

- Understanding of background is crucial
  - Most of which is due to important physics
  - at the heart of the gauge structure / symmetry of electroweak interaction

(Statistical significa

- Plot number of events or cross section as function of chosen variable
  - observed or measured (Data)
  - expected "background" (SM or some established theory)
  - ratio observed/SM
  - predicted by new physics theory

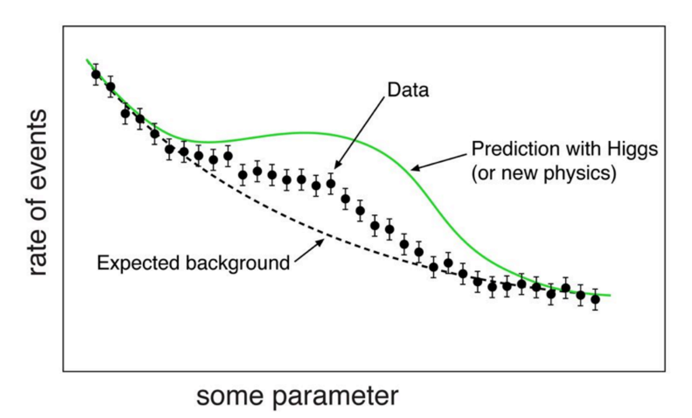


Figure B

- New Physics?
  - Local probability p_o for a background-only experiment to be more signal-like than the observation as a function of new particle mass
  - The higher the Significance, the lower the probability of background fluctuation

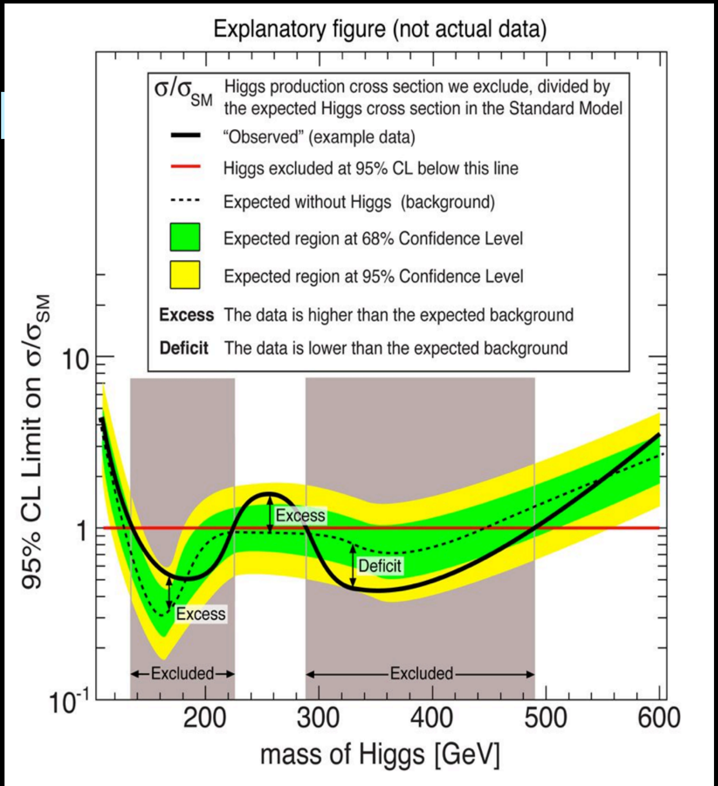
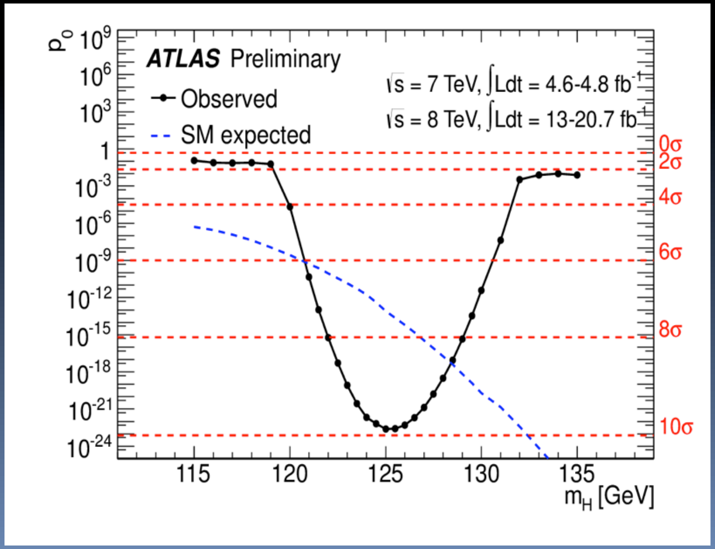
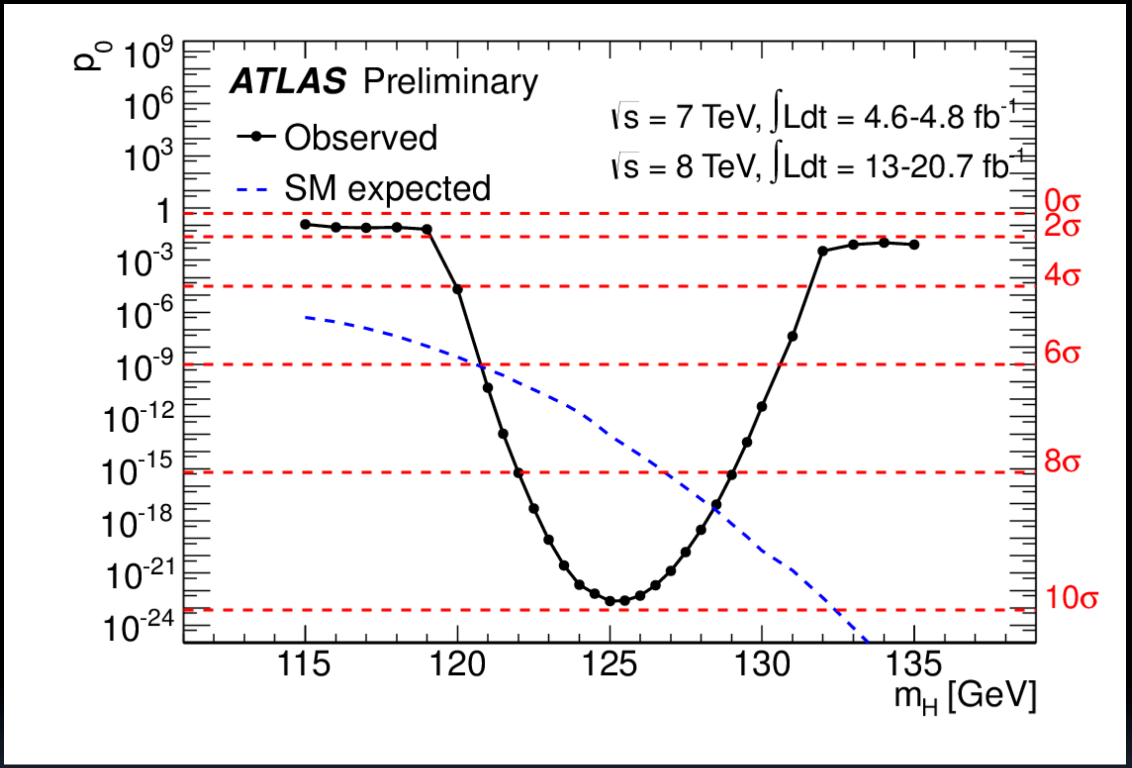


Figure A



A new particle discovered

- Local probability p_o for a background-only experiment to be more signal-like than the observation as a function of m_H

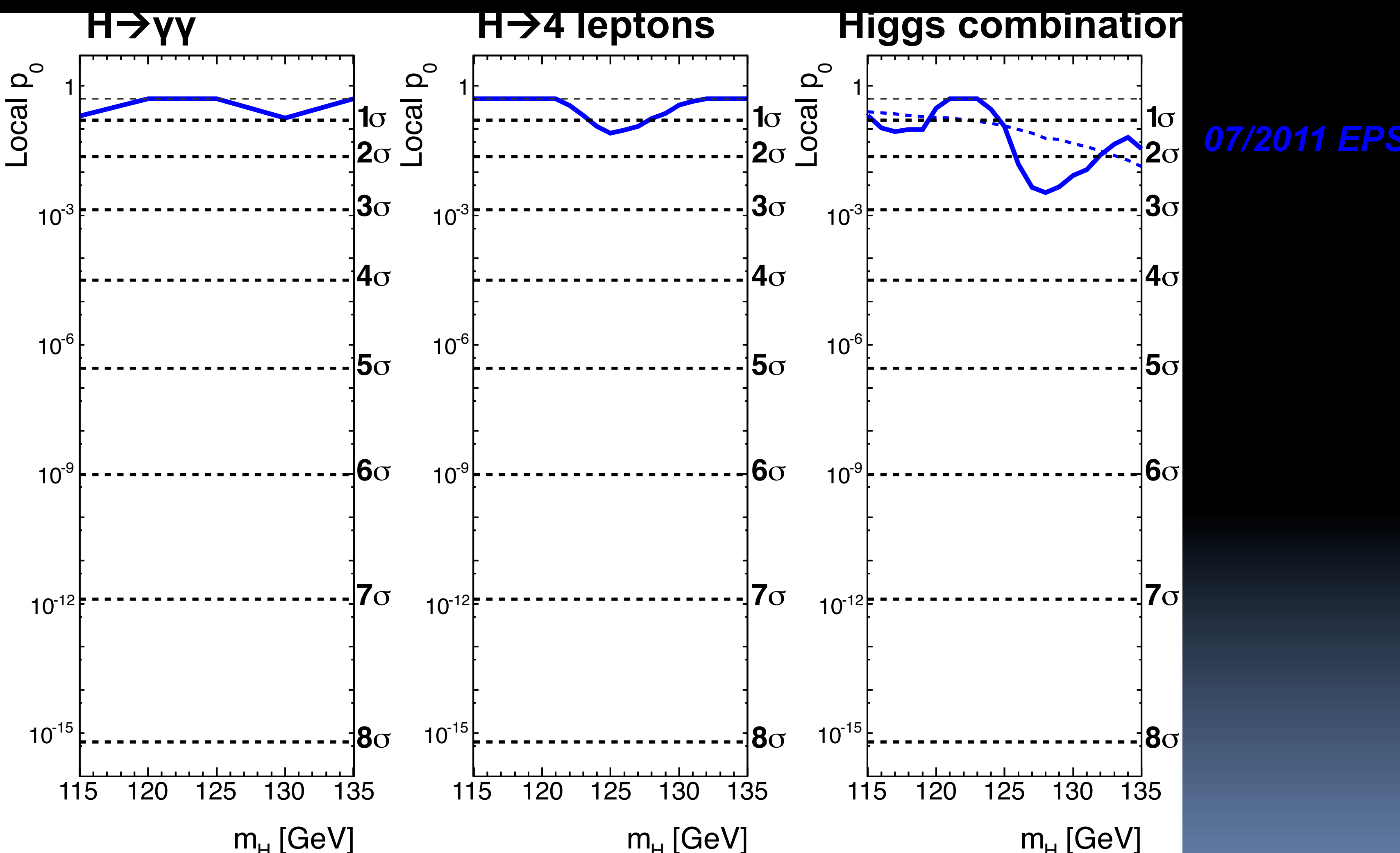


- 10σ signal @ M~125.5 GeV
- Probability of background fluctuation: ~10^{-23}

From excess to discovery (ATLAS)

progressive significance(p0) plots

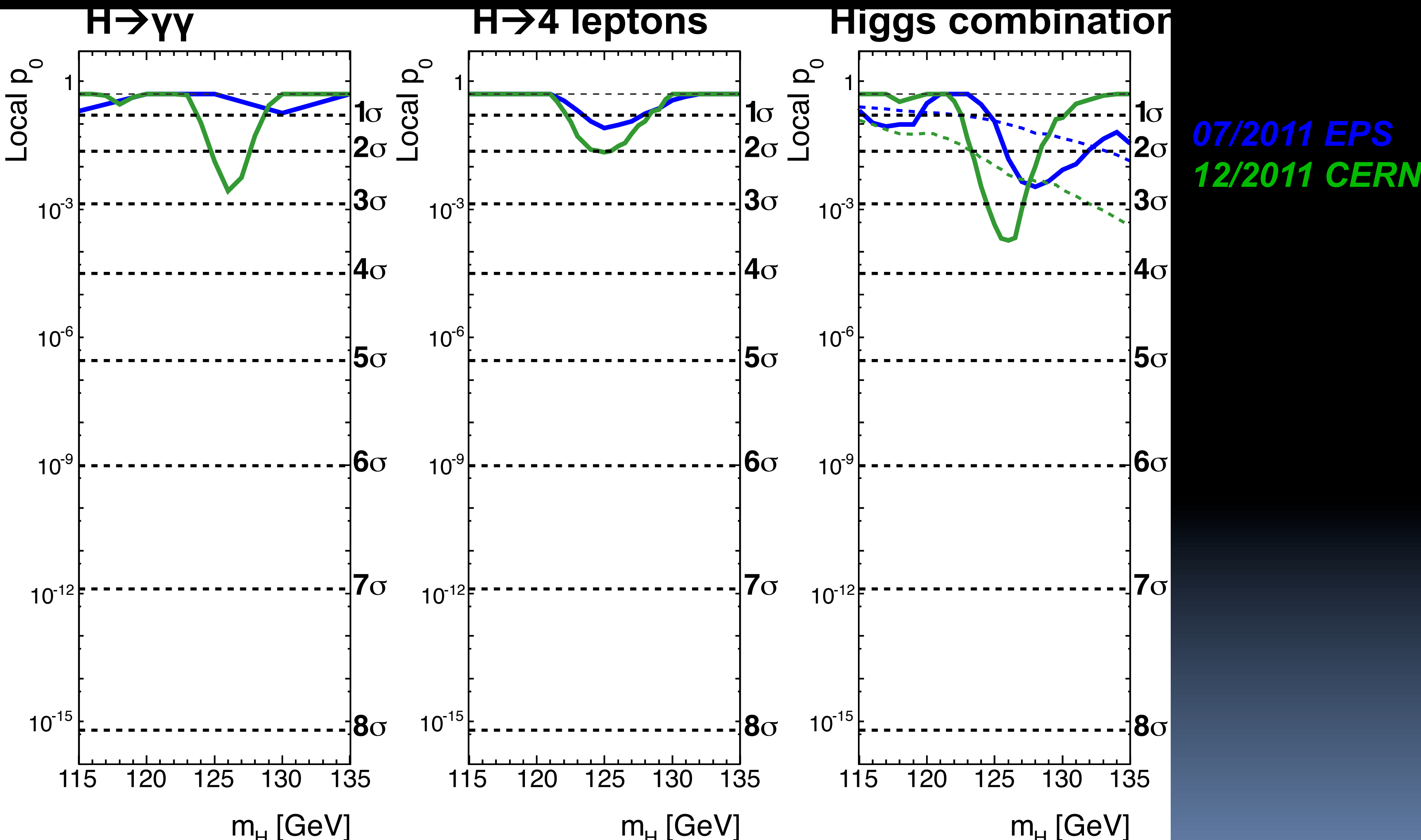
Local p_0: probability that the background fluctuates to the observed data (or higher)



From excess to discovery (ATLAS)

progressive significance(p0) plots

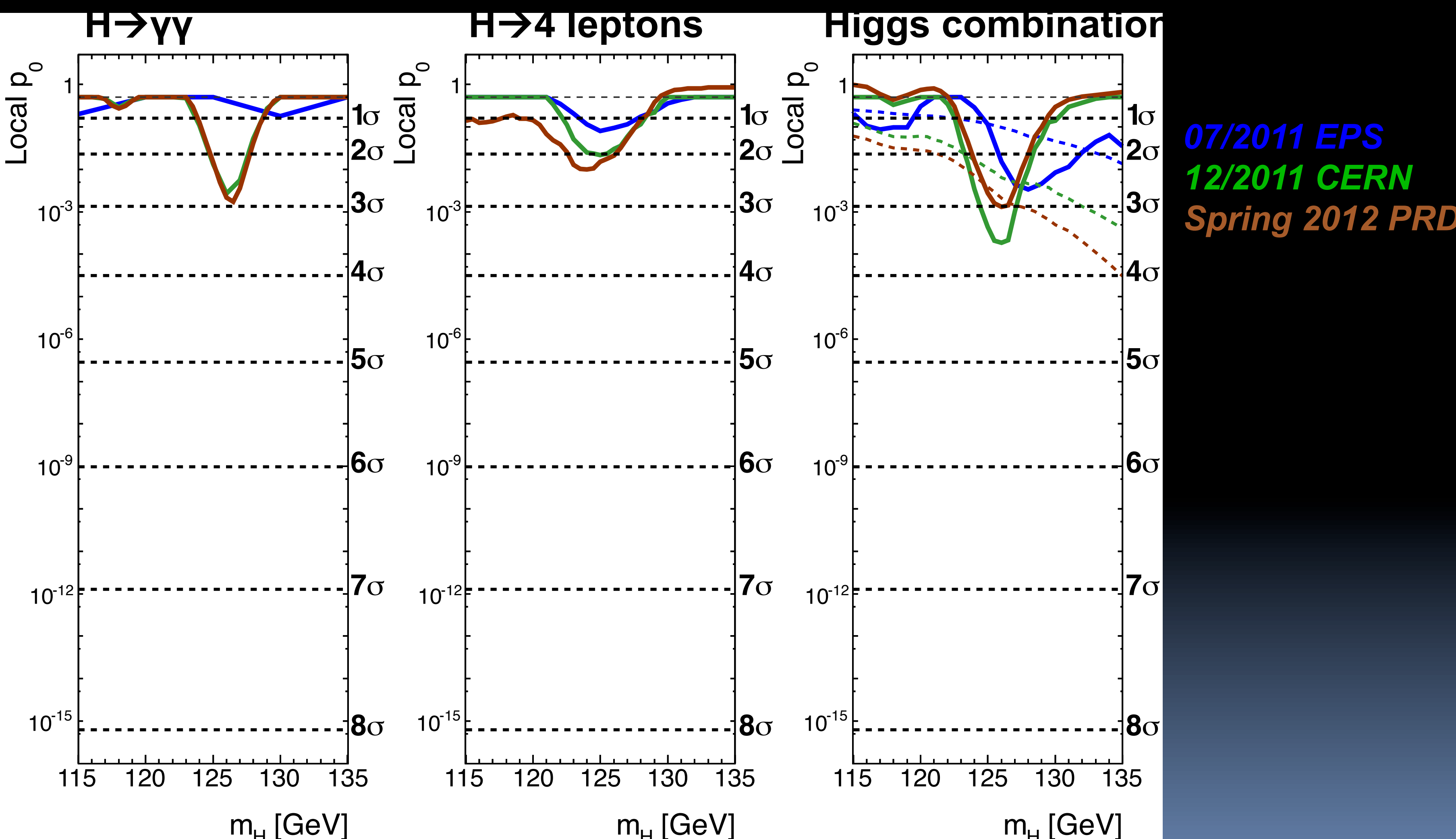
Local p_0: probability that the background fluctuates to the observed data (or higher)



From excess to discovery (ATLAS)

progressive significance(p0) plots

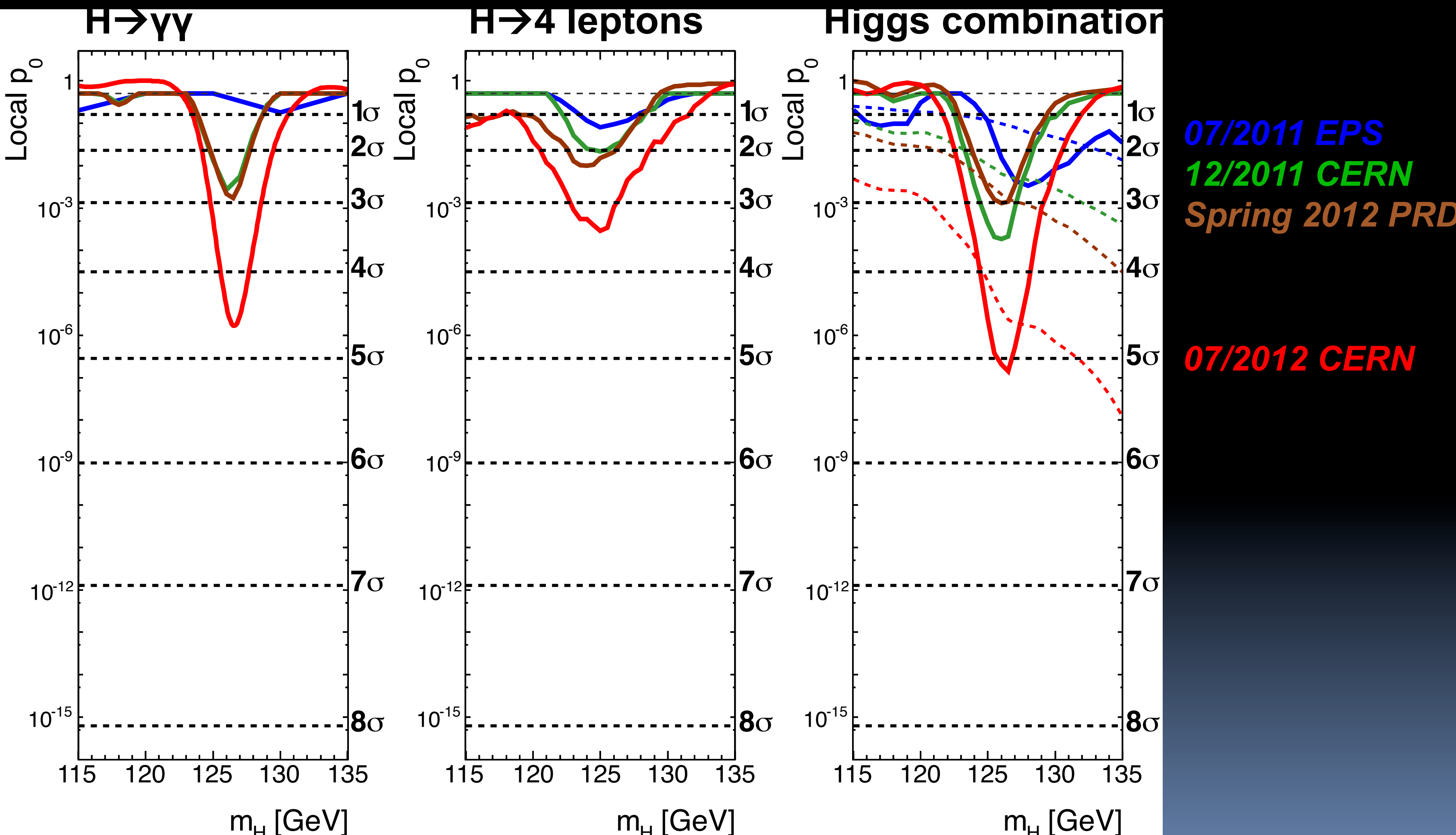
Local p_0: probability that the background fluctuates to the observed data (or higher)



From excess to discovery (ATLAS)

progressive significance(p0) plots

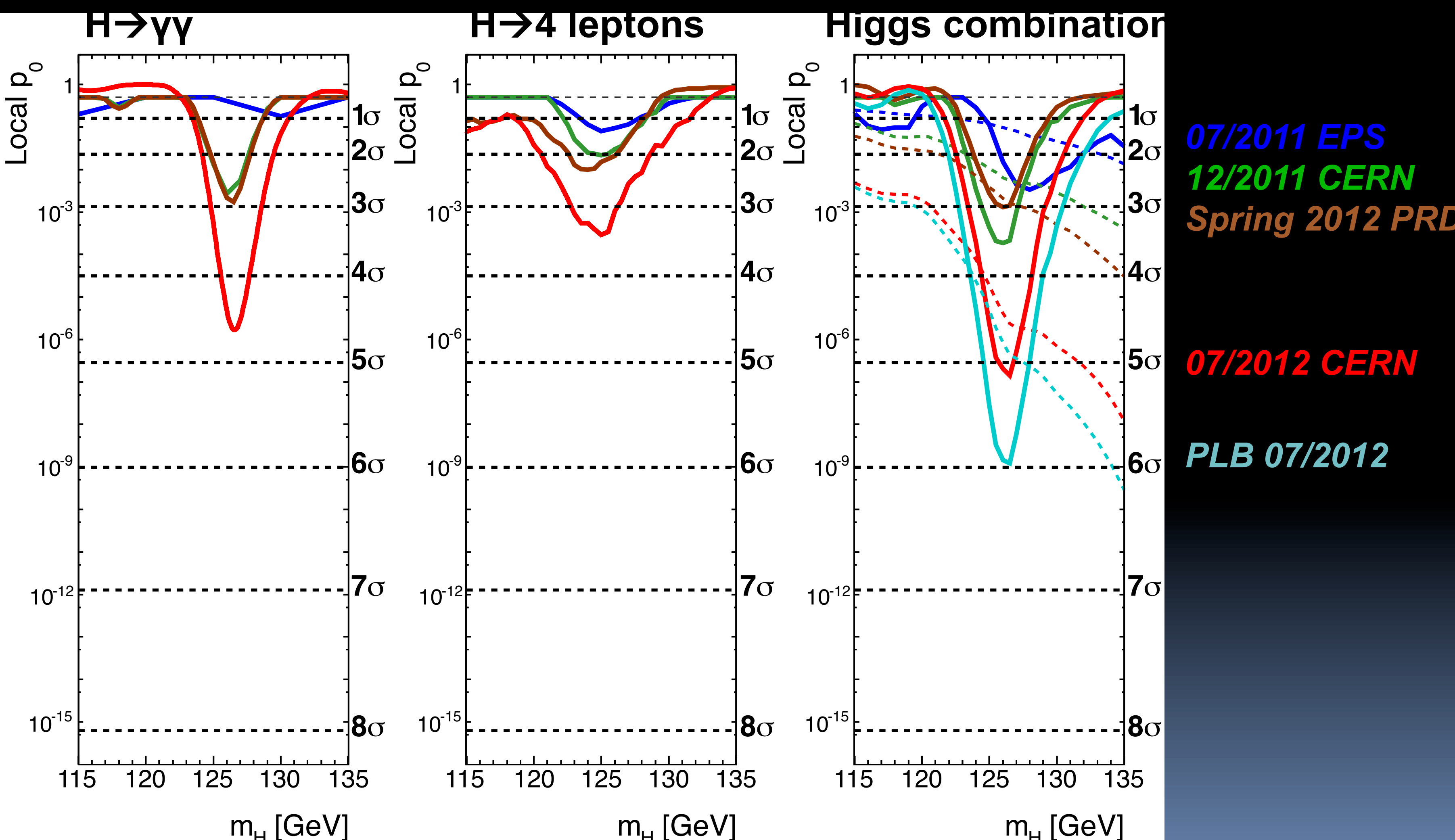
Local p_0: probability that the background fluctuates to the observed data (or higher)



From excess to discovery (ATLAS)

progressive significance(p0) plots

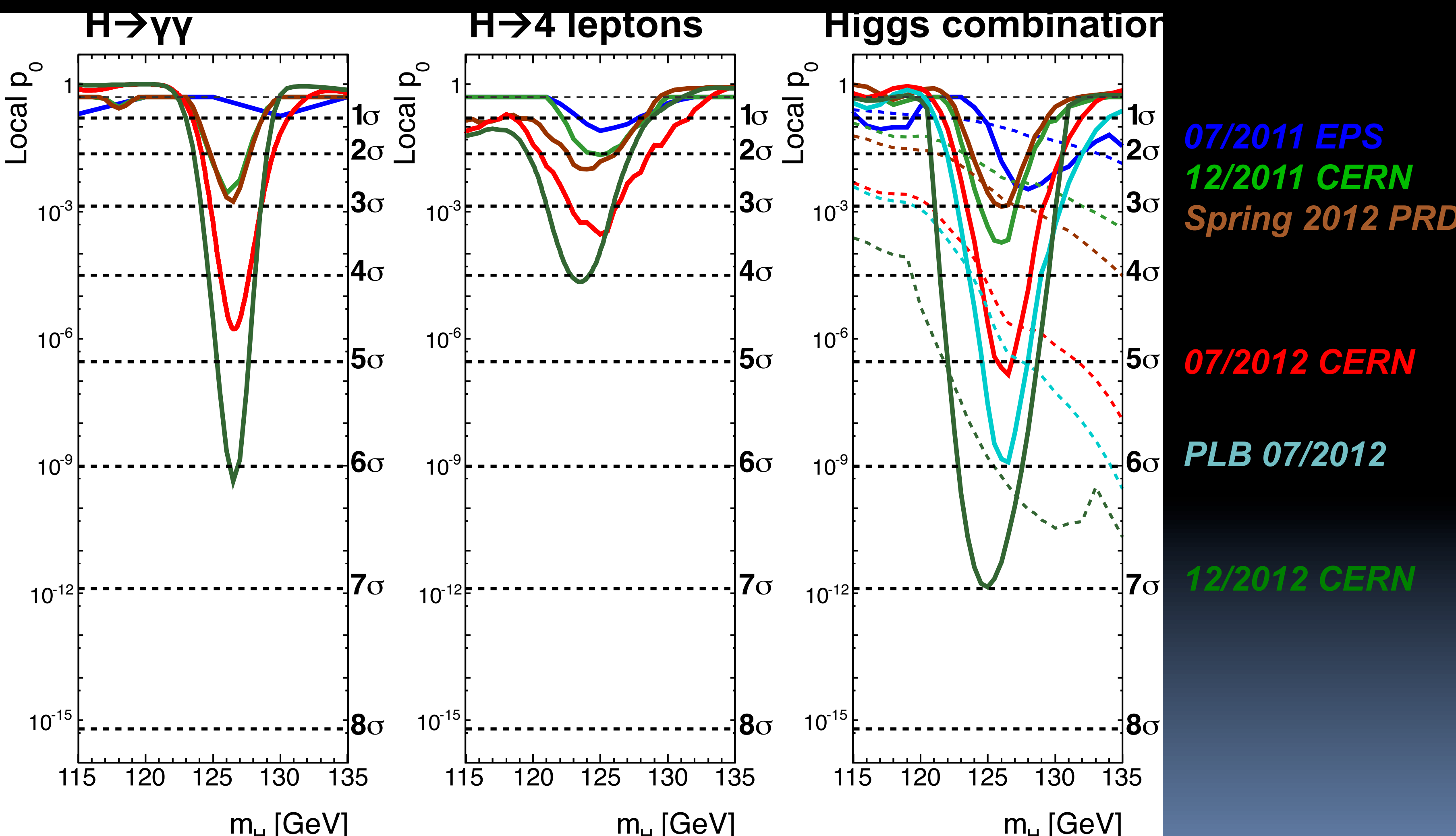
Local p_0: probability that the background fluctuates to the observed data (or higher)



From excess to discovery (ATLAS)

progressive significance(p0) plots

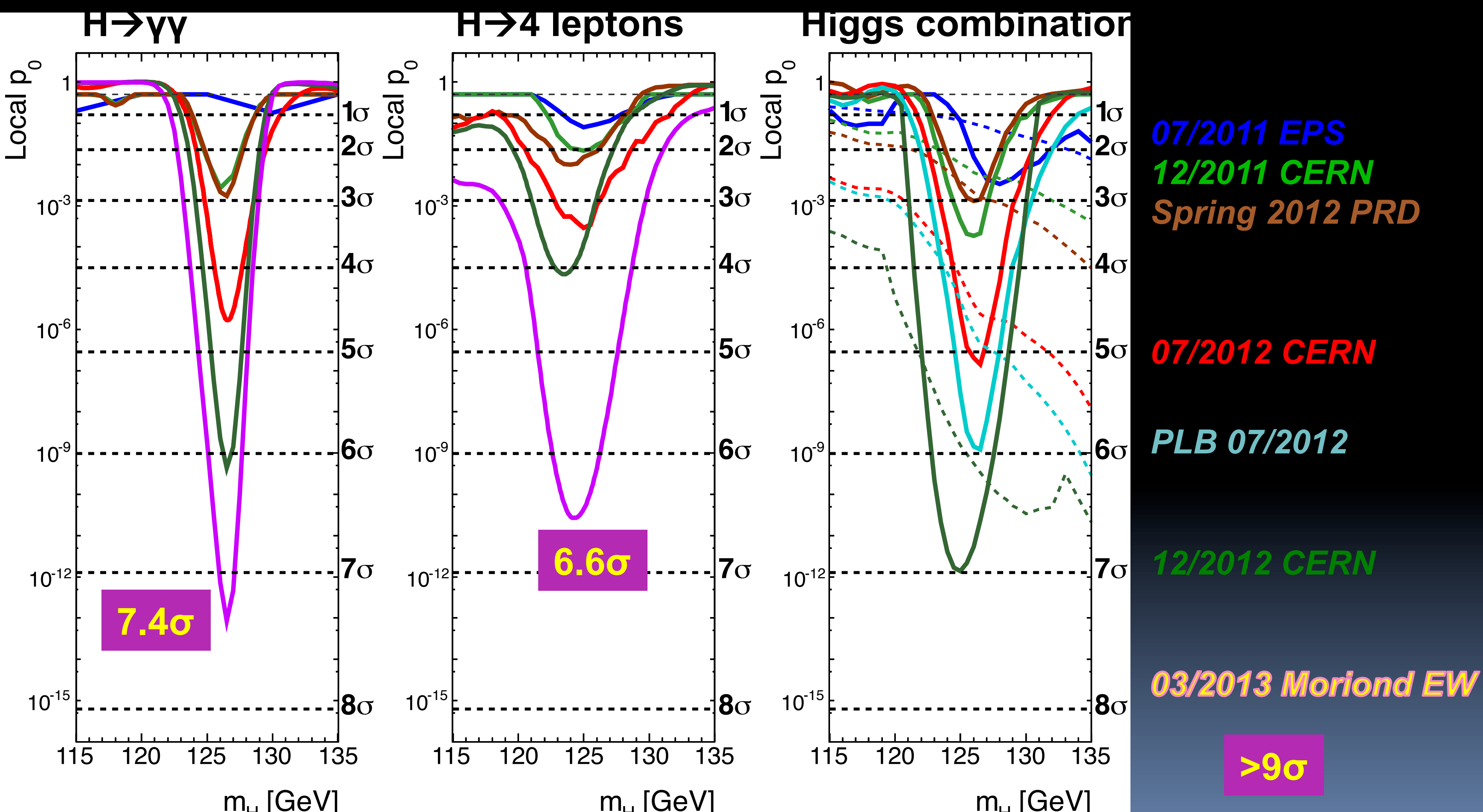
Local p_0: probability that the background fluctuates to the observed data (or higher)



From excess to discovery (ATLAS)

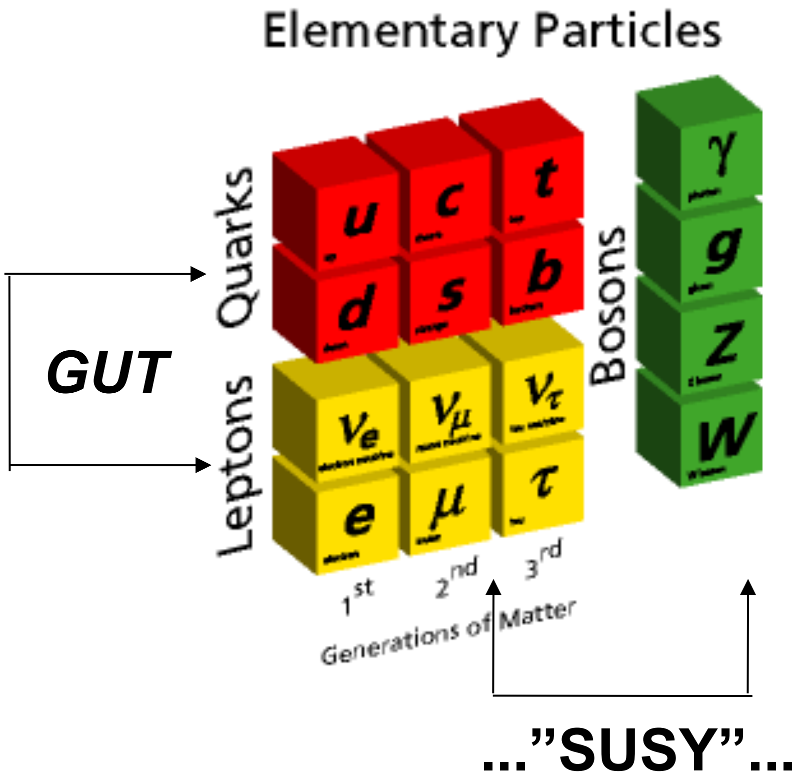
progressive significance(p0) plots

Local p_0: probability that the background fluctuates to the observed data (or higher)

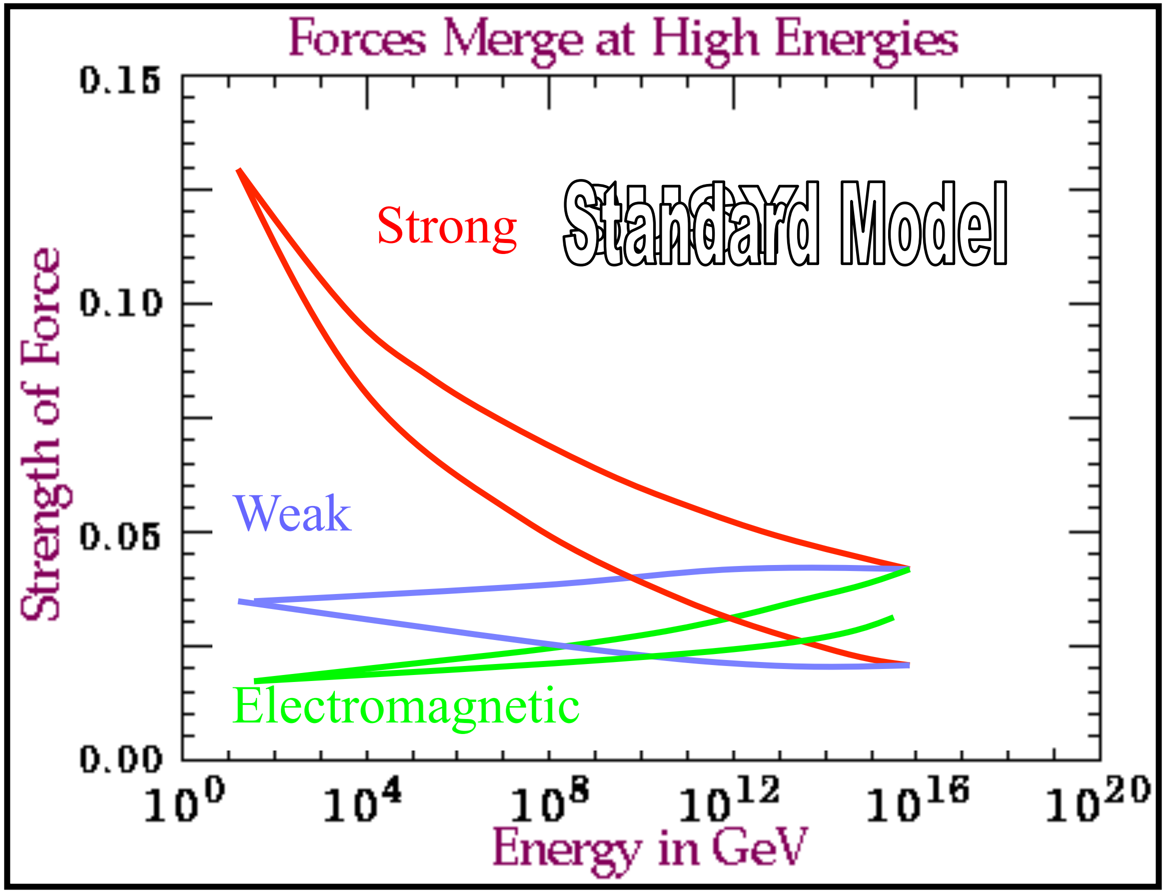


Grand Unification Theories (GUT) and SuperSymmetry (SUSY)

- Current data also hint at a unification between Strong and Electroweak forces … at much larger energies, GUT scale.
- GUT is a symmetry between Leptons and Quarks
  - unifies strong and electroweak forces
- SUSY unifies "matter and force particles": "matter-force duality"
  - relates particles of different spins: Fermions-Bosons (Susy does not really link
  - introduces super-partners to each SM particle the SM fermions and gauge bosons as illustrated in the figure; it predicts a superpartner for all SM particles)
  - requires 5 Higgs particles
  - provides DM candidate

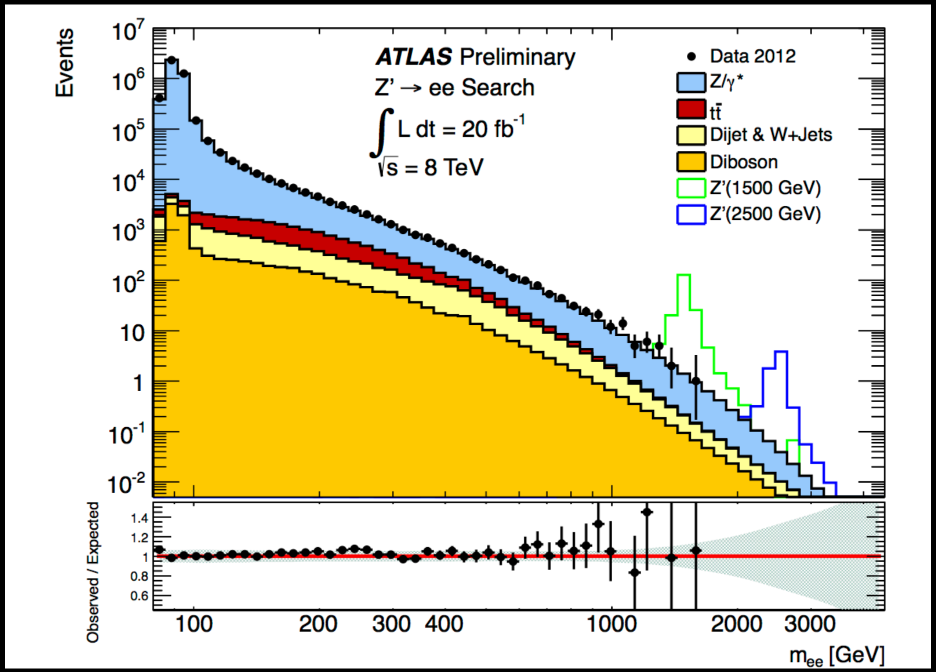


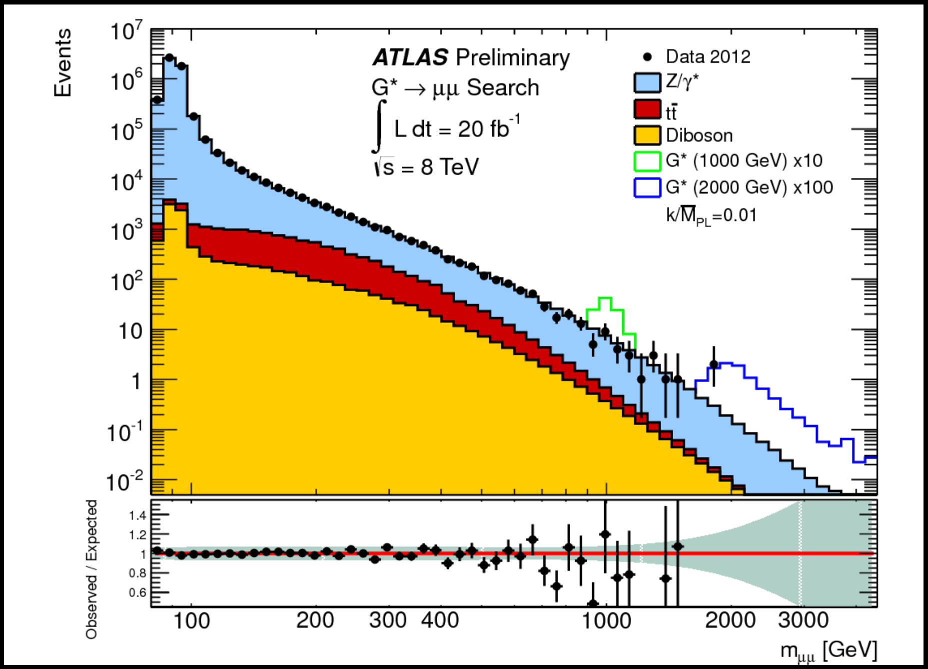
SUSY helps Grand Unification



Search for Di-lepton resonances (ee, μμ)

– New gauge bosons Z' – Graviton G*



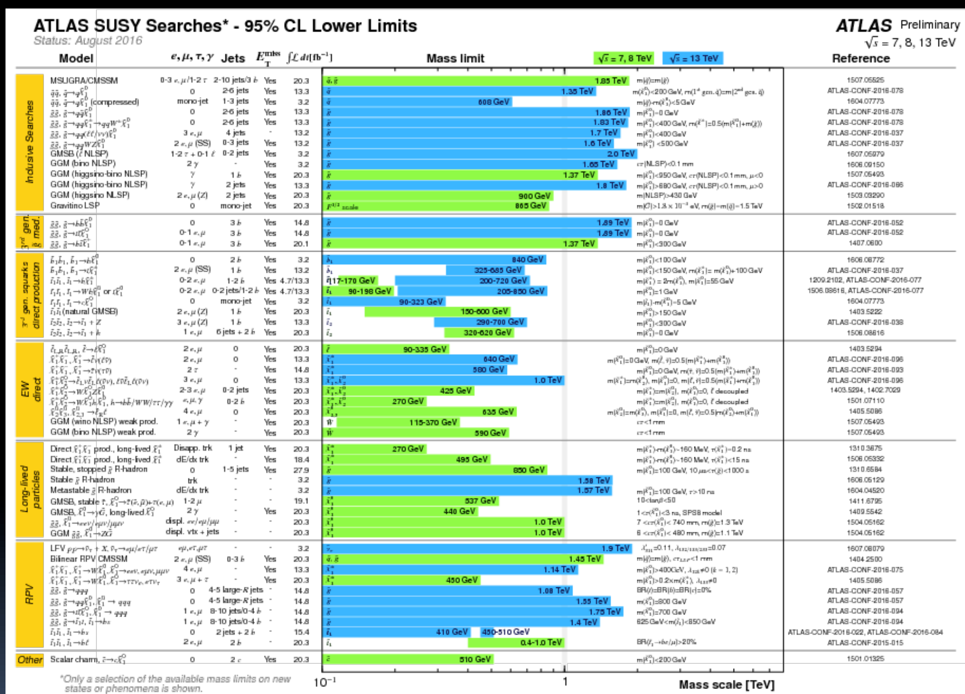


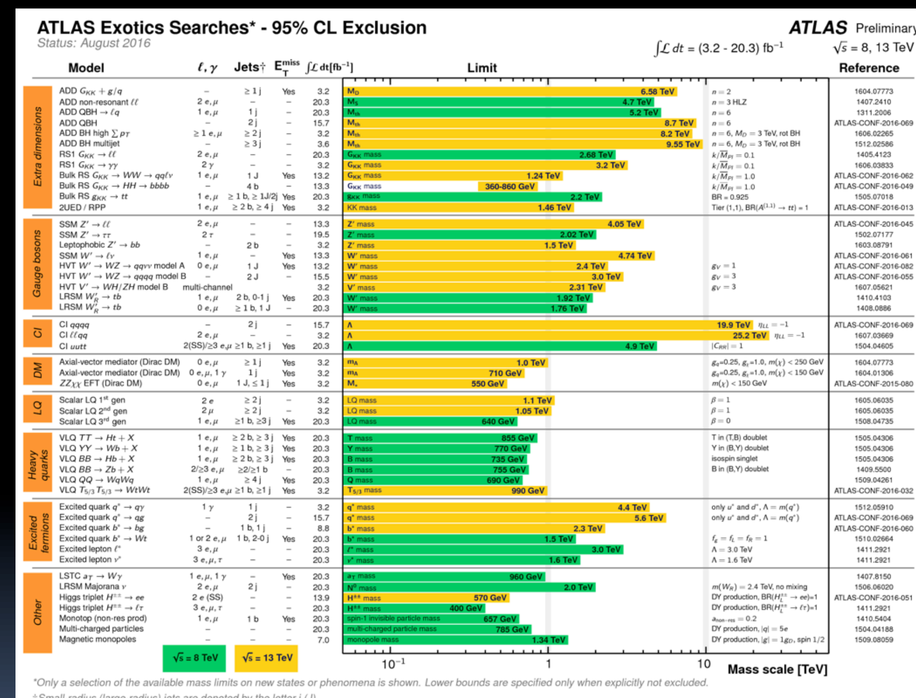
- Sequential SM
  - $M_{Z'} > 2.86$ TeV
- (Superstring) E_6-inspired models
  - $M_{Z'} > 2.38 – 2.54$ TeV

- Randall-Sundrum Graviton (extra space dimensions)
  - $M_{G*} > 2.47$ TeV

Physics of/beyond the Standard Model of EW+QCD

- Despite enormous gains in mass reach since the previous experiments, there is as yet no direct evidence for Supersymmetry or more exotic physics beyond the SM.

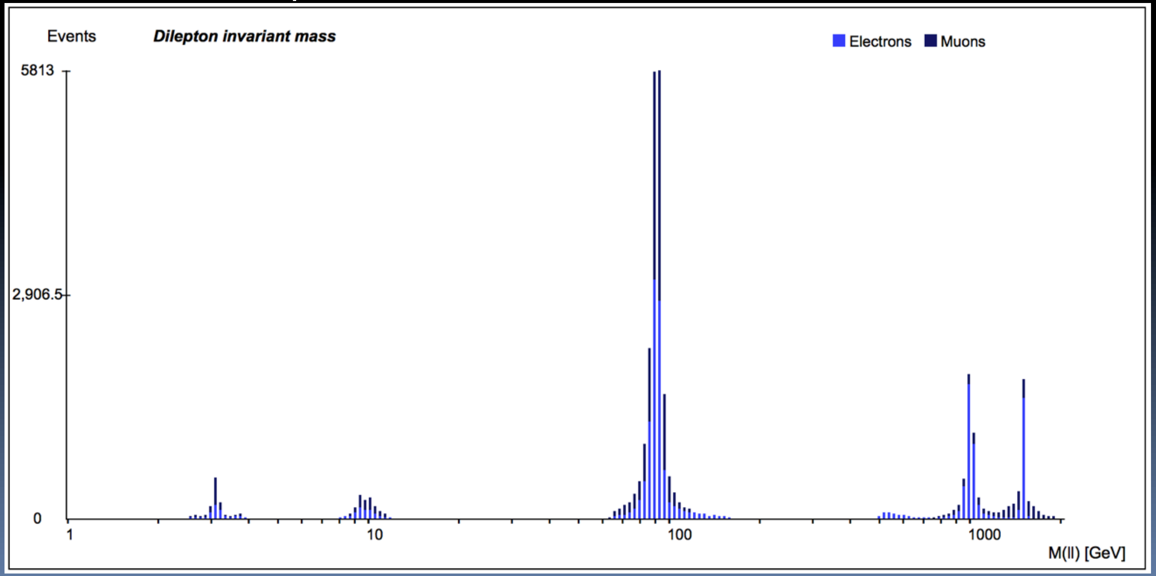




- However, we have collected only a few % of the data planned for the full LHC program ... stay tuned

Research-based education

- Sharing ATLAS data and discoveries with students
  - Masterclasses: high schools
  - Research-based student projects
- ZPATH [Z-Path]
  - most popular LHC educational material
  - Identify di-lepton, 4-lepton or di-photon final states.
  - Look for and study known (J/Psi, Upsilon, Z, Higgs)
  - Search for unknown particles (Z', Graviton) using the invariant mass concept




CERN Courier June 2014

Education

High-school students from all geographical regions master real event-display programmes, software tools and analysis methods. Having been introduced to the problem, they identify electrons, muons, photons and jets by exploiting their characteristic signals in various detector elements, perform event selection and categorization, and achieve the final analysis goals. (Image credits, left to right: Caroline Hamilton/CoEPP/University of Melbourne, Jayne Ion/iON creative, Franziska Viebach/TU Dresden.)

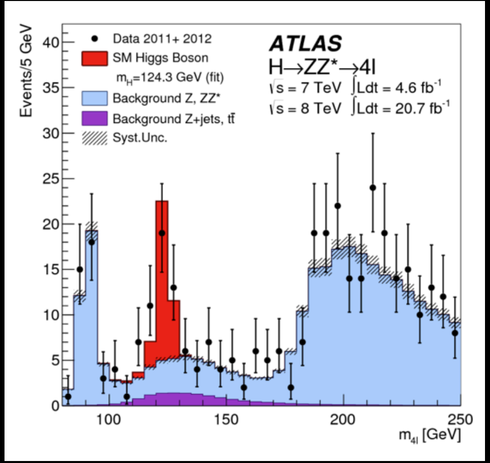
International Masterclasses in the LHC era

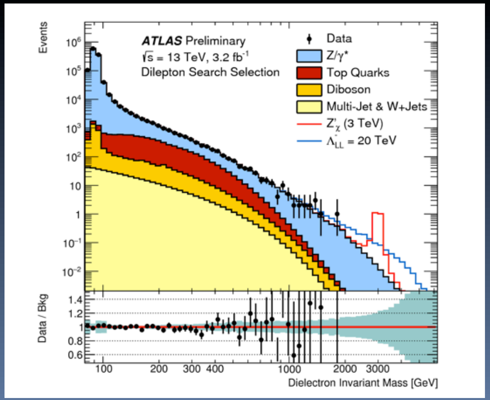
Each year in spring, the International Particle Physics Outreach Group organizes the International Masterclasses, which give students the opportunity to analyse data from the LHC.

The International Masterclasses (IMCs) began in 2005 as an ini-

ATLAS "discovery" data are available for students to search for a Higgs boson; CMS approved 13 Higgs candidates in the mass region of interest, which are mixed with a more abundant sample of W and Z events, for "treasure hunt" activities; ALICE data allow students to study the relative production of strange particles, which could be a tell-tale signal of quark–gluon plasma production; LHCb teaches students how to measure the lifetime of the D meson; and particles containing b and c quarks are studied extensively to shed light on the mystery of antimatter in the universe.

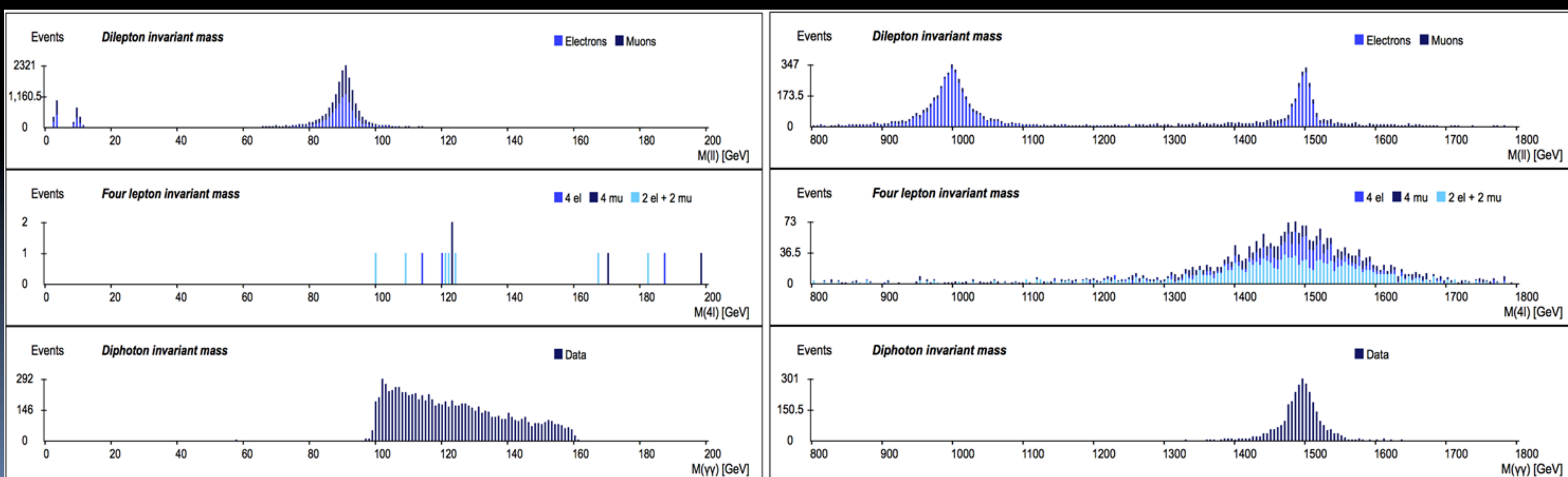
Students quickly master real event-display programmes – such





Follow the "heart beats" of LHC and bring the most recent discoveries and measurements to the students

- The Z-path and some of the accompanying tools
  - developed at Oslo and under constant development
- After Higgs discovery, Higgs boson part of Z-path
- In 2016, Graviton added …
  - In time with infamous 750 GeV di-photon excess observed in 2015
  - later proved to be only a statistical fluctuathe tion
- Supersymmetry and DM … ready



Students research-based project

- Olav Thon Foundation 2017
  - 1.5 MNOK research grant - 3y, Eirik, Magnar et al.
- Develop new courses based on measurements and discoveries at LHC and other research infrastructures.
- Further develop Z-path towards a standalone resource based on CERN data made public by experiments
  - use as support material by teachers and researchers
- Convey advanced physics concepts and phenomena and introduce new ideas beyond today's theoretical framework describing the content of the Universe and its evolution
- Interested?

Possibilities for Master Projects – High Energy Particle Physics

- Particle physics – measurement, analysis, interpretation – experiment & phenomenology
- Detector research & development
- Computing & software
- Research education

- *Possibilities for short and long stays at CERN, participation in measurements and data taking*

Searches for Dark Matter & new physics phenomena / symmetries

With the advent of higher energies and higher collision rates, the LHC continues the exciting voyage towards new physics phenomena, allowing physicists all over the world to explore a previously unknown territory full of promise.

The ambitious LHC physics programme may shed light on some of the greatest mysteries in physics today: (i) the nature of dark matter, and (ii) the behaviour of the gravitational force at the microscopic scale.

Symmetries play a crucial role in physics. Supersymmetry relates integer spin particles (bosons) and half-integer spin particles (fermions). It allows unification of the electroweak and strong interactions, proposes dark matter candidates, and predicts new Higgs bosons. Processes of interest involve superpartners of the leptons, of the gauge and Higgs boson, as well as a dark matter particle, which is predicted to be the lightest supersymmetric particle. The studies will include a search optimization, analysis of ATLAS data at 13 TeV and interpretation of results, making use of constraints from astrophysics and cosmology.

- *Prof. Farid Ould-Saada, FØ377, Farid.Ould-Saada@fys.uio.no*

Søk etter mørk materie i ATLAS eksperimentet på CERN.

Masterstudenten lage en analyse for å finne mørk materie signaler i ATLAS, enten ved å lete etter supersymmetri eller en mer generisk analyse. ATLAS får nye data i 2017-18. Studenten utvikler kunnskap bl. a. om partikkelfysikk, partikkeldetektorer, dataanalyse verktøy, programmering (C++, Root), statistikk. Studenten får anledning til kortere eller lengre utenlandsopphold ved CERN, f.eks. gjennom trening og/eller CERNs sommer skole.

- *Prof. Heidi Sandaker, FØ384, Heidi.Sandaker@fys.uio.no*

New fundamental Nature's fundamental forces

Do **new fundamental forces** show up at the LHC the way the Z and Higgs bosons did?

According to superstring theories, which propose to unify all fundamental forces, including gravity, there is room for new forces to be mediated by new gauge bosons, generically known as Z' and W'. A series of simplified models predict Dark Matter to couple to a variety of Z' bosons, including sometimes some new scalars.

This work consists in a detailed study and implementation into Monte Carlo generators of various theories beyond the Standard Model. This will be followed by an analysis of ATLAS data, taken at the highest available energies, a comparison to simulation data, and interpretation of the results.

- *Prof. Farid Ould-Saada, FØ377, Farid.Ould-Saada@fys.uio.no*

Gravity at the microscopic scale

Gravity as we know it is negligible at the subatomic level.
The addition of ***n*** space dimensions affect the behaviour of the gravitational force, changing from $1/r^2$ to $1/r^{(2+n)}$, thus enhancing its strength at very short distances ***r***.

A way to search for signatures of gravity at the LHC, and thus reveal the existence of microscopic space dimensions, is to look for graviton excitations and/or microscopic black holes.
Both would decay into SM particles, measurable in particle detectors. Advanced analysis and statistical methods are crucial to distinguish these new phenomena from competing standard as well as BSM processes.

- *Prof. Farid Ould-Saada, FØ377, Farid.Ould-Saada@fys.uio.no*

Model-independent searches for new physics

The various scenarios of new physics theories discussed above may show up in a given process at the LHC.
Model independent searches for new physics are proposed in final states with leptons recorded with the ATLAS detector.
New methods and tools involving neural networks and machine learning algorithms are to be used and optimized, using real data as well as Monte Carlo data based on various theoretical implementations, in order to correctly interpret any signal of new physics.

- *Prof. Farid Ould-Saada, FØ377, Farid.Ould-Saada@fys.uio.no*

Precision measurements of Higgs boson production in the decay channel to two photons in the ATLAS experiment at the LHC

Although the first measurements of the properties of the Higgs boson discovered at CERN in 2012 are consistent with the Standard Model, the uncertainties are large and there are many physically motivated models that would give small deviations from the Standard Model predictions. MSc projects in this activity include (a) the study of robust statistical models for the data-driven estimation of the background under the Higgs boson signal peak in the two-photon mass spectrum, (b) development of a new method to optimize the use of compute-intensive detailed simulations of the detector, (c) search for additional mass peaks below and far above the established mass peak at 125 GeV, (d) precision measurement of the Higgs boson mass, and (e) measurement of the transverse momentum spectrum of the Higgs boson. You will work with data taken during the 2015-18 runs of the LHC at 13 TeV, nearly twice the center of mass energy during 2011-12 (7 and 8 TeV). You will join the Hgamma working group in ATLAS, participate in the ongoing development of the data analysis strategies and code, learn, further develop and apply advanced statistical techniques, and, thus, contribute to furthering our understanding of the Brout-Englert-Higgs (mass-generating) mechanism and test whether there is new physics beyond the Standard Model (such as dark matter).

- *Prof. Alex Read, FØ381, a.l.read@fys.uio.no*

Developmet of pixel detectors for the upgrade of ATLAS

Når LHC blir oppgradert til høyere intensitet må mange av detektorene i ATLAS byttes. I Norge deltar vi i utviklingen av pixel detektorer og vi får nye sensorer sommeren 2017 som skal bygges til moduler og testes.

Studenten kan velge mellom følgende oppgaver:

- Sett opp og test et lasermålesystem for å karakterisere nye pixel sensorer;
- Delta i ATLAS-testbeam på CERN og bidra til analyse av testbeam-data;
- Videreutvikle en metode (basert på Compressed Sensing) for 3-D målinger av pixel sensorer;
- Karakterisering av nye tynne 3-D pixel sensorer produsert av SINTEF og bygging av detektor-moduler.

Studentene utvikler kunnskap om detektorutvikling, sensorutvikling i samarbeid med SINTEF, silisumdetektorer, dataanalyseverktøy, elektronikk. Studentene får anledning til kortere eller lengre utenlandsopphold ved CERN, f.eks. gjennom CERNs sommer skole, trening og testbeam aktiviteter.

- *Prof. Heidi Sandaker, FØ384, Heidi.Sandaker@fys.uio.no*
- *Prof. Alex Read, FØ381, a.l.read@fys.uio.no*

Path for education, research & discovery

The ambition to bring to the "classrooms" important LHC discoveries is realized using the discovery of the Higgs boson in 2012. Approximately 10% of the ATLAS discovery data were made available for students to search themselves for the Higgs boson. Promises of new discoveries in the 13 TeV LHC era and opportunities offered by the CERN open data have triggered new educational materials. We have room for 2 students to work on development of educational material based on new high energy particle physics research data and possible coming discoveries. We target high school as well as university students, including bachelor, master and PhD levels.

These educational materials follow the LHC 'heartbeats' and have the ambition to influence textbooks and teaching methods. This work is supported by the Thon Foundation (https://www.facebook.com/fysikk/posts/1276286769120085). We work in close contact with the International Particle Physics Outreach and the ATLAS collaborations.

- *Prof. Farid Ould-Saada, FØ377, Farid.Ould-Saada@fys.uio.no*

Computing & Software at the Exascale

Computing and software at the Exascale are crucial parts of the LHC physics experiments. The NorduGrid Advanced Resource Connector (ARC) middleware increases in popularity due its simplistic design and ease of deployment. This makes it the preferred choice of middleware for new and many existing sites particularly in Europe and Asia. ARC and its Control Tower allow seamless access to heterogeneous resources: Grid, High Performance Computers and Clouds. Moreover, ATLAS@home, based on BOINC and ARC, allow to access opportunistic resources made of personal computers.

We propose master thesis subjects on development of new computing software tools, distributed data management systems, and data models that will address the challenges of future LHC extreme conditions. This involves various aspects of software development including modern techniques making use of machine learning and anomaly detection. The importance of Multi-variate analysis or "Machine Learning" in High Energy Physics continues to increase, for applications as diverse as reconstruction, physics analysis, data quality monitoring and distributed computing.

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Anne-Marthe Hovda
Clara B. Salucci
Jürgen Pfingstner
Rune Sivertsen