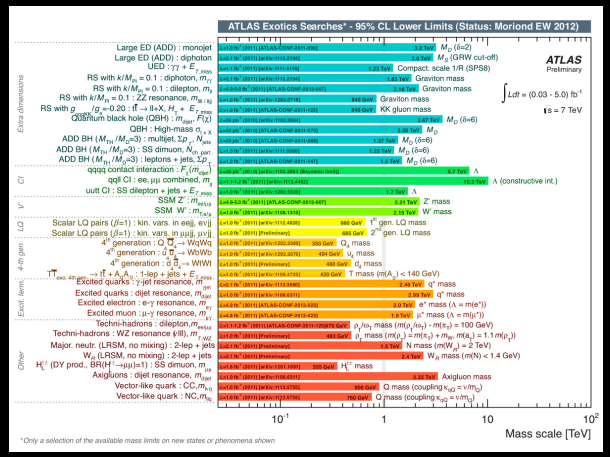
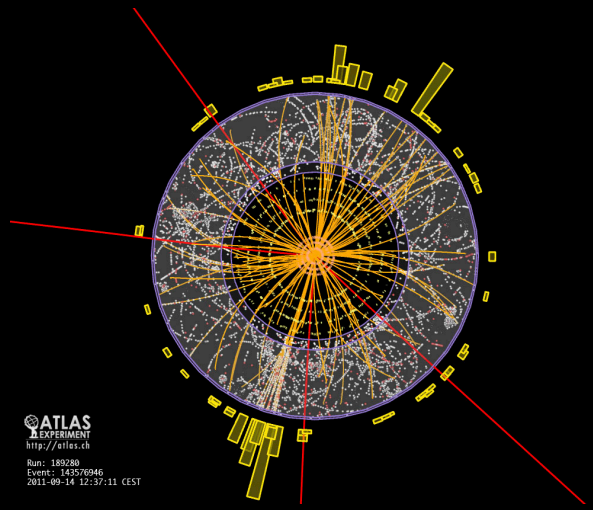




High Energy Particle Physics and the ATLAS experiment at LHC

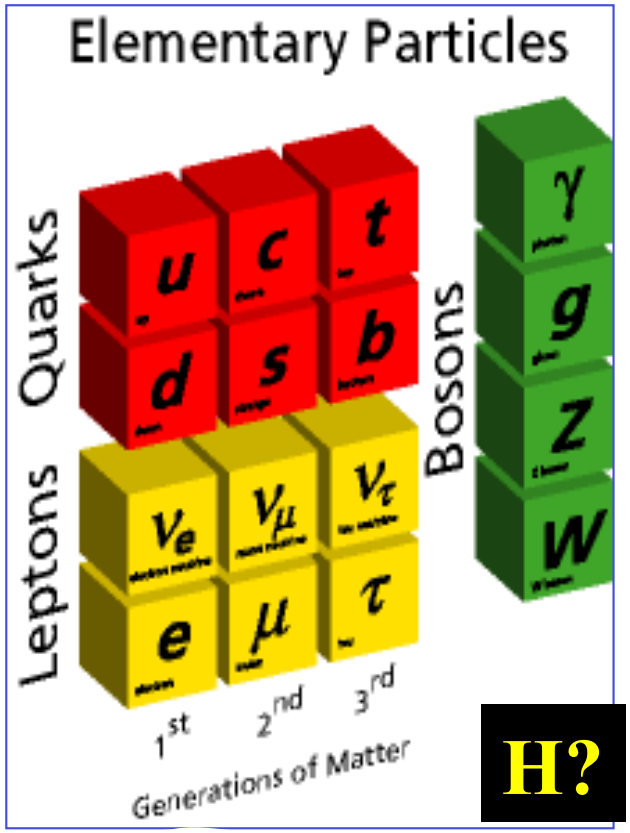
TeV scale Physics

FYS3510 CERN visit March 29th 2012

Why the Large Hadron Collider?

We need an instrument to

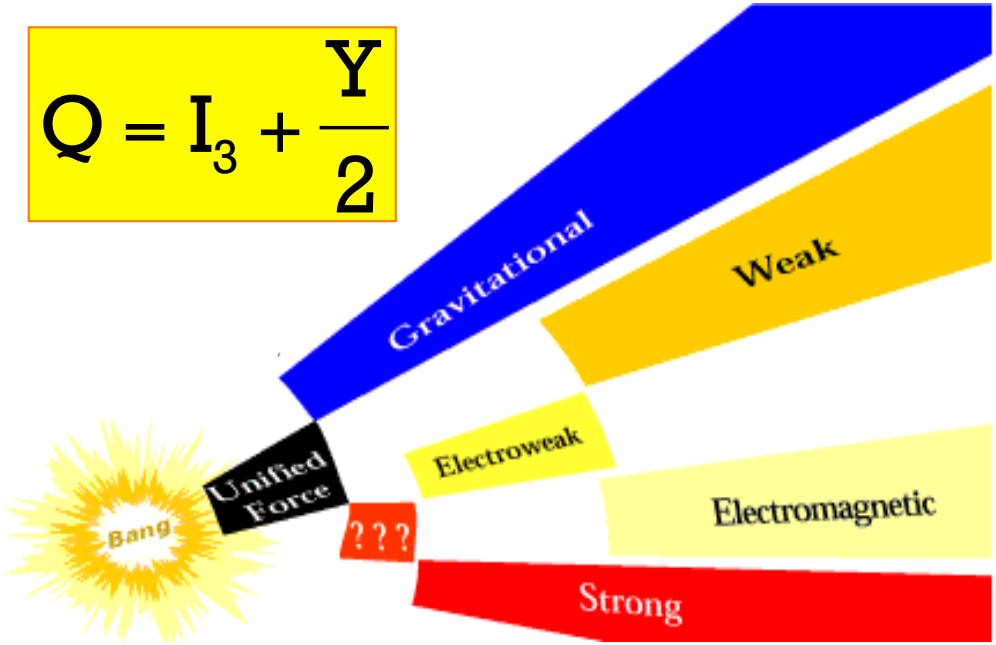
- study Nature's smallest constituents (particles) and their interactions
- reproduce the conditions that prevailed just after the Big Bang
- learn about the early Universe and its evolution



- All forces in nature obey a form of 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 have mass) … at high energies
describes (almost) all current particle physics data

$$Q = I_3 + \frac{Y}{2}$$



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 … Maybe being discovered…

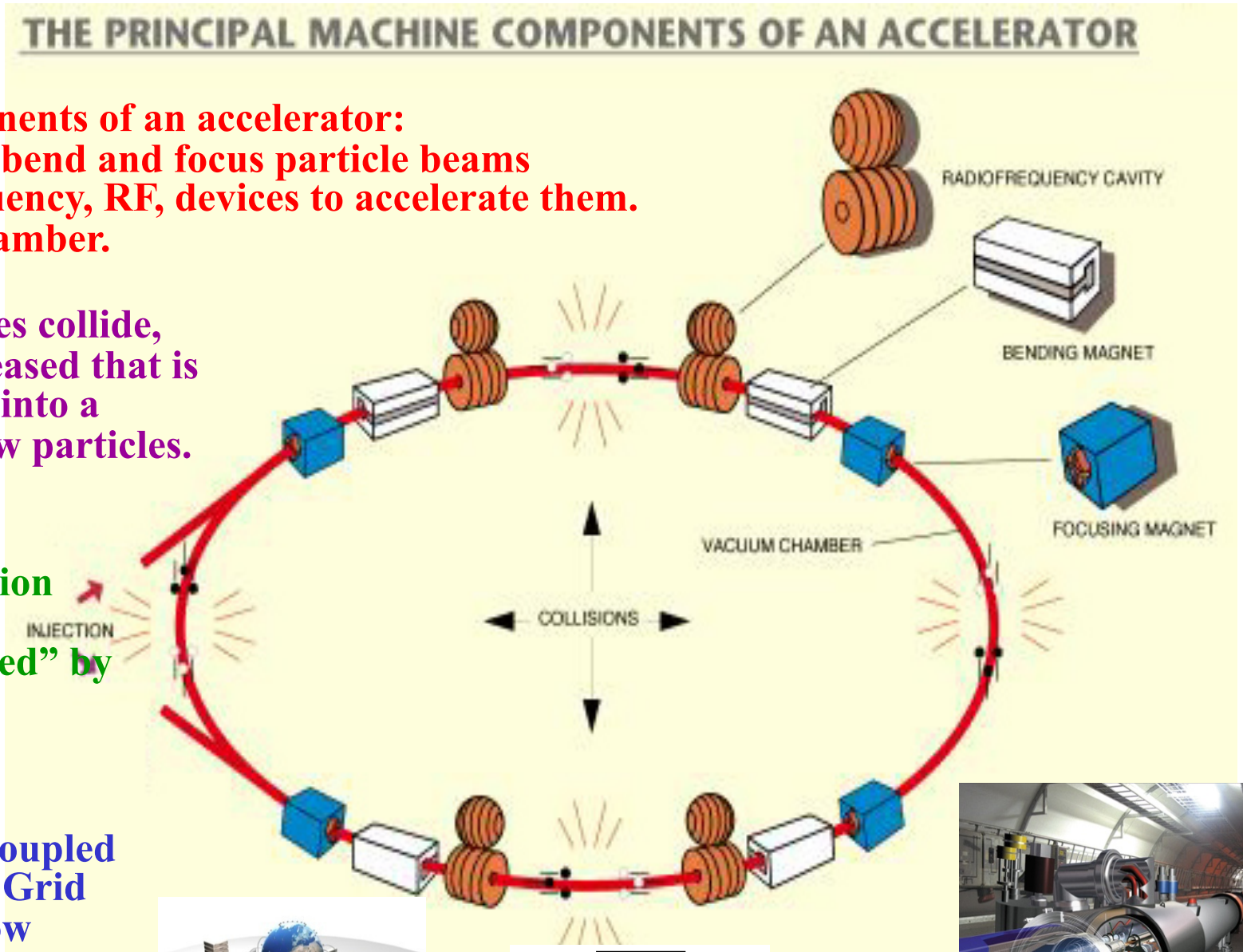
A “time travel” microscope

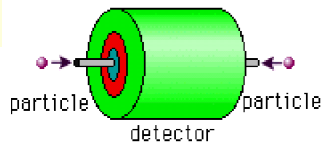
→ Main Components of an accelerator:
- Magnets to bend and focus particle beams
- Radio frequency, RF, devices to accelerate them.
- Vacuum chamber.

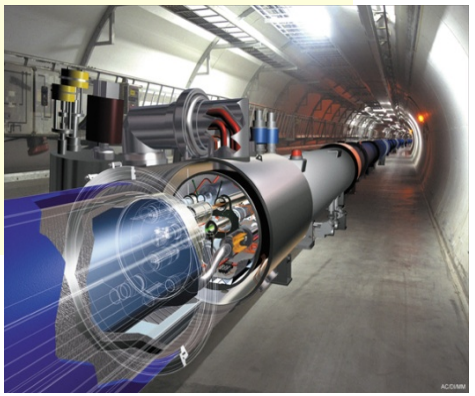
→ When particles collide, energy is released that is transformed into a shower of new particles.

→ Particle collision products are “photographed” by Detectors

→ Computers, coupled together in a Grid network, allow physicists to have access to information from each collision



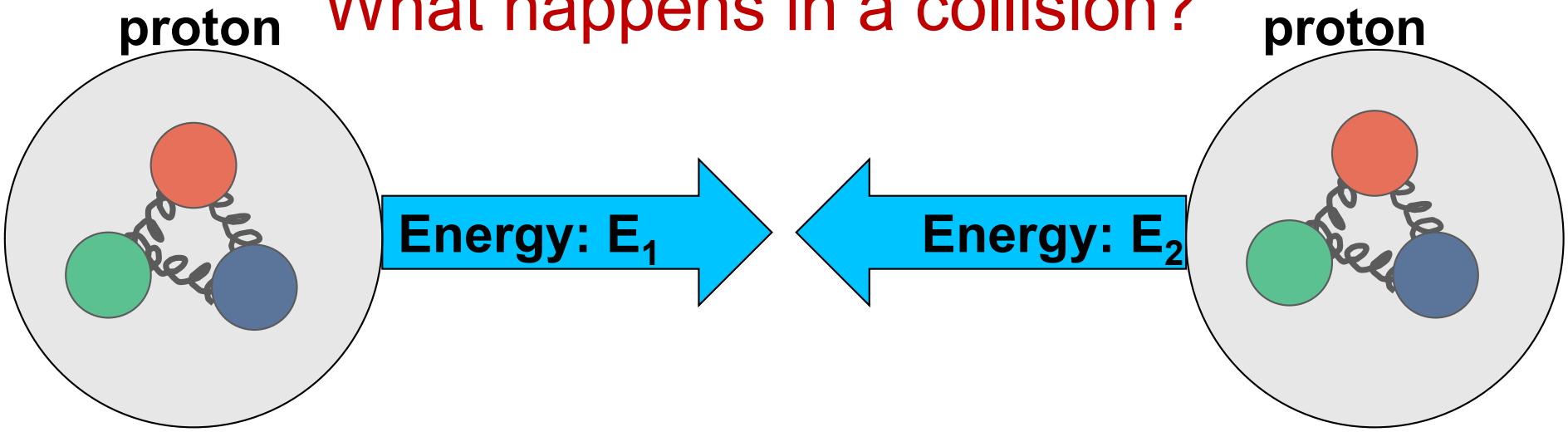




Large Hadron Collider

- 27km in circumference, 100 m underground
- proton bunches with 1000 billion protons circulate nearly at the speed of light :
  - v=0.99999991 c
- proton bunches collide every 25 / 50 ns:
  - 100μs per round … 10 000 rounds per second
- energy released enables creation of new particles

What happens in a collision?



The energy of each proton is:

$$E = \sqrt{m_0^2 c^4 + \vec{p}^2 c^2}$$

p **is the momentum**

- **the faster the particle the higher its momentum**

c **is the speed of light**

Einstein´s equation says

$$E = mc^2$$

… this means that …

Before collision

$$E_{total} = E_{proton1} + E_{proton2} = 2E$$

proton

proton

Energy: E_1

Energy: E_2

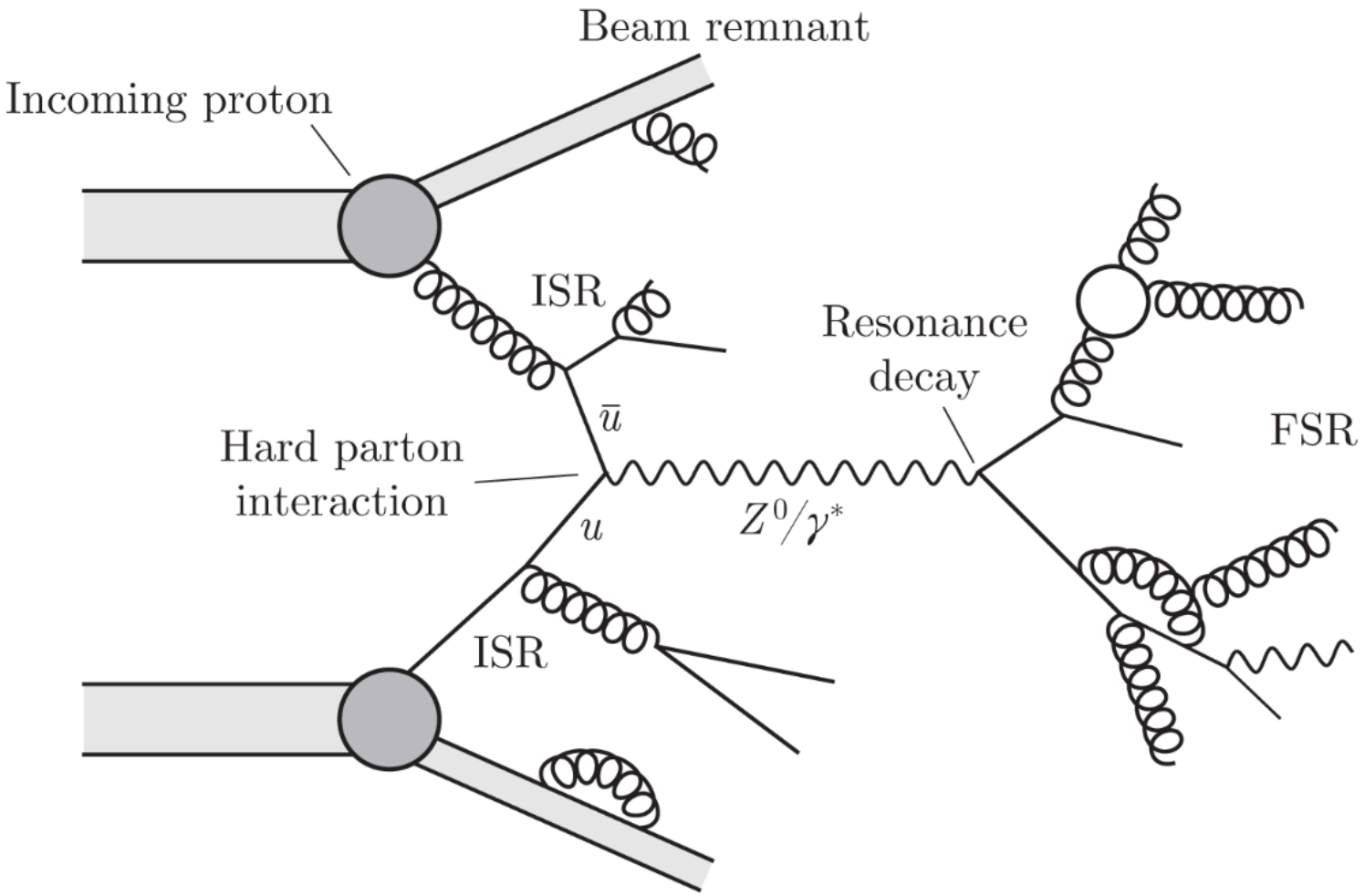
After collision

$$2E \rightarrow m$$

…new particles – known and unknown – are created from energy

… the higher the energy, the higher the probability to produce massive particles

In reality only a fraction of the pp energy is available to produce "new" particles



Complementary role of collisions with various beams:
- e+e-
- ep
- pp
- ppbar
- nuN
- nue …

- **Once good energy budget … give a chance to rare processes …**

Number of collisions
$N = L \cdot \sigma(pp \rightarrow X)$

Luminosity L

$$L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y}$$

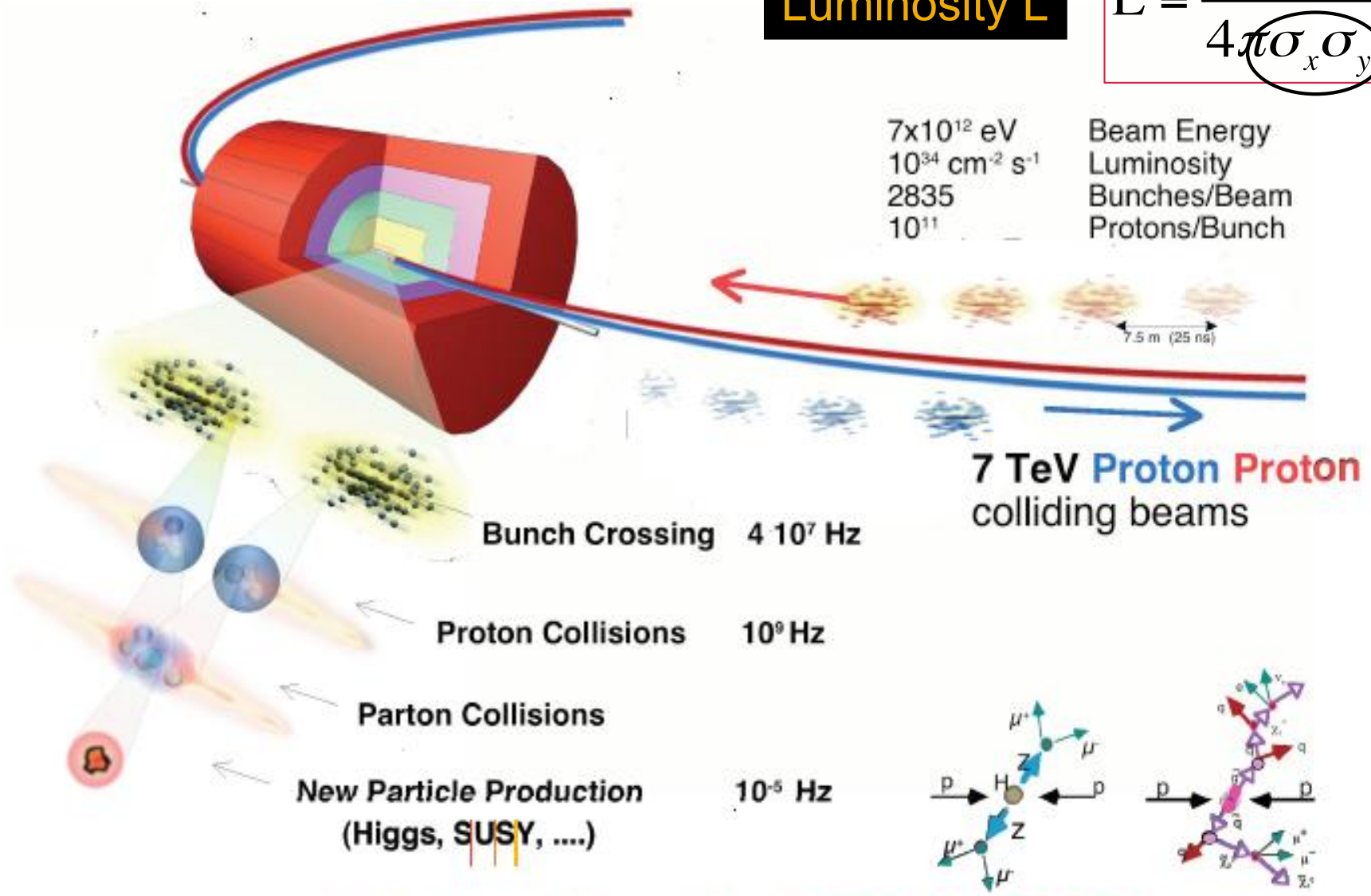
n. of protons per bunch

n. of bunches

n. of turns per second

beam size at IP ($\sigma_{x,y}$ = 16 μm)

7×10^{12} eV	Beam Energy
10^{34} cm^{-2} s^{-1}	Luminosity
2835	Bunches/Beam
10^{11}	Protons/Bunch



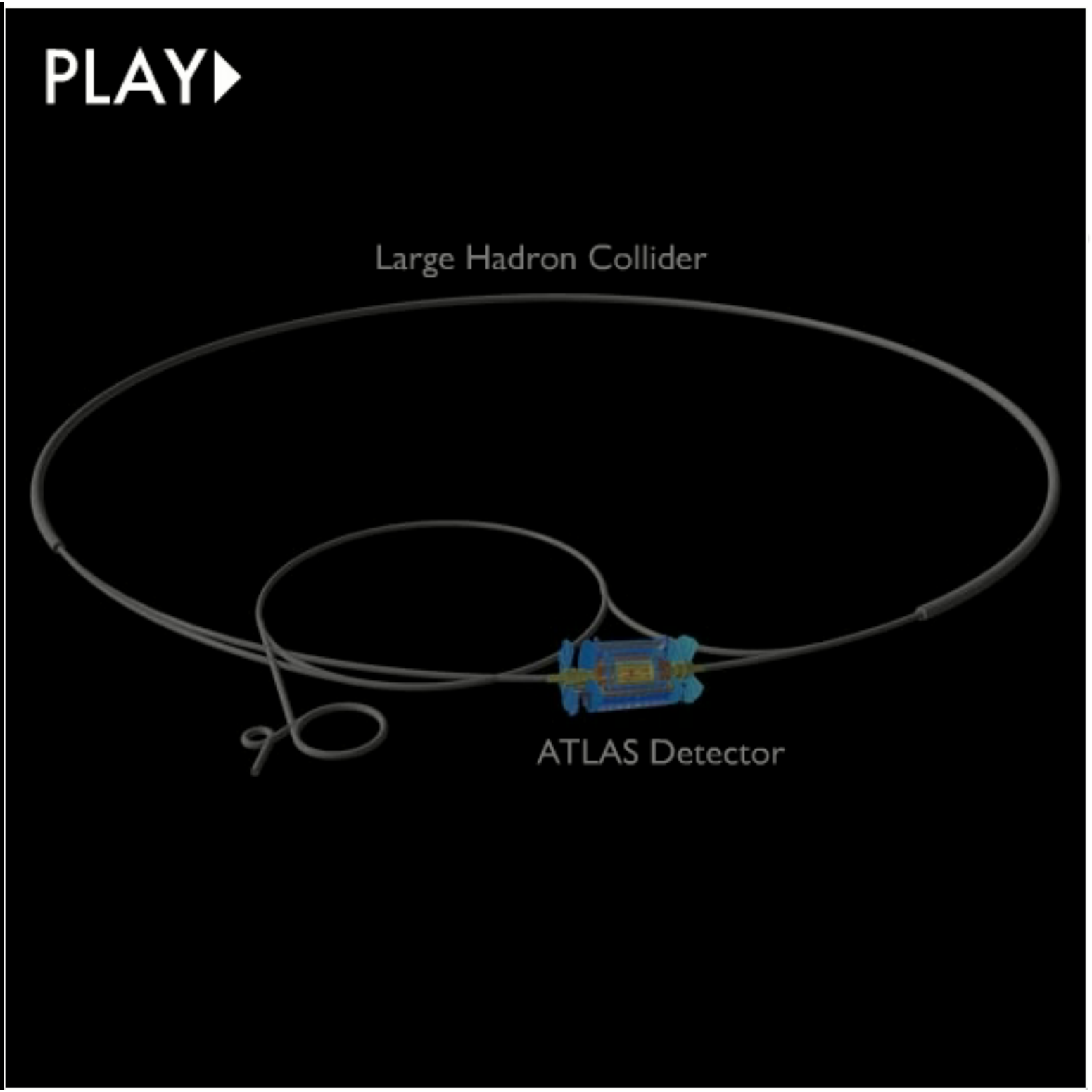
σ

Very small for new processes

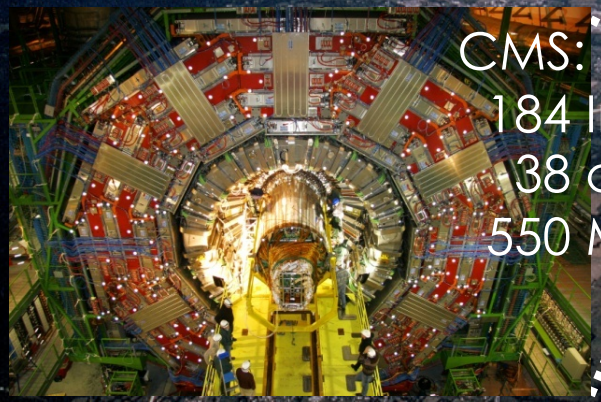
Selection of 1 event in 10,000,000,000,000

What happens?

- Collision at LHC
- Simulated black hole event



4 large experiments at LHC

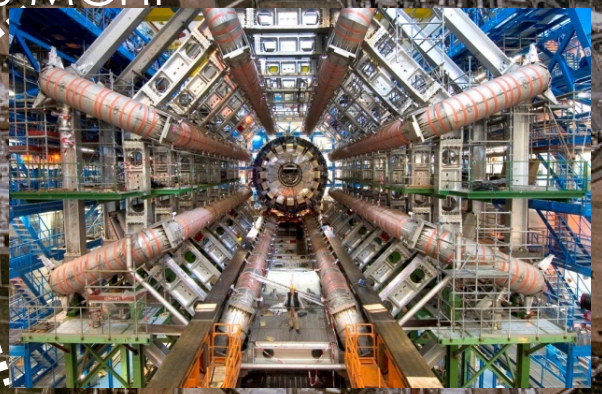


CMS: 2900 physicists
184 Institutions
38 countries
550 MCHF

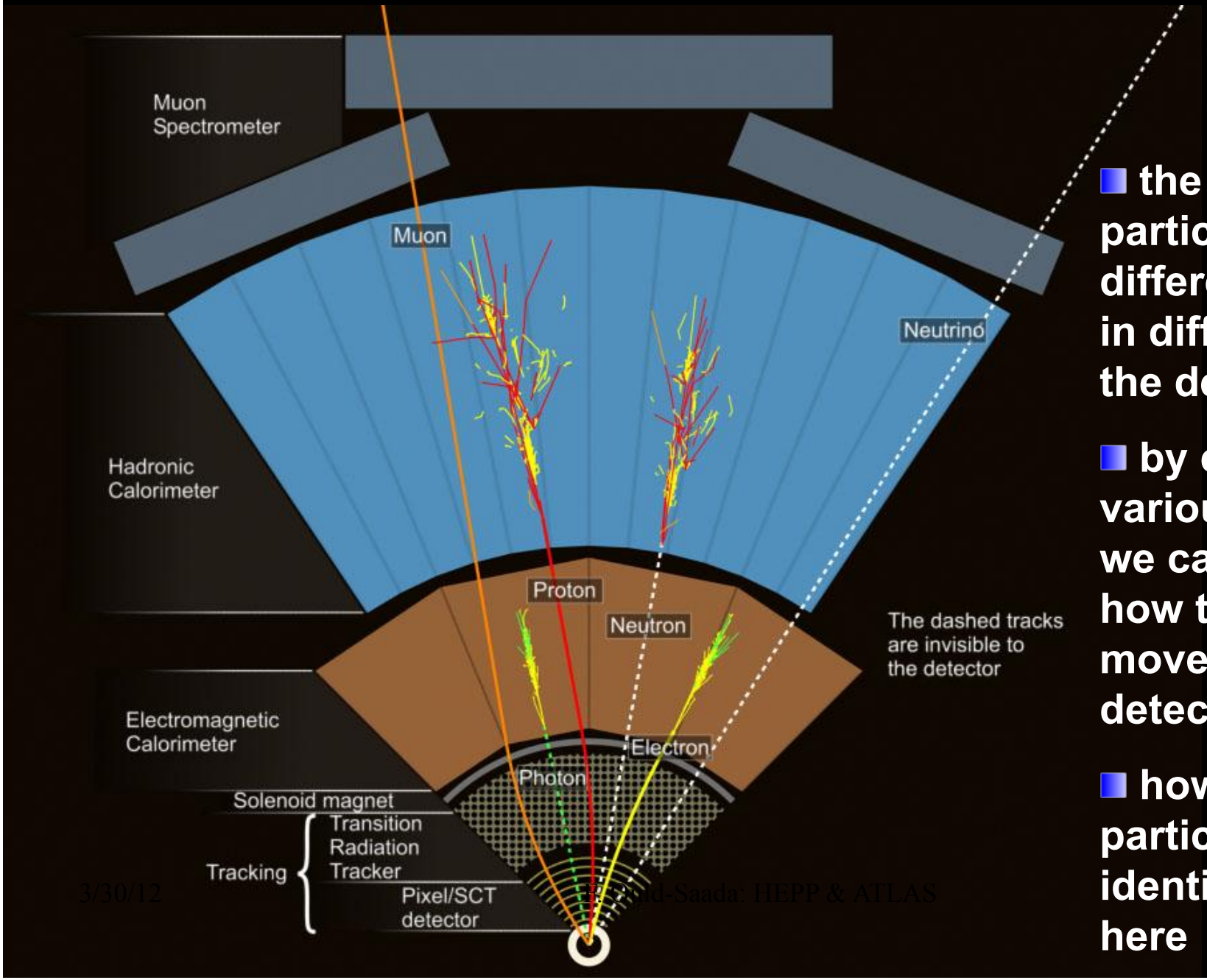
LHCB 700 physicists
52 Institutions
15 countries
75 MCHF

ALICE; 1000 physicists
105 Institutions
30 countries
150 MCHF

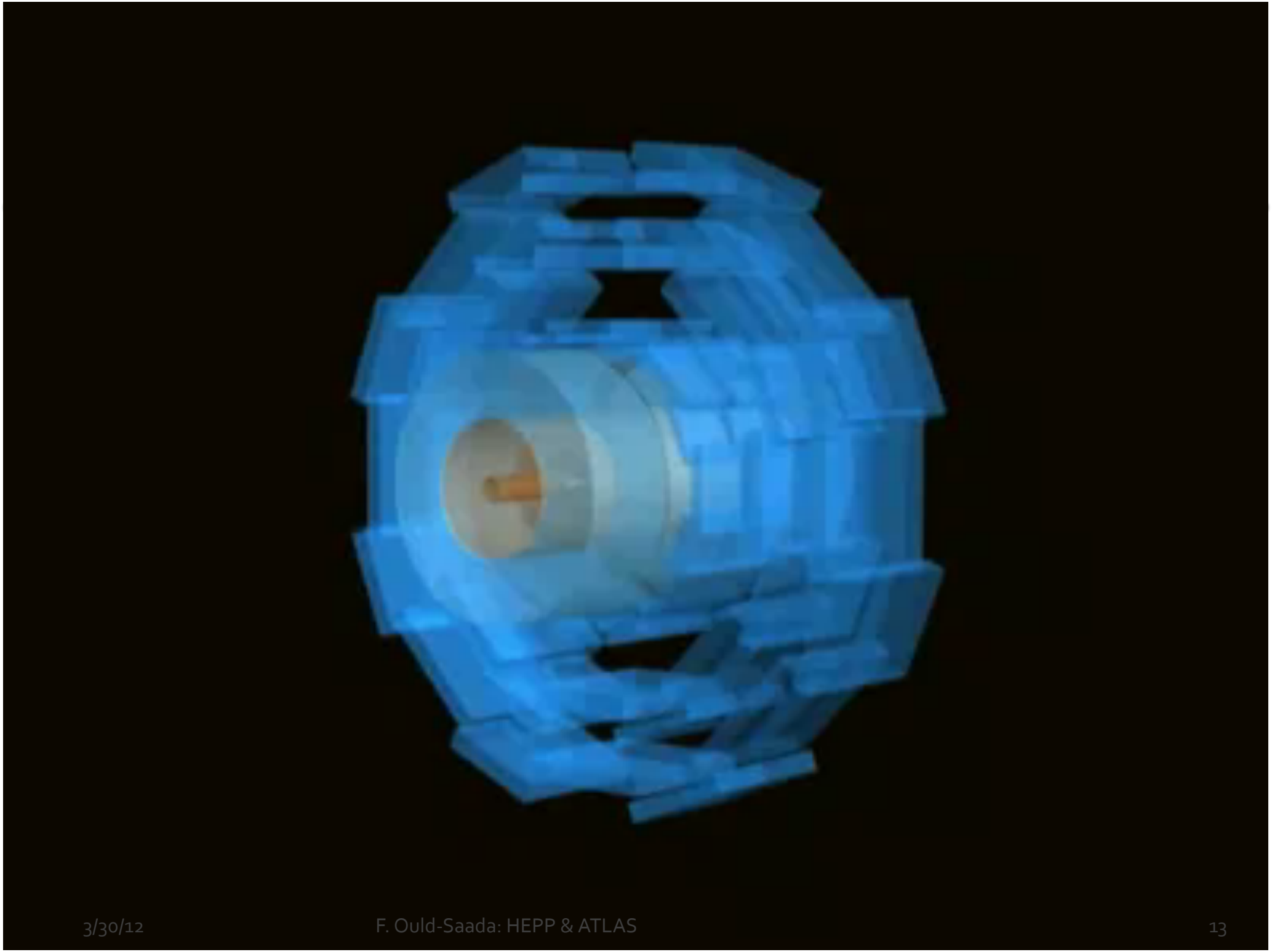
ATLAS : 3030 Physicists
174 Institutions
38 countries
550 MCHF



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
- how the various particles are identified is shown here

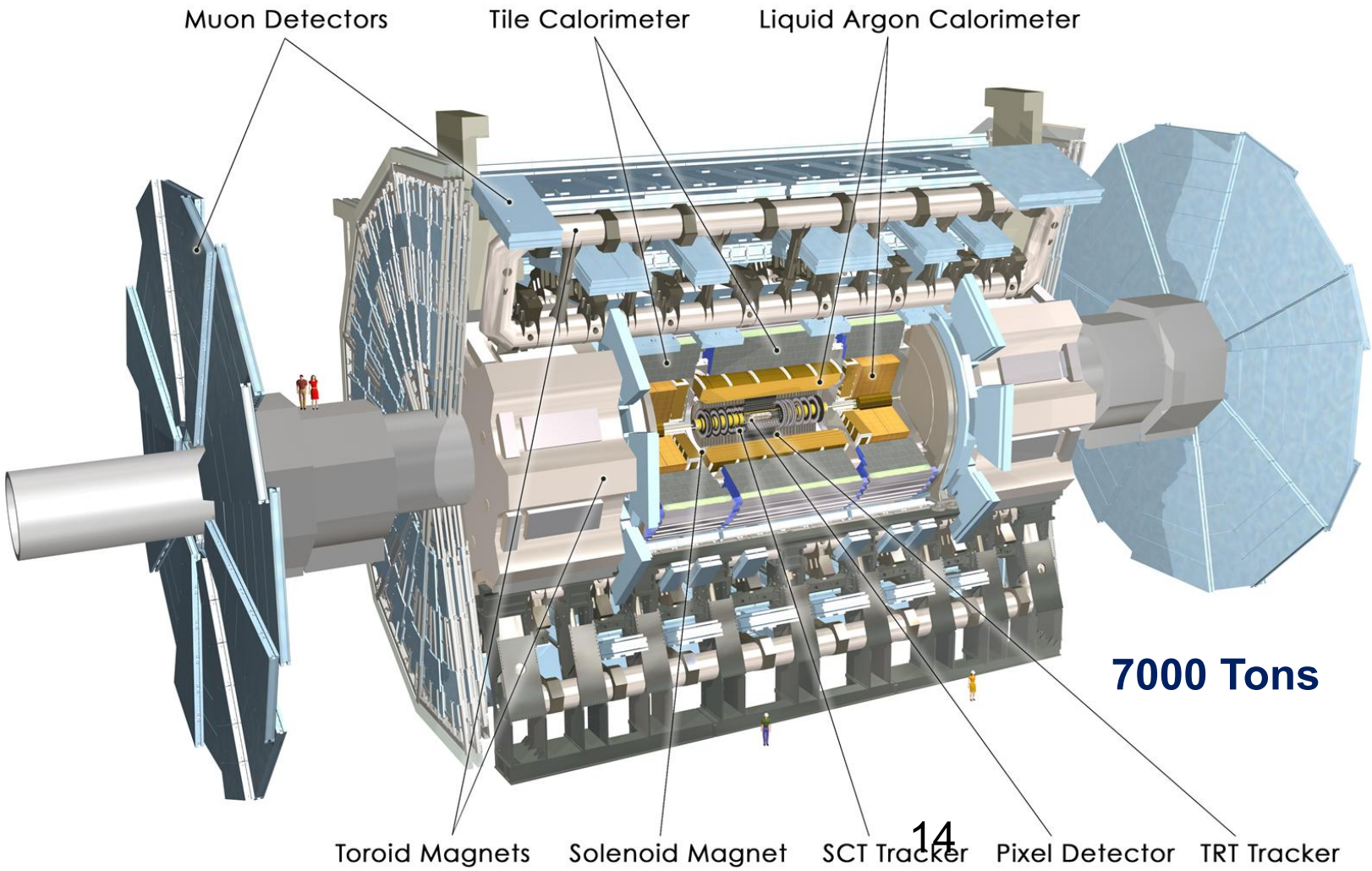


ATLAS Detector

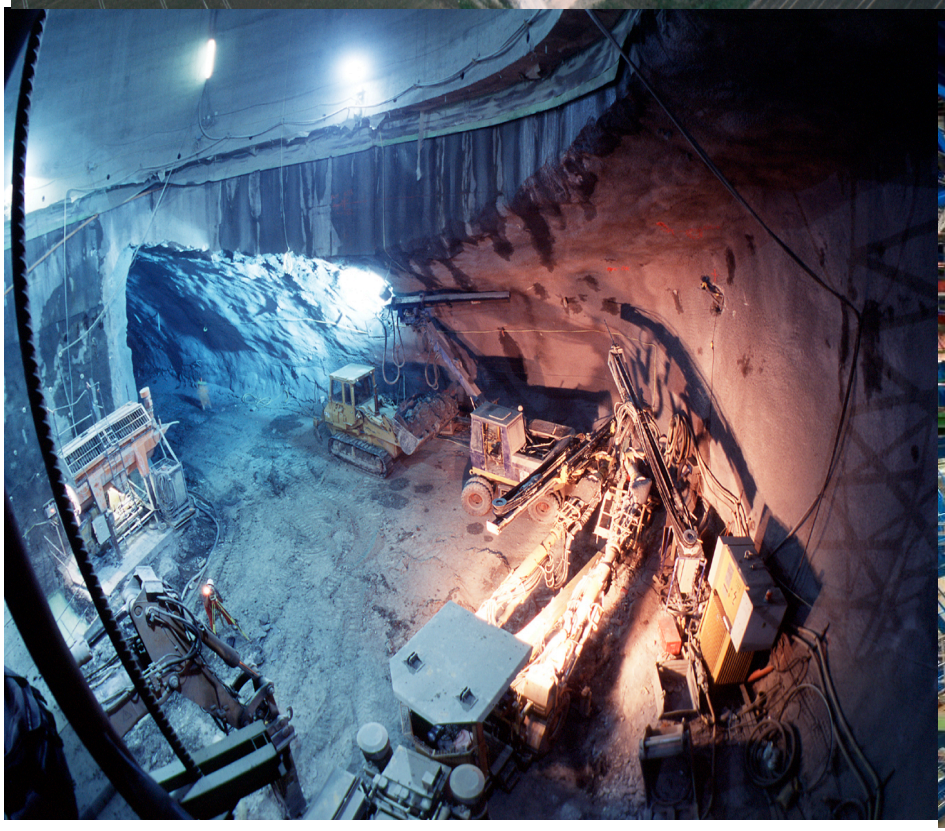
ATLAS superimposed to the 5 floors of building 40

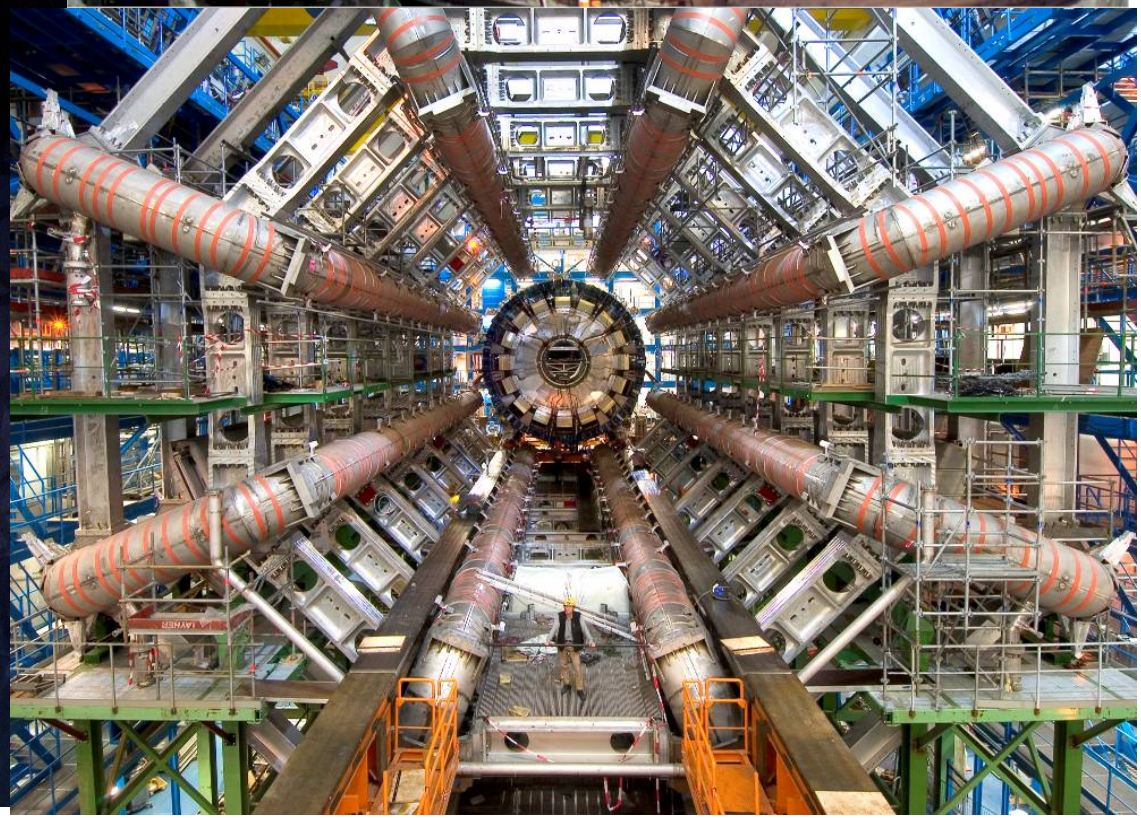
45 m

24 m



7000 Tons





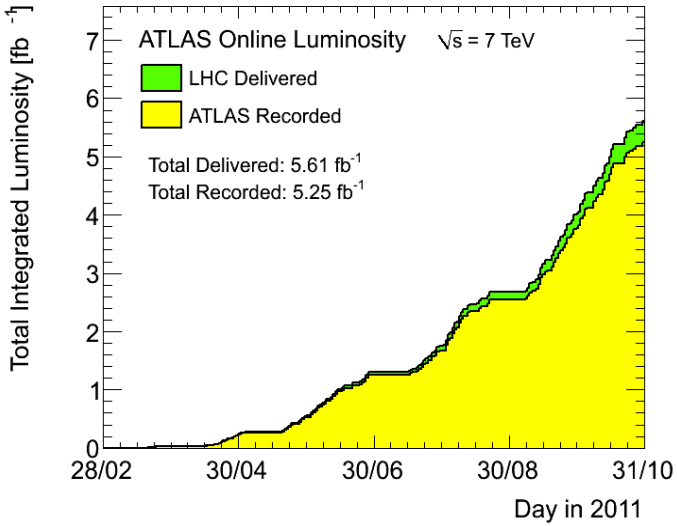
Let us build ATLAS in 1 minute!

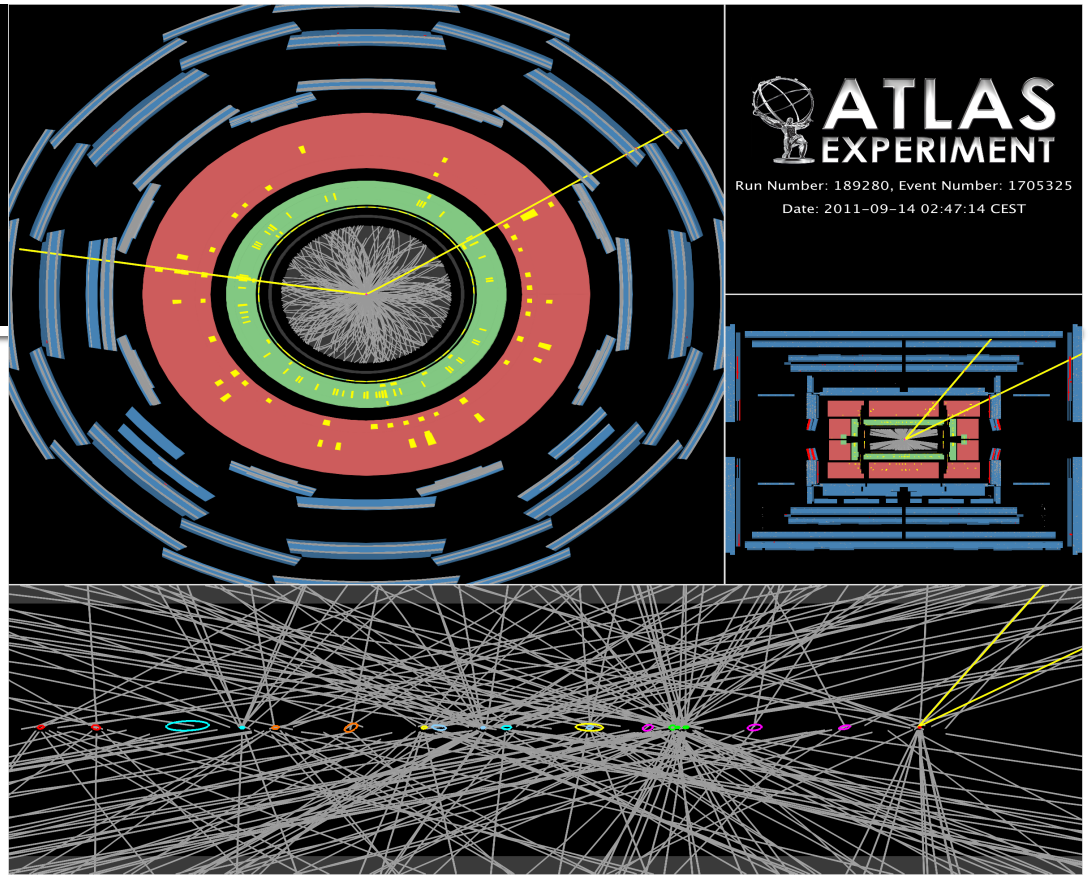
- 10 years construction in one minute

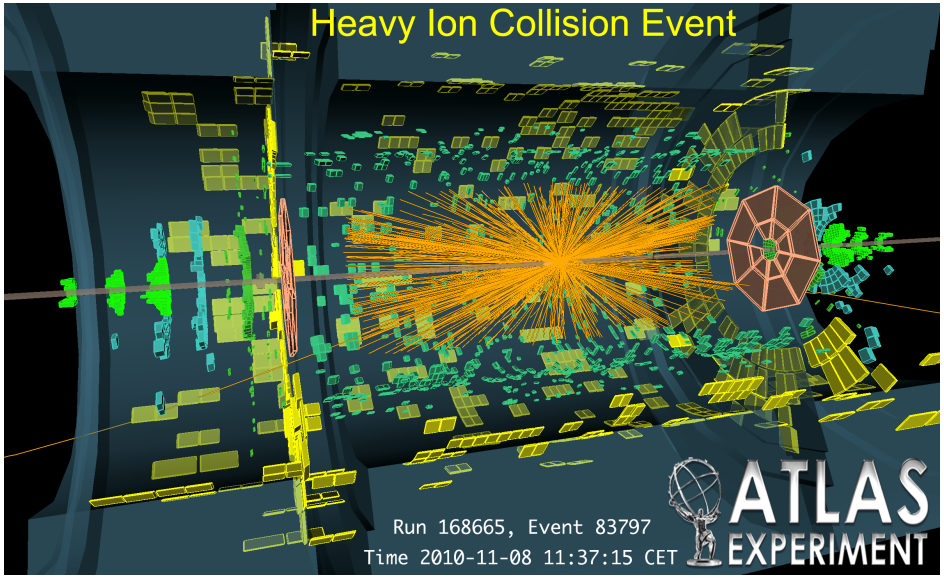
- Follow the link and you will watch this in 3 or 5 minutes!

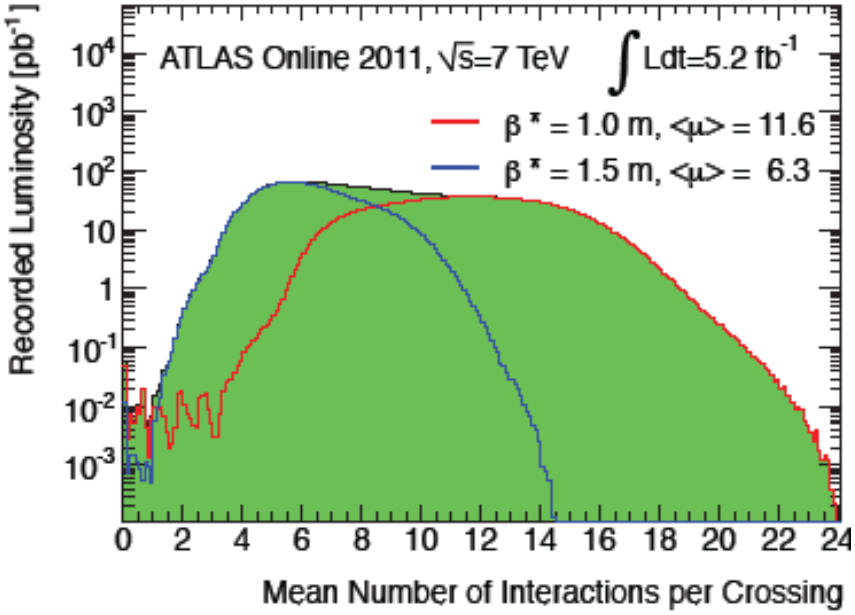
http://www.atlas.ch/multimedia/html-nc/atlas-built-in-one-minute.html

Extreme conditions

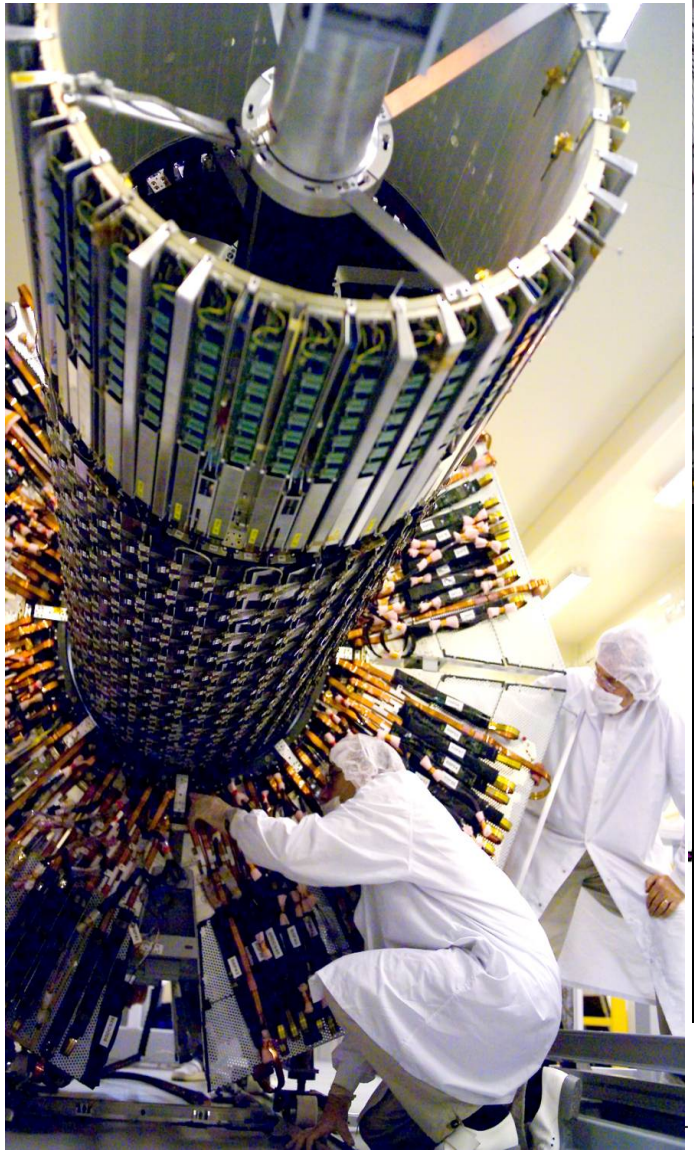


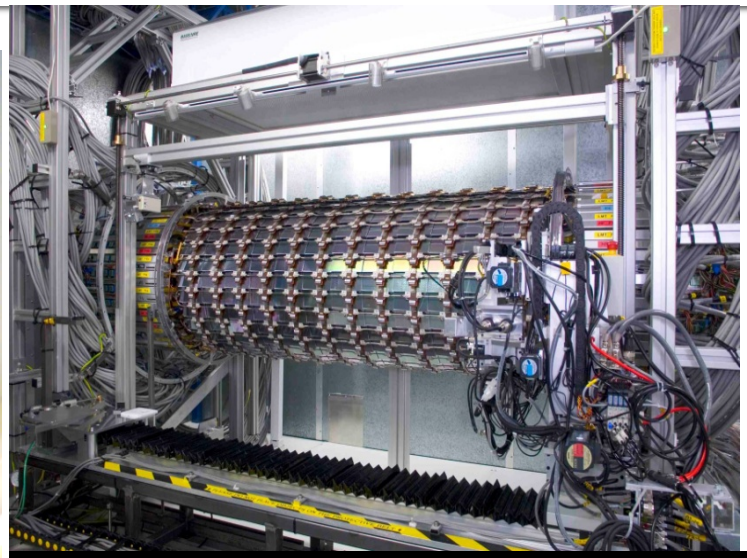






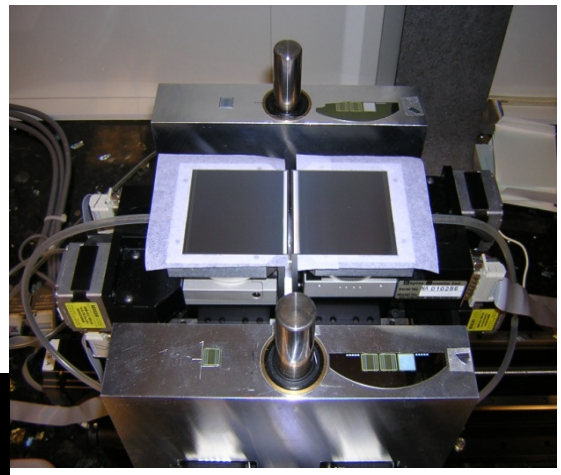
One of the Norwegian contributions to ATLAS: "Semi Conductor Tracker" (SCT) – Oslo, Bergen, Uppsala made 320 silicon-modules ~ 15% of Atlas needs



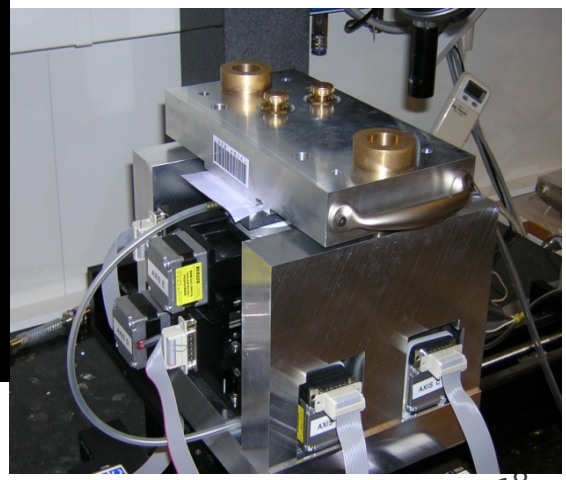


R&D project and ATLAS upgrade → 3D-Pixel

Inner Tracker



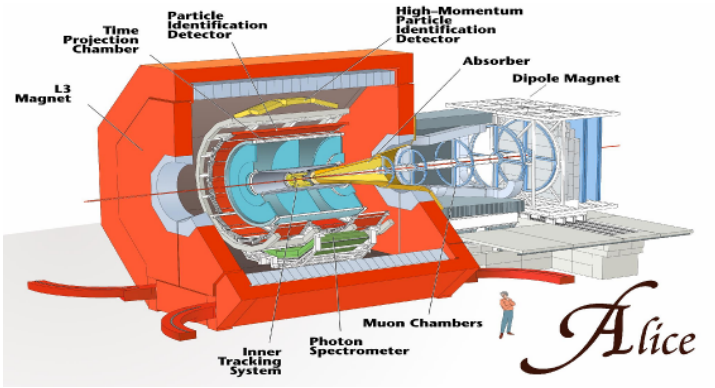
Mounting in Oslo

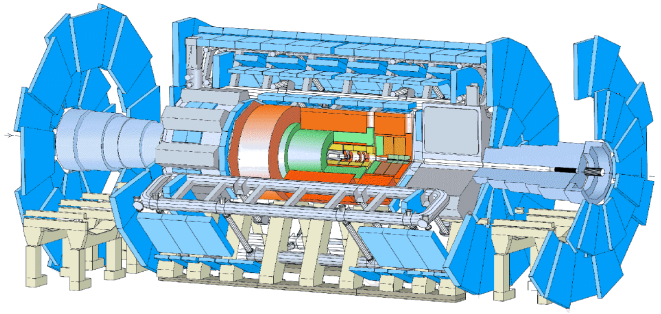


Norwegian participation at LHC

Forskningsrådet

- 2 Norwegian research projects linked to LHC physics
  - HENP (ALICE++): D. Röhrich, UiB
  - HEPP (ATLAS++): F. Ould-Saada, UiO
- Grid activities:
  - NorduGrid, NGIn, (NDGF, EMI): F. Ould-Saada





NORDUGRID
Grid Solution for Wide Area Computing and Data Handling

ARC

European Middleware Initiative

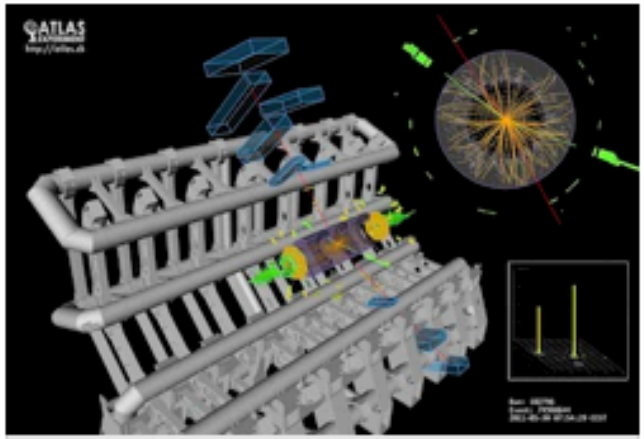
World Wide GRID

http://www.mn.uio.no/fysikk/english/research/projects/hepp/

High Energy Particle Physics - HEPP - Project

The goal of HEPP is to extend the frontiers of physics knowledge using the advanced technology of the world's largest and highest energy particle accelerator, the LHC, and, among others, the world's largest particle detector, ATLAS, to discover the last missing building block of the Standard Model of elementary particles, the Higgs boson, and identify the new physics which may be expected in a previously unexplored energy regime, the TeV scale.

The HEPP project is part of the Norwegian CERN-related program, funded by the Research Council (RCN). The 6-year period 2006-2011 came to an end in December 2011. Although the main activity has been the ATLAS experiment at the LHC, project members have also been involved in theoretical work related to and/or relevant for LHC physics, in Grid computing, in detector upgrade activities, in the BABAR detect at SLAC, as well as in a vast outreach program towards young students and media. The first 4-year period of the current program (2012-2019) started in January 2012 with main emphasis the ATLAS experiment. The partners UiO, UiB and HiG contribute with permanent staff members and PhD students. Post-docs are funded by RCN, as well as hardware, computing and operation of ATLAS.



Proton-proton collision leading to two Z particles: one Z decays to two muons, the other to two electrons. More statistics is needed to tell whether it is a Higgs signal. *Photo ATLAS.*

Project Partners

University of Oslo Experimental particle physics Theoretical particle physics

University of Bergen Subatomic physics Theoretical particle physics

University College Gjøvik

Contact

Project leader: Prof. Farid Ould-Saada

Deputy: Prof Anna Lipniacka

Participants

- Farid Ould-Saada
- Alexander Lincoln Read

Detailed list of participants

Participants: UiB

Research activities

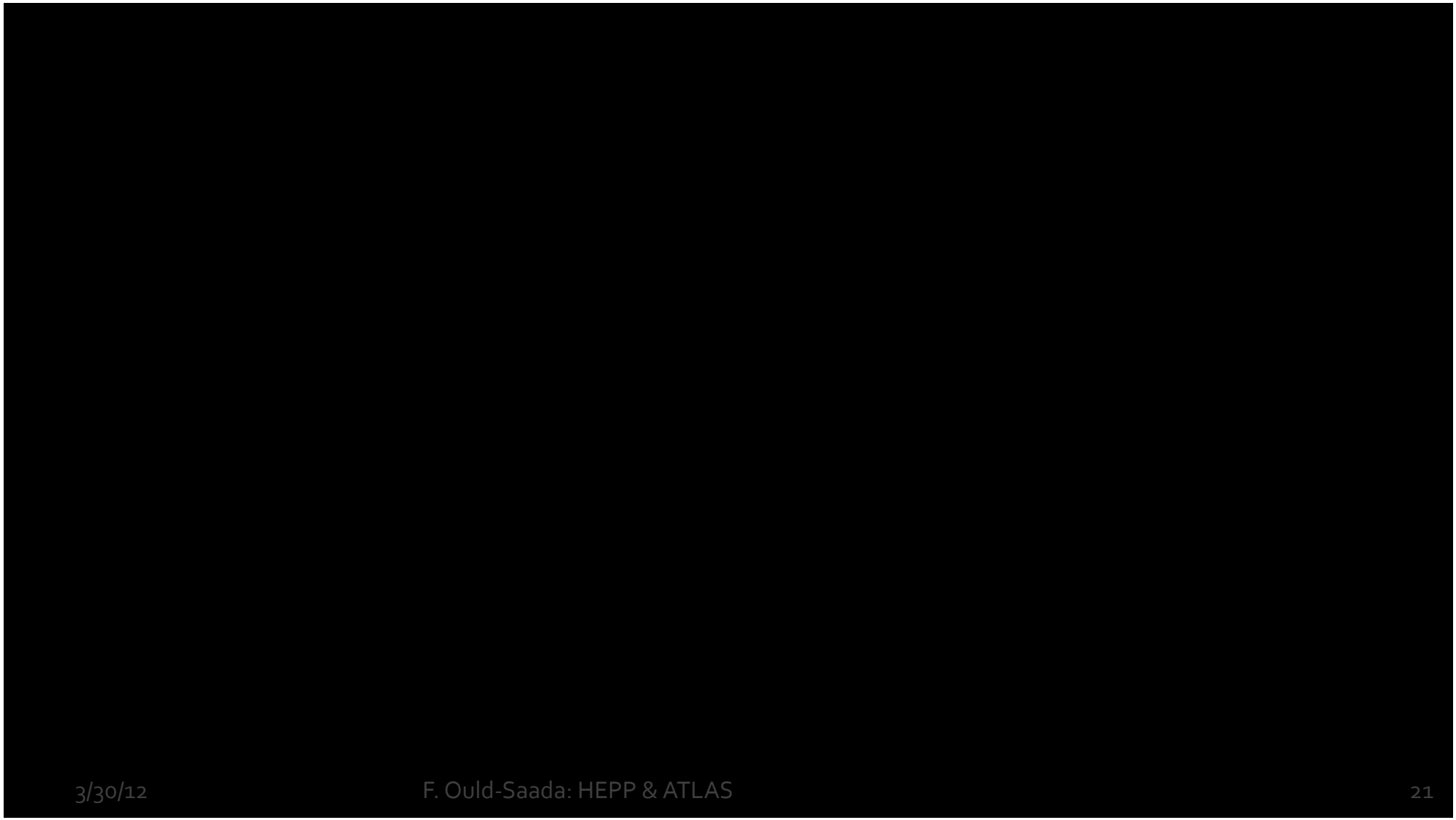
HEPP Twiki

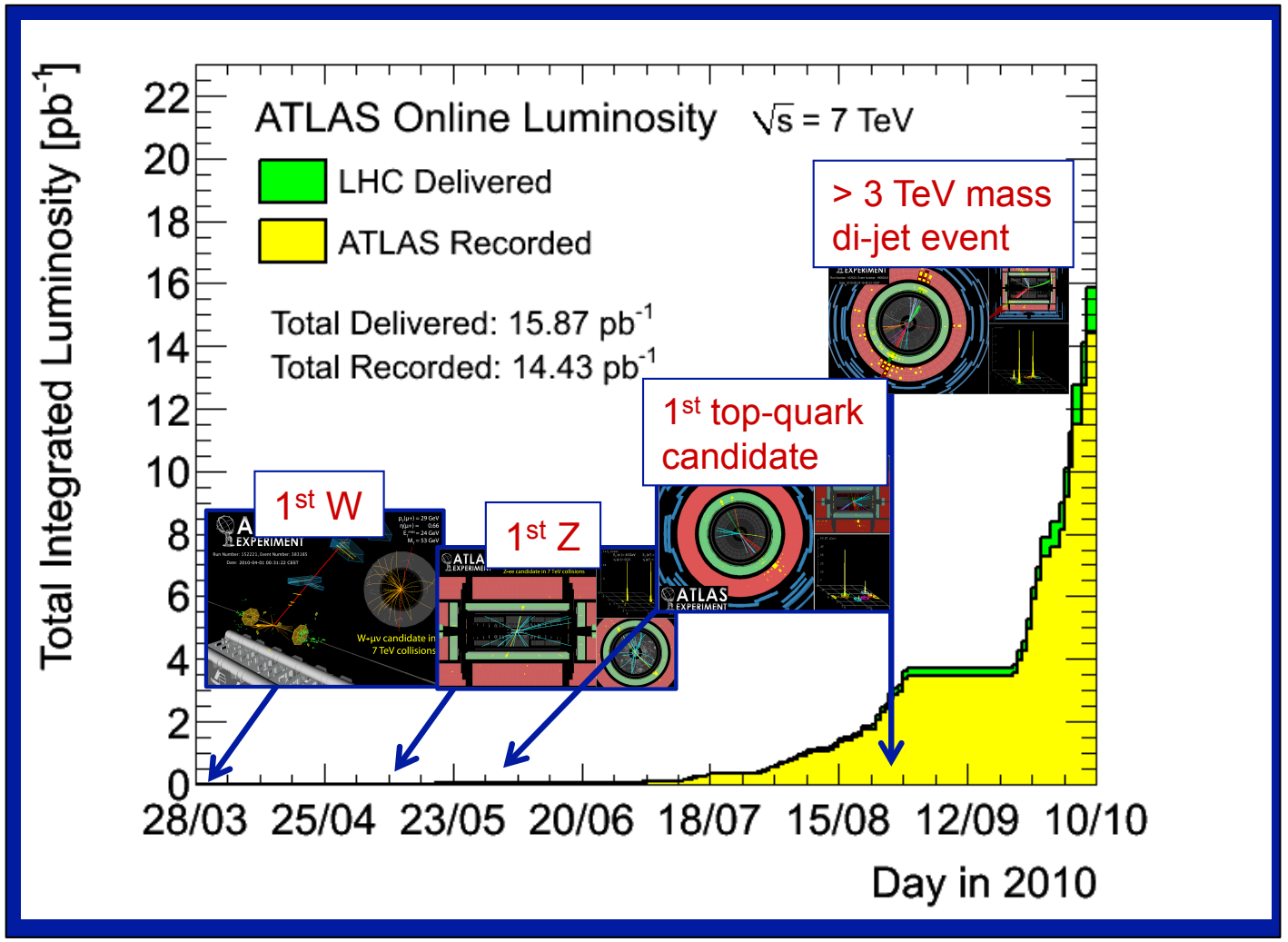
- ATLAS Physics
- ATLAS Upgrade
- Computing
- Theory
- Outreach

-Higgs
-SUSY
-New gauge bosons (W', Z'),
-Graviton
-New space dimensions

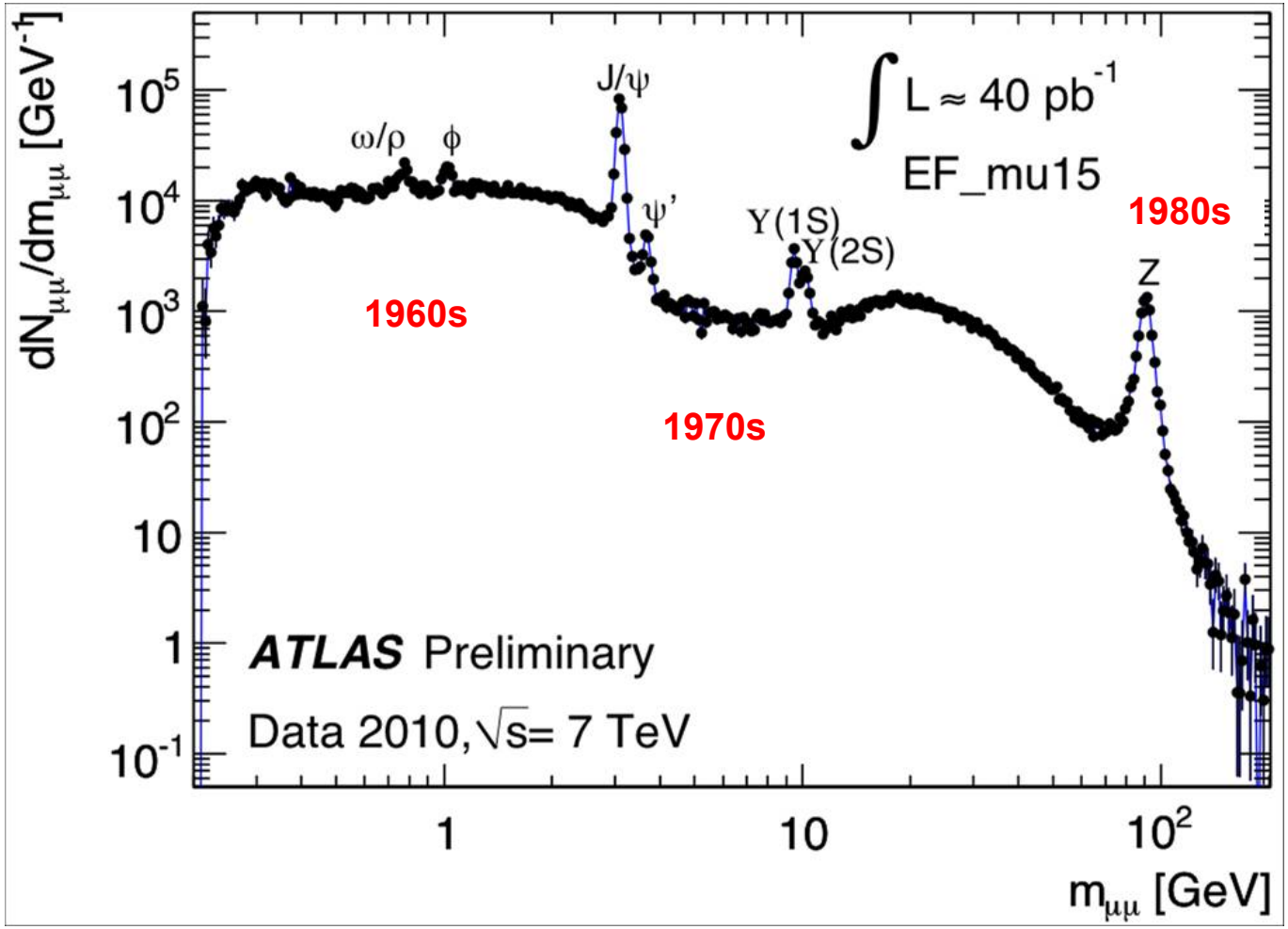
From simulation to reality

- Z-particle production and decay in ATLAS

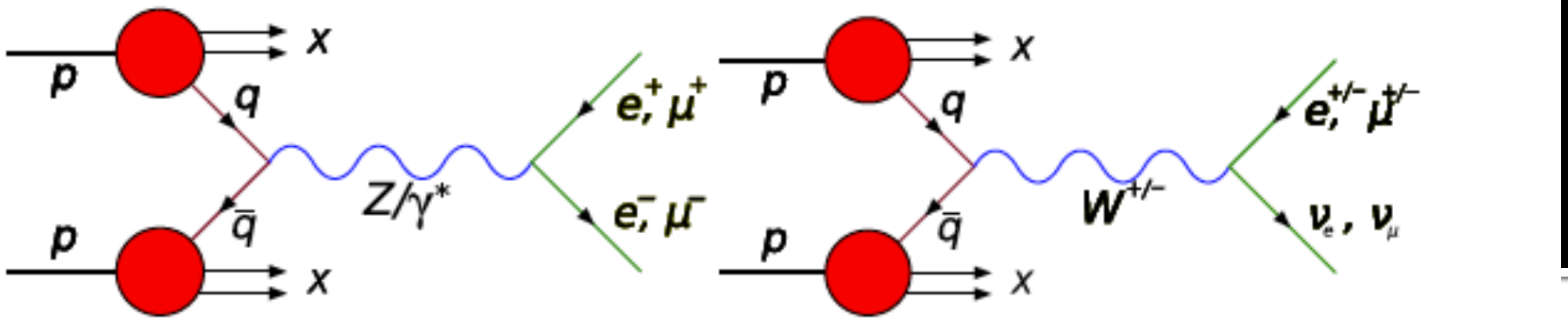


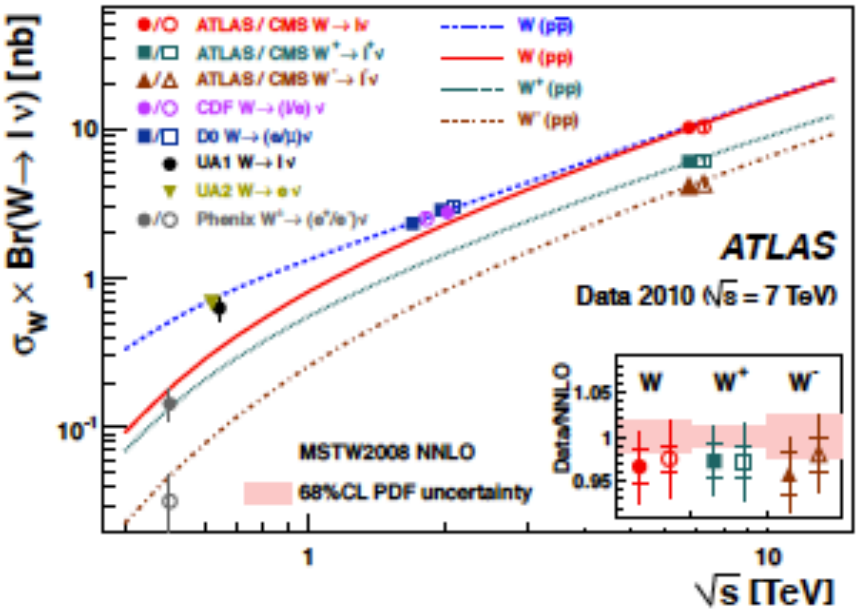

ATLAS Online Luminosity √s = 7 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 15.87 pb-1
Total Recorded: 14.43 pb-1
Total Integrated Luminosity [pb-1]
Day in 2010
28/03
25/04
23/05
20/06
18/07
15/08
12/09
10/10
> 3 TeV mass di-jet event
1st top-quark candidate
1st Z
1st W

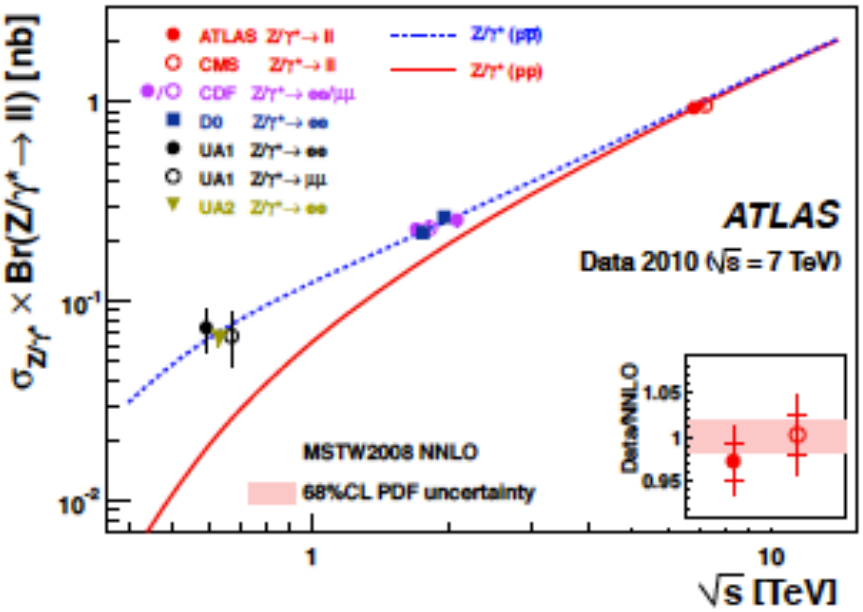
50 years of particle physics in a few months

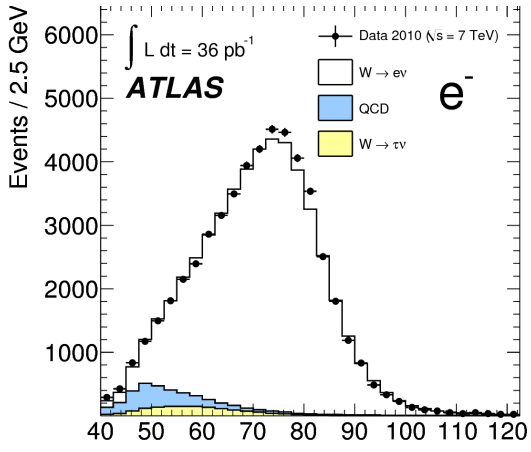


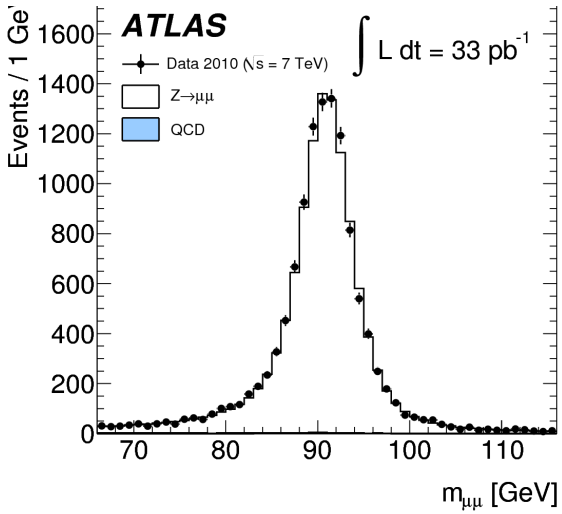
$$m_?c^2 = \sqrt{(m_1c^2)^2 + (m_2c^2)^2 + 2E_1E_2 - 2\vec{p}_1\vec{p}_2c^2}$$


p
p
q
$\bar{q}$
x
x
Z/γ^*
e^+, μ^+
e^-, μ^-
p
p
q
$\bar{q}$
x
x
$W^{+/-}$
$e^{+/-}, \mu^{+/-}$
ν_e, ν_μ

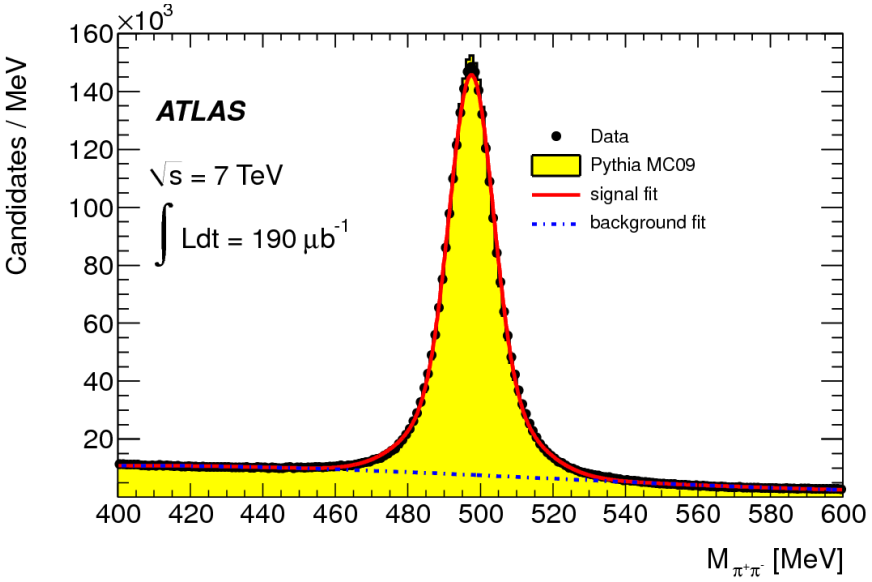

$\sigma_W \times Br(W \to l\nu)$ [nb]
ATLAS / CMS $W \to l\nu$
ATLAS / CMS $W^+ \to l^+\nu$
ATLAS / CMS $W^- \to l^-\nu$
CDF $W \to (l/e)\nu$
D0 $W \to (e/\mu)\nu$
UA1 $W \to l\nu$
UA2 $W \to e\nu$
Phenix $W^{\pm} \to (e^+/e^-)\nu$
$W(p\bar{p})$
$W(pp)$
$W^+(pp)$
$W^-(pp)$
ATLAS
Data 2010 $(\sqrt{s} = 7$ TeV)
MSTW2008 NNLO
68%CL PDF uncertainty
Data/NNLO
W
W^+
W^-
$\sqrt{s}$ [TeV]

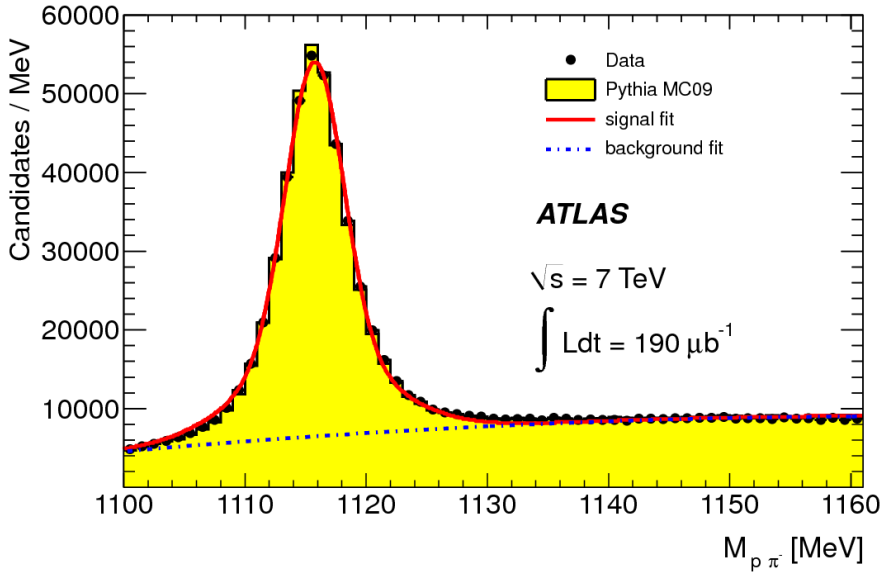

$\sigma_{Z/\gamma^*} \times Br(Z/\gamma^* \to ll)$ [nb]
ATLAS $Z/\gamma^* \to ll$
CMS $Z/\gamma^* \to ll$
CDF $Z/\gamma^* \to ee/\mu\mu$
D0 $Z/\gamma^* \to ee$
UA1 $Z/\gamma^* \to ee$
UA1 $Z/\gamma^* \to \mu\mu$
UA2 $Z/\gamma^* \to ee$
$Z/\gamma^*(p\bar{p})$
$Z/\gamma^*(pp)$
ATLAS
Data 2010 $(\sqrt{s} = 7$ TeV)
MSTW2008 NNLO
68%CL PDF uncertainty
Data/NNLO
$\sqrt{s}$ [TeV]

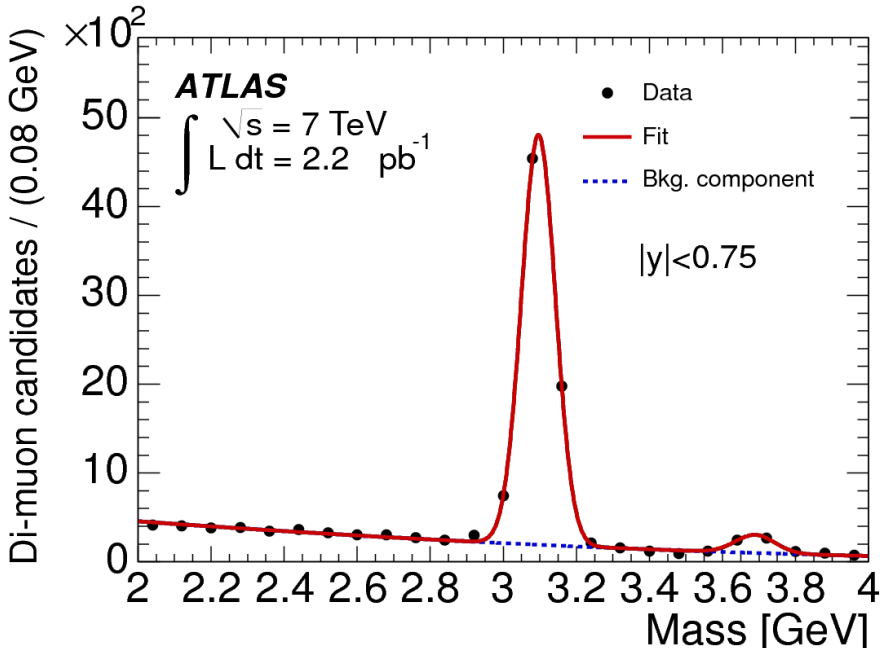

Events / 2.5 GeV
$\int$ L dt = 36 pb^{-1}
ATLAS
Data 2010 $(\sqrt{s} = 7$ TeV)
$W \to e\nu$
QCD
$W \to \tau\nu$
e^-
m_T [GeV]

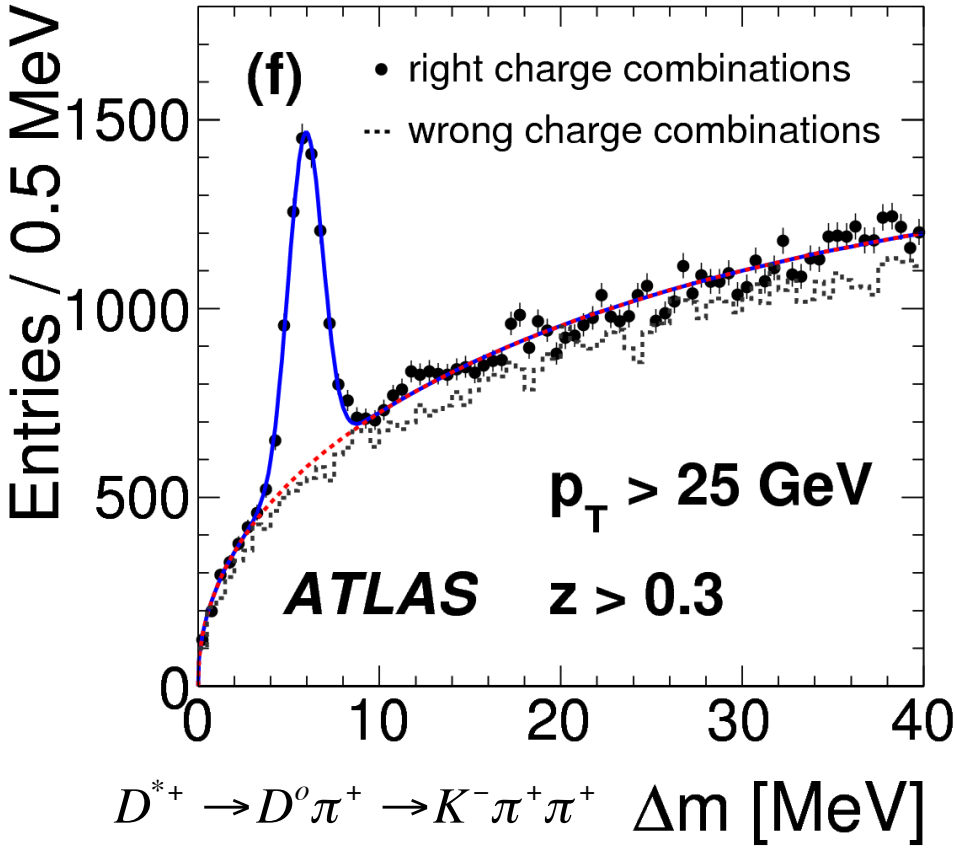

Events / 1 Ge
ATLAS
Data 2010 $(\sqrt{s} = 7$ TeV)
$Z \to \mu\mu$
QCD
$\int$ L dt = 33 pb^{-1}
$m_{\mu\mu}$ [GeV]

Strange and charm mesons

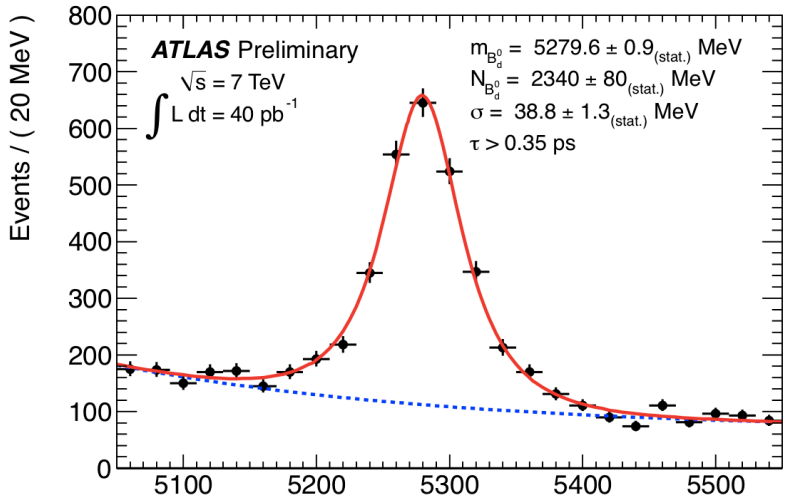




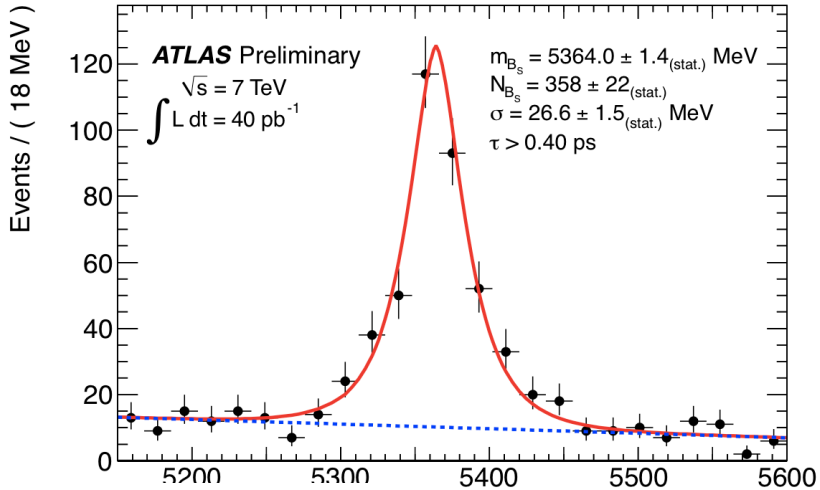




b-quark mesons … established & new

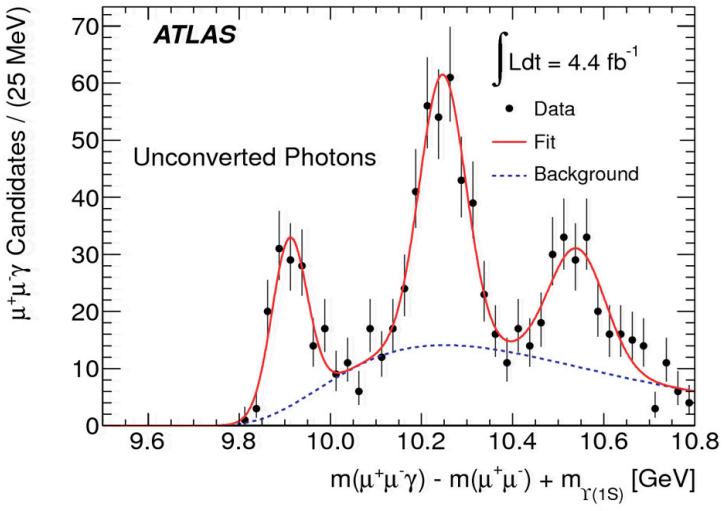


$B_d^o \rightarrow J/\psi \;\; K^{o*}$

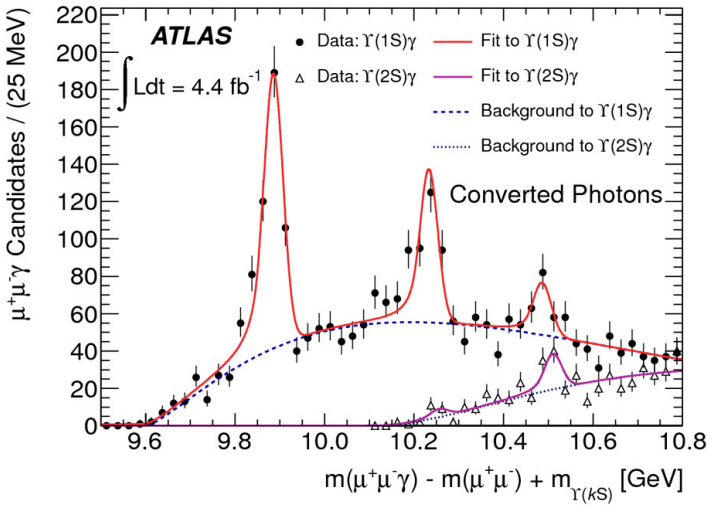


$B_s^o \rightarrow J/\psi(\mu\mu) \;\; \phi(KK)$

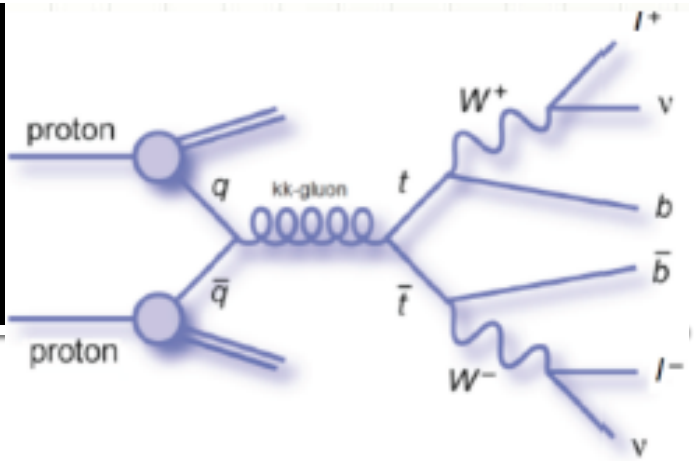
$\chi_b(3p) \rightarrow \Upsilon(1s,2s) + \gamma$



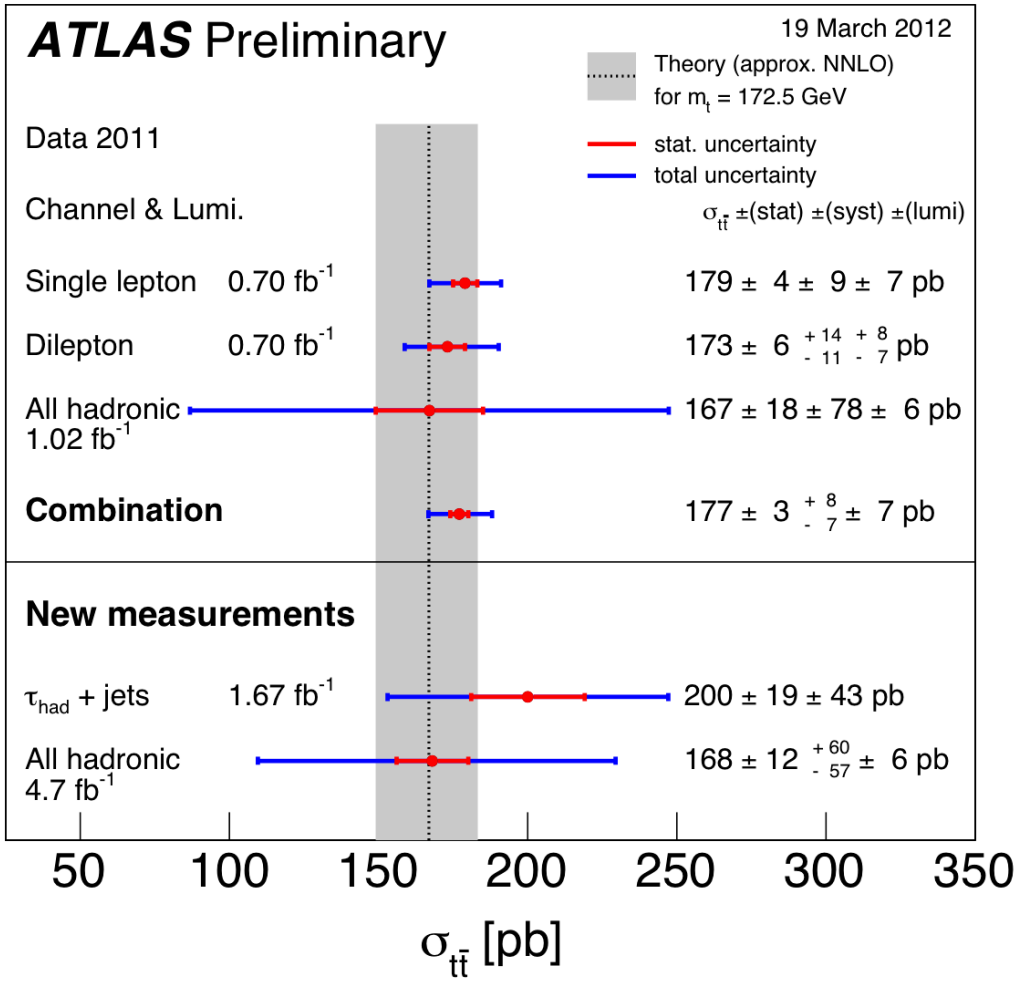
(a)



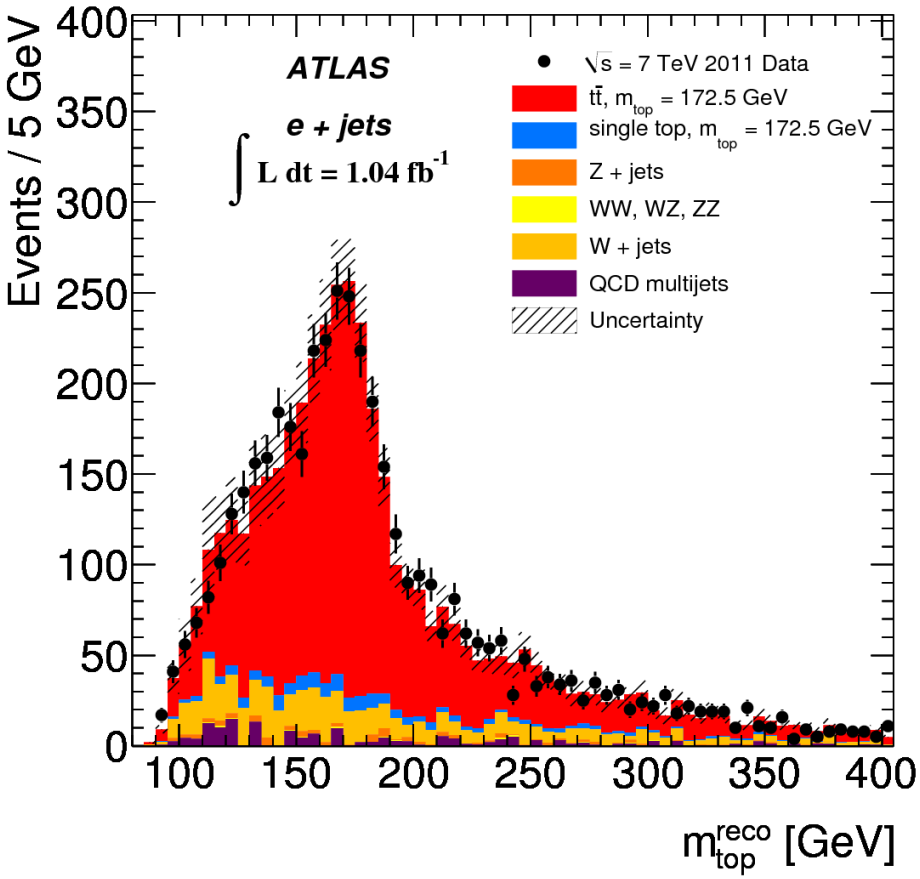
Top quark



$$\sigma_{t\bar{t}} = 177 \pm 3\ ^{+8}_{-7} \pm 7\ \ pb$$

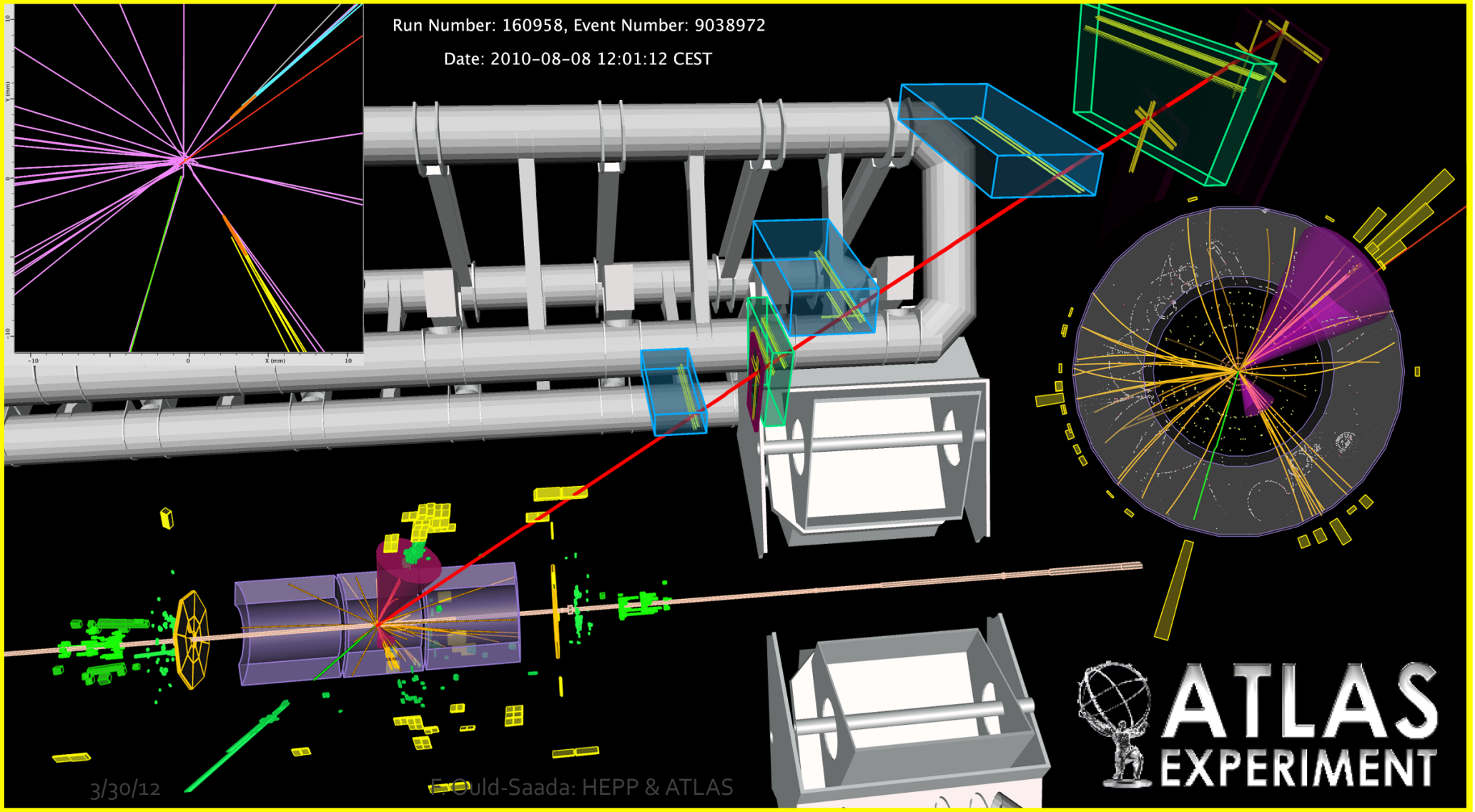


$$m_t = 174.5 \pm 0.6 \pm 2.3\ \ GeV$$



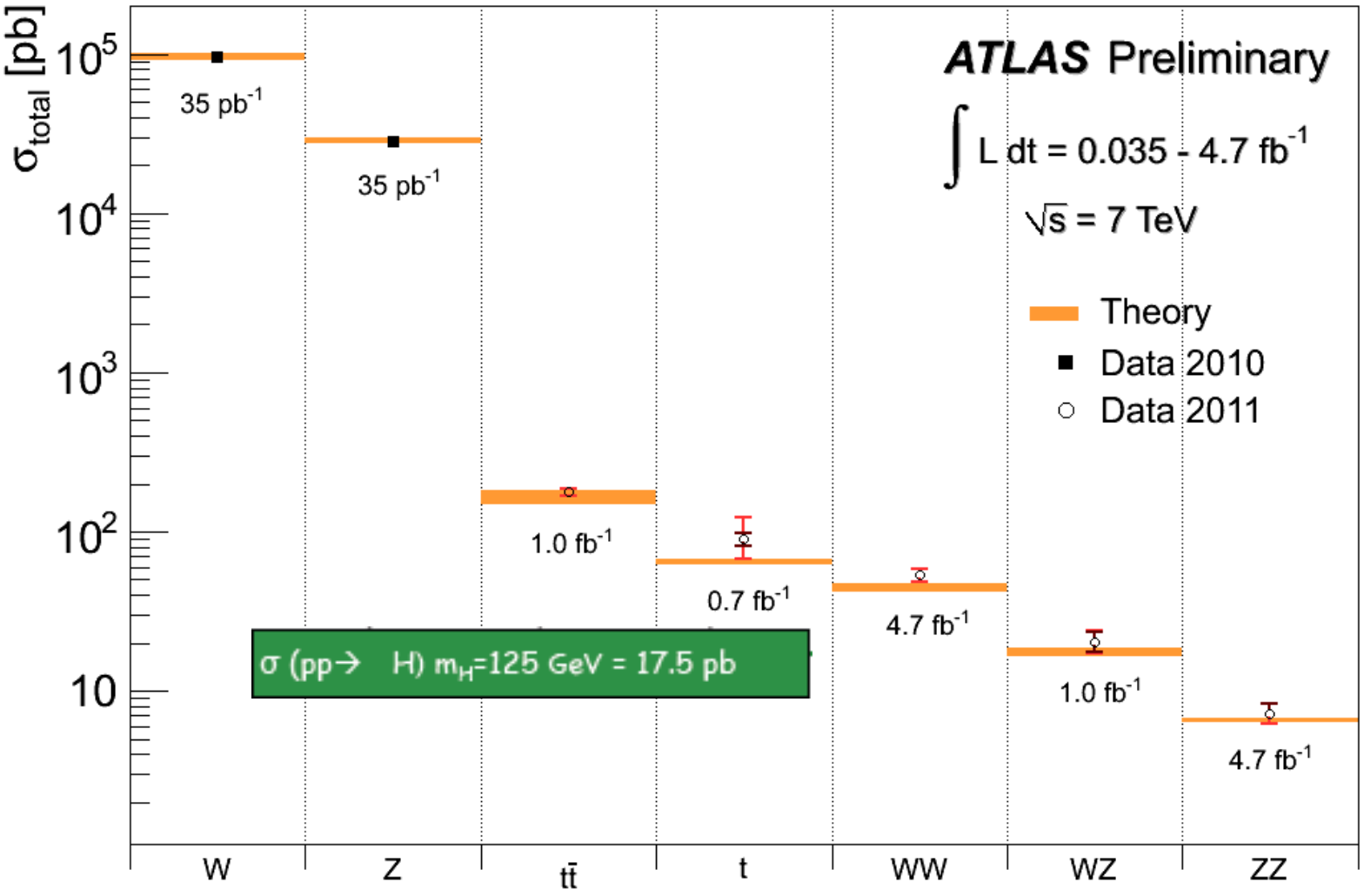
t-tbar→ bW(→eν) bW(→μν) candidate

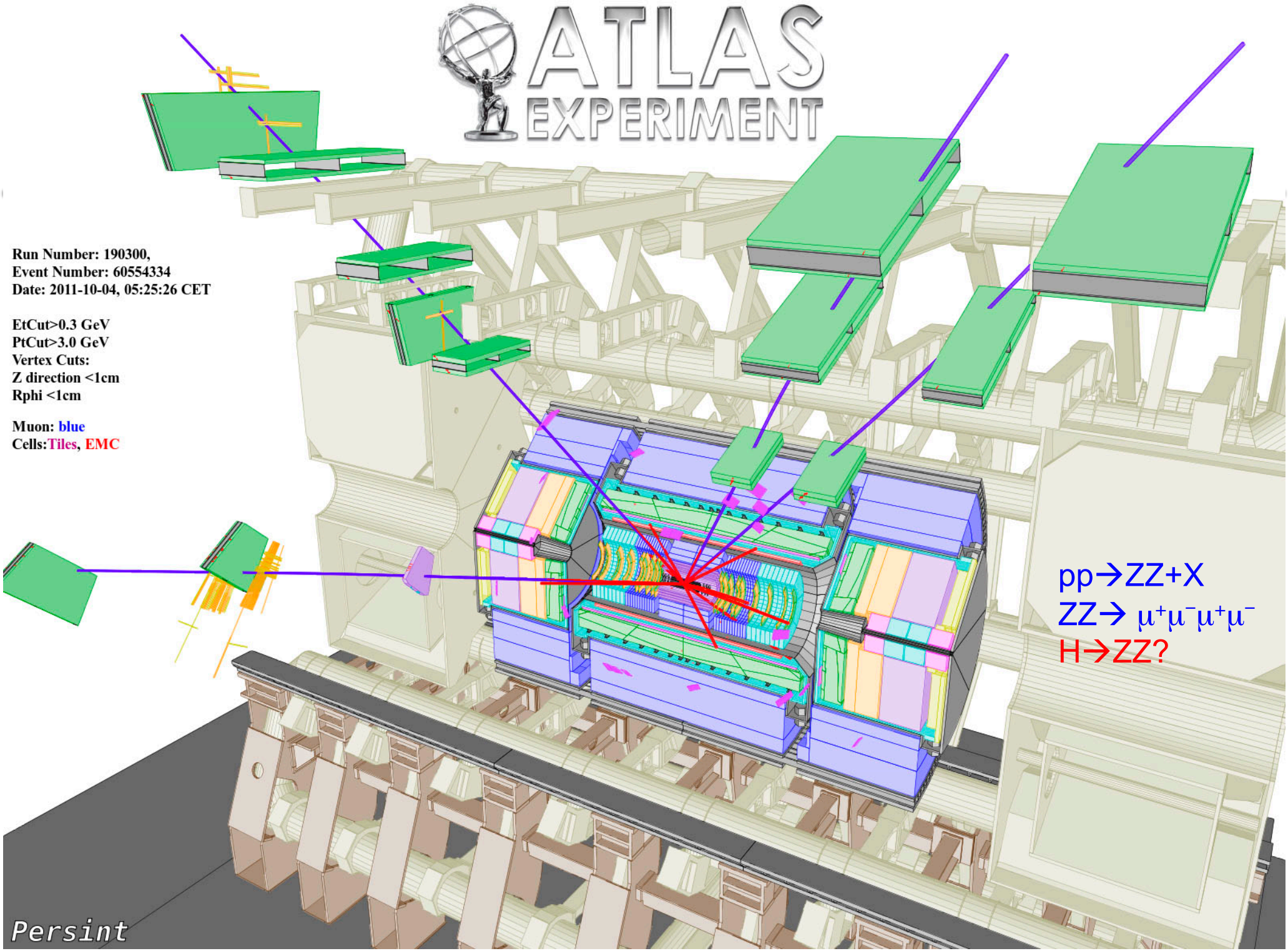
$p_T(\mu)$= 51 GeV $p_T(e)$=66 GeV p_T (b-tagged jets) = 174, 45 GeV E_T^{miss} = 113 GeV,
2 secondary vertices from b-decays



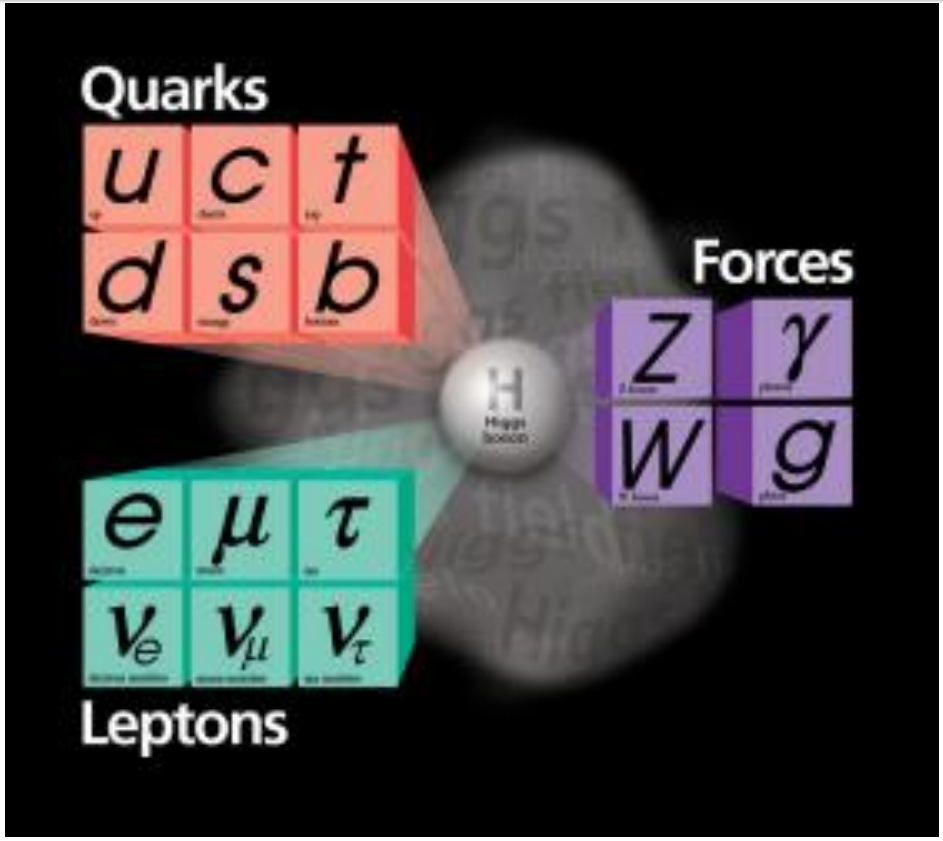
Summary of several Standard Model total production cross section measurements compared to the corresponding theoretical expectations.

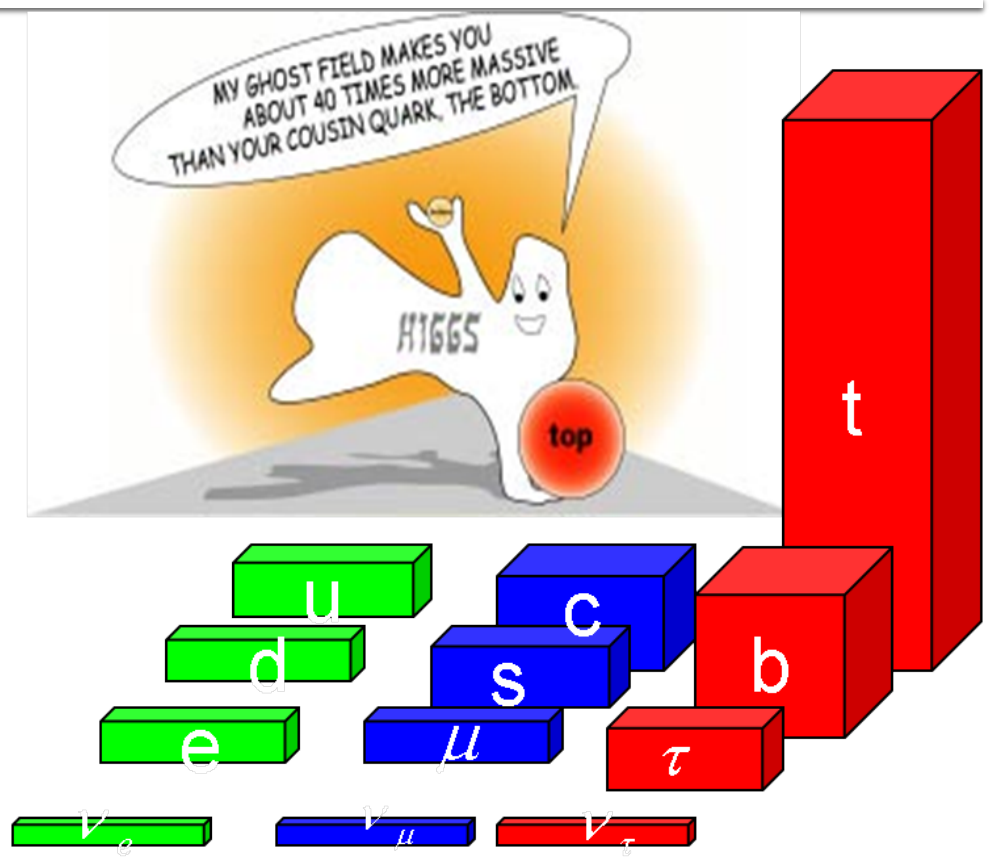
- Any search for new particles requires a good knowledge of SM processes, which represent the main source of backgrounds




ATLAS
EXPERIMENT
Run Number: 190300,
Event Number: 60554334
Date: 2011-10-04, 05:25:26 CET
EtCut>0.3 GeV
PtCut>3.0 GeV
Vertex Cuts:
Z direction <1cm
Rphi <1cm
Muon: blue
Cells:Tiles, EMC
pp→ZZ+X
ZZ→ μ⁺μ⁻μ⁺μ⁻
H→ZZ?
Persint

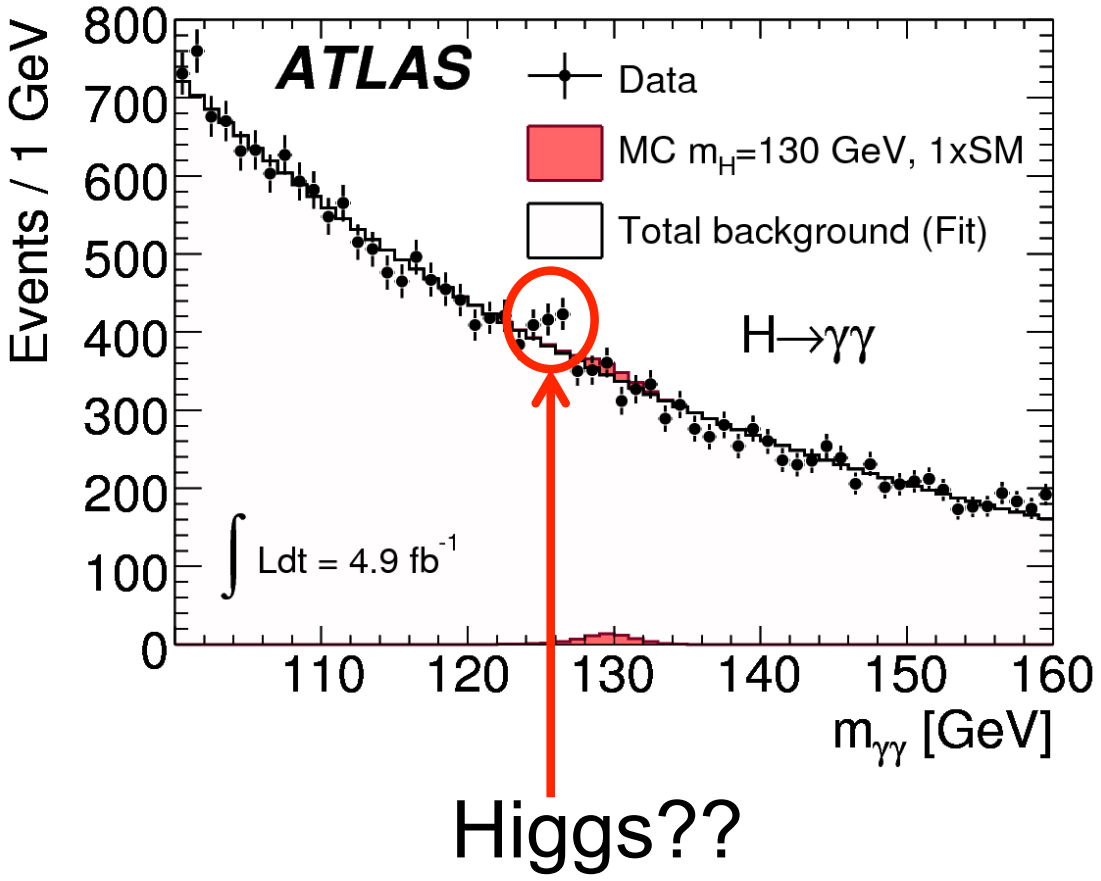
One of the mysteries LHC will resolve: Mass

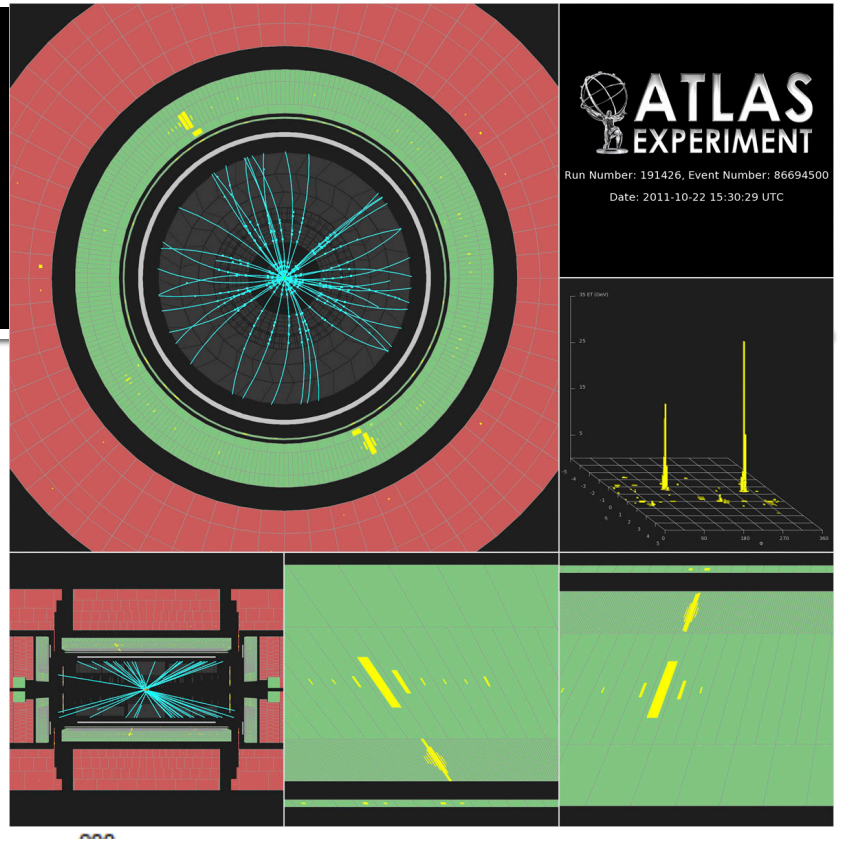


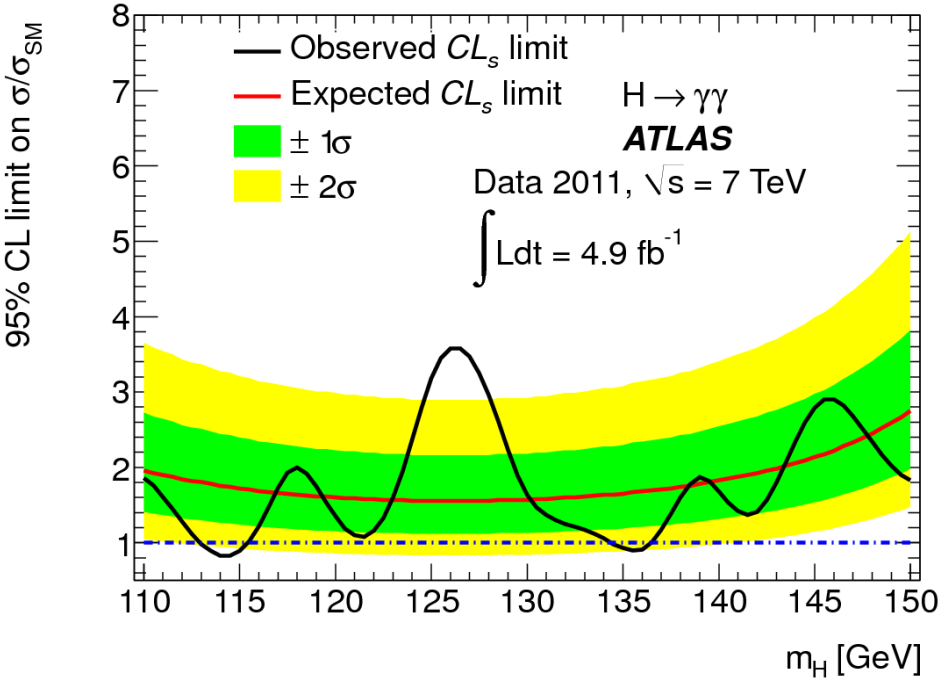


- Higgs boson: only particle predicted by the SM and not yet observed
- Higgs field responsible for EW symmetry breaking and "gives" masses to particles

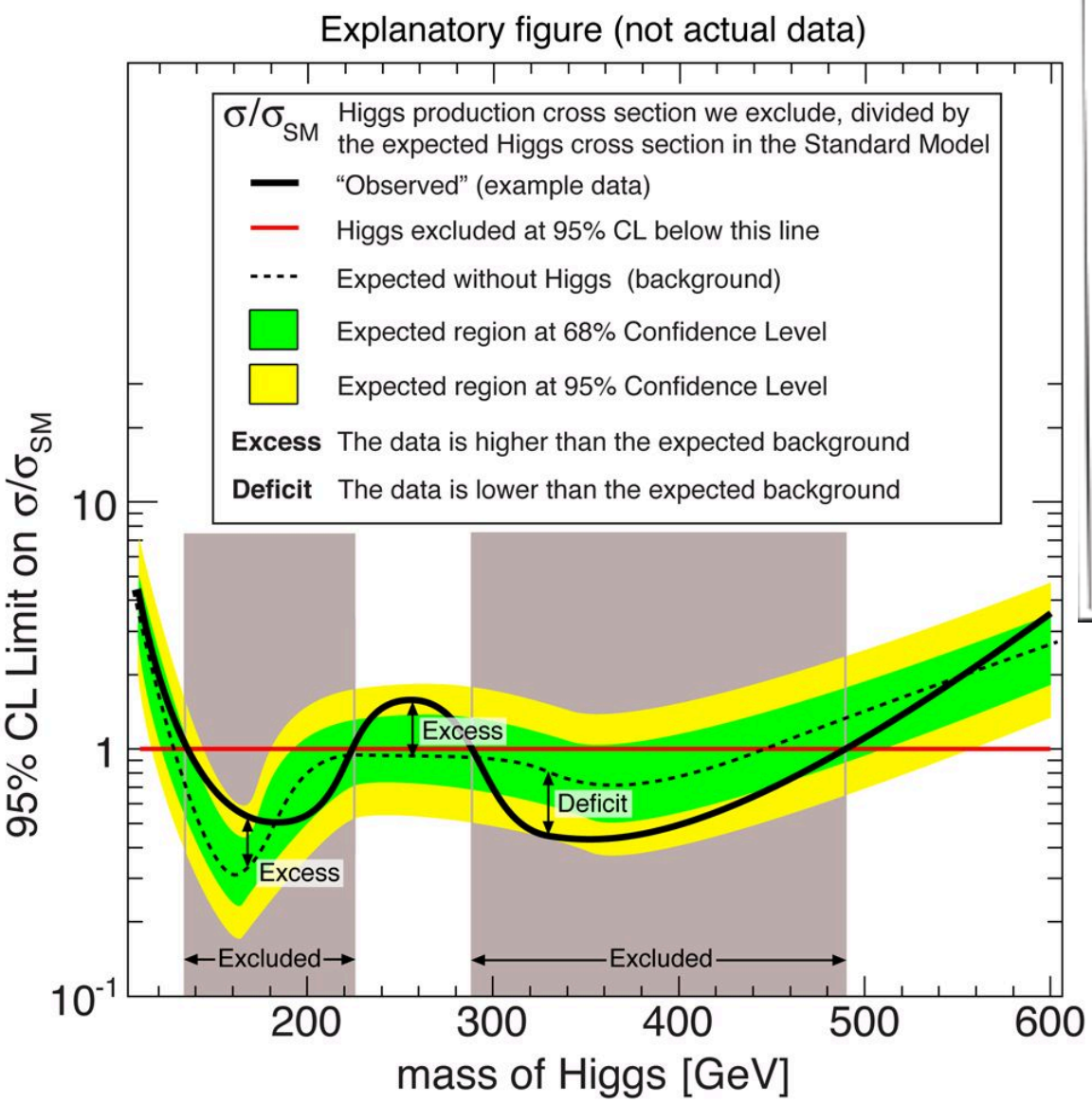
H→ γγ ?

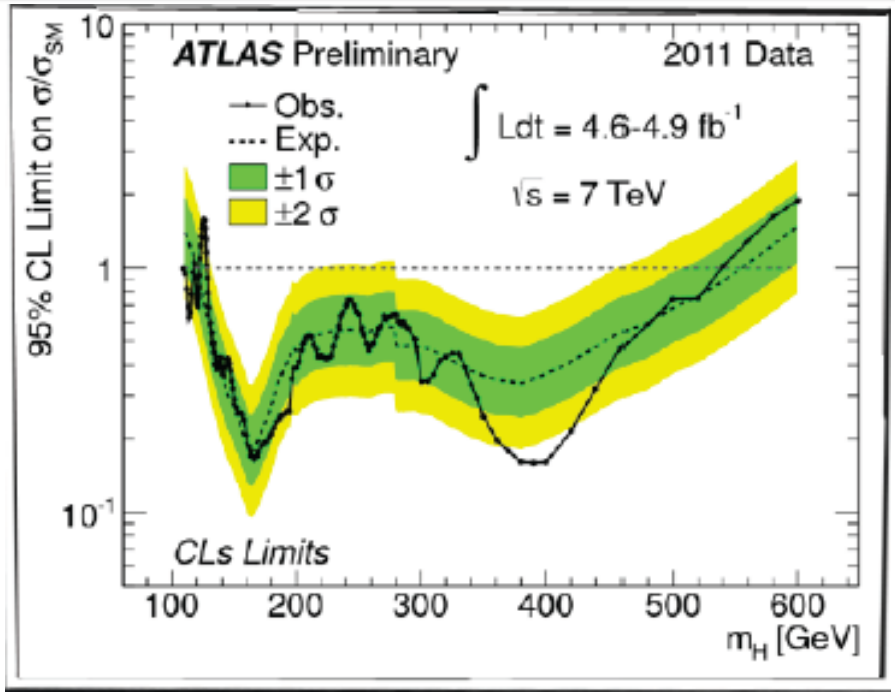






- Two-photon invariant mass The 2.8-σ enhancement around 126 GeV is possibly compatible with H→γγ.


Explanatory figure (not actual data)
σ/σSM Higgs production cross section we exclude, divided by the expected Higgs cross section in the Standard Model
"Observed" (example data)
Higgs excluded at 95% CL below this line
Expected without Higgs (background)
Expected region at 68% Confidence Level
Expected region at 95% Confidence Level
Excess The data is higher than the expected background
Deficit The data is lower than the expected background
95% CL Limit on σ/σSM
10
1
10-1
Excess
Deficit
Excess
Excluded
Excluded
200
300
400
500
600
mass of Higgs [GeV]


ATLAS Preliminary
2011 Data
Obs.
Exp.
±1 σ
±2 σ
∫ Ldt = 4.6-4.9 fb-1
√s = 7 TeV
95% CL Limit on σ/σSM
10
1
10-1
CLs Limits
100
200
300
400
500
600
mH [GeV]

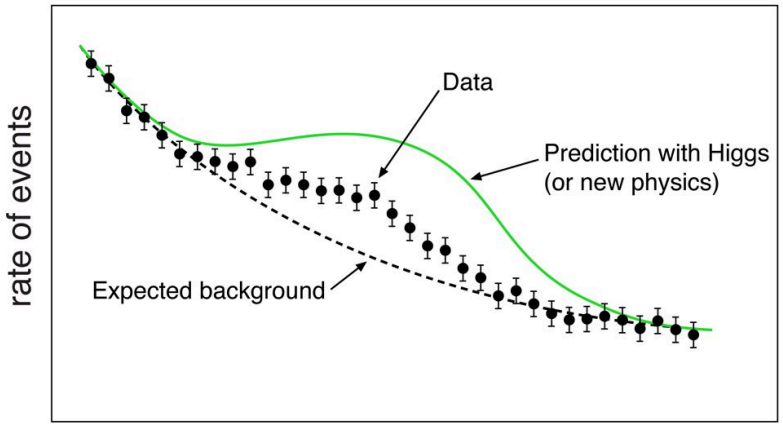
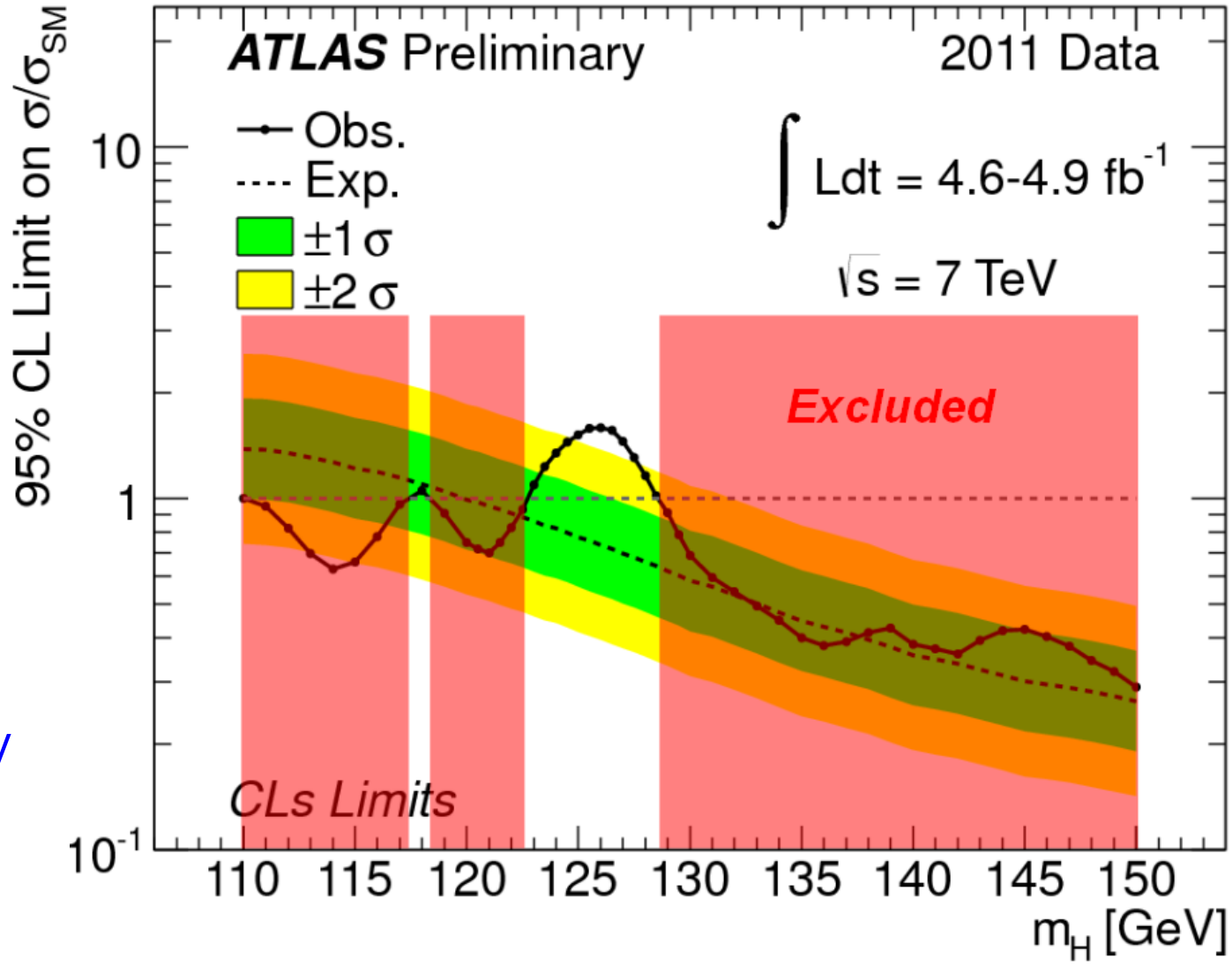

Data
Prediction with Higgs
(or new physics)
Expected background
rate of events
some parameter

Figure B

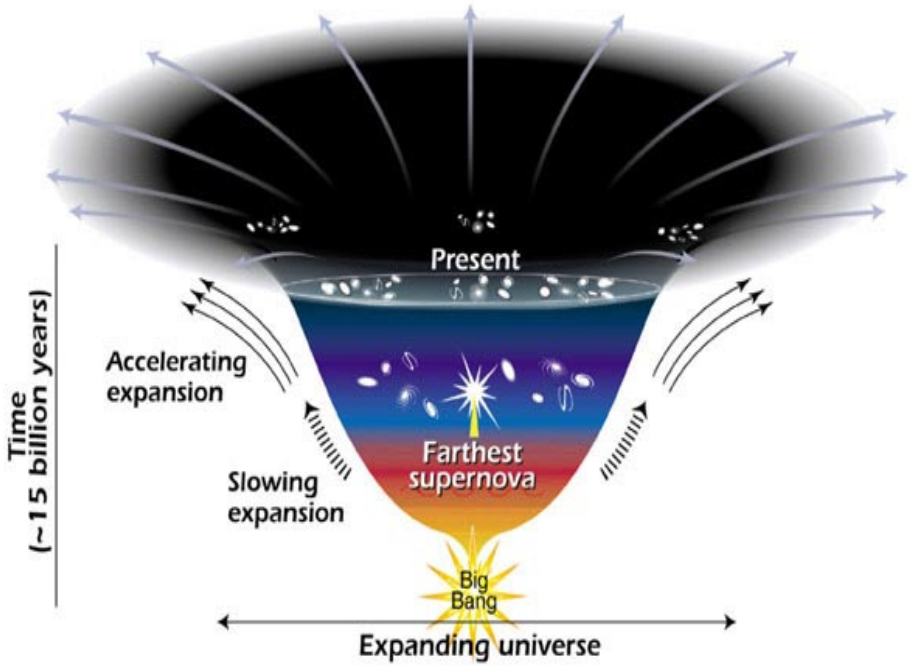
Parameter space where Higgs could hide is shrinking

- ATLAS 95% exclusions
  - $110 < m_H < 117.5$ GeV
  - $118.5 < m_H < 122.5$ GeV
  - $129 < m_H < 539$ GeV

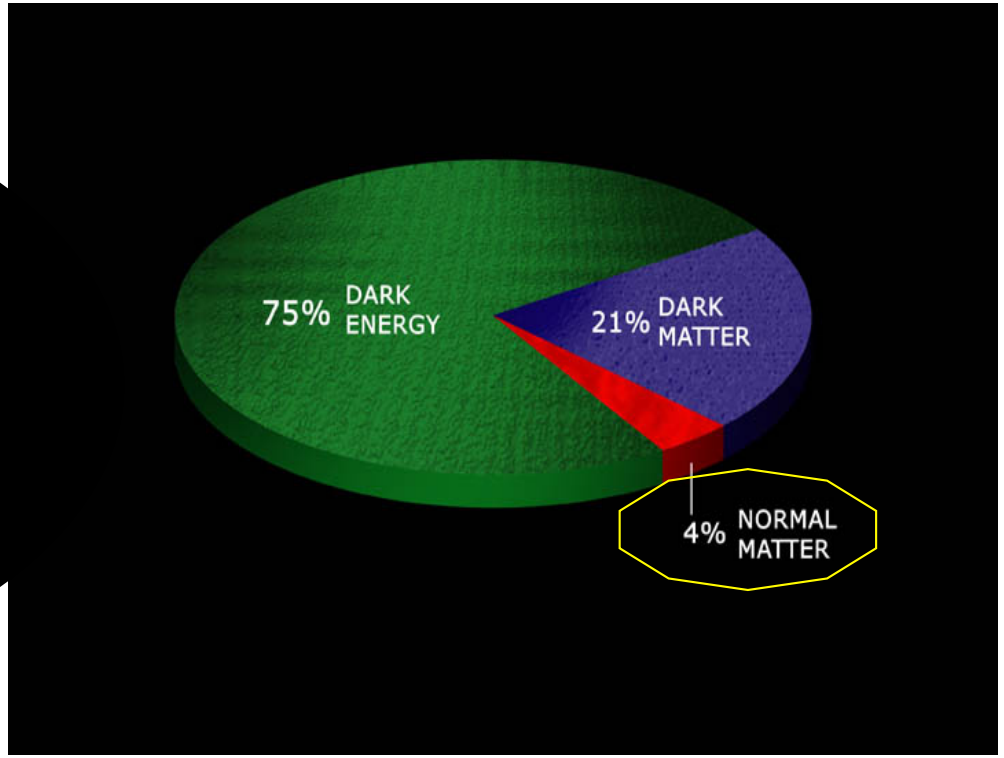


High Energy Physics may provide answers to some outsanding problems in Astrophysics and Cosmology

- What is the origin of mass?
- What is dark matter?
- What is dark energy?
- Do extra dimensions exist?
- What is the Universe's original symmetry?
- What happened with the original symmetry?
- What happened with the original antimatter?

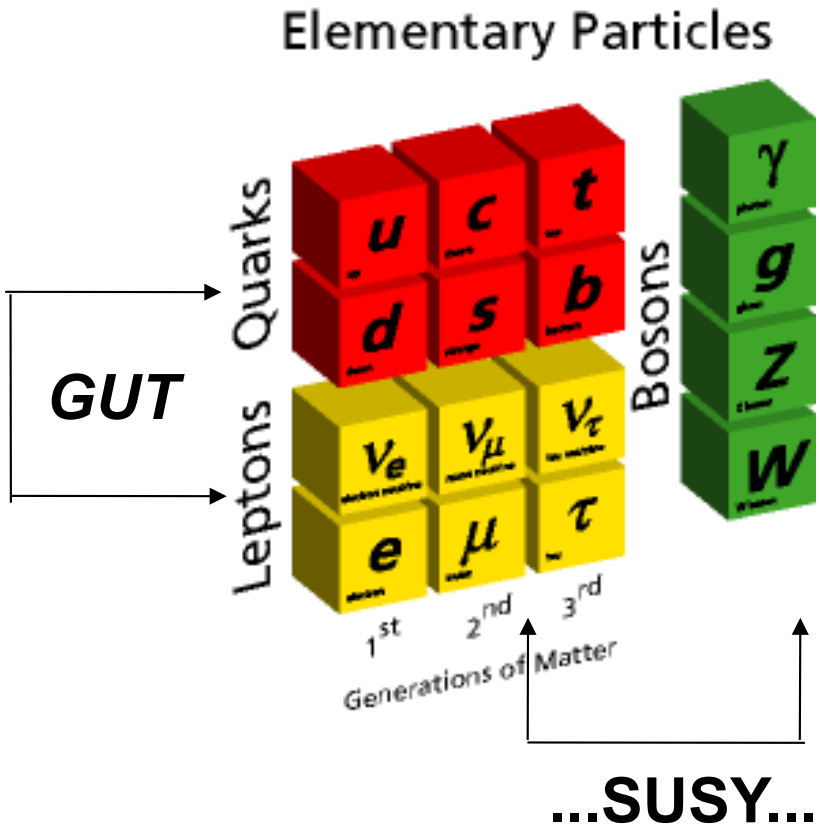


Vacuum with scalar field (`Higgs')
Spontaneous symmetry breaking
Supersymmetric particles
Extra dimensions, graviton

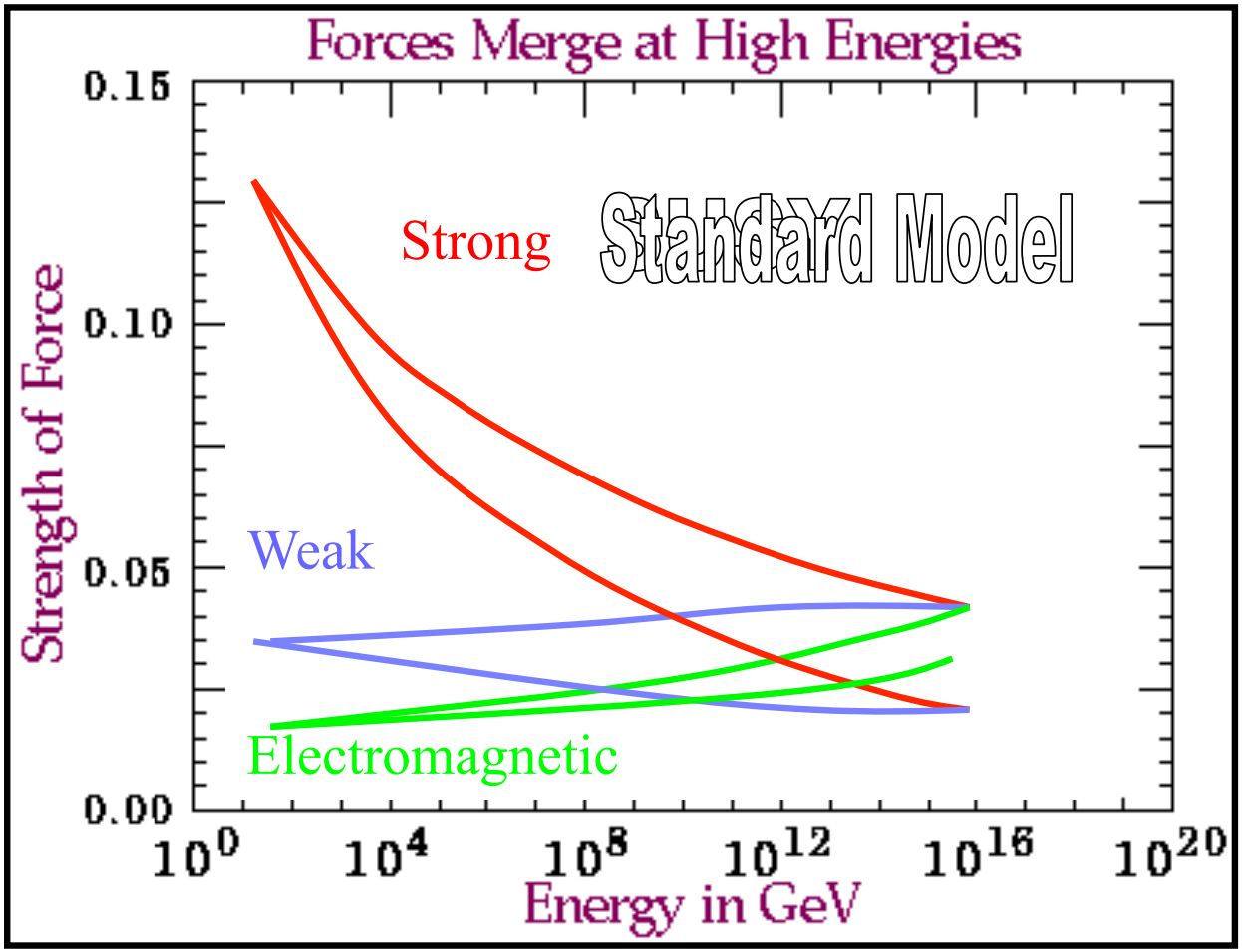


Grand Unification Theories (GUT) and SuperSymmetry (SUSY)

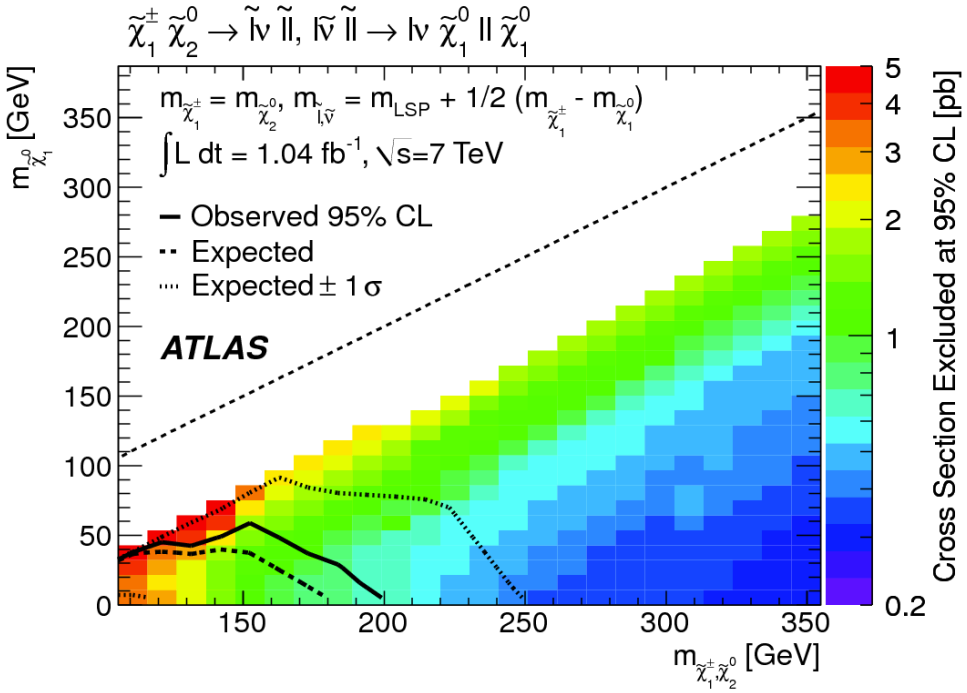
- Current data also hint at a unification between Strong and Electroweak forces … at much larger energies, GUT scale.
- GUT is a symmetry between Leptons and Quarks
  - unifies strong and electroweak forces
- SUSY unifies "matter and force particles": "matter-force duality"
  - relates particles of different spins: Fermions-Bosons
  - introduces super-partners to each SM particle
  - requires 5 Higgs particles
  - provides DM candidate

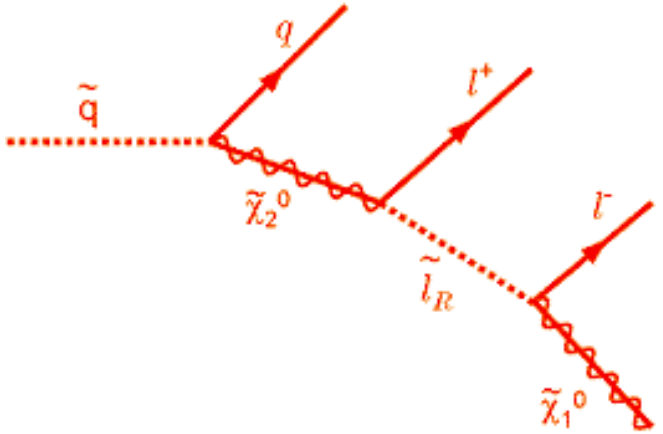


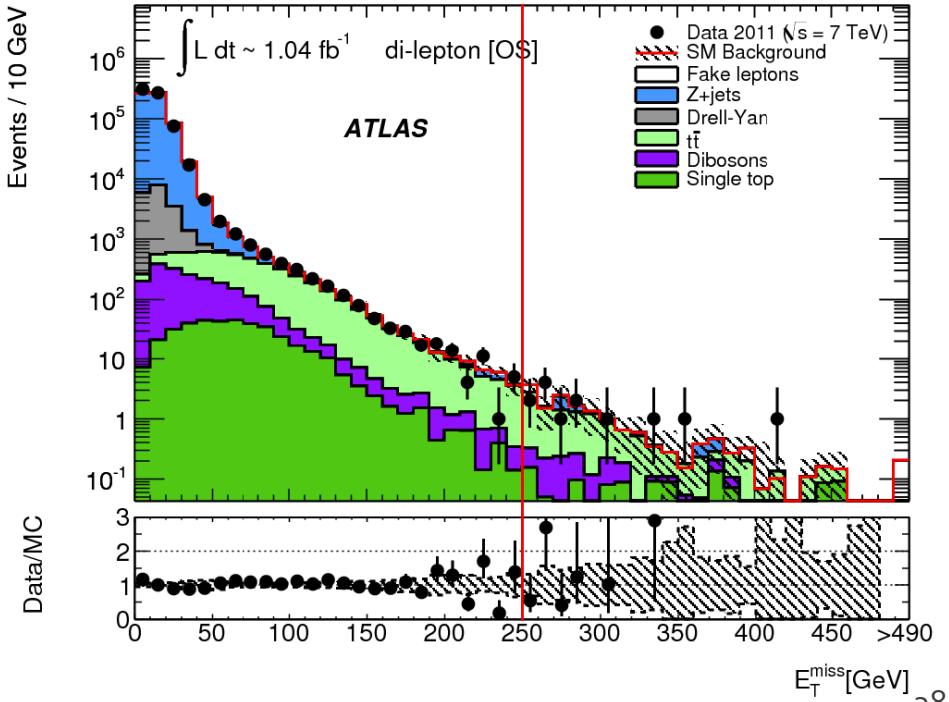
SUSY helps Grand Unification



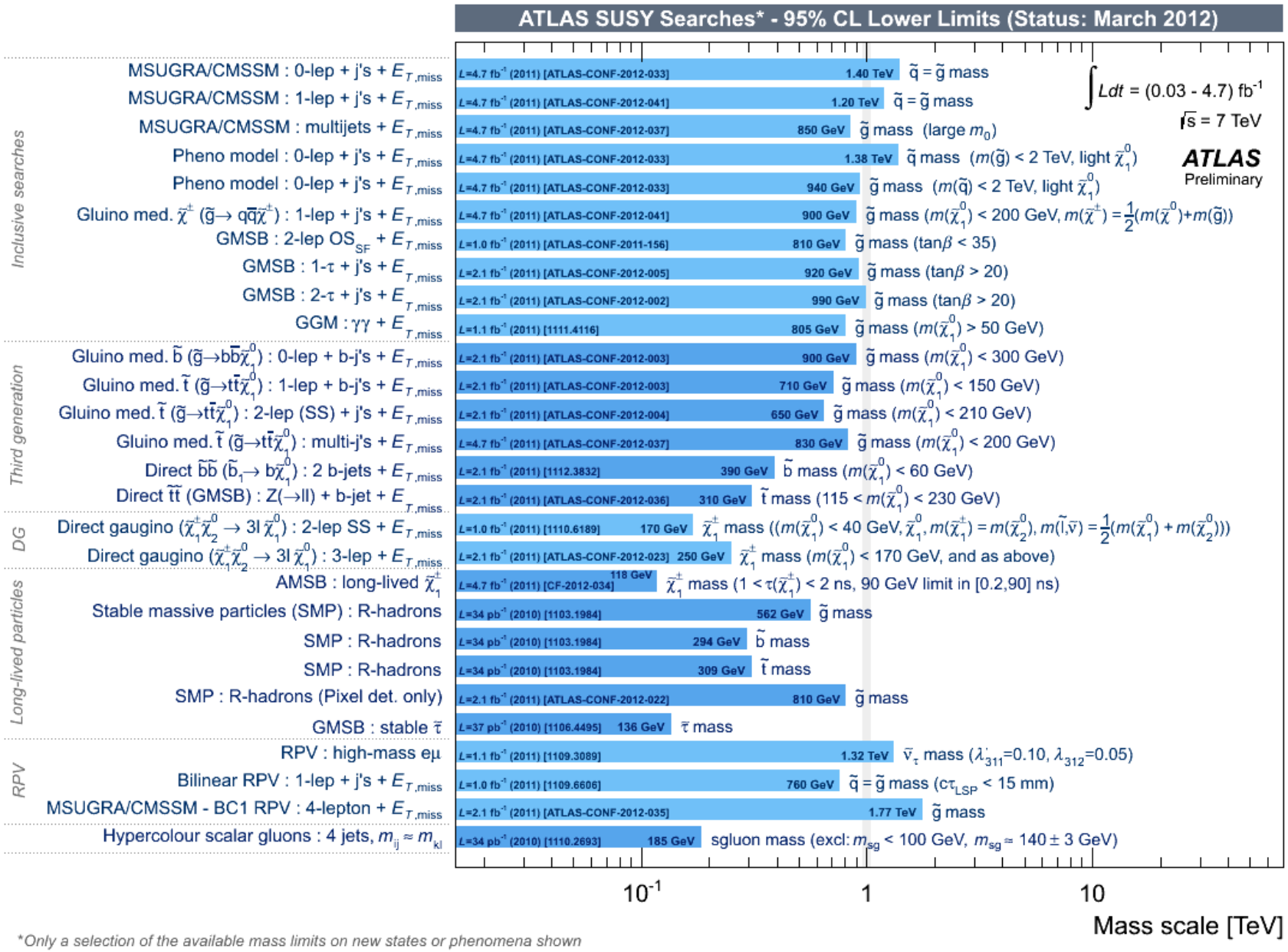
SUSY: 2leptons, missing energy







ATLAS SUSY searches



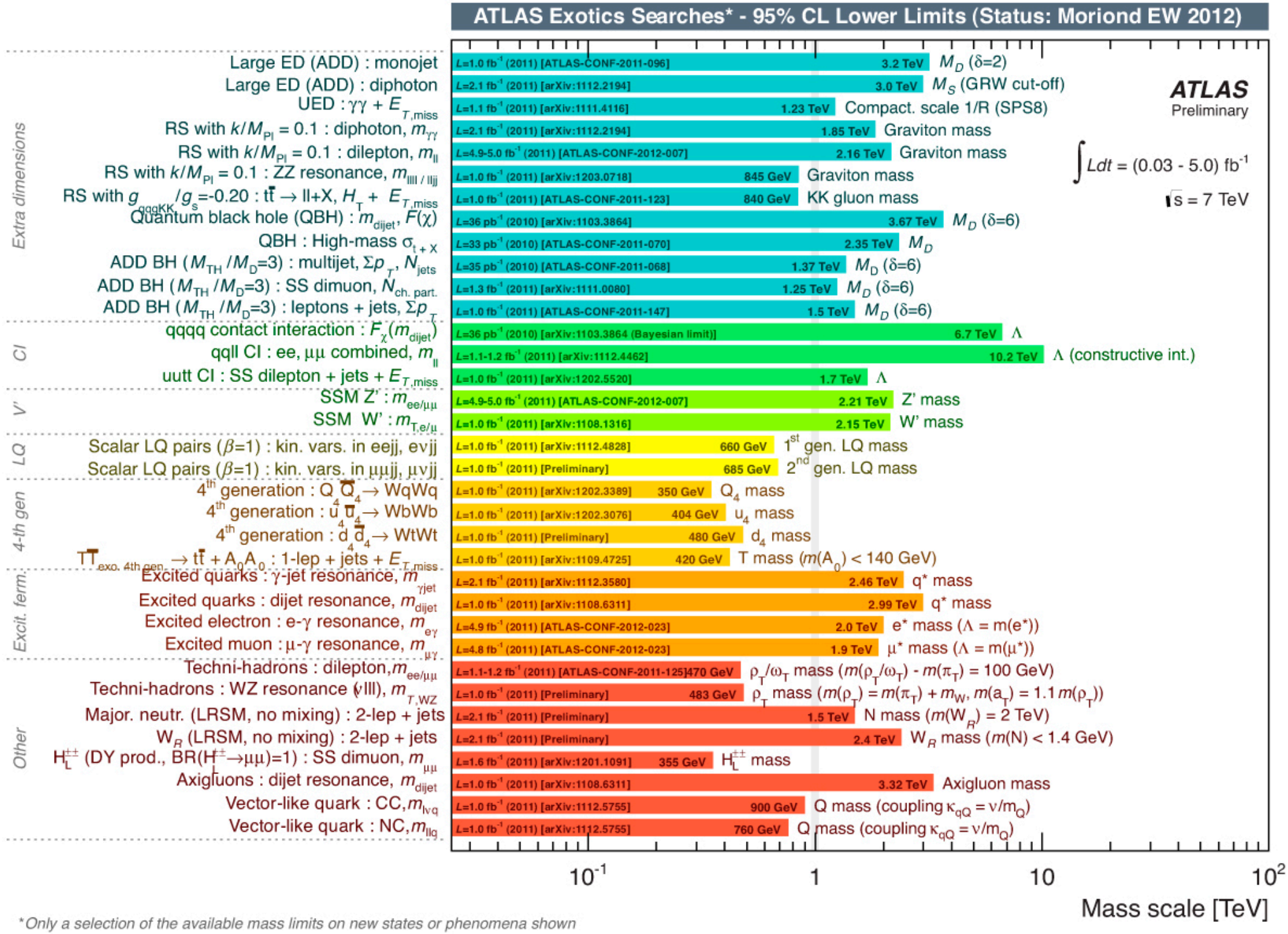
*Only a selection of the available mass limits on new states or phenomena shown

ATLAS constrains New Physics

Data shown at the "Rencontres de Moriond" meeting in March 2012

- The ATLAS Experiment is searching for an extremely broad variety of signs of new as-yet undiscovered physics. Many theories have been discussed in physics journals, and ATLAS has tremendous capabilities to investigate the signatures predicted by these theories.
- This plot gives an overview of a representative selection of the available results. Since there have been no discoveries with these early data, most results are summarized by saying that ATLAS has excluded a mass range below some value. In this plot, each bar shows the region that has been excluded at the 95% confidence level.

- Some of the abbreviations used are:
  ED = extra dimensions and UED = universal extra dimension
  BH = black holes and QBH = quantum black holes
  LQ = leptoquarks
  ADD, RS, and DY are refer to authors' initials.
  SS = same sign
  SSM = sequential Standard Model
  LRSM = left-right symmetric model
  BR = branching ratio

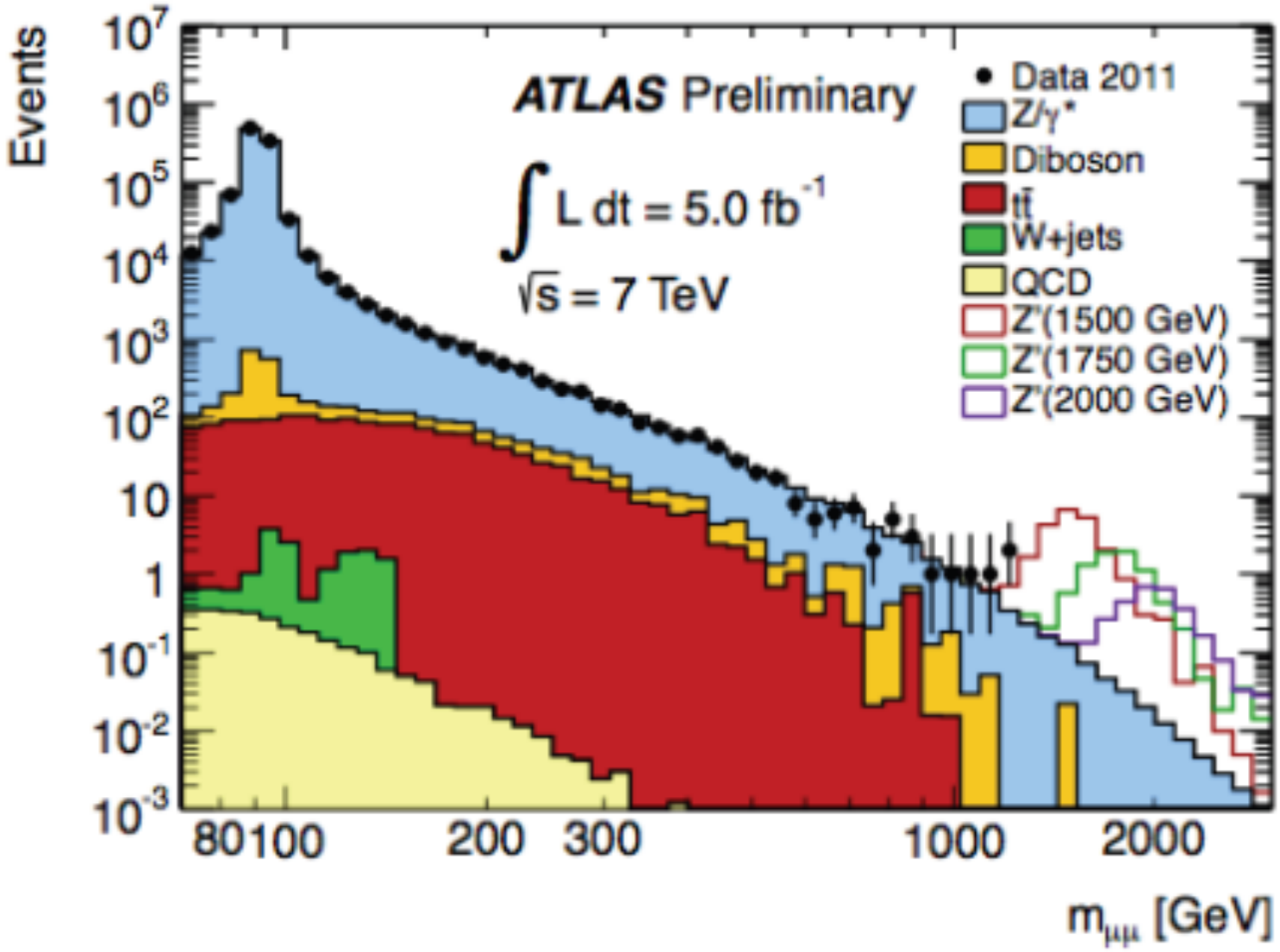


*Only a selection of the available mass limits on new states or phenomena shown

Any new physics out there?

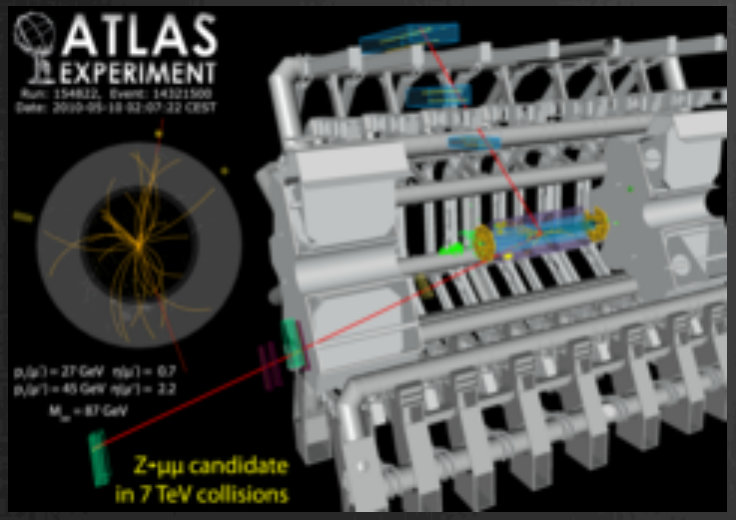
- Any new interactions mediated by
  - Z′
  - W′
- Any sign of the Graviton – hypothetic mediator of gravity?

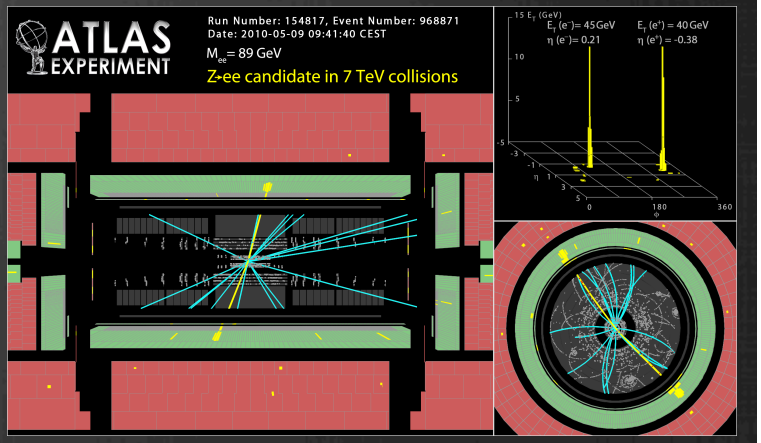
- M(Z′)>2.21 TeV
- M(G*)>2.16 TeV



https://kjende.web.cern.ch/kjende/en/index.htm

Actual LHC Results





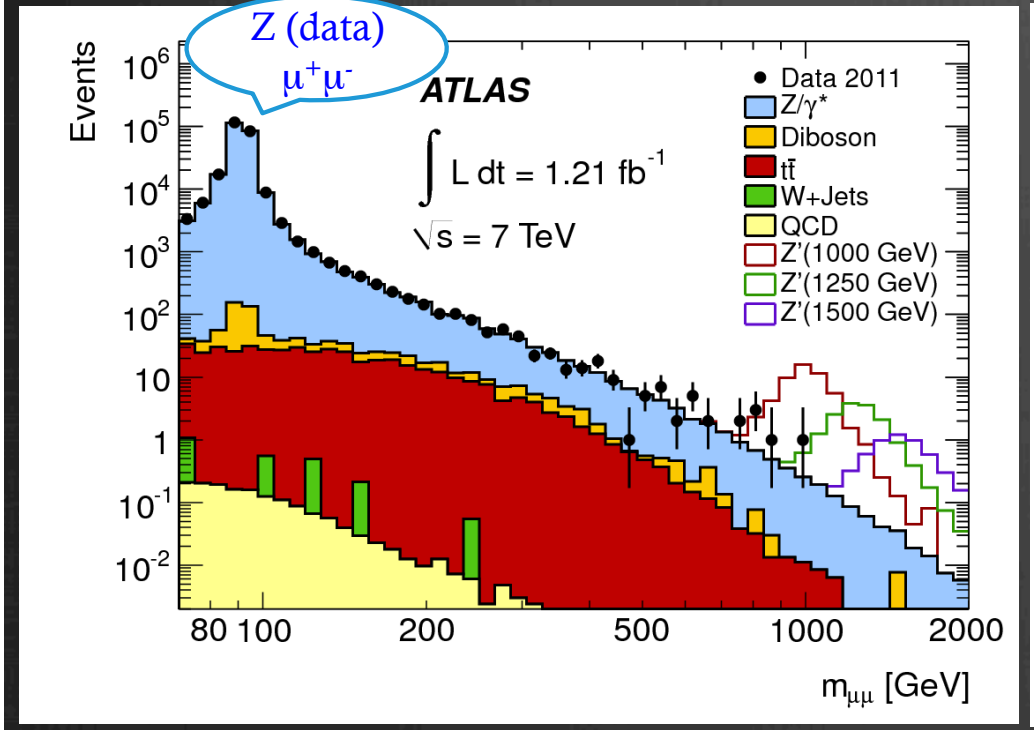
http://atlas.ch/photos/events-collision-proton.html

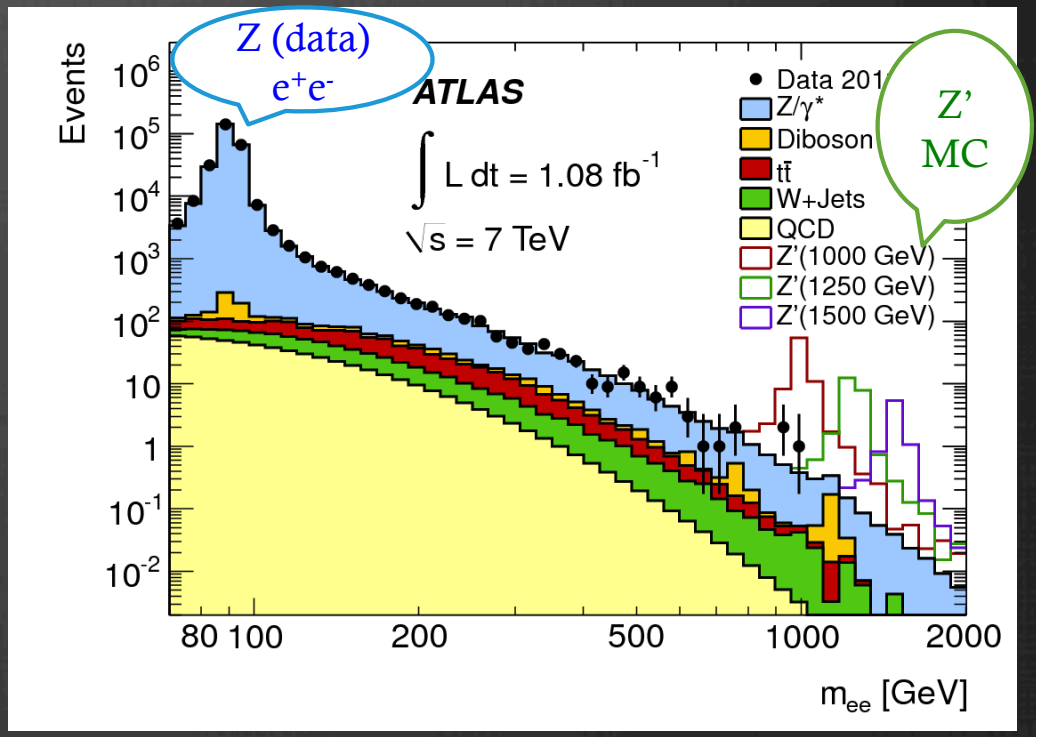
Prepared for the International Particle Physics Masterclasses 2012
F. Ould-Saada, M. Pedersen

Well done, you were so close to ATLAS!

Standard Model rediscovery at LHC with invariant mass technique

Is there any New Physics out there? For example a new weak interaction mediated by a Z' boson?





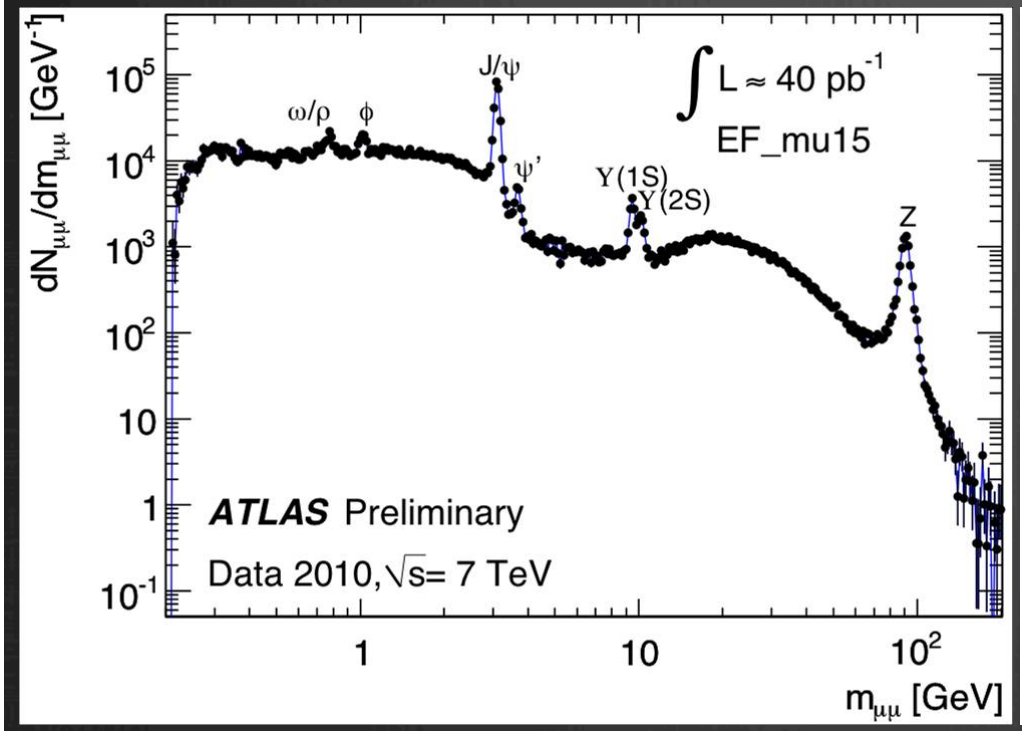
- **Z' must be heavier than 1-2 TeV**
- **Need more statistics to conclude**

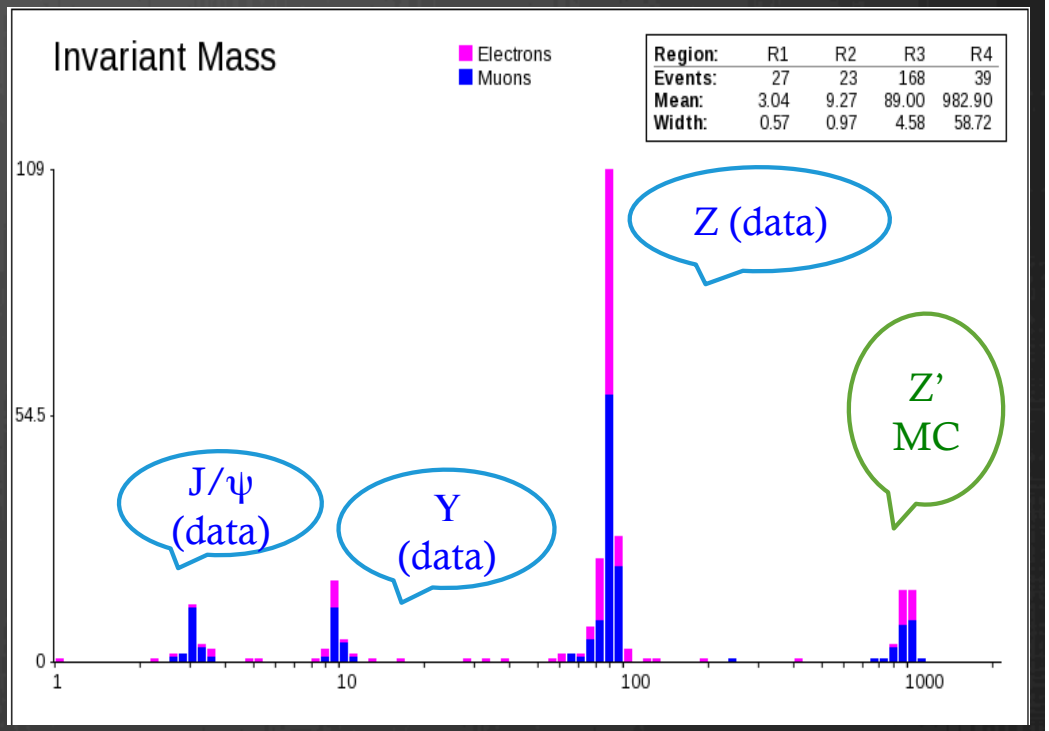
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome#Physics_papers

Well done, you were so close to ATLAS!

Standard Model rediscovery at LHC with invariant mass technique

Is there any New Physics out there? For example a new weak interaction mediated by a Z' boson?

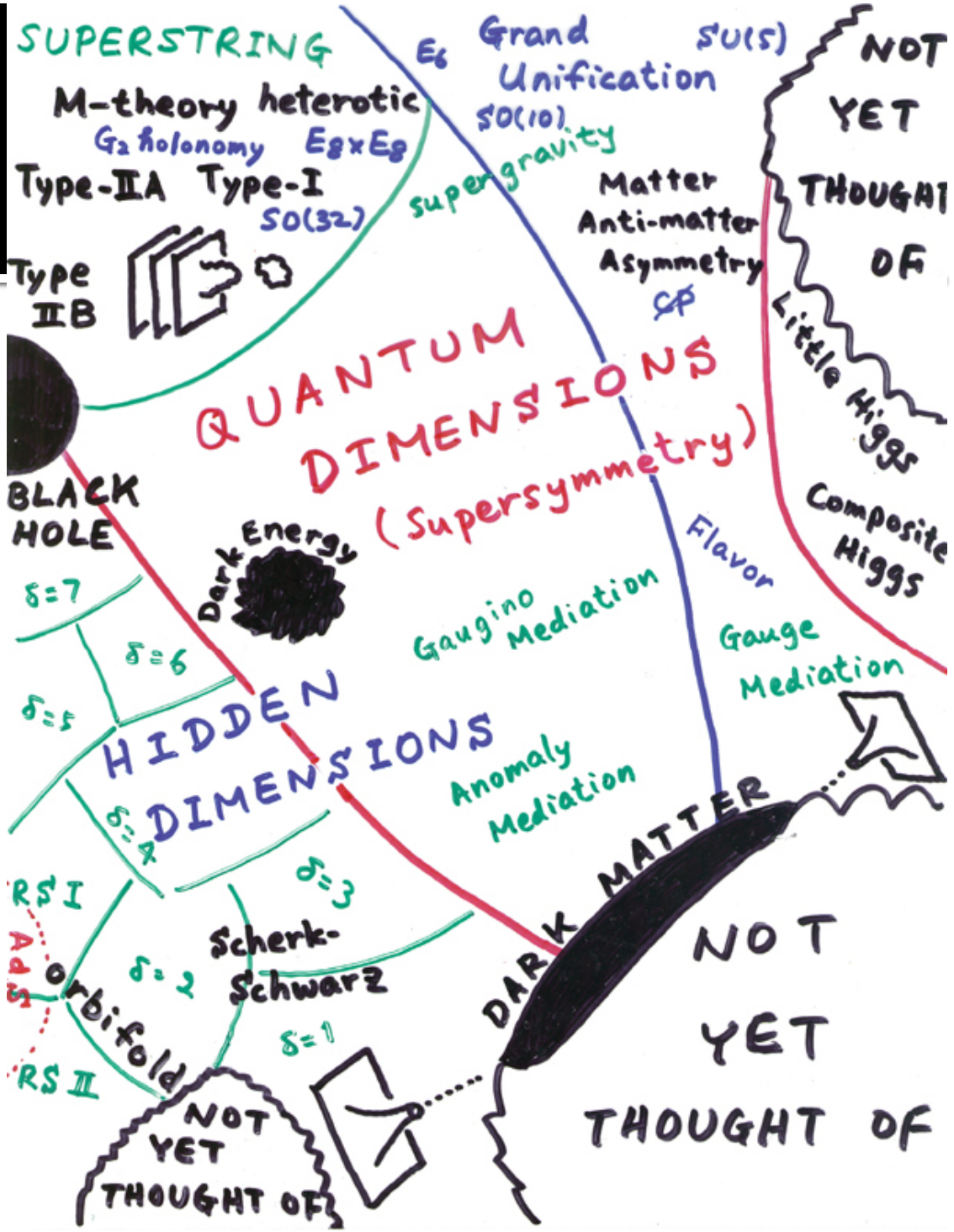




- **ATLAS and CMS have re-discovered many of the Standard Model particles**
- **You have discovered the J/ψ, Υ and Z**
- **The Z' signal at 1 TeV is Monte Carlo simulated!**

What more?

- Superstrings, GUT, Supersymmetry, Black holes, Extra dimensions, compositeness, …
- Maybe some new particle with some
  - **Newtyetthoughtov**



Let us see with LHC !

We must all be patient ☺