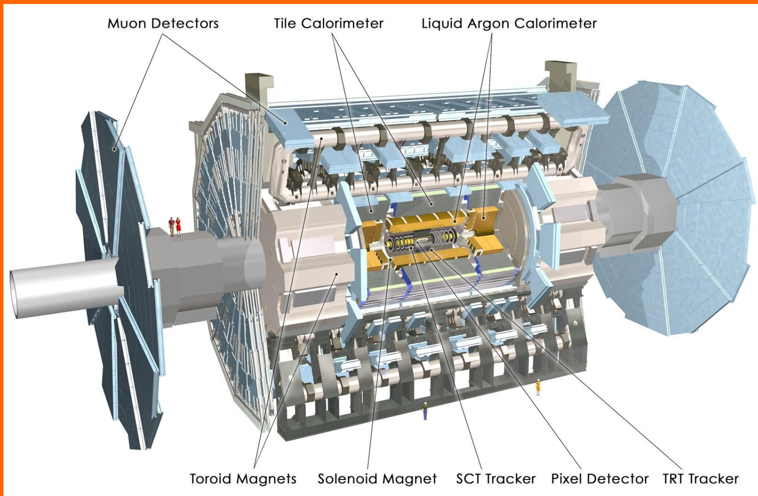
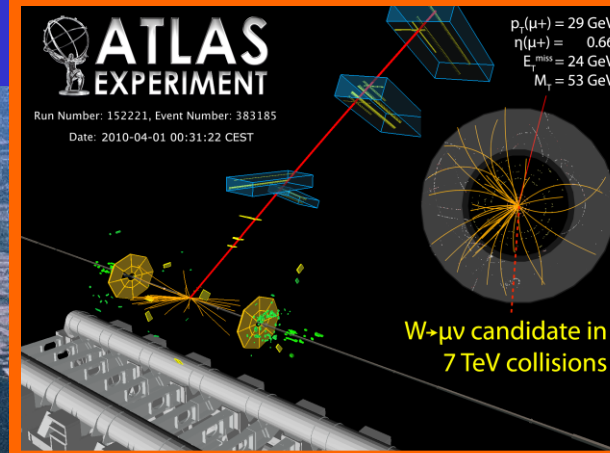




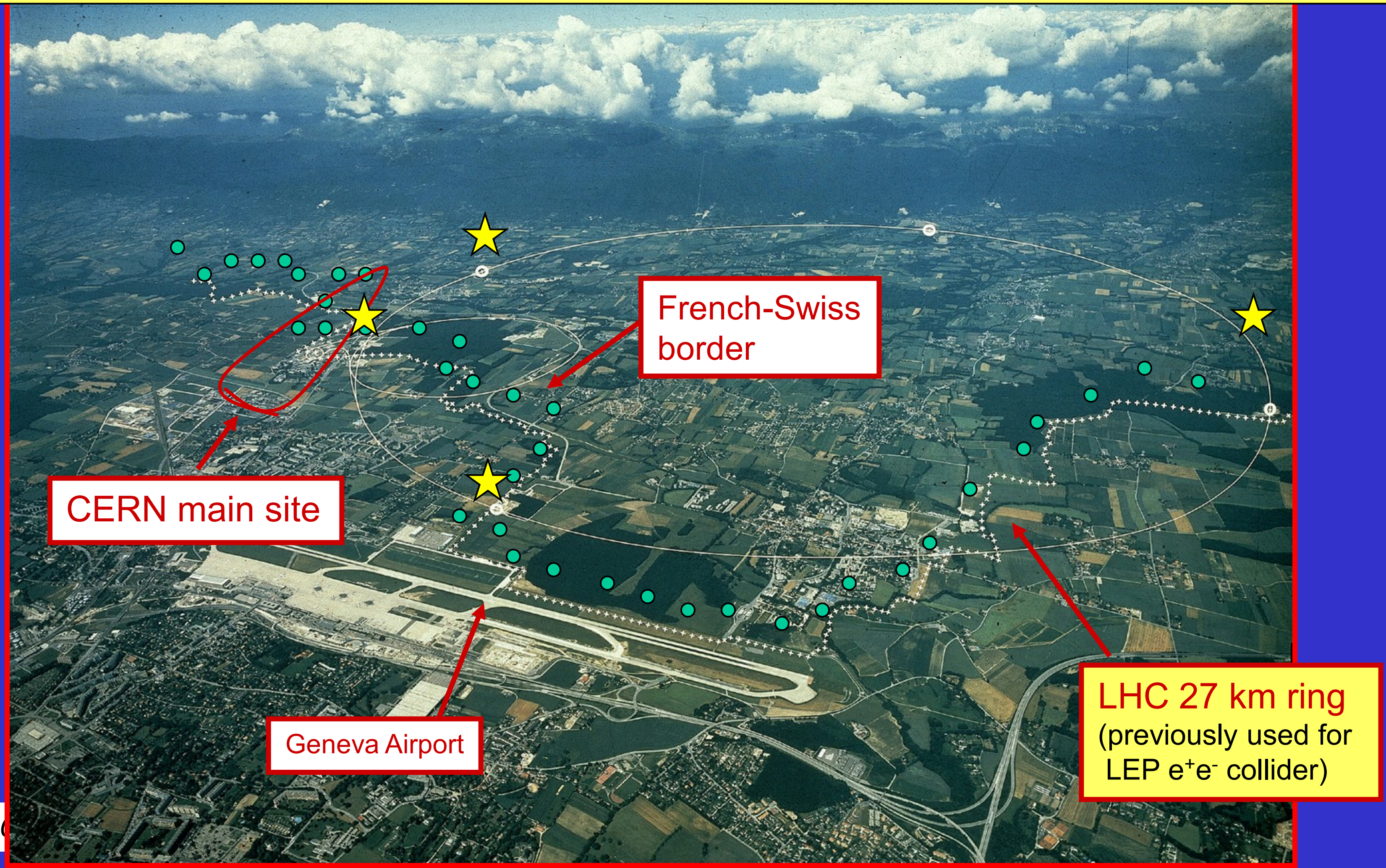
Crossing a new energy frontier: latest results from the ATLAS experiment at the LHC

- ❑ Introduction: the LHC and its physics goals
- ❑ The ATLAS experiment
- ❑ Latest physics results and prospects

Fabiola Gianotti (CERN) 011

Introduction

- The LHC is a 27 km accelerator ring, 100 m below ground, across the French-Swiss border
- Two proton beams are accelerated in opposite directions
  Beam energy today: 3.5 TeV → $\sqrt{s}$=7 TeV
  Design energy (to be achieved in 2014): $\sqrt{s}$=14 TeV
- They collide at four points, where four big experiments have been installed



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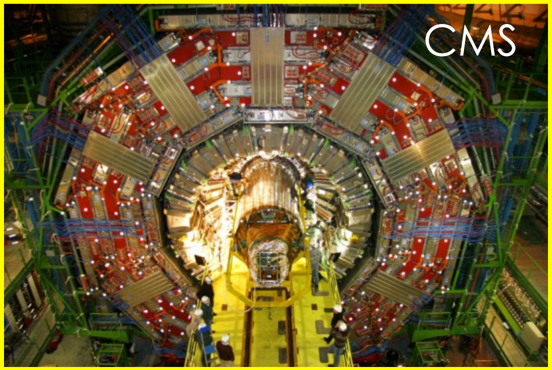
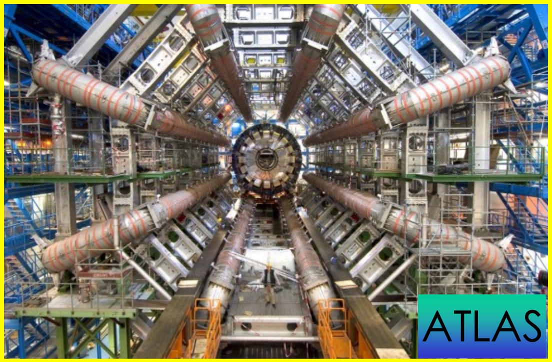


LHC ring:
27 km circumference



The LHC is one of the most spectacular projects in science ever …

1984 : First studies for a high-energy pp collider in the LEP tunnel
1989 : Start of SLC and LEP e^+e^- colliders
1993 : SSC is cancelled
1994 : LHC approved by the CERN Council
1995 : Top-quark discovery at the Tevatron
1996 : Construction of LHC machine and experiments start
2000 : End of LEP2
2003 : Start of LHC machine and experiments installation
2009 : 23 November: first LHC collisions ($\sqrt{s}$ = 900 GeV)
2010 : 30 March: first collisions at $\sqrt{s}$ = 7 TeV
→ Inauguration of a ~ 20-year long physics programme

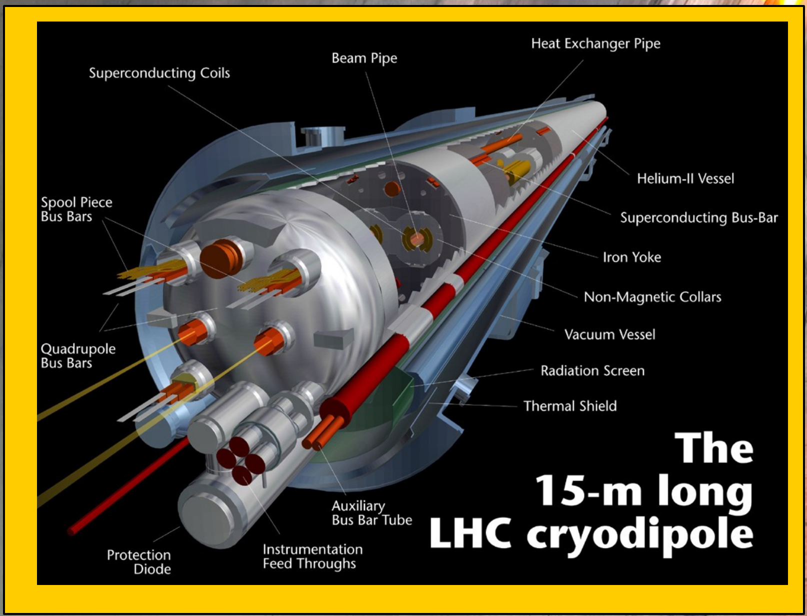
A ~ 45-year project:
- 25 years from concept to start of operation
- 20 years of physics exploitation

The LHC has required:
- most innovative technologies (superconducting magnets, cryogenics, electronics, data transfer and storage, etc…)
- new concepts, a lot of ingenuity to address challenges and solve problems
- huge efforts of the worldwide community (ideas, technology, people, money)

The most challenging component of the accelerator is the system of 1232 high-tech superconducting dipole magnets, providing a field of 8.3 T (needed to bend 7 TeV beams inside a 27 km ring). → p(TeV) = 0.3 B(T) R(km)

7600 km of NbTi superconducting cable.

Work at 1.9K in a bath of 120 tons of superfluid Helium



Built by 3 European industries: Alstom/France, Ansaldo/Italy, Babcok-Noell/Germany

A few numbers .....

Number of magnets in the accelerator: ~ 10000 (~ 7000 are superconducting)

Length of filaments of dipole magnet superconducting cable: enough to go 5 times to the sun and back plus a few trips to the moon

Number of turns of the LHC ring made by protons in one second: ~ 11000

Number of beam-beam colli ... 40 million
Beam cross secti ... than that
of a typical

Energy sto ... 12 knots

Accelerator temperatu

WHY ???

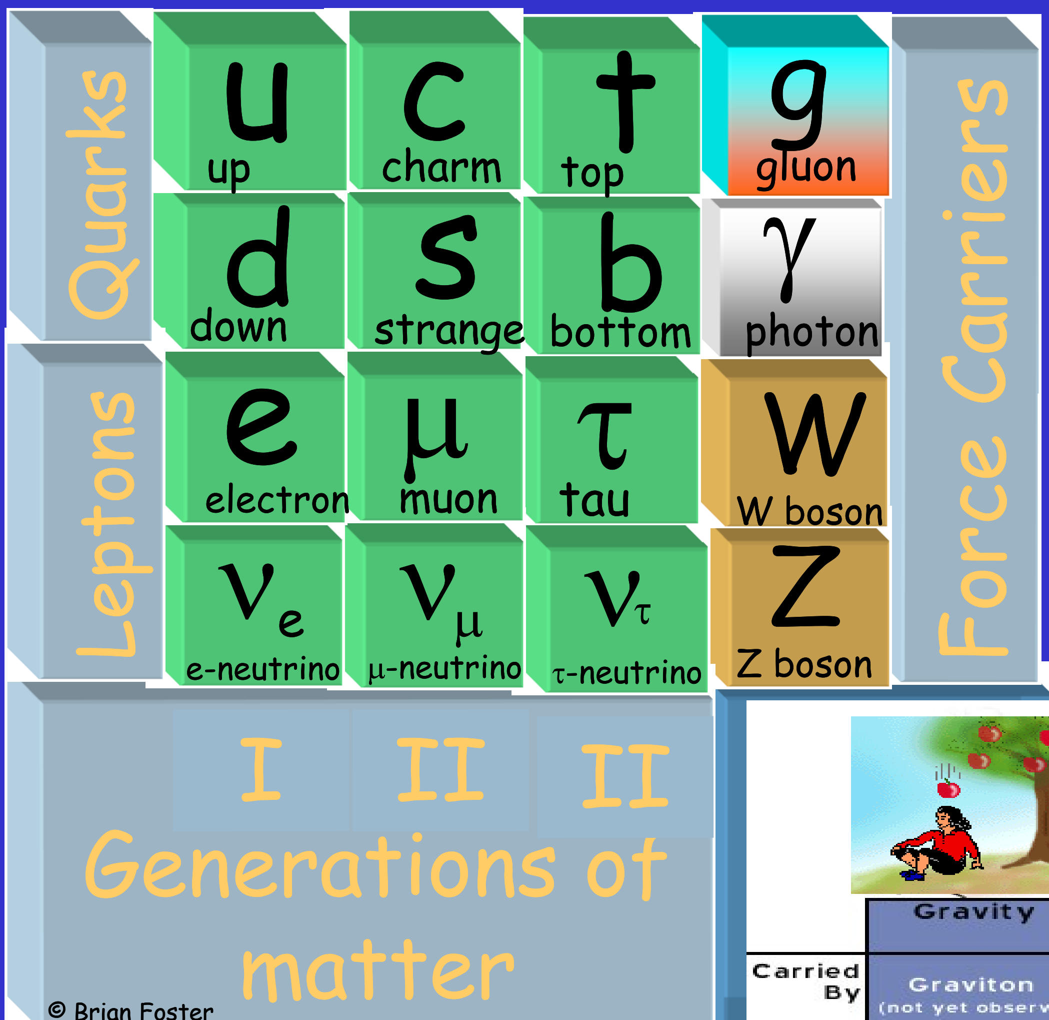
The CMS experiment weighs more (13000 tons) and contains more iron than the Tour Eiffel

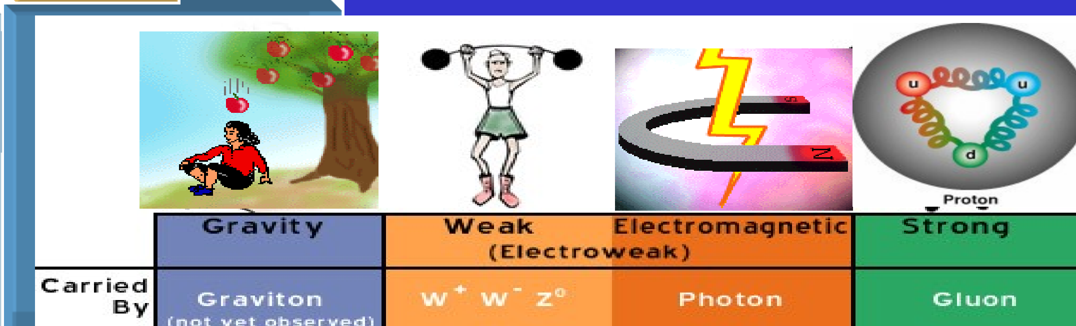
Amount of cables used to transfer the signals from ATLAS detector: ~3000 km

Etc. etc.

The elementary particles and their interactions are described by a very successful theory: the Standard Model. All particles foreseen by the SM (but one) have been observed, and the SM predictions have been verified with extremely high precision over the last 35 years by experiments at CERN and at other labs all over the world

Particles and forces





Some of the outstanding questions today

What is the origin of the particle masses ?
→ LHC can settle the Standard Model Higgs question by ~ end 2012 — **ATLAS,CMS**

What is the nature of the Universe dark matter ? — **ATLAS,CMS**

Why is there so little antimatter in the Universe ? — **LHCb**
(Nature's favouritism allowed us to exist …)

New Physics beyond the Standard Model is needed to answer these and other questions. The huge amount of precise experimental data collected so far indicate that this New Physics should manifest itself at the ~ TeV energy scale to be explored by the LHC

life (10^{-10} s after the Big Bang) ? — **ATLAS,CMS**

Are there other forces in addition to the known four ?
Are there additional (microscopic) space dimensions ? — **ATLAS,CMS**

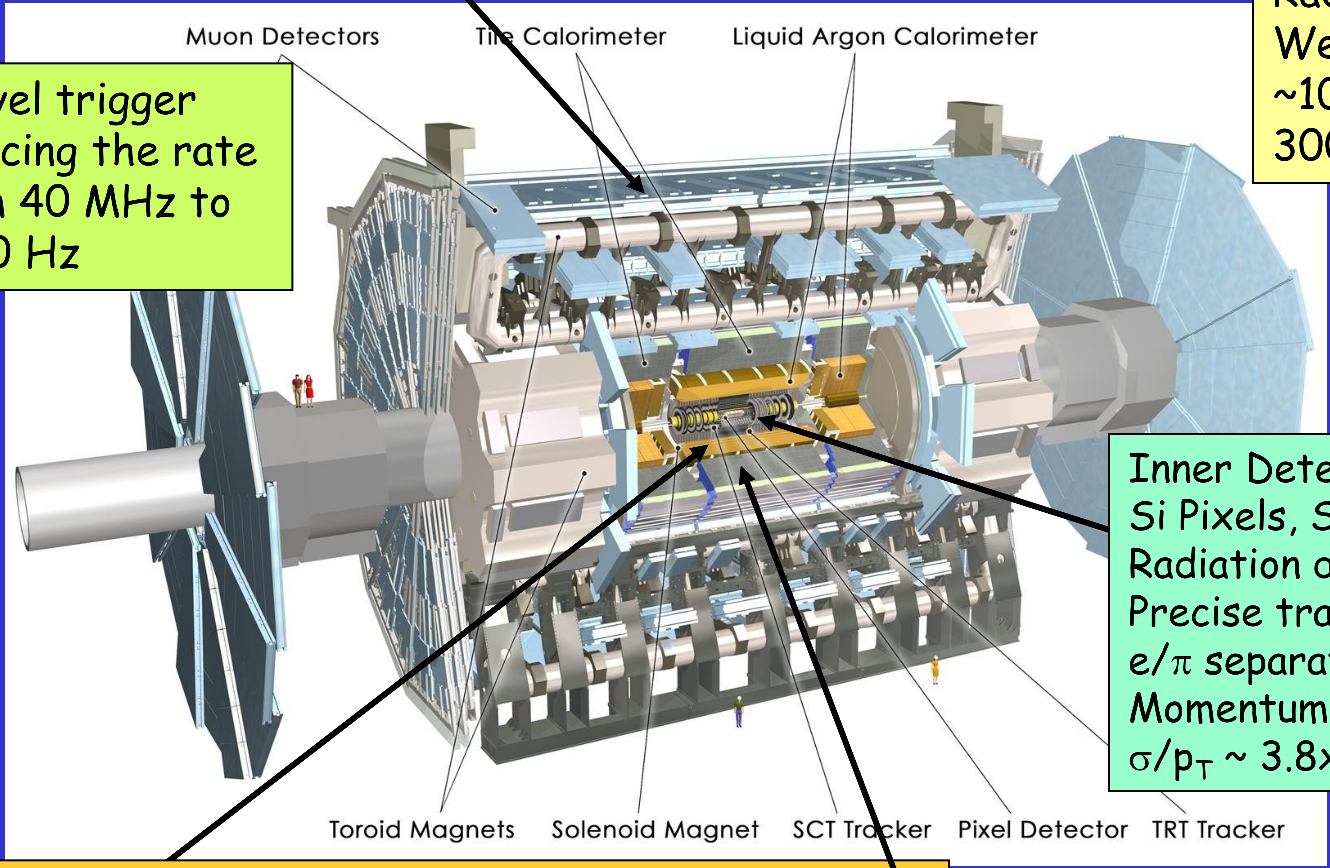
Etc. etc.

The ATLAS experiment

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger reducing the rate from 40 MHz to ~200 Hz



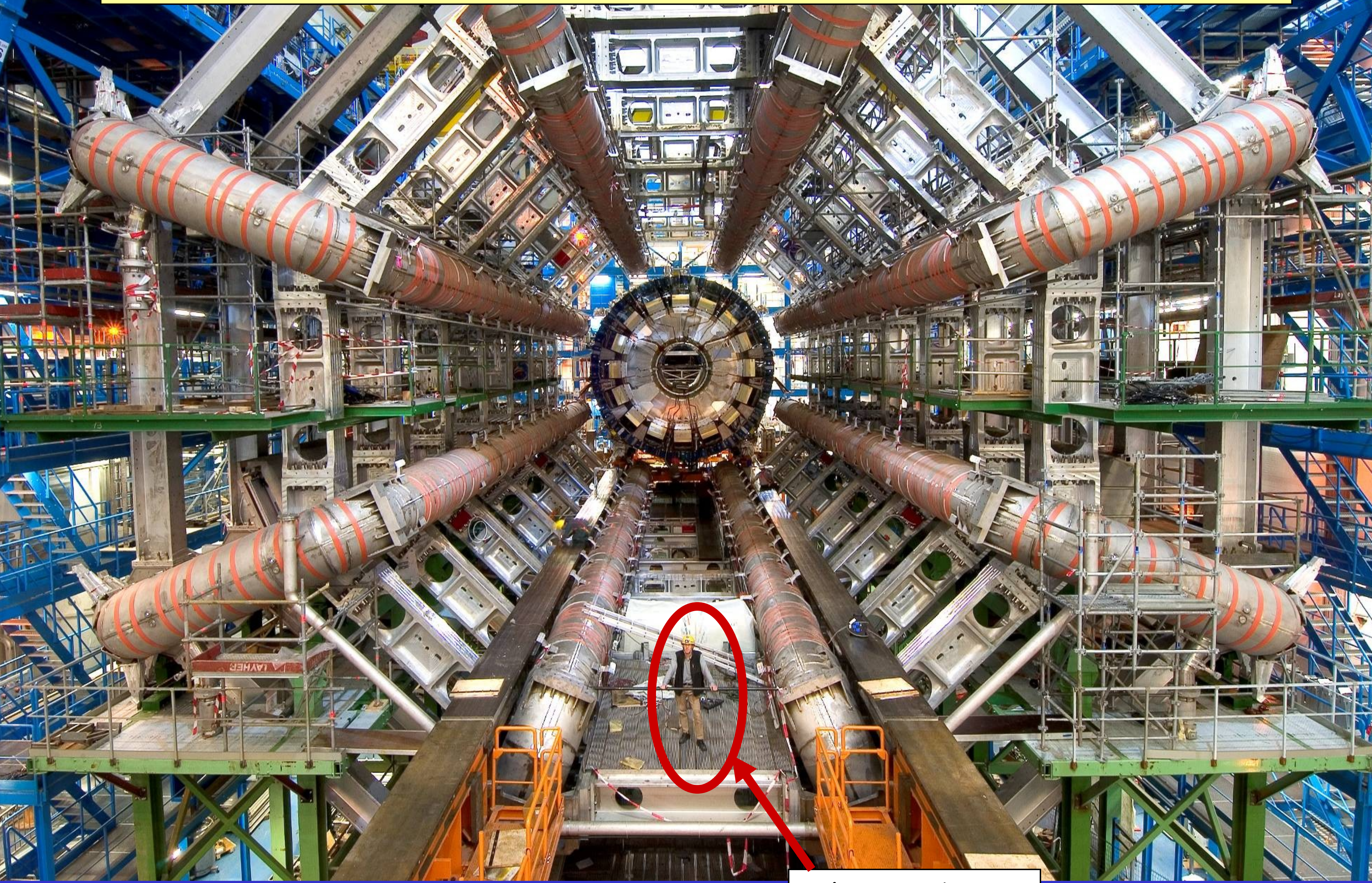
Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\text{GeV}) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

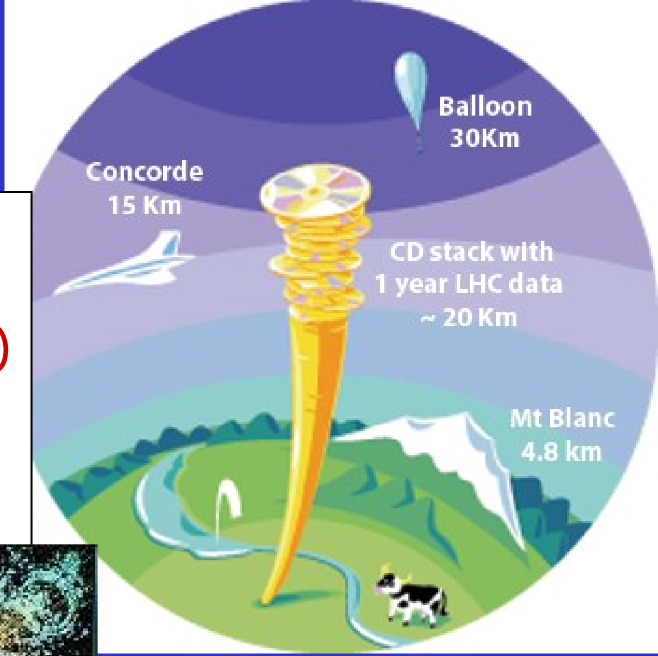
HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

ATLAS cavern (-100 m) in June 2003

October 2005: Barrel toroid magnet system in place



Computing



Each LHC experiment produces ~ 10 PB of data per year 1 PB=10^6 GB

This corresponds to ~ 20 million DVD (a 20 km stack …)

Data analysis requires computing power equivalent to ~100 000 today's fastest PC processors.

The experiment international Collaborations are spread all over the world → computing resources must be distributed.

↓

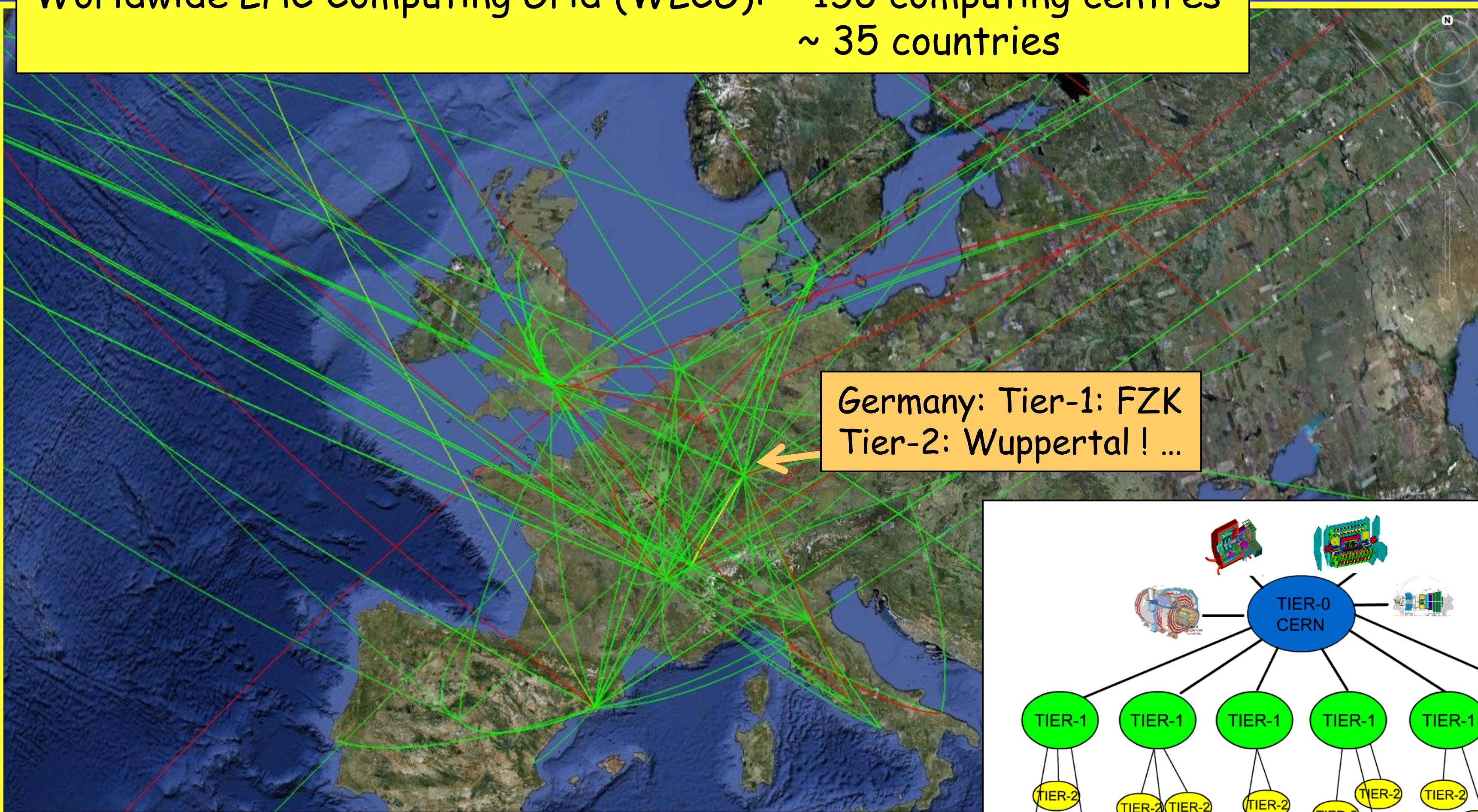
Cooperation of many computer centres all over the world is needed →

Grid

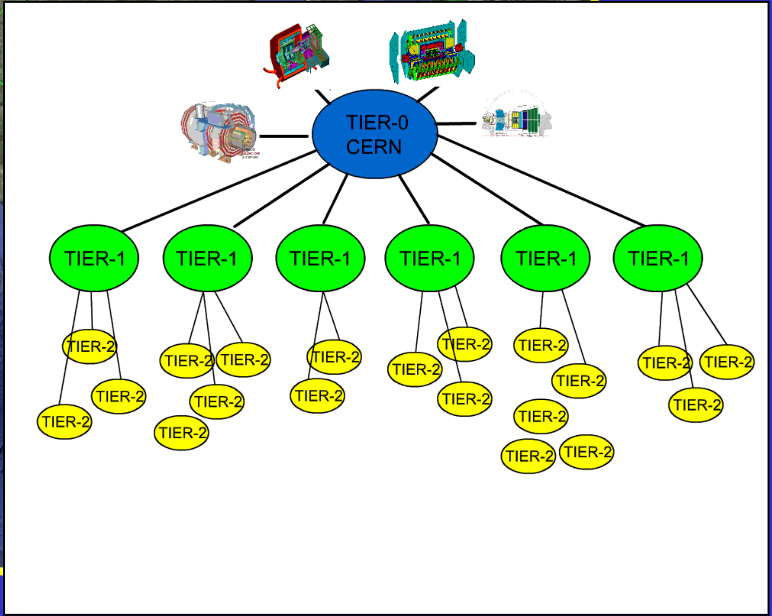
F. Gianotti, Wuppertal, 23/5/2011

The Grid provides seamless access to computing power and data storage capacity distributed over the globe

Worldwide LHC Computing Grid (WLCG): ~ 150 computing centres
~ 35 countries



Germany: Tier-1: FZK
Tier-2: Wuppertal ! …



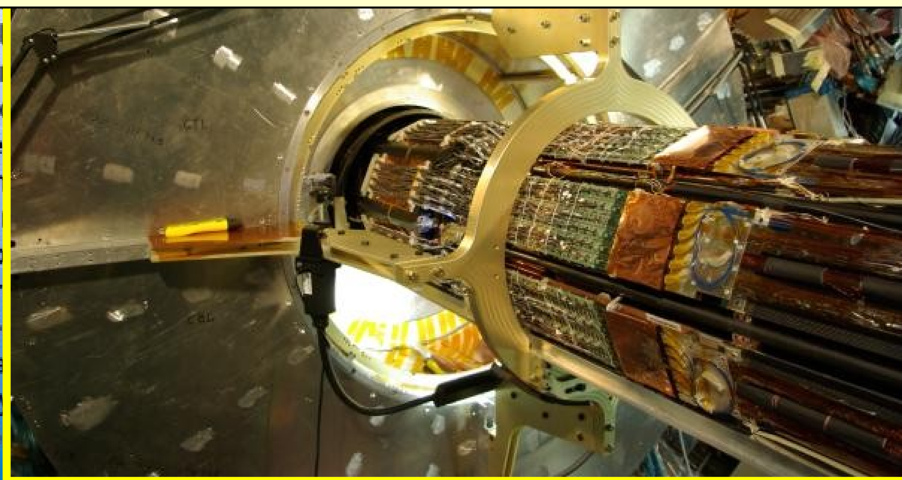
Very successful operation of the LHC Grid in first year of LHC operation allowed users from all over the world to analyse the data quickly
→ fast release of physics results

~ 3000 scientists from 174 Institutions from 38 Countries

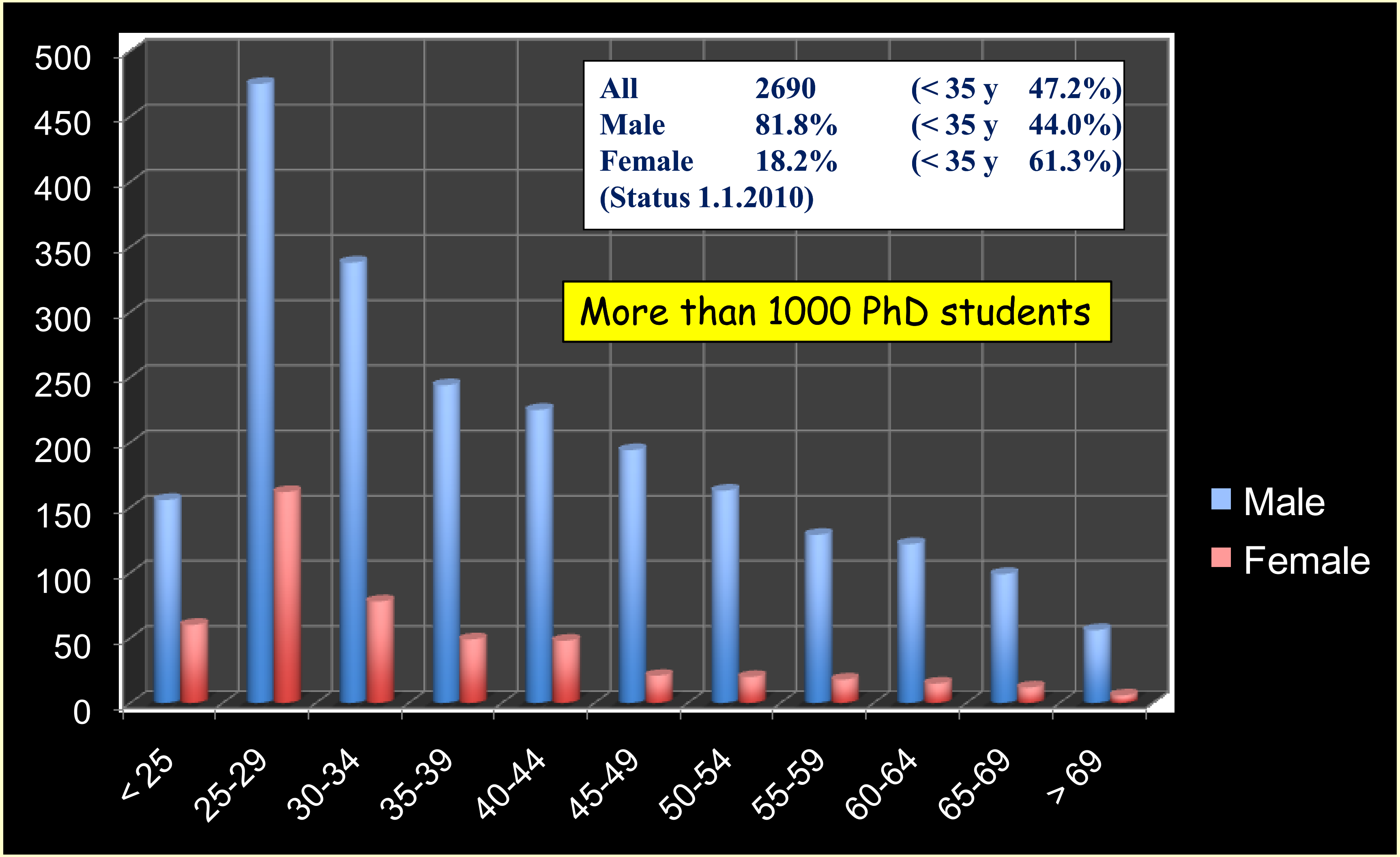
Germany:

- Berlin Humboldt, Bonn, DESY, Dortmund, Dresden, Freiburg, Giessen, Goettingen, Heidelberg, Mainz, Munich LMU, Munich MPI, Siegen, Wuerzburg, Wuppertal
- ~ 420 scientists (~200 students)
- Contributed to the whole detector, now strong impact in data analysis
- Wuppertal (~45 scientists): Pixel detector, software, physics (top-quark, ..), upgrade (new Pixel layers: high-tech, ultra-light support structures, high bandwidth data transmission, control systems)

ATLAS Pixel detector:
80 million high-tech Si pixels of size ~ 50µ
(big contributions by Wuppertal University group)



Age distribution of the ATLAS population



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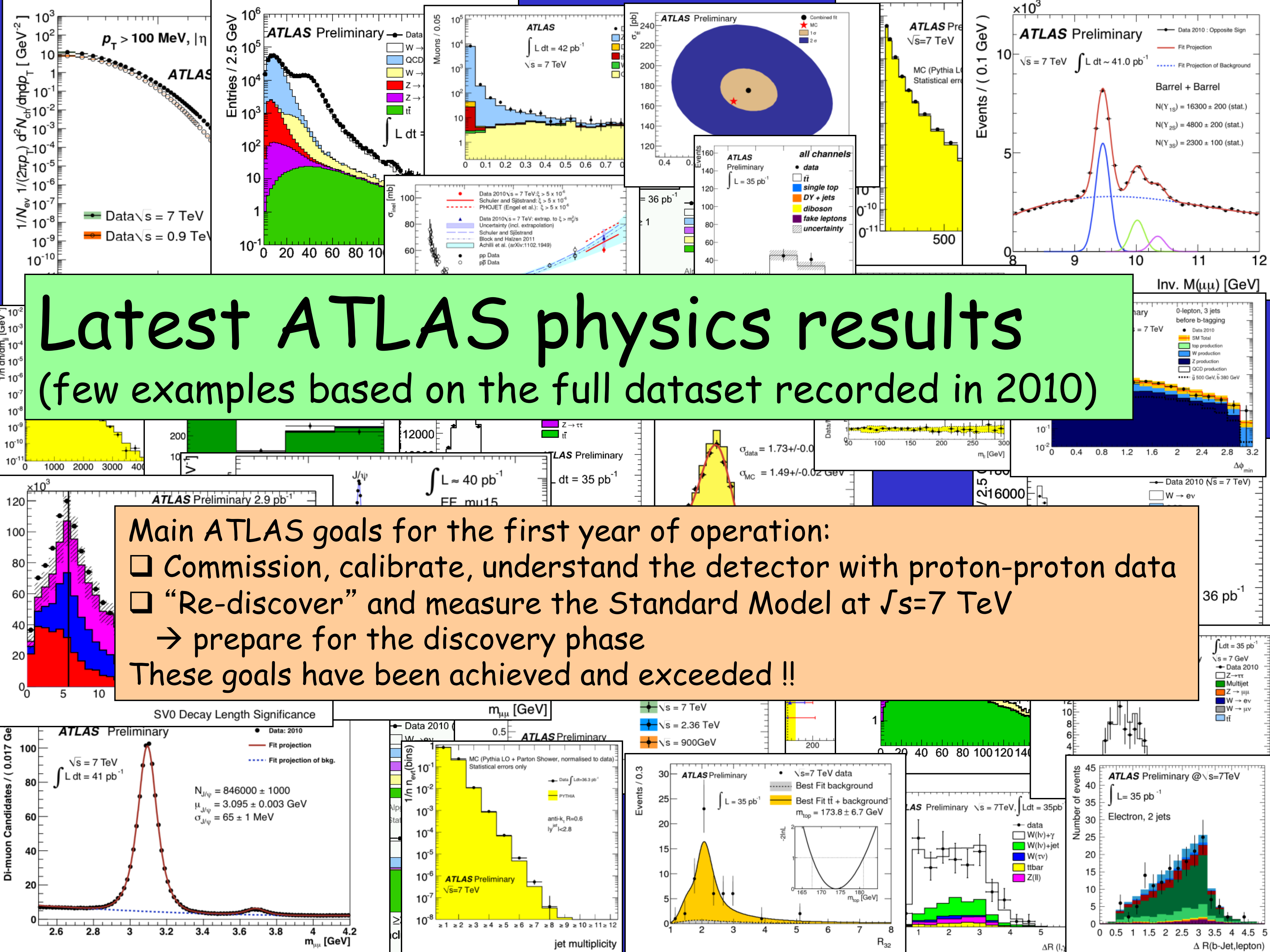
Latest ATLAS physics results

(few examples based on the full dataset recorded in 2010)



Main ATLAS goals for the first year of operation:

- ❑ Commission, calibrate, understand the detector with proton-proton data
- ❑ "Re-discover" and measure the Standard Model at $\sqrt{s}$=7 TeV
  → prepare for the discovery phase

These goals have been achieved and exceeded !!

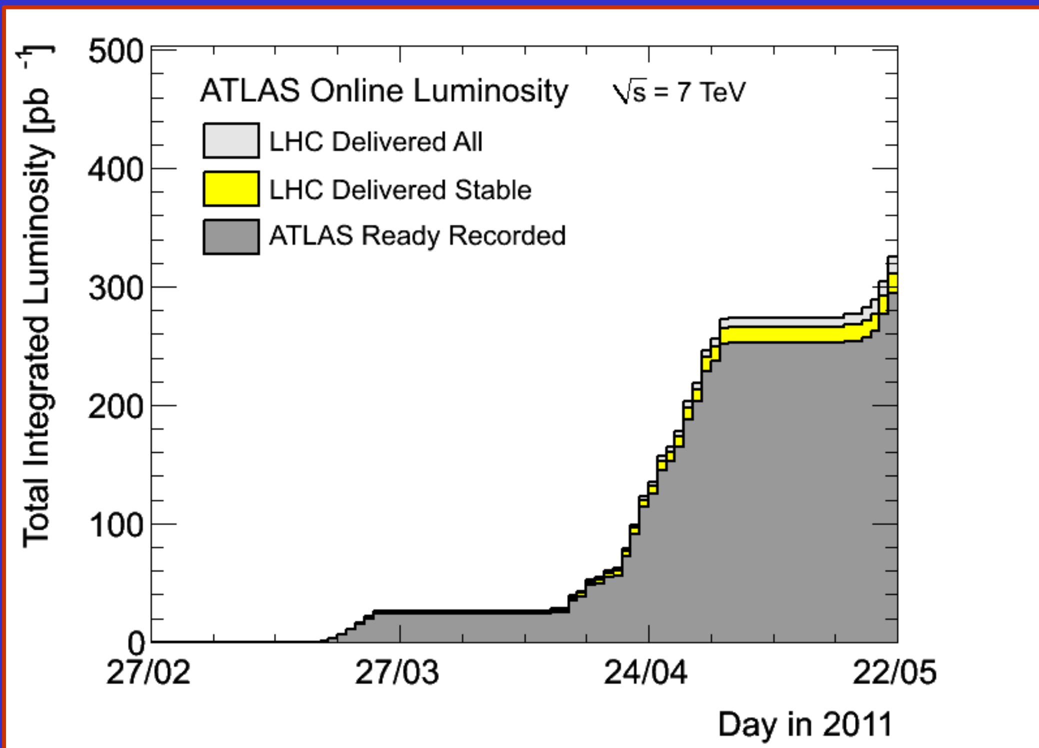
Chronology of the last (very exciting ..) year

- 30 March 2010: first collisions at $\sqrt{s}$ = 7 TeV (world record)
  → exploration of the new energy frontier begins
- 6 December 2010: end of the first LHC run → short technical stop
- 13 March 2011: operation resumes
- Will run until end 2012 (with short technical stop end 2011)
  → expect integrated luminosities of 5-10 fb^{-1} per experiment
- Then long shut-down (2013-2014) to achieve design energy ($\sqrt{s}$ = 14 TeV)

An impressive start !

The accelerator, experiments and computing performed beyond expectations:

- commissioning of accelerator, experiments, Grid much faster than expected
- the accelerator has achieved (today @ 2:14 AM) $L \sim 1.1\times10^{33}\ cm^{-2}\ s^{-1}$ (x2.5 the Tevatron record,). Design: $L=10^{34}\ cm^{-2}\ s^{-1}$



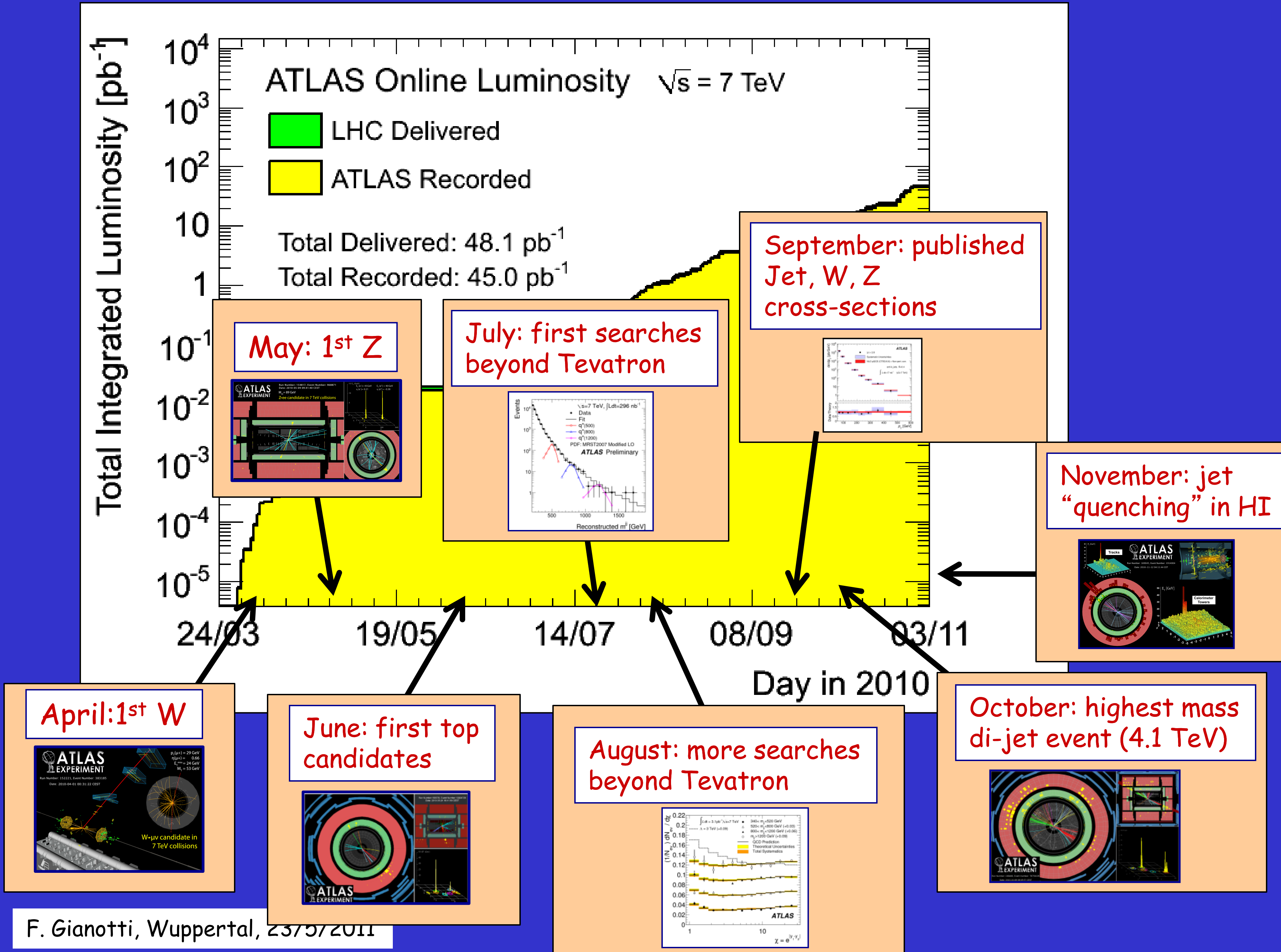
n. of protons per bunch — n. of bunches — n. of turns per second

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

beam size at IP

$$N = \int L dt \times \sigma(pp \rightarrow X)$$

Total integrated luminosity recorded by ATLAS: ~ 400 pb^{-1} (45 pb^{-1} in 2010)
Data-taking efficiency (recorded/delivered luminosity): ~ 95%



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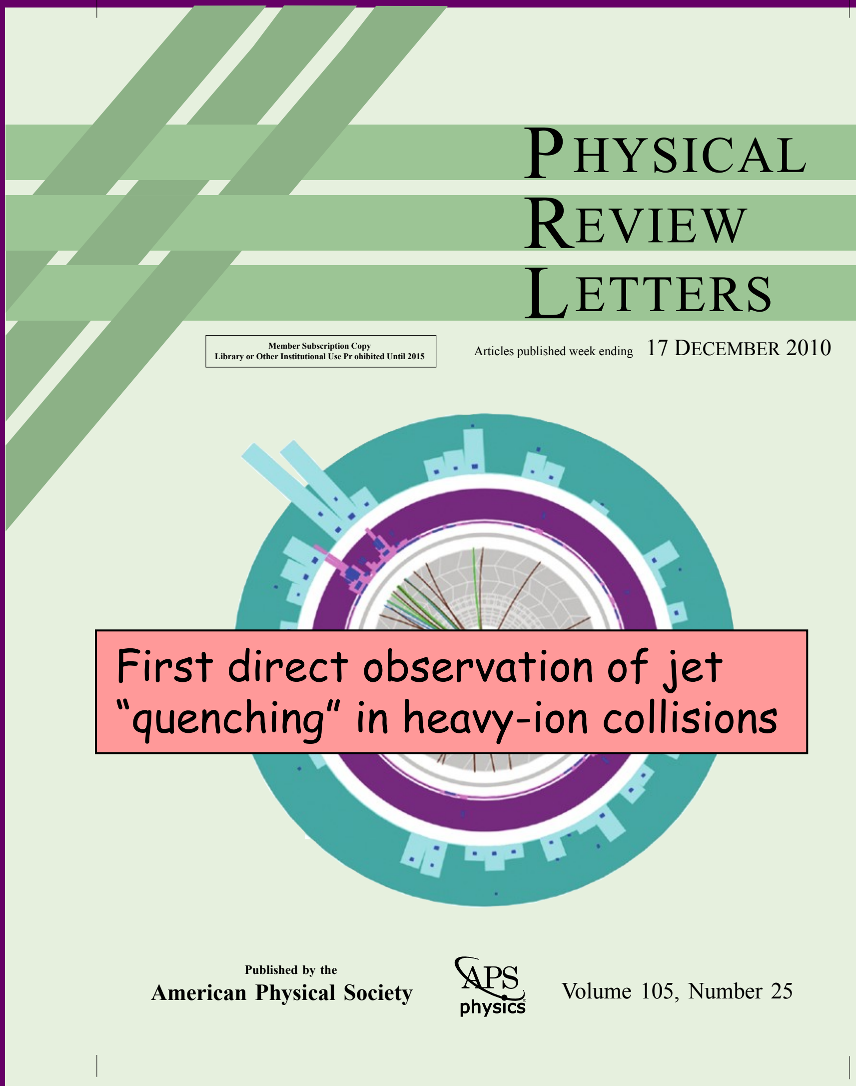
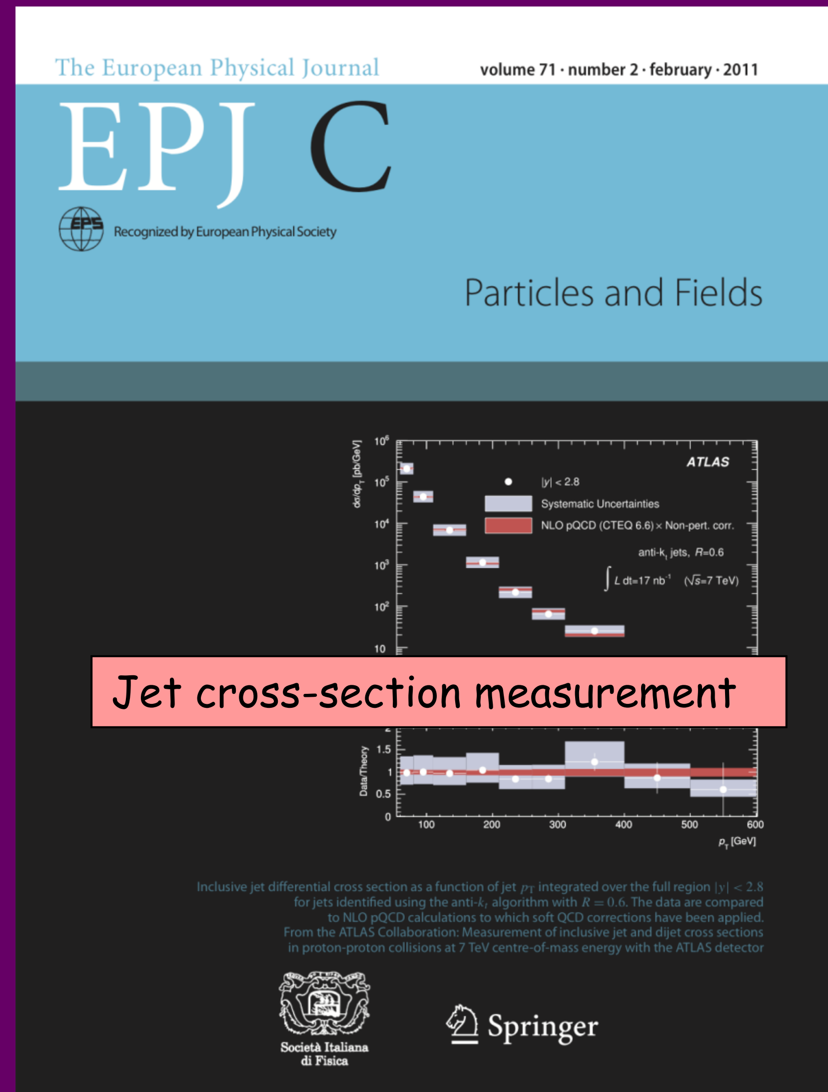
2010 data:

- 36 papers published or submitted for publication
- Huge number of physics results presented at 2010-2011 Conferences
  → documented in ~150 CONF-notes

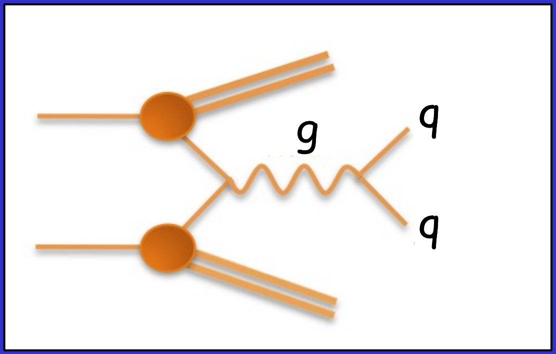


First direct observation of jet "quenching" in heavy-ion collisions

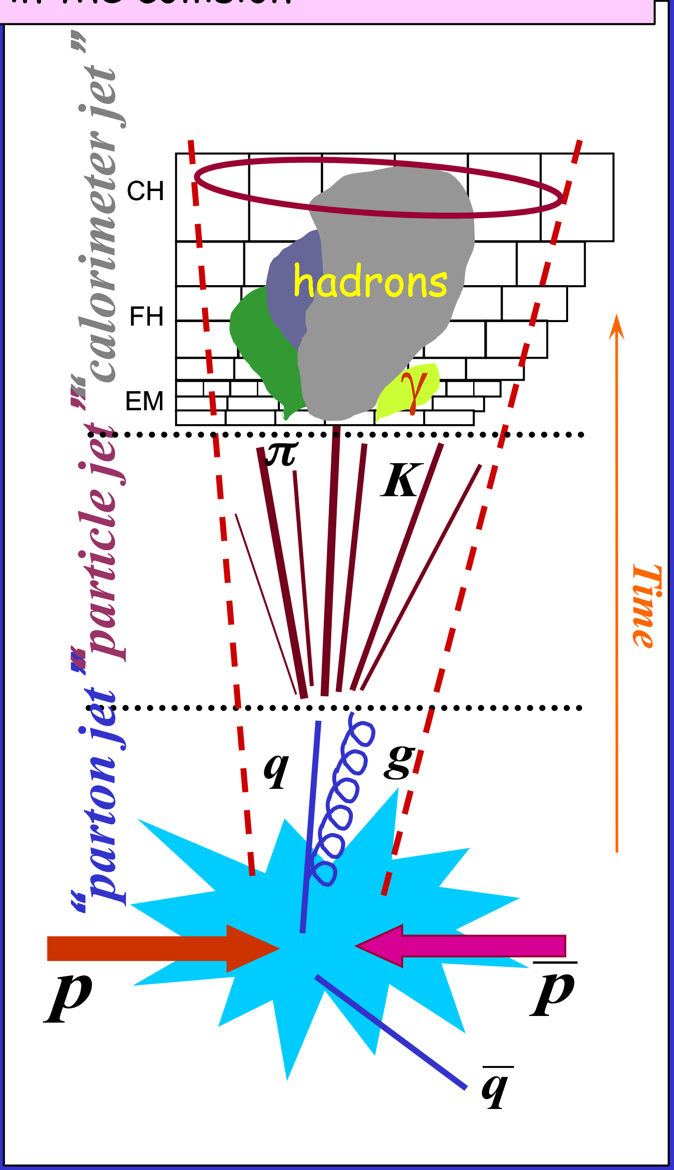


Jet cross-section measurement

Jet physics



Jets: result of hadronization of quarks and gluons produced in the collision



- Protons are made of partons (quarks and gluons). Gluons are carriers of strong force (described by QCD=Quantum Cromo Dynamics)
- In high-energy pp collisions, the elementary interactions occur between quarks and gluons from the two colliding protons.
- Parton Distribution Functions (PDFs): describe the fraction of the proton momentum carried by quarks and gluons.
- Jet physics: allows powerful tests of QCD, PDF, searches for new physics, etc.

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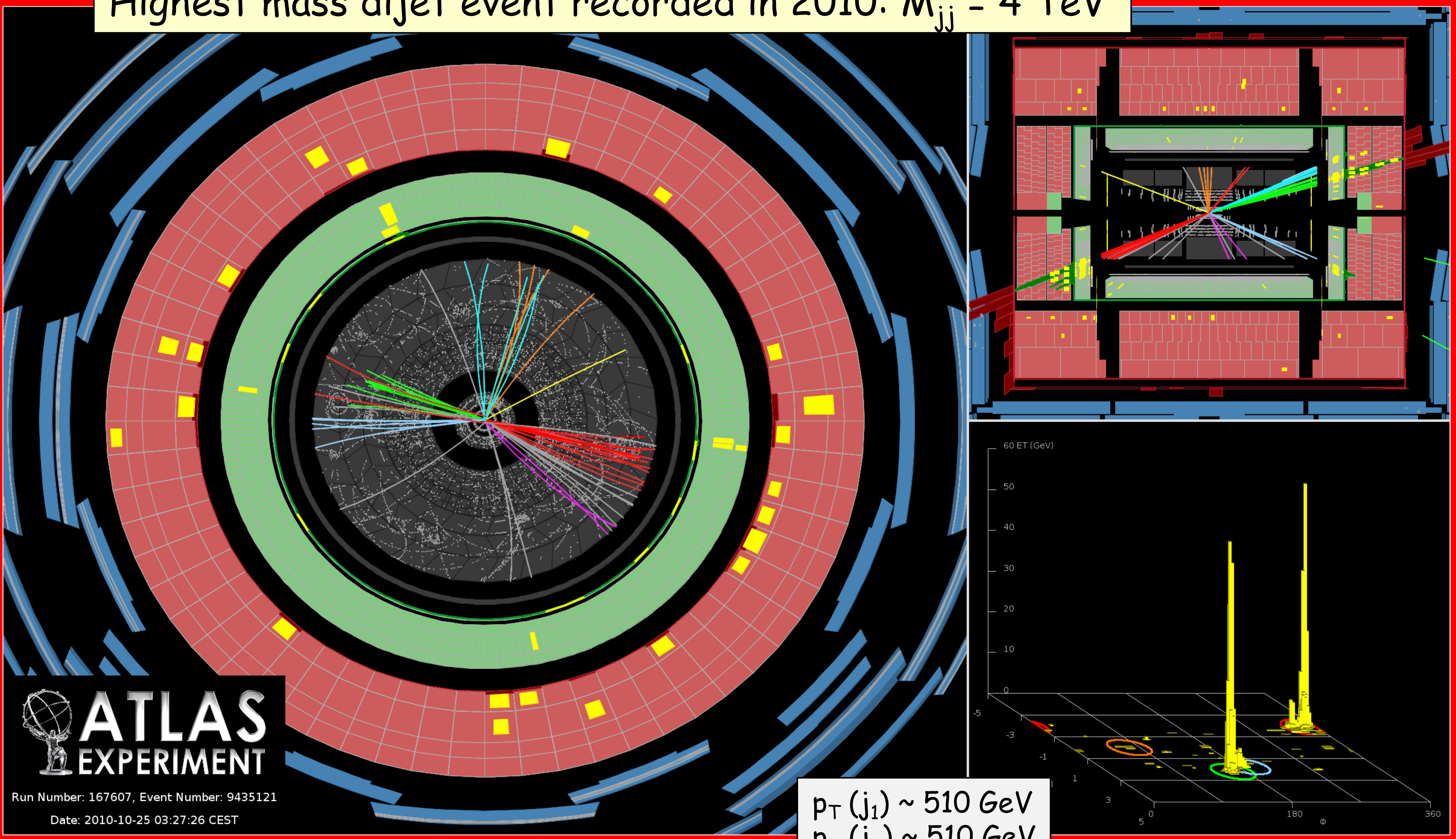
Jet physics

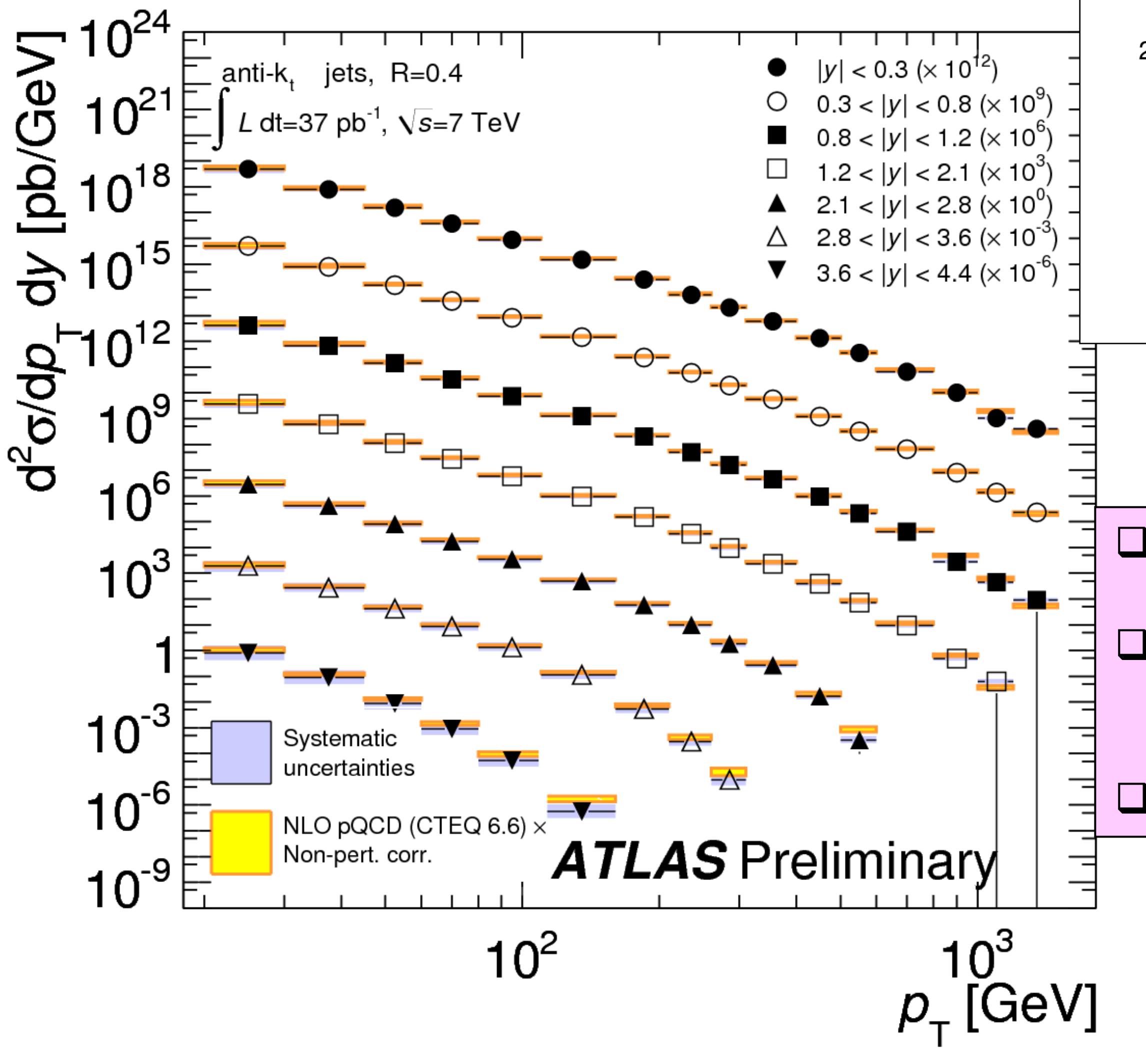
Highest mass dijet event recorded in 2010: M_{jj} = 4 TeV

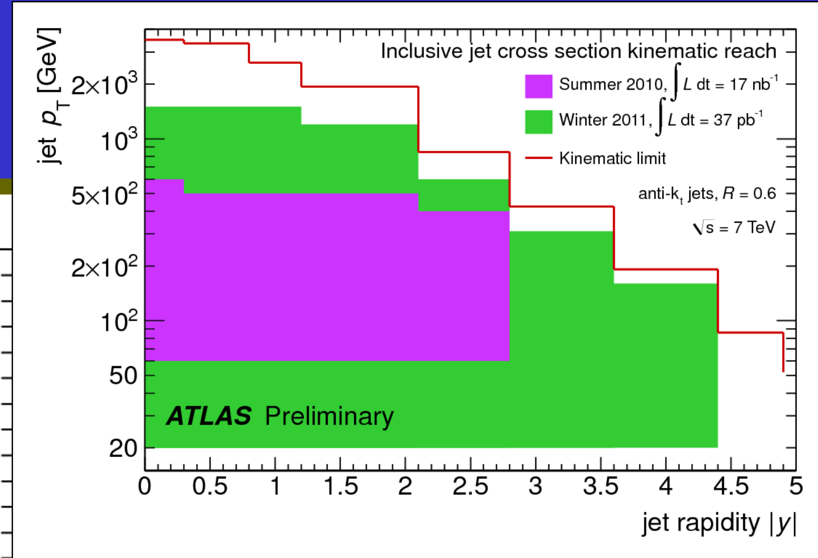


$p_T(j_1) \sim 510$ GeV
$p_T(j_2) \sim 510$ GeV

Inclusive jet cross-section

20 GeV < p_T(jet) < 1500 GeV, |y| < 4.5



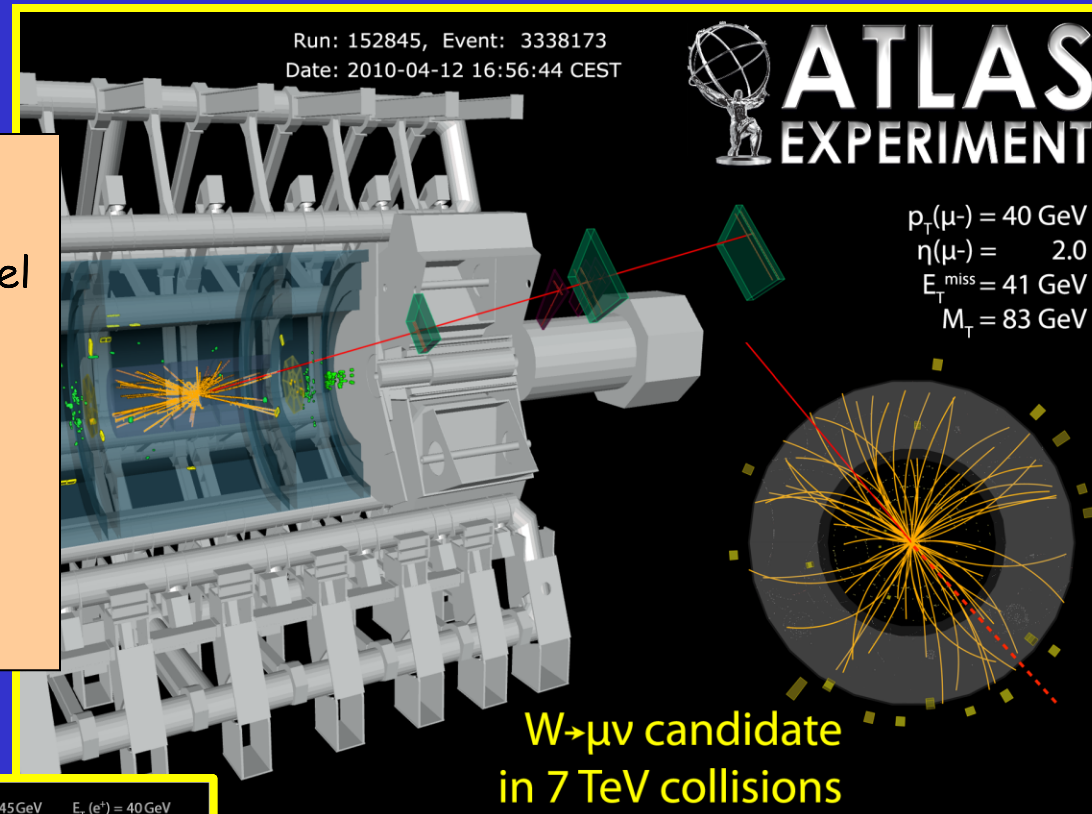


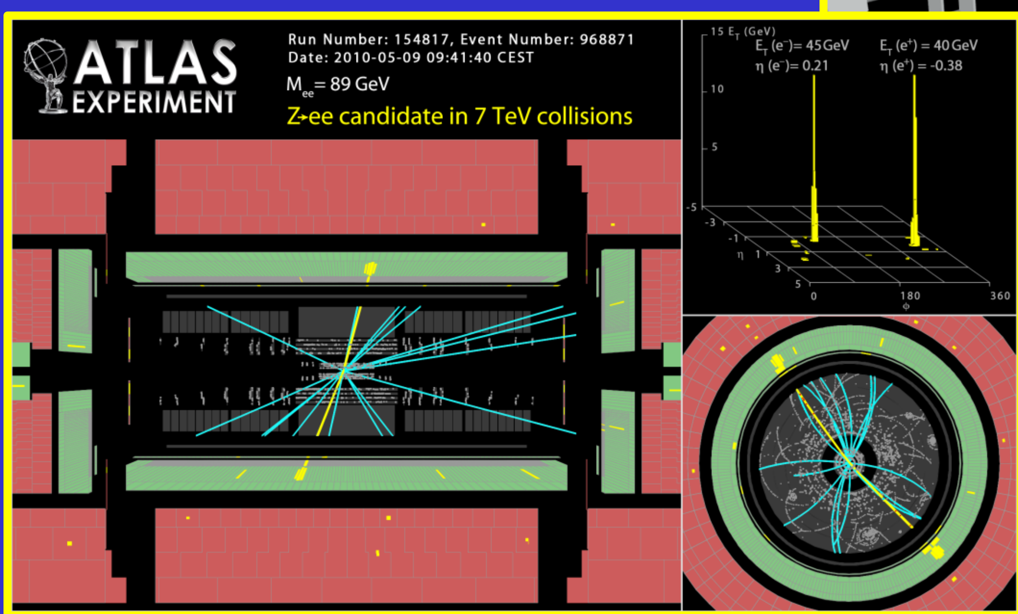
- Unprecedented kinematic range explored and compared to theory
- Experimental error ~ 25% (dominated by jet E-scale) approaches theory uncertainty
- Start to constrain PDFs

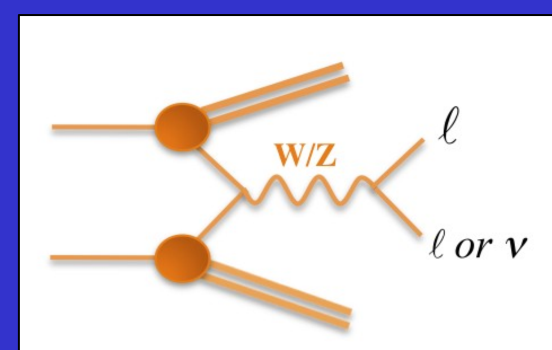
F. Good agreement data-NLO QCD over ~ 10 orders of magnitude !

W and Z physics

- Carrier of weak interactions
- Fundamental milestones in the "rediscovery" of the Standard Model at $\sqrt{s}$ = 7 TeV
- Provide several tests of SM
- Among dominant backgrounds to searches for New Physics
- Z → ll is gold-plated process to calibrate the detector to ultimate precision



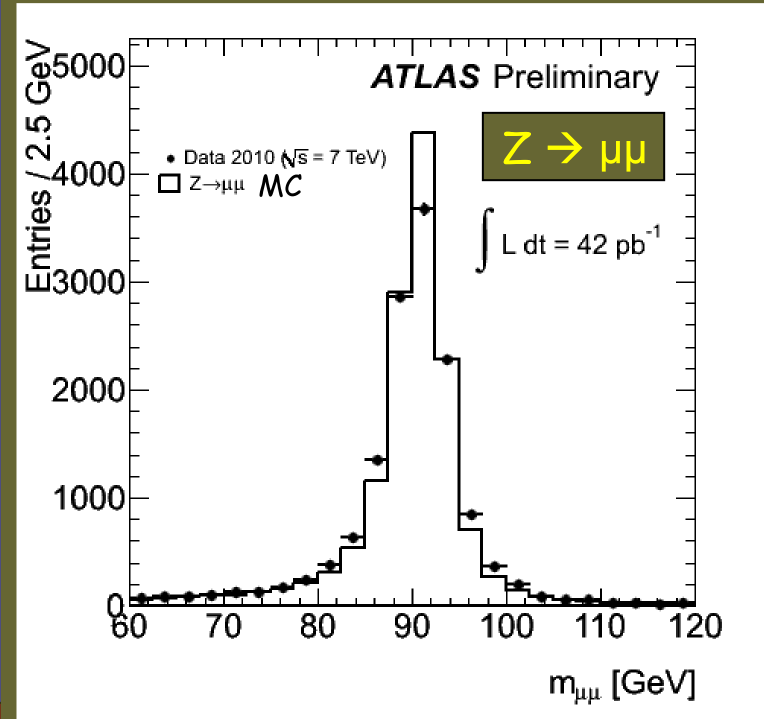


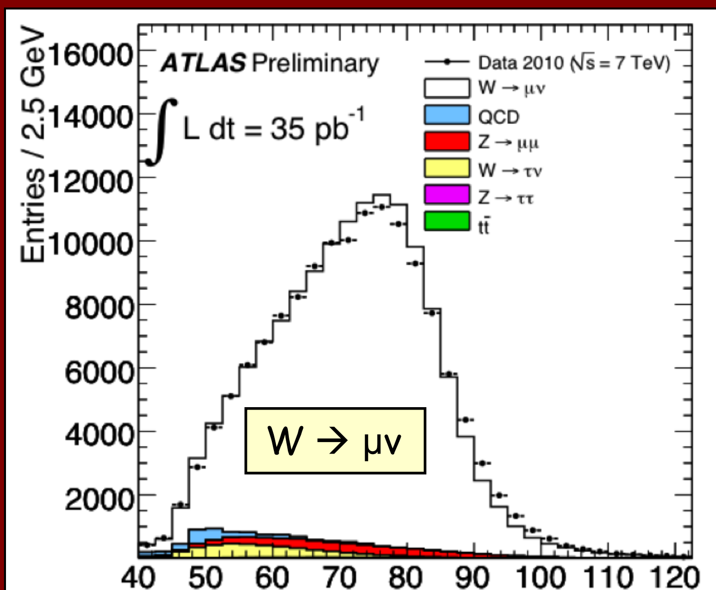


In the data sample recorded in 2010, ATLAS has:
~ 250k W→ μν, eν events
~ 23k Z → μμ, ee events

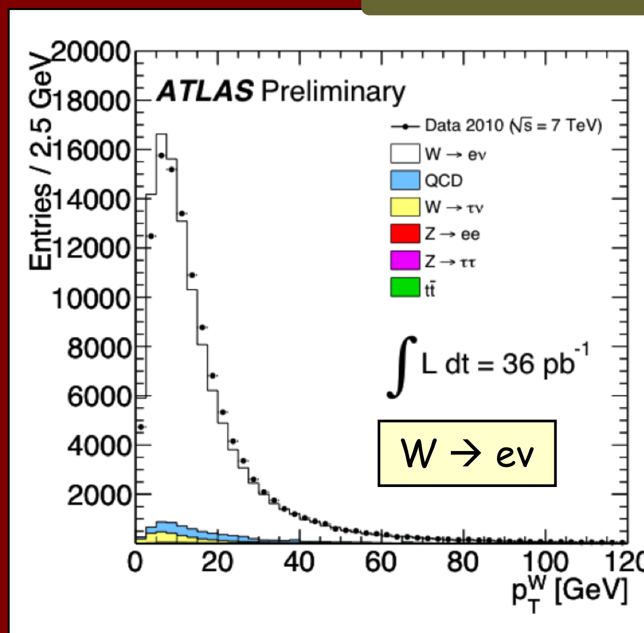
Measured Z peaks:

Z → μμ	90.9 ± 0.1 GeV	(MC: 91.3 GeV)
Z→ ee	90.8 ± 0.1 GeV	(MC: 91.6 GeV)

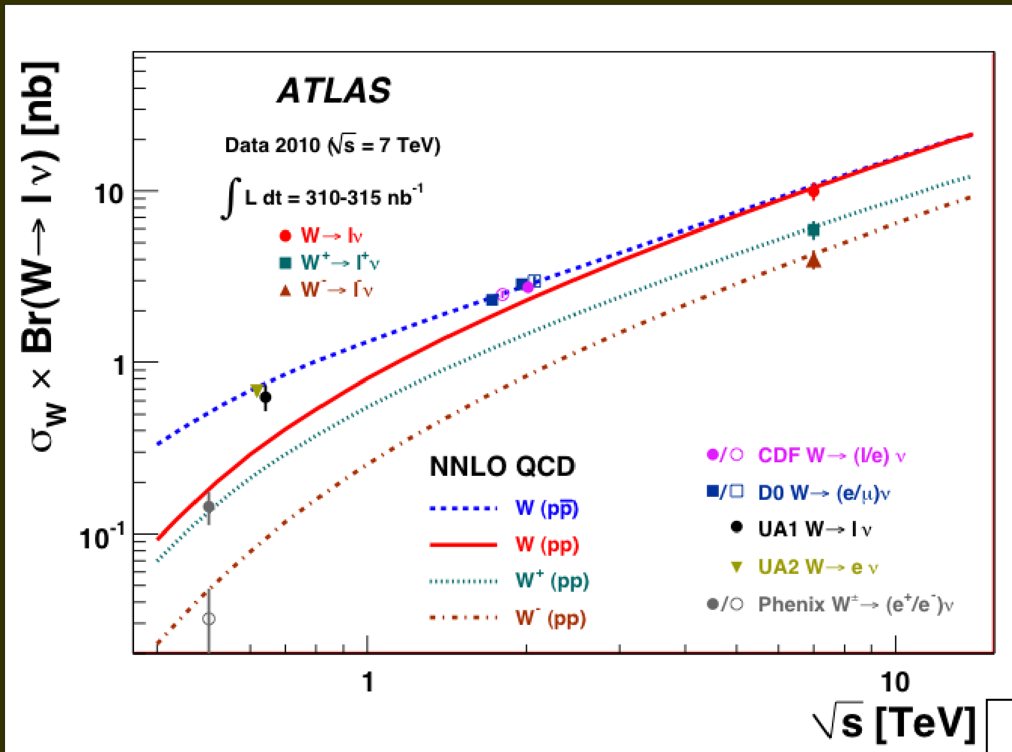




$$m_T = \sqrt{2 p_T^{\ell} p_T^{\nu} (1 - \cos(\phi^{\ell} - \phi^{\nu}))}$$

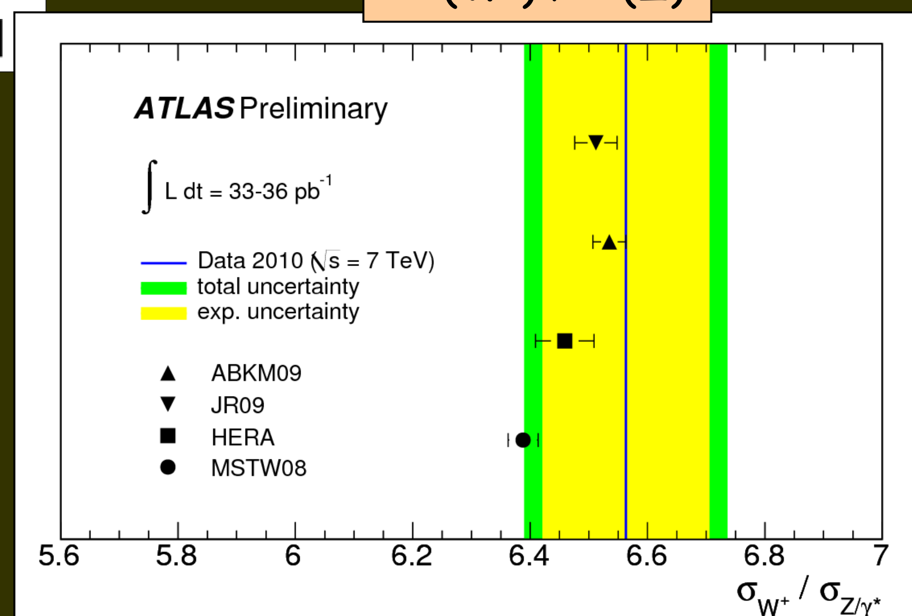


Era of W, Z precision measurements started



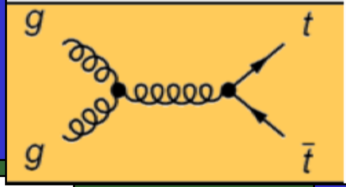
Experimental precision on W, Z cross-section measurements has reached percent level

σ (W⁺) /σ (Z)



Top-quark measurements

$\sigma(t\bar{t}) \cong 160\ \text{pb at}\ \sqrt{s} = 7\ \text{TeV}$



lepton + jets channel
$tt \rightarrow bW\ bW \rightarrow bl\nu\ bjj$
$\sigma \sim 70$ pb

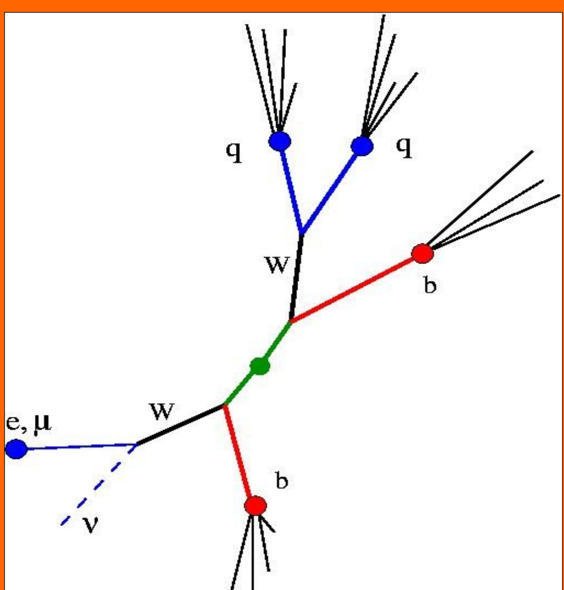
1 isolated lepton $p_T > 20$ GeV
$E_T^{miss} > 20$ GeV, $E_T^{miss} + m_T > 60$ GeV
≥ 4 jets $p_T > 25$ GeV
≥ 1 b-tag jet

Acceptance x efficiency ~ 15%

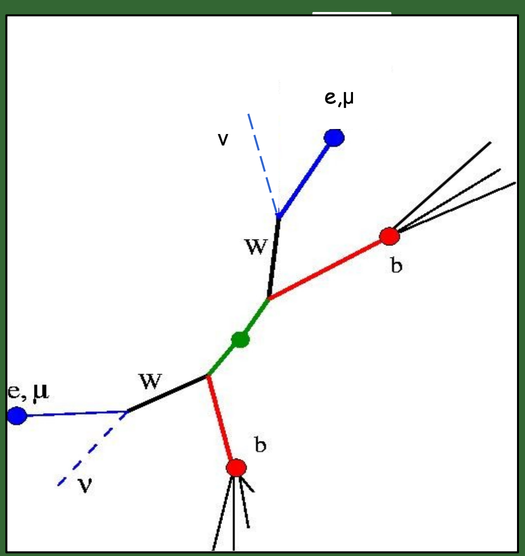
2-lepton channel
$tt \rightarrow bW\ bW \rightarrow bl\nu\ bl\nu$
$\sigma \sim 10$ pb

2 opposite-sign leptons: ee, eμ, μμ
both leptons $p_T > 20$ GeV
≥ 2 jets $p_T > 20$ GeV
ee: $E_T^{miss} > 40$ GeV $|M(ee)-M_Z| > 5$ GeV
μμ: $E_T^{miss} > 30$ GeV $|M(\mu\mu)-M_Z| > 10$ GeV
eμ: $H_T = \Sigma E_T$ (leptons, jets) > 150 GeV

Acceptance x efficiency ~ 25%

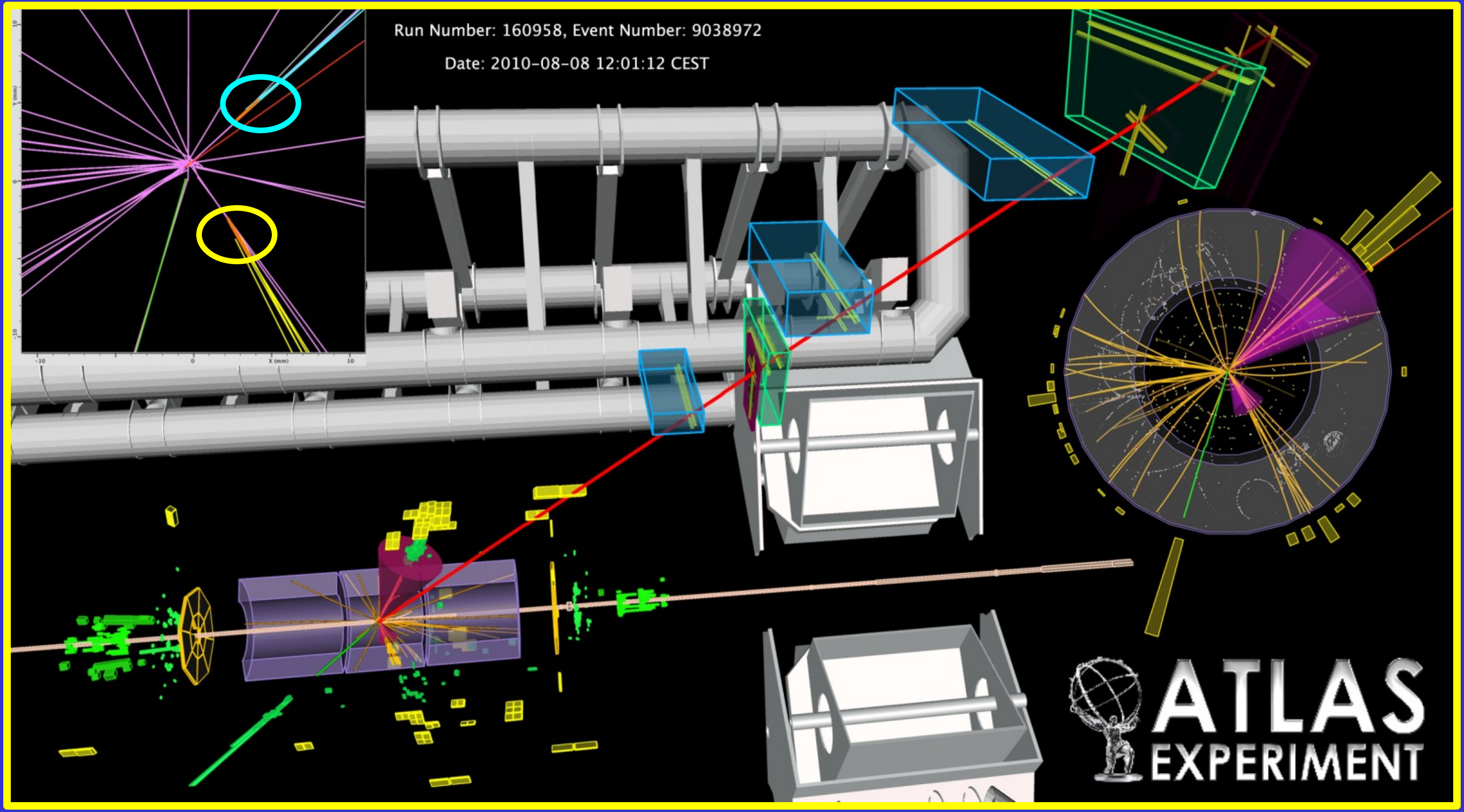


The heaviest (m_{top}=172 GeV) and most intriguing elementary particle observed so far. Discovered at the Tevatron in 1995; observed "for the first time in Europe" by ATLAS and CMS in July 2010



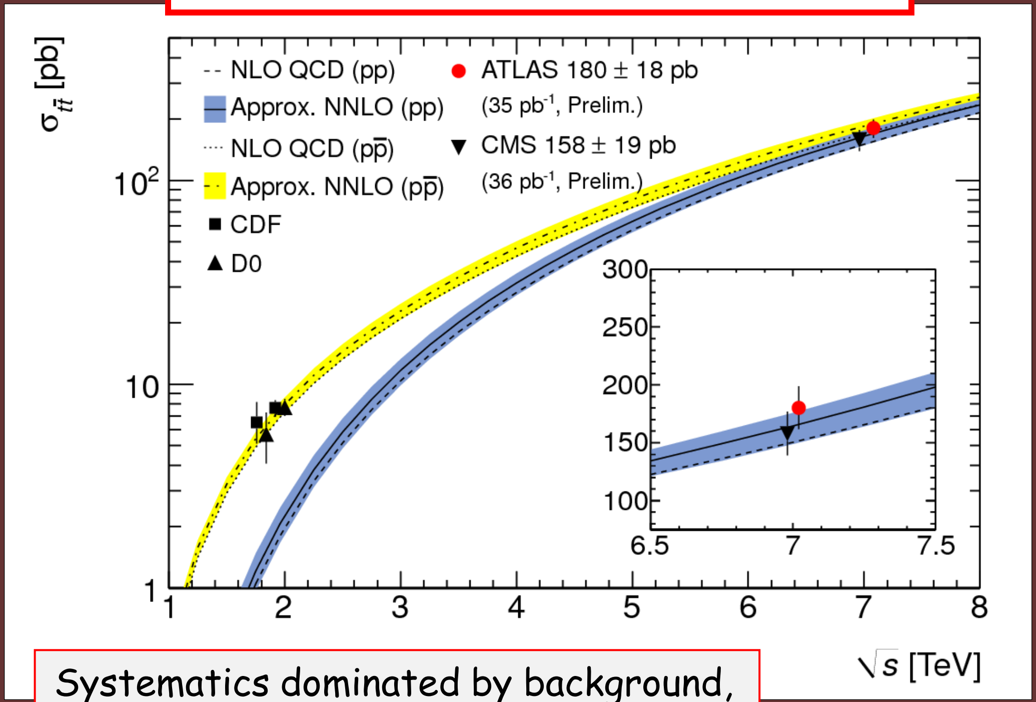
A spectacular ATLAS candidate: tt → bW bW → beν bμν

$p_T(\mu)$= 51 GeV $p_T(e)$=66 GeV p_T (b-tagged jets) = 174, 45 GeV
E_T^{miss} = 113 GeV,
Secondary vertices: distance from primary vertex: 4mm, 3.9 mm
vertex mass : ~2 GeV, ~ 4 GeV



ATLAS 2010 data sample: ~ 450 top events

$$\sigma_{t\bar{t}} = 180 \pm 9\ (\text{stat.}) \pm 15\ (\text{syst.}) \pm 6\ (\text{lumi.})\ \text{pb}$$

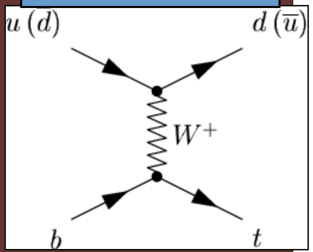


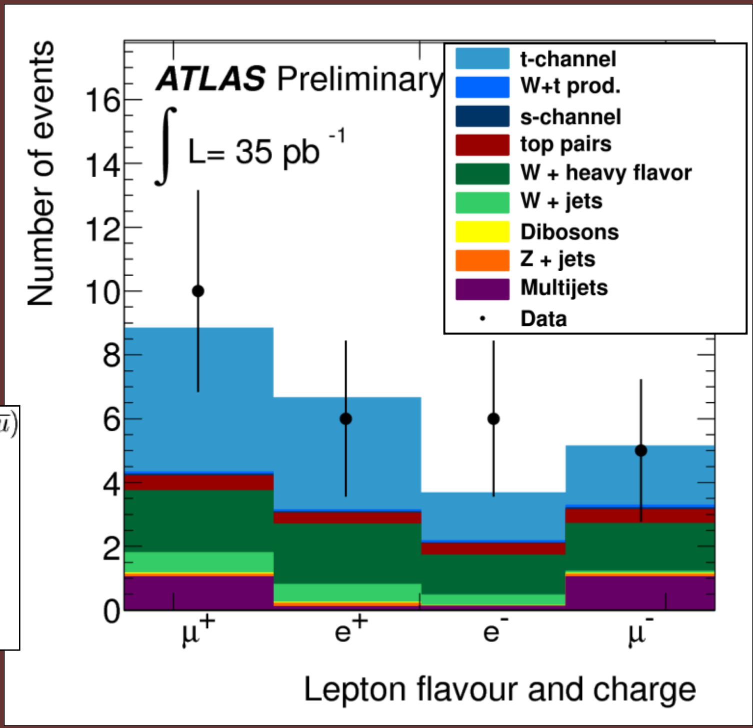
Very important contributions from Wuppertal !

Systematics dominated by background, b-tagging, ISR/FSR uncertainties

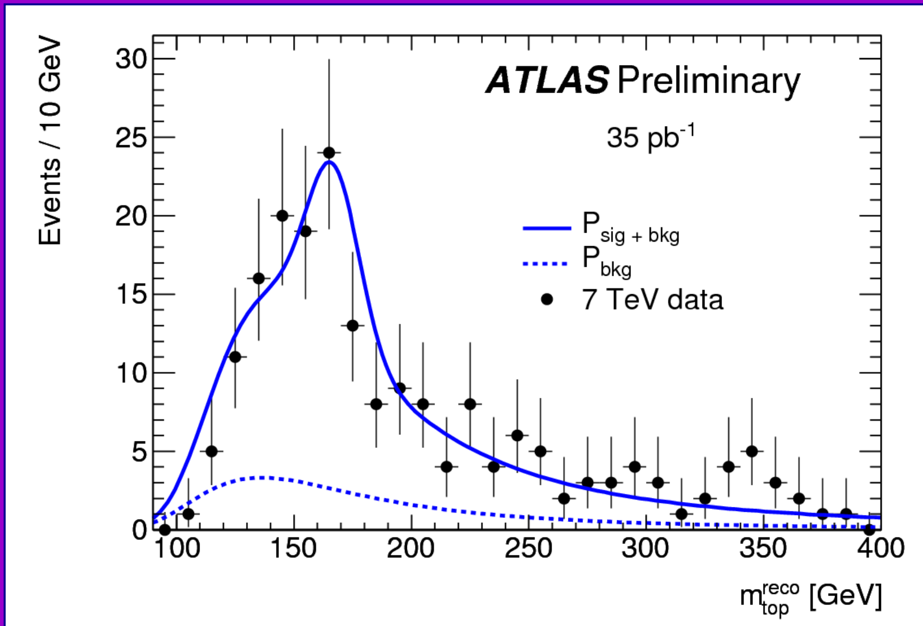
- Standard Model: σ ~ 70 pb
- Select events with 1 lepton, 2 jets of which one is b-tagged, E_T^{miss}
- Observed in data: 27 events
  Expected: ~ 24 (~11 from single top)
  → ~ 1.6 σ effect

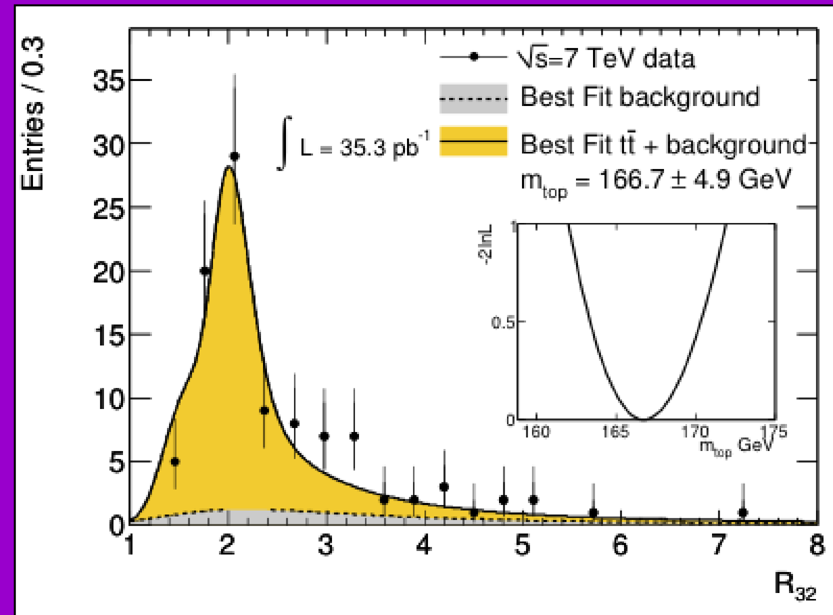
Single-top

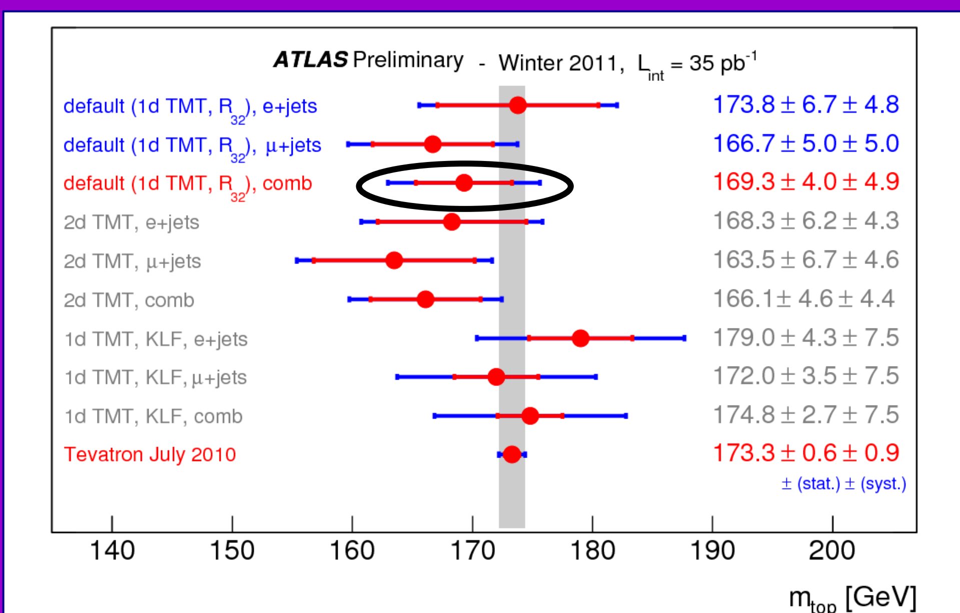




First ATLAS measurement of the top mass

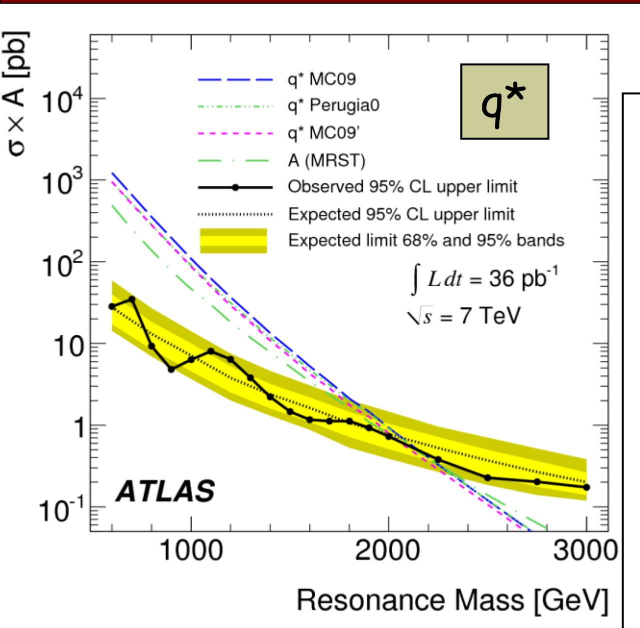


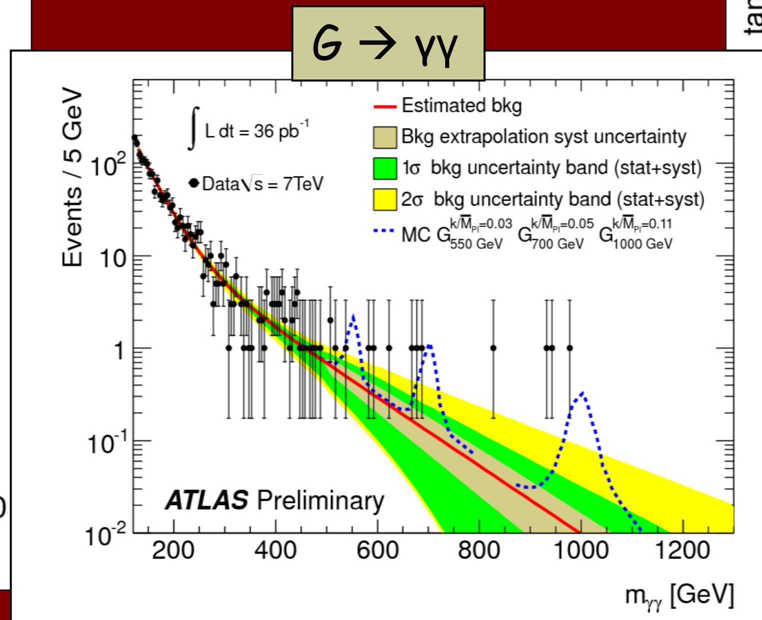


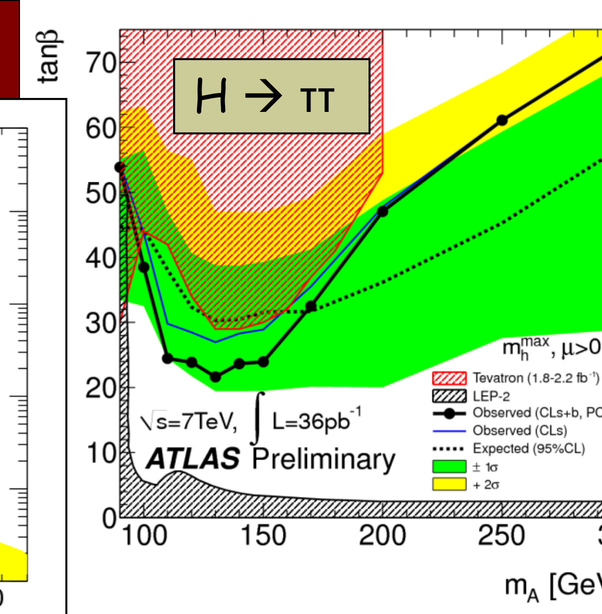


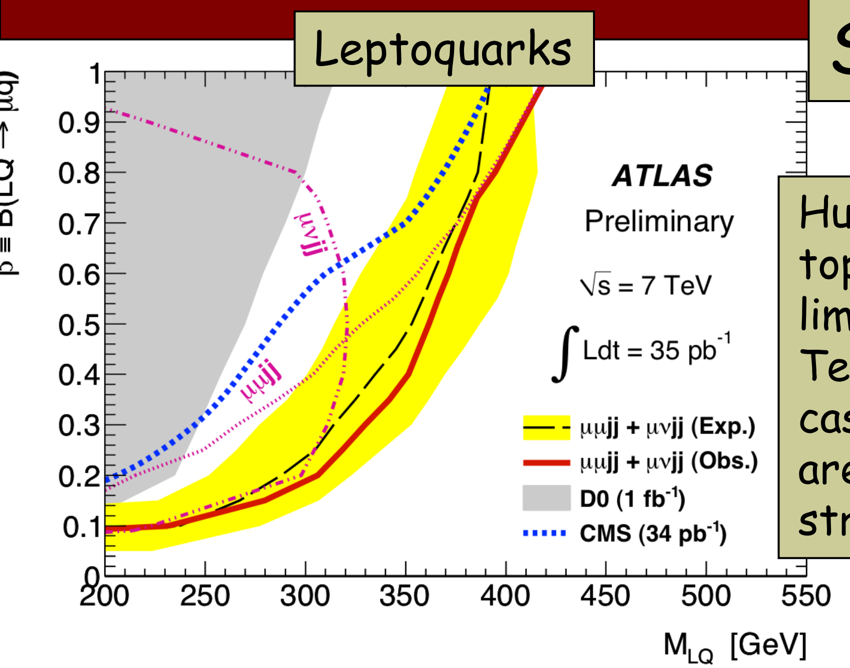
Demonstrates that the detector performance and reconstruction algorithms for the main physics objects (e, μ, E_T^{miss}, jets, b-jets) have reached maturity

Systematic uncertainty dominated by the b-jet E-scale, ISR/FSR



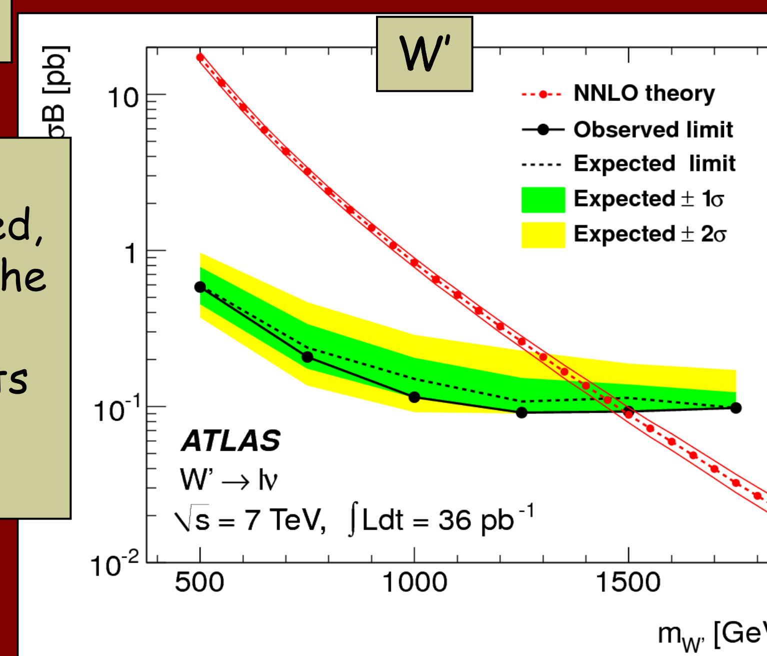






Searches

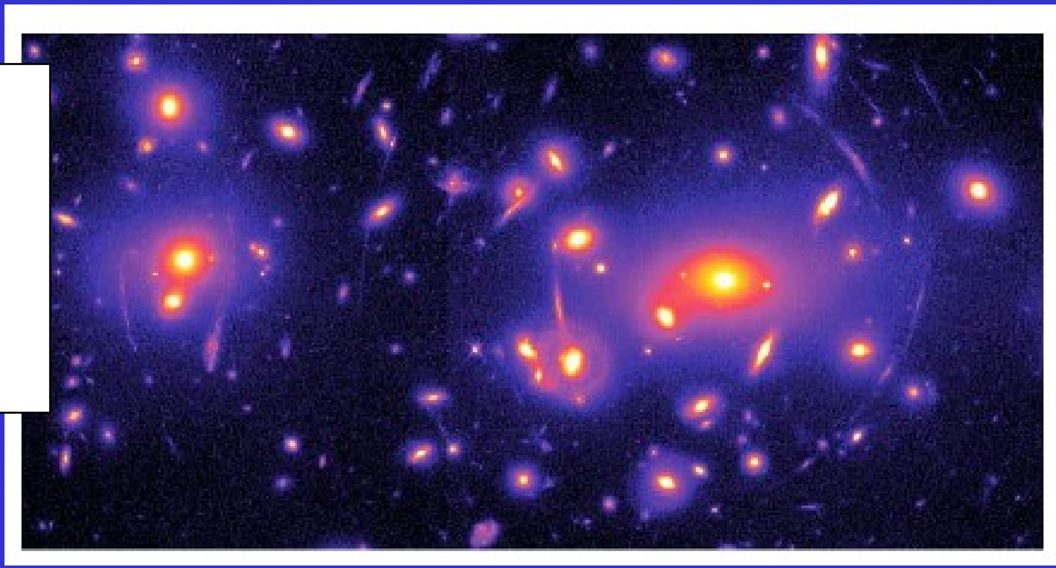
Huge number of topologies explored, limits exceeding the Tevatron in most cases, many results are the most stringent to date



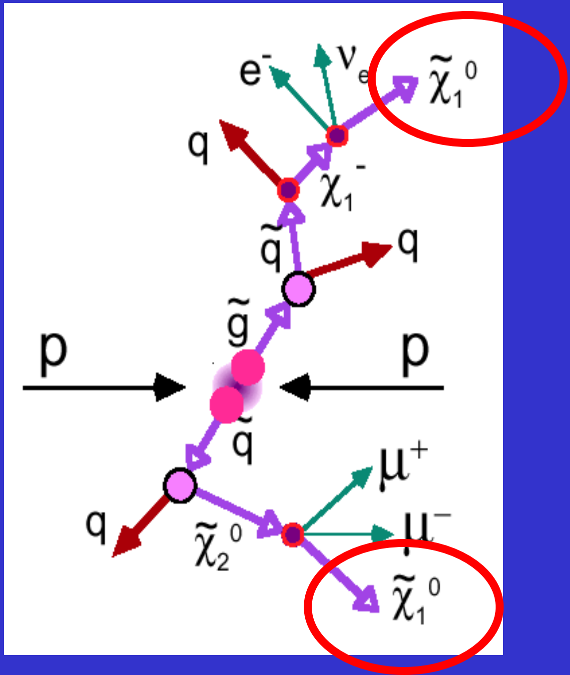
Supersymmetry and dark Matter

Astrophysical measurements indicate that the Universe is made of:

- 5% of known matter
- 25 % of "dark matter" (no known particle can explain it)
- 70% of "dark energy"



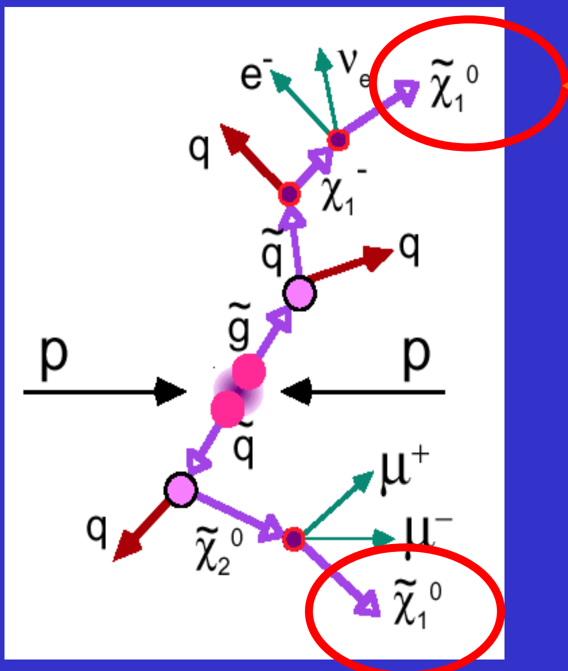
Supersymmetry (a theory beyond the Standard Model) predicts new (heavy) elementary particles, not yet observed. Among them the neutralino, our present best candidate for the Universe dark matter (its predicted features are in agreement with astrophysics observations and cosmological predictions).
It is expected to be light enough to be produced abundantly at the LHC



Dominant process: $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$, $\tilde{g}\tilde{g}$ strong production → huge cross-section

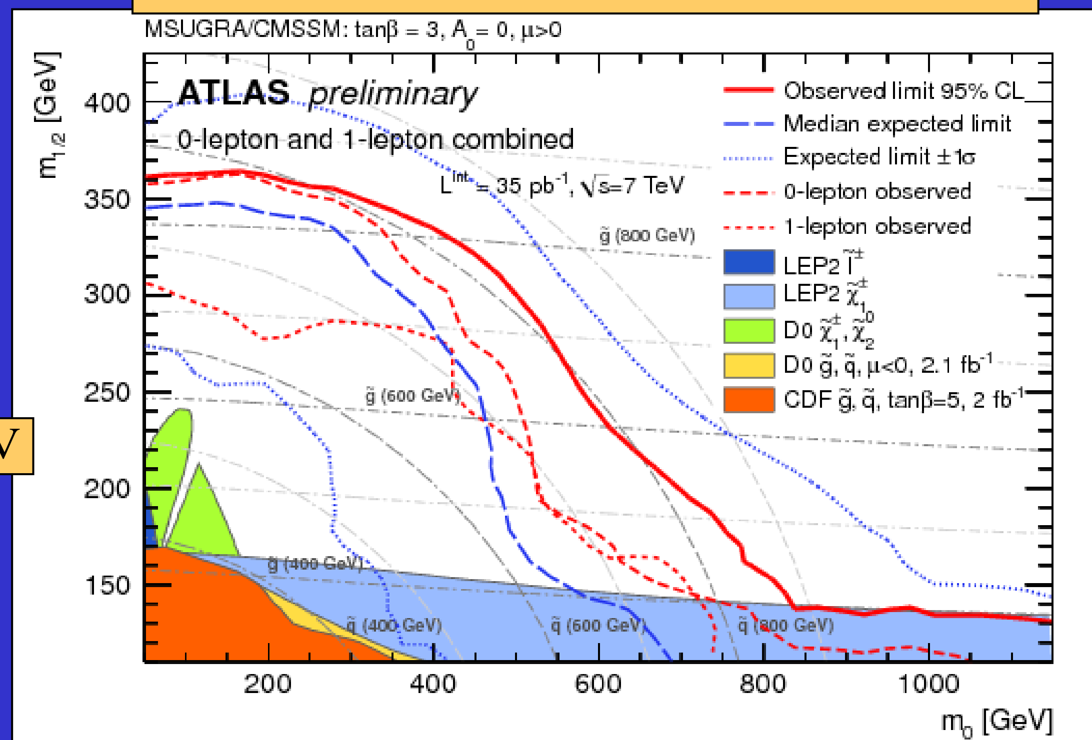
e.g. $m(\tilde{q}, \tilde{g}) \sim 1$ TeV → σ ~ 1 pb

Cascade decays of squarks and gluinos into SM particles plus the lightest neutralino
→ signature is jets, sometimes leptons, plus missing energy



Lightest neutralino is stable, neutral and weakly interacting
→ escapes detection → apparent missing E in final state

First ATLAS results based on 2010 data



$m(\tilde{g}) > 800$ GeV

for m($\tilde{g}$) □ m($\tilde{q}$)

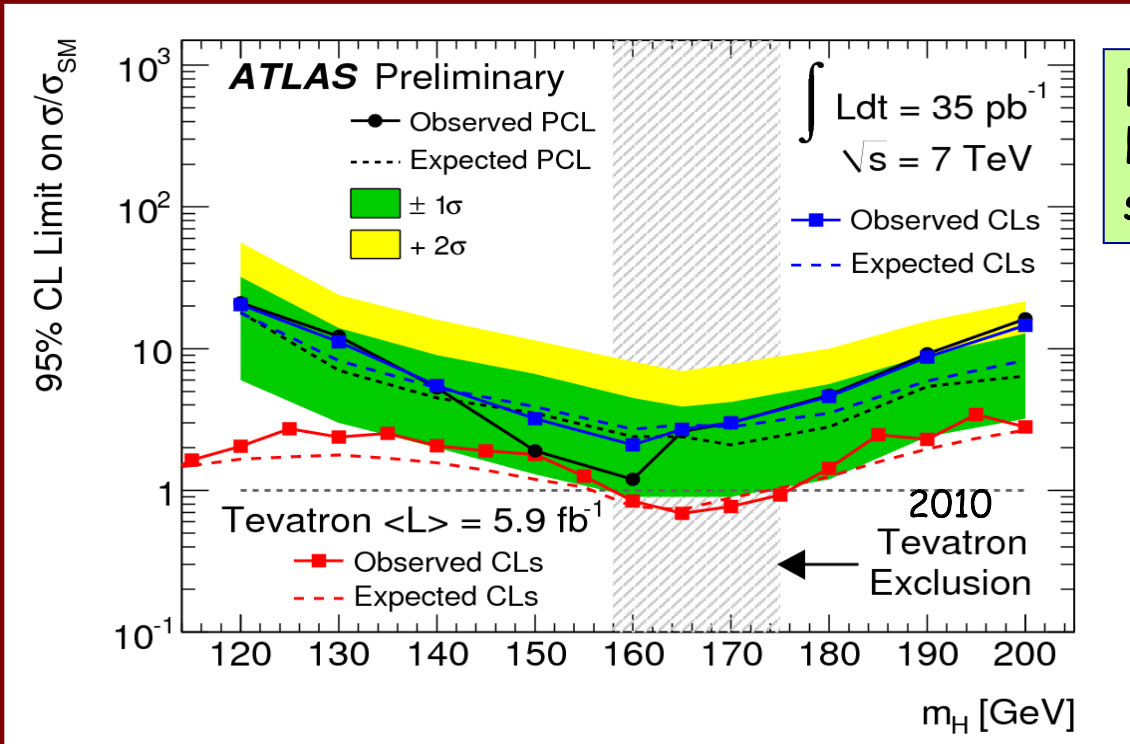
Sensitivity in 2011-2012 (> 5 fb^{-1}):
gluino masses >> 1 TeV
→ neutralino masses > 300 GeV

2011 (2012): the year(s) of the Higgs boson ?

What do we know today ?

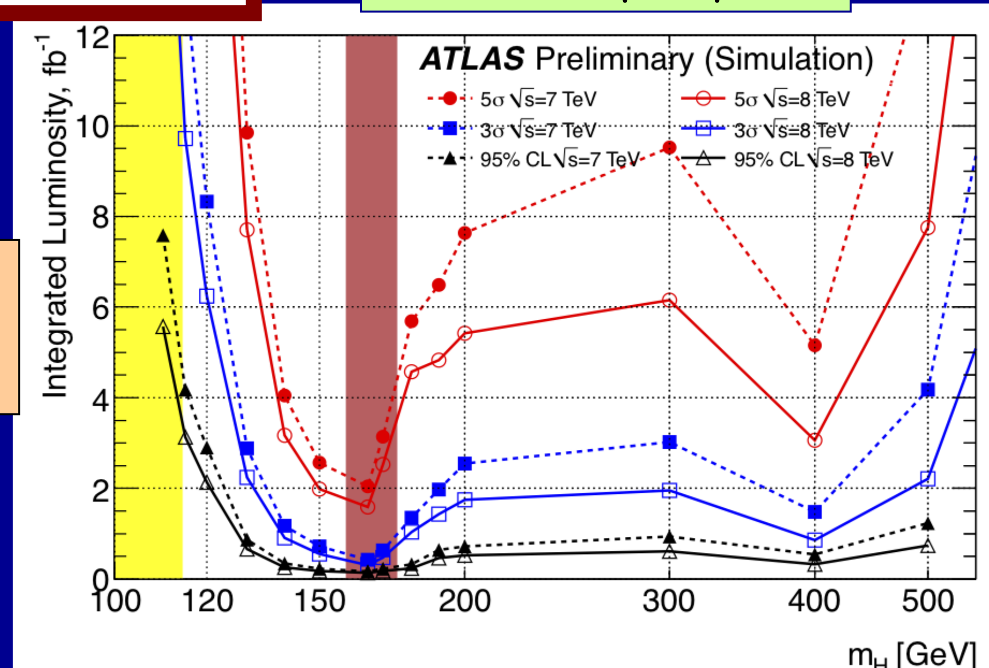
- Theory: $m_H < 1$ TeV
- Present experimental exclusion: $m_H > 114.4$ GeV (LEP), $158 < m_H < 173$ GeV (Tevatron)
- Favoured region (electroweak data → consistency of Standard Model): $m_H < 158$ GeV
  → 114.4-158 GeV is the best motivated region (although higher masses cannot be excluded)

Higgs in ATLAS



First limits from $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ searches in ATLAS

and future prospects

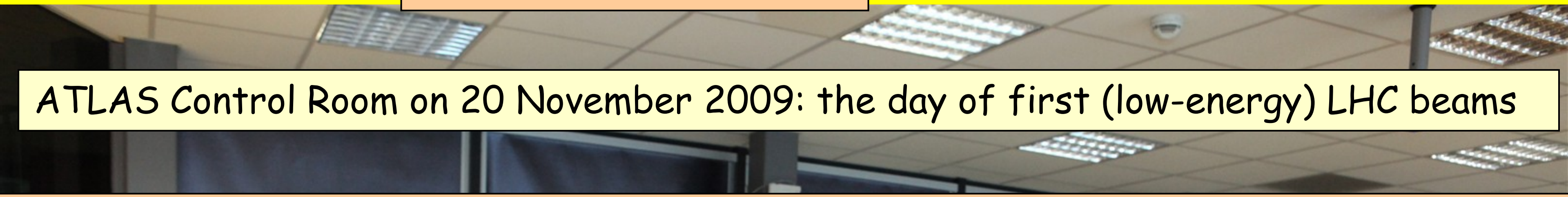


ATLAS + CMS (luminosity is per expt)

~ 2.5 fb^{-1}	95% C.L. exclusion	114-600 GeV
~ 5 fb^{-1}	3σ observation	114-600 GeV
~ 10 fb^{-1}	5σ discovery	117-530 GeV

Note: Tevatron end 2011 (~ 12 fb^{-1}):
95% C.L. exclusion: 114-185 GeV
3σ observation ~115, 150-180 GeV

CONCLUSIONS



ATLAS Control Room on 20 November 2009: the day of first (low-energy) LHC beams

With the advent of the LHC, the exploration of a new energy frontier has started

The first year of data-taking has demonstrated that the accelerator and the experiments work beautifully

Excellent achievements and physics results in only 1 year from first $\sqrt{s}=7$ TeV collisions:

- "Rediscovery" of the Standard Model essentially completed: jets, W, Z, top-quark, WW and di-bosons, first evidence for single-top, …
- Precision measurements (jets, W, Z, top, ..) started → will soon challenge theory
- Searches for new physics now exceed Tevatron sensitivity in most cases (e.g. SUSY exclusion approaching masses ~ 800 GeV; some limits reach ~2 TeV)

The coming two years are extremely exciting:

- the question of the Standard Model Higgs boson will be definitely settled
- other discoveries (surprises ?) can be just around the corner …

SPARES

Inclusive jet cross-section

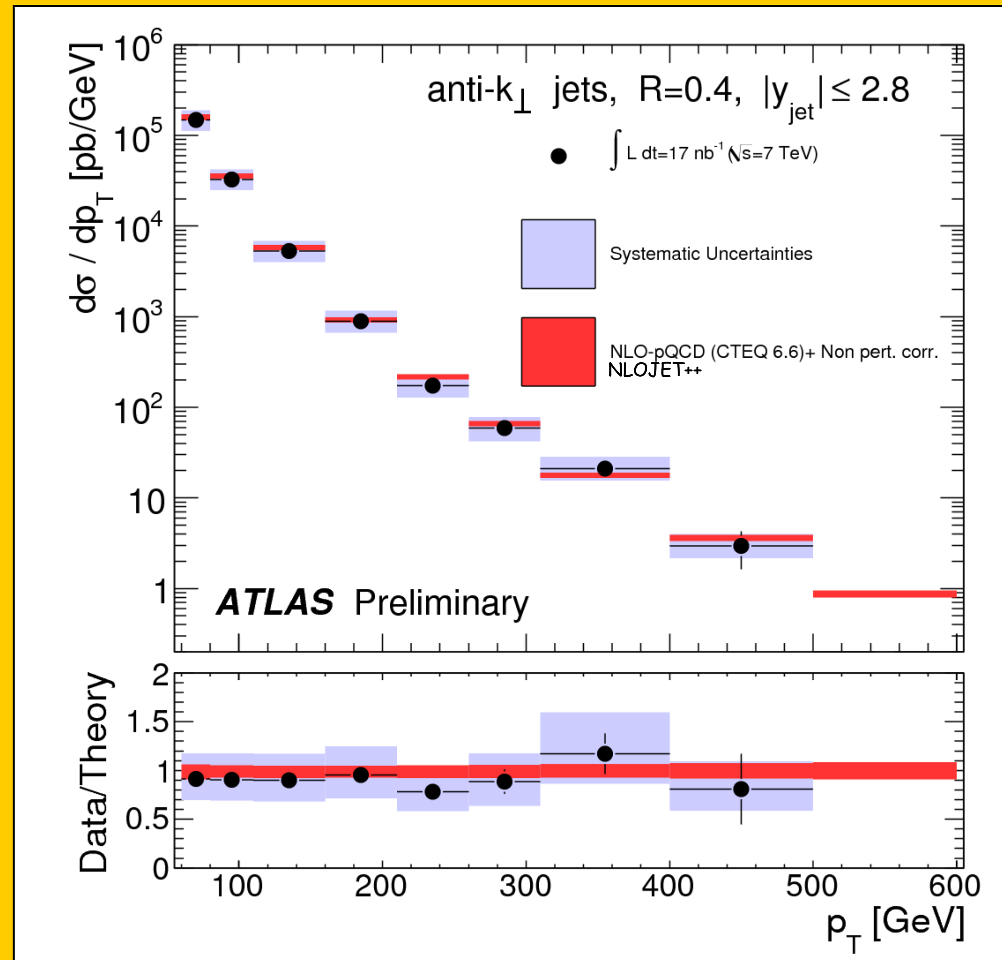
$p_T^j > 60$ GeV, $|y^j| < 2.8$

- Measured jets corrected to particle-level using parton-shower MC (Pythia, Herwig): justified by detailed comparison studies and good agreement with data

- Results compared to NLO QCD prediction after corrections for hadronization and underlying event

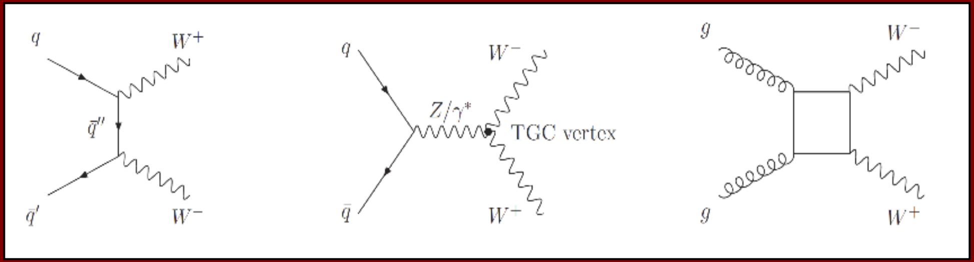
- Theoretical uncertainty: ~20%
  (up to 40% at large $|y_j|$)
  from variation of PDF, α_s, scale (μ_R, μ_F)

- Experimental uncertainty: ~30-40% dominated by Jet E-scale
  (known to ~7%, thanks to detailed data/MC comparison foundation work, see previous examples)
  Luminosity (11%) not included

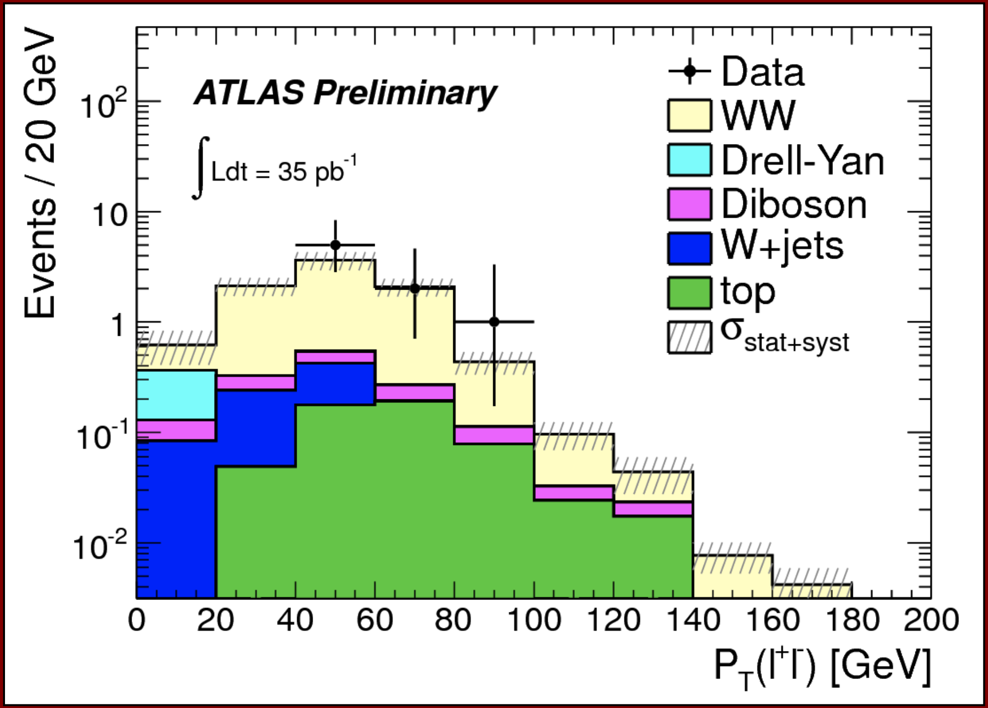


Good agreement data-NLO QCD over 5 orders of magnitude

Di-boson production: e.g. WW → lvlv



Sensitive to TGC (Triple Gauge Couplings)
Main irreducible background to H→ WW



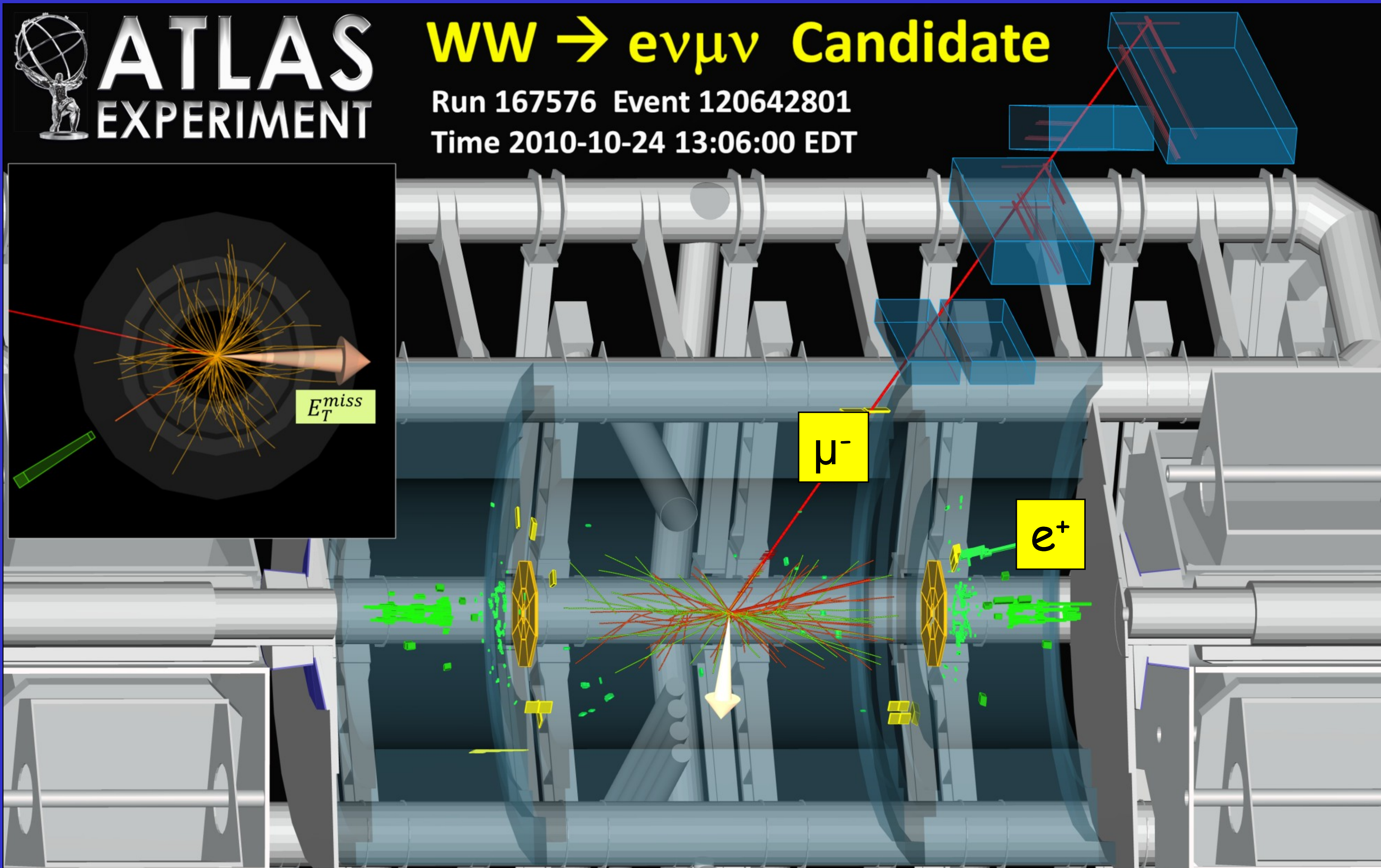
8 candidates selected in the 2010 data
(estimated background: 1.7 ± 0.6)

$$\sigma_{WW} = 40^{+20}_{-16}(\text{stat}) \pm 7(\text{syst})\ \text{pb}$$

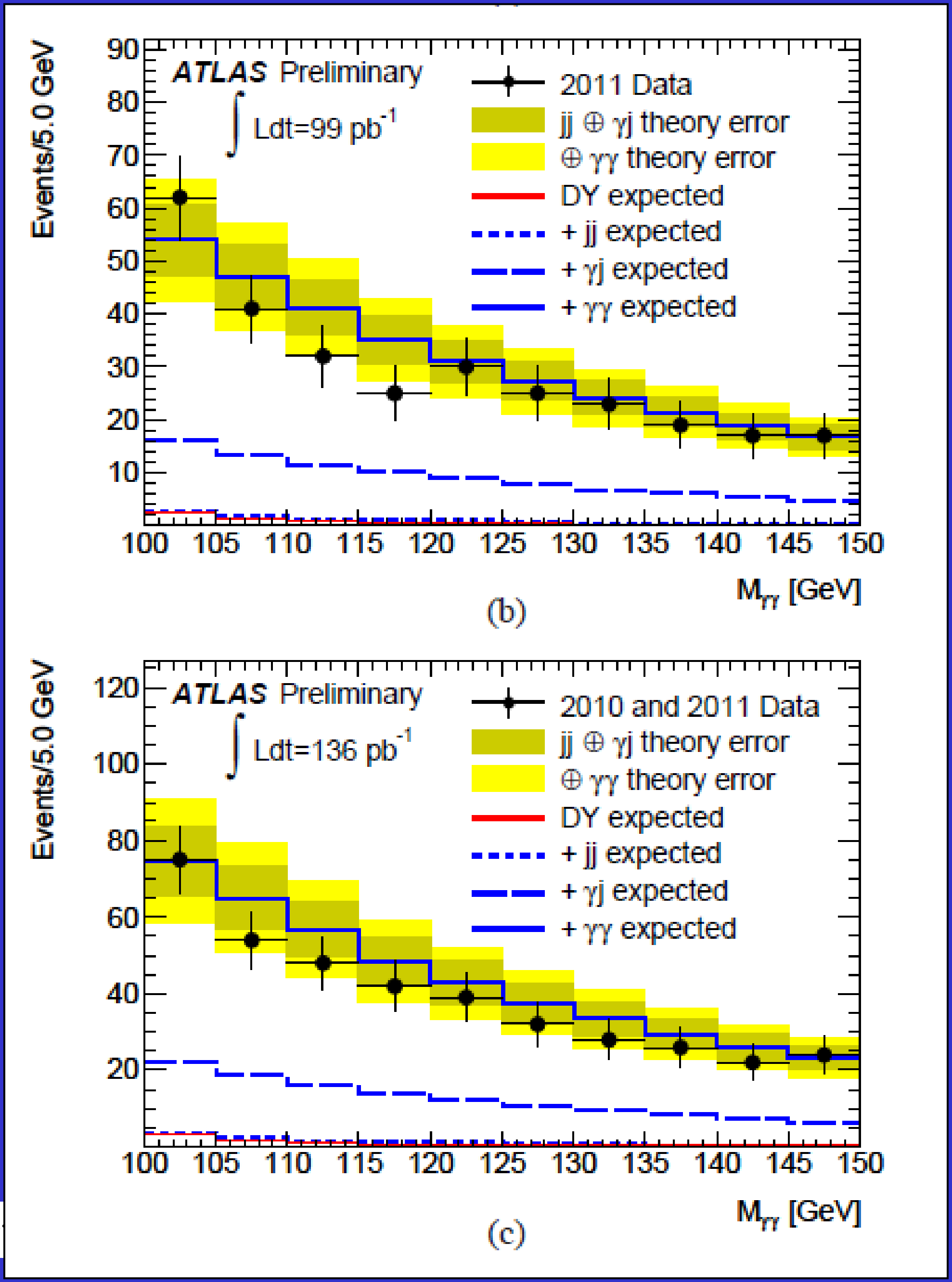
Standard Model prediction:
46 ± 3 pb

$W^+W^- \rightarrow e^+\nu\ \mu^-\nu$ candidate

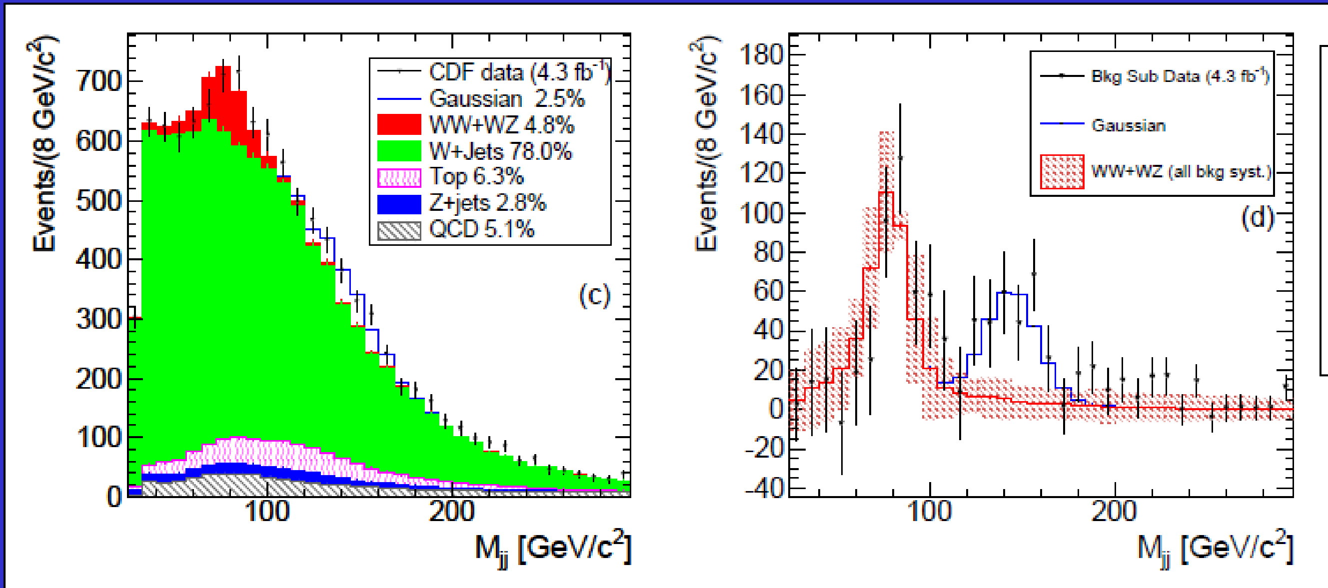
p_T (e)~ 20 GeV
p_T (μ)~ 68 GeV
E_T^{miss} ~ 70 GeV



Di-photon mass spectrum



CDF paper on a possible jj mass peak in W/Z + jj events

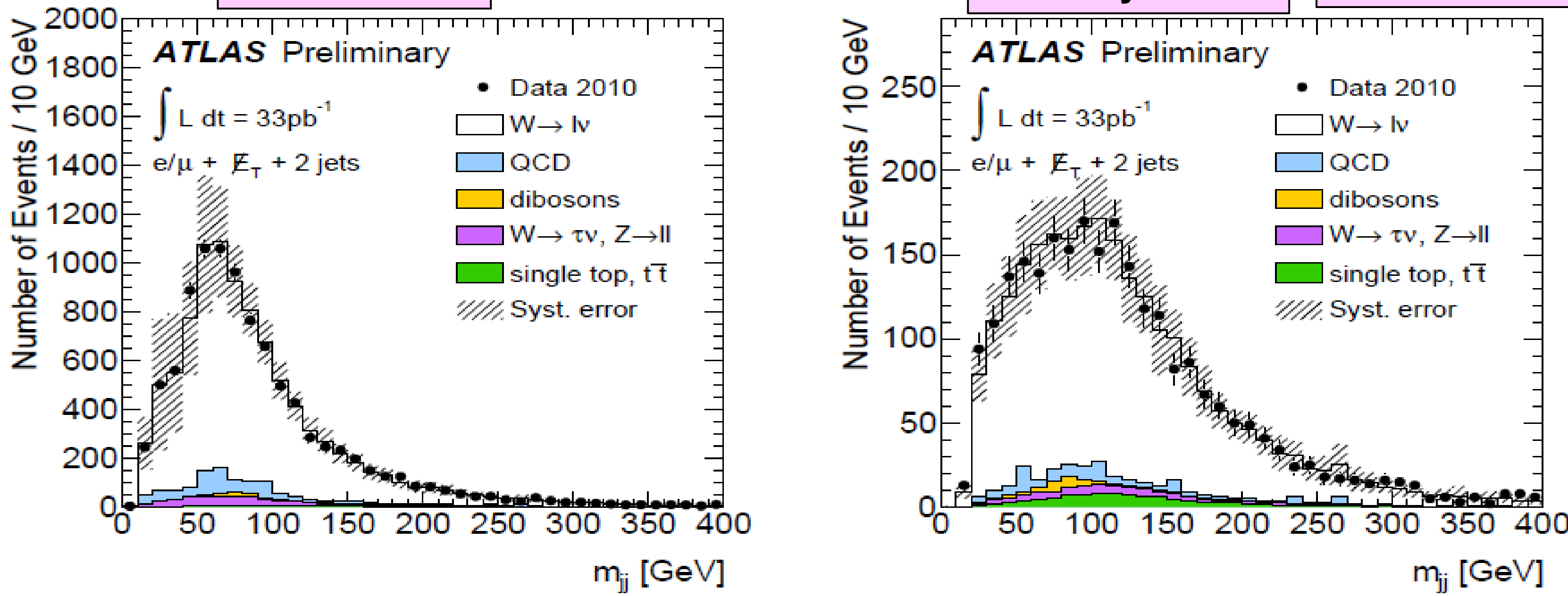


Phys. Rev. Lett. 106(2011)171801

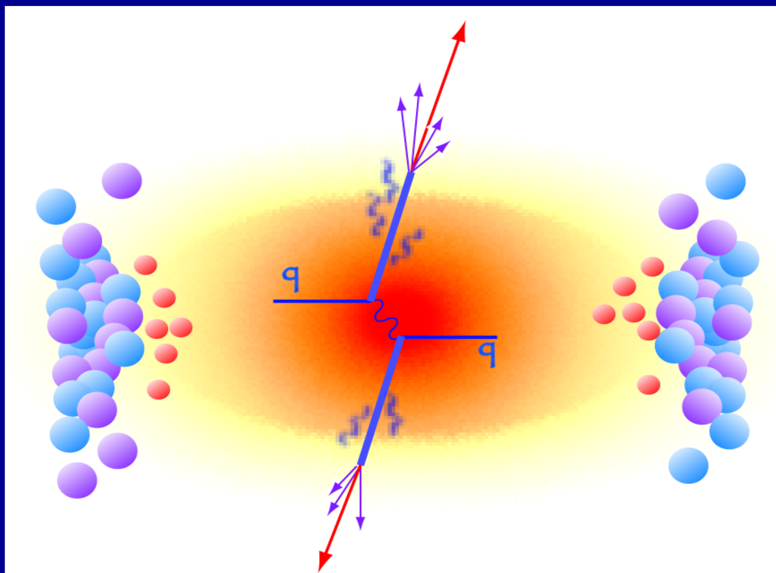
Standard cuts

'CDF-style' cuts

ATLAS-CONF-2011-069



Heavy-ion collisions: first direct observation of "jet quenching"



One of main goals of high-energy HI collisions: recreate "plasma of free quarks and gluons" "quark-gluon plasma" that (we think) permeated the Universe ~ 10 μs after Big Bang

Jets produced in HI collisions would be "quenched" by interacting with the (dense) plasma → expect asymmetric dijets final states

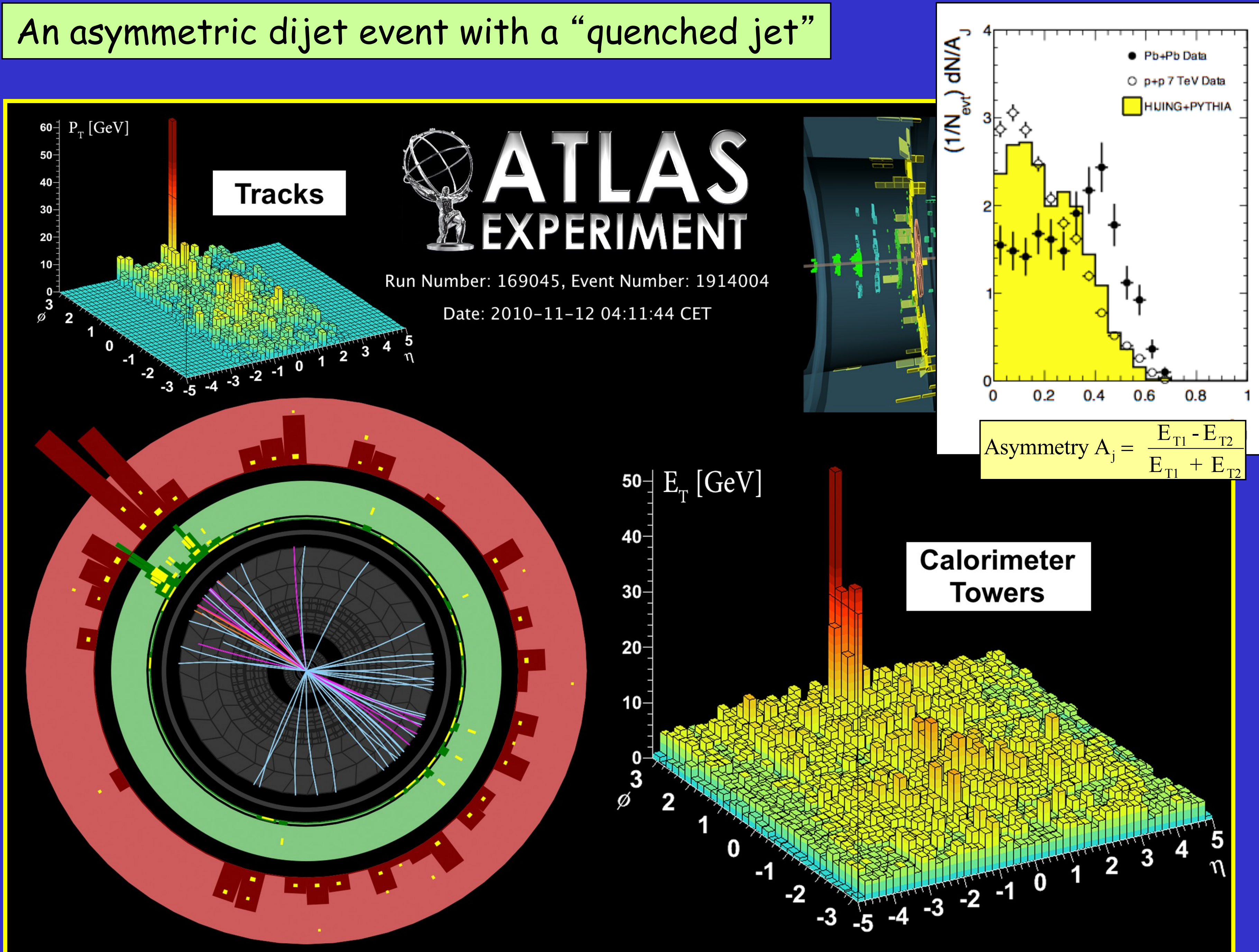
First asymmetric dijet events observed by ATLAS on 8 November (first day of Pb-Pb beams collisions)
→ paper accepted for publication in Physical Review Letters

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

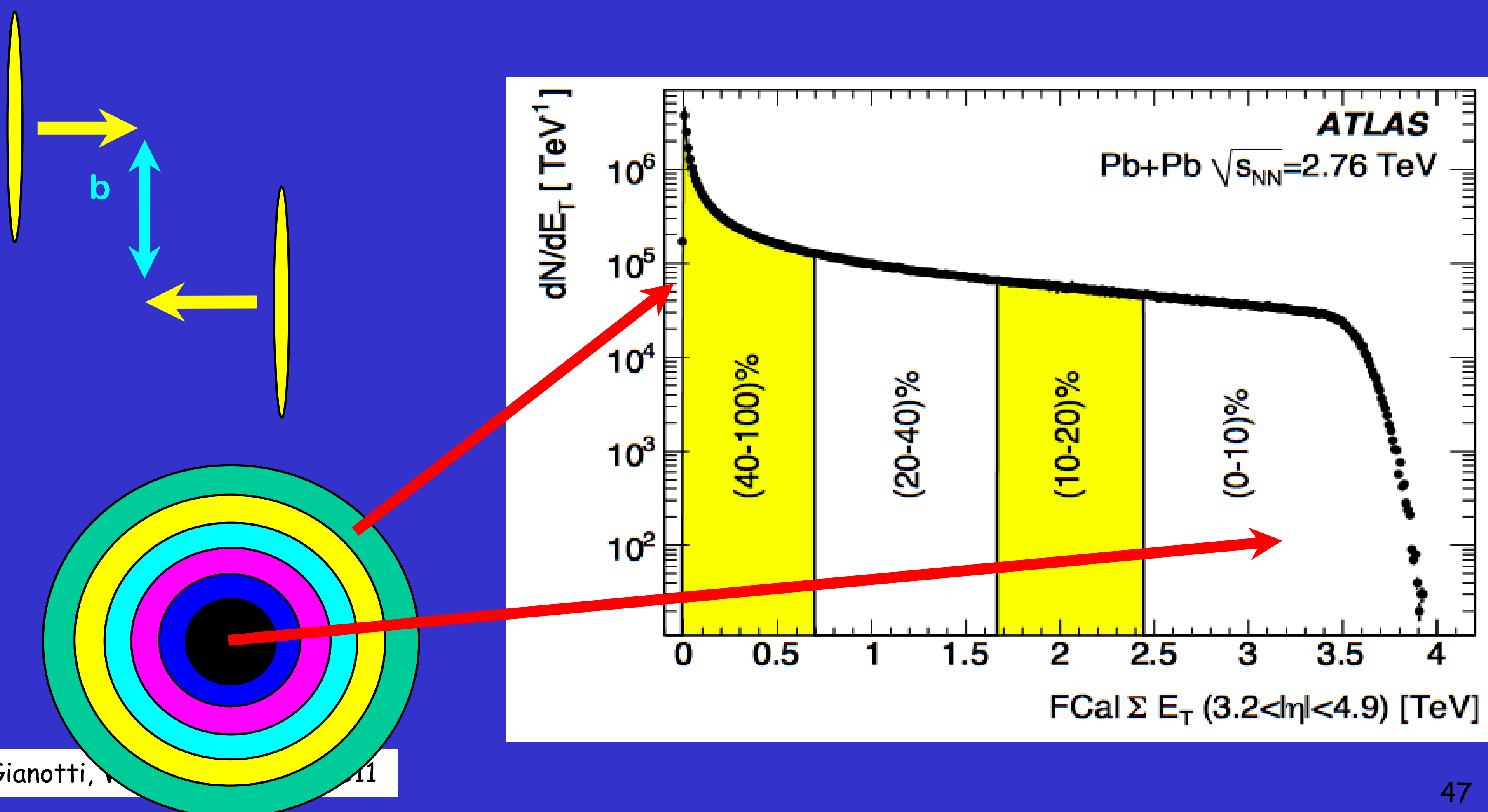
G. Aad *et al.* (The ATLAS Collaboration)*

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 underlying event is measured and subtracted event-by-event, giving estimates of jet transverse energy above the ambient background. The transverse energies of dijets in opposite hemispheres is 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.

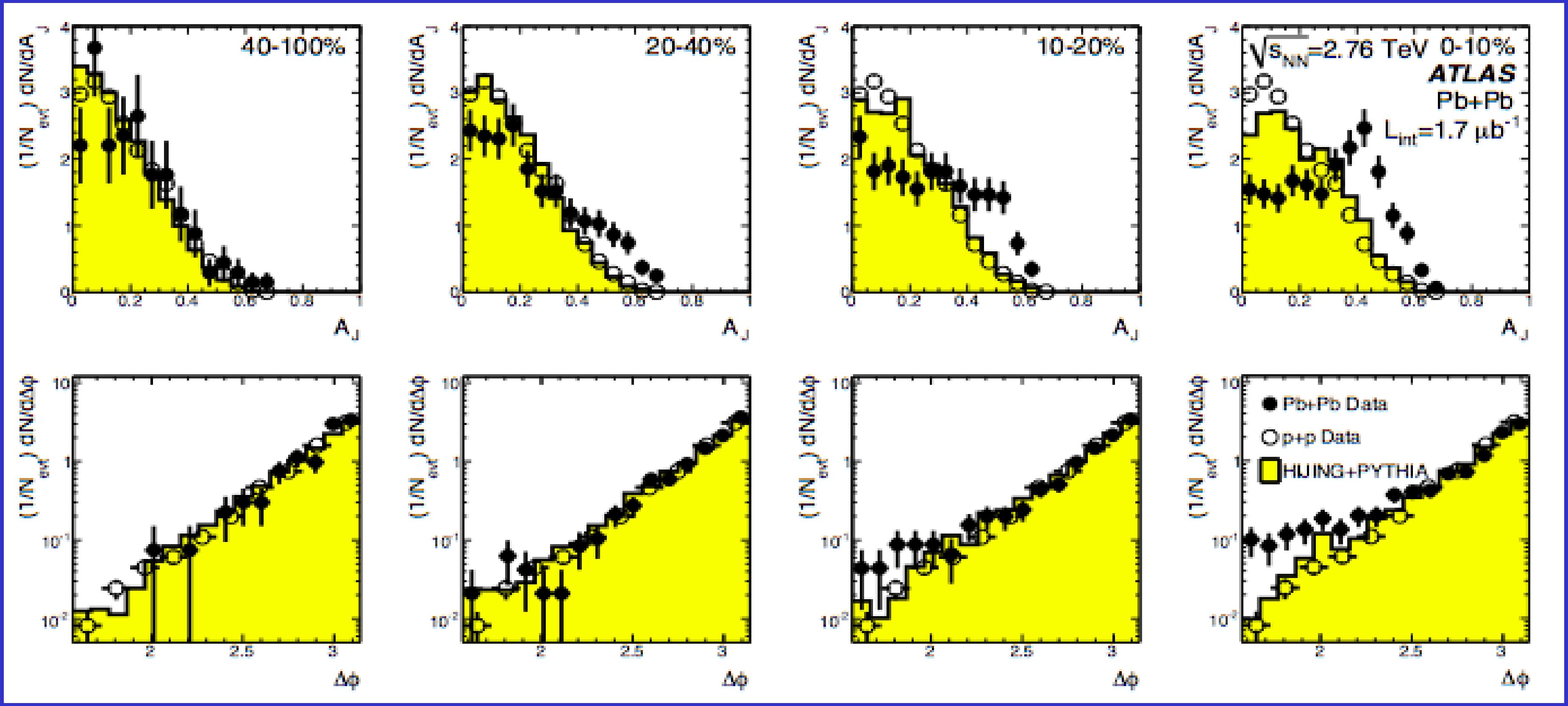
An asymmetric dijet event with a "quenched jet"



CENTRALITY



b
ATLAS
Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV
dN/dE_T [TeV^{-1}]
10^6
10^5
10^4
10^3
10^2
(40-100)%
(20-40)%
(10-20)%
(0-10)%
0
0.5
1
1.5
2
2.5
3
3.5
4
FCal Σ E_T (3.2<|η|<4.9) [TeV]

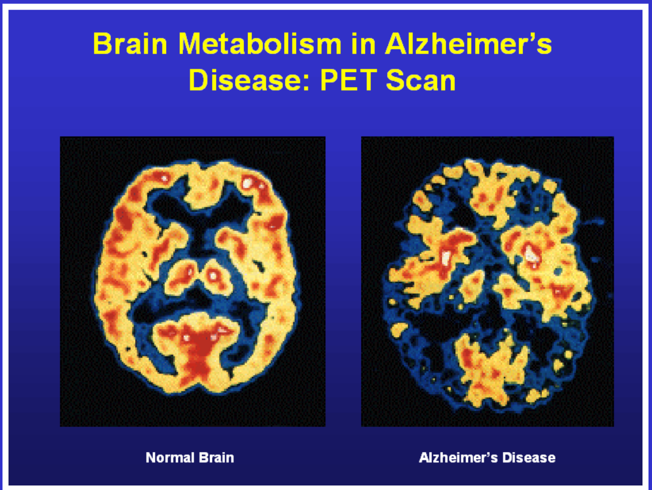


– For more central collisions, see:

- Reduced fraction of jets with small asymmetry
- Increased fraction of jets with large asymmetry

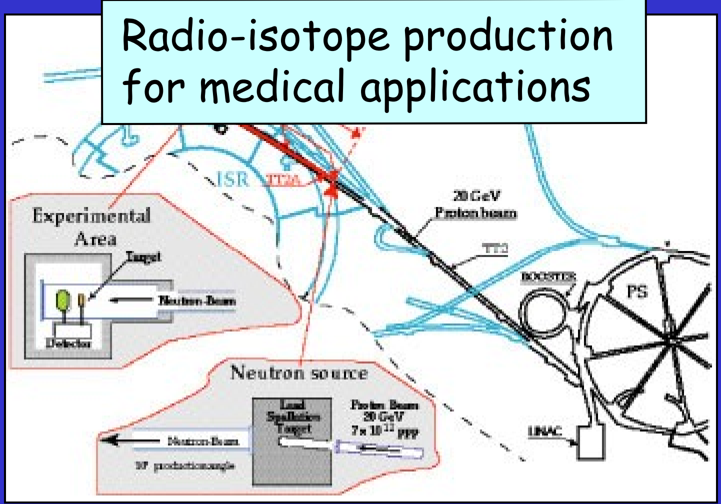
Technology transfer and spin-offs: from fundamental science to everyone's life

Extreme performance required in particle physics → cutting-edge technologies developed at CERN and collaborating Institutes and then transferred to society.



Applications: medical imaging (e.g. PET), cancer therapy, materials science, airport scanners, cargo screening, food sterilization, nuclear waste transmutation, etc. …
Not to mention the WEB and the GRID …

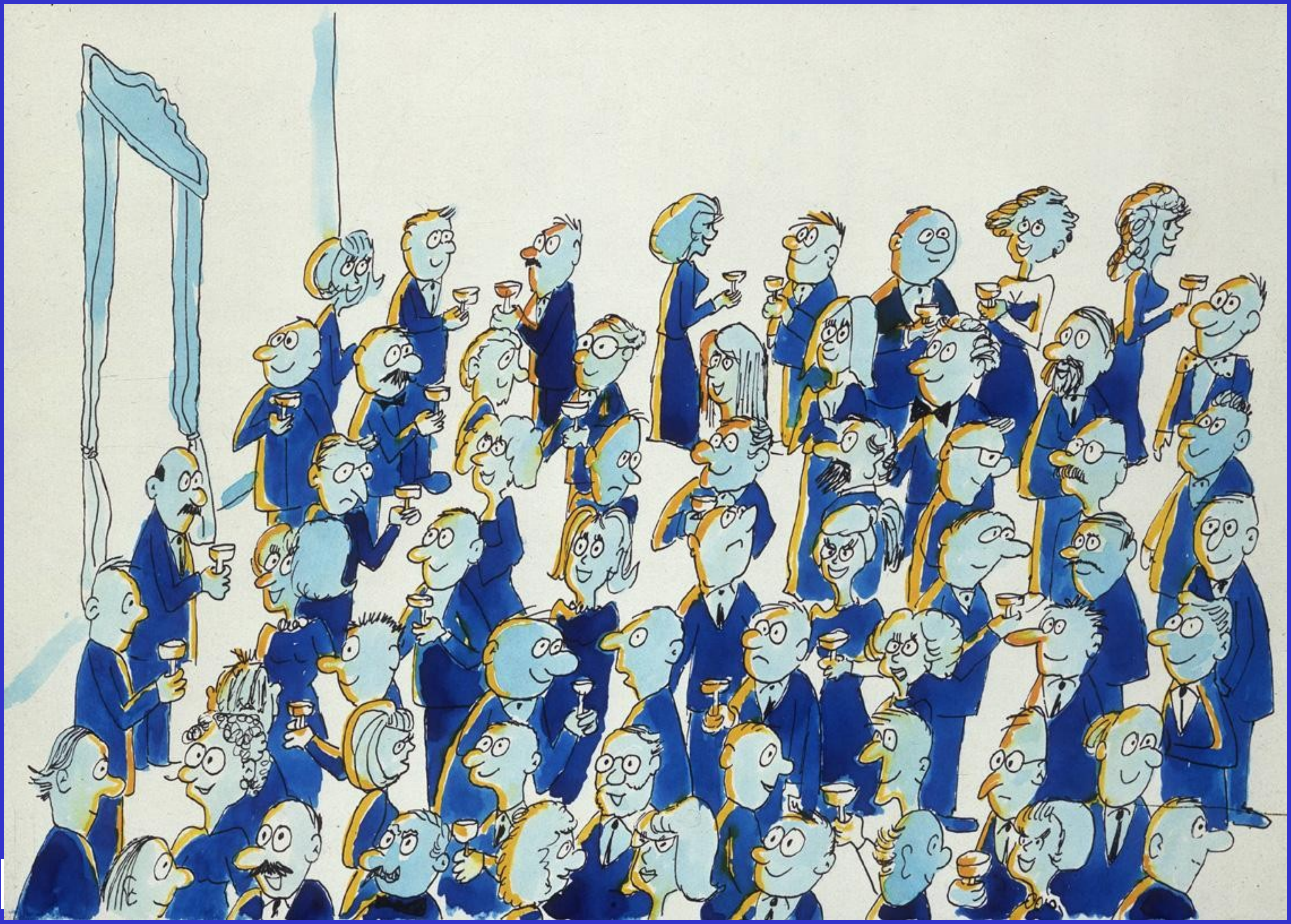
Radio-isotope production for medical applications



Hadrontherapy for cancer treatment

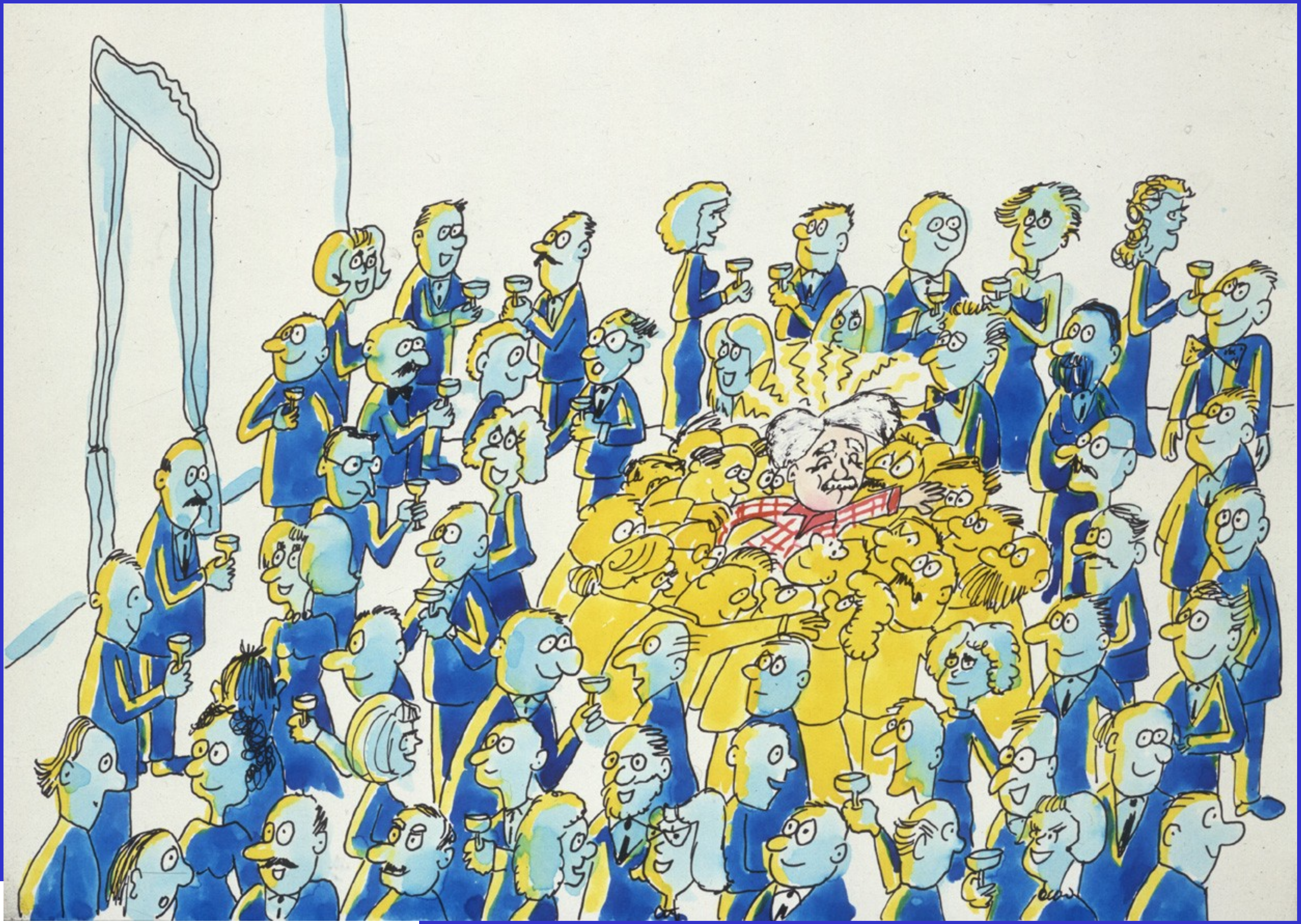
The Higgs mechanism … as exemplified by Prof. David Miller

Imagine a room full of people quietly chattering … this is like space filled only with the Higgs field ...

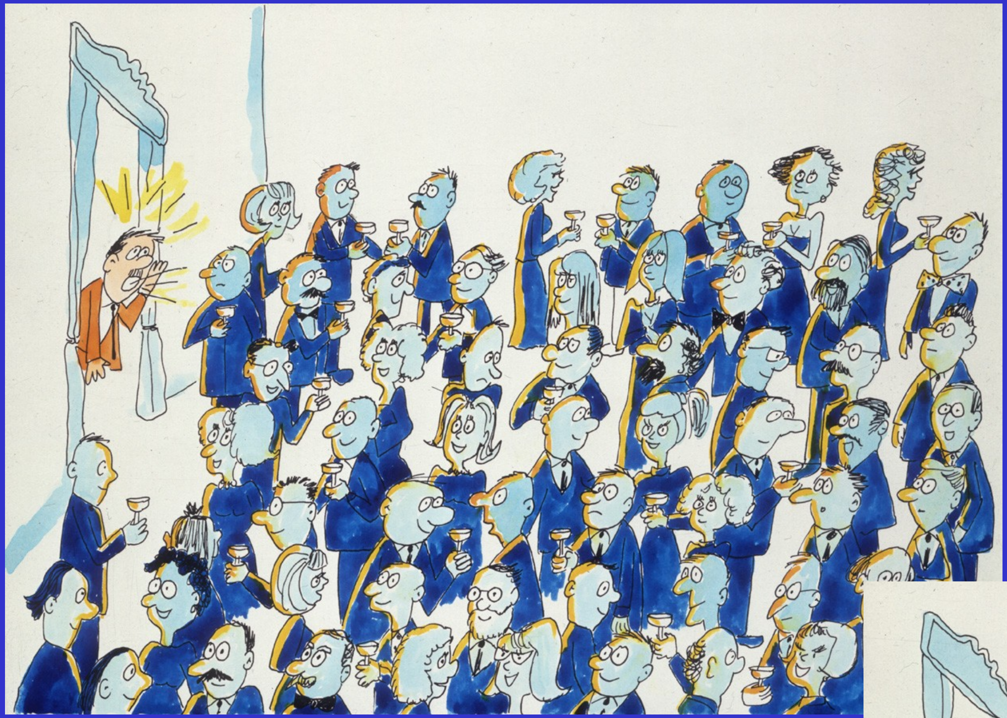


a well known actor walks in, creating a disturbance as he moves across the room, and attracting a cluster of admirers with each step ... the actor is like a particle traversing the Higgs field

this increase his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field ...



... Imagine now that a rumour crosses the room ...

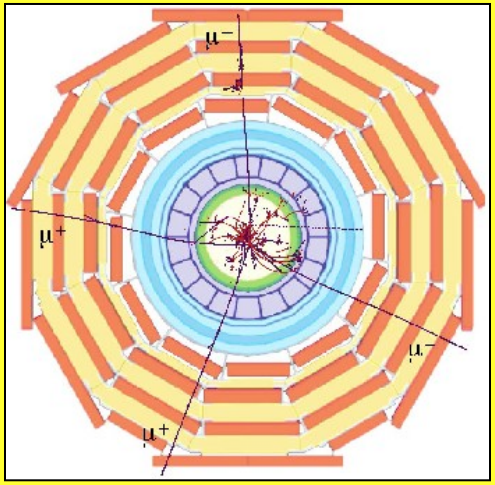


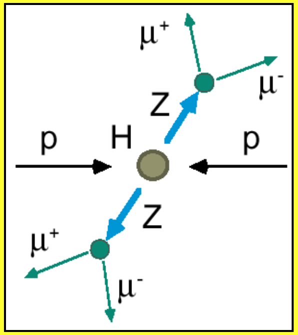
it creates the same kind of clustering, but this time among the people in the room. In this analogy, these clusters are the Higgs particle.

F. Gianotti, Wuppertal, 23/5/2011

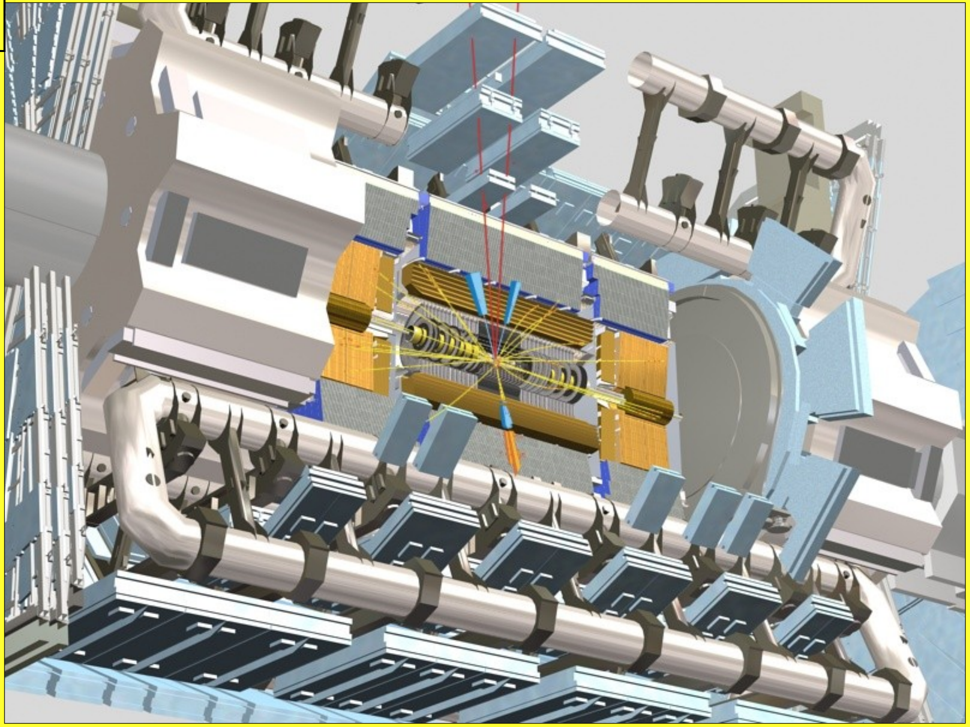
The Higgs boson in the LHC detectors

$H \to 4\mu$ in the CMS detector





$H \to 2\mu 2e$ in the ATLAS detector



$H \to \gamma\gamma$ in the CMS detector