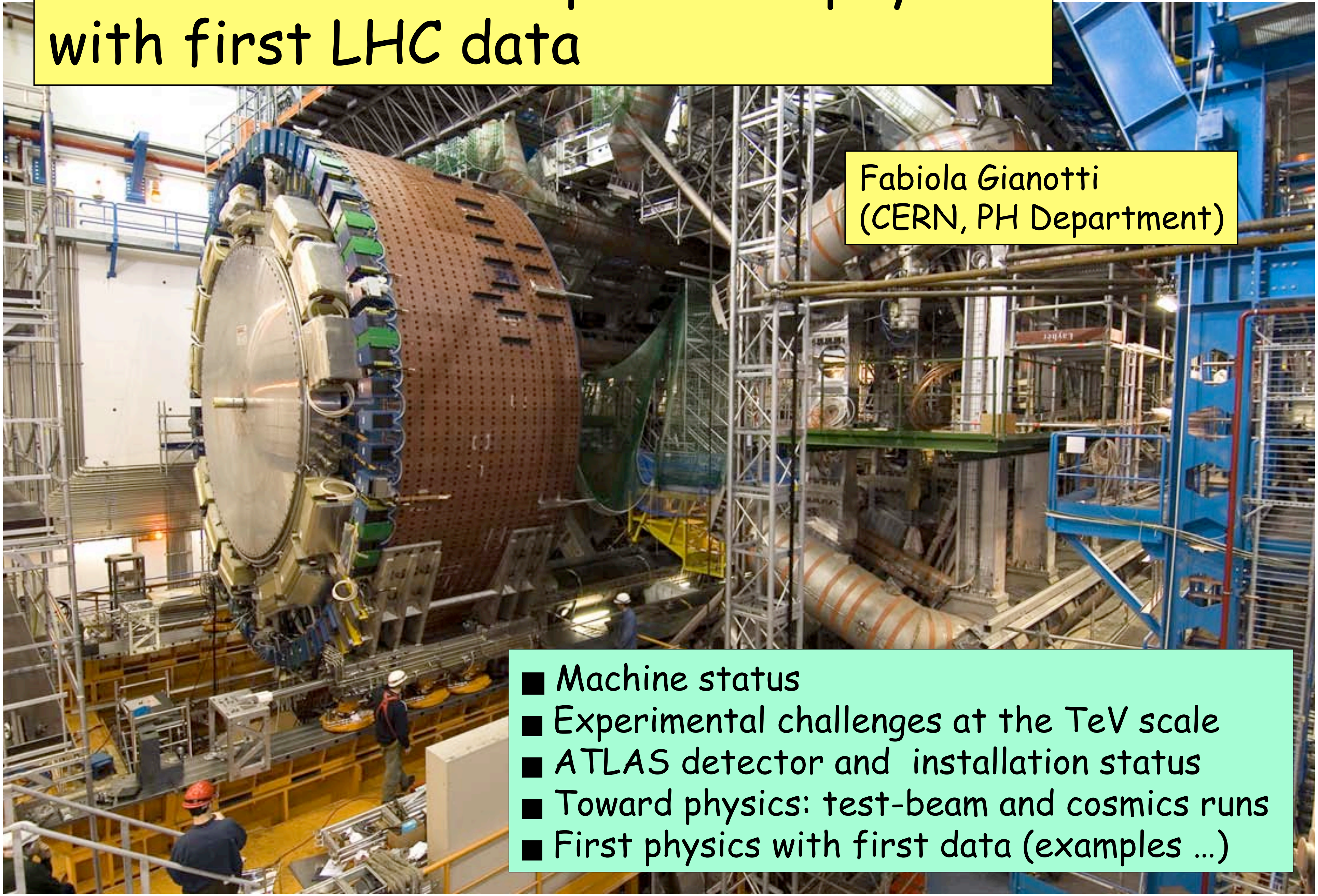
ATLAS status and plans for physics with first LHC data



Fabiola Gianotti
(CERN, PH Department)

- Machine status
- Experimental challenges at the TeV scale
- ATLAS detector and installation status
- Toward physics: test-beam and cosmics runs
- First physics with first data (examples …)

LHC

- pp, $\sqrt{s}$ = 14 TeV $L_{design} = 10^{34}\ cm^{-2}\ s^{-1}$ (after 2010)
  $L_{initial}$ up to few x $10^{33}\ cm^{-2}\ s^{-1}$ (before 2010)

  Note: $\sqrt{s}$ is x7 Tevatron, L_{design} is x100 Tevatron
- Heavy ions (e.g. Pb-Pb at $\sqrt{s}$ ~ 1000 TeV)

ALICE, heavy ions

CMS general purpose

ATLAS general purpose

LHCb : B-physics, CP-violation

CERN main site

Geneva Airport

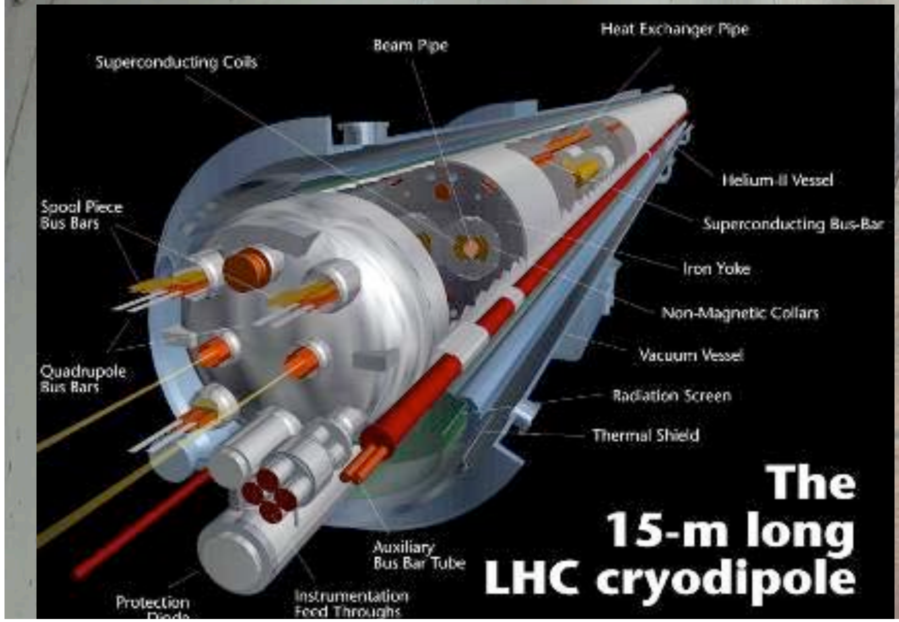
French-Swiss border

LHC 27 km ring
(previously used for LEP)

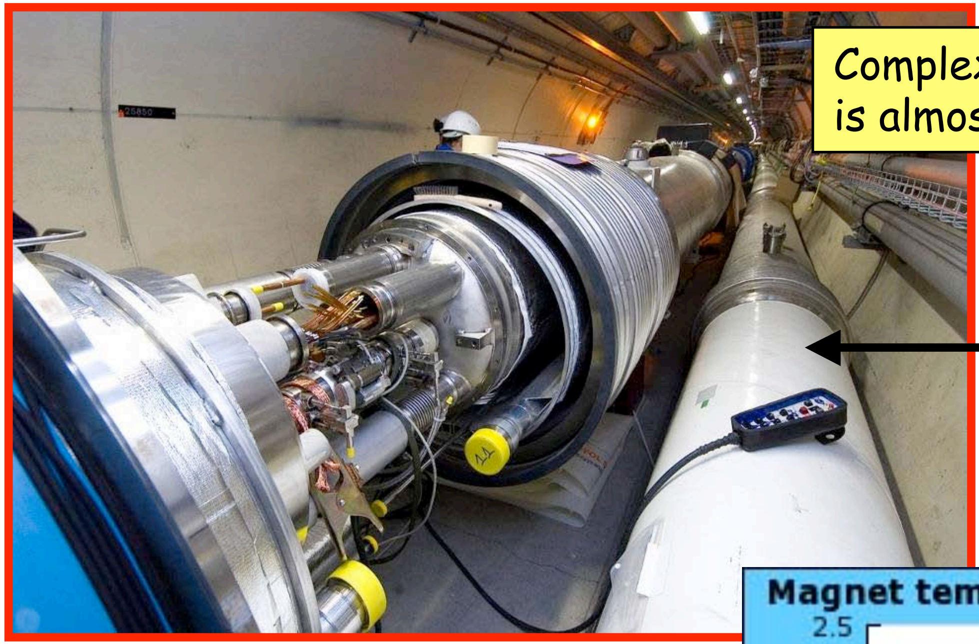
Machine most challenging component:
1232 high-tech superconducting dipole magnets

Dipole field: 8.4 T
Operation temperature: 1.9 K
Dipole current: 11700 A
Dipole weight: 34 tons
7600 km of Nb-Ti superconducting cable

Dipole installation completed

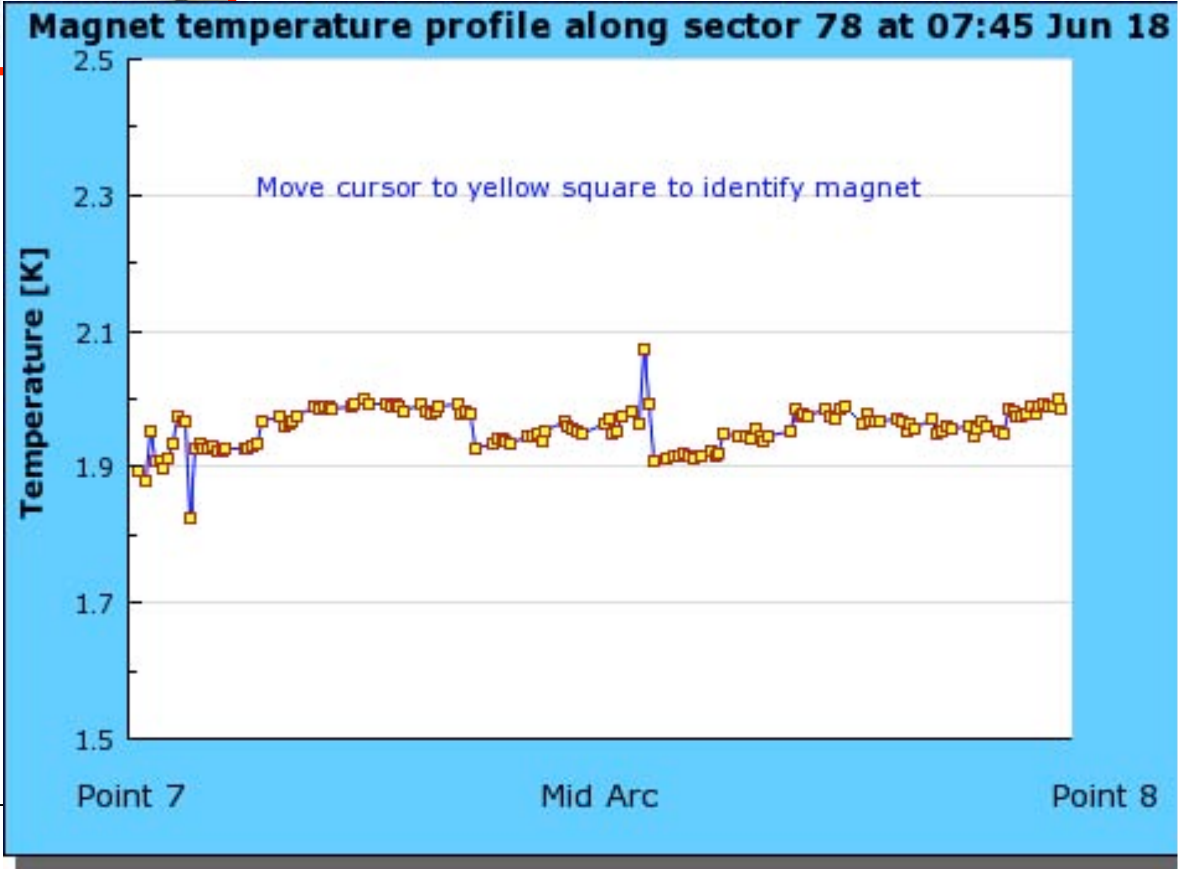


The 15-m long LHC cryodipole



Complex dipole interconnection work is almost finished

Cryogenic line

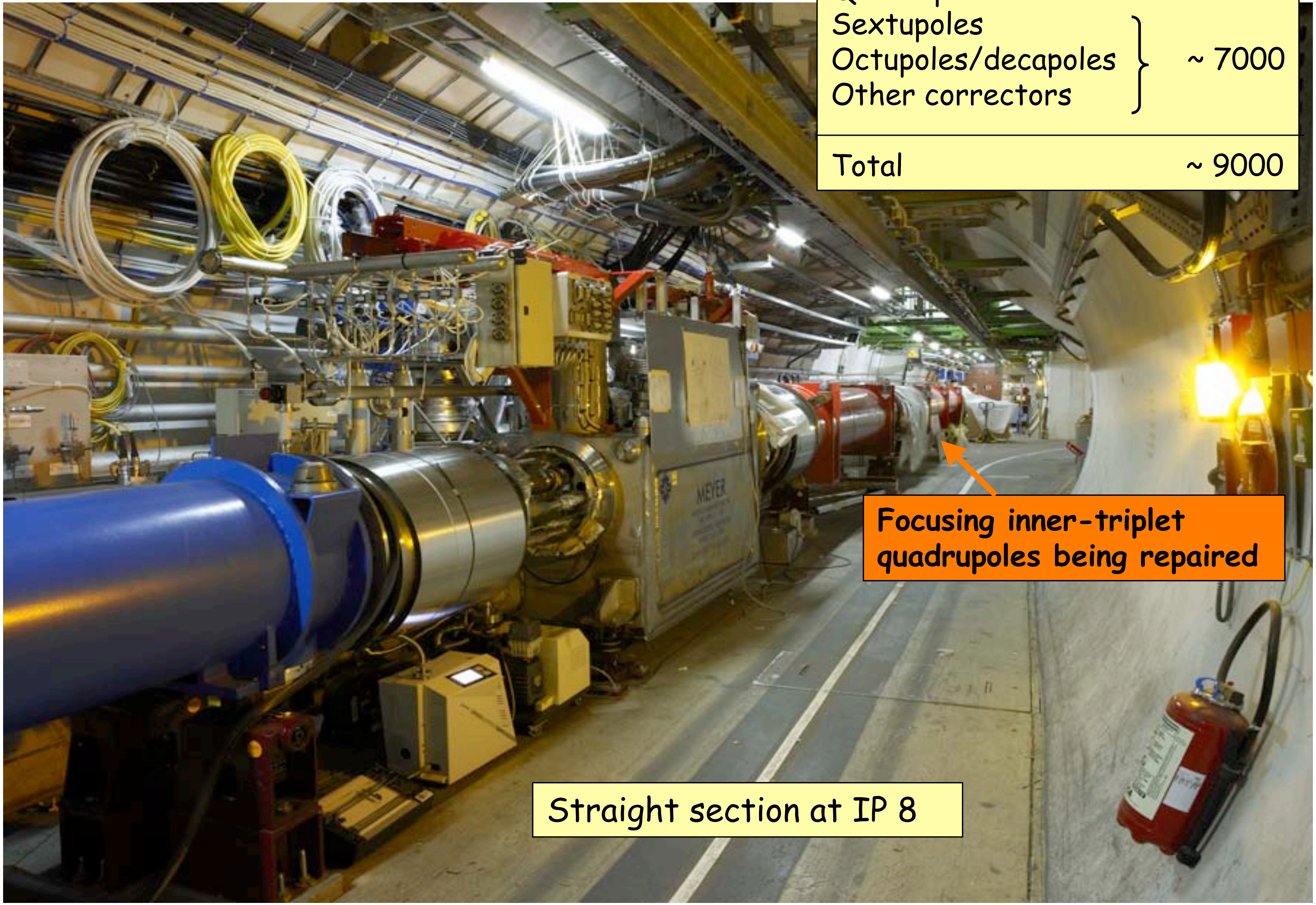


The first one of eight sectors (sector 7-8) was cooled down to 1.9 K in the first half of 2007

Cool-down of sector 4-5 started

One sector: 3.3 km, 154 dipoles

Not only dipoles ....



Main dipoles	1232
Quadrupoles	~ 400
Sextupoles	~ 7000
Octupoles/decapoles	
Other correctors	
Total	~ 9000

Focusing inner-triplet quadrupoles being repaired

Straight section at IP 8

Main parameters of the machine

	Design operation	
Beam energy	7	TeV
Dipole field	8.4	T
Dipole current	11700	A
Instantaneous luminosity L	10^{34}	$cm^{-2}s^{-1}$
Integrated luminosity/year	~ 100	fb^{-1}
Circulating current/beam	0.53	A
Number of bunches	2808	
Bunch spacing	25	ns
Protons per bunch	10^{11}	
R.m.s. beam radius at IP1/5	16	µm
R.m.s. bunch length	7.5	cm
Stored beam energy	360	MJ
Crossing angle	300	µrad
Number of events per crossing	~20	
Luminosity lifetime	10	hours

n. of protons per bunch

n. of bunches

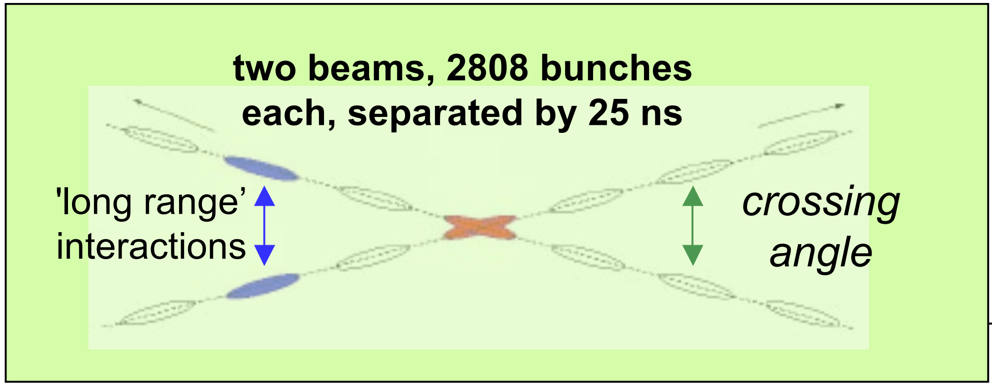
$$L = \frac{N^2 k_b f}{4\pi \sigma_x \sigma_y}$$

n. of turns per second

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

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

x200 Tevatron



two beams, 2808 bunches each, separated by 25 ns

Aircraft carrier at 12 knots

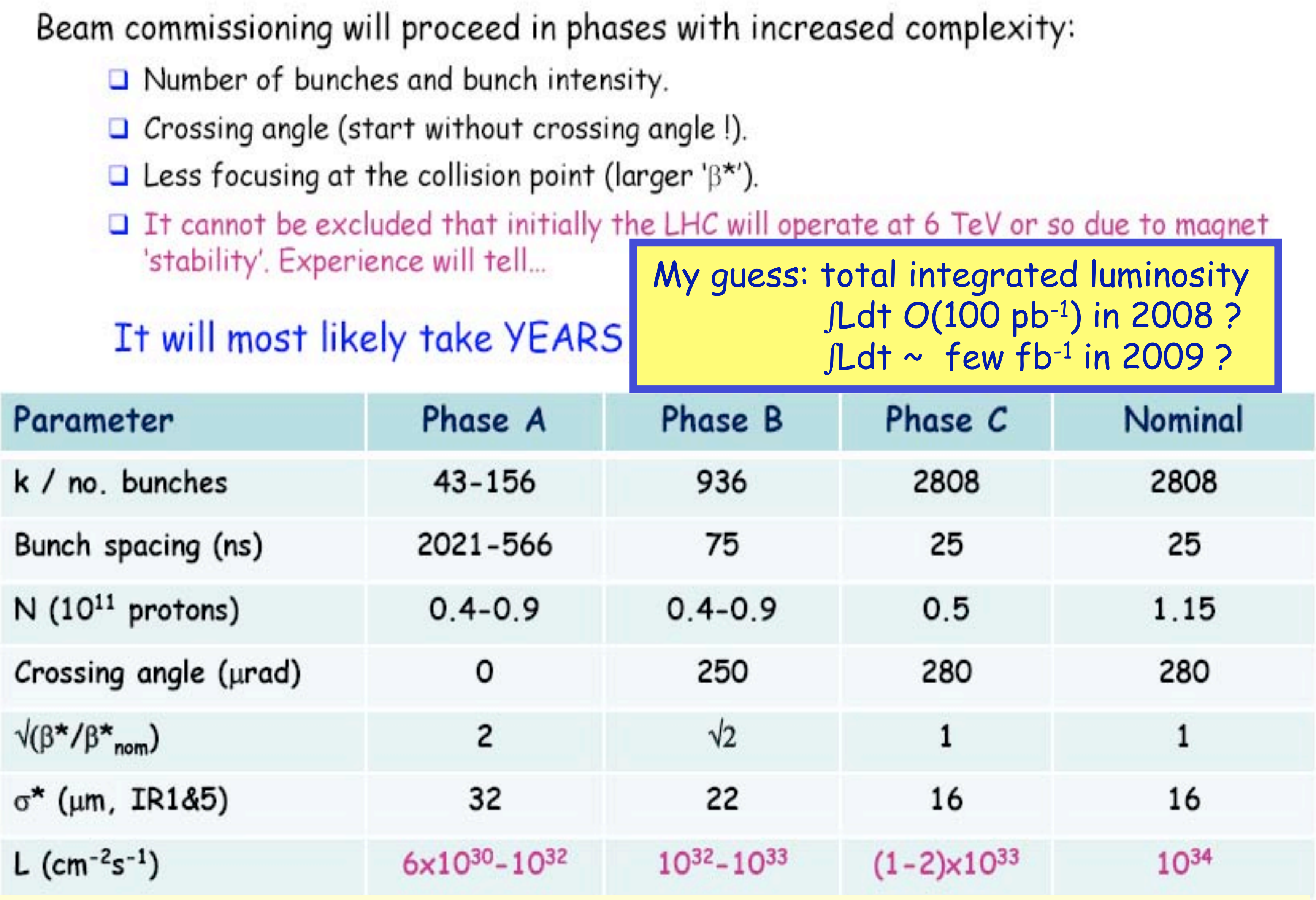
Lyn Evans
SPC 18-June-2007

General LHC Schedule

- Engineering run originally foreseen at end 2007 now precluded by delays in installation and equipment commissioning.
- 450 GeV operation now part of normal setting up procedure for beam commissioning to high-energy
- General schedule being reassessed, accounting for inner triplet repairs and their impact on sector commissioning
  - -- All technical systems commissioned to 7 TeV operation, and machine closed April 2008
  - -- Beam commissioning starts May 2008
  - -- First collisions at 14 TeV c.m. July 2008
  - -- Pilot run pushed to 156 bunches for reaching 10^{32} cm^{-2} s^{-1} by end 2008
- No provision in success-oriented schedule for major mishaps, e.g. additional warm-up/cooldown of sector

The various steps toward design luminosity

Jorg Wenninger
(machine team)



Beam commissioning will proceed in phases with increased complexity:

- Number of bunches and bunch intensity.
- Crossing angle (start without crossing angle !).
- Less focusing at the collision point (larger 'β*').
- It cannot be excluded that initially the LHC will operate at 6 TeV or so due to magnet 'stability'. Experience will tell...

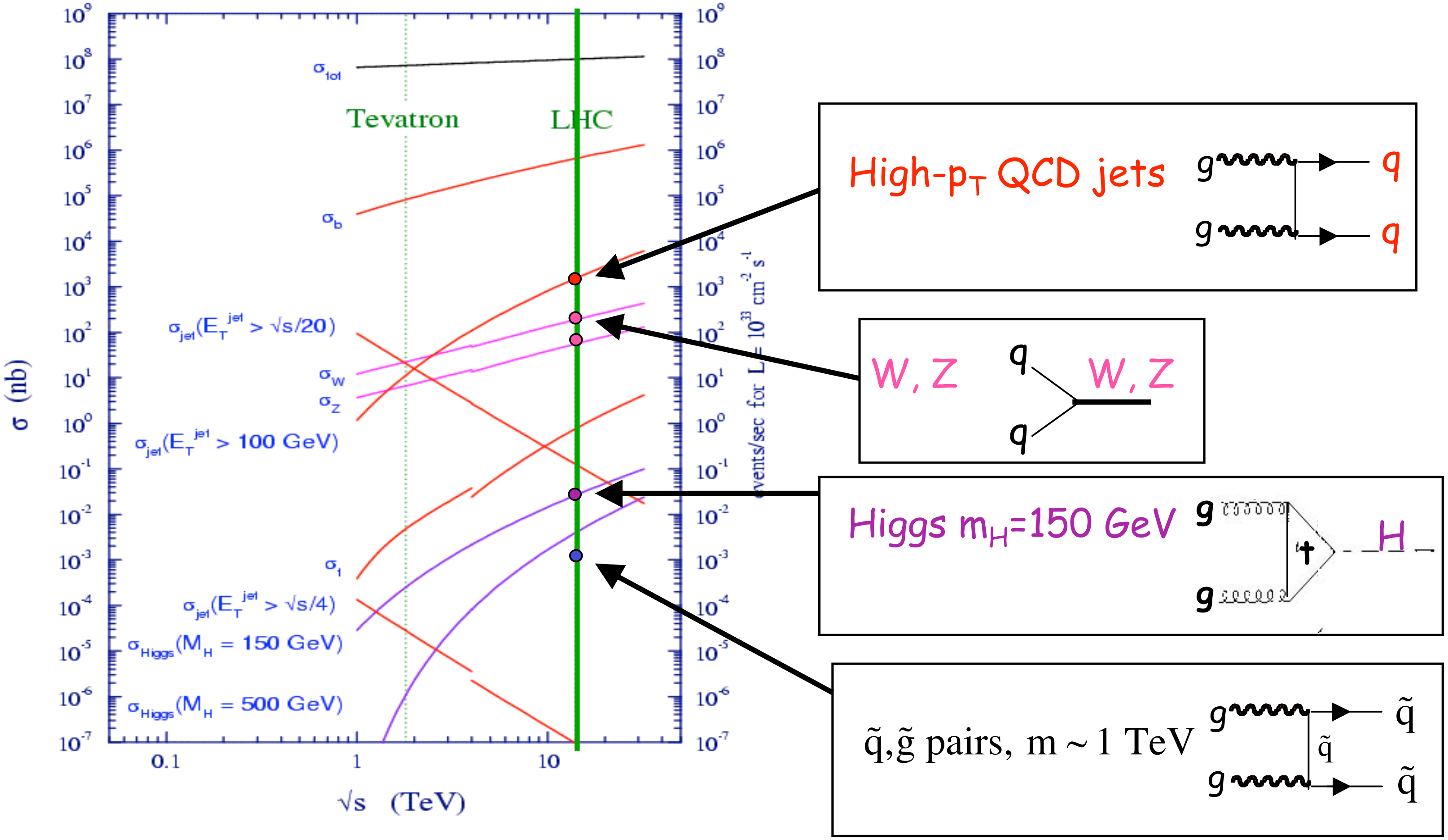
It will most likely take YEARS

My guess: total integrated luminosity
$\int L dt$ O(100 pb^{-1}) in 2008 ?
$\int L dt \sim$ few fb^{-1} in 2009 ?

Parameter	Phase A	Phase B	Phase C	Nominal
k / no. bunches	43-156	936	2808	2808
Bunch spacing (ns)	2021-566	75	25	25
N (10^{11} protons)	0.4-0.9	0.4-0.9	0.5	1.15
Crossing angle (μrad)	0	250	280	280
$\sqrt{(\beta^*/\beta^*_{nom})}$	2	$\sqrt{2}$	1	1
σ* (μm, IR1&5)	32	22	16	16
L ($cm^{-2}s^{-1}$)	$6\times10^{30}-10^{32}$	$10^{32}-10^{33}$	$(1-2)\times10^{33}$	10^{34}
Year (?)	2008	2009	2009-2010	> 2010

Main experimental challenges to be faced in order to explore the TeV scale

❶ Huge (QCD) backgrounds (consequence of high energy …)



High-p_T QCD jets

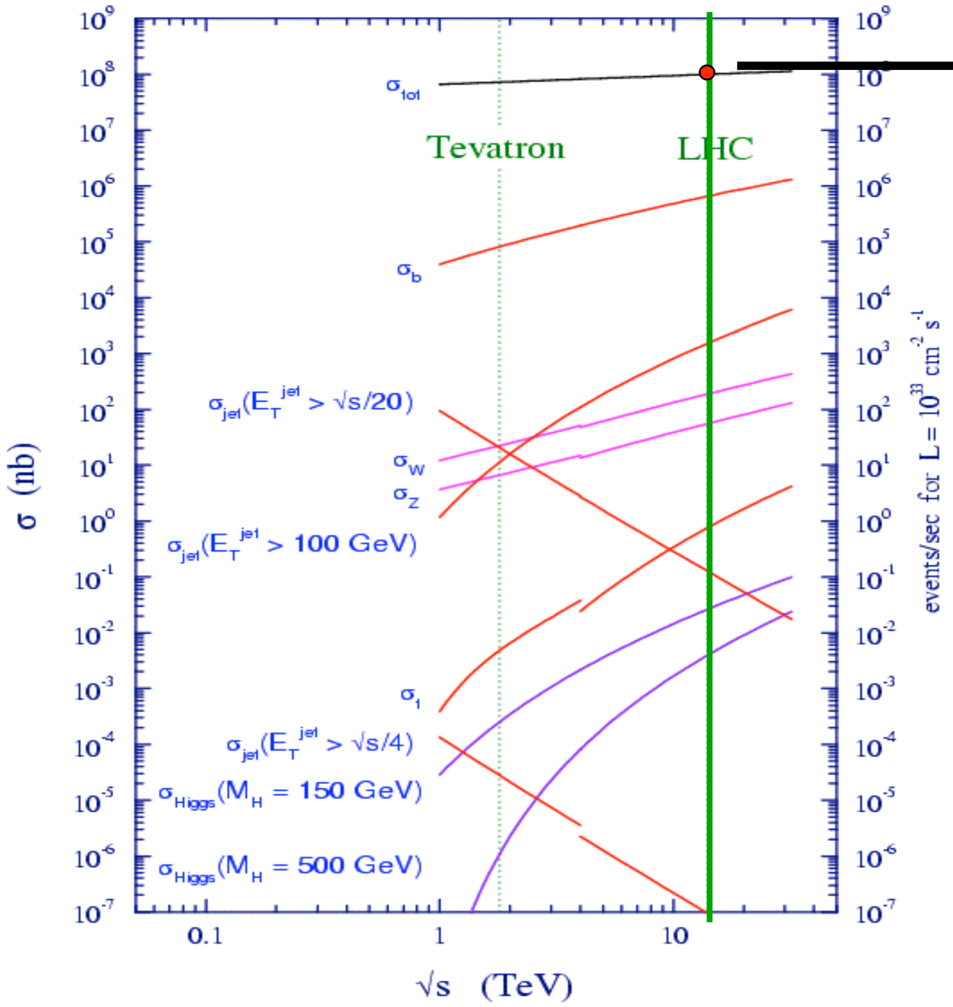
W, Z

Higgs m_H=150 GeV

q̃,g̃ pairs, m ~ 1 TeV

- No hope to observe light objects (W, Z, H ?) in fully-hadronic final states → rely on l, γ
- Mass resolutions of ~ 1% (10%) needed for l, γ (jets) to extract tiny signals from backgrounds, and excellent particle identification (e.g. e/jet separation)
- Fully-hadronic final states (e.g. q* → qg) can be extracted from backgrounds only with hard O(100 GeV) p_T cuts → works only for heavy objects
- Signal (EW) /Background (QCD) larger at Tevatron than at LHC

❷ Event rate and pile-up (consequence of machine high luminosity …)

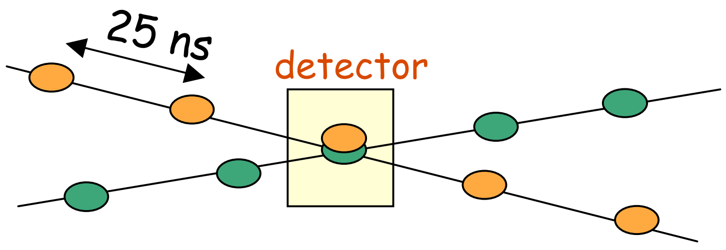


Event rate in ATLAS, CMS :

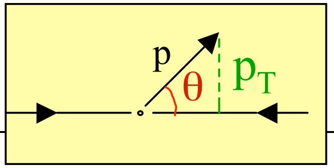
$N = L \times \sigma_{inelastic}(pp) \approx 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1} \times 70\ \text{mb}$

$\approx 10^9$ interactions/s

Proton bunch spacing : 25 ns
Protons per bunch : 10^{11}

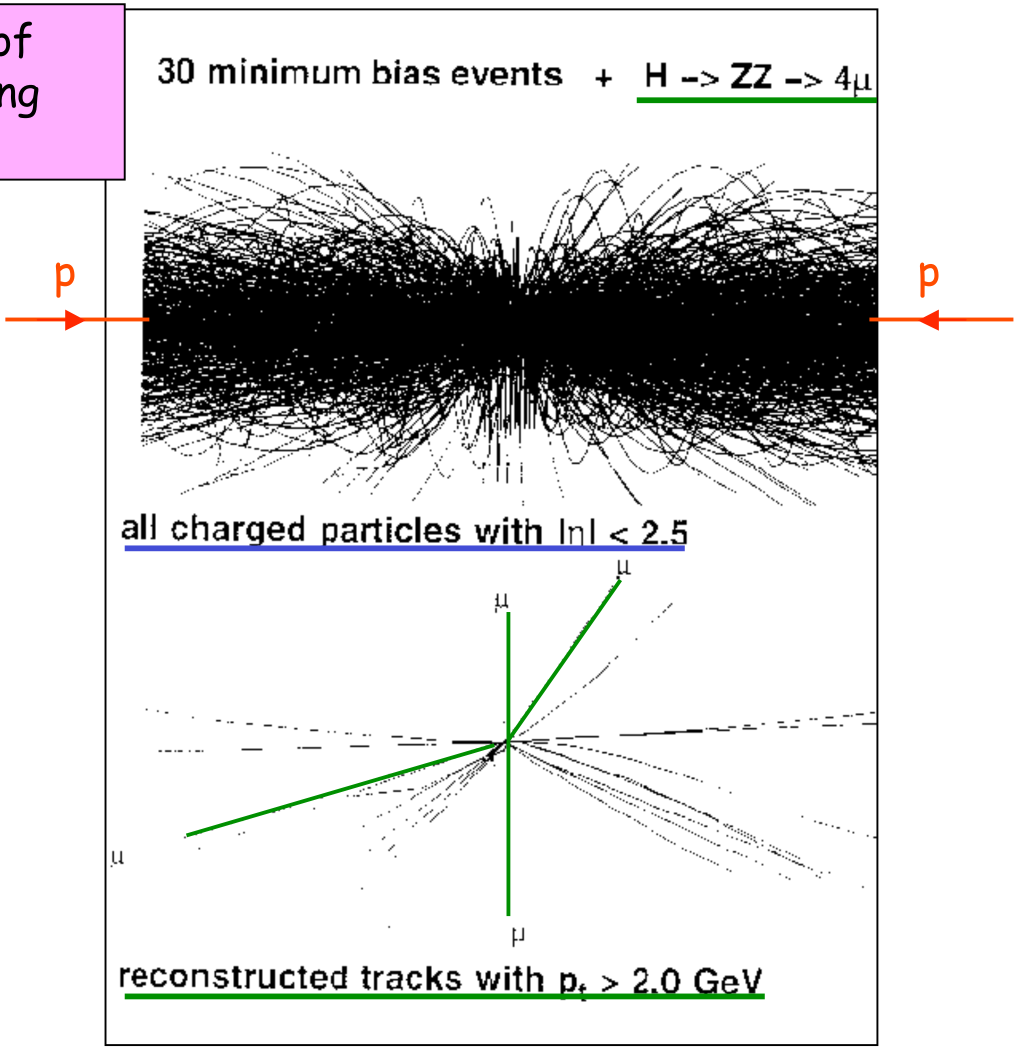


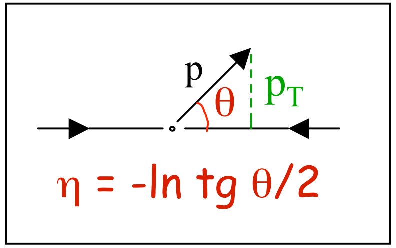
~ 20 inelastic (low-p_T) events ("minimum bias") produced simultaneously in the detectors at each bunch crossing → pile-up



Simulation of CMS tracking detector

At each crossing : ~1000 charged particles produced over $|\eta| < 2.5$ $(10^0 < \theta < 170^0)$
However : $< p_T > \approx 500$ MeV
→ applying p_T cuts allows extraction of interesting events





$\eta = -\ln \operatorname{tg} \theta/2$

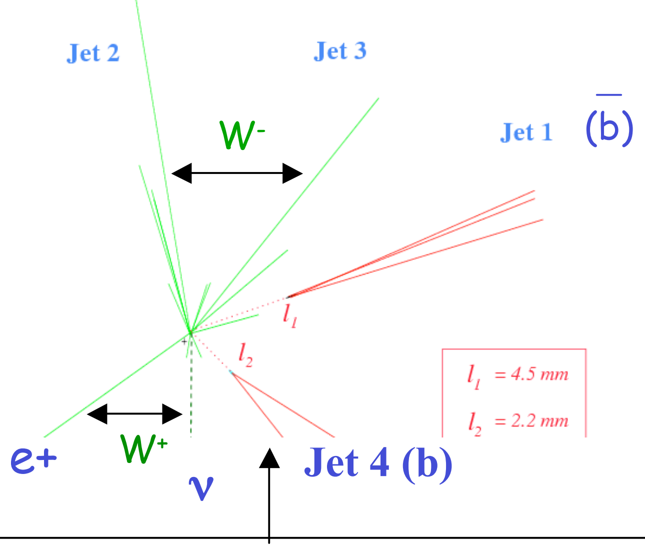
Impact of pile-up on detector requirements and performance:
- -- fast response : ~ 50 ns
- -- granularity : > 10^8 channels
- -- radiation resistance (up to 10^{16} n/cm^2/year in forward calorimeters)
- -- event reconstruction much more challenging than at previous colliders

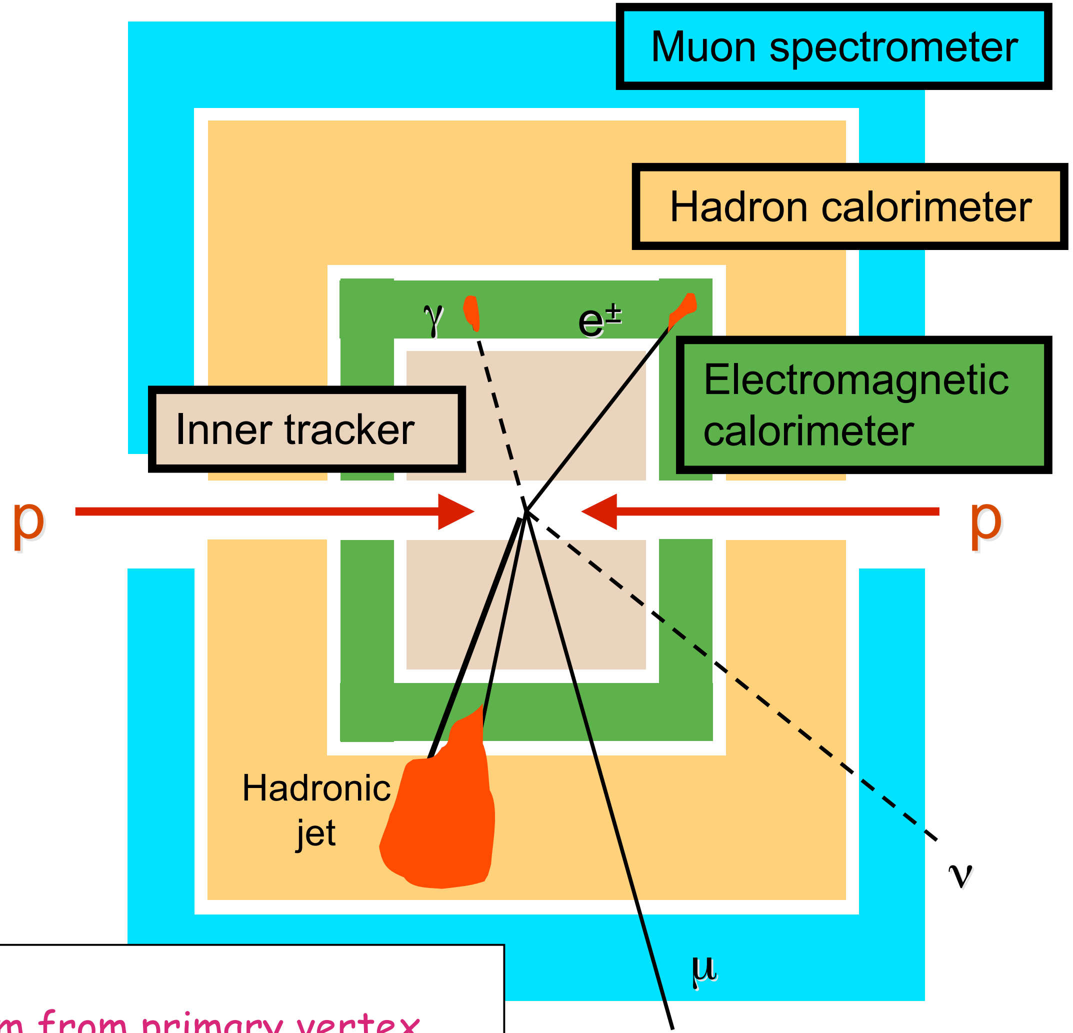
❸ Powerful high-performance experiments

Don’ t know how New Physics will manifest → detectors must be able to detect as many particles and signatures as possible: e, μ, τ, ν, γ, jets, b-quarks, ….
→ ATLAS and CMS are general-purpose experiments.

Excellent performance over
unprecedented energy range :
few GeV → few TeV

$t\bar{t} \rightarrow bW\bar{b}W \rightarrow bl\nu\bar{b}jj$ event
from CDF data





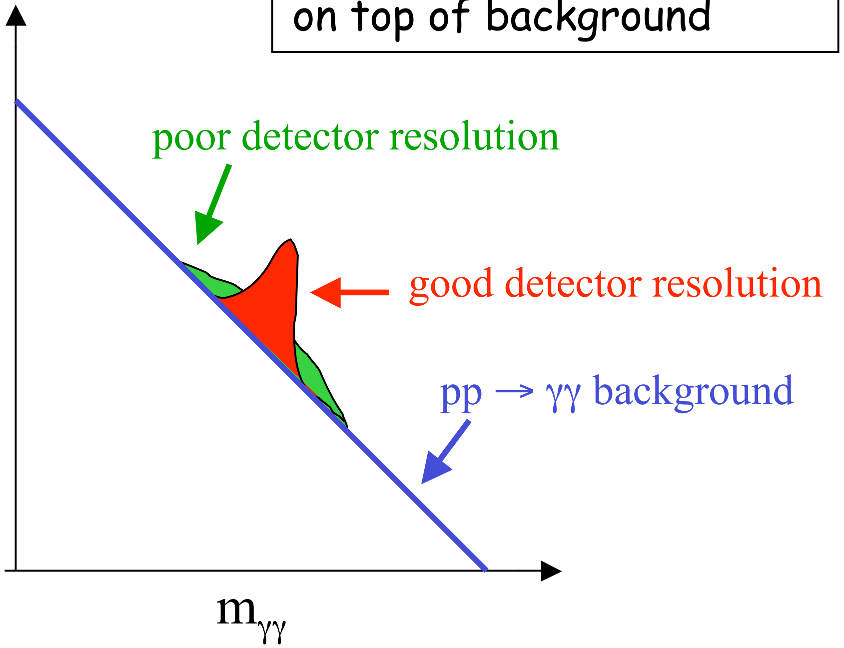
b-tagging (secondary vertices)
τ (b-hadrons) ~ 1.5 ps → decay at few mm from primary vertex
→ detected with high-granularity Si detectors

Examples of detector performance requirements:

Lepton measurement: $p_T \approx$ GeV → 5 TeV (b → l+X, W'/Z', …)

Mass resolutions:
- ≈ 1% decays into leptons or photons (Higgs, new resonances)
- ≈ 10% W → jj, H → bb (top physics, Higgs, …)

Hypothetical X → γγ signal on top of background



Particle identification:
- b/jet separation : ε (b) ≈ 50% R (jet) ≈ 100 (H → bb, SUSY, 3rd generation !!)
- τ/jet separation : ε (τ) ≈ 50% R(jet) ≈ 100 (A/H → ττ, SUSY, 3rd generation !!)
- γ/jet separation : ε (γ) ≈ 80% R(jet) > 10^3 (H → γγ)
- e/jet separation : ε (e) > 70% R(jet) > 10^5 (inclusive electron sample)

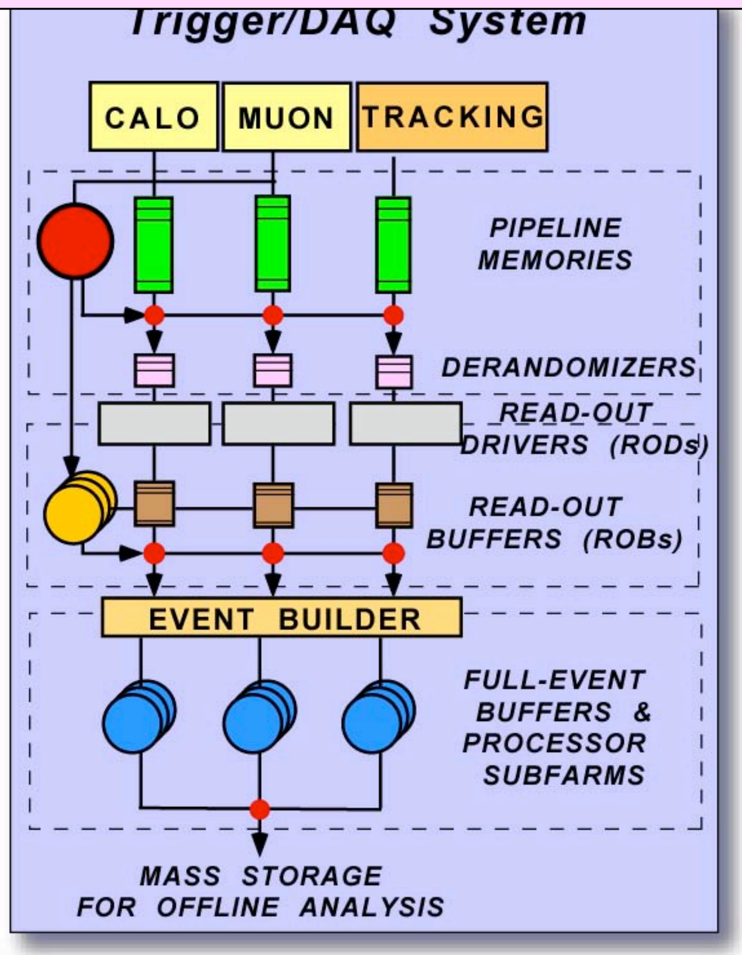
Trigger: one of the biggest challenges

More in S.Dasu's talk

Must reduce rate from 10^9 pp interactions/s (at design luminosity)
to ~ 200 Hz (affordable rate to storage)
Must be very selective and efficient: e.g. 1 H → 4e event every 10^{13} interactions
⇒ multi-level trigger systems

ATLAS 3-levelTrigger/DAQ system

RATES
- **40 MHz**
- **75 kHz**
- **2 kHz**
- **200 Hz**



LEVEL 1 TRIGGER
- **Hardware-Based (FPGAs ASICs)**
- **Coarse granularity from calorimeter & muon systems**
- **2 μs latency (2.5 μs pipelines)**

LEVEL 2 TRIGGER
- **Regions-of-Interest "seeds"**
- **Full granularity for all subdetector systems**
- **Fast Rejection "steering"**
- **O(10 ms) processing time**

EVENT FILTER
- **"Seeded" by Level 2 result**
- **Potential full event access**
- **Offline-like Algorithms**
- **O(1 s) processing time**

High Level Trigger

Finally, need massive (distributed) computing resources (CPU, storage)

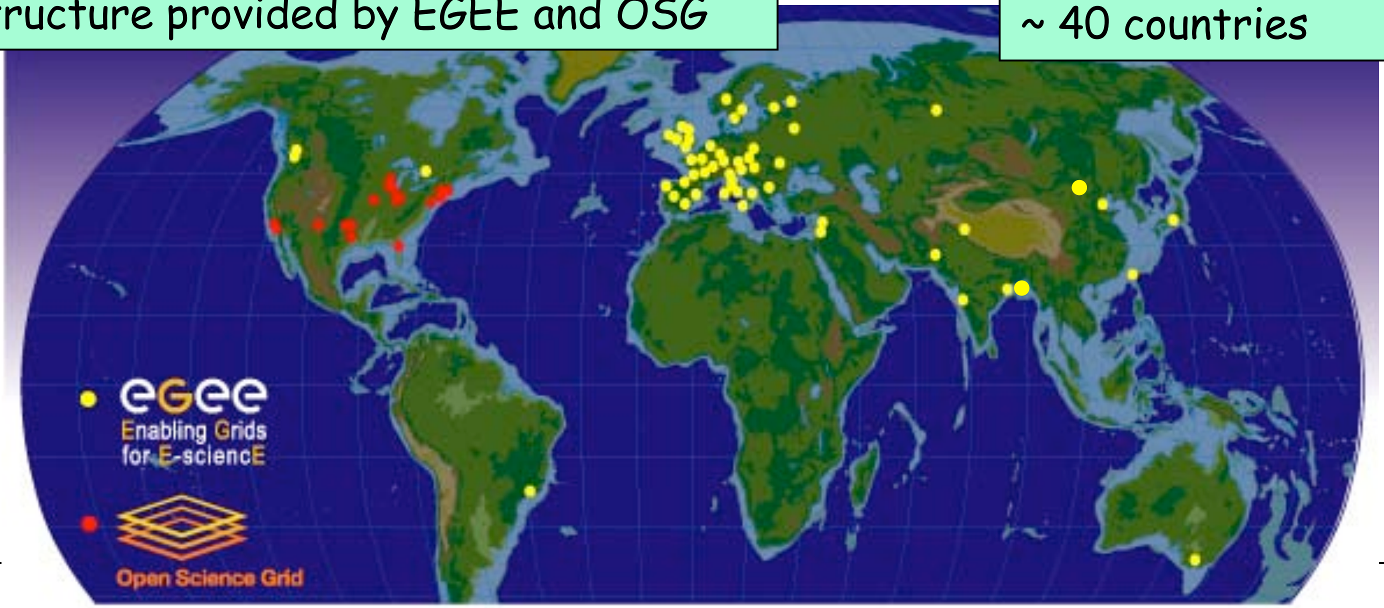
The LHC experiments will produce 10-15 PB of data per year:
corresponds to ~ 20 million CD (a 20 km stack …)

Data analysis requires computing power equivalent to ~10^5 today's fastest PC processors

The experiment Collaborations are spread all over the world

→ Computing resources must be distributed.

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



A map of the worldwide LHC Computing Grid infrastructure provided by EGEE and OSG

~120 computing centers
~ 40 countries

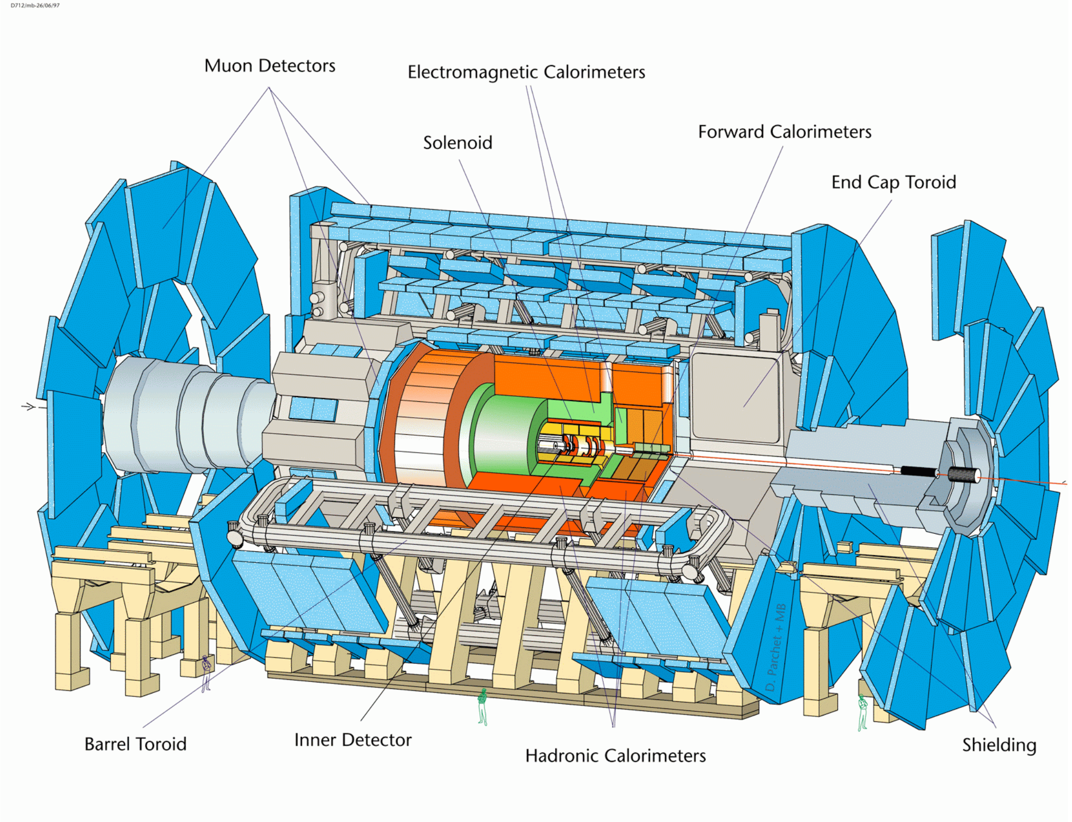
The ATLAS experiment:

- main features of the detector
- installation status

Construction : completed
Installation in underground cavern : almost completed
Commissioning with cosmics : ongoing

ATLAS

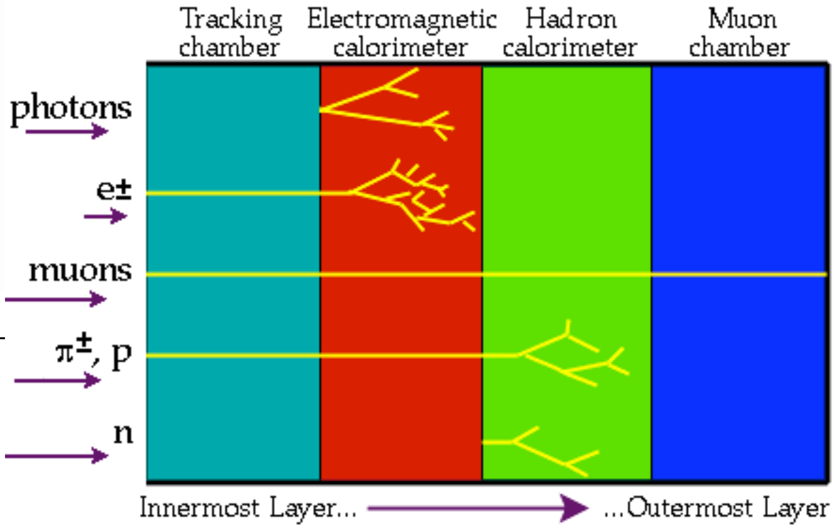
Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
~ 3000 km of cables



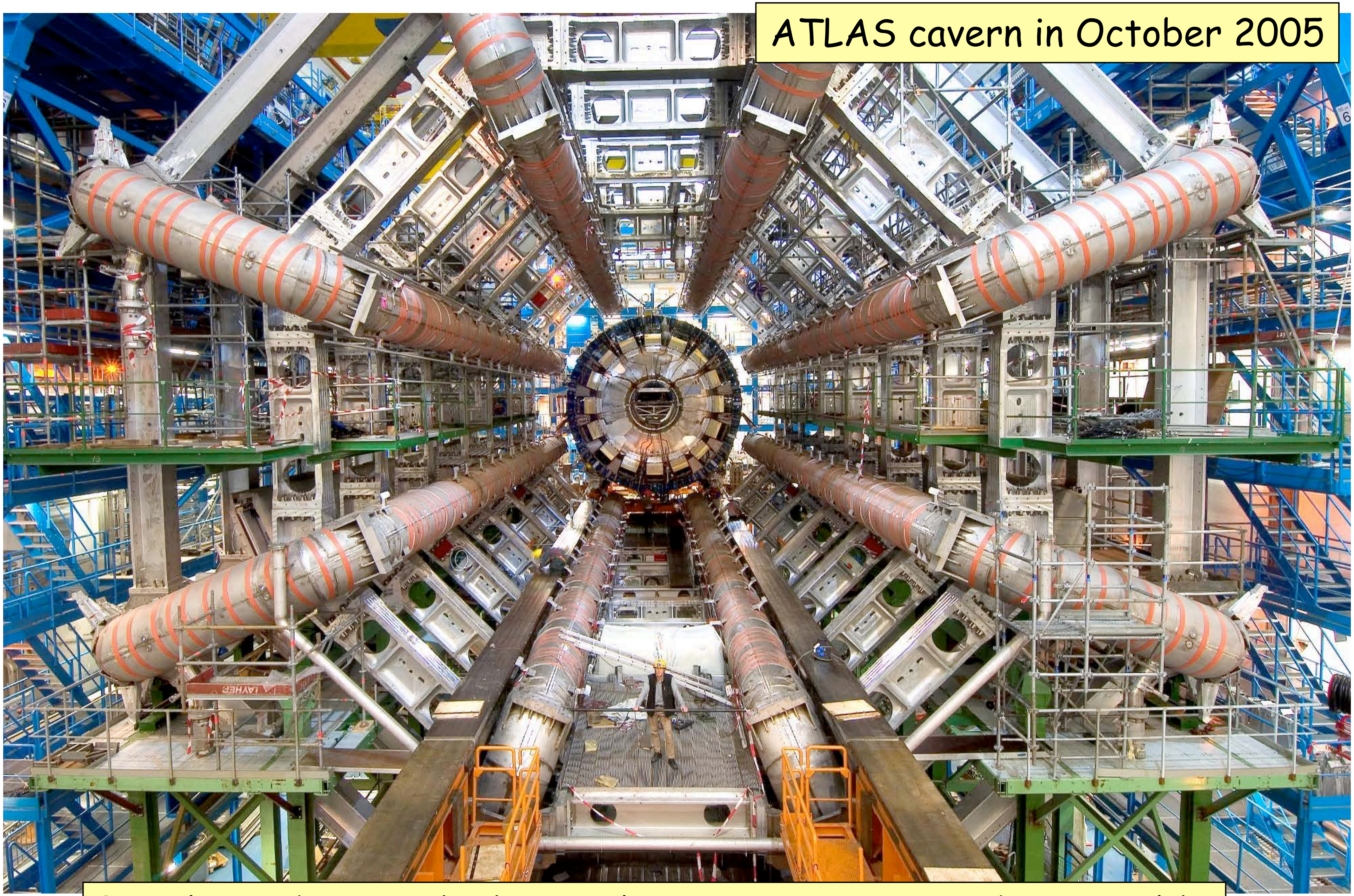
- Tracking ($|\eta|<2.5$, B=2T) :
  -- Si pixels and strips
  -- Transition Radiation Detector (e/π separation)

- Calorimetry ($|\eta|<5$) :
  -- EM : Pb-LAr
  -- HAD: Fe/scintillator (central), Cu/W-LAr (fwd)

- Muon Spectrometer ($|\eta|<2.7$) :
  air-core toroids with muon chambers



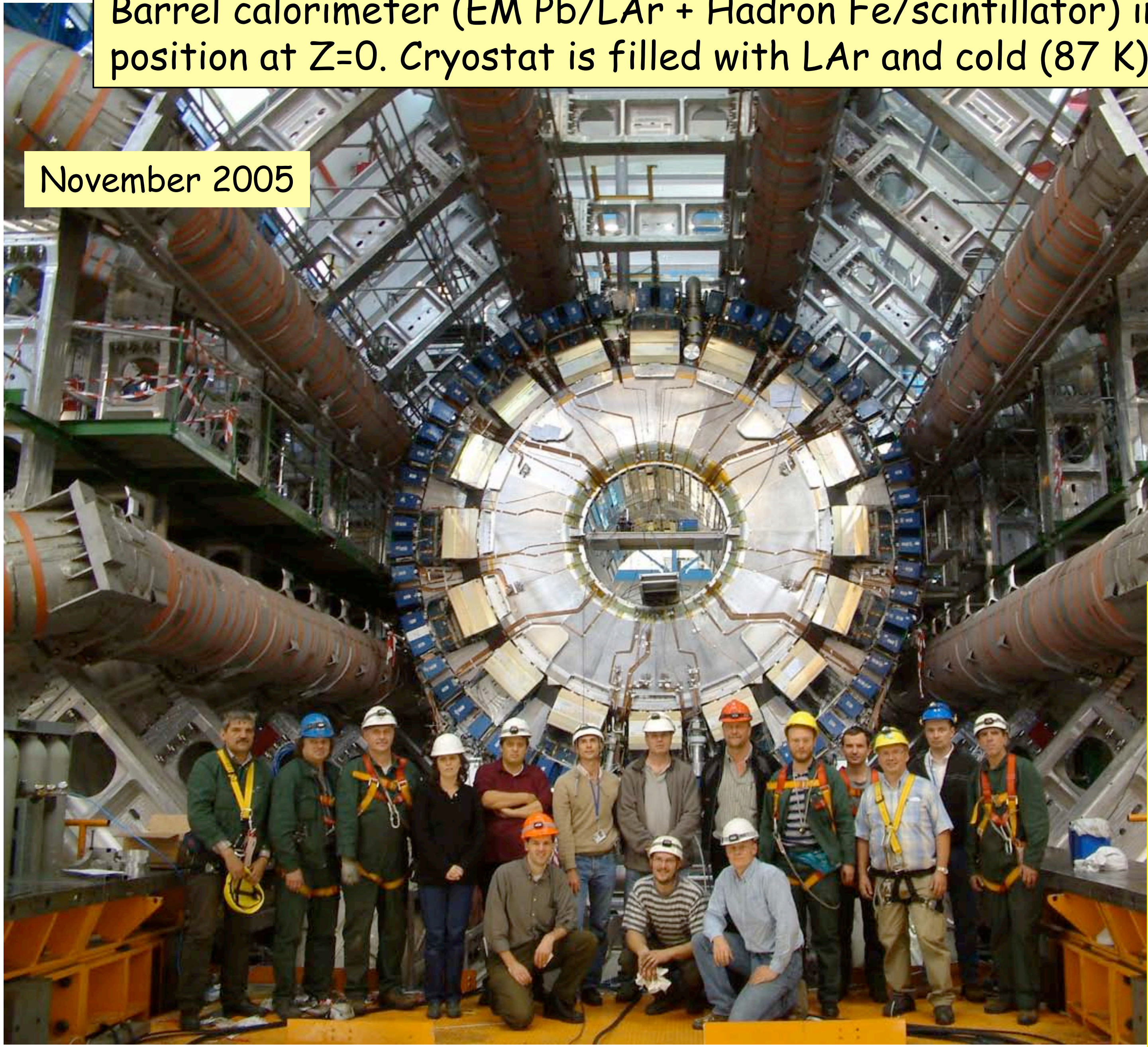
And .... 1900 physicists from
165 Institutions from 35 countries
from 5 continents



ATLAS cavern in October 2005

Barrel toroid system (eight 25m-long, 100 tons superconducting coils): tested at full field (20 kA current) in November 2006.

Barrel calorimeter (EM Pb/LAr + Hadron Fe/scintillator) in its final position at Z=0. Cryostat is filled with LAr and cold (87 K)


November 2005


October 2004

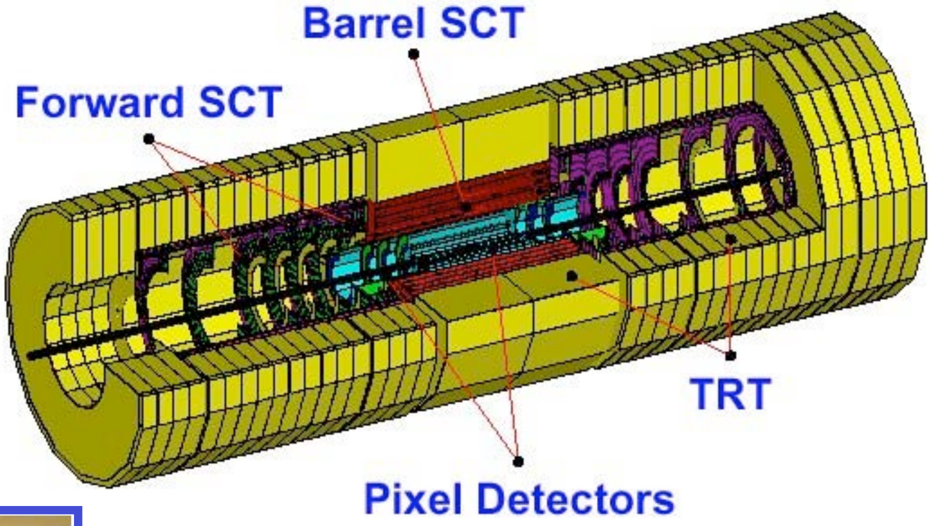
Inner tracker

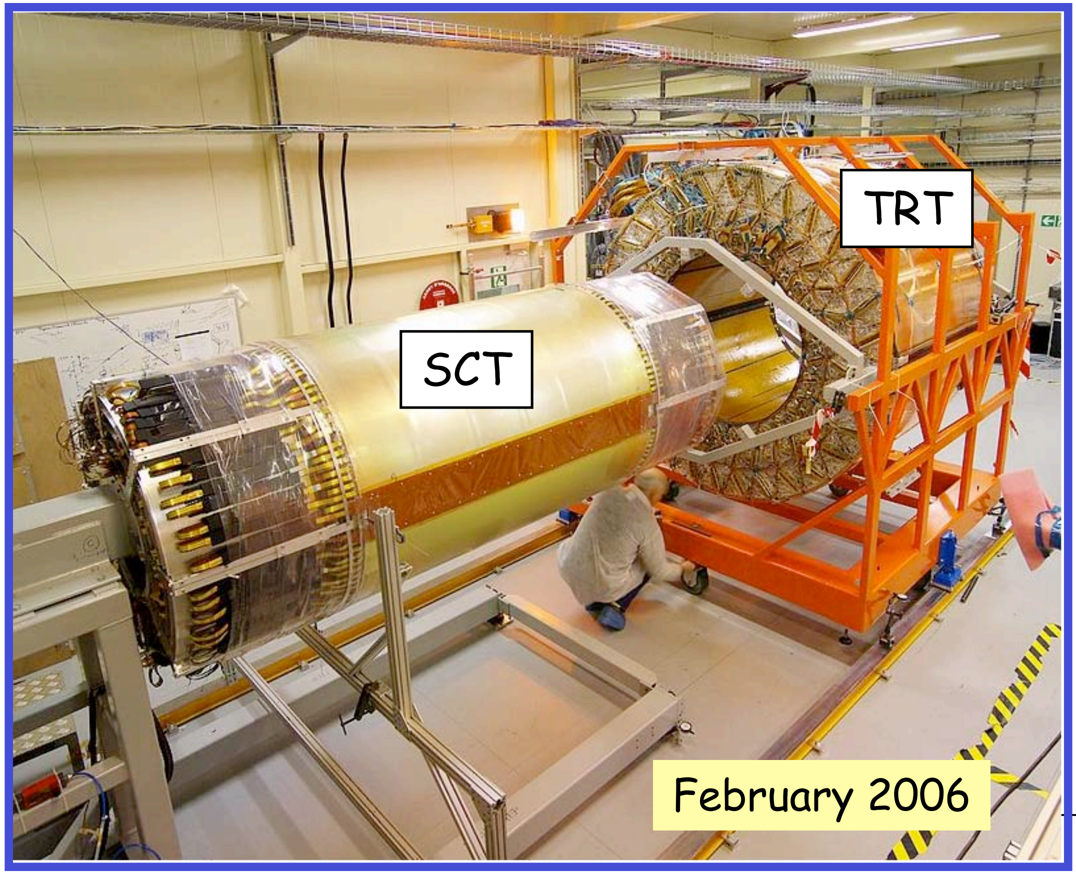
3 sub-systems:

Silicon pixels : 0.8 10^8 channels

Silicon strips (SCT) : 6 10^6 channels

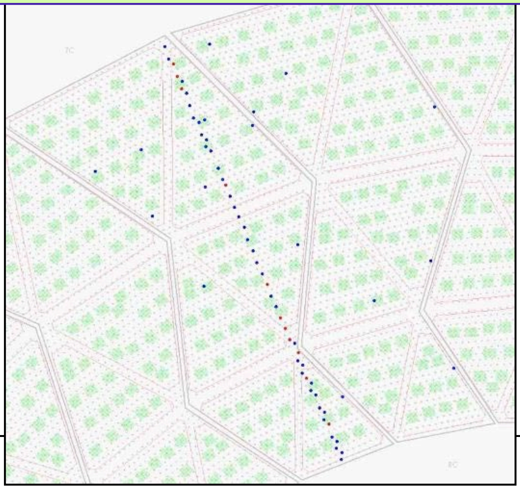
Transition Radiation Tracker (TRT) :
straw tubes filled with gas, 4 10^5 channels

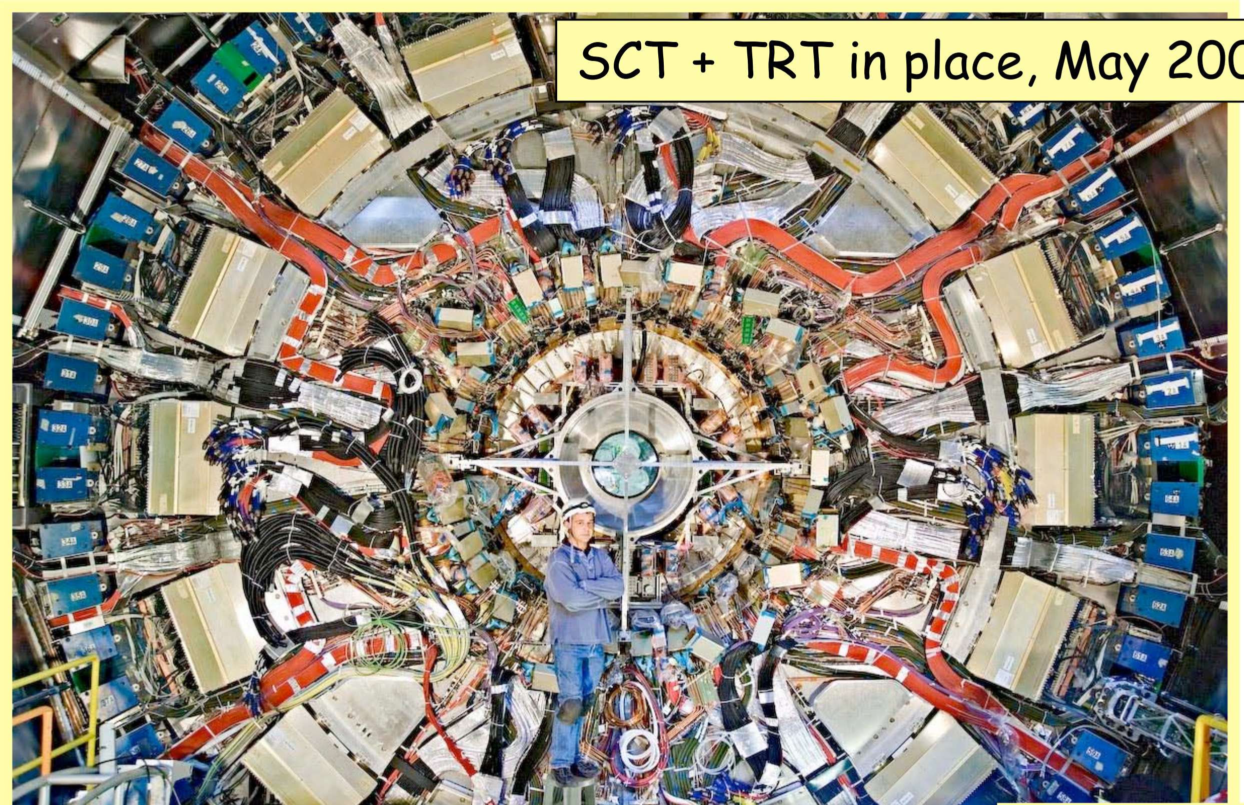




February 2006

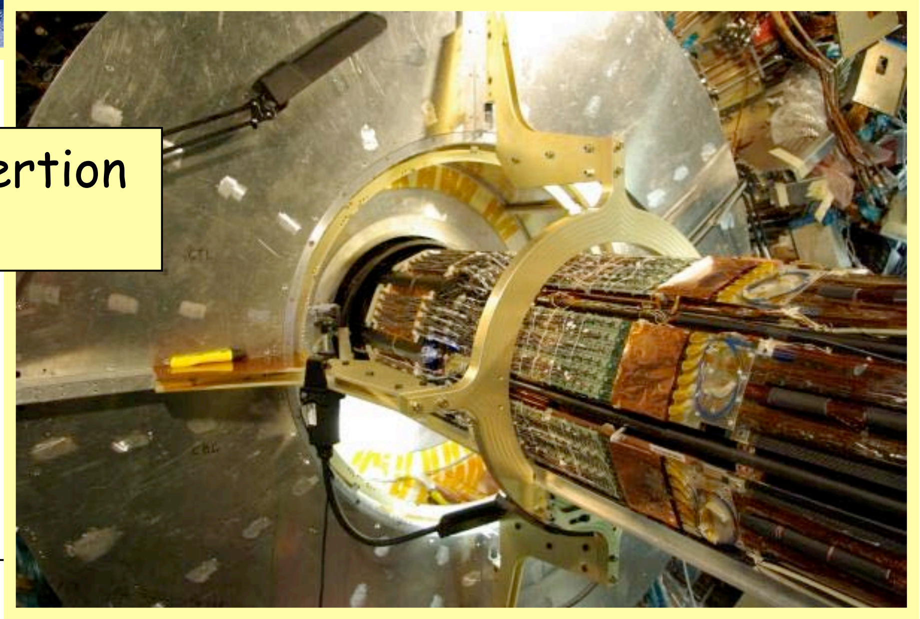
Cosmic muon recorded in the barrel TRT (in the assembly surface room)





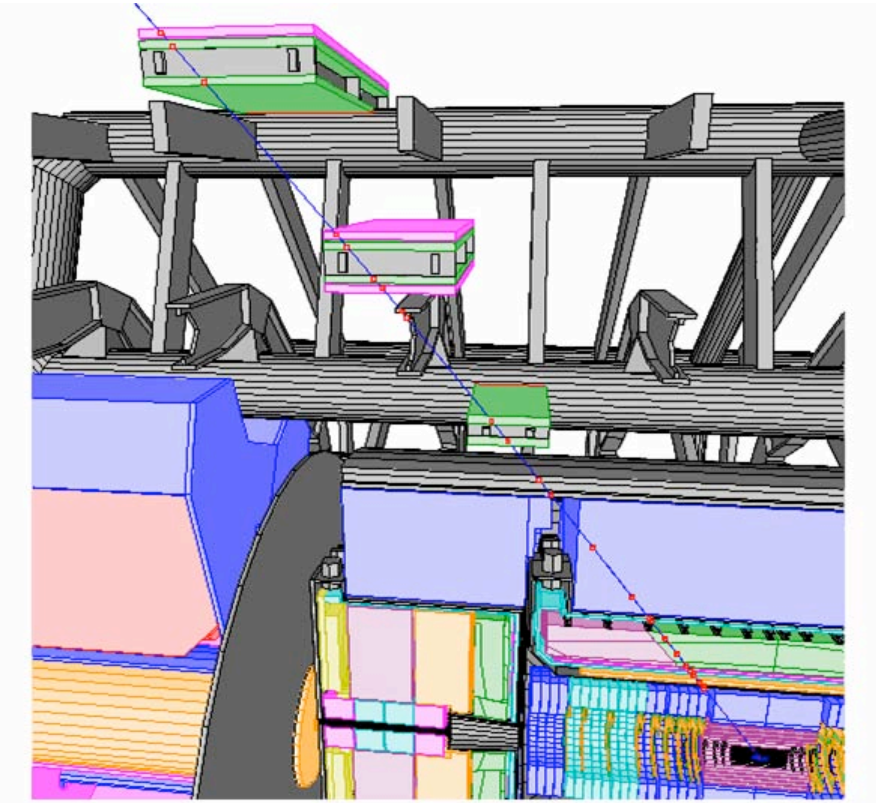
SCT + TRT in place, May 2007

Inner Detector installation in underground cavern completed

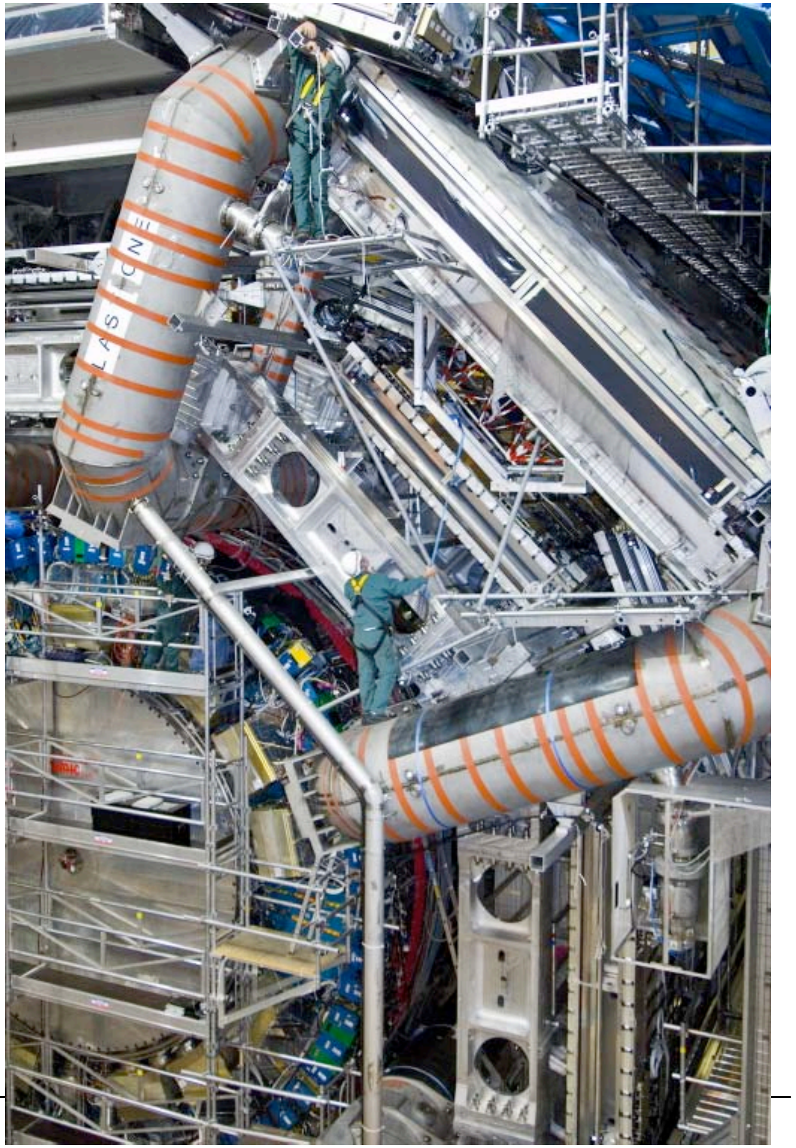


Pixels (+ beam pipe) insertion
June 2007

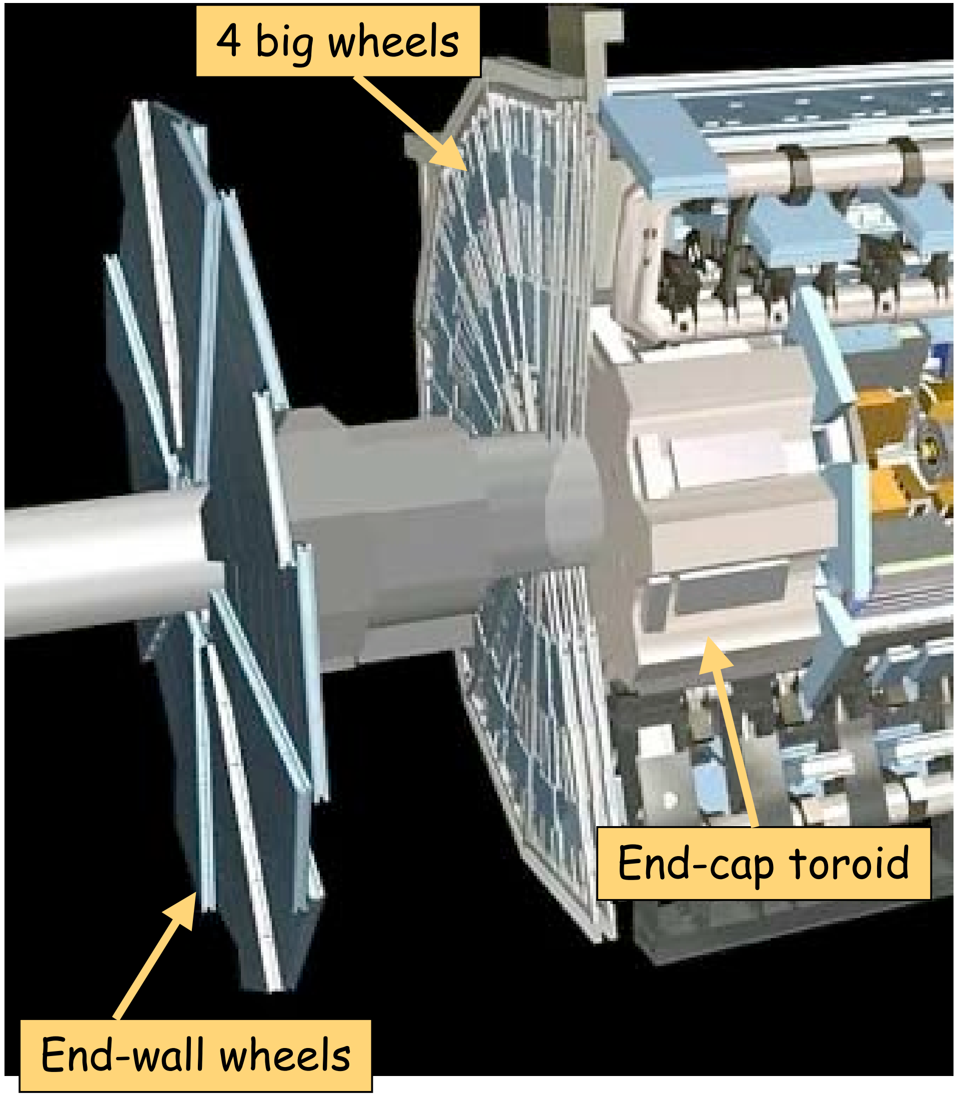
Made of ~ 80 million high-tech Si pixels
50μm wide, 400μm long, 250μm thick

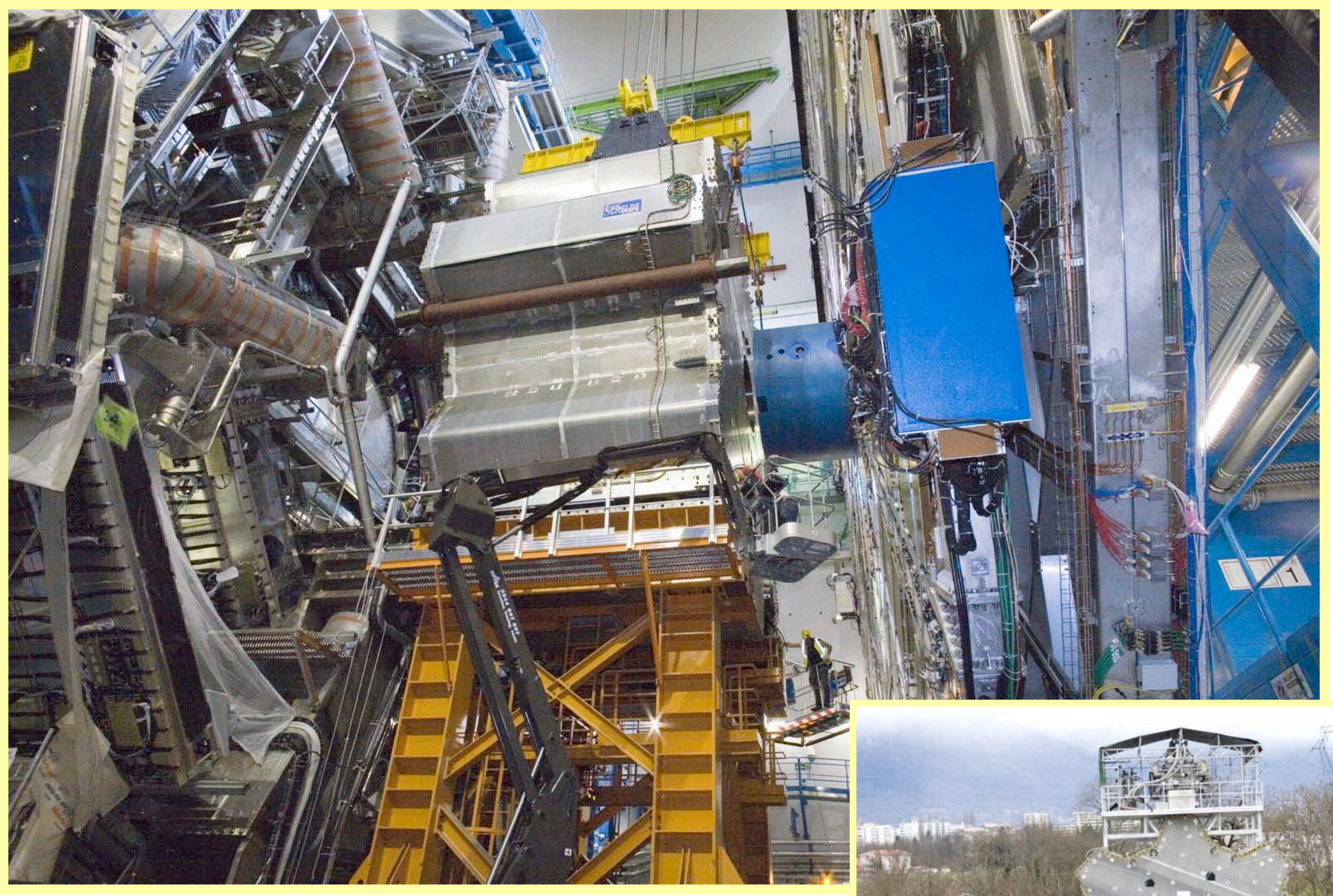


Installation of barrel muon chambers
(~ 700 stations) started in December 2005
and is ~ completed.



Forward muon spectrometer: 6 out of 8 big wheels installed in the cavern





The two end-cap toroid magnets installed in June-July 2007

Spectacular operations …

October 2004

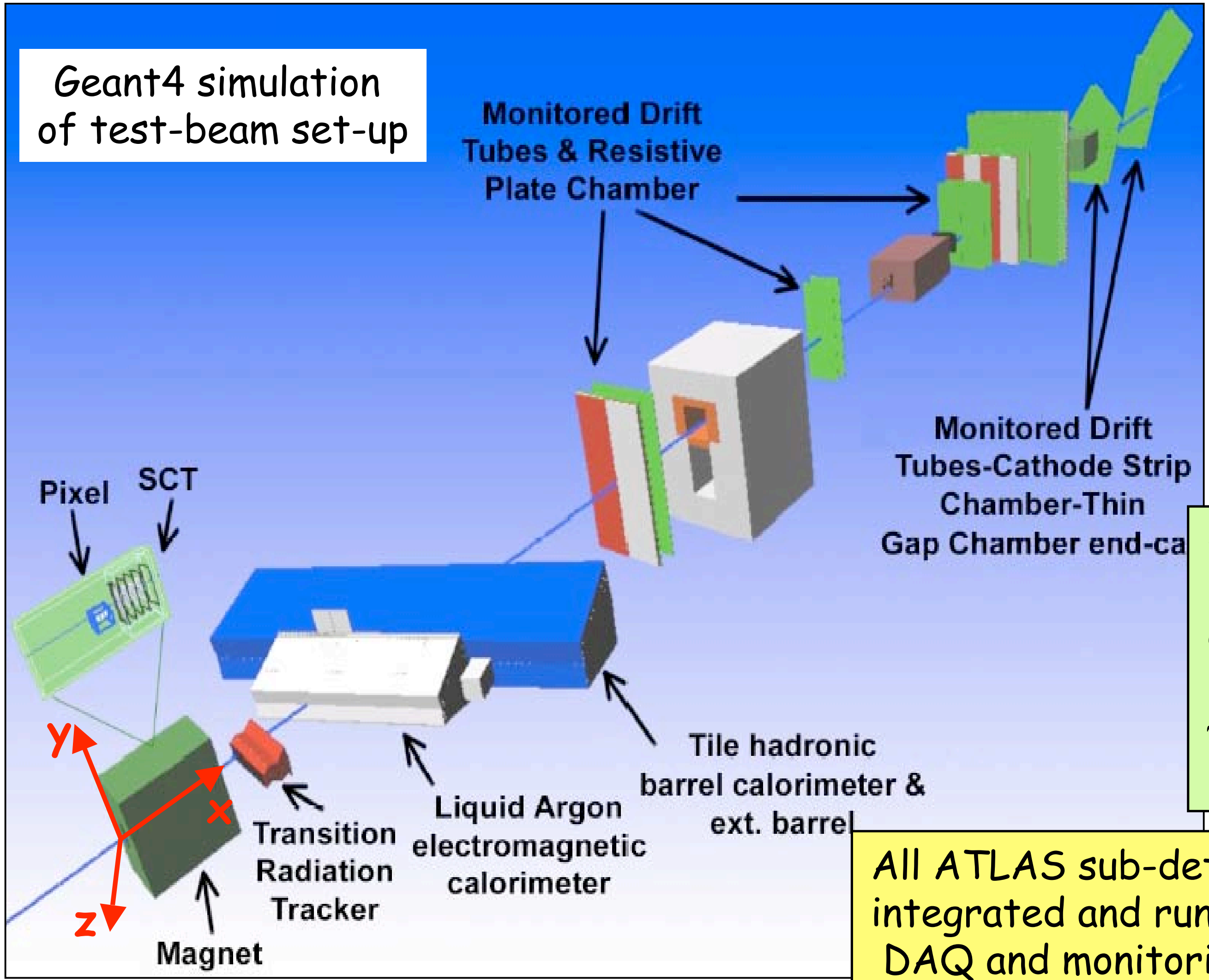
June 2007

Toward first physics:

- test-beam activities
- commissioning with cosmics
- expected performance

Towards Physics (1) : the 2004 ATLAS combined test beam

Full "vertical slice" of ATLAS tested on CERN H8 beam line May-November 2004


Geant4 simulation of test-beam set-up

O(1%) of ATLAS coverage

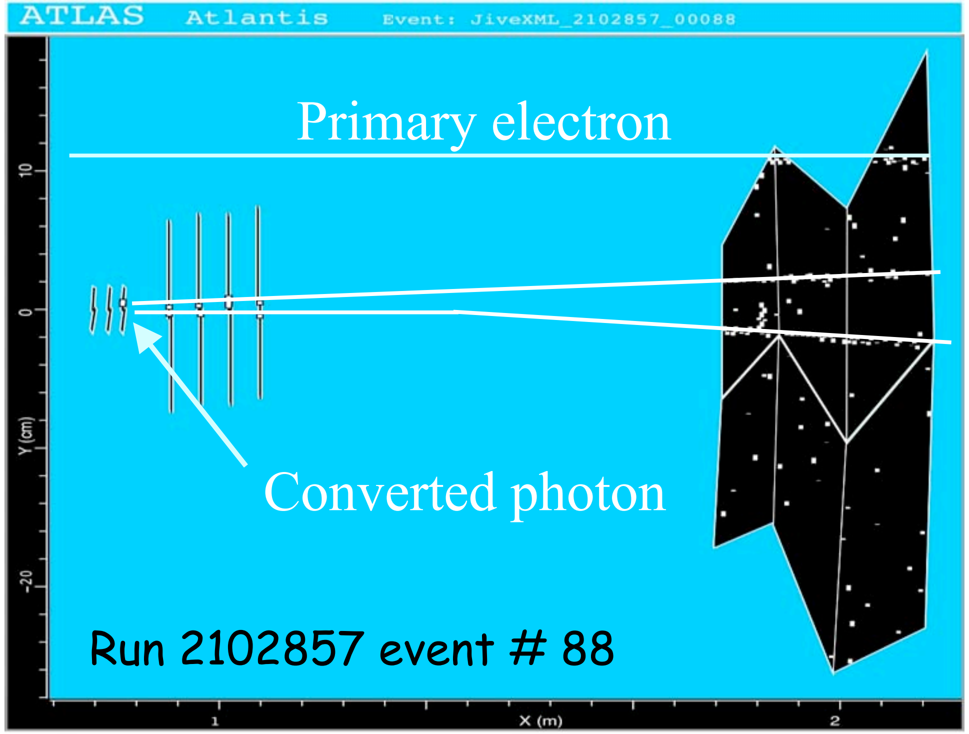
~ 90 million events collected (~4.5 TB of data):

$e^{\pm}$, $\pi^{\pm}$	1 → 250 GeV
$\mu^{\pm}$, $\pi^{\pm}$, p	up to 350 GeV
γ	20-100 GeV

B-field = 0 → 1.4 T

All ATLAS sub-detectors (and LVL1 trigger) integrated and run together with common DAQ and monitoring, "final" electronics, slow-control, etc. Data analyzed with common ATLAS software. Gained lot of global operation experience during ~ 6 month run.

ATLAS preliminary



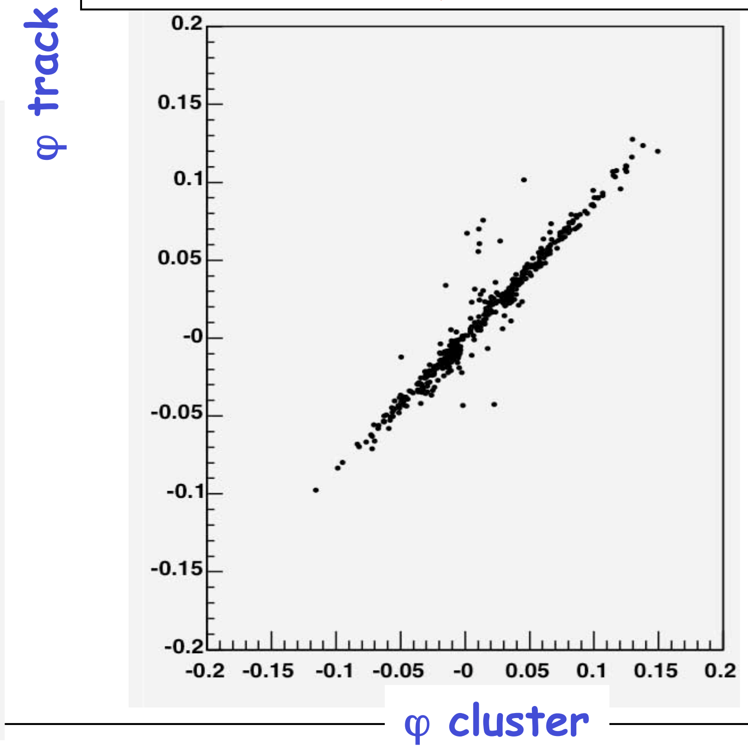
Primary electron

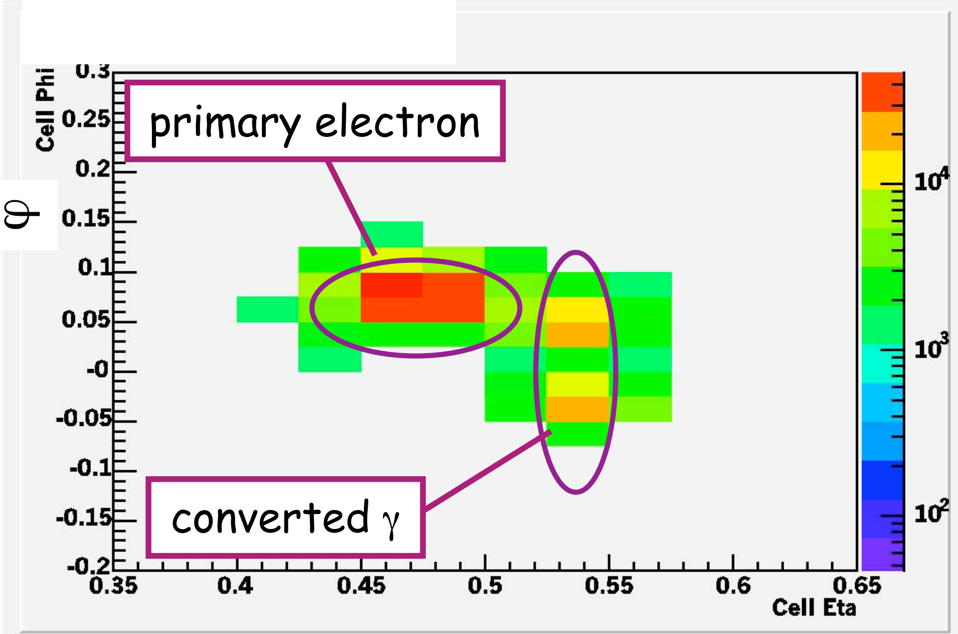
Converted photon

Run 2102857 event # 88

> 50% of (possible) H → $\gamma\gamma$ events will have at least one converted photon $\gamma \rightarrow e^+e^-$ in the tracker material→ important to develop (and validate !) efficient reconstruction tools

Inner Detector tracks extrapolated to ECAL and compared to calo clusters





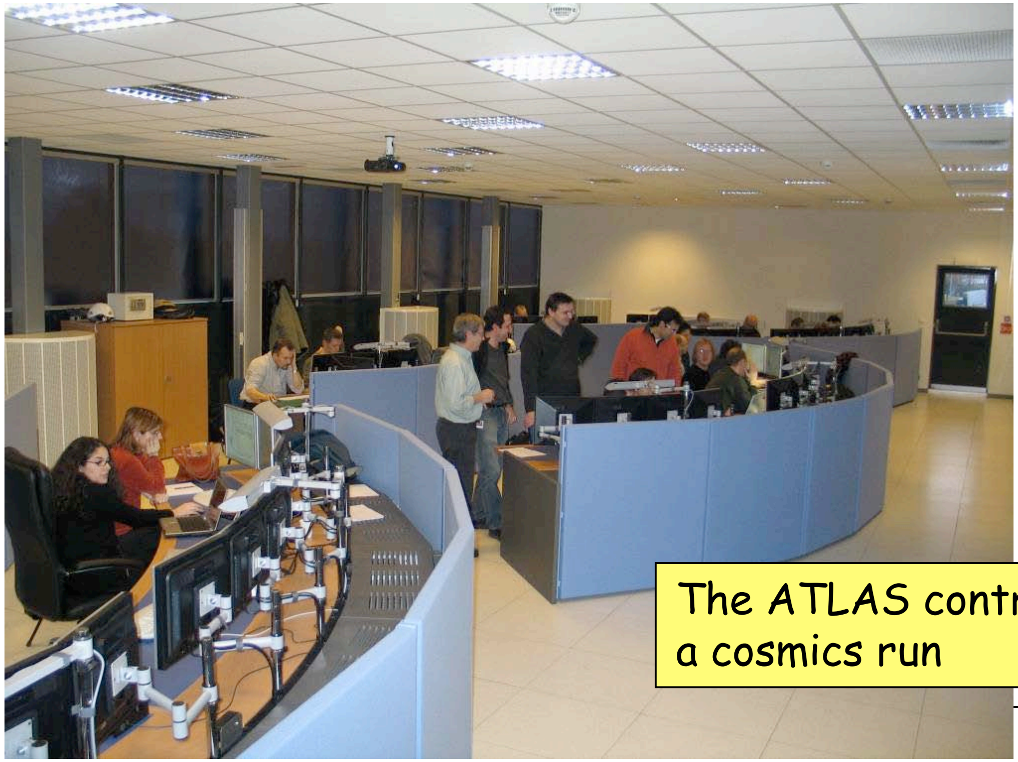
primary electron

converted γ

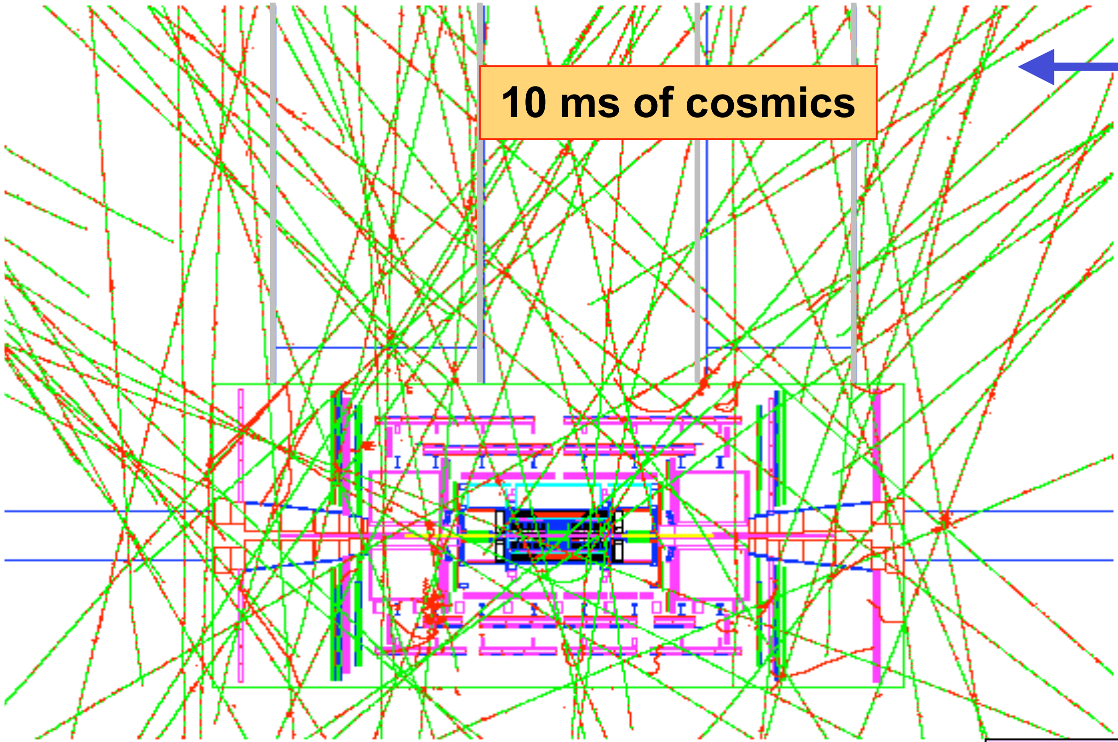
Towards Physics (2) : detector commissioning with cosmics in the underground cavern (the first real data in situ !)

Very useful to:

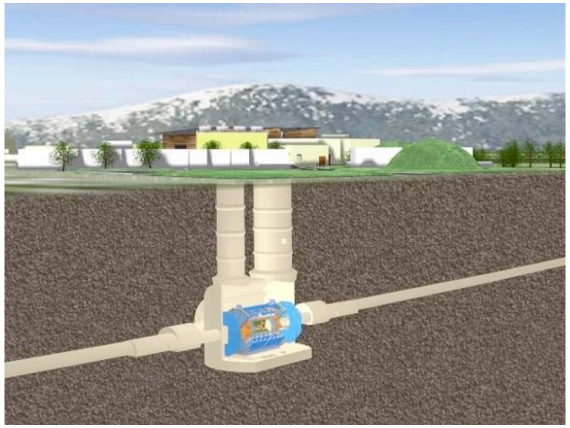
- Run an increasingly more complete detector with final trigger, data acquisition and monitoring systems. Data analyzed with final software
- Shake-down and debug the experiment in its final position → fix problems
- Gain global operation experience in situ before collisions start



The ATLAS control room during a cosmics run

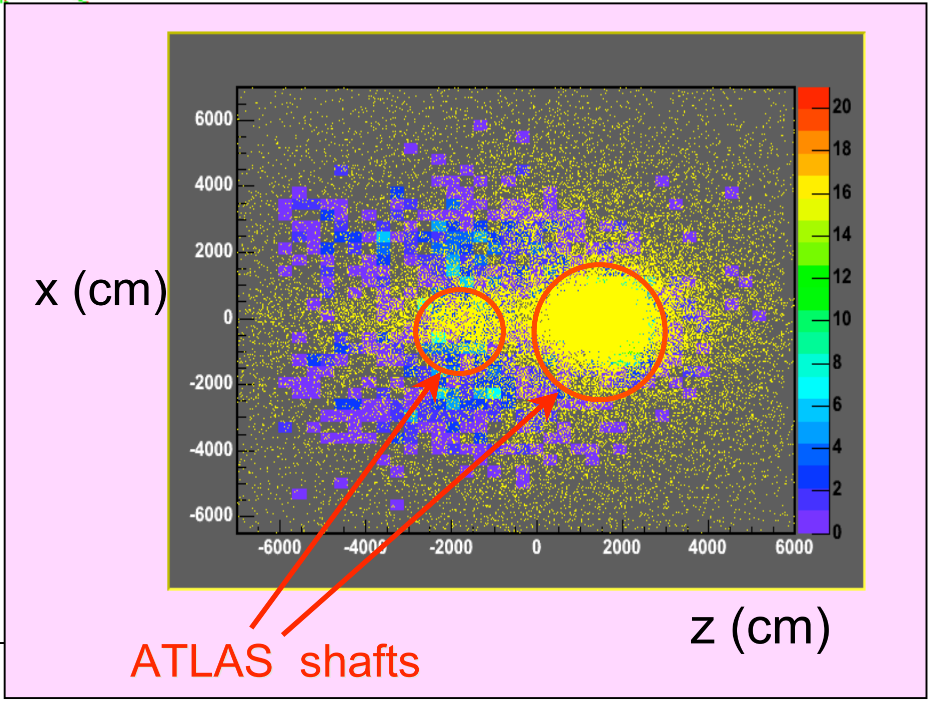


Simulated cosmics flux
in the ATLAS cavern

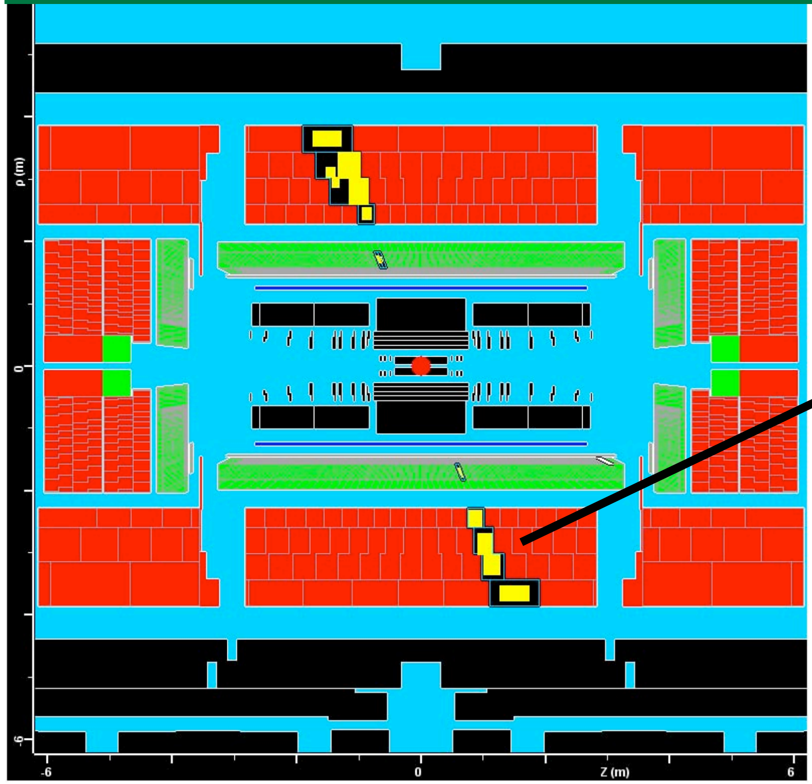


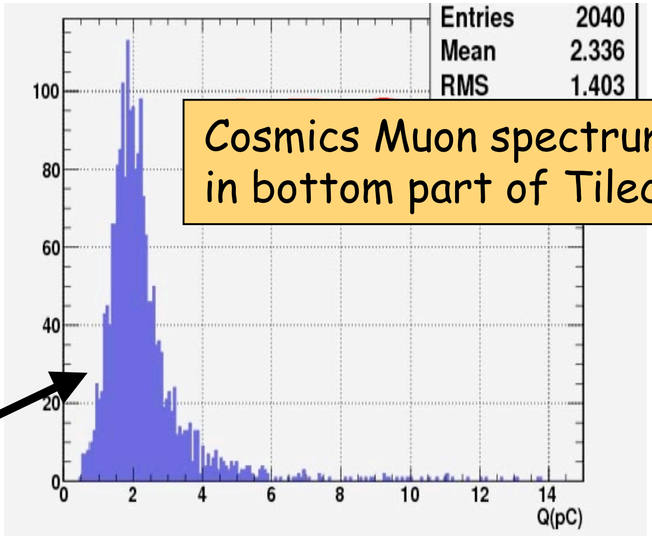
Cosmics data:
muon impact points extrapolated
to surface as measured by
Muon Trigger chambers (RPC)

Rate ~100 m below ground: ~ O(10 Hz)



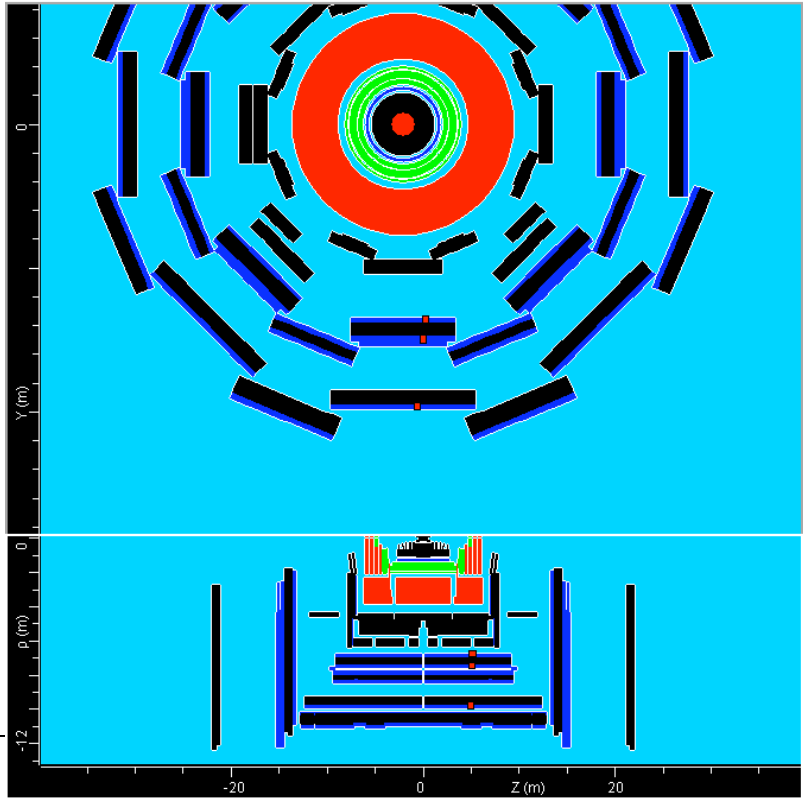
A cosmic muon in LAr EM calorimeter and Tile calorimeter





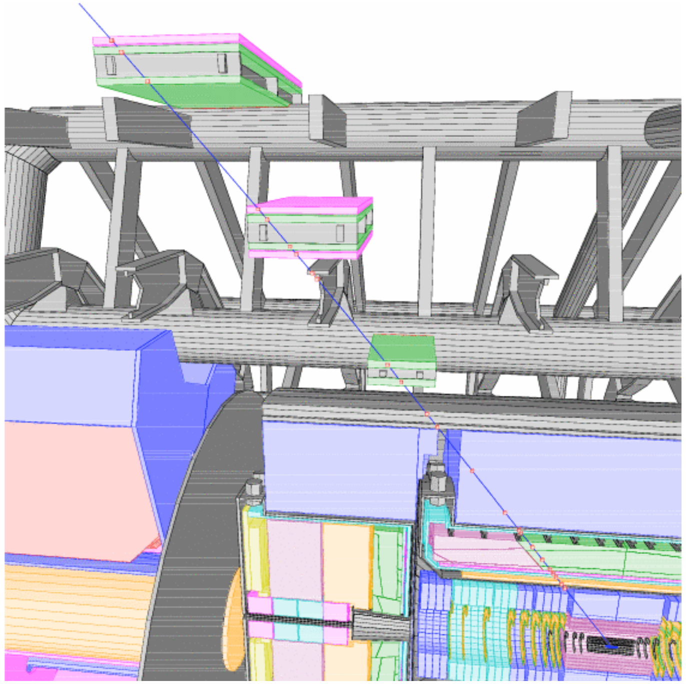
Cosmics Muon spectrum in bottom part of Tilecal

A cosmic muon in Muon Spectrometer



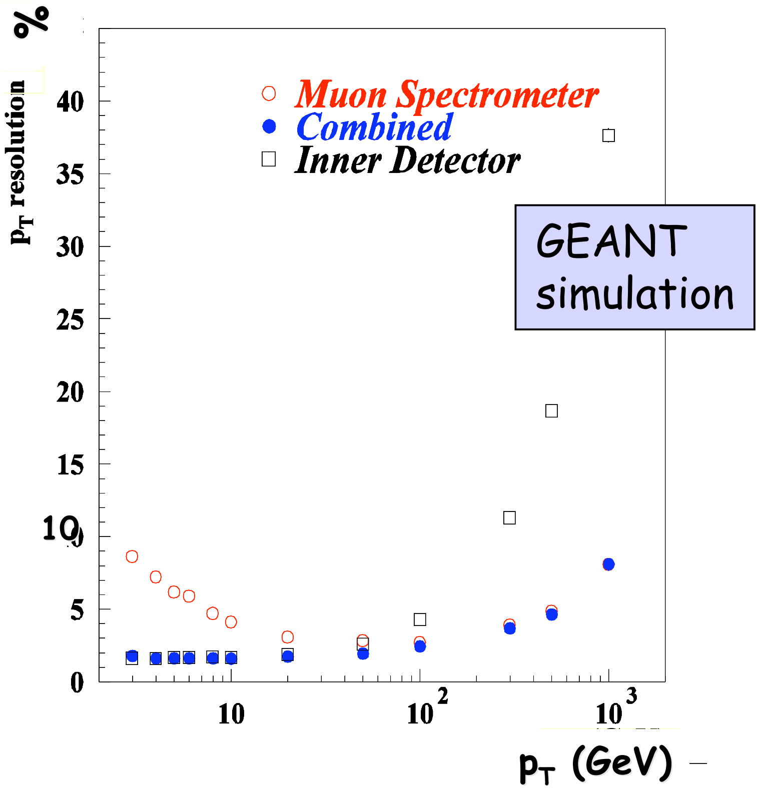
Expected performance: muon measurement

Combining the information from Inner Detector and Muon Spectrometer



$\sigma/p < 10\%$ for $E_\mu \sim$ TeV needed to observe a possible new resonance $X \rightarrow \mu\mu$ as "narrow" peak

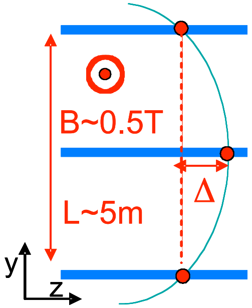
ATLAS Muon momentum resolution



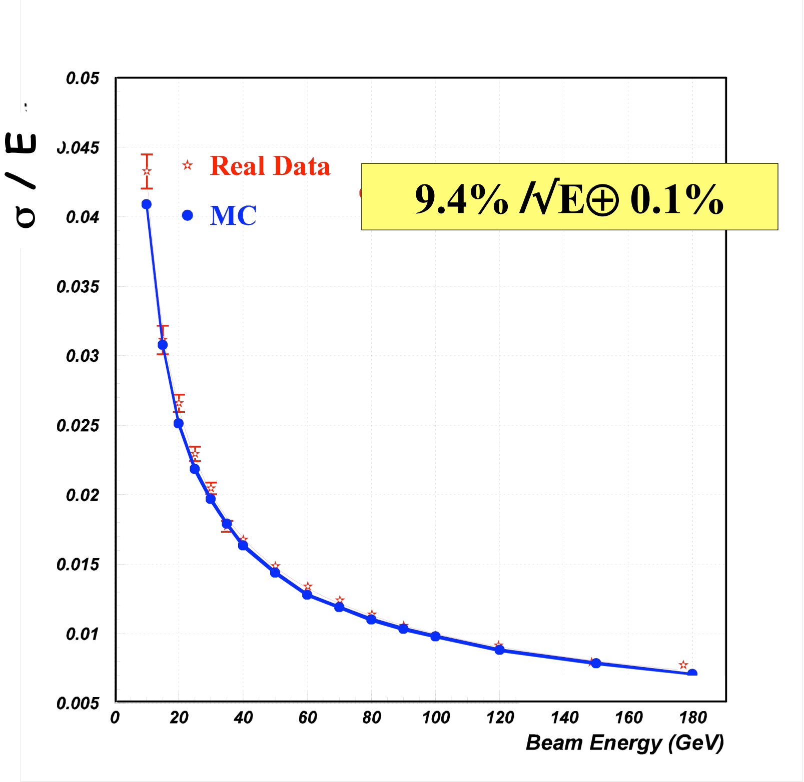
GEANT simulation

ATLAS Muon Spectrometer:
$E_\mu \sim 1$ TeV $\Rightarrow \Delta \sim 500\ \mu$m

– $\sigma/p \sim 10\%$ $\Rightarrow$ $\delta\Delta \sim 50\ \mu$m
- alignment accuracy to $\sim 20\ \mu$m

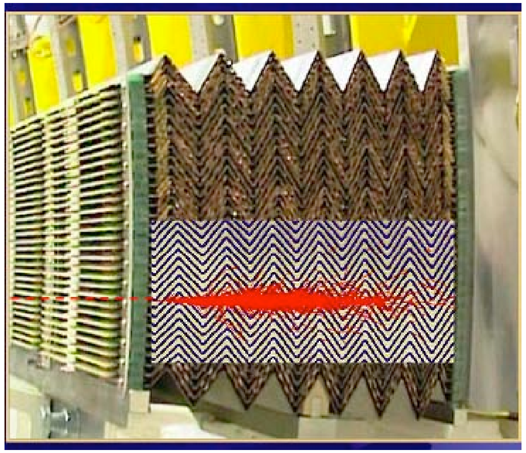


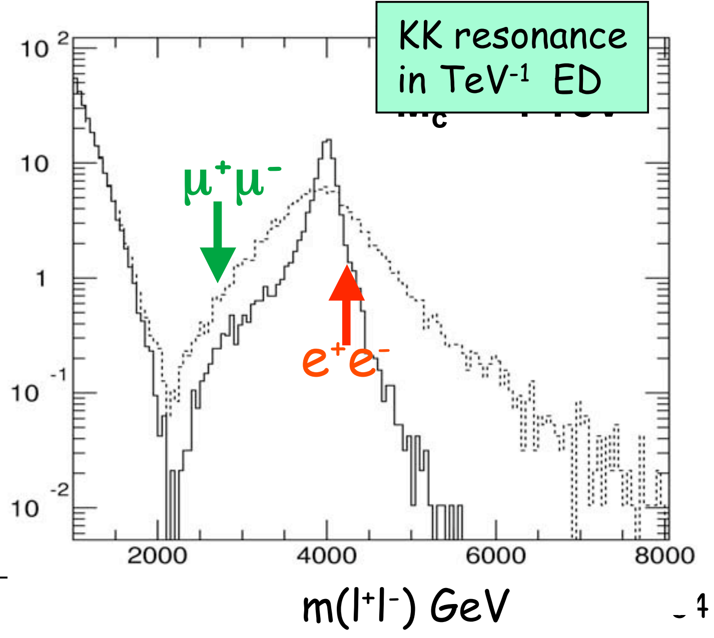
Expected performance: electron measurement



9.4% /√E ⊕ 0.1%

Electron E-resolution measured in beam tests of the ATLAS EM calorimeter (Pb/LAr)



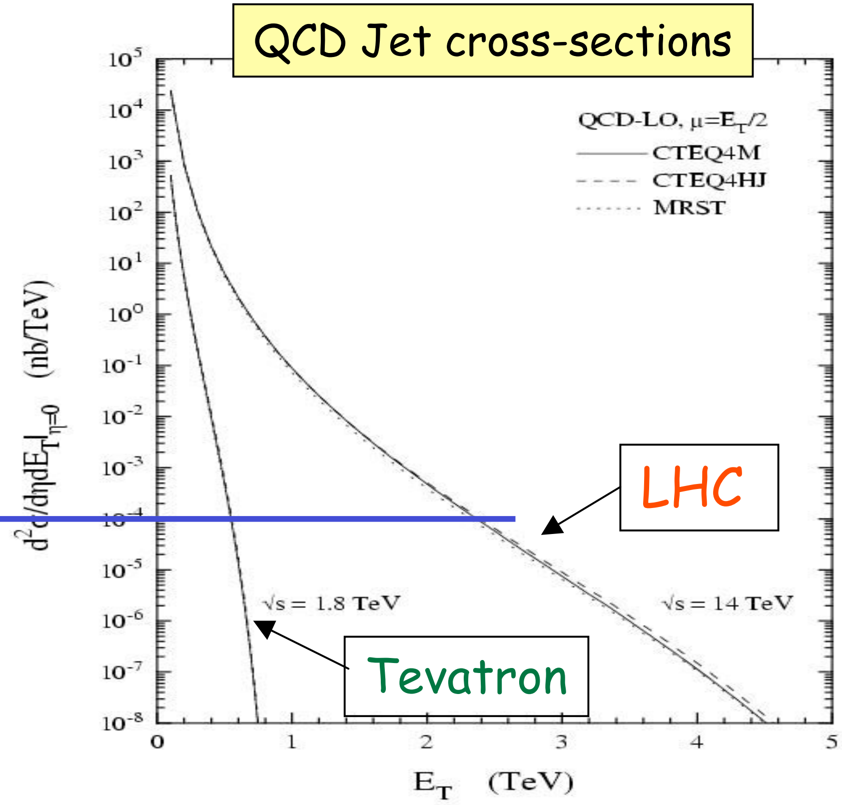


KK resonance in TeV^{-1} ED

1 TeV $e^\pm$: σ (E)/E ~ 0.5%
1 TeV $\mu^\pm$: σ (p)/p ~ 5%
→ heavy narrow resonances will likely be observed first in the X → ee channel

First physics with first data a few examples …

Jump immediately into a new territory …



QCD Jet cross-sections

10 events with 100 pb^{-1}

LHC

Tevatron

With the first physics data in 2008 ….

1 fb^{-1} (100 pb^{-1}) ≡ 6 months (few days) at L= 10^{32} $cm^{-2}s^{-1}$
with 50% data-taking efficiency
→ may collect O(100 pb^{-1}) per experiment by end 2008

Channels (examples …)	Events to tape for 100 pb^{-1} (ATLAS)	Total statistics from some of previous Colliders
$W \to \mu\nu$	~ 10^6	~ 10^4 LEP, ~ 10^6 Tevatron
$Z \to \mu\mu$	~ 10^5	~ 10^6 LEP, ~ 10^5 Tevatron
$tt \to WbWb \to \mu\nu + X$	~ 10^4	~ 10^4 Tevatron
QCD jets $p_T > 1$ TeV	> 10^3	---
$\tilde{g}\tilde{g}$ m = 1 TeV	~ 50	---

With these data:

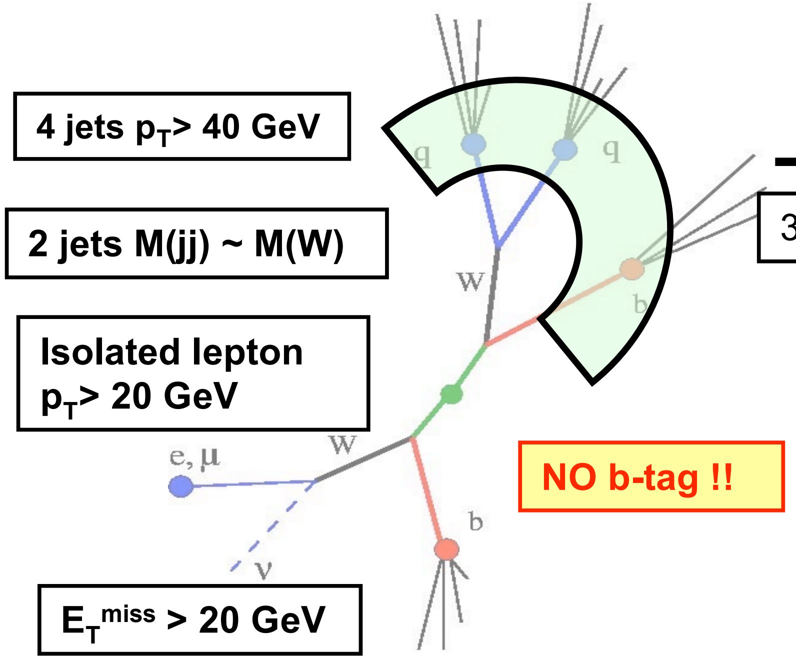
- Understand and calibrate detectors in situ using well-known physics samples
  e.g. - $Z \to ee, \mu\mu$ tracker, ECAL, Muon chambers calibration and alignment, etc.
  - $tt \to bl\nu\, bjj$ jet scale from $W \to jj$, b-tag performance, etc.
- "Rediscover" and measure SM physics at $\sqrt{s}$ = 14 TeV : W, Z, tt, QCD jets …
  (also because omnipresent backgrounds to New Physics)

→ prepare the road to discoveries …… it will take time …

Example of initial measurement: the first top quarks in Europe …

A top signal can be observed quickly, even with limited detector performance and simple analysis …. and then used to "calibrate" the detector and understand physics

$\sigma_{tt} \approx 250$ pb for tt → bW bW → blν bjj



4 jets p_T> 40 GeV

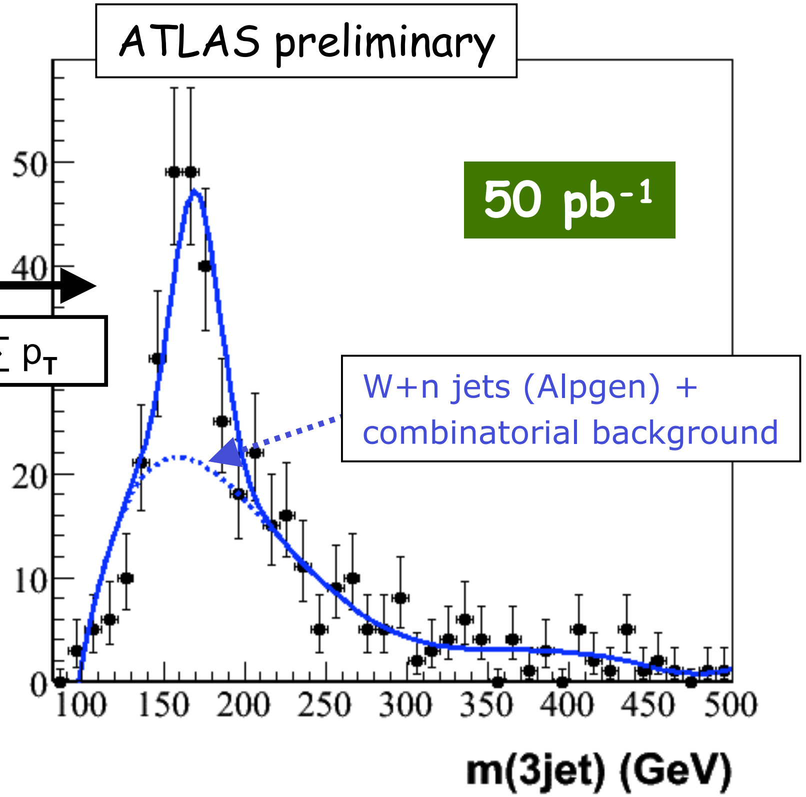
2 jets M(jj) ~ M(W)

Isolated lepton p_T> 20 GeV

E_T^{miss} > 20 GeV

NO b-tag !!

3 jets with largest ∑ p_T



Top signal observable in early days with no b-tagging and simple analysis (100 ± 20 evts for 50 pb^{-1}) → with ~100 pb^{-1} measure σ_{tt} to 20%, m_t to 10 GeV ? Note: ultimate LHC precision on m_t is ~ 1 GeV

In addition, excellent sample to:

- understand detector performance for e, μ, jets, b-jets, missing E_T, …
- understand / constrain theory and MC generators using e.g. p_T spectra

One of the best candidates for an early discovery :

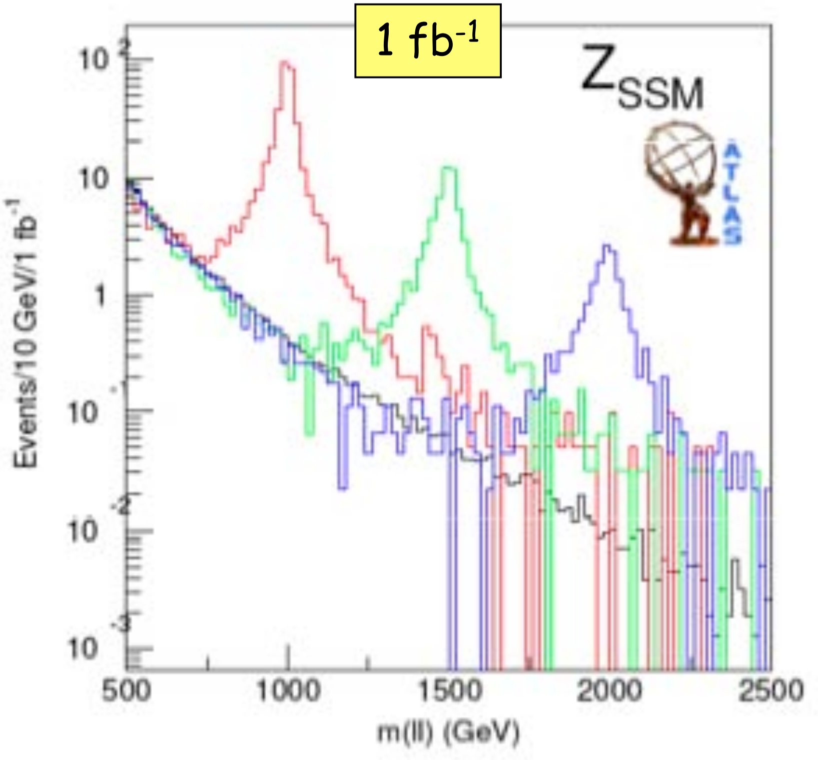
a narrow resonance with mass ~ 1 TeV decaying into e^+e^-

$Z' \rightarrow e^+e^-$ with SM-like couplings (Z_{SSM})

Mass	Expected events for 1 fb^{-1} (after all analysis cuts)	Integrated luminosity needed for discovery (corresponds to 10 observed evts)
1 TeV	~ 160	~ 70 pb^{-1}
1.5 TeV	~ 30	~ 300 pb^{-1}
2 TeV	~ 7	~ 1.5 fb^{-1}

- large enough signal for discovery with ~100 pb^{-1} up to m > 1 TeV
- small well-known SM background (Drell-Yan)
- signal is (narrow) mass peak on top of background

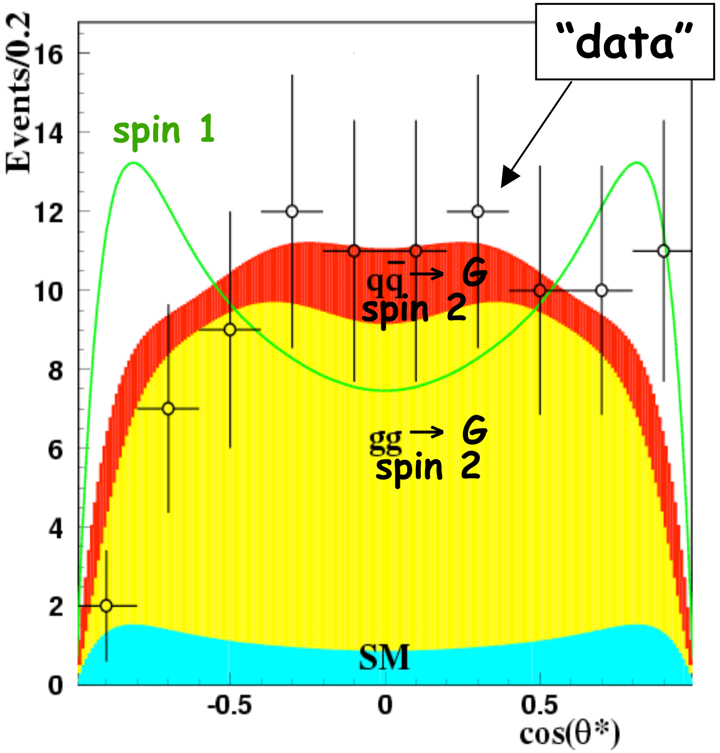
Ultimate ATLAS reach for Z' (300 fb^{-1}):
~ 5 TeV



Is it a Z′ or a Randall-Sundrum Graviton ?

Look at $e^{\pm}$ angular distributions to disentangle G (s=2) from Z′ (S=1)
Need more integrated luminosity …

ATLAS, 100 fb^{-1}, m_G=1.5 TeV

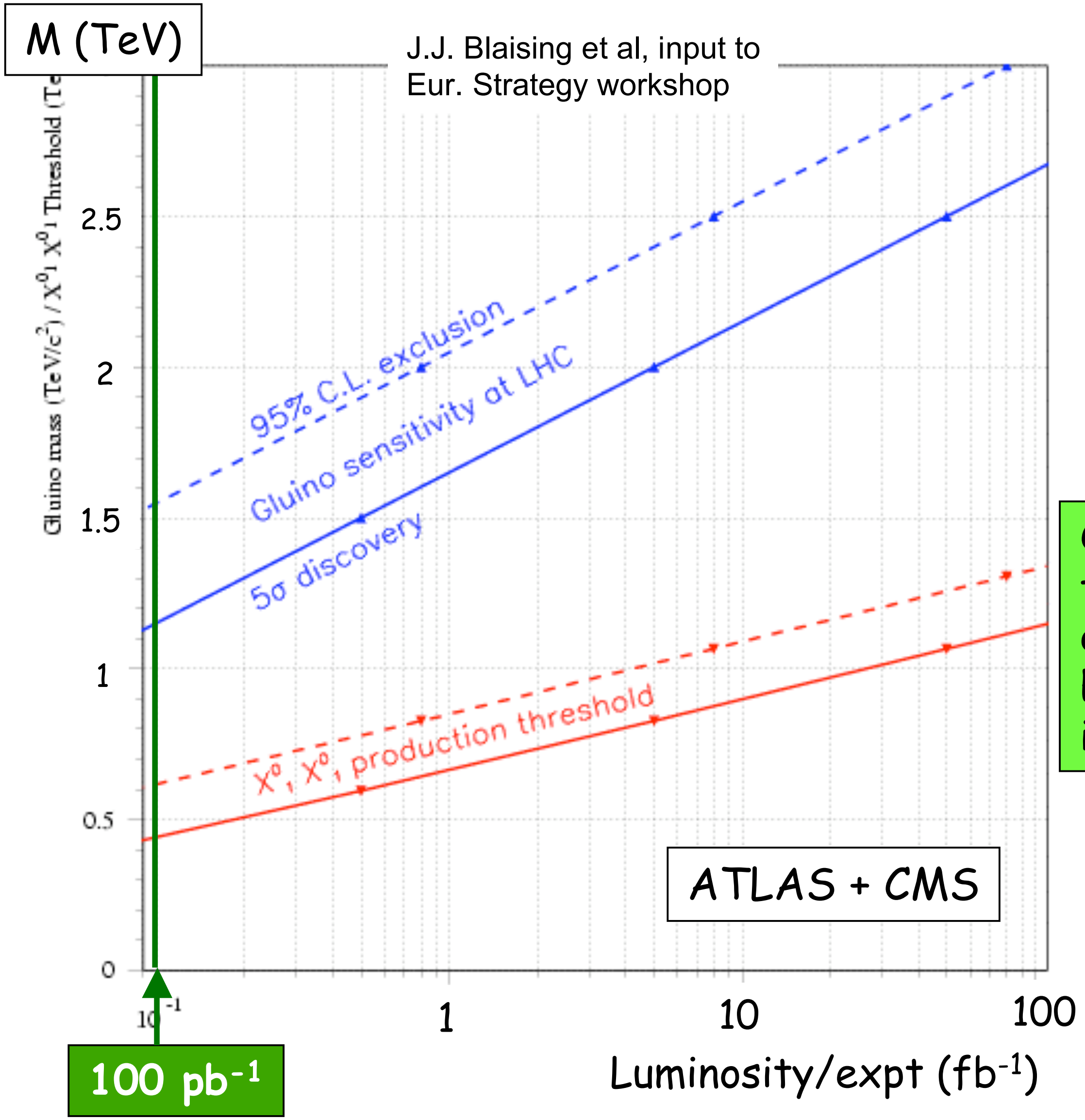


Allanach et al., JHEP 0009 (2000) 019

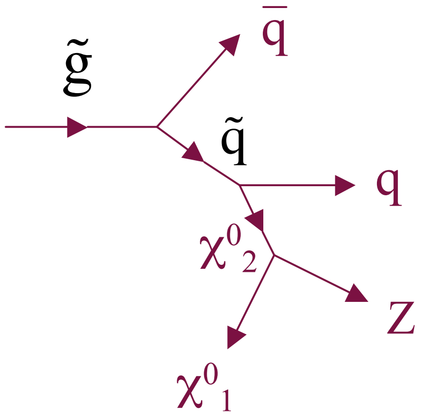
Another possible "early" discovery: Supersymmetry

If SUSY at TeV scale → could be found "quickly" …. thanks to:

- large $\tilde{q},\tilde{g}$ cross-section → ≈ 10 events/day at 10^{32} for $m\,(\tilde{q},\tilde{g}) \sim 1$ TeV
- spectacular signatures (many jets, leptons, missing E_T)



J.J. Blaising et al, input to Eur. Strategy workshop



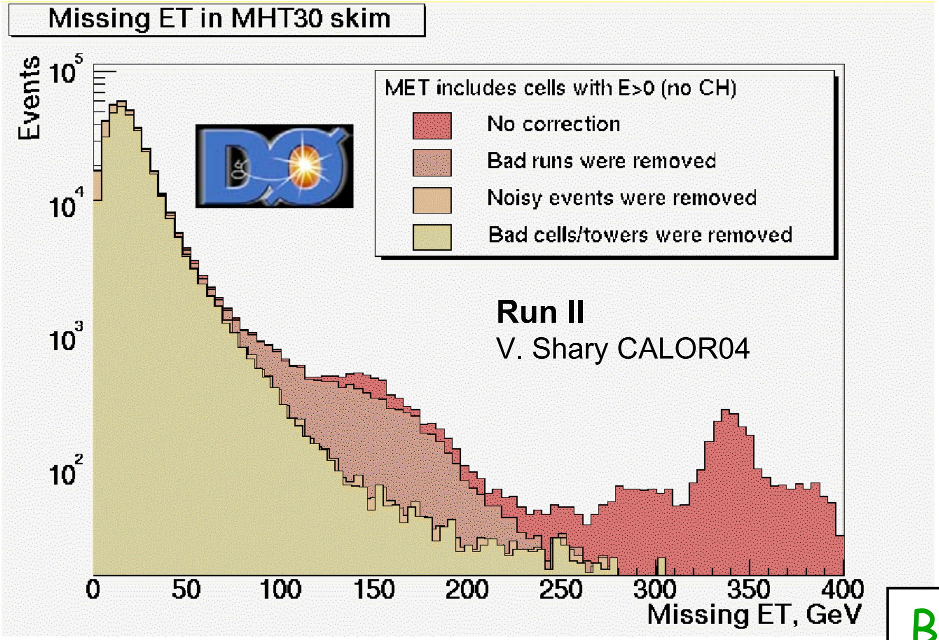
Our field, and planning for future facilities, will benefit a lot from quick determination of scale of New Physics. E.g. with 100 good pb^{-1} LHC could say if SUSY accessible to a ≤1 TeV ILC

BUT: understanding E_T^{miss} spectrum (and tails from instrumental effects) is one of the most crucial and difficult experimental issue for SUSY searches at hadron colliders.

Main backgrounds to SUSY searches in jets + E_T^{miss} topology

(one of the most "dirty" signatures ...) :

- W/Z + jets with $Z \rightarrow \nu\nu$, $W \rightarrow \tau\nu$; $t\bar{t}$; etc.
- QCD multijet events with fake E_T^{miss} from jet mis-measurements (calorimeter resolution and non-compensation, cracks, ...)
- cosmics, beam-halo, detector problems overlapped with high-p_T triggers, ...

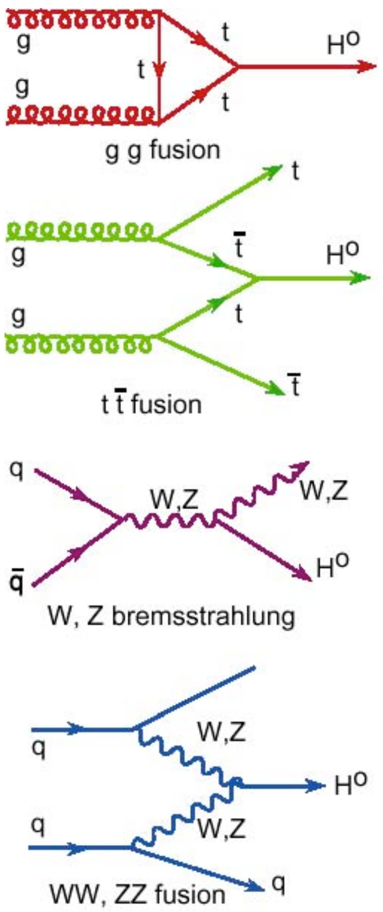


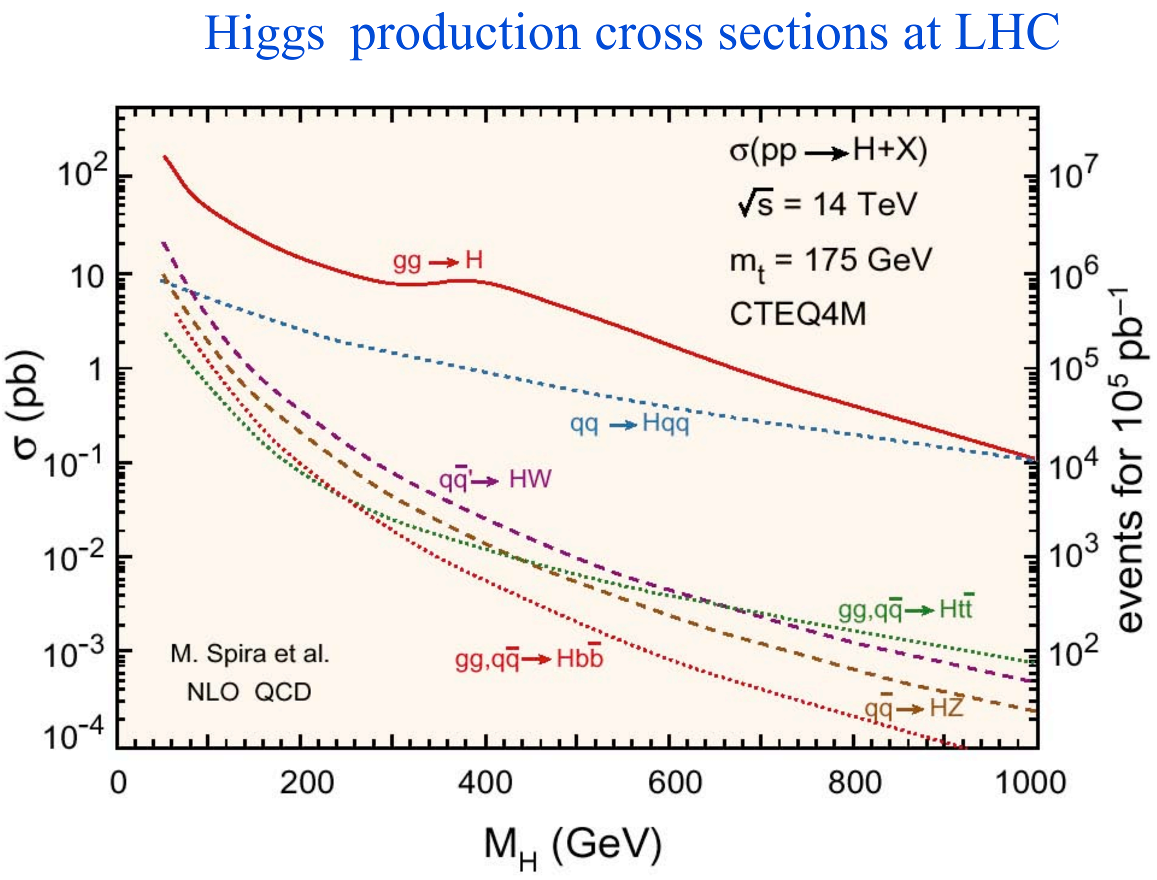
Understanding E_T^{miss} spectrum (and tails from instrumental effects) is one of most crucial and difficult experimental issues for SUSY searches at hadron colliders.
Note: can also use final states with leptons (cleaner ...)

Estimate backgrounds using as much as possible data (control samples) and MC

Background process (examples ....)	Control samples (examples ....)
$Z (\rightarrow \nu\nu)$ + jets	$Z (\rightarrow ee, \mu\mu)$ + jets
$W (\rightarrow \tau\nu)$ + jets	$W (\rightarrow e\nu, \mu\nu)$ + jets
$t\bar{t} \rightarrow bl\nu bjj$	$t\bar{t} \rightarrow bl\nu\, bl\nu$
QCD multijets	lower E_T sample

A more difficult case: a light Higgs (m_H ~ 115-150 GeV) …

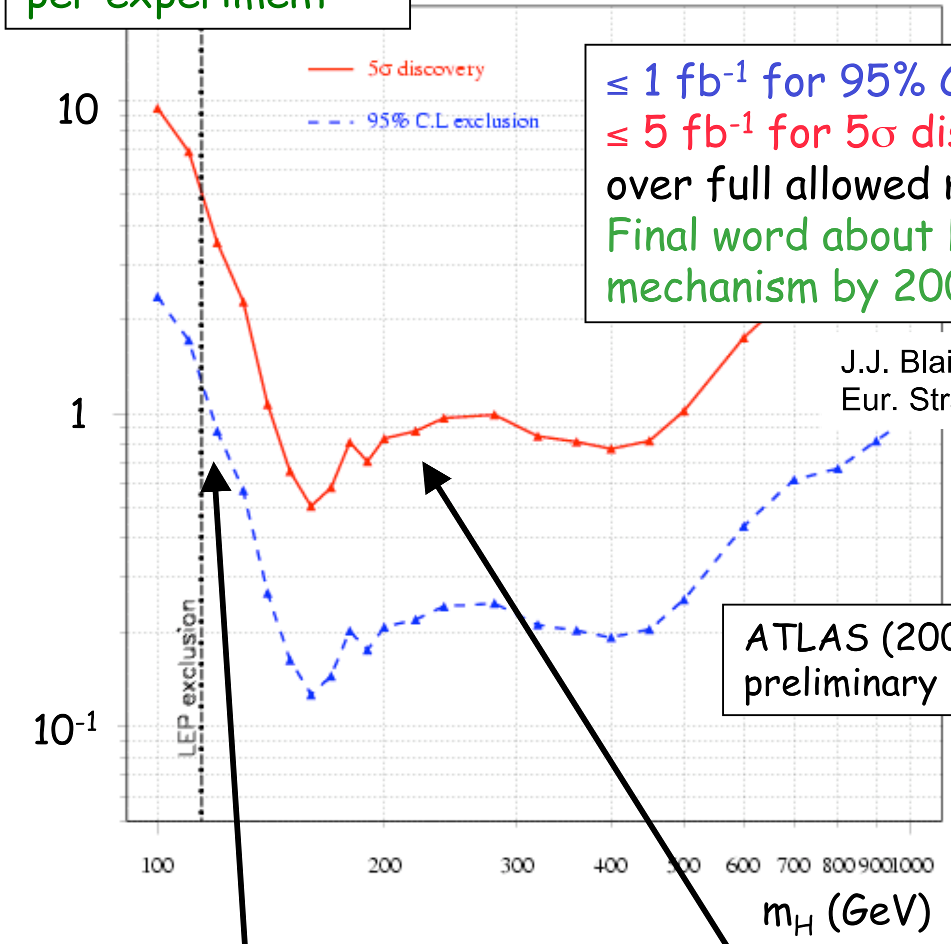



Higgs production cross sections at LHC

m_H < 130 GeV : $H \to bb$, $\tau\tau$ dominate
→ best search channels at the LHC : $qqH \to qq\,\tau\tau$, $H \to \gamma\gamma$, $ttH \to lbbX$
m_H > 130 GeV : $H \to WW^{(*)}$, $ZZ^{(*)}$ dominate
→ best search channels at the LHC : $H \to ZZ^{(*)} \to 4l$ (gold-plated)
$H \to WW^{(*)} \to l\nu\ l\nu$

Summary of Higgs discovery potential

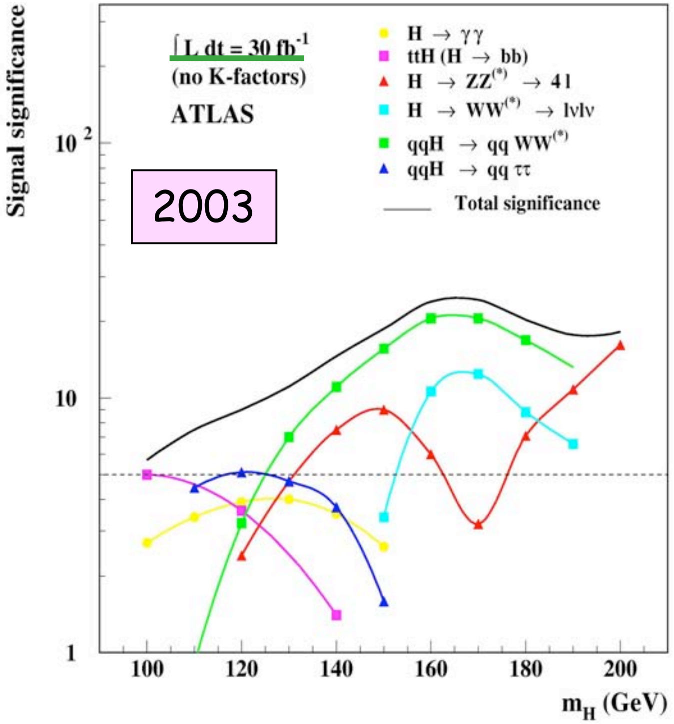
Needed ∫Ldt (fb^{-1})
per experiment



≤ 1 fb^{-1} for 95% C.L. exclusion
≤ 5 fb^{-1} for 5σ discovery
over full allowed mass range
Final word about Higgs
mechanism by 2009 ?

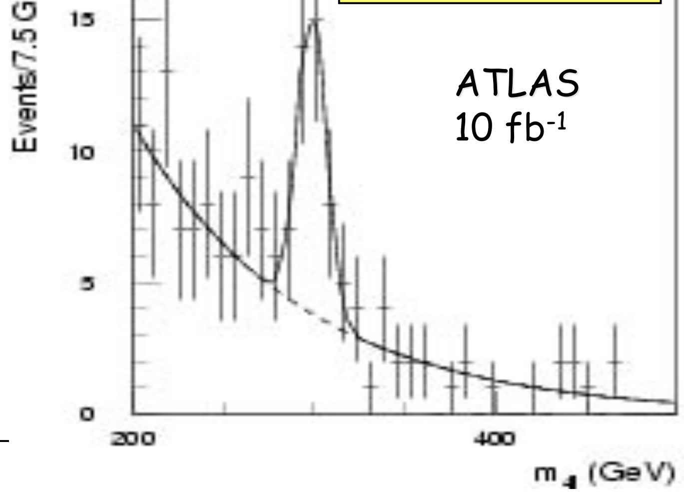
J.J. Blaising et al, input to
Eur. Strategy workshop

ATLAS (2003) + CMS
preliminary



2003

$H \to ZZ \to 4l$



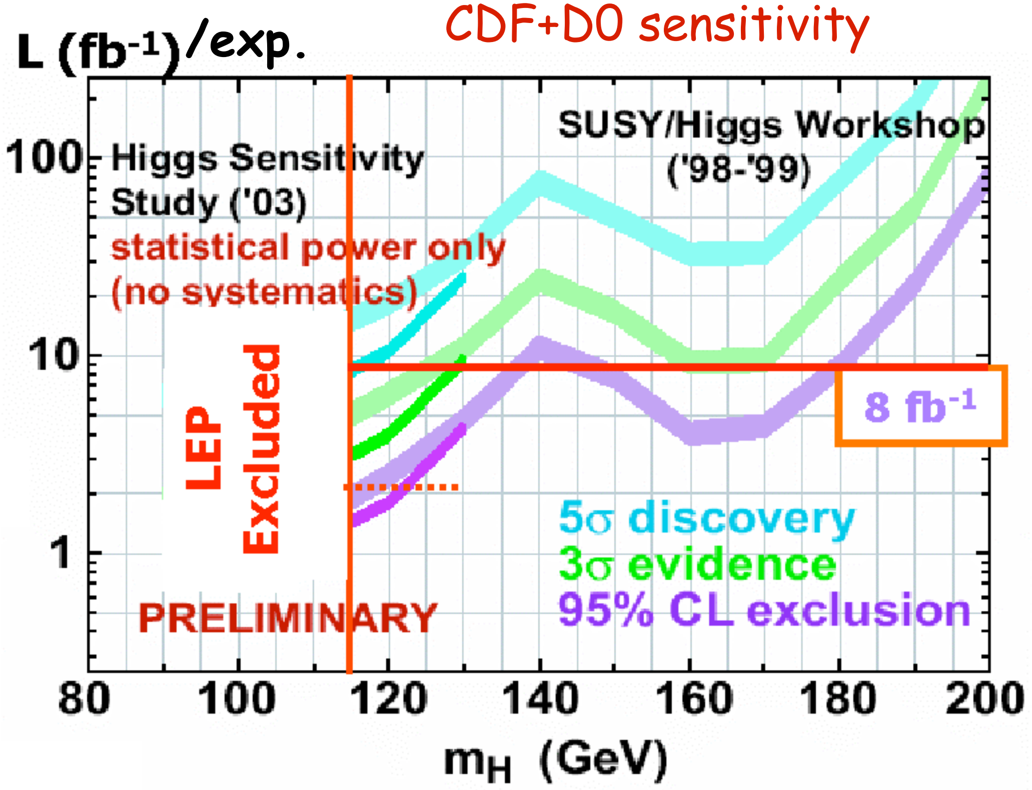
Most difficult region:
need to combined many
channels with small S/B

Here discovery easier with
gold-plated $H \to ZZ \to 4l$
narrow mass peak,
small background

If Higgs found, mass can be measured to 0.1%,
couplings to ~ 10-20% → useful insight into EWSB

What about the Tevatron ?

CDF+D0 sensitivity



Today : ~ 3 fb^{-1} /experiment
2009: expect 6-7 fb^{-1} /experiment
Tevatron operation in 2010 being discussed

With 4 (8) fb^{-1}:
~no 5σ sensitivity
3σ evidence up to 120 (130) GeV
95% C.L. exclusion up to ~ 130 (180) GeV

competition between Tevatron and LHC in 2009 if m_H < 130 GeV ?

Conclusions

- Impressive achievements on the machine side over last months:
  e.g. magnet installation completed, one full sector cooled down to 1.9 K,
  many components tested, inner triplets repair progressing,
  machine commissioning and operation plans better understood, etc.

- Revised LHC schedule foresees first collisions at 14 TeV in Summer 2008

- Luminosity projections: 6×10^{30}-10^{32} in 2008 → O(100 pb^{-1}) ?
  10^{32}-10^{33} in 2009 → few fb^{-1} ?

- ATLAS detector installation in the underground cavern is almost completed → ATLAS ready to close the beam pipe in April 2008 (as requested by the LHC schedule)

- An intense test-beam campaign over the last decade has demonstrated that the detector behaves as expected.
  These studies have also allowed validation and improvements of the software tools (simulation, reconstruction, etc.) with real data

- Cosmics data taking has started with the detector in its final position in the underground cavern → this commissioning effort will allow us to save time when first collisions will become available.

- A re-evaluation of the experiment's physics potential will be completed by the end of the year and documented in ATLAS notes.
  The huge number of channels and scenarios studied demonstrate the detector sensitivity to many signatures → robustness, ability to cope with unexpected scenarios

With the first collision data (1-100 pb^{-1}) at 14 TeV

Understand ATLAS detector performance in situ in the LHC environment, and perform first physics measurements:

- **Measure particle multiplicity in minimum bias (a few hours of data taking …)**
- **Measure QCD jet cross-section to ~ 30% ?**
  (Expect >10^3 events with E_T (j) > 1 TeV with 100 pb^{-1})
- **Measure W, Z cross-sections to 10% with 100 pb^{-1}?**
- **Observe a top signal with ~ 30 pb^{-1}**
- **Measure tt cross-section to 20% and m(top) to 10 GeV with 100 pb^{-1} ?**
- **Improve knowledge of PDF (low-x gluons !) with W/Z with O(100) pb^{-1} ?**
- **First tuning of MC (minimum-bias, underlying event, tt, W/Z+jets, QCD jets,…)**

And, more ambitiously:

- **Discover SUSY up to gluino masses of ~ 1.3 TeV ?**
- **Discover a Z' up to masses of ~ 1.3 TeV ?**
- **Surprises ?**

With more time and more data ….

The LHC will explore in detail the highly-motivated TeV-scale with a direct discovery potential up to m ≈ 5-6 TeV

→ if New Physics is there, the LHC should find it

→ it will say the final word about the SM Higgs mechanism and many TeV-scale predictions

→ it may add crucial pieces to our knowledge of fundamental physics → impact also on astroparticle physics and cosmology

→ most importantly: it will likely tell us which are the right questions to ask, and how to go on

This will be the best reward for 20 years of efforts to conceive and build a machine and detectors of unprecedented performance, complexity and technology