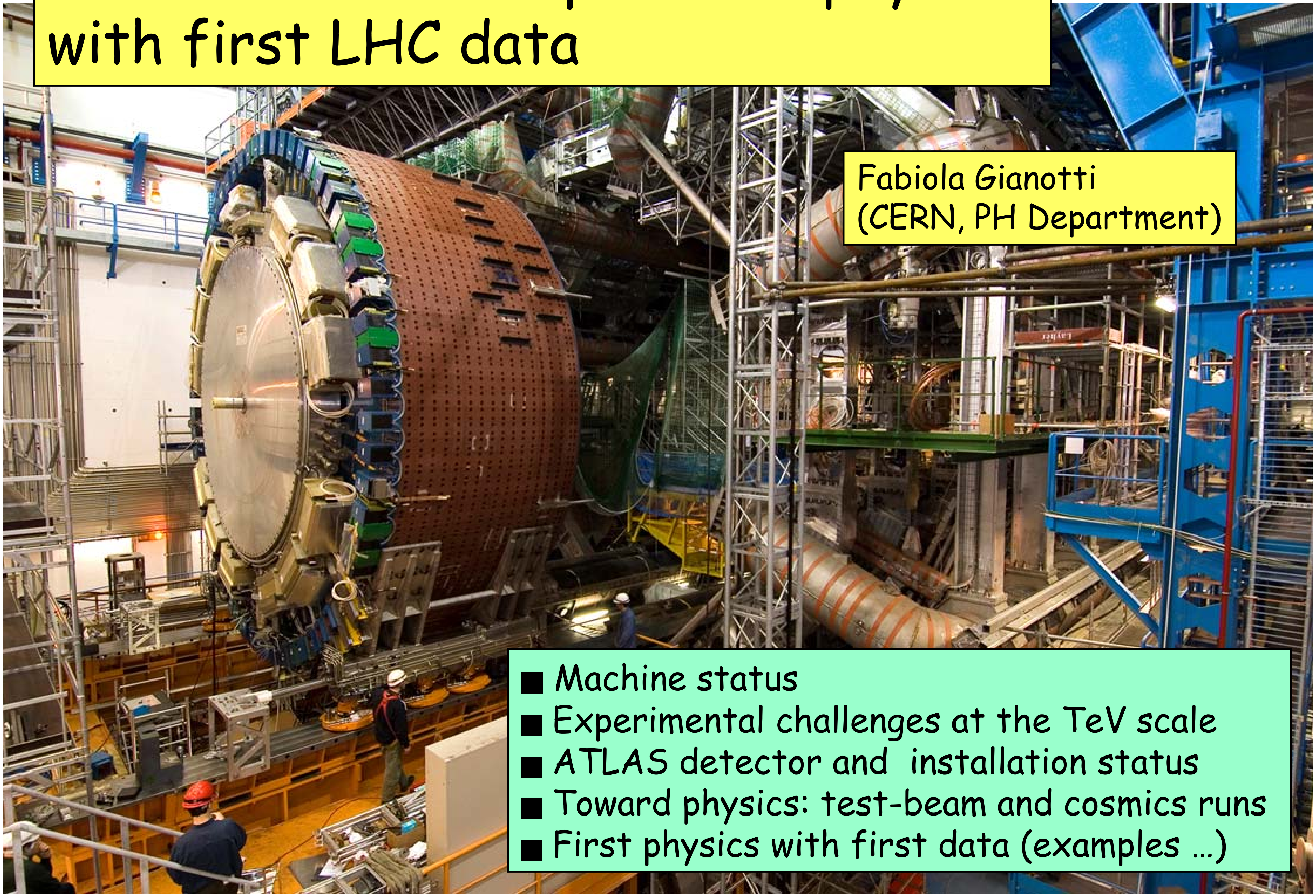
ATLAS status and plans for physics with first LHC data



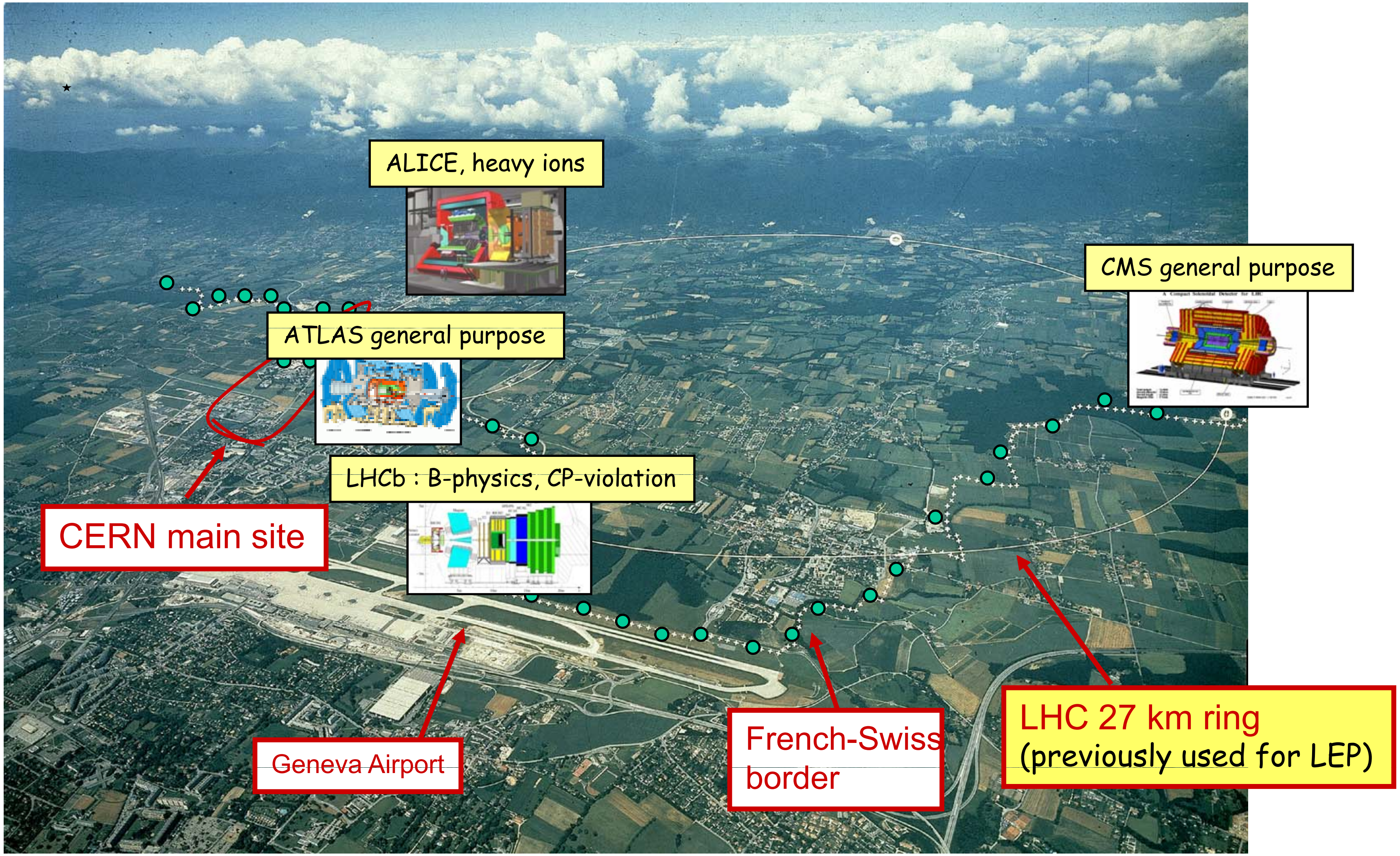
Fabiola Gianotti
(CERN, PH Department)

- 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

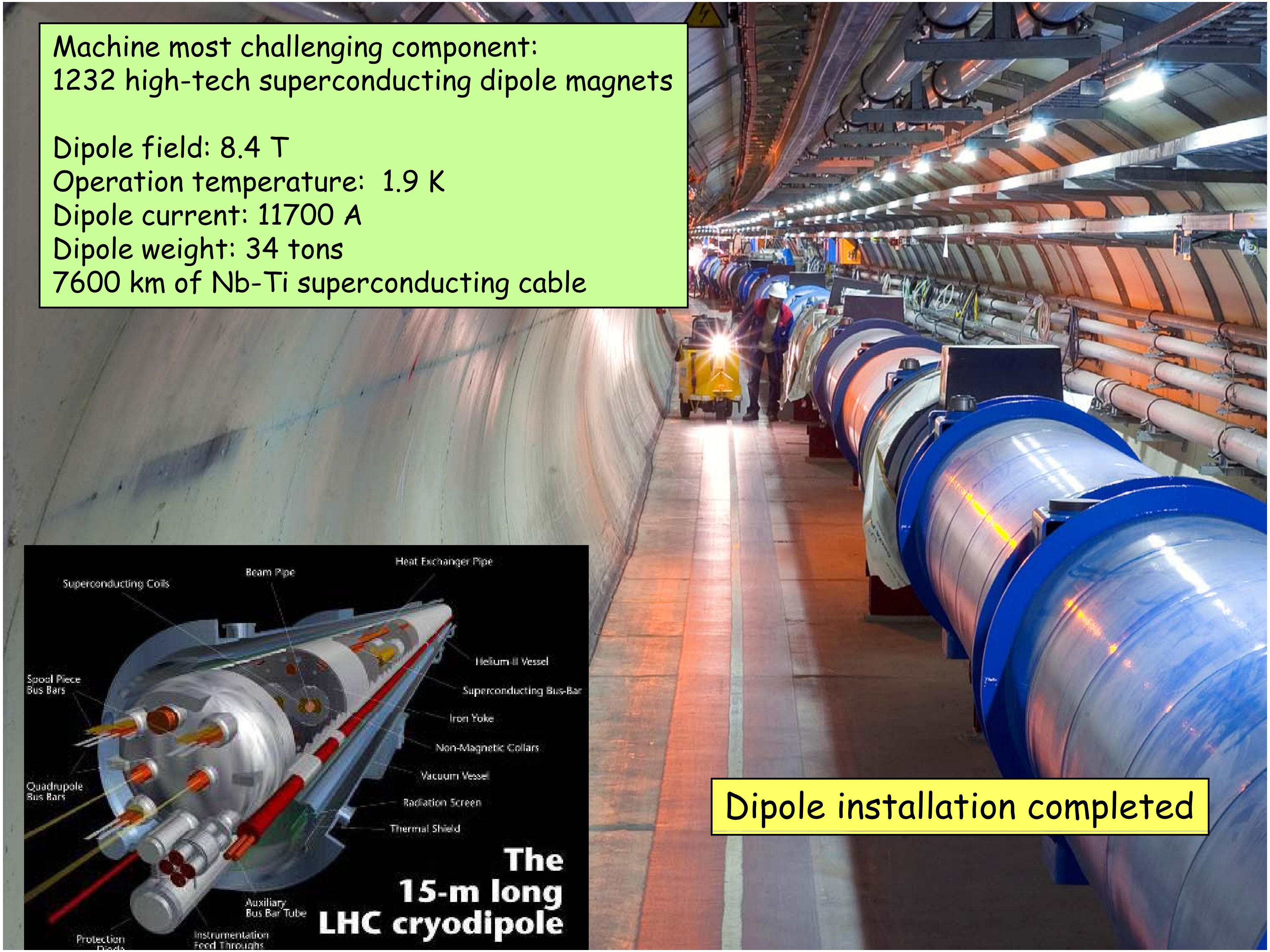
- pp, $\sqrt{s}$ = 14 TeV L_{design} = 10^{34} cm^{-2} s^{-1} (after 2010)
  $L_{initial}$ up to few x 10^{33} cm^{-2} s^{-1} (before 2010)

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

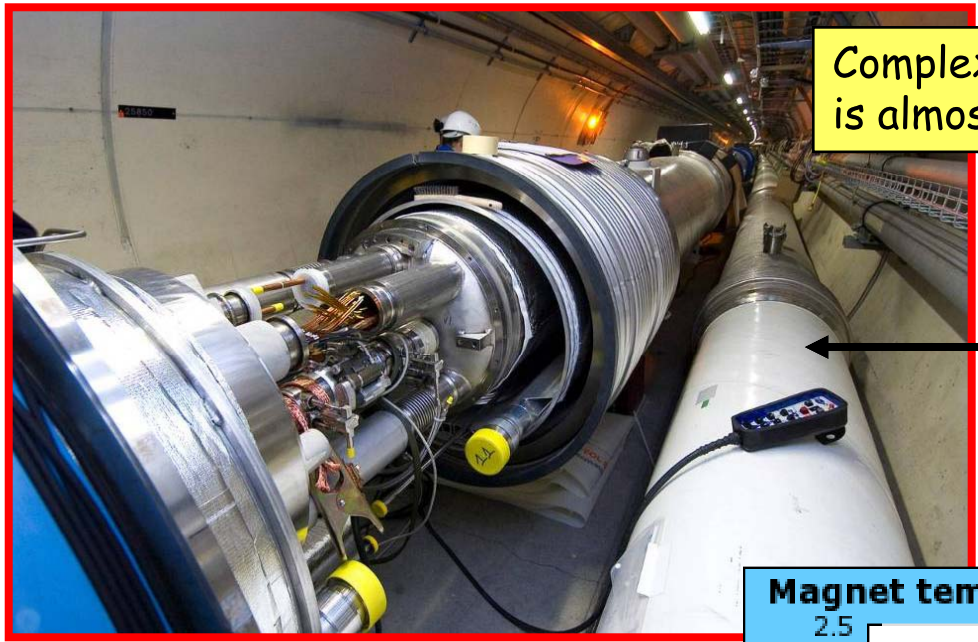


Machine most challenging component:
1232 high-tech superconducting dipole magnets

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

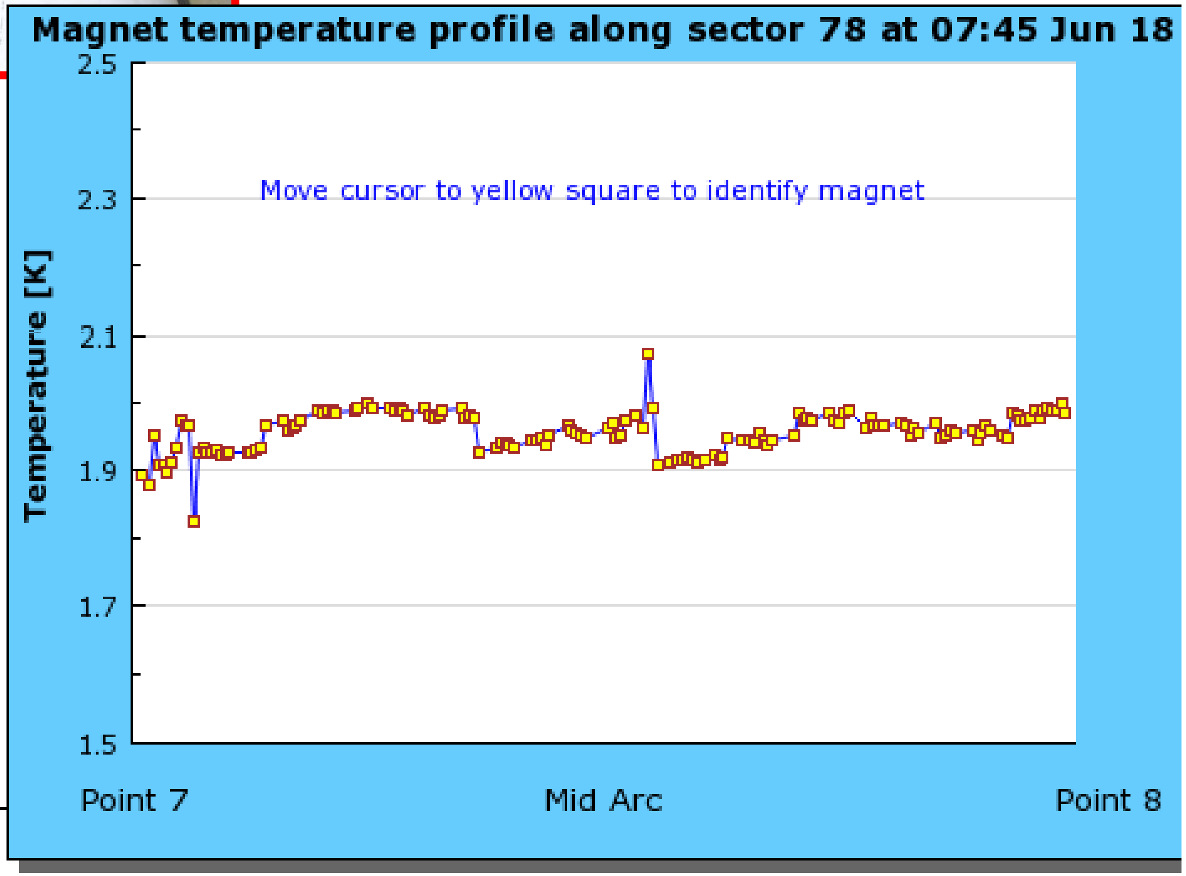


Complex dipole interconnection work is almost finished

Cryogenic line

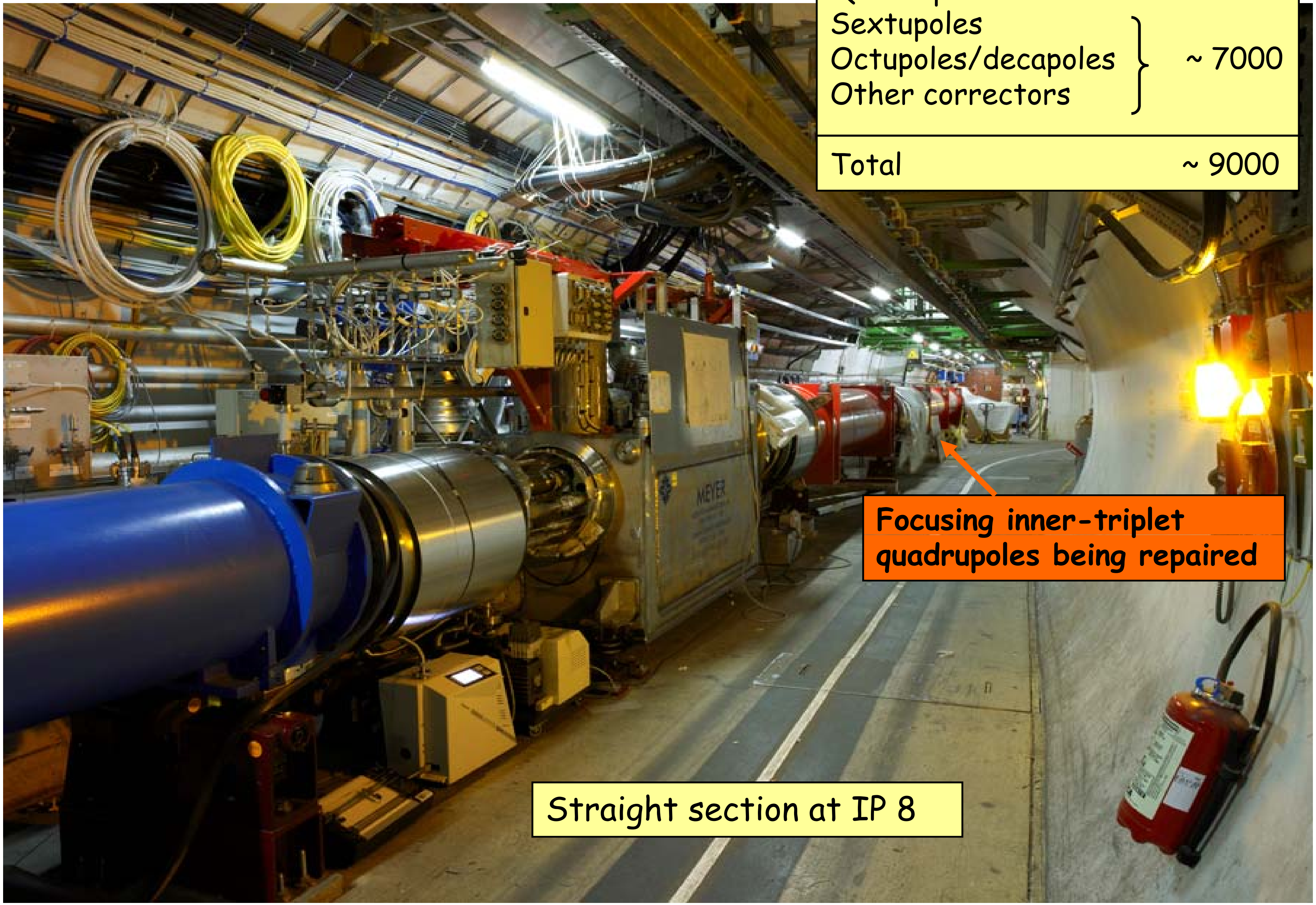
The first one of eight sectors (sector 7-8) was cooled down to 1.9 K in the first half of 2007
Cool-down of sector 4-5 started

One sector: 3.3 km, 154 dipoles



Not only dipoles ….

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



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

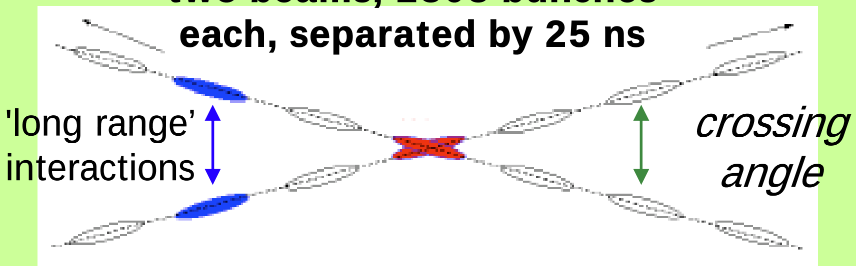
Stored beam energy: x200 Tevatron

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

n. of protons per bunch (N); n. of bunches (k_b); n. of turns per second (f); beam size at IP ($\sigma_{x,y}$ = 16 µm)

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

two beams, 2808 bunches each, separated by 25 ns



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...

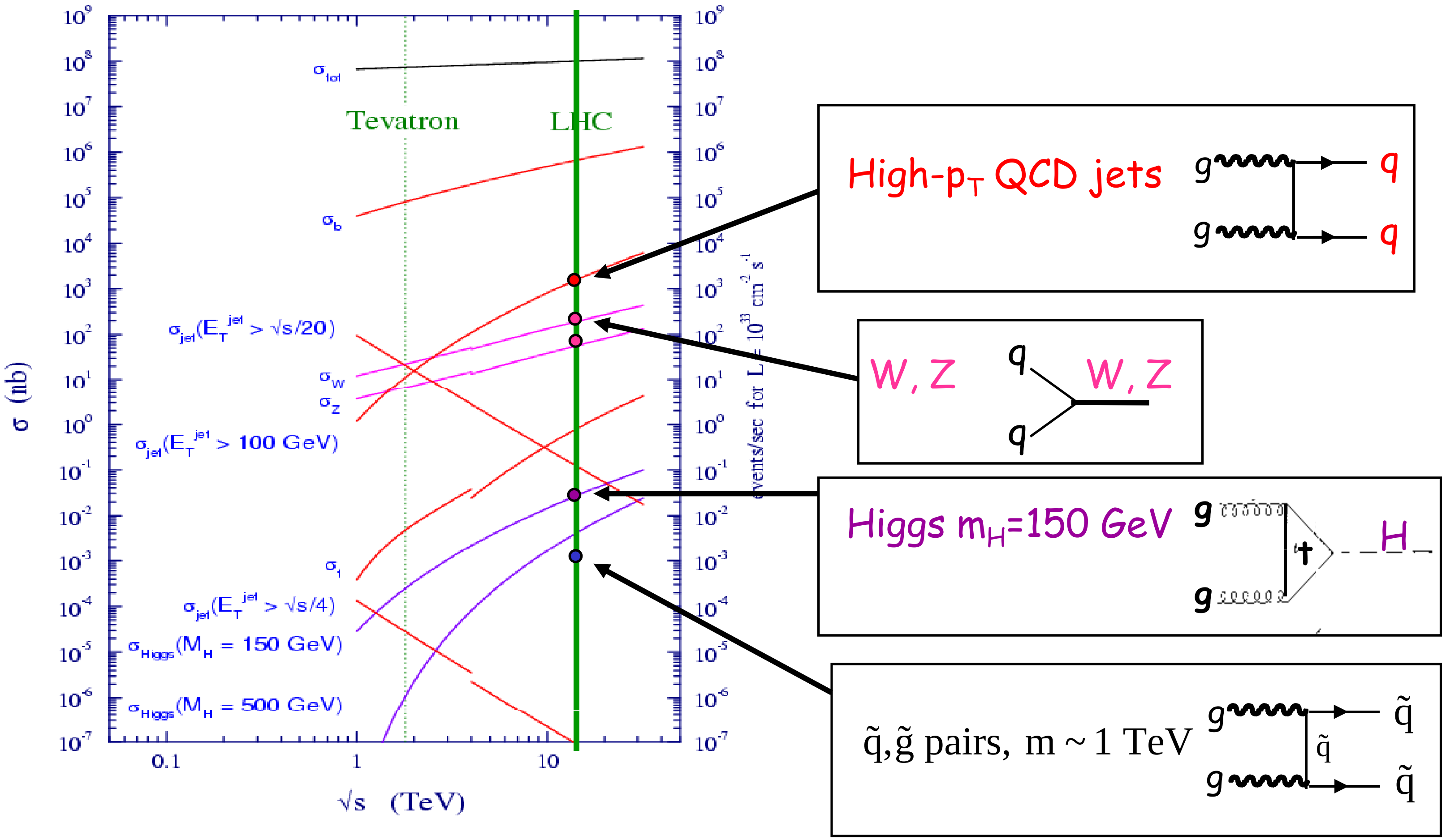
It will most likely take YEARS

My guess: total integrated luminosity
$\int Ldt$ O(100 pb^{-1}) in 2008 ?
$\int Ldt \sim$ 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

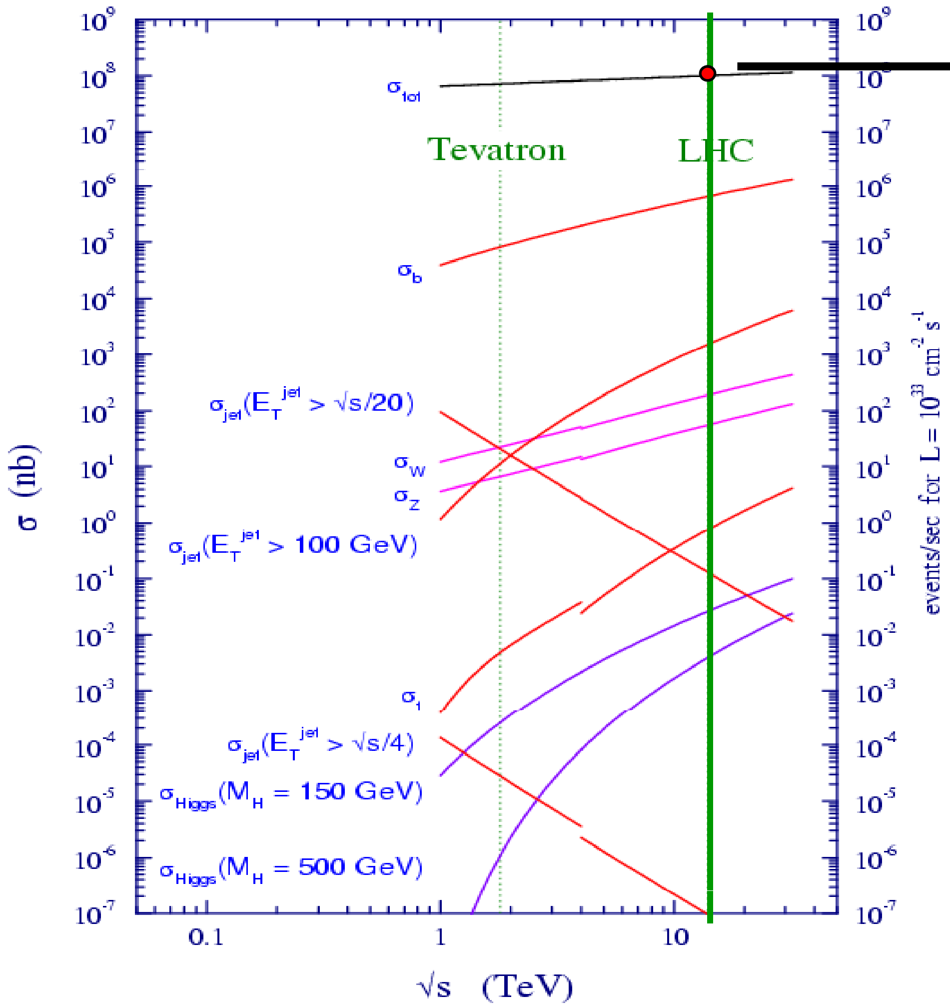
Main experimental challenges
to be faced in order
to explore the TeV scale

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



- 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

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



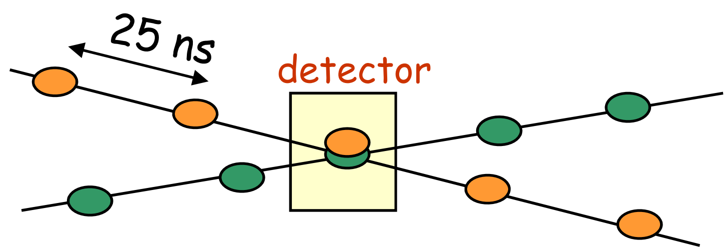
Event rate in ATLAS, CMS :

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

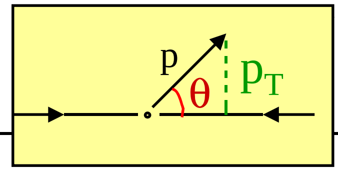
$\approx 10^{9}$ interactions/s

Proton bunch spacing : 25 ns

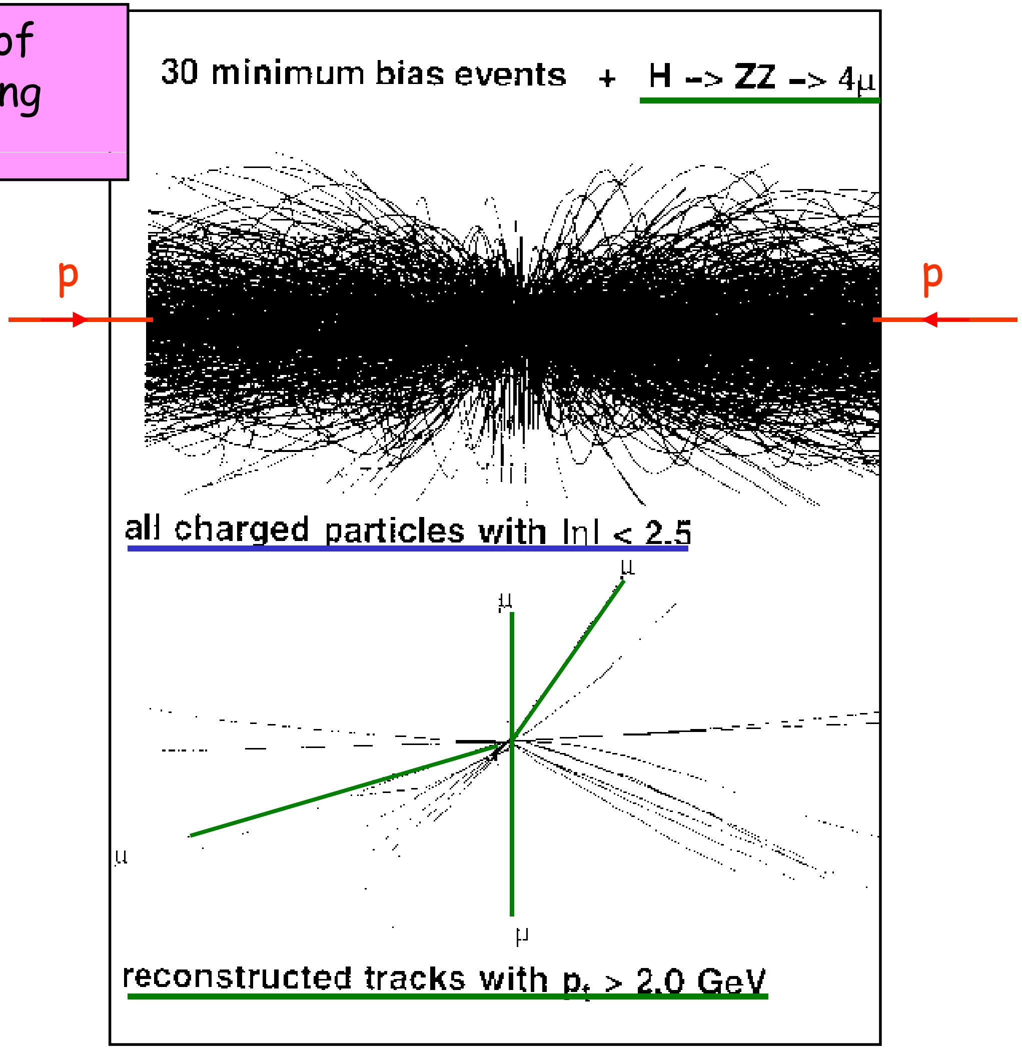
Protons per bunch : 10^{11}



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



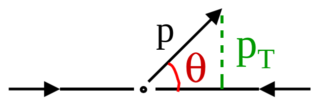
Simulation of CMS tracking detector



At each crossing : ~1000 charged particles produced over $|\eta| < 2.5$ ($10^0 < \theta < 170^0$)

However : $\langle p_T \rangle \approx 500$ MeV

→ applying p_T cuts allows extraction of interesting events



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

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)

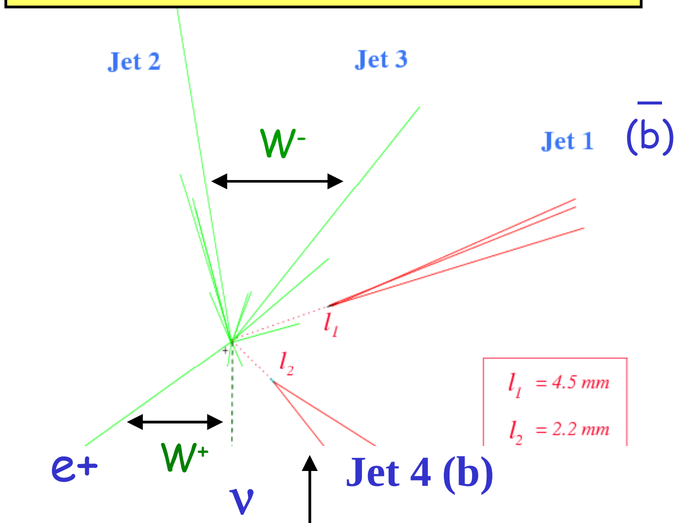
-- event reconstruction much more challenging than at previous colliders

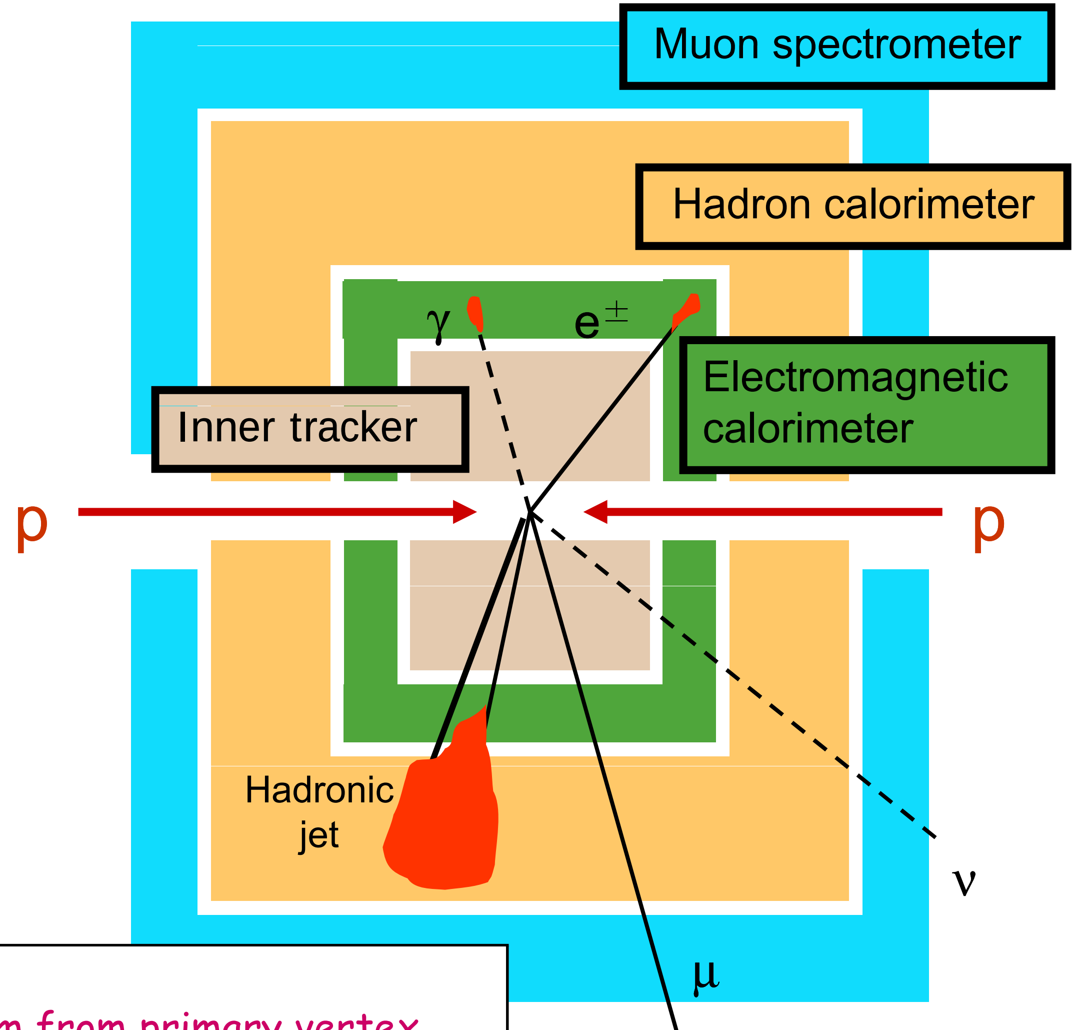
Powerful high-performance experiments

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

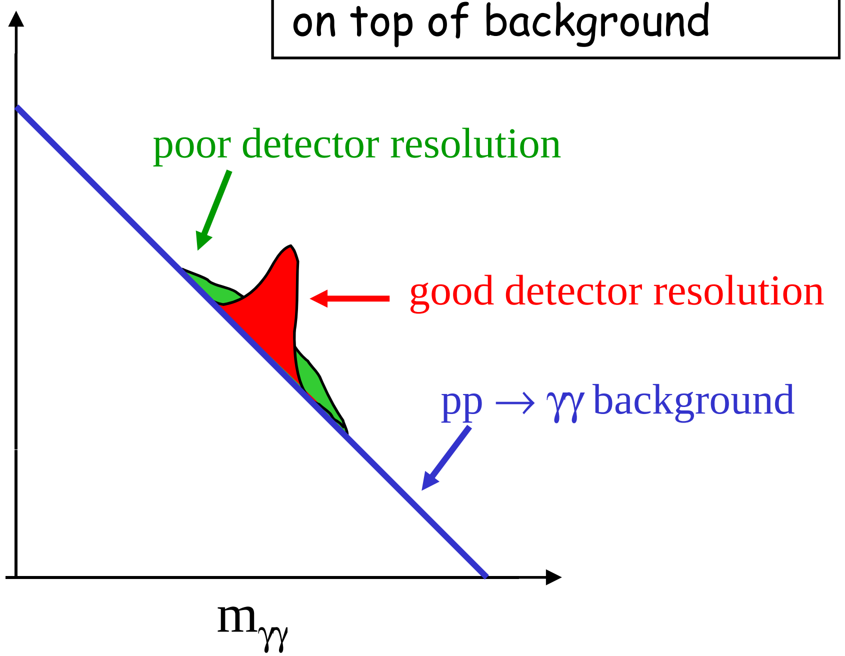
Examples of detector performance requirements:

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

Hypothetical X → γγ signal on top of background

Mass resolutions:

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



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)

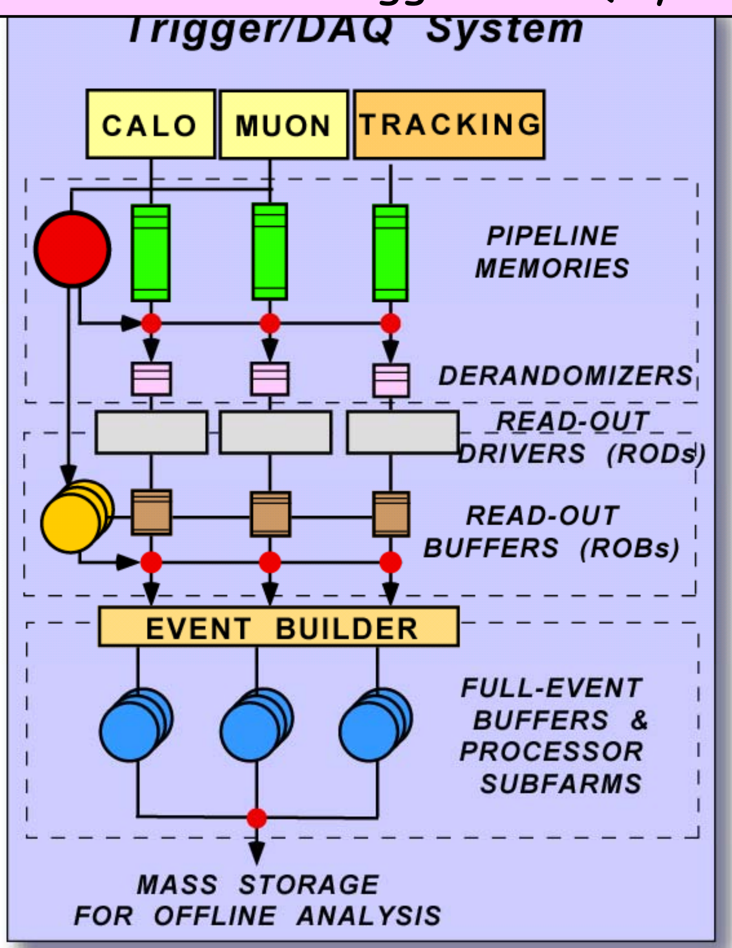
Must be very selective and efficient: e.g. 1 H $\rightarrow$ 4e event every 10^{13} interactions

$\Rightarrow$ multi-level trigger systems

ATLAS 3-level Trigger/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

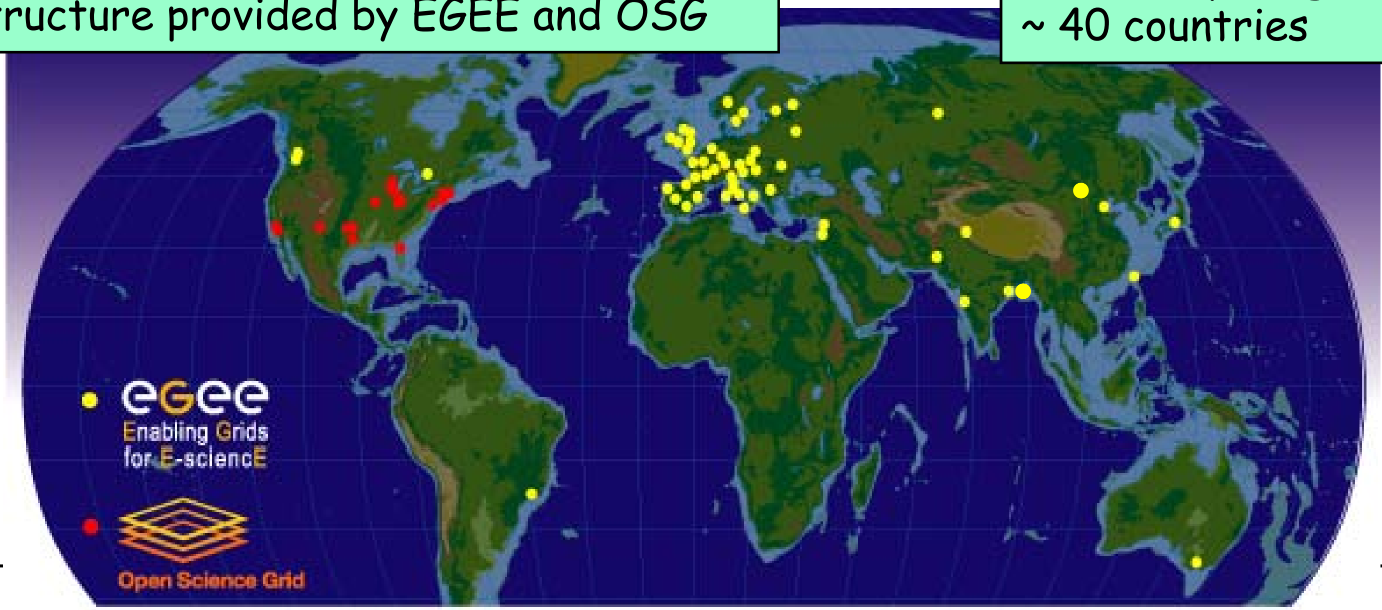
The experiment Collaborations are spread all over the world

→ 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

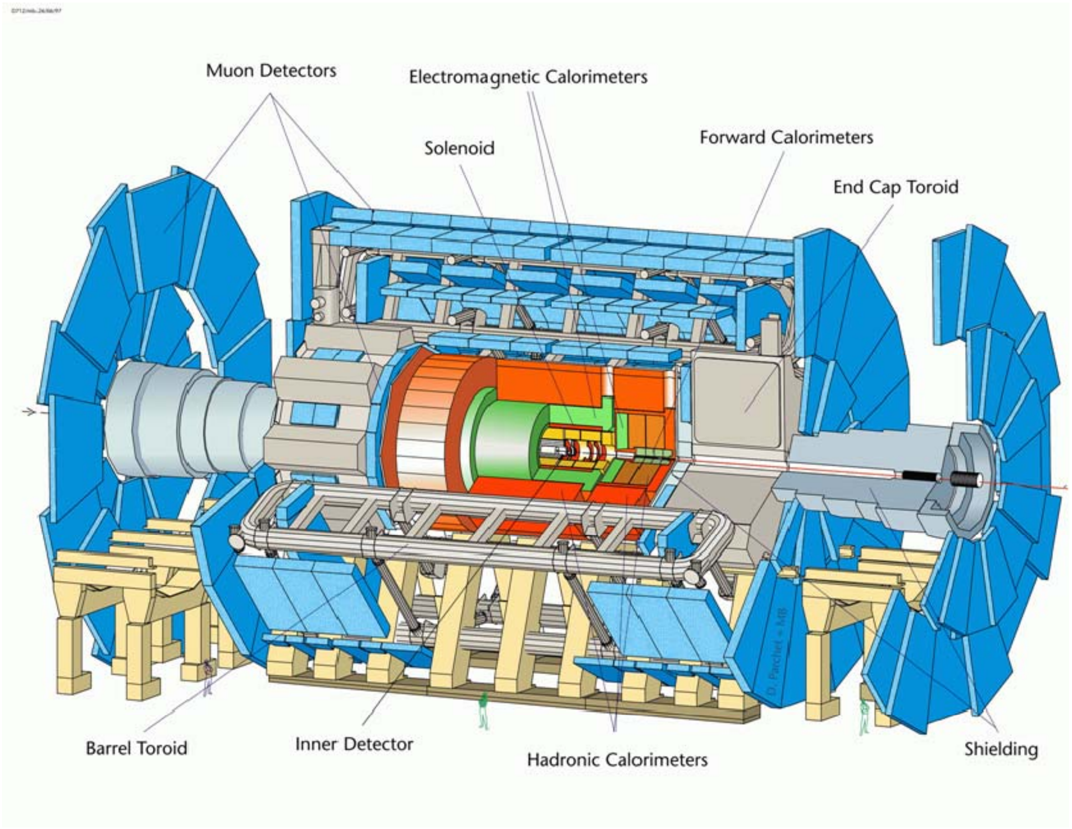
~120 computing centers
~ 40 countries



The ATLAS experiment:

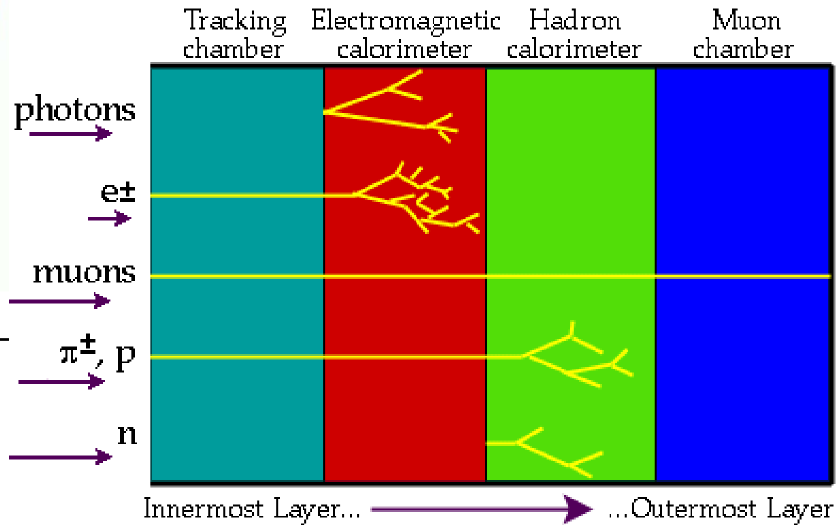
- main features of the detector
- installation status

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



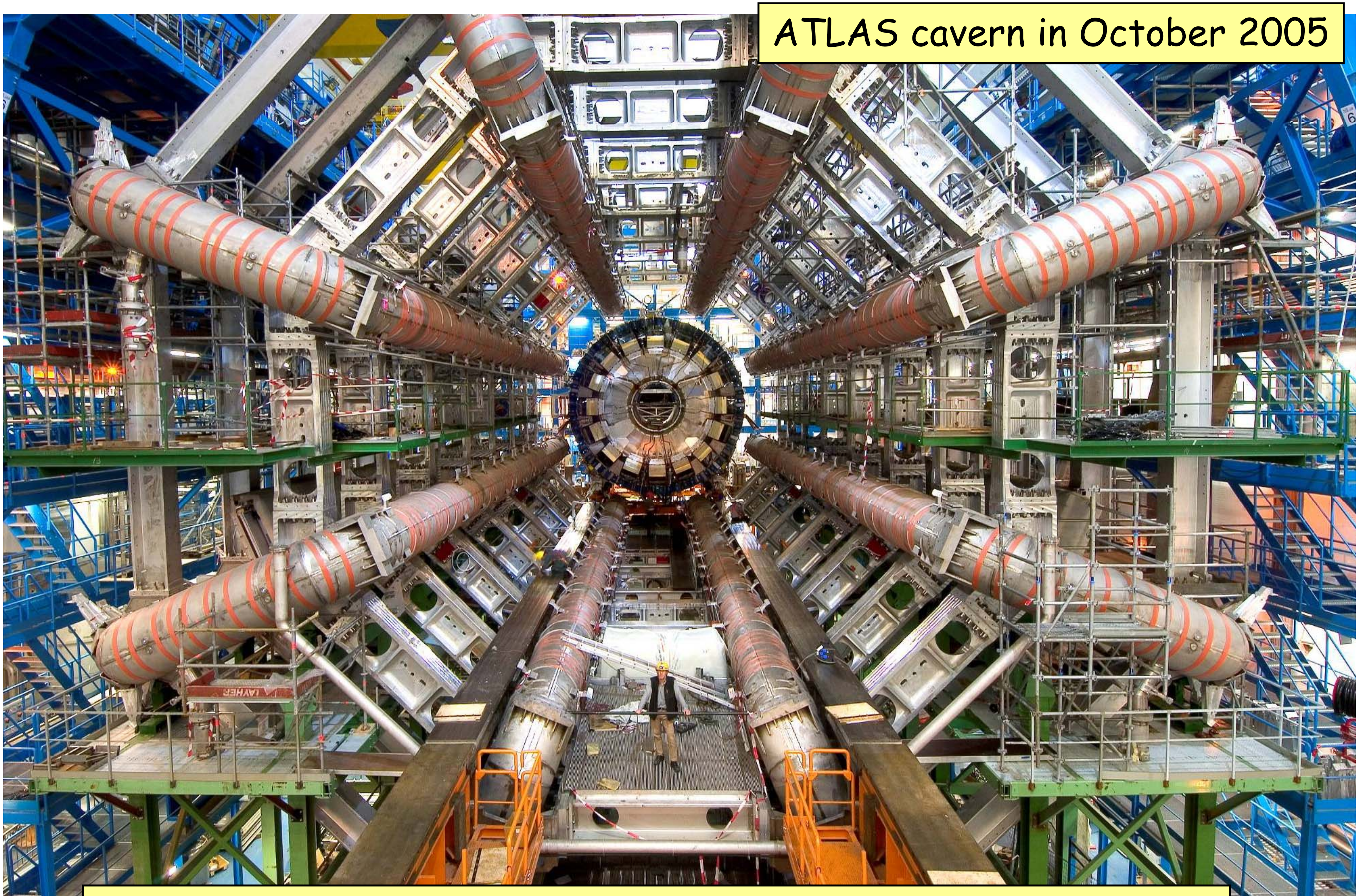
ATLAS

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

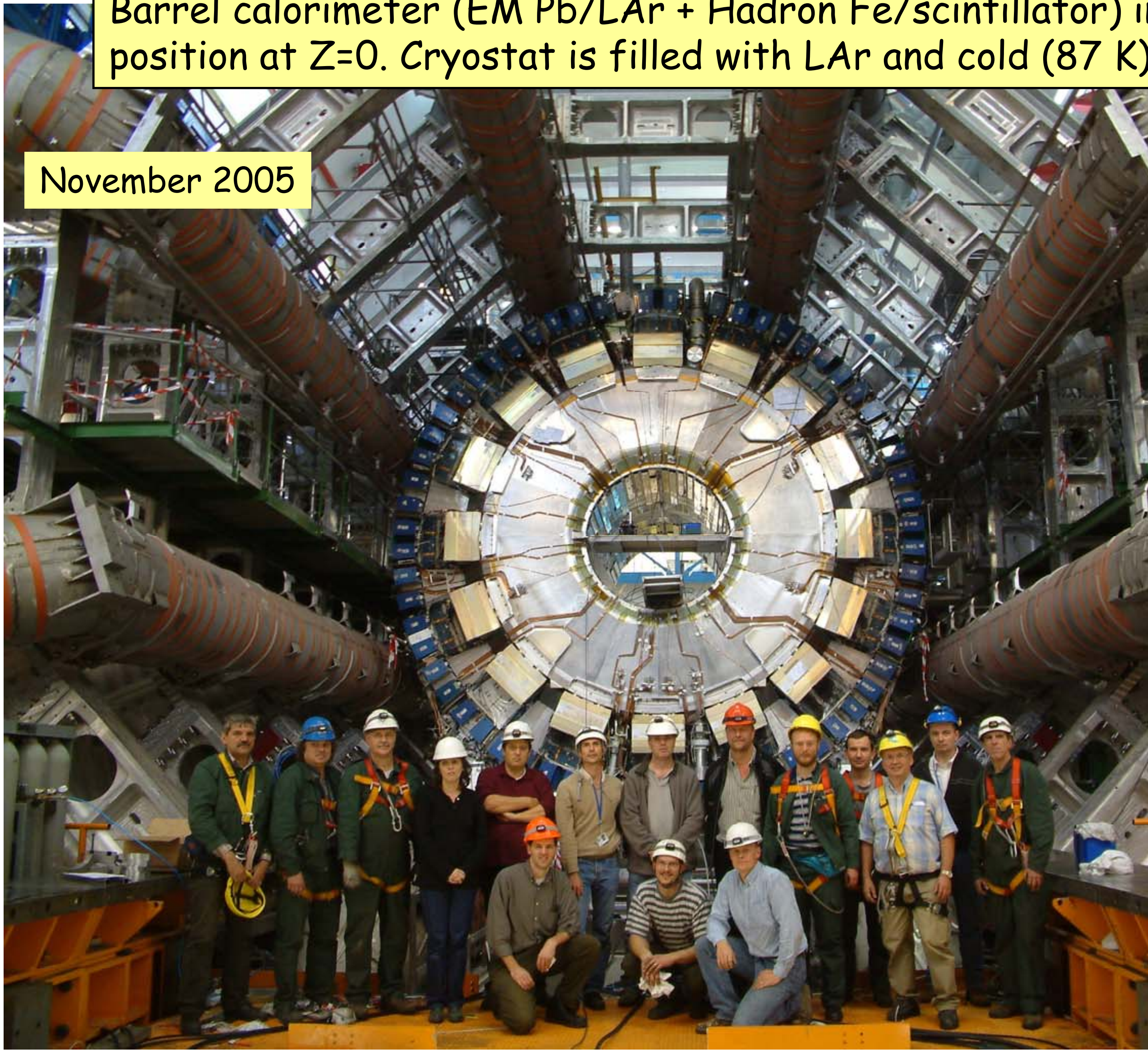
And …. 1900 physicists from
165 Institutions from 35 countries
from 5 continents



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.

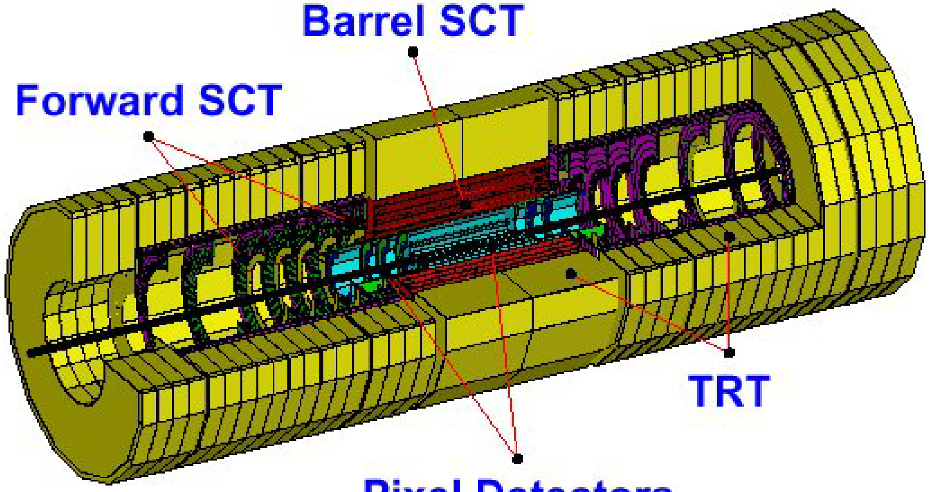
Barrel calorimeter (EM Pb/LAr + Hadron Fe/scintillator) in its final position at Z=0. Cryostat is filled with LAr and cold (87 K)

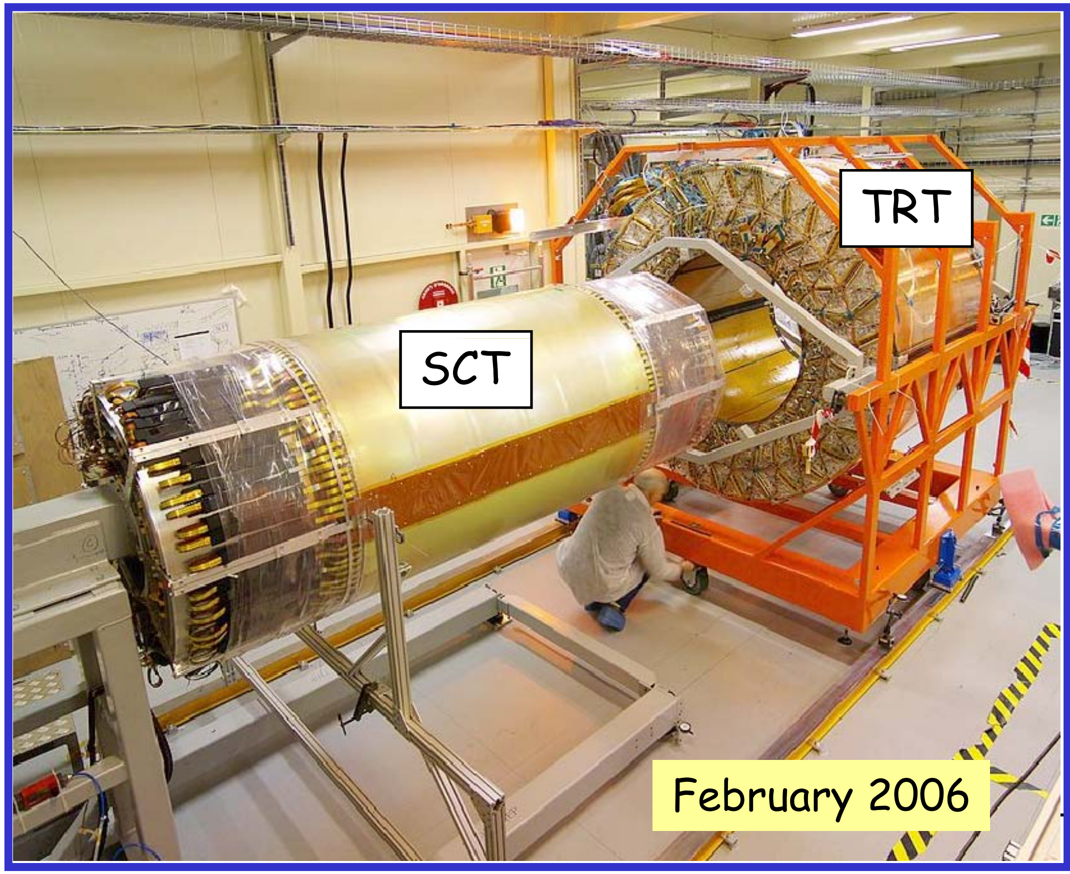

November 2005


October 2004

Inner tracker

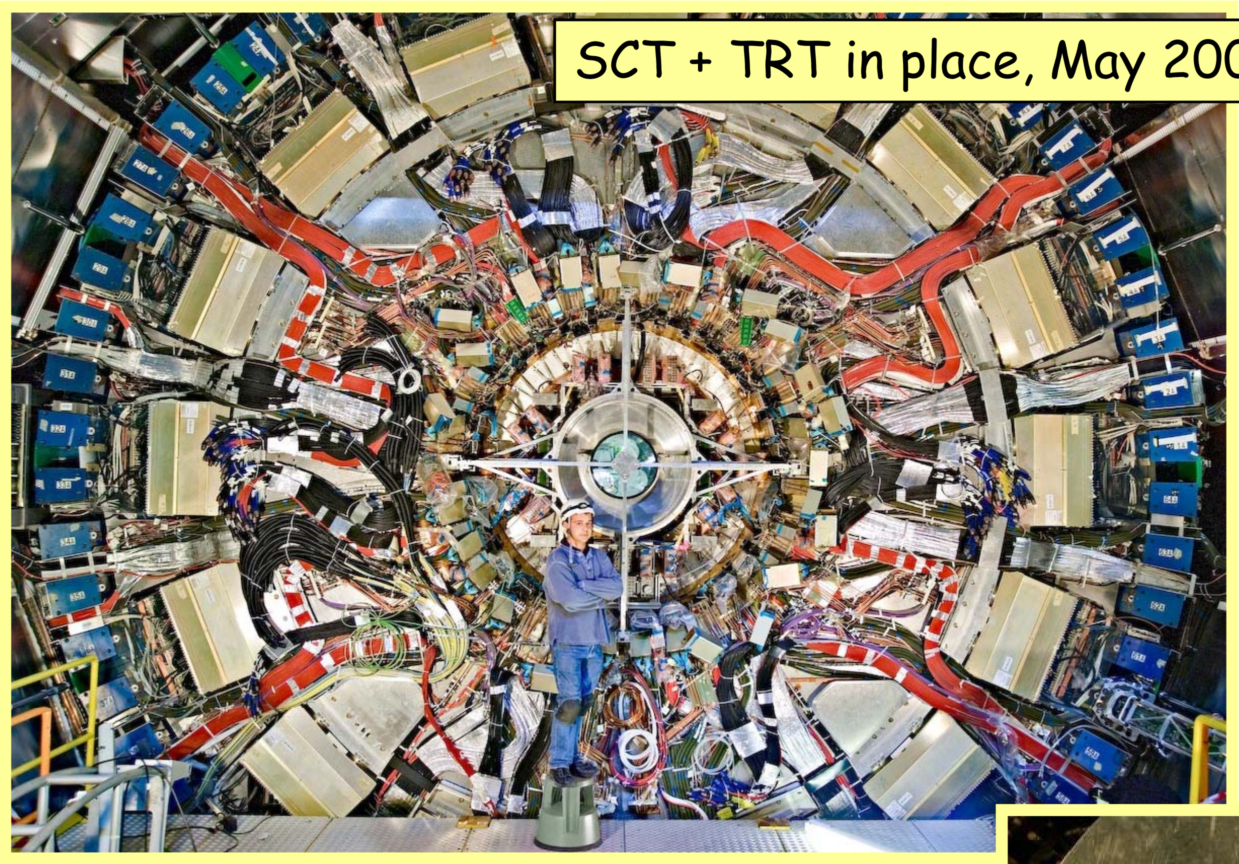
3 sub-systems:
Silicon pixels : 0.8 10^8 channels
Silicon strips (SCT) : 6 10^6 channels
Transition Radiation Tracker (TRT) :
straw tubes filled with gas, 4 10^5 channels





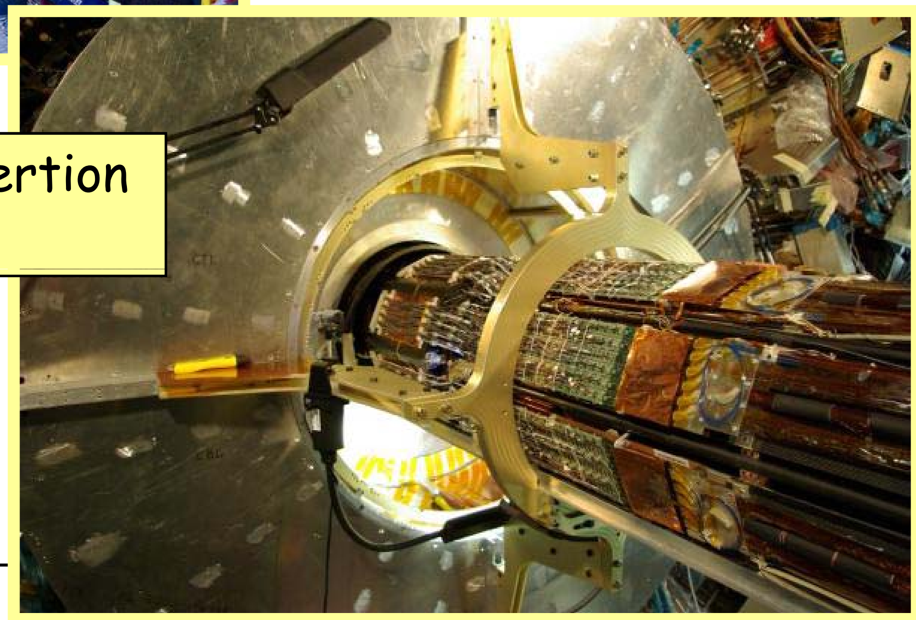
February 2006

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



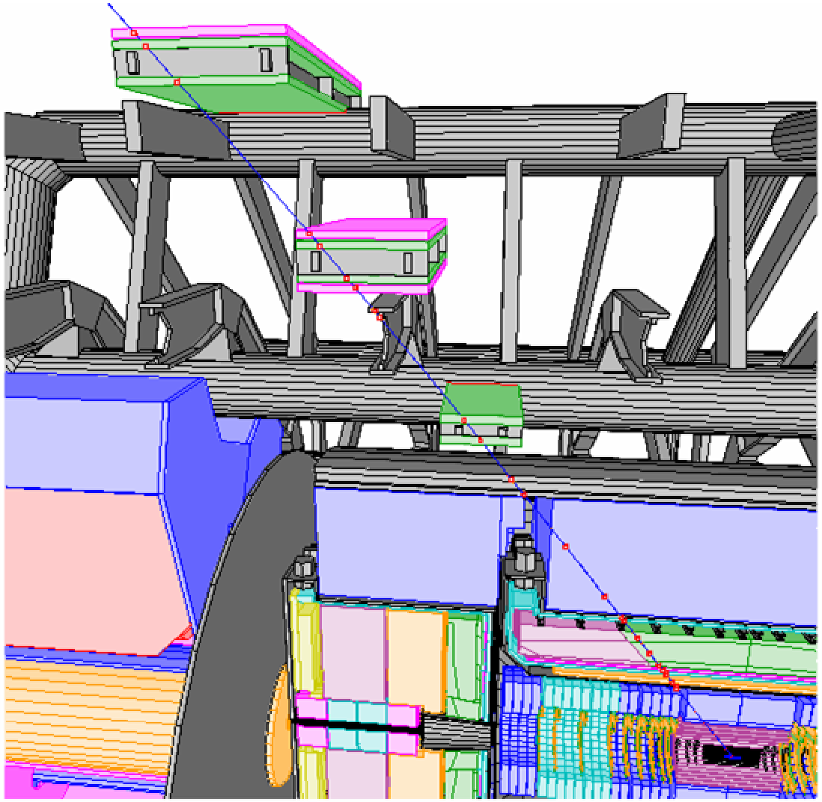
SCT + TRT in place, May 2007

Inner Detector installation in underground cavern completed

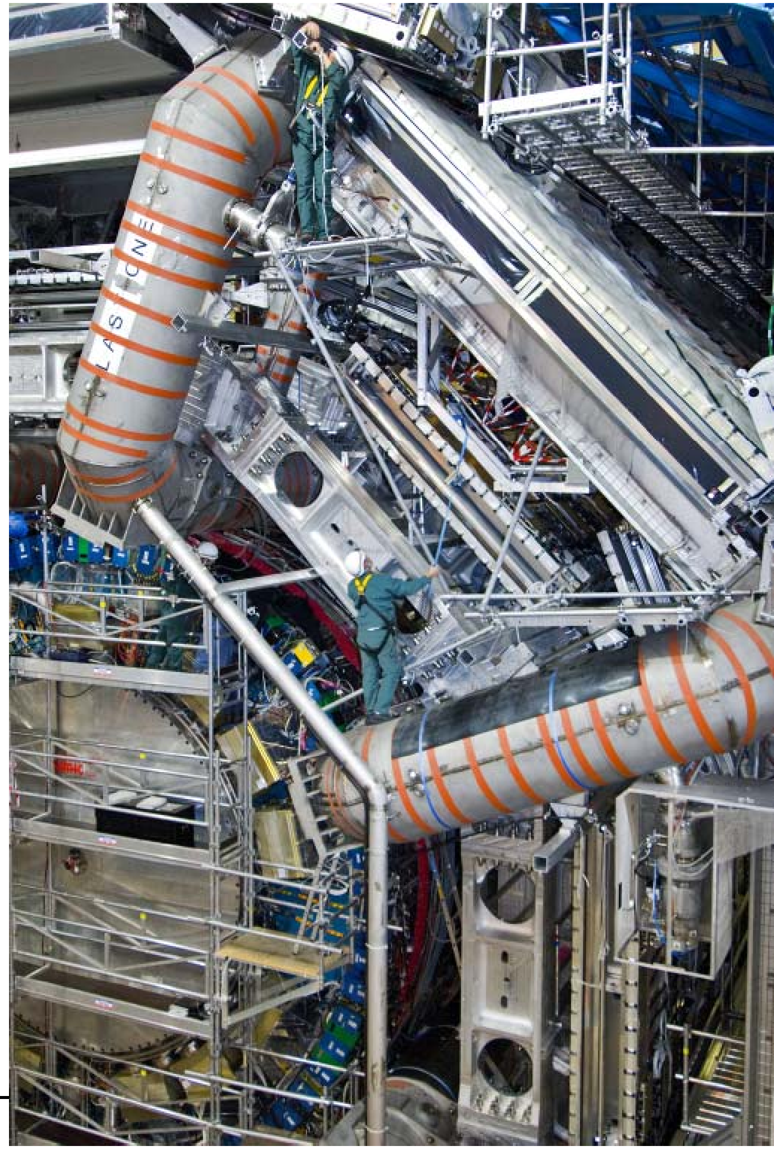


Pixels (+ beam pipe) insertion
June 2007

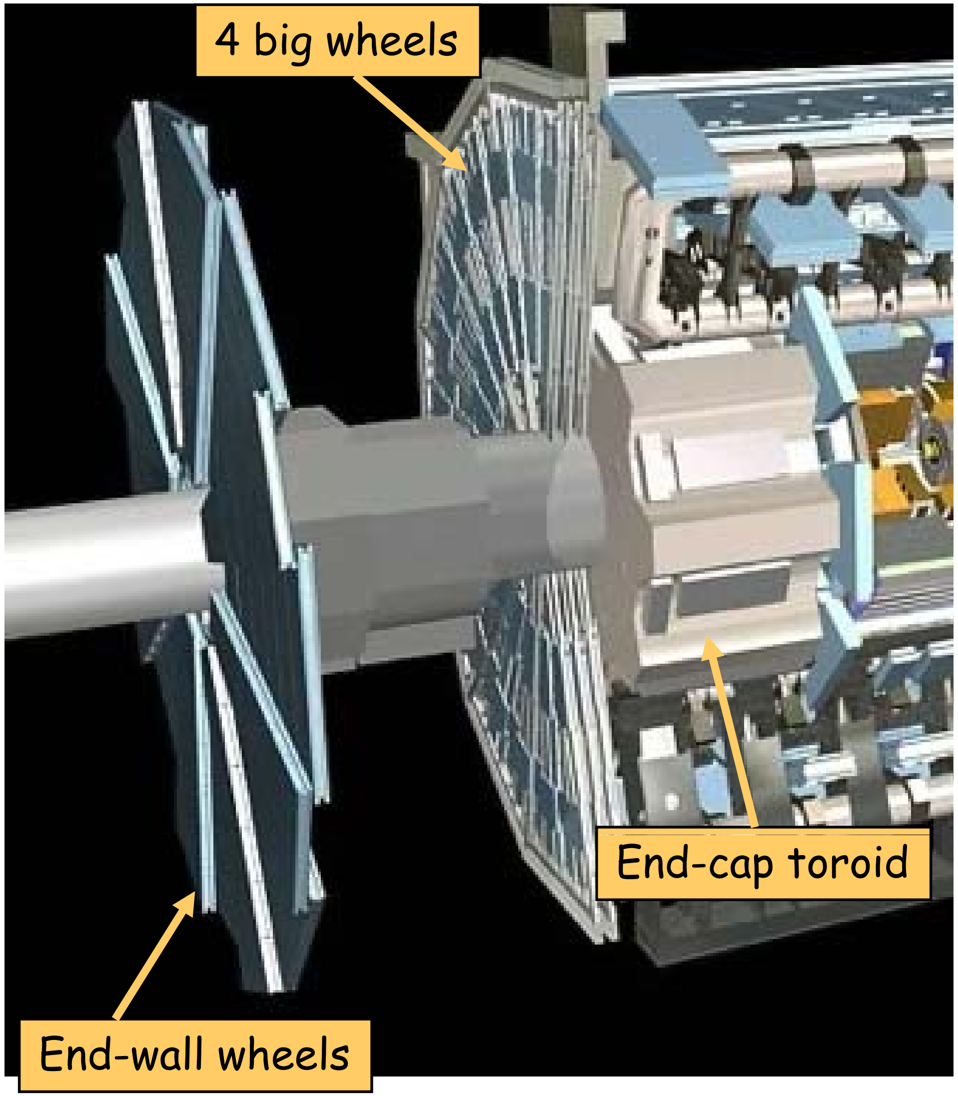
Made of ~ 80 million high-tech Si pixels
50μm wide, 400μm long, 250μm thick

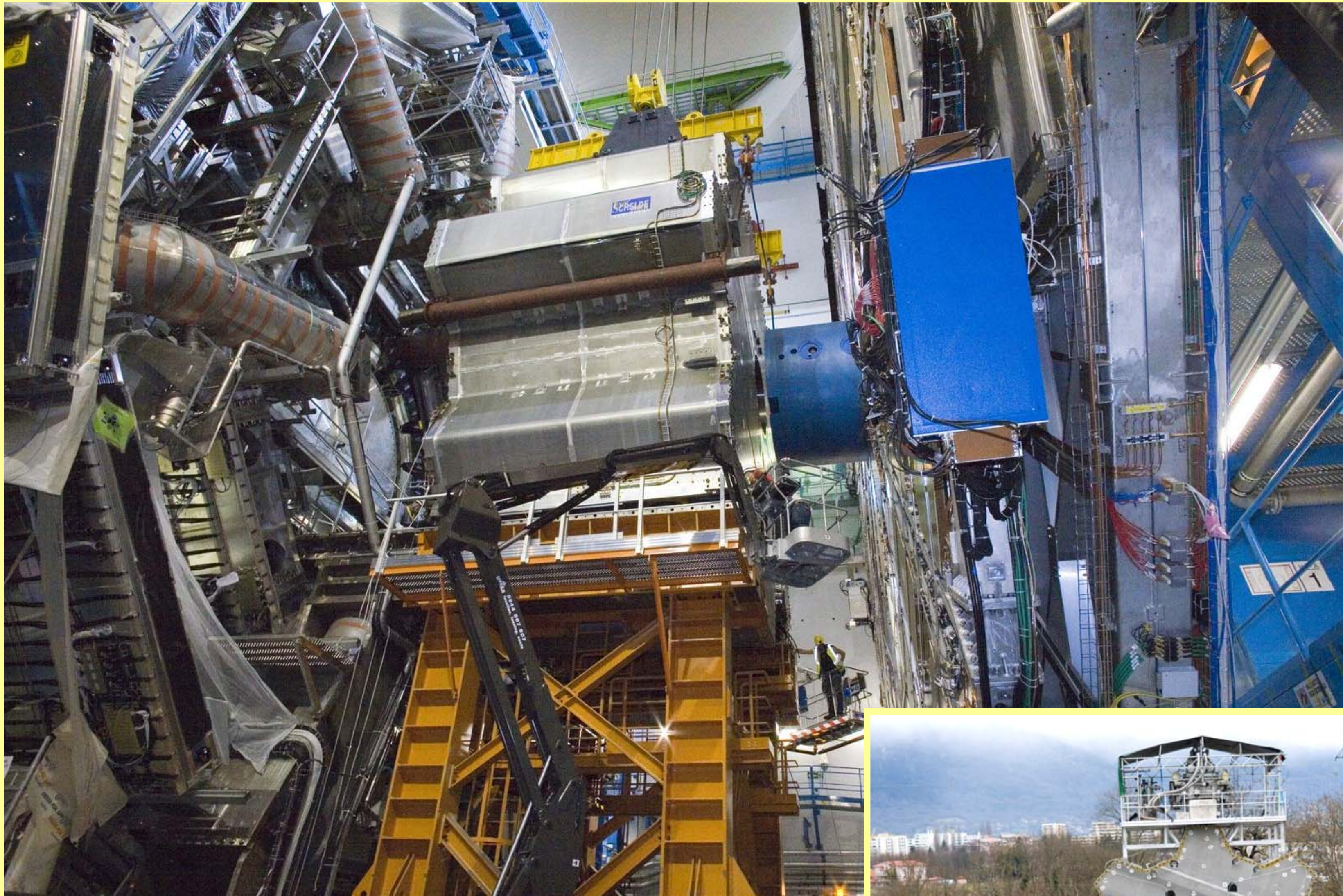


Installation of barrel muon chambers
(~ 700 stations) started in December 2005
and is ~ completed.



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

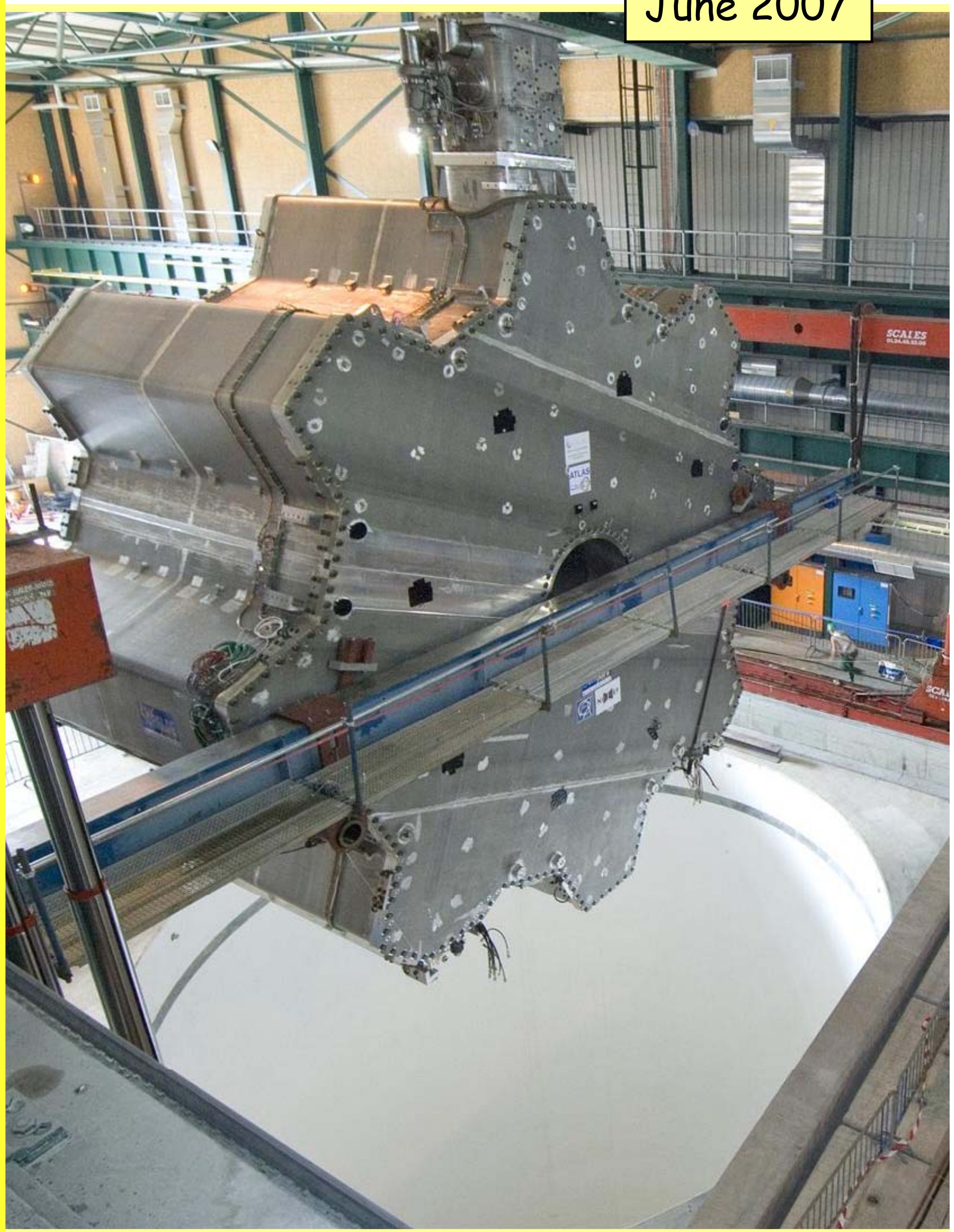




The two end-cap toroid magnets installed in June-July 2007

Spectacular operations …


October 2004


June 2007

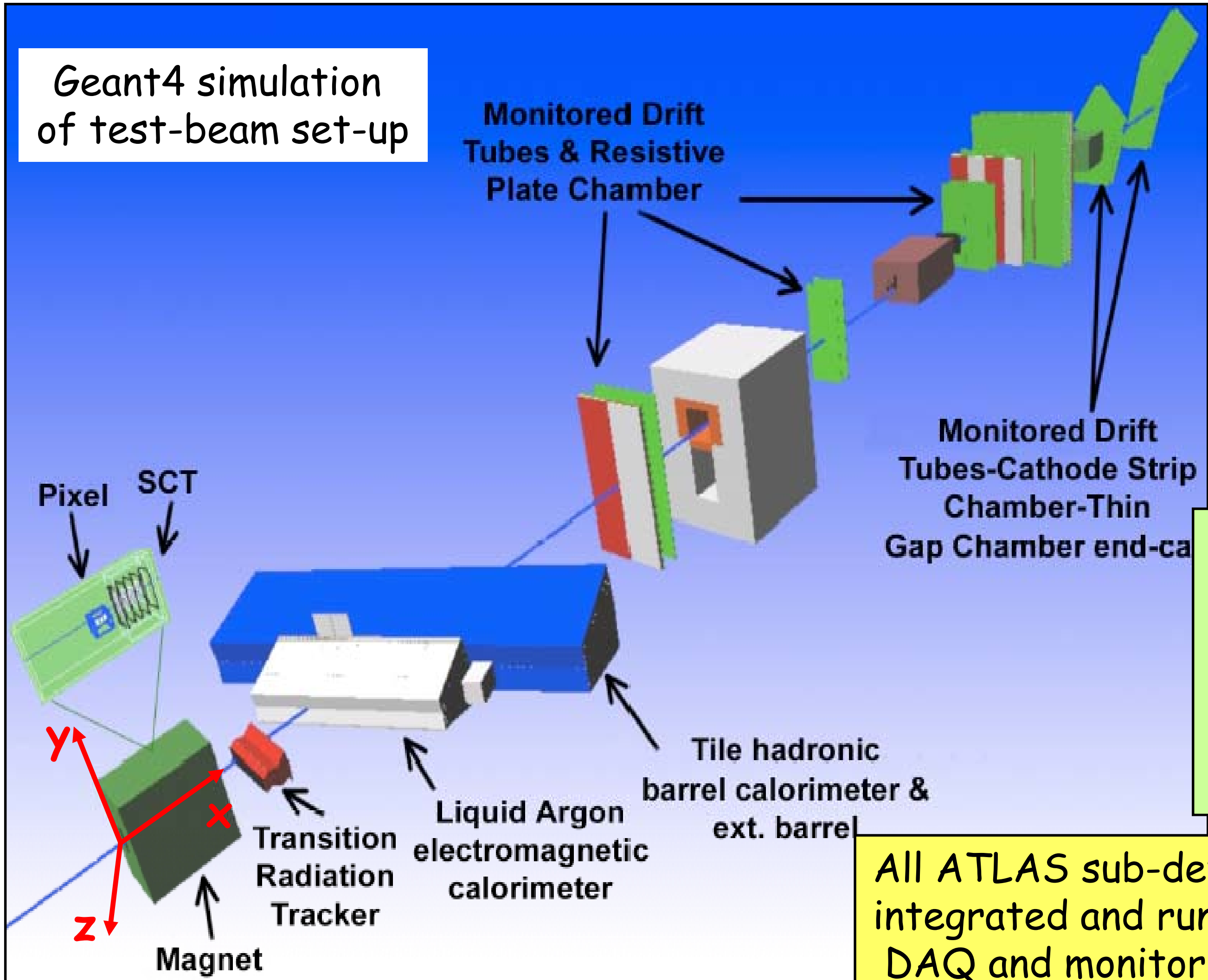
Toward first physics:

- 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



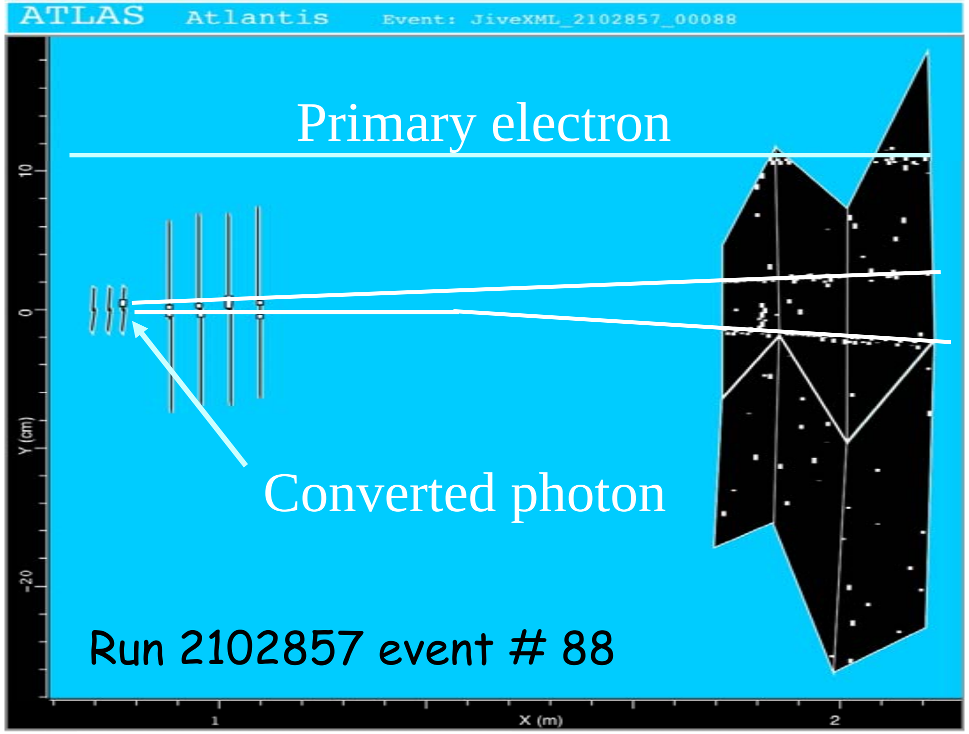
O(1%) of ATLAS coverage

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

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

B-field = $0 \rightarrow 1.4$ T

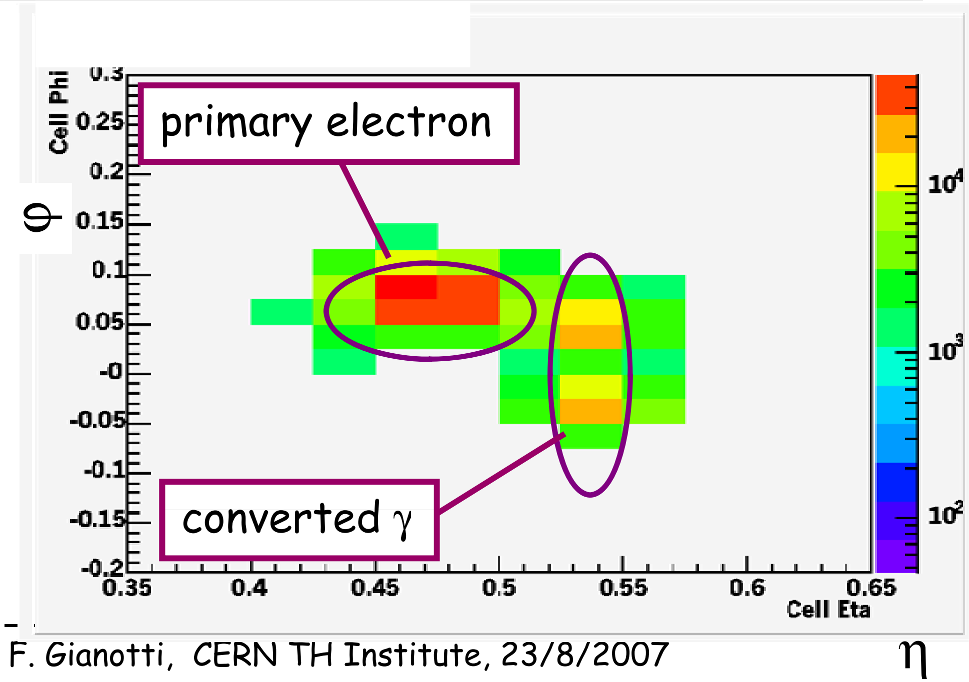
All ATLAS sub-detectors (and LVL1 trigger) integrated and run together with common DAQ and monitoring, "final" electronics, slow-control, etc. Data analyzed with common ATLAS software. Gained lot of global operation experience during ~ 6 month run.

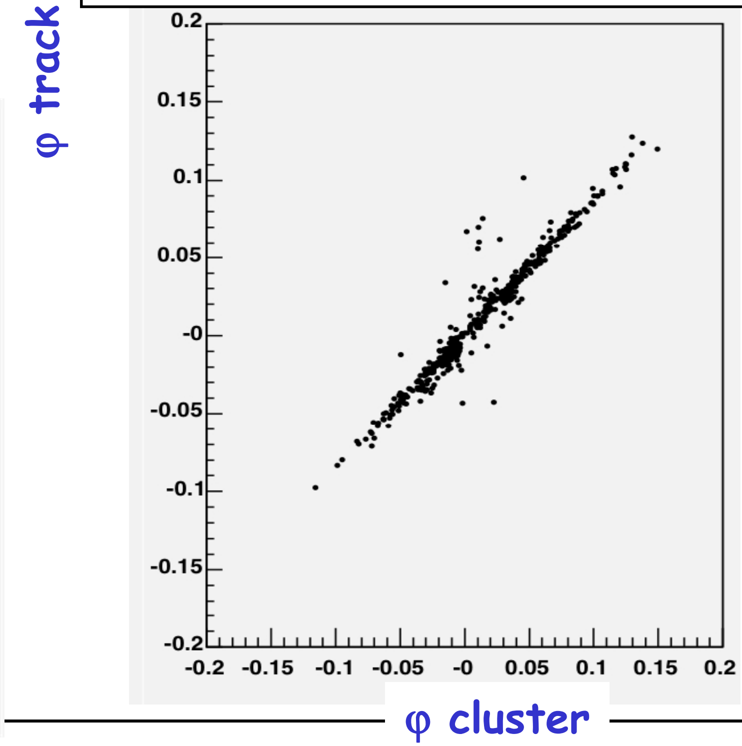


ATLAS preliminary

> 50% of (possible) $H \rightarrow \gamma\gamma$ 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



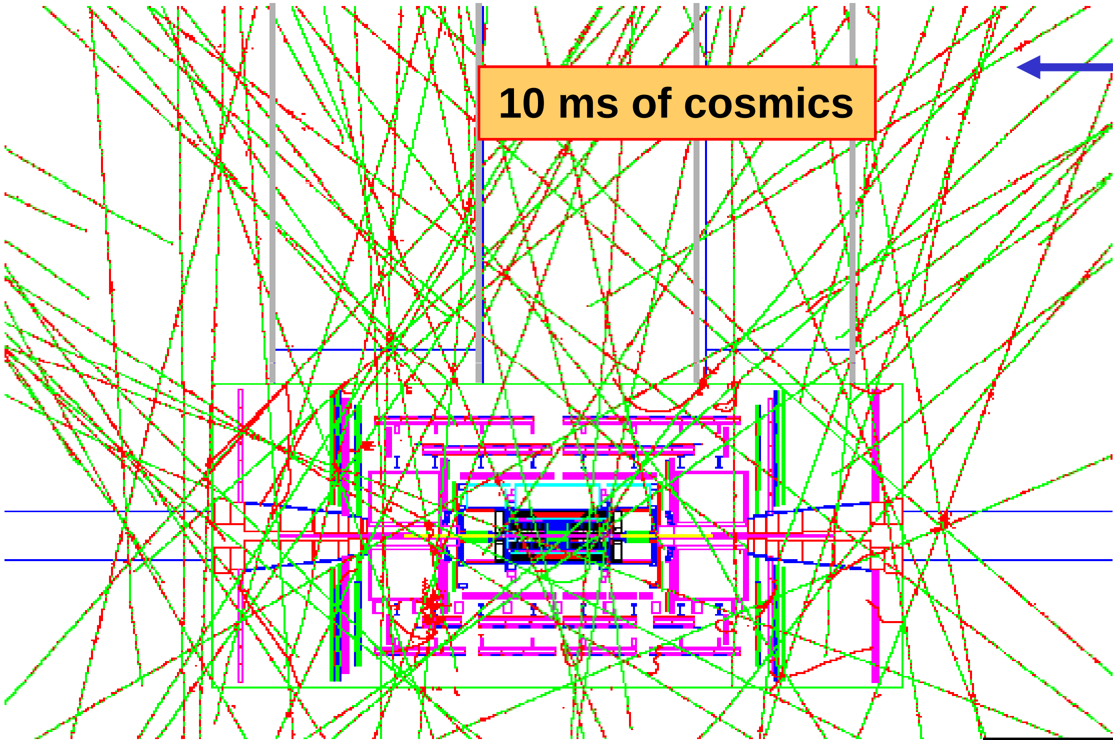


Towards Physics (2) : detector commissioning with cosmics in the underground cavern (the first real data in situ !)

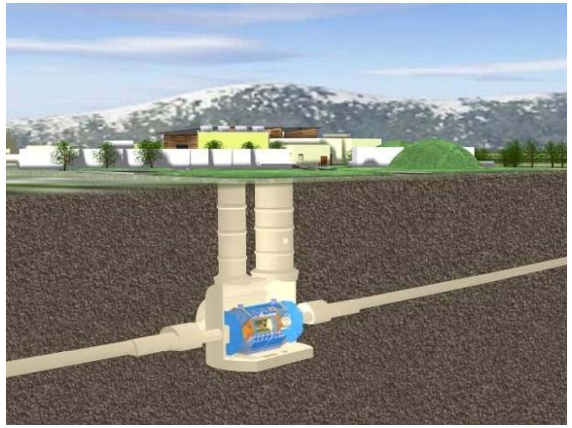
Very useful to:

- 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

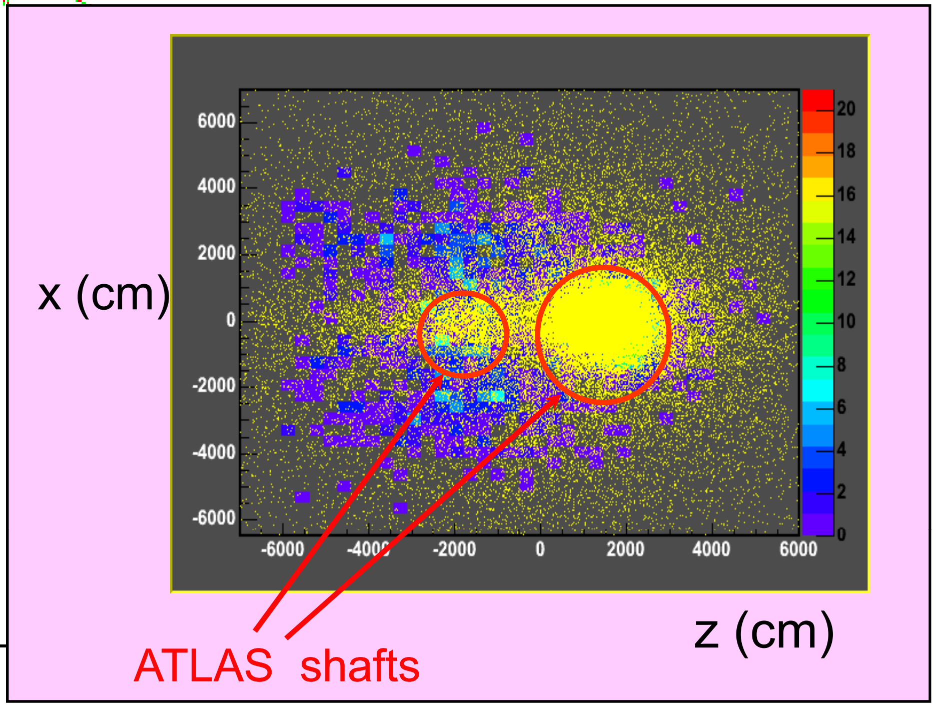


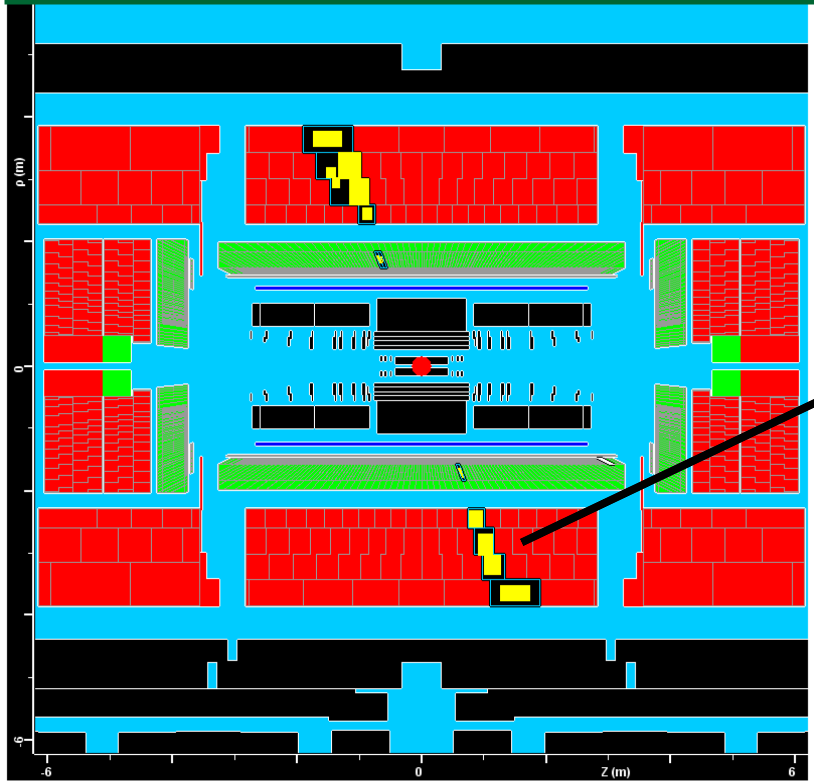
Simulated cosmics flux in the ATLAS cavern



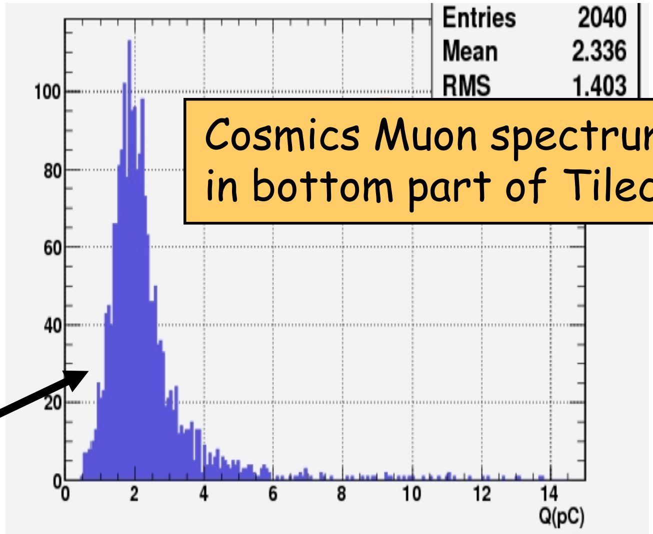
Cosmics data:
muon impact points extrapolated to surface as measured by Muon Trigger chambers (RPC)

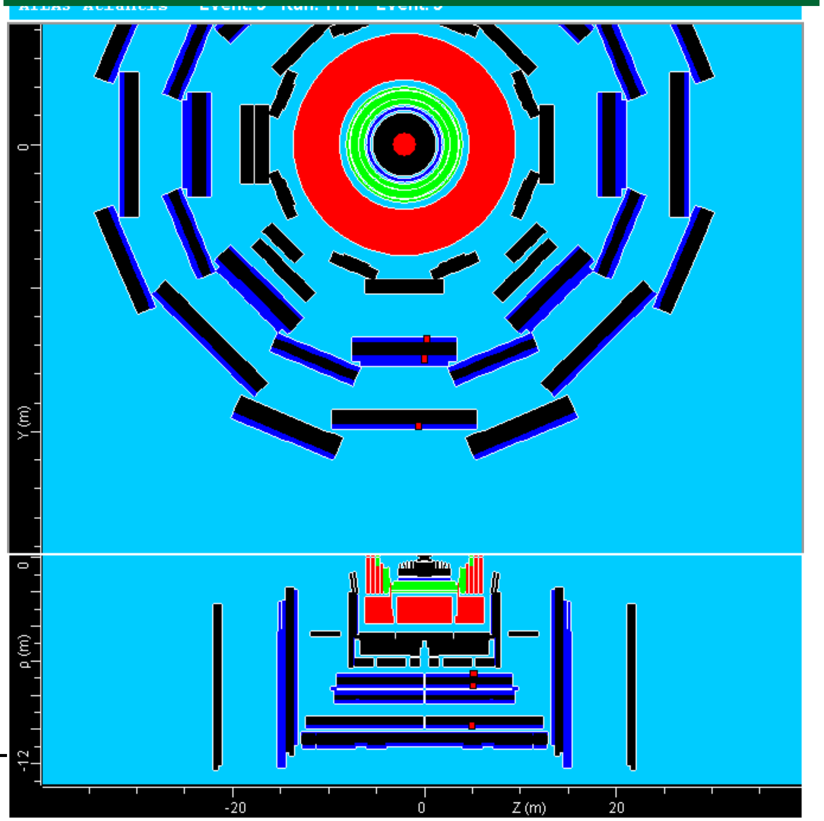
Rate ~100 m below ground: ~ O(10 Hz)





A cosmic muon in LAr EM calorimeter and Tile calorimeter

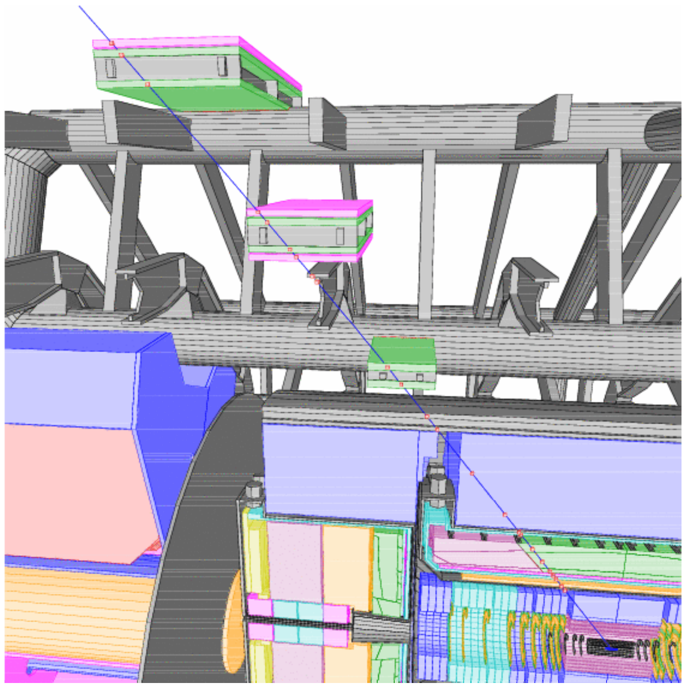




A cosmic muon in Muon Spectrometer

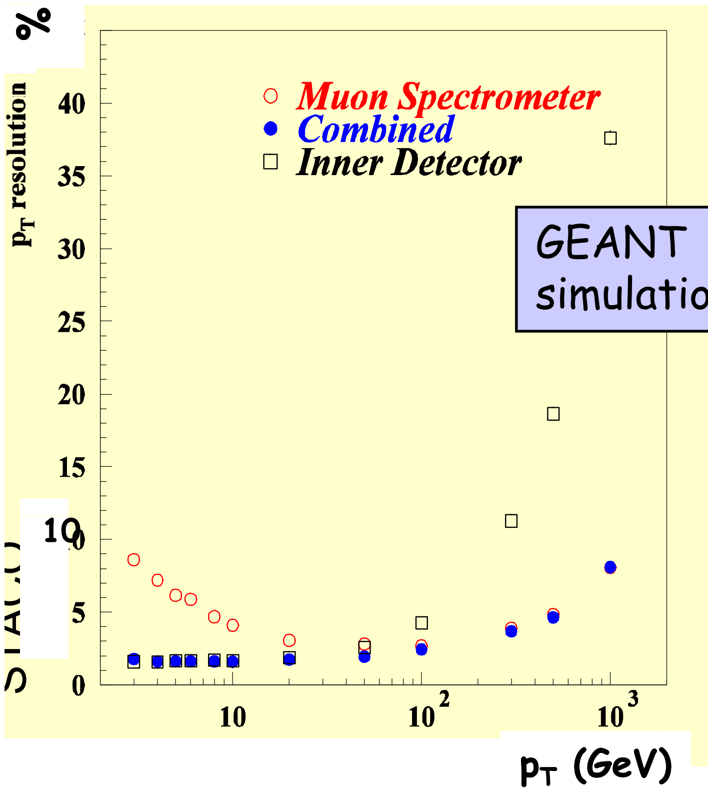
Expected performance: muon measurement

Combining the information from Inner Detector and Muon Spectrometer



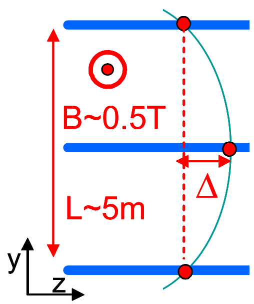
$\sigma/p < 10\%$ for $E_\mu \sim$ TeV needed to observe a possible new resonance $X \to \mu\mu$ as "narrow" peak

ATLAS Muon momentum resolution

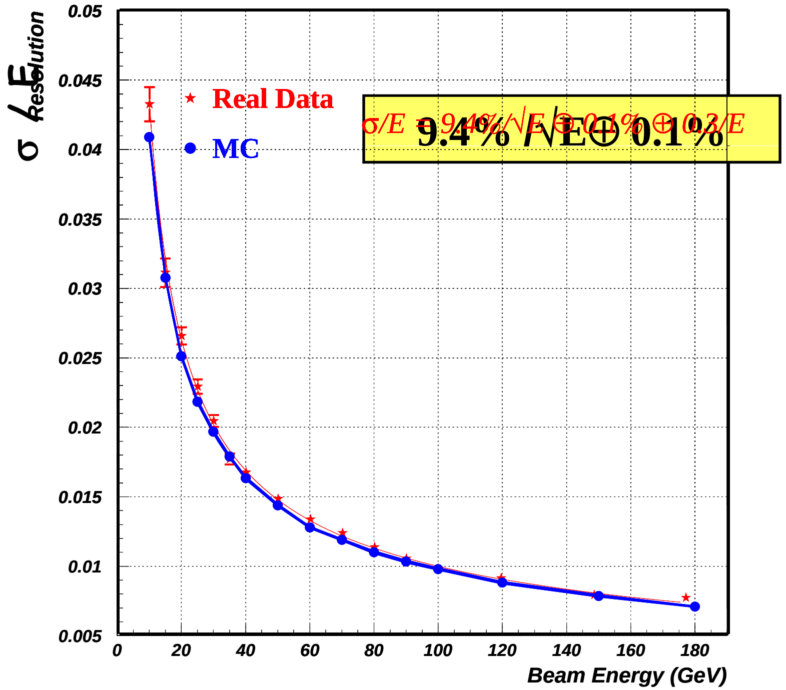


ATLAS Muon Spectrometer:
$E_\mu \sim 1$ TeV $\Rightarrow \Delta \sim 500\ \mu m$

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



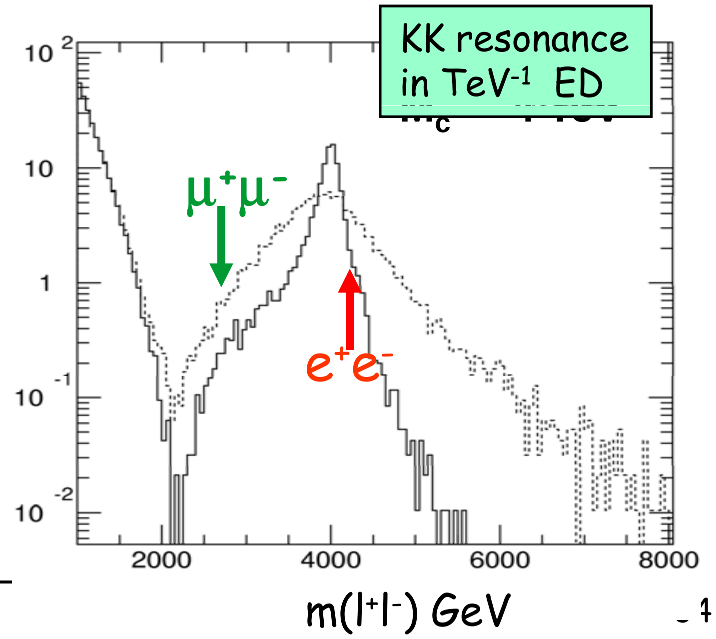
Expected performance: electron measurement



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

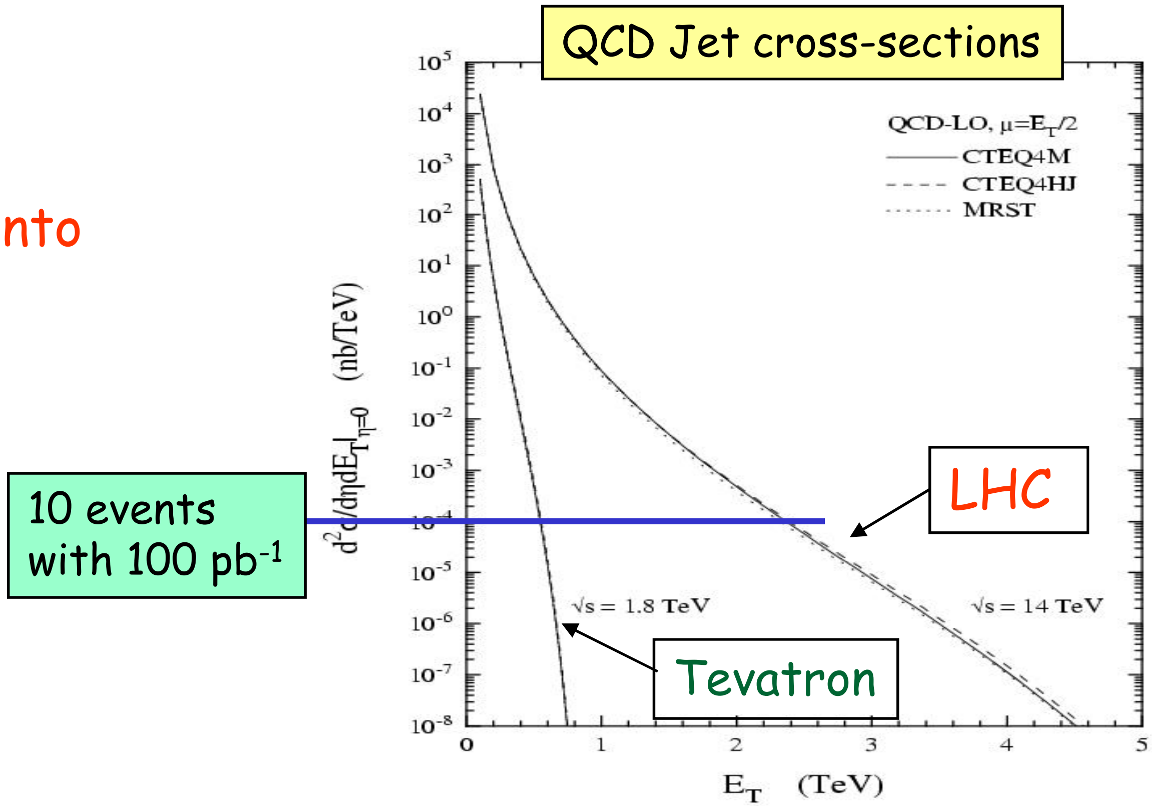
QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

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



First physics with first data
a few examples …

Jump immediately into
a new territory …



With the first physics data in 2008 ….

1 fb^{-1} (100 pb^{-1}) $\equiv$ 6 months (few days) at L= 10^{32} cm^{-2}s^{-1}
with 50% data-taking efficiency
$\rightarrow$ 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
$W \rightarrow \mu\nu$		~ 10^6
~ 10^4 LEP, ~ 10^6 Tevatron		
$Z \rightarrow \mu\mu$		
$\tilde{g}\tilde{g}$	~ 10^5	~ 10^6 LEP, ~ 10^5 Tevatron
$t\bar{t} \rightarrow W b W b \rightarrow \mu\nu + X$	~ 10^4	~ 10^4 Tevatron
QCD jets p_T > 1 TeV	> 10^3	---
m = 1 TeV	~ 50	---

With these data:

- Understand and calibrate detectors in situ using well-known physics samples
  e.g. - $Z \rightarrow ee, \mu\mu$ tracker, ECAL, Muon chambers calibration and alignment, etc.
  - $t\bar{t} \rightarrow bl\nu\, bjj$ jet scale from $W \rightarrow jj$, b-tag performance, etc.

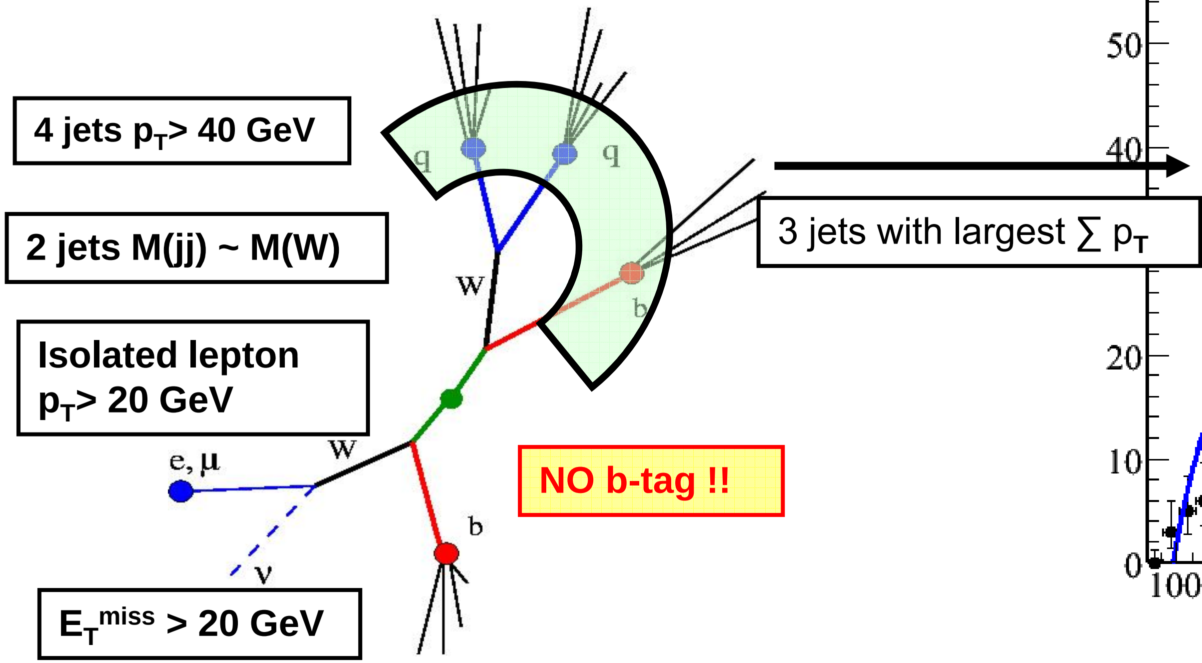
- "Rediscover" and measure SM physics at $\sqrt{s}$ = 14 TeV : W, Z, $t\bar{t}$, QCD jets …
  (also because omnipresent backgrounds to New Physics)

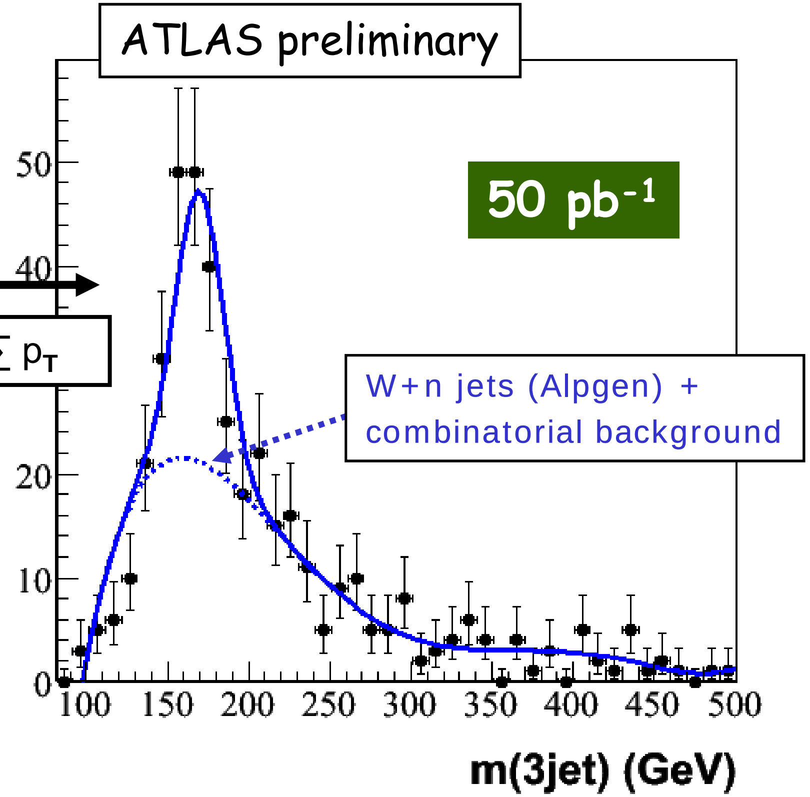
→ prepare the road to discoveries …… it will take time …

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 $tt \rightarrow bW\, bW \rightarrow bl\nu\, bjj$





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:

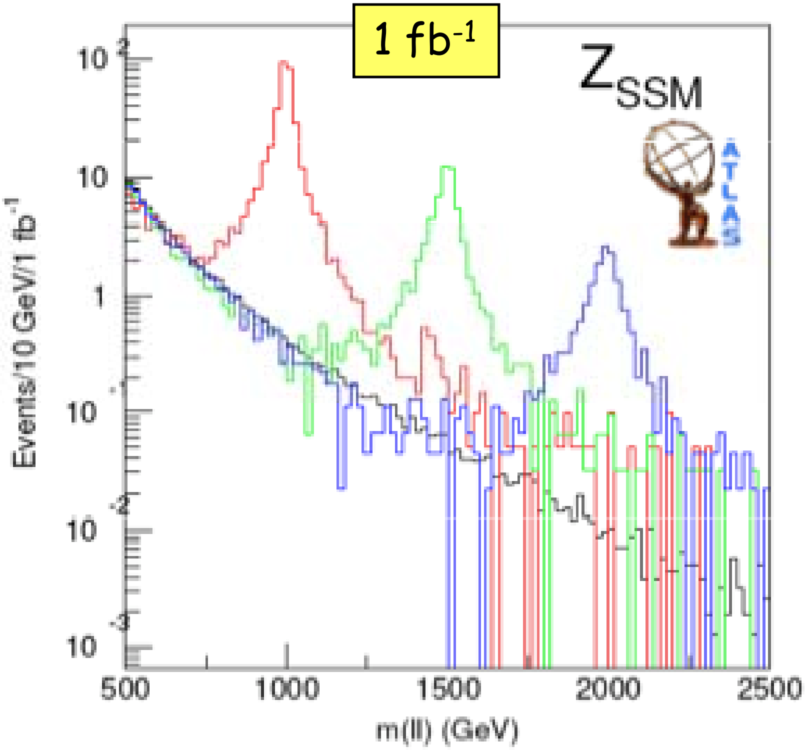
- **understand detector performance for e, μ, jets, b-jets, missing E_T, …**
- **understand / constrain theory and MC generators using e.g. p_T spectra**

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}



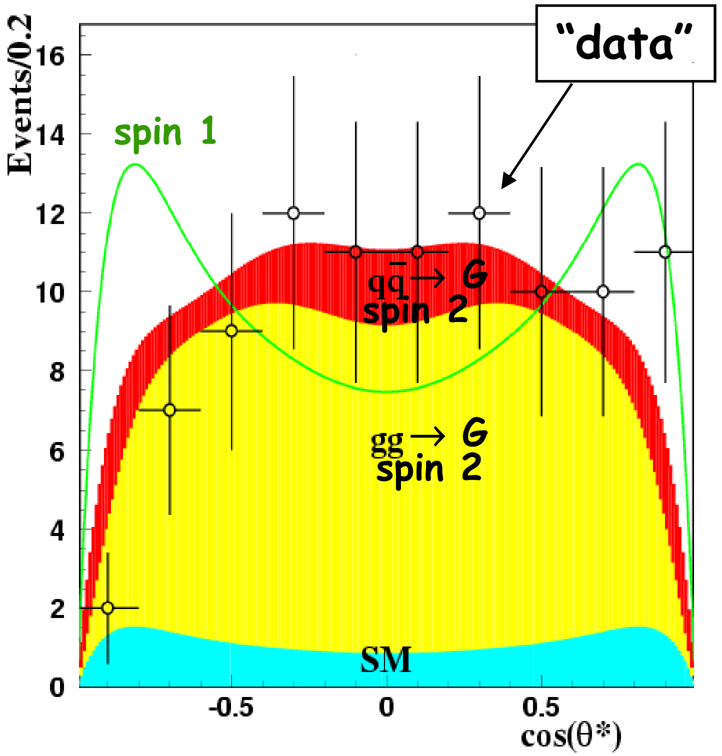
- large enough signal for discovery with ~100 pb^{-1} up to m > 1 TeV
- small well-known SM background (Drell-Yan)
- signal is (narrow) mass peak on top of background

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

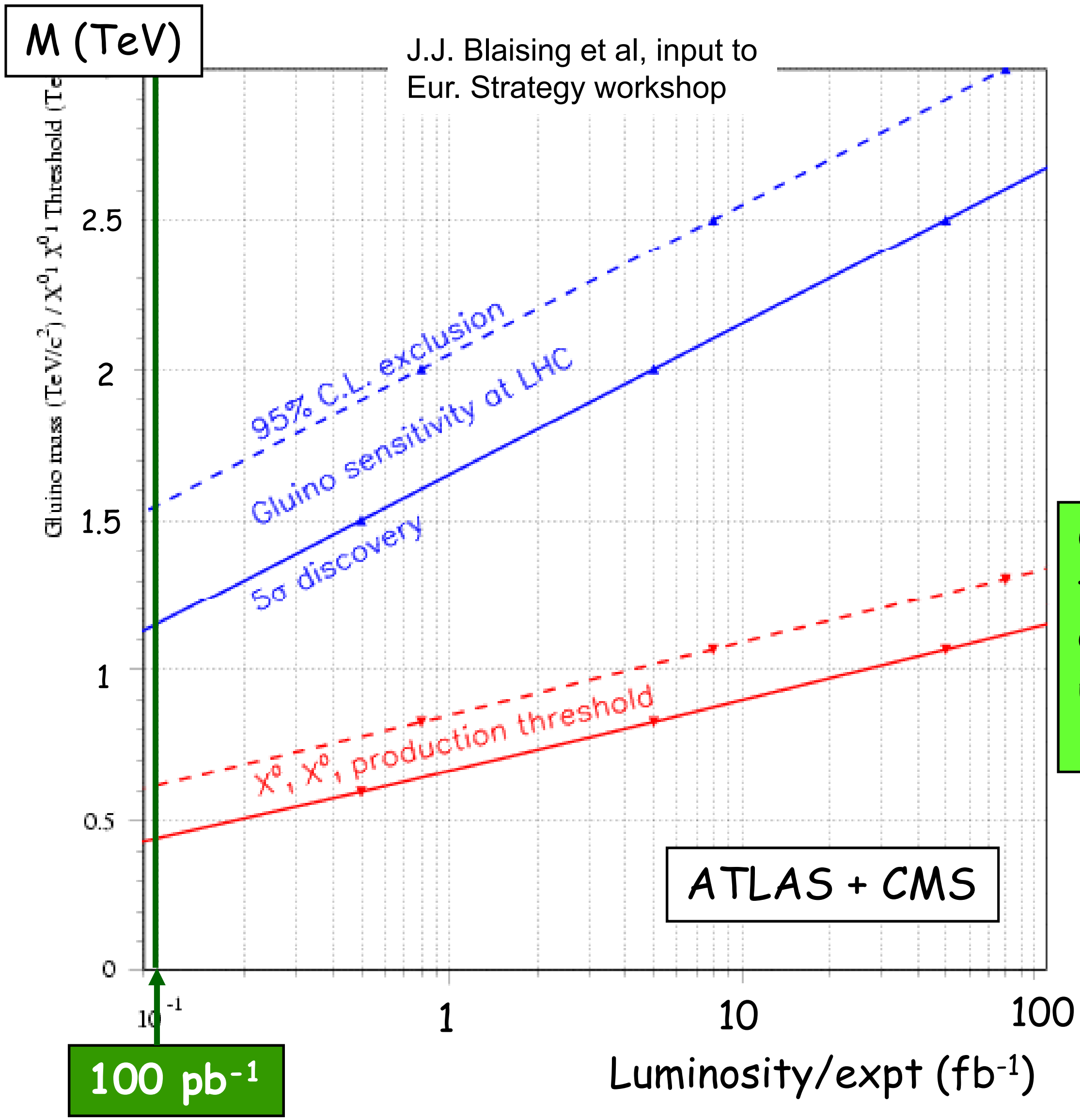


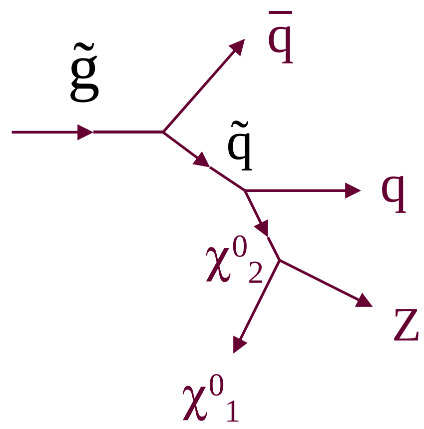
Allanach et al., JHEP 0009 (2000) 019

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)





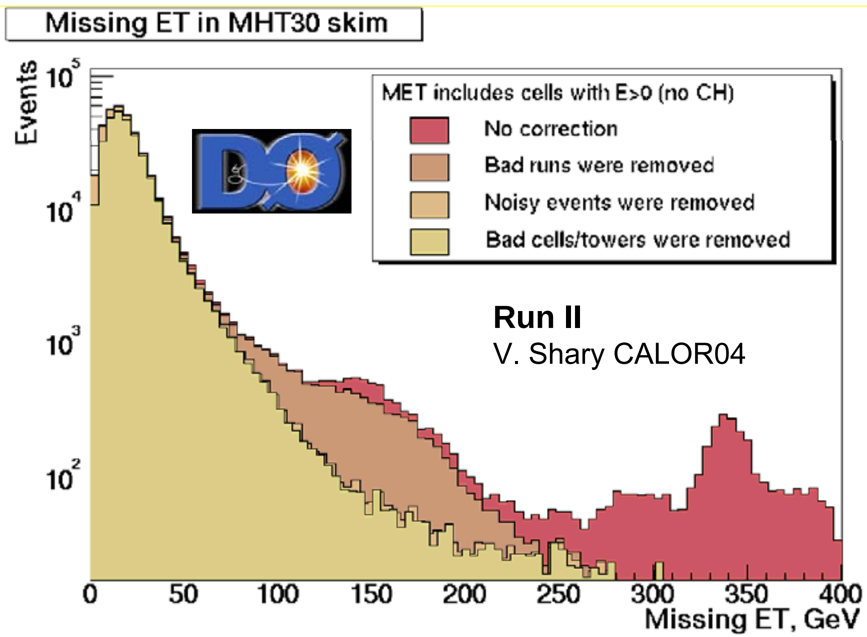
Our field, and planning for future facilities, will benefit a lot from quick determination of scale of New Physics. E.g. with 100 good pb^{-1} LHC could say if SUSY accessible to a ≤1 TeV ILC

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 $Z \to \nu\nu$, $W \to \tau\nu$; tt; 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, …

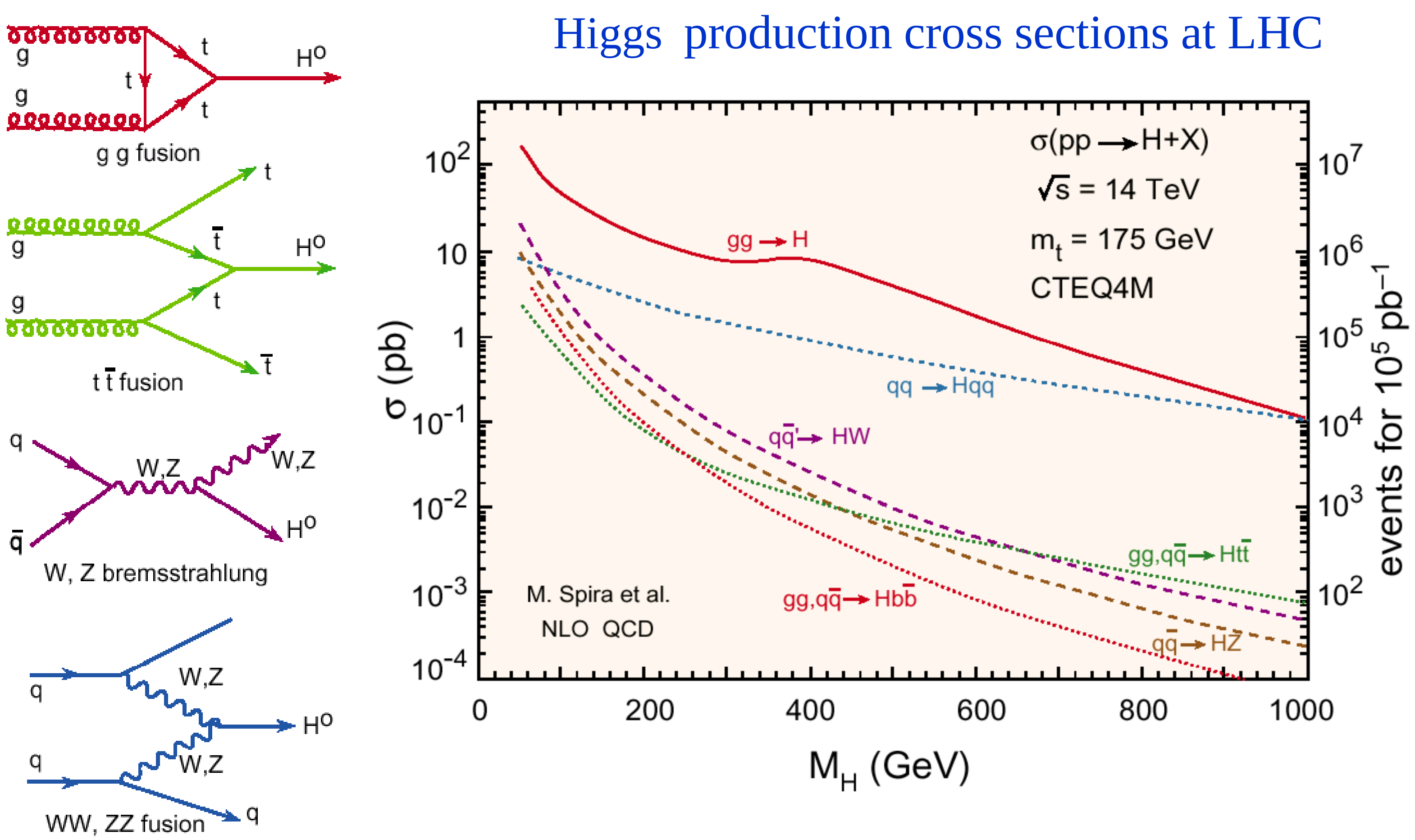


Understanding E_T^{miss} spectrum (and tails from instrumental effects) is one of most crucial and difficult experimental issues for SUSY searches at hadron colliders.
Note: can also use final states with leptons (cleaner …)

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

Background process (examples ….)	Control samples (examples ….)
$Z (\to \nu\nu)$ + jets	$Z (\to ee, \mu\mu)$ + jets
$W (\to \tau\nu)$ + jets	$W (\to e\nu, \mu\nu)$ + jets
$tt \to bl\nu bjj$	$tt \to bl\nu\ bl\nu$
QCD multijets	lower E_T sample

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



m_H < 130 GeV : H → bb, ττ dominate

→ best search channels at the LHC : qqH→qq ττ, H → γγ, ttH → lbbX

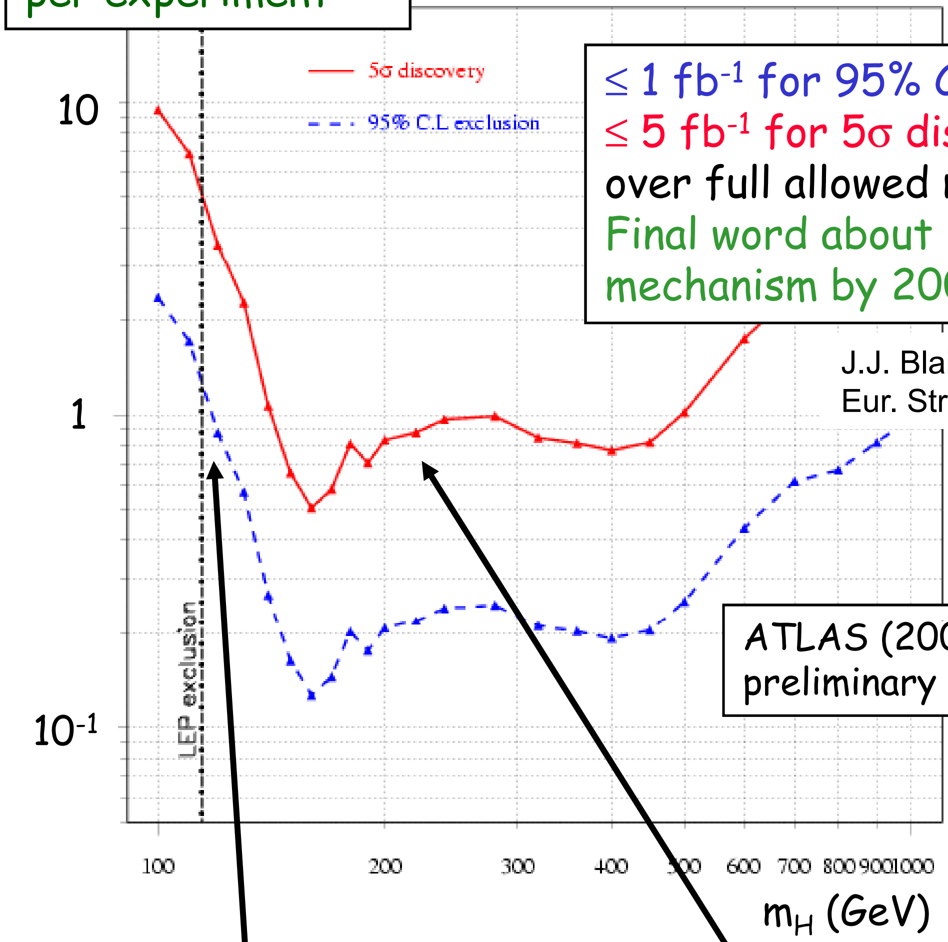
m_H > 130 GeV : H → $WW^{(*)}$, $ZZ^{(*)}$ dominate

→ best search channels at the LHC : H → $ZZ^{(*)}$ → 4l (gold-plated)

H → $WW^{(*)}$ → lν lν

Summary of Higgs discovery potential

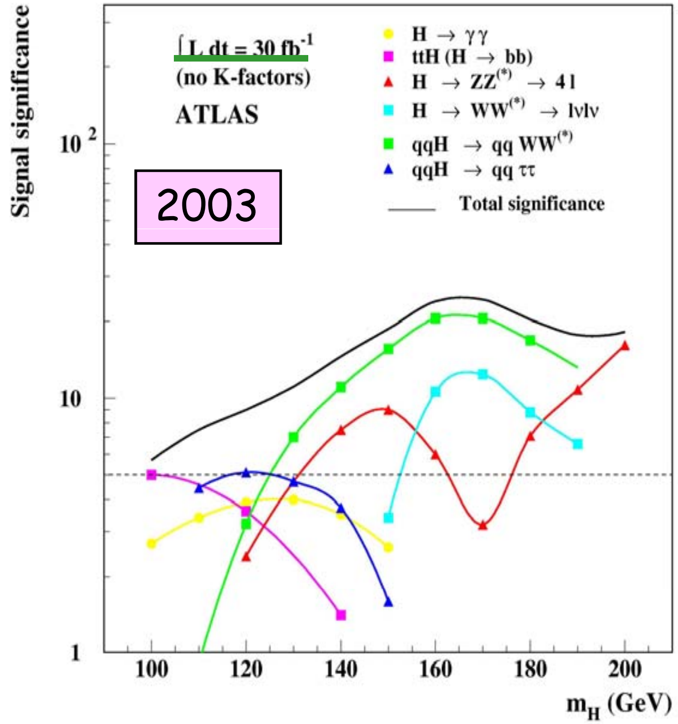
Needed ∫Ldt (fb^{-1})
per experiment



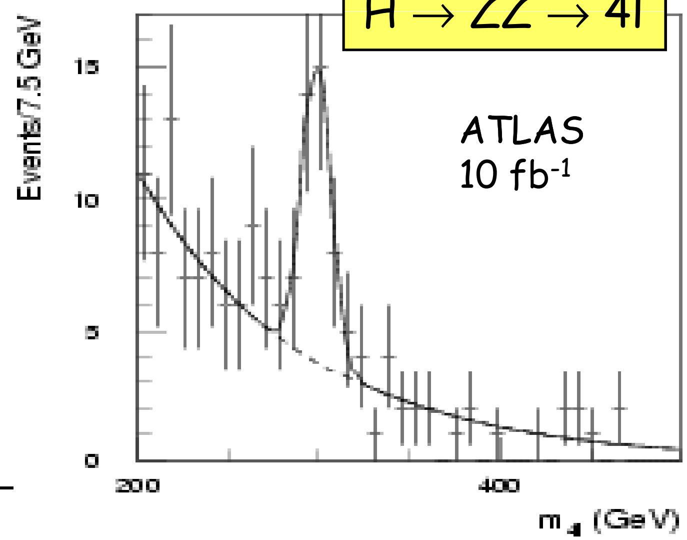
≤ 1 fb^{-1} for 95% C.L. exclusion
≤ 5 fb^{-1} for 5σ discovery
over full allowed mass range
Final word about Higgs mechanism by 2009 ?

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

ATLAS (2003) + CMS preliminary



$H \to ZZ \to 4l$



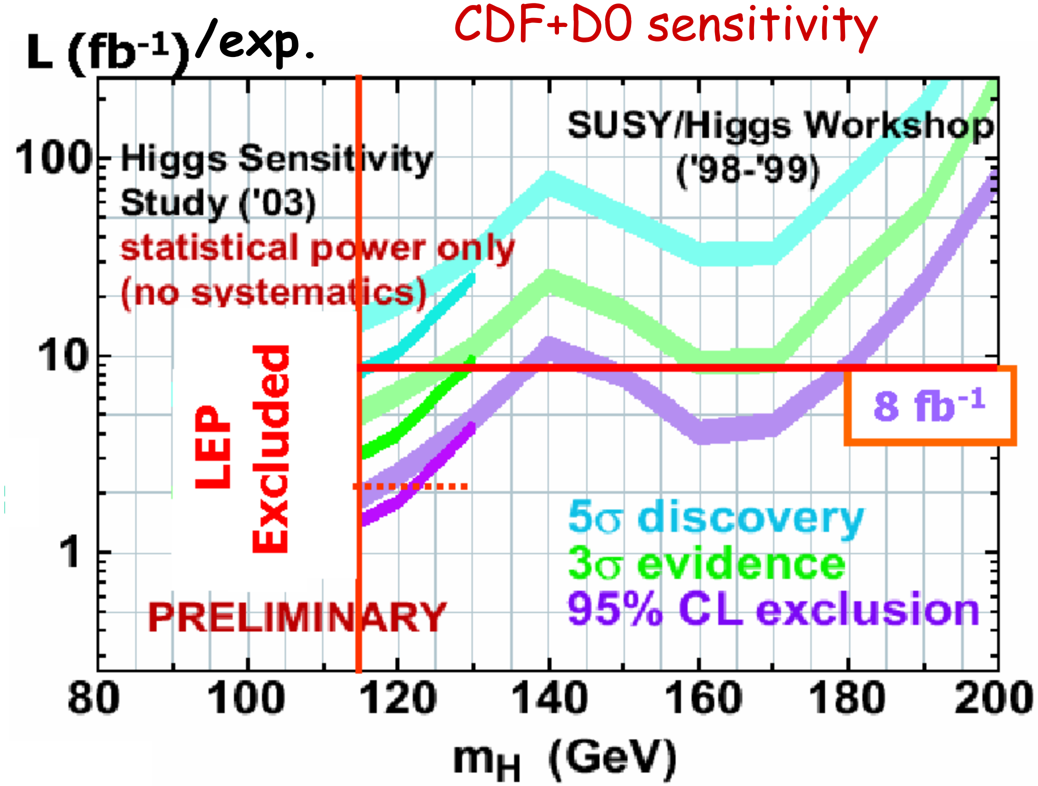
Most difficult region: need to combined many channels with small S/B

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 $\rightarrow$ O(100 pb^{-1}) ?
  10^{32}-10^{33} in 2009 $\rightarrow$ 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

Spare slides

Accelerating cavities

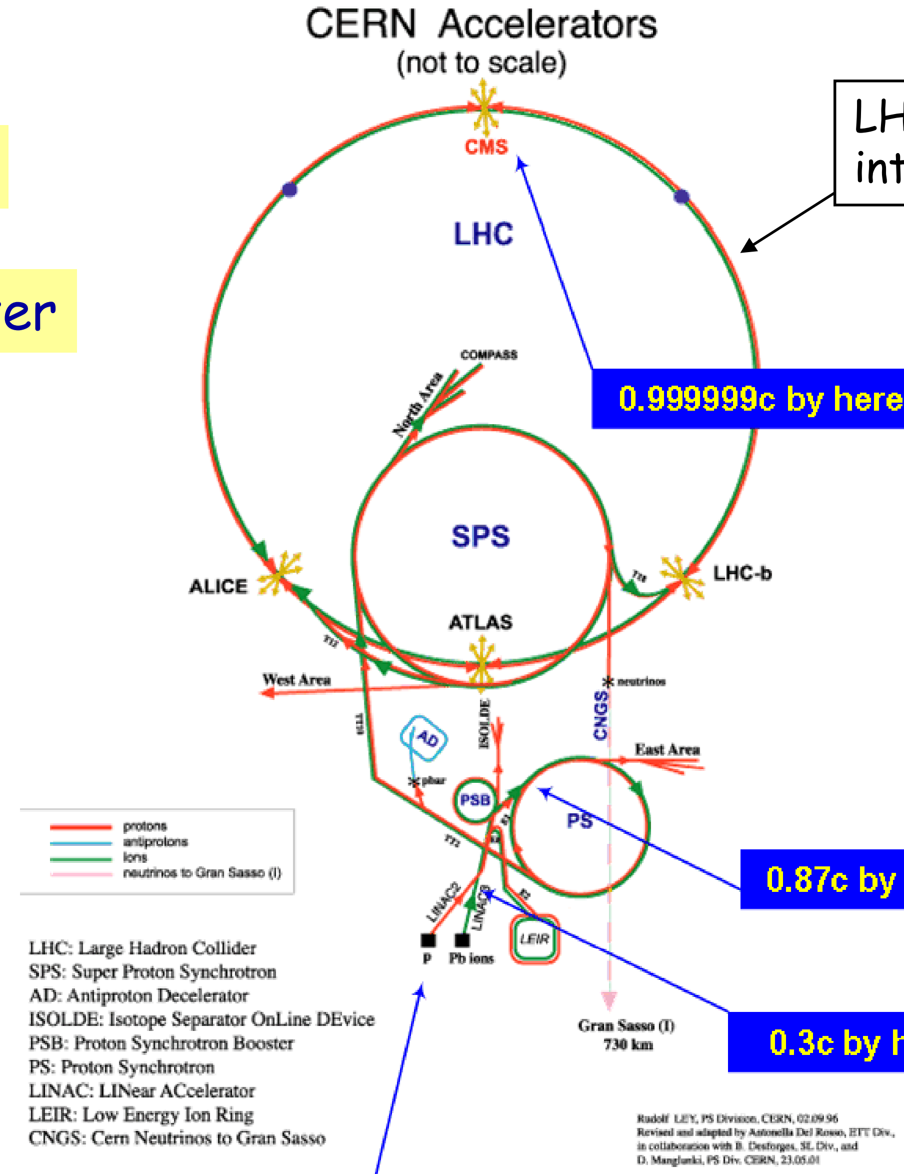
The LHC uses 8 superconducting cavities per beam, delivering 16 MV (an accelerating field of 5 MV/m) at 400 MHz.
The cavities will operate at 4.5 K.

Note : acceleration is not such a big issue in pp colliders (unlike in e^+e^- colliders), due to the $\sim 1/m^4$ behaviour of synchrotron radiation energy losses [$\sim E^4_{beam}/Rm^4$]

	LHC at 7 TeV	LEP at 100 GeV
Synchrotron radiation loss Peak accelerating voltage	6.7 keV/turn 16 MV/beam	3 GeV/turn 3600 MV/beam

The full accelerator complex

Linac → Booster → PS → SPS → LHC



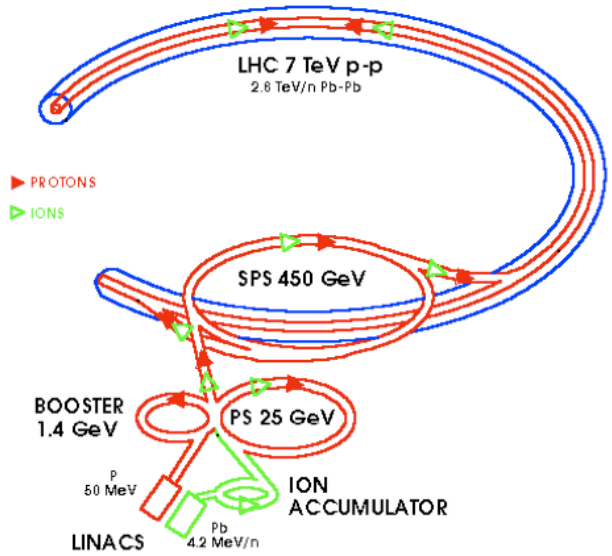
LHC ring is divided into 8 sectors

0.999999c by here

0.87c by here

0.3c by here

Start the protons out here



50 years of CERN history still alive and operational

Inner Triplet failure

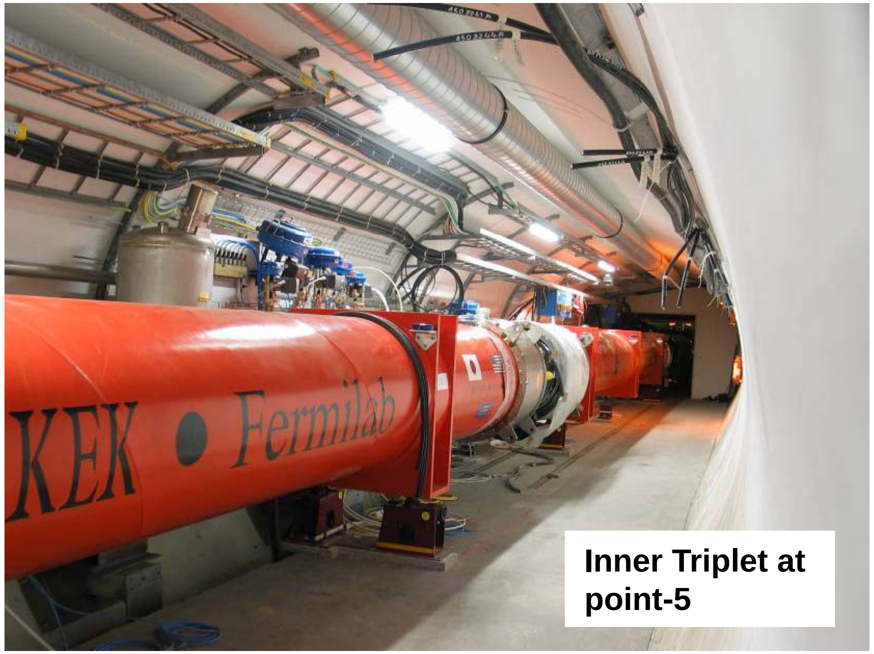
During pressure tests two failures were encountered

- One concerned a corrugated heat exchanger tube (back in November 2006)

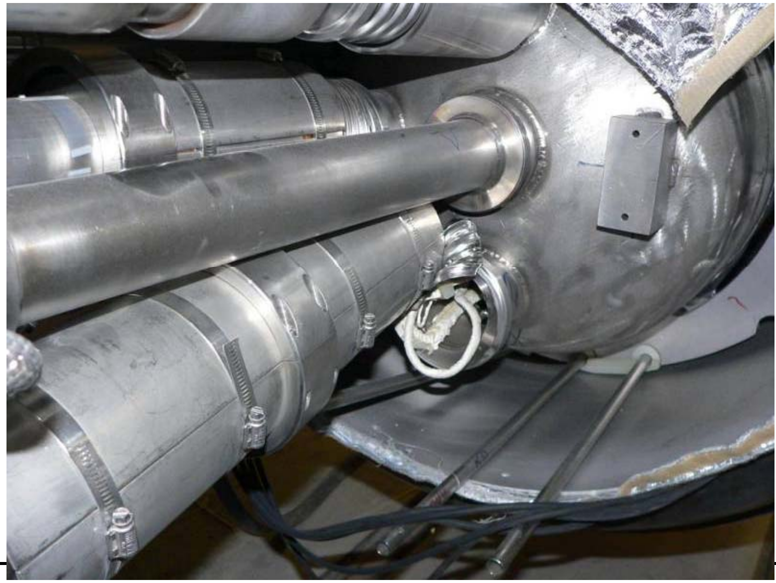
  New tubes were produced and the repair proceeds *in situ*

- The second failure in spring was a problem of the cold mass supports in a system pressure test of the full triplet installed at point-5

Detailed information about the Inner Triplet story is available on the FNAL Web

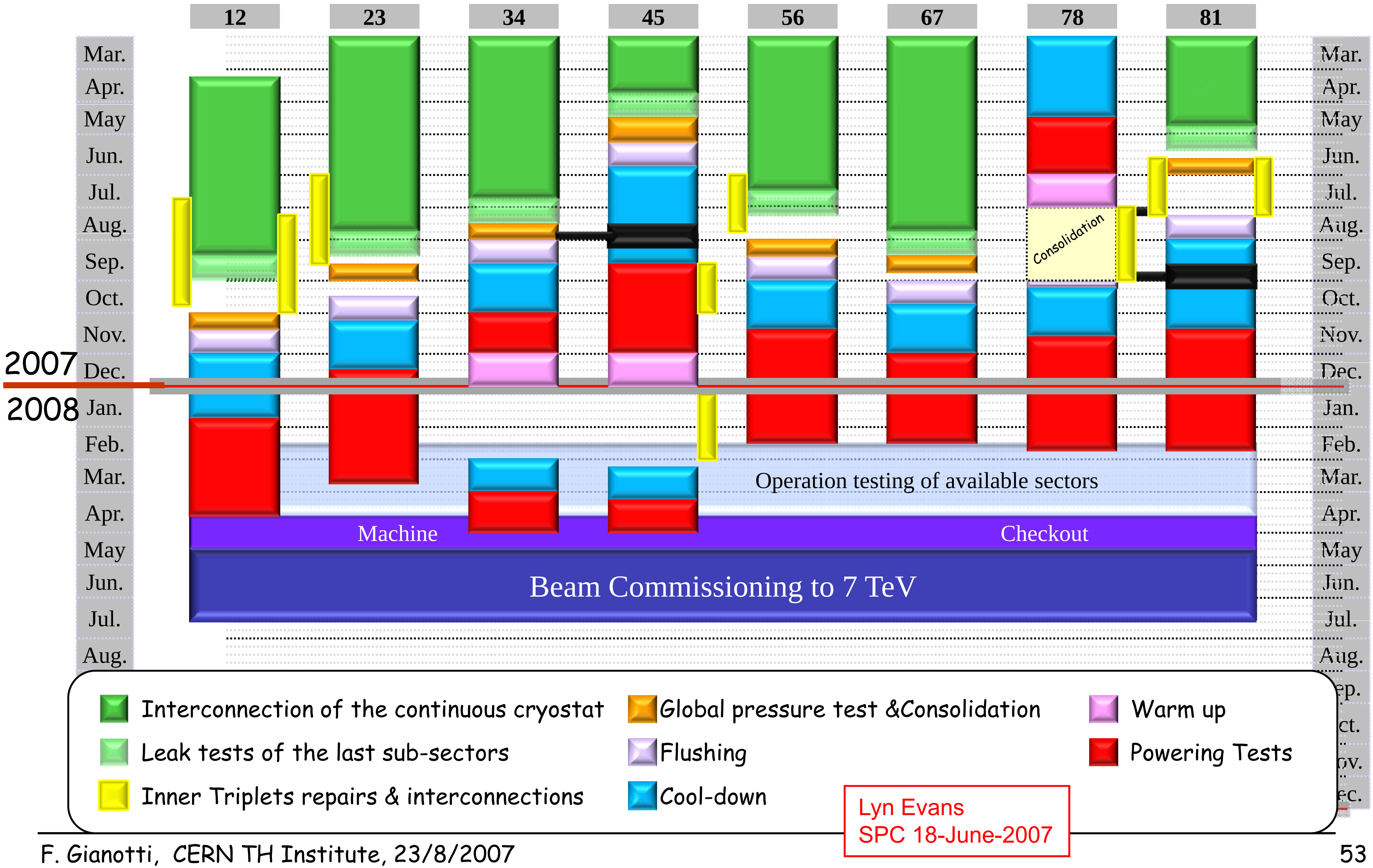


Inner Triplet at point-5



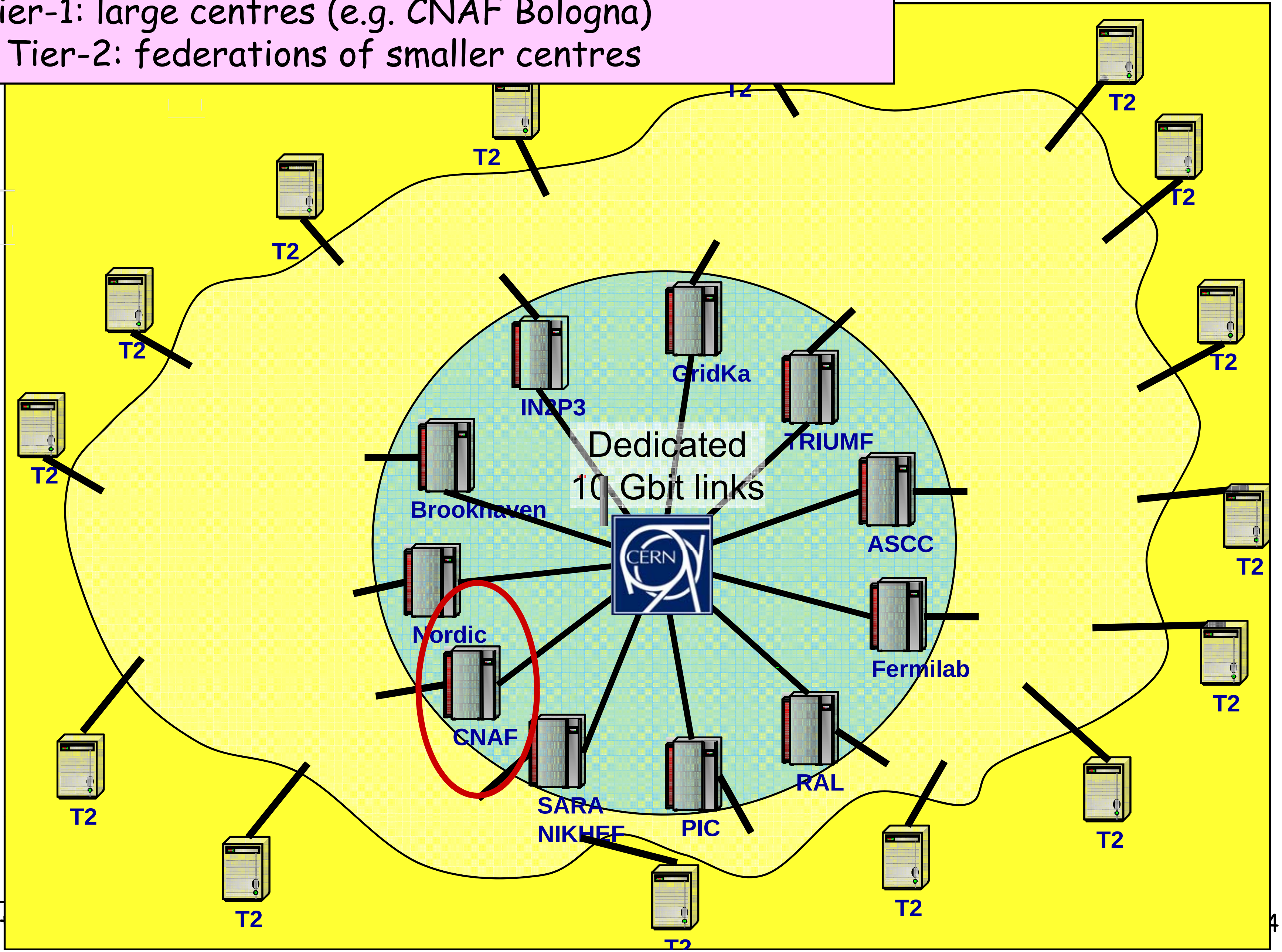
Damaged connections after pressure test failure

LHC General co-ordination schedule, EDMS 102509, 12 June 2007

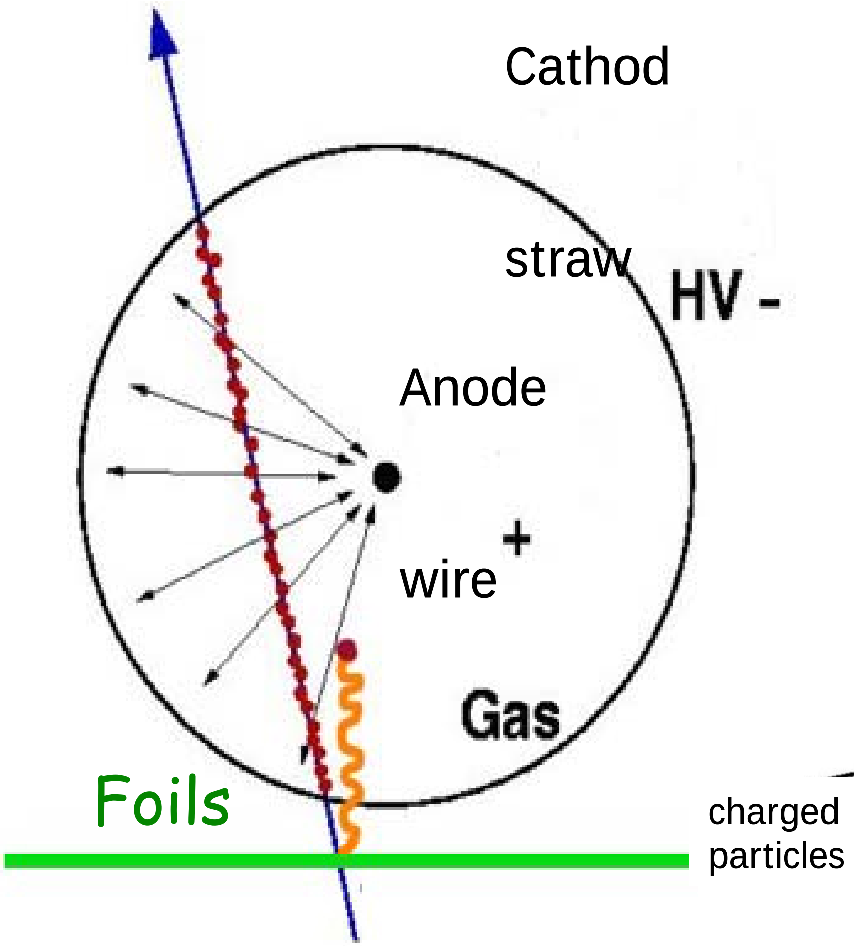


LCG computing centres: hierarchical structure by Tiers:

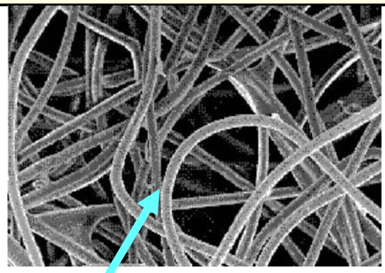
- 1 Tier-0 : the biggest/central centre: CERN
- 11 Tier-1: large centres (e.g. CNAF Bologna)
- ~40 Tier-2: federations of smaller centres



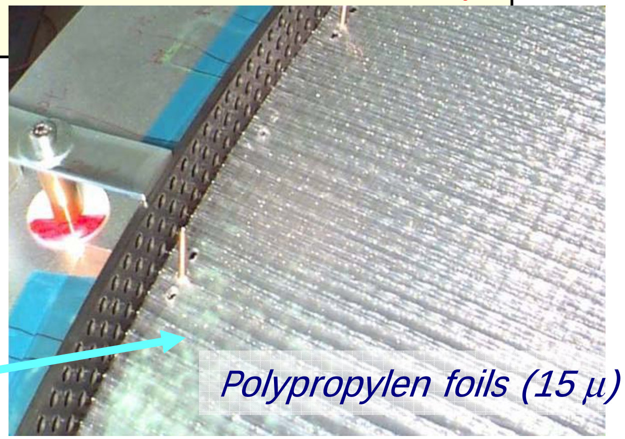
The TRT (Transition Radiation Tracker)

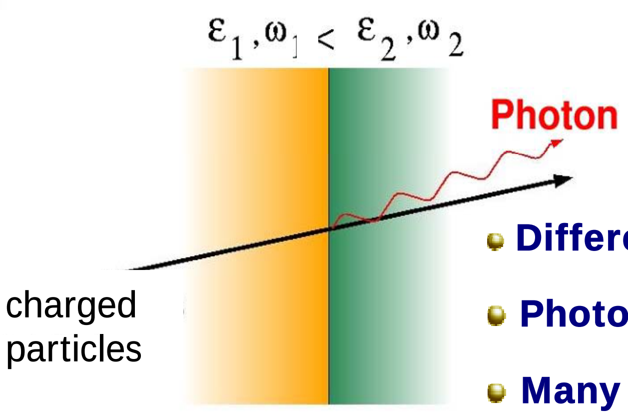


radiator



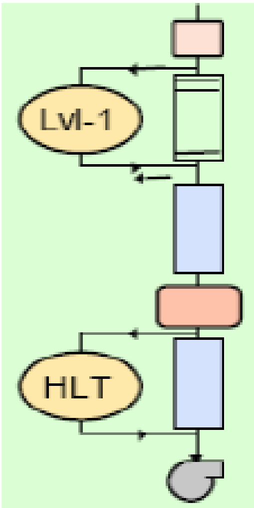
Barrel end-cap





- **Different dielectric constants**
- **Photon energy ~ ($\varepsilon_1 - \varepsilon_2$)**
- **Many transition to enhance probabil**
- **Photon energy (x-rays): 10-30keV**
- **Xe gas as good X-rays absorber**

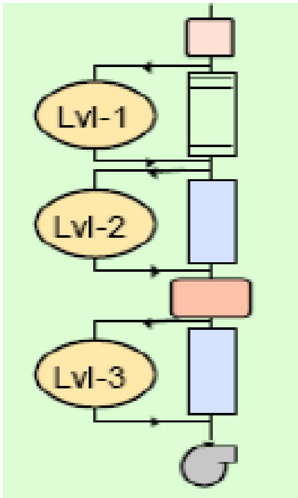
ATLAS/CMS trigger



Local trigger

Specialized processors

Online Farm



CMS

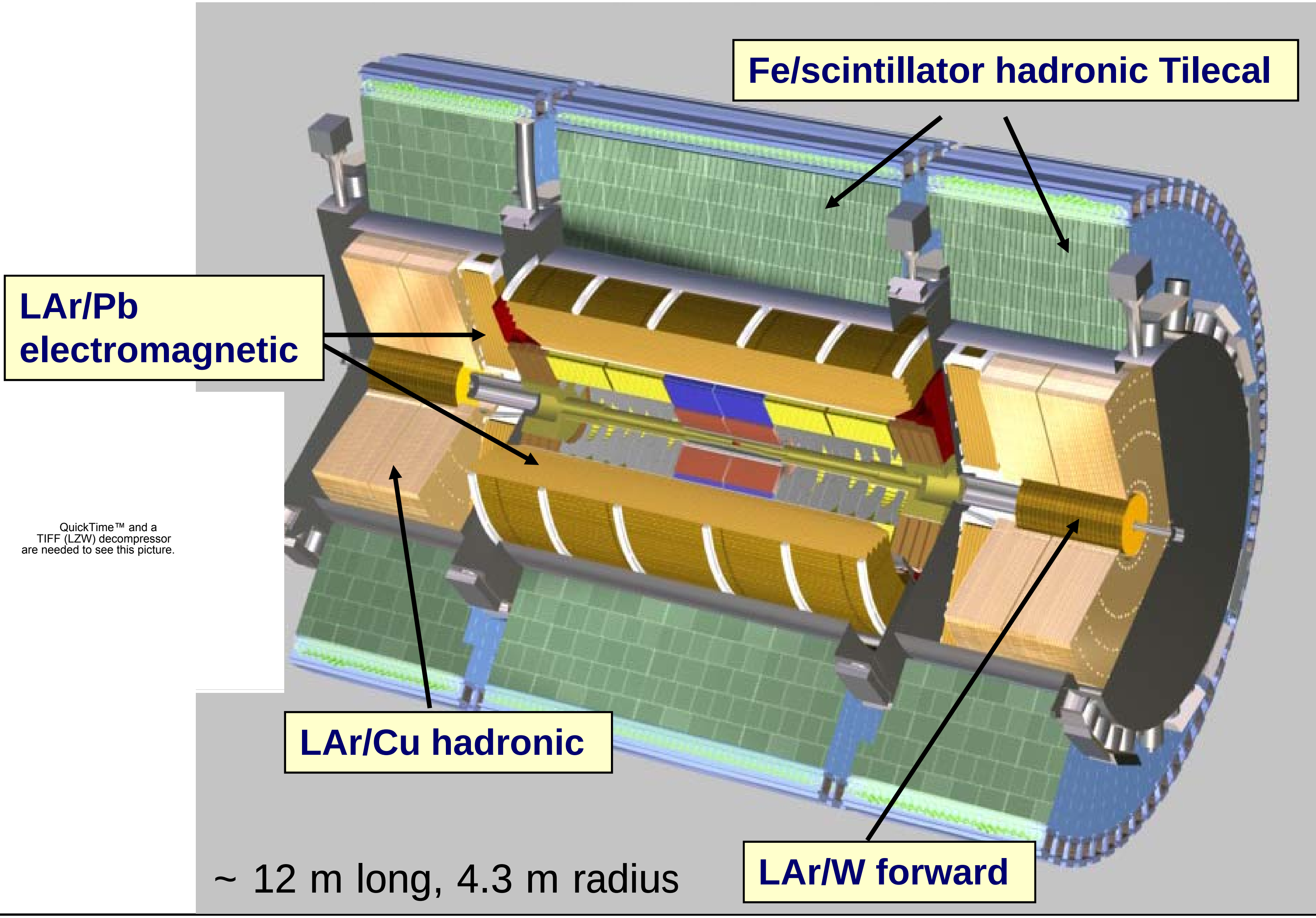
- CMS has a two-level DAQ/Trigger architecture:
  - Low level hardware trigger (L1)
  - Large online farm (HLT) doing event building and traditional L2, L3,..., LN triggering.
    - Full event information available
    - Highly flexible
    - Can be reprogrammed for specialized HI Triggering
      - Jet trigger including BG subtraction,
      - Dimuon trigger (Υ, J/ψ)

ATLAS

- ATLAS has a three-level DAQ/Trigger architecture:
  - Low level hardware trigger (L1)
  - Specialized Processors (L2)
    - ROI triggers
  - Large event filter farm (L3)
    - Evaluates ROIs for trigger decision
  - Trigger options for HI currently under evaluation

	ATLAS ≡ A Toroidal LHC ApparatuS	CMS ≡ Compact Muon Solenoid
MAGNET (S)	Air-core toroids + solenoid in inner cavity 4 magnets Calorimeters in field-free region	Solenoid Only 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5\text{x}10^{-4}\ p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\text{x}10^{-4}\ p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeV standalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV only combining with tracker

Calorimeters

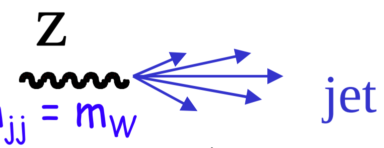


Lepton energy scale

- mainly from $Z \to ll$ events
- ~ 1 ‰ uncertainty achieved by CDF, D0 (dominated by statistics of control samples)
- goal : 0.2 ‰ , to measure m_W to ~ 15 MeV
- systematics dominated by detector: knowledge of tracker material to 1%, overall alignment to < 1μm, B-field to better than 0.1%, etc.

Jet energy scale

- mainly from $Z (\to ll)$ + 1 jet asking p_T (jet) = p_T (Z)
  and from $W \to jj$ in $tt \to bW\, bW \to bl\nu\, bjj$ events asking $m_{jj} = m_W$



- ~ 3 % uncertainty achieved by CDF, D0 (not enough tt statistics at Tevatron)
- goal : ~ 1 % , to measure m_{top} to ~ 1 GeV, SUSY, …
- systematics dominated by physics : FSR, underlying event, etc.

Particle identification:

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

Absolute luminosity to <5% (W/Z/tt cross-section measurements, new physics through σxBR measurements, ….)

Examples of open questions and mysteries that the LHC will address

What is the origin of the particle masses ? **ATLAS, CMS**

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

What is the origin of the Universe matter-antimatter asymmetry ? **LHCb** +ATLAS, CMS

What were the constituents of the Universe primordial plasma ~10 μs after the Big Bang ? **ALICE** +ATLAS, CMS

What happened in the first instants of the Universe life (10^{-10} s after the Big Bang) ? **ATLAS, CMS**

The LHC will help solve these and other mysteries … and .. determine the future course of high-energy physics

In more detail, the main LHC goals are:

Search for the Standard Model Higgs boson over $\sim 115 < m_H < 1000$ GeV.

Explore the highly-motivated TeV-scale, search for physics beyond the SM (Supersymmetry, Extra-dimensions, q/l compositness, leptoquarks, W'/Z', heavy q/l, etc.)

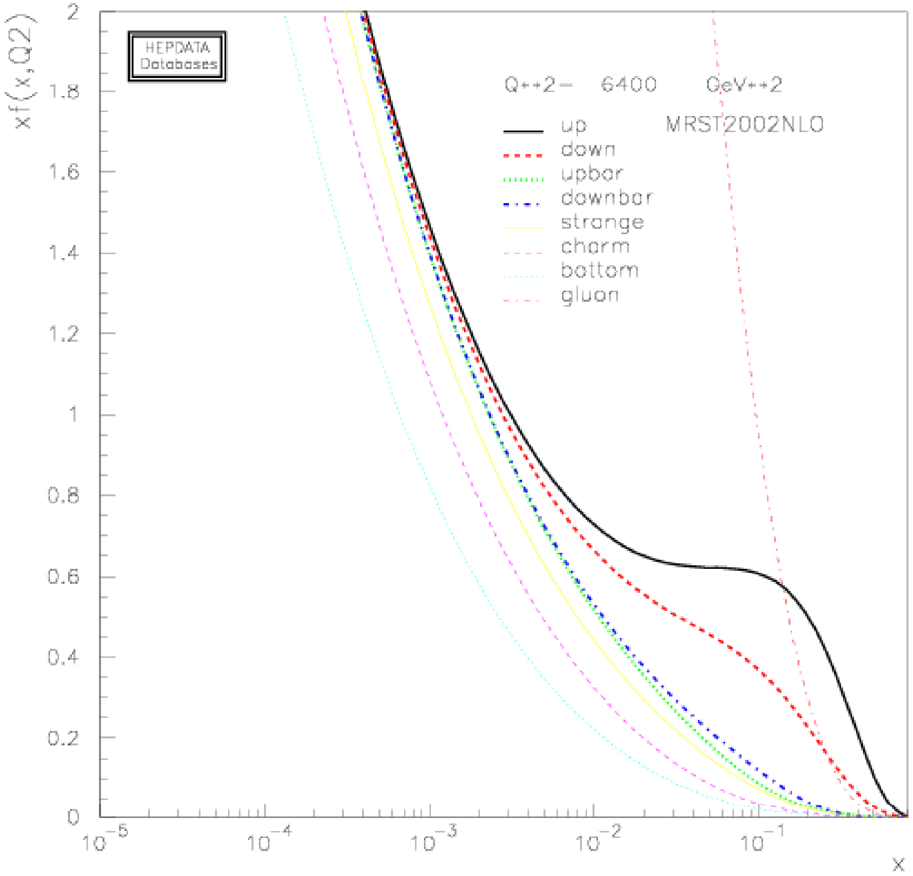
Precise measurements :

-- W mass
-- top mass, couplings and decay properties
-- Higgs mass, spin, couplings (if Higgs found)
-- B-physics (mainly LHCb): CP violation, rare decays, B^0 oscillations
-- QCD jet cross-section and α_s
-- etc. ….

Study phase transition at high density from hadronic matter to quark-gluon plasma (mainly ALICE).

Etc. etc. …..

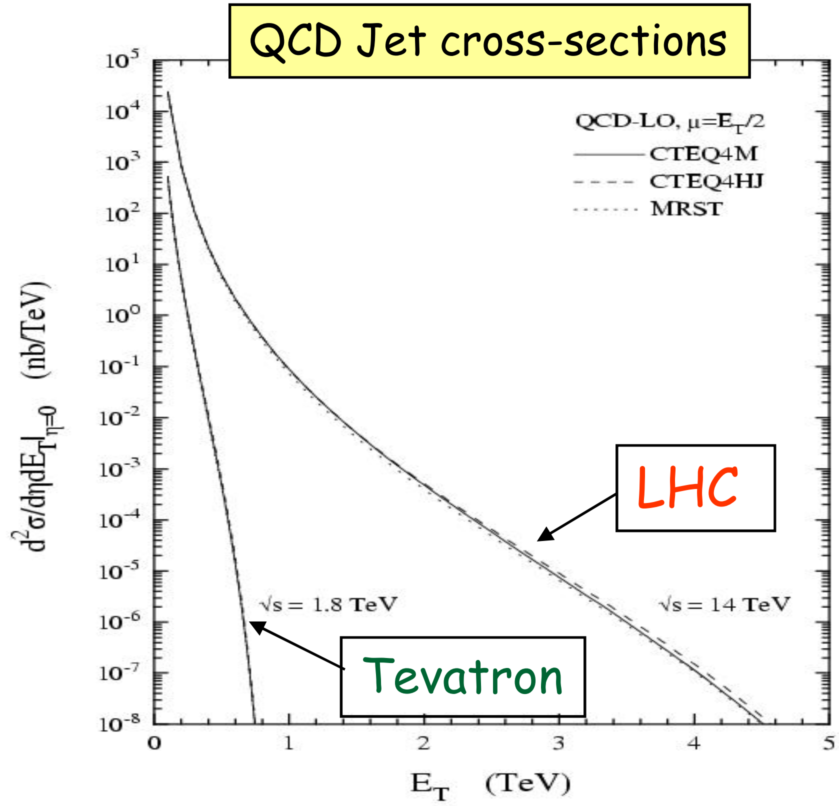
Here : focus on high-p_T physics (ATLAS and CMS)



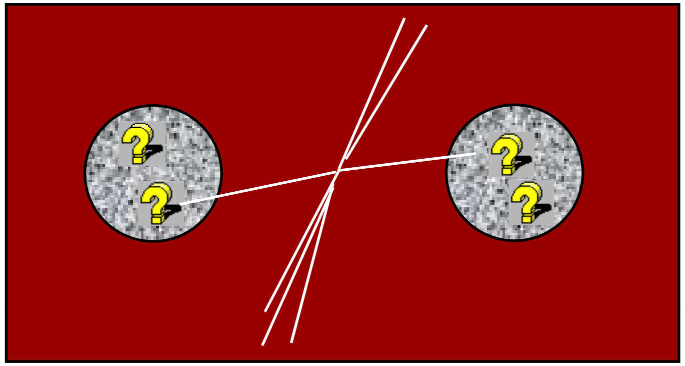
xf(x,Q2)
HEPDATA Databases
Q**2= 6400 GeV**2
MRST2002NLO
up
down
upbar
downbar
strange
charm
bottom
gluon
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x

Jump immediately into a new territory ..

- Explore E_T (jet) > 500 GeV after few weeks at 10^{31} $cm^{-2}s^{-1}$
- Expect >10^3 events with E_T(jet) > 1 TeV with 100 pb^{-1} (end 2008 ?)
- Going fast beyond the Tevatron reach
- Early sensitivity to quark compositeness: Λ ~ 5 (8)TeV with 100 (1000) pb^{-1}



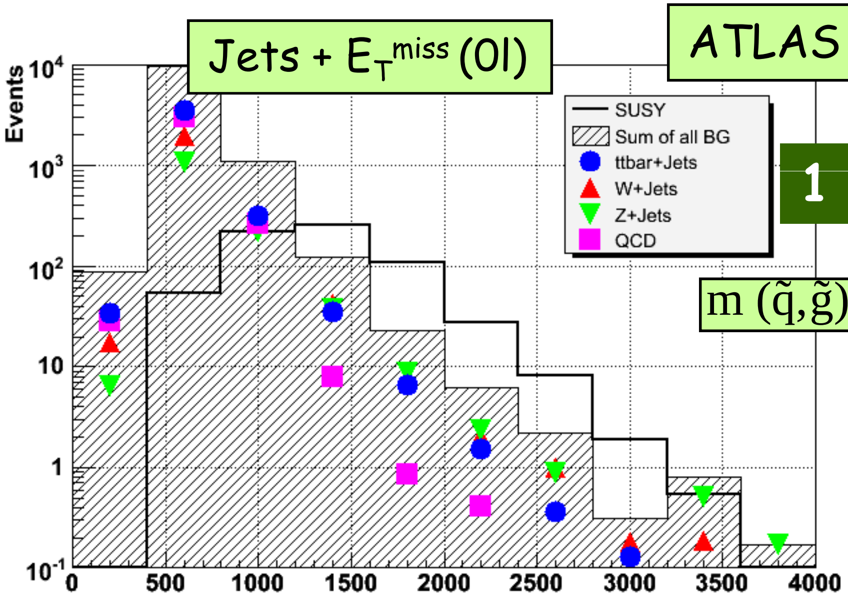
If quarks are composite : new $qq \to qq$ interactions with strength ~$1/\Lambda^2$, $\Lambda \equiv$ scale of New Physics.
$\Rightarrow$ expect excess of high-p_T jets compared to SM
The higher Λ the smaller the excess.
LHC ultimate sensitivity up to $\Lambda \approx 40$ TeV

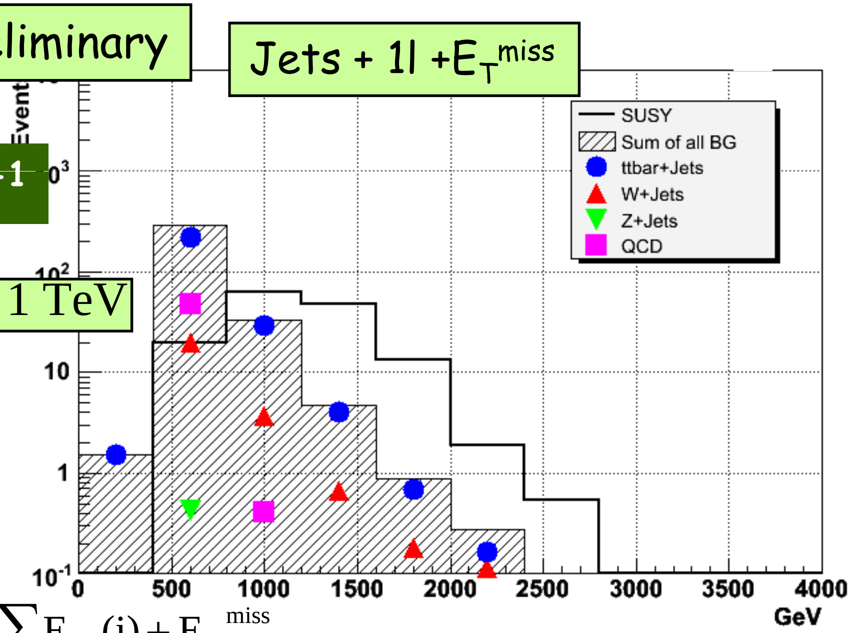


ATLAS preliminary

$1\ \mathrm{fb}^{-1}$

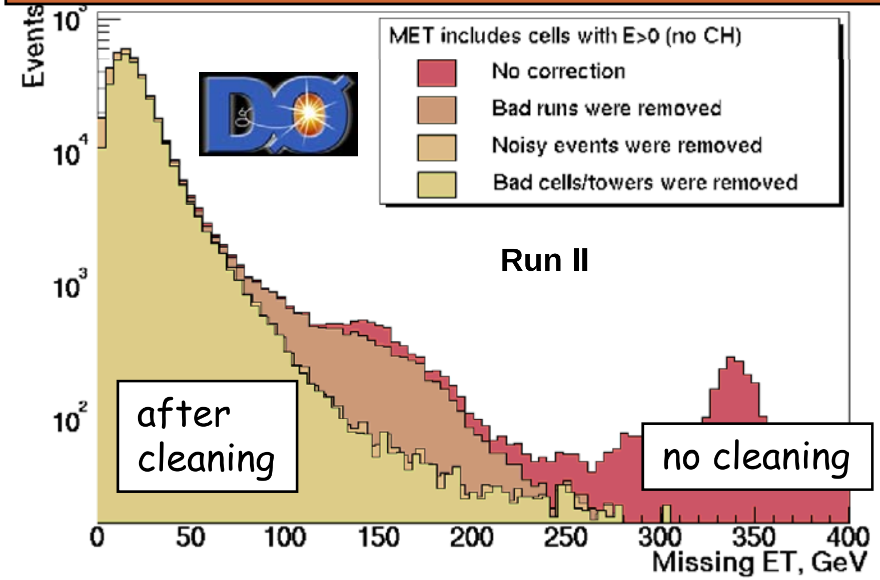
$m(\tilde{q},\tilde{g}) \sim 1\ \mathrm{TeV}$



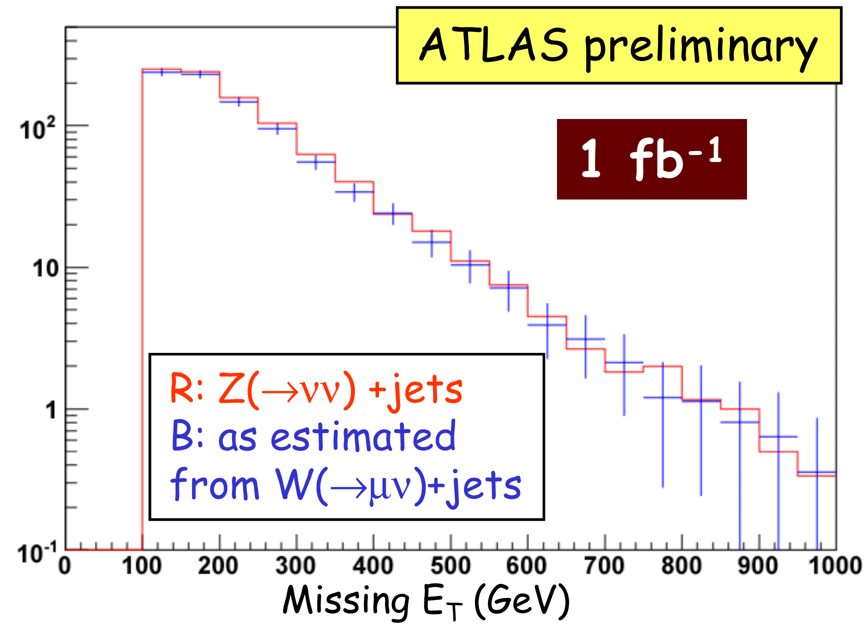


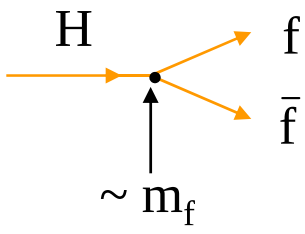
$$M_{eff}\ (\mathrm{GeV}) = \sum_{i=1,4} E_T\ (i) + E_T^{miss}$$

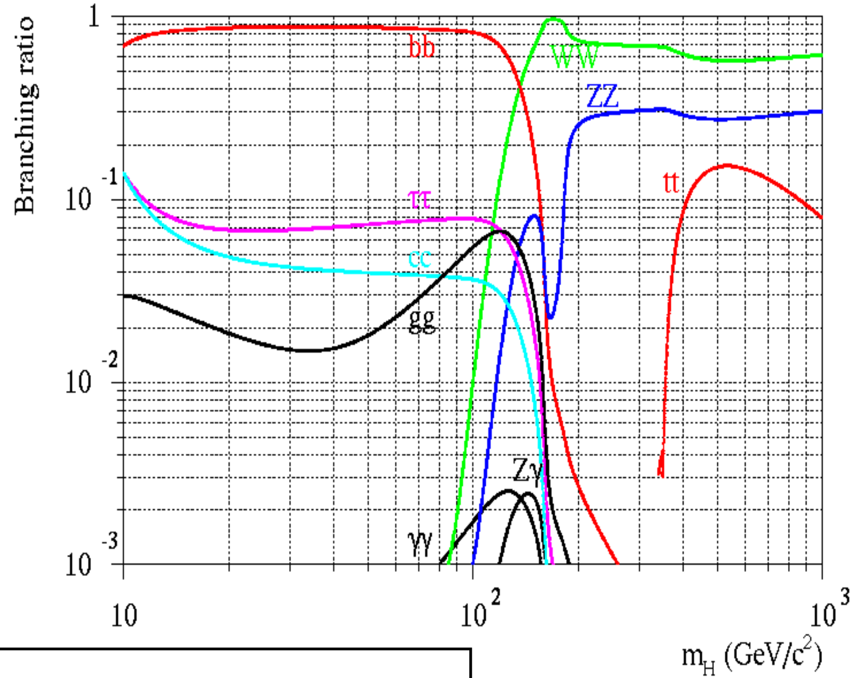
E_T^{miss} spectrum contaminated by cosmics, beam-halo, machine/detector problems, etc.



Estimate physics backgrounds using data (control samples)







Remember: light fully-hadronic final states cannot be extracted from QCD background at hadron colliders

m_H < 130 GeV : H → bb, ττ dominate
→ best search channels at the LHC : ttH → bb l+X, qqH→qq ττ
H → γγ (rare decay mode)
This is the most difficult region (S/B <<1) !

m_H > 130 GeV : H → $WW^{(*)}$, $ZZ^{(*)}$ dominate
→ best search channels at the LHC : H → $ZZ^{(*)}$ → 4l (gold-plated)
H → $WW^{(*)}$ → lν lν

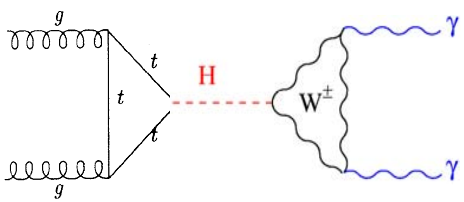
Especially in the region m_H<130 GeV, excellent detector performance needed to suppress the huge backgrounds: b-tag, l/γ E-resolution, γ/j separation, missing E_T resolution, forward jet tag, etc.
→ Higgs searches used as benchmarks for ATLAS and CMS detector design

The most difficult low-mass region:

ATLAS : m_H ~ 115 GeV   10 fb^{-1} : $S/\sqrt{B} \approx$ 4-5.6 ← range comes from $H \to \gamma\gamma$: LO vs NLO cross-section, cuts vs likelihood analysis

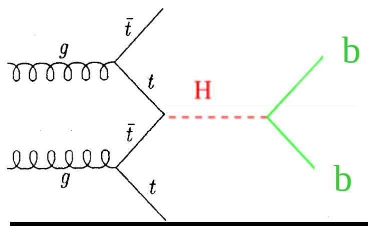
3 (complementary) channels with (similar) small significances:

$H \to \gamma\gamma$



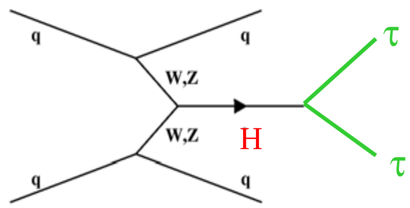
S=130, B=4300,
$S/\sqrt{B}$= 2 - 4.4

$ttH \to ttbb \to bl\nu bjjbb$



S=15, B=45, $S/\sqrt{B}$=2.2
being re-evaluated

$qqH \to qq\tau\tau$



S=10, B=10, $S/\sqrt{B}$=2.7

- different production and decay modes
- different backgrounds
- different detector/performance requirements:
  - -- ECAL crucial for $H \to \gamma\gamma$ (in particular response uniformity) : σ/m ~ 1% needed
  - -- b-tagging crucial for ttH : 4 b-tagged jets needed to reduce combinatorics (background being re-evaluated)
  - -- efficient jet reconstruction over $|\eta|$ < 5 crucial for $qqH \to qq\tau\tau$: forward jet tag and central jet veto needed against background

All three channels require very good understanding of detector performance and background control to 1-10% → convincing evidence likely to come mid-end 2009 …

With more time and more data, LHC can discover:

Excited quarks $q^* \to \gamma q$: up to $m \approx 6$ TeV
Leptoquarks: up to $m \approx 1.5$ TeV
Monopoles $pp \to \gamma\gamma pp$: up to $m \approx 20$ TeV
Compositeness: up to $\Lambda \approx 40$ TeV
$Z' \to ll$, jj: up to $m \approx 5$ TeV
$W' \to l\nu$: up to $m \approx 6$ TeV
etc.... etc....

Large number of scenarios studied
Main conclusions:

- ⇒ LHC direct discovery reach up to m ~ 5-6 TeV
- ⇒ demonstrated detector sensitivity to many signatures → robustness, ability to cope with unexpected scenarios