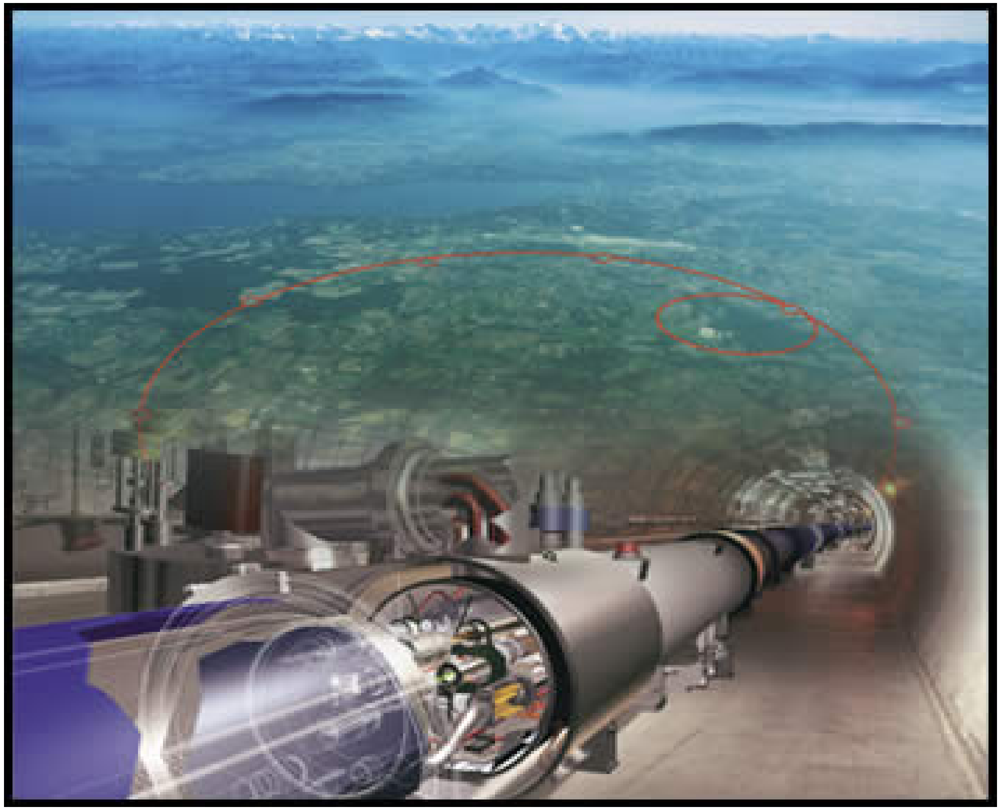
Large Hadron Collider (LHC)
A “Discovery” Machine



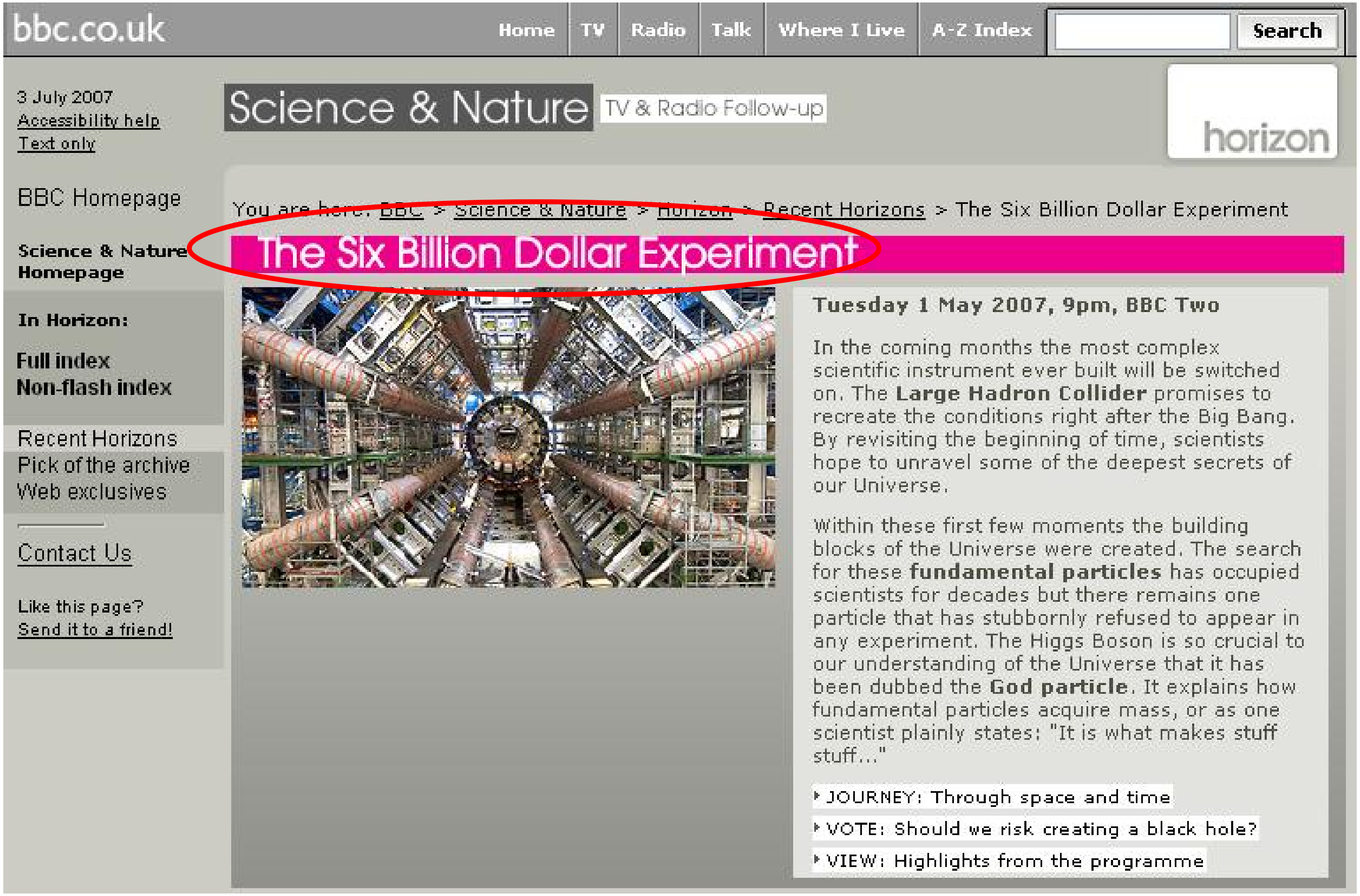
Hai-Jun Yang
University of Michigan

Tsinghua University
July 22, 2007

Outline

- LHC in News
- Why the LHC ?
- The LHC at CERN
- The ATLAS Detector
- LHC Discovery Potential

LHC in BBC News



LHC in New York Times

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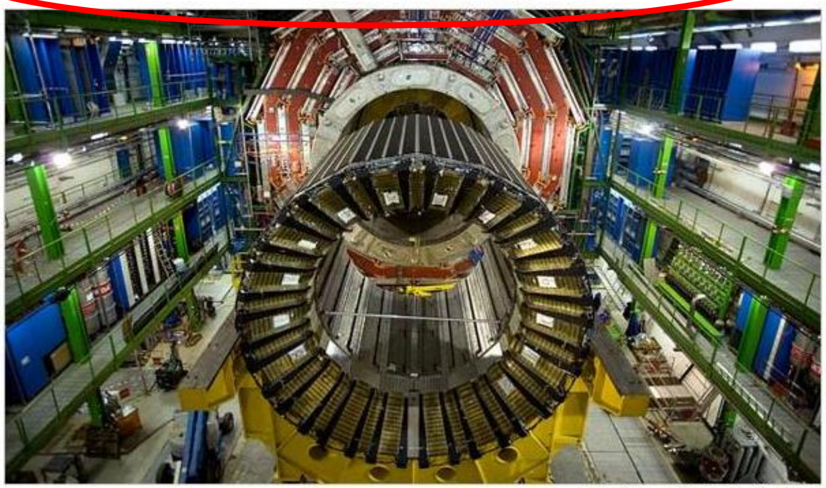
A Giant Takes On Physics' Biggest Questions



Valerio Mezzanotti for The New York Times

At Cern, the Large Hadron Collider could recreate conditions that last prevailed when the universe was less than a trillionth of a second old. Above is one of the collider's massive particle detectors, called the Compact Muon Solenoid. More Photos »

By DENNIS OVERBYE
Published: May 15, 2007

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Correction Appended

300 FEET BELOW MEYRIN, Switzerland — The first thing that gets you is the noise.

Multimedia

Physics, after all, is supposed to be a cerebral pursuit. But this cavern almost

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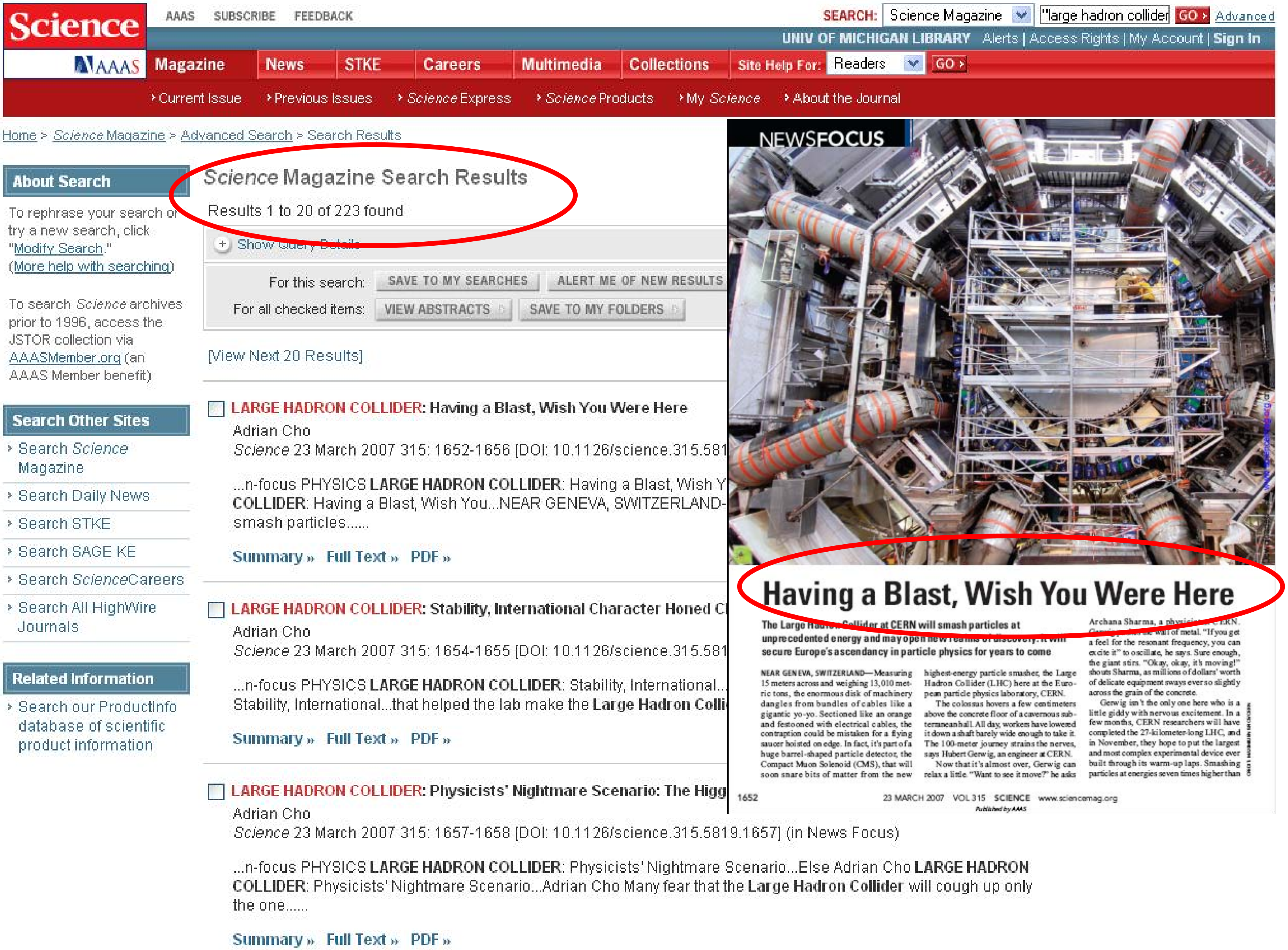
LHC in Science



LHC in Nature

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You have searched for ""large hadron collider"" - all of the words , in Multiple Journals

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1. **Particle physics: Search for the 'unparticles'**
   Alison Wright
   CONTEXT: ...of invisible particles. Seeing the invisible isn't impossible Â— the detectors due to turn on at CERN's **Large Hadron Collider** next year (such as CMS, pictured partway through its installation) could register amounts of missing energy...
   Nature Physics **3**, 446 - 446 (01 Jul 2007) News and Views
   Full Text | PDF | Rights and permissions | Save this link

2. **High-energy detectors might find 'unparticles'**
   Philip Ball
   SUMMARY: 'Stuff' not made of particles could be seen soon, in theory.
   CONTEXT: ...the unparticle stuff at all," says Georgi. But the high energies about to be probed by machines such as the **Large Hadron Collider** (LHC) at CERN, the European centre for particle physics near Geneva, Swizerland, might show up the...
   News@Nature (11 Jun 2007) News
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3. **Science in GermanyA beacon of reform**
   Alison Abbott
   SUMMARY: Long a symbol of East German pride, the CharitÃ© medical school is flourishing in the twenty-first-century shake-up of German universities. Alison Abbott reports.
   CONTEXT: ...the country's main particle accelerator HERA at the DESY lab (pictured), in good enough shape to exploit the **Large Hadron Collider** at CERN in Geneva when it starts pumping out the particles in 2008. Alison Abbott
   Nature **447**, 630 - 633 (06 Jun 2007) News Feature
   Full Text | PDF | Rights and permissions | Save this link

4. **Large Hadron Collider delayed**
   Katharine Sanderson
   SUMMARY: Scientists happy with extra time to tweak their instruments.
   CONTEXT: ...look for the mysterious particle that gives objects mass will not be seeing any live action this year. The **Large Hadron Collider** (LHC), based at CERN in Geneva, Switzerland, was due to do a trial run in November this year, before...
   News@Nature (04 Jun 2007) News
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nature Vol 446|19 April 2007

NEWS

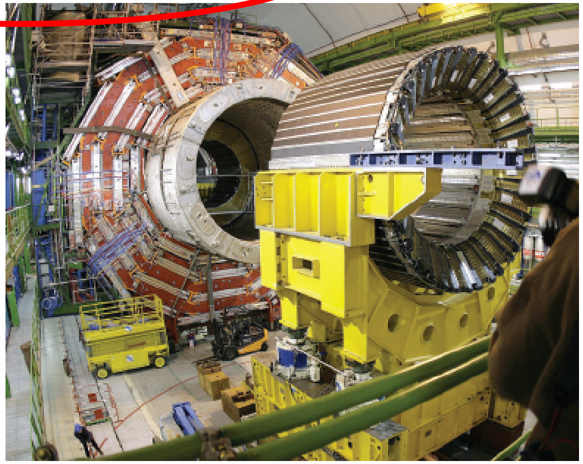
Colliders race for the Higgs

JACKSONVILLE, FLORIDA

Soon after the news emerged on 29 March that a magnet test in the Large Hadron Collider (LHC) atom-smasher had failed, two physics bloggers decided to have a bit of fun with the idea. On 1 April they posted blogs announcing news such as 'Three years of delay for LHC start-up'. Visitors found the reports all too easy to swallow, decrying it as a cruel blow. Only then did one blogger add an April Fool's spoiler, with an apology: "Sorry to those of you who got hurt by not understanding that in the first place."

If these blog postings were close to the bone for many, it is because the LHC is running hard up against its deadline to switch on later this year. Conspiracy theories were also quick to fly: any postponement at the LHC, near Geneva, Switzerland, means that the Tevatron collider at the Fermi National Accelerator Laboratory in Illinois has more time to discover the last part of the standard model of particle physics — the Higgs boson.

On 15 April, the race became even more heated. At a meeting of the American Physical Society in Jacksonville, Florida, Tevatron physicists announced refined measurements for the masses of two particles that, taken together, lower the expected mass of the Higgs. The new estimates — of the mass of the top quark and of the W boson — put an upper limit on the Higgs mass of 144 GeV. In January, the best estimate was 153 GeV (see *Nature* 445, 239; 2007). The lighter the Higgs, the better the chance the Tevatron has to detect it before it shuts down in 2009.



AP PHOTO/M. TREZZIN

Big bang: the experiments at Europe's Large Hadron Collider are unlikely to be running before 2008.

Researchers are more immediately worried about potential LHC delays caused by the failure of the magnet, which was supplied by Fermilab. "This does add to the burden of everything that has to be done before the machine switches on," says Pier Oddone, director of Fermilab. "We are embarrassed we created this additional problem." At the same time, some LHC researchers admit privately that the mistake might give them some breathing room.

"The magnet problem is a very small part of a bigger picture."

The magnet that failed was part of an inner triplet designed to focus the proton beams before they interact. During a pressure test to simulate conditions expected in the collider, the eight-tonne magnet jumped 13 centimetres, rupturing a pipe and causing a loud bang. The problem was quickly identified as a weakness in the supporting structure. "There was a definite oversight here," admits Stephen Holmes, head of accelerator physics at Fermilab.

The accident was not the first magnet failure: another Fermilab-supplied magnet had a faulty heat exchanger that had to be replaced a few months earlier. The second problem was one too many for Oddone, who has initiated an external review to figure out how the team missed such simple design flaws.

Meanwhile, CERN — the particle-physics laboratory in which the LHC is housed — and Fermilab are working together to find a fix and to minimize the effect on the LHC schedule. Options include reinforcing the triplet support structure with rods, or building physical buffers so that the magnets cannot move too far. Engineers hope to announce a solution by 25 April, and to test it on another triplet in the tunnel in early June.

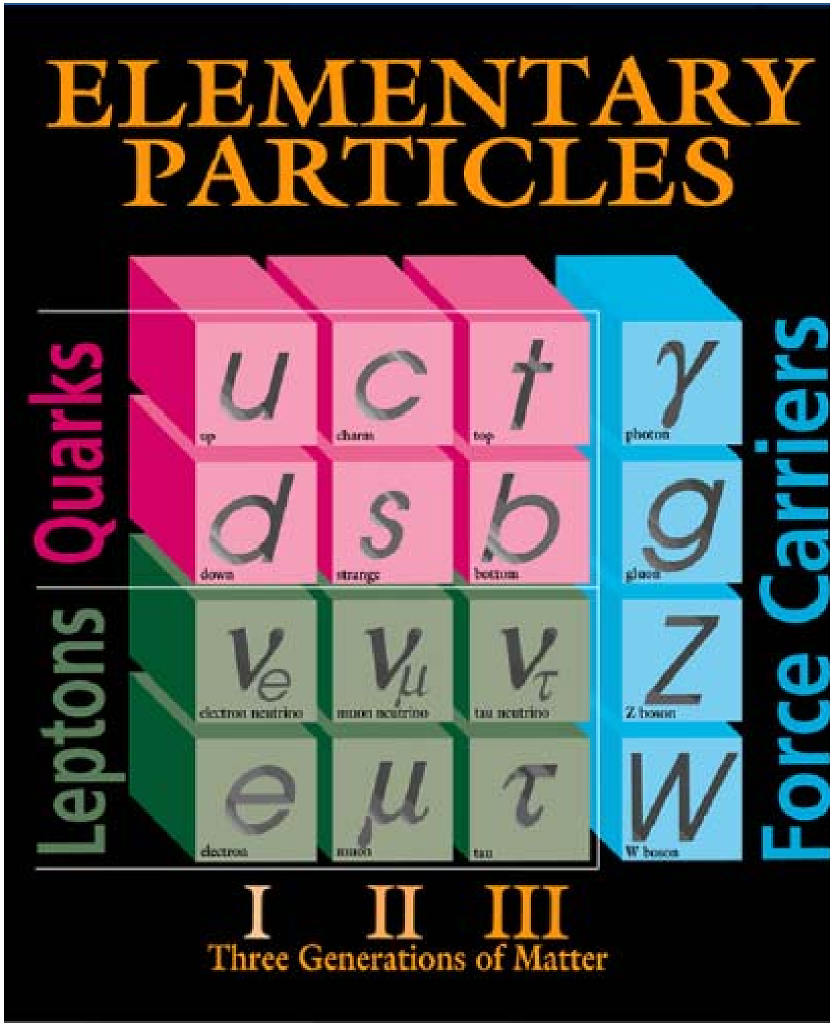
The time needed to repair the magnets will need to be factored into the overall LHC operation, which was already running five weeks behind schedule before the accident, says project manager Lyndon Evans. There is also pressure to get the repair right the first time around, because there are few spare magnets available.

The most likely victim of any slippage is the first engineering run, planned for late 2007. The LHC is being chilled down in sections; it took from January to March 2007 to cool the first eighth of the machine to 1.9 kelvin. The process will become quicker, but cooling the final sectors in just two weeks each — as Evans says the current schedule demands — will be challenging, with or without the magnet repairs. "In my view the magnet problem has been blown out of proportion," he says. "It is a very small part of a bigger picture."

Evans adds that he still hasn't given up on the LHC conducting its first run in 2007, but admits that only an extreme optimist would share his view. With delay building on delay, a formal announcement of when the LHC might come online isn't expected until mid-May. And with CERN closing as it usually does for the winter months, no run in 2007 could push the first science run later than planned in 2008. And by that point, the Tevatron will have had another year or more to hunt for the Higgs. ■

Sarah Tomlin

The Standard Model



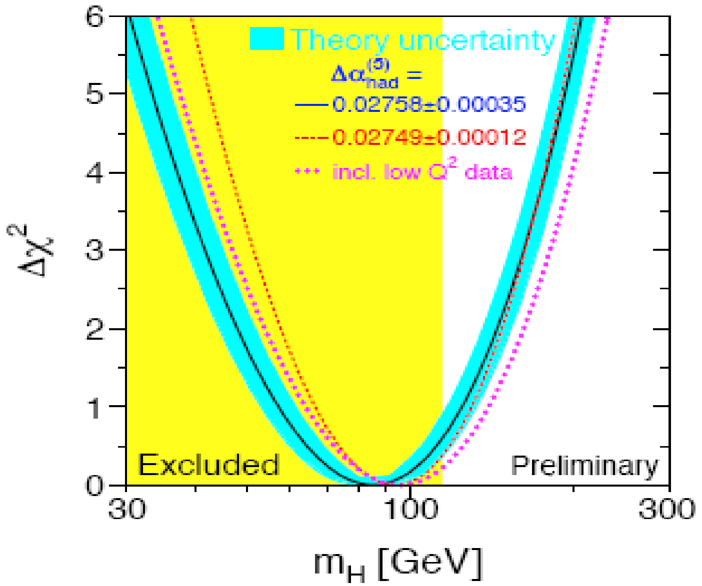
1900s: e discovered (cathode ray tube)
γ interpreted as a particle
1930s: μ discovered (cosmic rays)
1950s: ν_e observed (nuclear reactor)
ν_μ discovered (BNL)
1960s: 1^{st} evidence for quarks
u and d observed (SLAC)
s observed (BNL)
1970s: ***standard model is born***
c discovered (SLAC, BNL)
τ observed (SLAC)
b observed (FNAL)
1980s: W and Z observed (CERN)
1990s: t quark observed (FNAL)
2000s: ν_τ observed (FNAL)

Why the LHC ?

- The Standard Model of Particle Physics has made great achievement over last 30 years, but it is incomplete and has many unsolved questions.
- Why particles have mass?

  Higgs mechanism ?

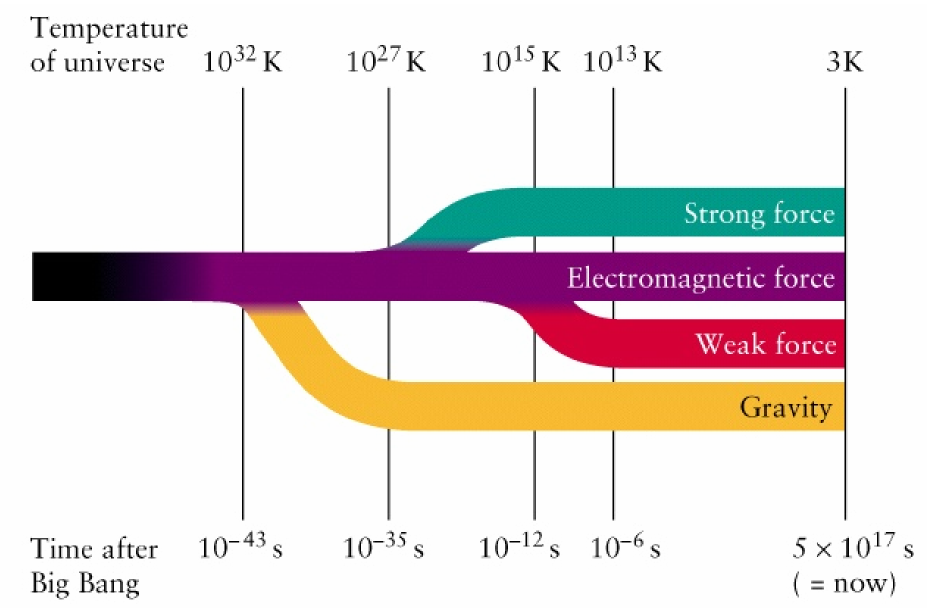
  If Higgs boson exists, the LHC will be able to make it detectable.

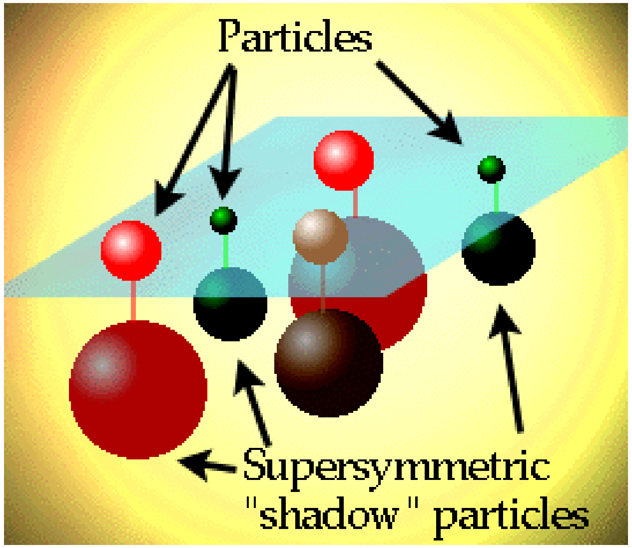


Standard-Model $M_H \lesssim 200$ GeV at 95% CL

Supersymmetry (SUSY) ?

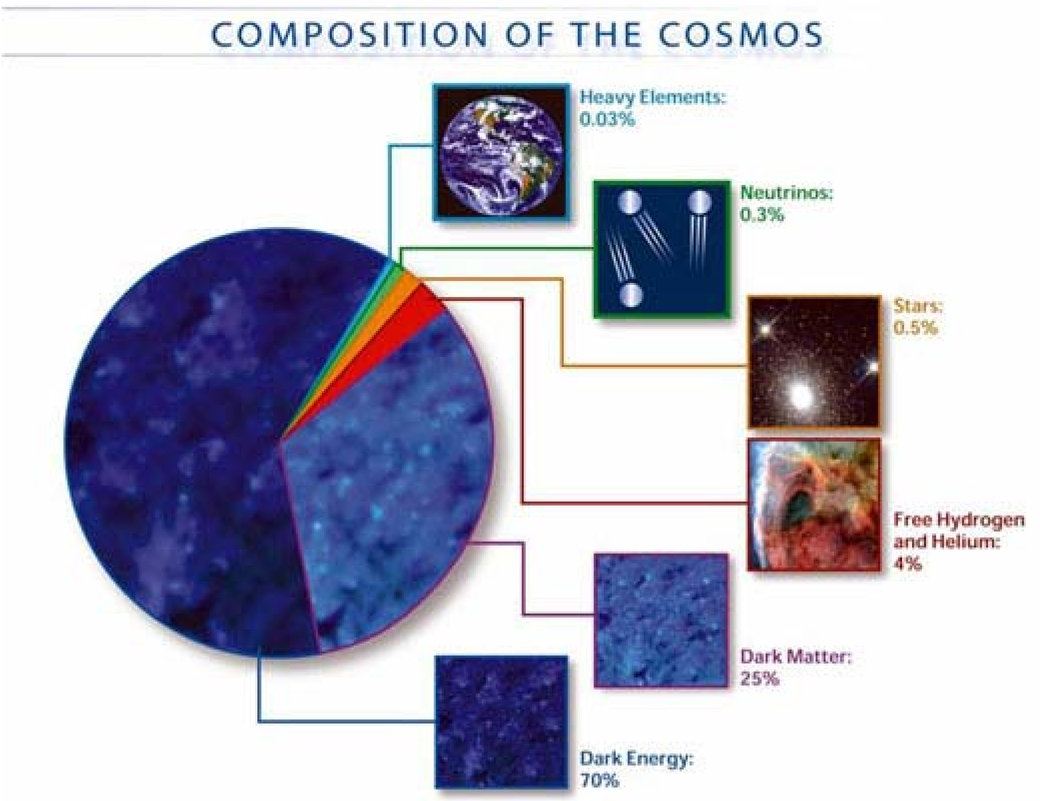
SUSY is a symmetry that relates fermions and bosons, all known particles have SUSY partners that differ by half a unit of spin.
If SUSY exists close to the TeV energy scale, some light SUSY particles should be found at the LHC. SUSY helps to solve the grand unification of forces.



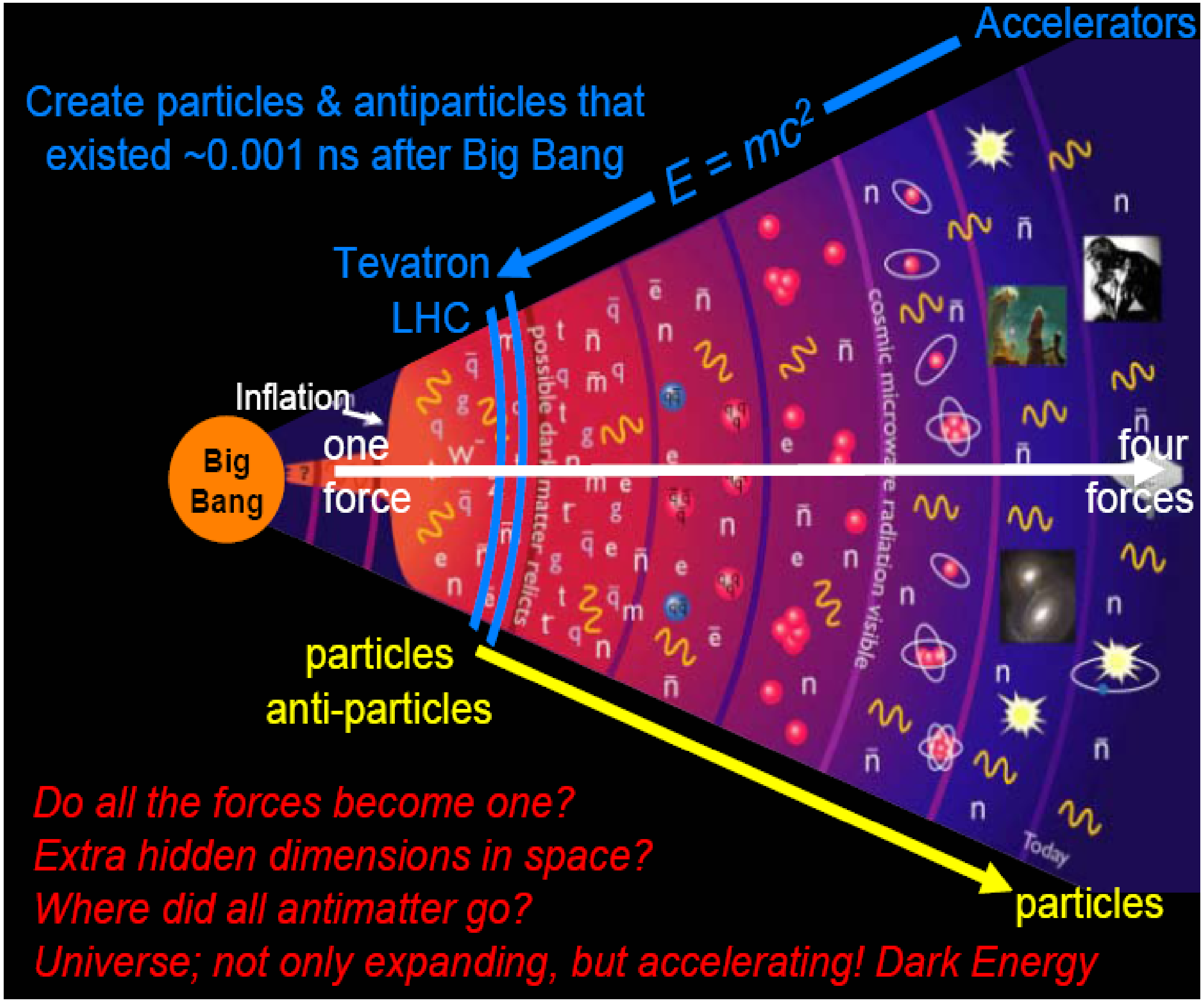


Dark Matter in the Universe ?

We only understand about 5% of matter in the Universe.
About 25% dark matter and 70% dark energy are unknown.
The lightest SUSY particle (LSP) is a promising candidate of dark matter, which is accessible at LHC if the mass of LSP less than about 1 TeV.



High Energy → Simulate Big Bang



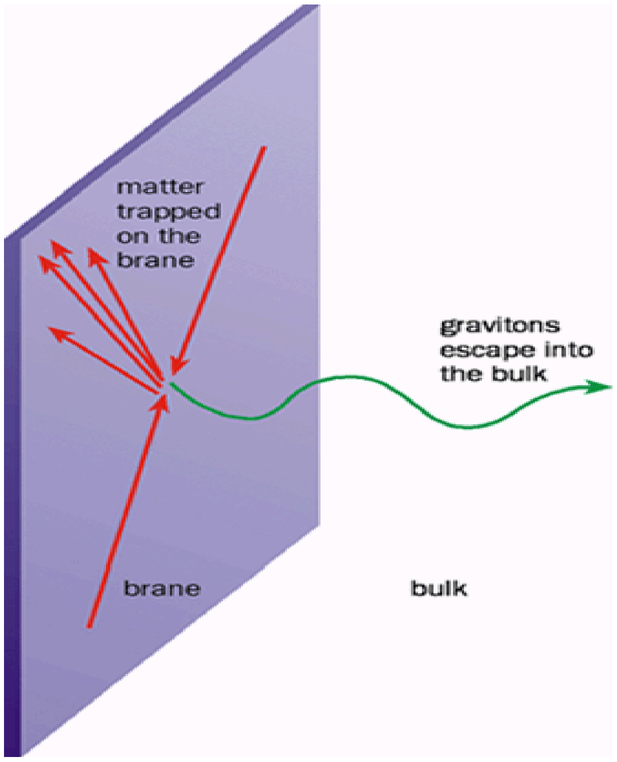
Extra Dimensions – Graviton ?

- Much recent theoretical interest in models with extra dimensions

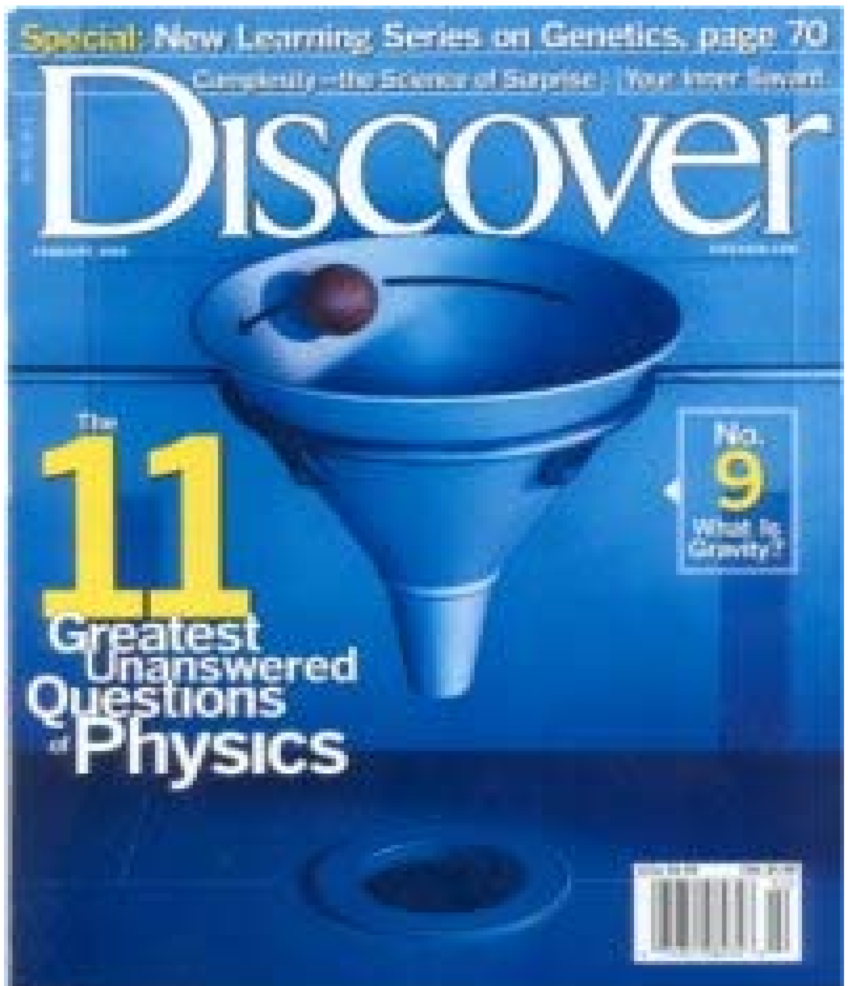
- New physics may appear at the TeV scale, accessible at the LHC

➔ Event signature with graviton:

Jets or Photons with large E_T^{miss}



The 11 Greatest Unanswered Questions of Physics (Discover, 2002) -6 are LHC related



1. What is dark matter ?
2. What is dark energy ?
3. How were the heavy elements from iron to uranium made ?
4. Do neutrinos have mass ?
5. Where do ultrahigh-energy particles come from ?
6. Is a new theory of light and matter needed to explain what happens at very high energies and temperatures ?
7. Are there new state of matter at ultrahigh temperate and dentisity ?
8. Are protons unstable ?
9. What is gravity ?
10. Are there additional dimensions ?
11. How did the universe begin ?

Why the LHC ?

- The LHC has good chance to answer some of these questions, however the history has shown that the greatest advances in science are often unexpected.

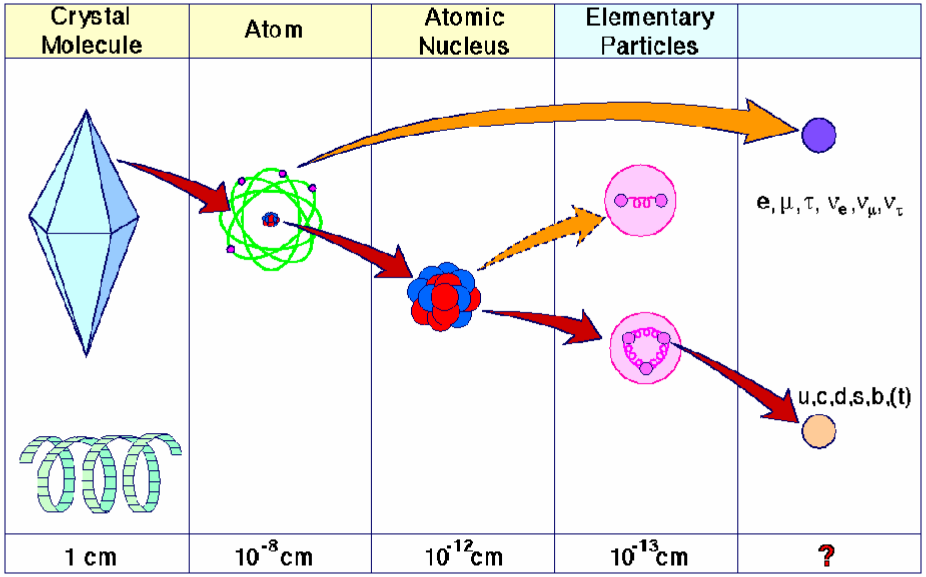
- The LHC will change our view of the Universe.

Why Need High Energy ?

- Particle physics have focused on the inner space frontier, pursuing the questions of the construction of matter and the fundamental forces at the smallest scale accessible.

De Broglie wavelength of particles

$$\lambda = \frac{h}{p}$$

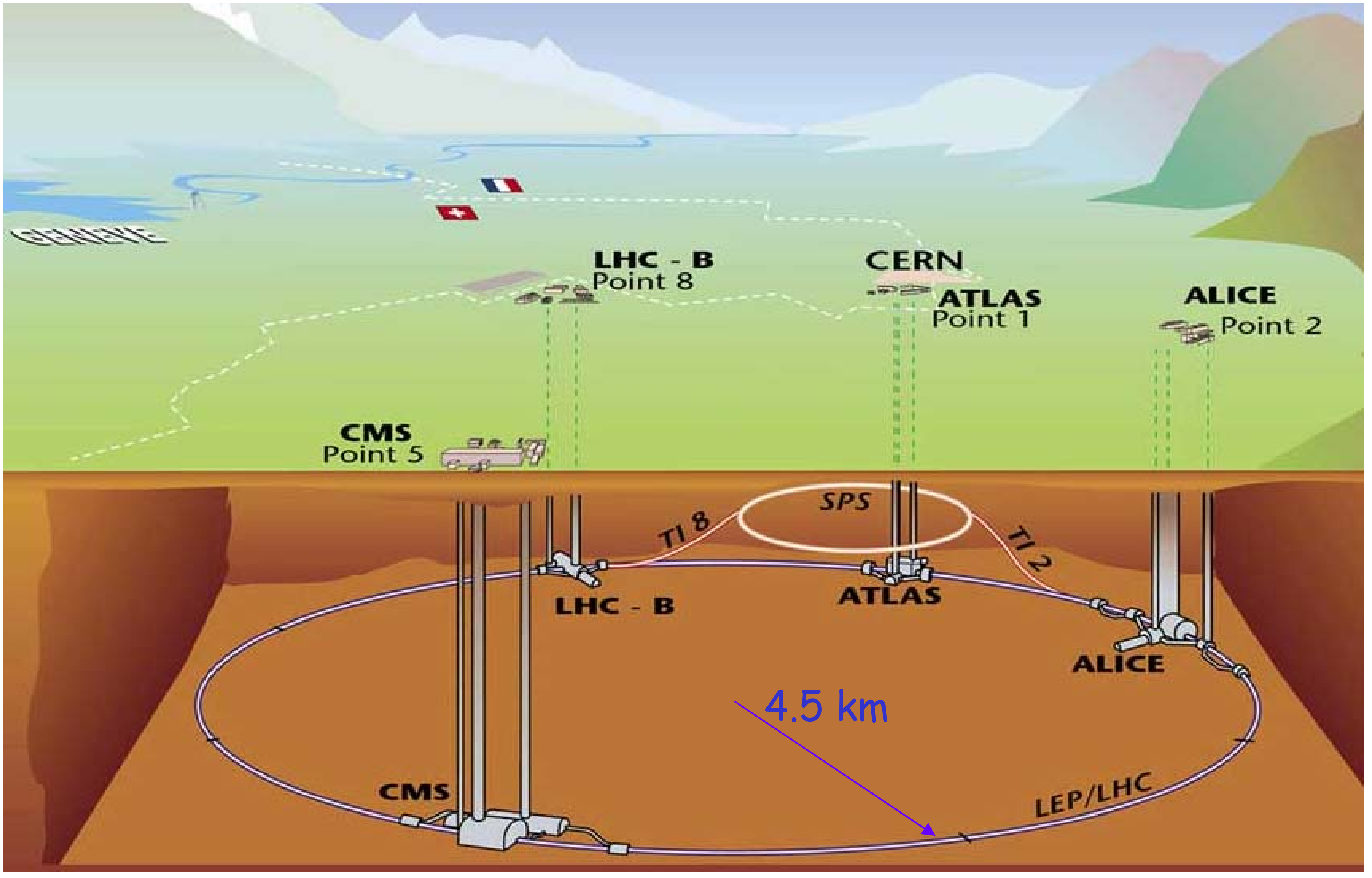


Smaller distance

➔ Higher energy

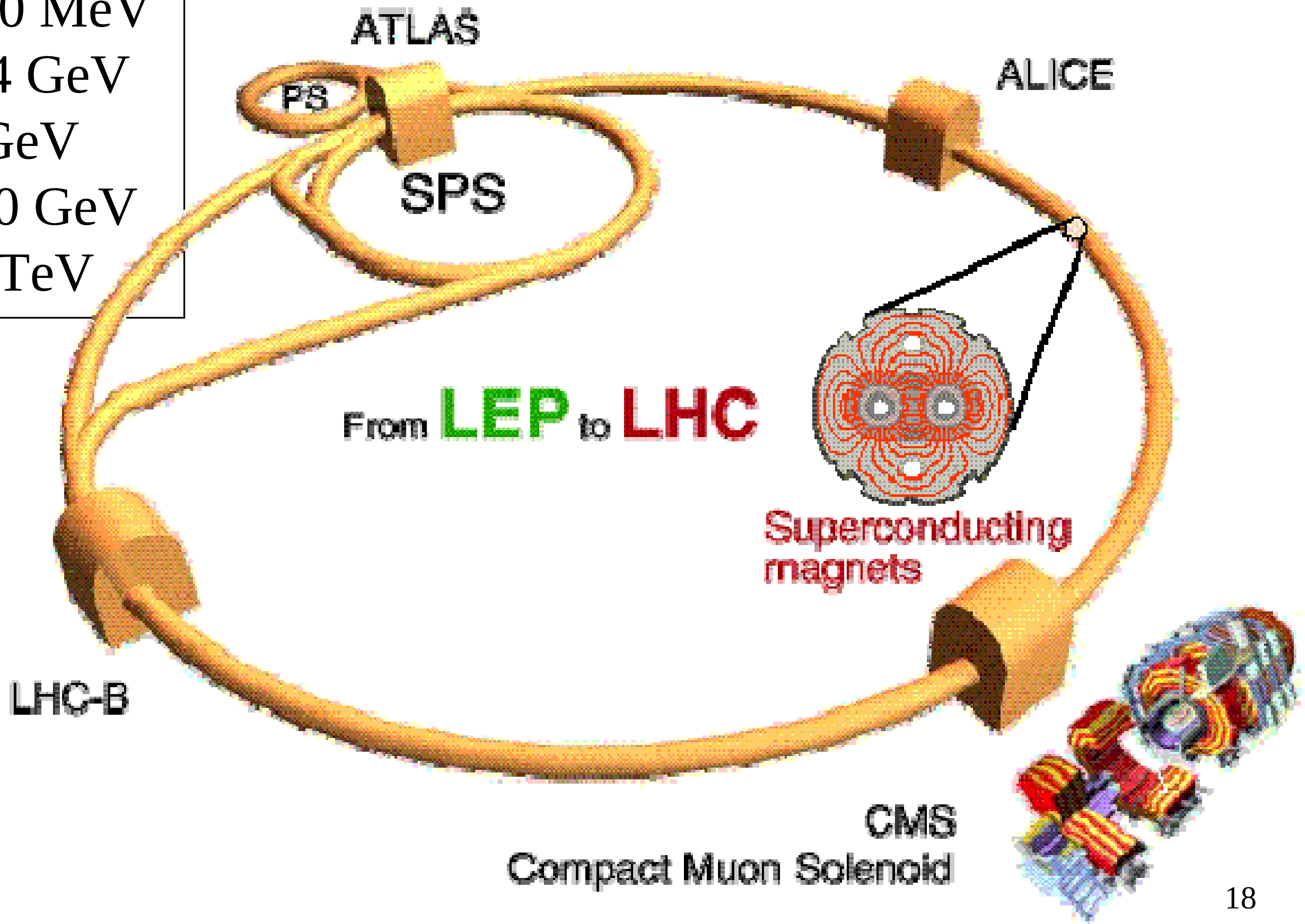
The LHC Experiment at CERN

LHC at CERN


GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
4.5 km
CMS
LEP/LHC

The LHC at CERN

Linac: 50 MeV
PSB: 1.4 GeV
PS: 28 GeV
SPS: 450 GeV
LHC: 7 TeV

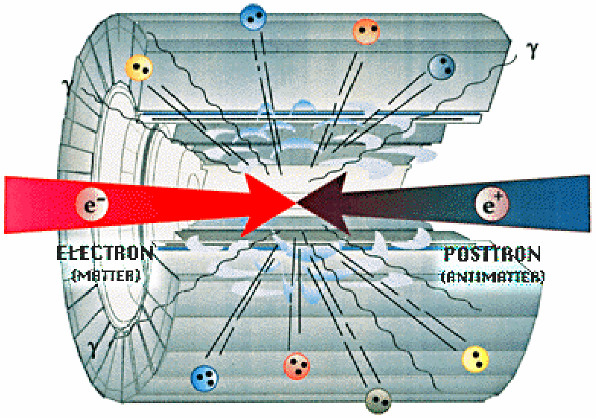


Why Hadron (pp) Collider ?

Electron-Position Collider: clean signature

Synchrotron Radiation:

$$P = \frac{2\, e^2\, c}{3\, R^2} \left(\frac{E}{mc^2} \right)^4$$

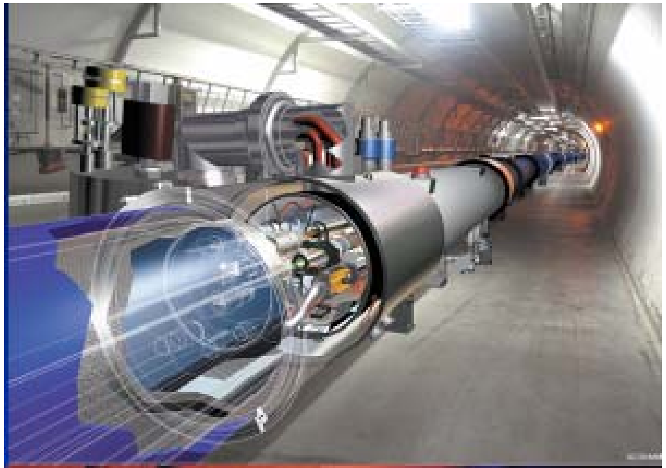


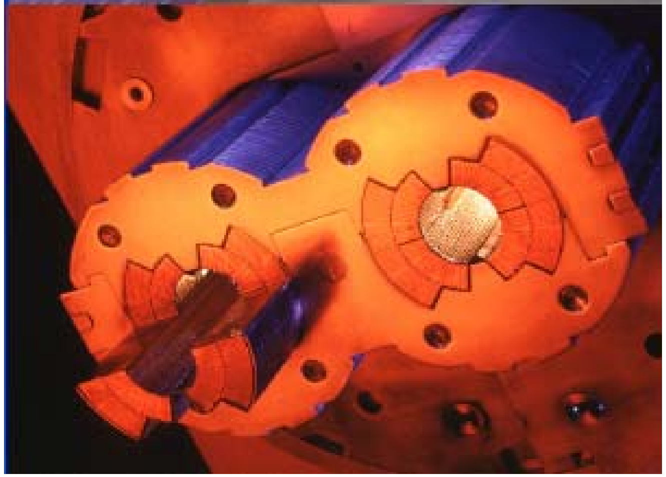
CERN LEP : R=4.5km, E_{beam} ~ 100 GeV

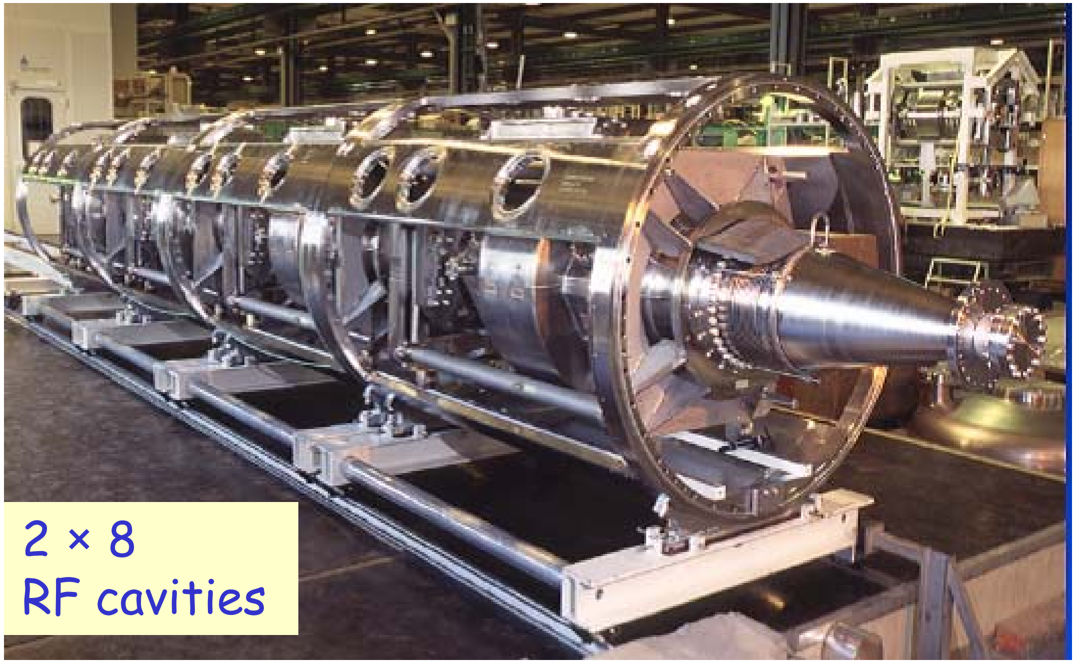
CERN LHC: R=4.5km, E_{beam} ~ 7000 GeV

$$\frac{\Delta E(e)}{\Delta E(p)} = \left(\frac{m_p}{m_e} \right)^4 \sim 10^{13}$$

LHC Key Components







Magnets: 9300
Dipole: 1232
B(max): 8.33 Tesla

LHC Magnets

1. Dipoles for bending the beams
2. Quadrupoles for strong focusing in the IP (223 T/m)

$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$

LHC: E = 7 TeV, ρ = 2.8 km ➔ B = 8.3 T

Technology constraint. Dipole magnetic field B

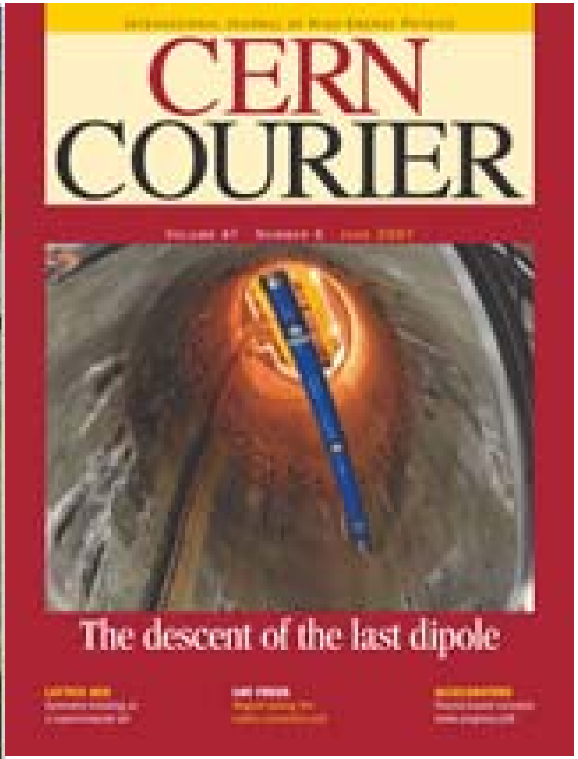
B_t <2 T for iron magnets

B_t <13 T for Nb-Ti superconducting magnets (10 T)

B_t <25 T for Nb_3Sn superconducting magnets (16-17 T)

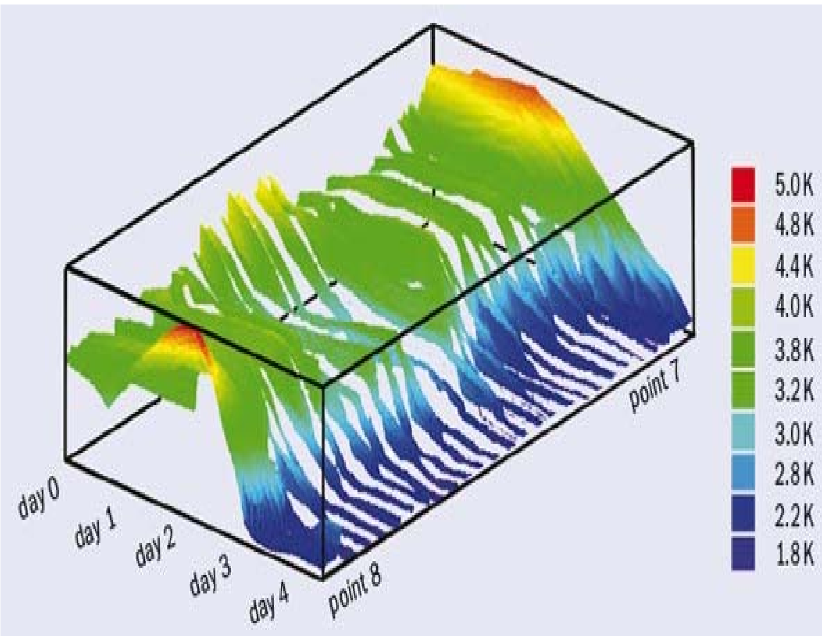
The Descent of the Last Dipole

On April 26, 2007, the last superconducting magnet (1232 in total, 15m, 34 tones) for the LHC descended into the accelerator tunnel.



LHC: the coldest place in the universe

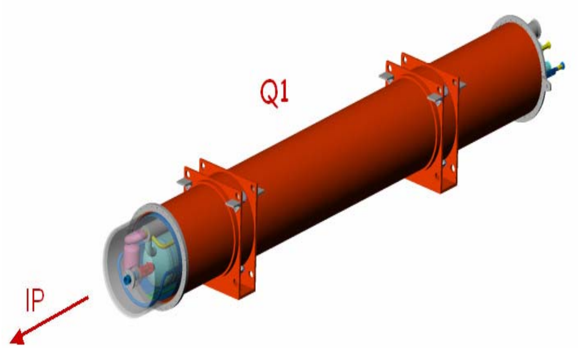
First LHC sector 7-8 (3.3km) reaches 1.9K on May 5, 2007

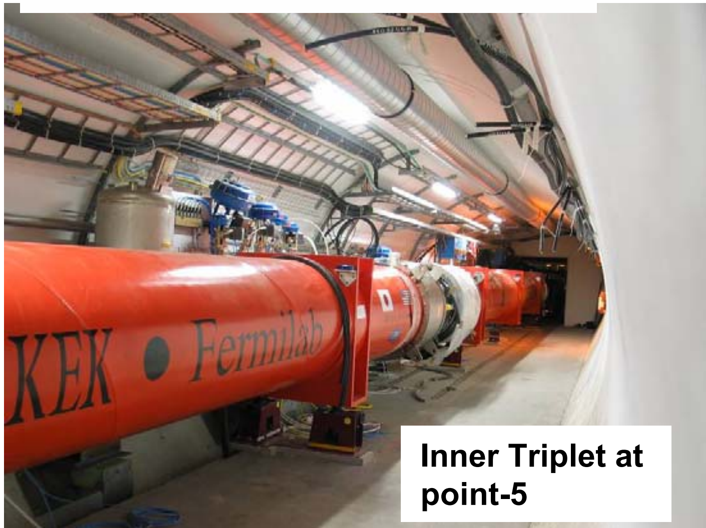


An Inner Triplet Fails the Test

March 27, 2007, a Fermilab-built quadrupole magnet, one of an "inner triplet" of three focusing magnets, failed a high-pressure test at Point 5 in the tunnel of the LHC.

Q1 Quadrupole Magnet – CERN and Fermilab agreed to repair to the structures that hold the cold mass (blue) in place within the cryostat (orange) in each magnet of the triplet on either side of the LHC's four interaction points. The Q1 magnet of each triplet is the magnet closest to the interaction point (IP).





Inner Triplet at point-5

LHC Delayed

Nov.07 → May 08

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OPEN The News in 2 minutes

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Last Updated: Tuesday, 3 April 2007, 16:34 GMT 17:34 UK

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Failure during Cern magnet test

A vital component in the Large Hadron Collider (LHC) particle accelerator at Cern has suffered a serious failure.

The inner triplets were installed in the LHC tunnel in 2006

The giant underground laboratory on the French-Swiss border is designed to probe the limits of physics.

It is the world's biggest facility of its type, and will collide sub-atomic particles in a 27km-long ringed tunnel.

One of eight magnet assemblies placed at points around the LHC failed in a test ahead of the lab's scheduled start-up in late 2007.

Large Hadron Collider delayed
Katharine Sanderson
SUMMARY: Scientists happy with extra time to tweak their instruments.
CONTEXT: ...look for the mysterious particle that gives objects mass will not be seeing any live action this year. The **Large Hadron Collider** (LHC), based at CERN in Geneva, Switzerland, was due to do a trial run in November this year, before...
News@Nature (04 Jun 2007) News
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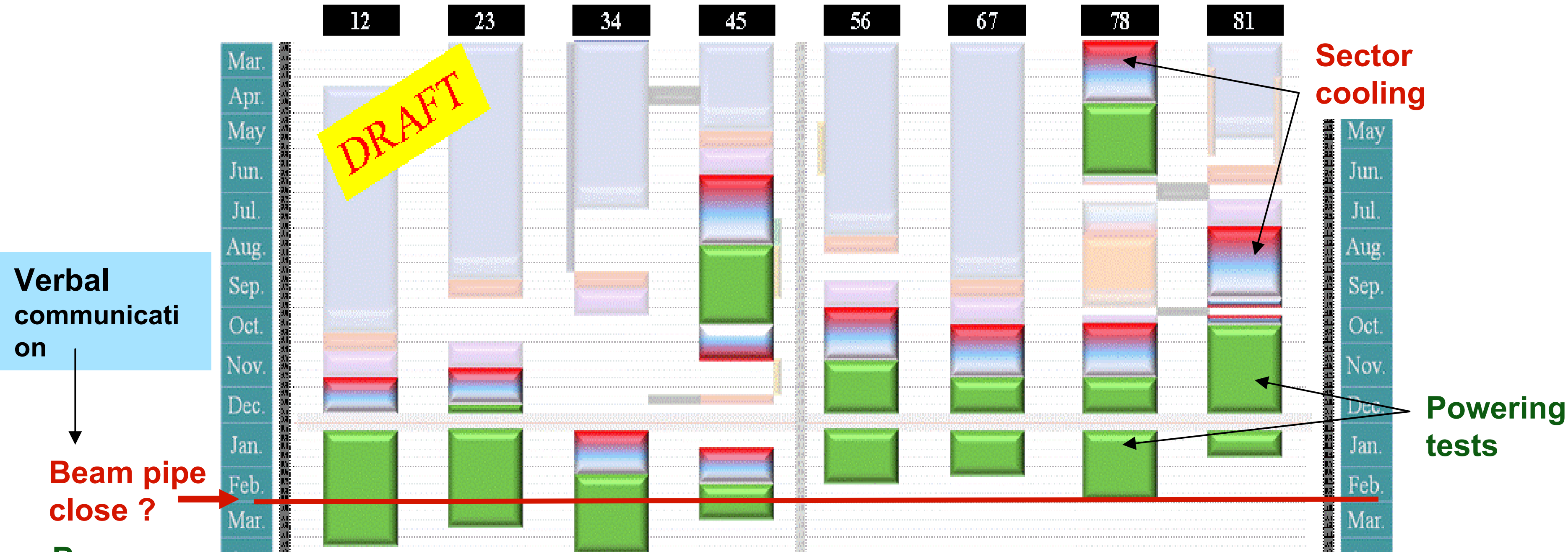
HIGH-ENERGY PHYSICS: Design Flaw Could Delay Collider
Adrian Cho
Science 6 April 2007 316: 31-34 [DOI: 10.1126/science.316.5821.31] (in News of the Week)



Cool-down:

- 45 ▶ 81 ▶ 56-67-78 ▶ 23-12 ▶ 34-45
- Quantity of helium needed by the end of 2007 : 6 sectors

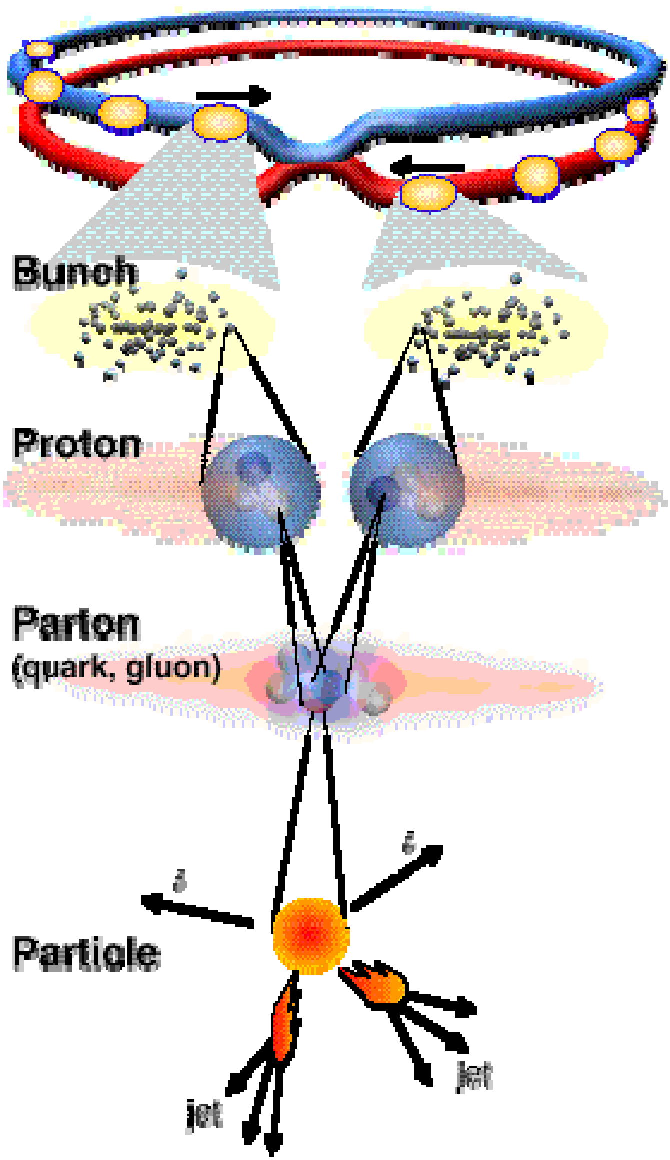
Powering tests: 45 ▶ 81 ▶ 56-67-78 ▶ 23-34-12

End of Powering tests : wk. 15 /08

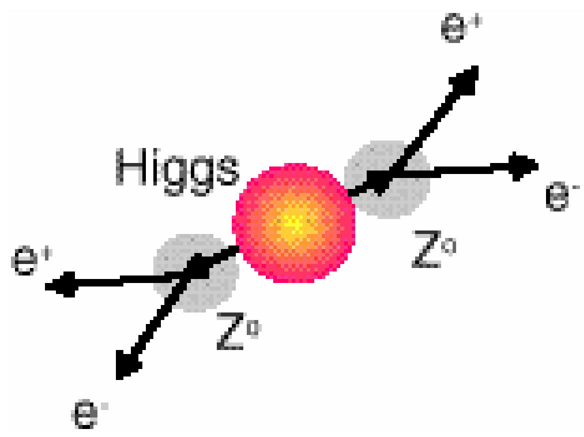
4/27/2007

http://lhc.web.cern.ch/lhc/Installation_Commissioning.htm

Collisions at LHC



Proton-Proton	(2835 x 2835 bunches)
Protons/bunch	10^{11}
Beam energy	7 TeV
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^7 - 10^9 Hz



Collaboration of ATLAS/CMS

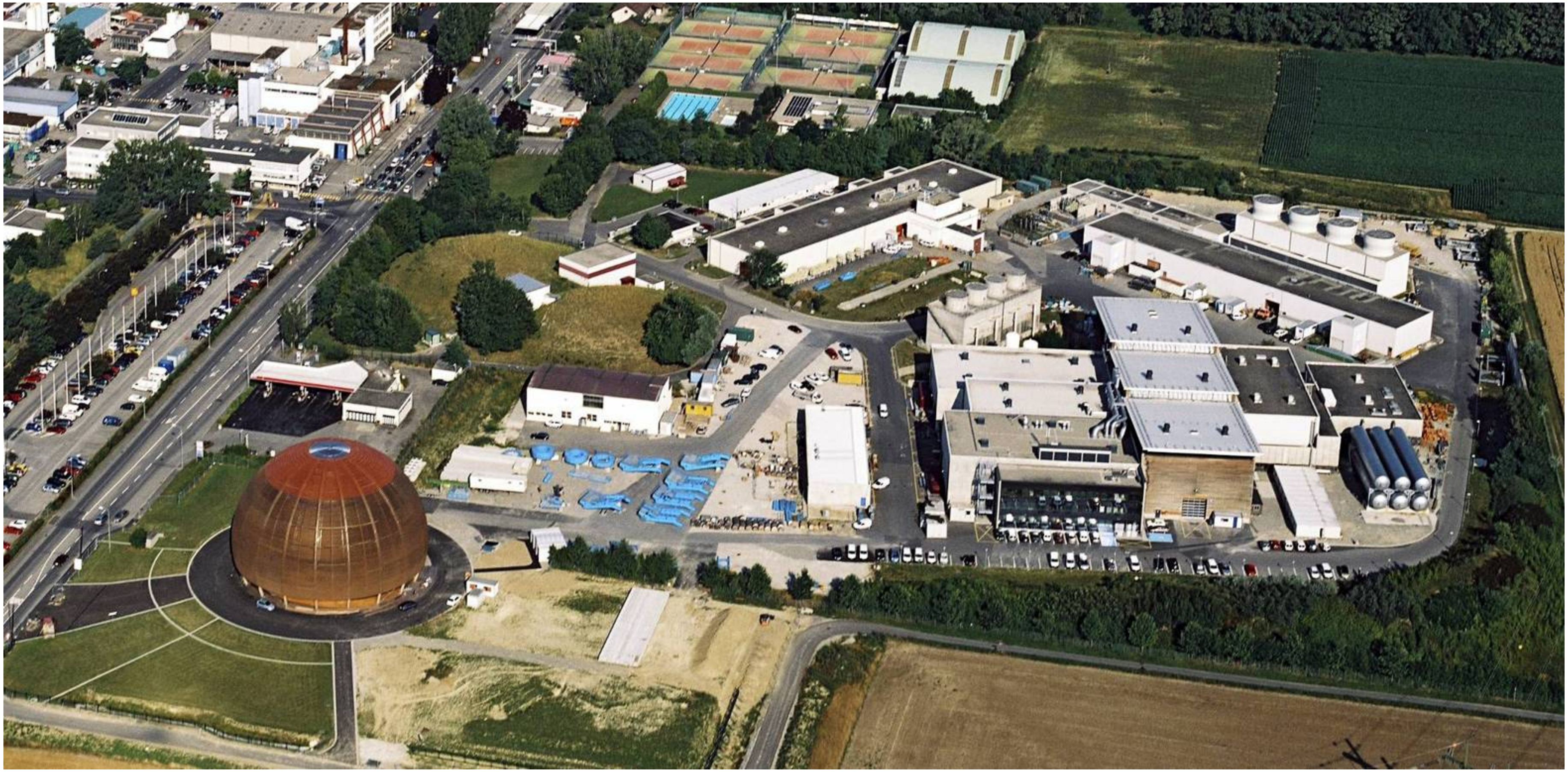
- ATLAS(35 countries, 162 institutes)
  - IHEP, USTC, Nanjing U., Shandong U.
  - CERN, Fermilab, ANL, BNL, LBNL
  - Harvard University
  - Yale University
  - MIT
  - Stanford University, SLAC
  - University of California, Berkeley
  - Cambridge University
  - Oxford University
  - University of Chicago
  - University of Columbia
  - University of Michigan
  - University of Pennsylvania
  - University of Wisconsin
  - University of Washington
  - SUNY, Stony Brook
  - Duke University
  - DESY, MPI, Humboldt University
  - ……
- CMS(38 countries, 181 institutes)
  - IHEP, USTC, Peking U., SIC
  - CERN，Fermilab, LLNL, DESY
  - MIT
  - California Institute of Technology
  - Princeton University
  - Cornell University
  - Swiss Federal Institute of Technology
  - University of Zurich
  - University of Wisconsin
  - Johns Hopkins University
  - University of Maryland
  - UC, Los Angeles
  - UC, Santa Barbara
  - Rice University
  - Brown University
  - RWTH
  - Rutherford Appleton Laboratory
  - …...

The ATLAS Collaboration

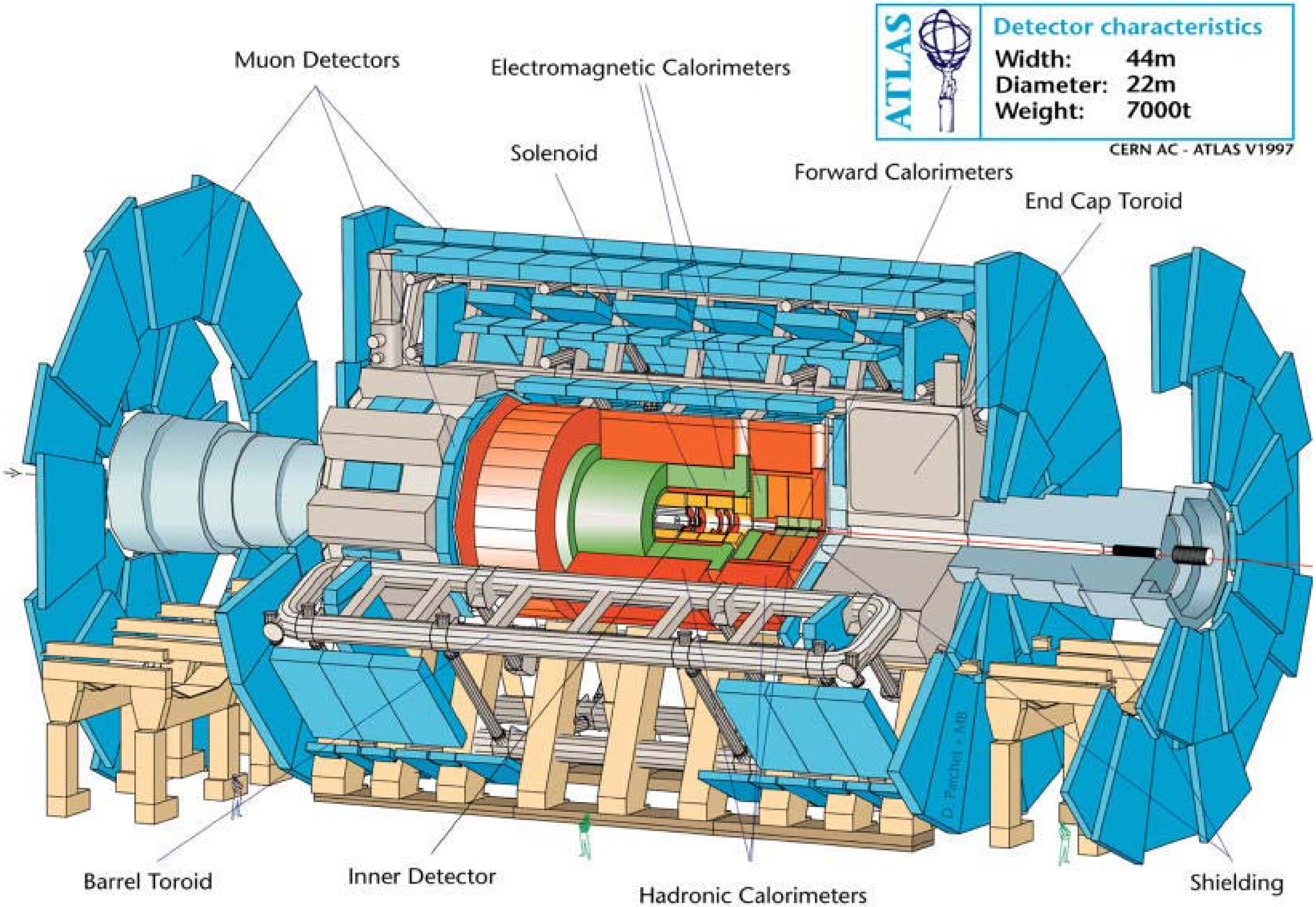
35 Countries, 162 Institutes, ~ 1800 Researchers

The ATLAS Collaboration

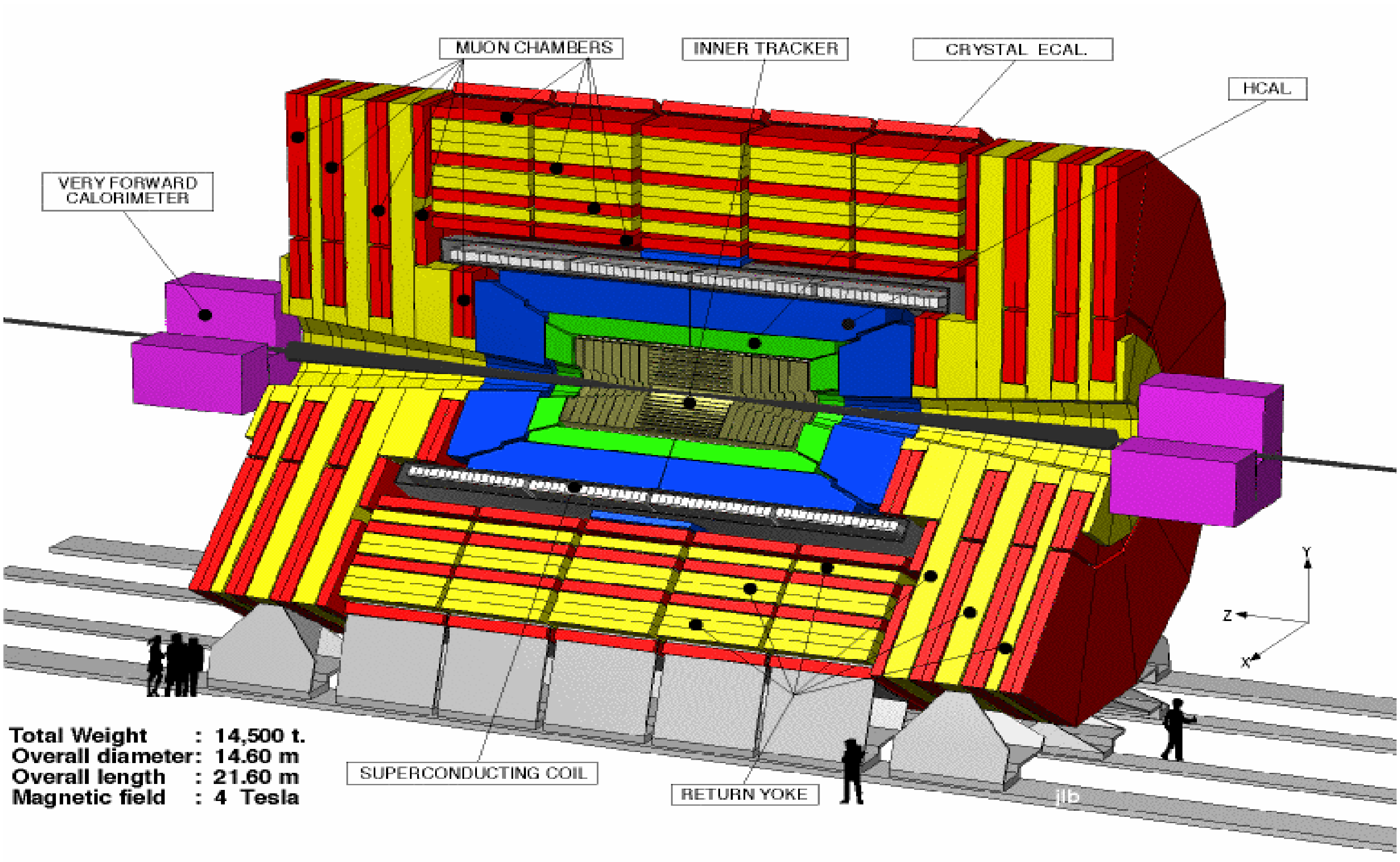
ATLAS – Point 1



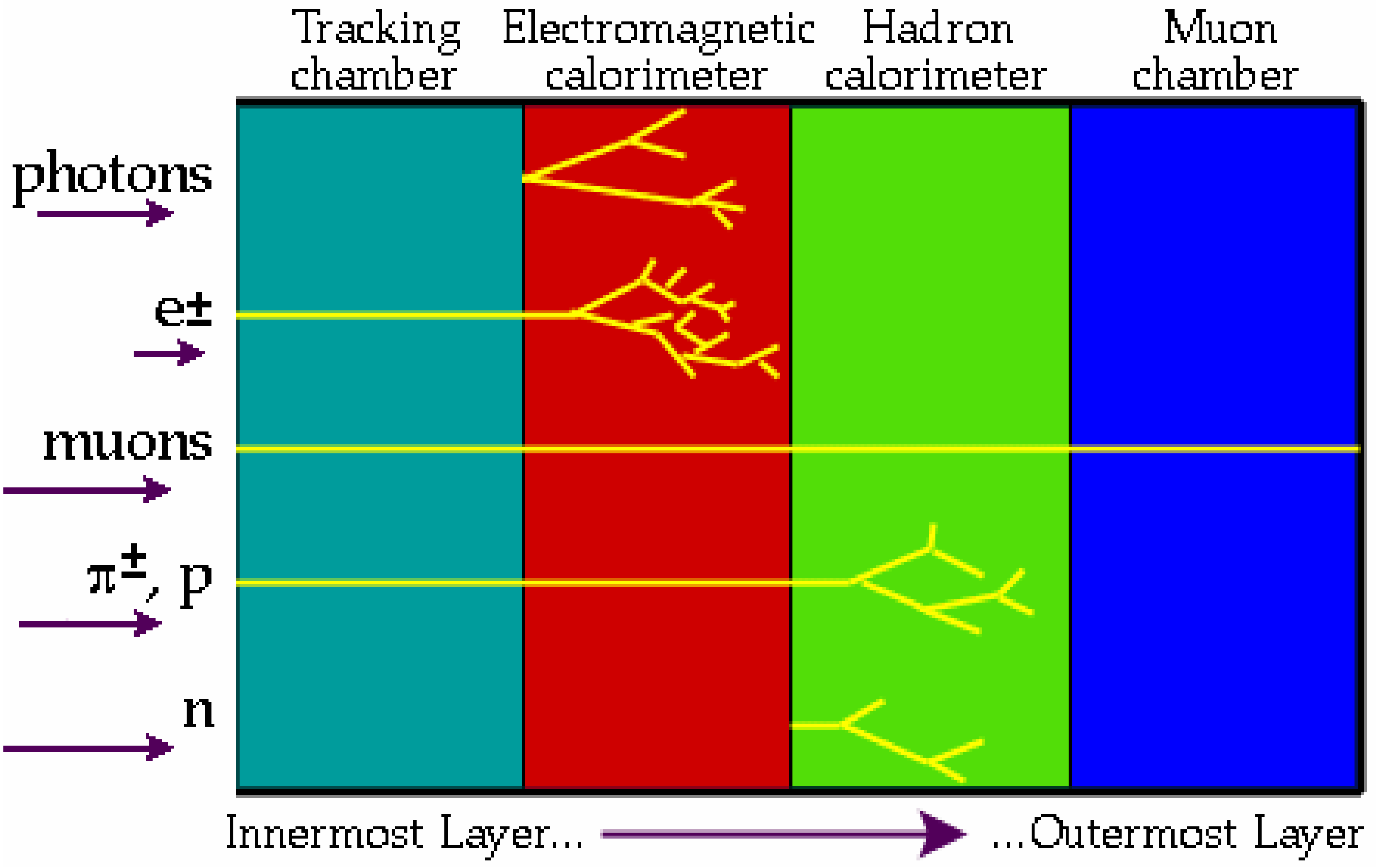
ATLAS Detector



CMS Detector

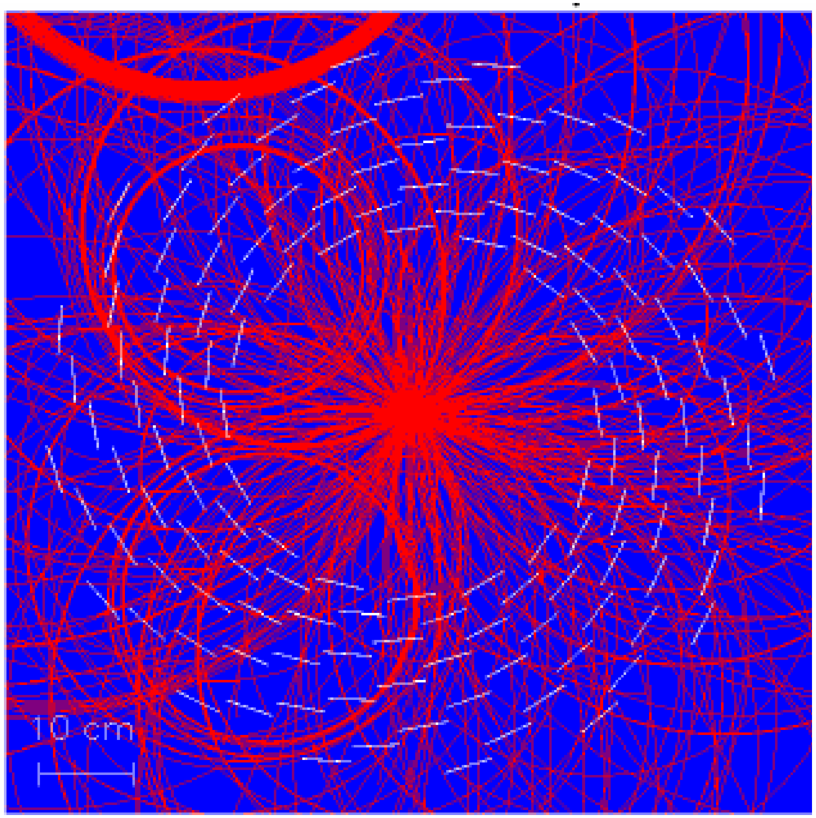


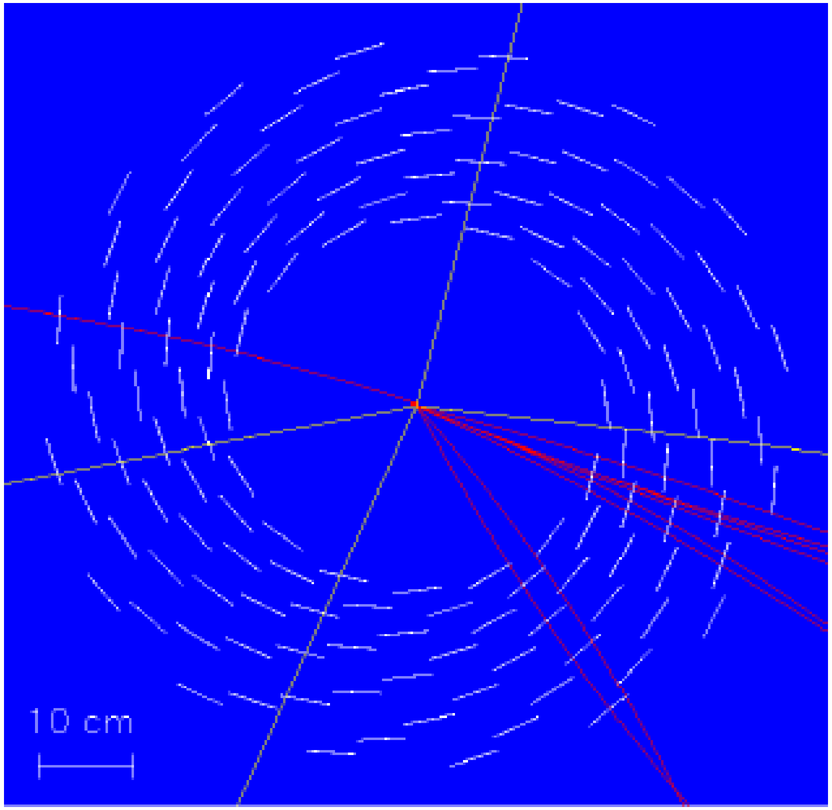
How to Detect Particles ?



Big Challenge to Detector

Challenge for Tracking H → ZZ → 4μ





Challenge to the Detector

LHC detectors must have:

• fast response, otherwise too large pile-up.
Typical response time 20-50 ns
- integrate over 1-2 bunch crossings
- pile-up of 25-50 minimum bias events
$\rightarrow$ very challenging readout electronics

• high granularity to minimize probability that pile-up particles be in the same detector element as interesting object
$\rightarrow$ large number of electronic channels, high cost

• high radiation resistant e.g. in forward calorimeters: up to 10^{17} n / cm^2 in 10 years of LHC operation

• good PID (particle identification)

• good E, P resolution

Precision Muon Spectrometer $\sigma / pT \sim 10\ \%$ at 1 TeV/c

Fast response for trigger

Good *p* resolution (e.g., $A/Z' \rightarrow \mu\mu$, $H \rightarrow 4\mu$)

EM Calorimeters $\sigma / E \sim 10\% / \sqrt{E(GeV)}$

excellent electron/photon identification

Good *E* resolution (e.g., $H \rightarrow \gamma\gamma$)

Hadron Calorimeters

Good jet and E_T miss performance

(e.g., $H \rightarrow \tau\tau$) $\sigma / E \sim 50\% / \sqrt{E(GeV)} \oplus 0.03$

Inner Detector

$\sigma / p_T \sim 5 \bullet 10^{-4}\ p_T \oplus 0.001$

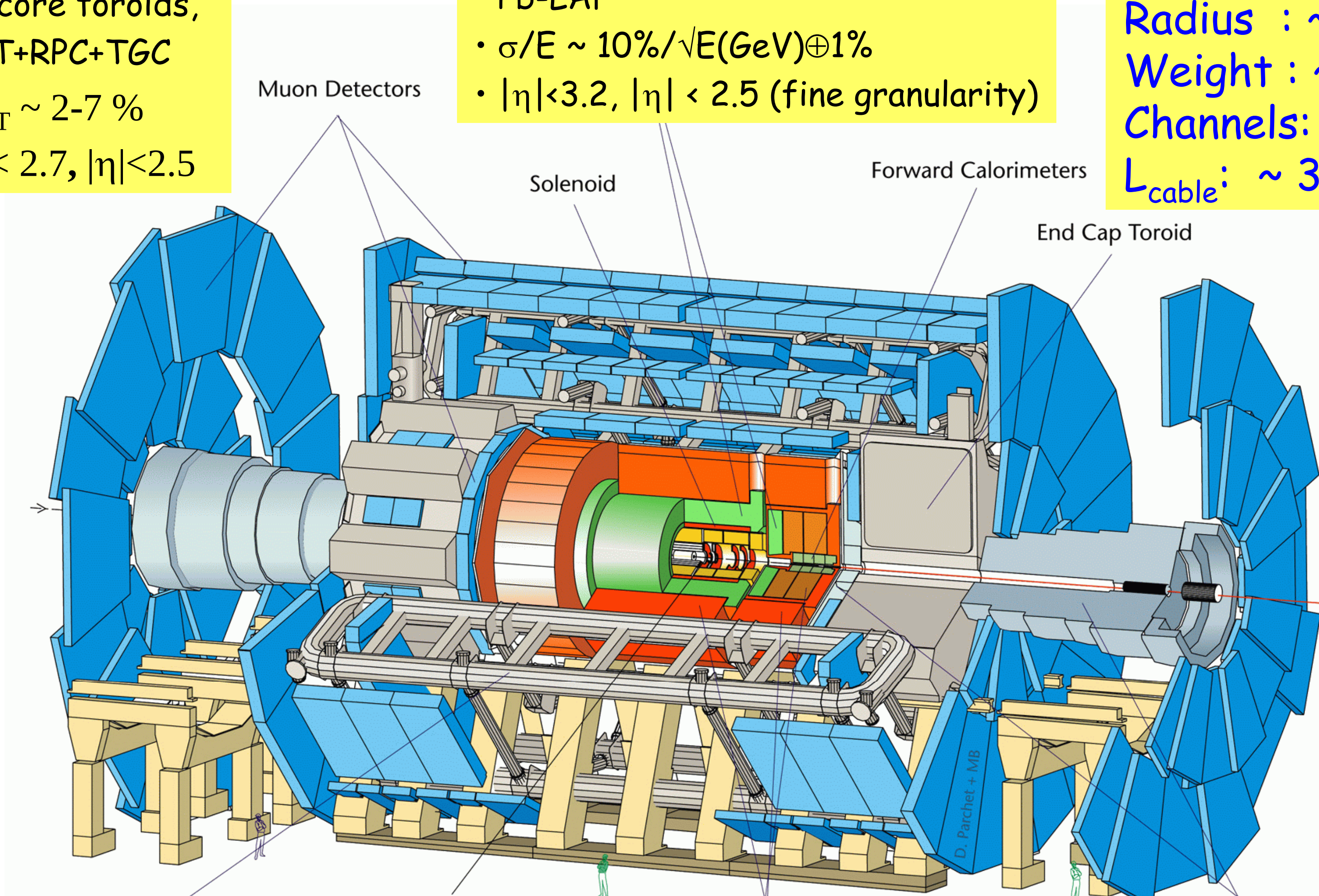
Good impact parameter res.

(e.g., $H \rightarrow bb$)

Muon Detector
- air-core toroids, MDT+RPC+TGC
- $\sigma/p_T \sim 2\text{-}7\ \%$
- $|\eta| < 2.7$, $|\eta|<2.5$

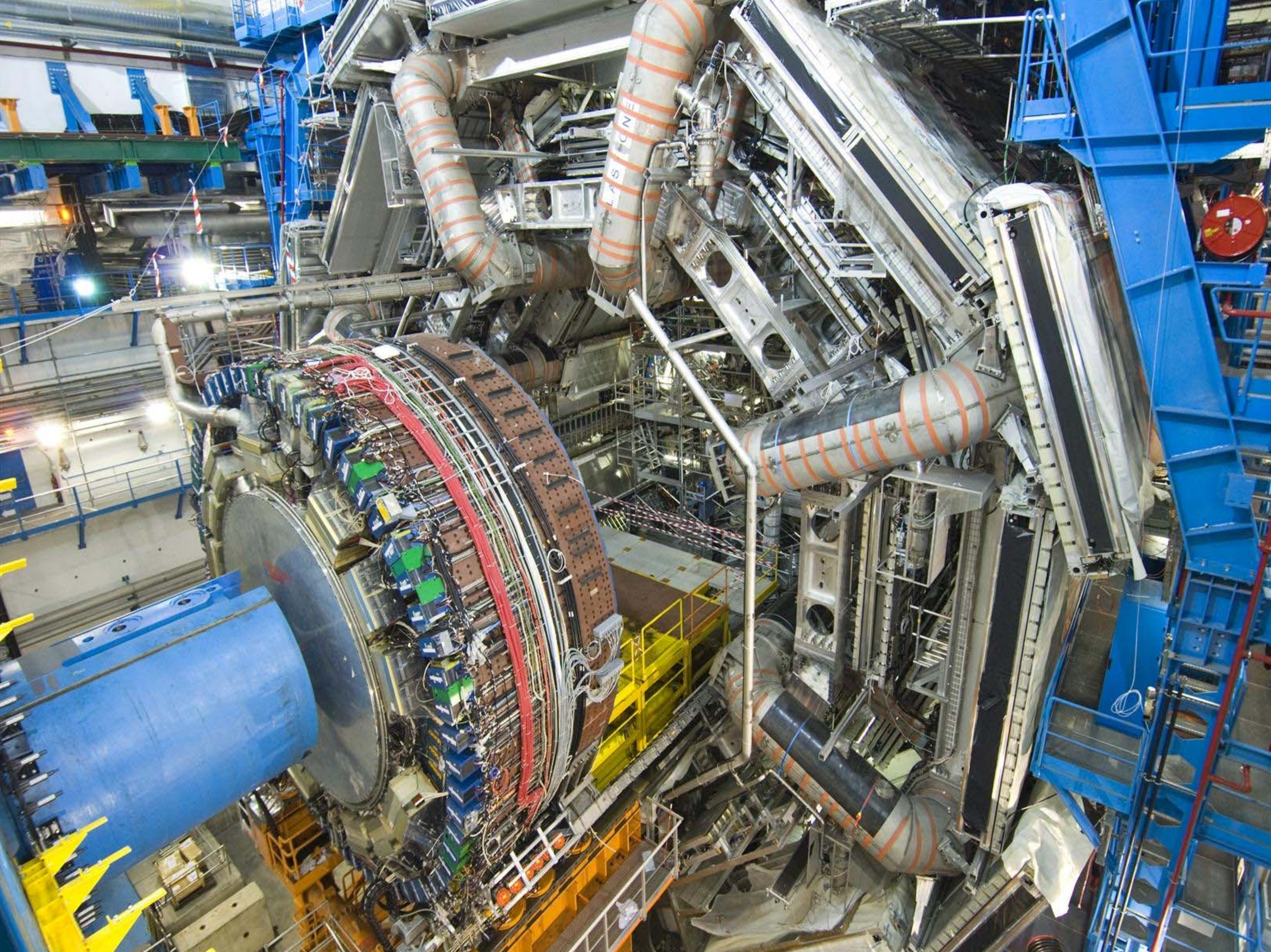
EM Calorimetry
- Pb-LAr
- $\sigma/E \sim 10\%/\sqrt{E(GeV)} \oplus 1\%$
- $|\eta|<3.2$, $|\eta| < 2.5$ (fine granularity)

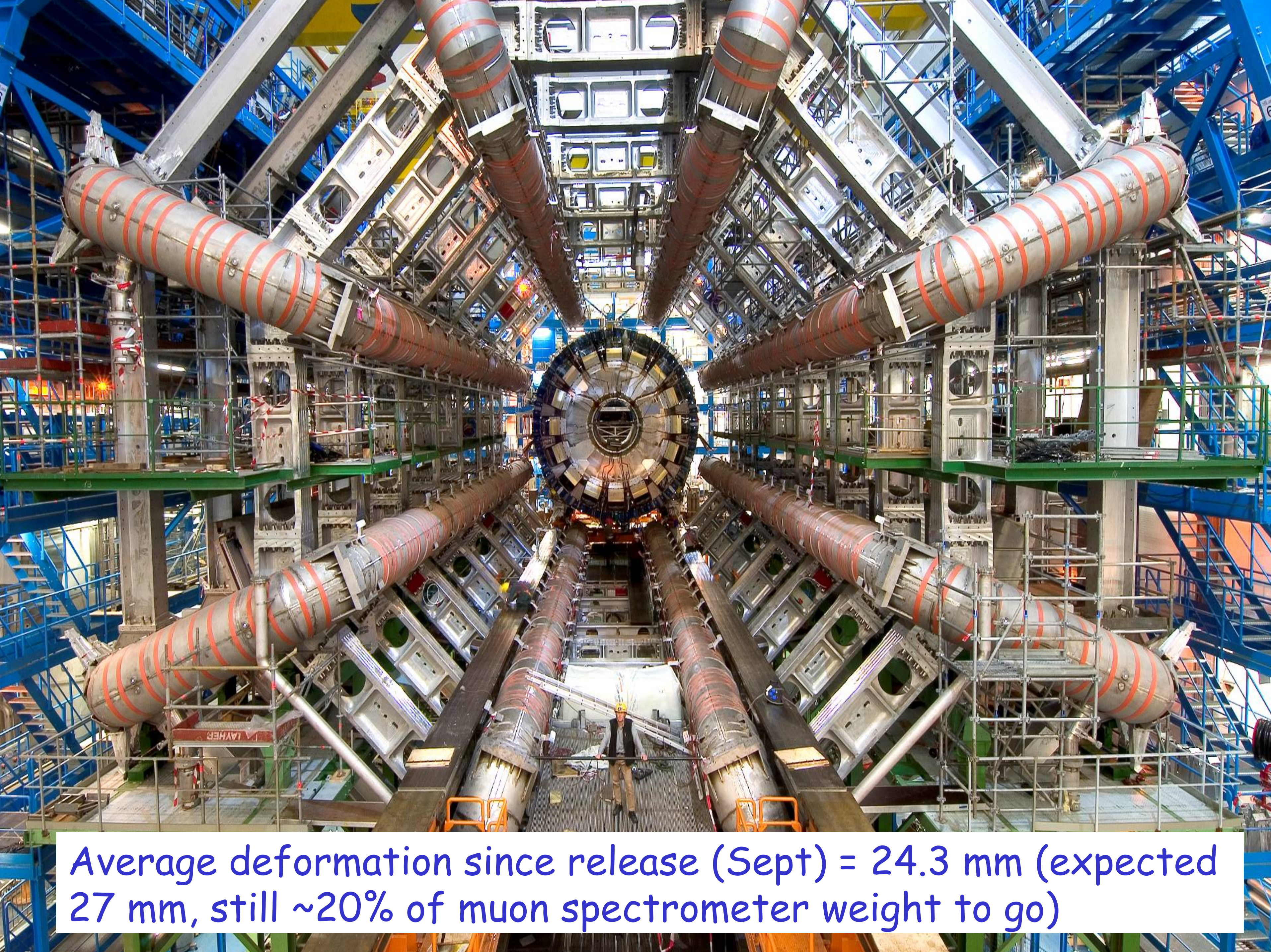
Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
Channels: ~ 10^8
L_{cable}: ~ 3000 km



Inner detector
- Si pixels and strips
- Transition Radiation Detector (e/π separation)
- $\sigma/p_T \sim 0.05\%\ p_T(GeV) \oplus 0.1\%$;
- $|\eta| < 2.5$, B=2 T(central solenoid)

Hadron Calorimeter
- Fe/scintillator (central), Cu/W-LAr (fwd)
- $\sigma/E \sim 50\%/\sqrt{E(GeV)} \oplus 3\%$
- $|\eta|<3$



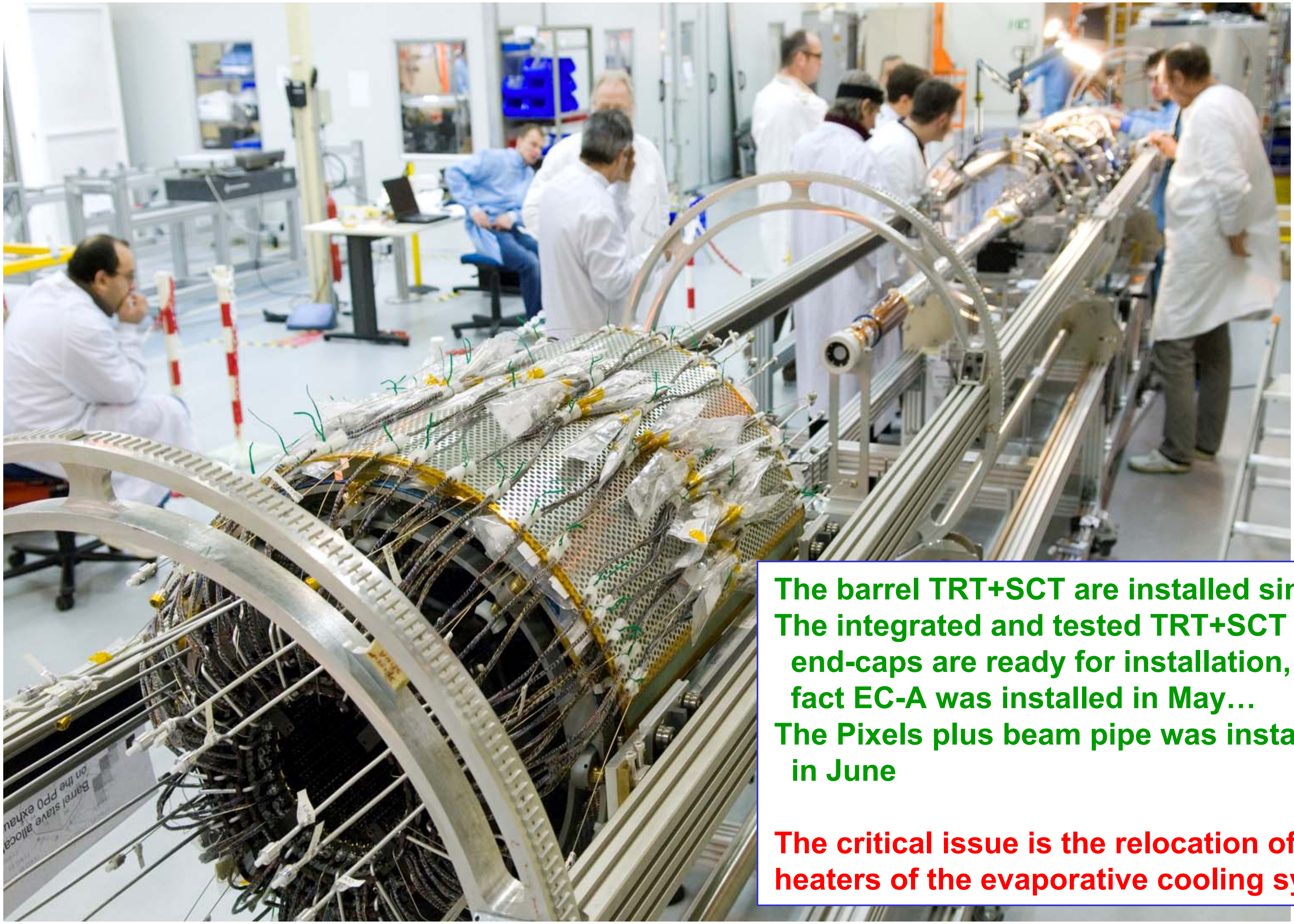


Average deformation since release (Sept) = 24.3 mm (expected 27 mm, still ~20% of muon spectrometer weight to go)

Toroid System - 4 T

Barrel Toroid parameters	End-Cap Toroid
25.3 m length	5.0 m axial length
20.1 m outer diameter	10.7 m outer diameter
8 coils	2x8 coils
1.08 GJ stored energy	2x0.25 GJ stored energy
370 tons cold mass	2x160 tons cold mass
830 tons weight	2x240 tons weight
4 T on superconductor	4 T on superconductor
56 km Al/NbTi/Cu conductor	2x13 km Al/NbTi/Cu conductor
20.5 kA nominal current	20.5 kA nominal current
4.7 K working point	4.7 K working point

Inner Detector status

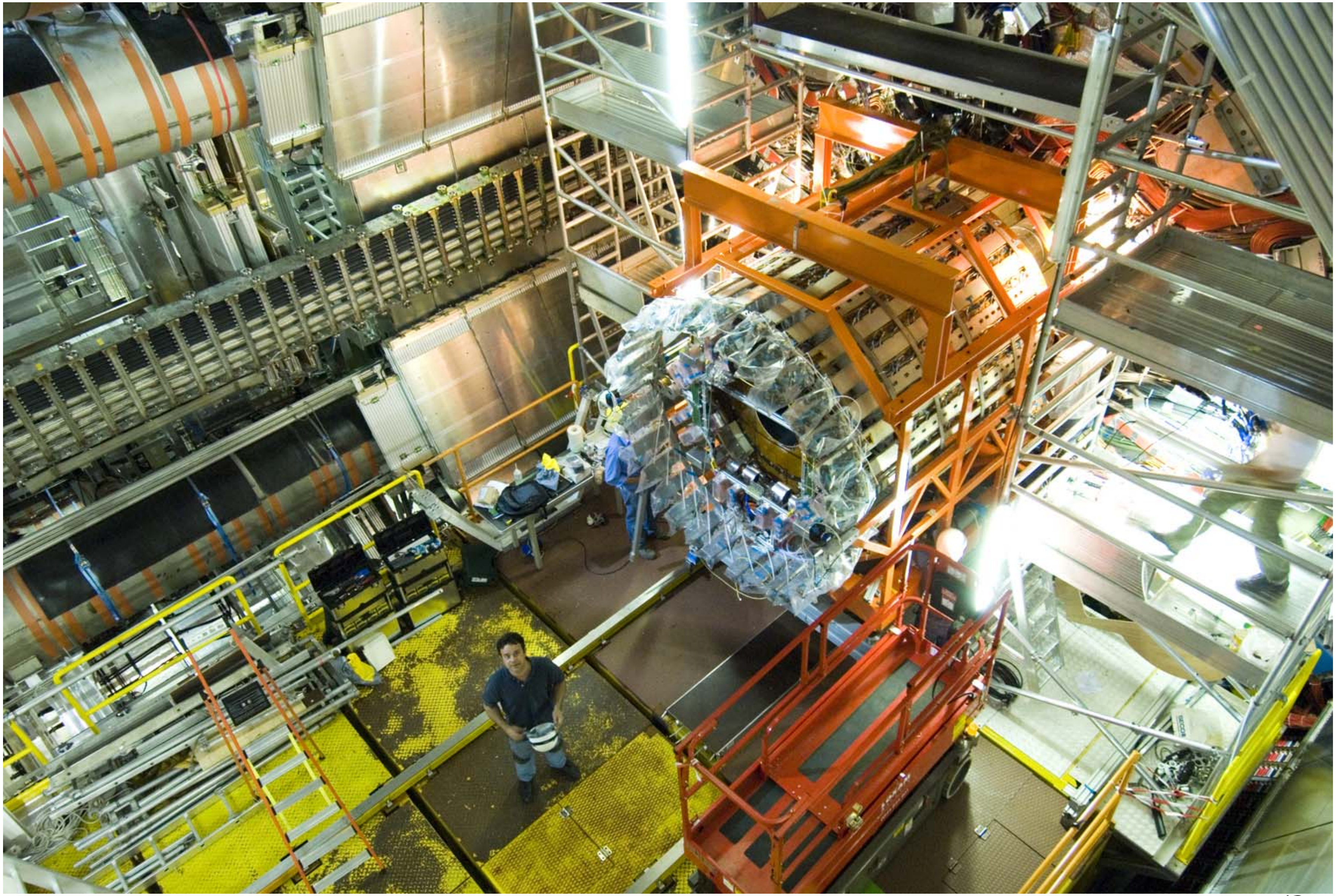


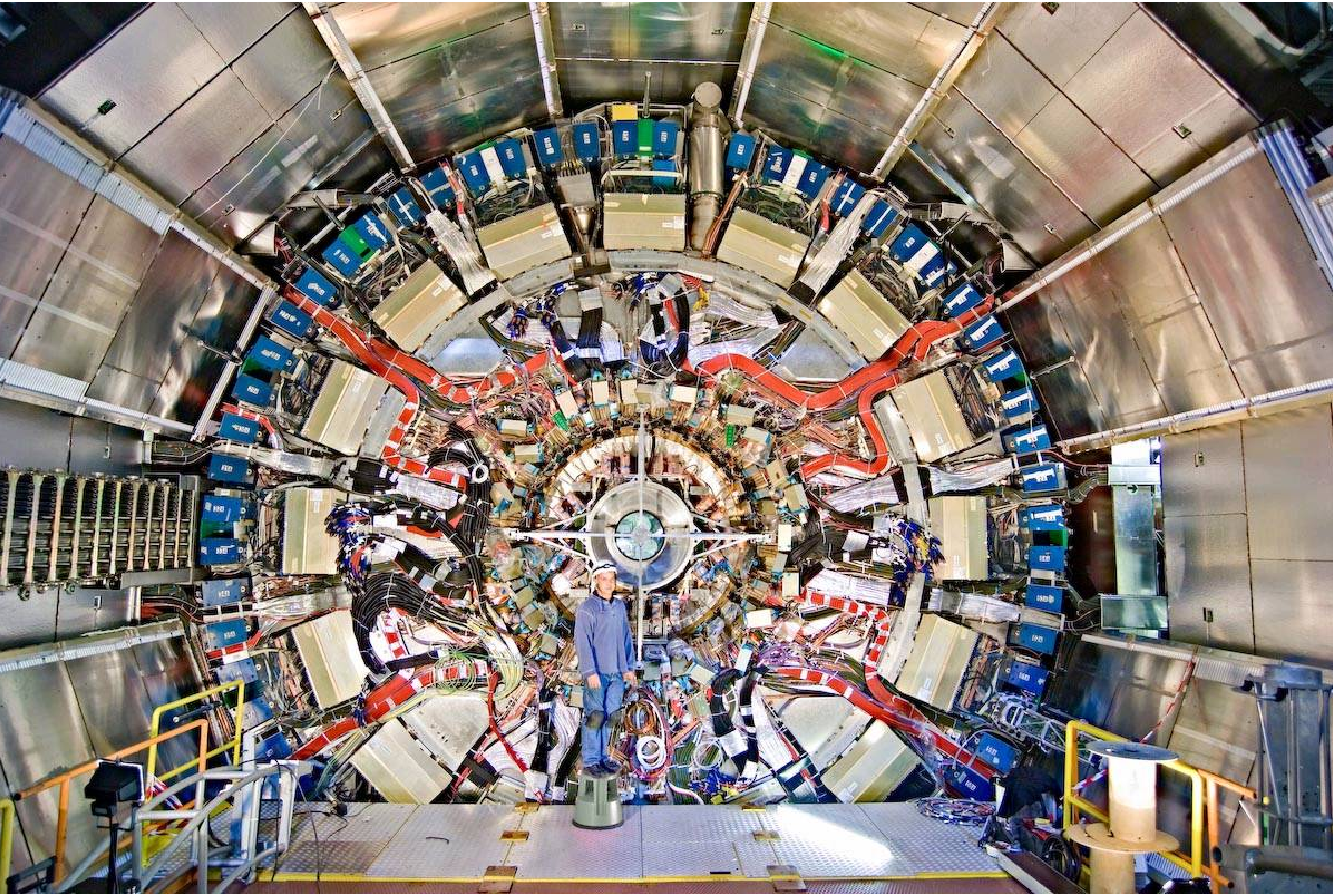
The barrel TRT+SCT are installed since long
The integrated and tested TRT+SCT end-caps are ready for installation, in fact EC-A was installed in May…
The Pixels plus beam pipe was installed in June

The critical issue is the relocation of the heaters of the evaporative cooling system

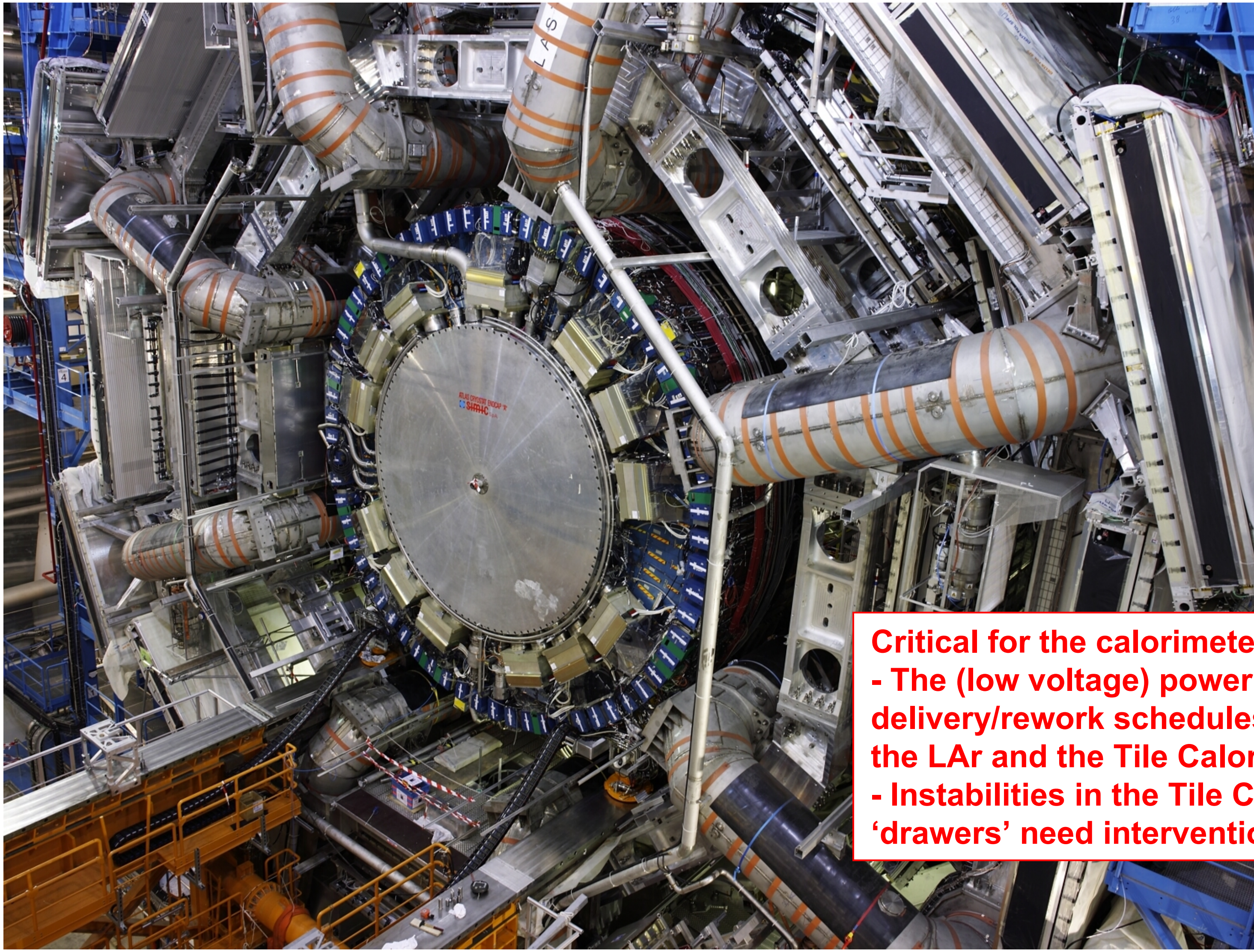
ATLAS Pixel detector integration (barrel, end-caps and beam pipe)

End-cap TRT+SCT side A was lowered into the detector on 24th May 2007





Calorimeter status



Critical for the calorimeters are:
- The (low voltage) power supply delivery/rework schedules for the LAr and the Tile Calorimeters
- Instabilities in the Tile Calorimeter ‘drawers’ need interventions

ATLAS side A (with the calorimeter end-cap partially inserted, the LAr end-cap is filled with LAr)

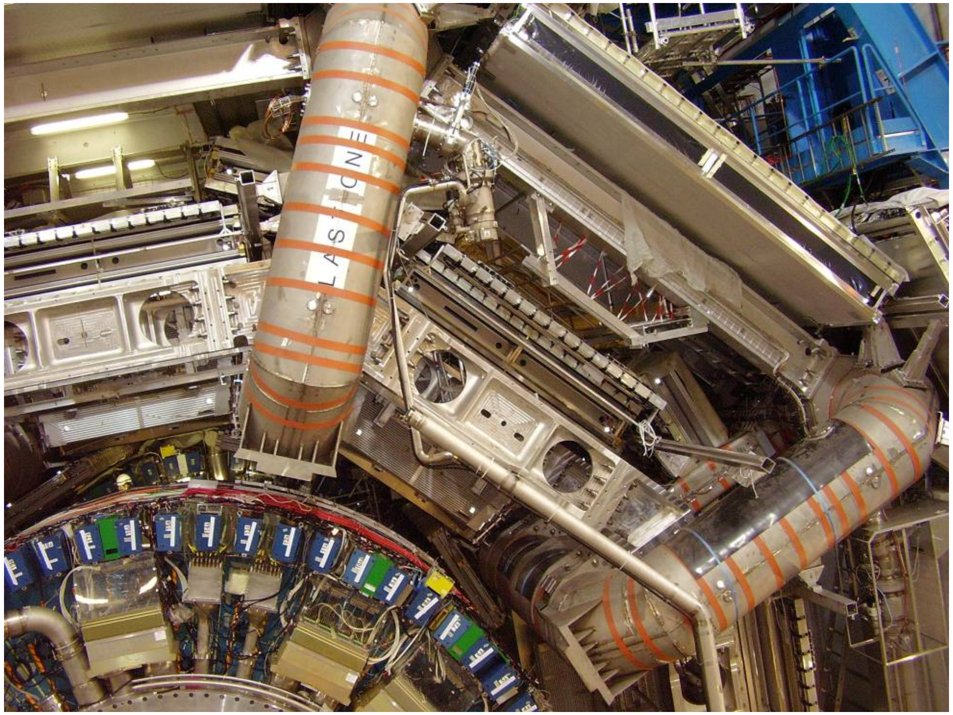
Muon system status

First complete MDT Big Wheel

Muon barrel chamber installation is nearing completion (~ 99% done)

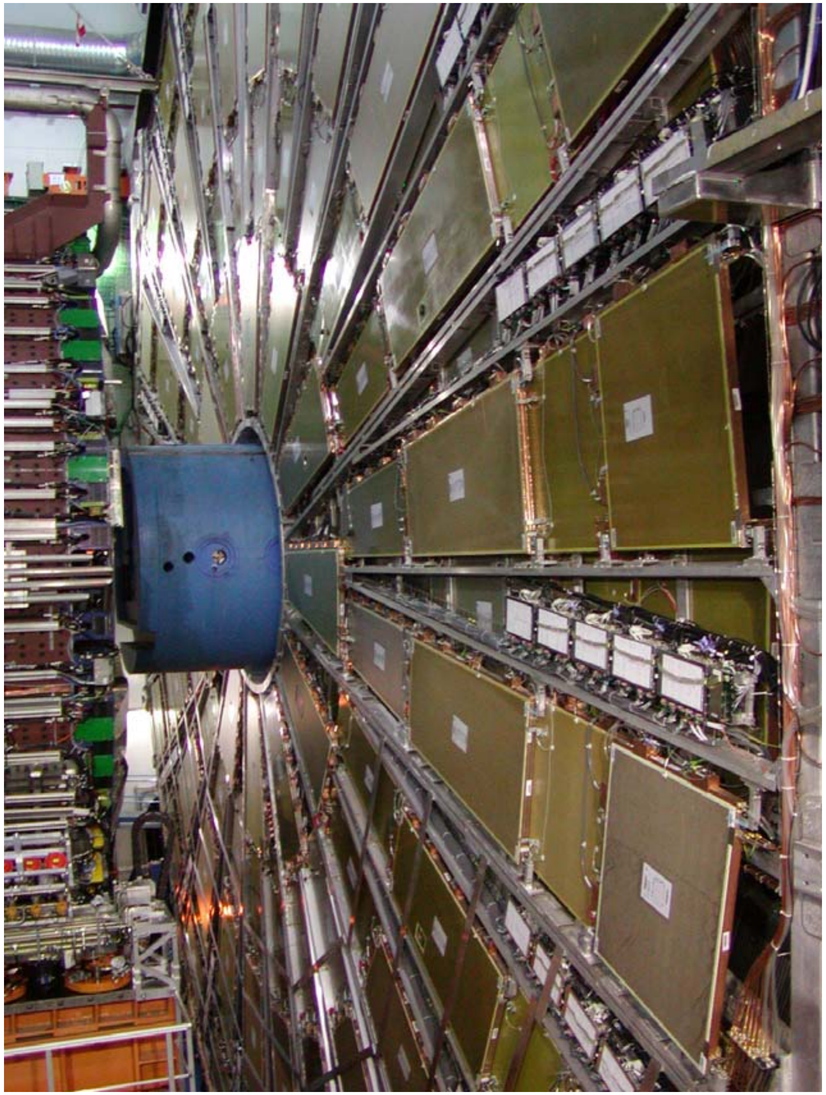
End-cap muon installation is now progressing in parallel on both sides (60% done)

Critical is the late delivery of power supplies from CAEN for the whole muon system, last ones will only be available in April 2008



Barrel muon stations

ATLAS Detector – UMich Group



End-Cap Toroids

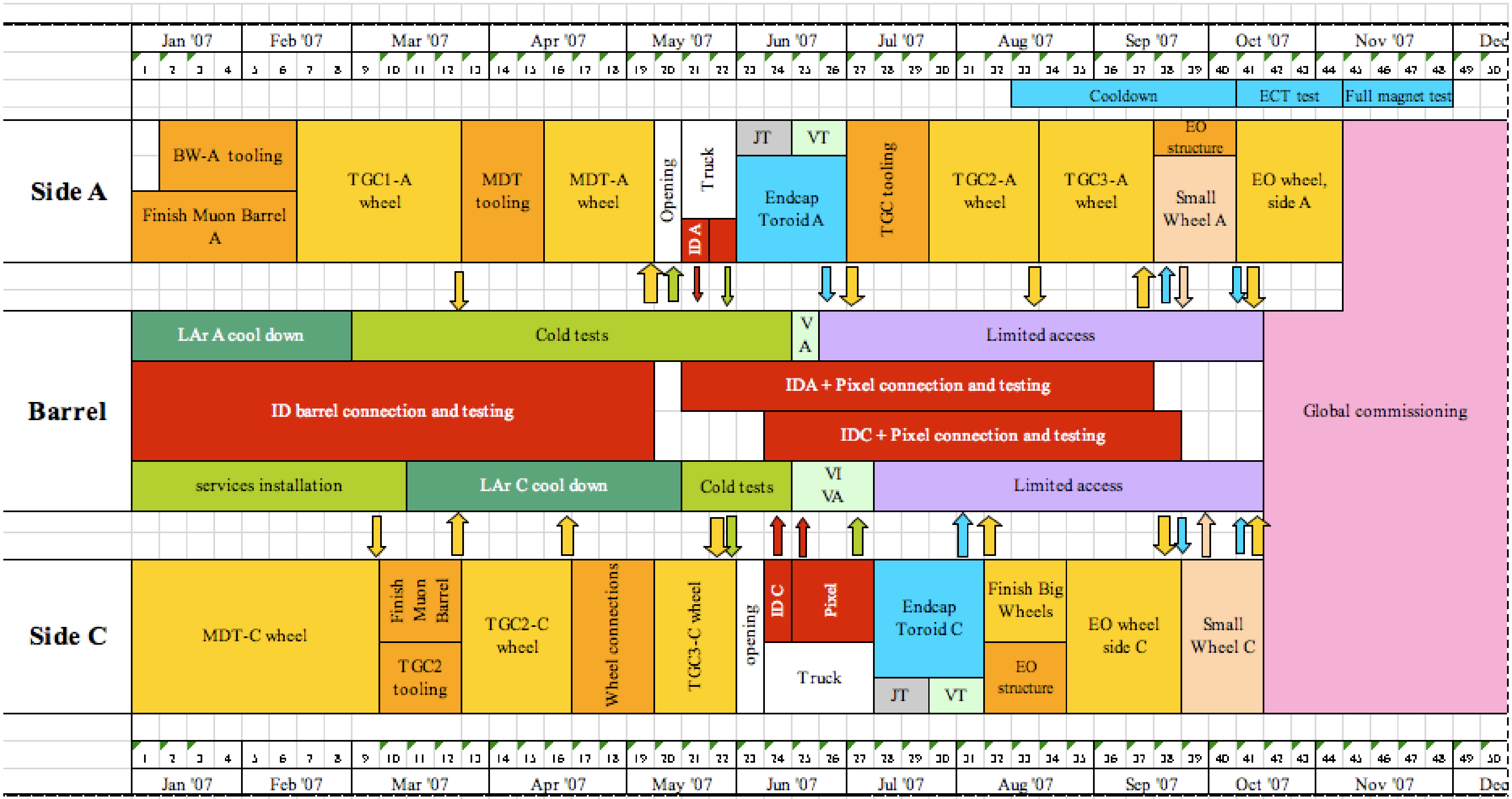
The first End-Cap Toroid was transported from Hall 191 to the outside test station in front of Hall 180 where it was mechanically cold tested at LN temperature (excellent results)

The integration of the second ECT went also well, and the tests just ended now in Hall 191

ECT-C installation to follow in early July

ATLAS Installation schedule version 9.1

M. Kotamäki, M.Nessi
20-Apr-2007

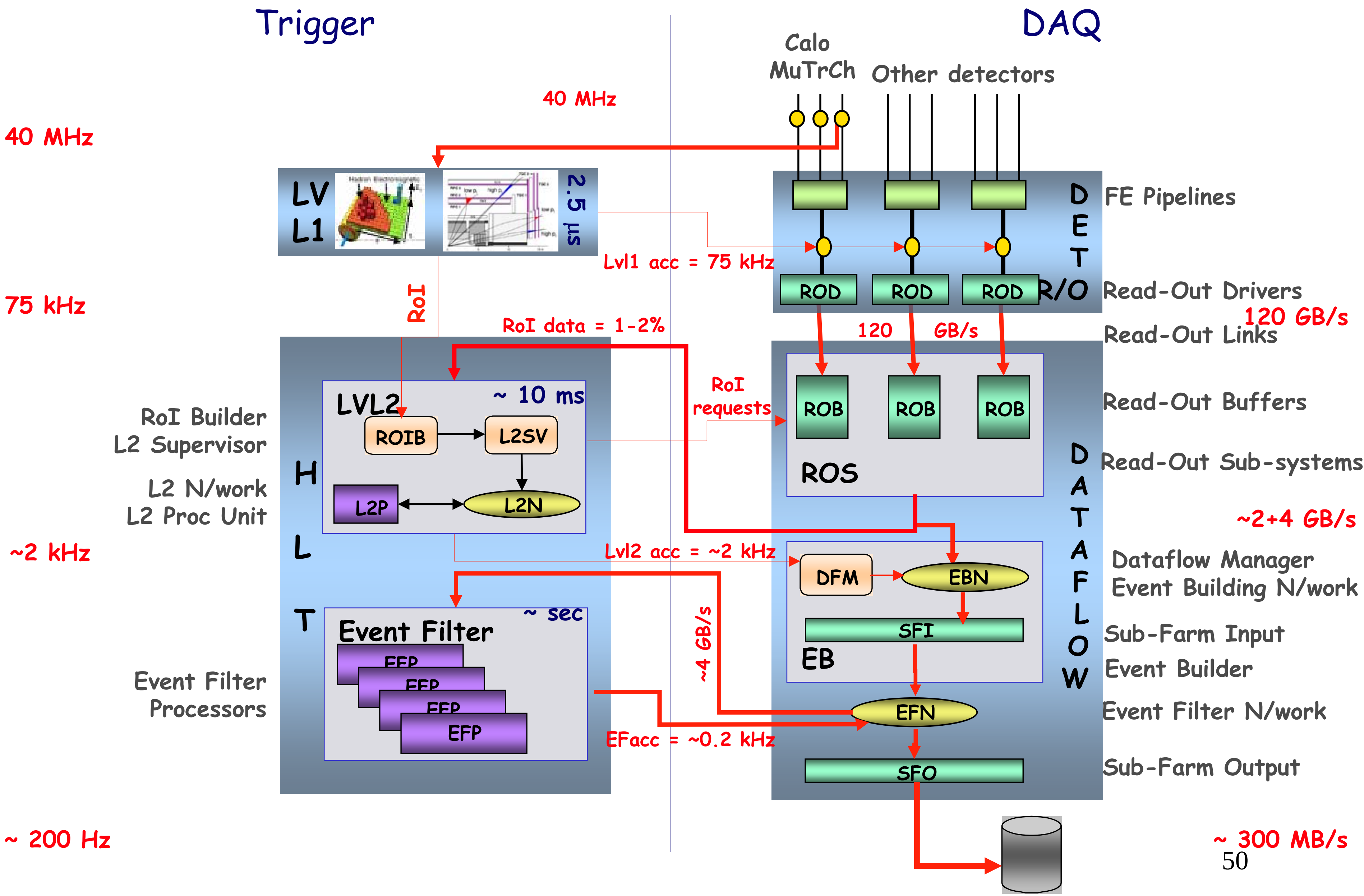


ATLAS main control room

The control room is operational and used during the cosmic ray commissioning runs integrating gradually more and more detector components

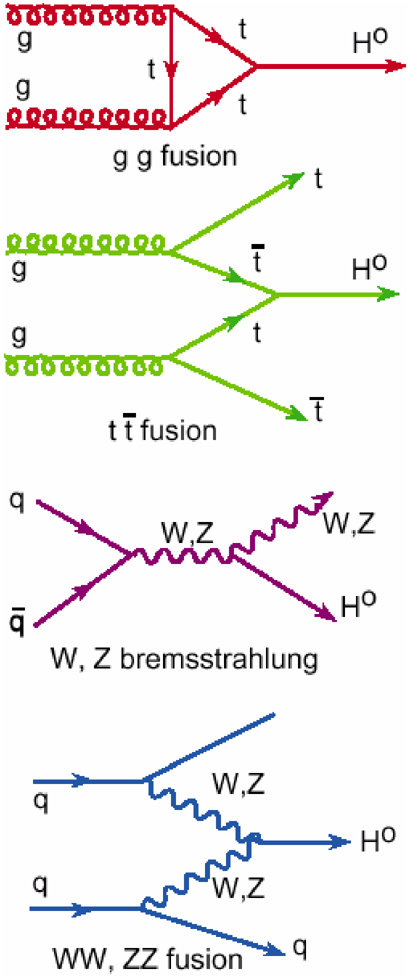
Cosmic ray data is collected through segments of the full final Event Building and DAQ system

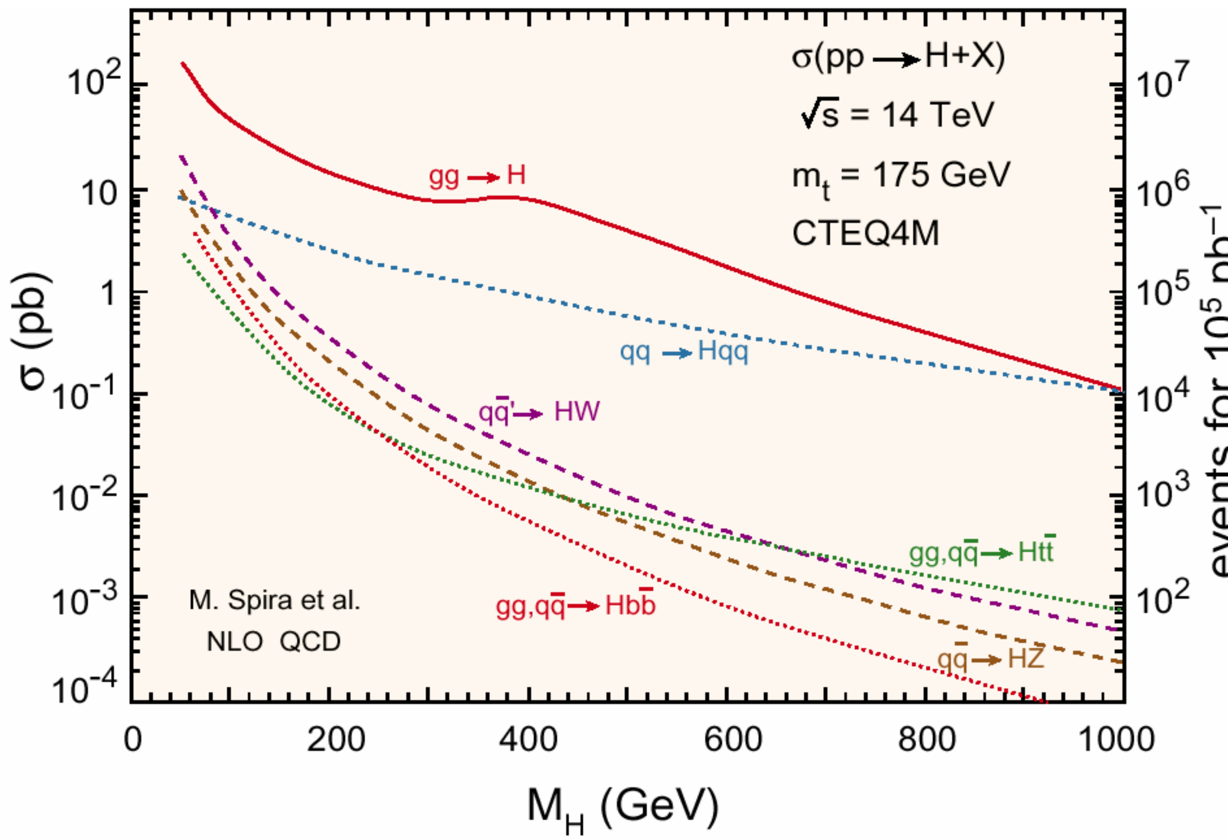
Trigger, DAQ and Detector Control



LHC Discovery Potential

Higgs Production at LHC

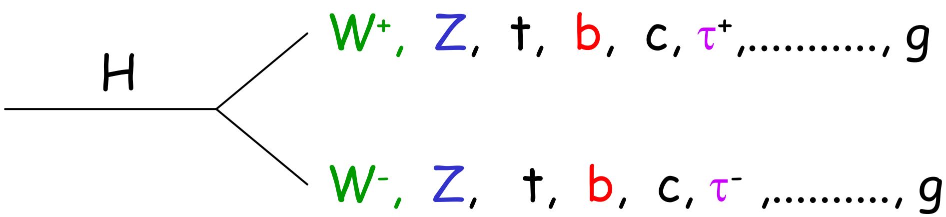




Having available four production mechanisms is a key for measurements of Higgs parameters

Properties of the Higgs Boson

The decay properties of the Higgs boson are fixed, if the mass is known:



$$\Gamma(H \to f\bar{f}) = N_C \frac{G_F}{4\sqrt{2}\pi} m_f^2(M_H^2)\, M_H$$

$$\Gamma(H \to VV) = \delta_V \frac{G_F}{16\sqrt{2}\pi} M_H^3 \,(1 - 4x + 12x^2)\, \beta_V$$

where: $\delta_Z = 1, \delta_W = 2, \quad x = M_V^2/M_V^2, \quad \beta =$ velocity

$$\Gamma(H \to gg) = \frac{G_F\ \alpha_s^2(M_H^2)}{36\sqrt{2}\pi^3} M_H^3 \left[1 + \left(\frac{95}{4} - \frac{7N_f}{6}\right)\frac{\alpha_s}{\pi}\right]$$

$$\Gamma(H \to \gamma\gamma) = \frac{G_F\ \alpha^2}{128\sqrt{2}\pi^3} M_H^3 \left[\frac{4}{3} N_C e_t^2 - 7\right]^2$$

Higgs Boson:

- It couples to particles proportional to their masses
- decays preferentially in the heaviest particles kinematically allowed

BR and Discovery Channels

Low mass region: m(H) < 2 m_Z

H → γγ,

H → bb

H → ττ, via VBF

H → ZZ* → 4ℓ

H → WW* → ℓνℓν or ℓνjj, via VBF

m(H) > 2 m_Z

H → ZZ → 4ℓ

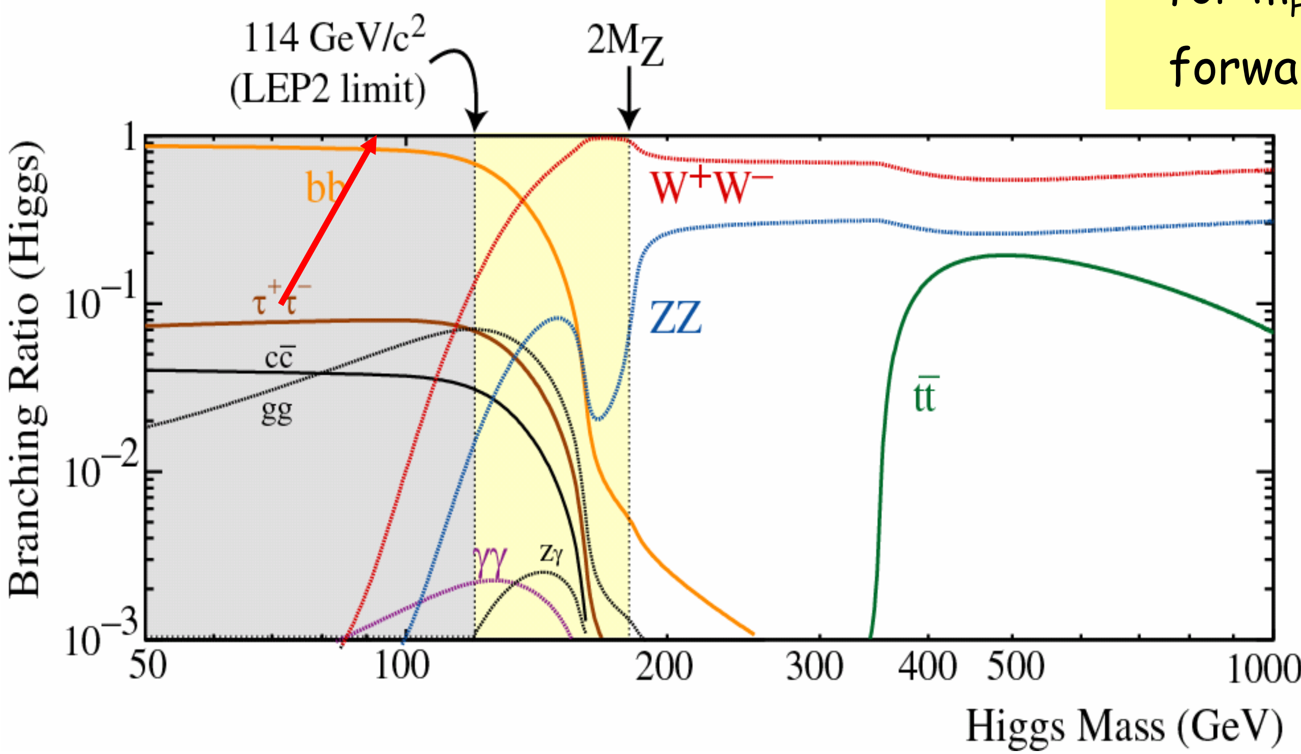
qqH → ZZ → ℓℓ νν *

qqH → ZZ → ℓℓ jj *

qqH → WW→ ℓνjj *

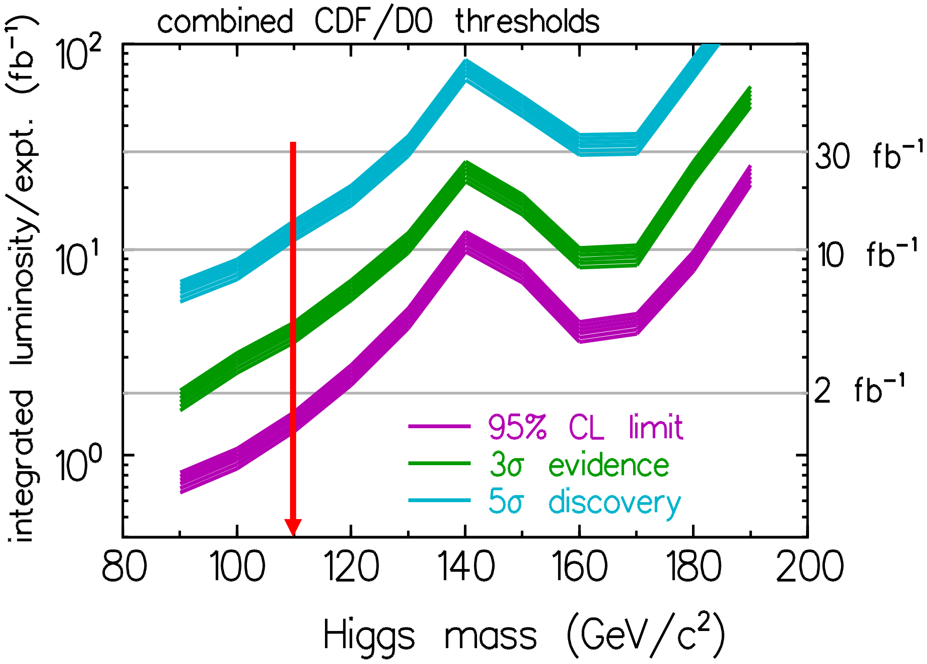
* for m_H > 300 GeV

forward jet tag



Tevatron Discovery Potential for LMH

Discovery in a single channel is not possible at Tevatron



For 10 fb^{-1}

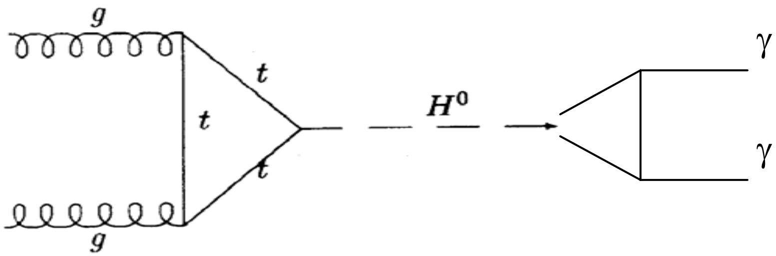
- 95% CL exclusion of a SM Higgs boson is possible over the full mass range (M_H<185 GeV)
- 3σ evidence for M_H < 130 GeV and 155 GeV < M_H < 175 GeV

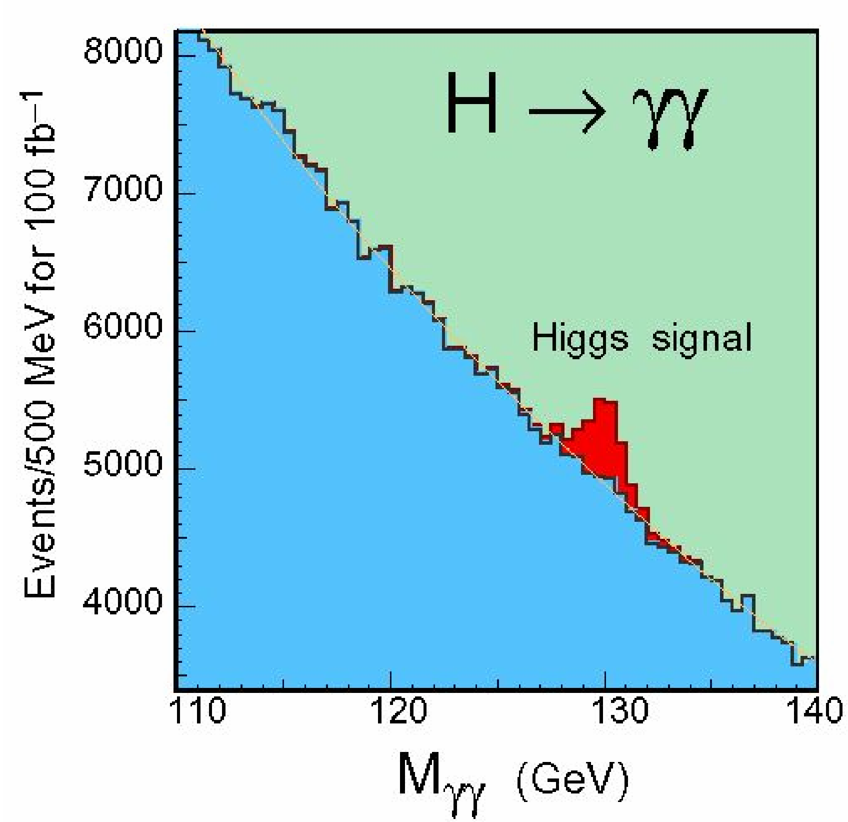
For 30 fb^{-1}

- 3σ evidence for the SM Higgs boson is possible over the full mass range (M_H < 185 GeV)

It's extremely important to search for Higgs at LHC in mass region 114 < m_H < 300 GeV.

Direct H $\to \gamma\gamma$



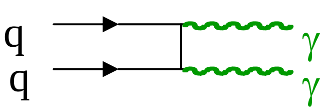


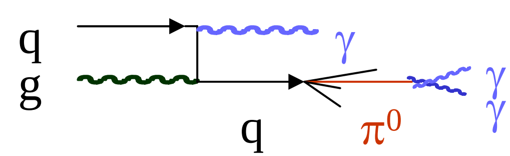
Background

dominated by smooth $\gamma\gamma$ pairs

- Irreducible

$gg\to\gamma\gamma$, $qq\to\gamma\gamma$, $qg\to q\gamma\to q\gamma\gamma\gamma$





Signal significance:

$2.8\sim4.3\sigma$ for 100fb^{-1}

VBF for Heavy Higgs

200 GeV < M_h < 600 GeV

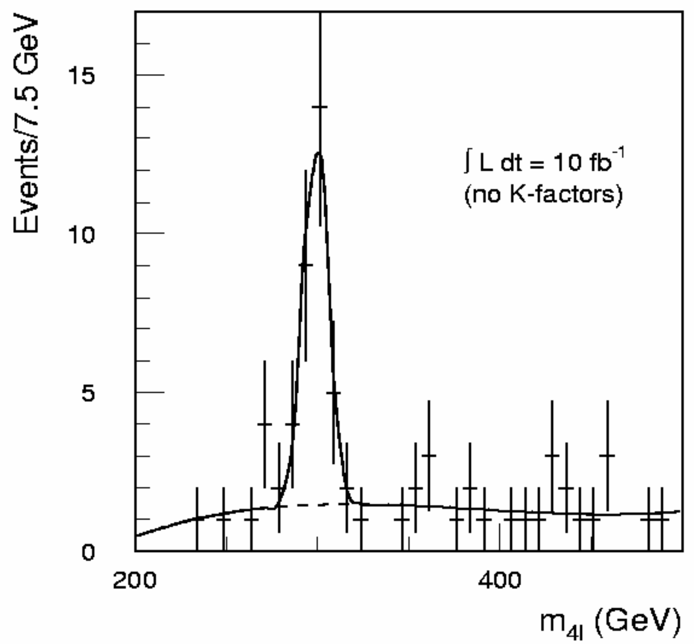
- Discovery in $h \to ZZ \to l^+l^- l^+l^-$
  - Background smaller than signal
  - Higgs width larger than exp. resolution (M_h > 300 GeV)
- Confirmation in $h \to ZZ \to l^+l^- jj$ channel

Mh > 600 GeV

- 4 lepton channel $h \to ZZ \to l^+l^- \nu\nu$ statistically limited
- $h \to ZZ \to l^+l^- jj$, $h \to WW \to l \nu jj$ has significantly larger BR than 4l channel

Golden Channel

$h \to ZZ \to l^+l^- l^+l^-$

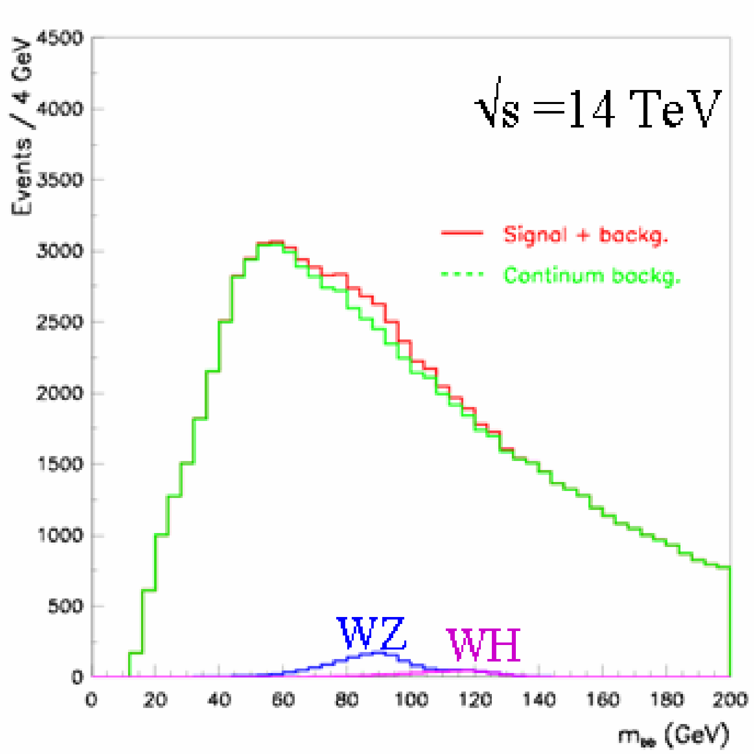


LMH Search: WH, $H \to b\bar{b}$

Expected WH, $H \to b\bar{b}$ signal and background rates for $L = 30\ fb^{-1}$

m_H (GeV)	80	100	120
WH, H→bb	**650**	**416**	**250**
WZ, Z→bb	**540**	**545**	**220**
Wbb	**3400**	**3650**	**2000**
tt→WWbb	**2500**	**3700**	**3700**
tb,tbq	**500**	**740**	**740**
Wbj, Wjj	**12500**	**7600**	**4160**
Total bkgd	**19440**	**16235**	**10820**
S/√B (syst.)	**3.0**	**1.9**	**1.7**

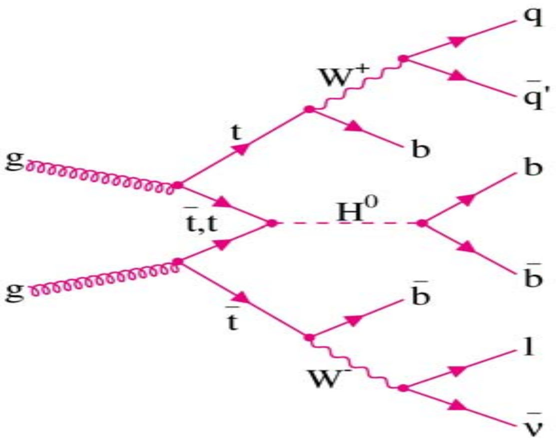
$M_H = 120$ GeV, $100\ fb^{-1}$



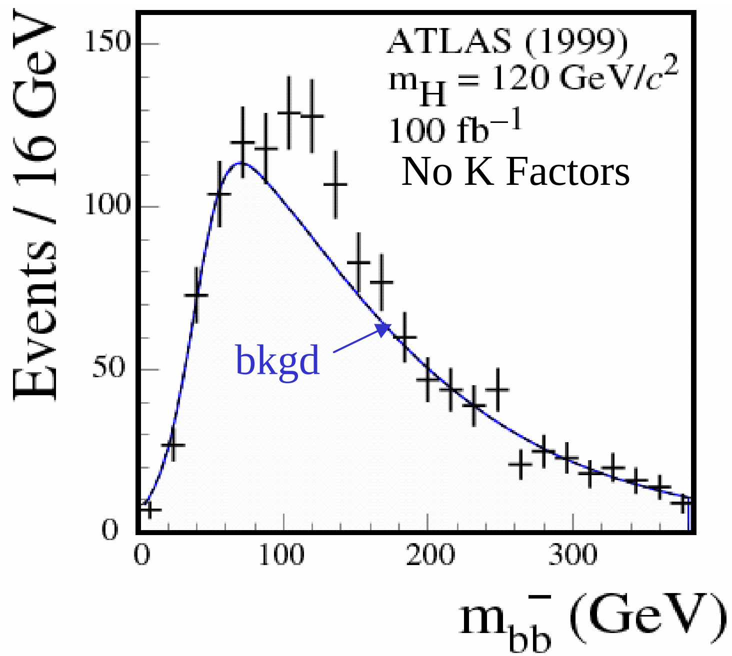
Difficult at LHC

LMH Searches: ttH → ttbb

- Complicated final state
- Trigger $W_1 \to \ell\nu$ and $W_2 \to qq$
- Require excellent b-tagging, and both t's are fully reconstructed
- Crucial to know the shape of the residual bkg from ttjj



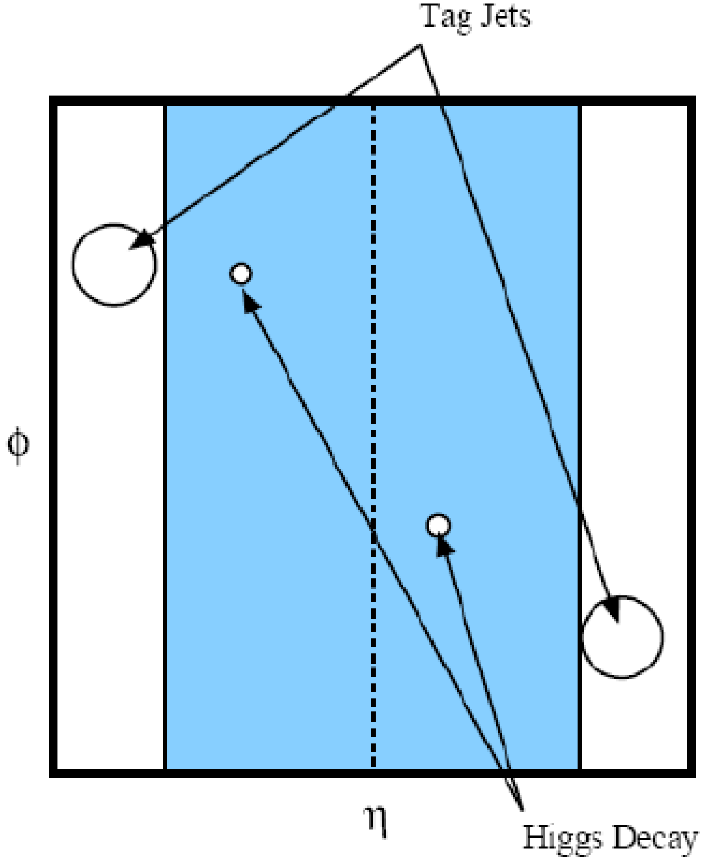
Expected ttH signal and bkg rates for L=30/100 fb^{-1}



m_H(GeV)	80	100	120
ttH →ttbb	81/140	61/107	40/62
ttZ	7/13	8/13	2/5
Wjjjjjj	17/35	12/15	5/10
ttjj	121/247	130/250	120/240
Total bkg	145/295	150/278	127/257
S/√B	6.7/8.2	5.0/6.4	3.6/3.9

VBF H→ττ, WW

- At low Higgs masses the largest sensitivity search channels are found in the vector boson fusion production mode.
- At least one of the W/τ's have to decay leptonically.
- Main backgrounds are $t\bar{t}$, Wt, WW+jets, γ^*/Z+jets.
- Some selection criteria ($e\mu$):
  - $p_T^e > 15$ GeV, $p_T^\mu > 10$ GeV.
  - $|\eta_\ell| < 2.5$ and $M_{\ell\ell} < M_H/2$.
  - Tag jet cuts, central jet veto.
- τ reconstruction provide extra sensitivity or rejection.

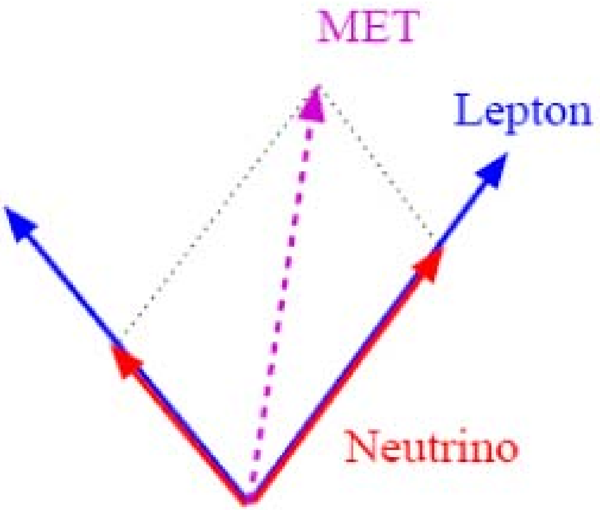


VBF H $\to \tau\tau$

$qq\,H \to qq\,\tau\,\tau$

$\to qq\ \ell\nu\nu\ \ell\nu\nu$

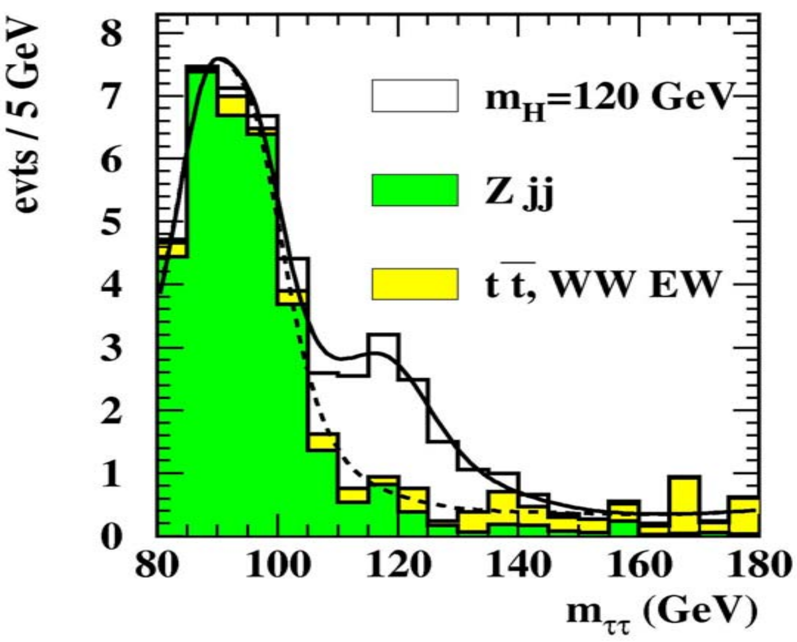
$\to qq\ \ell\nu\nu\ h\nu$



- Decay modes visible for a SM Higgs boson in VBF

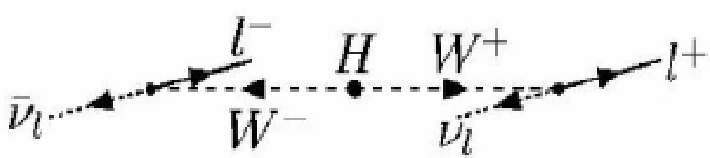
- large boost (high-P_T Higgs)
  - collinear approximation: assume neutrinos go in the direction of the visible decay products
  - Higgs mass can be reconstructed

- Main background: Z jj, $Z \to \tau\tau$



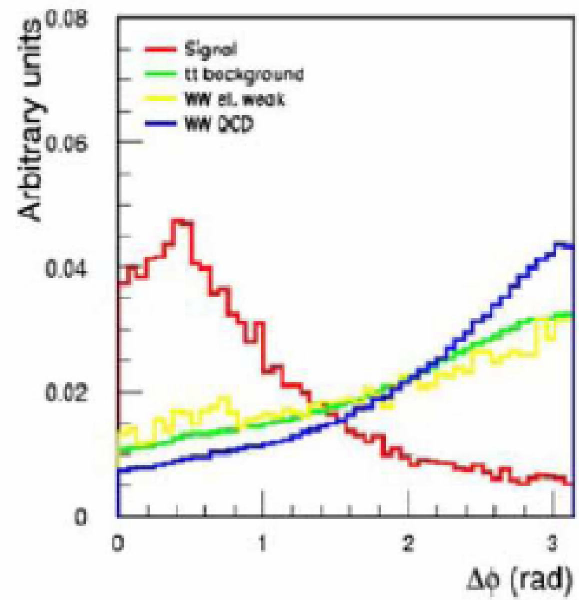
H → WW

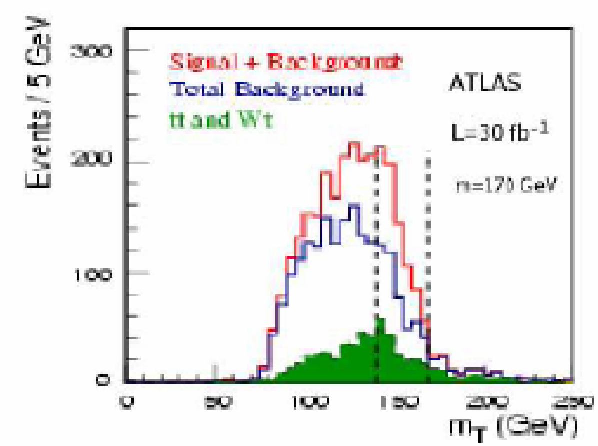
- $BR(H \to WW)$ is nearly 98% for a Higgs boson with $m_H \approx 160$ GeV.
- Backgrounds from WW, $t\bar{t}$, WZ.
- Use the lepton spin correlations:



- No mass peak, have to use m_T:

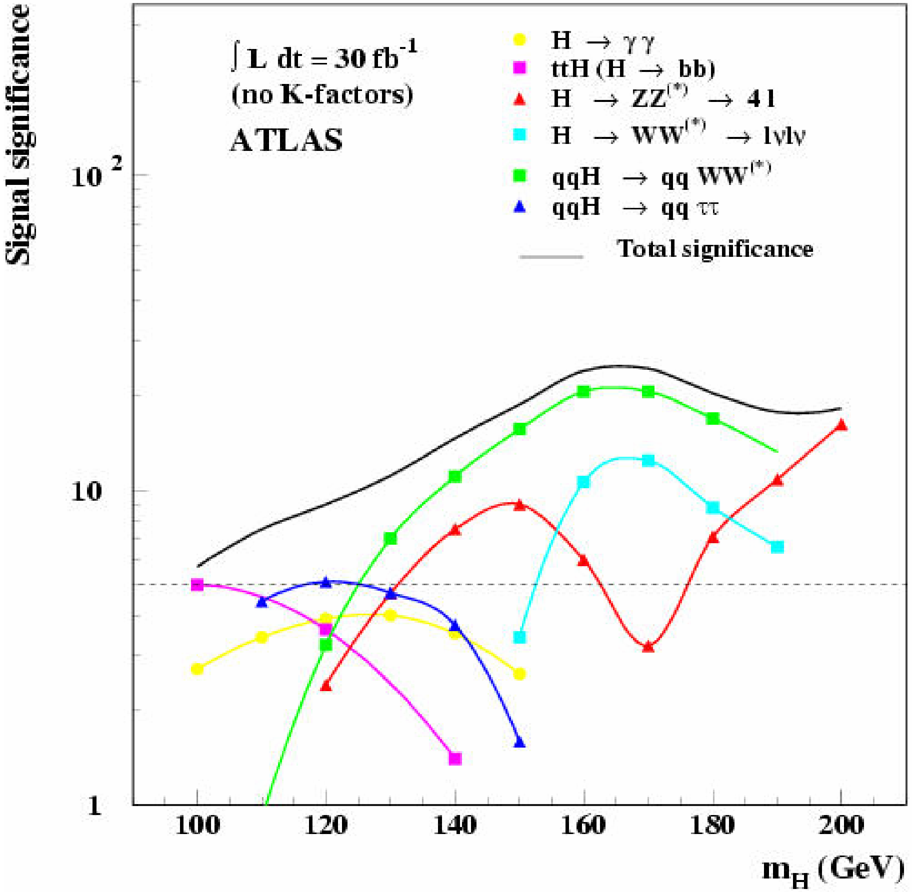
$$m_T = \sqrt{2 p_T^{\ell\ell} \not{E}_T (1 - \cos\Delta\phi)}$$





Signal significance: ATLAS

$k \equiv \sigma_{NLO}/\sigma_{LO}$ { 1.1-1.9 for signal.
Unknown in many case for bkg



LHC can probe entire set of "allowed" Higgs mass values (100 GeV–1 TeV) at least 2 channels for most of range

MSSM Higgs Bosons

SUSY: 5 Higgs particles H, h, A, H^+, H^-

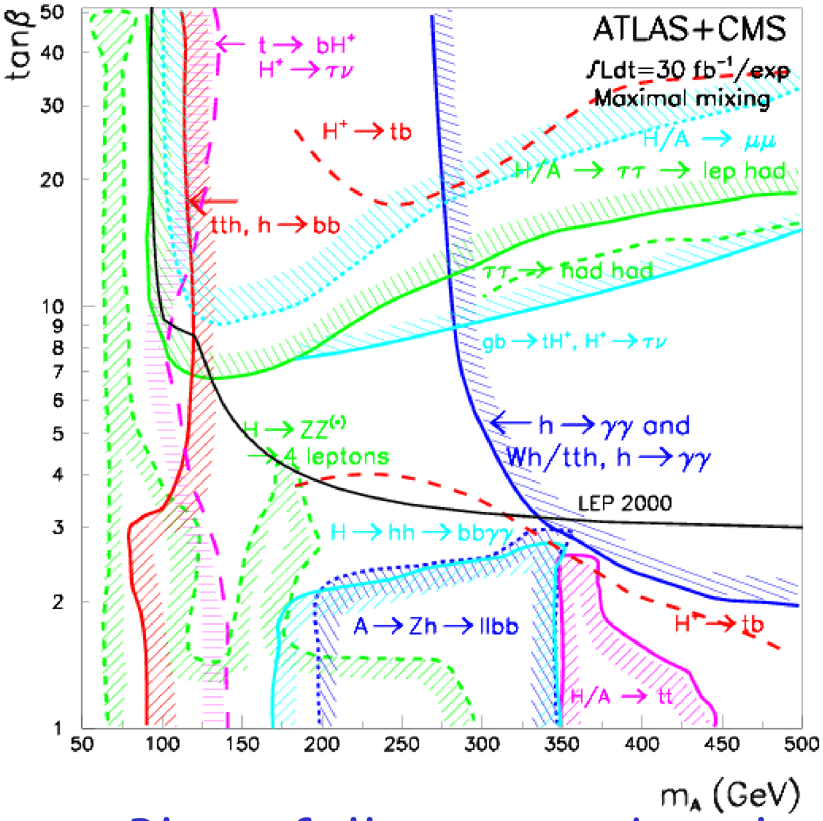
determined by two SUSY model parameters: m_A, $\tan\beta$

One of the Higgs bosons is light: $m_h < 135$ GeV

The others will most likely be heavy !

LHC Discovery Potential for MSSM Higgs Bosons

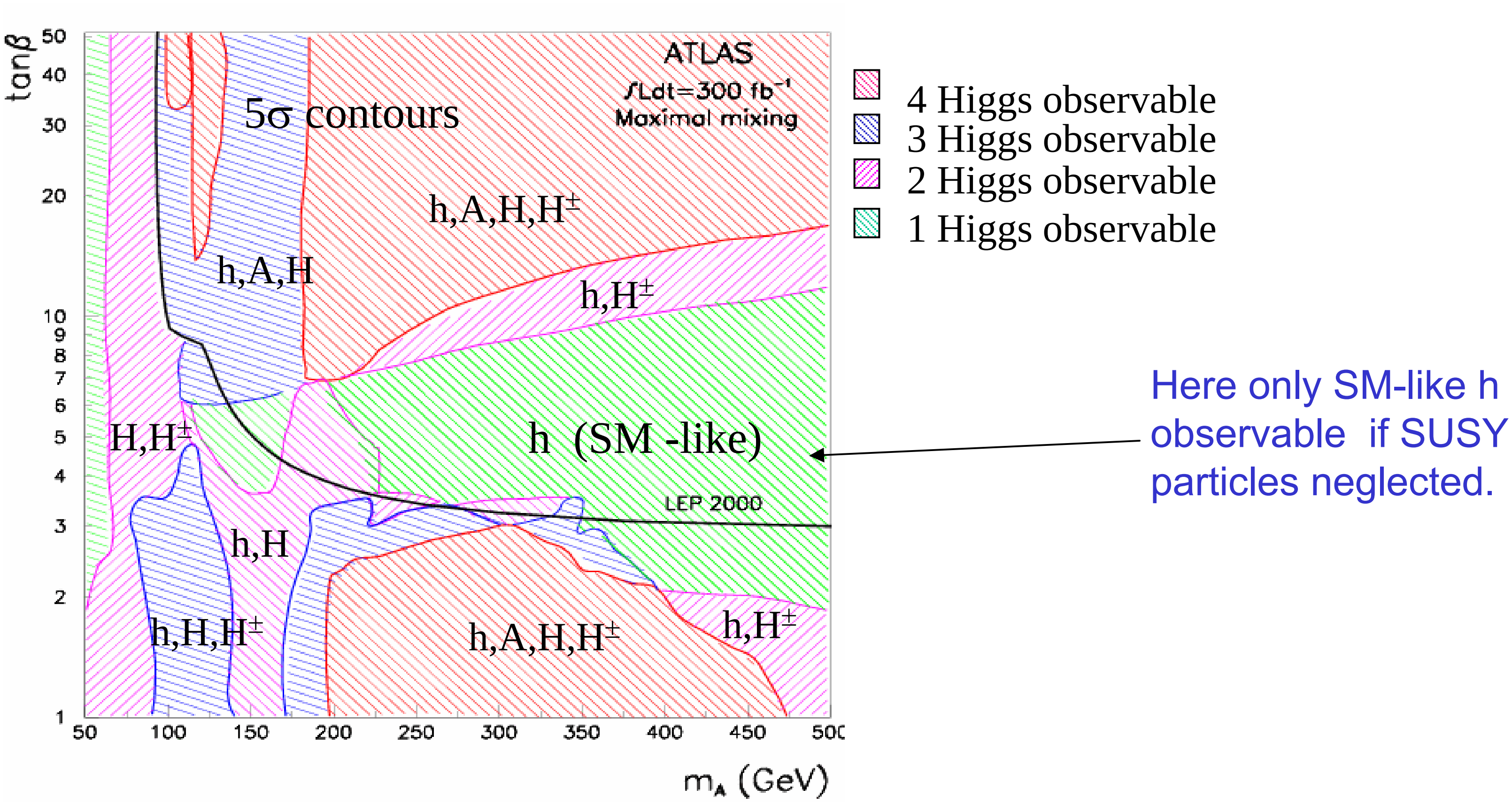
5σ discovery in m_A - tan β plane



- m_{SUSY} = 1 TeV, m_{top} = 175 GeV/c^2
-
- Two or more Higgs can be observed over most of the parameter space → disentangle SM / MSSM

- Plane fully covered at low L (30 fb^{-1})
- Main channels : h→gg, tth(h→bb), A/H→μμ, ττ , $H^{\pm}$ →τν

LHC discovery potential for SUSY Higgs bosons

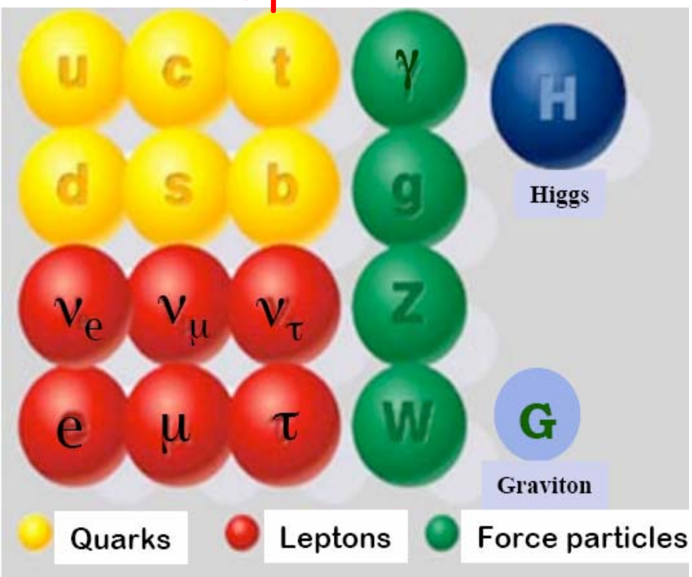


Parameter space is fully covered → in a SUSY world, Higgs bosons will be discovered at the LHC

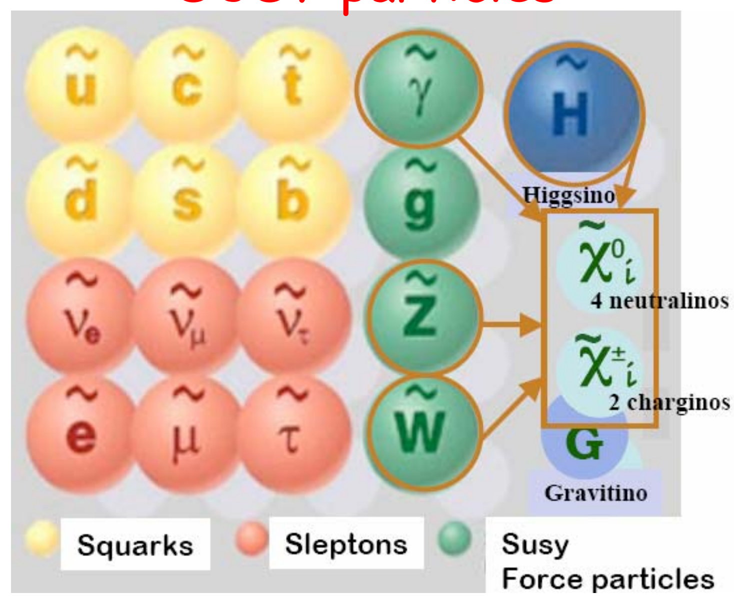
Supersymmetry

Extends the Standard Model by predicting a new symmetry
Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

SM particles



SUSY particles



New Quantum number: R-parity: $R_p = (-1)^{B+L+2s}$ = +1 SM particles
-1 SUSY particles

Consequences of R-parity conservation

- SUSY particles are produced in pairs

- Lightest Supersymmetric Particle (LSP) is stable.
  In most models LSP is also weakly interacting:
  LSP $\equiv \chi^0{}_1$ (lightest neutralino)

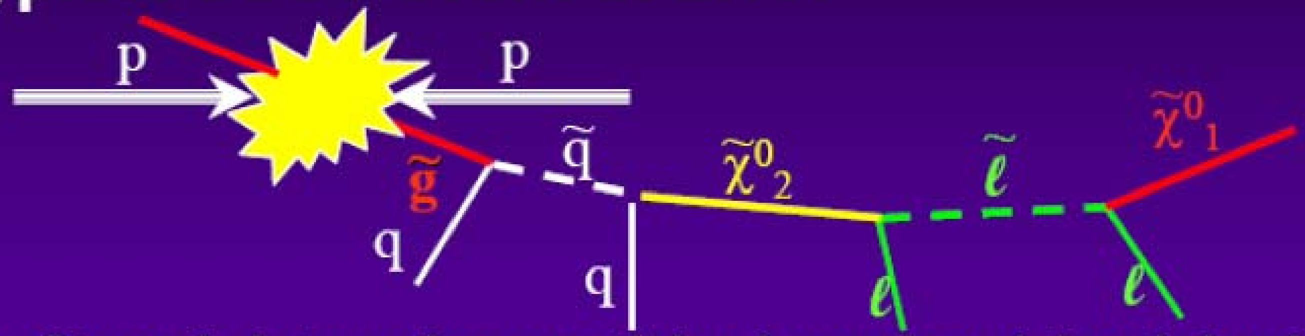
  - LSP is a good candidate for cold dark matter

  - LSP behaves like a ν $\rightarrow$ it escapes detection

  - very lager E_T^{miss} (typical SUSY signature)

Quick Search for SUSY Particles

Typical SUSY event at LHC:

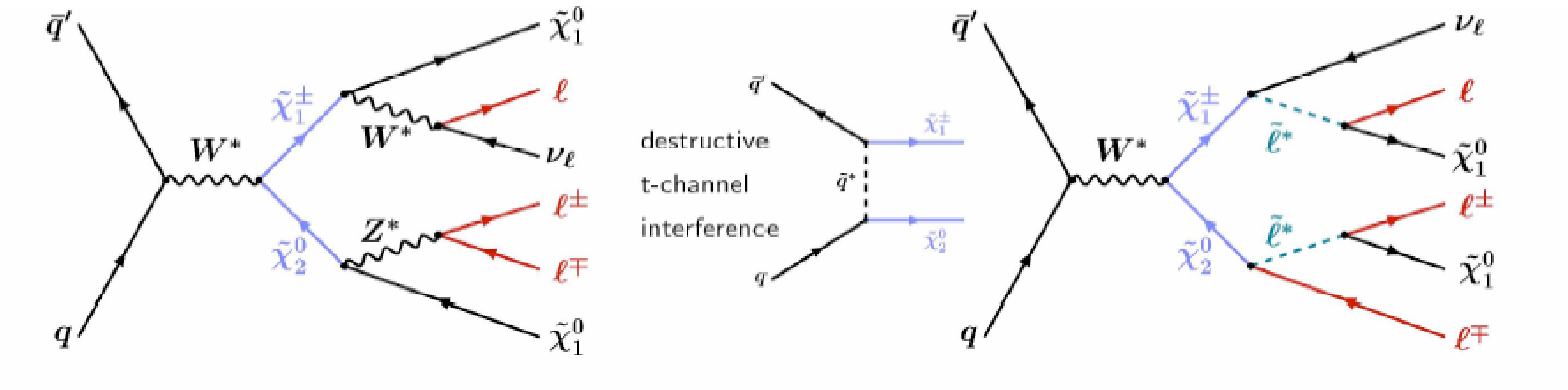


- Strongly interacting sparticles (squarks, gluinos) dominate production
  - Can have high cross-sections ⇒ good candidate for early discovery
- sleptons, gauginos etc. $\tilde{g}$ cascade decays to LSP.
- Long decay chains and large mass differences between SUSY states
  - Many high pT objects observed (leptons, jets, b-jets).
- If R-Parity conserved LSP stable and sparticles pair produced.
  - Large ETmiss signature
- Closest equivalent SM signature $t \rightarrow Wb$ with $W \rightarrow \ell \nu$

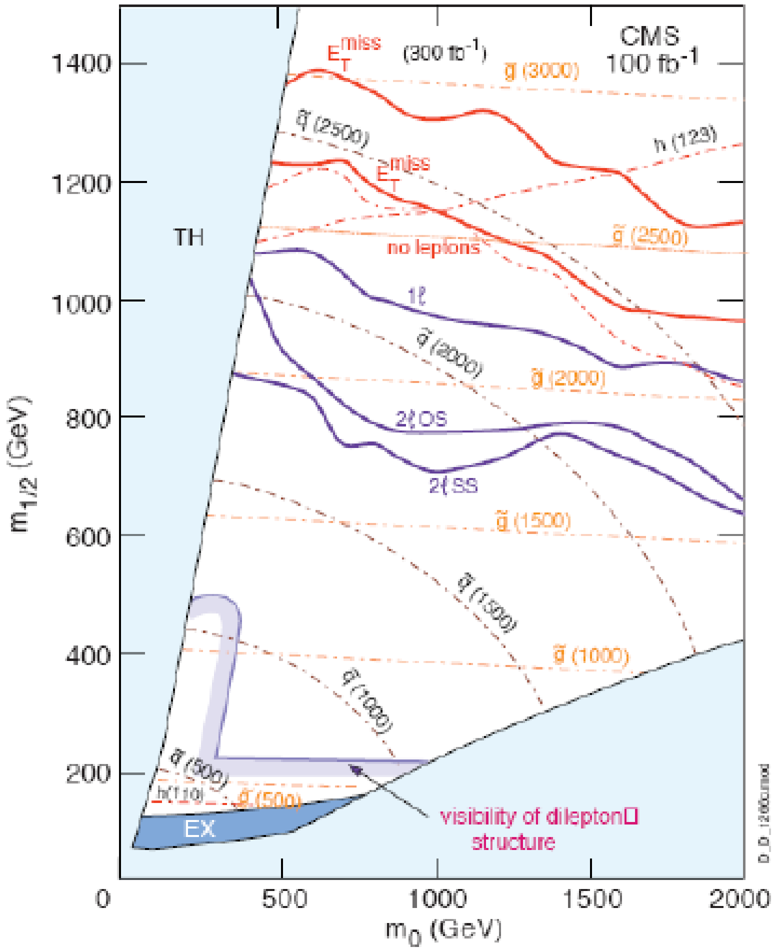
Charginos and Neutralinos

- Search for Charginos and Neutralinos:
  Multilepton + E_T^{miss}
  produced via electroweak processes
  (associated production)

$$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow l^\pm l^\mp l^\pm \tilde{\chi}_1^0 \tilde{\chi}_1^0 X$$



SUSY Discovery Potential



CMS 5σ reach for R-parity conserving mSUGRA in various inclusive channels:

- $\not{E}_T$
- $\not{E}_T$ with lepton veto
- One lepton channel
- Two opposite sign (OS) leptons
- Two same sign (SS) leptons

Probe Extra Dimensions ?

- Much recent theoretical interest in models with extra dimensions (Explain the weakness of gravity or hierarchy problem by extra dimensions)

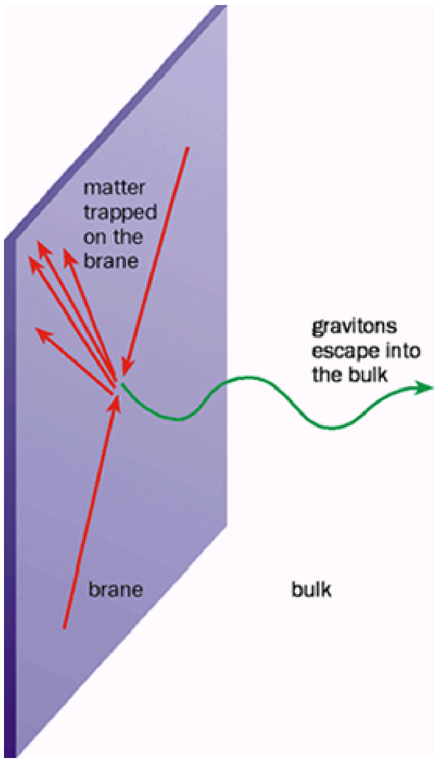
- New physics can appear at the TeV scale, i.e. accessible at the LHC

Example: Search for direct Graviton

$gg \rightarrow gG$, $qg \rightarrow qG$, $q\bar{q} \rightarrow Gg$

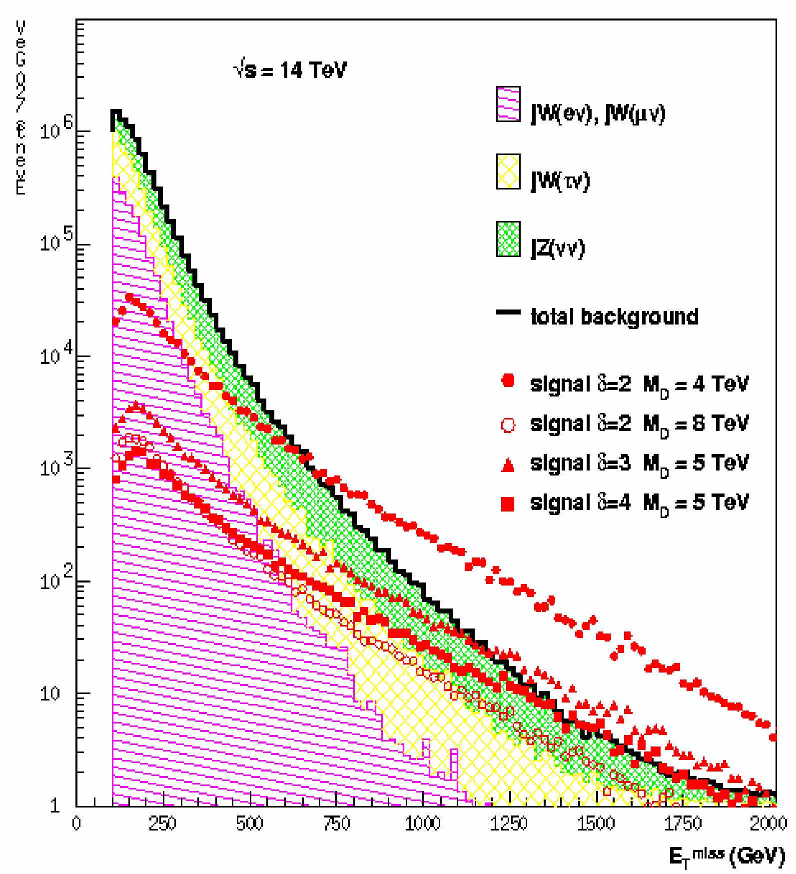
$q\bar{q} \rightarrow G\gamma$

Jets or Photons with large E_T^{miss}



Search for Gravitons

Jet + E_T^{miss} search



$$G_N^{-1} = 8\pi R^{\delta} M_D^{2+\delta}$$

δ : # extra dimensions

M_D = scale of gravitation

R = radius (extension)

M_D^{max}	=	9.1,	7.0,	6.0 TeV
δ	=	2,	3,	4
Extension:		10^{-5},	10^{-10},	10^{-12} m

Main backgrounds:

jet+Z(→νν),

jet+W→jet+(e,μ,τ)ν

Mini Black Holes at LHC

- The smallest mass of classical black hole is ~ plack mass, 2×10^{-8} kg or 1.1×10^{16} TeV, it is far higher than LHC can reach 14 TeV.
- Some string theorists have suggested that the multiple dimensions postulated by string theory might make the effective strength of gravity many orders of magnitude stronger at small distances (very high energies). This might effectively lower the Planck energy, and perhaps make black-hole-like descriptions valuable even at lower masses.

➔LHC may produce mini black holes.

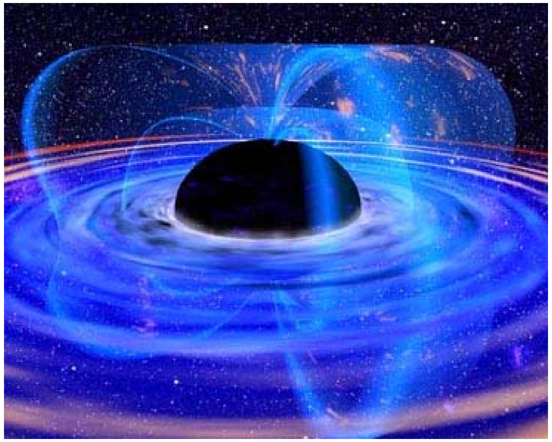
Mini Black Holes at LHC

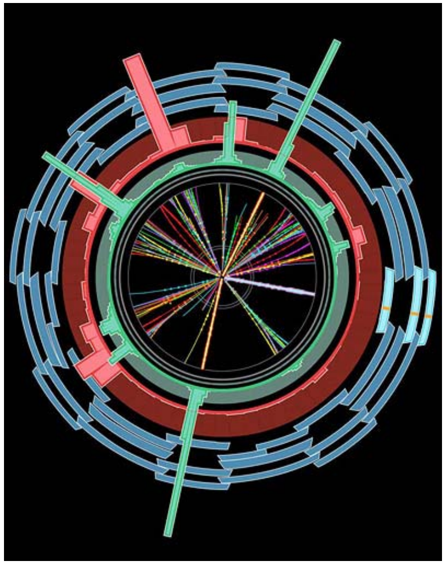
→ Hawking Radiation

$$P = \frac{\hbar c^6}{15360 \pi G^2 M^2}$$

$$t_{\mathrm{ev}} = \frac{5120 \pi G^2 M_0^3}{\hbar c^4}$$

- MBH = 2*10^{30} kg (Sun)
  - t_{ev} ~ 10^{67} years



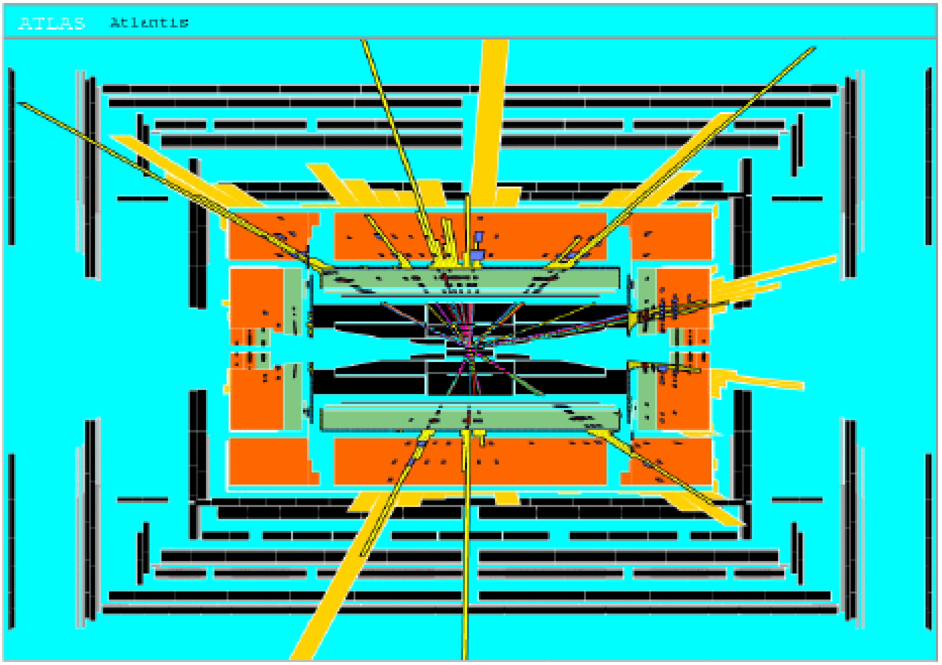


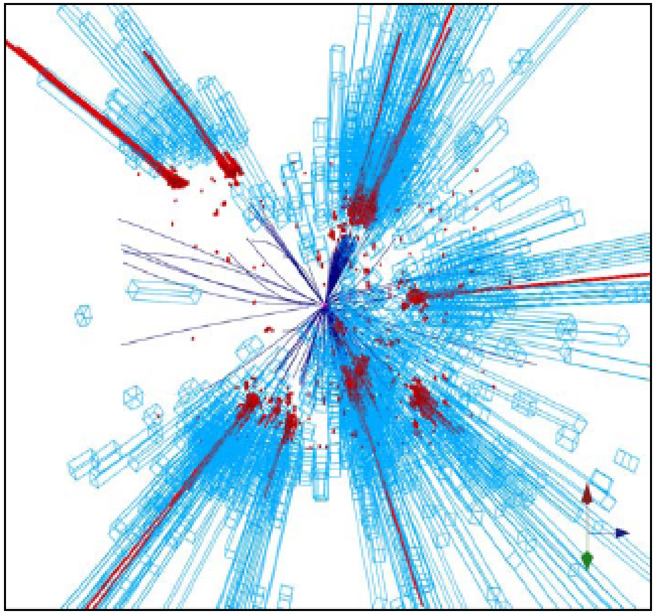
- MBH ~ few TeV (LHC)
  - t_{ev} ~ 10^{-26} s
  - Micro black holes are unstable & evaporated right after their creation.

Mini Black Holes at LHC

Simulation of a mini black hole event with M_{BH} ~ 8 TeV in ATLAS

... and in CMS





Micro Black Holes at LHC

PRL, vol. 87, Issue 16, id. 161602

$$\sigma(M_{\rm BH}) \approx \pi R_S^2 = \frac{1}{M_P^2}\left[\frac{M_{\rm BH}}{M_P}\left(\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right)\right]^{\frac{2}{n+1}}$$

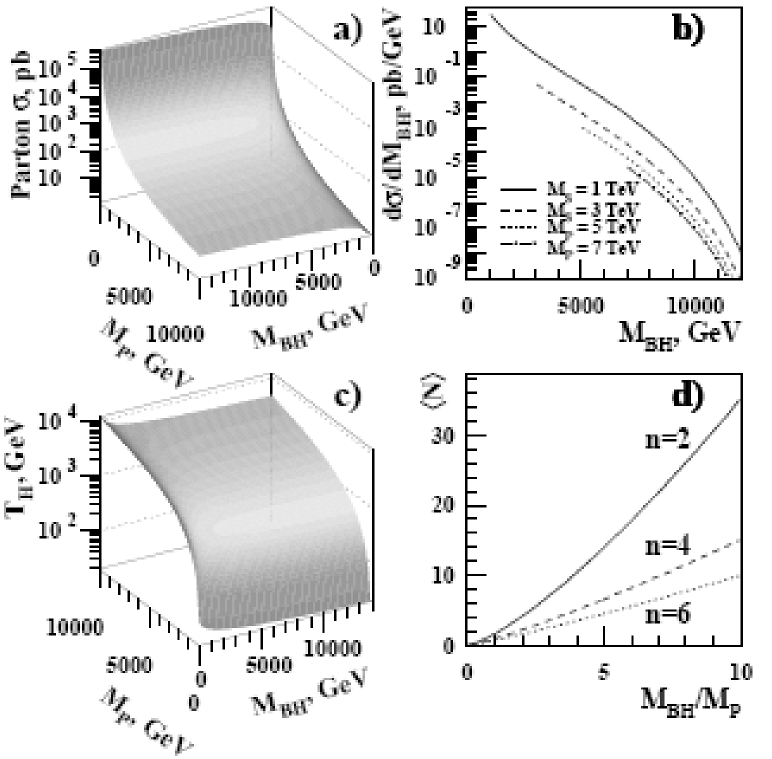


FIG. 1: a) Parton-level production cross section, b) differential cross section $d\sigma/dM_{\rm BH}$ at the LHC, c) Hawking temperature, and d) average decay multiplicity for a Schwarzschild black hole. The number of extra spatial dimensions $n = 4$ is used for a)-c). The dependence of the cross section and Hawking temperature on n is weak and would be hardly noticable on the logarithmic scale.

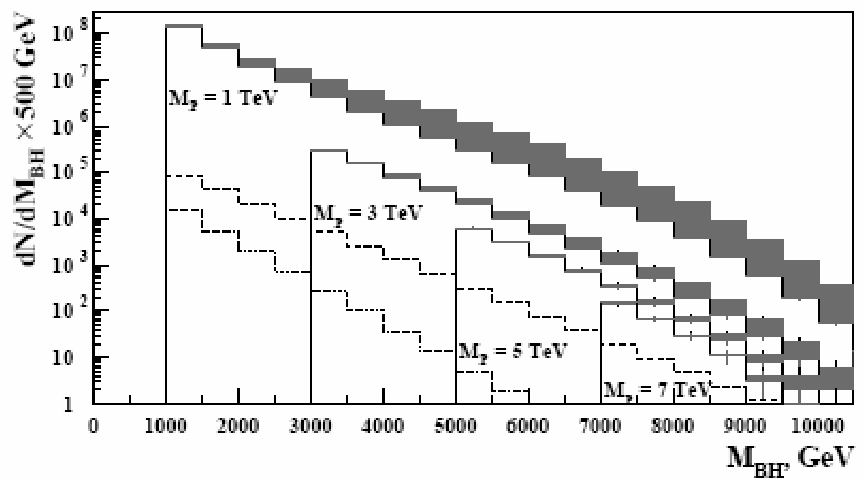
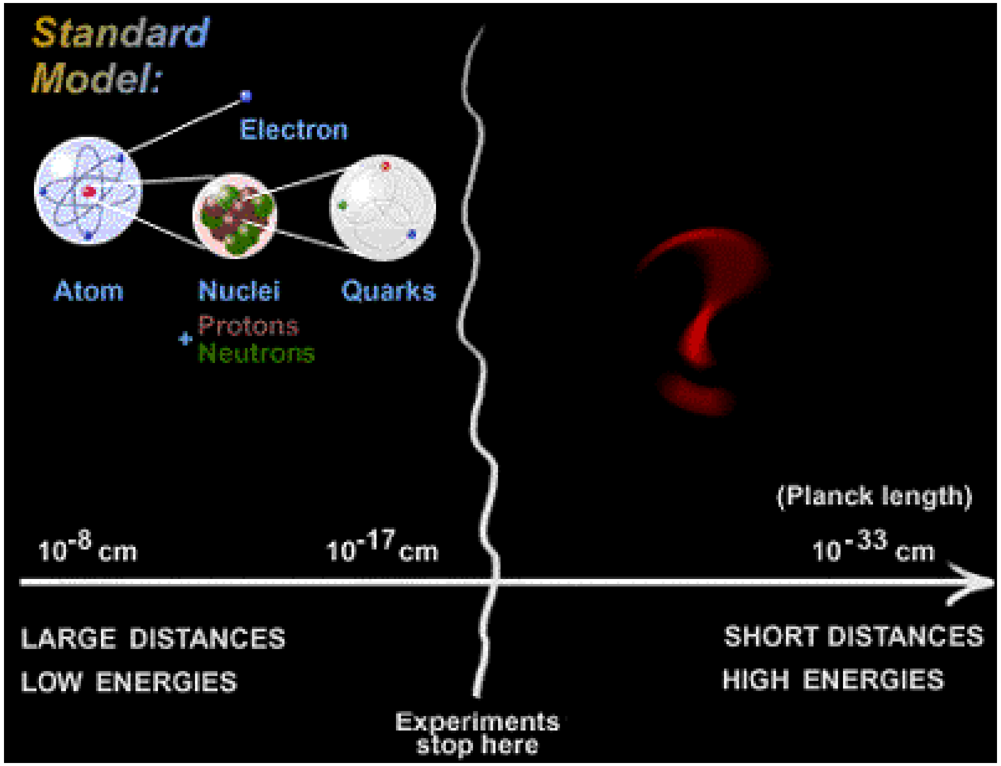
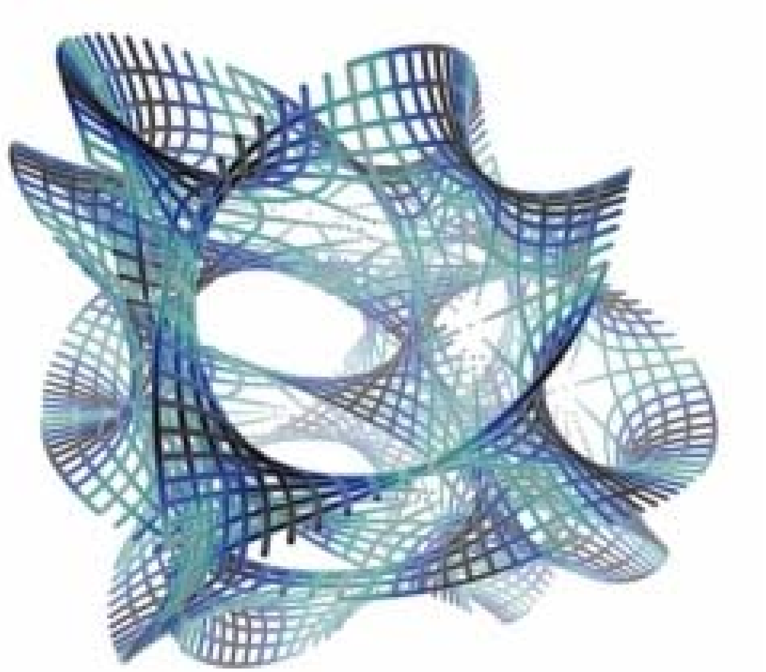


FIG. 2: Number of BHs produced at the LHC in the electron or photon decay channels, with 100 fb^{-1} of integrated luminosity, as a function of the BH mass. The shaded regions correspond to the variation in the number of events for n between 2 and 7. The dashed line shows total SM background (from inclusive $Z(ee)$ and direct photon production). The dotted line corresponds to the $Z(ee) + X$ background alone.

Extra Dimensions – New Frontier ?

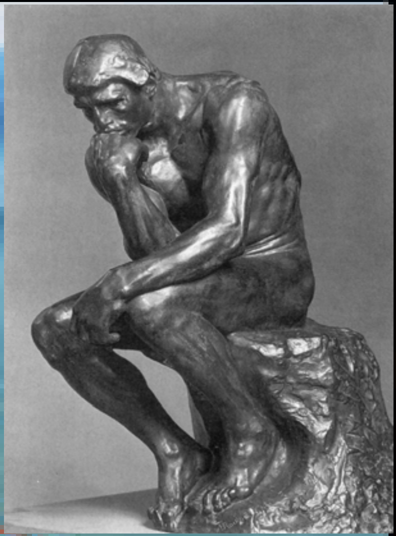
➔ LHC will address this question.





An extra-dimensional form: the Calabi-Yau space.

The LHC era is coming !



The LHC may have revolutionary discovery that will change the view of the time, space, matter, energy and the Universe !

Backup Slides

The ATLAS Experiment Getting Ready for LHC Physics at LHC (P. Jenni, CERN)

- Many important milestones have been passed in the construction, pre-assembly, integration and installation of the ATLAS detector components

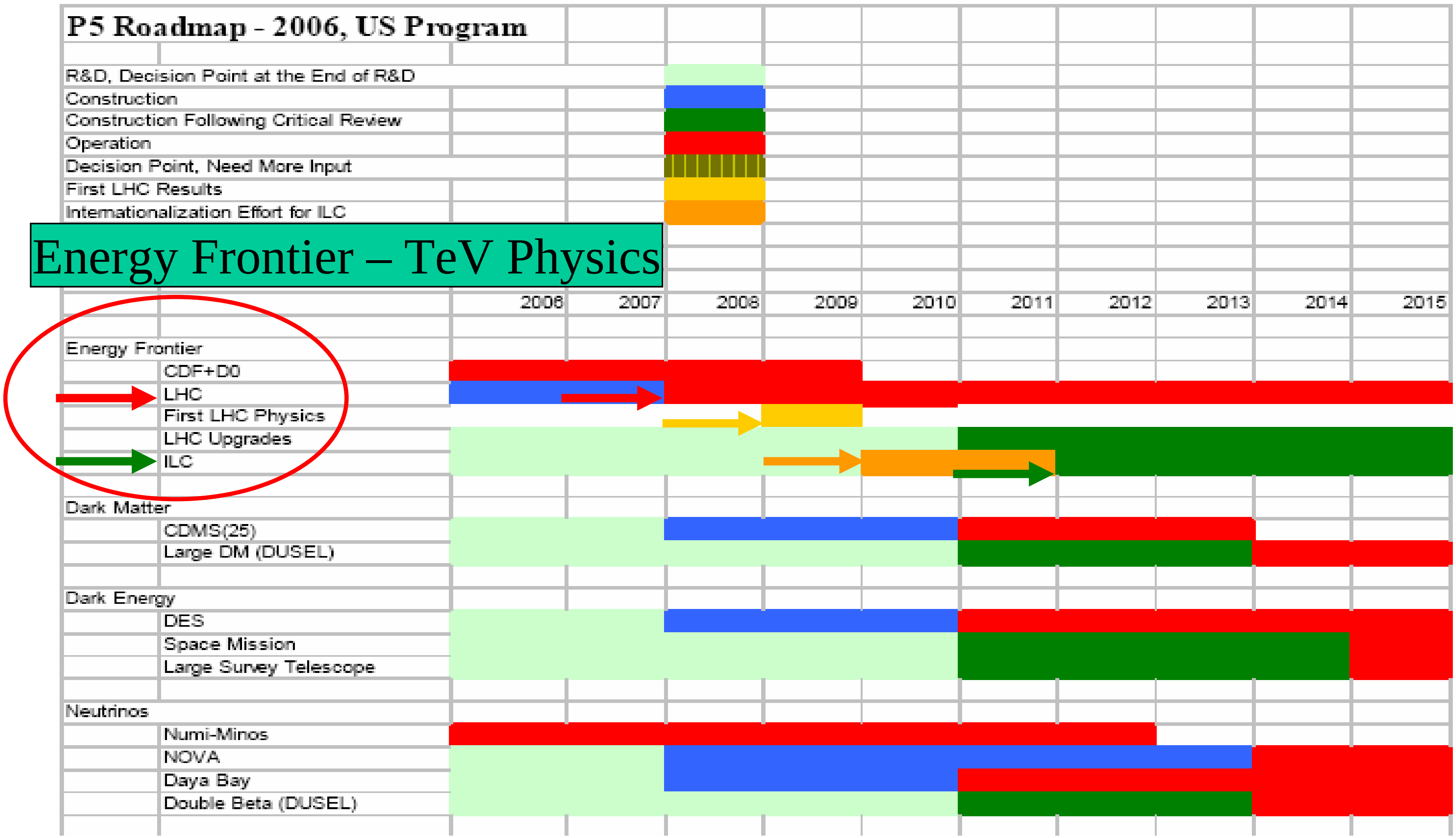
- Very major software, computing and physics preparation activities are underway as well, using the Worldwide LHC Computing Grid (WLCG) for distributed computing resources.

- Commissioning and planning for the early physics phases have started strongly

- ATLAS expects to remain at the energy frontier of HEP for the next 10 – 15 years, and the Collaboration has already set in place a coherent organization to evaluate and plan for future upgrades in order to exploit future LHC machine high-luminosity upgrades

US HEP 10-Year Roadmap

http://www.science.doe.gov/hep/P5RoadmapfinalOctober2006.pdf



Why do we think about extensions of the SM?

- SM is consistent with all experimental data so far
- Many open questions in the SM
  - Hierarchy problem: M_W (100 GeV) → M_{Planck} (10^{19} GeV)
  - Unification of couplings
  - Flavour / family problem
  - .....
- Gravity is not incorporated yet in the SM

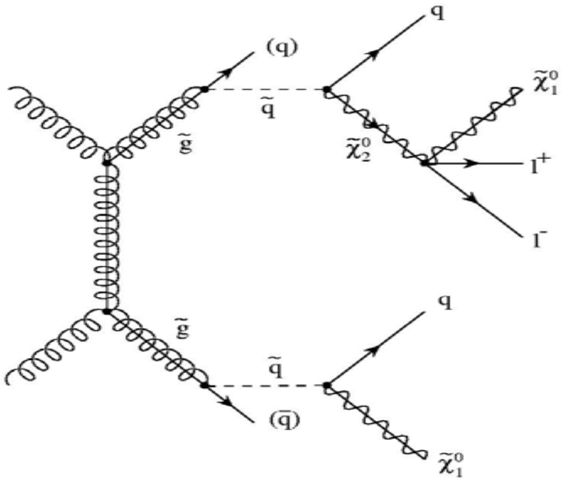
- Calling for a *more fundamental theory* of which the SM is a low energy approximation → New Physics

- Candidates: Supersymmetry, Extra Dimension, Technicolor.......
- All predict new physics at the TeV scale → LHC

Search for Supersymmetry

- If SUSY exists at the electroweak scale, a discovery at the LHC should be possible (easy?)

- Squarks and Gluinos are strongly produced
  - They decay through cascades to the lightest SUSYparticle (LSP)
  - final states is combination of jets, leptons and large missing energy

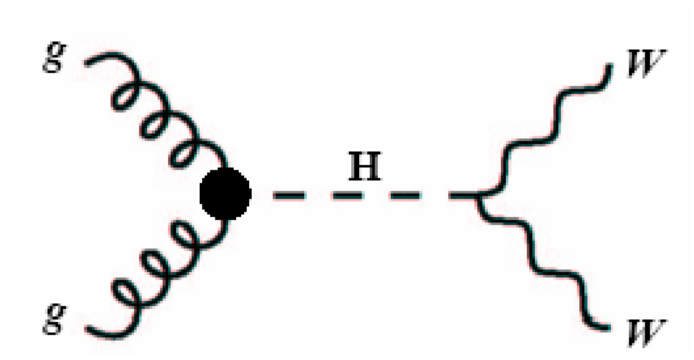


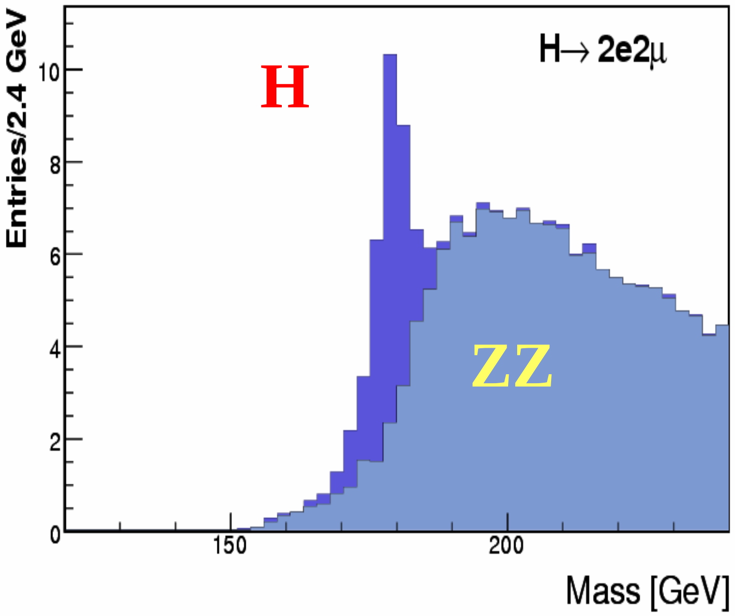
1. Look for deviations from the SM, e.g. Multijet + E_T^{miss} signature

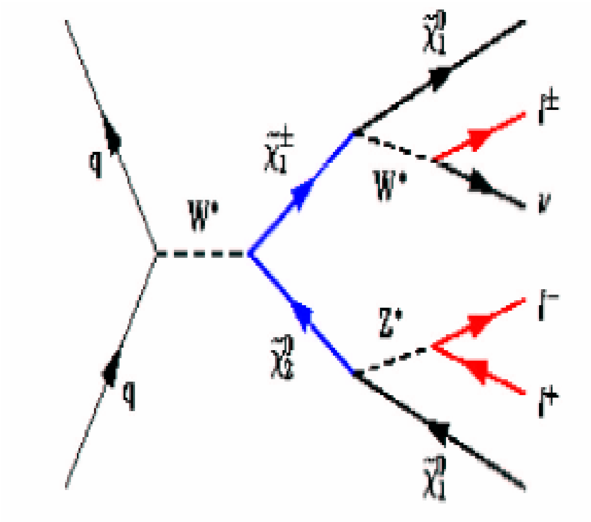
2. Establish the SUSY mass scale use inclusive variables, e.g. effective mass distribution

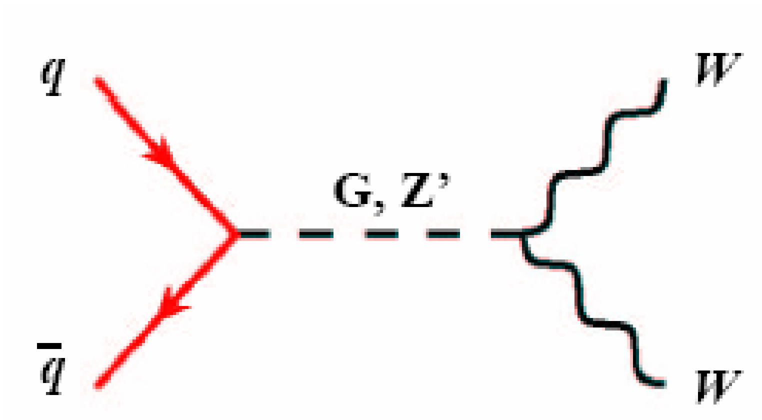
3. Determine model parameters (difficult) Strategy: select particular decay chains and use kinematics to determine mass combinations

Diboson as Background





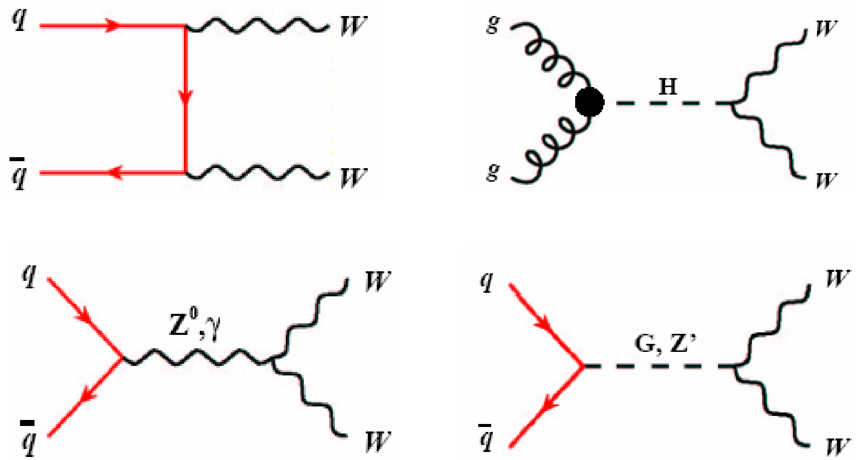




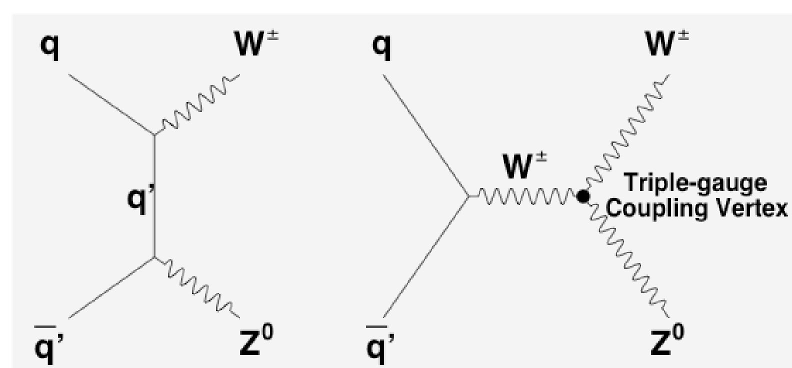
WW/WZ Analysis Based on BDT

Ref: H.J. Yang's talk on WW/WZ analysis based on BDT at ATLAS Trigger & Physics Week on June 7, 2007

- PP → WW → $l\nu$ $l\nu$
  - Simple Cuts, S/BG ~ 1.1
  - ANN, Signal/BG ~ 2 - 3
  - BDT, Signal/BG ~ 4 - 6



- PP → WZ → $l\nu$ ll
  - Simple Cuts, S/BG ~ 2.5
  - ANN, Signal/BG ~ 5 - 10
  - BDT, Signal/BG ~ 10 - 24

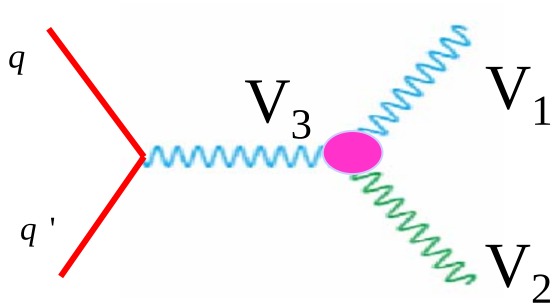


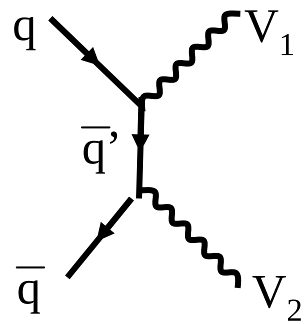
Motivations of diboson studies

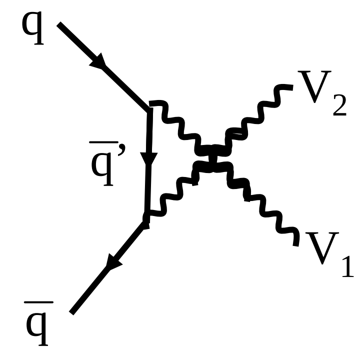
- **Measure dibson production σ and TGCs**
- **Explore none-Abelian SU(2)×U(1) gauge structure of SM and test the central part of the SM**
- **Probe new physics if production cross section, or TGCs deviate from SM prediction → complementary to direct search for new physics**
- **Understand the backgrounds of many important physics analyses**

  Search for Higgs, SUSY, graviton and study of ttbar

Diboson at hadron colliders





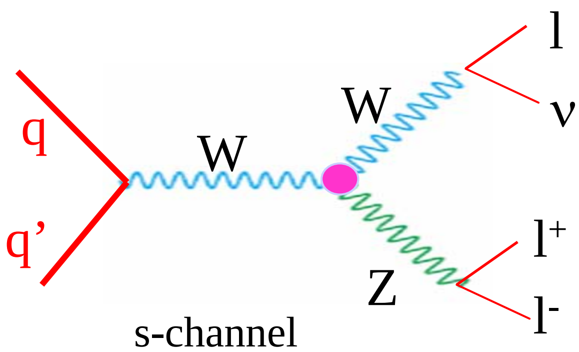


- LO Feynman diagram, V_1, V_2, V_3 = Z, W, $\gamma \rightarrow$ WW, ZW, ZZ, Wγ.
- Only *s* channel has three boson vertex
- Diboson final states have predictable $\sigma_{production}$ and manifest the gauge boson coupling

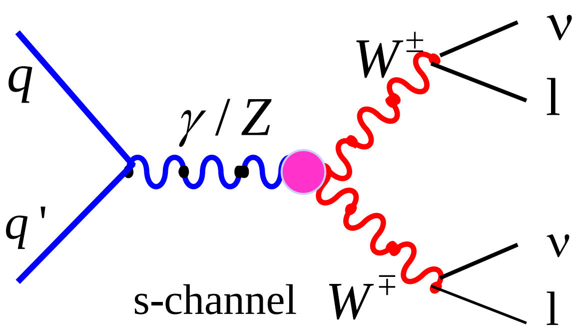
SM:

- Pure neutral vertexes ZZZ, ZZγ are forbidden (Z/γ carry no charge and weak isospin that needed for gauge bosons couple)
- Only charged couplings WWγ, WWZ are allowed

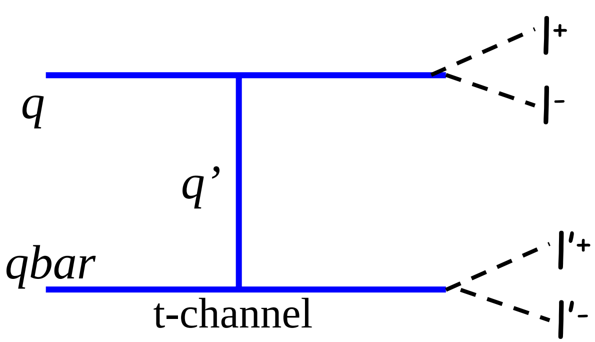
Study of WZ, WW and ZZ



- s-channel dominates, $\sigma(SM) = 57.7$ pb
- Sensitive only to WWZ coupling
- Clean signal eee, eeμ, $\mu\mu$e, $\mu\mu\mu$
- 3 isolated high p_T leptons with large E_T(miss)

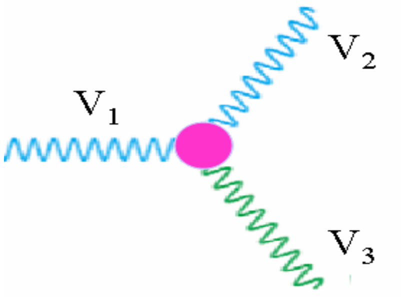


- $\sigma(SM) = 127.5$ pb
- Sensitive to WWZ and WWγ
- Clean signal ee, $\mu\mu$, eμ
- 2 isolated high p_T leptons with opposite charge and large missing E_T



- s channel suppressed by $O(10^{-4})$
- Only t-channel at tree level, $\sigma(SM) = 16.8$ pb
- 4 isolated high p_T leptons from the Z pair decays
- Clean signal eeee, ee$\mu\mu$, $\mu\mu\mu\mu$, almost bkg free

Triple Gauge Boson Couplings



$$L_{WWV}/g_{WWV} = ig_1^V (W_{\mu\nu}^+ W^\mu V^\nu - W_\mu^+ V_\nu W^{\mu\nu})$$
$$+ i\kappa_V W_\mu^+ W_\nu V^{\mu\nu} + i\frac{\lambda_V}{M_W^2} W_{\lambda\mu}^+ W_\nu^\mu V^{\nu\lambda}$$
$$- g_4^V W_\mu^+ W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu)$$
$$+ g_5^V \varepsilon^{\mu\nu\rho\alpha} (W_\mu^+ \overleftrightarrow{\partial}_\rho W_\nu) V_\alpha$$
$$+ i\tilde{\kappa}_V W_\mu^+ W_\nu \tilde{V}^{\mu\nu} + i\frac{\tilde{\lambda}_V}{M_W^2} W_{\lambda\mu}^+ W_\nu^\mu \tilde{V}^{\nu\lambda}$$

- Characterized by an effective Lagrangian, parameterized in terms of coupling parameters for new physics
- C, P and CP symmetry conservation, 5 free parameters:
  - λ_γ ,λ_Z: grow with s, big advantage for LHC
  - $\Delta\kappa_\gamma = \kappa_\gamma - 1$, $\Delta g_1^Z = g_1^Z - 1$, $\Delta\kappa_Z = \kappa_Z - 1$: grow with $\sqrt{s}$
- Tree level SM: $\lambda_\gamma = \lambda_Z = \Delta\kappa_\gamma = \Delta g_1^Z = \Delta\kappa_Z = 0$

Anomalous Coupling & Form Factor

- Cross section increase for coupling with non-SM values, yielding large cross section at high energies that violating tree level unitarity → form factor scale

$$a(s) = \frac{a_0}{(1 + s/\Lambda^2_{FF})^2}$$

s: subprocess CM energy. Λ: form factor scale

- TGCs manifest in
  - cross section enhancement
  - high $p_T(V=Z,W,\gamma)$
  - production angle

LHC Expectations for the TGCs

- High CM energy → larger s
- High luminosity → high statistics
- High sensitivity → Expected to be ~×10 improvement on LEP/Tevatron

Predictions for TGCs at 95% C.L. for L=30 fb^{-1} (inc syst)

$-0.0035 < \lambda_\gamma < +0.0035$
$-0.0073 < \lambda_Z < +0.0073$
$-0.075 < \Delta\kappa_\gamma < +0.076$
$-0.11 < \Delta\kappa_Z < +0.12$
$-0.86 < \Delta g^1_Z < +0.011$

Motivations

- Measure dibson production σ and TGCs
- Explore none-Abelian SU(2)$\times$U(1) gauge structure of SM and test the central part of the SM
- Probe new physics if production cross section, or TGCs deviate from SM prediction $\rightarrow$ complementary to direct search for new physics
- Understand the backgrounds of many important physics analyses

  Search for Higgs, SUSY, graviton and study of ttbar

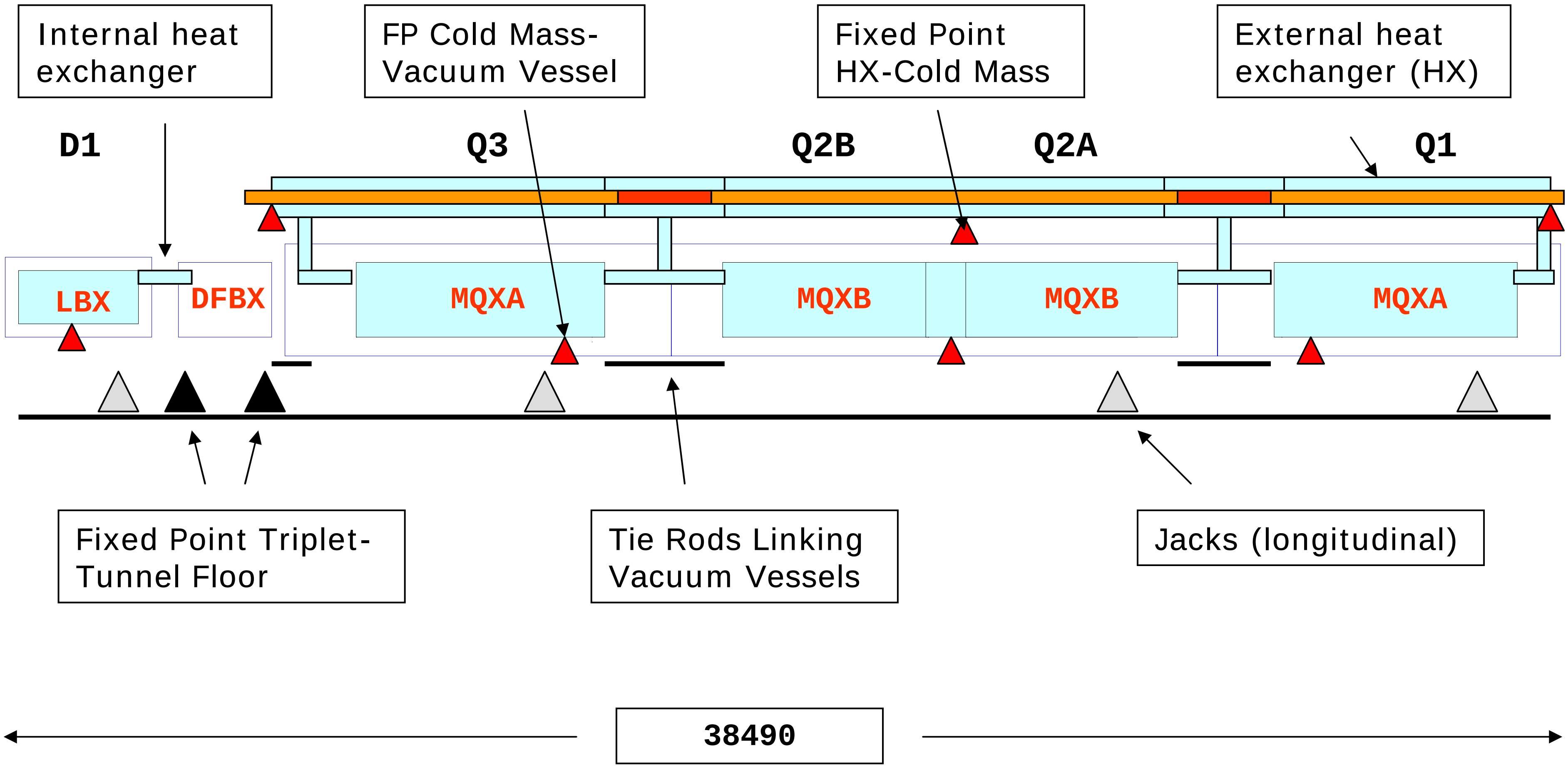
LHC low-β triplet – warm assembly

From L Evans
SPC 7-May-07

Inner Triplet at point-5

Fix Points

From L Evans
SPC 7-May-07



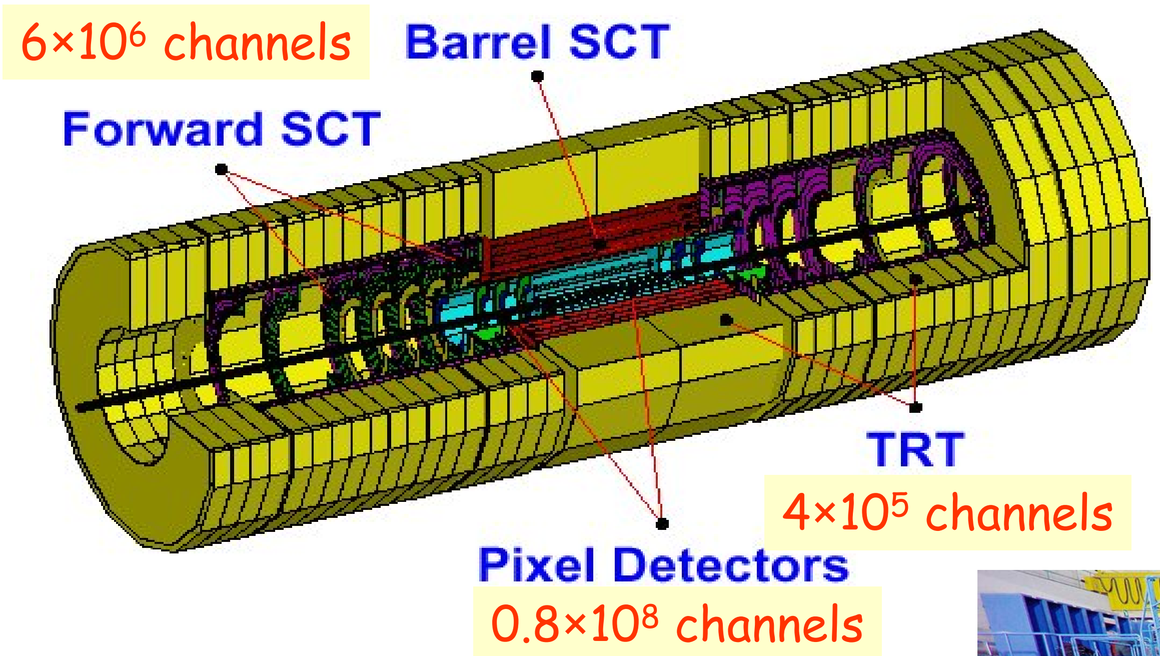
Inner Triplet Review

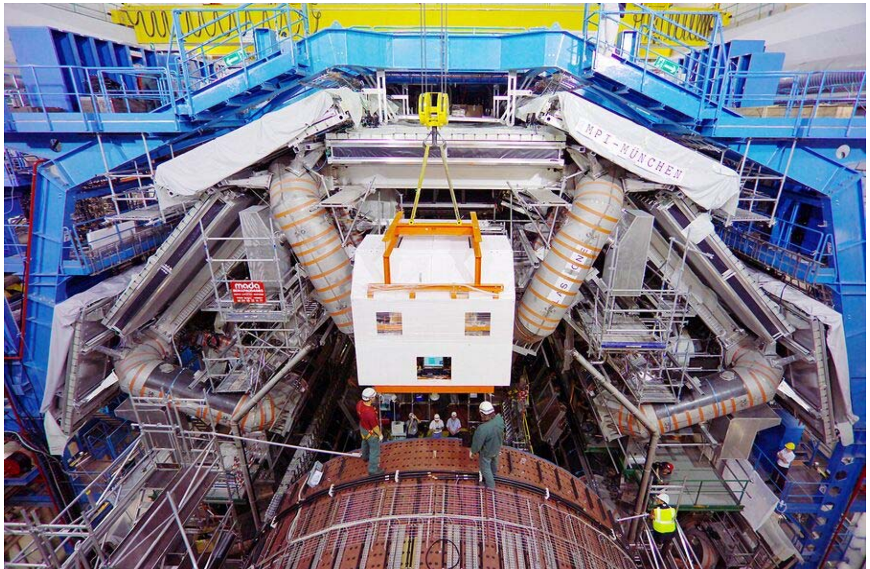
From L Evans
SPC 7-May-07

Internal piping and anchoring to cold masses (helium vessels)

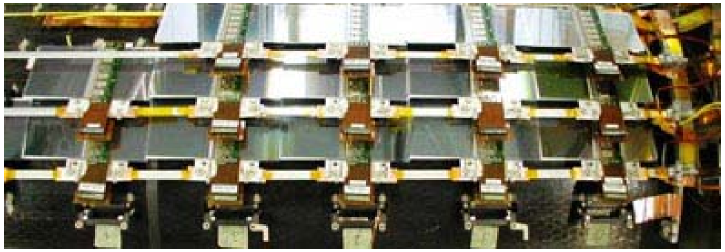
– Weak points located in the anchoring to cold masses. To be reinforced on Q1, Q3 and DFBX. *Can be done in-situ*

Inner Detector

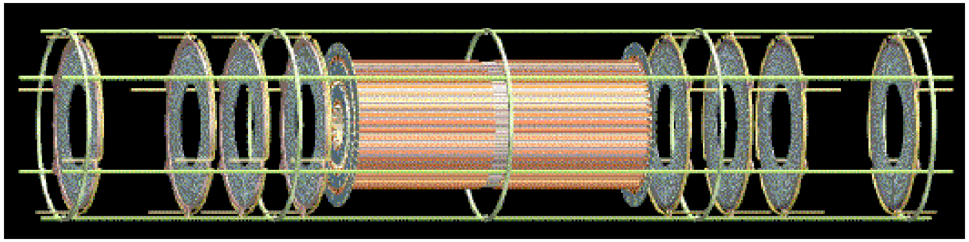




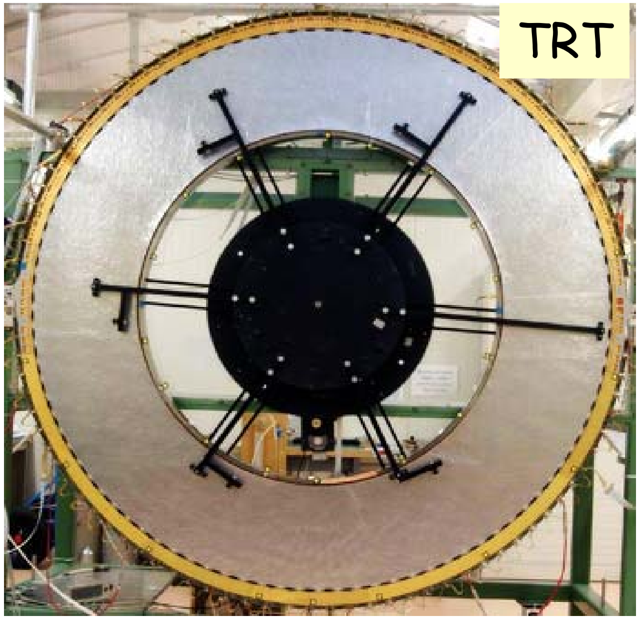
Central Tracker



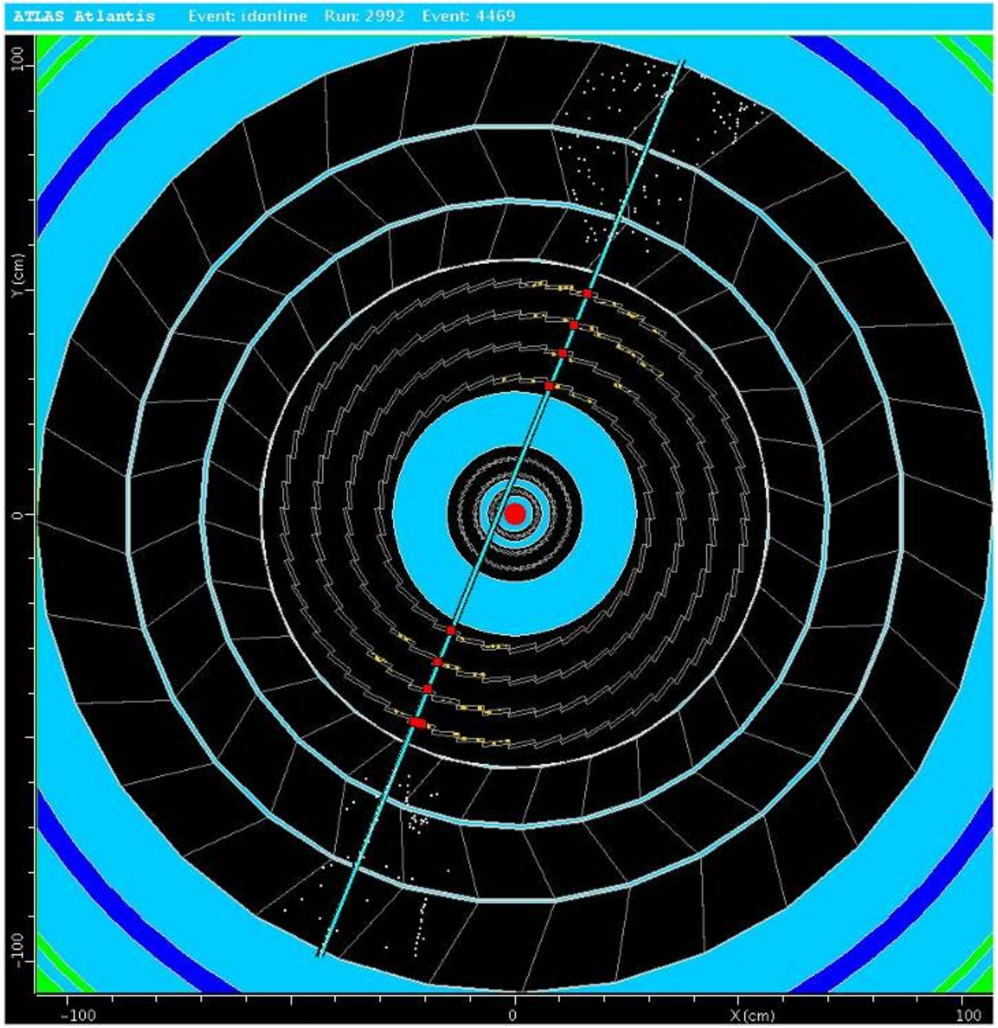
Silicon tracker:
- All four barrel cylinders are complete
- Test show 99.7% of all channels fully functional
- All end-cap disk finished



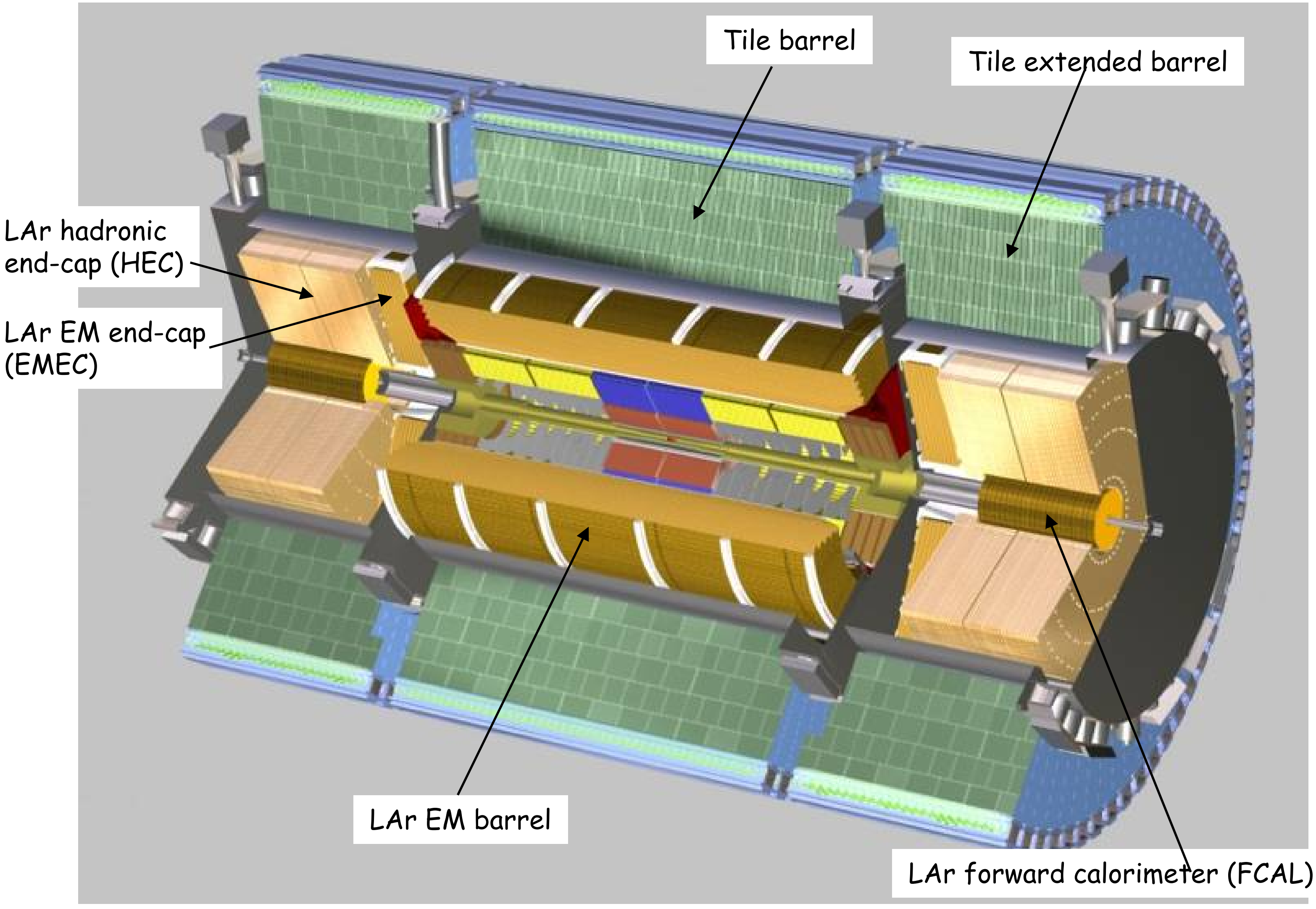
Pixel:
- Corrosion leaks in the barrel cooling tubes (now under control, repair ongoing)
- Broken low-mass cables for the barrel services (repair/replacement strategy being put into place)
- All efforts are made to have the full system ready for installation in time for May 2007



Cosmics in the barrel TRT plus SCT

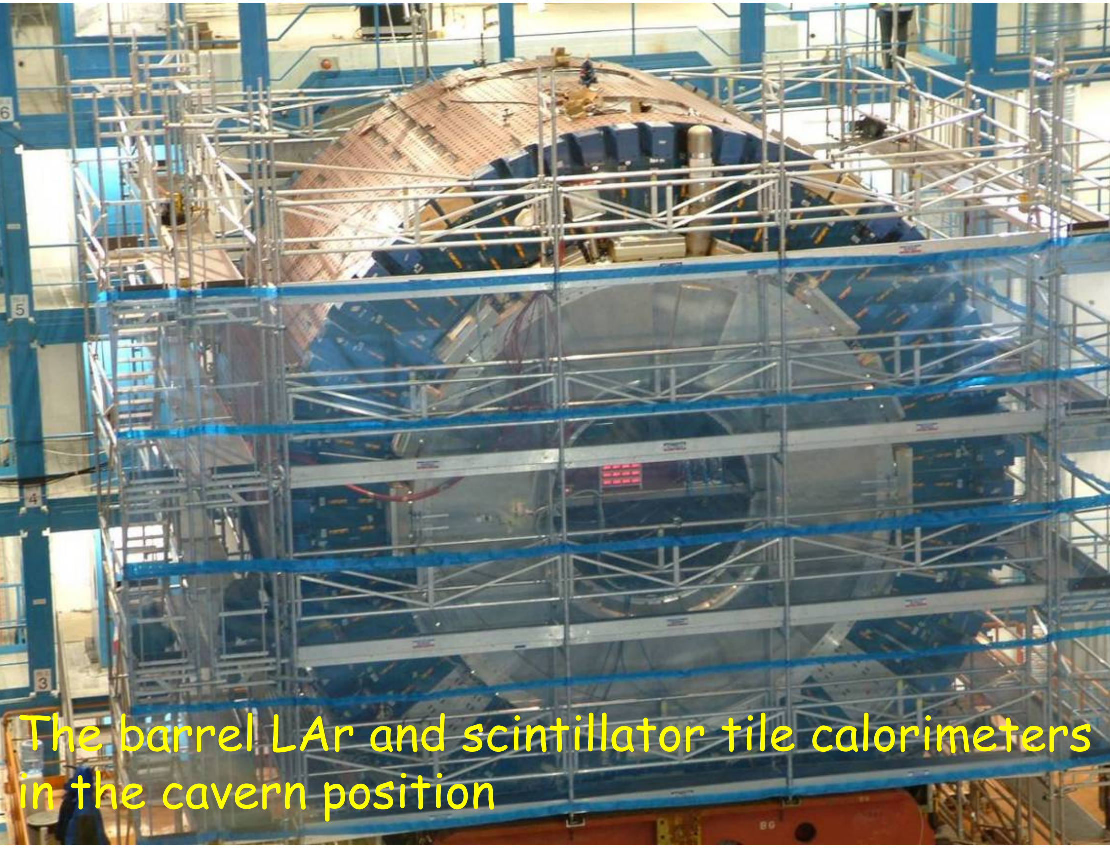


LAr and Tile Calorimeters

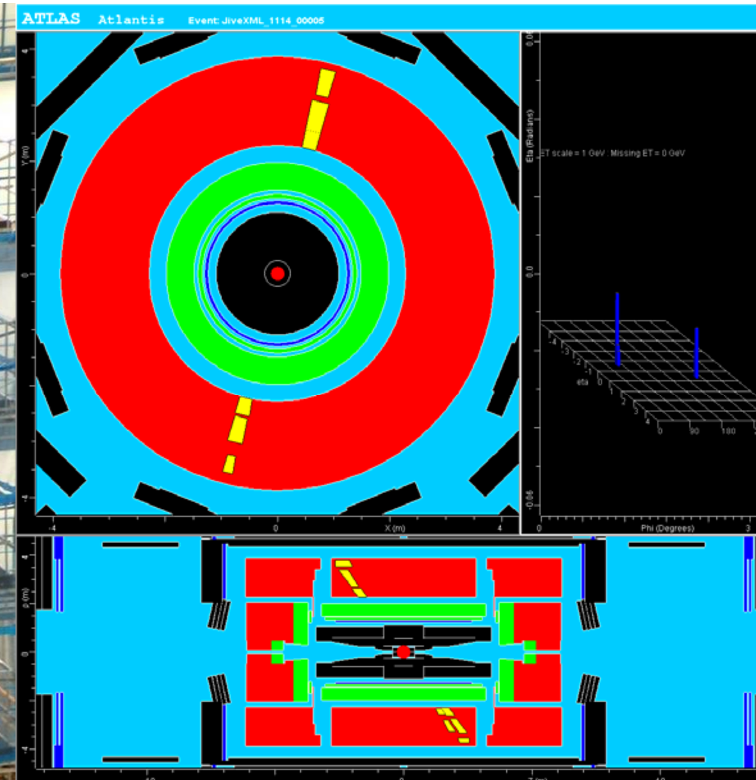


- A successful complete cold test (with LAr) was made.
- Dead channels much below 1%.

Barrel LAr and Tile Calorimeters



The barrel LAr and scintillator tile calorimeters in the cavern position

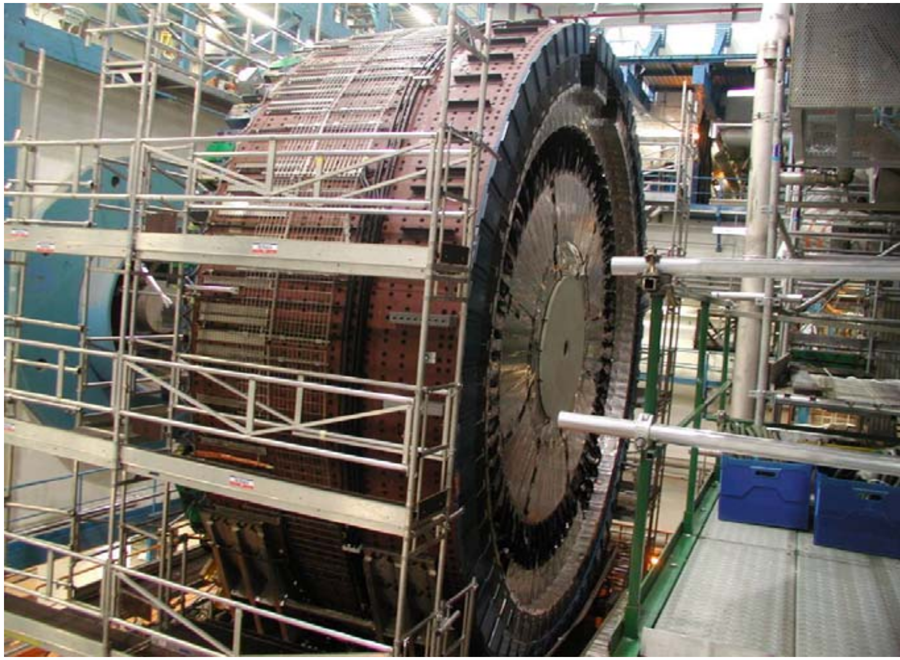


A cosmic ray muon registered in the barrel Tile Calorimeter

- Total 448 independent sectors
- All channels functioning

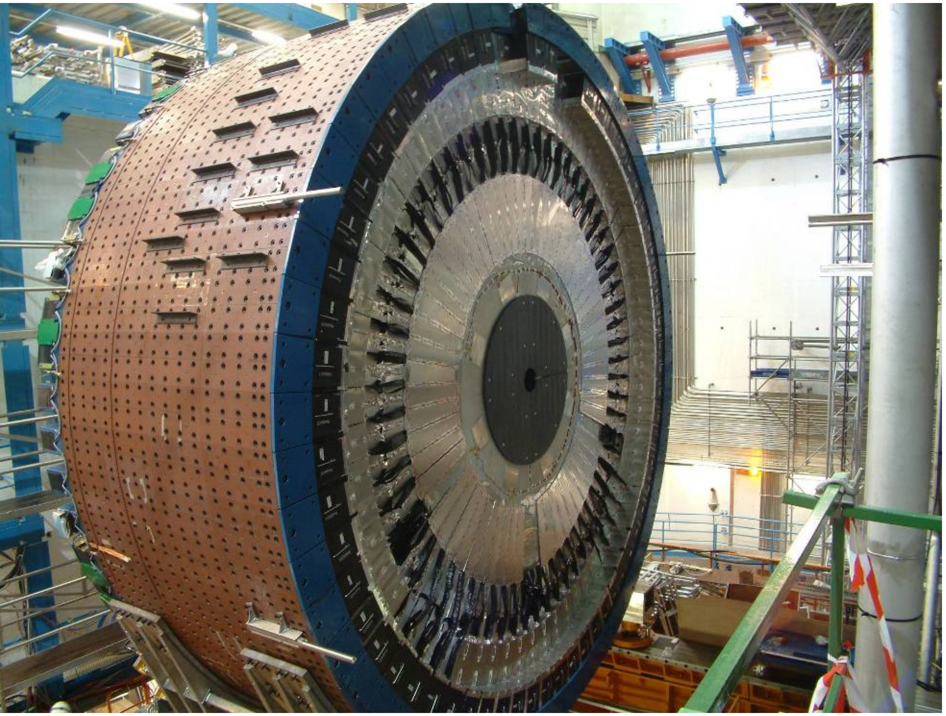
Calorimeter barrel in the center of the ATLAS detector

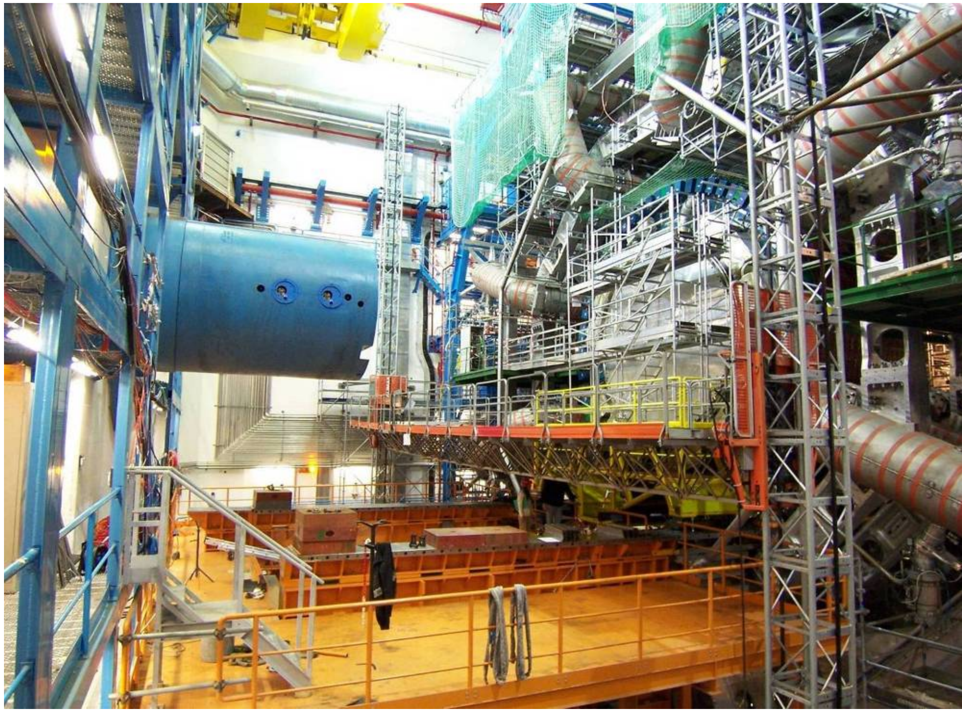
LAr End-Caps



- both end-caps mechanically assembled
- LAr infrastructure (pedestals, crates,…) installed
- gap, cryostat and minimum bias scintillators
  completely installed on both ext. barrels
- Dead channels well below 1%

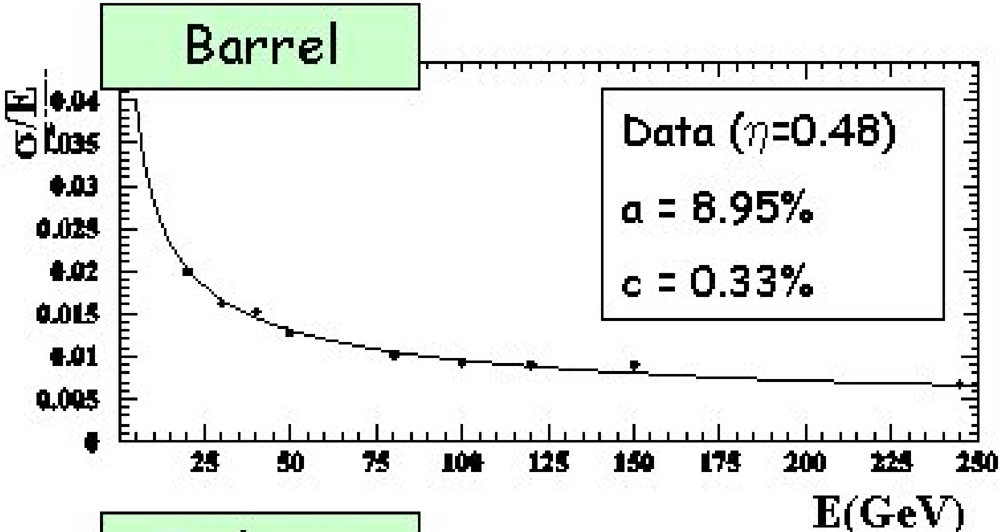
End-Cap LAr and Tile Calorimeters

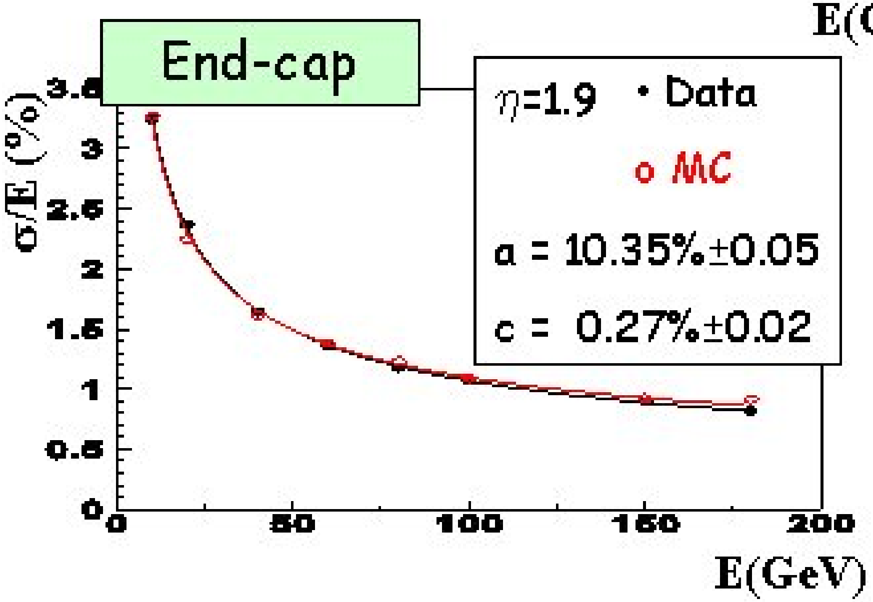




The mechanical installation is finished

Energy resolution from EM test beam





$$\sigma_E/E = a/\sqrt{E} \oplus c \oplus n/E$$

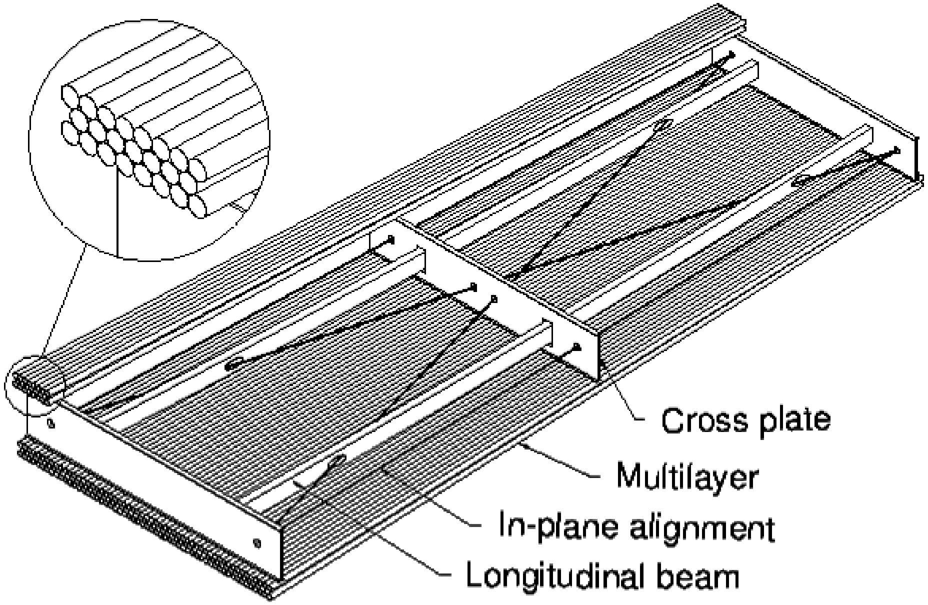
For every tested points:

Barrel	End-cap
a < 10%	a < 12.5%
c < 0.4%	c < 0.5%

↓

- Within specifications
- Good agreement with MC

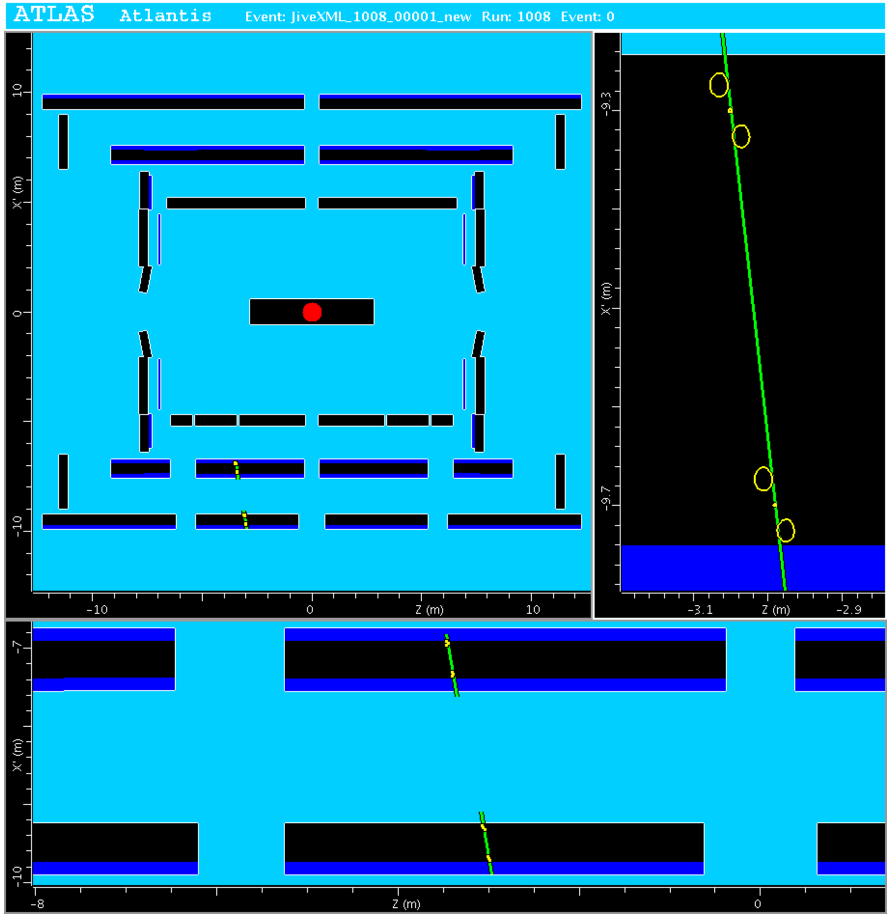
Barrel MDTs



- A major effort is spent in the preparation and testing of the barrel muon stations (MDTs and RPCs for the middle and outer stations) before their installation in-situ
- The electronics and alignment system fabrications for all MDTs are on schedule

First cosmics registered *in situ* for barrel chambers

In December 2005 in MDTs



in June 2006 in RPCs