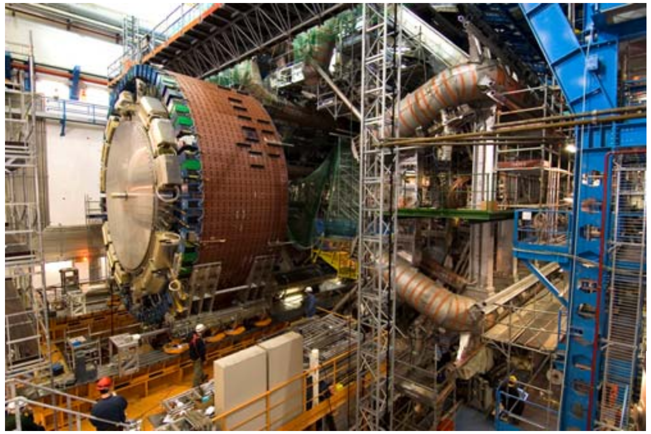
# The LHC Environment

## CTEQ Meeting 05/14/07

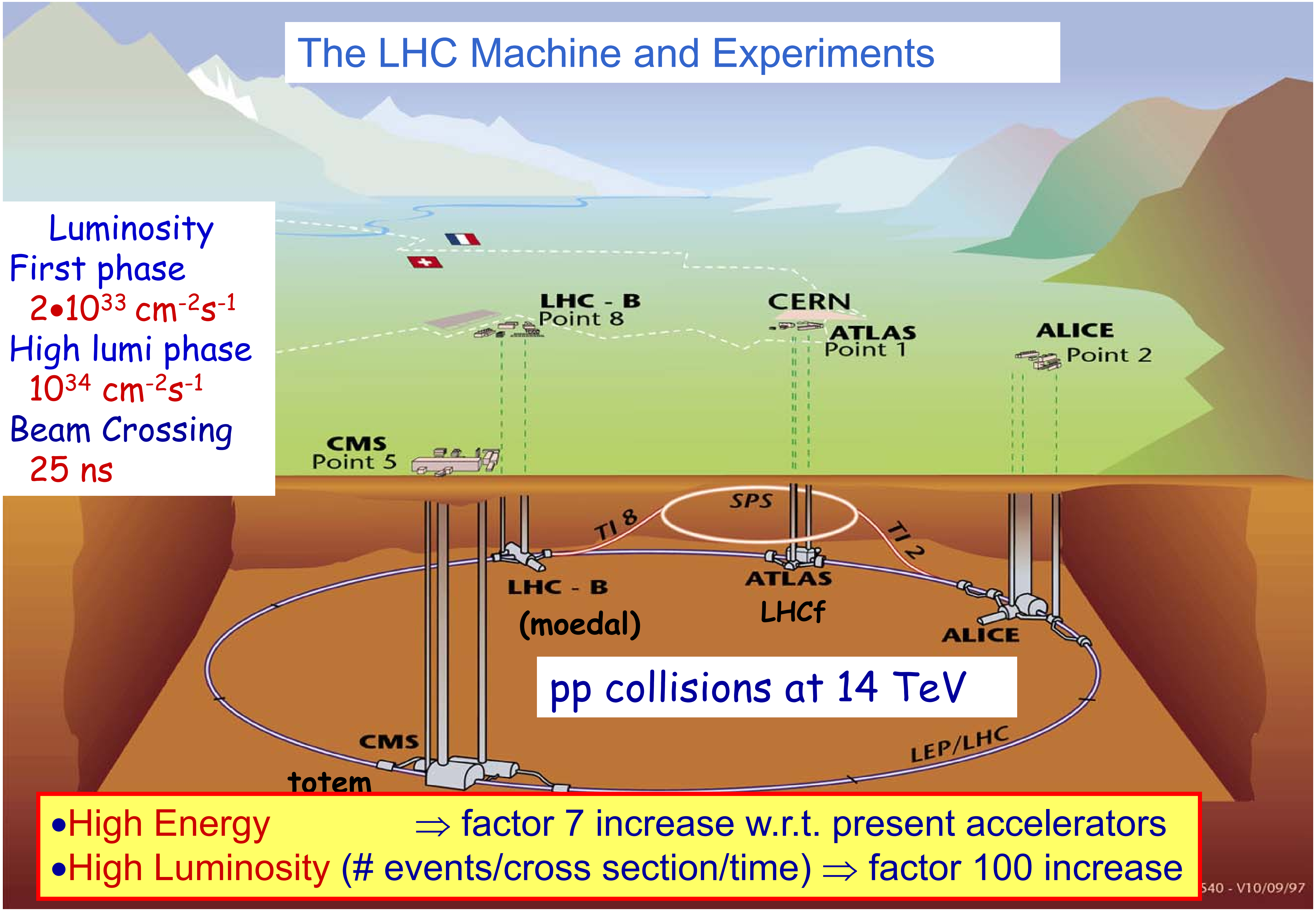
Albert De Roeck
CERN
and University of Antwerp
and the IPPP Durham

C T E Q



# Contents

# The LHC Machine and Experiments



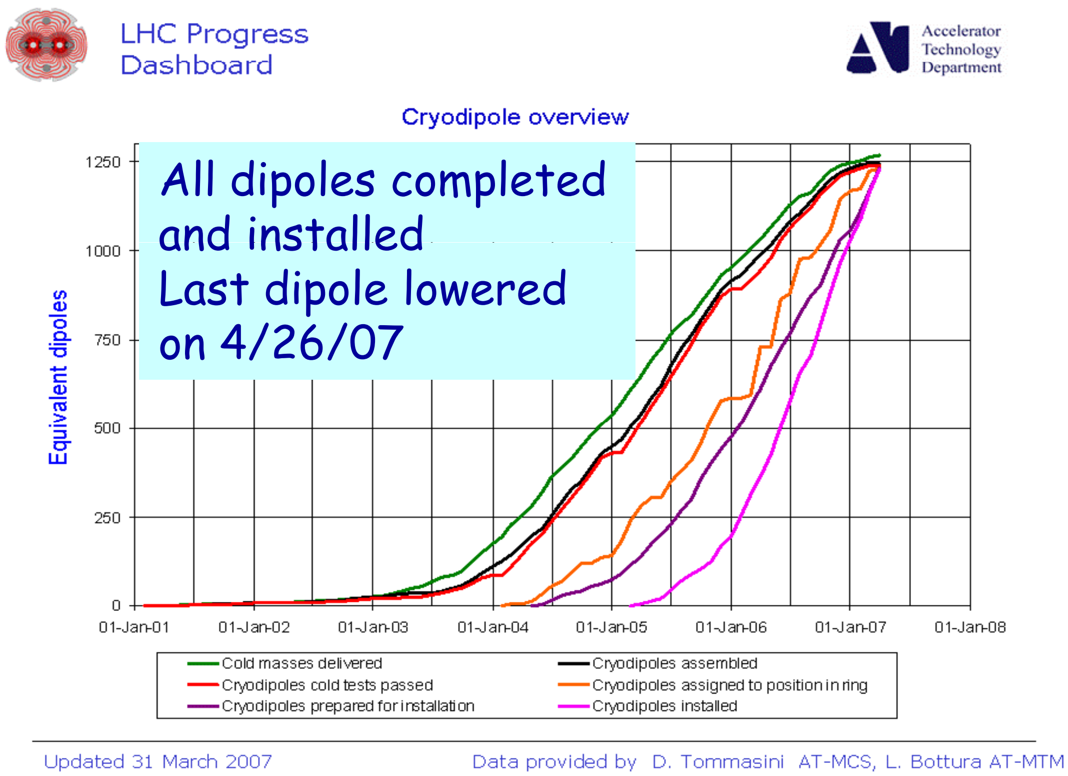

Luminosity
First phase
$2 \bullet 10^{33}$ $cm^{-2}s^{-1}$
High lumi phase
$10^{34}$ $cm^{-2}s^{-1}$
Beam Crossing
25 ns

pp collisions at 14 TeV

- High Energy $\Rightarrow$ factor 7 increase w.r.t. present accelerators
- High Luminosity (# events/cross section/time) $\Rightarrow$ factor 100 increase

# The LHC Progress & Schedule

Crucial part: 1232 superconducting dipoles
Can follow progress on the LHC dashboard
http://lhc-new-homepage.web.cern.ch/lhc-new-homepage/



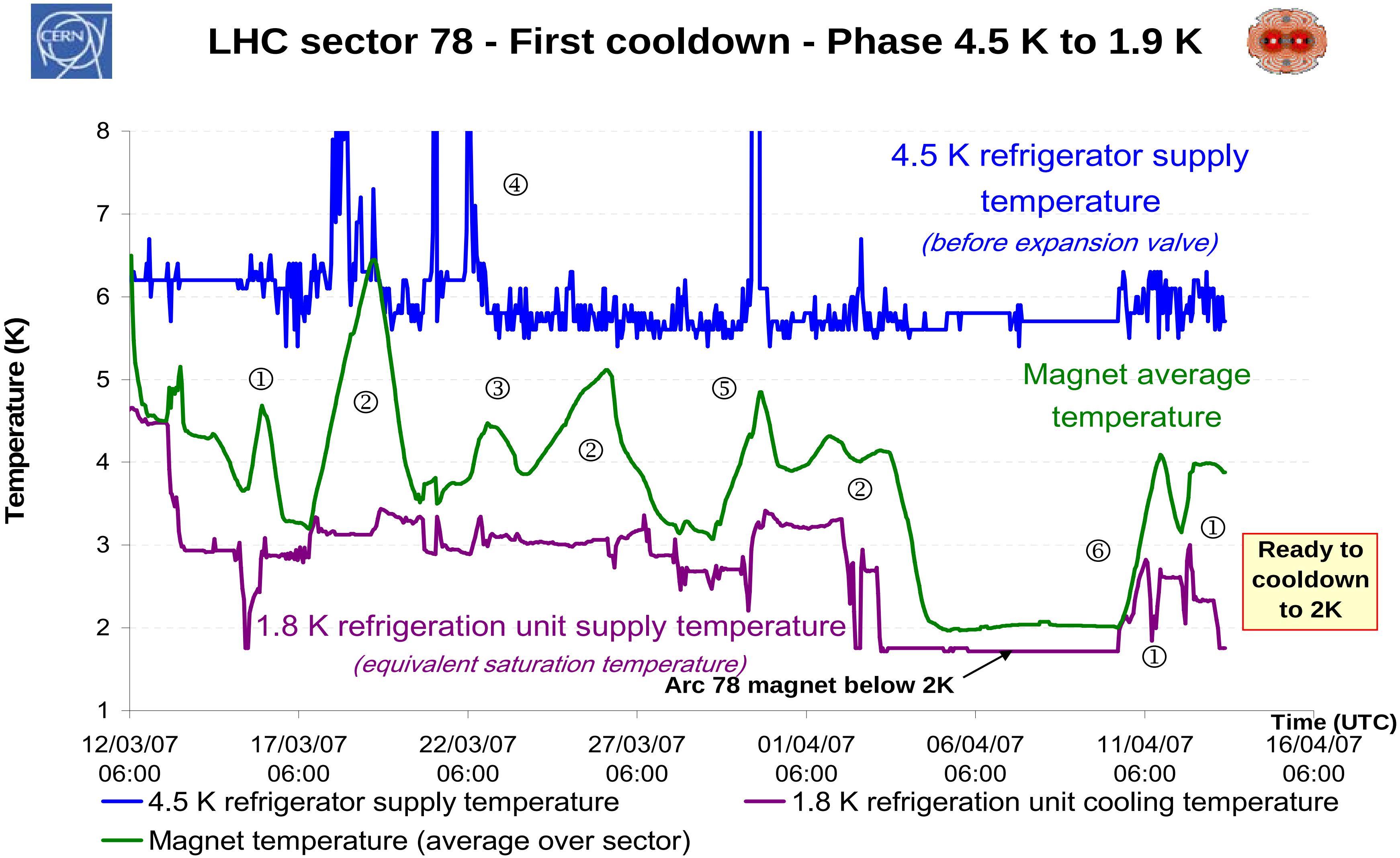

## The LHC Schedule(*)?

- LHC will be closed and set up for beam on 1 September 2007
  - LHC commissioning will take time!
- First collisions expected in November/December 2007
  - A short engineering run
  - Collisions will be at injection energy ie cms of 0.9 TeV
- First physics run in 2008
  - ~ 1 $fb^{-1}$? 14TeV!
- Physics run in 2009 +…
  - 10-20 $fb^{-1}$/year ⇒100 $fb^{-1}$/year

(*) eg. M. Lamont et al, June 2006.
⇒Still the official schedule

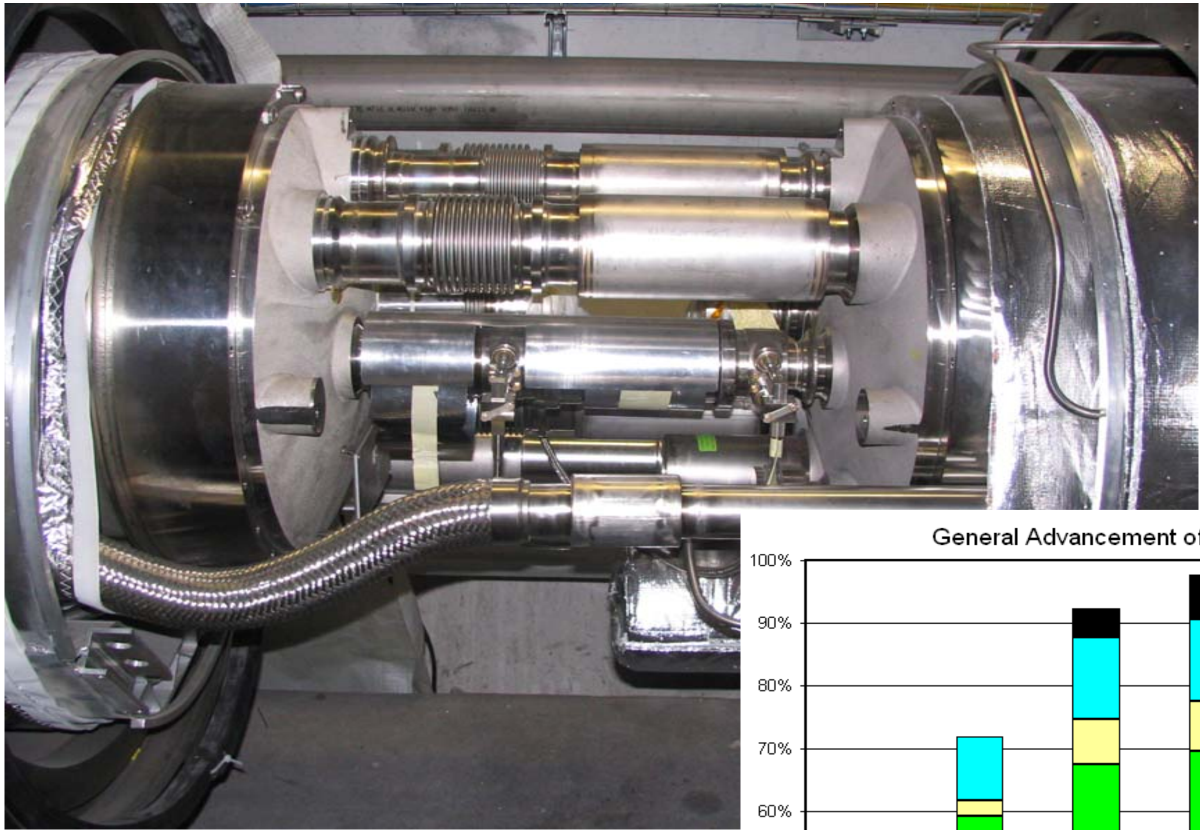
Achtung! Lumi estimates are mine, not from the machine

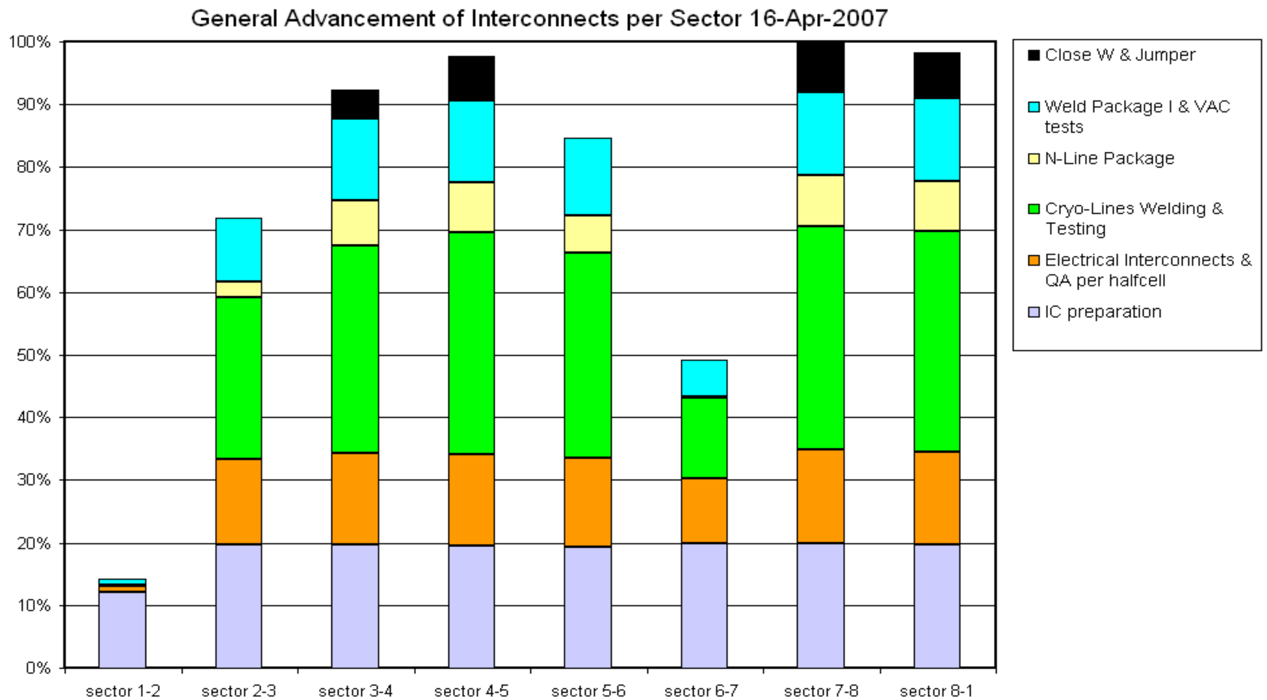
# Sector 7-8 Cooldown




Cooldown to 2K is non-trivial and takes time…

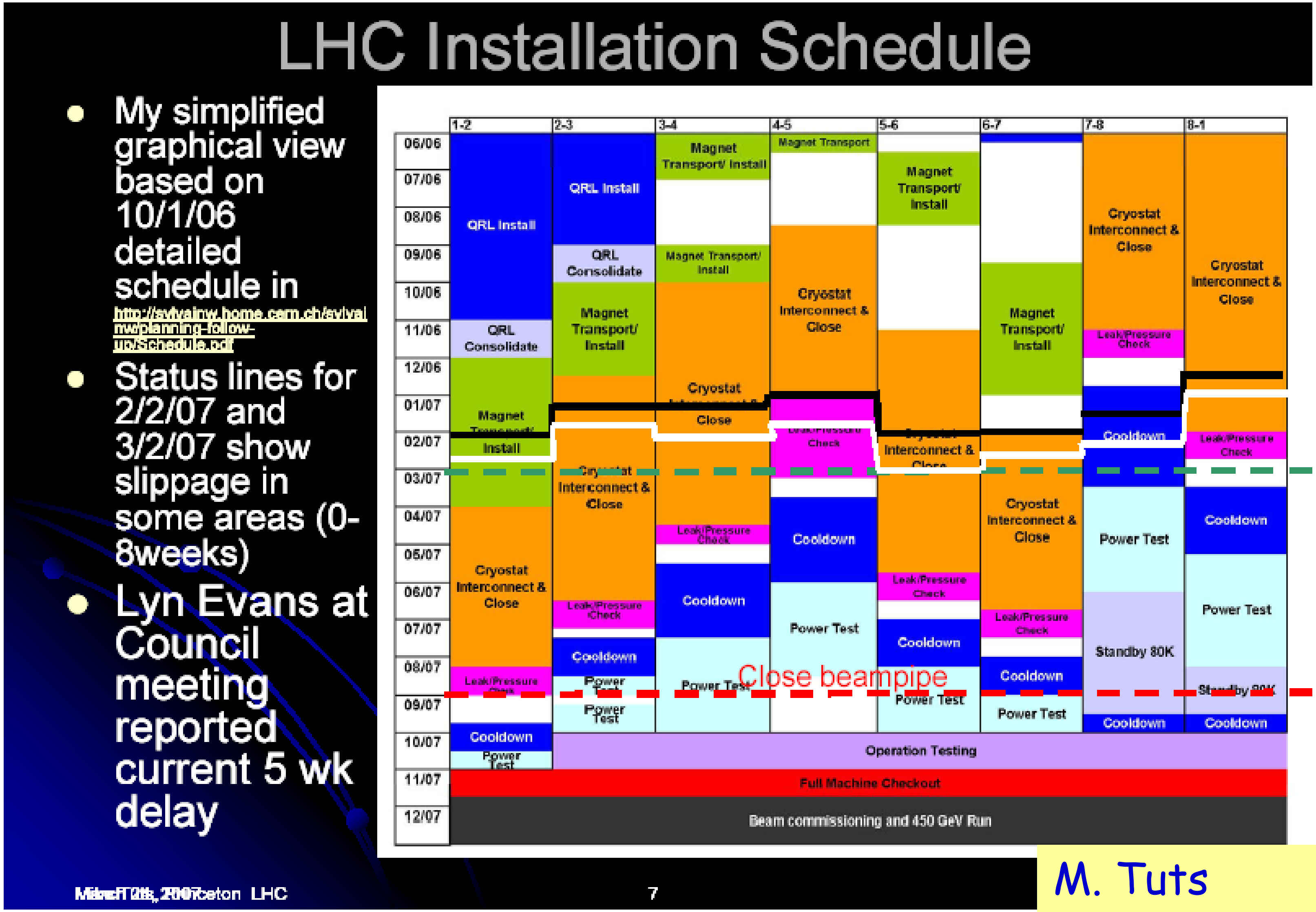
# Dipole-Dipole Interconnect





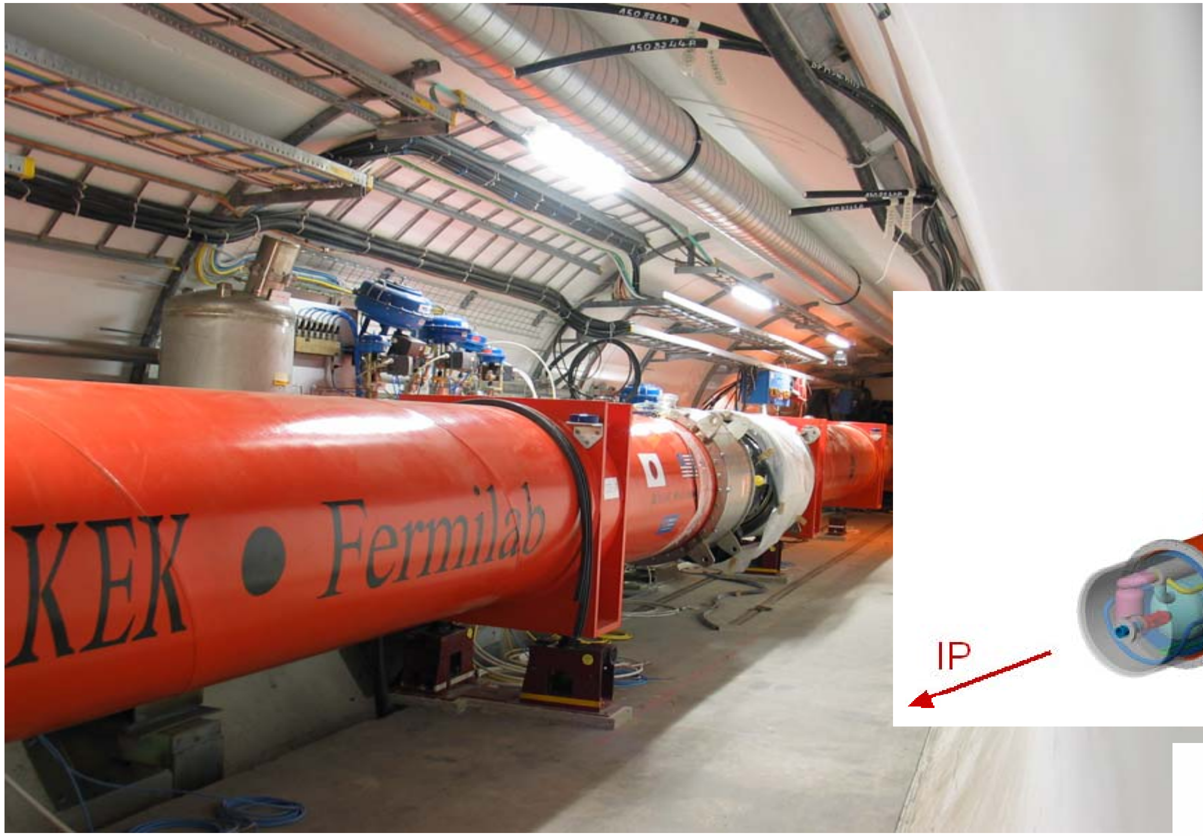

Good progress…
But a lot to do…

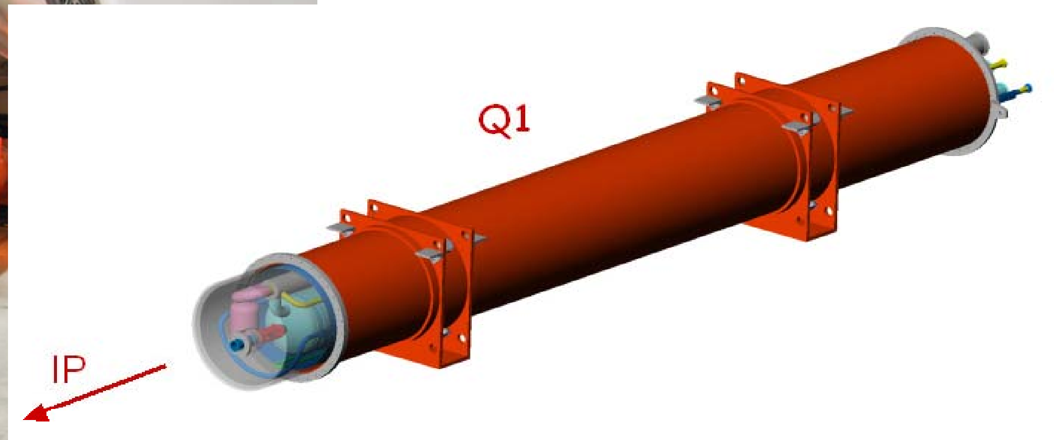
# Some delays…

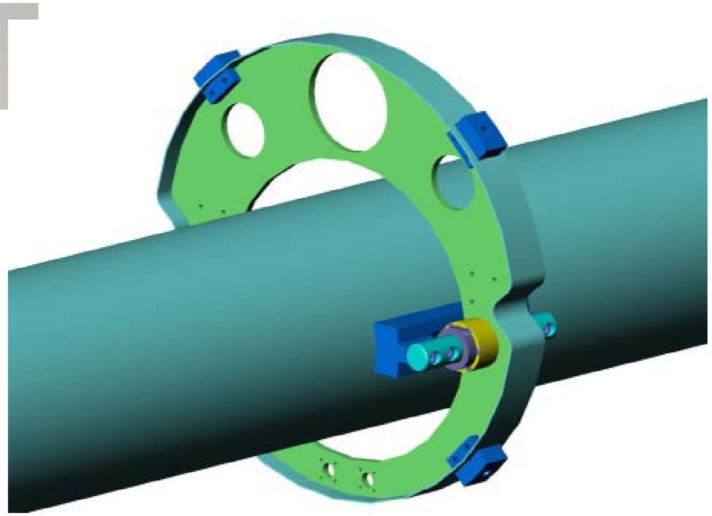



M. Tuts
Princeton, end of March

# Inner Triplet at Point 5



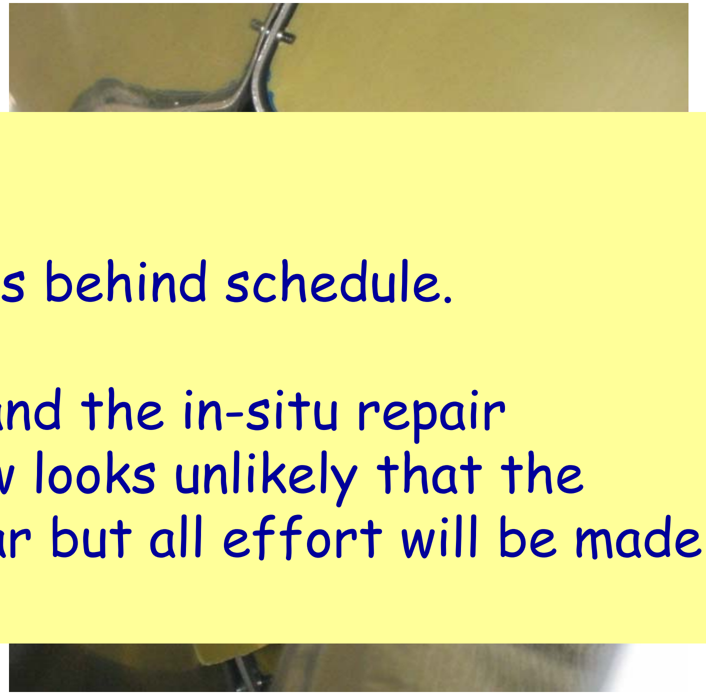



# Pressure test of Fermilab triplet in 5L

March 27
"Routine test"

April 24/25:
⇒Repair method proposed
Next pressure test in June



Lyn Evans RRB meeting at CERN 23/4/07

- Before the IT problem, we were about 5 weeks behind schedule.

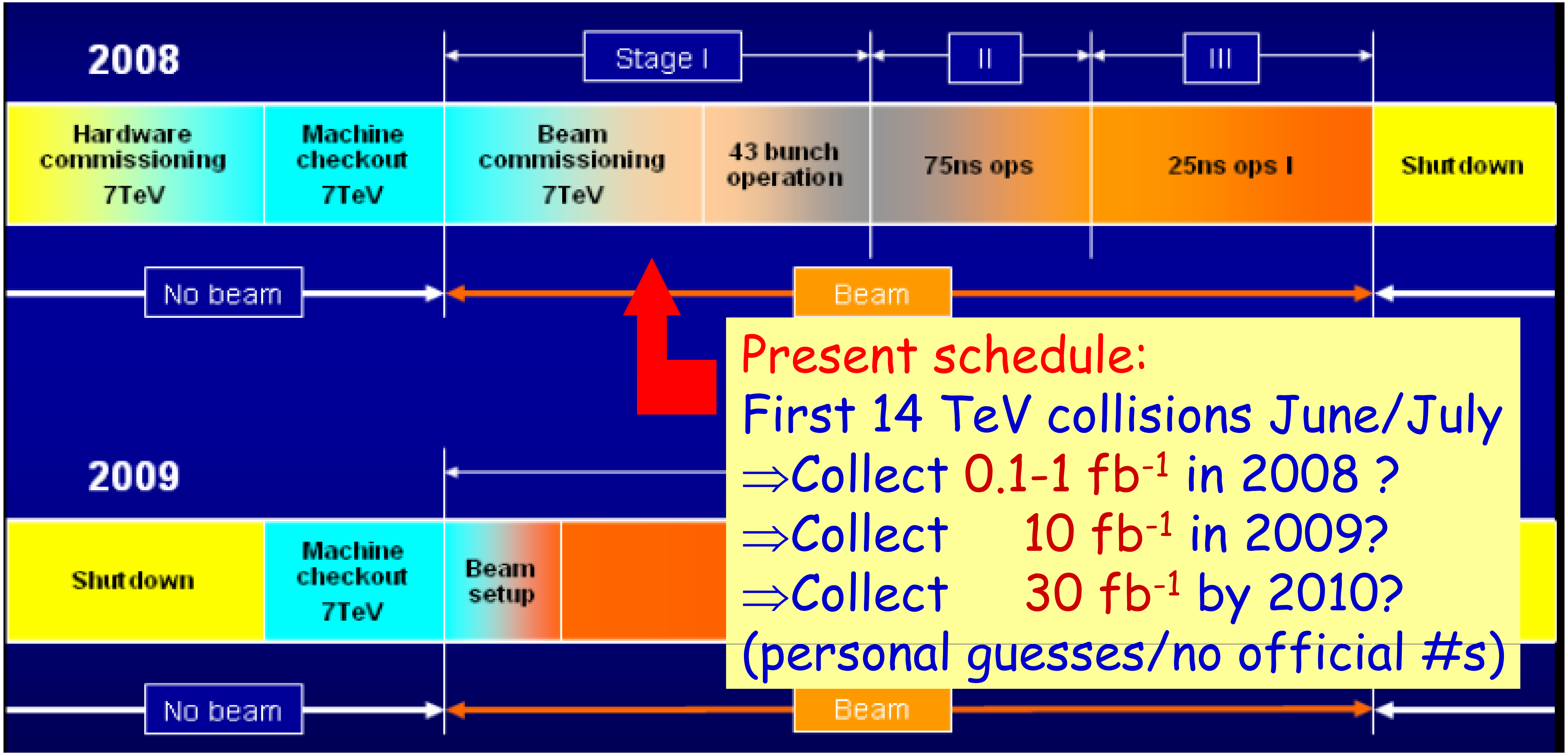
- Once the full extent of the damage is known and the in-situ repair validated, we will publish a new schedule. It now looks unlikely that the engineering run can occur at the end of the year but all effort will be made to maintain a physics run in 2008 as foreseen.

# Staged Commissioning for 2008

Stage I: "Pilot physics" ~1 month, 43 bunches, no crossing angle, $L<10^{32}\ cm^{-2}s^{-1}$

Stage II: 75ns operation, push crossing angle and squeeze, $L<10^{33}$

Stage III: 25ns operation, nominal crossing angle, $L<2*10^{33}$




Present schedule:

First 14 TeV collisions June/July

⇒Collect 0.1-1 $fb^{-1}$ in 2008 ?

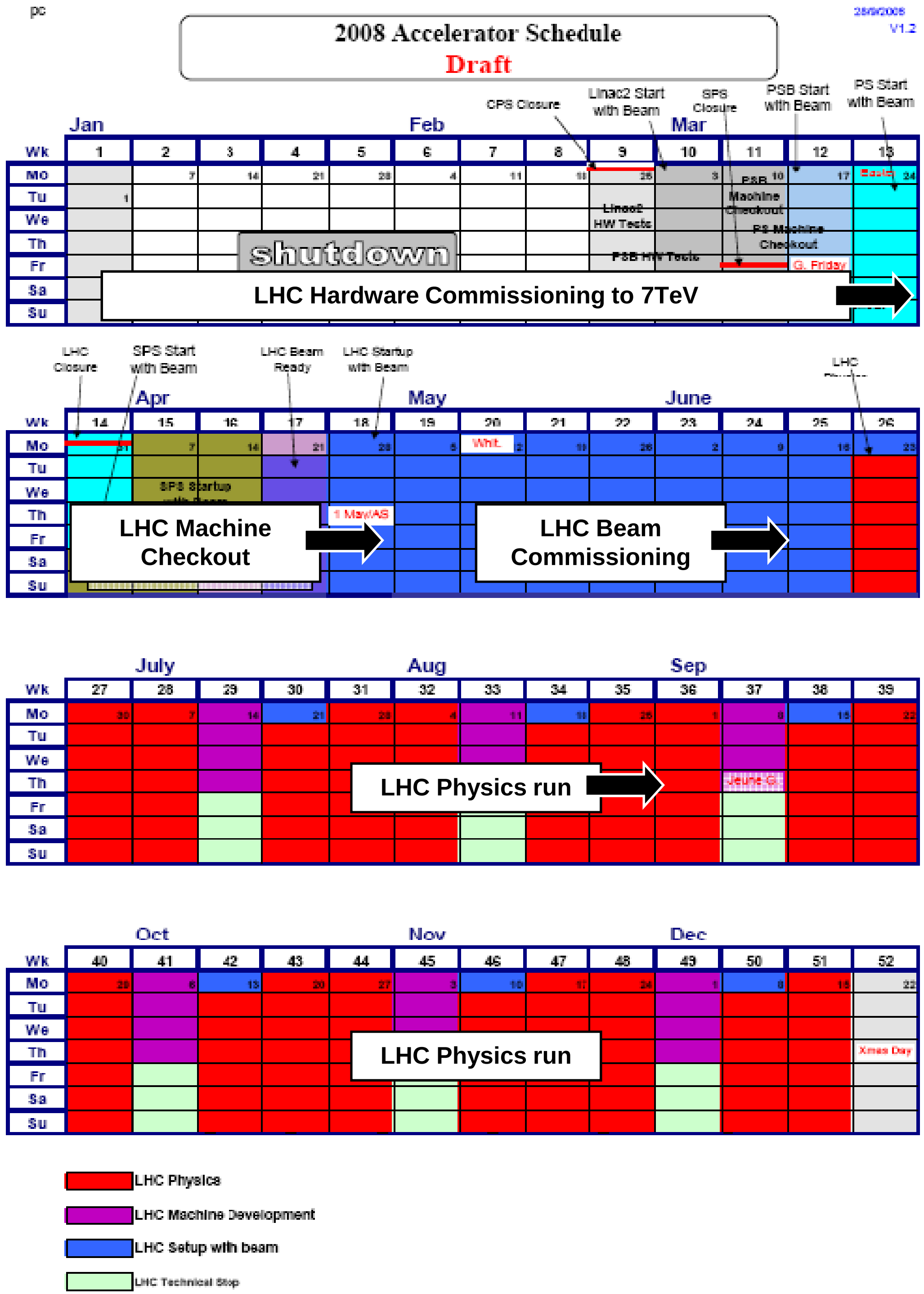
⇒Collect 10 $fb^{-1}$ in 2009?

⇒Collect 30 $fb^{-1}$ by 2010?

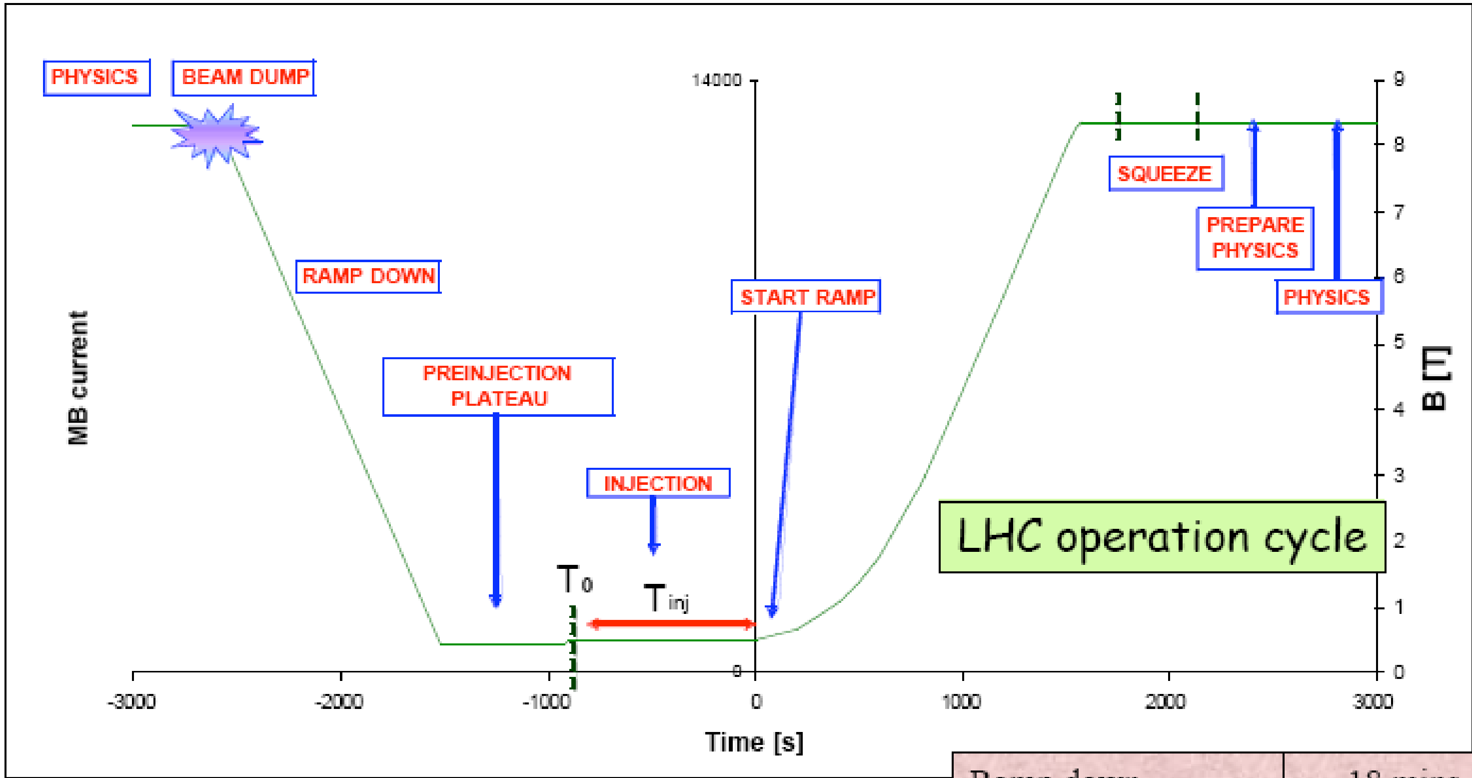
(personal guesses/no official #s)

# 2008 Draft Schedule

- 3 month ++ shutdown (no beam)
- 4 weeks checkout (no beam)
- 8 weeks beam commissioning
- 26 weeks -- physics run (protons)
  - 20 days physics
  - 4 days MD
  - 3 days technical stop



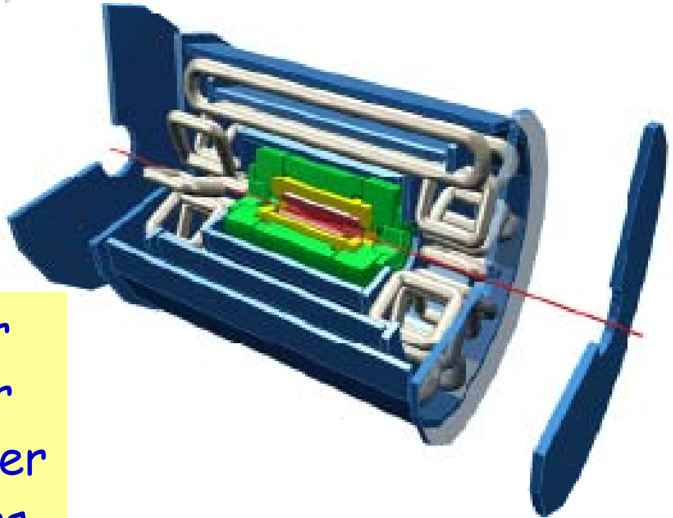
# Expected LHC operation Cycle

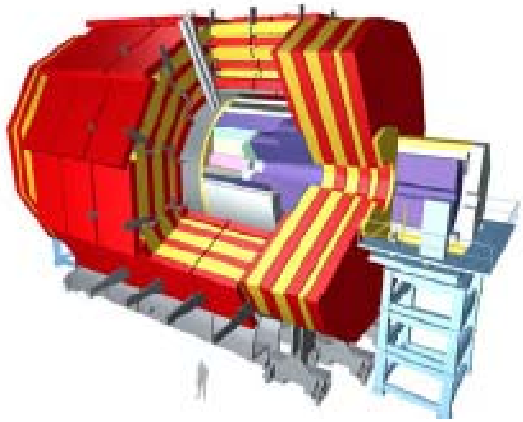



| | |
|---|---|
| Ramp down | ≈ 18 mins |
| Pre-injection plateau | 15 mins |
| Injection | ≈ 15 mins |
| Ramp | ≈ 28 mins |
| Squeeze | < 5 mins |
| Prepare physics | ≈ 10 mins |
| **Physics** | **10-20 hours** |

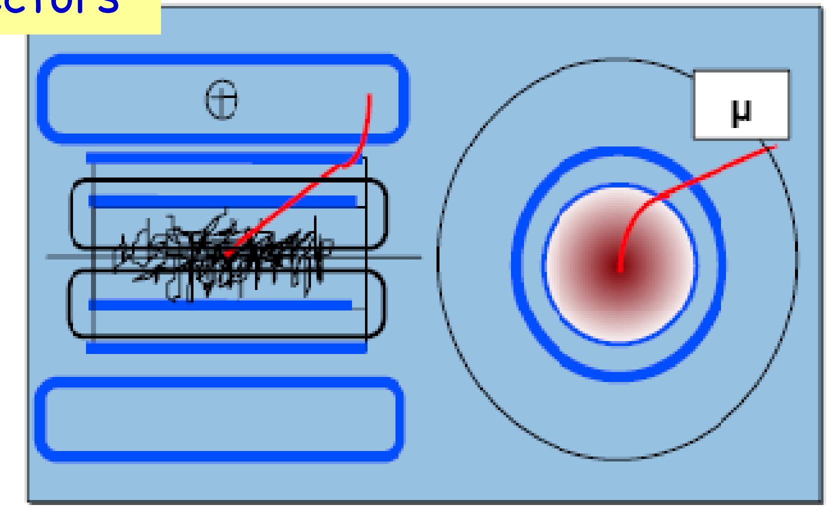
# General Purpose Detectors at the LHC

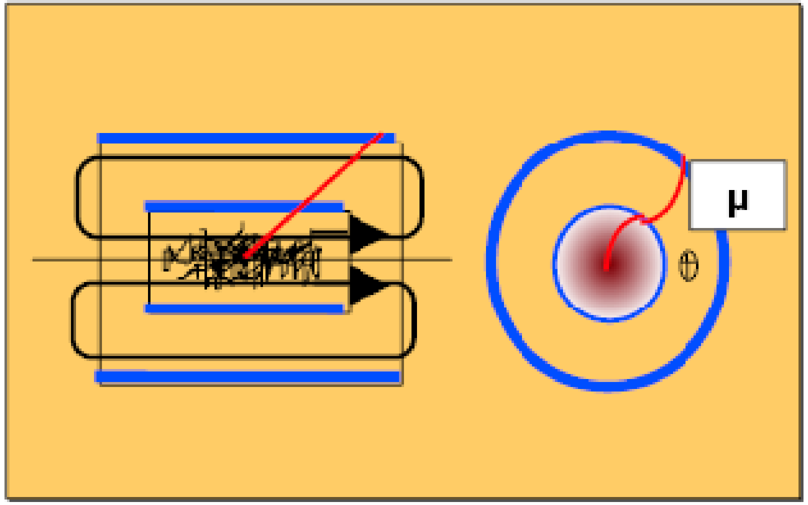
**ATLAS** A Toroidal LHC ApparatuS **CMS** Compact Muon Solenoid





- Central tracker
- EM calorimeter
- HAD calorimeter
- Muon Detectors




Trigger: Reduce 40 MHz collision rate to 100 Hz event rate to store for analysis

# ATLAS ⇔ CMS

**TABLE 3** Main parameters of the CMS and ATLAS magnet systems

| | CMS | ATLAS | | |
|---|---|---|---|---|
| **Parameter** | **Solenoid** | **Solenoid** | **Barrel toroid** | **End-cap toroids** |
| Inner diameter | 5.9 m | 2.4 m | 9.4 m | 1.7 m |
| Outer diameter | 6.5 m | 2.6 m | 20.1 m | 10.7 m |
| Axial length | 12.9 m | 5.3 m | 25.3 m | 5.0 m |
| Number of coils | 1 | 1 | 8 | 8 |
| Number of turns per coil | 2168 | 1173 | 120 | 116 |
| Conductor size ($mm^2$) | $64 \times 22$ | $30 \times 4.25$ | $57 \times 12$ | $41 \times 12$ |
| Bending power | $4\ T \cdot m$ | $2\ T \cdot m$ | $3\ T \cdot m$ | $6\ T \cdot m$ |
| Current | 19.5 kA | 7.6 kA | 20.5 kA | 20.0 kA |
| Stored energy | 2700 MJ | 38 MJ | 1080 MJ | 206 MJ |

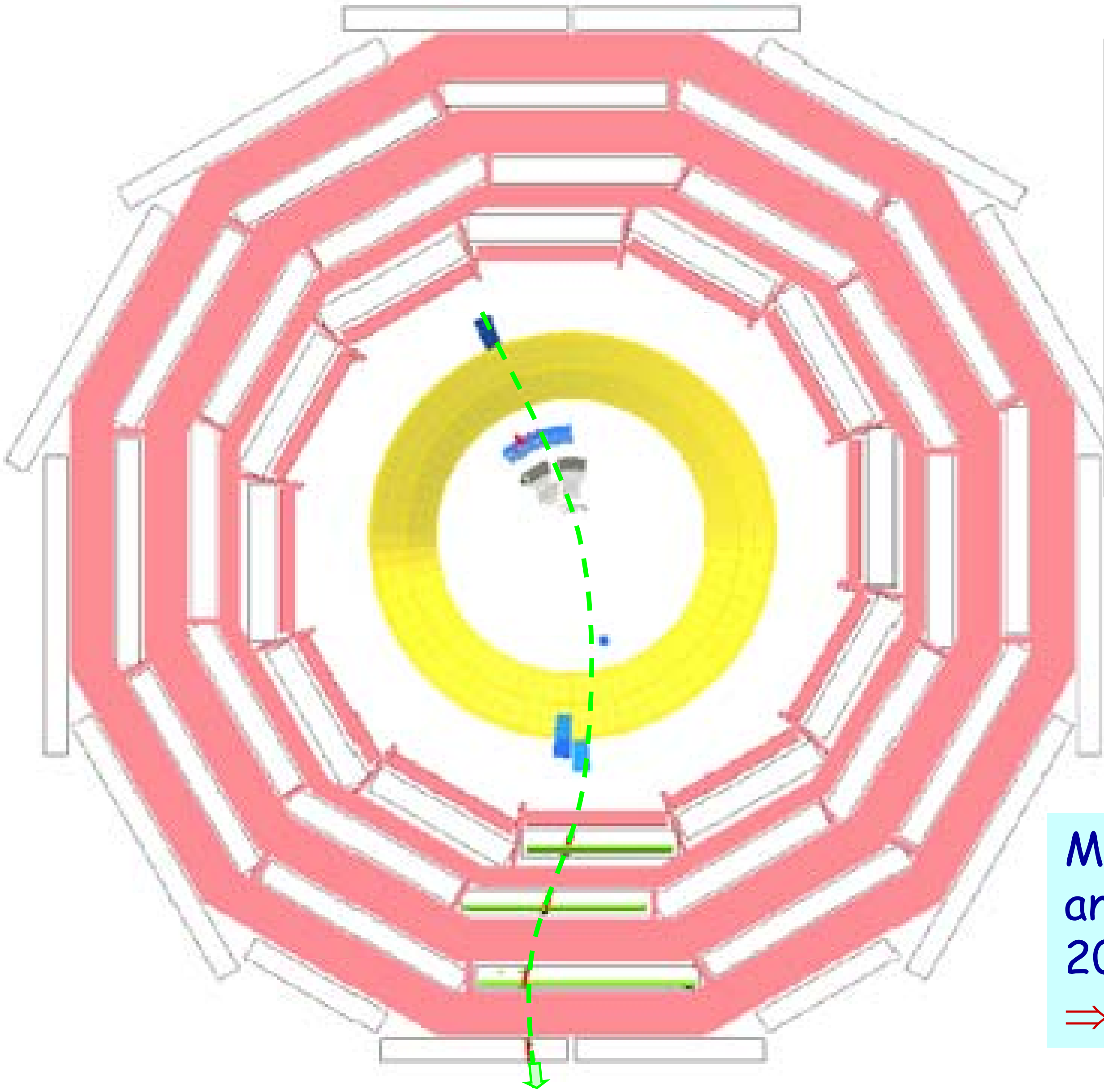
Three magnets have reached their design currents: a major technical milestone!

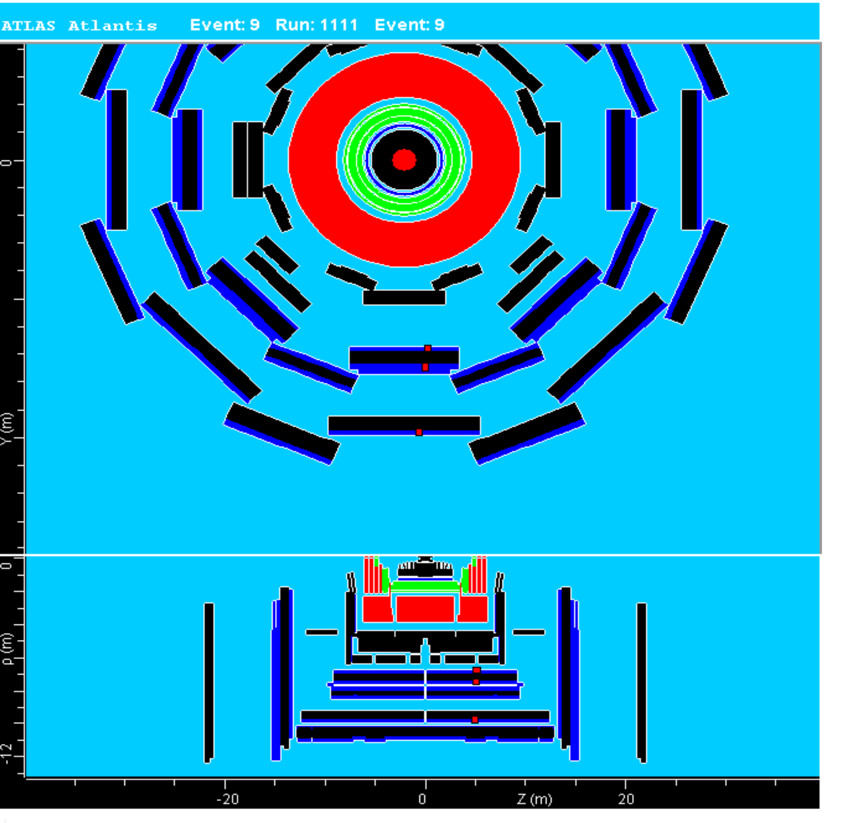
# ATLAS ⇔ CMS

| | ATLAS | CMS |
|---|---|---|
| MAGNET (S) | Air-core toroids + solenoid in inner cavity<br>4 magnets<br>Calorimeters in field-free region | Solenoid<br>Only 1 magnet<br>Calorimeters inside field |
| TRACKER | Si pixels+ strips<br>TRT → particle identification<br>B=2T<br>$\sigma/p_T \sim 3 \times 10^{-4}\, p_T \oplus 0.01$ | Si pixels + strips<br>No particle identification<br>B=4T<br>$\sigma/p_T \sim 1.5 \times 10^{-4}\, p_T \oplus 0.005$ |
| EM CALO | Pb-liquid argon<br>$\sigma/E \sim 10\%/\sqrt{E}$ uniform<br>longitudinal segmentation | $PbWO_4$ crystals<br>$\sigma/E \sim 2\text{-}5\%/\sqrt{E}$<br>no longitudinal segm. |
| HAD CALO | Fe-scint. + Cu-liquid argon (10 λ)<br>$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$ | Cu-scint. (> 5.8 λ +catcher)<br>$\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$ |
| MUON | Air → $\sigma/p_T \sim 7$ % at 1 TeV<br>standalone | Fe → $\sigma/p_T \sim 5\%$ at 1 TeV<br>combining with tracker |

Updated values: see Sphicas and Froidevaux An. Re. Nucl. Part. Sci 56 (375) 2006

# Cosmic Data Taking in 2006






Many of the subdetectors in CMS and ATLAS now tested with cosmics 2006: CMS made a combined run
⇒Excellent prospects for 2007!!

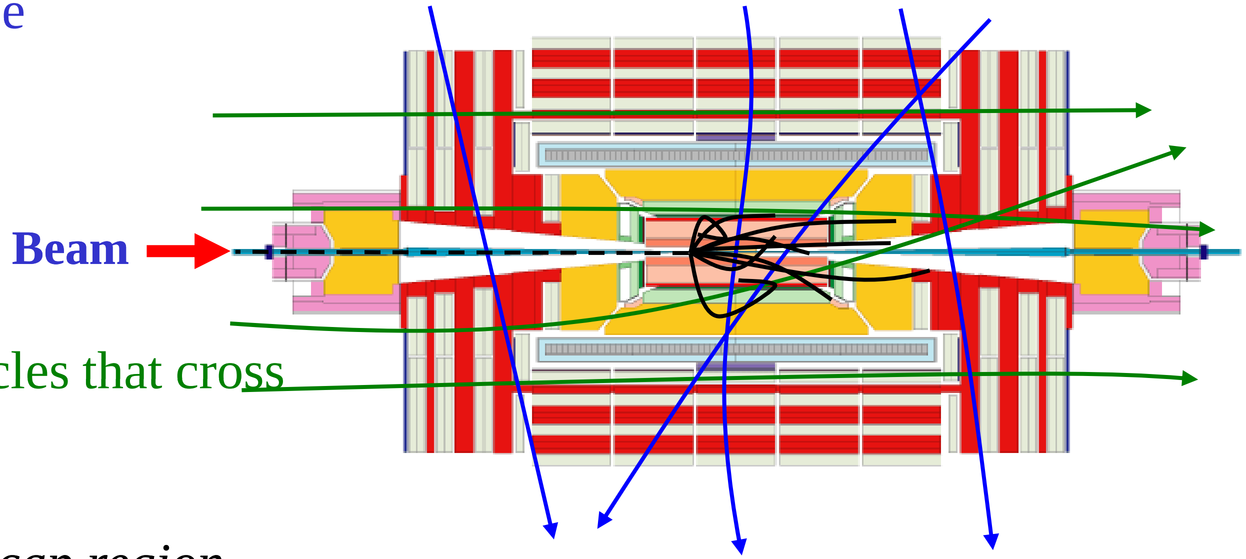
# Calibrating/alignment before collisions

Experiments will have ~3-4 months before collisions

***Cosmic Muons***

High energetic muons that traverse the detector vertically

→particular useful for alignment and calibration - *barrel region.*




***Beam Halo Muons (Hadrons)***

Machine induced secondary particles that cross the detector almost horizontally

→particular useful for alignment and calibration - *endcap region.*

***Beam Gas Interactions***

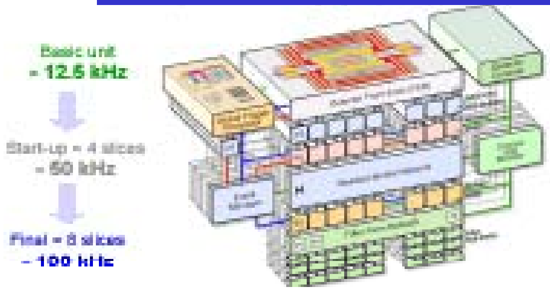
Proton-nucleon interaction in the active detector volume (7TeV→$E_{cm}$=115 GeV)

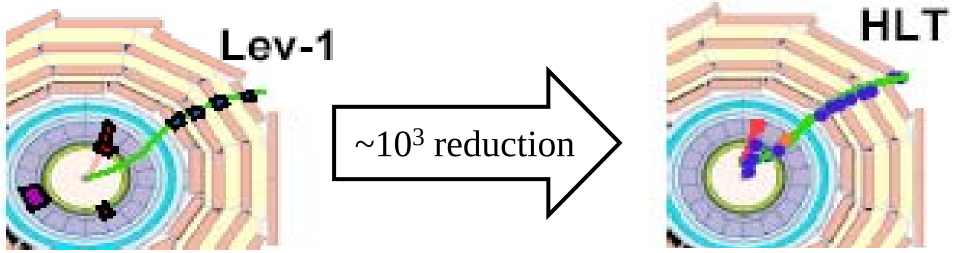
→resemble collision events but with a rather soft $p_T$ spectrum ($p_T$<2 GeV)

**All three physics structures are interesting for alignment, calibration, gain operational experience, dead channels, debug readout, etc …**

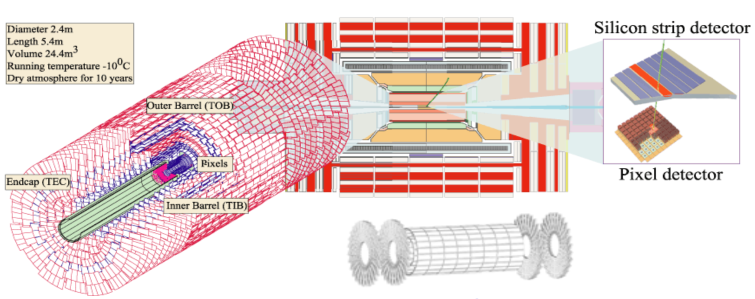
# Major Commissioning Challenges

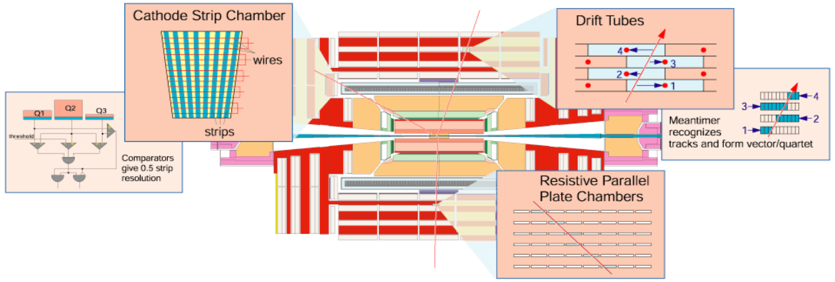
## Efficient operation of Trigger (Level1/HLT) and DAQ System



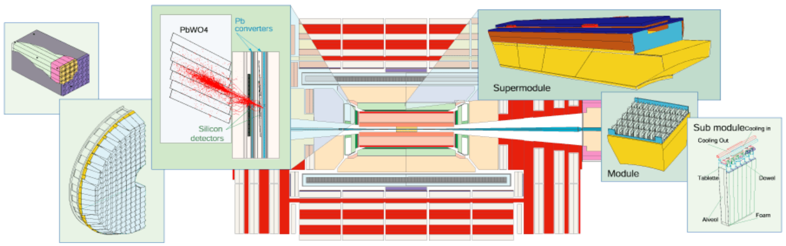



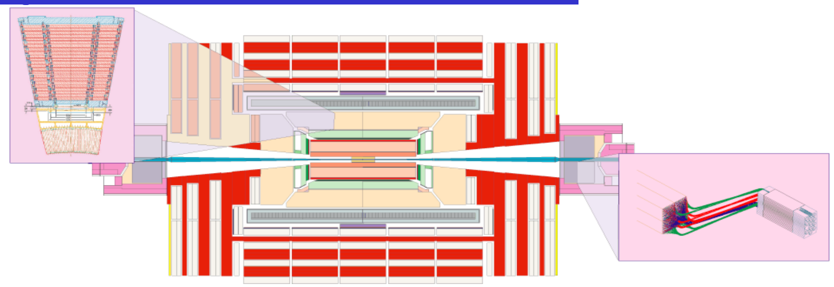

## Alignment of the tracking devices Tracker(PIXEL,Strip) and Muon System




## Calibration of the Calorimeter Systems ECAL and HCAL



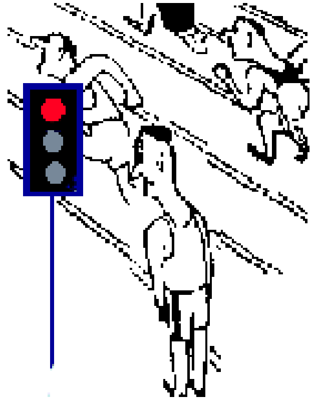
→form the base for the "commissioning of physics tools" like b and τ tagging, jets, missing $E_T$ …

# Detectors at Start-up in 2007/2008

❷ Which detectors the first year ?

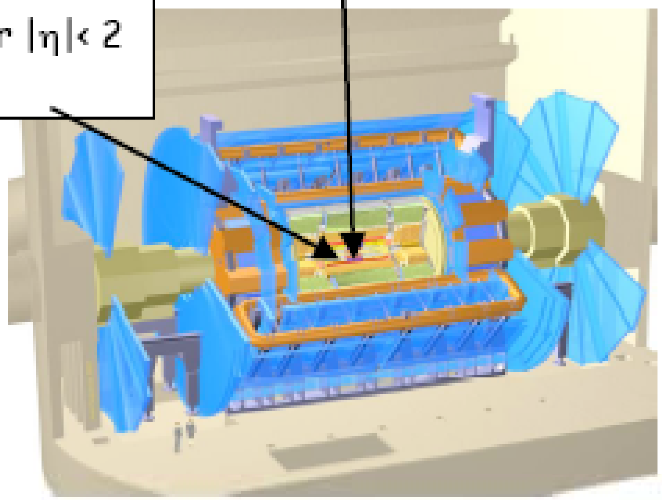
RPC over $|\eta|<1.6$ (instead of $|\eta|< 2.1$)
$4^{th}$ layer of end-cap chambers missing

CMS EM Endcap Detector should be ready for 2008 run



- Detectors progressing well and will be fairly complete at start-up
- Schedule is tight!

TRT acceptance over $|\eta|< 2$ (instead of $|\eta|< 2.4$)



Both experiments:
deferrals of high-level Trigger/DAQ processors
→ LVL1 output rate limited to
~ 50 kHz CMS (instead of 100 kHz)
~ 40 kHz ATLAS (instead of 75 kHz)

Impact on physics visible but acceptable
Main loss : B-physics programme strongly reduced (single μ threshold $p_T$> 14-20 GeV)

# Detector performance

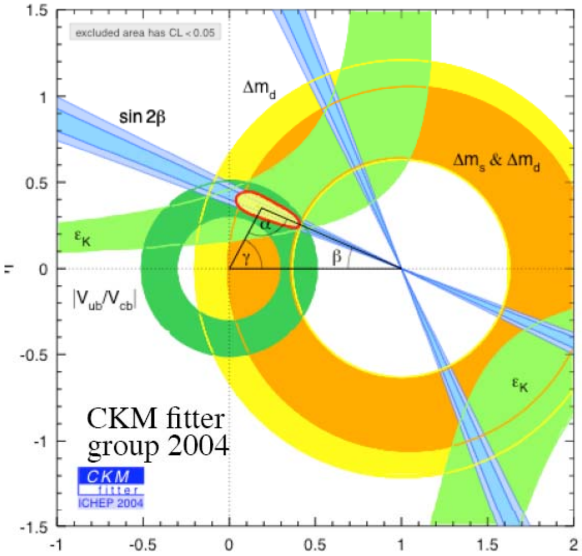
| | Expected Day 0 | Goals for Physics |
|---|---|---|
| ECAL uniformity | ~ 1% ATLAS<br>~ 4% CMS | < 1% |
| Lepton energy scale | 0.5—2% | 0.1% |
| HCAL uniformity | 2—3% | < 1% |
| Jet energy scale | <10% | 1% |
| Tracker alignment | 20—200 μm in Rφ | $\mathcal{O}$(10 μm) |

# LHCb: b-physics at the LHC

Examples

CKM triangle

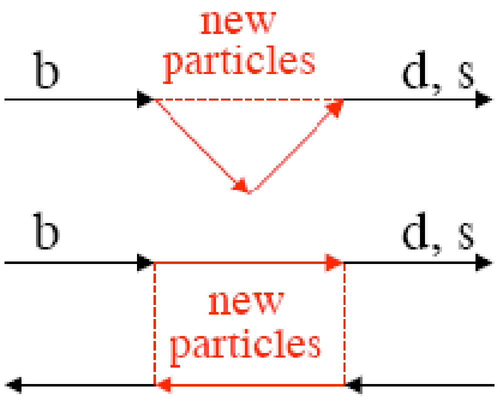
including $\not{C}\not{P}$ B and K



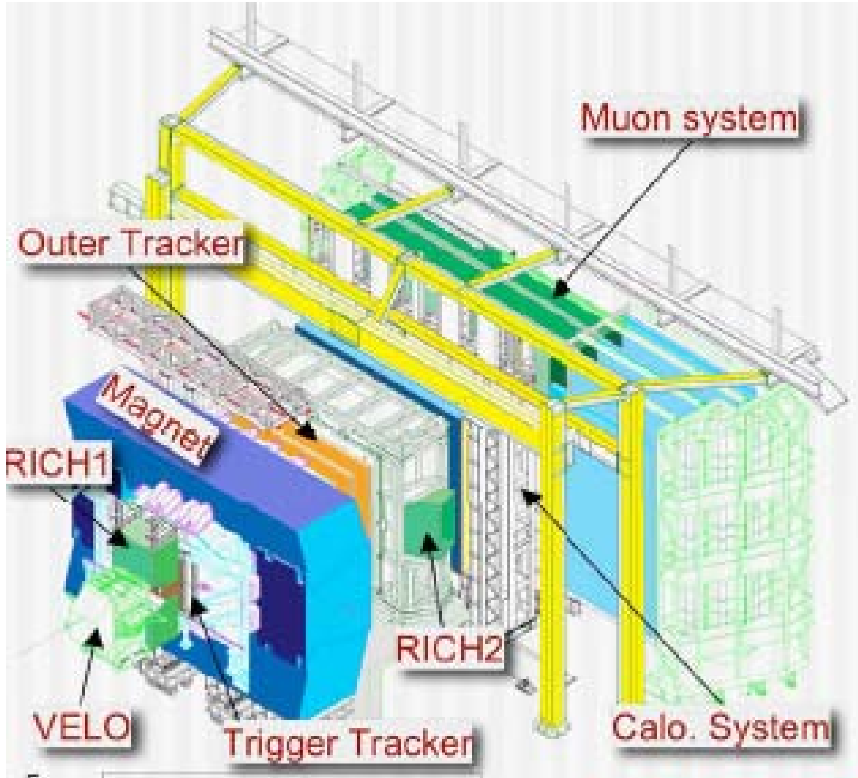

$B_s \rightarrow J/\psi\phi$ 120k signal events/year in LHCb

$\sigma(\sin\phi_s) \sim 0.06, \ \sigma(\Delta\Gamma_s/\Gamma_s) \sim 0.02$

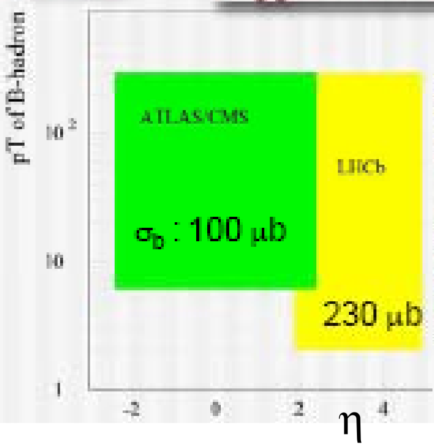
Measurement of $B_s$–$\overline{B}_s$ oscillation

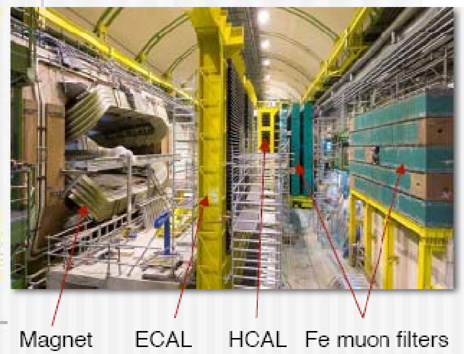



Sensitive to new physics complementary to ATLAS/CMS

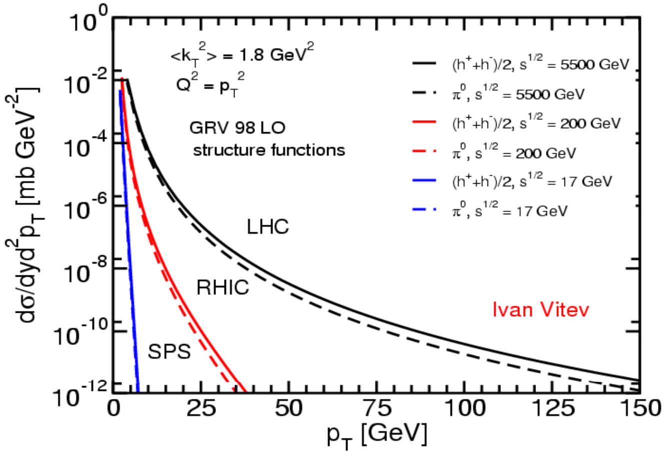



L ~ $2\times10^{32}$cm$^{-2}$s$^{-1}$

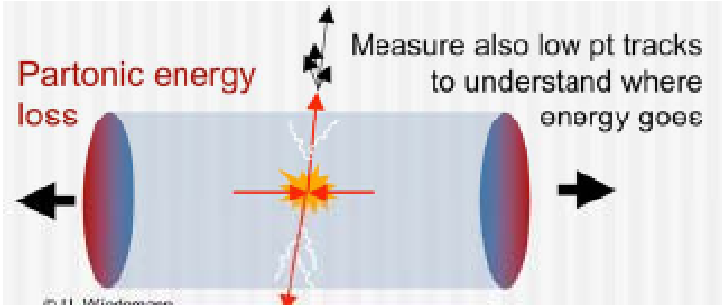


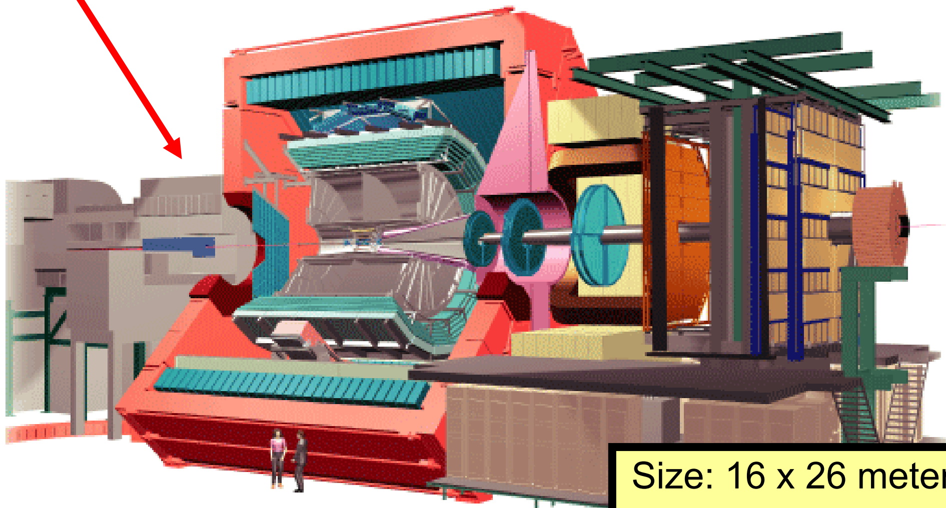
# Heavy Ion Physics at the LHC



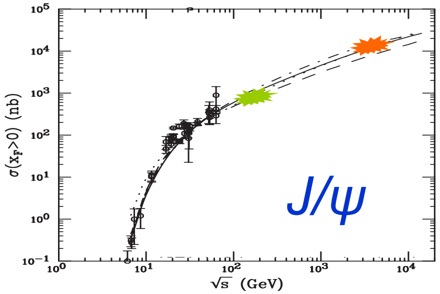

High $P_T$ particle and jet production Jet-quenching

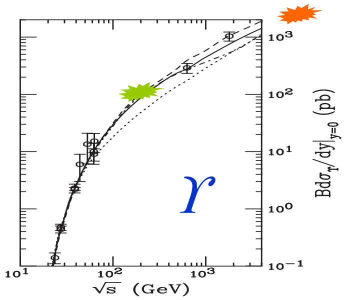



Heavy ions part of the LHC physics program with ALICE, but also CMS and ATLAS

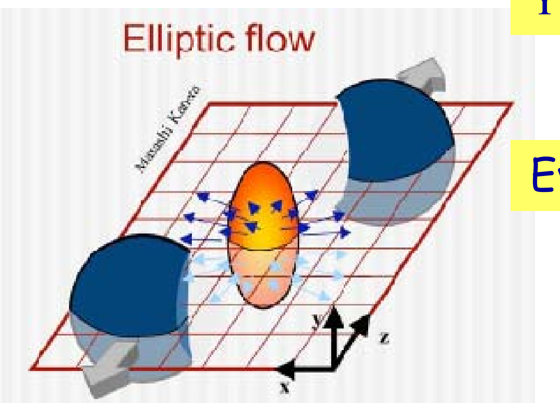


Size: 16 x 26 meters
Weight: 10,000 tons



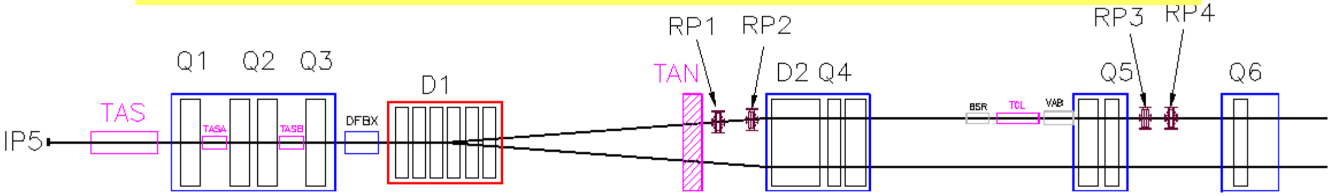

ϒ melt down

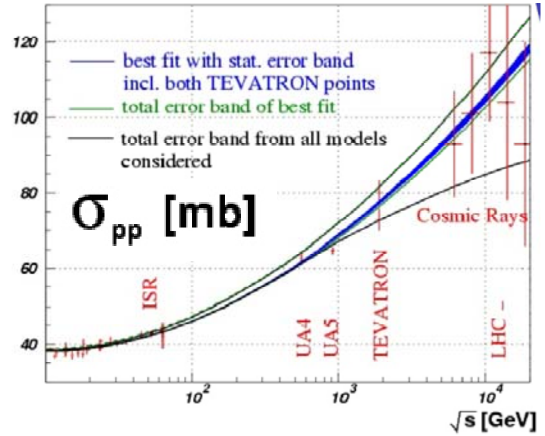



Event shapes

# Forward Coverage: TOTEM/LHCf

TOTEM: measuring the total, elastic and diffractive cross sections
Add Roman pots (and inelastic telescope) to CMS interaction regions.
Common runs with CMS planned

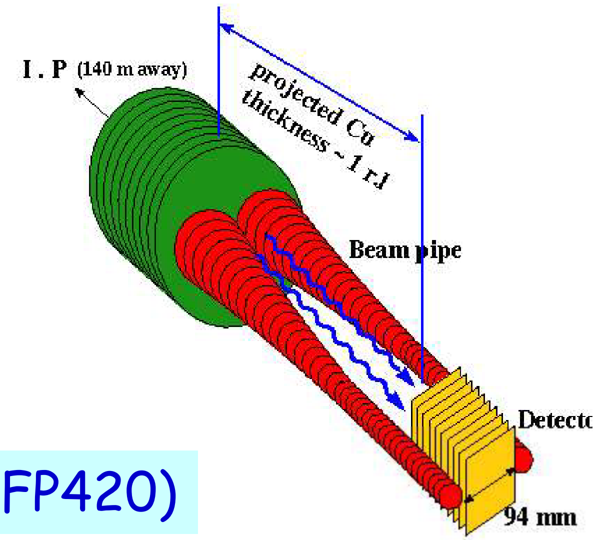


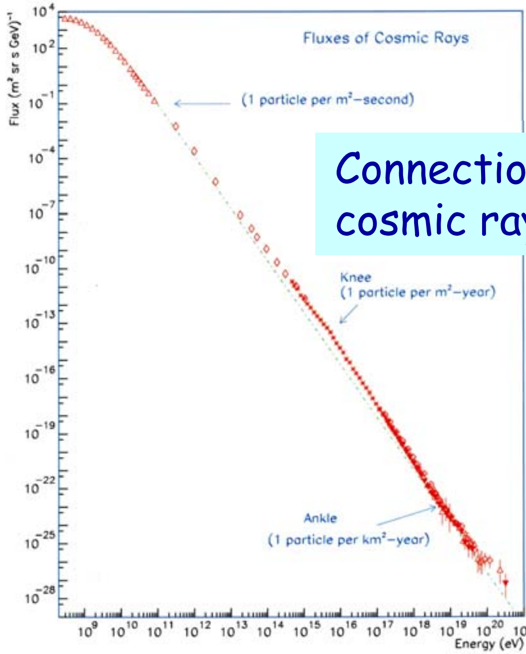




LHCf: measurement of photons and neutral pions in the very forward region of LHC

Add an EM calorimeter at 140 m from the IPof ATLAS

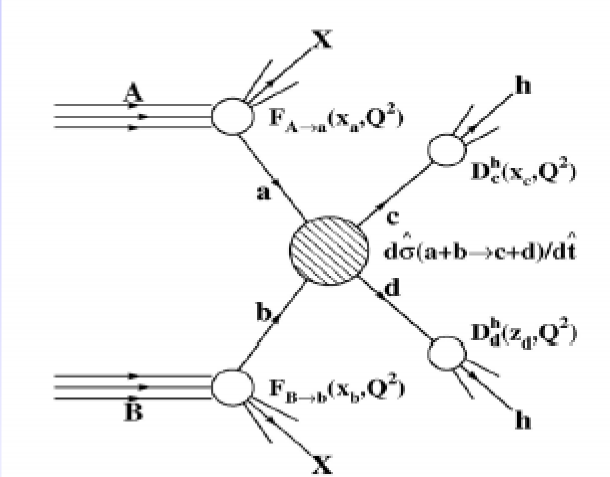
+R&D for detectors at 420 m (FP420)



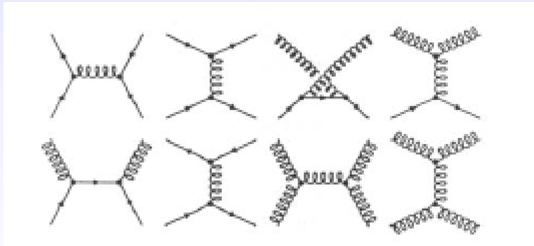

Connection with cosmic rays

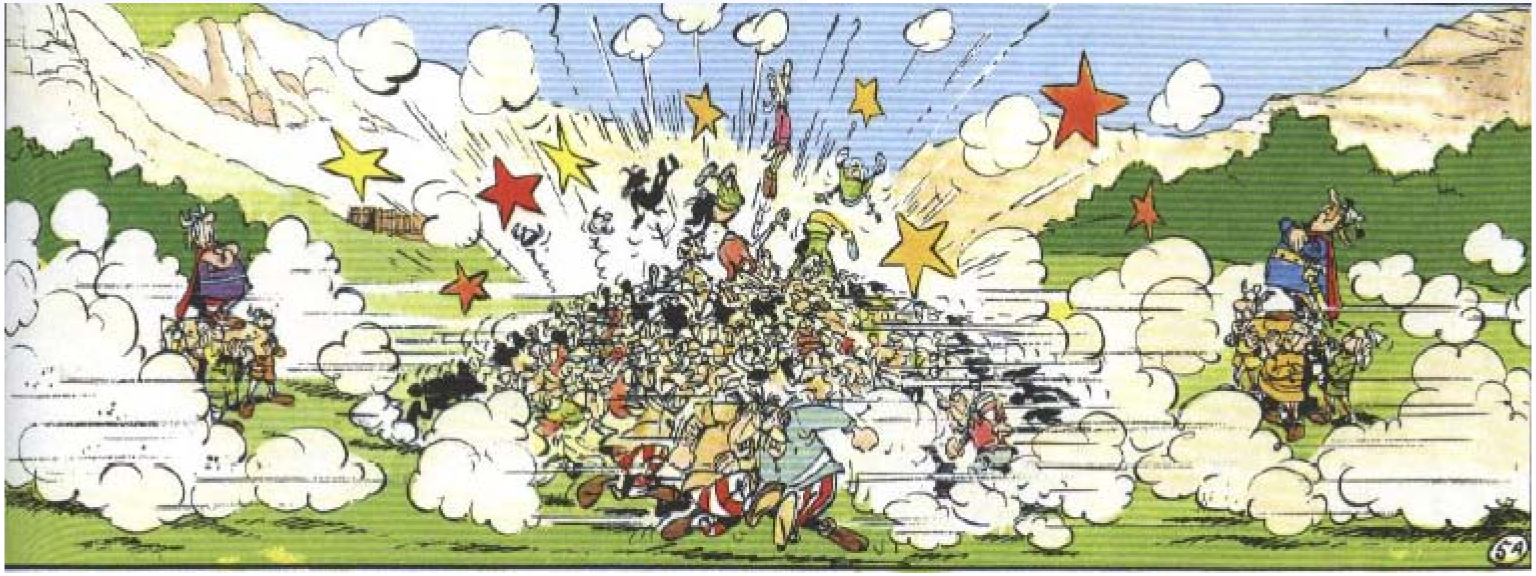
# Proton colliders




- Protons are complex objects:
  Partonic substructure:
  Quarks and Gluons
- Hard scattering processes:
  (large momentum transfer)

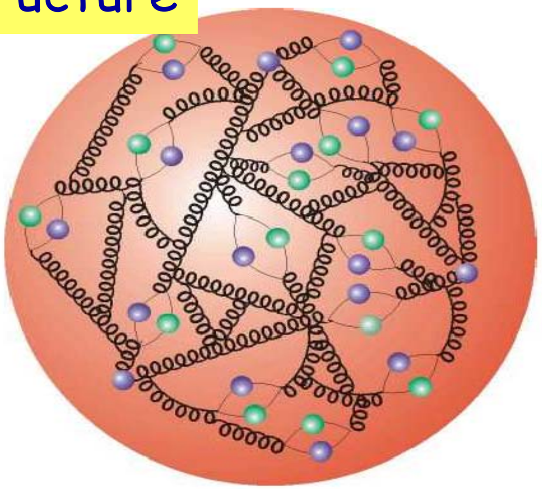
  quark-quark
  quark-gluon    scattering or annihilation
  gluon-gluon



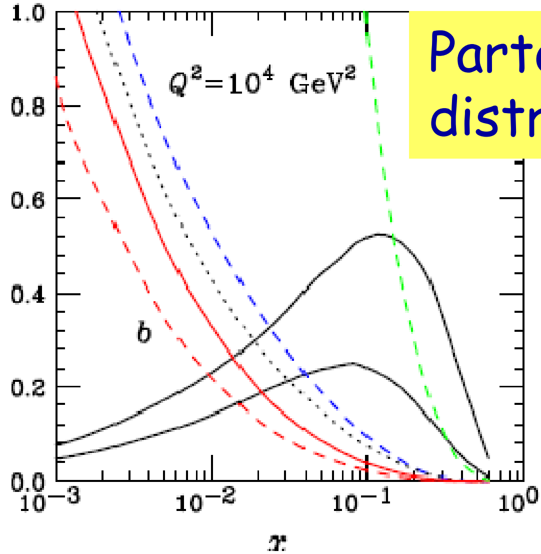


# pp collisons : complications

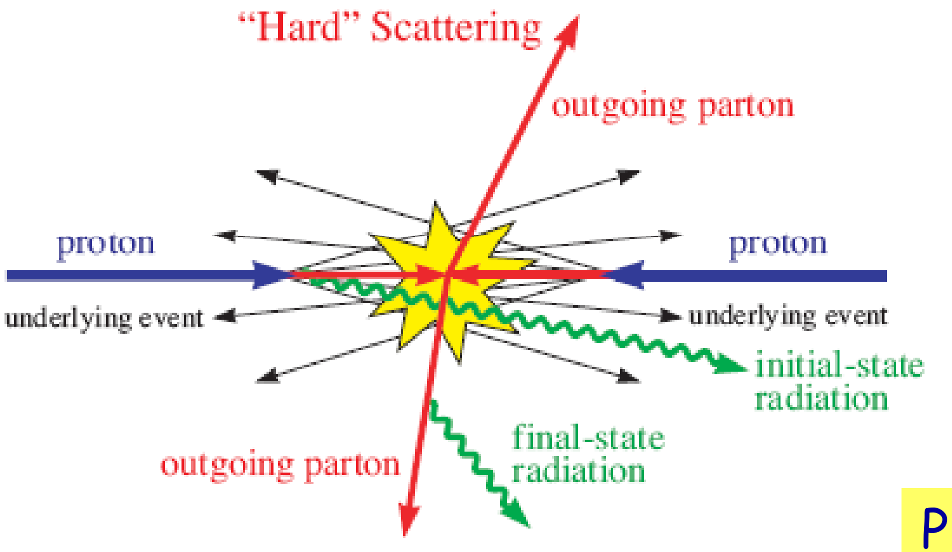
Protons have structure



Parton distributions

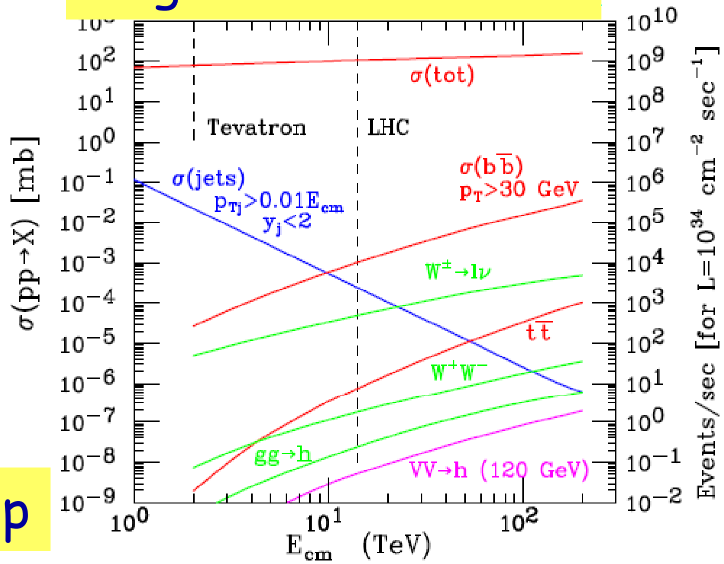



Underlying event




Scattering cross sections for various SM processes:

Huge cross sections




Pile-up

# Start-up Physics 2008

With the first physics run in 2008 ($\sqrt{s}$ = 14 TeV) ....

0.1-1 $fb^{-1}$

1 $fb^{-1}$ (100 $pb^{-1}$) ≡ 6 months (few days) at L= $10^{32}$ $cm^{-2}s^{-1}$ with 50% data-taking efficiency
→

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

In 2008 we have to rediscover the Standard Model at 14 TeV and compare to calculations and generators.
...And tune generators

With these data:

- Understand and calibrate detectors in situ using
  e.g. - $Z \to ee, \mu\mu$ tracker, ECAL, Muon cham
  - $t\bar{t} \to bl\nu\, bjj$ jet scale from $W \to jj$, b-
- Measure SM physics at $\sqrt{s}$ = 14 TeV : W, Z, $t\bar{t}$, Q
  (also because omnipresent backgrounds to New Physics)

→ **prepare the road to discovery ...... it will take time ...**

# Event Rates for pp at √s=14 TeV

| Process | Events/s | Events/y |
|---|---|---|
| $W \to e\nu$ | 15 | $10^8$ |
| $Z \to ee$ | 1.5 | $10^7$ |
| $t\bar{t}$ | 0.8 | $10^7$ |
| $b\bar{b}$ | $10^5$ | $10^{12}$ |
| $\tilde{g}\tilde{g}$ (m=1 TeV) | 0.001 | $10^4$ |
| H (m=0.8 TeV) | 0.001 | $10^4$ |
| Black Holes $M_D$=3 TeV n=4 | 0.0001 | $10^3$ |

In the first 3 minutes at $10^{33} cm^{-2}s^{-1}$ LHC will produce per experiment:

- ~5000 $W \to \mu\nu, e\nu$ decays
- ~ 500 $Z \to \mu\nu, e\nu$ decays
- >2.$10^7$ bottom quark pairs
- ~150 top quark pairs
- ~10 Higgs particles ($M_H$=120 GeV)
- ~20 gluino pairs with mass 500 GeV
- A quantum black hole ($M_D$ = 2TeV)
- ....

Startup luminosity at 14 TeV will be much lower, perhaps like $10^{31}$-$10^{32}$ $cm^{-2}s^{-1}$ (less bunches/current)

Record ~ 20K events/30Gbyte

$L = \frac{N}{\sigma}$

# Luminosity Measurements

Goal: Measure $L$ with $\lesssim$ 3% accuracy (long term goal)

How? Three major approaches

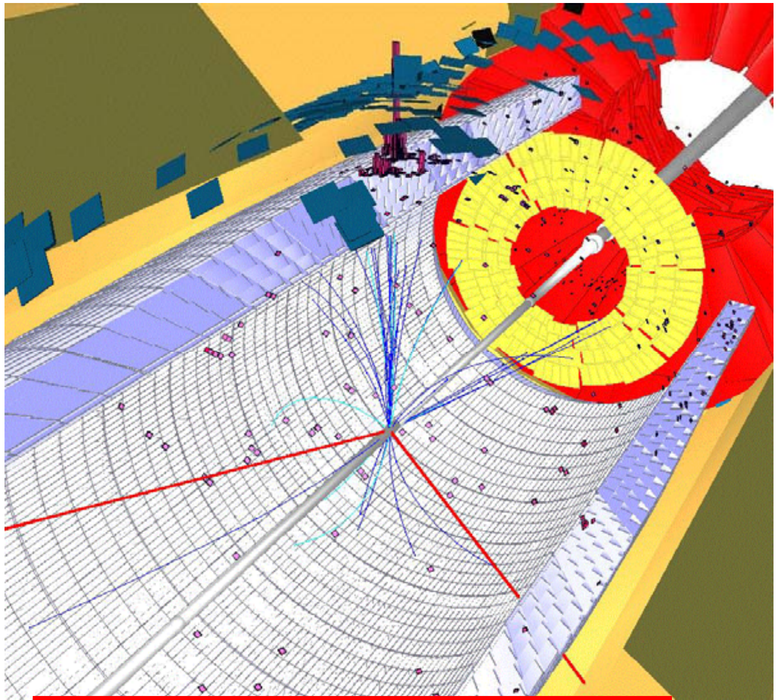
- LHC Machine parameters
- Rates of well-calculable processes:
  e.g. QED (like LEP), EW and QCD (2$\mu$ production, W/Z…)
- Elastic scattering
  - Optical theorem: forward elastic rate + total inelastic rate:
  - Luminosity from Coulomb Scattering
  - Hybrids
    - » Use $\sigma_{tot}$ measured by others
    - » Combine machine luminosity with optical theorem

CMS TDR $\Rightarrow$ Luminosity uncertainty: 10-20% for L<< 1 $fb^{-1}$
5% for L ~ 1 $fb^{-1}$
2-3% for L~ 30 $fb^{-1}$

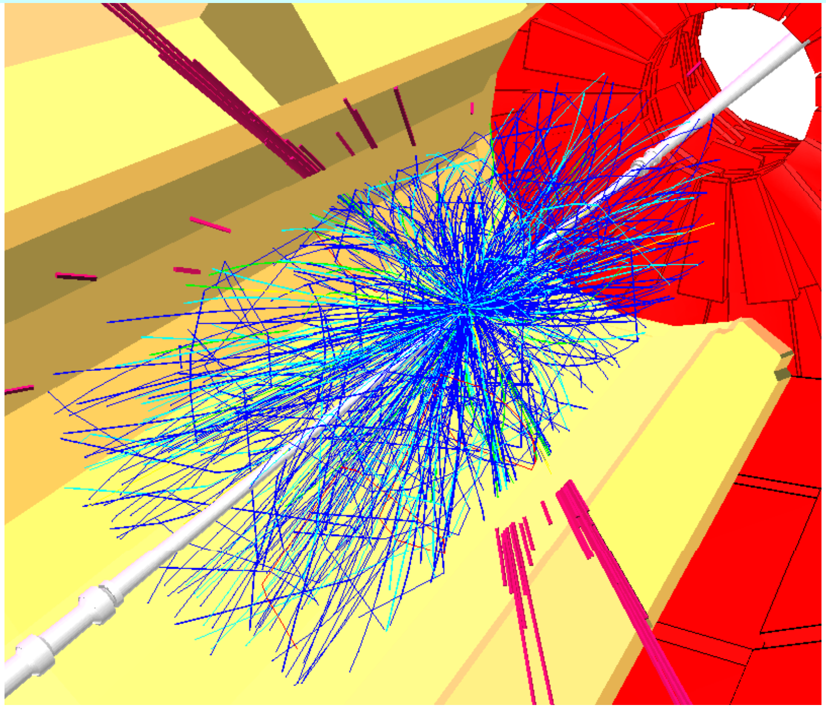
# Pile-up at the LHC

Pile-up ⇒ additional -mostly soft- interactions per bunch crossing
(minimum bias events→ huge cross section ~ 100 mb)

Startup luminosity $2 \bullet 10^{33} cm^{-2}s^{-1}$ ⇒ 4 events per bunch crossing(*)
High luminosity $10^{34} cm^{-2}s^{-1}$ ⇒ 20 events per bunch crossing
Luminosity upgrade $10^{35} cm^{-2}s^{-1}$ ⇒ 200 events per bunch crossing



SUSY event (no pileup)



SUSY event ($10^{34} cm^{-2}s^{-1}$)

(*) Non-diffractive inelastic events… otherwhise~ 5 events/bc

# Pile-up at the LHC

What do we expect roughly speaking at $L = 10^{34}\ cm^{-2}s^{-1}$?

$dn_{charged}/d\eta \approx 7.5$ per $\Delta\eta = 1$

$n_{charged}$ consists mostly of $\pi^{+-}$ with $\langle p_T \rangle \approx 0.6$ GeV

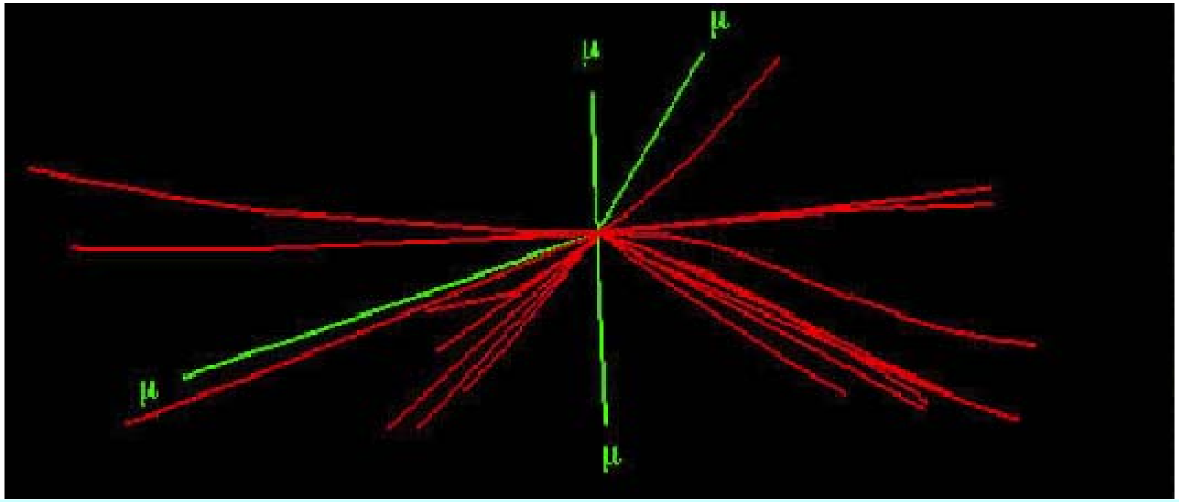
$dn_{neutral}/d\eta \approx 7.5$, $n_{neutral}$ consists mostly of $\gamma$

from $\pi^0$ decay with $\langle n_{\pi 0} \rangle \approx 4$ and $\langle p_T^{\gamma} \rangle \approx 0.3$ GeV

Assume detector with coverage over $-3 < \eta < 3$ ($\theta = 5.7^o$)
for tracks and $-5 < \eta < 5$ ($\theta = 0.8^o$) for calorimetry:

- Most of the energy is not seen! (300 TeV down the beam pipe)
- ~ 900 charged tracks every 25 ns through inner tracking
- ~ 1400 GeV transverse energy (~ 3000 particles) in
- calorimeters every 25 ns

# Pile-up at the LHC




Minimising the impact of pile-up on the detector performance has been one of the driving requirements on the initial detector design:

- a precise (and if possible fast) detector response minimises pile-up in time
  - → very challenging for the electronics in particular
  - → typical response times achieved are 20-50 ns (!)
- a highly granular detector minimises pile-up in space
  - → large number of channels (100 million pixels, 200 000 cells in electromagnetic calorimeter)

+30 min. bias events

# Event filtering: the

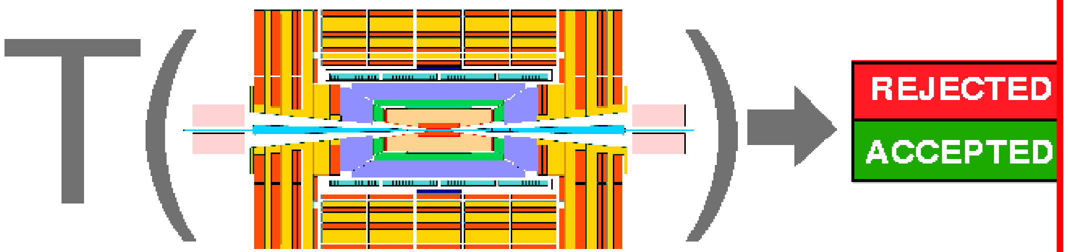
Collision rate is 40 MHz Event

2007 technology (and budget) allow

of events to tape

need a

The trigger is a function of :



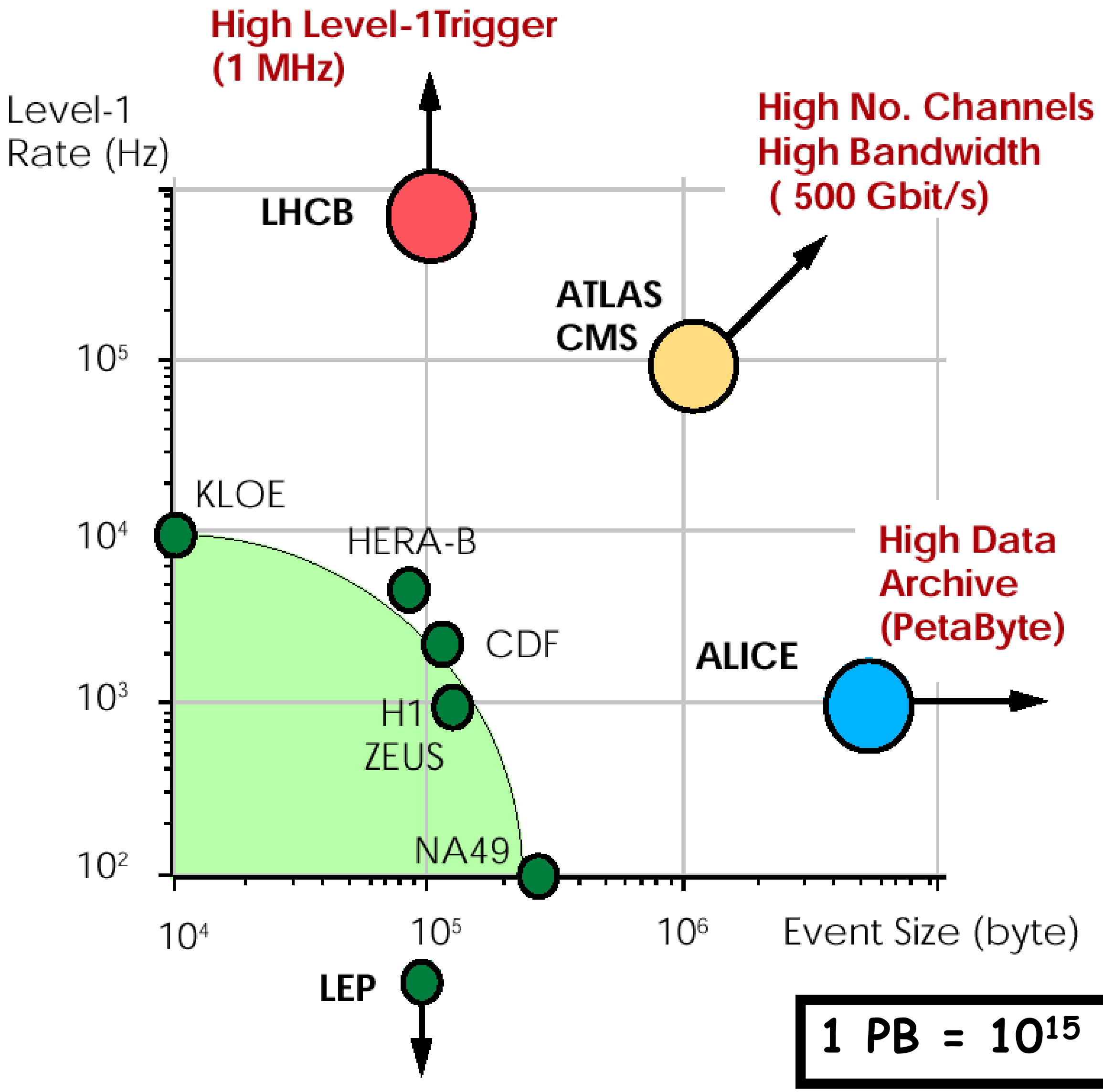

Event data & Apparatus
Physics channels & Parameters

The event trigger is one of the bigg
⇒ Based on hard scattering signatu
missing Et,...

Table E.12: The High-Level Trigger Menu at $\mathcal{L} = 2 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for an output of approximately 120 Hz. The $E_T$ values are the kinematic thresholds for the different trigger paths.

| Trigger | Level-1 bits used | Level-1 Prescale | HLT Threshold (GeV) | HLT Rate (Hz) |
|---|---|---|---|---|
| Inclusive $e$ | 2 | 1 | 26 | $23.5 \pm 6.7$ |
| $e$-$e$ | 3 | 1 | 12, 12 | $1.0 \pm 0.1$ |
| Relaxed $e$-$e$ | 4 | 1 | 19, 19 | $1.3 \pm 0.1$ |
| Inclusive $\gamma$ | 2 | 1 | 80 | $3.1 \pm 0.2$ |
| $\gamma$-$\gamma$ | 3 | 1 | 30, 20 | $1.6 \pm 0.7$ |
| Relaxed $\gamma$-$\gamma$ | 4 | 1 | 30, 20 | $1.2 \pm 0.6$ |
| | | | | |
| Inclusive $\mu$ | 0 | 1 | 19 | $25.8 \pm 0.8$ |
| Relaxed $\mu$ | 0 | 1 | 37 | $11.9 \pm 0.5$ |
| $\mu$-$\mu$ | 1 | 1 | 7, 7 | $4.8 \pm 0.4$ |
| Relaxed $\mu$-$\mu$ | 1 | 1 | 10, 10 | $8.6 \pm 0.6$ |
| | | | | |
| $\tau + E_T^{miss}$ | 10 | 1 | 65 ($E_T^{miss}$) | $0.5 \pm 0.1$ |
| Pixel $\tau$-$\tau$ | 10, 13 | 1 | — | $4.1 \pm 1.1$ |
| Tracker $\tau$-$\tau$ | 10, 13 | 1 | — | $6.0 \pm 1.1$ |
| $\tau + e$ | 26 | 1 | 52, 16 | $< 1.0$ |
| $\tau + \mu$ | 0 | 1 | 40, 15 | $< 1.0$ |
| $b$-jet (leading jet) | 36, 37, 38, 39 | 1 | 350, 150, 55 (see text) | $10.3 \pm 0.3$ |
| $b$-jet (2$^{nd}$ leading jet) | 36, 37, 38, 39 | 1 | 350, 150, 55 (see text) | $8.7 \pm 0.3$ |
| | | | | |
| Single-jet | 36 | 1 | 400 | $4.8 \pm 0.0$ |
| Double-jet | 36, 37 | 1 | 350 | $3.9 \pm 0.0$ |
| Triple-jet | 36, 37, 38 | 1 | 195 | $1.1 \pm 0.0$ |
| Quadruple-jet | 36, 37, 38, 39 | 1 | 80 | $8.9 \pm 0.2$ |
| $E_T^{miss}$ | 32 | 1 | 91 | $2.5 \pm 0.2$ |
| | | | | |
| jet + $E_T^{miss}$ | 32 | 1 | 180, 80 | $3.2 \pm 0.1$ |
| acoplanar 2 jets | 36, 37 | 1 | 200, 200 | $0.2 \pm 0.0$ |
| acoplanar jet + $E_T^{miss}$ | 32 | 1 | 100, 80 | $0.1 \pm 0.0$ |
| 2 jets + $E_T^{miss}$ | 32 | 1 | 155, 80 | $1.6 \pm 0.0$ |
| 3 jets + $E_T^{miss}$ | 32 | 1 | 85, 80 | $0.9 \pm 0.1$ |
| 4 jets + $E_T^{miss}$ | 32 | 1 | 35, 80 | $1.7 \pm 0.2$ |
| | | | | |
| Diffractive | Sec. E.3 | 1 | 40, 40 | $< 1.0$ |
| $H_T + E_T^{miss}$ | 31 | 1 | 350, 80 | $5.6 \pm 0.2$ |
| $H_T + e$ | 31 | 1 | 350, 20 | $0.4 \pm 0.1$ |
| | | | | |
| Inclusive $\gamma$ | 2 | 400 | 23 | $0.3 \pm 0.0$ |
| $\gamma$-$\gamma$ | 3 | 20 | 12, 12 | $2.5 \pm 1.4$ |
| Relaxed $\gamma$-$\gamma$ | 4 | 20 | 19, 19 | $0.1 \pm 0.0$ |
| Single-jet | 33 | 10 | 250 | $5.2 \pm 0.0$ |
| Single-jet | 34 | 1 000 | 120 | $1.6 \pm 0.0$ |
| Single-jet | 35 | 100 000 | 60 | $0.4 \pm 0.0$ |
| | | | | |
| *Total HLT rate* | | | | $119.3 \pm 7.2$ |

# Comparison of LHC with other experiments




**Huge computing Effort!**

- ~1 PB of raw data/year
- 3000 CPU's at CERN
  + >5000 in regional centers
- Data GRID project
  ⇒ LHC experiments are heavily involved

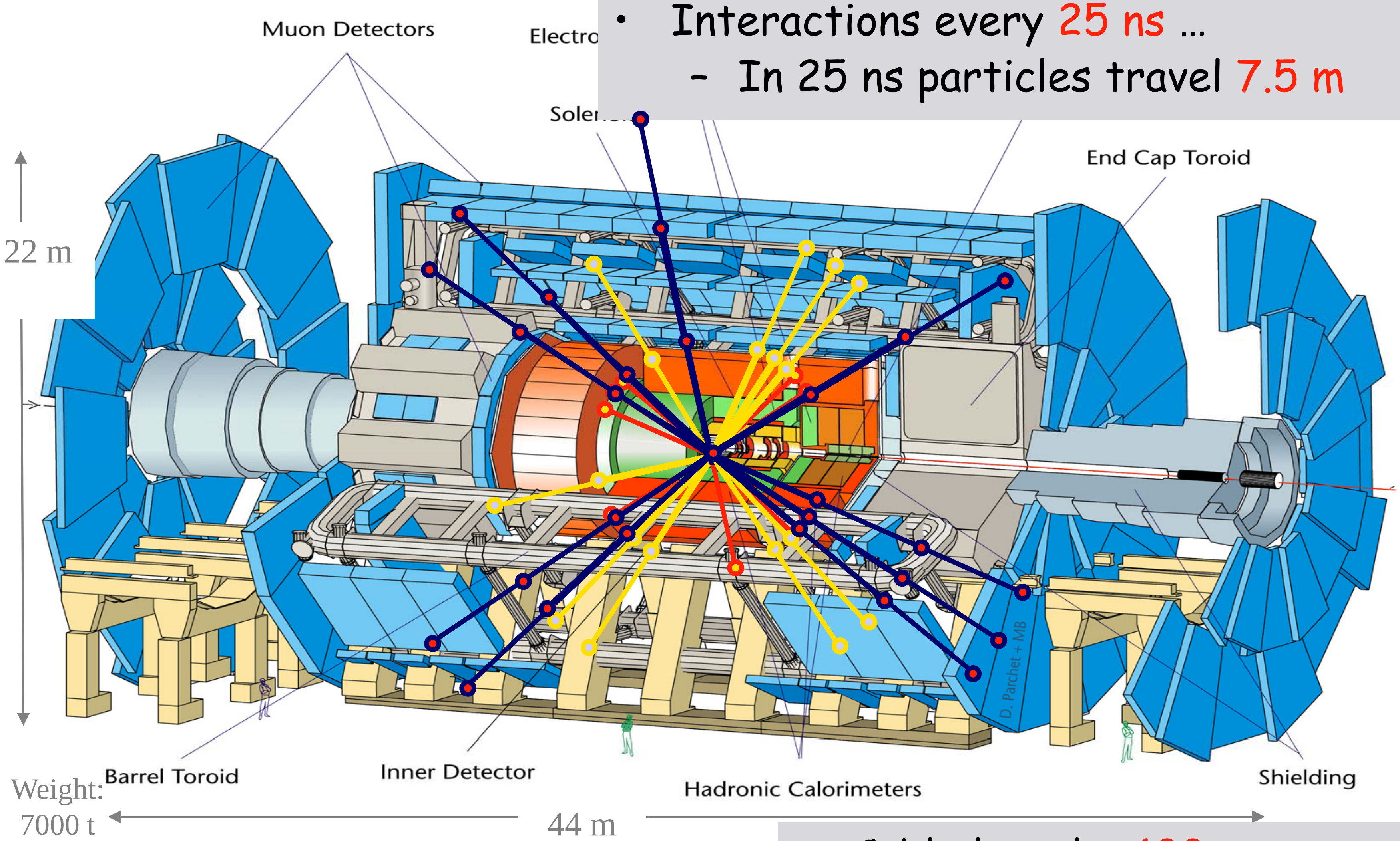
**The grid will be important for LHC data analysis**

1 PB = $10^{15}$ B =1 000 000 000 000 000 Bytes

# Physics at the LHC: the environment

Time-of-flight

- Interactions every 25 ns …
  - In 25 ns particles travel 7.5 m




- Cable length ~100 meters …
  - In 25 ns signals travel 5 m

# Startup Concerns

- Prime concern now is to get ready for the LHC startup (2007) 2008
    - Min bias, Jets, W-Z-t(t)+ njets, WW-ZZ+njets, W-Zbb, ttbb, W$\gamma$, Z$\gamma$,…
- Strategy
    - Measure min-bias, underlying event, QCD jet, W, Z, top with first data.
        - Tune MC's to the data
    - Measure W, Z, top + njets in data in available control regions
        - Tune/Normalize MC's and extrapolate in new regions (tails)

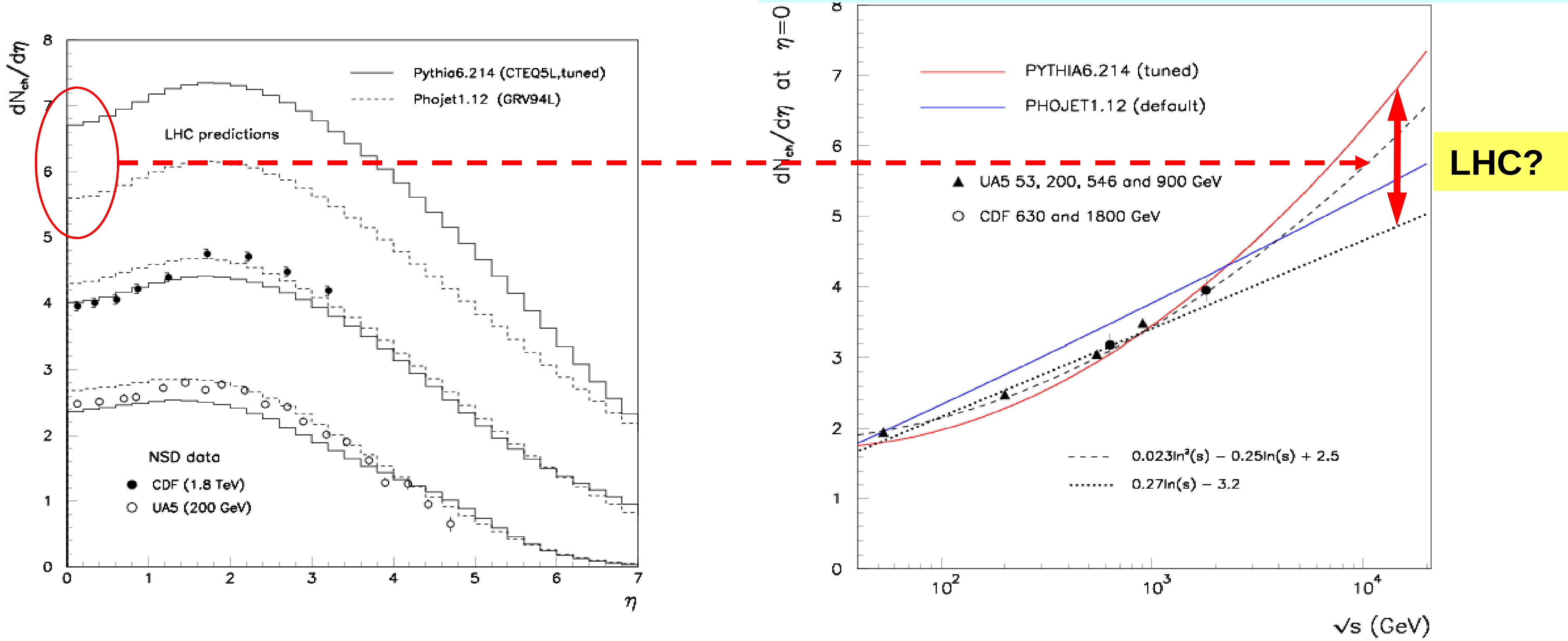
            $\Rightarrow$ Remember: early discoveries are possible!

- MC production choices for startup physics for 2008
    - Choice of models and model versions (PYTHIA/HERWIG/Alpgen/…)
    - What settings/parameters? PDFs (LO/NLO?), underlying evts, PS/ME…
    - What processes are still missing?
    - LO/NLO importance? Alternative showering (SCET…)
    - Do we understand QCD sufficiently in the new LHC kinematic regime?
    - How to normalize the MC's

# Early Soft Minimum-Bias Measurements

Charged particle density

The pile-up for the future: ~4 events at low and ~20 events at high luminosity




- Energy dependence of dN/dη ?
- Vital for tuning UE model
- Only requires a few thousand events.

- PYTHIA models favour $\ln^2(s)$;
- PHOJET suggests a ln(s) dependence.

At 14 TeV startup!!

# Likely one of the first papers…

1 September 2008

## Charged particle multiplicity in pp collisions at $\sqrt{s}$ = 14 TeV

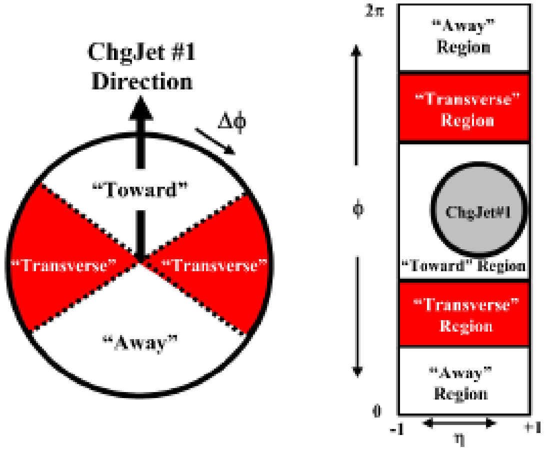
*CMS collaboration*

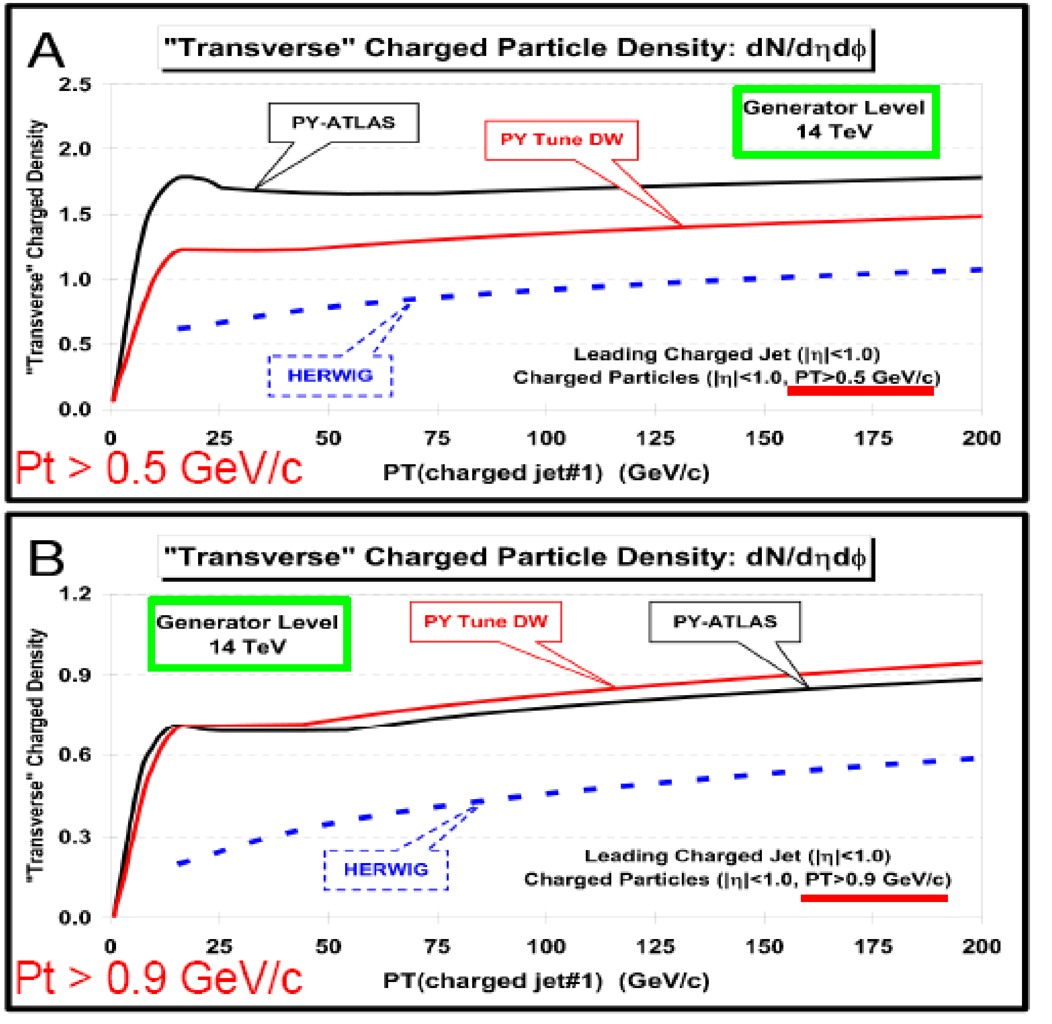
**Abstract**

We report on a measurement of the mean charged particle multiplicity in minimum bias events, produced in the central region $|\eta| < 1$, at the LHC in pp collisions with $\sqrt{s}$ = 14 TeV, and recorded in the CMS experiment at CERN. The events have been selected by a minimum bias trigger, the charged tracks reconstructed in the silicon tracker and in the muon chambers. The track density is compared to the results of Monte Carlo programs and it is observed that all models fail dramatically to describe the data.

Submitted to *European Journal of Physics*

# Underlying Event Studies




MC comparison for two different Pythia tunes of multiple interactions:
- PY ATLAS
- PY Tune DW by R. Field fitting CDF Run 1 and 2 UE data

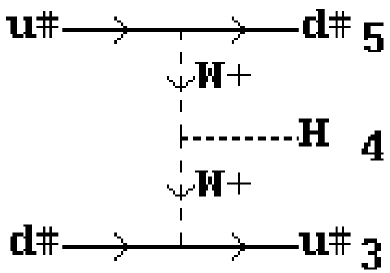
and HERWIG

- MI energy dependence parameter PARP(90) = 0.16 (ATLAS), 0.25 (DW)
- „Softer" charged part. Spectrum for ATLAS tune

**Getting ready for studies with first data**

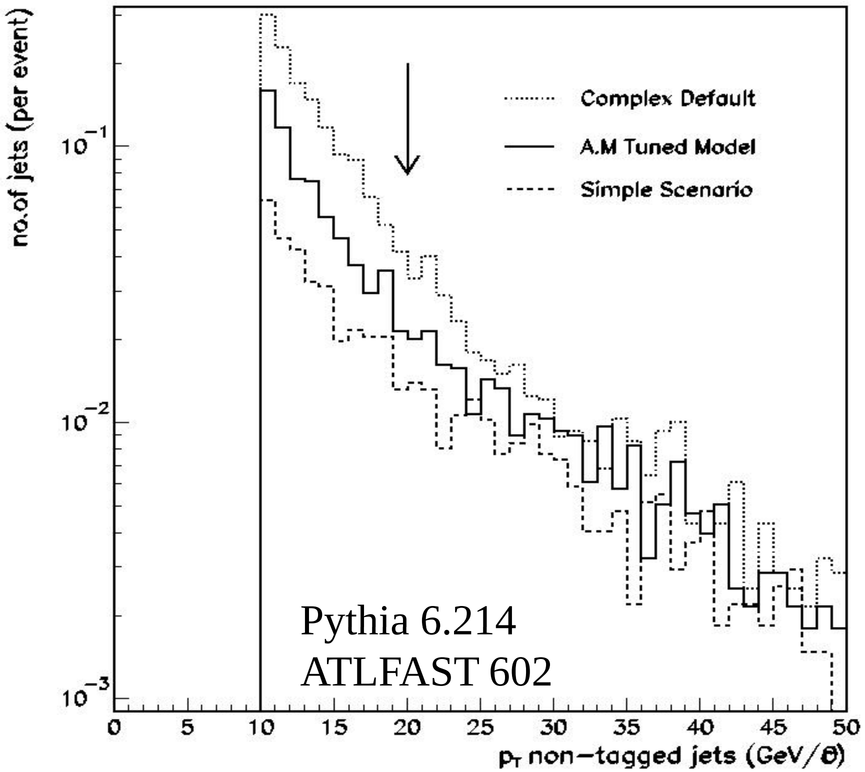
CMS PTDR

# Effect of underlying event on central jet veto in VBF Higgs

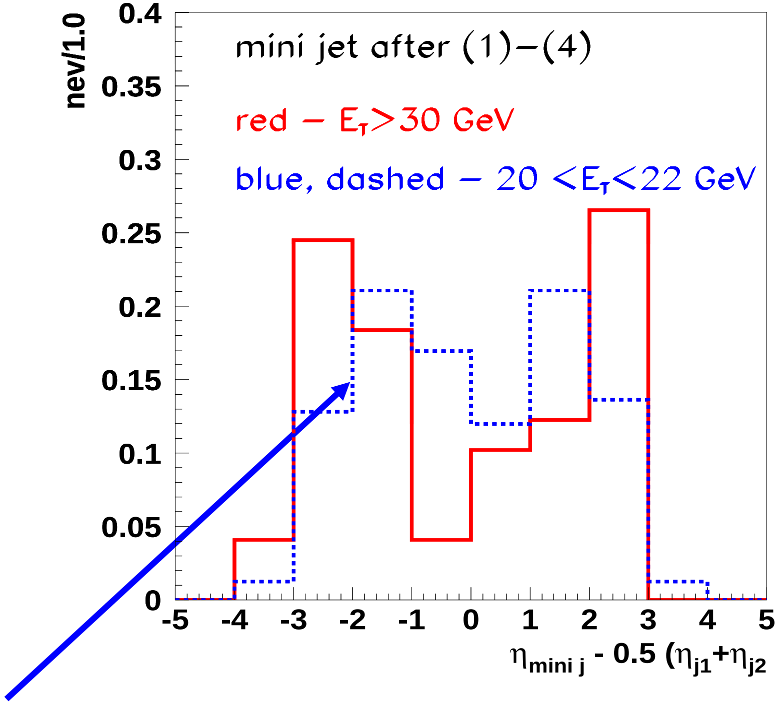



**H->WW*->2l in qqH prod.**

*Uncertainty of the central jet veto efficiency due to UE model; ATLAS.*




Rapidity of the central jet in Higgs events; CMS; full simulation, L=2x10$^{33}$cm$^{-2}$s$^{-1}$




| Model | CJV efficiency | Significance |
|---|---|---|
| Default pythia | 85% | 8.2 |
| Default DG | 75% | 7.7 |
| AM tuning | 79% | 7.9 |

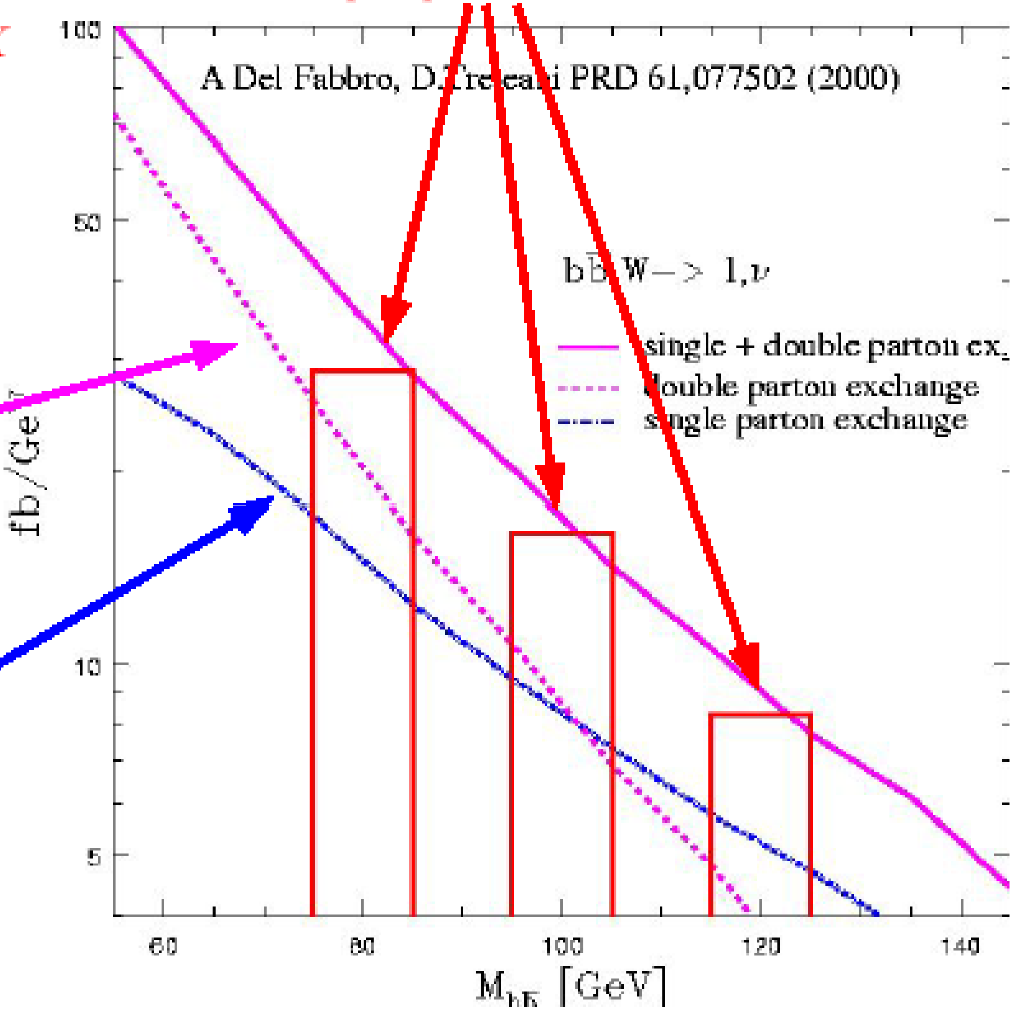
"bkg. like" behaviour for soft jets; fake jets: pile up+UE+detector

# Double Parton interactions

- Higgs: $p+p \rightarrow W+H+X$
  with $W \rightarrow l\nu,\ H \rightarrow b\bar{b}$

- Double parton scattering:
  ➔ $p+p \rightarrow W+X$
  $p+p \rightarrow b\bar{b}X$

- compared to single parton scattering
  $p+p \rightarrow W+b\bar{b}+X$

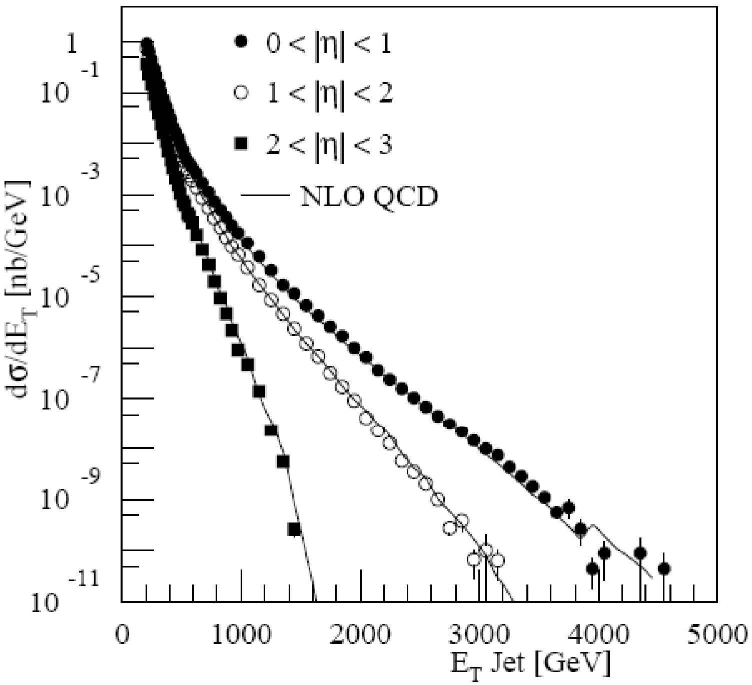



Not well known what to expect…

# QCD Studies @ LHC

E.g. Jet Physics

Huge cross sections:
Eg for 1 $fb^{-1}$ ~ 10000 events with $E_T$> 1 TeV
100 events with $E_T$> 2 TeV




- PDFs
- Jet shape
- Underlying event
- $\alpha_s$
- Diffraction
- BFKL studies
- low-x
- New physics?
- …

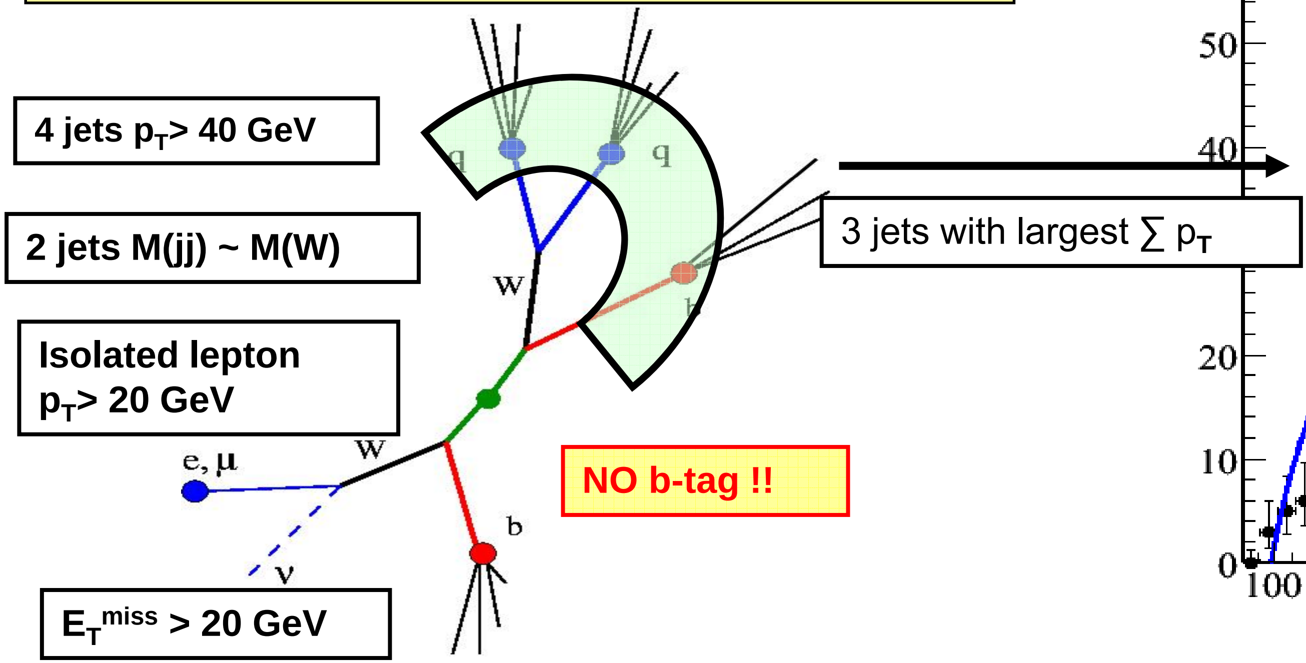
•Understanding QCD at 14 TeV will be one of the first topics at LHC

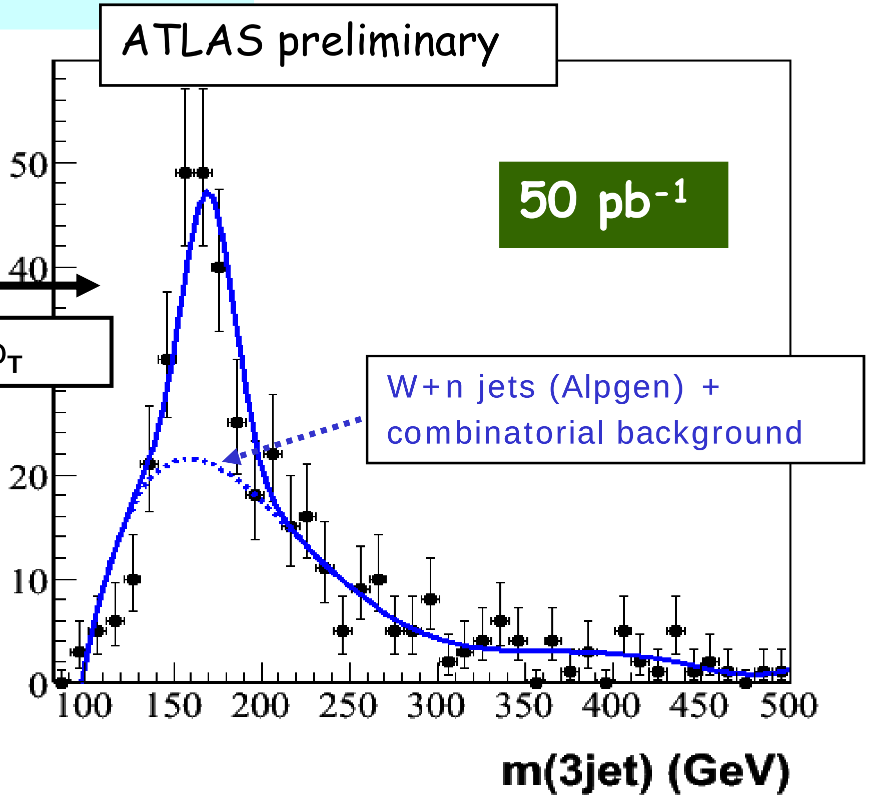
…and a whole b-physics and top-physics program

# Early Top-quark events

Can we observe an early top signal with limited detector performance ?
And use it to understand detector and physics ?

$\sigma_{tt} \approx 250$ pb for $tt \to bW\, bW \to bl\nu\, bjj$

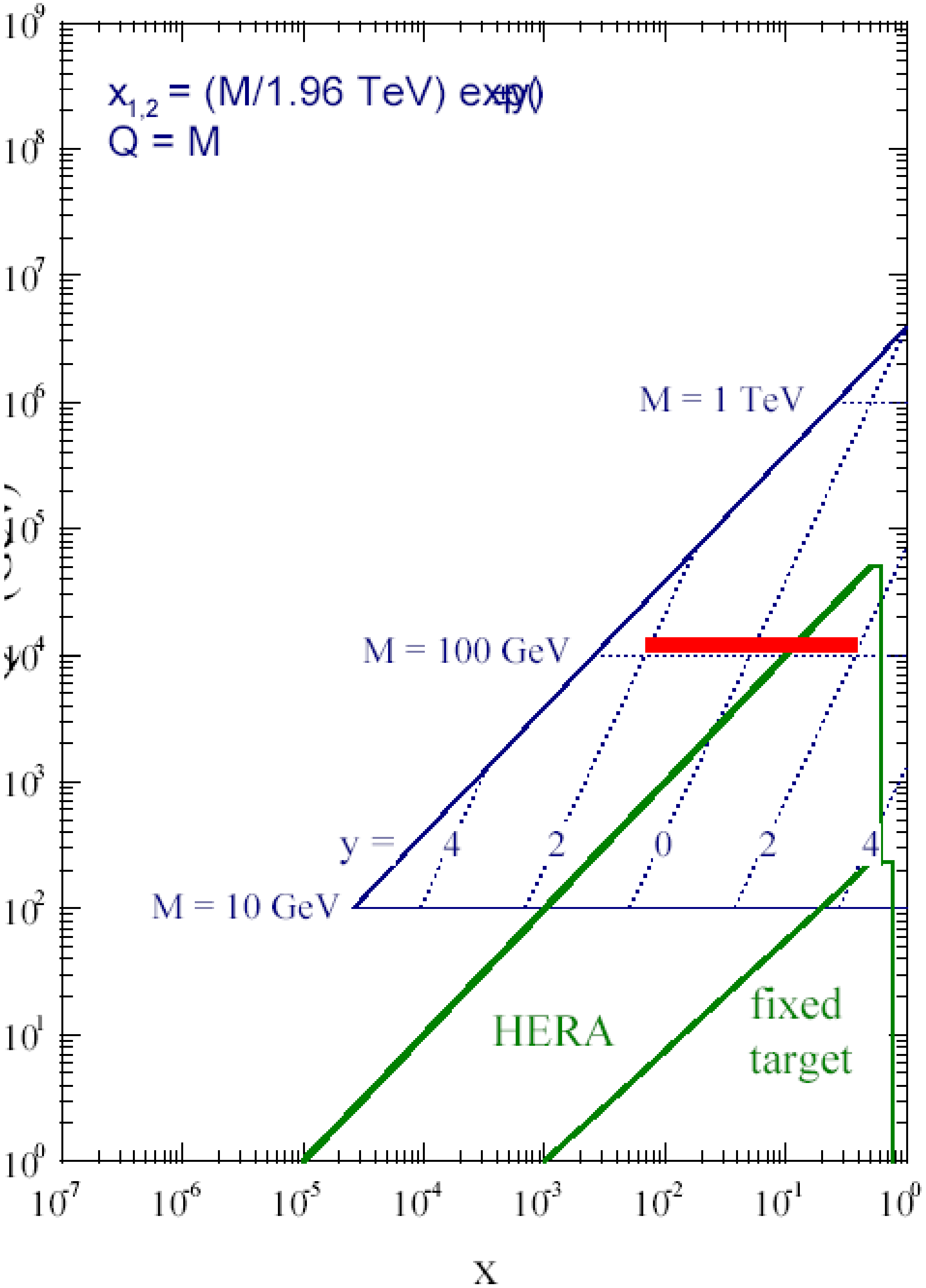


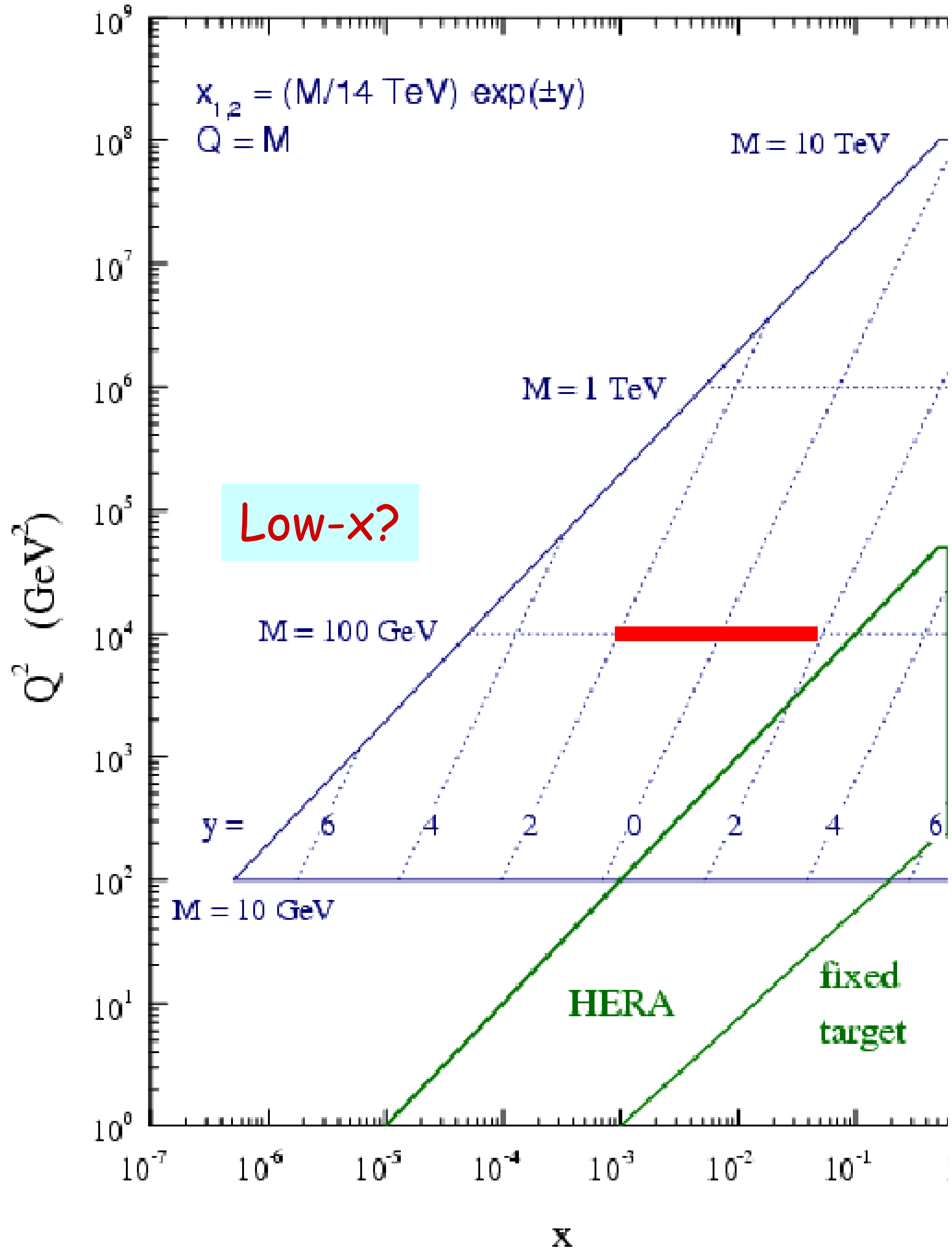

Top signal observable in early days with no b-tagging and simple analysis
$\to$ measure $\sigma_{tt}$ to 20%, m to 10 GeV with ~100 $pb^{-1}$ ?

- commission b-tagging, set jet E-scale using $W \to jj$ peak
- understand detector performance for e, μ, jets, b-jets, missing $E_T$, …
- understand / constrain theory and MC generators using e.g. $p_T$ spectra

Tevatron parton kinematics




LHC parton kinematics



# CTEQ6.1 ↔CTEQ6.5

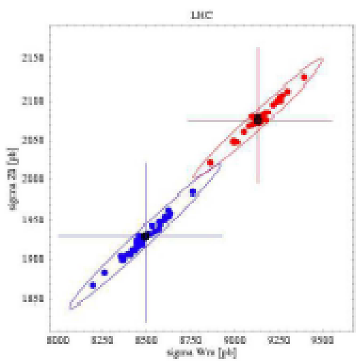
## HERA-LHC Meeting; March 07

**Huston**

Summary on CTEQ6.5
Large shift in LHC cross sections (comparison CTEQ6.1 vs. CTEQ6.5)

Conclusions on CTEQ6.5

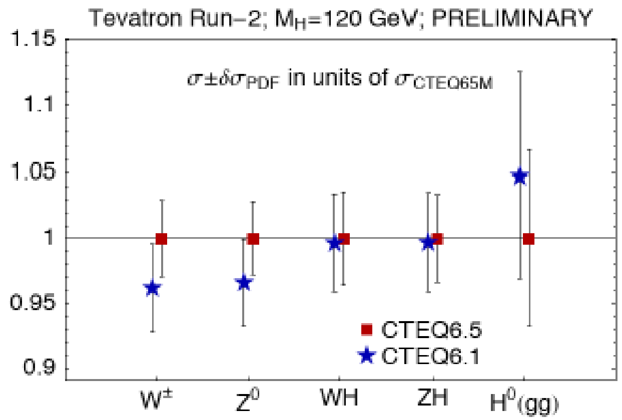
1. Improved Input
   - HQ formalism implemented
   - Use HERA measured cross sections directly
   - Include HERA CC data and NuTeV dimuon data (weight=2.0)
2. Gives better fit ($\chi^2$ lower by $\sim 200$), suggesting that the physics is better! :)
3. CTEQ6.1 uncertainties were not unreasonable
4. Little or no decrease in estimated uncertainty – though the agreement with CTEQ6.1 (except where difference is expected) inspires increased confidence.
5. Larger $q$ and $\bar{q}$ distributions at $x \sim 10^{-3}$ from correcting the former ZM approximation implies larger cross sections at LHC.

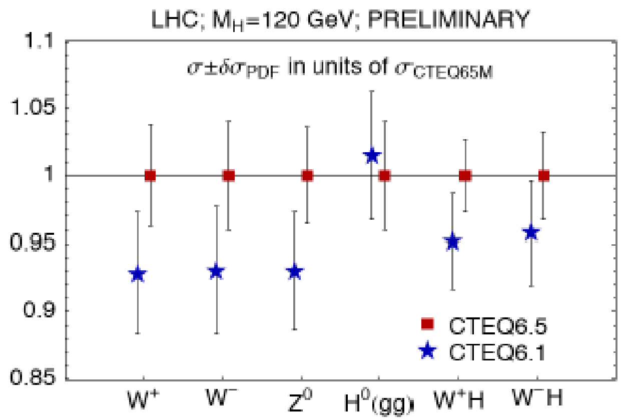



LHC

W- and Z0 cross sections for CTEQ6.1 (Blue) and CTEQ6.5 (Red)

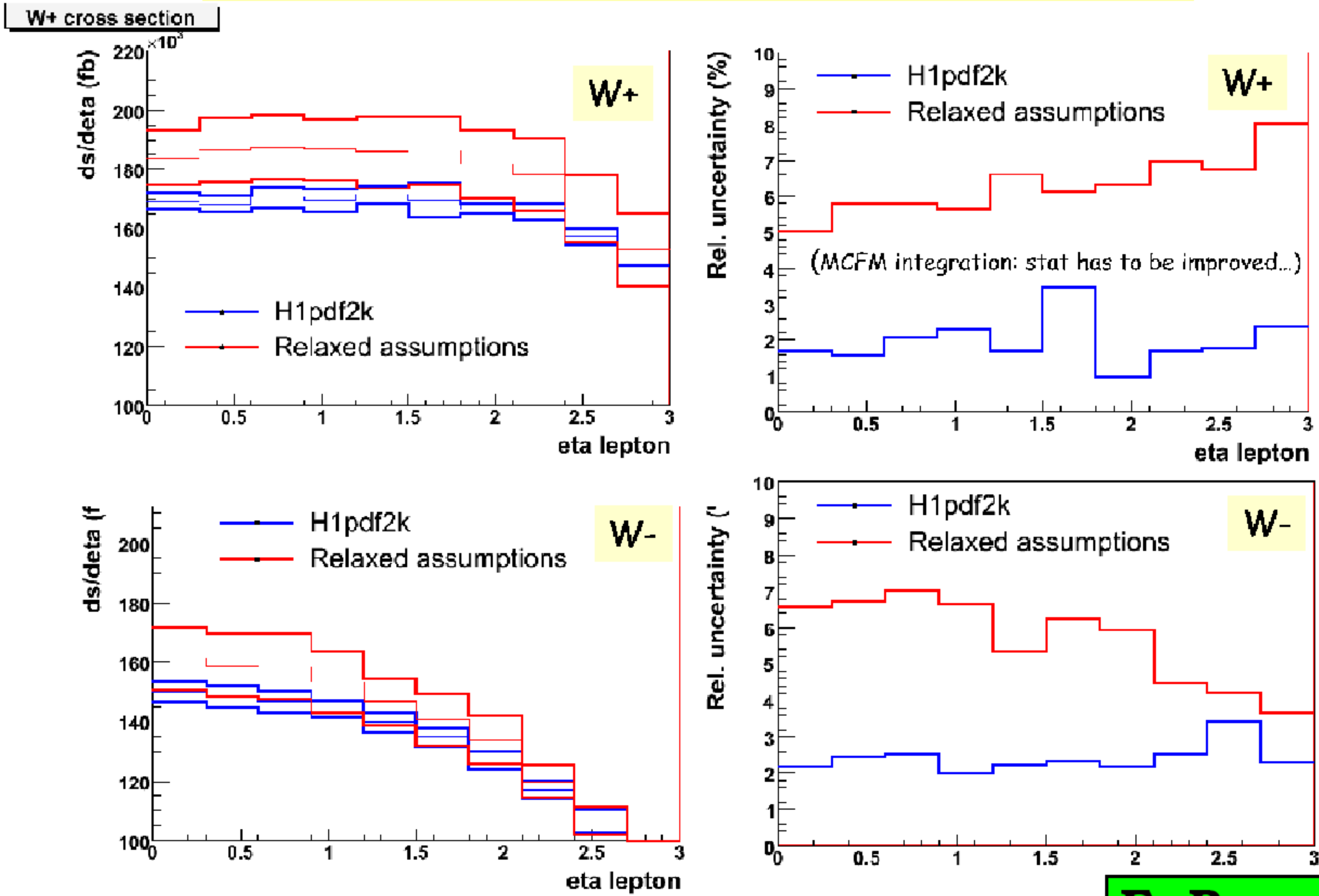
Uncorrelated uncertainties and correlated error ellipses.




Luminosity via W,Z measurements? precision?

# Uncertainties on W x-sections




E. PEREZ

Relaxing the $\bar{d}$~$\bar{u}$ constrained in the fits…
Measure at LHC via W leptonic asymmetries?

# PDFs

Call for a working group/task force/LHC-study group …

FITPDF?

⇒The PDF + uncertainties

NEED A JOINT EFFORT OF THEORISTS AND LHC EXPERIMENTALISTS:

- WHICH PRECISION MEASUREMENTS ARE LIMITED BY PDFS?
- WHEN DOES LACK OF PDF KNOWLEDGE HIDE/SIMULATE NEW PHYSICS?
- HOW CAN LHC MEASUREMENTS IMPROVE PDF DETERMINATION?

Interest from theorists/fitters/HERA/… LHC? CTEQ?

# Higher QCD corrections/K factors

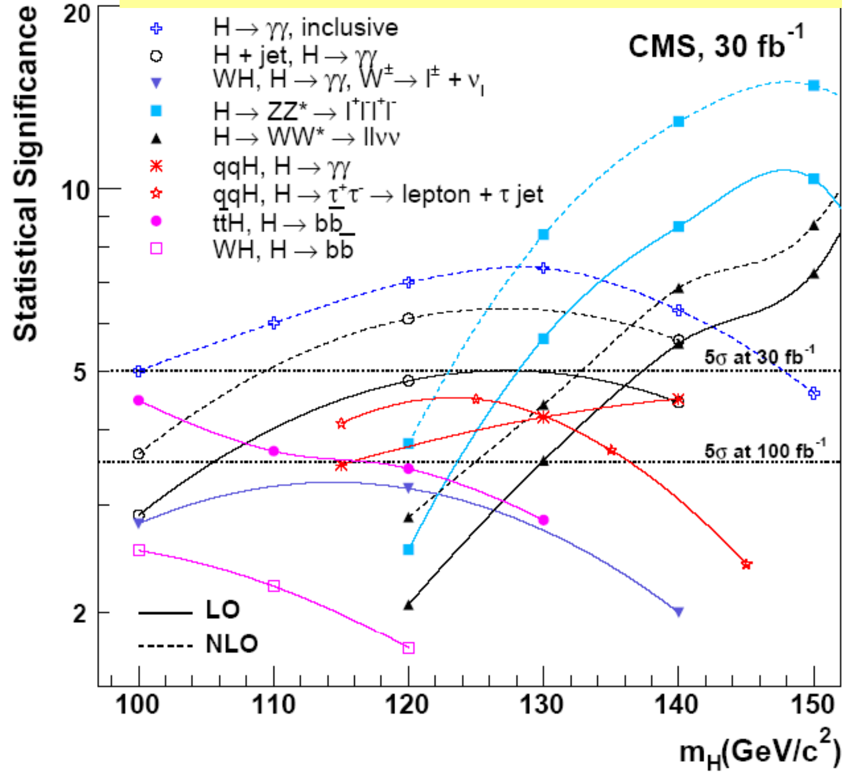
- Many cross sections now calculated to NLO
- K factors? Not always sufficient/can be huge in some phase space parts
- Reweighting Monte Carlo? Select key weighting variables

Complete NLO Monte Carlo! Quite some progress in the last years.
More processes wanted ☺!!

Table 42: The LHC "priority" wishlist for which a NLO computation seems now feasible.

| process ($V \in \{Z, W, \gamma\}$) | relevant for |
|---|---|
| 1. $pp \to V\,V$ jet | $t\bar{t}H$, new physics |
| 2. $pp \to t\bar{t}\,b\bar{b}$ | $t\bar{t}H$ |
| 3. $pp \to t\bar{t} - 2$ jets | $t\bar{t}H$ |
| 4. $pp \to V\,V\,b\bar{b}$ | VBF $\to H \to VV$, $t\bar{t}H$, new physics |
| 5. $pp \to V\,V + 2$ jets | VBF $\to H \to VV$ |
| 6. $pp \to V + 3$ jets | various new physics signatures |
| 7. $pp \to V\,V\,V$ | SUSY trilepton |

## Effect on Higgs 'discovery'

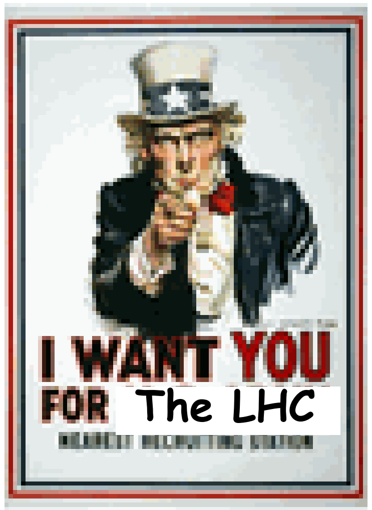



Priority wish list from the experiments
hep-ph/0604120 (Les Houches 05)

+ Zbb, Hbb

# Tools & Theoretical Estimates

The LHC will be a precision and hopefully discovery machine
But it needs strong collaboration with theorists




Examples

- Precision predictions of cross sections
- Estimates for backgrounds to new physics
- Monte Carlo programs (tuned) for SM processes: W,Z,t.. + njets and more..
- Monte Carlo programs for signals (ED's,…)
- Evaluation of systematics due to theory uncertainties
- Higher order calculations
- New phenomenology/signatures to look for
- Discriminating variables among different theories
- Getting spin information from particles
- Tools to interprete the new signals in an as model independent way as possible (MARMOSET?)
- …

# Summary

- The LHC and its experiments are on track for physics runs at 14 TeV starting from middle 2008 onwards
  - Challenge: commissioning of machine and detectors of unprecedented scale, complexity, technology and performance
- The LHC environment is a novel one with
  - High pile-up
  - Huge event rate/large data volume (few pentabyte/year)
  - Sever trigger selection/rejection $O(10^6)$
  - Short time between bunches (25 ns)
  - $O(10^8)$ detector channels
  - Huge radiation
  - …

  ⇒ Experimenting at LHC is a new challenge
- To extract the most of the LHC physics, theory and phenomenology will need to match with the with the upcoming measurements.

There is still a lot to do

# A usefull review and future meeting…

Standard Model benchmarks

http://stacks.iop.org/0034-4885/70/89

REVIEW ARTICLE

## Hard Interactions of Quarks and Gluons: a Primer for LHC Physics

J. M. Campbell
Department of Physics and Astronomy
University of Glasgow
Glasgow G12 8QQ
United Kingdom

J. W. Huston
Department of Physics and Astronomy
Michigan State University
East Lansing, MI 48824
USA

W. J. Stirling
Institute for Particle Physics Phenomenology
University of Durham
Durham DH1 3LE
United Kingdom



**Abstract.** In this review article, we will develop the perturbative framework for the calculation of hard scattering processes. We will undertake to provide both a reasonably rigorous development of the formalism of hard scattering of quarks and gluons as well as an intuitive understanding of the physics behind the scattering. We will emphasize the role of logarithmic corrections as well as power counting in $\alpha_S$ in order to understand the behaviour of hard scattering processes. We will include "rules of thumb" as well as "official recommendations", and where possible will seek to dispel some myths. We will also discuss the impact of soft processes on the measurements of hard scattering processes. Experiences that have been gained at the Fermilab Tevatron will be recounted and, where appropriate, extrapolated to the LHC.

Submitted to: *Rep. Prog. Phys.*

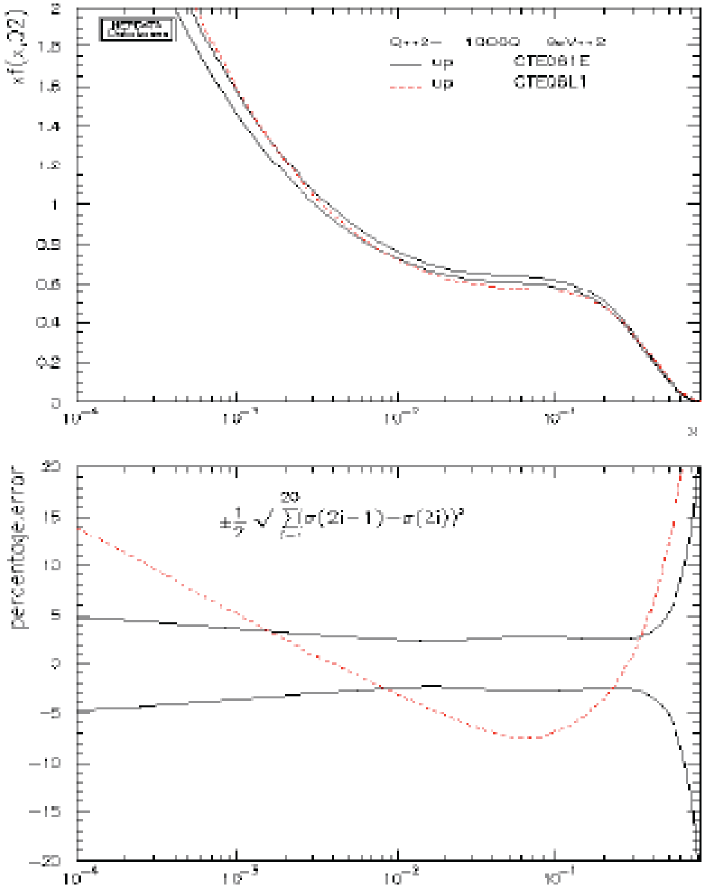
LES HOUCHES
centre de physique

See www.pa.msu.edu/~huston/Les_Houches_2005/Les_Houches_SM.html

# Using NLO PDFs for (LO) MC's?

## LO vs NLO pdf's for parton shower MC's

- For NLO calculations, use NLO pdf's (duh)
- What about for parton shower Monte Carlos?
  - somewhat arbitrary assumptions (for example fixing Drell-Yan normalization) have to be made in LO pdf fits
  - DIS data in global fits affect LO pdf's in ways that may not directly transfer to LO hadron collider predictions
  - LO pdf's for the most part are outside the NLO pdf error band
  - LO matrix elements for many of the processes that we want to calculate are not so different from NLO matrix elements
  - by adding parton showers, we are partway towards NLO anyway
  - any error is formally of NLO
- (my recommendation) use NLO pdf's
  - pdf's must be + definite in regions of application (CTEQ is so by def'n)
- Note that this has implications for MC tuning, i.e. Tune A uses CTEQ5L
  - need tunes for NLO pdf's




. . . but at the end of the day this is still LO physics

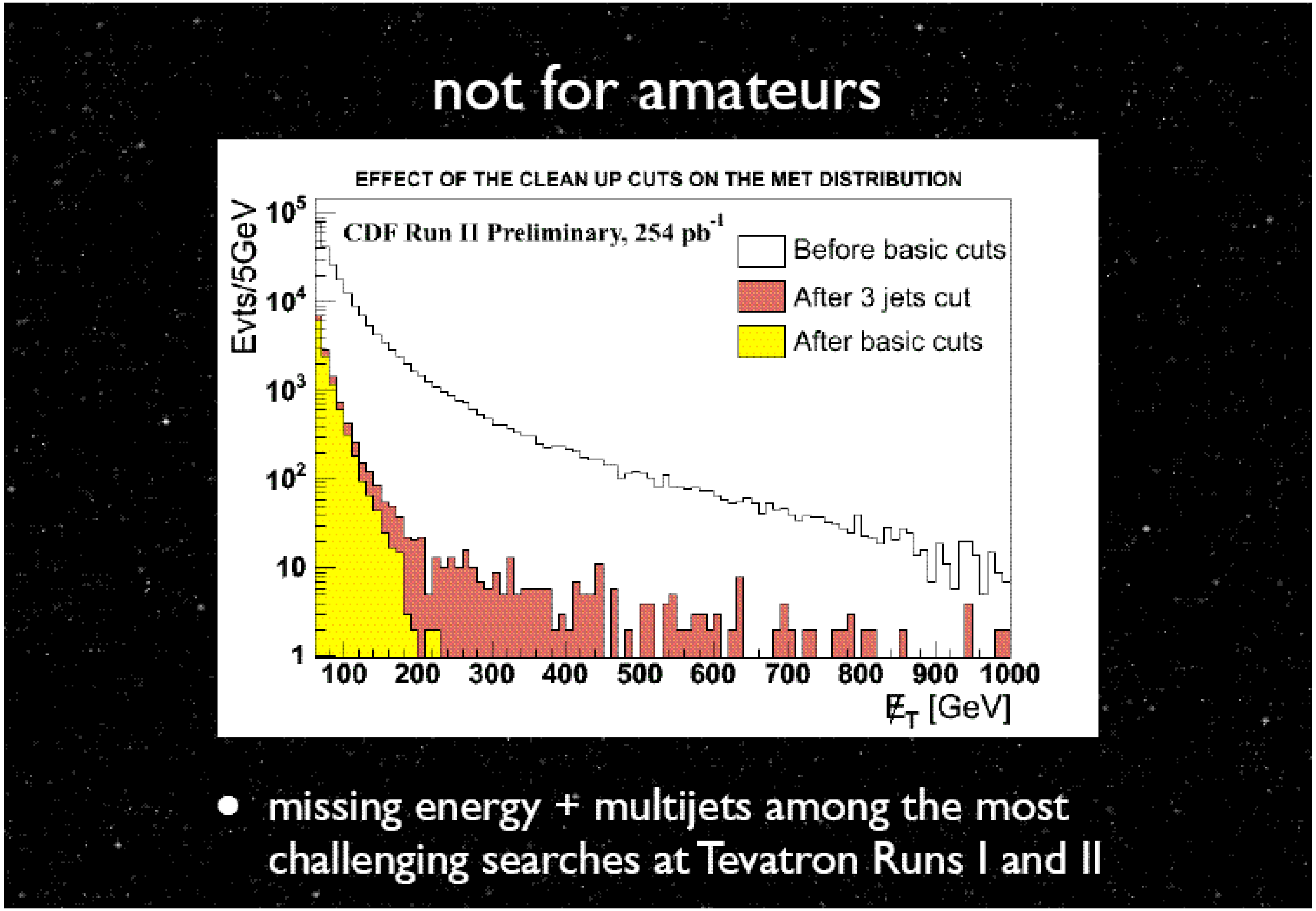
There's no substitute for honest-to-god NLO.

Proposal by
J. Huston et al

Still matter of debate...
Currently
ATLAS → LO
CMS → discussing

New: R. Thorne: "special" PDFs for MC generators
More soon!

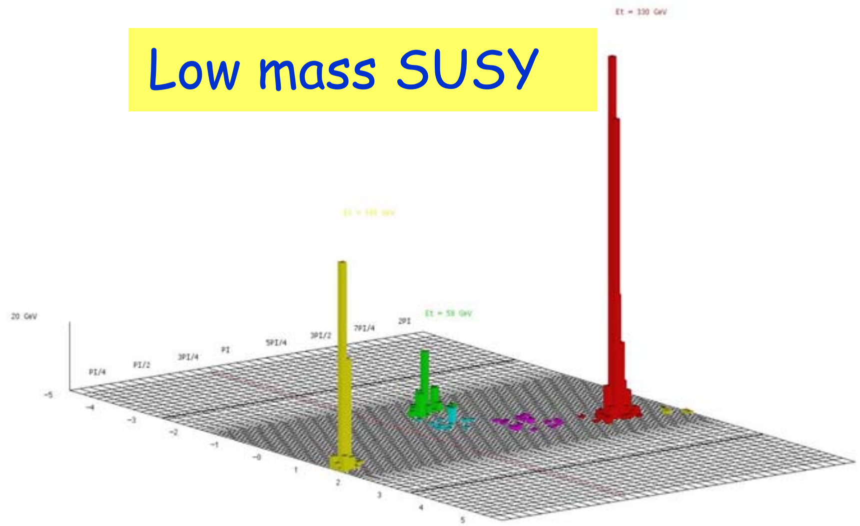
# Missing Transverse Energy

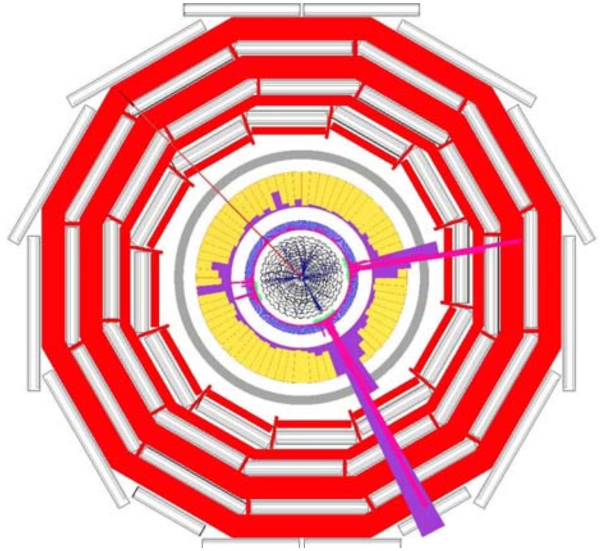



Tevatron experience!
Clean up cuts: cosmics, beam halo, dead channels, QCD

# Detailed Simulation: Missing $E_T$

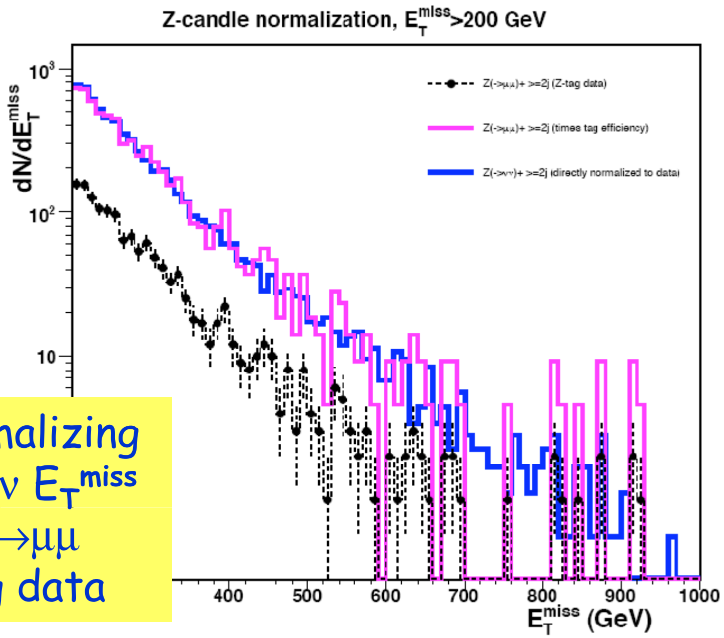
Low mass SUSY



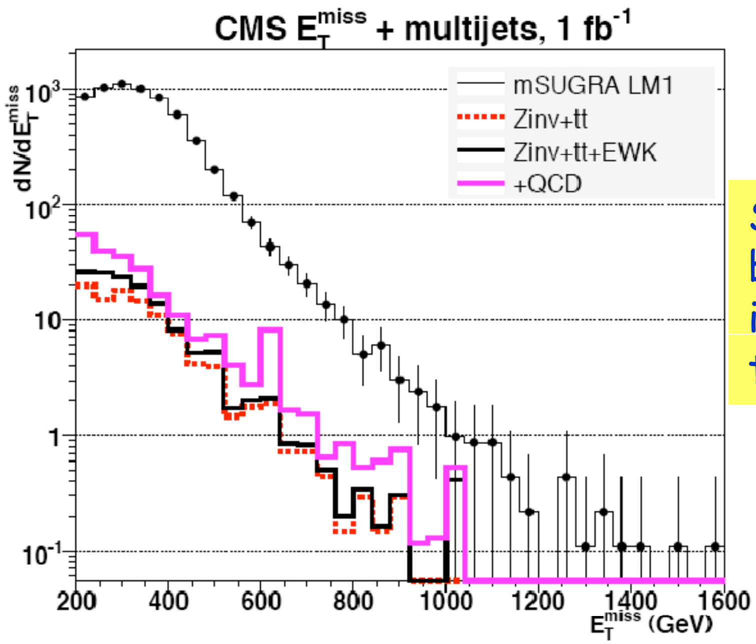


Missing $E_T$ is a difficult measurement for the experiments

CMS PTDR



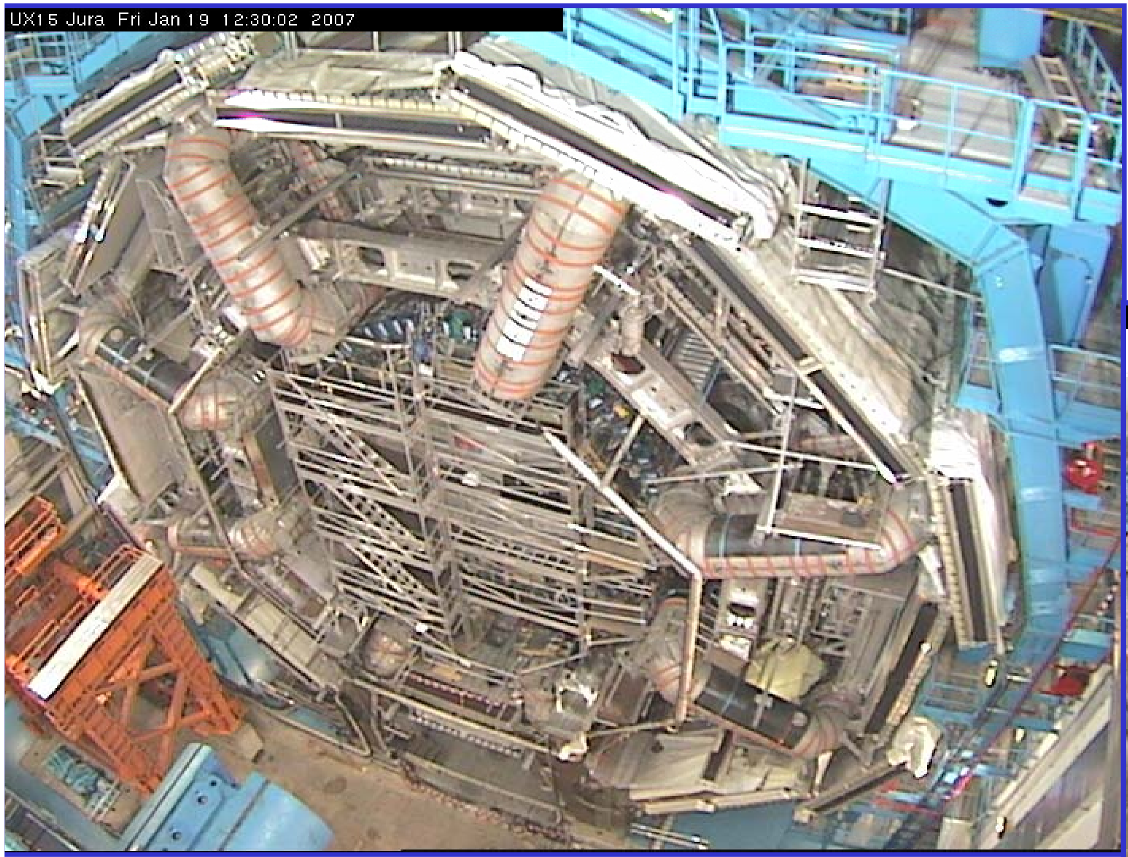

Normalizing $Z \to \nu\nu$ $E_T^{miss}$ to $Z \to \mu\mu$ using data




Signal over background in $E_T^{miss}$ for the LM1 point

# Muon Spectrometer

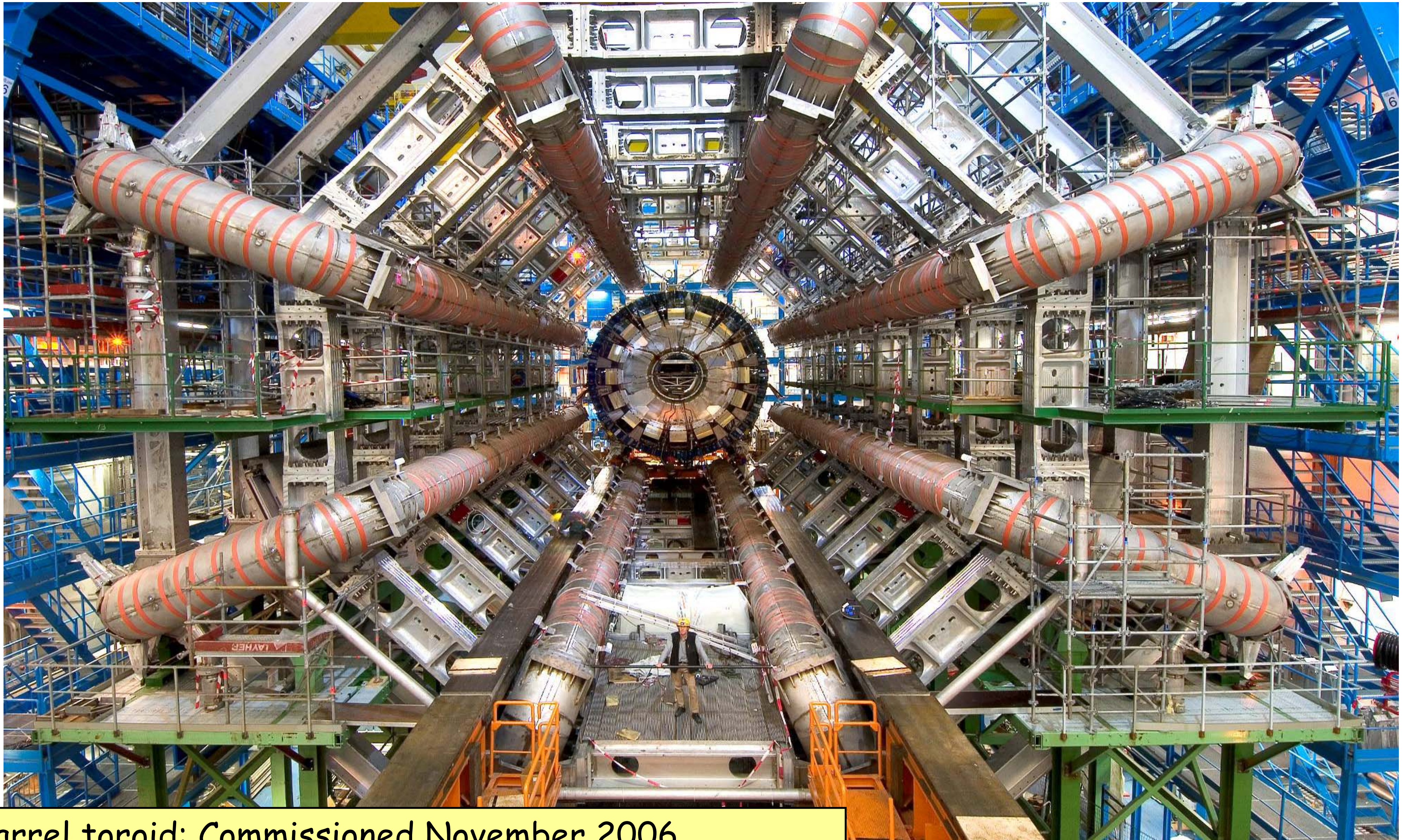
Measurement chambers MDT, CSC (innermost forward)
Trigger chambers RPC (barrel), TGC (end-caps)




Barrel stations installed

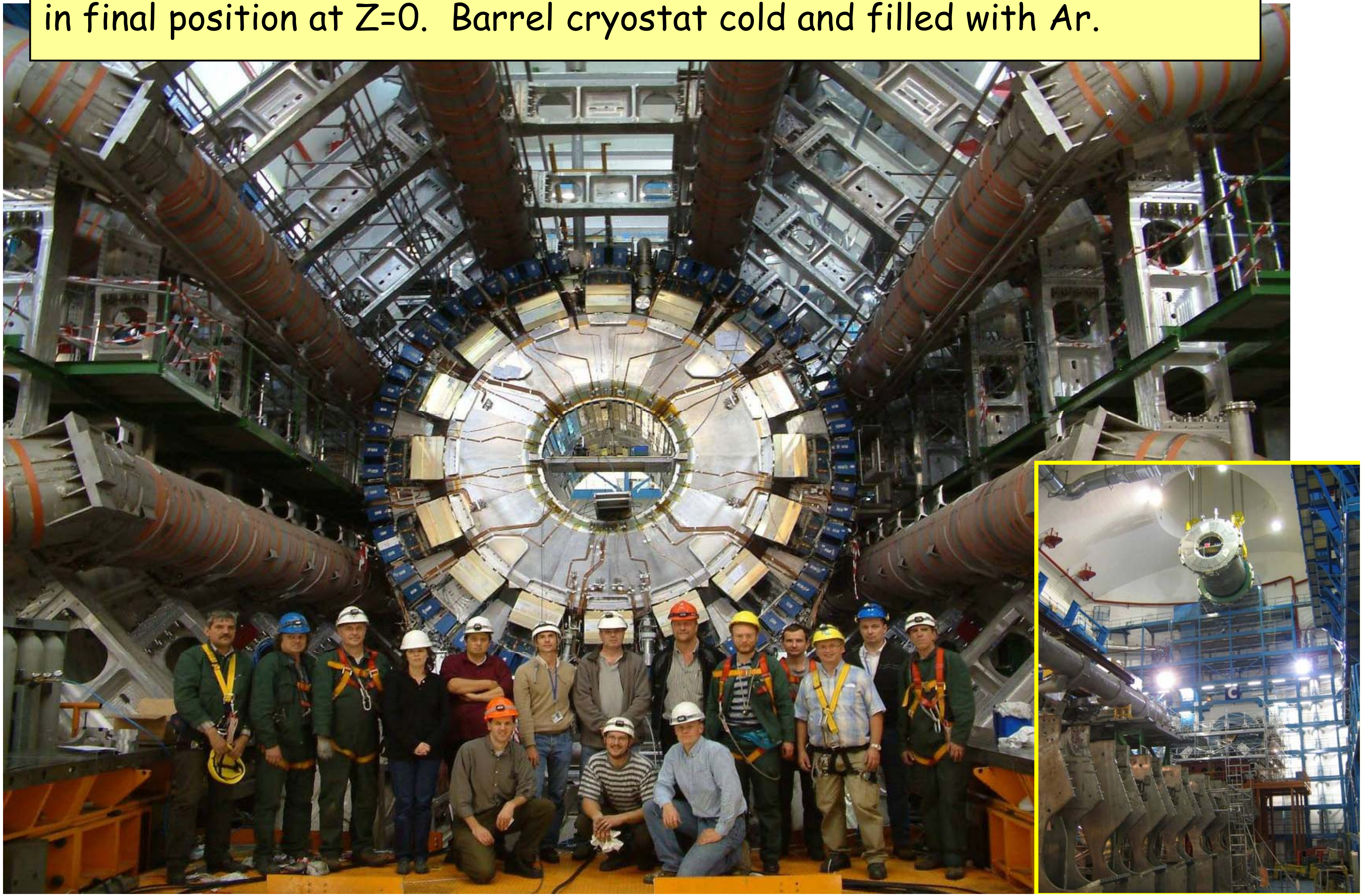

First TGC end-cap "big-wheel" installed

# ATLAS: Barrel Toroid

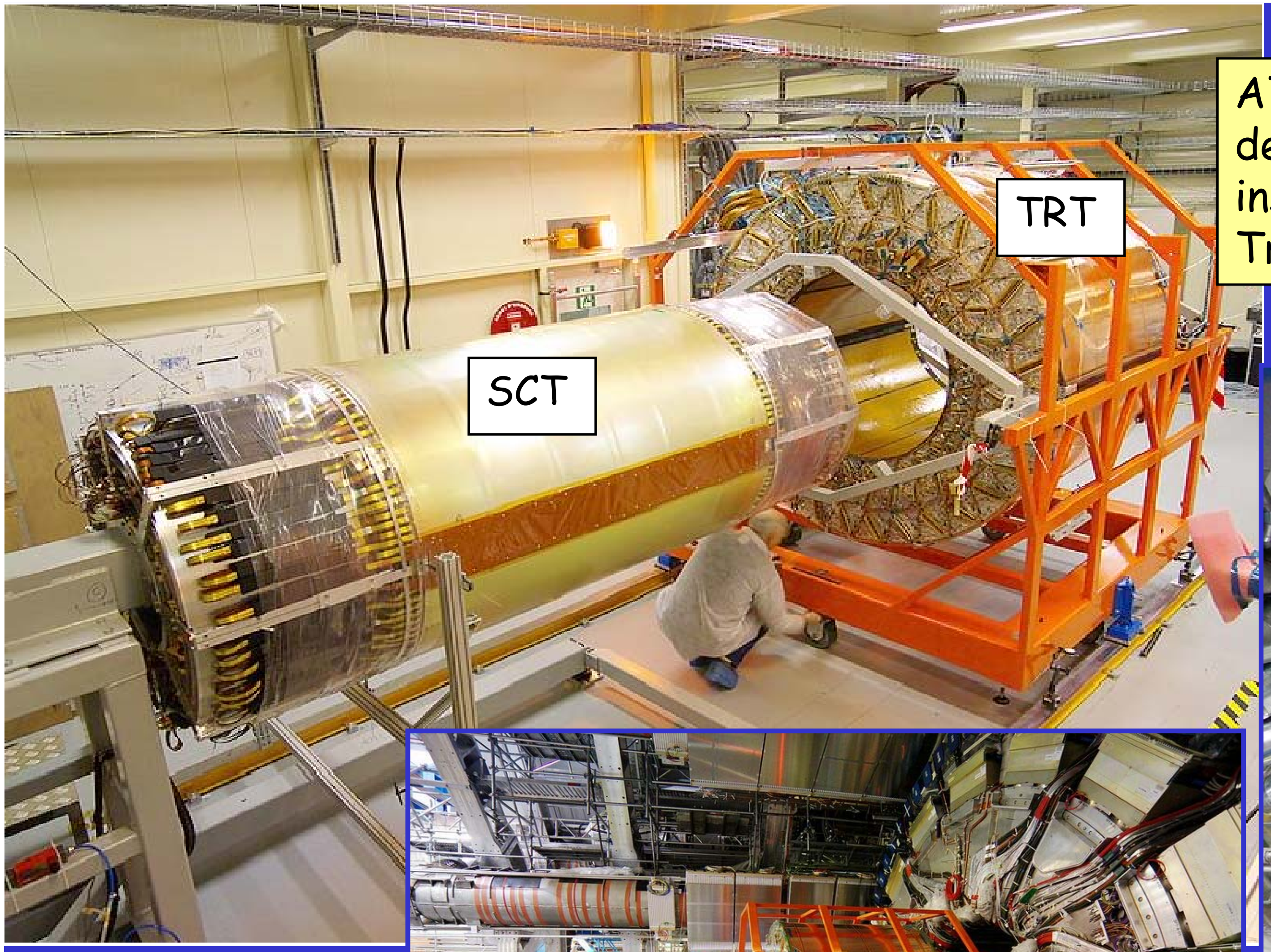


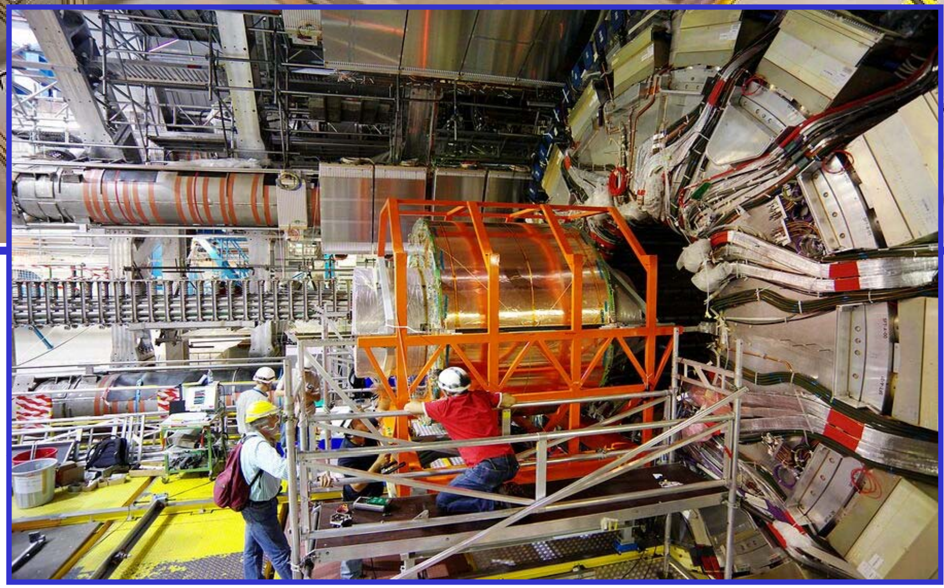
Barrel toroid: Commissioned November 2006
End-cap toroids: endcap A to be installed Feb 07

Barrel calorimeter (EM liquid-argon + HAD Fe/scintillator Tilecal)
in final position at Z=0.  Barrel cryostat cold and filled with Ar.

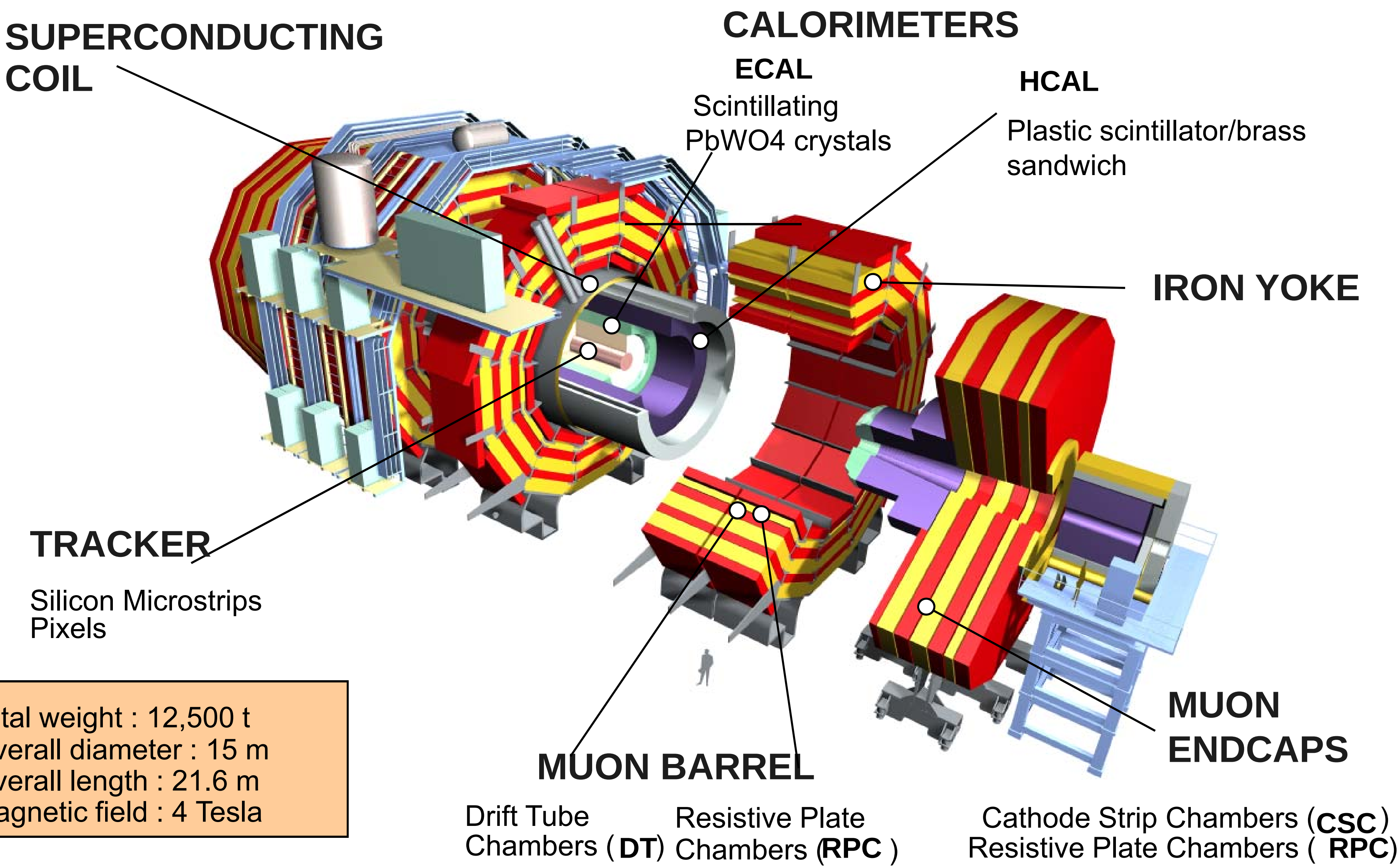


ATLAS Tracker:barrel Si detector (SCT) was inserted into barrel TRT Tracker lowered into cavern



# The CMS Detector

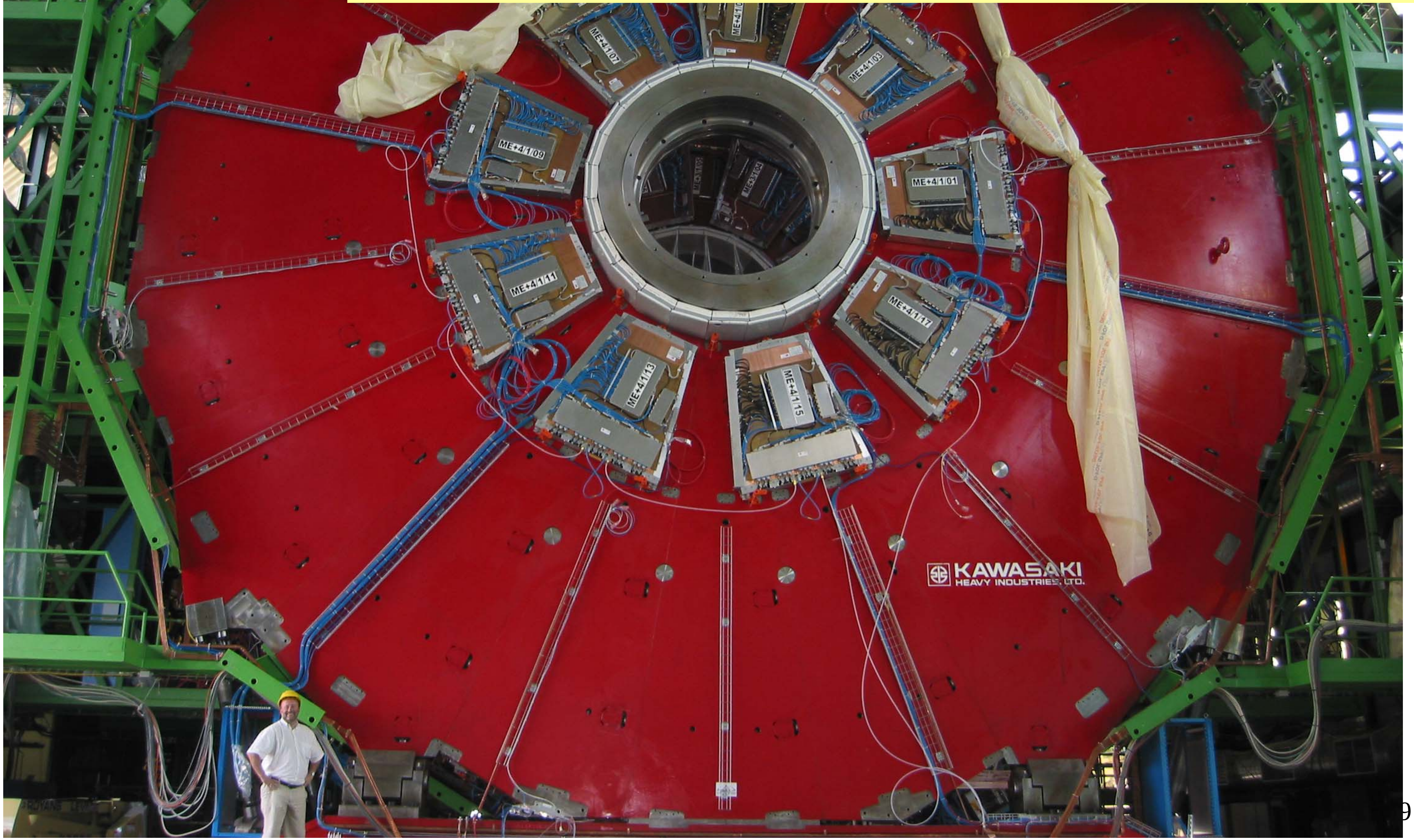



Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

Muon Chambers: Drift Tubes (DT) Cathode Strip Chambers (CSC) and RPCs have all been built

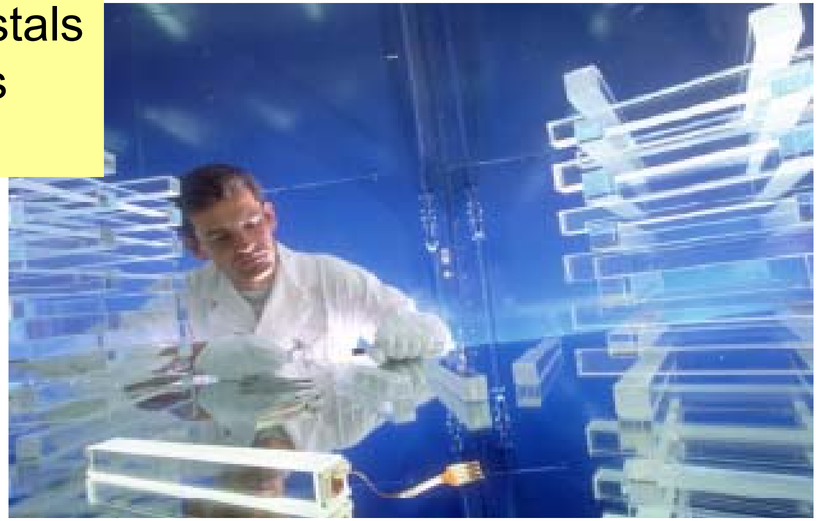
⇒ Barrel (DT+RPC) >90% installed

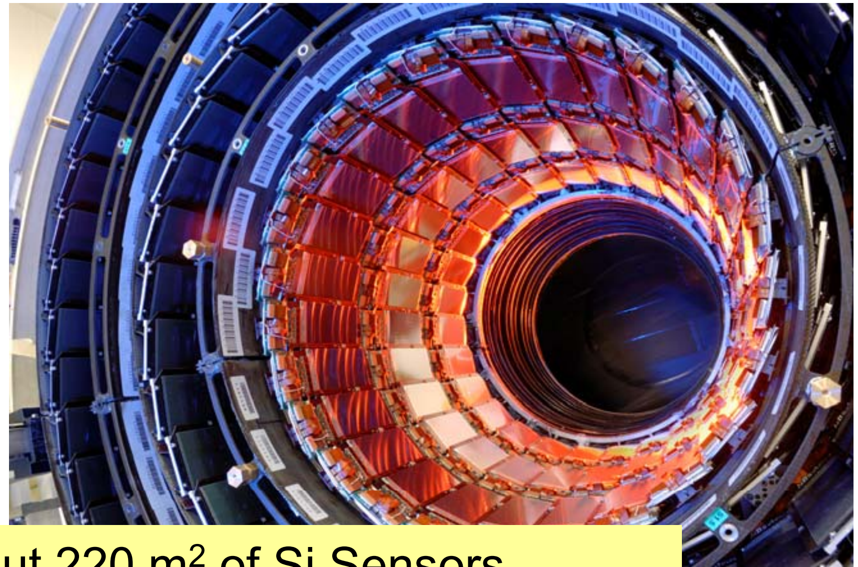
⇒ Endcap (CSC+RPC) fully installed



# The CMS Detector

ECAL: Barrel 36 super modules/1700 crystals
Total of ~100% delivered (61000) crystals
Endcaps will be finalized February 2008





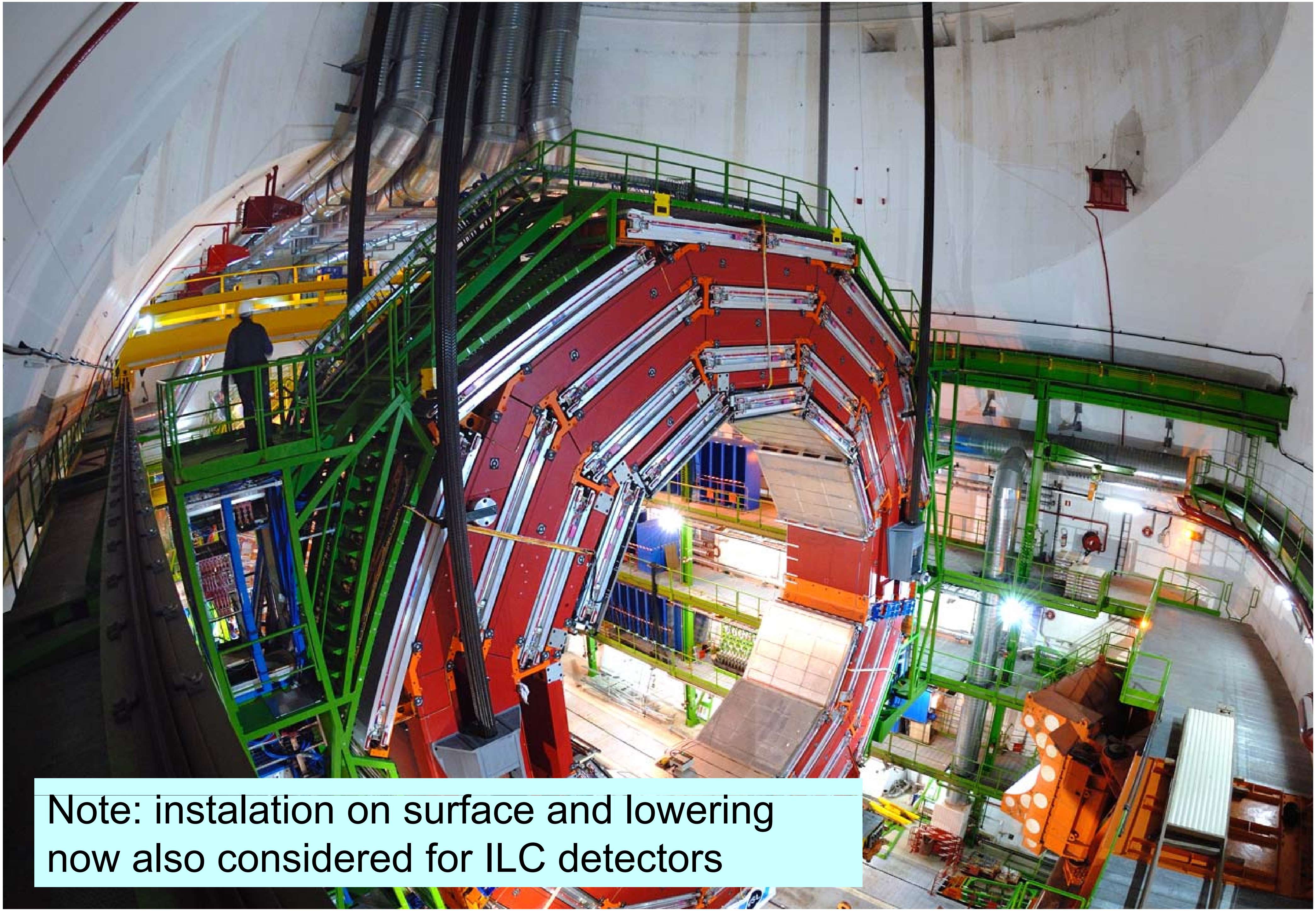
About 220 $m^2$ of Si Sensors
$\Rightarrow 10^7$ Si strips
$\Rightarrow 6.5 \bullet 10^7$ pixels
16000 Si strip modules ready

HCAL completed in 2006
Lowering of the calorimeter

# Heavy lowering: CMS parts going 100m down

30 Nov: Y\\\E+3 leaves SX5 and 11 hours later touches down safely in UXC

The first force studied carefully by CMS is Gravity

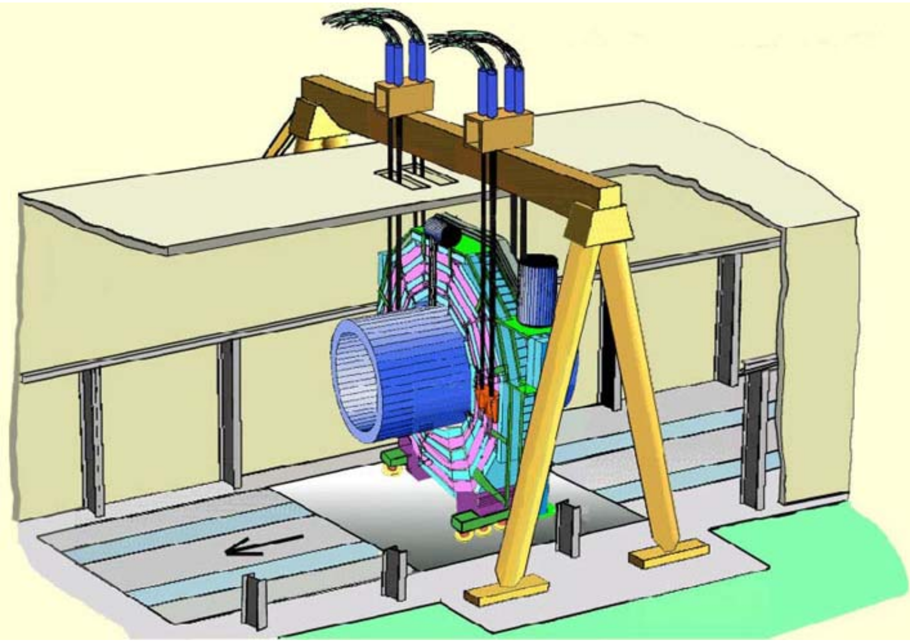


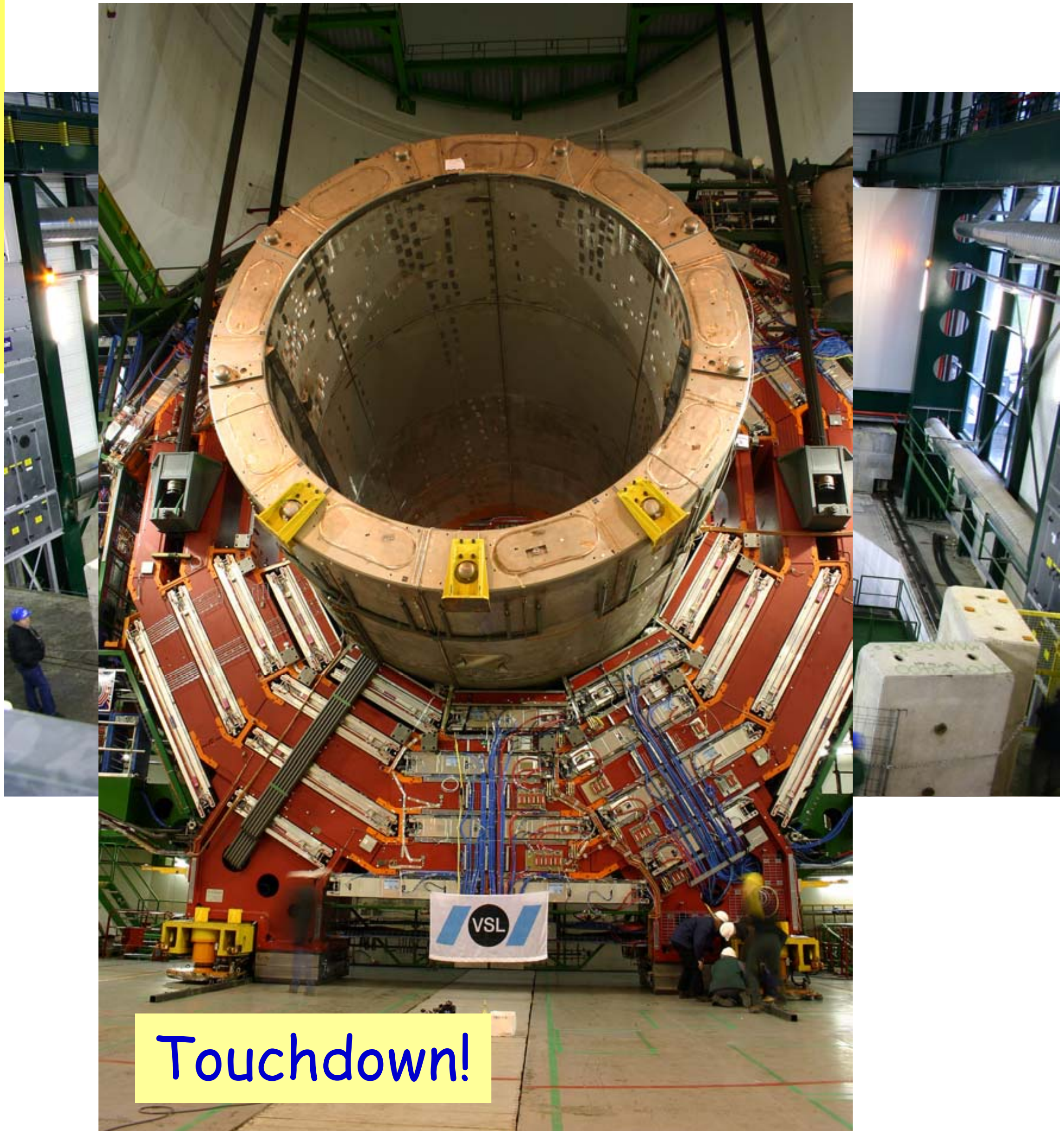
Note: instalation on surface and lowering
now also considered for ILC detectors

# Lowering of the Solenoid

The Central piece of CMS
⇒The barrel wheel with the solenoid

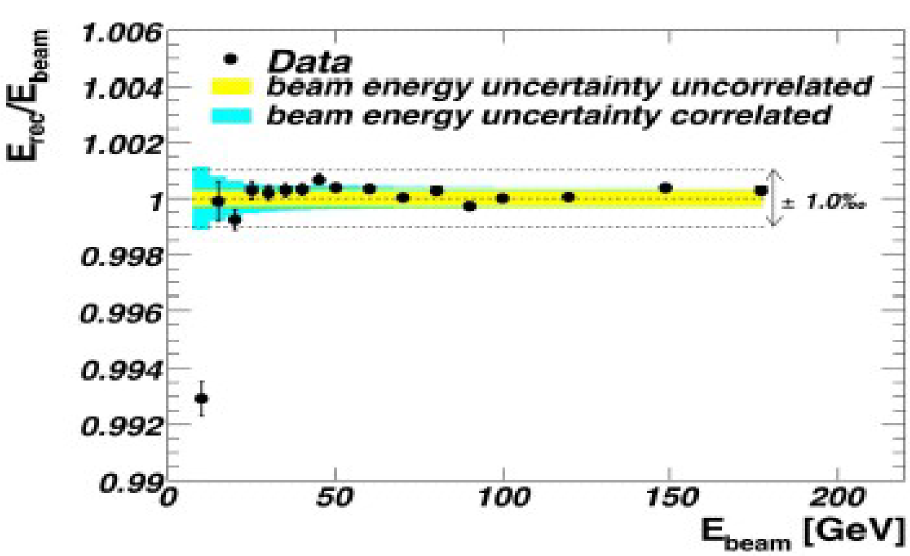
Total weight ~ 2Ktons
= 5 jumbo jets
Lowered February 28

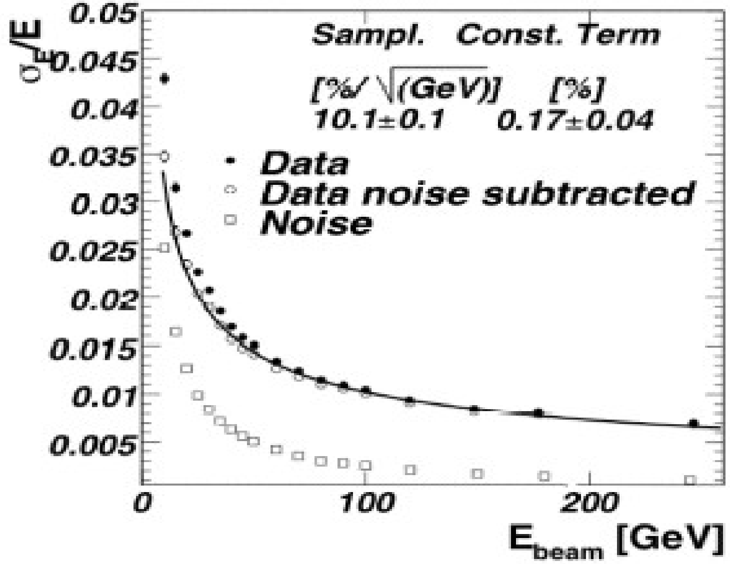


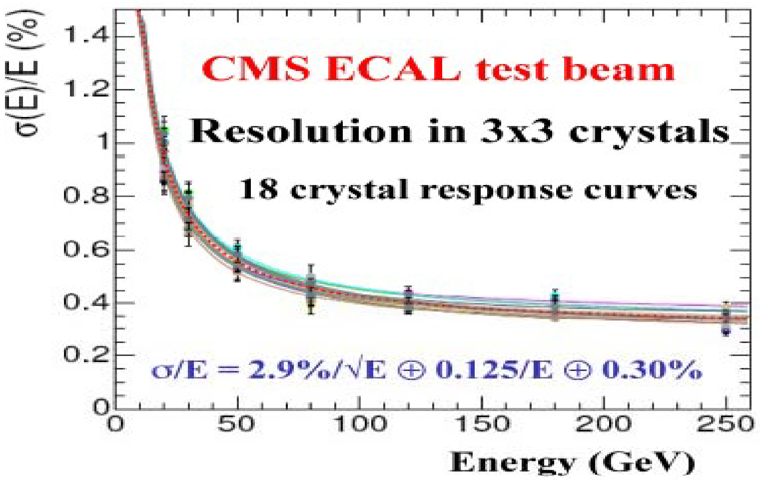


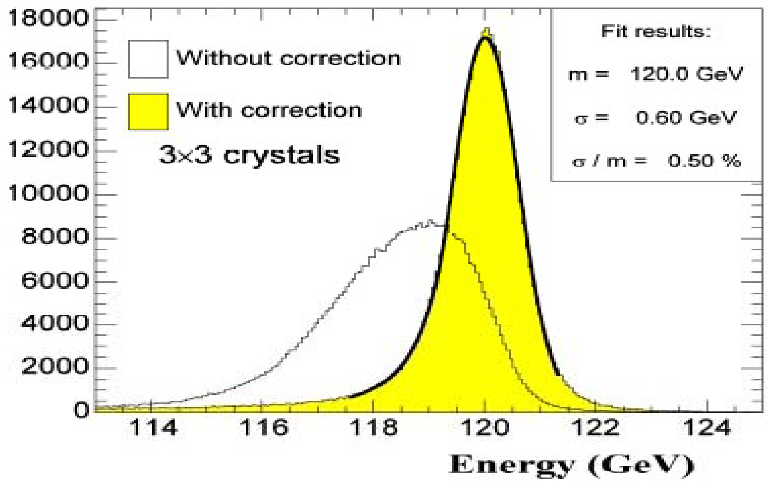
# ATLAS/CMS: from design to reality

## R&D and construction for 15 years → excellent EM calo intrinsic performance




- Standalone performance measured in beams with electrons from 10 to 250 GeV

# ATLAS/CMS: from design to reality

**TABLE 5** Evolution of the amount of material expected in the ATLAS and CMS trackers from 1994 to 2006

| Date | ATLAS $\eta \approx 0$ | $\eta \approx 1.7$ | CMS $\eta \approx 0$ | $\eta \approx 1.7$ |
|---|---|---|---|---|
| 1994 (Technical Proposals) | 0.20 | 0.70 | 0.15 | 0.60 |
| 1997 (Technical Design Reports) | 0.25 | 1.50 | 0.25 | 0.85 |
| 2006 (End of construction) | 0.35 | 1.35 | 0.35 | 1.50 |

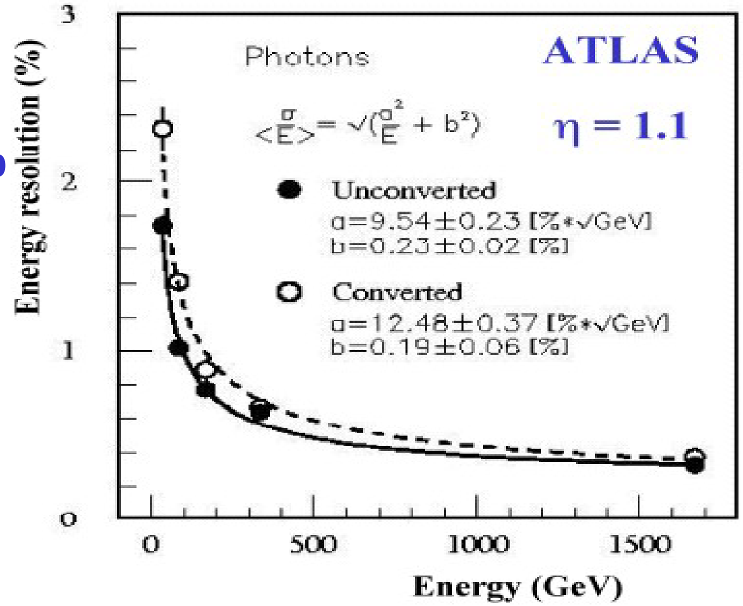
The numbers are given in fractions of radiation lengths ($X/X_0$). Note that for ATLAS, the reduction in material from 1997 to 2006 at $\eta \approx 1.7$ is due to the rerouting of pixel services from an integrated barrel tracker layout with pixel services along the barrel LAr cryostat, to an independent pixel layout with pixel services routed at much lower radius and entering a patch panel outside the acceptance of the tracker (this material appears now at $\eta \approx 3$). Note also that the numbers for CMS represent almost all the material seen by particles before entering the active part of the crystal calorimeter, whereas they do not for ATLAS, in which particles see in addition the barrel LAr cryostat and the solenoid coil (amounting to approximately $2X_0$ at $\eta = 0$), or the end-cap LAr cryostat at the larger rapidities.

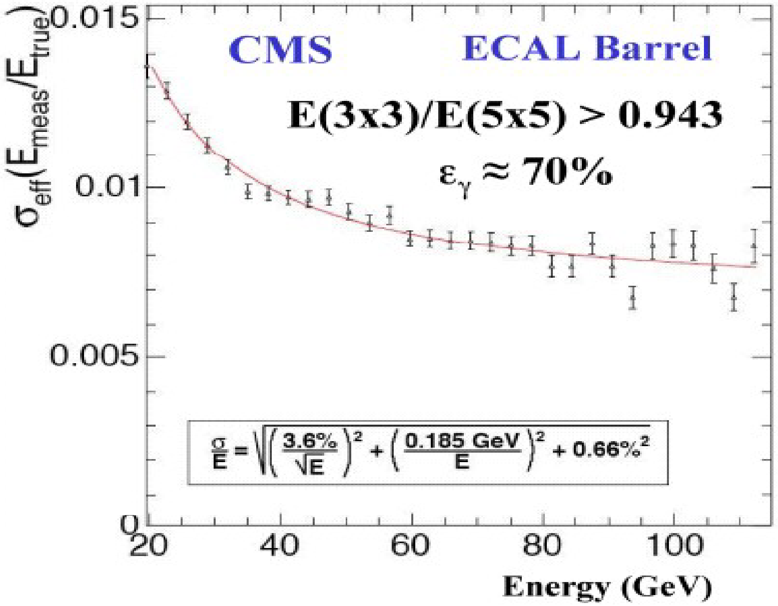
- **Material increased by ~ factor 2 from 1994 (approval) to now (end constr.)**
- **Electrons lose between 25% and 70% of their energy before reaching EM calo**
- **Between 20% and 65% of photons convert into $e^+e^-$ pair before EM calo**
- **Need to bring 70 kW power into tracker and to remove similar amount of heat**

# ATLAS/CMS: from design to reality

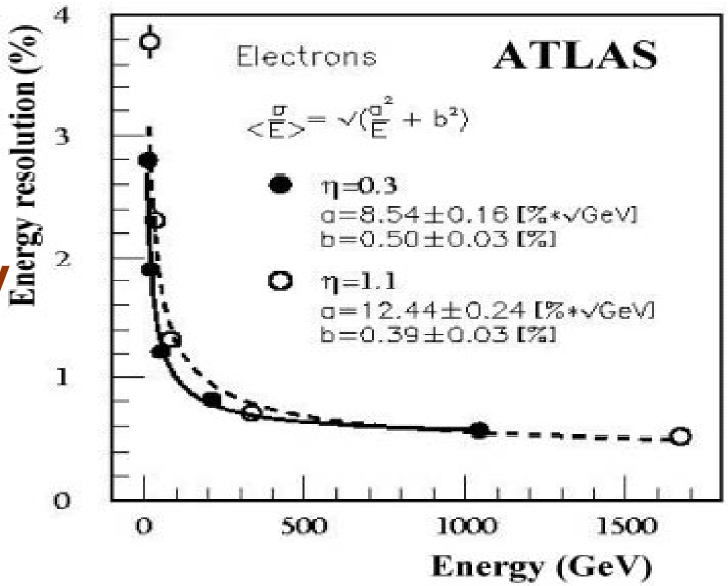
## Actual performance expected in real detector quite different

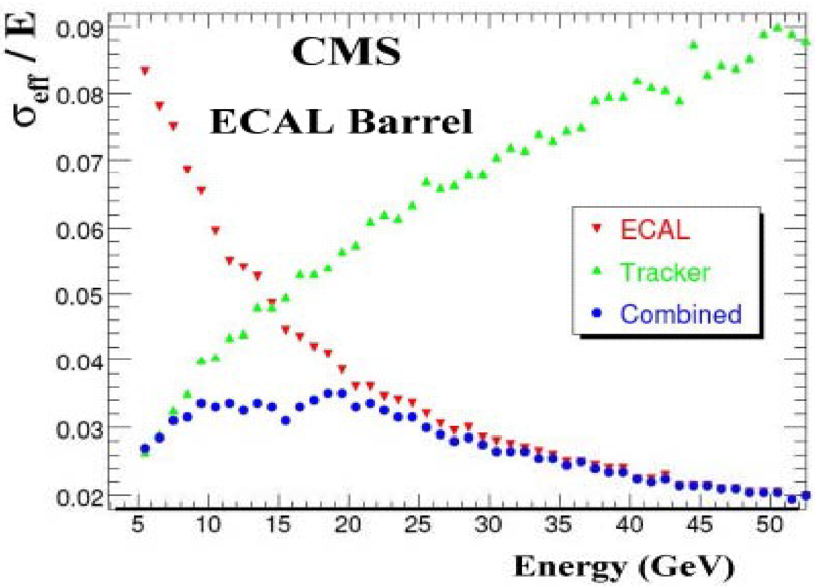
**Photons at 100 GeV** ATLAS: 1-1.3% energy resol. (all $\gamma$)
CMS: 0.8% energy resol. ($\varepsilon_\gamma$ ~ 70%)




**Electrons at 50 GeV** ATLAS: 1.3-2.3% energy resol. (use EM calo only)
CMS: ~ 2.0% energy resol. (combine EM calo and tracker)



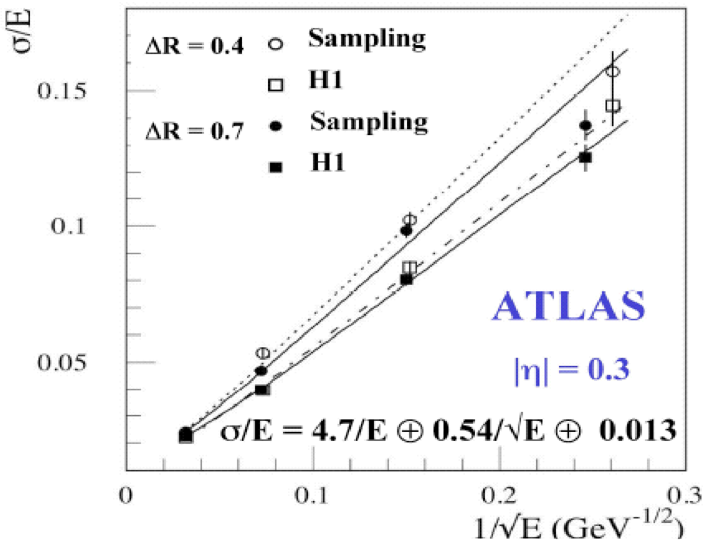
# ATLAS/CMS: from design to reality

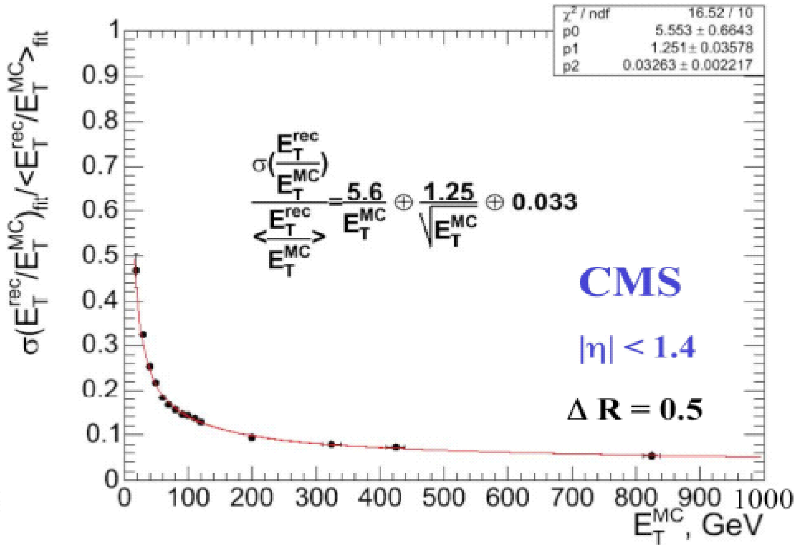
## Biggest difference in performance perhaps for hadronic calo

**Jets at 1000 GeV**

ATLAS ~ 2% energy resolution

CMS ~ 5% energy resolution, but expect sizable improvement using tracks (especially at lower E)



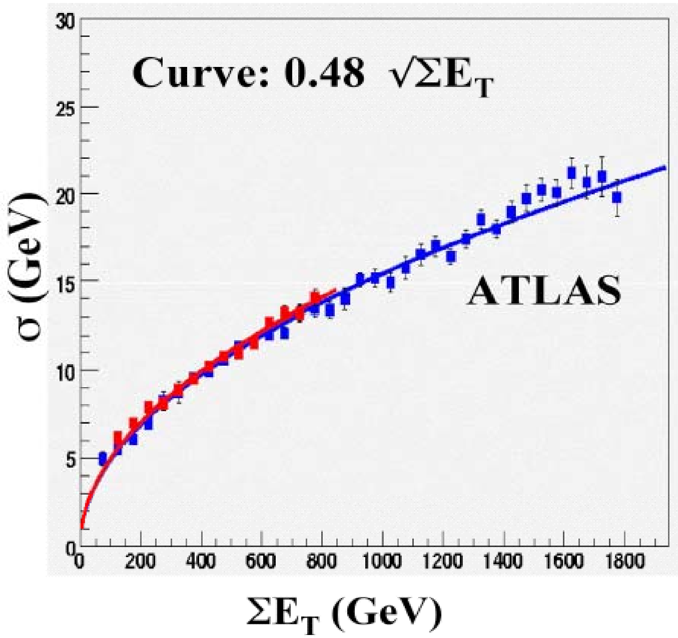



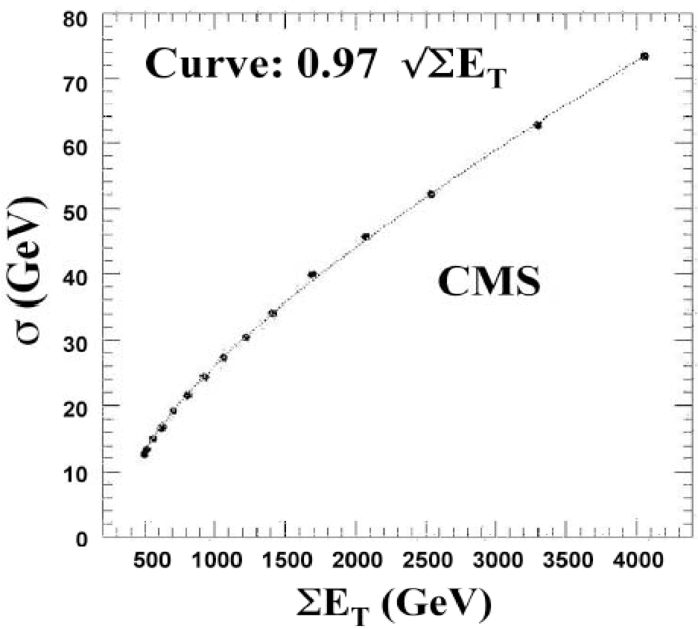

$E_T^{miss}$ at $\Sigma E_T$ = 2000 GeV

ATLAS: σ ~ 20 GeV

CMS: σ ~ 40 GeV

This may be important for high mass H/A to ττ



# ATLAS/CMS: from design to reality

**TABLE 12** Main parameters of the ATLAS and CMS muon measurement systems as well as a summary of the expected combined and stand-alone performance at two typical pseudorapidity values (averaged over azimuth)

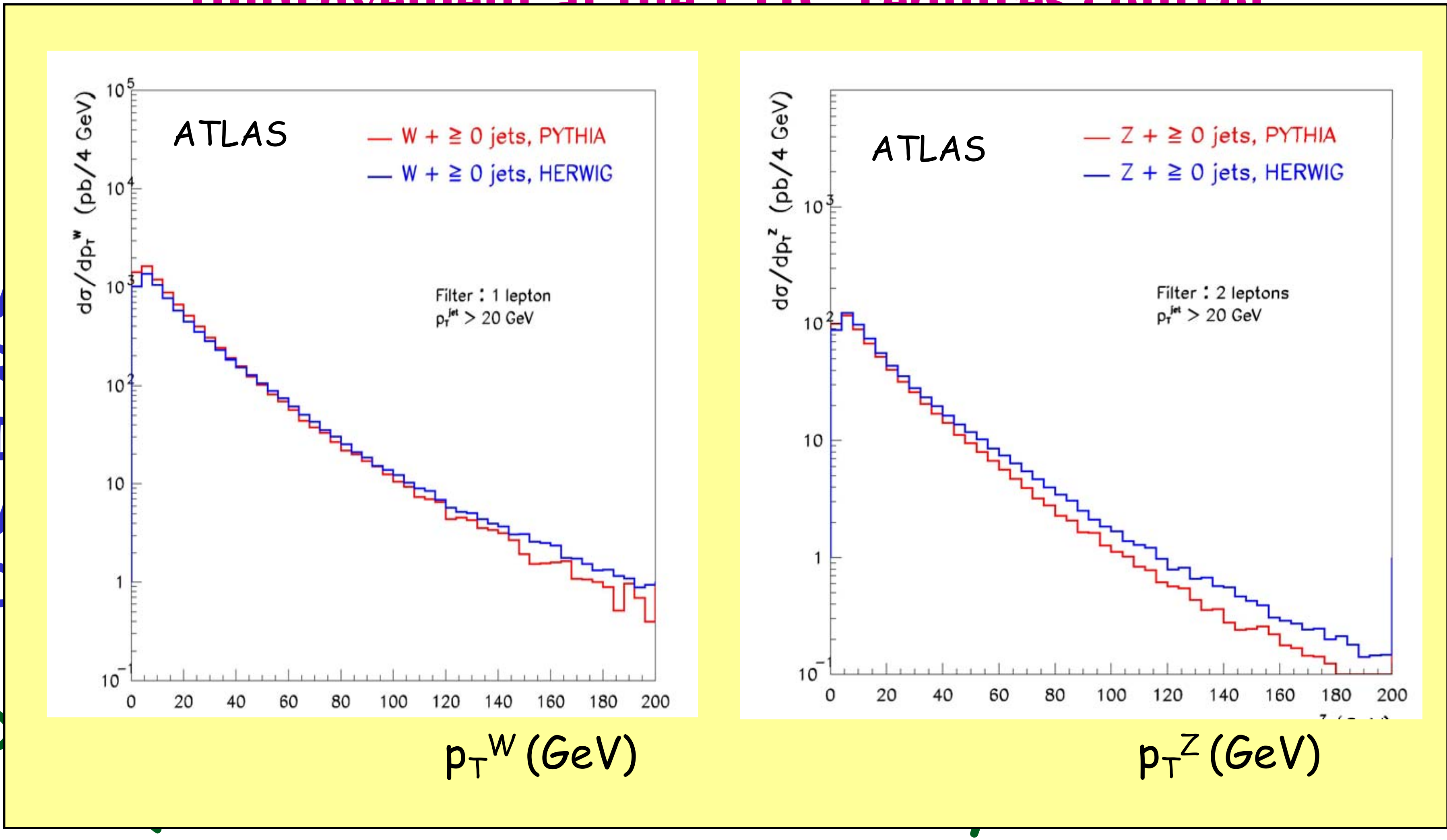
| Parameter | ATLAS | CMS |
|---|---|---|
| Pseudorapidity coverage | | |
| -Muon measurement | $\|\eta\| < 2.7$ | $\|\eta\| < 2.4$ |
| -Triggering | $\|\eta\| < 2.4$ | $\|\eta\| < 2.1$ |
| Dimensions (m) | | |
| -Innermost (outermost) radius | 5.0 (10.0) | 3.9 (7.0) |
| -Innermost (outermost) disk ($z$-point) | 7.0 (21–23) | 6.0–7.0 (9–10) |
| Segments/superpoints per track for barrel (end caps) | 3 (4) | 4 (3–4) |
| Magnetic field B (T) | 0.5 | 2 |
| -Bending power (BL, in T· m) at $\|\eta\| \approx 0$ | 3 | 16 |
| -Bending power (BL, in T· m) at $\|\eta\| \approx 2.5$ | 8 | 6 |
| Combined (stand-alone) momentum resolution at | | |
| -$p$ = 10 GeV and $\eta \approx 0$ | 1.4% (3.9%) | 0.8% (8%) |
| -$p$ = 10 GeV and $\eta \approx 2$ | 2.4% (6.4%) | 2.0% (11%) |
| -$p$ = 100 GeV and $\eta \approx 0$ | 2.6% (3.1%) | 1.2% (9%) |
| -$p$ = 100 GeV and $\eta \approx 2$ | 2.1% (3.1%) | 1.7% (18%) |
| -$p$ = 1000 GeV and $\eta \approx 0$ | 10.4% (10.5%) | 4.5% (13%) |
| -$p$ = 1000 GeV and $\eta \approx 2$ | 4.4% (4.6%) | 7.0% (35%) |

**CMS muon performance driven by tracker: better than ATLAS at η ~ 0**
**ATLAS muon stand-alone performance excellent over whole η range**

# Electroweak Physics: W mass measurement

## Improvement at the LHC requires control

1) W
2) P
3) I
4) W
5) D



# ATLAS/CMS: from design to reality

**TABLE 7** Main performance characteristics of the ATLAS and CMS trackers

| | ATLAS | CMS |
|---|---|---|
| Reconstruction efficiency for muons with $p_T = 1$ GeV | 96.8% | 97.0% |
| Reconstruction efficiency for pions with $p_T = 1$ GeV | 84.0% | 80.0% |
| Reconstruction efficiency for electrons with $p_T = 5$ GeV | 90.0% | 85.0% |
| Momentum resolution at $p_T = 1$ GeV and $\eta \approx 0$ | 1.3% | 0.7% |
| Momentum resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ | 2.0% | 2.0% |
| Momentum resolution at $p_T = 100$ GeV and $\eta \approx 0$ | 3.8% | 1.5% |
| Momentum resolution at $p_T = 100$ GeV and $\eta \approx 2.5$ | 11% | 7% |
| Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (μm) | 75 | 90 |
| Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (μm) | 200 | 220 |
| Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ (μm) | 11 | 9 |
| Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ (μm) | 11 | 11 |
| Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (μm) | 150 | 125 |
| Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (μm) | 900 | 1060 |
| Longitudinal i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ (μm) | 90 | 22–42 |
| Longitudinal i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ (μm) | 190 | 70 |

**Performance of CMS tracker is undoubtedly superior to that of ATLAS in terms of momentum resolution. Vertexing and b-tagging performances are similar. However, impact of material and B-field already visible on efficiencies.**

# ATLAS/CMS: from design to reality

**TABLE 10** Main performance parameters of the different hadronic calorimeter components of the ATLAS and CMS detectors, as measured in test beams using charged pions in both stand-alone and combined mode with the ECAL

| | ATLAS | | | | CMS | |
|---|---|---|---|---|---|---|
| | Barrel LAr/Tile | | End-cap LAr | | | |
| | Tile | Combined | HEC | Combined | Had. barrel | Combined |
| Electron/hadron ratio | 1.36 | 1.37 | 1.49 | | | |
| Stochastic term | $45\%/\sqrt{E}$ | $55\%/\sqrt{E}$ | $75\%/\sqrt{E}$ | $85\%/\sqrt{E}$ | $100\%/\sqrt{E}$ | $70\%/\sqrt{E}$ |
| Constant term | 1.3% | 2.3% | 5.8% | $< 1\%$ | | 8.0% |
| Noise | Small | 3.2 GeV | | 1.2 GeV | Small | 1 GeV |

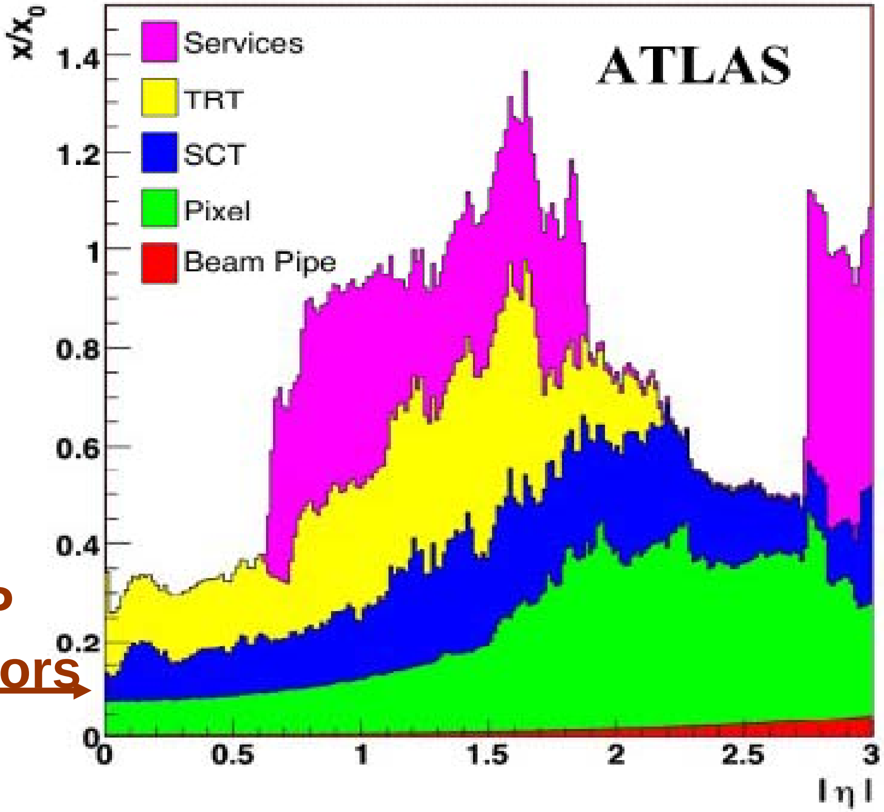
The measured electron/hadron ratios are given separately for the hadronic stand-alone and combined calorimeters when available, and for the contributions (added quadratically except for the stand-alone ATLAS tile calorimeter) to the pion energy resolution from the stochastic term, the local constant term, and the noise are also shown, when available from published data.

**Huge effort in test-beams to measure performance of overall calorimetry with single particles and tune MC tools: not completed!**

# ATLAS/CMS: from design to reality

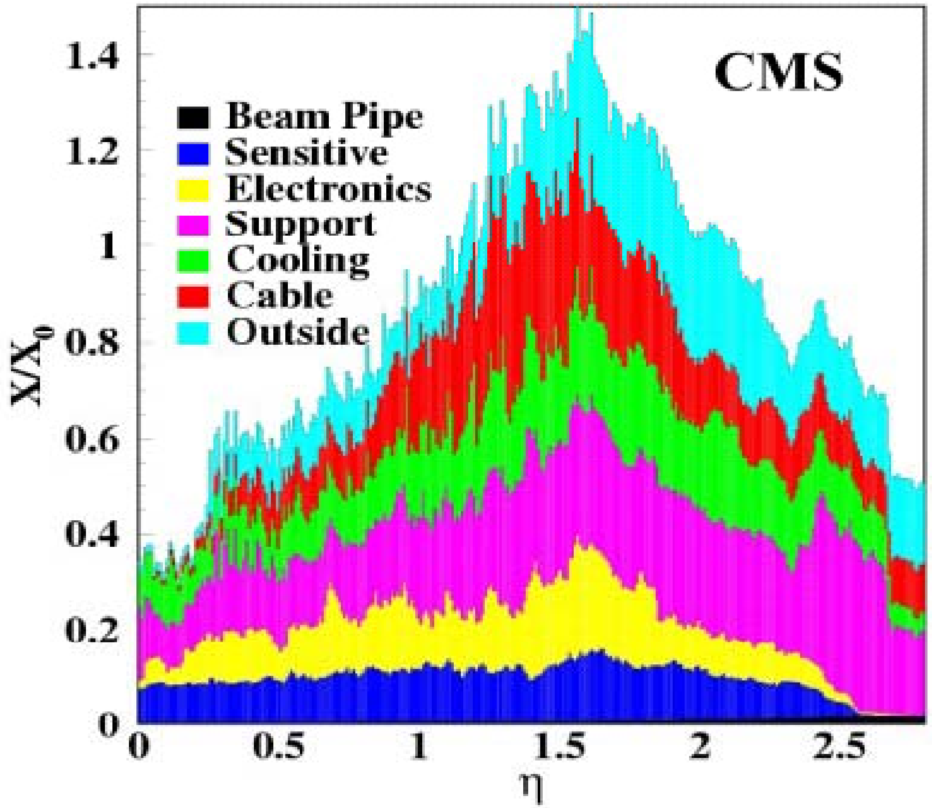
## Amount of material in ATLAS and CMS inner trackers

Weight: 4.5 tons




LEP detectors

Weight: 3.7 tons




- Active sensors and mechanics account each only for ~ 10% of material budget
- Need to bring 70 kW power into tracker and to remove similar amount of heat
- Very distributed set of heat sources and power-hungry electronics inside volume: this has led to complex layout of services, most of which were not at all understood at the time of the TDRs