Taking the first data at the LHC: part1

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LHC: pp Collider $\sqrt{s}$=14 TeV Startup: mid-2007

Main motivations:

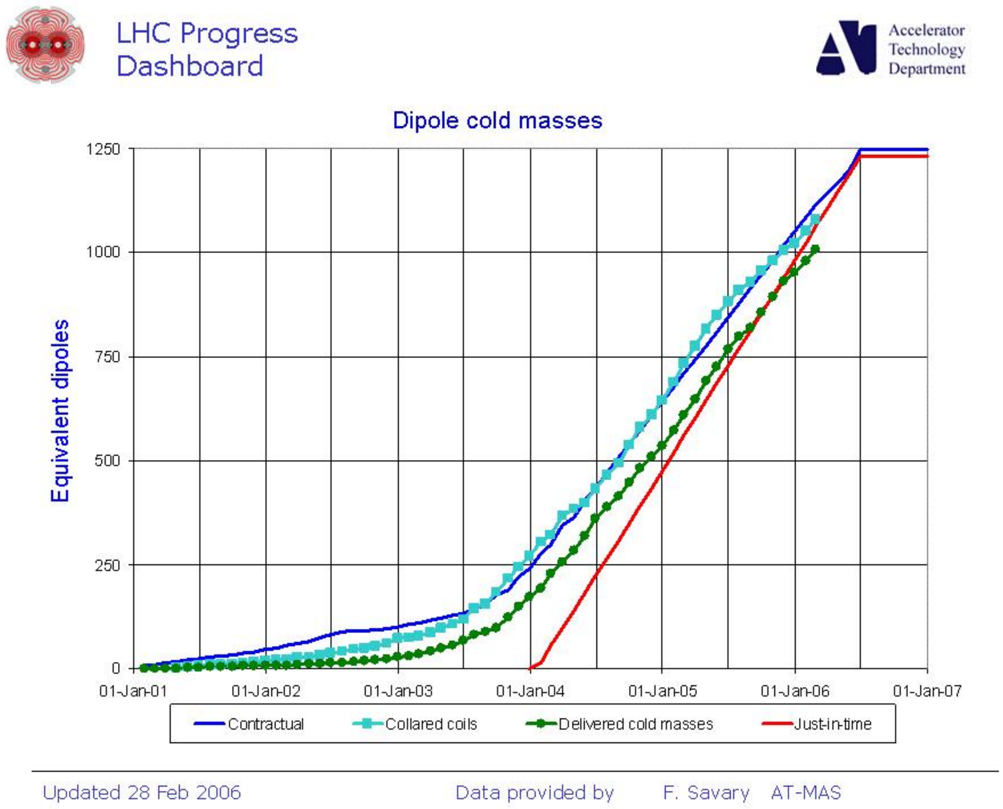
- Elucidate the mechanism of ElectroWeak Symmetry breaking:
  - Look for Higgs boson in allowed interval 100 GeV-1 TeV
  - In absence of low mass Higgs, study production of longitudinal gauge boson pairs.
- Find evidence for possible deviation from the Standard Model
  - Strong theoretical motivations to think that SM is only effective theory
  - In order to solve some of the theoretical difficulties with SM, deviations should be observable at $\sim$TeV scale

LHC Energy

$\sqrt{s} = 14$ TeV: explore the TeV scale, search for new massive particles up to 5 TeV

Maximum energy limited by the bending power needed to fit ring in 27 Km circumference LEP tunnel

$$p(\text{TeV}) = 0.3\text{B (T) R(km)}$$



LHC: $B = 8.4$ T:

$\sim$1300 superconducting dipoles working at 1.9 K

On track for closing the machine in 2007

Luminosity:

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

with $\mathcal{L}$: Luminosity N: event frequency, σ: cross-section

Two luminosity scenarios:

- peak $\sim 10^{33}$ cm^{-2}s^{-1} - initial "low luminosity": $\int \mathcal{L}\mathrm{dt} = 10\ \mathrm{f}b^{-1}$ per year
- peak $\sim 10^{34}$ cm^{-2}s^{-1} - design "high luminosity": $\int \mathcal{L}\mathrm{dt} = 100\ \mathrm{f}b^{-1}$ per year

Benchmark: ensure detection of Higgs boson in the range 100 GeV-1 TeV

$m(H) \sim 100 - 150$ GeV	$H \rightarrow \gamma\gamma$	$\sigma \times BR \times \epsilon \sim 10 - 20$ fb	$S/B \sim 1/50$
$m(H) = 1$ TeV	$H \rightarrow WW \rightarrow \ell\nu jj$	$\sigma \times BR \times \epsilon \sim 2 - 3$ fb	$S/B \sim 1/2$

Discovery when statistical significance for signal $S/\sqrt{B} > 5 \rightarrow$

Required integrated luminosity for discovery (no K-factors):

- $H \rightarrow \gamma\gamma$: $\sim$1000 events ~ 100 fb^{-1}
- $H \rightarrow WW$: $\sim$50 events ~ 20 fb^{-1}

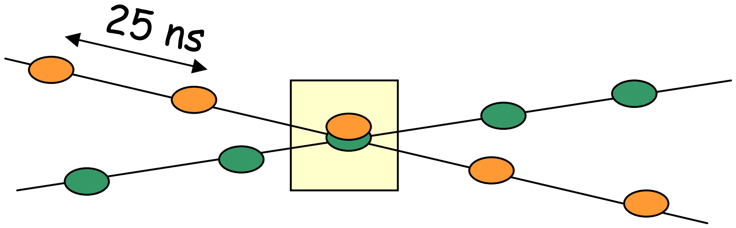
How is luminosity $\mathcal{L}$ achieved?

If two beams containing n_1 and n_2 particles collide with a frequency f:

$$\mathcal{L} = f \frac{n_1 n_2}{4\pi\sigma_{beam}^2}$$

with σ_{beam} gaussian transverse beam profile

LHC values: $n_1 = n_2 = 10^{11}$, and $\sigma_{beam} \sim 16 \times 10^{-6}$ m, determined by the physics of colliding beams.



To achieve $\mathcal{L} = 10^{34}$ cm^{-2}s^{-1}, LHC has to run with a bunch crossing every 25 ns

Inelastic proton-proton cross-section at $\sqrt{s} = 14$ TeV is ~ 70 mb $\Rightarrow$

LHC interaction rate at high luminosity: $\sim 7 \times 10^{-2} \times 10^{-24} \times 10^{34} = 7 \times 10^{8}$ Hz

40 MHz crossing frequency: $\Rightarrow \sim 25$ superimposed interactions per crossing (pile-up)

Characteristics of pile-up interactions

Soft partonic interactions: describe with non-perturbative phenomenological models

Collider jargon: "Minimum bias": experimental definition: depends on experiment's trigger. Usually associated to non-single diffractive events

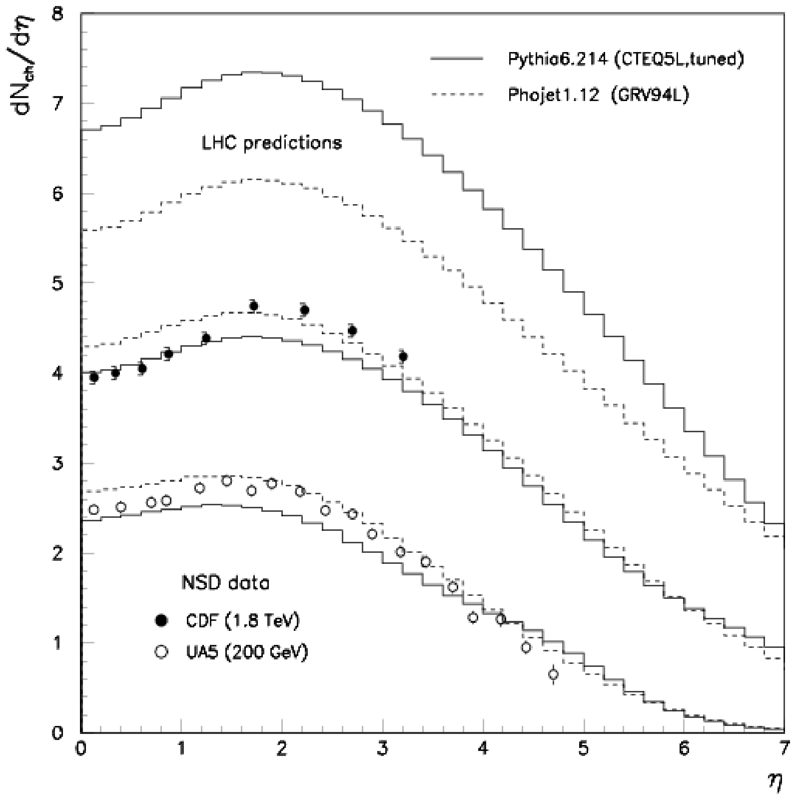
Measured at $S\bar{p}pS$ and Tevatron, large uncertainties in extrapolation to LHC

Main features:

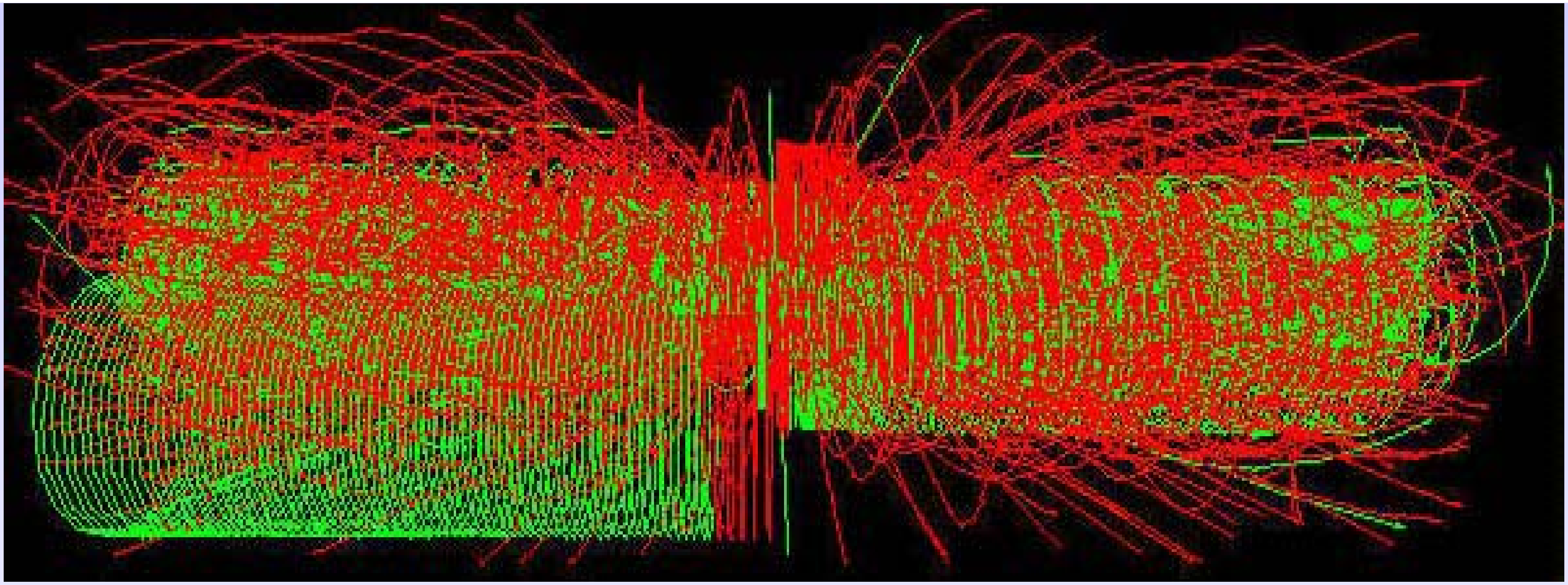
~7 charged particles per unit of rapidity⇒ $\sim$ 100 charged particles over $|\eta| < 2.5$ per crossing at low luminosity

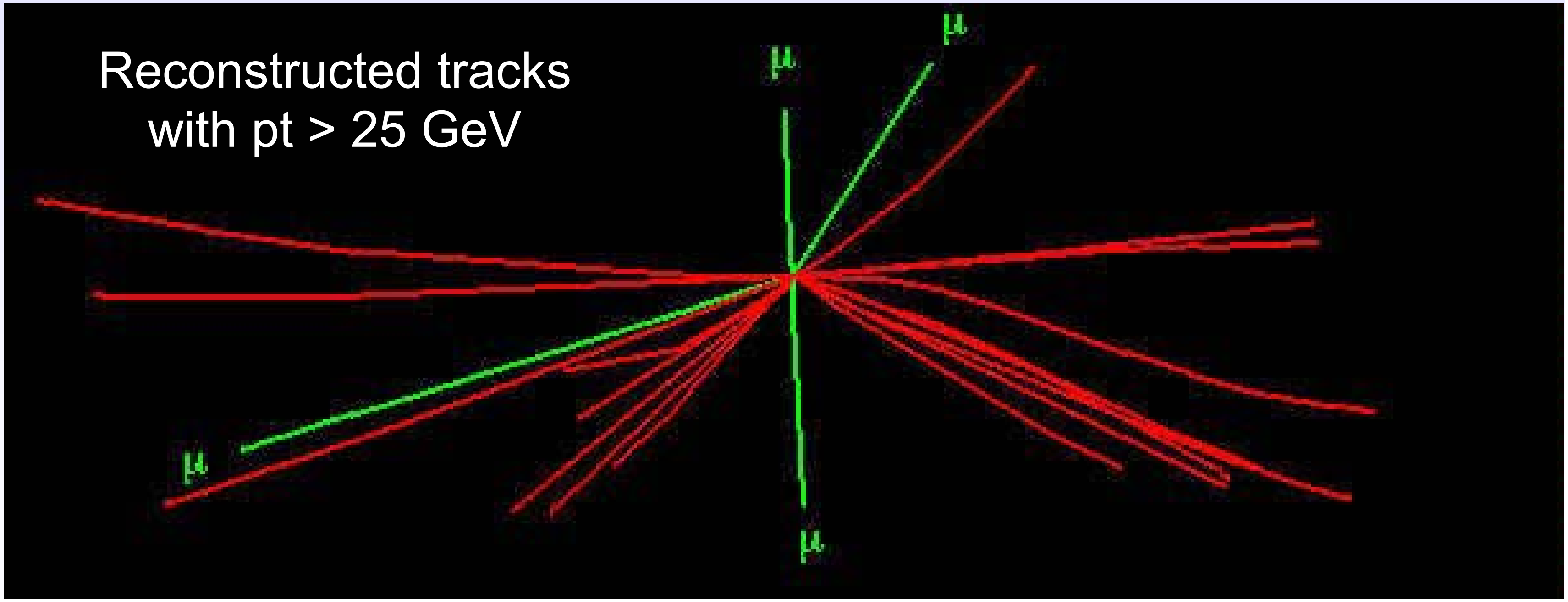
Significant radiation damage from interaction!

$< p_T > \sim 500$ MeV ⇒ can select interesting particles by cut in p_T



Example: $h \rightarrow 4\mu$ event in CMS at high luminosity





Reconstructed tracks with pt > 25 GeV

Large impact on detector design:

- Speed:

  LHC detectors must have fast response otherwise integrate over too many bunch crossings

  Typical response time: 20-50 ns$\longrightarrow$ integrate over 1-2 bunch crossings

  $\Rightarrow$ very challenging readout electronics

- Granularity:

  LHC detectors must be highly granular to minimise probability that pile-up particles in same detector element as interesting object

  $\Rightarrow$ Large number of electronics channels

- Radiation hardness:

  High flux of particles from pp collisions $\Rightarrow$ high radiation environment

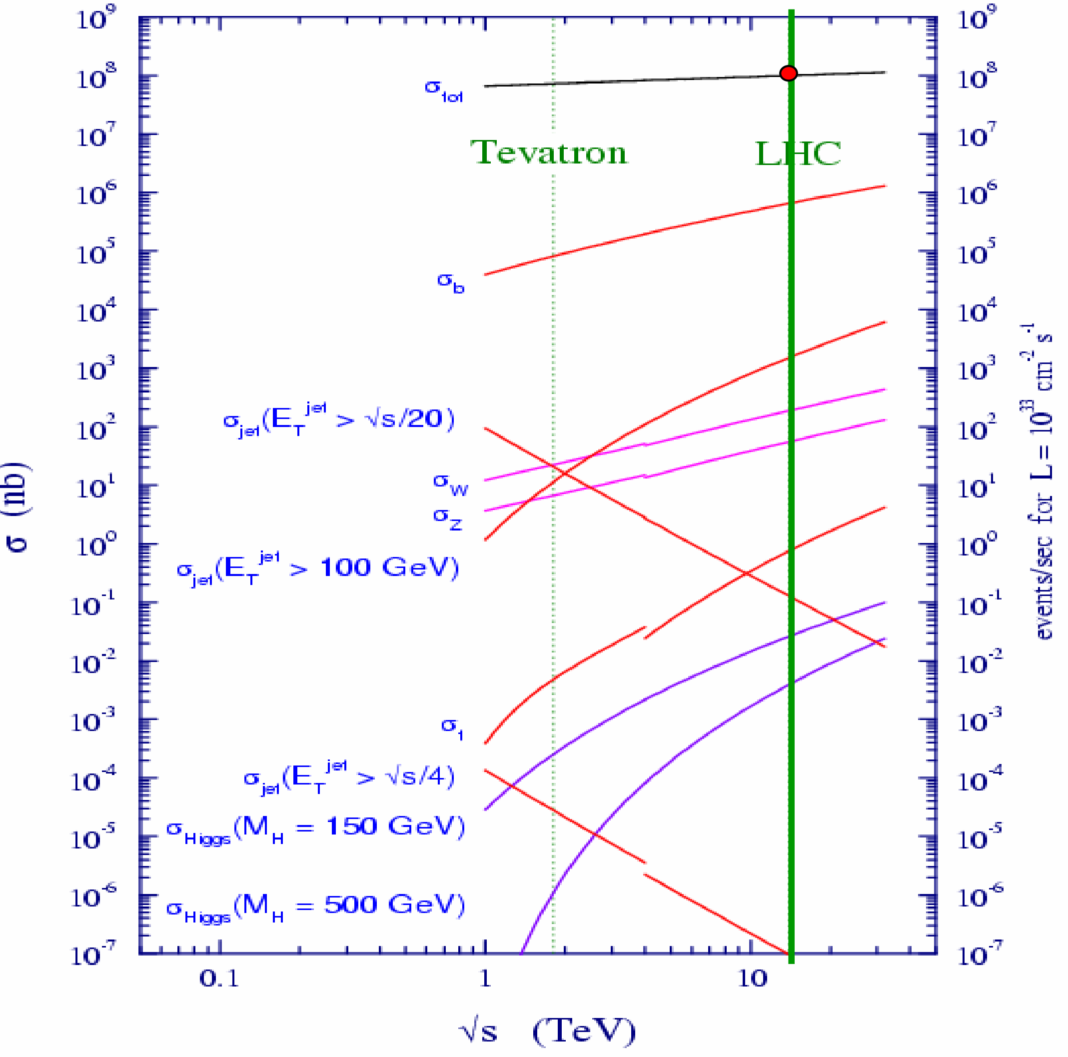
  In 10 years of LHC data: up to $10^{17} n$ cm^{-2}, up to 10^7Gy

  Radiation decrease like d^2 from beam: detectors near beam pipe mostly affected

  $\Rightarrow$ Need radiation resistant detector technologies especially at high $|\eta|$

  $\Rightarrow$ Need also radiation hard electronics

Backgrounds to discovery physics



High p_T events dominated by QCD jet production:

- Strong production
- Many contributing diagrams

$\sigma_{jet}(E_T^{jet} > 100$ GeV$) \sim \mu$b

Signal processes rare:

- Involve heavy particles:

$\sigma_{\tilde{q}\tilde{q}}(m(\tilde{q}) \sim 1$ TeV$) \sim$ pb

- Have weak cross-section

$\sigma_{Higgs}(m(Higgs) = 100$ GeV$) \sim 30$ pb

QCD background from 5-6 orders of magnitude larger than signals

Overwhelming QCD backgrounds in exclusively hadronic channels

$\Rightarrow$ rely on final states involving γ, leptons, $\not{E}_T$, b-jets $\Rightarrow$ pay additional price in BR

Typical cross-section values:

Process	σ	Events/s	Events/year (low L)
$W \rightarrow e\nu$	15 nb	15	10^8
$Z \rightarrow ee$	1.5 nb	1.5	10^7
$\bar{t}t$	800 pb	0.8	10^7
$\bar{b}b$	500 μb	10^5	10^{12}
$\tilde{q}\tilde{q}$ (m$_{\tilde{q}}$ =1 TeV)	1 pb	0.001	10^4
Higgs (m$_H$ =0.8 TeV)	1 pb	0.001	10^4

Large statistics for discovery physics up to the TeV scale.

Large cross-section for Standard Model processes:

- Large backgrounds to discovery
- Large control samples to calibrate backgrounds

Precision measurements dominated by systematic effects

ATLAS and CMS detectors

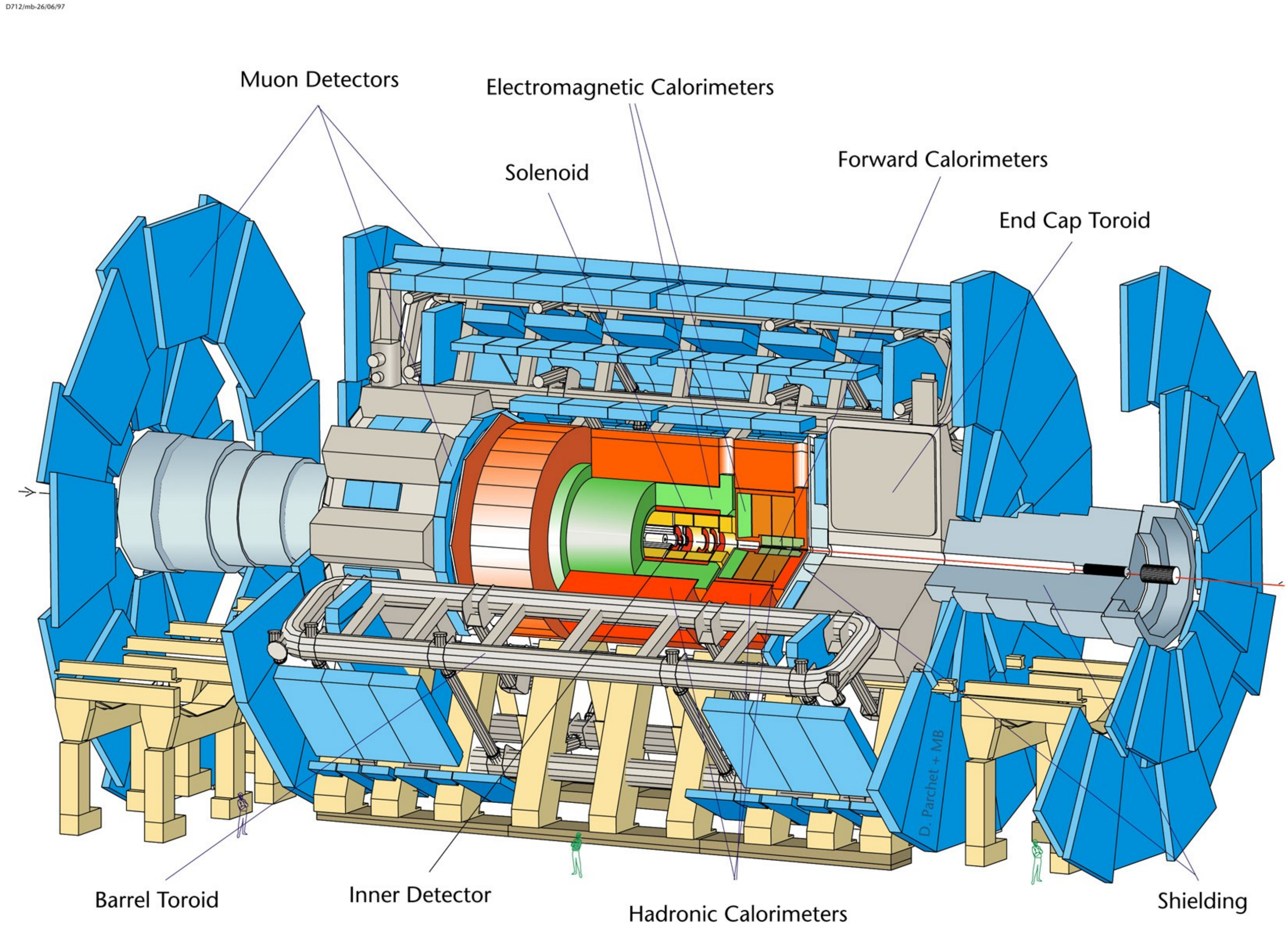
Do not know how new physics will manifest itself:

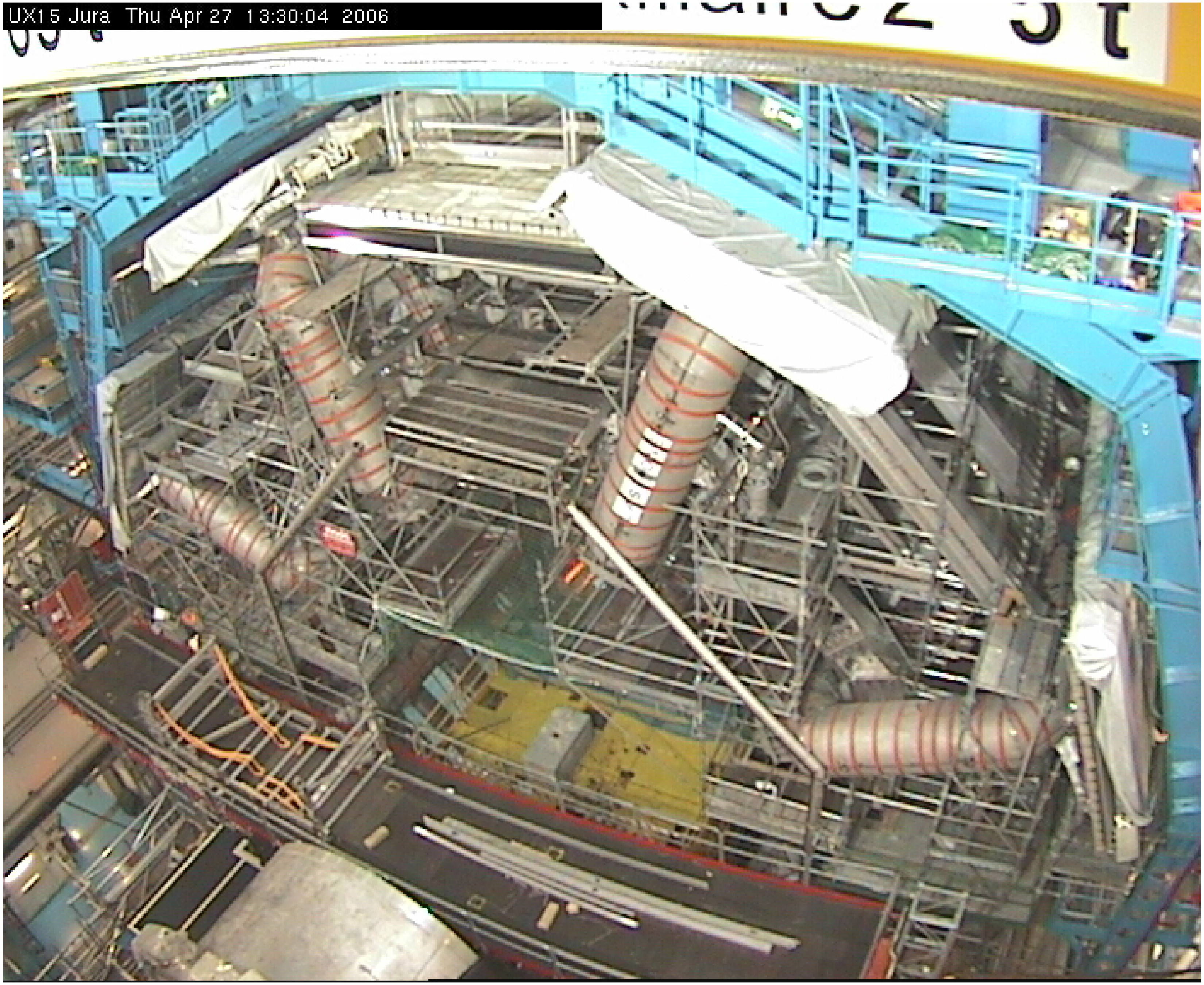
⇒ Detectors must be sensitive to as many particles and signatures as possible:

$$e,\ \mu,\ \tau,\ \nu,\ \gamma,\ \text{jets},\ b - \text{quarks}$$

- Momentum/charge of tracks and secondary vertexes (e.g. from b-quark decays) measured in central tracker. Excellent momentum and position resolution required
- Energy and position of electrons and photons measured in electromagnetic calorimeters. Excellent position and energy resolution required
- Energy and position of hadrons and jets measured mainly in hadronic calorimeters. Good coverage and granularity required
- Muons identified and momentum measured in external muon spectrometer ($+$ central tracker). Excellent resolution required.
- Neutrinos "detected and measured" through measurement of missing transverse energy $\not{E}_T$. Calorimeter coverage over $|\eta| < 5$ needed

ATLAS detector

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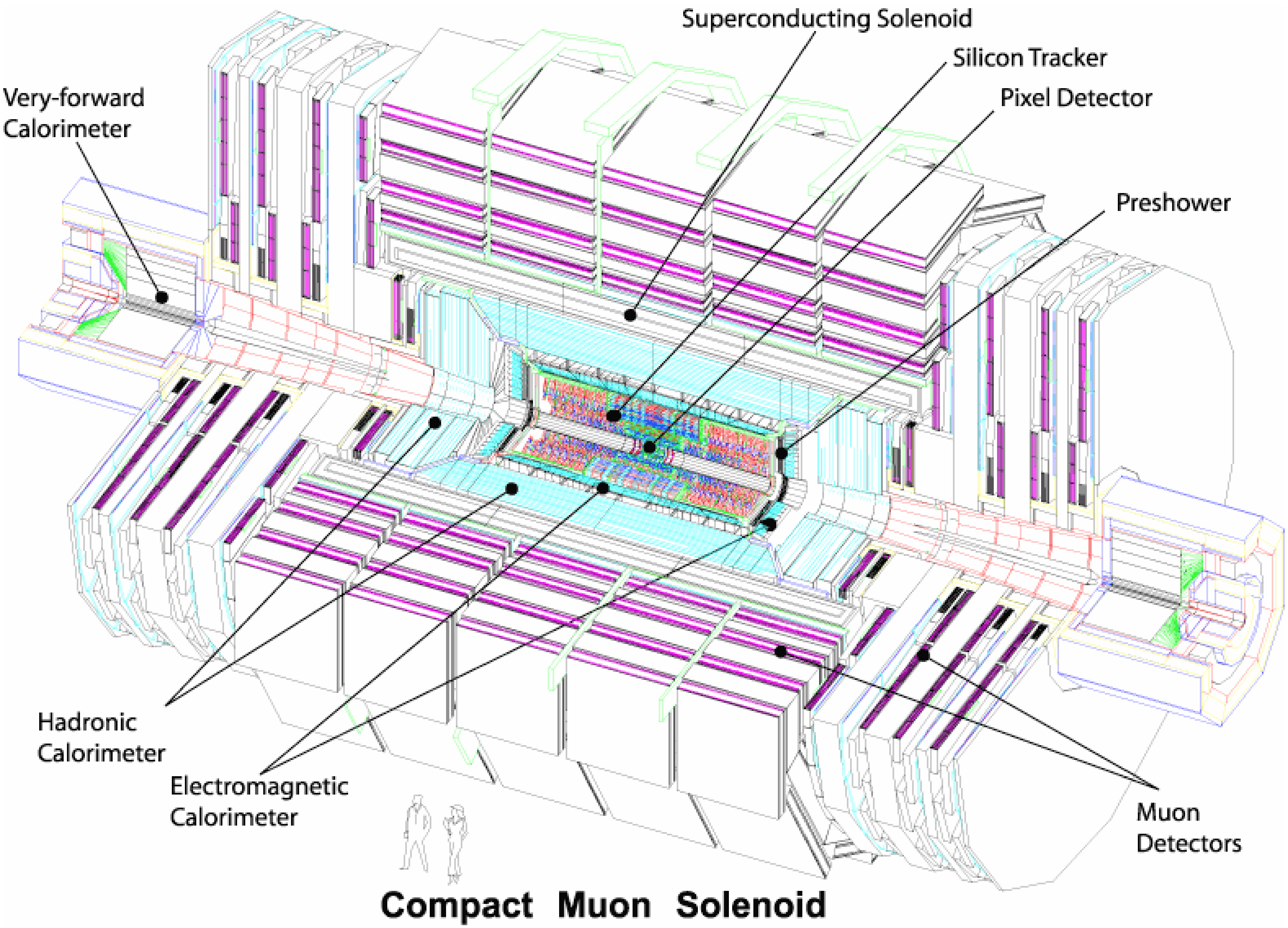
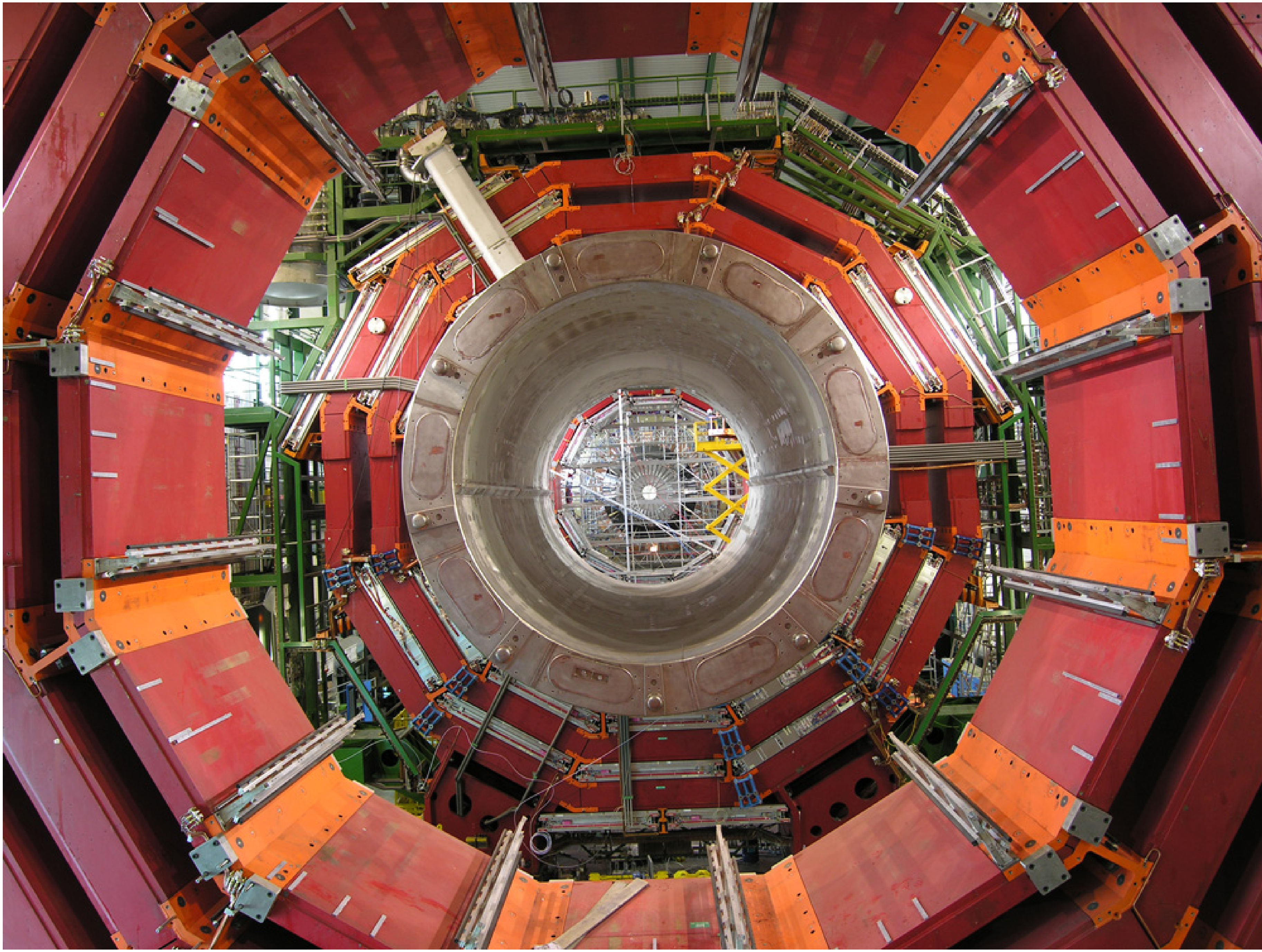
CMS detector





	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixel + strips TRD → particle identification B=2T $\sigma/p_T \sim 5x10^{-4}\, p_T \oplus 0.01$	Si pixel + strips No particle identification B=4T $\sigma/p_T \sim 1.5x10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb - liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbW0_4$ crystals $\sigma/E \sim 3\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scintillator + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ + catcher) $\sigma/E \sim 65\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeV standalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

A few examples of required performance:

- Lepton measurement: $p_T \sim \mathrm{GeV} \rightarrow 5\mathrm{TeV}$ ($b \rightarrow lX$, W', Z')
- Mass Resolution (m~ 100 GeV):

  $\sim 1\%$ $(H \rightarrow \gamma\gamma, 4l)$

  $\sim 10\%$ $(W \rightarrow jj,\ H \rightarrow bb)$

- Calorimeter coverage: $|\eta| < 5$ (E_T^{miss}, forward jet tag)
- Particle identification :

  $\epsilon_b \sim 50\%$ $R_j \sim 100$ $(H \rightarrow bb$, SUSY)

  $\epsilon_\tau \sim 50\%$ $R_j \sim 100$ $(A/H \rightarrow \tau\tau)$

  $\epsilon_\gamma \sim 80\%$ $R_j \sim 10^3$ $(H \rightarrow \gamma\gamma)$

  $\epsilon_e > 50\%$ $R_j \sim 10^5$

- Trigger: 40 MHz→ 100 Hz reduction

Crucial parameters for precision measurements

- Absolute luminosity: Goal: $< 5\%$

  Use: Machine, Optical theorem, Cross-Section for known processes

  (W, Z production, QED $pp \to pp\ell\ell$)

- Lepton energy scale: Goal: 0.1% (General)

  0.02% (W mass)

  Use: $Z \to \ell\ell$ (1 ev/s at low L)

  High precision possible for W, low mass h as mass close to Z

- Jet energy scale: Goal: 1%

  Use: $Z + jets(Z \to \ell\ell)$, $\gamma + jets$, $W \to jj$ from top decay, multi-jet balance

  Needed for for SUSY parameter, top mass, jet cross-section

  Limited by physics effects

Commissioning scenarios

Ambitious performance goals driven by very precise requirements from physics

Large amount of work (and time) required to control detector at this level

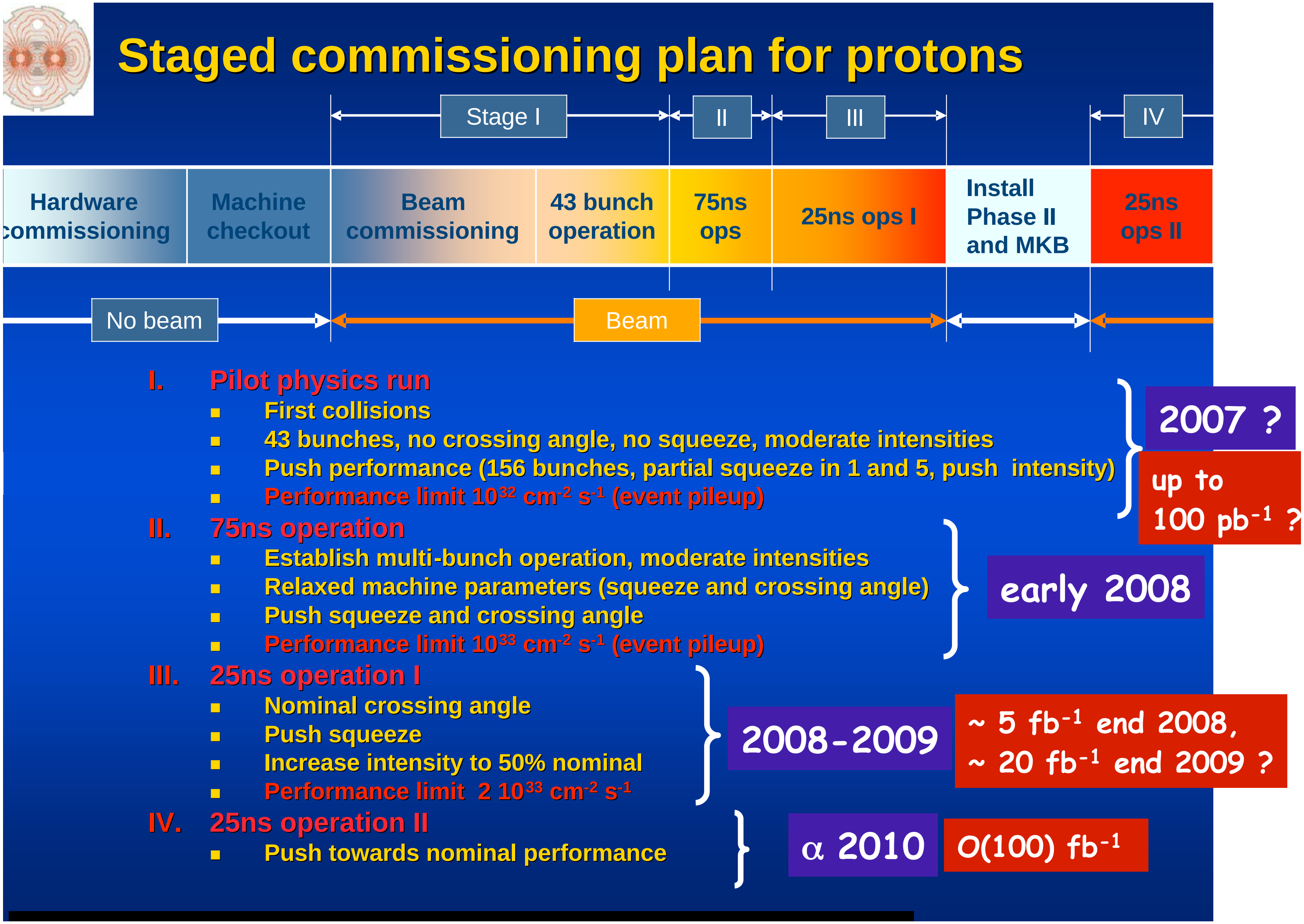
Pressure to extract physics results as soon as possible, competition between experiment, need to feed back to HEP community possible signs for new physics to allow specification of projects for next decade

Final understanding of detectors only achievable with real collisions in LHC environment

Try to exploit time from now to collisions to achieve detector understanding adequate to fully take advantage of data from the first day

Need to develop detailed strategy based on hypothesis on the main unknown in the game: the LHC commissioning schedule

Possible scenario for machine startup (machine presentation)



Staged commissioning plan for protons

		Stage I		II	III		IV
Hardware ommissioning	Machine checkout	Beam commissioning	43 bunch operation	75ns ops	25ns ops I	Install Phase II and MKB	25ns ops II
No beam		Beam					

I. **Pilot physics run**
- First collisions
- 43 bunches, no crossing angle, no squeeze, moderate intensities
- Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)
- Performance limit 10^{32} cm^{-2} s^{-1} (event pileup)

2007 ?

up to 100 pb^{-1} ?

II. **75ns operation**
- Establish multi-bunch operation, moderate intensities
- Relaxed machine parameters (squeeze and crossing angle)
- Push squeeze and crossing angle
- Performance limit 10^{33} cm^{-2} s^{-1} (event pileup)

early 2008

III. **25ns operation I**
- Nominal crossing angle
- Push squeeze
- Increase intensity to 50% nominal
- Performance limit 2 10^{33} cm^{-2} s^{-1}

2008-2009

~ 5 fb^{-1} end 2008,
~ 20 fb^{-1} end 2009 ?

IV. **25ns operation II**
- Push towards nominal performance

α 2010

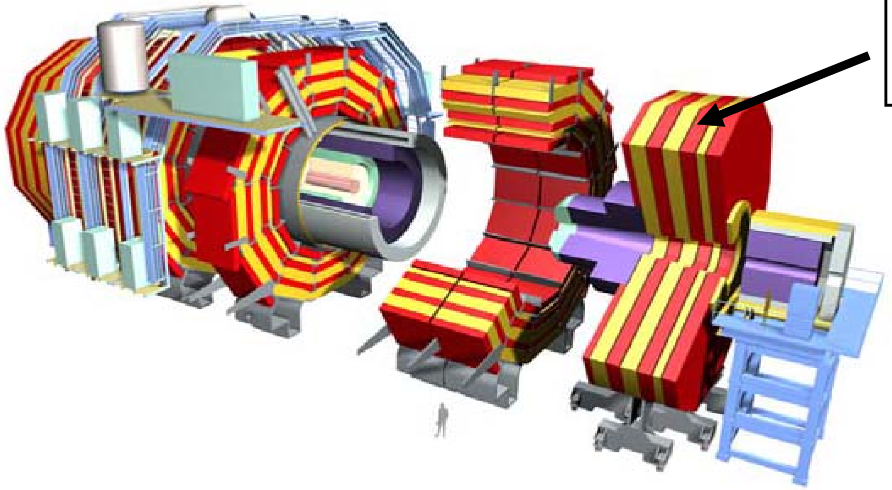
O(100) fb^{-1}

Integrated luminosities and dates: guesses by F. Gianotti

Based on this information develop start-up strategy

- Last few years: extensive test-beam activities with final detector components to achieve basic calibration. Notably: ATLAS combined test-beam of full slice of detector
- Now, extending up to most of 2007: Cosmics data taking. Detector timing and alignment
- From first injections: beam-halo and beam-gas interactions. More specialised alignment work
- First interactions:
  - Understand and calibrate detector and trigger in situ using well-known physics samples:
    - $Z \to ee, \mu\mu$: tracker, ECAL, muons system
    - $tt \to b\ell\nu bjj$: Jets scale, b-tag performance, $\not{E}_T$
  - Understand basic SM physics at 14 TeV: first checks of MonteCarlo
    - jets and W, Z cross-section top mass and cross-section
    - Event features: Min. bias, jet distributions, PDF constraints
  - Prepare road to discovery: background to discovery from tt, W/Z + jets.

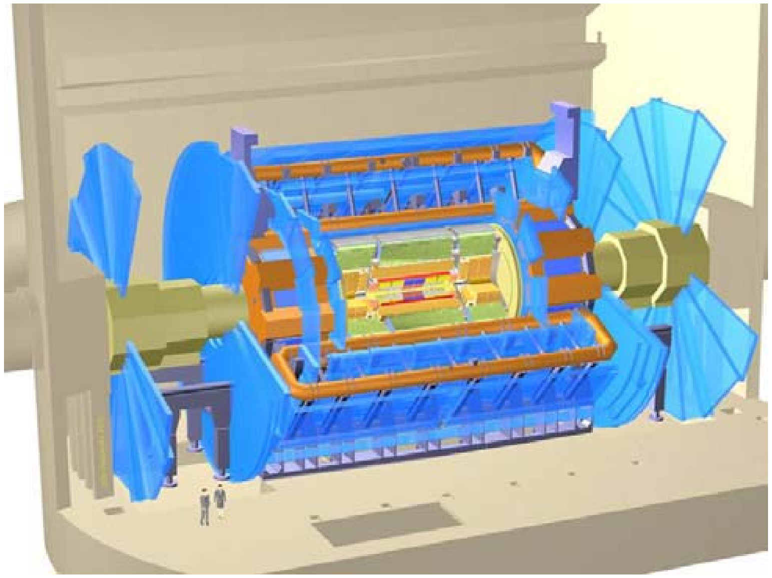
Status of experiments at startup



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

Pixels and end-cap ECAL installed during first shut-down

ATLAS: because of staging TRT coverage over $|\eta| > 2.0$ instead of $|\eta| > 2.4$



For both detectors: reduced trigger bandwidth due to deferrals on HLT processors

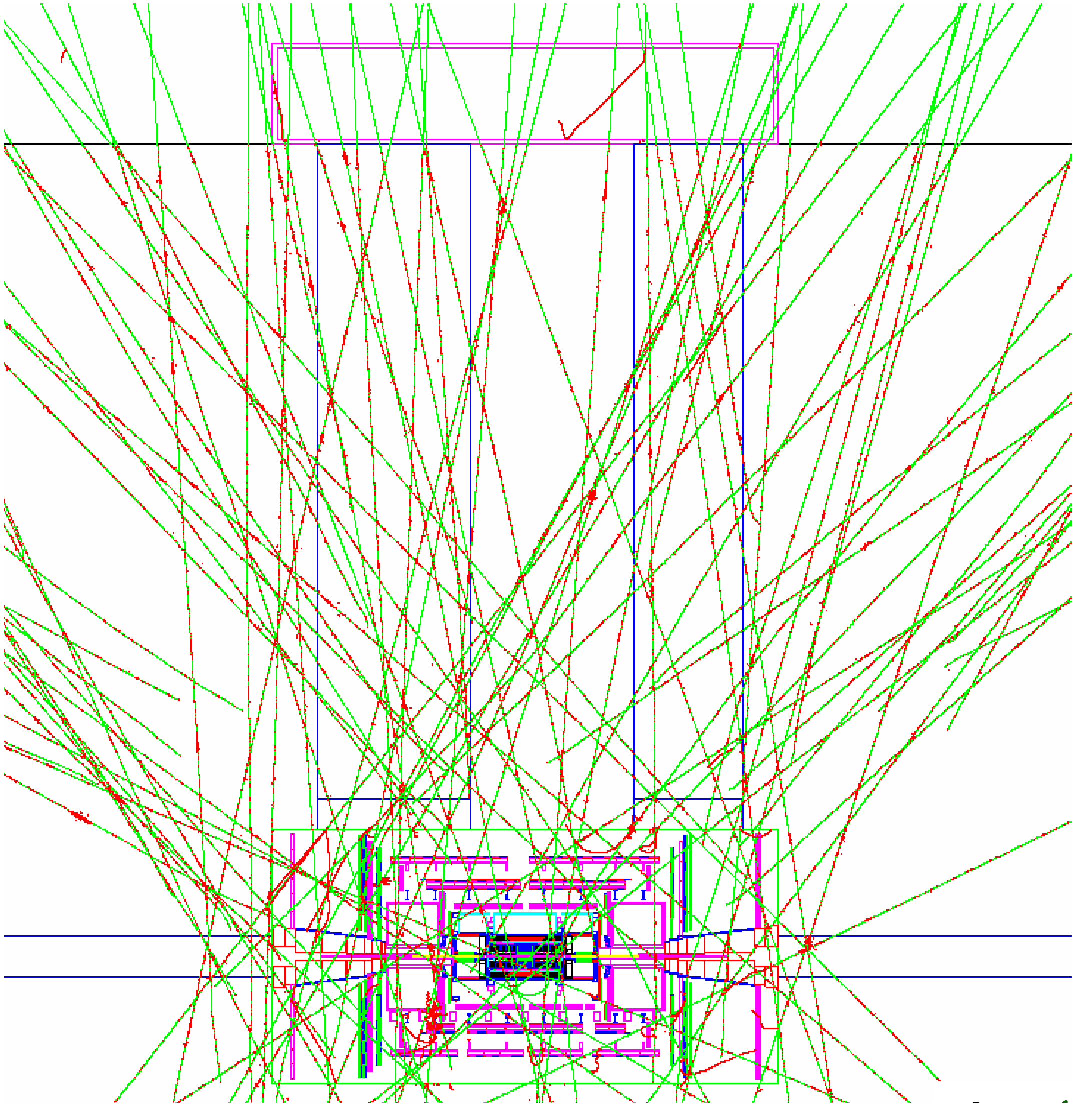
Pre-Collision phase

First detector understanding before commissioning with real collisions.

- Cosmics running (spring 2007)
  - Initial alignment of detector with particles
  - Timing-in of detectors
  - Debugging of sub-systems, mapping of dead channels, etc.
- One beam in the machine
  - beam halo muons and beam-gas events
  - more detailed alignment/calibrations for relevant detectors

Both ATLAS and CMS have developed simulation studies in order to better understand how to use these data

Cosmics



Rate from full simulation of ATLAS (including cavern overburden) validated by measurement with a scintillator telescope in cavern

0.01 seconds shown in figure

Location	Cut	Rate (Hz) (E(surface) >10 GeV)
UX15		4900
Ecal	$E_T^{total} > 5$ GeV	0.4
Tile Cal	$E^{total} > 20$ GeV	1.2
HEC	$E^{total} > 20$ GeV	0.1
FCAL	$E^{total} > 20$ GeV	0.02

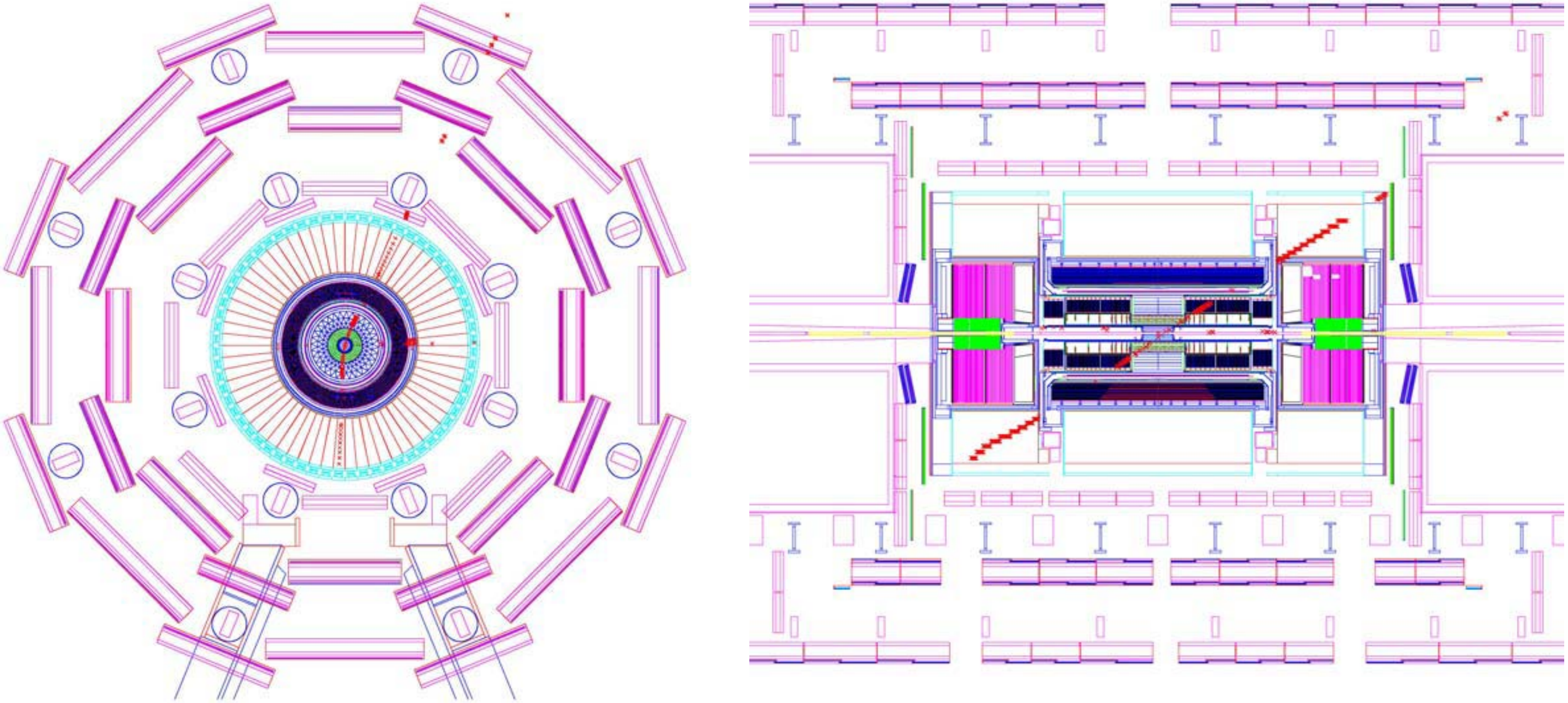
For CMS expect ~1800 Hz over full detector

"Typical" cosmic event from ATLAS full sim

One track reconstructed in Muon chambers

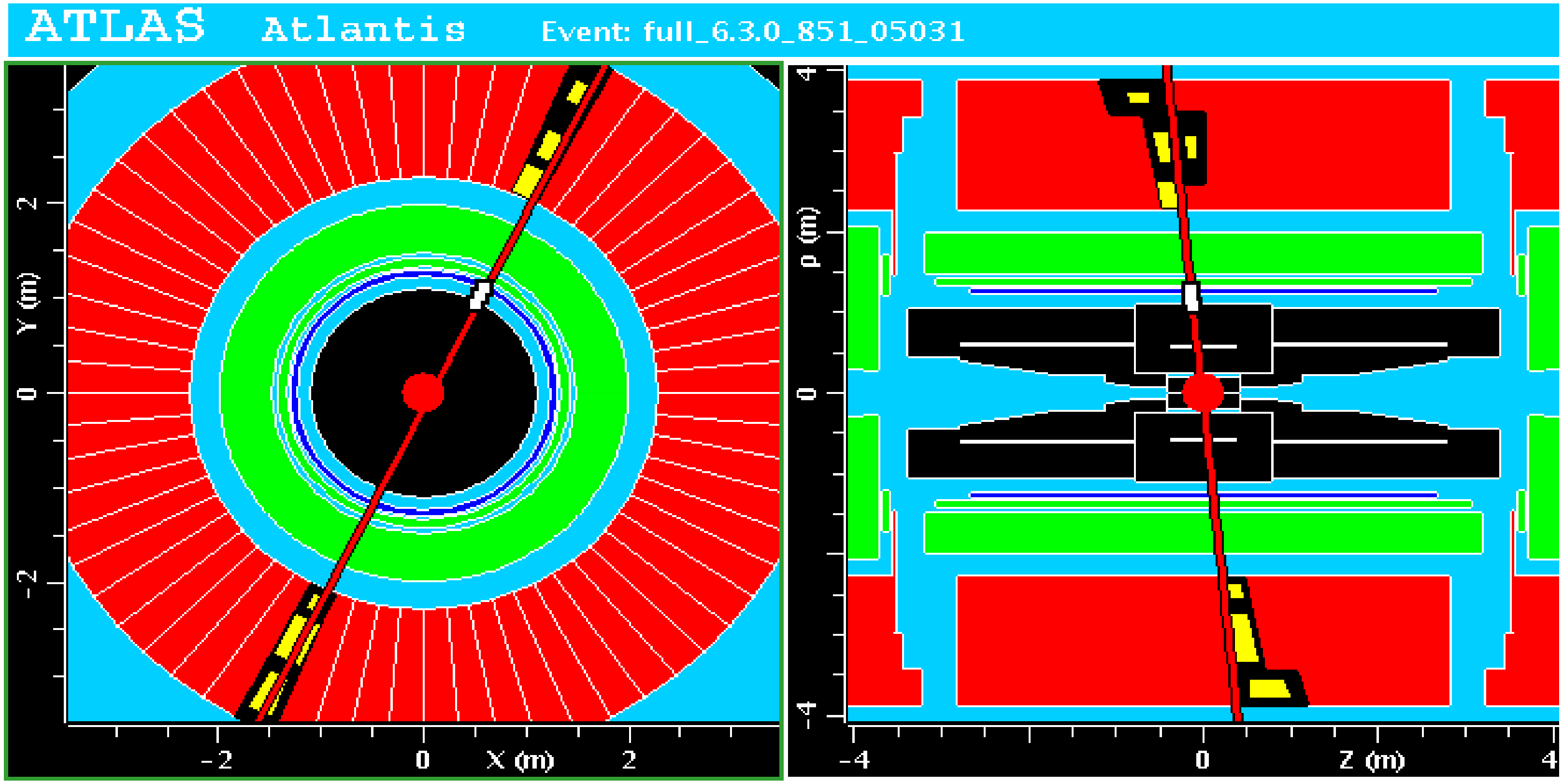
Two tracks reconstructed in Inner Detector

Will happen every $\sim$10 s



Cosmic data taking in the cavern with HCAL

Real, not simulation. Based on ad-hoc energy trigger in ECAL



Also cosmics already read out in installed sector of muon spectrometer

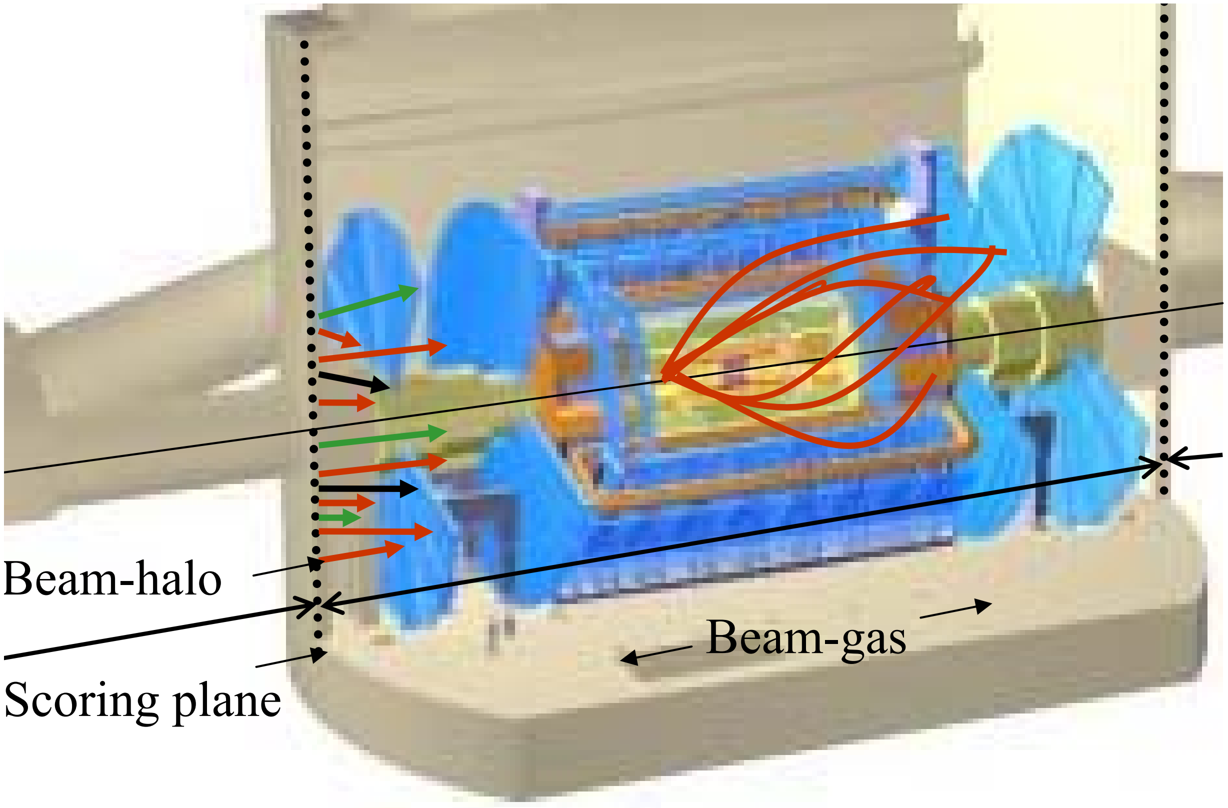
Single beam period

Beam halo:

- Low p_T muons particles from the machine
- Simulation of machine background by machine experts (V. Talanov), transported into full simulation of detectors
- Use for alignment and calibration in endcaps

Beam-gas

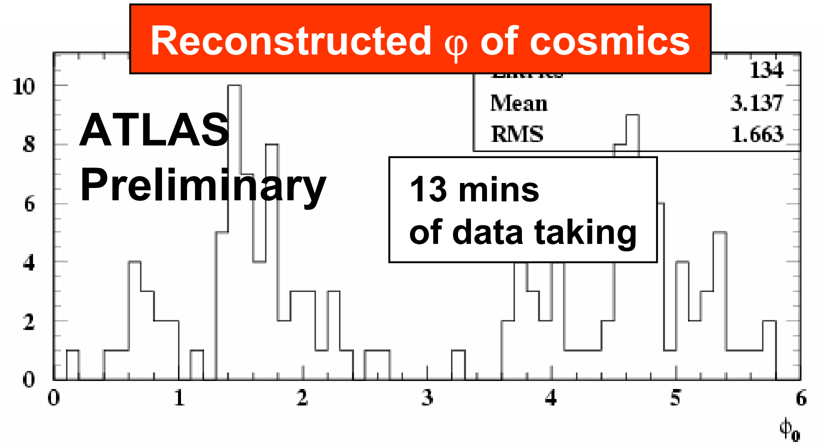
- Vacuum not perfect 3×10^{-8} Torr
- Proton-nucleon p(7 TeV)+p(rest)
- Resemble collision events but with soft spectrum



Use of pre-collision data for ATLAS inner detector

Cosmics : O (1Hz) tracks in Pixels+SCT+TRT

- **useful statistics for debugging readout, maps of dead modules, etc.**
- **check relative position Pixels/SCT/TRT and of ID wrt ECAL and Muon Spectrometer**
- **first alignment studies: may achieve statistical precision of ~ 10 μm in parts of Pixels/SCT**
- **first calibration of R-t relation in straws**


Reconstructed φ of cosmics

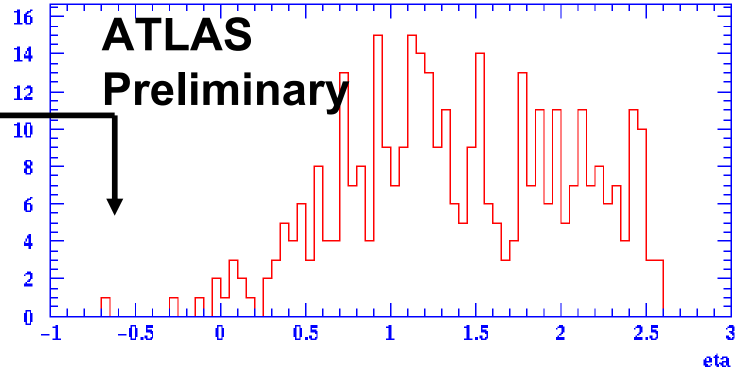
standard ATLAS pattern recognition
(no optimisation for cosmics ...)

Beam-gas :

- **~ 25 Hz of reconstructed tracks with $p_T > 1$ GeV and $|z|<20$ cm**

→ $>10^7$ tracks (similar to LHC events) in 2 months

- **enough statistics for alignment in "relaxed" environment → exceed initial survey precision of 10-100 μm**



η of beam-gas tracks

Steps in detector calibration/alignment

- Strict quality control on construction tolerances
- Redundant hardware calibration and alignment systems
- Extensive test beam characterization of prototypes and final modules

  → Also used for validation of G4 simulations
- "In situ" detector calibration:
  - Cosmics runs (end 2006-2007)
  - Single beam and beam gas runs during LHC commissioning
  - Calibration with physics processes (e.g $Z \to \ell\ell$, $\bar{t}t$)

Procedure valid for all sub-detectors, ECAL, HCAL, inner trackers, Muon Chambers

As an example, concentrate on ECAL and inner silicon trackers

Example of calibration steps: ATLAS EM calorimeter

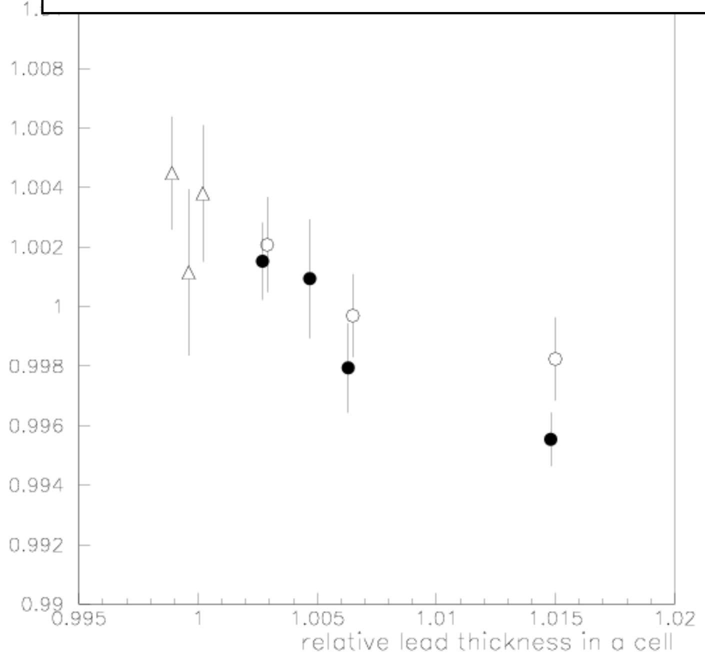
Pb-liquid argon sampling calorimeter with Accordion shape

Main requirement: response uniformity $\leq 0.7\%$ over $|\eta| < 2.5$ driven by $h \rightarrow \gamma\gamma$ search

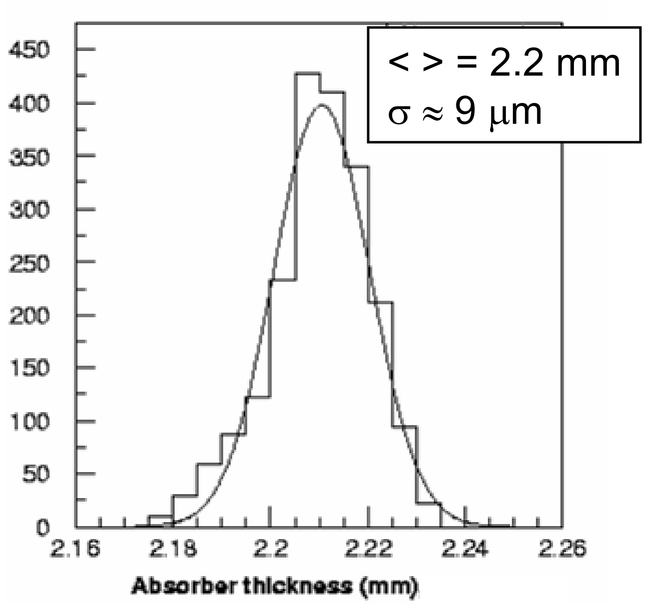
Step 1: Tight control of mechanical tolerances

1% more lead in cell leads to response drop of 0.7% $\Rightarrow$ control plate thickness to 0.5% ($\sim 1\mu$m)

287 GeV electron response variation with Pb thickness from ‘93 test-beam data



Thickness measurement of 1536 absorber plates



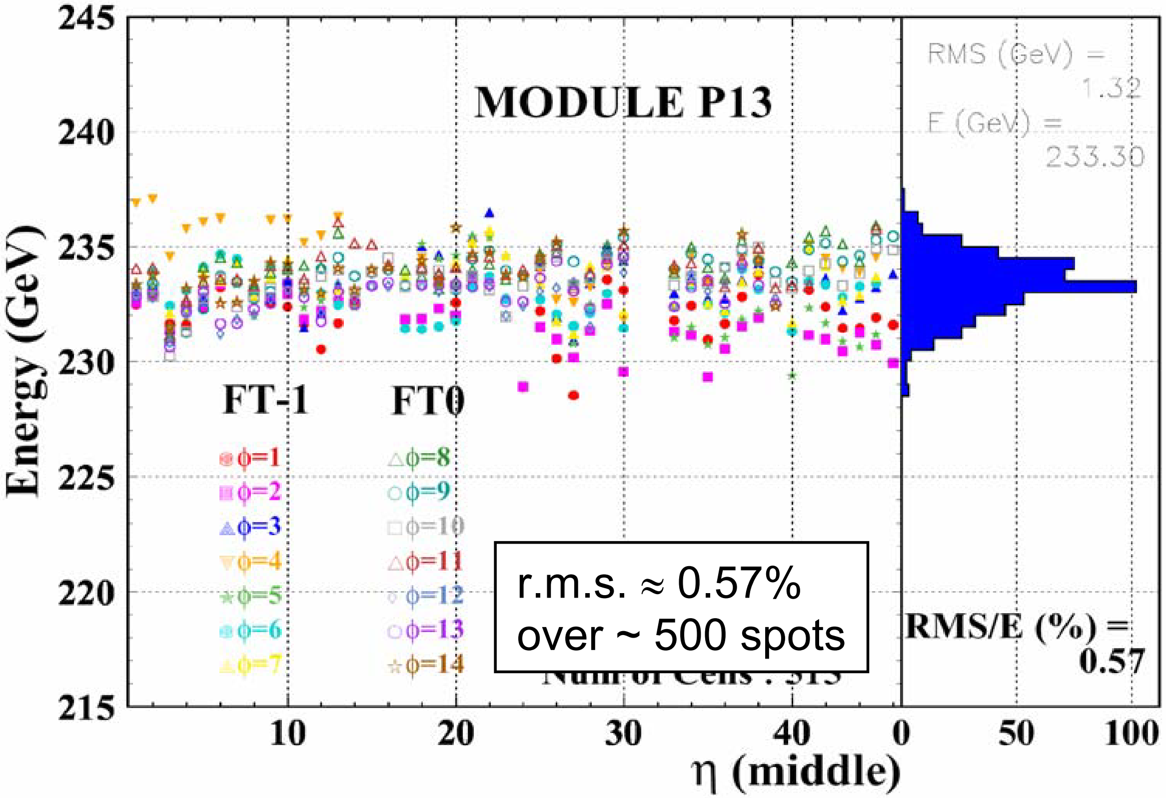
Step 2: Test beam uniformity studies

Beam test of 4 (out of 32) barrel modules and 3 (out of 16) EC modules

Uniformity over "units" of size $\Delta\eta \times \Delta\phi = 0.2 \times 0.4 :\sim 0.5\%$

400 such units over the full ECAL

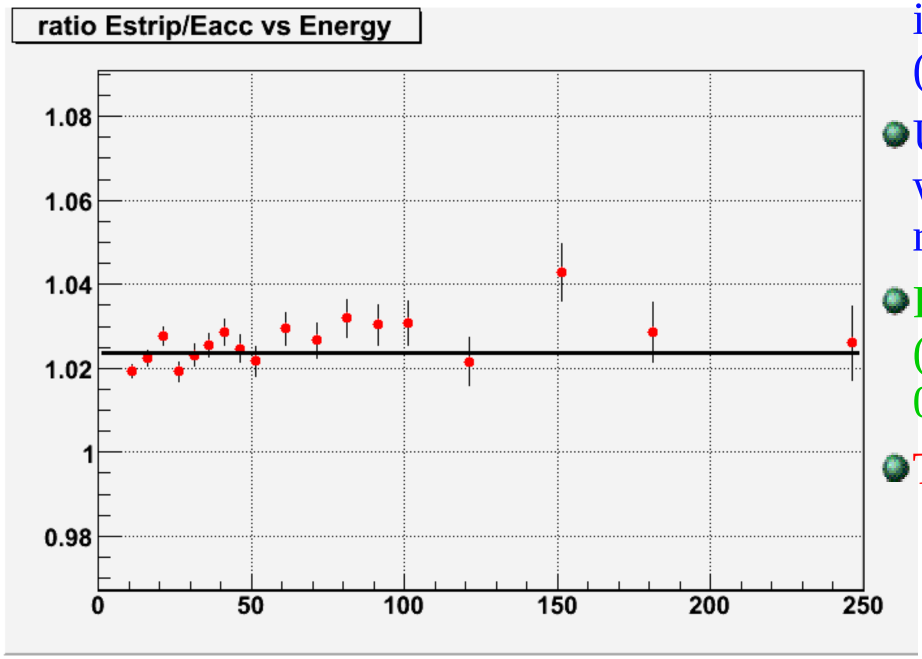
Scan of a barrel module with 245 GeV e^-



r.m.s. ≈ 0.57%
over ~ 500 spots

From detector to physics: CTB (6)

I. Wingerter

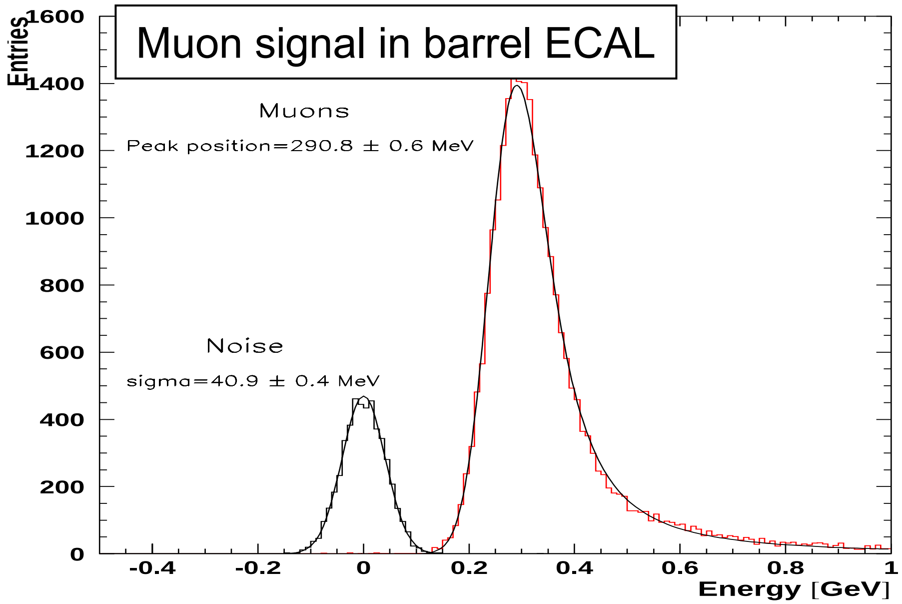


- Absolute lead thickness was nominal; it is now as measured during construction (+1%)
- Until now, lead thickness was taken at warm: at cold, lead gets denser and X^0 reduces
- Ratio Strips/Middle increases by 2% (1.4% from increased lead thickness + 0.6% from effect at cold)
- Two effects going the *right* way.

Lead thickness + contraction at cold

M. Aleksa, G. Unal

Step 3: Calibration check with cosmic muons



- Through-going muons ~ 25 Hz

  (hits in ID $+$ top and bottom muon chambers)

- Pass by origin ~ 0.15 Hz

  ($|z| < 60$ cm, $R < 20$ cm, hits in ID)

- Useful for ECAL calibration ~ 0.5 Hz

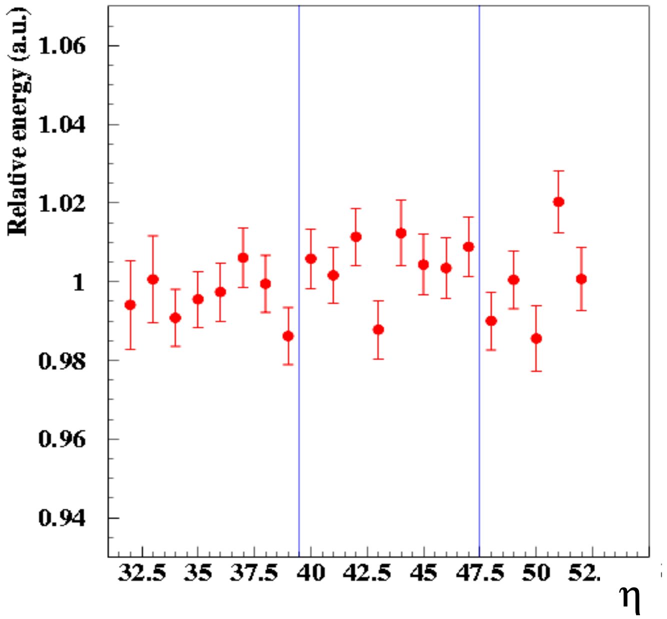
  ($|z| < 30$ cm, $E_{cell} > 100$ MeV, $\sim 90°$)

$\sim 10^6$ events in $\sim$3 months data taking

From test-beam results:

With this μ statics can check calorimeter response

variations versus η to 0.5%



Step 4: Equalization with $Z \rightarrow e^+e^-$

Constant term $c_{tot} = c_L + c_{LR}$ composed of two terms:

- c_L: local term. $c_L \simeq 0.5\%$ demonstrated at the test-beam over units of $\Delta\eta \times \Delta\phi = 0.2 \times 0.4$
- c_{LR} long-range response non-uniformities from unit to unit (400 in total): from module-to-module variations, different upstream material, etc.

Use $Z \rightarrow ee$ and Z mass constraint to correct for long-range uniformities

From full simulation: $\sim 250\ e^{\pm}$ per unit to achieve $c_{LR} \leq 0.4\%$

$\Rightarrow \sim 10^5\ Z \rightarrow ee$ events, few days of data-taking at 10^{33}

Worst case scenario: no corrections applied

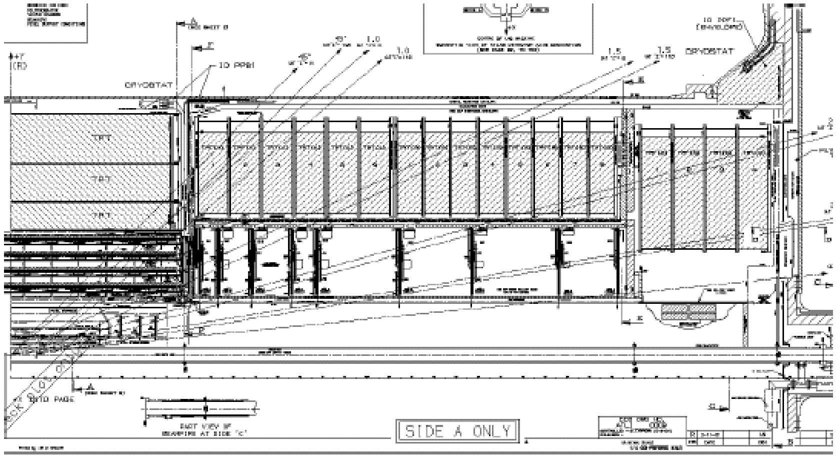
$c_L = 1.3\%$ "on-line" non uniformity of individual modules

$c_{LR} = 1.5\%$ no $Z \rightarrow ee$ corrections, poor knowledge of upstream material

ATLAS Tracker alignment

Module positioning on supports to 17-100 μm

Supports positioned to 20-200μm



ID positioned to ± 3 mm wrt beam axis

Rotation < 1mrad wrt solenoid axis

With initially foreseen misalignment can build tracks with 40-60% precision

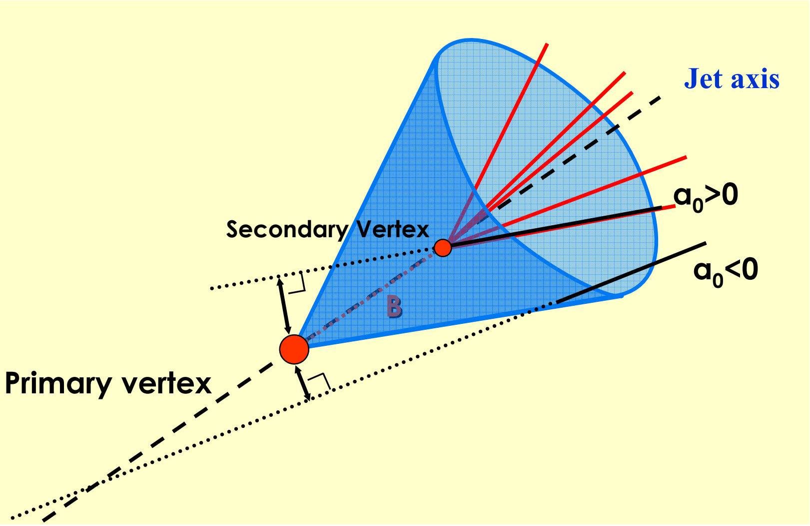
Can use either all tracks or just overlaps

Can collect statistics for alignment of pixels to 1-2 μm and SCT to 2-3 μm in one day, but probably dominated by systematic

Monitoring of detector conditions necessary for systematics

Thermal instability relevant below 100 μm

Physics impact of pixel alignment: b-tagging



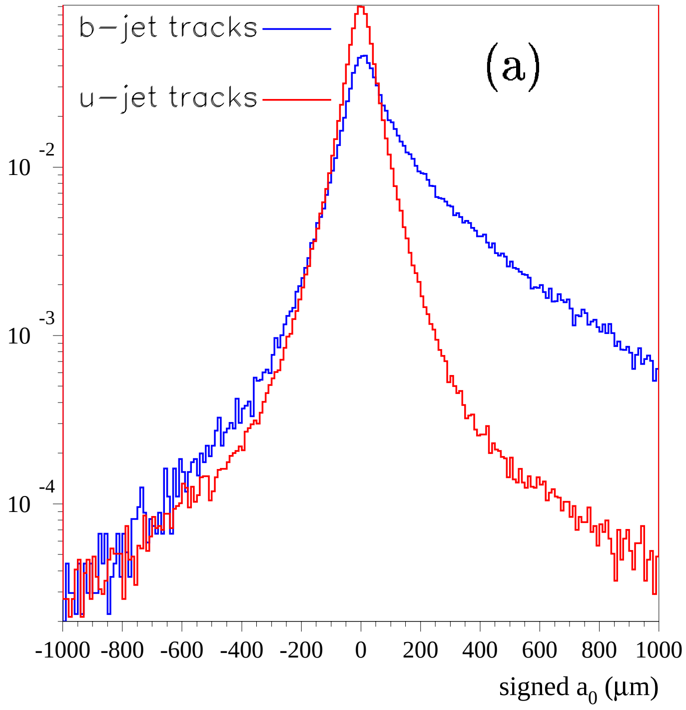
b-hadrons decay a a few mm away from interaction vertex

Measure decay path of b-hadrons through impact parameter: minimum distance from primary vertex

Distribution of impact parameter symmetric for tracks from fragmentation of light quarks

Significant enhancement of positive impact parameters for tracks from b-hadron decays

Rejection on light jets strongly dependent on width of impact parameter distribution



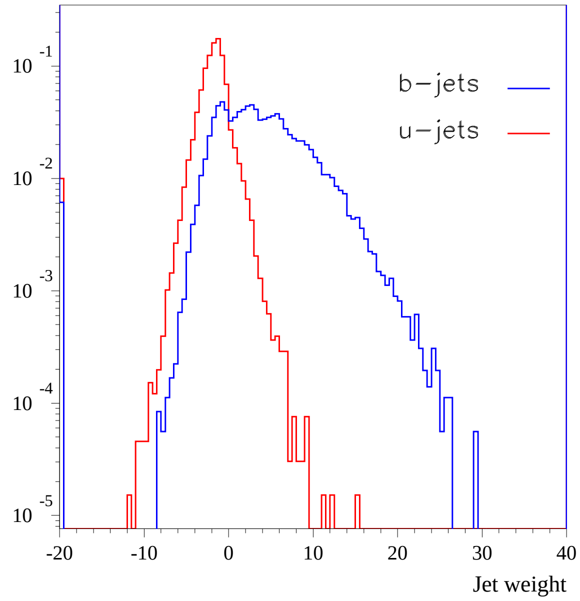
B-tagging: performance with aligned detector

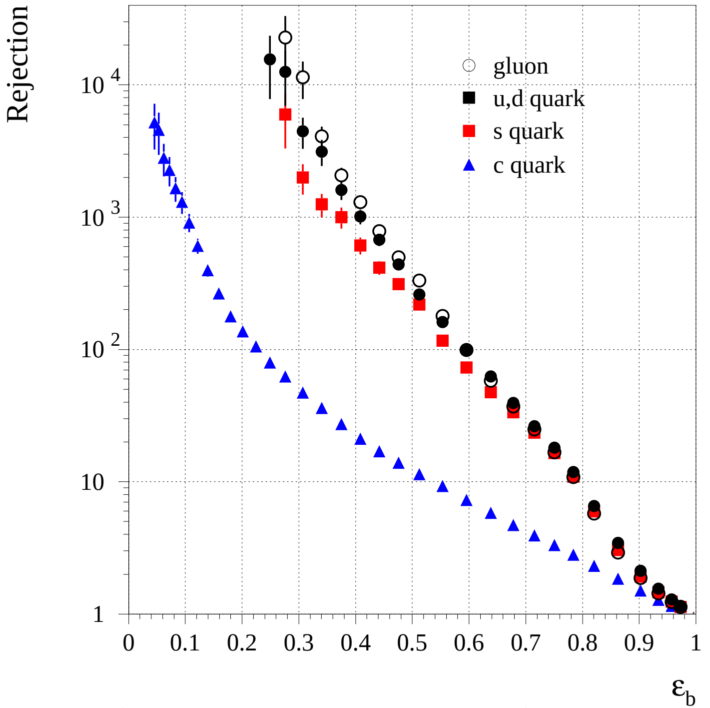
Nominal alignment of pixel barrel: $\sigma_{R\phi} = 5\mu m$, $\sigma_Z = 10\mu m$

Build likelihood function from impact parameters of tracks associated to a jet

ATLAS: Study samples of fully simulated WH, ttH, $\bar{t}t$ events

Measure rejection on QCD jets as a function of tagging efficiency



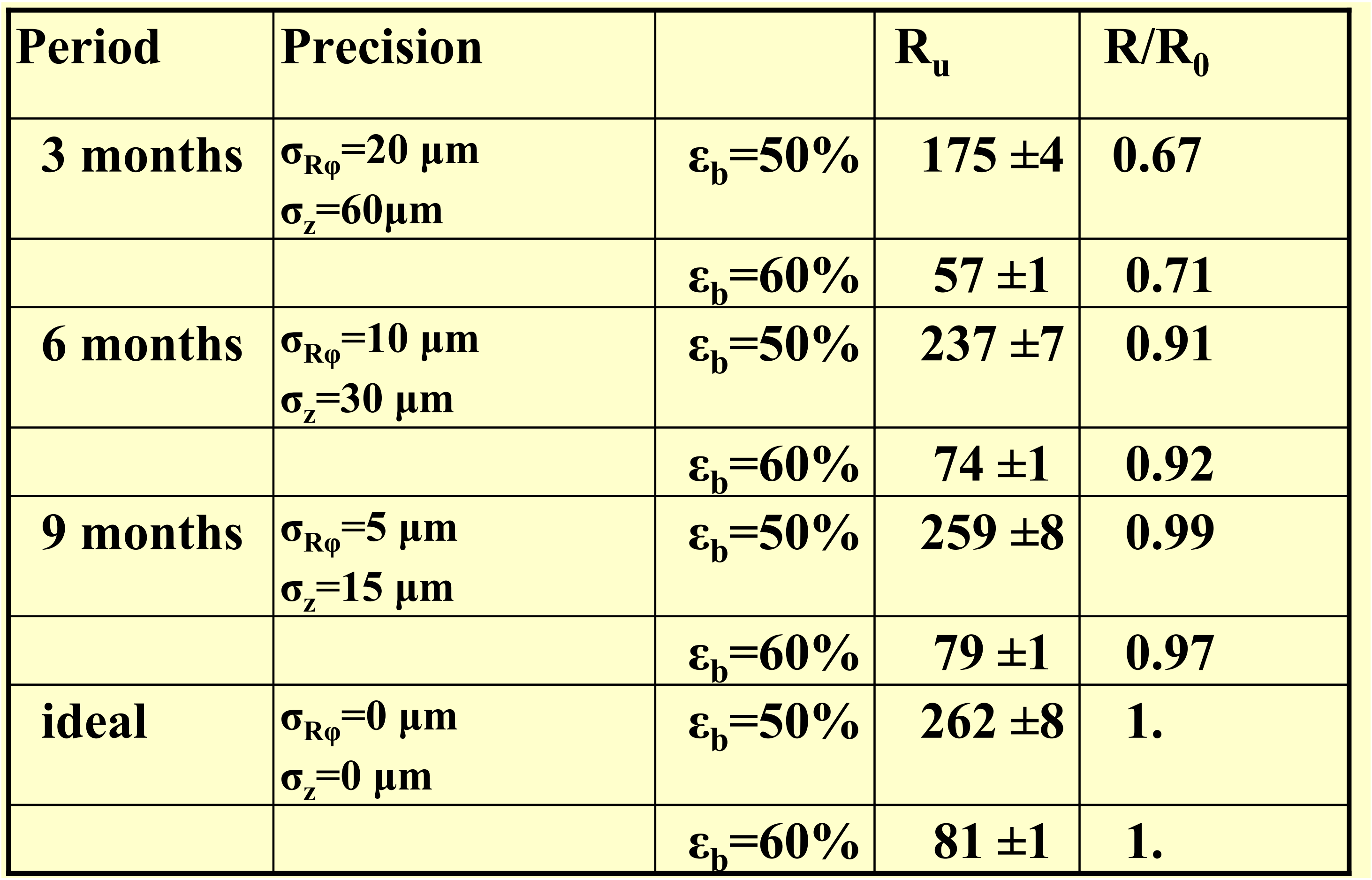


ATLAS TDR: rejection factor of 100 on light jets for $\epsilon_b = 60\%$

Misalignment versus time

Study performance as a function of time on a simulated sample of $\bar{t}th$.

Include in study effect of detector inefficiencies



Period	**Precision**		**R_u**	**R/R_0**
3 months	**$\sigma_{R\varphi}$=20 μm** **σ_z=60μm**	**ε_b=50%**	**175 ±4**	**0.67**
		ε_b=60%	**57 ±1**	**0.71**
6 months	**$\sigma_{R\varphi}$=10 μm** **σ_z=30 μm**	**ε_b=50%**	**237 ±7**	**0.91**
		ε_b=60%	**74 ±1**	**0.92**
9 months	**$\sigma_{R\varphi}$=5 μm** **σ_z=15 μm**	**ε_b=50%**	**259 ±8**	**0.99**
		ε_b=60%	**79 ±1**	**0.97**
ideal	**$\sigma_{R\varphi}$=0 μm** **σ_z=0 μm**	**ε_b=50%**	**262 ±8**	**1.**
		ε_b=60%	**81 ±1**	**1.**