– The ATLAS Detector –

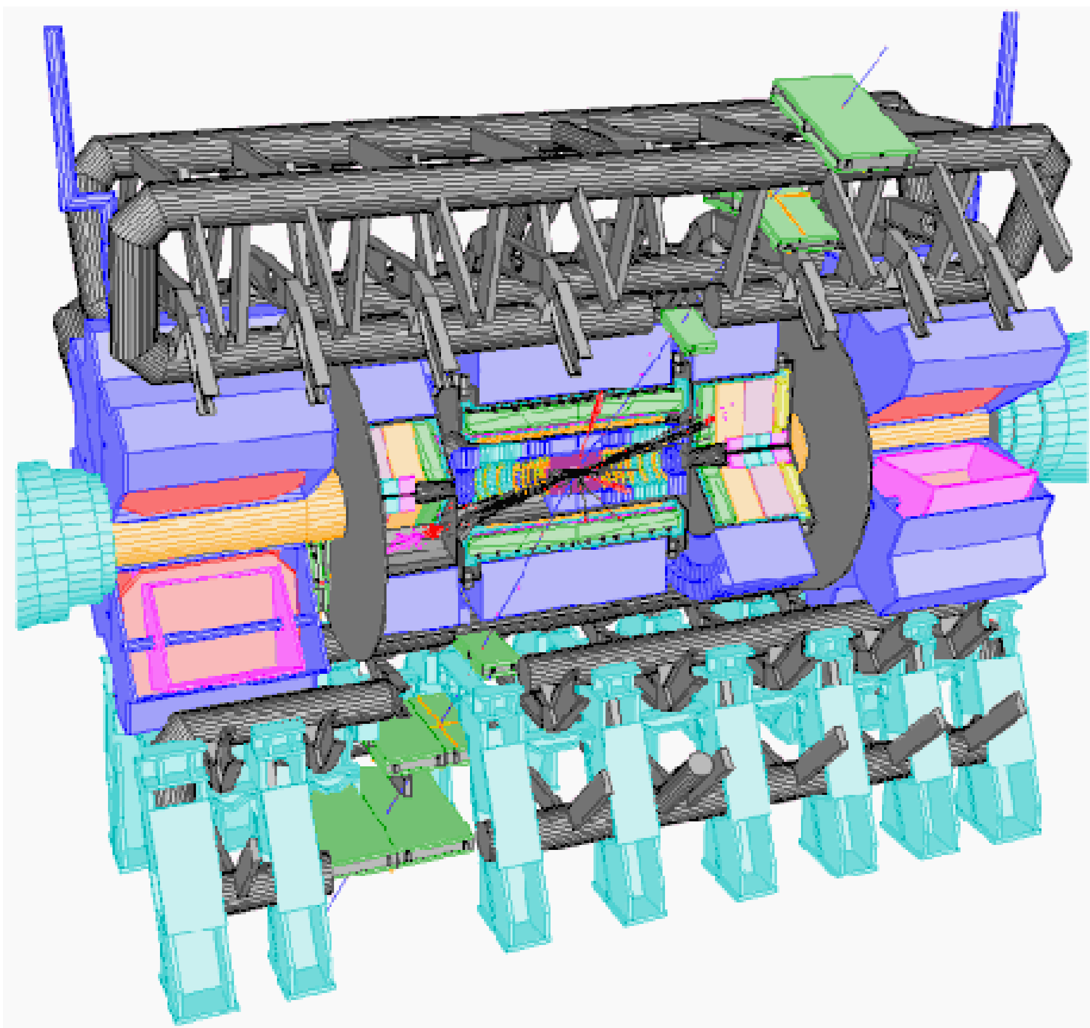
an introduction to theorists and students

Kiyotomo Kawagoe †

Kobe University

Collider Workshop@ICEPP, Tokyo

July 19th, 2001



†email address : kawagoe@phys.sci.kobe-u.ac.jp

Outline of this talk

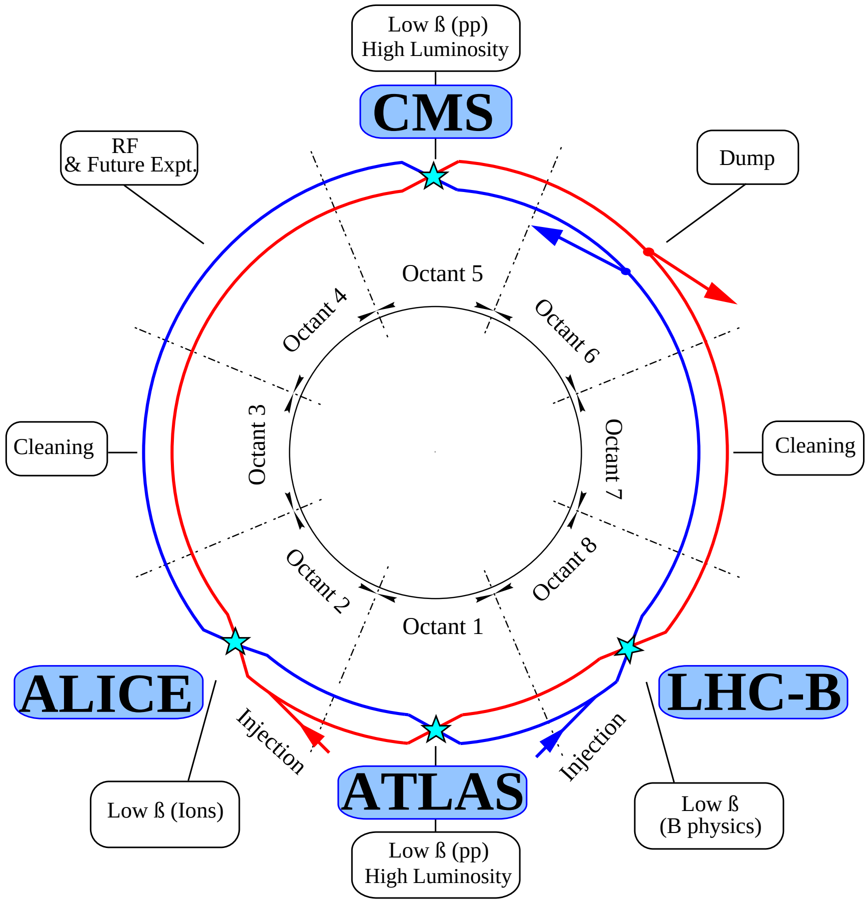
1. Introduction
2. Inner Detector
3. Calorimeter
4. Muon Spectrometer
5. Trigger
6. *b*-tagging
7. ATLFAST
8. Conclusion

References

- http://atlasinfo.cern.ch/Atlas
- ATLAS Technical Proposal CERN/LHC/94-43
- ATLAS Detector and Physics Performance TDR
- ATLAS Inner Detector TDR
- ATLAS Liquid Argon TDR
- ATLAS Tile Calorimeter TDR
- ATLAS Muon Spectrometer TDR
- ...

1 Introduction

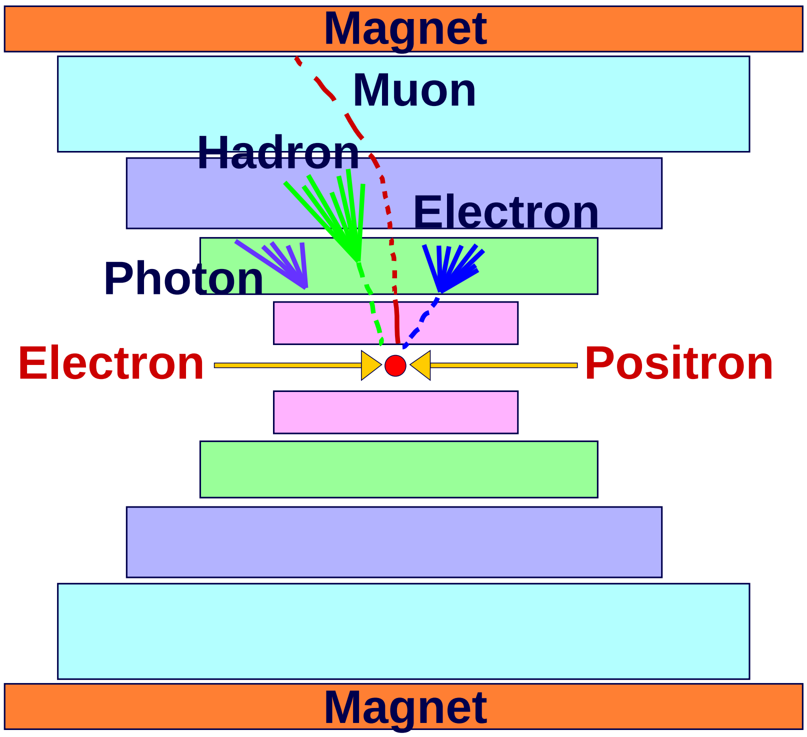
Experiments at LHC



- First Collision expected in 2006 4/1∼30
- $E_{beam} = 7$ TeV, $\sqrt{s} = 14$ TeV
- Low L $= 10^{33}$ cm^{-2}s^{-1} (10 fb^{-1}/yr, 3 yrs)
- High L $= 10^{34}$ cm^{-2}s^{-1} (100 fb^{-1}/yr, ?? yrs)

A Collider Detector

This is an example, taken from L3 at LEP.



Inner Detector

Trajectories of Charged Particles

Momentum of Charged Particles (with B)

Calorimeter

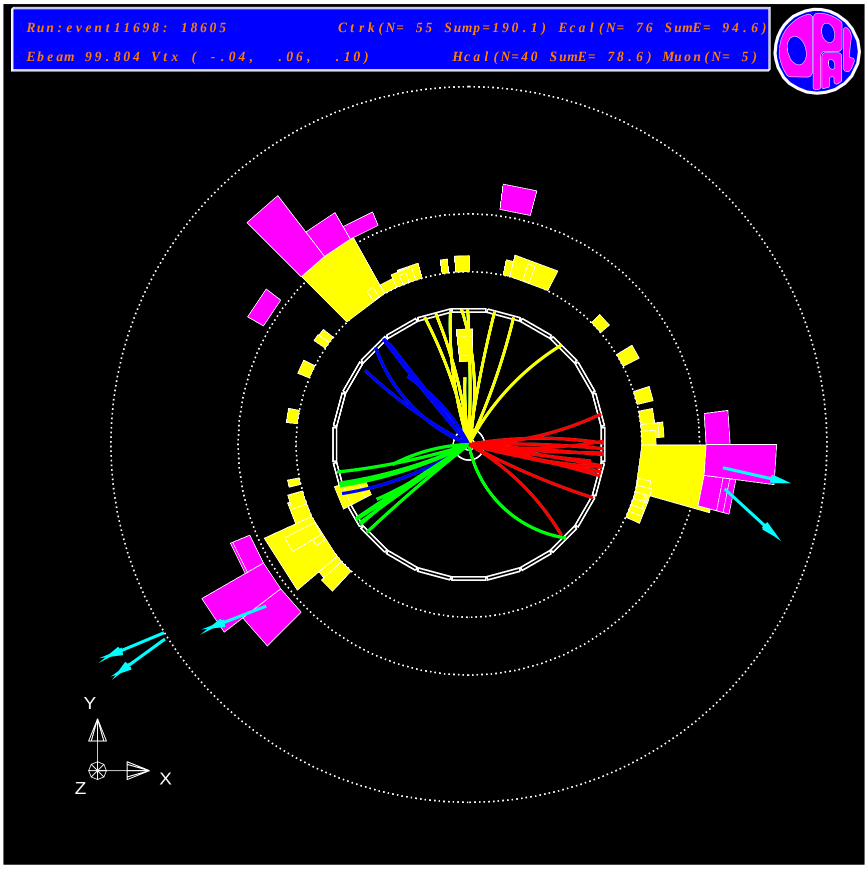
Detection of Photons, Neutral Hadrons

Electromagnetic/Hadronic Energies

Muon Detector

Trajectories of Penetrating Muons

Momentum Measurement

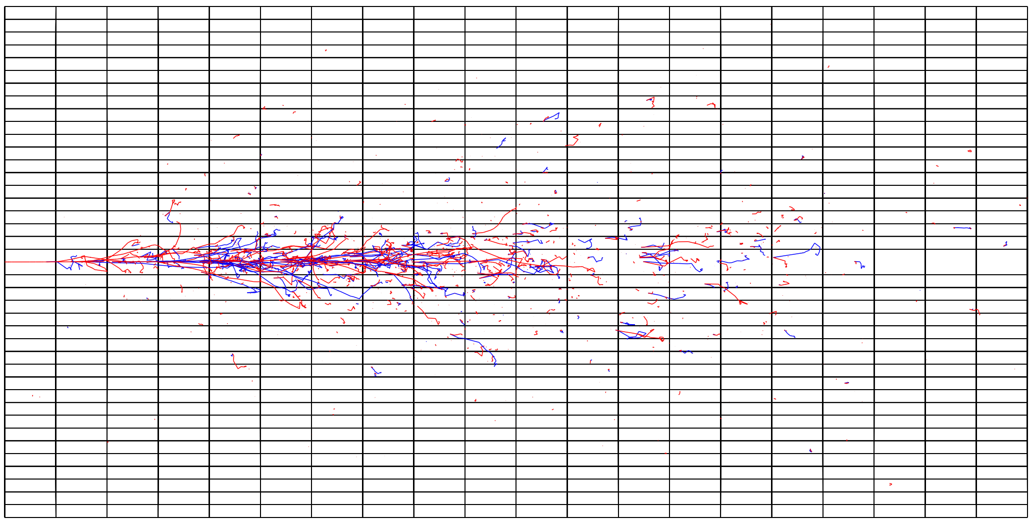


$$p_T = eB_zR = 0.3B_zR$$

(p_T in GeV/c, B_z in Tesla, R in m)

$$\frac{\sigma_{p_T}}{p_T} \propto p_T$$

Energy Measurement



Energy deposit of
electromagnetic/hadronic showers

$$\frac{\sigma_E}{E} = \frac{\sigma_{stochastic}}{\sqrt{E}} \oplus \sigma_{constant}$$

$$\sigma_{stochastic} = \sigma_{intrinsic} \oplus \sigma_{sampling} \oplus \sigma_{photostat}$$

$\sigma_E/E < \sigma_{p_T}/p_T$ for high energy electrons.

Requirements for LHC Detectors

General Requirements

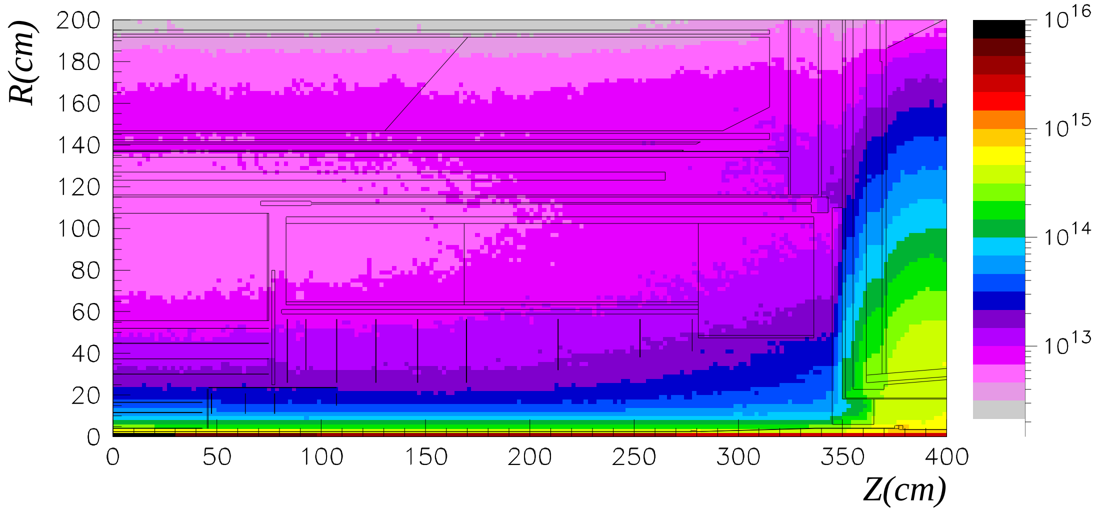
- Good Energy/Momentum Resolutions up to a few TeV
- Granularity (for High Multiplicity, Narrow Jets) ⇒ Huge Numbers of Readout Channels
- Hermeticity (for Missing E_T) ⇒ No Detector Holes except Beam Pipe
- Particle ID (lepton (e, μ, τ)-tag, b-tag)

Special Requirements at LHC

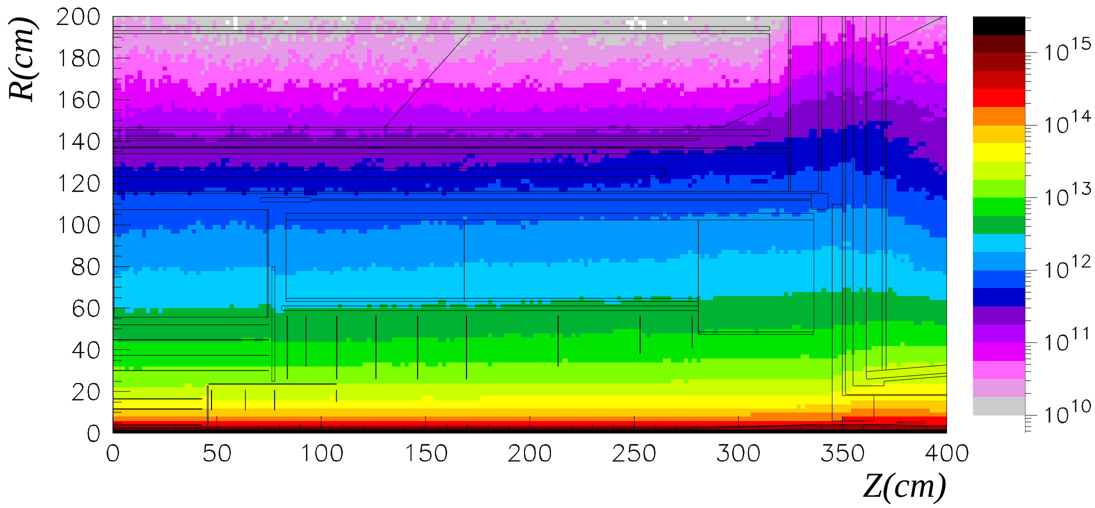
- Huge Event Rate ⇒ Fast Trigger/Readout System
- Extremely High Radiation Level ⇒ Radiation Tolerant Detector

Radiation Environment

1 MeV equivalent neutrons per cm^2 per year

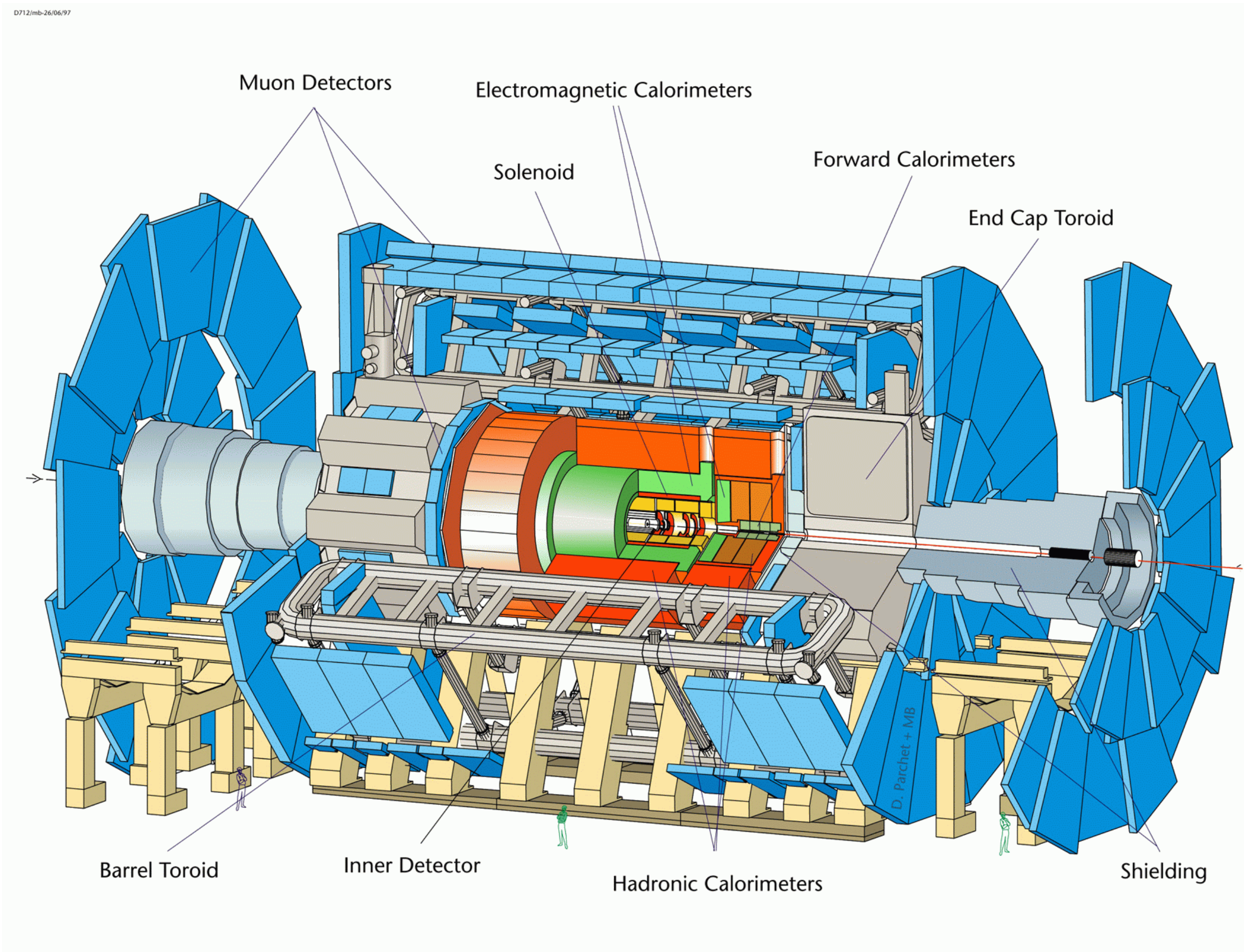


charged hadrons per cm^2 per year



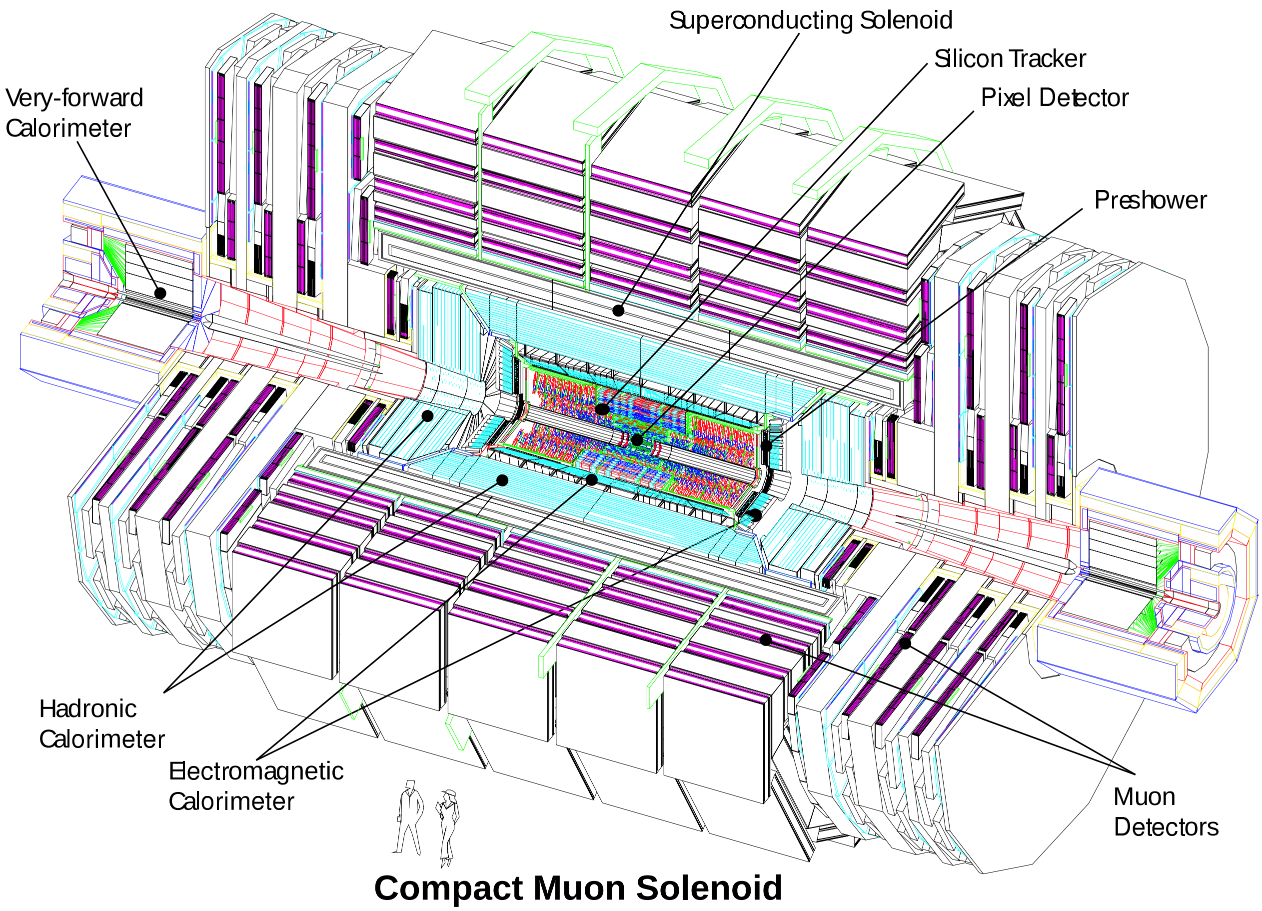
The expectations are still increasing ...

A Toroidal LHC ApparatuS (ATLAS)



- Inner Detector in Solenoid Magnet (2 T)
- ID : Pixel + Silicon + TRT
- Liq-Ar Calorimeter + Barrel TileCal
- Muon Spectrometer with Toroidal Magnet

Compact Muon Solenoid (CMS)



- ID and CAL in Solenoid Magnet (4 T)
- ID : Pixel + Silicon + MSGC
- EMCAL : Crystal ($PbWO_4$)
- HCAL : Cu + Scintillation Tile
- Muon Chambers in the Return Yoke (2 T)

	ATLAS	**CMS**
Inner Detector		
SC solenoid	B=2 T (2.4 m$\phi \times$ 5.3 m)	B=4 T (6 m$\phi \times$ 13 m)
Tracker	Si-pixel Si-strip TRT	Si-pixel Si-strip
Calorimetry		
location	outside solenoid	inside solenoid
ECAL	Pb LAr	$PbWO_4$ Crystal
HCAL barrel	Tile (Fe scinti)	Tile (Cu scinti)
endcap	Cu LAr	Tile (Cu scinti)
forward	Cu LAr	Quarts Fiber
Muon Spectrometer		
B-field	Toroidal magnet	Return yoke
Precision barrel	MDT	DTBX
endcap	MDT, CSC	CSC
Trigger barrel	RPC	RPC
endcap	TGC	RPC
Overall		
size	22 m $\times$ 46 m	15 m $\times$ 22 m
weight	7,000 t	12,500 t
cost	$\sim$475 MSFr	$\sim$475 MSF

Contribution of ATLAS Japan

In ATLAS Group

- $\sim$2000 collaborators from 34 countries
- Total detector cost : 475 MSFr

ATLAS Japan

- $\sim$50 physicists from 17 institutes
  and many students
- the Japanese share : 32.1 MSFr.

is responsible for

- Endcap Muon Trigger (with Israel & China)
- TDC for MDT (100 %)
- SCT (with other countries)
- DAQ (with other countries)
- Computing (with other countries)
- SC Solenoid (100 %)

(Pseudo-)Rapidity

While we use $\cos\theta$ at e^+e^- colliders, we use pseudo-rapidity at hadron colliders.

Rapidity y is defined by

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) = \tanh^{-1}\left(\frac{p_z}{E}\right)$$

When boosted in the z-direction with β:

$y \to y - \tanh^{-1}\beta$

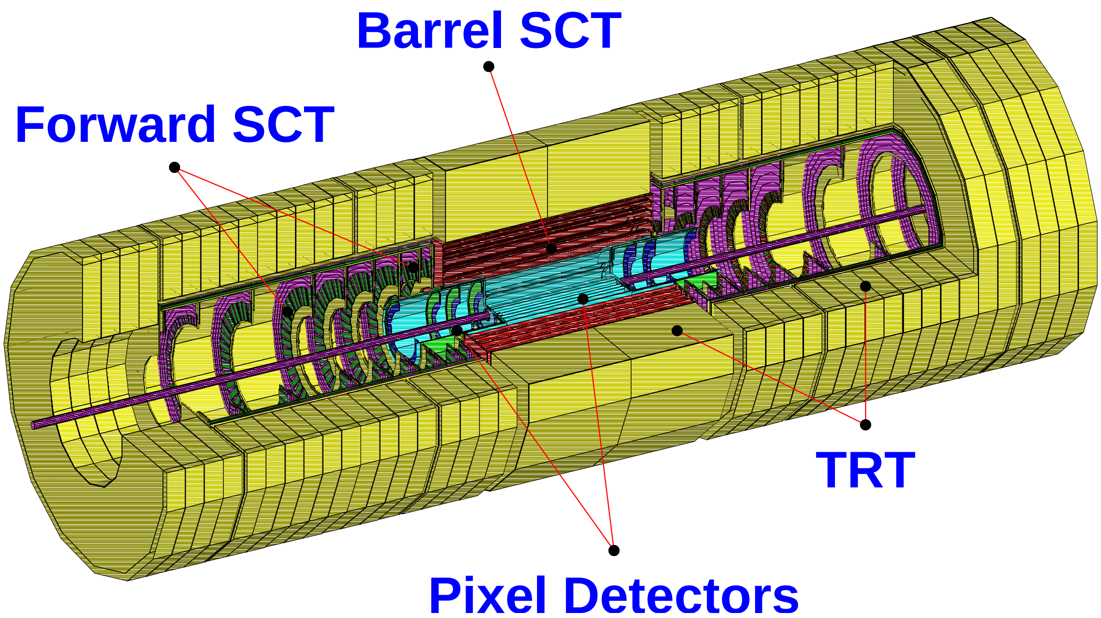
dN/dy does not change the shape.

Pseudo-rapidity η : in the high energy limit,

$$y \to \eta = \frac{1}{2}\ln\left(\frac{|\vec{p}|+p_z}{|\vec{p}|-p_z}\right) = -\ln\tan\frac{\theta}{2}$$

$$\begin{aligned} p_x &= p_T\cos\phi \\ p_y &= p_T\sin\phi \\ p_z &= p_T\sinh\eta \\ E \approx |\vec{p}| &= p_T\cosh\eta \end{aligned}$$

2 Inner Detector



- A cylinder of length 7 m and a radius of 1.15 m
- Angular coverage of $|\eta| < 2.5$
- Momentum resolution

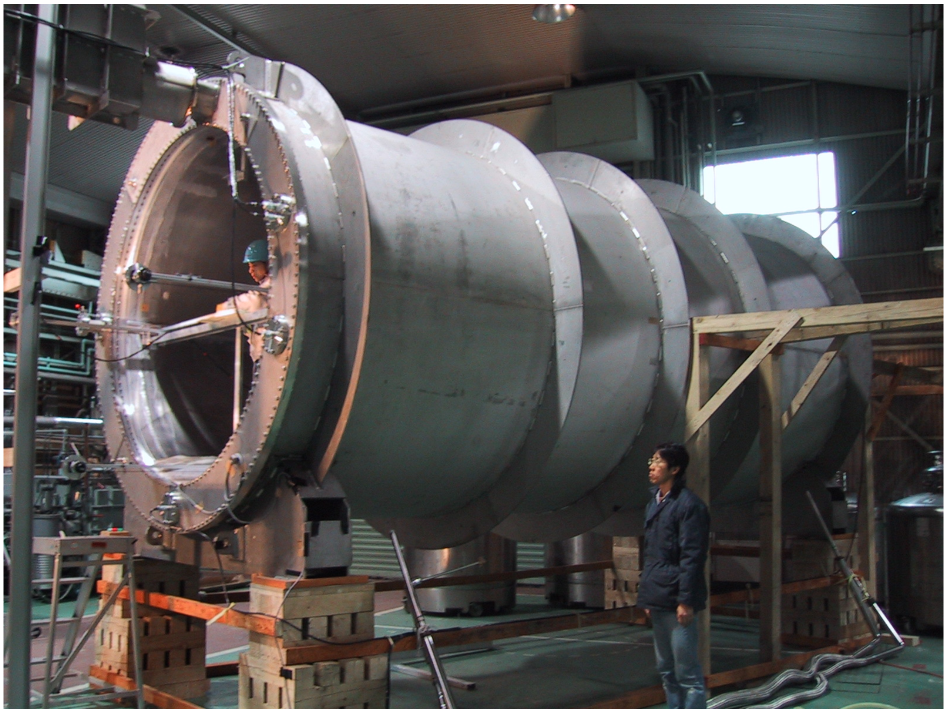
$$\sigma(\frac{1}{p_T}) \approx 3.6 \times 10^{-4} \oplus \frac{1.3 \times 10^{-2}}{p_T\sqrt{\sin\theta}} \text{ GeV}^{-1}$$

- Vertex resolution (impact parameter)

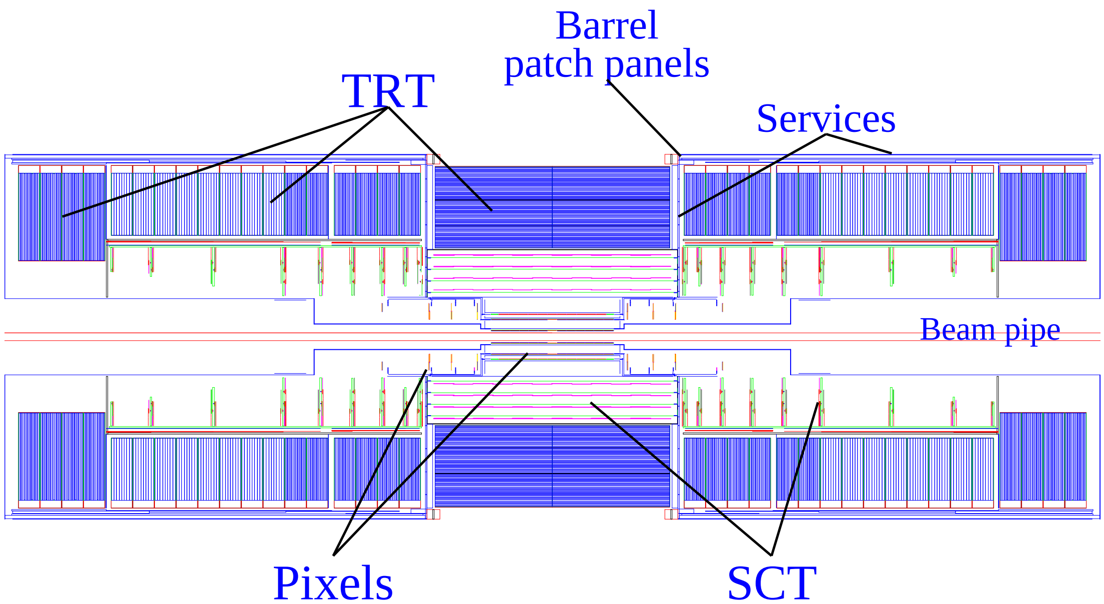
$$\sigma(d_0) \approx 11 \oplus \frac{73}{p_T\sqrt{\sin\theta}} \ \mu\text{m}$$

Excitation Test of Solenoid

Successful test in Dec.2000–Jan.2001

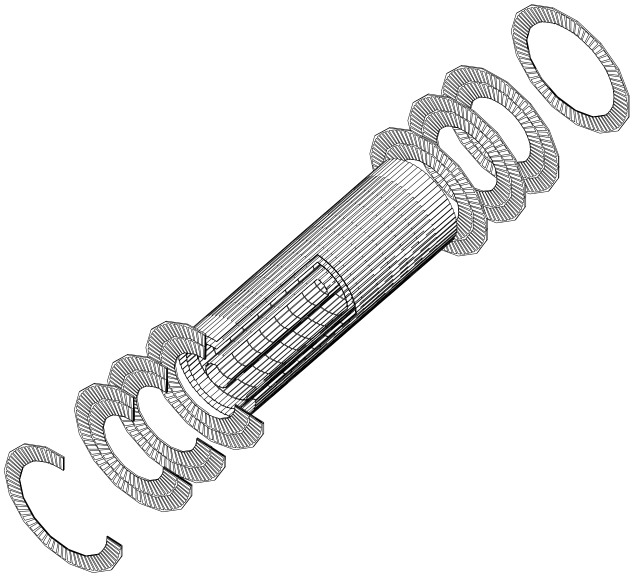


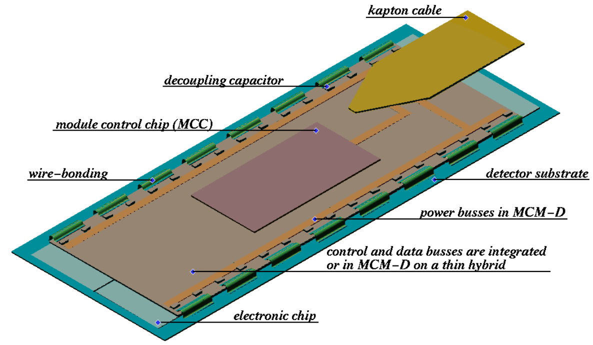
ID Components



- **Pixel Detector**
- **SemiConductor Tracker**
- **Transition Radiation Tracker**

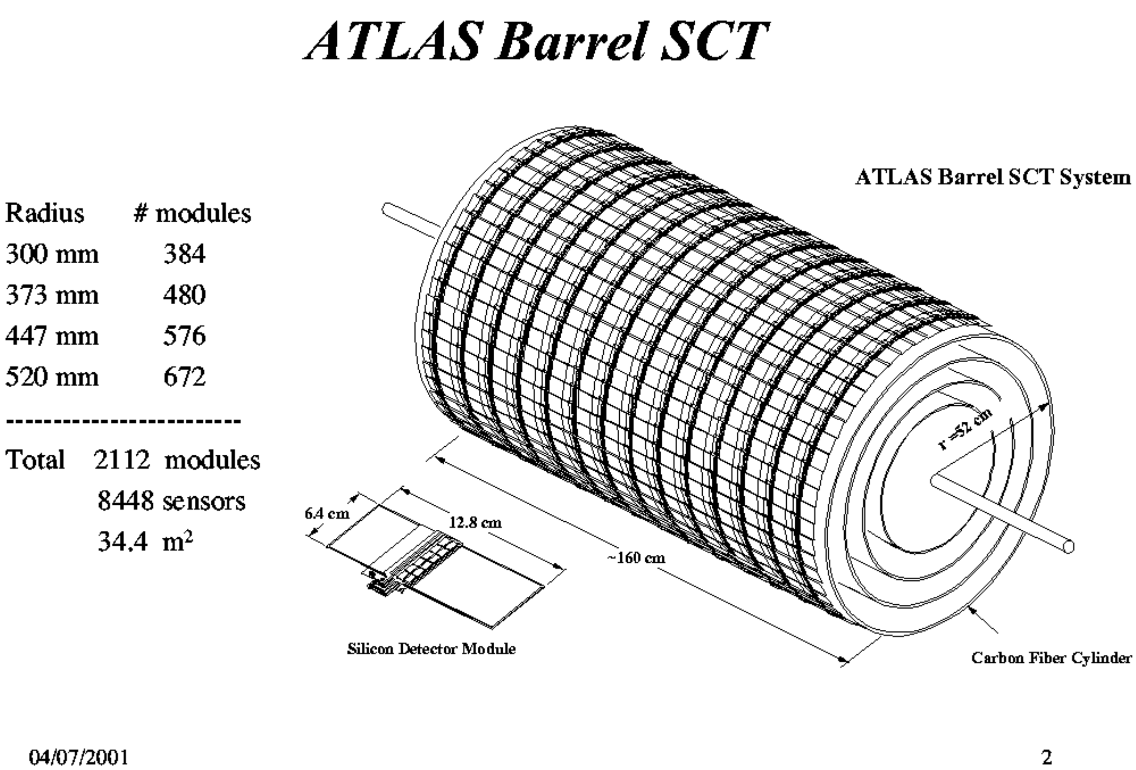
Pixel Detector





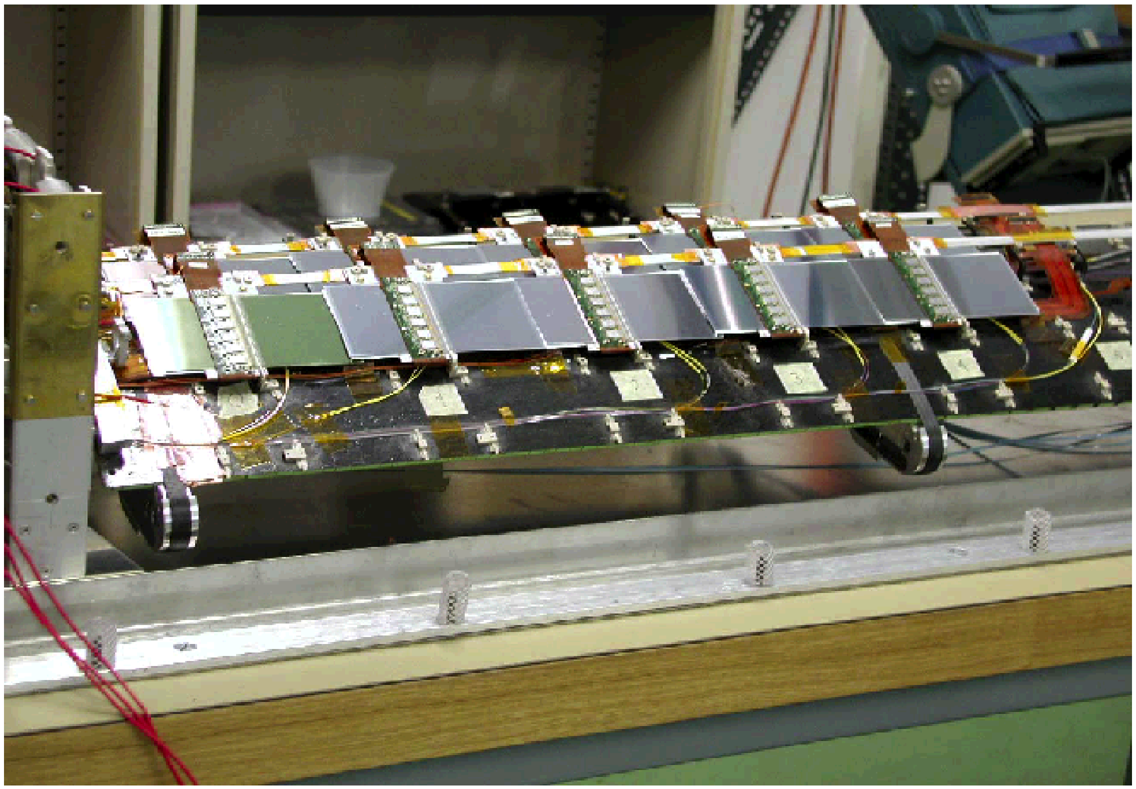
- A pixel module
  - 21.4 mm wide, 62.4 mm long
  - pixel size : 50 μm and 300 μm (61,440 pixels)
- barrel detector
  - 1 B-layer + 2 layers (R=$\sim$4, 10, 13 cm)
  - $\sigma_{R\phi} = 12\mu$m, $\sigma_z = 66\mu$m
- endcap detectors
  - 5 discs ($R = 11 \sim 20$ cm)
  - $\sigma_{R\phi} = 12\mu$m, $\sigma_R = 77\mu$m
- 1.4×10^8 channels in total !!

SemiConductor Tracker (SCT)



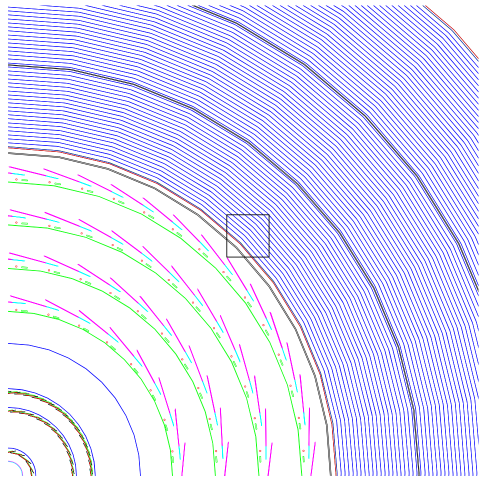
- 4 double layers of silicon strips
- A silicon detector
  - 6.36×6.40 cm^2
  - 768 readout strips of 80 μm pitch
- Two detectors were wire-bonded to form 12.8 cm long strips

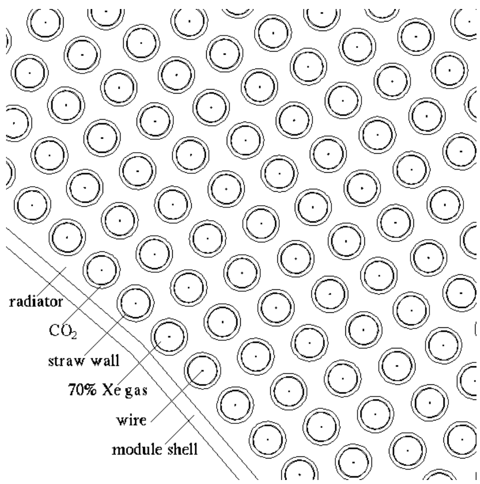
System test at CERN

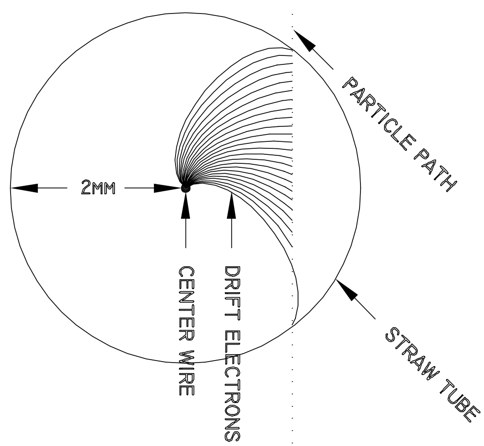


Run as many modules as possible in the close-to-final physical configuration with opto-harnesses, power cables, grounding etc.

Transition Radiation Tracker (TRT)



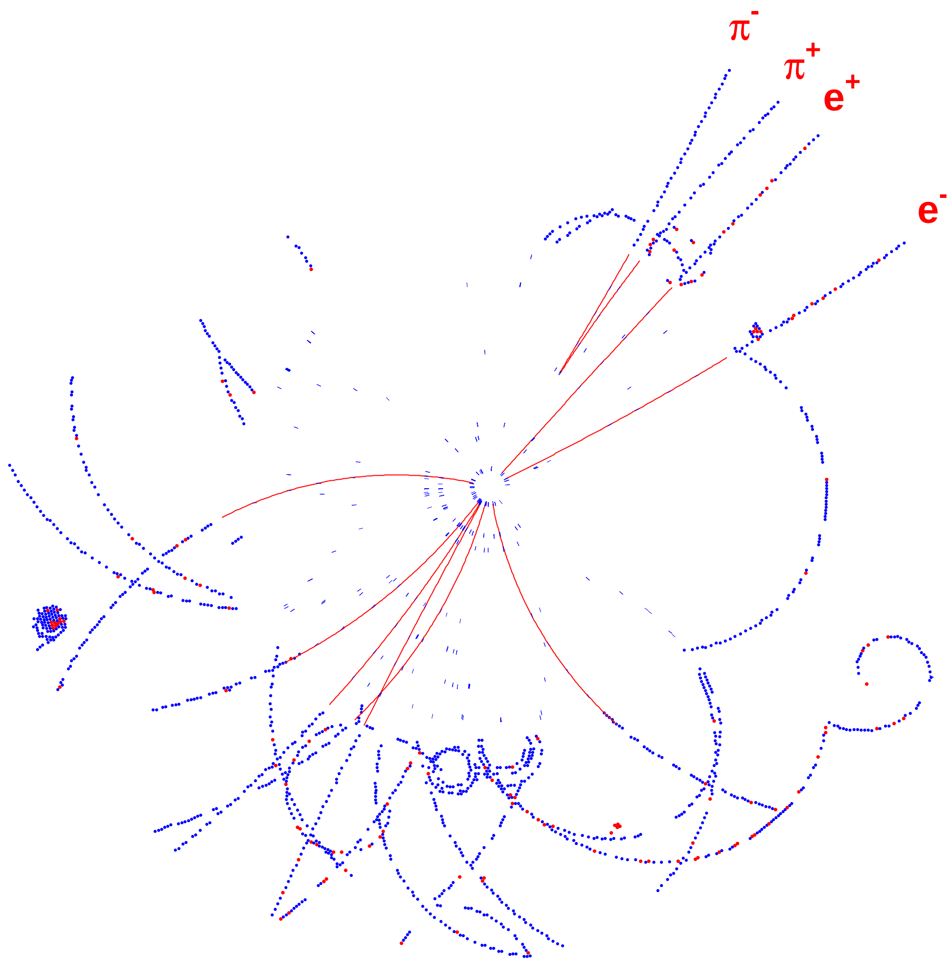




- $\sim$ 36 layers of 4 mm diameter straw tubes
- 50,000 in the barrel, 42,000 in each endcap
- position resolution$\sim$ 200μm
- low/high thresholds for hits and TR photons
- radiator : polypropylene foils (15-20 μm thick, 200-300 μm spacing)

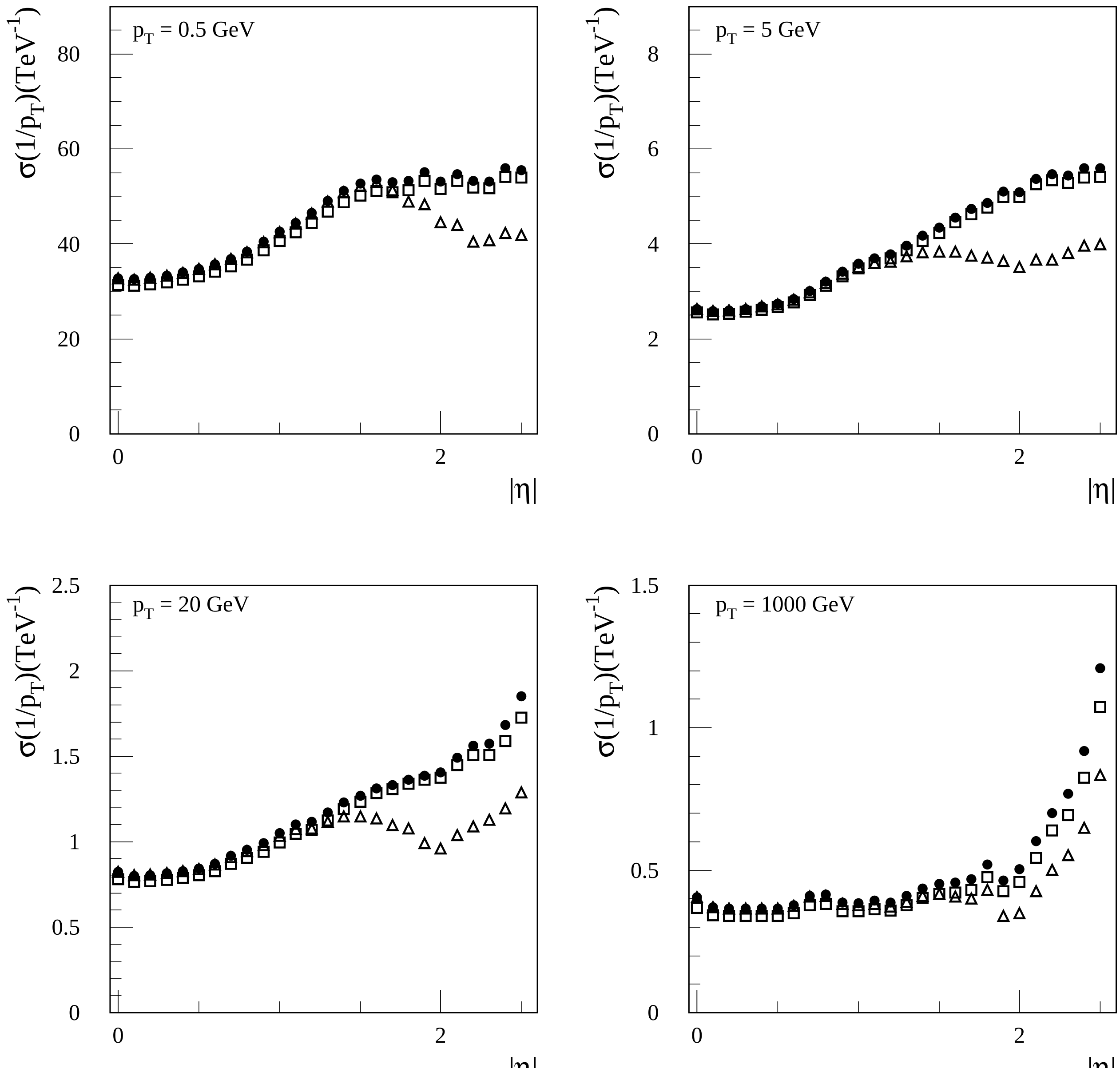
ATLAS Inner Detector

$B_d^o \rightarrow J/\psi\ K_s^o$



- Precision hits for $0 < \eta < 0.7$
- TRT hits for $Z > 0$ in the barrel
- Red points for high threshold TRT hits
- Fitted tracks with $p_T > 0.5$ GeV and $0 < \eta < 0.7$

Momentum resolution for muons

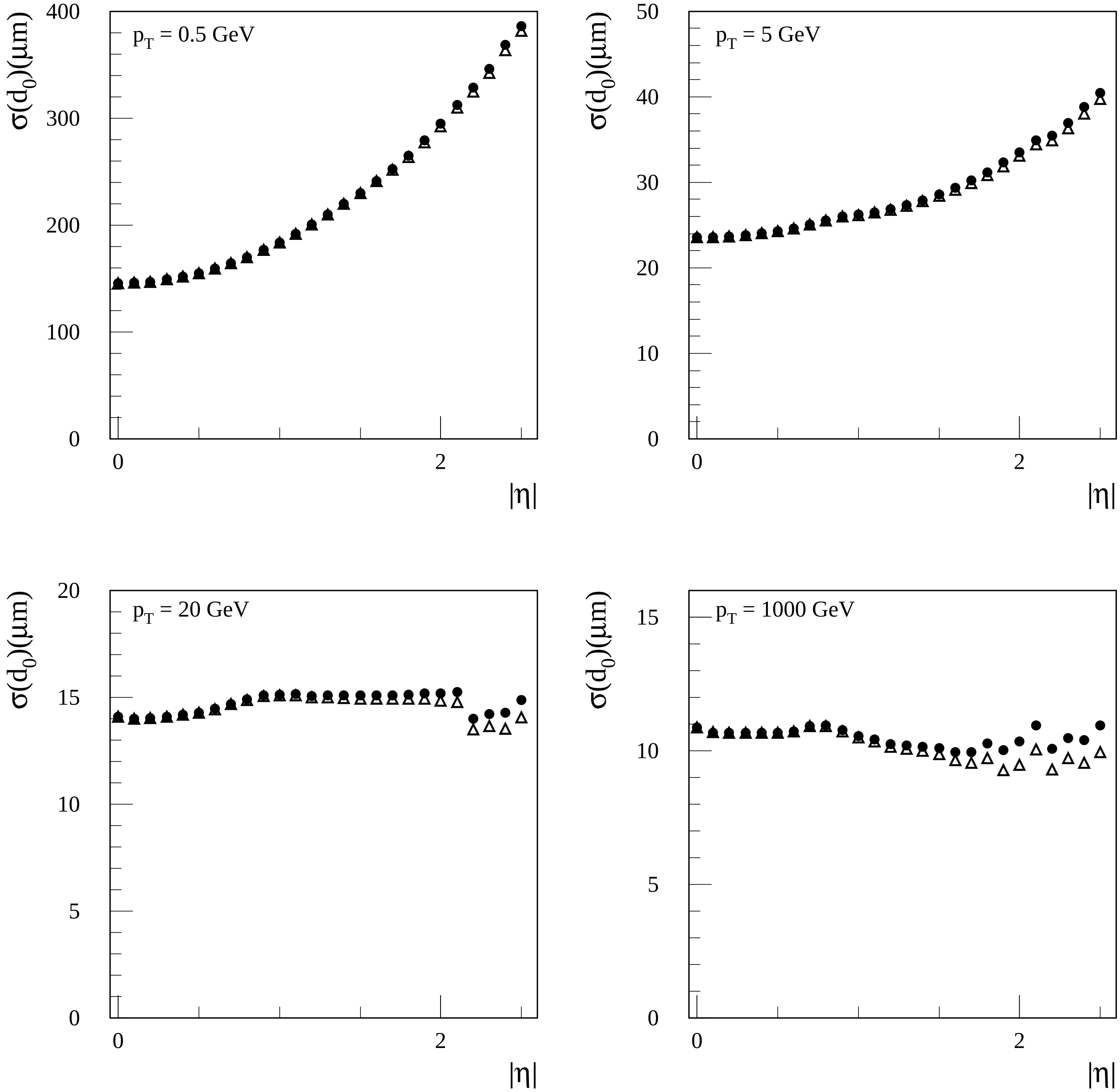


with (□) and without (●) beam constraint,

and with uniform field without beam constraint (△)

$$\sigma(\frac{1}{p_T}) \approx 3.6 \times 10^{-4} \oplus \frac{1.3 \times 10^{-2}}{p_T\sqrt{\sin\theta}}\ \mathrm{GeV}^{-1}$$

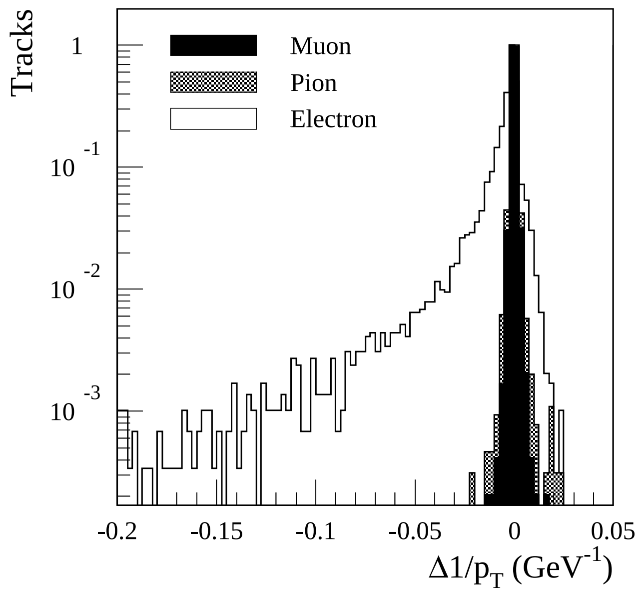
d_0 resolution for muons

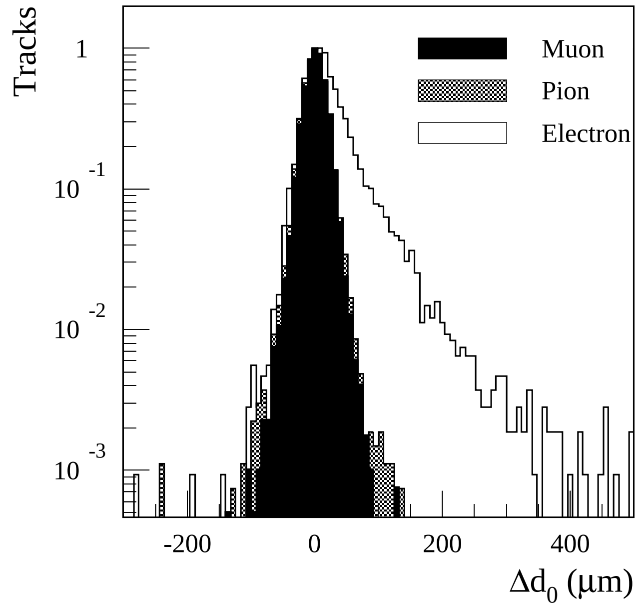


for solenoidal field (•) and uniform field (△), without beam constraint.

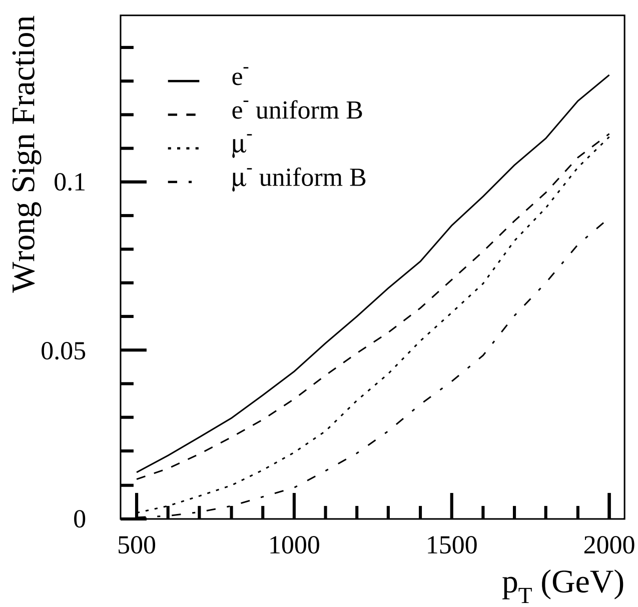
$$\sigma(d_0) \approx 11 \oplus \frac{73}{p_T\sqrt{\sin\theta}}\ \mu\mathrm{m}$$

Comparison of e, μ, and π

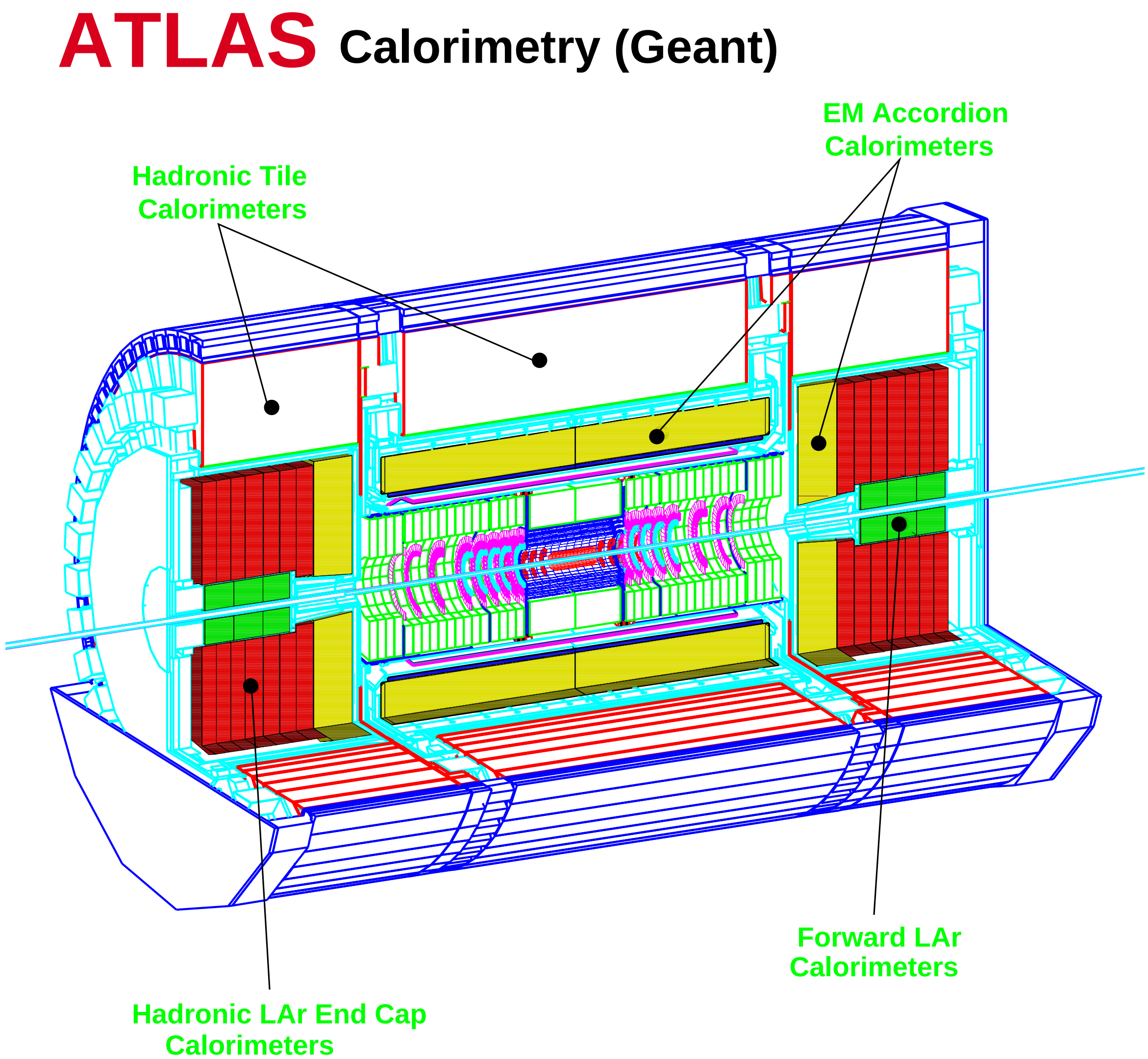




Wrong sign fraction

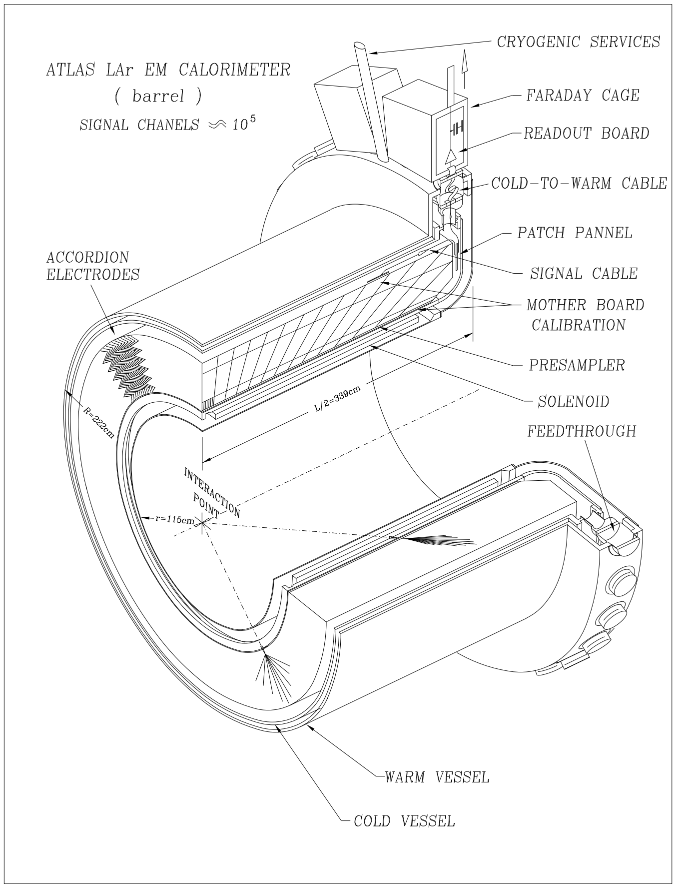


3 Calorimeter

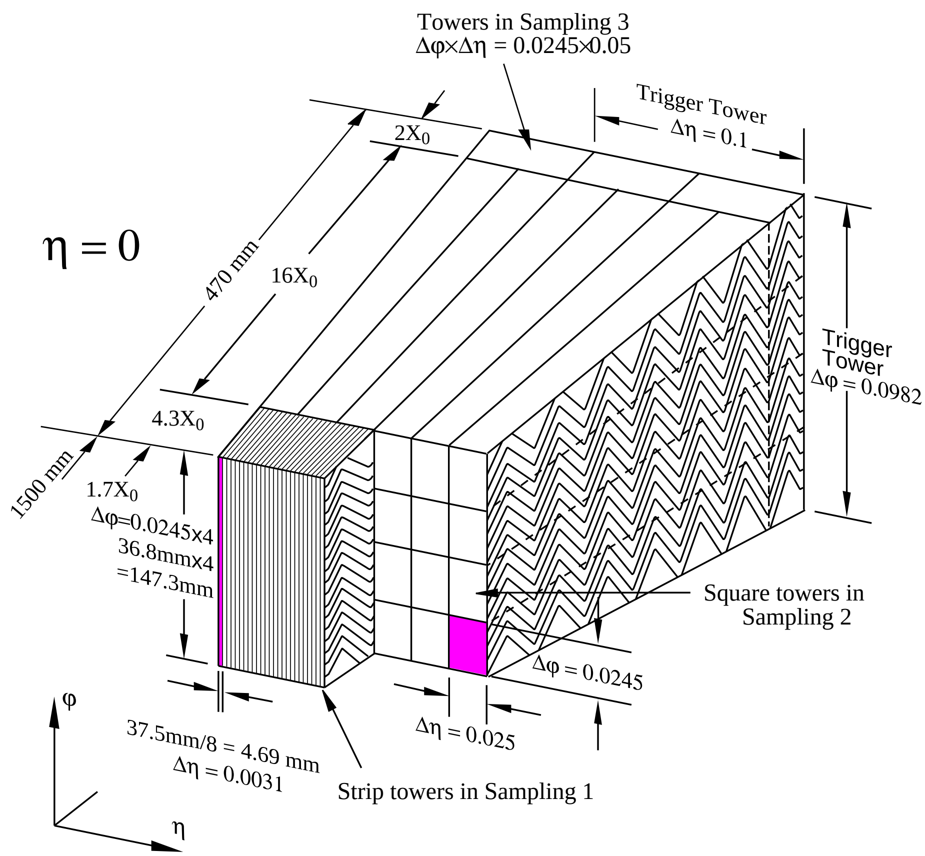


- Angular coverage of $|\eta| < 4.9$
- LAr calorimetry : $R_{out} = 2.25$ m, $|z| < 6.65$ m
- Tile calorimetry : $R_{out} = 4.25$ m, $|z| < 6.10$ m

Liquid Argon Calorimeter



- Lead plates (accordion geometry) and LAr ionization chambers
- $\sigma_E/E \sim 10\%/\sqrt{E}$
- Barrel calorimeter $|\eta| < 1.475$
- Endcap calorimeter $1.375 < |\eta| < 3.2$

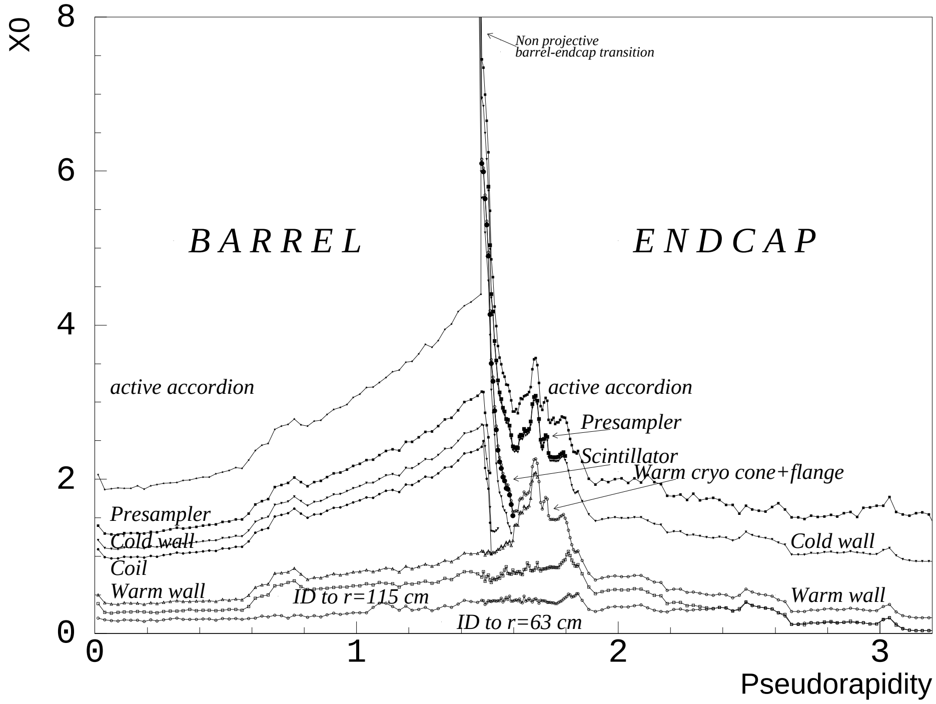


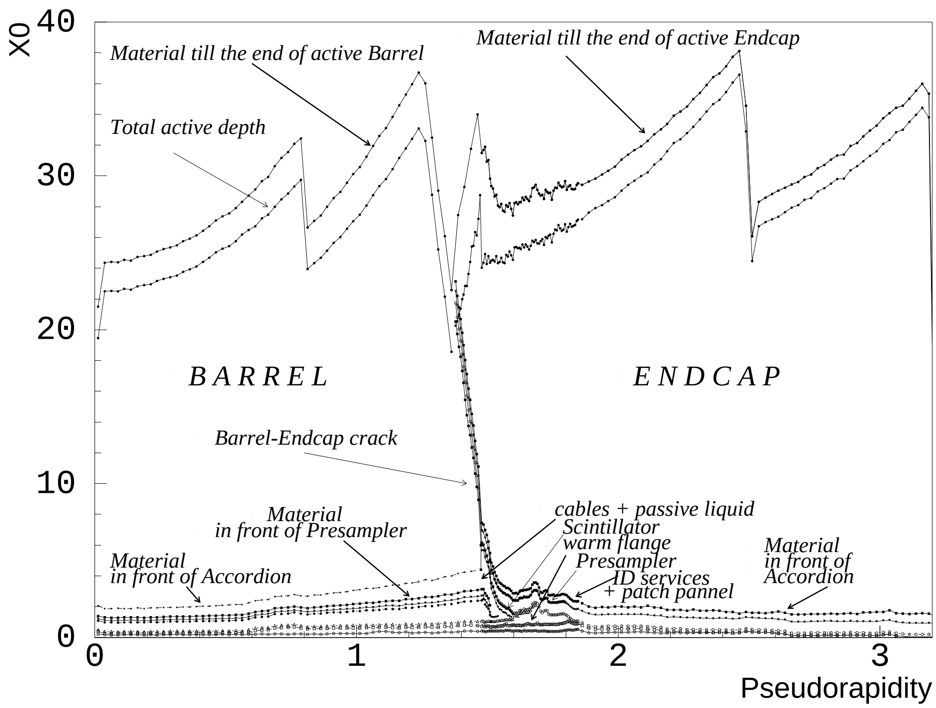
Granularity ($\Delta\eta \times \Delta\phi$)

η range	0 to 1.4	1.4 to 1.8	1.8 to 2.5	2.5 to 3.2
Presampler	0.025×0.1	0.025×0.1		
Sampling 1	0.003×0.1	0.003×0.1	0.004-0.006×0.1	0.1×0.1
Sampling 2	0.025×0.025	0.025×0.025	0.025×0.025	0.1×0.1
Sampling 3	0.050×0.025	0.050×0.025	0.050×0.025	
Trigger	0.1×0.1	0.1×0.1	0.1×0.1	0.2×0.2

A total of 173,952 readout channels

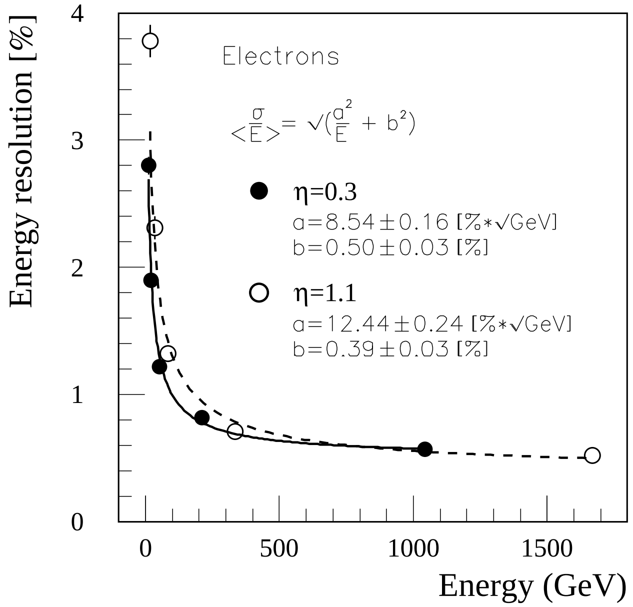
Material thickness of ECAL

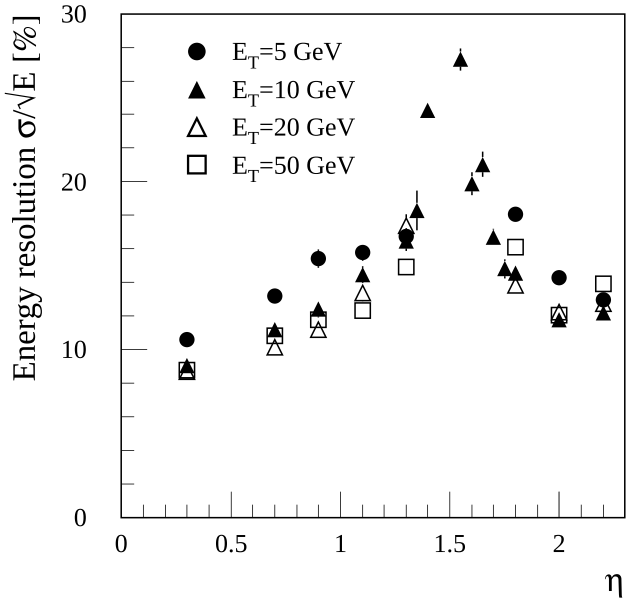




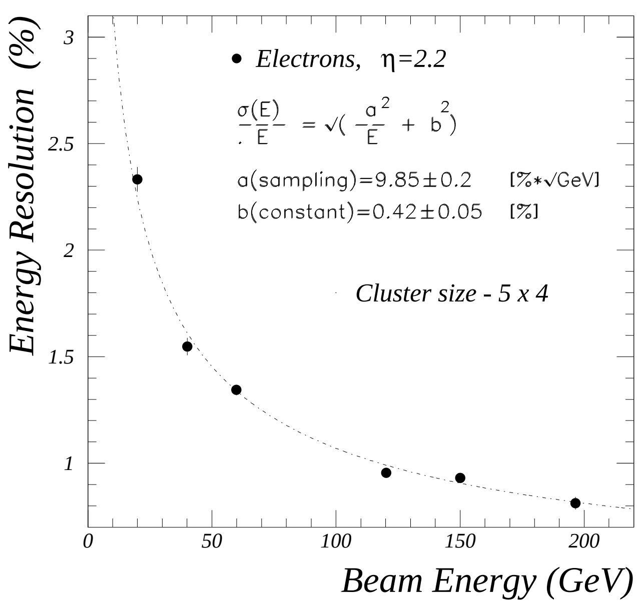
Energy Resolution

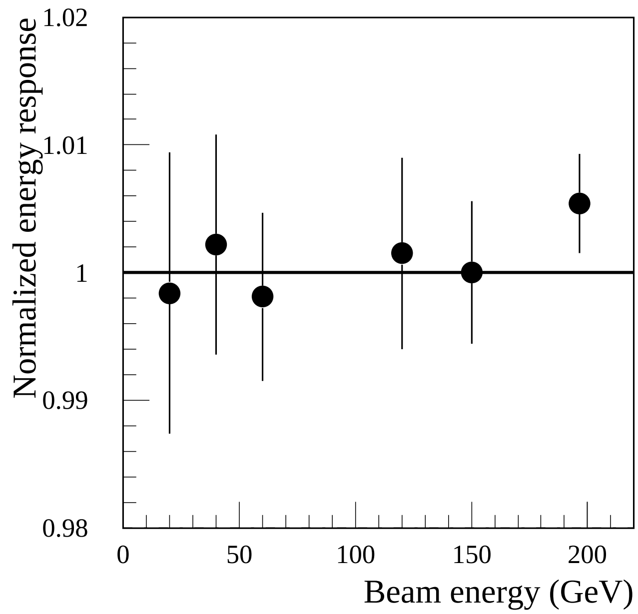
GEANT simulation





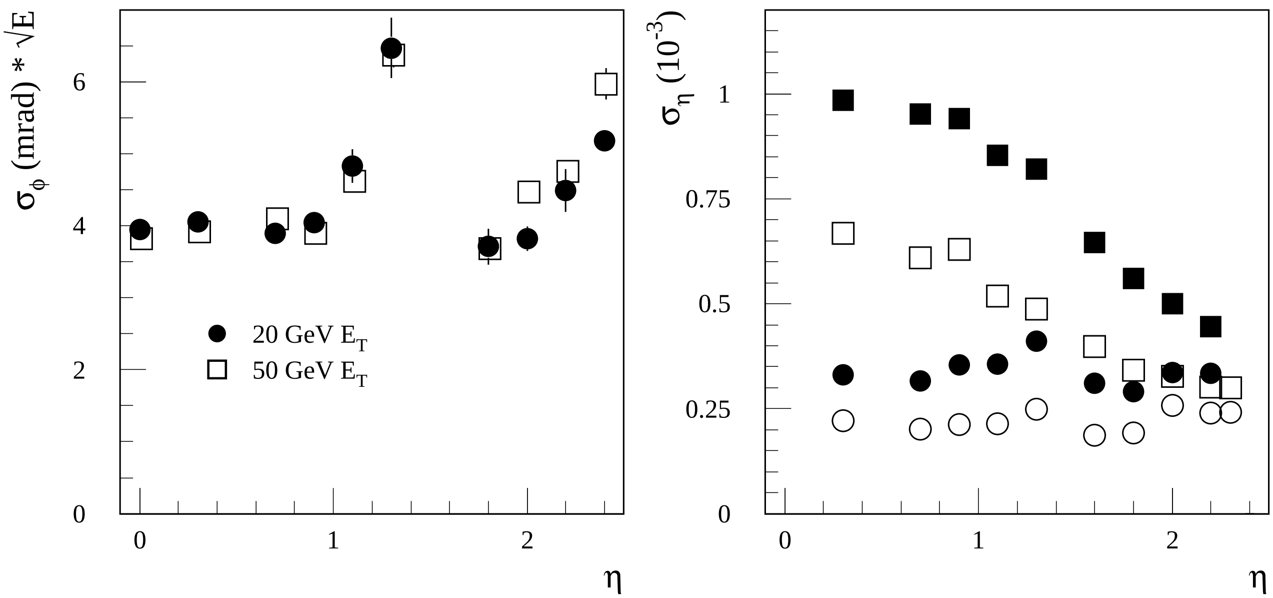
Beam-test of module zero





Angular Resolution

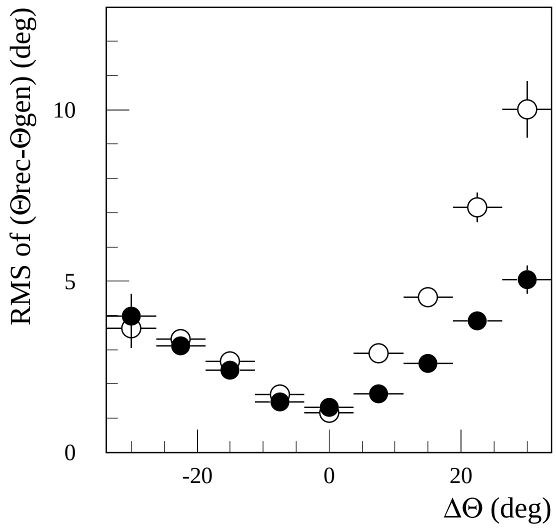
GEANT simulation



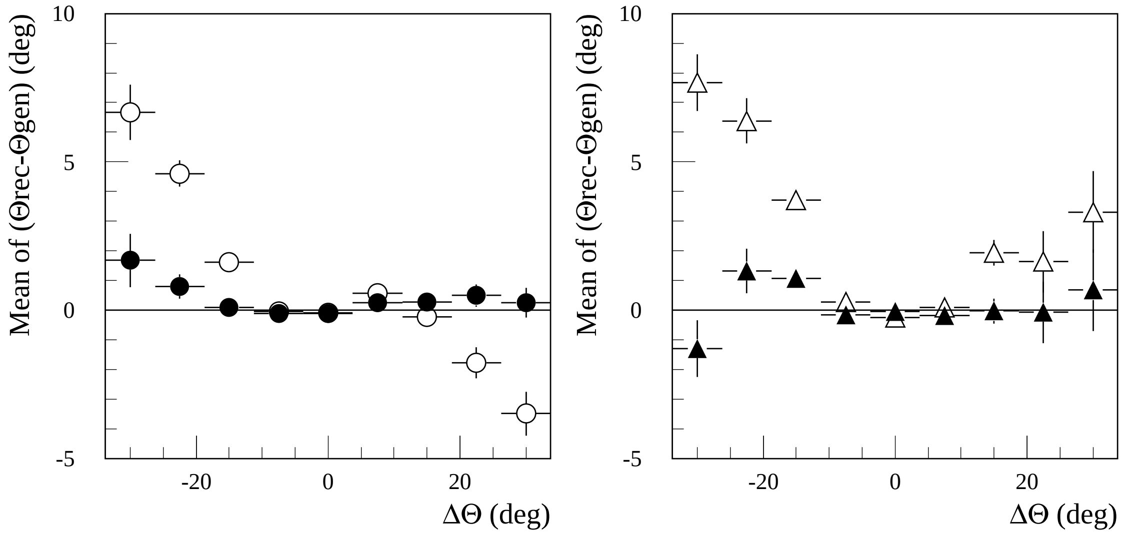
left position resolution in ϕ,

right position resolution in η, measured in strips (●) and in the middle compartment (□), $E_T = 20$ and 50 GeV.

Non-pointing Photons

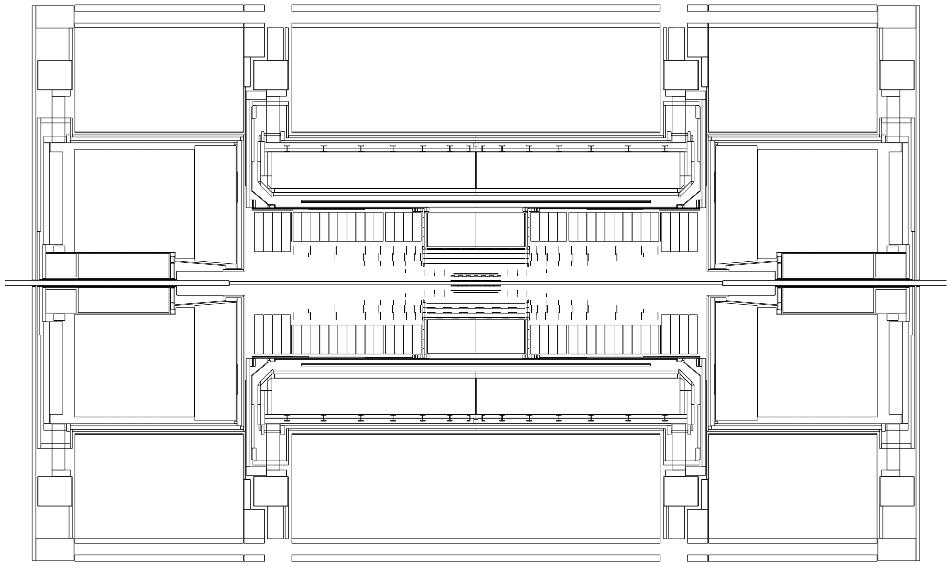


RMS of $\Theta_{rec} - \Theta_{gen}$ for $0 < \eta < 1.4$, with the standard reconstruction (○) and a neural network (●).



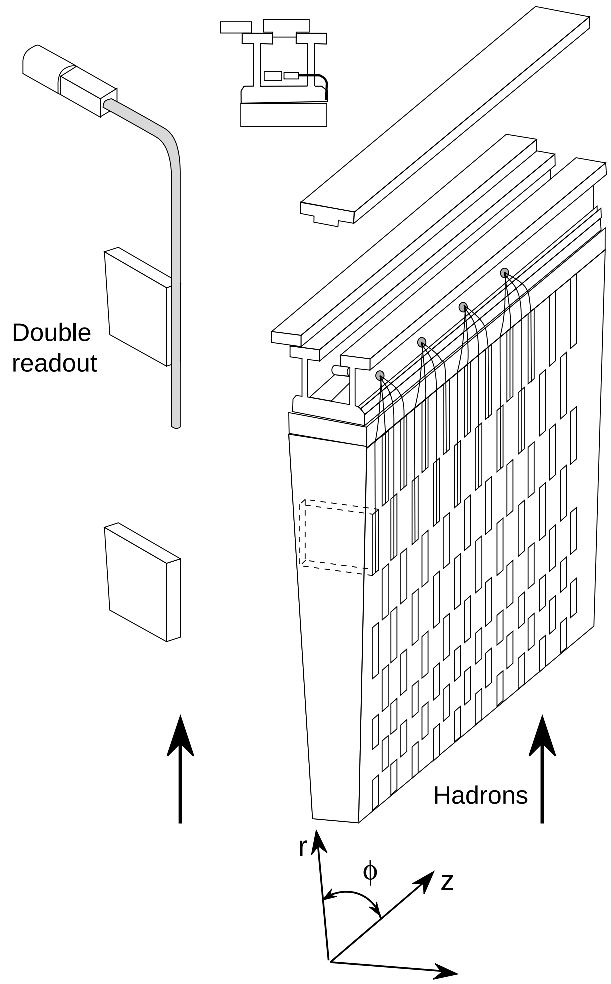
Average of $\Theta_{rec} - \Theta_{gen}$ for $0 < \eta < 0.6$ (left) and $0.6 < \eta < 1.2$ (right) with the standard reconstruction (open symbols) and a neural network (closed symbols).

Hadron Calorimeter



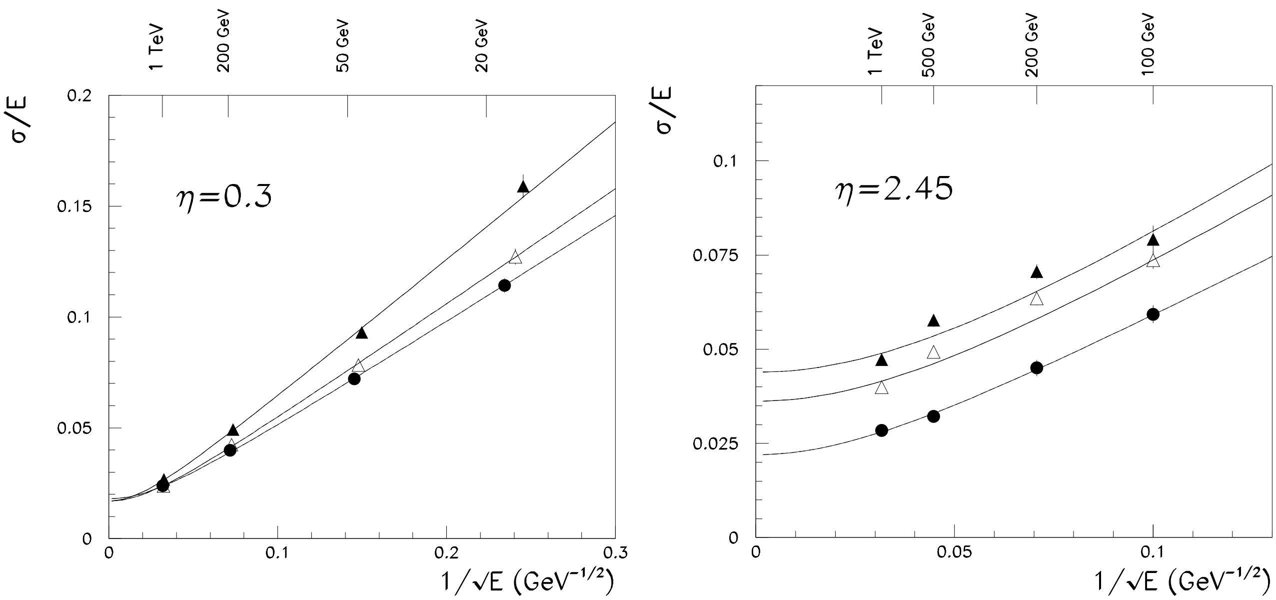
- Hadronic Tile
  $|\eta| < 1.0$ (barrel)
  $0.8 < |\eta| < 1.7$ (extended barrel)
- Hadronic LAr (Copper LAr)
  $1.5 < |\eta| < 3.2$
- Forward Calorimeter (Tungsten LAr)
  $3.1 < |\eta| < 4.9$

Tile Calorimeter

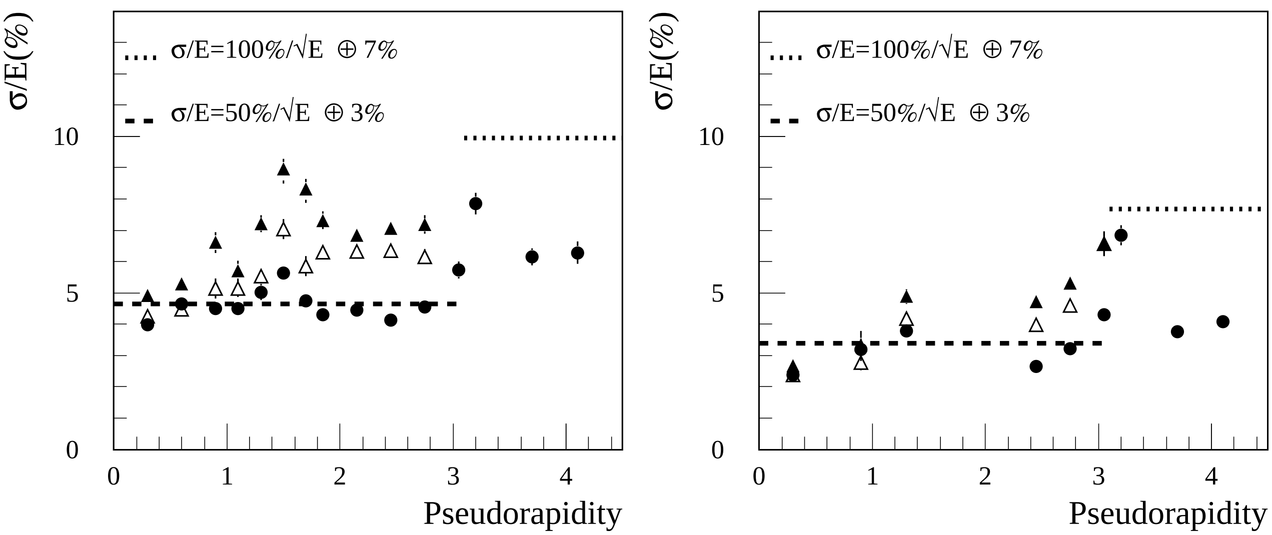


- Steel + Scintillator Tile
- $\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$ for hadrons
- $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
- 3 longitudinal samplings

Jet Energy Resolution



$\Delta R = 0.4,\ 0.7,$ and full calorimeter.

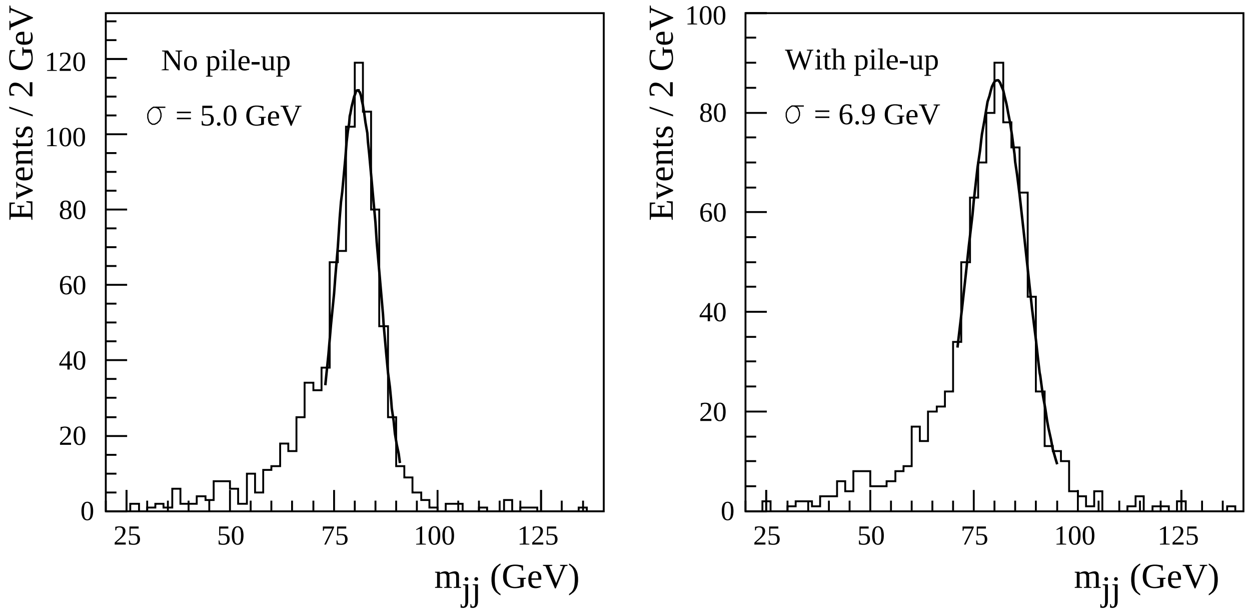


(left) E=200 GeV and (right) E=1 TeV.

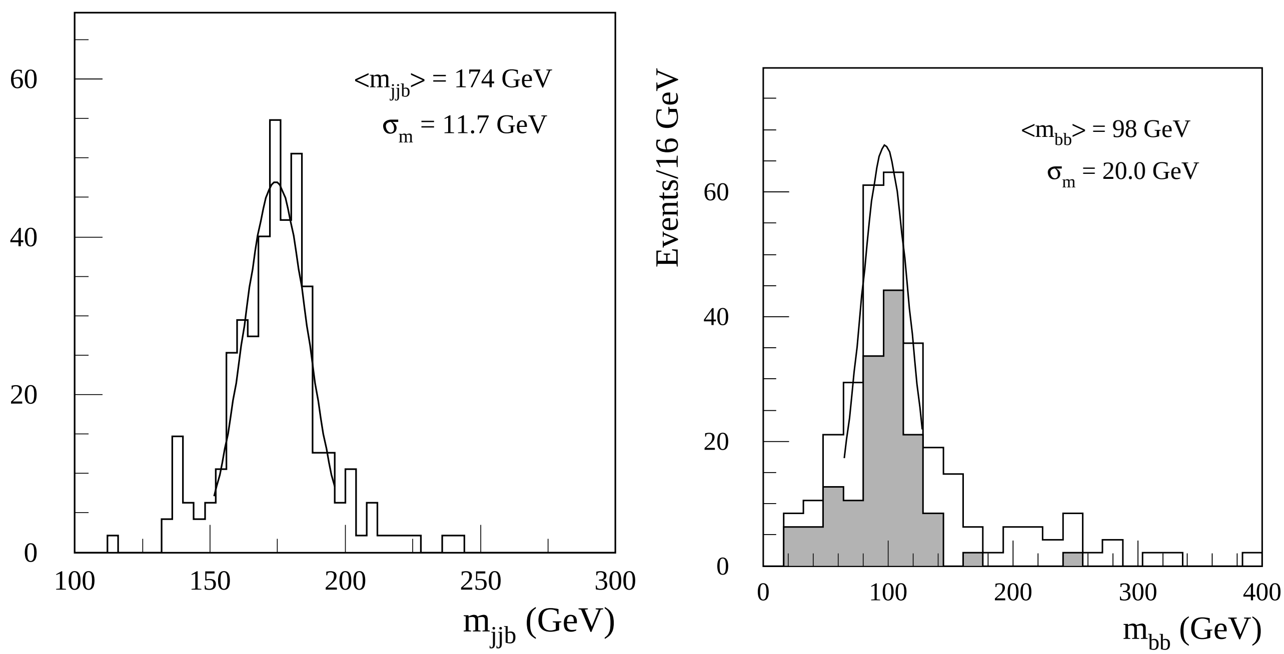
$\Delta R = 0.4,\ 0.7,$ and full calorimeter.

Mass Reconstruction Resolution

M_{jj} from W decay (low and high lumi.)

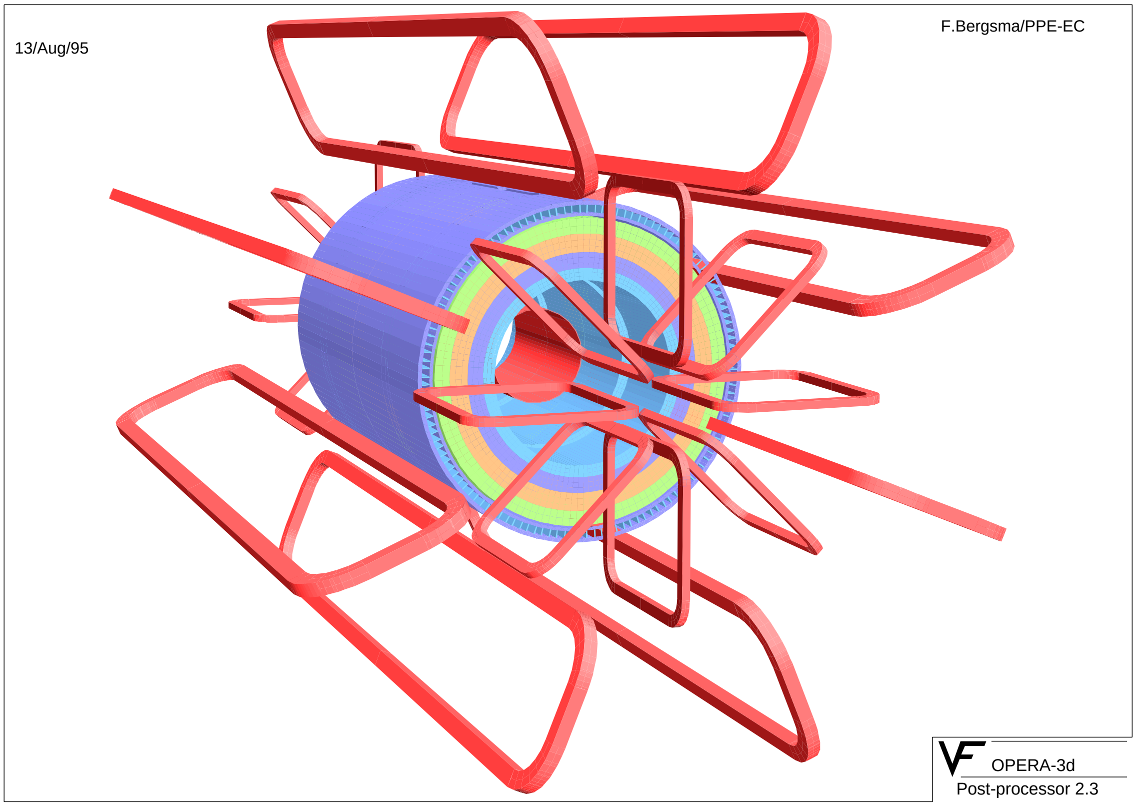


M_{jjb} from top decay & M_{bb} from $H \to b\bar{b}$

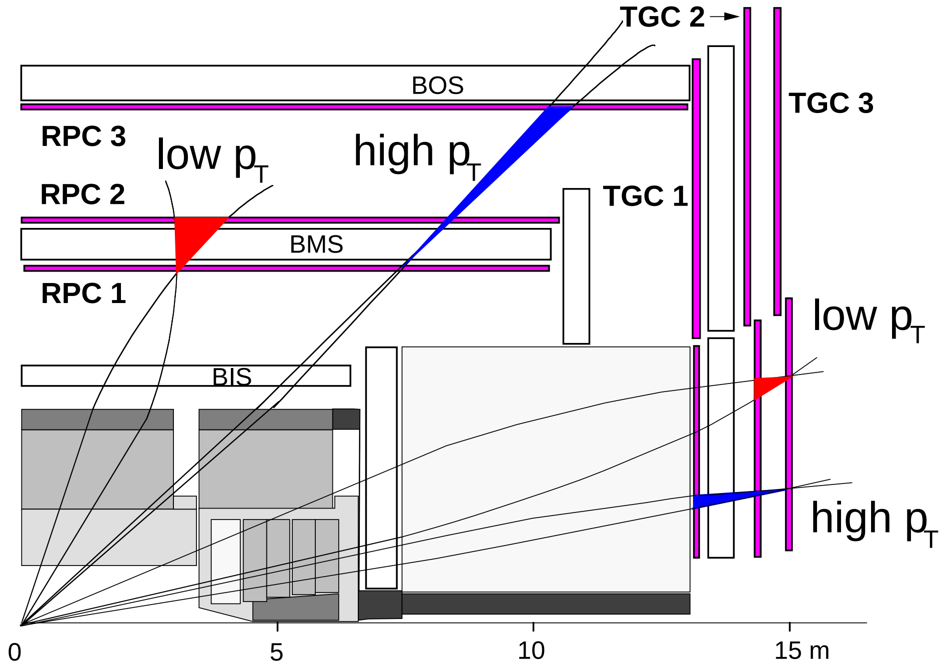


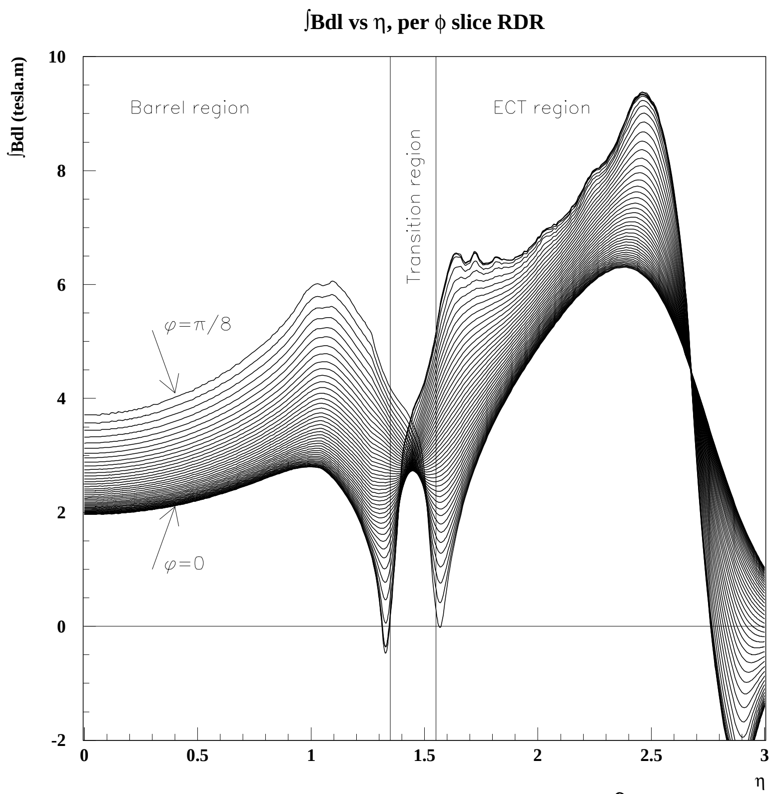
4 Muon Spectrometer

Air-core Toroid Magnets



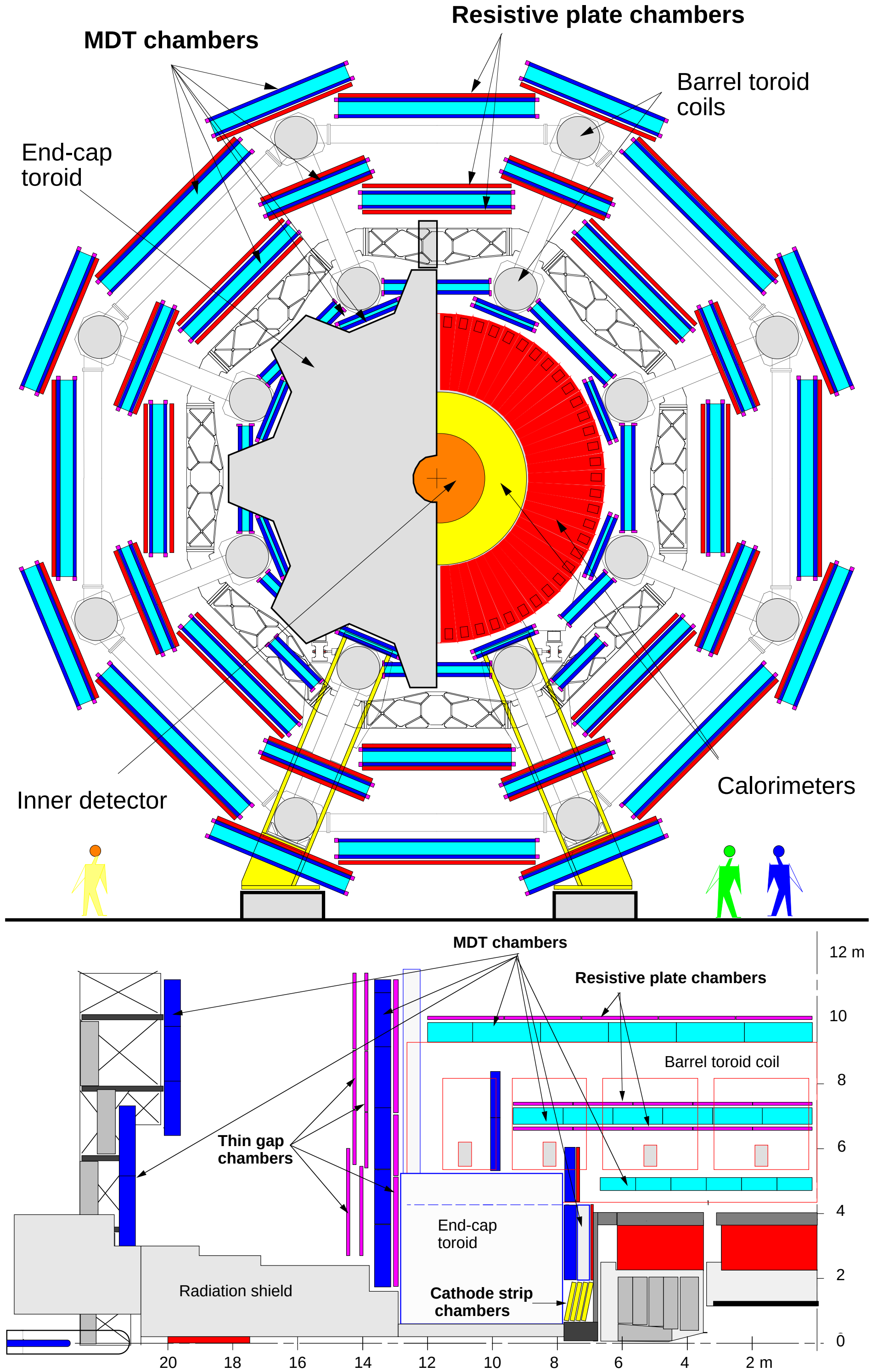
- One barrel and two endcap toroids
  - $|\eta| < 1.0$: barrel region
  - $1.0 \leq |\eta| \leq 1.4$: transition region
  - $1.4 \leq |\eta| \leq 2.7$: endcap region
- p_t resolution ~ 2 % for 5–100 GeV p_t
- B-field is almost perpendicular to the tracks
- "Air-core" minimizes multiple scattering



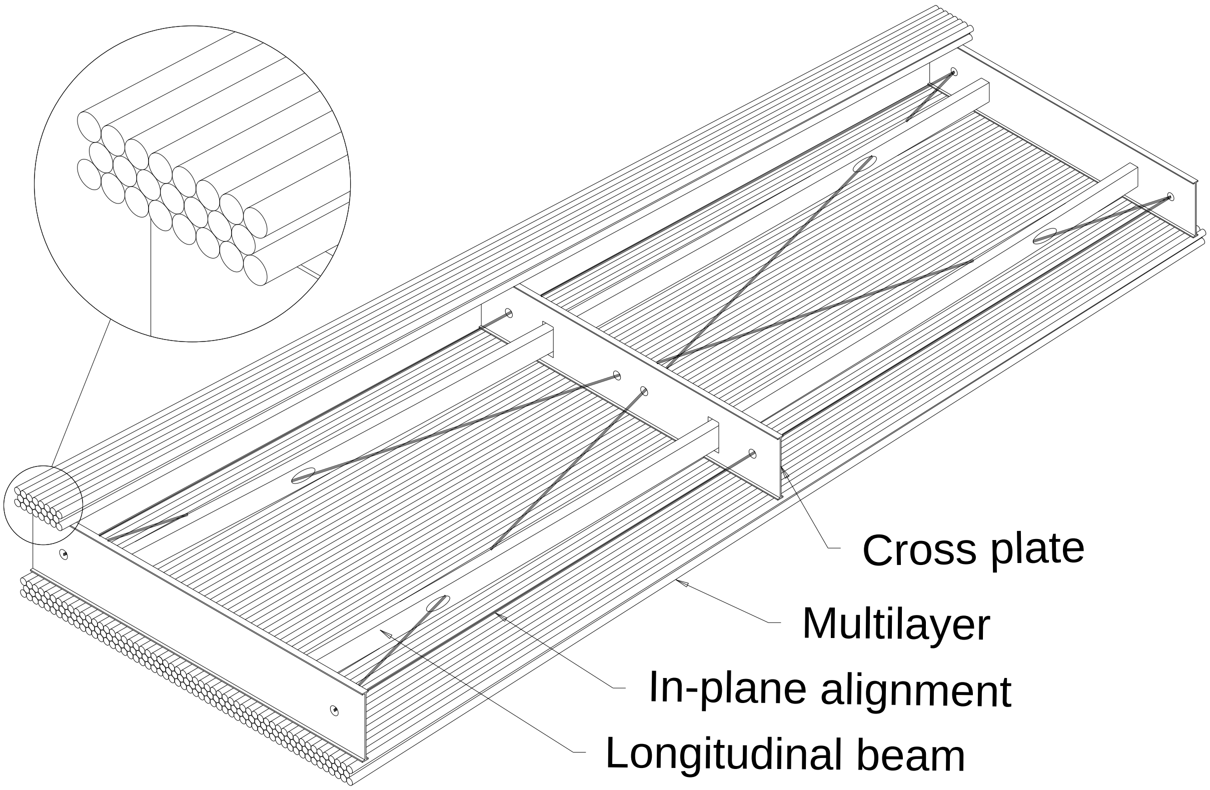


$$Sagitta\ of\ a\ track \propto \int Bd\ell$$

Muon Spectrometer



Precision Chambers (MDT)

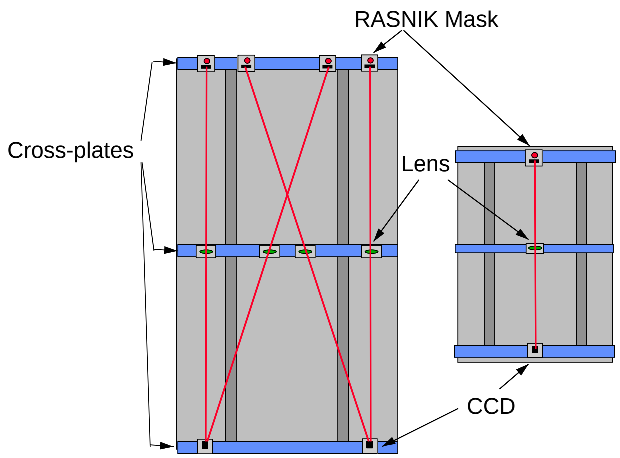


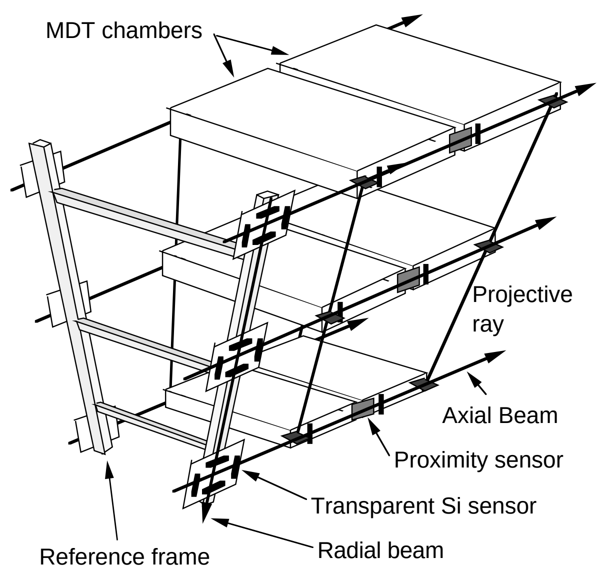
- Drift tube : 30 mmϕ, 1.4-6.3 m long
- Ar (93%) CO_2 (7%) with 3 bar pressure
- Single wire resolution $\sim 80\mu$m
- Mechanical Accuracy $\sim 30\mu$m

Alignment

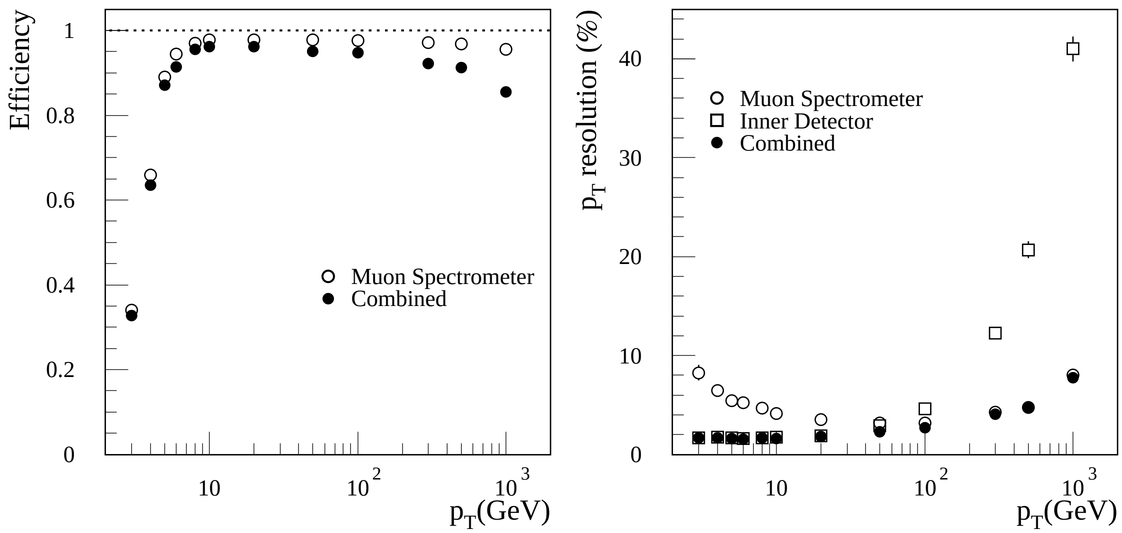
Positions of chambers are monitored;

- $\sim 30\mu$m within a projective tower
- $\sim$mm for relative position of different towers



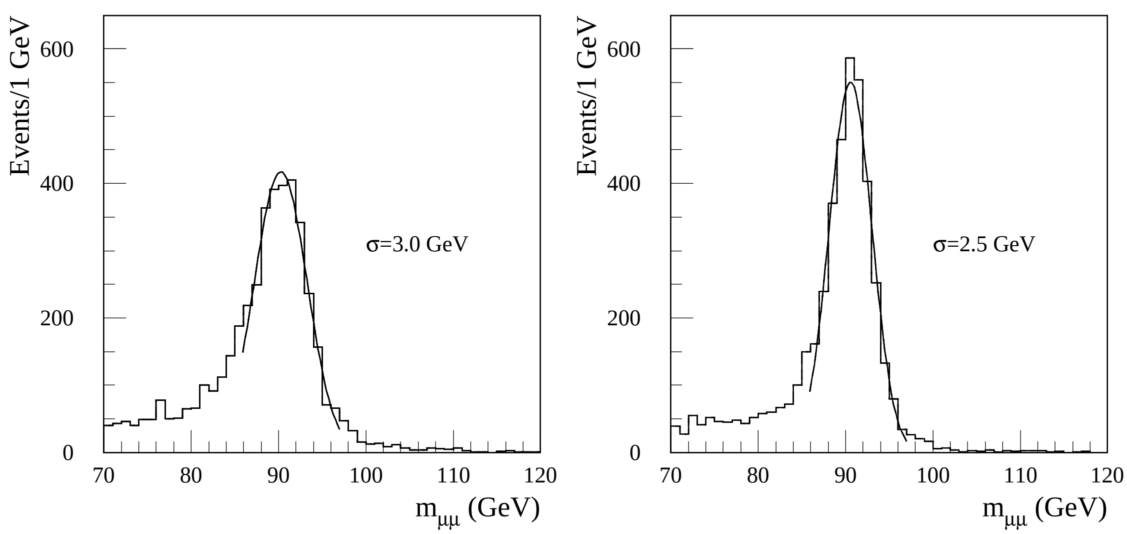


Efficiency and Resolution

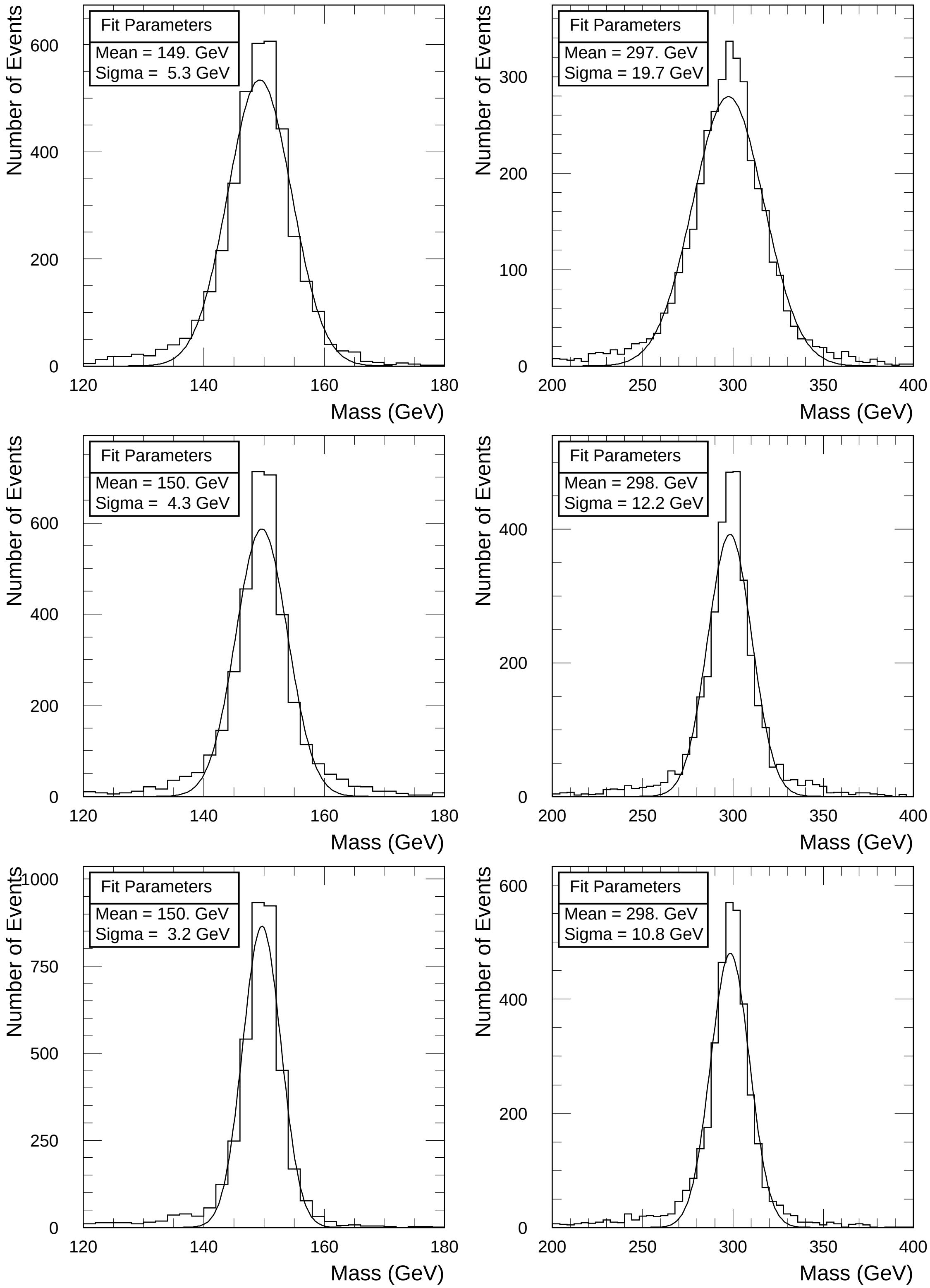


Low efficiency at high p_T is due to EM shower produced in the dense material in front

$M_{\mu\mu}$ resolution for $Z^0 \to \mu^+\mu^-$



Dimuon Mass Resolution



Trigger Chambers

To trigger high p_T muons,

- Good time resolution ($<$ 25ns) and modest position resolution
- Barrel : Resistive Plate Chambers (RPC)
- Endcaps : Thin Gap Chambers (TGC)

Schematic View of TGC

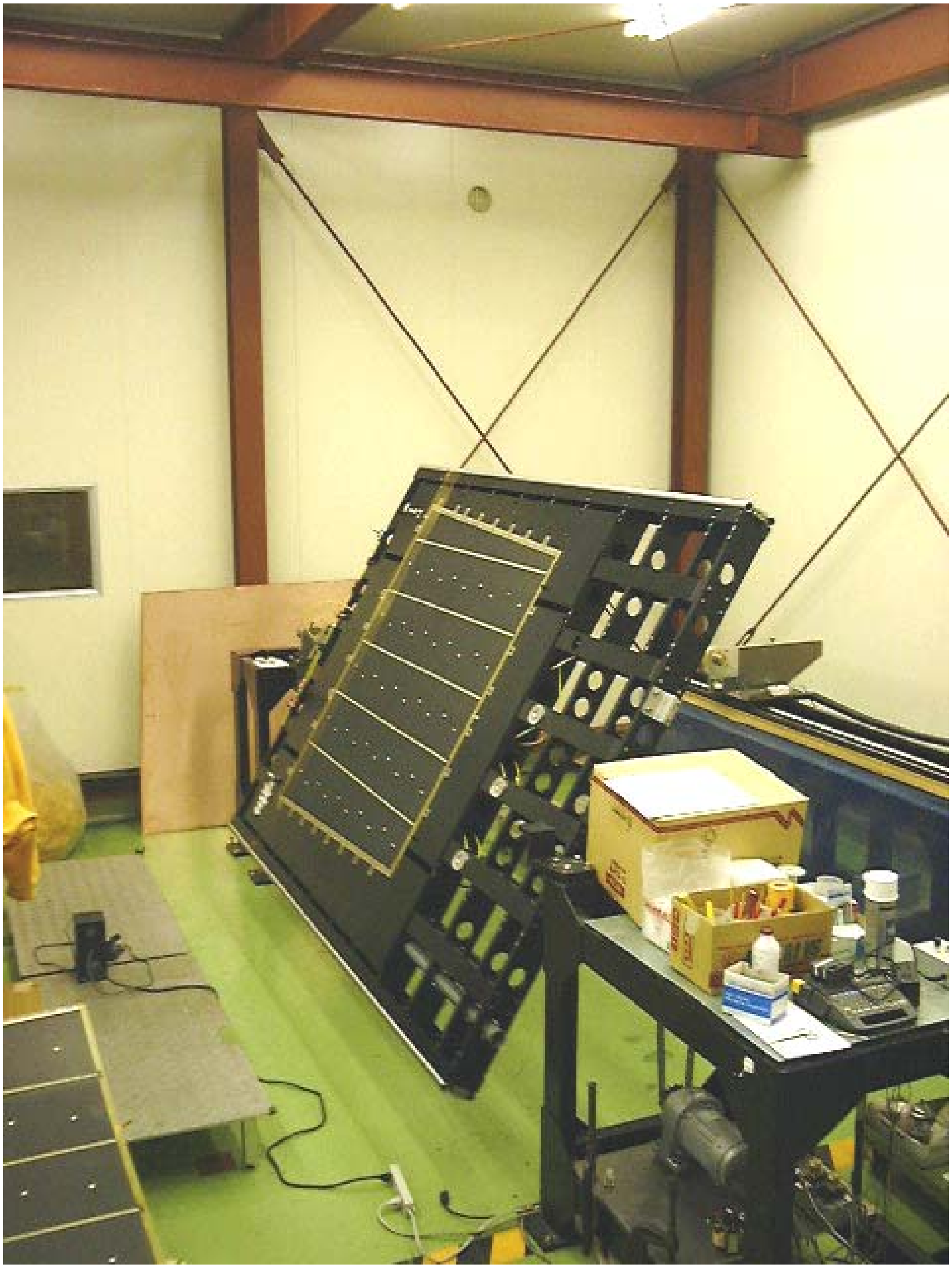
-
-
-

Mass Production of TGC

- Production at KEK ($\sim$ 1000 TGCs by the end of 2003)
- Cosmic-ray test at Kobe
- shipped to CERN

Carbon spray (collaborator's duty)

Wire-winding machine (KEK Fuji B4)

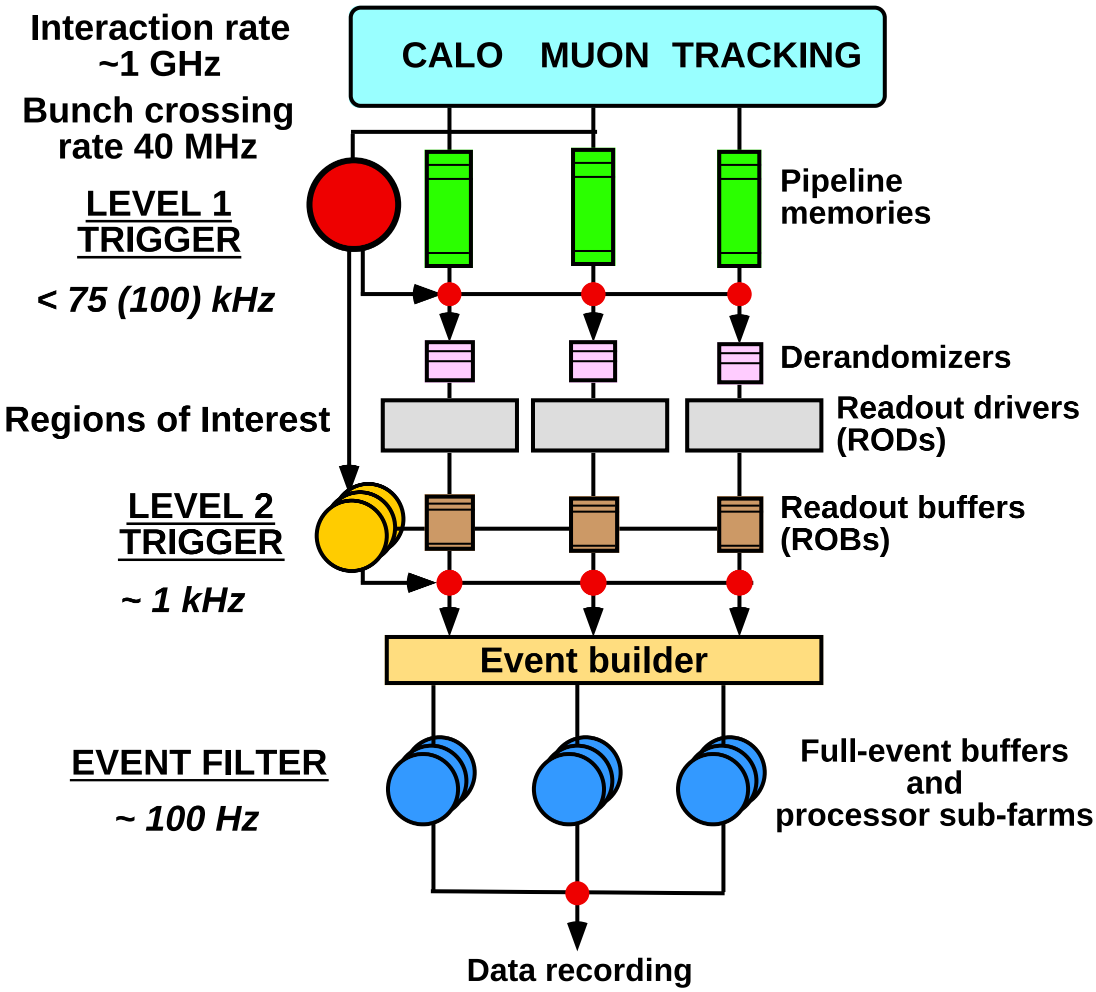


5 Trigger System

Trigger system identifies interesting events with

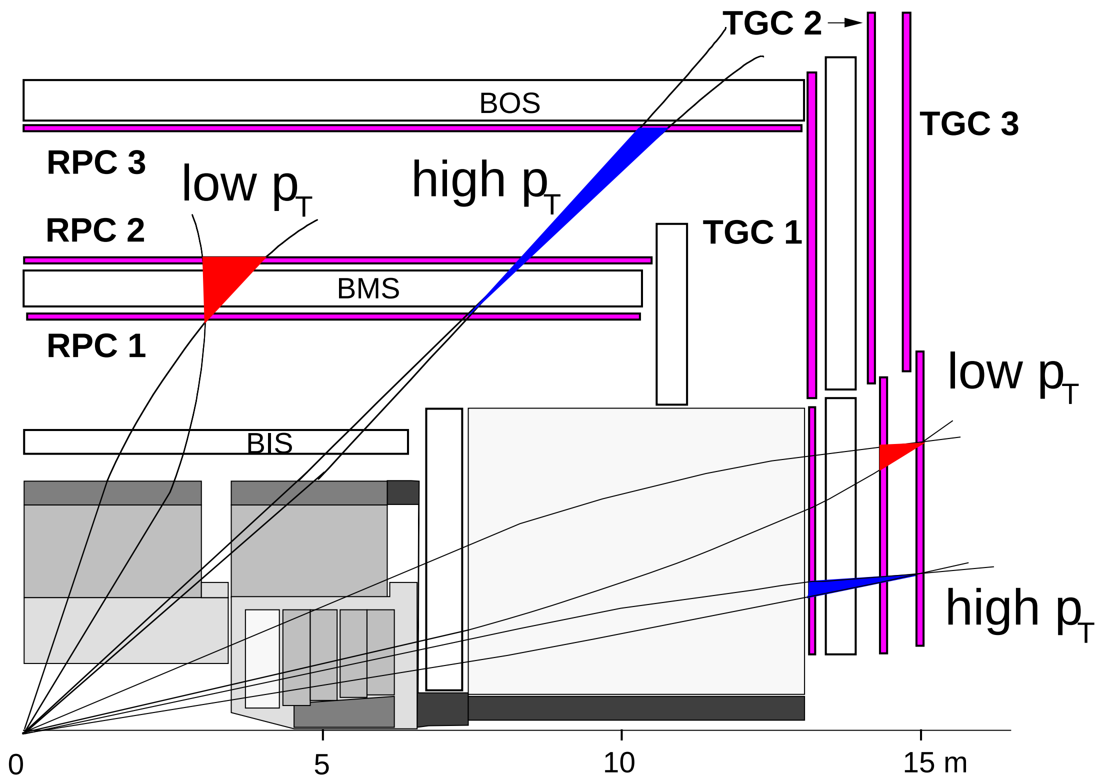
- high p_T charged leptons for detecting decays of heavy particles,
- low p_T charged leptons for B-physics,
- high p_T quark and gluon jets,
- electroweak gauge bosons (W, Z, γ),
- missing E_T.

Trigger Levels



- **LVL1** trigger identifies **Regions of Interest (RoIs)** using reduced granularity data.
- **LVL2** trigger uses full-granularity, full-precision data in RoIs (a small fraction of full data).
- **Event Filter** (LVL3) uses full reconstruction.

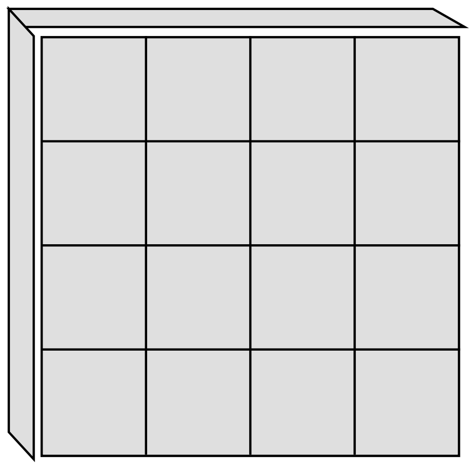
Muon LVL1 Trigger



At low luminosity	
$\geq 1\mu \; p_T > 6$ GeV	8 kHz

At high luminosity	
$\geq 1\mu \; p_T > 20$ GeV	4 kHz
$\geq 2\mu \; p_T > 6$ GeV	1 kHz

Calorimeter LVL1 Trigger



OUTER SUM

LVL2 Trigger Conditions

At low luminosity	
B-physics LVL2 triggers	0.8 kHz
$\geq 1\ \mu\ p_T > 20$ GeV	0.2 kHz
≥ 1 e $p_T > 20$ GeV	0.2 kHz
$\geq 1\ \gamma\ p_T > 40$ GeV	0.06 kHz
≥ 2 e $E_T > 15$ GeV	0.01 kHz
$\geq 2\ \gamma\ E_T > 20$ GeV	0.01 kHz
≥ 1 jet $p_T > 200$ GeV	0.06 kHz
≥ 3 jet $p_T > 100$ GeV	0.02 kHz
Large E_T^{miss}	0.01 kHz
Other prescaled triggers	0.1 kHz
Total	≤ 1.5 kHz

At high luminosity	
≥ 1 isol. μ $p_T > 20$ GeV	0.2 kHz
≥ 1 μ $p_T > 40$ GeV	0.1 kHz
≥ 1 e $p_T > 30$ GeV	0.3 kHz
≥ 1 γ $p_T > 60$ GeV	0.1 kHz
≥ 2 μ $p_T > 10$ GeV	0.08 kHz
≥ 2 isol. μ $p_T > 6$ GeV	0.1 kHz
≥ 2 e $E_T > 20$ GeV or	
≥ 2 γ $E_T > 20$ GeV	0.2 kHz
≥ 1 jet $p_T > 200$ GeV	
≥ 1 jet $p_T > 300$ GeV	0.1 kHz
≥ 3 jet $p_T > 150$ GeV	0.04 kHz
Large E_T^{miss}	0.1 kHz
Other prescaled triggers	0.1 kHz
Total	≤ 1.4 kHz

6 b-tagging

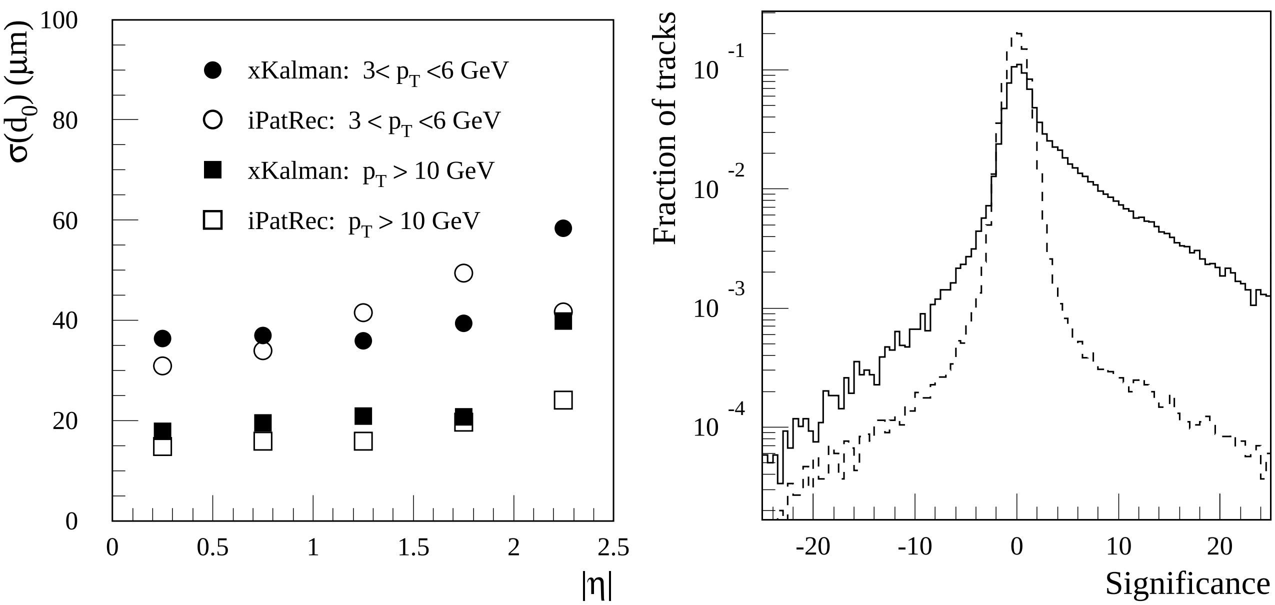
Vertex-tagging

The jet-weight W is calculated as follows.

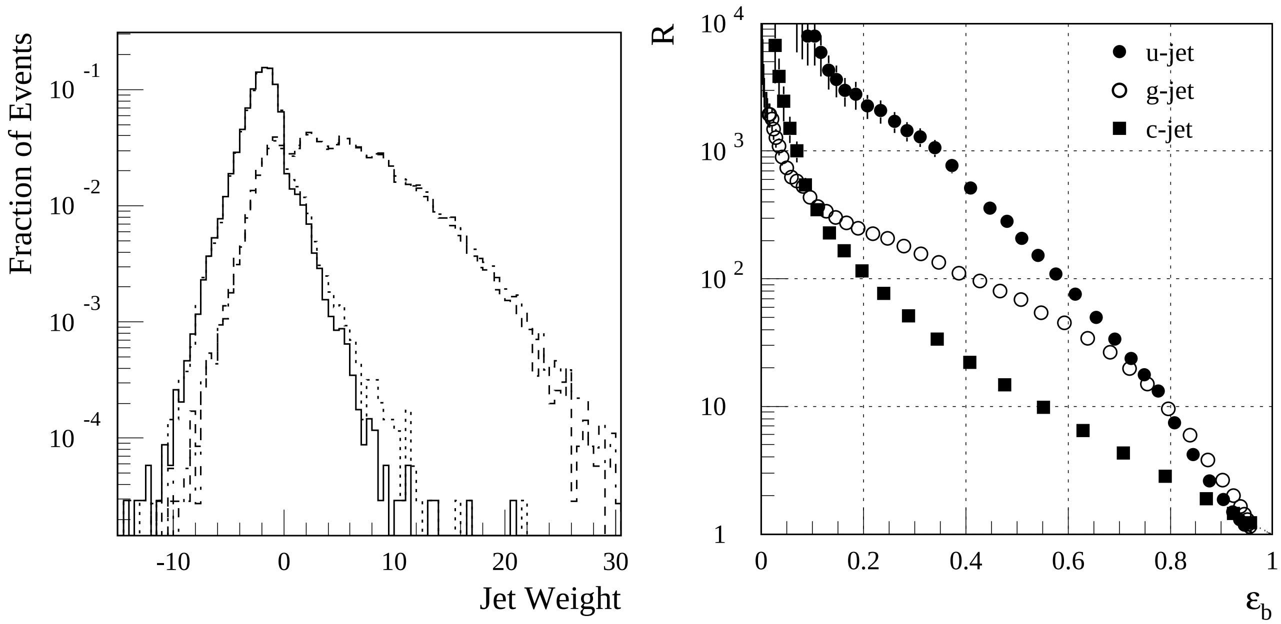
$$W = \sum \log r_i \quad ,$$

- $d_{0,i}$ and $\sigma_{d_0,i}$ are the impact parameter and its error of each track in a jet,
- $S_i = d_{0,i}/\sigma_{d_0,i}$ is the significance of each track,
- $r_i = f_b(S_i)/f_u(S_i)$ is the ratio of significance p.d.f's for b-jet and u-jet.

σ_{d_0} and S_i

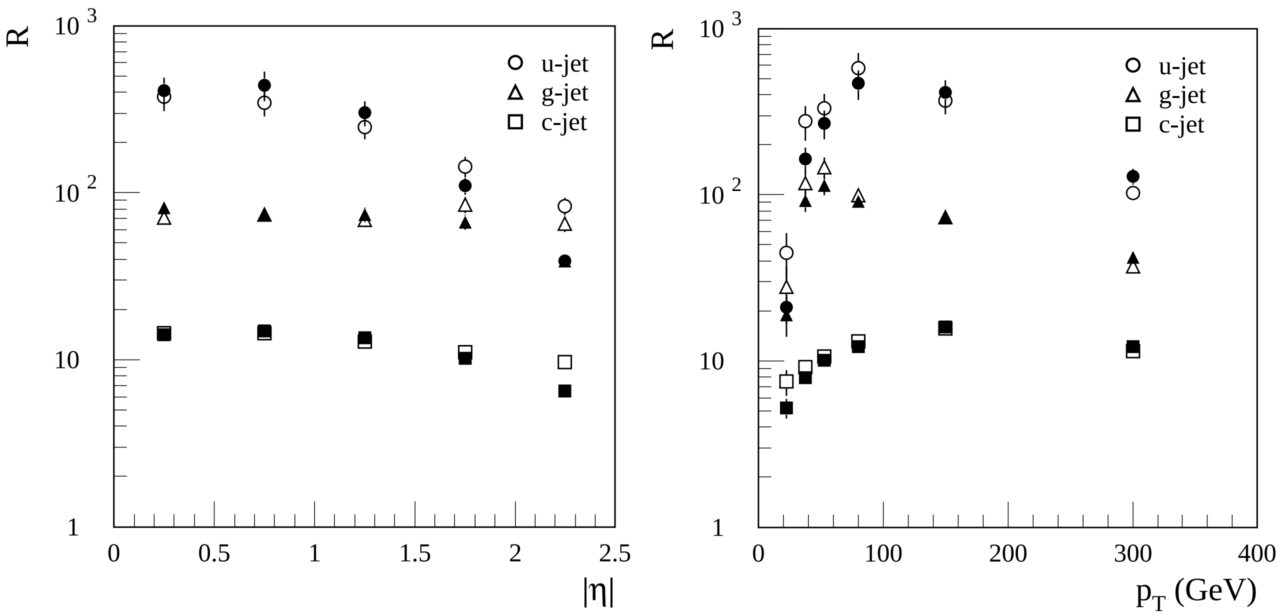


Jet weight and rejection factors

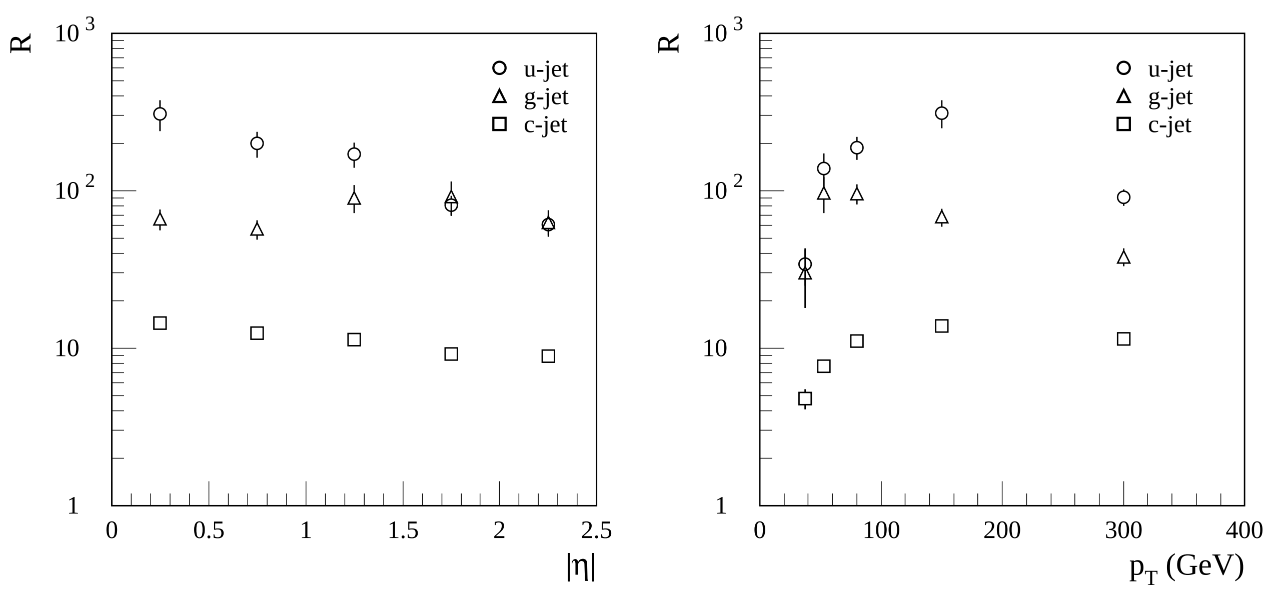


Rejection factors ($\epsilon_b = 50$ %)

low luminosity



high luminosity (degraded by pile-up)



7 ATLFAST

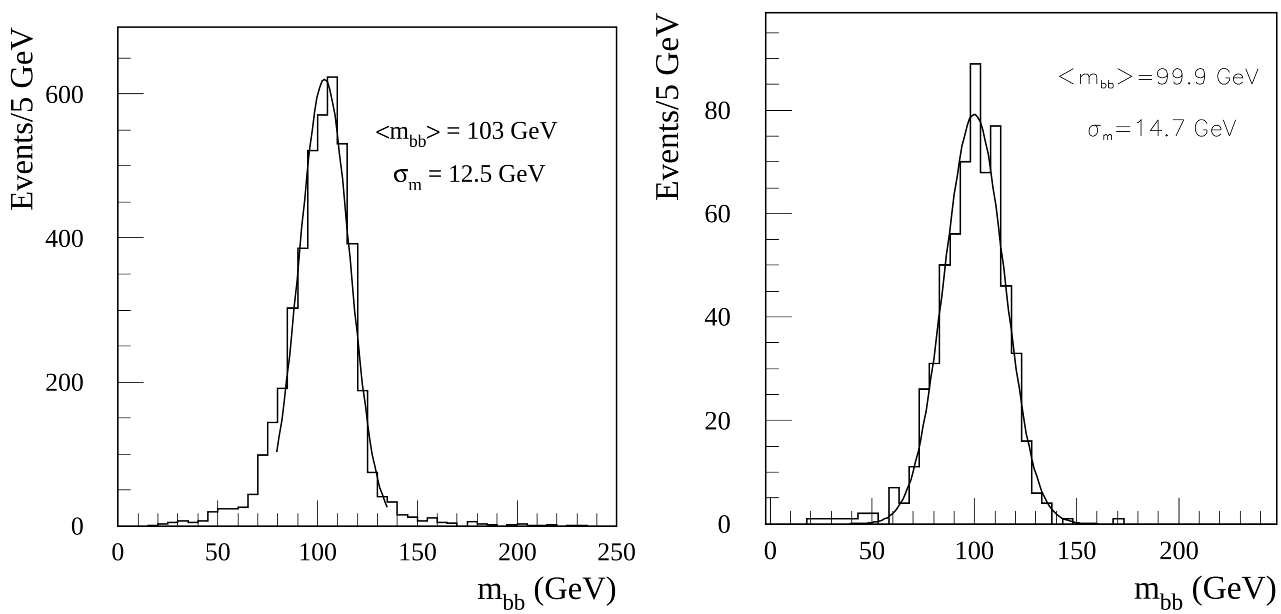
Fast simulation/reconstruction of ATLAS events designed to reproduce full simulation (GEANT) results as well as possible.

Most of Physics TDR studies are based on this.

ATLFAST simulates ;

- Calorimeter clusters
- Isolated electrons and photons
- Isolated muons
- Jets and pile-up
- Jet energy calibration
- b-tagging
- τ-tagging and τ-veto
- Track reconstruction
- Missing transverse energy
- Trigger selections

Comparison of m_{bb} resolutions
with $M_H = 100$ GeV, $H \to b\bar{b}$
(left=FAST, right=FULL)



Contact Kanzaki-san to use "RUNATLF", an integration of atlfast/generators/ntuple

8 Conclusion

The ATLAS detector will be ready and will be waiting for the first collision of LHC in April 2006.

Hope great discoveries !!