LECTURE 4   DETECTORS

- Hadronic Calorimetry
- Systems and Tracking

Very good reference – Particle Data Group

http://pdg.lbl.gov/2009/reviews/rpp2009-rev-particle-detectors-accel.pdf

http://pdg.lbl.gov/2009/reviews/rpp2009-rev-passage-particles-matter.pdf

Development of Hadronic Showers

Hadronic shower

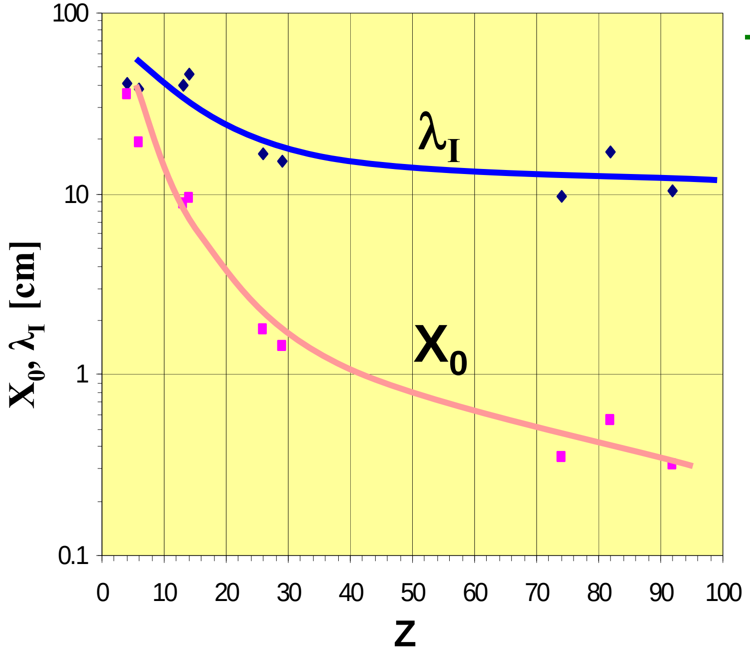
→ At **energies > 1 GeV**, cross-section depends little on energy:

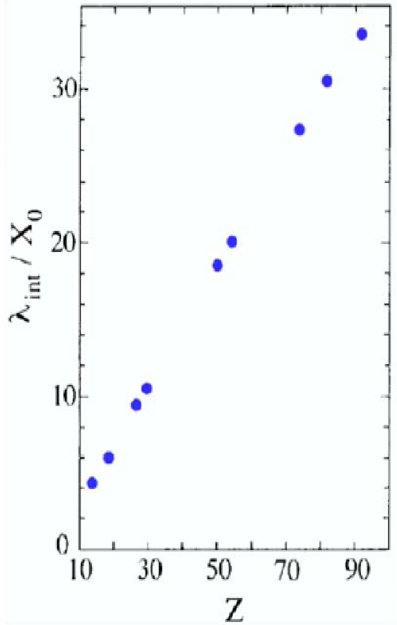
$$\sigma_{abs} \approx \sigma_0 A^{0.7}\ ,\quad \sigma_0 \approx 35\ mb \quad \Rightarrow$$

$$\boxed{\lambda_I \propto A^{1/3}}$$

→ For $Z > 6$ → $\lambda_I > X_0$

Material	Z	A	ρ [g/cm³]	X_0 [g/cm²]	λ_I [g/cm²]
Hydrogen (gas)	1	1.01	0.0899 (g/l)	63	50.8
Helium (gas)	2	4.00	0.1786 (g/l)	94	65.1
Beryllium	4	9.01	1.848	65.19	75.2
Carbon	6	12.01	2.265	43	86.3
Nitrogen (gas)	7	14.01	1.25 (g/l)	38	87.8
Oxygen (gas)	8	16.00	1.428 (g/l)	34	91.0
Aluminium	13	26.98	2.7	24	106.4
Silicon	14	28.09	2.33	22	106.0
Iron	26	55.85	7.87	13.9	131.9
Copper	29	63.55	8.96	12.9	134.9
Tungsten	74	183.85	19.3	6.8	185.0
Lead	82	207.19	11.35	6.4	194.0
Uranium	92	238.03	18.95	6.0	199.0





Comparing X_0 and λ_I, we understand why Hadronic calorimeters are in general larger than EM calorimeters

Mauricio Barbi
Univ. of Regina,
TRIUMF Summer School 2007

Hadronic Calorimeter

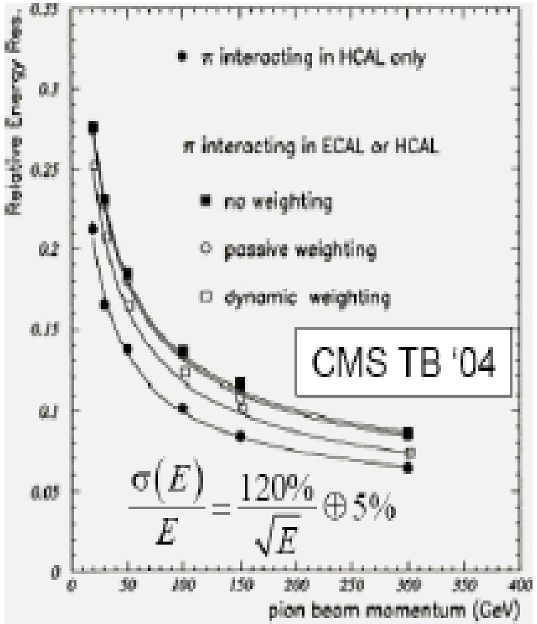
Hadronic Calorimeter (HCAL)

→ CMS hadron calorimeter

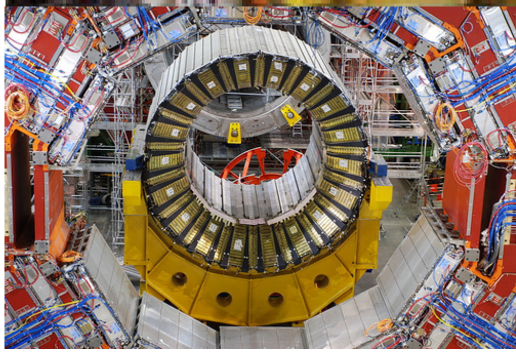
→ 16 scintillator 4 mm thick plates (active material)
Interleaved with 50 mm thick plates of brass

→ Energy resolution:

$$\boxed{\frac{\sigma(E)}{E} \propto \frac{(120\%)}{\sqrt{E}} \oplus 5\%}$$



Hadronic energy resolution compromised in favor of a much higher EM energy resolution



http://www.flickr.com/photos/naezmi/365114338/

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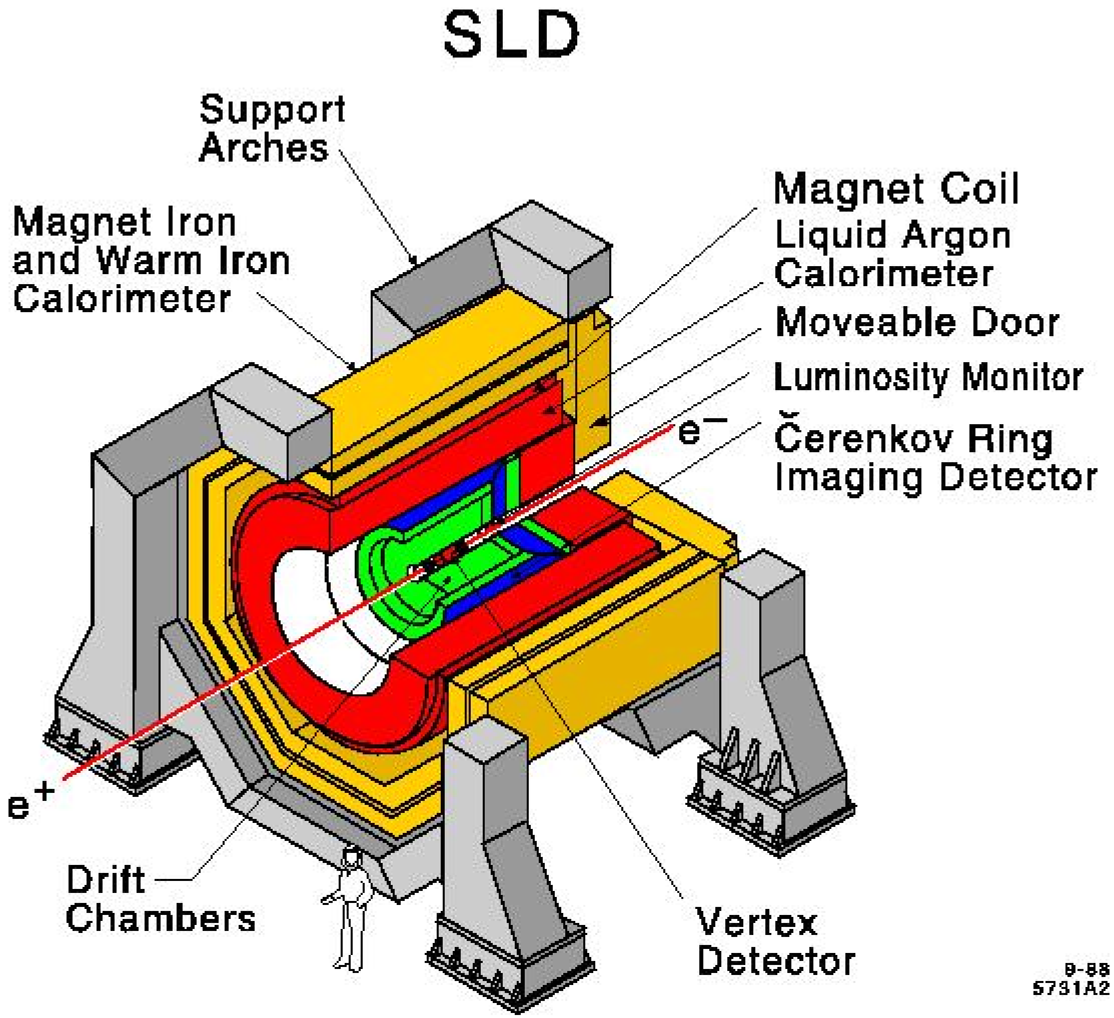
Particle Data Group

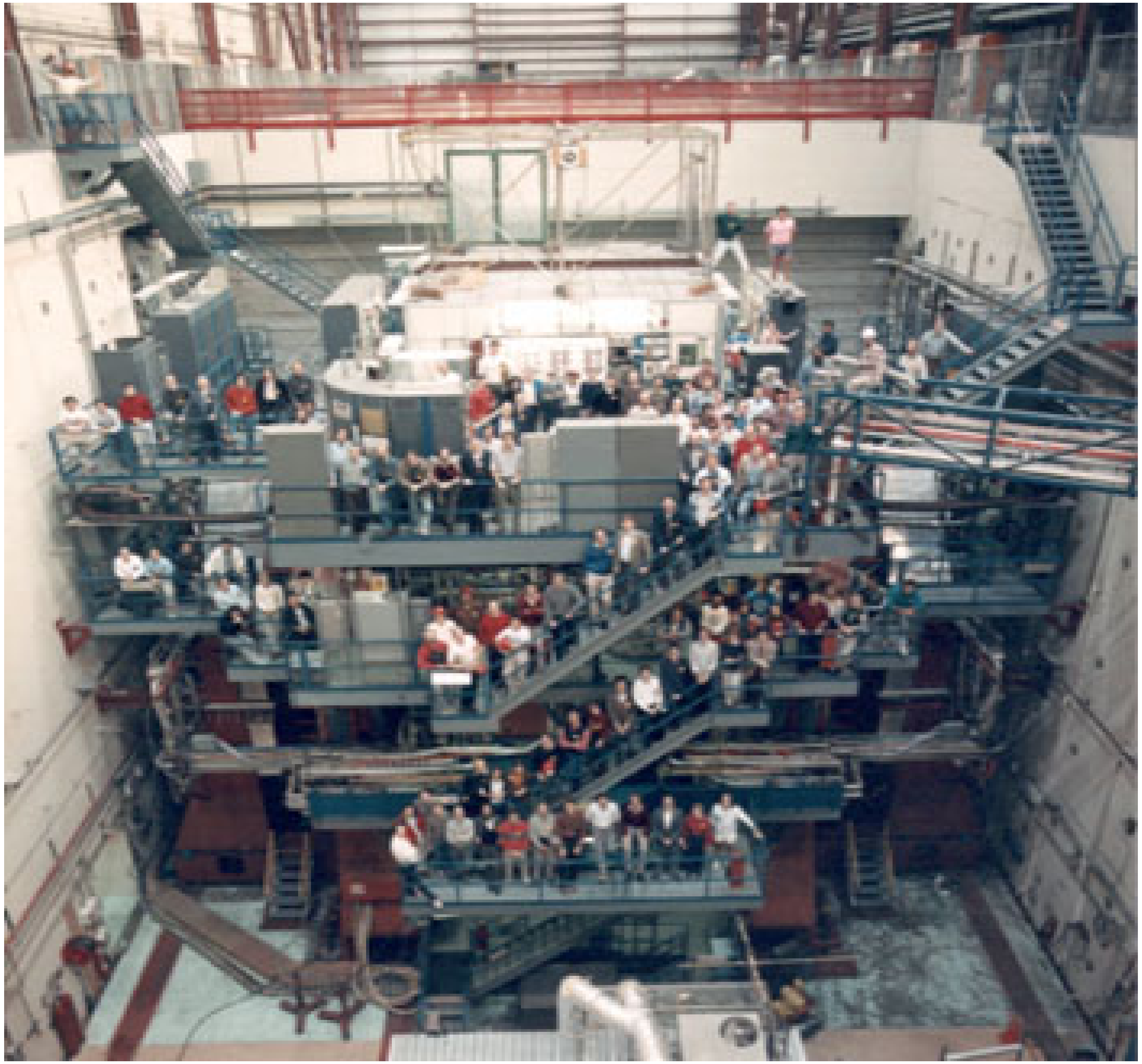
Table 28.8: Resolution of typical electromagnetic calorimeters. E is in GeV.

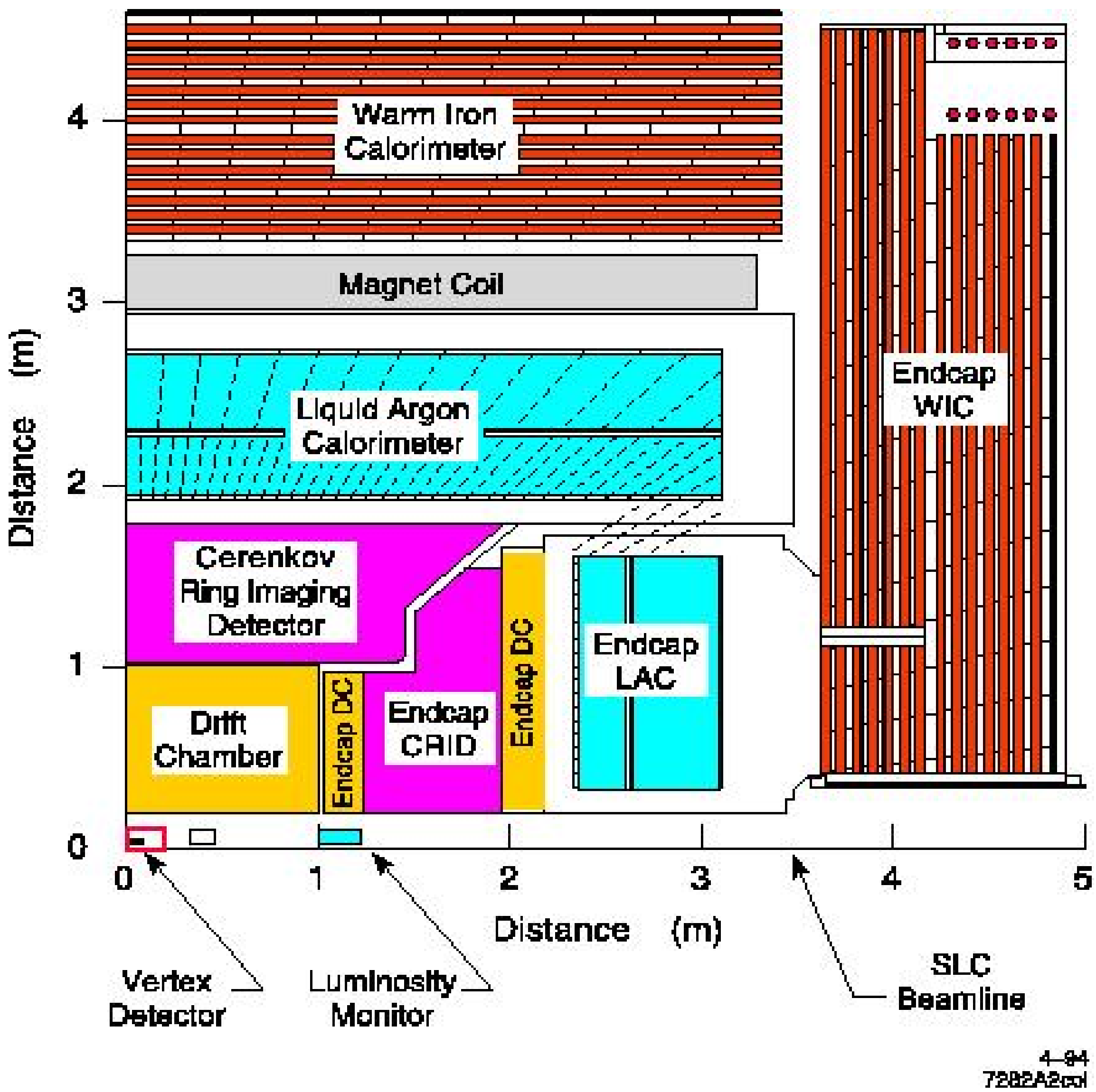
Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	20–$30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	20–$30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

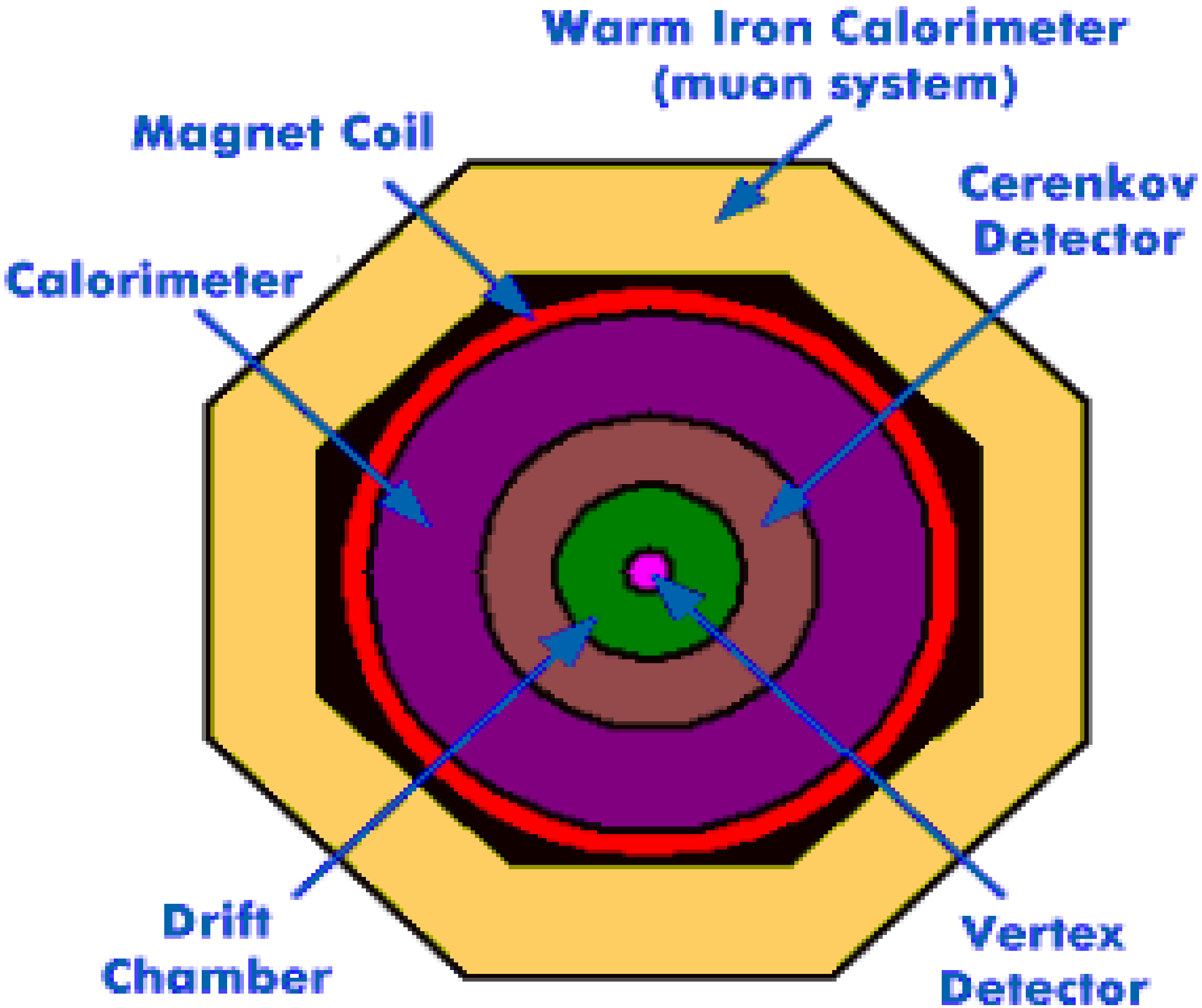
SYSTEMS - Around 1990. SLAC Linear Collider



Centre of Mass Energy around 91 GeV electron-positron
Incident particles are “point-like”. Carry all the energy.

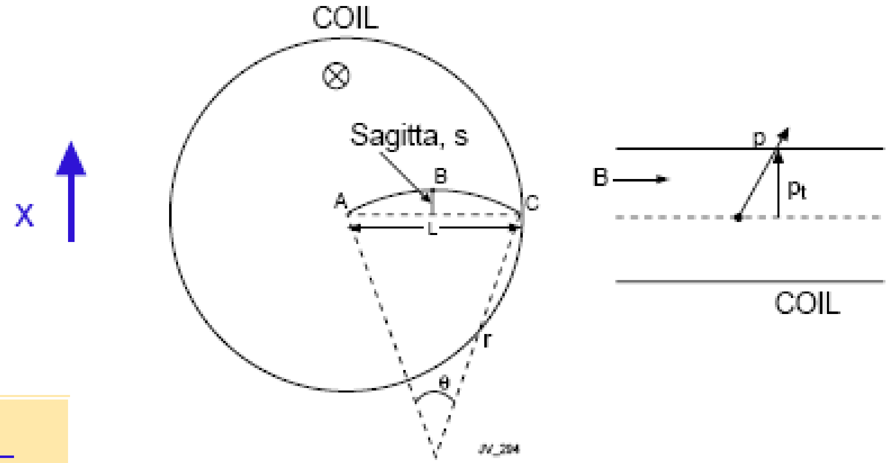



Warm Iron Calorimeter
Magnet Coil
Liquid Argon Calorimeter
Cerenkov Ring Imaging Detector
Drift Chamber
Endcap DC
Endcap CRID
Endcap DC
Endcap LAC
Endcap WIC
Distance (m)
Distance (m)
Vertex Detector
Luminosity Monitor
SLC Beamline
4–94
7282A2col


Warm Iron Calorimeter
(muon system)
Magnet Coil
Cerenkov
Detector
Calorimeter
Drift
Chamber
Vertex
Detector

http://oldweb.ct.infn.it/~rivel/Didat/2Tracking.pdf

Charged Particle in a Magnetic Field



Radius of curvature $r = \dfrac{p_T}{0.3B}$

If r>>L then $\sin\dfrac{\theta}{2} = \dfrac{L}{2r} \Rightarrow \dfrac{\theta}{2} \approx \dfrac{L}{2r} \Rightarrow \theta \approx \dfrac{0.3BL}{p_T}$

Sagitta

$$s = r - r\cos(\theta/2)$$

$$\approx r\left[1 - \left(1 - \frac{1}{2}\frac{\theta^2}{4}\right)\right]$$

$$= \frac{r\theta^2}{8} \approx \frac{0.3BL^2}{8p_T}$$

e.g. s ≈ 3.75 cm
for p_T=1 GeV/c, L=1m and B=1T

http://oldweb.ct.infn.it/~rivel/Didat/2Tracking.pdf

Relative Momentum Resolution

$$\frac{dp_T}{p_T} = \frac{\sigma_s}{s} = \frac{\sqrt{(3/2)}\ \sigma_x}{s}$$

$$\frac{dp_T}{p_T} = \frac{\sqrt{3}}{2}\sigma_x \frac{8p_T}{0.3BL^2} \qquad (2)$$

Momentum resolution degrades linearly with increasing momentum, improves for higher field and the larger radial size of tracking cavity (quadratic in L)

Arrangement of measuring points

Uniform spacing

$$\frac{dp_T}{p_T} = \frac{\sigma_x p_T}{0.3BL^2}\sqrt{\frac{720}{N+4}}$$

e.g. $dp_T/p_T \approx 0.5\%$ for p_T=1 GeV/c, L=1m, B=1T, σ_x = 200 μm and N=10

BUT in a real tracker errors due to multiple scattering has to be included .

http://oldweb.ct.infn.it/~rivel/Didat/2Tracking.pdf

Multiple Scattering

- Electric field close to atomic nucleus may give large acceleration to a charged particle.
- For a heavy charged particle ($m \geq m_\mu$) results in a change of direction

Small impact parameter

single large angle scatter can occur (Rutherford Scattering)

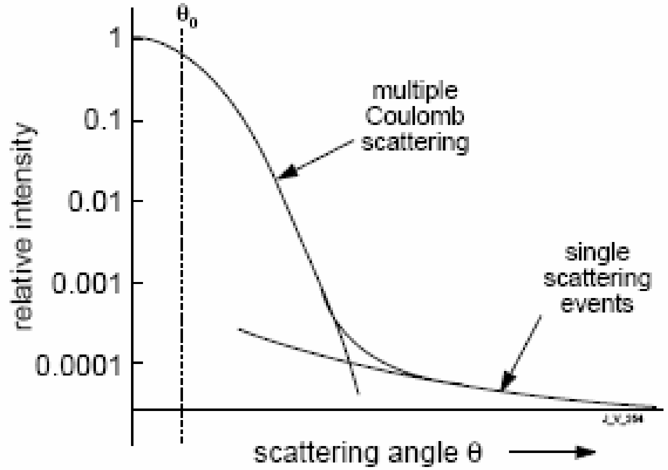
$$\frac{d\sigma}{d\Omega} \propto \frac{1}{\sin^4 \theta / 2}$$

Large impact parameter

- more probable

nuclear charge partly screened by atomic electrons, scattering angle is small

- thick material → large no. of random and small deflections - multiple Coulomb scattering



rms of scattering angle

$$\theta_0 \approx \frac{13.6\ MeV}{\beta pc} Z_{inc} \sqrt{\frac{L}{X_0}}$$

CSS99

http://oldweb.ct.infn.it/~rivel/Didat/2Tracking.pdf

Multiple Scattering

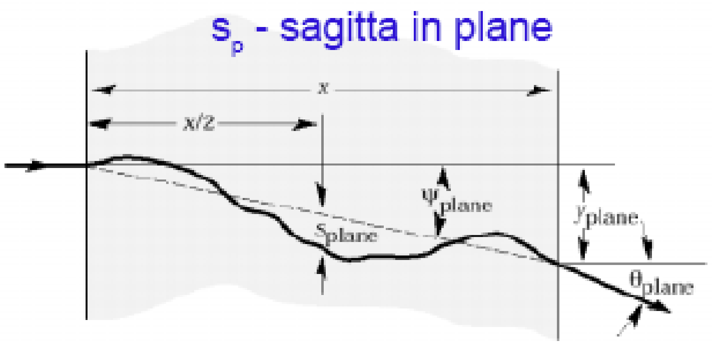


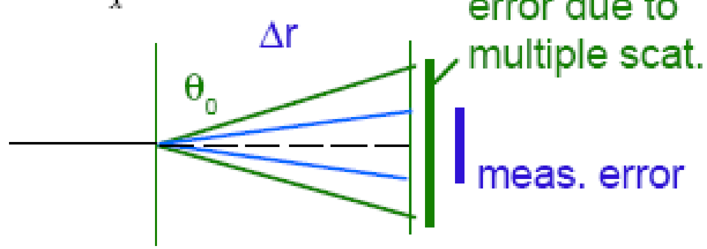
Figure 23.5: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

Apparent sagitta due to multiple scattering

$$s_p = \frac{L\theta_0}{4\sqrt{3}}$$

If extrapolation error from one plane to next is larger than the point resolution then momentum resolution is degraded i.e. if

$$\theta_0 \ \Delta r > \sigma_x$$



Relative momentum resolution due to multiple scattering is

$$\therefore \ \frac{s_p}{s} = \left.\frac{dp}{p}\right|_{ms} \approx 0.05 \frac{1}{B\sqrt{LX_0}} \quad \text{since } s = \frac{0.3BL^2}{8p}$$

B in T, L and X_0 in m

i.e. Resolution is independent of p and α 1/B

http://oldweb.ct.infn.it/~rivel/Didat/2Tracking.pdf

Momentum Resolution

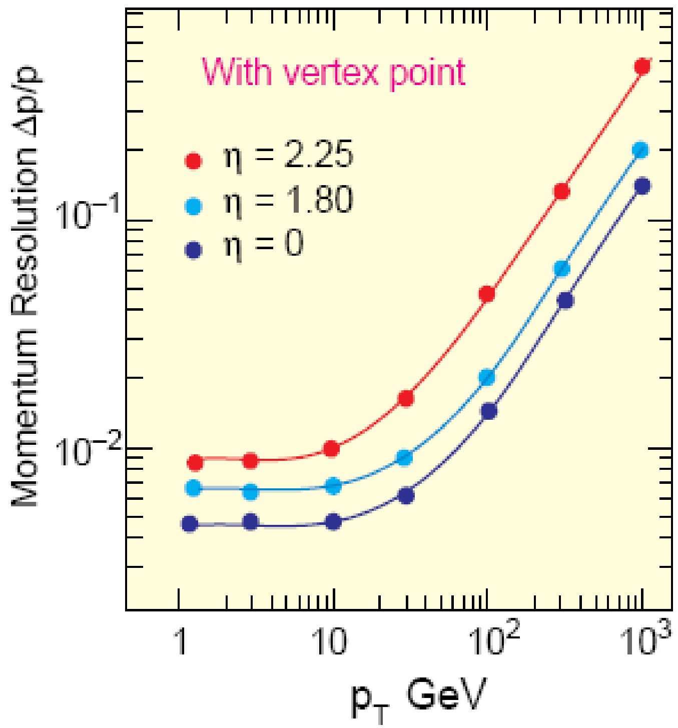
e.g. argon gas, L = 1 m, B = 1 T

$$\left.\frac{dp}{p}\right|_{ms} \approx 0.5\%$$

Material	X_0 (cm)
Argon	11000
Al	8.9
Si	9.4
Pb	0.56

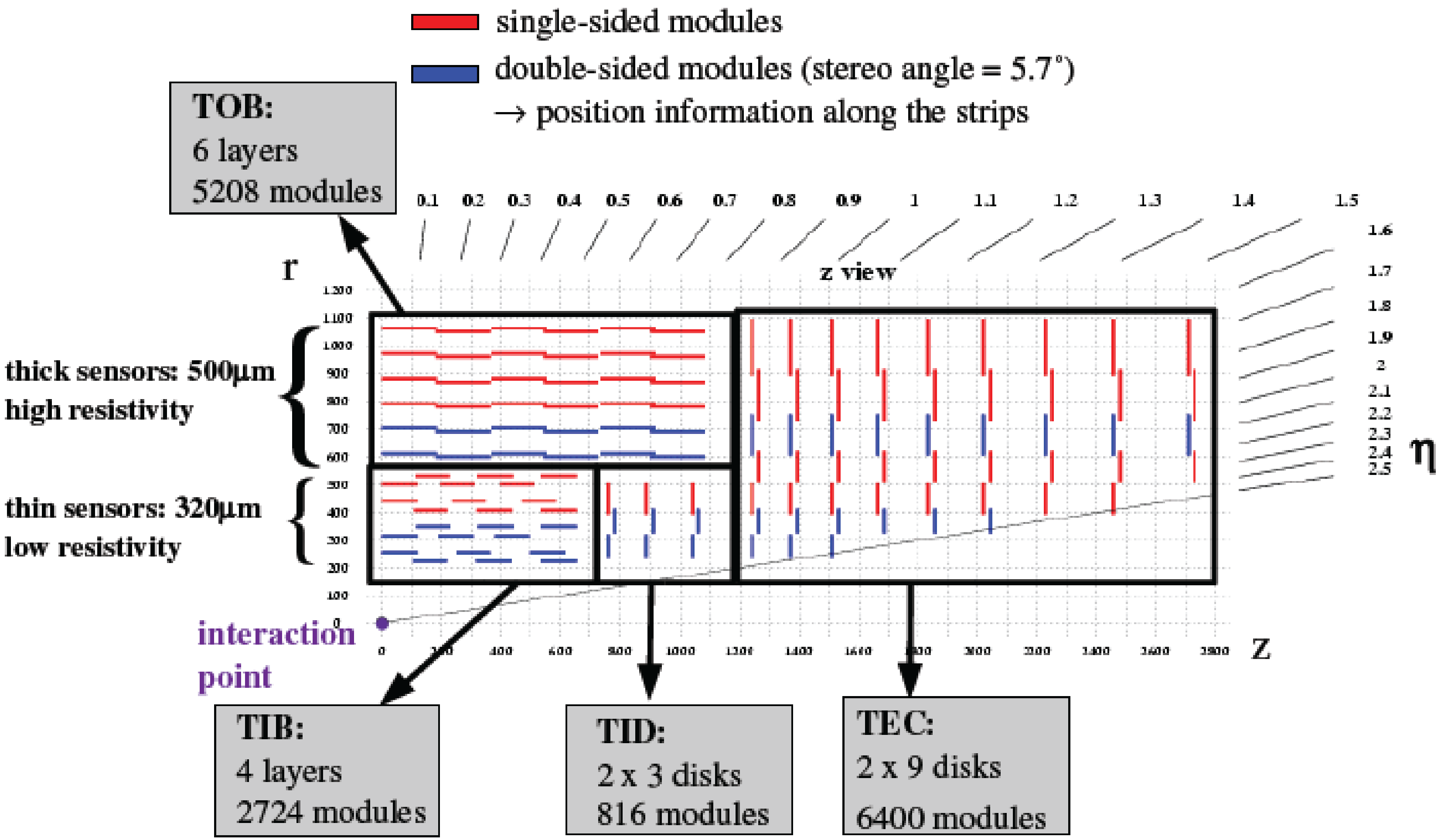
Use low Z, low mass material for tracking

Estimated Momentum Resolution v/s p_T in CMS

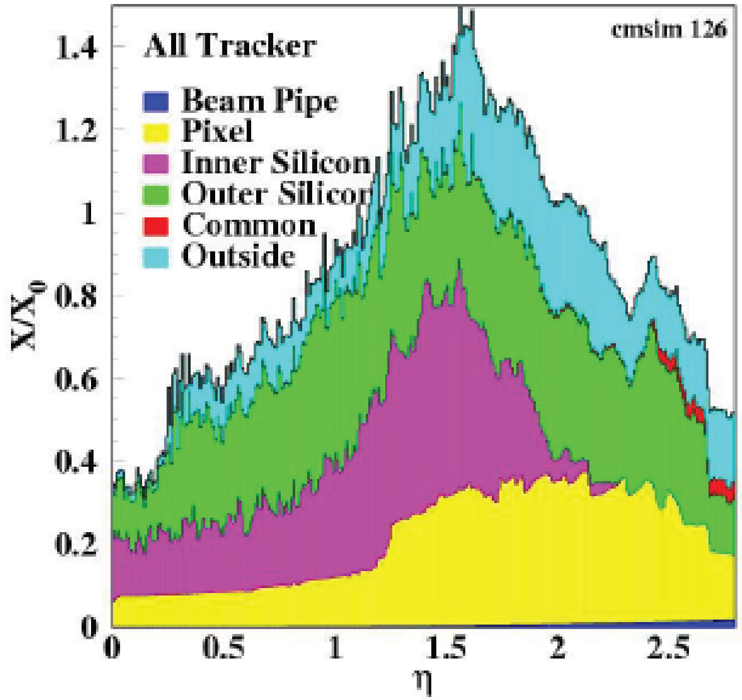


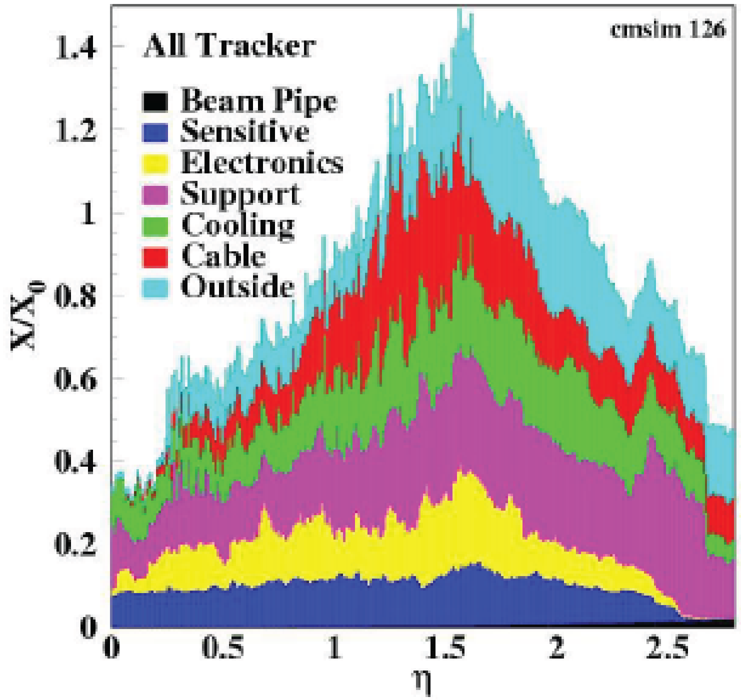
COMMENT : CMS USE SILICON DETECTORS .

Schematic cross section of one quarter of the tracker:



Tracker Material Budget

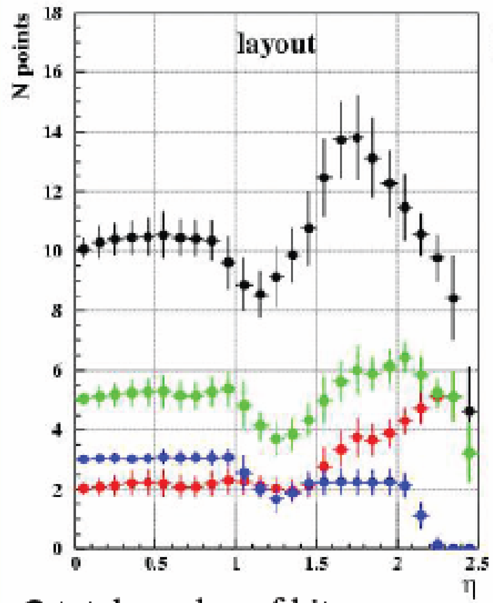




- Conversion probability for photons almost 50%
- Material budget dominated by services

Performance of the CMS Tracker

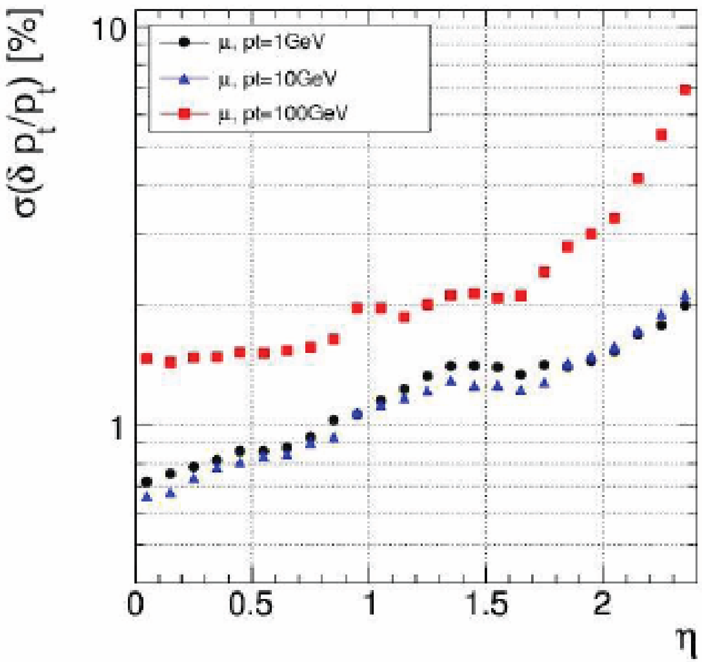
# of hits per track in the strip tracker:



- total number of hits
- total number of double-sided hits
- double-sided hits in thin detectors
- double-sided hits in thick detectors

⇒ At least 10 measurement points, except for region between barrel and end cap

Transverse momentum resolution for muons with p_T = 1 GeV, 10 GeV, 100 GeV:



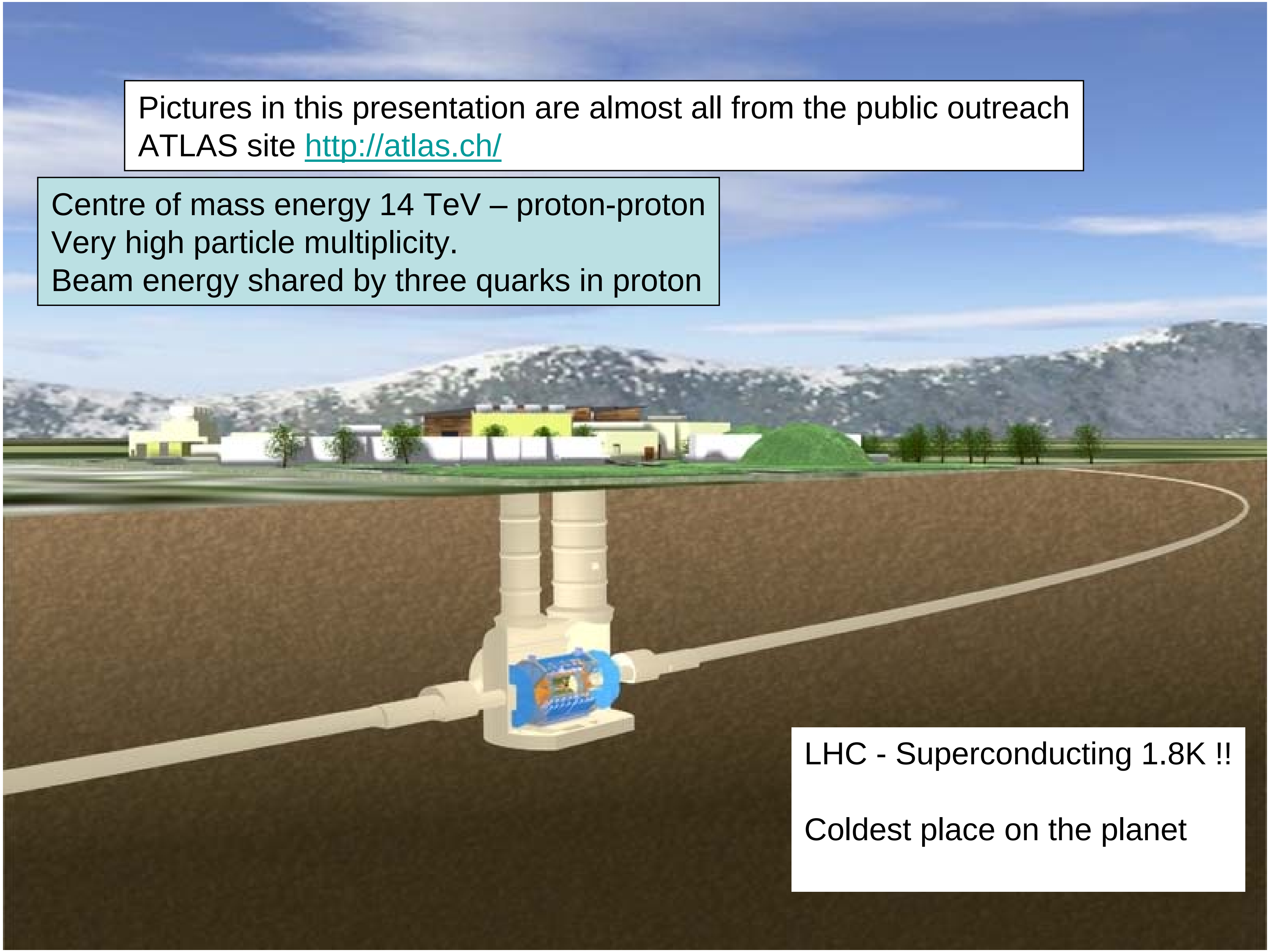
⇒ Resolution dominated by tracker lever arm

⇒ Barrel: resolution of 1.5% for p_T=100 GeV

Conclusion; gets 0.5% to 1.5% with around 10 hits

Pictures in this presentation are almost all from the public outreach ATLAS site http://atlas.ch/

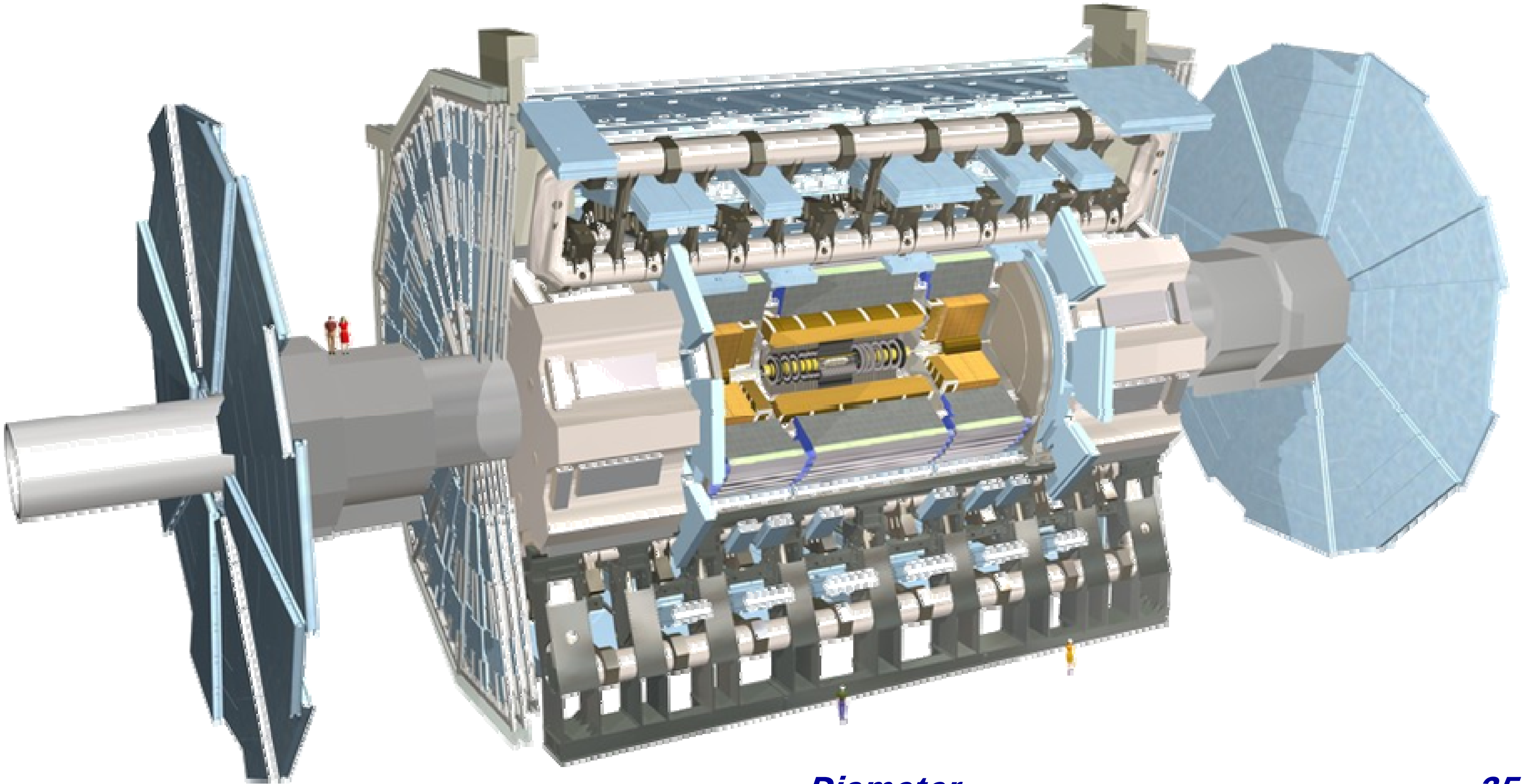
Centre of mass energy 14 TeV – proton-proton
Very high particle multiplicity.
Beam energy shared by three quarks in proton



LHC - Superconducting 1.8K !!

Coldest place on the planet

The ATLAS Detector



Diameter	*25 m*
Barrel toroid length	*26 m*
End-cap end-wall chamber span	*46 m*
Overall weight	*7000 tons*

ATLAS Collaboration

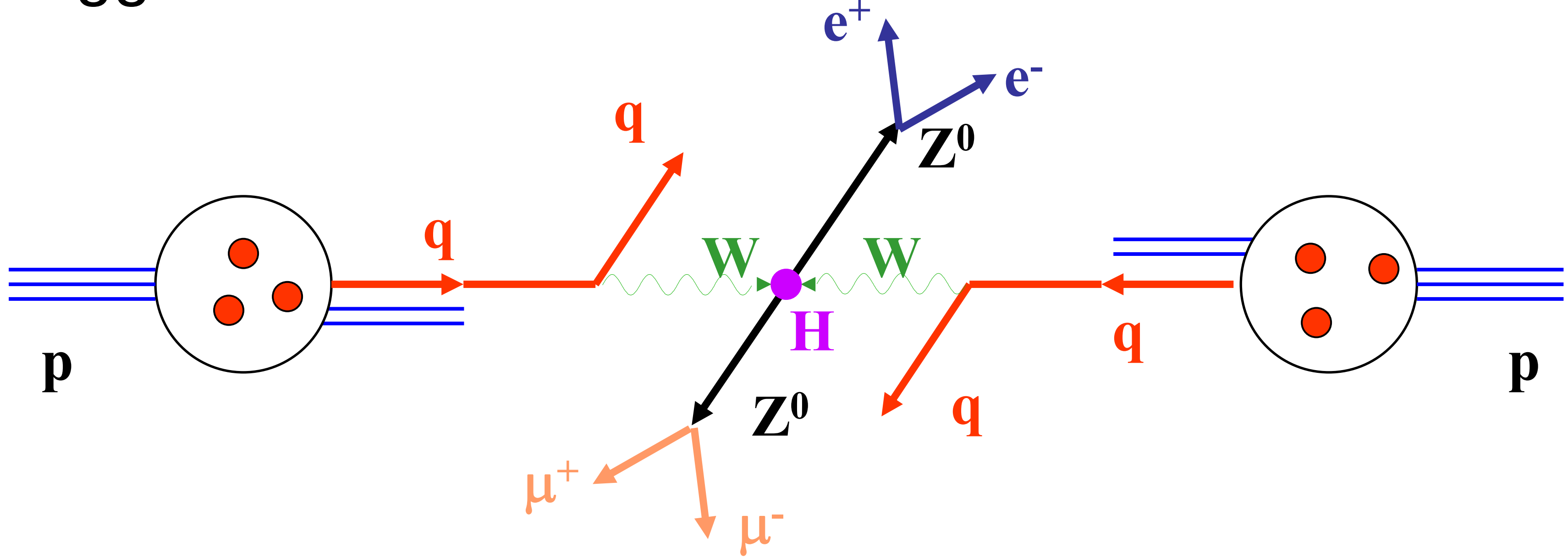
> 35 Countries
> 164 Institutions
2500 Scientific Authors

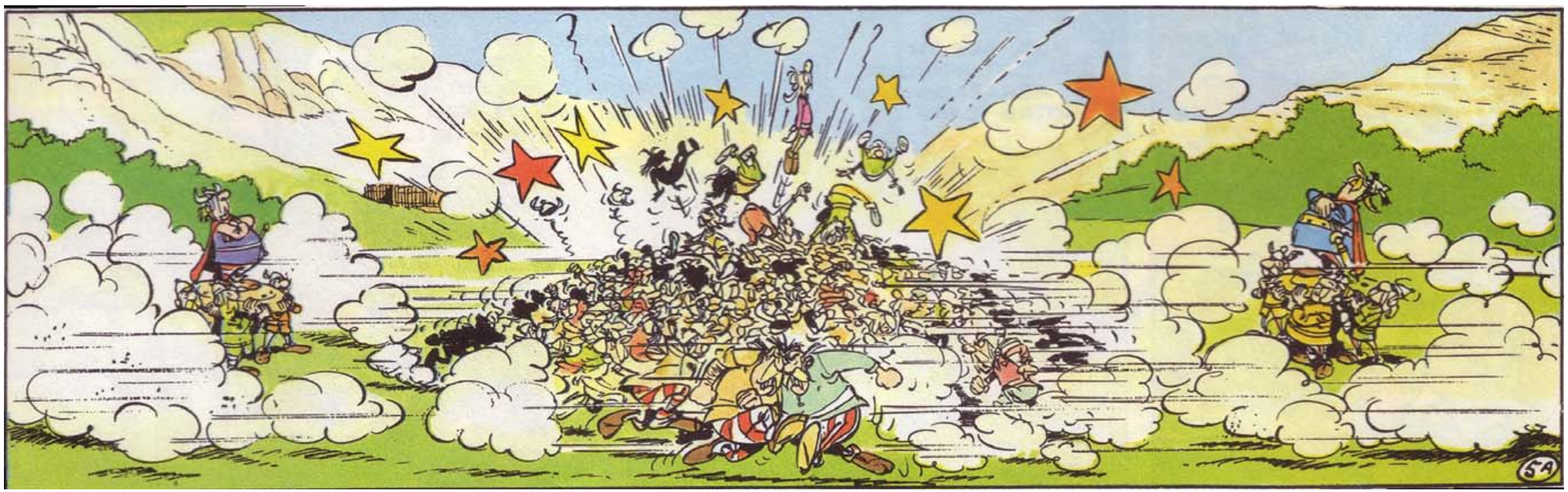
Hard to keep up to date on these numbers!

Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, **Bern**, Birmingham, Bologna, Bonn, Boston, Brandeis, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, Casablanca/Rabat, CERN, Chinese Cluster, Chicago, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Irvine UC, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, Mannheim, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, Munich LMU, MPI Munich, Nagasaki IAS, Naples, New Mexico, New York, Nijmegen, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Ritsumeikan, UFRJ Rio de Janeiro, Rochester, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, Southern Methodist Dallas, NPI Petersburg, Stockholm, KTH Stockholm, Stony Brook, Sydney, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Toronto, TRIUMF, Tsukuba, Tufts, Udine, Uppsala, Urbana UI, Valencia, UBC Vancouver, Victoria, Washington, Weizmann Rehovot, Wisconsin, Wuppertal, Yale, Yerevan

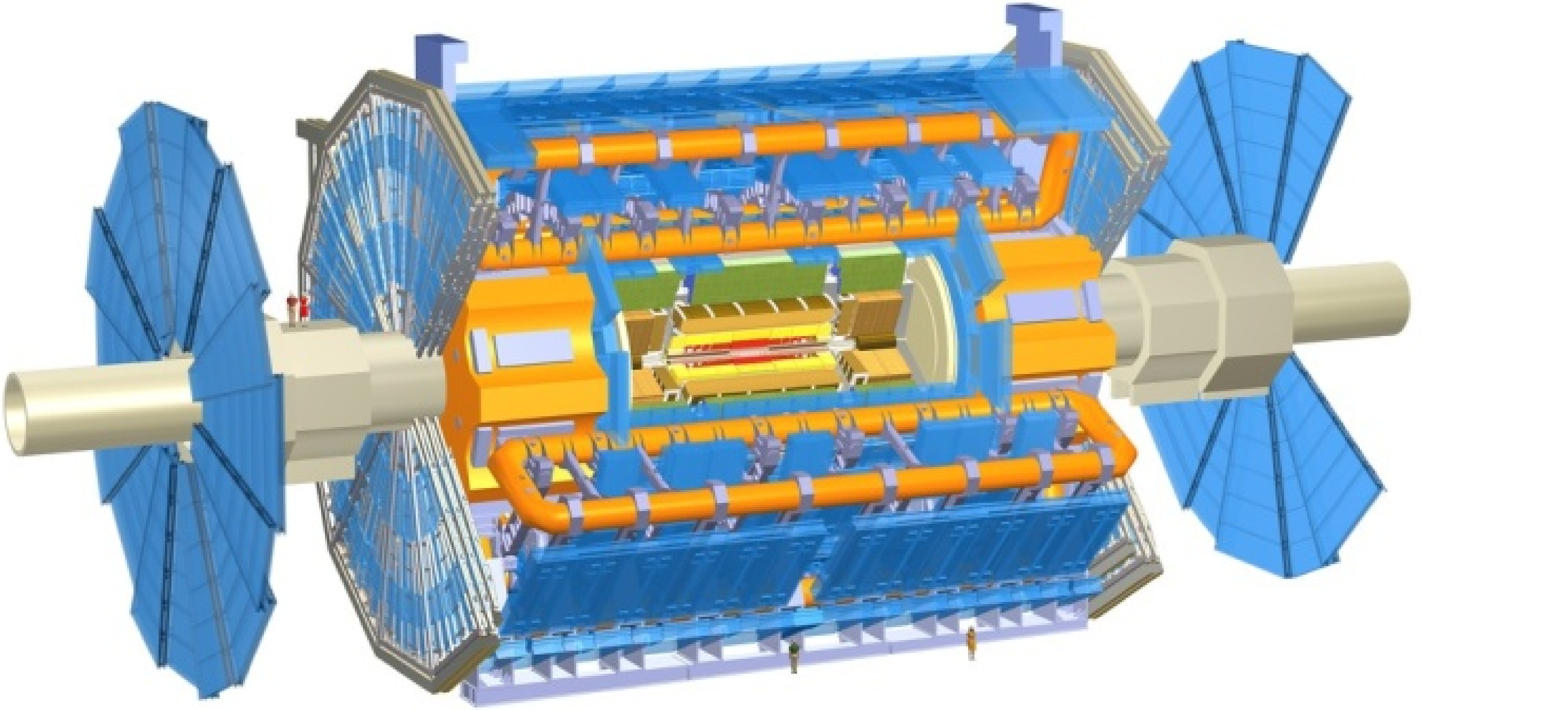
Oxford, Cambridge, UCL, Glasgow, Liverpool, Lancaster, Manchester, Queen Mary, Royal Holloway, RAL, Birmingham

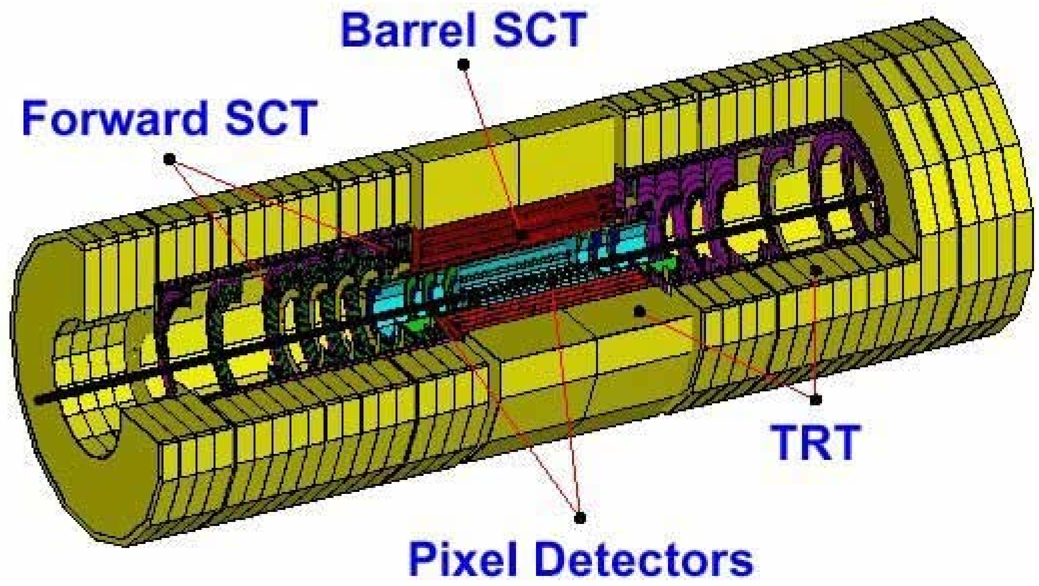
Higgs Production in Proton-Proton Collisions

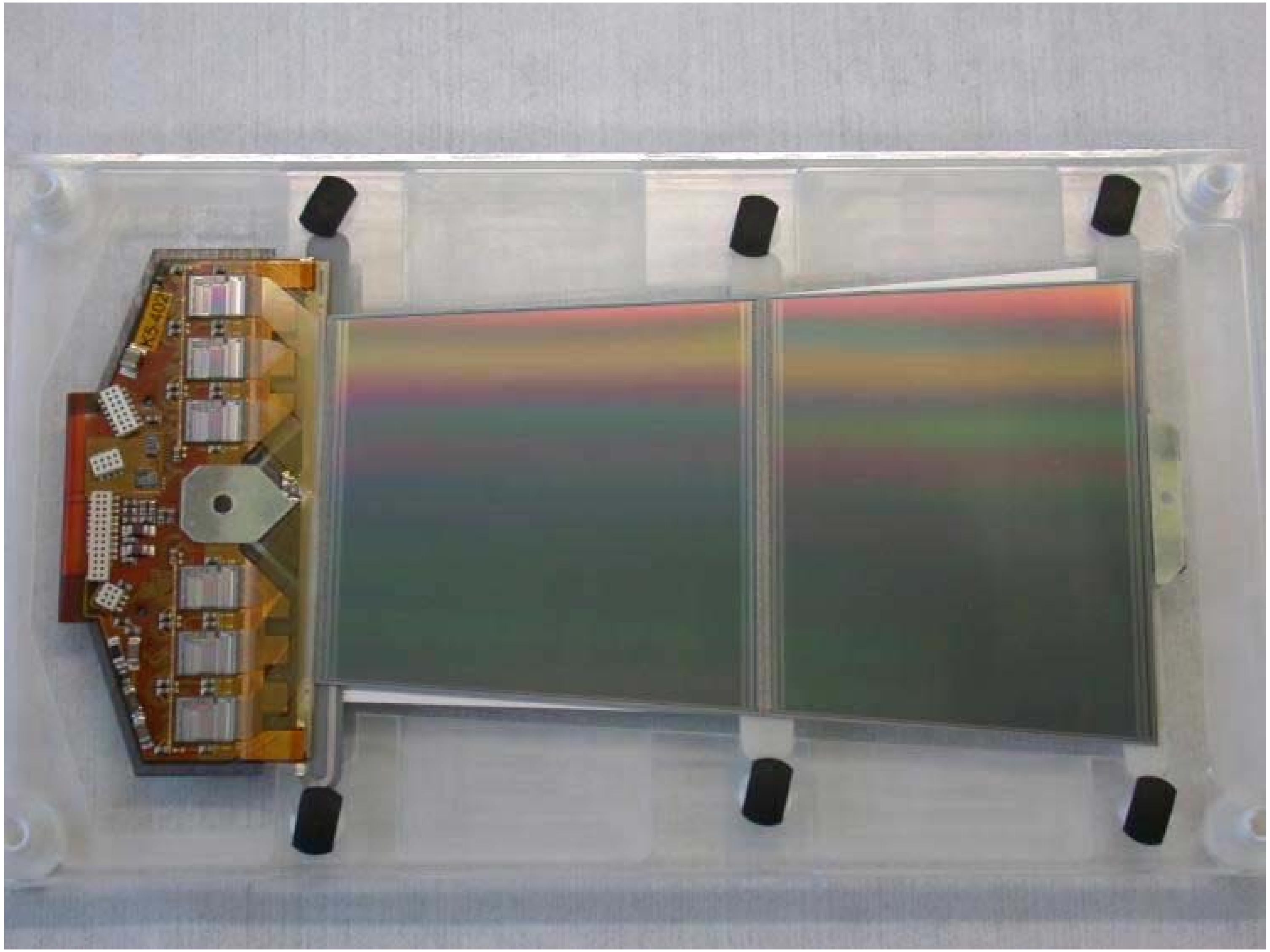


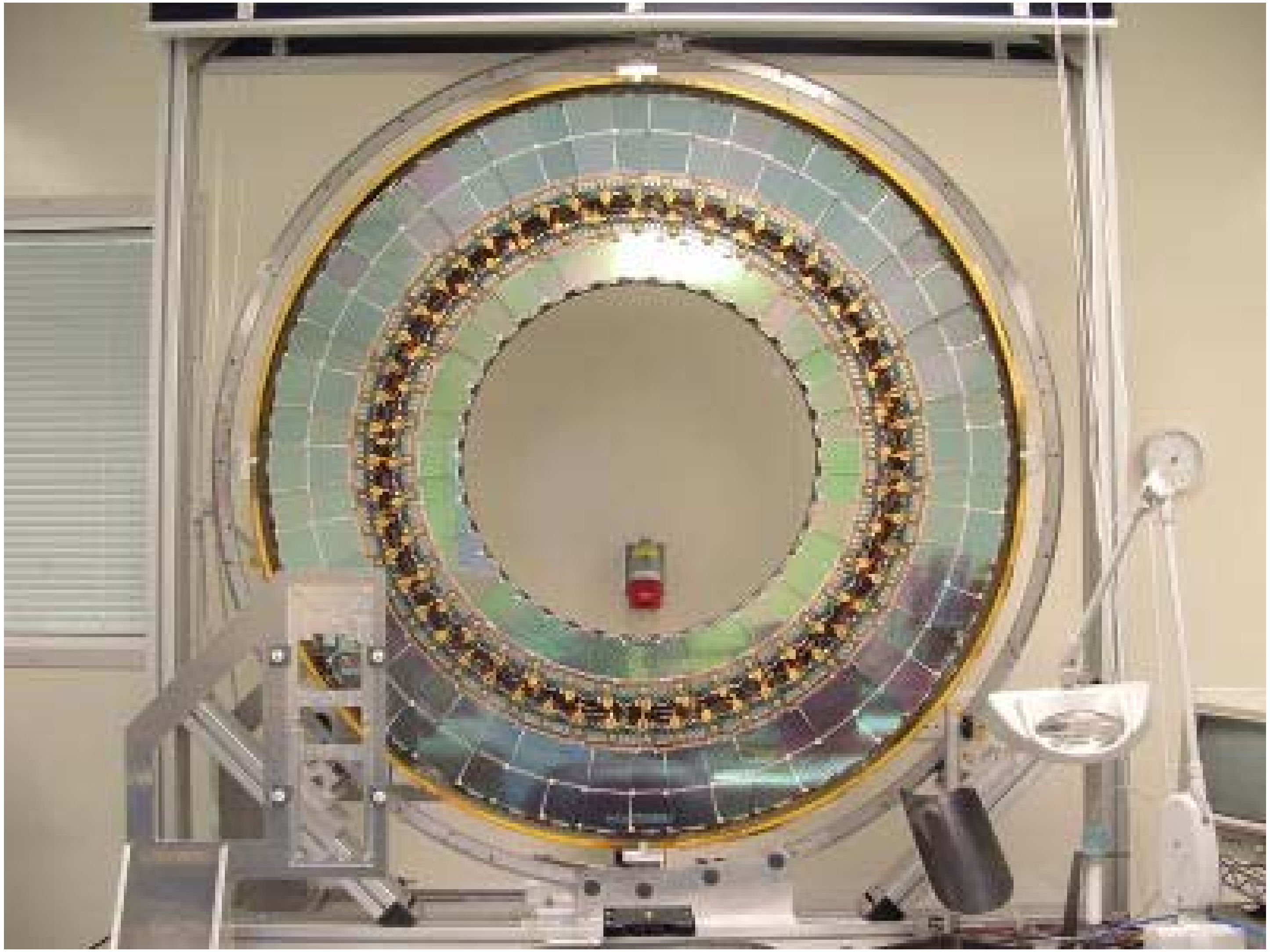


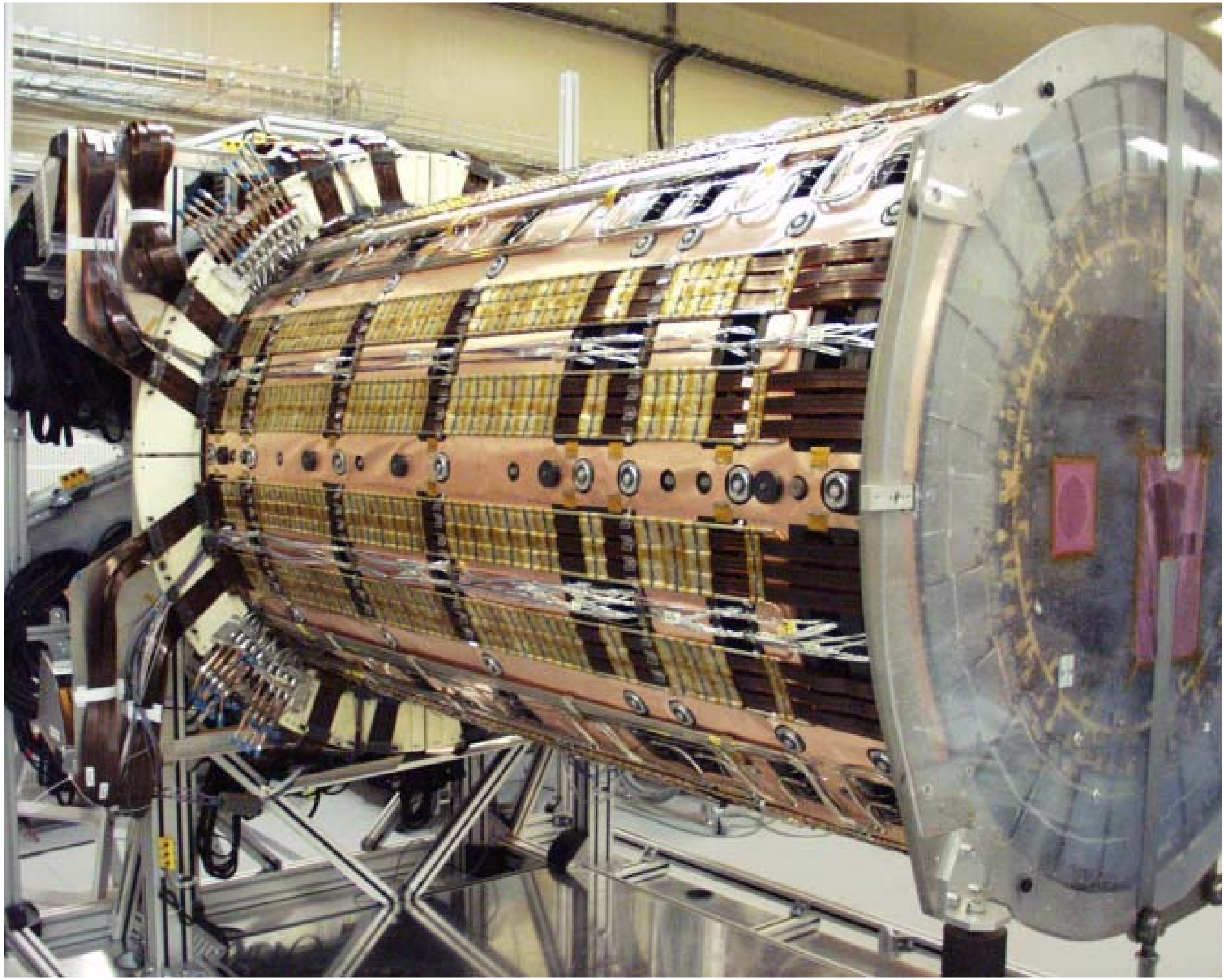
Thanks to H P Beck, University of BERN

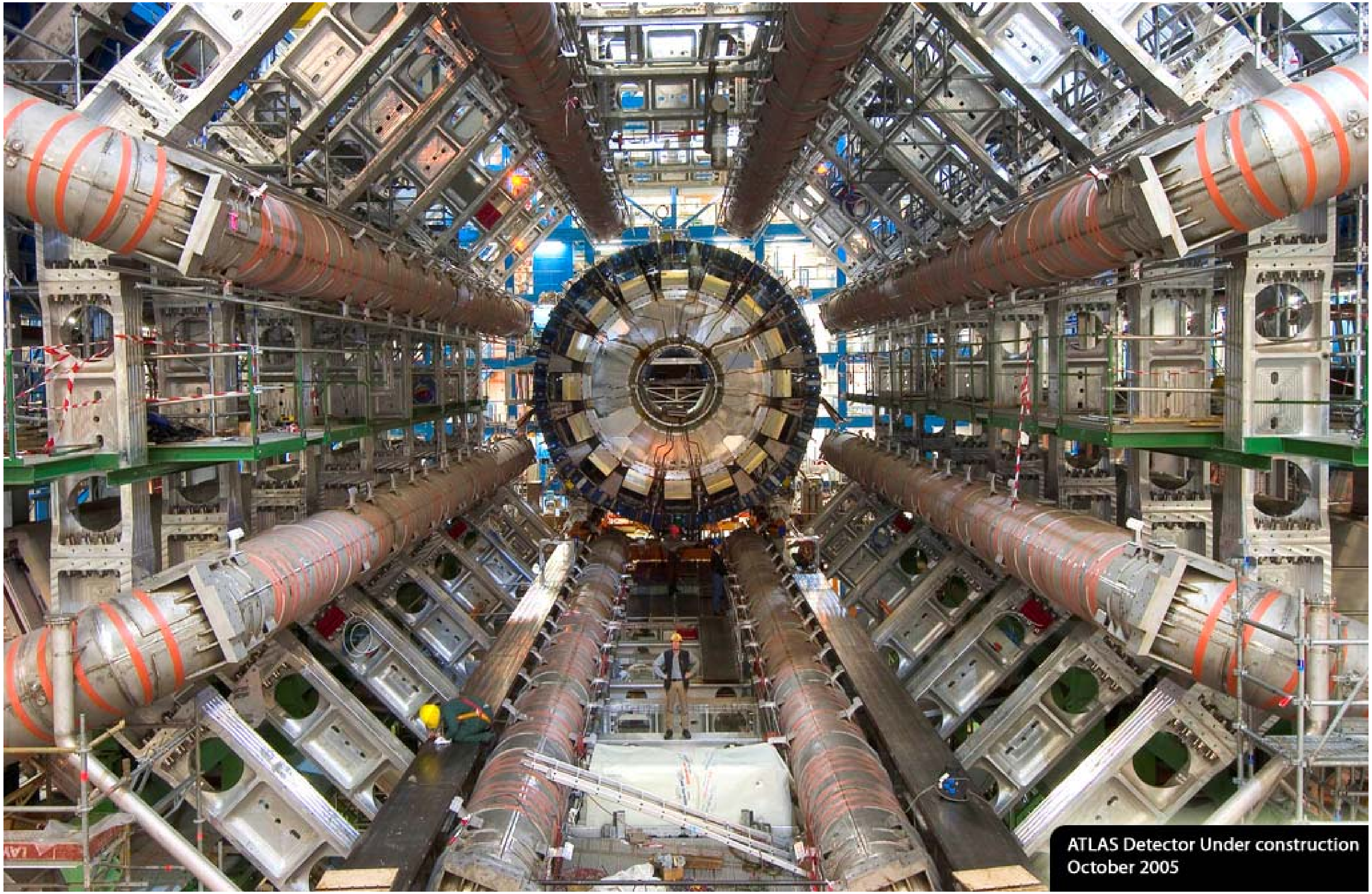



Barrel SCT
Forward SCT
TRT
Pixel Detectors

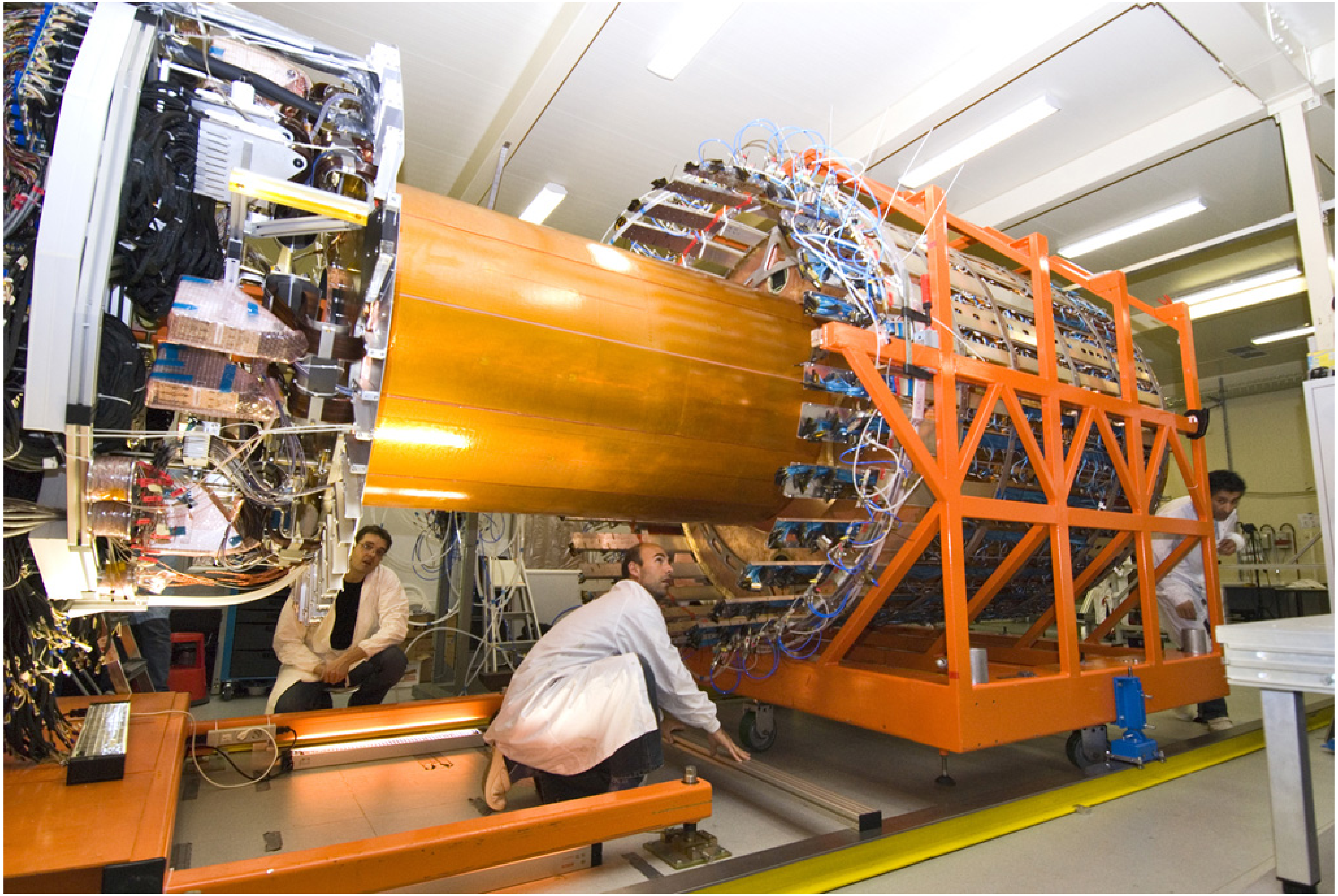


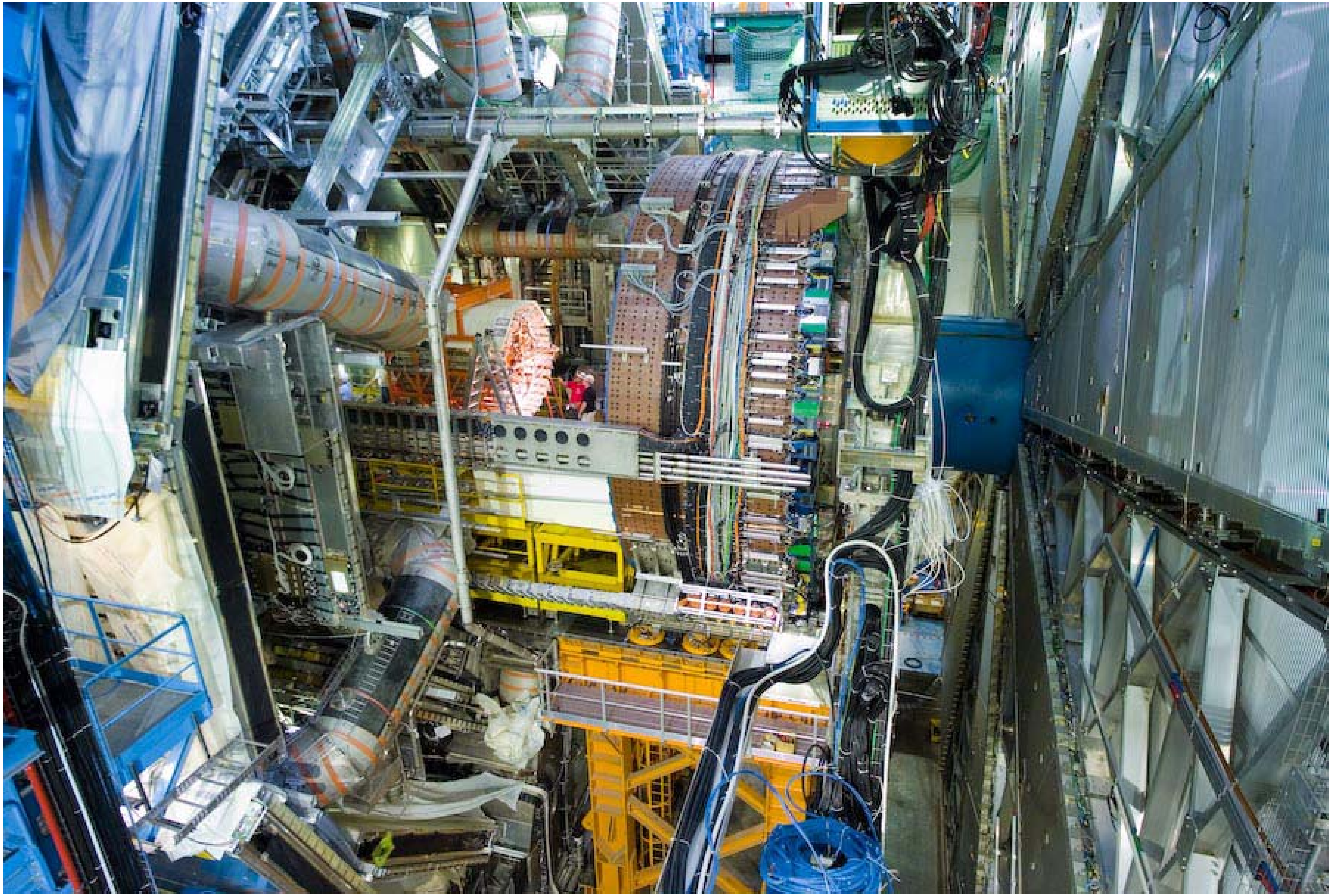


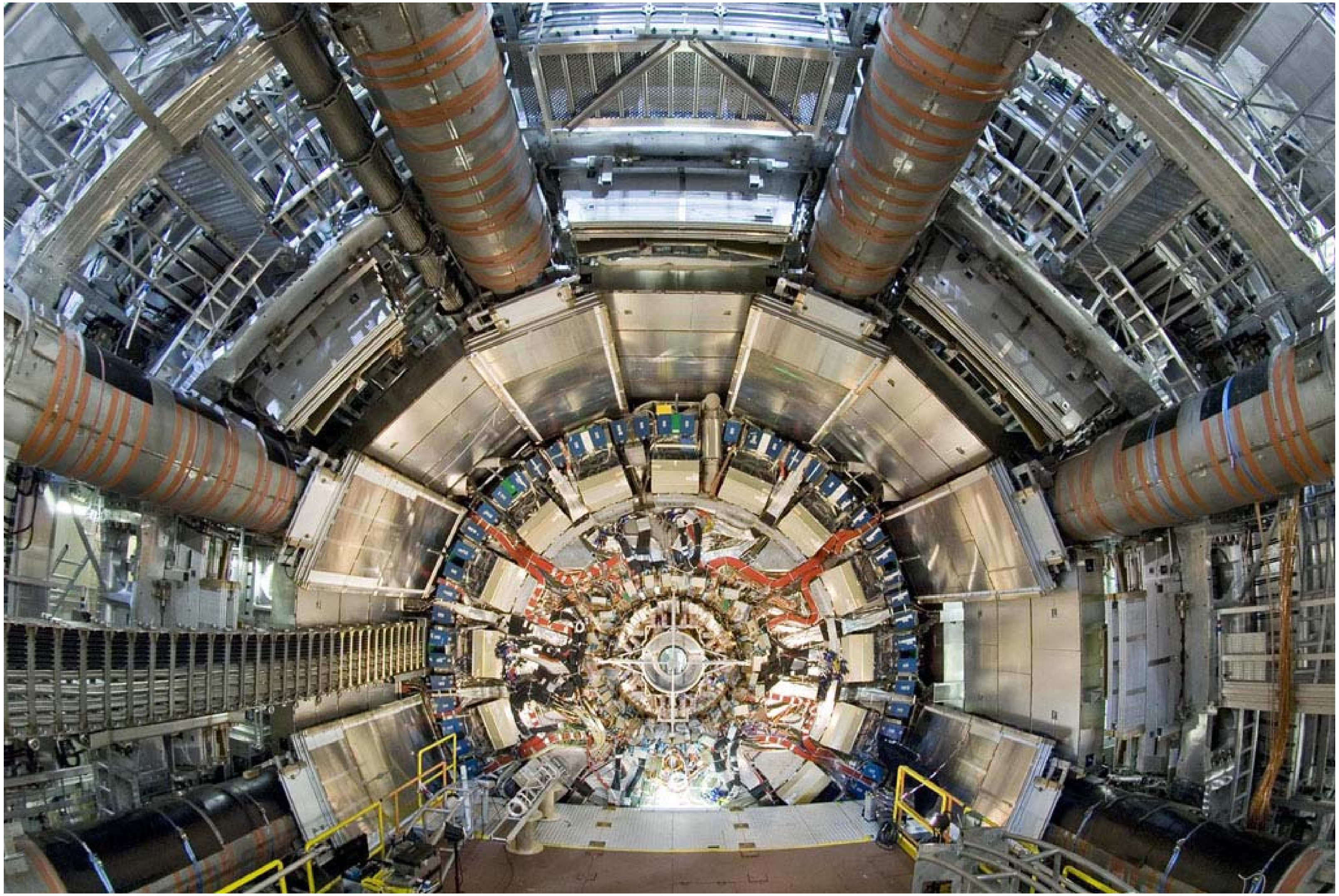


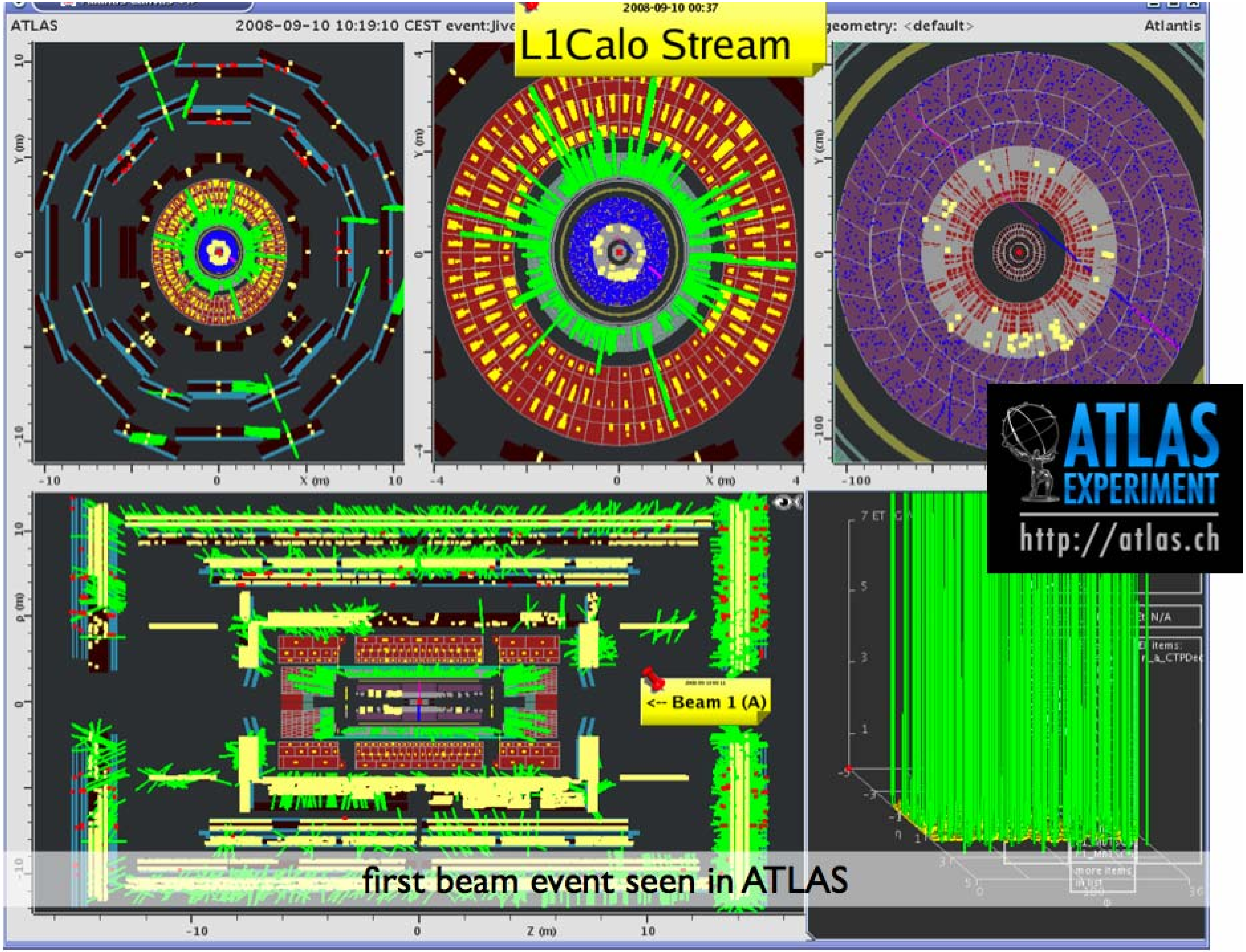


ATLAS Detector Under construction
October 2005





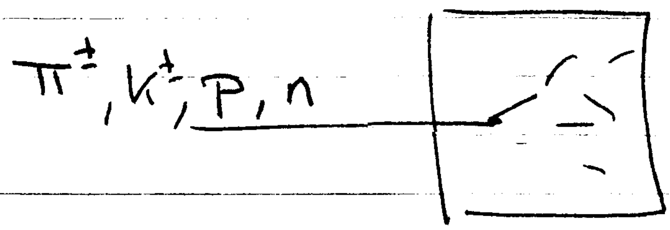




ATLAS
2008-09-10 10:19:10 CEST
geometry: <default>
Atlantis
2008-09-10 00:37
L1Calo Stream
<-- Beam 1 (A)
ATLAS EXPERIMENT
http://atlas.ch
first beam event seen in ATLAS

Lecture 4

Hadron Calorimeters



No equivalent to processes in e.m. shower.

So shower profile very different.

Controlled by nuclear interaction.

Length scale set by λ_I – nuclear interaction length

$$\sigma_{inel} = \sigma_0 A^{0.7} \qquad \sigma_0 \sim 35\,\text{mb}$$

↑ Atomic Mass Number.

$$\lambda_I = \frac{A}{N_A \sigma_{inel}}$$ Property of material

[See plot in slides]

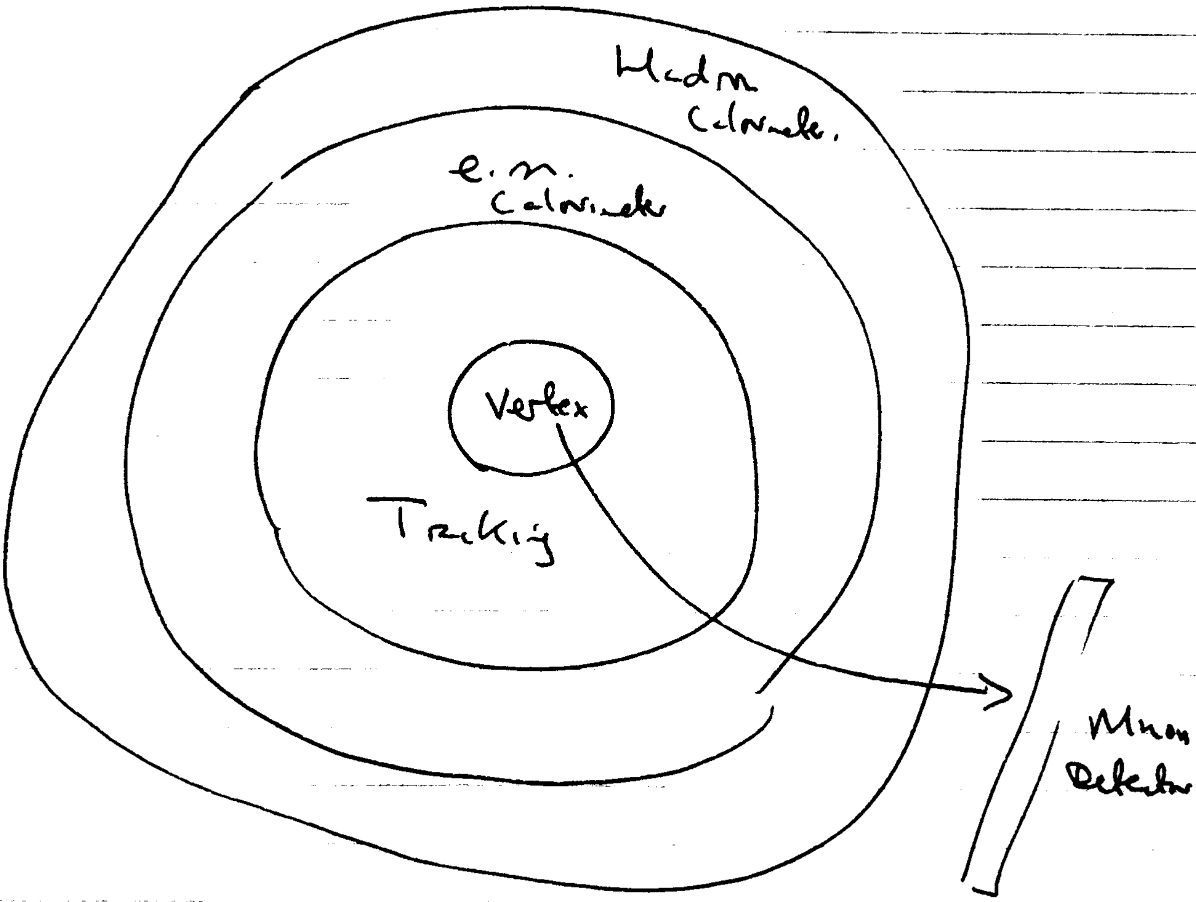
$$I = I_0 e^{-x/\lambda_I}$$ So depth of shower is related to λ_I

Need several λ_I to stop hadron

$$\Rightarrow \frac{\sigma(E)}{E} \propto \frac{(50-100)\%}{\sqrt{E}}$$ Worse than e.m. calorimeters.

$\Rightarrow$ Use sampling calorimeter.

Detector Systems



- No single detector can get all the information.

Low mass detectors

- Vertex Detector to identify particles containing charm, beauty, top quarks
  Silicon detectors are vital.
- Tracking to measure momentum – B field
  e.g. CMS 4T field. See slides
  Silicon now used. Drift chambers &
  TPC's used in the past.
- Measure the energy (destructive)
  electromagnetic calorimeter. e's, γ's, $\pi^0 \to \gamma\gamma$
  hadronic calorimeter $p, n, K^\pm, \pi^\pm$

- Only weakly interacting particles left.

  In particular, muon ($\mu^{\pm}$) survives to last layer.

  But charged, so leaves ionization.

  Muon detectors usually simple gaseous detectors of some form.

- Finally, some particles still escape.

  $\Rightarrow$ neutrinos

  Make system hermetic

  Energy In = Beam Energy

  Energy Out = Energy in the detector.

  Missing Energy $\Rightarrow$ Missing particle
  Neutrinos most likely!