Getting Ready for the LHC: Accelerator, Detectos and Physics

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Nasu, Tochigi, Sep. 26, 2006

Contents

putting emphases on experimental aspects…

1. Introduction


David Gross


David Politzer


Frank Wilczek

Brief History of Particle Physics


Sheldon Glashow


Abdus Salam


Steven Weinberg

1970’s

- Rise of the Standard Model theory (Electroweak and QCD)
- Discovery of J/Ψ (charm quark) in 1974, November Revolution
- Discovery of τ lepton, bottom quark, gluon


Burt Richter


Sam Ting


Martin Perl

Never trust a theorist.

1980’s

- Discovery of weak $W^\pm$ and Z^0 bosons


Carlo Rubbia


Simon van der Meer

1990’s

- Discovery of top quark
- $N_\nu=3$, great success of the Standard Model (gauge theory)
- Discovery of neutrino oscillation

Revolution


Gerardus 't Hooft


Martinus Veltman

Physics in the 21st century ?

- Find the Higgs particle (last Standard Model particle unobserved)
- Find the TeV scale new physics. → **New Revolution ?**

High Energy Particle Physics

- Hierarchy problem and Naturalness
- Fine tuning: $\frac{M_Z^2}{\Lambda^2} \rightarrow \frac{M_Z^2}{M_{GUT}^2} \approx 10^{-28}$

→ There must be new physics in TeV energy range.

  - Unitarity violation without Higgs above 1TeV (W_L W_L scattering)
  - Prediction of light Higgs with LEP data (M_H<207 GeV@95%C.L).
  - (sub-)TeV WIMP dark matter (SUSY-LSP, axion, $\tilde{\nu}_R$ etc.)

LHC proves directly TeV energy range for the first time!

  - Origin of the electroweak symmetry breaking (EWSB)
    - Higgs, compositeness, Higgsless, others?
  - Unification with quantum gravity, Space-Time structure
    - （super）string theory

Standard Model Lagrangian

R. Barbieri, hep-ph/0410223

$$\begin{aligned}\mathcal{L} = &-\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}D\psi \\ &+\psi_i\lambda_{ij}\psi_j h + h.c. \\ &+|D_\mu h|^2 - V(h) \\ &+\frac{1}{M}L_i\lambda^\nu_{ij}L_j h^2 \text{ or } L_i\lambda^\nu_{ij}N_j\end{aligned}$$

	Experiments
The gauge sector	**LEP, SLC, Tevatron**
The flavor sector	**B factories**
The EWSB sector	**LHC, ILC(CLIC)**
The ν−mass sector	**ν factories**

Physics at LHC - main goals for energy frontier machine

1) Probe the origin of the ElectroWeak Symmetry Breaking (EWSB)
2) Search for new physics beyond the Standard Model

Electroweak Symmetry Breaking (EWSB)

Extended Gauge Symmetry

Little Higgs, Higgsless, Left-Right Symmetric Model

Higgs-Gauge Unification

SUSY

(m)SUGRA

GMSB

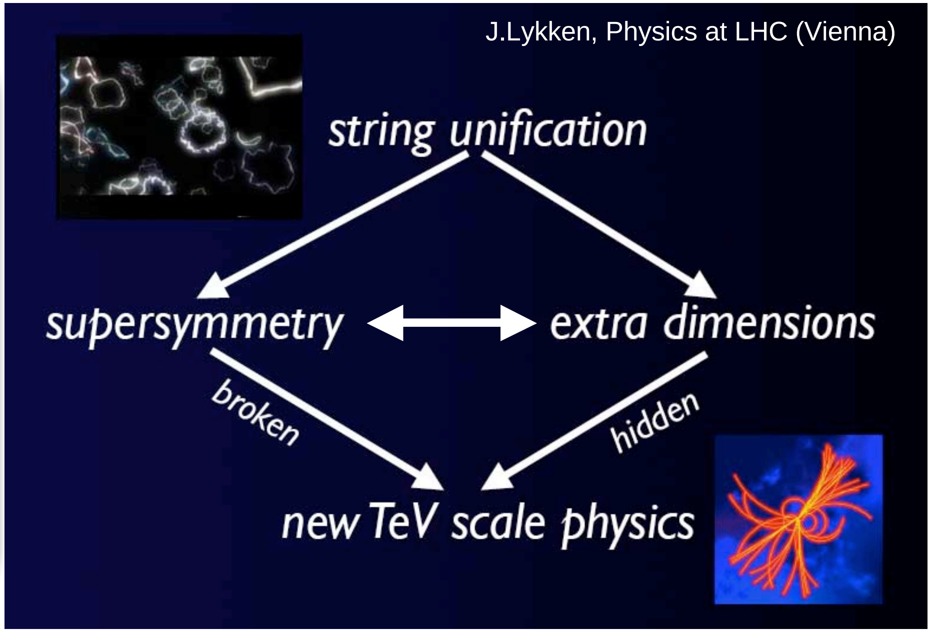
AMSB

Mirage

Split SUSY

RPV

…



J.Lykken, Physics at LHC (Vienna)

Extra-Dimension

LED(ADD)

Randall-Sundrum

Universal ED(KK)

…

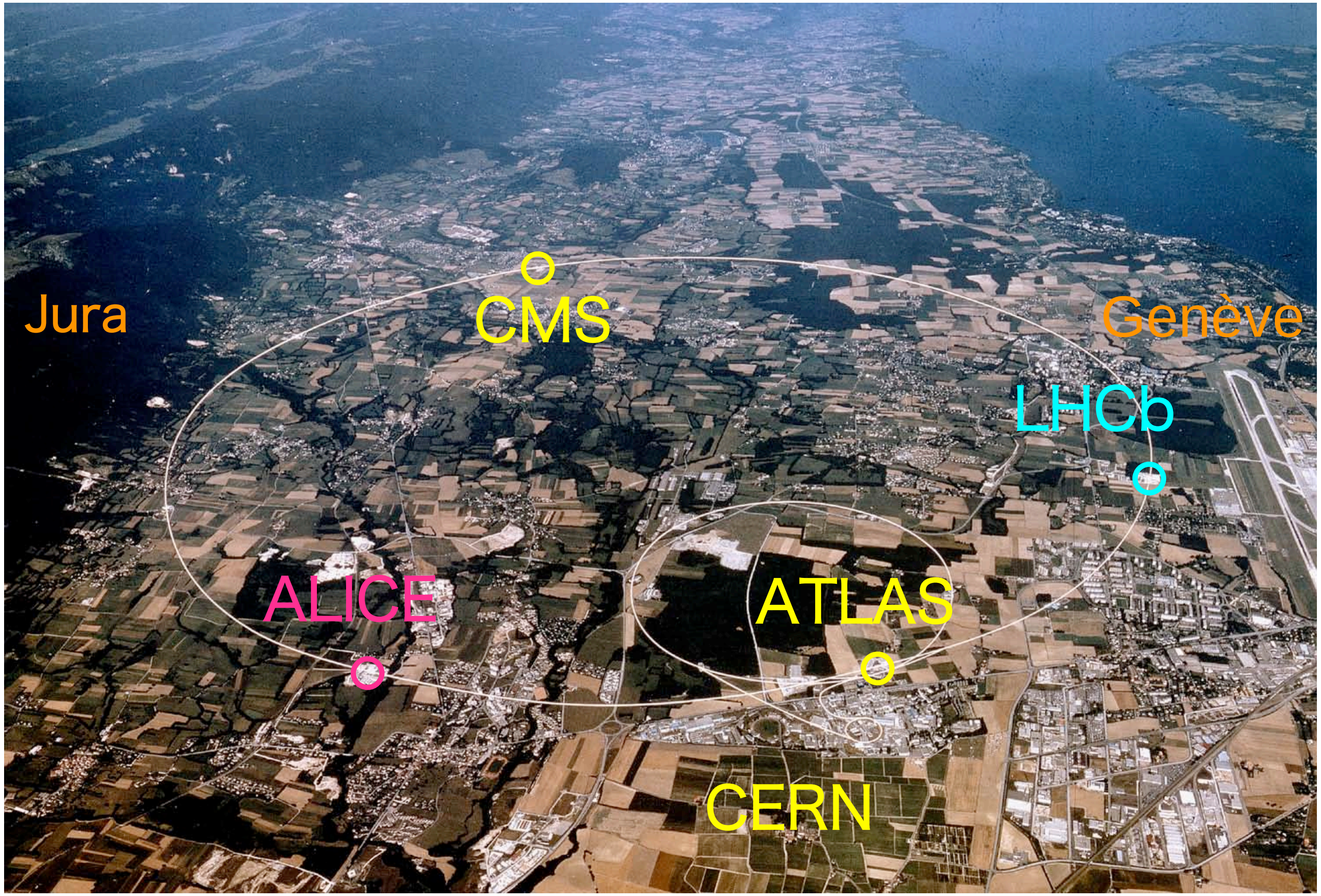
Dynamical Symmetry Breaking

Strong EWSB, Chiral Lagrangian, Technicolor, Composite Higgs, Top-quark Condensation

Precision EW data

Exotics: Compositeness, Lepto-quarks, Monopole …

2. LHC Accelerator

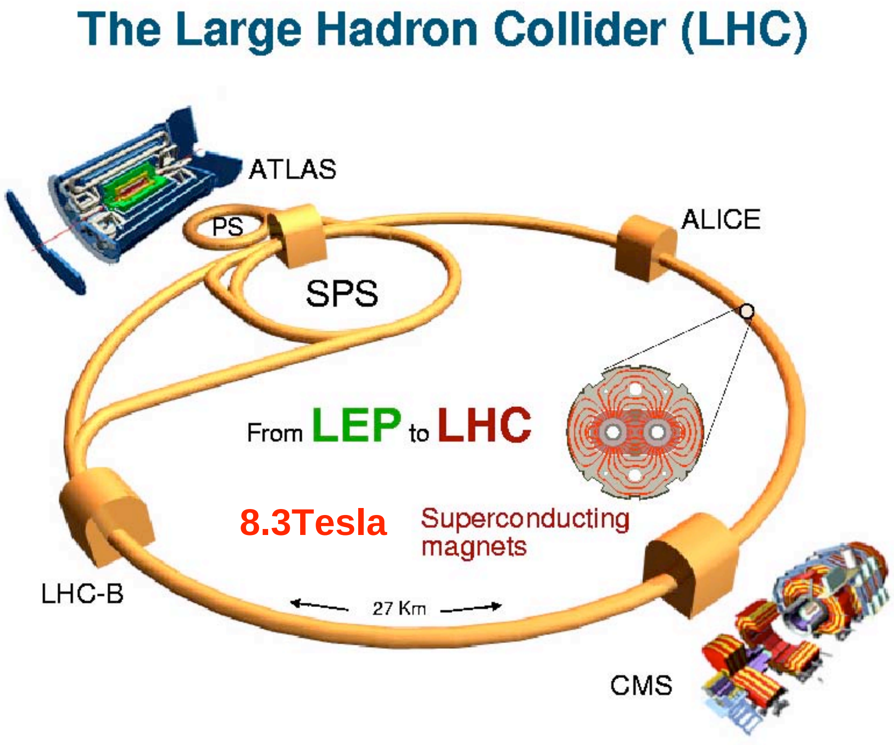


©CERN Photo

LHC Accelerator

Proton-Proton Collider

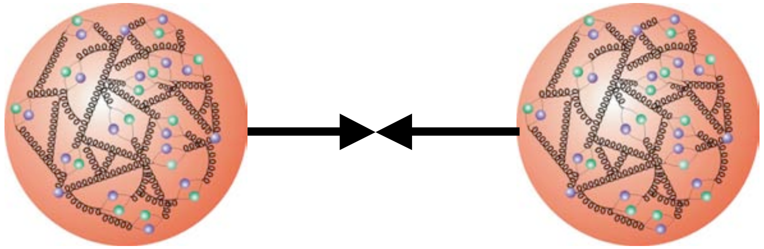
- Centre-of-mass Energy = 14TeV
- Not all energies are available,
- but able to search new particles 3-5TeV.


The Large Hadron Collider (LHC)

Proton

3 valence quarks (uud)

sea quarks + gluons



$$\frac{d\sigma}{dX}=\sum_{j,k}\int_{\hat{X}} f_j(x_1,Q_i)\, f_k(x_2,Q_i)\,\frac{d\hat{\sigma}_{jk}(Q_i,Q_f)}{d\hat{X}}\,F(\hat{X}\rightarrow X;Q_i,Q_f)$$

f_i: PDF(Parton Distribution Function)

	Beams	Energy		Luminosity
LEP	e^+ e^-	200	GeV	10^{32} $cm^{-2}s^{-1}$
LHC	p p	14	TeV	10^{34}
	Pb Pb	1312	TeV	10^{27}

LHC Accelerator

$$L = \frac{\gamma\, f\, k_b N_p^2}{4\pi\varepsilon_n \beta^*} F$$

f	revolution frequency
k_b	no. of bunches
N_p	no. of protons/bunch
ε_n	norm transverse emittance
β^*	betatron function
F	reduction factor xing angle

Magnetic Field

p (TeV) = 0.3 B(T) R(km)

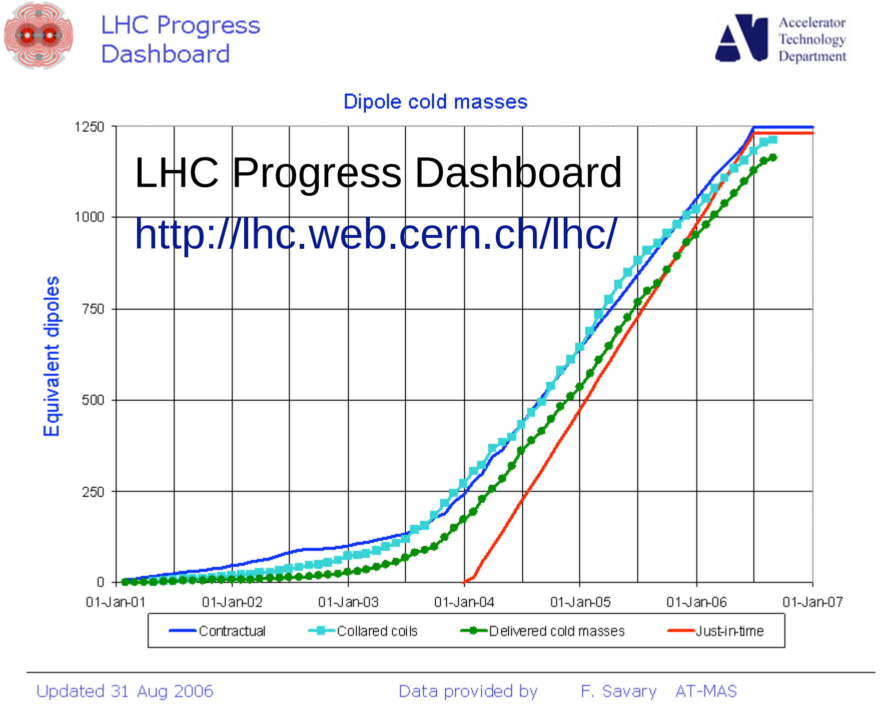
For p= 7 TeV, R= 4.3 km

⇨ **B = 8.4 T**

Beam-beam tune shift $\xi = \frac{N r_p}{4\pi\varepsilon_n}$

Energy at collision	E	7	TeV
Dipole field at 7 TeV	B	8.33	T
Luminosity	L	10^{34}	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Beam beam parameter	ξ	3.6	10^{-3}
DC beam current	I_{beam}	0.56	A
Bunch separation		24.95	ns
No. of bunches	k_b	2835	
No. particles per bunch	N_p	1.1	10^{11}
Normalized transverse emittance (r.m.s.)	ε_n	3.75	μm
Collisions			
β-value at IP	β^*	0.5	m
r.m.s. beam radius at IP	σ^*	16	µm
Total crossing angle	ϕ	300	μrad
Luminosity lifetime	τ_L	10	h
Number of evts/crossing	n_c	17	
Energy loss per turn		7	keV
Total radiated power/beam		3.8	kW
Stored energy per beam		350	MJ

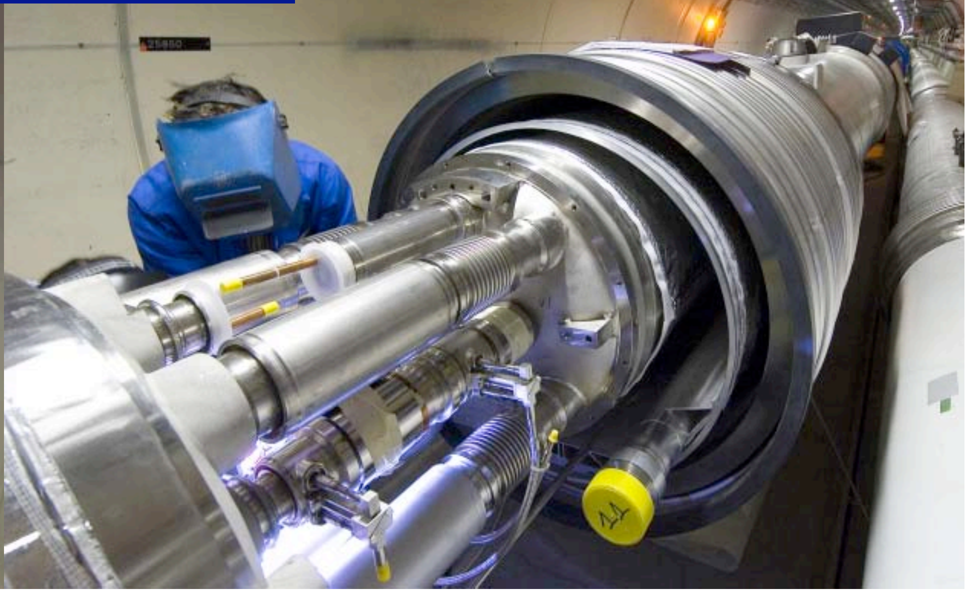
CERN Control Centre (CCC)



LHC Progress Dashboard

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

1232 SC Dipole Magnets (8.36Tesla, 15m length, 35tonne)
installation will finish in March 2007.



LHC Start-up Scenario

Stage 1

Initial Commissioning
43x43 to 156x156, $N=3\text{-}9\times10^{10}$
$L=4\times10^{29}$ - 10^{32}

Stage 2

75ns operation
936x936, $N=4\text{-}8\times10^{10}$
$L=2\times10^{31}$ - 5×10^{32}

Stage 3

25ns operation
2808x2808, $N=4\text{-}6\times10^{10}$
$L=2\times10^{32}$ - 3×10^{33}

Nominal

25ns operation
2808x2808, $N=8\text{-}12\times10^{10}$
$L=10^{33}$ - 10^{34}

Schedule (CERN Council, June 23, 2006)

Oct. 2006	- Last magnet delivery
Dec. 2006	- Conclude magnet testing
Mar. 2007	- The last magnet installation
Aug. 2007	- Machine closure ready for commissioning
Nov. 2007	- 2 months commissioning@0.9TeV, $L=10^{29}$ → Machine/Detector/QCD bkg/SM
winter	- Commissioning without beam

Spring-Summer 2008 - First Physics RUN@14TeV !

Data collection will continue until a pre-determined amount of data has been accumulated, allowing the experimental collaborations to announce their first results.

Integrated Luminosity O(few fb^{-1})

Nov.-Dec. 2007 Commissioning at E_{CMS}=900GeV

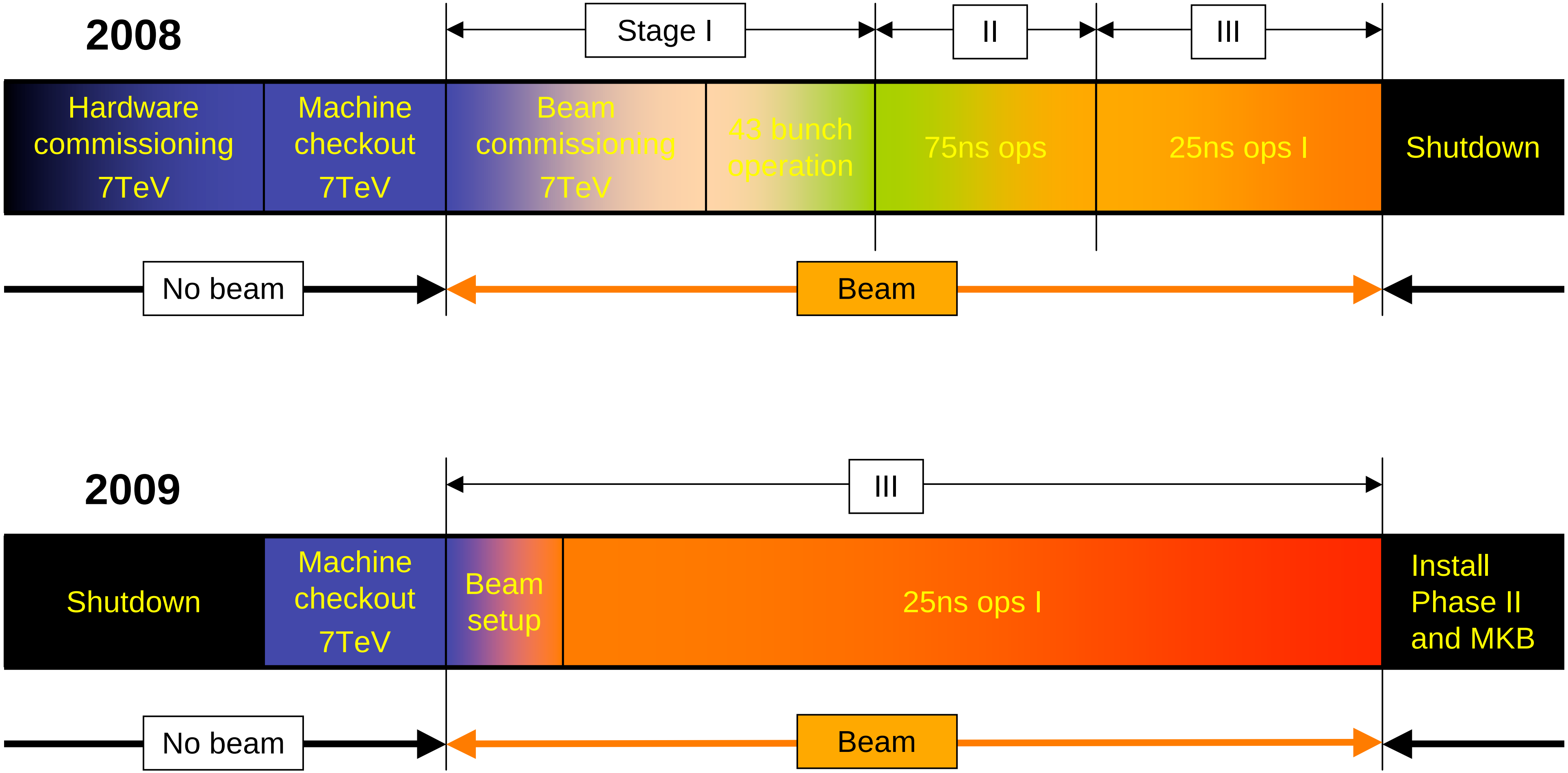
http://lhc-commissioning.web.cern.ch/lhc-commissioning/

- 3 weeks beam commissioning
  - Essentially single beam, low intensity for the most part
- 3 weeks collisions
  - Low intensities initially, with staged increase to an optimistic 156 x 4 x 10^{10}
  - hope to push over 10^{29} $cm^{-2}s^{-1}$

k_b	43	43	156	156
i_b (10^{10})	2	4	4	10
b^* (m)	11	11	11	11
intensity per beam	8.6 10^{11}	1.7 10^{12}	6.2 10^{12}	1.6 10^{13}
beam energy (MJ)	.06	.12	.45	1.1
luminosity	10^{28}	7.2 10^{28}	4.8 10^{29}	3 10^{30}
event rate [1](kHz)	0.4	2.8	10.3	64
W rate [2] (per 24h)	0.5	3	11	70
Z rate [3] (per 24h)	0.05	0.3	1.1	7

Assuming 450GeV
1. inelastic cross section 40mb
2. $W \rightarrow l\nu$ cross section 1nb
3. $Z \rightarrow ll$ cross section 100pb

Staged commissioning plan for E_{CMS}=14TeV



2008

Stage I

II

III

Hardware commissioning 7TeV

Machine checkout 7TeV

Beam commissioning 7TeV

43 bunch operation

75ns ops

25ns ops I

Shutdown

No beam

Beam

2009

III

Shutdown

Machine checkout 7TeV

Beam setup

25ns ops I

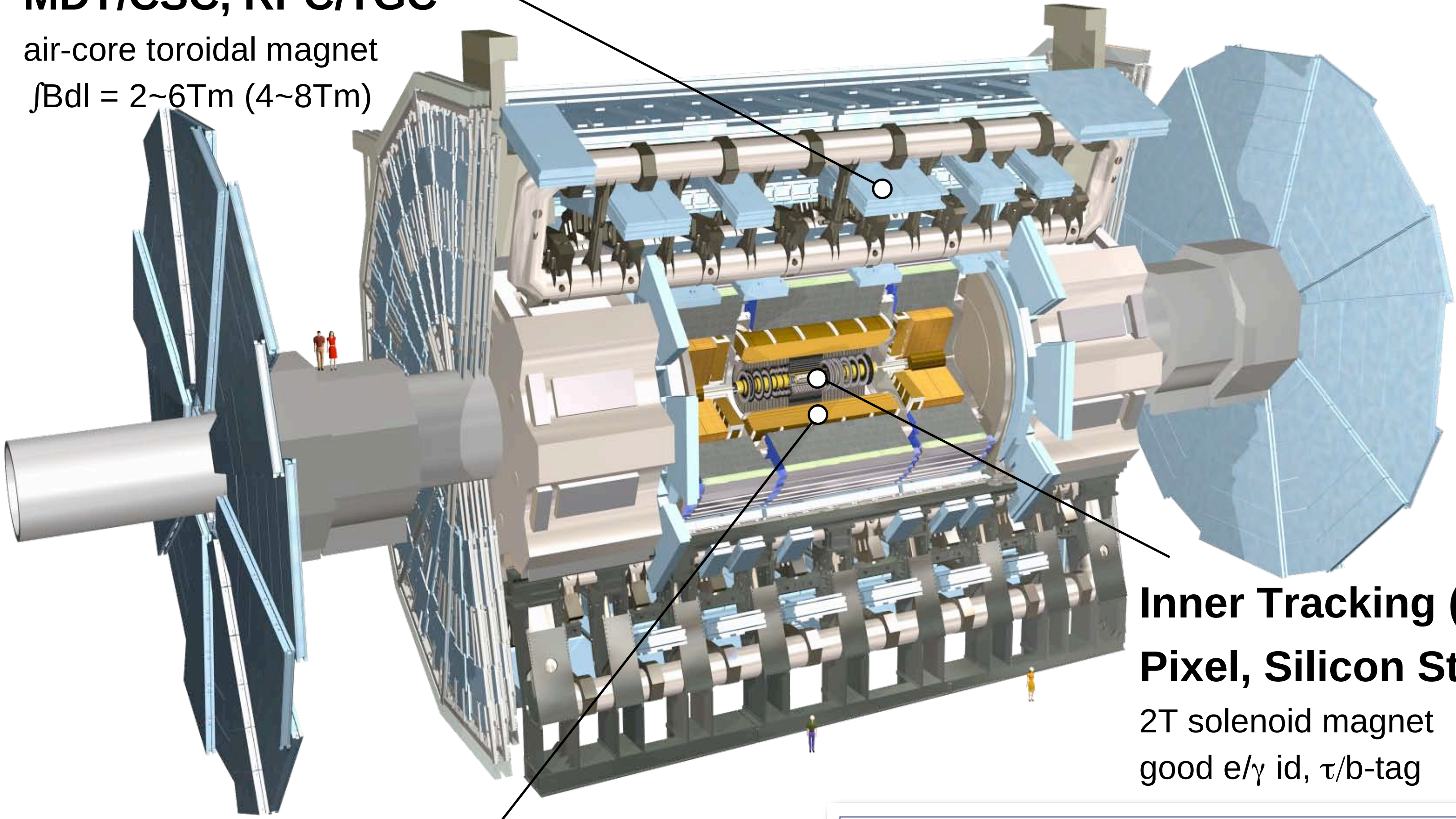
Install Phase II and MKB

No beam

Beam

3. ATLAS/CMS Detector

A Toroidal LHC ApparatuS (ATLAS)



Muon Spectrometer($\eta<2.7$)

MDT/CSC, RPC/TGC

air-core toroidal magnet

$\int Bdl$ = 2~6Tm (4~8Tm)

Inner Tracking ($\eta<2.5$)

Pixel, Silicon Strip, TRT

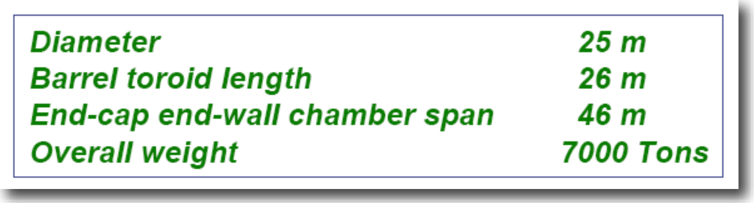
2T solenoid magnet

good e/γ id, τ/b-tag

Calorimeter ($\eta<4.9$)

Liq.Ar EM/HAD/FCAL, Tile HAD, FCAL

good e/γ id, energy, E_T^{miss}

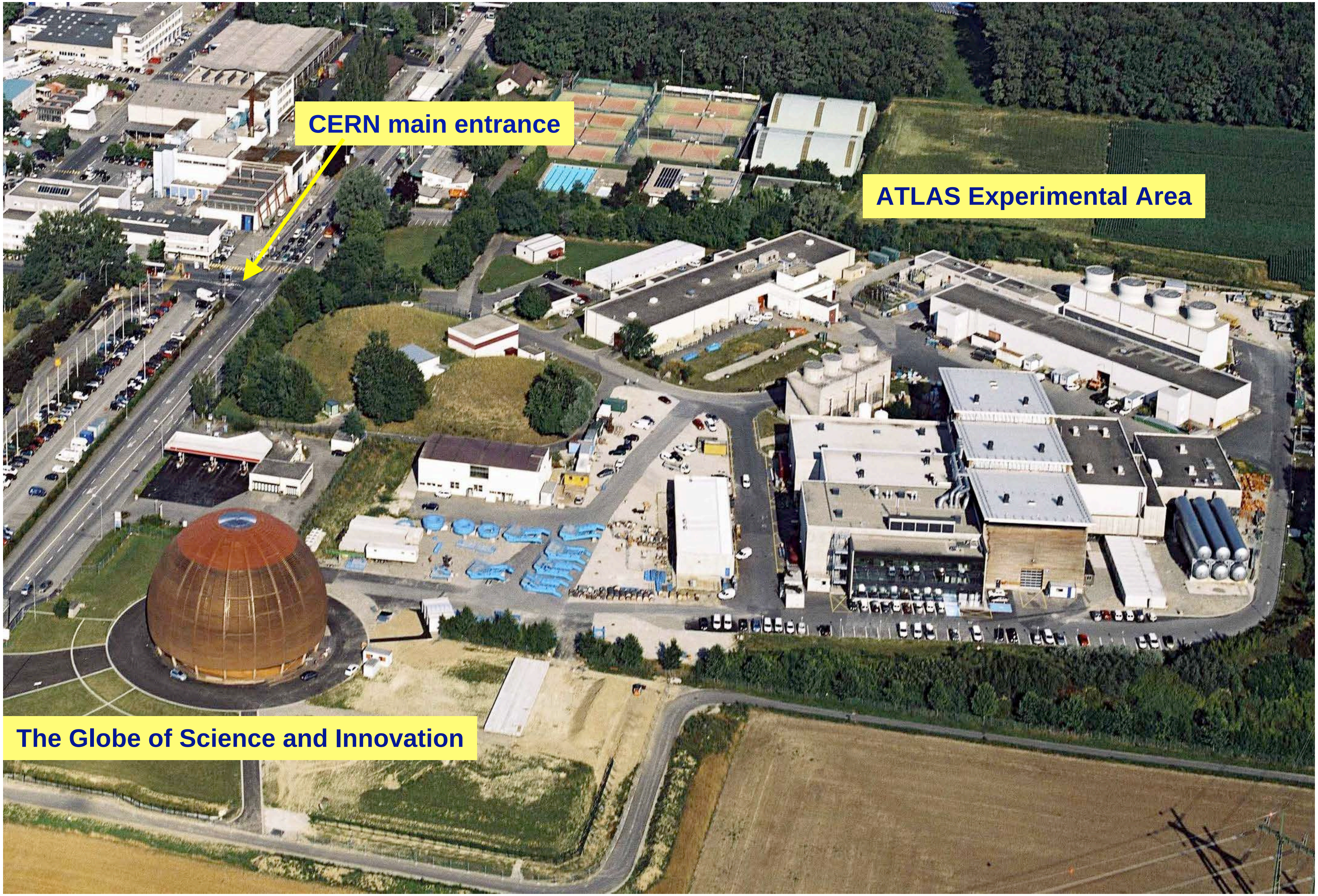


Diameter	*25 m*
Barrel toroid length	*26 m*
End-cap end-wall chamber span	*46 m*
Overall weight	*7000 Tons*

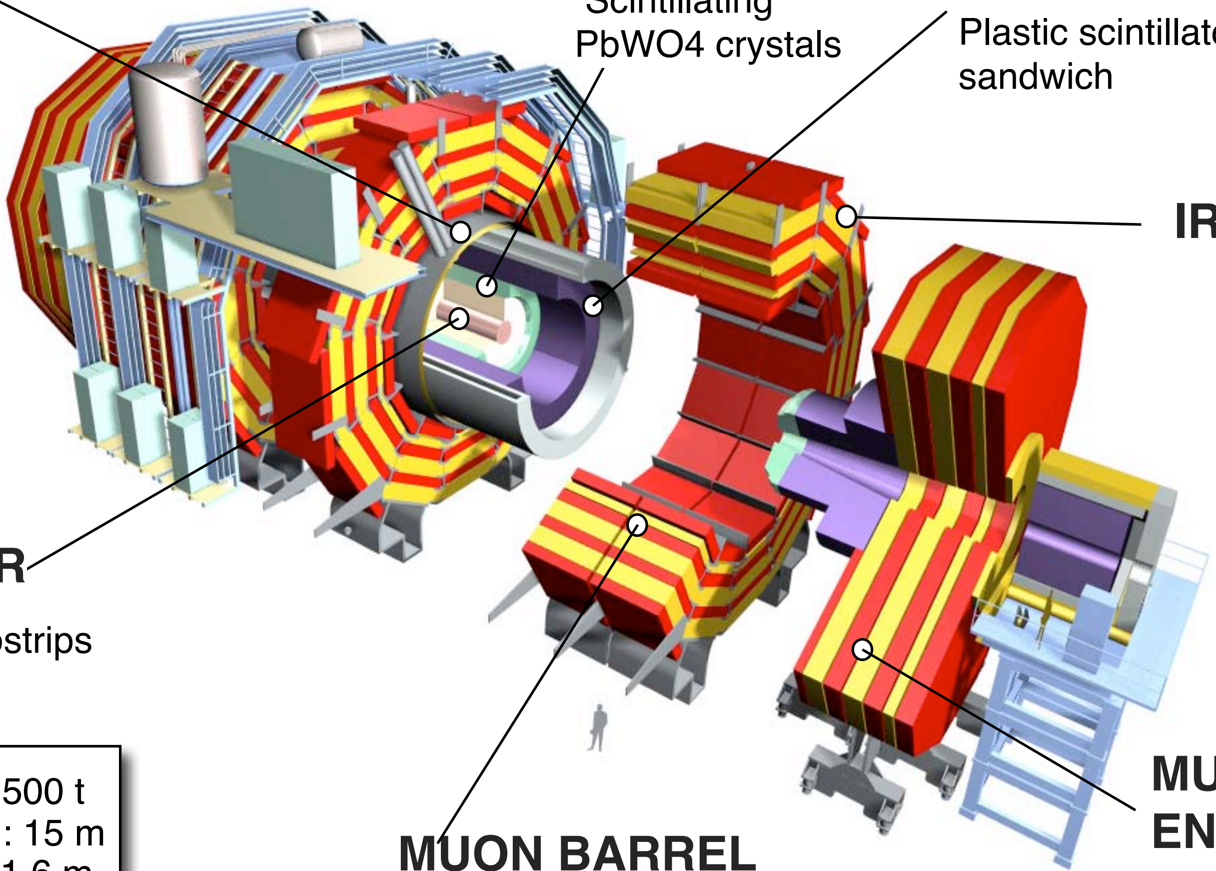
The ATLAS Collaboration

35 nations
158 institutions
~1650 scientists

Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, 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, INP Cracow, FPNT Cracow, 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, Naruto UE, New Mexico, 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, 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


CERN main entrance
ATLAS Experimental Area
The Globe of Science and Innovation

CMS (Compact Muon Spectrometer)



SUPERCONDUCTING COIL

CALORIMETERS

ECAL

Scintillating
PbWO4 crystals

HCAL

Plastic scintillator/brass
sandwich

IRON YOKE

TRACKER

Silicon Microstrips
Pixels

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

MUON BARREL

Drift Tube
Chambers (**DT**)

Resistive Plate
Chambers (**RPC**)

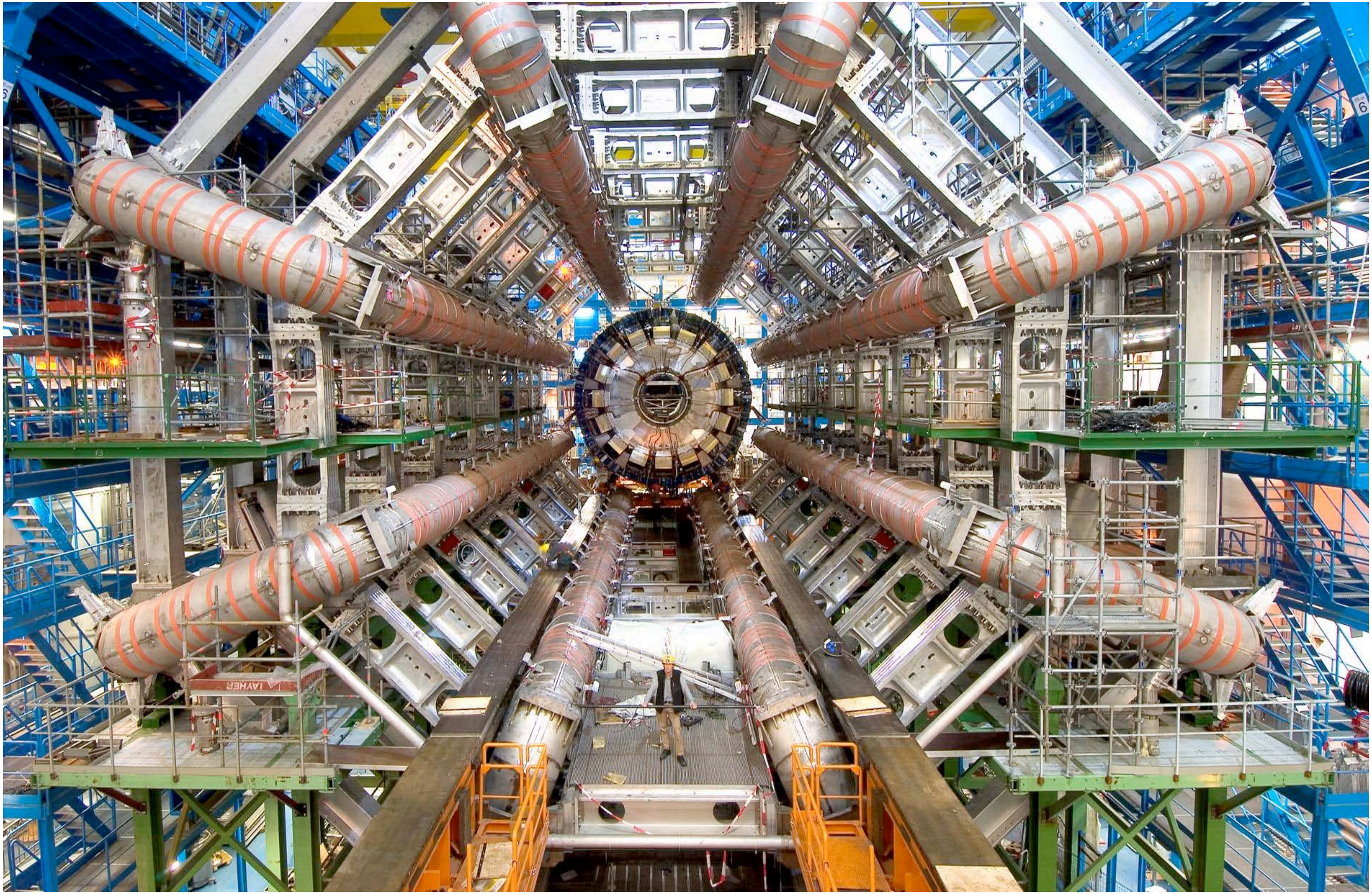
MUON ENDCAPS

Cathode Strip Chambers (**CSC**)

Resistive Plate Chambers (**RPC**)

Magnet / Muon Spectrometer

The ATLAS Detector Nov.2005

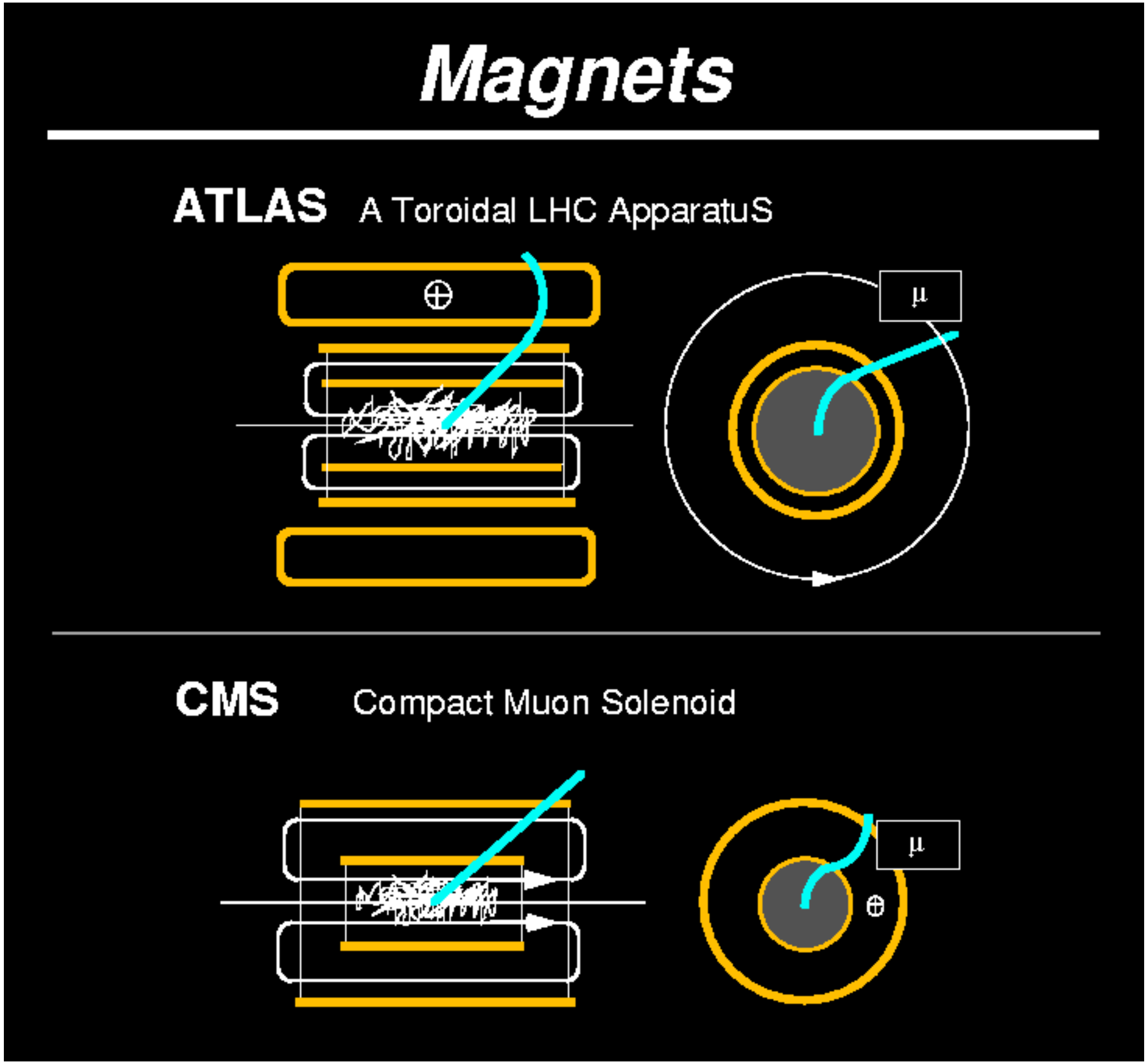


Troid +

2T solenoid

4T solenoid

1Tesla
=10^4Gauss

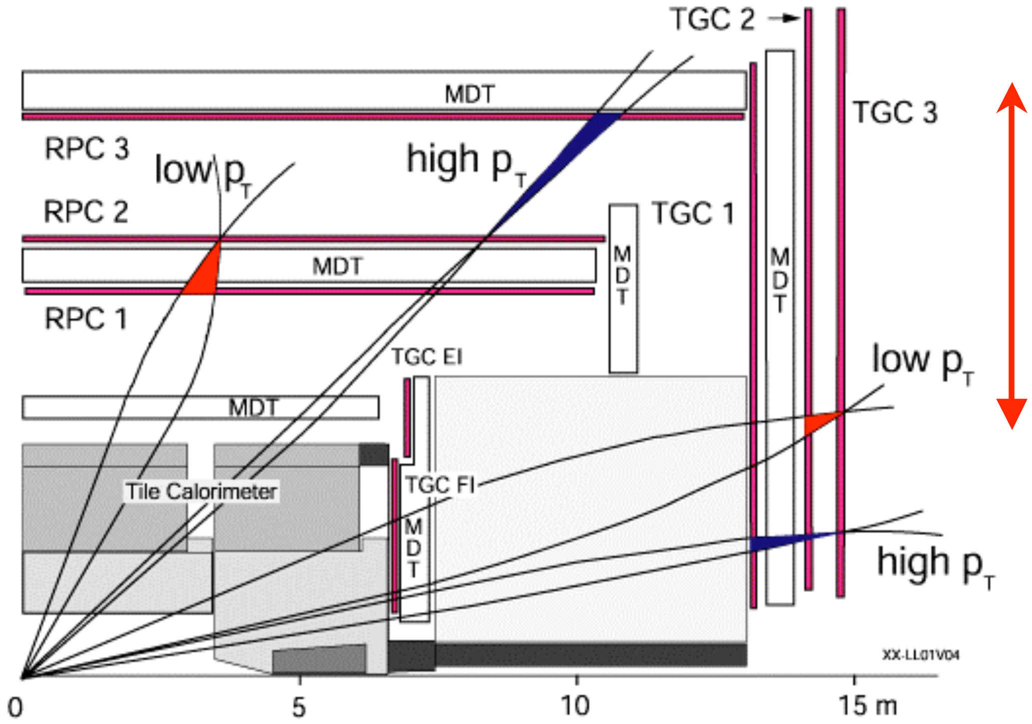


Magnets

ATLAS A Toroidal LHC ApparatuS

CMS Compact Muon Solenoid

Muon Spectrometer



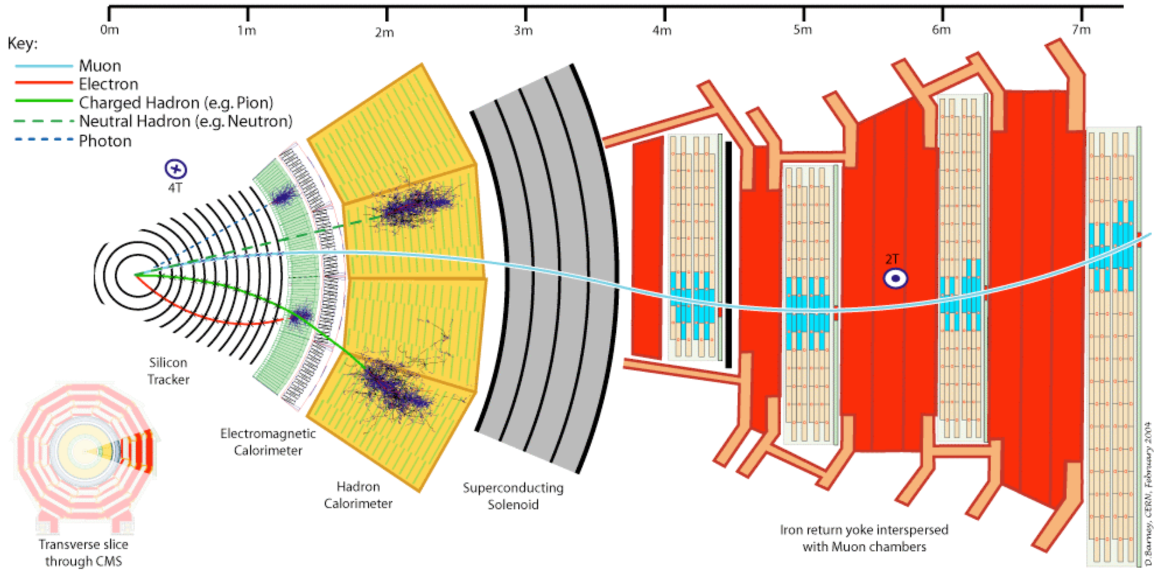
6m←**ATLAS : Troidal magnetic field**

（y-z view)

3m

CMS: Solenoidal magnetic Field →

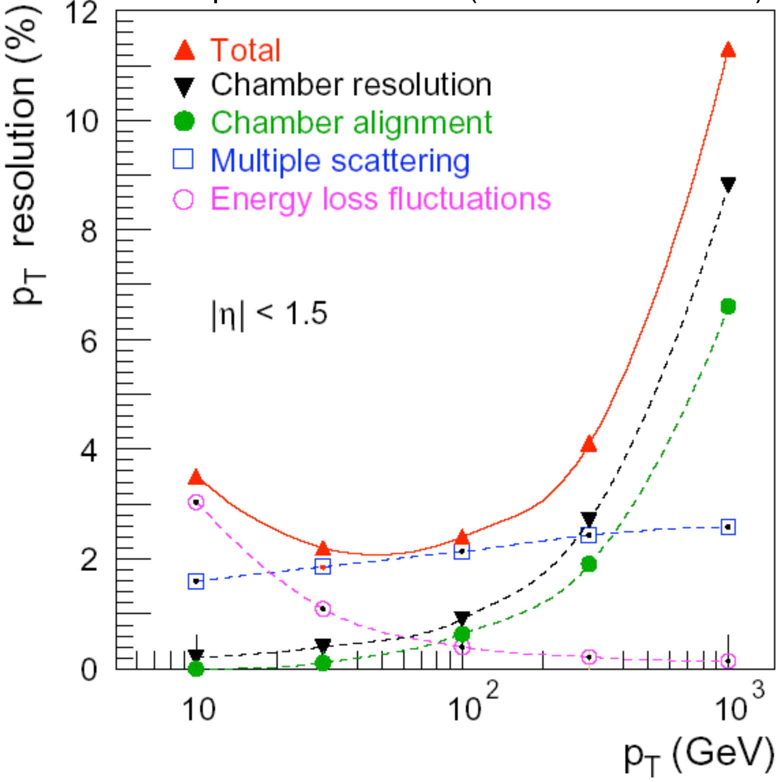
(r-φview)



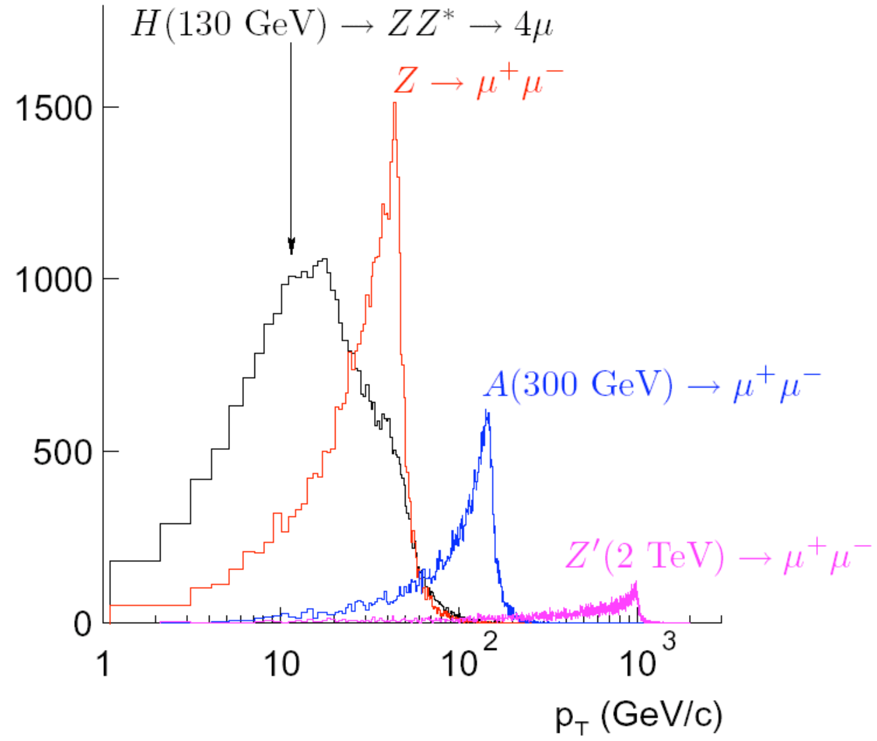
Muon Momentum Resolution and p_T distribution

ATLAS

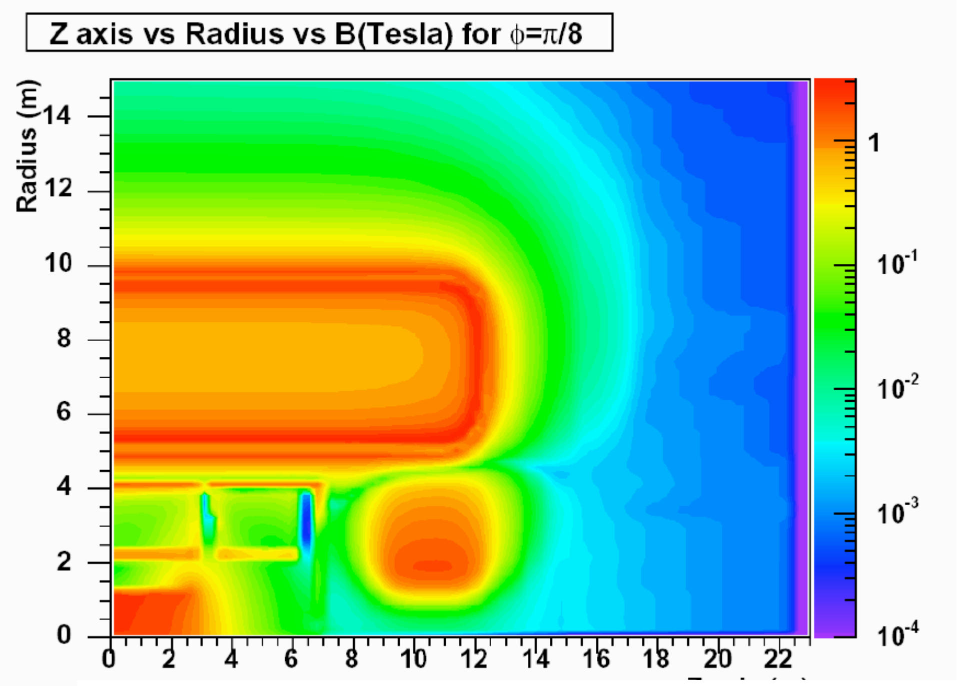
Muon spectrometer TDR (CERN/LHCC 97-22)

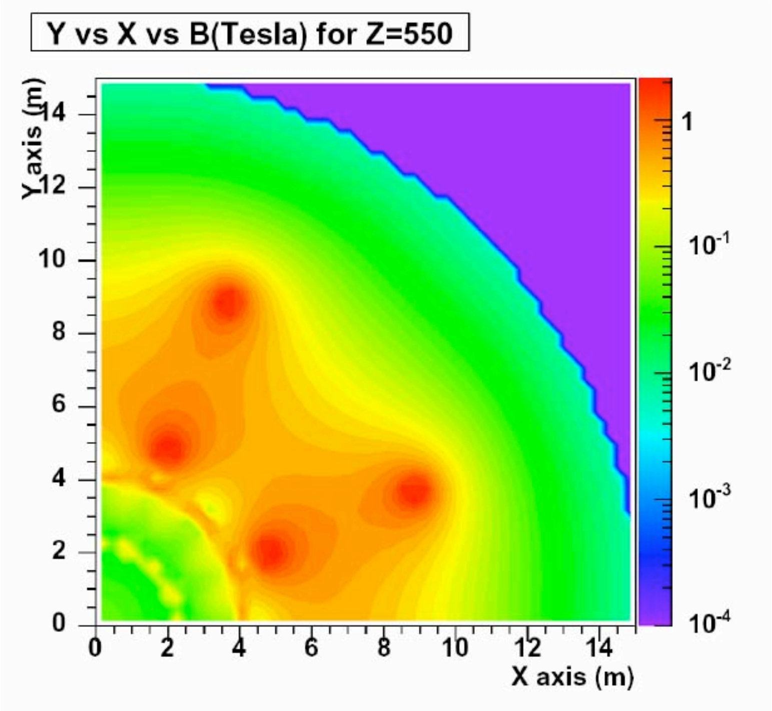


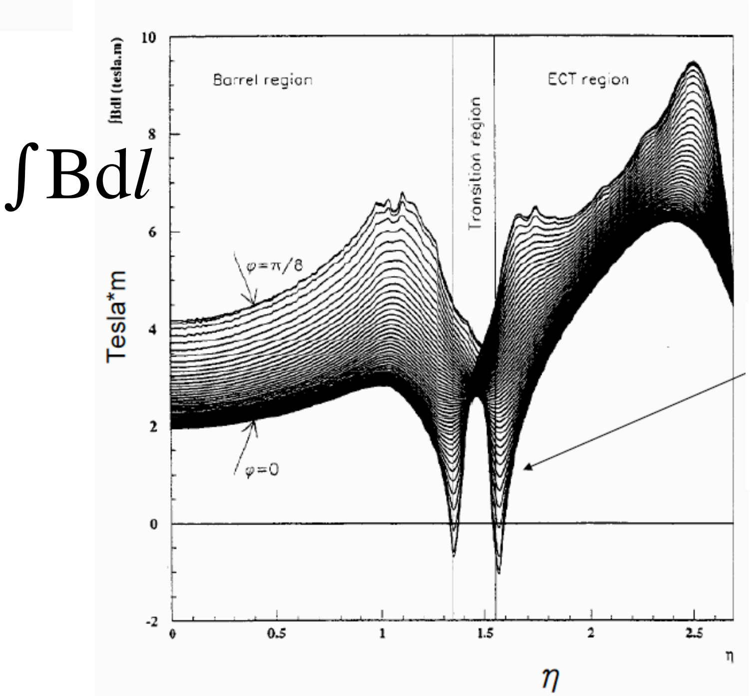
Oliver Kortner (MPI), HCP2006 (Duke, May 22-26, 2006)



Calibration & alignment are critical at high p_T





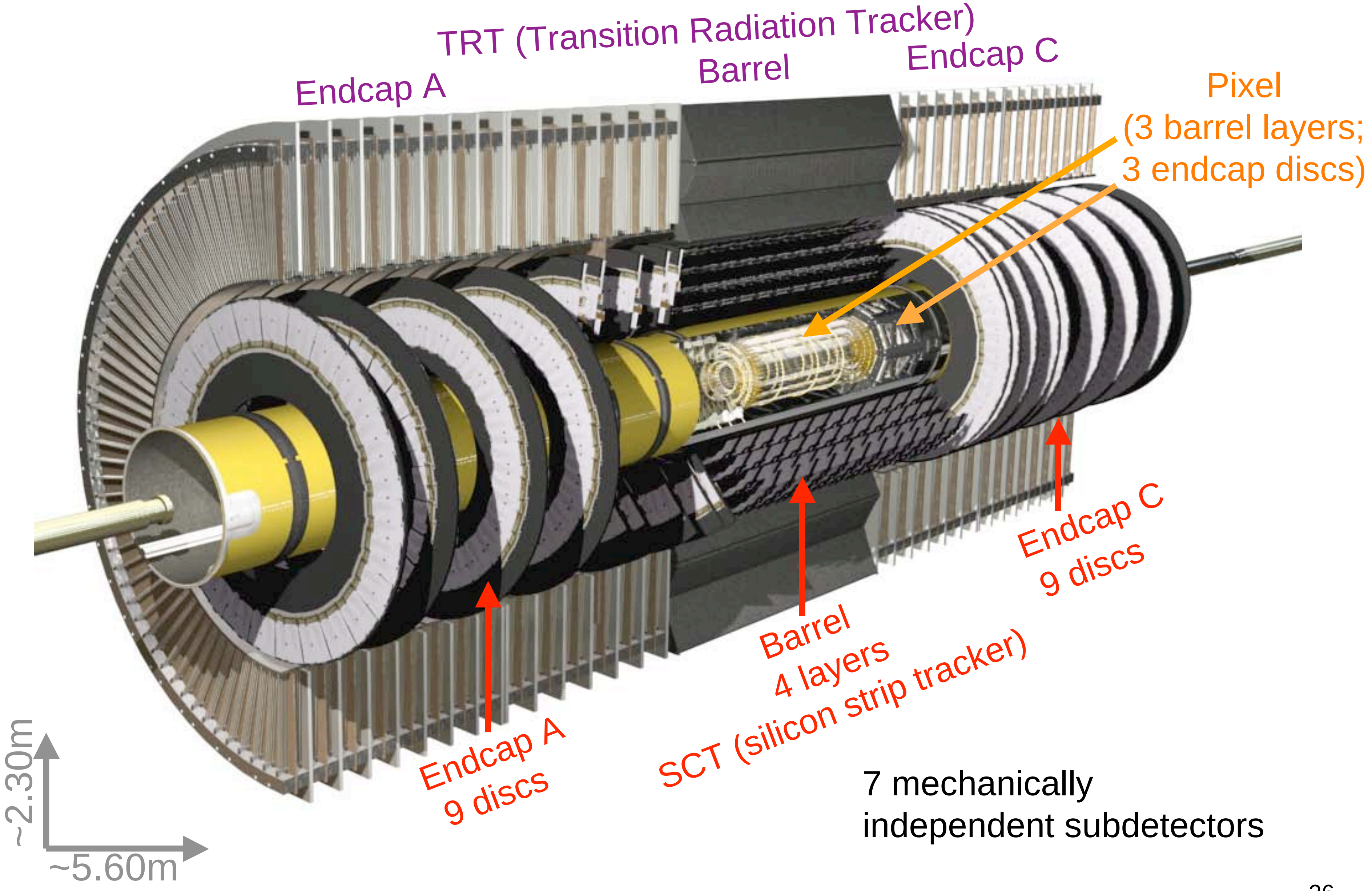


Troidal Magnet
Bending power vs rapidity

Very complicated, even negative!

Inner Detector (Tracker)

Atlas Inner Tracker



7 mechanically
independent subdetectors

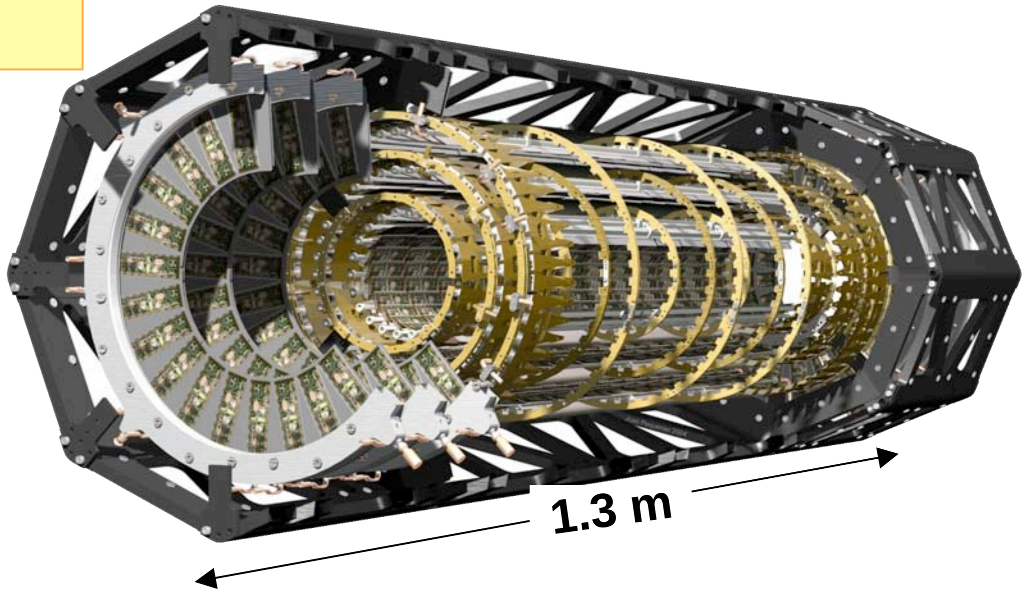
PIXEL

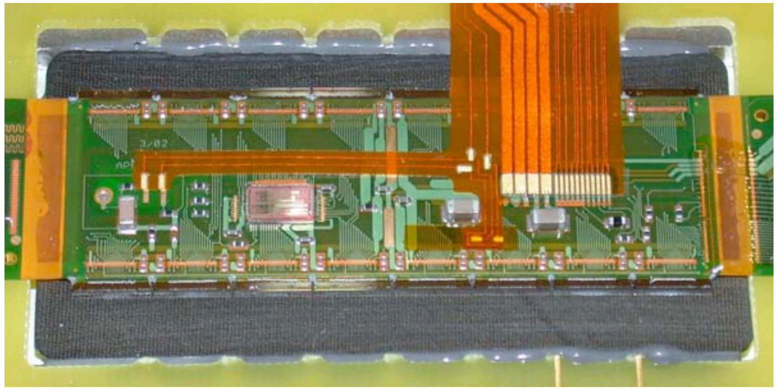
Barrel: 1456 modules
<u>Endcap: 2 x 144 modules</u>
1744 modules

One module: 46.080 pixels
Total: ~80.000.000 pixels

One pixel: 50μm x 400 μm
Resolution: 12μm x 60 μm

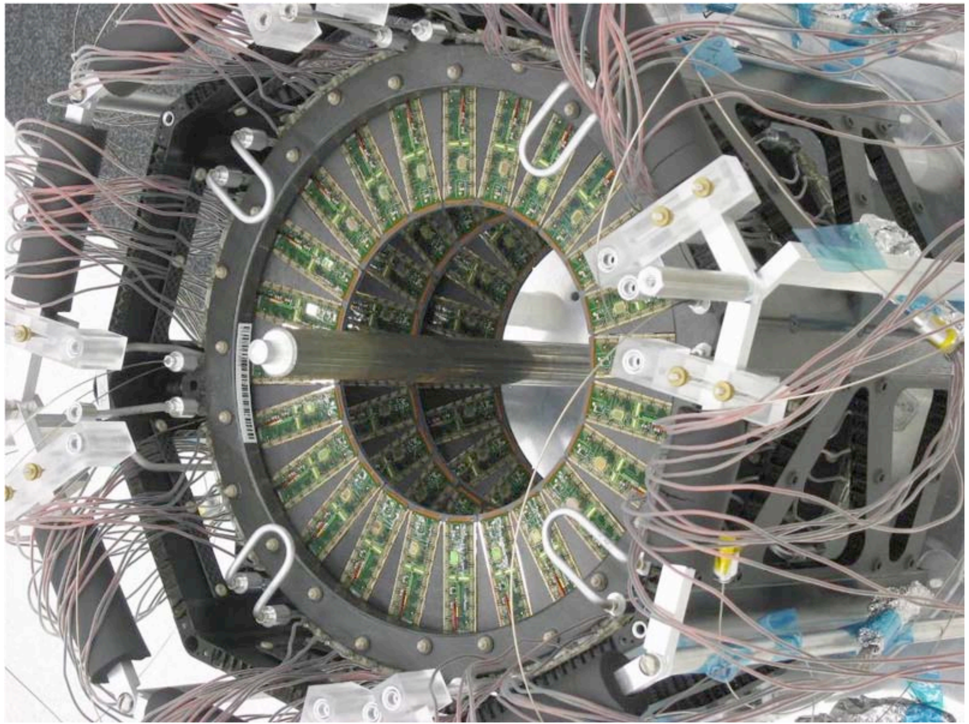
Hits per track: 3





Single Pixel module

All modules have same layout



A view of 3 completed discs of one Endcap

SCT (Silicon Strip)

Barrel: 2112 modules
Endcap: 2 x 988 modules
4088 modules

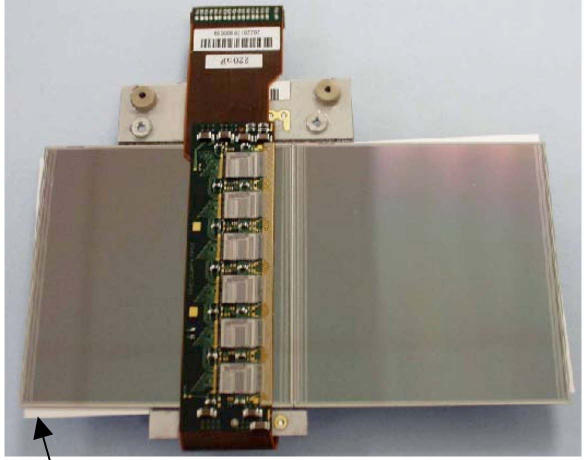
One module: 2 layers x 768 channels
Total: ~ 6.000.000 channels

Channel size: 80μm x 120 mm
Resolution: 16μm x 580 μm

Hits per track: Barrel: 4 Endcap: 9

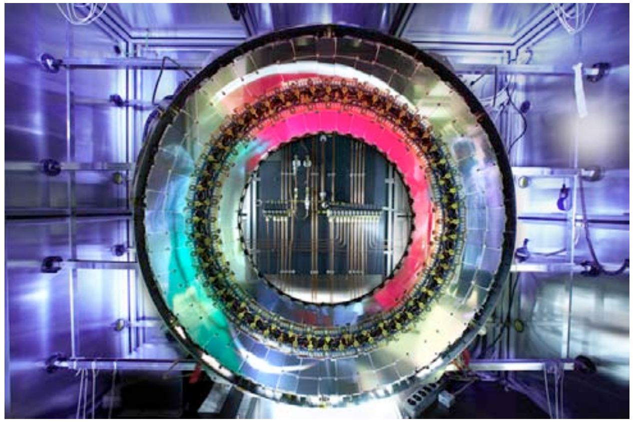
Endcap module

Barrel module

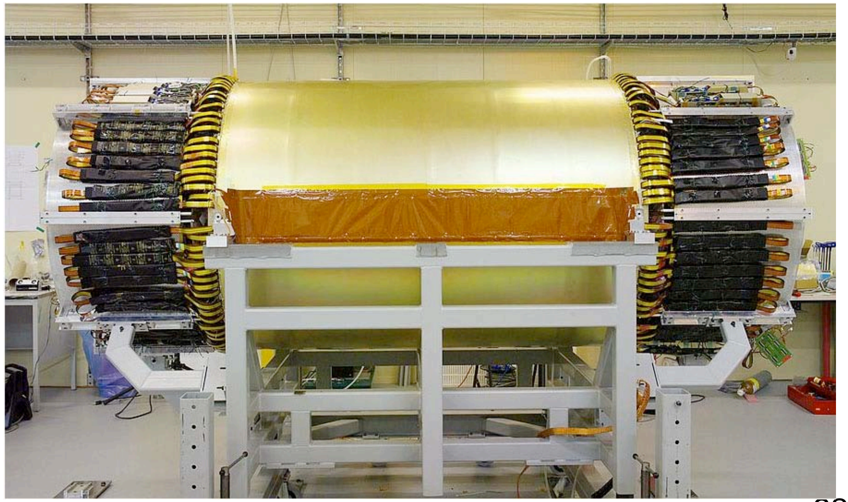


One module has 2 layers with 40 mrad stereo angle

4 different module layouts (3 endcap, 1 barrel)



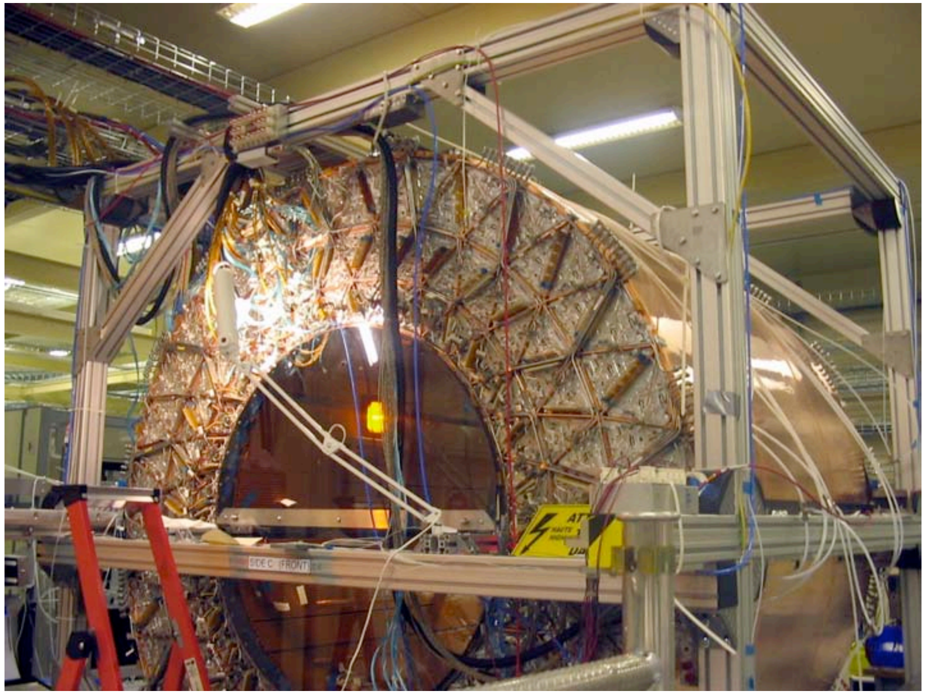
SCT EndCap



Fully assembled SCT Barrel

TRT (Transition Radiation using straw tubes)

TRT Barrel detector



Barrel: 96 modules
Endcap: 28 modules 2

Total: 300.000 straw tubes

Channel size: 4mm x 740 mm
Resolution: 170 μm (perpendicular to wire)

Hits per track: 36

radiator: poly-propylene
gas mixture: $XeCO_2O_2$ (70+27+3%)

Alignment is an issue !

ID consists of 1744 Pixel, 4088 SCT and 124 TRT modules

⇒ 5956 modules x 6 DoF ~ 35.000 DoFs

⇒ This implies an inversion of a 35k x 35k matrix

1st LHC Detector Alignment Workshop

4-6 September 2006

CERN, Geneva

The aim of the workshop is to exchange ideas and information on the issues related to alignment of detectors

- Mathematical & statistical methods
- Lessons from previous & running experiments
- Alignment software framework
- Alignment plans for LHC experiments

More Information : http://lhc-detector-alignment-workshop.web.cern.ch

Organising Committee :

S. Blusk	(Syracuse)
O. Buchmuller	(CERN)
A. Jacholkowski	(Catania)
S. Marti i Garcia	(Valencia)
T. Ruf	(CERN)
K. Safarik	(CERN)
J. Schieck	(Munich)
S. Viret	(Glasgow)

Sponsored by LCG and CERN PH department

1st LHC Detector Alignment Workshop
CERN 4-6 Sep.

Supported by LCG & CERN PH

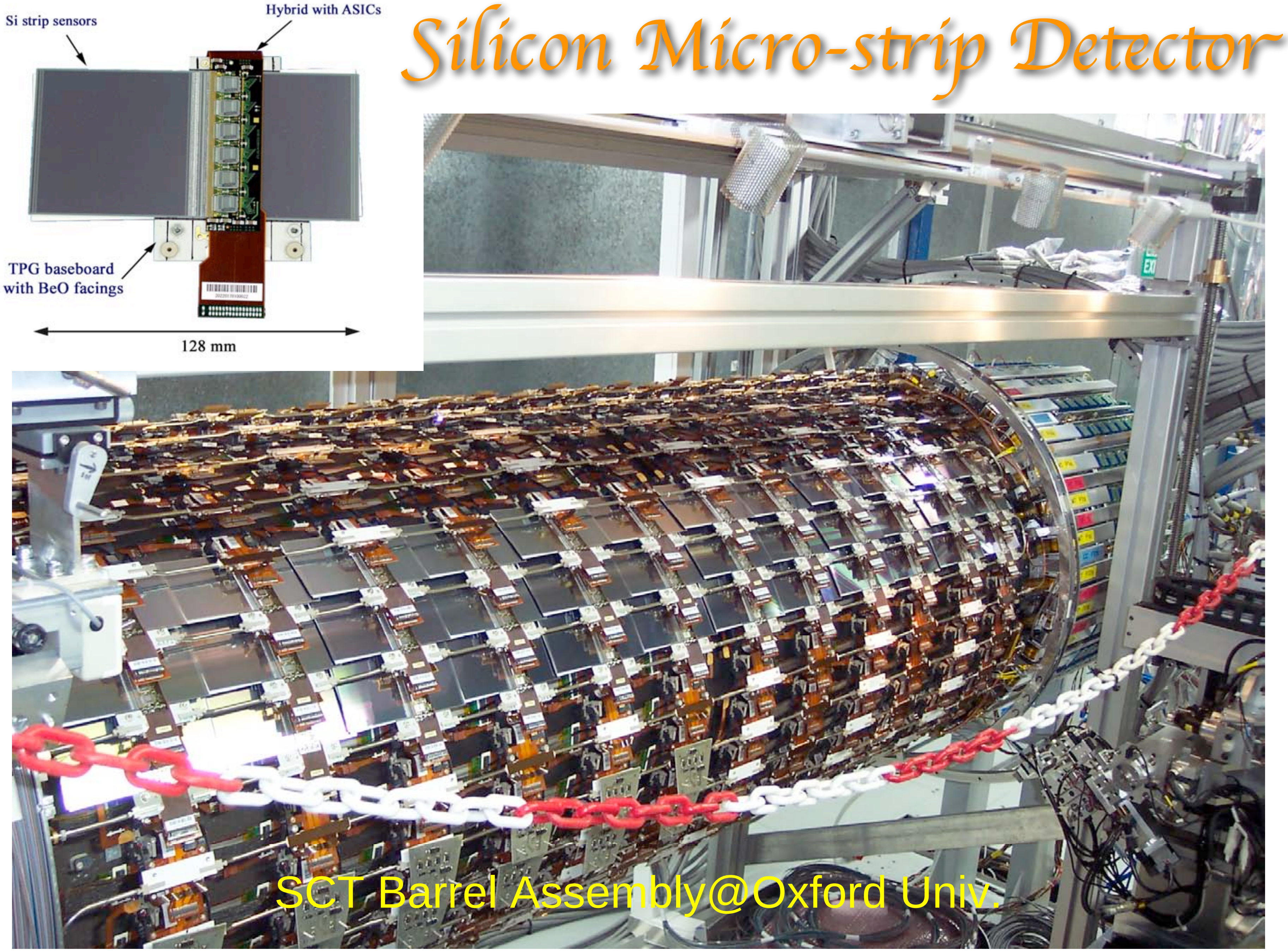
Workshop Scope

- *Mathematical & Statistical Methods*
- *Lessons from previous & running Experiments*
- *Alignment Software Infrastructure*
- *Alignment Plans for the LHC Experiments*

Invited Speakers

- Volker Blobel(Algorithm)
- Rudi Fruehwirth(Algorithm)
- Dave Brown(ALEPH/BABAR)
- Claus Kleinwort(H1/Zeus)
- Aart Heijboer(CDF)
- Spyridon Margetis(STAR)
- Fred Wickens(SLD)

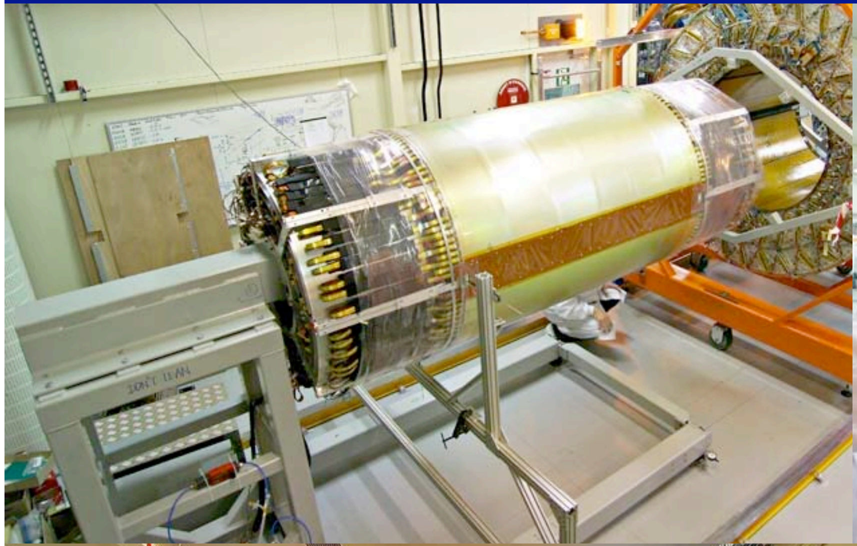
Silicon Micro-strip Detector

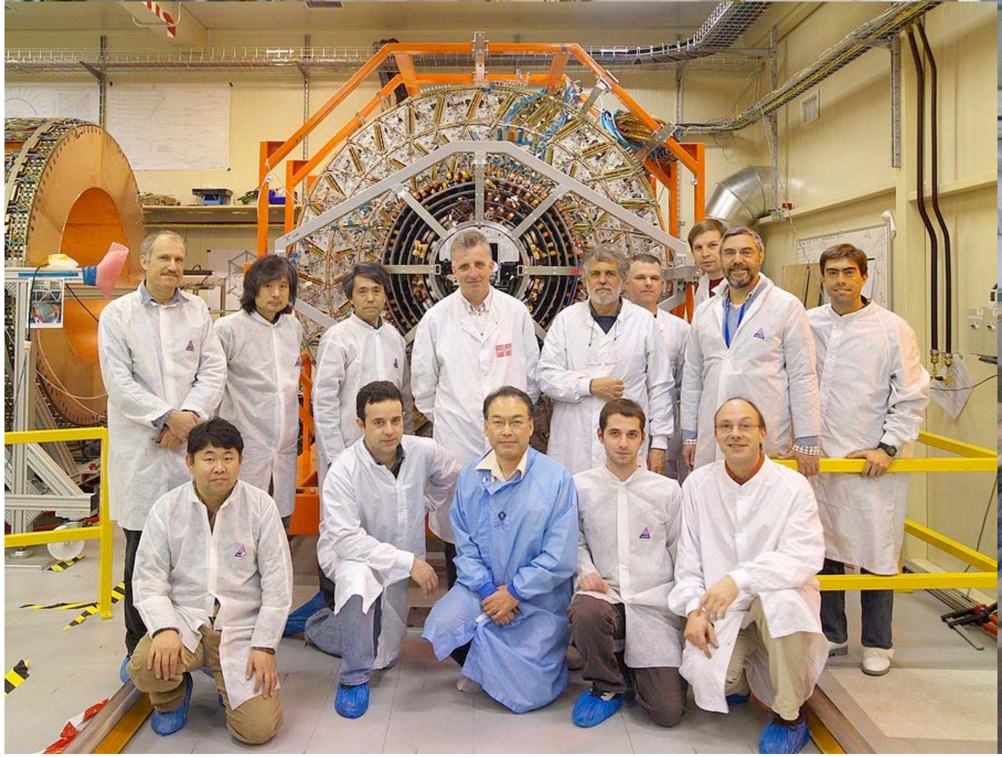


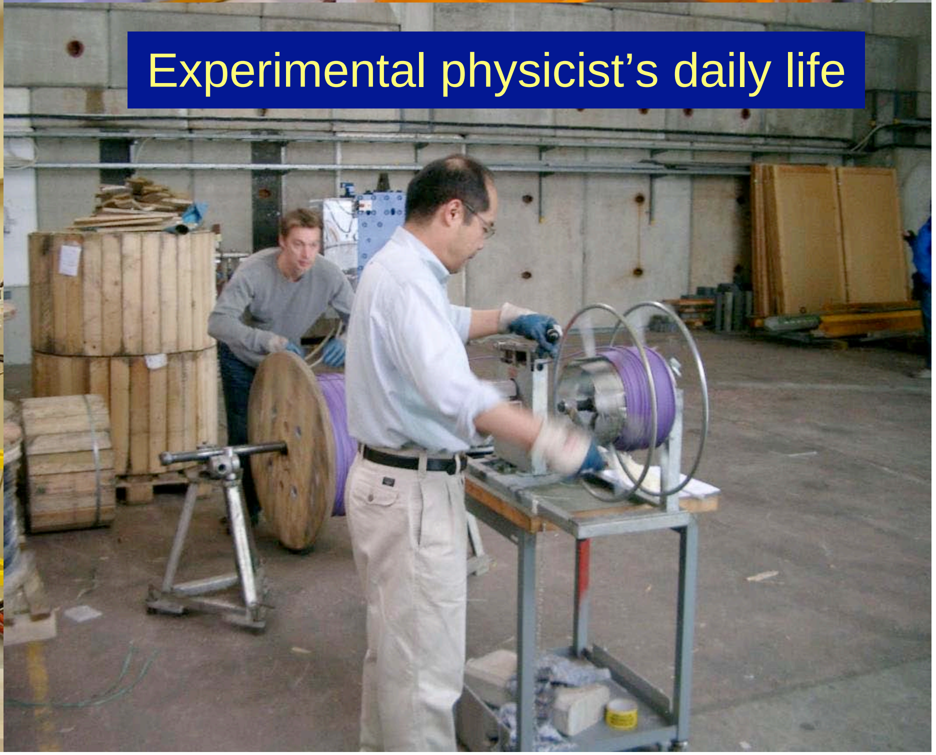
SCT Barrel Assembly@Oxford Univ.

SCT(SemiConductor Tracker) barrel cylinders insertion into TRT(Transition Radiation Tracker)

Feb.17, 2006

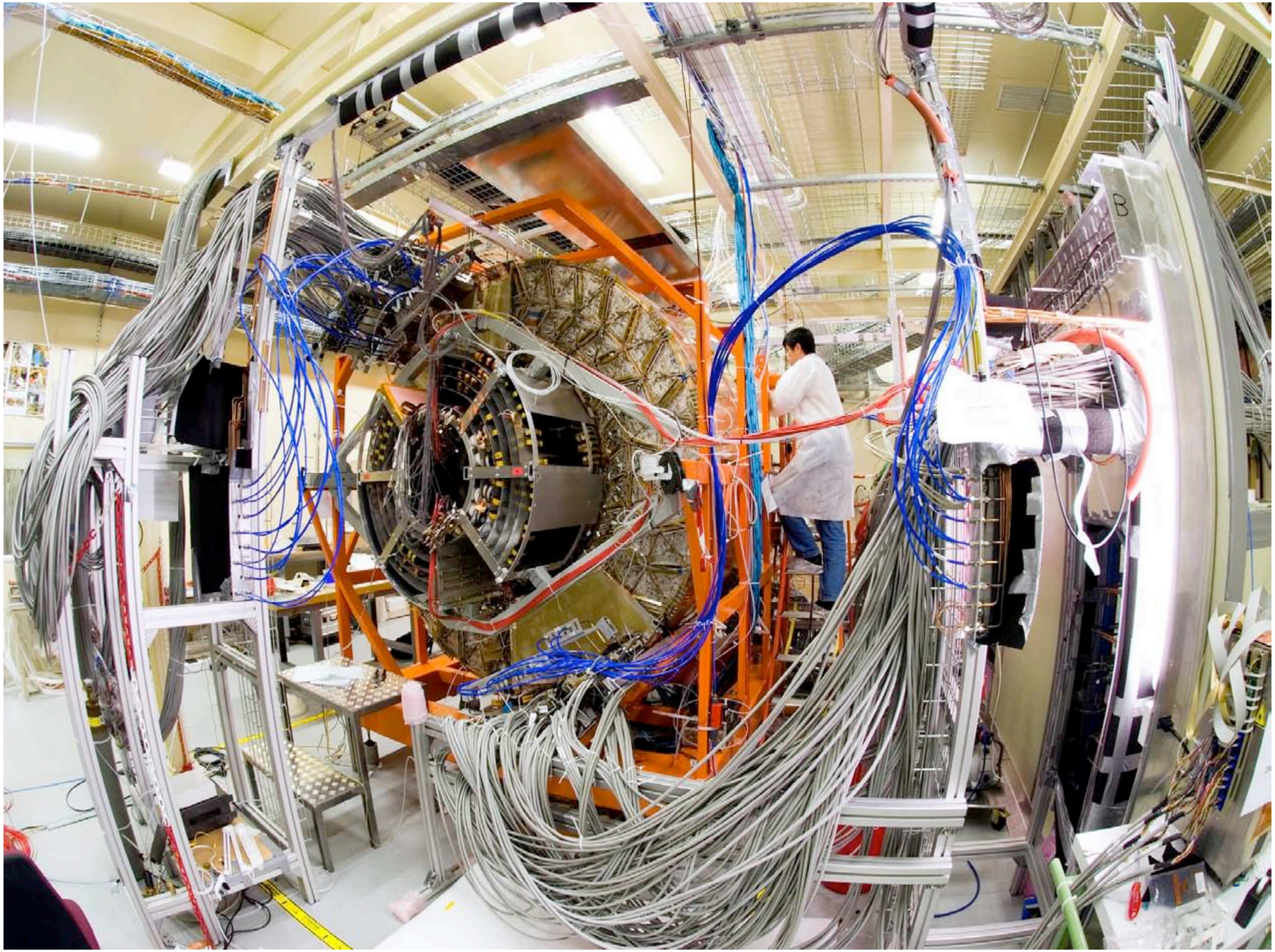






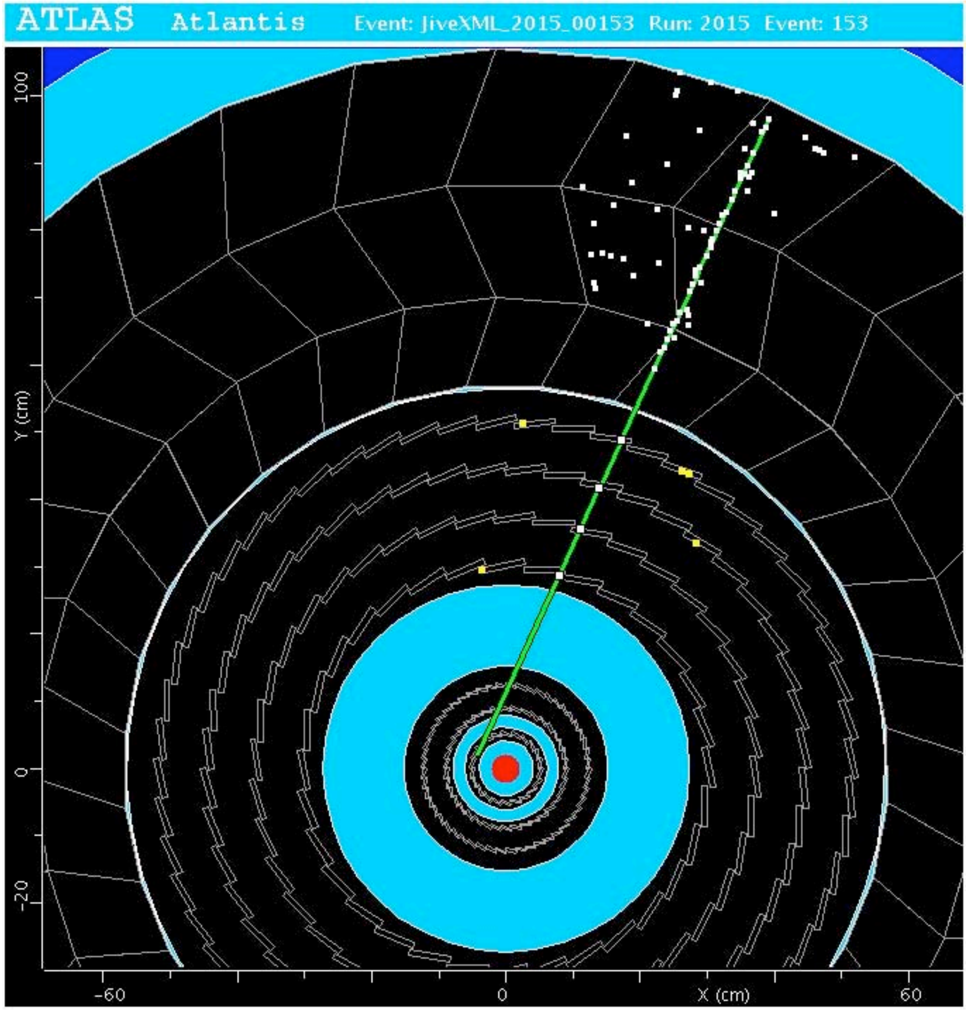
Experimental physicist’s daily life

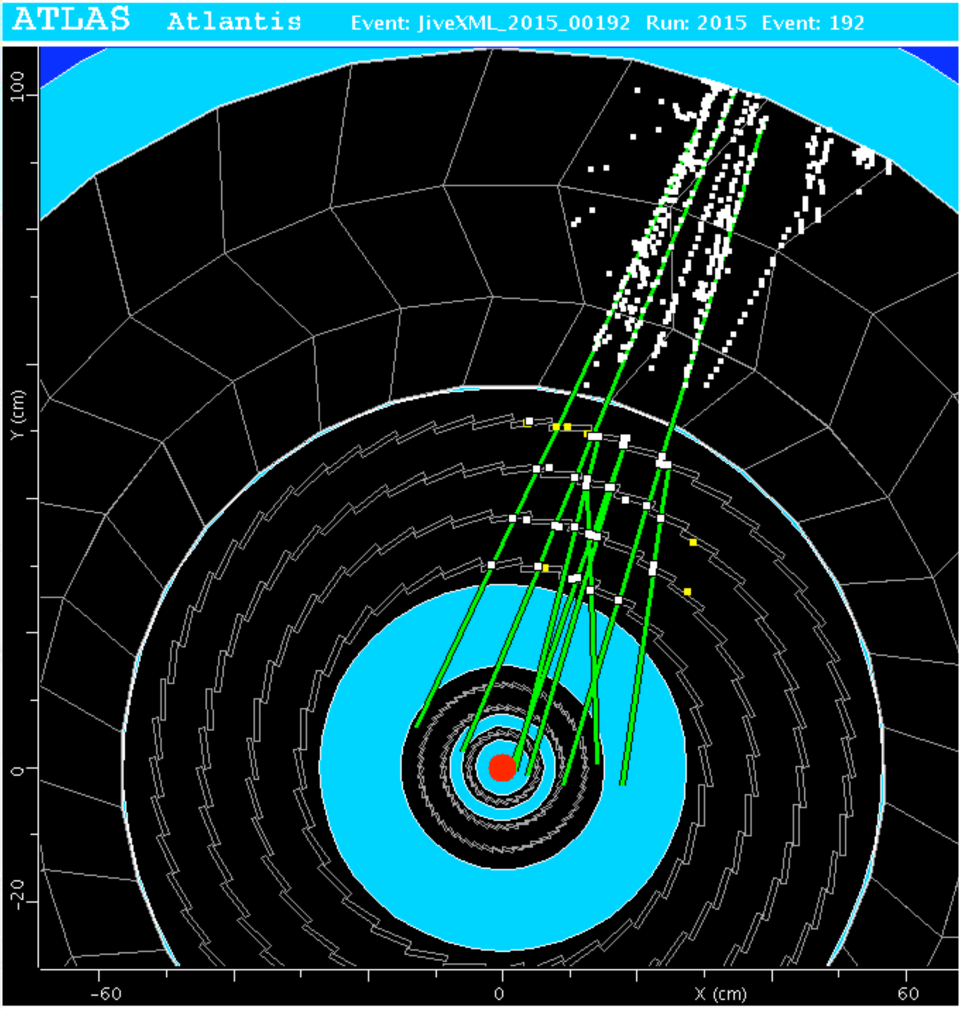
SCT and TRT barrel test



First cosmic events in SCT+TRT

May 2006

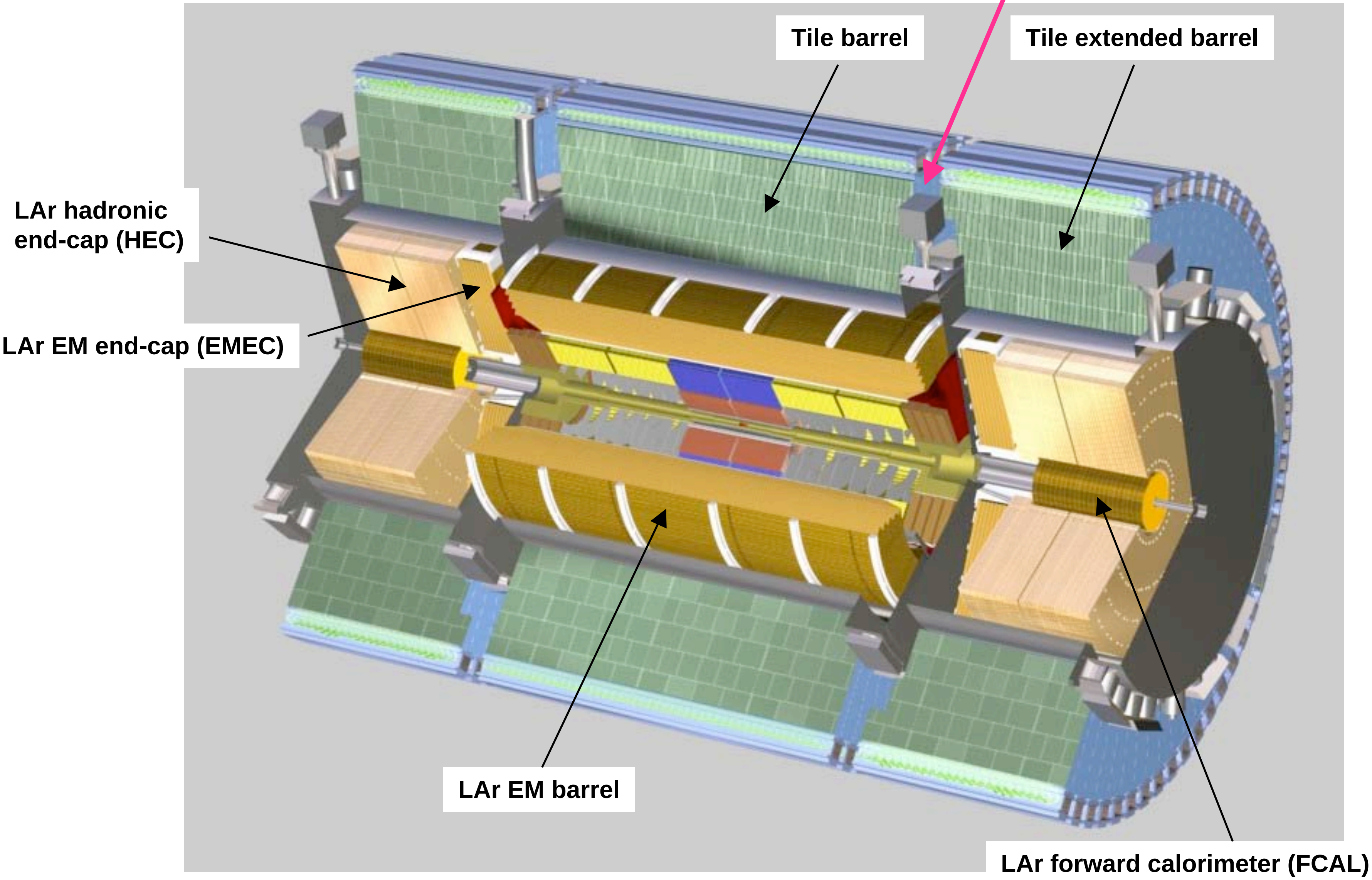




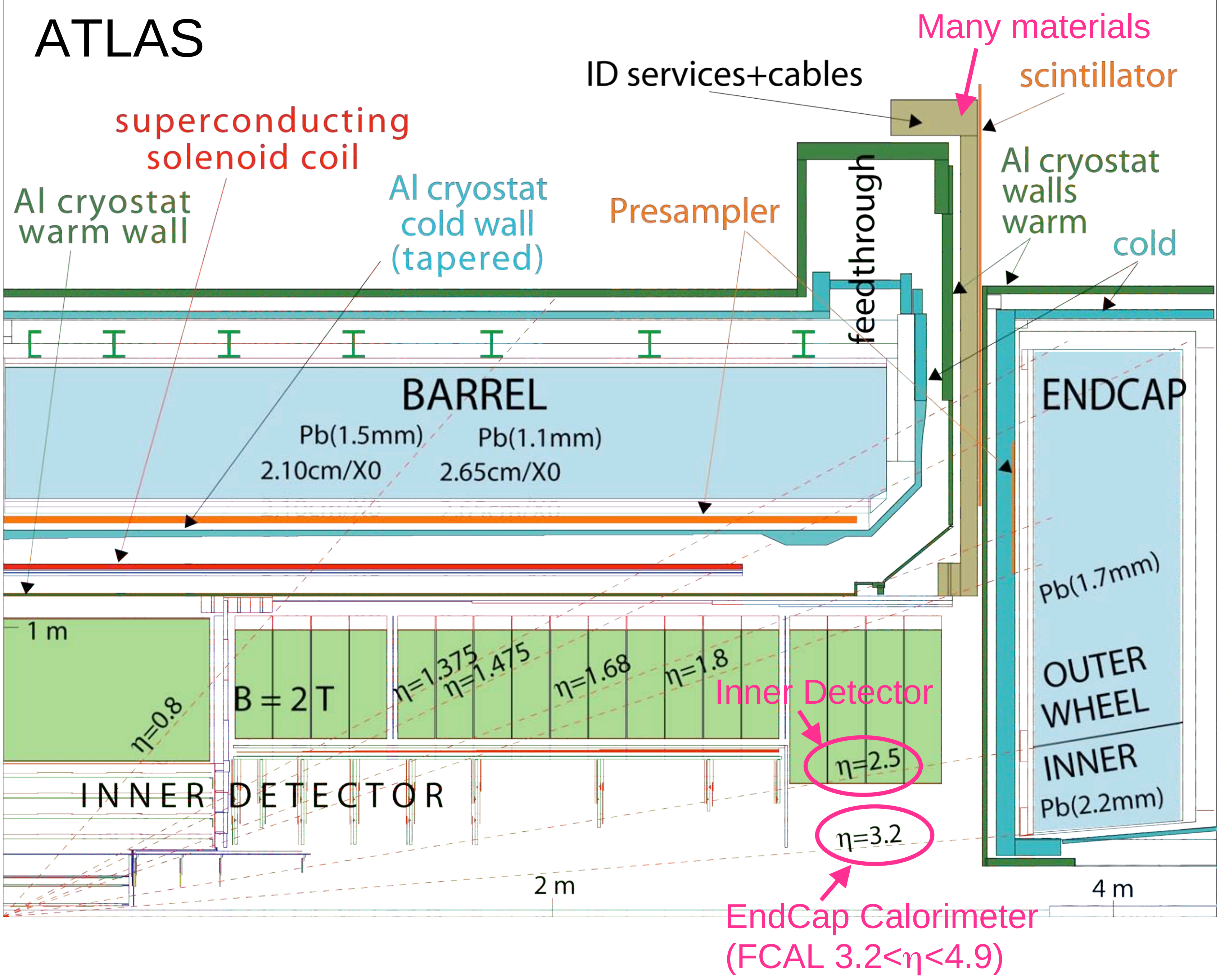
Calorimeter

ATLASLiq.Ar and Tile Calorimeters

Many passive materials due to
Inner Detector and Liq.Ar readout cables
（η~1.5）



ATLAS


Many materials
ID services+cables
scintillator
superconducting solenoid coil
Al cryostat warm wall
Al cryostat cold wall (tapered)
Presampler
feedthrough
Al cryostat walls warm
cold
BARREL
Pb(1.5mm)
2.10cm/X0
Pb(1.1mm)
2.65cm/X0
ENDCAP
Pb(1.7mm)
OUTER WHEEL
INNER
Pb(2.2mm)
1 m
η=0.8
B = 2 T
η=1.375
η=1.475
η=1.68
η=1.8
Inner Detector
η=2.5
η=3.2
INNER DETECTOR
2 m
4 m
EndCap Calorimeter
(FCAL 3.2<η<4.9)

EM Calorimeter Performance

Physics benchmark process: $H \rightarrow \gamma\gamma$, $4e^{\pm}$

Good Detector … can measure 4-momentum (E,**p**) or (t,**x**). Example：Kamiokande

ATLAS Liquid Argon Calorimeter can do this !

– Energy resolution	**$\sigma/E = 10\%/\sqrt{E} \oplus 200(400)\mathrm{MeV}/E \oplus 0.7\%$**
– Angular resolution	**4-6 mrad/$\sqrt{E}$** （φ-direction, Middle Layer）
	50 mrad/$\sqrt{E}$ （η-direction, Strip+Middle Layer→Z vertex measurement）
– Time resolution	**100 ps** (1ns at 1GeV)
– Particle Identification	$e^{\pm}$/jets, $\gamma/\pi^0 > 3$ at E_T=50GeV
– Linearity	< 0.1%
– Dynamic range	20MeV(can detect MIP μs) - 2TeV（signals from extra-dimension etc.）

ATLAS Liquid Argon Calorimeter

- Pb/Liq.Ar sampling calorimeter (accordion geometry)
- Azimuthal angle=2π(no crack), covers pseudo-rapidity $\eta<3.2$ (FCAL <4.9)
- Liquid Argon is intrinsically radiation-hard.

H→γγ

$$\frac{\sigma_M}{M} = \frac{1}{2}\left[\frac{\sigma_{E_1}}{E_1} \oplus \frac{\sigma_{E_2}}{E_2} \oplus \frac{\sigma_\theta}{\tan(\theta/2)}\right]$$

ATLAS

better uniformity and angular resolution

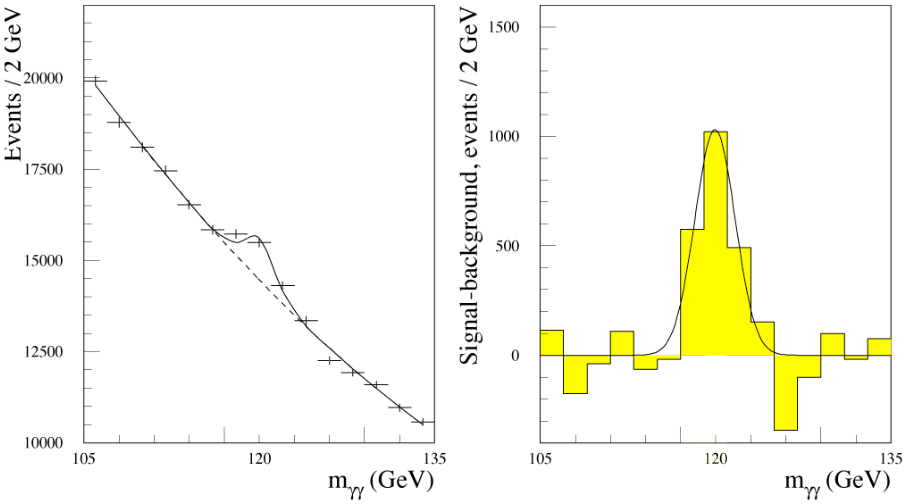
$$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{200(400)\mathrm{MeV}}{E} \oplus 0.7\%$$

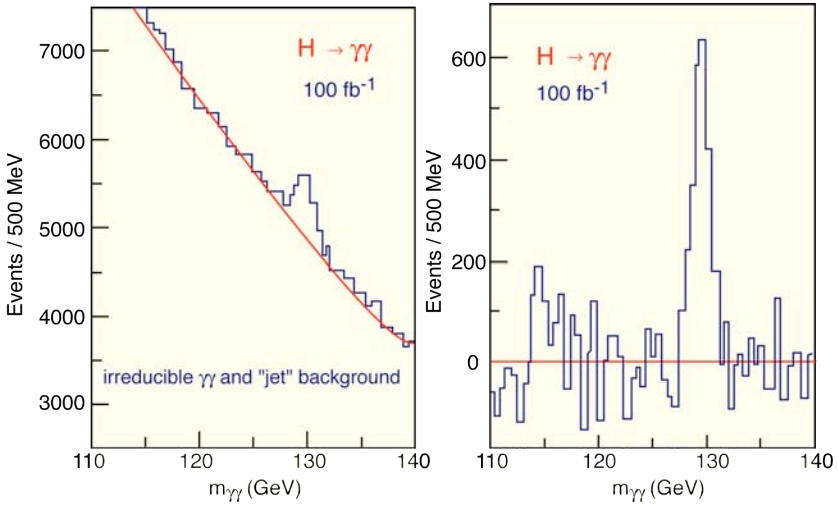
$$\sigma_\theta = \frac{50\mathrm{mrad}}{\sqrt{E}}$$

CMS

better energy resolution

$$\frac{\sigma_E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus \frac{155(210)\mathrm{MeV}}{E} \oplus 0.55\%$$



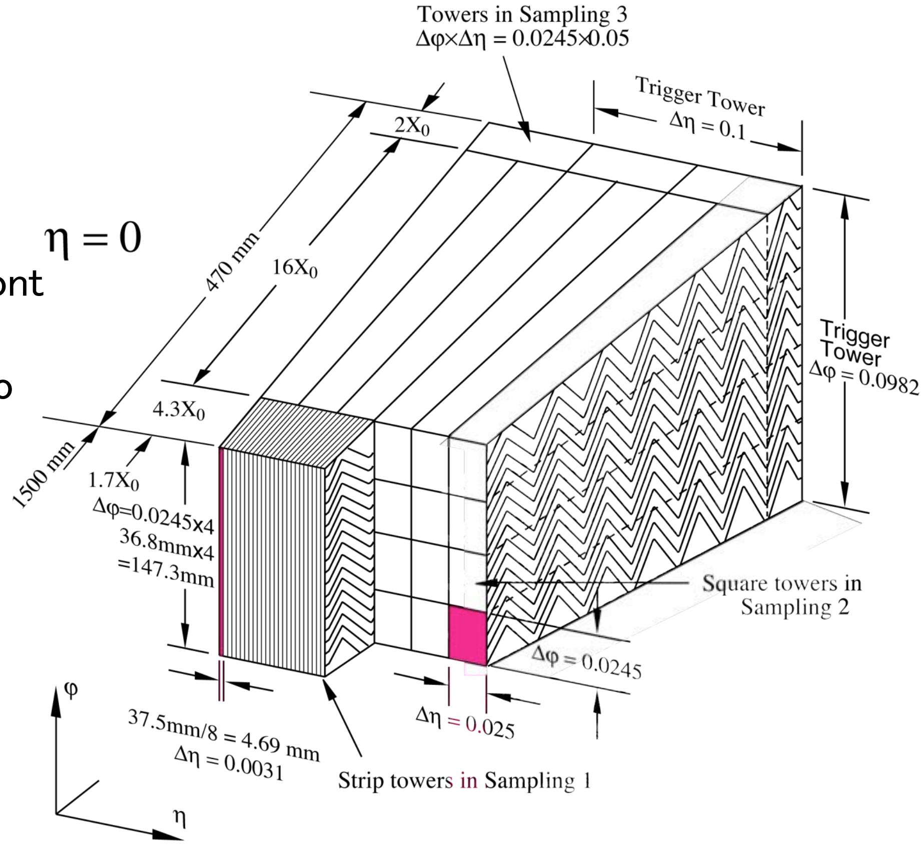


ATLAS Liquid Argon Calorimeter

1990: D.Fournier introduced a novel design "accordeon" for the ATLAS em calorimeter.

Advantages over conventional design:

- Less dead space between towers
- Better uniformity of response
- Less cables, signals can be extracted from front and back face
- Fast signal extraction (50 ns) possible due to low capacitance



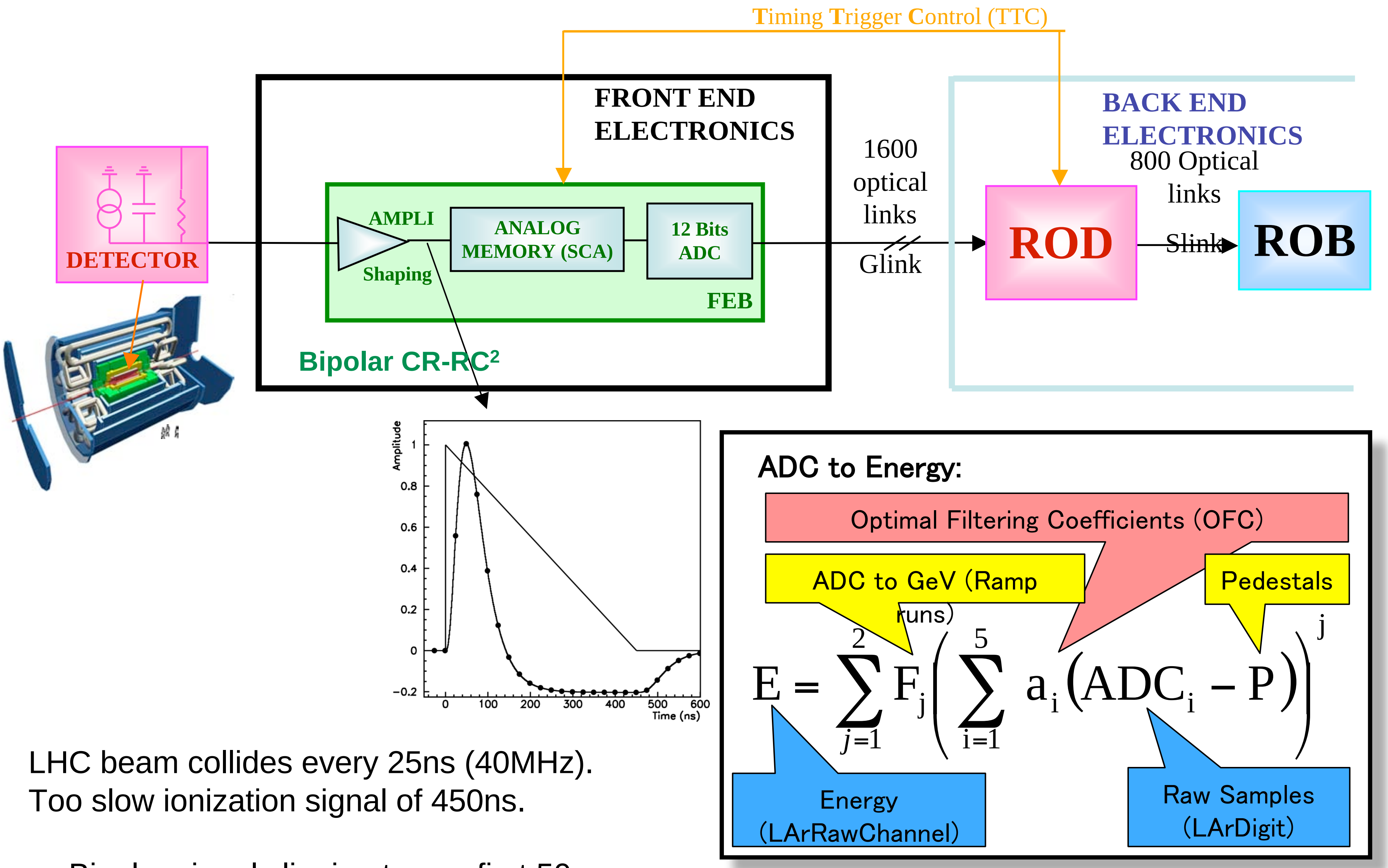
Performance tests

B.Aubert et al (RD 3 Coll.),CERN/DRDC/90-31

B.Aubert et al. NIM A 309 (1991) 438-449

The barrel EM calorimeter is installed in the cryostat. (2003.9)

The calorimeter electronic chain

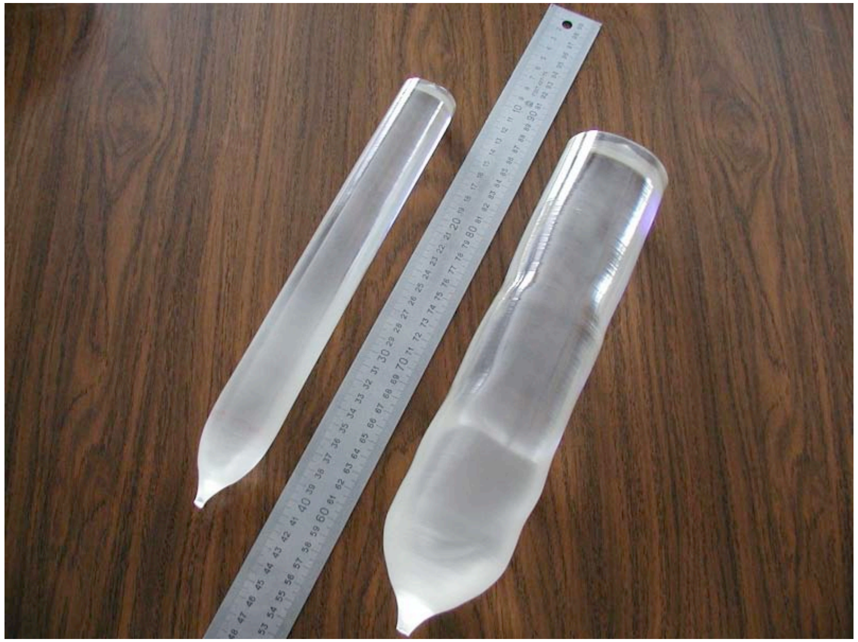


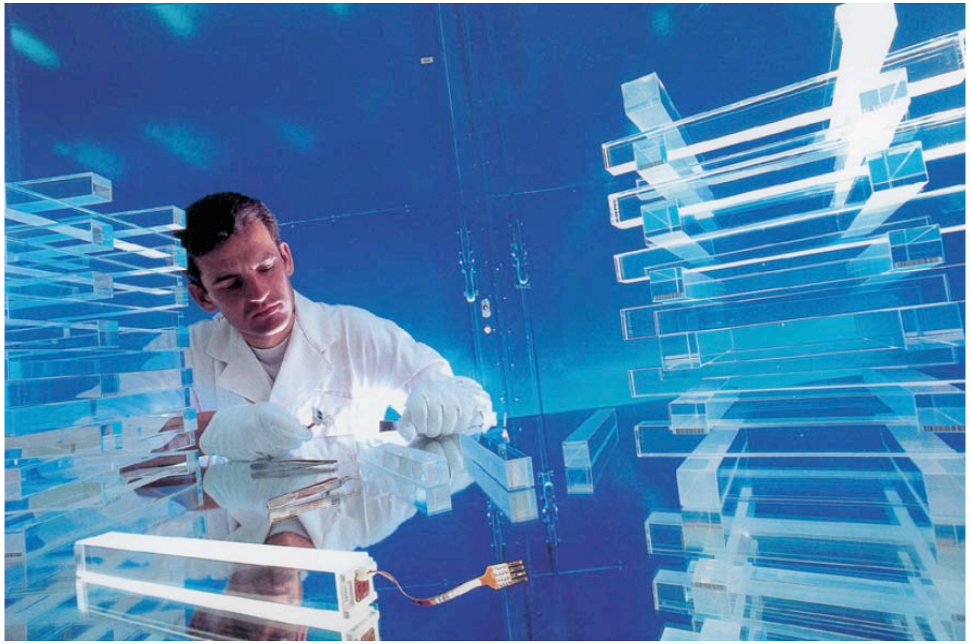
$$E = \sum_{j=1}^{2} F_j \left(\sum_{i=1}^{5} a_i \left(ADC_i - P \right) \right)^{j}$$

LHC beam collides every 25ns (40MHz).
Too slow ionization signal of 450ns.

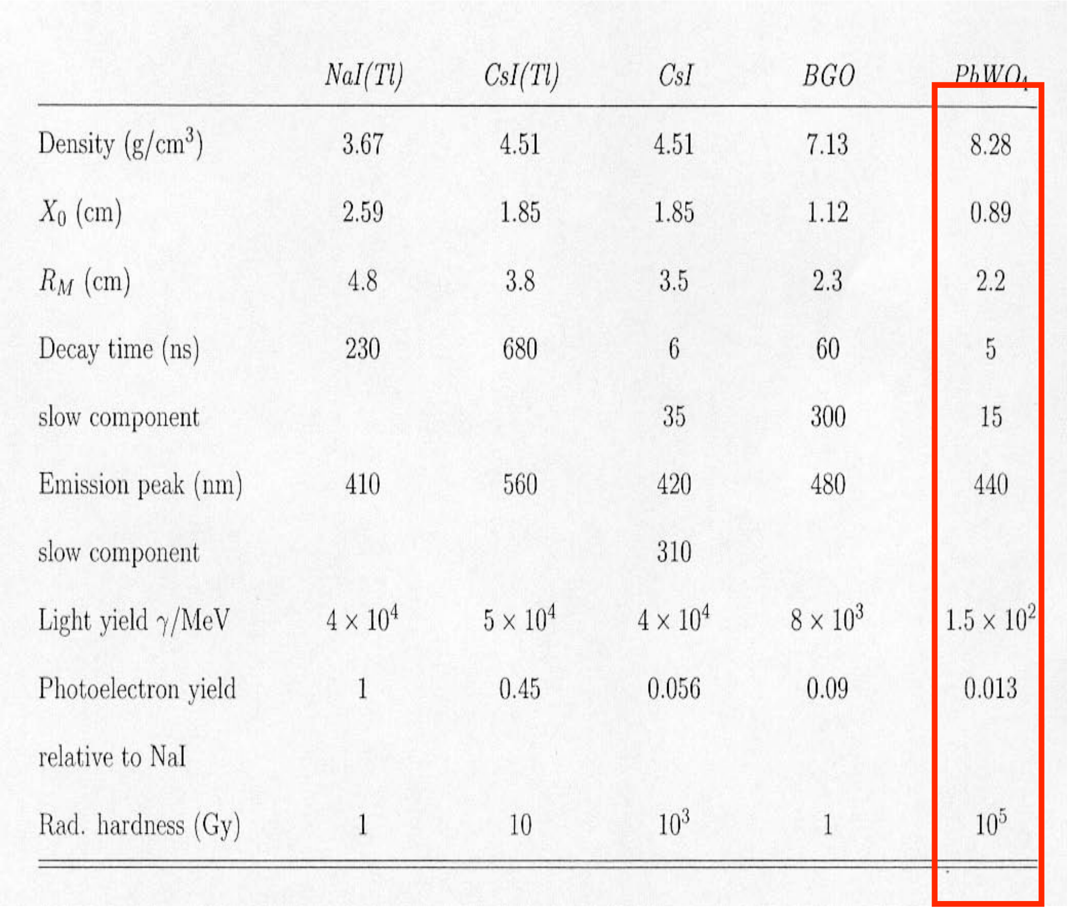
→ Bipolar signal clipping to see first 50ns only. Long undershoot signal.

CMS
Electromagnetic Calorimeter
$PbWO_4$ Scintillator





Crystals commonly used at high energy physics experiments

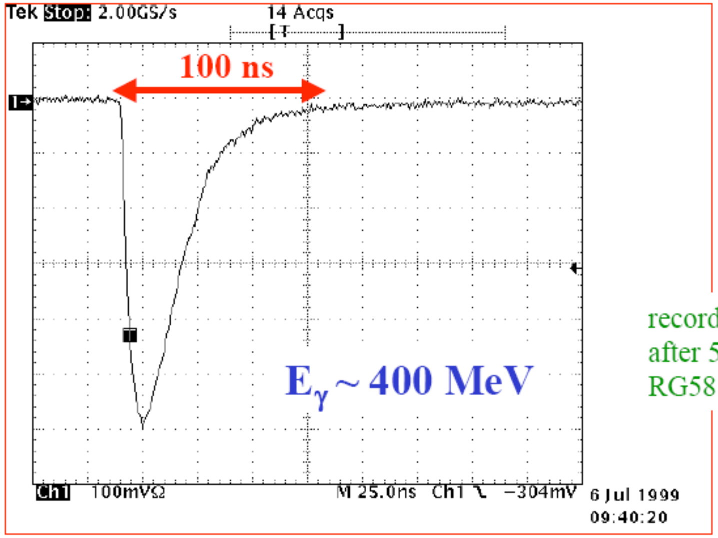


	NaI(Tl)	CsI(Tl)	CsI	BGO	$PbWO_4$
Density (g/cm^3)	3.67	4.51	4.51	7.13	8.28
X_0 (cm)	2.59	1.85	1.85	1.12	0.89
R_M (cm)	4.8	3.8	3.5	2.3	2.2
Decay time (ns)	230	680	6	60	5
slow component			35	300	15
Emission peak (nm)	410	560	420	480	440
slow component			310		
Light yield γ/MeV	4×10^4	5×10^4	4×10^4	8×10^3	1.5×10^2
Photoelectron yield relative to NaI	1	0.45	0.056	0.09	0.013
Rad. hardness (Gy)	1	10	10^3	1	10^5

Because of high resolution and compactness
widely used in collider experiments:
CUSB (NaI(Tl) +Pb glass),
CLEO II (CsI(Tl),KTEV,
BABAR, BELLE, CMS ($PbWO_4$)

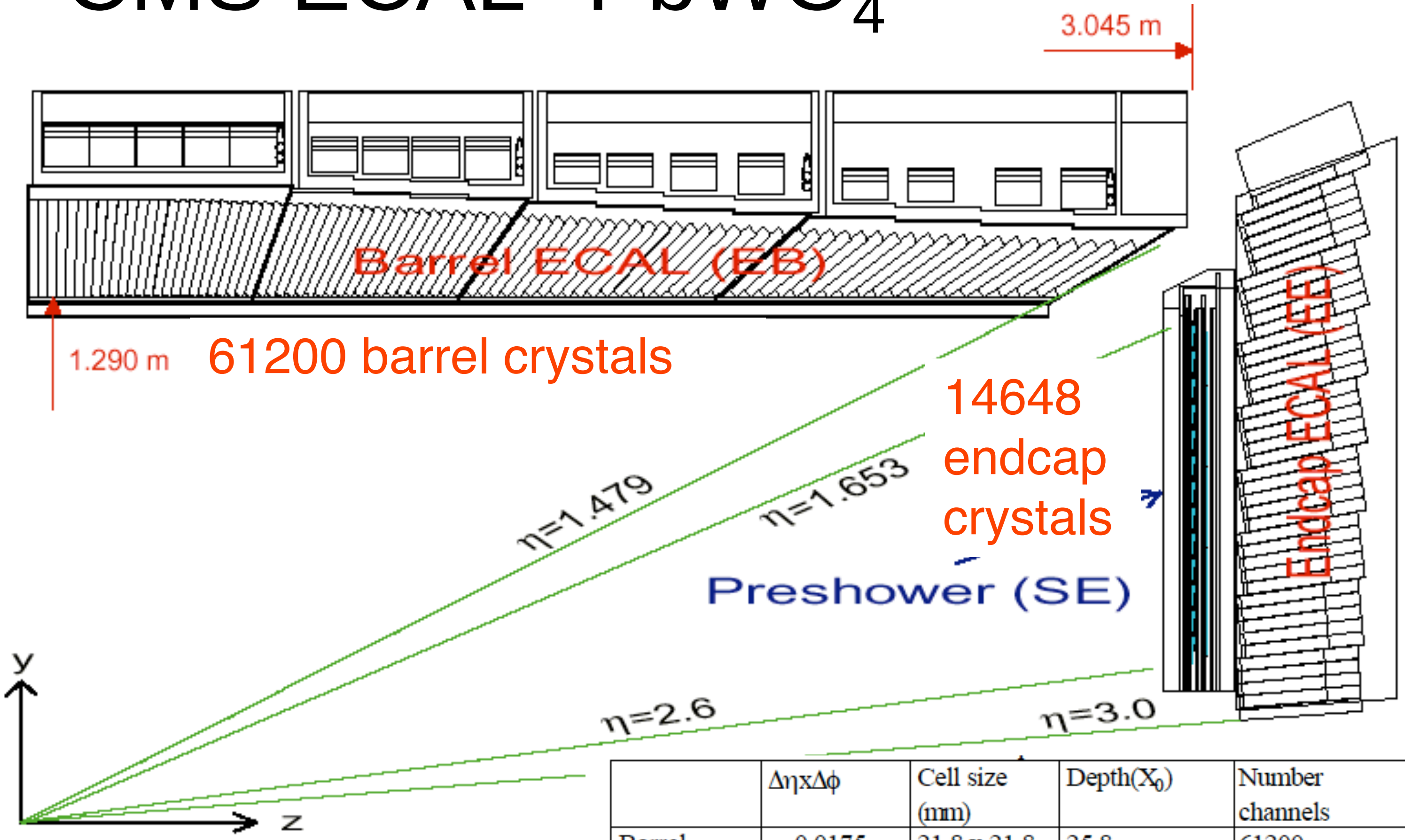
$PbWO_4$ signal

digital scope: Tektronix TDS 744A



recorded
after 50 m
RG58 cable

CMS ECAL $PbWO_4$

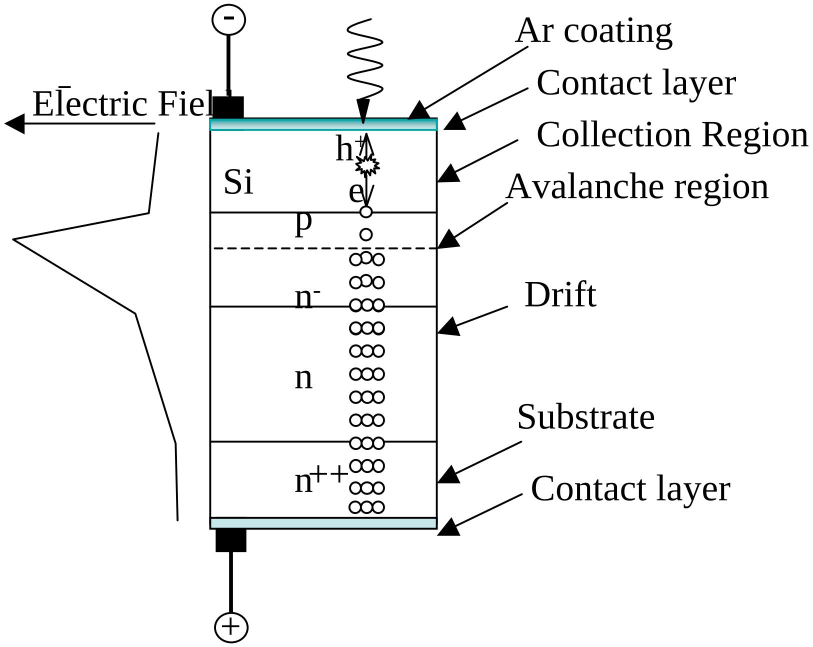


61200 barrel crystals

14648 endcap crystals

	ΔηxΔφ	Cell size (mm)	Depth(X_0)	Number of channels
Barrel η<1.48	0.0175 x 0.0175	21.8 x 21.8	25.8	61200
Endcap 1.48<η<3.0	variable	29.6x29.6	23	15632
End-cap preshower 1.65<η<2.6		63 x 1.9	3	~130000

Avalanche Photodiode (APD)



Gain ~ 50 (PIN photodiode G=1)
Excess noise factor ~ 2
F = kM+(1-k)(2-1/M)

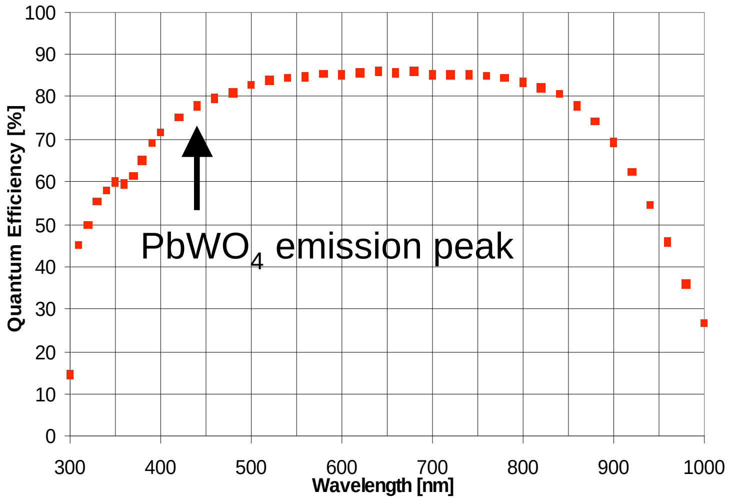
Gain variation

$$\frac{dM}{dT} = -M \times 2.2\ \% / C^{o}$$

Voltage dependence

$$\frac{dM}{dV} = M \times 3.15\ \% / V$$

Quantum Efficiency

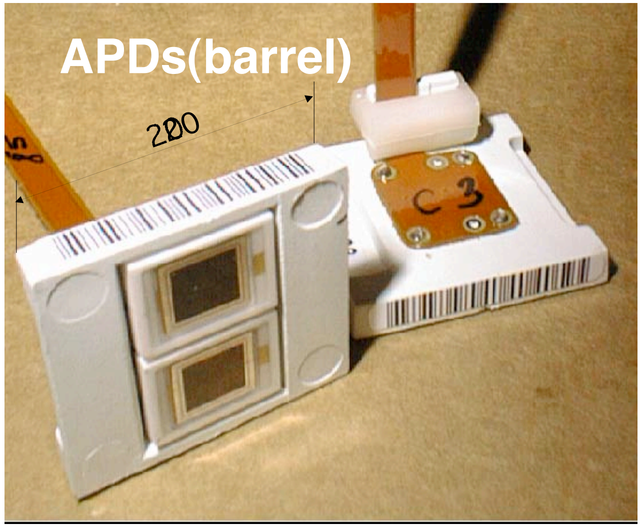


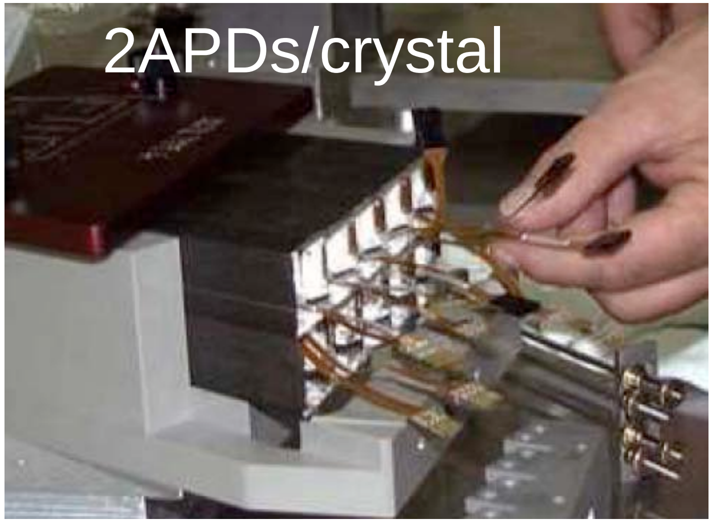
$PbWO_4$ emission peak

Avalanche Photodiode (APD)

Summary of APD parameters

Active Area	**5x5 mm^2**
Operating Voltage @ M=50	**~380 V**
Capacitance @ M=50	**80 pF**
Serial Resistance	**3 Ω**
Dark Current @ M=50	**< 10 nA**
Excess Noise Factor @ M=50	**~2**
Quantum Efficiency @ 470 nm	**80 %**
dM/dV x 1/M @ M=50	**3.0 %/V**
dM/dT x 1/M @ M=50	**-2.4 %/K**


APDs(barrel)


2APDs/crystal

Hamamatsu Photonics
Cost ≈30＄／APD

All 130k APDs are delivered.
Endcap 8000 VPTs

Material description

ATLAS

ATLAS/CMS 0.4~1.4X_0 for η<1.5

ID + Solenoid + Cryostat

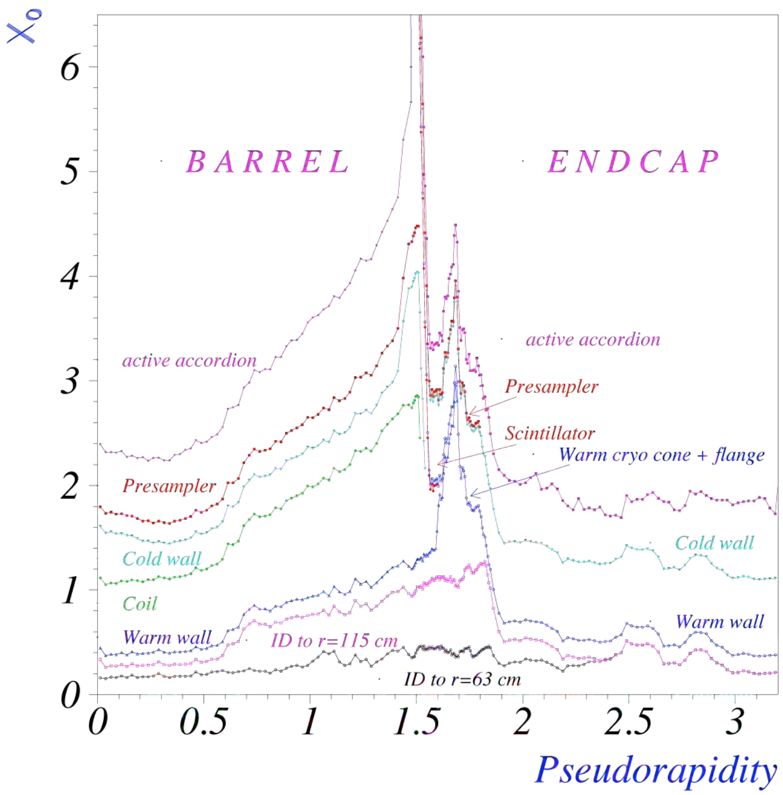
H→γγ Photon 30% converts at ID

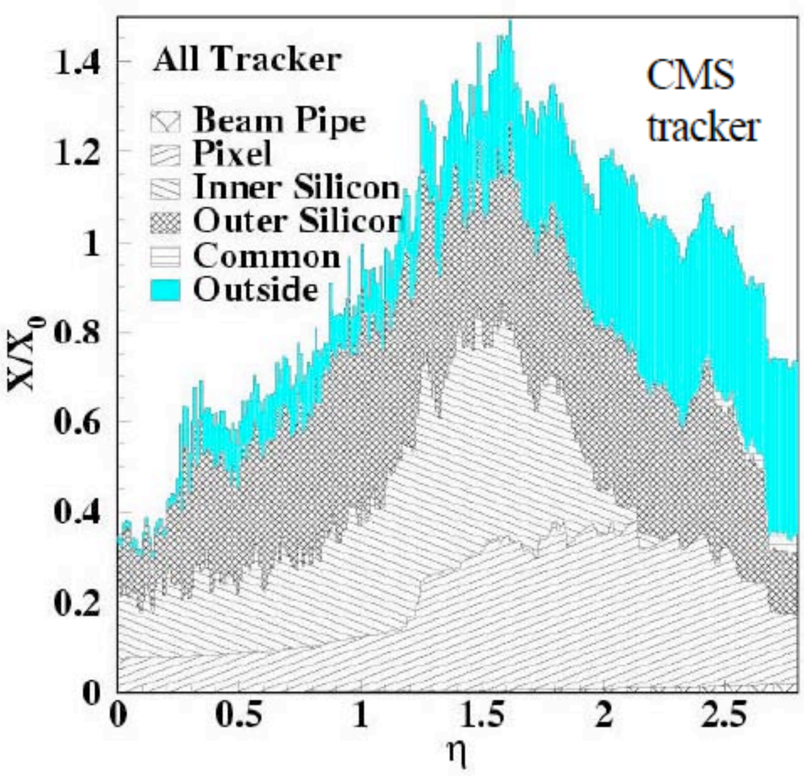
(Photon conversion length = $9X_0/7$)

Validation with real data !

$\gamma \to e^+e^-$ conversion, $\pi^0 \to \gamma\gamma$

Also important ofr W→eν





Energy resolution - constant term

- To observe $H \rightarrow \gamma\gamma$, we need to keep constant term below 0.7%(ATLAS) or 0.55%(CMS).

  ATLAS EM Liq.Ar Calorimeter

  $\sigma_E / E = 10\% / \sqrt{E} \oplus 200(400)\mathrm{MeV}/E \oplus 0.7\%$
- It is hard to achieve constant term below 1% in HEP.

- There are many sources of errors
  - Detector response (geometry), mechanics (absorber thickness)
  - Calibration uniformity
  - Temperature dependence
    - $PbWO_4$+APD **-4.3%/K** (Crystal -2.4%/℃, APD -1.9%/℃)
  - Shower leakage
  - Response difference to e/h
  - Radiation damage
  - Etc.

4. Physics Performance

Detector Commissioning and Physics

Commissioning (2006-2007)

Cosmic Muons, Beam-Halo Muons, Beam-Gas Events
→ initial detector alignment and calibration.

Pilot Run @ 0.9TeV (Nov.-Dec. 2007)

Minimum Bias Events, Di-jet events, Pile-up Events
→ modeling underlying event, jet calibration.

First Physics Runs @ 14TeV (2008~)

- First “good” $10pb^{-1}$ data
  - 20k $W \rightarrow l+\nu$, 2.5k $Z \rightarrow l+l$, 200 semi-leptonic top-pair
- First “good” $100pb^{-1}$ data
  - W(Z)+jets for jet calibration, missing E_T for SUSY
- From $100pb^{-1}$ to $1fb^{-1}$ data
  - Standard Model process study: top, W/Z, QCD, b-jet
  - Extensive MC tuning

→ early Higgs boson search ($H \rightarrow \gamma\gamma$, WW, ZZ).

→ early SUSY-BSM search, missing E_T, di-jet, di-leptons…

QCD

- N(N)LO, ME+PS matching
- Parton Distribution Function（PDF）
- Underlying Events
- Jet Algorithms
  - Jet cone vs k_T
  - Jet energy calibration

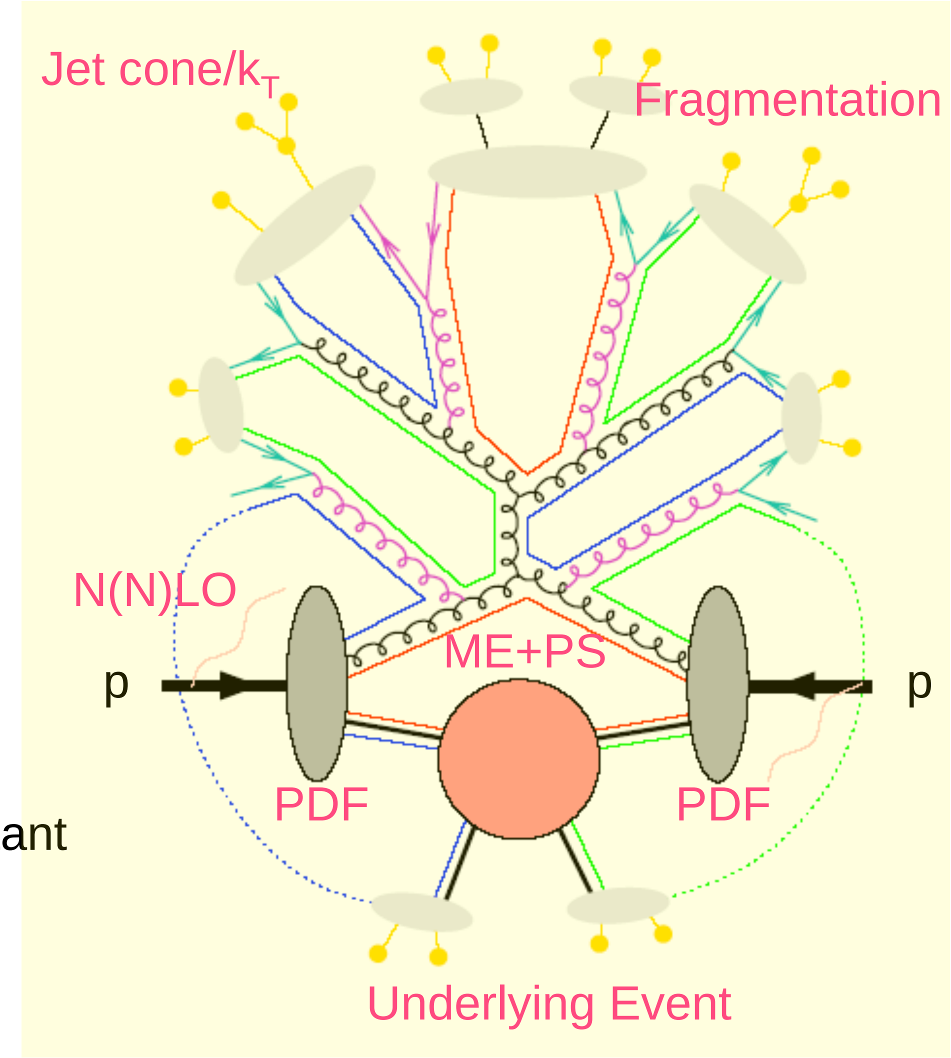
We need to understand the QCD backgrounds and the detector performance (ex. E_T missing).

Example:

VBF($H \rightarrow \tau\tau$), ttH for low M_H

W/Z+n-jets, tt+n-jets are very important

B.Webber TeV4LHC@FNAL



Event at LHC

A simulated event in ATLAS (CMS) H → ZZ → 4μ

pp collision at √s = 14 TeV

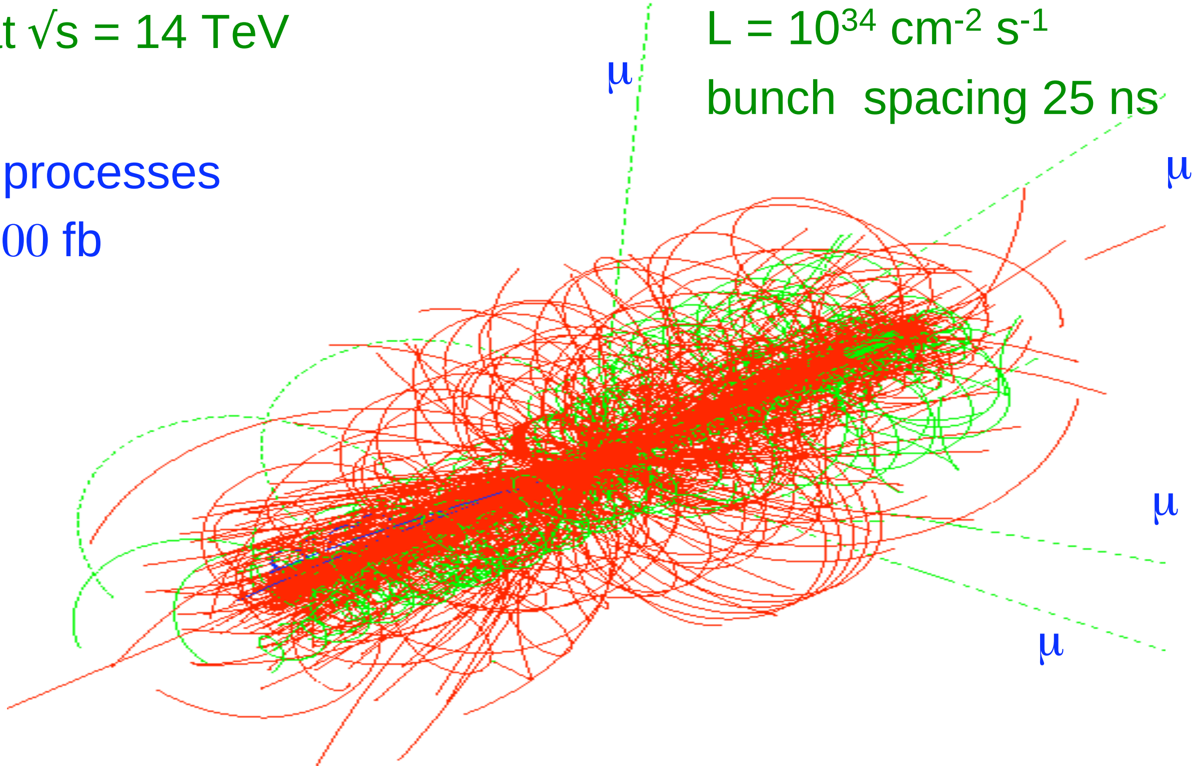
$\sigma_{\text{inel.}} \approx$ 70 mb

Interested in processes

with $\sigma \approx 10\text{–}100$ fb

$L = 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$

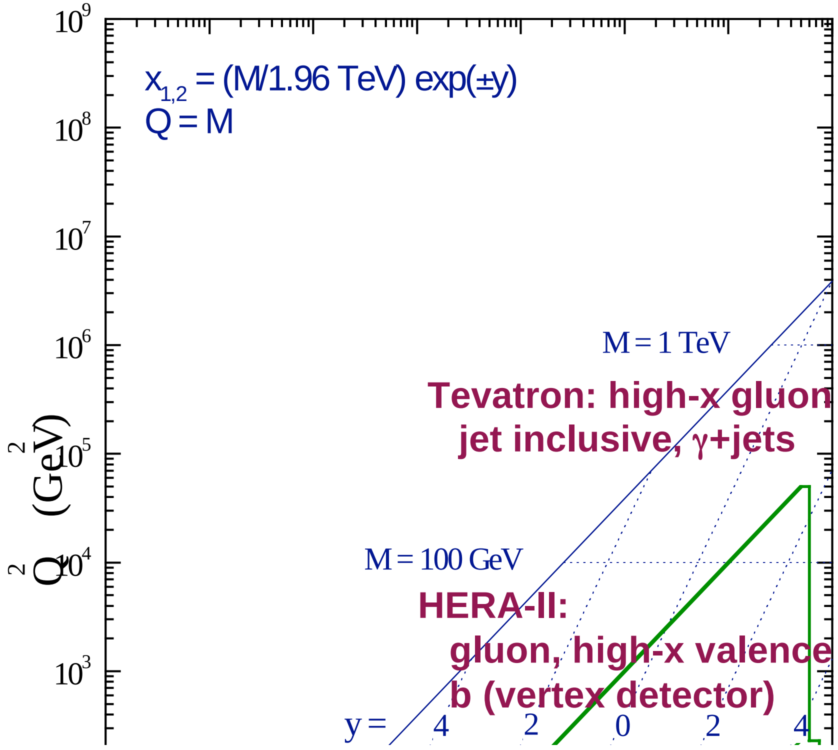
bunch spacing 25 ns



≈ 23 overlapping minimum bias events / Beam Crossing

≈ 1900 charged + 1600 neutral particles / Beam Crossing

Tevatron parton kinematics

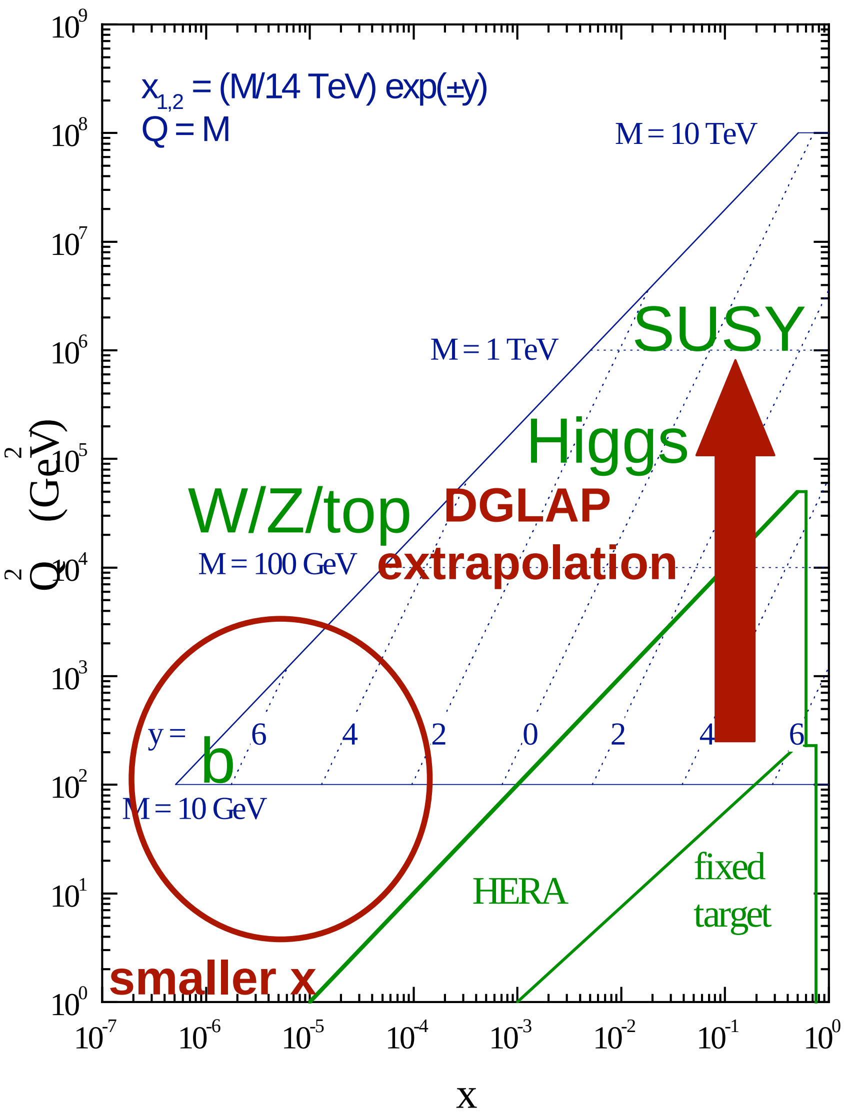


Tevatron: high-x gluon jet inclusive, γ+jets

HERA-II: gluon, high-x valence b (vertex detector)

Process	Main Subprocess	PDFs Probed
$\ell^\pm N \to \ell^\pm X$	$\gamma^* q \to q$	$g(x \lesssim 0.01), q, \bar{q}$
$\ell^+(\ell^-)N \to \bar{\nu}(\nu)X$	$W^* q \to q'$	
$\nu(\bar{\nu})N \to \ell^-(\ell^+)X$	$W^* q \to q'$	
$\nu\ N \to \mu^+\mu^- X$	$W^* s \to c \to \mu^+$	s
$pp \to \gamma X$	$qg \to \gamma q$	$g(x \sim 0.4)$
$pN \to \mu^+\mu^- X$	$q\bar{q} \to \gamma^*$	$\bar{q}$
$pp, pn \to \mu^+\mu^- X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{u} - \bar{d}$
	$u\bar{d}, d\bar{u} \to \gamma^*$	
$ep, en \to e\pi X$	$\gamma^* q \to q$	
$p\bar{p} \to W \to \ell^\pm X$	$ud \to W$	$u, d, u/d$
$p\bar{p} \to$ jet $+X$	$gg, qg, qq \to 2j$	$q, g(0.01 \lesssim x \lesssim 0.5)$

LHC parton kinematics



SUSY

Higgs

W/Z/top

DGLAP extrapolation

b

smaller x

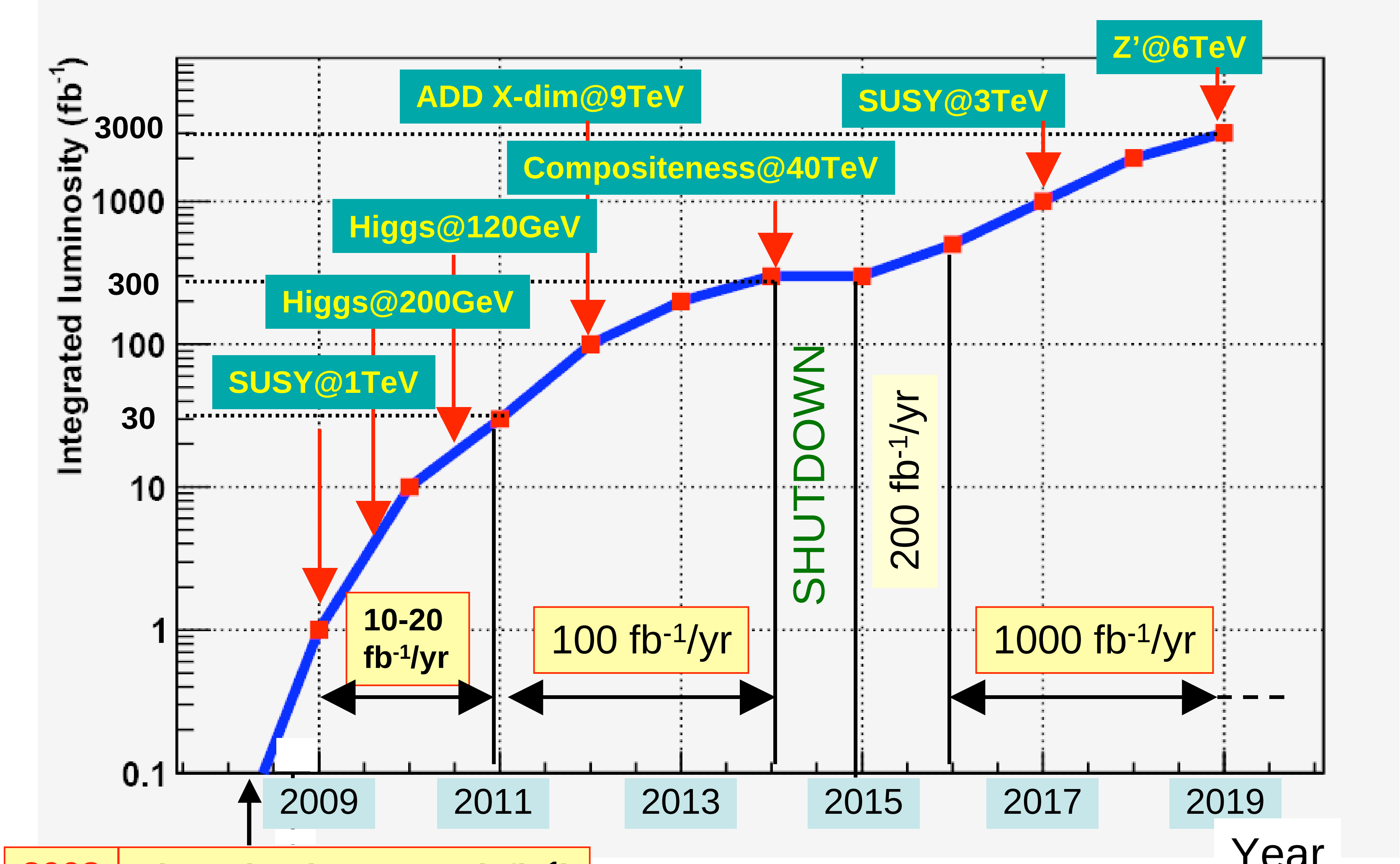
J.Stirling ICHEP2004@Bejing

HERA-LHC Workshop (2004-2005)
http://www.desy.de/~heralhc/

LHC Luminosity Profile

Michel Della Negra

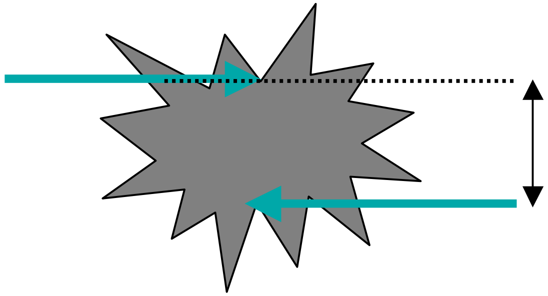
$L = 2\times10^{33}$ $L = 10^{34}$ SLHC: $L = 10^{35}$ ($cm^{-2}s^{-1}$)



2008 **First physics run: O(1fb^{-1})**

Black Hole

J.Tanaka et al. Eur.Phys.J.C41(2005) 19-33
C.M.Harris et al. JHEP 0505(2005) 053



$d < R_s$

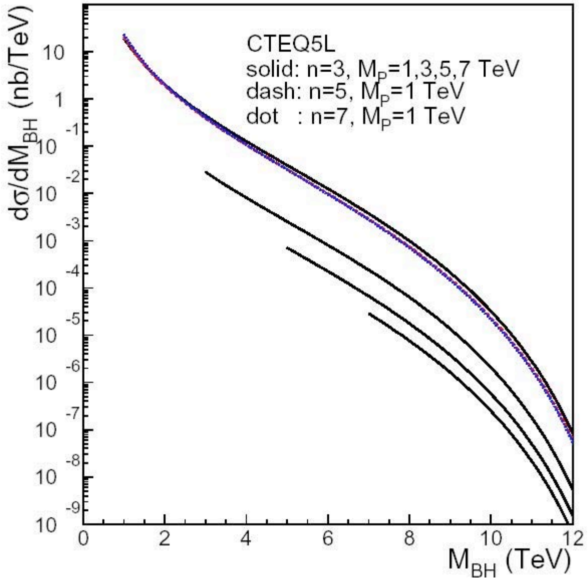
Gravity Scale ~ TeV
Parton collision at d < Schwarzschild radius R_s
→ Black Hole formation
Very large cross section

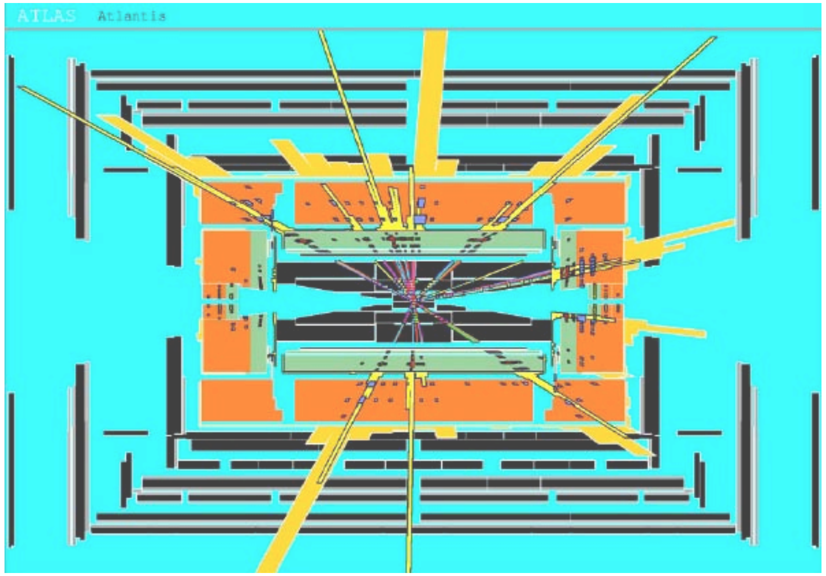
$$R_S = \frac{1}{\sqrt{\pi}M_P}\left[\frac{M_{BH}}{M_P}\left(\frac{8\Gamma(\frac{n+3}{2})}{n+2}\right)\right]^{\frac{1}{1+n}}$$

Parton invariant mass M_{BH}(Black Hole mass)

main phase ? Black body radiation
= Hawking radiation or evaporation
+ ‘Grey-body’ effects (Herwig)
+ Time variation of Hawking temperature
emission of particles

- high multiplicity (a lot of jets)
- “democratic” emission
- spherical distribution





Supersymmetry

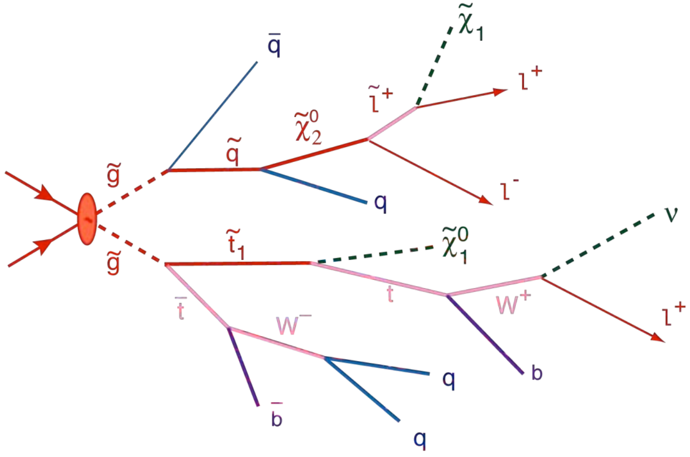
Large cross section via strong interaction

$$\tilde{q}\tilde{q},\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g}$$

$$\sigma \approx 3\text{pb for m}(\tilde{q},\tilde{g}) = 1\text{ TeV}$$

$$\Rightarrow\ 100\text{ events/day@}10^{33}\text{cm}^{-2}\text{s}^{-1}$$

Easy discovery M~1TeV within 1 month ?



3 isolated leptons
+ 2 b-jets
+ 4 jets
+ E_t^{miss}

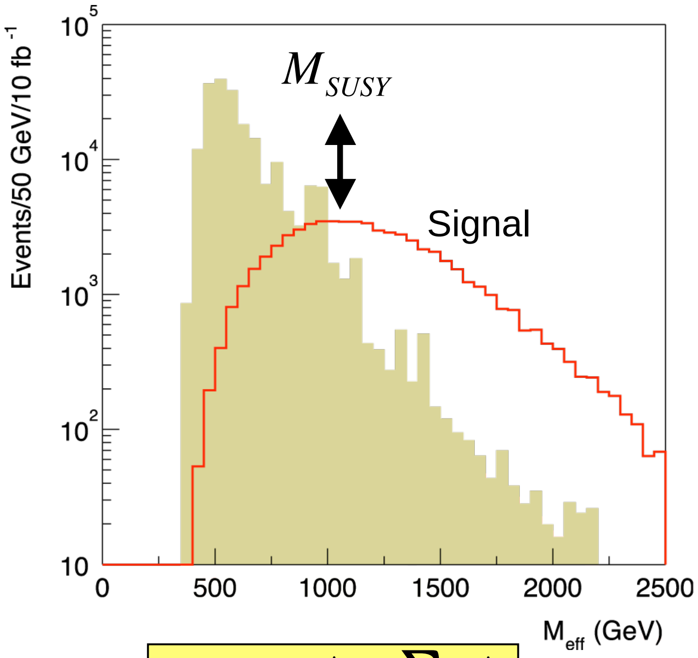
Missing E_T + high p_t jets + Leptons
(Model indep. Analysis, R-parity conserv.)

SUSY Scale

$$M_{SUSY} = min(m(\tilde{q}), m(\tilde{g}))$$

20% accuracy（L=10fb^{-1}, mSUGRA）

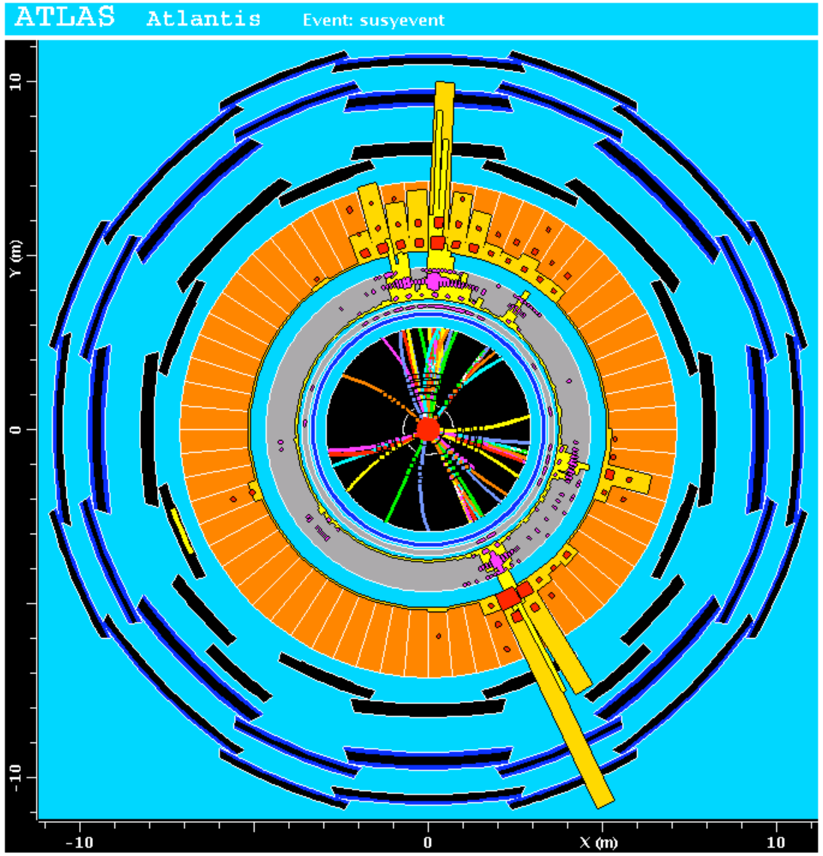
Missing E_T is important（calibrate with Z→*ll*+jets)



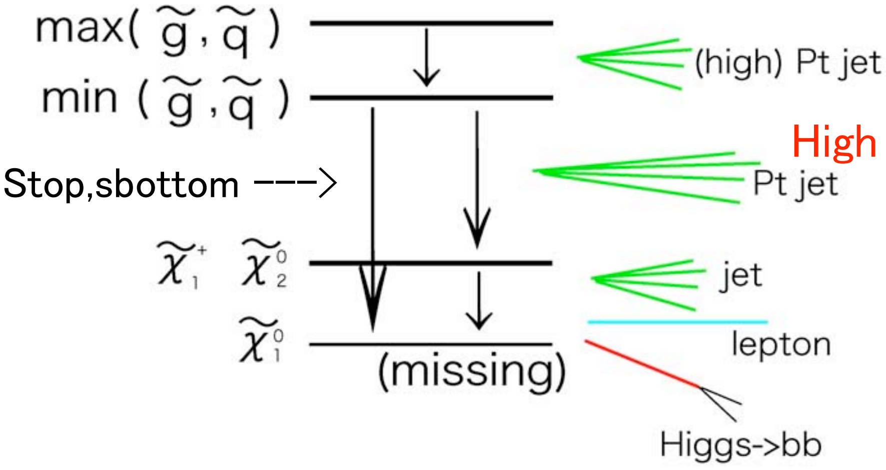
$$\boxed{M_{eff} = E_T^{miss} + \sum p_T^{jet}}$$

J.G. Branson *et al.*, Eur.Phys.J.direct **C4**(2002)N1

SUSY event topology
(Gravity- mediation + R-parity)



Gluino/squark are produced copiously,
"Cascade decay" follows after.



$\max(\tilde{g},\tilde{q})$

$\min(\tilde{g},\tilde{q})$

Stop,sbottom --->

$\tilde{\chi}_1^+$ $\tilde{\chi}_2^0$

$\tilde{\chi}_1^0$

(missing)

(high) Pt jet

High Pt jet

jet

lepton

Higgs->bb

High P_T leptons
$\not{E}_T$ + **multi-jets** + b-jets
τ-jets

(1) E_T^{miss} should be controlled in multi-jets topology (N>=4).

(2) High Pt multi-jets are important to estimate SM background contributions and SUSY reconstruction.

N.Kanaya (Kobe)

SUSY inclusive search

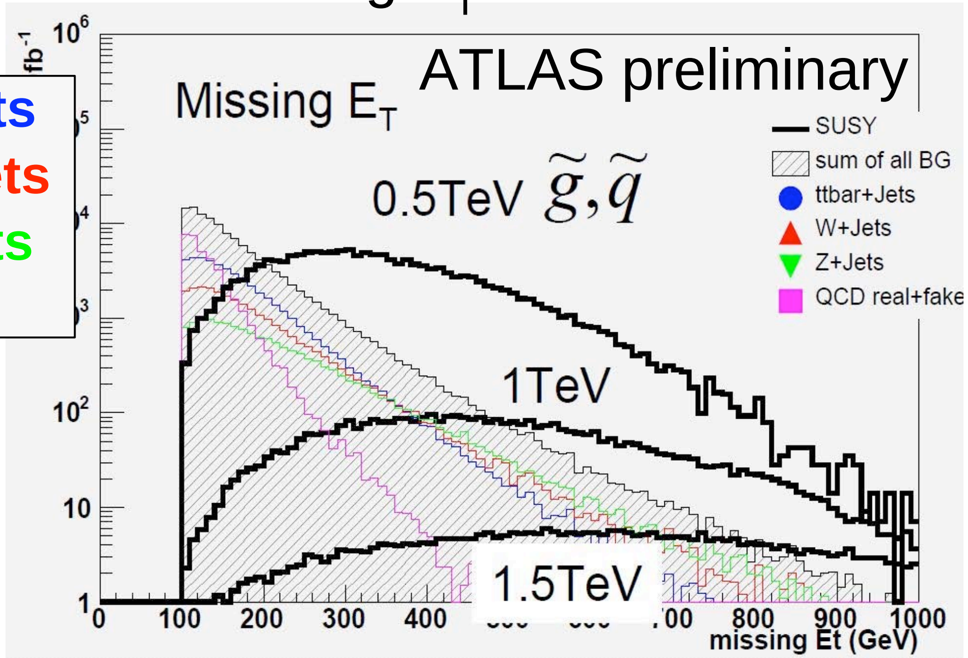
Missing E_T has excellent power to distinguish signal from SM background. - but very challenging !

SUSY standard cut

- Missing E_T > 100GeV
- p_T^{1st}>100GeV, p_T^{4th}>50GeV
- Transverse sphericity>0.2

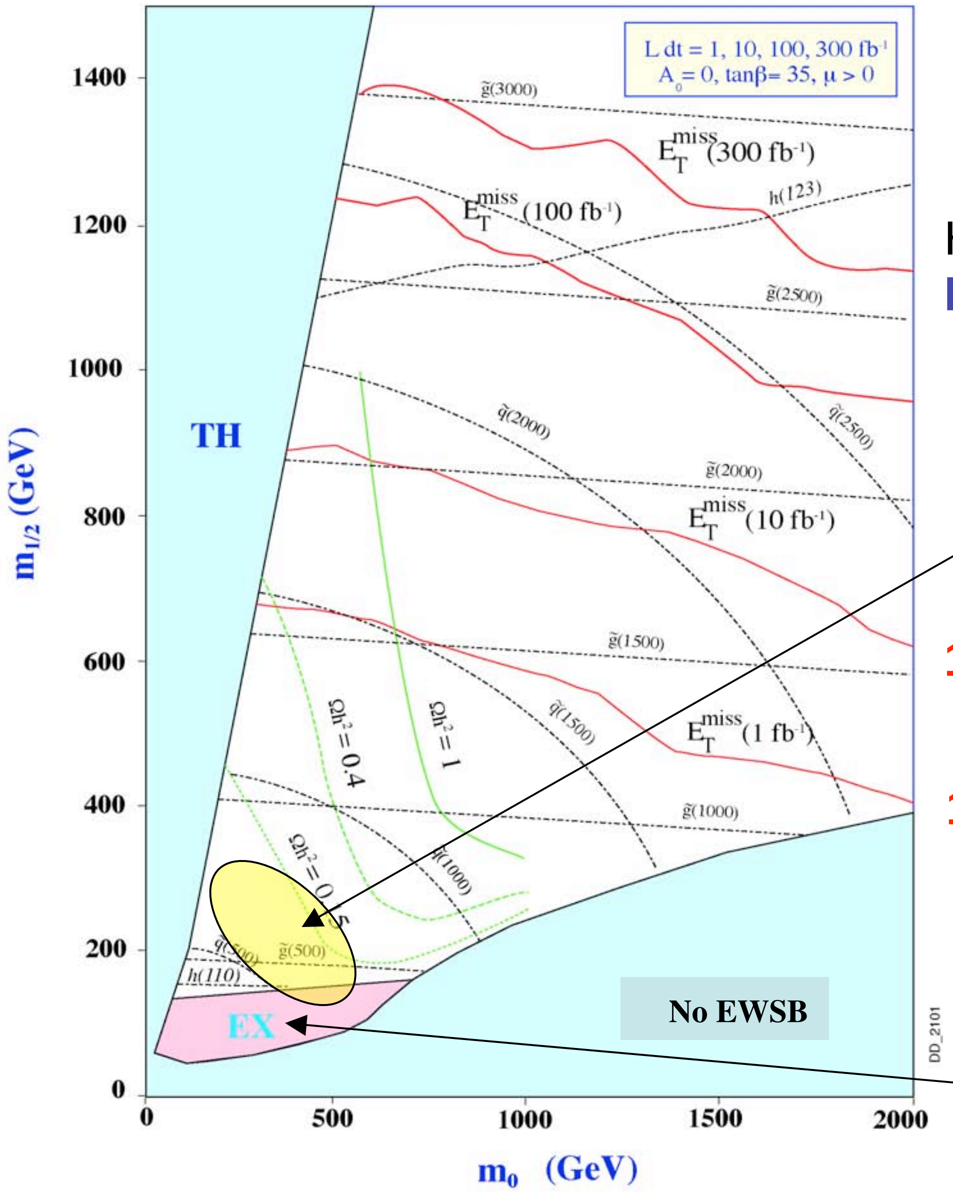
tt+njets
W+njets
Z+njets
QCD

Missing E_T distribution



* background is generated by Alpgen MC.

With 100pb^{-1} data, LHC could say if <1 TeV scale SUSY is accessible to ILC.



mSUGRA
discovery potential

High Lum. 3 year run (L=300fb^{-1})
M≤2.5TeV

Cold Dark Matter
1 week run is enough.

WMAP $0.0094<\Omega_m h^2<0.129$

1 year run (L=10fb^{-1}) **M≤2TeV**

1 month run (L=1fb^{-1})
$m(\tilde{q},\tilde{g}) \sim$ **1.5TeV** 5σ discovery

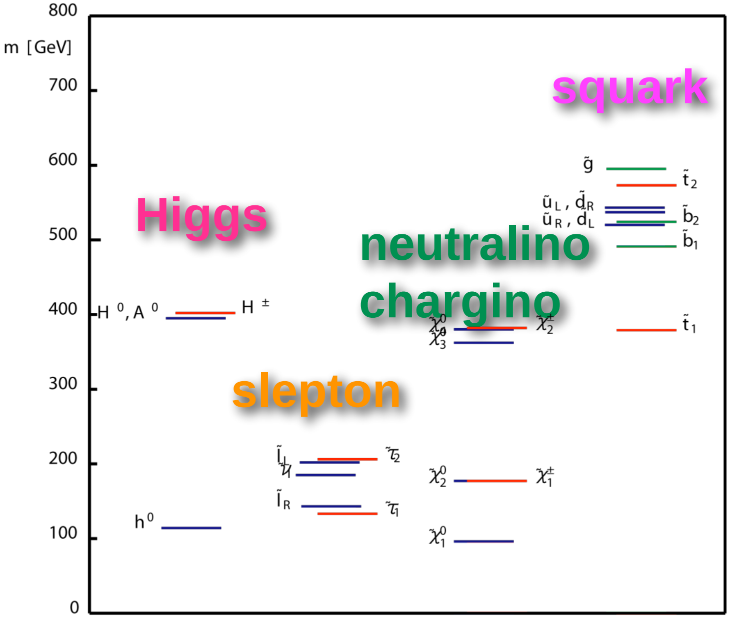
LEP & Tevatron region

Supersymmetry vs Extra-Dimension

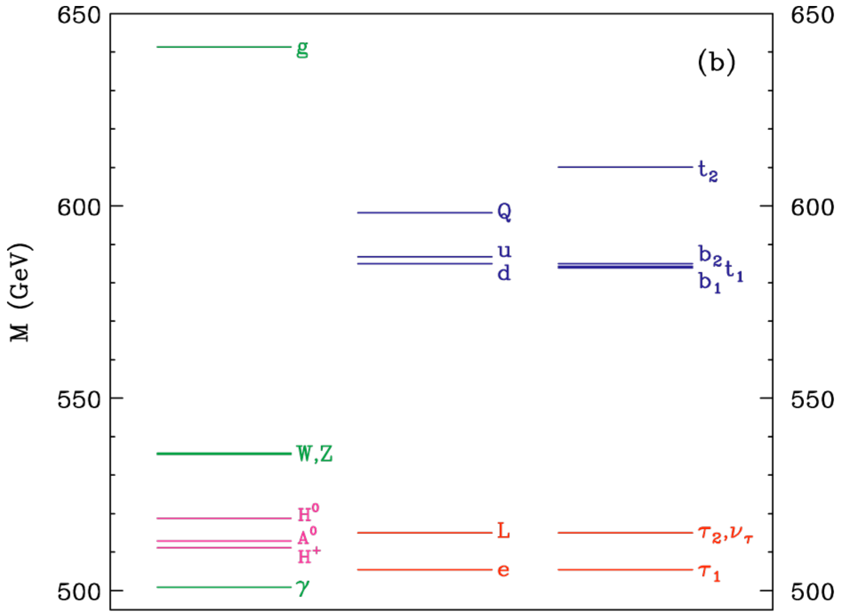
Typical mSUGRA scenario ⟷ Universal Extra-Dimension scenario

Use spin !

B.C.Allanach *et al.*, Eur.Phys.J.**C25**(2002)113



H-C.Cheng *et al.*,
Phys.Rev.**D66**(2002)036005, *ibid.* 056006

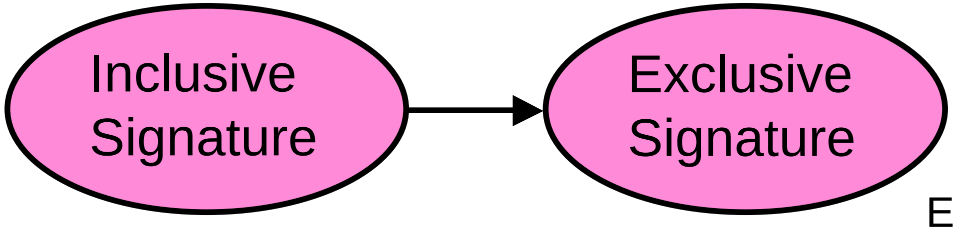


LHC - Higgs, squark/gluino

Testing the underlying theory … not trivial …

- Determination of SUSY model parametres

C.G. Lester, M.A. Parker, M.J. White, JHEP 0601(2006)080



Cross sections

M_{eff}

N_{lepton}

…

Markov chain sampling technique

Inclusive Signature → Exclusive Signature

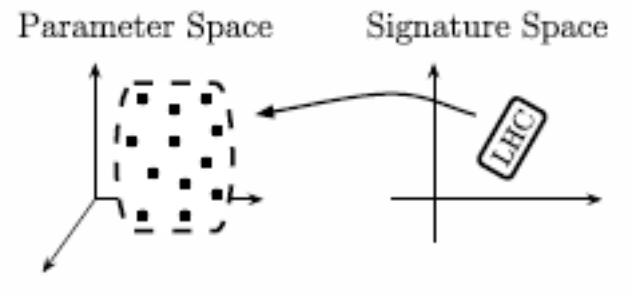
Kinematics

Endpoints(mass)

Easy for theory

- SUSY “inverse map” LHC signatures → theoretical models

N. Arkani-Hamed et al., hep-ph/0512190

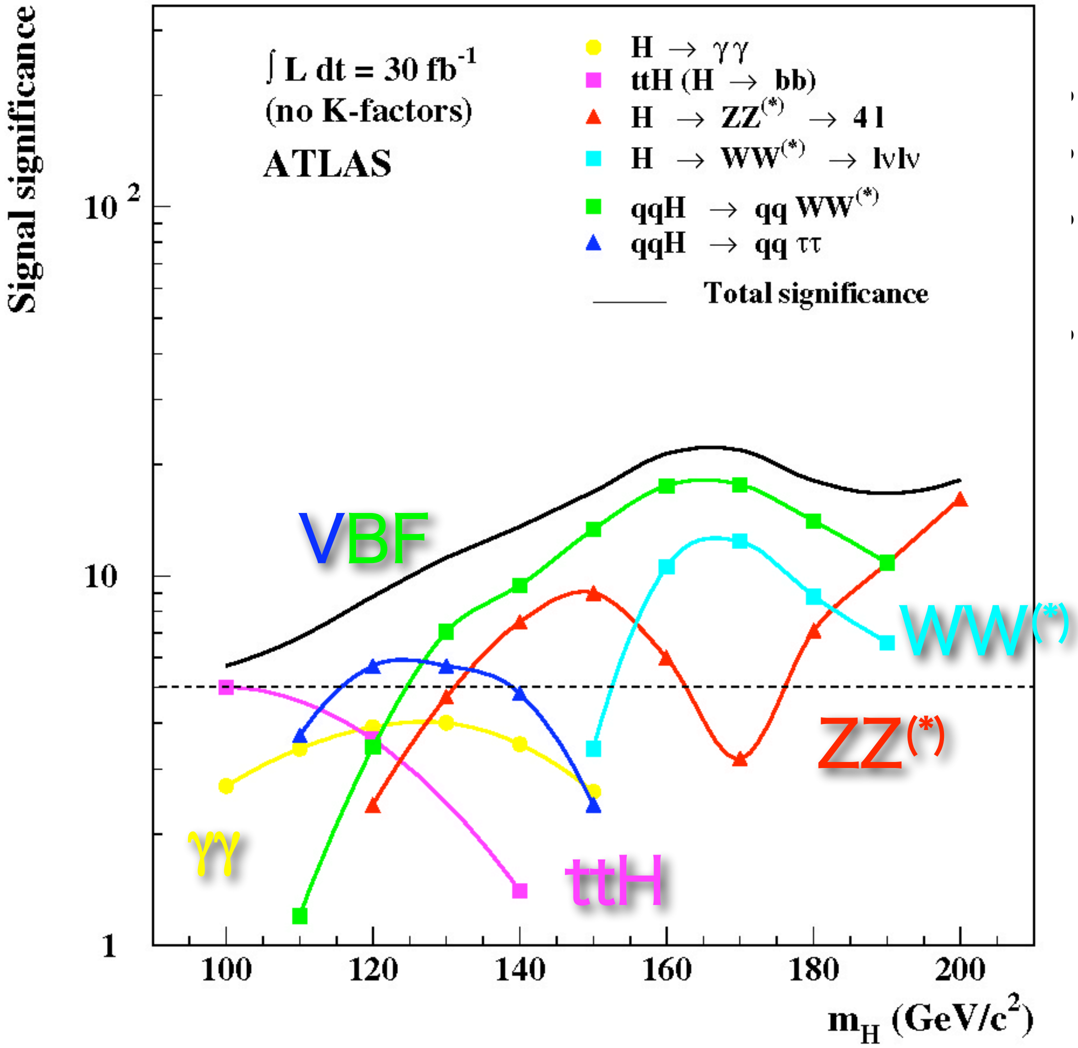


15 dimensional parametrization

1808 LHC observables

Higgs discovery potential

S.Asai *et al.*, Eur.Phys.J.direct C32 Suppl. 2 (2004) 19



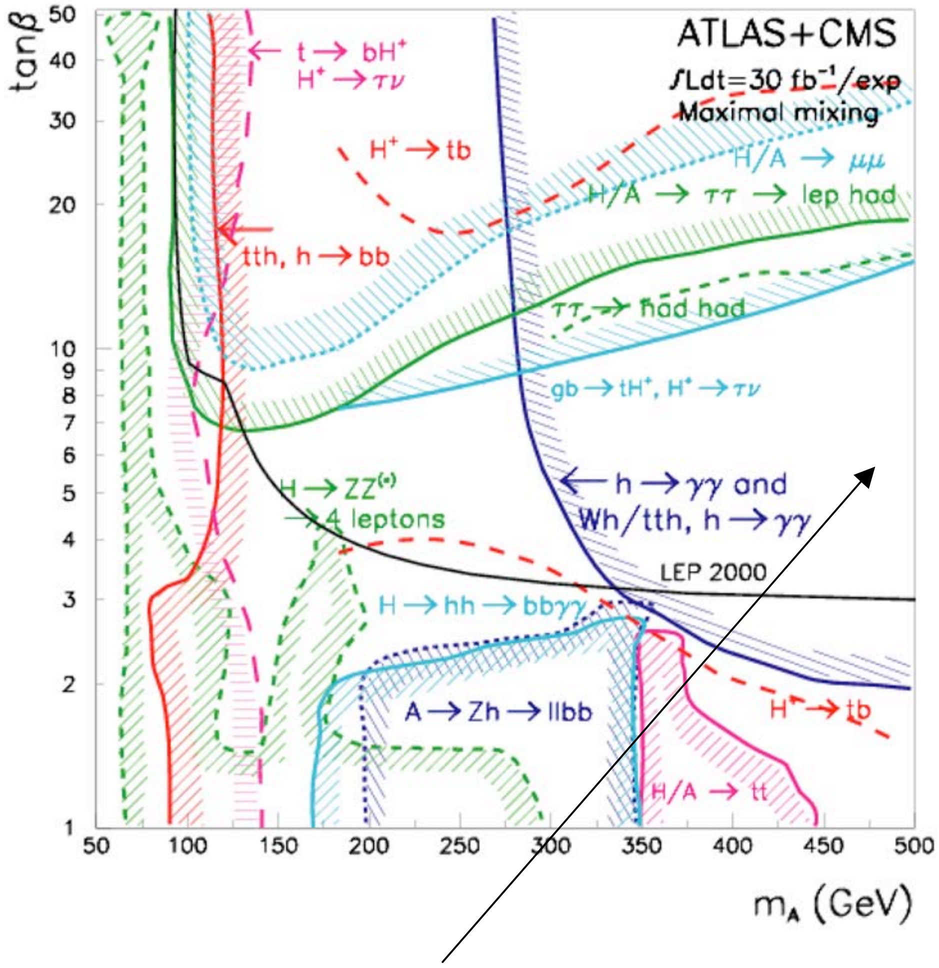
L=30fb^{-1} >8σ significance
(M$_H$>114GeV:LEP limit)

- Light Higgs VBF・H→ττ
- Heavy Higgs VBF・H→WW
- Multiple discovery modes for M$_H$<200GeV
- M$_H$>200GeV
  H→ZZ→4 lepton (gold plated)
  >20σ

L=10fb^{-1} > 5σ

→ Discovery after 1year LHC RUN

MSSM Higgs discovery potential



Observe only h similar to H_{SM}.

5 Higgs bosons h,H,A,$H^{\pm}$

Descrive m_A and tanβ at tree level.

Larege bbH/A coupling at large tanβ
H/A→ττ, μμ, bb

μμ channel is important at the beginning of LHC
∵ Commissioning μμ＜ττ＜＜bb

Can observe charged Higgs
via gb→tH^- at tanβ>10

Cover whole (m_A, tanβ) plane
for MSSM Higgs
with L=30fb^{-1} data

Light Higgs Boson (M_H<140GeV)

Vector Boson Fusion

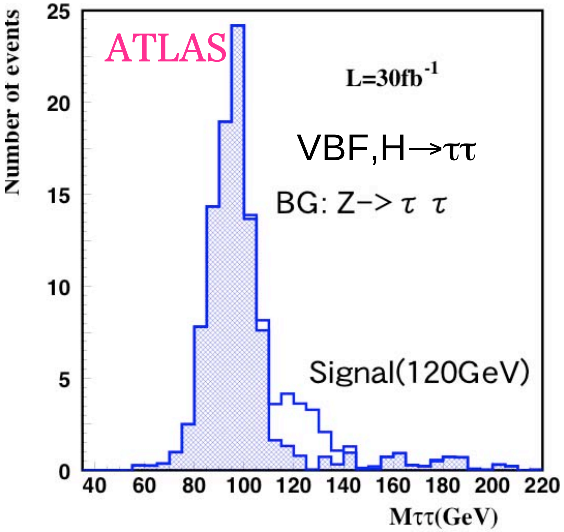
VBF (H→ττ) σxBr≈300fb

Need forward jet reconstruction

& centra jet veto.

Yukawa coupling meas., **No b-tag !**

Backgrounds: Z+jets (Drell-Yan)



ttH (H→bb) σxBr≈300fb

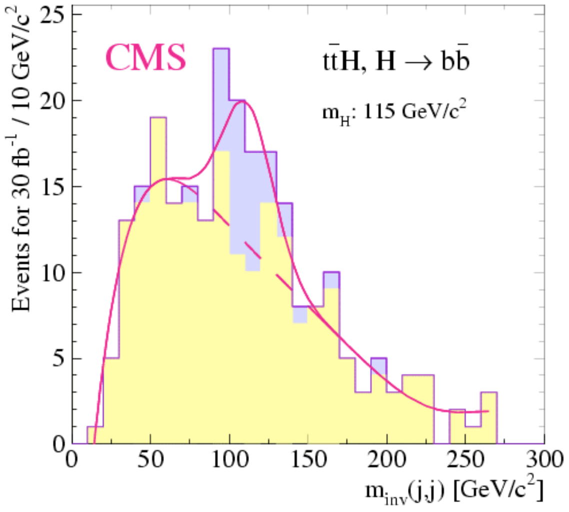
Very important for top-Yukawa coupling

b-tag efficiency ε_b=60%, R_j(uds)~100

Backgrounds **(needs @ 5-10% level precision)**

ttjj, Wjjjjjj,WWbbjj etc.

combinatorials (4-b's)



W/Z+n-jets, ttbar+n-jets studies are very important.

Higgs $J^{PC}=0^{++}$

Ex. π^0 $J^P=0^-$ ← double Dalitz decay

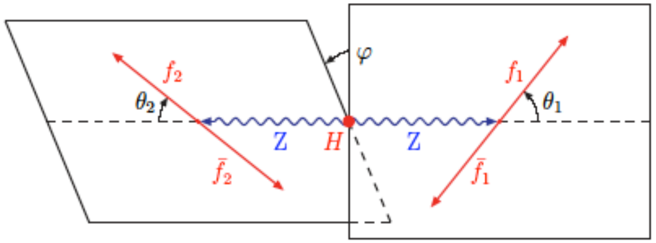
H→ZZ→4*lepons* (S/B>3)

⇒ Angle between decay planes of two Z's from Higgs decay

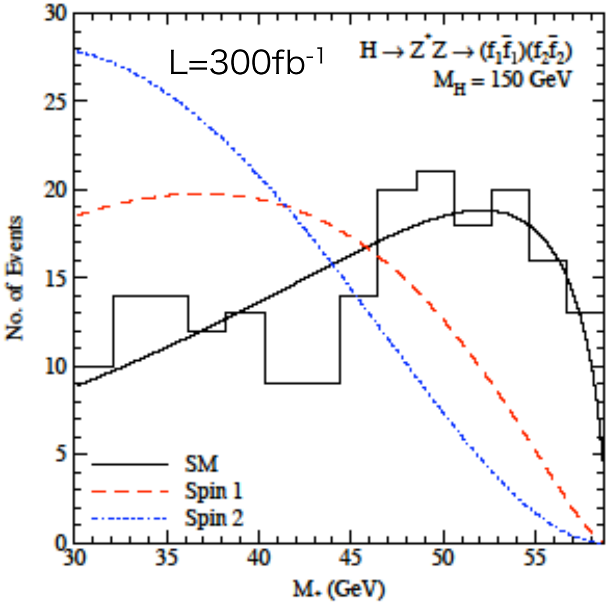
C.A. Nelson, Phys.Rev.D37(1988)1220,

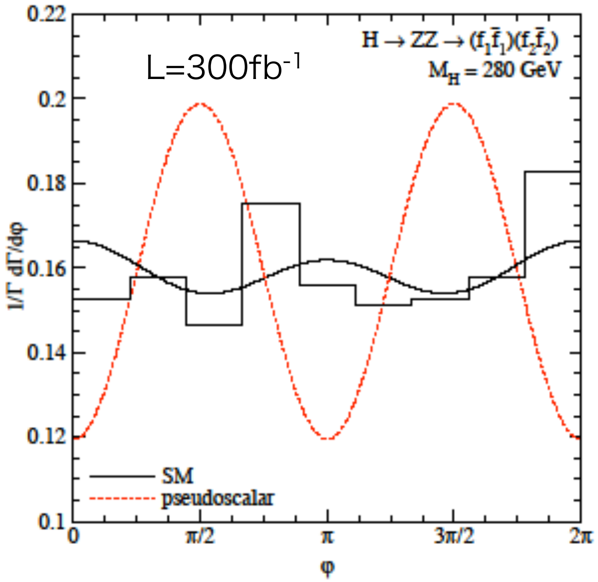
C.P. Buszello *et al.,* Eur.Phys.J. C32(2004)209

Also studies VBF H→WW→lνlν spin correlation、ttH/ttA etc.



S.Y. Choi *et al.,* Phys.Lett. B553(2003) 61





Yukawa coupling

$$g_{\mathrm{f\bar{f}H}} = \frac{m_{\mathrm{f}}}{v} \qquad (v = 246\,\mathrm{GeV})$$

Higgs-W/Z coupling

$$g_{\mathrm{VVH}} = 2\frac{M_{\mathrm{V}}^2}{v} \qquad g_{\mathrm{VVHH}} = 2\frac{M_{\mathrm{V}}^2}{v^2}$$

Higgs boson self-coupling

$$g_{\mathrm{HHH}} = 3\frac{M_{\mathrm{H}}^2}{v} \qquad g_{\mathrm{HHHH}} = 3\frac{M_{\mathrm{H}}^2}{v^2}$$

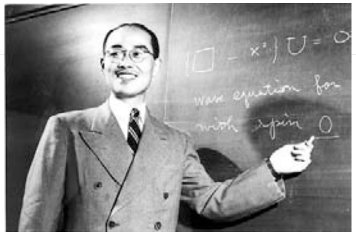
Non-linear Yukawa couplings
⇒ direct evidence of physics beyond the Standard Model.

Example. In MSSM,

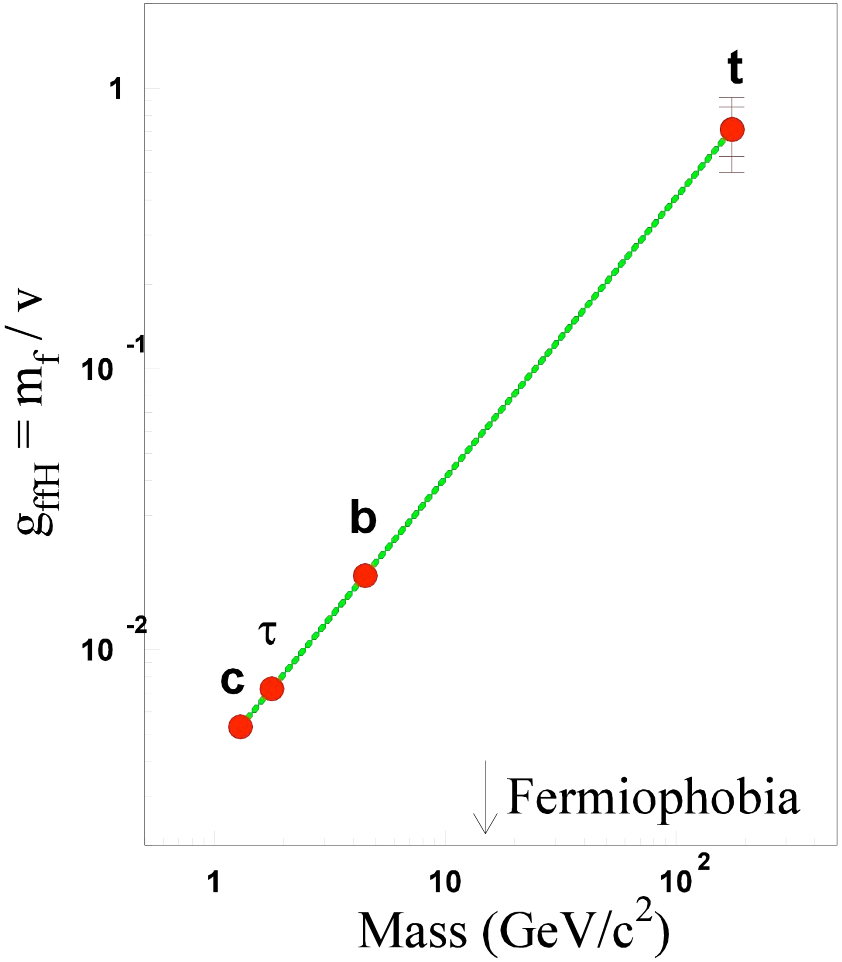
$$\frac{g_{bbh,\tau\tau h}^{\mathrm{MSSM}}}{g_{bbh,\tau\tau h}^{\mathrm{SM}}} = -\frac{\sin\alpha}{\cos\beta}, \quad \frac{g_{tth}^{\mathrm{MSSM}}}{g_{tth}^{\mathrm{SM}}} = \frac{\cos\alpha}{\sin\beta}$$

(M. Carena, H.E. Haber hep-ph/0208209)

湯川



Yukawa Coupling



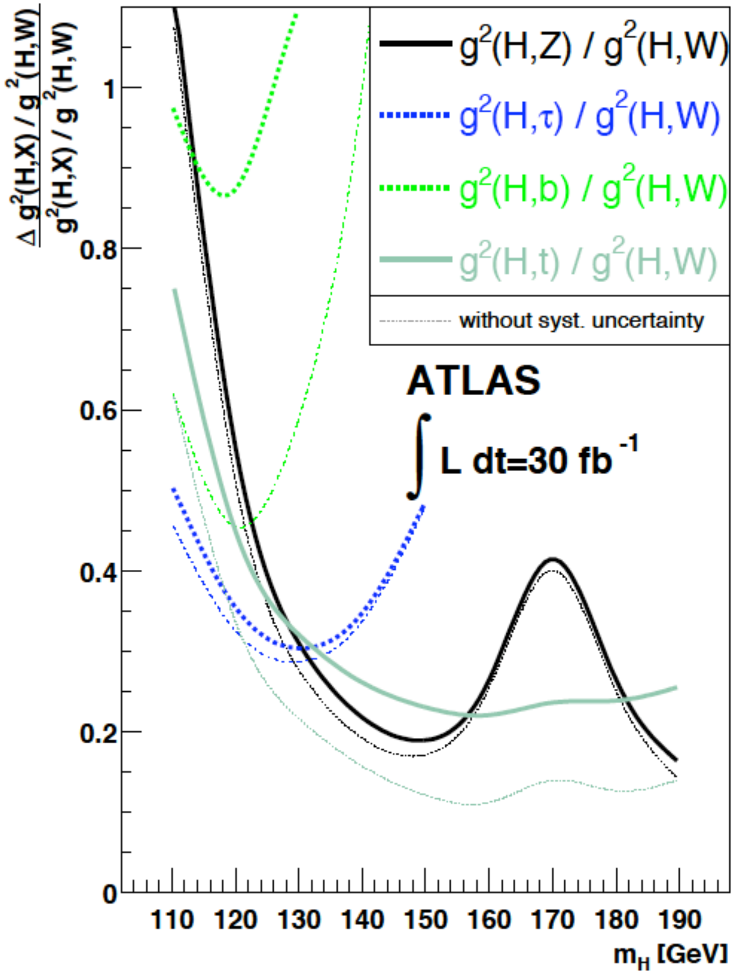
top-Yukawa coupling plays the key role

Yukawa Coupling

Precision of the coupling constants
(relative, normalized with HWW)

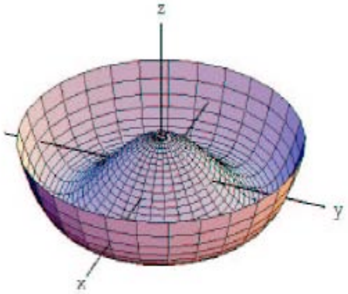
- ttH, $\tau\tau$H ~ 15-20% precision
- bbH ~ 45% (needs VBF bb)
- ZZH ~ 10-25%

M.Dührssen *et al.*,
ATL-PHYS-2003-030, hep-ph/0406323



Higgs self-coupling

Higgs self-potential



$$V = \lambda\left(|\varphi|^2 - \frac{1}{2}v^2\right)^2$$

$$V = \lambda v^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

$$M_H = \sqrt{2\lambda}v$$

trilinear coupling $\lambda^{\mathrm{SM}}_{\mathrm{HHH}} = 3\frac{M_H^2}{v}$

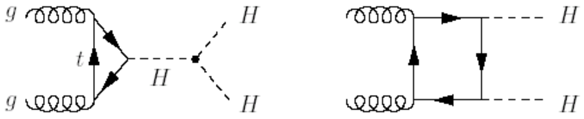
quadrilinear coupling $\lambda^{\mathrm{SM}}_{\mathrm{HHHH}} = 3\frac{M_H^2}{v^2}$

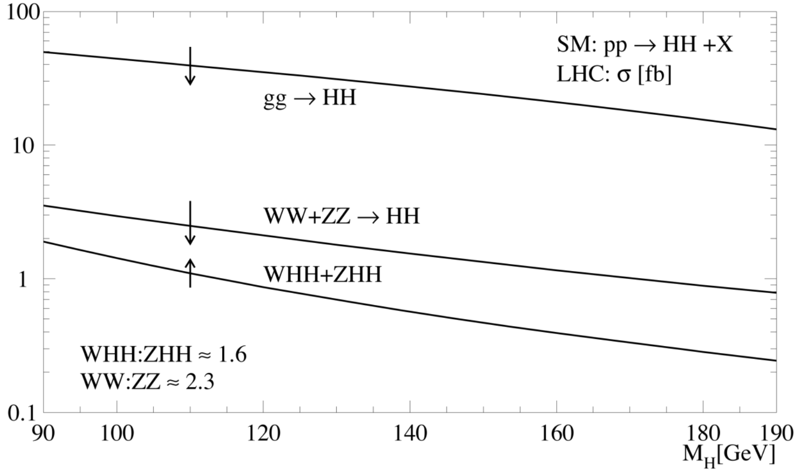
SLHC High Luminosity Upgrade L=10^{35} cm^{-2}s^{-1}

gg→HH→WWWW→$l\nu jjl\nu jj$ (like-sign di-lepton)
L=6 ab^{-1} (!)
⇒ Significance 5.3(3.8) for M_H=170(200) GeV

$\Delta\lambda_{\mathrm{HHH}}/\lambda_{\mathrm{HHH}}$(stat.) = ±19(25)%

F.Gianotti *et al.*, hep-ph/0204087





Extra-dimension *ADD*

ADD

- Large flat compactified extra dimensions

⇒ conjecture:

- SM particles localized in 4D brane

- gravity propagates in the bulk of higher dimension

$$M^2_{Pl_{(4)}} = M^{\delta+2}_{Pl_{(4+\delta)}} R^\delta_C \equiv M_D^{\delta+2} R^\delta_C$$

δ	M_D^{max} (TeV) LL, 30 fb^{-1}	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	7.7	9.1	~ 4
3	6.2	7.0	~ 4.5
4	5.2	6.0	~ 5

Uncertainty in σ(*Z+jets*) will lower the reach

Reach in M_D for γG

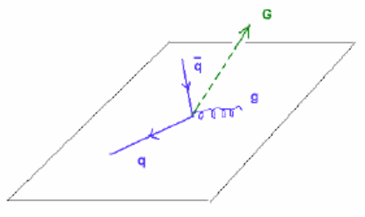
δ	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	4	~ 3.5

Ex. Direct Graviton production at LHC

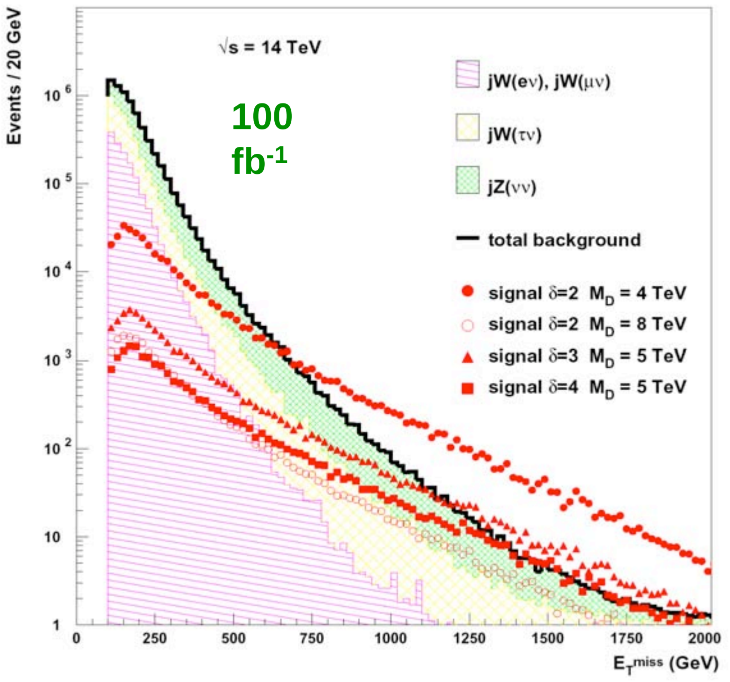
L. Vacavant, I. Hinchliffe, J.Phys.**G27**(2001)1839

Signals in ATLAS:

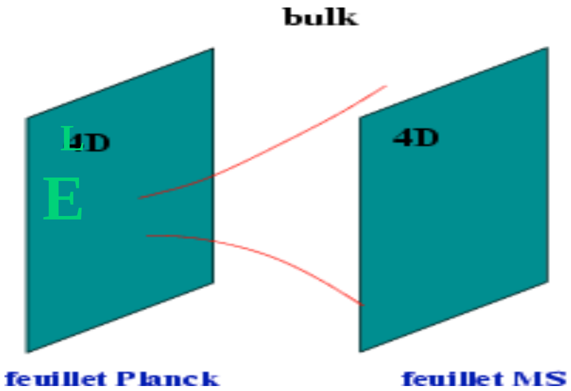
$$\left.\begin{array}{l} \bar{q}q \to gG^{(k)}, \gamma G^{(k)} \\ qg \to qG^{(k)} \\ gg \to gG^{(k)} \end{array}\right\} \text{jets} + \not{E}_T,\ \gamma + \not{E}_T$$



cf. SUSY → Multi-jets



Randall-Sundrum



KK graviton excitations $G^{(k)}$

- scale Λ_π
- coupling & width determined by:
  $c = k/M_{Pl}$
- $0.01 < k/M_{Pl} < 0.1$
- mass spectrum:
  $m_n = k\, x_n \exp(-k\pi r_c)$

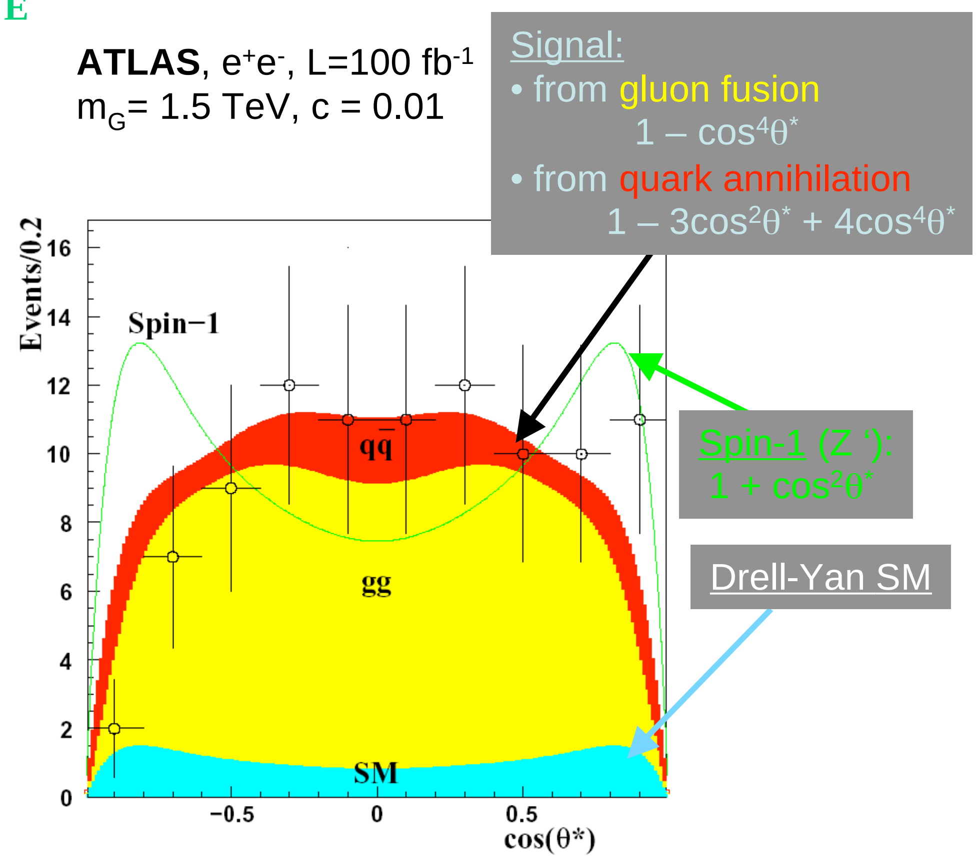
L

E

Golden channel: $G^{(1)} \rightarrow e^+e^-$

spin-2 could be determined (spin-1 ruled out) with 90% CL up to graviton mass of 1720 GeV.

ATLAS, e^+e^-, $L=100\ \text{fb}^{-1}$
m_G= 1.5 TeV, c = 0.01



Signal:
• from gluon fusion
$1 - \cos^4\theta^*$
• from quark annihilation
$1 - 3\cos^2\theta^* + 4\cos^4\theta^*$

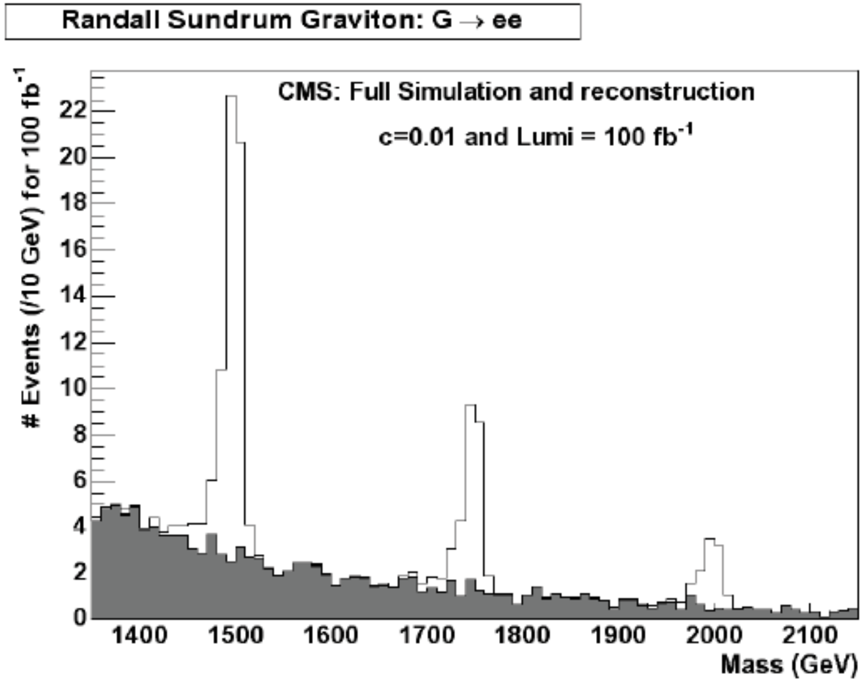
Spin-1 (Z '):
$1 + \cos^2\theta^*$

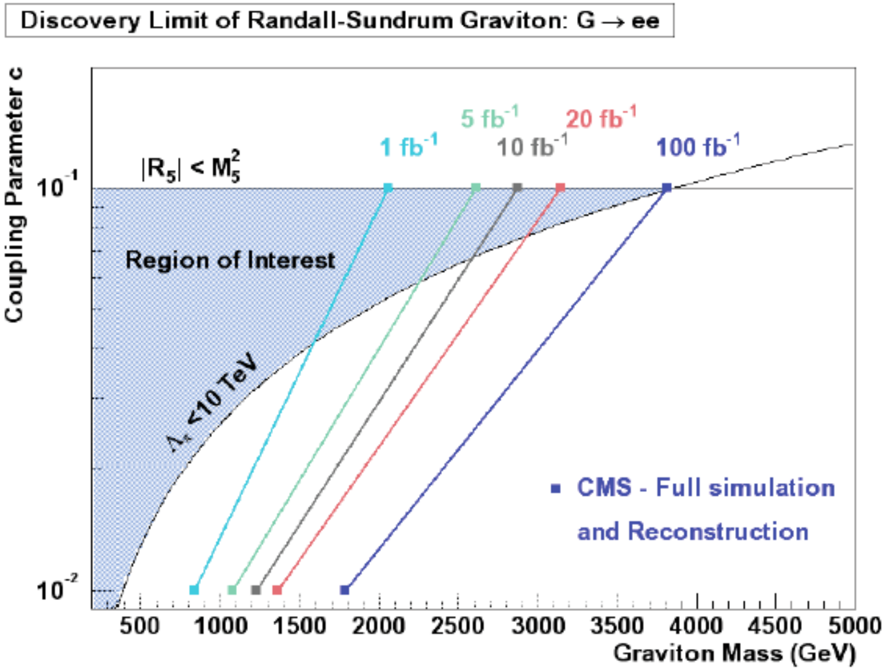
Drell-Yan SM

B.C. Allanach, *et al.*, JHEP**09**(2000)019, *ibid.***12**(2002)039

CMS full simulation study

C. Collard and M.C. Lemaire
Eur.Phys.J.C40N5 (2005) 15-21



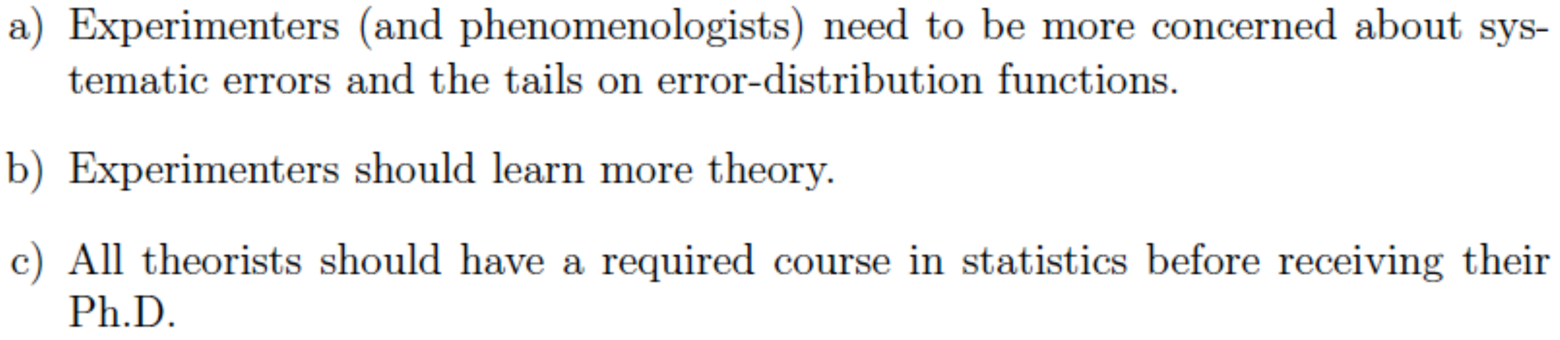


Tips for young theorists

When building your model to be tested at LHC,

1) Mind the reconstruction efficiency
   - can be few % at hadron collider (tens of % at ILC)
2) Mind the trigger efficiency (100%@ILC)
   - difficult with all-jets final state, use leptons, b, missing E_T etc.
3) Mind the total effective cross section
   - cross section < 1fb ... mostly hopeless
4) Become a good friend with experimentalists (important)
5) Follow B.Richter’s Concluding Observations (L&P’99)

hep-ex/0001012



a) Experimenters (and phenomenologists) need to be more concerned about systematic errors and the tails on error-distribution functions.

b) Experimenters should learn more theory.

c) All theorists should have a required course in statistics before receiving their Ph.D.

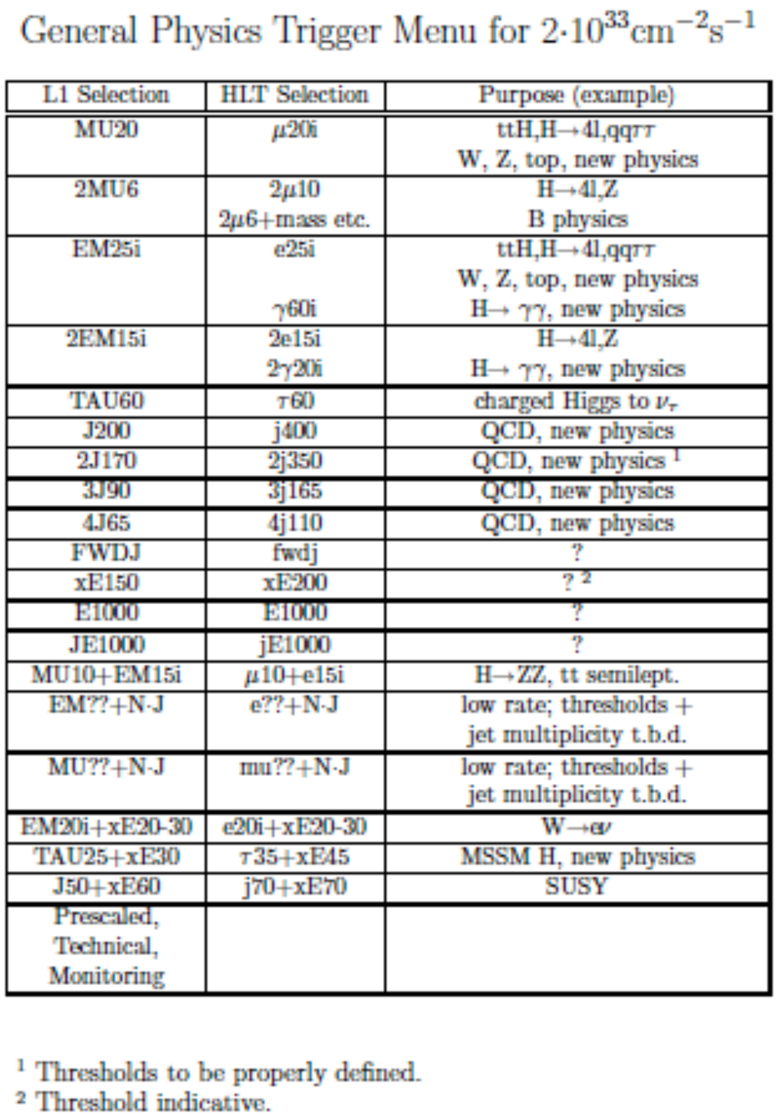
5. Summary

- Discovery first !
- LHC is capable to find new particles (SUSY, ED, Z’ etc.) up to 3-4 TeV (up to ~10TeV with interference effect).
- Model discrimination / parametre determination under study.
- Experimental issues: commissioning/calibration
- Needs to understand SM bkg from data and tuned MC.
- Tools: t, b, W/Z and even Higgs!

- We do hope major breakthrough in HEP (SUSY, ED etc.)
- Important decision in 2010 about HEP’s future…

backup

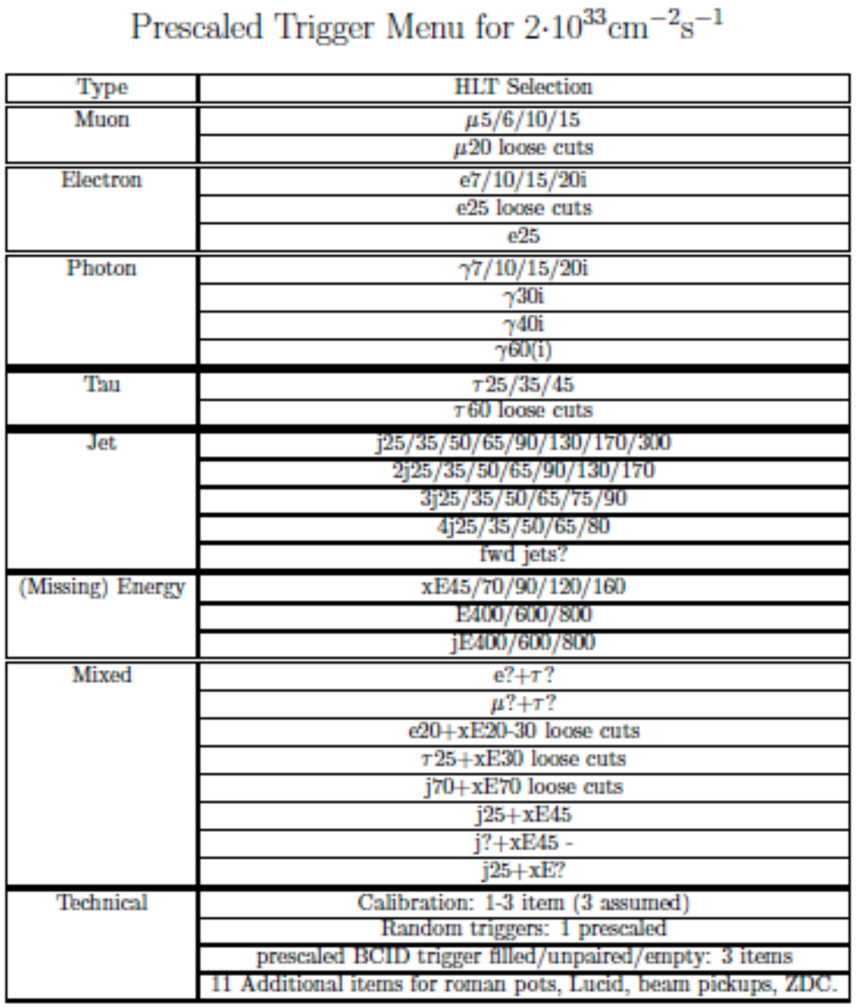
ATLAS Trigger



General Physics Trigger Menu for $2 \cdot 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

L1 Selection	HLT Selection	Purpose (example)
MU20	μ20i	ttH,H→4l,qq$\tau\tau$ W, Z, top, new physics
2MU6	2μ10 2μ6+mass etc.	H→4l,Z B physics
EM25i	e25i γ60i	ttH,H→4l,qq$\tau\tau$ W, Z, top, new physics H→ $\gamma\gamma$, new physics
2EM15i	2e15i 2γ20i	H→4l,Z H→ $\gamma\gamma$, new physics
TAU60	τ60	charged Higgs to ν_τ
J200	j400	QCD, new physics
2J170	2j350	QCD, new physics [1]
3J90	3j165	QCD, new physics
4J65	4j110	QCD, new physics
FWDJ	fwdj	?
xE150	xE200	? [2]
E1000	E1000	?
JE1000	jE1000	?
MU10+EM15i	μ10+e15i	H→ZZ, tt semilept.
EM??+N·J	e??+N·J	low rate; thresholds + jet multiplicity t.b.d.
MU??+N·J	mu??+N·J	low rate; thresholds + jet multiplicity t.b.d.
EM20i+xE20-30	e20i+xE20-30	W→eν
TAU25+xE30	τ35+xE45	MSSM H, new physics
J50+xE60	j70+xE70	SUSY
Prescaled, Technical, Monitoring		

[1] Thresholds to be properly defined.
[2] Threshold indicative.



Prescaled Trigger Menu for $2 \cdot 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Type	HLT Selection
Muon	μ5/6/10/15
	μ20 loose cuts
Electron	e7/10/15/20i
	e25 loose cuts
	e25
Photon	γ7/10/15/20i
	γ30i
	γ40i
	γ60(i)
Tau	τ25/35/45
	τ60 loose cuts
Jet	j25/35/50/65/90/130/170/300
	2j25/35/50/65/90/130/170
	3j25/35/50/65/75/90
	4j25/35/50/65/80
	fwd jets?
(Missing) Energy	xE45/70/90/120/160
	E400/600/800
	jE400/600/800
Mixed	e?+τ?
	μ?+τ?
	e20+xE20-30 loose cuts
	τ25+xE30 loose cuts
	j70+xE70 loose cuts
	j25+xE45
	j?+xE45 -
	j25+xE?
Technical	Calibration: 1-3 item (3 assumed)
	Random triggers: 1 prescaled
	prescaled BCID trigger filled/unpaired/empty: 3 items
	11 Additional items for roman pots, Lucid, beam pickups, ZDC.

LHC Upgrades

CERN Council Strategy Group Open Symposium 2006
January 30 - February 1, 2006 (*LAL - Orsay, France*)
http://events.lal.in2p3.fr/conferences/Symposium06/

Luminosity Upgrade (SLHC)

towards

$L=10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Physics

20-30% increase

in discovery potential

Better stat. precsion

P.Raimondi

parameter	symbol	nominal	ultimate	shorter bunch	longer bunch
no of bunches	n_b	**2808**	**2808**	**5616**	**936**
proton per bunch	$N_b\ [10^{11}]$	**1.15**	**1.7**	**1.7**	**6.0**
bunch spacing	$\Delta t_{sep}[\mathrm{ns}]$	**25**	**25**	**12.5**	**75**
average current	I [A]	**0.58**	**0.86**	**1.72**	**1.0**
normalized emittance	$\varepsilon_n\ [\mu\mathrm{m}]$	**3.75**	**3.75**	**3.75**	**3.75**
longit. profile		**Gaussian**	**Gaussian**	**Gaussian**	**flat**
rms bunch length	σ_z [cm]	**7.55**	**7.55**	**3.78**	**14.4**
ß* at IP1&IP5	ß* [m]	**0.55**	**0.50**	**0.25**	**0.25**
full crossing angle	$\theta_c\ [\mu\mathrm{rad}]$	**285**	**315**	**445**	**430**
Piwinski parameter	$\theta_c \sigma_z/(2\sigma^*)$	**0.64**	**0.75**	**0.75**	**2.8**
peak luminosity	$L\ [10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$	**1.0**	**2.3**	**9.2**	**8.9**
events per crossing		**19**	**44**	**88**	**510**
luminous region length	σ_{lum} [mm]	**44.9**	**42.8**	**21.8**	**36.2**

LHC Luminosity Upgrade: tentative milestones

accelerator	WorkPackage	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	after 2015
LHC Main Ring	Accelerator Physics	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩		
	High Field Superconductors	🟥	🟥	🟨	🟨	🟨	🟩	🟩	🟩			
	High Field Magnets		🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟦	
	Magnetic Measurements			🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟦	
	Cryostats					🟥	🟨	🟨	🟩	🟩	🟦	
	Cryogenics: IR magnets & RF		🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟦	
	RF and feedback	🟥	🟨	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟦	
	Collimation & Machine Protection	🟥	🟨	🟨	🟩	🟦	🟥	🟥	🟥	🟥		
	Beam Instrumentation	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟦	
	Power converters					🟥	🟨	🟨	🟩	🟩	🟦	
SPS	SPS kickers			🟥	🟥	🟥	🟨	🟨	🟩	🟦		
	Tentative Milestones	Beam-beam compensation test at RHIC	SPS crystal collimation test	LHC collimation tests	LHC collimation tests	Install phase 2 collimation	LHC tests: collimation & beam-beam			Install new SPS kickers	new IR magnets and RF system	
	Other Tentative Milestones	Crab cavity test at KEKB	Low-noise crab cavity test at RHIC	**LHC Upgrade Conceptual Design Report**		LHC Upgrade Technical Design Report	Nominal LHC luminosity 10^34			Ultimate LHC luminosity 2.3x10^34	beam-beam compensation	Double ultimate LHC luminosity 4.6x10^34
		LHC Upgrade Reference Design Report										

R&D - scenarios & models	🟥
specifications & prototypes	🟨
construction & testing	🟩
installation & commissioning	🟦

Reference LHC Upgrade scenario: peak luminosity 4.6x10^34/(cm^2 sec)

Integrated luminosity 3 x nominal ~ 200/(fb*year) assuming 10 h turnaround time

new superconducting IR magnets for beta*=0.25 m

phase 2 collimation and new SPS kickers needed to attain ultimate LHC beam intensity of 0.86 A

beam-beam compensation may be necessary to attain or exceed ultimate performance

new superconducting RF system: for bunch shortening or Crab cavities

hardware for nominal LHC performance (cryogenics, dilution kickers, etc) not considered as LHC upgrade

R&D for further luminosity upgrade (intensity beyond ultimate) is recommended: see Injectors Upgrade

LHC Energy Upgrade (DLHC)

- E_b=7 TeV → 14 TeV
- Physics Motivation Eur.Phys.J **C39** (2005) 293-333
  - Higgs self-coupling ~ λ_{HHH} determination with 20-30% accuracy

unprecedented dipole field

> 17 Tesla

- Conductor options;

  NbTi, Nb_3Sn, Nb_3Al(KEK)

←15-20 year program ?