Search for the Higgs at the LHC

1. The Large Hadron Collider
2. The General Purpose Detectors
3. Tools and Algorithms
4. Search for the SM Higgs
5. Search for the Supersymmetric Higgs''
6. Conclusions

Tejinder S. Virdee
CERN/Imperial College

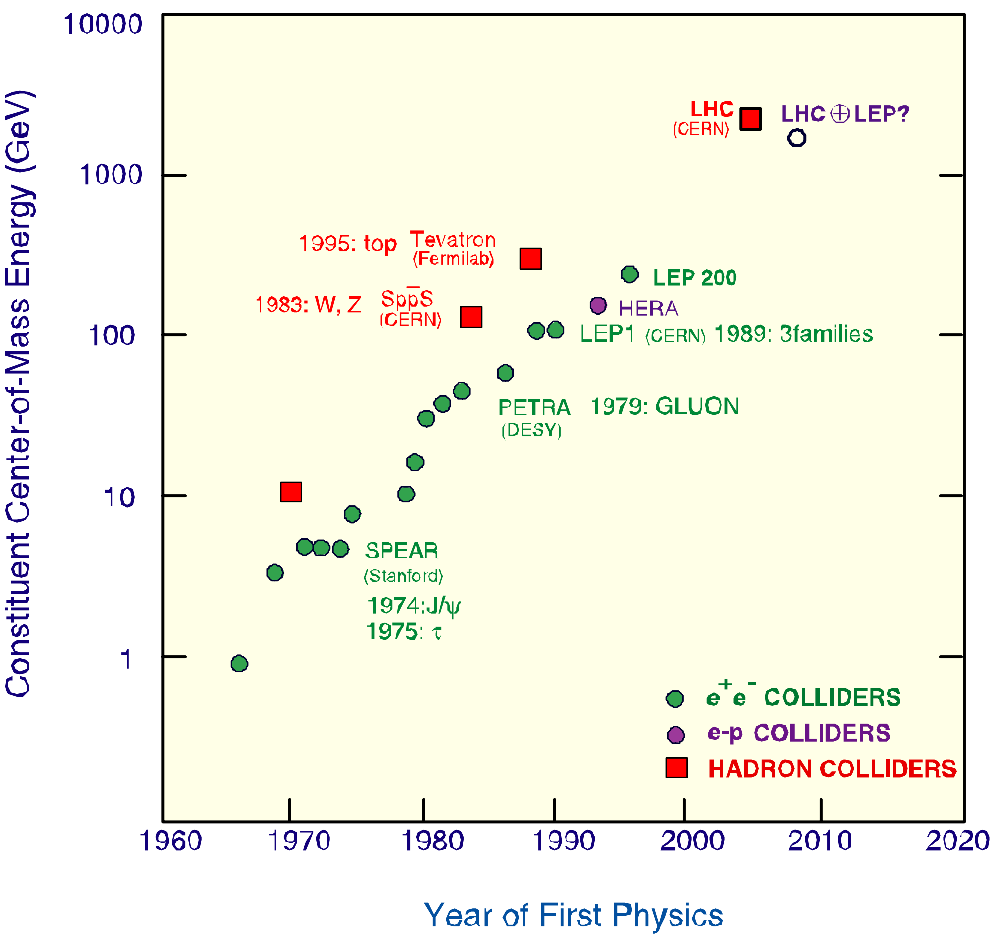
1. The Large Hadron Collider

i. The Machine Parameters
ii. Machine Schedule
iii. Experimental Challenge

Energy Frontier

New Energy Domain
Search for the unexpected
Cover domain ~ 1 TeV in which SM without the Higgs (or equivalent) gives nonsense

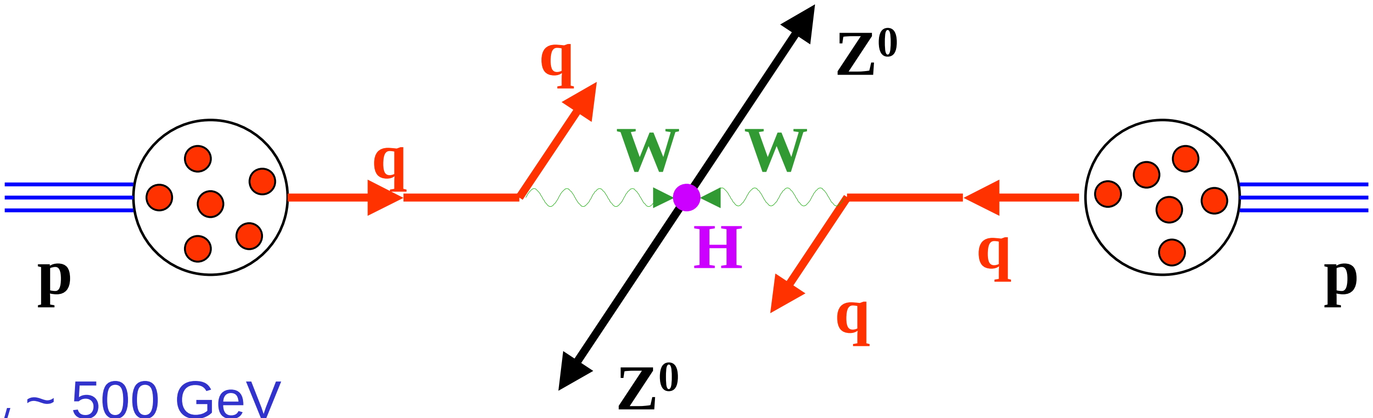
Exploratory machine required
⇨ hadron-hadron collider with:
Largest possible primary energy
Largest possible luminosity



Energy and Luminosity

Hadron colliders are broad-band exploratory machines

May need to study W_L-W_L scattering at a cm energy of ~ 1 TeV



⇨ E_W ~ 500 GeV

⇨ E_{quark} ~ 1 TeV

⇨ E_{proton} ~ 6 TeV

⇨ **pp collisions at 7 + 7 TeV**

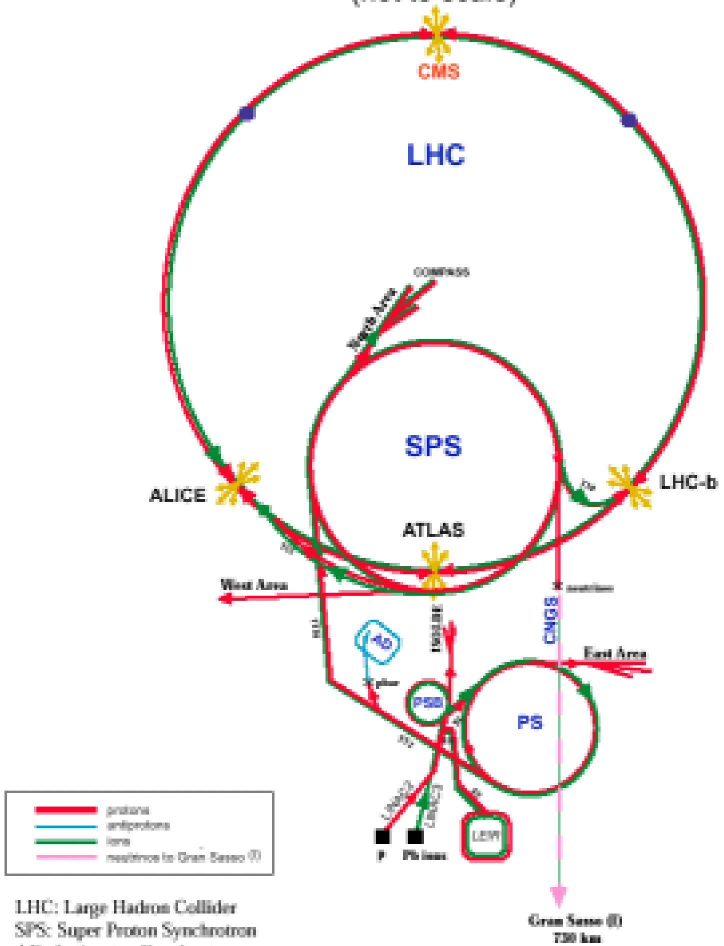
Event Rate = L.σ.BR

e.g. H(1 TeV) → ZZ → 2e+2μ or 4e or 4μ

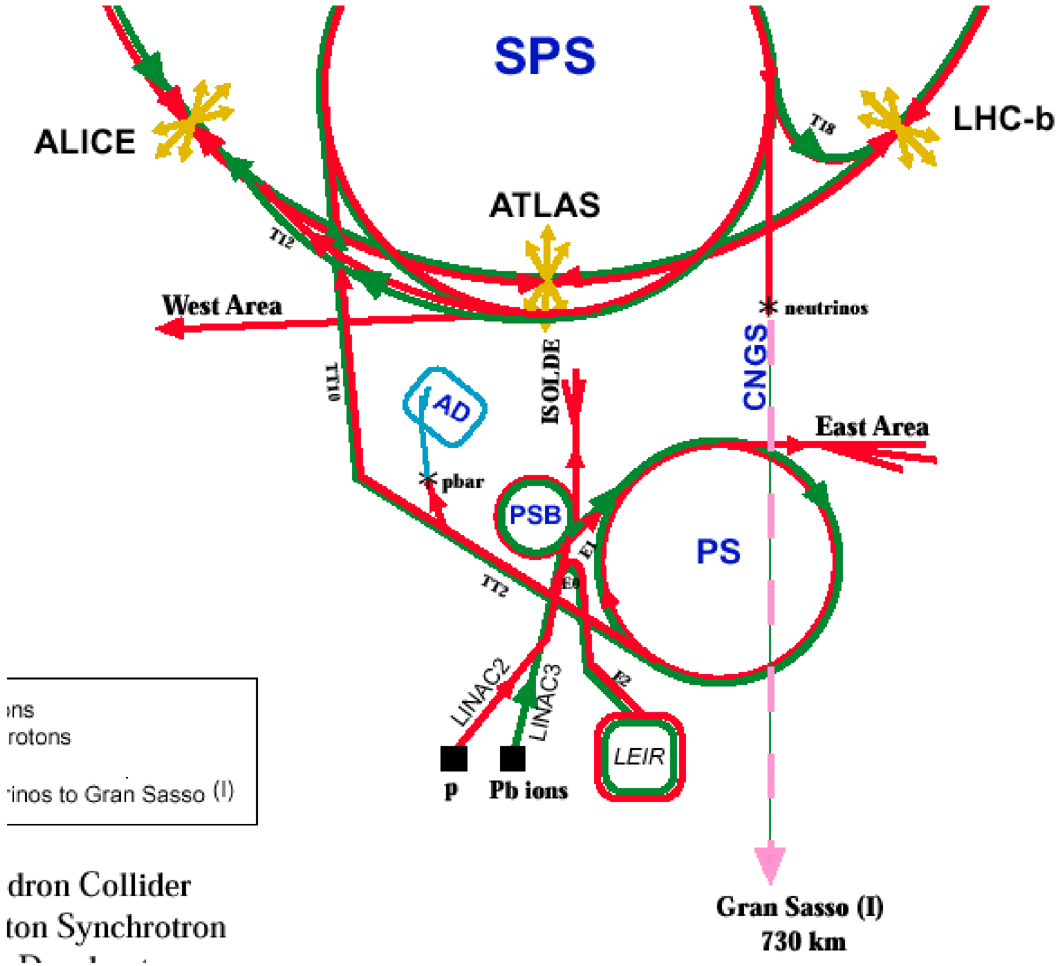
For L ~10^{34} , Evts/yr = **10^{34}** $10^{-37}.10^{-3}.10^{7}$ ~ 10 /yr !!

CERN Site

CERN Accelerator Complex



LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso



LHC Layout and Parameters

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

- 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)

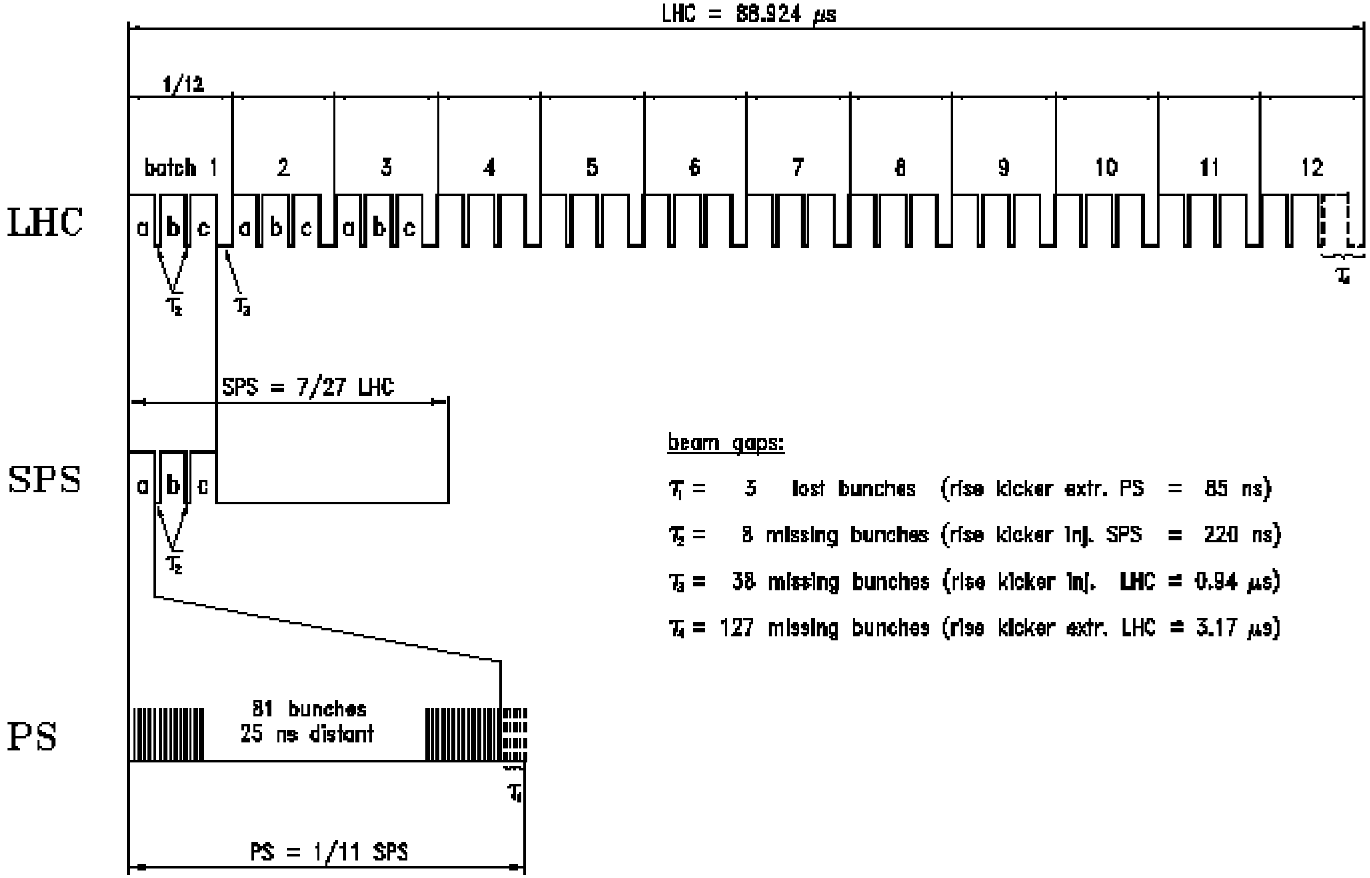
For p= 7 TeV, R= 4.3 km

⇨ **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}	$cm^{-2}s^{-1}$
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

LHC Beam Structure



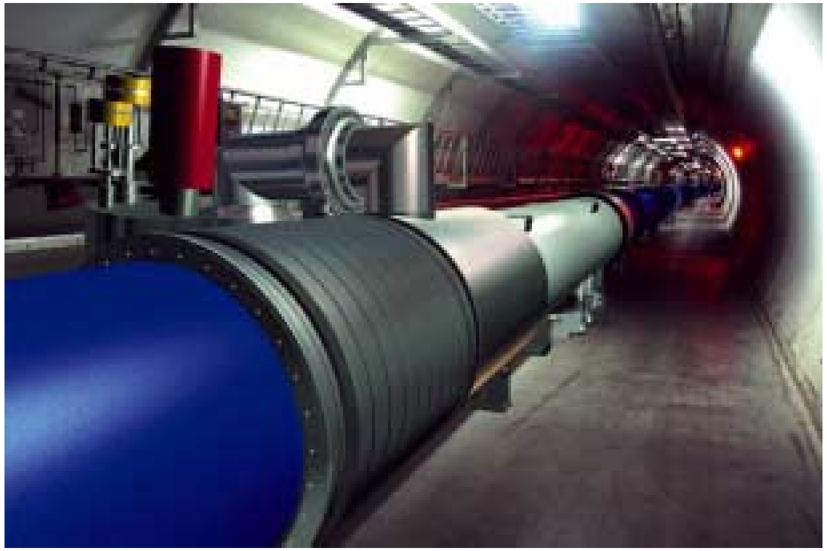
Detailed beam structure is determined by injection scheme and properties of the dump system. Bunches are formed in the 26 GeV PS with the correct 25ns spacing.

Beam is subsequently accelerated to 450 GeV and transferred to the LHC. This operation is repeated 12 times for each counter-rotating beam.

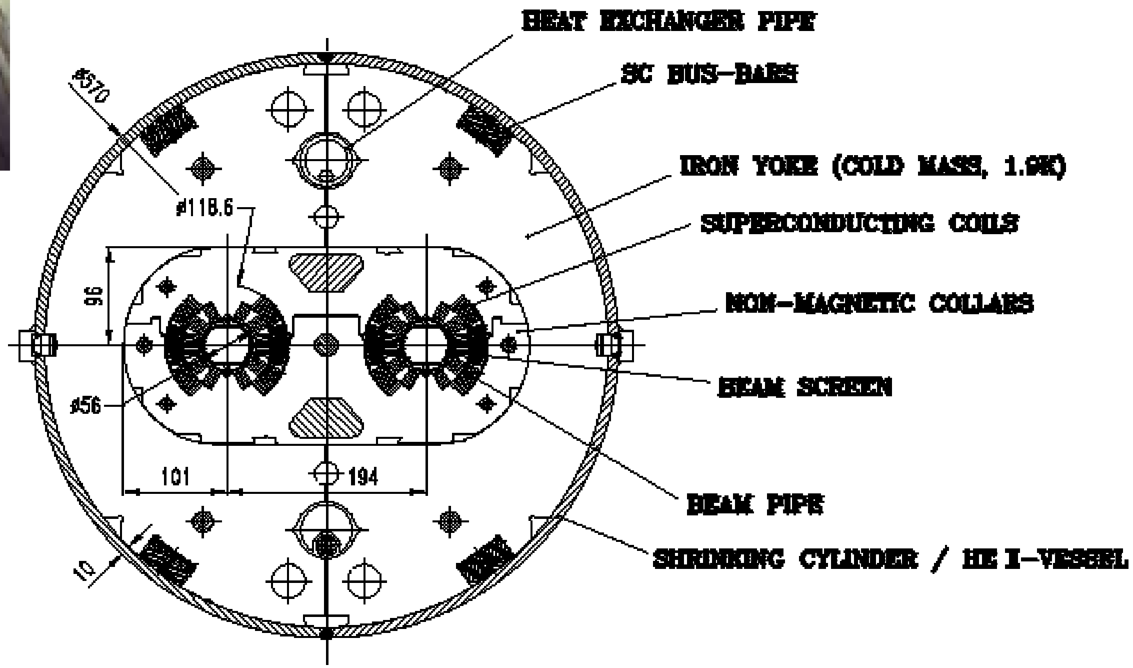
At each transfer, enough space has to be reserved to accommodate rise time of injection kickers

Finally a longer gap of 3.17 μs is reserved for rise time of dump kicker by eliminating 1 PS batch

Dipole Magnets

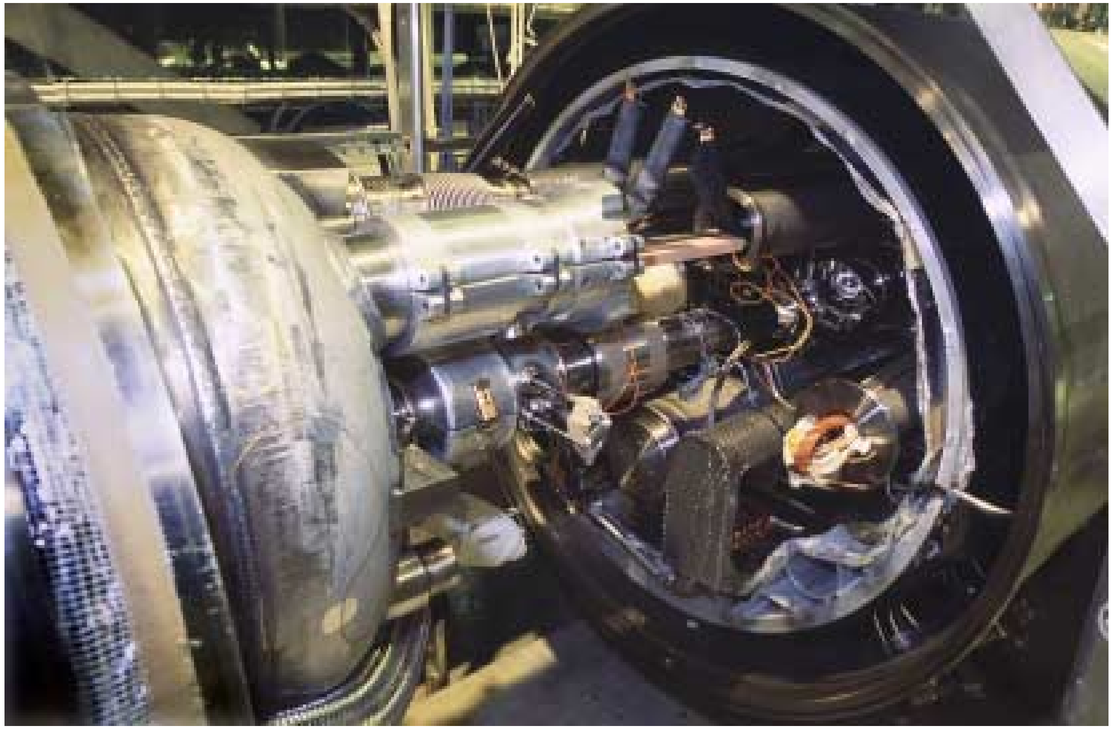


1232 superconducting dipoles



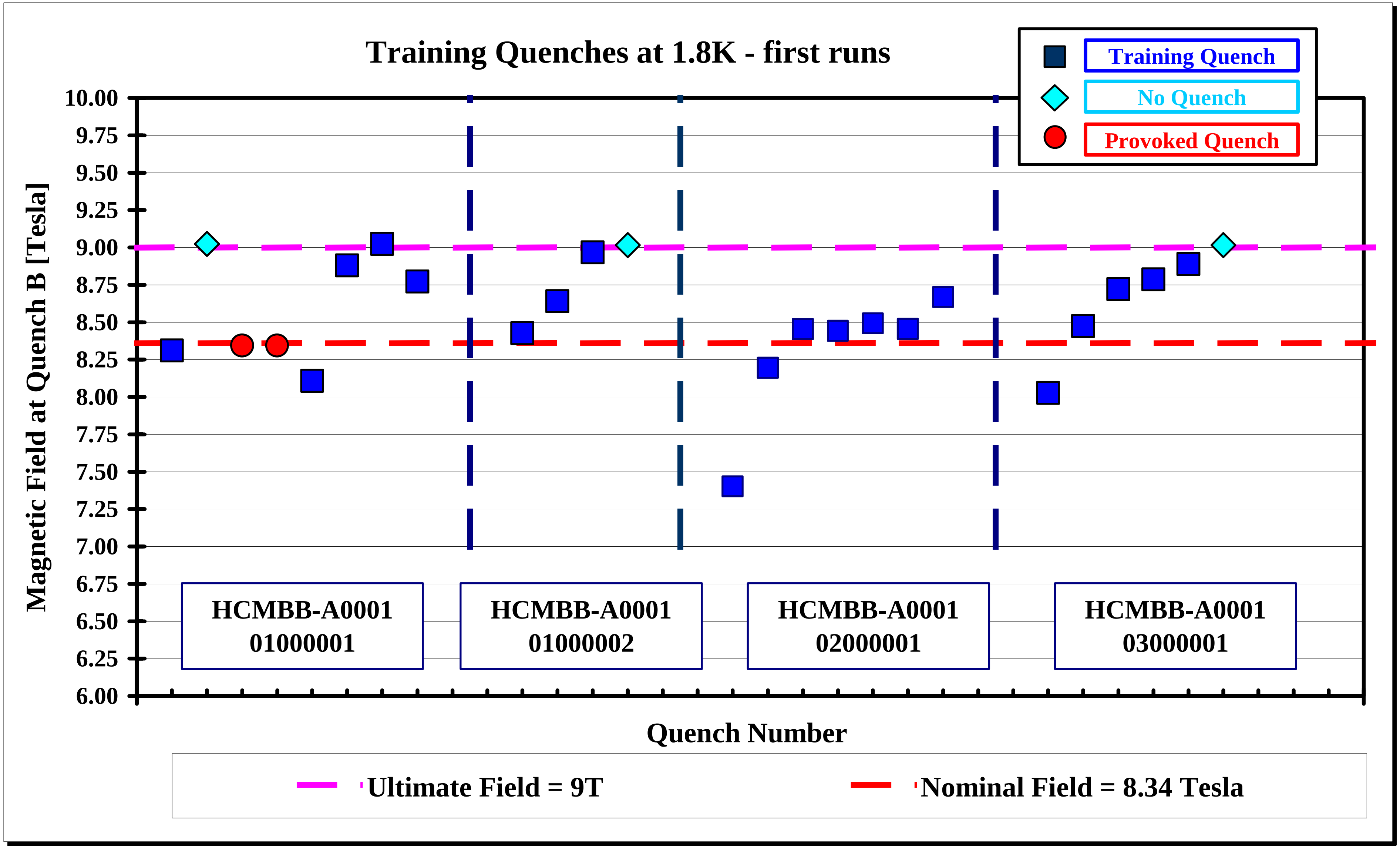
Dipole Magnets

Alsthom LHC Dipole No. 1



Dipole/quadrupole Interconnect

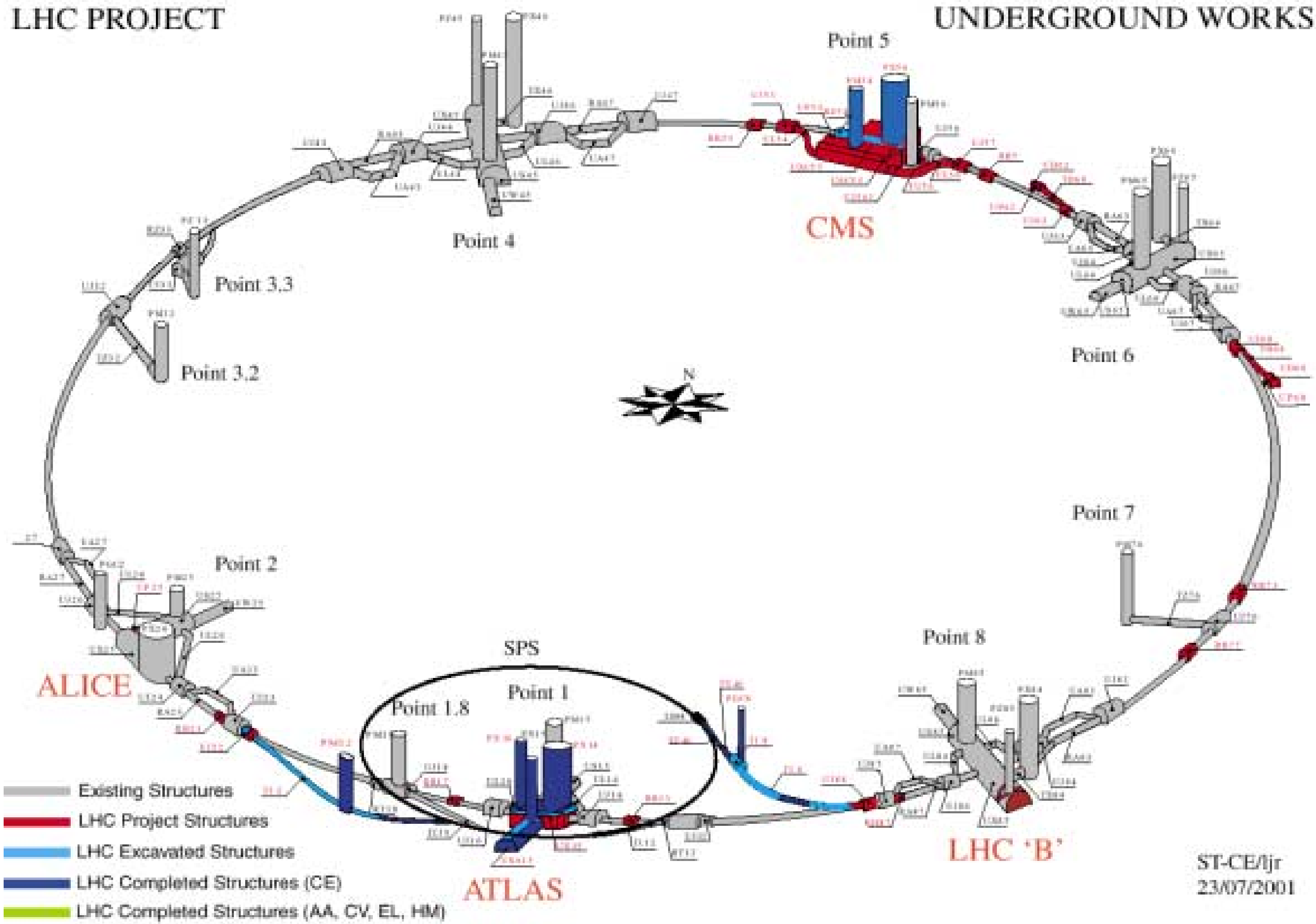
Pre-series Dipole Magnets



String 2

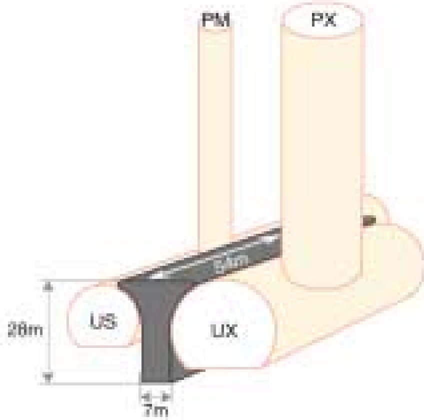
- String 2: under construction
  - Full LHC cell
    - 6 dipoles + 4 quads
  - Last tests before commissioning
  - String 2 has the same layout as a LHC cell in the regular part of an arc and follows the curvature of the tunnel. The first half-cell starts with a Short Straight Section (SSS), which is connected to the cryogenic line and is followed by three 15-m dipoles. Following the simplified cryogenic scheme, the second half-cell is not connected to the cryogenic line.

Civil Engineering



Civil Engineering: Progress

CMS Underground Hall
Ready in mid-04

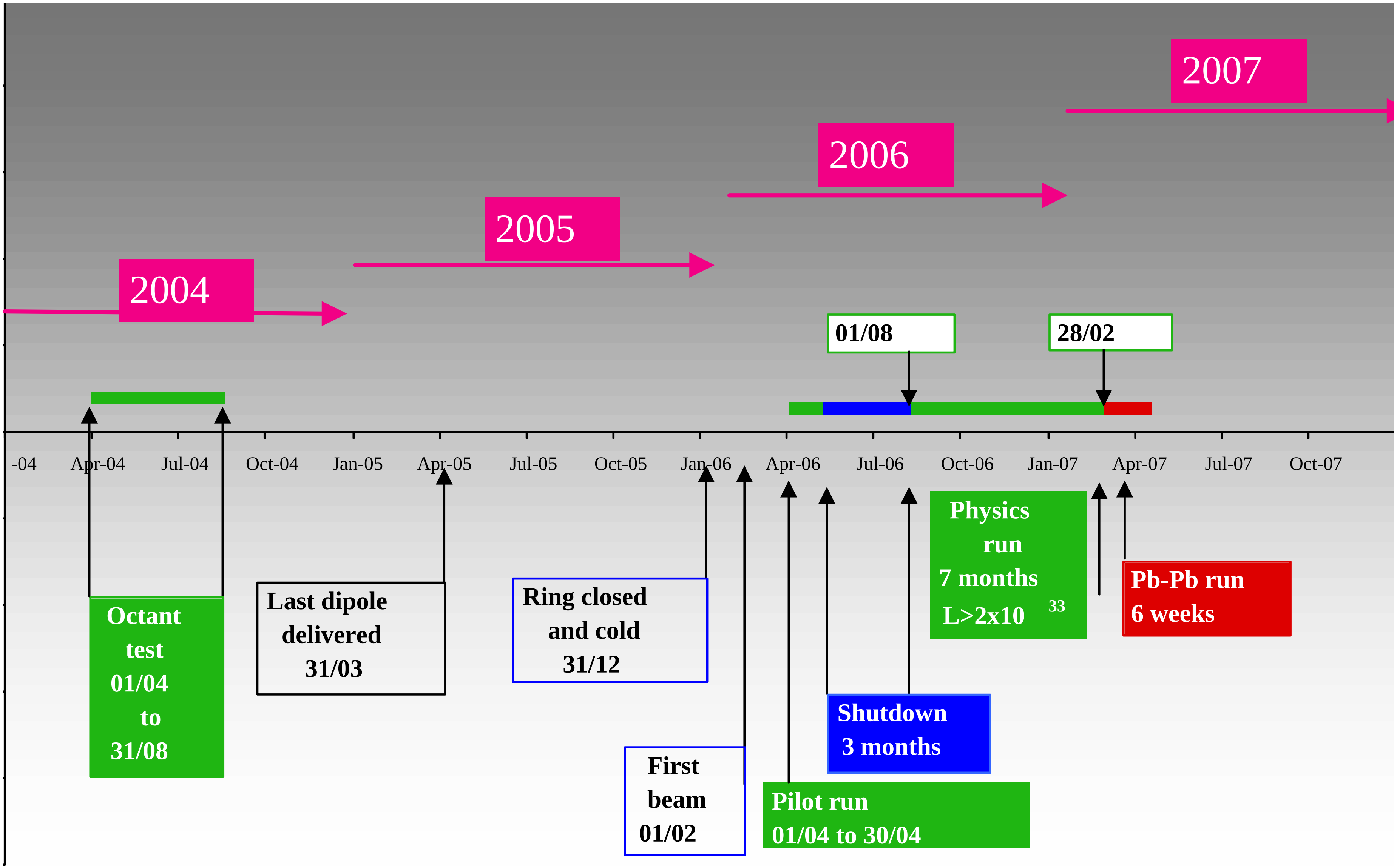


ATLAS Underground Hall
Ready in mid-03

LHC Schedule

01/04/04 to 30/09/04	Octant test	
31/03/05	Last dipole delivered	
31/12/05	Ring closed and cold	Full access to experimental caverns
01/01/06 to 31/01/06	Full machine commissioning Beam pipes in place	Full access to experimental caverns
01/02/06 to 31/03/06	1 beam (2 months)	Restricted access to experimental caverns
01/04/06 to 30/04/06	First Collisions 1 month Pilot run	Luminosity: 5×10^{32} to 2×10^{33}
01/05/06 to 31/07/06	Shutdown	Full access to experimental caverns
01/08/06 to 28/02/07	Physics run: 7 months	Luminosity: $\geq 2 \times 10^{33}$ ($\geq 10\ fb^{-1}$)
01/03/07 to 12/04/07	Lead ion run, 6 weeks	

LHC Schedule



Experimental Challenge

High Interaction Rate

pp interaction rate 10^9 interactions/s

data for only ~100 out of the 40 million crossings can be recorded per sec

Level-1 trigger decision will take ~2-3 ms

⇨ electronics need to store data locally (pipelining)

Large Particle Multiplicity

~ <20> superposed events in each crossing

~ 1000 tracks stream into the detector every 25 ns

need highly granular detectors with good time resolution for low occupancy

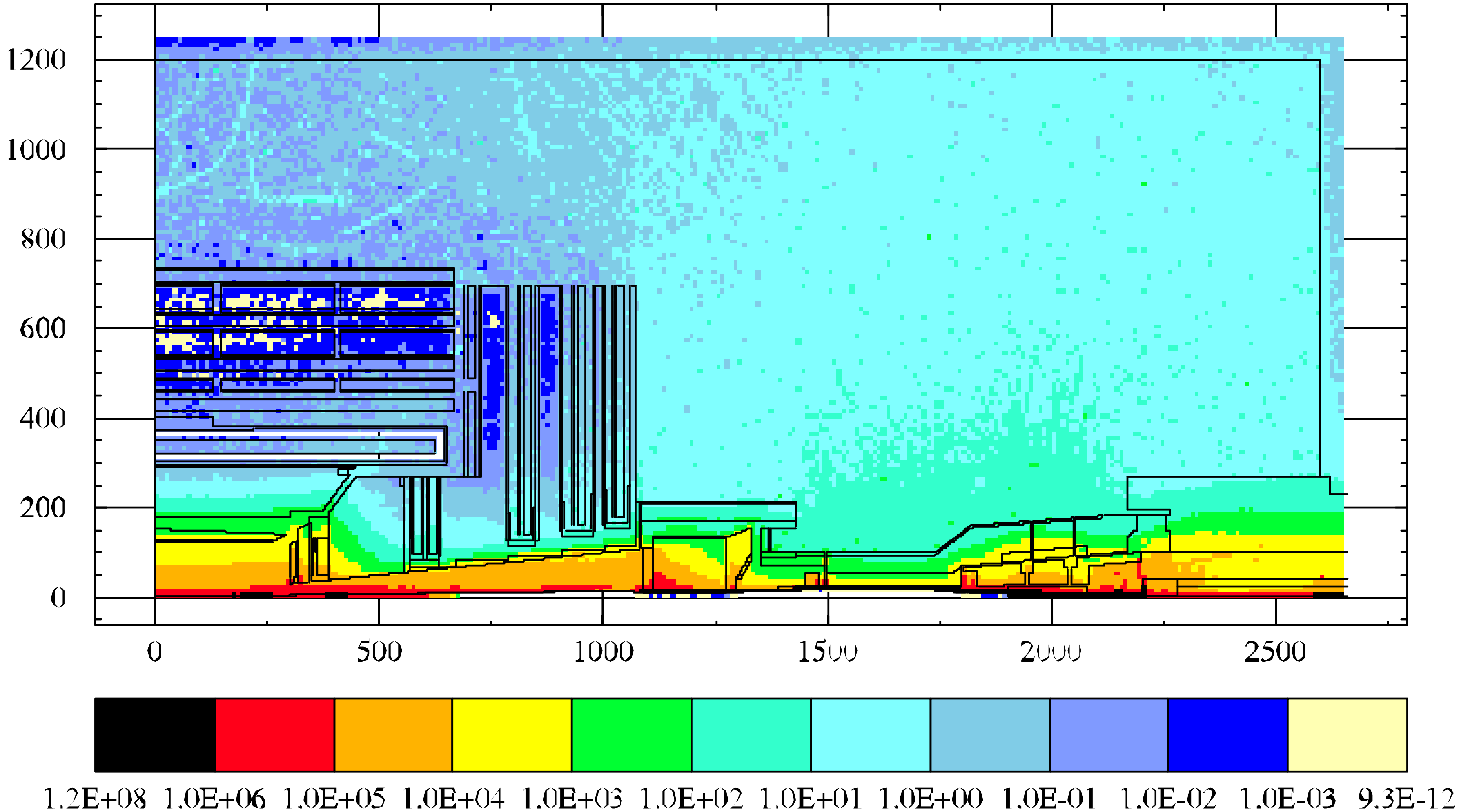
⇨ large number of channels

High Radiation Levels

⇨ radiation hard (tolerant) detectors and electronics

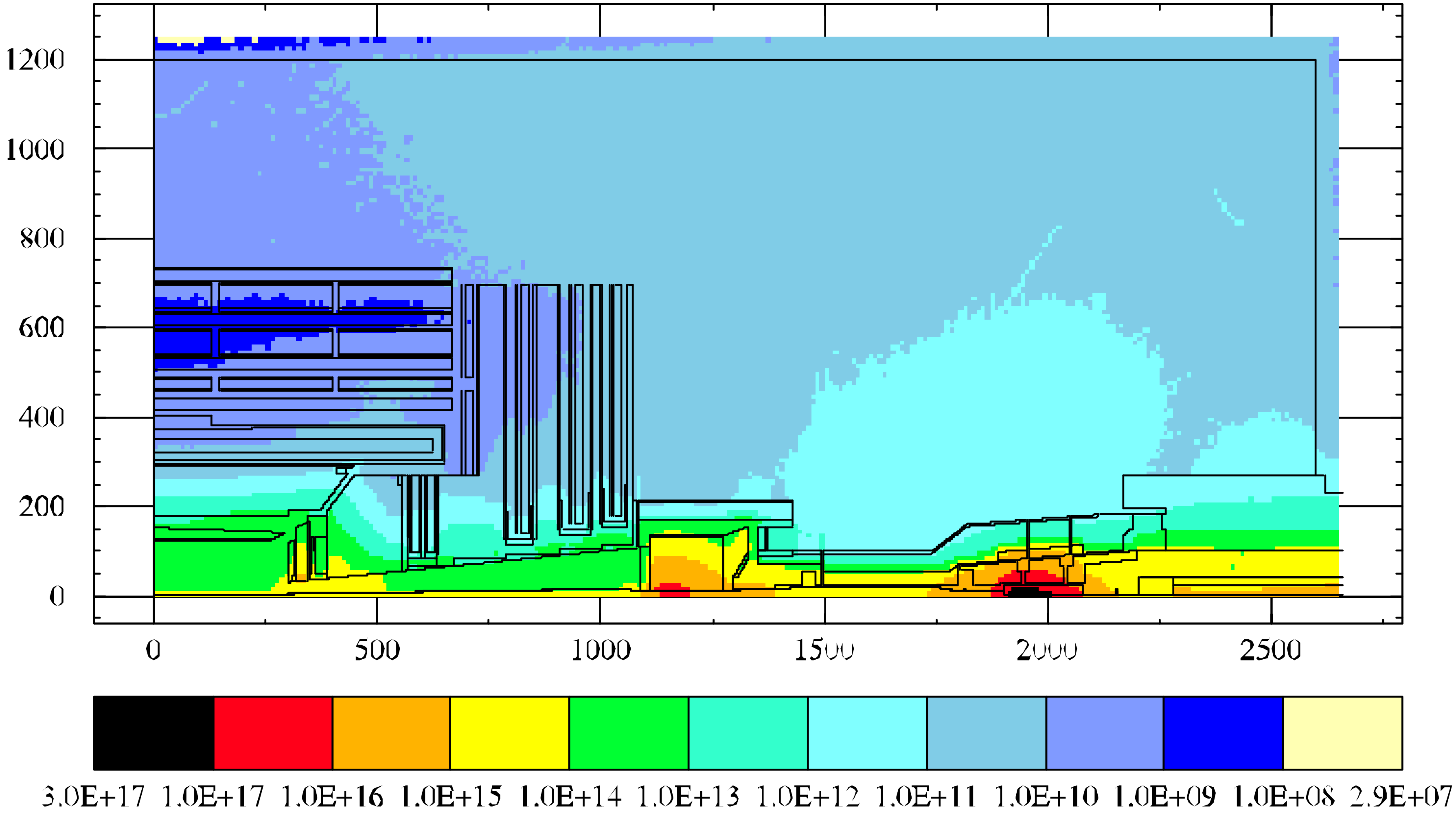
Radiation Levels: Dose

Dose in CMS for an integrated luminosity of 5.10^5 pb^{-1} (~ 10 years)



Radiation Levels: Neutron Fluence

n fluence in CMS for an integrated luminosity of 5.10^5 pb^{-1} (~ 10 years)

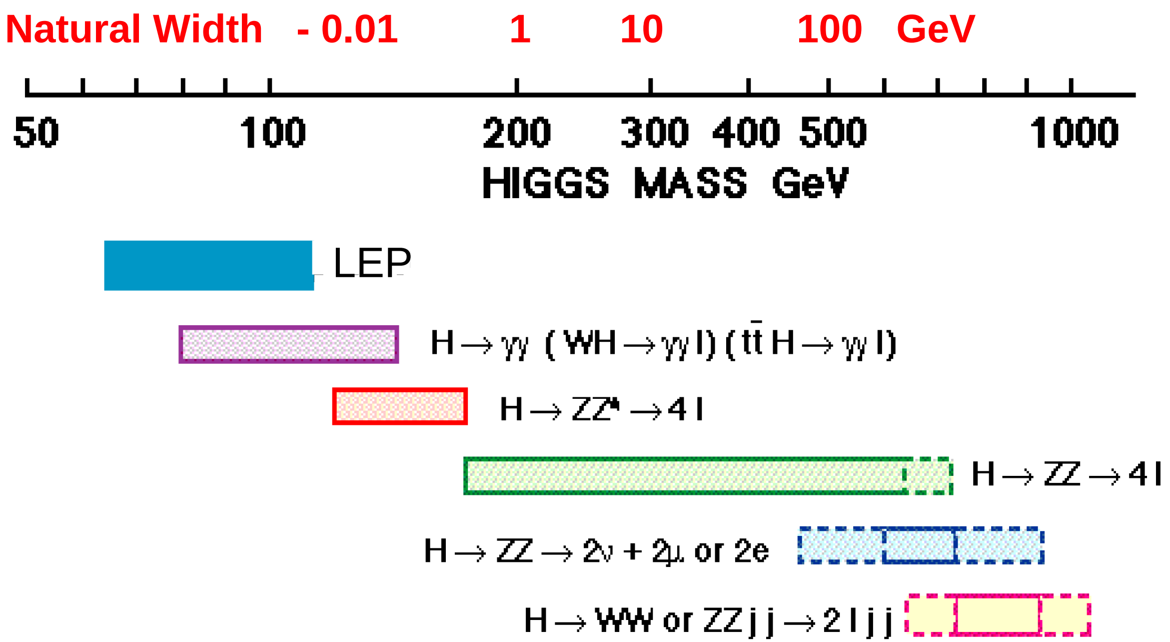


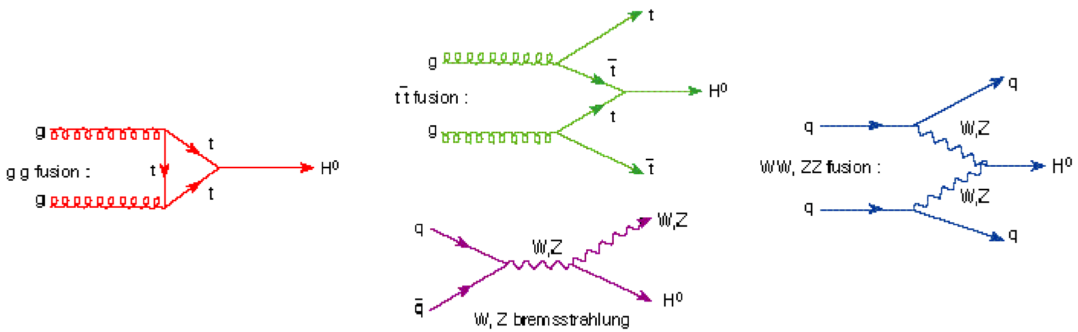
2. The General Purpose Detectors

i. Physics Requirements
ii. GPDs: ATLAS and CMS
iii. Physics Performance of GPDs

Physics Requirements I

At the LHC the SM Higgs provides a good benchmark to test the performance of a detector





Physics Requirements II

Very good muon identification and momentum measurement

trigger efficiently and measure sign of a few TeV muons

High energy resolution electromagnetic calorimertry

~ 0.5% @ E_T~50 GeV

Powerful inner tracking systems

factor 10 better momentum resolution than at LEP

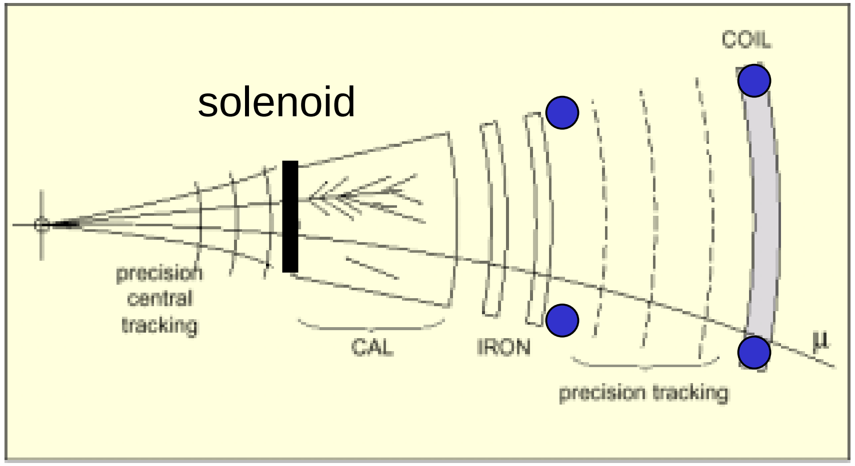
Hermetic calorimetry

good missing E_T resolution

(Affordable detector)

Designs of General Purpose Detectors

Complementary Conception

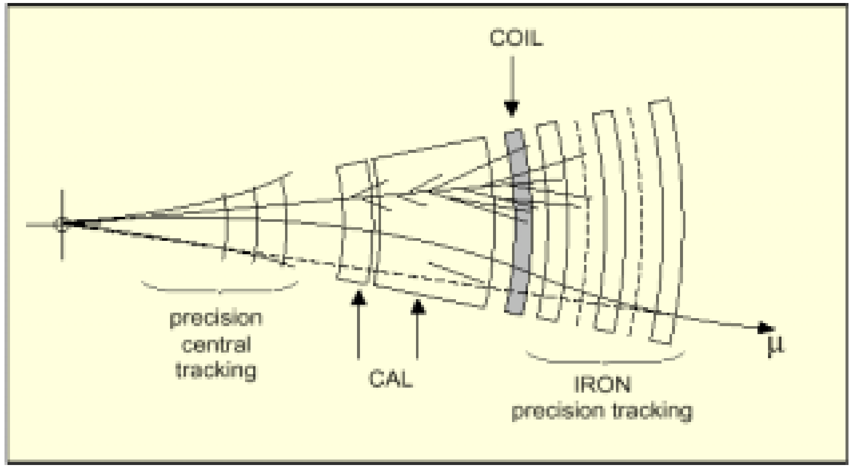


ATLAS

Standalone p measurement;
safe for high multiplicities;

Air-core toroid

Property: σ_p flat with η



CMS

Measurement of p in tracker
and B return flux;

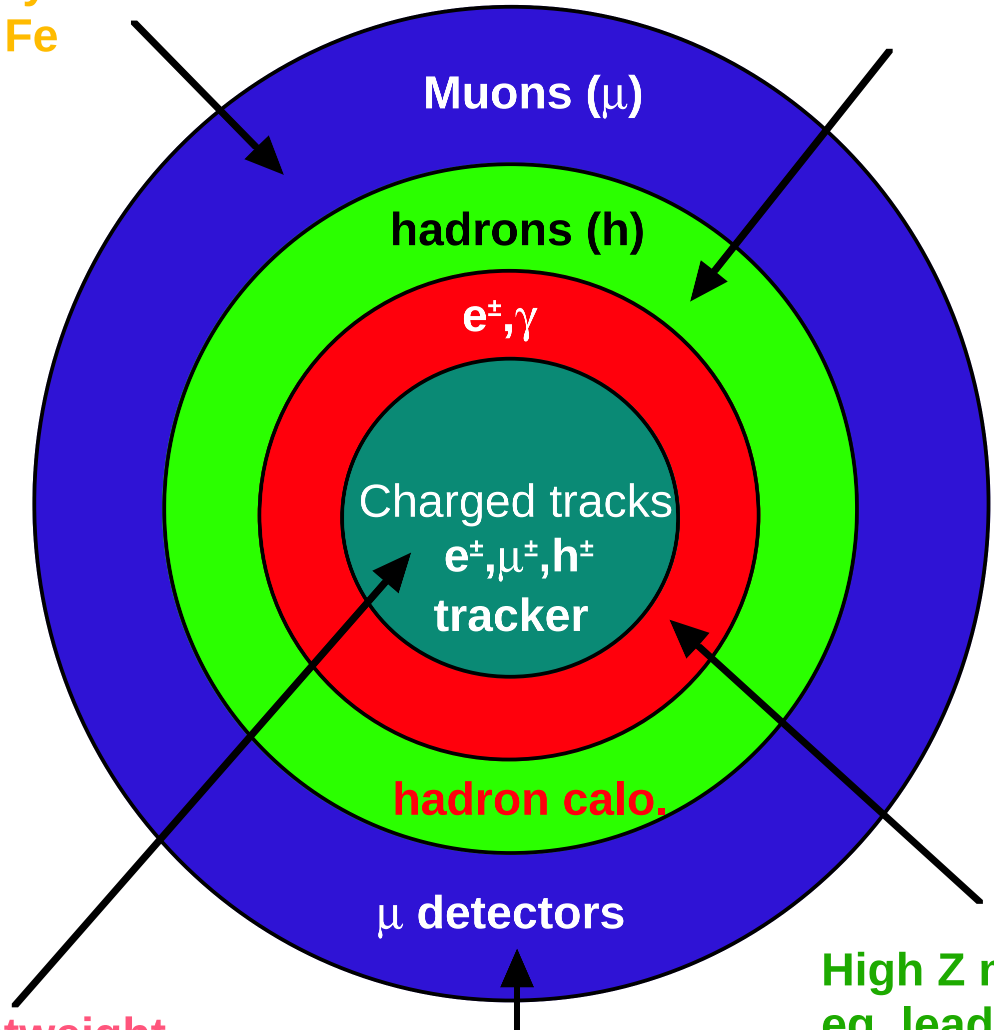
Solenoid with Fe flux return

Property: muon tracks point back to vertex

Onion-like Structure of HEP Experiments

Heavy Absorber
e.g. Fe

Heavy materials
eg. Iron or Copper +
active media

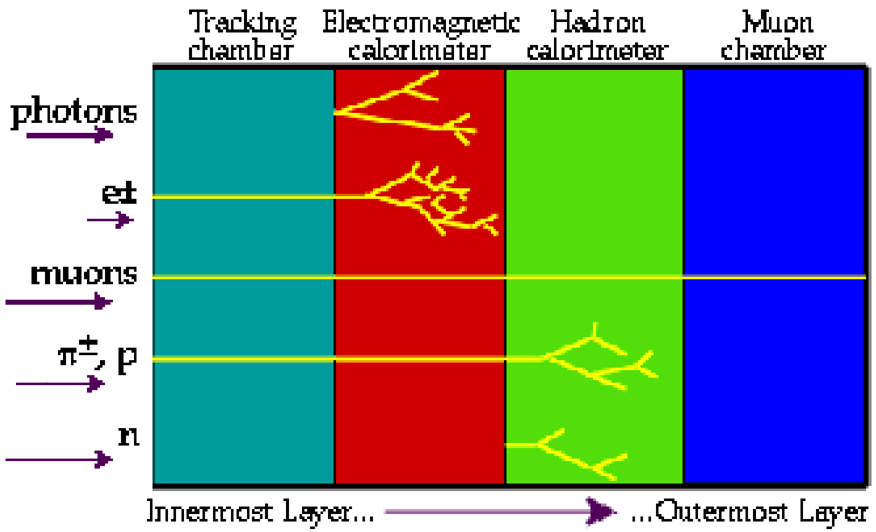


Lightweight
materials

Zone in which only
ν and μ remain

High Z materials
eg. lead tungstate
crystals

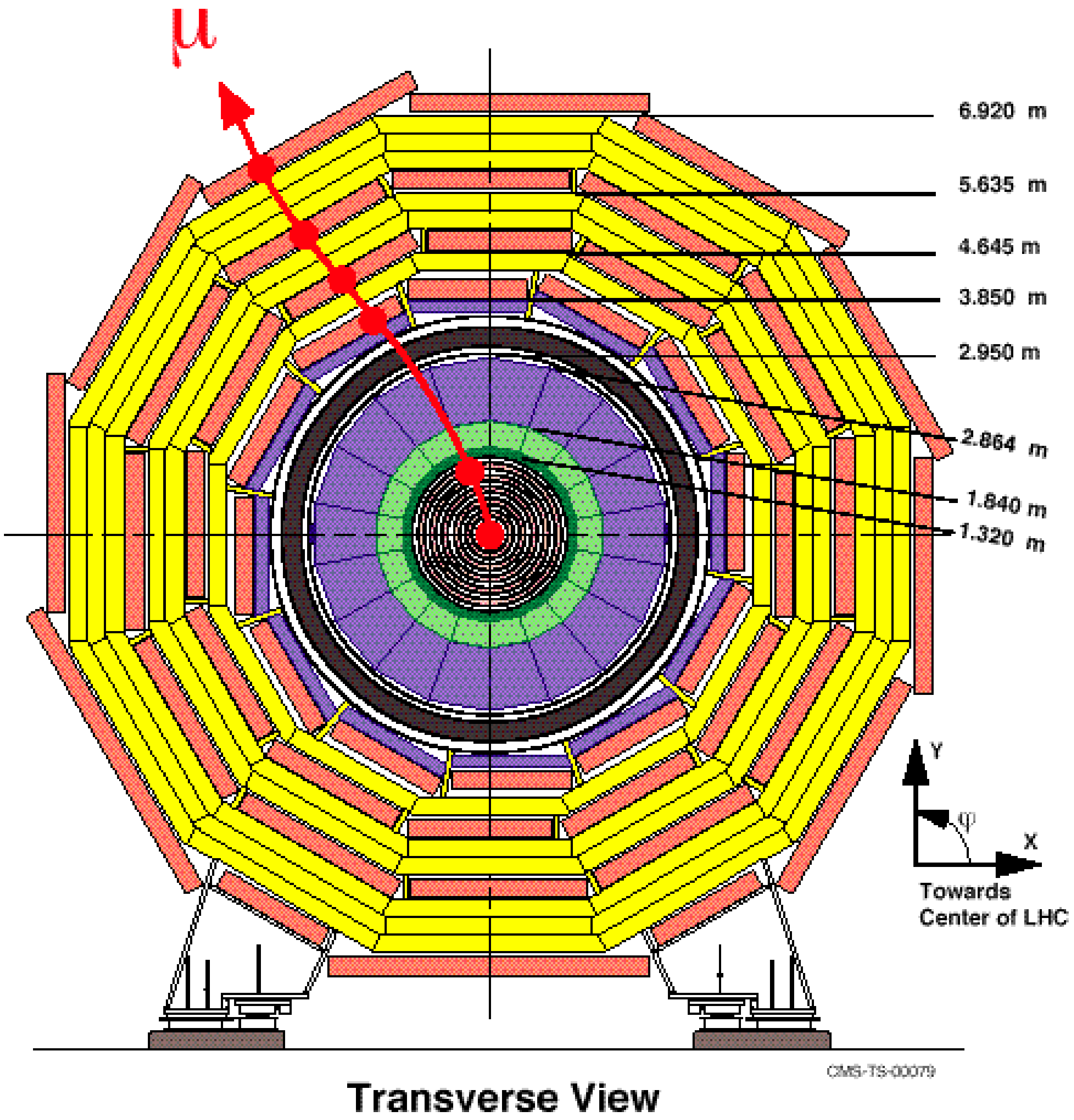
Each layer identifies and measures (or remeasures) the energy of particles unmeasured by the previous layer



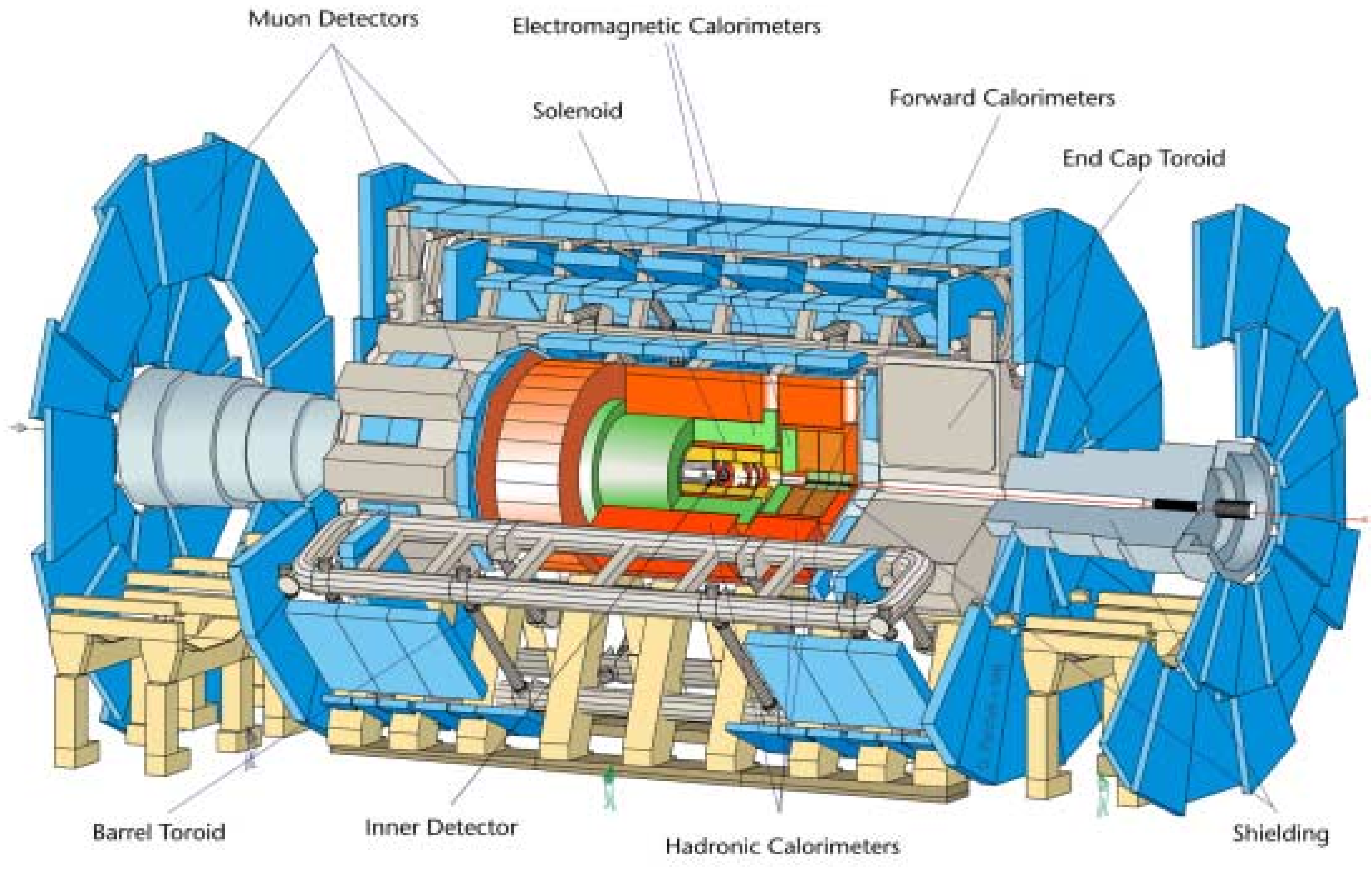
No single detector can determine identity and measure energies/momenta of all particles

CSS00

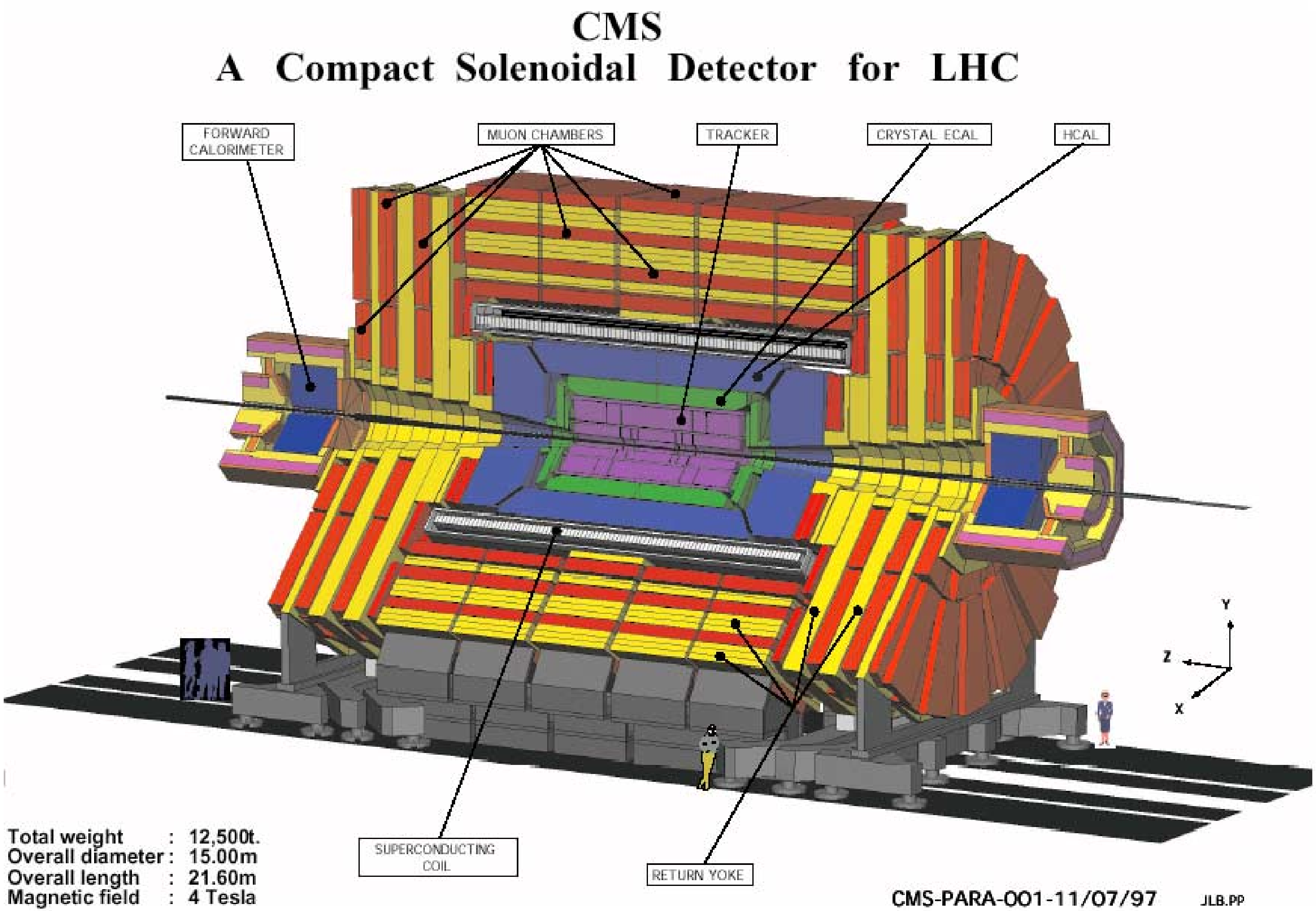
Transverse View of CMS



The ATLAS Detector

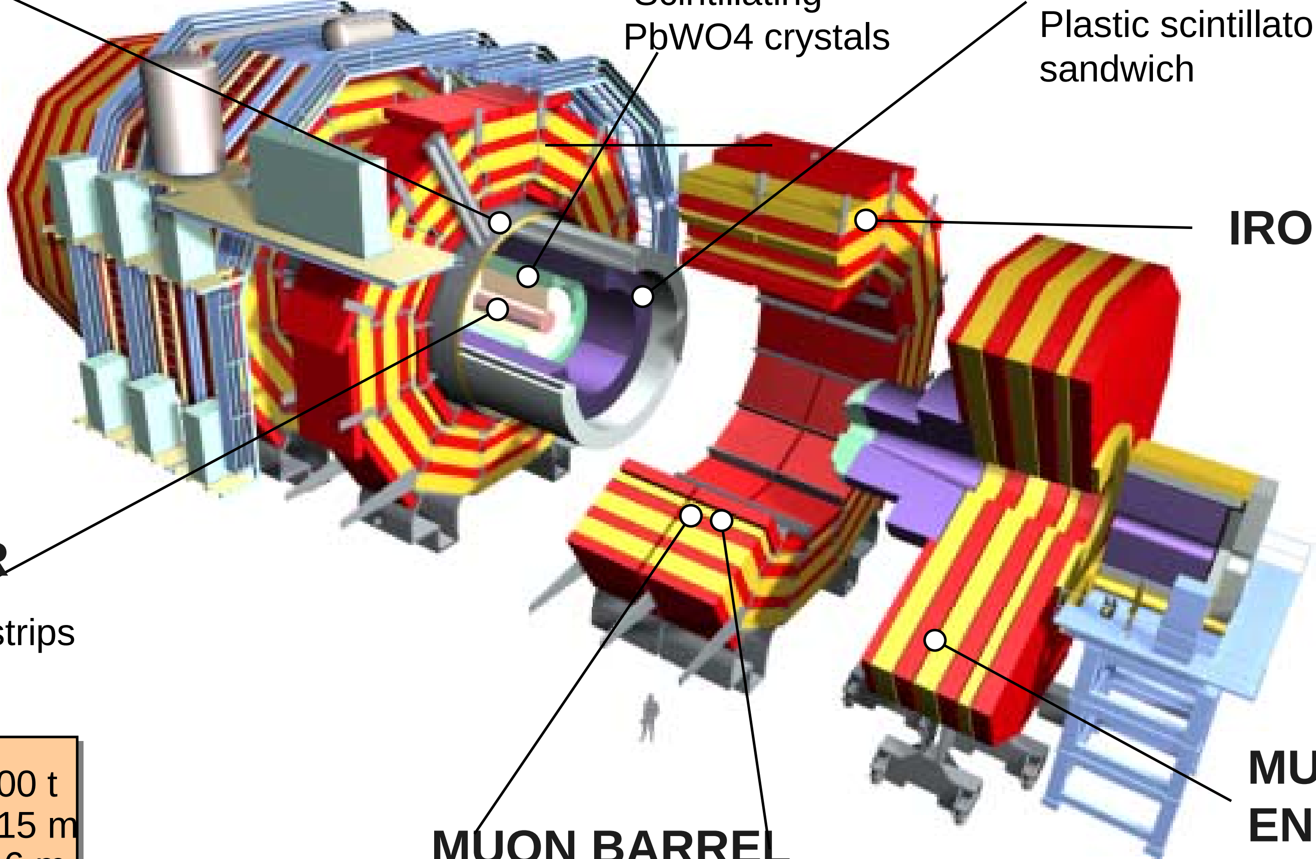


CMS



CMS
A Compact Solenoidal Detector for LHC
FORWARD CALORIMETER
MUON CHAMBERS
TRACKER
CRYSTAL ECAL
HCAL
SUPERCONDUCTING COIL
RETURN YOKE
Y
Z
X
Total weight : 12,500t.
Overall diameter : 15.00m
Overall length : 21.60m
Magnetic field : 4 Tesla
CMS-PARA-001-11/07/97
JLB.PP

The CMS Detector

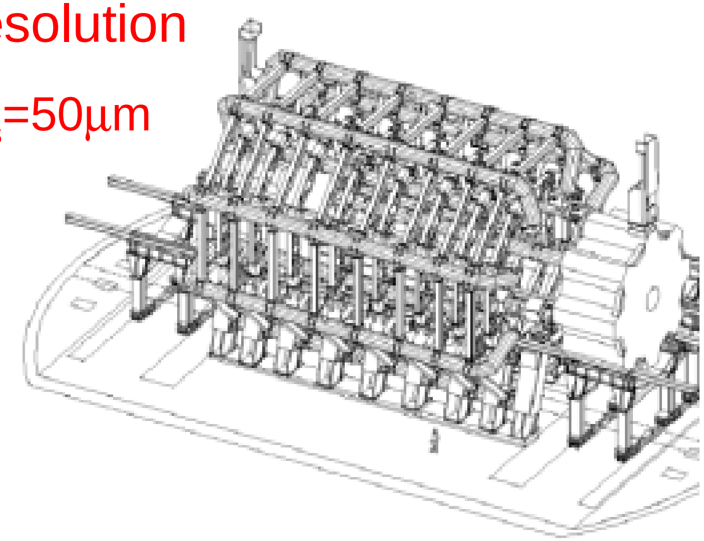


Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

Choice of the Magnets

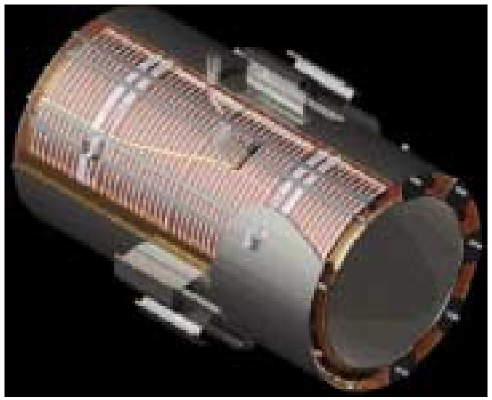
Design goal: measure 1 TeV muons with 10% resolution

ATLAS: <B>~0.6T over 4.5 m $\rightarrow$ s=0.5mm $\rightarrow$ need σ_s=50μm

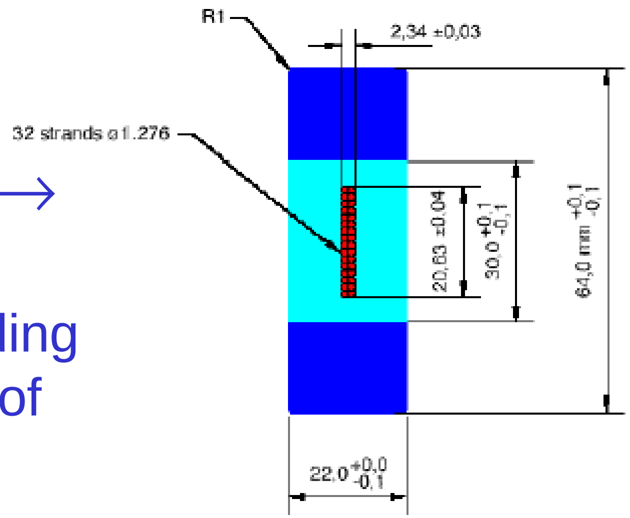


- Ampere's thm: $2\pi RB=\mu_0 nI \longrightarrow nI=2\times10^7$ At
- With 8 coils, 2x2x30 turns: I=20kA (superC)
- Challenges: mechanics, 1.5GJ if quench, spatial & alignment precision over large surface area

CMS: B=4T (E=2.7 GJ!)



- $B=\mu_0 nI$; @2168 turns/m$\longrightarrow$ I=20kA (SuperC)
- Challenges: 4-layer winding to carry enough I, design of reinforced superC cable



Magnet Construction

Completed ATLAS solenoid and cryogenics chimney during tests at Toshiba (for KEK)

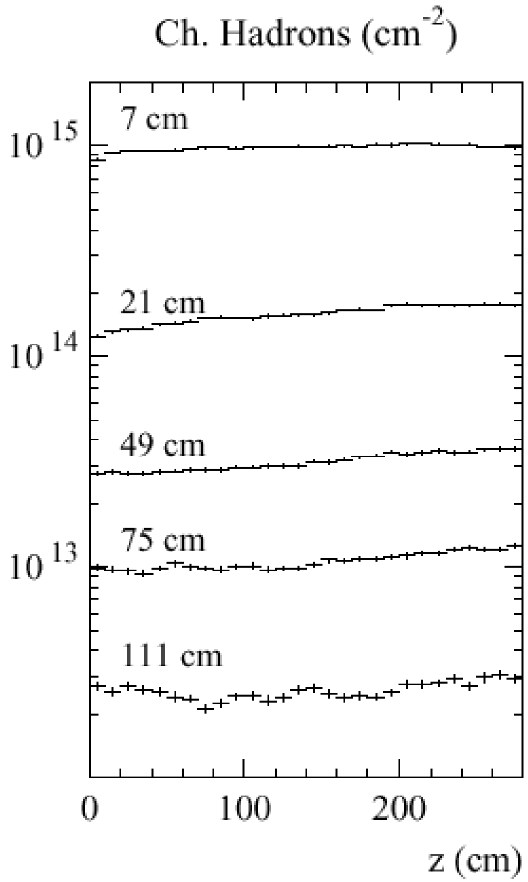
CMS barrel yoke wheels assembled at SX5 (point 5)
Central wheel supports the coil, barrel HCAL, ECAL and tracker

Tracking at LHC

Factors that determine performance

Track finding efficiency – occupancy
Momentum resolution
Secondary vertex reconstruction

Fluence over 10 years

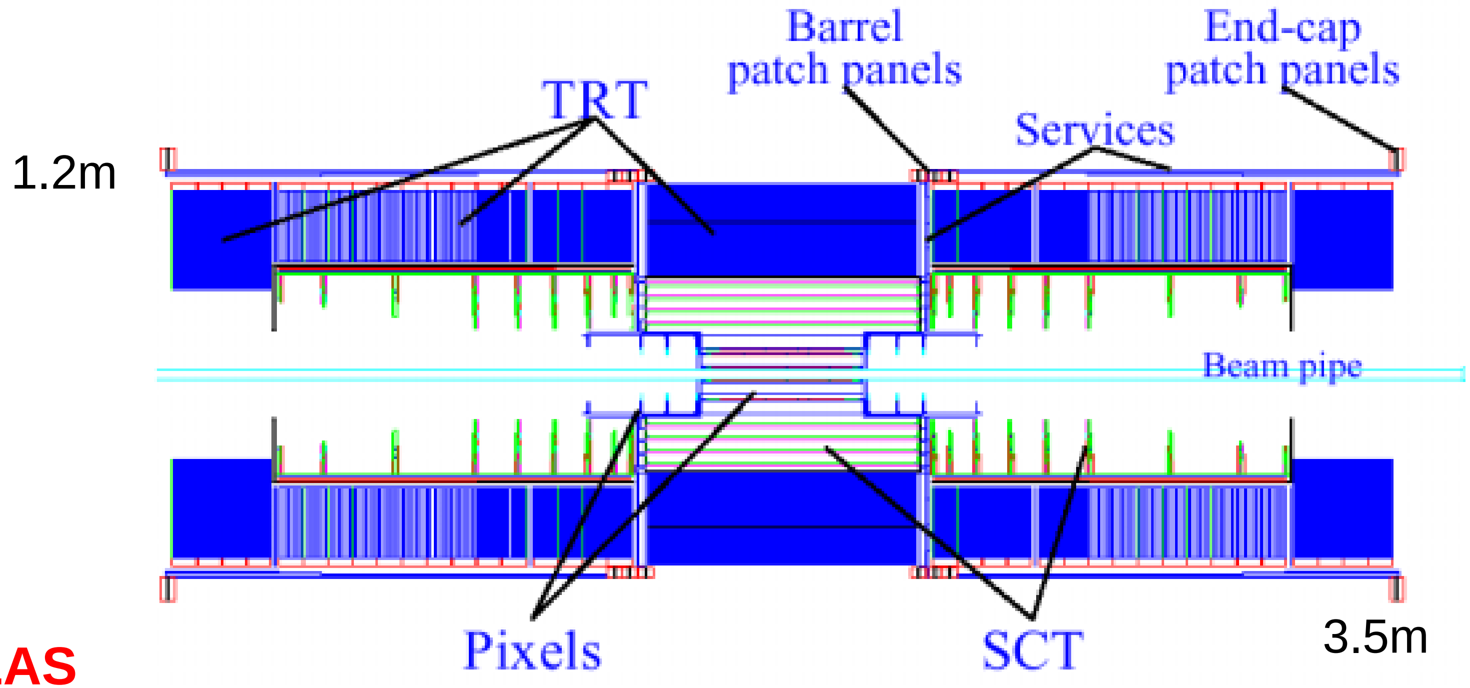


$\leq 4.10^7$ h±/cm²/s
pixels (≈10^4 μm²)
occupancy ≈ 10^{-4}

$\leq 4.10^6$ h±/cm²/s
Si μ-strip det.
(≈10 mm²)
occupancy ≈ 1%

$\leq 4.10^5$ h±/cm²/s
Si or Gas detectors.
(≈1 cm²)
occupancy ≈ 1%

Trackers at LHC



ATLAS

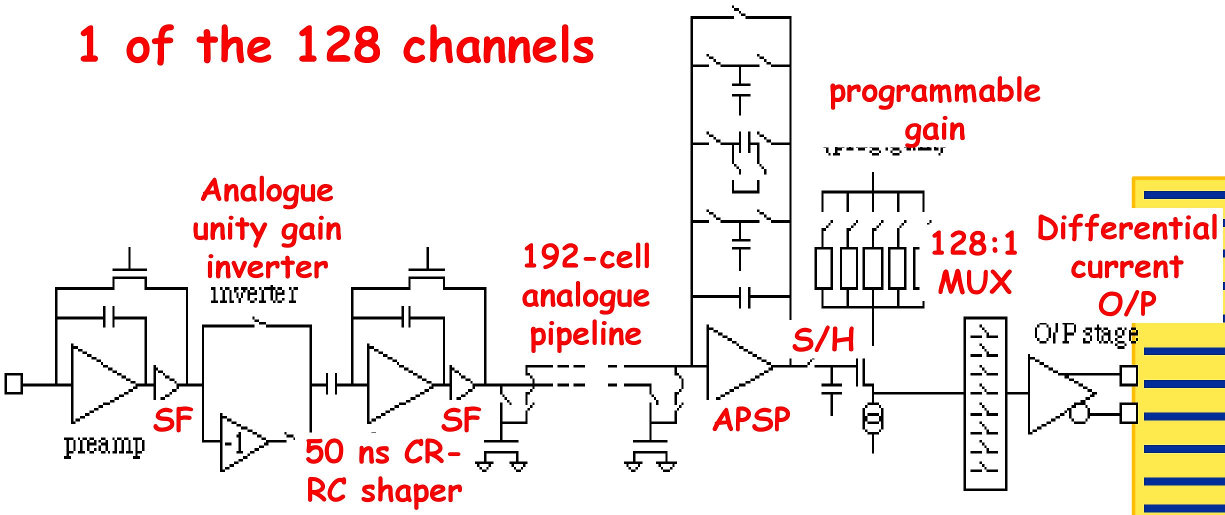
Pixels: ~ 2.3 m^2 of silicon sensors, 140 M pixels, 50x300 μm^2, r = 4, 10, 13 cm
Si μ-strips : 60 m^2 of silicon sensors, 6 M strips, 4 pts, r = 30 - 50 cm
Straws TRT: 36 straws/track, Xe-CO_2-CF_4 ϕ=4mm, r = 56 - 107 cm

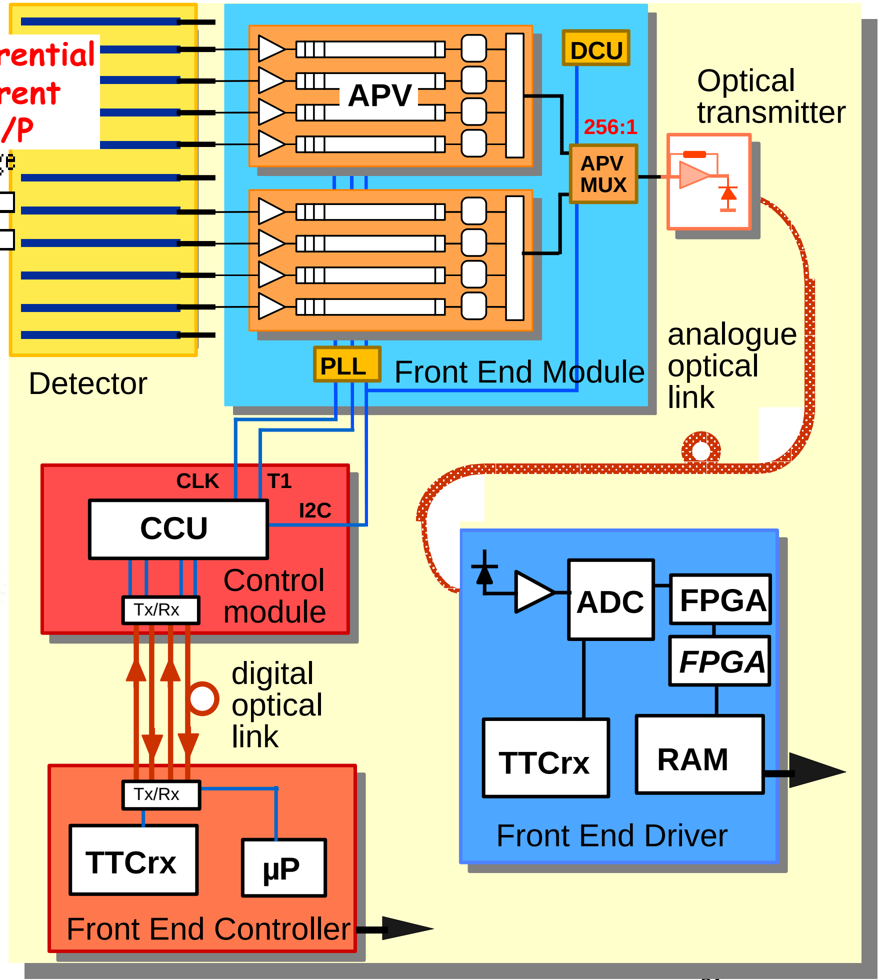
CMS: **Si pixels surrounded by silicon strip detectors**

Pixels: ~ 1 m^2 of silicon sensors, 40 M pixels, 150x150 μm^2 , r = 4, 7, 11 cm
Si μ-strips : 223 m^2 of silicon sensors, 10 M strips, 12 pts, r = 20 – 120 cm

Front-end Electronics

1 of the 128 channels





Each microstrip is read out by a charge sensitive amplifier with τ= 50 ns.
The o/p voltage is sampled at the beam crossing rate of 40 MHz.
Samples are stored in analog pipeline for up to Level-1 latency (3.2 μs)
Following a trigger form a weighted sum of 3 samples in analog circuit
This confines signal to single bx and gives pulse height
Buffered pulse height data multiplexed out on optical fibres
Output of laser modulated by the pulse height for each strip

Electromagnetic Calorimetry at LHC

In several scenarios moderate mass narrow states decaying into photons or electrons are expected:

SM : intermediate mass $H \rightarrow \gamma\gamma$, $H \rightarrow Z Z^* \rightarrow 4e$
MSSM: $h \rightarrow \gamma\gamma$, $H \rightarrow \gamma\gamma$, $H \rightarrow Z Z^* \rightarrow 4e$

In all cases the observed width will be determined by the instrumental mass resolution. Need :

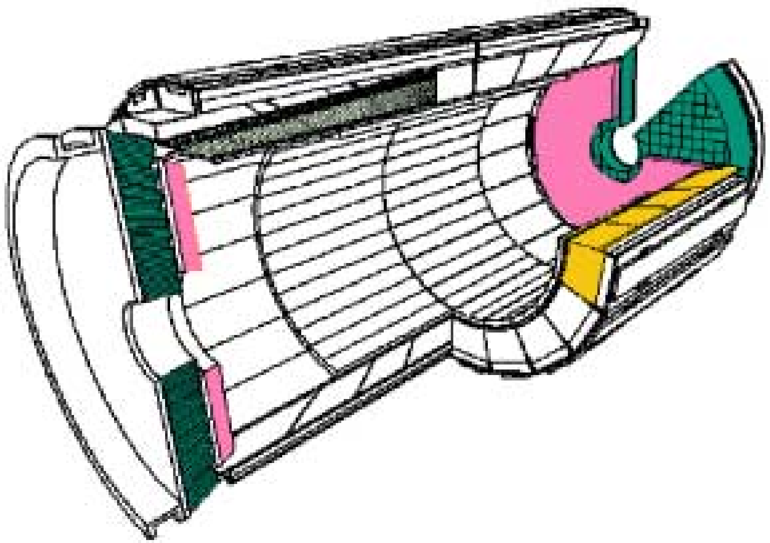
- good e.m. energy resolution
- good photon angular resolution
- good two-shower separation capability

Hadronic Calorimetry at LHC

- **Jet energy resolution**
  - Limited by jet algorithm, fragmentation, magnetic field and energy pileup at high luminosity
  - Can use the width of jet-jet mass distribution as a figure of merit
    - Low p_t jets: W, Z → Jet-Jet, e.g. in top decays
    - High p_t jets: W', Z' → Jet-Jet
  - Fine lateral granularity (≤ 0.1) high p_t W's, Z's
- **Missing transverse energy resolution**
  - Gluino and squark production
    - Forward coverage up to $|\eta| = 5$
    - Hermeticity - minimize cracks and dead areas
    - Absence of tails in the energy distribution is more important than a low value for the stochastic term
  - Good forward coverage is also required to tag processes initiated vector boson fusion

CMS Calorimeters

ECAL: $PbWO_4$ crystals



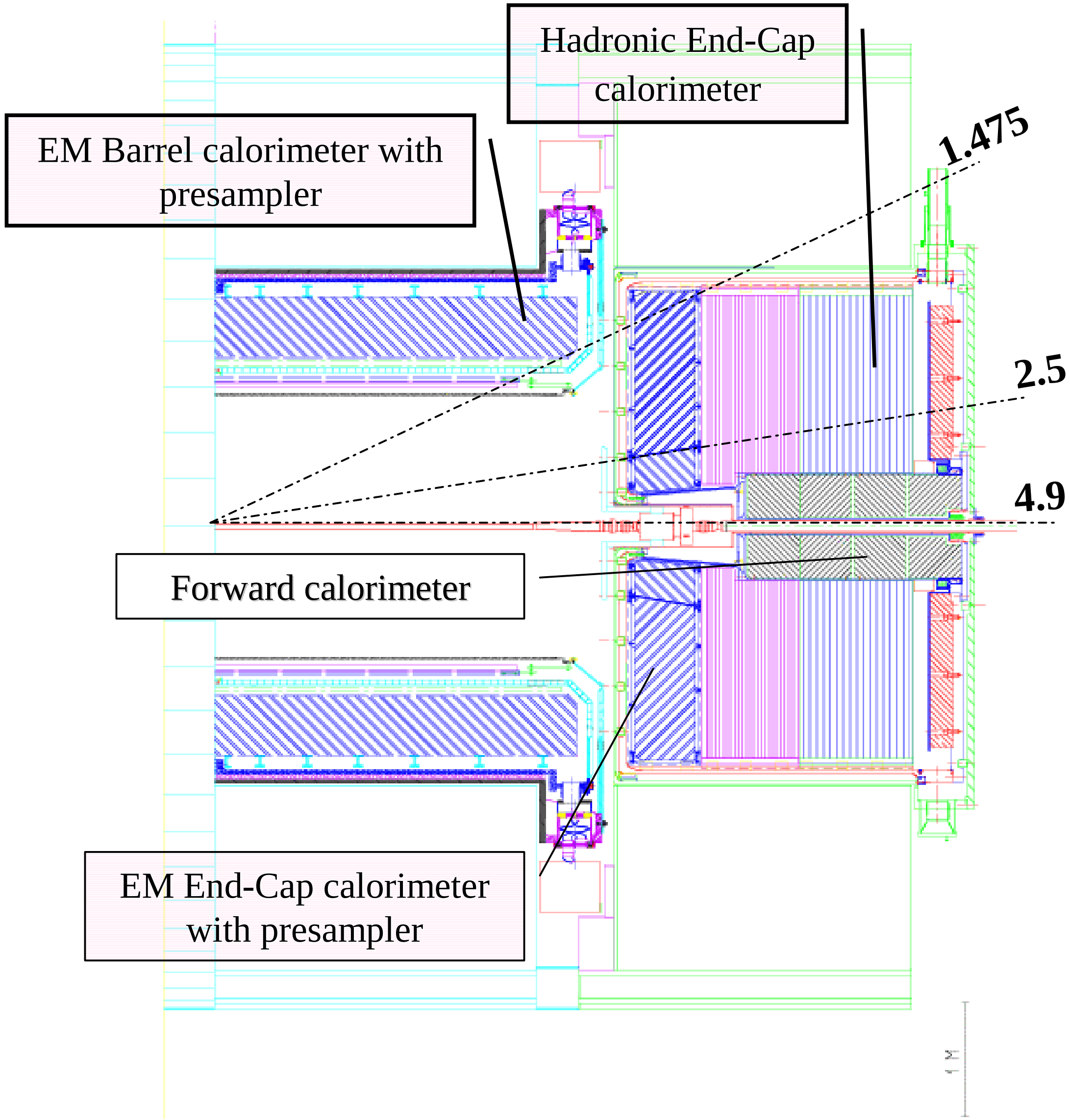
Parameter	Barrel	Endcap
η coverage	$\lvert\eta\rvert < 1.48$	$1.48 < \lvert\eta\rvert < 3.0$
Granularity ($\Delta\eta\times\Delta\phi$)	0.0175×0.0175	varies in η
Crystal Dims. (cm^3)	$2.18\times2.18\times23$	$2.85\times2.85\times22$
Depth in X_0	25.8	24.7 (+3X_0)
No. of crystals	61,200	14,950
Crystal Volume (m^3)	8.14	3.04
Photodetector	APDs	VPTs
Modularity	36 supermodules	4 Dees

HCAL

Central Region ($|\eta|<3$) : Brass/Scintillator with WLS fibre readout, projective geometry, granularity $\Delta\eta x\Delta\phi$ = 0.0875x0.0875

Forward Region ($3<|\eta|<5$): Fe/Quatz Fibre, Cerenkov light

ATLAS Calorimeters



ECAL

Accordion Pb/LAr

$|\eta|<3.2$, 3 samplings

S1: $\Delta\eta x\Delta\phi = 0.025x0.1$

S2: $\Delta\eta x\Delta\phi = 0.025x0.025$

S3: $\Delta\eta x\Delta\phi = 0.05x0.025$

HCAL

Barrel: Fe/Scintillator with WLS fibre readout

3 samplings - $\Delta\eta x\Delta\phi = 0.1x0.1$

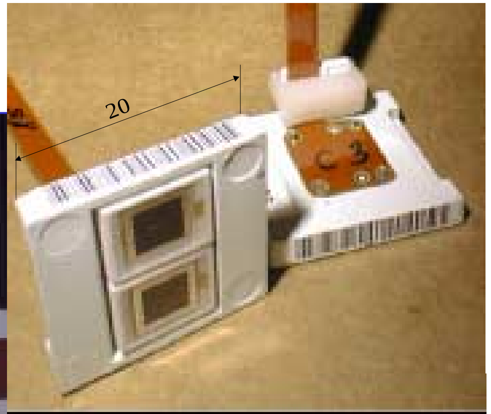
Endcap: Fe/LAr

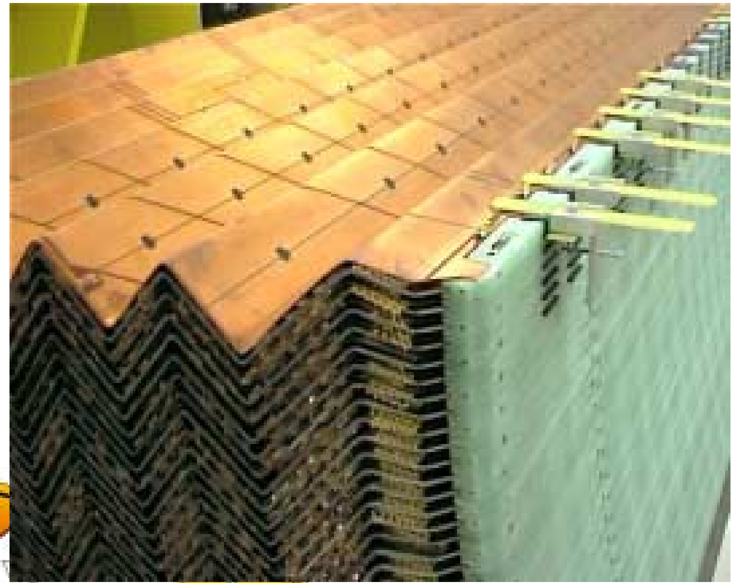
Forward: W/LAr

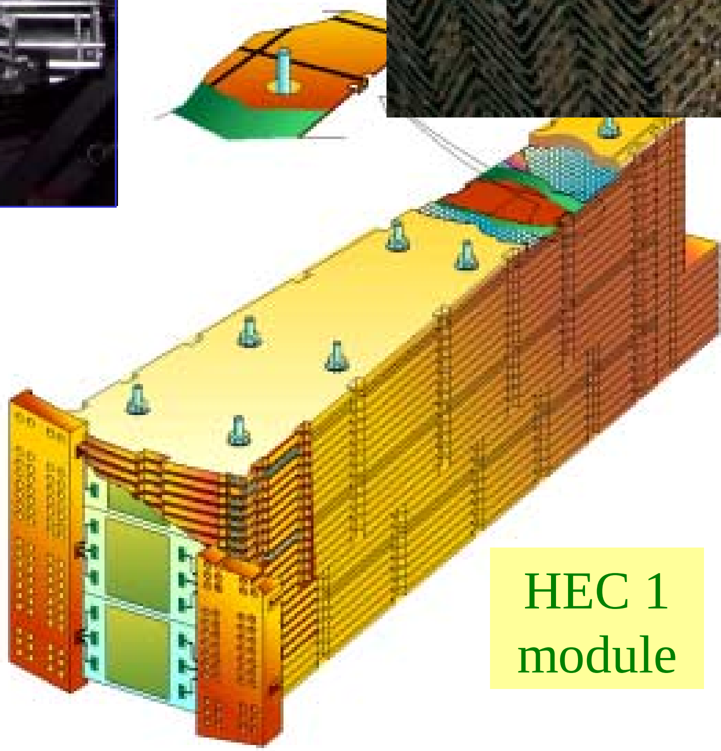
$3.1<|\eta|<4.9$

$\Delta\eta x\Delta\phi = 0.2x0.2$

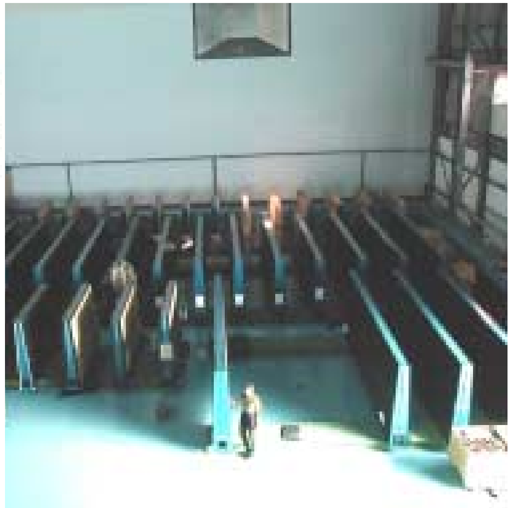
The Calorimeters







HEC 1 module



Muons

Muon identification should be easy at L ~ 10^{34} cm^{-2} s^{-1}

Muons can be identified inside jets

b-tagging, control efficiency of isolation cuts

Factors that determine performance

Level-1 Trigger

rate from genuine muons (b,c → μX) is very high ⇨ must make a p_T cut with v. high efficiency – flexible threshold (p_T in the range 5 – 75 GeV)

Pattern Recognition

hits can be spoilt by correlated backgrounds (δs, em showers, punchthrough) and uncorrelated ones (ns and associated photons)

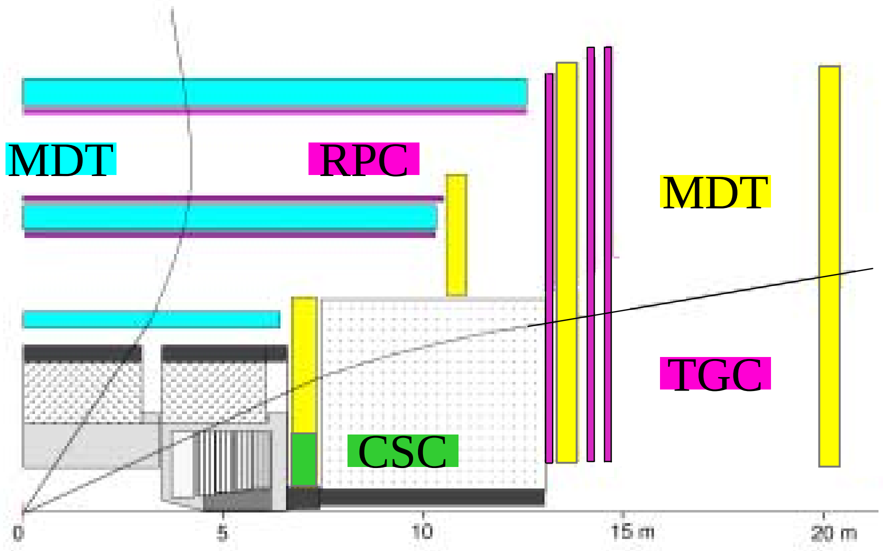
Momentum Resolution

high momenta involved ⇨ high B.dl

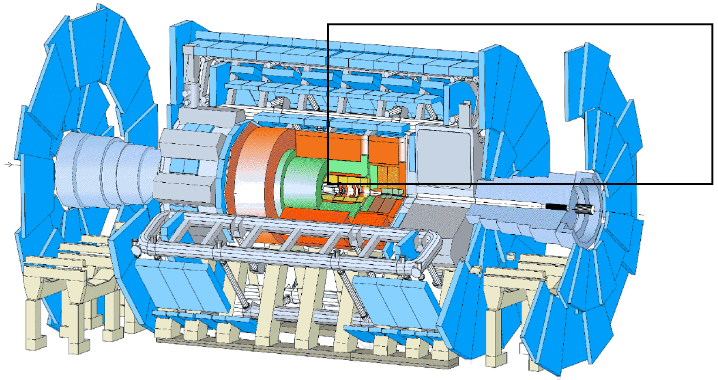
good chamber resolution (~ 100 μm) and good alignment

for low momenta precision comes from inner tracking

ATLAS Muon Detectors



Each detector has 3 stations.
Each station consists of 2-4 layers.



Precision chambers

Monitored **D**rift **T**ubes ($|\eta| < 2$)
with a single wire resolution of 80 μm
1194 chambers, 5500m^2

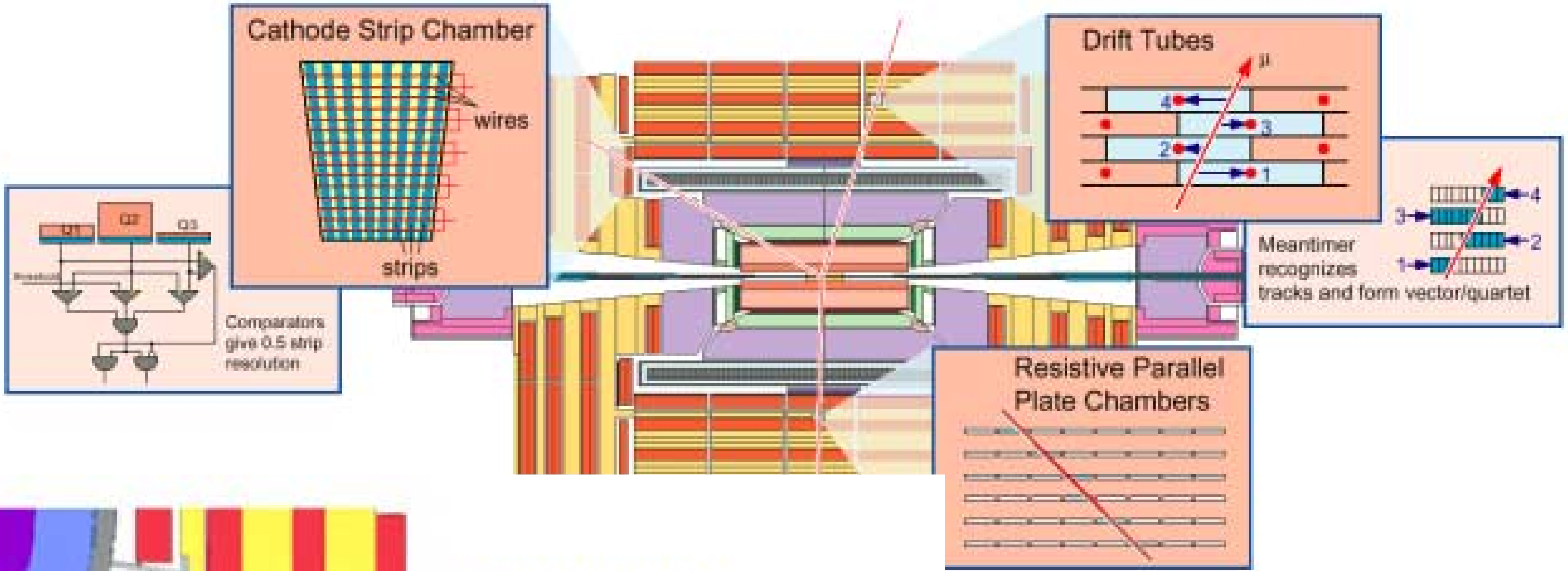
Cathode **S**trip **C**hambers ($2 < |\eta| < 2.7$)
at higher particle fluxes
32 chambers, 27 m^2

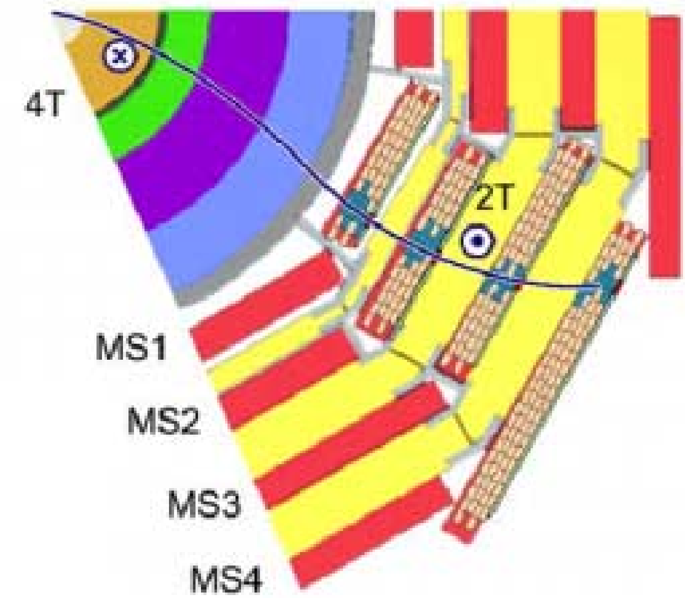
Trigger chambers

Resistive **P**late **C**hambers ($|\eta| < 1.05$)
with a good time resolution of 1 ns
1136 chambers, 3650 m^2

Thin **G**ap **C**hambers ($1.05 < |\eta| < 2.4$)
at higher particle fluxes
1584 chambers, 2900 m^2

CMS Muon Detectors





4 Muon Stations
- redundancy
- acceptance

Per Station
- barrel – 12 measuring planes
- endcap – 6 measuring planes

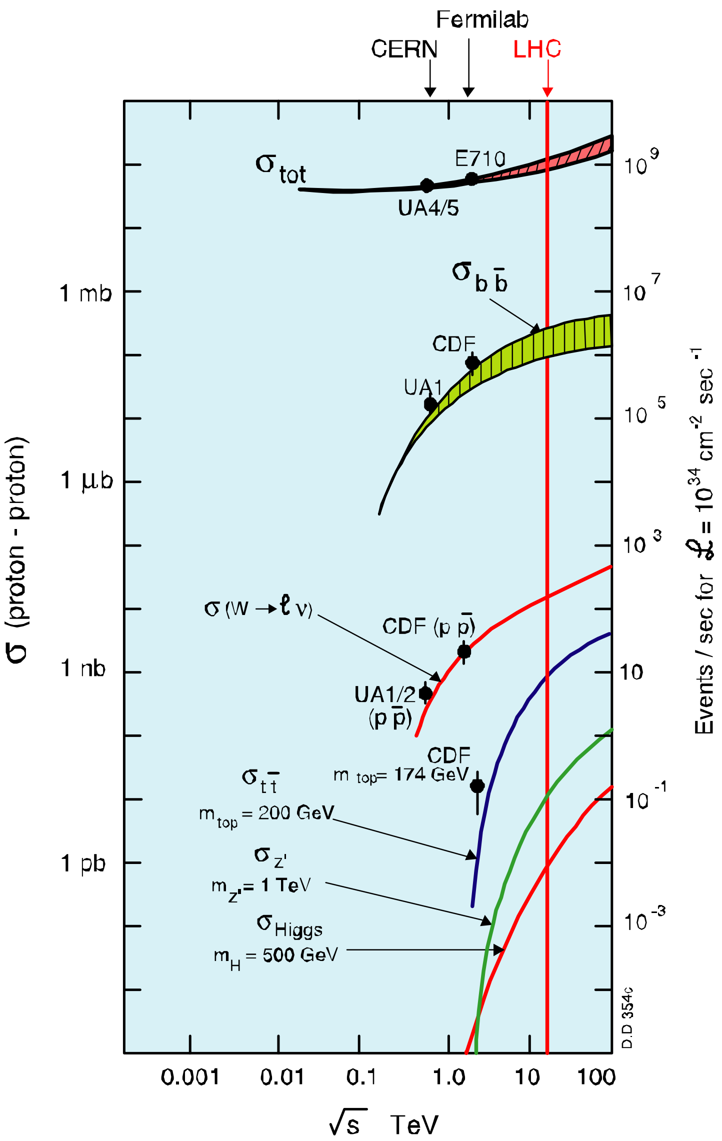
Measurement Accuracy
- position 70 – 100 μm /station
- direction ~ 1 mrad

Muon Chambers

3. Tools and Algorithms

i. Minimum Bias Events
ii. Isolation Criteria
iii. Muon/electron/gamma reconstruction
iv. Jet reconstruction and Missing E_T
v. b/t tagging
vi. Triggering

Production Cross-sectons



At sqrt(s)=14 TeV

σ_{tot}	~ 105 mb
$\sigma_{\varepsilon\lambda\alpha\sigma\tau\iota\chi}$	~ 28 mb
$\sigma_{single\ diffractive}$	~ 12 mb
$\sigma_{double\ diffractive}$	~ mb
σ_{inel}	~ 60 mb

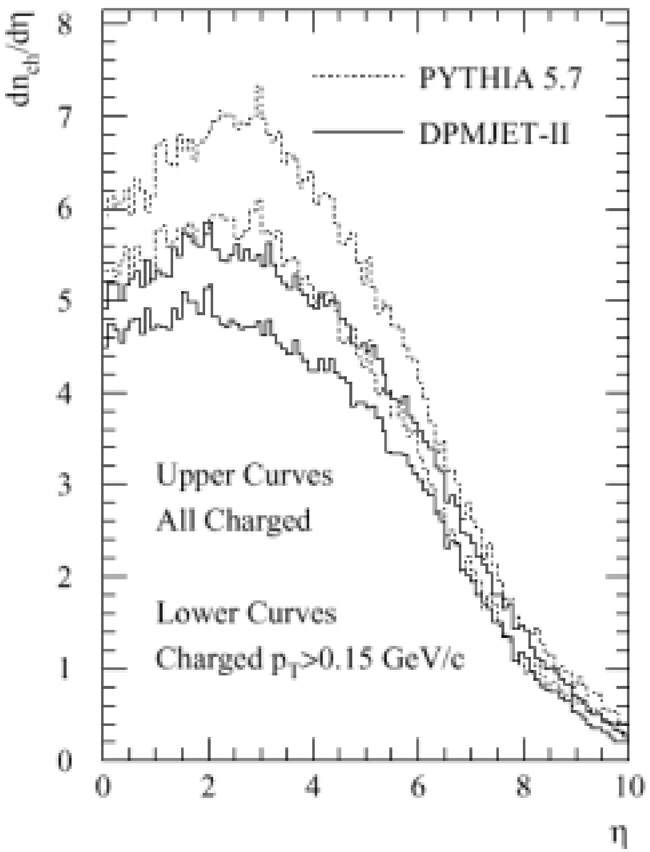
Evt rate = $L.\sigma = 10^{34} \times 60\ 10^{-27}$ /s
= 6×10^{8} /s

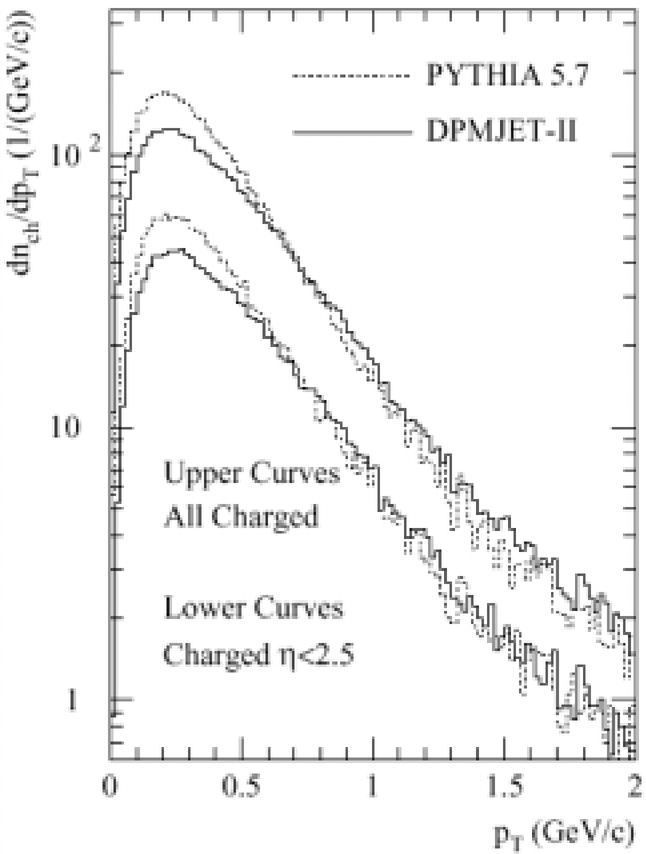
Not all bunches are full (2835/3564)
➪ events/crossing ~ 20

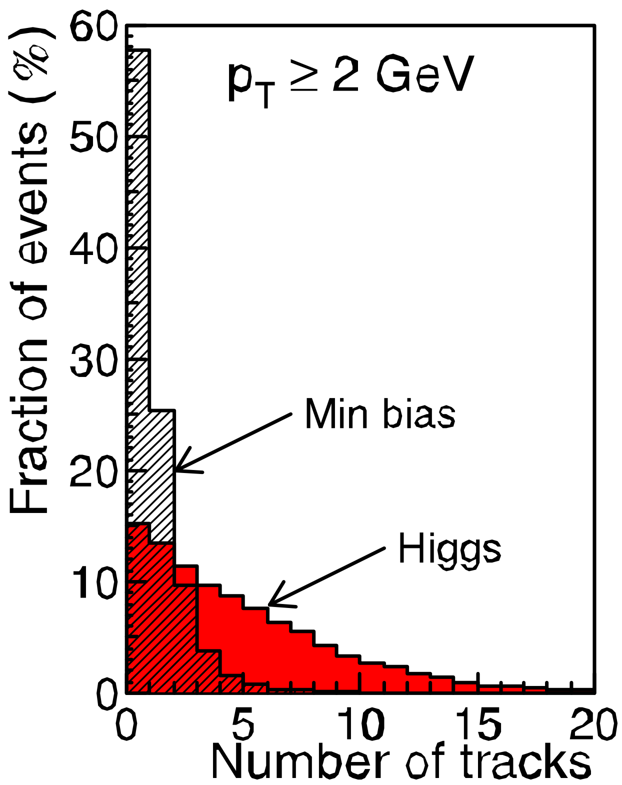
Operating Conditions

For every ‘good’ event containing a Higgs decay there are ~ 20 extra ‘bad’ minimum bias interactions superposed

Characteristics of MB Events: Tracks



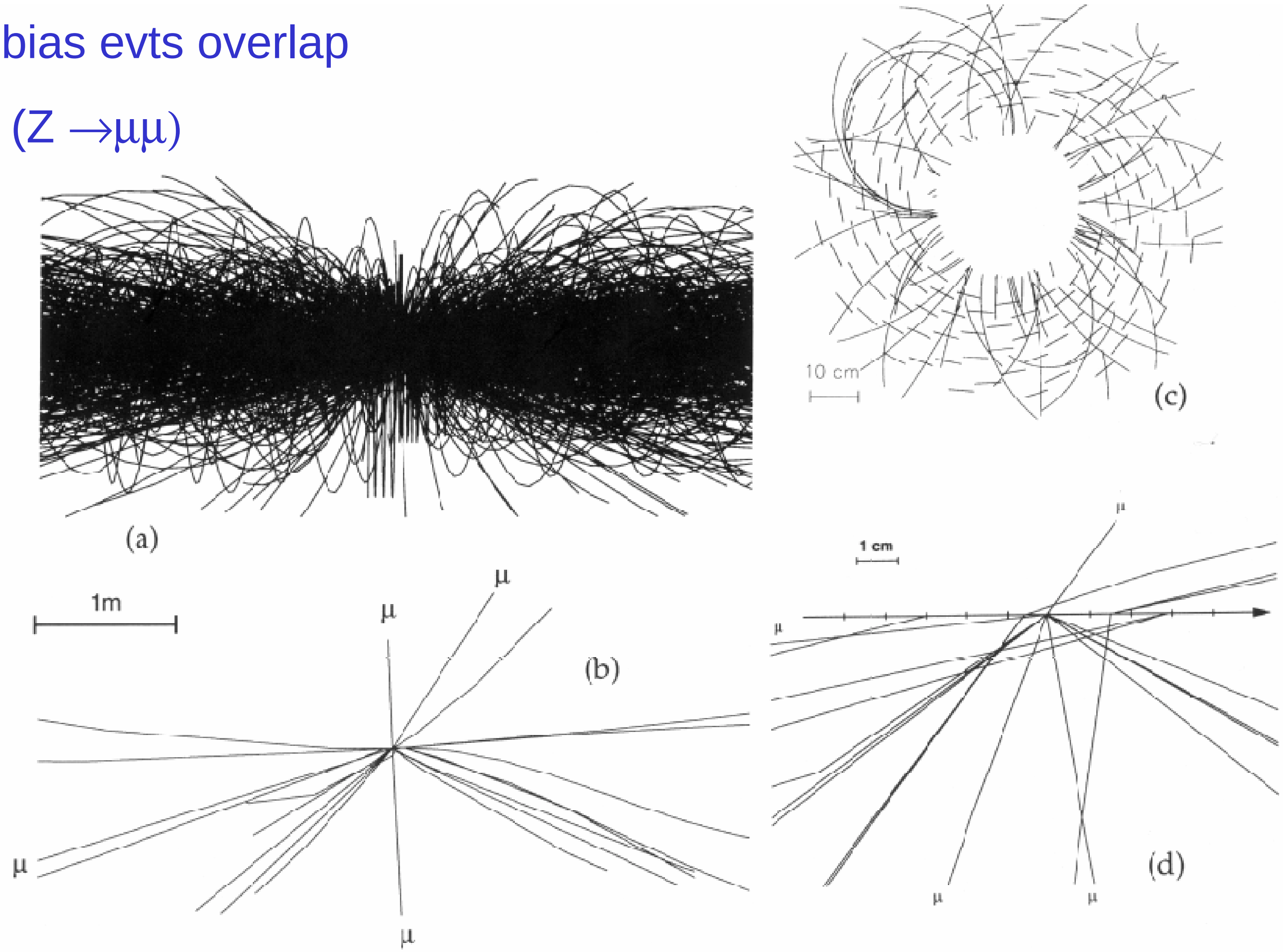




Event Pileup

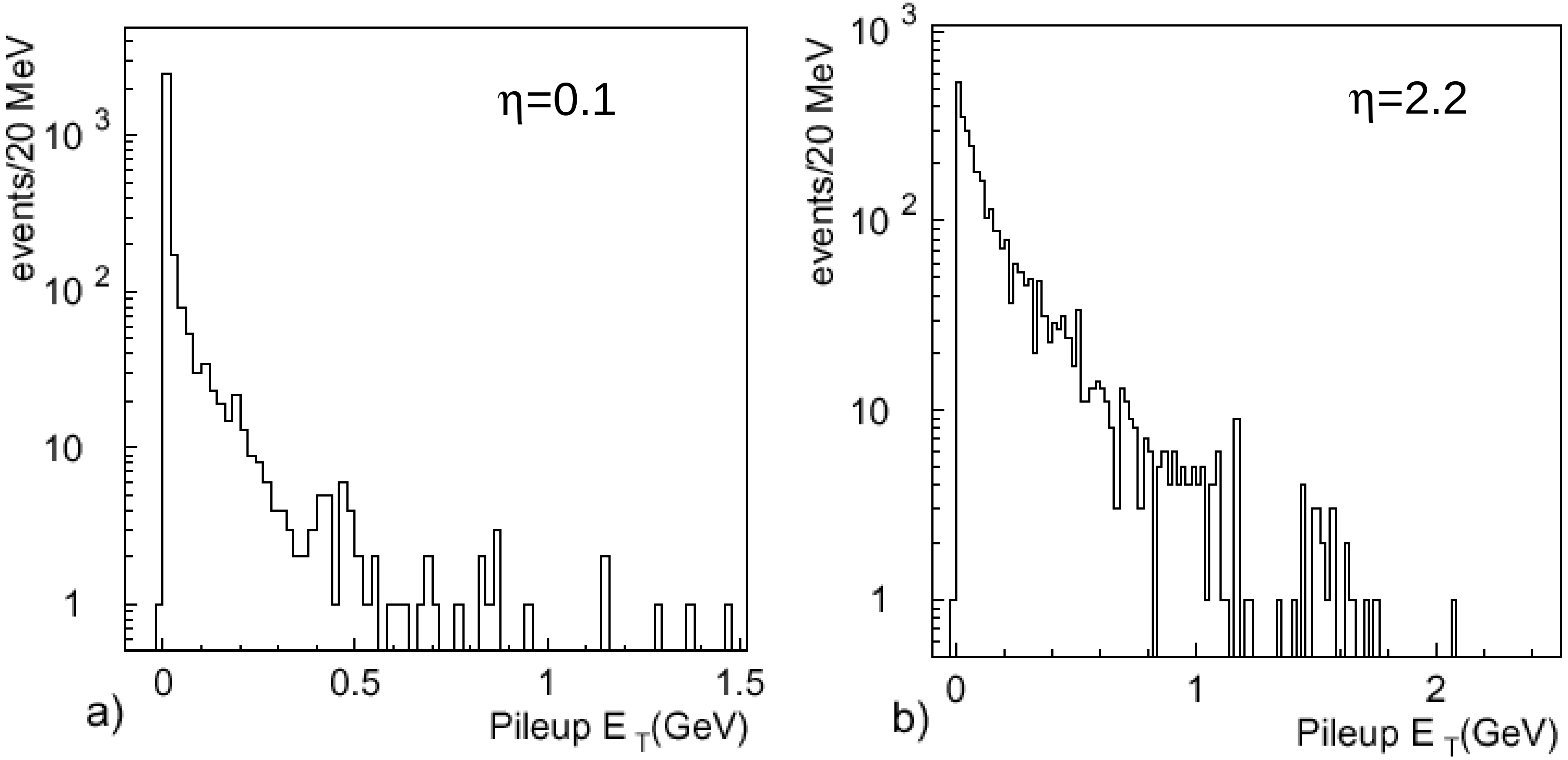
20 min bias evts overlap

$H \rightarrow ZZ$ $(Z \rightarrow \mu\mu)$



Characteristics of MB Events: Energy

CMS: Transverse energy flow in $\Delta\eta x \Delta\phi$ ~ 0.1x0.1 at $L=10^{34}$ $cm^{-2}s^{-1}$

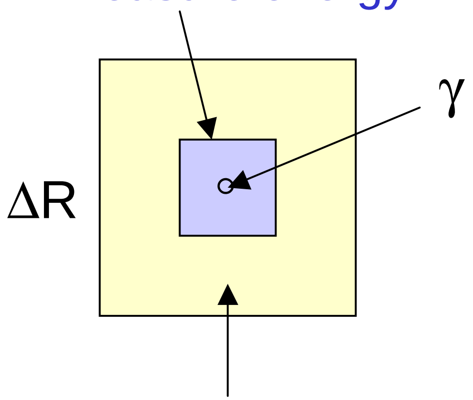


Isolation Criteria

Isolation is one of the most powerful tools at Hadron Colliders – leptons and photons from sub-processes are isolated

e.g. γ isolation using charged tracks (CMS) – energy deposits can also be used

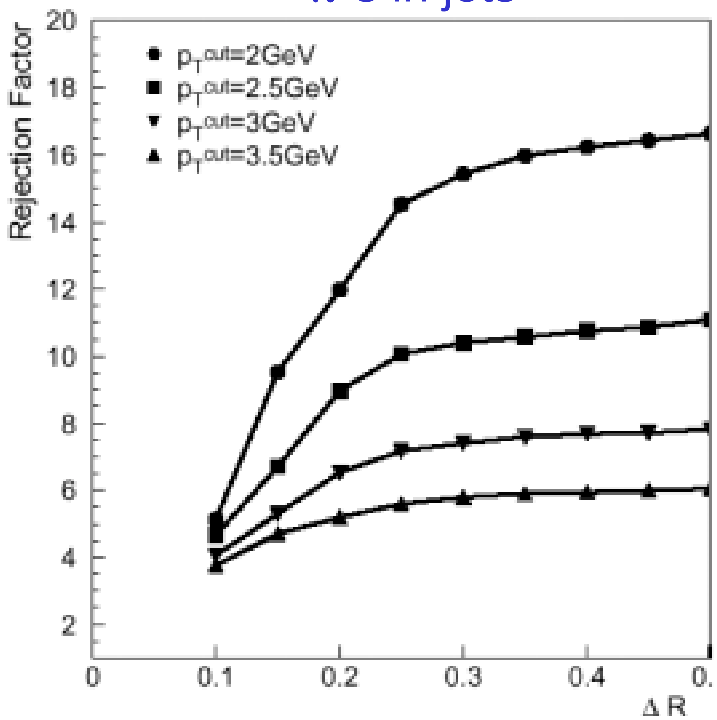
area used to measure energy



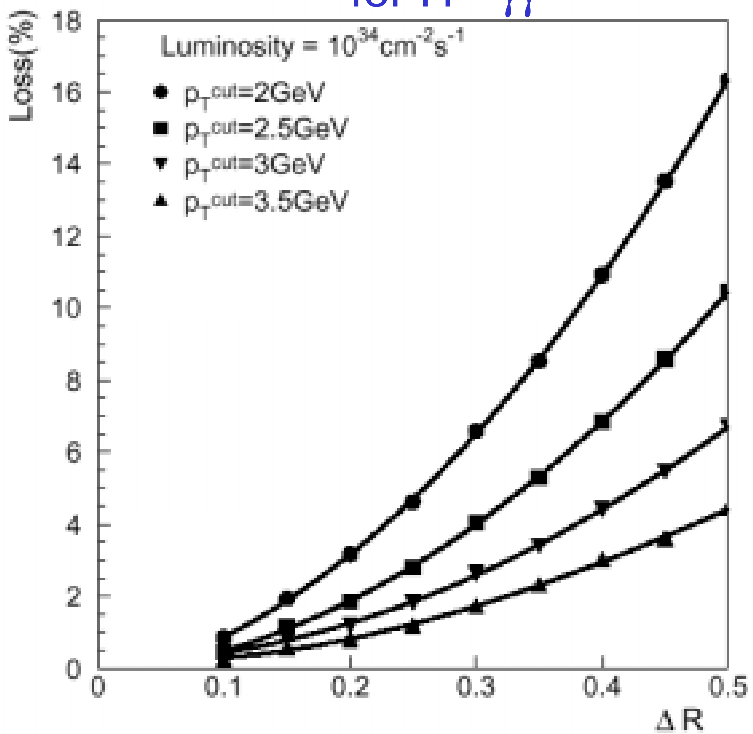
area used for isolation

$\Delta R = \mathrm{sqrt}(\Delta\phi^2 + \Delta\eta^2)$

Rejection power against π^0s in jets

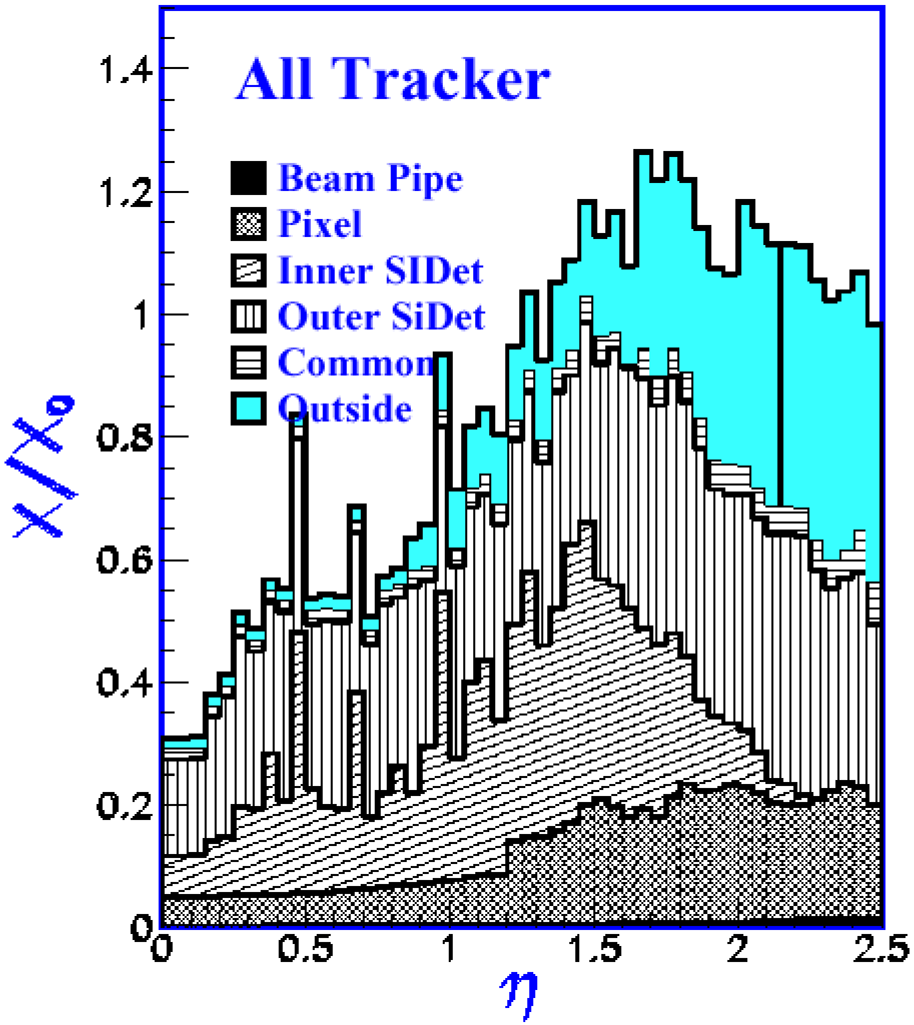


Loss of efficiency at Hi L for $H \rightarrow \gamma\gamma$

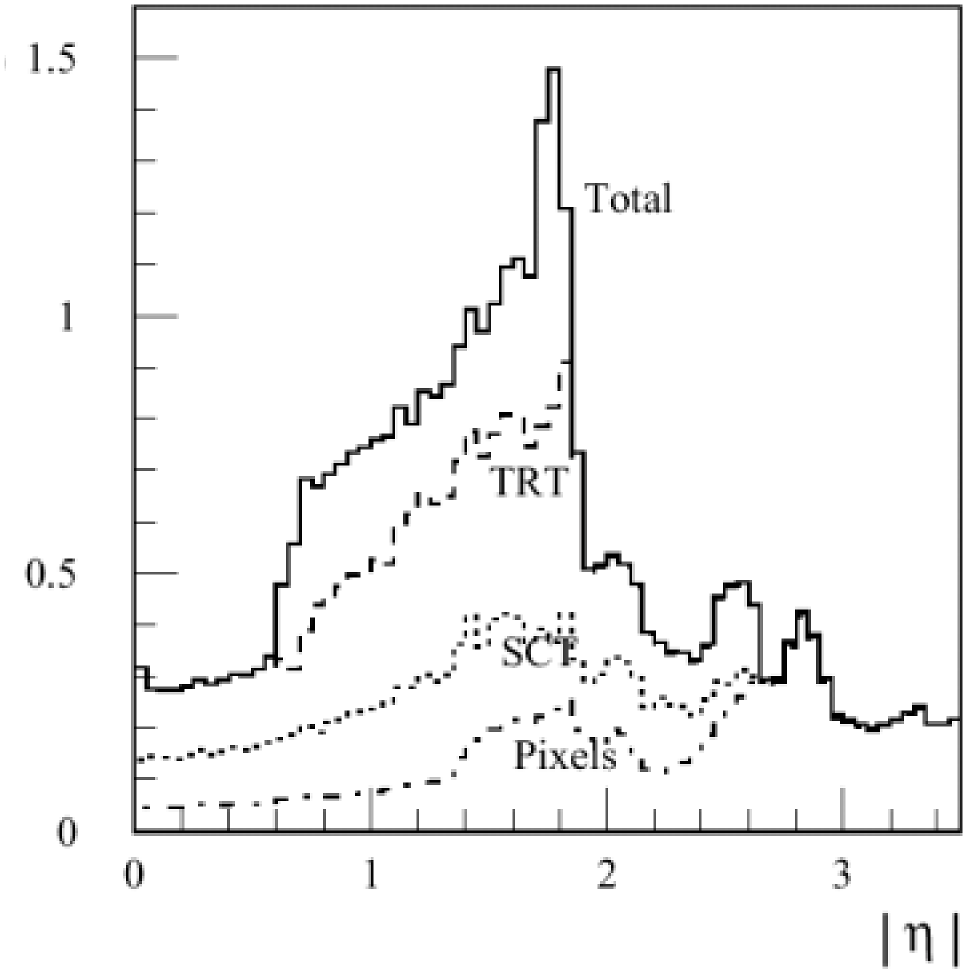


Material in Trackers

CMS

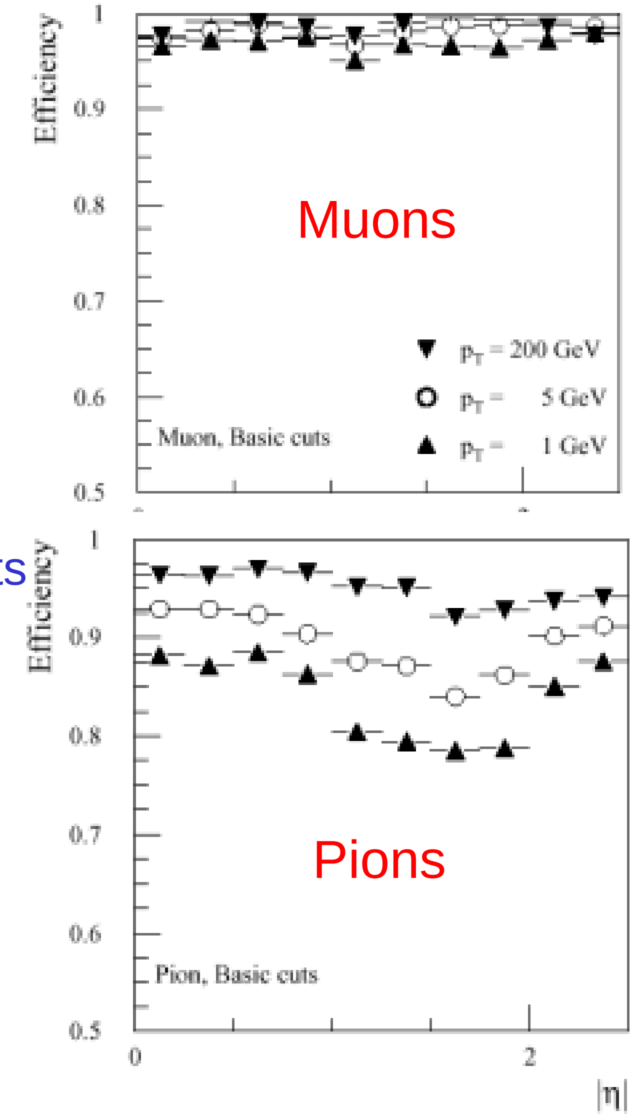


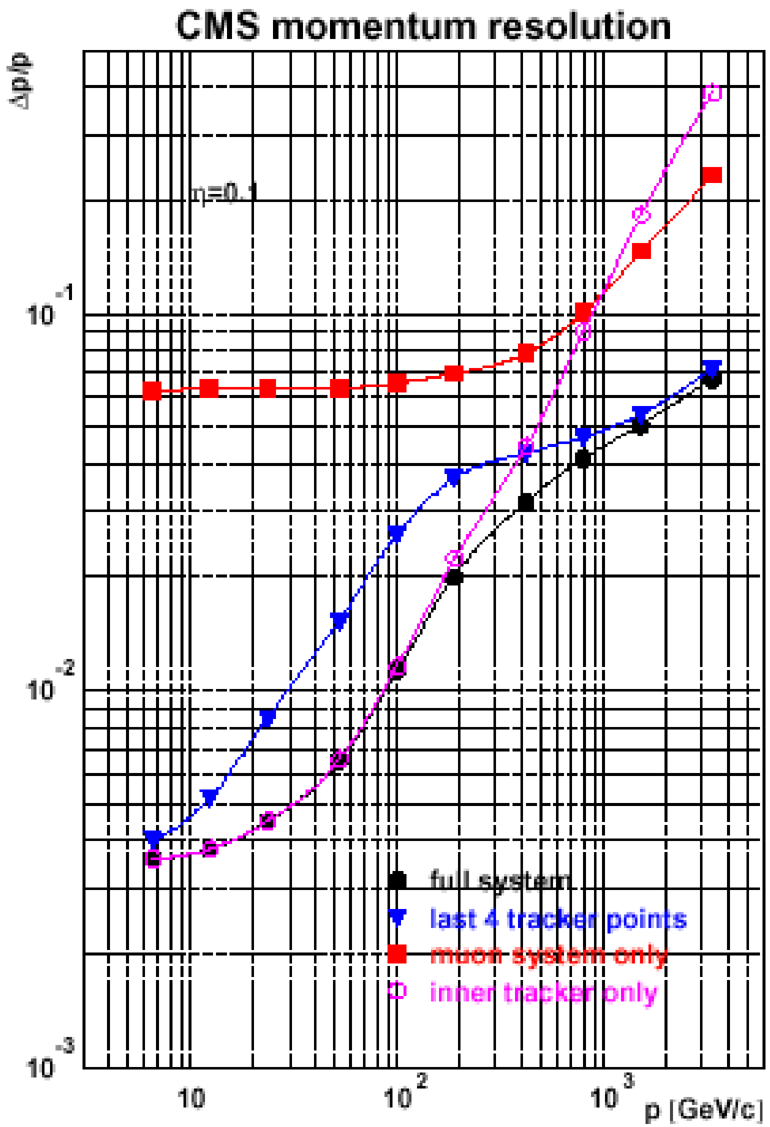
ATLAS



Charged Track Reconstruction

ATLAS
Pattern
Recognition
>9 precision hits
+ 2 pixel hits
+ σ_d < 1mm

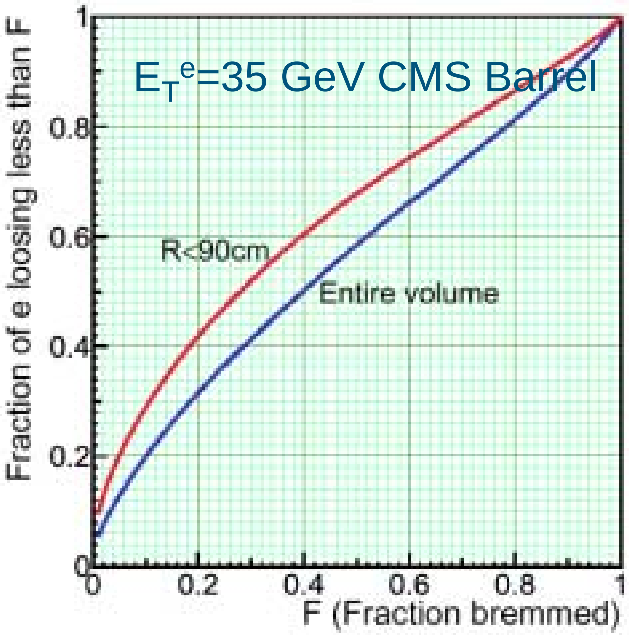


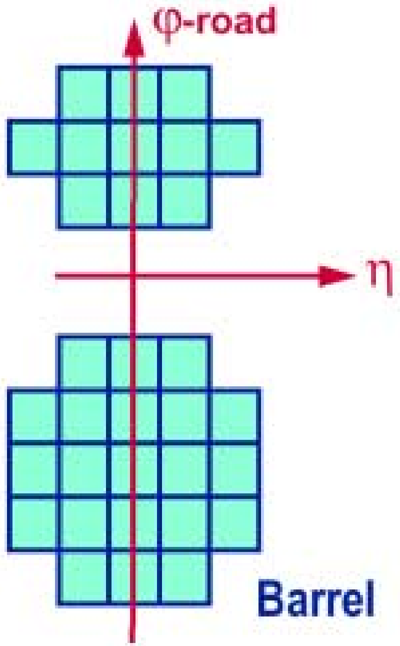


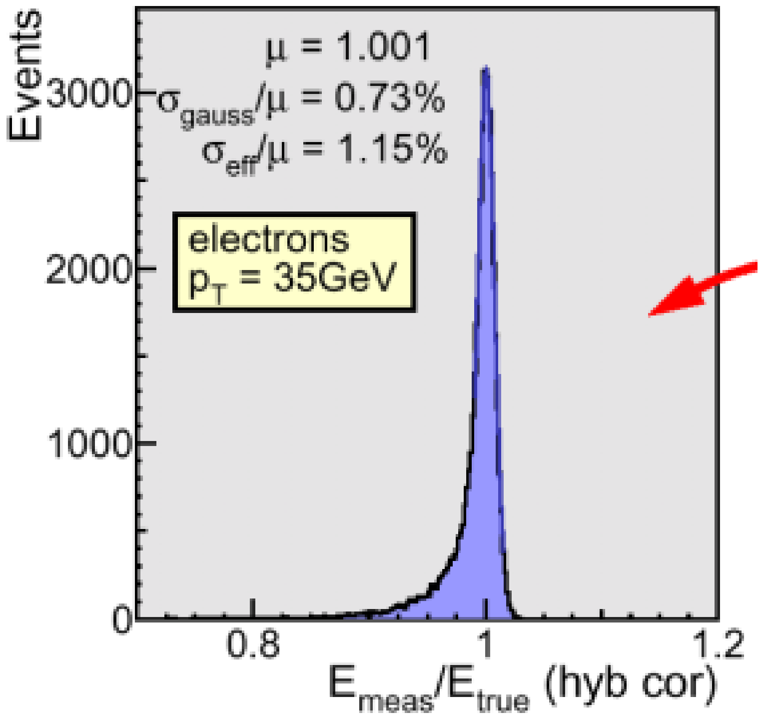
Electron Reconstruction

Reconstruction of electrons that radiate little (and unconverted γs) is simple : eg. CMS -collect energy in an array of 5 x 5 crystals centred on ~ impact point

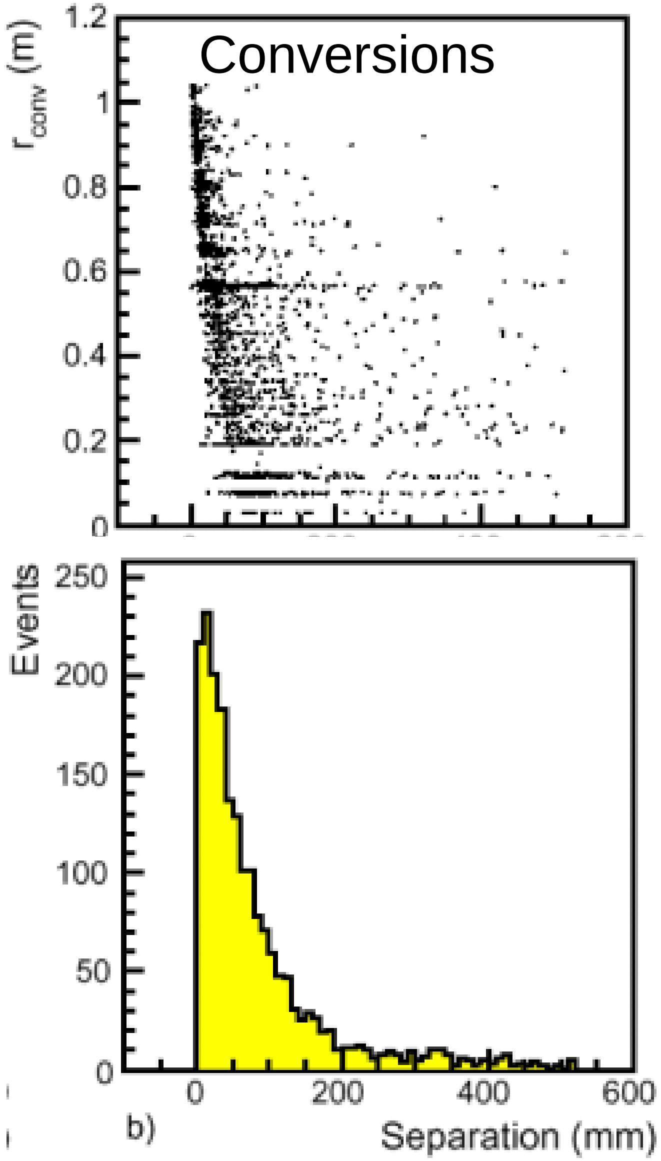
For 'bremming' e's and converting γ's, challenge is in coping with the combined result of tracker material and the 4T magnetic field (CMS) – problem is not energy loss but spraying/spreading of energy







Gamma Reconstruction



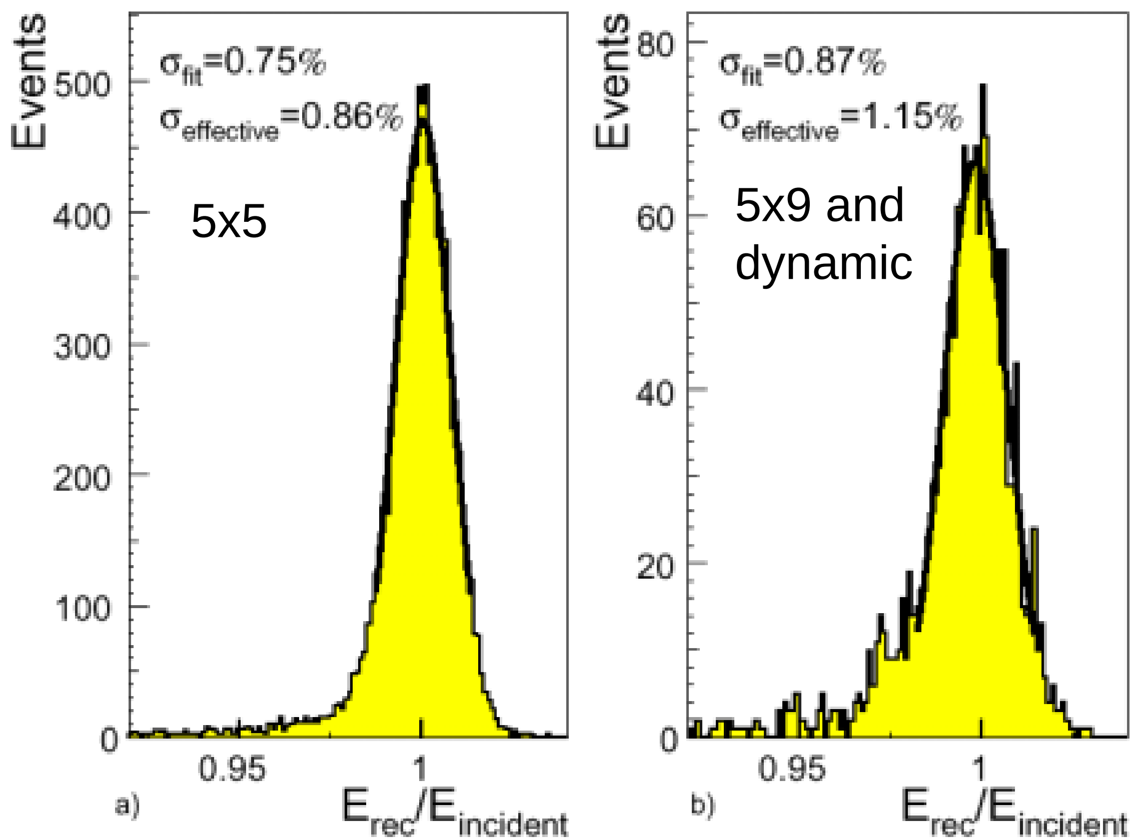
CMS Barrel

Higgs → γγ

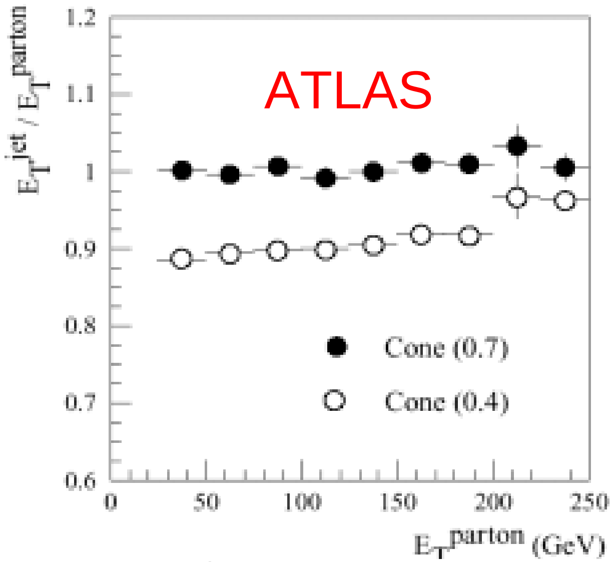
ε_γ **~ 90%**

¼ of conversions cannot be reconstructed

Unconverted γs **Converted γs**



Jet Reconstruction

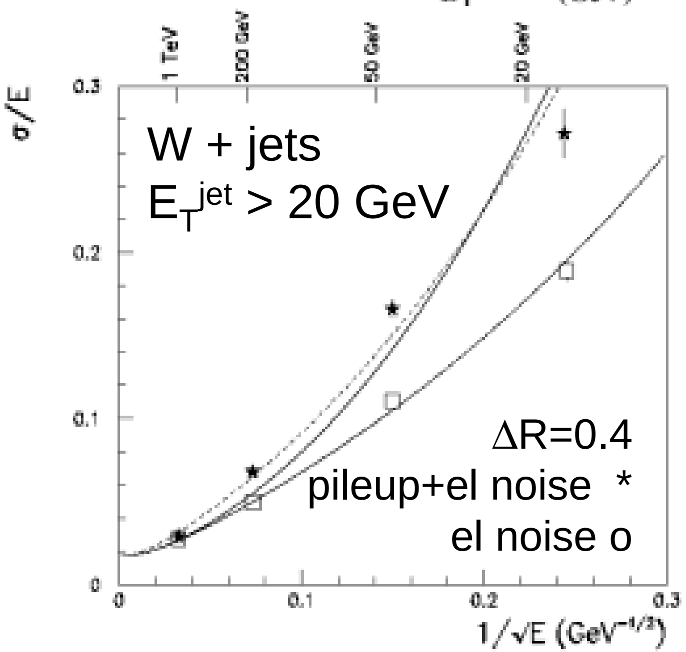


Classical 'cone' algorithm - jet built around a seed

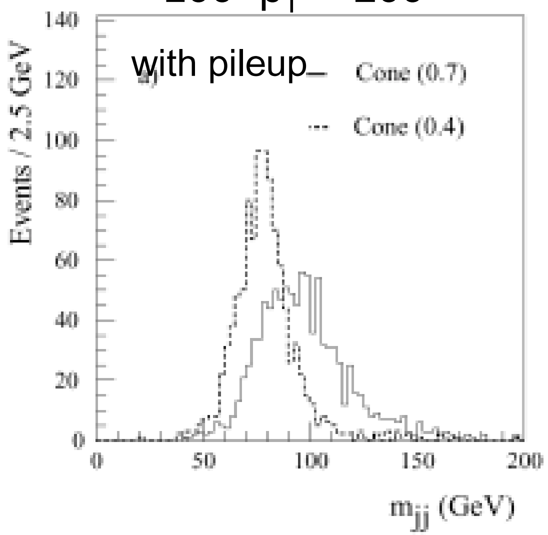
- parameters: E_T^{seed} cut, cone opening radius ΔR

ATLAS: W → jet-jet mass resolution

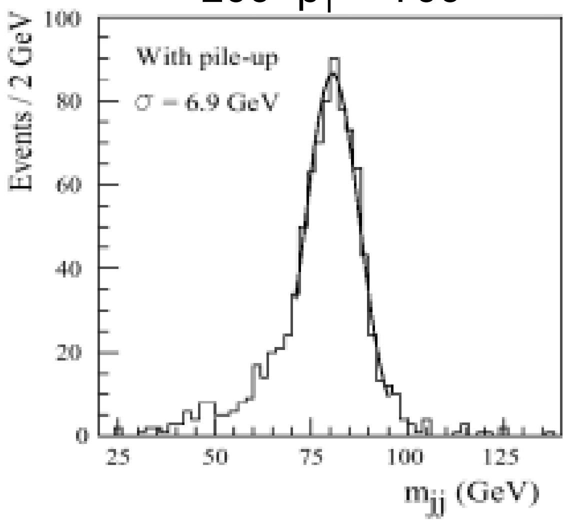
p_T^W(GeV)	ΔR	σ_{LoL}	σ_{HiL} (GeV)
p_T<50	0.4	9.5	13.8
100<p_T<200	0.4	7.7	12.9
200<p_T<700	0.3	5.0	6.9



100<p_T^W<200

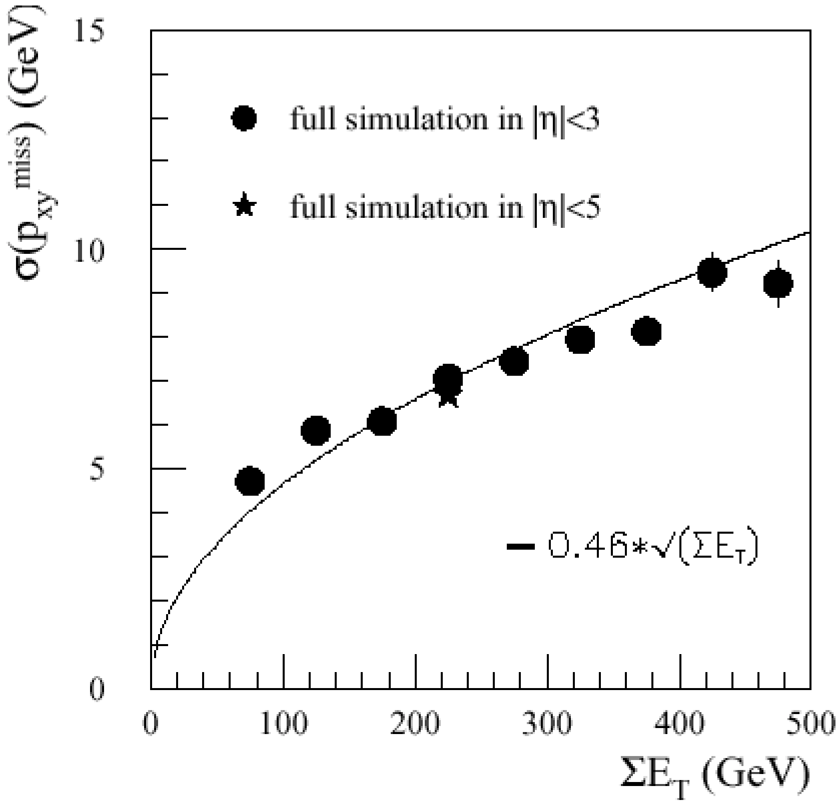


200<p_T^W<700



Missing E_T

$A \rightarrow \tau\tau$ m_A=150 geV



γ-Jet Rejection

Cuts (ATLAS)

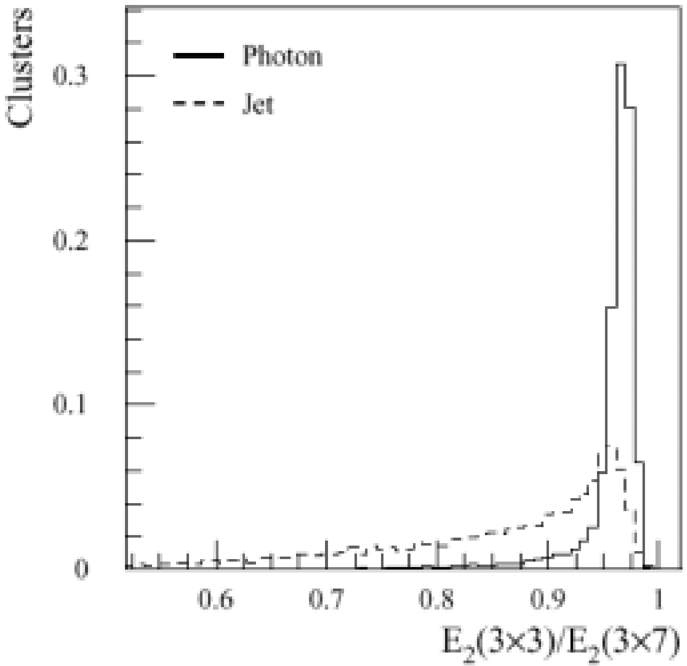
$E_{T\gamma 1}, E_{T\gamma 2} > 40, 25$ GeV with $|\eta| < 2.5$

E_{H1}/E_{em}

$E_{em2}^{3x3}/ E_{em2}^{7x7}$

Shower width in η

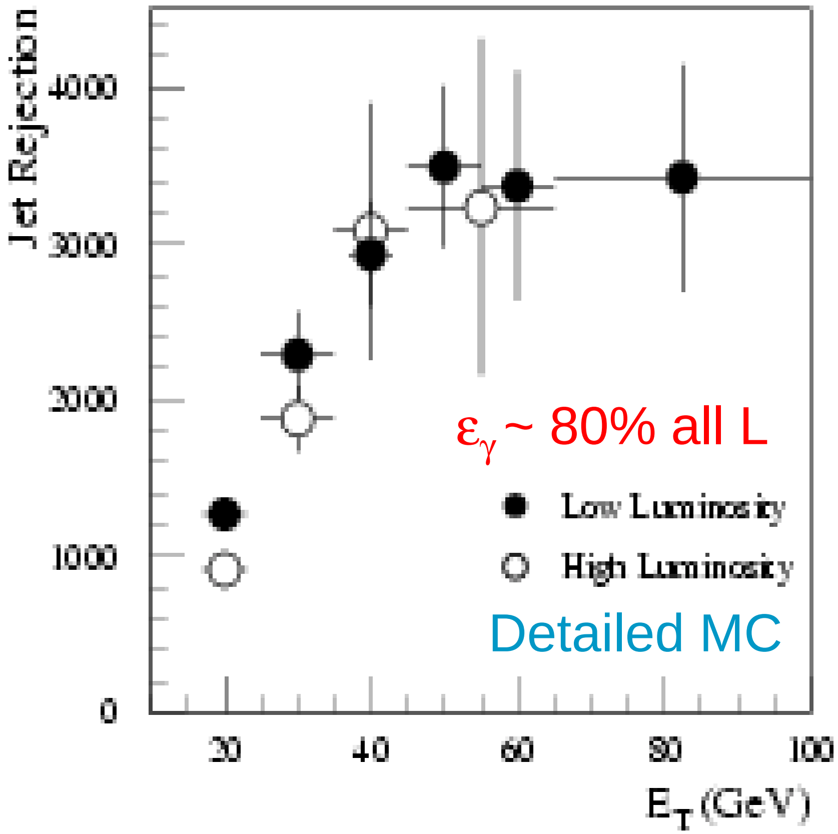
Track Veto



ATLAS EM calorimeter

4 mm η-strips in first compartment

3 longitudinal segments



⇨ (γ–jet + jet-jet) < 40% γγ

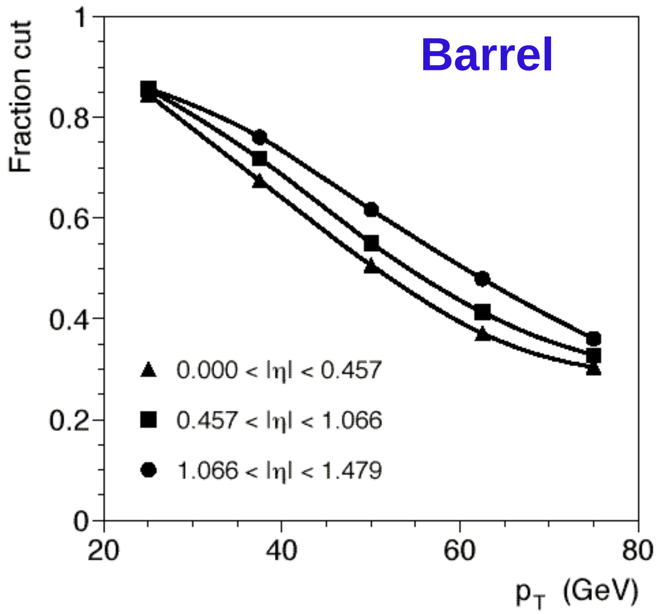
γ / π^0 Separation

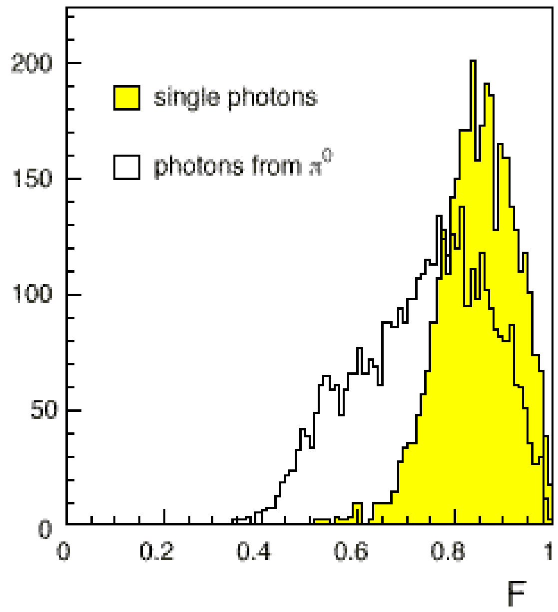
Isolated π^0's - detect presence of 2 em showers.

CMS Barrel

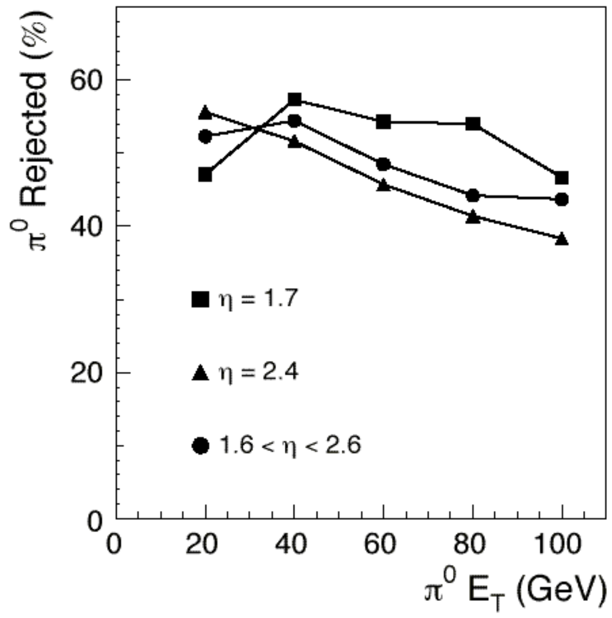
- use fine transverse crystal granularity (2.2×2.2 cm^2)
- Compare energy deposited by single γ and π^0 in 3×3 crystal array

variables - 9-energies, x and y position, and a pair measuring the shower width





Endcap



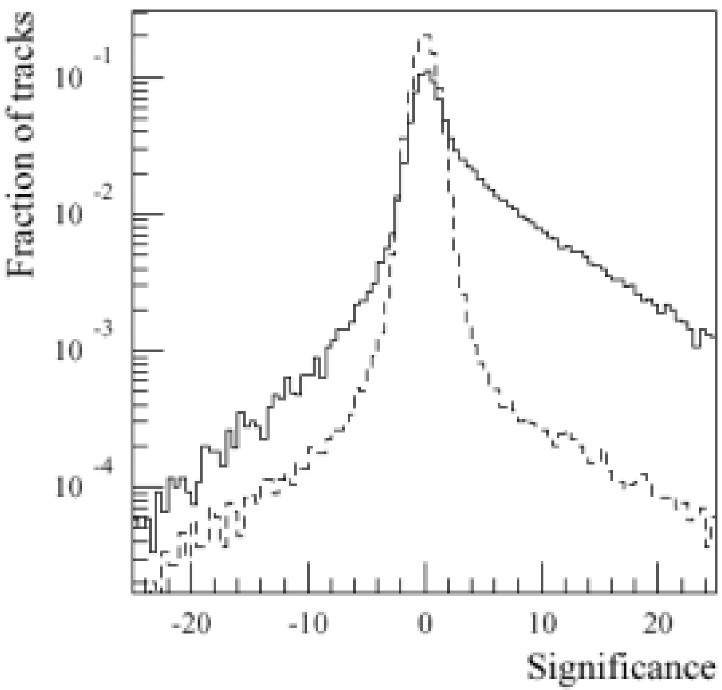
CMS Endcap

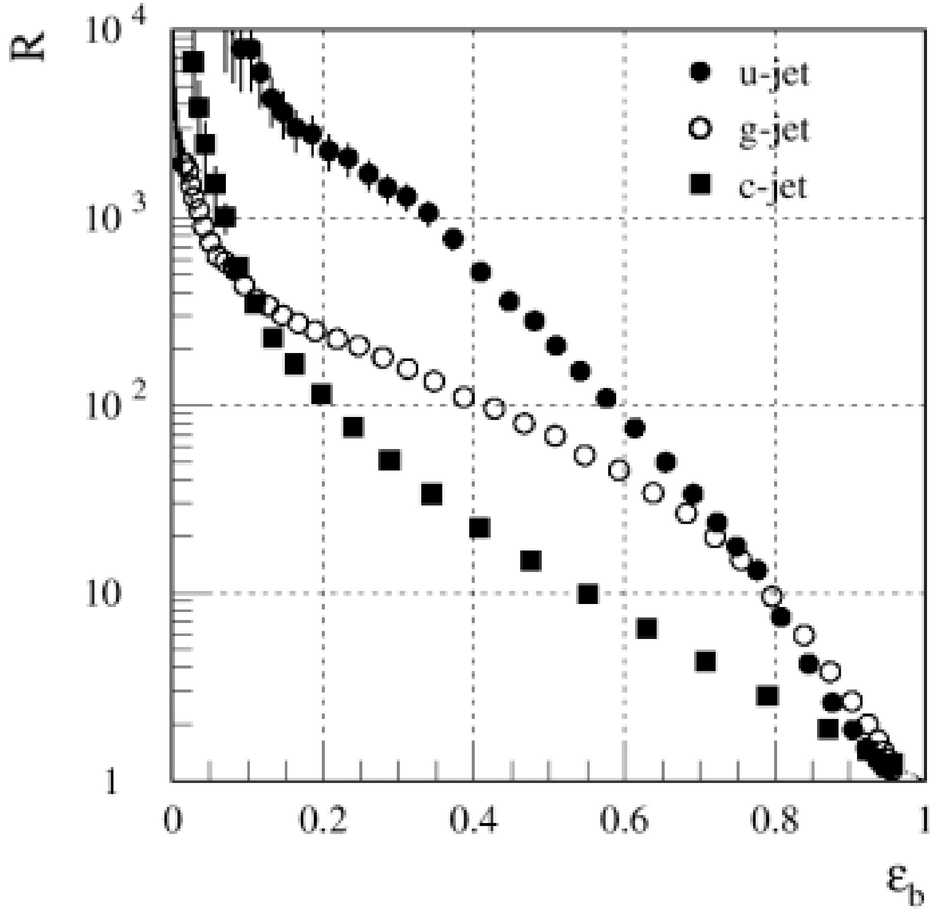
- use preshower - two planes of Si strips with fine pitch (≈2mm)

compare signal (summed in 1,2 or 3 adjacent strips with the total signal in 21 adjacent strips centred on strip with highest signal

b-jets

Likelihood method
Form significance S_i for i-th trk in jet
Form $r_i=f_b(S_i)/f_u(S_i)$
Form Jet weight W = Slog r_i





τ-jets

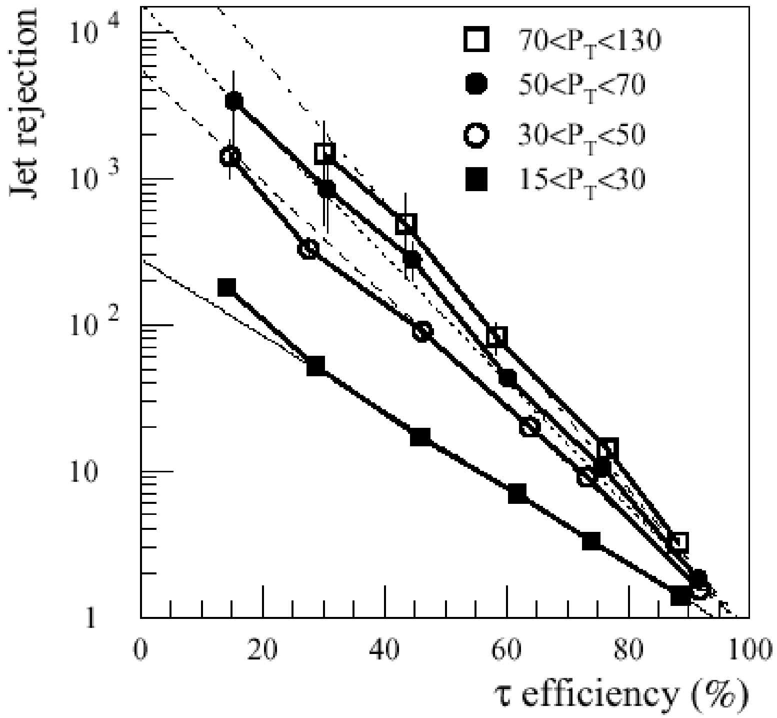
ATLAS

τ-identification – variables

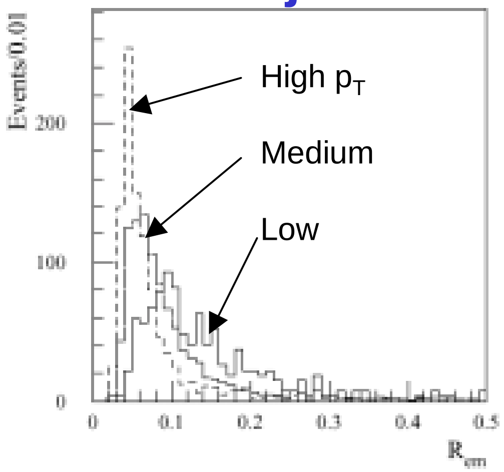
R_{em} – jet radius using em cells

ΔE_T^{12} – E_T^{em}/E_t^{had} within $0.1<\Delta R<0.2$

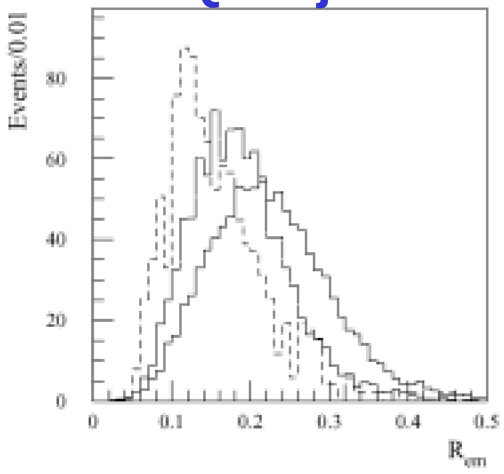
N_{tr} – no. charged trks $p_T>$ 1,2,5 GeV within $\Delta R=0.3$



τ-jets



QCD jets



τ-jet separation

	$A\to\tau\tau$	QCD	b-jets	tt
$p_T(\tau)$	73	44	58	65
$R_{em} < 0.07$	45%	1.1%	1.9%	1.3%
$\Delta E_T^{12} < 0.1$	32%	0.6%	0.9%	0.7%
$N_{tr}(p_T>2)$:1or 3	25%	0.2%	0.2%	0.2%

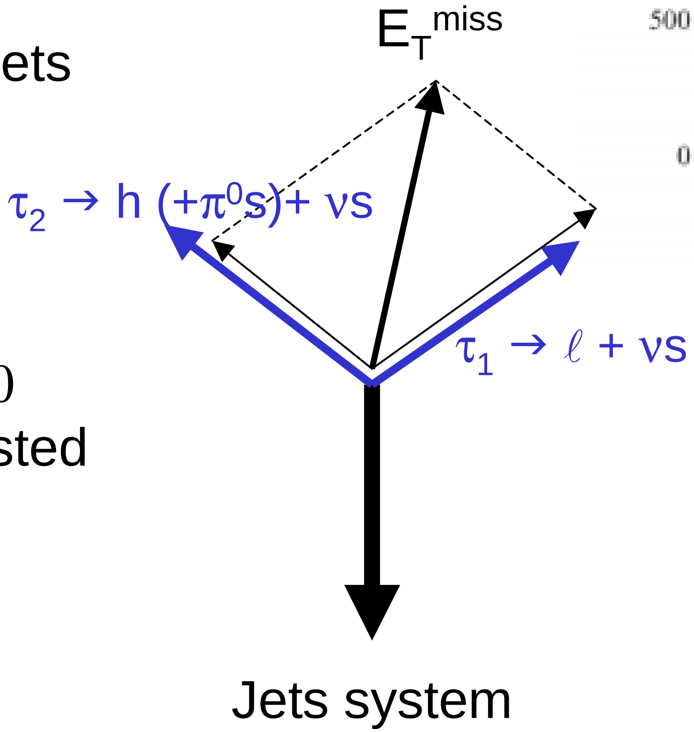
$\tau-\tau$ mass reconstruction

Invariant mass of $\tau\tau$ pair can be reconstructed assuming m_τ=0 and νs go in the direction of τ-jets

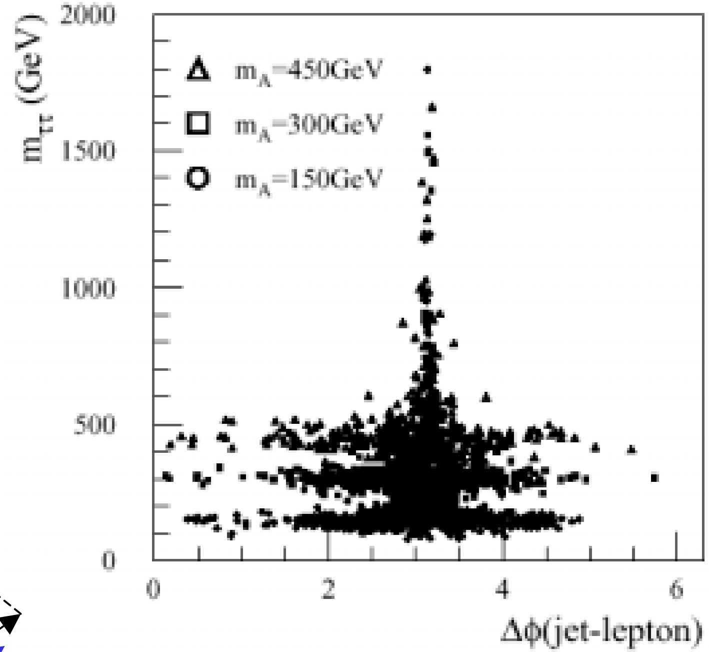
$$m_{\tau\tau} = \sqrt{2(E_1 + E_{\nu 1})(E_2 + E_{\nu 2})(1 - \cos\theta)}$$

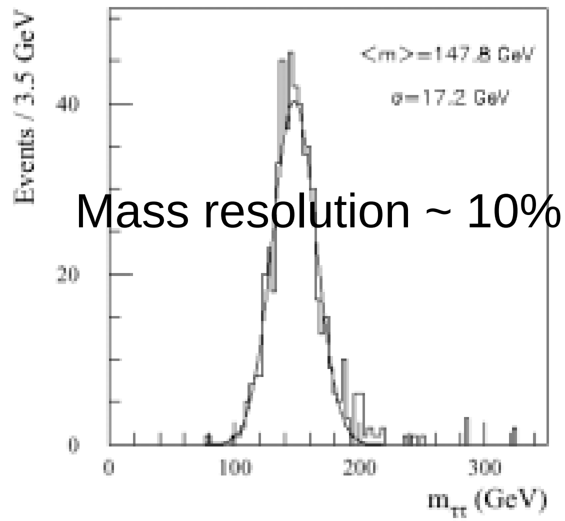
$$p_x^{miss}(p_y^{miss}) = (E_{\nu 1}\bar{u}_1)_{x(y)} + (E_{\nu 2}\bar{u}_2)_{x(y)}$$

$\underline{u}_1$ and $\underline{u}_2$ are directions of jets
p_x^{miss}, p_y^{miss} components of E_T^{miss} vector



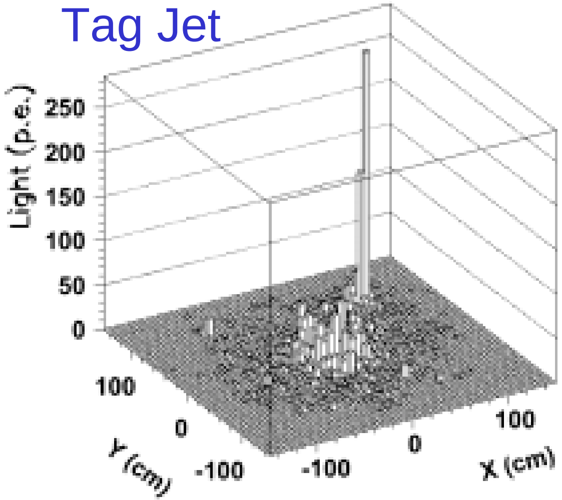
Solve equation if sin$\Delta\phi$ ne 0
i.e. $\tau\tau$ system must be boosted
($\tau\tau$ are not back to back)



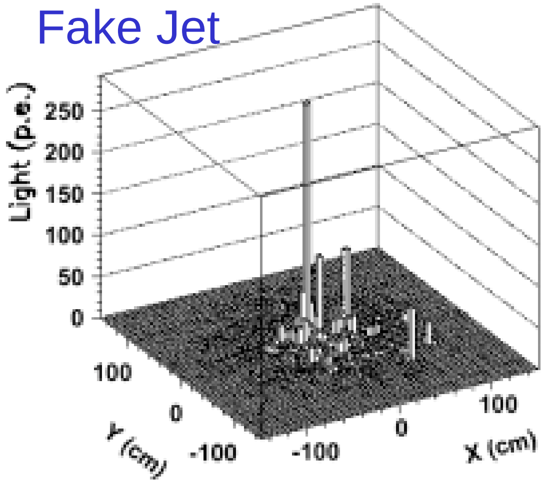


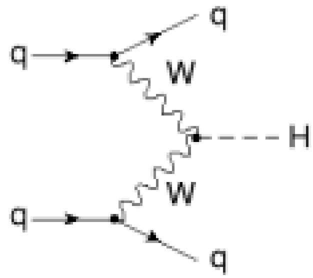
Forward Jet Tagging

Tag Jet

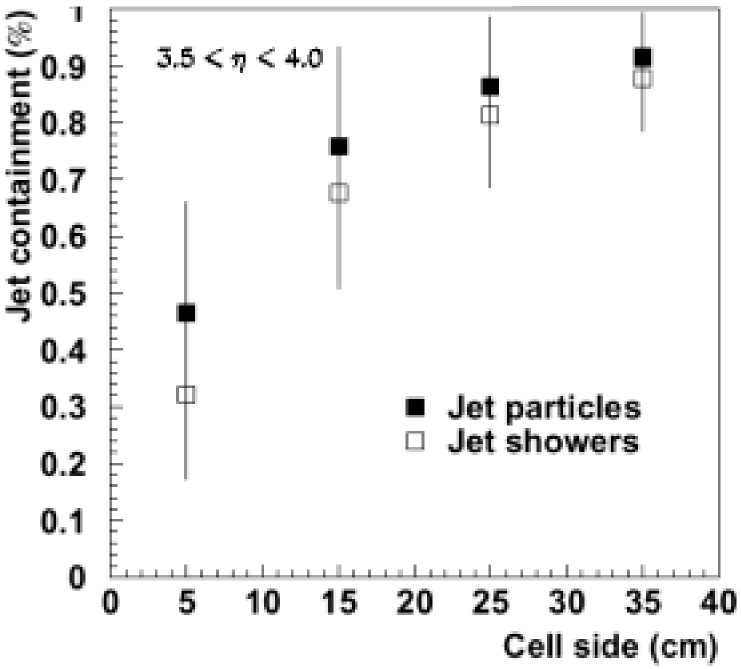


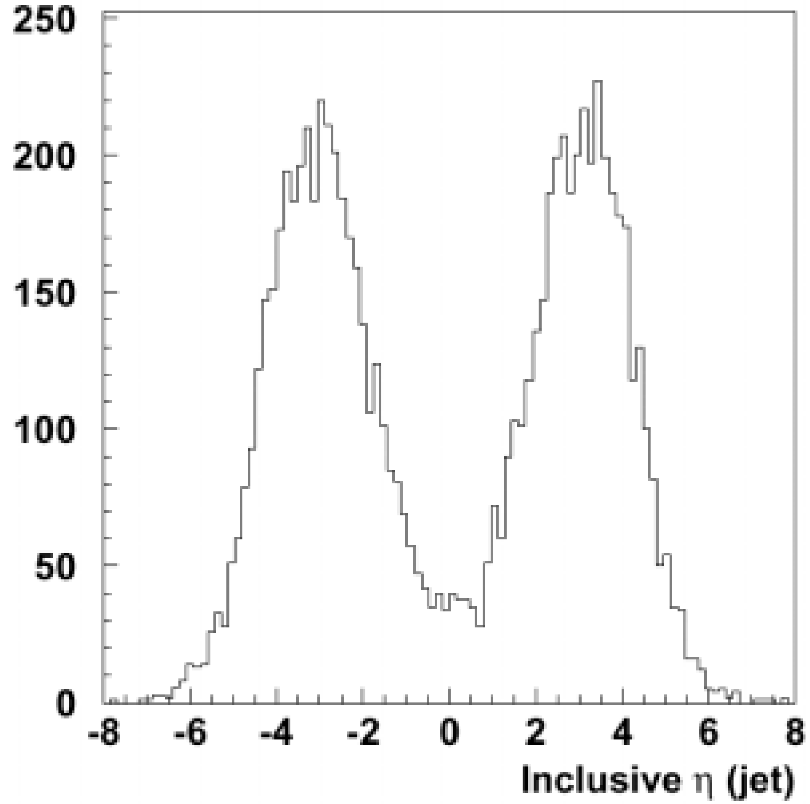
Fake Jet



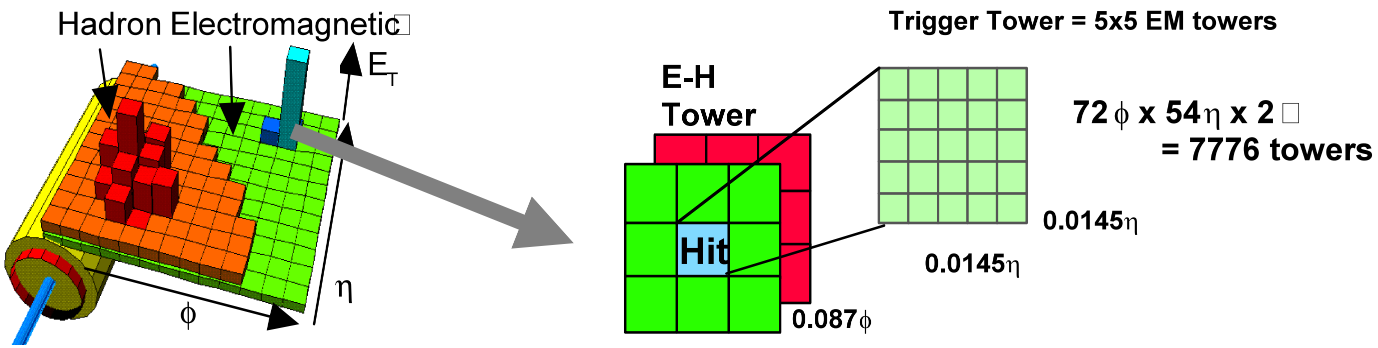


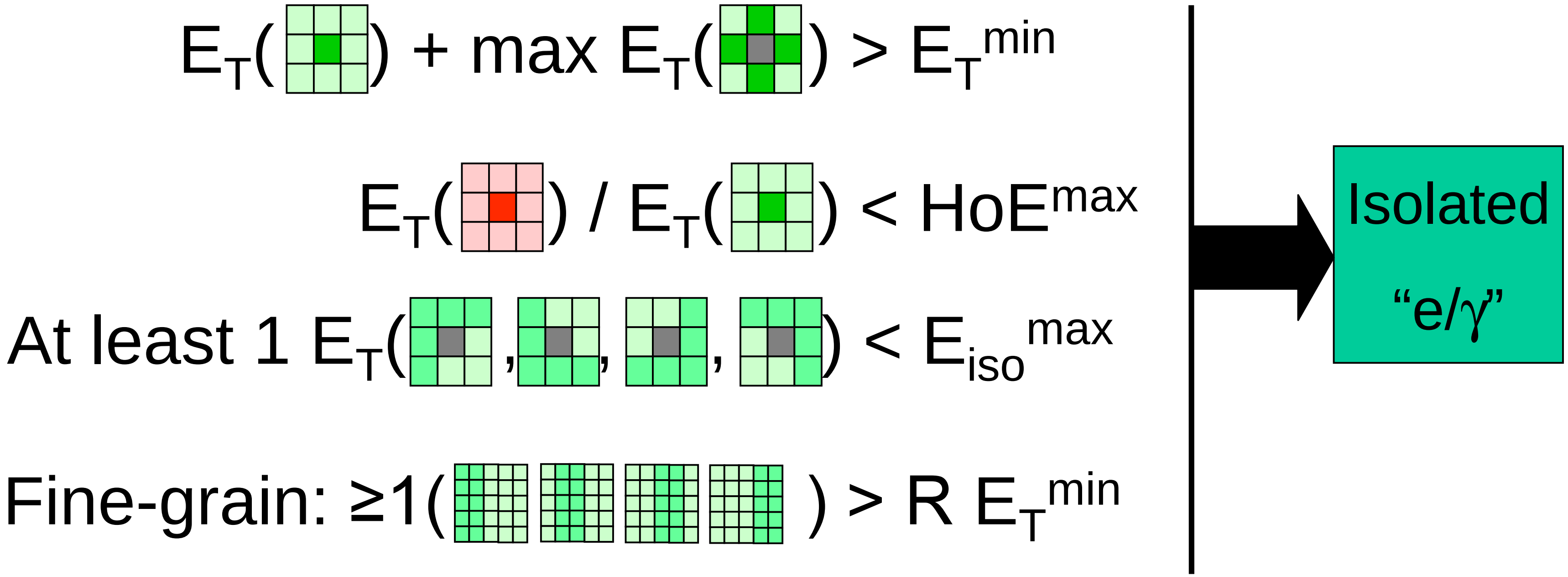
Tagging Jets





Level-1 Isolated Electron Trigger

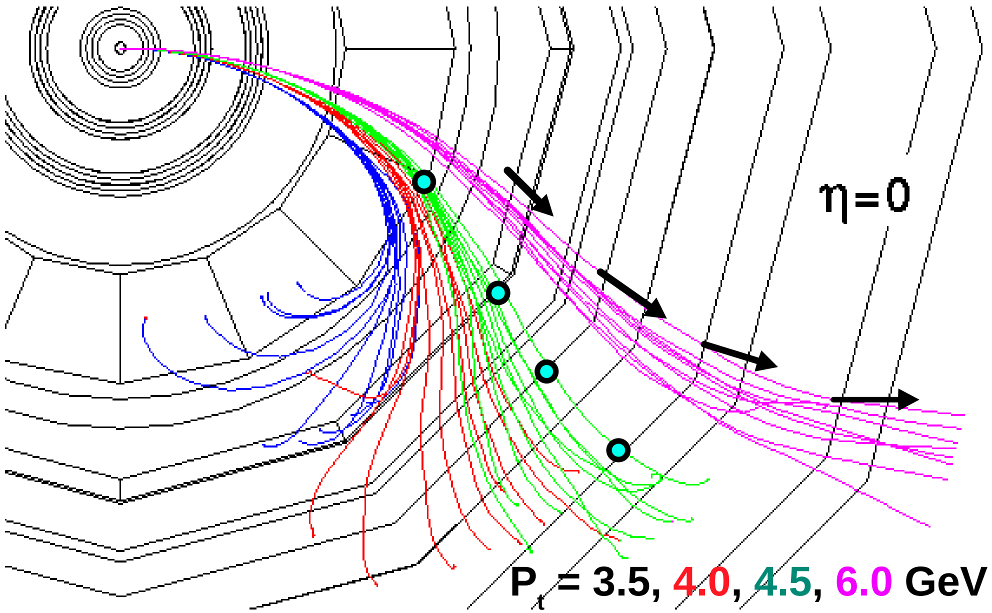




Level-1 Muon Trigger

Trigger based on tracks in external muon detectors that point to interaction region

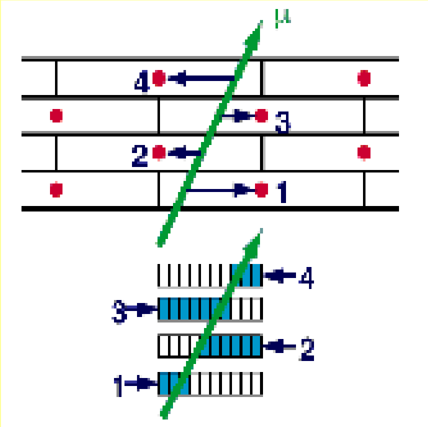
- Low-p_T muon tracks don't point to vertex
  - Multiple scattering
  - Magnetic deflection
- Two detector layers
  - Coincidence in "road"



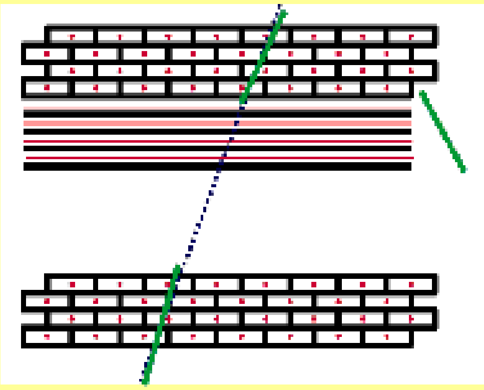
Detectors:
RPC (pattern recognition)
DT(track segment)

Level-1 Muon Trigger

Drift Tubes

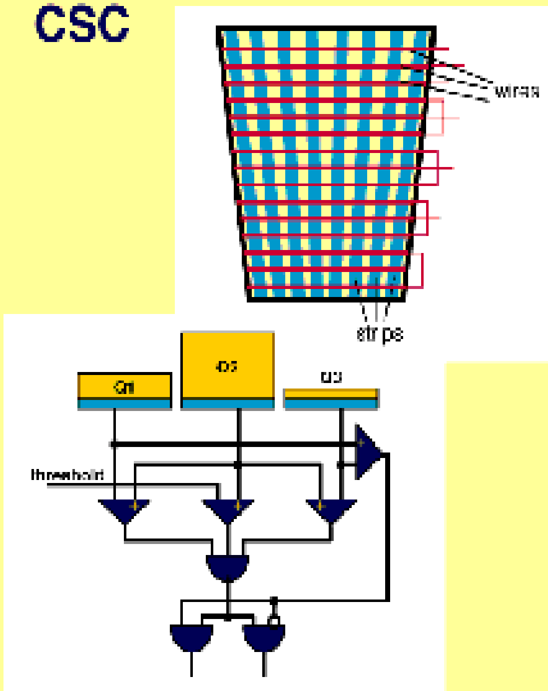


Meantimers recognize tracks and form vector / quartet.

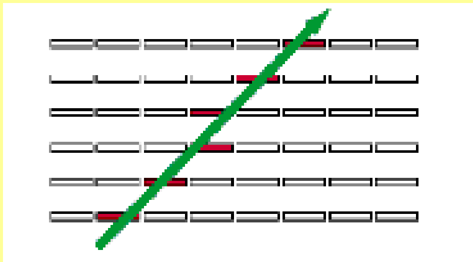


Correlator combines them into one vector / station.

CSC

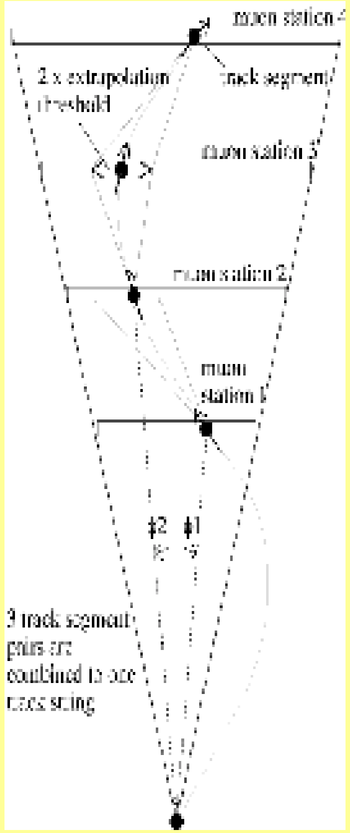


Comparators give 1/2strip resol.



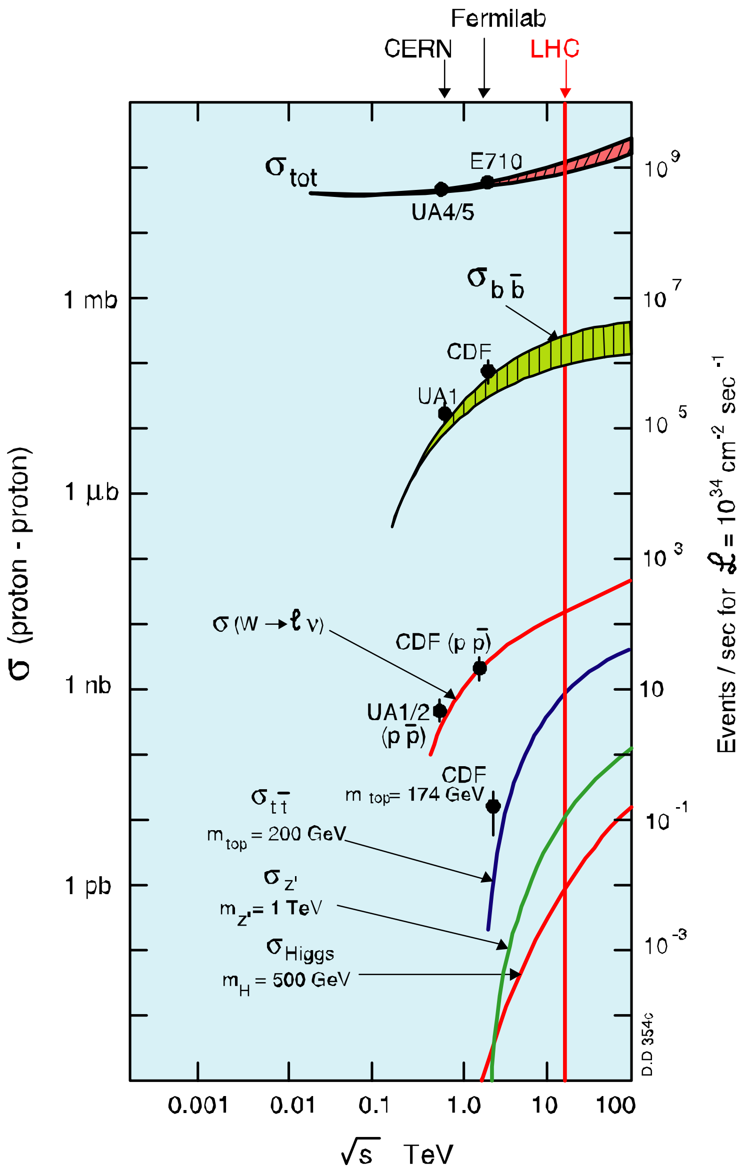
Hit strips of 6 layers form a vector.

Track Finder



combines vectors,
forms a track,
assigns p_t value.

Level-1 Trigger Rates



	e	ee	τ	ττ	j	jj	jjj	jjjj
Low ℒ	24	18	95	75	150	115	95	75
High ℒ	35	20	180	110	285	225	125	105
	τe	je	MET	e+MET	j+MET	e(NI)	ee(NI)	ΣET
Low ℒ	80,14	125,14	275	12,175	65,175	NA*	NA*	1000
High ℒ	125,20	165,20	350	18,250	95,250	58	28	1500
	μ	μμ	μe	μτ	μj	μ+ET	μ+MET	Rate:
Low ℒ	10	3	4,12	4,80	4,80	4,600	4,140	25 kHz
High ℒ	25	8,5	5,32	5,140	5,155	5,800	5,200	25 kHz

75 kHz x 33% safety factor = 25 kHz target for simulated rates
Threshold is defined as either 95% (e/γ, τ, j) & 90% (MET, μ) efficiency

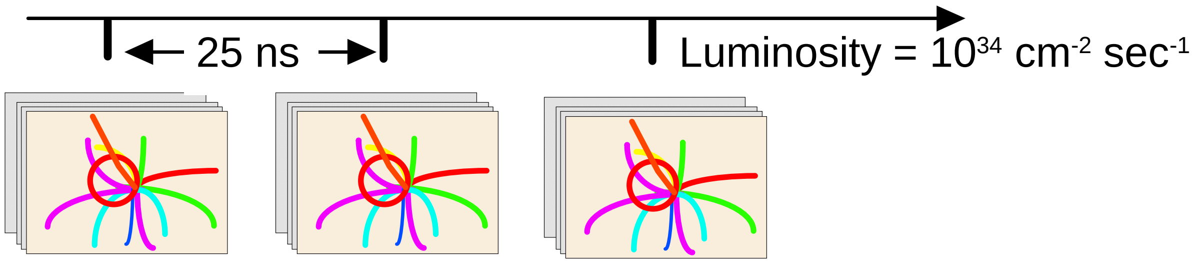
Physics efficiencies

Channel	10^{33}	10^{34}
H(200)→ττ→*hadrons*	0.93	0.60
H(500)→ττ→*hadrons*	0.99	0.86
H(170)→*eeee*	1.00	0.99
H(110)→γγ	0.99	0.98
H(135)→ττ→*e, hadron*	0.96	0.72
H(200)→ττ→*e, hadron*	0.96	0.74
H(120)→*Invisible (tag j)*	0.96	0.58
tt →e, X	0.97	0.82

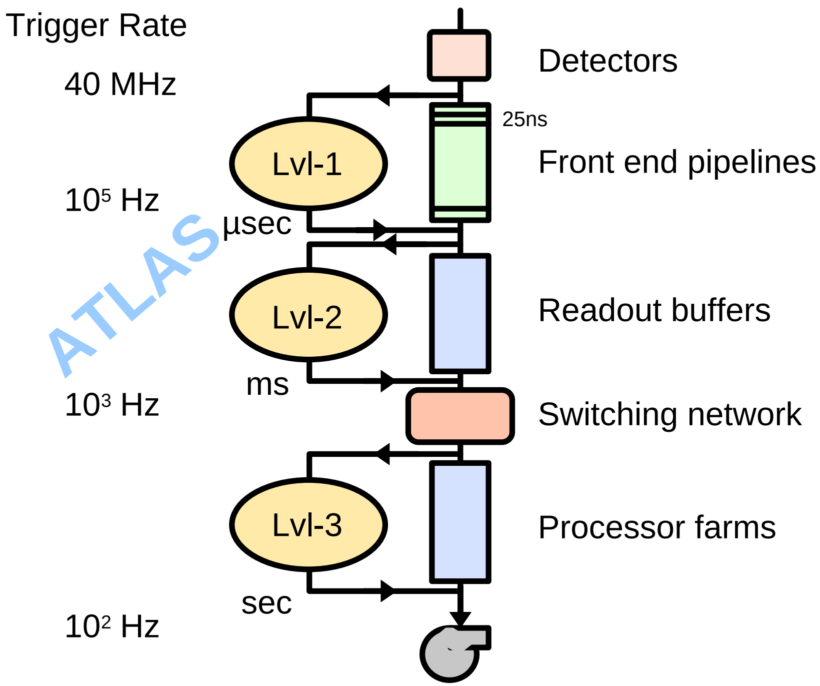
Trigger Architectures

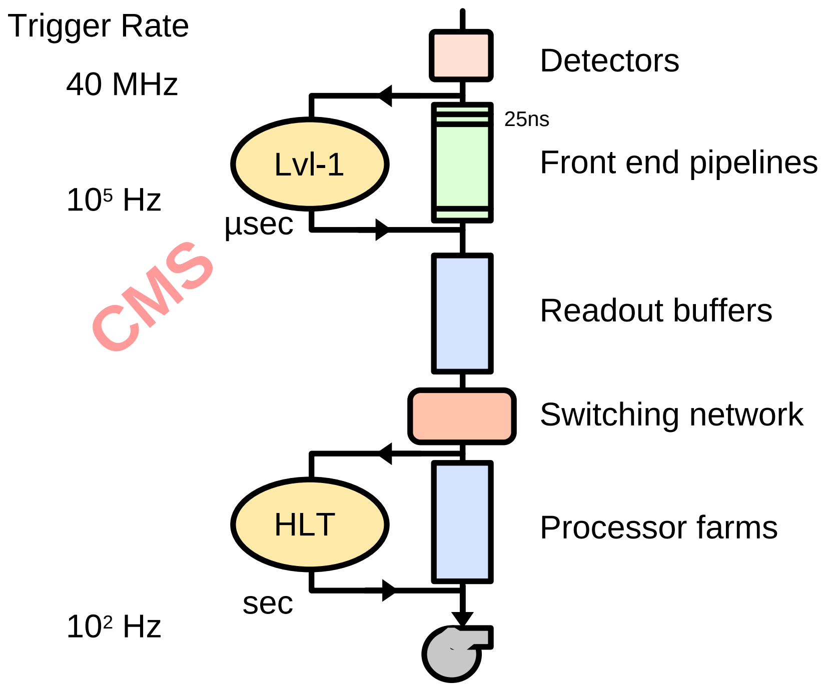
- 30 Collisions/25ns
(10^9 event/sec)

10^7 channels
(10^{16} bit/sec)

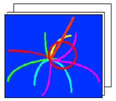


Multilevel trigger and readout systems





Data Acquisition



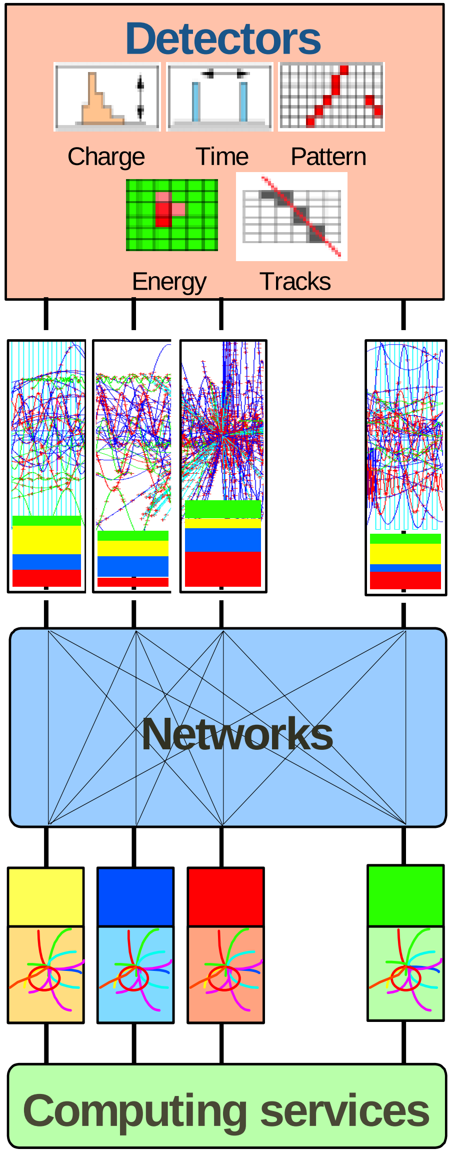
40 MHz
COLLISION RATE

100 kHz
LEVEL-1 TRIGGER

1 Terabit/s
(50000 DATA CHANNELS)

500 Gigabit/s

Gigabit/s SERVICE LAN



16 Million channels
3 Gigacell buffers

1 Megabyte EVENT DATA

200 Gigabyte BUFFERS
500 Readout memories

EVENT BUILDER. A large switching network (512+512 ports) with a total throughput of approximately 500 Gbit/s forms the interconnection between the sources (Readout Dual Port Memory) and the destinations (switch to Farm Interface). The Event Manager collects the status and request of event filters and distributes event building commands (read/clear) to RDPMs

5 TeraIPS

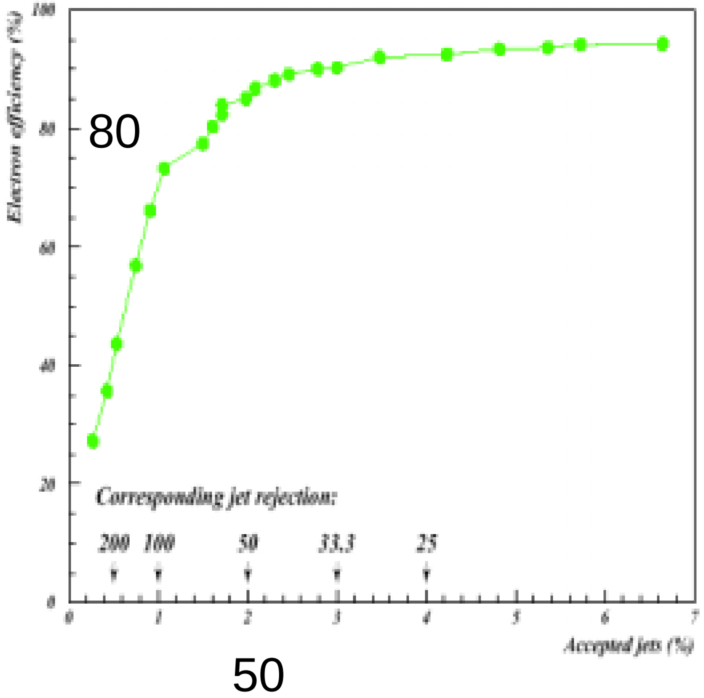
EVENT FILTER. It consists of a set of high performance commercial processors organized into many farms convenient for on-line and off-line applications. The farm architecture is such that a single CPU processes one event

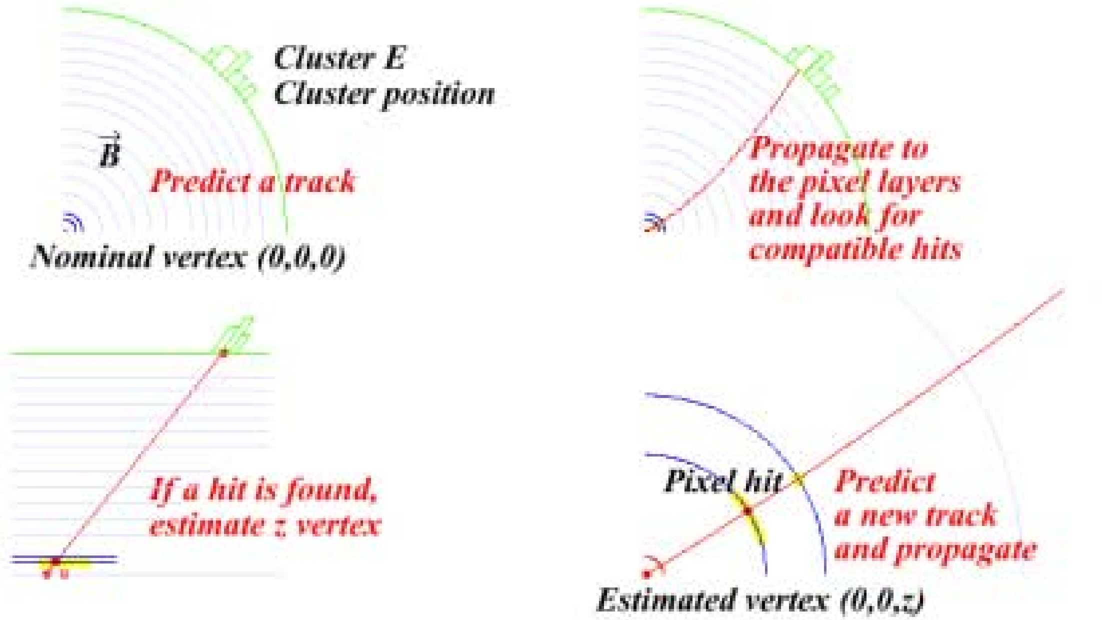
Petabyte ARCHIVE

Higher Level Trigger

- Example: inclusive electron trigger from Lvl-1
  - Step 1: fetch calo (& muon data)
    - Apply Lvl-1 verification; sharper threshold
    - Apply π^0 rejection (based on crystals only)
    - Apply isolation but skip if pixel info can be used immediately
  - Accept (say) 10-20% of the events
    - Draw road inside tracker (this road would contain all hits from the electron track if this is indeed an electron)
    - Fetch all tracker modules that have geometrical boundaries inside the road
  - Find charged particle track
    - From CDF: track gives factor ~50; but factor 5 above, so this is factor 10 now. If event passes, read in rest of the tracker

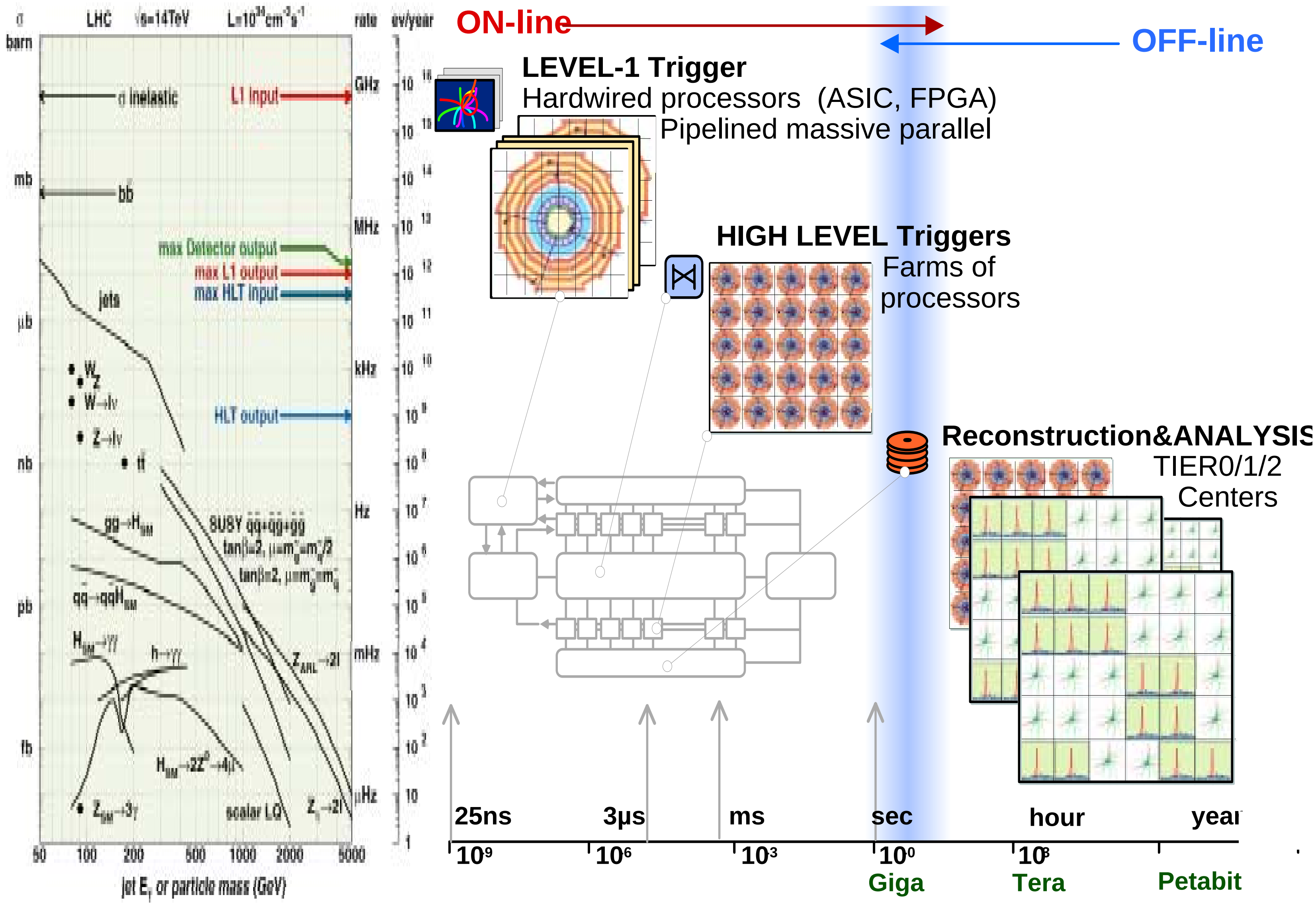
HLT – Electron Trigger





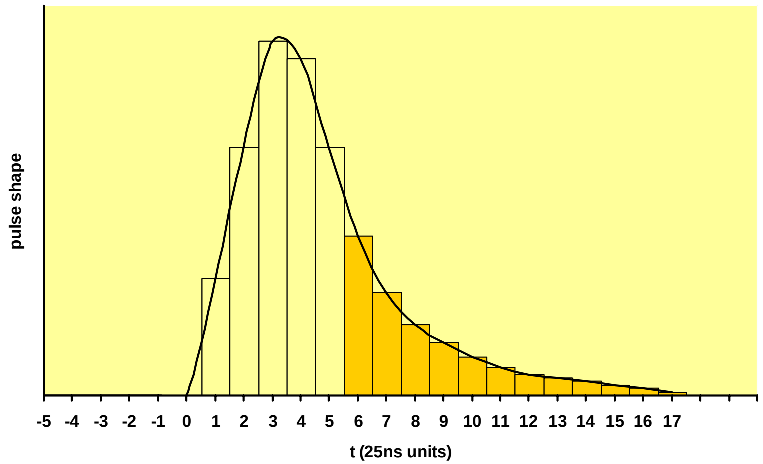
If compatible hits found in two different pixel layers: accept, if not: reject.

Physics Selection at LHC



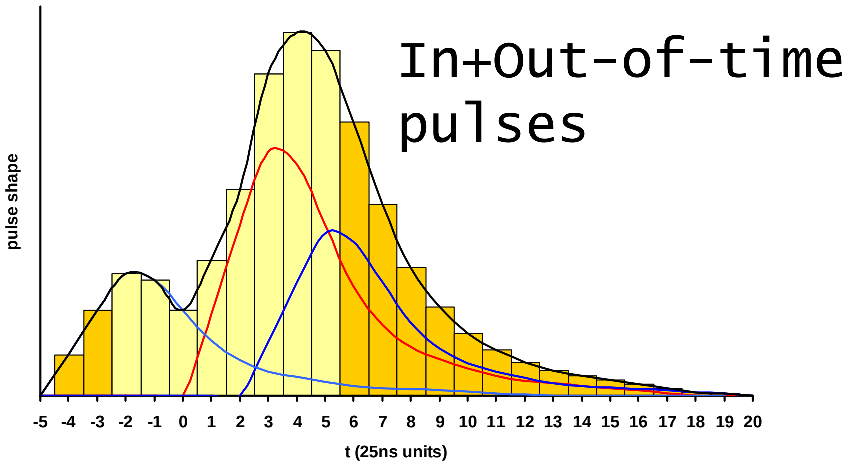
Physics Studies : Simulation

From an in-time pulse to observable at $10^{34} cm^{-2} s^{-1}$



- Trigger evt generated at bx=0, Pile-Up generated from bx=-5 to bx=+3;
- Pulse shape computed every 25ns (time-samples) for each hit;
- Signal processing:
Add samples if several hits in same cell; Pile-Up treated like Trigger evt, i.e. add samples;

- Gaussian, uncorrelated noise injected in each time-sample
  - Energy extracted from 3 pedestal + 5 signal samples(ECAL)
    - Weights chosen for optimal energy resolution;
  - Timing and goodness-of-fit also available



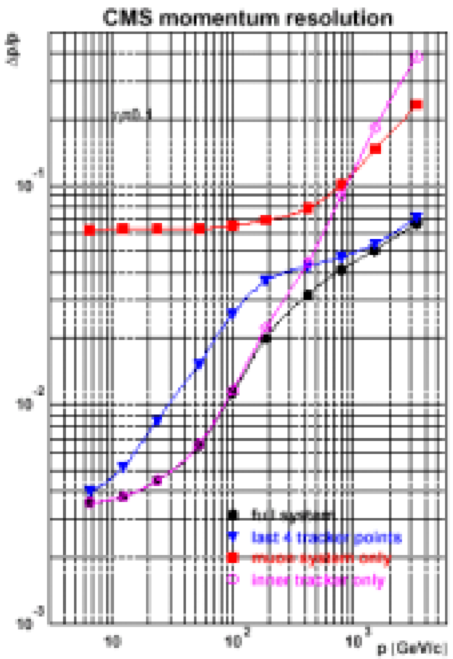
Physics Performance

SOLENOID B = 4 Tesla, R=3m

Radius of tracking cavity = 1.3 m

Muon Momentum Resolution

Spatial resolution
Š 100 µm/station



$\delta p_t/p_t$ - 10%
at p_t=500 GeV at η=2

High Granularity Tracker

Track Finding Efficiency

p_t > 2 GeV, $|\eta|$ < 2.5

isolated µ tracks	98%
isolated $h^{\pm}$ tracks	92%
trks in 300 GeV b-jets	90%

b - tagging

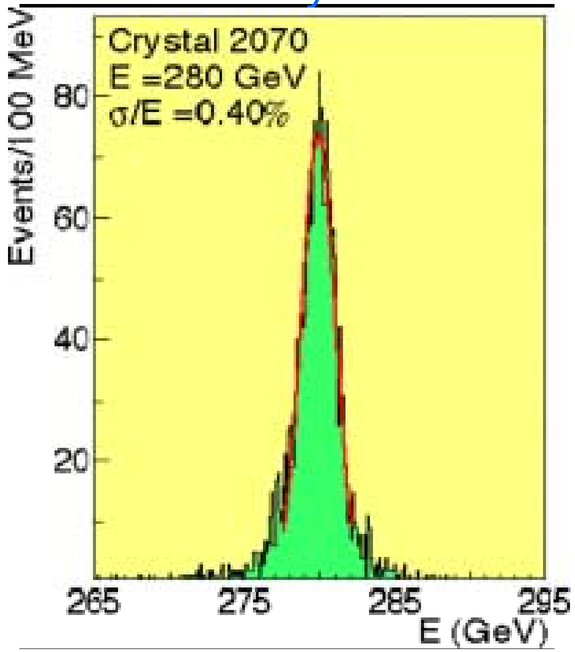
50% efficiency for a rejection factor of 100 against u, d and s jets

Momentum Resolution

$\Delta p_t/p_t$ - $0.15 p_t \oplus 0.5\%$ (p_t in TeV)

$PbWO_4$ CRYSTAL ELECTROMAGNETIC CALORIMETER

Energy reconstructed in 3 x 3 crystals



σ / E - 2.7% / ¦ E $\oplus$ 0.5% $\oplus$ 20%/E
(E in GeV)