Performance of CMS Calorimeter to Hadrons and SUSY Search with Jets+MET

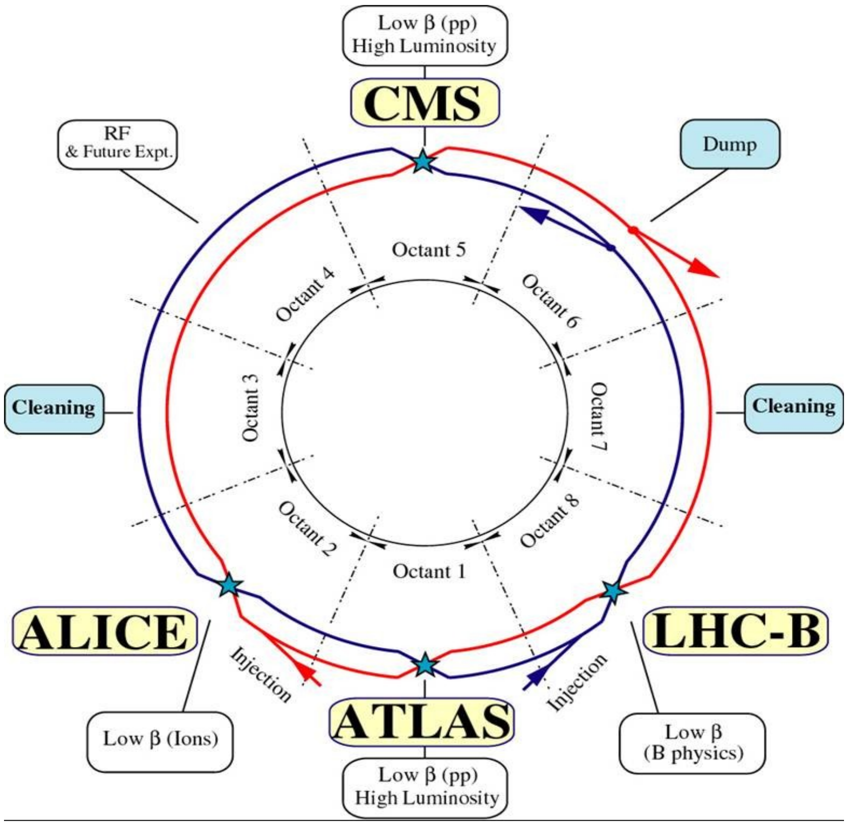
Seema Sharma

July 1, 2008

Outline

- Introduction
  - Large Hadron Collider
  - Compact Muon Solenoid
- Supersymmtery in Jets + Missing E_T
  - SUSY @ LM2 point
  - Final State Topology
  - Rejection of Standard Model Backgrounds
  - Exploring Taus in Final state
- CMS Calorimeter
  - ECAL
  - HCAL
  - Outer Hadron Calorimeter (HO)
- Simulation Validation
  - Test Beam Set-up
  - Energy Measurement
  - Validation of GEANT4
- Summary

Large Hadron Collider



- Goals: To Explore Physics at TeV Scale (Higgs, SUSY ...)
- Collide protons at a Centre of Mass Energy of 14 TeV
- Luminosity : $10^{34} cm^{-2} s^{-1}$
- One bunch crossing every 25 ns

Detectors to be used at LHC

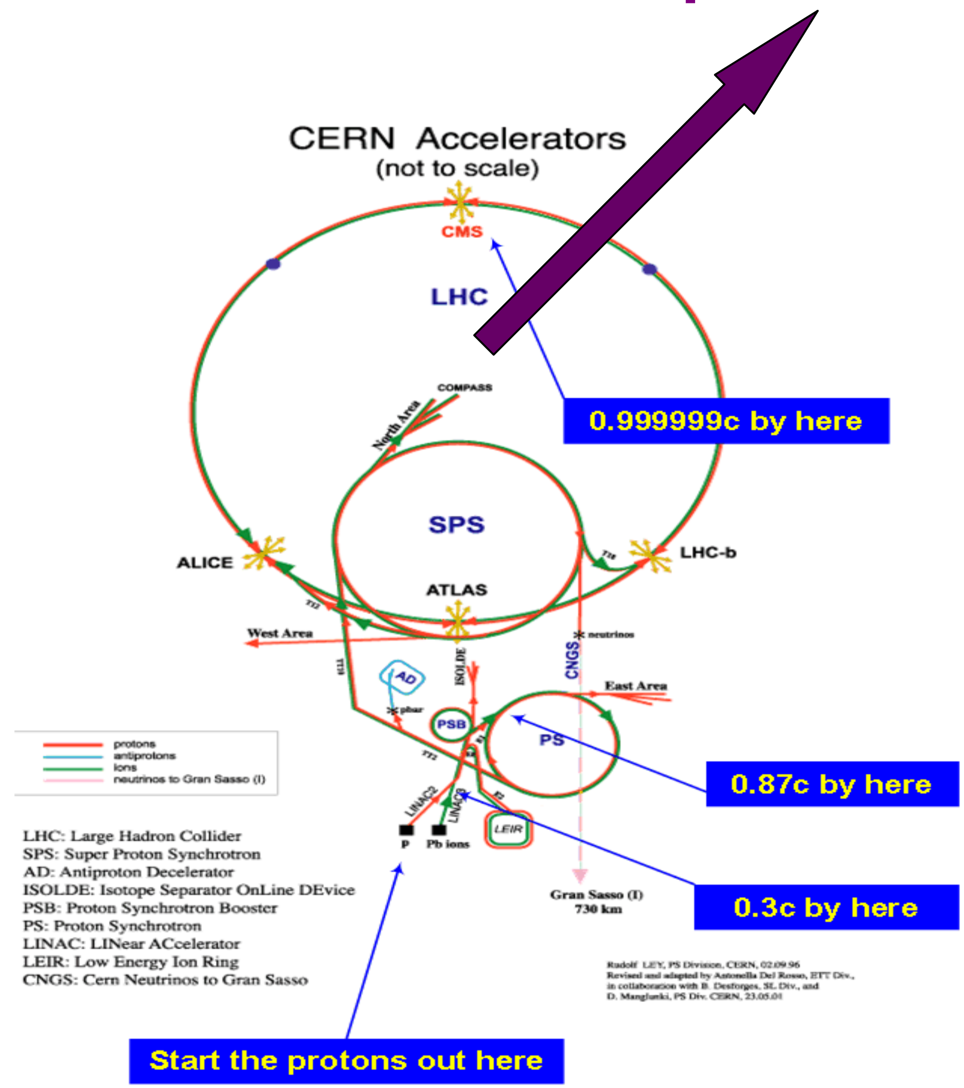
- CMS and ATLAS – General purpose
- LHCb – B physics
- ALICE – Heavy Ion Collisions

A complex environment : Need to understand the detector, test the various components of the system from hardware to the reconstruction software, get the initial energy scales to begin with in start up scenarios and validate the Monte Carlo to describe the known physics

CERN Accelerator Complex

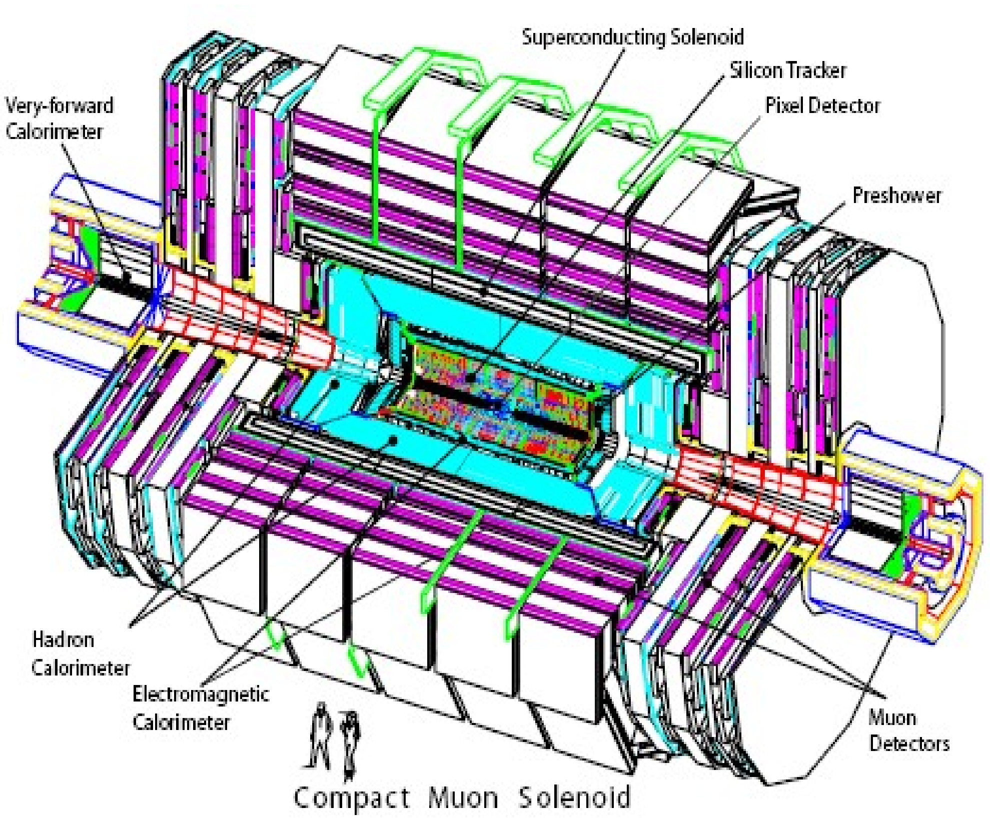
- A Proton Source
- Radio Freq Quadrupole (750 keV)
- LINAC2 (50 MeV)
- PS Booster (1.4 GeV)
- PS (25 GeV)
- SPS (450 GeV)
- LHC (7 TeV)

Beams to test beam experimental areas



Using 400 GeV Protons from SPS, derive secondary beams of hadrons in momentum range 2-300 GeV/c

Compact Muon Solenoid



Design Goals :

Good momentum resolution to muons of momentum up to 1 TeV and an unambiguous determination of their charge....

Efficient tracker to measure the momenta of charged particles, to reconstruct the interaction vertex, b-tagging ....

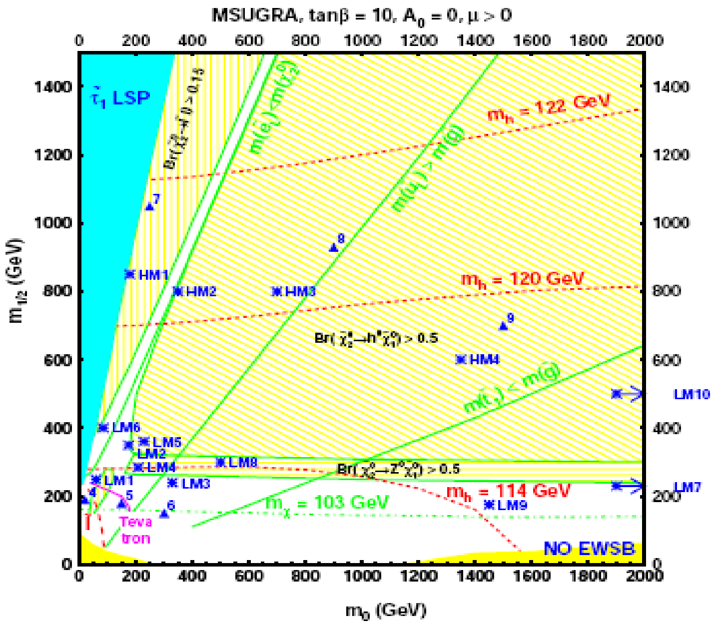
Good diphoton mass resolution, good isolation of electrons and photons ....

Good dijet mass resolution, missing ET measurement....

A solenoidal magnetic field of 4 Tesla is used to measure the momenta of charged particles with an accuracy better than 1% for p_T=100 GeV/c

SUSY@LM2 Point

CMS test points to study SUSY are based on mSUGRA framework



SUSY phase space can be explored in terms of five parameters

- Common Scalar Mass **m_0**
- Common Gaugino Mass **$m_{1/2}$**
- Ratio of Higgs Vaccum Expectation Values **tan(β)**
- Trilinear Couplings **A**
- Parameter **μ**

Mass spectrum of all the particles can be determined using these 5 parameters along with SM couplings

Benchmark Point LM2 : m_0=185 GeV $m_{1/2}$=350 GeV tan(β)=35 A=0 sign(μ)=+ve

(squark masses ~770 GeV, gluino mass 826 GeV, sleptons ~300 GeV)

Lightest SUSY particle (LSP) : $M\chi_1^0$ = 141.48 GeV

Next to Lightest SUSY particle (NLSP) : M(stau) = 156.46 GeV

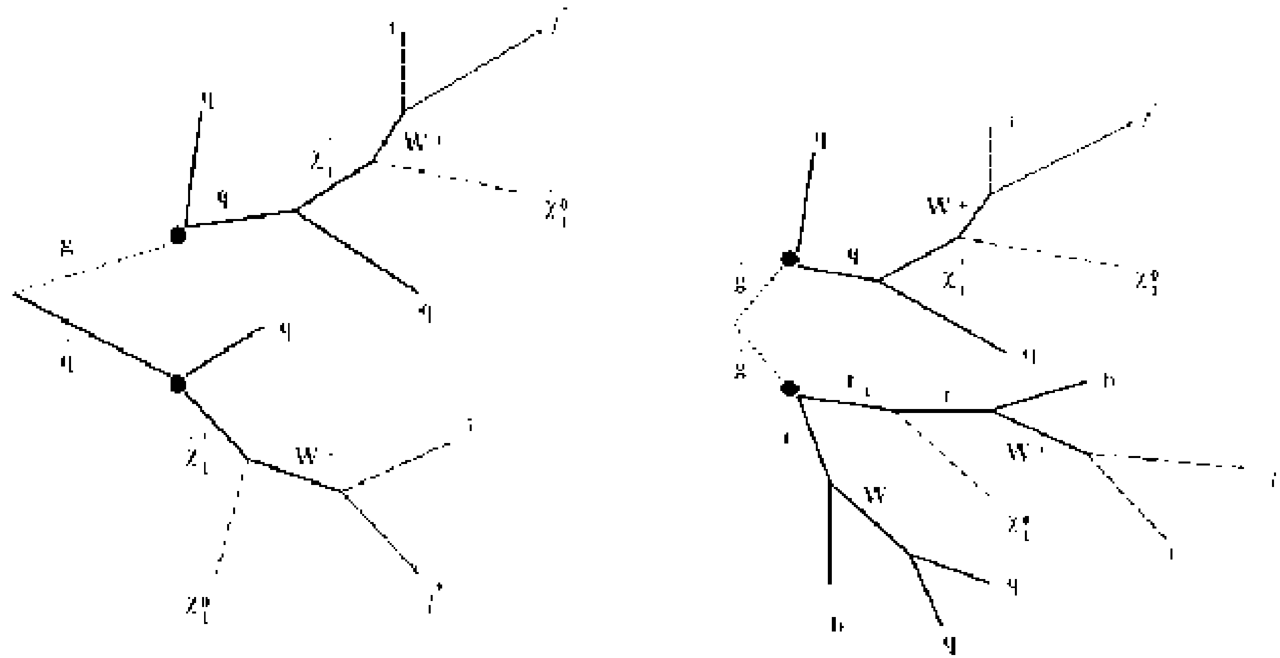
BR(χ_2^0 -> stau + tau) = 96%

BR(χ_1^+ -> stau + ν_τ) = 95%

Cross-section – 7.2 pb

Final State Topology

squarks and gluinos decay and create a cascade of particles



Initial kinematic requirements to select events

At least 3 Jets with $p_T > 30.0$ GeV

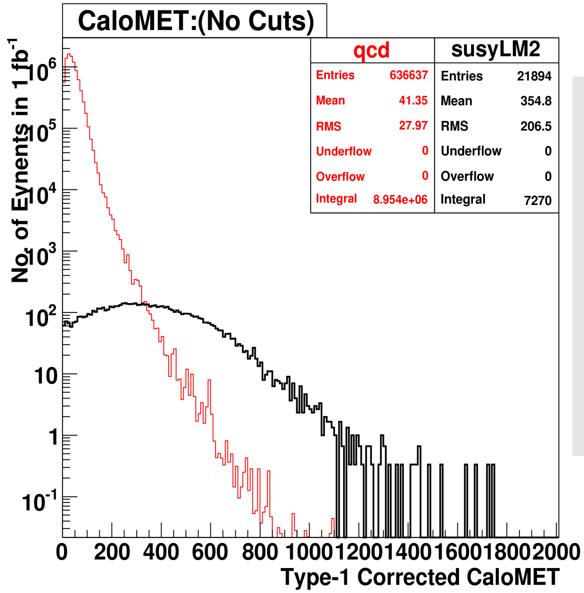
Leading Jet $p_T > 100$ GeV

Leading Jet should be with $|\eta| < 1.3$

Missing Transverse Energy > 200 GeV

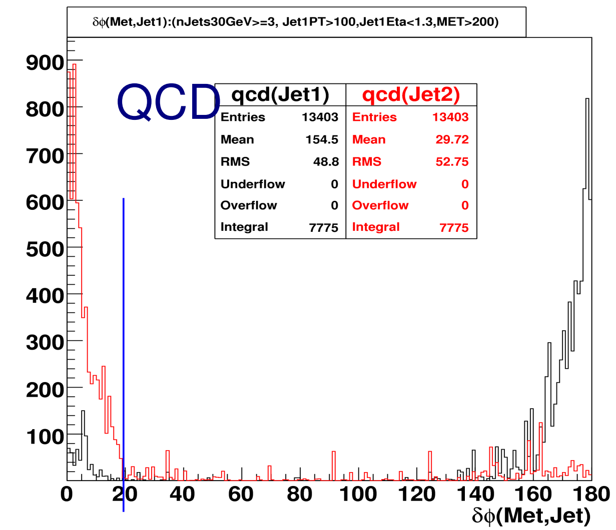
~60% of SUSY events survive these preselection cuts

Rejection of QCD Background



MET due to mis-measurement of Jets (resolution of the detector) is usually aligned to the first or second leading Jet

Use δΦ(MET, 2nd Jet) > 20

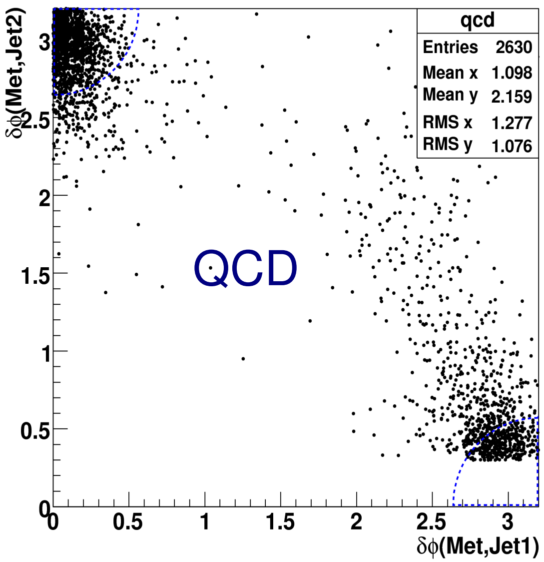


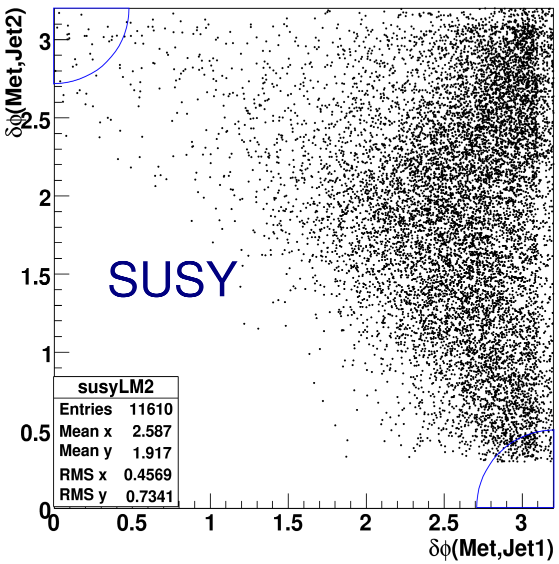
Define angular variables

$$R_1 = \sqrt{\delta\phi_1^2 + (\pi - \delta\phi_2)^2}$$

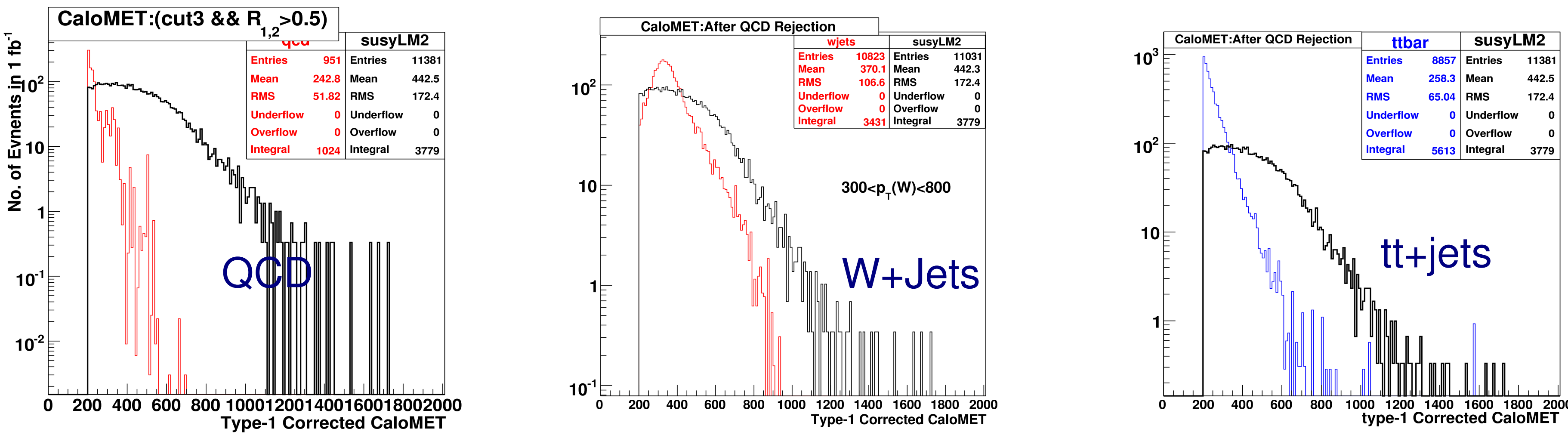
$$R_2 = \sqrt{\delta\phi_2^2 + (\pi - \delta\phi_1)^2}$$

Require $R_{1,2} > 0.5$ to reject QCD





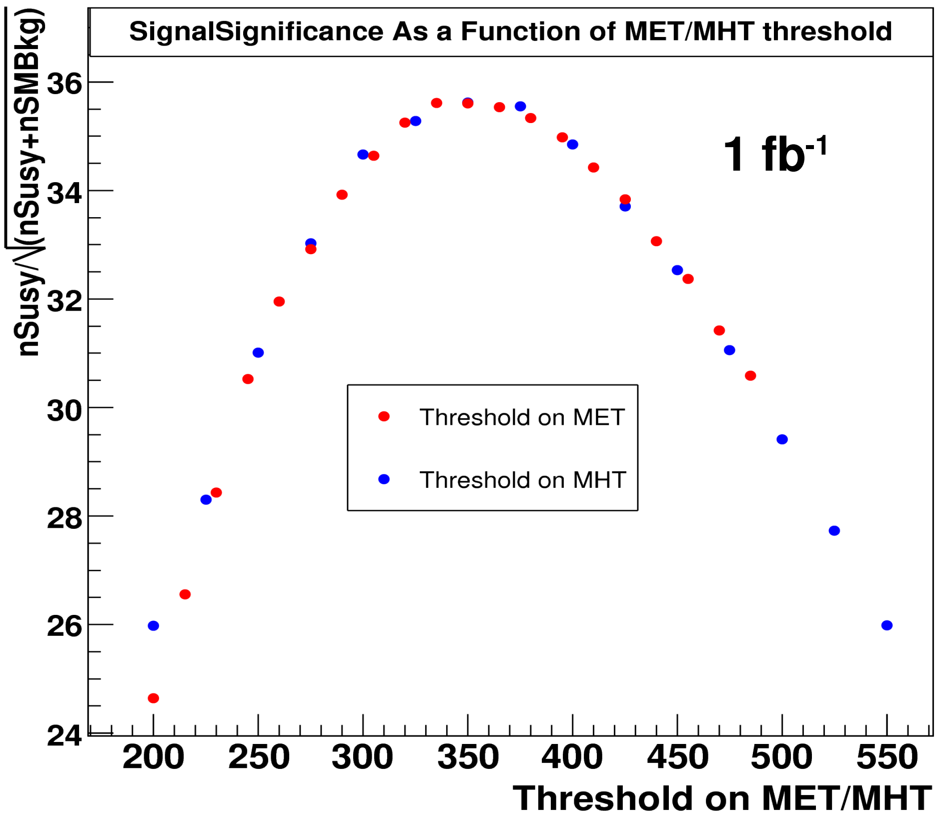
Standard Model Backgrounds



Dataset	No. of Events After QCD Rejection
QCD (300-380 to 1800-2200GeV)	1212
ttbar+N Jets (N=0, 1,2,3,4)	5613
W+NJets (N=1 to 5) (0< $P_T(W)$ <300) (300< $P_T(W)$ <800)	7995 3423
Z+NJets (N=1 to 5),(0< $P_T(Z)$ <300)	631
WW(Inclusive)	250
WZ(Inclusive)	149
ZZ(Inclusive)	52
susyLM2	3779

Signal Significance

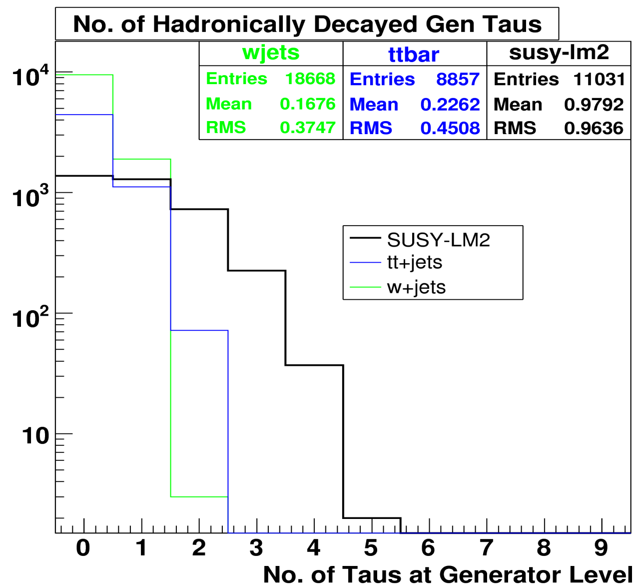
Define Signal Significance as $\frac{Signal}{\sqrt{(Signal+Background)}}$



SUSY as low mass points can be observed with a signal significance above 30 with a threshold on MET or MHT of 350 GeV in 1 fb^{-1} data

(MHT is defined at the total transverse momentum calculated from the vector sum of all jets with p_T>15 GeV)

Taus in Final State

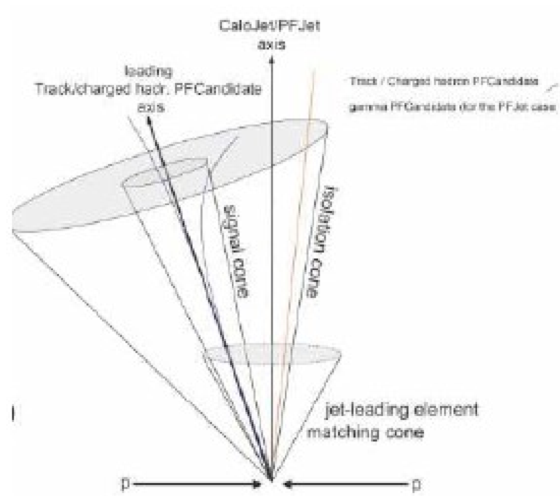


An access of taus is expected in SUSY final states at LM2 benchmark point (generator level)

Identification of Taus

➔ Tracker isolation

- leading track (PT>5 GeV) around jet axis
- signal cone size 0.07<5.0/ET<0.15
- no tracks in(>1.0 GeV) in isolation annulus



➔ Calorimeter isolation

- no photon candidate(>1.0 GeV) in isolation cone
- leading charged hadron candidate > 5.0 GeV
- no charged hadron candidate (>1.0 GeV) in isolation cone of 0.5

Taus in Final State

Preliminary

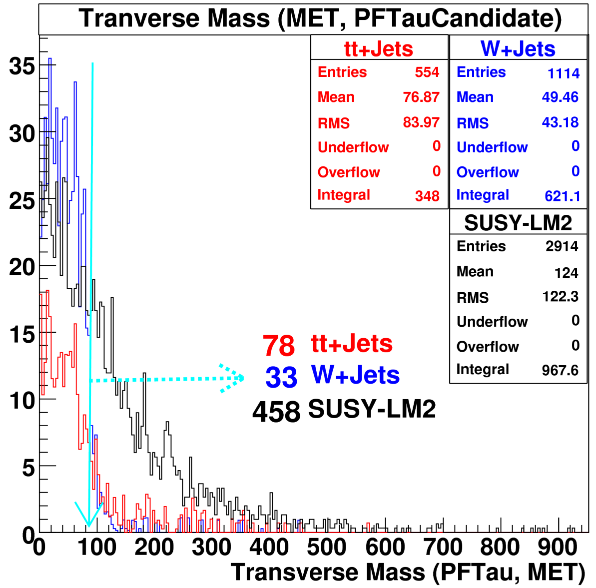
How to reject W and Top ??

MET tends be aligned to one of the leptons in case of leptonic decays of W

The correlation is expected to be weaker in SUSY

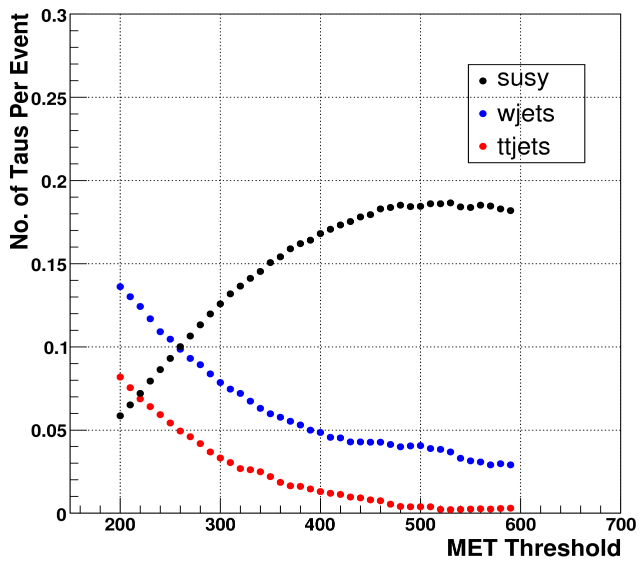
Use Transverse Mass of MET and leading Tau

$$\mathrm{MT}(\tau, \mathrm{MET}) = \sqrt{2. * \mathrm{E}_{\mathrm{T}}^{\tau} * \mathrm{MET} * (1 - \cos(\delta\phi))}$$

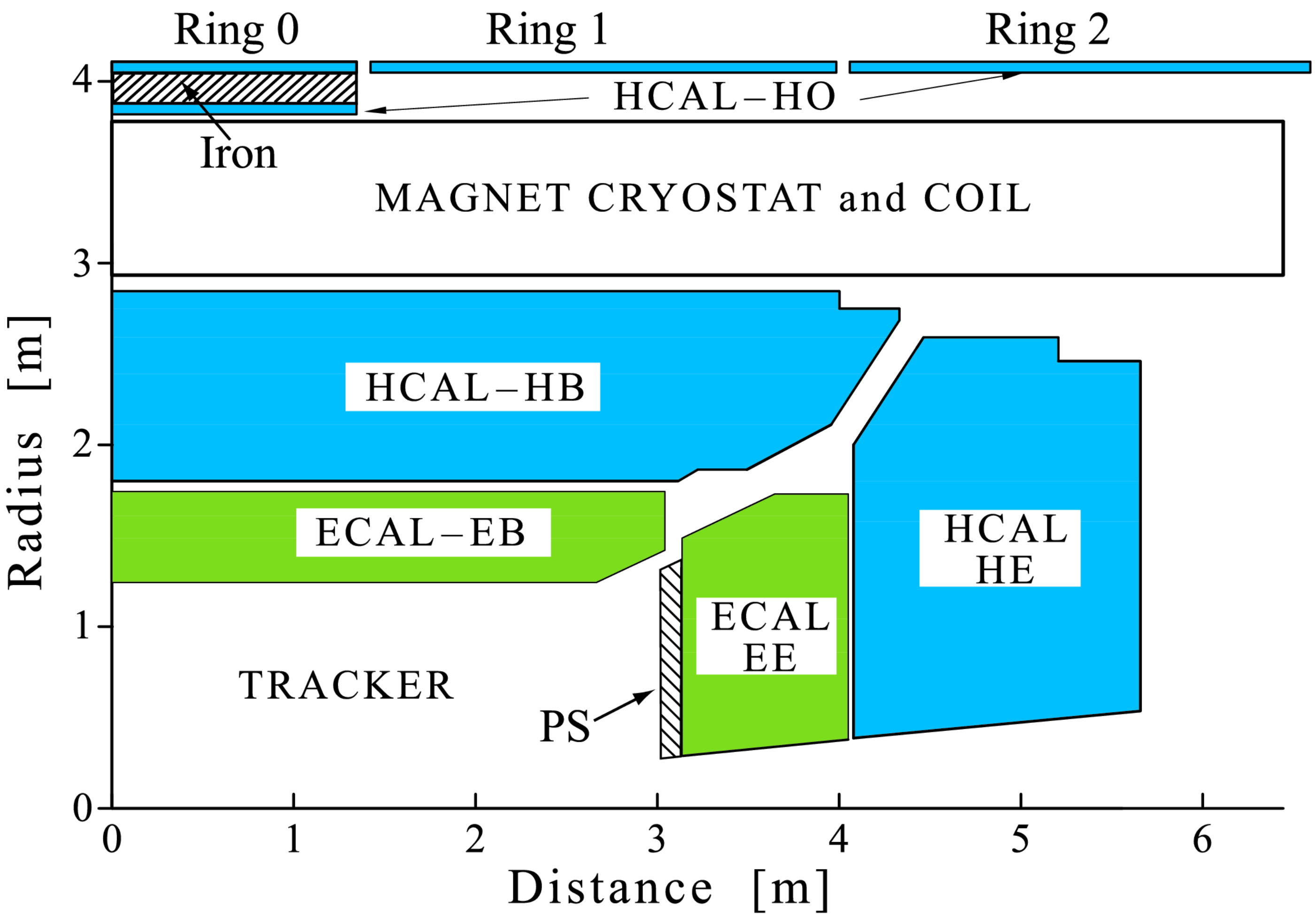


Number of τ per event

Excess of τ's over other leptons in this sample will be a clear indication of BSM physics

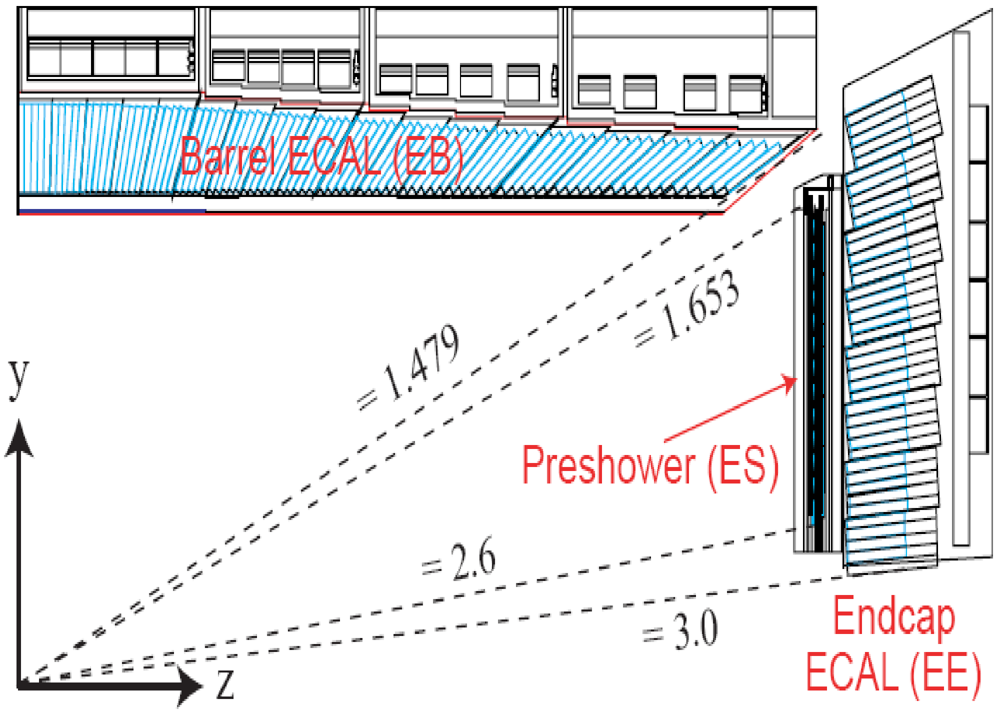


CMS Calorimeter System



Electromagnetic Calorimeter

CMS ECAL is a homogeneous calorimeter made of Lead Tungstate



Material Properties of Lead Tungstate

Radiation Length – 0.89 cm

Moliere radius – 2.2 cm

Dimensions of ECAL crystals

Length – 23 cm long

Front face – 2.2 cm X 2.2 cm

Material Budget

Radiation length : 25.8

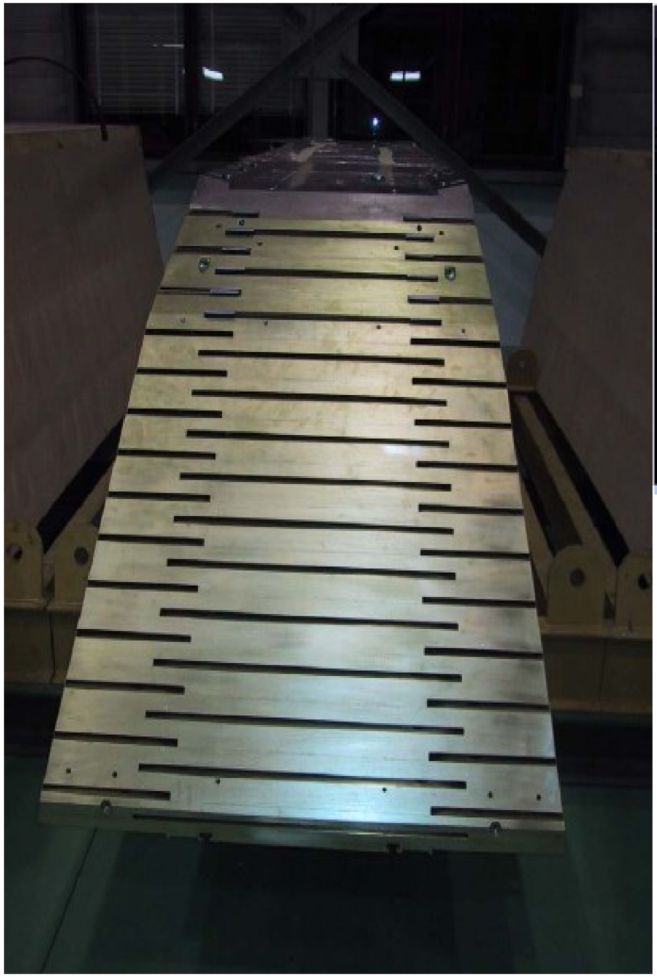
Nuclear Interaction Length : 1.1

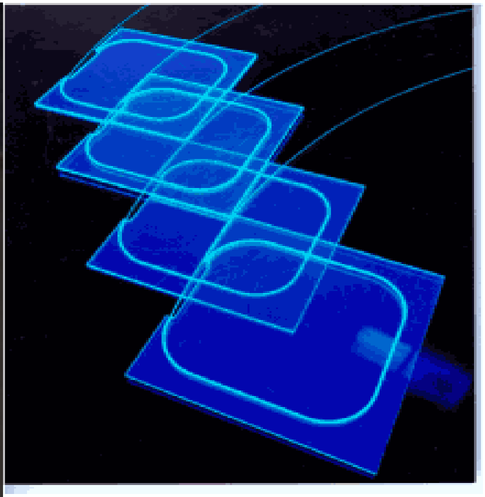
Granularity

$\Delta\eta \times \Delta\Phi = 0.0175 \times 0.0175$

Every crystal is equipped with an Avalanche Photo Diode at the rear end to convert the optical signal to electronic signal

Hadron Calorimeter





- Brass layers 50-56 mm thick
- 17 scintillator layers (3.7 mm) (layer 0&16 are 8.0 mm)
- Each tile is equipped with a WLS fibre to collect scintillation photons produced on the passage of a particle

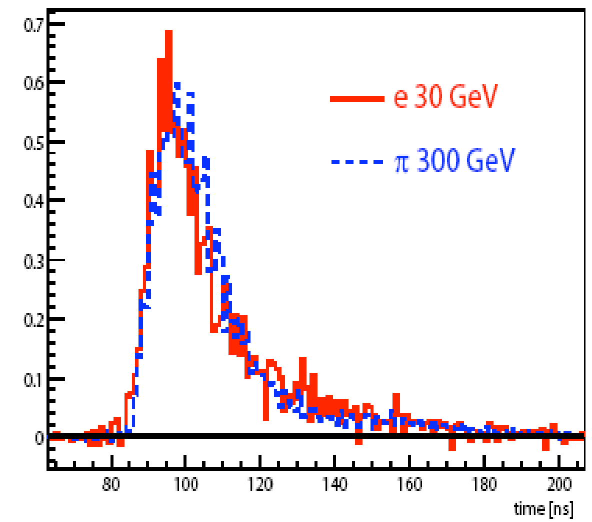
Sampling fraction ~1%

- Each wedge covers up to $|\eta|=1.3$
- EndCaps extend the coverage of HCAL to $|\eta|=3.0$
- Thickness : 5.8 λ_I at $\eta = 0$
- Transverse granularity $\Delta\eta \times \Delta\Phi = 0.087 \times 0.087$

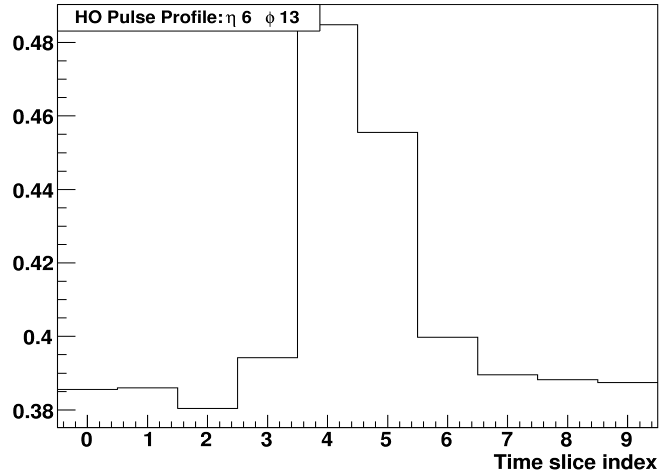
The optical signal collected using the fibres is converted to electronic signal using Hybrid Photodiodes

Digitization of signal

The analog signal obtained from the HPDs is spread over nearly 100 ns



The signal is digitized using an analog-to-digital converter Charge(Q) Integrator(I) and Encoder(E) in the bins of 25 ns



More than 90% of the signal is usually contained in the sum of two time slices

Charge contained in four time slices is used in the test beam data analysis

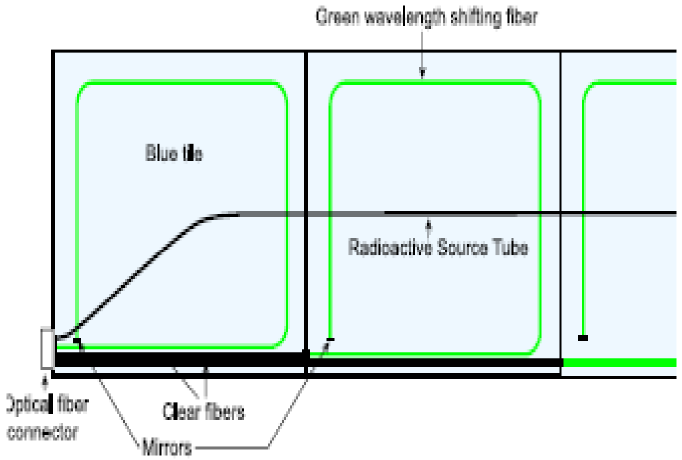
Calibration of HCAL Channels

The variation in signal produced can come from the tile-to-tile variation in the amount of scintillation light produced, the light transported by WLS fibres, number of photo-electrons produced at HPDs ...

- ***ADC to Charge***
- ***Inter-calibration of channels using Radioactive Source***
- ***Determination of absolute energy scale***

Wire Source Calibration

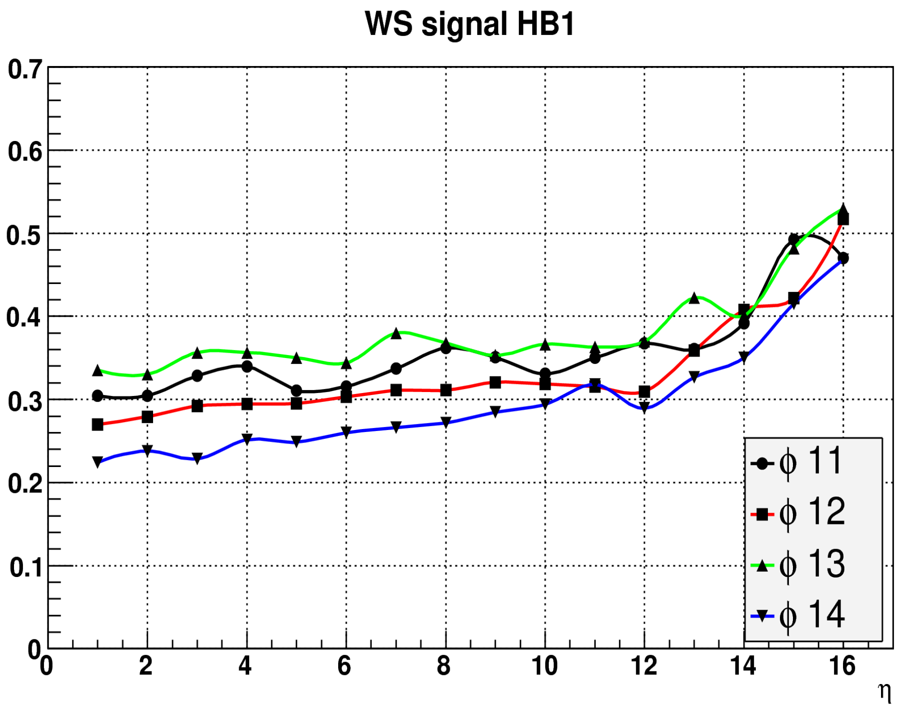
- Every mega tile of HB/HO/HE is equipped with a stainless steel tube running along its length at a constant φ



- A radioactive point source (Co-60) mounted on the tip of a flexible wire is driven through this tube by an electric motor and the data is recorded simultaneously for all the tiles of tray
- The QIE is operated in high gain mode (1/3 fC/ADC count)
- The digitization is performed at the rate of 40 MHz
- The source moves at typical speed of 10cm/s which means nearly 400 measurements are recorded by the time the source moves by 1mm

Calibration of HB Towers

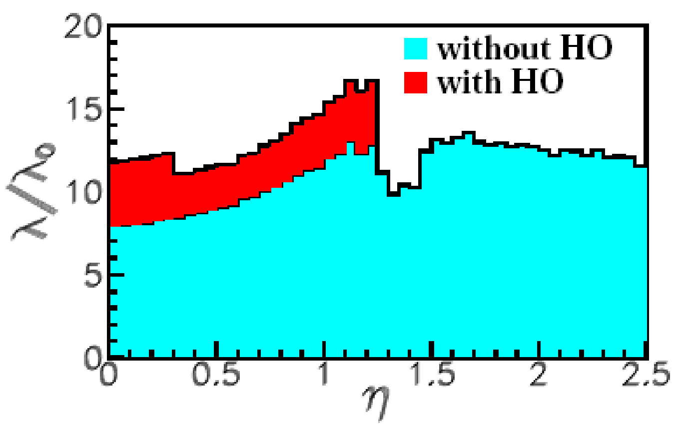
- Each scintillator tile is calibrated using wire source
- The gain for a readout channel is formed by taking an average of measurements of the layers in the tower
- Uniform inter-calibration of channels is obtained by correcting the effects of the light attenuation in the optical fibres and HPDs



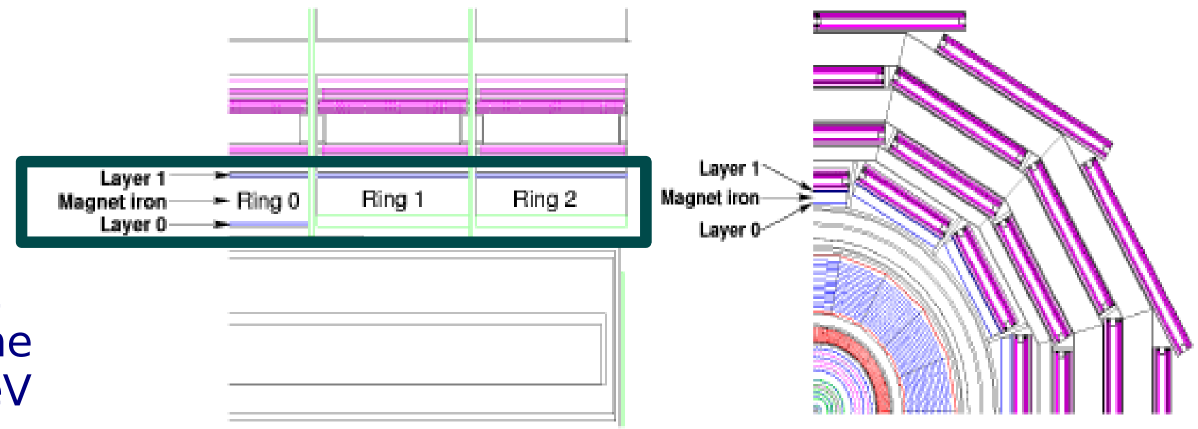
Using these relative calibrations, the HCAL is calibrated to 50 GeV pions such that the average signal deposited by 50 GeV pion beam corresponds to 50 GeV

Outer Hadron Calorimeter

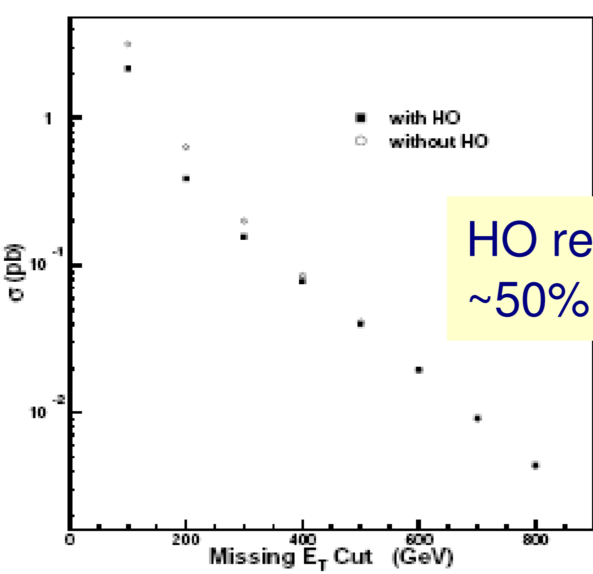
Thickness of HCAL in terms of interaction lengths



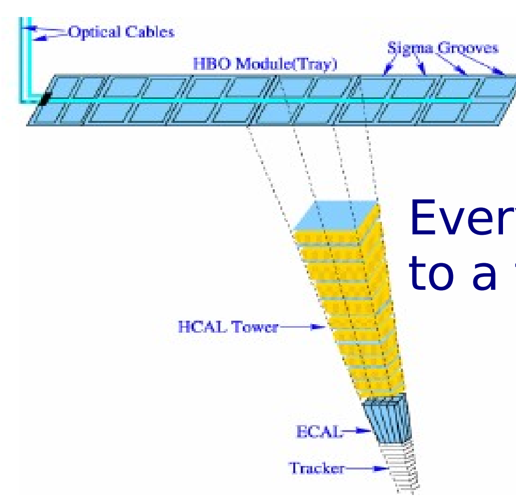
One(two) layer of scintillators are installed in region |η|<1.3(0.35) just outside the magnet coil which provides an additional thickness of 1.5 λ



7-8 Interaction Lengths at η=0 with HCAL alone and is insufficient to fully contain the shower generated by pions above 100 GeV



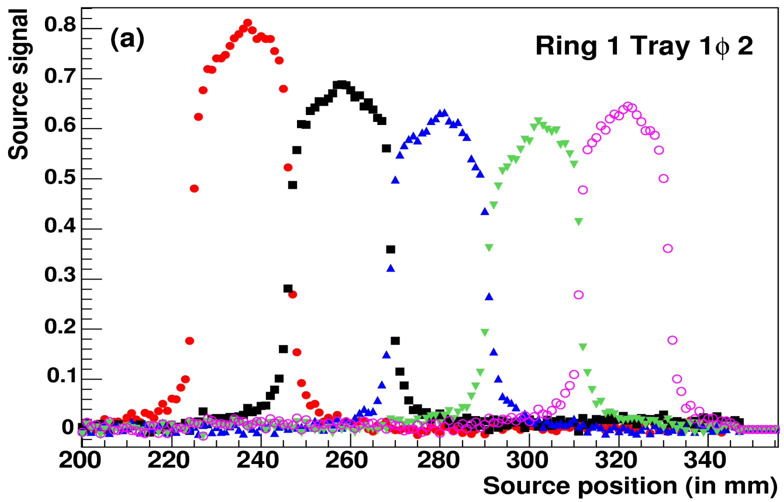
HO reduces QCD BG by ~50% for moderate MET



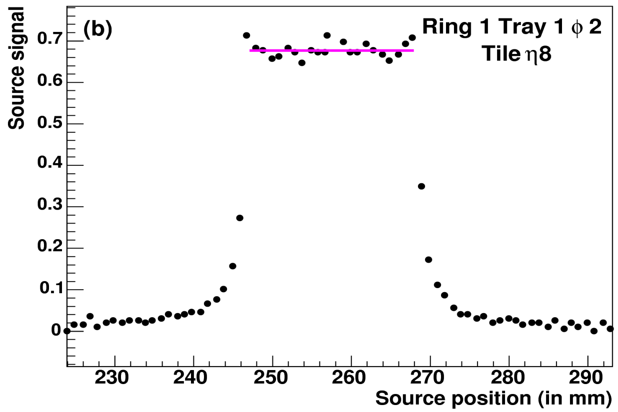
Every tile is mapped to a tower of HB

Source Signal in HO

- As the source approaches a tile, there is an upward shift in the signal



There is a leakage of the signal to the neighbouring tiles when source is at the edge of the tile

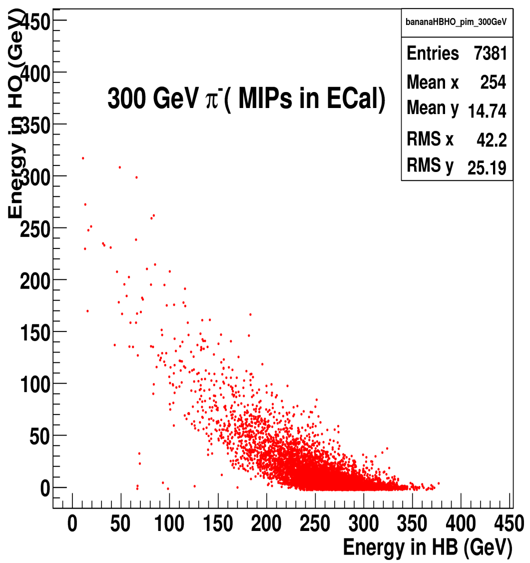


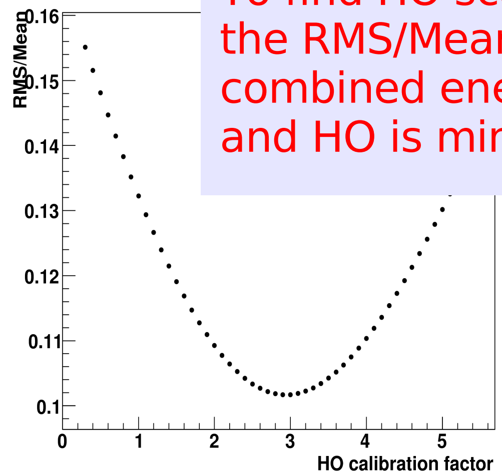
Add the signal from neighbouring tiles with a proper weight to get the total signal
and fit with a straight line
Iterate the procedure till stable weight factors are obtained

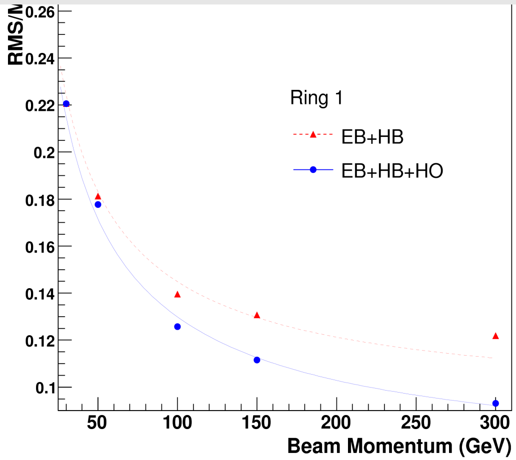
Pion Signal in HO

$\sigma/E = 1.12E^{-1/2} + .0917(0.066)$

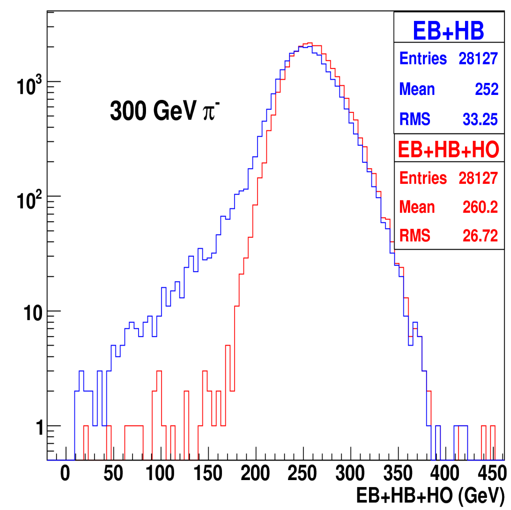
To find HO scale factor, the RMS/Mean of combined energies of HB and HO is minimized

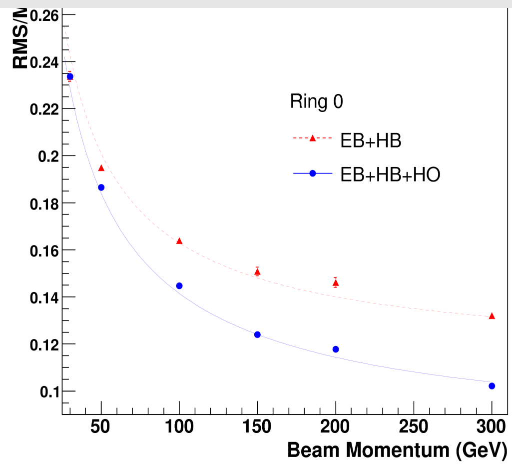






$\sigma/E = 1.17E^{-1/2} + 0.112(0.079)$

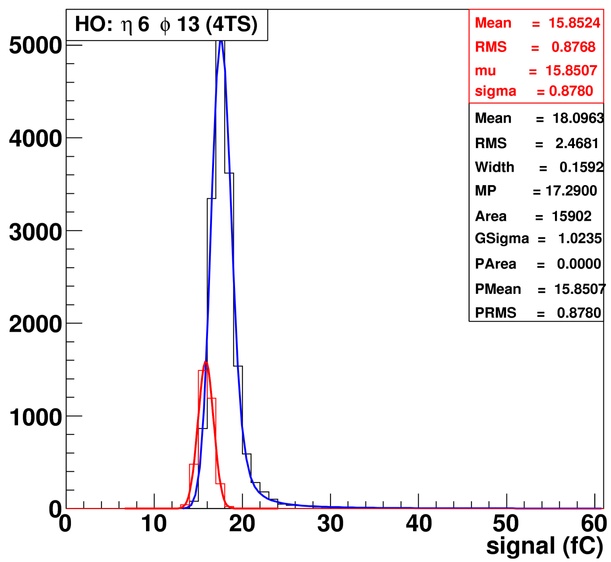




Energy leakage is captured by HO and low energy tails are removed

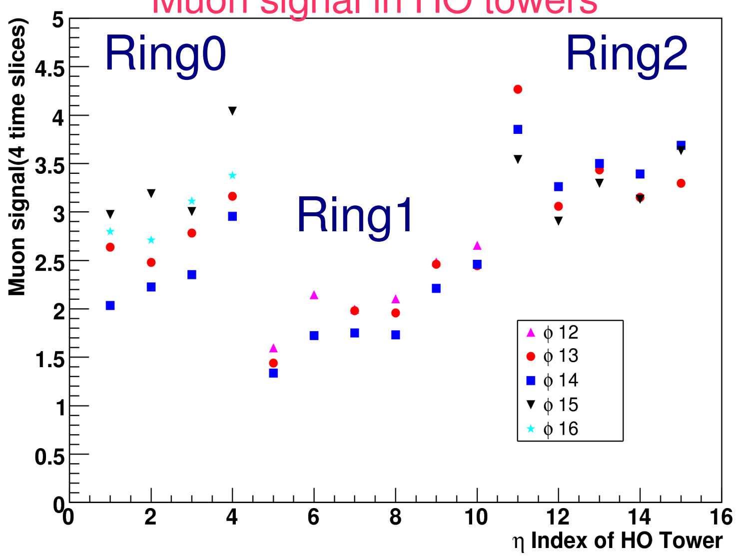
Including HO in the energy measurement improve the resolution by 3-4% both in Ring 0 and Ring 1

Muon Signal in HO

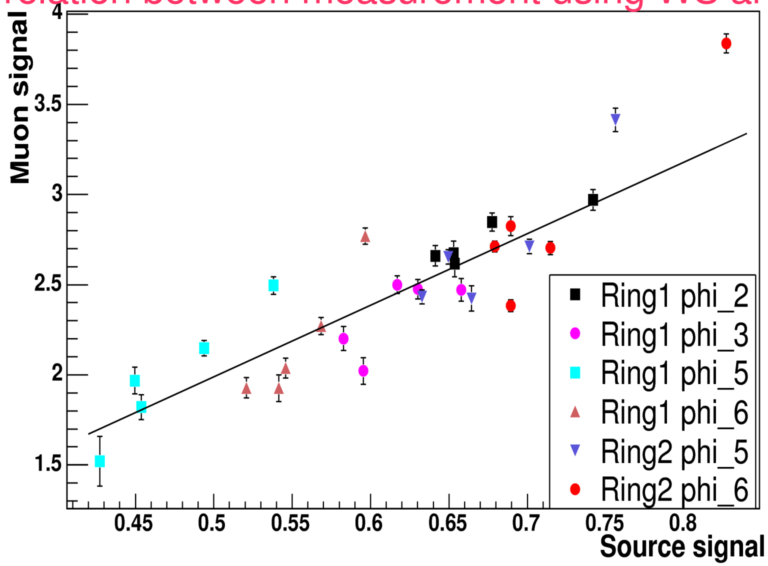


- Pedestal is fitted with a Gaussian
- Muon spectrum is fitted with a Landau convoluted with a Gaussian
- Peak of the fitted function is taken as Muon Signal
- Signal significance is > 3 σ_{noise} in Ring 0,2 and it is <2 σ_{noise} in Ring1

Muon signal in HO towers



Correlation between measurement using WS and Muons

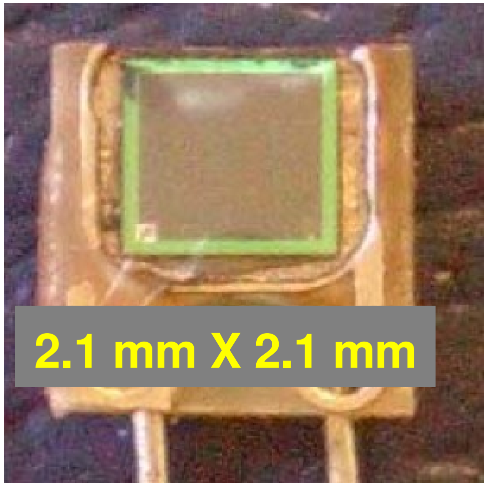


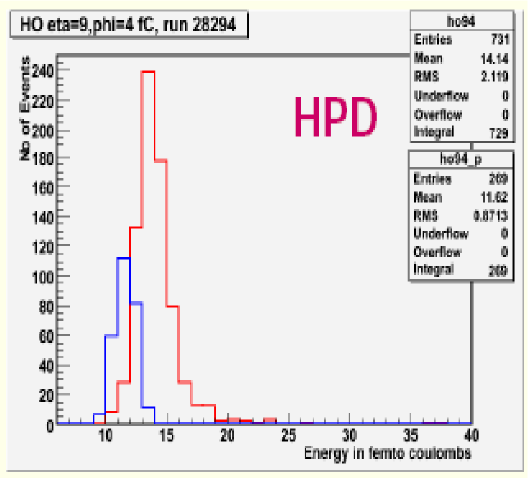
Silicon Photomultiplier

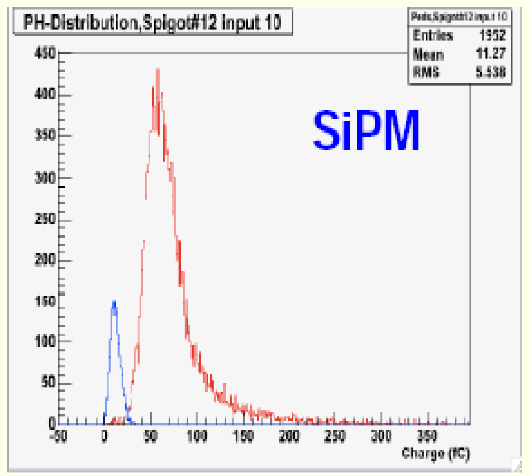
SiPM – an array of 45μm X 45μm pixels

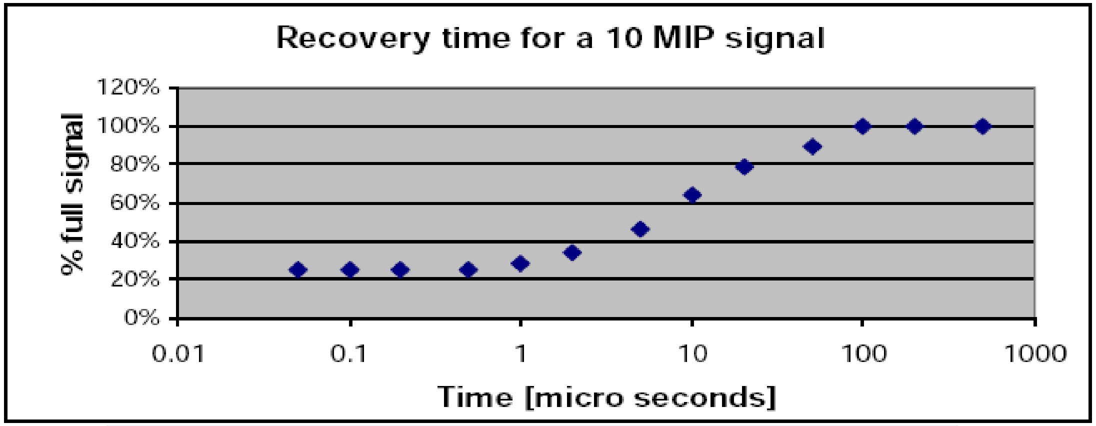
Each pixel operates in limited Geiger

region (gain 10^6 at 40V)









Recovery period can be upto 100 μs

It is important to know the occupancy of HO towers in the LHC environment to ensure that the slower recovery time does not degrade the physics performance of HO

Occupancy of HO towers

QCD sample generated in 21 p_T bins is used to estimate the event rate in HO towers (total cross-section of the order of milibarns)

Maximum contribution to the event rate in every tower comes from the lowest p_T bins

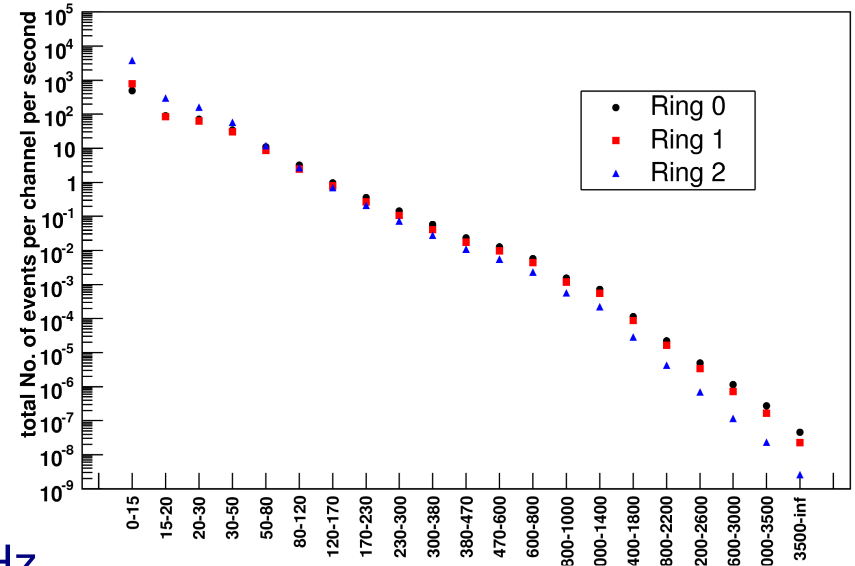
On an average, a signal of 1.3 MIPs at the rate of 2 kHz

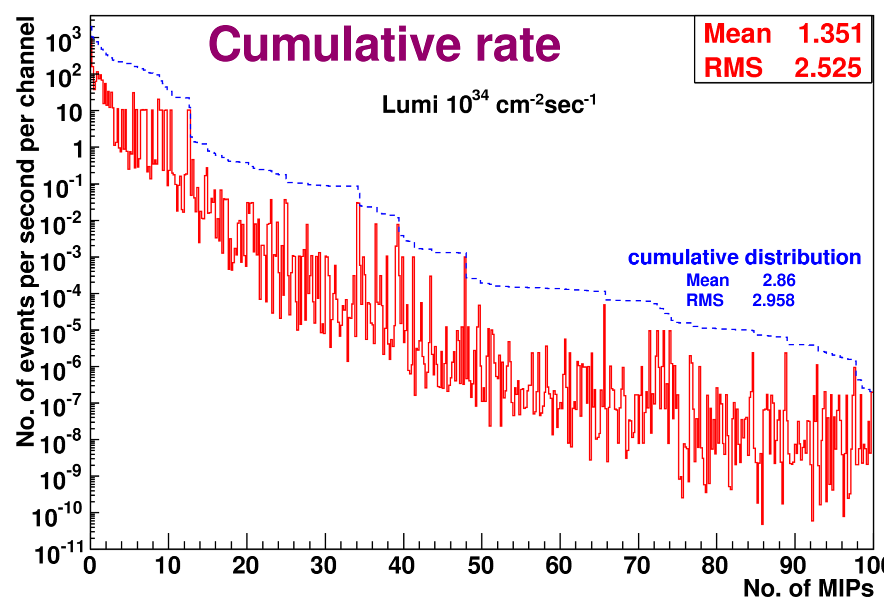
SiPM results : ~20 Pixels fired per MIP

With a recovery time of 100 μs, ~5 pixels are in recovery state (~0.25% for a SiPM having 2000 pixels)

The events overlapping in time or in space in a window of 100 μs do not affect the linearity of SiPM response

Event rate due to various p_T bins





Detector Simulation

- CMS needs good simulation at the start-up for jet energy scales
- CMS uses the tool kit GEANT4 for the detailed simulation
- GEANT4 provides a framework to describe the experimental set-up (both materials and geometry)
- It provides a facility to track the particles through the detector and store the runtime quantities required to reproduce the experimental measurements
- GEANT4 models the interaction between the particles and matter using all possible physics processes over a wide range of energy
- A number of physics models are provided by GEANT4 to describe the hadronic showers. The models are based either on theory (QGSP, QGSP_BERT) or on parametrization of experimental data (LHEP)
- **The physics models of GEANT4 needs extensive validation**

Test Beam Setup

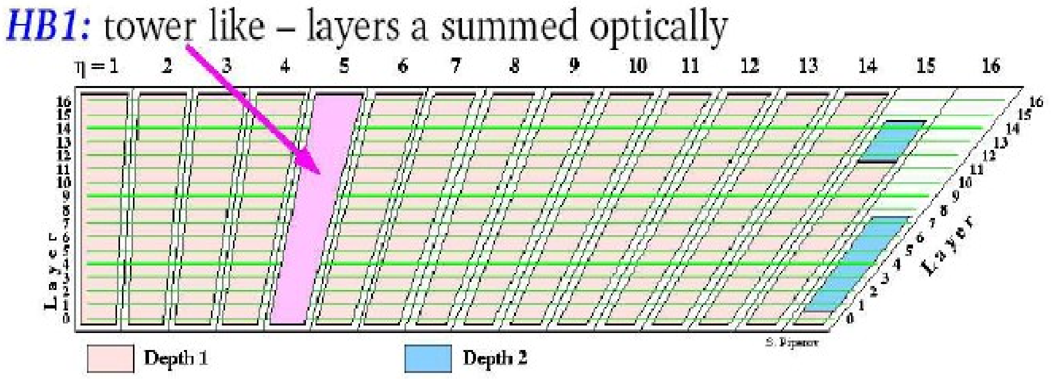
The experimental set-up consists of

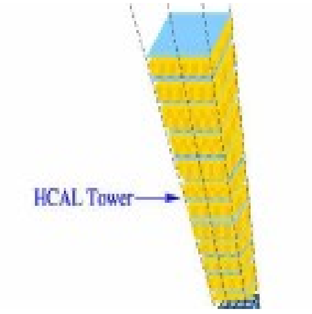
- Two wedges of HCAL half-barrel
- Six Φ sections of HO trays
- A wedge of HE
- EB super module (for 2006) or 7x7 crystal matrix (2004)
- Mock-up of cable, CMS magnet and tail catcher iron
- A set of wire chambers, scintillators, Cerenkov counters to define beam line and to identify particle type

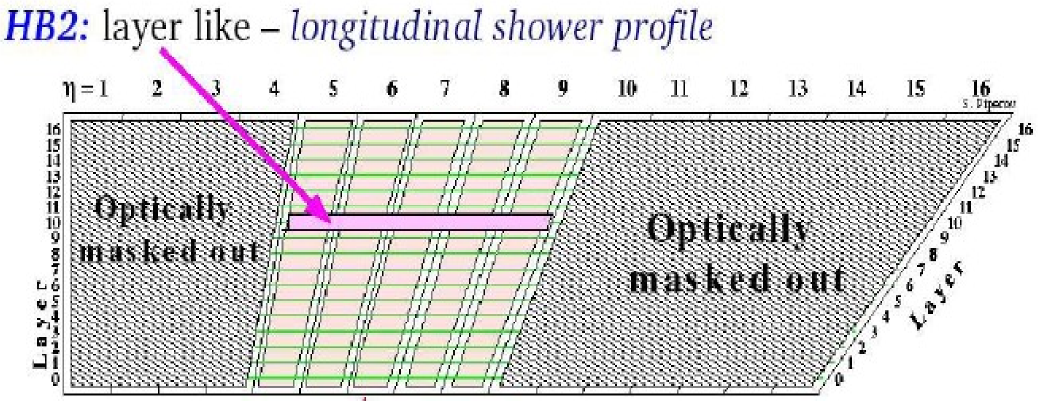
The complete set-up is mounted on a movable table such that the pivot of the table mimics the actual interaction point

Readout Configuration for HCAL

- HB1 : signal from 17 scintillator tiles is combine to make a readout tower in Δη x ΔΦ (no longitudinal information available)

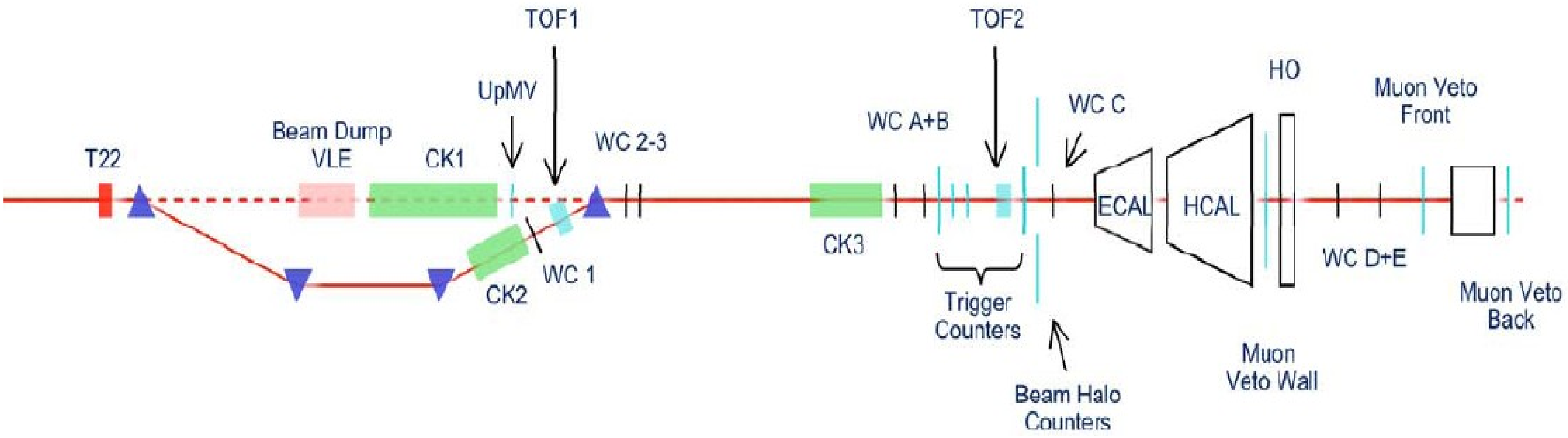






- HB2 : each layer of upper wedge is readout independently (summing up 5 η segments but keeping Φ intact)

Beam Line Elements

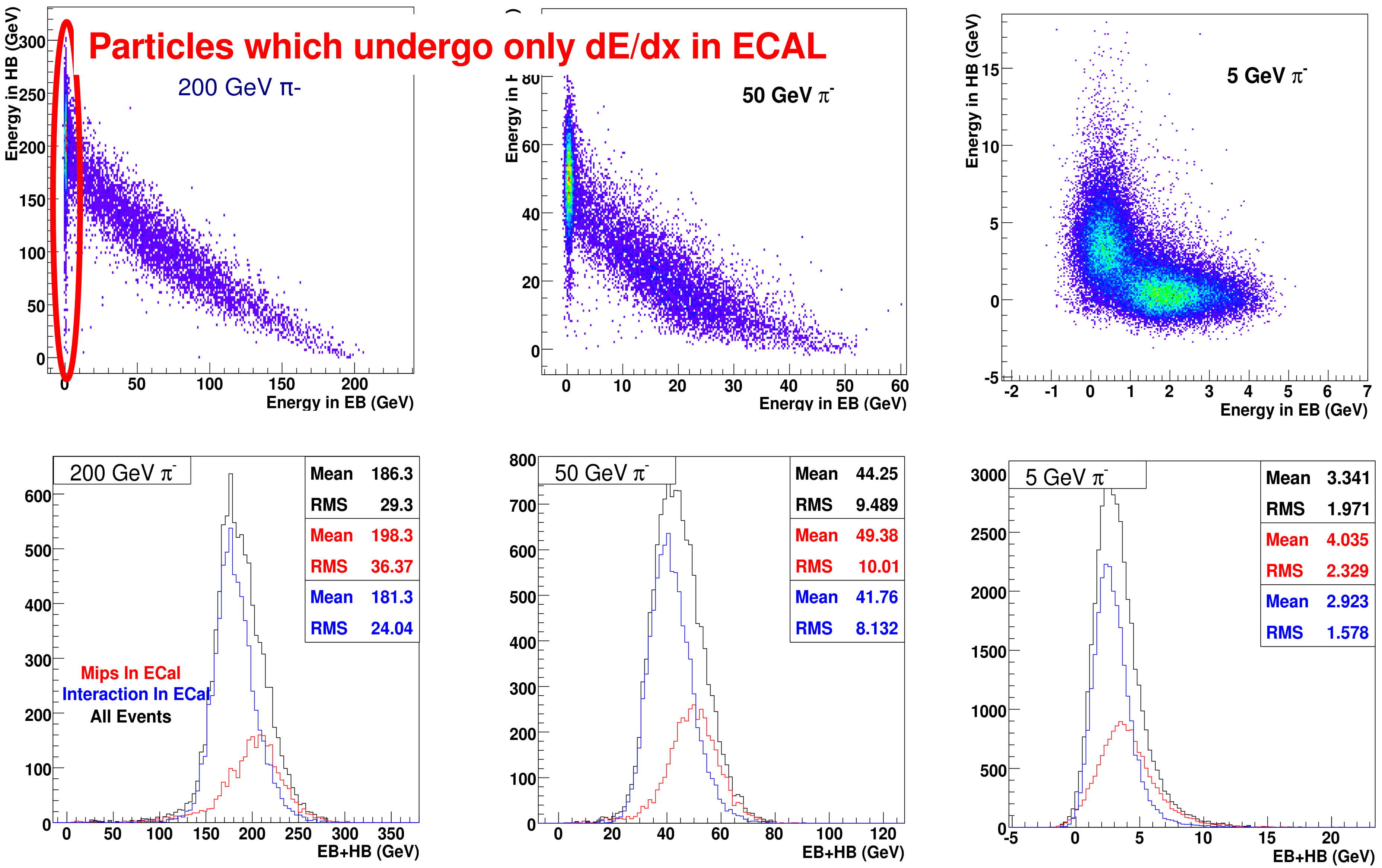


A number of detectors to identify beam particles

- Wire chambers
- Trigger Scintillators
- Beam Halo Counters
- Muon Veto Counters
- Cerenkov Counters
- CK2 – filled with CO2
- CK3 – filled with Freon
- Time of Flight System

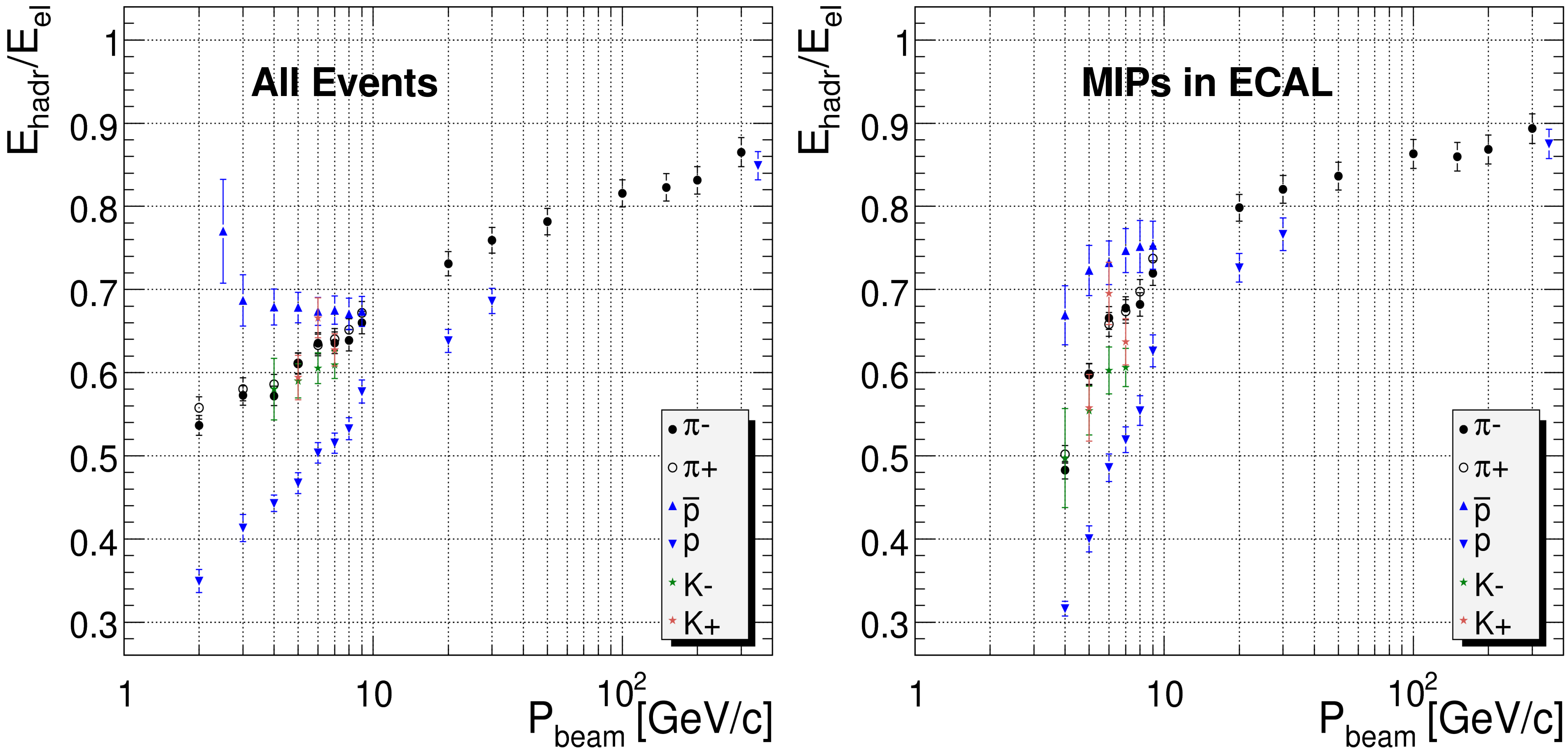
Energy Measured in ECAL and HCAL

Energy in ECAL is measured from 7x7 crystals and in HCAL from 3x3 towers



e/h is different in ECAL and HCAL. This increases non-linearity in energy response.

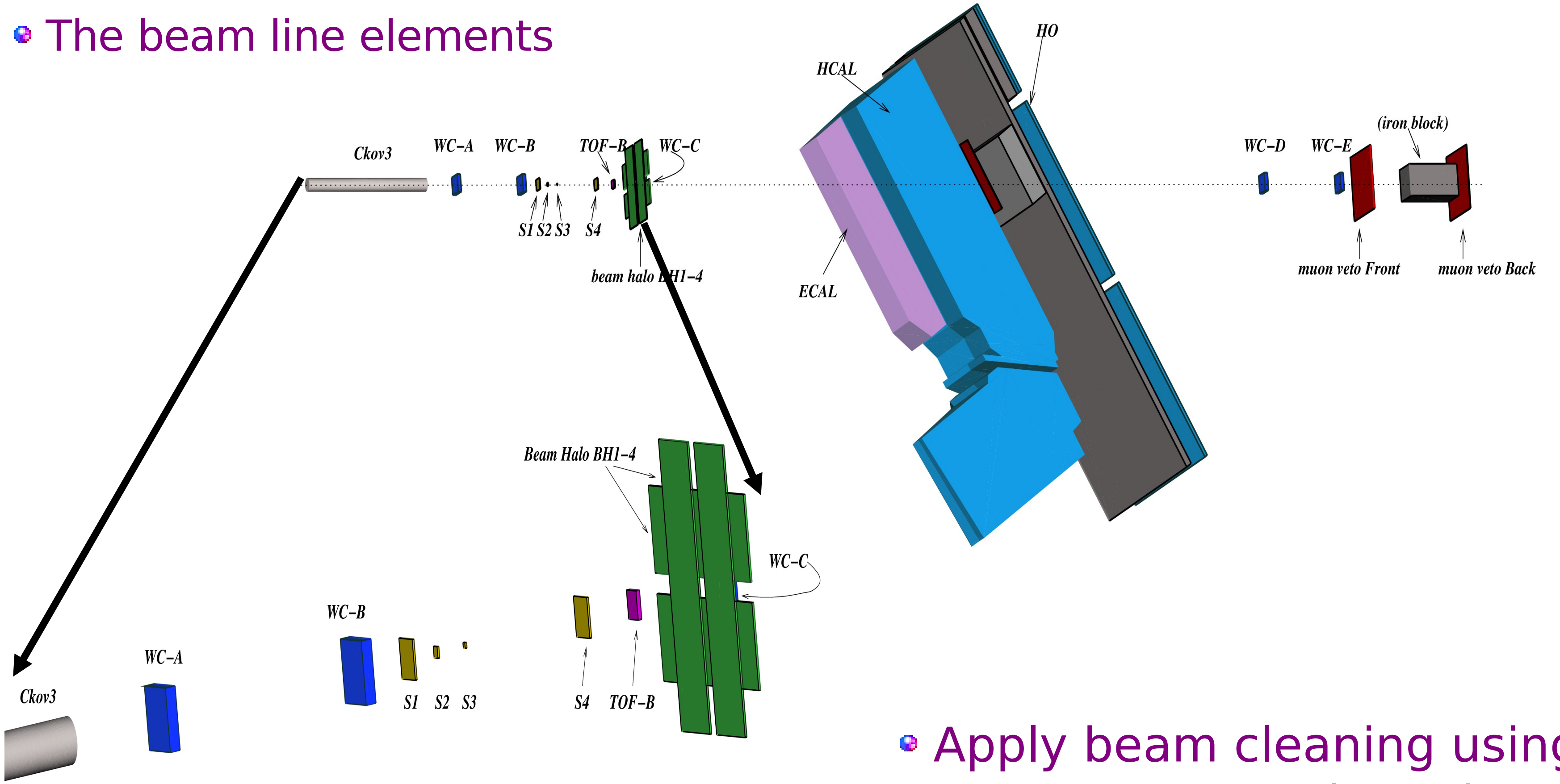
TB2006 Dataset



- Response of calorimeter to π^- and π^+ (response of π^+ is higher by ~1.5 %)
- For a given beam momentum, the response of pions is higher than the response of protons
- The pions which are MIPs in ECAL are important to calibrate HCAL towers in situ

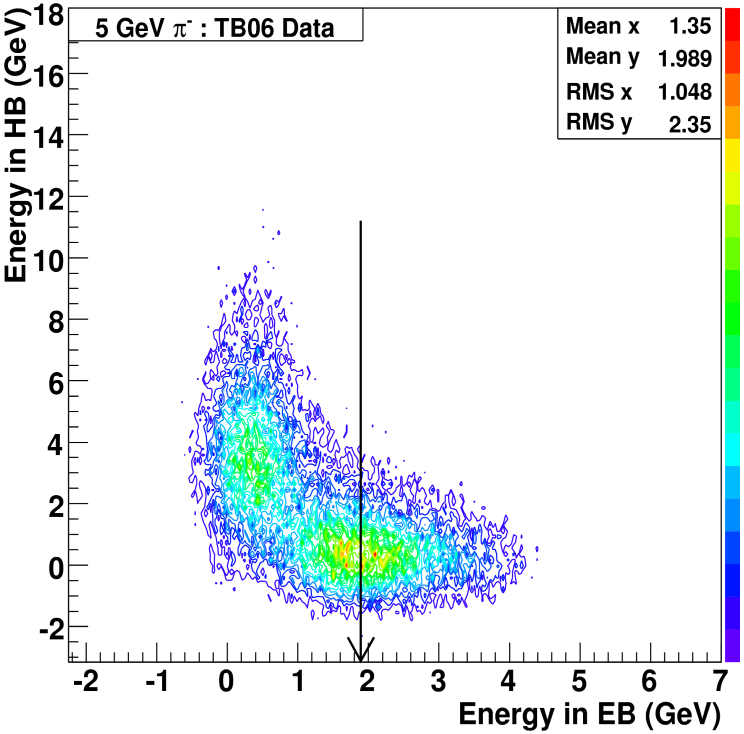
TB06 Experimental Set-up in GEANT4

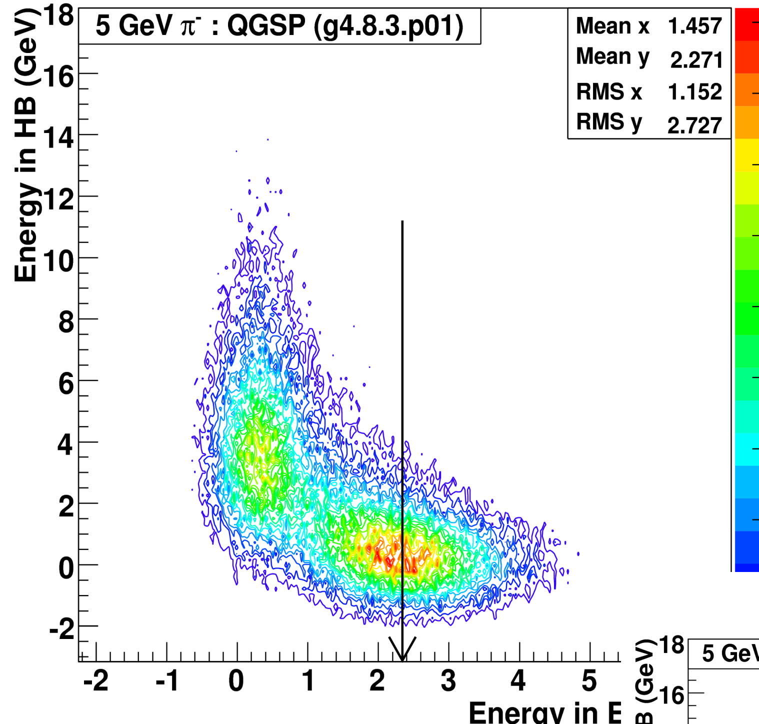
- Try to simulate the experimental conditions as closely as possible
- The calorimeter components
- The beam line elements



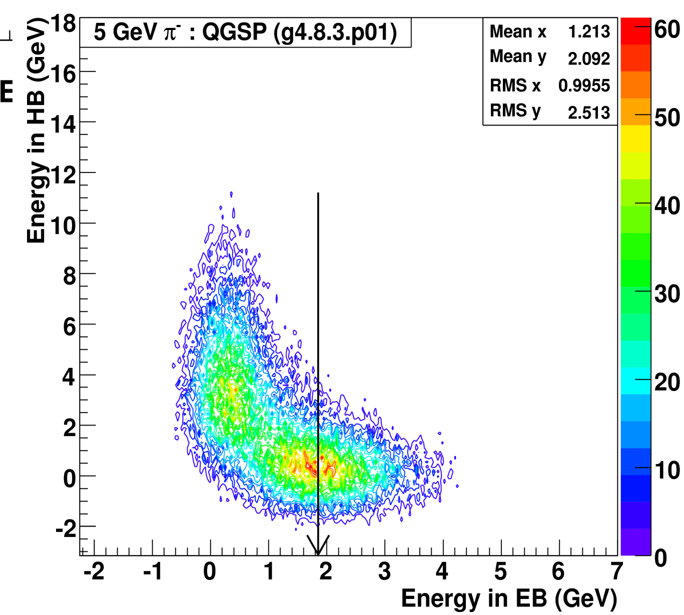
- Apply beam cleaning using S1...S4, BeamHalo and Scintillators as done in data

Energy Measured in ECAL





The centre-of-gravity of pion showers predicted by QGSP in ECAL is higher by 20-25% for low energies than measured in data

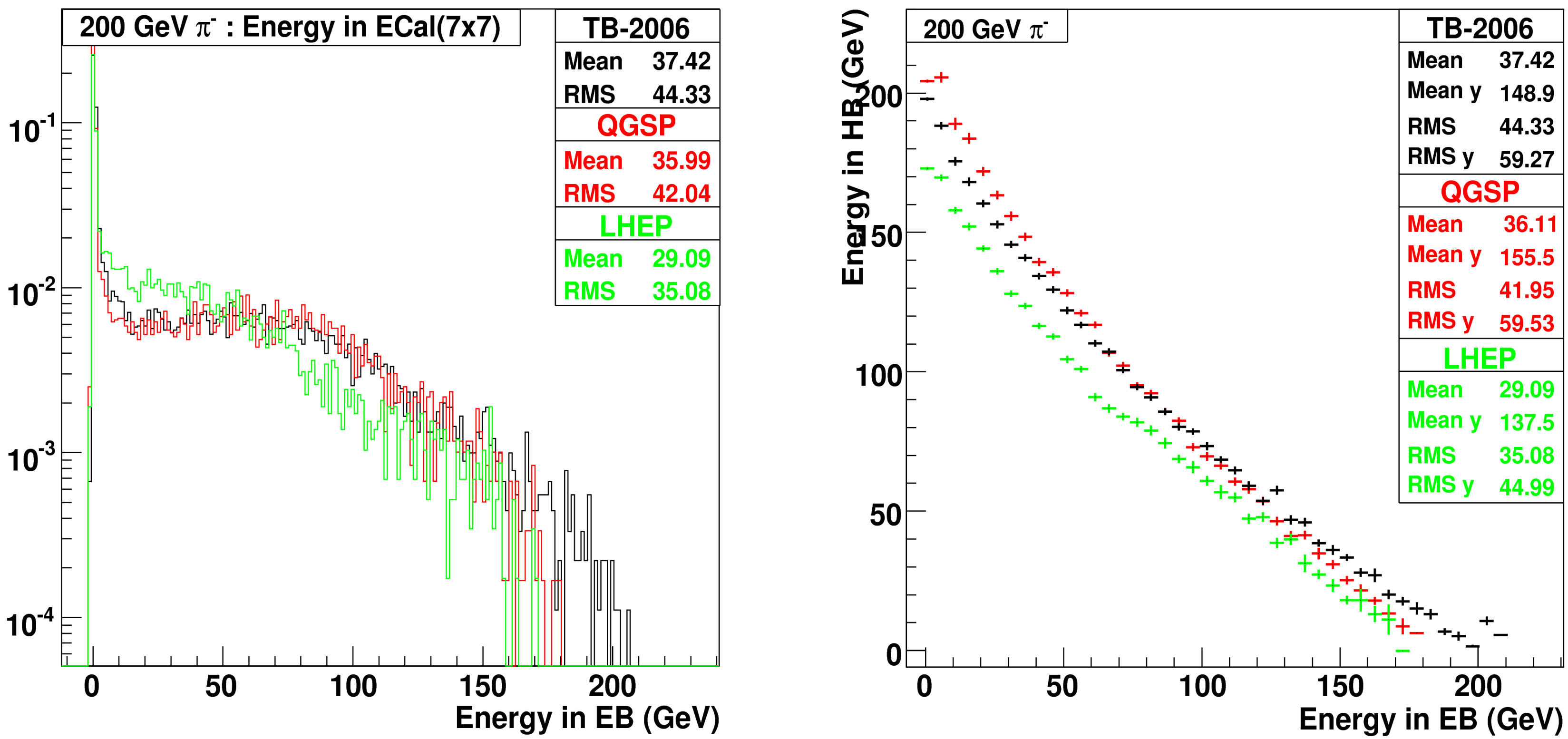


Invoke the Birk's suppression in GEANT4 for both the crystals and the scintillators

$$\frac{dS}{dX} = C \frac{dE/dx}{(1 + kB\, dE/dx)}$$

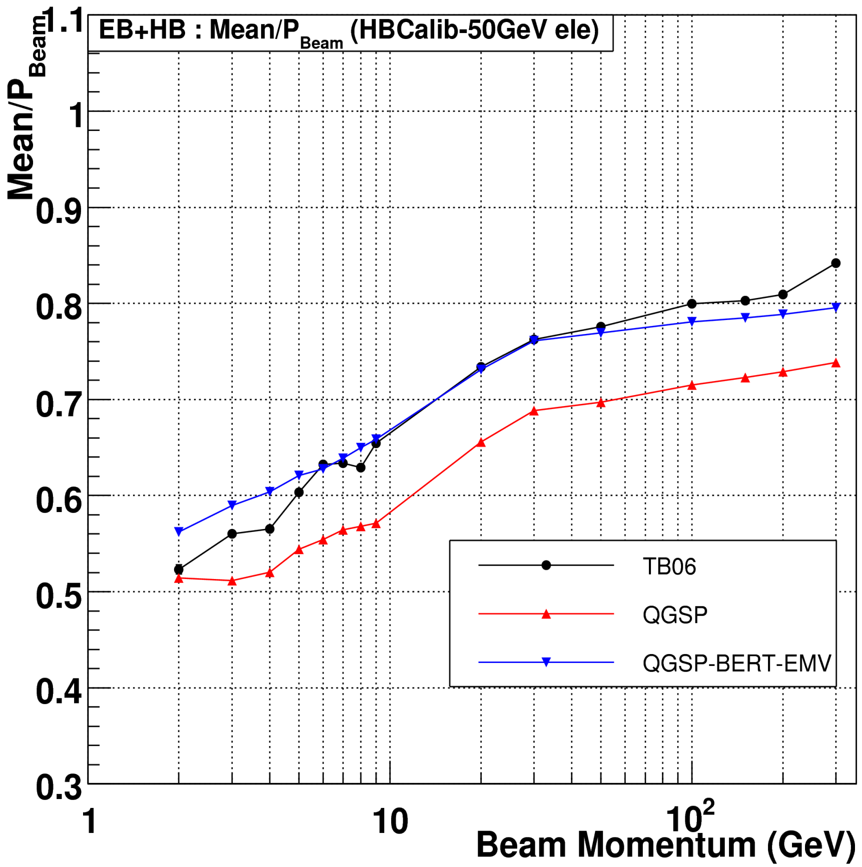
Centre-of-Gravity of Shower is matched with data at low energies (< 9 GeV)

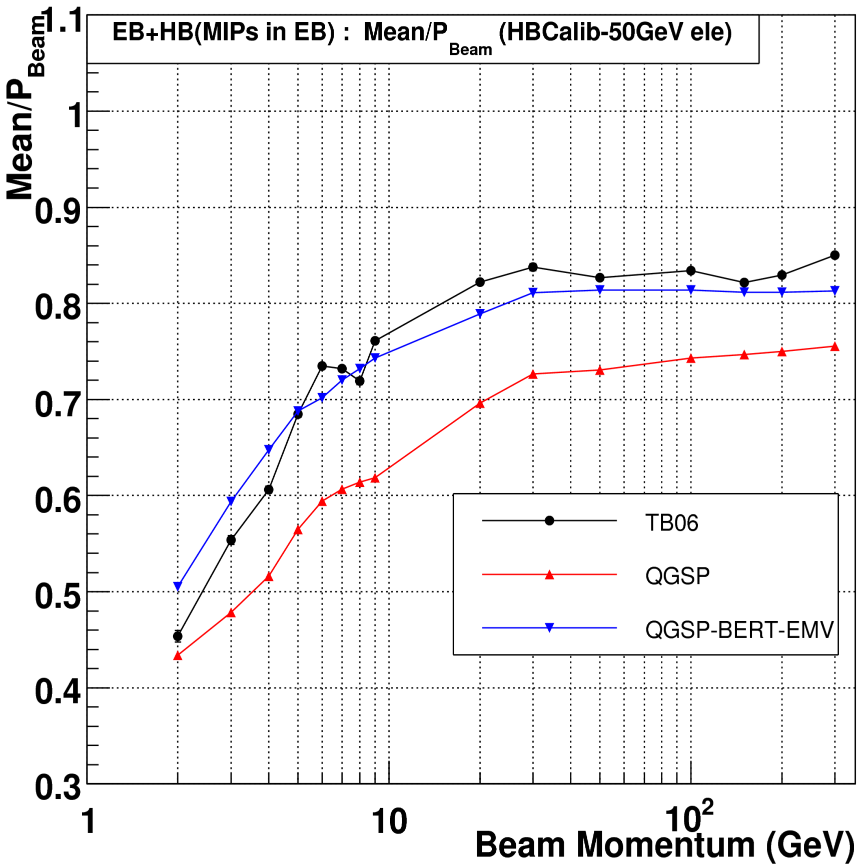
How Good is LHEP ?



LHEP cannot reproduce the energy sharing between ECAL and HCAL for showers generated by high energy pions

How Good is QGSP ?

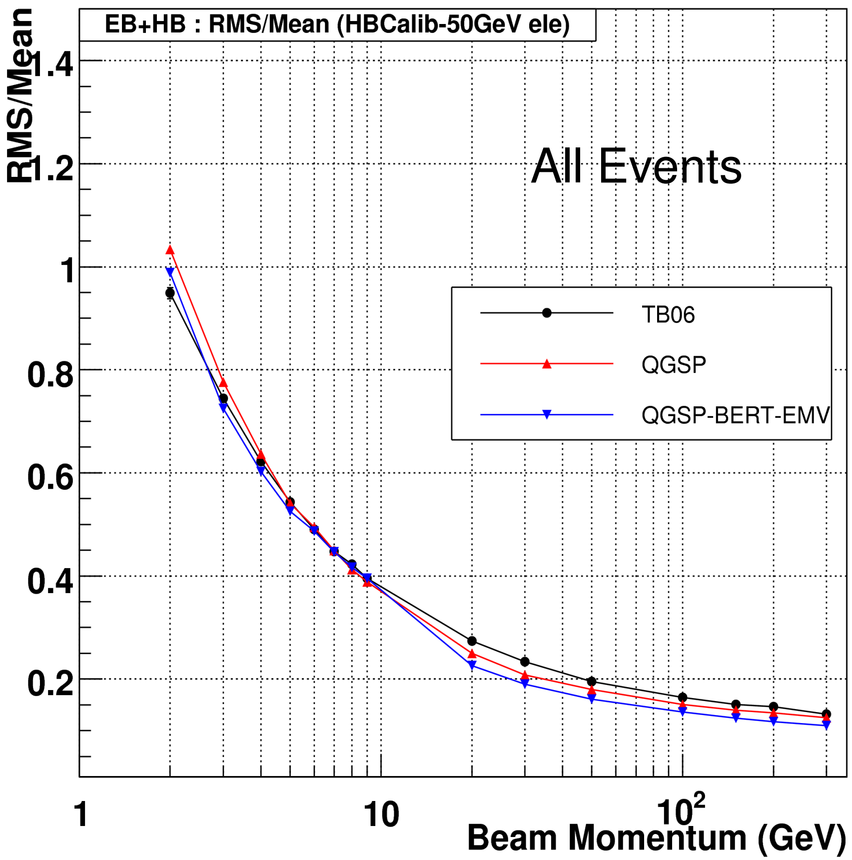




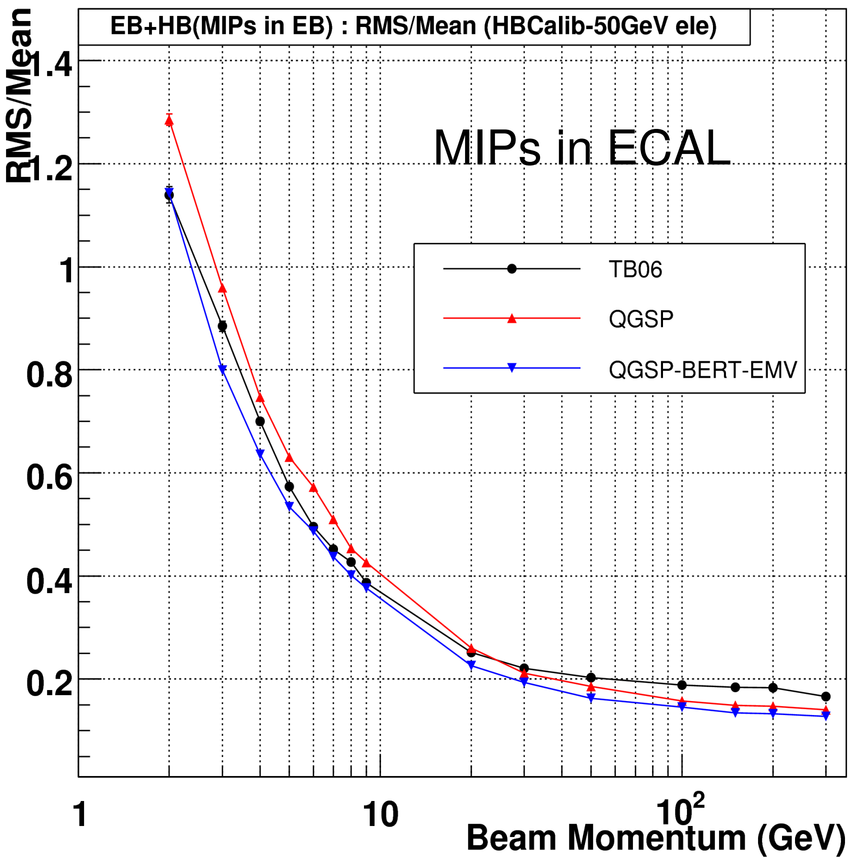
QGSP predicts smaller response as compared to data when layer-to-layer variation is included in calibration of HCAL using electrons. Moreover, QGSP cannot explain the response of both HCAL-ECAL combined system and HCAL alone (using MIPs in ECAL)

The response of the CMS calorimeter as predicted by QGSP_BERT matches well with the test beam measurements within systematic uncertainties (estimated to be 2-3%)

Resolution



$\sigma/E = 1.12E^{-1/2} + 0.12 + 0.80E^{-1}$



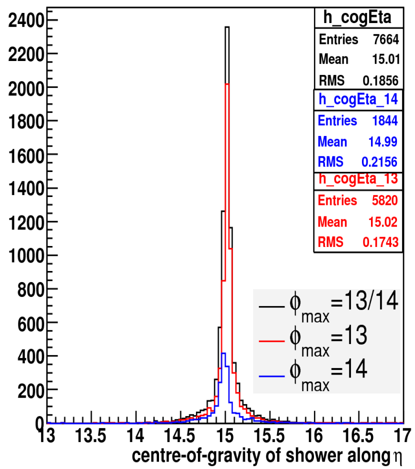
$\sigma/E = 1.15E^{-1/2} + 0.13 + 0.80E^{-1}$

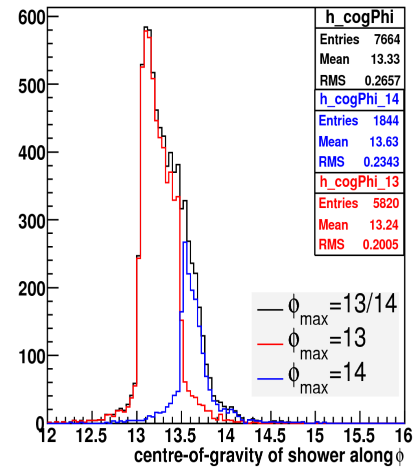
QGSP_BERT reproduces the data for energy resolution (RMS/Mean) for HCAL+ECAL combined system

GEANT4 prediction is better than that of test beam measurements for MIP-like events in ECAL

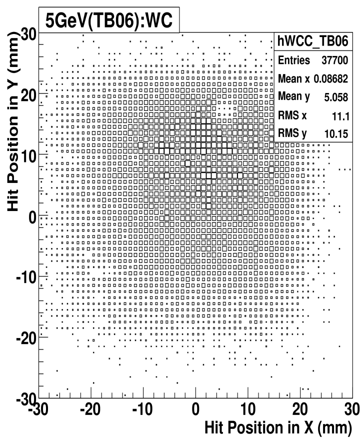
Transverse Profiles In ECAL

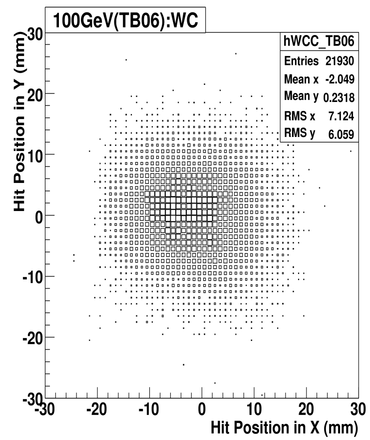
Centre-of-gravity of the shower in ECAL depends upon the depth and nature of first hadronic interaction and it varies from event-to-event by large amount

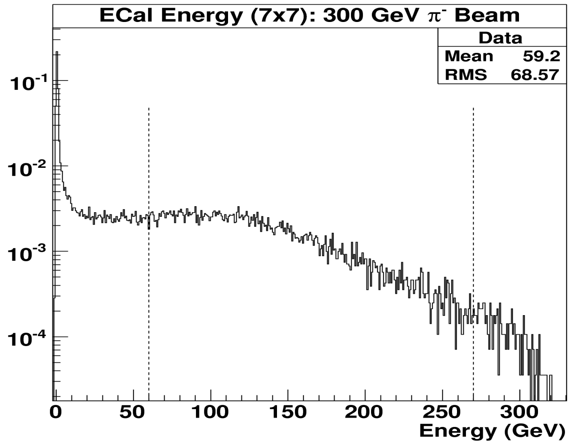


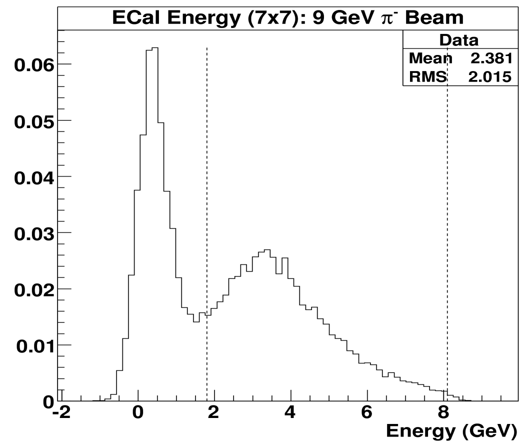


Additional smearing from beam profile which are different for various beam tunes









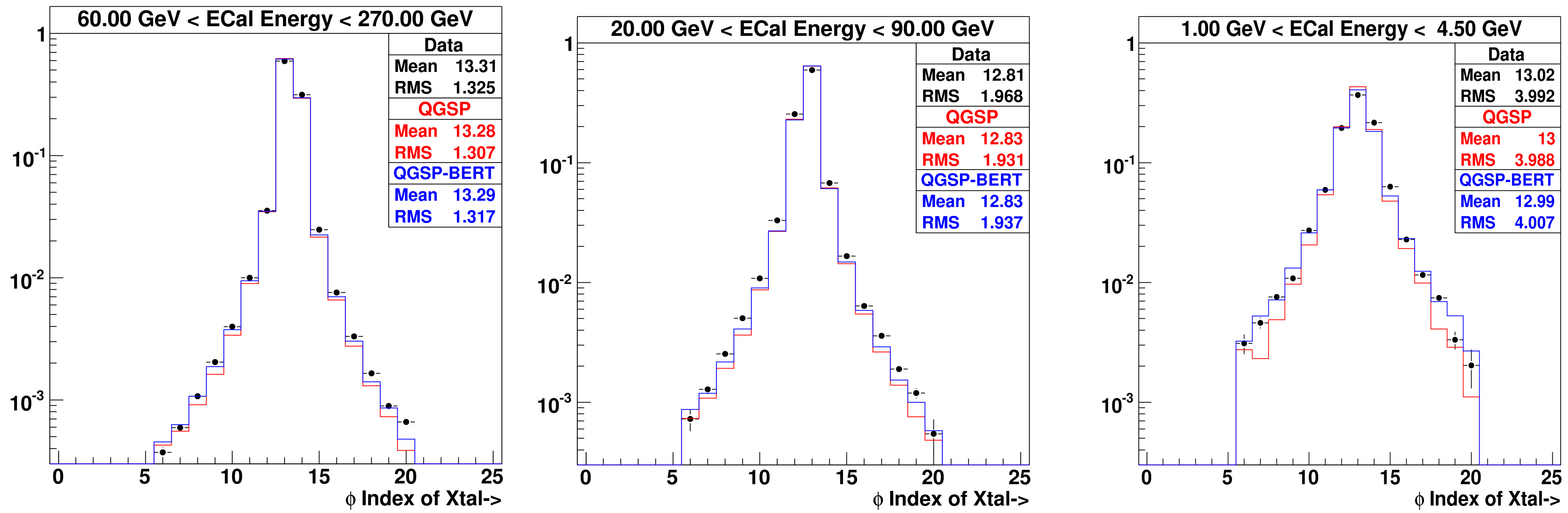
Derive beam profile from data to compare the transverse profiles in ECAL crystals with GEANT4

Consider the events which start interacting in ECAL

($0.2\ P_{beam}$ < ECAL Energy < $0.9\ P_{beam}$)

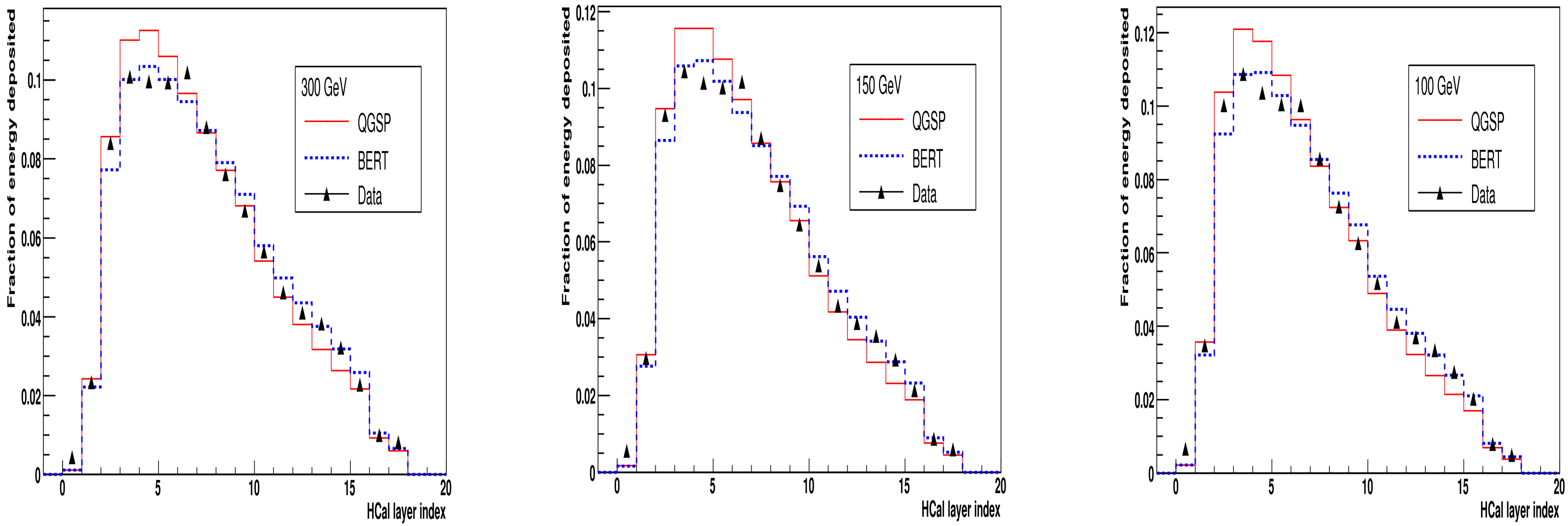
Transverse Profiles In ECAL

Sum up energies measured in 7 crystals in η(φ) to get the shower profiles along (φ)η



The tranverse showers in ECAL are faithfully reproduced by the QGSP_BERT physics list

Longitudinal Shower Profiles

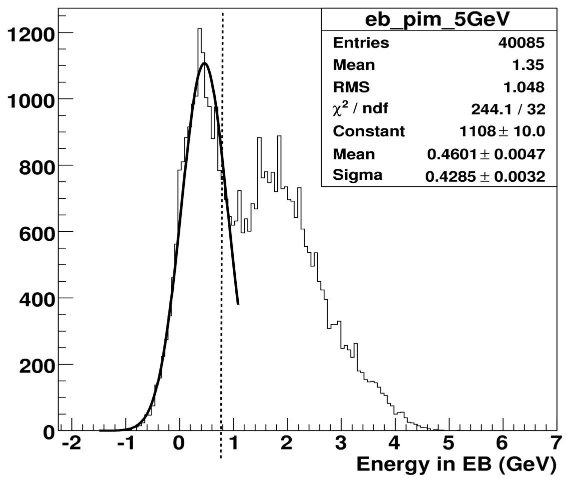


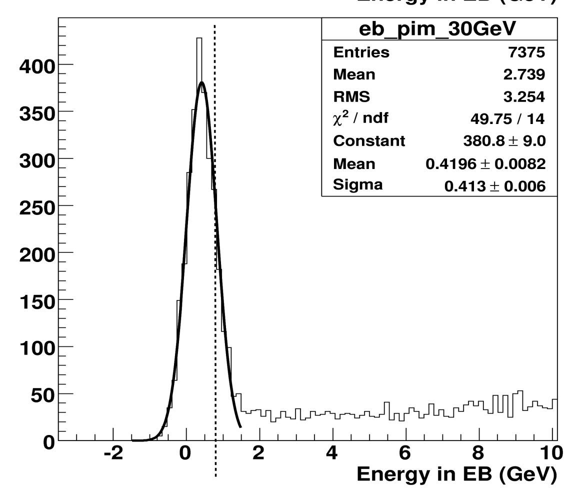
- The QGSP physics list produces shorter shower profiles than measured in test beam
- The longitudinal shower profiles predicted by QGSP_BERT for pions in HCAL are in good agreement with data

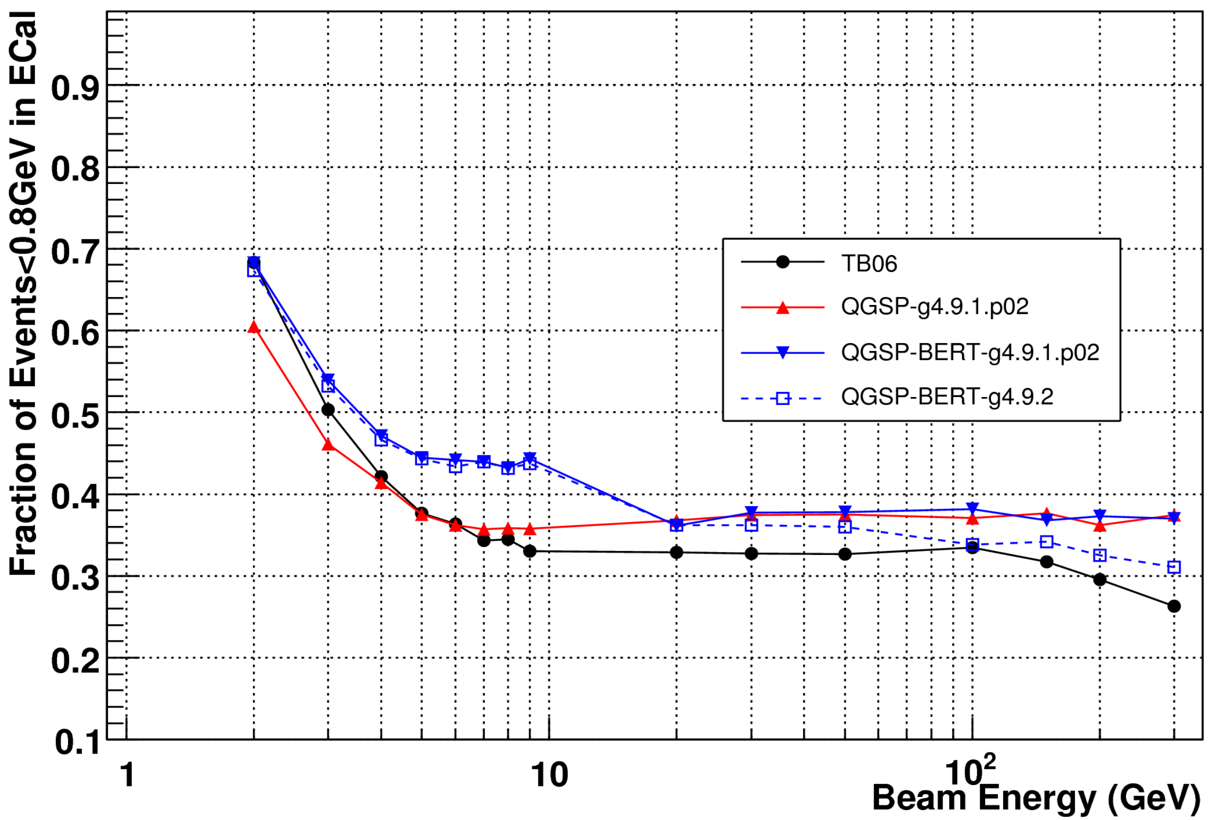
Remaining Issues

Consider particles for which energy measured in ECAL < 800 MeV to study HCAL alone system

- Observe discontinuity in the fraction of MIP-like events in ECAL below 10 GeV (in QGSP-BERT)
- No. of MIP-like events is higher in by 3-4% than in data in the energy range 20-50 GeV

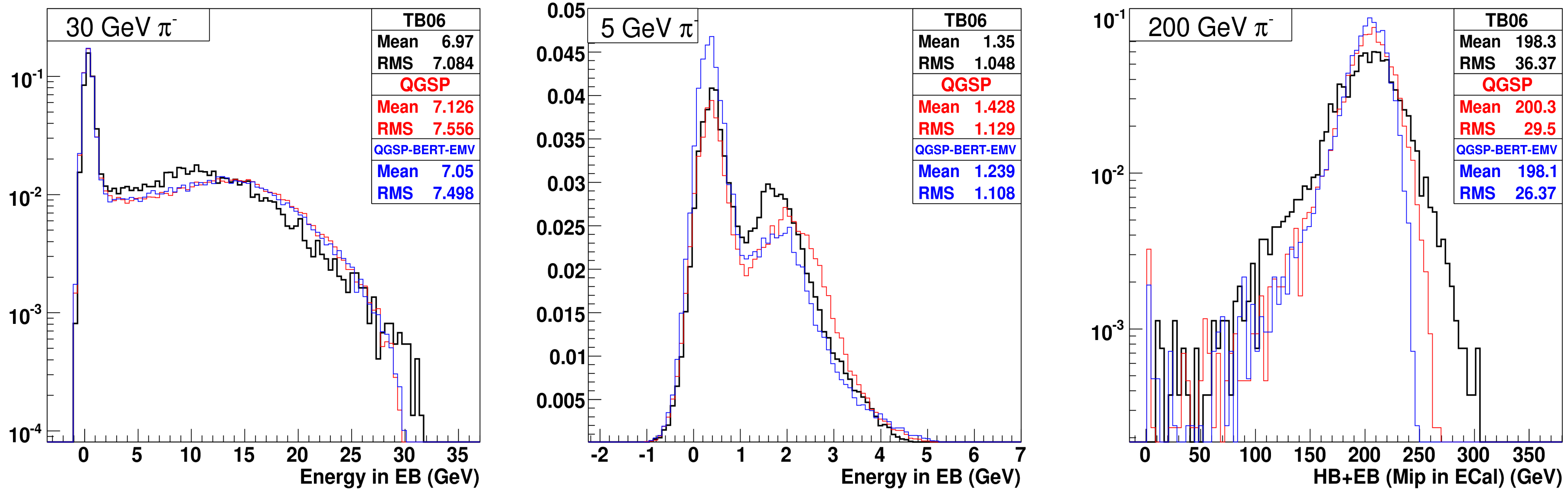






Pions with energy > 100 GeV start loosing energy by Bremsstrahlung – included in latest GEANT4 release

Remaining Issues (continued)



The energy distributions of pions in ECAL are faithfully reproduced at high energies but the shape is different in the intermediate energy regime

In low energy regime, the QGSP_BERT predicts more MIP like events in ECAL

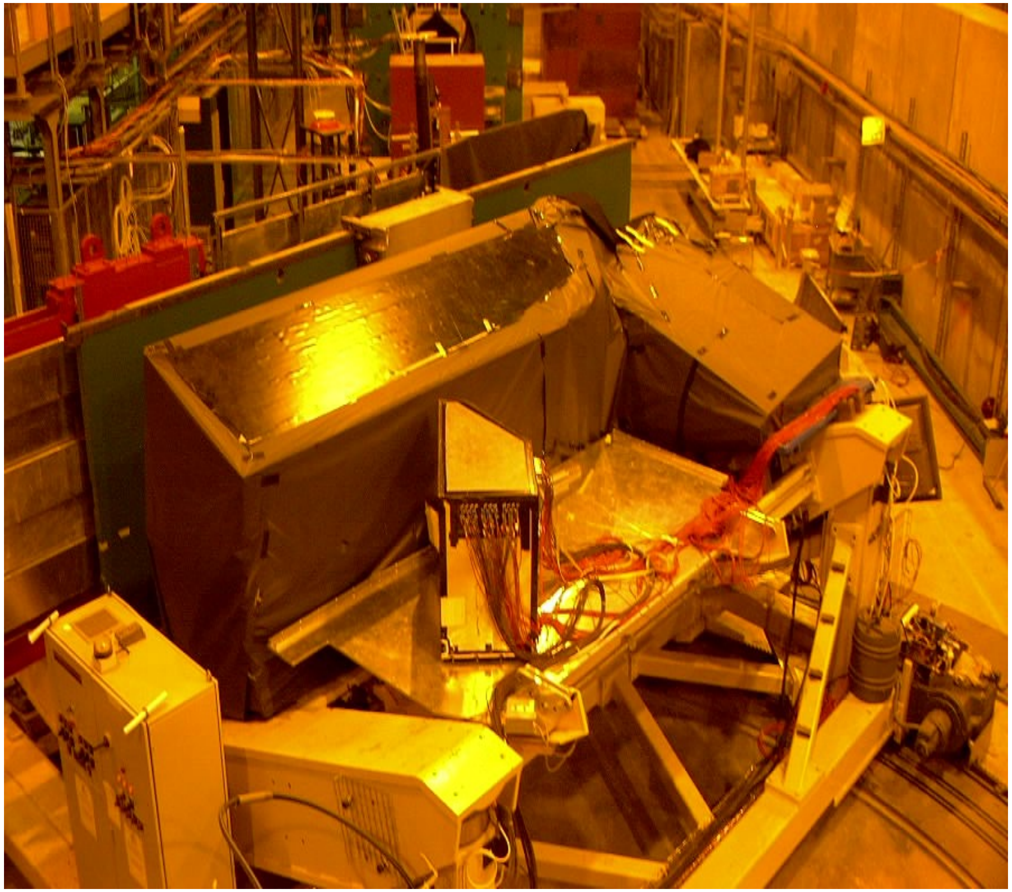
Monte Carlo predicts narrower energy distributions in HCAL

Summary

- 1 fb^{-1} of LHC data will enable CMS to see SUSY if it exists with parameter values close to the LM2 point
- Non universality in the leptonic sector will be a good indication of physics beyond the Standard Model
- Addition of layers of scintillators beyond the hadron barrel detector improves missing E_T measurement at CMS
- Sensitivity to muon measurement demands improvement in the readout scheme for HO
- Extensive tests of the simulation software using test beam data has given rise to a new strategy for CMS simulation
- Looking forward to collision data by end of this year

Back Up

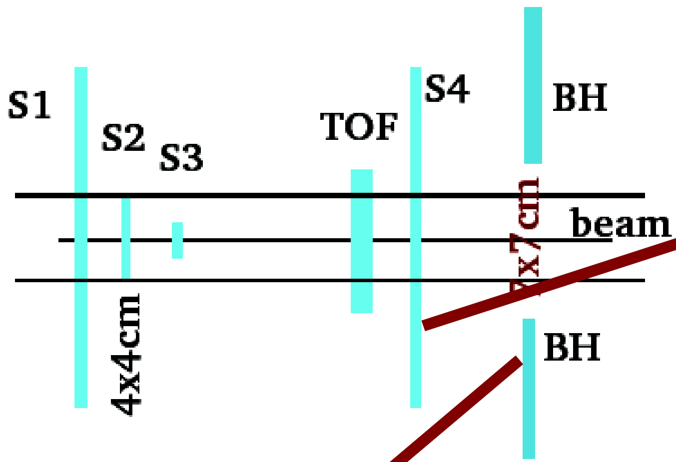
Test Beam-2004 Setup

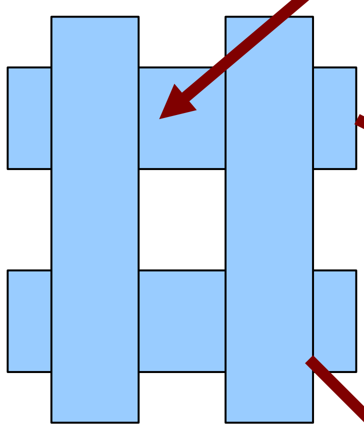


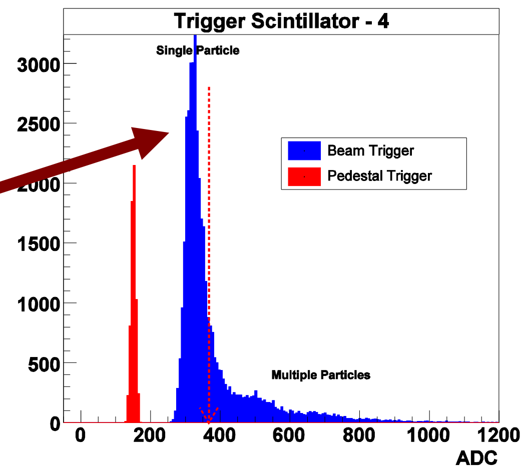
The experimental setup consists of

- Two wedges of Hcal half-barrel
- Six Φ sections of HO trays
- A wedge of HE
- A prototype of Ecal (49 crystals)
- Mock-up of cable, CMS magnet and tail catcher iron
- A set of wire chambers, scintillators, cerenkov counters to define beam line and to identify particle type

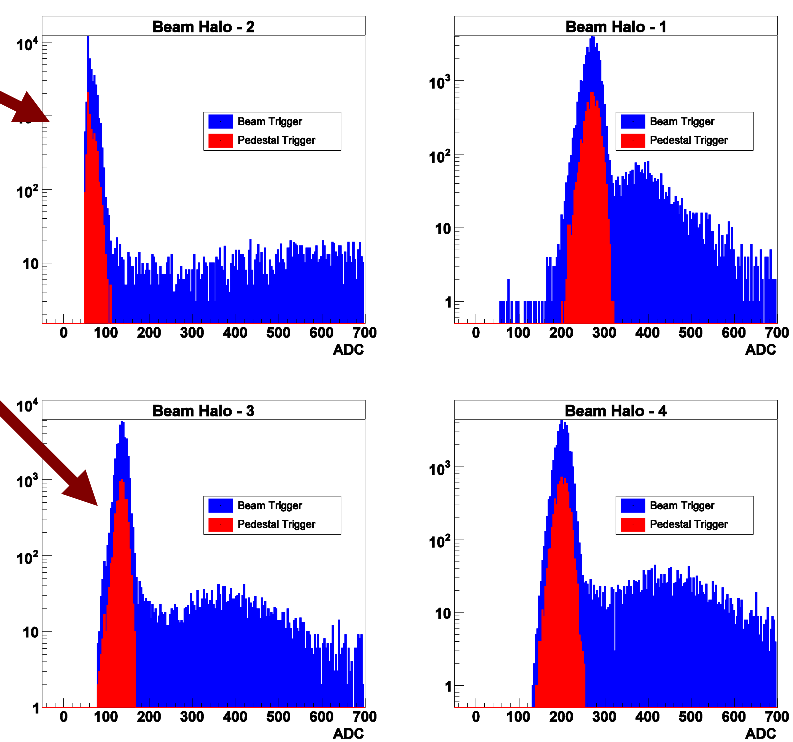
Rejecting Interactions in Beam line







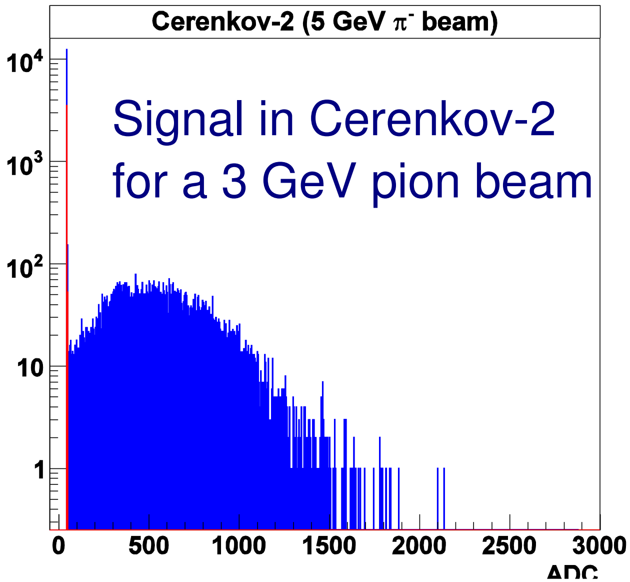
Reject the events with more that one particle in trigger scintillator

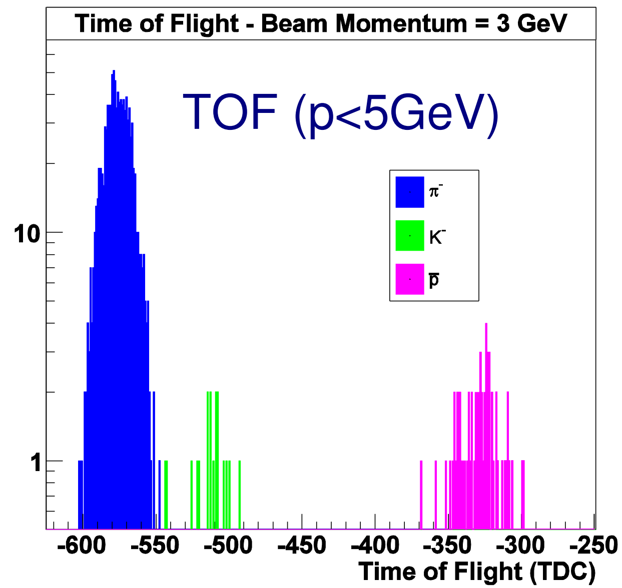


Beam Halo
7cm X 7cm hole

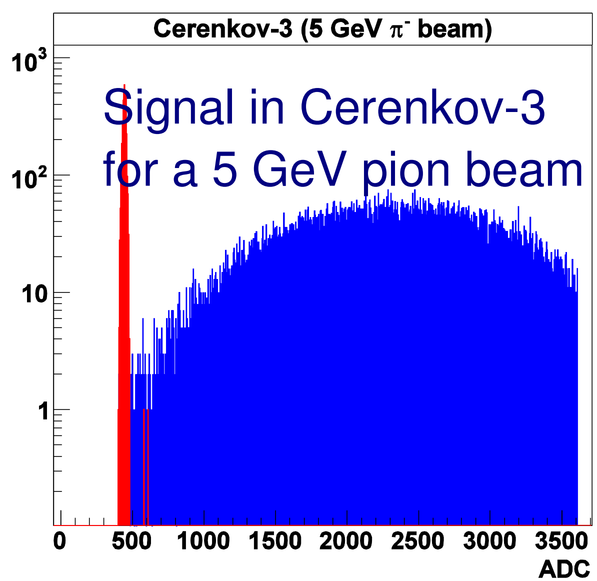
Reject wide angle secondaries produced in interactions with beamline elements by using BeamHalo

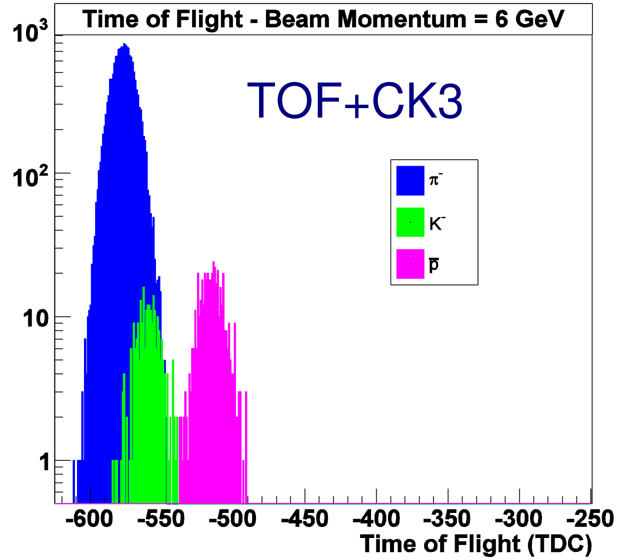
Particle Identification : e/π/p/K





- Tag **e** using CK3 for 1-9GeV
- TOF to separate **π/p/K** (<5GeV)
- CK3 to tag **π** (5-9 GeV)
- TOF to separate **p/K** (5-9 GeV)



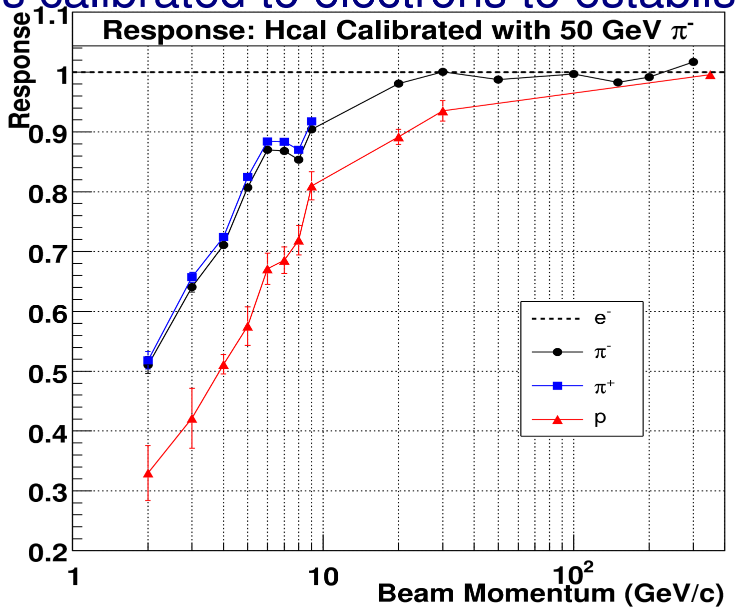


Beam Composition

Beam Mom. [GeV/c]	π^- [%]	e^- [%]	$\bar{p}$ [%]	K^- [%]
9	73.0	22.1	2.7	2.3
8	56.9	39.8	1.9	1.4
7	61.8	35.5	1.7	1.0
6	57.7	40.1	1.5	0.77
5	53.2	44.9	1.2	0.67
4	40.9	58.0	0.87	0.21
3	25.9	73.7	0.34	0.054
2	10.6	89.3	0.06	0.0046

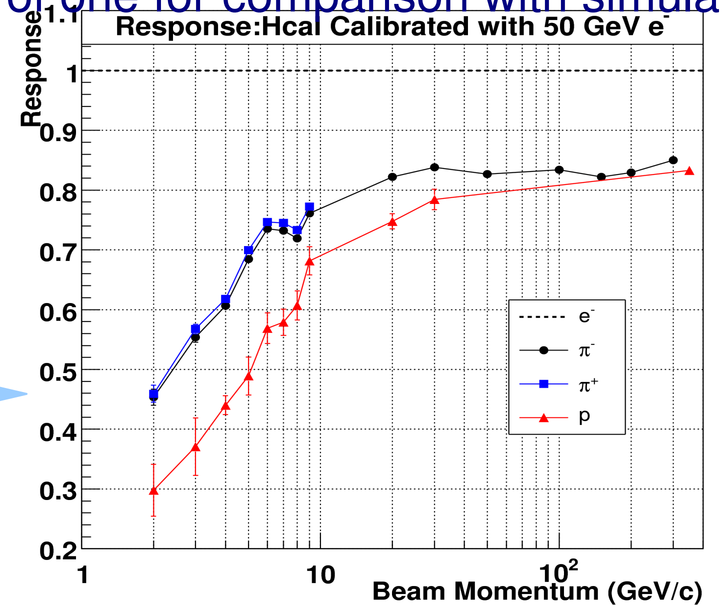
Response of Calorimeter with HCAL calibrated to 50 GeV electrons

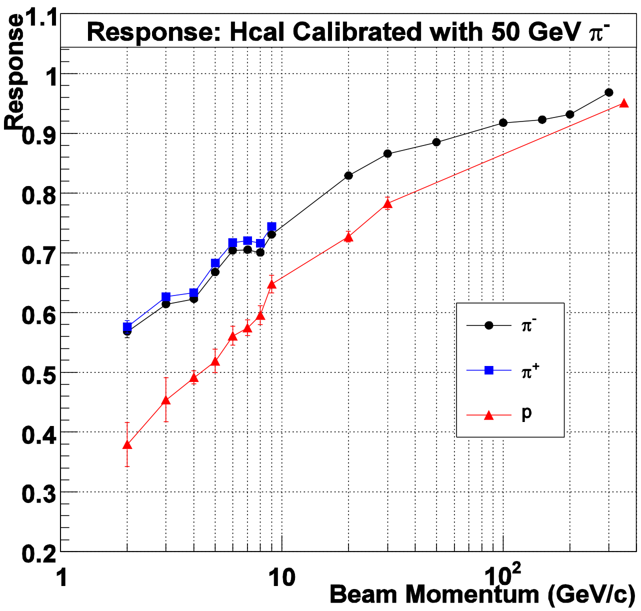
HCAL is calibrated to electrons to establish an absolutre scale of one for comparison with simulation



$$\frac{\Pi}{e}(50\,GeV)=0.836$$

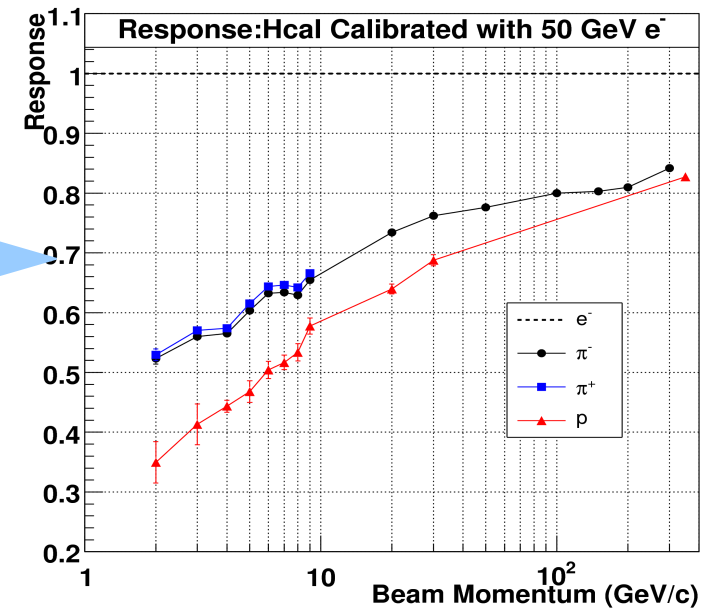
MIPs in ECAL





All particles

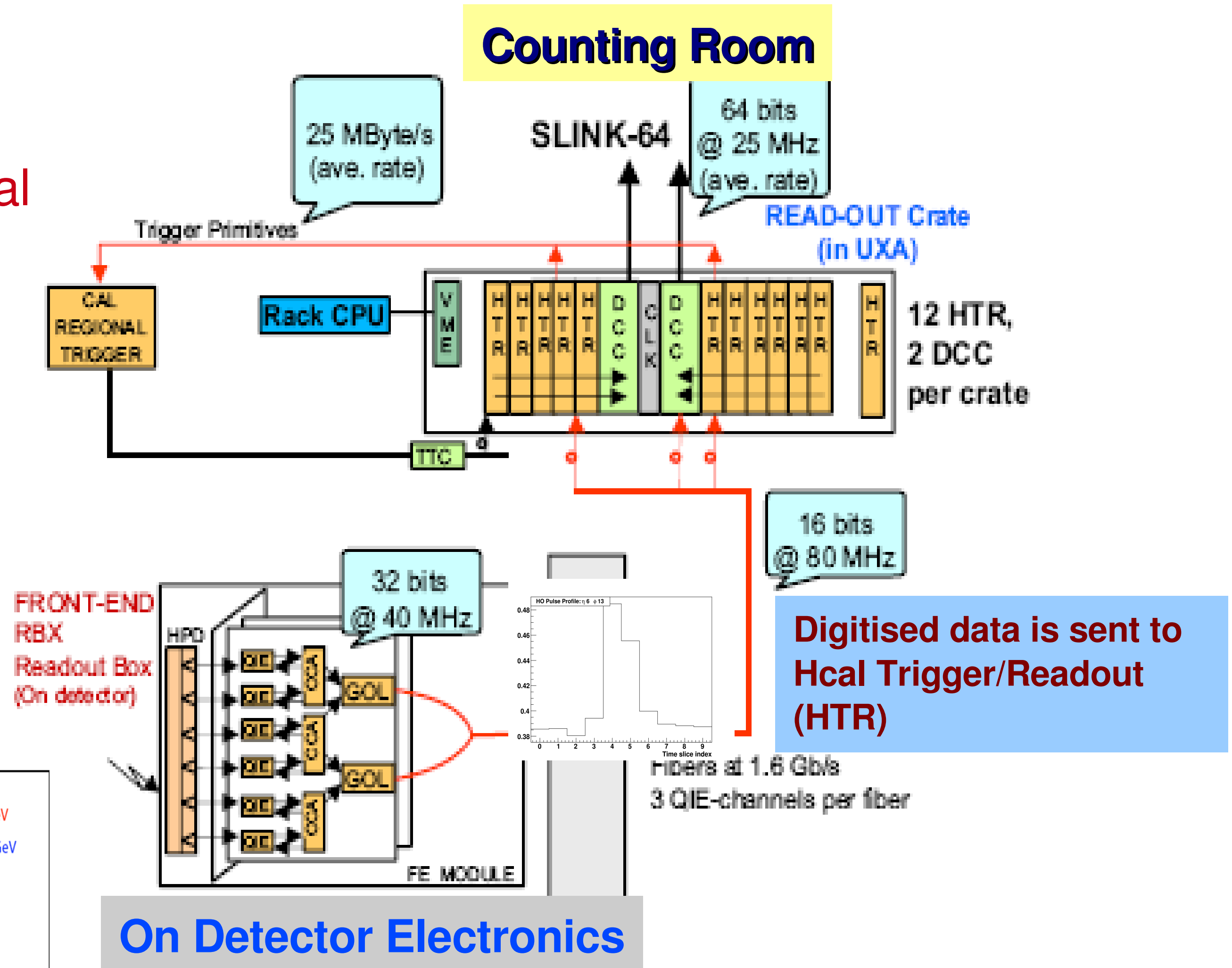
$$ECal+\frac{\Pi}{e}(HCal)$$

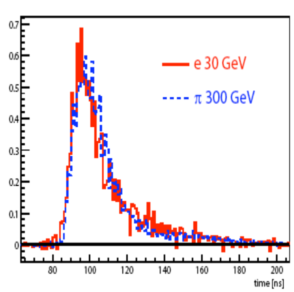


Electronics And Data Acquisition

The analog signal from HPDs is digitized using an analog-to-digital converter – QIE circuit
(Charge(Q) Integrator(I) and Encoder(E)

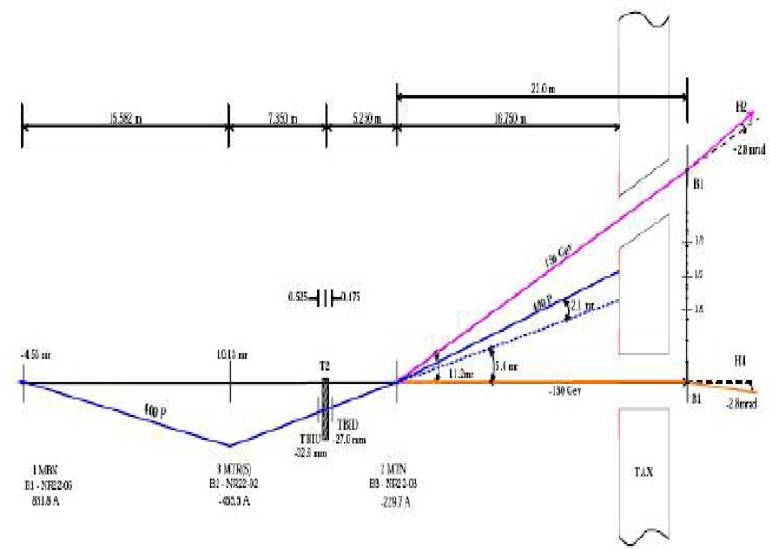
- The signal is integrated over four different ranges of ADC
- The digitized output is stored in a floating point format
- Four sets of integrators(capIds), each one integrates for 25 ns



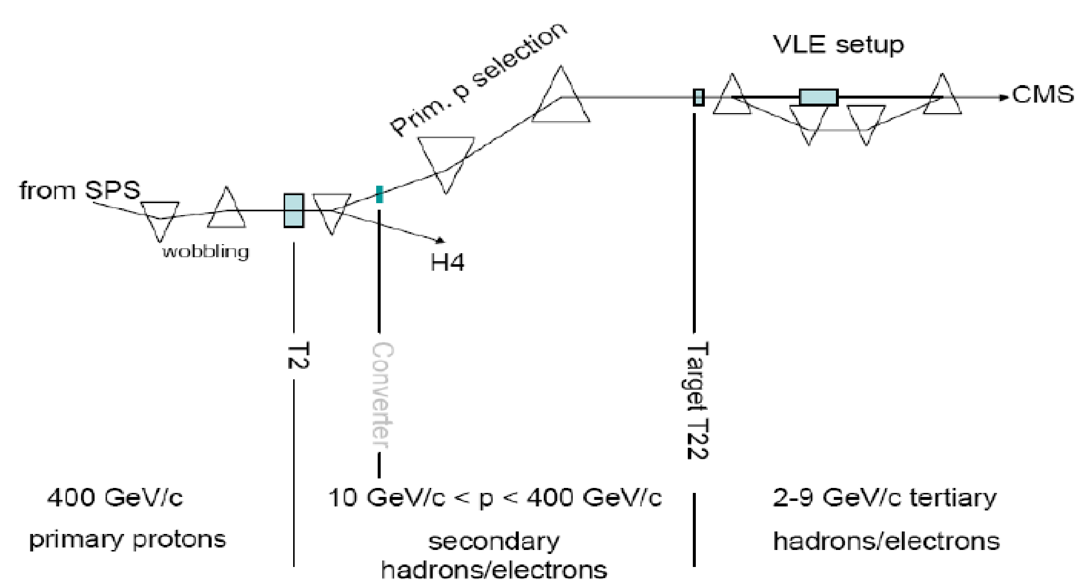


H2 Beam Line

- A 400 GeV/c primary proton is extracted from SPS and are directed to a primary target (T2) made of Beryllium
- A wide variety of secondary particles are produced
  - – pions, kaons and nucleons in hadronic interactions
  - - electrons from π° decays and conversions
- Select the required beam momentum (p) by bending particles in magnetic field $\Theta = 0.3BL/p$



- Total primary beam length : 615 m
- For 9 GeV pions, $\gamma\beta c\tau \sim 500$m
- Nearly 67% of pions decay before reaching calorimeters downstream
- A secondary target T22 – near the experimental hall



Mass Spectrum at LM2 point

	$\tilde{u}$	$\tilde{d}$	$\tilde{c}$	$\tilde{s}$	$\tilde{t}$	$\tilde{b}$
(L)	777.40	773.36	777.40	773.36	**678.19**	**581.20**
(R)	747.87	749.50	747.87	749.50	731.09	750.13

	$\tilde{e}$	$\tilde{\mu}$	$\tilde{\tau}$
(L)	300.90	300.90	**156.46**
(R)	229.42	229.42	312.12

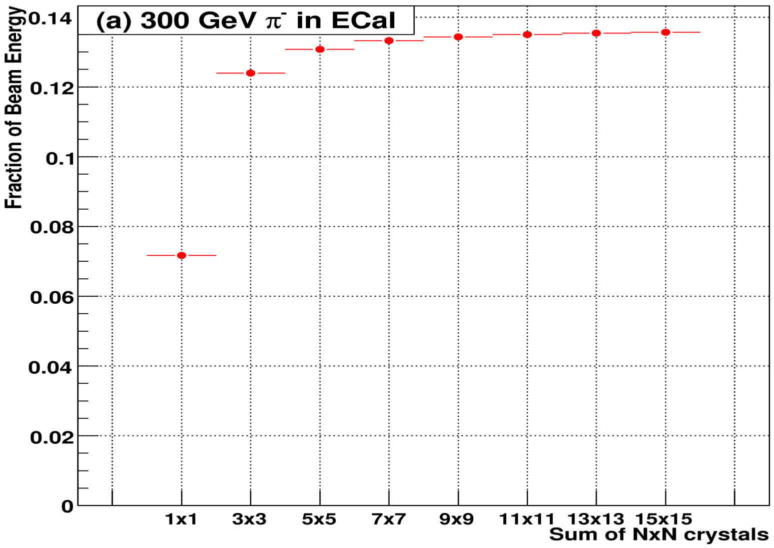
$\tilde{\nu}_e$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$
290.42	290.42	278.09

$\tilde{g}$	$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$	$\tilde{\chi}_4^0$	$\tilde{\chi}_1^+$	$\tilde{\chi}_2^+$
826.86	**141.48**	264.98	451.73	467.18	264.79	467.88

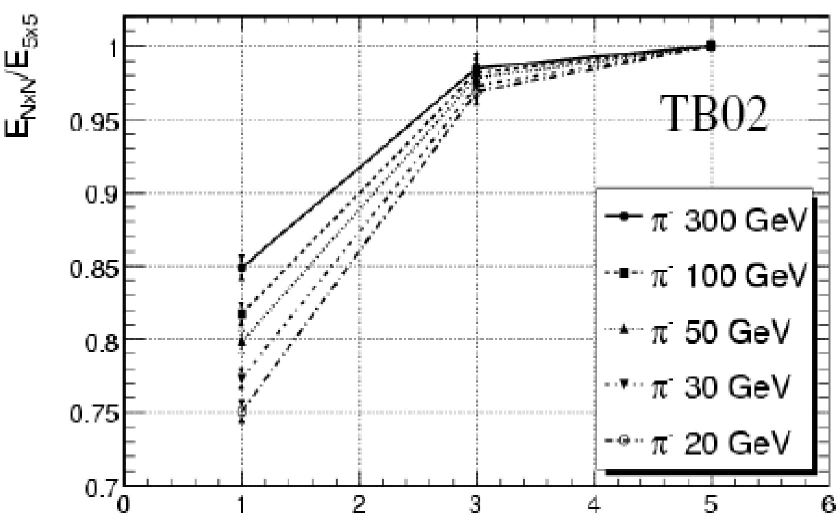
- $\tilde{\chi}_1^0$ is the Lightest SuperSymmetric Particle and is stable
- $\tilde{q} \Rightarrow q + \tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ (BR($\tilde{\chi}_2^0 \rightarrow \tilde{\tau}\tau$) = 96 % and BR($\tilde{\chi}_1^+ \rightarrow \tilde{\tau}\nu_\tau$) = 95 %)
- $\sim$ 58 % events have a τ which decayed hadronically and can be tagged as a τ-jet

Energy Measurement

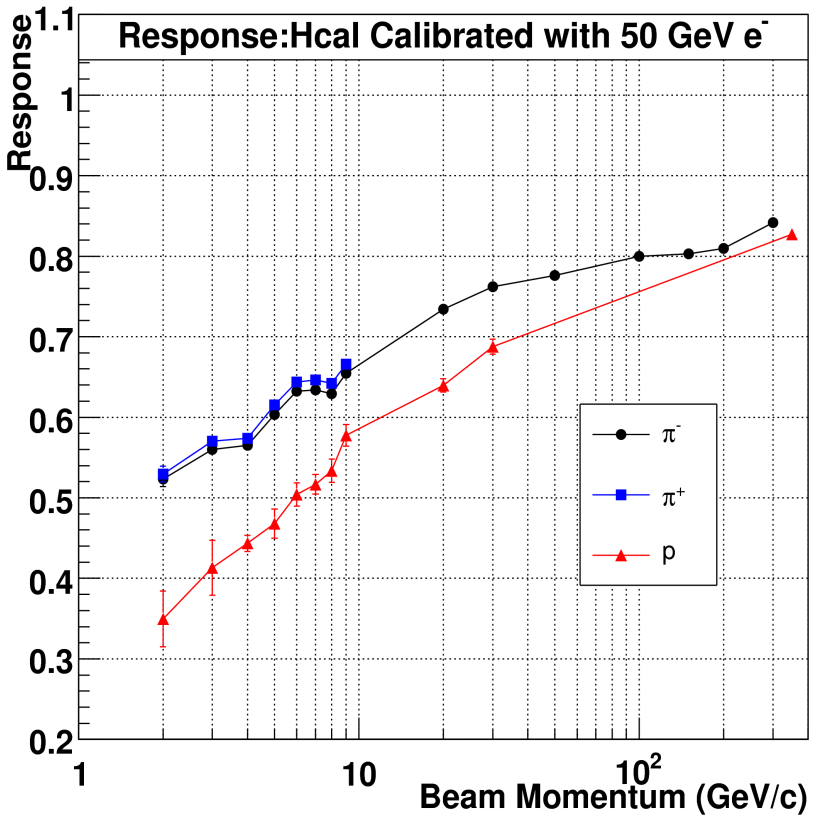
Sum 7x7 crystals to get the total energy in ECAL

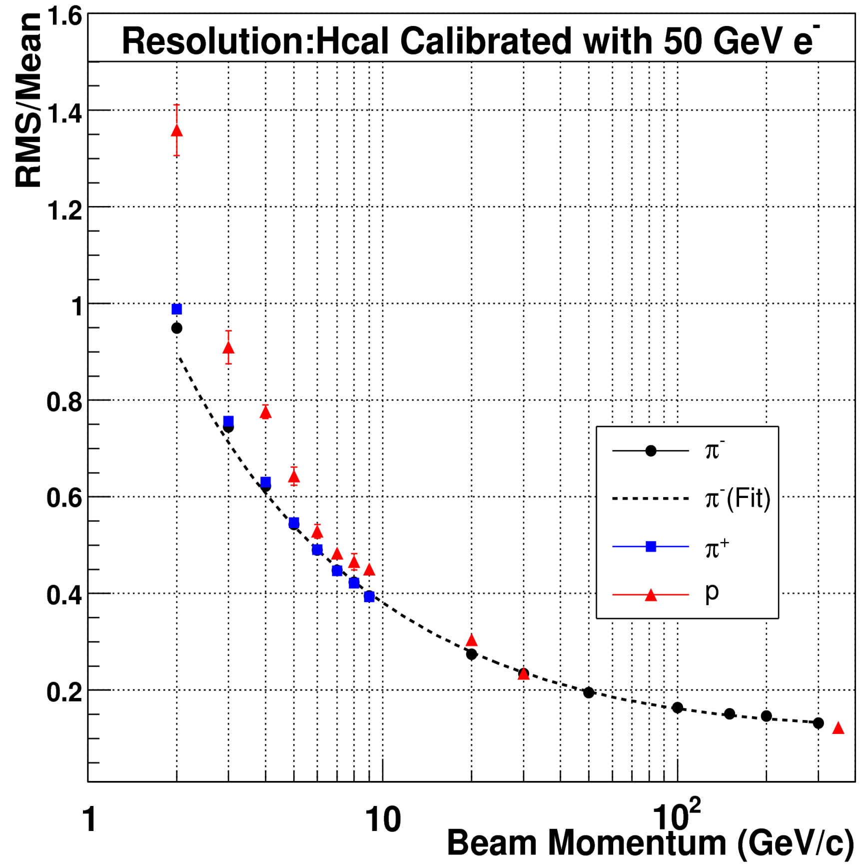


Add 3x3 HB towers to get the total energy in HCAL



Response and Resolution





The calorimeter responds identically to pi-/pi+ (response of pi+ is higher by ~1.5 %)

For a given beam momentum, the response of pions is higher than the response of protons (energy dependent)

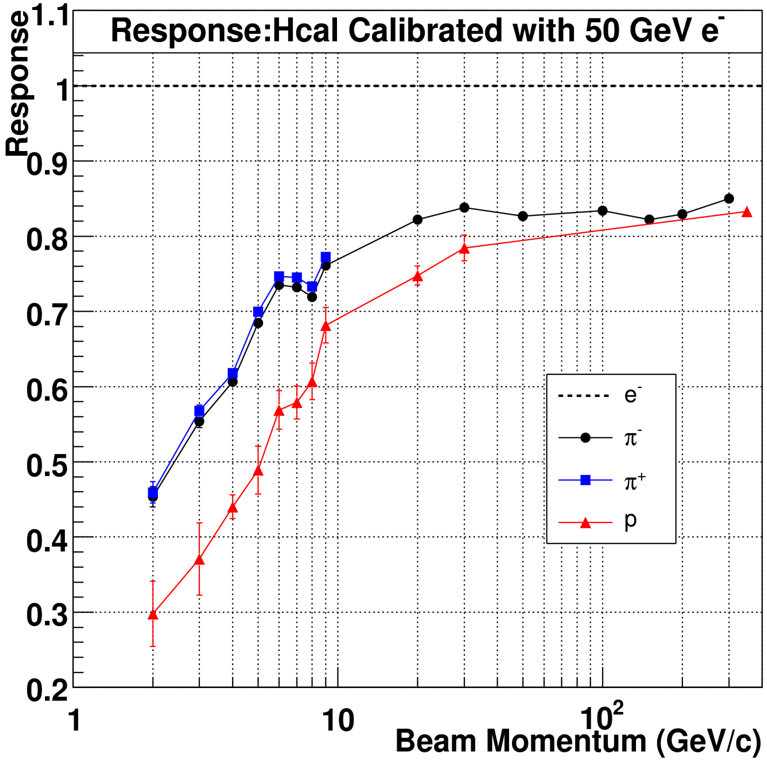
a=1.125

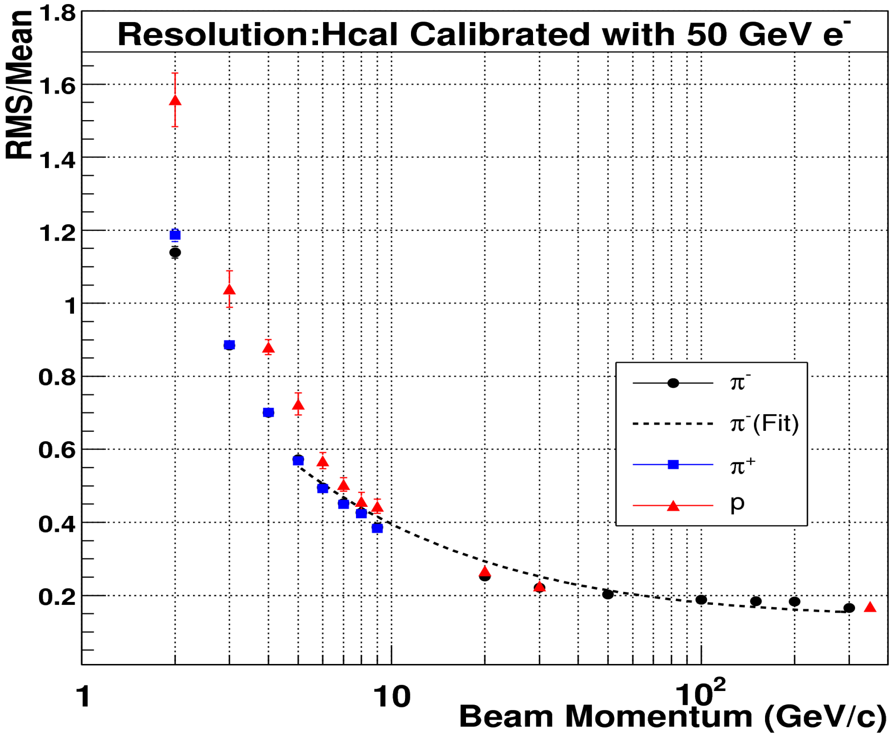
b=0.116

c=0.800

Response and Resolution (MIPs in ECAL)

The particles which behave like MIPs in ECAL are important to calibrate the HCAL towers in situ using isolated tracked produced in pp collision





The resolution of HCAL to the particles which don't shower in ECAL (> 4 GeV) is

a=1.153, b=0.13, c=0.800

The constant term is worsened by the longitudinal leakage of the late starting showers at higher energies and can be improved by including HO in energy measurement