Outline – If Time Permits

- Lecture V
  - Collider Detectors – Vertex and Tracking
  - Electromagnetic Calorimetry
  - Hadronic Calorimetry
  - Radiation Field, Neutrons

Particle ID

Particle type	Tracking	ECAL	HCAL	Muon
γ				
e				
μ				
Jet				
Et miss				

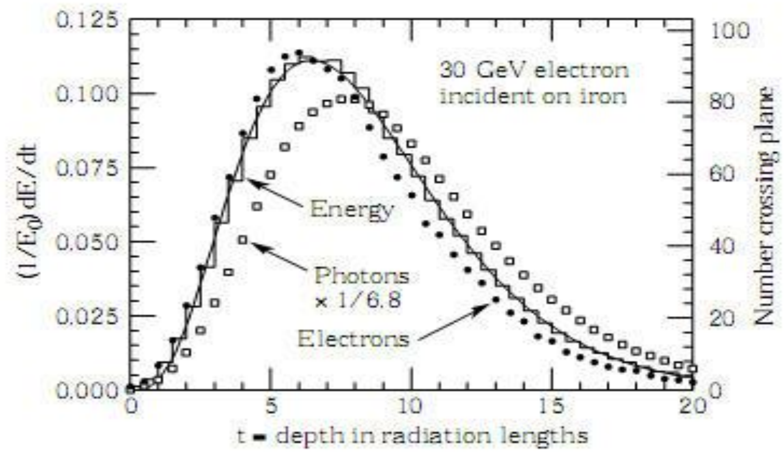
Use subsystems – tracking, calorimetry (ECAL, HCAL) and muon detectors to identify the SM particles.

Electromagnetic Calorimeter

Physics driver: Z width

$$\Gamma_Z = 2.5\,GeV, M_Z = 91.2\,GeV$$

$$(dE/E)_{ECAL} < \Gamma_Z / (2.36 M_Z) = 1.2\%$$



EM Shower

$$t = L / X_o$$

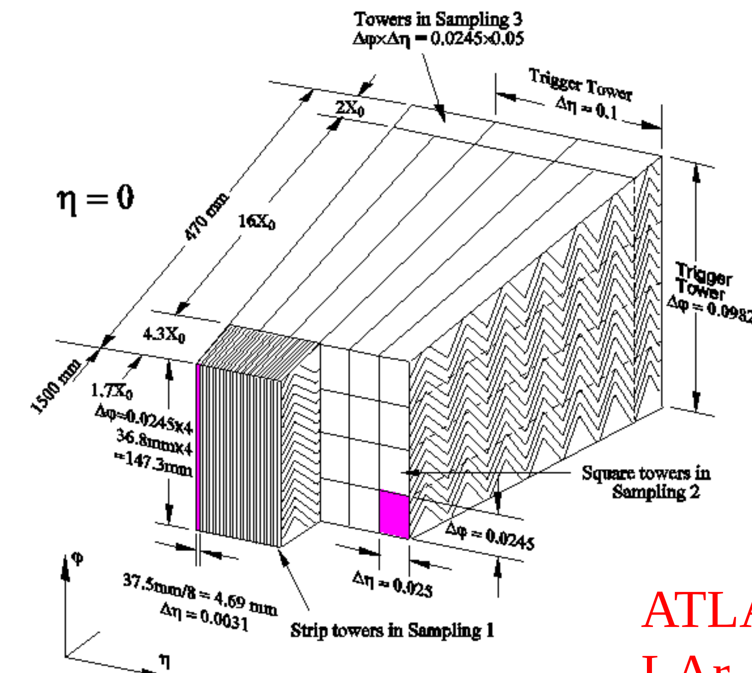
$$dE/dt = E_o b (bt)^{a-1} e^{-bt} / \Gamma(a)$$

$$t_{\max} = (a-1)/b, b \sim 0.5$$

a~1+(ln)y))/2

$$N_s \sim (E/E_c) \sim 2^{t_{\max}}$$

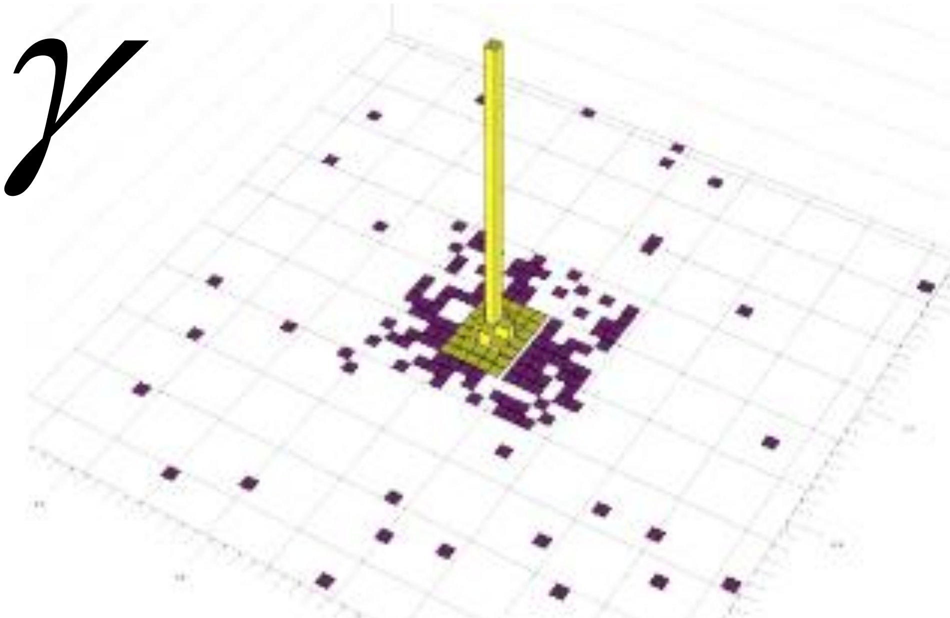
$$t_{\max} \sim \ln(E/E_c)$$



ATLAS
LAr

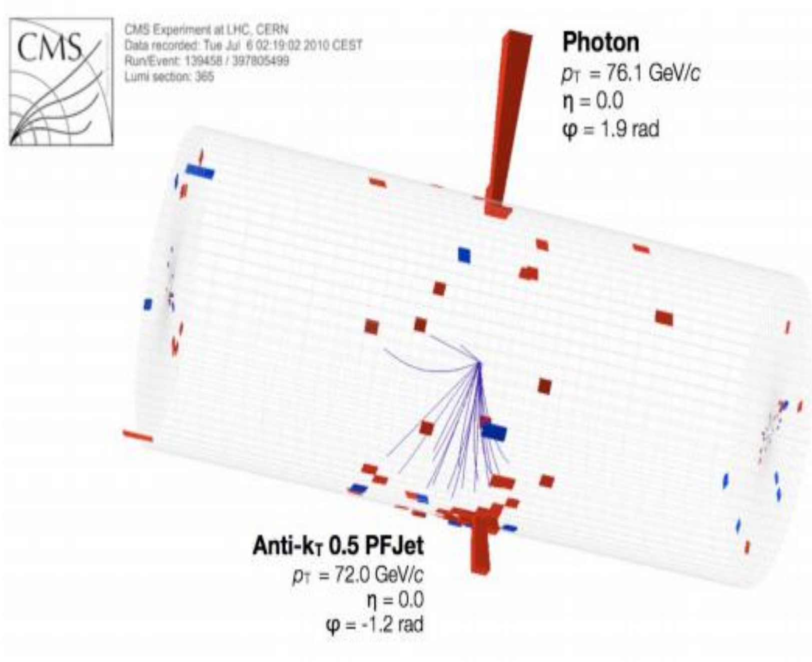
Photons, Electrons and ECAL

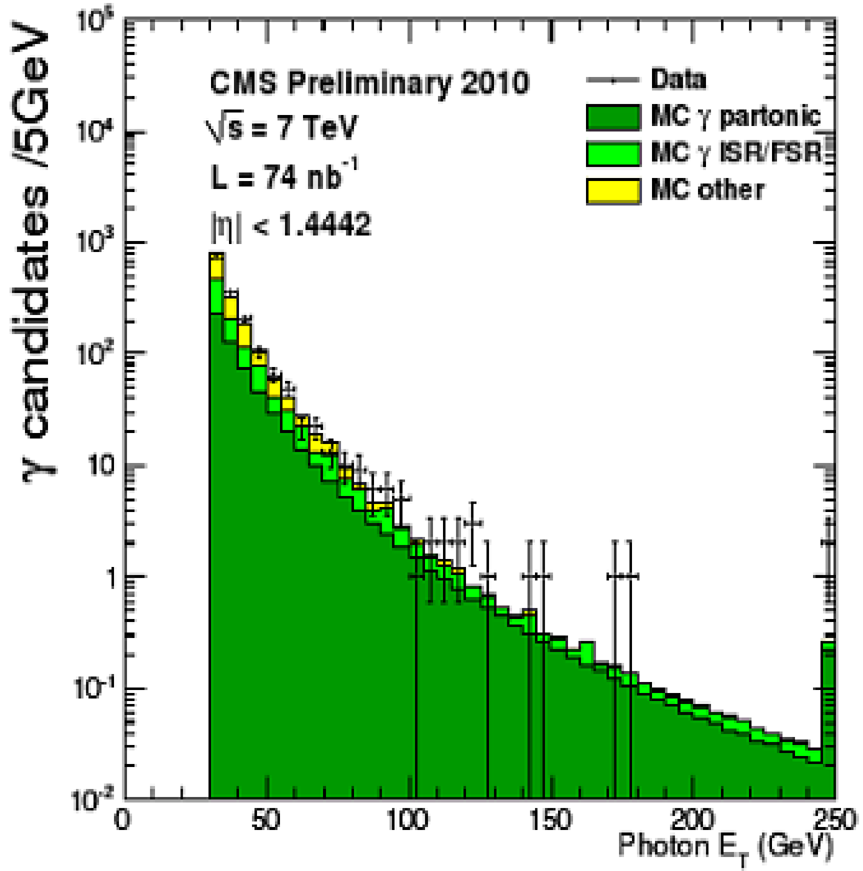
γ



The CMS ECAL has a transverse segmentation ~ 1 Moliere radius. Use that fine granularity for photon ID and for track matching in the case of electrons. ECAL energy resolution is very good for E/p matching of the e track. Tracker is best below ~ 20 GeV, ECAL above.

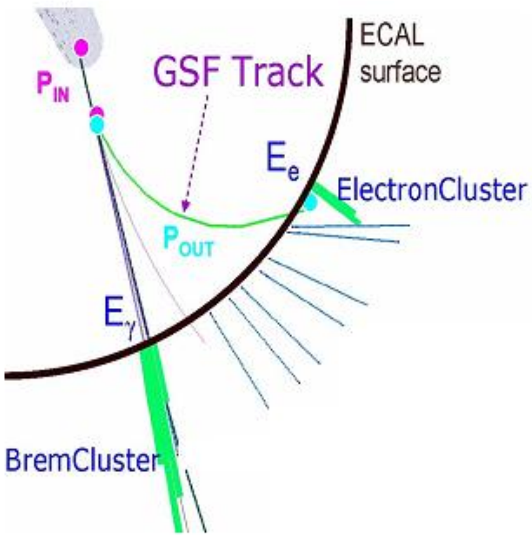
Photon Commissioning



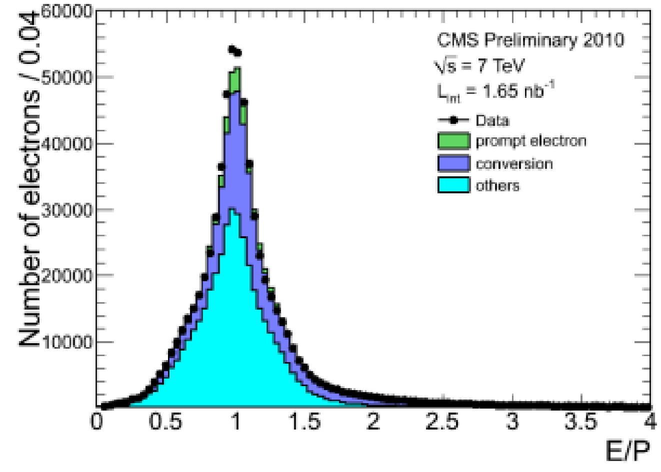


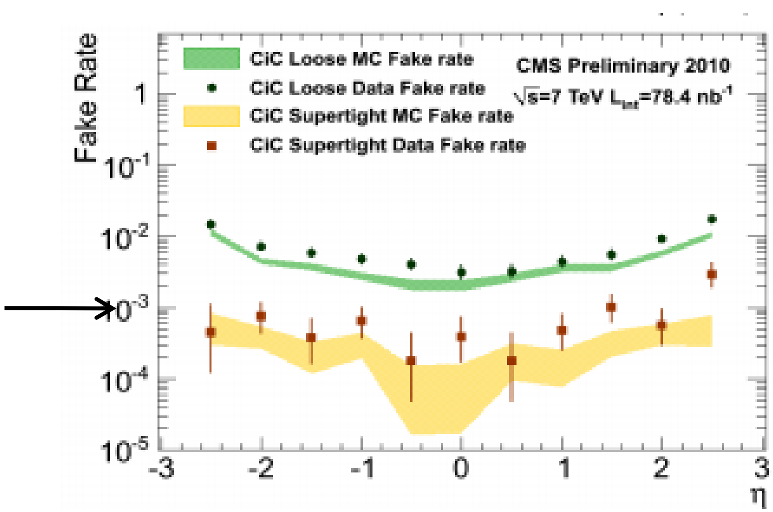
Clean photon + J events ("Compton scattering with initial state gluons in the p). Photon spectrum quite clean for high Pt photons, > 100 GeV. Data /Monte Carlo agreement is good.

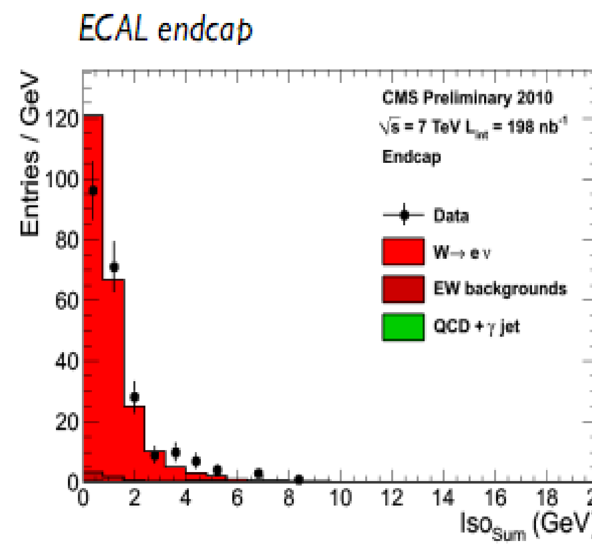
Electrons – Track + ECAL



Understanding material of the CMS tracker is crucial. Bremm in pipe and Si -> collect E in φ Use E/p and isolation







Eiso

Muon Systems

$b \rightarrow c + \mu + \nu$

At low muon Pt the rate is dominated by HF decays

σ_μ ~ 60 μb

$R_\mu = \sigma_\mu L$ ~ 0.6 MHz

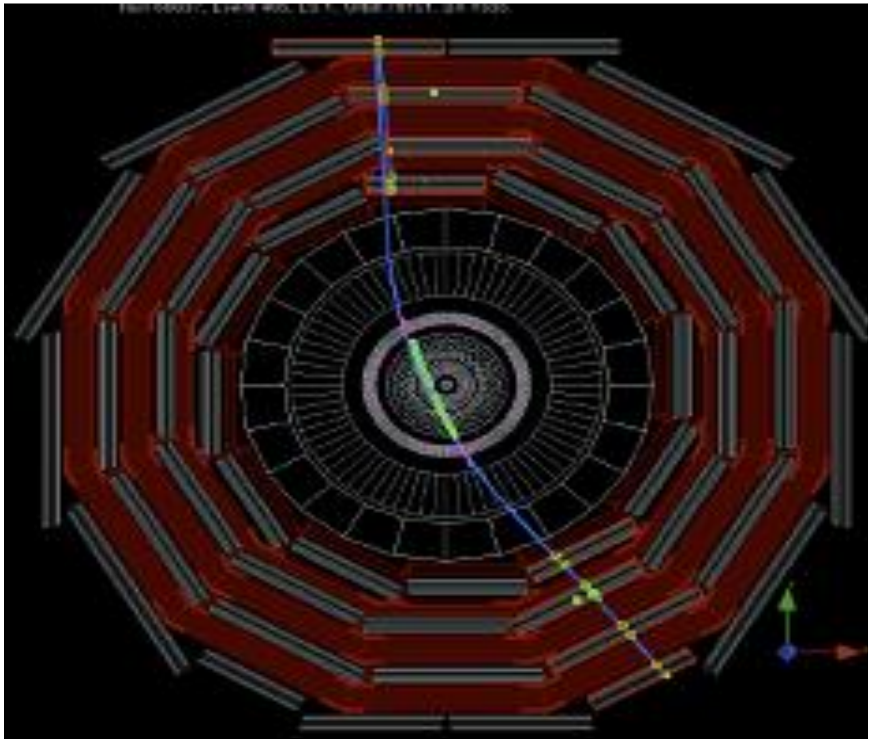
The muon trigger must have a sufficient resolution to reject these low momentum muons.

$d\sigma / dP_{T\mu} = ae^{-P_{T\mu}/P_o}$

$e^{(\Delta P/P_o)/2}$

With a steeply falling spectrum, resolution is crucial in control of trigger rates.

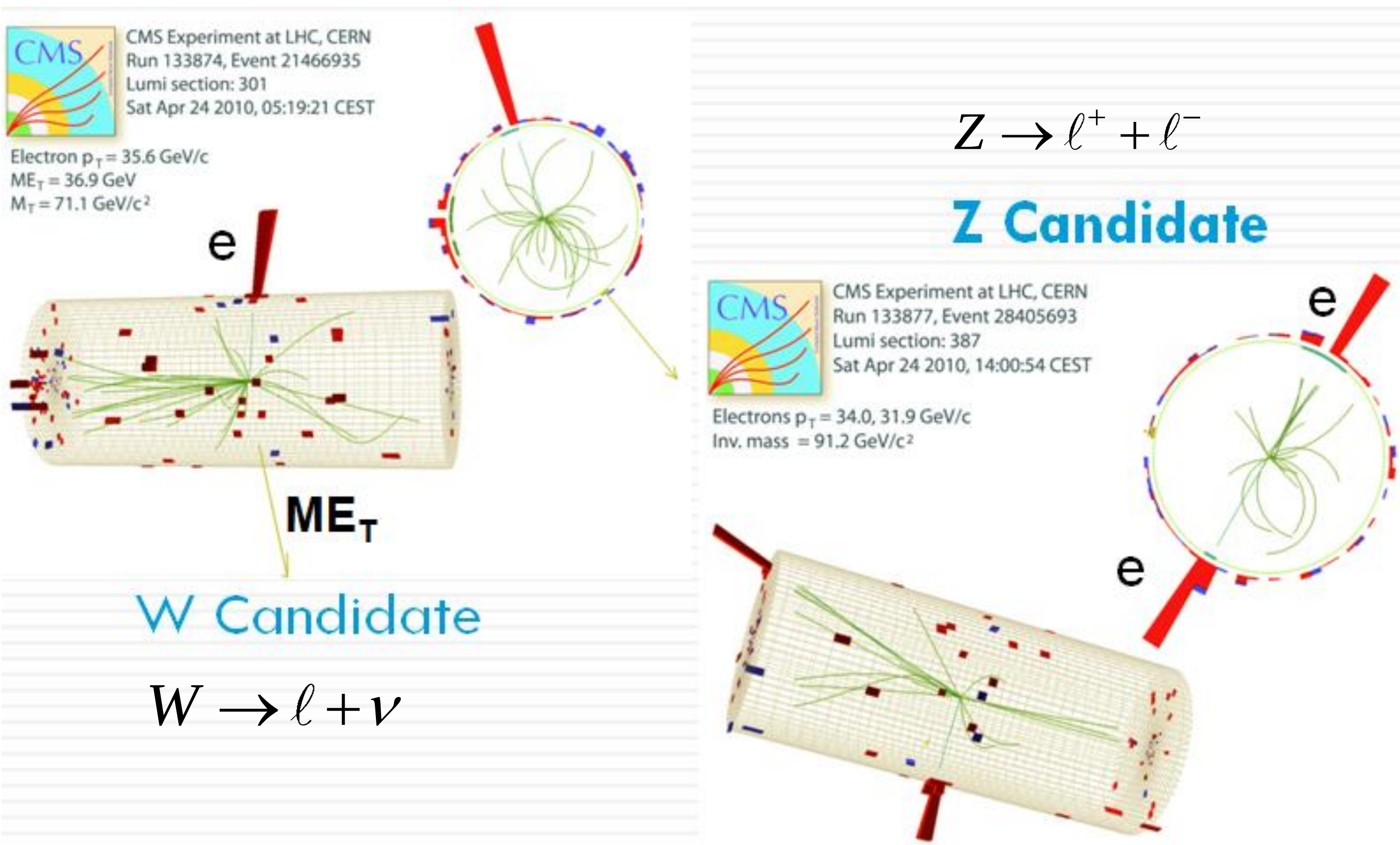
Muon Commissioning



CMS – DT/CSC in Fe return yoke => multiple scattering limited.

Experience from ~ 10^9 muons recorded before beam in the LHC. Muons up to 1 TeV in cosmics – gives experience with showering muons (critical energy). LHC “halo” also used for alignment of large |y| muon and tracking detectors - break alignment degeneracies.

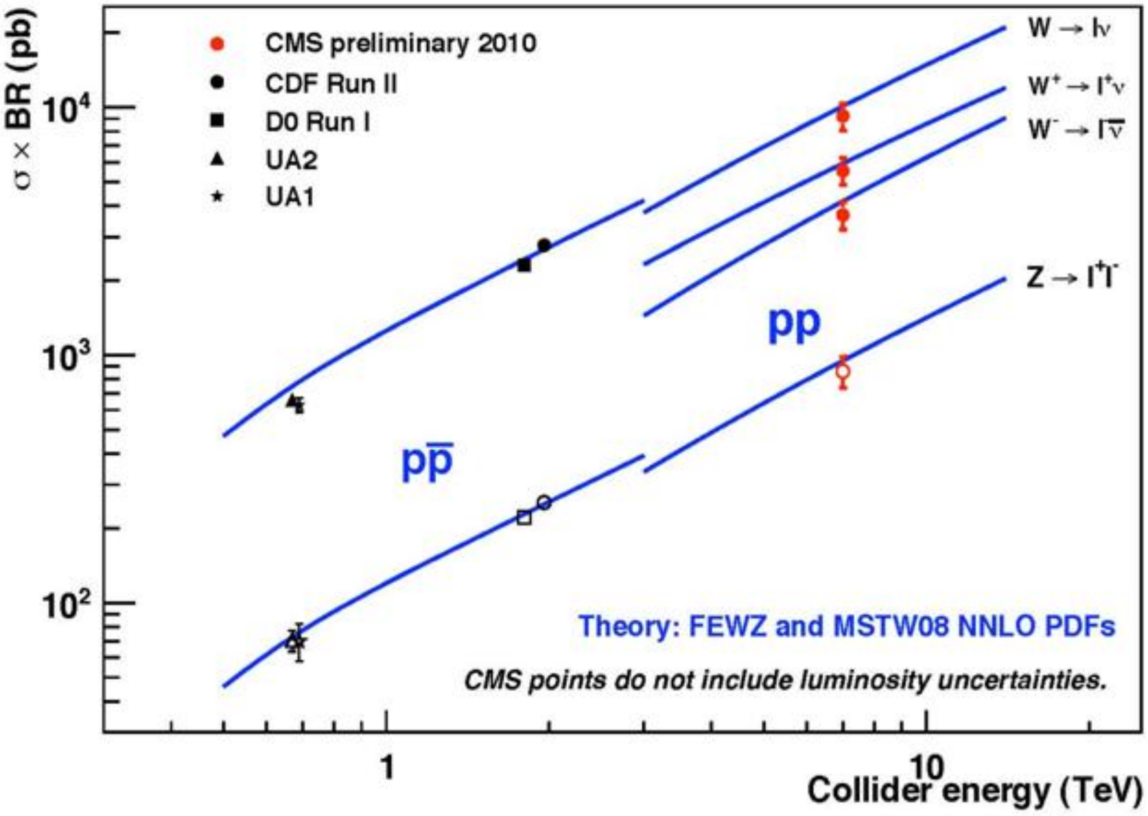
EW Physics – W and Z, Electrons



$$Z \rightarrow \ell^{+} + \ell^{-}$$

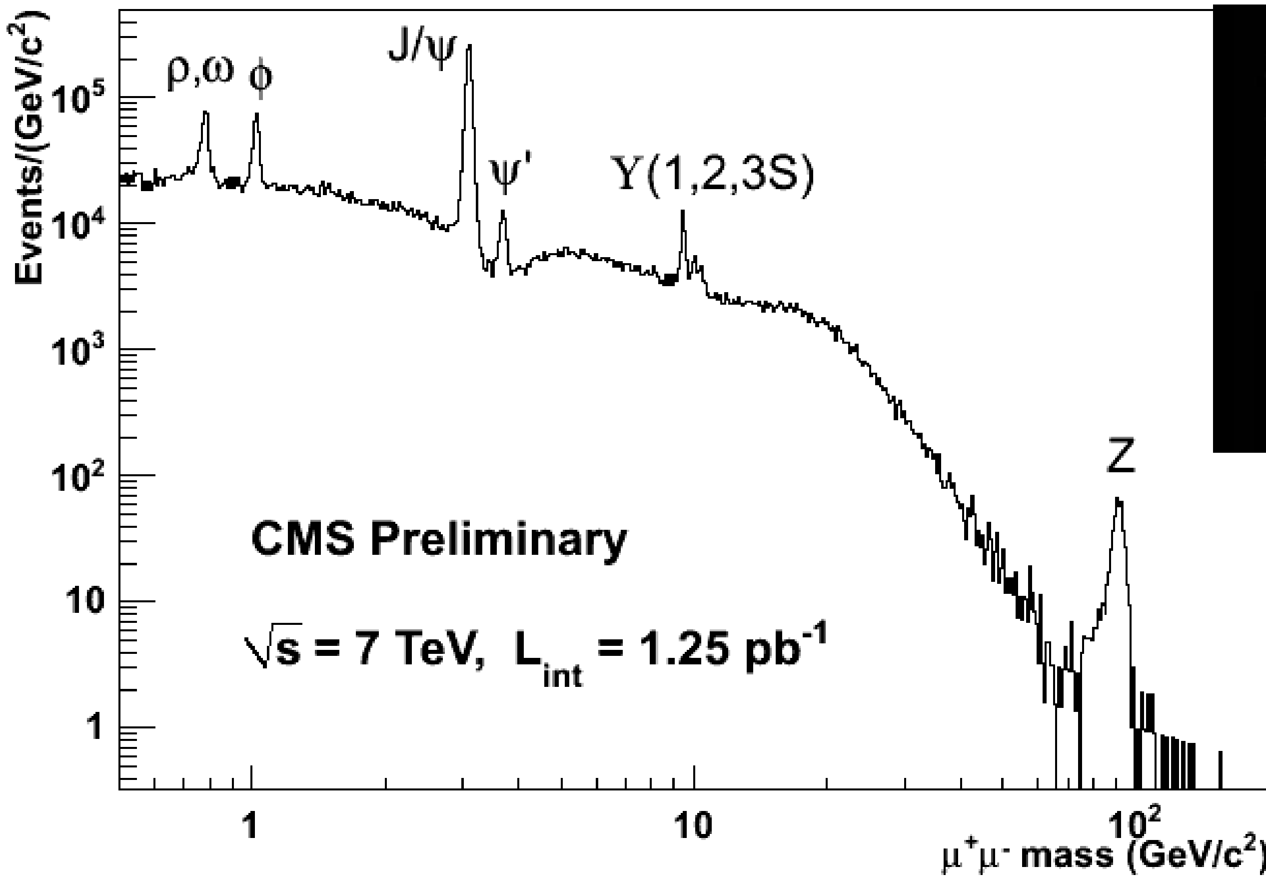
$$W \rightarrow \ell + \nu$$

EW Cross Sections



Luminosity error at ~ 4%. Use W/Z calculations and van der Meer methods as a cross check.

Dilepton “Standard Candles”

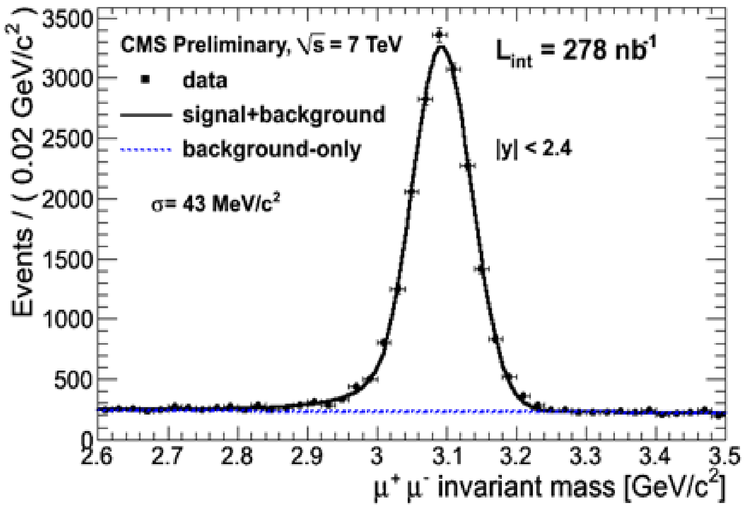


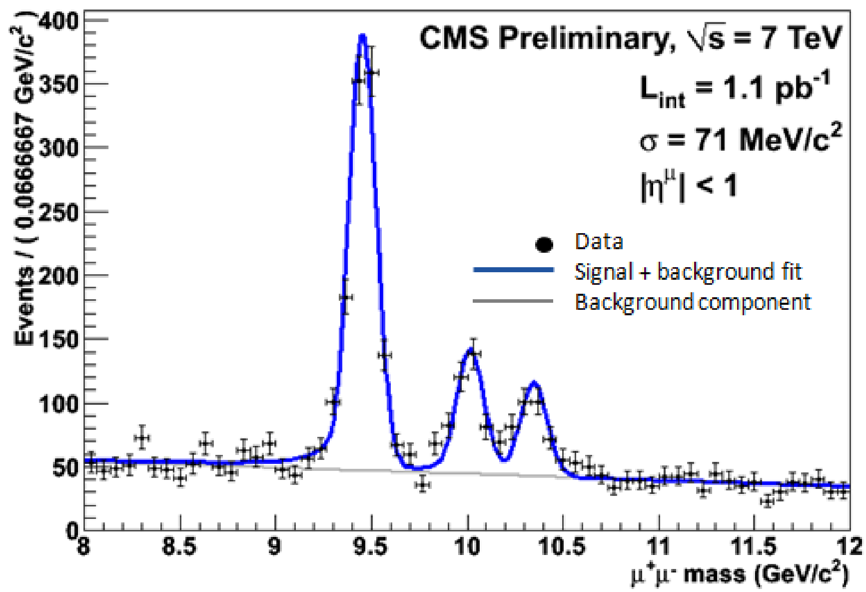
Use known resonances for mass scale, mass resolution and trigger/reco efficiency – “tag and probe”

Mass Scale and Resolution

ψ

Υ - $\sigma / M \sim 0.7\%$





The several "standard candles" will light our way to new discoveries. Used to cross check the momentum resolution of the tracker and the energy resolution of the ECAL.

Hadron Calorimeter - HCAL

Physics goal –
Hadronic W width

$$W^+ \to u + \bar{d}, c + \bar{s}$$
$$\Gamma_W / M_W = 2.6\%$$
$$(dE/E)_{HCAL} \sim 1.1\%$$

How "deep" should the HCAL be?

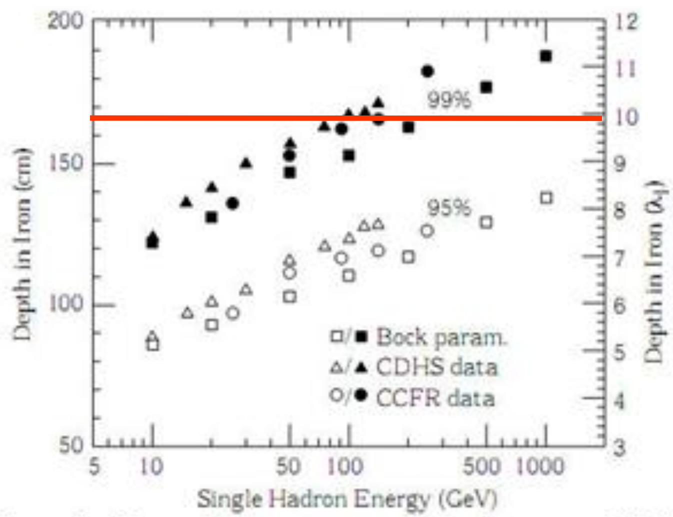


Figure 16: Depth needed for a shower energy containment of 95 % and 99 % as a function of hadron energy. Note the logarithmic dependence of depth on incident energy [8]

E Resolution, Segmentation

$$E_{th} \sim 2m_\pi$$ **= 0.28 GeV**

As with ECAL, there is a limit due to stochastic number of cascade particles. Analogue to critical energy is the threshold for pion production. This means that hadronic calorimetry will have worse resolution than ECAL – estimate 53% stochastic coefficient.

$$\delta\eta = \delta\phi = 0.094 \sim \lambda_o / r_H$$

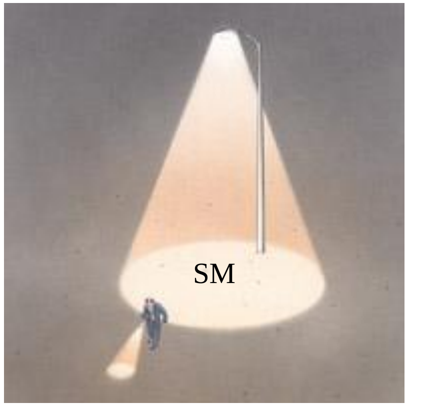
$$(D_c = 6)(N_I = 25)(\delta\eta)^2 / 2\pi$$ **= 0.21**

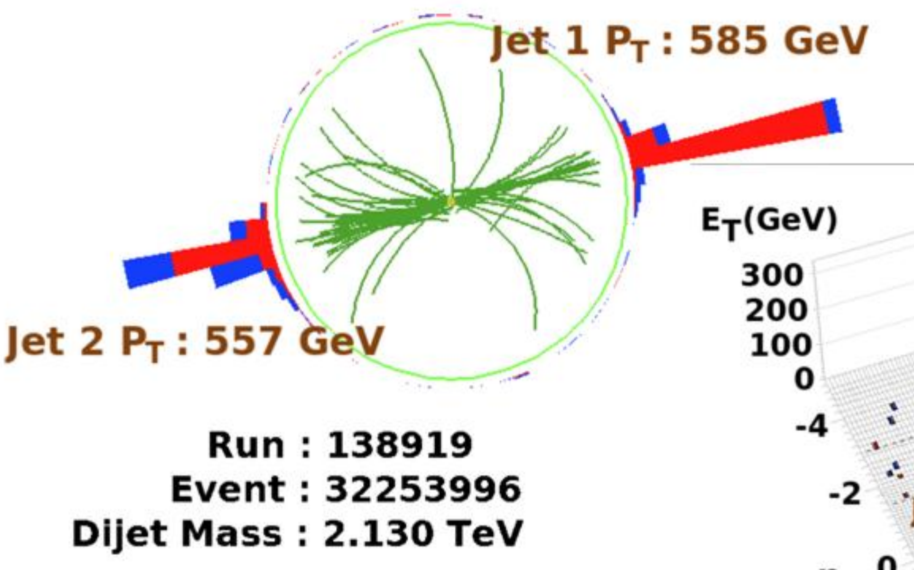
3 depth segments – 13,470 channels in barrel

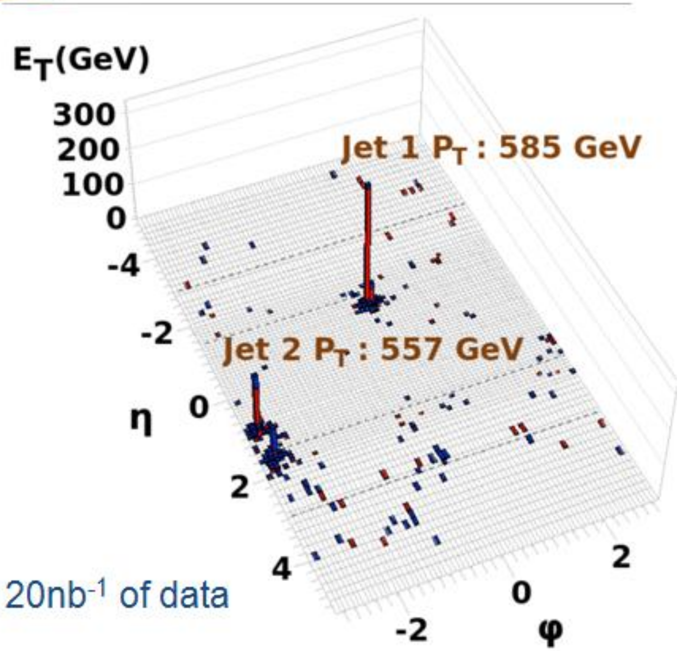
Transverse size is also large, ~ inelastic interaction length. HCAL towers are coarser than ECAL -- ~ 25 ECAL towers = 1 HCAL tower. The probability to have a PU hit in a tower per bx is that factor higher.

Searches in Jet Events

Having commissioned SM, go out from under the lamp post….. First event above the Tevatron kinematic limit…..

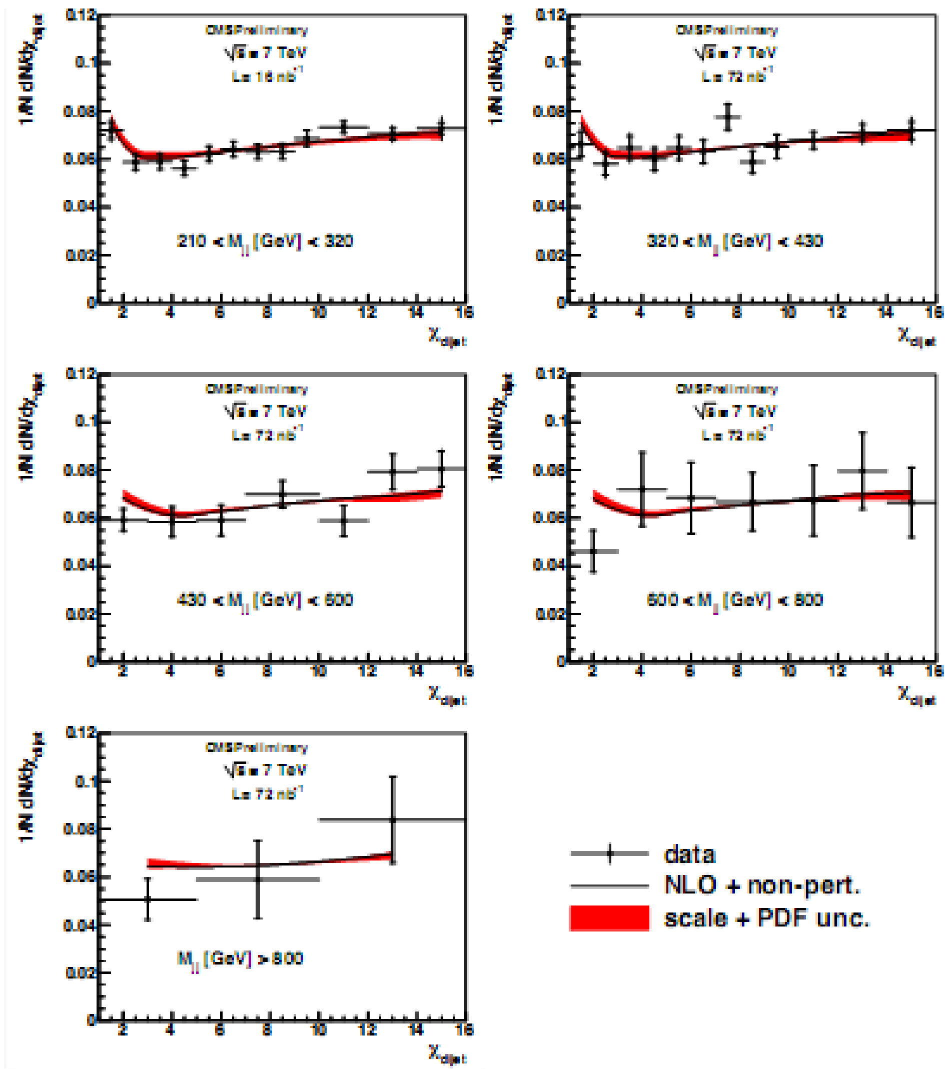






The highest mass dijet event in the first 120nb^{-1} of data

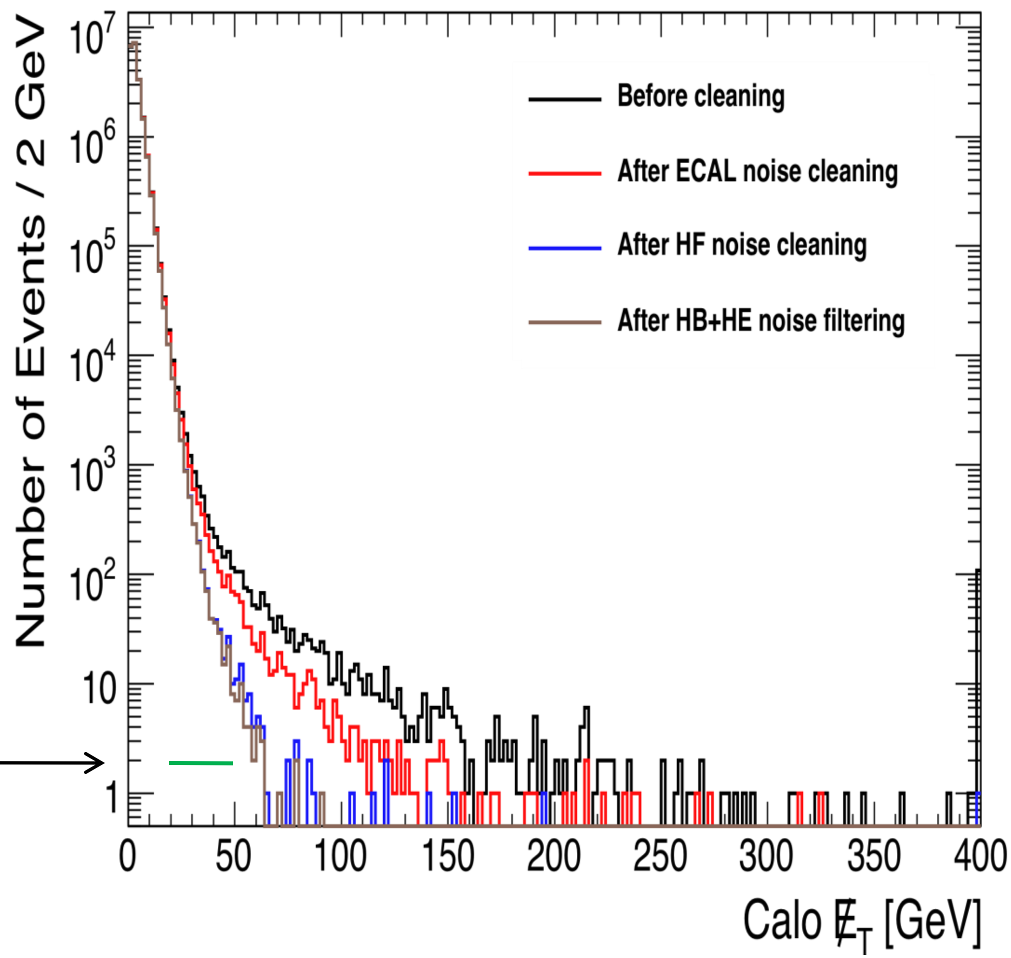
Jet Angular Distributions



Look for more central, S wave, BSM effects. SM is t channel dominated -> flat chi distribution.

MET – "Tail" and Noise Filtering

10x
EW



MB events :
The MET noise filtering greatly reduces the tail. An irreducible floor is set by the EW processes, which are ~ 10^7 times smaller in cross section than the inclusive MB events.

MET commissioned to ~ EW scale – ν_e, ν_μ, ν_τ

Pileup/Fragmentation and Jets

As the LHC luminosity increases the pileup of events becomes more difficult. Jet fragmentation favors low energy particles. These become hard to distinguish from the particles from minimum bias events – use PF and vertex sorting for the charged particles. A jet (R = 0.5) has $N_I D < P_T > / 2\pi$ ~ 28.6 GeV of pileup pions which need to be removed.

$$D(z) \sim (1-z)^a / z$$

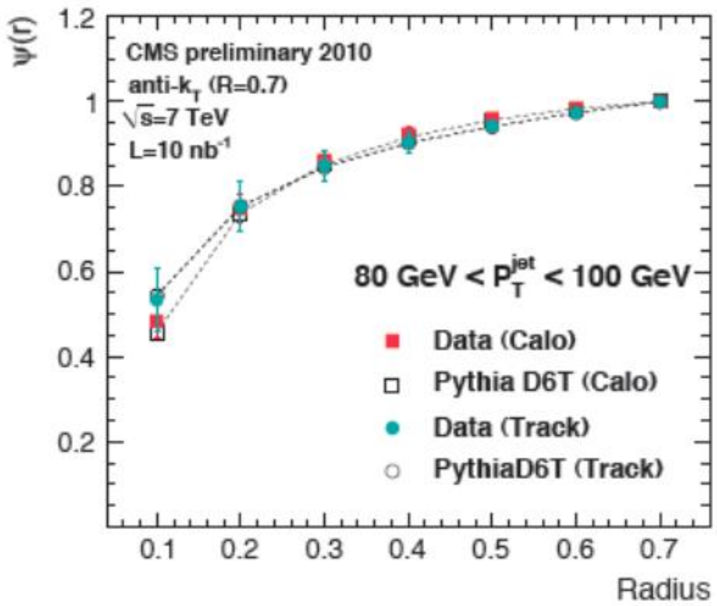
$$F \sim 1-(1-z_{\min})^{a+1},\ z_{\min} = (p_{had})_{\min} / P_{jet}$$

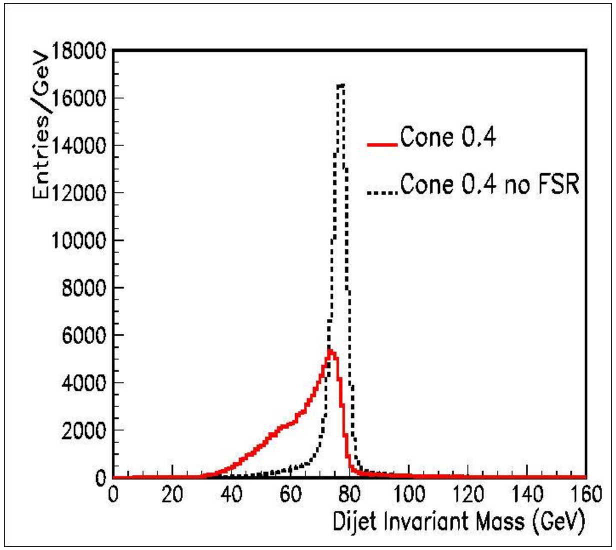
A 50 GeV jet has ~ 45% of its energy carried by hadrons with momenta less than 5 GeV and ~ 12 % carried by hadrons with momenta less than 1 GeV. Thus the soft hadrons from the jet are easily confused with the soft pions from the pileup which then limits the achievable jet energy resolution.

FSR – Jet Spectroscopy.

$$R = \sqrt{\delta\eta^2 + \delta\phi^2}$$

A "cone size" of ~ 0.5 is needed to contain most of the jet energy - fluctuations

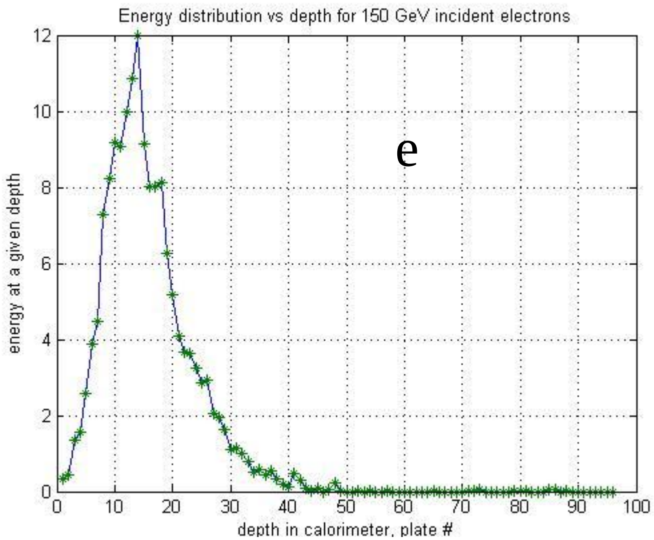


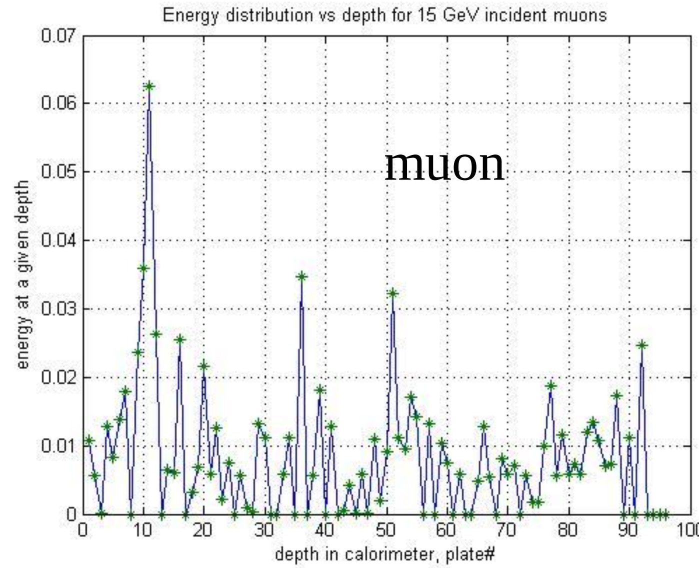


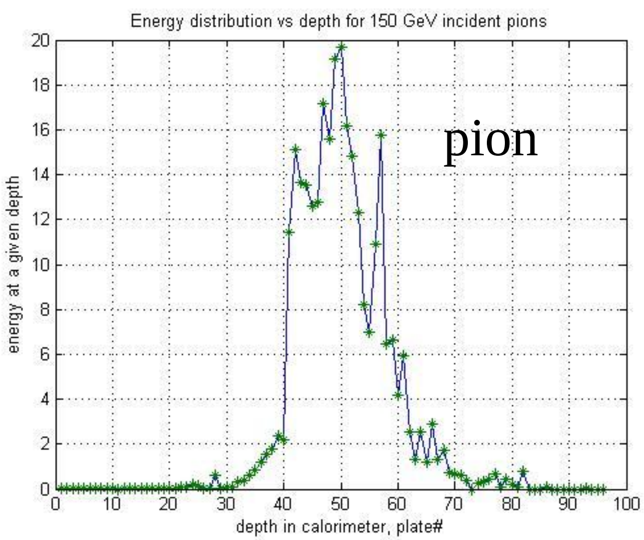
$$fract \sim (\alpha_s / \pi)[3\log(R) + 4\log(R)\log(2\varepsilon) + \pi^2/3 - 7/4]$$

A 10 % radiation of the total jet energy outside a cone of R = 0.5 occurs ~ 12.5 % of the time. Gluon ISR and FSR is a limitation.

Demo - Calorimetry - I

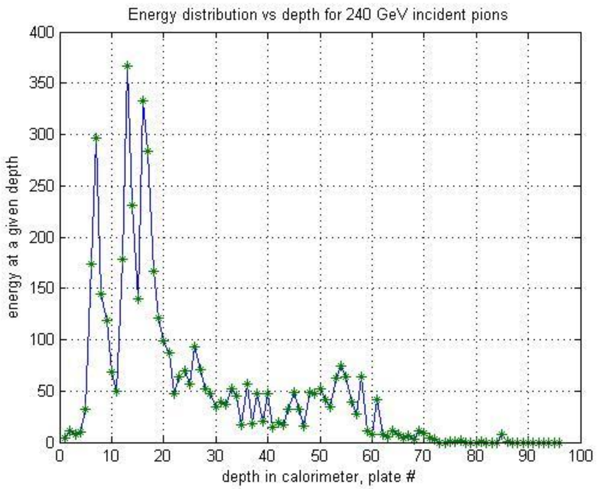


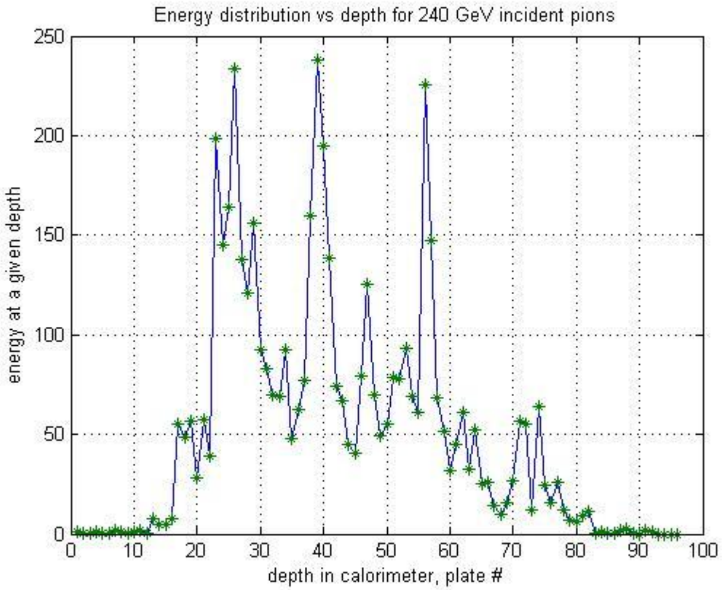


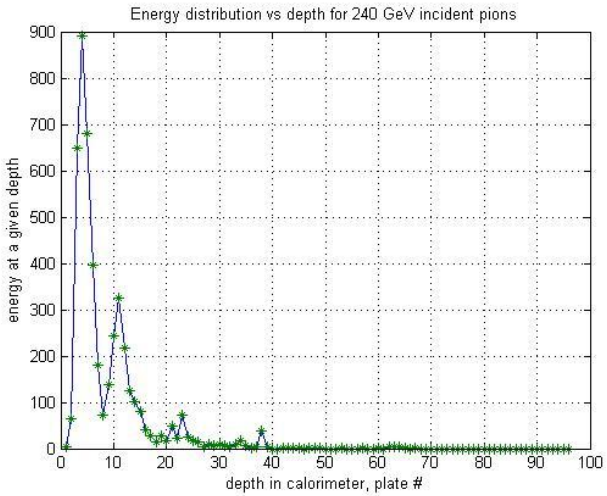


This is a “classical” ECAL+HCAL. Test beam data where each sampling layer is read out.

Demo - Calorimetry - II

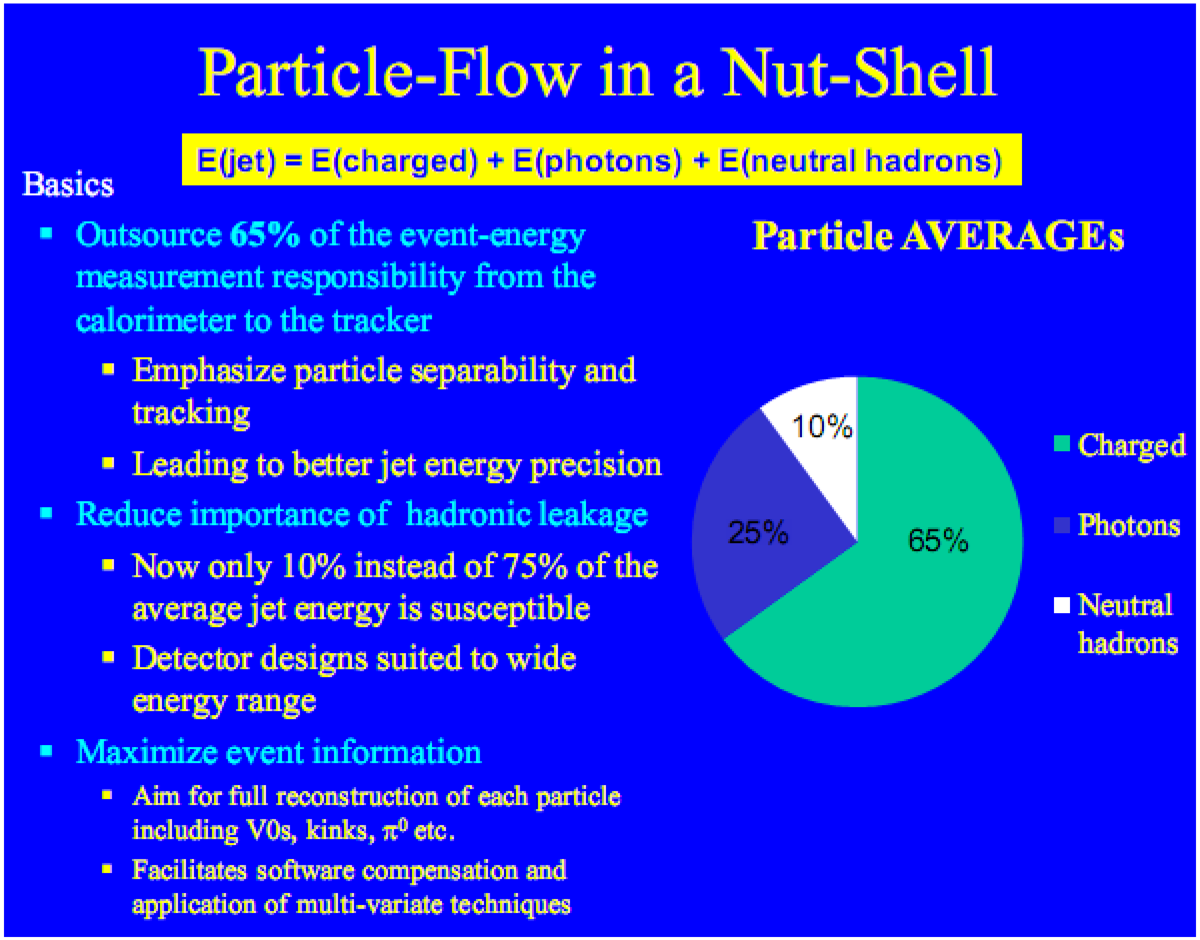






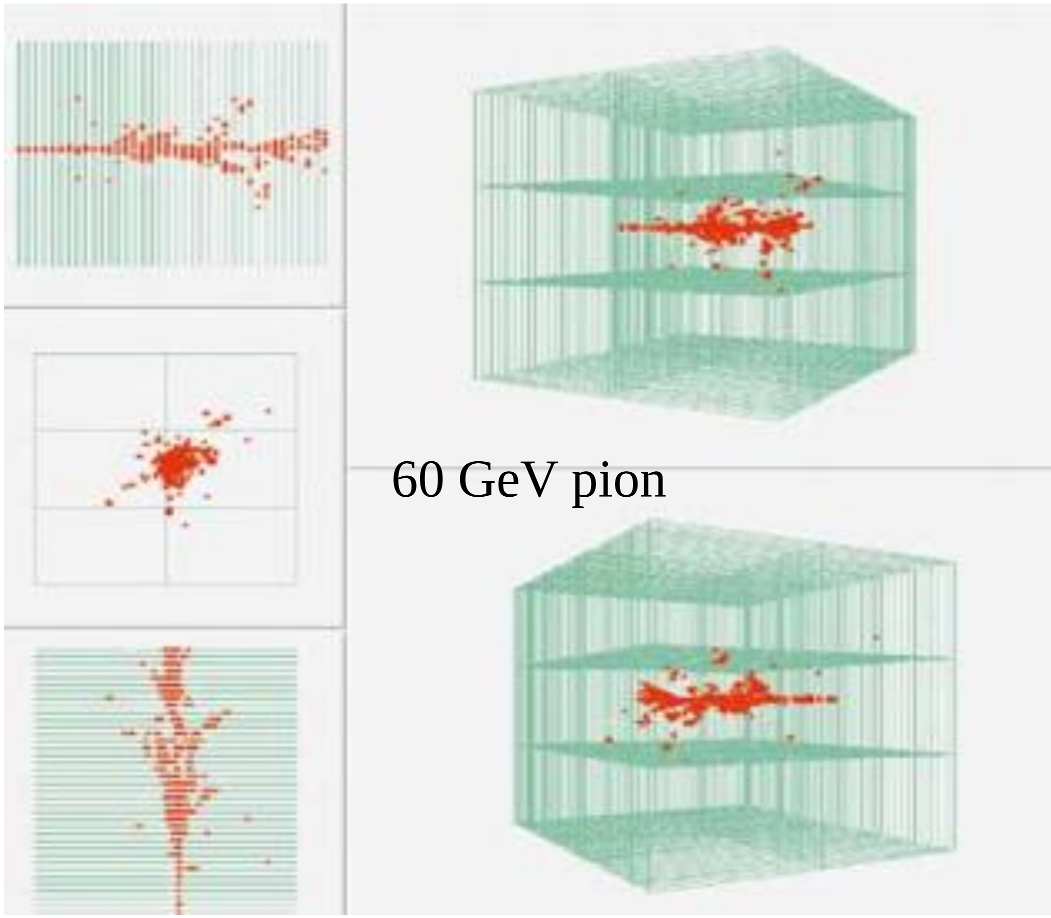
Pions incident on a homogeneous Pb calorimeter. This array has a large Xo to interaction length ratio so that the neutral pions from the sequential hadronic interactions are quite visible.

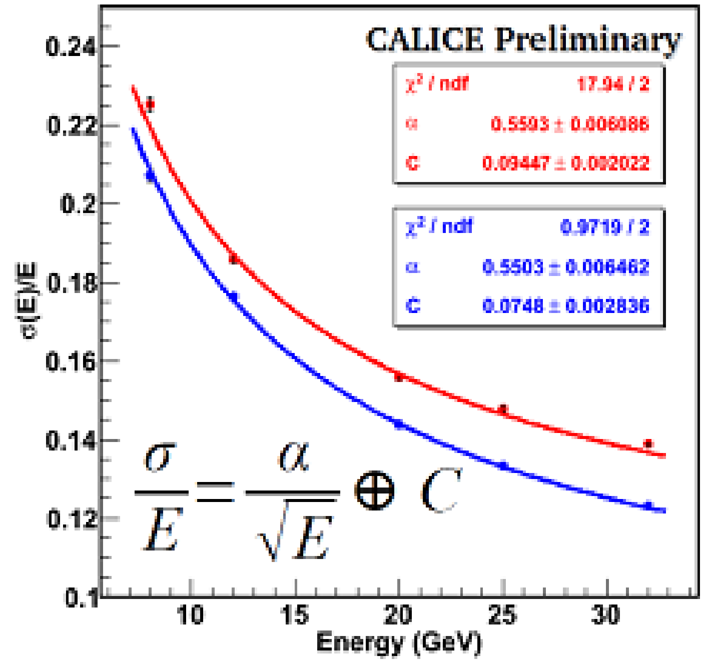
Particle Flow and Calorimetry



Tracking has a fractional momentum resolution that is ~ p, while calorimetry has a a resolution that goes as a constant or as the inverse sqrt of the energy. Therefore, combine the measurements so that the best resolution obtains.

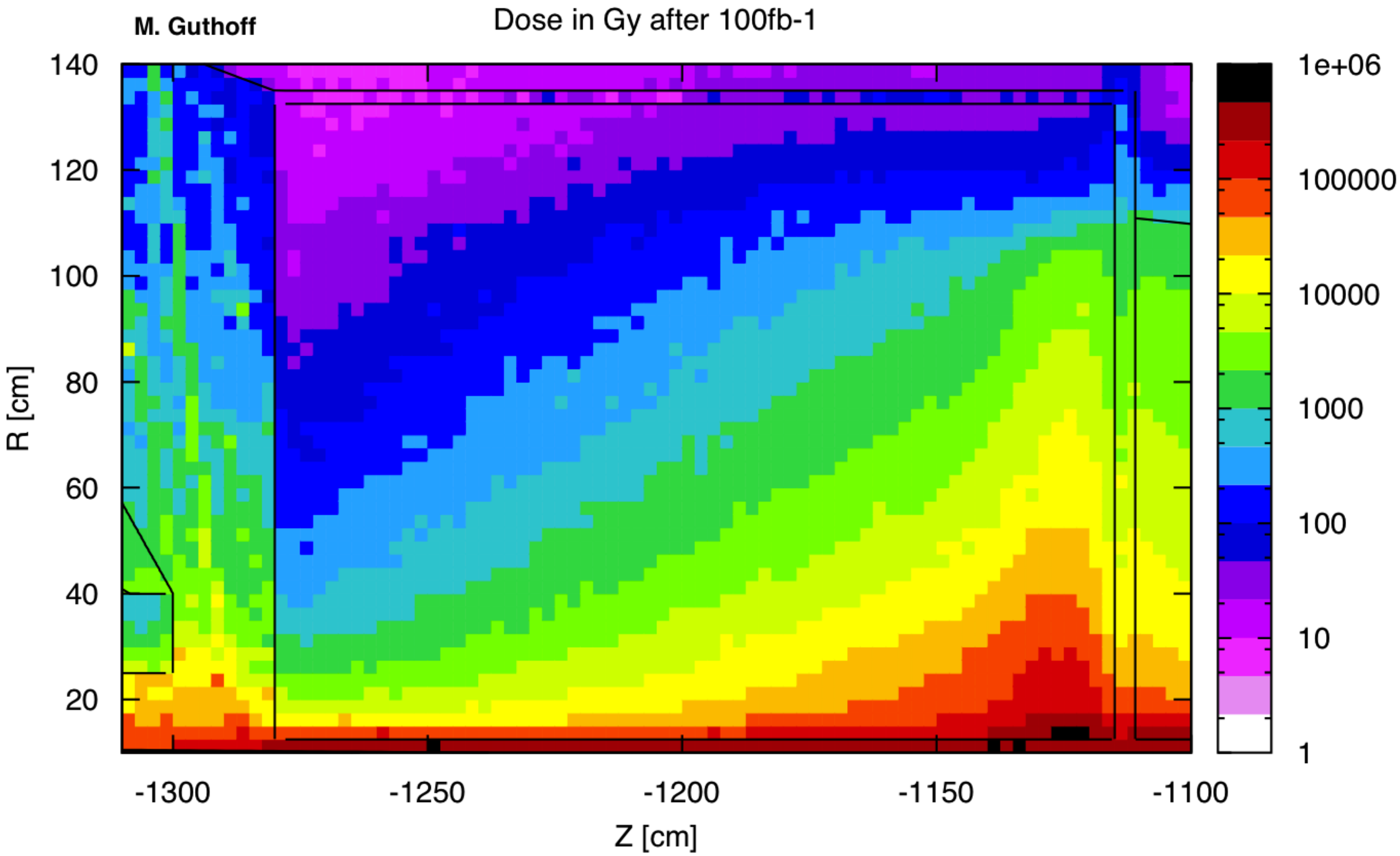
DHC Calice





To match tracks to energy deposits very fine grained , dx ~ Xo ~ dy~dz, calorimetry is needed. ILC prototypes are exploring these concepts.

Radiation Dose - CMS



The radiation dose in hadron colliders requires radiation resistant detectors and front end electronics. This is a major problem at the SLHC.

Neutrons

$$\sigma_I LTD_c (1/2\pi r_F^2) = 9.5x10^{11}\ \pi^{\pm}/cm^2 yr$$

At r = 1 m.

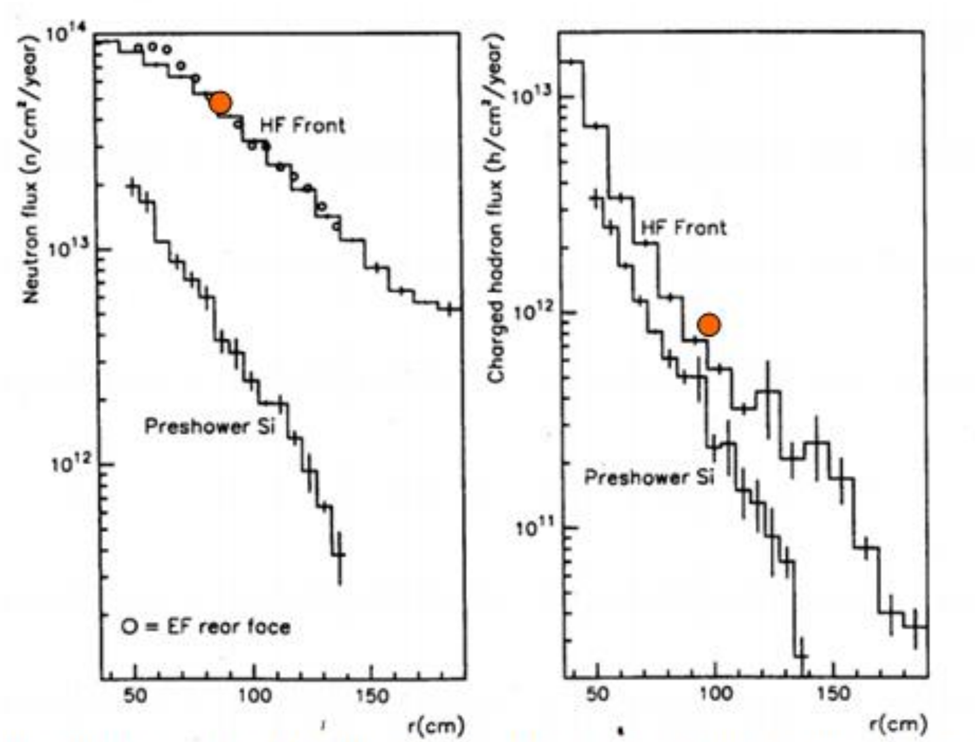


Figure 20: Charged particle flux, right, and neutron flux, left, as a function of radius for calorimetry at z = 10 m [4].

Interactions in HCAL disrupt the nucleus – which de-excites and recoils – emitting neutrons. As a crude rule of thumb there are about 5 neutrons with a few MeV kinetic energy produced per GeV of absorbed hadrons.

$$3.82x10^{13}\ n/(cm^2 yr)$$

The intense n "sea" is ~ specific to hadronic detectors and is a serious rad issue.