Hadron Collider Detectors
“Generic LHC”

Dan Green
Fermilab

EWSB and Why LHC?

- There are many theoretical speculations. One thing is certain, W+W scattering at a CM energy of ~ 1.8 TeV violates perturbative unitarity.

$$A_o = \alpha_W \hat{s} / 16 M_W^2 < 1$$

$$\alpha_W = \alpha / \sin^2 \theta_W \sim 1/31.6$$

$$\sqrt{s} < 4 M_W / \sqrt{\alpha_W}$$ **= 1.8 TeV**

- Therefore, design the LHC and the LHC detectors to comprehensively study WW scattering at ~ 1 TeV

WW Scattering at the LHC - LT

- **The vector bosons decay to either quark or lepton pairs. However, the enormous backgrounds which exist at the LHC due to strongly produced QCD processes make the detection of leptonic decays experimentally favored. This fact explains why LHC detectors tend to focus on lepton detection. The branching ratio for a W to decay to a muon plus neutrino is ~ 1/9. A crude estimate of the cross section for electroweak W+W production at the LHC with subsequent W decay to muons is:**

$$\sigma(p+p \to W^+ + W^- \to \mu^+ + \nu_\mu + \mu^- + \bar{\nu}_\mu) \sim (\alpha_W^2 / \hat{s}) B_\mu^2$$

- **This estimate gives a 5 fb cross section times branching ratio squared for a W pair mass of = 1 TeV.**
- **The cross section for W + W mass above 1 TeV is 640 fb (LO). Requiring two muons in the final state yields a cross section of 7.9 fb in reasonable agreement with the previous estimate. In order to have sufficient statistical power in studying this process, the LHC should provide 100 fb^{-1}/year. Taking a running time, T, of 10^7 sec/yr (~ 30 % of the calendar year) there will be ~ 790 W+W events produced per year with a mass above 1 TeV which decay into the experimentally favorable final state containing two muons. A similar event sample will be available in the two electron final state and twice that in the muon plus electron final state (3160 events).**

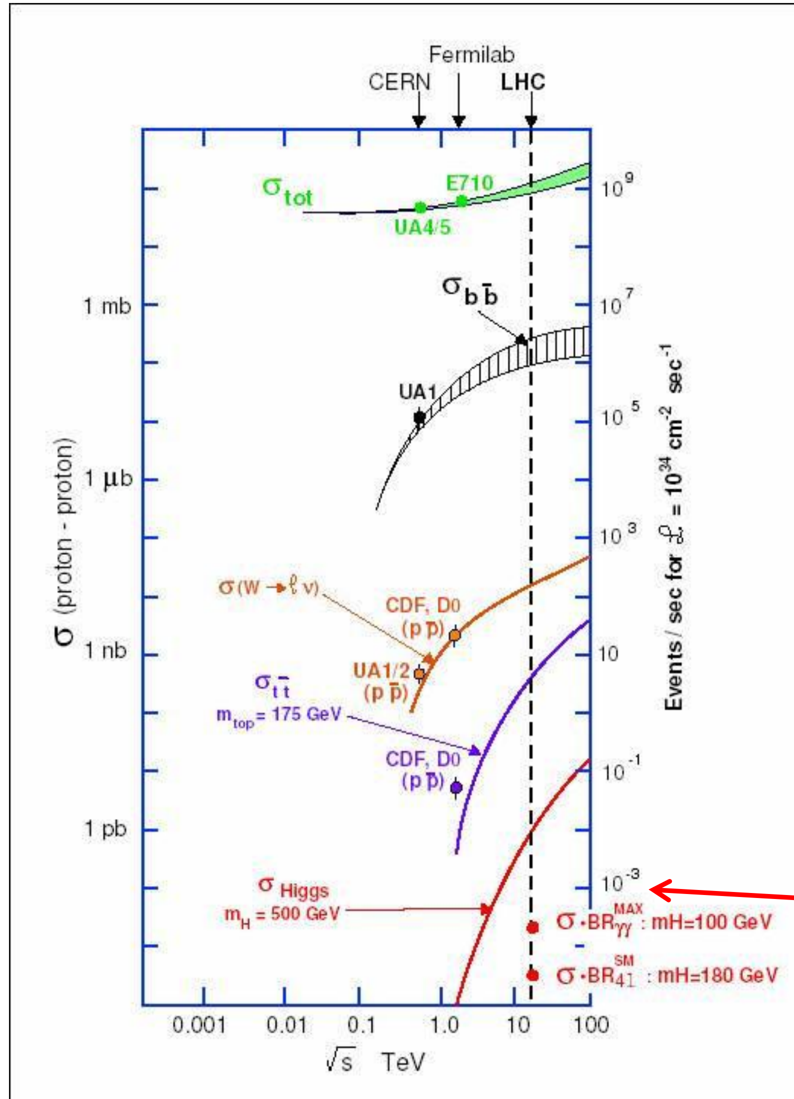
Cross Sections – S/B, Pileup

$$L = 10^{34} / cm^2 \sec, T = 10^7 \sec$$

$$LT = 10^{41} / cm^2 yr = 100 \ fb^{-1} / yr$$

Detector resolving times, e.g. Silicon strips, ~ 25 nsec =>

Inelastic rate ~ 1 GHz - 40 MHz of bx - 25 int/bx => PU, radiation issues

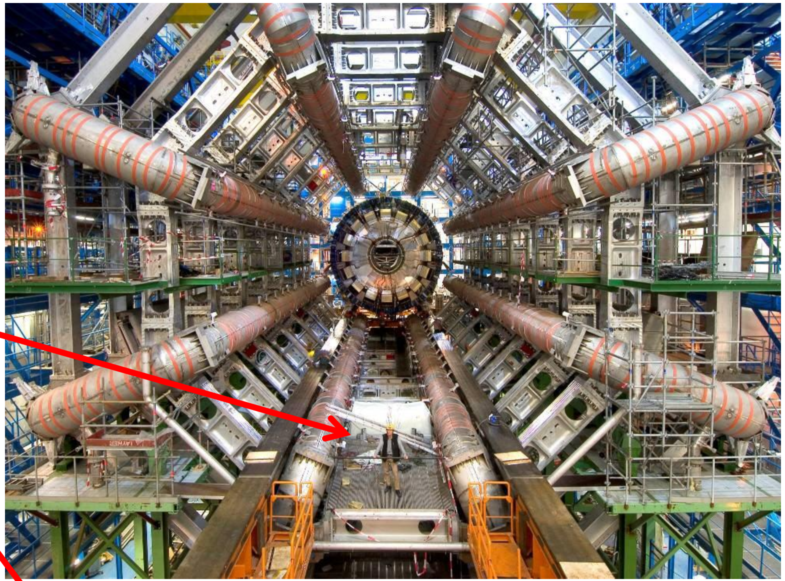


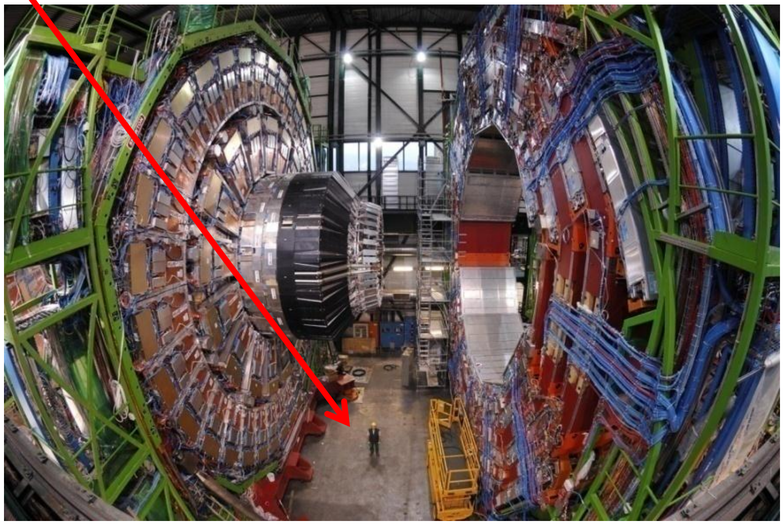
10^{-12}

The ATLAS and CMS Experiments – at the Leading Edge

Each detector is like a 100 megapixel camera which takes 40 million pictures per second. The largest and most complex scientific instruments ever built.

- Highest energy proton collider
- 1 billion interactions per second
- First silicon pixels in a proton collider
- First all silicon tracker
- 100 million channels of radiation hard electronics
- Calorimeter with 60,000 PbWO4 crystals
- First use of accordion liquid argon calorimeter
- Largest magnetic toroids
- Largest magnetic solenoid
- Selection of one in 10 million interactions at a 40 MHz speed.
- Enormous data logging rate – 1 million CD per year
- Worldwide grid computing analysis





Where Are the Particles?

$$d^4P\delta(P^2 - M^2) = d\vec{P}/E = \pi dy dP_T^2$$

$$E = M_T \cosh y,\ M_T^2 = M^2 + P_T^2$$

$$y \to \eta = -\log(\tan\theta/2),\ P >> M$$

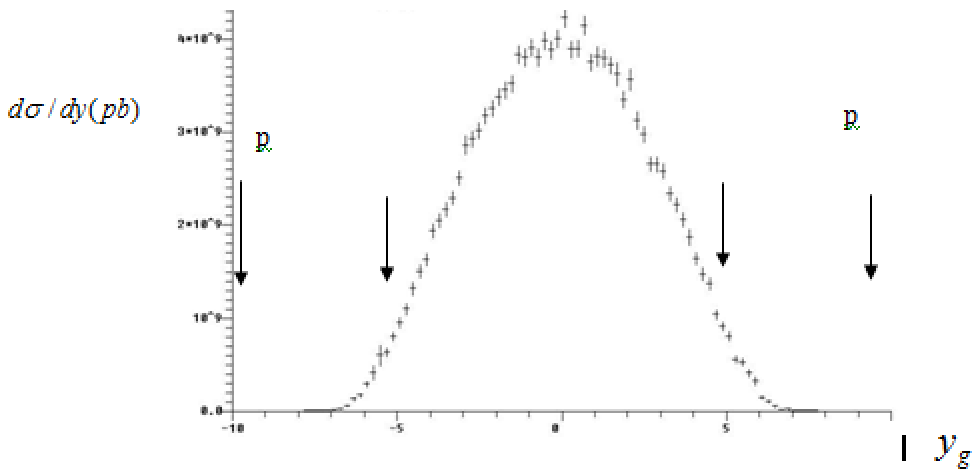


Figure 5: Rapidity distribution of low transverse momentum gluon jets at the LHC. Generic detector coverage and the incoming proton rapidities are indicated by the arrows.

$$D \sim 9\,\pi/unit\ of\ \ y,\ 6\,\pi^{\pm} + 3\,\pi^{o} \qquad D = 1/\sigma(d\sigma/d\eta)$$

$$< P_T >\sim 0.8\,GeV$$

$$N_I(2y_{\max})D = 2250\ \ particles, 1.8\,TeV\ total \sum P_T$$

Heavy Particles => "Barrel"+ "Endcap"

$$x_1 x_2 = M^2 / s,\ x_1 - x_2 = x$$

$$x_1 = [M / \sqrt{s}]e^{-y}$$

$$x_2 = [M / \sqrt{s}]e^{y}$$

$$y_{\max}(M) \sim \ln(\sqrt{s} / M)$$ ~ 1.9 for 2 TeV

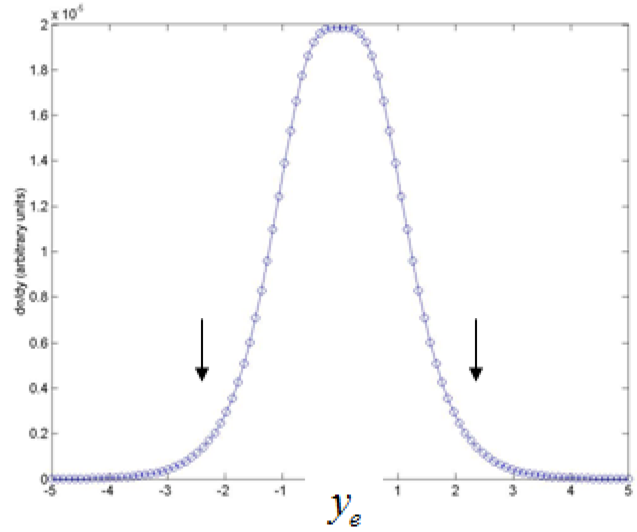


Figure 7: Rapidity distribution for the electrons resulting from the two body decay of a hypothetical 2 TeV mass recurrence of the Z boson. The limit for precision detection systems at |y| < 2.5 is indicated by the arrows.

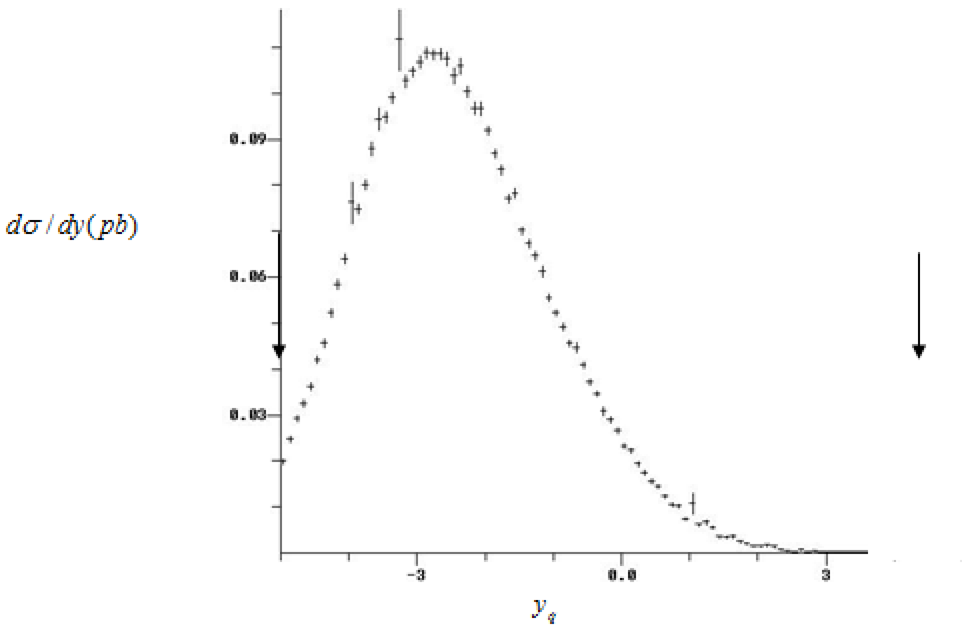
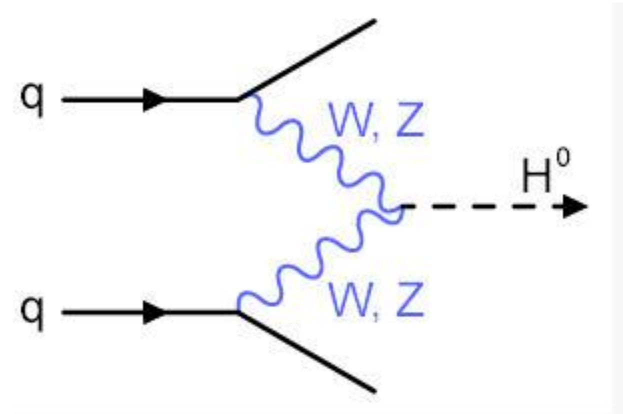


Figure 8: Rapidity distribution of the final state quark after virtual emission of a W boson in the formation of a W+W resonance of 0.2 TeV mass via the vector boson fusion mechanism. Coverage of ± five units of rapidity is needed for efficient detection of this process.



Isolate WW, WZ, ZZ scattering => jet coverage to |y| = 5, θ = 0.0135

$$
\begin{aligned}
d\eta &= [e^{\eta} d\theta]/(1+\cos\theta) \\
&\rightarrow d\theta, \eta \sim 0 \\
&\rightarrow e^{\eta} d\theta / 2 = d\theta/\theta, \ \ \eta >> 1
\end{aligned}
$$

“Generic” LHC Detector

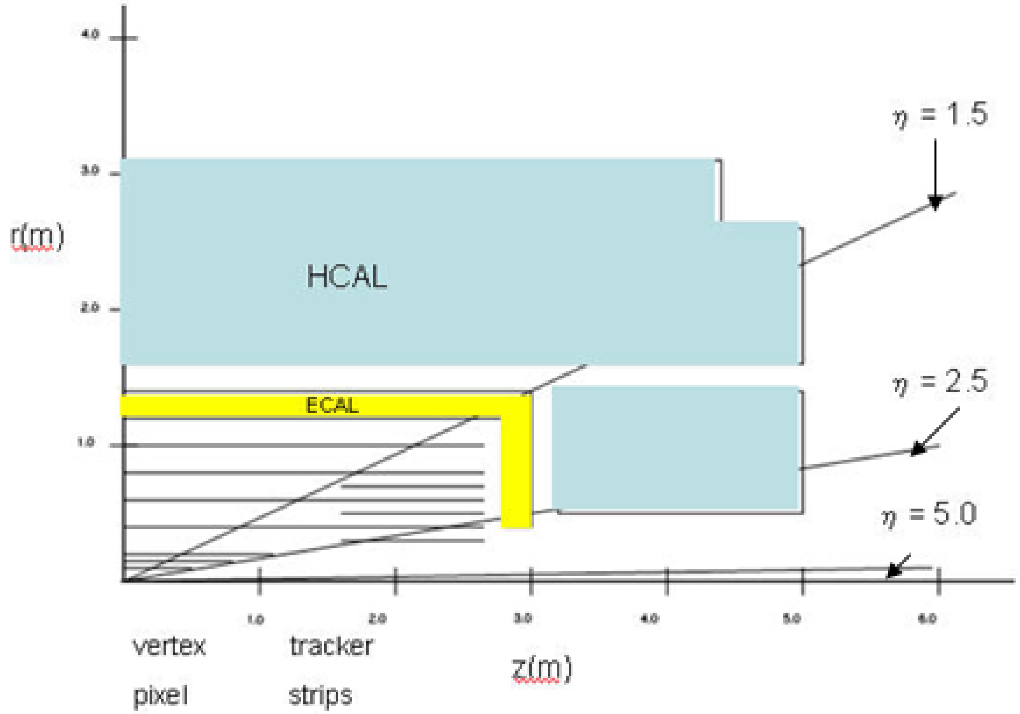


Figure 9: A “generic” LHC detector which covers ± 5 units of pseudorapidity. Only the central ± 2.5 units of coverage are shown here. The remaining small angle calorimetry is at z = 10 m. The muon detection system is also not shown.

$$(X_o)_{Pb} = 0.56\,cm$$

$$(\lambda_o)_{Fe} = 16.8\,cm$$

20 Xo for ECAL = 11.2 cm

10 λo for HCAL = 1.7 m

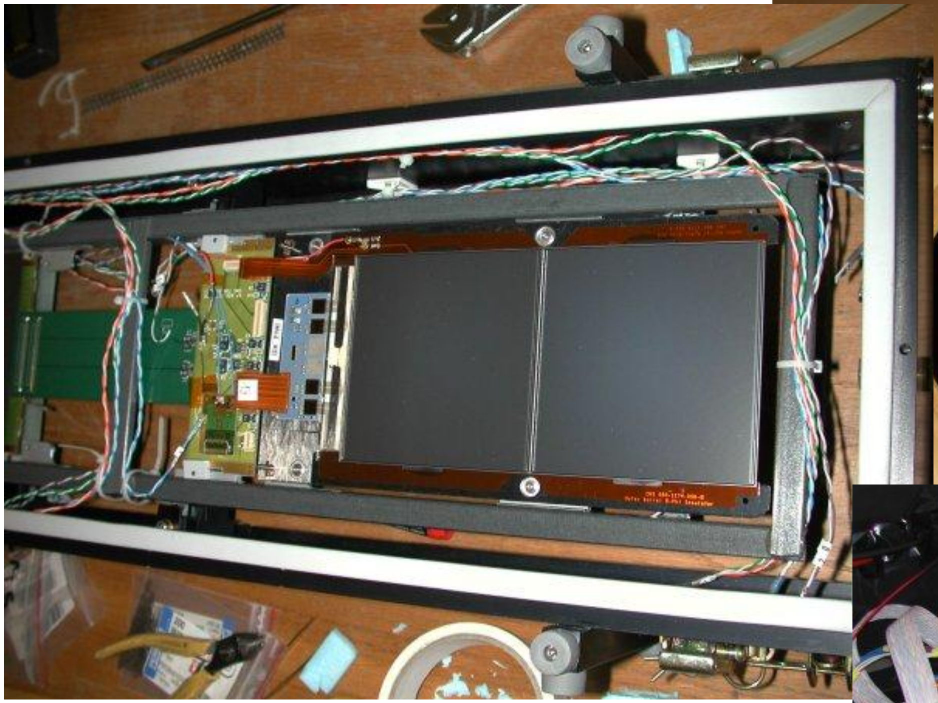
Subsystems and SM Particles

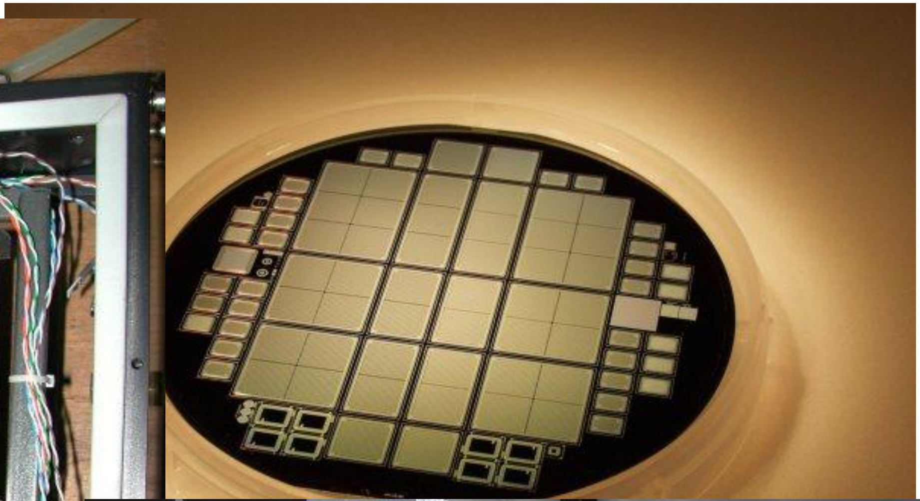
Table 1
Particles of the SM and Detection
And Identification in Detector Subsystems

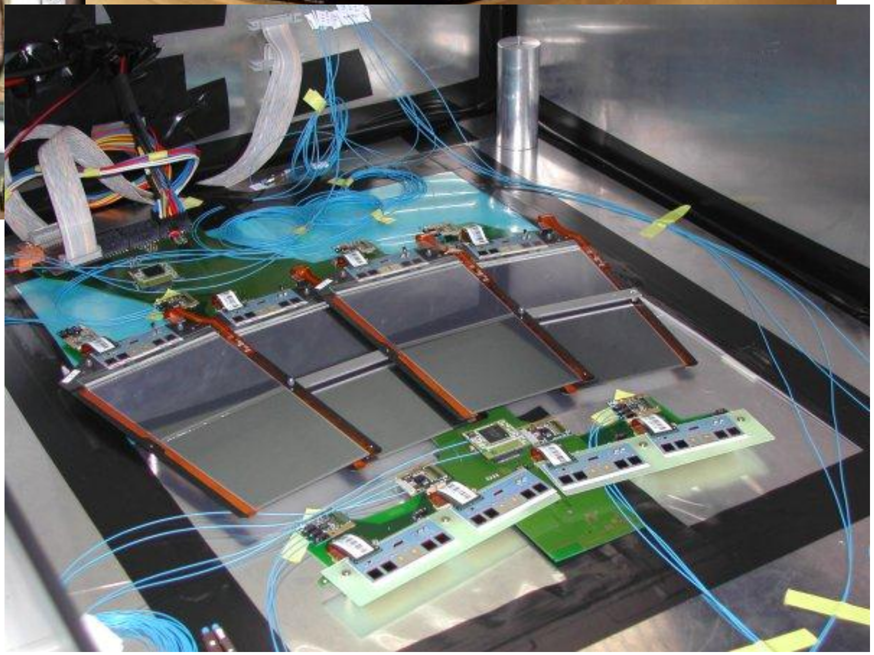
Particle	**Signature**	**Generic Subsystem**
$u,c,t \rightarrow W+b$ d,s,b Quarks g	Jet of hadrons (λ_o)	Calorimeter ECAL+HCAL
e, γ	Electromagnetic shower (X_o)	Calorimeter ECAL Tracker
ν_e,ν_μ,ν_τ $W \rightarrow \mu+\nu_\mu$	Missing transverse energy (MET)	Calorimeter ECAL+HCAL
$\mu,\tau \rightarrow \mu+\nu_\tau+\bar{\nu}_\mu$ $Z \rightarrow \mu+\mu$	Only ionization dE/dx	Muon absorber and detectors Tracker
c, b, τ	Secondary decay vertices	Vertex + Tracker

Whatever the New Physics is, it will cascade down to SM particles: q, g, leptons, gauge bosons. Favor W,Z for EWSB and leptons because they can be selected in a sea of QCD (S/B).

Tracking - Pixels and Strips







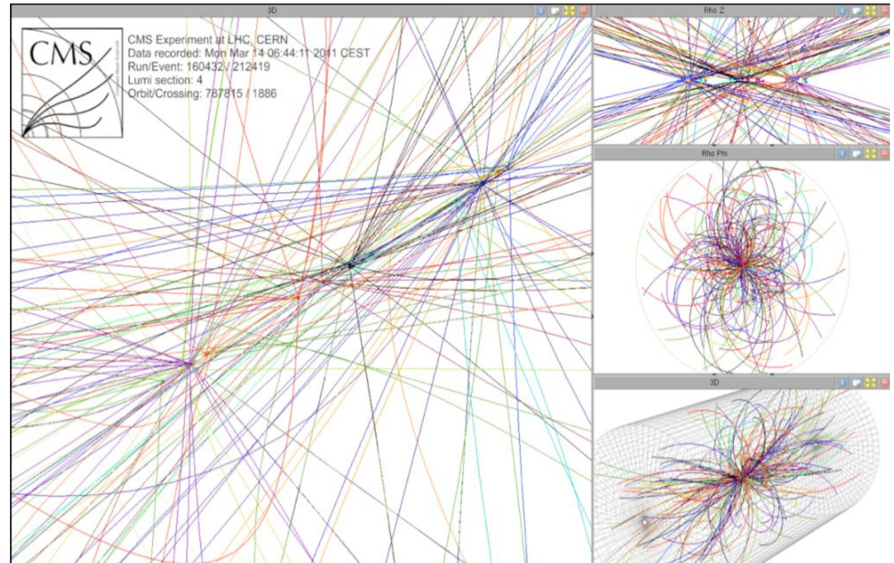
"vertex" pixels ~ 200 um x 200 um. Silicon strips ~ 200 um x 20 cm. For V=50 V, d = 300 um, uE = 42 um/nsec, time~ 7 (21) nsec for e (h). 100 M pixels, |y| < 2.5.

Vertex Detectors

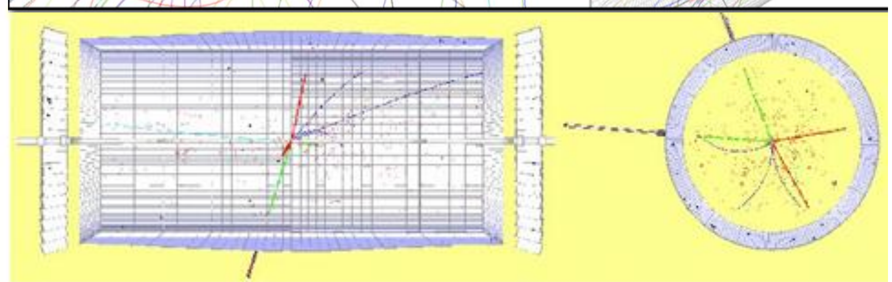
$$(c\tau)_\tau = 87\ \mu m$$

$$(c\tau)_b \sim 475\ \mu m$$

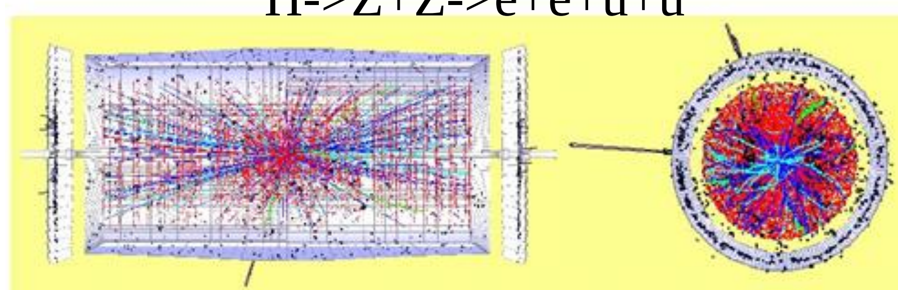
$$(c\tau)_c \sim (123, 312)\ \mu m \quad (D^o, D^\pm)$$



Pixel size scale set by the lifetimes. PU is a problem so that means occupation of a pixel must be small in order to do robust tracking.



H->Z+Z->e+e+u+u



b Tagging

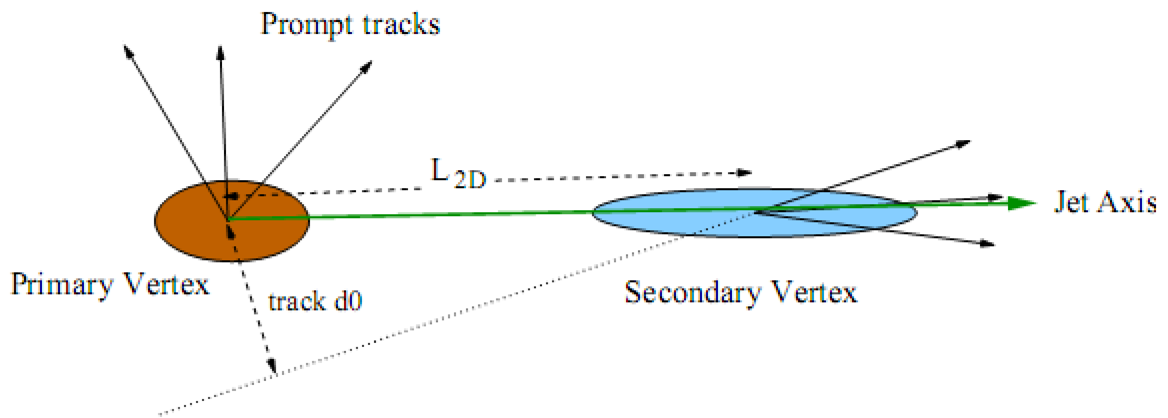
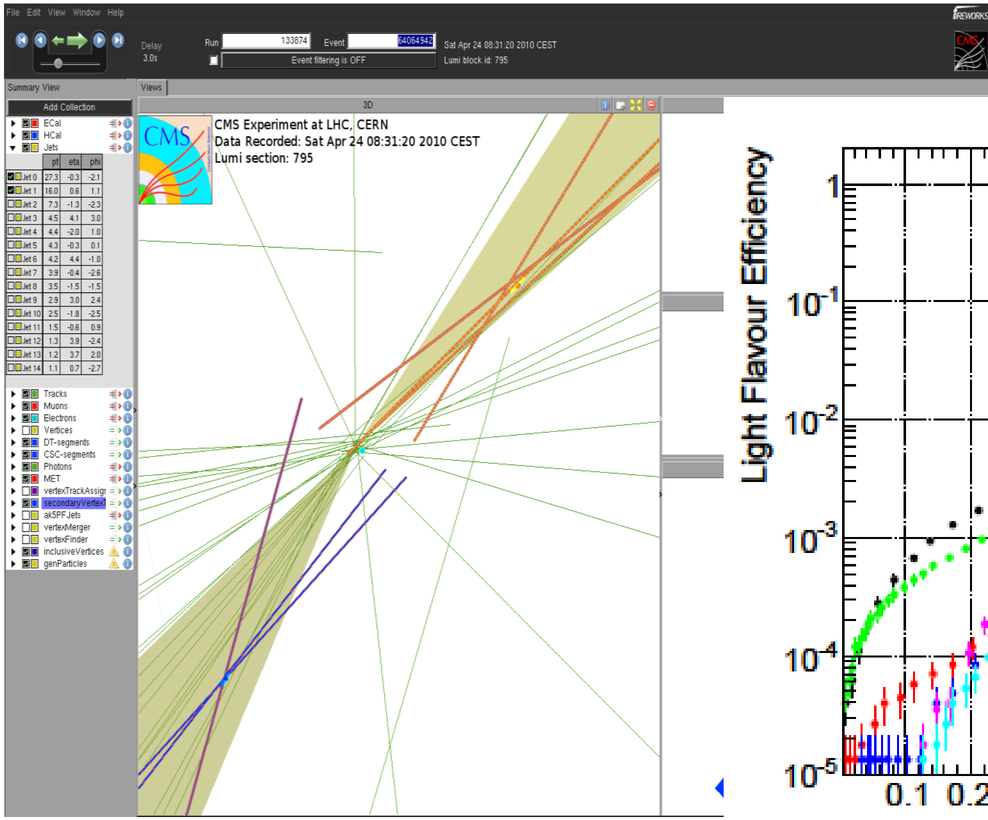
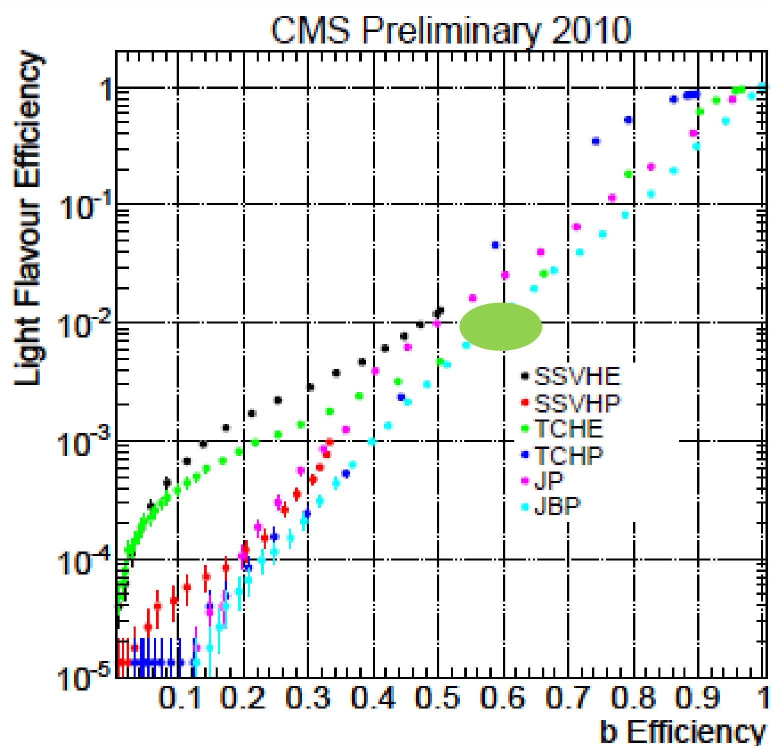


Figure 4: Displaced secondary vertex from decay of a long-lived particle. Tracks from the decay are not expected to point back to the primary vertex as prompt tracks do. Flavor tagging (b-tagging) algorithms are designed to identify tracks with significant impact parameter d_0 and a vertex with significant decay length L_{2D}.

7 TeV – Heavy Flavor, (b)





Note error ellipses on the primary and secondary vertices. Typical operating point is 60% efficient with a light flavor rejection of 100.

Radiation Field

$$P_{pix} \sim D_c N_I (\delta z / r)(\delta s / 2\pi r)$$

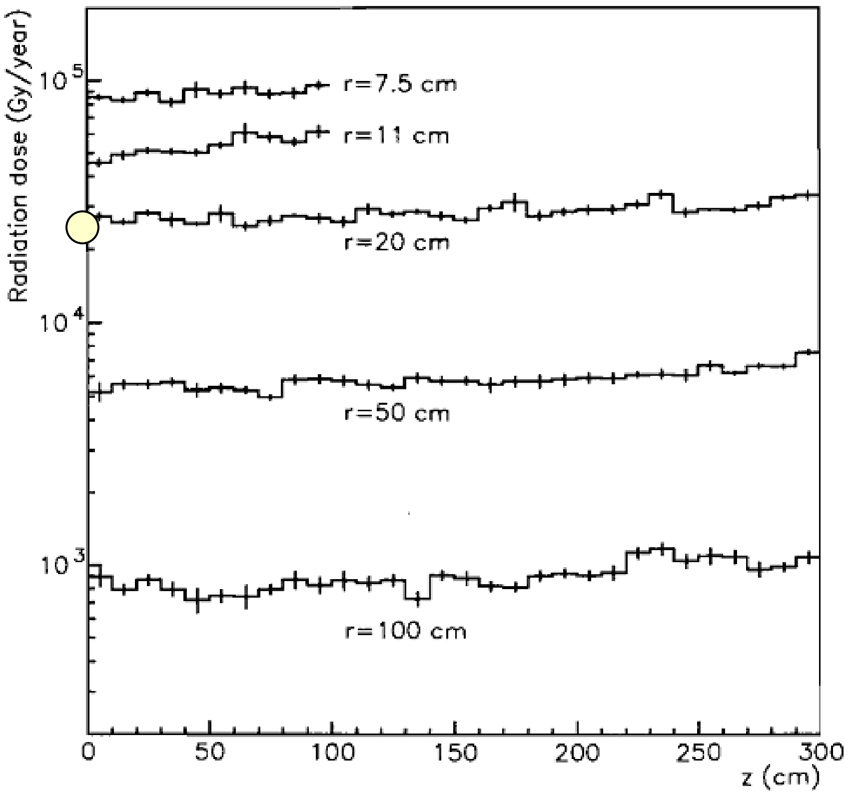
D_c=6, N_I = 25, r = 10 cm, $P_{pix}\sim$ 0.0001 – track reco in to out

$$(Dose)_{pix} \sim \sigma_I LTD_c (1/2\pi r^2) dE_{ion} / d(\rho_{Si}\delta r)$$

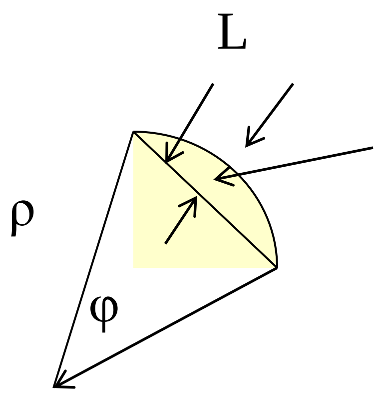
$9.5x10^{14}\ \pi^{\pm}/cm^2 yr$, 10 cm

$dE_{ion}/d(\rho_{Si}\delta r)$ **=1.66 MeV/(gm/cm²)**

Radiation goes as 1/r^2. Dose of ~ 2.5 Mrad/yr for inner pixel detectors. Higher due to interactions, loopers.



Sagitta and Track Momentum



The sagitta s is:

$$s = \rho(1-\cos(\phi/2)) \sim \rho\phi^2/8$$

$$\phi \sim L/\rho$$

$$s \sim L^2/8\rho = 0.3B(T)L^2(m)/8P_T$$

FOM = BL^2

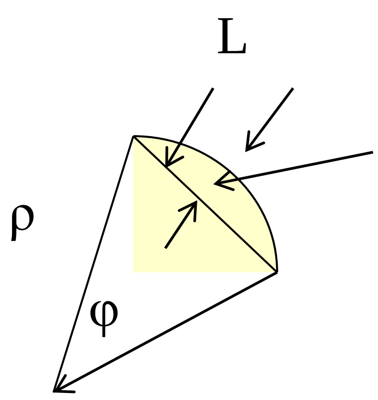
Impulse is transverse -> use 10 cm strips in z but 400 um in azimuth. Occupation ~ 0.6% at r=40 cm (inner barrel). 4.6 M strips in 8 layers

e.g. L = 1m, B = 5T, impulse = 1.5 GeV, P_T = 100 GeV -> s = 1.9 mm = 1900 um.
Si strip width d ~ 400 um, σ = 115 um.
Note that for a uniform distribution, binary readout:

$$\sigma^2 = \int_{-d/2}^{d/2} x^2 dx/d = d^2/12$$

, with charge sharing across strips one can do better

Sagitta and Track Momentum



The sagitta s is:

$$s = \rho(1-\cos(\phi/2)) \sim \rho\phi^2/8$$

$$\phi \sim L/\rho$$

$$s \sim L^2/8\rho = 0.3B(T)L^2(m)/8P_T$$

FOM = BL^2

Impulse is transverse -> use 10 cm strips in z but 400 um in azimuth. Occupation ~ 0.6% at r=40 cm (inner barrel). 4.6 M strips in 8 layers

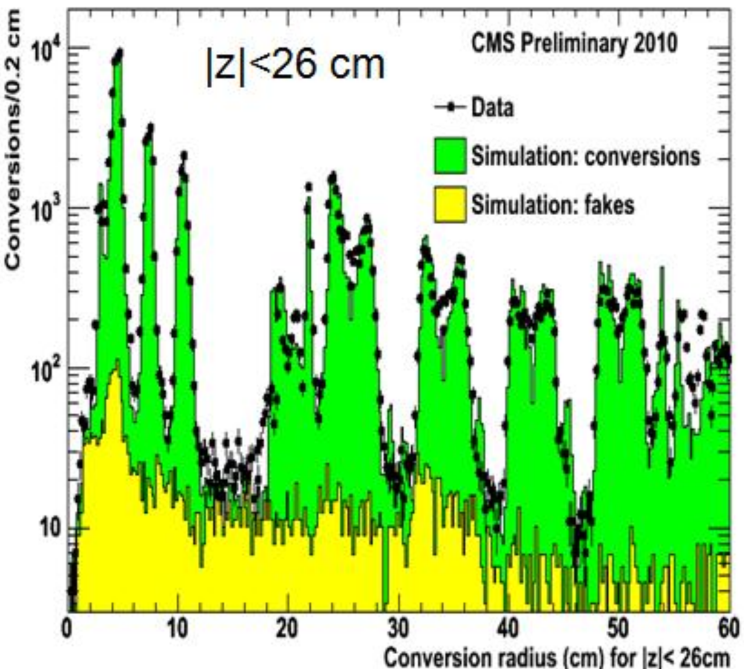
e.g. L = 1m, B = 5T, impulse = 1.5 GeV, P_T = 100 GeV -> s = 1.9 mm = 1900 um.
Si strip width d ~ 400 um, σ = 115 um.
Note that for a uniform distribution, binary readout:

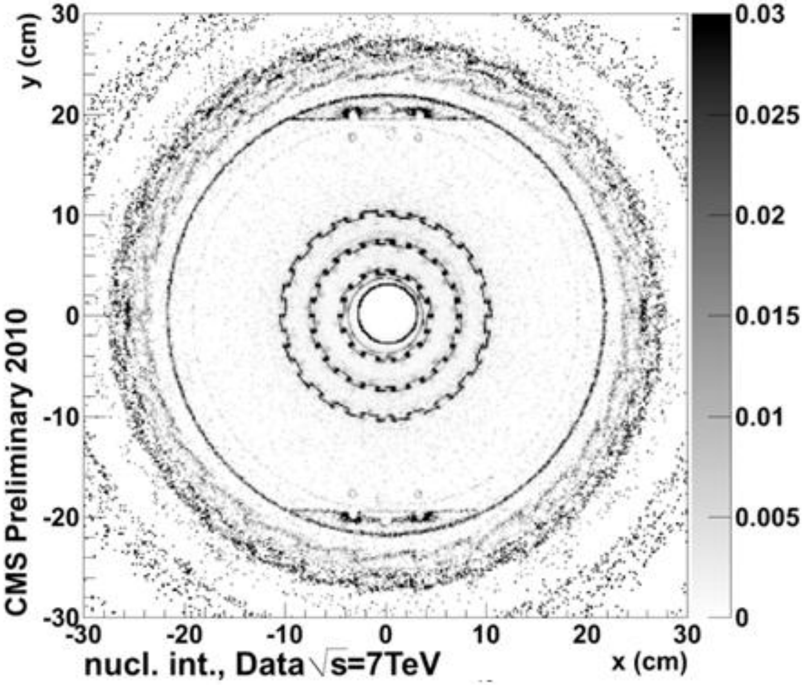
$$\sigma^2 = \int_{-d/2}^{d/2} x^2 dx/d = d^2/12$$

, with charge sharing across strips one can do better

Tracker Material

beam pipe, pixels, strips





radius

For a complete understanding of the momentum scale and resolution a detailed understanding of the tracker material throughout the system is needed – use photon conversions for high Z and nuclear interactions for low Z material.

P Resolution vs. P

$$(\Delta P_T)_B = erB = 0.3rB$$ T, m units

$$d(1/P_T) = dP_T / P_T^2 = d(\Delta\phi_B)/(\Delta P_T)_B \sim ds / er^2 B$$ FOM ~ $r^2 B$

1.5 mrad at 1 TeV, 7.7 %

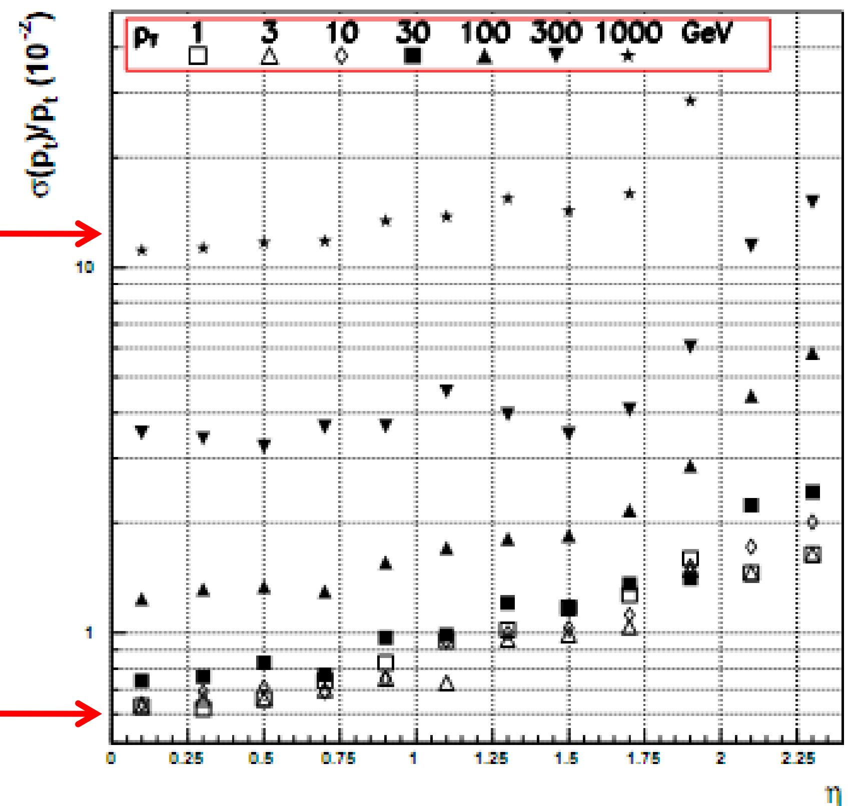
$$dP_T / P_T \sim (\Delta P_T)_{MS} / (\Delta P_T)_B$$

$$(\Delta P_T)_{MS} = E_s \sqrt{\sum L_i / 2X_o}$$

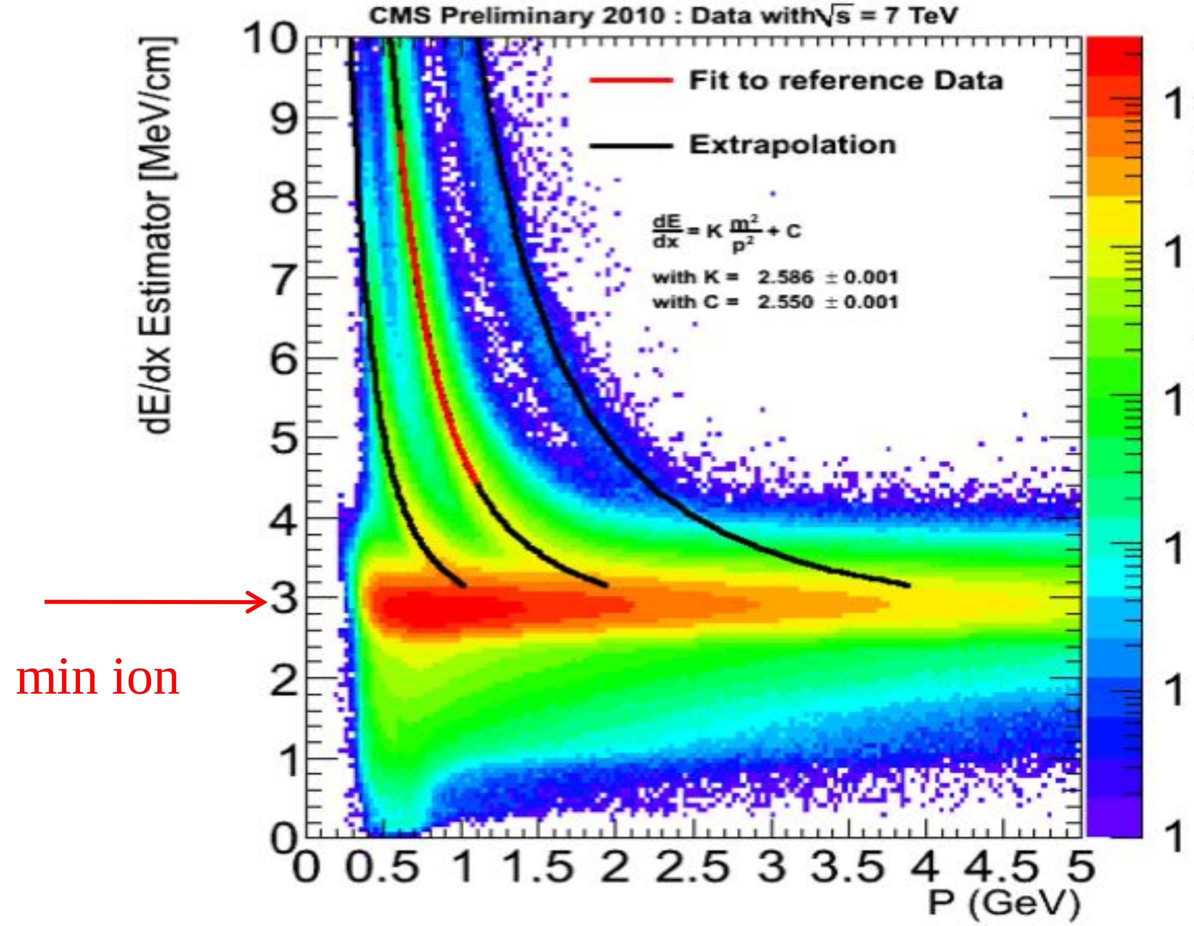
0.1 Xo, 6.4 MeV - MS, res = 0.0042 MS. Crossover at 54 GeV, 0.6 % total

$$(\Delta P_T)_B = 2(P_T)_{loop} = erB/2$$

"loopers" < 0.75 GeV



Particle ID – dE/dx in Tracker



Use energy deposited in several Si strip layers to measure dE/dx. Useful for particle id. Once commissioned, use in heavy stable particle searches.

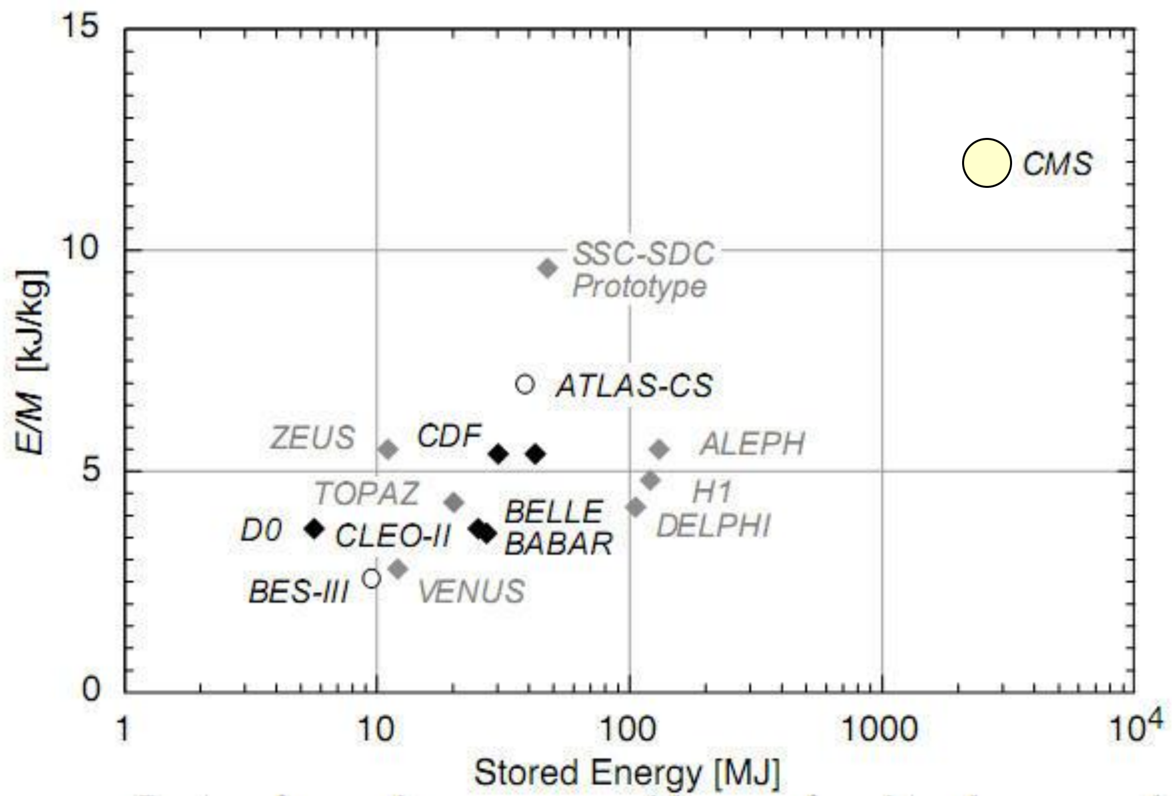
$$dE/dx \sim 1/\beta^2 \sim M^2/P^2$$

-mass measurement using P and dE/dx from tracker

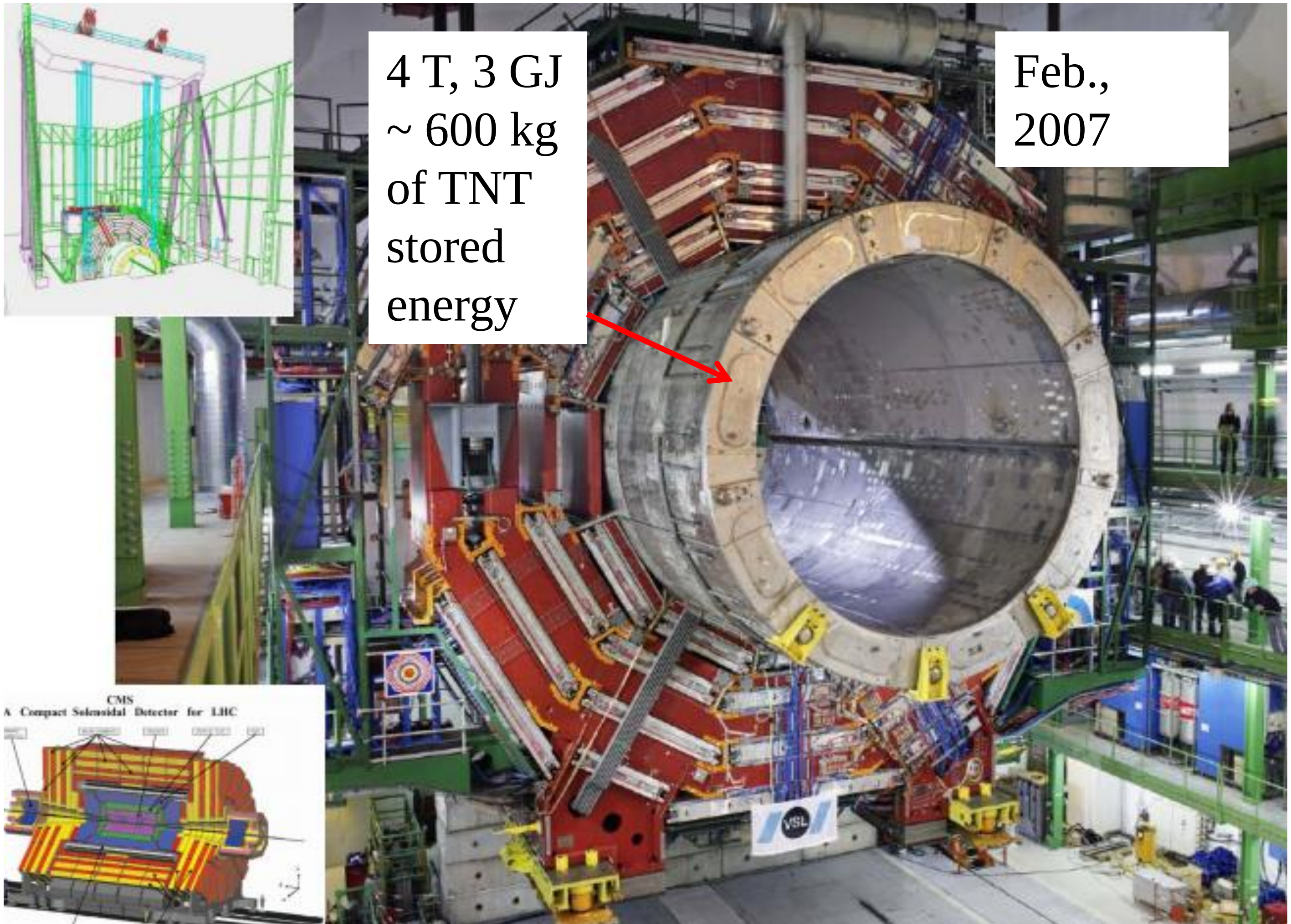
Solenoid Magent

$$B = \mu_o n I$$

Conductors of size 2 cm in z all stacked by 4 in r for a total of n= 200 turns/m. Then to achieve a field of 5 T, 20.8 kA of current is required



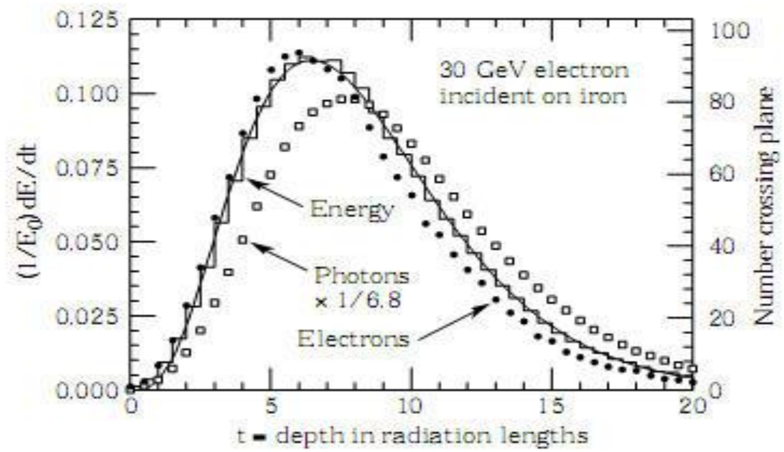
World’s Largest Solenoid



Electromagnetic Calorimeter

Physics driver: Z width

$$\Gamma_Z = 2.5\,GeV, M_Z = 91.2\,GeV$$
$$(dE/E)_{ECAL} < \Gamma_Z/(2.36 M_Z) = 1.2\%$$

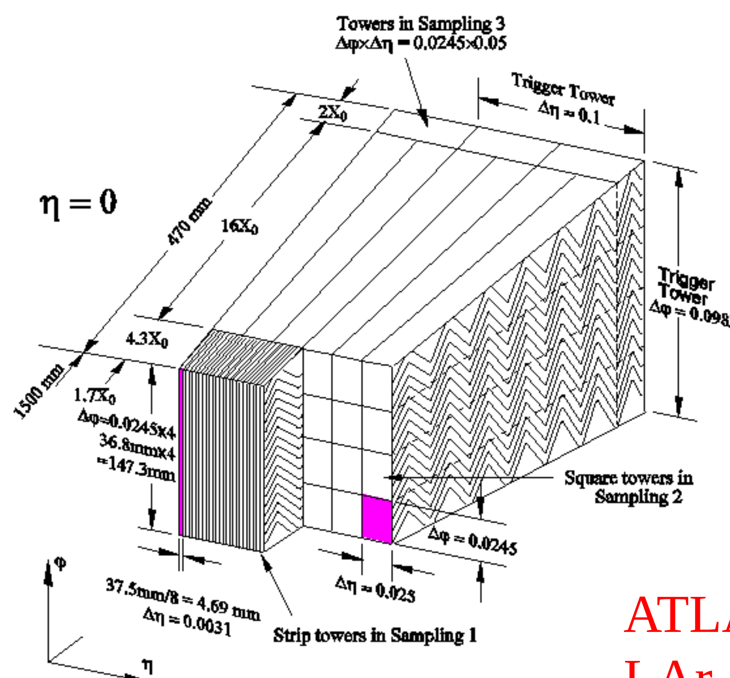


EM Shower

$t = L/X_o$ A~1+(ln)y))/2

$$dE/dt = E_o b(bt)^{a-1} e^{-bt} / \Gamma(a)$$
$$t_{\max} = (a-1)/b,\, b \sim 0.5$$

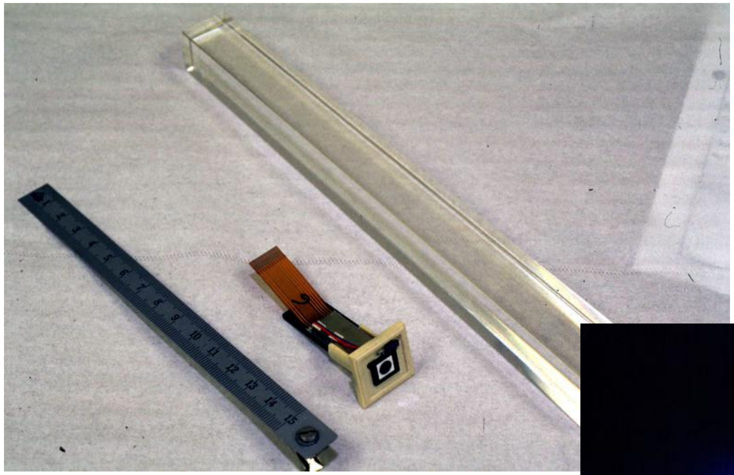
$$N_s \sim (E/E_c) \sim 2^{t_{\max}}$$
$$t_{\max} \sim \ln(E/E_c)$$

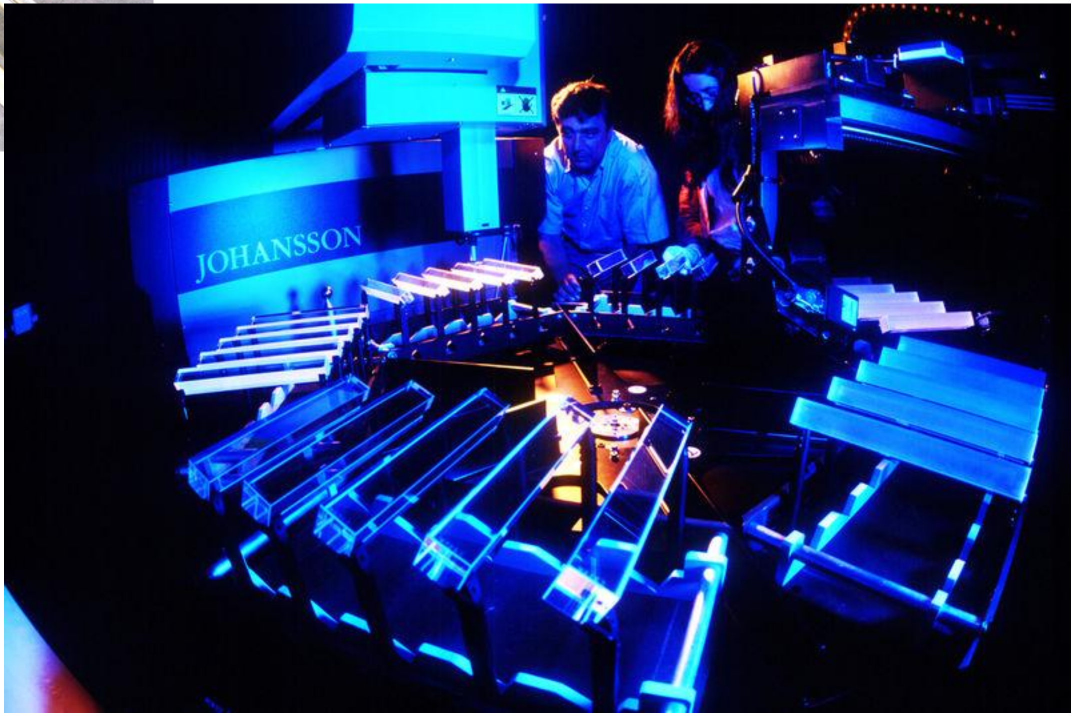


ATLAS
LAr

ECAL Crystals - Testing

$$(D_o = 3)(N_I = 25)(\delta\eta)^2 / 2\pi$$ **= 0.0087**





The Moliere radius size at r = 1 m, the probability of a tower hit per bx is small.

Estimate of E Resolution

$$dE/E = a/\sqrt{E} \oplus b$$

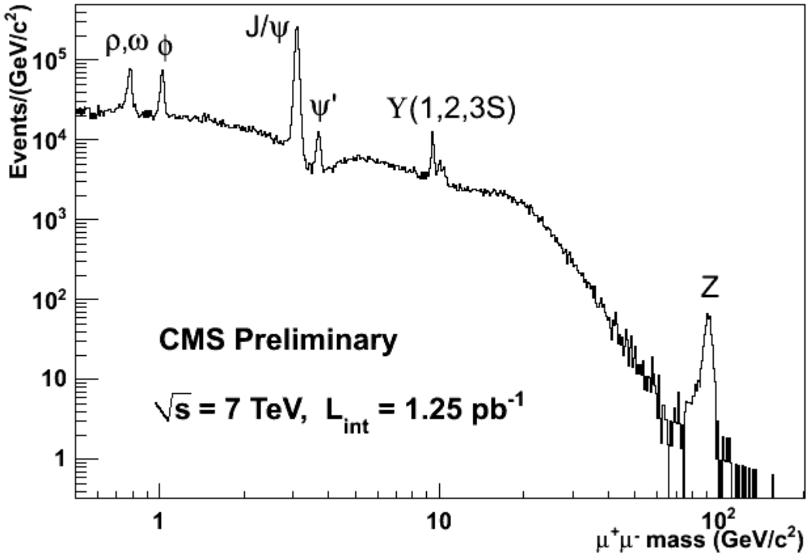
Tower Segmentation – Moliere radius

$$dE/E \sim 1/\sqrt{N_s} \sim \sqrt{E_c/E}$$ E_c **is 7.3 MeV**

$$r_M = 1.6\,cm$$

$$a = \sqrt{E_c} = 8.5\%$$

$$\delta\eta = \delta\phi \sim (2r_M)/r_E = 0.027$$



3 depth segments for particle id – 124,000 channels in the ECAL barrel

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

Radiation Dose - ECAL

As with the tracker, the # of neutrals goes as 1/r^2. However, the interaction is destructive – with all the energy deposited in a few Xo – note dose is energy deposit/mass.

$$(Dose)_{ECAL} \sim \sigma_I LTD_o (1/2\pi r_E^2) < P_T > /(\rho_E \Delta t X_o)$$

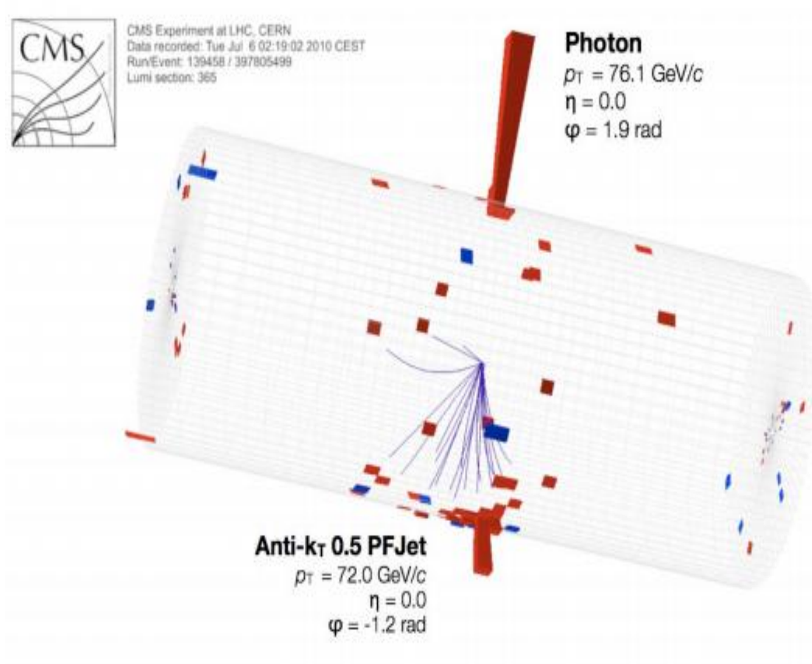
Deposit at shower max with width ~ 7 -> 0.1 Mrad/yr - barrel

The particles are emitted with ~ fixed Pt – energy ~ 1/θ and into an endcap radius ~ 1/θ ^{2} . The dose increases dramatically with |y| and most precision ECAL measurements are restricted to |y| < 2.5.

$$(Dose)_{endcap} / (Dose)_{barrel} \sim (r_E / z_E)^2 / \theta^3$$

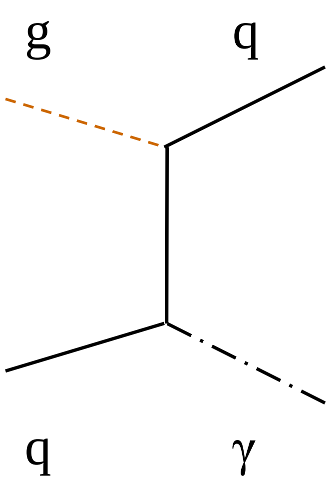
Endcap at |y| = 2.5 -> 4 Mrad/yr.

Photon Commissioning - Compton



Clean photon + J events. Photon spectrum quite clean for high Pt photons, > 100 GeV. Data /Monte Carlo agreement is good. Used as a calibration tool for HCAL.

Photons Measured (γ)



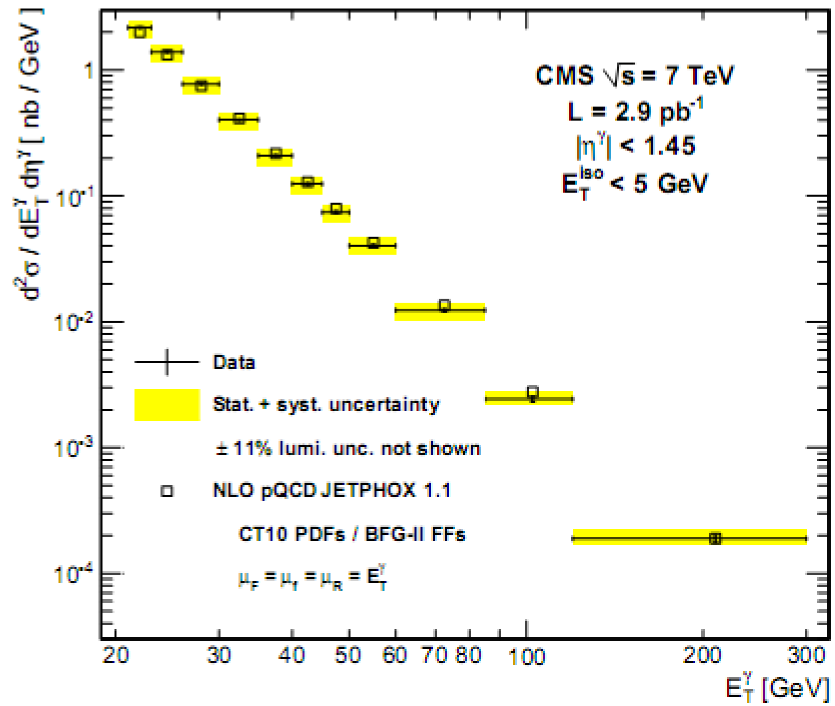
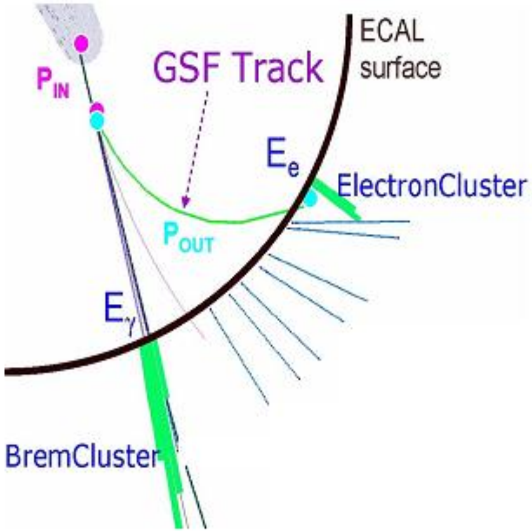


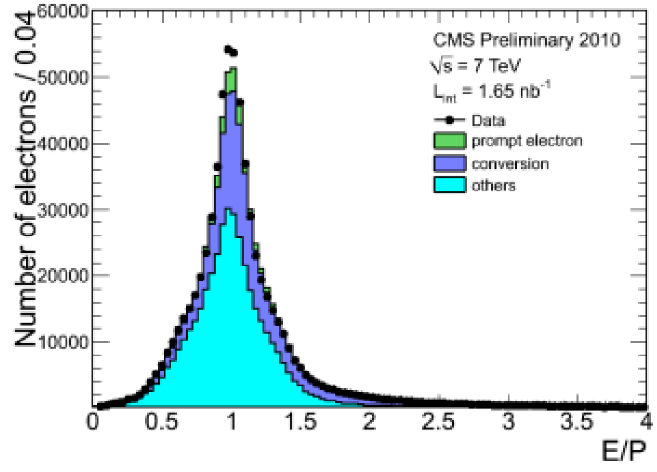
Figure 2: Measured isolated prompt photon differential cross section and NLO pQCD predictions, as a function of E_T^γ. The vertical error bars show the statistical uncertainties, while the shaded areas show the statistical and systematic uncertainties added in quadrature. A correction to account for extra activity ($C = 0.97 \pm 0.02$) is applied to the theoretical predictions, as explained in the text. The 11% luminosity uncertainty on the data is not included.

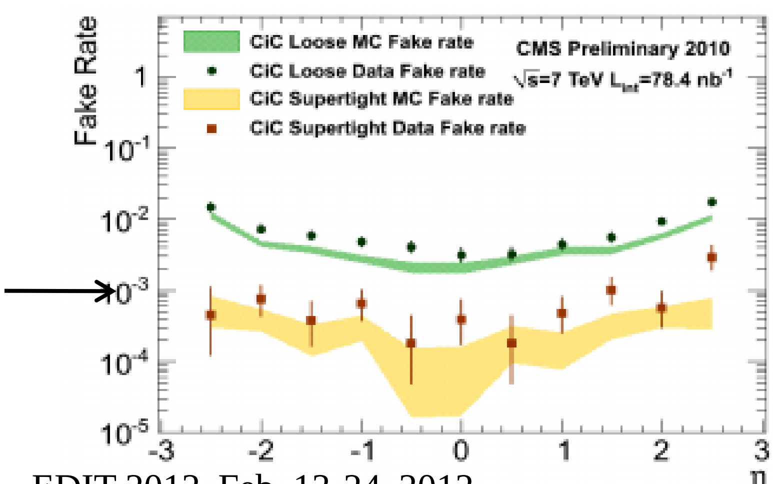
ECAL calibration and photon + J = Compton topology

Electrons – Track + ECAL

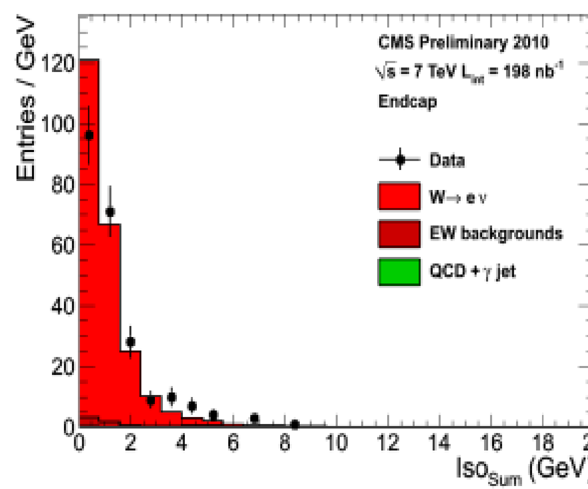


Understanding material of the CMS tracker is crucial. Bremm in pipe and Si -> collect E in φ Use E/p and isolation



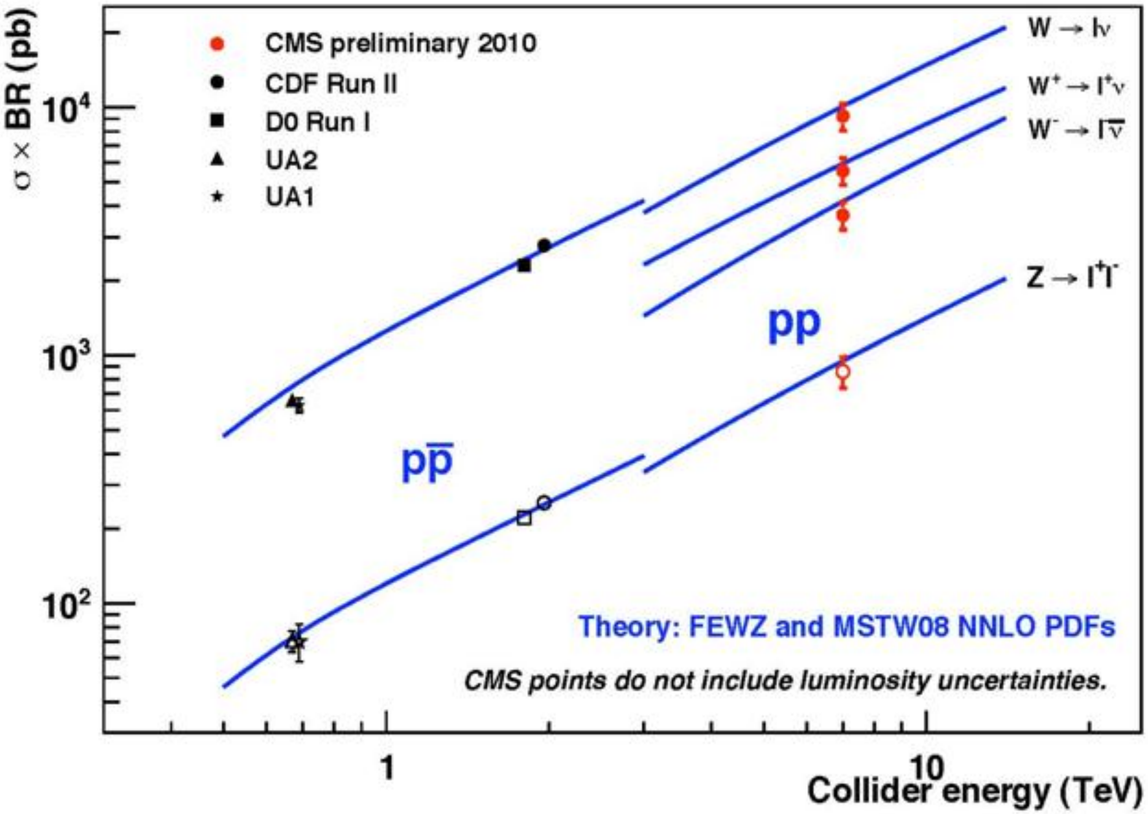


ECAL endcap



Eiso

EW Cross Sections



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

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?

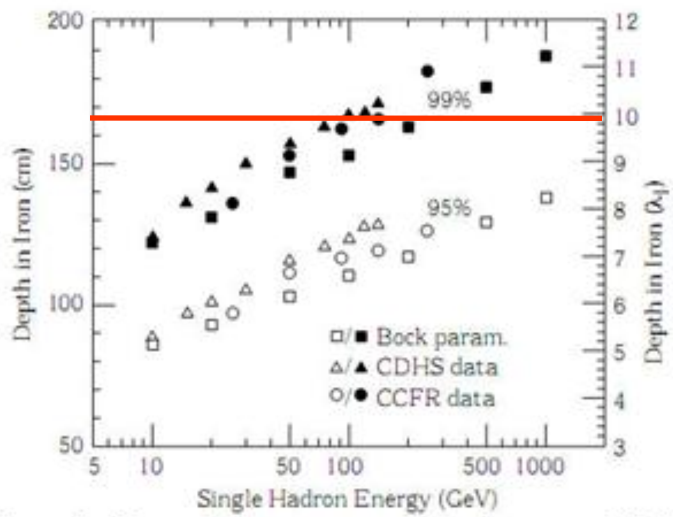


Figure 16: Depth needed for a shower energy containment of 95 % and 99 % as a function of hadron energy. Note the logarithmic dependence of depth on incident energy [8]

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.

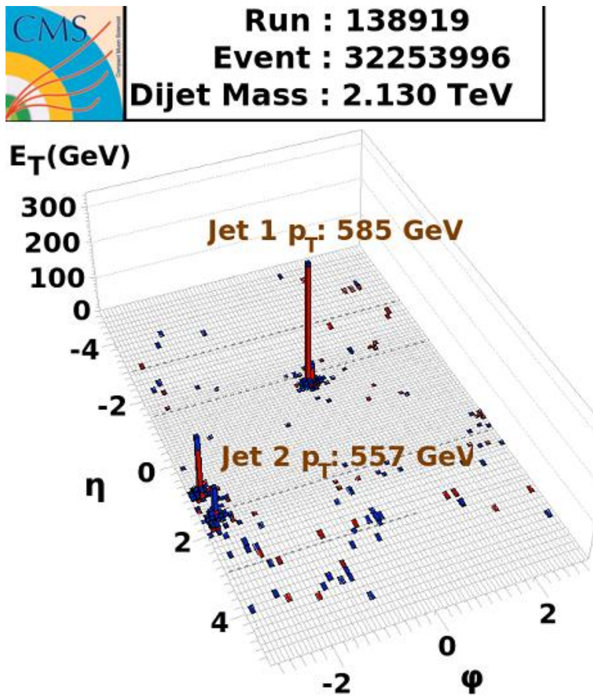
HCAL Assembly – ATLAS/CMS

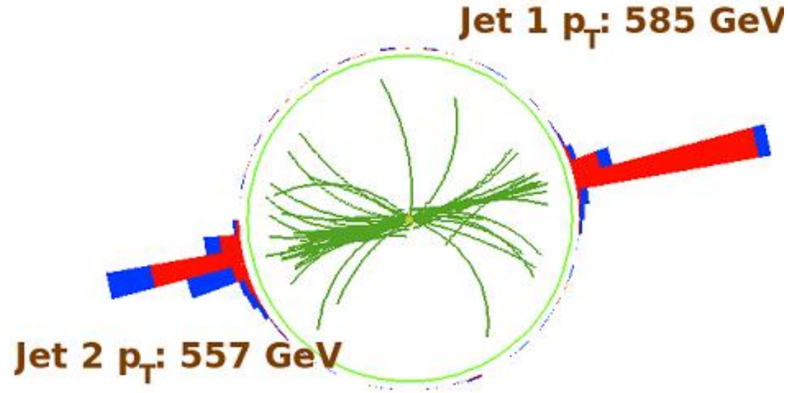
(b)

ATLAS - Tilecal

CMS - HCAL

Jets of Quarks and Gluons





$$(Dose)_{forward} \sim \sigma_I L T D_o (1/2\pi z_F^2 \theta^3) < P_T > /(\rho_{forward} \Delta t X_o)$$

Forward calorimetry, |y| < 5 will suffer ~ 1 Grad in 10 year LHC operation! (EM energy, 280 Mrad/yr)

Neutrons

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

At r = 1 m.

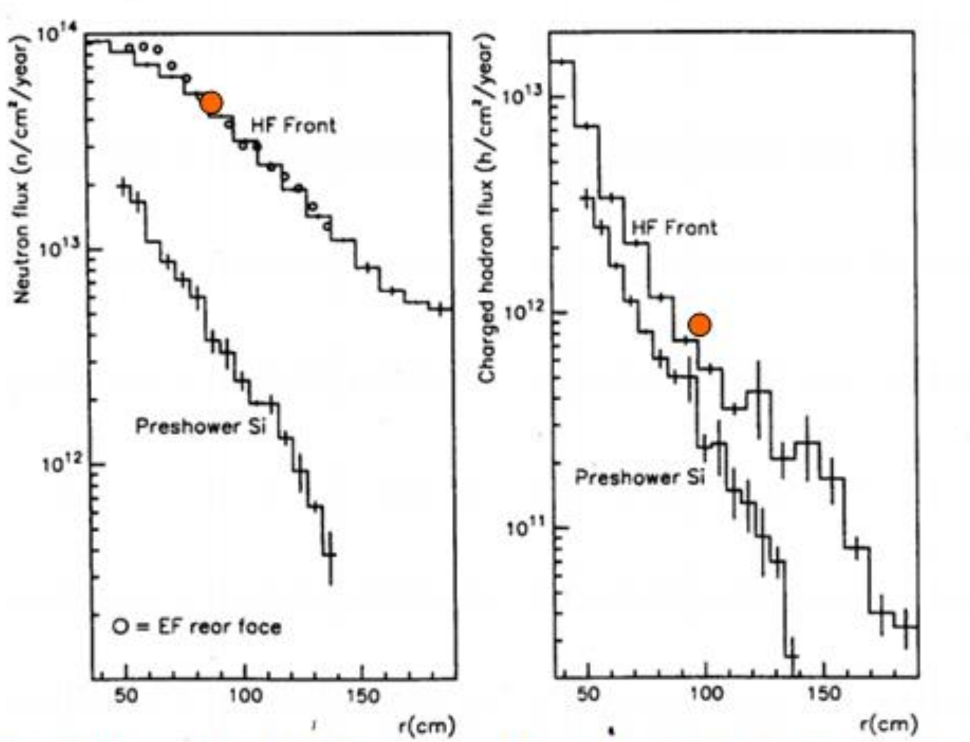


Figure 20: Charged particle flux, right, and neutron flux, left, as a function of radius for calorimetry at z = 10 m [4].

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.

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

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

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.**

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

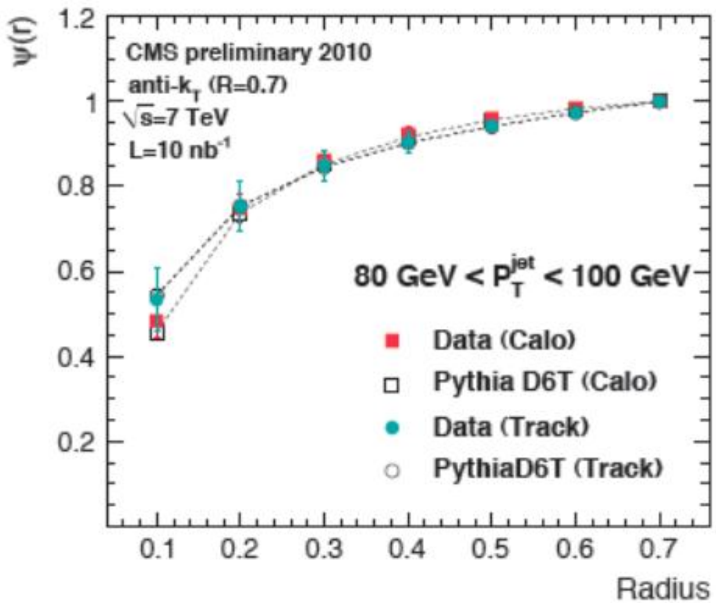
$$F \sim 1-(1-z_{\min})^{a+1},\ z_{\min} = (p_{had})_{\min} / P_{jet}$$

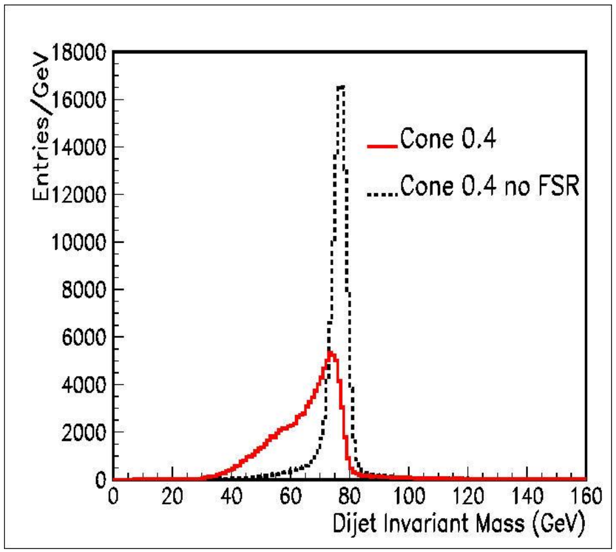
A 50 GeV jet has ~ 45% of its energy carried by hadrons with momenta less than 5 GeV and ~ 12 % carried by hadrons with momenta less than 1 GeV. Thus the soft hadrons from the jet are easily confused with the soft pions from the pileup which then limits the achievable jet energy resolution.

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.

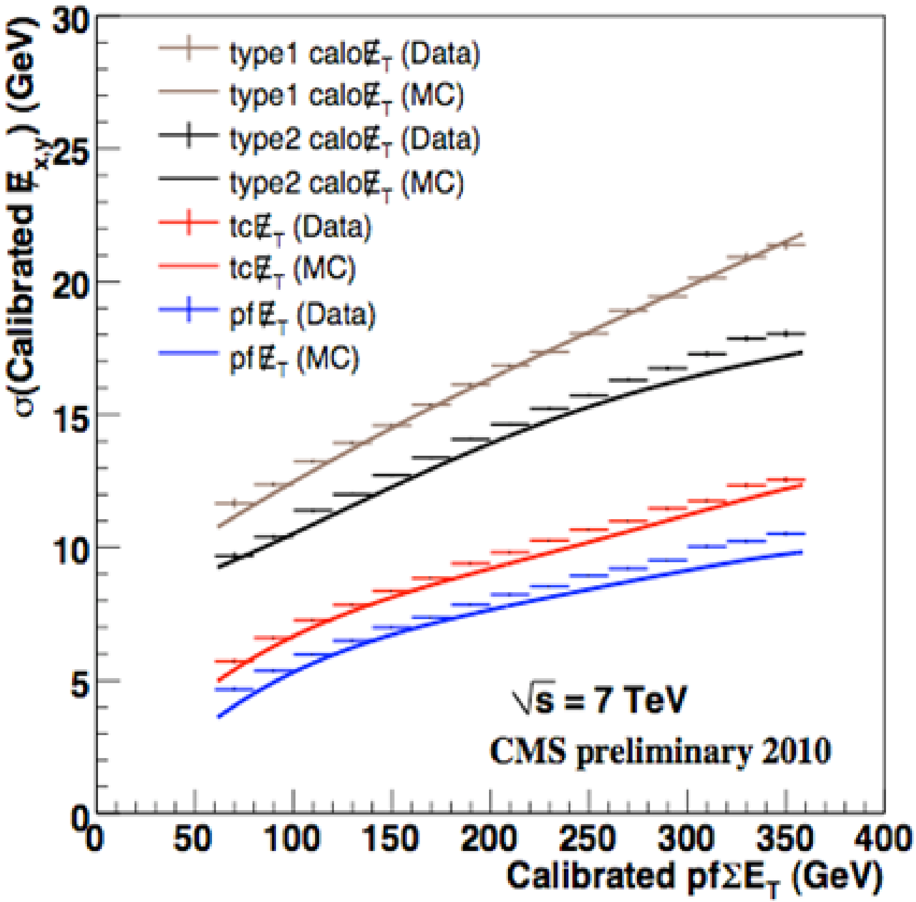
PF, ILC, CLIC, Dual Readout

- **An additional issue is that the low transverse momentum charged hadrons do not even reach the calorimetry and register their energy. These "loopers" must be efficiently detected in the tracking system and the measured jet energy incremented to properly account for them. Recoup the soft jet fragments.**

- **These considerations imply that precision multijet spectroscopy is difficult at the LHC. In a more benign environment such as the proposed ILC with much less pileup and no "underlying event", improved calorimetry with greatly expanded numbers of shower samples have been proposed which aim to improve the calorimetric energy resolution by a factor of roughly two with respect to the LHC detectors. Using the more precise tracking measurement of low charged particle energy ("particle flow") can also improve the energy resolution of the detector overall. Another potential path to improved performance is "dual readout calorimetry" where energy measurements of the charged and neutral components of a hadronic shower are measured independently, thus allowing for different calorimetric response to these two components to be compensated for.**

- **Note that** $dP_T \sim P_T^2$ **for tracking which does well at low momentum while** $dE \sim a\sqrt{E} \oplus b$ **for calorimetry which favors higher energy.**

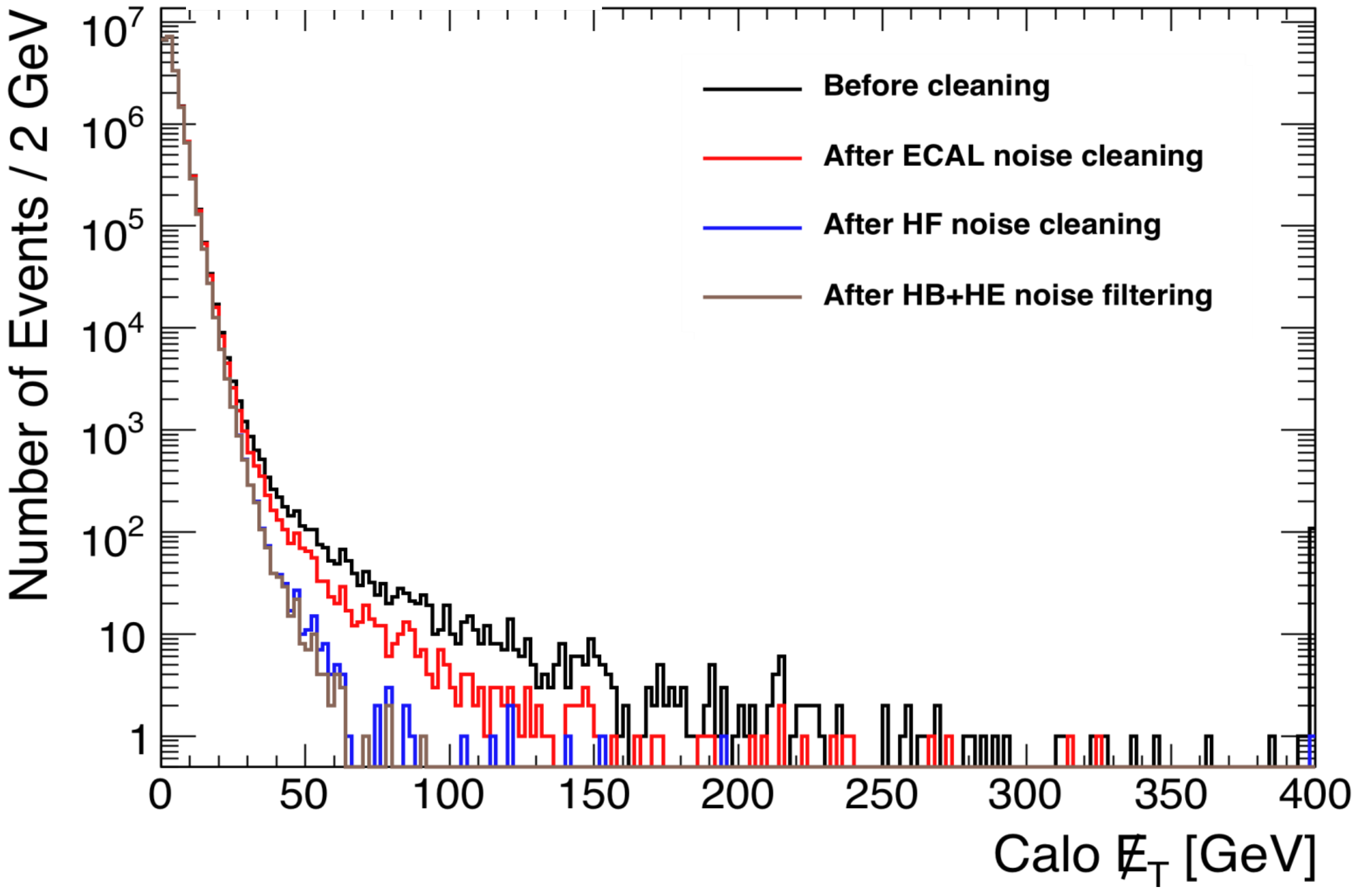
MET (ν) - The MET "Core"



PF: Use calorimetry and tracking to improve the MET resolution. Tracker has better resolution at low E and there are many soft particles in UE and jet fragments. Cleaning of cosmics, beam halo and calorimeter discharges is needed. Gaussian core of MET resolution is

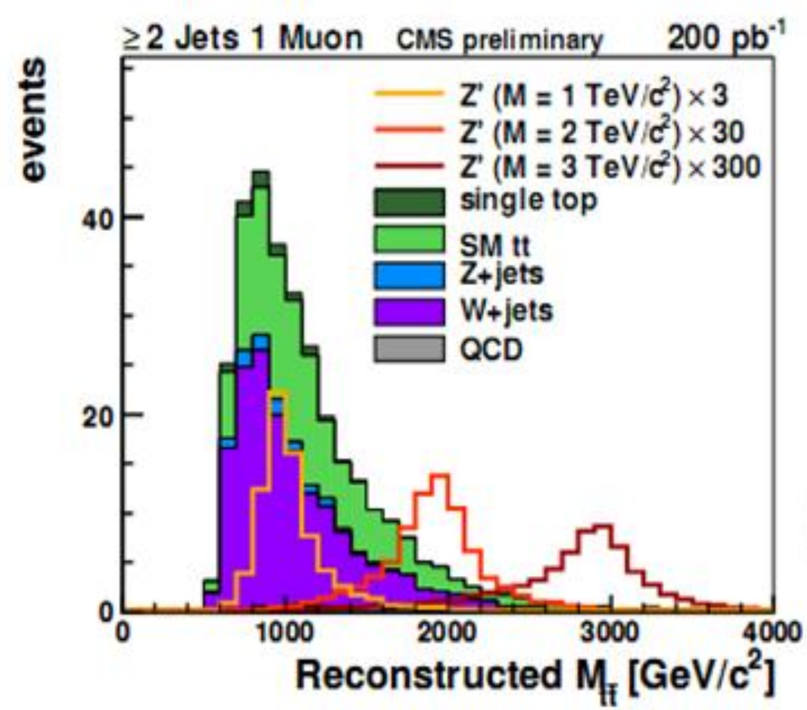
$$\sim 50\% / \sqrt{\sum E_T}$$

MET "Tail"



No true MET in Dijet events. Is a large MET event SUSY or Z ->v+v (real MET) or simply and instrumental glitch……

Top Tagging



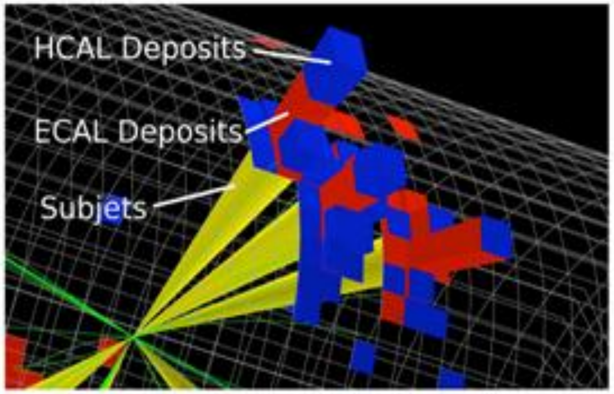


Figure 1: Reconstructed top-quark jet in cylindrical view with p_T = 800 GeV/c. The cones represent the subjets. The HCAL and ECAL deposits, and the subjets are indicated on the figure.

High mass parent decaying into a top pair will cause a "fat jet" with W and b jets merged. Look at jet mass and other variables to distinguish from QCD J backgrounds. Jet substructure needs to be understood and QCD (g) jets removed. High mass in 2012 data taking.

Muon Systems

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

σ_μ ~ 60 μb

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

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

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

At low muon Pt the rate is dominated by HF decays

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

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

Muon Systems

$$dP/P = (E_s/\sqrt{2})[1/eB\sqrt{LX_o}]$$

$$P_{T\mu} \sim M_W/2$$

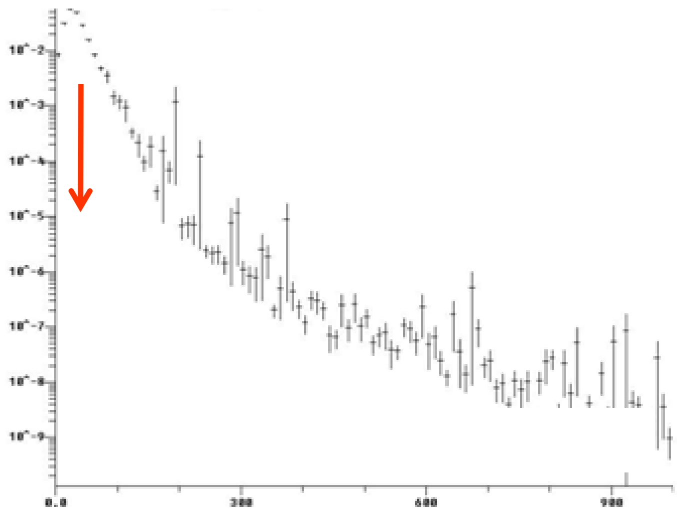


Figure 21: Muon transverse momentum spectrum in W pair electroweakly produced events with no cuts on the W pair mass.

For B = 2T in steel with L = 2m, the dP/P is 13%.

In the case of detectors in the magnet return yoke, the muon P measurement is multiple scattering dominated. In that case precision muon measurements come from the tracking system. The role of the system is to provide a robust trigger and redundancy

Muons Only Ionize?

$$(E_c)_\mu \sim (E_c)_e (m_\mu / m_e)^2$$

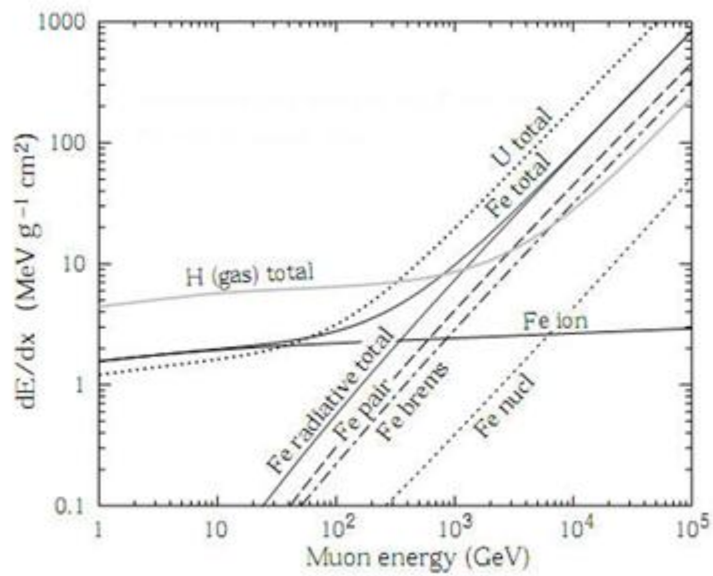


Figure 22: Energy loss of muons in iron showing ionization, pair production and bremsstrahlung contributions to the total rate of energy loss as a function of muon energy [8]

Critical energy for muons is ~ 300 GeV in Fe. Future (and LHC) muon systems must be robust and redundant in the face of muon EM radiation.

Note that the W Jacobean peak (W mass / 2) at |y| = 2.5 is P ~ 240 GeV.

Muons – As You Like It

- For the generic detector no attempt is made to specify the muon system in detail as to detectors, magnetic field type, or medium in which the detectors are immersed. Many different choices are possible and defensible and there is no consensus on the design choices. Specific choices for ATLAS (air + toroid) and CMS(in steel yoke, dipole return flux) differ.

ATLAS Toroids/Chambers

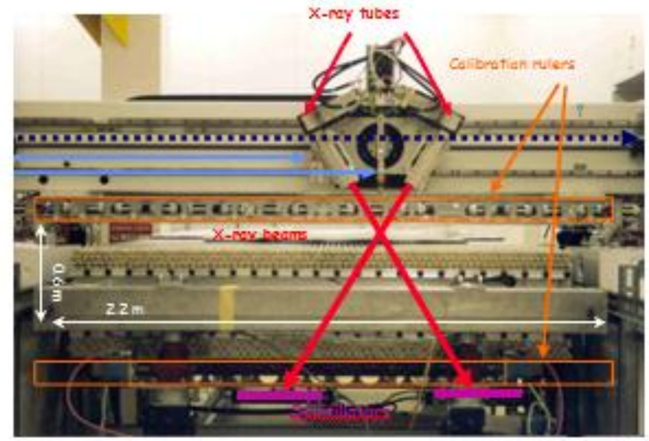


Figure 11: Picture of the X-ray tomography facility showing the 2 X-ray tubes as well as an MDT Chamber being measured.

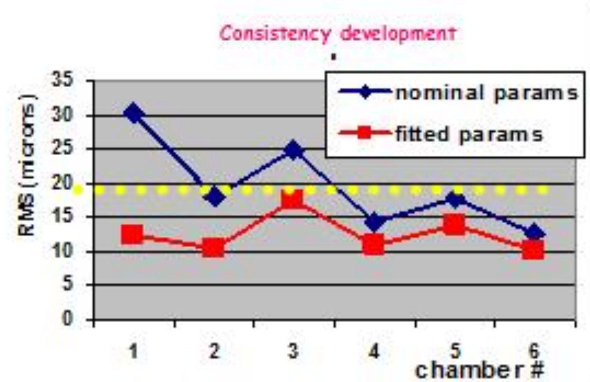
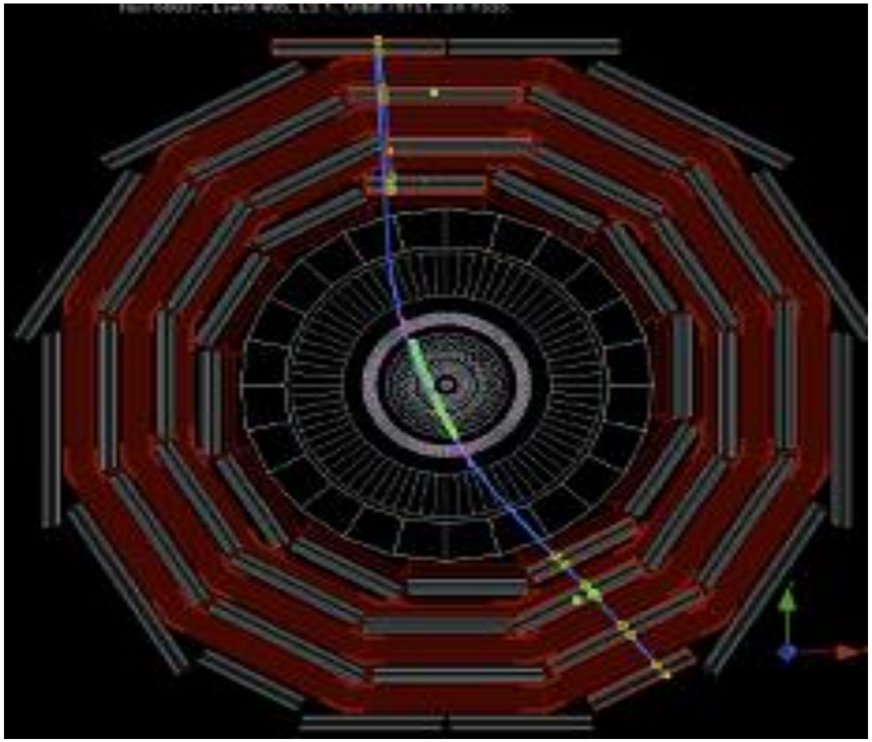


Figure 12: typical reproducibility of the MDT wire positions in the tomography for 6 chambers of the same type.

Muon Commissioning



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.

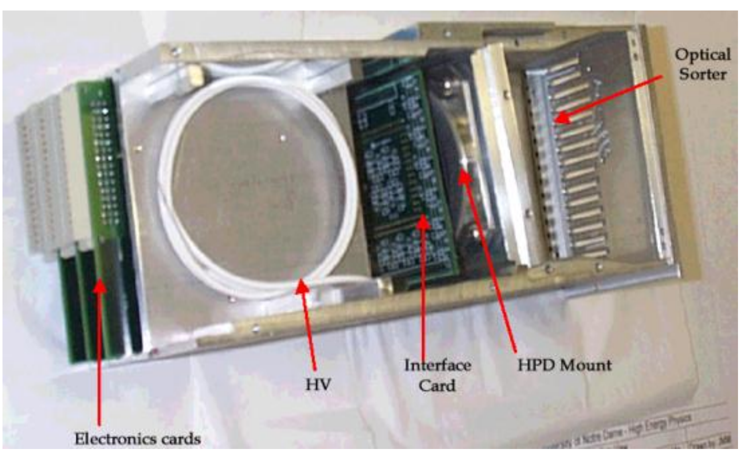
CMS – DT/CSC in Fe return yoke => multiple scattering limited.

Muon Assembly and Installation

Front End Electronics

- The discussion so far has been about the connection between physics needs and the resultant generic detector requirements. Many of the detailed choices made by ATLAS and CMS differ. In many cases those choices have broken new ground in detector development

- The front end electronics at the LHC experiments is clocked at the r.f. bunch crossing frequency of 40 MHz. As seen in the discussion above, the radiation field is typically 1 Mrad/yr or larger which means that the electronics on the detector must be quite radiation hard. The exact front end electronics choices are very detector dependent so that a "generic" discussion is not very illuminating and has not been attempted here. The electronics must also be resistant to the large neutron background which is a characteristic feature of hadron colliders.



ATLAS - LAr

Figure 11. Liquid argon calorimeter RODs in USA15. 192 RODs housed in 16 VME64x 9U crates readout 1524 128-channel front-end boards.

Triggers - Commissioning

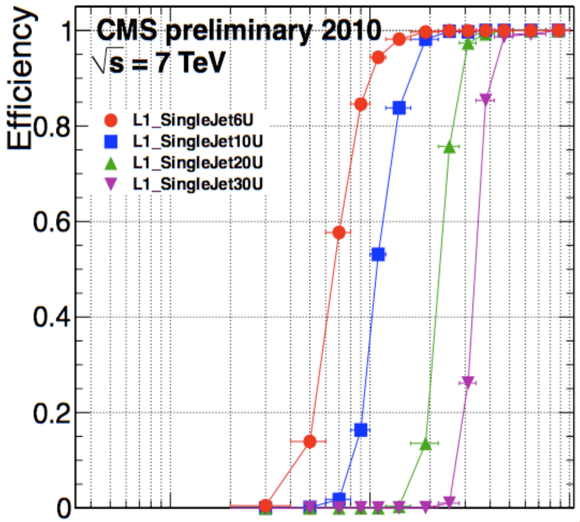


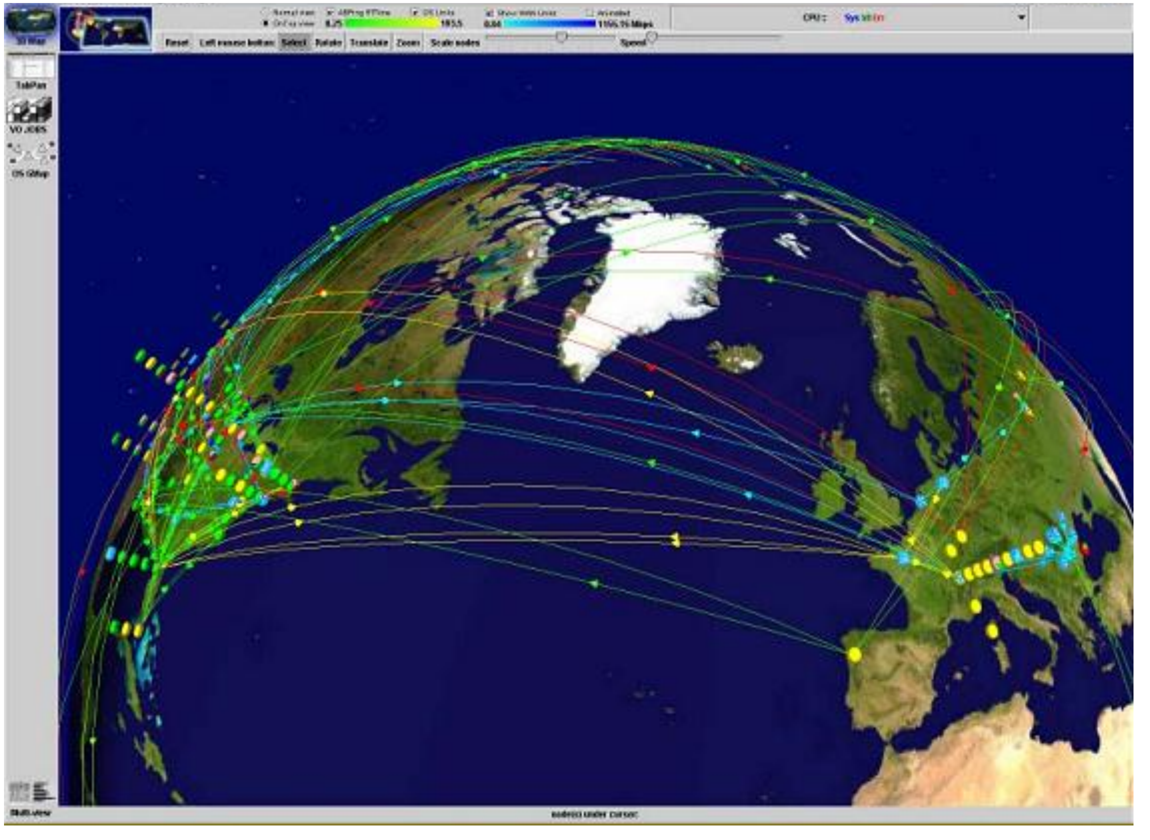
Fig. 7. Part of the ATLAS HLT farm. Each of the one-unit box is a dual-process quad-core computer. There are 31 PCs per rack.

ATLAS - HLT

Triggers need to be sharp in Pt due to steeply falling spectrum. Start with MB and look at "mark and pass" triggers. Establish the turn on curves , behavior in Pt. As luminosity increases, commission higher rejection triggers - bootstrap.

Data Analysis -It Takes a “Grid”

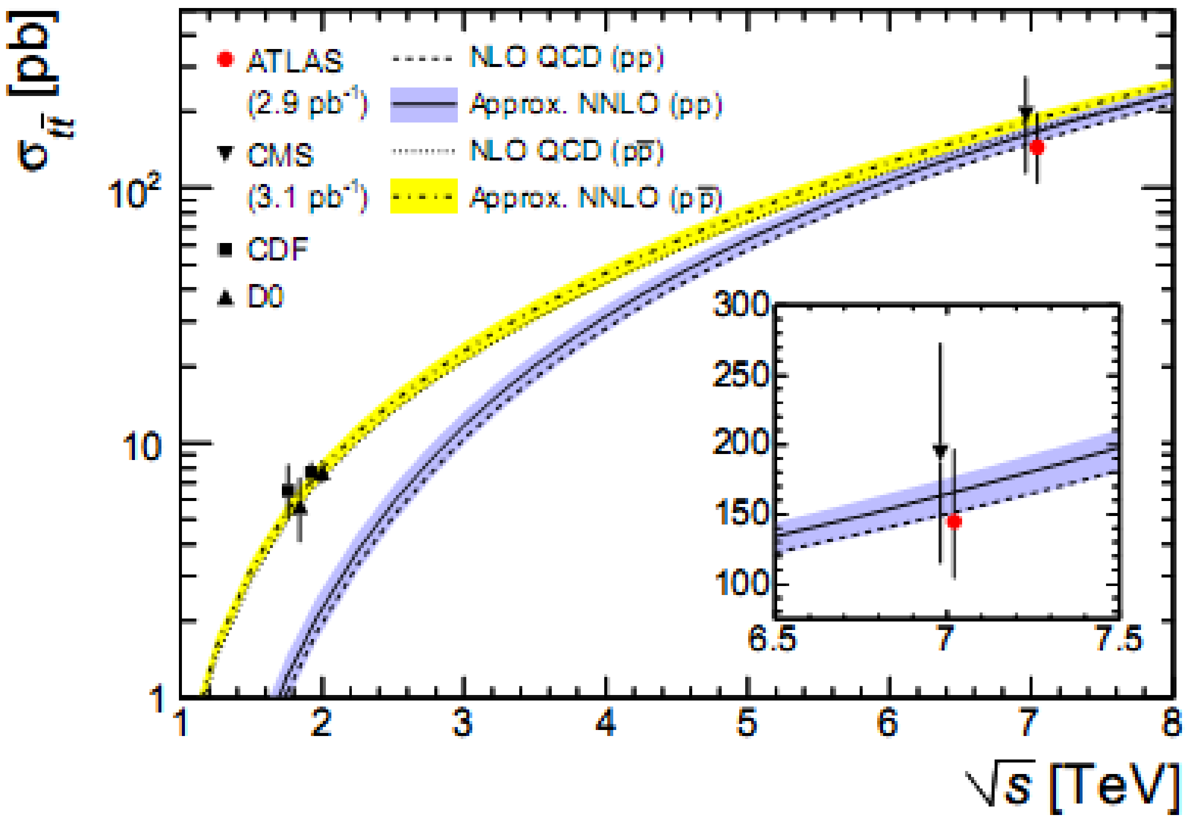
Worldwide LHC Computing Grid connects 100,000 processors in 34 countries with ultra-high-speed data transfers



References

- http://en.wikipedia.org/wiki/ATLAS_experiment - and links therein
- http://en.wikipedia.org/wiki/Compact_Muon_Solenoid
- http://lhc.web.cern.ch/lhc/
- http://ab-div.web.cern.ch/ab-div/Publications/LHC-DesignReport.html
- http://public.web.cern.ch/PUBLIC/en/LHC/CMS-en.html
- http://atlas.web.cern.ch/Atlas/index.html
- "The CERN Large Hadron Collider: Accelerator and Experiments", Journal of Instrumentation,3, SO8001-SO8007, 2008
- General-Purpose Detectors for the Large Hadron Collider, D. Froidevaux, P. Sphicas, Ann. Rev. Nucl. Part. Sci., 56, 375, Nov. 2006
- Review of Particle Physics, C. Amsler et al., Physics Letters B 667, 1 (2008)
- http://en.wikipedia.org/wiki/Dark_matter and links and references therein
- The Higgs Hunter's Guide, J. Gunion, H. Haber, S. Dawson and G. Kane, Westview Press, 2000
- http://en.wikipedia.org/wiki/CompHEP and links and references therein
- Jets from Quantum Chromodynamics, G. Sterman and S. Weinberg, Phys. Rev. Lett., 39, 1436 (1977)
- "Fragmentation, Underlying Event and Jet Shapes at the Tevatron CDF)" in Hadron Collider Physics 2005, Springer, 54, 2006
- http://www.linearcollider.org/cms/?pid=1000000 – home page for the ILC
- http://physics.uoregon.edu/~lc/wwstudy/concepts/ - links to 4 design concepts
- At the Leading Edge – the ATLAS and CMS LHC Experiments, World Scientific, Ed. D. Green, 2010

Top Cross Section



Note the rapid rise from Tevatron to LHC by a factor ~ 20. The LHC is therefore a "top factory".

Top Mass - 2010

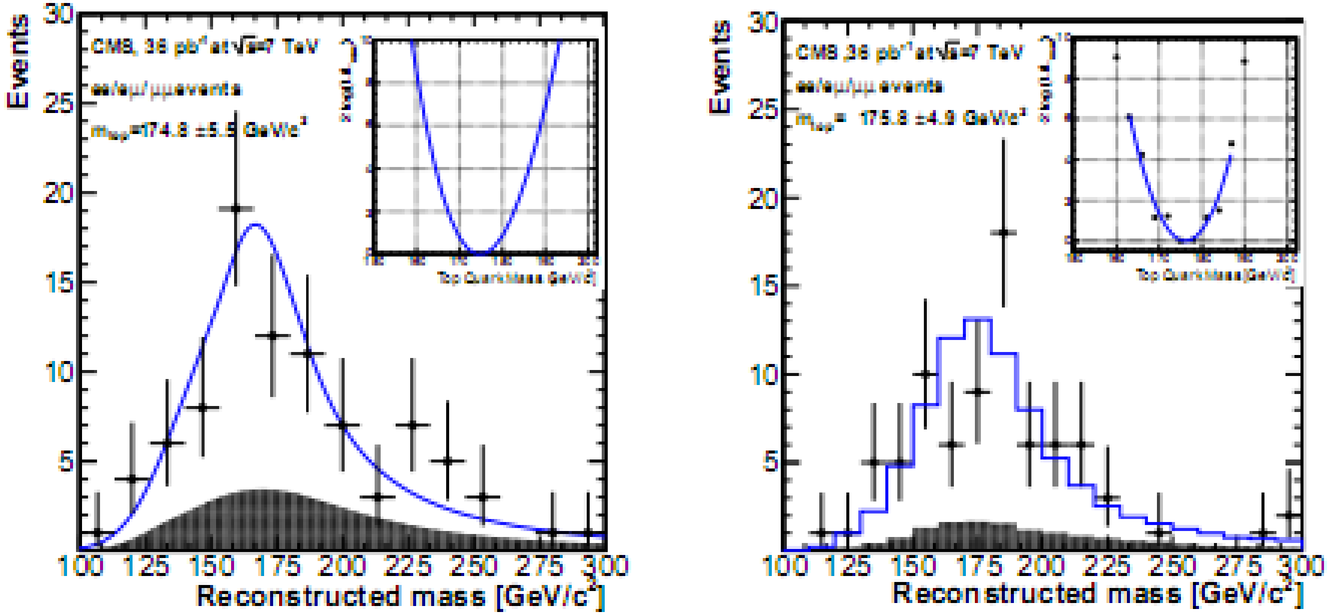
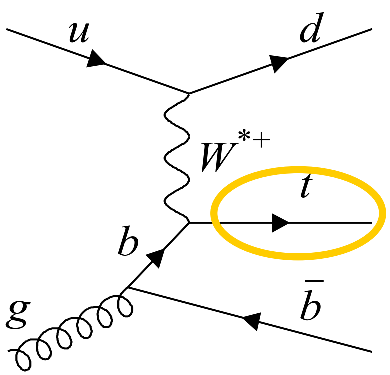
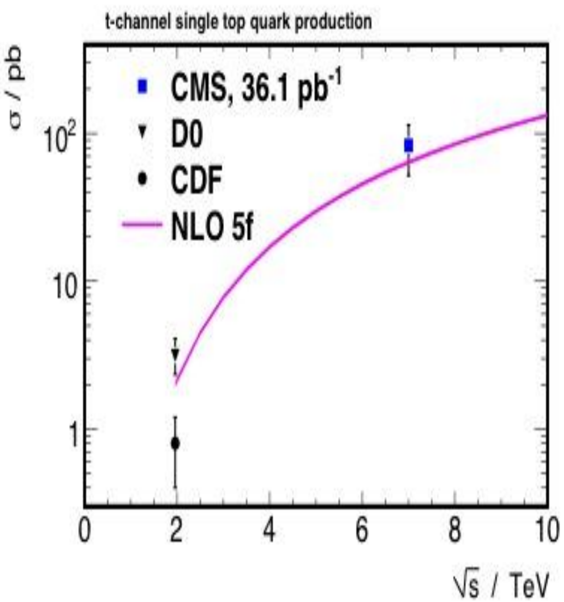


Figure 8: Reconstructed top quark mass distributions from the KINb (left) and AMWT (right) methods. Also shown are the total background plus signal models, and the background-only shapes (shaded). The insets show the likelihoods as functions of m_{top}.

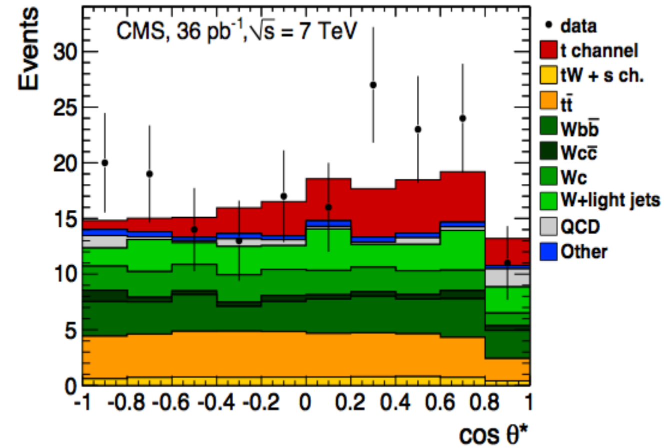
LHC is capable of making precision top measurements as well as searching for new physics

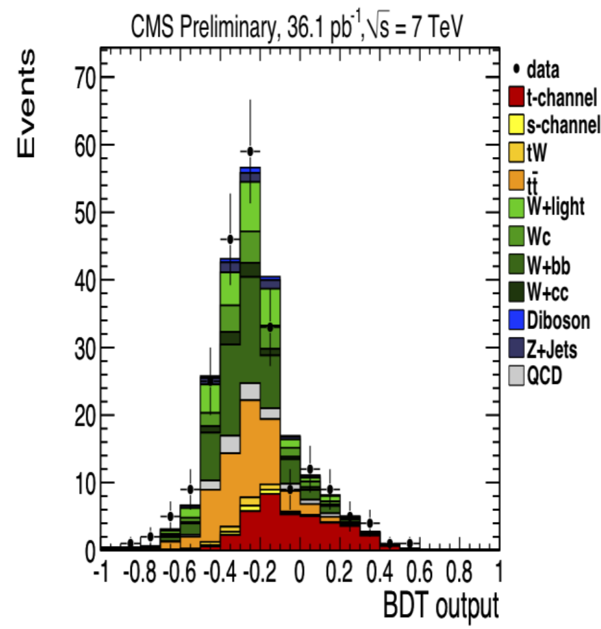
Single Top





Advanced statistical methods are now deployed in CMS. Cross section for single top is much larger at the LHC than the Tevatron, ~ 40 x, making the single top detection easier.

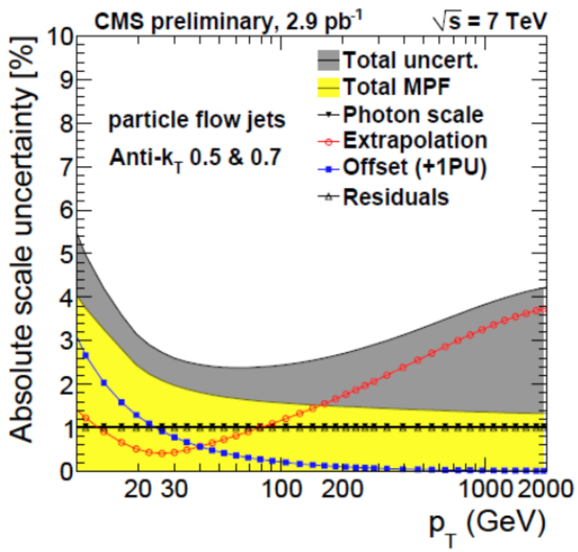


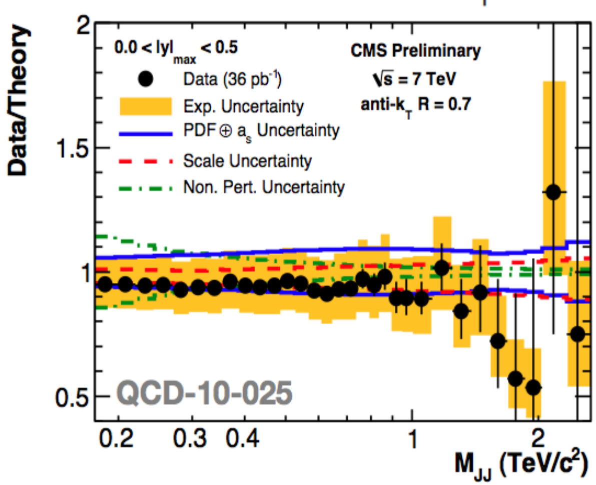


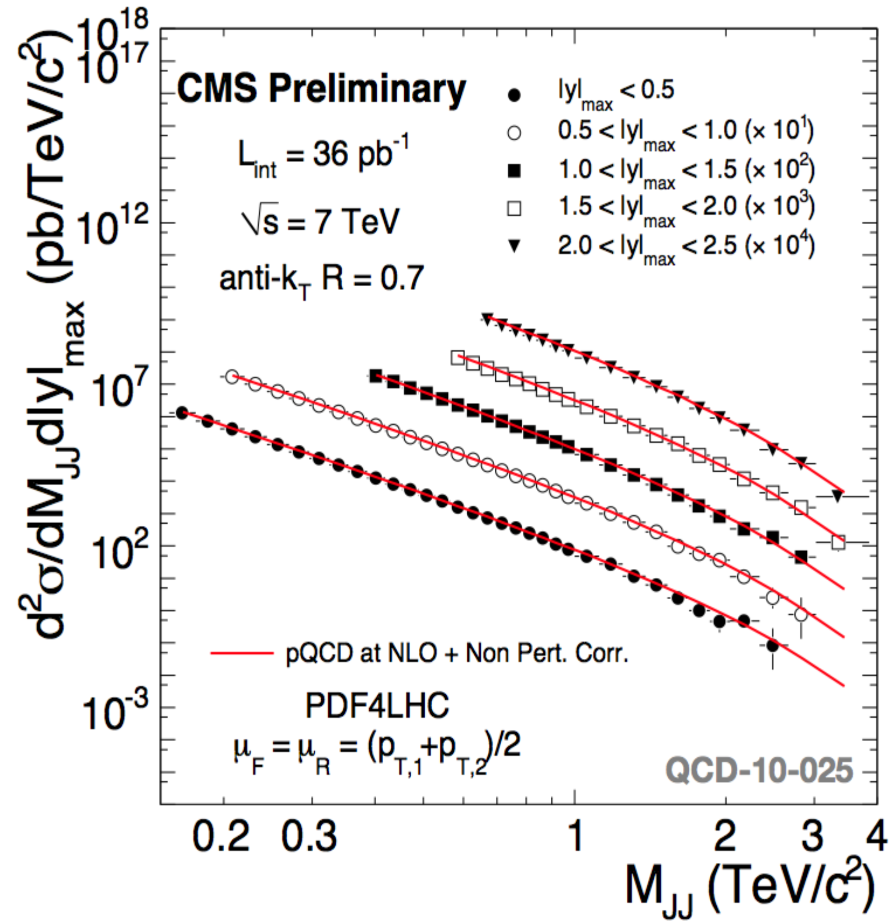
Luminosity and Detectors

- **The high luminosity which is required of the LHC by our need to explore terascale physics means that the detectors will be exposed to high particle rates. Therefore LHC experiments will require fast, radiation hard and finely segmented detectors. The speed of the detectors sets a scale for the accelerator radiofrequency, r.f., bunch structure. It is assumed in what follows that all the detectors can be operated at a speed which can resolve the time between two successive r.f. bunches which is 25 nsec at the LHC.**
- **Consider, for example, a silicon solid state detector operated with a bias voltage which creates an electric field, E. The charge collection time is,** $\tau = d / \mu E$ **, where d is the thickness of the detector and is the hole or electron mobility. Numerically, for** $d = 300 \mu m$ **, the electron drift velocity at a typical depletion voltage of ~ 50 V = dE is** μE **~** $42 \mu m / n\sec$ **leading to a charge collection time of ~ 7 nsec. The holes are ~ 3 times slower, so a charge collection of 25 nsec is well matched to the LHC bunch crossing spacing. Shorter bunch crossing times are not useful because the detectors would simply be forced to integrate over the multiple bunch crossings occurring within their resolving time.**

Commission Jets (q , g)

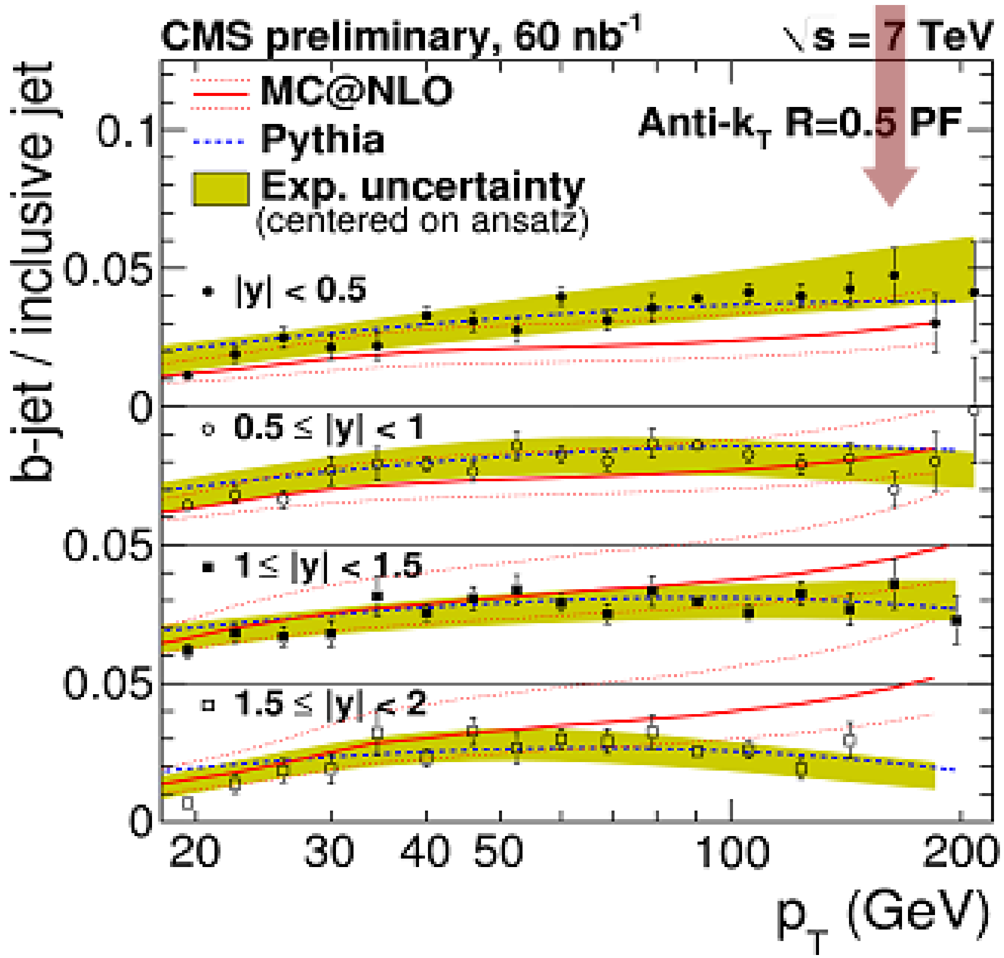






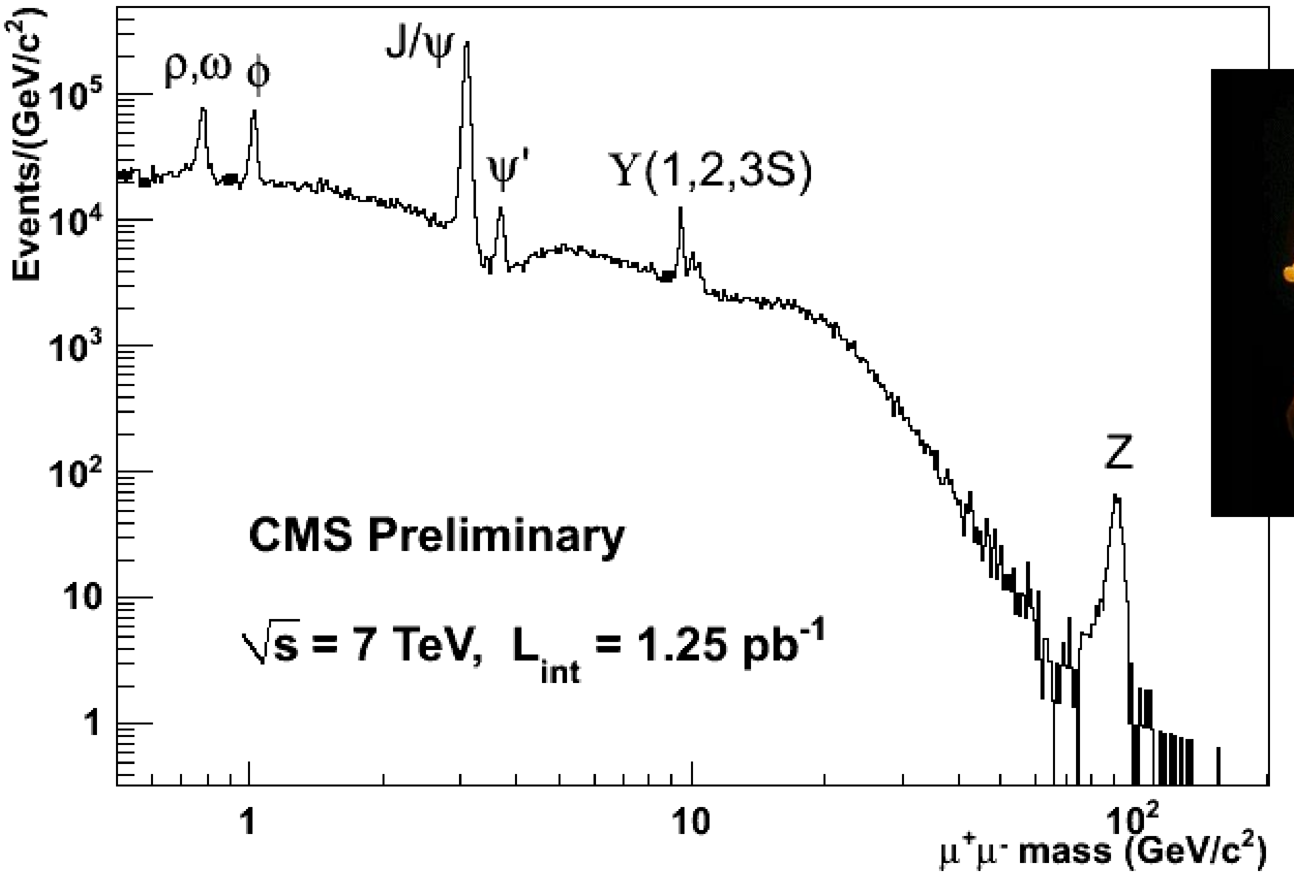
Establish the jet cross section as a function of y and Pt. Monte Carlo agreement is good. Now ready to look at high masses for BSM Physics.

b Cross Section



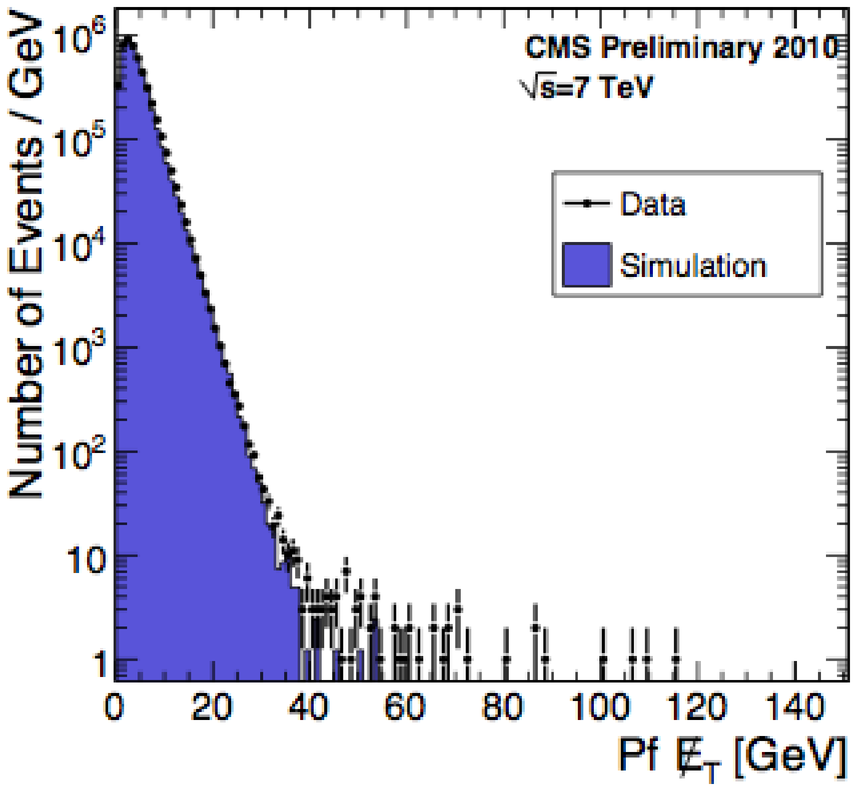
At the LHC the b cross section is large -> LHCb. The b jet rate is ~ 2 % (Pt dependent) of the inclusive jet rate. Well modeled by PYTHIA Monte Carlo. Use secondary vertex mass, Ptrel templates for u+d+g, c, and b – efficient b tagging with good u+d+g rejection

Dilepton "Standard Candles"



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

MET (ν)



In dijet events there is ~ no true MET and there is a ~ 6 order of magnitude smooth fall of the observed MET. The existence of real MET indicates the escape of a neutrino or other neutral, weakly interacting object.

CMS Solenoid Design