The First Years of the LHC Experimental Program

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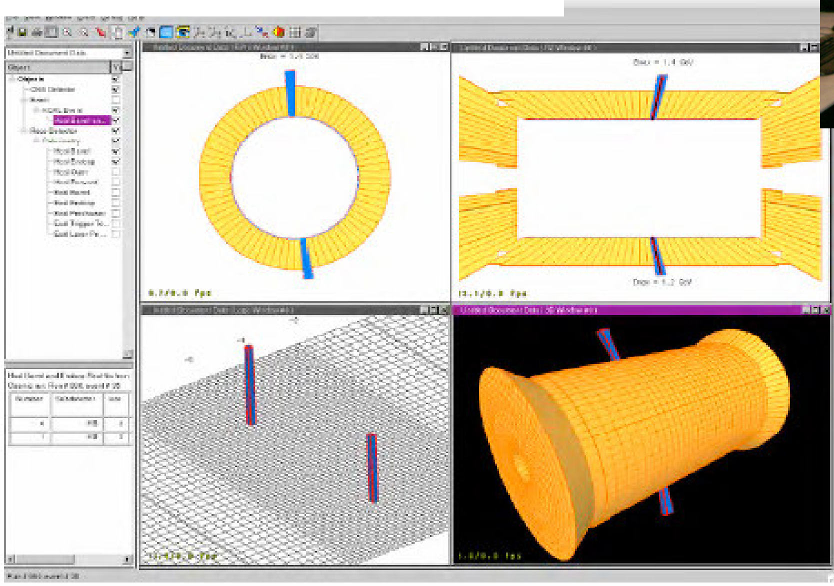
Outline

- Pre-operations – synchronization, alignment and calibration – Monte Carlo
- First Five Orders in Cross Section: 10/mb to 1/nb
  - Minbias
  - Jets, dijet balance
  - Direct photons
  - Launch Dijet search
- Next Six Orders in Cross Section: 10/nb to 1/fb
  - b pairs and tagging
  - Ψ calibration
  - Υ calibration ← Pilot Run
  - W calibration
  - Z calibration
  - Z+J balance, diphotons, top pairs (Jets, leptons and MET)
  - Jest Energy Scale with W -> J + J.
  - Launch dilepton (and leton+MET), diphoton and J(s)+lepton(s)+MET.

Pre-Operations

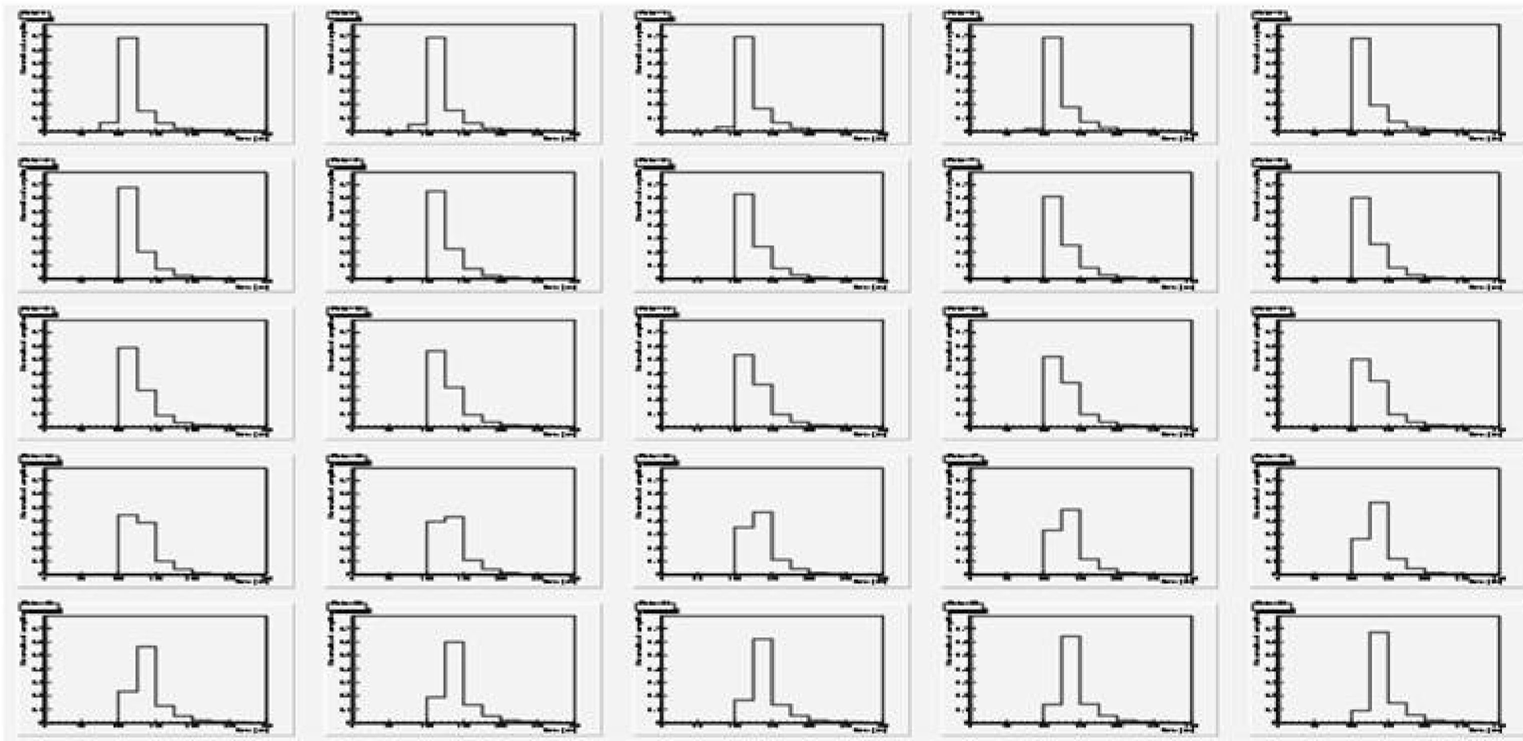
- Set relative timing to 1 nsec using lasers, pulsers – all subsystems
- Set ADC counts to Et conversion to 5% using radioactive sources, muons, and test beam transfer of calibrations – e.g. ECAL and HCAL.
- Set alignment of muon chambers using cosmic ray muons and optical alignment system MB and ME. Track motion with field on (first test in SX5 in cosmic challenge).
- Set alignment of tracker (pixels + strips) using muons, optical alignment and survey. Check with muons and laser "tracks".

CMS _ Magnet Test + Cosmics



HCAL – 1 nsec Phase

1

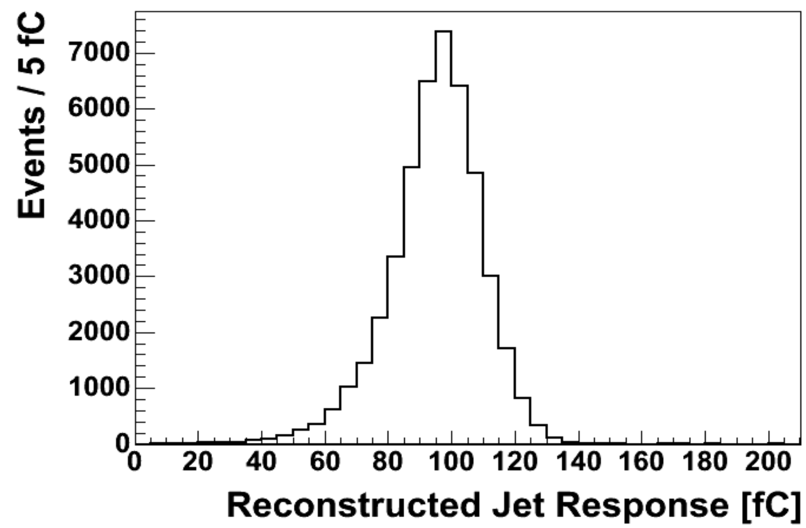


25

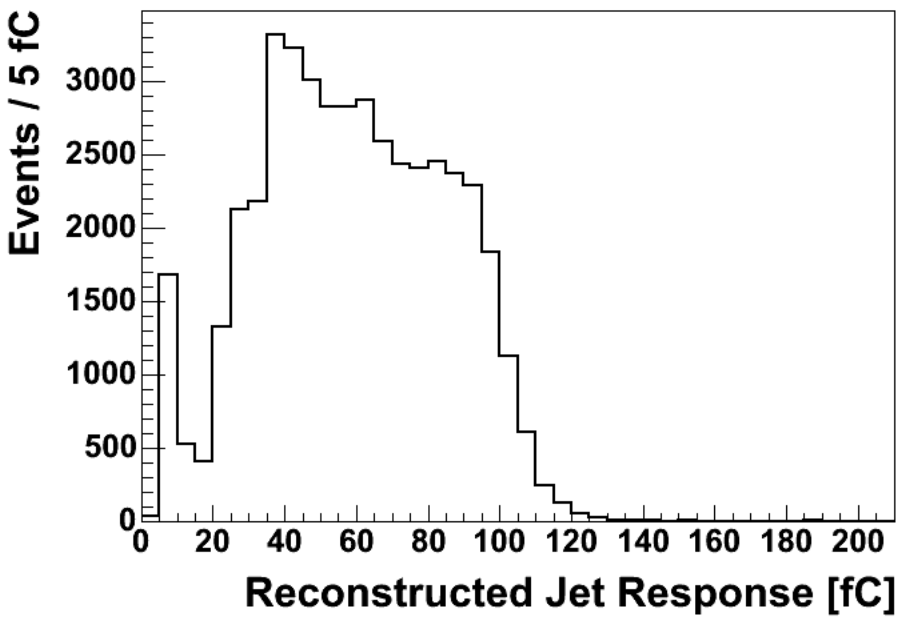
Time each channel with laser + variable delay. Check that pulse shape is consistent. Can easily see 1 nsec variations with sufficient photo-statistics.

Timing is the First Task

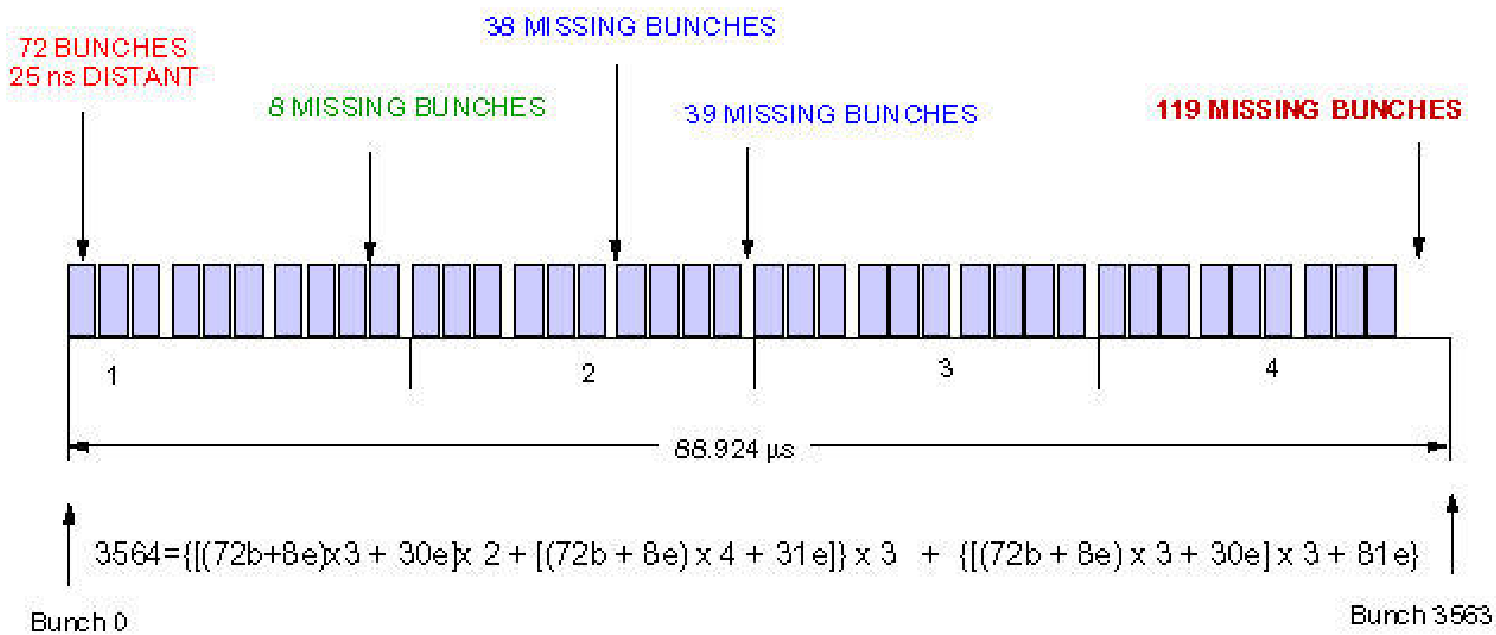
100 GeV pions when properly timed in



100 GeV pions when late by one bucket
(same events)

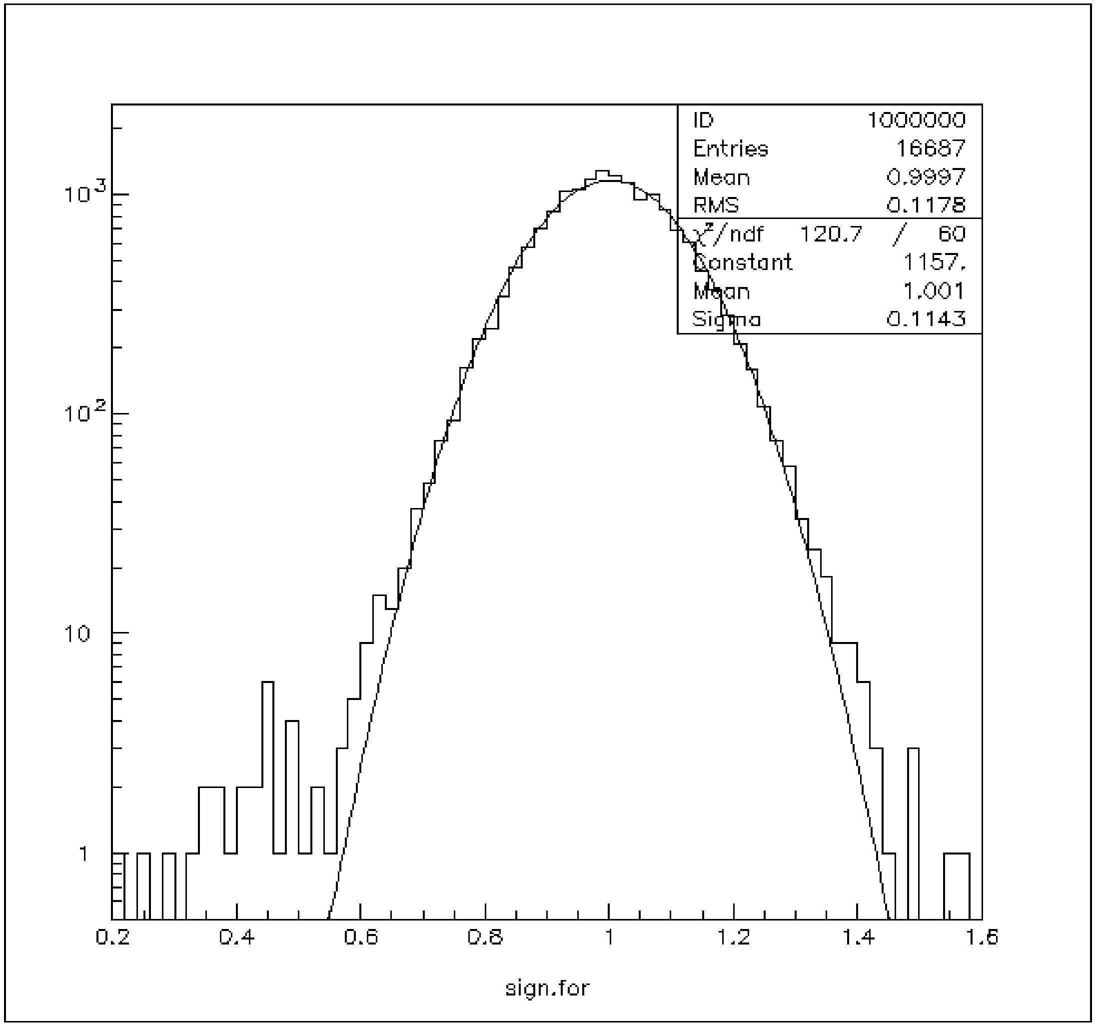


Beam Structure at LHC



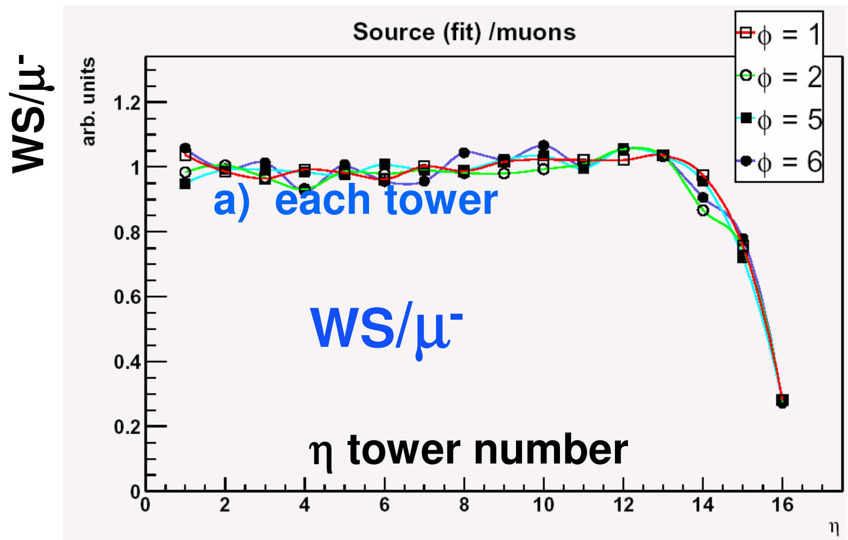
Collect minbias energy deposits as a function of bunch crossing for a given detector (e.g. HCAL). The overall, absolute, timing is set by finding the abort gap.

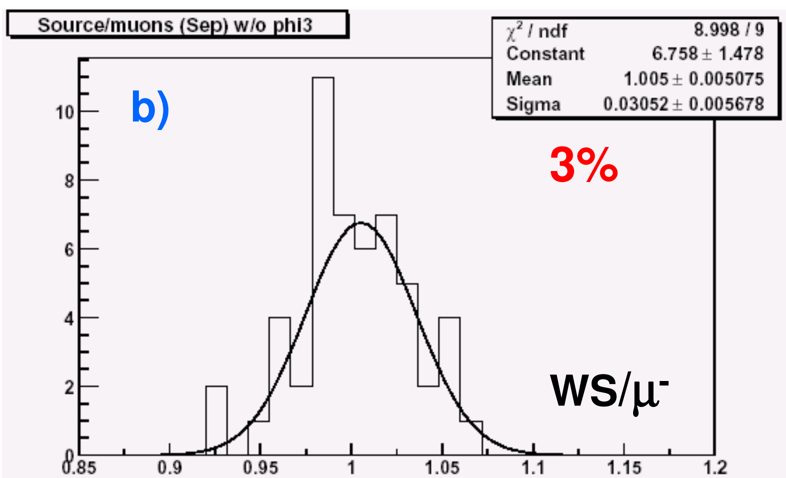
HCAL - Calibration



Over 16,000 entries, individual tile wire source RMS= 11% - agrees with QC at factory. Allows HCAL to transfer calibration from a few towers in a test beam to all tiles in the calorimeter.

HCAL-Muons and e vs Sources

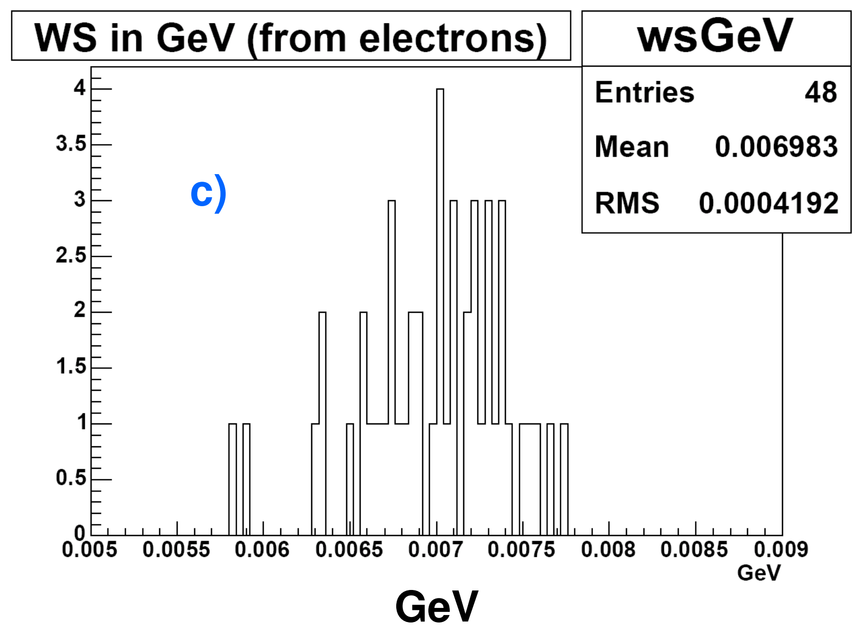




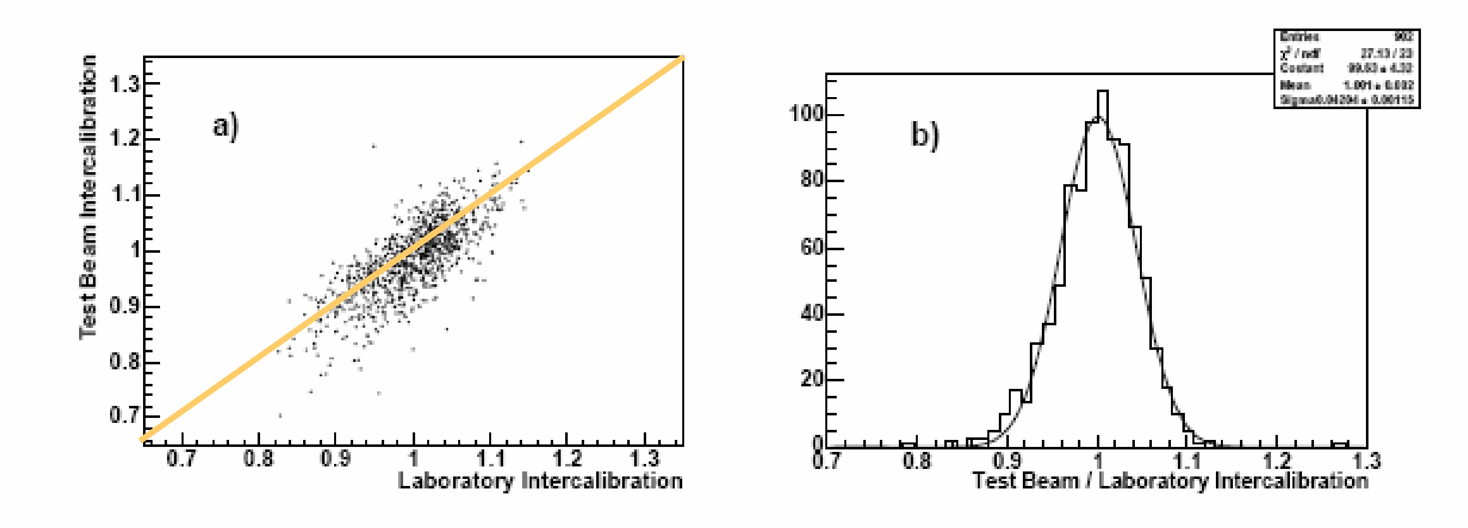
a,b) Comparison with muon beam.

c) Calibration of wire source with 100GeV electron beam.
→ 6.98 MeV equivalent as of 2005-01-31

6% - to be improved



ECAL – Laser vs Test Beam



Laser light yield at manufacture correlates with test beam electrons to ~ 4%.

ECAL – Cosmics vs Test Beam

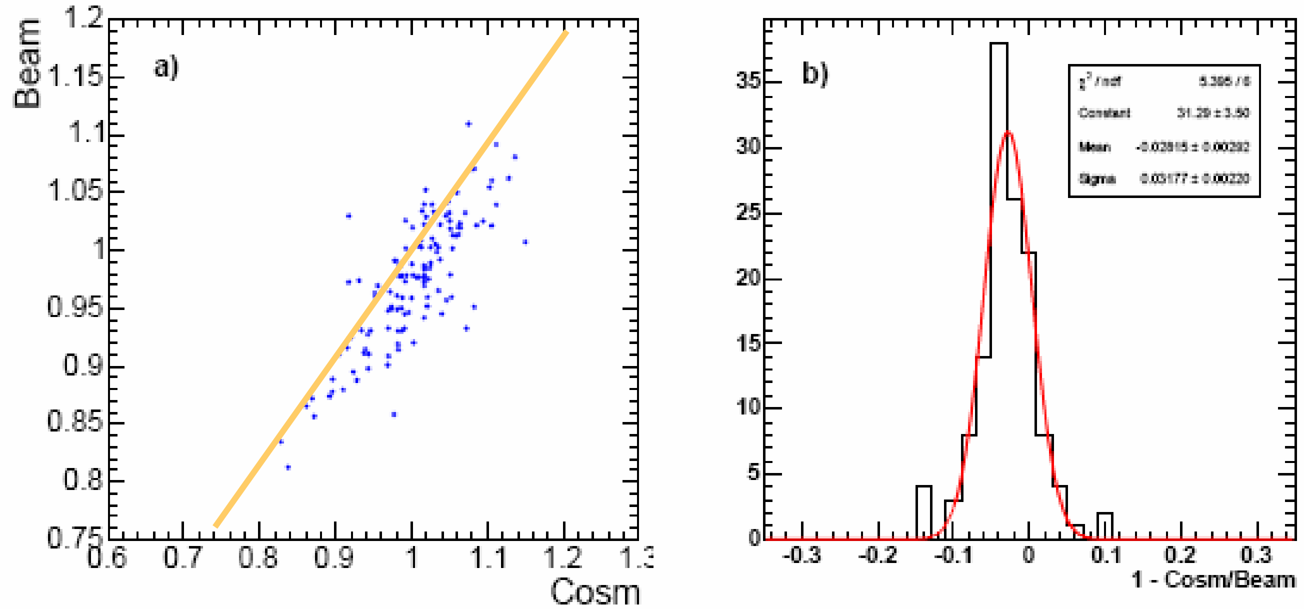


Figure 4.17: Correlation between (a) the testbeam calibration coefficients and cosmic ray muon coefficients, and (b) relative precision of the cosmic muon calibration constants. Only those channels with more than 50 cosmic muon events are considered.

Use cosmic muons and compare to electron beam – good to ~ 4%. Better calibration must rely on in situ electrons from vector boson resonances, e.g. Z.

Tracker Alignment

$R \sim 1m, B \sim 4T$

$1\% \sim dP/P \; at \; 100 \; GeV - design$

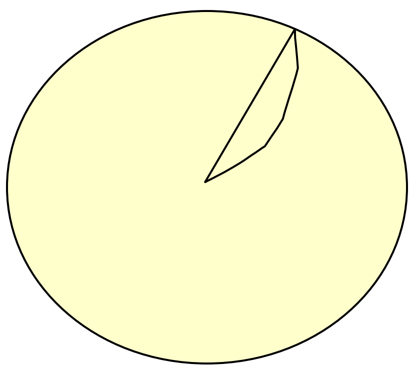
Bend angle depends on magnetic field length, R, and strength B. CMS sets a goal of 10% at 1 TeV or a 2 TeV object decaying into di-muons. Resolution of pixels is ~ 10 um, strips ~ $\sigma \sim d/\sqrt{12} \sim 50 \mu m$

$P = 0.3B(T)\rho(m), \phi \sim R/\rho = aBR/P, a = 0.3$

$100 \; GeV, 1m, 1\% \; error$

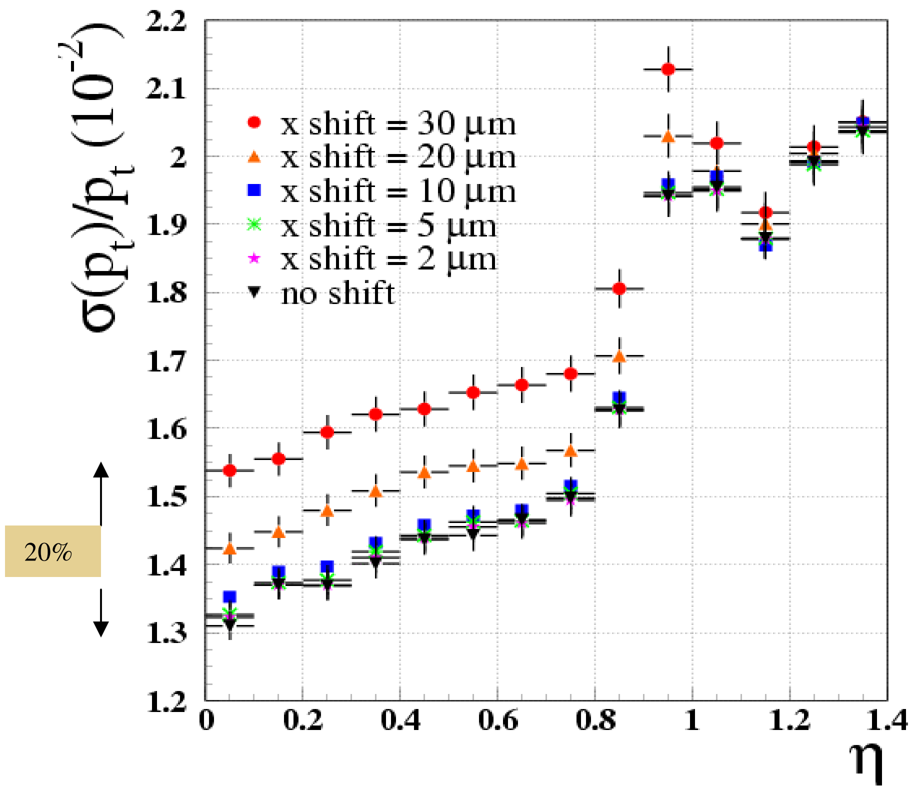
$d\phi \sim RaB(dP/P^2) \sim 1.2x10^{-4}$

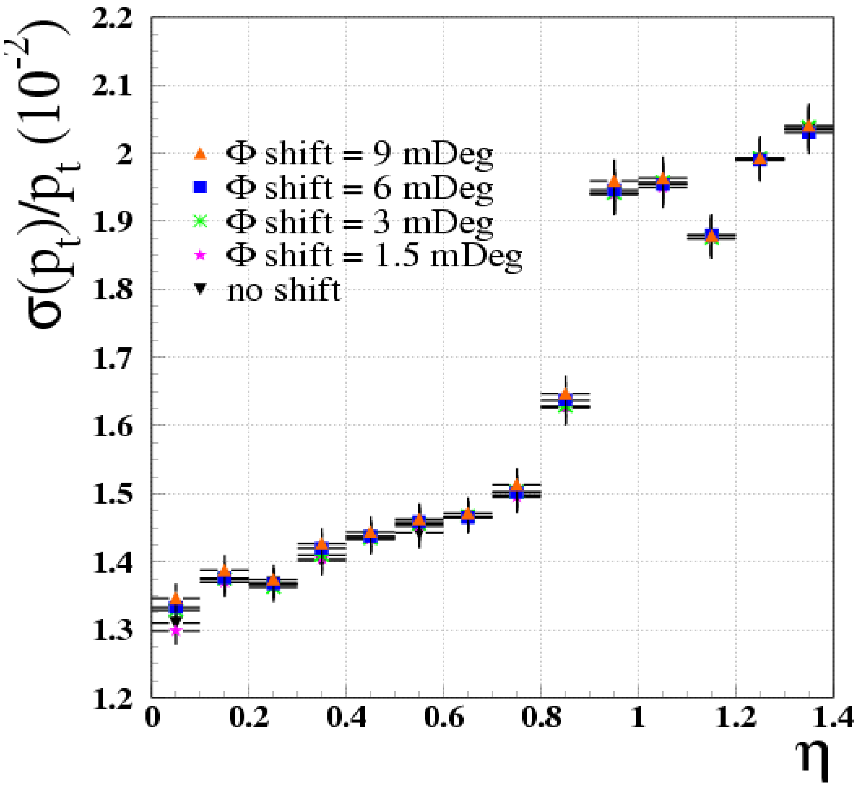
$ds \sim d\phi R/2 \sim 60 \; \mu m$



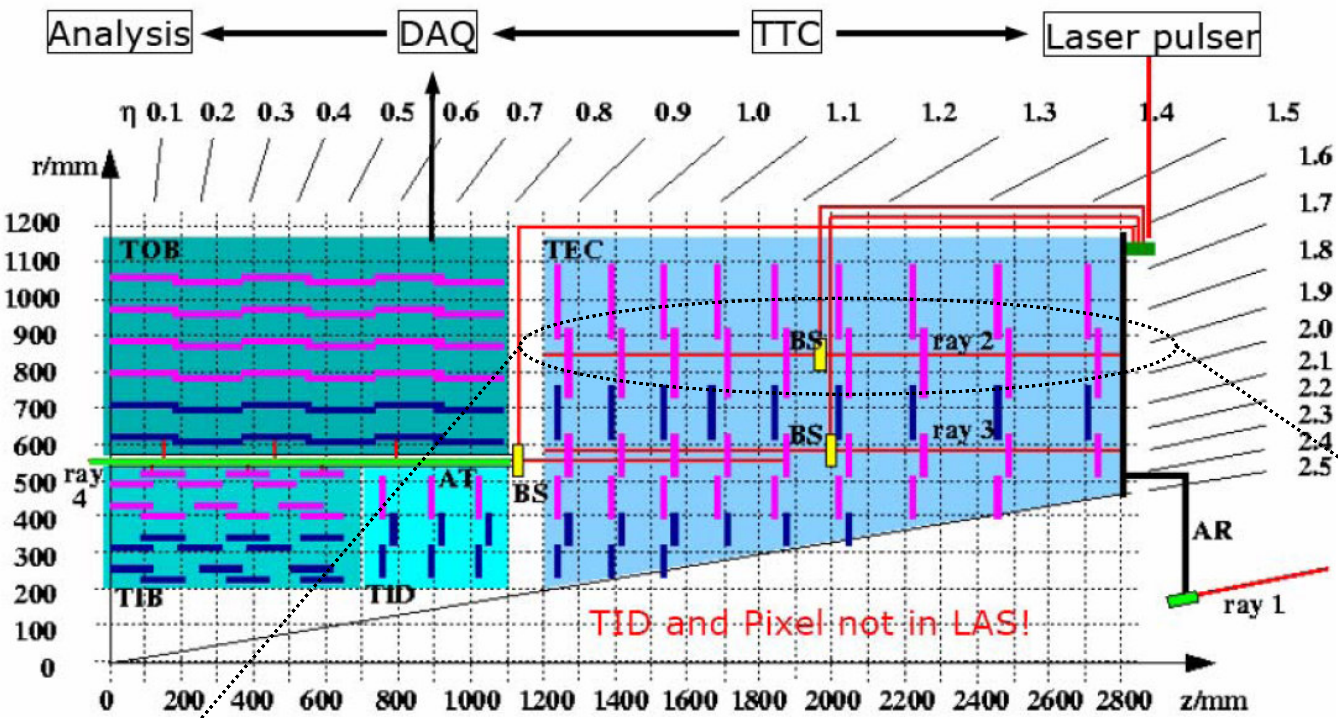
Tracker -Misalignments and P_T Resolution

Only shifts greater than 10 µm degrade Pt resolution for a 100 GeV muon.



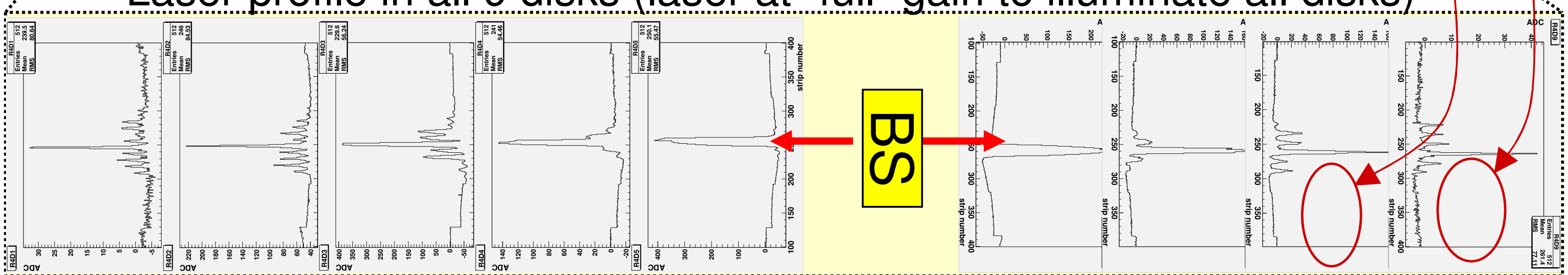


Laser Alignment System



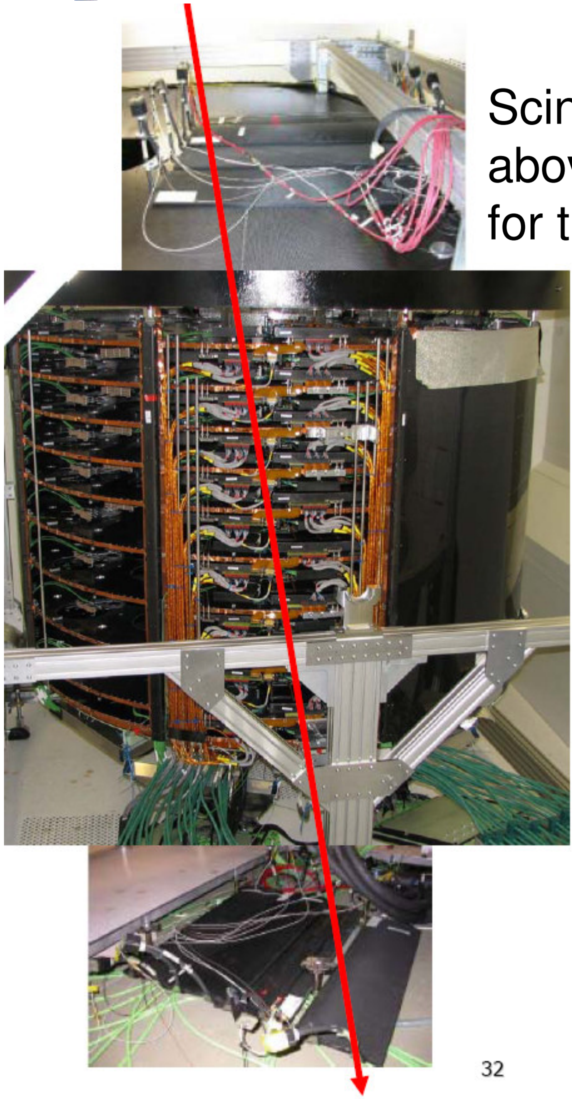
Laser Alignment System proven

Laser profile in all 9 disks (laser at "full" gain to illuminate all disks)



NB:diffraction patterns from strips

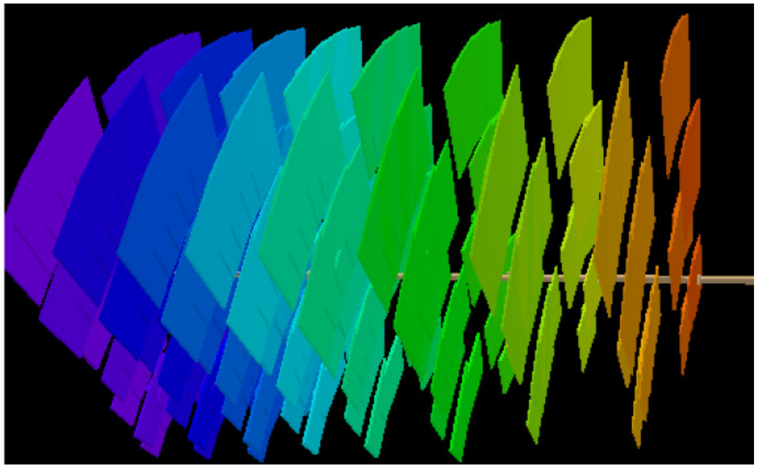
TEC Verification with Cosmics

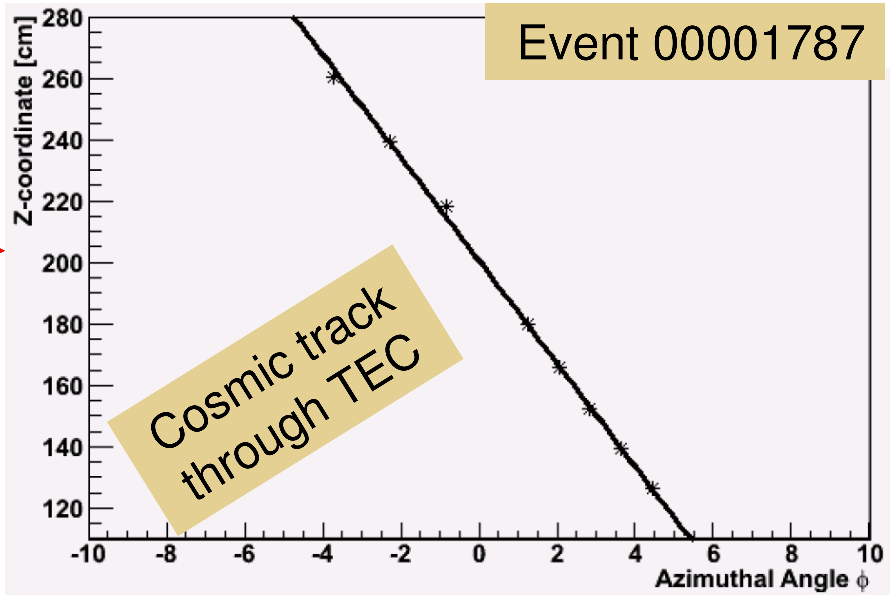


Scintillator panels above and below for triggering

Tracker Endcap (TEC)

Software reconstruction of a "Laser track"





Tracker - Misalignments

40%

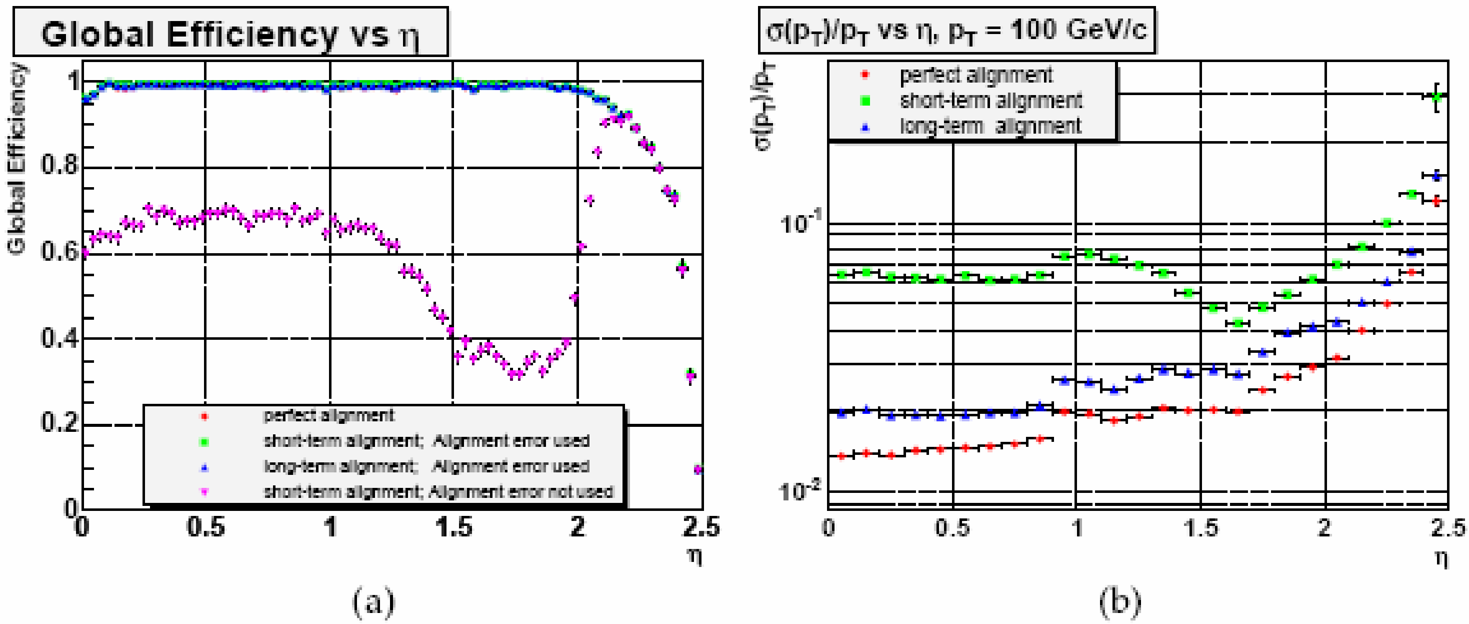


Figure 6.26: Impact of misalignment on (a) the track finding efficiency and (b) the transverse momentum resolution as a function of η for single muons.

4x worse

An in situ alignment with high Pt tracks (due to multiple scattering where dP/P_{ms}~constant) is needed to achieve an alignment which does not compromise reconstruction efficiency or momentum resolution. Initial alignment by survey, coordinate measuring machine or laser is only good to $\sim 200\mu m$

Tracker Material

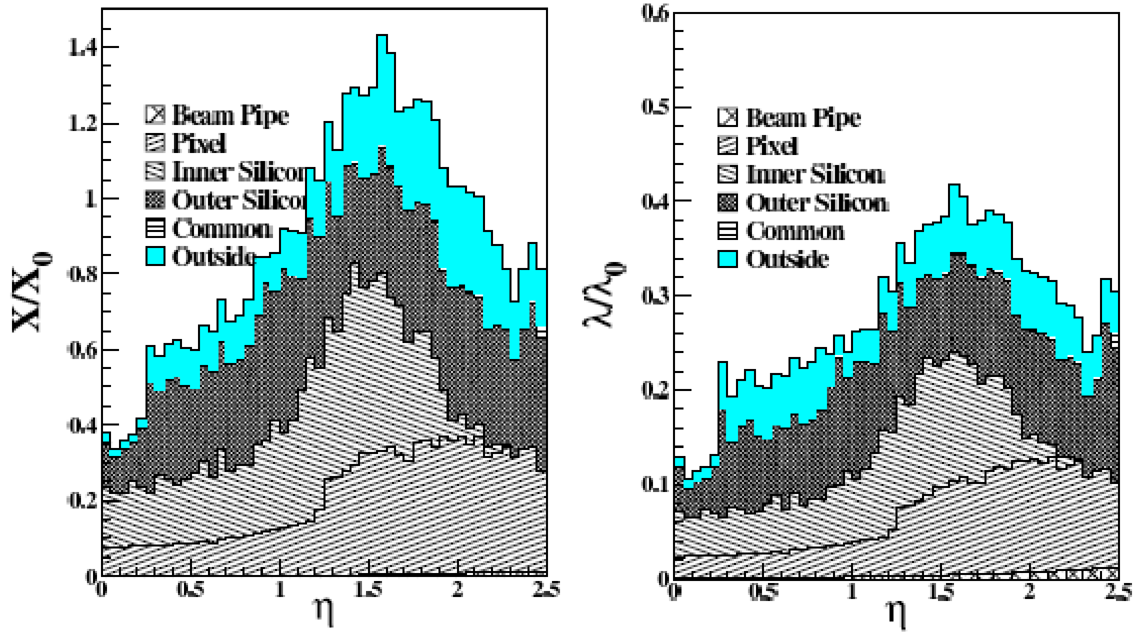
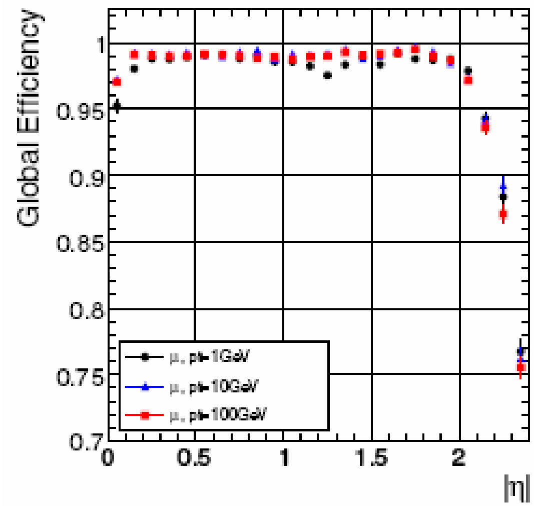
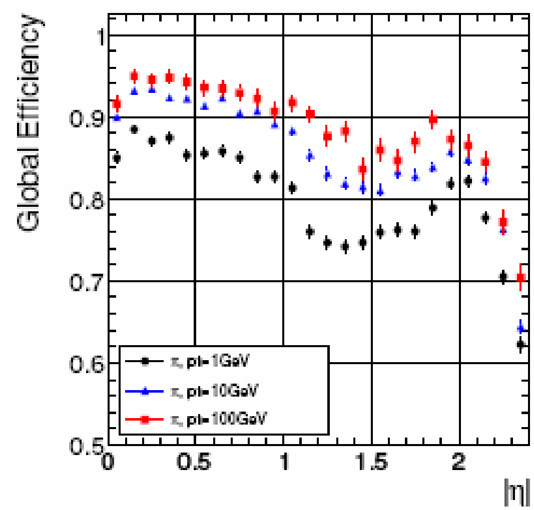


Figure 6.1: Material budget in units of radiation length (left) and in units of interaction length (right) as a function of η for the different subunits.



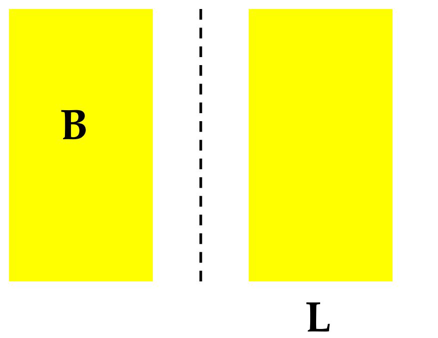
μ



π

There is enough material in the tracker to compromise the pion reconstruction efficiency.

Muon Alignment – Cosmic Rays



Multiple Scattering

$$\theta_{ms} = 0.015(GeV)\sqrt{L/X_0}/P(GeV)$$

$$X_0 = 1.76\,cm\,(Fe)$$

$$\phi = L/\rho = 0.3BL/P$$

$$\theta_{ms}/\phi = 0.015/\sqrt{LX_0}[0.3*B]$$

$$\sim 4\%$$

$$\phi = L/\rho,\ P(GeV) = 0.3B(T)\rho(m)$$

$$ds \sim \phi L/2$$

$$L \sim 30\,cm,\ B \sim 2T\ (Fe)$$

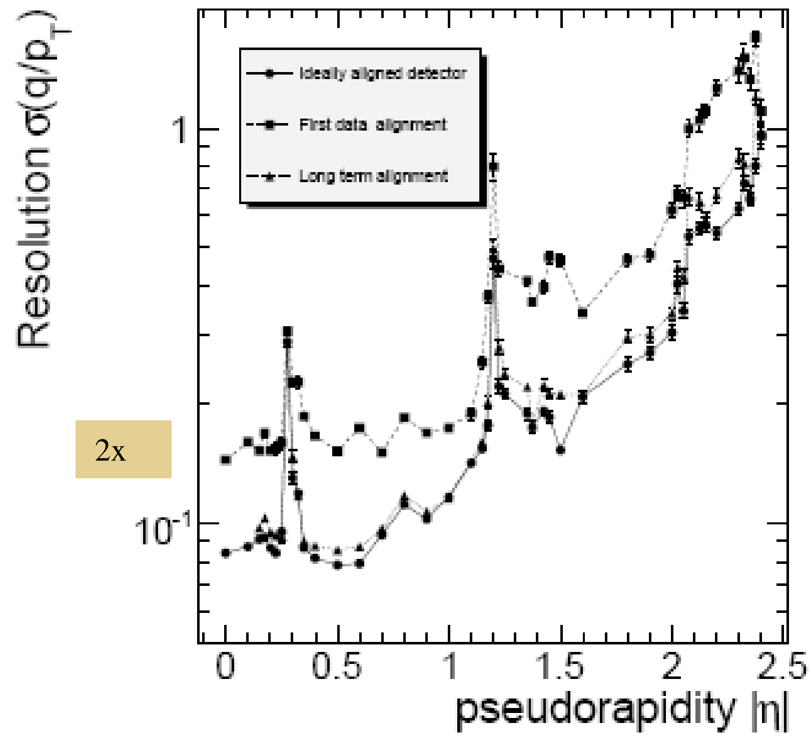
$$dx \sim 200\mu m\ \ for\ P \sim 270\,GeV$$

The muon momentum resolution is dominated by multiple scattering. Therefore, dP/P ~ constant. This means that the alignment requirements for the Muon systems are somewhat relaxed. (not true in ATLAS).

Muon Alignment

Table 3.2: Alignment precisions used in the 2 misalignment scenarios. Displa
mm and rotations are in mrad.

	MB	CSC	Tracker-Muon
First Data Taking Scenario			
Displacement (x-y)	1.0	1.0	1.0
Displacement (z)	1.0	2.0	1.0
Rotations	0.25	0.5	0.2
Long Term Scenario			
Displacement (x-y)	0.2	0.2	0.2
Displacement (z)	0.2	0.4	0.2
Rotations	0.05	0.1	0.04

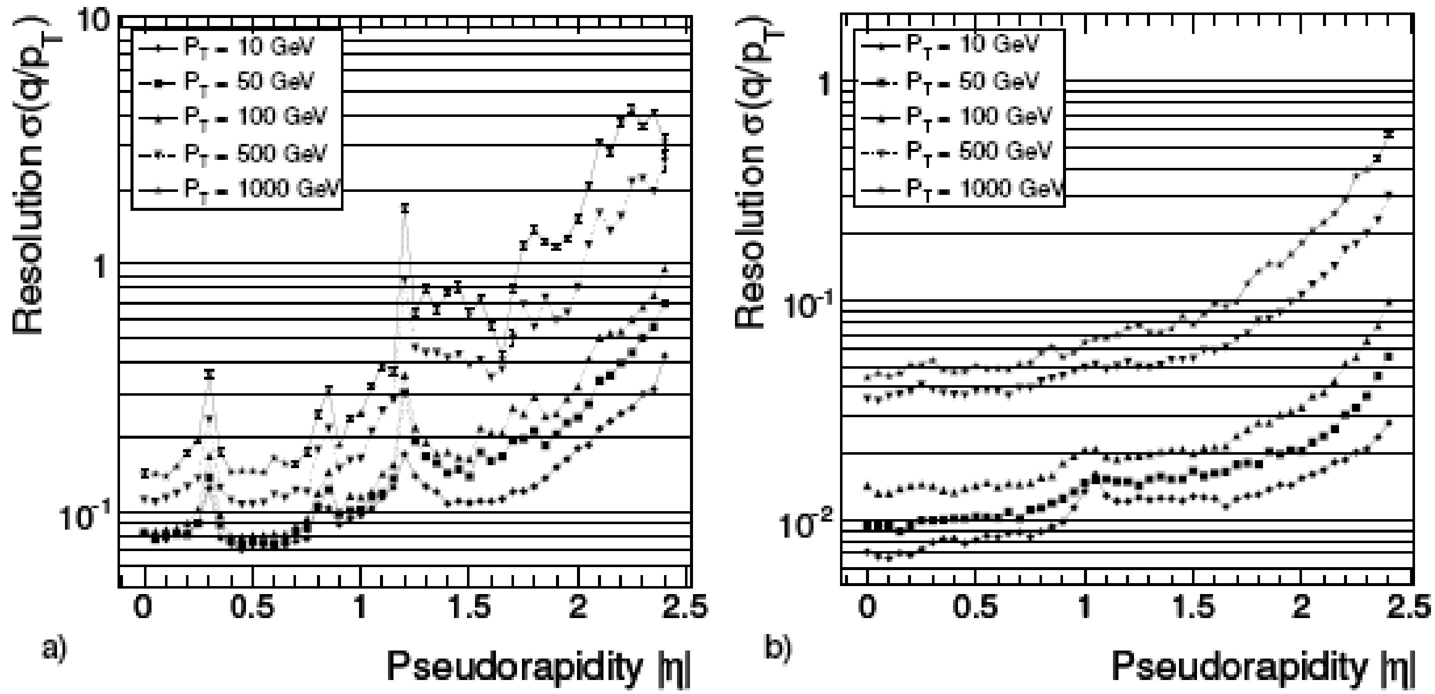


2x

Note 1000 um displacements do not do great damage to the stand alone muon momentum measurement.

Tracker – Muon Alignment

10%



1%

Figure 9.2: The q/p_T resolution for standalone (a) and globally (b) reconstructed muons (combined muon system and silicon tracker) as a function of pseudorapidity.

Note muon dP/P ~ const ~ 10% and tracker dP/P ~ 1/P. Note also tracker is ~ 10x more accurate → Muon for ID and Trigger, Tracker for kinematics.

Monte Carlo Models

- Before first data make as complete a model as possible of the detector response.
- At each luminosity generate and process the appropriate SM reactions which will populate the trigger cuts appropriate to the data set.
- Compare to data and see if SM is reproduced – subject to plausible "fudge factors"
  - Minbias
  - QCD Jets, b jets
  - Photons
  - Vector Bosons
  - Top pairs
- Strategy used in D0 – Sleuth and CDF – Vista. Appropriate if theoretical guidance is not crisp.

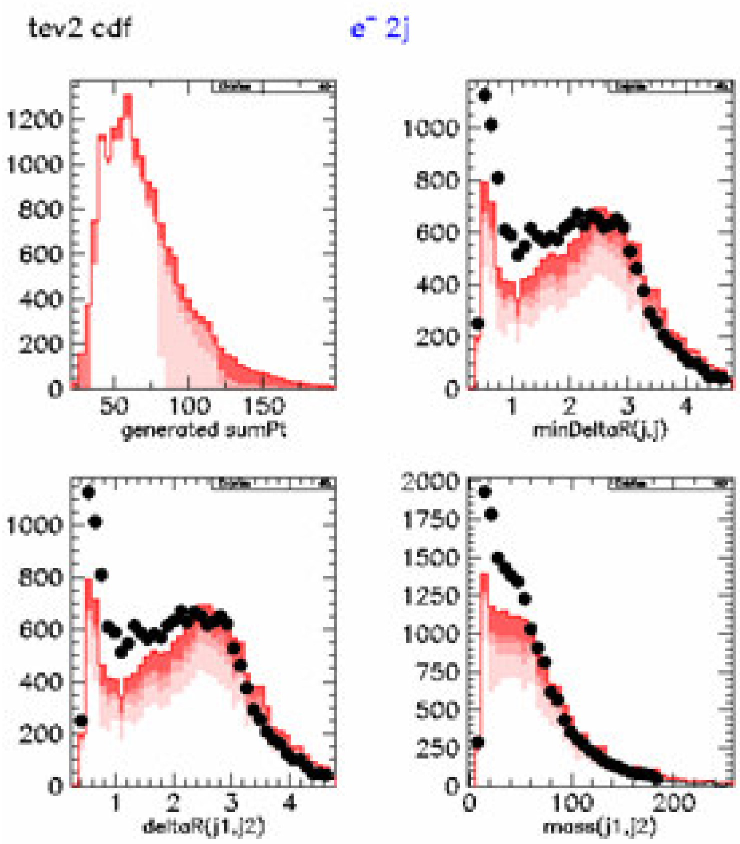
Models and SM

- Have SM Monte Carlo and data. Comparison is made up to factors of experimental uncertainty (trig eff, reco eff) and theoretical uncertainty (pdf, FSR, k factor, hadronization…).
- Differences will point experimenters to areas where repairs may need to be made
- Consider the final state objects to be exclusive final states of any number of:

$$e, \gamma, J, \mu, b, \tau, \not{E}_T = MET$$

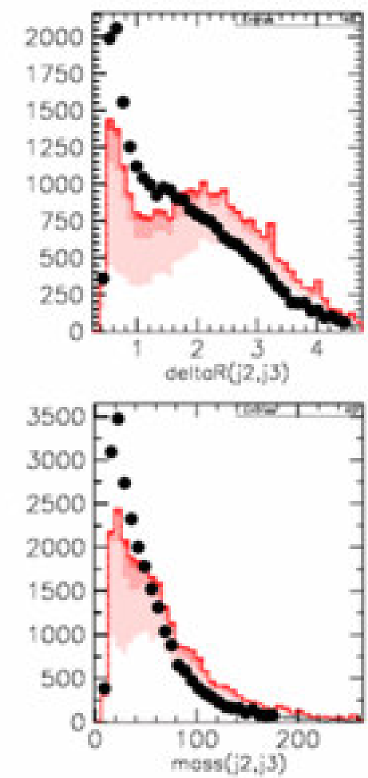
- Not as incisive as directed searches, but with a first startup of detector and accelerator the procedure will point to problem areas.
- Also, in the absence of definite theoretical guidance (e.g. W, Z in 1980) a general approach is called for. Fundamentally, the experiment must re-establish the full SM before a discovery search would become believable.

CDF – Run II



e JJ final states – some poorly modeled – perhaps feed through from J misidentified as e

Reminiscent of ***3j:***



LHC Run Plan

Table 1.2: Expected evolution of LHC performance parameters during 2007–2008 [11].

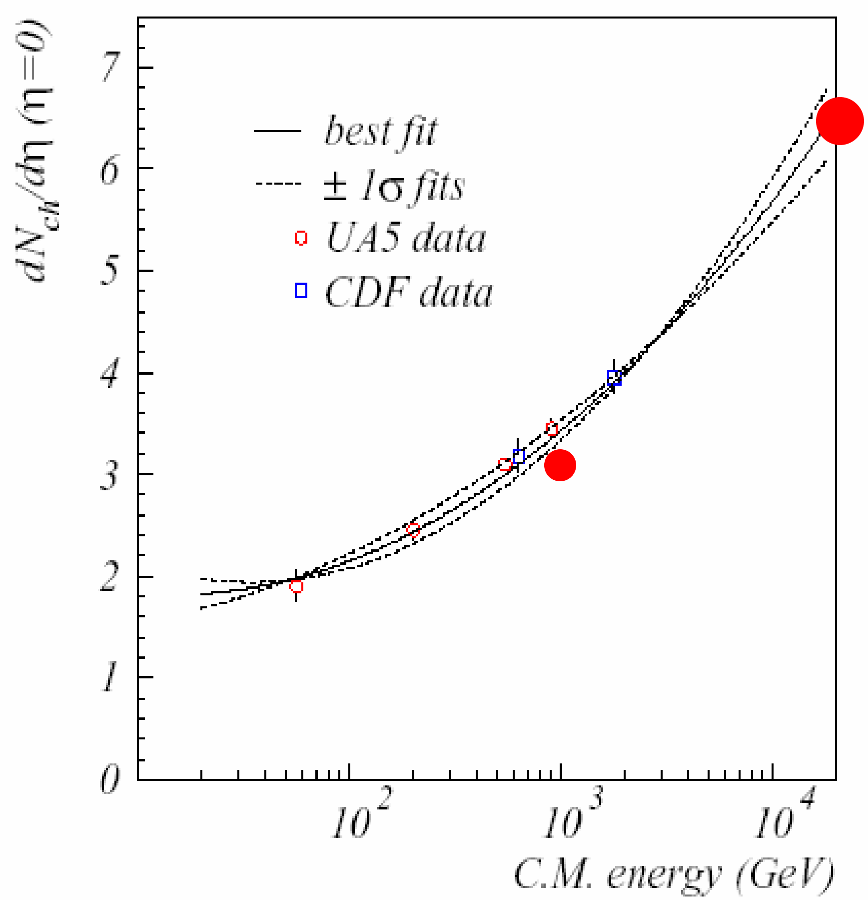
	Pilot run 2007	First Physics 2008
Number of bunches	43→156	936→2808
β^*	18 m→2 m	2 m→ 0.55 m
Protons per bunch	$10^{10} \to 4 \times 10^{10}$ (10^{11})	4×10^{10}
Luminosity	$3 \times 10^{29} \to 2 \times 10^{31}$ (10^{32})	$10^{32} \to 2 \times 10^{33}$
Integrated Luminosity	10 pb^{-1}	< 5 fb^{-1}

The 2007 run at 0.9 TeV will be for a short period and log only < 10/pb. The 2008 run will be at 14 TeV and log ~ "few" /fb. We must extract all possible information from the 2007 data.

From 10^{23} to 10^{27} /(cm^{2}sec)

L for 1 month run (10^6 sec)	Integrated L	Trigger	Process	Comments
10^{23}	100 mb^{-1}	None σ_I~ 50 mb	Inelastic non-diff	Input to tweak Pythia
10^{24}	1 μb^{-1}	Setup Jet	Inelastic non-diff	Calib in azimuth
10^{25}	10 μb^{-1}	Jet $\sigma(gg)$ ~ 90 μb $\sigma(ggg)$ ~ 6 μb	g+g -> g+g g+g -> g+g+g	Establish JJ cross section
10^{26}	100 μb^{-1}	Jet	g+g -> g+g g+g -> g+g+g	Dijet balance for polar angle – Establish MET
10^{27}	1 nb^{-1}	Jet Setup Photon $\sigma(q\gamma)$ ~ 20 nb	g+g -> g+g g+g -> g+g+g q+g -> q+γ	Dijet masses > 2 TeV, start discovery search. J+γ calib

Minbias Rapidity Density



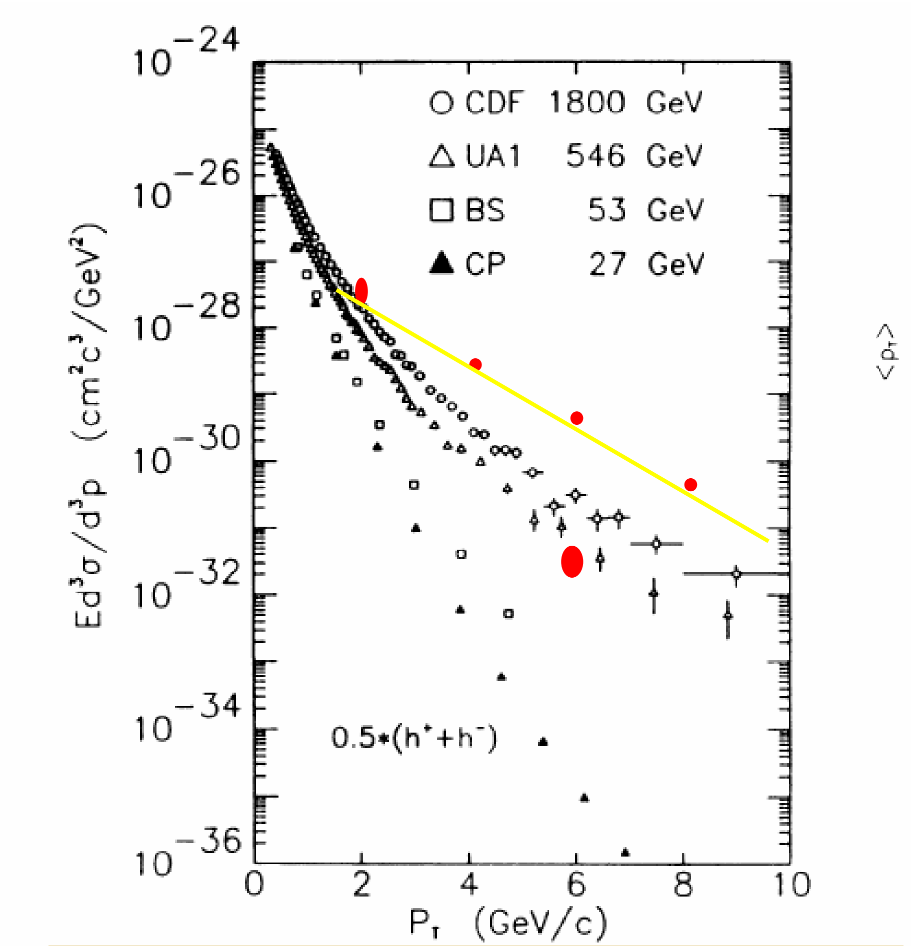
Using data from 0.2 to 1.8 TeV to extrapolate the plateau rapidity density. For all pions expect

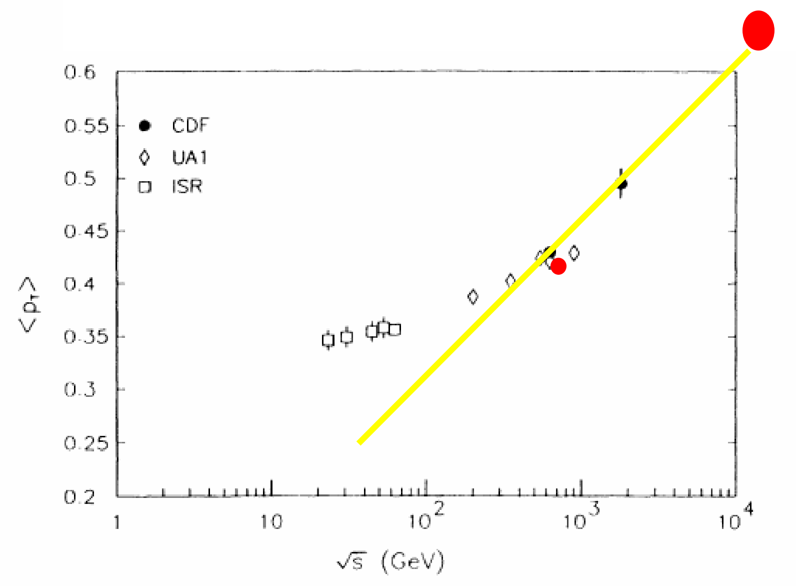
$$\rho = 1/\sigma(d\sigma/d\eta) \sim 9$$

$$\pi^+ = \pi^- = \pi^o$$

Note – 2x extrapolation from 0.9 TeV

Minbias – Pt Data



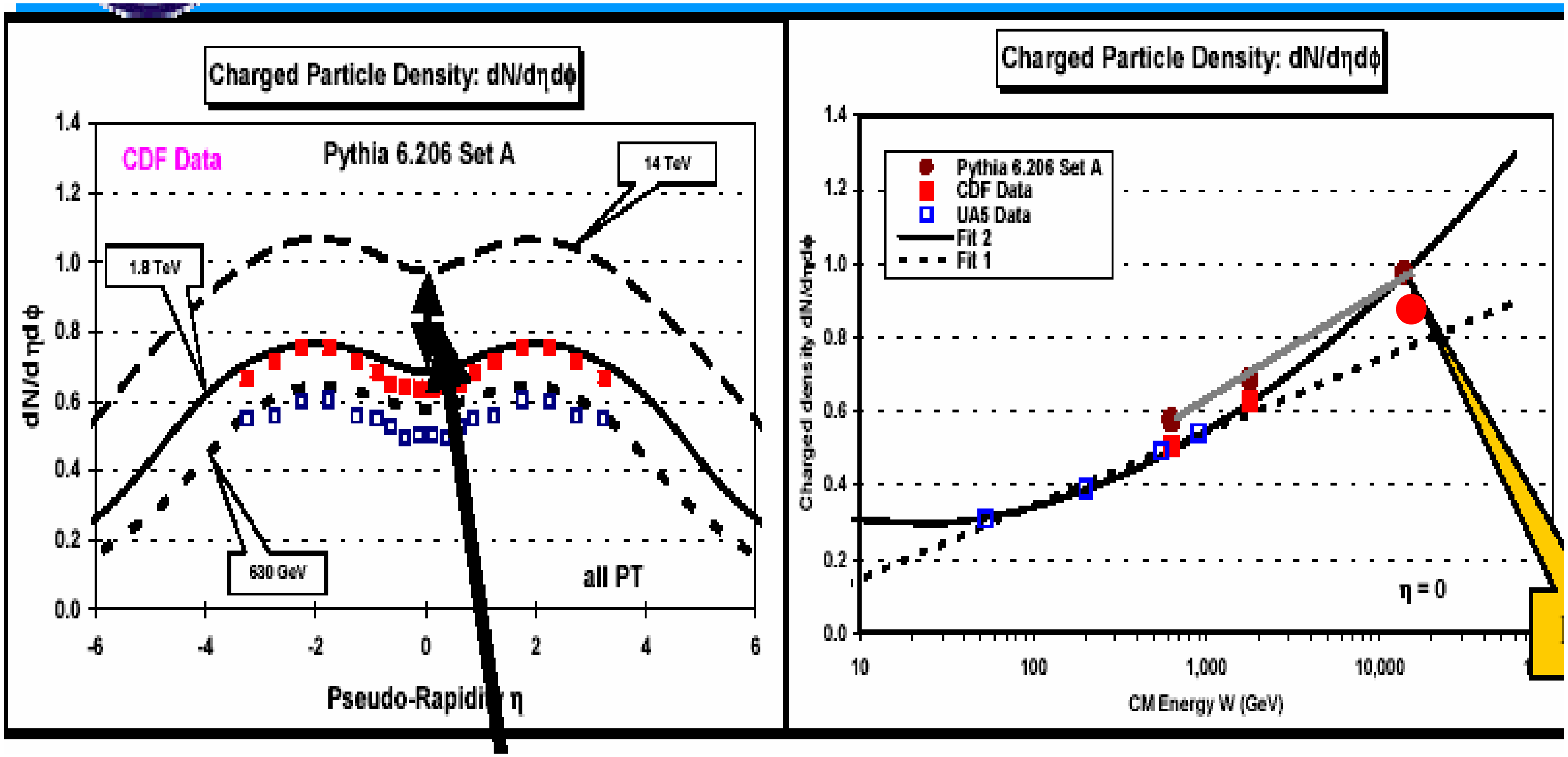


Note the factor ~ 100 drop in single tracks (tracker alignment) from 14 ->0.9 TeV for Pt = 6 GeV

Extrapolations of the Pt distribution and average values.

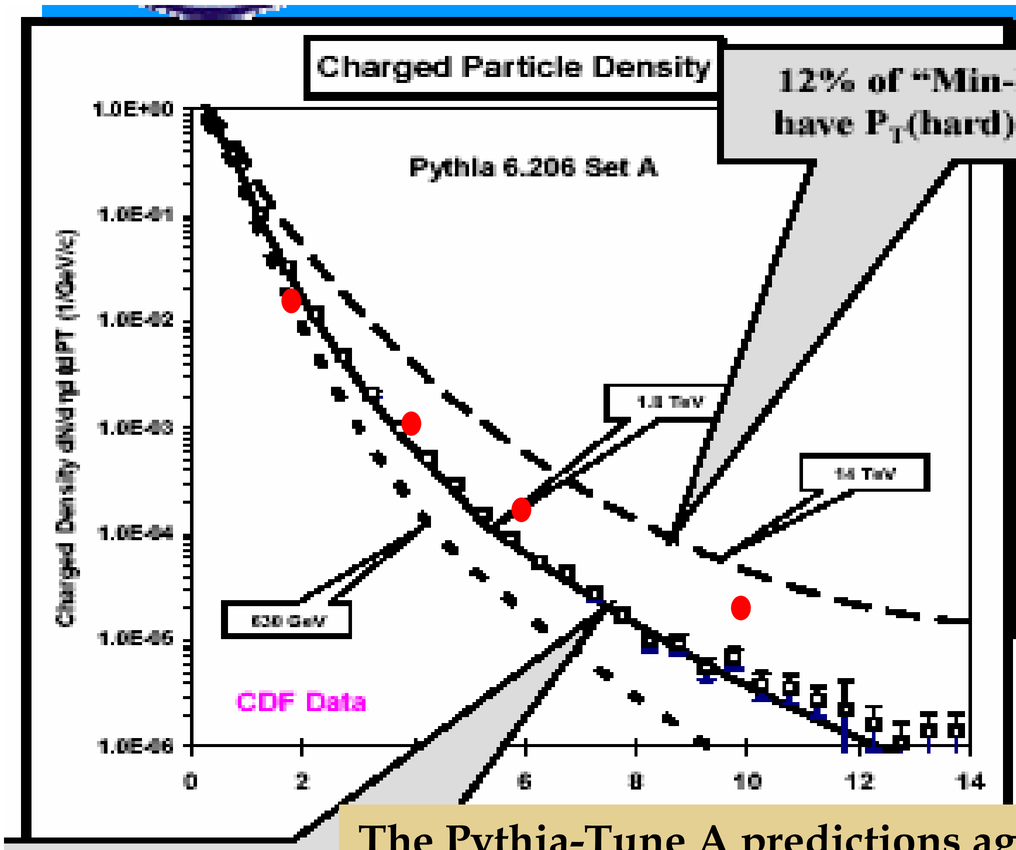
Expect <Pt> ~ 0.65

Rapidity Density at LHC



Minbias predictions from Pythia – Tune A agree with the simple extrapolations. Density rise is faster than lns. –R. Field

Pt in Minbias - LHC



The Pythia-Tune A predictions agree well with the simple extrapolation for minbias data. Important to measure and tune Pythia to represent well the minbias background for pileup and to set trigger strategies, e.g. isolation. Can only be done in 2008 after first 14 TeV data is taken..

Minbias Calibration – Azimuthal Balance, HCAL and ECAL

- Error on Mean E_T

$$< E_T > = \sum_i \varepsilon_{Ti} / N$$

$$d < E_T > = \sqrt{d\varepsilon_{T1}^2 + d\varepsilon_{T2}^2 + ...} / N$$

$$= d\varepsilon_T / \sqrt{N}$$

$$d\varepsilon \sim a / \sqrt{\varepsilon} \quad (stochastic, low\ energy\ \pi)$$

$$d < E_T > / < E_T > \sim [a / \sqrt{\varepsilon}] / \sqrt{N}$$

- Minbias Events and HCAL Towers

$$NT = \#hits / tower * event$$

$$= \rho_{ch} \varepsilon_y \varepsilon_\phi$$

$$\rho_{ch} \sim 6, \varepsilon_y \sim 0.1, \ \varepsilon_\phi \sim 1/72$$

$$NT \sim 0.0083$$

Minbias Calibration -II

- Calibrate to 2%

$$0.02 \sim [a/\sqrt{\varepsilon}]/\sqrt{N}$$
$$a \sim 1.0, \varepsilon \sim 0.6\, GeV$$
$$N \sim 4167$$

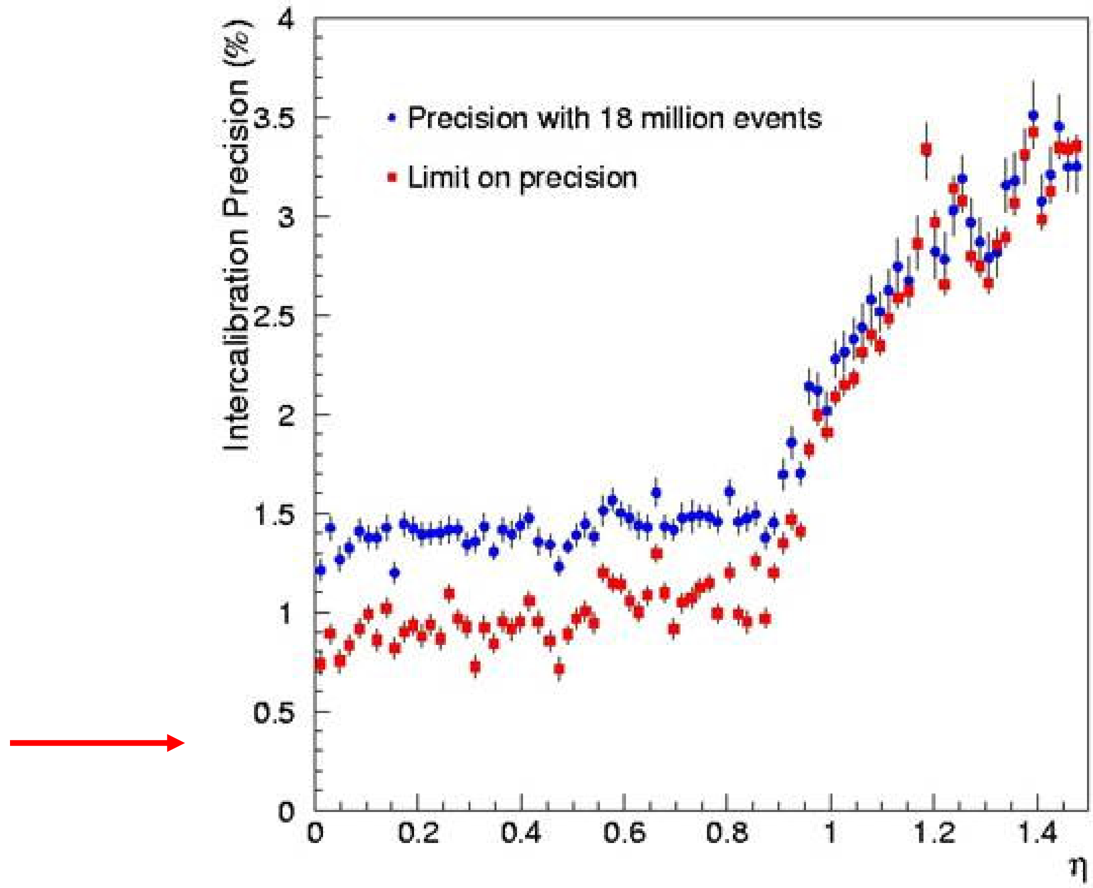
- Minbias Events

$$NT \sim 0.0083$$
$$N\min \sim 4167/NT \sim 500{,}000$$
$$100\, Hz, 360{,}000\, Events/hr$$

- ECAL has 25 fold smaller tower area and sees only the neutral pions. Noise dominates, 0.15/0.6

$$NTecal \sim 0.00017$$
$$0.02 \sim (0.15/0.6)/\sqrt{Necal}$$
$$Necal \sim 156$$
$$N\min \sim 920{,}000$$

Monte Carlo Study - ECAL



Ultimately limited because the detector is not azimuthally symmetric. ECAL dependence on η is due to material in the EB/EE boundary and different noise in the ECAL endcap. Estimated 1% calibration takes 3.6 million minbias events, but there are tower sharing losses, conversions etc.

Minbias Pions and ECAL

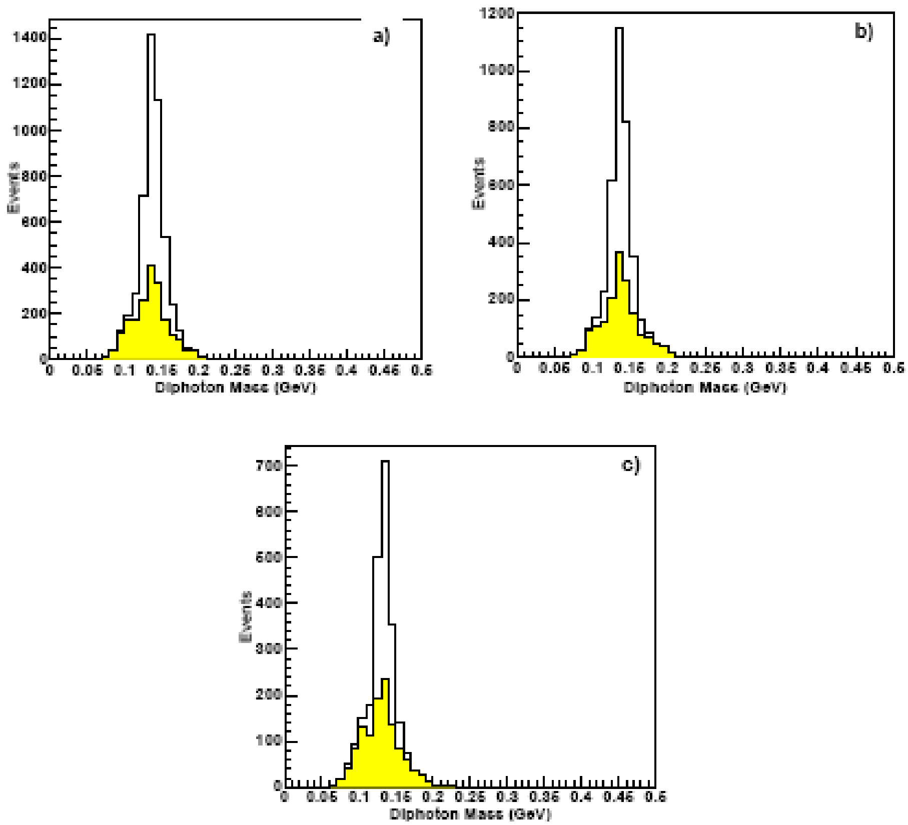
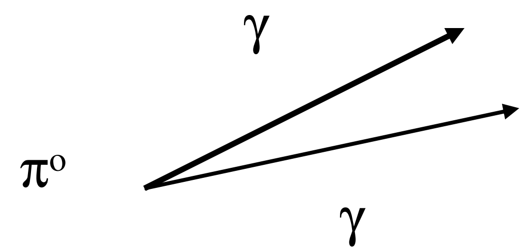


Figure 4.27: Reconstructed mass of π^0 candidates in 3 regions of the barrel: a) $|\eta| < 0.5$, b) $0.5 < |\eta| < 1.0$, and c) $|\eta| > 1.0$. The unshaded histograms represent the signal while the shaded ones the background.



$$\pi^o \rightarrow \gamma + \gamma$$

$$\theta \sim 0.14\, GeV / P_\pi$$

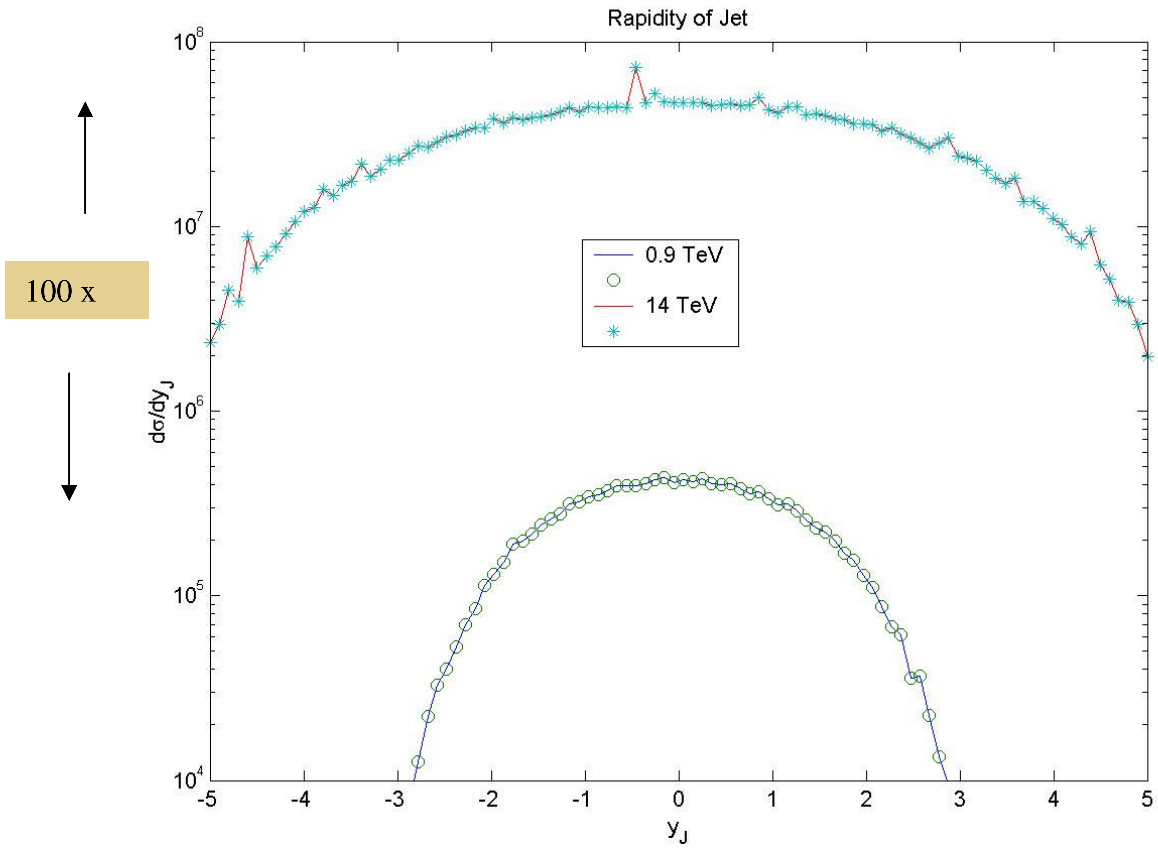
$$ds \sim R\theta \sim 14\, cm / P_\pi (GeV)$$

Use charged pions at moderate Pt to start tracker alignment in 2007 and start in situ HCAL. Neutral pions can be used for ECAL.

Jets and Di-jets

- In the minbias calibration sample look for events passing jet algorithms. Get an estimate of the L1 and high level trigger and reconstruction efficiencies. For 10 million minbias have 20,000 dijets with Et>30 GeV.
- As L rises, impose a Jet Trigger. Check the cross section vs Pt and Mass.
- Check the angular distribution.
- Establish the MET distribution. Check that tails are consistent with ISR, FSR.
- Use di-jets, when understood, to cross calibrate the η "rings" of the calorimetry using jet balance.
- Having established di-jets, launch a Jet – Jet mass search (wait until 2008 run…).

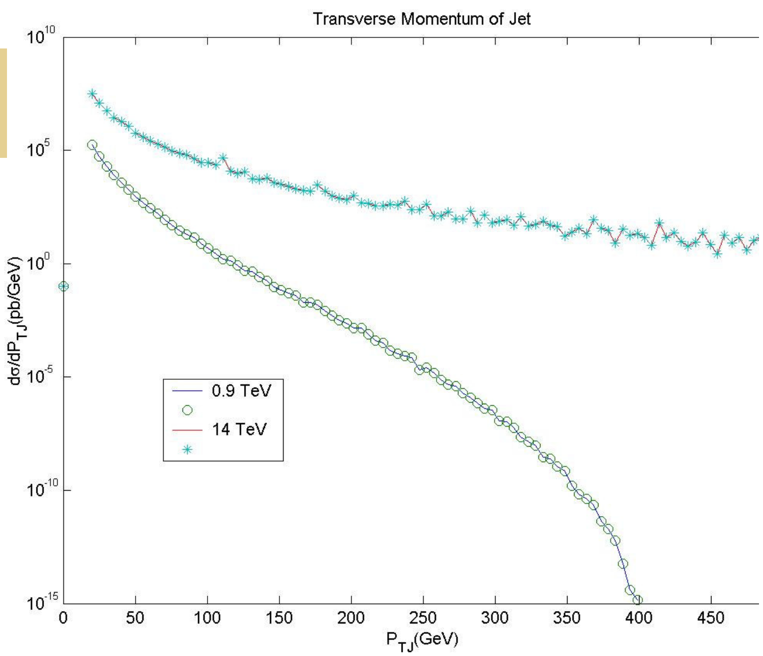
2007 Run at 0.9 TeV

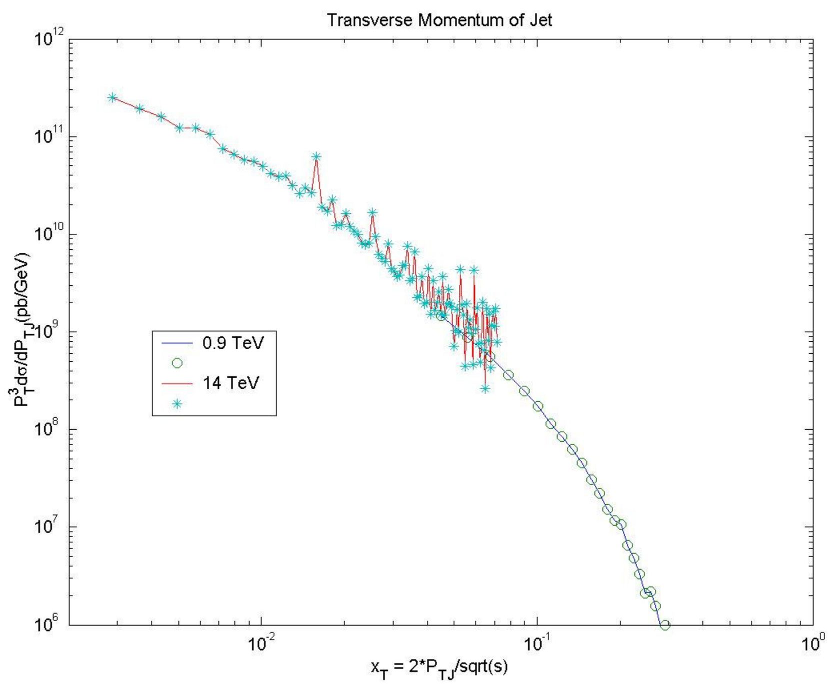


Cut jet Pt > 20 GeV and |y| < 5. Cross section is a factor ~ 200 less at 0.9 TeV w.r.t. 14 TeV (280 ub vs. 1.3 ub). HF will not be strongly illuminated by jets because plateau is too short. Concentrate on Barrel and Endcap regions. In 10 million minbias only 250 dijets with Et > 20 GeV

Jet Transverse Momentum

10^5





The 0.9 TeV pilot run has a severely limited jet Pt range compared to 14 TeV C.M. energy. The <x> range at 0.9 TeV is, for (20,500) GeV, (0.044,1), while at 14 TeV the <x> range is (0.0029,0.071). Use scaling arguments to connect the 2 C.M. energies? The 2007 data will be limited to jets < 50 GeV

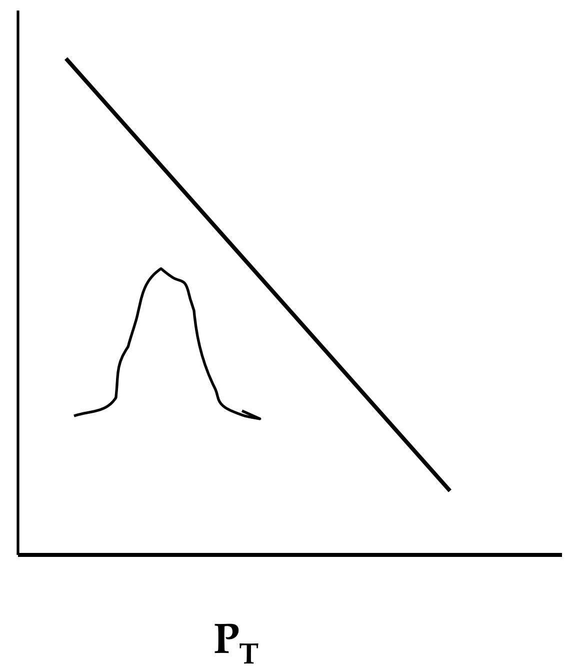
Resolution and Cross Section

To understand the cross section, the resolution for steeply falling spectra must be well understood.

$$d\sigma / dP_T \sim a e^{-P_T / P_o}$$

$$\mathrm{P}(x, y) \sim e^{-(x-y)^2 / 2\sigma^2}$$

$$d\sigma / dP_T^{'} \sim \int d\sigma / dP_T \mathrm{P}(P_T, P_T^{'}) dP_T$$



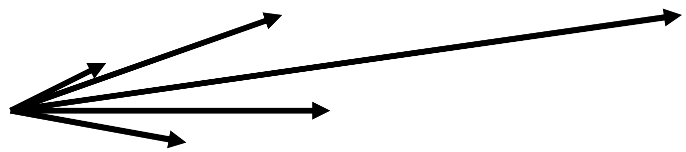
Fold Gaussian into exponential. Result is again exponential (far from edges) but with increased normalization.

$$d\sigma / dP_T^{'} \sim a e^{\sigma^2 / 2 P_o^2} e^{-P_T^{'} / P_o}$$

Jets and Dijets – 14 TeV

- For jets, require Pt > 30 GeV (reasonable reconstruction efficiency) and |y|<5 (HB + HE + HF).
- The cross section in COMPHEP is ~ 90 ub. If no trigger in 100 ub^{-1} (5 M minbias) have 900 0Jets with no trig efficiency. Establish trig and reco efficiency (2J/1J).
- Setup single jet trigger at 1 ub^{-1} and start to trigger at 10 ub^{-1}.
- 900 dijets at 10 ub^{-1}, 90,000 at 1 nb^{-1}. Do dijet balance for η "towers" which are already azimuthally equalized (connect the "rings").
- For 0.9 TeV run in 2007, scale needed luminosity by ~ 100.

Jet Energy



Assuming a jet is an ensemble of particles moving ~ in the same direction, then the Jet Et is a local scalar variable as is the dijet mass.

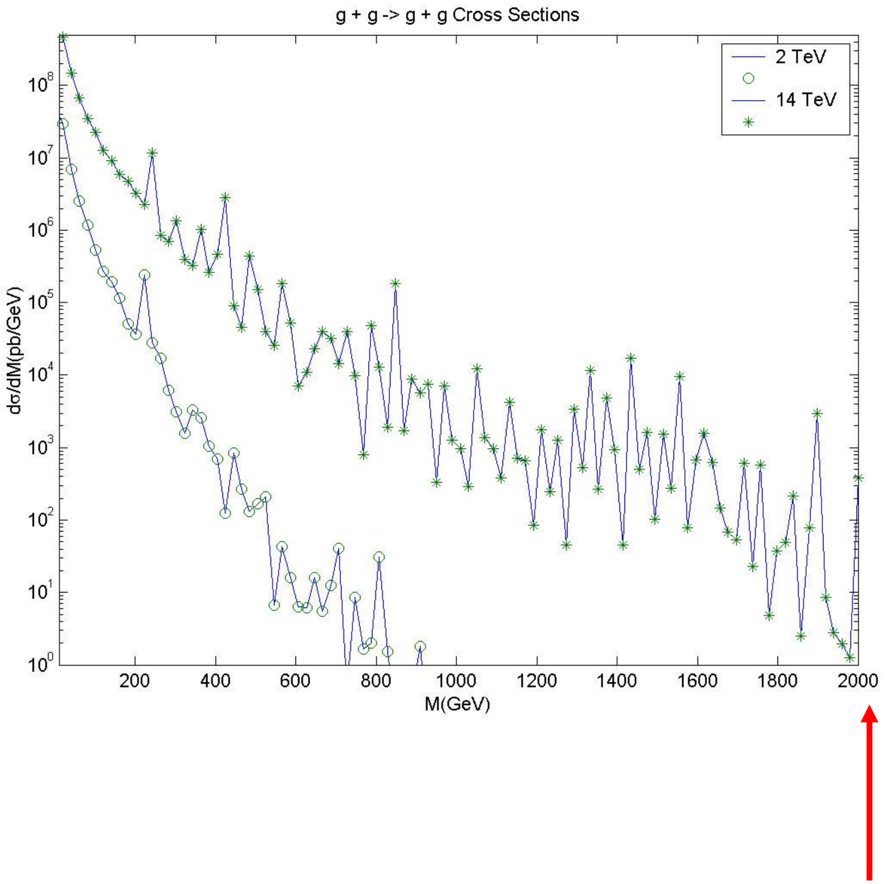
$$E_{TJ} \sim E_{T1} + E_{T2} + E_{T3} .....$$

$$dE_{Ti} \sim a\sqrt{E_{Ti}}$$

$$dE_{TJ} / E_{TJ} \sim a / \sqrt{E_{TJ}}$$

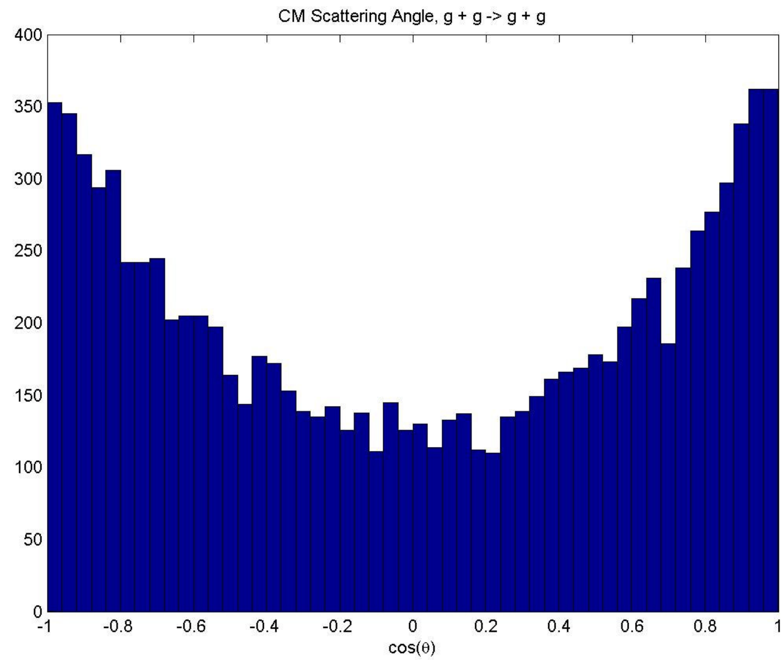
If dominated by stochastic coefficient, then jet energy resolution is the same as the single particle resolution. But there are many other contributions, one of the largest being FSR.

Establish the Jet Cross Section



Clearly see enormous mass range increase due to PDF evaluated at much lower <x>. Expect at fixed mass the ratio is ~ $[xg(x)]^2$ at x ~ M/√s. Will very quickly get beyond the Tevatron kinematic limit during the 2008 run at 14 TeV.

Angular Distribution



$$\chi = (1-\cos\hat{\theta})/(1+\cos\hat{\theta})$$

Establish angular distribution – t channel, flat χ. Look at 2J/1J to extract trigger and reconstruction efficiencies. Check Pt spectrum against Monte Carlo for overall normalization. Look at J-J Et balance to calibrate towers in η (towers in azimuth done with minbias). Look at tails of $\delta = (E_{T1}-E_{T2})/(E_{T1}+E_{T2})$ **distribution for missing Et. Does it point in ϕ to J for dijet events? Can we define dijet events (FSR)?**

Calibration – Di-Jet Balance

Suppose a tower is calibrated. To then calibrate a second tower with the opposite azimuth and any polar angle, use jet balancing.

$$E_{T1} = E_{T2} = E_T, true$$

$$\varepsilon_{T1} = E_{T1}, \varepsilon_{T2} = GE_{T2}$$

$$\delta = [\varepsilon_{T1} - \varepsilon_{T2}]/[\varepsilon_{T1} + \varepsilon_{T2}]$$

$$G = [1-\delta]/[1+\delta]$$

$$\varepsilon'_{T2} = \varepsilon_{T2} / G$$

$$dG / G \sim \sqrt{2} d\delta$$

$$d\delta = dE_T / \sqrt{2} E_T$$

$$100\% / \sqrt{E_T} = 2\%, E_T \sim 2500\, GeV$$

Suppose a calibration, G, is needed to 2%. The energy is needed to 2% or 2500 GeV is needed, which could be 50 jets with 50 GeV in that tower. The 90 ub cross section is 900 nb into a given tower (Δη~0.1, 100 towers in |η|<5) or a 50 /ub exposure. Also jet spans several towers. Core has dR~0.2 or ~ 16 towers.

With photons the cross section is lower but the photon is measured more accurately and the signal is not shared over as many towers as a jet.

Di-Jet Balance Study

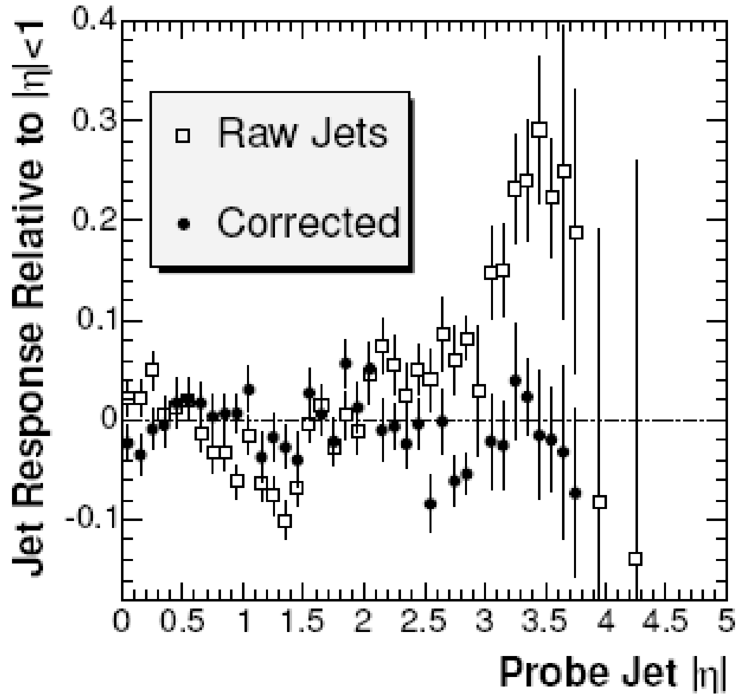
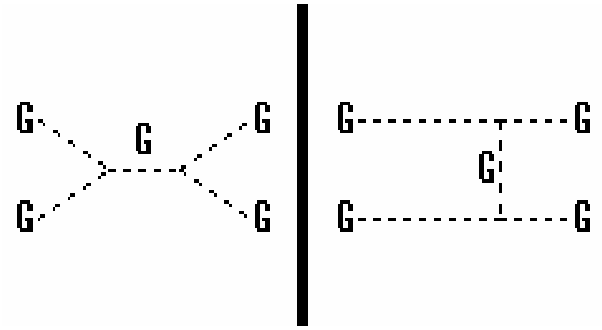


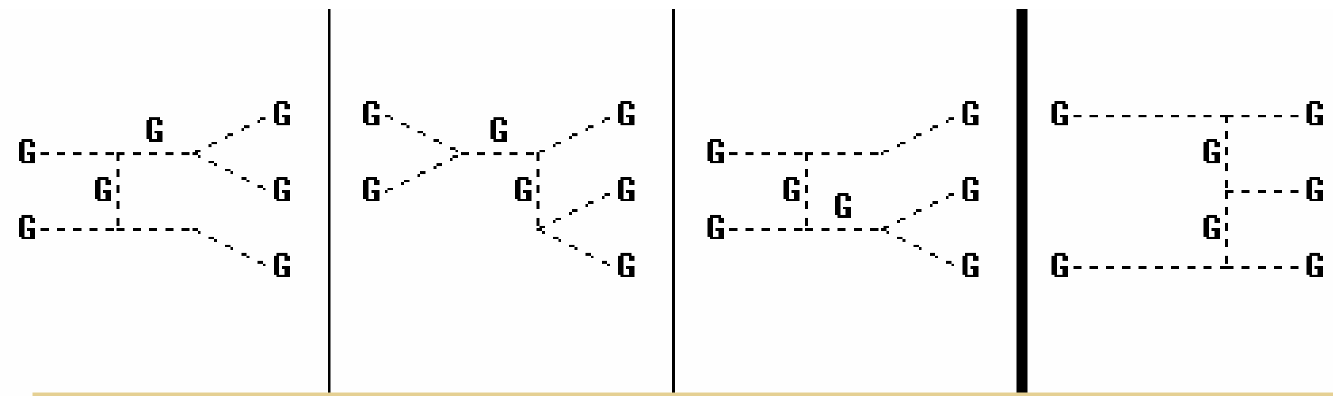
Figure 11.21: Jet response as a function of $|\eta|$ for 120 GeV/c <dijet $p_T <$ 250 GeV/c. The graphs compares raw jets (open boxes) with corrected jets (solid circles). The indicated level of precision may be obtained on 1 hour of data taking.

Use di-jets to compare the calibration of jet "rings" at different η values.

FSR – 2 Jets and 3 Jets



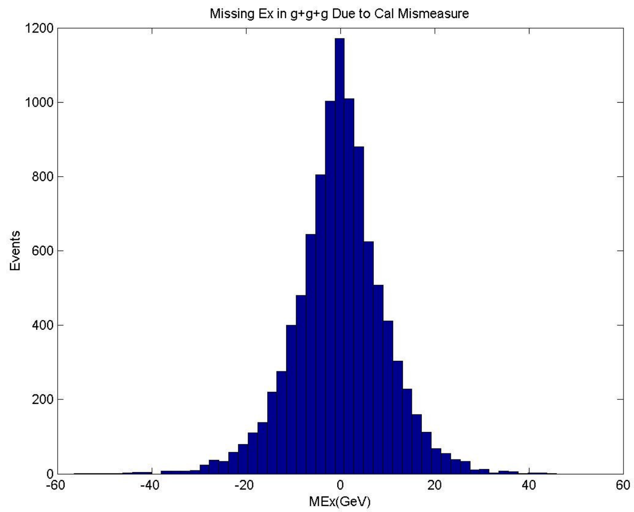
JJ



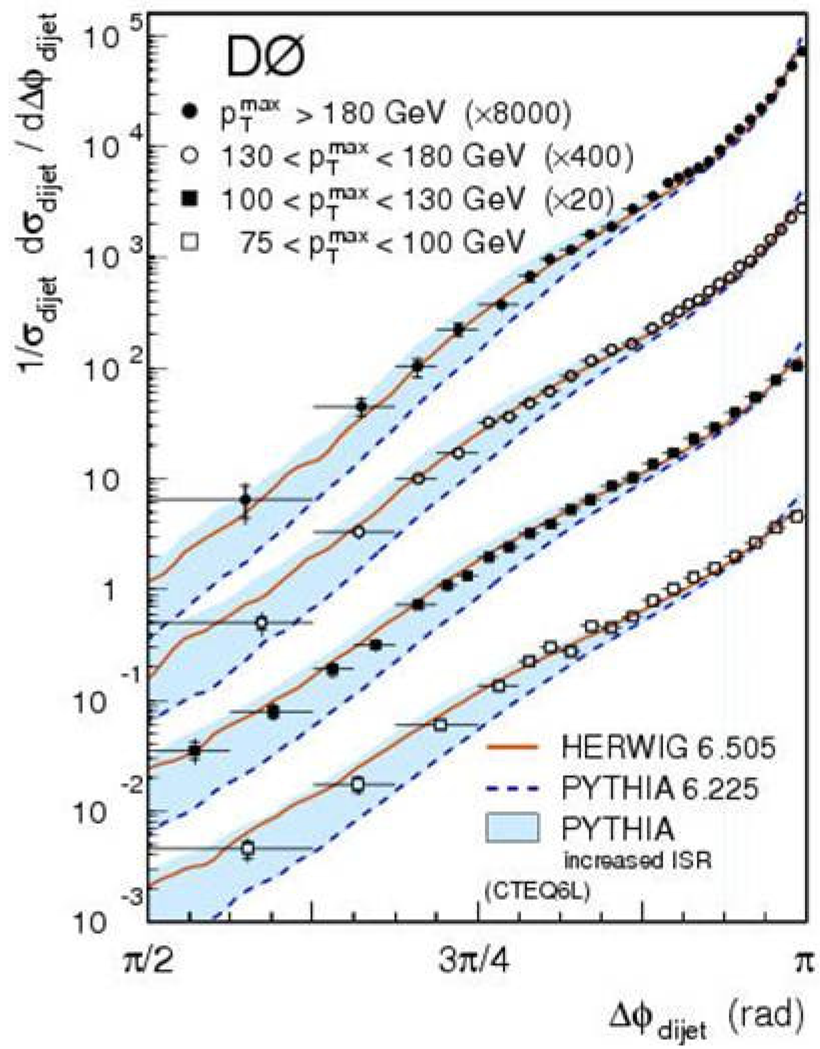
JJJ

The cross section for 2 jets with Pt > 30 GeV is only ~ twice that for 2 jets with Pt>30GeV and a third with Pt>5 GeV. There is s channel FSR, t channel FSR and ISR. Argues for good jet finding efficiency to the lowest Et so as to be able to veto on FSR.

Missing Ex in g+g+g, MET

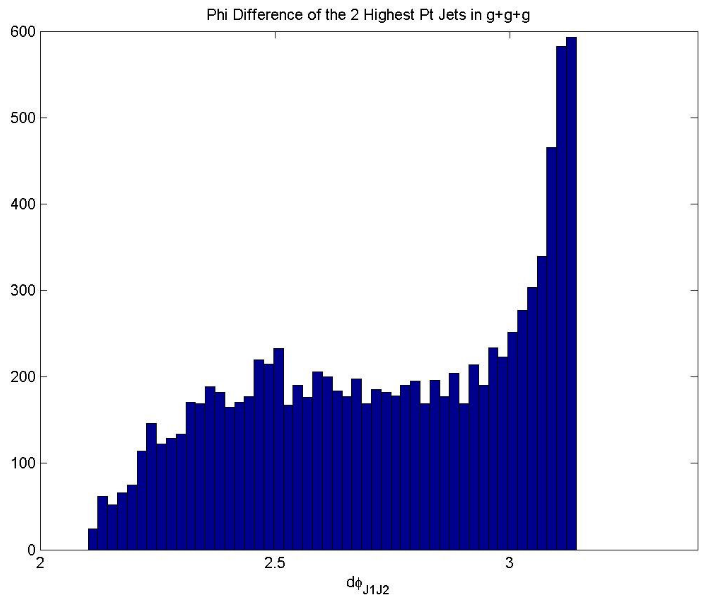


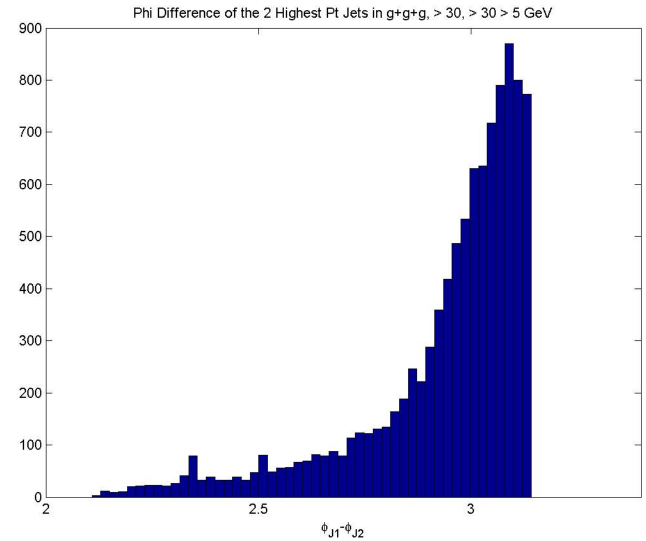
ISR, FSR



Large missing energy due to bad measures of jet energies cannot be removed in a multi-jet topology. Plot for 10,000 3J events, each J with Pt > 30 GeV.

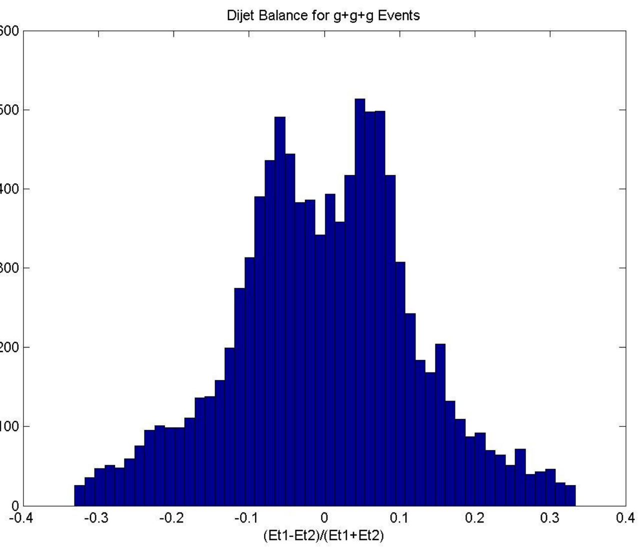
FSR and Jet Balance

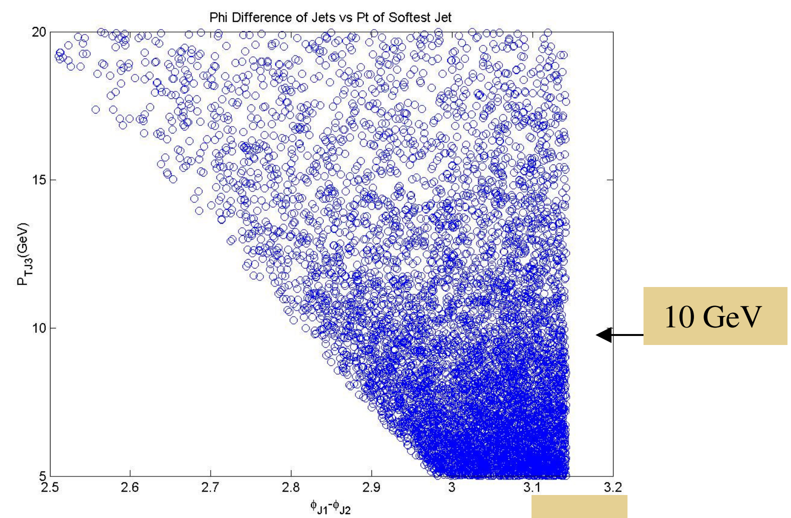


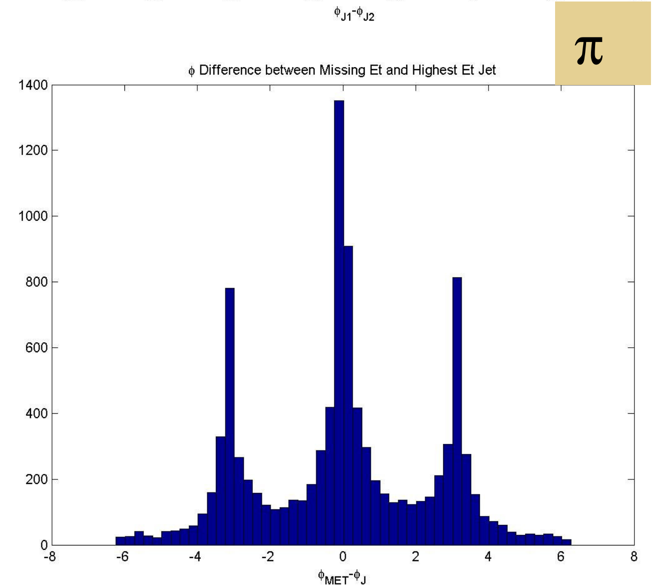


In g+g+g events the 2 hardest jets will not balance in Pt. They will also not be back to back in azimuth. Note that those which are ~ back-to-back have emitted a fairly soft third gluon. Cut on dφ and veto any observable hard third jet to get a "di-jet" sample for calibration purposes. Plots are for all jets > 30 GeV (L) and for 2 leading jets > 30 GeV and third > 5 GeV (R).

FSR and Jet Balance

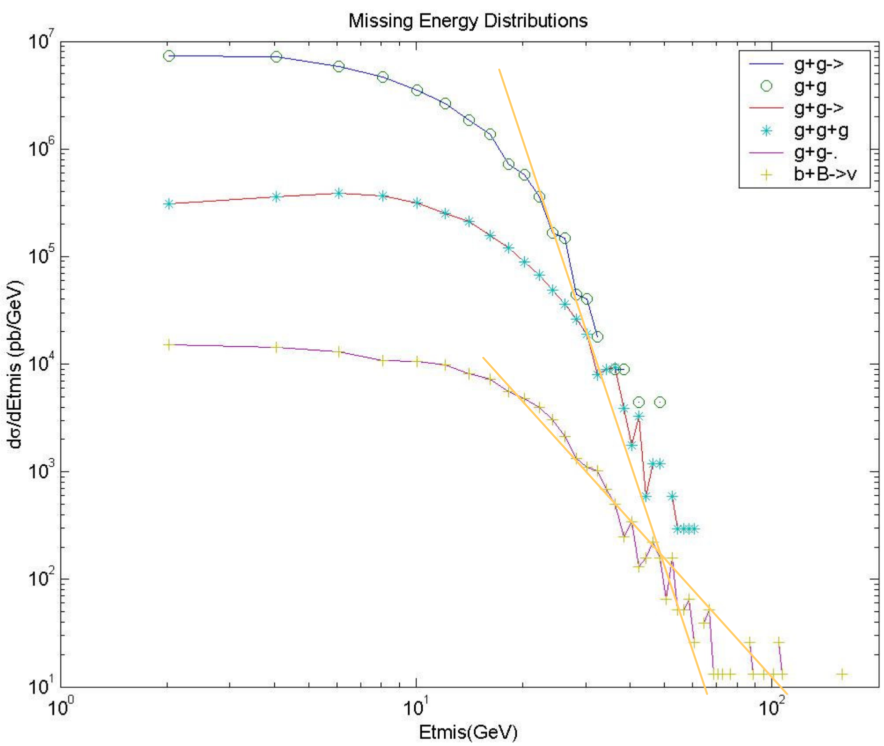






Plots for 3 jet events, with 1 soft jet. Note the E balance broadening. Note also the lack of back to back leading jets. Three jet events with ~ back to back leading jets are due to emission of soft third jets. The QCD radiation places a limit on jet balancing.

Understanding MET



For b+B there are real v from b->c+l+v. Important for MET > 100 GeV

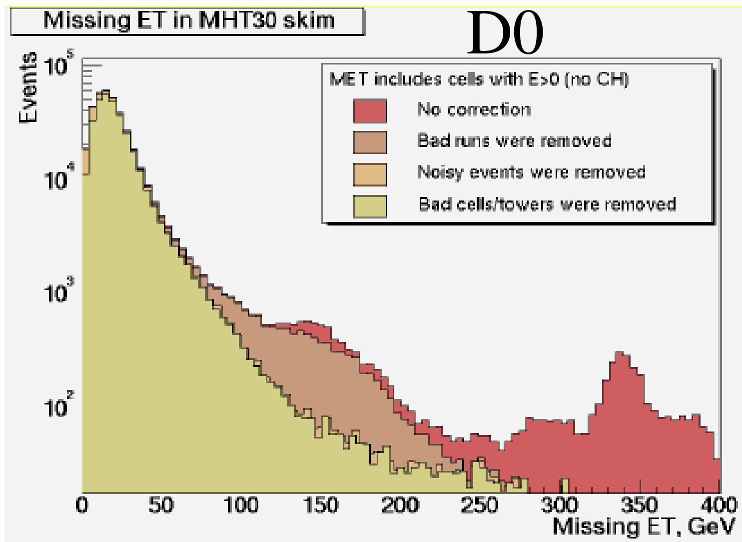
The cross section with all 3 gluons having Pt> 30 GeV and |y|<5 is ~ 6 ub, which is ~ 1/15 the g+g cross section. Observing 3J events is a useful check of the reconstruction efficiency, if the dynamics is assumed to be understood.

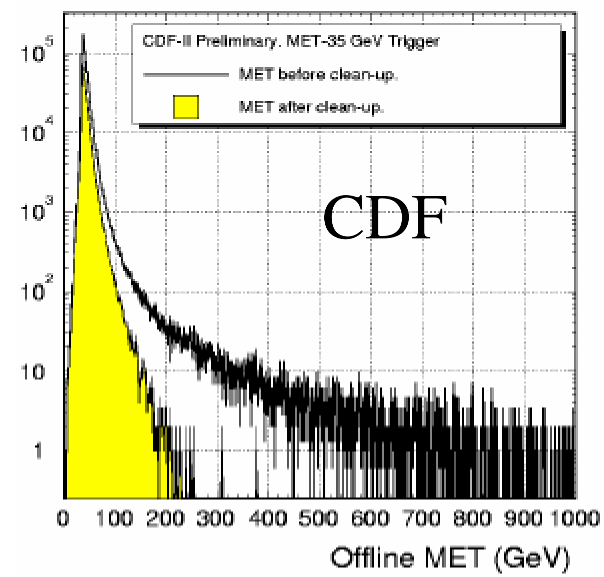
MET is due to energy mismeasures. Assume jet error is $dE_J \sim 1.0\sqrt{E_{TJ}}$

No jet angular error. For g+g cut on ϕ of MET w.r.t. J. For g+g+g this does not work. Gaussian errors? If tails of errors are under control then b pairs and t pairs dominate MET at large (> 100 GeV) MET values.

Missing Et ?

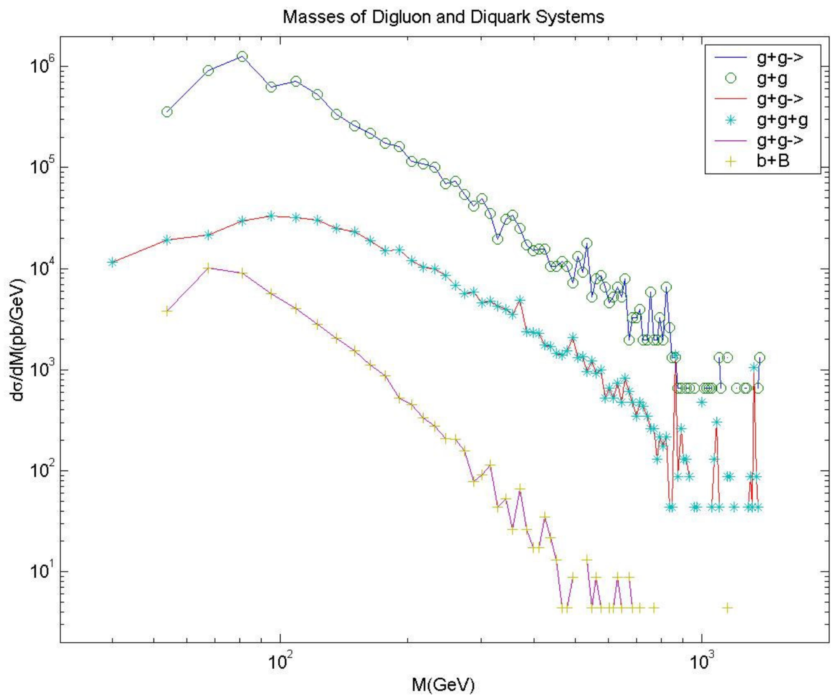
A trigger on $\not{E}_T$ provides an excellent test sample for data quality control:





V. Buscher – Run II at CDF and D0 shows that with all the preparation it still will be hard. Try to use top pairs as a benchmark. Top samples will have jets, leptons and MET. Need to establish MET before searching for SUSY.

Dijet Mass Search, g + g



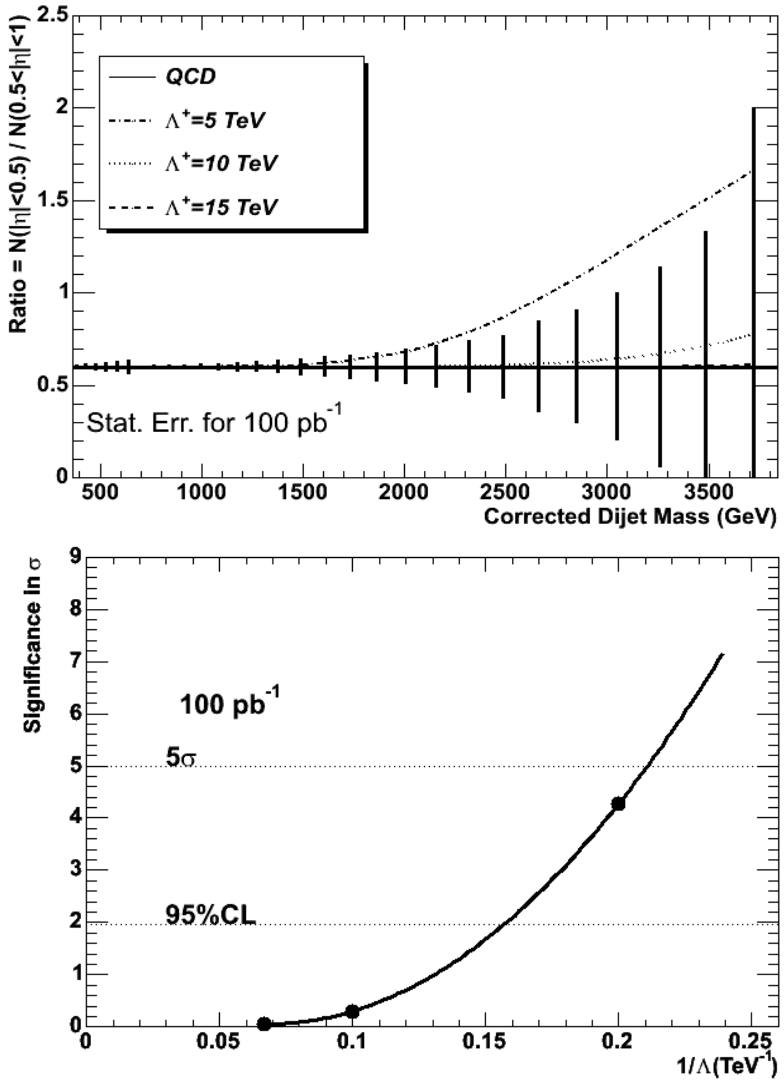
If low Pt is understood, explore dijet mass. At 1 nb^{-1} have ~ 40 events at 2 TeV mass. (note log/log power law Physics and PDF)

$$d\sigma / dM \sim 200\ pb / GeV$$

$$@\ 2\,TeV\ in\ \Delta M \sim 0.2\,TeV$$

Now in new territory early in the 2008 run – look at 2 TeV and above as luminosity increases. Mass "reach" is roughly 1 TeV gain for each 10x in integrated L.

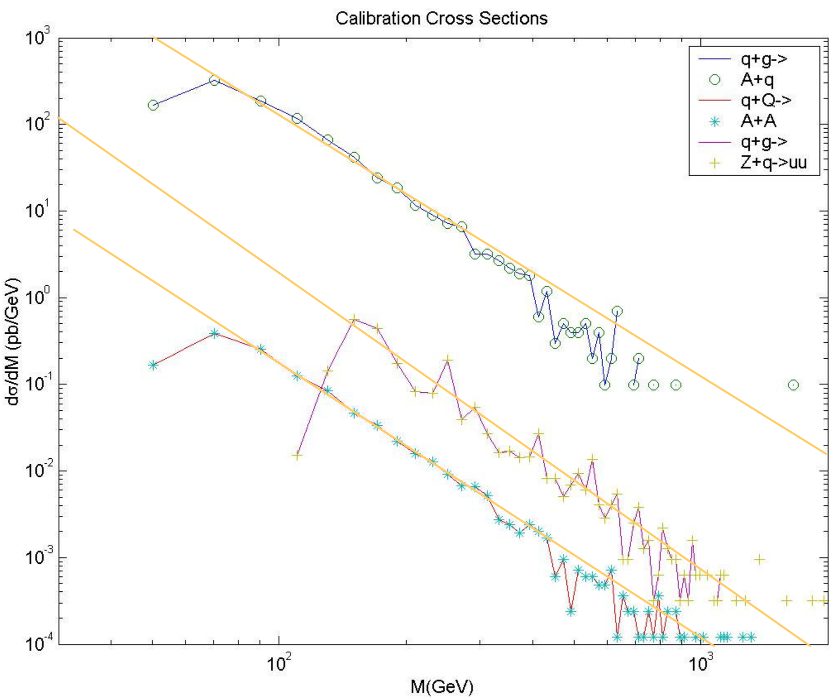
Significance Estimates for 100/pb



For 100 /pb the 95% CL for contact interactions is 6.4 TeV. Published D0 limit at 95% CL is 2.7 TeV.

2008 LHC run at 14 TeV is ~ few /fb ➔ be prepared very early in 2008.

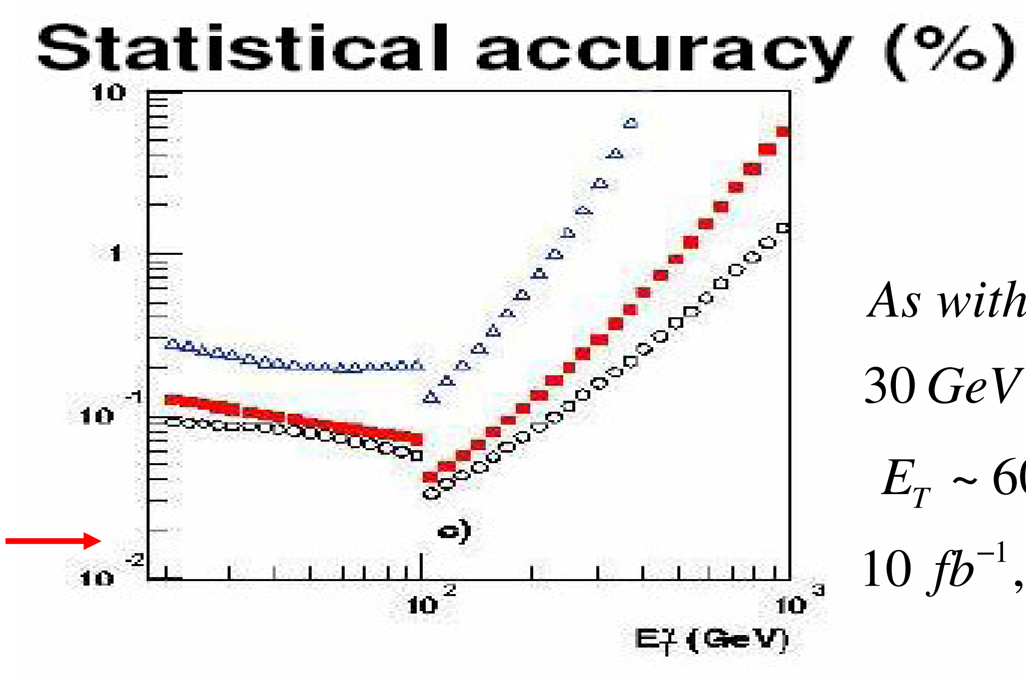
Calibration Processes – Jet/Photon Balance



γ+J, γ+γ, Z+J->μ+μ+J

g+q -> q + γ events with the Pt of the q and photon > 30 GeV and the photon with |y| < 2.5 (in ECAL) has a cross section of ~ 20 nb. At 1 nb^{-1} can plan to find a few events using photon isolation cuts. For 1 pb^{-1} there will be 20,000 J + γ events. Assuming the azimuthal calibration is done using minbias and/or dijet balance, there are then 200 jets/HCAL η "tower" (summed over azimuth) or > 6000 GeV. At higher L the q + Z and diphoton events can be used to cross check the initial HCAL and ECAL calibrations.

Photon + J - Statistics



$As\ with\ di-jet\ balance$

$30\ GeV, 1 pb^{-1}\ 200\ jets / HCAL\ tower$

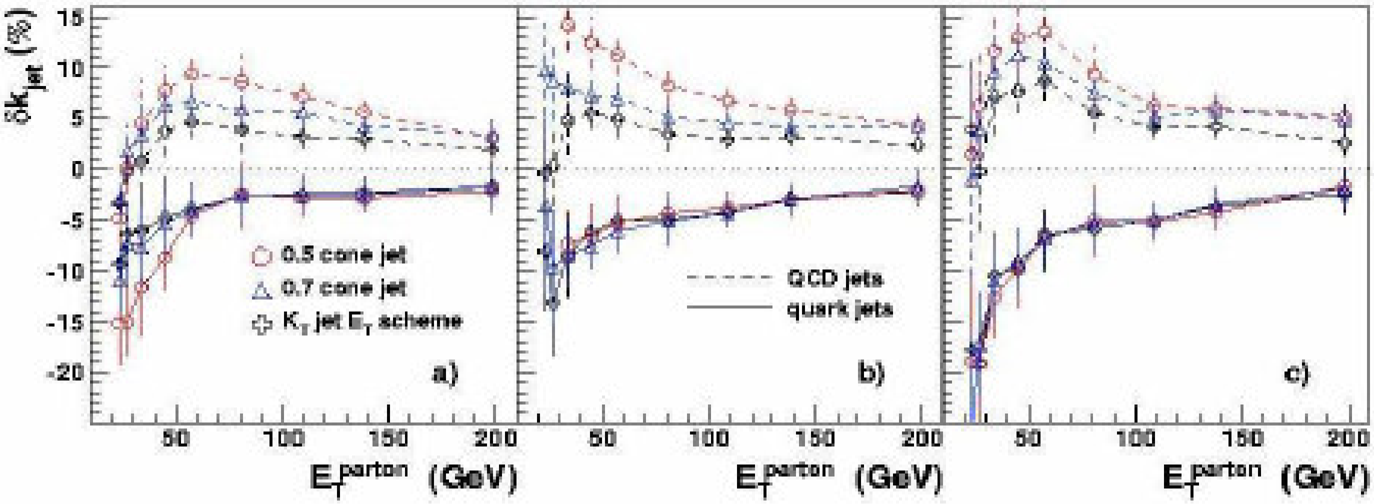
$E_T \sim 6000\ GeV, 100\% / \sqrt{E_T} = 1.3\%$

$10\ fb^{-1}, 0.013\%$

Use e/photon trigger. Plot is for 10 /fb.

Jet spreads over ~ 16 HCAL towers.

Photon + J - Systematics



+-5%

The main sources of systematic bias are:

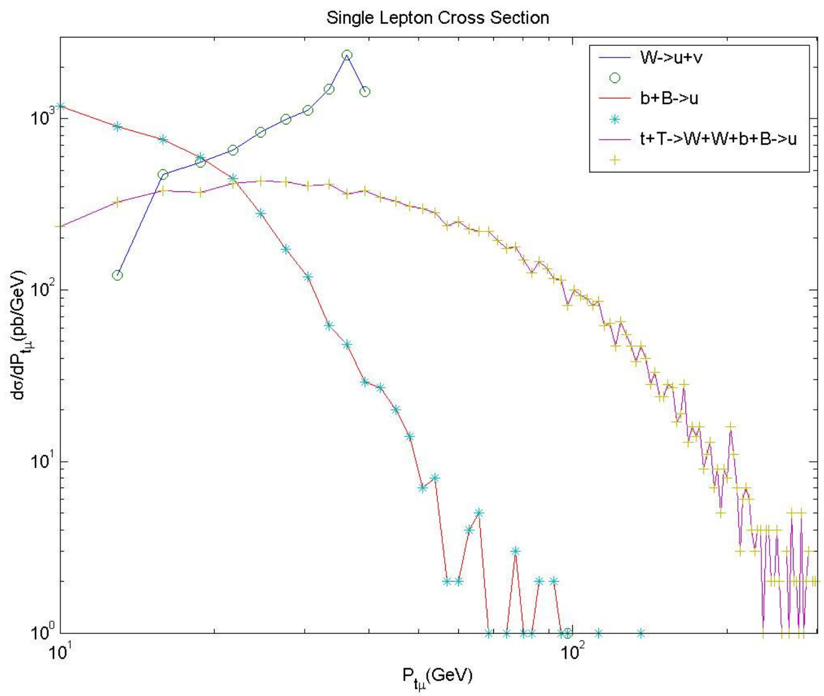
- bias due to non-leading radiation effects
- background from QCD dijet events
- event selection may bias true energy scale

Method is systematics limited at the few % level. At low Pt there are severe QCD backgrounds. FSR also limits the accuracy.

From 10^{28} to 10^{33} /(cm^{2}sec)

L for 1 month run	Integrated L	Trigger	Process	Comments
10^{28}	10nb^{-1}	σ_{bB} ~ 600 nb. Setup – run single electron, muon, photon	g+g -> b+B ψ	900,000 JJ, 6000 bB, 1200 1μ, 60 2μ Establish μ jet tag 80 2e and 2μ events from ψ
10^{29}	100 nb^{-1}	Setup dimuon, dielectron $\sigma_{\mu\nu}$ ~ 10 nb	q+Q->W->μ+ν (D-Y) Υ	1000 μ from W->μ + ν Lumi – standard candle (look at high Mt tail) 100 2e and 2μ events from Υ
10^{30}	1 pb^{-1}	Run dilepton trigger $\sigma_{\mu\mu}$ ~ 1.5 nb σ_{tT} ~ 630 pb	q+Q->Z->μ+μ (D-Y) g+g->t+T	1500 dimuons from Z-mass scale, resolution Lumi- standard candle, high M 600 t + T produced
10^{31}	10 pb^{-1} End of '07 Pilot Run	Setup, J*MET $\sigma_{q\mu\mu}$ ~ 40 pb $\sigma_{\gamma\gamma}$ ~ 24 pb	g+q->Z+q->μ+μ+q q+Q->γ+-γ (tree) τ	400 Z + J events with Z->dimuons – Z+J balance, calib Estimate J + MET (q + ν) 240 diphoton events with M > 60 GeV 6000 t + T 150 Z->tau pairs into dileptons > 8 GeV * MET > 15 GeV
10^{32}	100 pb^{-1}	σ_{qQZ} ~ 170 pb σ_{qgZg} ~ 32 pb σ_{tT} ~ 630 pb	g+g->q+Q+Z g+q->q+g+Z+g	3000 J+J+Z->νν events, Pt>30 500 J+J+Z->μ+μ events, Pt>30 600 J+J+J+Z->νν events 10000 J+J+J+J+μ+ν events
10^{33}	1 fb^{-1} (1% of design L for 1 yr) End of '08 Physics Run			M of dijet in 100000 top events, W-> μ +ν – set Jet energy scale with W mass. Dimuon mass > 1 TeV, start discovery search, diphoton search, SUSY search

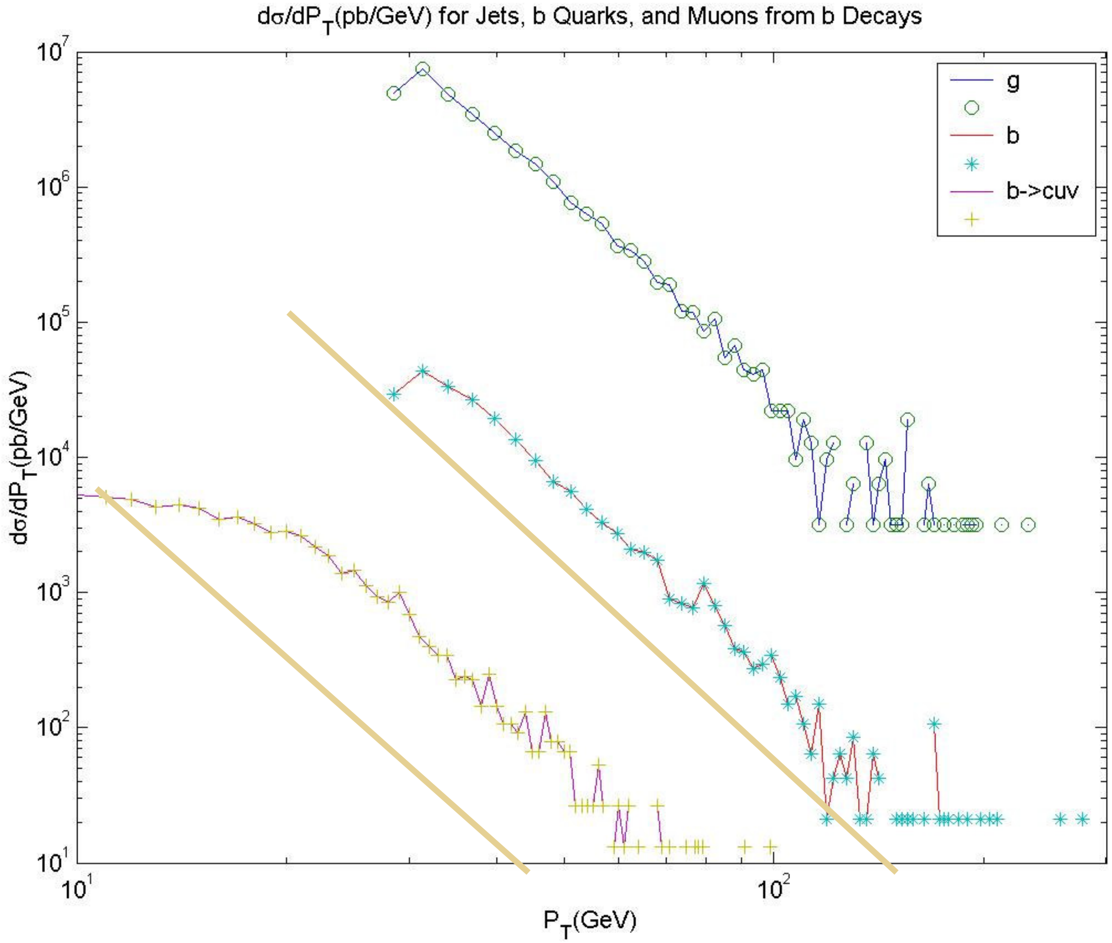
Single Muon Spectrum



Low Pt dominated by b pairs. W dominates at Jacobean peak. At high Pt top pairs dominate.

With no cuts the b+B cross section is ~ 300 μb. Requiring Pt > 30 GeV for both jets and |η| < 5, σ ~ 0.6 μ b. The BR for b -> c + μ + v is ~ 10%, so that there are ~ 120 nb for a single muon, ~ 6 nb for a dimuon topology. Look for muons in jets to establish a trigger and reco efficiency (2 μ /1 μ). Then set up a muon trigger and search for 2 muons in the b+B events (20 x reduction). Look for missing Et – shape and magnitude. Use soft muon tagged jets to establish b tag efficiency? (1 tag/2 tags) Start in situ muon alignment using 1 μ trigger. Similarly for single e trigger with isolation.

"Cascade" Decays



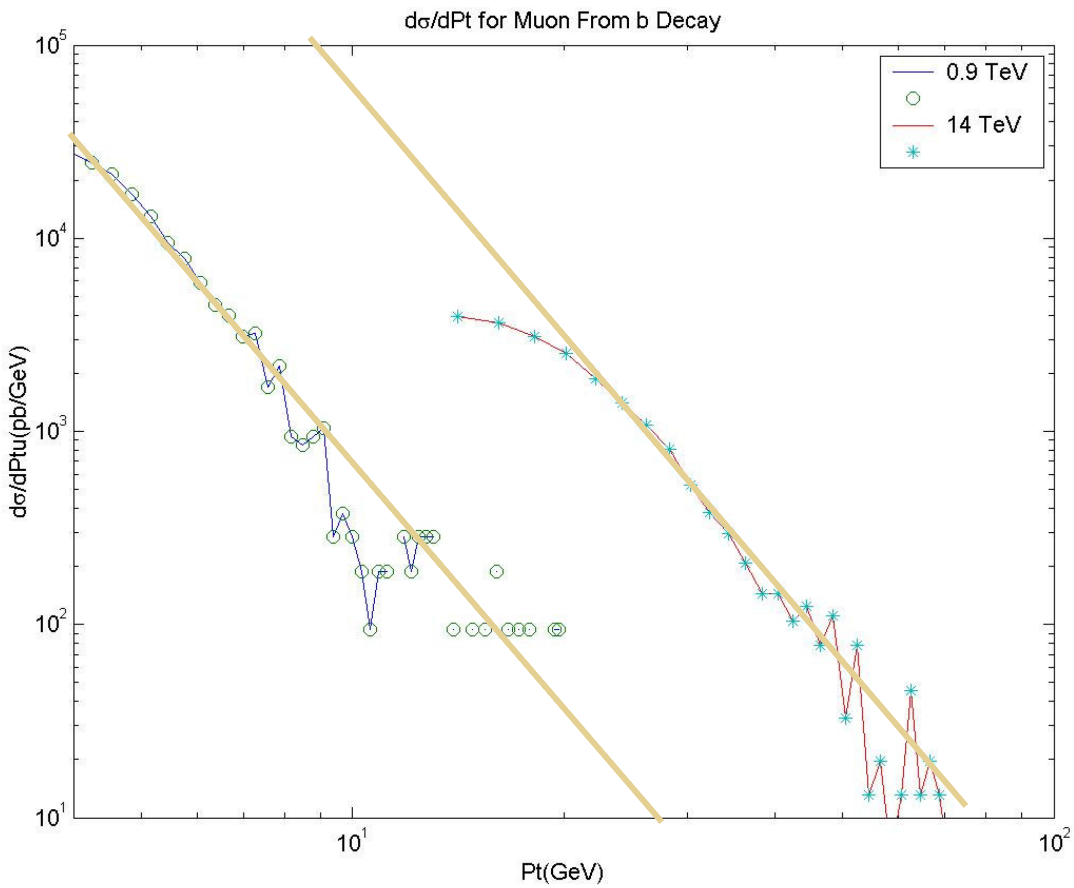
$$g \rightarrow b + \bar{b}, \alpha_s / \pi, \quad P_T / 2$$

$$b \rightarrow c + \ell + \nu, BR, \quad P_T / 3$$

Decay to n massless particles ->

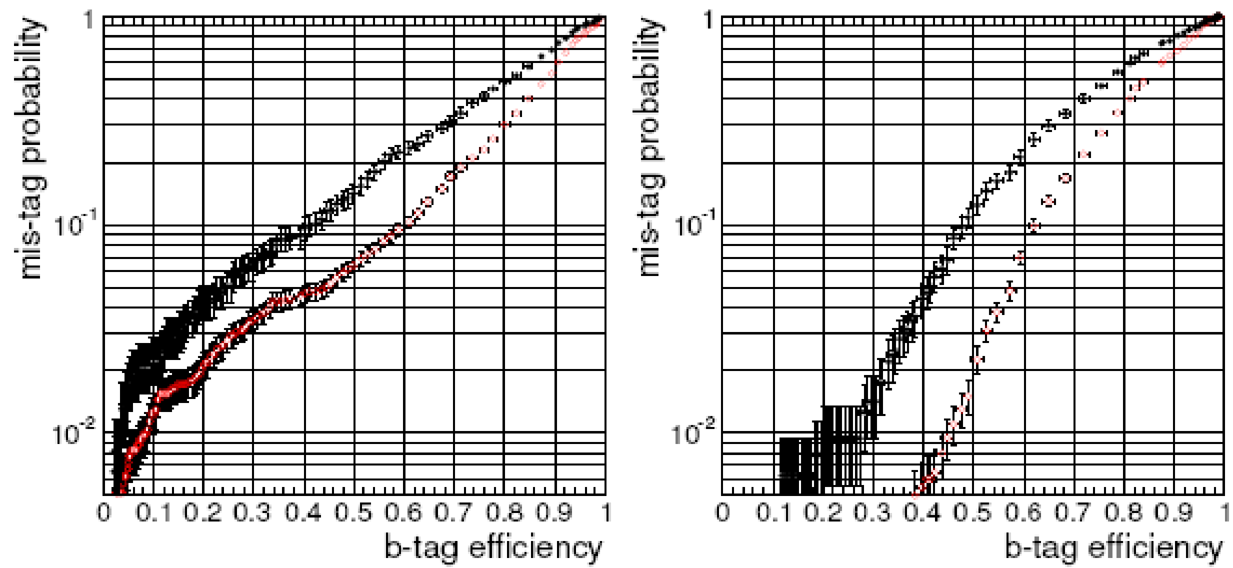
Pt ~ P_T/n with vertex factors for gluon "splitting" into b quarks which then decay into leptons. Gives a rough estimate, but recall spillover to higher PT with smearing of spectra. At a fixed Pt of ~ 40 GeV, there are ~ 10,000 more jets than muons.

14 TeV and 0.9 TeV



Rate above any threshold for triggers should be scaled down by ~ 100x for 2007 run.

B Tags with Secondary Vertex



50% b

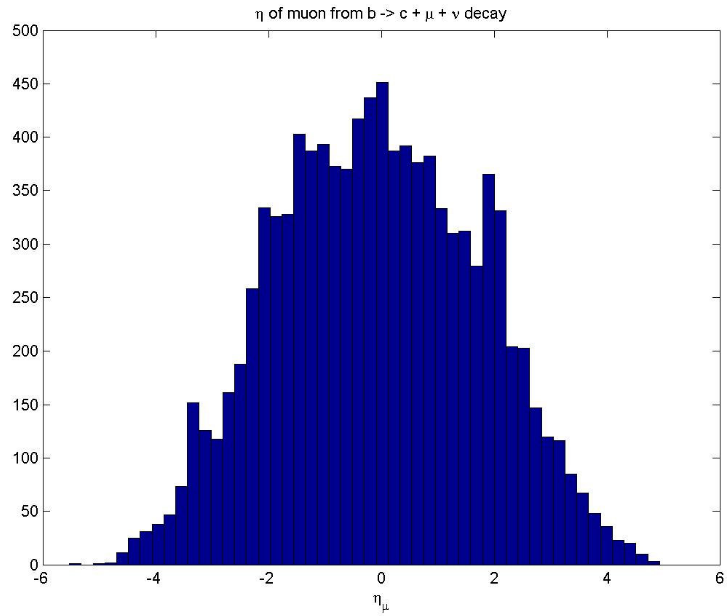
2% u,d

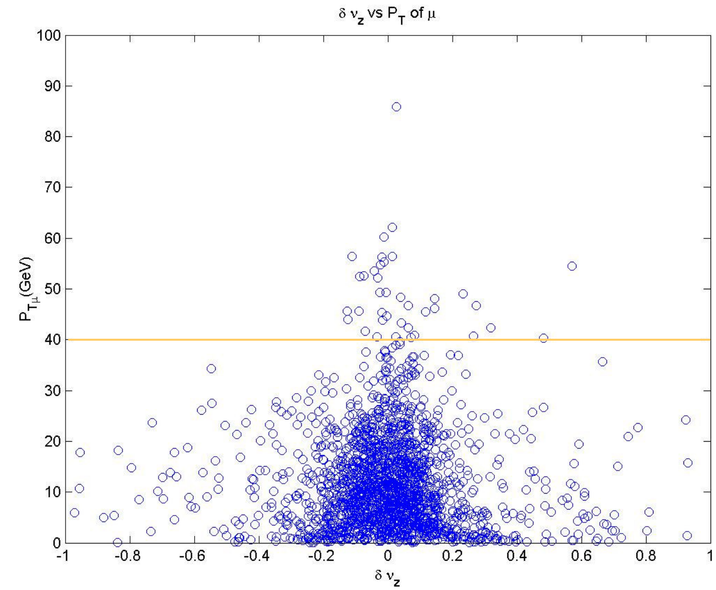
10% c

Figure 12.32: Regional (leftmost figure) and pixel-only (rightmost figure) reconstruction b-tagging efficiency and light jet rejection for the track counting algorithm on a sample of hadronically decaying top pairs. The curves are obtained by scanning over the signed 3D IP significance for the N^{th} track in the jet (ordered in order of decreasing significance), where $N = 2$ for pixel-only reconstruction and $N = 3$ for regional reconstruction. The curve for b-jets versus light jets is shown with open markers, while that for b-jets versus c jets has filled markers.

Note that $(c\tau)_b \sim 450\mu m, (c\tau)_\tau \sim 87\mu m$ **Earliest attempt to establish b tags comes with b jet events.**

Muons and Neutrinos in b Pairs





$$[P_{z\nu} - P'_{z\nu}]/[P_{z\nu} + P'_{z\nu}]$$

Run at 0.9 TeV will not well populate the endcap muon detectors. Look at approximation of massless jet decaying collinearly to massless final state particles. Compare neutrino z momentum to estimate using MET and the Jet axis. Works well above lepton momentum of ~ 40 GeV (jet above 120 GeV).

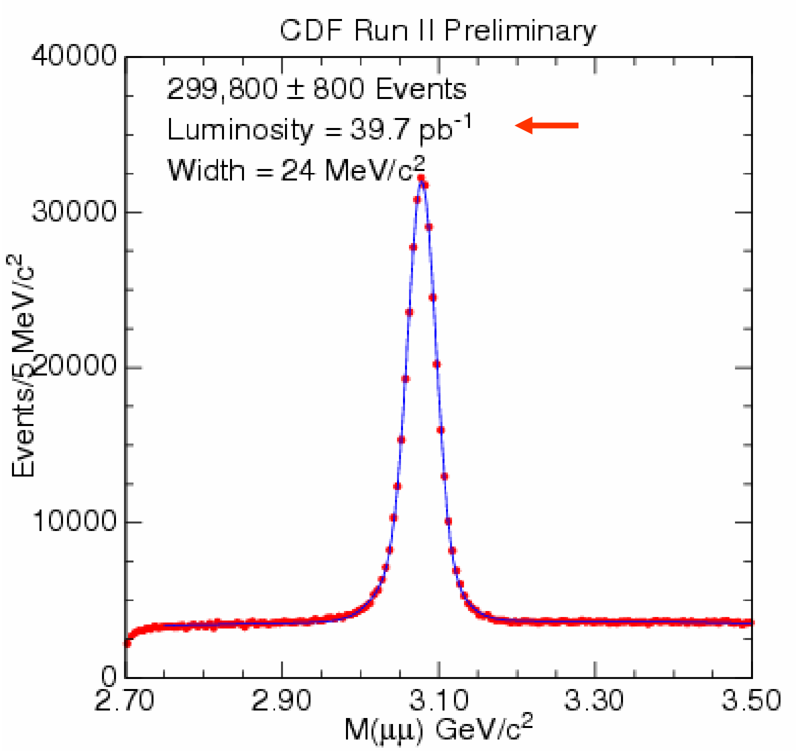
Vector Boson Di-Lepton Calib

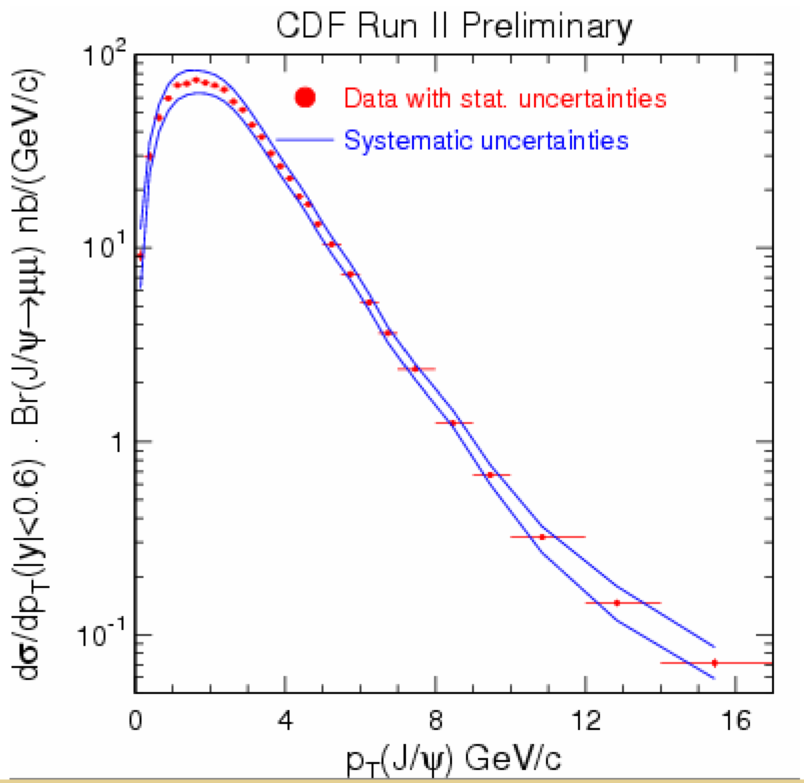
$$\hat{\sigma} \sim \pi^2 \Gamma(2J+1) B_{\ell\ell} / M^3$$

Type	M(Gev)	Γ(GeV)	B(%)	$\hat{\sigma}(nb)$
ψ	3.1	0.000091	5.9	2.1
Y	9.46	0.000053	2.5	0.018
Z	91.2	2.5	3.4	1.3

Since the structure functions favor low mass, expect that ψ production is largest.

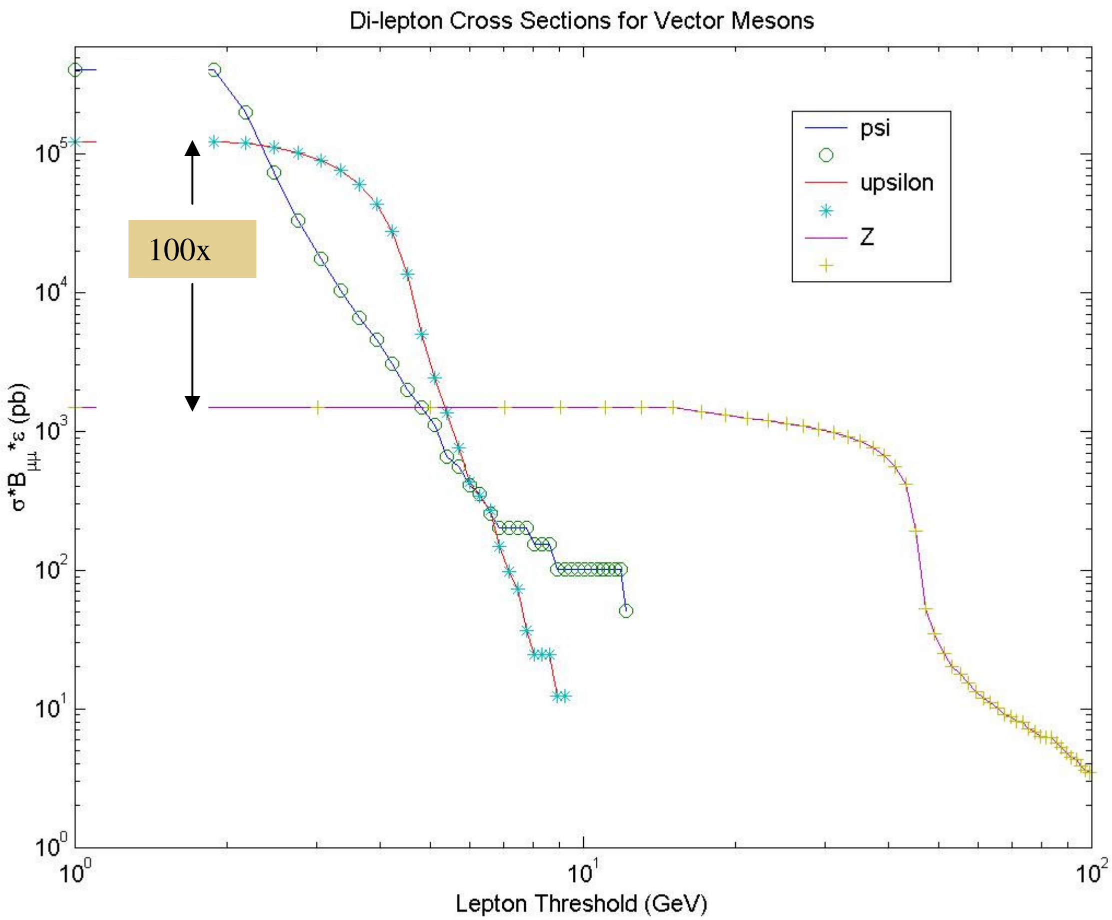
Charmonium Calibration





Cross section * BR in |η|<1.5 is ~ 8 nb. Get ~ 80 dielectron and dimuon events which are prompt in 10 /nb. Confirm di-lepton mass scale and mass resolution. Triggers will need to operate at reduced threshold and for muons, use only first layer of muon chambers. Sort on primary and secondary to see if B tags are functioning properly? B ->ψ

Dilepton Resonances - Thresholds



If thresholds of 3 to 4 GeV can be used in triggers, then high cross section resonances can be used to establish Tracker and Muon alignment and check the mass scale and resolution.

Rapidity of Leptons From ψ andY

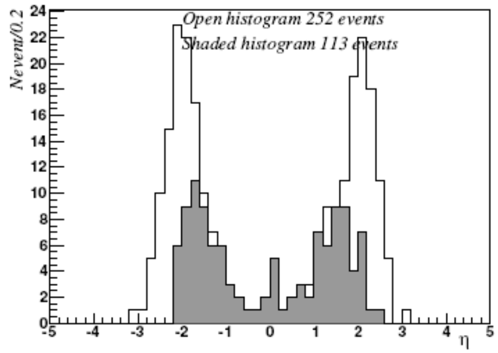


Figure 9.35: The η distribution of J/ψs with both muons triggered by the "Open Level-1" and Level-2 trigger combination (solid-line histogram) as compared with the more stringent Level-1 and Level-2 trigger (shaded histogram). Two opposite-sign Level-1 or 2 opposite-sign Level-2 candidates are required. See text for details.

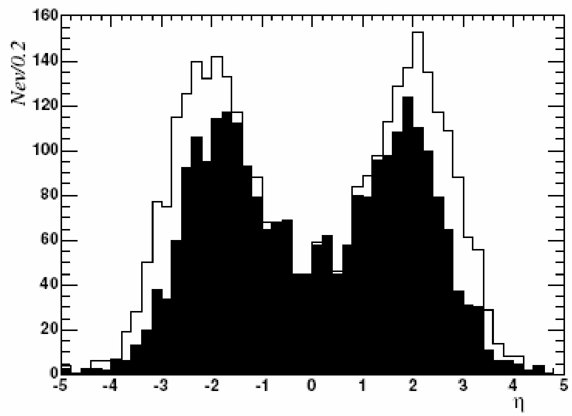
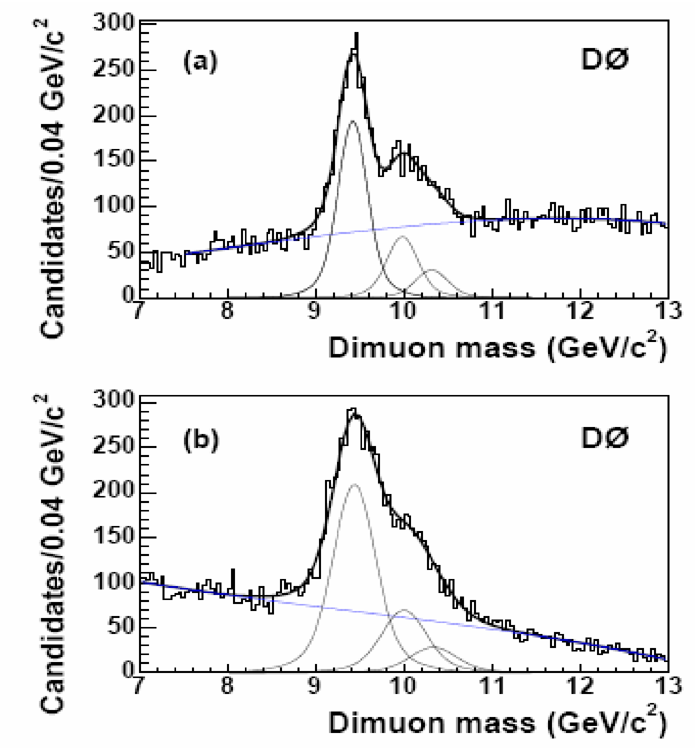
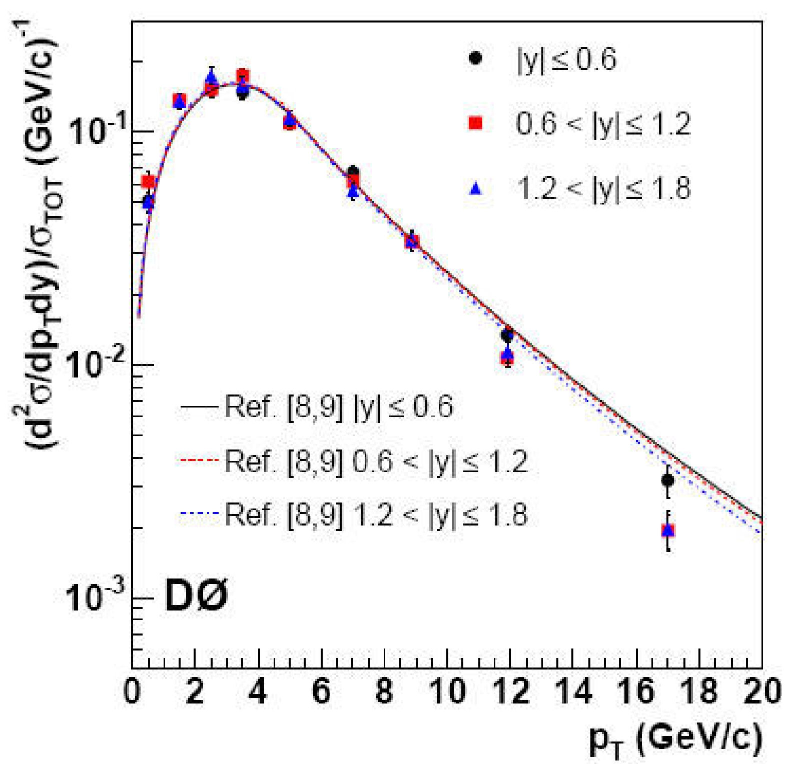


Figure 9.37: The η distribution of Υs with both muons triggered by the Open Level-1 and Level-2 trigger (solid-line histogram) as compared with the Level-1 and Level-2 trigger (shaded histogram). Two opposite-sign Level-1 or 2 opposite-sign Level-2 candidates are required.

Lepton signals for Tracker and Muon systems will be "barrel poor" until the heavier bosons, W and Z become available as the luminosity increases.

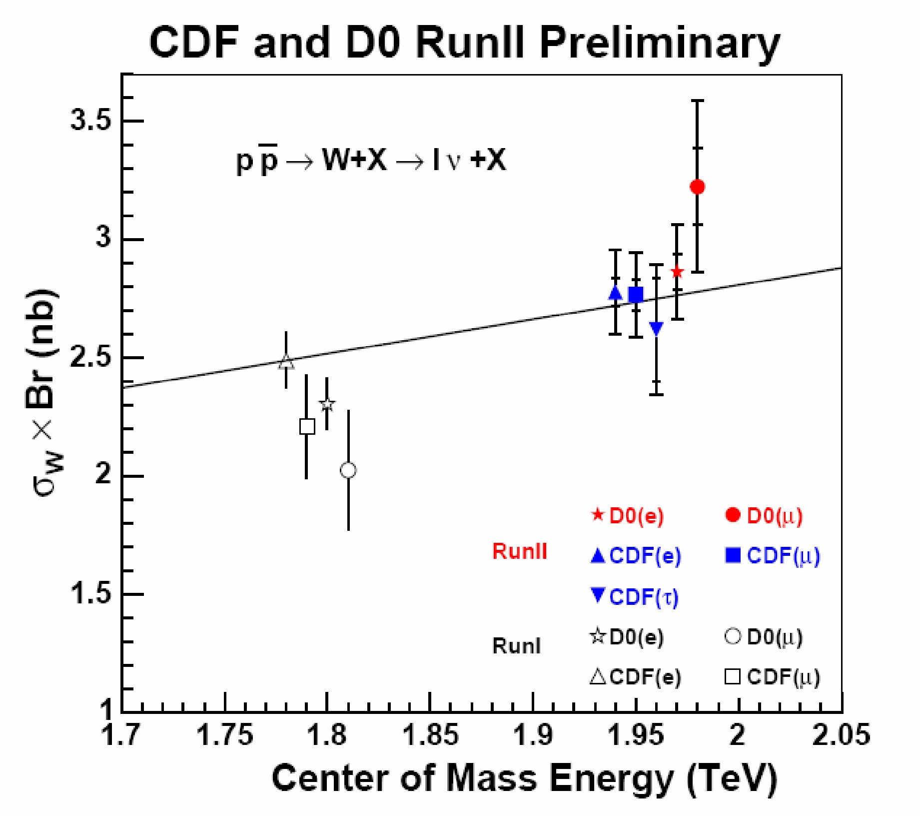
Upsilon Calibration





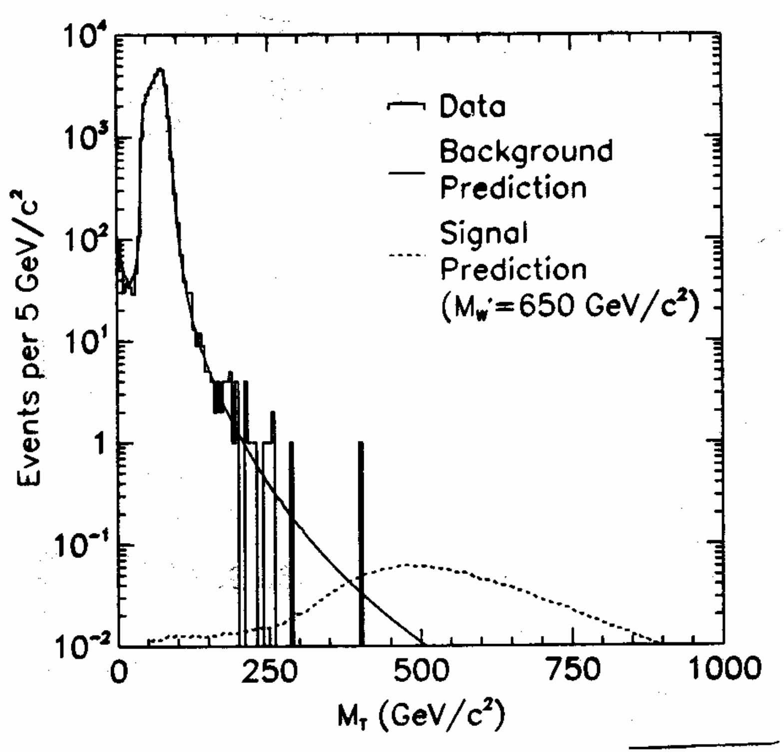
Cross section * BR about 1 nb. Resolve the spectral peaks? Mass scale correct?

Standard W Candle?

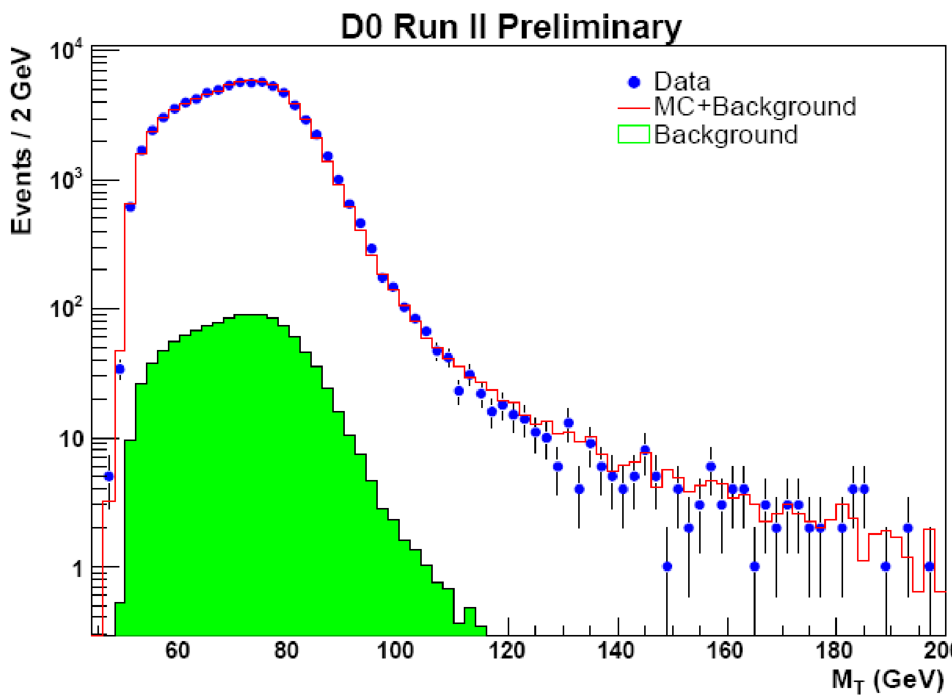


Use W -> μ + ν as a "standard candle" to set the LHC luminosity? Expect ~ 2% accuracy on the predicted cross section. Cross section for W-> μ +ν with |η|<2.5 * Pt > 15 GeV is ~ 10 nb. In isolated muon triggers look for MET and for Jacobean peak indicating cleanly identified W D-Y production. Once established, look at transverse mass tail in isolated leptons. In new territory above Run II mass reach – start a discovery search in 2008.

Run I, II W Transverse Mass



Reach at high Mt is ~ 400 GeV. Will have greatly enhanced mass reach at the LHC.



Missing ET

- Since the pion density is ~ 9 and the mean transverse energy is ~ 0.6 GeV, there is 54 GeV of E_T per minbias event or ~ 1 TeV per bunch crossing at design luminosity.
- Missing transverse energy, MET, is a global vector (2-d) variable.

$$0 = \sum E_{xi} + MET_x$$
$$0 = \sum E_{yi} + MET_y$$

- If the energy measurement is dominated by the stochastic term

$$dMET_x = \sqrt{\sum a^2 E_{Ti} \cos^2 \phi_i} \sim aE_T / \sqrt{2}$$
$$dMET_y = \sqrt{\sum a^2 E_{Ti} \sin^2 \phi_i} \sim aE_T / \sqrt{2}$$

- Then the magnitude of MET is the length of MET in the transverse plane

$$dMET \sim a\sqrt{E_T} = a\sqrt{\sum E_{Ti}}$$

- If stochastic coefficient is 100%, then dMET~ 30 GeV for 1 crossing at design L at the LHC.

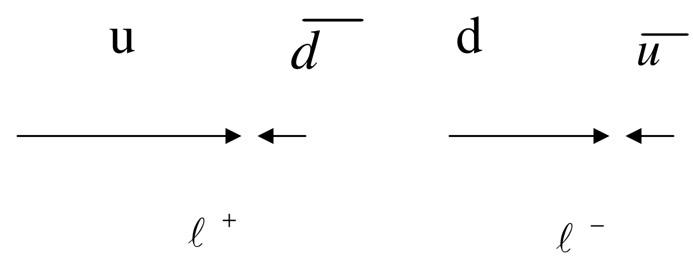
Solving W -> μ + ν

$$M_W^2 = 2[P_\ell \sqrt{P_{T\nu}^2 + P_{Z\nu}^2} - (P_{\ell x}P_{\nu x} + P_{\ell y}P_{\nu y} + P_{\ell z}P_{\nu z})]$$

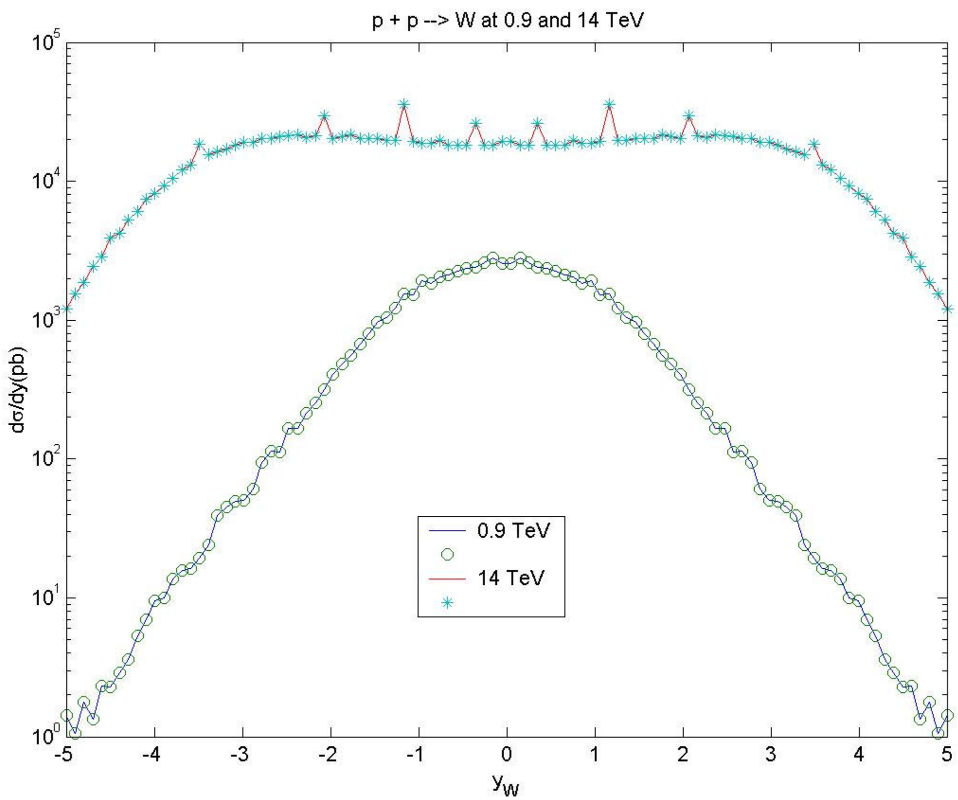
➔ Solve for neutrino z momentum

The transverse neutrino momentum comes from MET. The z component of neutrino momentum is unmeasured. Use W mass constraint to solve for it. Quadratic -> 2 solutions.

$\overline{q}$ are from the proton sea.

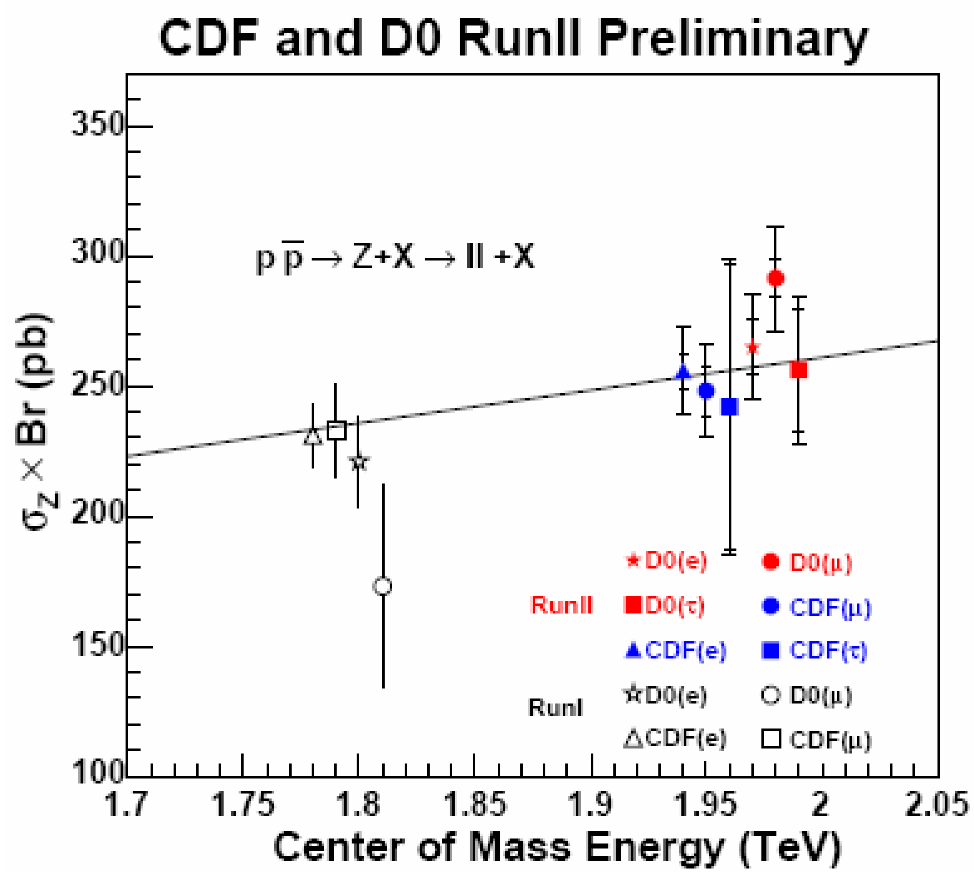


0.9 and 14 TeV W Production



For W and Z production requires anti-quarks. J, b, ψ, Y are gluon produced and ratios are ~ 200. In the case of antiquarks, <x> ~ 0.09 for W at 0.9 TeV, so production is largely off the "sea". At the barrel, ratio is ~ 10, while y plateau expands for 14 TeV. Overall ratio is ~ 25.

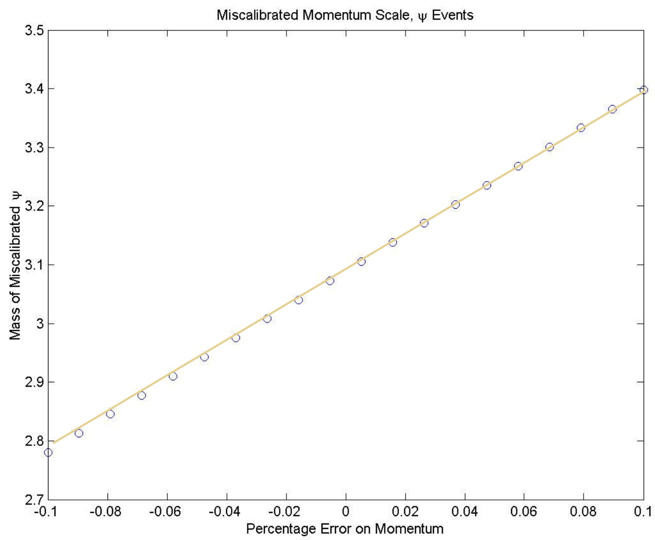
Standard Z Candle?



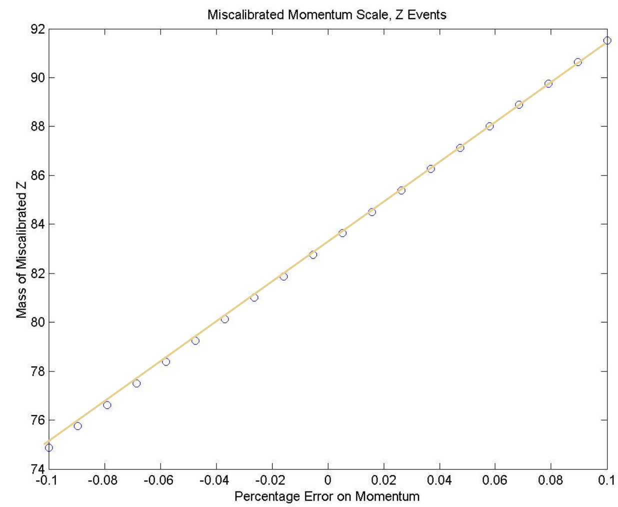
Use Z-> μ+μ as second "standard candle" to determine the LHC luminosity. Expect ~ 2% accuracy in cross section prediction. Find cross section for Z-> μ+μ decay with |η|<2.5 * Pt > 15 GeV is ~ 600 pb. Note slow rise from Run II cross section values.

Lepton Momentum Scale

M



α



$$M^2 = 2P_1P_2(1-\cos\theta_{12})$$

$$P \rightarrow P(1+\alpha), \alpha = dP / P$$

$$(M+dM)^2 = 2P_1P_2(1+\alpha)^2(1-\cos\theta_{12})$$

$$dM / M \sim \alpha = dP / P$$

Z->e+e in Situ ECAL Calibration

Accurate ECAL calibration depends on using Z as a narrow di-electron resonance.

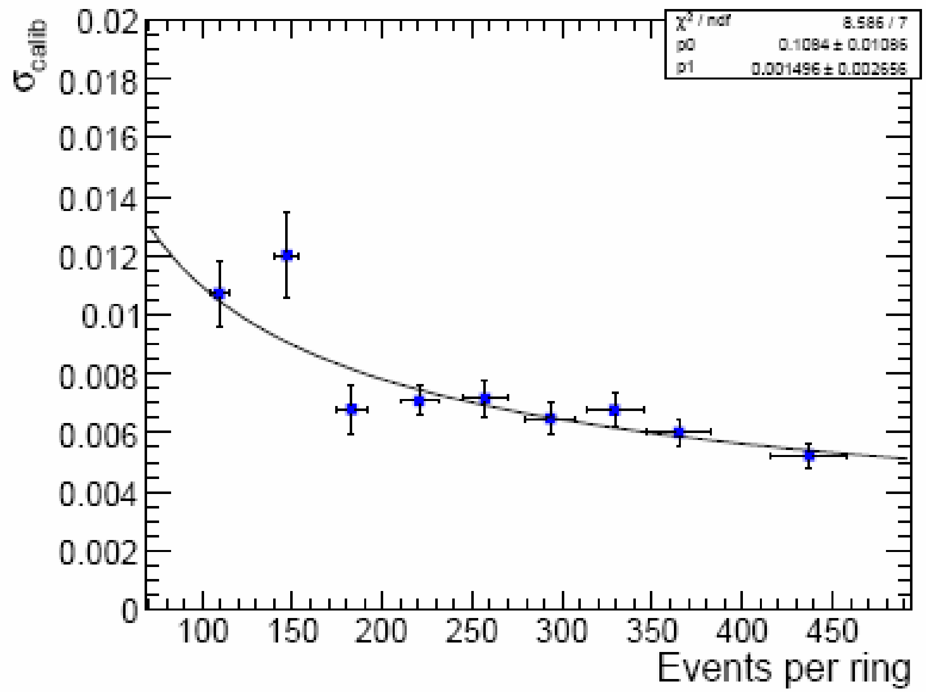
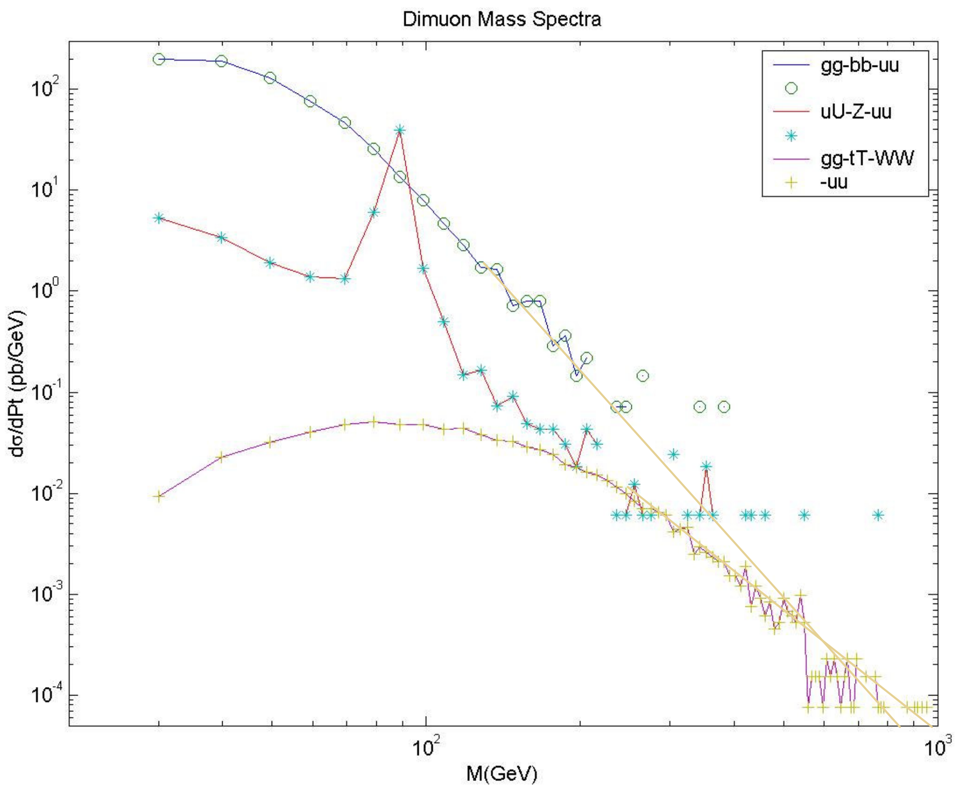


Figure 4.26: Ring-to-ring calibration precision achieved versus average number of events per ring. An average of 370 events per ring corresponds to an integrated luminosity of 2.0 fb^{-1}. The full curve is a fit to the sum of a statistical term and a constant term.

0.5% in situ calibration requires about 400 electrons per η "ring" with 250 rings in ECAL – requires ~ 2 /fb.

Dimuon Spectrum and Search



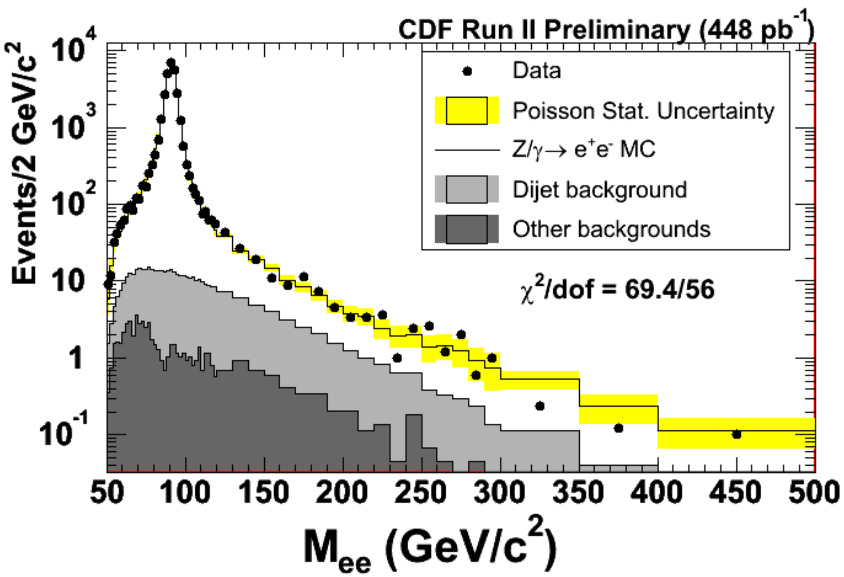
At low mass, b pairs dominate. Peak for Z is above background. Top pairs dominate at high mass.

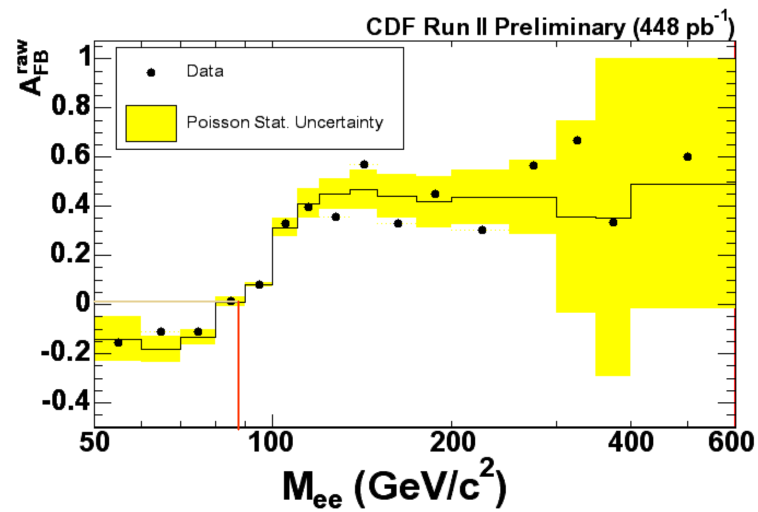
Establish Z production in isolated dimuons and dielectrons. Establish cross section – understand trigger and reco efficiency. Confirm mass resolution and mass scale for leptons using the Z . Cross check luminosity determination found from W.

Set up search for high mass dileptons using the di-lepton data stream.

Get to the 1 TeV mass scale by 1 fb^{-1}. Start discovery search with ~ 10 events.

CDF -High Mass Dileptons, F/B

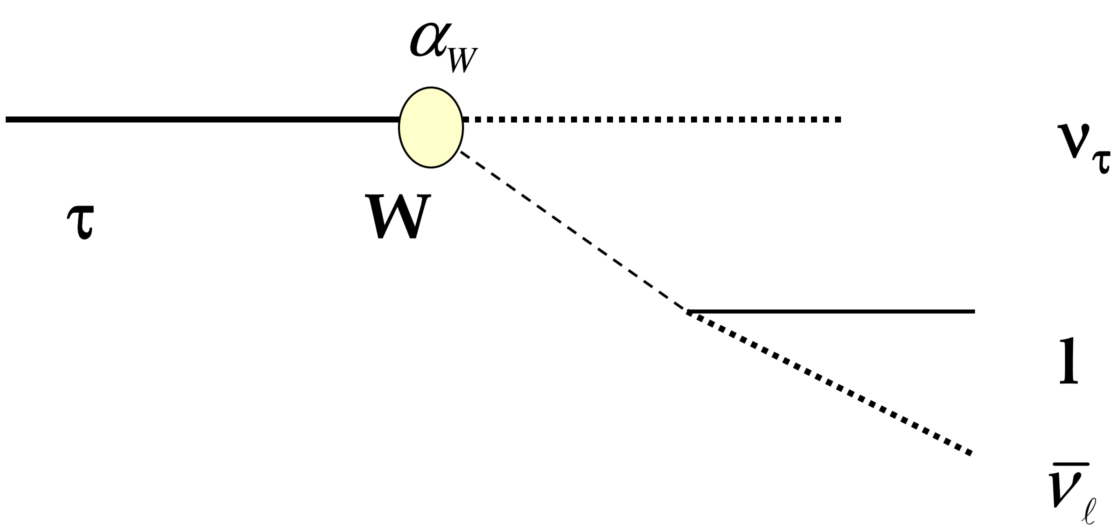




Look at high mass isolated dimuons. Establish the F/B asymmetry above the Z. Limit of ~ 500 GeV in tail. No evidence of F/B asymmetry which deviates from SM. If Z′ , then A_{FB} -> 0.

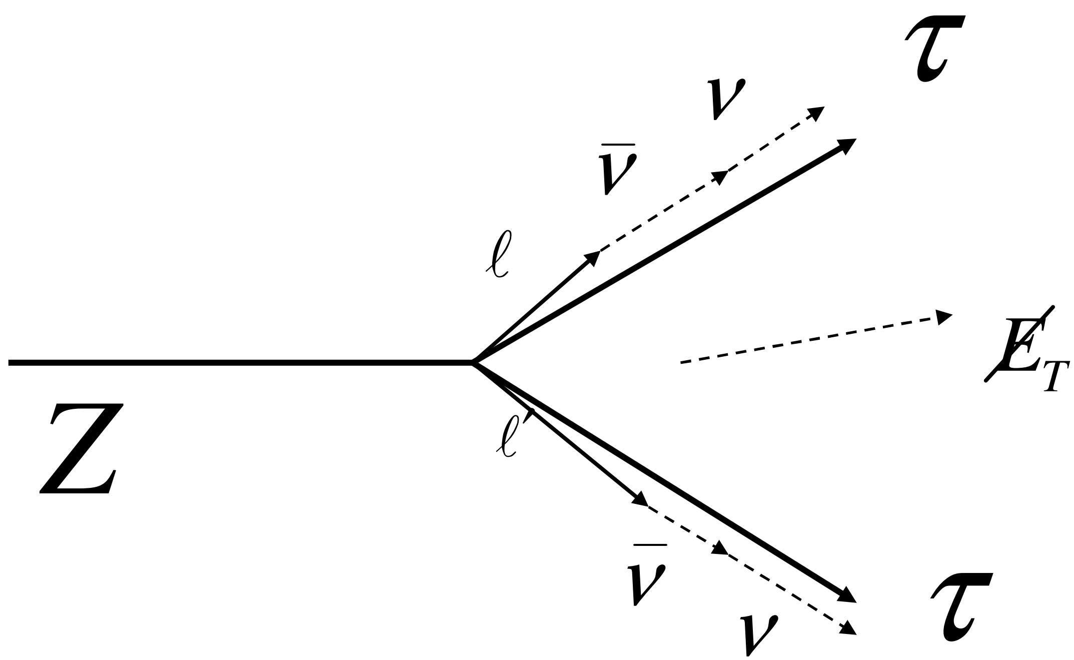
Establish tau in Z Decays

Z -> τ + τ decays as with muon and electron pairs.



Decays appear in dilepton trigger stream. BR is 35% for tau into muon or electron.

Z Decay to Tau Pairs - Collinear



Assume collinear neutrinos. Then have 2 Eqs in 2 unknowns. Must cut on determinant

$$\det = \sin\theta_{\ell 1}\sin\theta_{\ell 2}\sin(\phi_{\ell 1}-\phi_{\ell 2})$$

|det|>0.005 is ~ 70% efficient after cuts on Pt of the leptons and MET.

$$M_{\tau\tau} \sim \sqrt{2(E_{\ell 1}+E_{\nu\nu 1})(E_{\ell 2}+E_{\nu\nu 2})(1-\cos\theta_{\ell 1\ell 2})}$$

$$METx = E_{\nu\nu 1}\alpha_{x\ell 1} + E_{\nu\nu 2}\alpha_{x\ell 2}$$

$$METy = E_{\nu\nu 1}\alpha_{y\ell 1} + E_{\nu\nu 2}\alpha_{y\ell 2}$$

Tau Triggering

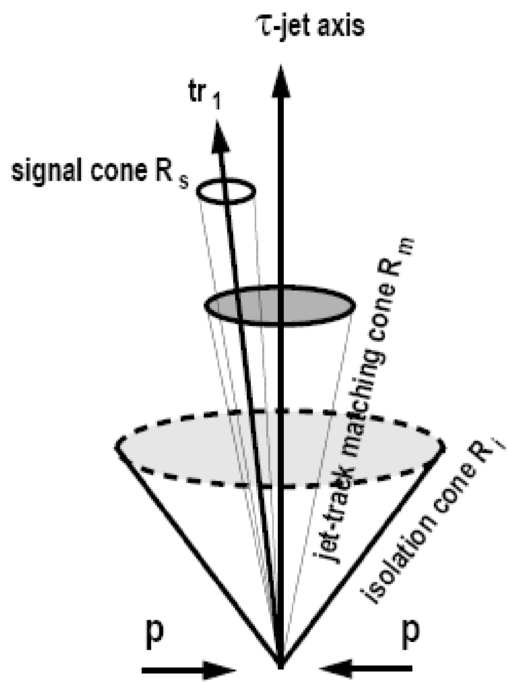
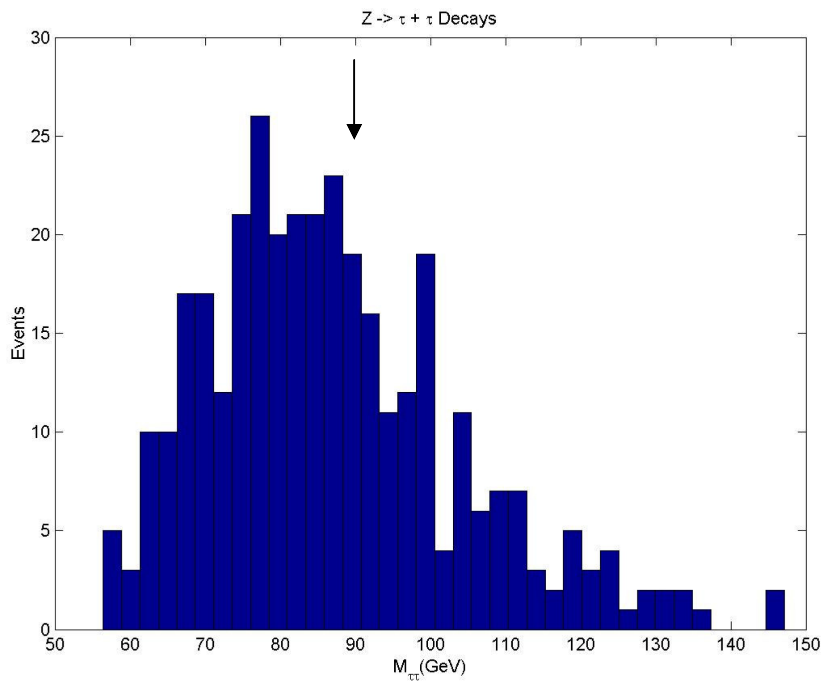


Figure 12.8: Sketch of the basic principle of τ-jet identification using the tracker isolation.

$$\tau^- \rightarrow \nu_\tau + W^- \rightarrow \ell^- + \overline{\nu}_\ell$$
$$\rightarrow \overline{u} + d \rightarrow \pi^-, \rho^-, \ldots$$

Require a "narrow" jet in the calorimetry. Require confirmation from the tracking, and isolation around the narrow jet.

Tau Signal



Tau mass is 1.76 GeV, Z is 91 GeV. Thus, all tau decay products are ~ collinear with the tau direction.

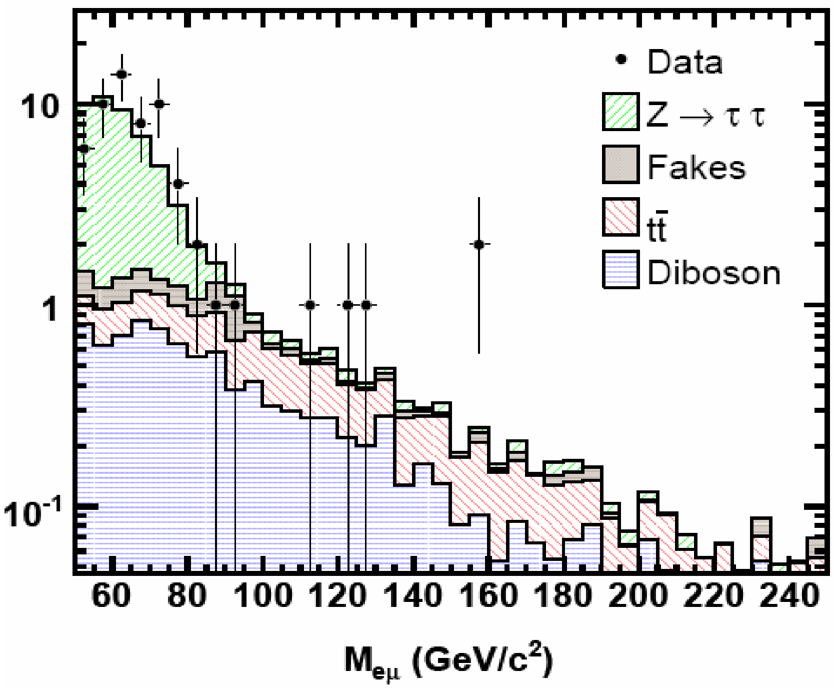
Cut with Pt of both leptons > 8 GeV and MET > 15 GeV

Trigger efficiency is ~ 5%. Thus many fewer tau pairs than direct dilepton pairs.

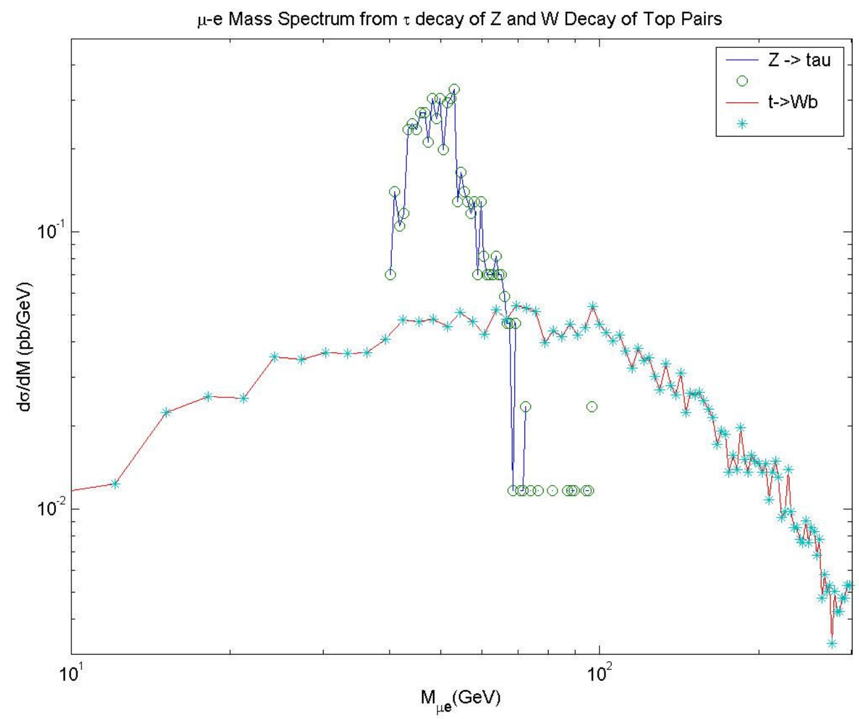
Plot of mass of Z using tau energy inferred fron lepton energy and the projection of MET along the lepton ~ tau direction. Mean dilepton mass = 46 GeV. Mean MET (cut > 15 GeV) is 21 GeV. Mean tau pair mass is 92 GeV.

Di-lepton Search

Tevatron



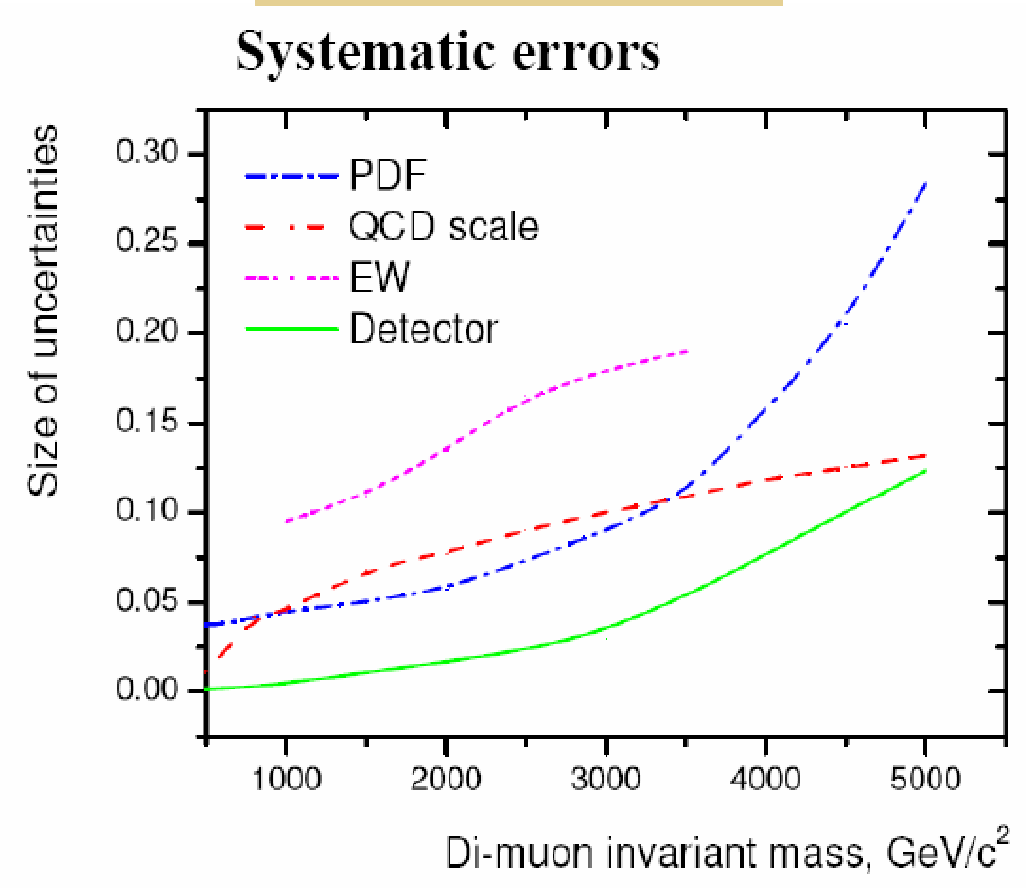
LHC



Having established clean electron, muon and tau "objects" a look at di-lepton masses can be taken with some confidence. The top pair background dominates the dilepton mass spectrum at high masses.

High Mass Di-Lepton Cross Sections

LHC – 2008 Run

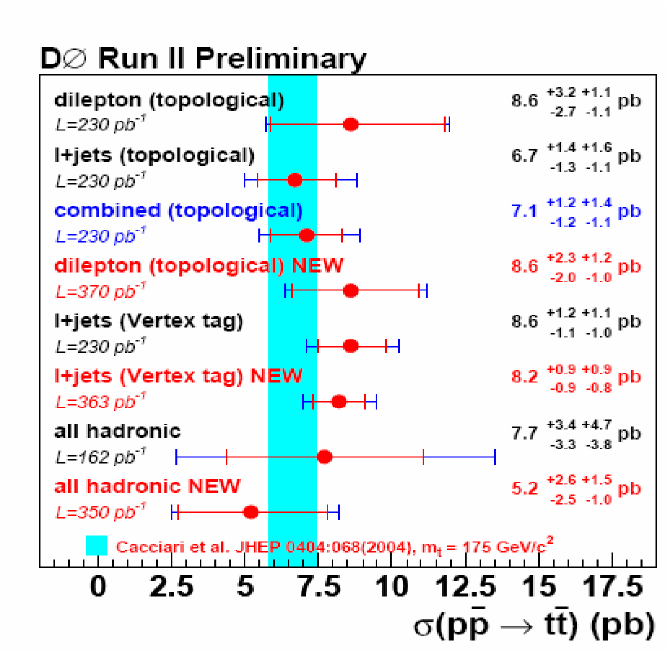


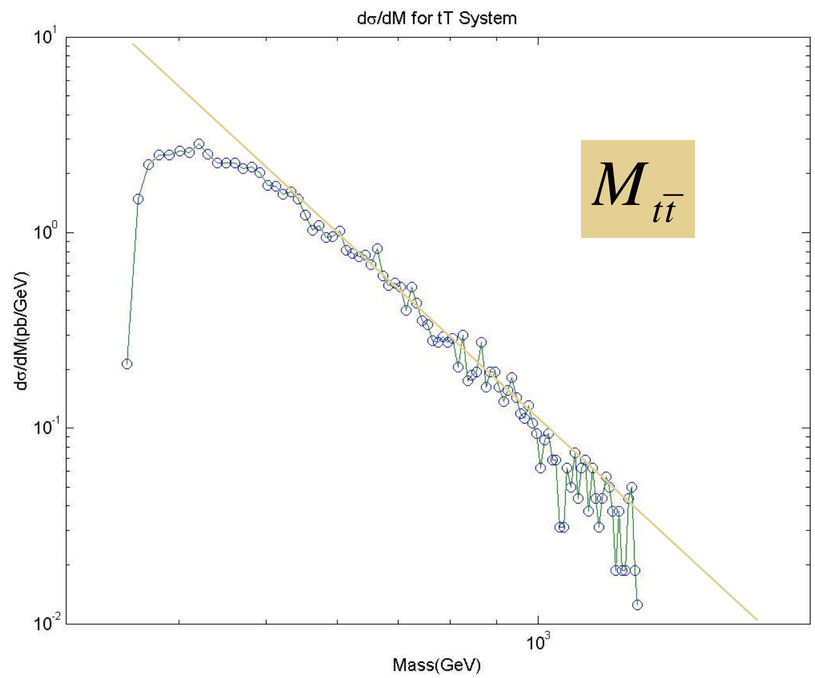
PDF at higher mass than Z means higher x,

$$< x > \sim M / \sqrt{s}$$

and perturbation theory means scale dependence. Detector effects are not dominant at high masses, > 1 TeV.

Top Pair Production – Run II ->LHC

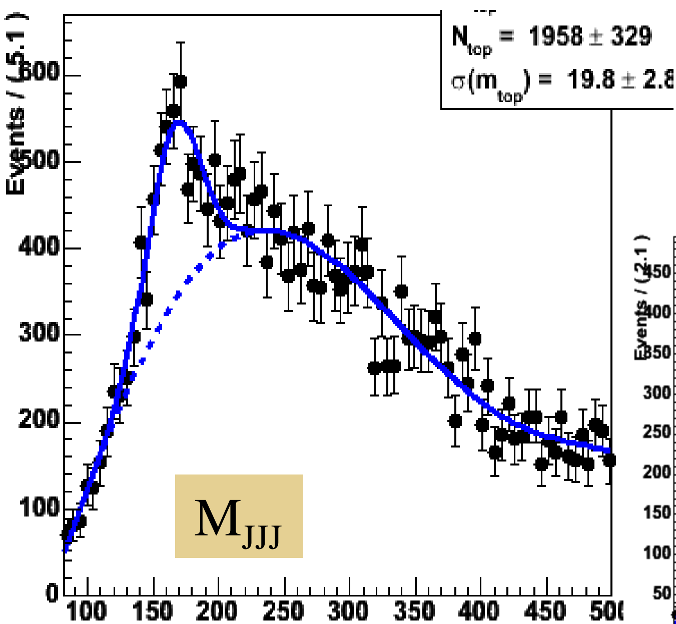




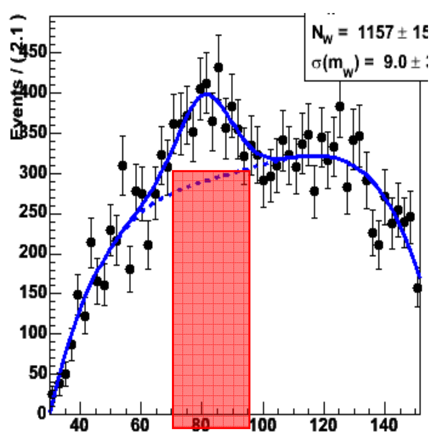
Same Feynman diagrams as b+ B. Ask top jets with Pt > 30 GeV and |η| < 5.0. The cross section is ~ 630 pb (big rise – 100 x- from Run II – made by g at LHC not quarks as at Run II). The mass spectrum is the same in magnitude and shape as b+B at masses > 500 GeV. Events appear in di-lepton trigger stream.

Hadronic Top Reco - ATLAS

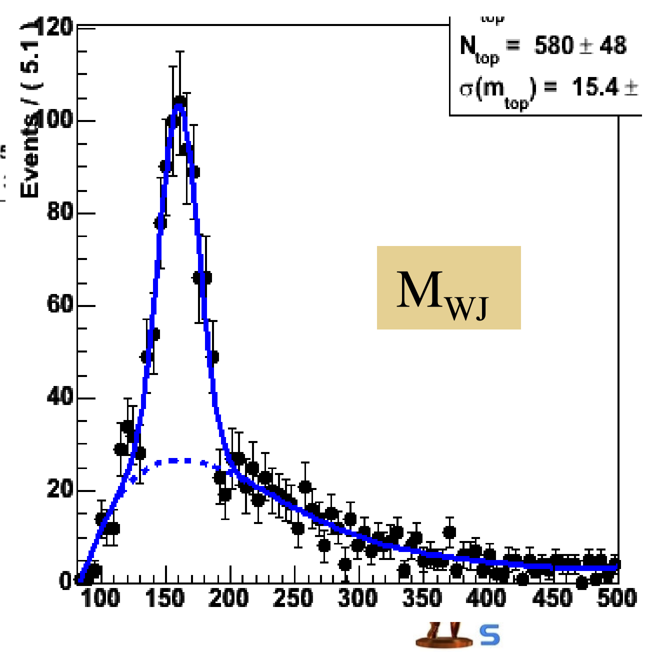
Three jets with highest vector-sum P_T as the decay products of the top – lepton trigger. Two jets in hadronic top with highest momentum in reconstructed J+J+J C.M. frame. Lumi = 300 /pb. Top mass with cut on W in M_{JJ}.



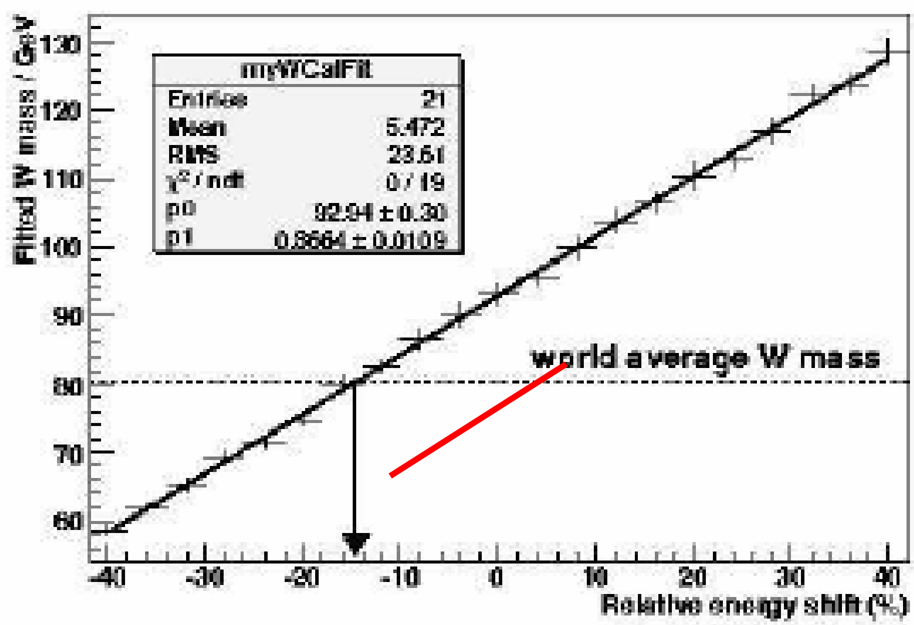
W



t

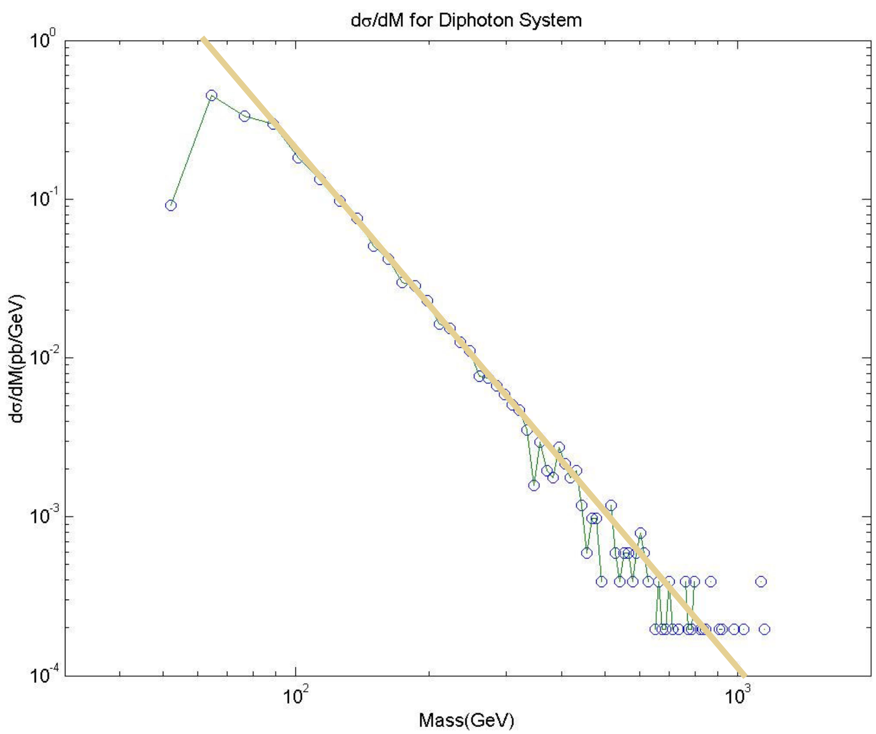


W -> J + J Mass and Jet E Scale



Get 1% statistics for Jet energy scale in 1 /fb. Need to understand the issues of backgrounds, pile up, etc. dM/M ~ dP/P

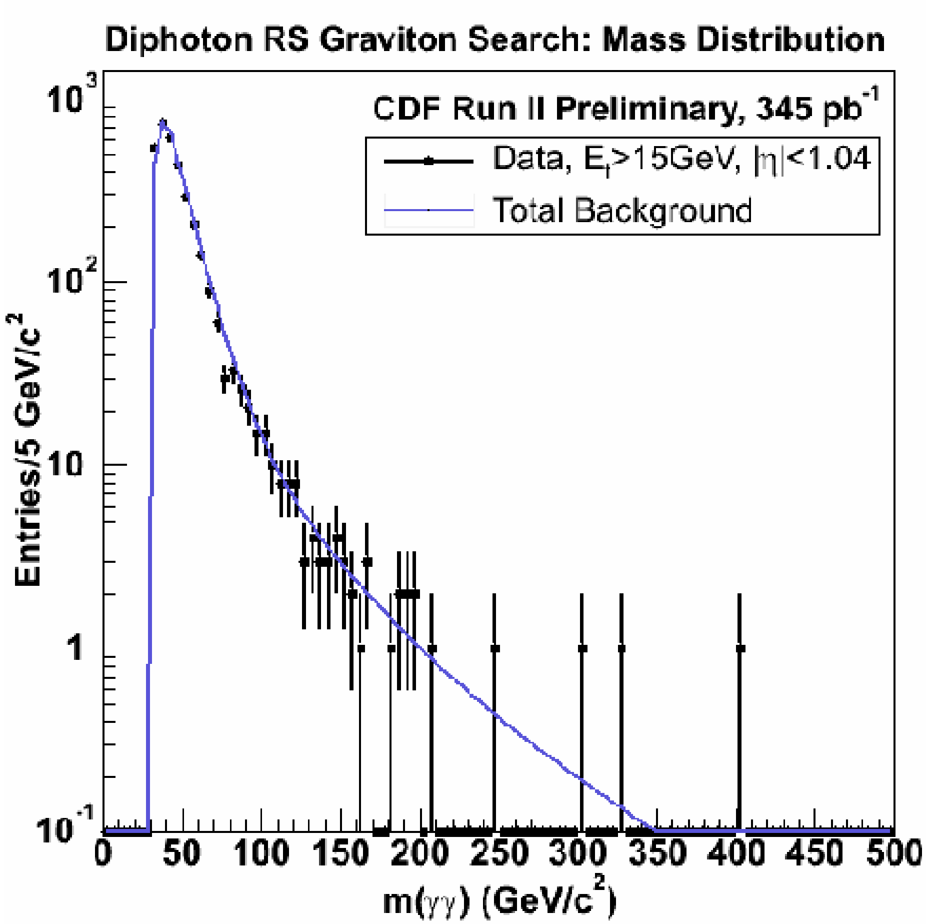
LHC - γ + γ Search



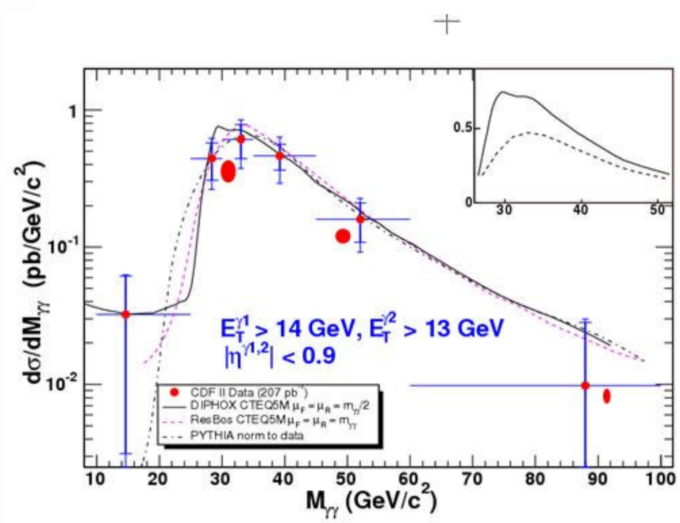
q + Q -> diphotons. Require Pt > 30 GeV and |η| < 2.5 to simulate ECAL acceptance. Cross section (tree diagrams only) is ~ 24 pb. This is ~ 3 million times smaller than g+g dijets (need rejection per jet > 2000). Need to establish the correct cross section in diphoton trigger stream. Mass distribution is ~ 0.2 pb/GeV at 100 GeV mass.

Run II limit is ~ 300 GeV. At LHC - Higgs search at low mass. At high mass, have ~ 100 events at 1 TeV mass in the first fb^{-1}. Start diphoton discovery search.

CDF - Diphotons

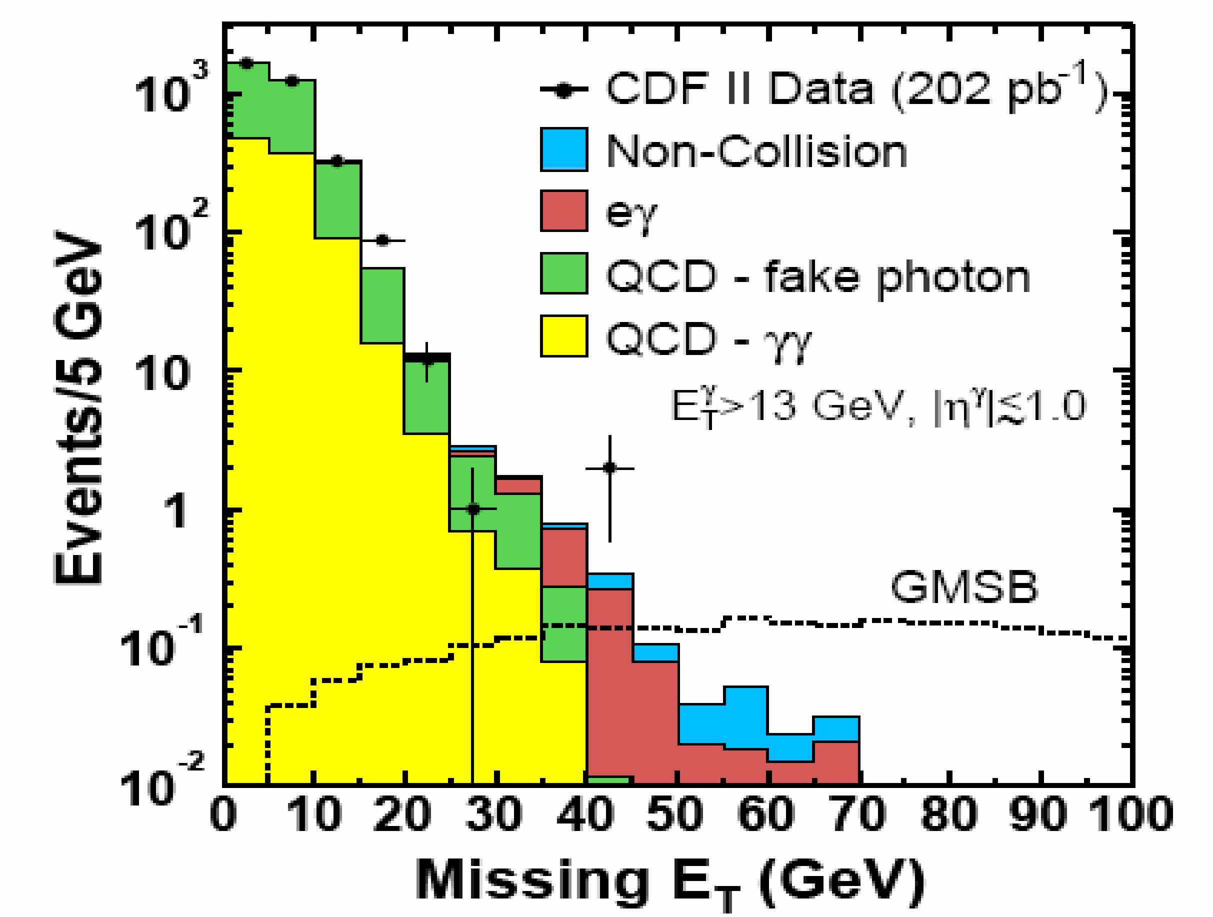


Mass spectrum explored to ~ 300 GeV. Large increase in mass reach at the LHC.



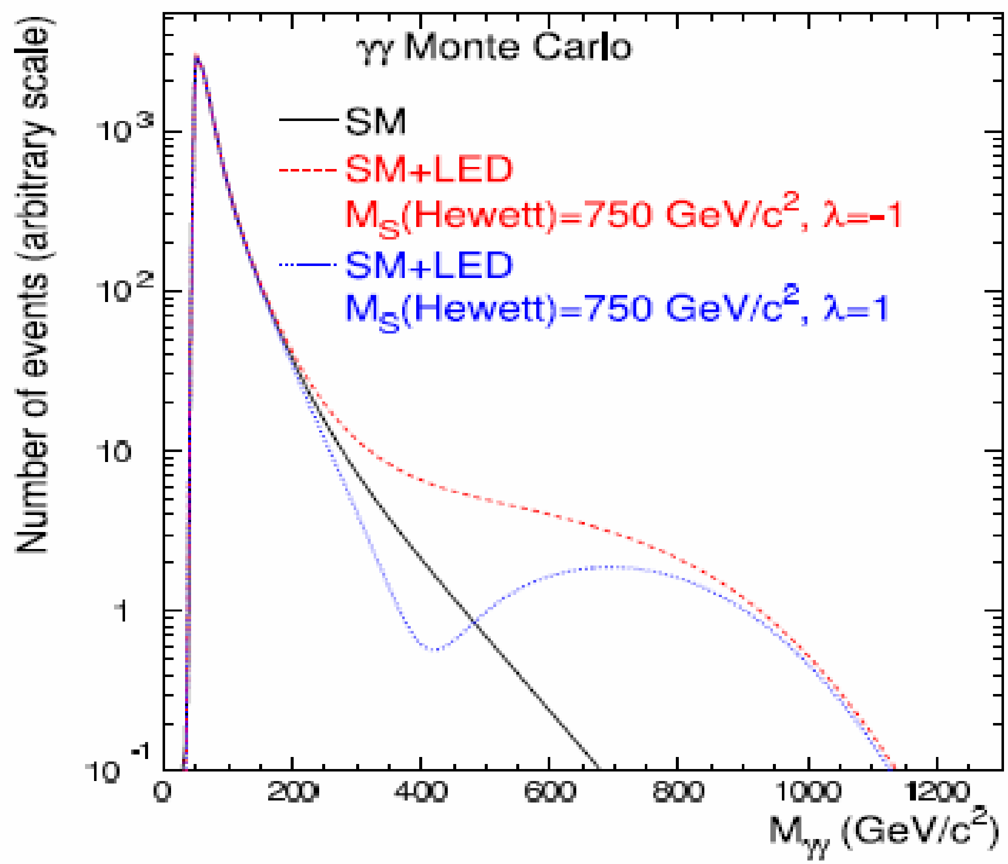
- COMPHEP – tree diagrams

SUSY- GMSB



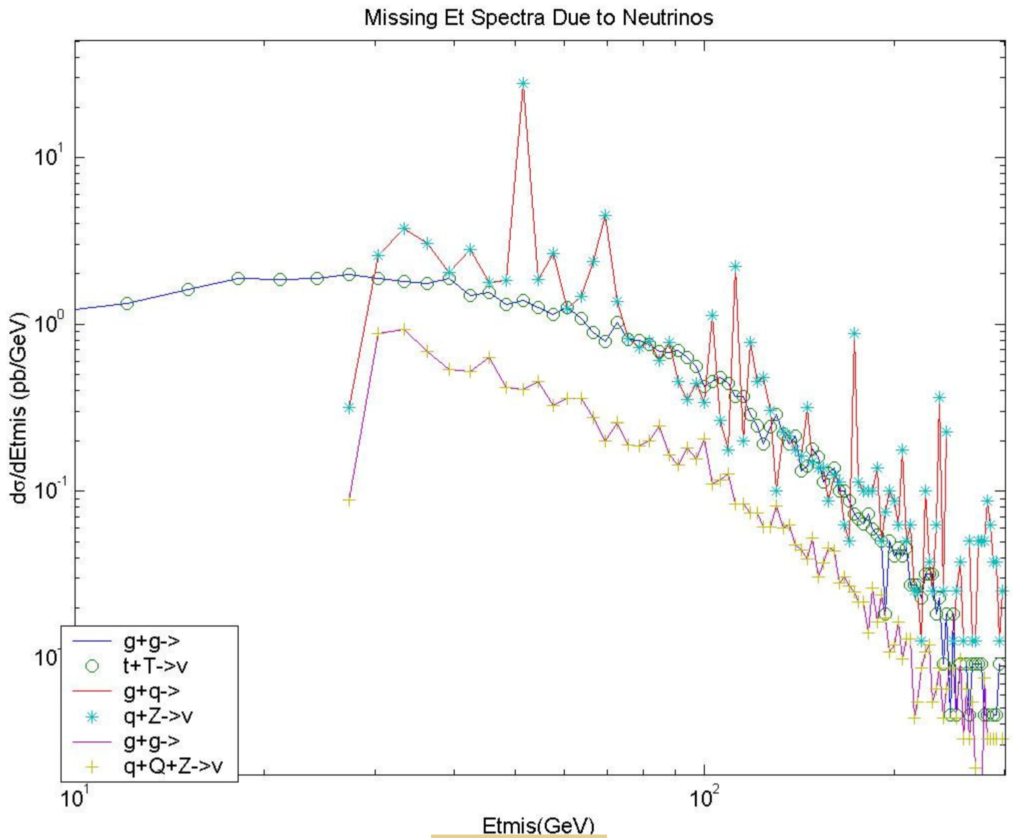
In GMSB the SUSY LSP is the graviton. The SUSY pairs cascade down to a pair of neutralinos which each decay to photon + graviton – signature is diphoton + MET

Di-photons at High Mass



Gravity couples to all mass "democratically". Therefore look at rare processes with SM weak couplings. LHC will be in new territory by 1 /fb.

MET from Z->v+v and Top Pairs at LHC



MET

J*MET: Compton scatt q+g->Z+q with q having Pt > 30 GeV and |η| < 5 and Z->v+v. Cross section is ~ 280 pb. Use dimuon events, Z + J balance, in calibration.

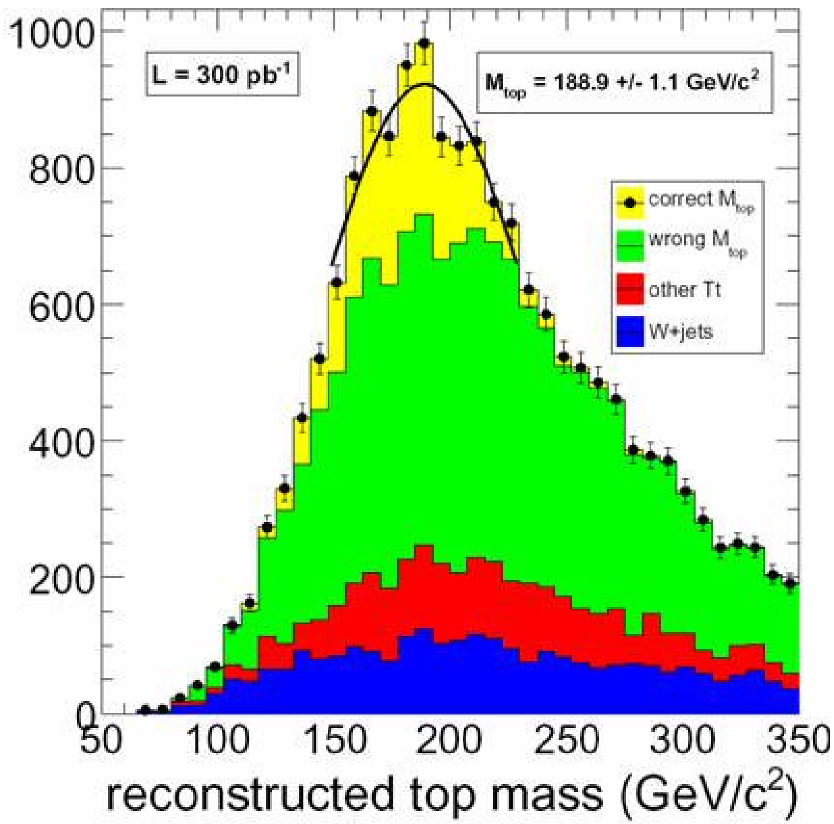
J*J*MET: In g + g -> q + Q + Z have Z radiation (FSR) diagrams. Require quark jets to have |η|<5 and Pt>30 GeV and Z to have Pt>30 GeV. Thus, dijet + missing Et cross section for missing Et>30GeV is ~ 170 pb *BR(vv) ~ 34 pb . Use Z->μ+μ events to validate missing Et. Set up for SUSY search.

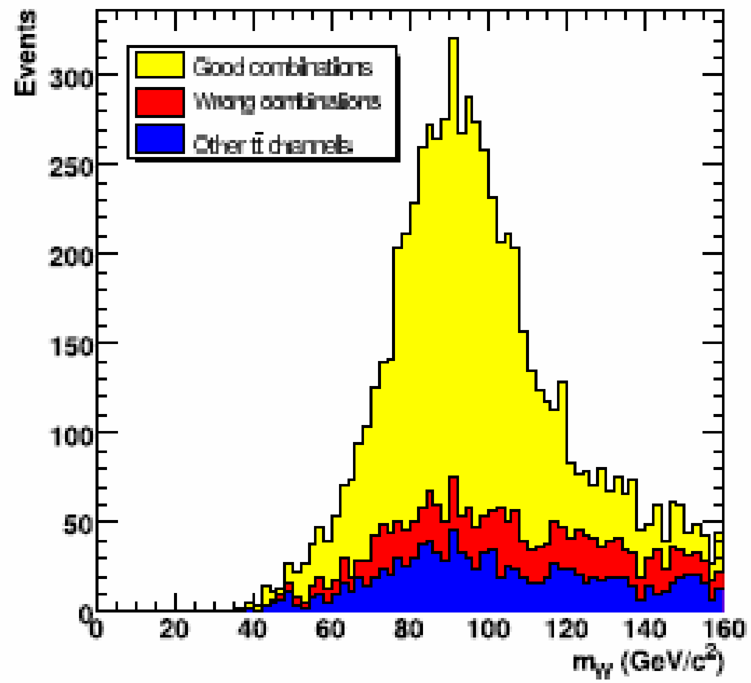
J*J*J*J*MET*: In t + T, single muon events have a cross section ~ 100 pb

Summary

- **Pre-operations will prepare ATLAS/CMS for first beam.**
- **The 2007 run will give operational experience with the detectors and some calibration/alignment data to begin startup for Physics.**
- **In 2008 the first 5 orders of magnitude in luminosity, up to $10^{27}/cm^2*sec$, will allow calibration checks, jet and MET establishment, and dijet mass search.**
- **The next 6 orders of magnitude, to $10^{33}/cm^2*sec$, allow the setting up of lepton triggers, standard candles for cross sections (W and Z), jet mass scale (W from top) and dilepton (including lepton+MET) and diphoton mass searches well beyond Tevatron limits.**
- **Look in tails of $l + \nu$, $l + l$ and $\gamma + \gamma$ masses, l=e, μ, or τ.**
- **Look at Jets + MET (plus lepton(s)). Estimate the irreducible Z backgrounds using dilepton Z events in the dilepton trigger stream.**
- **Each decade in integrated luminosity opens up a new discovery opportunity at the LHC – be ready!**

CMS – Tops Pairs





Want to establish top pair signal in SM as soon as possible. Can be done with loose criteria or, at lower efficiency, with tighter cuts. Use W->JJ to establish absolute jet energy scale