# Massive High $P_T$ Jets: Preliminary Results from CDF

## Outline

1. Introduction and Motivation
2. Data Selection
3. Calibrating and Correcting Jet Mass
4. Systematic Uncertainties
5. Results (Mostly Next Talk)
6. Next Steps


**Representing CDF Collaboration**

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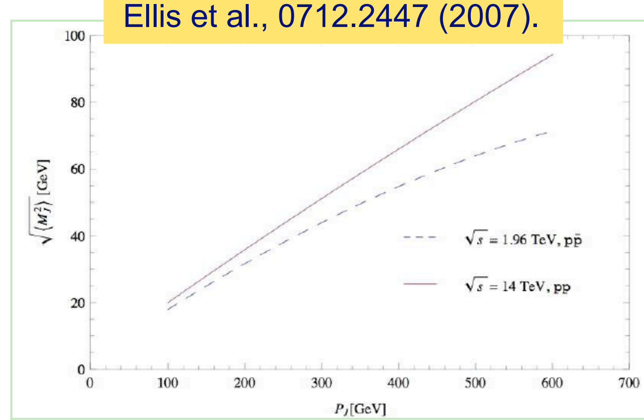
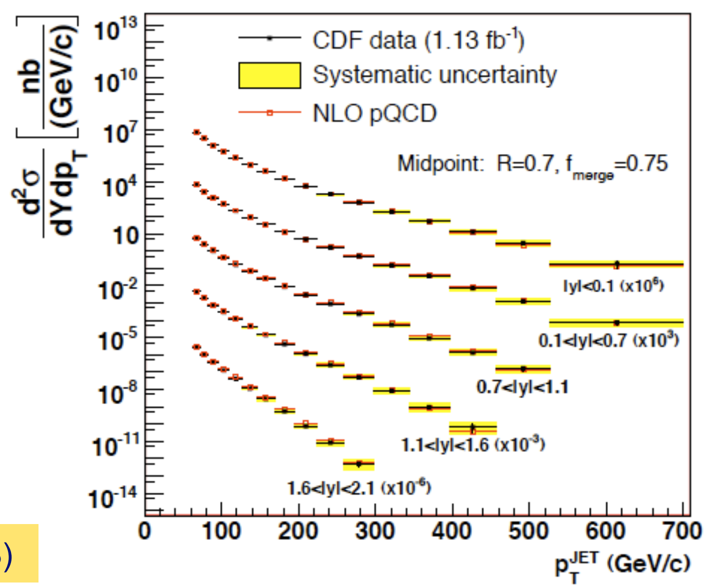
# Study Motivation

- **Mass of high-$p_T$ jets important property, but only theory studies**
  - **High mass: QCD at NLO predicts jet mass (eg., Ellis et al, 0712.2447, Alemeida, et al. 0810.0934)**
  - **Such jets form significant background to new physics signals**
    - Examples: high $p_T$ tops, Higgs, neutralino …
- **Focus on jets with $p_T$>400 GeV/c**
  - **CDF II has collected ~8 $fb^{-1}$**
  - **Have several thousand jet candidates**
  - **Reporting first systematic study of substructure**

Ellis et al., 0712.2447 (2007).

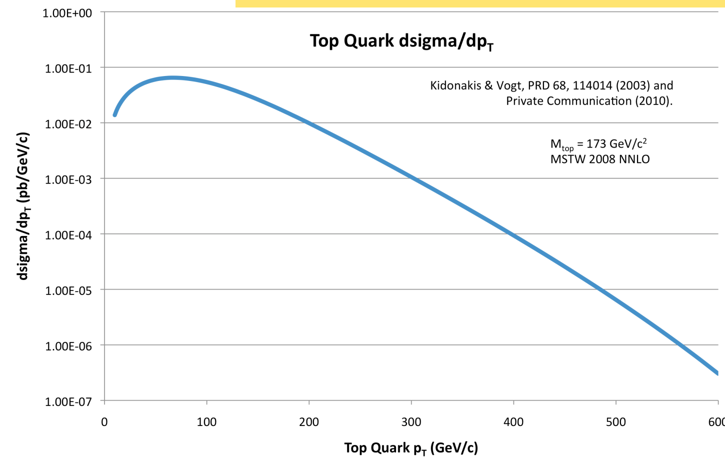


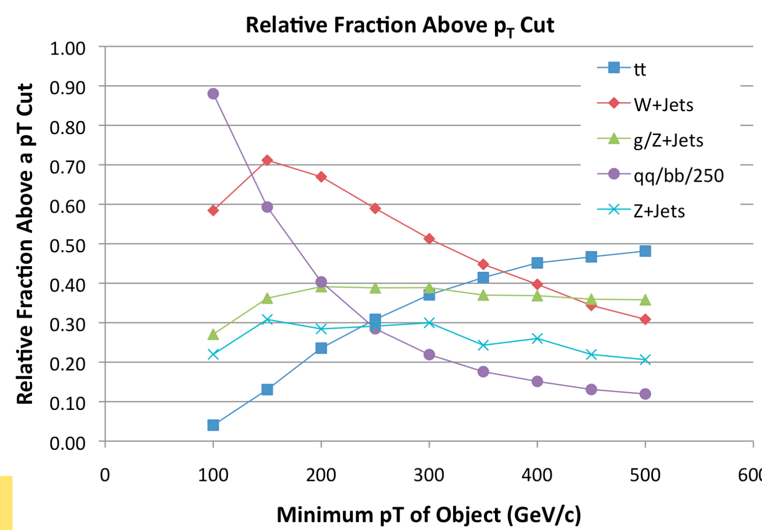

CDF Collaboration, PRD 78, 052006 (2008)

# Boosted Objects at Tevatron

Kidonakis & Vogt, PRD 68, 114014 (2003)



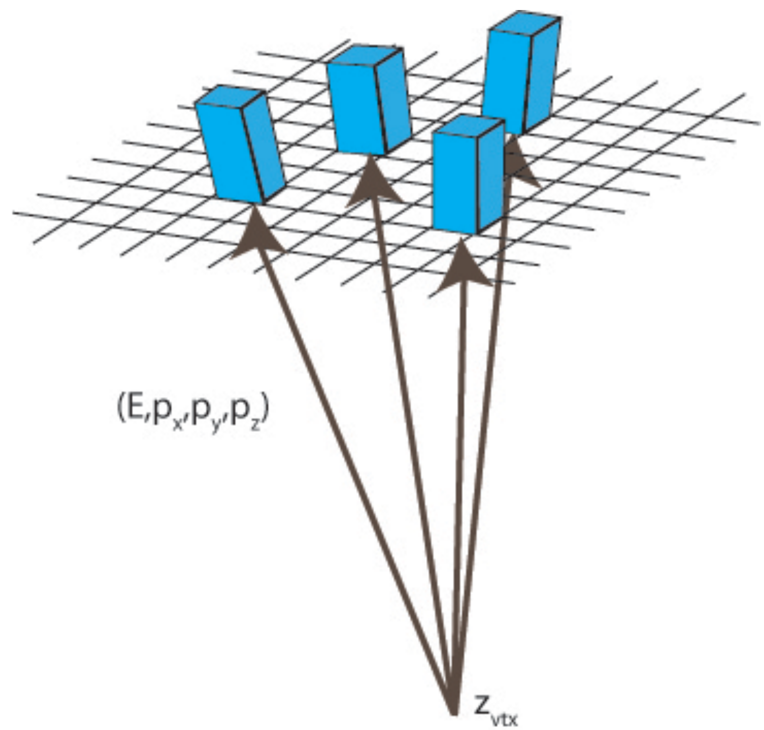

- **SM sources for high-$p_T$ objects calculable**
  - **Dominated by light quarks & gluons**
- **However, do expect other contributions**
  - **Fraction of top quarks ~1.5% for $p_T$>400 GeV/c**
    - Total rate 4.45±0.5 fb (Kidonakis & Vogt)
  - **Expect W/Z production of similar order**




PYTHIA 6.4 Calculation

# Strategy for Analysis

- **Select high $p_T$ jets in CDF central calorimeter**
  - **Use tower segmentation to measure jet mass**
    - Confirm with tracking information
  - **Employ standard "e-scheme" for mass calculation**
    - 4-vector sum over towers in jet
    - Each tower is a particle with m = 0
    - Four vector sum gives $(E, p_x, p_y, p_z)$




- **Employ Midpoint cone jets**
  - **Best understood in CDF II context**
  - **However, not fully IR-safe**

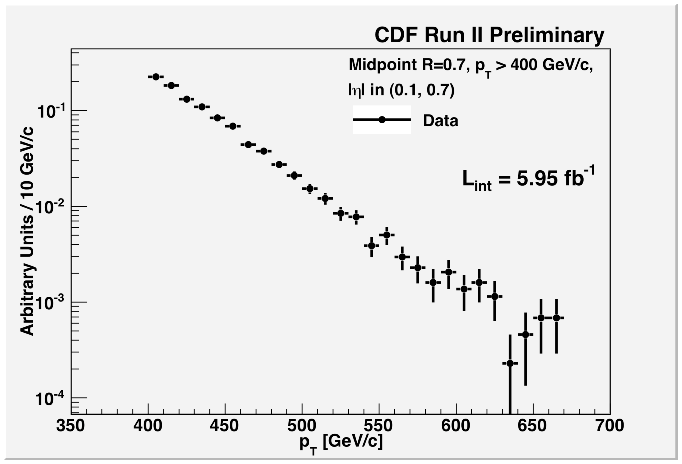
N.B. CDF central towers are $\Delta\eta \times \Delta\phi \sim 0.11 \times 0.26$

# Data Selection

- **Analyzed inclusive jet sample**
  - **Trigger requires $E_T$>100 GeV**
  - **Have available 5.95 $fb^{-1}$ sample**
- **Selected data with focus on high $p_T$ objects**
  - **Kept any event with**
    - Jet with $p_T$>300 GeV/c and |η|<0.7
    - Used cones of R=0.4, 0.7 and 1.0
- **Processed 76M events**
  - **Selected subsample with**
    - $p_T$>400 GeV/c
    - |η| ∈ (0.1,0.7)
- **Performed cleaning cuts**

$$S_{MET} \equiv E_T^{MISS} \Big/ \sqrt{\sum_{i\ towers} E_T^i}$$

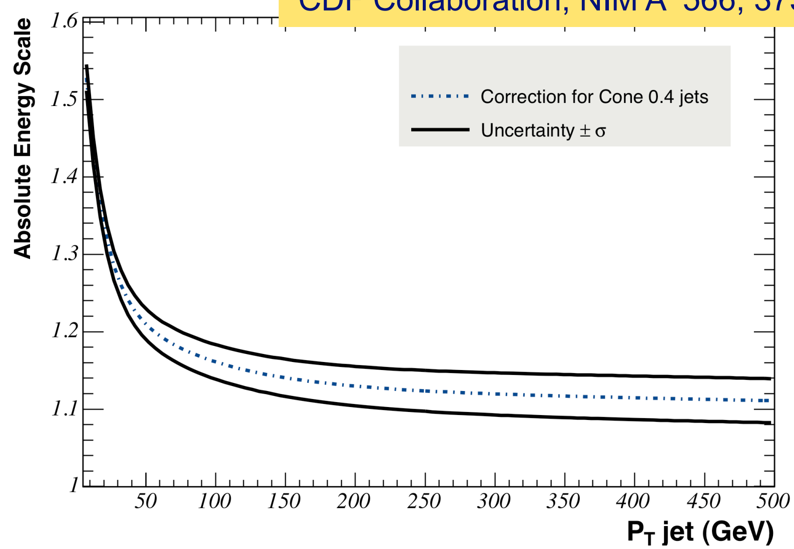
  - **Event vertex, jet quality and loose $S_{MET}$ (< 14)**
- **Resulted in 3621 events using jets with R=0.7**
  - **3136 events with R=0.4**



# Jet Mass Corrections

- **Corrected jet mass using standard jet corrections**
  - **Further correction needed for multiple interactions (MI)**
  - **Use Nvtx=1 and Nvtx>1 events to determine MI**

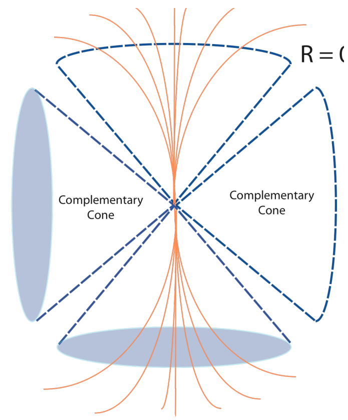
CDF Collaboration, NIM A 566, 375 (2006)

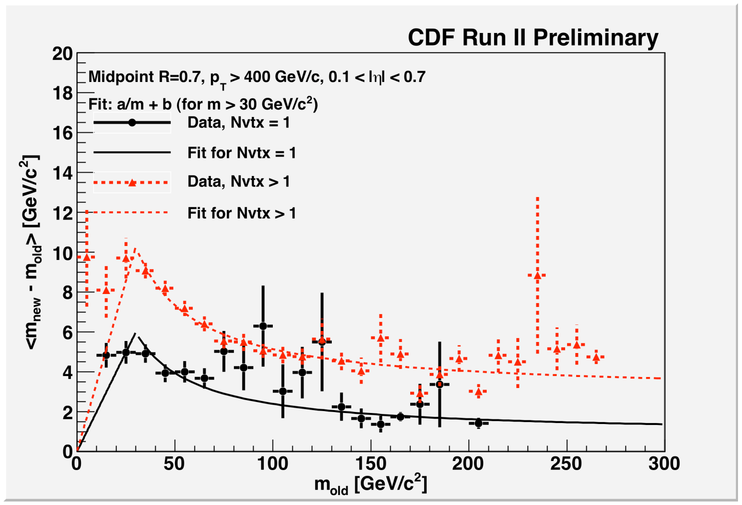



- **Investigated other effects:**
  - **Cluster merging**
  - **Effect of calorimeter inhomogeneity at η=0**
    - Varied pseudorapidity window – no significant changes in mass
  - **Calorimeter segmentation and jet recombination**
    - Varied position of towers (especially azimuth) and corrections for geometry
  - **Calorimeter response across face of jet**
    - Detailed study of tracking/calorimeter response in data and MC/detector simulation

# MI and UE Corrections

- Additional contribution from
  - Underlying Event (UE)
  - Multiple Interactions (MI)
    - Average # interactions 2-3
  - Corrected for MI
- Looked at purely dijet events
  - Defined cones (same size as jet) at 90° in azimuth (same η)
  - Took towers in cones, and added to jet in event
    - Mass shift, on average, same shift coming from UE and MI
- Separately measure $N_{vtx}$=1 events
  - Gives UE correction separately

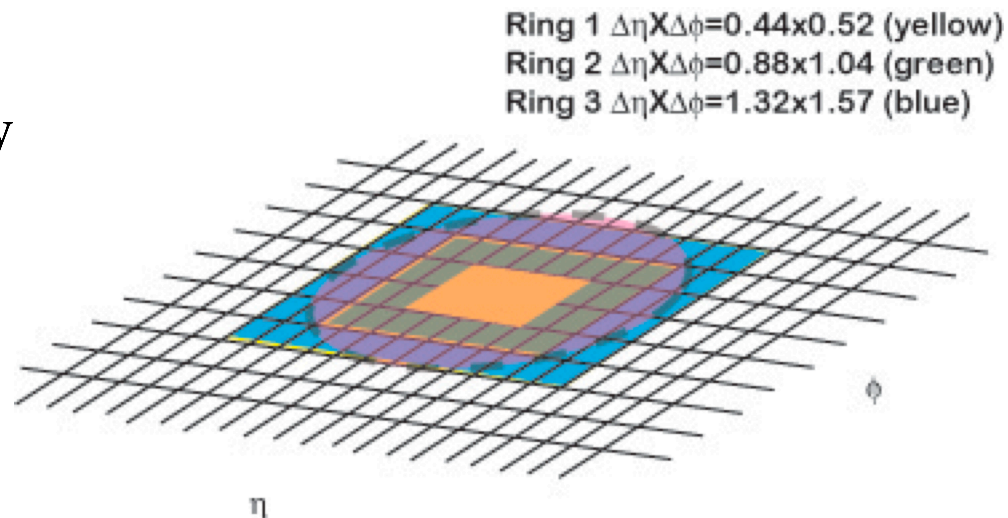


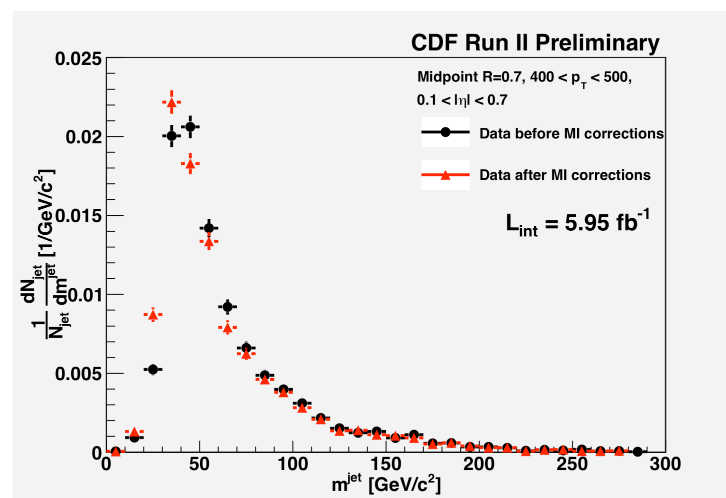




Correction scales as $R^4$

# Inter-Jet Energy Calibration

- **Jet mass arises from deposition of varying energy per tower**
  - **Performed study to compare momentum flow vs calorimeter energy internal to jet**
    - Defined 3 rings and compared observed pT/ET with simulation
- **Resulted in constraints on calorimeter relative response**
  - **At $m^{jet}$=60 GeV/$c^2$, $\sigma_m$=1 GeV/$c^2$**
  - **At $m^{jet}$=120 GeV/$c^2$, $\sigma_m$=9.6 GeV/$c^2$**
- **Largest source of systematic uncertainty**



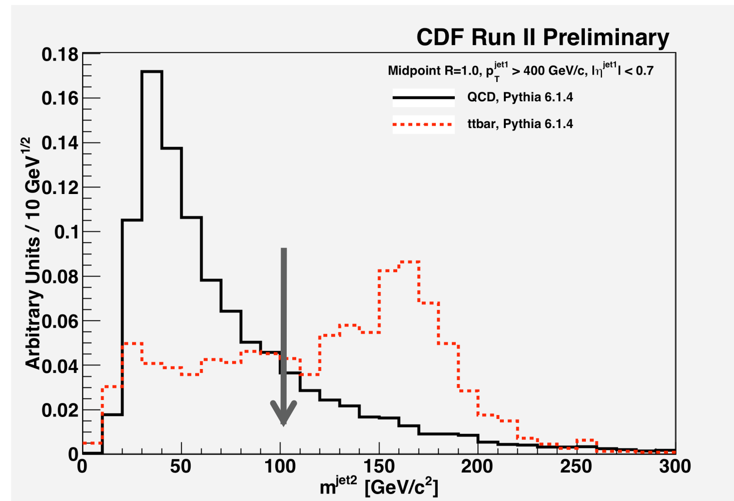



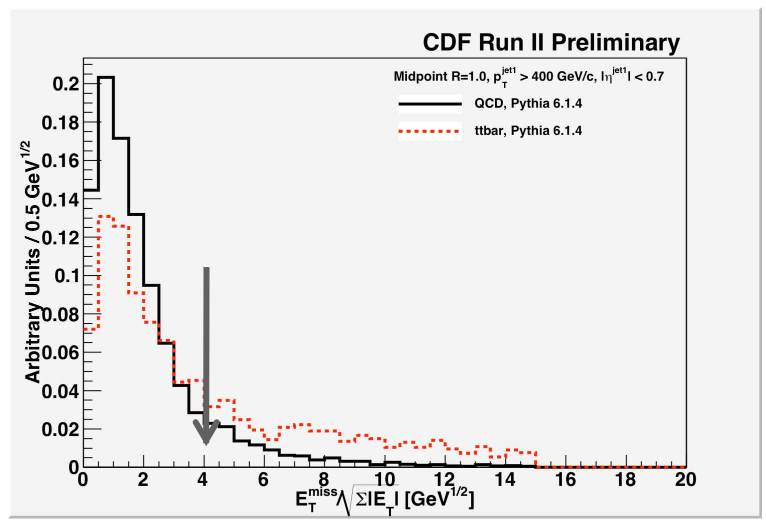
# Systematics on $m^{jet}$

- **Sources of systematics:**
  - **Calorimeter energy scale**
    - Varies from 1 to 9.6 GeV/$c^2$ for 65 to 120 GeV/$c^2$ mass jets
  - **UE and MI modelling**
    - Estimate 2 GeV/$c^2$ based on uncertainty in high mass correction
  - **Recombination scheme & calorimeter segmentation**
    - Estimate 2.2 GeV/$c^2$ based on comparison of offline and ntuple results
  - **PDF Uncertainties**
    - Used standard 20 eigenvector decomposition to assess MC uncertainties
- **Believes uncertainties on data are uncorrelated**
  - **Combined in quadrature, gives total jet mass uncertainty of**
    - 3.4 GeV/$c^2$ for $m^{jet}$ = 60 GeV/$c^2$
    - 10.5 GeV/$c^2$ for $m^{jet}$ > 100 GeV/$c^2$
- **Effects jet mass distributions arising from bin-to-bin migration**
  - **Don't see a systematic shift in other substructure variables**
  - **Still more detailed investigation underway**

# Reducing Top Contamination

- **Expect about 2.2 fb of high $p_T$ jets from top in sample**
  - **Eliminate by rejecting events with**
    - $m^{jet2} > 100$ GeV/$c^2$
    - Missing $E_T$ Significance ($S_{MET}$) > 4
  - **Use jet cone of R=1.0 for improving top jet tagging**
    - See clear peak in MC for second jet mass
  - **Lose 29% of jet candidates**
    - 2576 events using R=0.7 jets
    - 145 events with jet with $p_T$ > 500 GeV/c

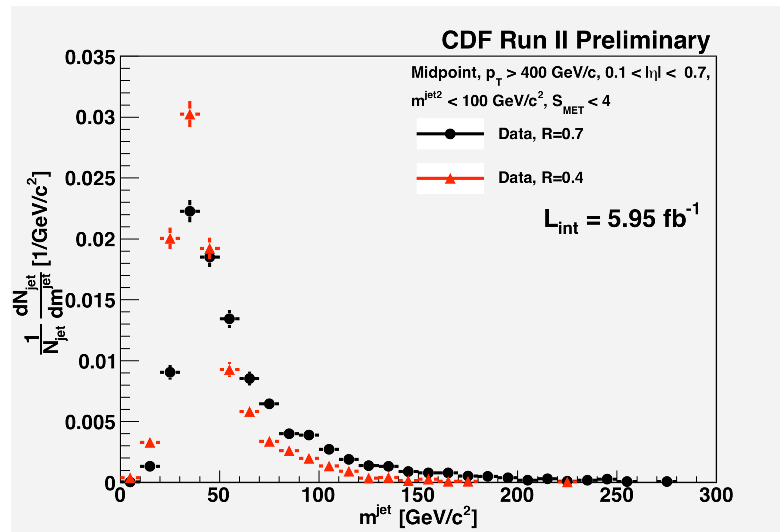



- **After top-rejection, expect ~0.5 fb of top jets**
  - **Comparable rates for W/Z jets**

# Focus on QCD Behaviour

- **After top rejection**
  - **Left with sample dominated by light quarks and gluon**
  - **Compare high mass region with QCD theory**
  - **Use cones of R=0.4 and R=0.7**

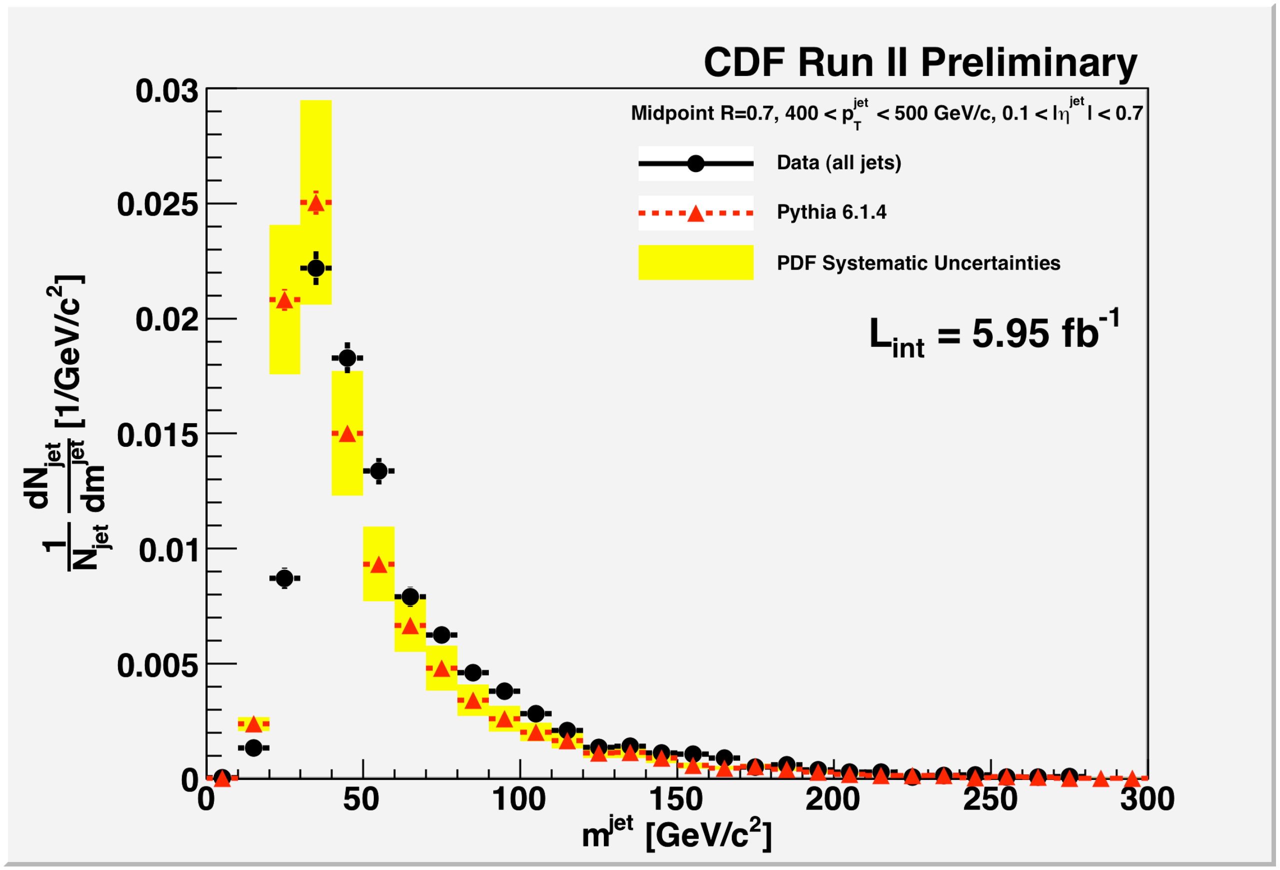



| Cut Flow | | |
|---|---|---|
| All Data, 5.95 $fb^{-1}$ | 75,764,270 events | |
| | **R = 0.4** | **R = 0.7** |
| At least one jet with $p_T$ > 400 GeV/c, \|η\| in (0.1, 0.7), and event quality cuts | 3136 events | 3621 events |
| $m^{jet2}$ < 100 GeV/$c^2$ and $S_{MET}$ < 4 (with $p_T^{jet2}$ > 100 GeV/c and MI corrections) | 2579 events | 2576 events |

- **Low-mass peak arises from non-perturbative QCD effects**
  - **Opportunity to study the properties of the high mass jets**
  - **Gilad will say more…**

# Comparison with PYTHIA

- **PYTHIA 6.1.4**
  - Standard CDF II QCD sample
  - PDF uncertainties based on eigenvector decomposition
- **Agreement is just "OK"**
  - Low-mass peak few GeV/$c^2$ lower
  - Systematic underestimate at higher masses

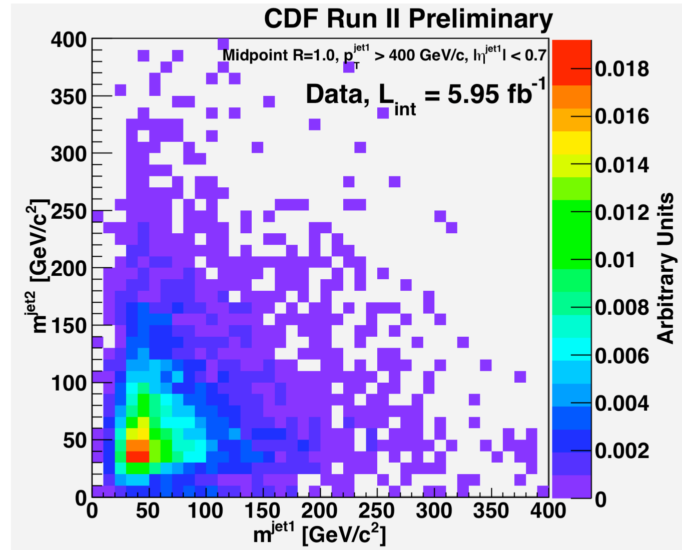


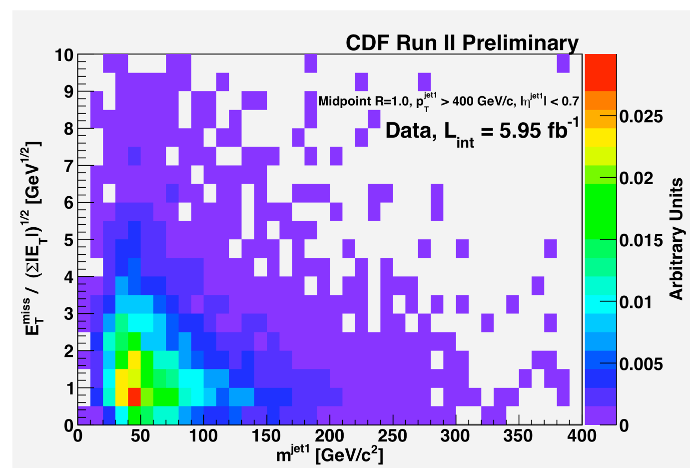
# What About Boosted Top?

- **Is it possible to detect top (or place meaningful upper limits)?**
- **Two topologies:**

  $\gamma \sim 2.5$

  1. **All hadronic**
     - Two massive jets recoiling ($\varepsilon$ ~15%)
  2. **Semi-leptonic (neutrino)**
     - Require $S_{MET} > 4$ ($\varepsilon$ ~ 10%)




- **MC predicts ~2.2 fb**
  - **Divided about 60:40 between topologies**
    - Highest efficiency channel for top (>20%)
  - **Important handles for background:**
    - masses of QCD di-jets not correlated
    - Jet mass and $S_{MET}$ not correlated
  - **Still to come….**

# Conclusions

- **First measurement of jet mass and substructure for high $p_T$ jets**
  - **Being confronted by data forces one to understand systematics**
    - Multiple interaction corrections
    - Calibration of mass scale
  - **Allows for test of QCD predictions:**
    - Jet mass
    - Angularity
    - Planar Flow
- **Next talk will show results for high mass jets**
- **Top counting experiment looks do-able**
  - **Does b-tagging help? We're trying it out….**
  - **Need to assess systematics**
- **Next steps:**
  - **Compare results with anti-kT clustering**
  - **Compare predictions of Sherpa Monte Carlo calculation**
  - **More work on systematics**
    - Currently limited by MC statistics and time

# BACKUP SLIDES

# MI/UE Corrections

- Looked at how to make MI correction in a variety of ways
  - Looked at mass corrections event-by-event
  - But statistical fluctuations large, event-to-event
  - Chose to develop a parametrized correction
- Note that:

$$\delta m^{jet} \simeq \frac{E_{tower} E_{jet} \Delta R}{m^{jet}}$$

- Expect MI correction to scale with $R^4$:
  - Exactly what we see when comparing R=0.4 and R=0.7
- PYTHIA UE agrees well with data – same UE mass correction
- Use that to scale corrections for R=1.0
  - Method doesn't work with larger cone because of overlap

# Internal Jet Energy Scale

- Overall jet energy scale known to 3%
  - The relative energy scale between rings known to 10-20%, depending on ring
  - Use this to constrain how far energy scale can shift
- Do first for $m^{jet} \sim 60$ GeV/$c^2$ – use average jet profile
  - Extract from that a limit on how much "Ring 1" energy scale can be off - ± 6%
  - Then do the same for mjet ~ 120 GeV/$c^2$
- Resulting systematic uncertainty is 9.6 GeV/$c^2$
  - Conservative estimate – used a very broad energy profile
    - No localized substructure assumed
- Take this as systematic uncertainty
  - Could constrain it better using single particle response
  - Note that fixed cone size is an advantage here

# Reconstruction of Top

- Leading jet in ttbar events has clear top mass peak
  - All events between 70 and 210 GeV/$c^2$ for R=1.0
  - See clear W peak
    - B quark jet presumably nearby in those cases
  - Clear that higher mass cut gives greater QCD rejection
  - Much optimization to do
- B tagging not yet used
  - Now investigating what its impact will be
  - Will need to assess efficiencies and mis-tagging rates