Massive High P_T Jets: Updates from CDF

Outline

1. Introduction and Motivation
2. Data Selection
3. Calibrating and Correcting Jet Observables
4. Systematic Uncertainties
5. Algorithm Dependencies
6. Next Steps

Representing CDF Collaboration

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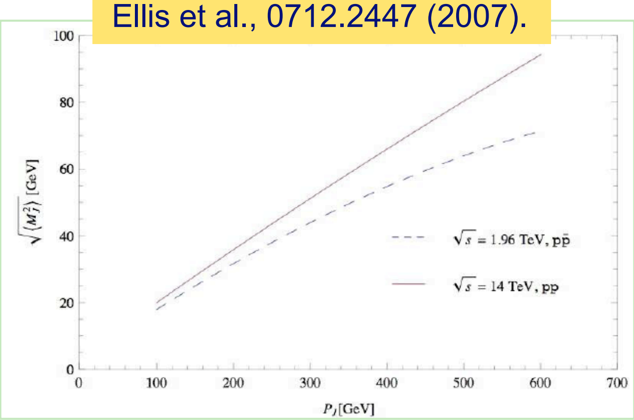
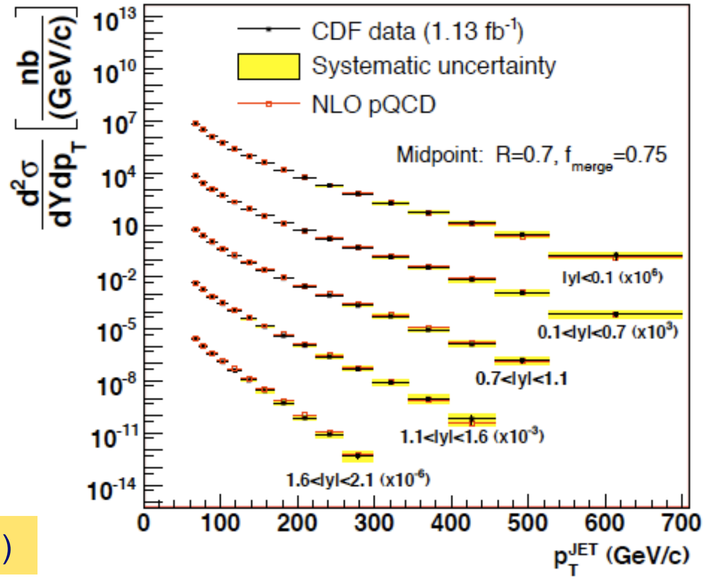
Study Motivation

- **Mass of high-p_T jets important property – but mostly 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 ~9 fb^{-1}**
  - **Have several thousand jet candidates**
  - **Opportunity for 1stsystematic study of jet mass, other substructure observables**



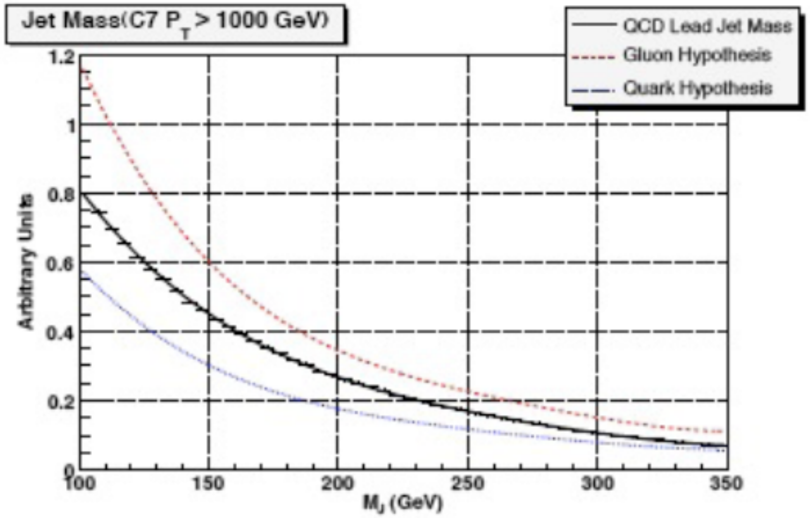
Ellis et al., 0712.2447 (2007).



CDF Collaboration, PRD 78, 052006 (2008)

NLO QCD Predicts Jet Function

- **Expect high mass jets arise primarily from 1-gluon radiation**



$$\frac{\sigma}{dp_T\, dm^{jet}} \quad J^{q,g}(m^{jet}, p_T, R)\frac{d\hat{\sigma}}{dp_T}$$

$$J^{q,g}(m^{jet}, p_T, R) \cong \alpha_s\left(m^{jet}\right)\frac{4C^{q,g}}{\pi m^{jet}}\log\left(Rp_T / m^{jet}\right)$$

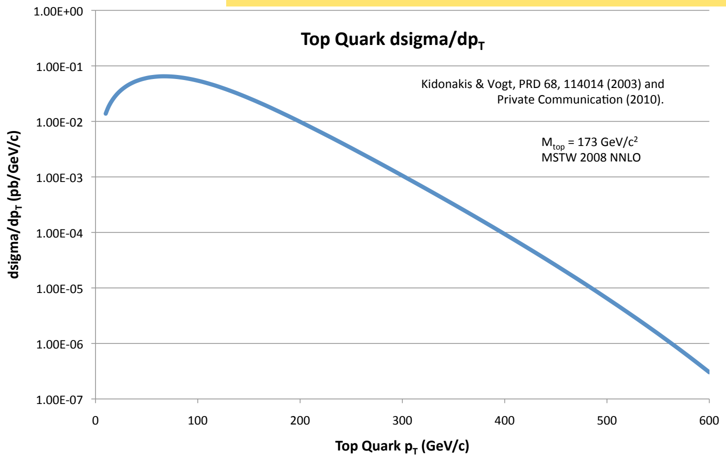
Alemeida, et al. 0810.0934

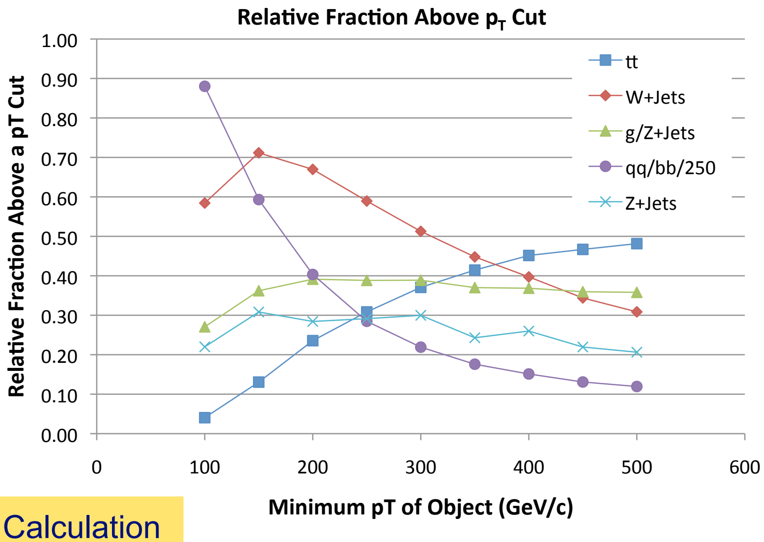
  - **Robust NLO prediction for**
    - Shape of high mass tail (and quark/gluon difference)
    - Relative rate of high mass QCD jets

Boosted Objects at Tevatron

- SM sources for high-p_T objects calculable
  - Dominated by light quarks & gluons
- Expect other contributions
  - Fraction of top quarks ~1.5% for $p_T > 400$ GeV/c
    - Total rate 4.45±0.5 fb (Kidonakis & Vogt)
    - PYTHIA 6.216 rate is 6.4 fb (scaling total cross section to measured world average)
  - Expect W/Z production of similar order

Kidonakis & Vogt, PRD 68, 114014 (2003)

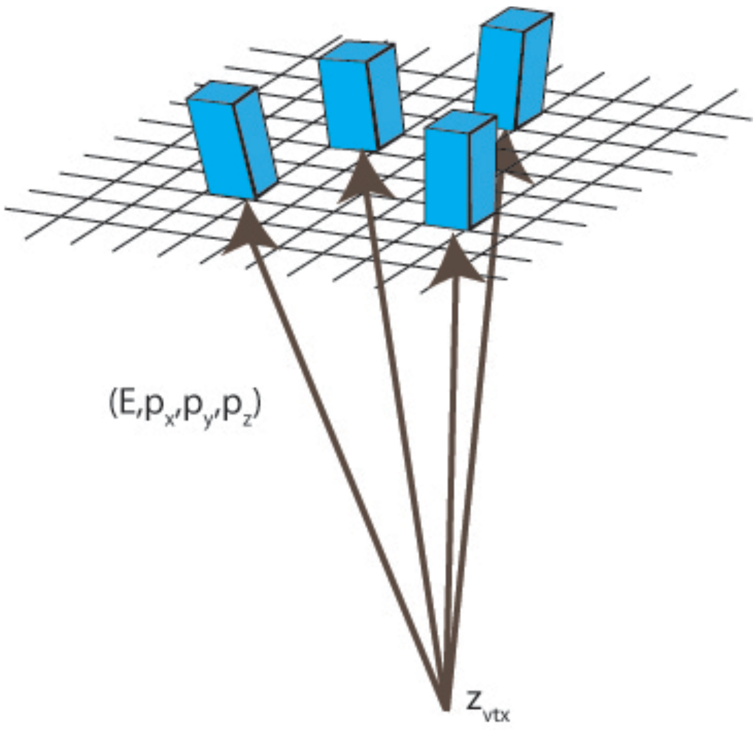




PYTHIA 6.4 Calculation

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**
  - **Compare results with anti-k_T and Midpoint with "search cones" (Midpoint/SC)**

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

Jet Algorithms

- Cone algorithms used for most Tevatron studies
  - Long history – quite separate from e^+e^- work
  - JetClu was CDF reference
    - Required "seed" to initiate
    - Significant IRC sensitivity
- Midpoint developed to reduce IRC sensitivity
  - Use seeds, but then recluster with seeds "midway" between all jets

Use Fastjet Framework!

M. Cacciari, G.P. Salam and G. Soyez,
Phys. Lett. B641, 57 (2006) [hep-ph/0512210].

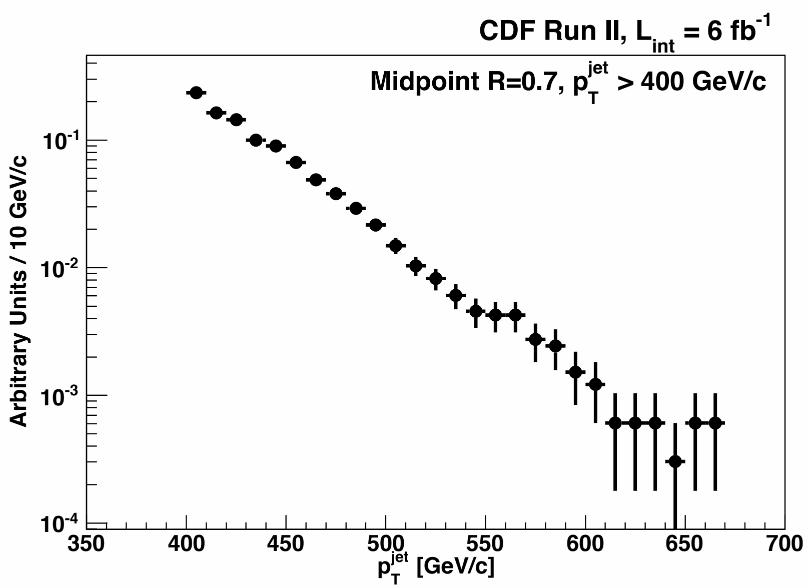
- Cone algorithms had "dark tower" problem
  - Unclustered energy due to split/merge/iteration procedure
  - Proposed solution: Midpoint with "search cones"
    - Find jets with cone size R/2
    - Fix jet direction, cluster with size R
  - Midpoint/SC was used for various studies 2006-2008
- Anti-k_T algorithm developed
  - No IR sensitivity
  - Still retained many of the benefits of a "cone" algorithm

Data Selection

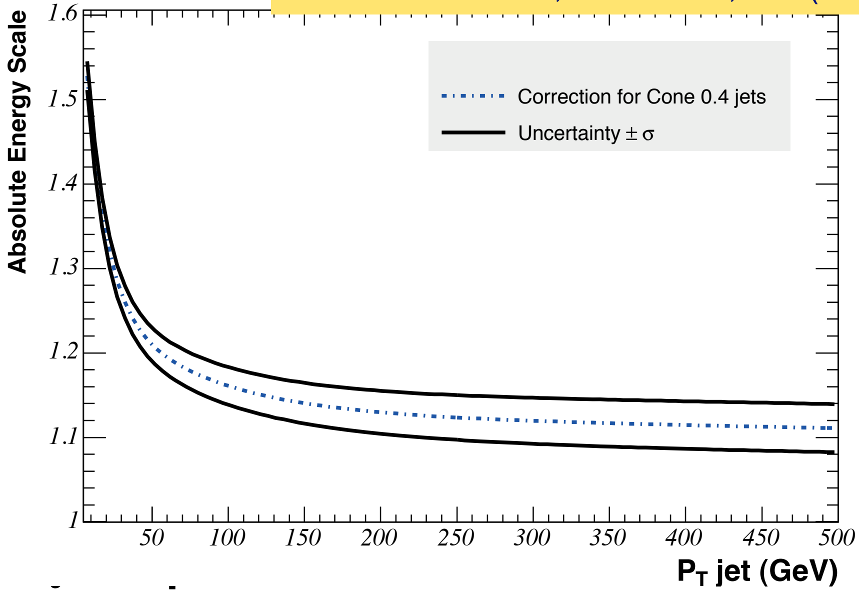
- **Analyzed inclusive jet sample**
  - **Trigger requires $E_T > 100$ GeV**
  - **Analyzed 5.95 fb^{-1} sample**
- **Selected data with focus on high p_T objects**
  - **Kept any event with**
    - Jet with $p_T > 300$ GeV/c and $|\eta| < 0.7$
    - Used cones of R=0.4, 0.7 and 1.0
- **Processed 76M events**
  - **Selected subsample with**
    - $p_T > 400$ GeV/c
    - $|\eta| \in (0.1, 0.7)$
- **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 2700 events using jets with R=0.7**



Jet Mass Corrections

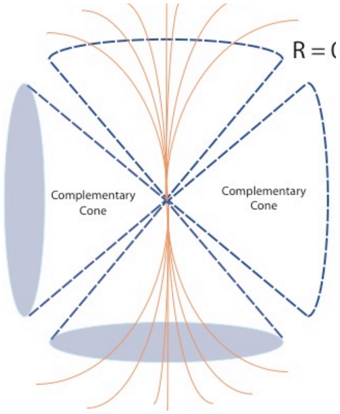


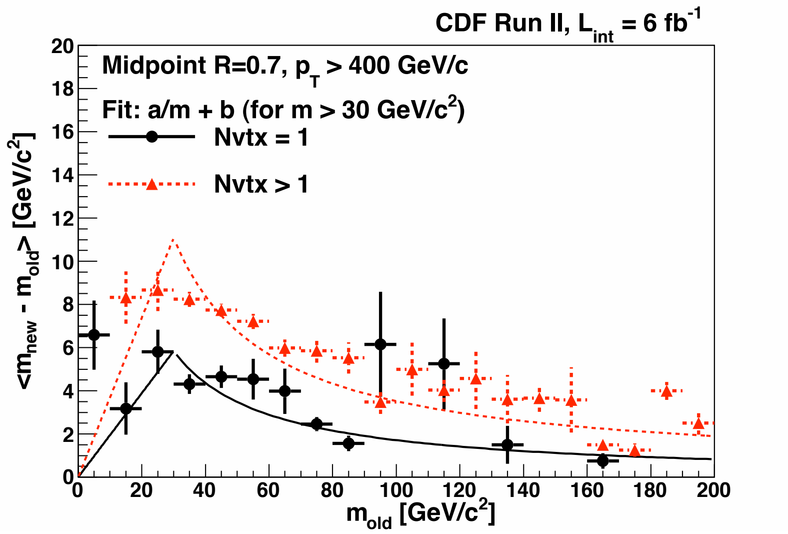
CDF Collaboration, NIM A 566, 375 (2006)

- **Corrected jet mass using standard jet corrections**
  - **Further correction needed for multiple interactions (MI)**
  - **Use N_{vtx}=1 and N_{vtx}>1 events to determine MI effect**
- **Investigated other effects:**
  - **Effect of calorimeter inhomogen**
    - 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
  - **Jet energy scale vs algorithm (Midpoint, Midpoint/SC, anti-k_T)**
    - Saw < 1 % difference

Effects of MI and UE

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

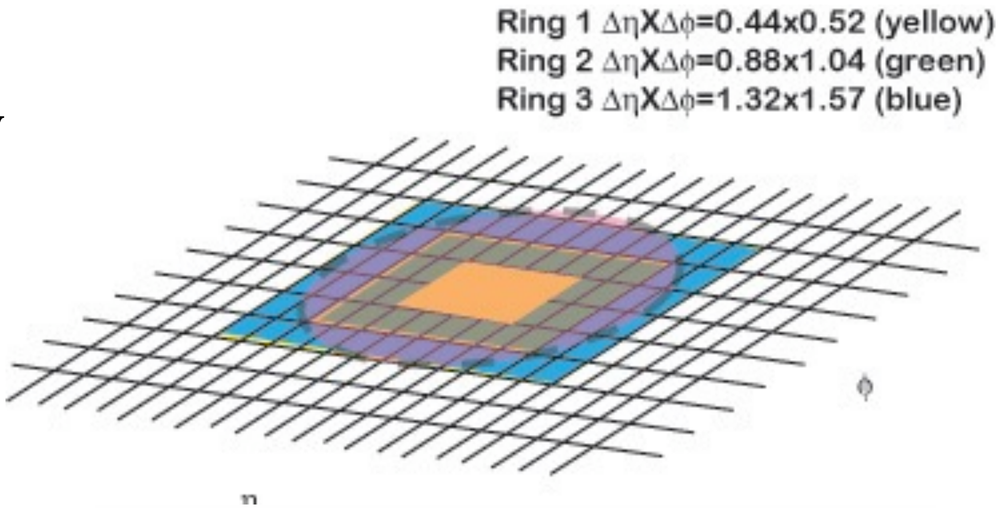


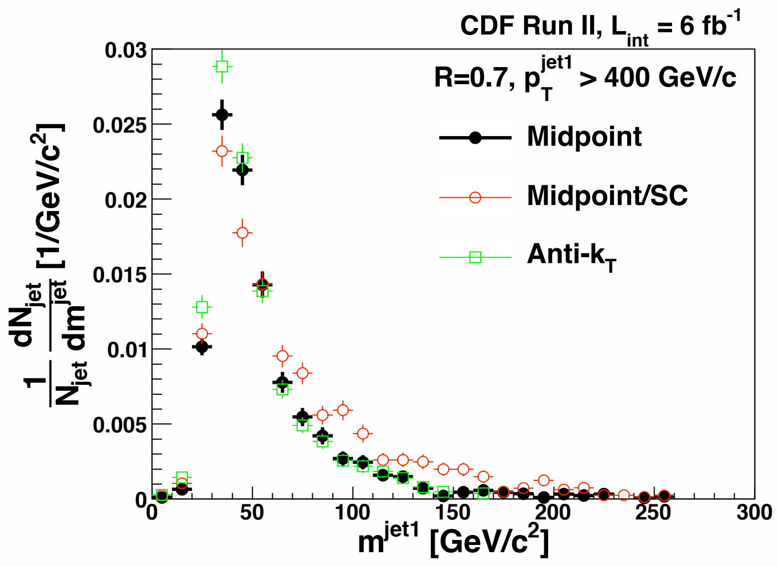


Correction scales as R^4

Inter-Jet Energy Calibration

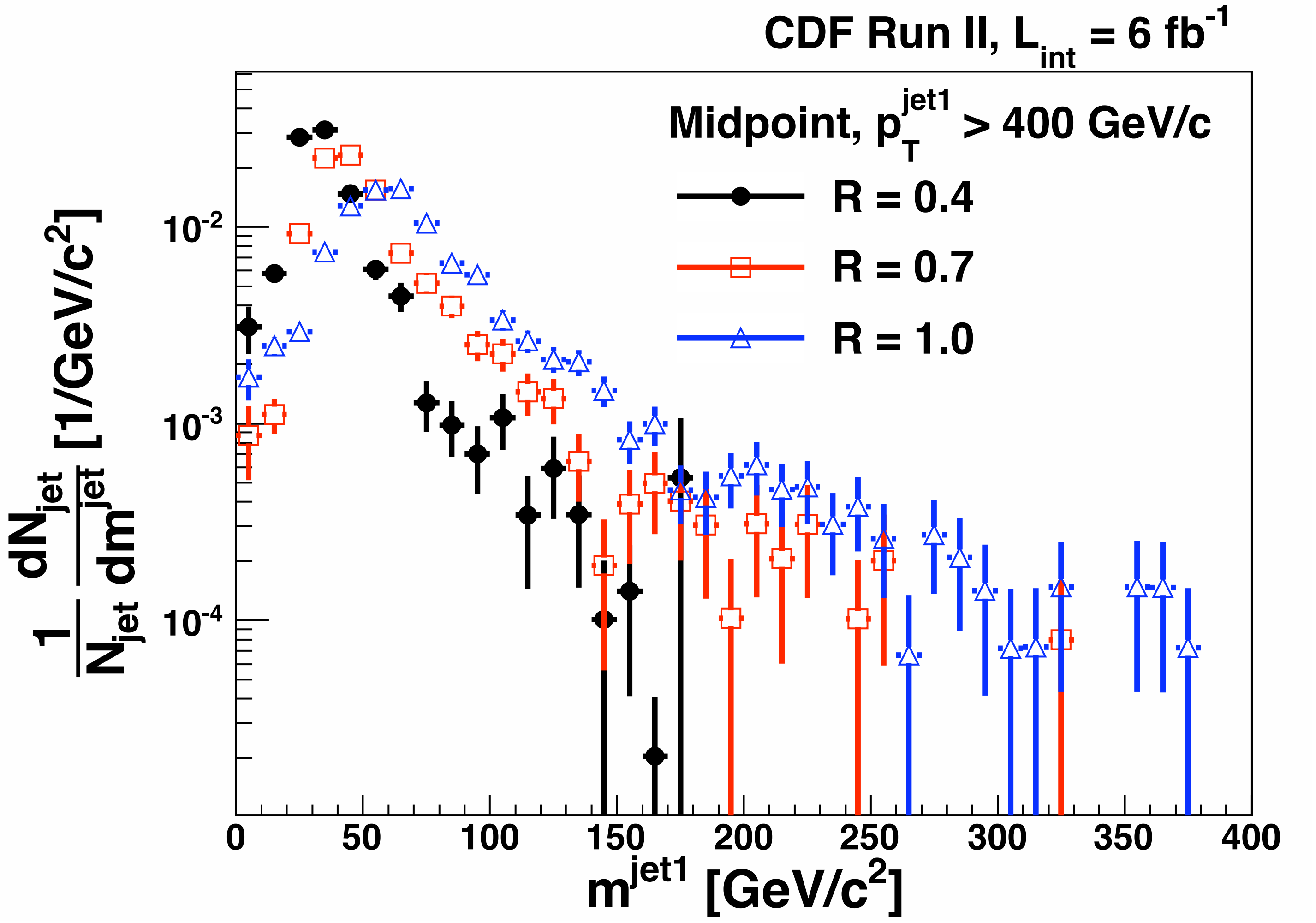
- **Jet mass arises from deposition of varying energy per tower**
  - **Performed study to compare momentum flow vs calorimeter energy internal to jet**
    - Defined 3 rings and compared observed p_T/E_T with simulation
- **Resulted in constraints on calorimeter relative response**
  - **At m^{jet}=60 GeV/c^2, σ_m=1 GeV/c^2**
  - **At m^{jet}=120 GeV/c^2, σ_m=10 GeV/c^2**
- **Largest source of systematic uncertainty**





Comparison with Cone Size

- **Compare**
  - ○ R=0.4
  - ○ R=0.7
  - ○ R=1.0



Systematics on m^{jet}

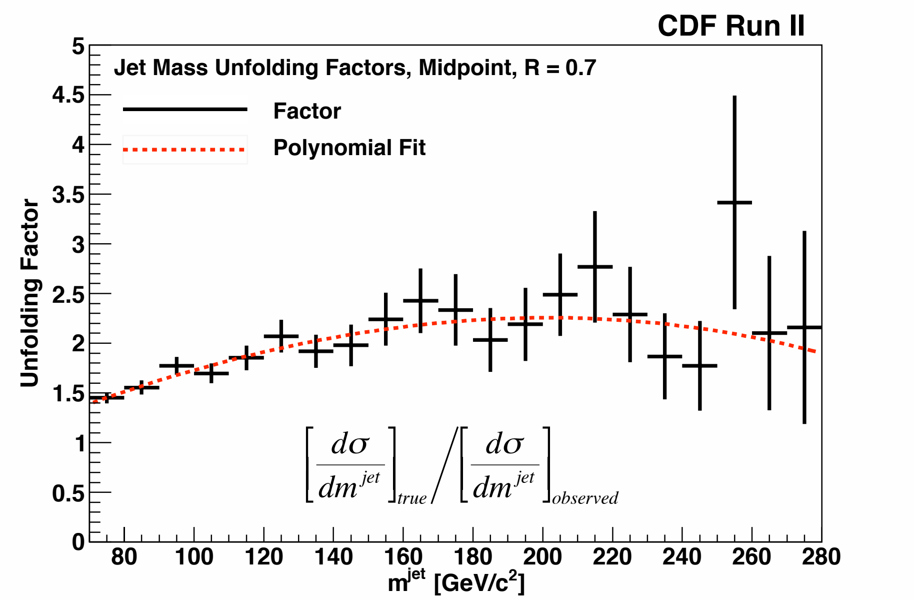
- **Sources of systematics:**
  - **Calorimeter energy scale**
    - Varies from 1 to 10 GeV/c^2 for 65 to 120 GeV/c^2 mass jets
  - **UE and MI modelling**
    - Estimate 2 GeV/c^2 based on uncertainty in high mass correction
  - **PDF Uncertainties**
    - Used standard 20 eigenvector decomposition to assess MC uncertainties
    - Shown when direct comparison made with PYTHIA 6.216
- **Uncertainties are uncorrelated**
  - **Combined in quadrature, gives total jet mass uncertainty of**
    - 3.4 GeV/c^2 for m^{jet} = 60 GeV/c^2
    - 10.2 GeV/c^2 for $m^{jet} >$ 100 GeV/c^2
- **Effects jet mass distributions arising from bin-to-bin migration**
  - **Small systematic shifts in other substructure variables**
  - **Determined using 90° cone approach (see G. Perez's talk)**

Determining Jet Function

- Key prediction is “jet function”

$$J^{q,g}(m_{jet},p_T,R) \cong \alpha_s\left(m_{jet}\right)\frac{4C^{q,g}}{\pi m_{jet}}\log\left(Rp_T/m_{jet}\right)$$

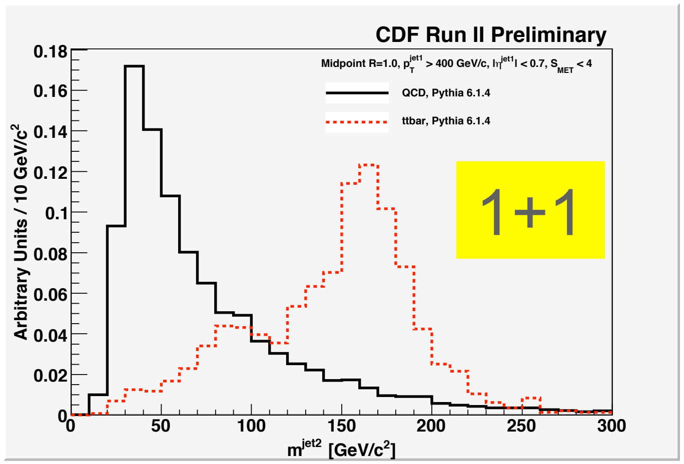
  - Just m^{jet} distribution?
- However, large correction comes from jet p_T cut
  - p_T of low mass jets has ~10% broader resolution than high mass jets
  - More events in sample with true $p_T < 400$ GeV/c at low m_{jet} vs high m_{jet}
    - Aggravated by much larger rate at low jet mass

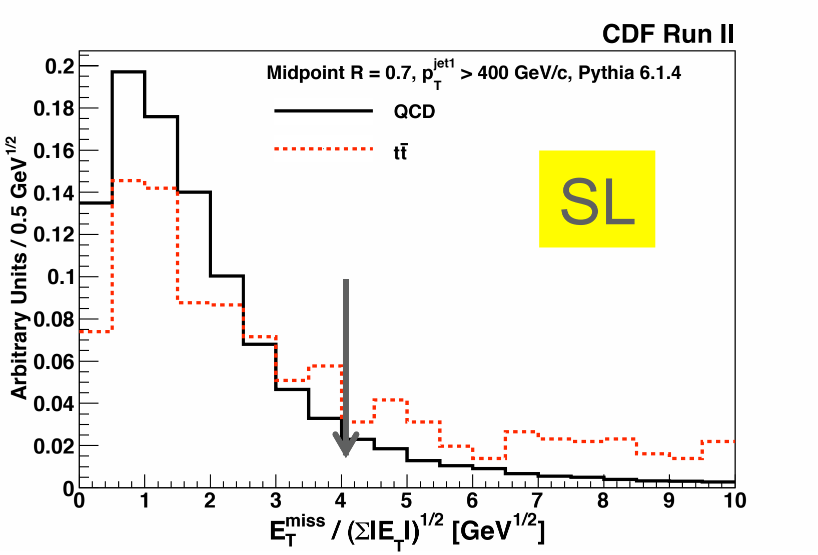


- Verified by studies of recoil jet
  - No intrinsic p_T bias
- Calculated correction with MC
  - Hadronization uncertainty 10%

Reducing Top Contamination

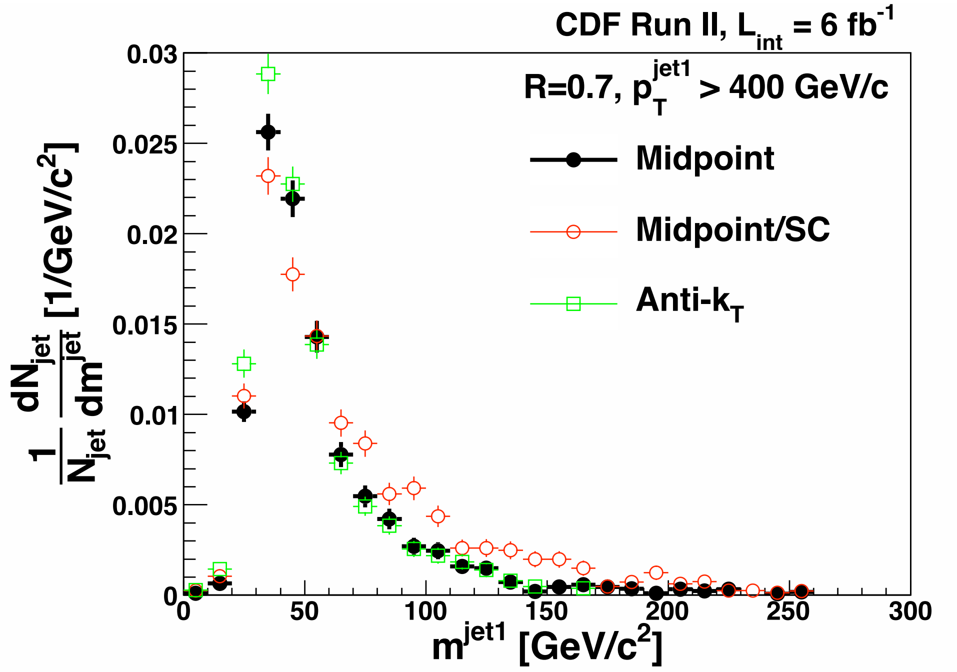
- **Expect about 1.6 fb of high p_T jets from top in sample**
  - **Eliminate by rejecting events with**
    - $m^{jet2} > 100$ GeV/c^2
    - Missing E_T Significance (S_{MET}) > 4
  - **Use jet cone of R=1.0 for improving top jet tagging**
  - **Lose 28% of jet candidates**
    - 2576 events using R=0.7 jets
    - 145 events with jet with $p_T > 500$ GeV/c
- **After top-rejection, expect ~0.3 fb of top jets**
  - **Comparable rates for W/Z jets**





Properties of QCD Jet Sample

- **After top rejection**
  - **Left with sample dominated by light quarks and gluon**
  - **Compare high mass region with QCD theory**
  - **Algorithm dependence?**
    - Midpoint and anti-k_T very similar
    - Midpoint/SC quite different

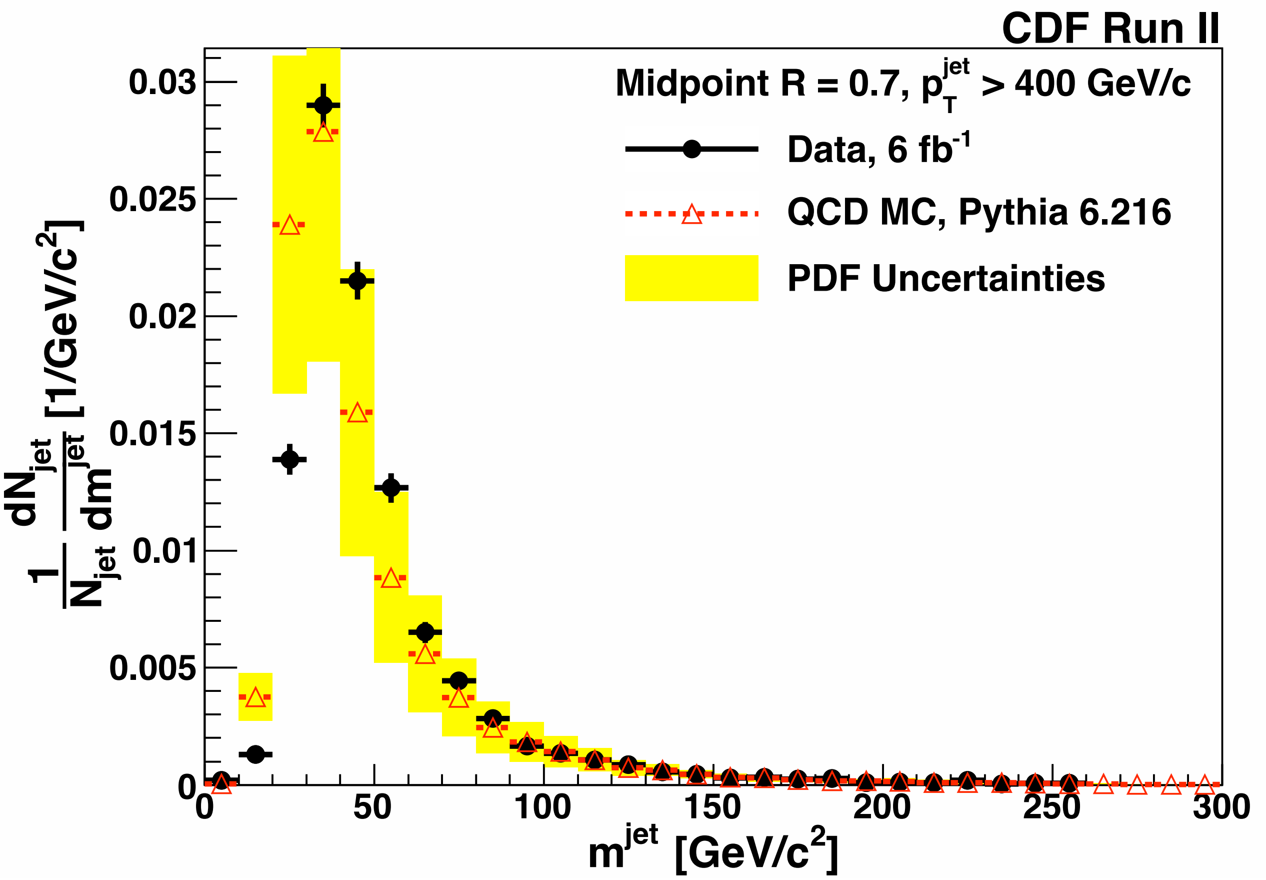


Cut Flow		
All Data, 5.95 fb^{-1}	75,764,270 events	
	R = 0.4	**R = 0.7**
At least one jet with $p_T > 400$ GeV/c, $\|\eta\|$ in (0.1, 0.7), and event quality cuts	2153 events	2700 events
$m^{jet2} < 100$ GeV/c^2 and $S_{MET} < 4$ (with $p_T^{jet2} > 100$ GeV/c and MI corrections)	1837 events	2108 events

- **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 6.216**
  - Standard CDF II QCD sample
  - PDF uncertainties based on eigenvector decomposition
- **Agreement is reasonable**
  - Low-mass peak few GeV/c^2 lower
  - Large PDF uncertainties at low mass

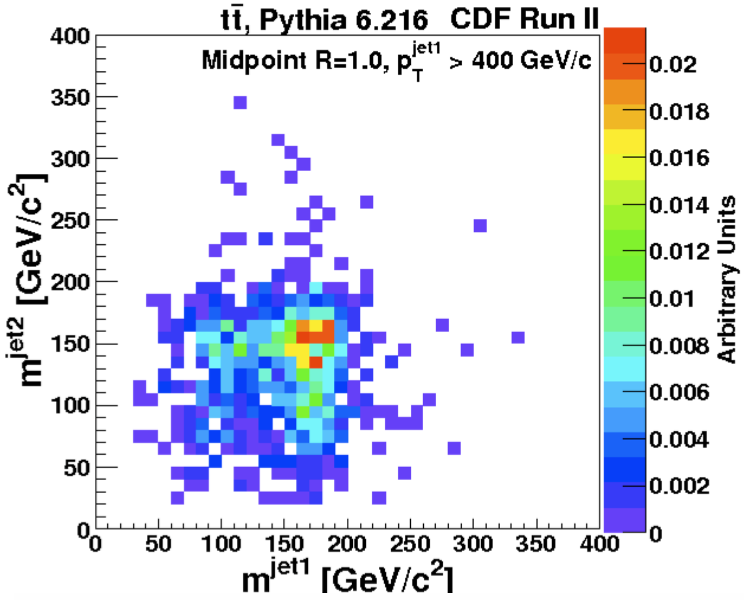


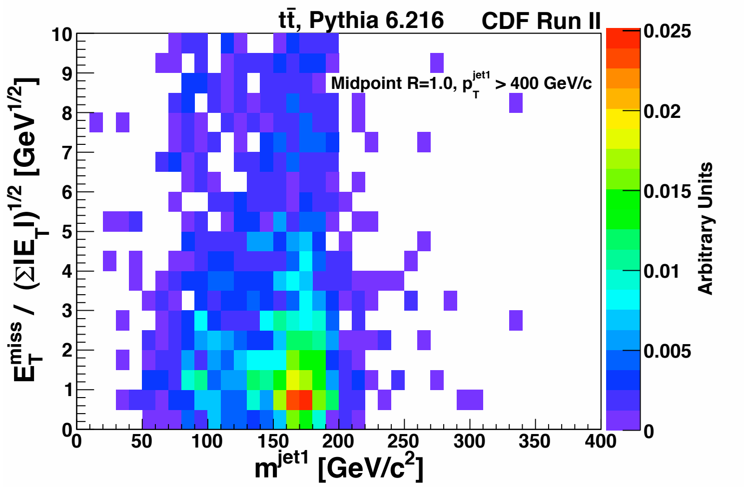
Search for Boosted Top

- **Analysis suggests sensitivity to boosted top**

$\gamma \sim 2.5$

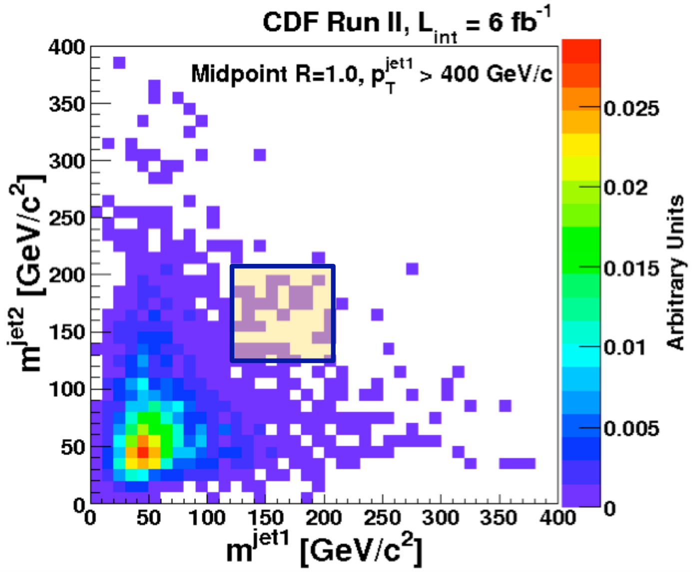
- **Two topologies:**
  1. **All hadronic ("1+1")**
     - Two massive jets recoiling ($\varepsilon \sim 11\%$)
  2. **Semi-leptonic decay ("SL")**
     - Require $S_{MET} > 4$ ($\varepsilon \sim 7\%$)
- **MC predicts ~0.8 fb**
  - ○ **Divided about 60:40 between topologies**
    - Highest efficiency channel for top (~18%)
  - ○ **Important handles for background:**
    - masses of QCD di-jets not correlated
    - Jet mass and S_{MET} not correlated

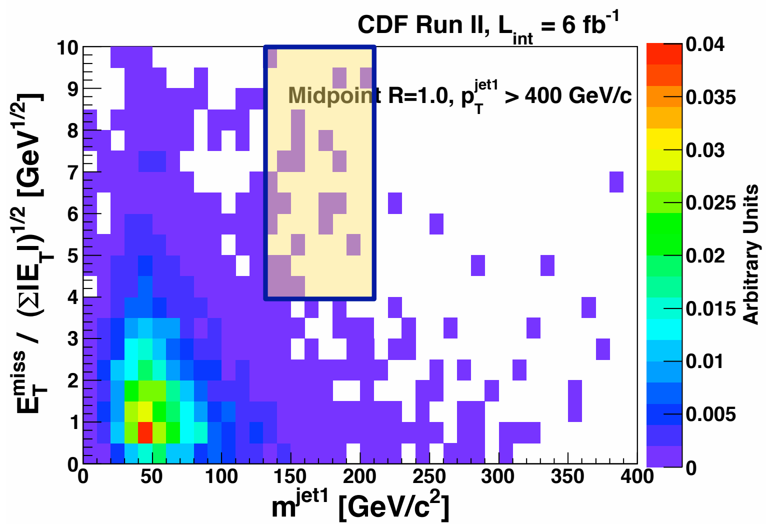




Strategy for Detecting Top

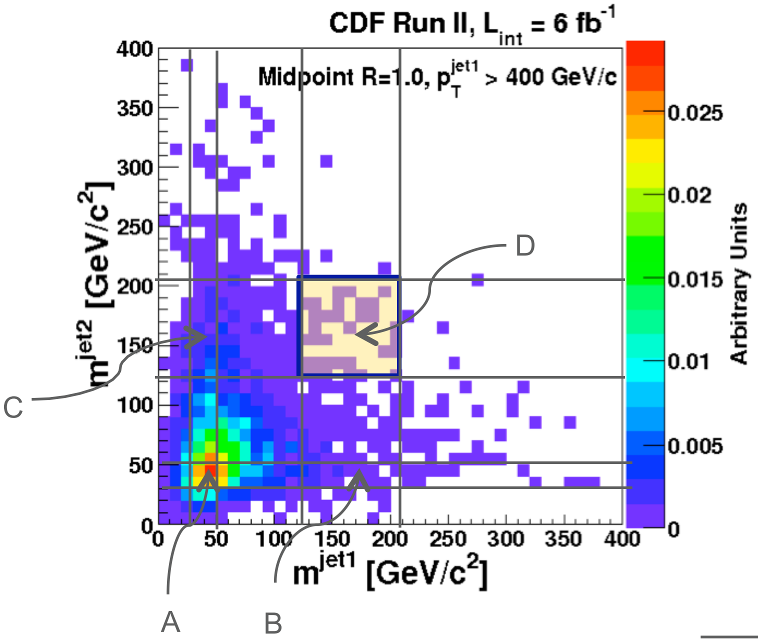
- **Keep selection simple**
    - Focus on two separate channels
- **All Hadronic Top (1+1)**
    - Require 2 jets with $130 < m^{jet} < 210$ GeV/c^2
    - Require $S_{MET} < 4$
    - Estimate background using "ABCD" technique
- **Semi-leptonic top**
    - Require $4 > S_{MET} > 10$
    - Require 1 jet with $130 < m^{jet} < 210$ GeV/c^2
    - Estimate background using "ABCD" technique





Best “Simple” Counting of 1+1

- With R=1.0 cones, m^{jet1} and m^{jet2} are equally powerful
  - Use jet mass (130,210) GeV/c^2 to define ttbar candidates
  - Expect 3.0±0.8 top quark events to populate this region

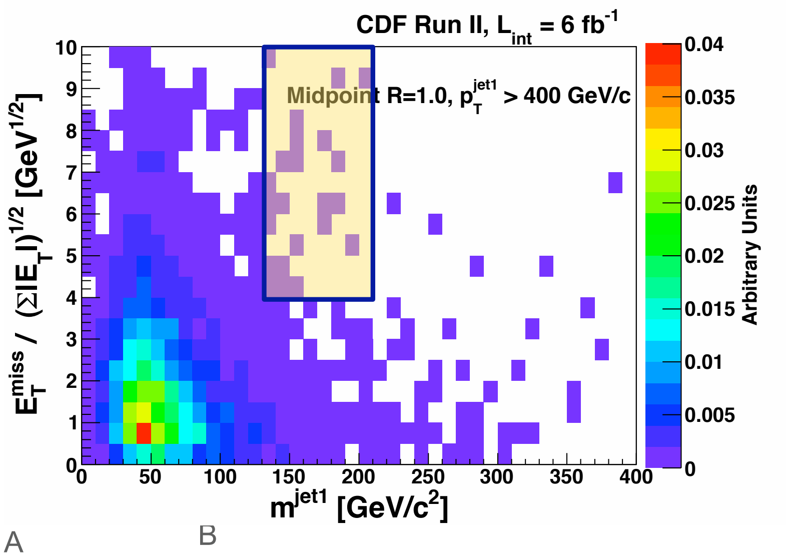


- Employ data to estimate backgrounds
  - Define mass windows
    $m^{jet} \in (130,210)$ GeV/c^2
    $m^{jet} \in (30,50)$ GeV/c^2
    - Use fact that m^{jet} distributions uncorrelated for background
    - Signal is region D
    - In “1+1” sample, predict 13±2.4 (stat) bkgd events
      - Observe N_D=32 events

$$N_D^{Pred} = N_C \left[\frac{N_B}{N_A} \right]$$

Best "Simple" Counting for SL

- In case of recoil semileptonic top, use m^{jet1} and S_{MET}
  - Assumption is the S_{MET} and m^{jet1} are uncorrelated
  - Expect 1.9±0.5 top quark events to populate this region



- Employ data to estimate backgrounds
  - Use regions $m^{jet1} \in (30,50)$ & (130,210) GeV/c^2
  - $S_{MET} \in (2,3)$ & $S_{MET} \in (4,10)$
    - In "SL" sample, predict 31±8 (stat) bkgd events
      - Observe N_D=26 events
      - About a -0.6 σ deficit!

Region	m^{jet1} (GeV/c^2)	S_{MET} ($\sqrt{GeV/c^2}$)	Data (Events)	MC (Events)
A	(30, 50)	(2, 3)	256	0.01
B	(130, 210)	(2, 3)	42	1.07
C	(30, 50)	(4, 10)	191	0.03
D (signal)	(130, 210)	(4, 10)	26	1.90
Predicted QCD in D			31.3 ± 8.1	

Uncertainties

- Background uncertainty (±10.2 GeV/c^2 jet mass scale)
  - ±30% uncertainty
- Uncertainties on top efficiency (SM production)
  - Primarily jet energy scale of ±3% on pT -> ±25% on σ
- Background statistics
  - ±11% from counting
- Luminosity
  - ±6% on integrated luminosity
- MC m^{top} (±2 GeV/c^2)
  - ±0.3%
- Overall uncertainties added in quadrature
  - ±41% overall
- Incorporated into upper limit calculation
- Use a CL_s frequentist method
  - Marginalize nuisance parameters
  - Same as used in Higgs and single top searches

Top Quark Cross Section Limit

- **Assume we observe signal + background**
  - **Set upper limit on SM production σ for top quark with $p_T > 400$ GeV/c**
- **Observe 58 events with 44+/-8 background**
  - **Calculate 95% CL upper limit using CL_s method**
    - Systematic uncertainties incorporated a la CDF 8128 (T. Junk)
    - $N_{LIM} = 43.3$ events
  - **Efficiency from MC**
    - 452 & 283 ttbar expected in 2 channels (out of 4041 MC events)
    - Efficiency = 0.182
- **Upper limit on cross section for $p_T > 400$ GeV/c**

$$\sigma_{95\%} = \frac{N_{LIM}}{\int L\,dt\;\varepsilon}$$

$$= \frac{43.3}{(5.95)(0.182)} = 40 \text{ fb}$$

- **Can also set limit on 1+1 only**
  - **Assume massive (m ~ mtop) object, pair-produced, decaying hadronically**
  - **Include SM top as background**

$$\sigma_{95\%} = \frac{N_{LIM}}{\int L\,dt\;\varepsilon}$$

$$= \frac{30.2}{(5.95)(0.254)} = 20 \text{ fb}$$

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**
  - **Algorithm dependence**
    - Anti-k_T and Midpoint very similar
    - Midpoint/SC produces "fatter" jets
- **Next talk will show substructure results**
- **Search for boosted top possible**
  - **Achieve**

$$S/\sqrt{B} \approx 0.75$$

  - **Set $\sigma < 40$ fb at 95% CL**
  - **Limited by statistics!**
- **Real task is to observe at LHC**
  - **Tevatron program will end 2011**
  - **ATLAS and CMS already have comparable sized samples with 50 pb^{-1}**
  - **Much higher p_T jets already!**

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:

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

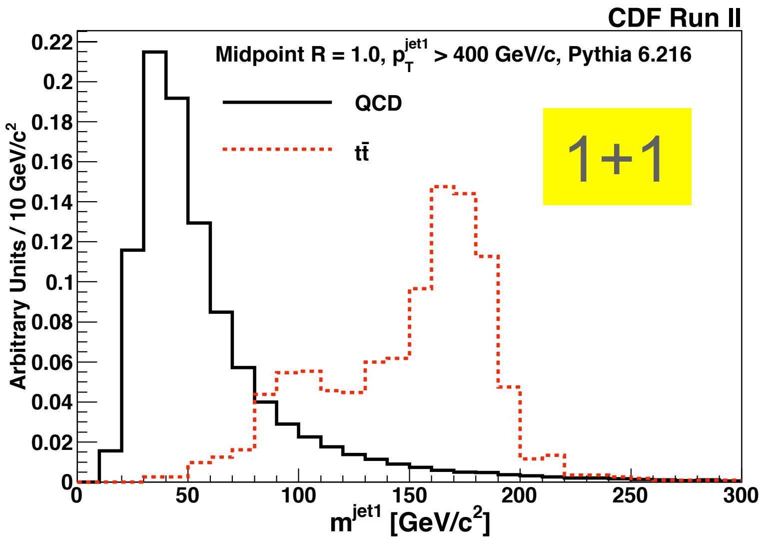
- Expect MI correction to scale with R^4:
  - Exactly what we see when comparing R=0.4 and R=0.7
- PYTHIA UE agrees well with data – same UE mass correction
- Use that to scale corrections for R=1.0
  - Method doesn't work with larger cone because of overlap

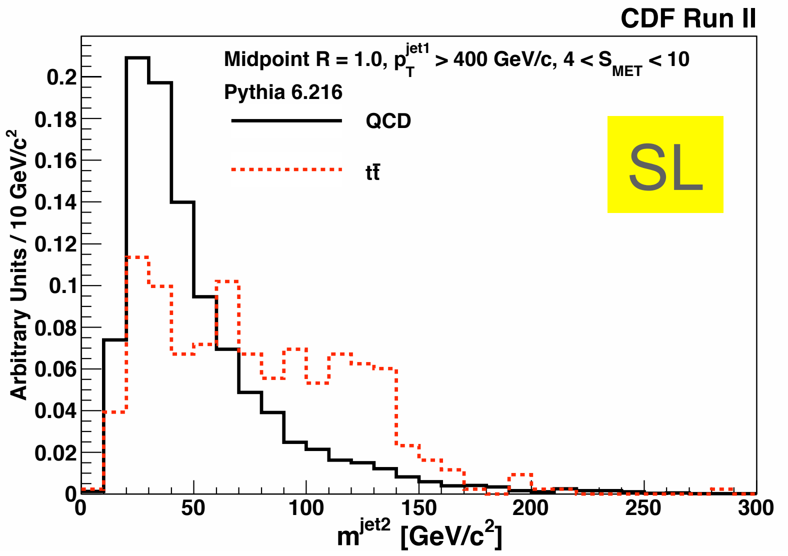
Internal Jet Energy Scale

- 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

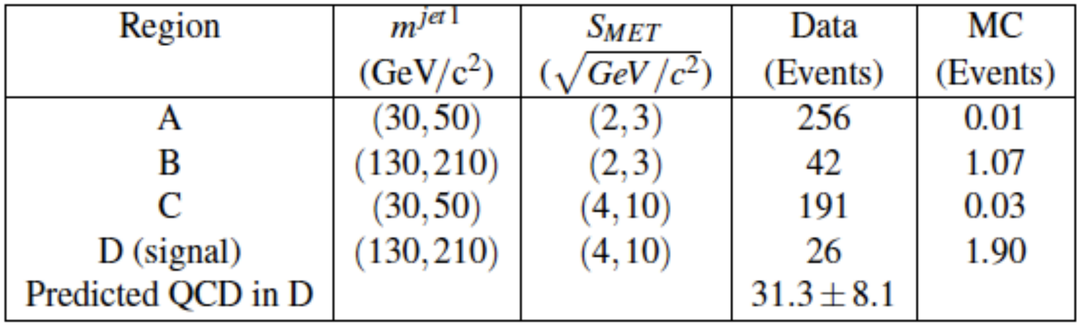
- **Leading jet in ttbar events has clear top mass peak**
  - **All events between 70 and 210 GeV/c^2 for R=1.0**
  - **See evidence of W peak**
    - B quark jet presumably nearby in those cases
  - **Clear that higher mass cut gives greater QCD rejection**
    - But also start to lose efficiency
  - **S_{MET} cut effectively identifies semi-leptonic decays (8%)**
- **B tagging not used**
  - **Can estimate mis-tags using data -> ~0.05%/jet**
  - **But large uncertainty in tagging efficiency in high pT jets**





Background Calculations

- **Background calculations used "ABCD" technique**
- **SL**



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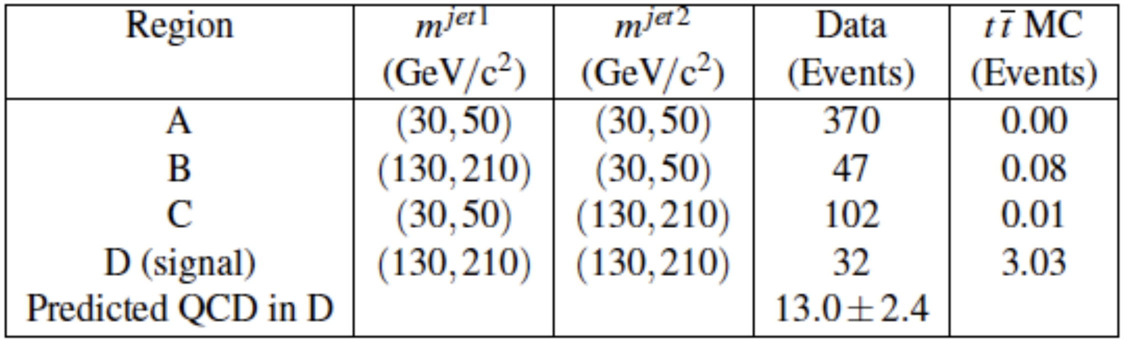
Predicted QCD in D			31.3 ± 8.1	

- **1+1**



Region	m^{jet1} (GeV/c^2)	m^{jet2} (GeV/c^2)	Data (Events)	$t\bar{t}$ MC (Events)
A	(30,50)	(30,50)	370	0.00
B	(130,210)	(30,50)	47	0.08
C	(30,50)	(130,210)	102	0.01
D (signal)	(130,210)	(130,210)	32	3.03
Predicted QCD in D			13.0 ± 2.4	