Understanding Really Boosted Objects

Outline

1. What do I mean by "Boosted Objects"?
2. What have we learned at Tevatron
3. First LHC results
4. Questions Raised….

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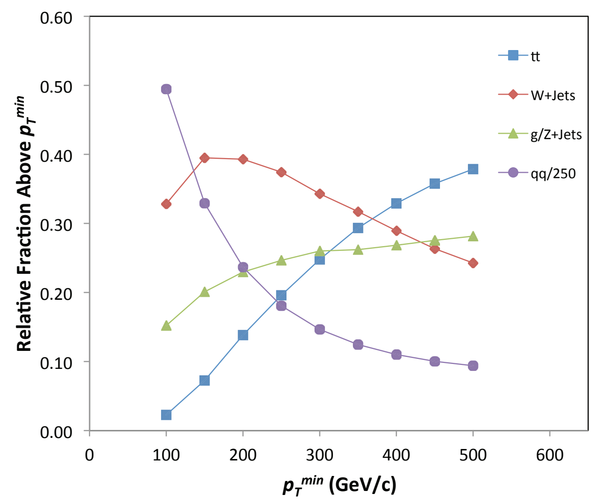
What's a Boosted Object?

- **Term used to categorize "very energetic" particles**
  - **$\gamma >> 1$**
  - **Assumption is that one is in a new regime**
    - Typified by jets with $p_T > 1$ TeV
    - Looking for relatively massive objects
  - **Boosted bosons (W/Z/H) and top quarks of particular interest**
  - **Challenge is to be able to identify and separate these from QCD backgrounds**

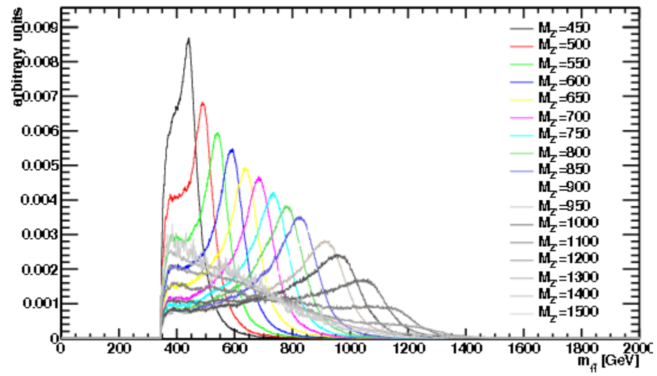
PYTHIA 6.4 Calculation



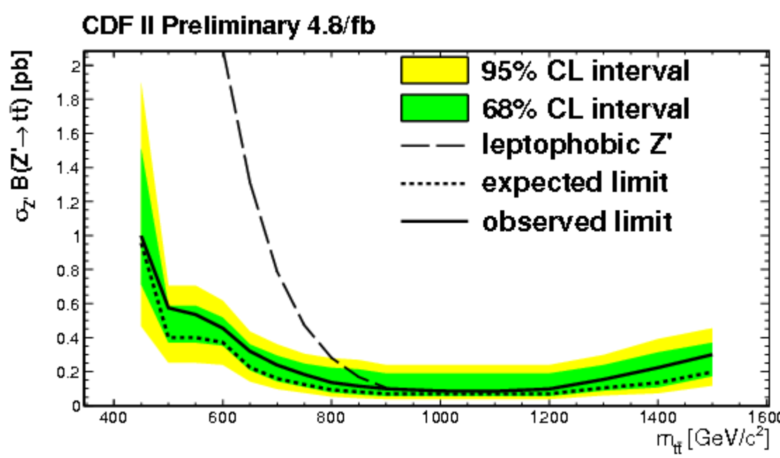
- **Prediction:**
  - **SM top rises out of background when $p_T > 400$ GeV/c at Tevatron**
  - **Need ~250 rejection against QCD jet production**
  - **x3 worse at LHC at 7 TeV**

Boosted Top Quarks

- **Boosted top quarks a signature for several new physics models**
  - **Typically looking for resonances that decay to top-antitop pairs**
  - **Searches have focused on "resolved final states"**
    - Lepton+jets with b-tagging
    - Best limit is 70 fb at m_{tt}~1 TeV
    - Acceptance is 3.6%
  - **Limited by acceptance & production rate**
    - Observe 1217 candidates
    - Exclude leptophilic Z' < 900 GeV/c^2

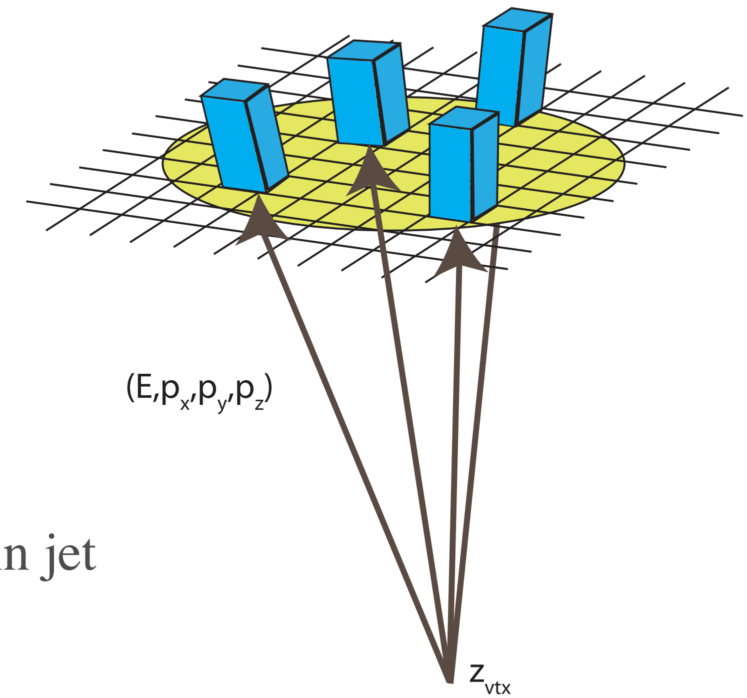


CDF preliminary (2010)



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 massless towers in jet
    - 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)**

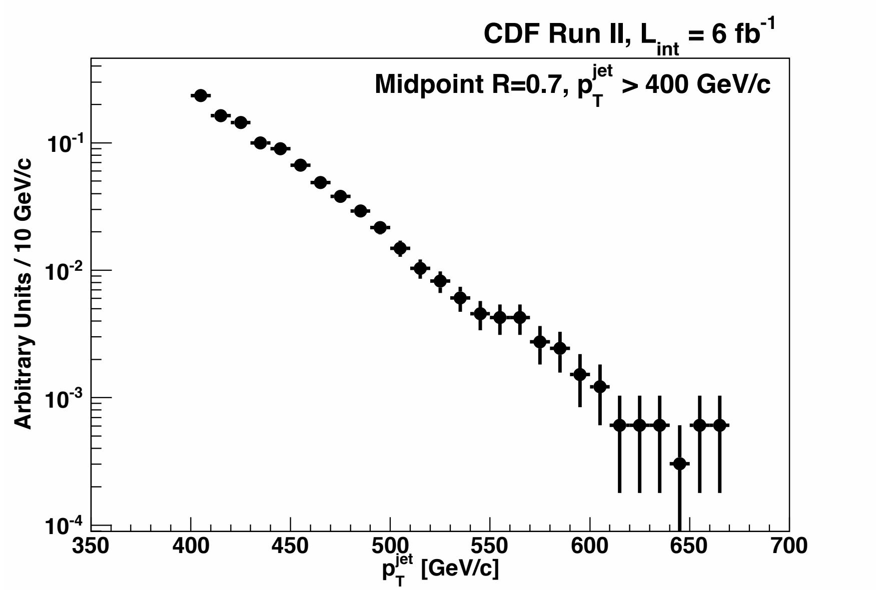
N.B. CDF central towers are $\Delta\eta \times \Delta\phi \sim 0.11 \times 0.26$

Data Selection

- **Analyzed inclusive jet sample**
  - **Trigger requires $E_T^{jet} > 100$ 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**

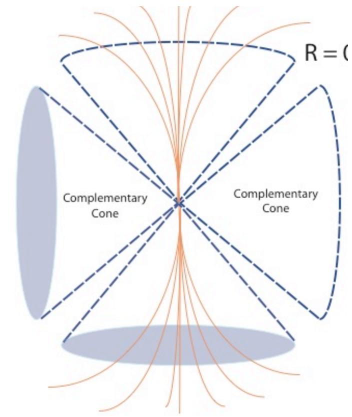
$$S_{MET} \equiv E_T^{MISS} \Big/ \sqrt{\sum_{i\ towers} E_T^i}$$

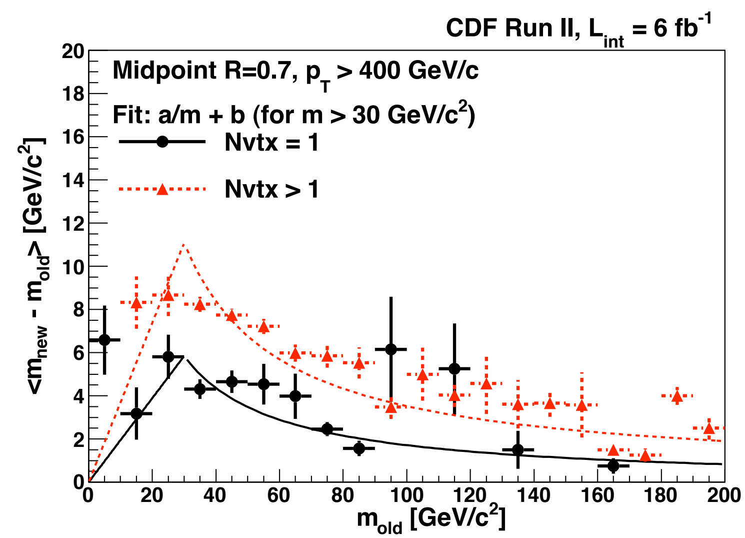
  - **Event vertex, jet quality and loose S_{MET} (< 14)**
- **Resulted in 2700 events using jets with R=0.7**



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 90º 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

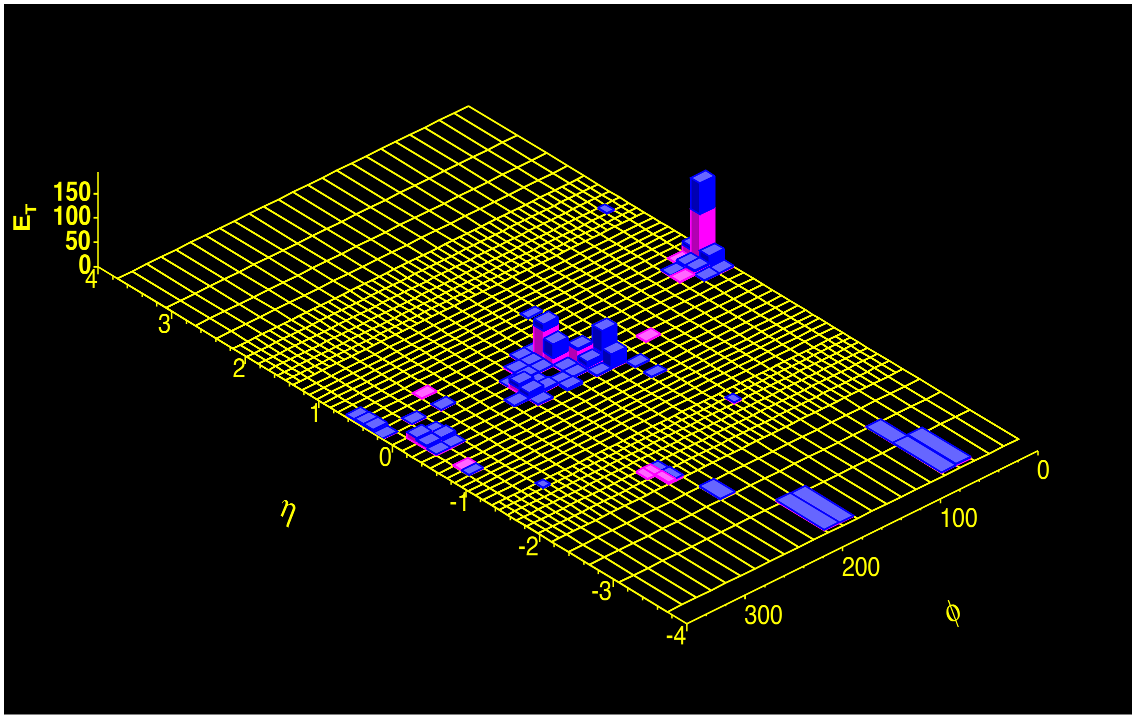




R. Alon et al., arXiv:1101.3002

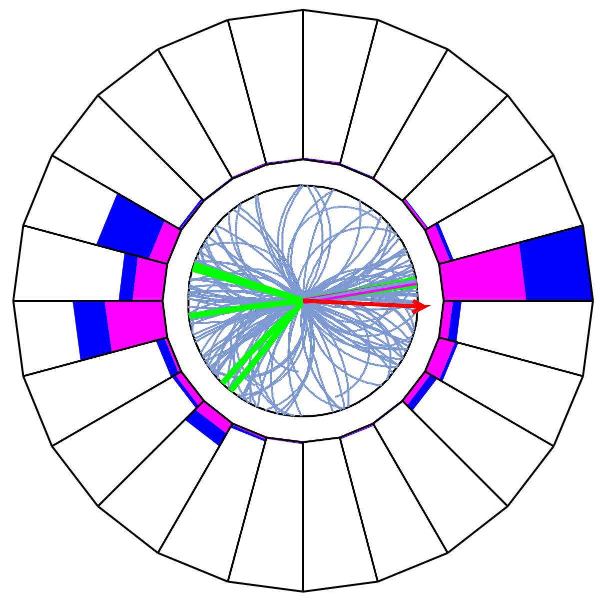
Correction scales as R^4

Typical Event



Run 286857 Event 79179

p_T	ϕ	m^{jet}	τ_{-2}	Pf
387	-3.11	175	0.024	0.66
344	0.09	113	0.019	0.40

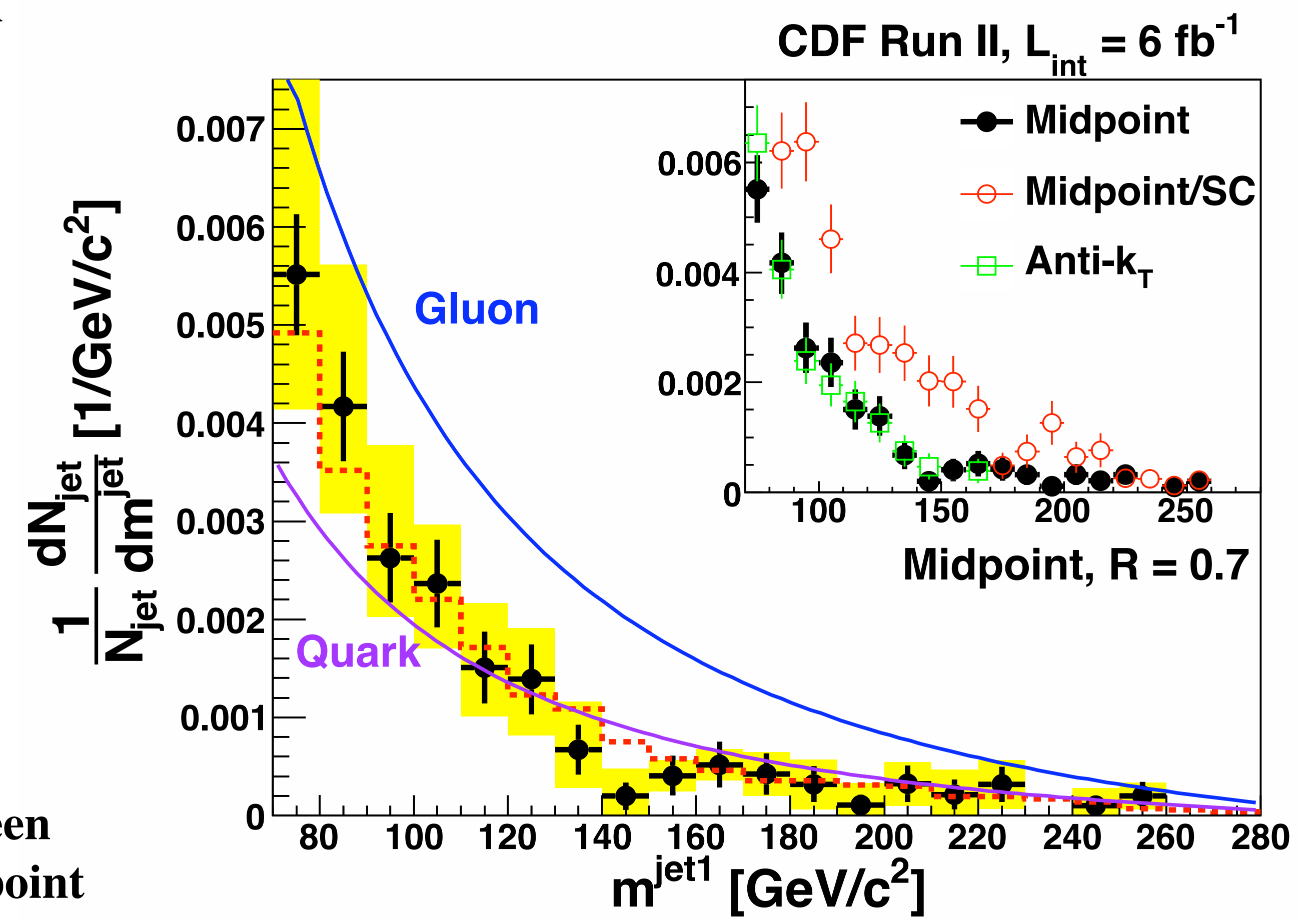


Typical QCD configuration:

- Dijet with back-to-back recoil
- Recoil jet less massive

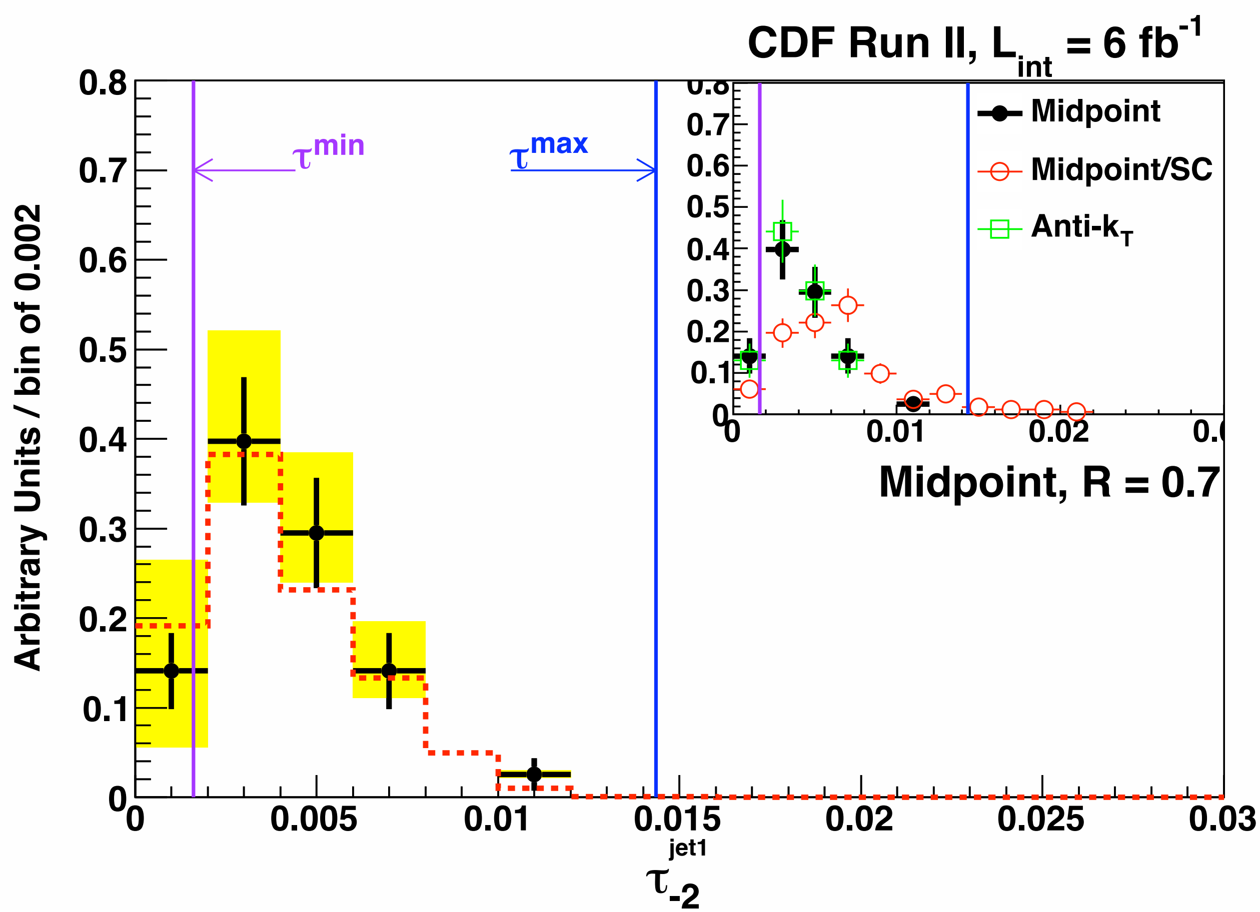
Jet Substructure – Mass

- **Massive jet**
  - Leading jets with $m_{jet} > 70$ GeV/c^2
  - Perform an "unfolding" correction
- **Agreement consistent with quark jets**
  - Expect ~85% of jets to be quark-initiated
  - No significant differences between anti-k_T and Midpoint algorithms



Jet Substructure – Angularity

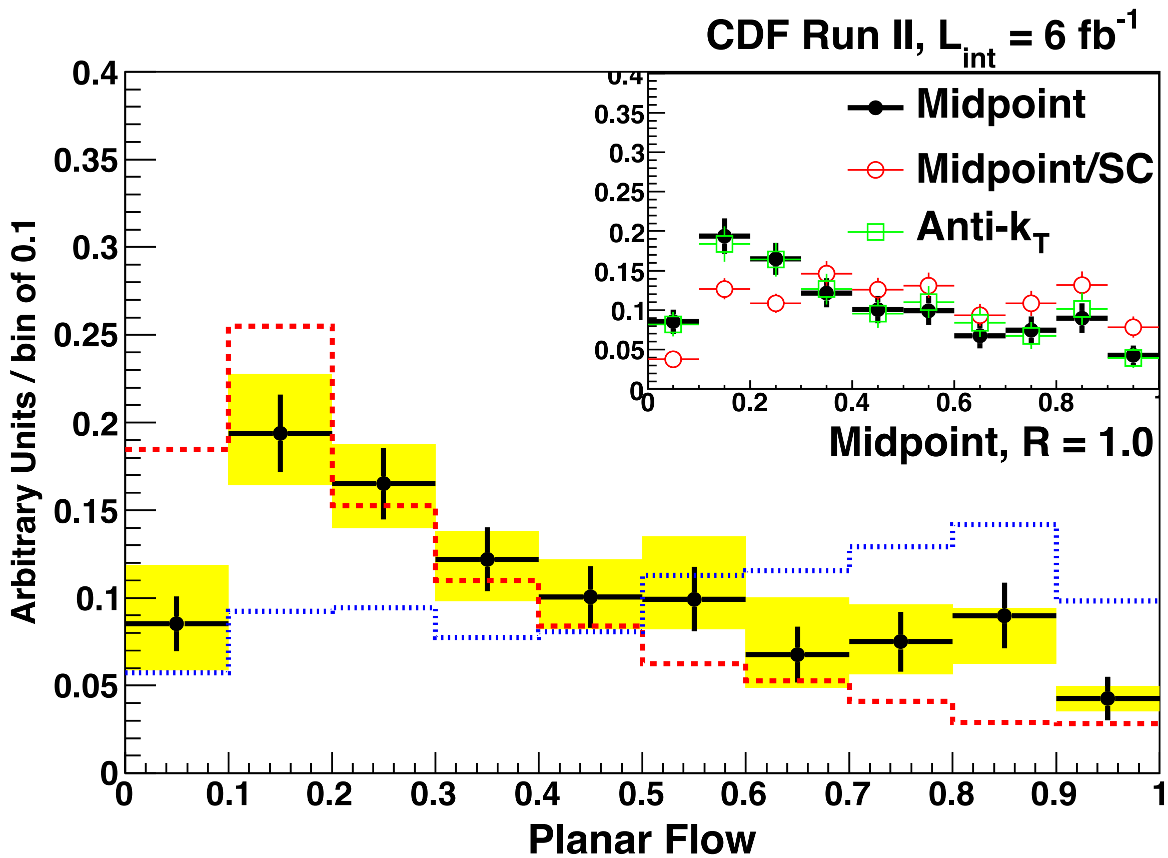
- **Angularity measures**
  - **Standard CDF II QCD sample**
  - **PDF uncertainties based on eigenvector decomposition**
- **Good agreement**
  - **The min and max bounds are "real"**
    - Two-body behaviour
  - **Falls like ~1/τ**



$90 < m_{jet} < 120$ GeV/c^2

Jet Substructure – Planar Flow

- **Planar Flow is also IR-safe**
  - Low Pf -> two-body kinematics
  - Not strongly correlated to m^{jet} for high mass
- **Consistent with QCD predictions**
  - See the expected low Pf peak
  - Contrasts with top quark jets – larger planar flow

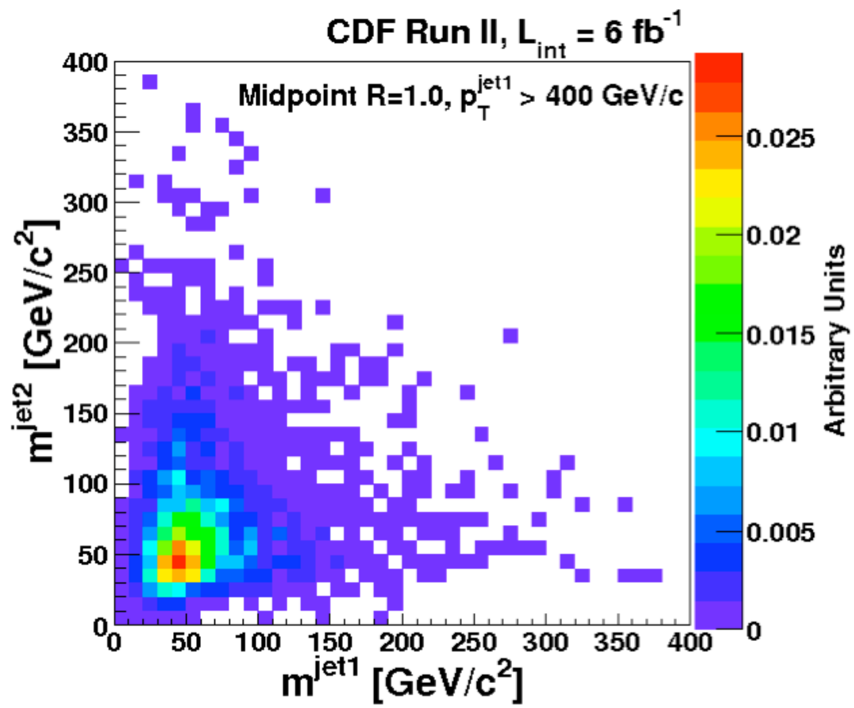


$130 < m_{jet} < 210$ GeV/c^2

Summary of Substructure Studies

- **Results show:**
  - **High p_T jets look like QCD light quark jets**
    - m^{jet} good discriminant
    - 1.4±0.3% of QCD jets have $m^{jet} > 140$ GeV/c^2
  - **Internal structure looks "two-body"**
    - Angularity & planar flow
  - **pQCD gives good description of m^{jet}**
    - Other substructure measures well-modelled with PYTHIA

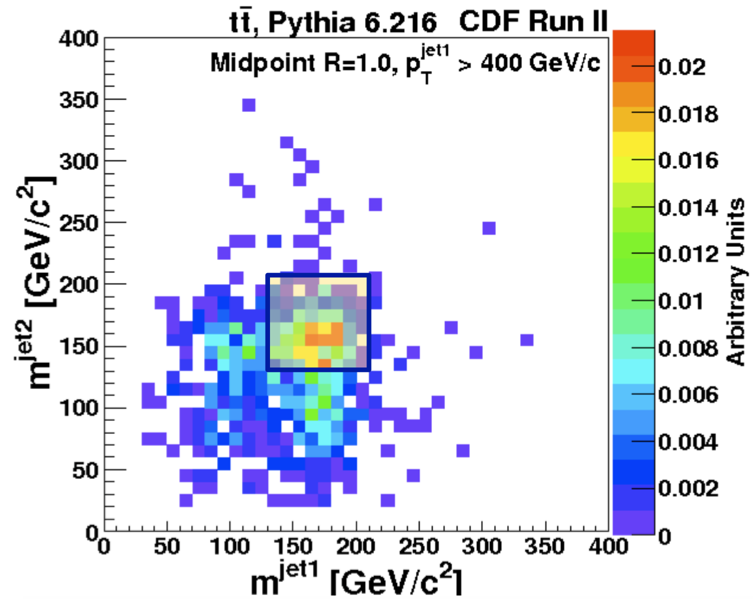
- **Jet masses are largely uncorrelated**
  - **Recoil jet doesn't know about leading m^{jet}**

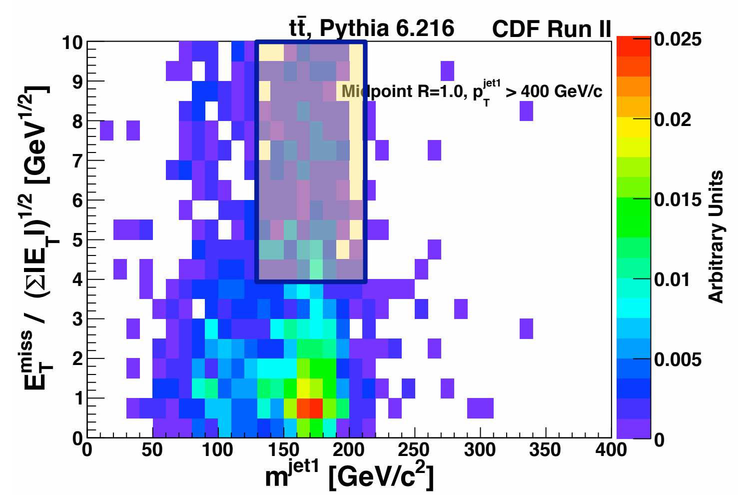


Strategies for Boosted Top

- **Two topologies:**
  1. **All hadronic ("1+1")**
     - Two massive jets recoiling (ε ~11%)
  2. **Semi-leptonic decay ("SL")**
     - Require $S_{MET} > 4$ (ε ~ 7%)
- **MC predicts ~0.8 fb**
  - **Divided 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

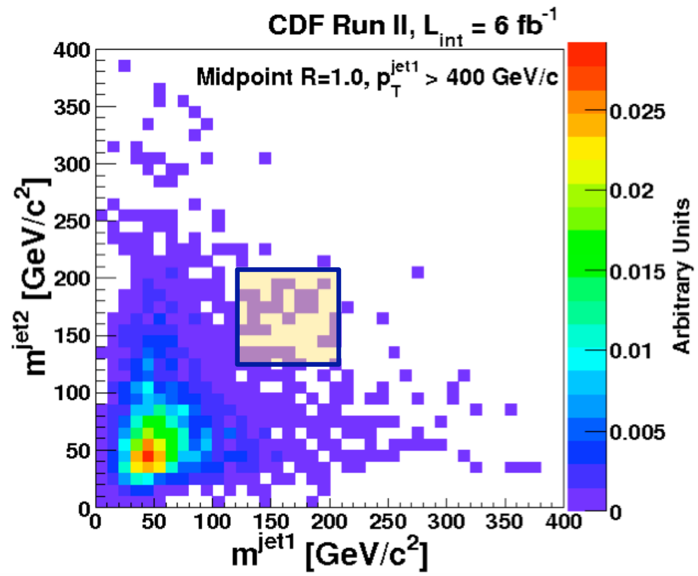
γ ~ 2.5

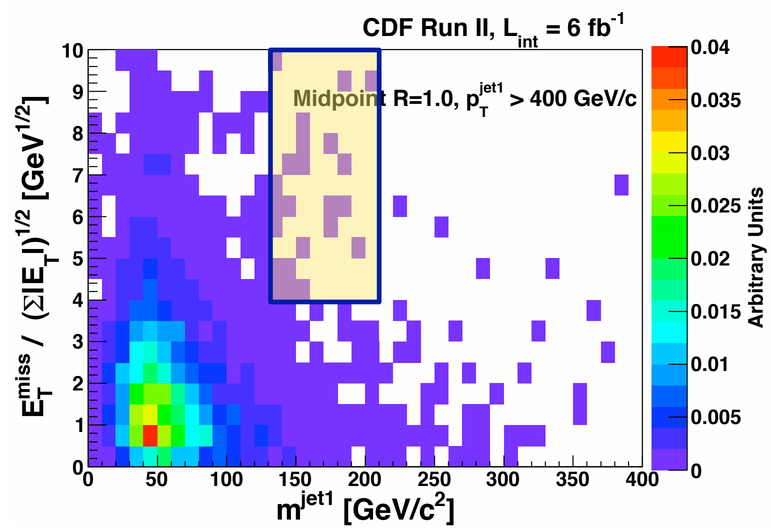




Selection Requirements

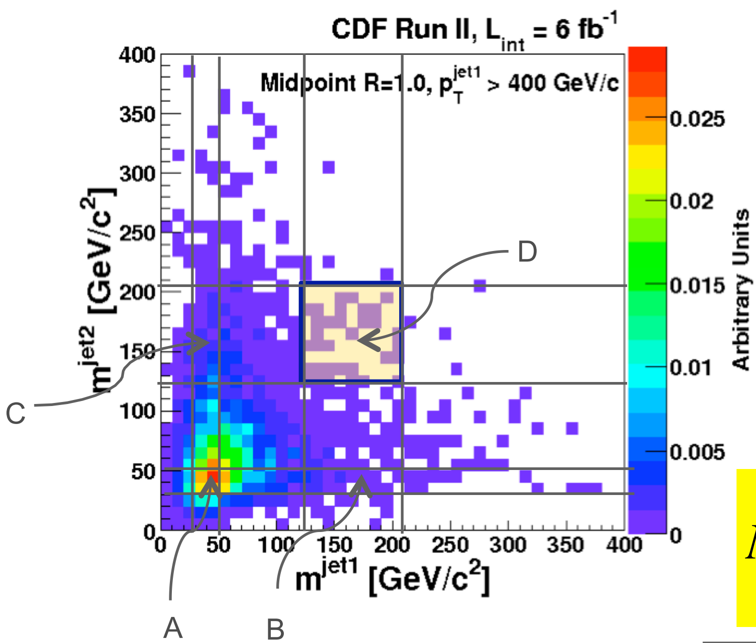
- **Keep selection simple**
  - **Focus on two separate channels**
- **All Hadronic Top (1+1)**
  - **Require 2 jets with $130 < m^{jet} < 210$ GeV/c²**
  - **Require $S_{MET} < 4$**
  - **Estimate background using "ABCD" technique**
- **Semi-leptonic top (SL)**
  - **Require $4 > S_{MET} > 10$**
  - **Require 1 jet with $130 < m^{jet} < 210$ GeV/c²**
  - **Estimate background using "ABCD" technique**





“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



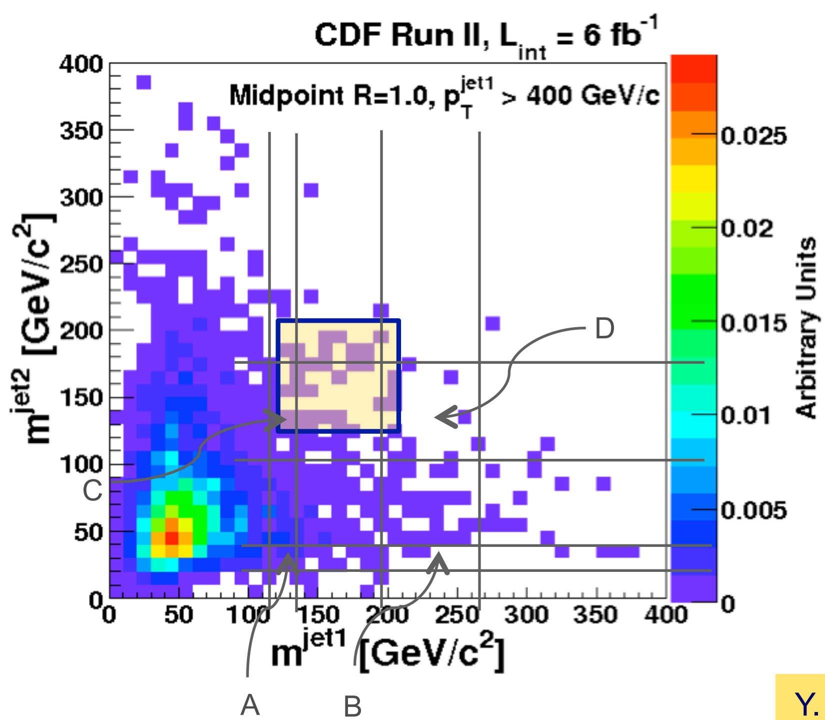
- Employ data to estimate backgrounds
  - Define mass windows
    $m^{jet} \in (130,210)$ GeV/c^2
    $m^{jet} \in (30,50)$ GeV/c^2
    - Use fact that m^{jet} distributions uncorrelated for background
    - Signal is region D
    - In “1+1” sample, predict 14.6±2.8 (stat) bkgd events

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

- Observe N_D=31 events

Investigated m^{jet} Correlations

- **We have been assuming that m^{jet1} and m^{jet2} are uncorrelated**
  - **Recent MC studies have shown this to be not exact**



- **NLO effects increase rate of two massive QCD jets**
  - **Quantified by defining R_{mass}**

$$R_{mass} \equiv \left[\frac{N_C N_B}{N_A N_D}\right]$$

$$N_D^{pred} = \left[\frac{N_C N_B}{N_A R_{mass}}\right]$$

  - **POWHEG: R_{mass}=0.89±0.03**

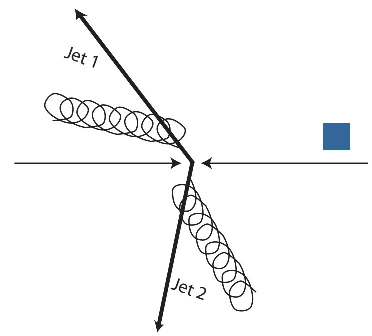
MC tools	Matching	R_{mass}
Sherpa	Yes	0.88 ± 0.03
MadGraph	Yes	0.86 ± 0.04
MadGraph	No	0.76 ± 0.04
Herwig	No	0.86 ± 0.02

Y. Eschel et al., arXiv:1101.2898

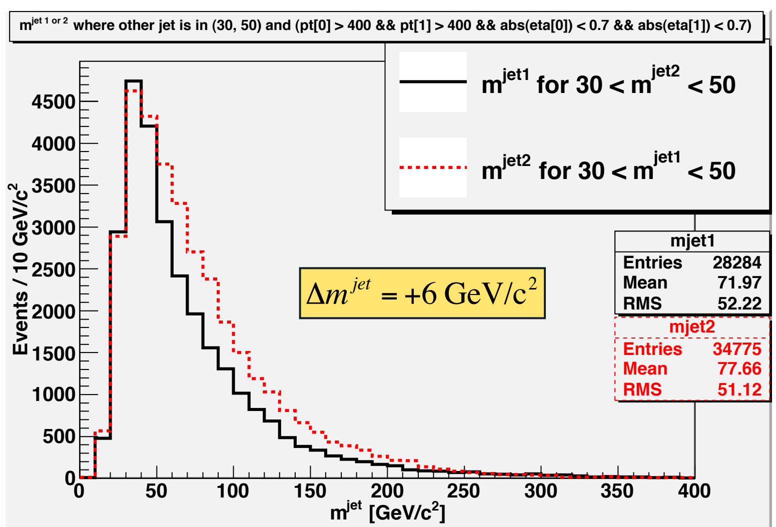
R_{mass} Isn't Something Universal

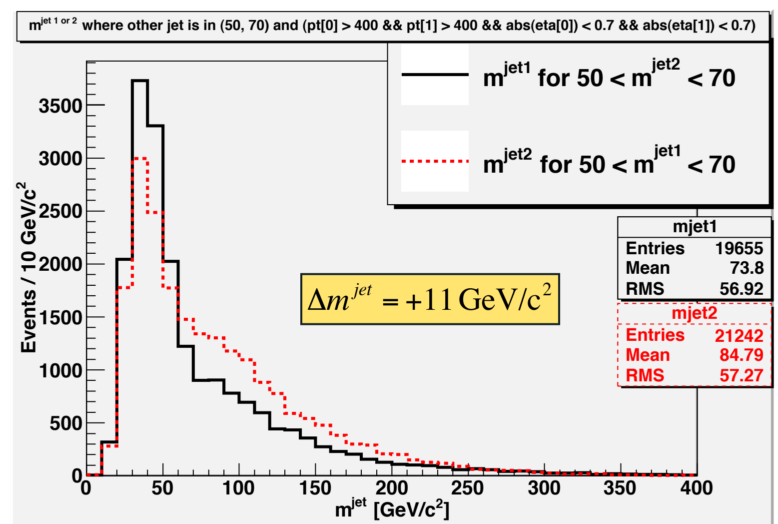
- **Why are m^{jet1} and m^{jet2} correlated?**
  - **Naïvely don't expect it**
  - **Used POWHEG to explore**
  - **Mass window matters:**
    - 30-50 GeV gives R_{mass}= 0.89
    - 50-70 GeV gives R_{mass}= 1.48

- **"Difficult" calculation – NNLO**



- **+ other terms**





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**
- **m^{top} uncertainty (±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**
    - 1+1: 11.1%
    - SL: 7.0%

- **Upper limit on cross section for $p_T > 400$ GeV/c**

$$\sigma_{95\%} = \frac{N_{LIM}}{\int L\,dt\ \varepsilon} = \frac{43.3}{(5.95)(0.182)} = 40 \text{ fb}$$

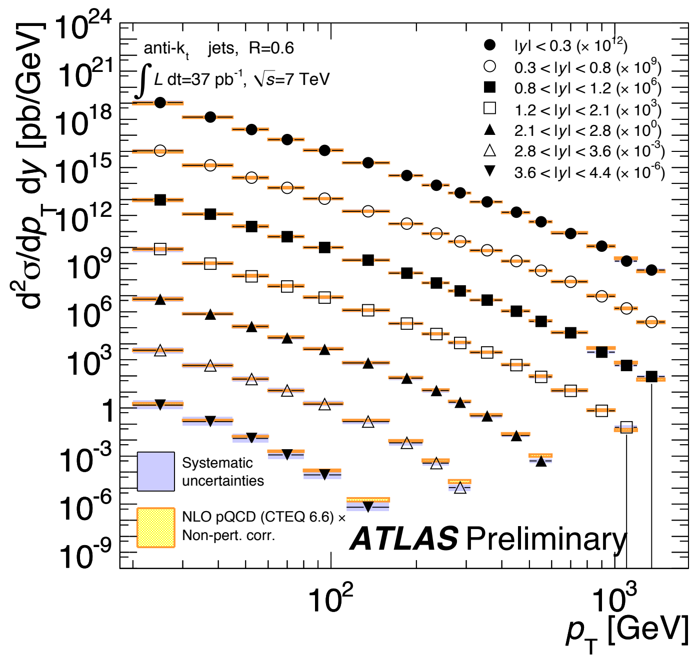
- **Can also set limit on 1+1 only**
  - **Assume massive ($m \sim m_{top}$) object, pair-produced, decaying hadronically**
  - **Include SM top as background**

$$\sigma_{95\%} = \frac{N_{LIM}}{\int L\,dt\ \varepsilon} = \frac{30.2}{(5.95)(0.254)} = 20 \text{ fb}$$

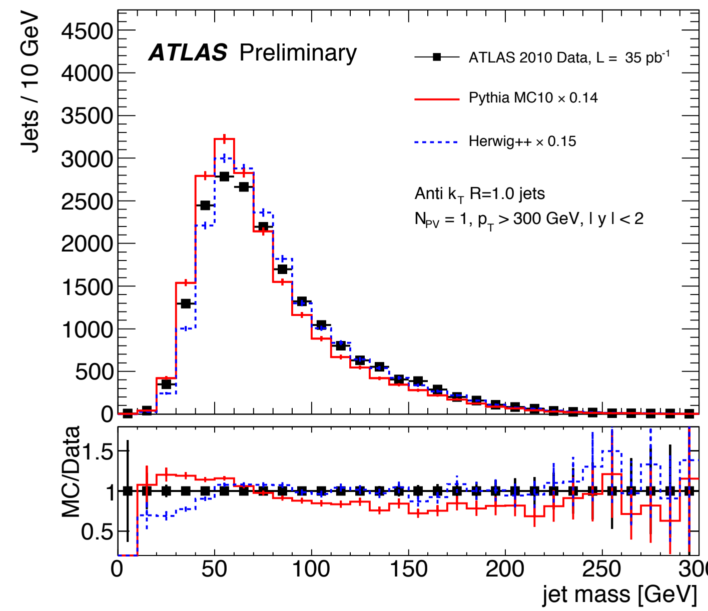
Also ~3σ excess above SM top

Early LHC Results

- **See lots of high p_T jets**
  - **Most recent published ATLAS data**
    - 37 pb^{-1}
    - Highest p_T ~ 1.5 TeV



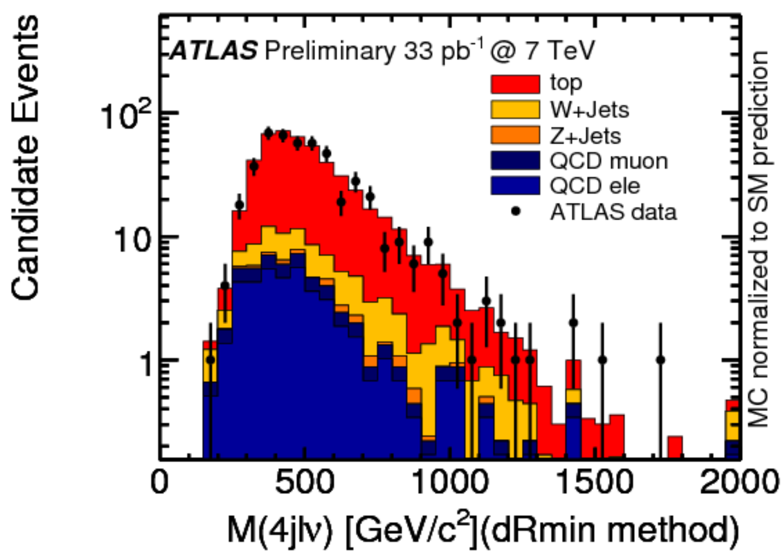
- **First substructure measurements underway**



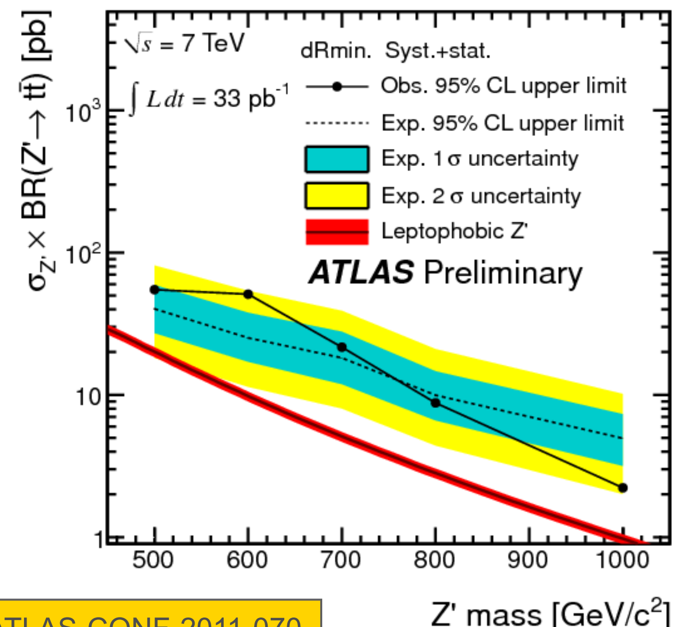
  - **Jet mass is obvious**
    - Also "hardest" due to sensitivity
    - Other taggers being commissioned

Boosted Top Searches Started

- **Focus has been on resolved final states**
  - **Look for reconstructed ttbar – invariant mass**
    - 35 pb^{-1}
    - Lepton, Met + ≥4 jets
    - Observe 475 candidates



- **Can set upper limits on non-SM contributions**
  - **Use "standard" TopColor model**
    - Leptophobic Z', $\Gamma = 1.3\%$ M



ATLAS-CONF-2011-070

Conclusions

- **Search for boosted top at Tevatron close to SM rate**
  - **Achieve**

    $$S/\sqrt{B} \approx 0.75$$
  - **Set $\sigma < 40$ fb at 95% CL**
  - **Limited by statistics**
- **Doesn't take advantage of substructure (aside from m^{jet})**
  - **E.g., planar flow cut > 0.5 improves S/N by ~1.5**
  - **And haven't used**
    - B-tagging
    - For SL, look for isolated charge track
- **Next steps:**
  - **At Tevatron, can improve statistics by x2**
  - **Tantalizing close to SM**
- **LHC taking over**
  - **Now recorded sample with x10 more SM ttbar**
    - But QCD backgrounds are larger
  - **Jet substructure is clearly essential tool**
    - Fully characterize QCD jets at higher energies
    - Understand what the best tools are
    - Improve background calculations

BACKUP SLIDES

Substructure Measures

Berger et al. ph/0303051;
Almeida et al., 0807.0234

- **Angularity**
  - **Emphasizes breadth of jet**
    - Large angularity – broad energy deposition
  - **QCD predicts minimum & maximum value**

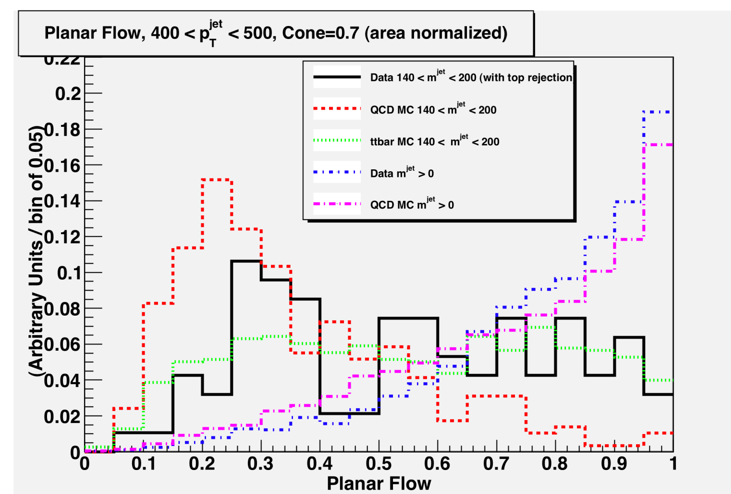
$$\tau_a(R, p_T, M_J)_{a<2} = \frac{1}{m^{jet}} \sum_{i \in \text{jet}} E_i \sin^a \theta_i \left[1 - \cos\theta_i\right]^{1-a}$$

$$\tau_a \sim \sum_{i \in R} \frac{E_i}{m^{jet}} \theta_i^{2-a} = \sum_{i \in R} \frac{E_i}{m^{jet}} \theta_i^4 \Big|_{a=-2}$$

- **Planar Flow**
  - **Determinant of 2-D energy flow matrix**
  - **Low planar flow implies two-body kinematics**
  - **Higher planar flow associated with many-body decays**

$$I_w^{kl} = \frac{1}{m^{jet}} \sum_i \frac{p_{i,k}}{E_i} \frac{p_{i,l}}{E_i}$$

$$Pf \equiv \frac{4\lambda_1 \lambda_2}{(\lambda_1 + \lambda_2)^2}$$



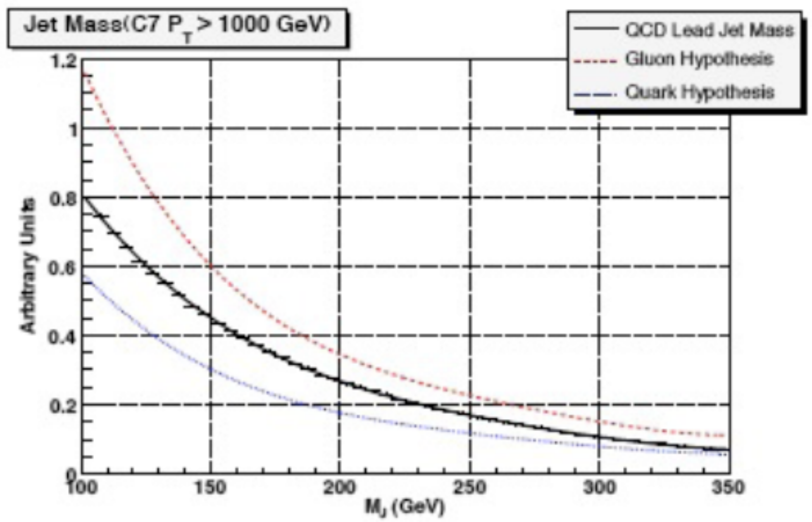
Perturbative QCD Predictions

- **Assume that we can "factorize"**

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

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

  - **Jet function at high mass comes from single-gluon emission**
  - **Robust NLO prediction for**
    - Shape of high mass tail (and quark/gluon difference)
    - Relative rate of high mass QCD jets
    - Jet substructure should be "two-body"
- **These are the BACKGROUND**



Almeida et al., 0810.0934

Few caveats:

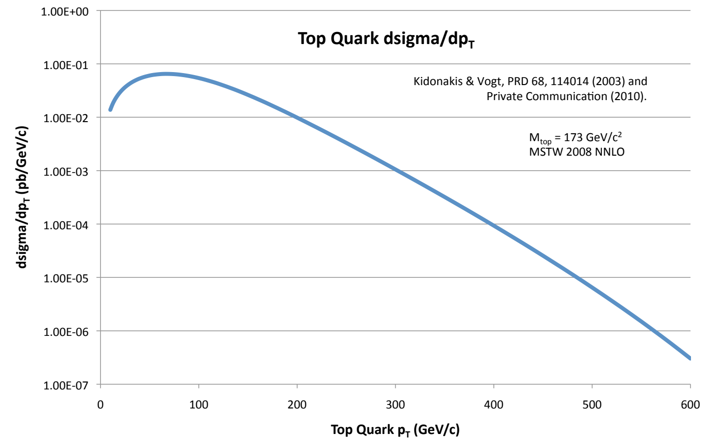
$$m^{jet} << \left(Rp_T\right) \approx 280 \text{ GeV/c}^2$$

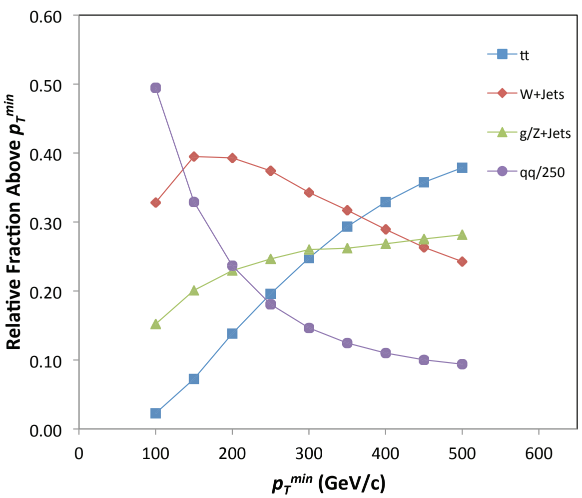
$$m^{jet} >> m^{peak} \approx 50 \text{ GeV/c}^2$$

Boosted Objects at Tevatron

- **SM sources for high-p_T objects calculable**
  - **Dominated by light q & gluons**
  - **Need x250 rejection to observe other sources**
- **Other sources:**
  - **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)



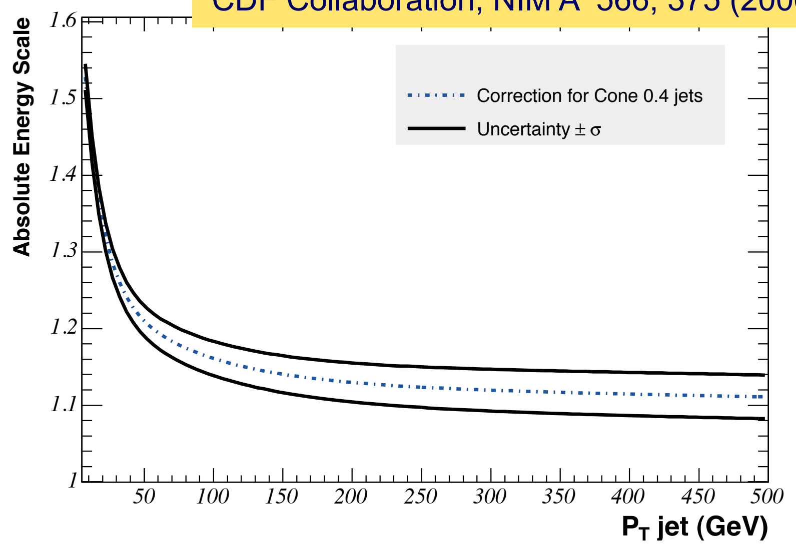


PYTHIA 6.4 Calculation

Jet Mass Corrections

- **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**

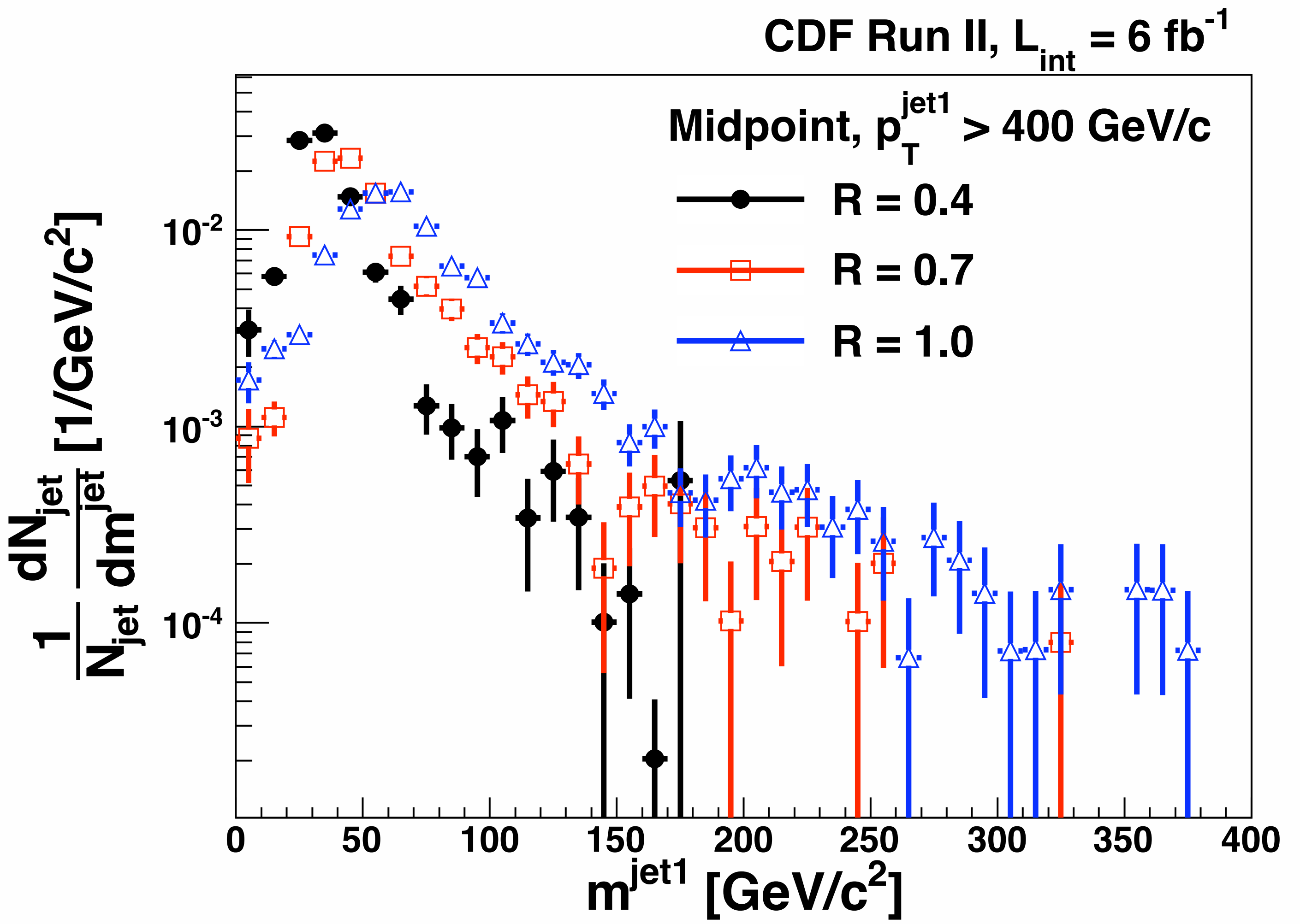
CDF Collaboration, NIM A 566, 375 (2006)



- **Investigated other effects:**
  - **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
  - **Jet energy scale vs algorithm (Midpoint, Midpoint/SC, anti-k_T)**
    - Saw < 1 % difference

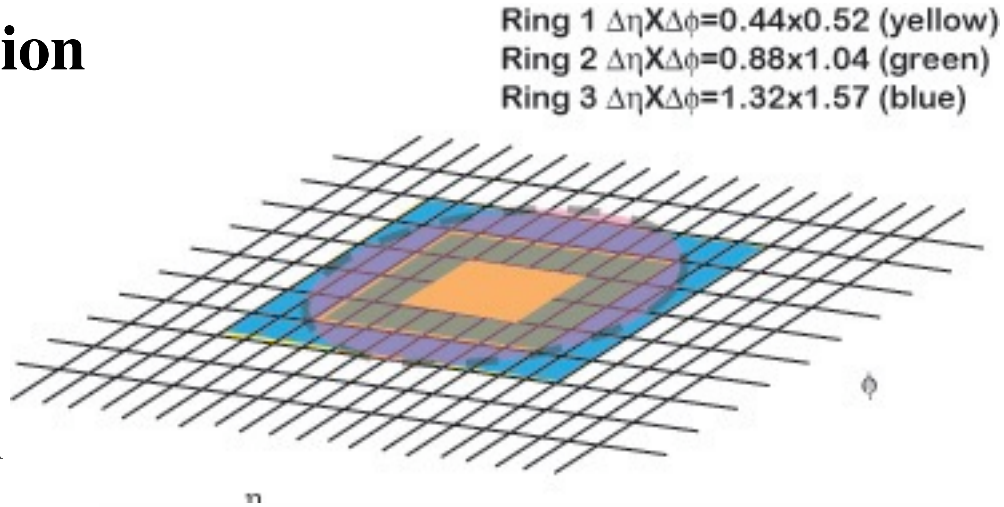
Comparison with Cone Size

- Compare
  - R=0.4
  - R=0.7
  - R=1.0

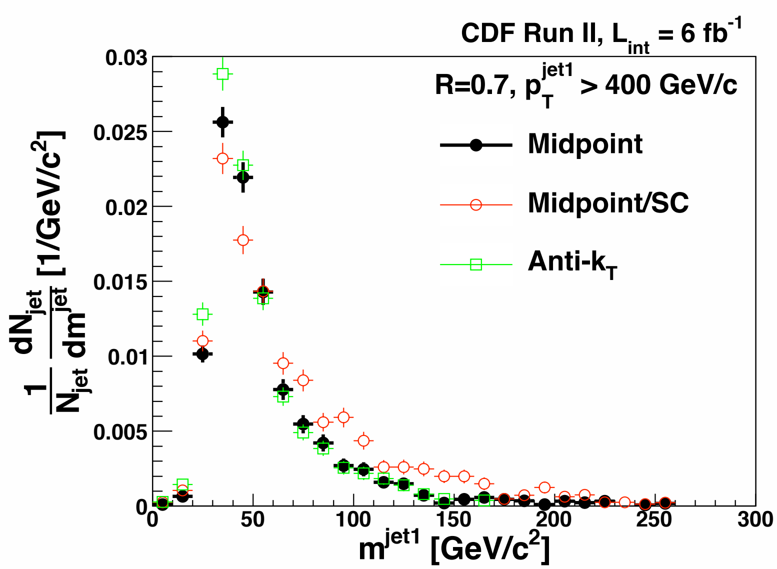


Inter-Jet Energy Calibration

- **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, Δm^{jet}=1 GeV/c^2**
  - **At m^{jet}=120 GeV/c^2, Δm^{jet}=10 GeV/c^2**
- **Largest source of systematic uncertainty**



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**

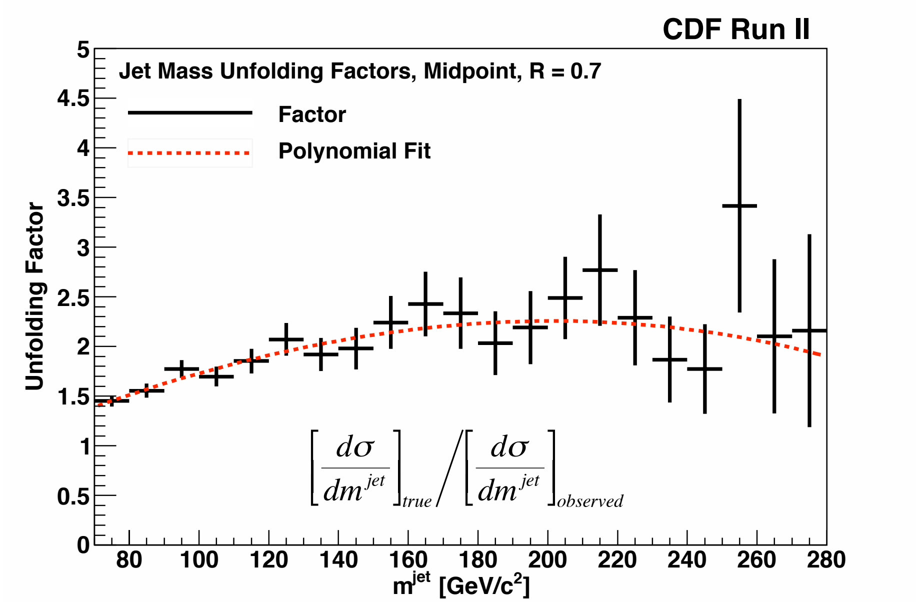
Determining Jet Function

- **Key prediction is "jet function"**

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

  - **Use observed m^{jet} distribution?**

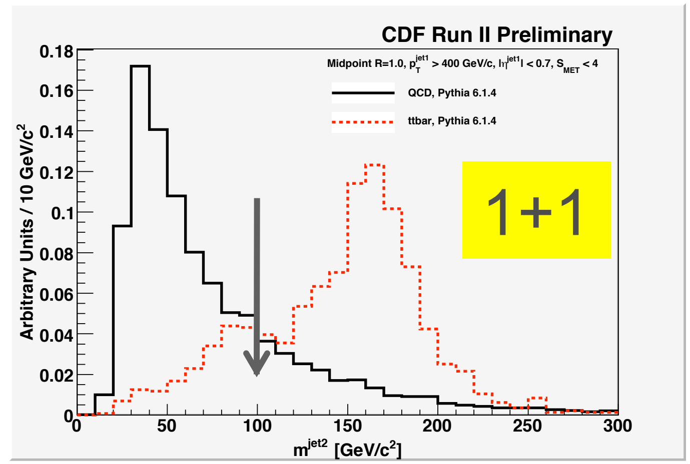
- **No. Large correction comes from jet p_T cut**
  - **p_T of low mass jets has ~10% broader resolution than high mass jets**
  - **More events in sample with true p_T < 400 GeV/c at low m_{jet} vs high m_{jet}**
    - Aggravated by steeply falling p_T spectrum

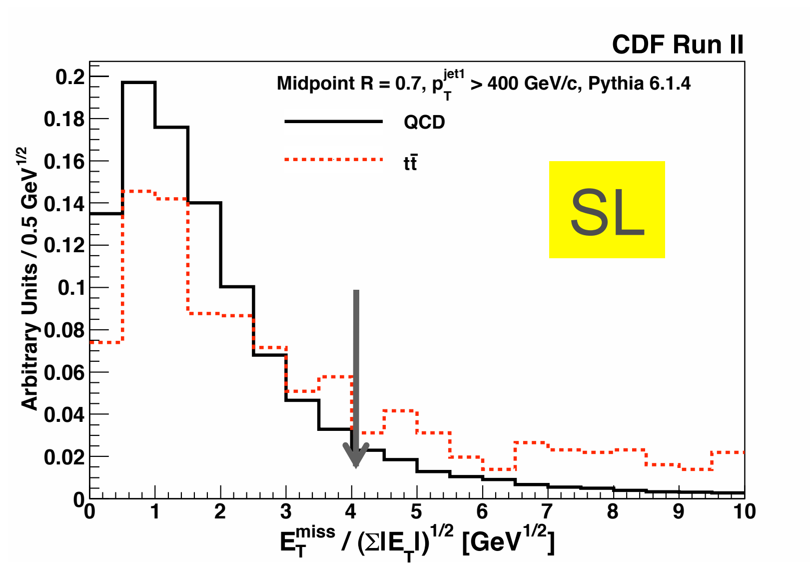


- **Verified by studies of recoil jet**
  - **No intrinsic p_T bias**
- **Calculated correction with MC**
  - **Hadronization uncertainty 10%**

Reducing Top Contamination

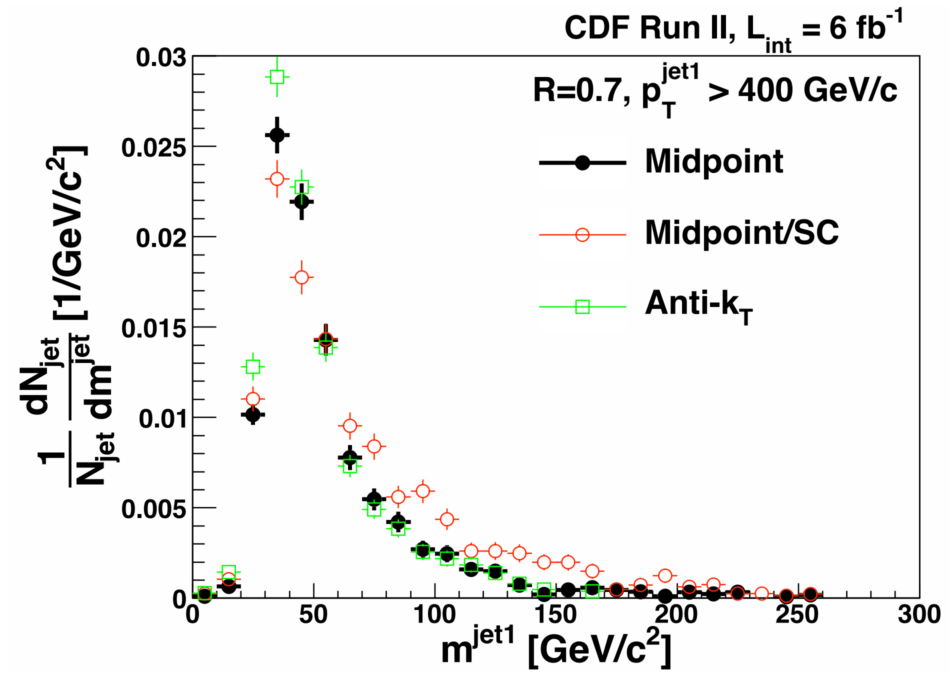
- Expect about 1.6 fb of high p_T jets from top in sample
  - Eliminate by rejecting events with
    - $m^{jet2} > 100$ GeV/c^2
      - Use jet cone R=1.0 for improved top tagging
    - Missing E_T Significance (S_{MET}) > 4
  - Lose 28% of jet candidates
    - 2576 events using R=0.7 jets
    - 145 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

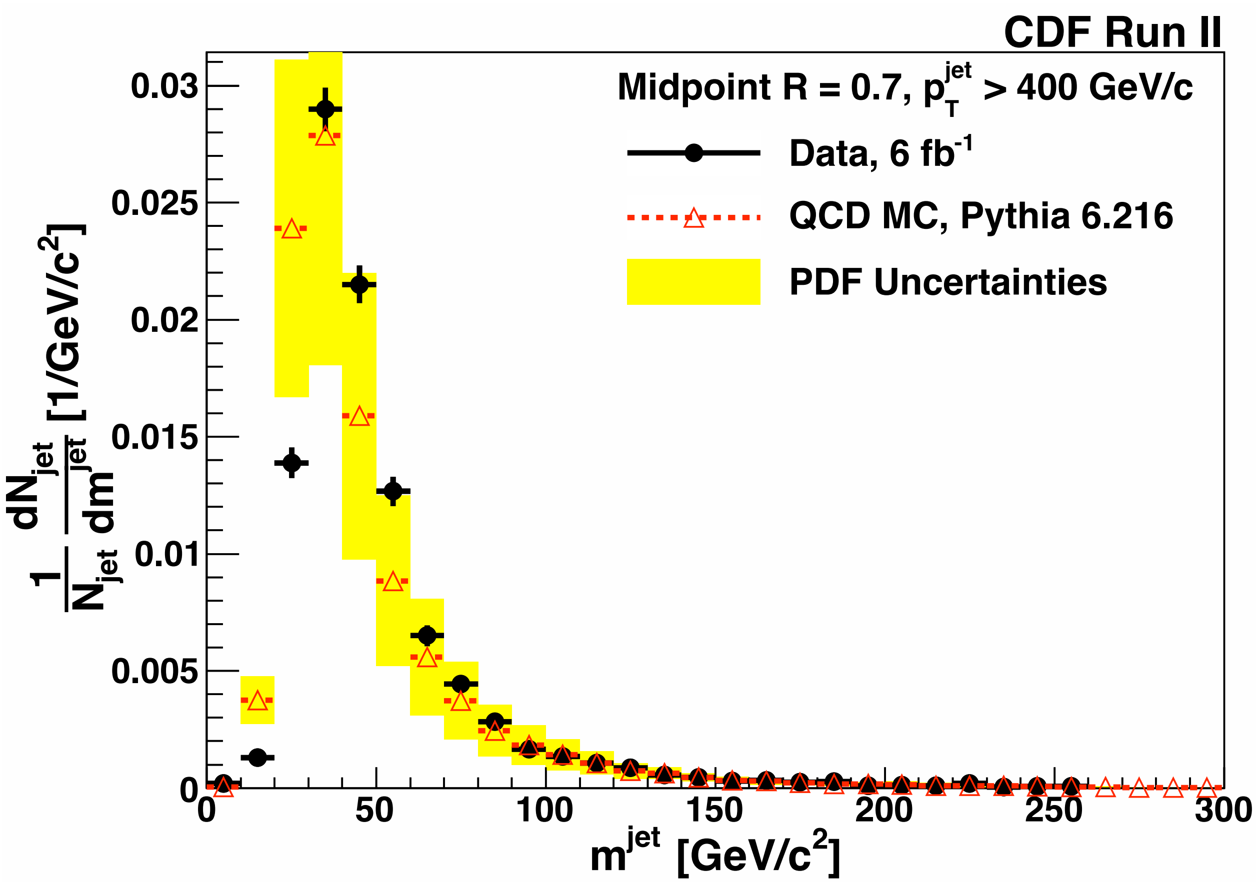


Cut Flow		
All Data, 5.95 fb^{-1}	75,764,270 events	
	R = 0.4	**R = 0.7**
At least one jet with $p_T > 400$ GeV/c, $\lvert\eta\rvert$ in (0.1, 0.7), and event quality cuts	2153 events	2700 events
$m^{jet2} < 100$ GeV/c^2 and $S_{MET} < 4$ (with $p_T^{jet2} > 100$ GeV/c and MI corrections)	1837 events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

- **Low-mass peak arises from non-perturbative QCD effects**
  - **Sensitive to non-perturbative effects and detector modelling**
  - **Higher mass jets are of particular interest**

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
  - Larger PDF uncertainties at low mass



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

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:

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

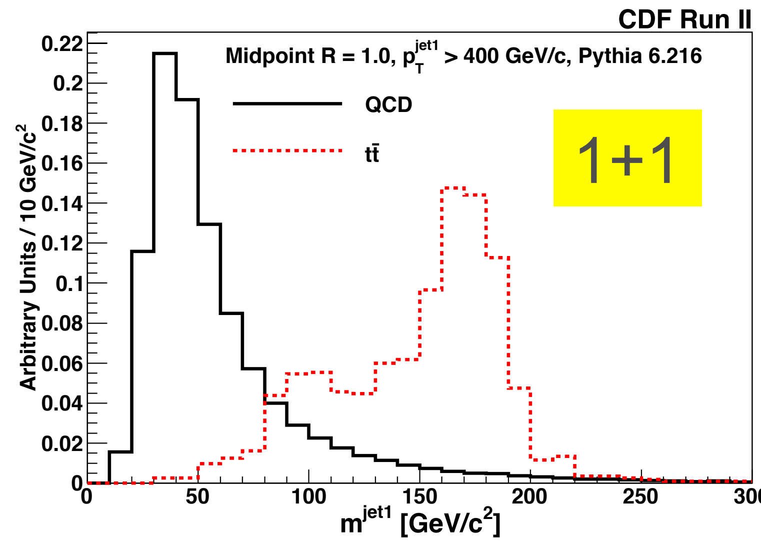
- Expect MI correction to scale with R^4:
  - Exactly what we see when comparing R=0.4 and R=0.7
- PYTHIA UE agrees well with data – same UE mass correction
- Use that to scale corrections for R=1.0
  - Method doesn't work with larger cone because of overlap

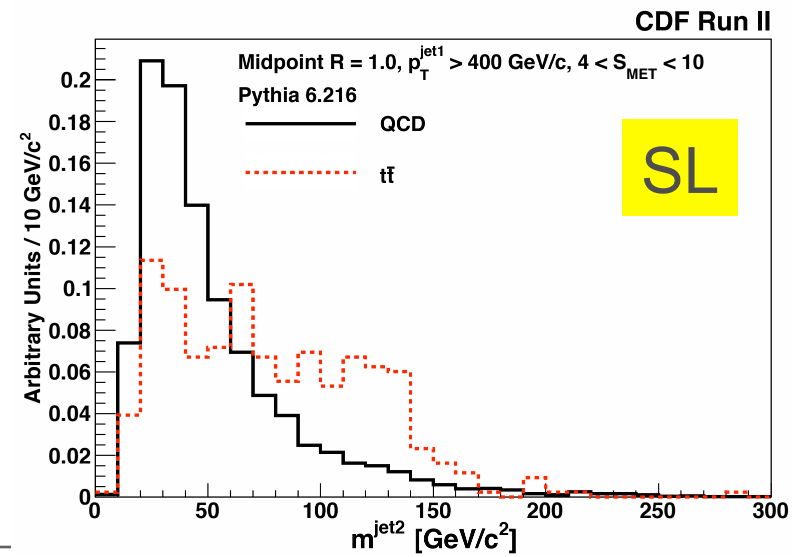
Internal Jet Energy Scale

- 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

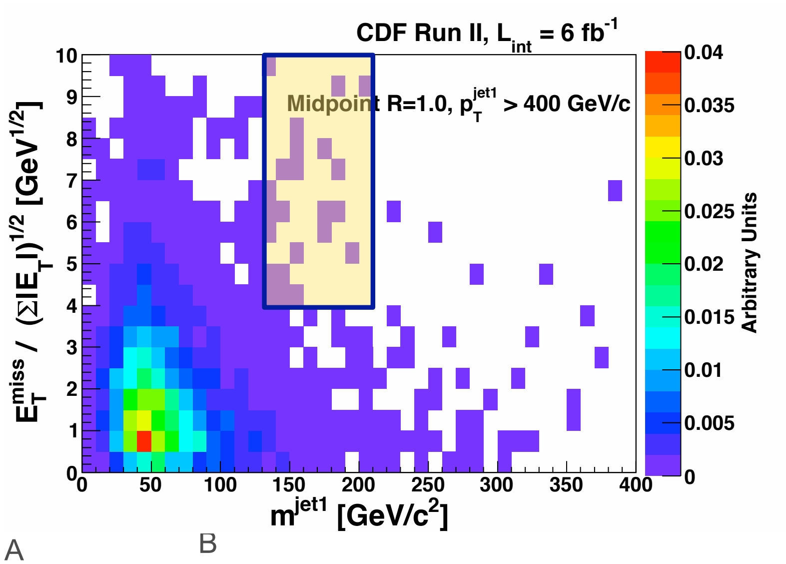
Region	m^{jet1} (GeV/c^2)	S_{MET} ($\sqrt{GeV/c^2}$)	Data (Events)	MC (Events)
A	(30, 50)	(2, 3)	256	0.01
B	(130, 210)	(2, 3)	42	1.07
C	(30, 50)	(4, 10)	191	0.03
D (signal)	(130, 210)	(4, 10)	26	1.90
Predicted QCD in D			31.3 ± 8.1	

- 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	

"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/c²**
  - **$S_{MET} \in (2,3)$ & $S_{MET} \in (4,10)$**
    - **In "SL" sample, predict 31±8 (stat) bkgd events**

Observe N_D=26 events

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	