# Search for Boosted Top Quarks at CDF

## Outline

1. Introduction and Motivation
2. Data Selection & Jet Calibration
3. Boosted Top Signals
4. Results
5. Conclusions

Representing the CDF Collaboration

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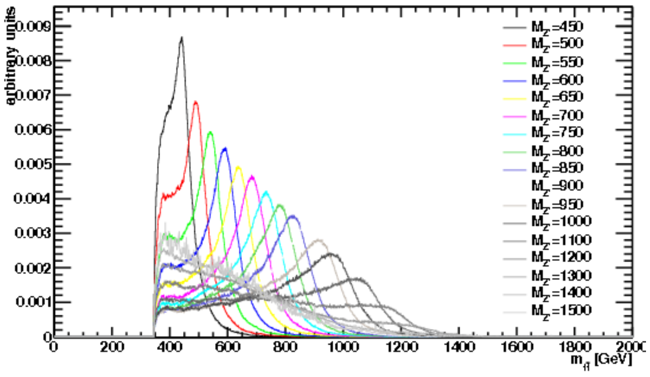
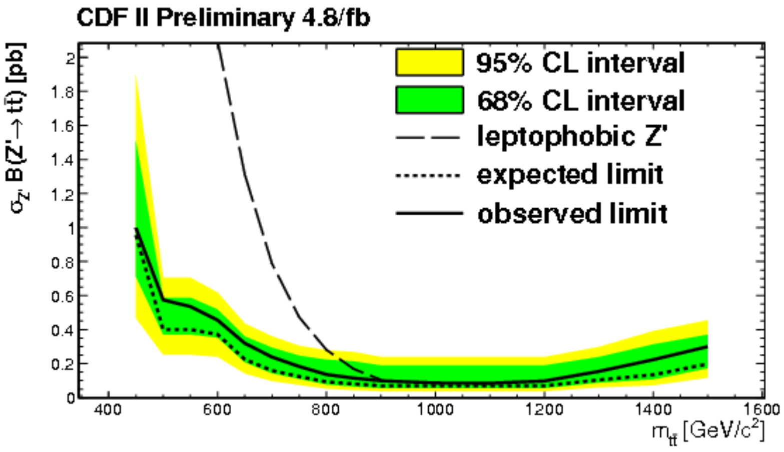
# Boosted Top Quarks

- **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 and production rate**
    - Exclude leptophilic Z' < 900 GeV/$c^2$
- **Our focus has been on unresolved final states**

CDF

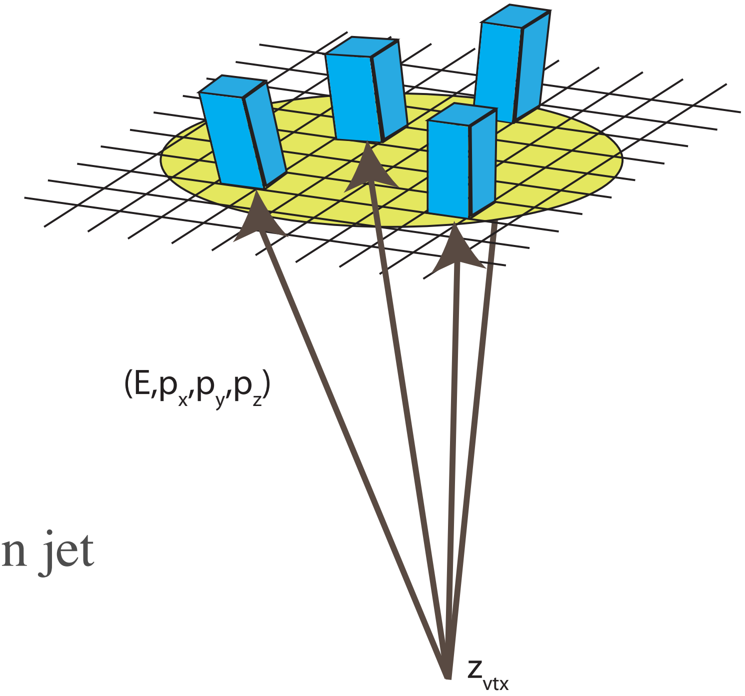


CDF, PRD 78, 052006 (2008)



# 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 $(E, p_x, p_y, p_z)$



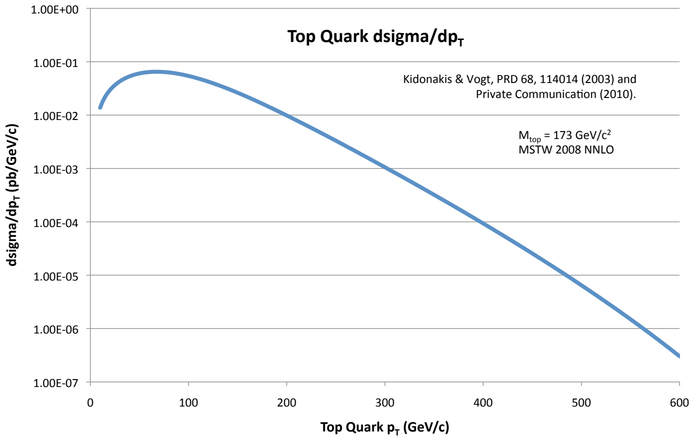
- **Employ Midpoint cone jets**
  - **Best understood in CDF II context**
  - **Compare results with anti-$k_T$ and Midpoint with "search cones" (Midpoint/SC)**

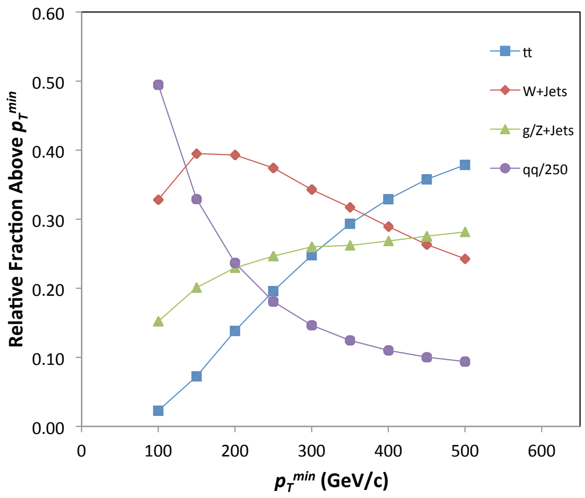
N.B. CDF central towers are $\Delta\eta \times \Delta\phi \sim 0.11 \times 0.26$

# 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

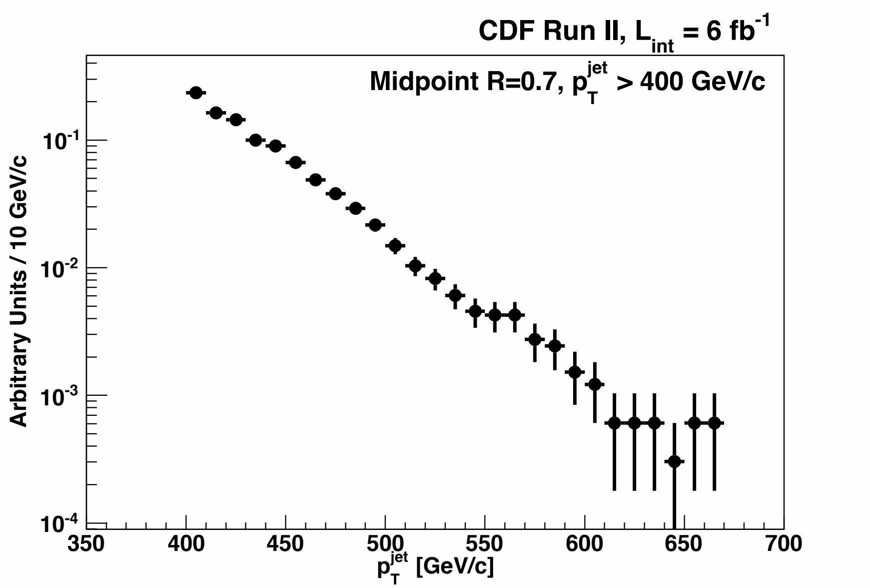
# Data Selection

- **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**

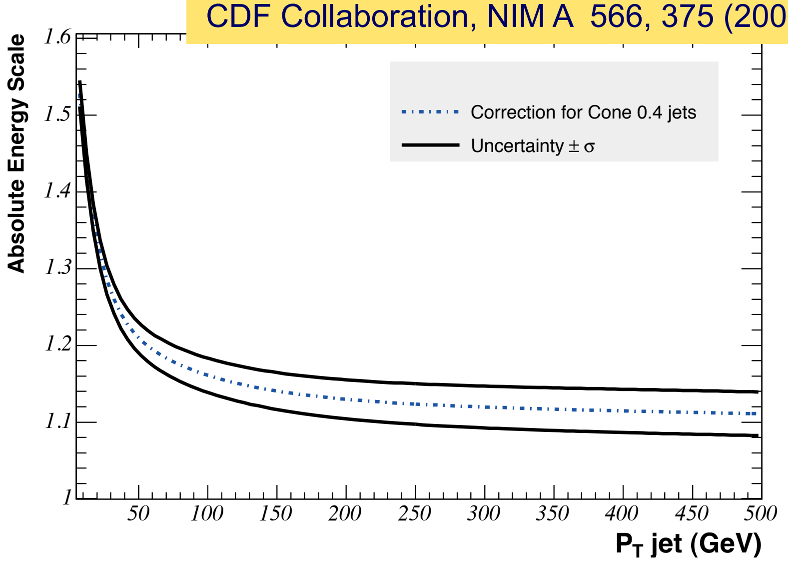
$$S_{MET} \equiv E_T^{MISS} \Big/ \sqrt{\sum_{i\ towers} E_T^i}$$

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



# 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**

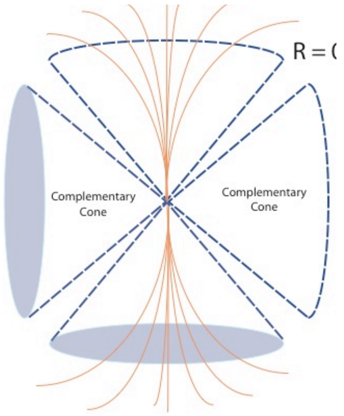


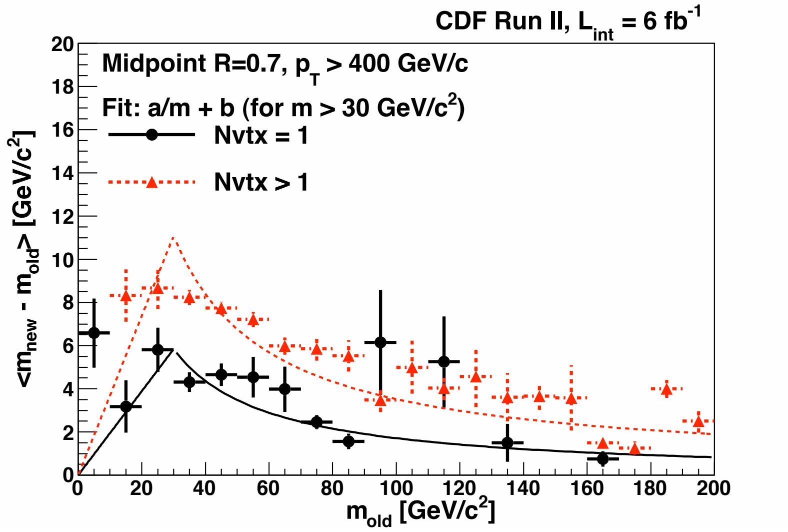
CDF Collaboration, NIM A 566, 375 (2006)

- **Investigated other effects:**
  - **Effect of calorimeter inhomogeneity at $\eta=0$**
    - 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

# 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**



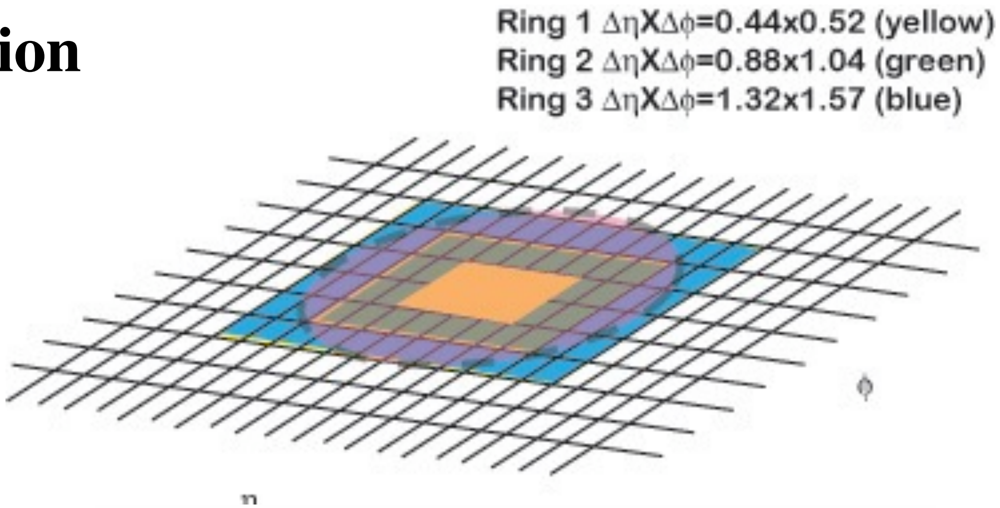


R. Alon et al., arXiv:1101.3002

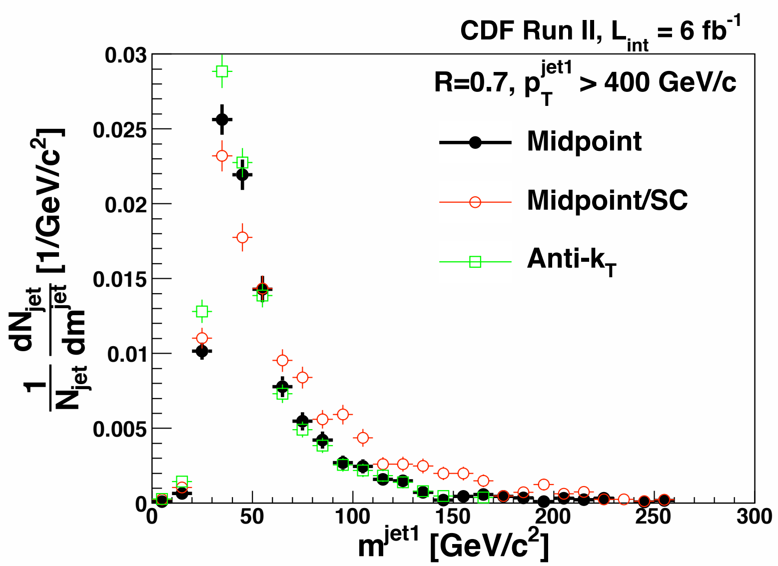
Correction scales as $R^4$

# Inter-Jet Energy Calibration

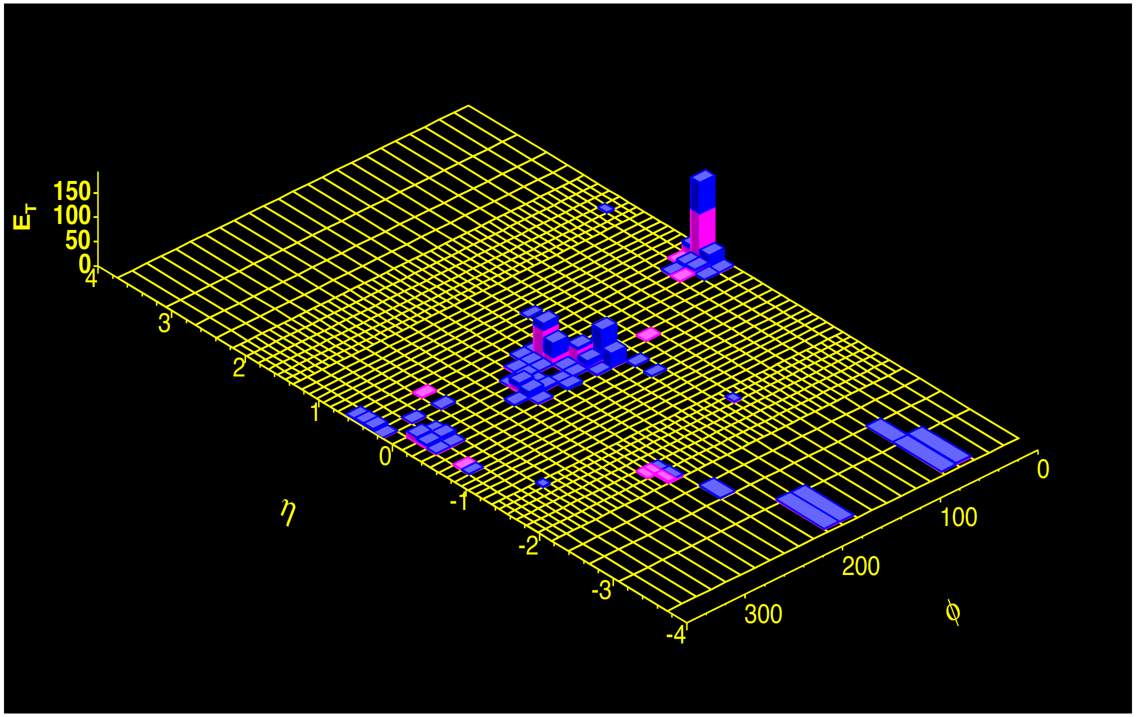
- **Jet mass arises from deposition of varying energy per tower**
  - ○ **Performed study to compare momentum flow vs calorimeter energy internal to jet**
    - ➢ Defined 3 rings and compared observed $p_T/E_T$ with simulation



- **Resulted in constraints on calorimeter relative response**
  - ○ **At $m^{jet}$=60 GeV/c$^2$, $\Delta m^{jet}$=1 GeV/c$^2$**
  - ○ **At $m^{jet}$=120 GeV/c$^2$, $\Delta m^{jet}$=10 GeV/c$^2$**
- **Largest source of systematic uncertainty**

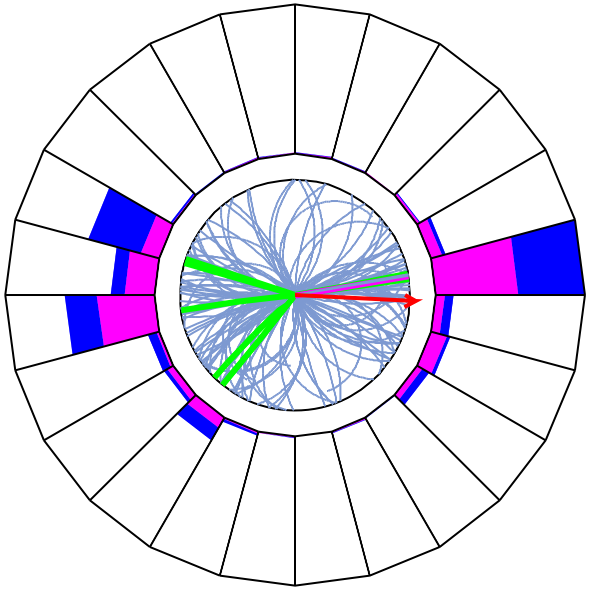


# Typical Event



**Run 286857 Event 79179**

| $p_T$ | $\phi$ | $m^{jet}$ | $\tau_{-2}$ | Pf |
|---|---|---|---|---|
| 387 | -3.11 | 175 | 0.024 | 0.66 |
| 344 | 0.09 | 113 | 0.019 | 0.40 |

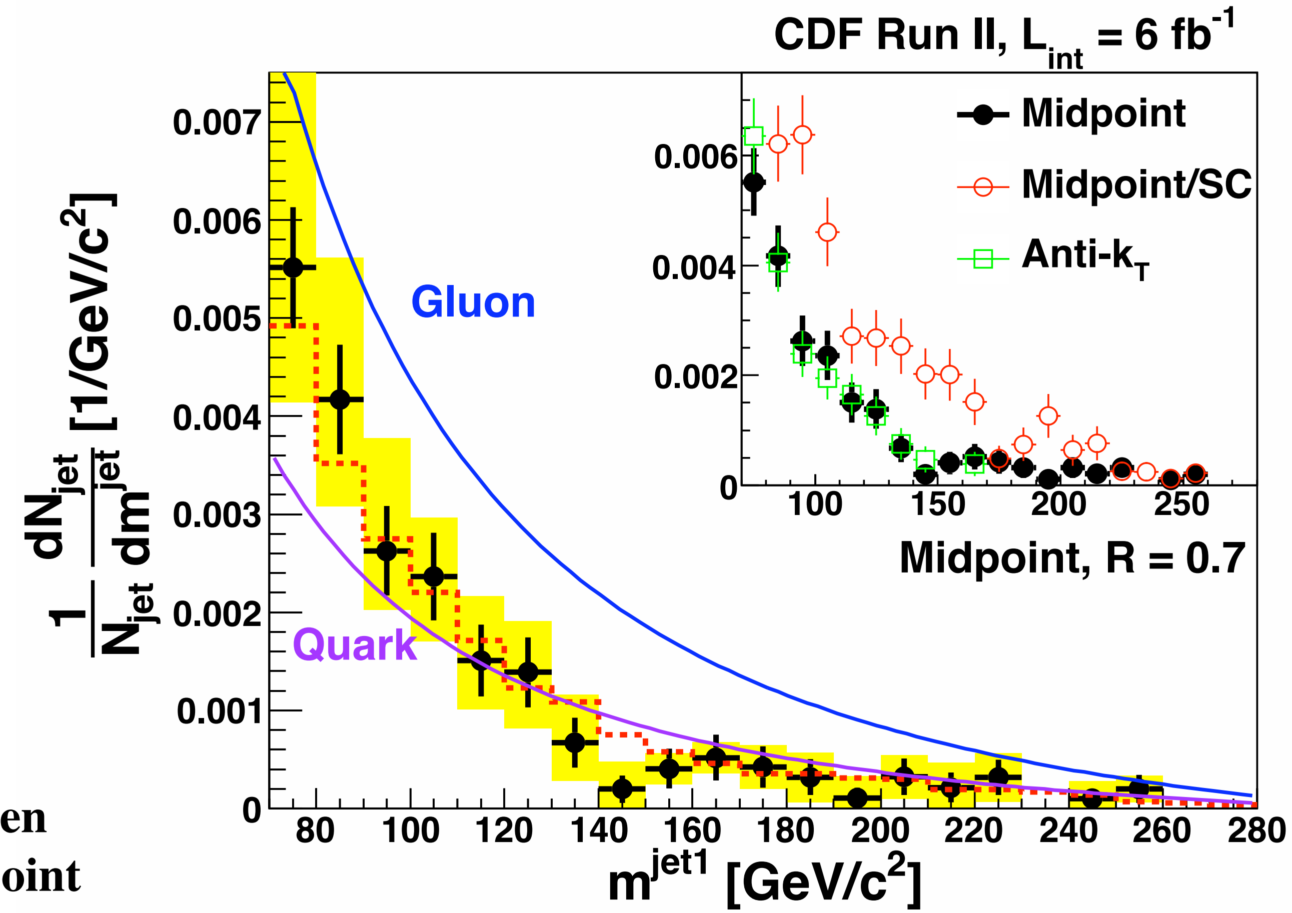


## Typical QCD configuration:

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

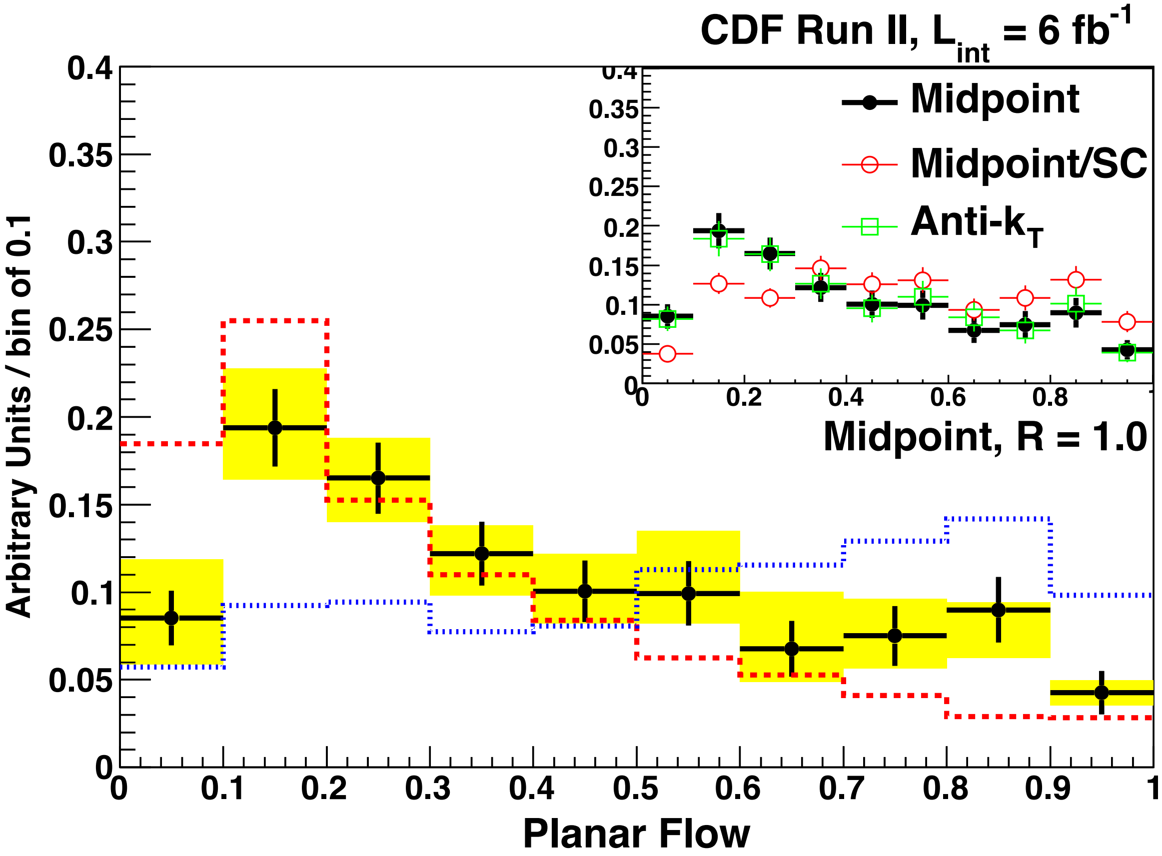
# Jet Substructure – Mass

- 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 – 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**

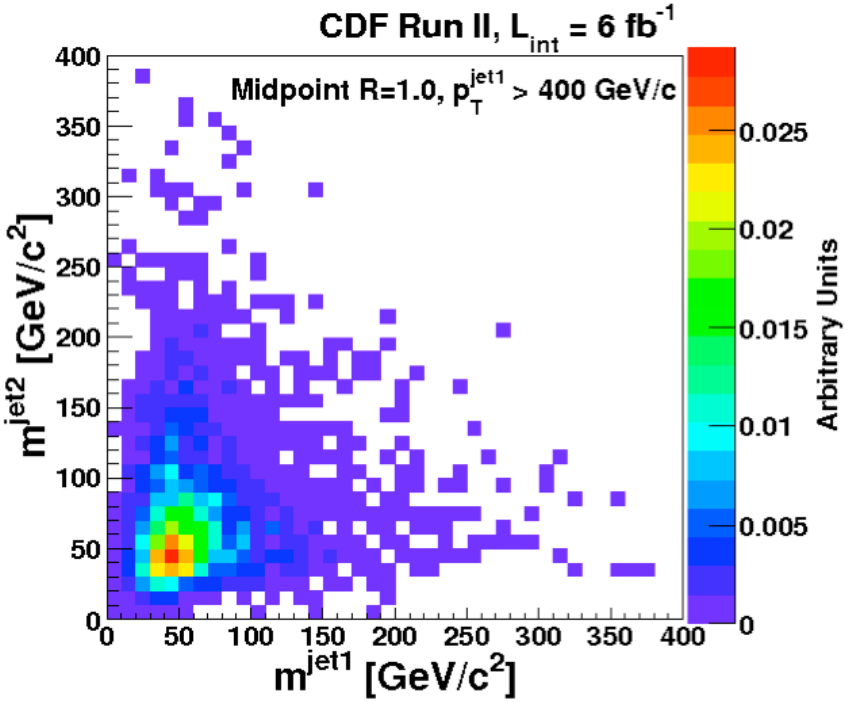


$130 < m_{jet} < 210$ GeV/$c^2$

# Summary of Substructure Studies

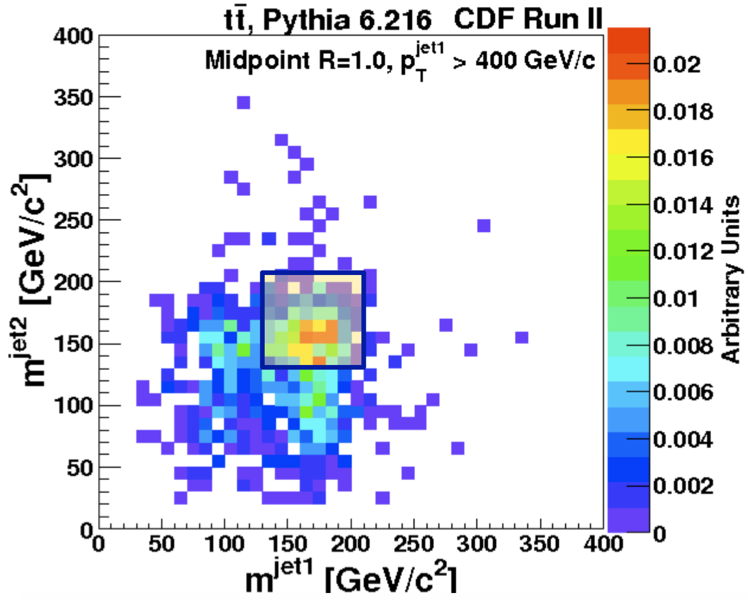
- **Results show:**
  - **High $p_T$ jets look like QCD light quark jets**
    - $m^{jet}$ good discriminant
    - 1.4±0.3% of QCD jets have $m^{jet} > 140$ GeV/$c^2$
  - **Internal structure looks "two-body"**
    - Angularity & planar flow
  - **pQCD gives good description of mjet**
    - Other substructure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

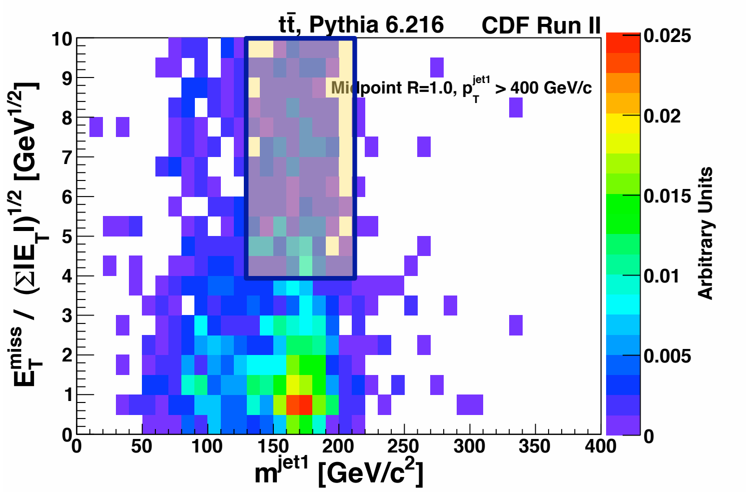
- **Jet masses are largely uncorrelated**
  - **Recoil jet doesn't know about leading $m^{jet}$**



# 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

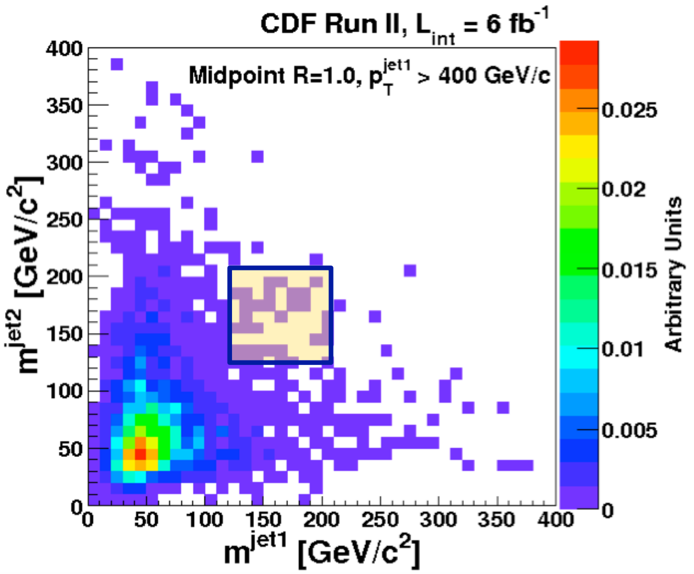


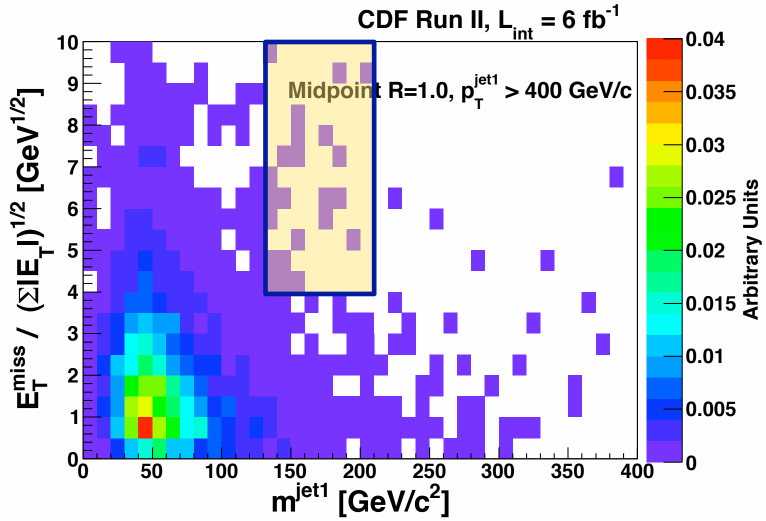


γ ~ 2.5

# Selection Requirements

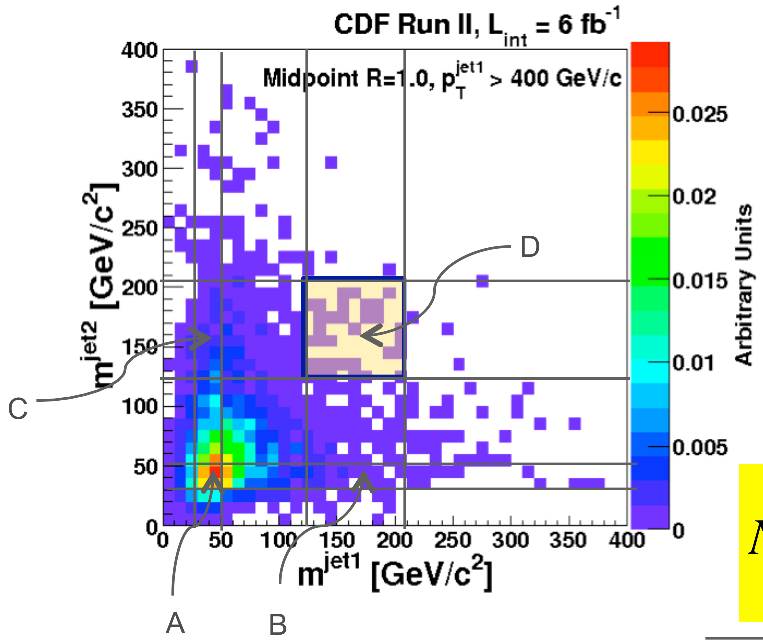
- **Keep selection simple**
  - Focus on two separate channels
- **All Hadronic Top (1+1)**
  - Require 2 jets with $130 < m^{jet} < 210$ GeV/c$^2$
  - Require $S_{MET} < 4$
  - Estimate background using "ABCD" technique
- **Semi-leptonic top (SL)**
  - Require $4 > S_{MET} > 10$
  - Require 1 jet with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



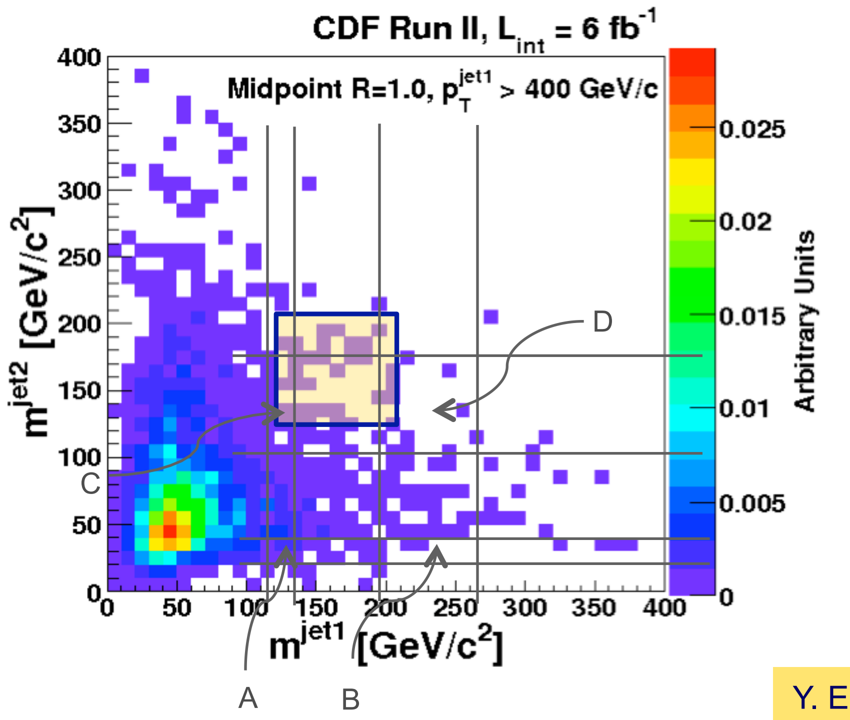
- Employ data to estimate backgrounds
  - Define mass windows
    $m^{jet} \in (130,210)$ GeV/$c^2$
    $m^{jet} \in (30,50)$ GeV/$c^2$
    - Use fact that $m^{jet}$ distributions uncorrelated for background
    - Signal is region D
    - In “1+1” sample, predict 13±2.4 (stat) bkgd events

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

- Observe $N_D$=32 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 $R_{mass}$

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

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

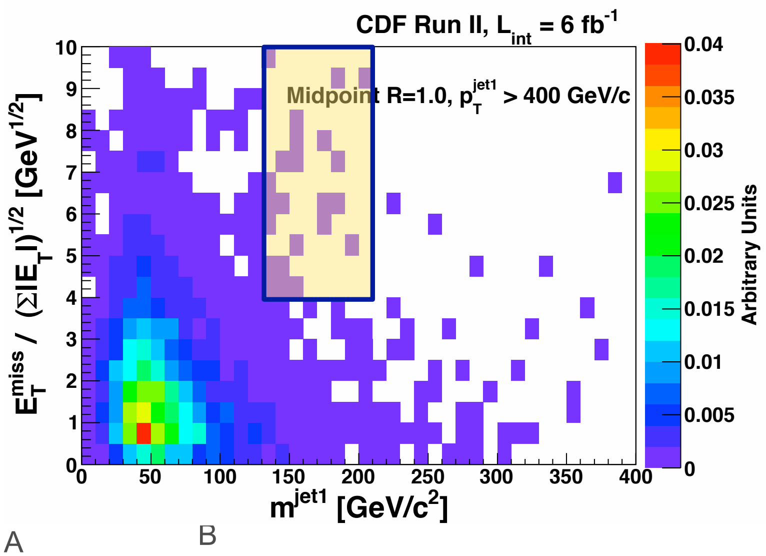
  - POWHEG: Rmass=0.89±0.03

| MC tools | Matching | $R_{mass}$ |
|---|---|---|
| Sherpa | Yes | $0.88 \pm 0.03$ |
| MadGraph | Yes | $0.86 \pm 0.04$ |
| MadGraph | No | $0.76 \pm 0.04$ |
| Herwig | No | $0.86 \pm 0.02$ |

Y. Eschel et al., arXiv:1101.2898

# “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**

| 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**
- **$m^{top}$ 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

# Conclusions

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

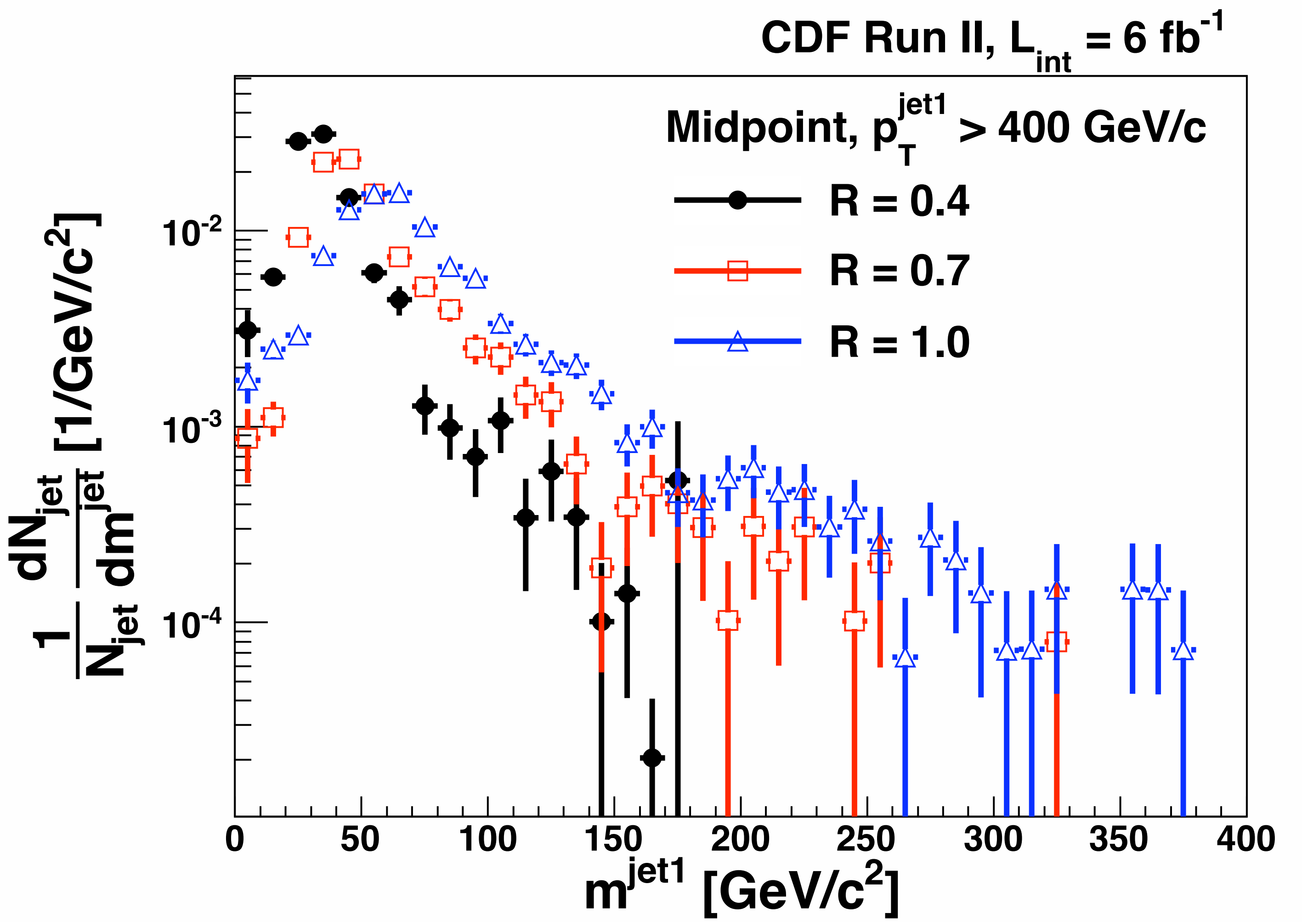
$$S/\sqrt{B} \approx 0.75$$

  - **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**
  - **Ultimately limited by rate**
- **Real focus are LHC expts**
  - **Now recorded sample with similar # of boosted SM ttbar**
    - But QCD backgrounds are larger
  - **Jet substructure is clearly essential tool**
    - Fully characterize QCD jets
    - Understand what the best tools are

# BACKUP SLIDES

# Comparison with Cone Size

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



# 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:

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

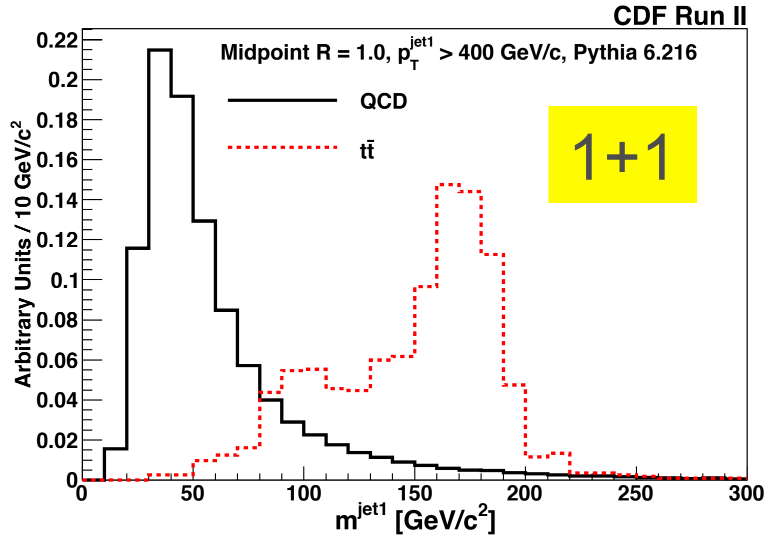
- Expect MI correction to scale with $R^4$:
  - Exactly what we see when comparing R=0.4 and R=0.7
- PYTHIA UE agrees well with data – same UE mass correction
- Use that to scale corrections for R=1.0
  - Method doesn't work with larger cone because of overlap

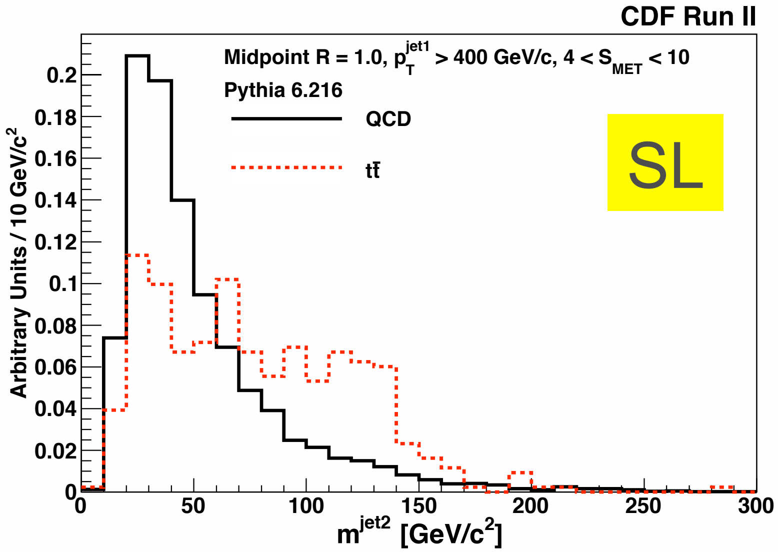
# Internal Jet Energy Scale

- 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 $m^{jet}$ ~ 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



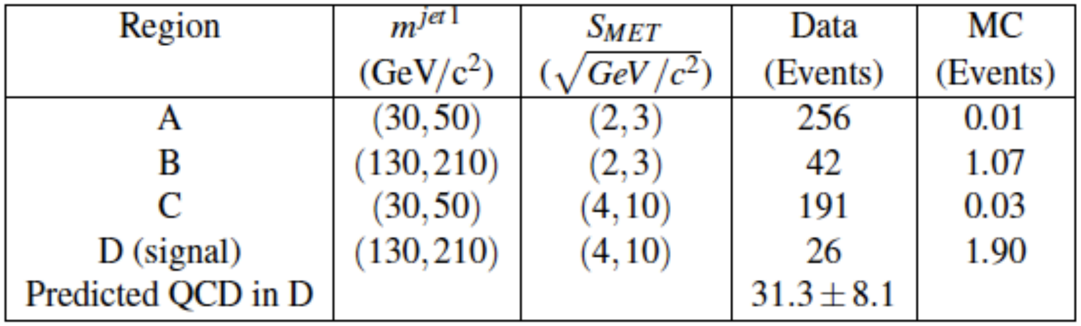


CDF Collaboration

# Background Calculations

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

- **SL**



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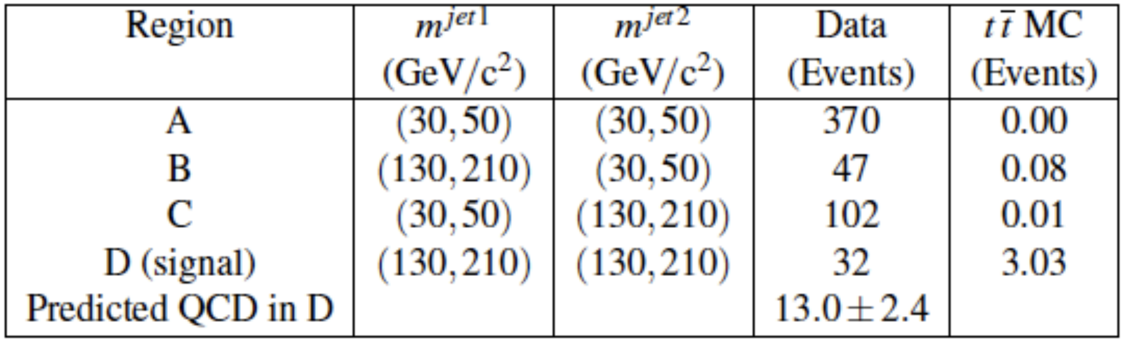
- **1+1**



| 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 | |