Select Recent Tevatron Results Tutorial for LHC

Outline

1. **Introduction**
2. **Boosted Objects Search – Testing QCD**
3. **Searching for Boosted Top Quarks**
4. **Forward-Backward Production Asymmetry**
5. **Improvements to Higgs search**
    - ○ **Adding γγ Final States**
    - ○ **More Data**
6. **Summary**

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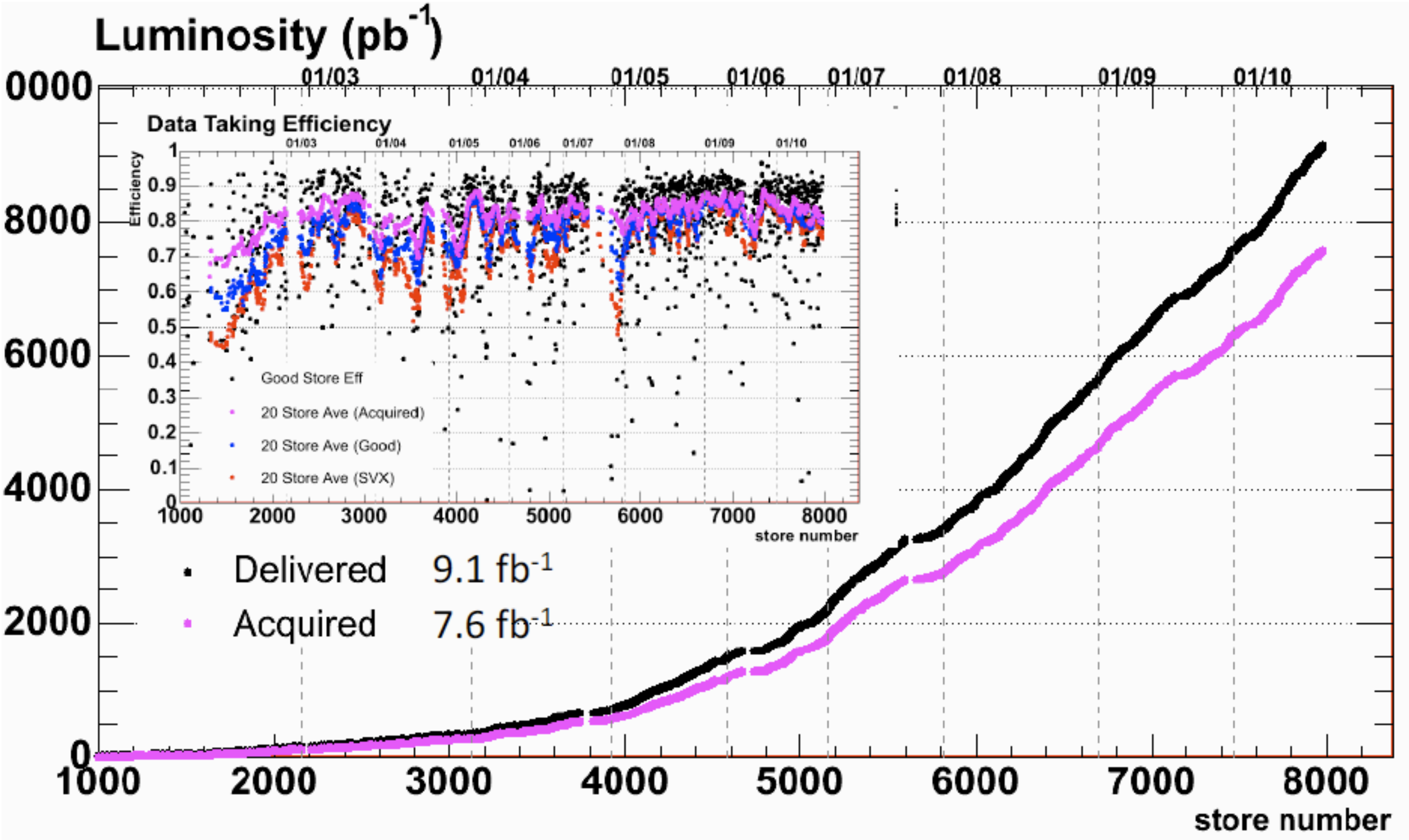
Goals of this Talk

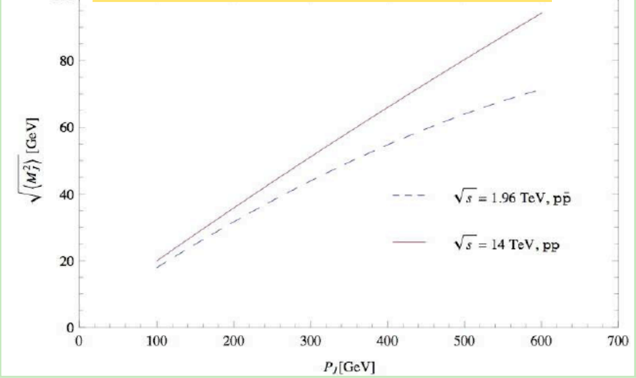
- **CDF II now has ~8 fb-1**
  - **Starting to explore kinematic boundaries**
  - **Working with multiple interactions (3-4/ crossing)**
- **LHC-like conditions for $L_{LHC} \sim 5 \times 10^{30}$ cm^{-2}s^{-1}**
  - **Have comparable number of multiple interactions**
- **Focus on a couple of "new" analyses**
  - **Massive, boosted objects**
    - Study QCD predictions for jet mass for $p_T > 400$ GeV/c
    - Measure substructure
      - **Angularity**
      - **Planar flow**
  - **Boosted top search**
    - Use high p_T jet sample
  - **Latest Higgs search**
    - Additional channels and statistics

Integrated Luminosity is Key

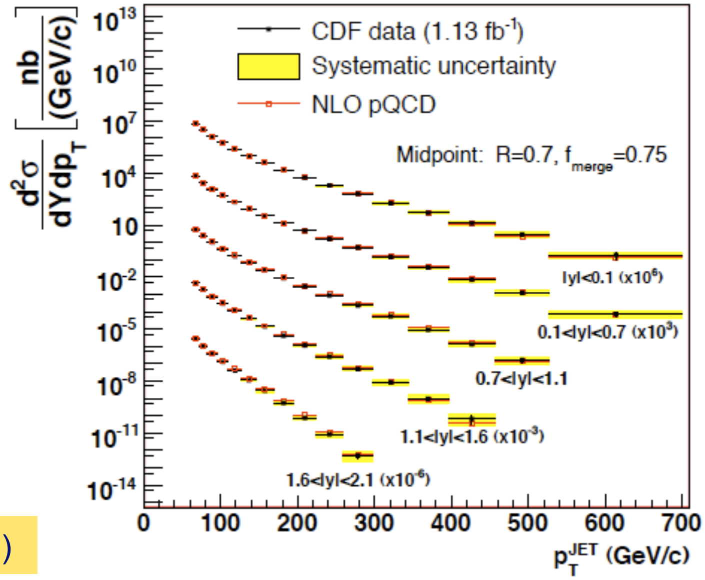


Boosted Study Motivation

- 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 3-4 thousand jet candidates
  - ○ Reporting first systematic study of substructure
  - ○ First look for boosted top quarks



Ellis et al., 0712.2447 (2007).

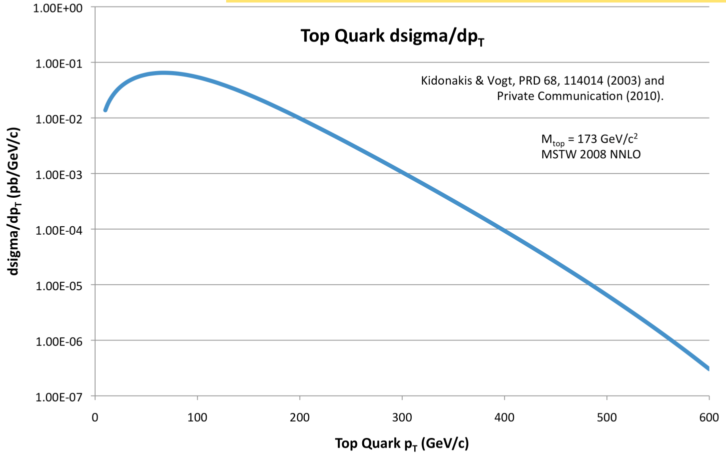


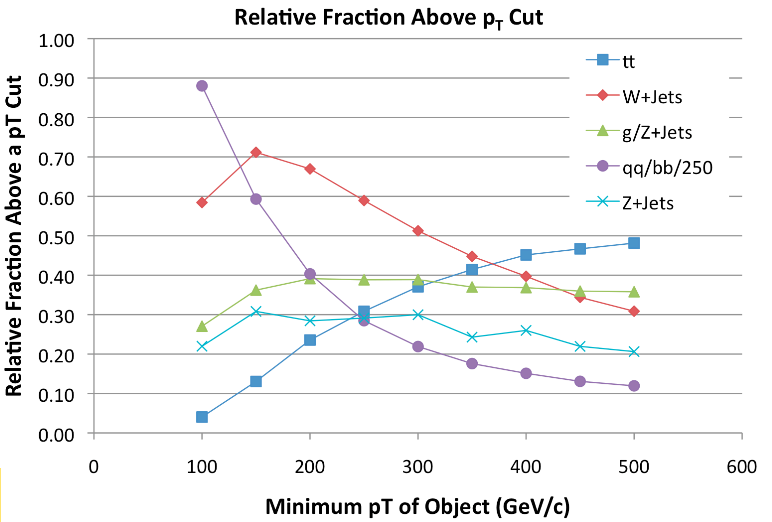
CDF Collaboration, PRD 78, 052006 (2008)

Boosted Objects at Tevatron

- **SM sources for high-p_T objects calculable**
  - **Dominated by light quarks & gluons**
  - **Mostly qq/qg final states**
- **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**

Kidonakis & Vogt, PRD 68, 114014 (2003)

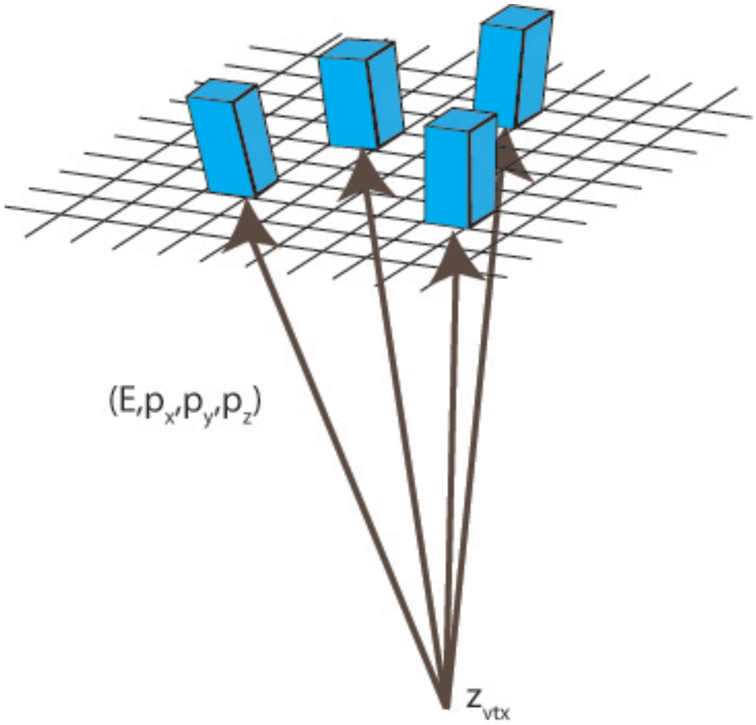




PYTHIA 6.4 Calculation

Strategy for Analysis

- **Select high p_T jets in CDF central calorimeter**
  - **Use tower segmentation to measure jet mass**
    - Calibrate with tracking information
  - **Employ standard “e-scheme” for mass calculation**
    - Each tower is a particle with m = 0
    - Four vector sum gives (E, p_x, p_y, p_z)
    - Have ~50 towers in R=0.7 jet
- **Employ Midpoint cone jets**
  - **Best understood in CDF II context**
  - **However, not fully IR-safe**



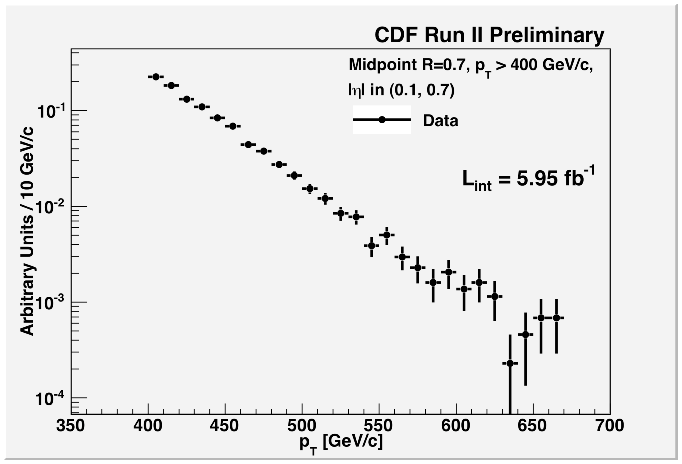
N.B. CDF central towers are $\Delta\eta \times \Delta\phi \sim 0.11 \times 0.26$

Data Selection

- Analyzed inclusive jet sample
  - Trigger requires E_T>100 GeV
  - Fully efficient for E_T>130 GeV
- Selected data with focus on high p_T objects
  - Kept any event with
    - Jet with p_T>300 GeV/c and |η|<0.7
    - Use 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

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

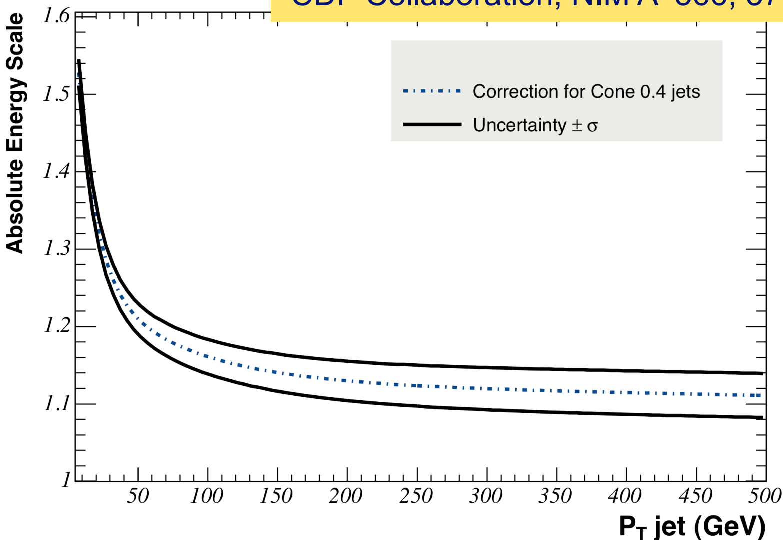
  - Event vertex, jet quality and loose S_{MET} (< 14)
- Resulted in 3621 events using jets with R=0.7
  - 3136 events with R=0.4



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

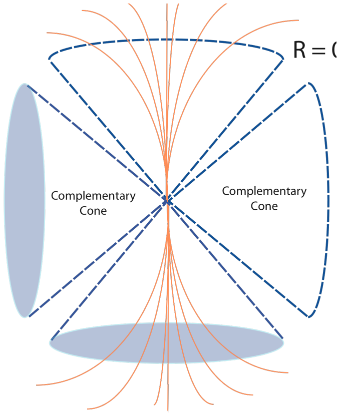
CDF Collaboration, NIM A 566, 375 (2006)

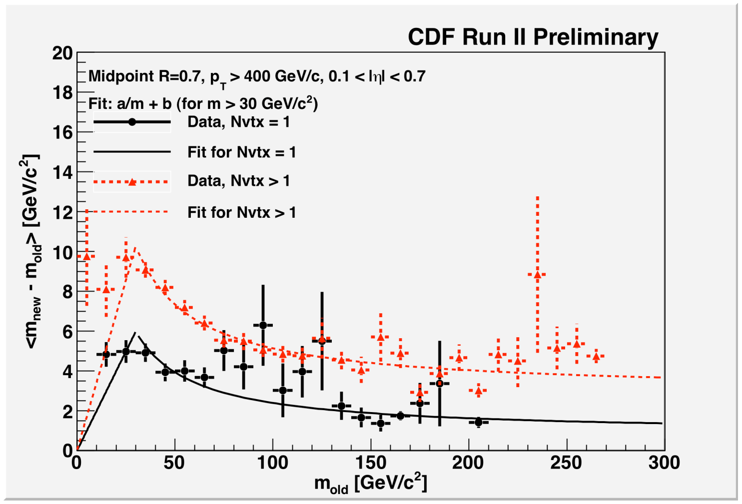


- Investigated numerous effects
  - Cluster merging
  - Effect of calorimeter inhomogeneity at $\eta=0$
    - Varied pseudorapidity window – no significant changes in mass
  - Calorimeter segmentation and jet recombination
    - Varied position of towers (especially azimuth) and corrections for geometry
  - Jet mass and substructure resolution/systematics
    - Detailed study of tracking/calorimeter response in data and MC/detector simulation

MI and UE Corrections

- Additional contributions from
  - Underlying Event (UE)
  - Multiple Interactions (MI)
    - Average # interactions ~3
  - Corrected for MI
- Looked at purely dijet events
  - Defined cones (same size as jet) at 90^o 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



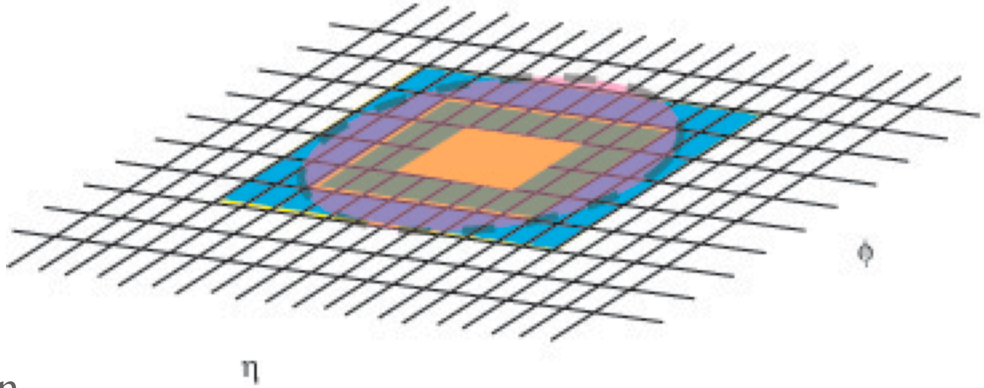


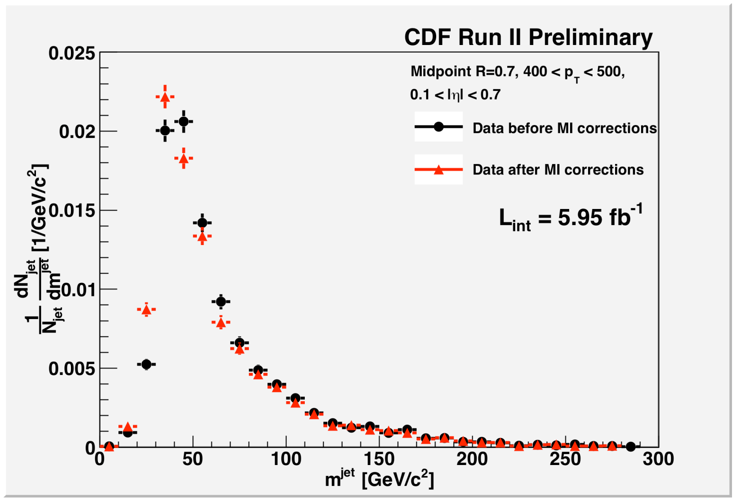
Correction scales as R^4

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, σ_m=1 GeV/c^2**
  - **At m^{jet}=120 GeV/c^2, σ_m=9.6 GeV/c^2**
- **Largest source of systematic uncertainty**

Ring 1 $\Delta\eta X \Delta\phi$=0.44x0.52 (yellow)
Ring 2 $\Delta\eta X \Delta\phi$=0.88x1.04 (green)
Ring 3 $\Delta\eta X \Delta\phi$=1.32x1.57 (blue)





Systematics on m^{jet}

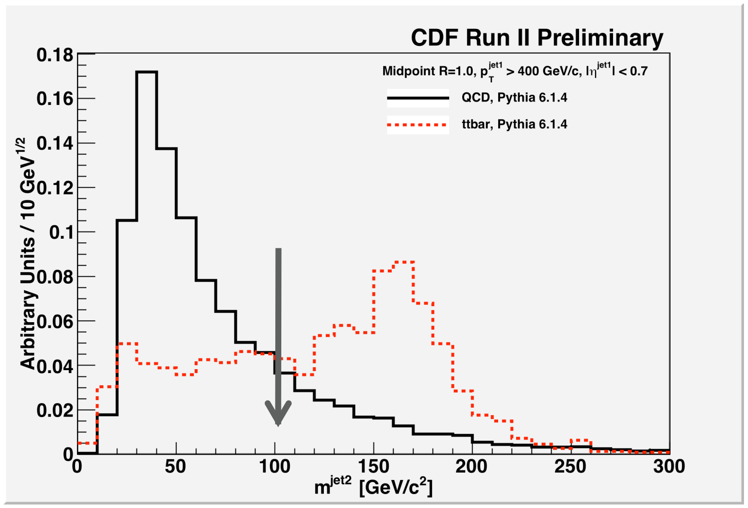
- **Sources of systematics:**
  - **Calorimeter energy scale**
    - Varies from 1 to 9.6 GeV/c^2 for 65 to 120 GeV/c^2 mass jets
  - **UE and MI modelling**
    - Estimate 2 GeV/c^2 based on uncertainty in high mass correction
  - **Recombination scheme & calorimeter segmentation**
    - Estimate 2.2 GeV/c^2 based on comparison of offline and ntuple results
  - **PDF Uncertainties**
    - Used standard 20 eigenvector decomposition to assess MC uncertainties

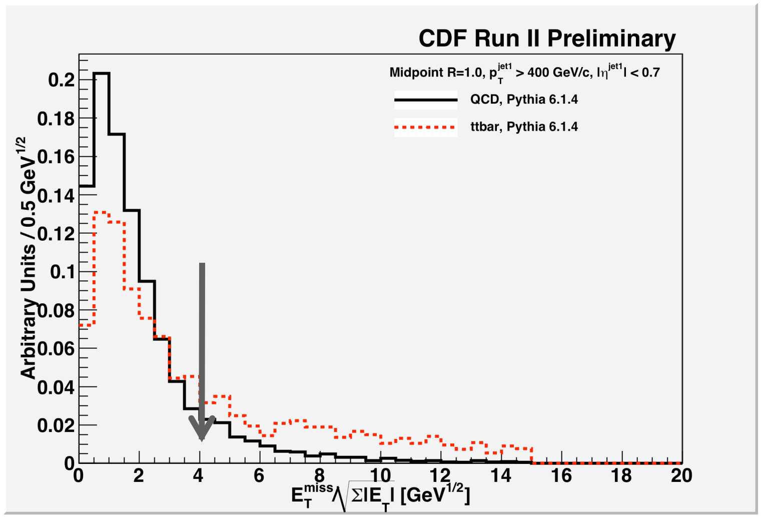
- **Believes uncertainties on data are uncorrelated**
  - **Combined in quadrature, gives total jet mass uncertainty of**
    - 3.4 GeV/c^2 for $m^{jet} = 60$ GeV/c^2
    - 10.5 GeV/c^2 for $m^{jet} > 100$ GeV/c^2

- **Effects jet mass distributions arising from bin-to-bin migration**
  - **See a small systematic shift in other substructure variables**
  - **More detailed investigation underway**

Reducing Top Contamination

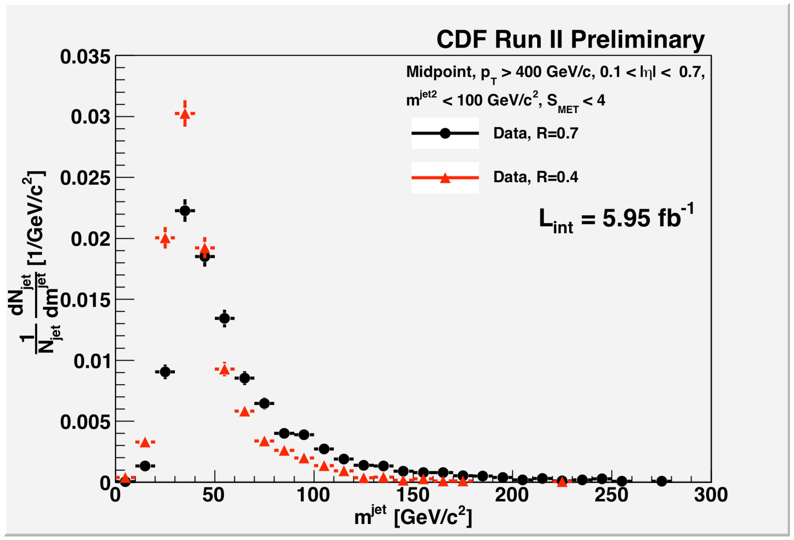
- **Expect about 2.2 fb of high p_T jets from top in sample**
  - **Eliminate by rejecting events with**
    - $m^{jet2} > 100$ GeV/c^2
    - Missing E_T Significance (S_{MET}) > 4
  - **Use jet cone of R=1.0 for improving top jet tagging**
    - See clear peak in MC for second jet mass
  - **Lose 29% of jet candidates**
    - 2576 events using R=0.7 jets
    - 145 events with jet $p_T > 500$ 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**
  - **General structure:**
    - Low mass peak ~ 30-40 GeV/c^2
    - Long high-mass tail

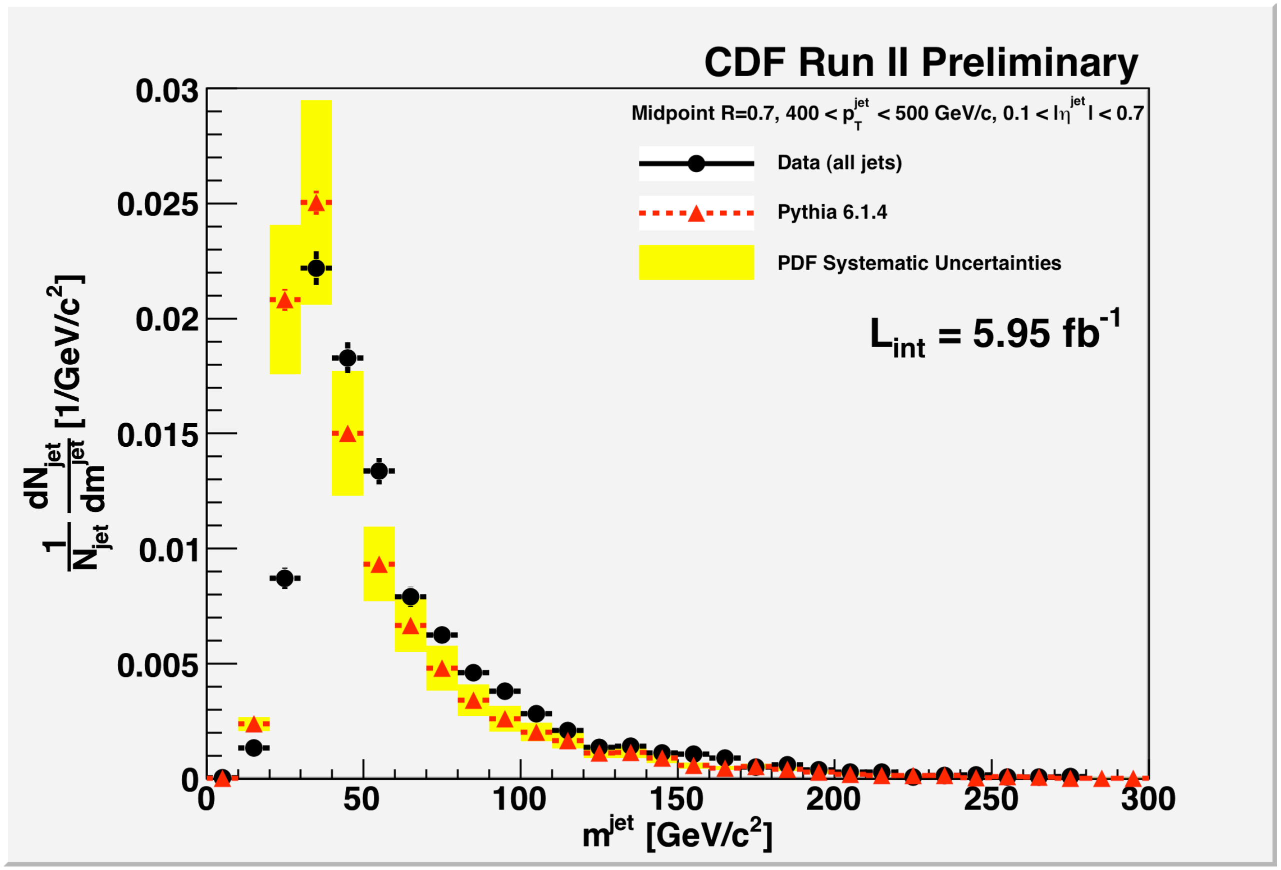


Cut Flow		
All Data, 5.95 fb^{-1}	75,764,270 events	
	R = 0.4	**R = 0.7**
At least one jet with $p_T > 400$ GeV/c, $\|\eta\|$ in (0.1, 0.7), and event quality cuts	3136 events	3621 events
$m^{jet2} < 100$ GeV/c^2 and $S_{MET} < 4$ (with $p_T^{jet2} > 100$ GeV/c and MI corrections)	2579 events	2576 events

- **Low-mass peak arises from non-perturbative QCD effects**
  - **Challenge to understand – nonperturbative effects & resolution**
  - **High mass tail predicted by NLO QCD**

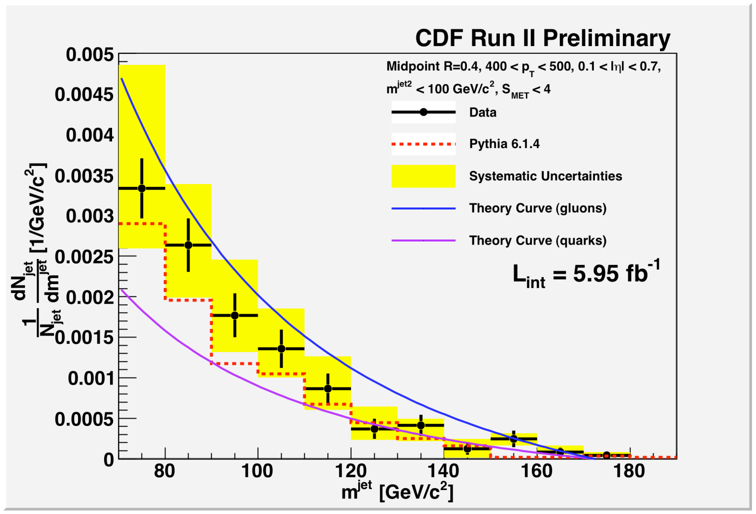
Comparison with PYTHIA

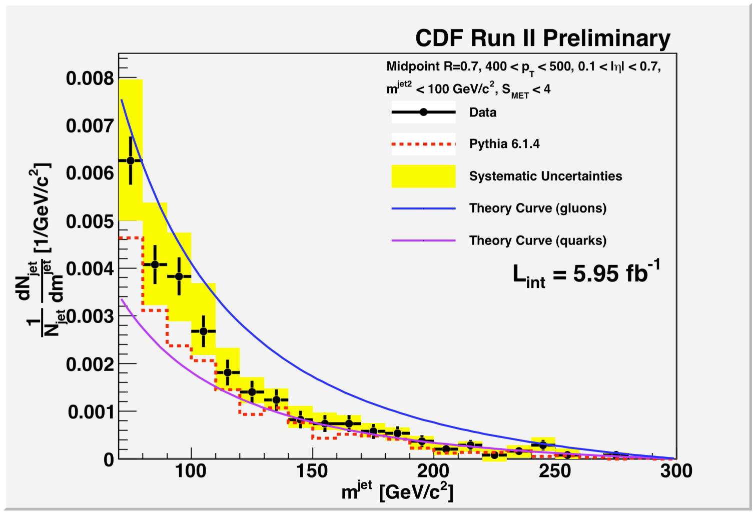
- PYTHIA 6.1.4
  - Standard CDF II QCD sample
  - PDF uncertainties based on eigenvector decomposition
- Agreement “OK”
  - PYTHIA Low-mass peak few GeV/c^2 lower
  - Systematic underestimate at higher masses



Jet Mass Compared with QCD

- **Make a direct comparison with QCD theory**
  - **Good agreement with data and QCD theory prediction**
    - Data interpolates between quark and gluon predictions
  - **Also agreement with PYTHIA MC calculation**





- **Important point:**
  - **Agreement in both rate and shape of distribution**
  - **Cone size dependence correctly predicted**

Angularity

- **Angularity is defined as**

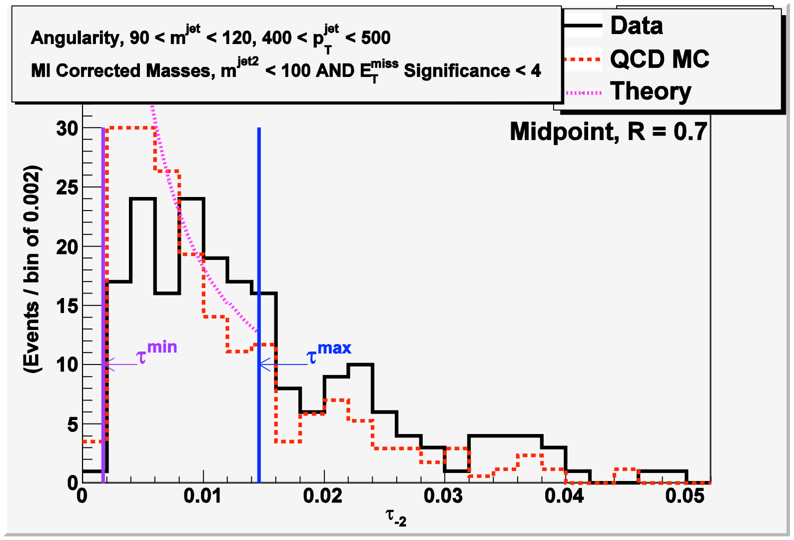
(Berger et al. ph/0303051;
Almeida et al., 0807.0234)

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

  - ○ **Emphasizes cone-edge radiation**

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

  - ○ **For large m^{jet}, have analytic approximation (peaks at low value with large tails)**
    - ➢ Expected to behave like 1/τ within a specific region
  - ○ **Start to see difference in data and QCD predictions**
    - ➢ See fewer jets at low angularity
    - ➢ On average, more "spherical" jets



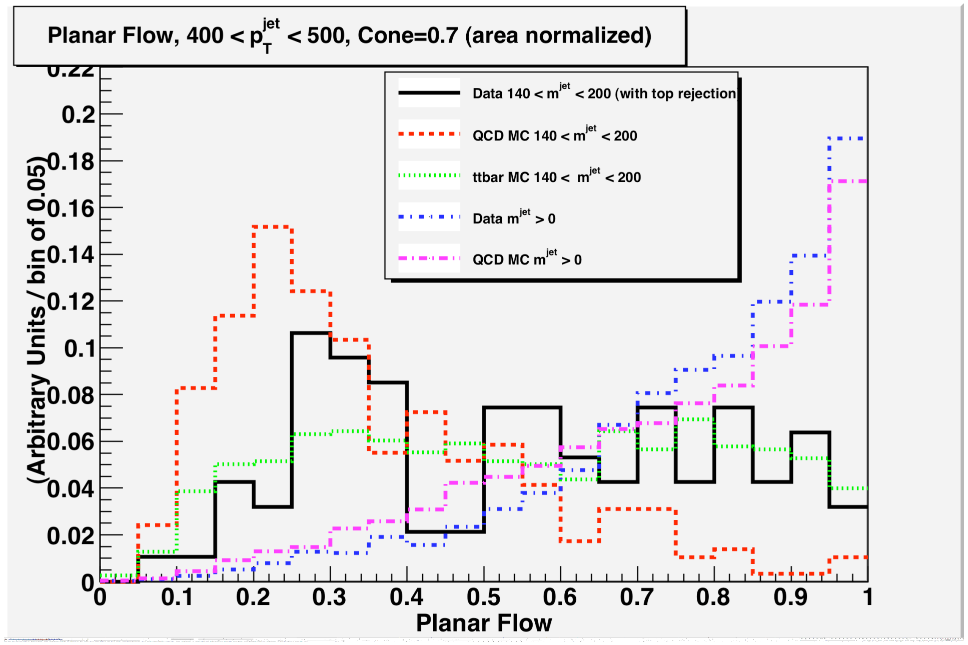
Planar Flow

- Planar flow complementary substructure variable
  - Large Pf -> more planar energy distribution
  - Predicted to provide separation between QCD and top
- Definition:
  - w_i energy of particle I

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

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

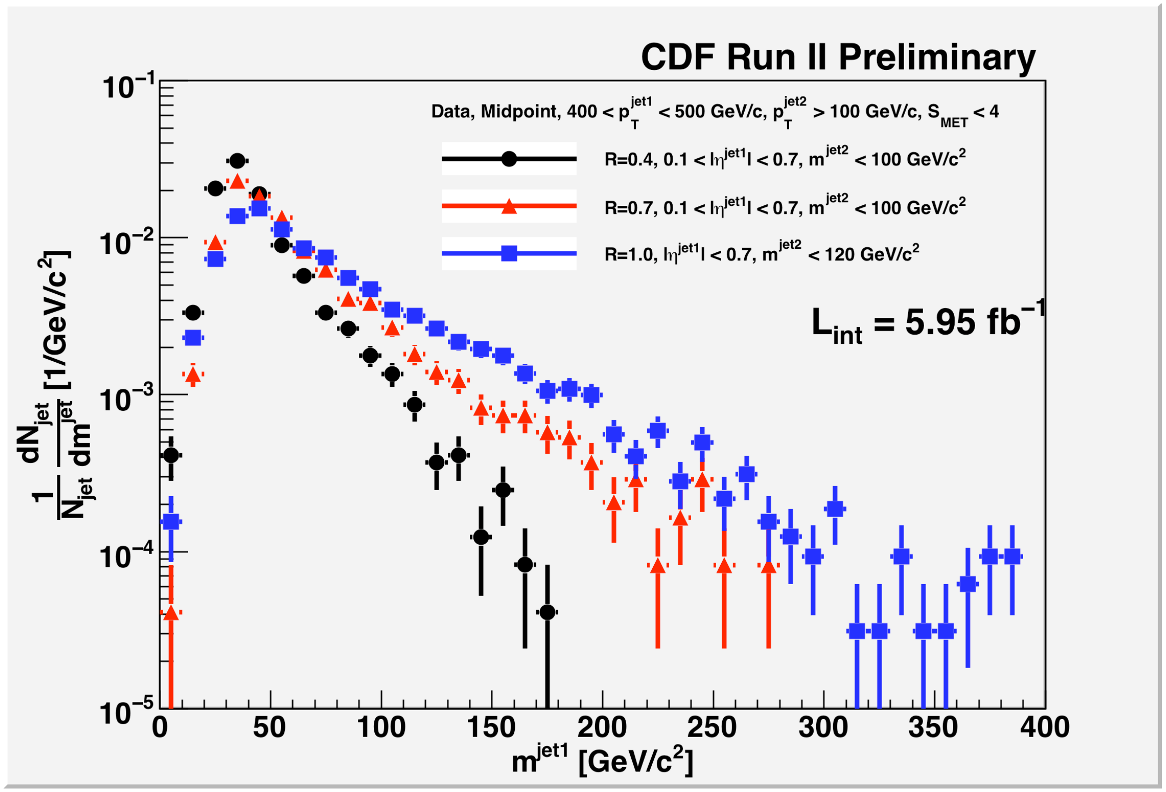
  - λ_1, λ_2 are eigenvalues



- Data prefers somewhat more aplanar configuration than QCD
  - PYTHIA differs significantly – data more "top-like"

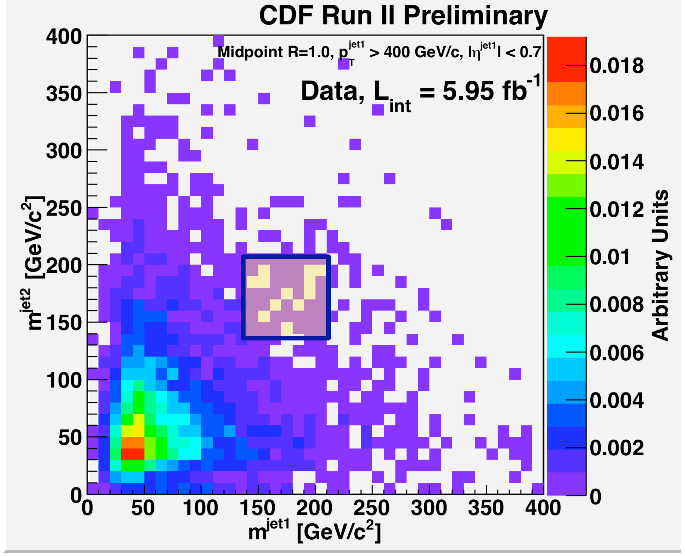
Jet Mass vs Cone Size

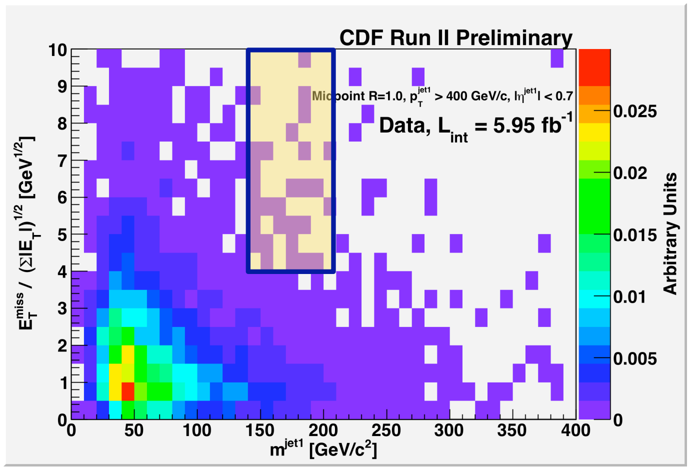
- **Comparison of cone sizes**
  - Expect cone size to have an effect on how large-angle radiation is included
  - These agree with PYTHIA predictions (see backup slides)



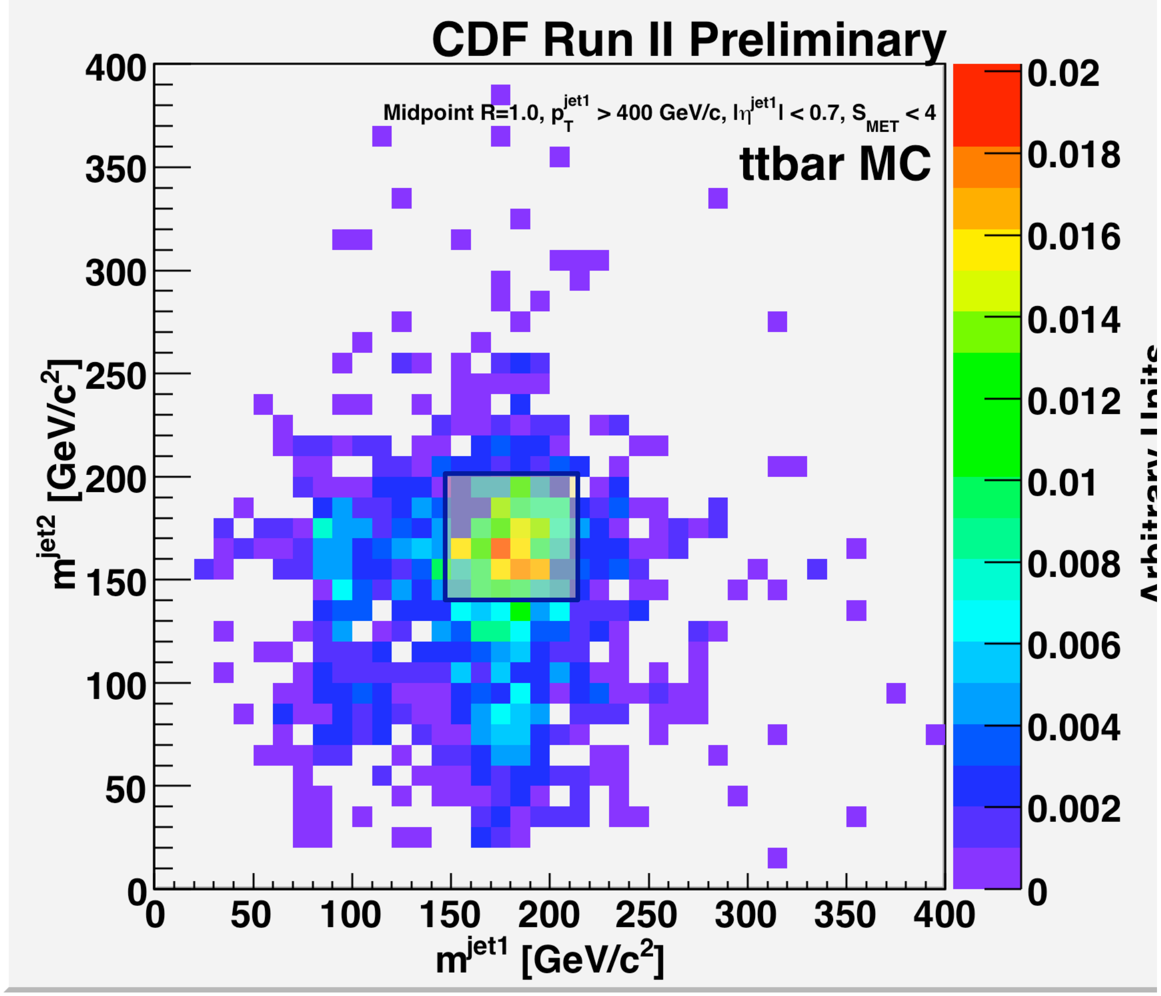
Strategy for Detecting Top

- Keep selection simple
  - Focus on two separate channels
- All Hadronic Top
  - Require $S_{MET} < 4$
  - Require 2 jets with $140 < m^{jet} < 210$ GeV/c^2
  - Estimate background using "ABCD" technique
- Semi-leptonic top
  - Require $4 > S_{MET} > 10$
  - Require 1 jet with $140 < m^{jet} < 210$ GeV/c^2
  - Estimate background using "ABCD" technique

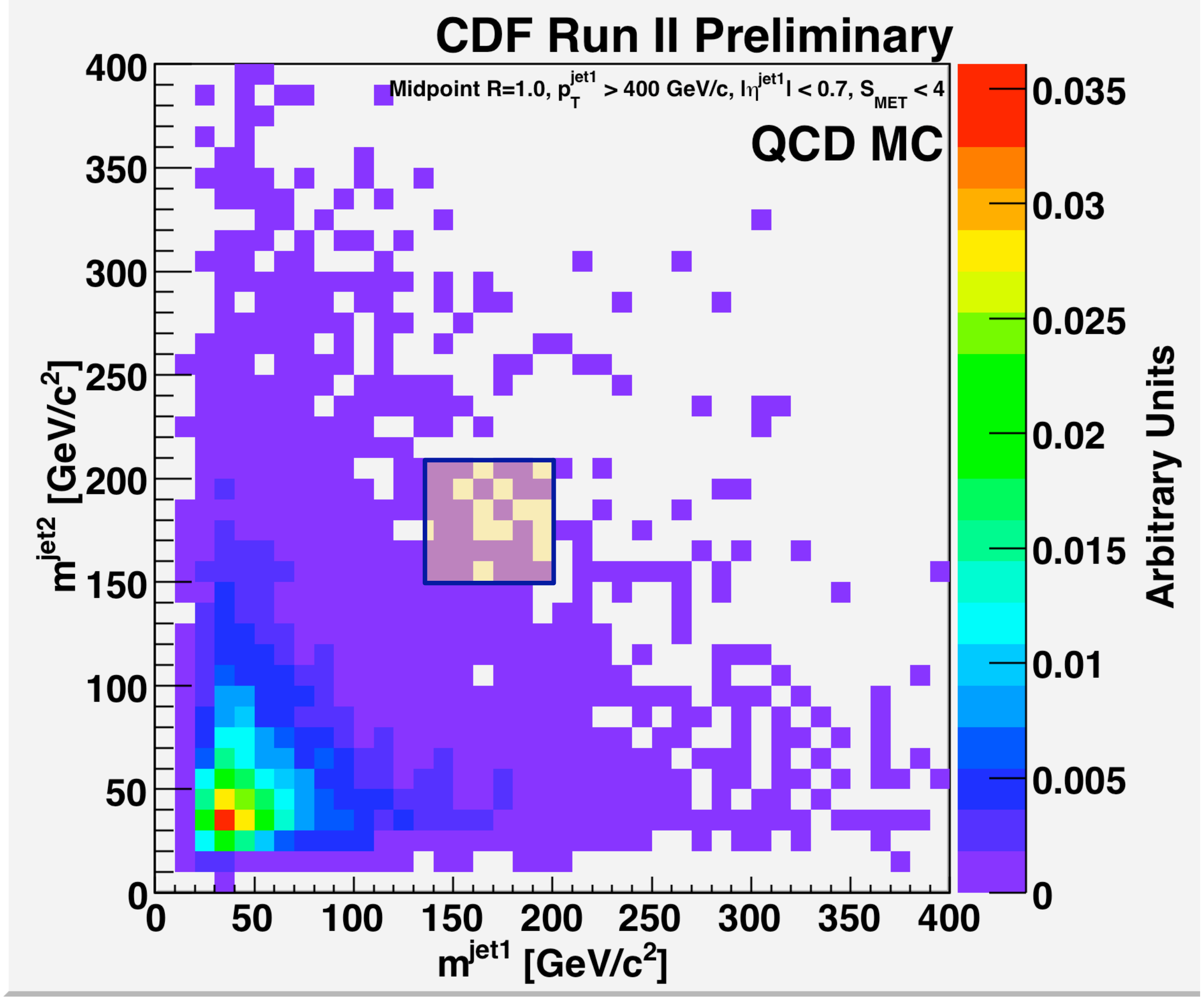




m^{jet2} vs m^{jet1} for Top MC

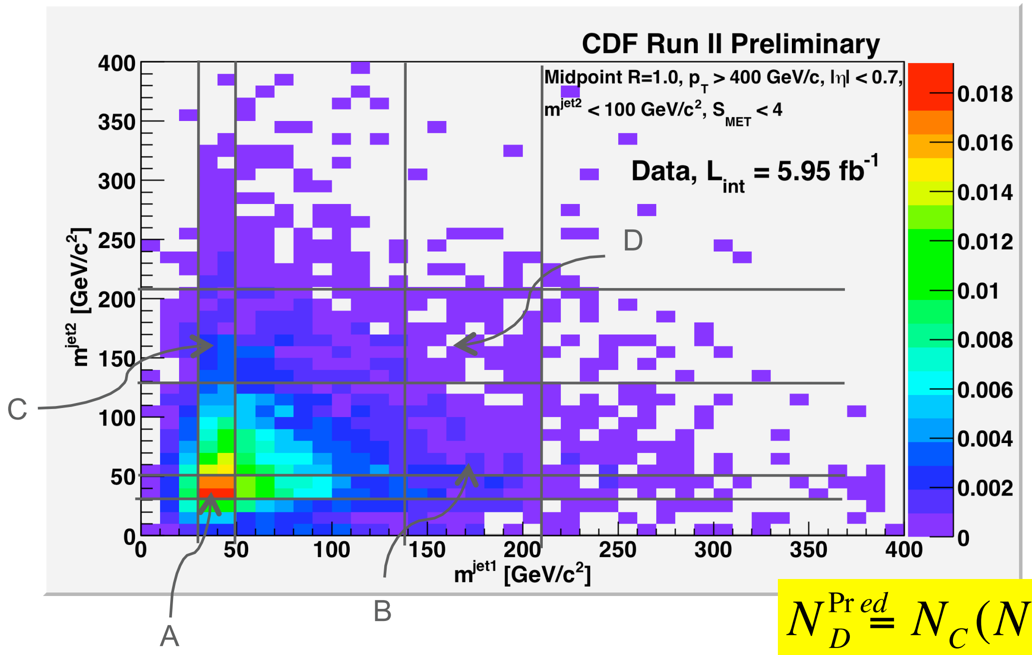


m^{jet2} vs m^{jet1} for QCD MC



Best "Simple" Counting of 1+1

- With R=1.0 cones, m^{jet1} and m^{jet2} are equally powerful
  - Use jet mass (140,210) GeV/c^2 to define ttbar candidates
  - Expect 3.5±0.5 top quark events to populate this region

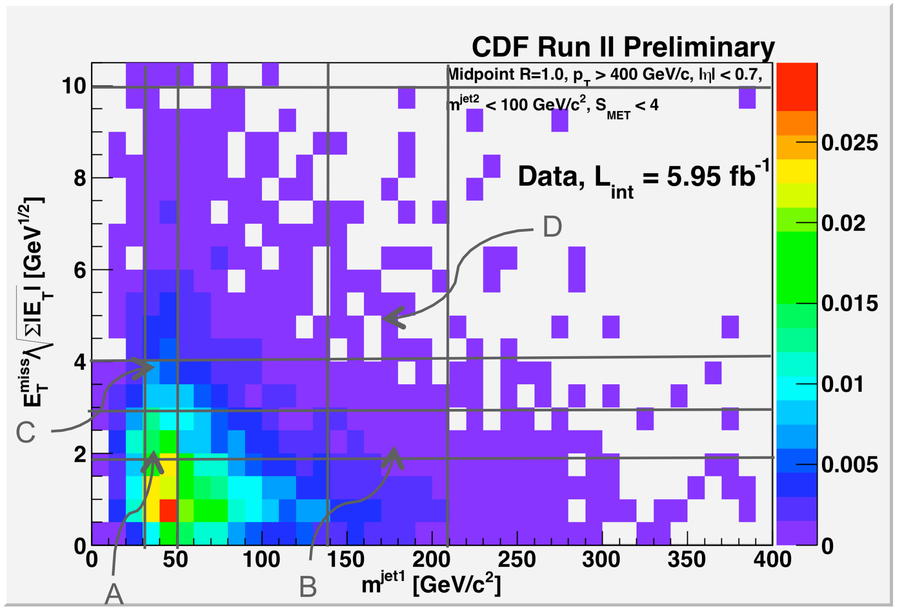


- Employ data to estimate backgrounds
  - Define mass windows
    $m^{jet} \in (140,210)$ GeV/c^2
    $m^{jet} \in (30,50)$ GeV/c^2
    - Use fact that m^{jet} distributions uncorrelated for background
    - Signal is region D
    - In "1+1" sample, predict 31±5 (stat) bkgd events
      - Observe N_D=61 events

$$N_D^{Pred} = N_C(N_B / N_A)$$

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 2.3±0.3 top quark events to populate this region



- Employ data to estimate backgrounds
  - Use regions $m^{jet1} \in (30,50)$ & (140,210) GeV/c²
  - $S_{MET} \in (2,3)$ & $S_{MET} \in (4,10)$
    - In “SL” sample, predict 45±7 bkgd events
      - Observe N_D=42 events
      - About a -0.4 σ deficit!

$$N_D^{\mathrm{Pred}} = N_C (N_B / N_A)$$

Uncertainties

- Background uncertainty (±11 GeV/c2 jet mass scale)
  - Shift window up/down
  - -26% and +34%
- Uncertainties on top efficiency (SM production)
  - Primarily jet energy scale of ±3% -> 24.5%
- Background statistics
  - 11.1% from counting
- Luminosity (±6%)
- MC m^{top} (± 2 GeV/c^2)
  - Shift window -> 0.3% change

- Overall uncertainties added in quadrature
  - -38% and + 44%
- Incorporated into upper limit calculation
- Use frequentist method
  - Marginalize nuisance parameters

Top Quark Cross Section Limit

- **Assume we observe signal + background**
  - **Set upper limit on SM production σ for top quark $p_T > 400$ GeV/c**
- **Observe 103 events with 76+/-9 background**
  - **Calculate 95% CL upper limit using CLs method**
    - Systematic uncertainties incorporated in same way as Higgs search
    - $N_{LIM} = 69.3$ events
  - **Efficiency from MC**
    - 553 & 343 ttbar expected in 2 channels (out of 4041)
    - Efficiency = 0.212

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

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

$$= \frac{69.3}{(5.95)(0.212)} = 54 \text{ fb}$$

- **Compare with other limits (using specific Z' models):**
  - **~600 fb in l+jets (0.96 fb^{-1})**
  - **~200 fb in all-hadronic (2.8 fb^{-1})**

Top Quark Production Asymmetry

- **D0 has made studies of the production asymmetry**

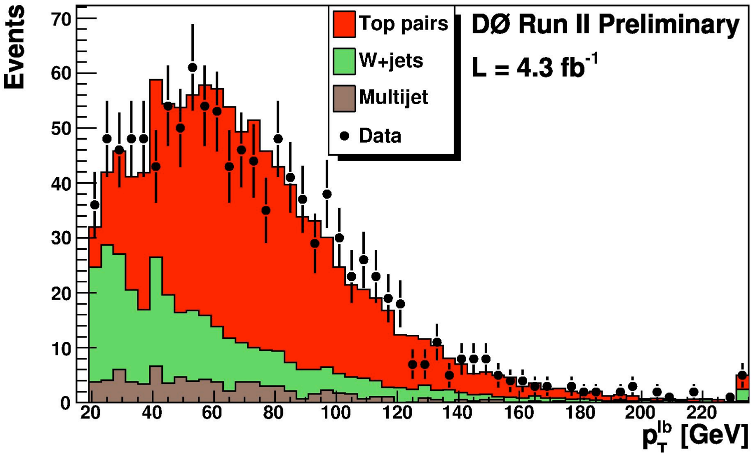
$$A_{fb} \equiv \frac{N^{\Delta y>0} - N^{\Delta y<0}}{N^{\Delta y>0} + N^{\Delta y<0}}$$

  - **SM predicts a small asymmetry**
    - ~ 0.01±0.02
  - **Earlier D0 measurement gave an interesting value (0.9 fb^{-1})**

$$A_{fb} = 0.12 \pm 0.08(stat) \pm 0.01(syst)$$

- **D0 and CDF have reported new measurements**

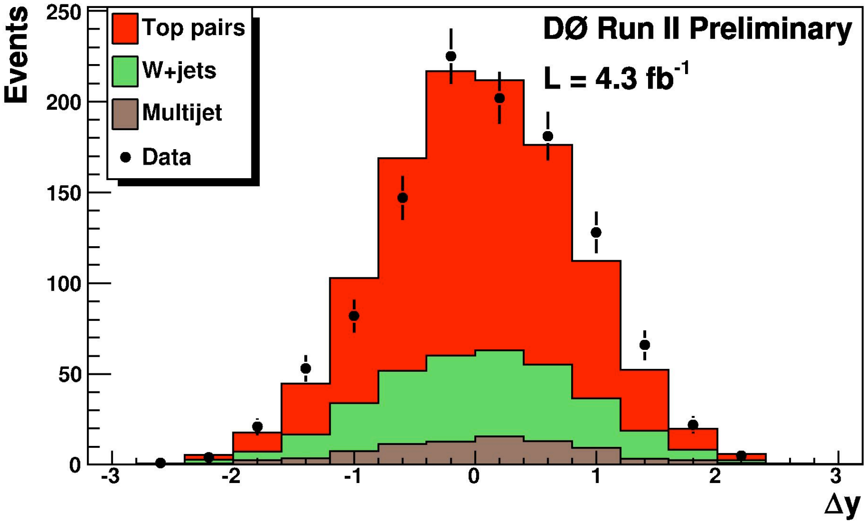
- **Idea is to fully reconstruct lepton+jets events**
  - **Then work hard to measure systematic effects**
  - **Use 4.3 fb^{-1}, and select:**
    - lepton+jet events
    - B-tag one of the 4 leading jets
    - Find best kinematic reconstruction to measure rapidity



A_{fb} Results

- **D0 observes 1137 events**
  - **Expect 808±37 from ttbar**
  - **Fit Dy distribution to templates**
    - Signal from MC@NLO
    - Background primarily from data – W +jets where anti-lepton cuts applied

$$A_{fb} = 0.08 \pm 0.04(stat) \pm 0.01(syst)$$



- **Systematic uncertainties small**
  - **Primarily W+jets asymmetry (+0.006)**
  - **Interesting result as it still suggests larger asymmetry than predicted**
- **What makes this even more interesting is that CDF also has a larger asymmetry (5.3 fb^{-1})**

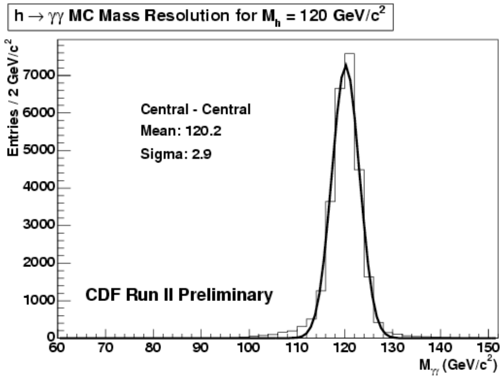
$$A_{fb} = 0.150 \pm 0.050(stat) \pm 0.024(syst)$$

$$A_{fb}^{pred} = 0.050 \pm 0.015$$

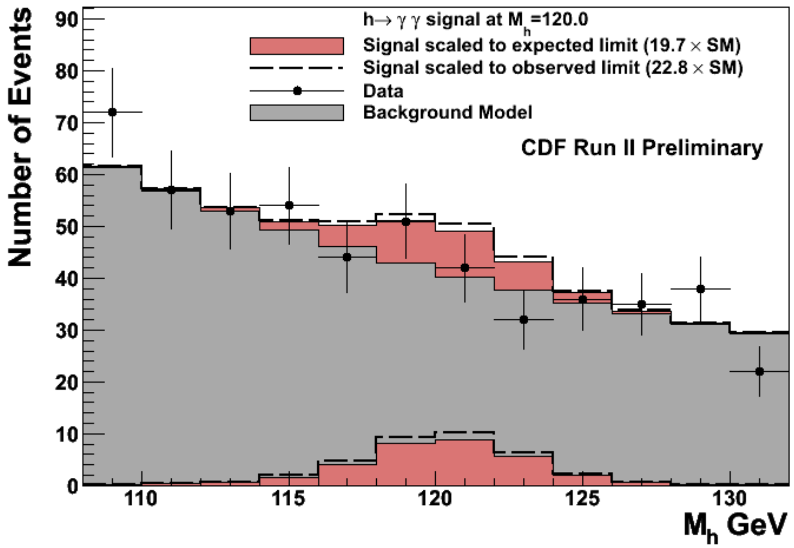
Update to Higgs Search

- Not a “new” analysis
  - However, opposite challenge:
    - Sensitivity comes from many channels being combined
  - Latest results add
    - H → γγ, (CDF)
    - H→W$^+$W$^-$→lνqq (D0)
    - More luminosity
  - Why not γγ before?
    - Very low rate
    - Backgrounds thought to be insuperable

- OK mass resolution: 3 GeV/c^2

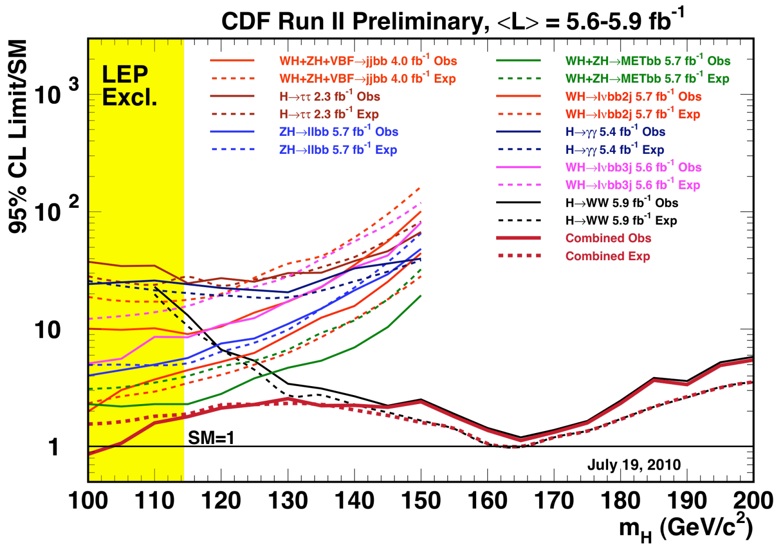


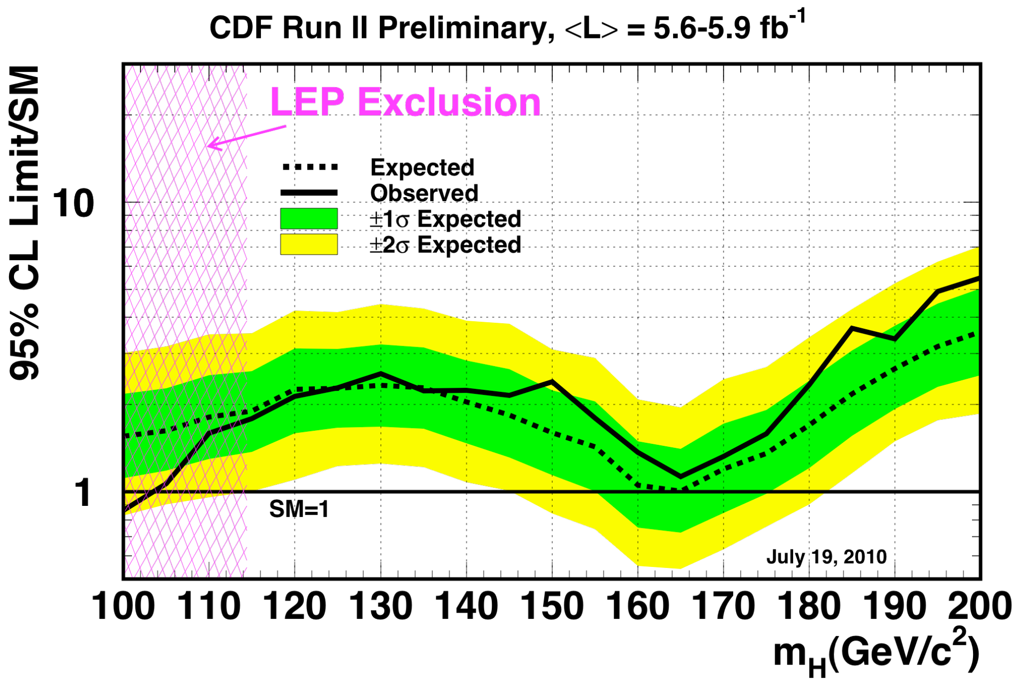
- Challenge is background



Combine CDF Channels

- Perform a combined channel analysis
  - Essentially identical to single top machinery
- Limit is incremental improvement
  - No evidence!

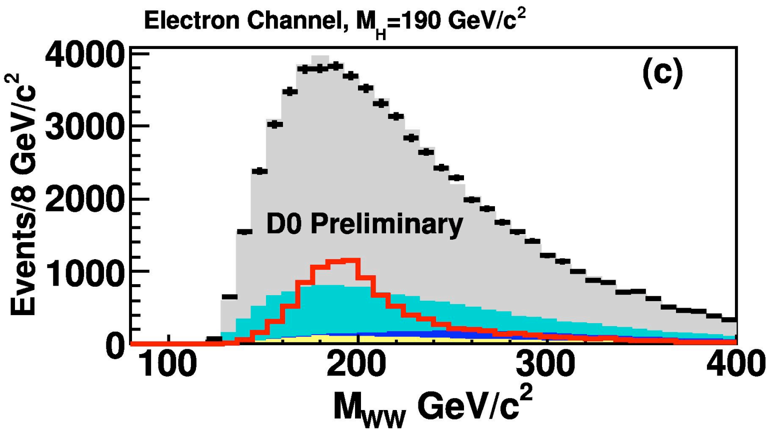


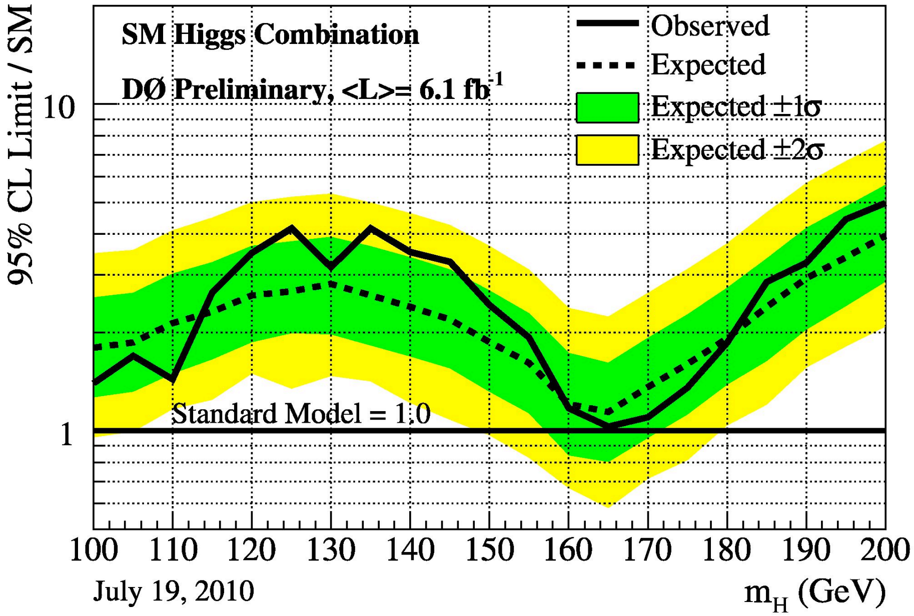


Combine D0 Channels

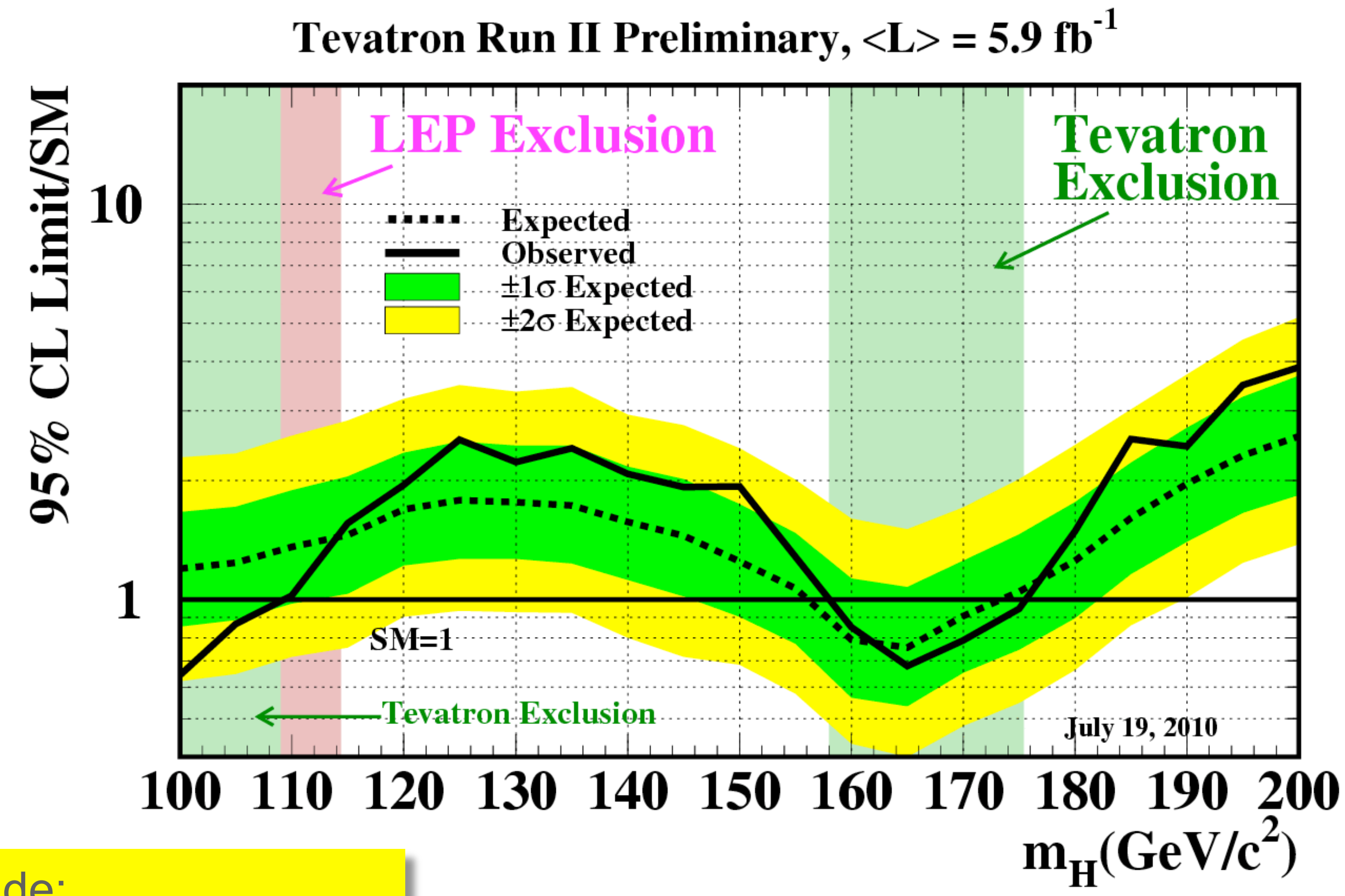
- Perform a combined channel analysis
  - Somewhat more channels -- 73

- Limit is incremental improvement
  - No evidence!





Tevatron Higgs Limit



Exclude:
$100 < m_H < 109$ GeV/c^2
$158 < m_H < 175$ GeV/c^2
at 95% confidence level

Conclusions

- **First measurement of jet mass and substructure for high p_T jets**
  - **Confronted by data forces one to understand systematics**
    - Multiple interaction corrections
    - Calibration of mass scale
  - **Allows for test of QCD predictions:**
    - Jet mass, substructure
- **First attempt at boosted top detection**
- **Top production asymmetry plot thickens**
- **Higgs search progresses**
  - **Exclusion region for SM Higgs growing**
  - **Expect improvements from**
    - Integrated luminosity
    - Analysis innovations
- **Lessons for LHC?**
  - **Think "simple"**
    - … and data-driven
  - **Coherent analysis efforts**
    - Higgs search involves >100 collaborators
    - Right balance of "internal competition" and collegiality

BACKUP SLIDES

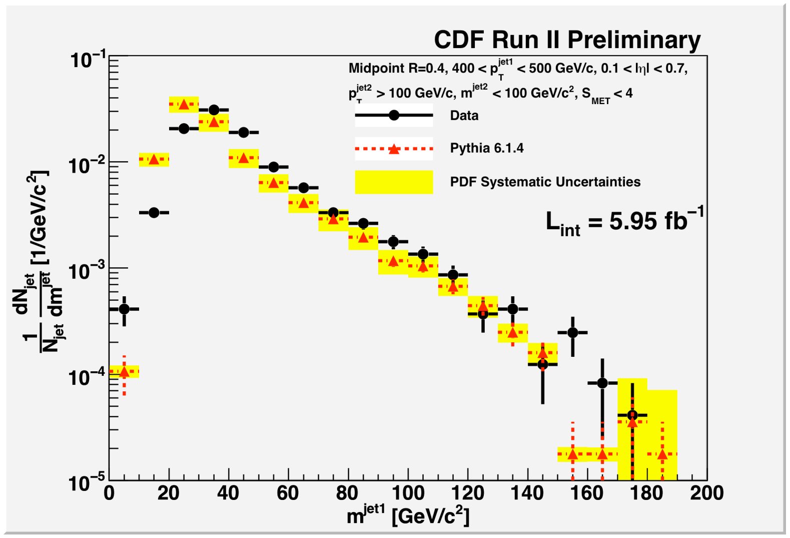
MI/UE Corrections

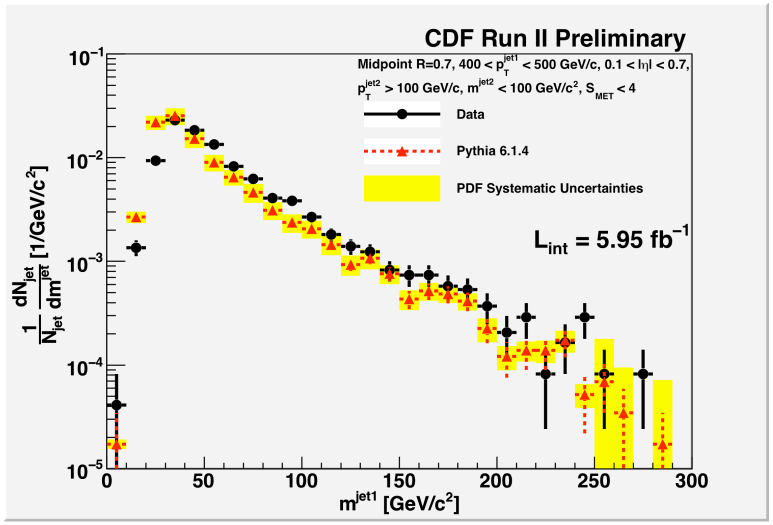
- **Looked at how to make MI correction in a variety of ways**
  - **Looked at mass corrections event-by-event**
  - **But statistical fluctuations large, event-to-event**
  - **Chose to develop a parametrized correction**
- **Note that:**

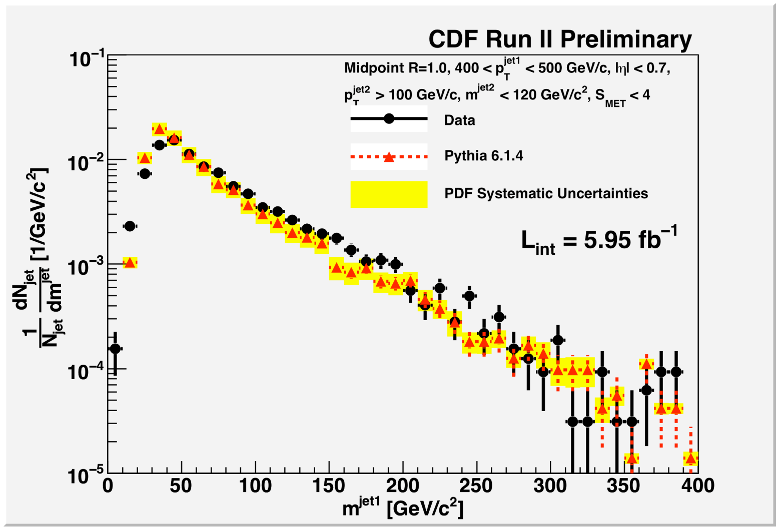
$$\delta m^{jet} \simeq \frac{E_{tower} E_{jet} \Delta R}{m^{jet}}$$

- **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**

Jet Mass: Data vs PYTHIA





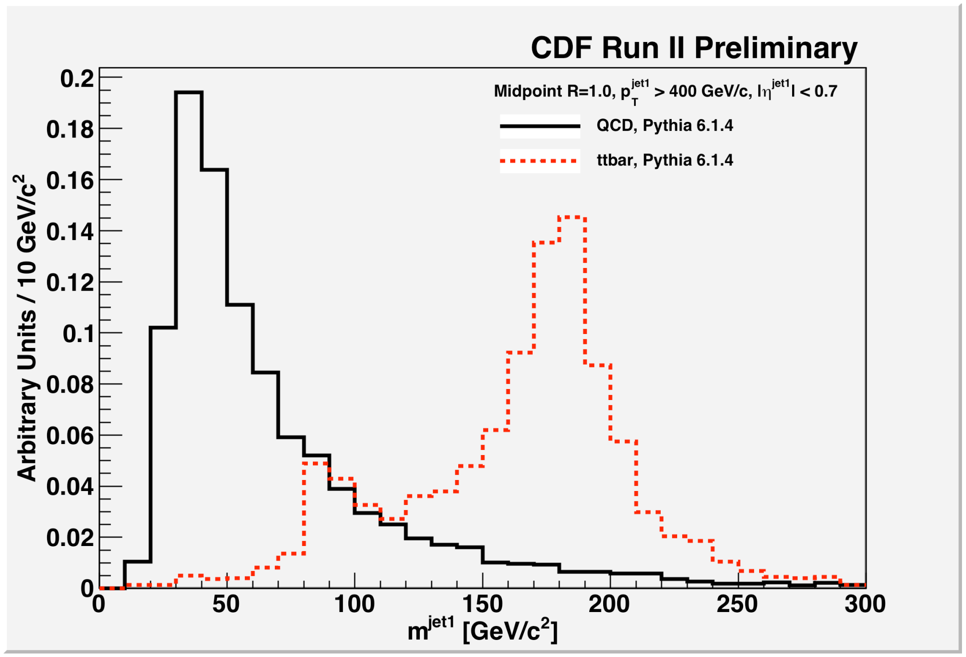


Internal Jet Energy Scale

- 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**



Comparison of Cone Sizes