QCD Results from the Tevatron

Shulamit Moed Sher
Fermilab

On behalf of the CDF and D0 collaborations

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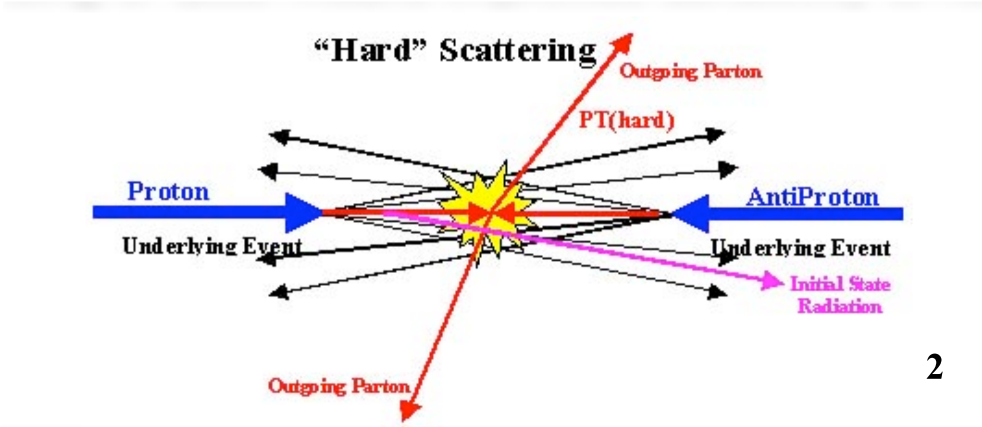
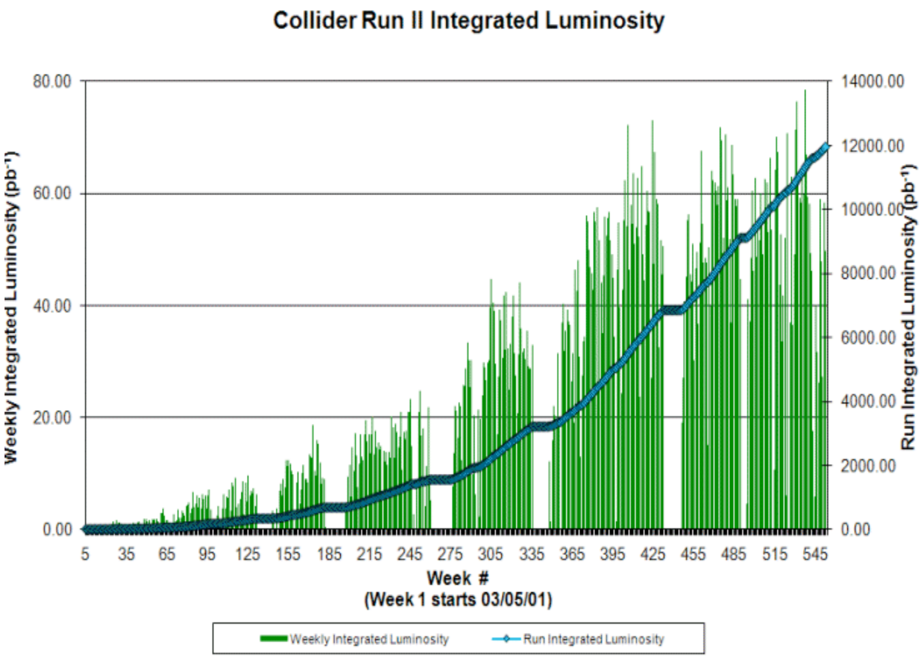
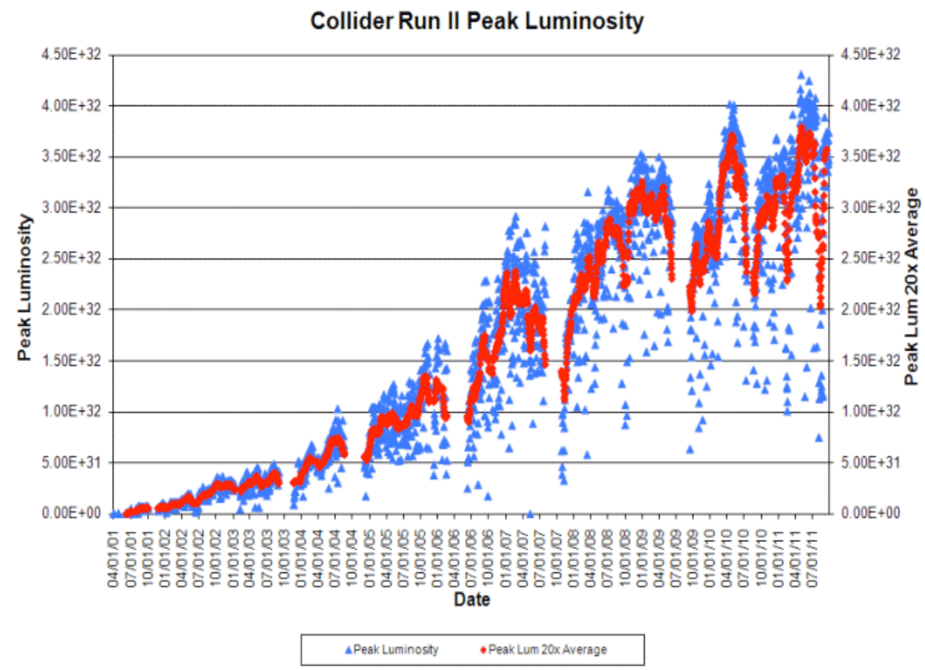
Introduction

- Mature QCD studies at the Tevatron benefit physics program at the LHC.
  - Challenging measurements, sensitive to (N)NLO as well as non perturbative physics.
  - Mature experiments have had time to think about conditions and detector effects especially in terms of reducing uncertainties. (JES 1-3%, PDF inputs, very precise jets and dijets cross sections.)
- QCD is part of almost any New Physics search.
  - PDFs for background and signal processes.
  - QCD is often a dominant background to Higgs and New Physics searches.
    - e.g. boosted Higgs searches, diphotons for Higgs searches.
- Better understanding of QCD means improved sensitivity to New Physics.



Tevatron Performance





- Collide protons with anti-protons at sqrt(s)=1.96TeV
- Run II ended September 30th, 2011
  - Delivered 12/fb
  - Peak luminosity 4.3×10^{32} $cm^{-2}s^{-1}$
- For comparison, Run I delivered 120/pb

Angular Decorrelations in γ+2(3) Jet Events

The analysis: 1/fb

Measuring differential cross sections vs. azimuthal angles in γ+2 (3) jet events.

$\Delta\phi(\gamma$+jet1,jet2)

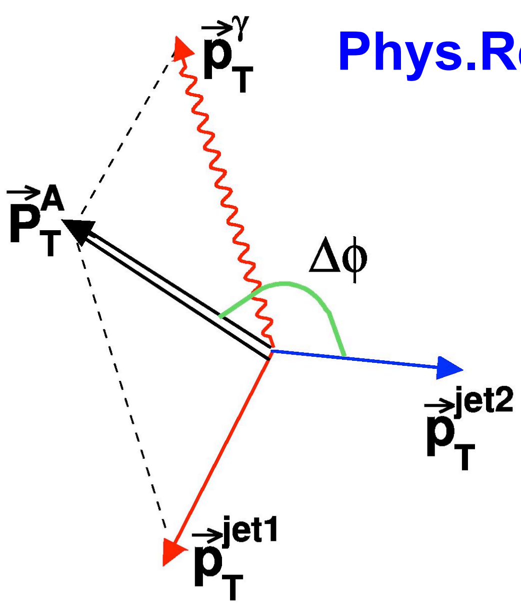
In 3 bins of 2nd jet P_T:

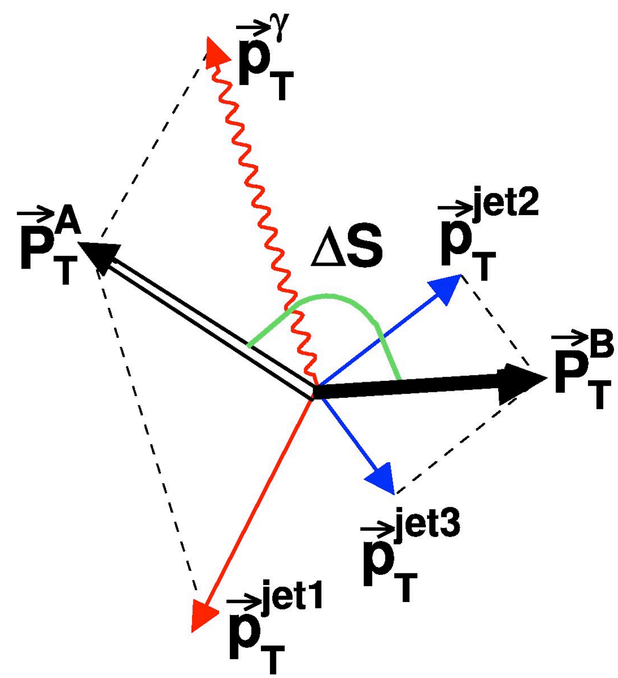
(15-20,20-25,25-30) GeV

$\Delta S(\gamma$+jet1,jet2+jet3)

for 2nd jet Pt of 15-30 GeV

Phys.Rev.D83,052008(2011)



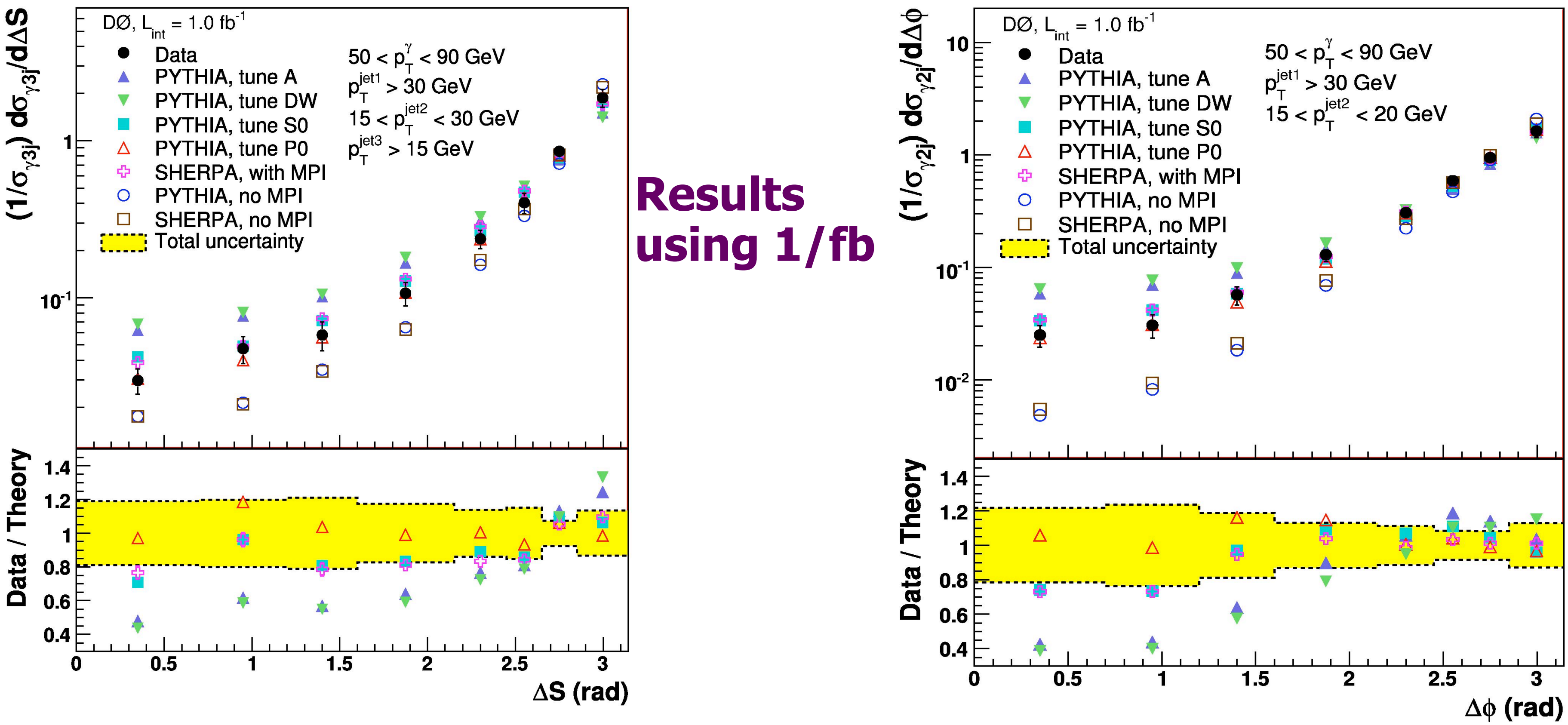


Angular Decorrelations in γ +2(3) Jet Events

Motivation

- **Better understanding of non-perturbative QCD.**
  - **Improve MPI models and constrain existing theories.**
- **Provides information about proton substructure.**
  - **Spatial distribution of parton.**
  - **Possible parton-parton momentum and color correlations.**
- **Realistic model gives a better handle on background estimation for different analyses.**
  - **Rare processes**
  - **Higgs searches**
- **Differentiation in jet P_T increases sensitivity to MPI models even further.**

Angular Decorrelations in γ +2(3) Jet Events



Results using 1/fb

- **Predictions of Single Parton models do not provide a good description of the data.**
- **Additional description of Double Parton events is required.**
- **New PYTHIA MPI models with P_T-ordered showers are favored, as well as the SHERPA default ones.**
- **Fractions of DP events decrease in bins of P_T.**

3-jet Mass Cross-sections

The analysis: 0.7/fb

Phys. Lett. B 704, 434 (2011)

Differential measurement of 3-jet mass:

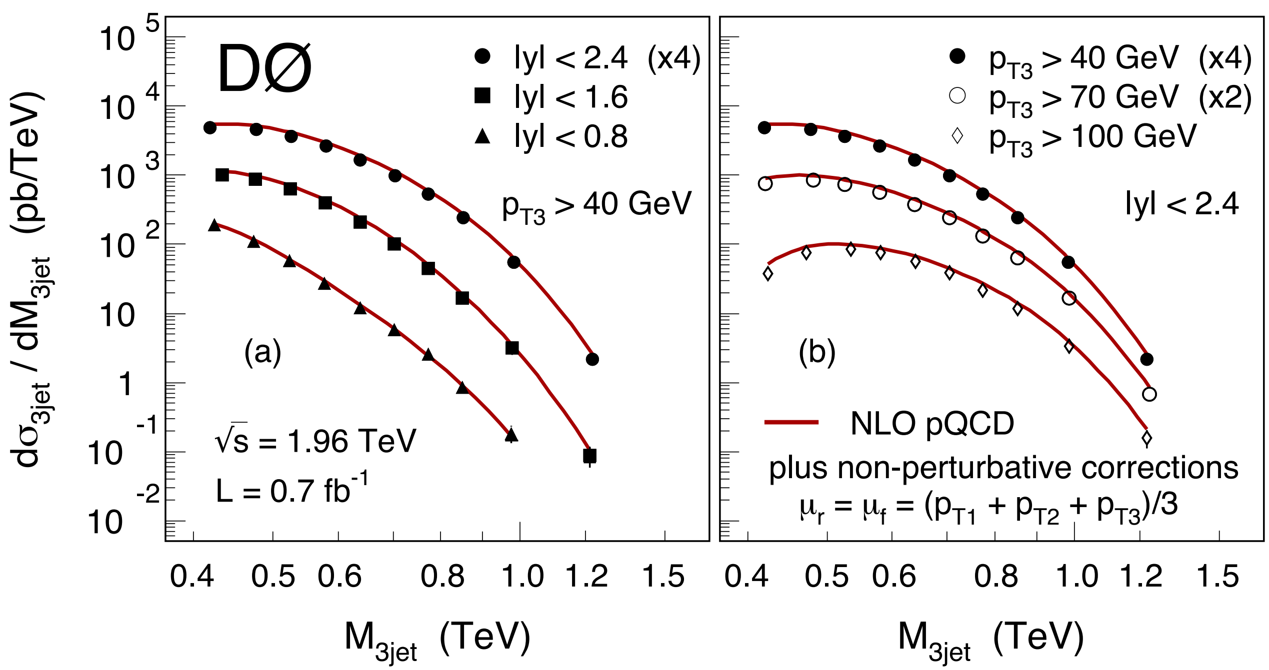
P_T^{lead} >150GeV, P_T^{3rd}>40GeV, ΔR_{jj}>1.4

- **The measurement is done for 5 scenarios - in 3 rapidity intervals and 3 P_T intervals of the 3^{rd} jet (P_T ordered).**
- **3-jet calculations available at NLO.**
  - **Use fastNLO with MSTW2008**
  - **Default scale $\mu=1/3(P_{T1}+P_{T2}+P_{T3})$**
- **NLO non-peturbative correction: vary between (-2,+10)% .**

3-jet Mass Cross-sections

Motivation:

- **Testing QCD at higher orders of α_s.**
  - **Directly sensitive to the pQCD matrix elements of $O(\alpha_s^3)$.**
- **pQCD calculation available in NLO in α.**
  - **Can be used for precision phenomenology from the experimental data.**
- **Provides information that can help decorrelate α and PDFs.**



Total systematic uncertainties: (20-30)%. Dominated by JES, momentum resolution and luminosity.

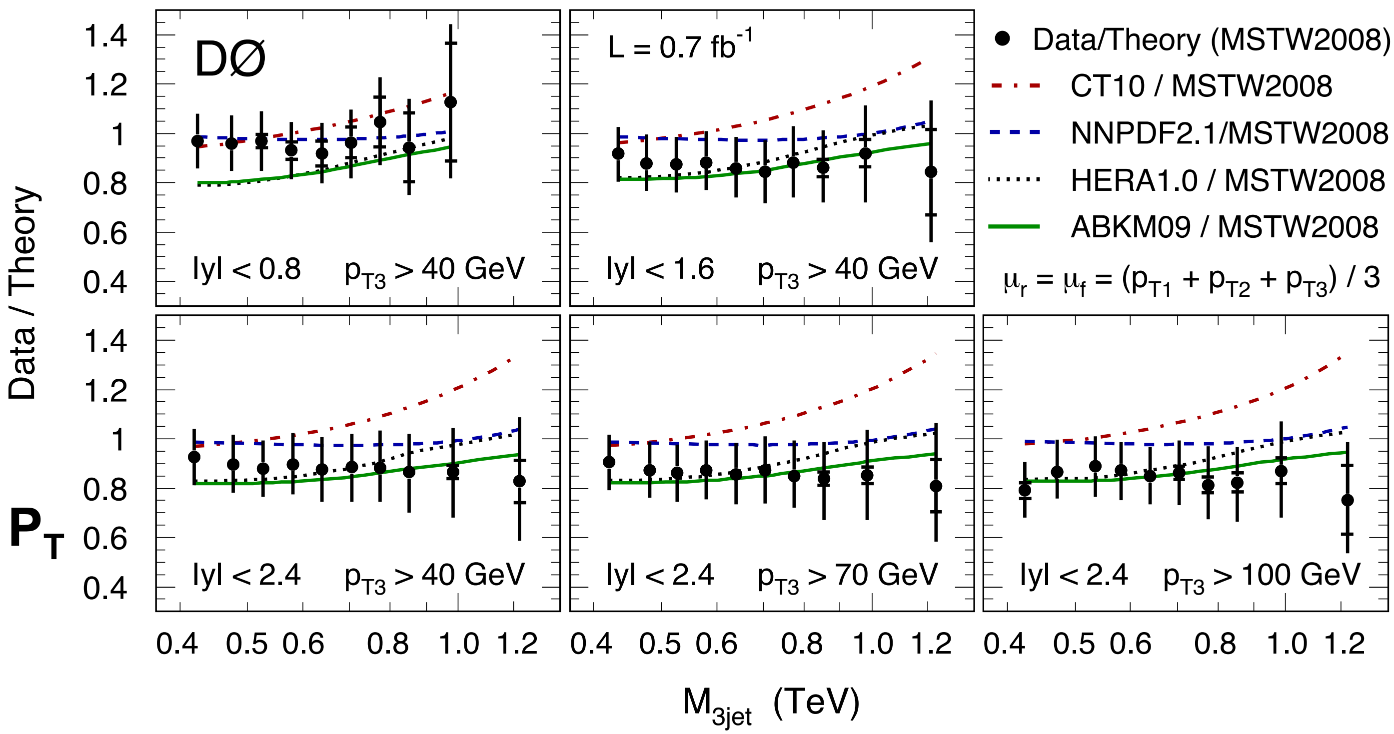
3-jet Mass Cross-sections

Results:

- **Perform χ^2 calculations for different scale choices and α values.**
- **Best agreement between data MSTW2008NLO for all cases.**
  - **CT10 and HERAPDFv1.0 PDF sets are in poorer agreement with the data.**

Differential in rapidity

Differential in P_T



W+jets Production

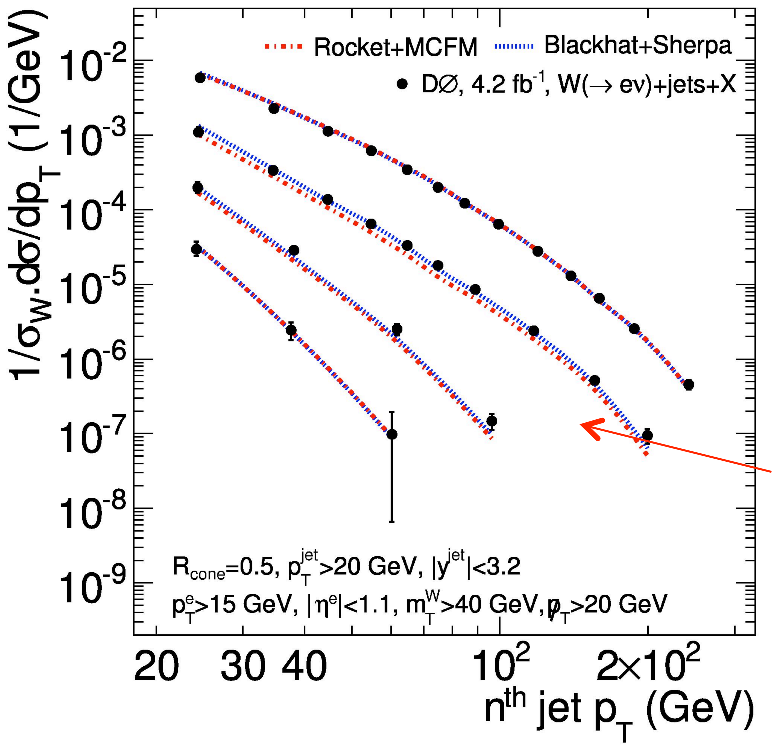
The analysis: 4.2/fb http://arxiv.org/abs/1106.1457

- Measure the differential cross-section of W+n jets (n=1,2,3,4) as a function of the nth jet P_T.
  - W reconstructed in leptonic channel W→eν
- Results are normalized to the measured inclusive W+njets cross section.
  - Uncertainties reduced due to cancellation of some systematic uncertainties.
- First inclusion of W+4jets cross-section measurement.

Motivation:

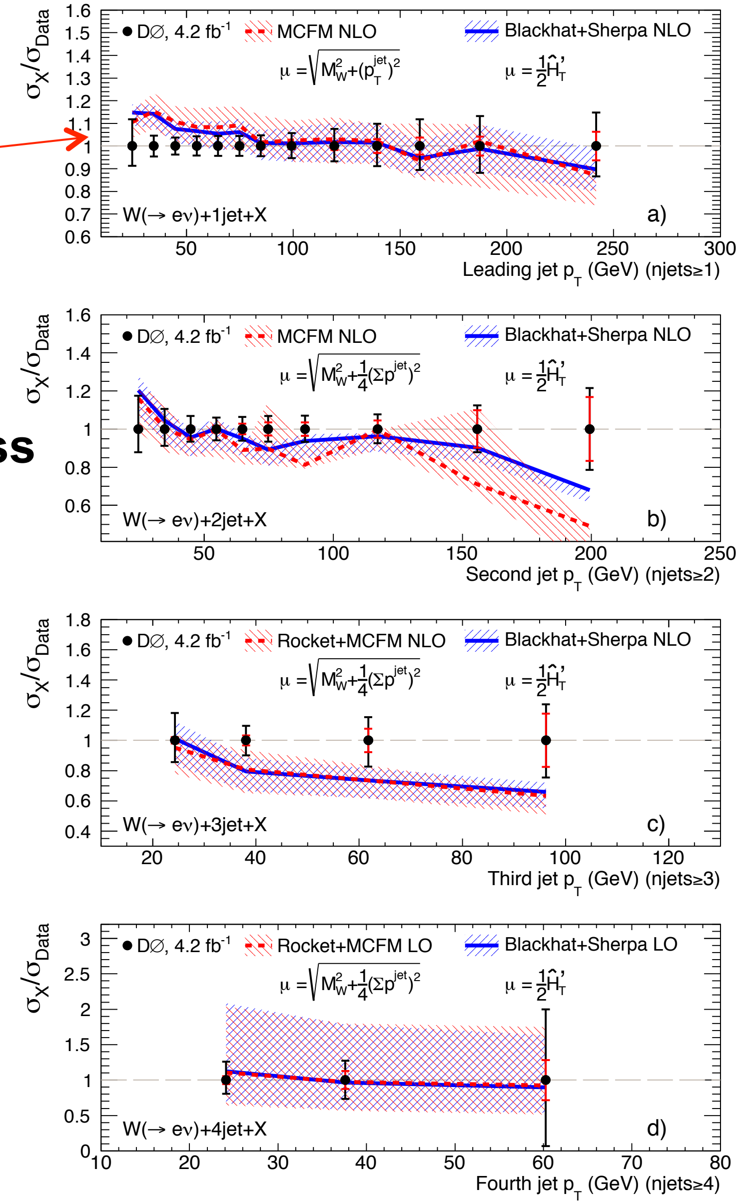
- Fundamental test of pQCD, at high momentum scales.
- Dominant background for other measurements.
  - Higgs and NP searches, tt and single top production.
- Large theoretical uncertainties (30%-40%) on W+HF production limits the ability to determine contributions in searches for NP.
  - Precision measurements are crucial to improve these as inputs to such analyses.

W+jets Production



Differential cross sections

Comparisons with theory



- **W+1jet agrees with both NLO calculations.**
- **W+2 jets: MCFM significantly below the data.**
  - Indicates that the scale uncertainties are larger than what is seen by conventional variations of μ.
- **W+3 jets: theory smaller than data, but consistent within uncertainties.**
- **W+4jets: consistent with LO, though large uncertainties. No NLO calculation available for Tevatron energies.**

First Observation of W+Single Charm Production

Motivation:

- **Production of W+c proceeds at LO through gluon-quark fusion.**
  - **90% through sg fusion (PDF suppression but CKM enhancement of dg fusion).**
- **Measure cross section times leptonic W branching fraction $\sigma \cdot B(W \to l\nu)$ for charm parton.**

  $P_T > 20$ GeV and $|\eta| < 1.5$
  - **Alpgen LO: ~7.5 pb**
  - **NLO K factor from MCFM: 1.5 ± 0.3 pb (uncertainty due to ren./fact. scale)**
  - **Therefore NLO $\sigma \cdot B(W \to l\nu)$ = 11.3 ± 2.2 pb for $p_{Tc} > 20$ GeV and $|\eta_c| < 1.5$**
- **Understand background of low jet multiplicity bins for single top and W+Higgs, as well as control region for top pair production.**
- **Identify W+charm events among W+H.F events**

First Observation of W+Single Charm Production

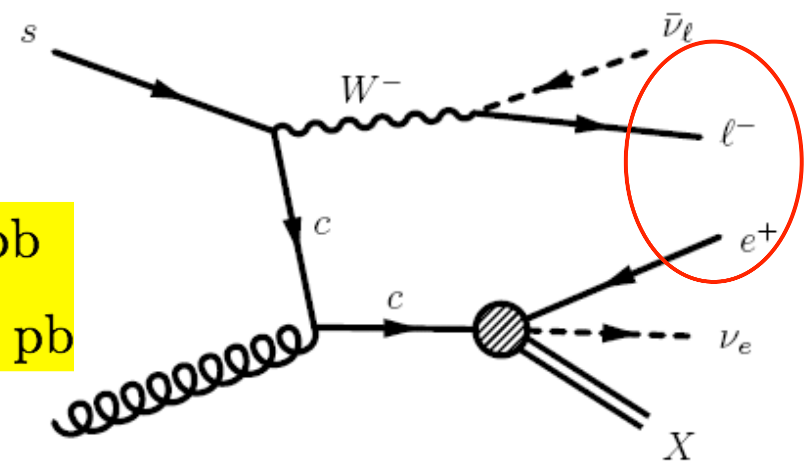
The analysis: http://www-cdf.fnal.gov/physics/new/qcd/QCD.html

- **W boson: =1 central lepton (e or μ) with P_T>20 GeV and MET>25 GeV and transverse mass > 20 GeV.**
- **1 central jet pT>15 GeV and |η|<2.0 (JetClu 0.4 cone).**
- **Drell-Yan suppression: M$\mu\mu$ outside of 8-11 GeV or 70-110 GeV, Mee<45 GeV, $\Delta\Phi$jet-MET>0.3 for ee case.**
- **Identify heavy flavor quarks by using soft lepton tagging to find soft electrons or muons embedded in jets.**
- **≥1 SLTe/μ: near the jet (ΔR<0.4 for SLTe and ΔR<0.6 for SLTμ)**
- **Look for excess of opposite-sign (OS) lepton-pairs over same-sign (SS) lepton pairs.**
- **Consider 3 classes of backgrounds:**
  - **W+jet, QCD multijet production Background estimated from MC**

$$\sigma_\mu = 13.2 \pm 2.3\,(\mathrm{stat})^{+2.2}_{-1.6}\,(\mathrm{syst})^{+1.2}_{-1.0}\,(\mathrm{lumi})\ \mathrm{pb}$$

$$\sigma_\mathrm{e} = 14.5 \pm 6.6\,(\mathrm{stat})^{+4.2}_{-2.5}\,(\mathrm{syst}) \pm 1.2(\mathrm{lumi})\ \mathrm{pb}$$

$$\sigma_{Wc}^{combined} \cdot BR(W \to l\nu) = 13.3^{+3.3}_{-2.9}(stat. + syst.)$$



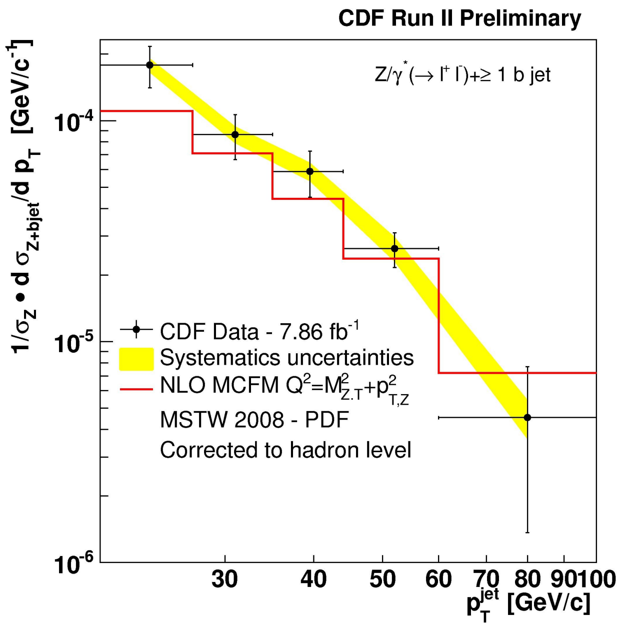
Z+b Production

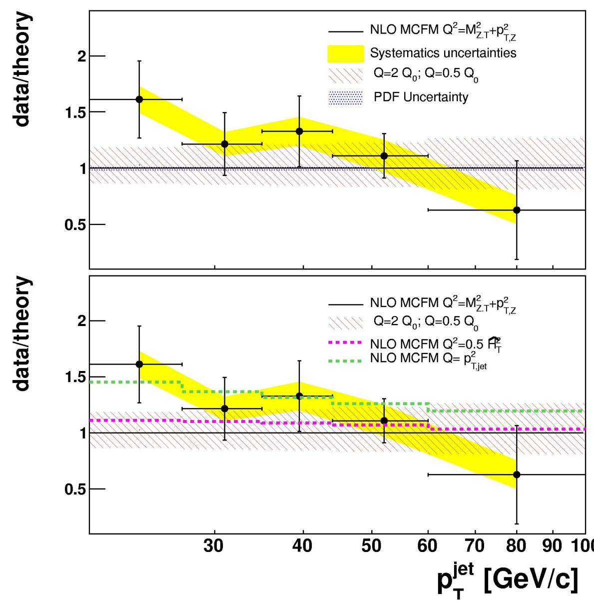
- **The analysis: 7.8/fb**

  http://www-cdf.fnal.gov/physics/new/qcd/QCD.html

- **Select Z→ee($\mu\mu$) +b +X**
  - **66<Mz<116 GeV**
- **Et(e)>25GeV, at least one central electron.**
- **Muons are identified with a new ANN separating real Z muons from ones coming from jet fragmentation or from decay in flight.**
- **Midpoint cone jets with R=0.7**
- **Jet Pt > 20 Gev, jet $|\eta|$ <1.5**
- **Rjet-lepron>0.7**
- **B-tag with secondary vertex.**
- **Estimate fractions in tagged sample from a maximum likelihood fit to the secondary vertex invariant mass.**
  - **Templates obtained from ALPGEN.**
- **Dominant backgrounds: top pair production and diboson events.**
- **Dominant systematic uncertainties: b-tag efficiency, light-jet templates for fit, track reconstruction efficiencies.**

Z+b Production





$$\frac{\sigma_{Z+bjets}}{\sigma_Z} = 0.293 \pm 0.030^{stat} \pm 0.036^{syst}\%$$

$$\frac{\sigma_{Z+bjets}}{\sigma_{Z+jets}} = 2.31 \pm 0.23^{stat} \pm 0.32^{syst}\%$$

- **Measured ratios larger than ones from ALPGEN by about 1.6, in agreement with MCFM within uncertainties.**
- **Results favor predictions with lower renormalization and factorization scales.**

Most recent D0 result (4.2/fb): $\frac{\sigma_{Z+bjets}}{\sigma_{Z+jets}} = 1.93 \pm 0.22^{stat} \pm 0.15^{syst}\%$

PRD83,031105 (2011)

Jet Substructure

Motivation:

- **Test QCD, tune MC – especially wrt parton showering mechanism.**
- **Considerable LHC program to search for New Physics with boosted objects.**
  - **Z′ to boosted tops, W/Z+boosted Higgs, GMSB+boosted Higgs, etc.**

- **The analysis: 6/fb arXiv:1106.5952**
- **Compare distributions of jet substructure variables with MC predictions and analytical calculations.**
- **Compare differential jet cross section as a function of jet mass for different algorithms and cone sizes.**

Jet Substructure

Selection: ≥1 central jet, P_T>400 GeV. 0.1<| η |<0.7, jet R = 0.4,0.7,1.0

Test two jet Shape variables:

1. **Angularity**

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

measures the energy distribution inside the jet

sensitive to the degree of symmetry in the energy deposition

pQCD predicts angularities of high mass jets to have sharp kinematic edges, with give min and max that can be tested on data.

2. **Planar flow**

$$I_w^{kl} = \frac{1}{m_J} \sum_i w_i \frac{p_{i,k}}{w_i} \frac{p_{i,l}}{w_i} \qquad Pf = 4\frac{\det(I_W)}{\mathrm{tr}(I_W)^2} = \frac{4\lambda_1\lambda_2}{(\lambda_1+\lambda_2)^2}$$

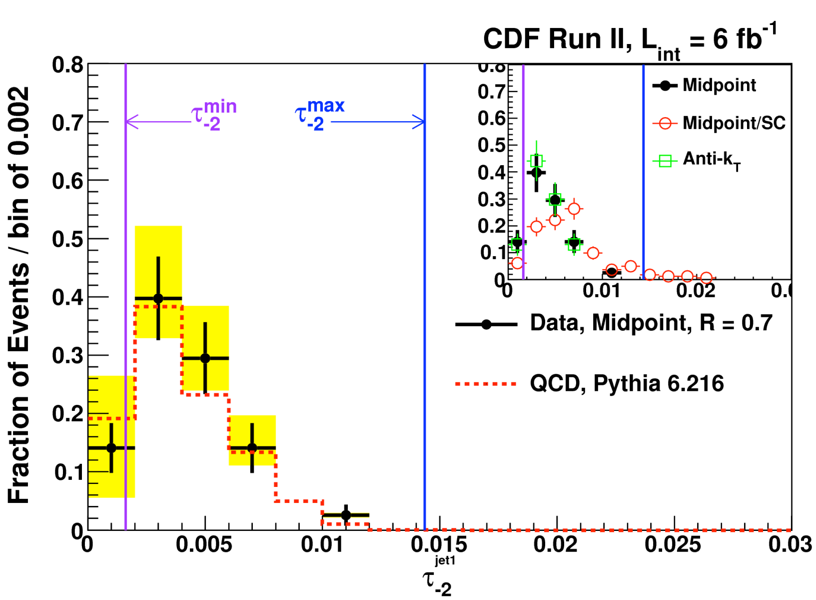
λ s are eigenvalues of I_W

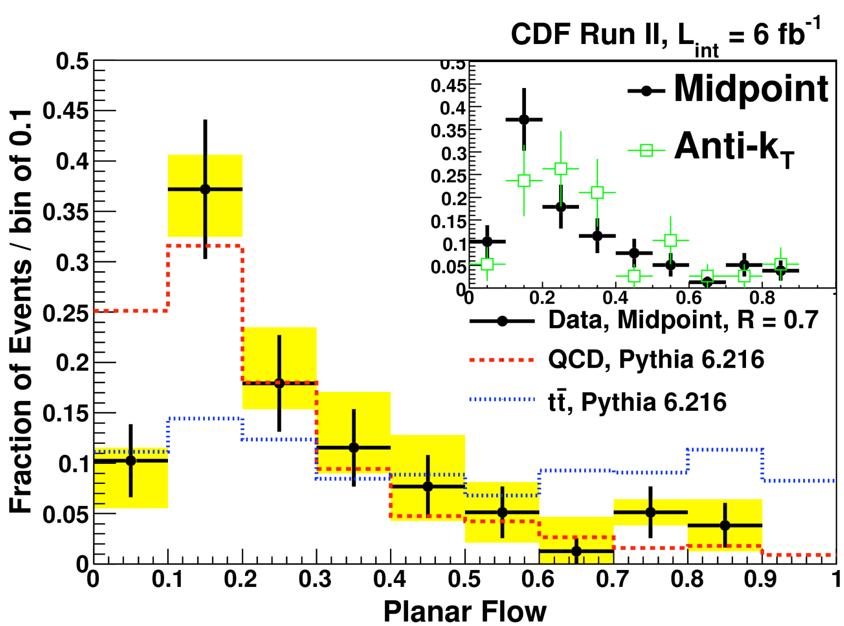
Should be close to unity for isotropic depositions of energy, high values when hard gluons are emitted and low values when soft gluon are emitted

- **Main background : top pair production**
  - Suppress by cut on P_T and mass of second jet and missing E_T in the event

Jet Substructure - Results

- **Good Agreement between data and QCD and MC predictions over jet mass range 100-250 GeV.**
- **Similar results obtain when using the anti-Kt and Midpoint algorithms.**





Summary

Public webpages:

CDF: **http://www-cdf.fnal.gov/physics/new/qcd/QCD.html**

D0: **http://www-d0.fnal.gov/Run2Physics/qcd/D0_public_QCD.html**

- **Several recent Tevatron results are presented:**
  - **Current level of understanding jet ID, systematics and JES ends up in experimental uncertainties similar or lower than theoretical uncertainties.**
  - **Precision measurements of fundamental observables are allowed.**
- **New techniques and larger datasets**
  - **First observation of W+single Charm production.**
  - **First measurement of its kind – Jet Substructure at the Tevatron ("jetography").**
- **Tevatron measurements provide important feedback to MC tunning and QCD modeling.**
  - **Many analyses show importance of NNLO terms and of having better experimental constraints on theories.**

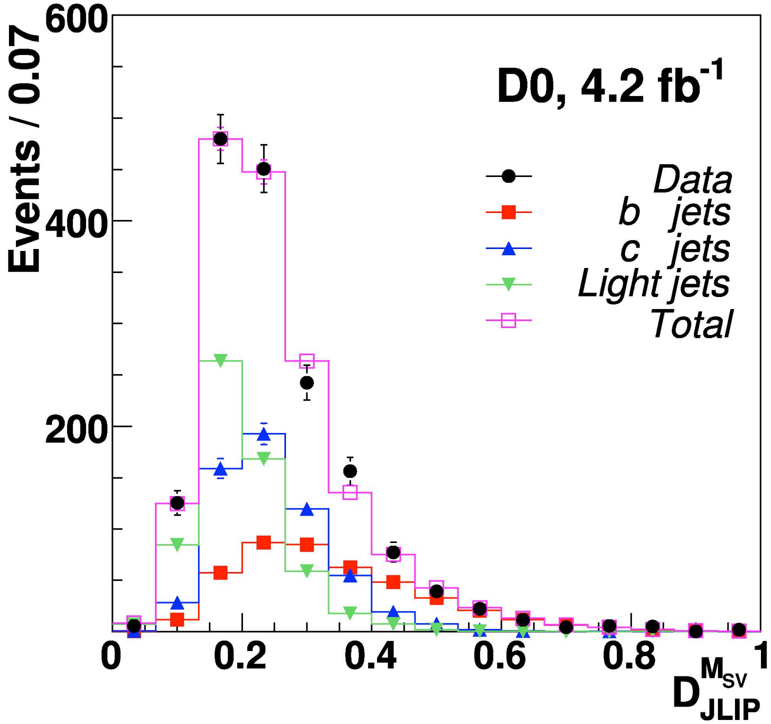
Backups

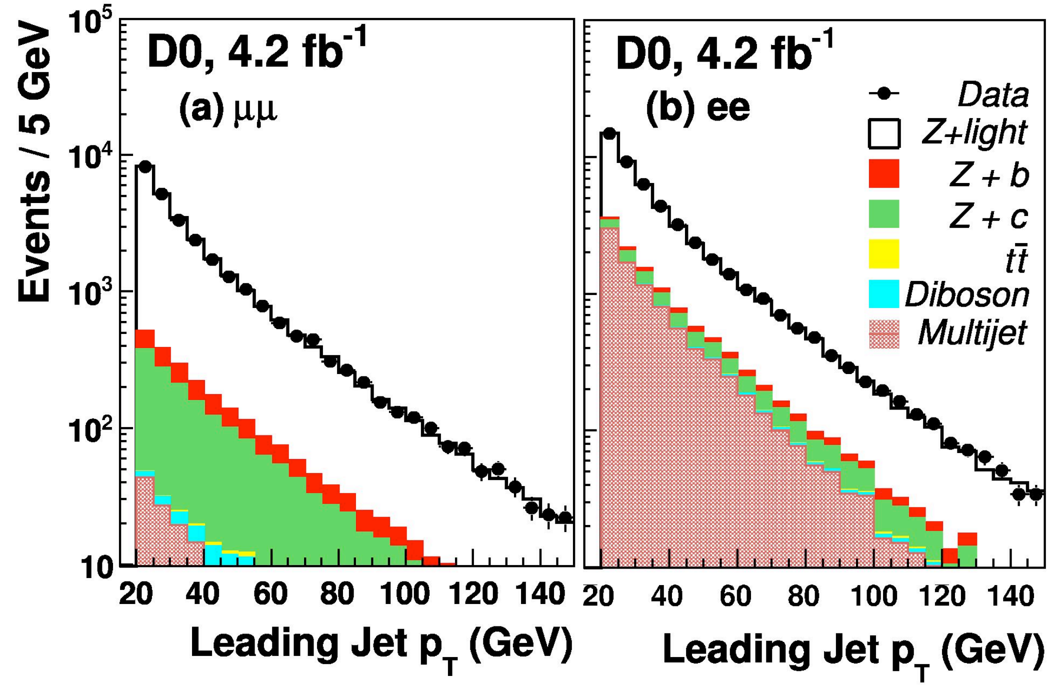
σ (Z+b)/ σ (Z+jets)

The analysis: 4.2/fb PRD83,031105 (2011)

- Select Z→ee($\mu\mu$) +b +X
  - 70<Mz<110 GeV
- Pt(e)>15GeV, Pt(μ)>10GeV
- Midpoint cone jets with R=0.5
- Jet Pt > 20 Gev, jet |η| <2.5
- Secondary vertex tagging
  - Apply NN selection to enrich sample with b-jets
- Use the long B lifetime to discriminate between b/c/ light jets
  - Use log-likelihood fit to extract b-jet fractions
  - Templates to likelihood fit are taken from MC and corrected to match data for b and c jets. Template for light jets is taken from data.

σ (Z+b)/ σ (Z+jets) Results





- **Measurements yield the ratio:**

  0.0193±0.0022(stat) ±0.0015(syst)
- **Most precise measurement of this fraction**
- **Consistent with NLO QCD calculations**