QCD Studies at CDF II

Anwar A Bhatti
The Rockefeller University
Los Alamos National Laboratory
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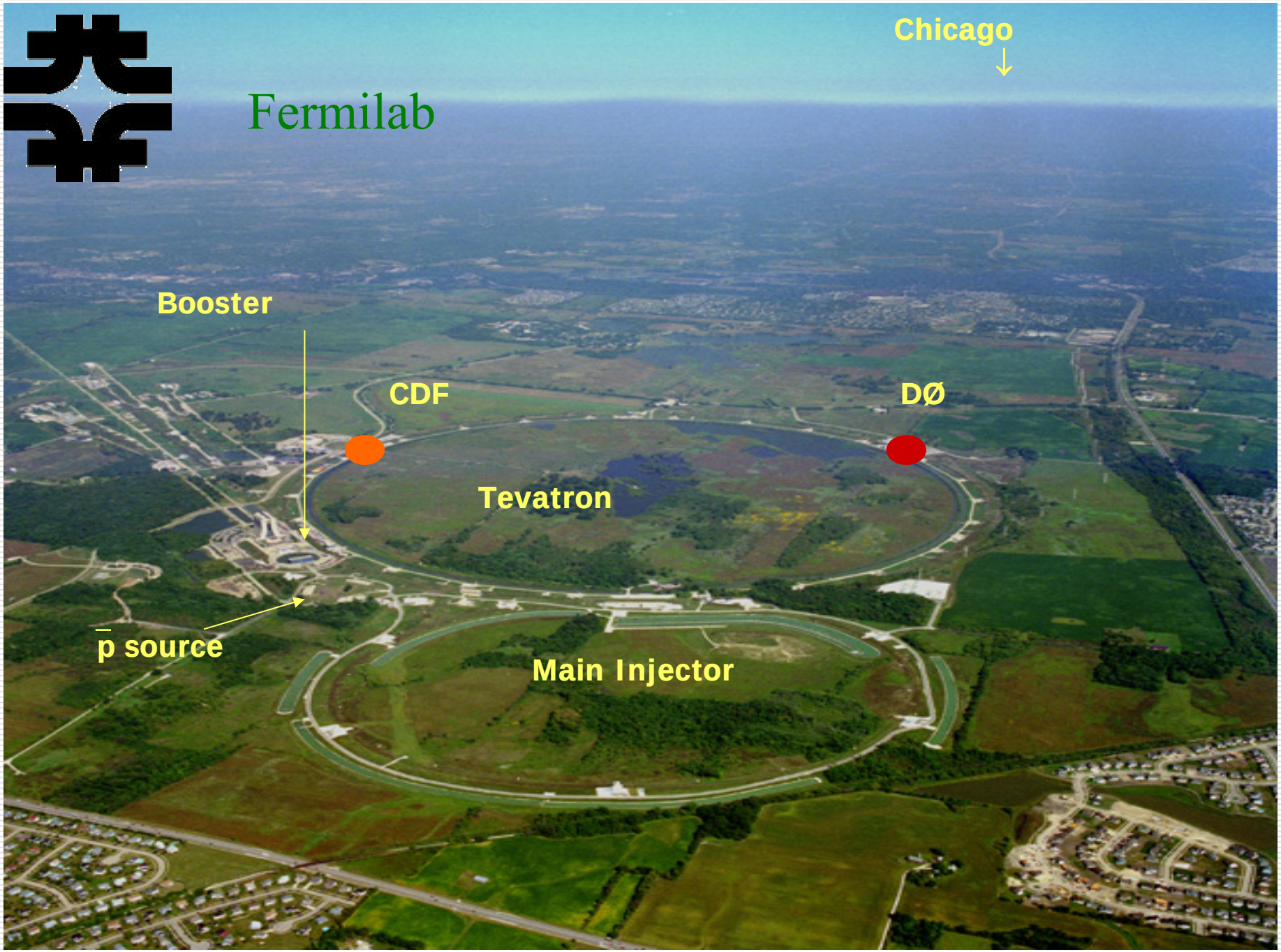
Outline

Introduction
Inclusive Jet Cross Section
Underlying Event Studies
Inclusive *b*-jet cross section
W+Jet Production
Z+jet-jet Production
Diffractive Dijet Production
Conclusions

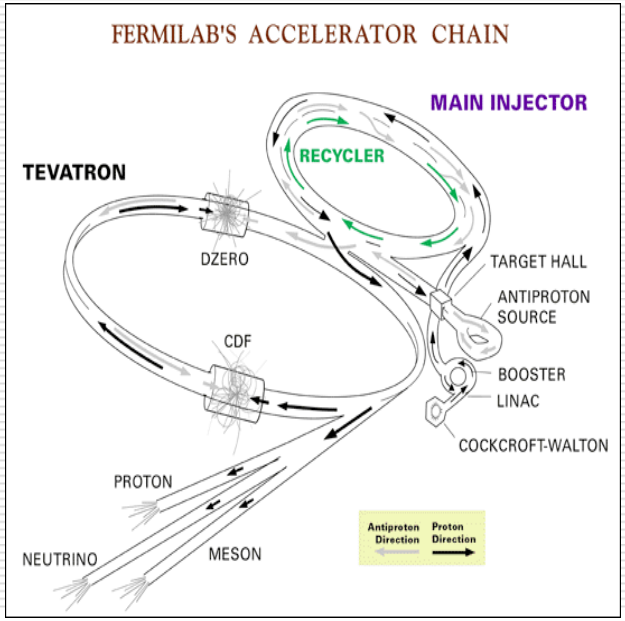

Fermilab
Chicago
Booster
CDF
DØ
Tevatron
p̄ source
Main Injector

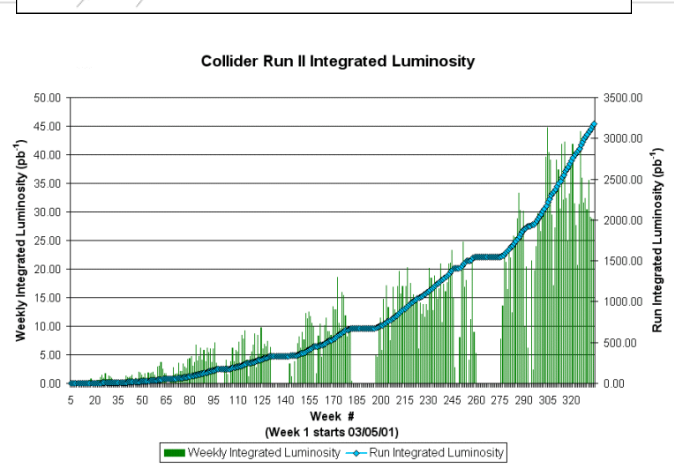
Fermilab Tevatron $p\bar{p}$ Collider

- Proton-Antiproton collisions
  $\sqrt{s} = 1.96\ \text{TeV}\ (\text{Run I} \rightarrow 1.8\ \text{TeV})$
- 36 bunches (396 ns crossing time)
- Main injector
  (120 GeV proton storage ring)
- Antiproton storage ring (recycler) 05
- Electron cooling 05
  - 40% increase in Luminosity

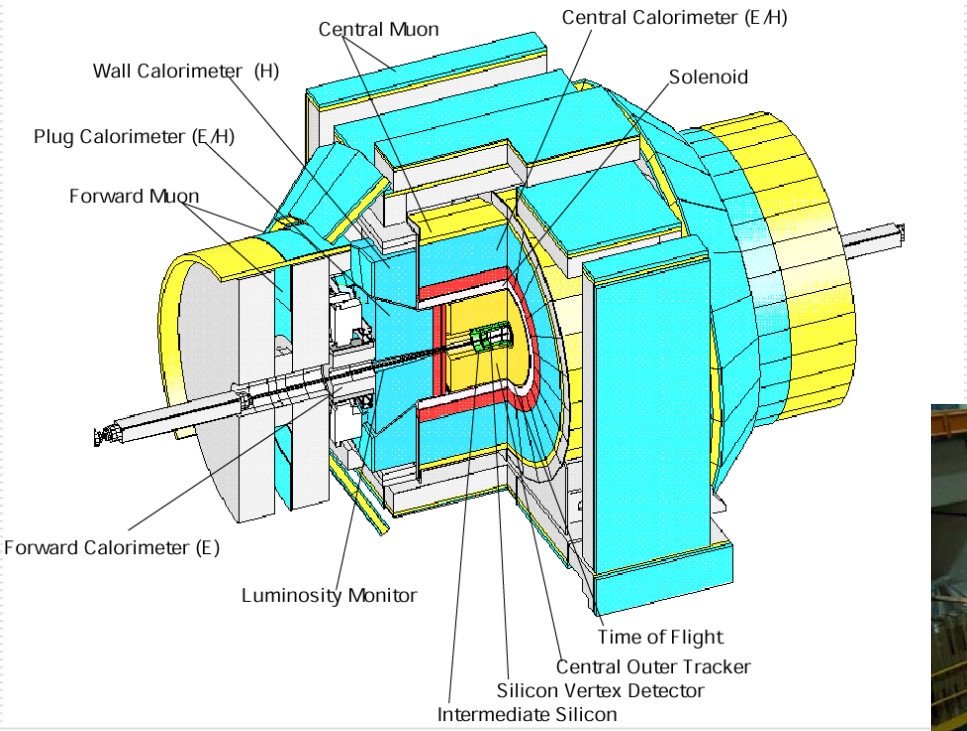
- Run II ~ 3.2 fb-1 delivered.
  - 1 fb^{-1} May 2005
  - 2 fb^{-1} October 2006
  - 3 fb^{-1} June 2007
- Run I (1992-95) ~0.1fb-1

Luminosity projection 2009 6-8 fb^{-1}
Run may be extend the run though 2010.



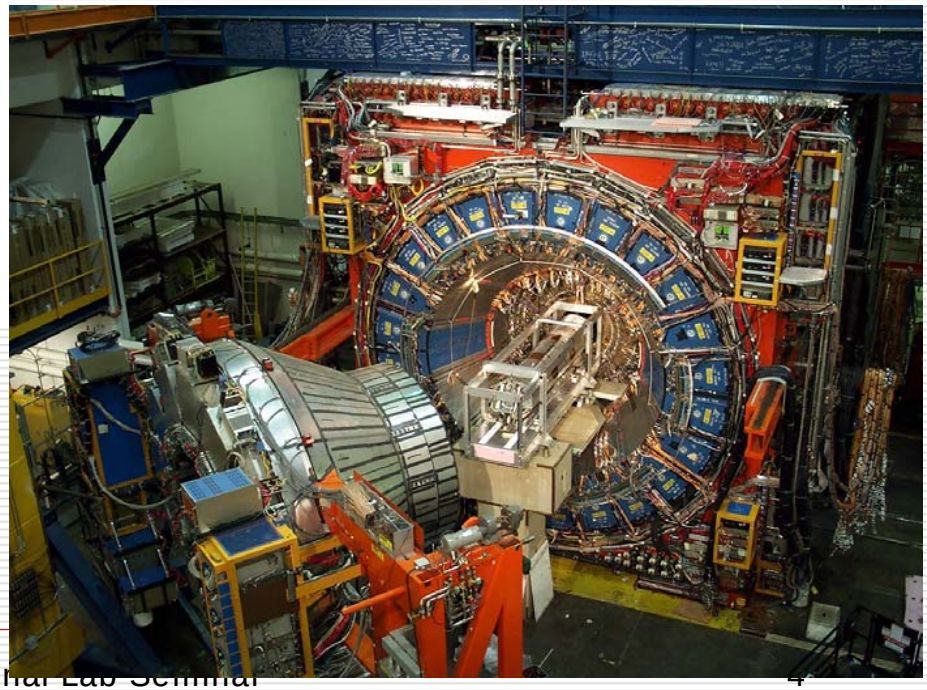


Collider Detector at Fermilab (CDF)



Multi-purpose detectors

- Silicon vertex detector
- Central drift chamber (COT)
- Solenoid magnet
- EM and hadron calorimeters
- Muon chambers

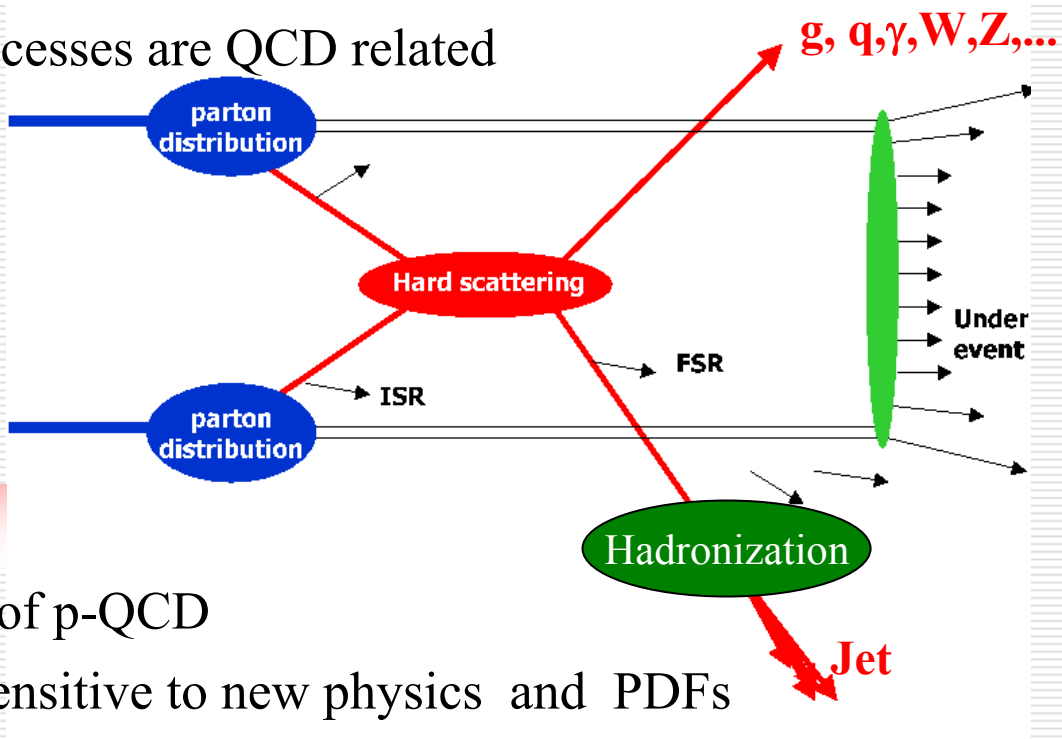


- Data taking efficiency ~ 85 %
- About 2.7 fb^{-1} on tape

Results shown here use up to 1.7 fb^{-1}

QCD at Hadron Collider

- ✓All production processes are QCD related



Jet Production

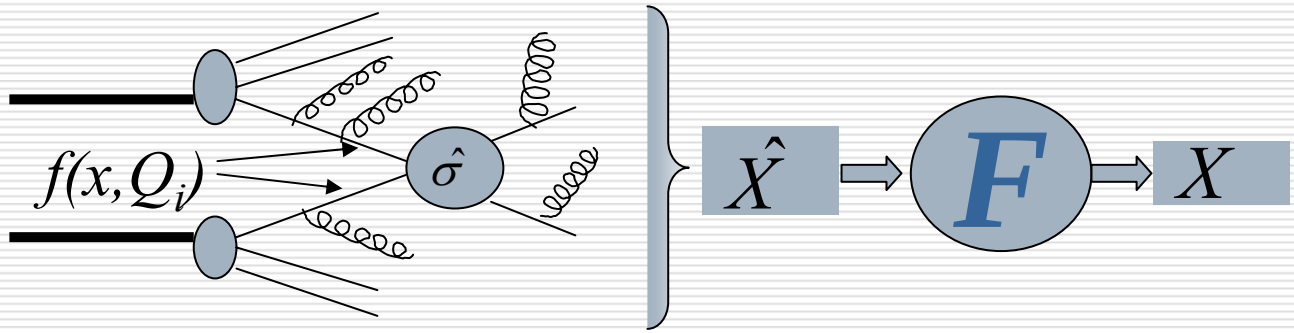
- ✓Stringent test of p-QCD
- ✓High-p_T tail sensitive to new physics and PDFs

Non-perturbative QCD contributions: Underlying event , Jet Hadronization

Other studies of interest: W+jets, diphoton, γ + heavy quark, inclusive b-jet production, diffraction

QCD at Hadron Collider

$$\frac{d\sigma}{dX} = \sum_{j,k} \int_{\hat{X}} f_j(x_1, Q_i)\, f_k(x_2, Q_i) \frac{d\hat{\sigma}_{jk}(Q_i, Q_f)}{d\hat{X}} F(\hat{X} \to X; Q_i, Q_f)$$



$f_j(x,Q)$

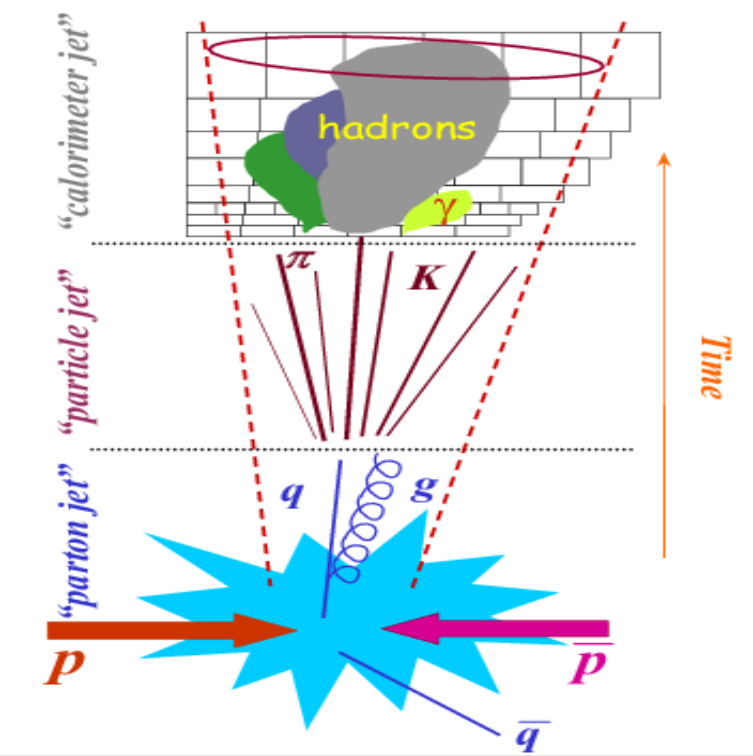
$F(\hat{X} \to X; Q_i, Q_f)$

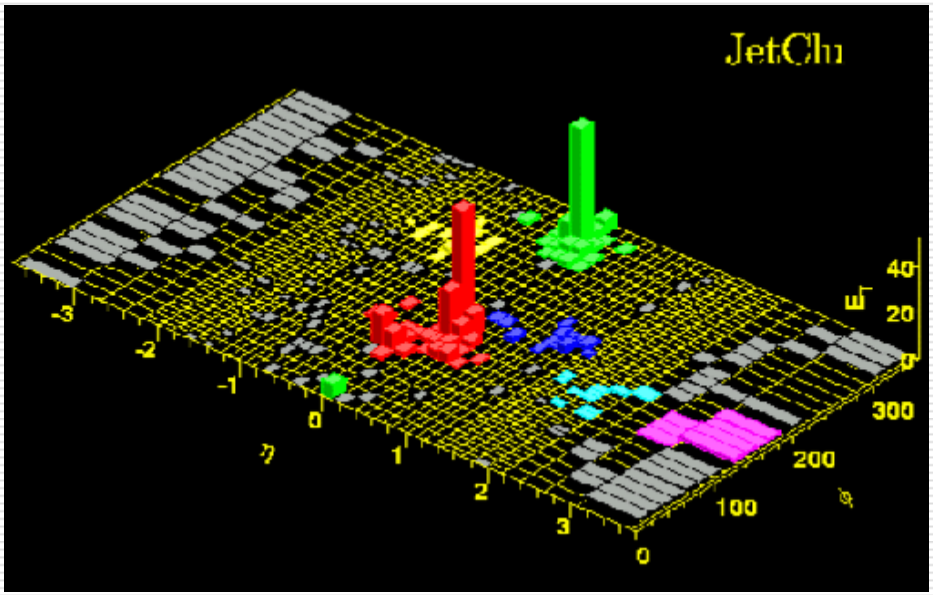
- sum over all initial state histories leading, at the scale Q, to:

$$\vec{p}_j = x\,\vec{P}_{proton}$$

- transition from partonic final state to the hadronic observable (hadronization, fragm. function, jet definition, etc)
- Sum over all histories with $\hat{X}$ in them

Jet Reconstruction

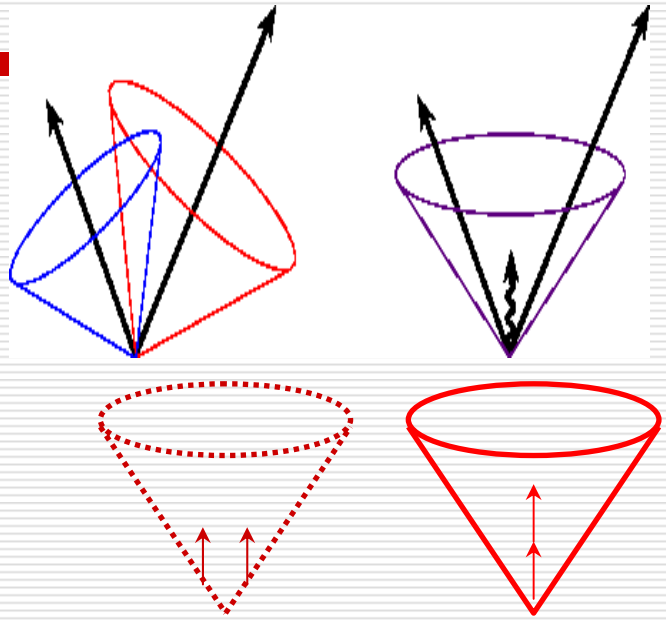




A well define jet reconstruction algorithm is a must for a meaningful comparison of data with the theory.

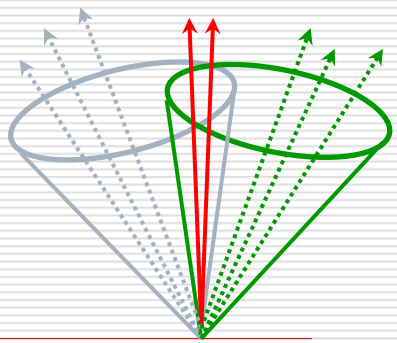
Cone clustering algorithms

- Iterative cone algorithms
  - Staring from seeds, iteratively cluster particles in cones of radius R_{CONE} and look for stable cones
  - (geometrical center = p_T-weighted centroid)
- Infrared and Collinear Safety
  - Fixed order pQCD contains not fully cancelled infrared divergences
    - Inclusive jet cross section affected at NNLO
  - Tevatron Run II Cone Algorithm: Midpoint
    - Uses midpoints between pairs of proto-jets as additional seeds → Infrared and collinear safety restored
- Merging/Splitting
  - Emulated in NLO pQCD calculation by merging 2 partons only if they are within $R = R_{CONE} \times R_{SEP}$ of each other
    - Arbitrary parameter R_{SEP}: prescription $R_{SEP} = 1.3$ (based on parton level approximate arguments)



below threshold (no jets)

above threshold (1 jet)



MidPoint-Cone algorithm

1. Define a E_T-ordered list of seeds using Calorimeter towers with $E_T > 1$ GeV
2. Draw a cone of radius R around each seed and form "proto-jet", calculate jet axis

$$E^{Jet} = \sum_k E^k \qquad \bar{P}^{Jet} = \sum_k \bar{P}^k$$

Massive jet use p_T^{Jet}, rapidity y^{Jet}

3. Draw new cones around "proto-jets" and iterate until jets are stable.
   - A stable cone has a property that the geometric center of cone coincides with the direction of jet given by four-momentum sum of the particles it contains.
4. Put seed at Midpoint (η-ϕ) for each pair of proto-jets **separated by less than 2R** and iterate to find additional stable jets, if any.
5. Merge two jets if overlap energy >75%, otherwise assign towers to the closest jet.

Kt Clustering Algorithm

- Infrared and collinear safe to all orders in pQCD
- No merging/splitting parameter
- Loop over all particles and calculate i,j

$$d_{ij} = \min(P^2{}_{T,i}, P^2{}_{T,j}) \frac{\Delta R^2}{D^2} \qquad d_i = (P_{T,i})^2$$

Seedless Infrared Safe Cone Algorithm

- Check stability for each and every subset of particles.
- Brute force approach, manageable for small number (N)of particle but unrealistic for large *N*. It is used in MCFM (N ≤4).
  - (Complexity $O(N2^N)$ **10^{17} years for N = 100)**
- A circle enclosing a set of particles can be moved around such that two of the particles lie on it circumference and it still encloses the same set of particles.
- Conversely, one can determine all stable cones by investigating all circles defined by all pairs of particles.
- For given particle ***i,***
  - find all circles with ***i, j*** *(j=1,N Rij<2R)* on the circumference.
  - Calculate Pt-weighted centroid of all the particles in this circle.
  - This subset of particles is stable if the cone centered on this centroid (y,φ) contains all the initial particles and no additional particle.
  - Complexity is ***O****(Nn ln n),* *n* is number of particles in cone *R*.

Gavin Salam *et el.*,JHEP 05 (2007) 086 [arXiv:0704.0292 [hep-ph]].

Inclusive Jet Cross Section

$$\frac{1}{\Delta p_T \Delta y}\int\int dy dp_T \frac{d\sigma}{dp_T dy} \leftrightarrow \frac{N_{jet}}{\Delta p_T \Delta y \varepsilon \int L dt} \text{ vs. } p_T$$

$\Delta p_T \rightarrow p_T$ *bin size*

$\Delta y \rightarrow y$ *bin size*

Njet $\rightarrow$ *# of jets in the bin*

$\varepsilon \rightarrow$ *selection efficiency*

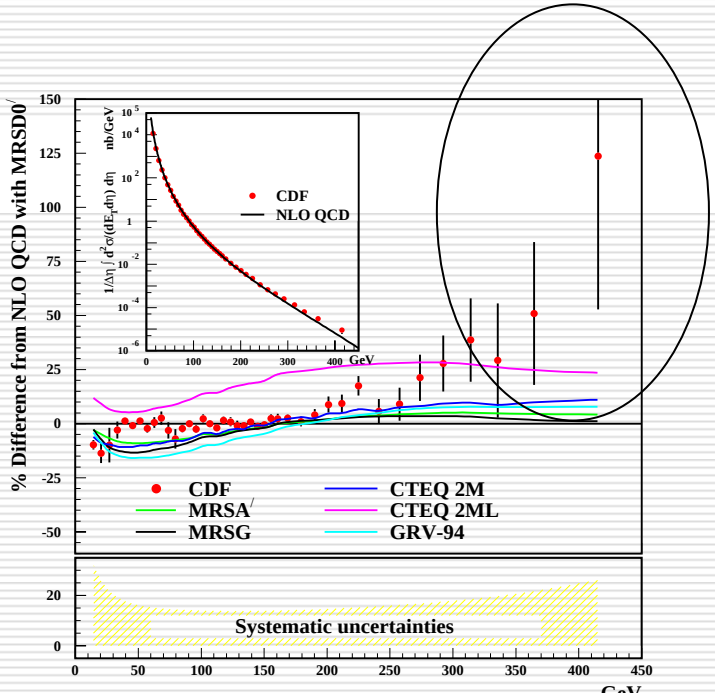
$L \rightarrow$ *integrated luminosity*

$$P = \Sigma P^i \quad P_T = \sqrt{p_x^2 + p_y^2} \quad E_T = E \sin\theta$$

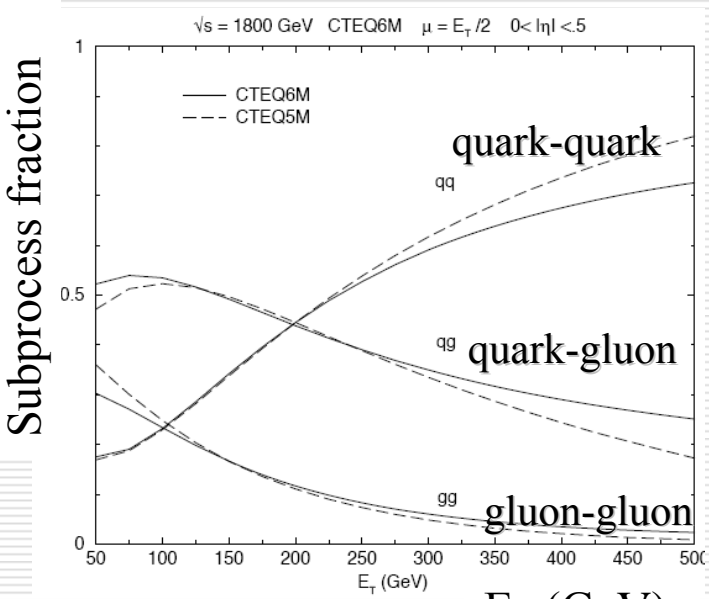
$$y = \ln \frac{E + p_z}{E - p_z} \qquad \eta = -\ln\left(\tan(\theta/2)\right)$$

Inclusive Jet Production

- Test perturbative QCD predictions over ~8 orders of magnitude in cross section
- Measure QCD parameters: parton distribution functions, α_s
- Probe very small distances ~ 10^{-19} m, sensitive to new physics.



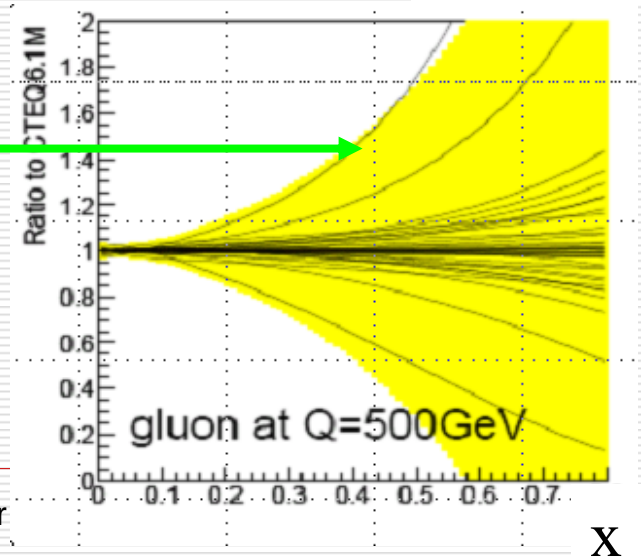
E_T (GeV)



E_T (GeV)

- Sizable cross section from quark-gluon sub-process
- High-x gluon not well known

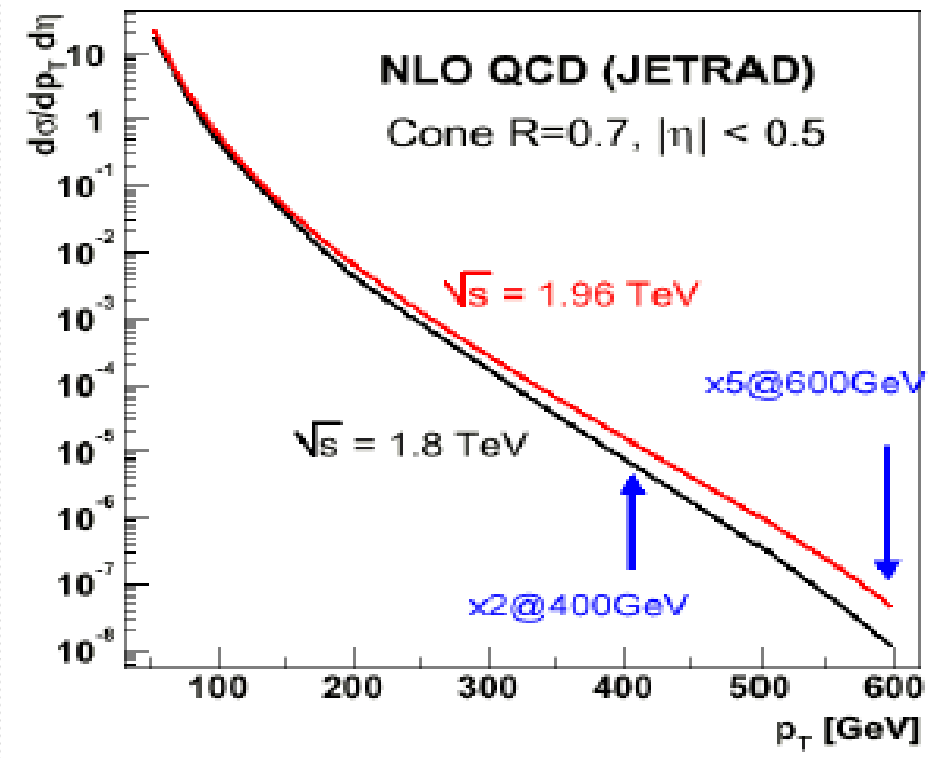
…can be accommodated in the Standard Model



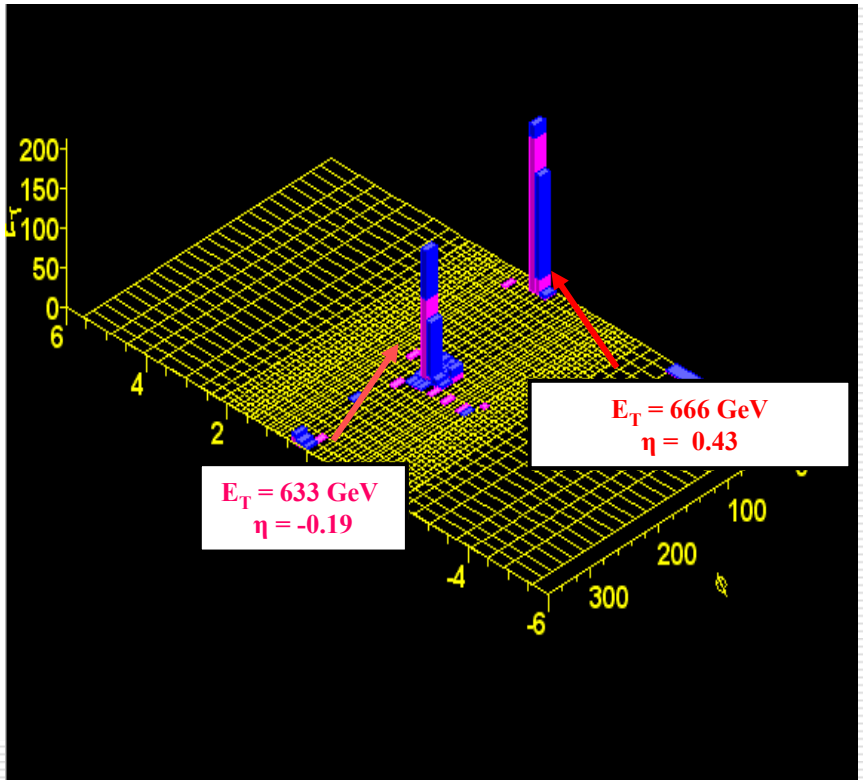
x

Inclusive Jet Cross Section

Inclusive Jet Cross Section



Highest dijet mass so far
Mass ≅1.3 TeV

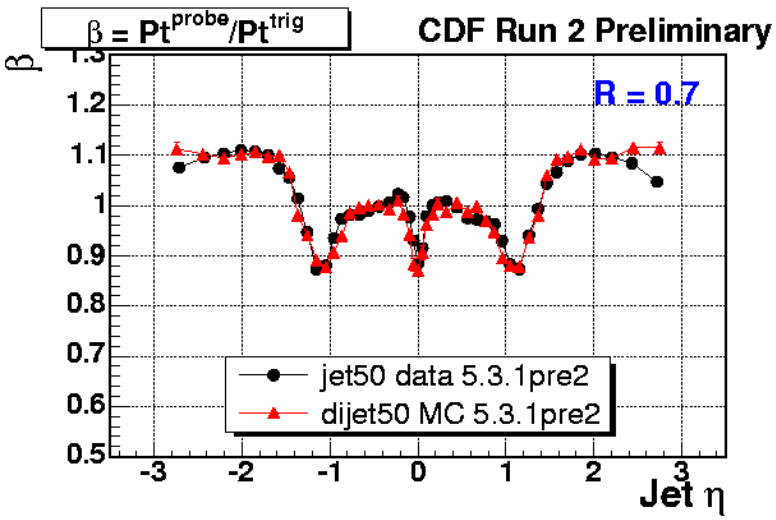


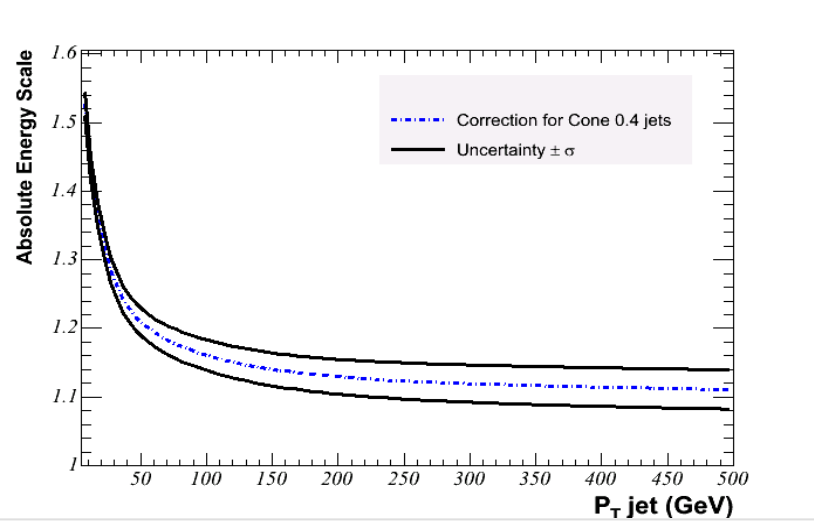
Higher σ_{jet} with respect to Run I

Increase p_T range for jet production

Jet Energy Corrections

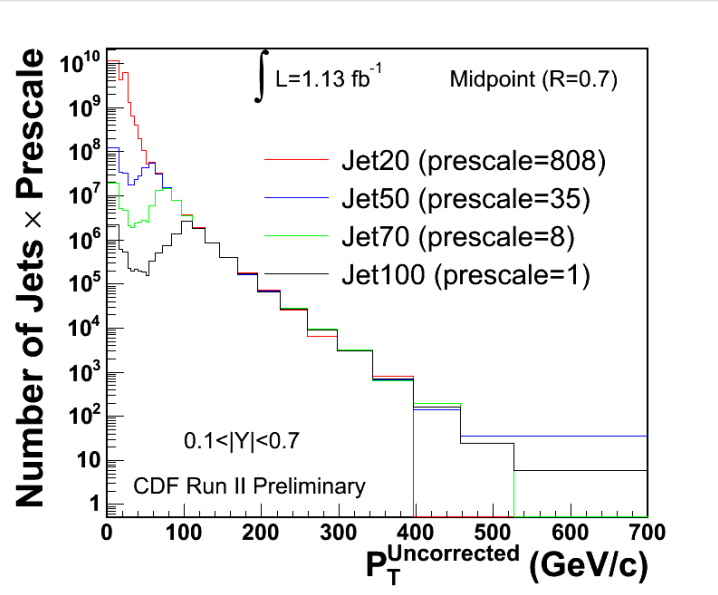
- Jets are collection of different type of particles.
- Particle Type (mean, rms)%
  - Neutral pions $\pi^{0}(\rightarrow\gamma\gamma)$ (~25, 16)%
  - Charged hadron (~67, 17)%
  - Neutrons/K_L (~ 8, 11)%
- Jet are normally measured by calorimeter.
- Calorimeter response to photons is linear.
- Calorimeter response to charged hadrons, neutrons, K_L is non-linear and different than the response to the photons.
- The precise jet energy scale determination is complex due to large fluctuations in the particle composition and momentum, and large fluctuations in the calorimeter response. It also depend on the jet flavor.

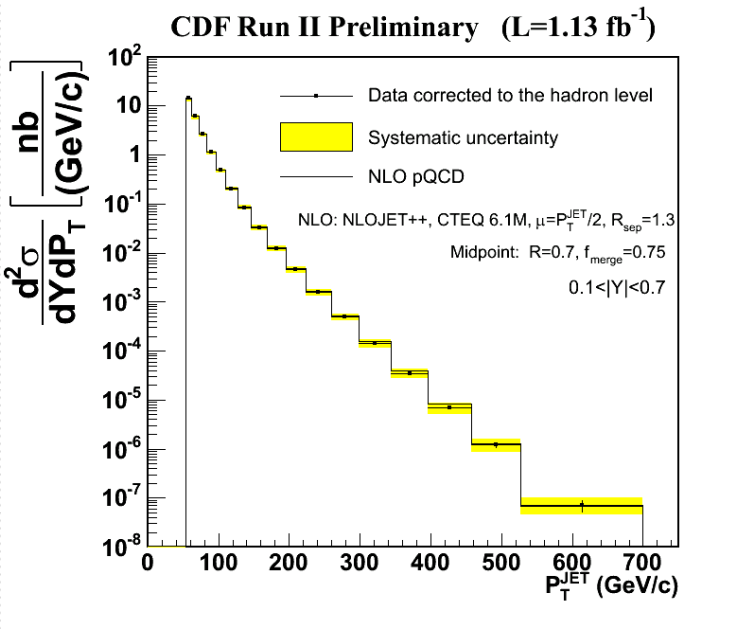




Inclusive Jet Cross Section

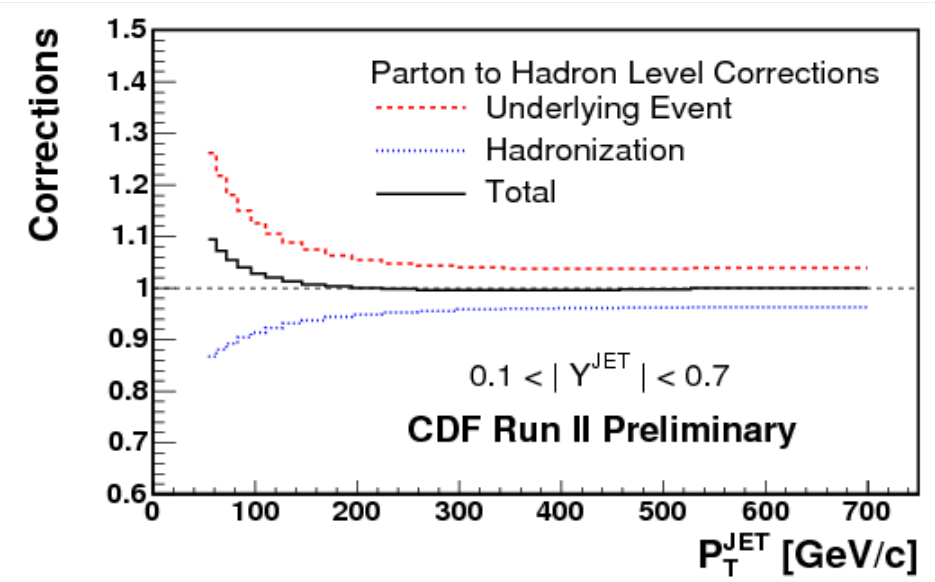
- Very high rate process, multiple triggers to span whole Pt range
- Jet clean up, remove detector problem, cosmic rays events
- Require $|z_{vertex}| < 60$ cm
- Correct jet energy scale
- Correct for smearing due to finite calorimeter energy resolution



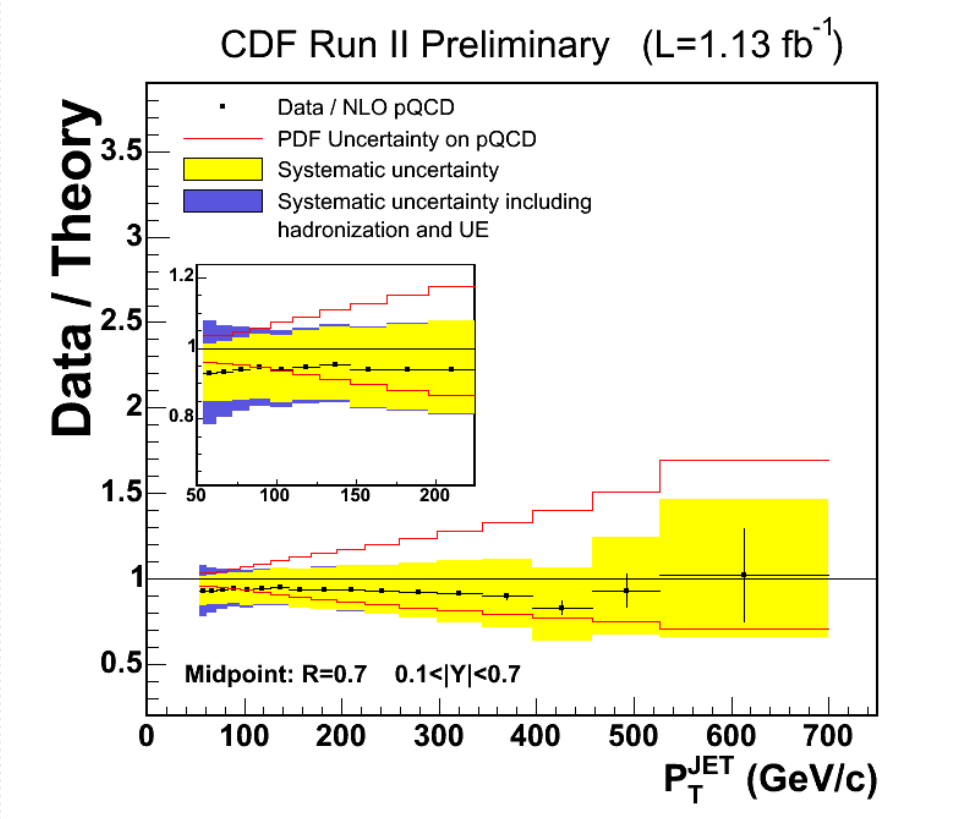


Comparison with perturbative QCD

- Event generators for inclusive jet productions at NLO are not available.
- NLO pQCD predictions are available at parton level only. Thus parton showering, hadronization and underlying event effects are not included in theory.
- Size of these effect is estimated using Pythia, LO event generator



Comparison with perturbative NLO QCD

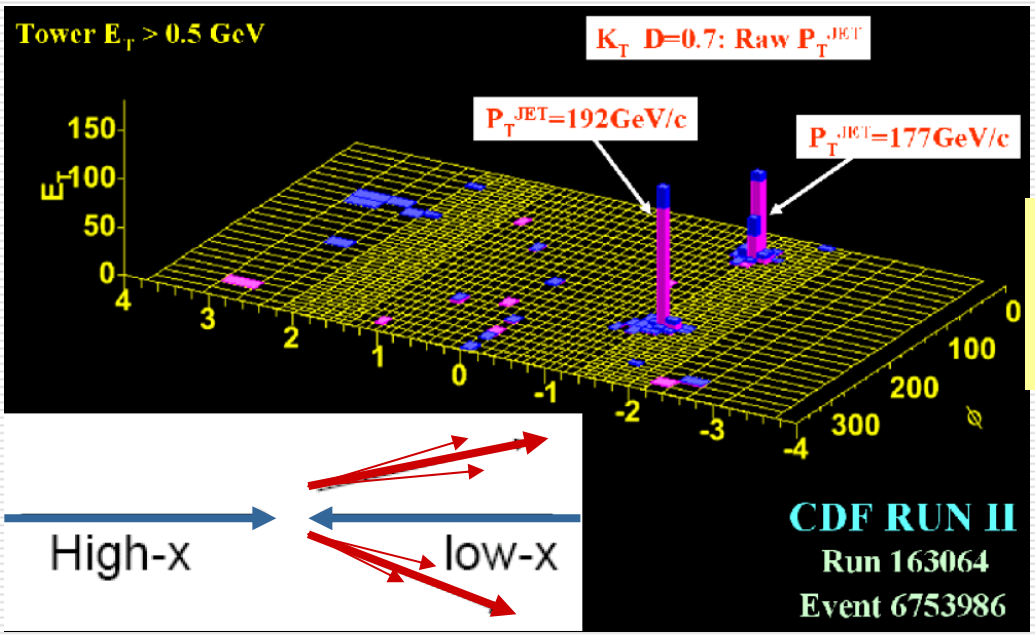


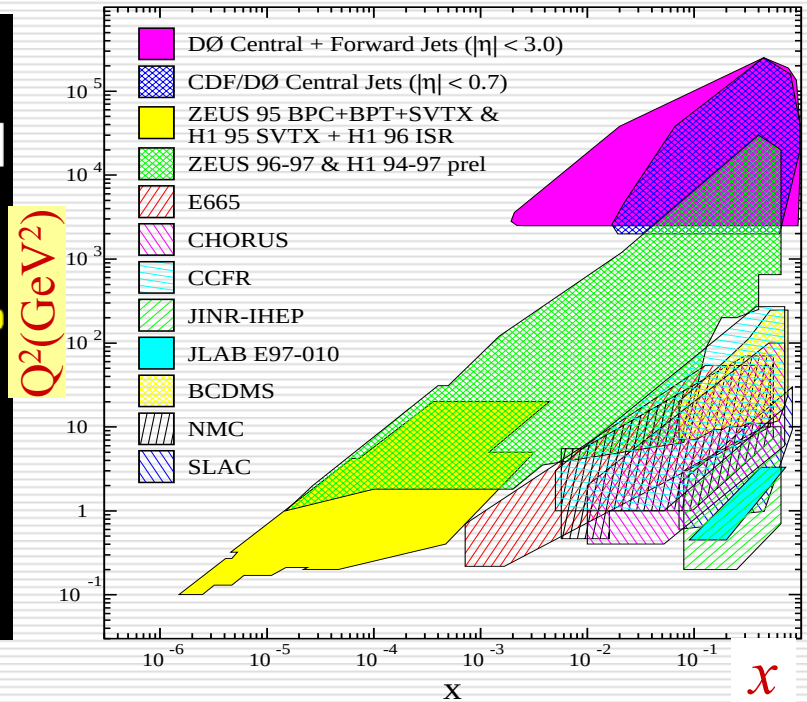
- Very good agreement with NLO QCD predictions.
- Theory uncertainty dominated by the PDFs.
- Experimental uncertainties dominated by the jet energy scale.

Forward Jets

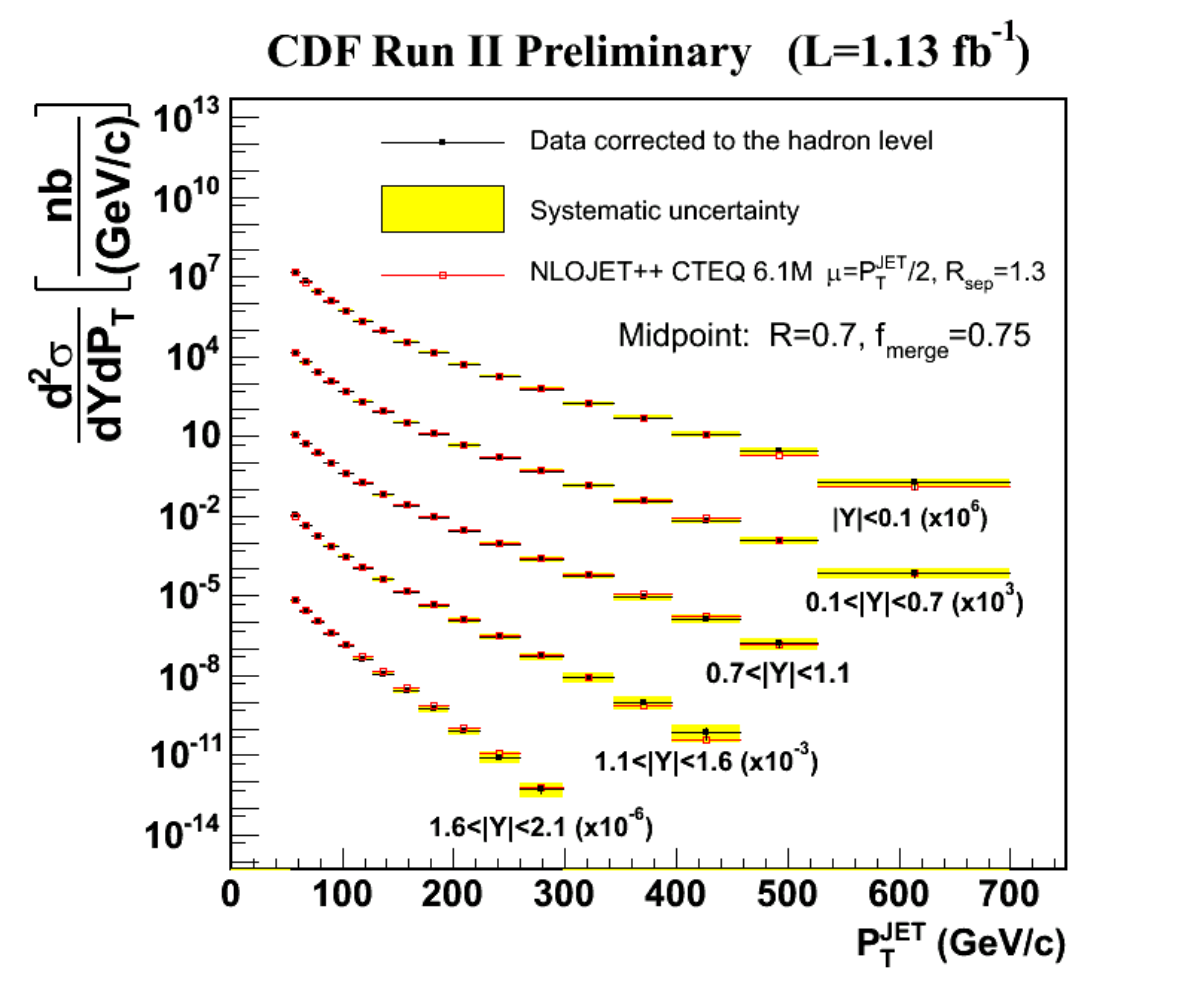
Measurements in different rapidity regions allow to further constrain the PDFs

- Forward jets probe high x but lower Q^2 (= $-q^2$) than central jets
  - Q^2 evolution given by DGLAP
  - Essential to probe possible new physics at high x and high Q^2
- Also, extend the PDF sensitivity to lower x

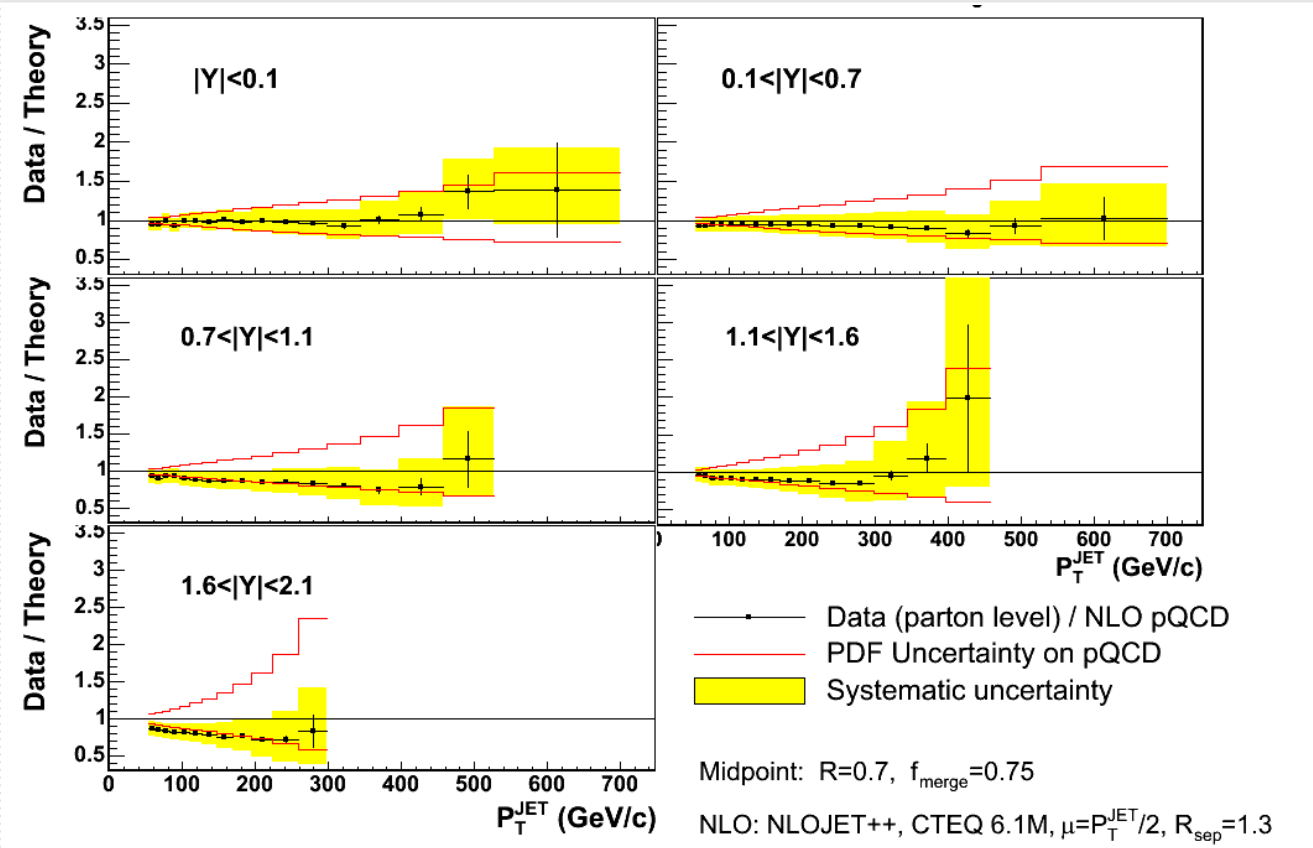




Forward Jets



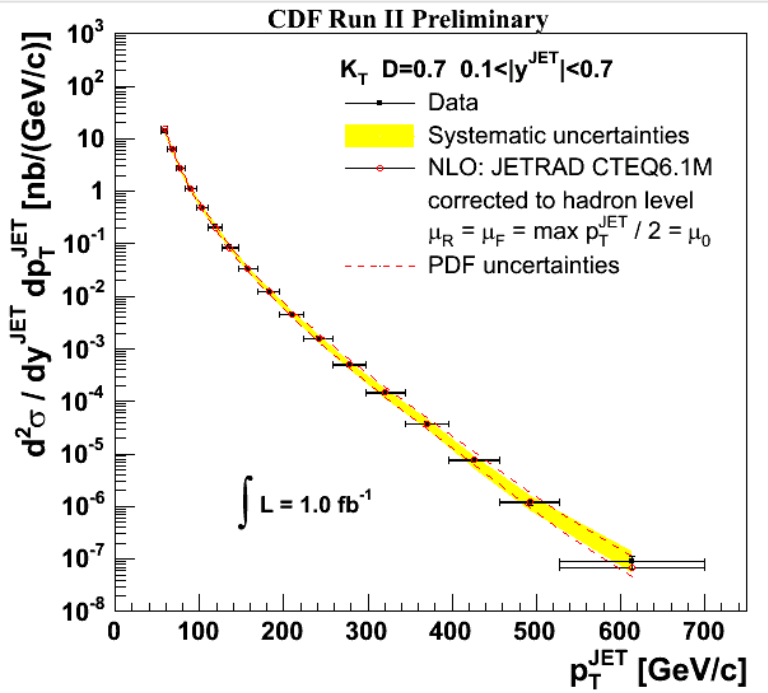
Forward Jets

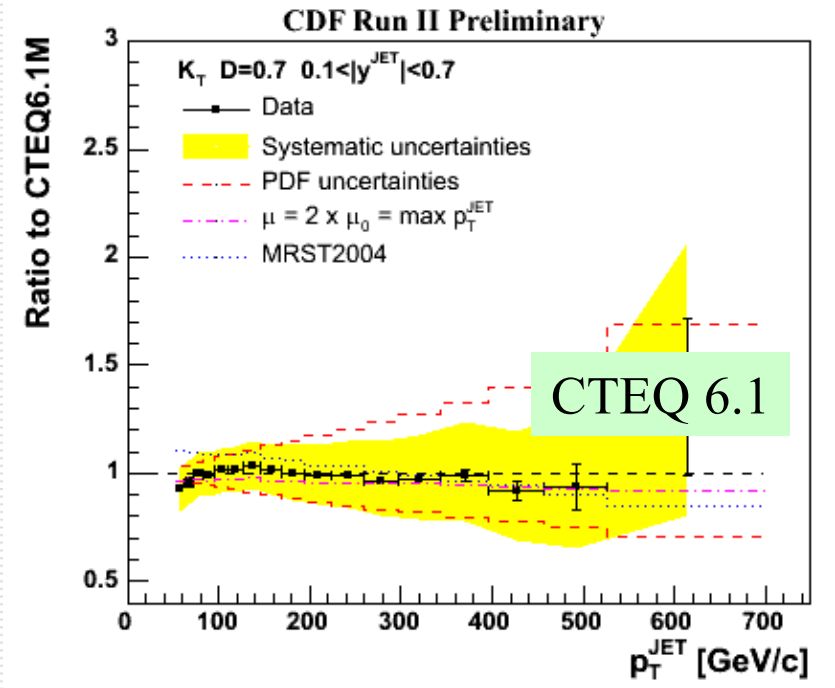


- Data consistent with NLO pQCD predictions in all rapidity regions
- Experimental uncertainty in the forward region smaller than the PDF uncertainty → will contribute to further constrain PDFs

Inclusive Jet Cross Section with K_T

Data is not corrected for hadronization and underlying event energy.
NLO QCD prediction is modified for hadronization/UE effect.

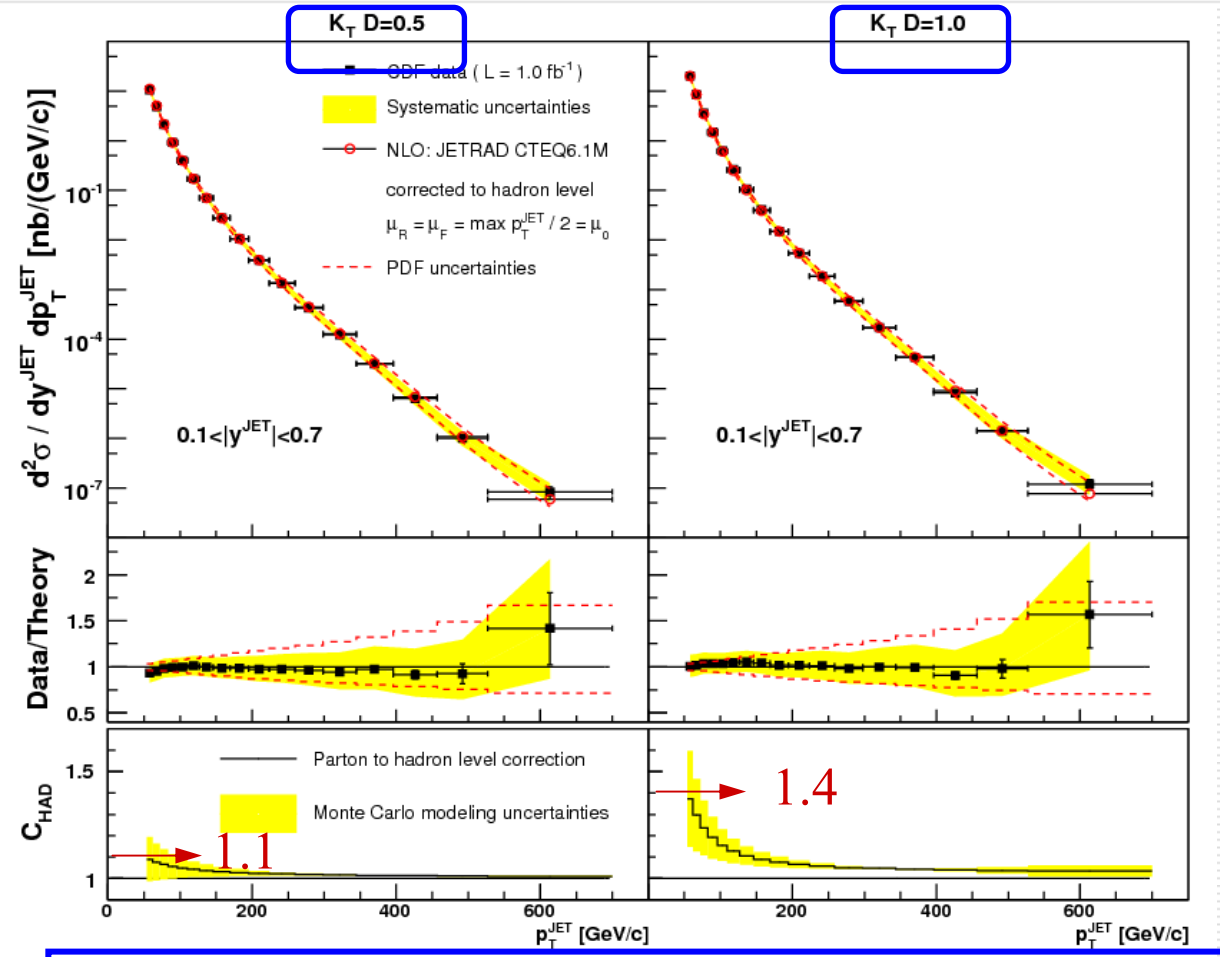




Experimental uncertanty is dominated by 3% uncertainty on jet energy scale.

Good data-theory agreement

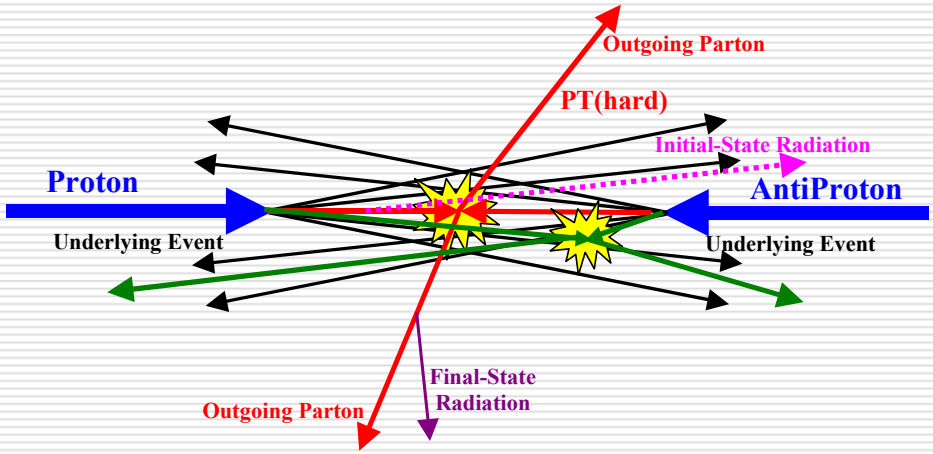
Inclusive Jets with k_T vs. D



- Measurement with different *D* parameters (*D:* separation parameter that characterizes the size of jets)
- Parton-to-hadron level corrections larger for larger *D* parameters (larger UE contributions)
- Both measurements in good agreement with NLO pQCD after UE and hadronization corrections

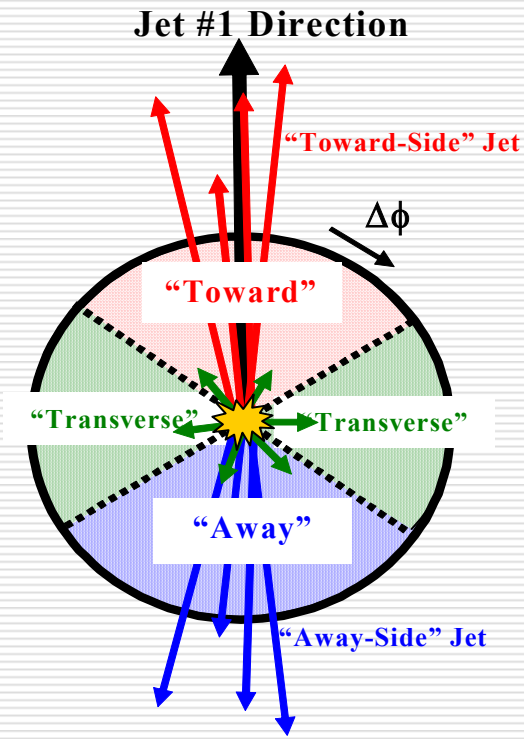
NLO pQCD provides a reasonable description of dependence on jet size.

Underlying Event Studies



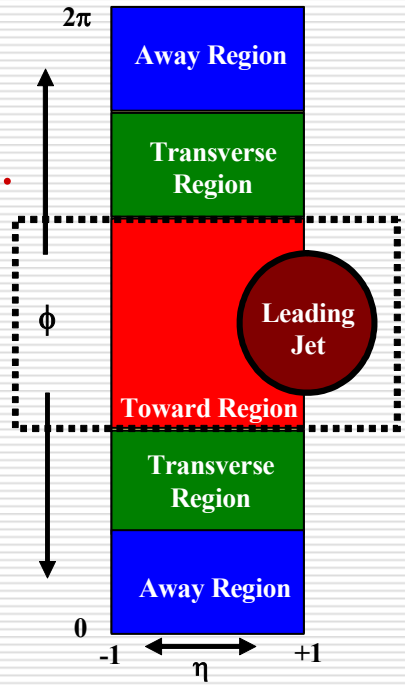
- Multi-parton interactions, generally soft, produce particles which are in same physics space as the jets from hard interaction in the same event.
- This extra energy must be subtracted from jets if the results are compared to parton level calculation.
- Underlying event energy also effect lepton/photon isolation cuts. It will be particularly important at LHC environment.
- CDF has an extensive plan to tune the parameters in Pythia UE model.

Δφ Correlations relative to the leading jet



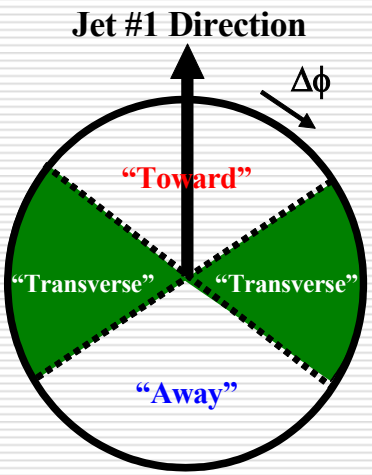
Each region

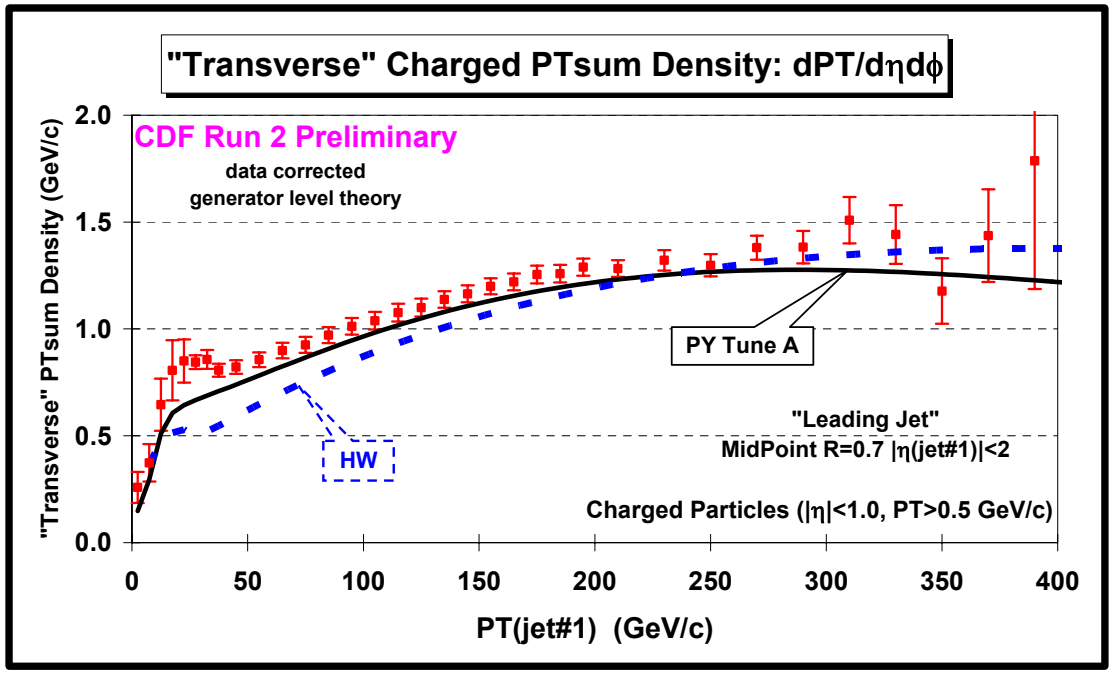
$\Delta\eta\Delta\varphi = 4\pi/3.$



- Transverse region is sensitive to underlying event and initial state radiations.
- The multi-parton interactions and initial state radiations (ISR) are tuned to reproduce the particle and energy density in transverse region.

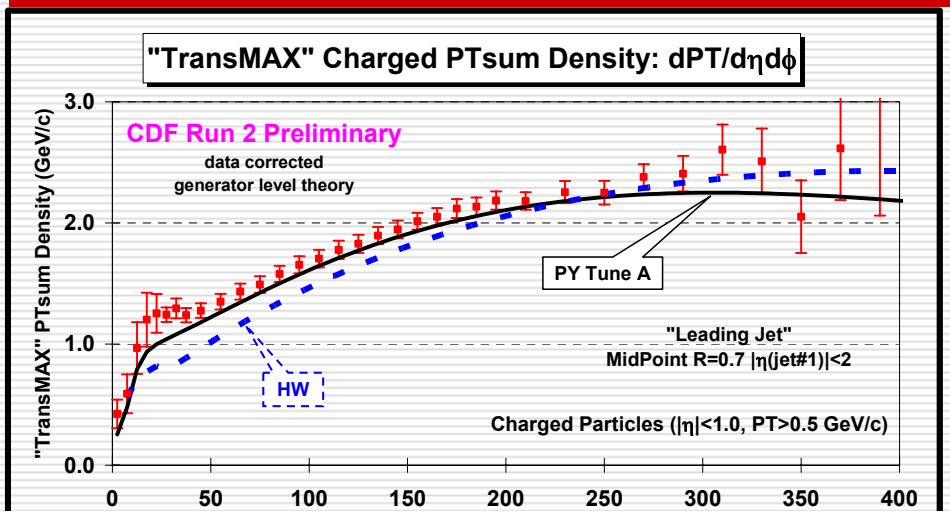
The "Transverse" Region

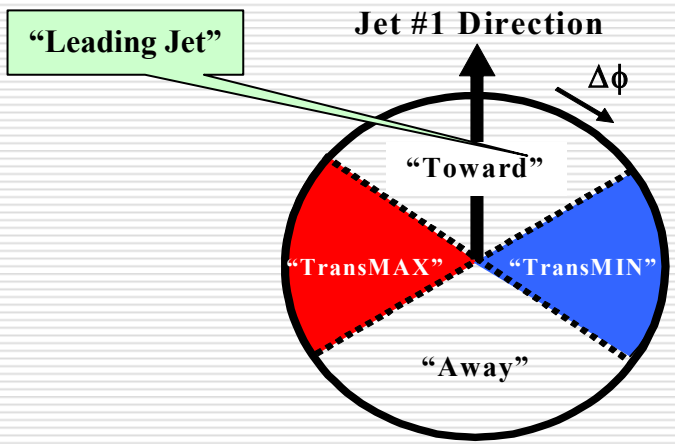


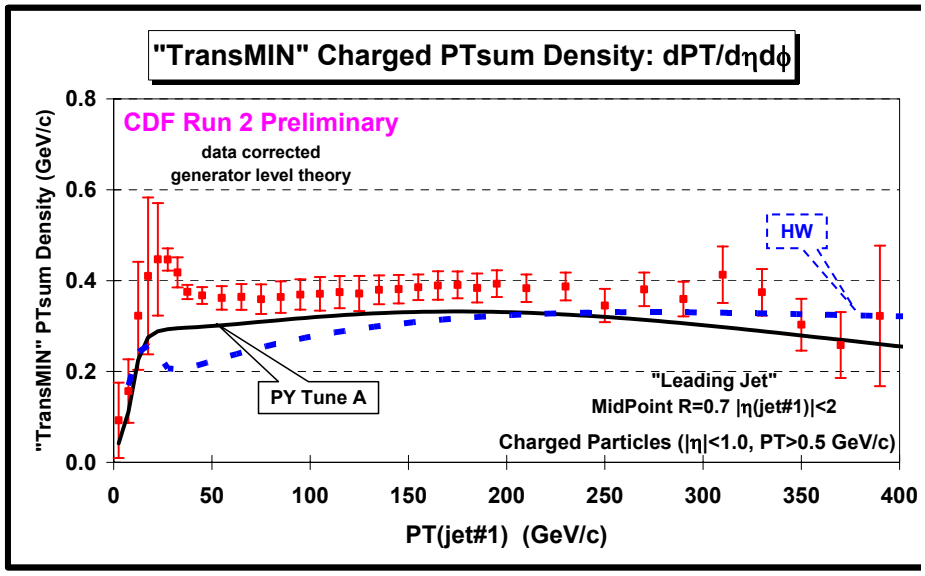


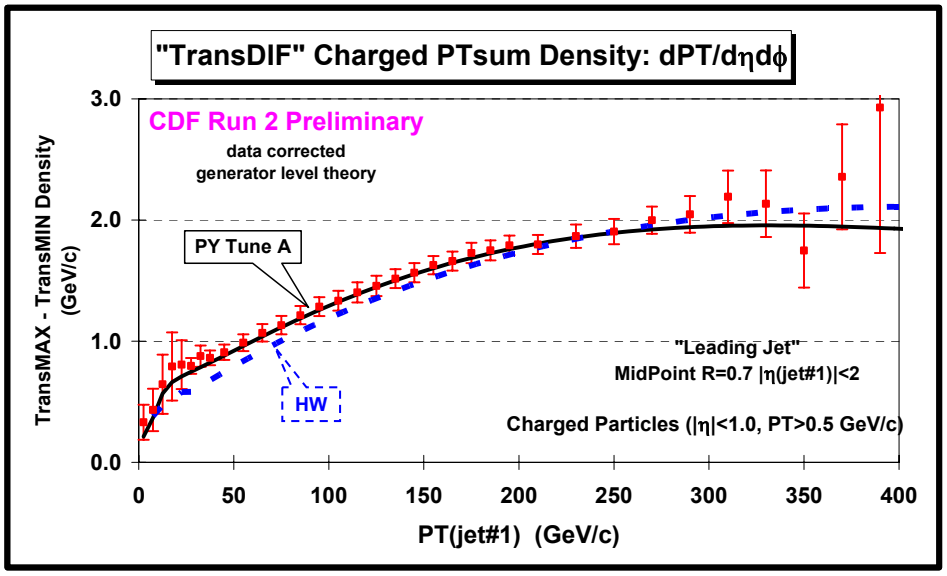
- Data at 1.96 TeV on the charged *scalar* p_T sum density, $dPT/d\eta d\phi$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "leading jet" events as a function of the leading jet p_T for the "transverse" region. The data are corrected to the particle level and are compared with PYTHIA Tune A and HERWIG (without MPI) at the particle level.

The "TransMAX/MIN" Regions

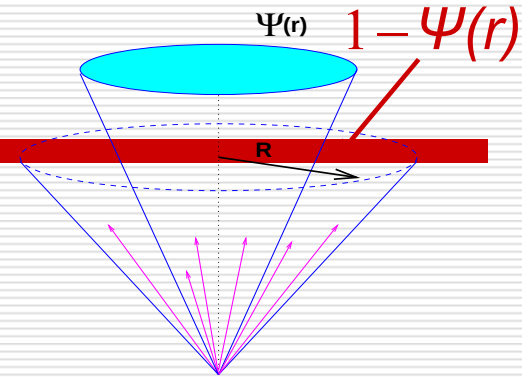




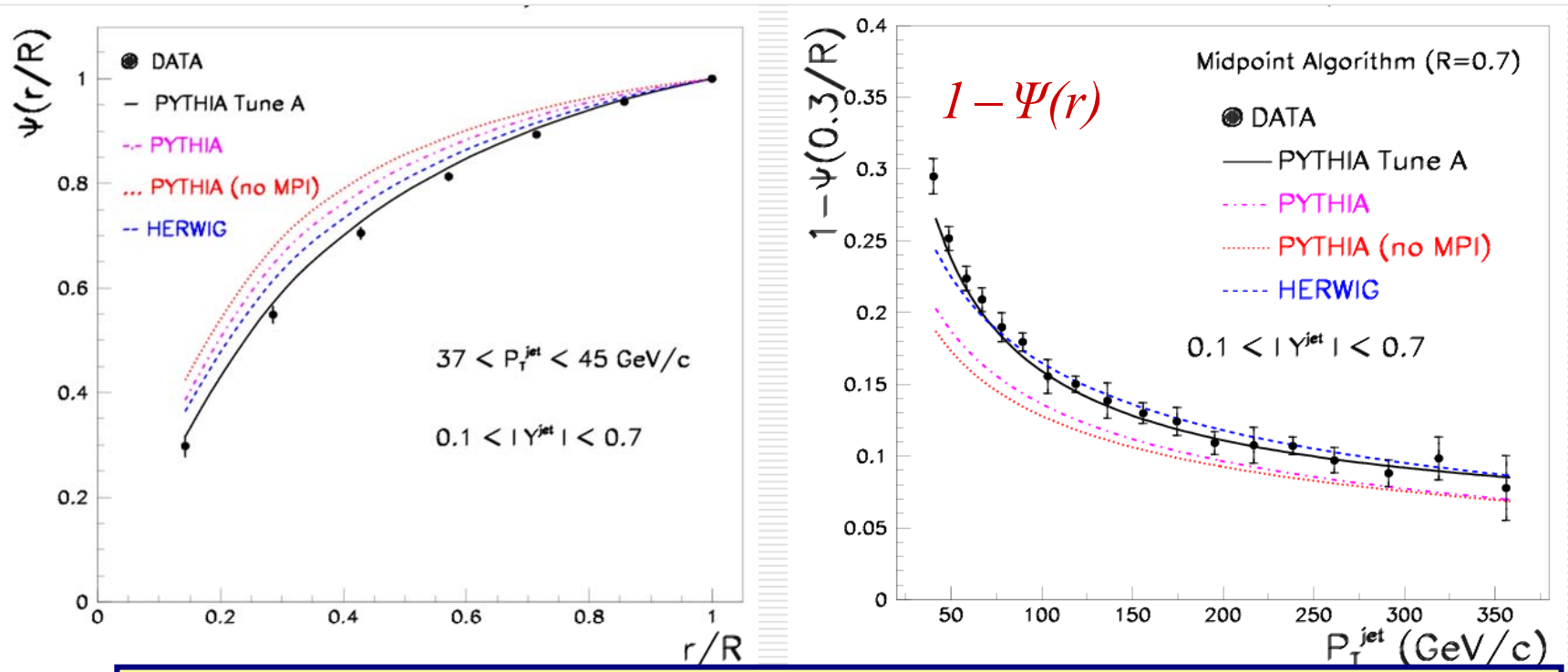




Energy flow within a jet



$$\Psi(r) = \frac{1}{N_{jets}} \Sigma_{jets} \frac{p_T(0,r)}{p_T^{jet}(0,R)}$$



Tuned MC, PYTHIA Tune A (enhanced ISR + MPI), describes the data.

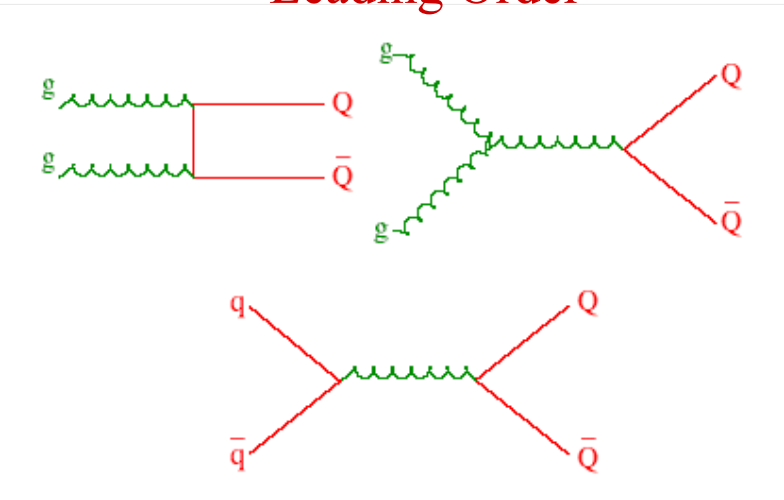
Theory Predictions

- PYTHIA: Event generator, LO Matrix Element coupled with parton showers, underlying event, multiple parton interactions
- HERWIG: Event generator, LO Matrix Element coupled with parton showers, underlying event from UA5, addon Jimmy for multiple-parton interactions
- MC@NLO: Event generator with Next-to-Leading-Order calculations of rates for QCD processes. (Stefano Frixione *et al.,* JHEP06(2002)029)
- MCFM (Monte Carlo for FeMtobarn processes at Hadron Collider) A parton-level Monte Carlo program which gives NLO predictions for a range of processes at hadron colliders. (J.M. Campbell, R.K. Ellis)

Beauty Production

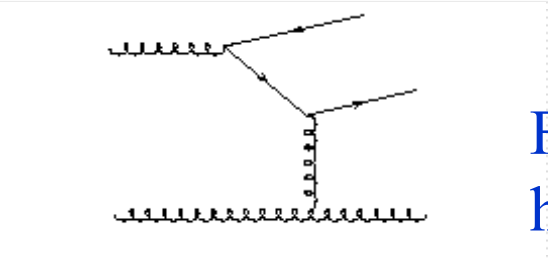
- To understand and probe perturbative QCD
- at E_{cm}=1.96 TeV σ(bb) ~ 50 $\overline{m}$b → few kHz event rate

Leading Order

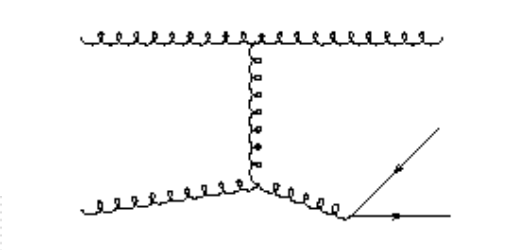


Flavor creation

Next to Leading Order



Flavor excitation



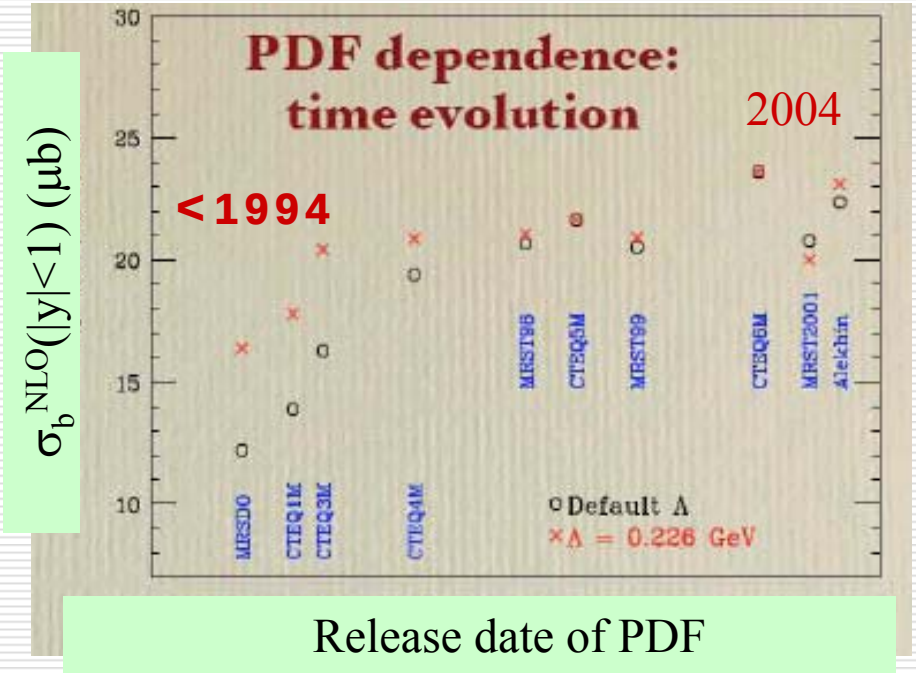
Gluon splitting

Full calculation have been done up to NLO and beyond ….

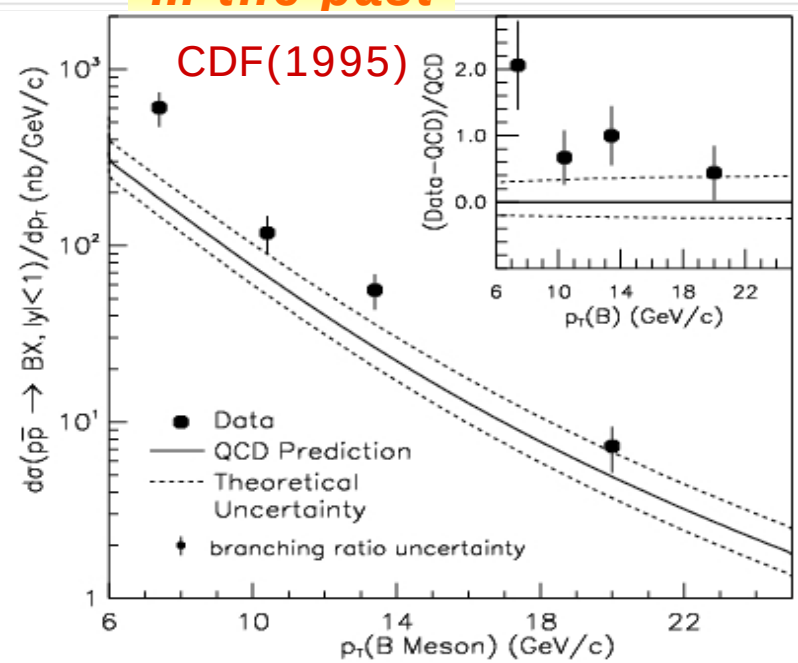
Many developments in the theoretical approach in the recent years

Not so recent developments

- Beyond NLO: resummation of $\log(p_T/m)$ terms → FONLL
- Substantial change in fragmentation function extraction (LEP data)
- new PDF functions



... the past



- Measure b-jet and b-hadron rates instead of b-quark rates.
- Separate prompt b from ψ' decay
- Measure spectrum down to P_T=0

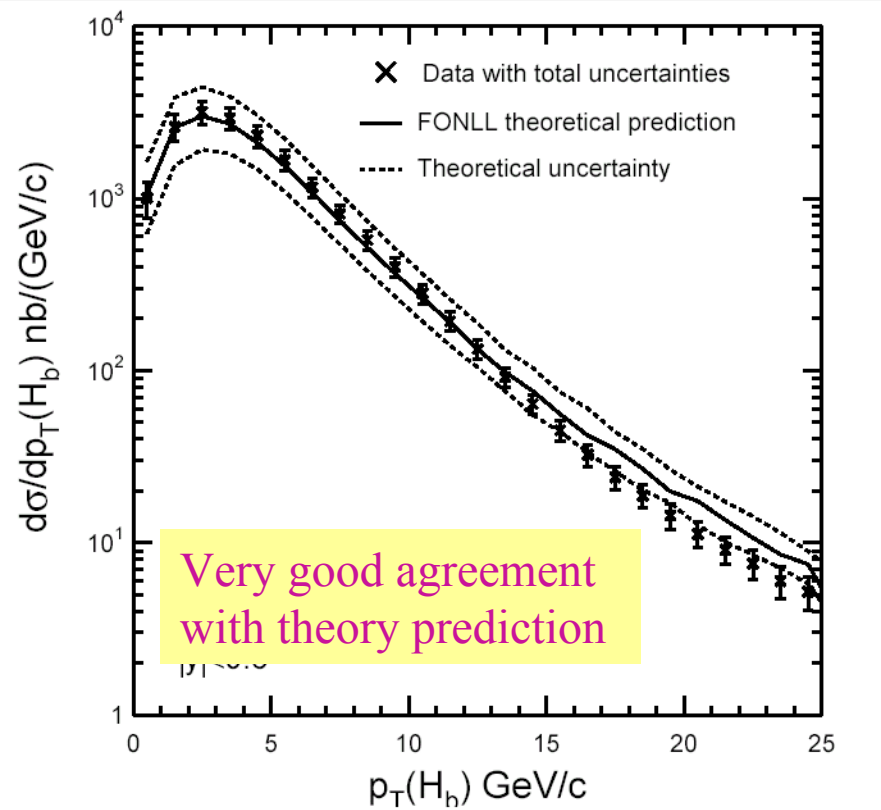
... the present →

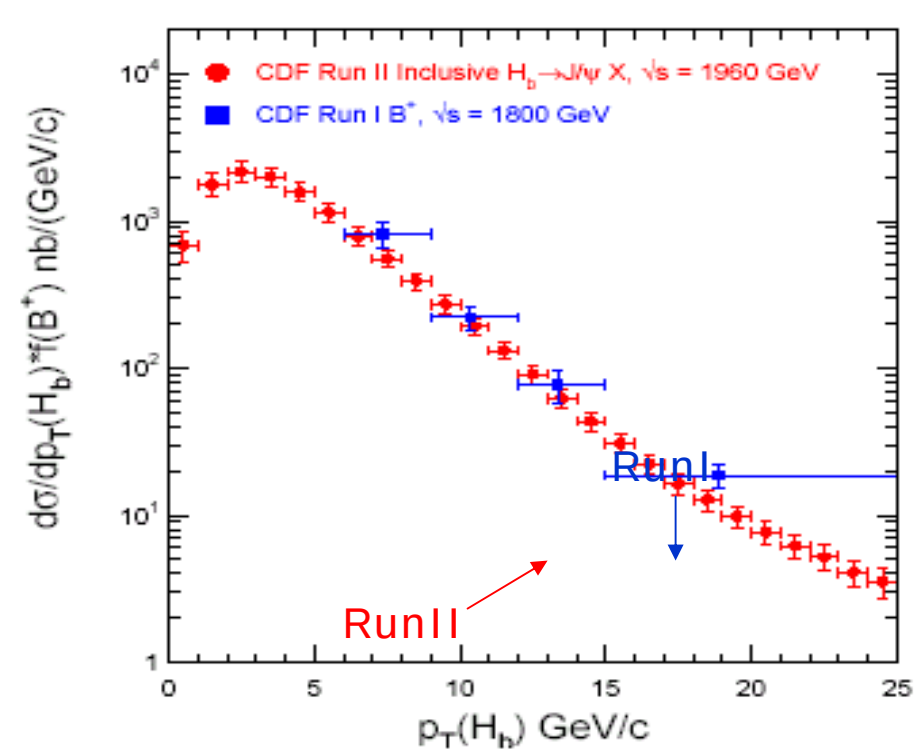
B hadron production cross section

Total inclusive single b-hadron (H_b) cross section

$$\sigma(p\bar{p} \to H_b X, |y| < 0.6) = 17.6 \pm 0.4(stat)^{+2.5}_{-2.3}(syst)\ \mu\text{b}$$

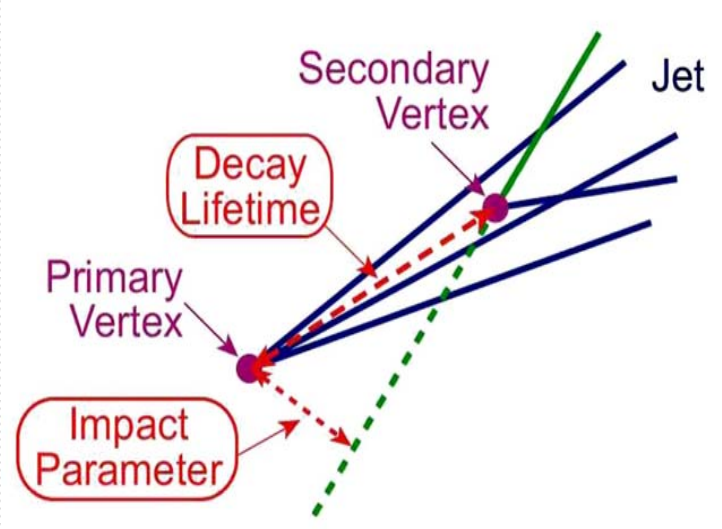
Using $Br(H_b \to J/\psi X) = 1.16 \pm 0.10\%$ and $Br(J/\psi \to \mu\mu) = 5.88 \pm 0.10\%$





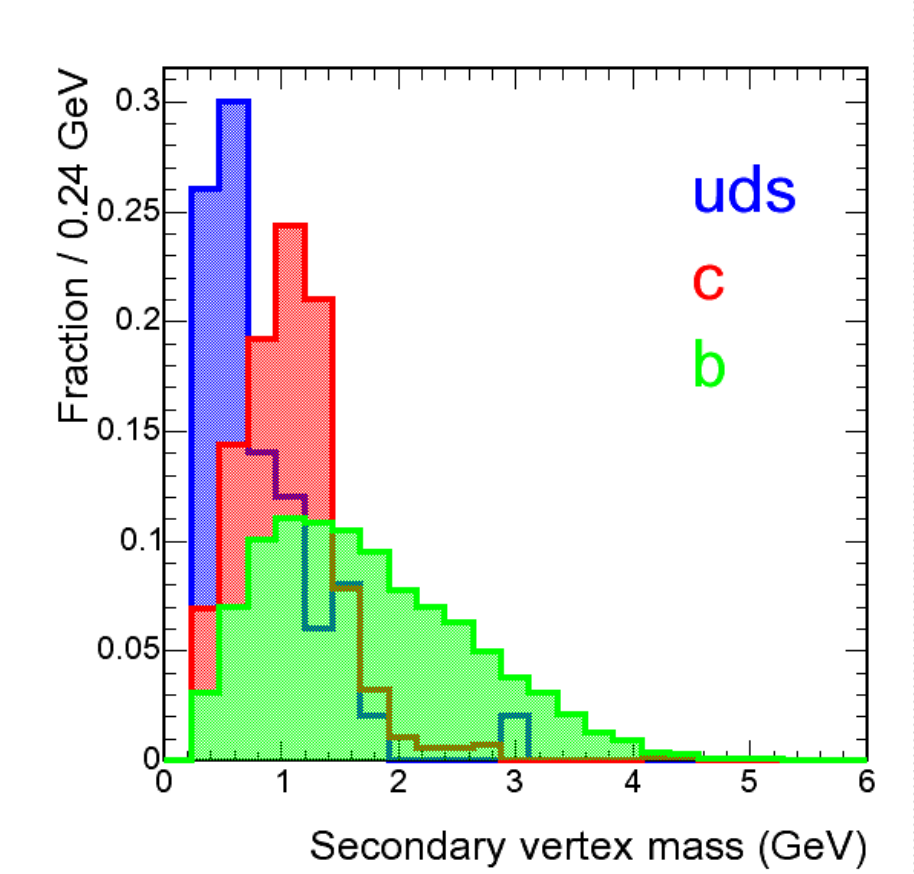
Inclusive b-jet cross section

- Motivation
  - b-jets part of many SM and BSM signals
    - Top pair quark / Single Top
    - Low mass SM Higgs in WH/ZH channels
    - Low mass SUSY Higgs
  - Check pQCD calculations
- Data Analysis
    - Same data as inclusive jet analysis
    - Tag b-jets using secondary vertex



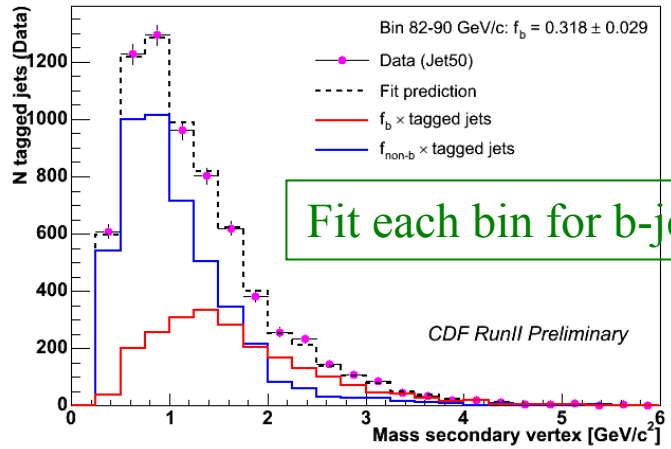
•b-hadrons decay ~450 μm
•Reconstruct secondary vertex using tracks in silicon tracker
• b-tagging efficiency in inclusive jet events:
50%(50 GeV)→25%(350 GeV)

b-jet tagging

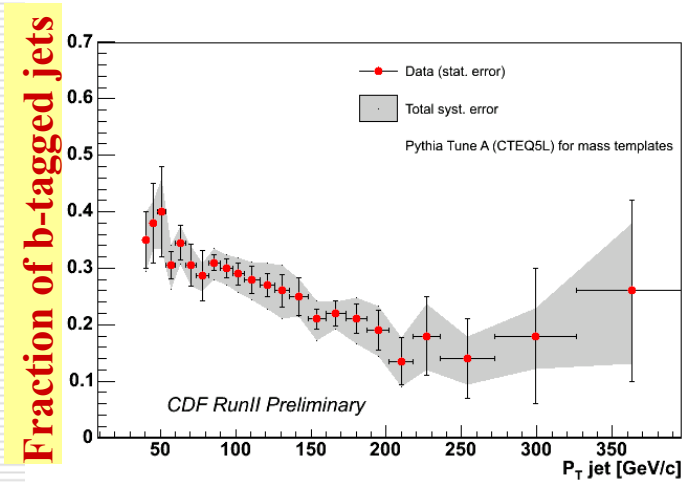


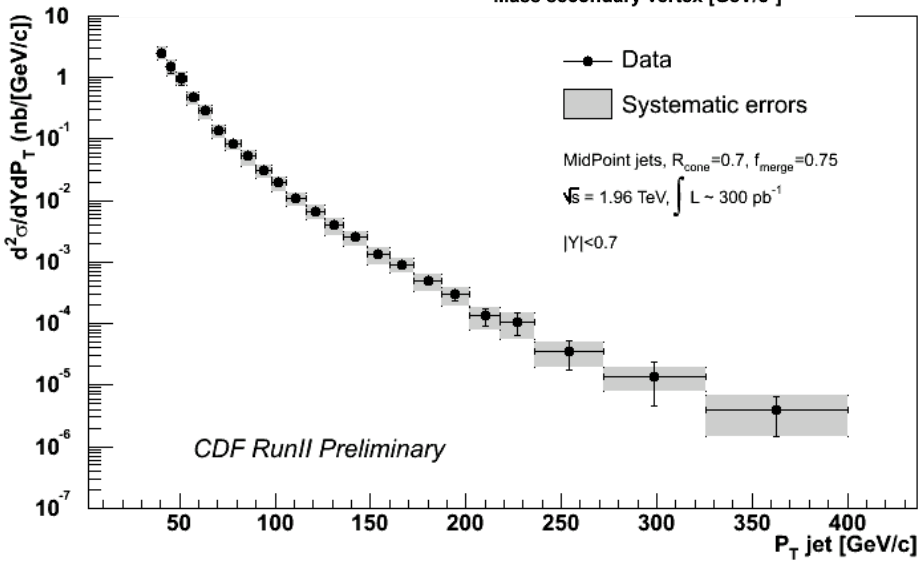
Use secondary vertex mass to separate b-jets from c and light jets.

Inclusive b-jet cross section



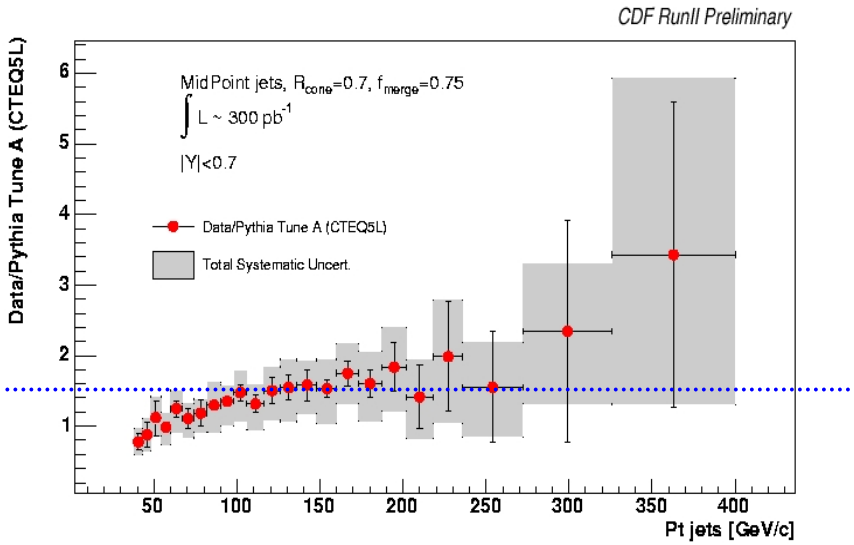
Fit each bin for b-jet fraction





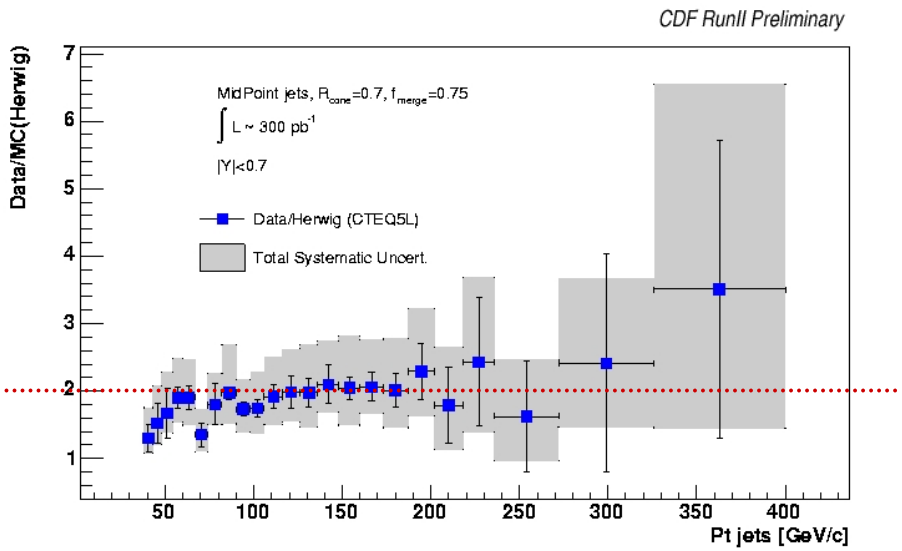
Systematic Error	low P_T	high P_T
Luminosity	6%	6%
Absolute Energy Scale	15-20%	40%
Jet energy resolution	6%	6%
B-tagging efficiency	10%	15%
B-tagged jets fraction	10-15%	40%
Unfolding	8%	8%

Comparison with LO pQCD



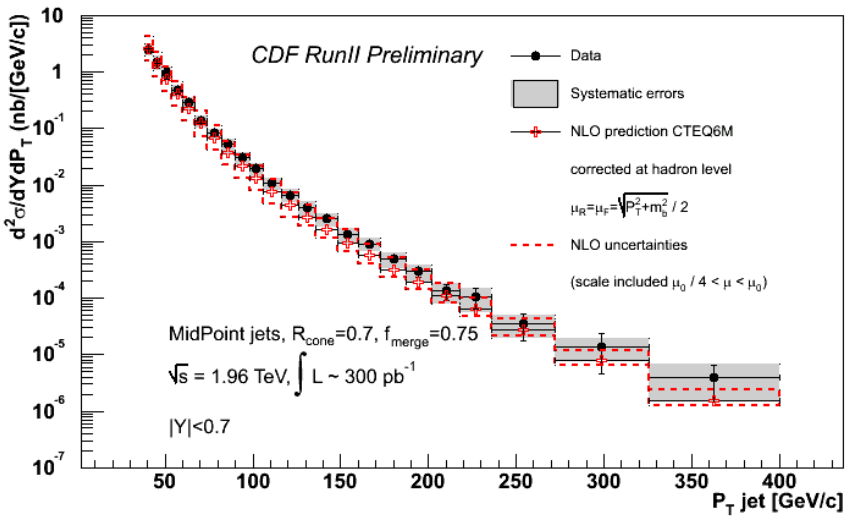
Pyhtia LO ME+Parton Shower
Underlying Event Tuned to CDF data
Data/Pythia ~ 1.5

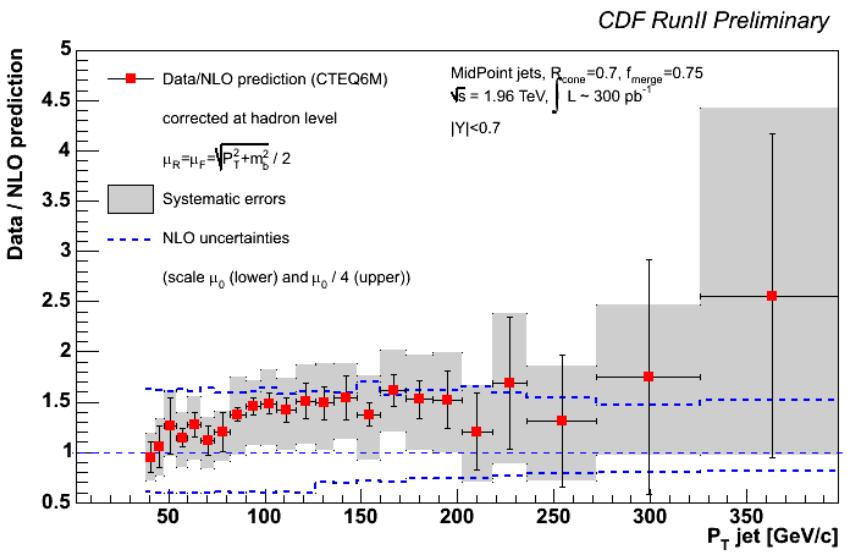
HERWIG LO ME+Parton showers
No multiple-parton interactions
Data/HERWIG ~2.0



Comparison with NLO pQCD

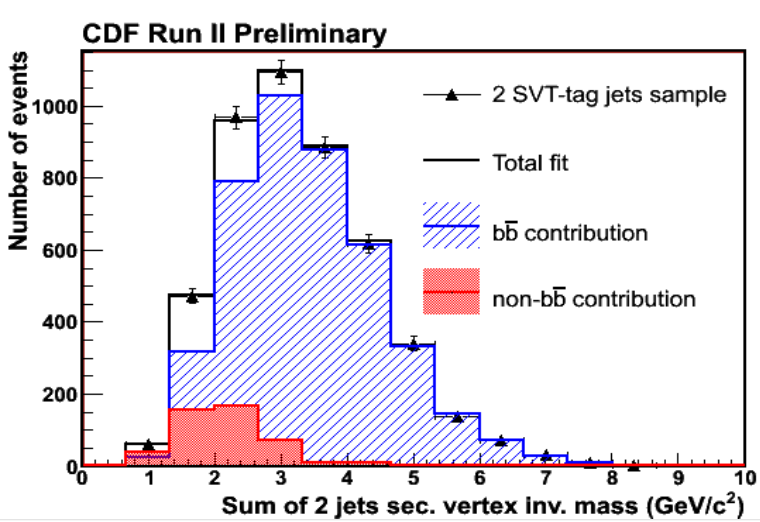
- Next-to-Leading Order perturbative QCD predictions for b-jet production (Nucl. Phys. B483, 321 (1997) -- M.Mangano et al.)
- LO $gg \rightarrow Q\overline{Q}, q\overline{q} \rightarrow Q\overline{Q}$
- NLO: $gg \rightarrow Q\overline{Q}g, q\overline{q} \rightarrow Q\overline{Q}g, qg \rightarrow Q\overline{Q}q$

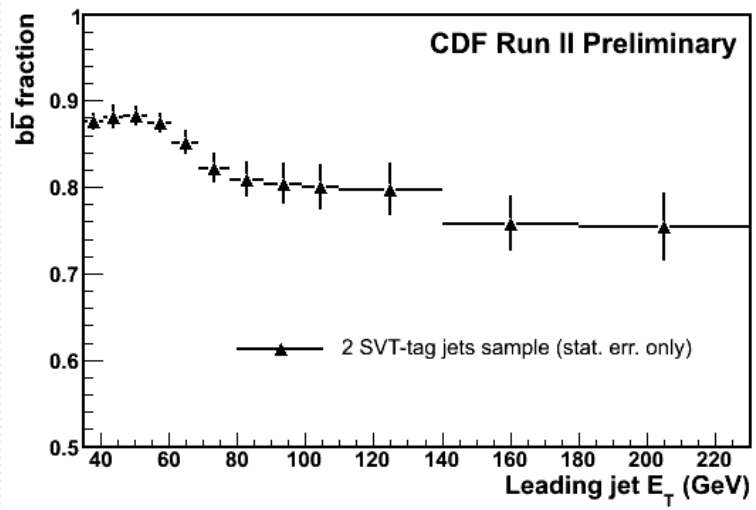




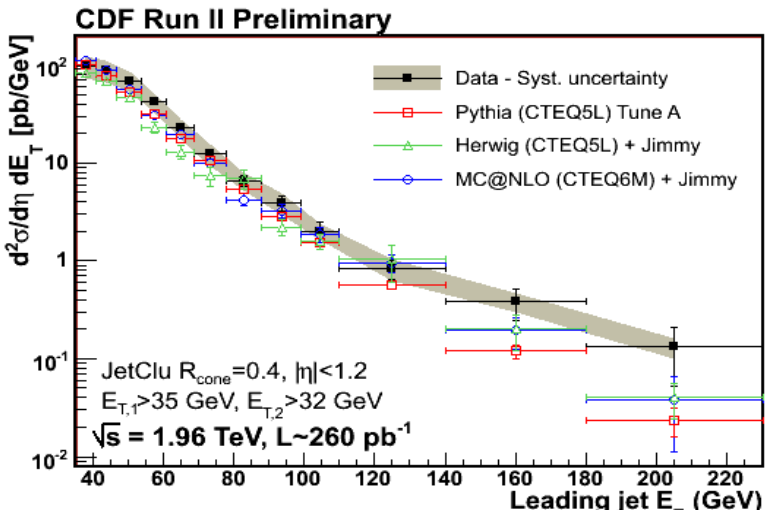
$b\bar{b}$ Dijet Production

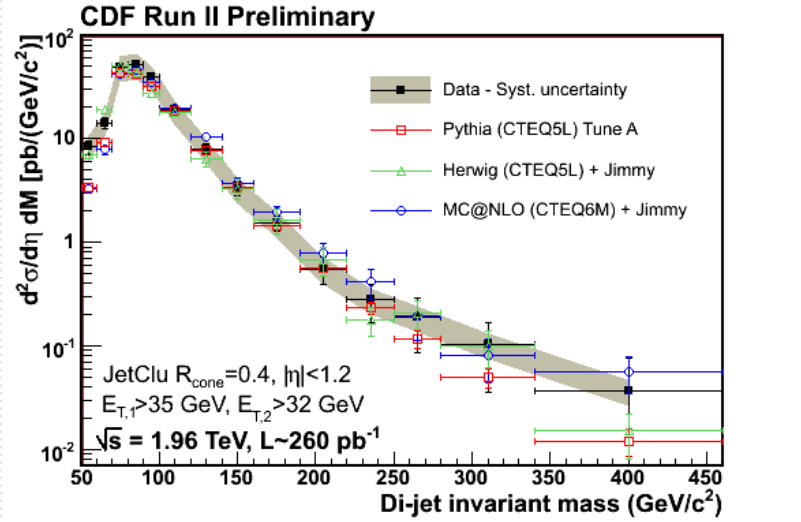
- 260 pb^{-1} of data, dominated by flavor creation $q\bar{q} \rightarrow Q\bar{Q}$
- L2 trigger 2 jets P_T^{Jet}>20 GeV, 2 SVT displaced tracks
- Two leading jets R=0.4, $|\eta_{jet}|$<1.2, P_T^{Jet}> 30 GeV
- Both jets Sec-Vtx tagged
- Each jet associated to a SVT track with P_T>2 GeV and |d0|>120 μm
- Use sum of two secondary vertex masses to measure b-jet fraction
  - Use MC to correct for selection efficiency
  - MC scale factor 1.029 +/- 0.009 (stat) +/- 0.034 (syst).

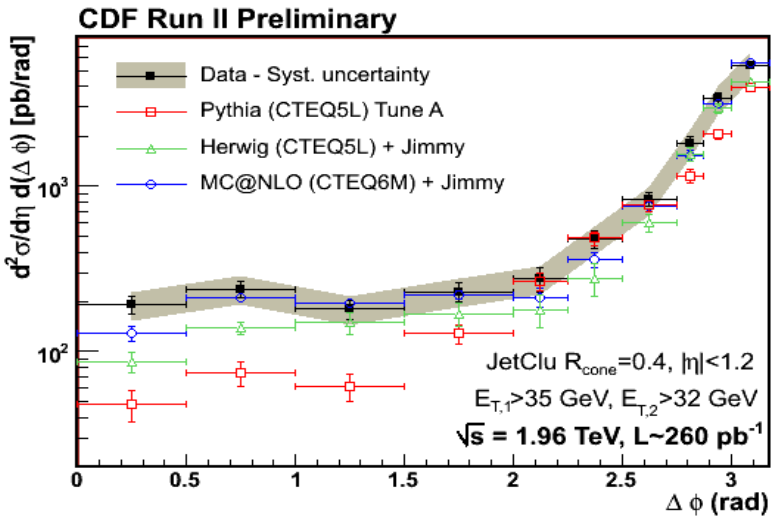




$b\bar{b}$ Dijet Production



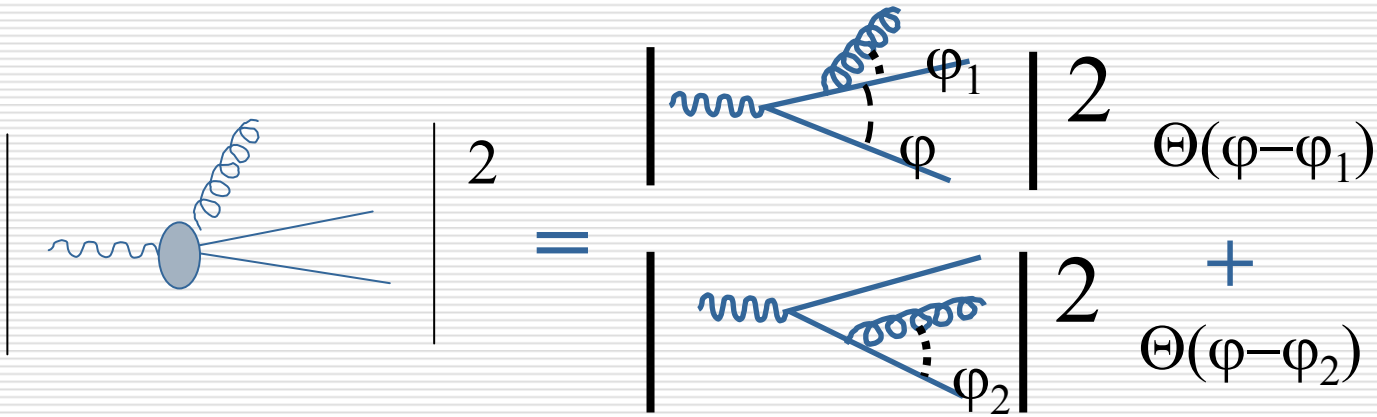




CDF Run II Preliminary	σ [pb] $\lvert\eta_{1,2}\rvert < 1.2$, $E_{T,1} > 35$ GeV, $E_{T,2} > 32$ GeV
Data	$\sigma = 5664 \pm 168$ (stat.) ± 1270 (syst.)
Pythia (CTEQ5L) Tune A	$\sigma = 5136 \pm 52$ (stat.)
Herwig (CTEQ5L) + Jimmy	$\sigma = 5296 \pm 98$ (stat.)
MC@NLO (CTEQ6M) + Jimmy	$\sigma = 5421 \pm 105$ (stat.)

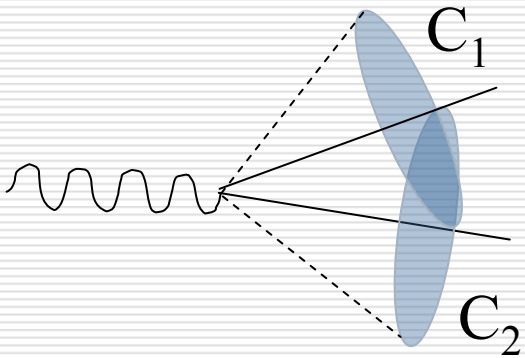
MC@NLO describe Δφ distribution
Addition of Multiple Parton Interaction improves MC@NLO agreement.

Angular ordering Approx. in parton showering



Drawbacks:

- No emission outside $C_1 \oplus C_2$:
  - Lack of hard, large angle emission
  - Poor description of multijet events



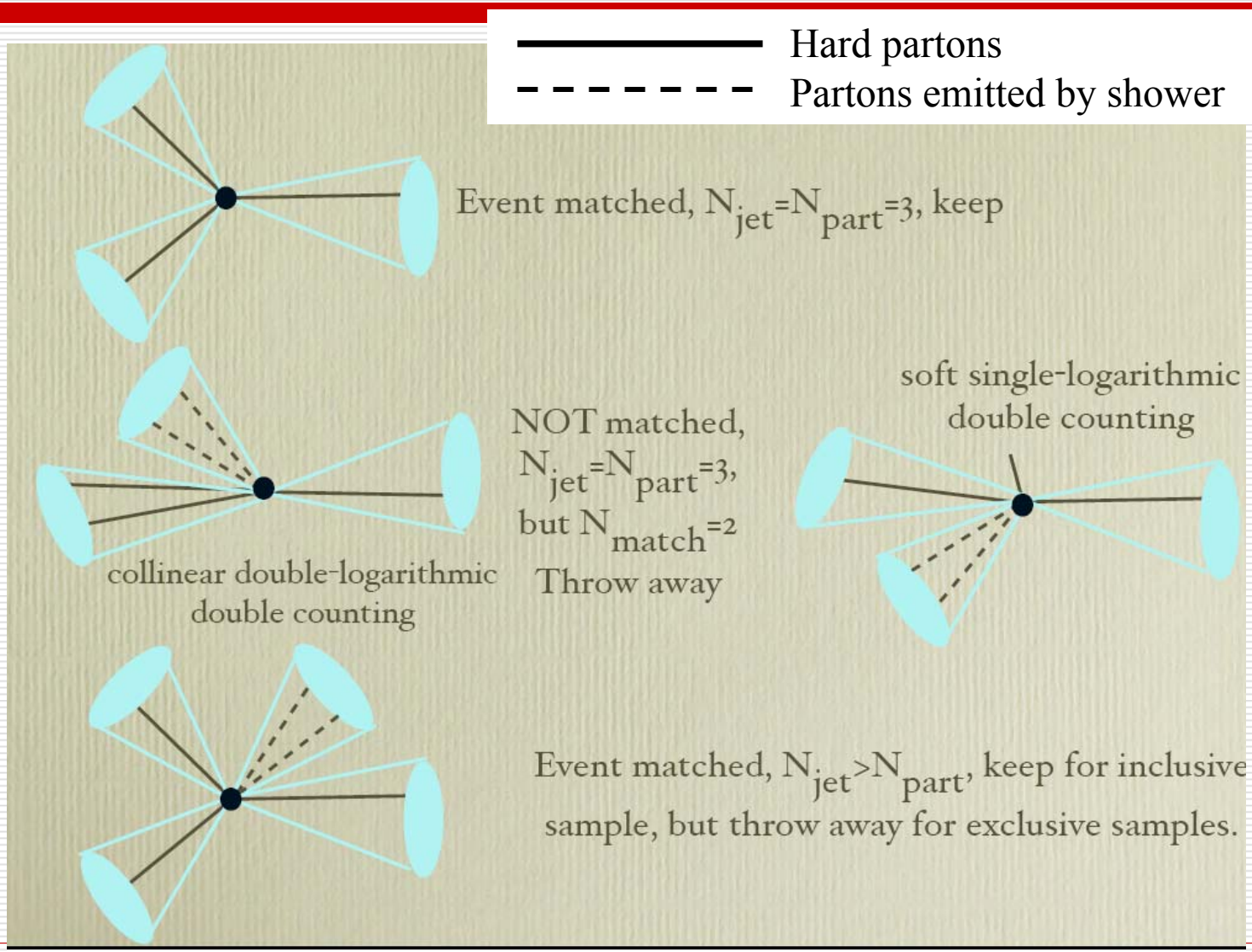
- Incoherent emission inside $C_1 \oplus C_2$:
  - Loss of intrajet radiation

Alpgen + MLM matching

- Generate parton level configuration for hard parton configuration Npart, with $P_T > P_T^{min}$ and $\Delta Rjj > R_{min}$
- Perform jet showering using HERWIG/Pythia algorithms
- Clustered the partons with a cone jet algorithm, defined by P_T^{min} and Rjet;
- For each, hard partons, find the jet with minimum ΔRj-parton
  - if ΔRj-parton < Rjet, the hard parton is matched
  - a jet can only be matched to a single hard parton
  - if all partons are matched keep the event, else discard it
- This prescription defines an inclusive sample of N = Npart jets
- Define an exclusive N-jet sample by requiring Njet=Npart
- Combine 1-jet (exclusive), 2-jet (exclusive),N-1-jet (exclusive) and N-jet (inclusive) samples to determine inclusive jet rate

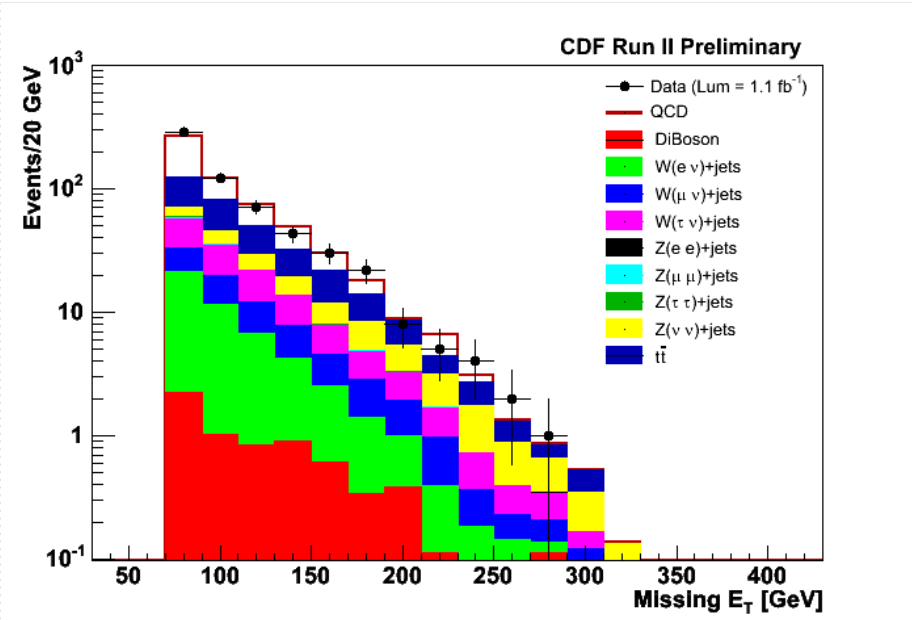
M.L. Mangano *et al*., J. High Energy Phys. **0307**, 001 (2003)

Few examples:

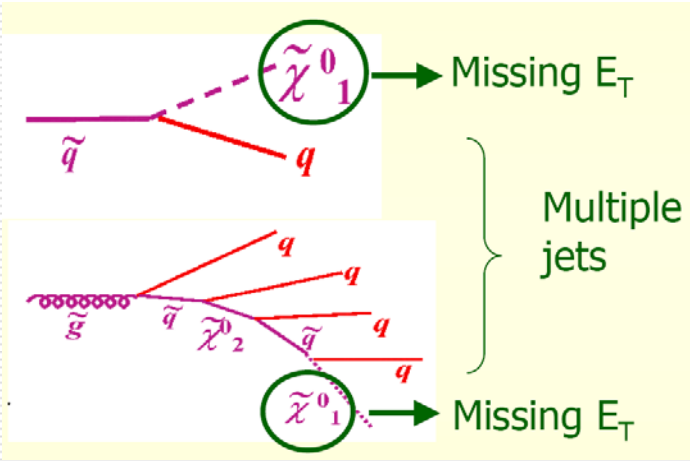


Boson+Jets Production

- Important for many physics searches



SUSY searches in the missing E_T + Jets channel



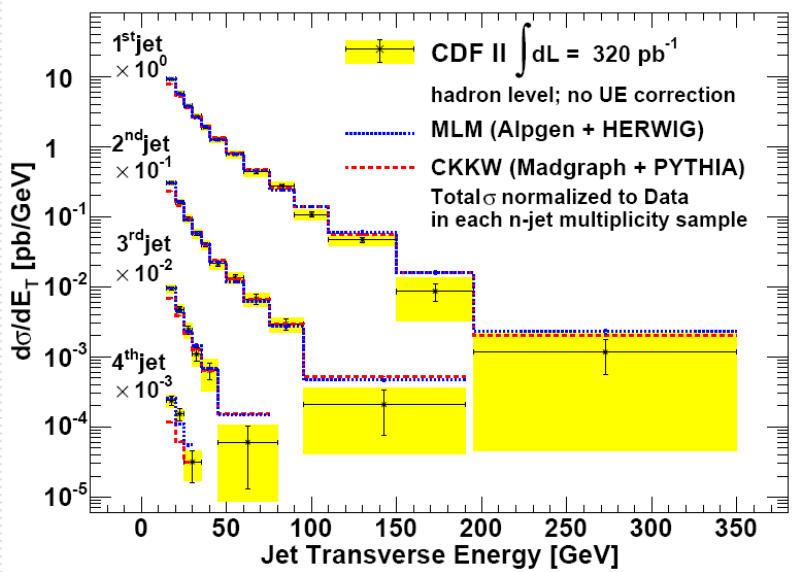
Major backgrounds

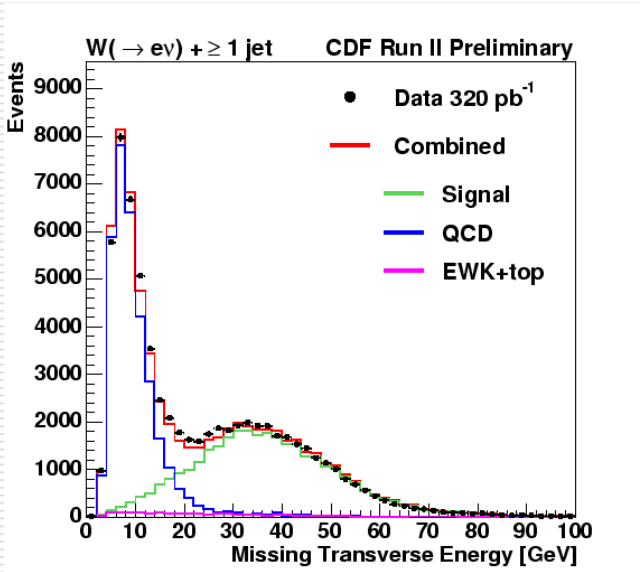
- $Z \rightarrow \nu\nu$ + jets
- $W \rightarrow l\nu$ + jets
- QCD, Top, WW…

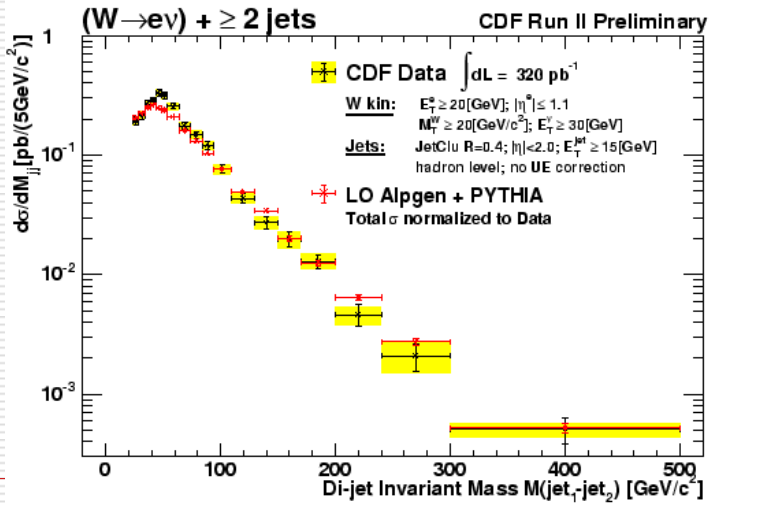
Crucial to understand boson-jets production!

W+ jet(s) Production (JetClu R=0.4)

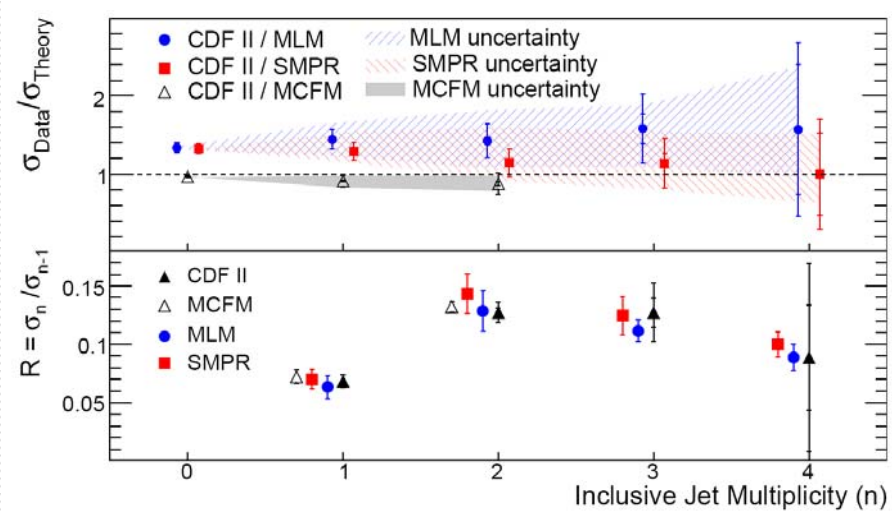
- W decay phase space:
  E_T^{ele}>20 GeV, $|\eta^{ele}|$<1.1, E_T^{ν},M_T^W>20 GeV
- Jet Clu, R=0.4, ETJet>15, |ηJet|<2.0
- Correct for QCD/top/EWK backgrounds
- Correct for jet smearing, jet promotion due to additional $p\bar{p}$ interactions <5% at low P_T

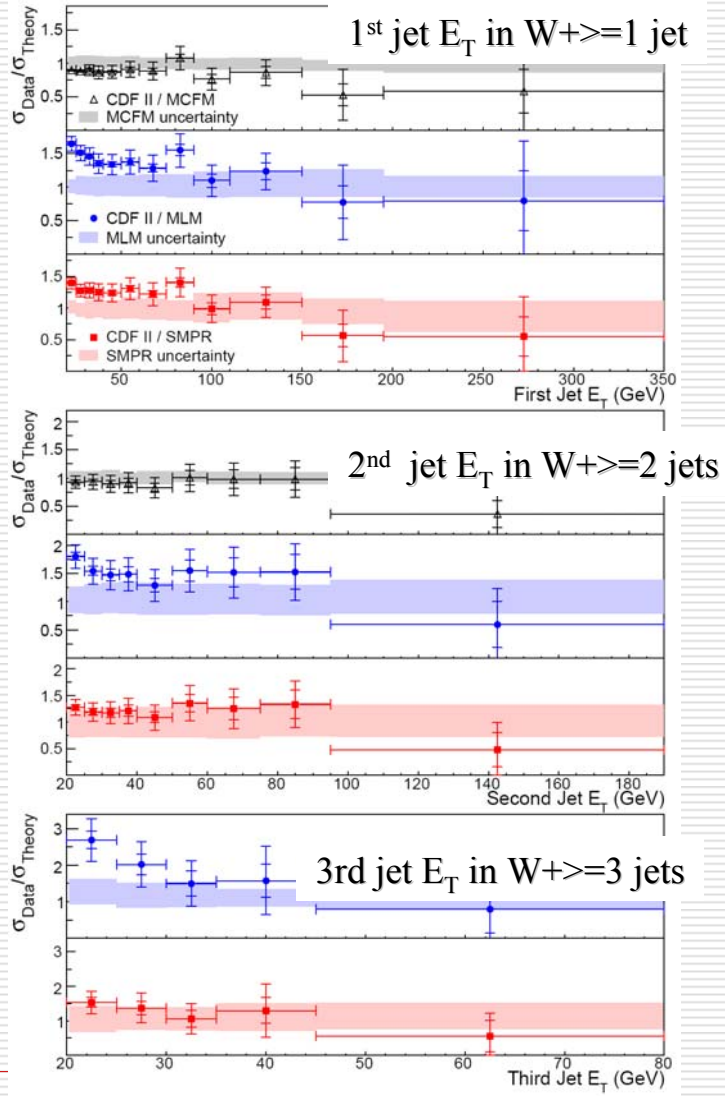






W+jets production





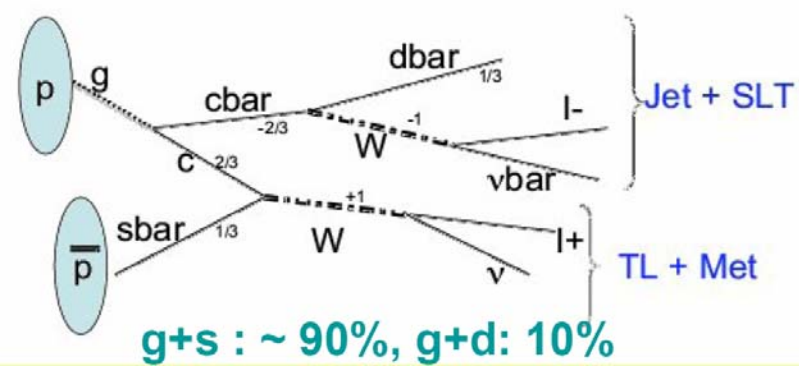
The W+1jet and W+2jet cross section prefers MCFM.

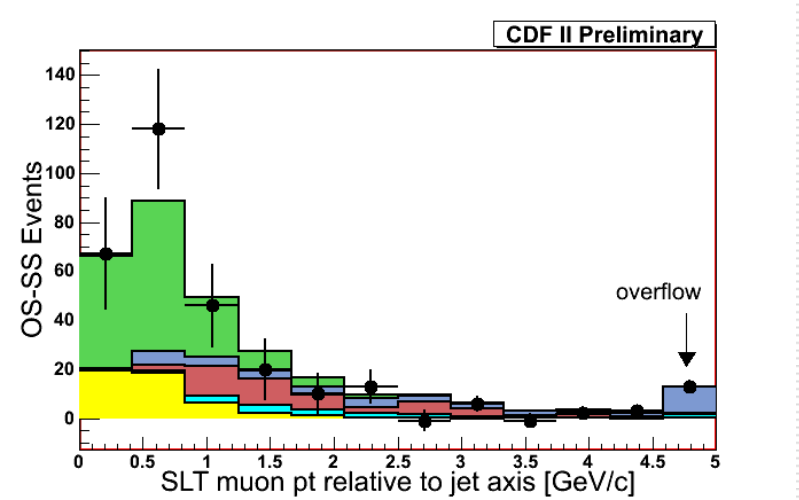
W+c production

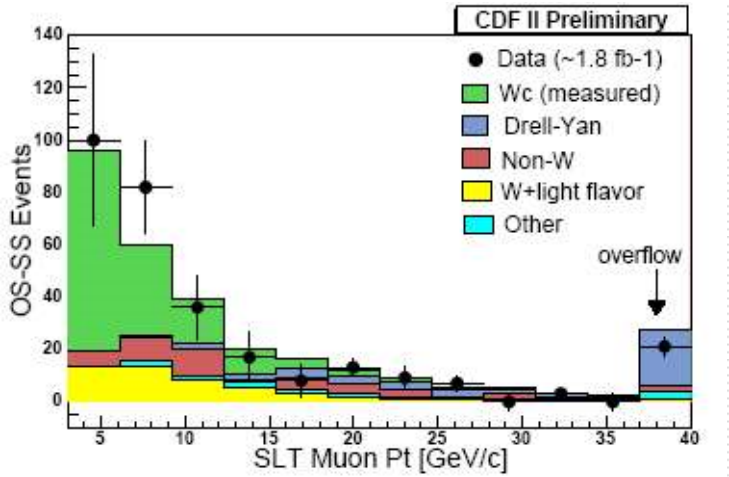
- Require a lepton and E_T^{miss} from W
- One or two jets, one c-tagged jet
- c-jet is tagged by a soft muon
- W boson charge is opposite to c-jet(muon) charge.
- Use charge asymmetry
  [N(OS)-N(SS)]/[N(OS)+N(SS)],
- Signal Asymmetry (Alpgen) 0.72±0.1
- Background,
  - W+light jets, non-W QCD, Drell-Yan
- OS-SS Events (1.8 fm^{-1})
- Data 296
- BG 149±15
- Wc 147±42(stat)±15(sys)

$$\sigma_{Wc}(p_t^c>20\ GeV\ ,\ |\eta_c|<3.0)*BR(W\rightarrow l\nu)$$
$$= 28.5\pm2.8(stat)\ ^{+4.1}_{-4.4}\ (sys)+/-1.7(lum)pb$$

$$\sigma_{Alpgen} = 22.2\pm1.2(PDF)\ ^{+3.8}_{-3.9}(scale)\ pb^{-1}$$



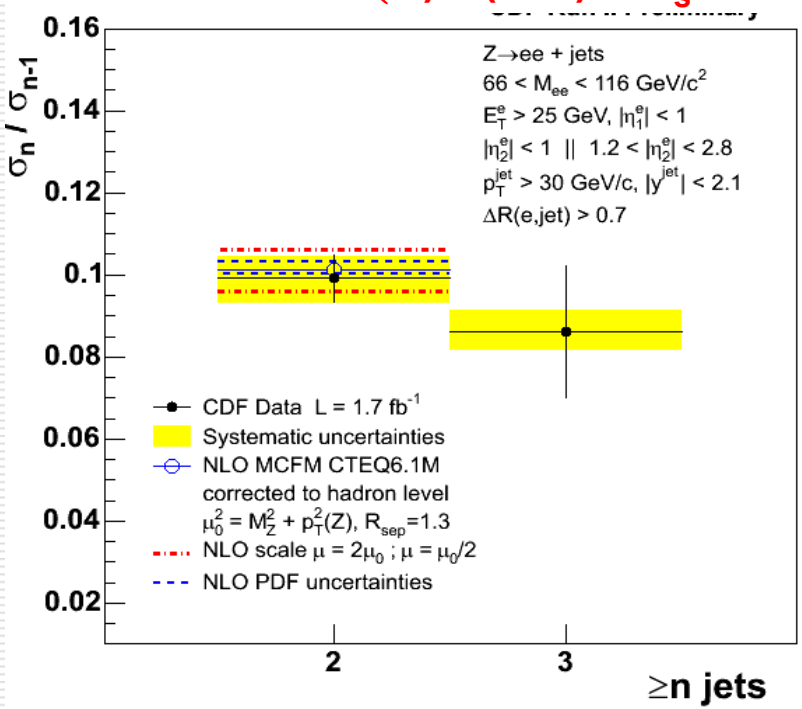


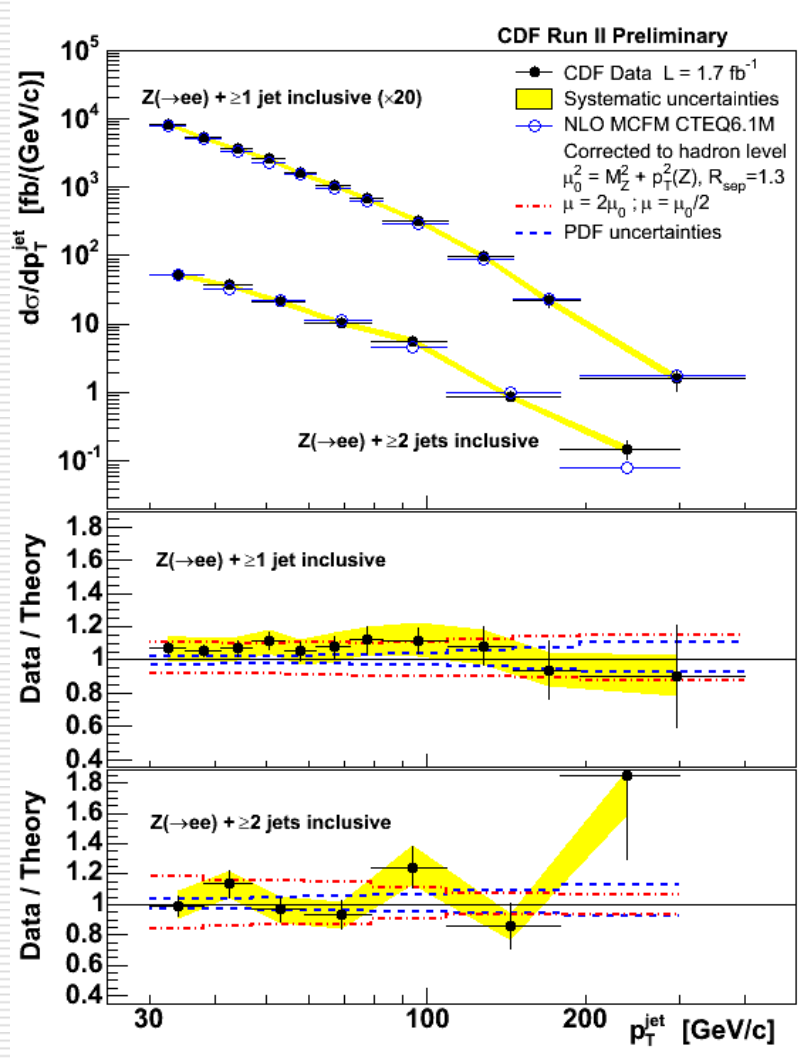


Z+jet production

- Test pQCD predictions
- Important Background
  - Associated Higgs Boson *ZH*
  - SUSY through MET+jets

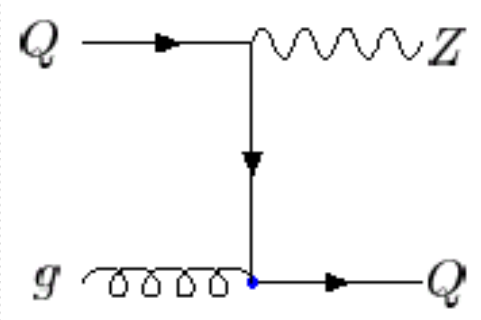
Ratio of $\sigma(N)/\sigma(N-1) \approx \alpha_s$

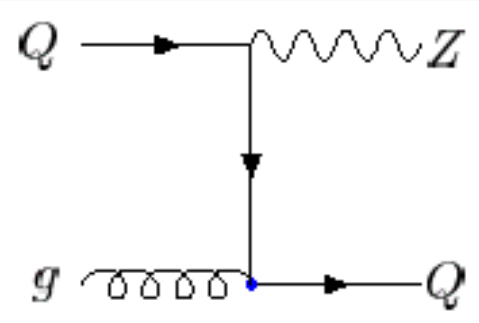




Z+b jet cross section

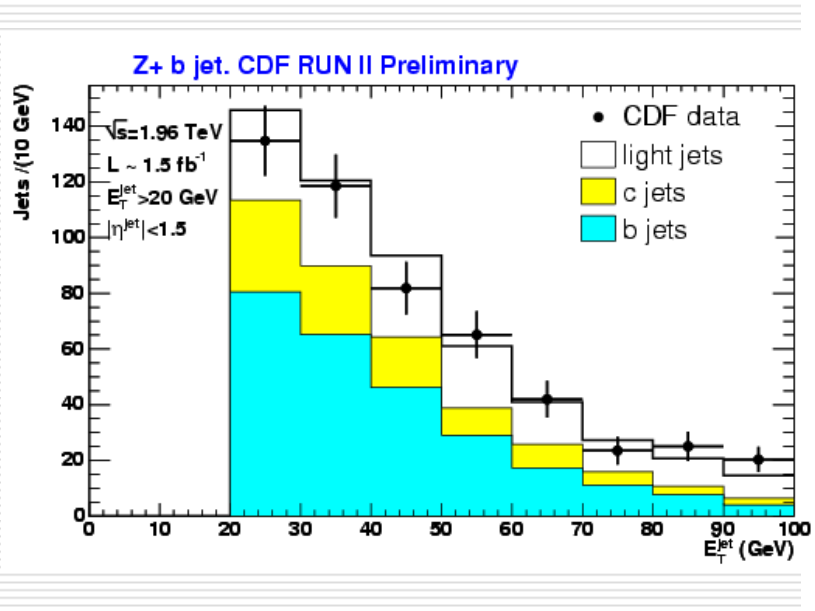
- Probe heavy flavor content of proton
- Important background to single top, *ZH*, SUSY Higgs
- Large Q, hence NLO QCD more reliable

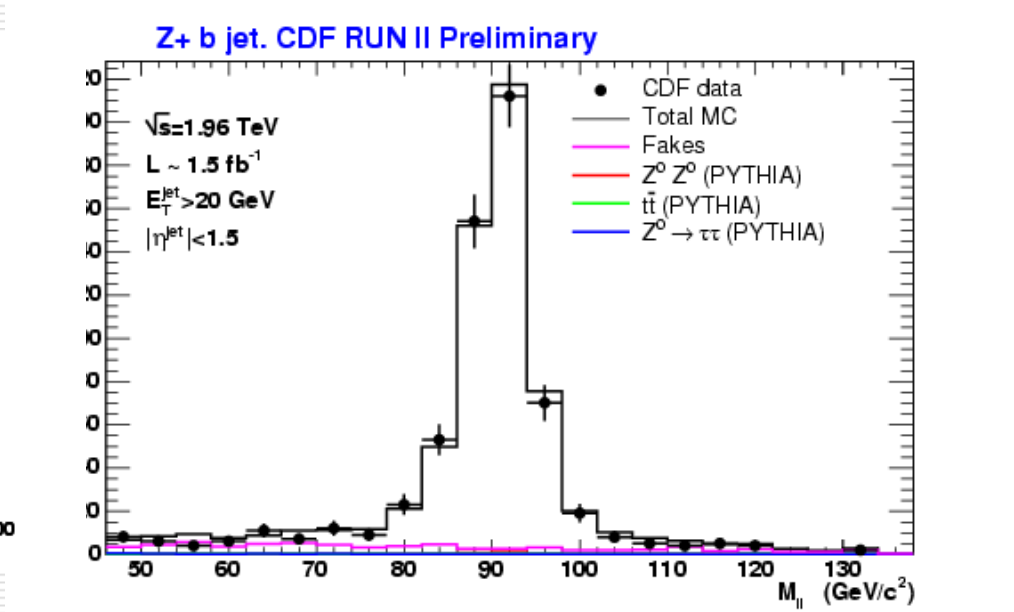




- Select Z (→μμ and *ee*) events
- Use b-vertex mass to separate b,c and light quark jets.

Z+b jet cross section





	CDF Run II Preliminary Data	PYTHIA	MCFM NLO	MCFM NLO +ue +had
$\sigma(Z^0 + b\,\text{jet})$	$0.94 \pm 0.15 \pm 0.15$ pb	0.84	0.51	0.56
$\sigma(Z^0 + b\,\text{jet})/\sigma(Z^0)$	$0.00369 \pm 0.00057 \pm 0.00055$	0.0035	0.0021	0.0023
$\sigma(Z^0 + b\,\text{jet})/\sigma(Z^0 + \text{jet})$	$0.0235 \pm 0.0036 \pm 0.0045$	0.0218	0.0188	0.0177

Summary and Conclusions

RunII at Tevatron will define a new level of precision for QCD studies in hadron-hadron collisions

CDF has a rich program: Inclusive jet cross section, W+jets, diphoton, γ + heavy quark, b-jet production, Underlying event studies, diffractive studies

Jet production studies with the MidPoint/K_T algorithm

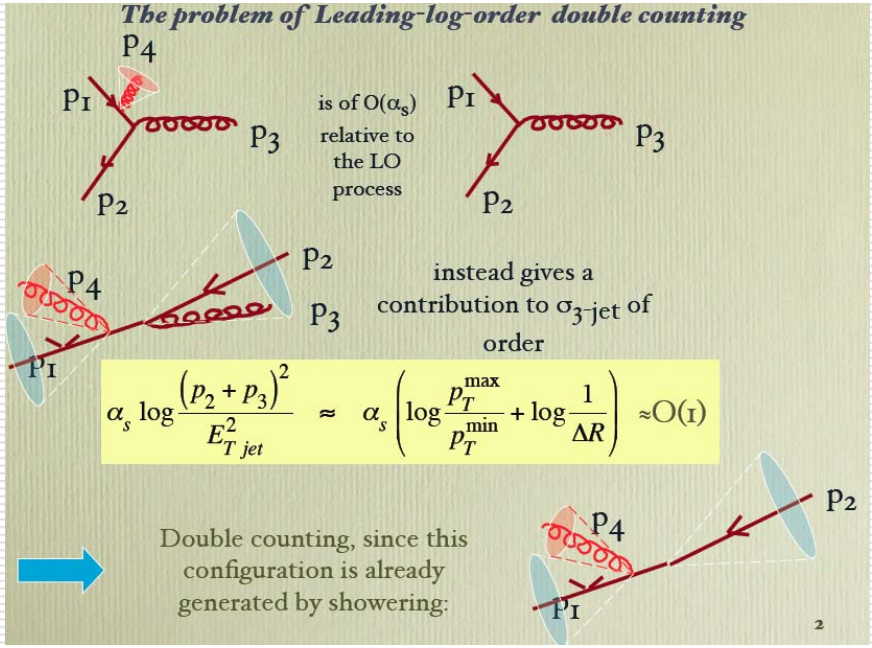
Good agreement with NLO QCD

B-Jet jet cross section measured upto 300 GeV, consistent with PYTHIA
B-jet through J/psi good agreement with theory.
B+heavy flavour agrees with LO Pythia predictions.

DiPhoton cross section, NLO fragmentations needed to describe $\Delta\varphi$ and qt distributions. Gluon resummation needed at large qt

A lot of work to understand W+multi jet production.

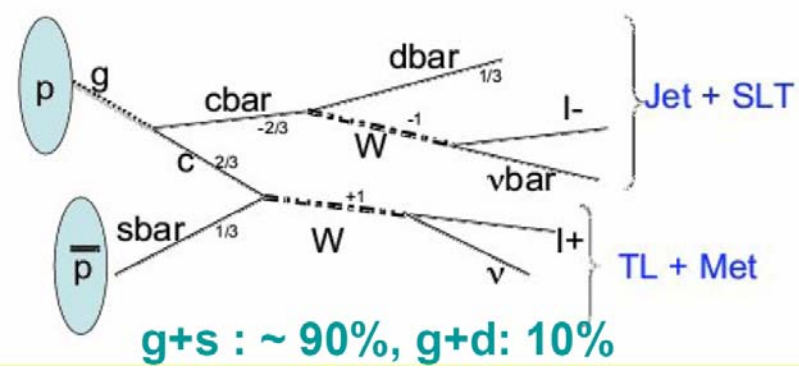
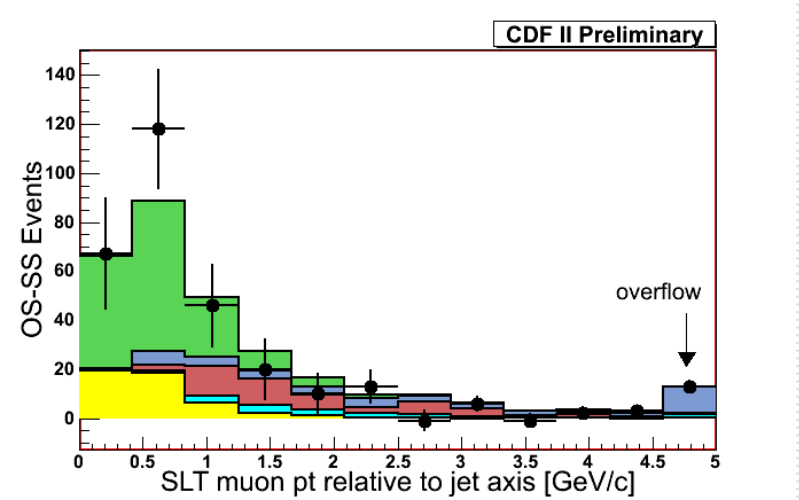
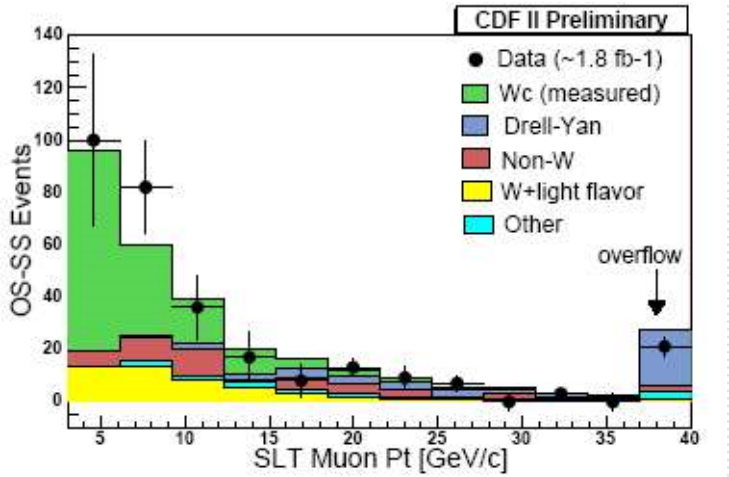
1. W + jets comparisons at the Tevatron->predictions for the LHC
   - -NLO->MCFM
   - -CKKW
     - -Mrenna-Richardson
     - -Sherpa
2. parton shower/resummation
   - -predictions for tt, Higgs
   - -impact of new parton shower algorithms



- need to control size of unwelcome logs when interfacing ME and PS
- mlm and CKKW approaches for controlling logs both in use at Tevatron

W+c production

- Require a lepton and E_T^{miss} from W
- One or two jets, one c-tagged jet
- c-jet is tagged by a soft muon
- W boson charge is opposite to c-jet(muon) charge.
- Use charge asymmetry
  [N(OS)-N(SS)]/[N(OS)+N(SS)],
- Signal Asymmetry (Alpgen) 0.72±0.1
- Background,
  - W+light jets, non-W QCD, Drell-Yan
- OS-SS Events (1.8 fm^{-1})
- Data 296
- BG 149±15
- Wc 147±42(stat)±15(sys)

$$\sigma_{Wc}(p_t^c>20\ GeV\ ,\ |\eta_c|<3.0)*BR(W\rightarrow l\nu)$$
$$= 28.5\pm2.8(stat)\ ^{+4.1}_{-4.4}\ (sys)+/-1.7(lum)pb$$

$$\sigma_{Alpgen} = 22.2\pm1.2(PDF)\ ^{+3.8}_{-3.9}(scale)\ pb^{-1}$$