Jet Physics at CDF

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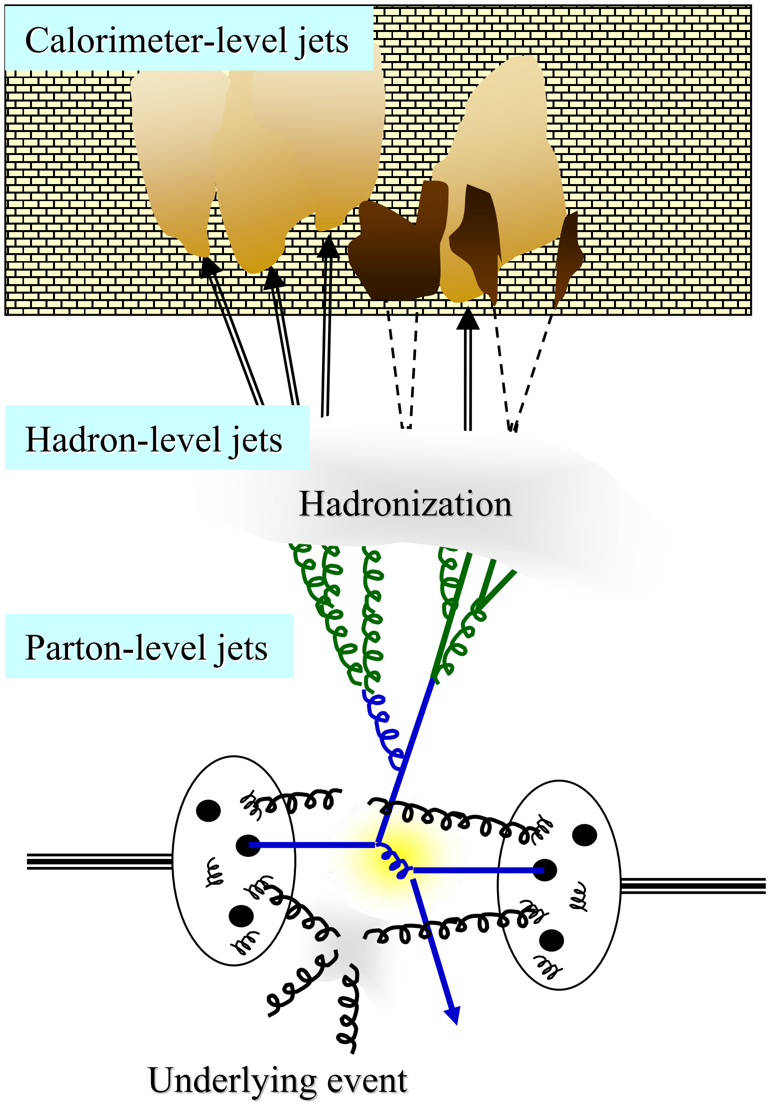
Jet Production



- Jets are collimated spray of hadrons originating from quarks/gluons coming from the hard scattering

  (Jets are experimental signatures of quarks and gluons)

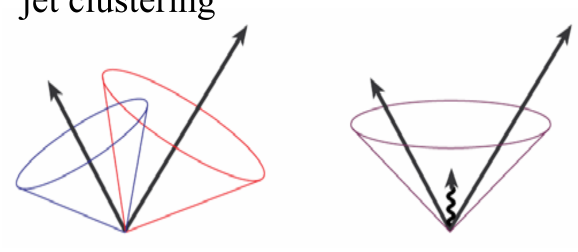
- Unlike photons, leptons etc, jets have to be defined by an algorithm for quantitative studies

- Need a well-defined algorithm that gives close relationship between calorimeter-level jets, hadron-level jets, and parton-level jets

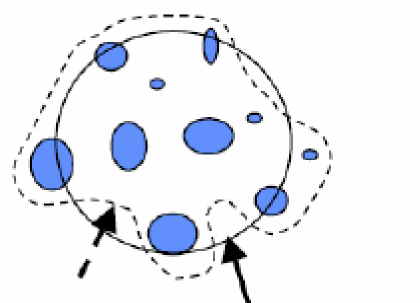
Jet "Definitions" - Algorithms at CDF

- Cone algorithms (JetClu, Midpoint)
  - Cluster objects based on their proximity in $y(\eta)$-ϕ space
  - Starting from seeds (calor. towers/particles above threshold), find stable cones (p_T-weighted centroid = geometric center).
  - In Run II QCD studies, often use "Midpoint" algorithm, i.e. look for stable cones from middle points between stable cones → Infrared safe to NNLO
  - Stable cones sometime overlaps → merge cones when overlap > 75%

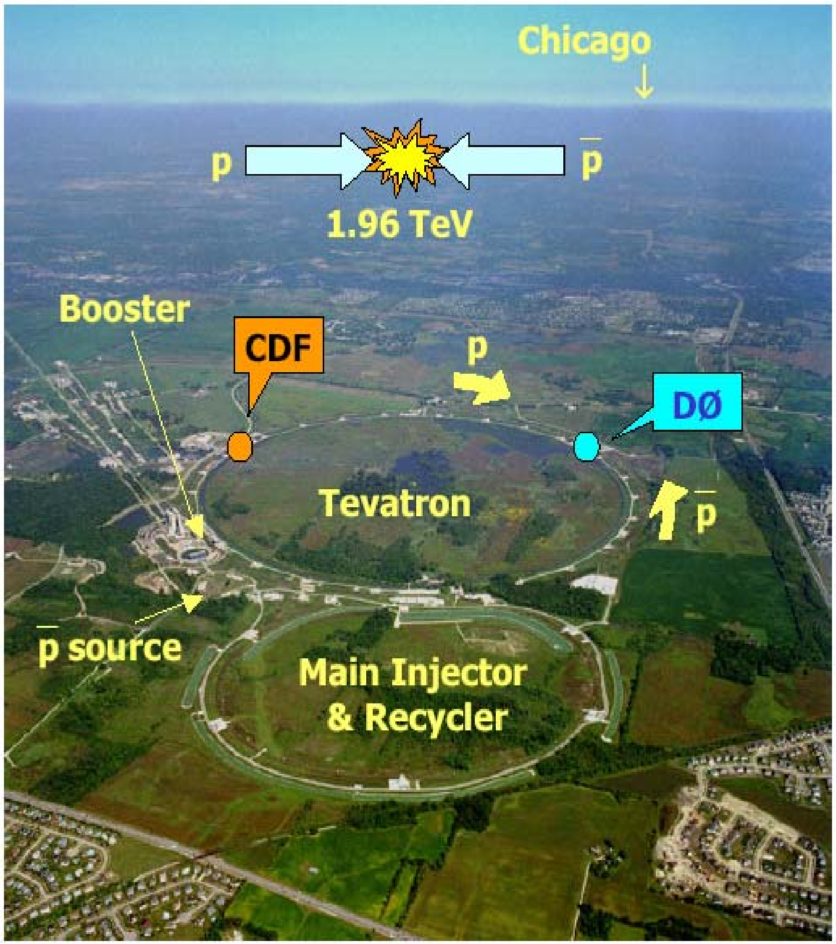
Infrared unsafety:
soft parton emission changes jet clustering



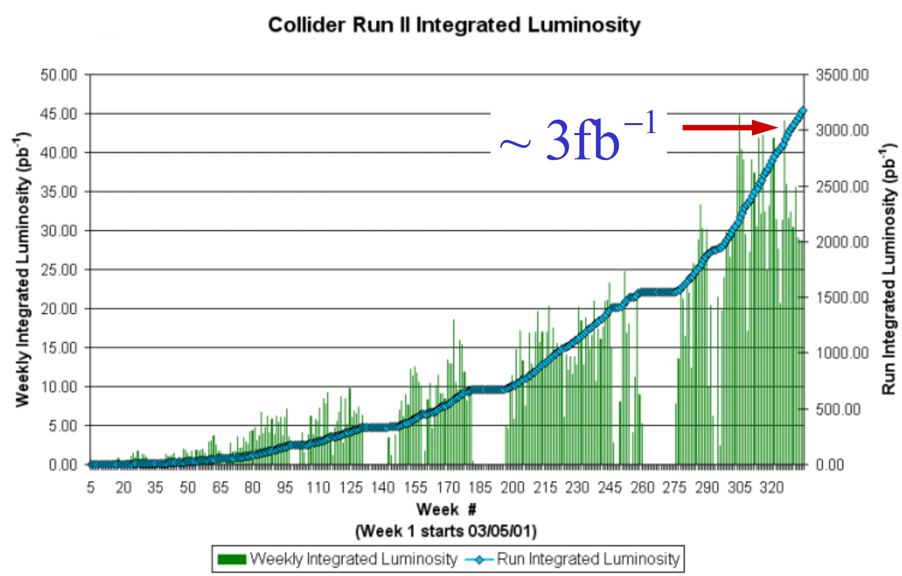
- k_T algorithm
  - Cluster objects based on their relative transverse momentum (k_T)
  - Iteratively cluster pairs of close objects until all objects become part of jets
  - No issue of splitting/merging. Infrared and collinear safe to all orders of QCD.
  - Successful at LEP & HERA, but relatively new at the hadron colliders
    - More difficult environment (underlying event, multiple $p\bar{p}$ interactions…)



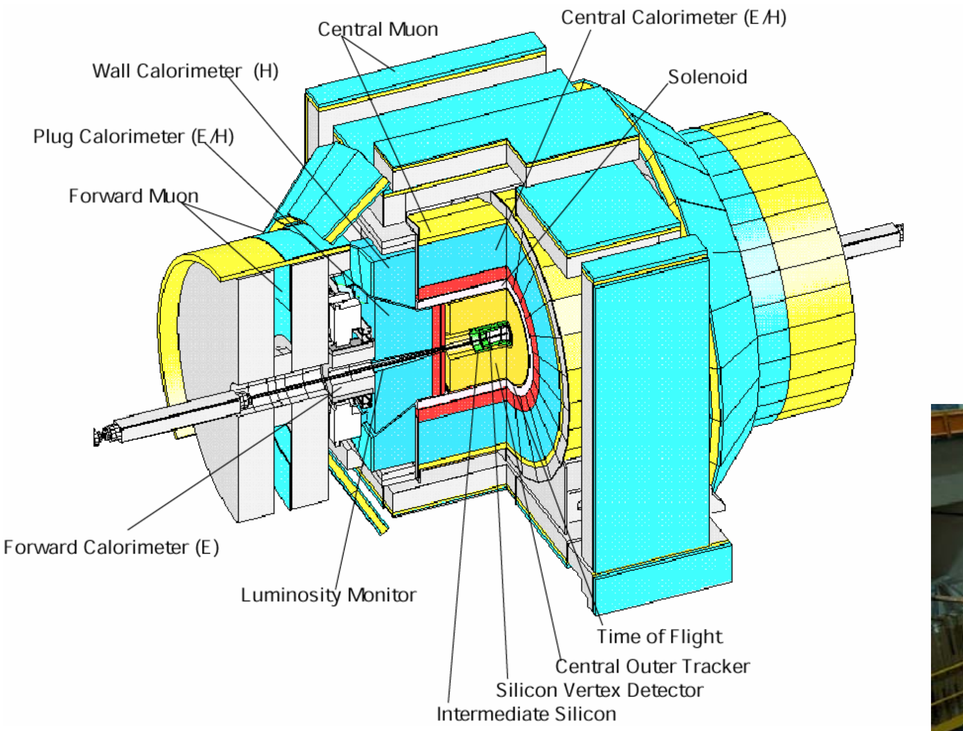
Tevatron at Run II



- Proton-antiproton collisions at $\sqrt{s}$ = 1.96 TeV
- Run II started in March 2001
- Delivered luminosity now >3 fb^{-1}
- Projection ~ 6-8 fb^{-1} by 2009

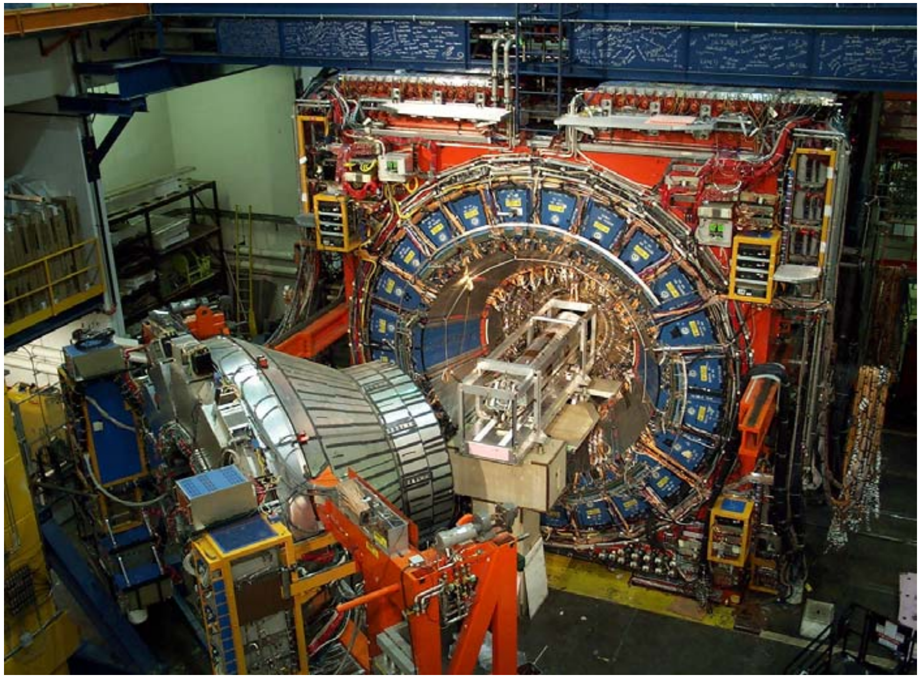


Collider Detector at Fermilab (CDF)



Multi-purpose detectors

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



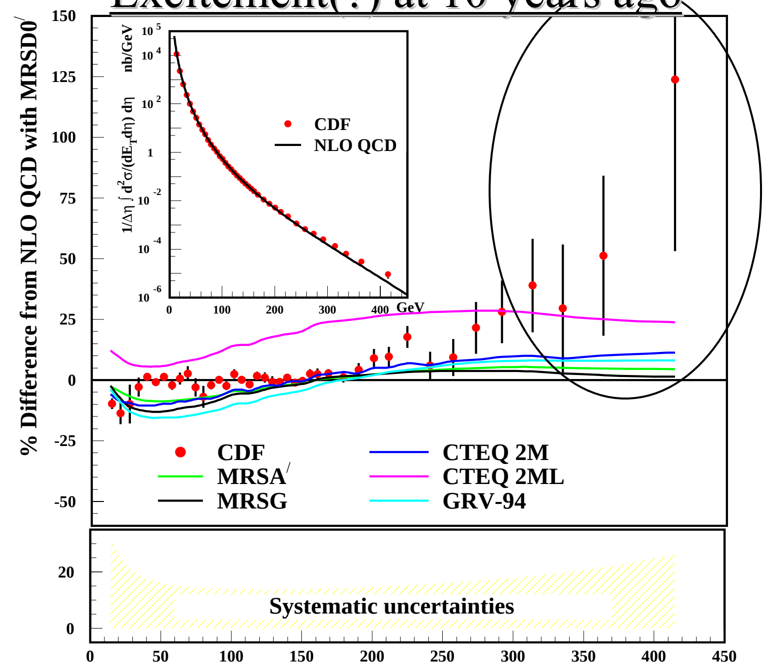
- Data taking efficiency ~ 85 %
- About 2.7 fb^{-1} on tape

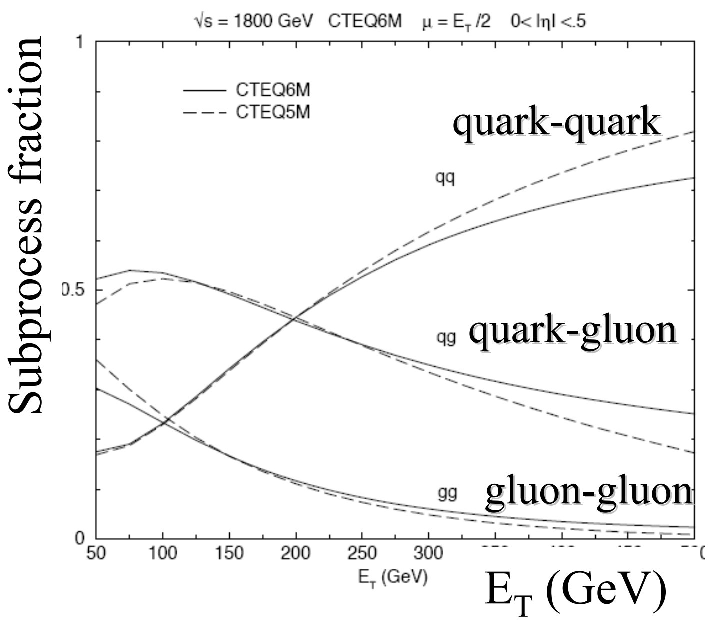
Results shown here use up to 1.7 fb^{-1}

Inclusive Jet Production

- Test perturbative QCD predictions over ~8 orders of magnitude in cross section
- Constrain QCD parameters (PDF, α_s)
- Potentially sensitive to new physics
  - Probing distances ~ 10^{-19} m

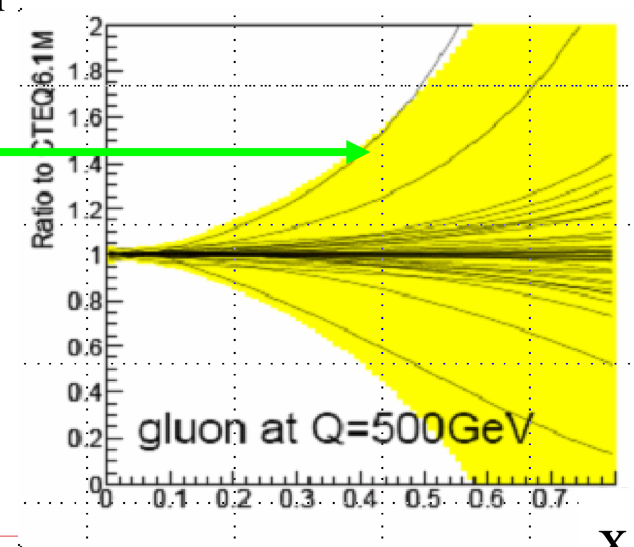
Excitement(?) at 10 years ago





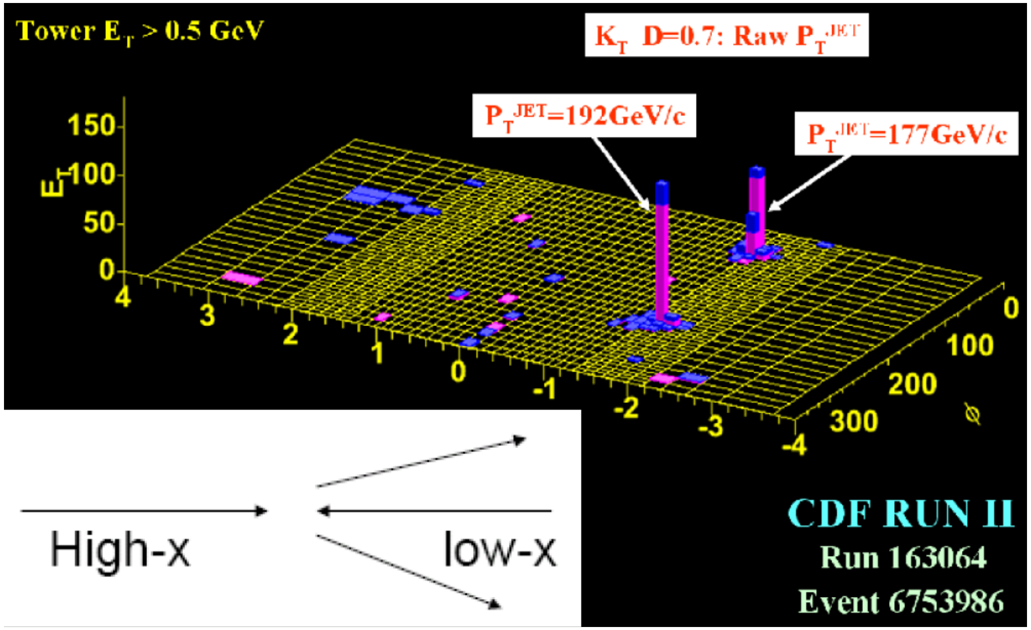
- Sizable cross section from quark-gluon sub-process
- High-x gluon not well known

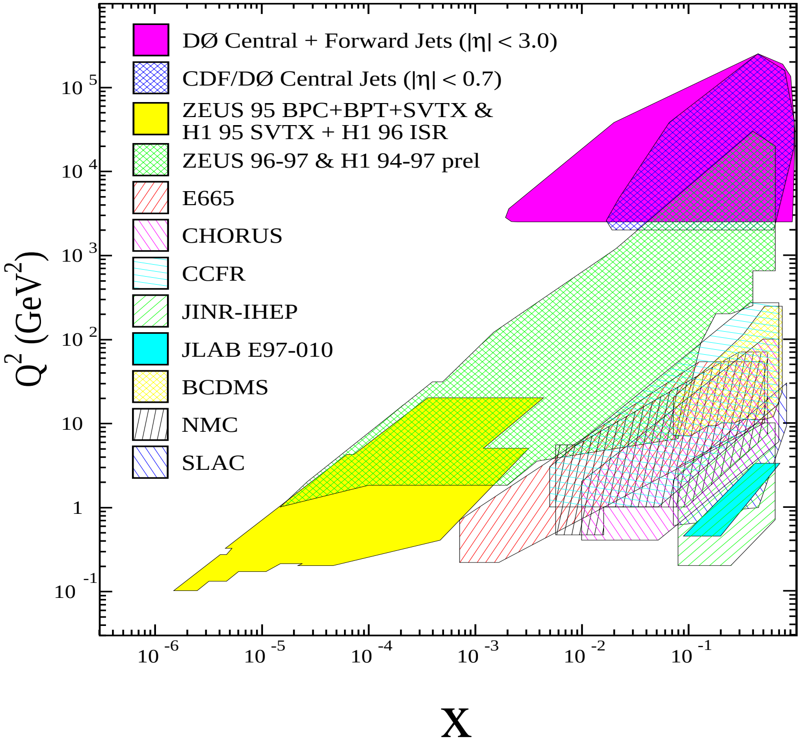
…can be accommodated in the Standard Model



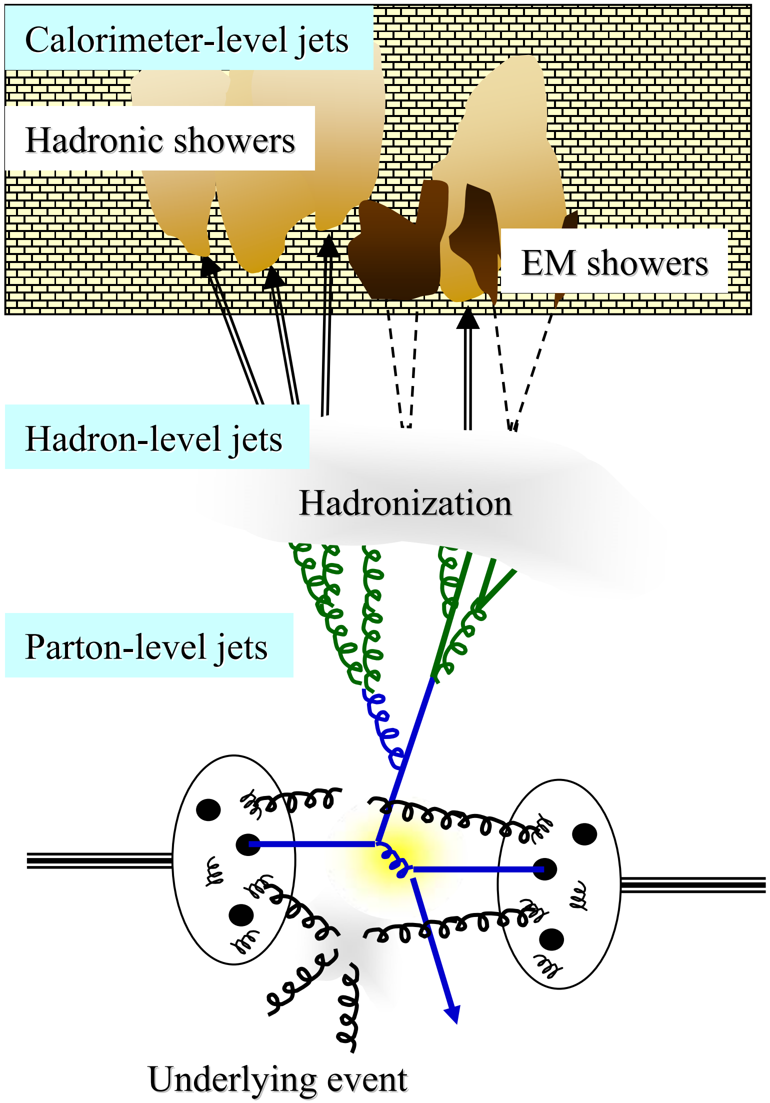
Forward Jet Measurement

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





Jet Energy Corrections



Measure calorimeter-level jets. Then, correct for:

- Energy from additional $p\bar{p}$ collisions
- Calorimeter non-uniformity
- Average energy loss and smearing effect in calorimeter energy measurement
  - Shower simulation tuned to data
- ➡ Hadron-level jet cross section

To make fair comparisons with parton-level pQCD predictions, need to account for:

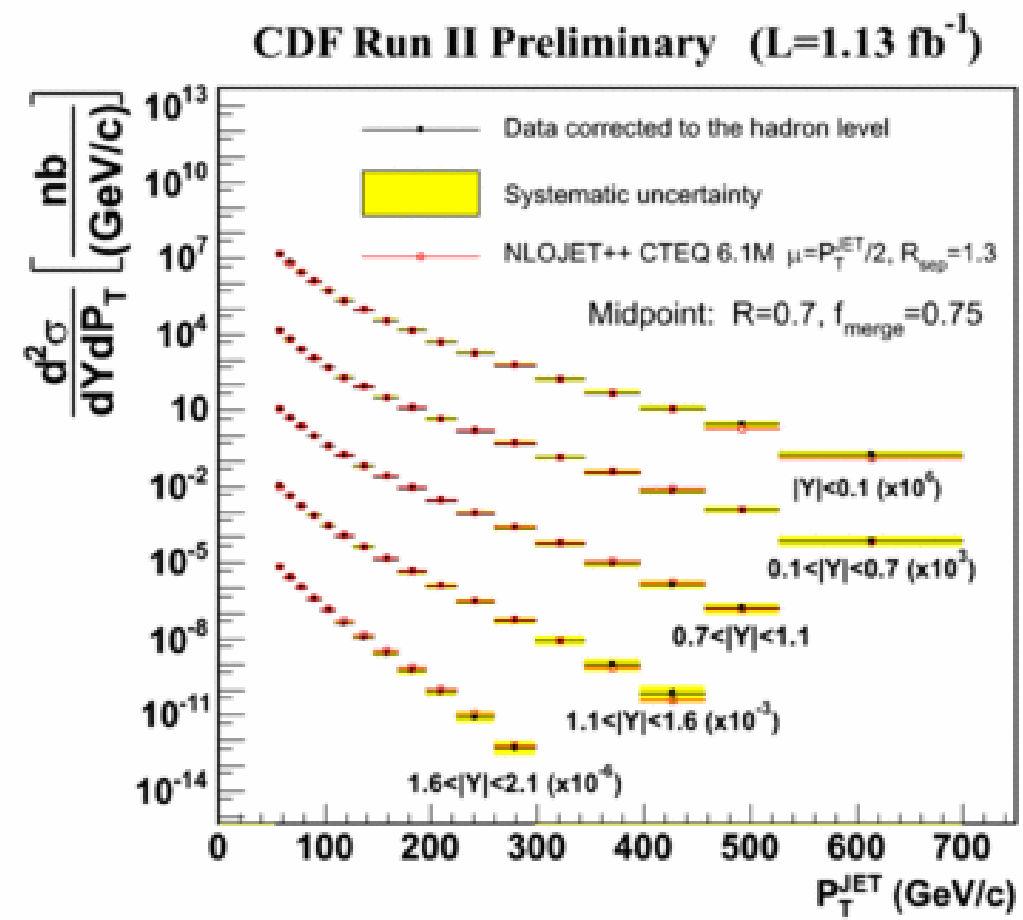
- Underlying event
- Hadronization

Effects evaluated from simulated jet events. Underlying event in MC is tuned to data.

Inclusive Jets with Midpoint

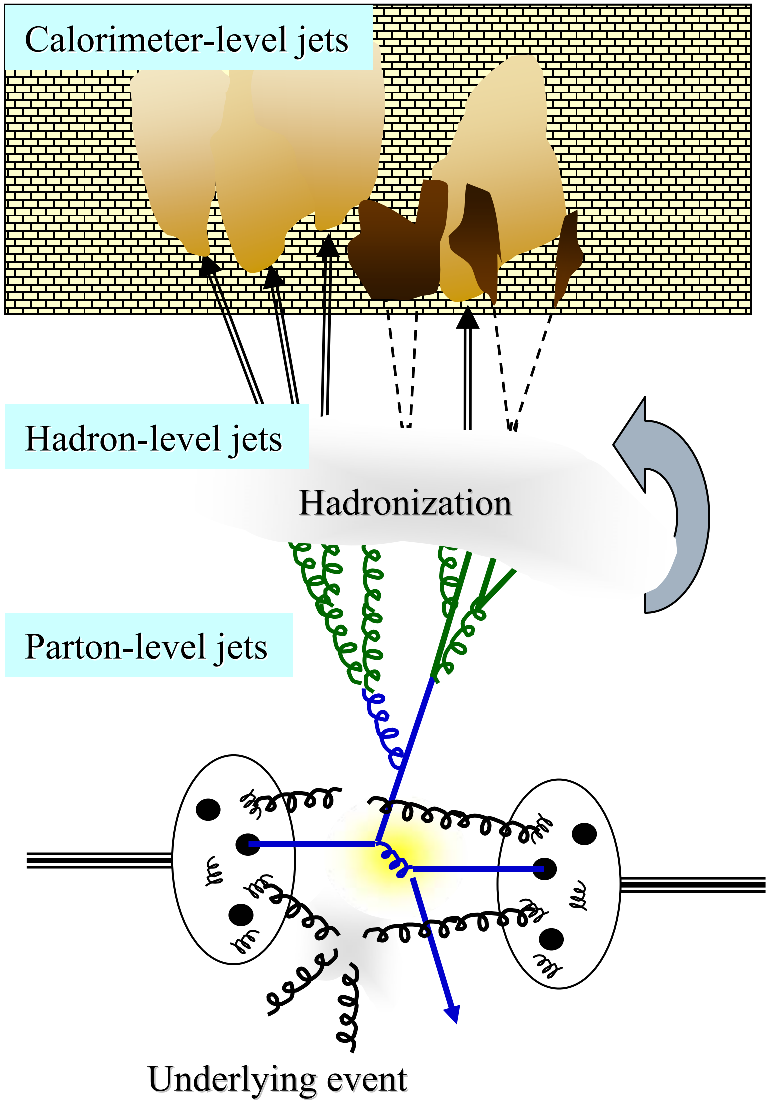
- $L = 1.1\ fb^{-1}$
- Jets reconstructed with Midpoint algorithm, R = 0.7

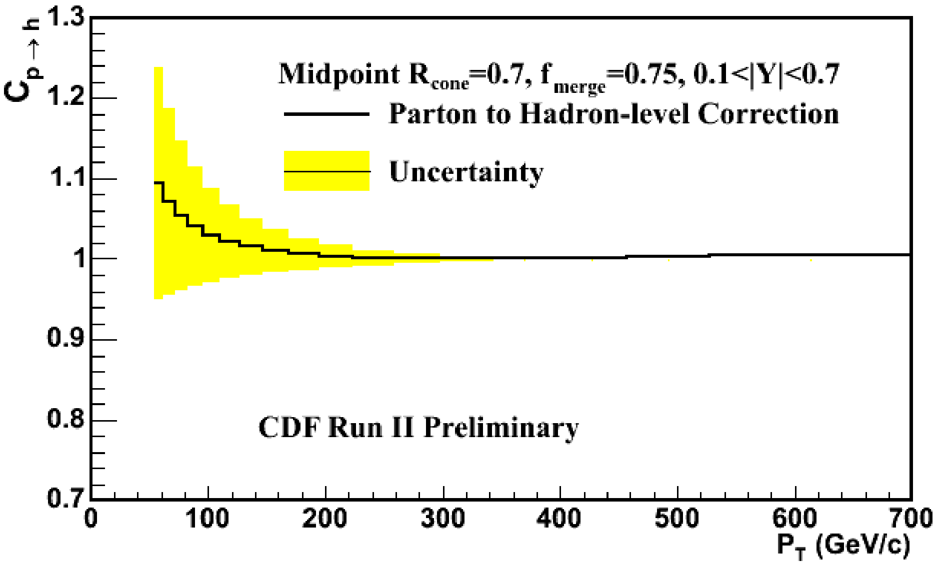
- Consistent with NLO pQCD predictions
  - Experimental uncertainties dominated by jet energy scale (2-3%)
  - Theoretical uncertainties mainly from PDF (gluon at high x)



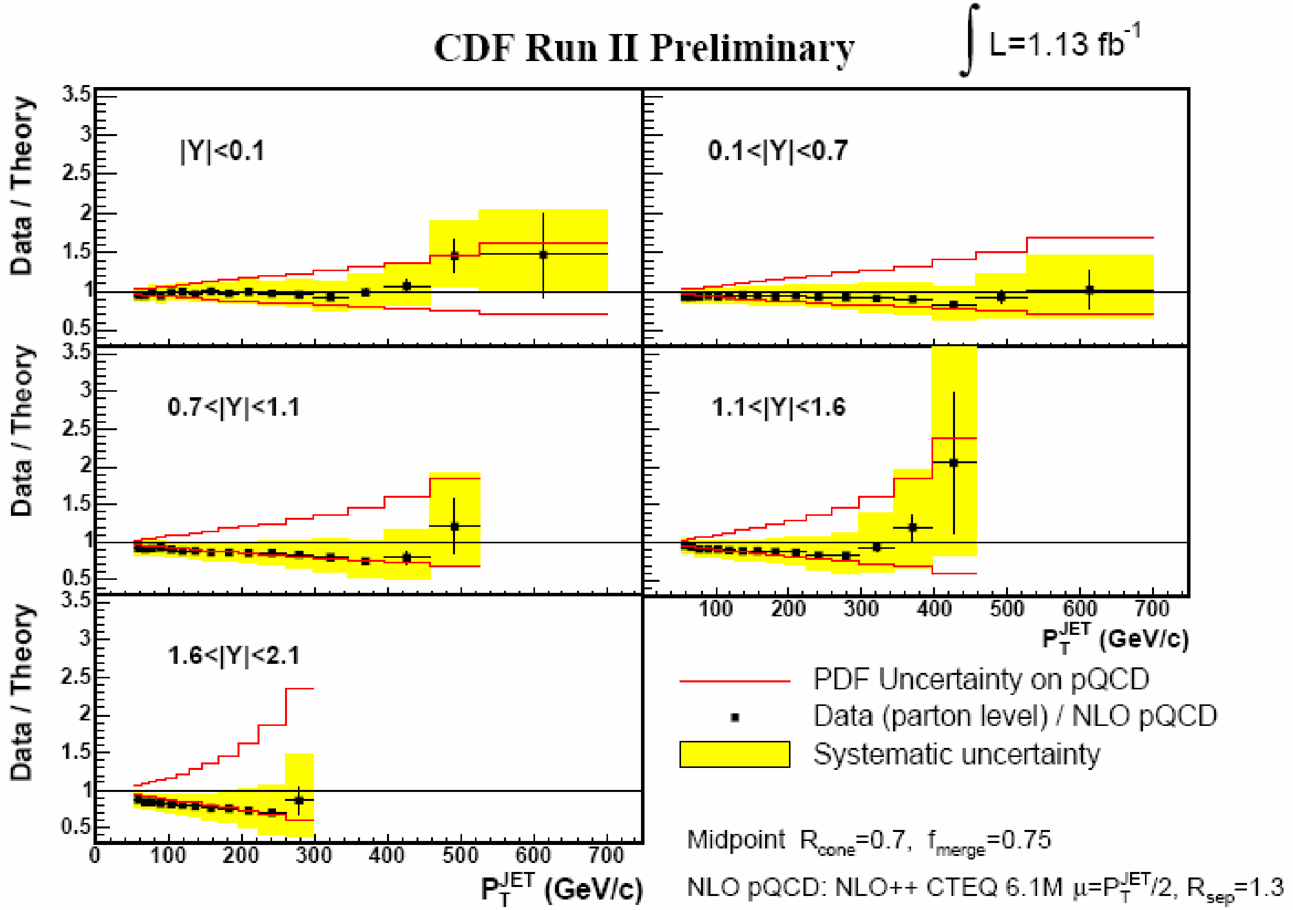
(6% luminosity uncertainty not included)

Underlying Event & Hadronization Correction



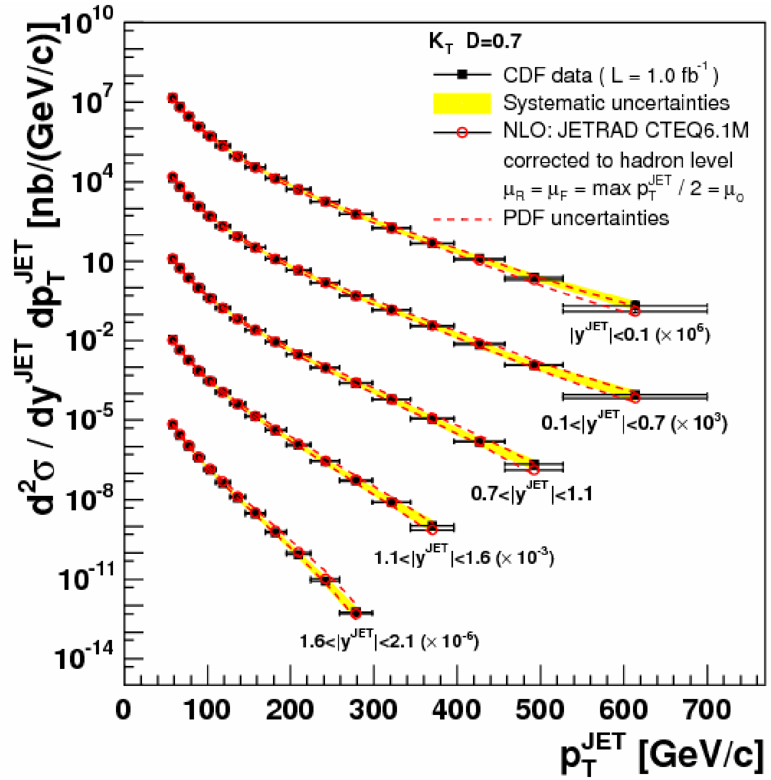


Inclusive Jet Production with Midpoint

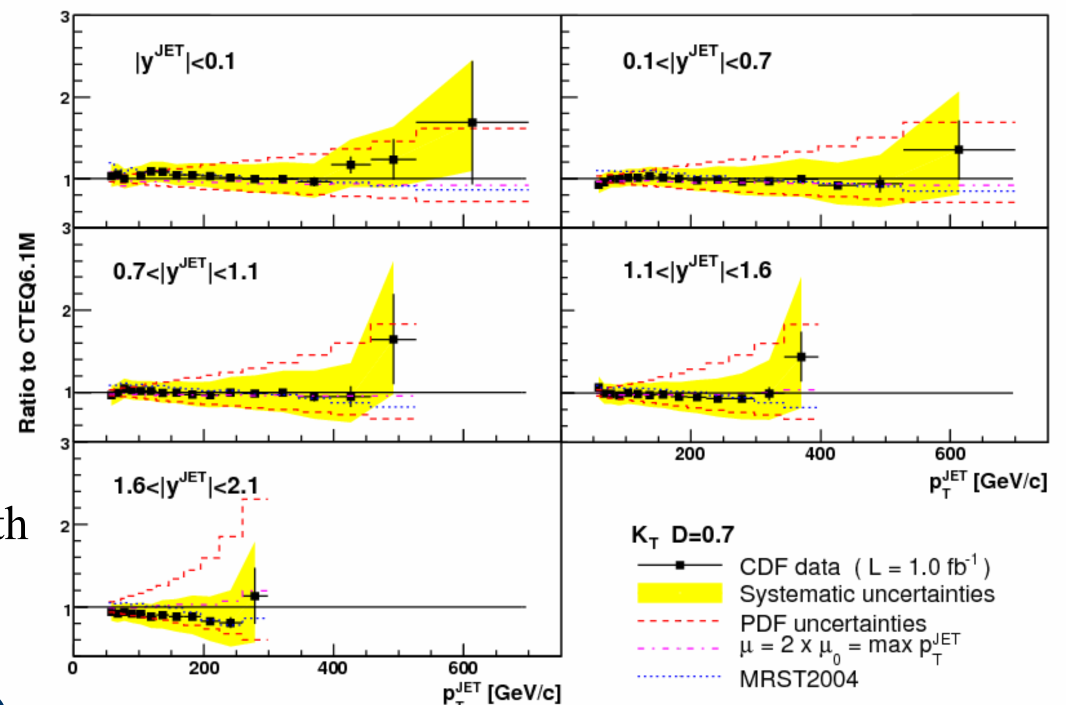


- Data consistent with NLO pQCD predictions in all rapidity region
- Experimental uncertainty in the forward region smaller than the PDF
  → will contribute to further constrain PDFs

Inclusive Jets with k_T Algorithm



- L = 1.0 fb^{-1}
- Jets reconstructed with the k_T algorithm, D= 0.7.



Again, data in good agreement with NLO pQCD predictions

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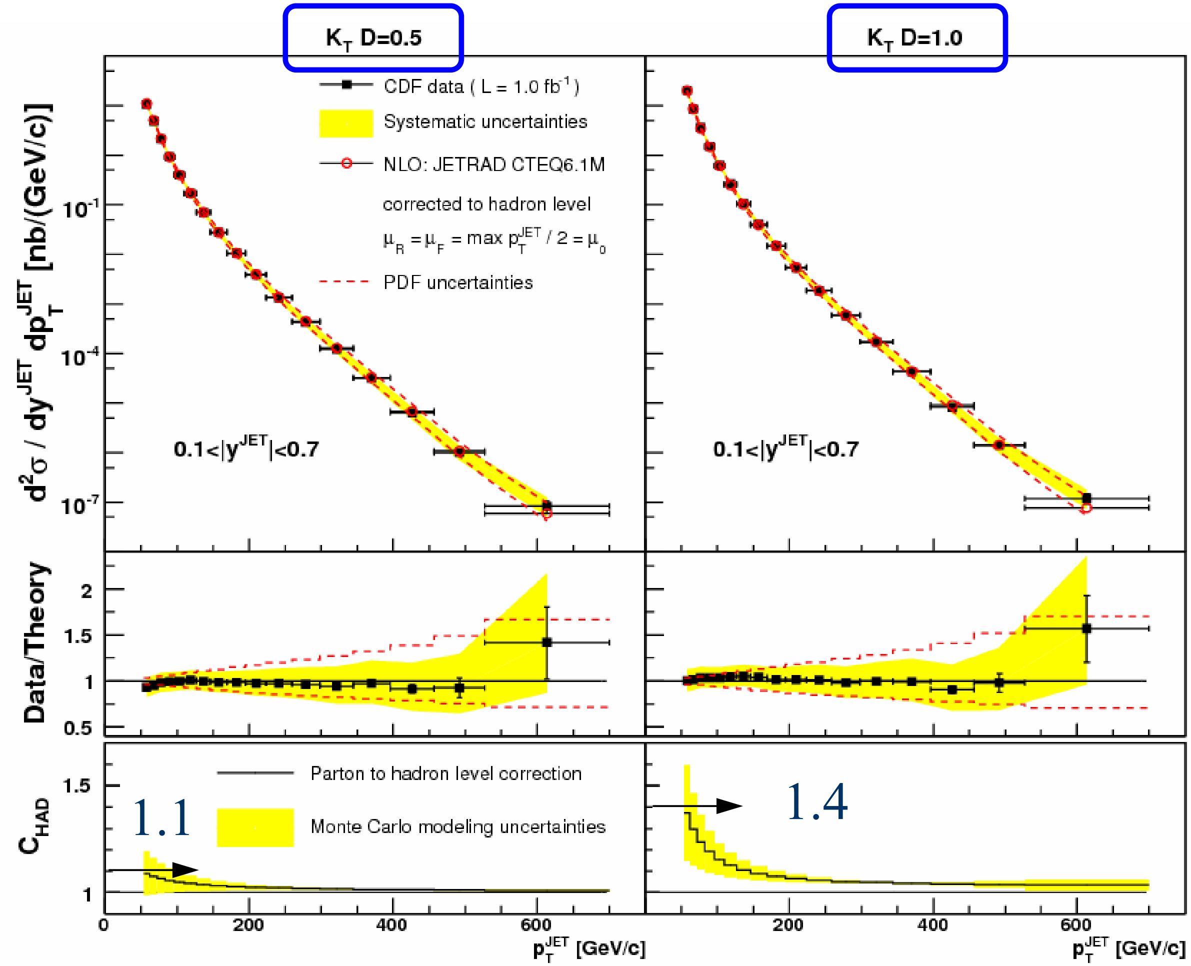
Inclusive Jets with k_T vs. D

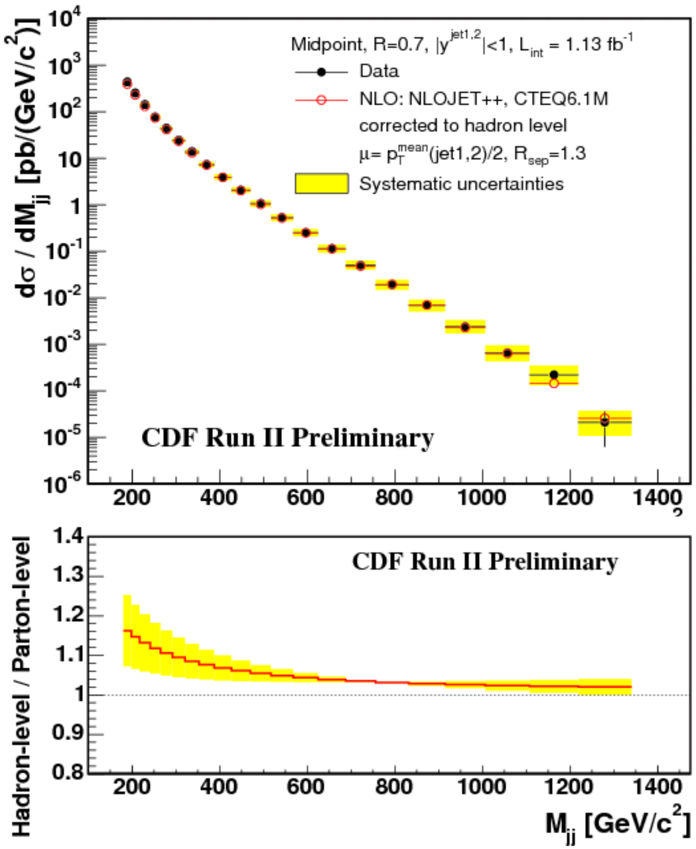


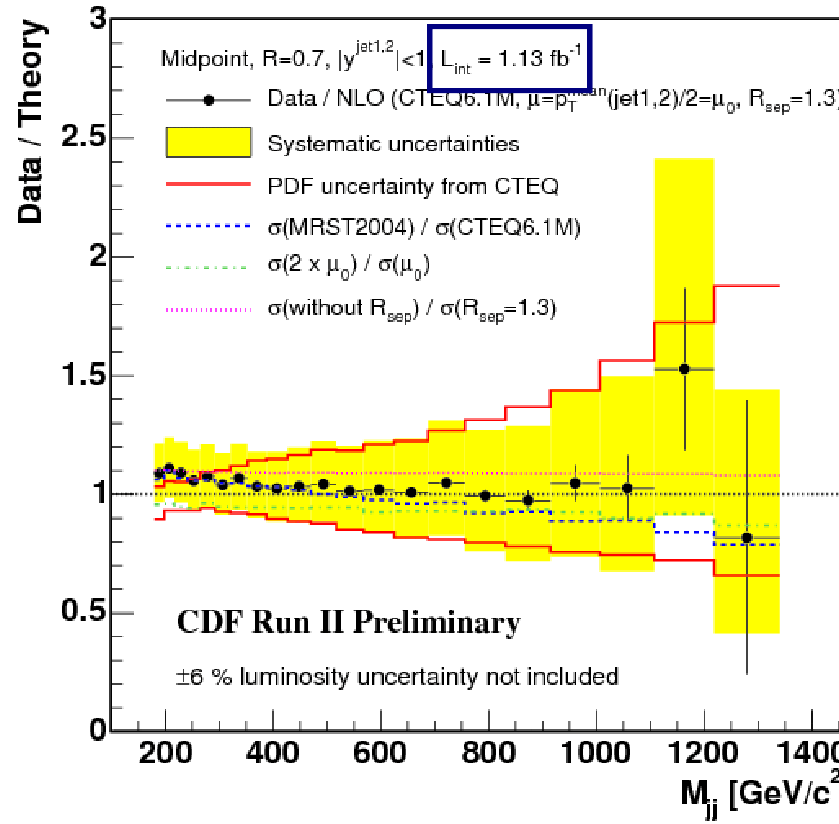
- Measurement with different *D* parameters (*D:* separation parameter that characterizes the size of jets)
- Parton-to-hadron level corrections larger for larger *D* parameters (larger UE contributions)
- Both measurements in good agreement with NLO pQCD after UE and hadronization corrections

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

Dijet Production

- Test of pQCD predictions
- Sensitive to new physics: decays of massive particles, compositeness



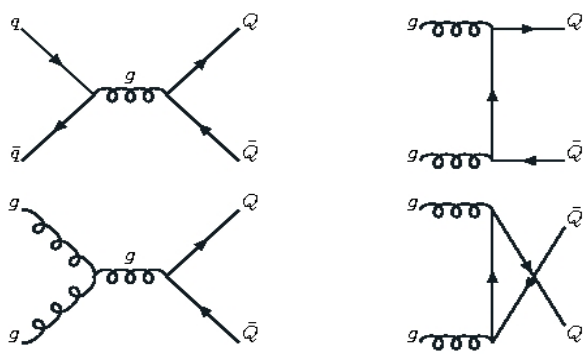


- Consistent with NLO pQCD predictions
  - Experimental uncertainties comparable to PDF uncertainties
- Limits on new physics being worked out…

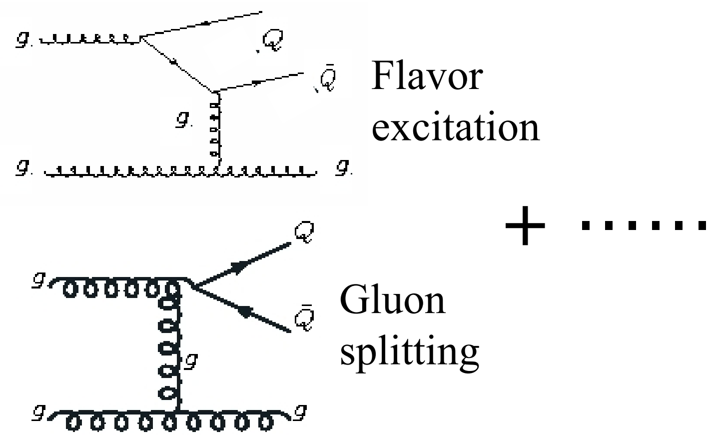
b-jet Production

- *b*-jets are signatures of many important and possible new physics processes.
- Understanding *b*-jet production has been a big challenge in QCD.
  - Only recently, data and theory started to show agreement; more precise measurements, fixed order + NLL, improved fragmentation function, PDFs

Flavor creation



Leading order processes



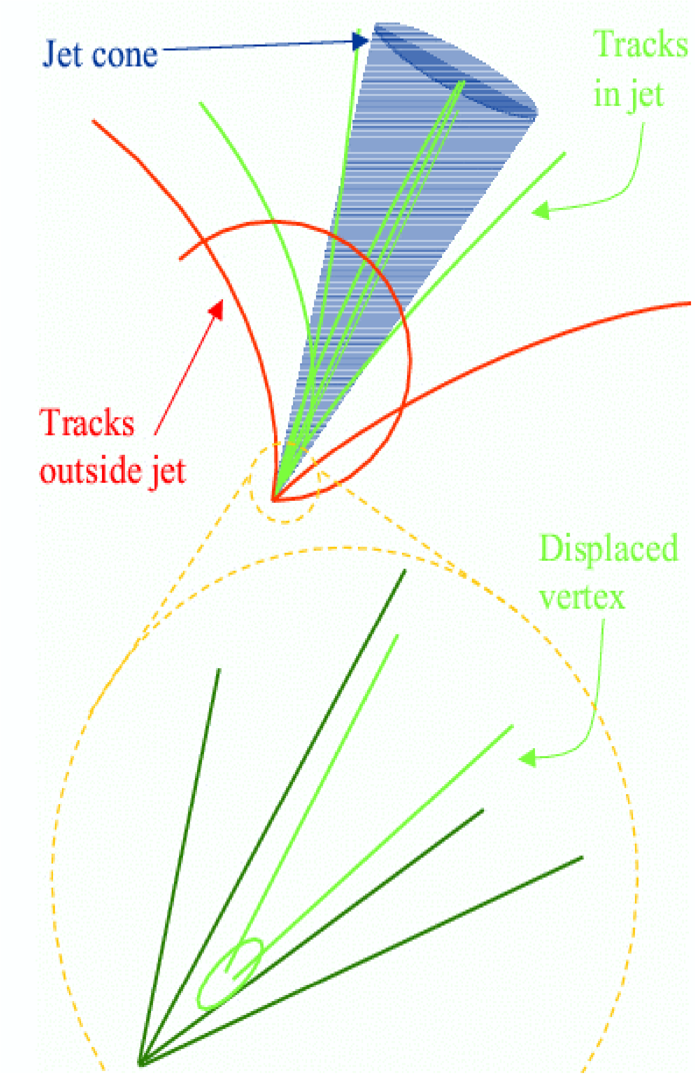
Next-to-leading order processes

- Measurement on $b\overline{b}$ dijet production is sensitive to different production mechanisms:
  - Flavor creation at high $\Delta\phi$
  - Flavor excitation or gluon splitting at low $\Delta\phi$

b-jet Identification

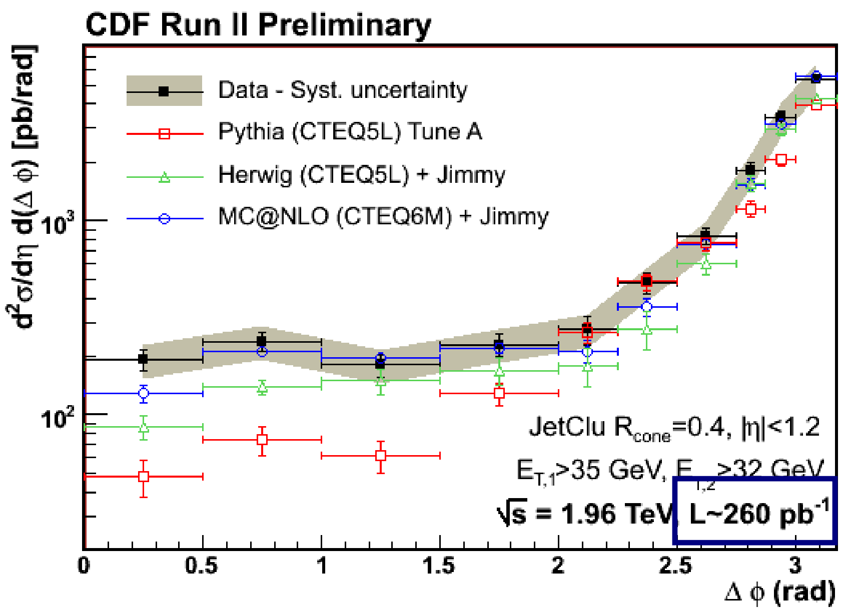
The most commonly used "tagging" technique at CDF identifies *b*-jets with a displaced secondary vertex (long *B* hadron lifetime, $c\tau \sim 450\ \mu m$)

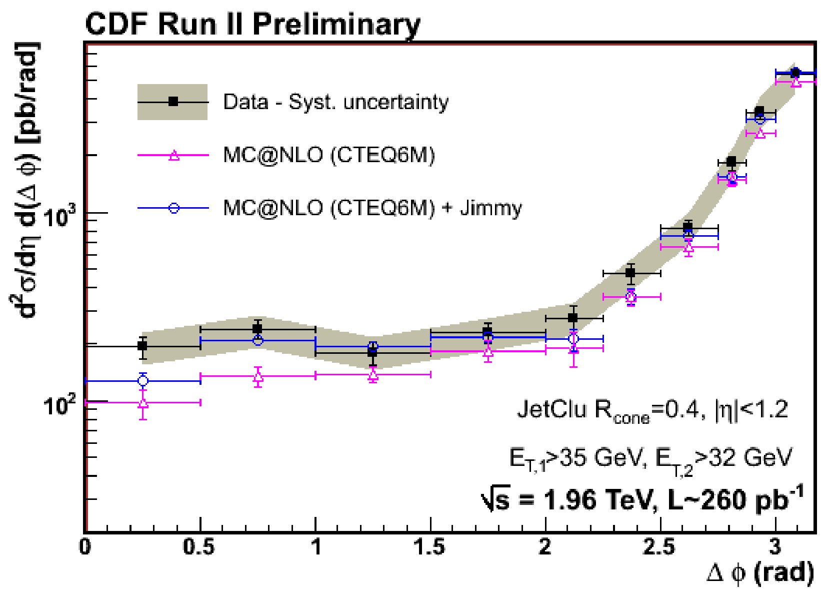
- consider tracks in η-φ cone of 0.4 around jet axis
- reconstruct secondary vertex from displaced tracks
- If the vertex has large transverse displacement (Lxy), the jet is "*b*-tagged"



$b\bar{b}$ Dijet Production

- *b*-jets selection using secondary vertex tagging both at the trigger and offline levels
- Comparisons with LO MC (Pythia and Herwig) and NLO MC (MC@NLO with/without Jimmy for multiple-parton-interactions)



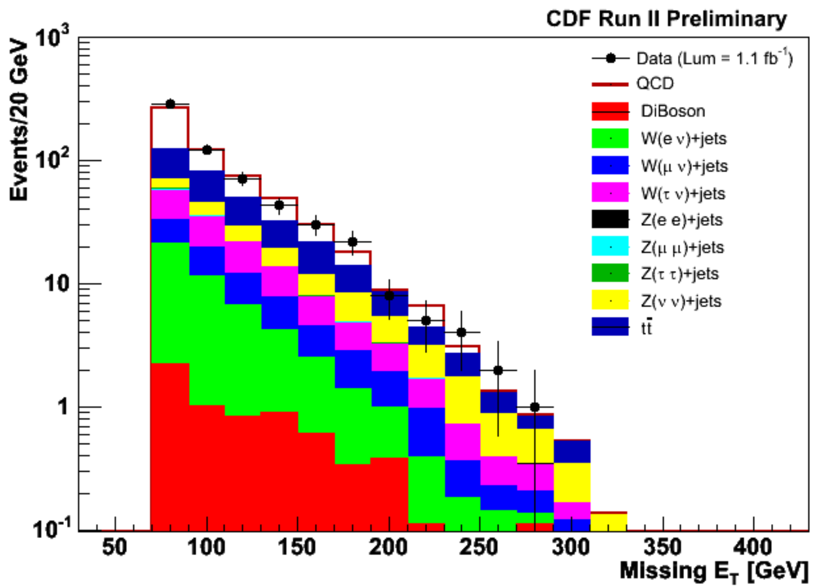


- MC@NLO reproduces data within errors

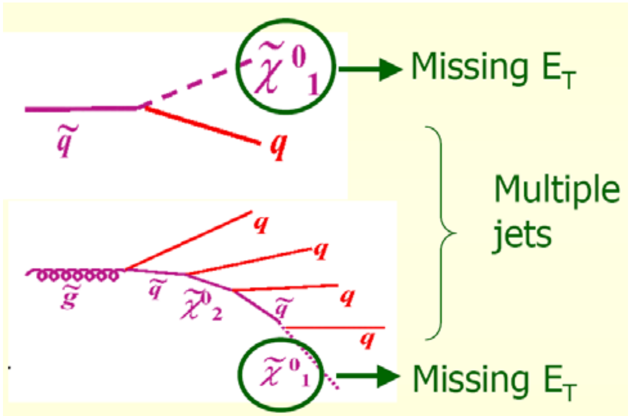
  (at low $\Delta\phi$, MC@NLO> Herwig > Pythia)
- Simulation of underlying event (Jimmy) improves data-theory agreement

Boson+Jets Production

- Test of pQCD at high Q^2
- Important for many physics searches



SUSY searches in the missing E_T + Jets channel



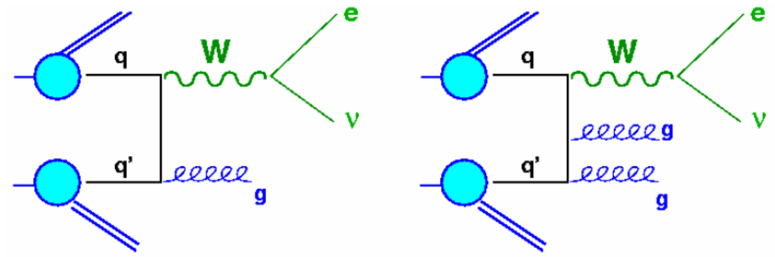
Major backgrounds

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

Crucial to understand boson-jets production!

W+Jets Production

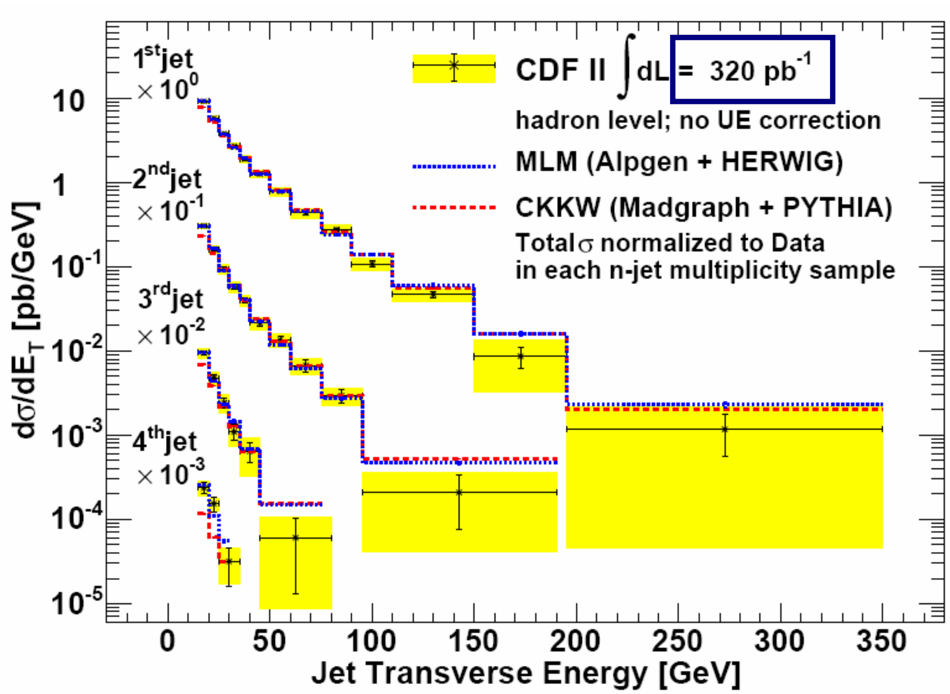
- W events selected with electron+missing E_T ($W \to e\nu$)
- Jets clustered with JetClu R=0.4
  $E_T^{jet} > 15$ GeV ; $|y^{jet}| < 2$.



... + parton showers

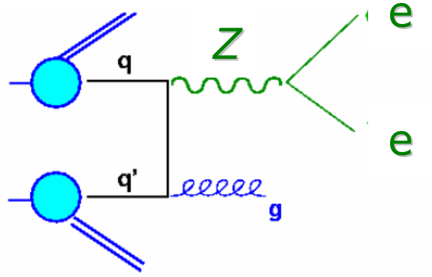
- Compare with matrix element + parton shower (ME+PS) Monte Carlo predictions
  - Special ME-PS matching (MLM, CKKW) to avoid double counting
  - Comparisons in shape only

CDF Run II Preliminary



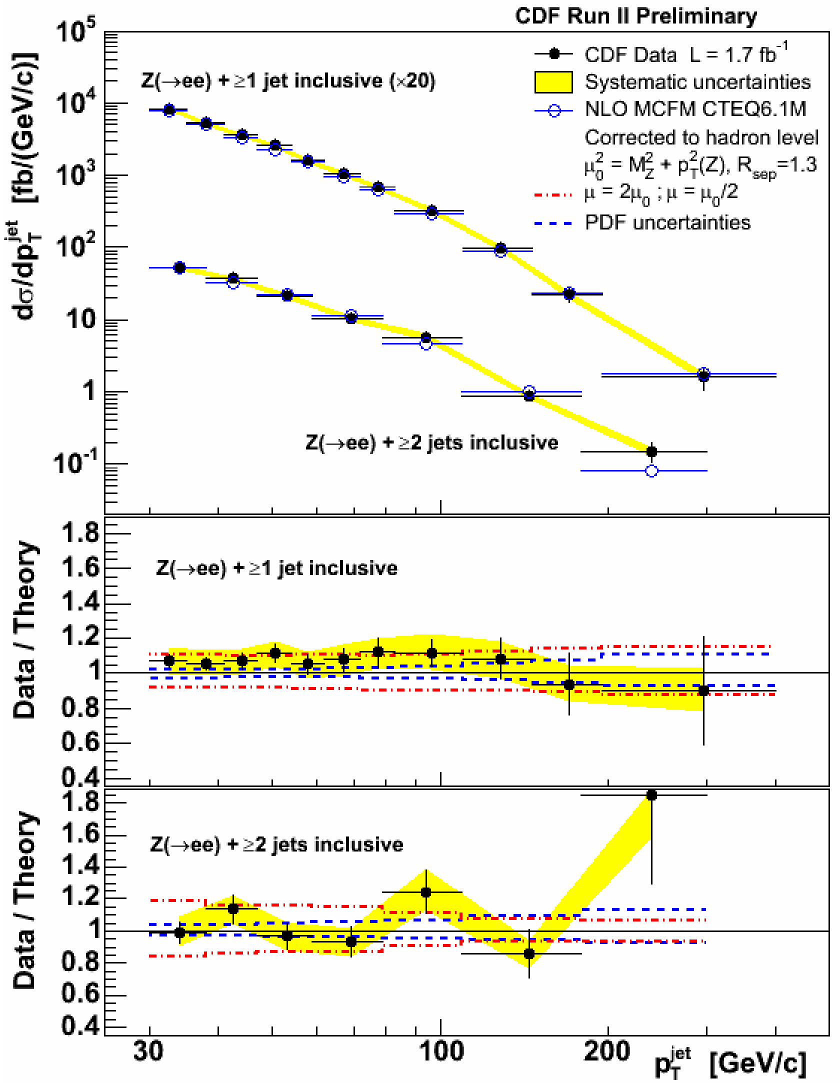
Reasonable agreement with ME+PS MC predictions

Z+Jets Production

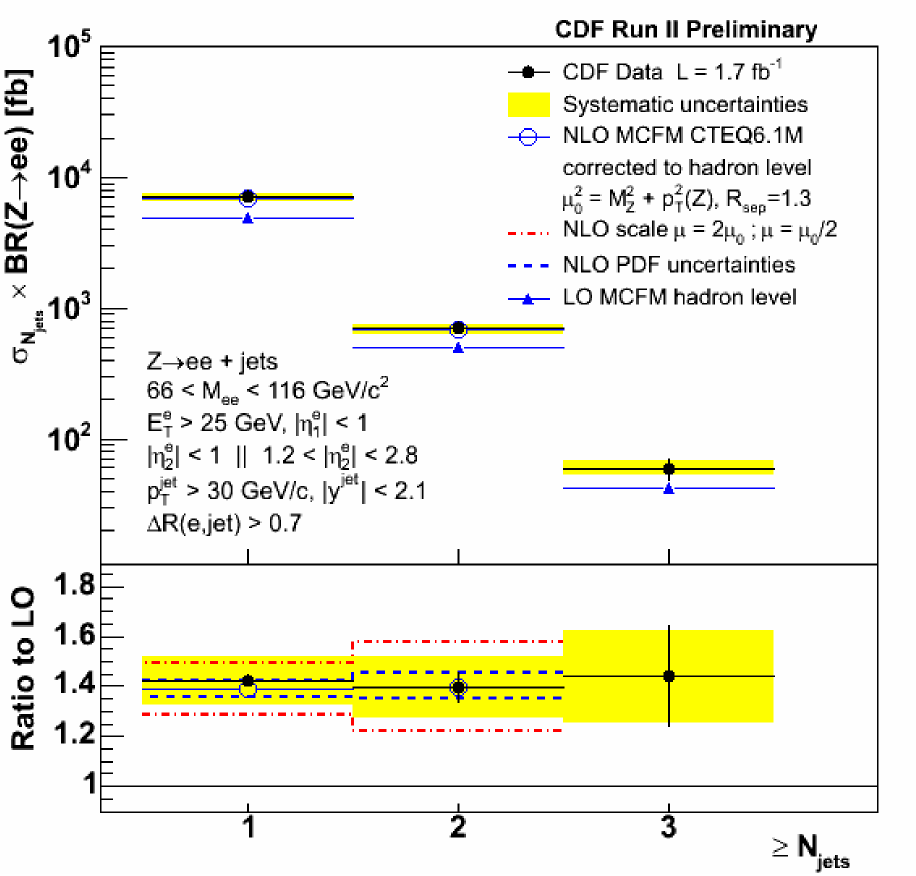


- L = 1.7 fb^{-1}
- Z events selected with di-electrons
- Jets clustered with Midpoint algorithm R=0.7,
  $p_T^{jet} > 30$ GeV ; $|y^{jet}| < 2.1$.

Good agreement with NLO pQCD predictions

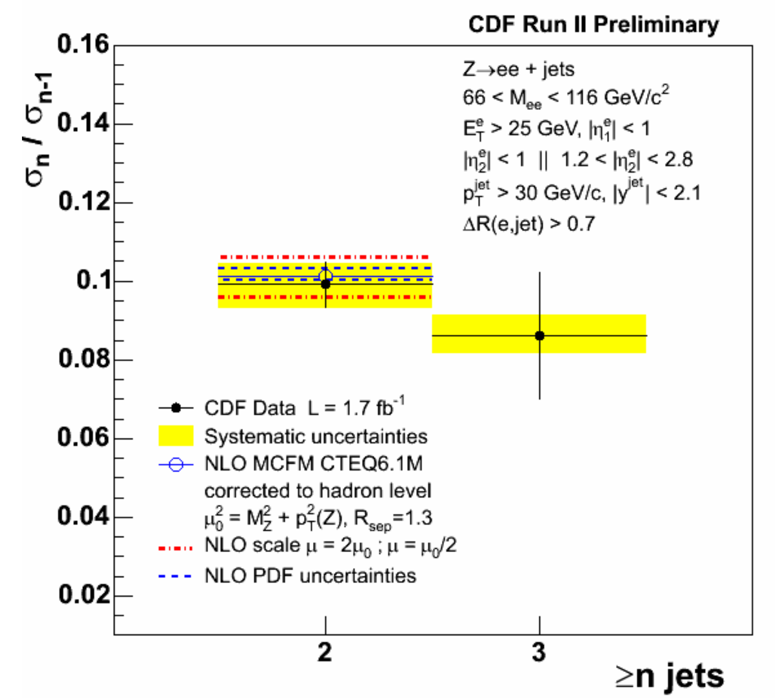


Z+Jets Production



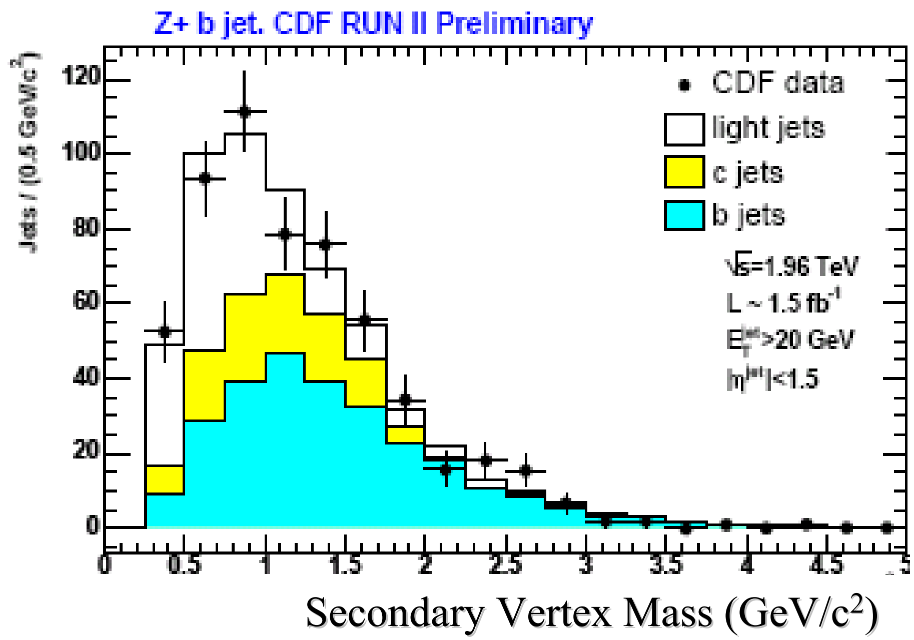
- Data/LO and NLO/LO ratios ~ constant

- Ratio of σ(n)/σ(n-1) ~ α_s



Z+*b* Jets Production

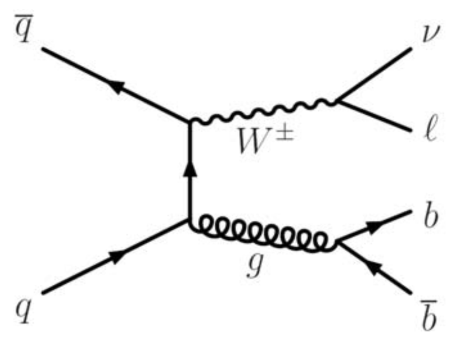
b, c and light fractions determined from the template fit of the secondary vertex mass distributions



E_T^{jet}>20 GeV, $\|\eta^{jet}\|$<1.5 R_{jet}=0.7	CDF Run II Preliminary measurement	PYTHIA	MCFM NLO	MCFM NLO + UE + hadr.
σ(Z+*b*-jet)	0.94 ± 0.15 ± 0.15 (pb)		0.51 pb	0.56(pb)
σ(Z+*b*-jet)/ σ(Z)	0. 369 ± 0.057 ± 0.055 %	0.35 %	0.21 %	0.23 %
σ(Z+*b*-jet)/ σ(Z+jet)	2.35 ± 0.36 ± 0.45 %	2.18 %	1.88 %	1.77 %

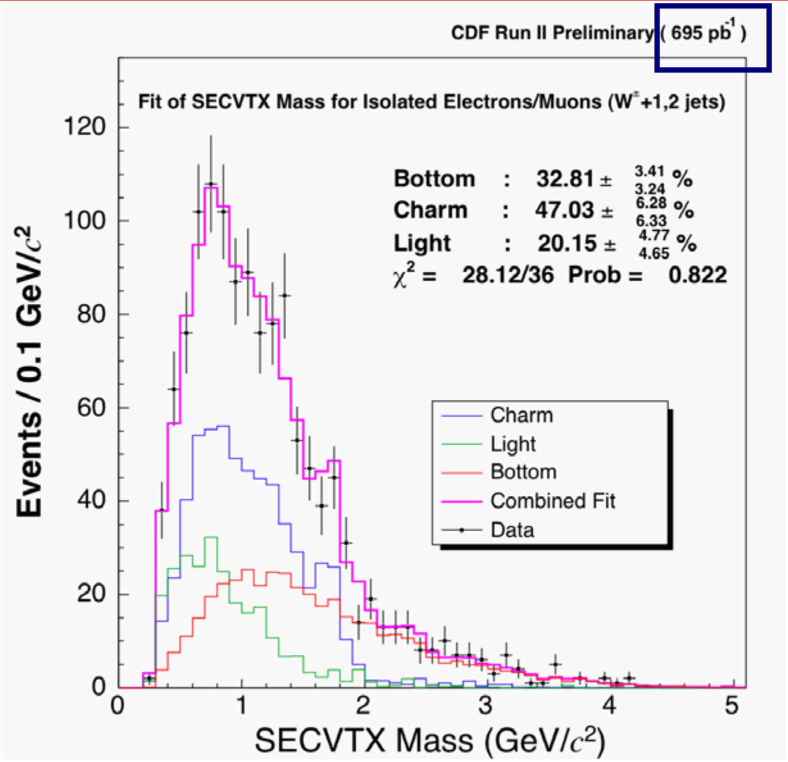
Data somewhat higher than NLO predictions. Theorists are contacted for further investigation.

W+$b\bar{b}$ production



Large background for many analyses

- SM Higgs (WH) production
- Single top quark production
- $t\bar{t}$ production

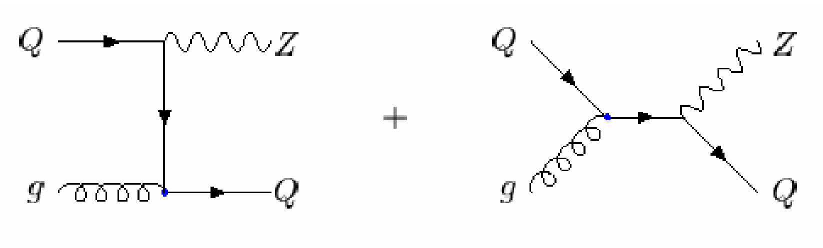


In secondary-vertex-tagged sample, fit for light, c, b contributions.

$$\sigma(W^{\pm}b\bar{b}) \times BR(W^{\pm} \to l^{\pm}\nu) = 0.90 \pm 0.20(\text{stat.}) \pm 0.26(\text{syst.})\ \text{pb}$$

$(E_T^{jet} > 20\,\text{GeV}, |\eta^{jet}| < 2)$ Alpgen predictions: (0.74±0.18pb)

Z + *b*-Jet Production

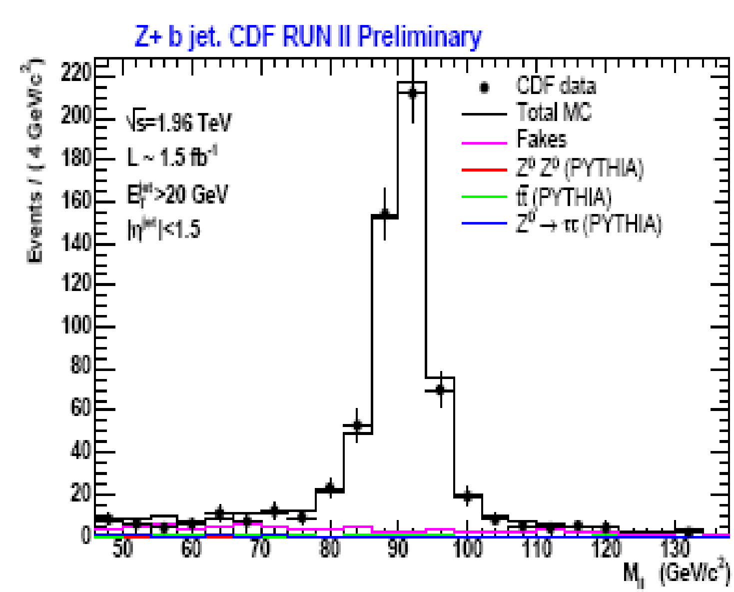


Probe the less-well-known heavy flavor content of the proton. Important for

- Single top: $qb \rightarrow q't$ and $gb \rightarrow Wt$
- SUSY higgs: $gb \rightarrow hb, bb \rightarrow h$

Major background for SM higgs searches $(ZH, H \rightarrow b\bar{b})$

- L = 1.5 fb^{-1}
- Z events selected with di-leptons (ee and μμ).
- Jets clustered with a cone algorithm R=0.7
- *b*-jet identification: secondary vertex tagging

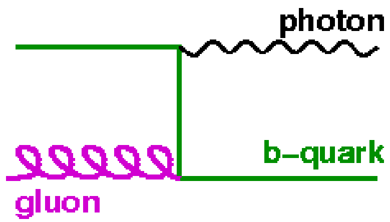


Conclusions

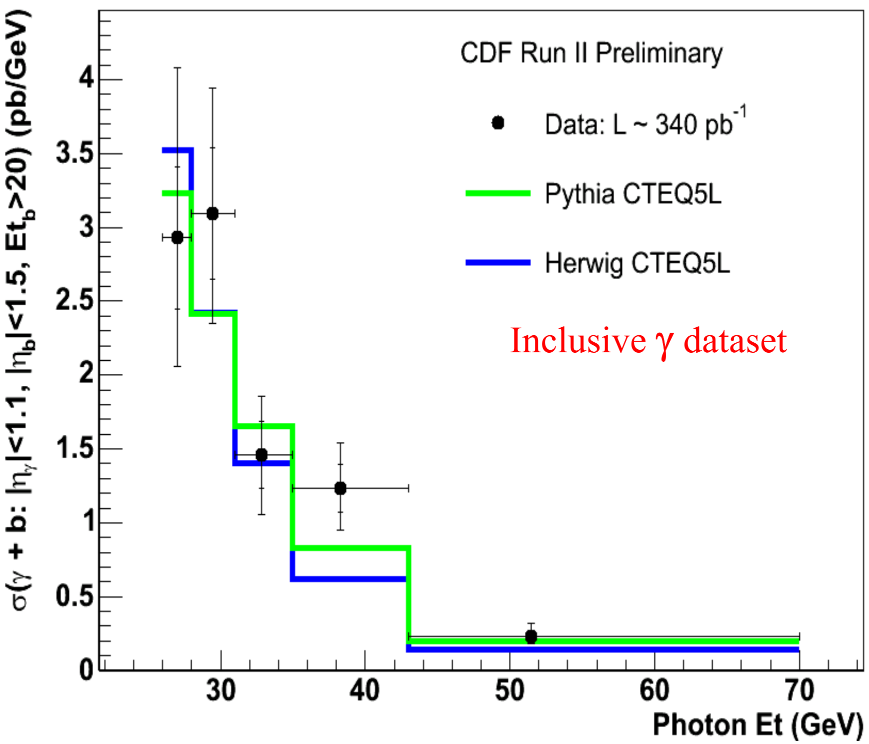
CDF has a broad program on jet physics which is making a significant impact on better understanding of jet production mechanisms and QCD.

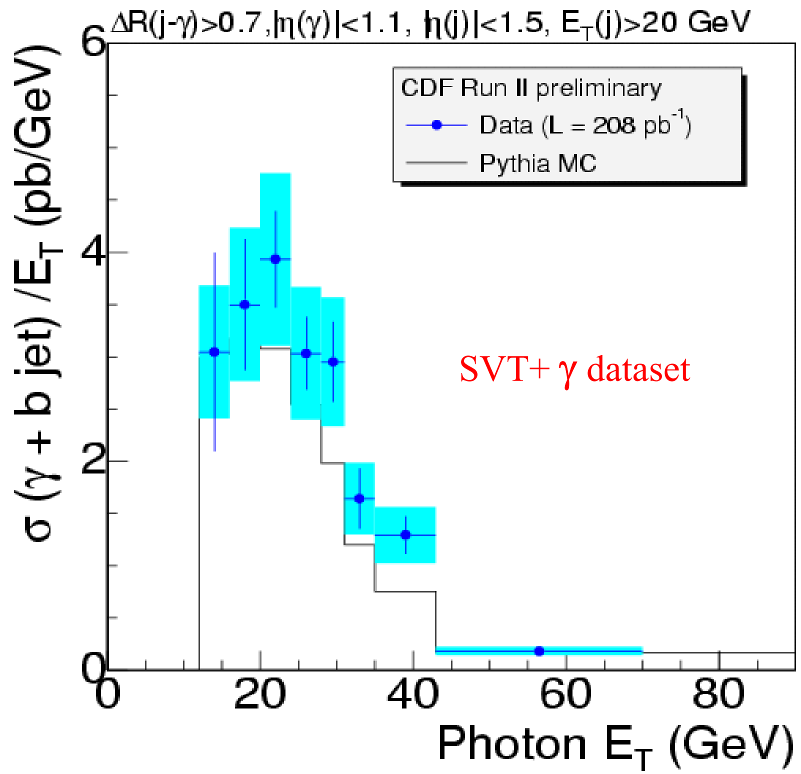
- Inclusive jets, dijets, $b\bar{b}$ dijets, boson+jets, boson+b-jets
- Providing stringent tests of QCD calculations and further constraints on QCD parameters
  - NLO pQCD calculations, ME-PS matching techniques
  - Proton PDFs (especially high-x gluons)
- QCD processes often the most important background to electroweak and possible new physics processes
  - Better understanding will enhance the potential for new physics discoveries at the Tevatron and also at the upcoming LHC!

γ + b Jet production results



- Probes heavy-quark PDFs
- Background for SUSY (light stop)
- Experimentally difficult because of large background from π^0 decays





Lower E_T^{γ} thresholds to 12 GeV