QCD Results from the Tevatron

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Aspen Winter 2011

Outline

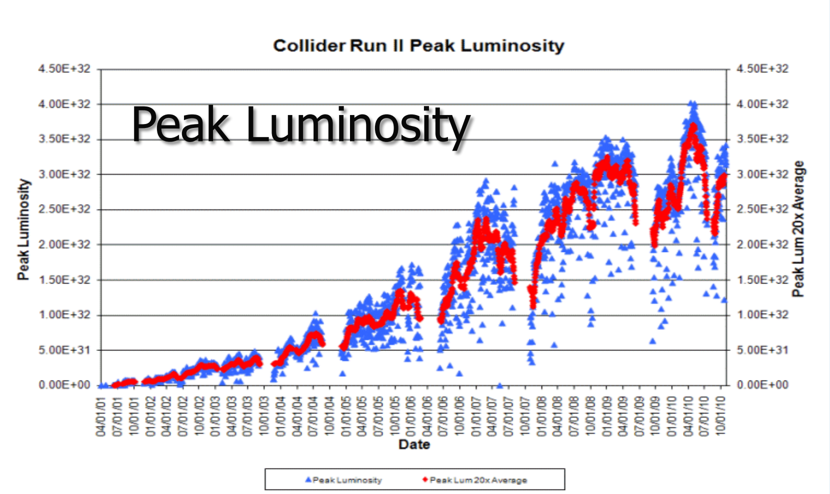
- Fermilab Tevatron, CDF and D0 Detectors
- Motivation
- Photons
- Jets
- Vector boson + jets (Heavy Flavor Jets)
- Photon + Heavy Flavor Jets
- Summary

Only a small fraction of extensive QCD results from the Tevatron can be covered in 25 minutes. Selected some of the latest results. More results can be found on:

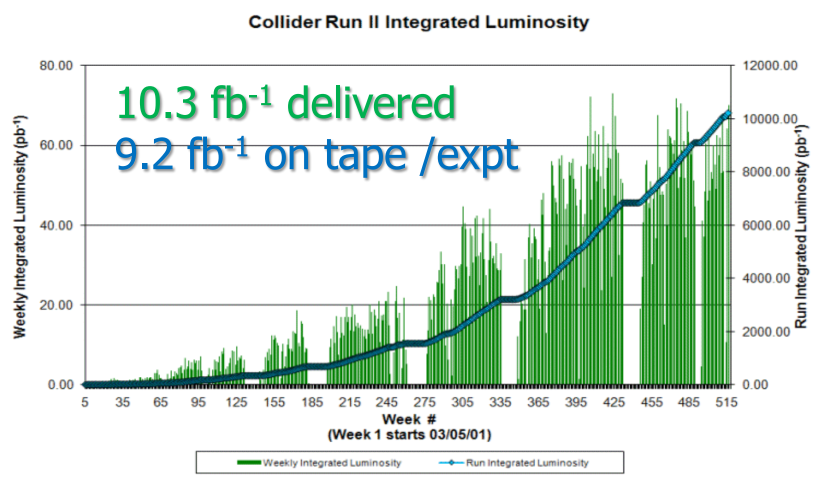
- http://www-cdf.fnal.gov/physics/new/qcd/QCD.html
- http://www-d0.fnal.gov/Run2Physics/WWW/results/qcd.htm

The Tevatron Collider at Fermilab

- $p\bar{p}$ collisions @ $\sqrt{s}$ = 1.96 TeV
  - 36 bunches, 396 ns
- Excellent performance
  - Peak lumi : 3.5 E32 $cm^{-2}s^{-1}$
  - $\int Ldt$ /week ~ 50 pb^{-1}
- Both expts performing well : ~90% data taking efficiency

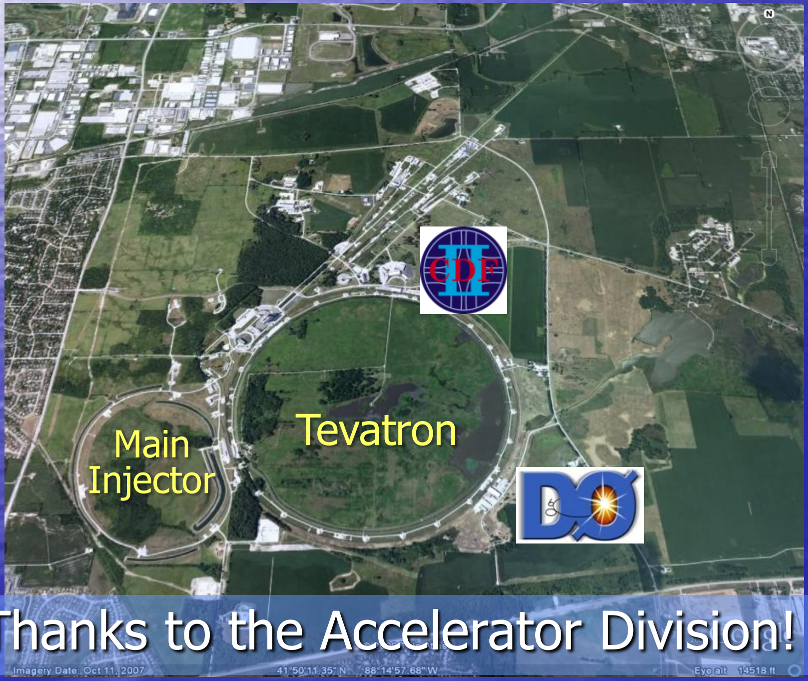


Peak Luminosity



10.3 fb^{-1} delivered

9.2 fb^{-1} on tape /expt



Thanks to the Accelerator Division!

Hope ~12 fb^{-1} delivered by FY11

Results presented based on 1 – 6 fb^{-1}

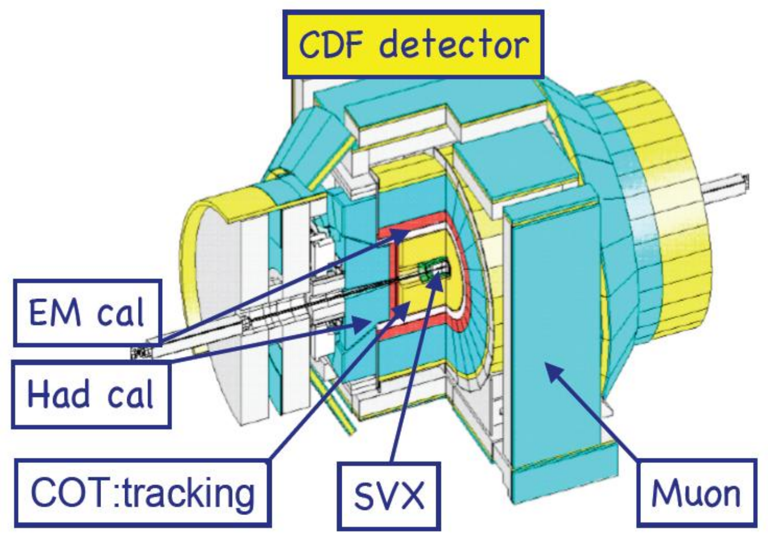
CDF & DØ Run II Detectors

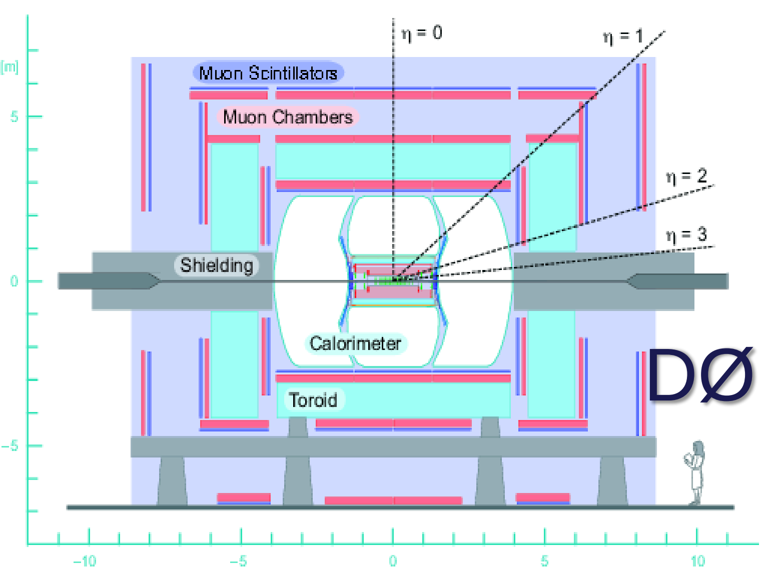
- Multi-purpose detectors with broad particle identification capabilities

- Common features
  - Tracking in magnetic field with silicon vertexing
  - EM and Hadron calorimeters
  - Muon systems

- Competitive advantages
  - **CDF** : better track momentum resolution & displaced track trigger at Level 1
  - **D0** : finer calorimeter segmentation, and forward muon system

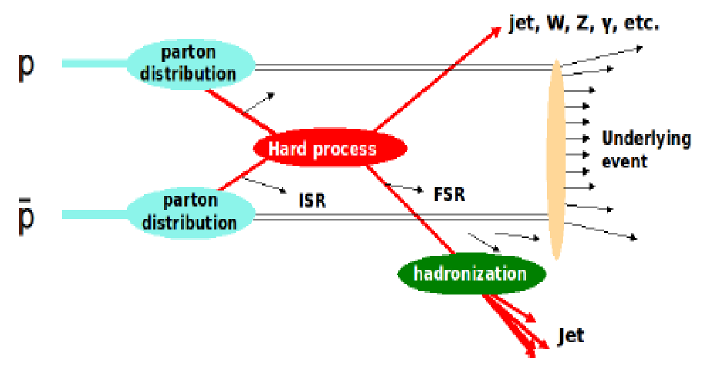
Performing well making use of all detectors capabilities





QCD at the Tevatron

- Test of pQCD calculations at new level
  -- NLO +Higher order corrections
  -- resummations, fragmentation and ISR/FSR models
  -- tuning of event generators
- Constrain structure of the proton→ Parton distribution functions (PDFs)
  gluon (←inclusive jets)
  HF (←W/Z/γ+HF)
- Measure important backgrounds to searches for Higgs, SUSY and other new physics
- Unique sensitivity to new physics (e.g. resonances in signatures with jets)



Photons

Precision test of pQCD predictions

-- come unaltered from the hard subprocess

-- direct probe of the hard scattering dynamics

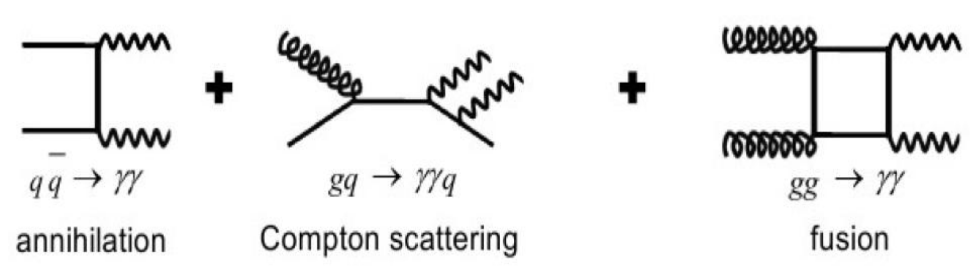
-- clean probe w/o complications from jet fragmentations and systematics.

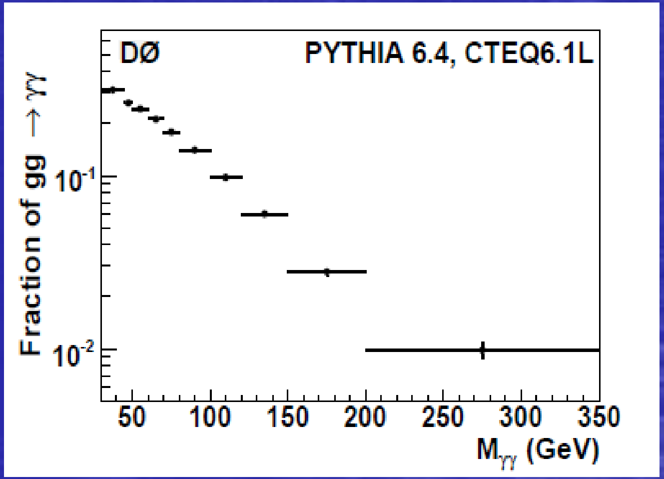
Sensitivity to gluon PDFs

Direct Photon Pair Production

- Large irreducible background to many interesting physics processes
  - SM Higgs searches ($H \to \gamma\gamma$)
  - BSM searches (new heavy resonances, extra spatial dimensions etc.)
  - Precise understanding of QCD production mechanisms indispensable to searches for new physics
- Test of pQCD calculations and soft-gluon resummation methods implemented in theoretical calculations

- At the Tevatron, production dominated (at high $M_{\gamma\gamma}$) by qqbar annihilation.
- At the LHC, contributions from gg fusion and qg initiated processes will be significant



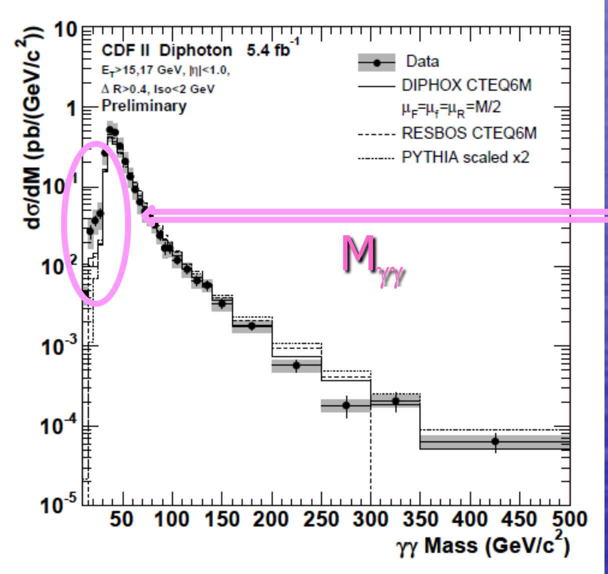


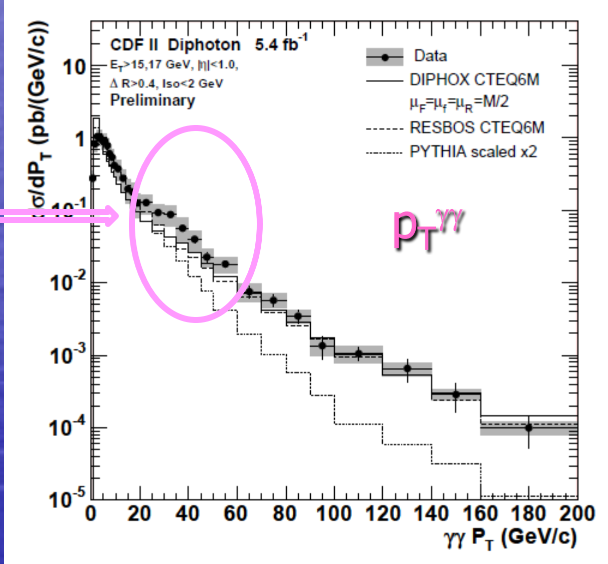
Diphoton Cross Sections

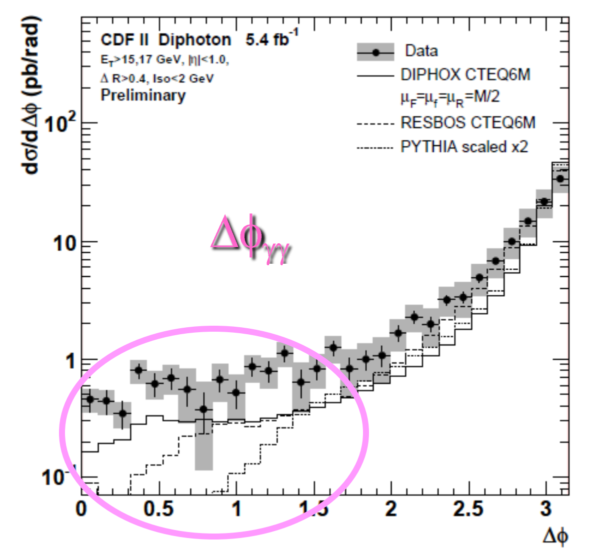
Measurement of differential cross sections vs different kinematic variables probing different aspects of production mechanism

- $p_T^{\gamma\gamma}$, $\Delta\phi_{\gamma\gamma}$: initial-state gluon radiation & fragmentation effects
- $M_{\gamma\gamma}$: potential contributions from new phenomena

$\mathcal{L} = 5.4\ \text{fb}^{-1}$







Theoretical predictions

RESBOS: NLO, resummation of soft-gluon emissions

DIPHOX: NLO, gg fusion @ LO

PYTHIA: LO

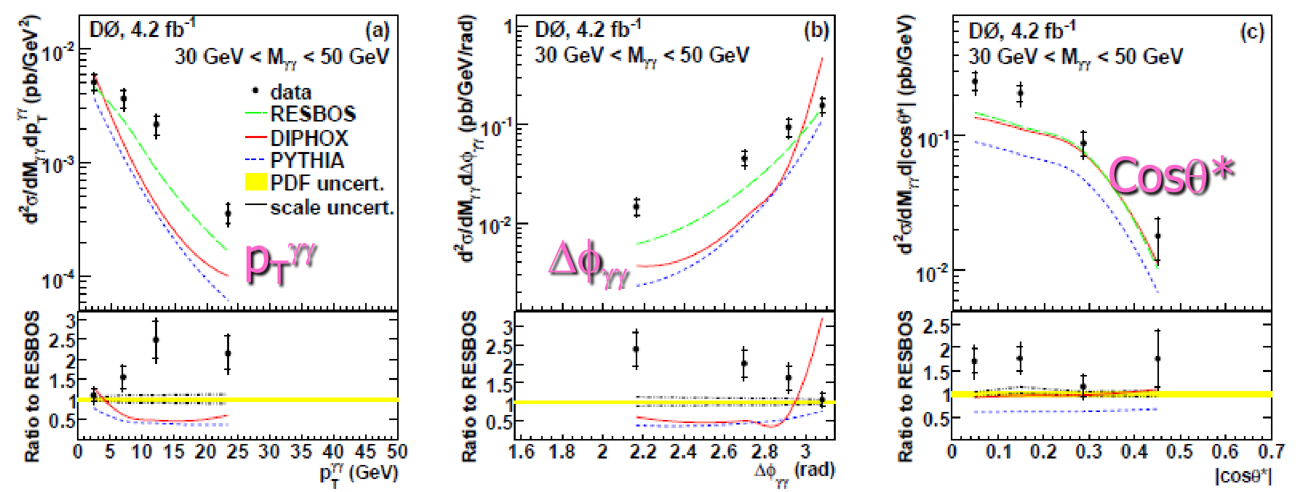
No model describes the data well over the full kinematic range, in particular at low $M_{\gamma\gamma}$ and low $\Delta\phi_{\gamma\gamma}$ where gluon scattering & fragmentations surviving the isolation cut are expected to contribute strongly.

PLB 690, 108 (2010)

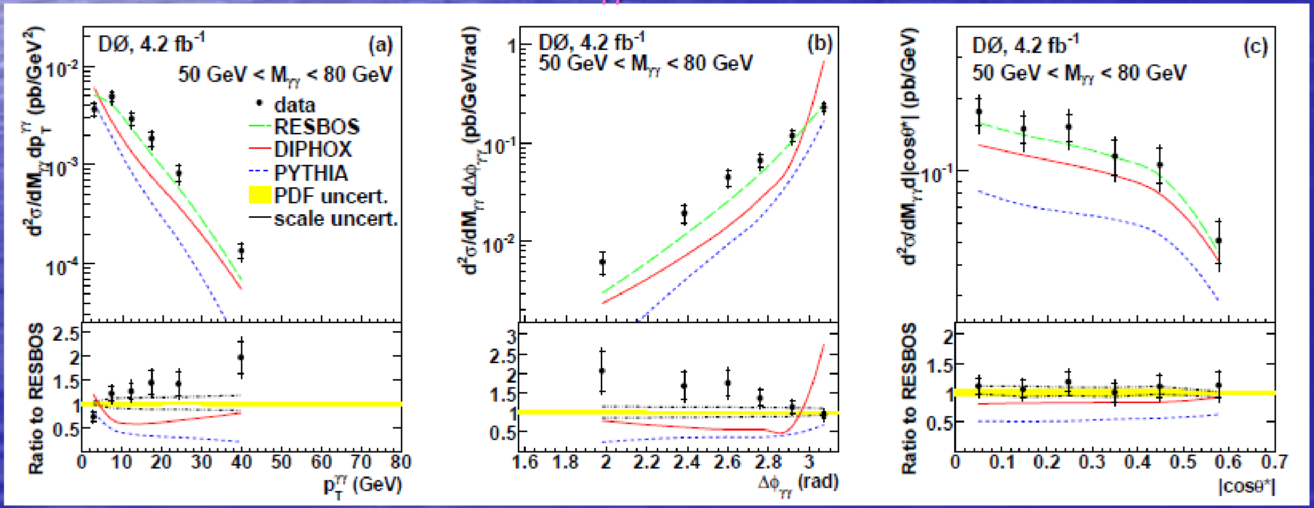
Diphoton Cross Sections

$\mathcal{L} = 4.2\ \mathrm{fb}^{-1}$

30 GeV < $M_{\gamma\gamma}$ < 50 GeV



50 GeV < $M_{\gamma\gamma}$ < 80 GeV



- Also looked double diff x-sections
- Additional variable Cosθ*

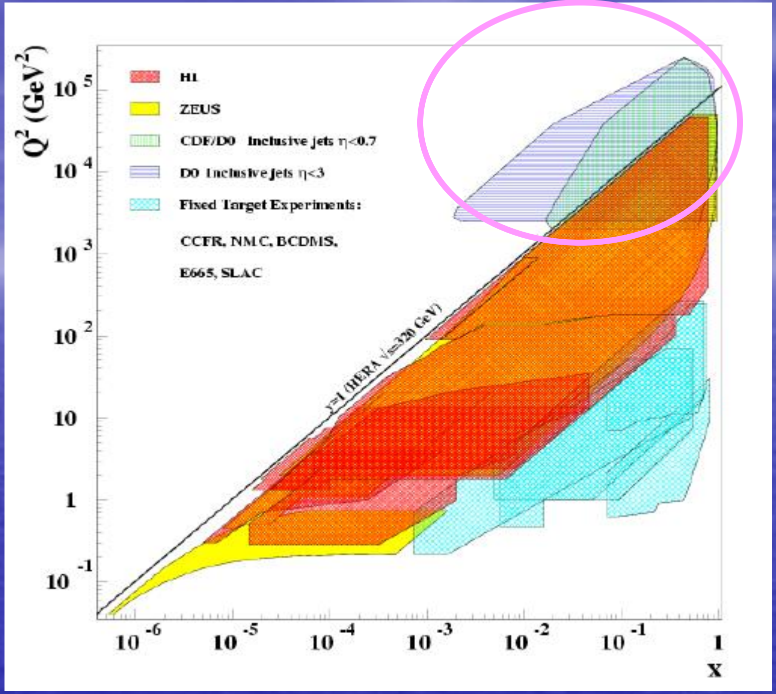
- RESBOS shows the best agreement $_{\gamma}$
- Agreement with RESBOS fair at intermediate $M_{\gamma\gamma}$ and good at high $M_{\gamma\gamma}$.
- Need for including higher order corrections beyond NLO as well as complete resummation of soft and collinear initial state gluons.

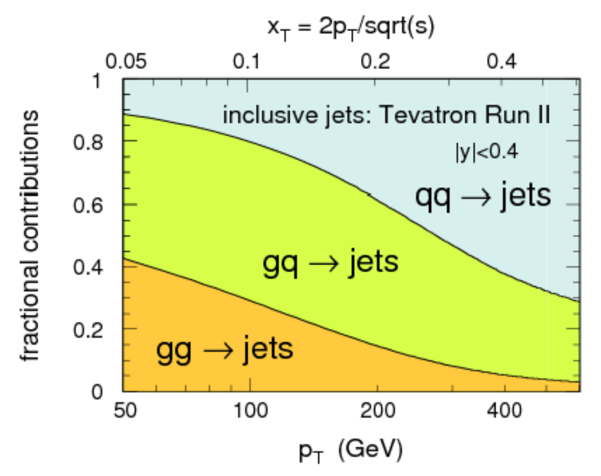
Jets

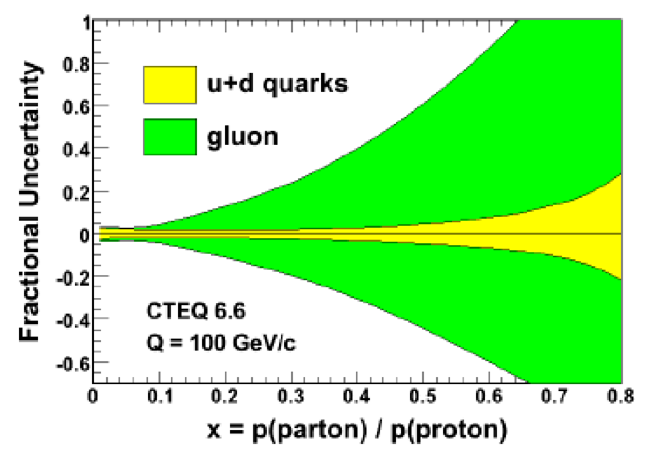
- Collimated sprays of hadrons generated by the fragmentation of partons originating from the hard scattering.

Jet Production

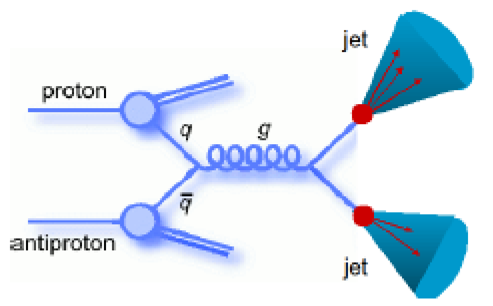
- Kinematic reach in (x,Q^2) compared to HERA and fixed target experiments -- sensitive to PDFs at large momentum fractions x and scales Q^2
- Sensitive to gluon content of the proton at high x where it is weekly constrained. Well constrained at low x by HERA data.

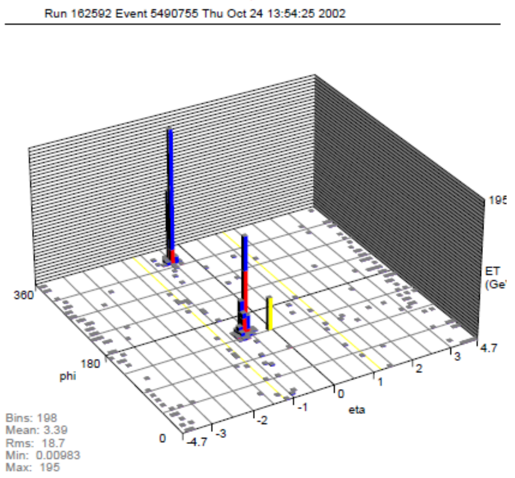






Jet Reconstruction and Measurements

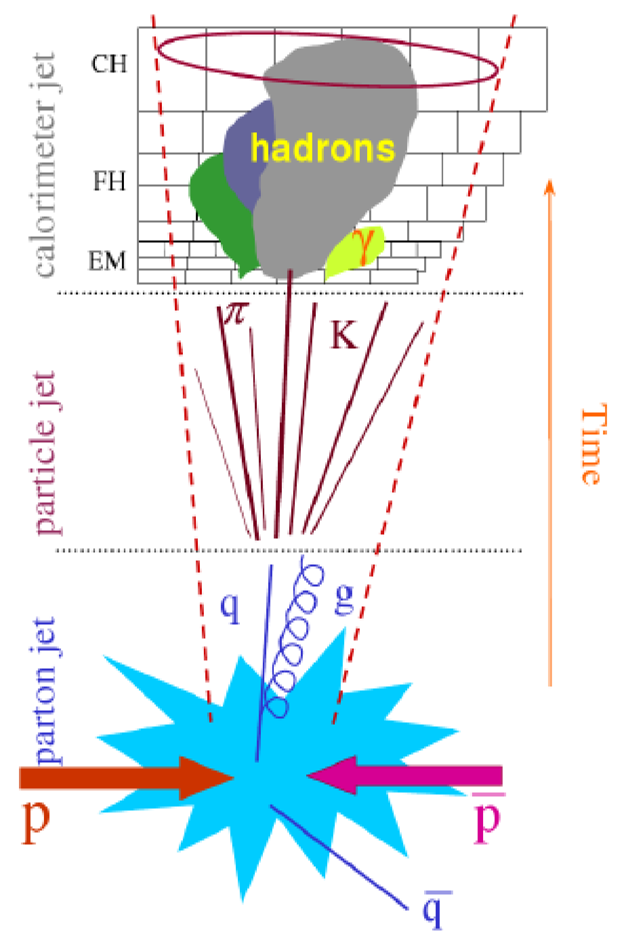




Unfold measurements to hadron (particle) level – need jet energy scale calibration and energy resolution

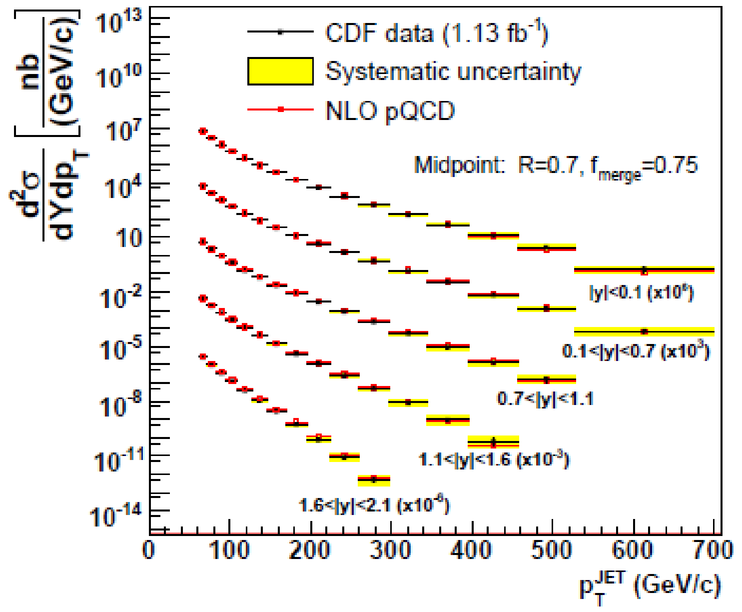
Data – Theory comparison at hadron (particle) level

Correct parton-level theory for non-perturbative effects -- fragmentation/ hadronization underlying event

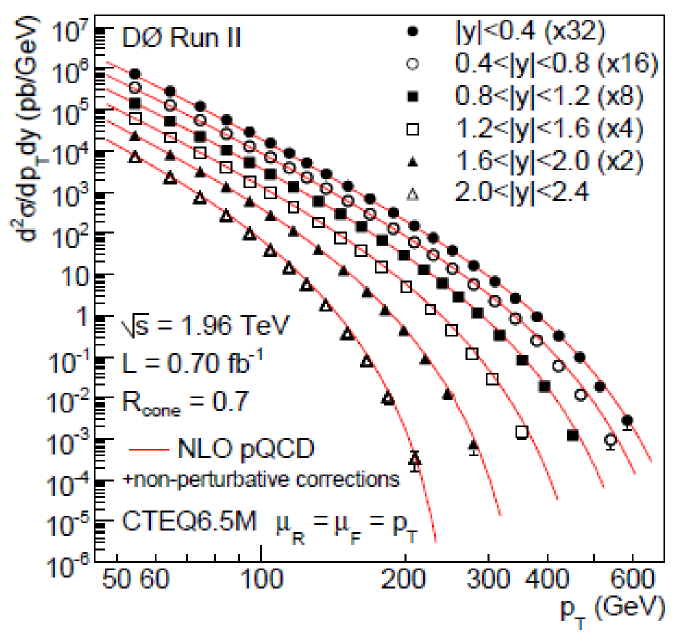


Use midpoint cone algorithm in η-ϕ space to reconstruct jets -- calorimeter towers as seeds

Inclusive Jet Cross Sections



Phys. Rev. D 78, 052006 (2008)

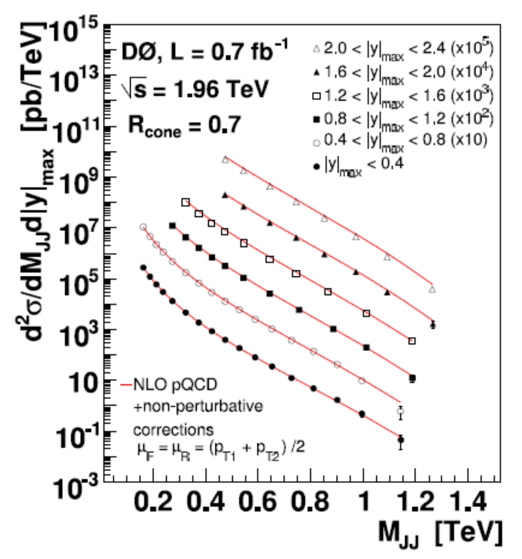


Phys. Rev. Lett. 101, 062001 (2008)

- One of most direct probes of the physics at small distances
  - directly sensitive to α_s and PDFs of the proton
- Measurements test pQCD over 8 order of magnitude in $d\sigma^2/dp_T dy$
- Both measurements in agreement with NLO QCD
- High p_T tail probes distances down to 10^{-19}m and is sensitive to new physics.

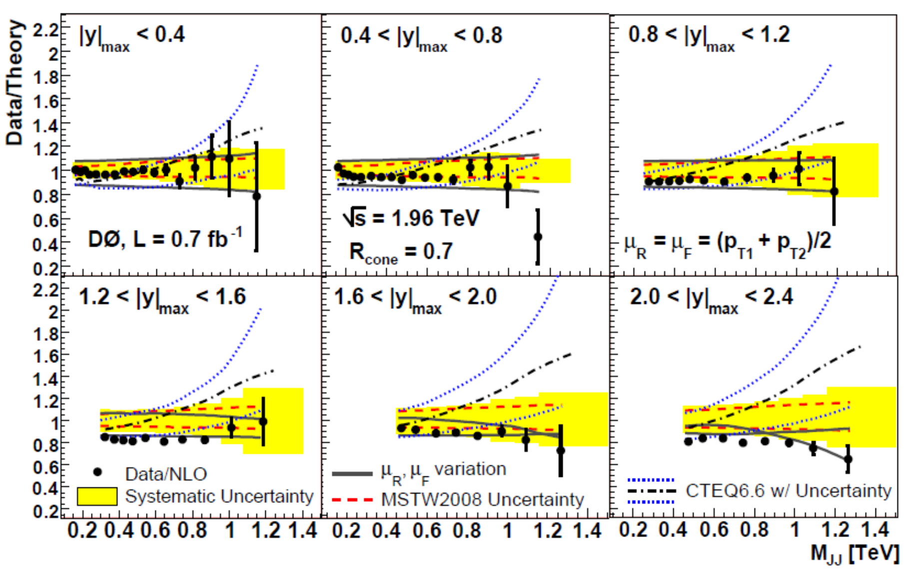
Dijet Mass Spectrum

- D0 measurement of $d^2\sigma/dM_{jj}d|y|_{max}$
  -- p_T (j1,j2) > 40 GeV
  -- six $|y|_{max}$ regions, $0 < |y|_{max} < 2.4$
- Extends kinematic range beyond previous experiments ($|y| < 1.0$)
- Sensitive to PDF of gluons at high x
- Sensitive to new particles (q*,W',Z')



PLB 693, 531 (2010)

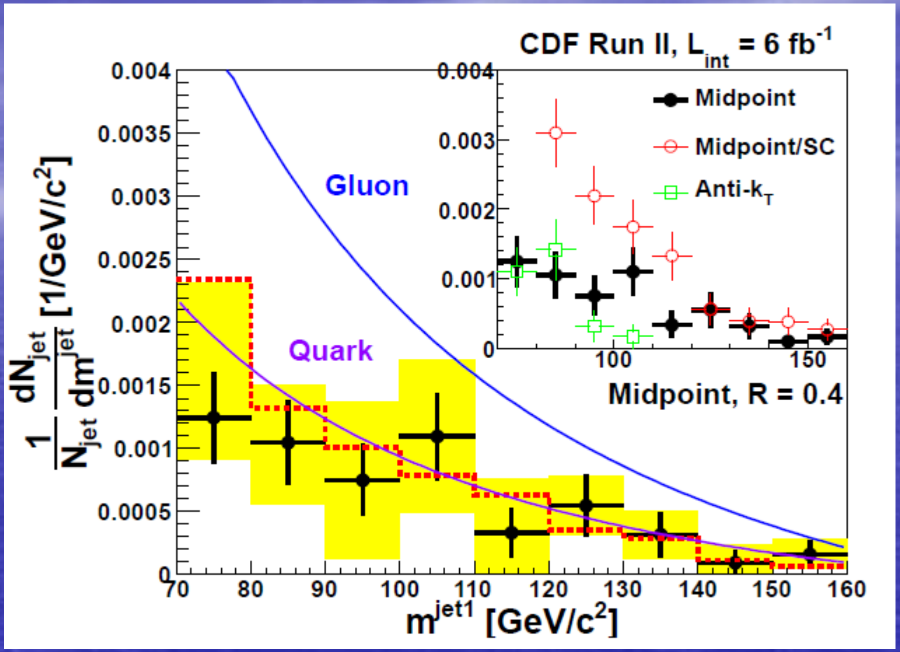
- Data compared to NLO calculations (fastNLO)
  - MSTW2008NLO PDFs describes the shape better than CTEQ6.6
  - MSTW2008 PDFs include Run II incl. jets measurement
- Exp. uncert. similar in size to theory uncert. from PDF & scale



CDF Note 10199

Substructure of High E_T Jets

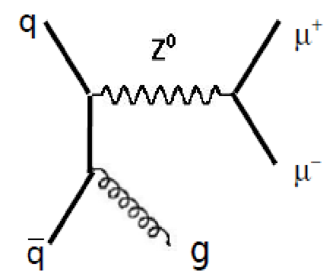
- Jet shape variables for high p_T (> 400 GeV) QCD jets
  Jet mass, Angularity, Planar Flow
- Study of massive jets:
  -- Test of pQCD predictions
  -- Tuning MC generators
  -- massive boosted jets comprise important background for high p_T top, Higgs and various BSM searches



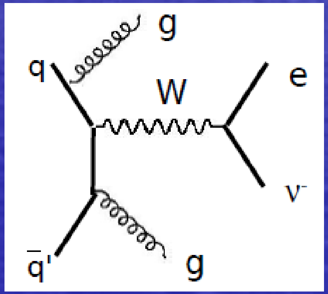
- Jet Mass : Standard E-scheme for mass calculation : vector sum over (E,px,py,pz) of towers in jets.

- Data in agreement with PYTHIA prediction
- Data between quark and gluon prediction (consistent with the expectation that over 80% of jets would arise from quark showering)

W/Z + Jets



- Test of pQCD in multijet environment
  - Presence of W/Z ensure high Q^2: pQCD
  - Clean environment: leptonic final state provides clean signature, low BG
  - High statistics allows precision tests
- Test of MC Models
  - Key sample to validate available MC tools using experimental data
- W/Z+HF production sensitive to HF PDFs
- Significant irreducible background
  - Top, Higgs, SUSY and many BSM scenarios
  - In particular, W/Z+bb



CDF Note 10216

$Z/\gamma^* \rightarrow \mu^+\mu^-$ + Jets Cross Sections

$\mathcal{L} = 6\ \text{fb}^{-1}$

Kinematic selection

- Two central μ's

$p_T^\mu > 25$ GeV, $|\eta| < 1.0$

$66 < M_{\mu\mu} < 106$ GeV

- ≥1 jet, R = 0.7

$p_T^{jet} > 30$ GeV, $|y| < 2.1$

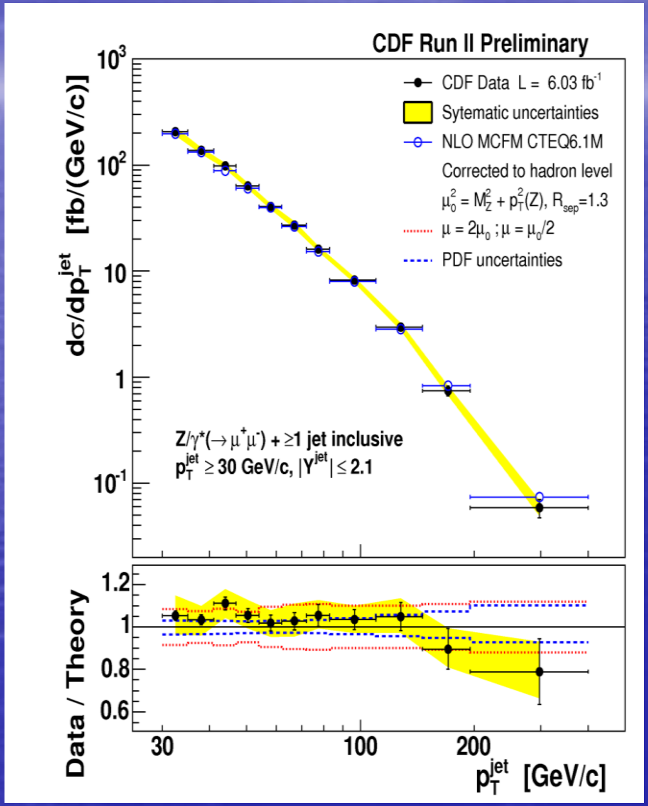
NLO MCFM :

CTEQ6.1 PDF

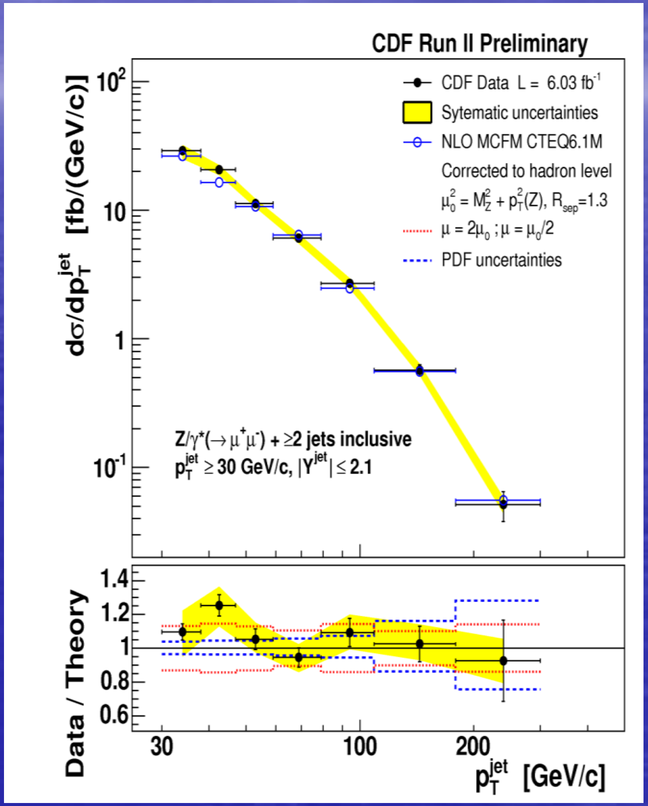
$\mu_0^2 = M_Z^2 + p_T^2(Z)$

Non-pert. Corr. for fragmentation and UE estimated from Pythia -Tune A

$N_{jet} \geq 1$



$N_{jet} \geq 2$



Data well described by NLO QCD (MCFM)
Scale uncertainties : 10-15%

CDF Note 10394

$Z/\gamma^* \rightarrow e^+e^-$ + Jets Cross Sections

$\mathcal{L} = 6\ \text{fb}^{-1}$

Kinematic selection

- Two central μ's

$p_T^{\mu} > 25$ GeV, $|\eta| < 1.0$

$66 < M_{\mu\mu} < 106$ GeV

- ≥1 jet, R = 0.7

$p_T^{jet} > 30$ GeV, $|y| < 2.1$

NLO MCFM :

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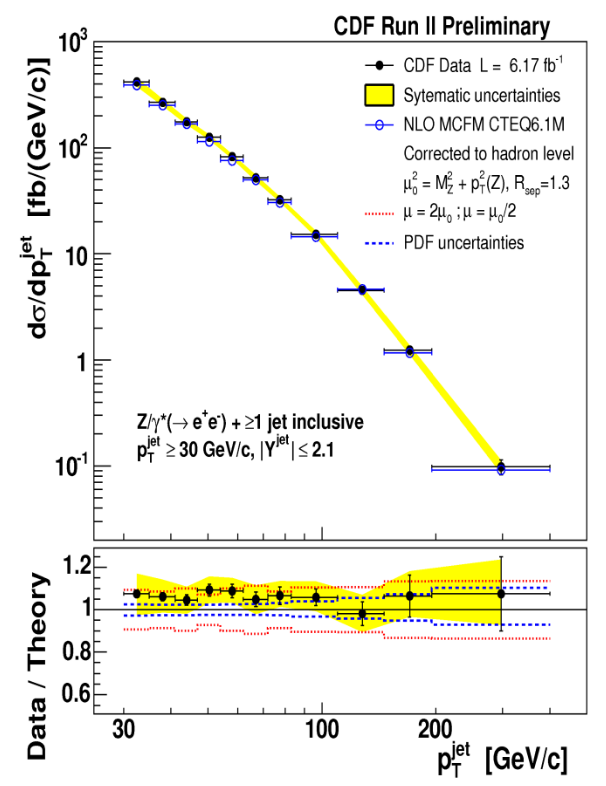
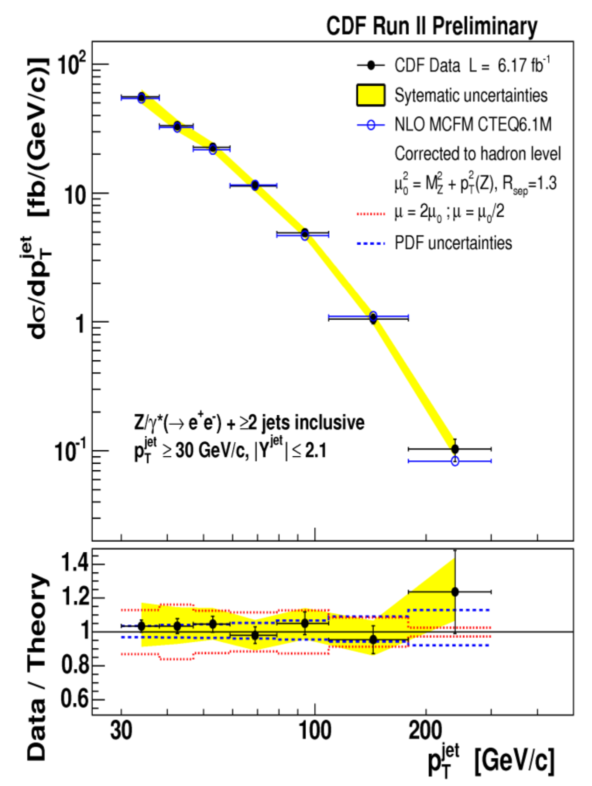


$N_{jet} \geq 2$



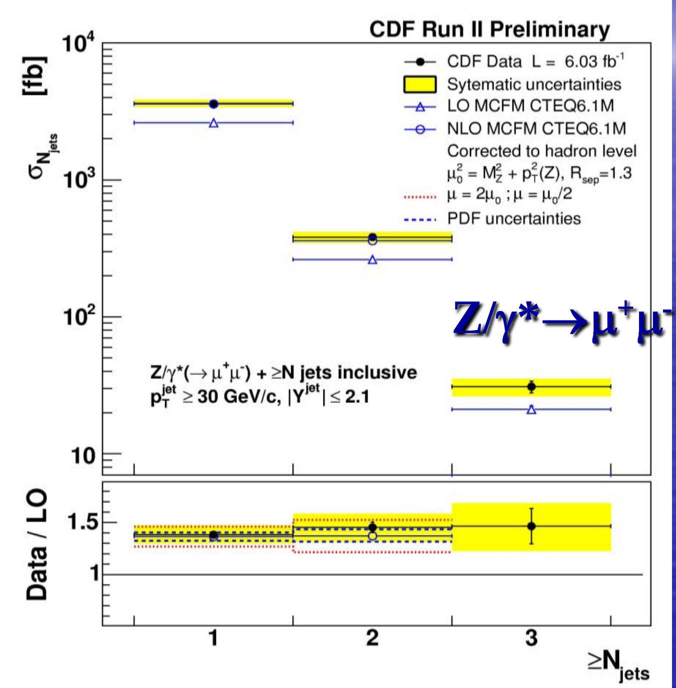
Measurements are well described by MCFM NLO
Scale uncert. : 10 - 15%, PDF uncert. : 2 – 15%

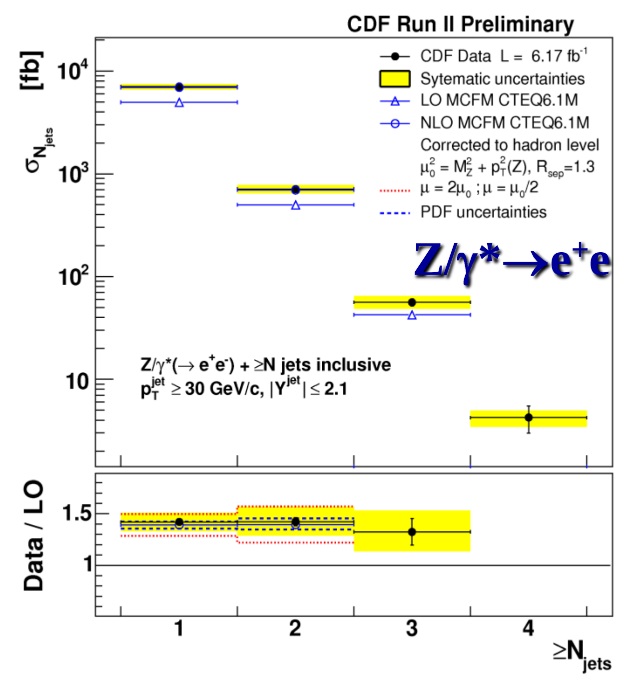
CDF Note 10216,10394

Z/γ*+Jets Cross Sections

$\mathcal{L} = 6\ \mathrm{fb}^{-1}$

Total incl. cross sections in inclusive jet multiplicities





- Good agreement between data & NLO prediction in ≥1, ≥2 jet bins
- For $N_{jet} \geq 3$, only LO calculation available
- Systematic uncertainties : 5–15%, JES dominant
- Data suggest a common ratio to LO of ~ 1.4

$Z/\gamma^*(\rightarrow\mu^+\mu^-)$ + jet(s) : Angular Correlations

PLB 682, 370 (2010)

$\mathcal{L} = 1\ \mathrm{fb}^{-1}$

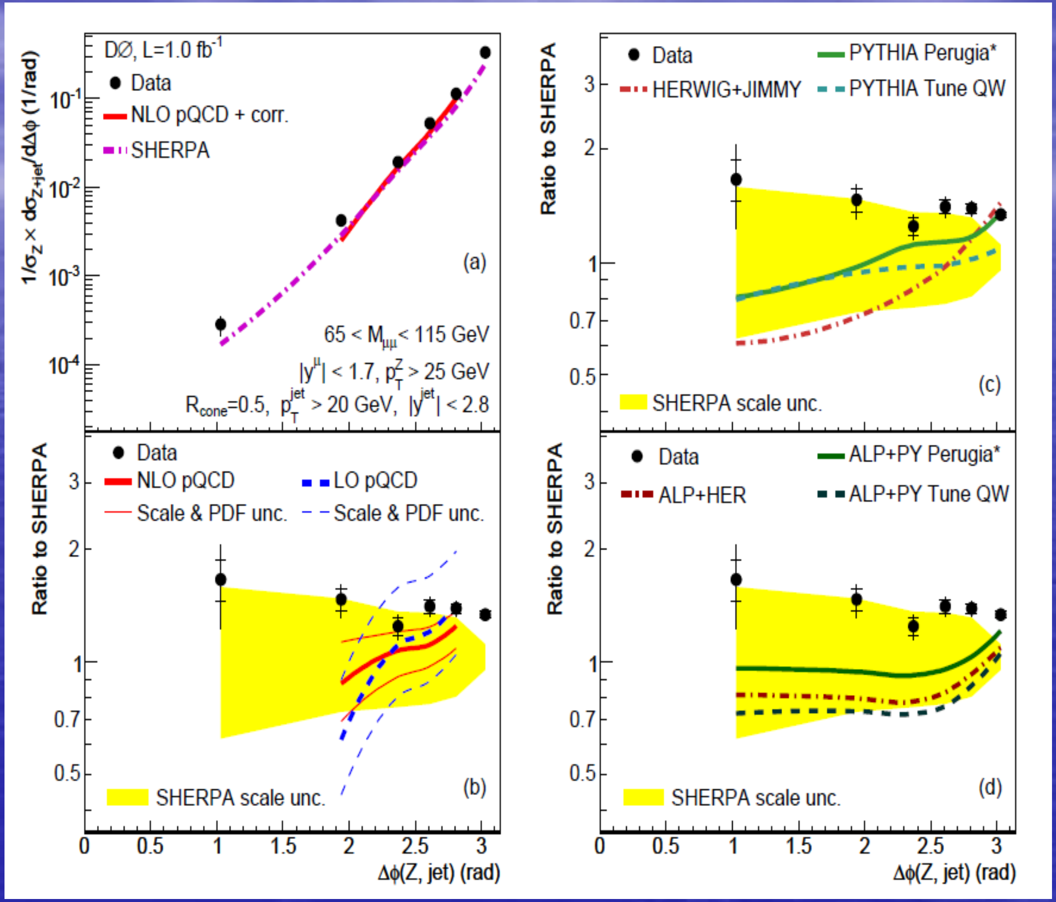
First measurements of angular correlations between Z and leading jet

$\Delta\phi$(Z, jet), Δy(Z, jet)

$y_{boost}=1/2(y_Z + y_{jet})$

Sensitive to QCD radiation : Test of PS model assumptions.

- The diff. cross-sections are normalized to incl. σ(Z)
- Avoids systematic of JES
- p_T^Z>25 GeV (avoid soft effects)
- Small $\Delta\phi$(Z,jet) excluded from MCFM due to importance of non pert. Effects – reasonable agreement

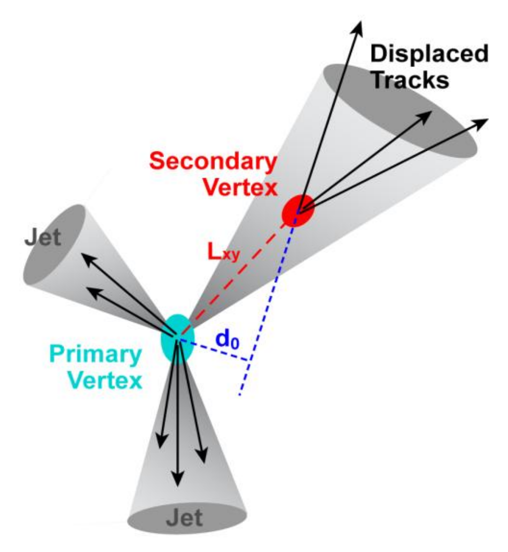


Shape of angular observables best described by SHERPA, but large scale uncertainties. Alpgen + Pythia (perugia) close to SHERPA.

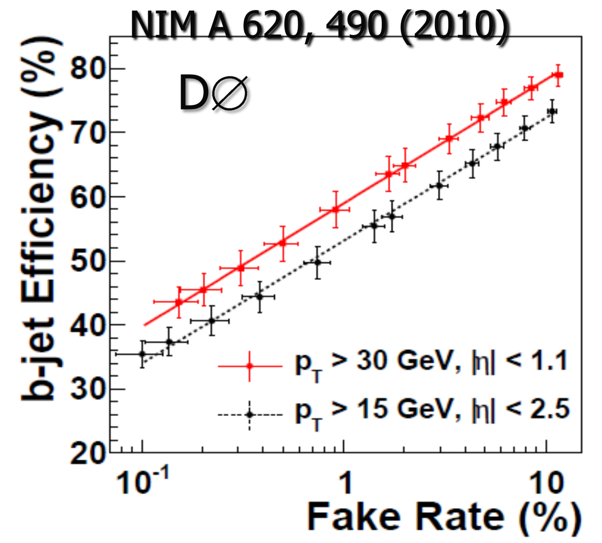
W/Z/γ + b/c Jets

Identifying b-jets

- Most common b-tagging technique exploits long lifetime of b-hadrons
  - Reconstruct secondary vertex from displaced tracks (not from primary vertex) inside jet
- CDF' : SecVtx tagging based on large transverse displacement (L_{xy})
- D0 : NN based on combination of variables sensitive to presence of displaced tracks forming sec. vtx.

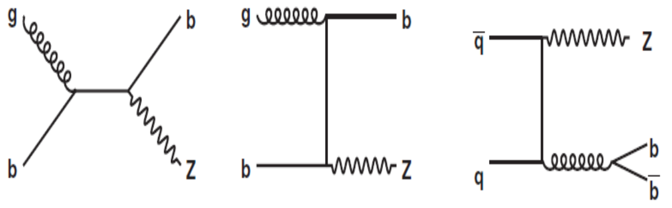


NIM A 620, 490 (2010)



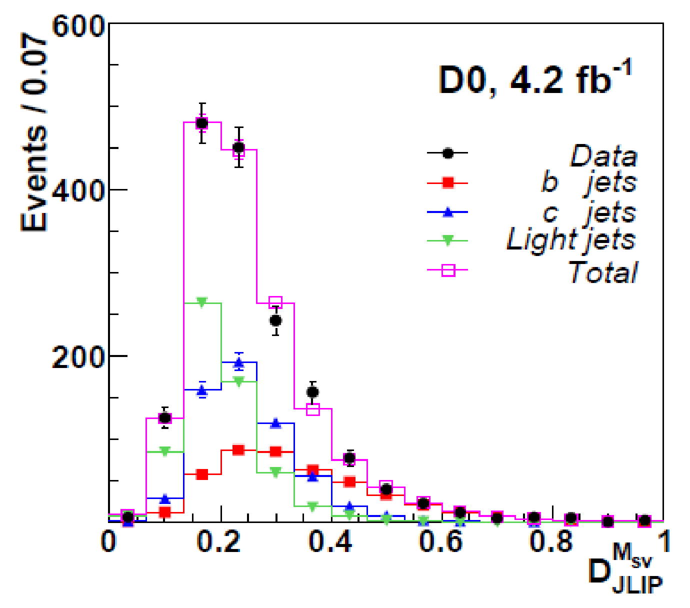
hep-ex/1010.6203
To appear in PRD-RC

Z + b-jets / Z + jets



- Important background to the SM Higgs search in ZH channel
- Sensitive to b-quark PDF
- Cancellation of many systematics $\Rightarrow$ precise comparison with theory

- Consider ee/$\mu\mu$ channels
- Jets : R=0.5, p_T>20 GeV, $|\eta|$<2.5
- Events with ≥1 b-tags identified using NN tagger
- Use discriminant with Secondary vertex Mass and jet lifetime prob. to separate b-jets from c & light
- Fit Data – Bkgd with templates of discriminant to extract Z+b fraction



$\sigma(Z+b)/\sigma(Z+jet)$

= 0.0192 ± 0.0022 ± 0.0015

MCFM NLO = 0.0185 ± 0.0022

-Most precise till date

-Extends kinematic region of jets

-Consistent with CDF result @ 2 fb^{-1}: 0.0208 ± 0.0033 ± 0.0034

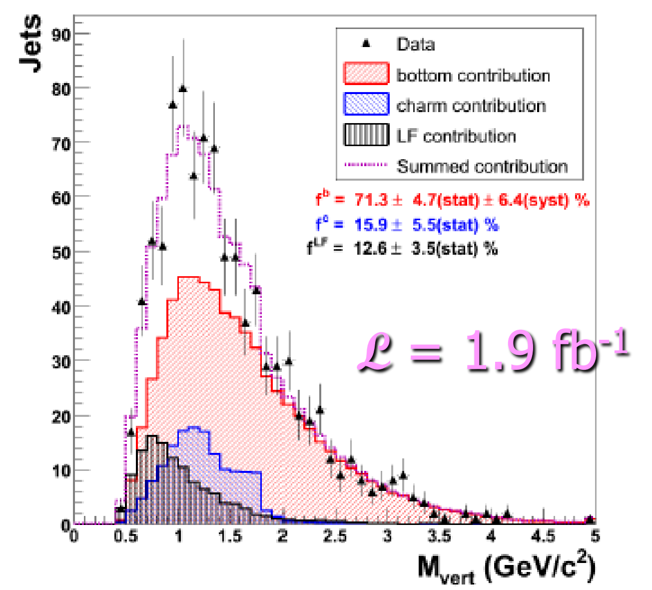
PRL 104, 131801 (2010)

W + b jets

- Important background to the Higgs search in WH channel and study of top quark properties

- $W \to l\nu$ ($l=e,\mu$) selection
  $p_T>20$ GeV, $|\eta|<1.1$, $p_T^{\nu}>25$ GeV
- Jets : 1 or 2 in final state
  R = 0.4, $p_T>20$ GeV, $|\eta|<1.5$
- ≥1 b-tagged jet, SecVtx algorithm
- Determine W+b fraction from fit to Vertex Mass distribution M_{vert}

- Major backgrounds
  ttbar (40%), single top (30%)
  Fake W (15%), WZ (5%)



- Measurement
  σxBR = 2.74 ± 0.27± 0.42 pb
- Prediction
  NLO : 1.22 ± 0.14 pb
  (Campbell, Cordero, Reina)
  Pythia : 1.10 pb, Alpgen : 0.78 pb

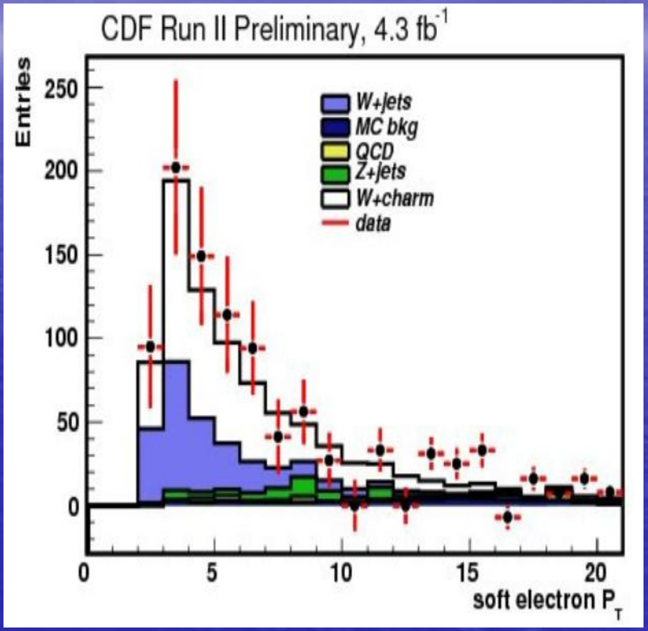
→Measurement substantially higher

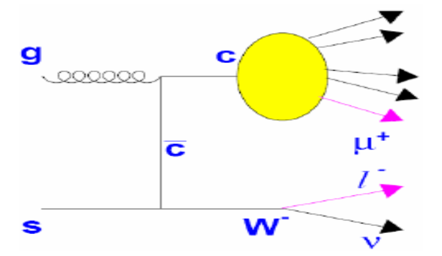
CDF Note 10089

W + c jet

- s + g fusion : ~90%
  →sensitive to gluon and s-quark PDF
- BG for single top, WH

- Strategy
  - $W \to l\nu$ selected by high p_T e/μ+MET
  - c-jets are identified by soft lepton tagging (SLT) algorithm
  - Exploit charge correlation between lepton from W decay and SLT lepton
  - Wc events : Opp. Sign.
    Most of BG processes like Wcc give opp. sign & same sign almost equally
  - Look for excess of $N^{OS} - N^{SS}$





CDF @ 4.3 fb^{-1}
$p_T^{c\text{-jet}} > 20$ GeV, $|\eta^{c\text{-jet}}| < 1.5$
$\sigma \times BR = 33.7 \pm 11.4 \pm 7.3$ pb
Alpgen = 16.5 ± 4.7 pb

Summary & Outlook

- Tevatron has a rich physics program for QCD analyses which has significantly advanced our understanding over the years
  - Many interesting results
  - Enormous data leading to better precision
- Good understanding of these processes critical for SM Higgs and NP searches
- More results with better statistics will become available soon.
- ~12 fb-1 data expected by end of Tevatron operation in 2011.
- Stay tuned for the more exciting results from the Tevatron experiments

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

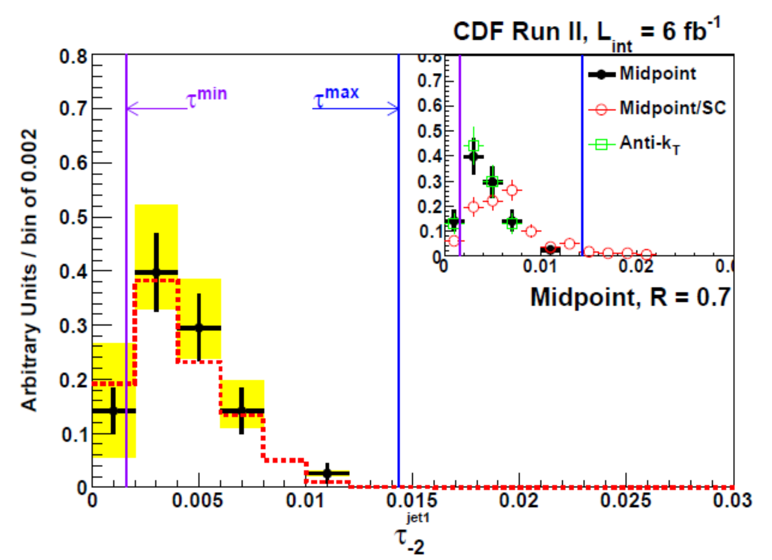
http://www-d0.fnal.gov/Run2Physics/qcd/

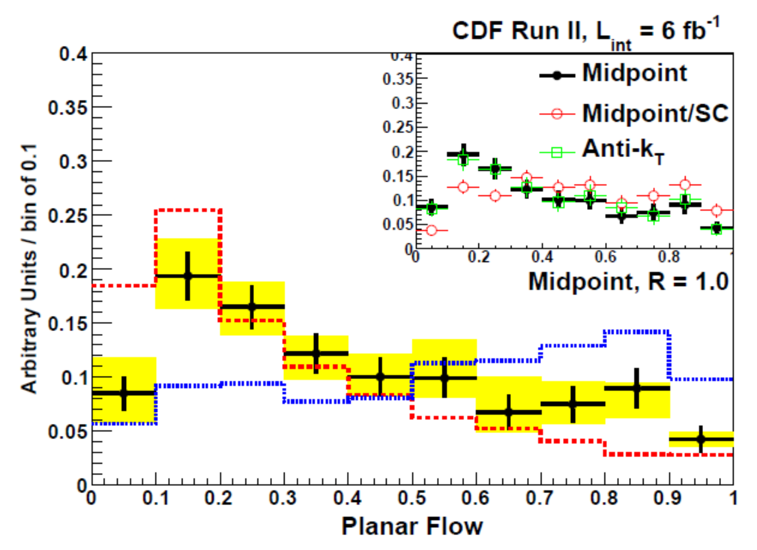
Substructure of High p_T Jets –II

- Angularity and Planar flow are jet shape variables expected to provide discrimination of massive jets arising from QCD production and other sources such as top production.

  --Angularity is sensitive to the degree symmetry of energy deposition

  --Planar flow distinguishes planar from linear configurations
- Both variables are IR-safe and less dependent on jet finding algorithm.





Substructure of High p_T Jets –II

Angularity

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

where ω_i is the energy of a component inside the jet (such as a calorimeter tower). Limiting the parameter $a \leq 2$ ensures IR safety, as can be directly seen from the expression on the right hand side of the equation which is valid for small angle radiation $\theta_i << 1$.

Substructure of High p_T Jets –III

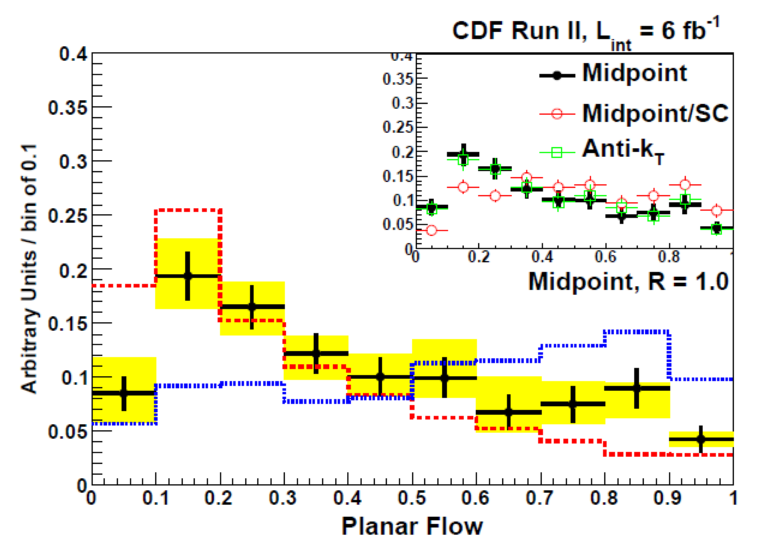
Planar Flow

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

where m_J is the jet mass, w_i is the energy of particle i in the jet, and $p_{i,k}$ is the k^th component of its transverse momentum relative to the jet momentum axis. Given I_w, we define Pf for that jet as

$$Pf = 4 \frac{\det(I_w)}{\mathrm{tr}(I_w)^2} = \frac{4\lambda_1\lambda_2}{(\lambda_1 + \lambda_2)^2}$$

where $\lambda_{1,2}$ are the eigenvalues of I_w. P_f vanishes for linear shapes and approaches unity for isotropic depositions of energy.



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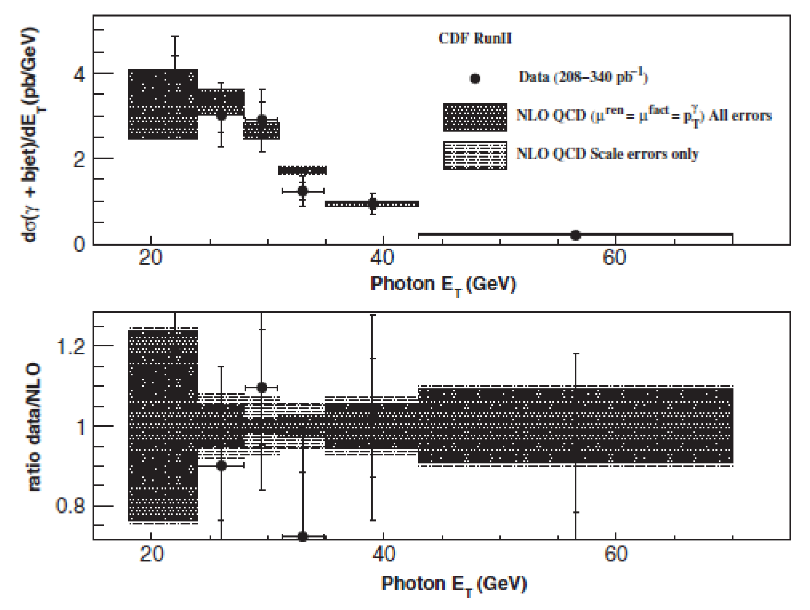
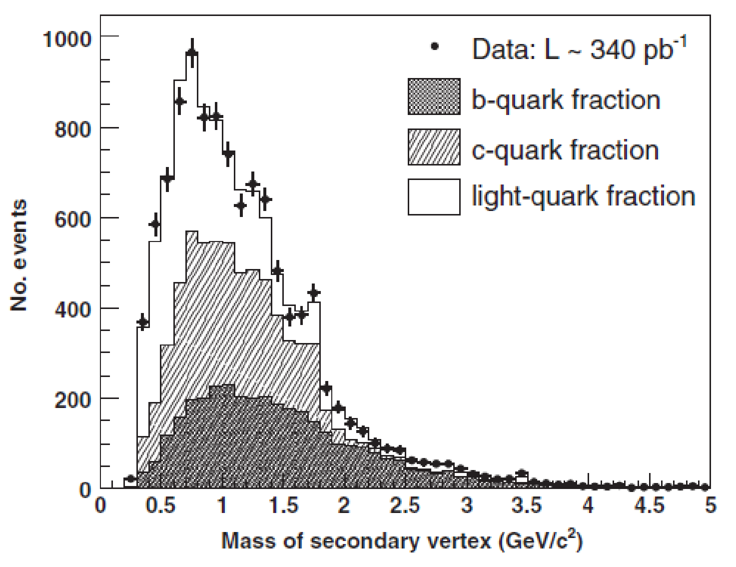
γ + b jet

- Isolated γ^s : $E_T^\gamma > 20$ GeV, $|y^\gamma| < 1.1$
- Jets : $E_T^{jet} > 20$ GeV, $|y^{jet}| < 1.5$
- Identify b-jet using displaced secondary vertices
- Determine the fraction of γ+b jet by fitting the secondary vertex mass templates



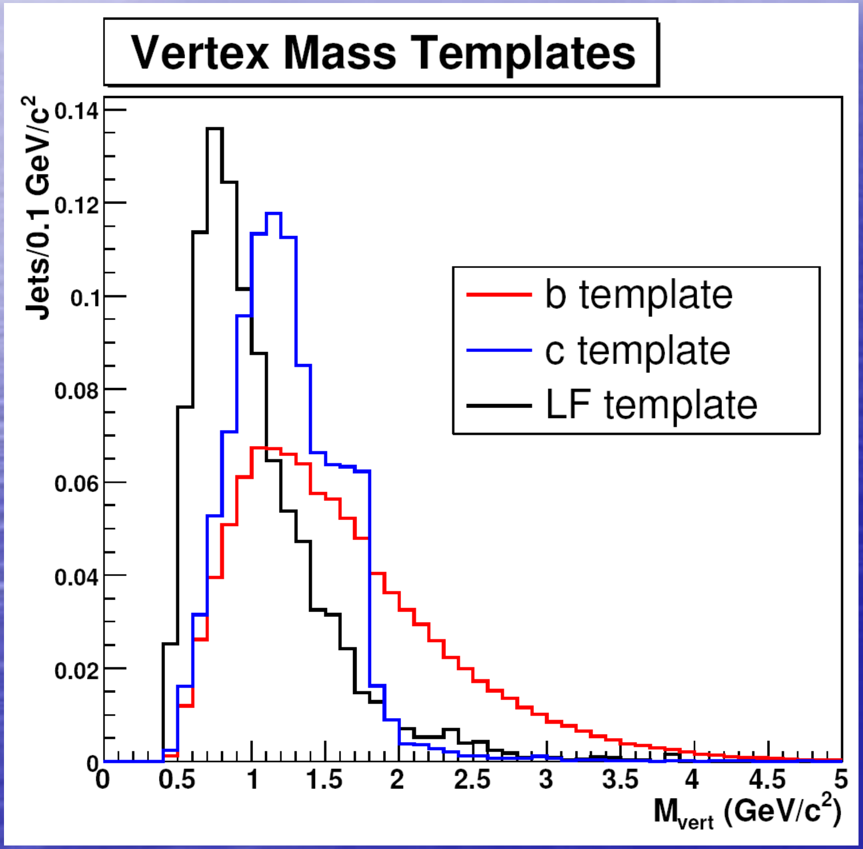


- Data well described by NLO calculations using CTEQ6.6 PDFs.
- Measured total cross section = 54.22±3.26 (stat)±5.1(syst) pb
- NLO : 55.62±3.87 pb

W + c jet Measurement

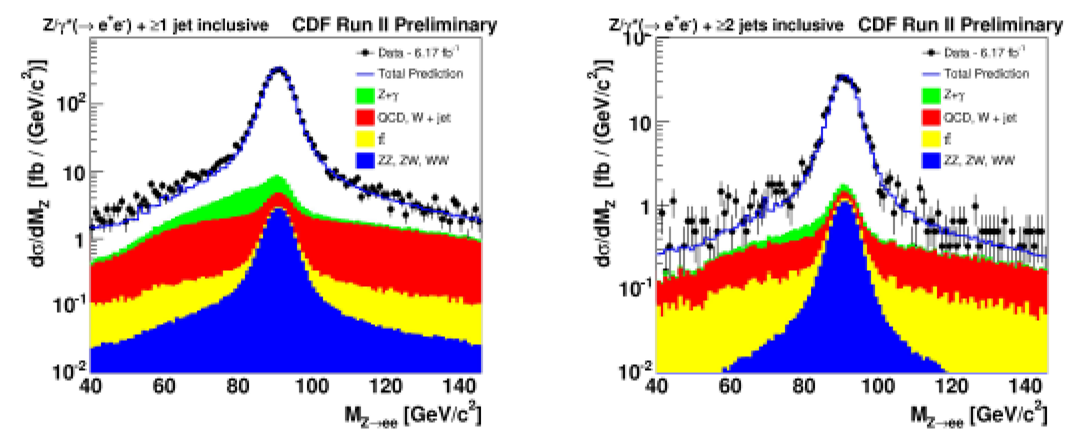
Source	Relative Uncertainty (%)
Jet energy scale	± 6.0
W-lepton ID	± 2.0
Luminosity	± 8.3
BKG cross sections	± 5.0
Tagging Efficiency	± 8.8
Fake matrix	± 5.0
Conversion scale factor	± 3.3
Calorimeter modeling	± 3.8
ISR/FSR	± 7.0
Q^2	± 10.0
QCD estimation	± 1.7
PDF	± 8.0
Total	± 21.8

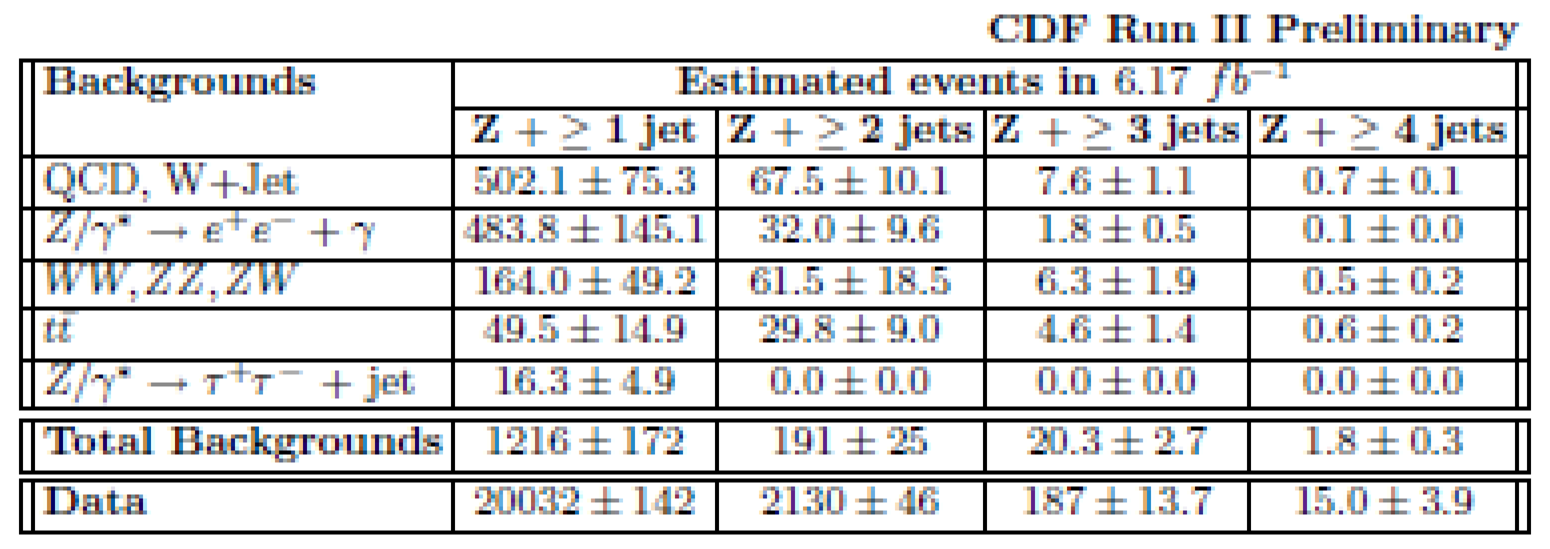
W + b jet Measurement



Source	$\frac{\delta_{\sigma_{b-\text{jets}}\times BR}}{\sigma_{b-\text{jets}}\times BR}$ (%)
b shape modeling	8
c shape modeling	1
LF shape modeling	3
UT tag efficiency	6
Luminosity	6
Top Cross Sections	2
Fake $W^{\pm}$ $\not{E}_T$ fits	1
Tagged Fake $W^{\pm}$ b fraction	1
Jet Energy Scale	3
Q^2	3
PDF	2
$\lvert z_0 \rvert$ efficiency	<1
Trigger efficiency	<1
Lepton ID efficiency	<1

Z(ee)+jets Measurement





CDF Run II Preliminary

Backgrounds	Estimated events in 6.17 fb^{-1}			
	$Z + \geq 1$ jet	$Z + \geq 2$ jets	$Z + \geq 3$ jets	$Z + \geq 4$ jets
QCD, W+Jet	502.1 ± 75.3	67.5 ± 10.1	7.6 ± 1.1	0.7 ± 0.1
$Z/\gamma^* \to e^+e^- + \gamma$	483.8 ± 145.1	32.0 ± 9.6	1.8 ± 0.5	0.1 ± 0.0
WW, ZZ, ZW	164.0 ± 49.2	61.5 ± 18.5	6.3 ± 1.9	0.5 ± 0.2
$t\bar{t}$	49.5 ± 14.9	29.8 ± 9.0	4.6 ± 1.4	0.6 ± 0.2
$Z/\gamma^* \to \tau^+\tau^- +$ jet	16.3 ± 4.9	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Total Backgrounds	1216 ± 172	191 ± 25	20.3 ± 2.7	1.8 ± 0.3
Data	20032 ± 142	2130 ± 46	187 ± 13.7	15.0 ± 3.9

$Z/\gamma^* \rightarrow \mu^+\mu^- +$ Jets

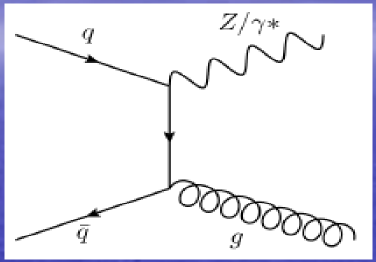
Latest results with 6 fb^{-1}

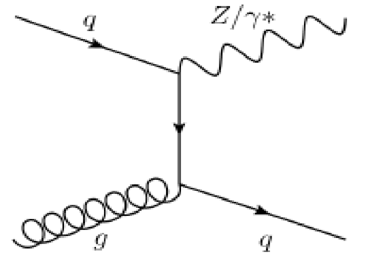
- Kinematic selection

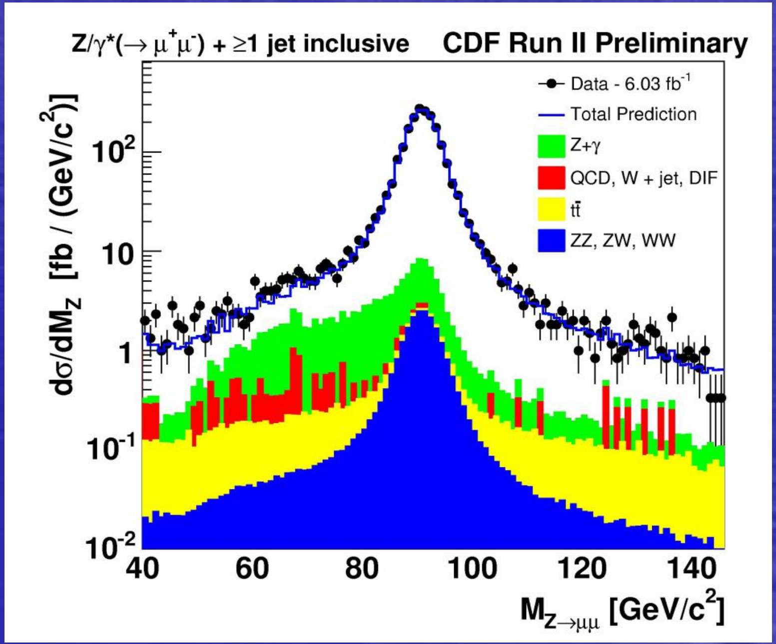
$p_T^{\mu} > 25$ GeV, $|\eta| < 1.0$, $66 < M_{\mu\mu} < 106$ GeV
$p_T^{jet} > 30$ GeV, $|y| < 2.1$, R = 0.7

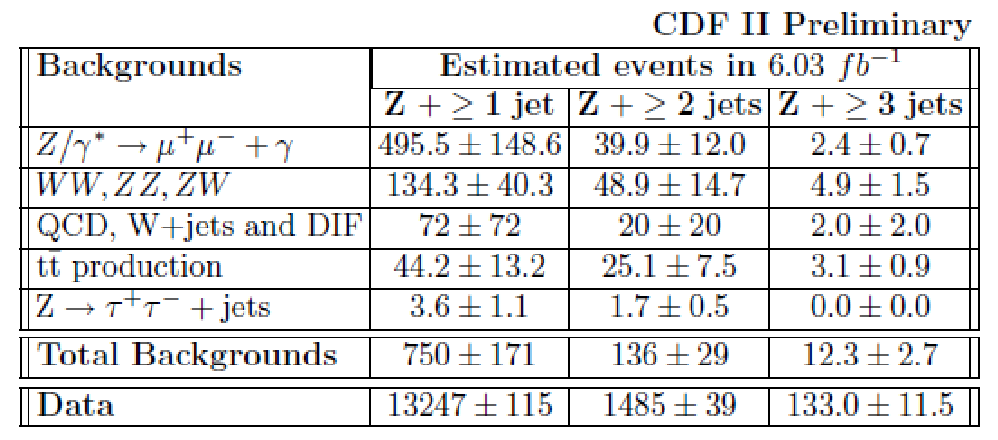
- Events :13000, 1500, 130 in Z+≥1 jet, ≥2, ≥3 jet bins
- Backgrounds:

  QCD multi-jet, W+jets (data-driven)
  $Z\gamma$, Top, Diboson, $Z \rightarrow \tau\tau$ (MC)
  - Total BG 5-10%









CDF II Preliminary

Backgrounds	Estimated events in 6.03 fb^{-1}		
	$Z + \geq 1$ jet	$Z + \geq 2$ jets	$Z + \geq 3$ jets
$Z/\gamma^* \rightarrow \mu^+\mu^- + \gamma$	495.5 ± 148.6	39.9 ± 12.0	2.4 ± 0.7
WW, ZZ, ZW	134.3 ± 40.3	48.9 ± 14.7	4.9 ± 1.5
QCD, W+jets and DIF	72 ± 72	20 ± 20	2.0 ± 2.0
$t\bar{t}$ production	44.2 ± 13.2	25.1 ± 7.5	3.1 ± 0.9
$Z \rightarrow \tau^+\tau^-$ + jets	3.6 ± 1.1	1.7 ± 0.5	0.0 ± 0.0
Total Backgrounds	750 ± 171	136 ± 29	12.3 ± 2.7
Data	13247 ± 115	1485 ± 39	133.0 ± 11.5