Study of Hard QCD at the Tevatron

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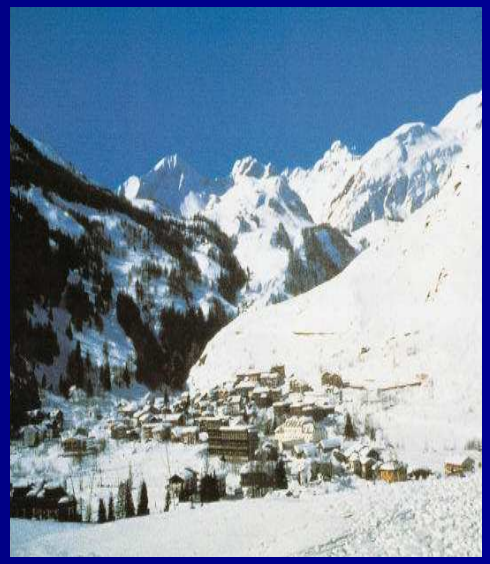
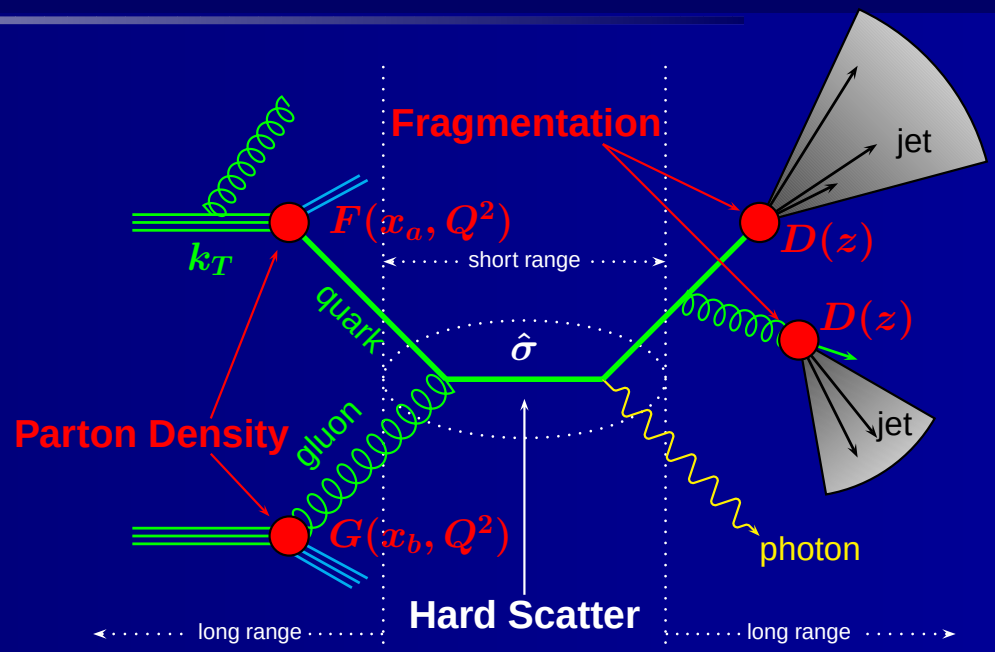


QCD Hard Scatters

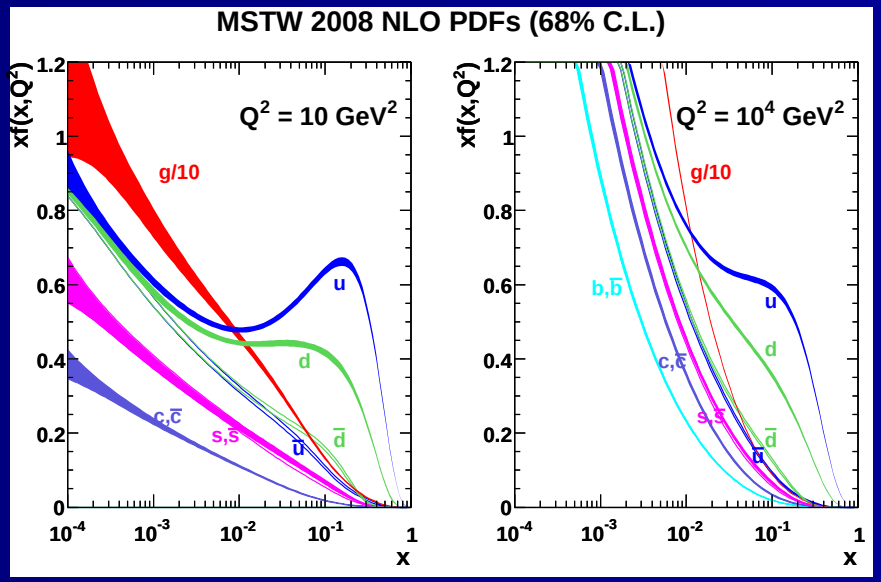
Large p_T processes originate in the hard scattering of partons:

- allow precision tests of pQCD
- constrain parton distribution and fragmentation functions
- sensitive to the presence of new physical phenomena

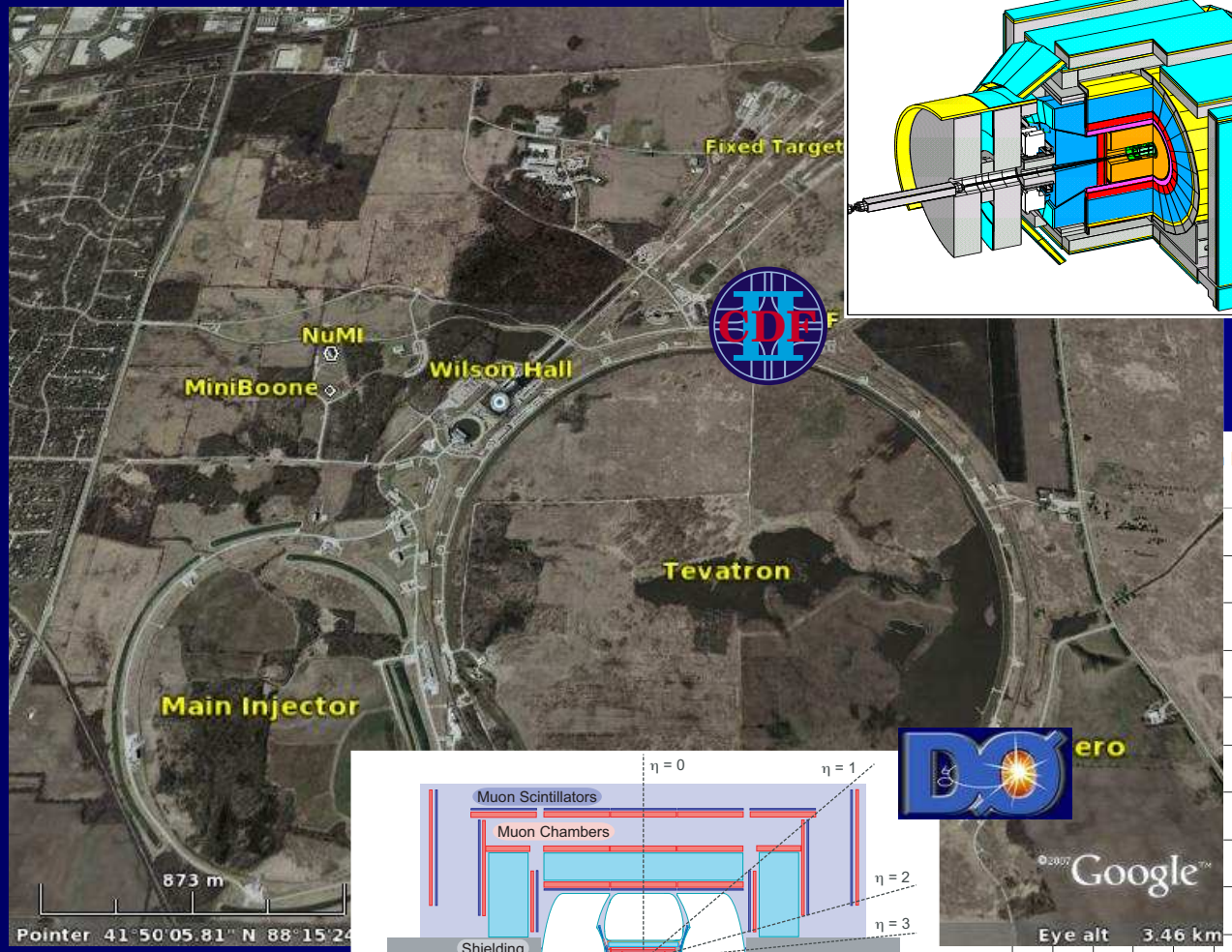


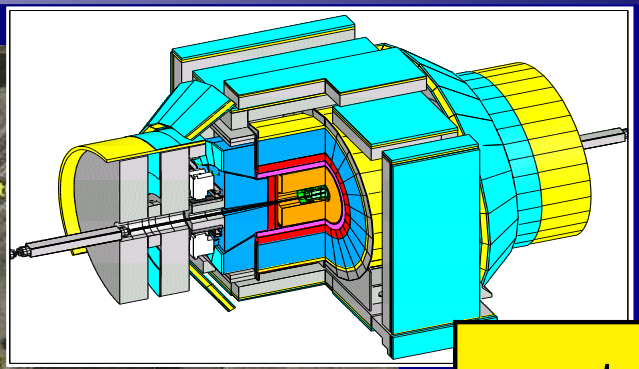
Measurements covered in this talk:

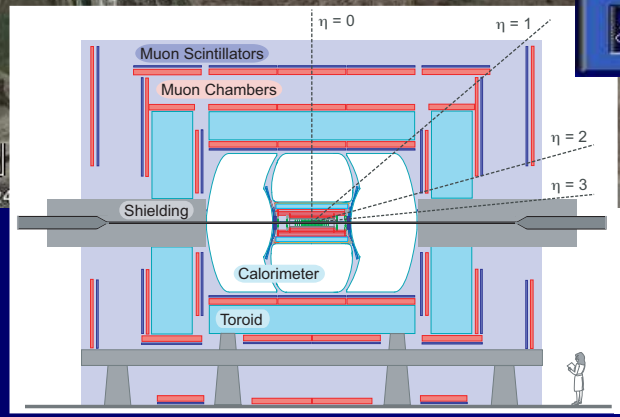
- inclusive jets
- dijets
- direct photons
- γ+jet
- Z+jet
- W+jet
- $W + b$ jet
- $W + c$ jet
- $\gamma + c/b$ jet
- $Z + b$ jet



Fermilab Tevatron Collider

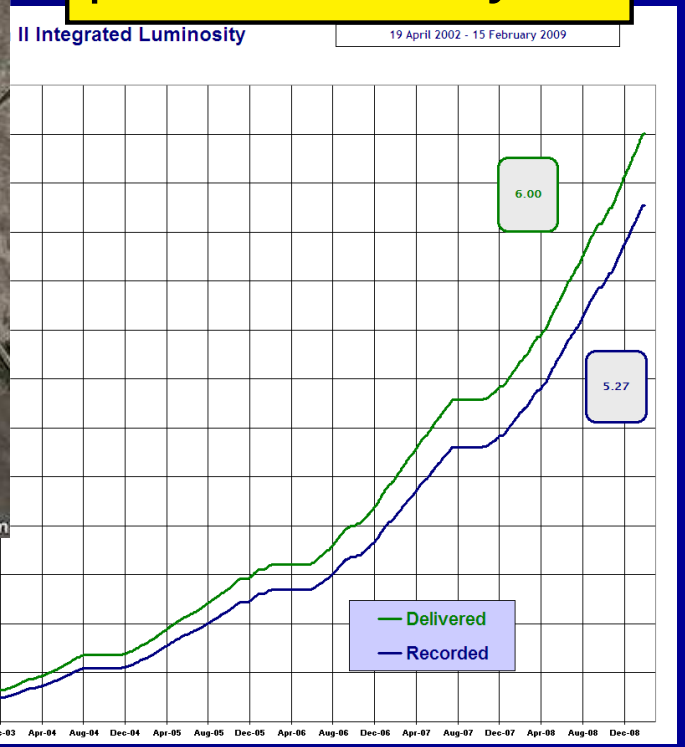






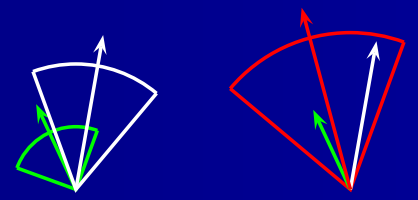
$p\bar{p}$ collider
$\sqrt{s}$ =1.96 TeV

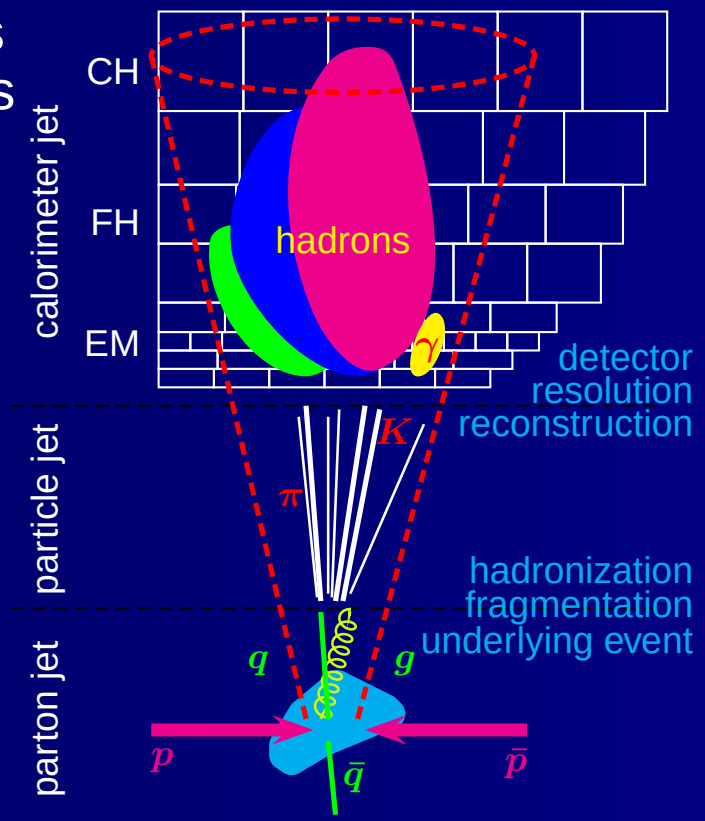
up to 2.5 fb^{-1} in presented analyses

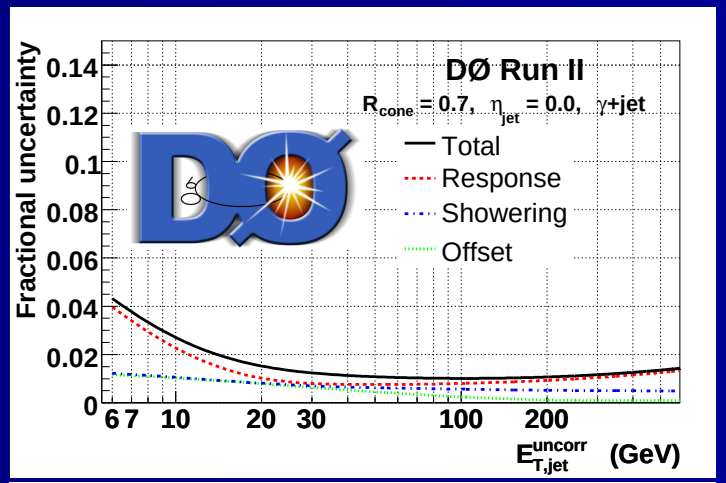


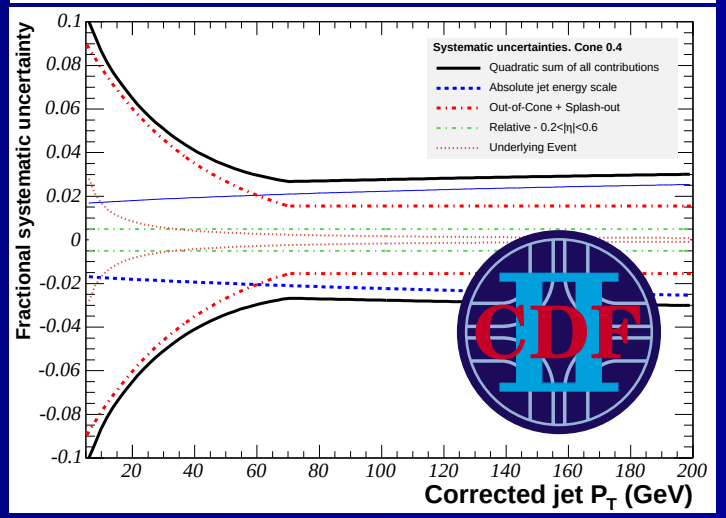
Jets

- Reconstruct jets using iterative cone algorithm with mid-points ($\mathcal{R} = 0.7$)
- Calibrate jet energies to particle level
  - zero and minimum bias events
  - single particles
  - γ+jet events
  - Z+jet events
  - dijet events
  - simulation
- Correct to parton level (CDF)
- Correlation matrix (DØ)







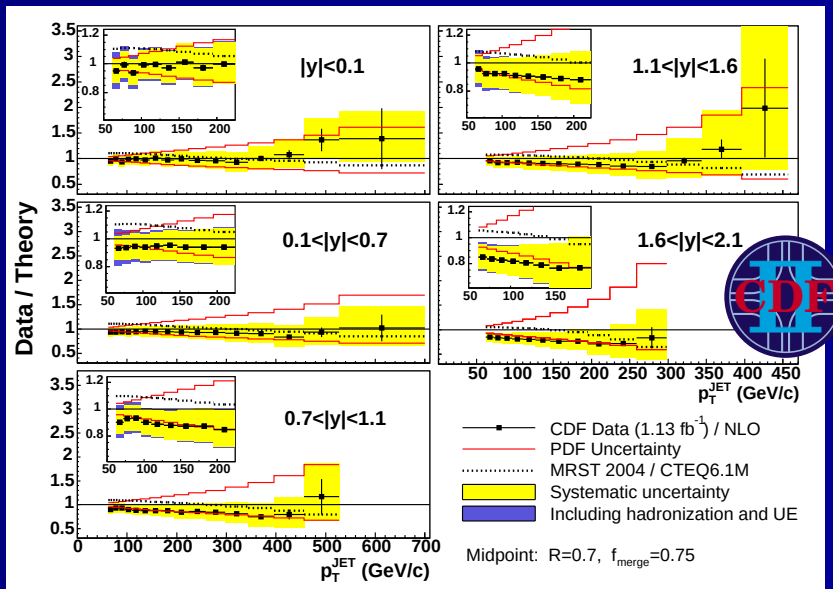


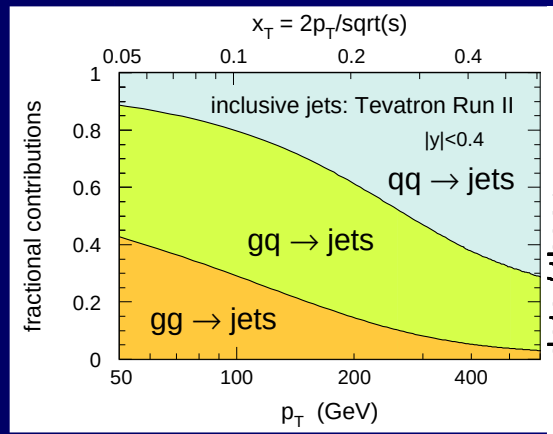
Inclusive Jet Production

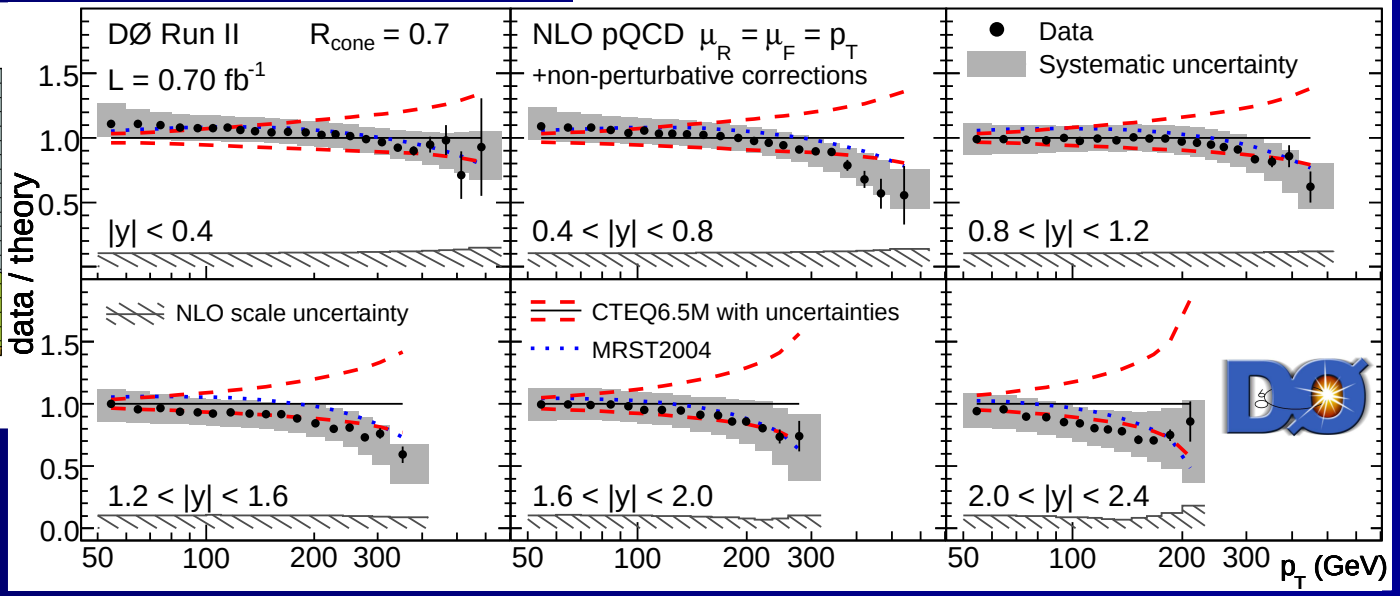
Inclusive jet production tests pQCD and is sensitive to the gluon distribution and to new physics.

Important to measure cross section over wide rapidity range to both constrain gluon PDF and maintain sensitivity to new physics.

These measurements are important inputs in the current round of global PDF fits.





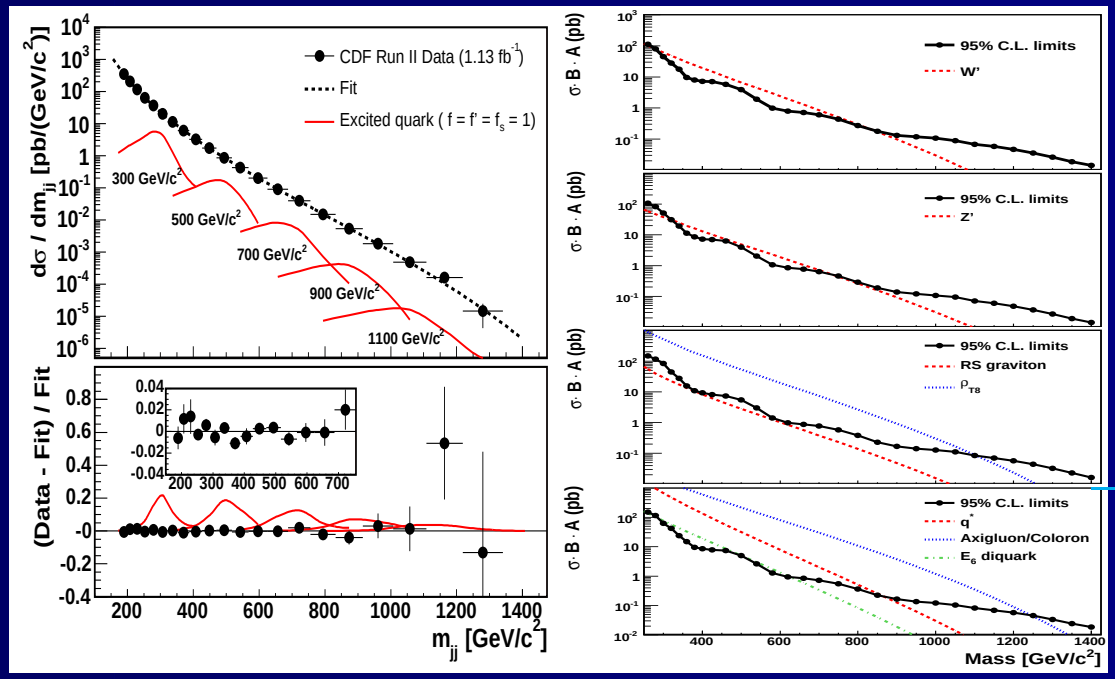


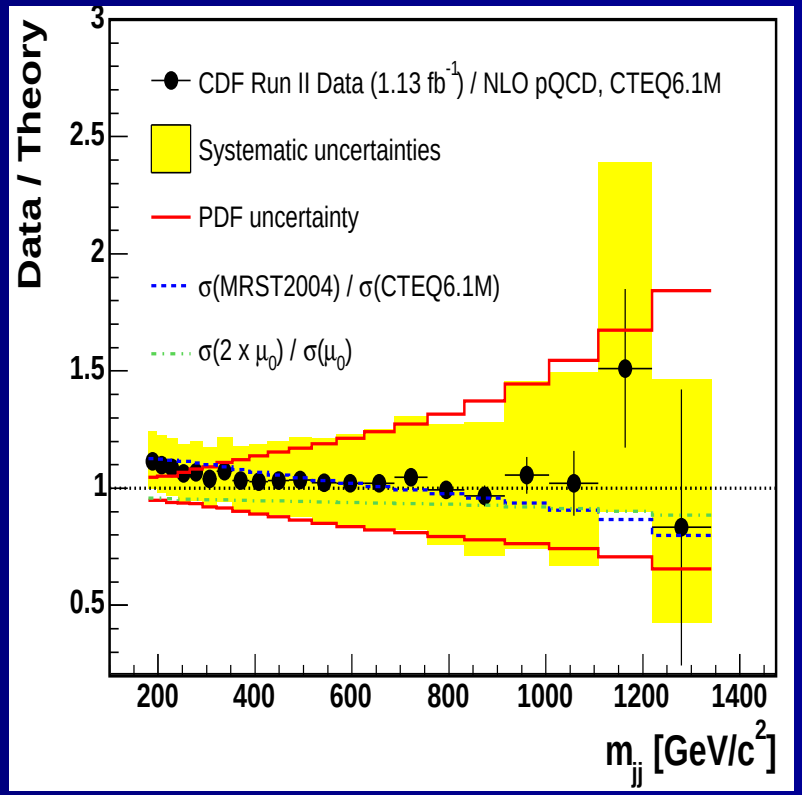
PRL 101, 062001 (2008) [DØ]

PRD 78, 052006 (2008) [CDF]

Dijet Mass Distribution

Dijet mass distributions test pQCD and have sensitivity to the presence of new physical phenomena as many models predict dijet resonances (width dominated by detector resolution).





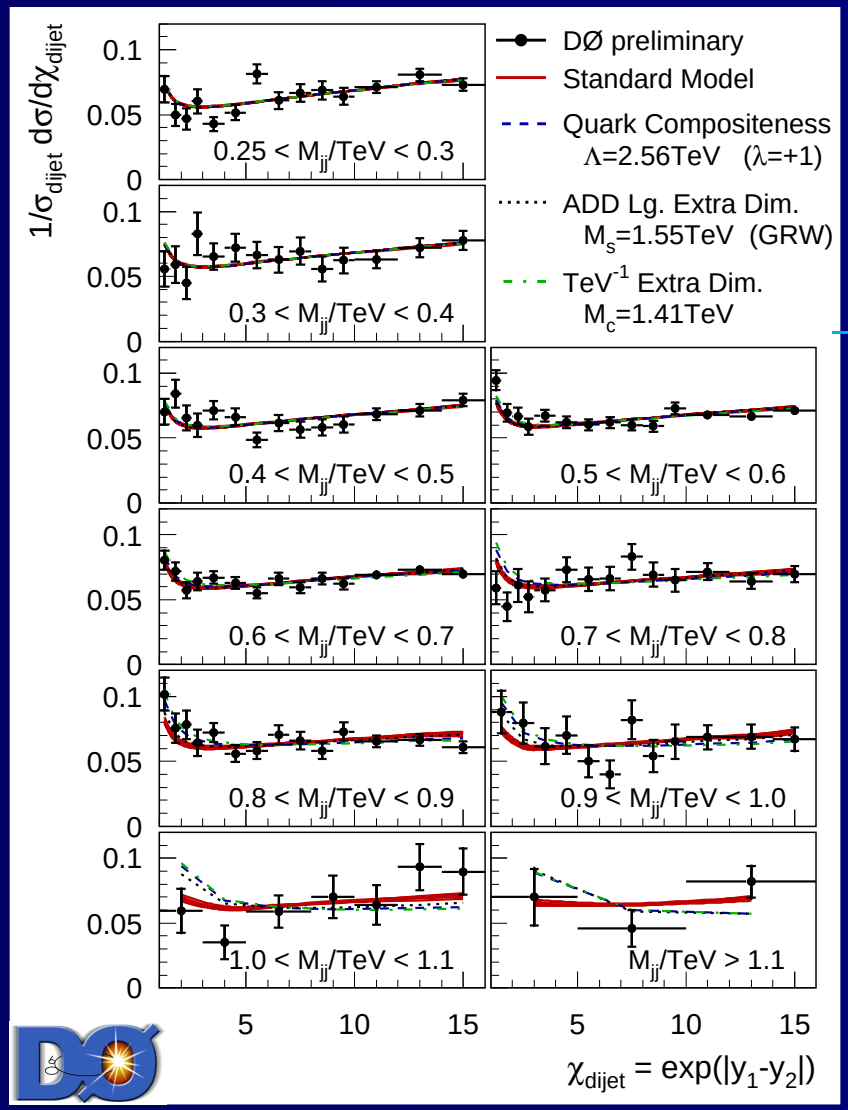
Observed Exclusion	Model
280 — 840 GeV	W' (SM couplings)
320 — 740 GeV	Z' (SM couplings)
260 — 870 GeV	Excited quark (SM couplings)
260 — 1100 GeV	Color-octet technirho
260 — 1250 GeV	Axigluon & flavor-universal coloron
290 — 630 GeV	$E6$ diquark

No significant indication of resonant structure in dijet mass spectrum has been observed.

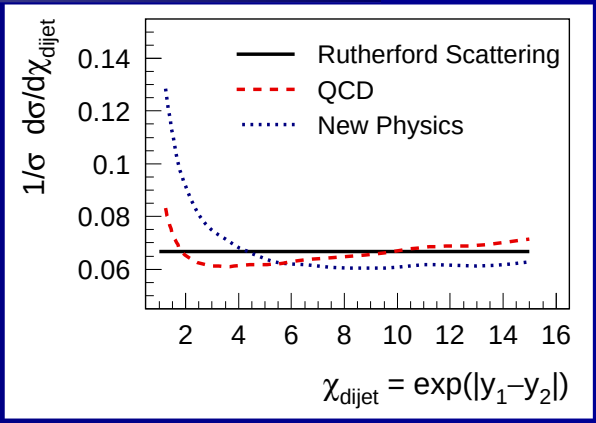
hep-ex/0812.4036 [CDF]

Dijet χ Distribution

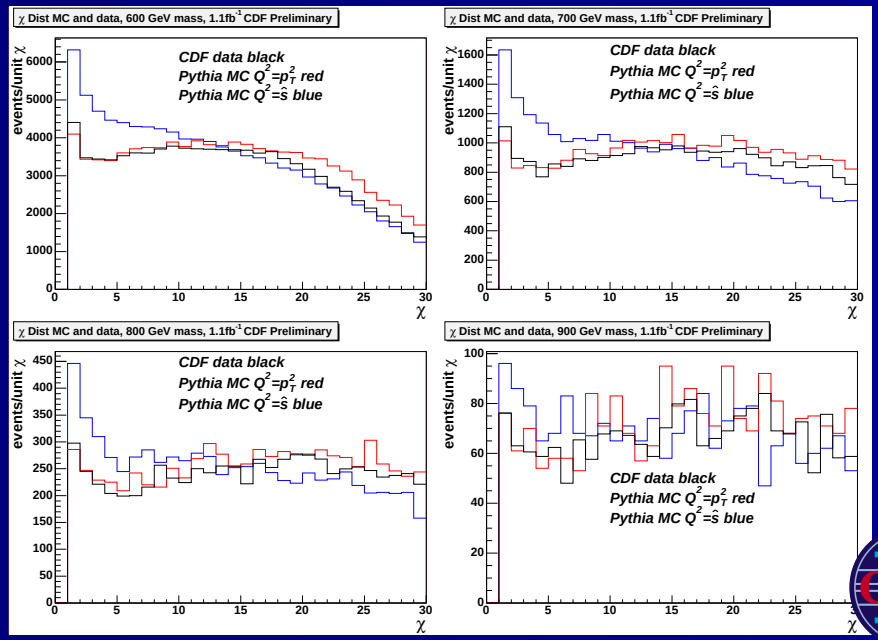
Some models include contact interactions. . . but none are observed.



$$\chi_{\mathrm{dijet}} = e^{|y_1 - y_2|}$$



Observed Exclusion	Model
(DØ) $\Lambda > 2.56$ TeV (CDF) $\Lambda > 2.4$ TeV	quark compositeness
$M_S = 1.55$ TeV	ADD lg. Extra Dim. (GRW)
$M_c = 1.41$ TeV	TeV^{-1} Extra Dim.

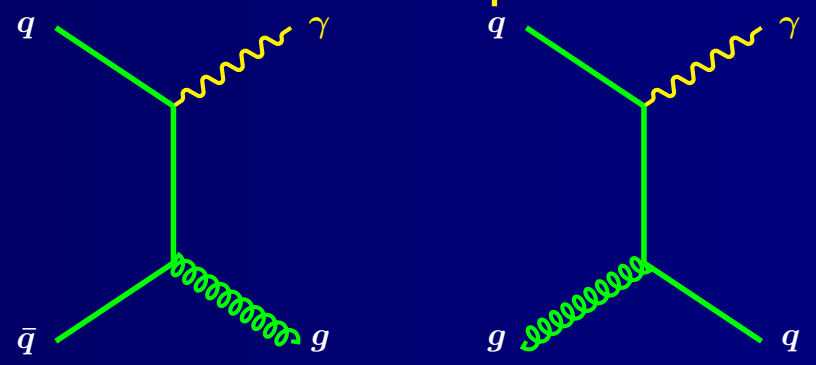


Direct Photon Production

Direct photon production is sensitive to the gluon distribution:

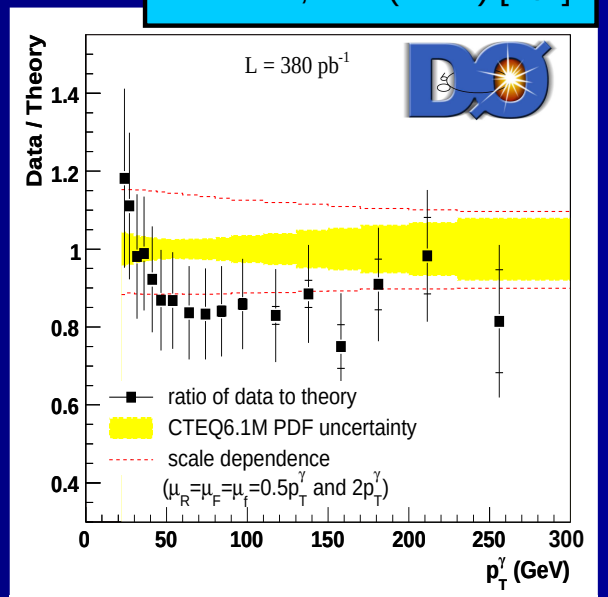
- only two diagrams contribute at leading order:

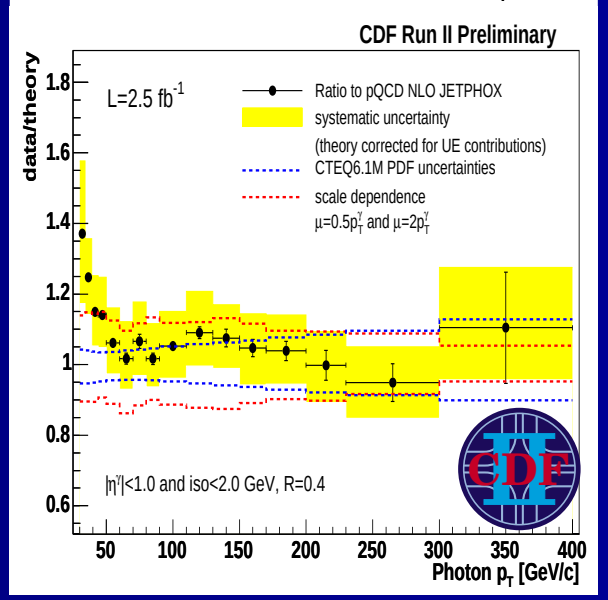
Annihilation Compton Scattering



- important higher-order diagrams include diphoton production and fragmentation diagrams ($q \longrightarrow \gamma$)
- backgrounds significant but measurable

PLB 639, 151 (2006) [DØ]

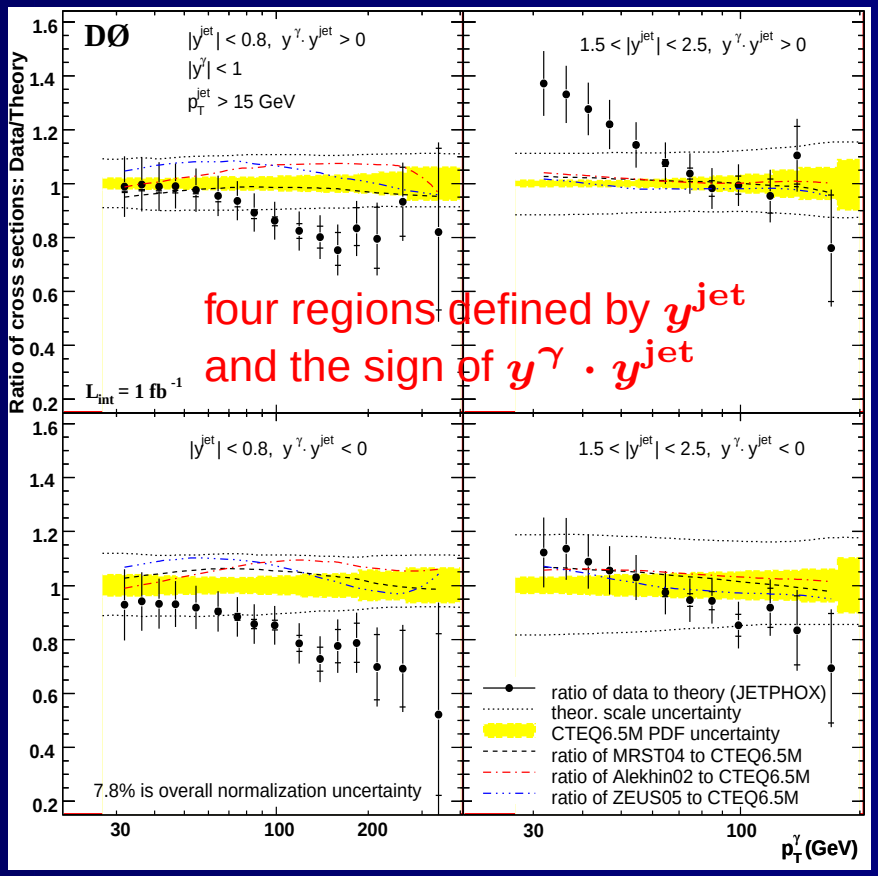


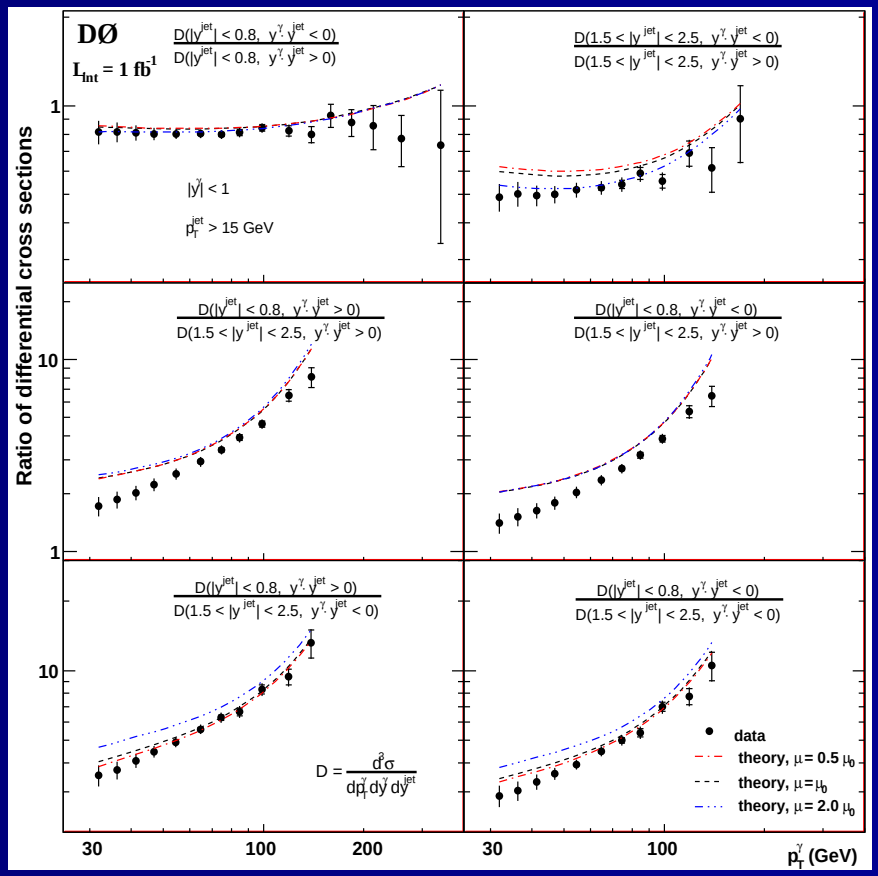


Theory agrees with data within uncertainties but discrepancy in shape similar to other experiments (CDF Run I, UA2, E706, . . .)

Photon+Jet Production

Measuring isolated photons with associated jet production increases sensitivity to the gluon distribution.





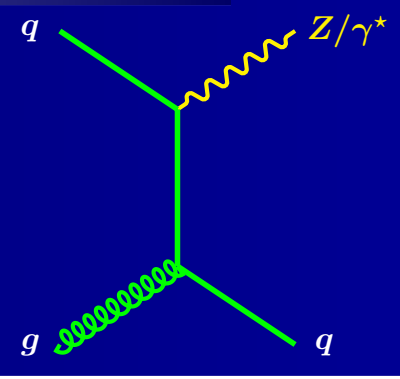
Disagrees in shape like inclusive results; also significant disagreement in ratios of one region to another.

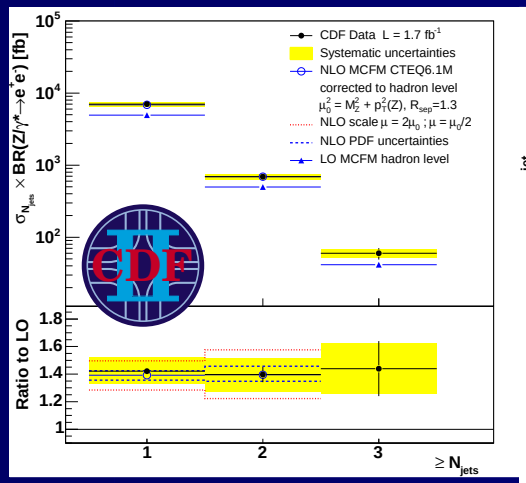
PLB 666, 2435 (2008) [DØ]

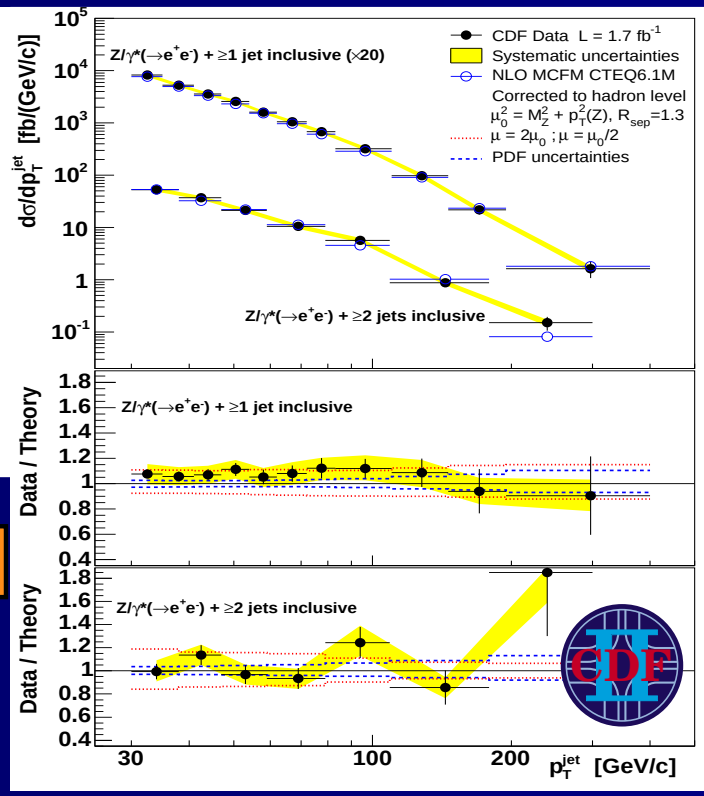
Z+Jet Production

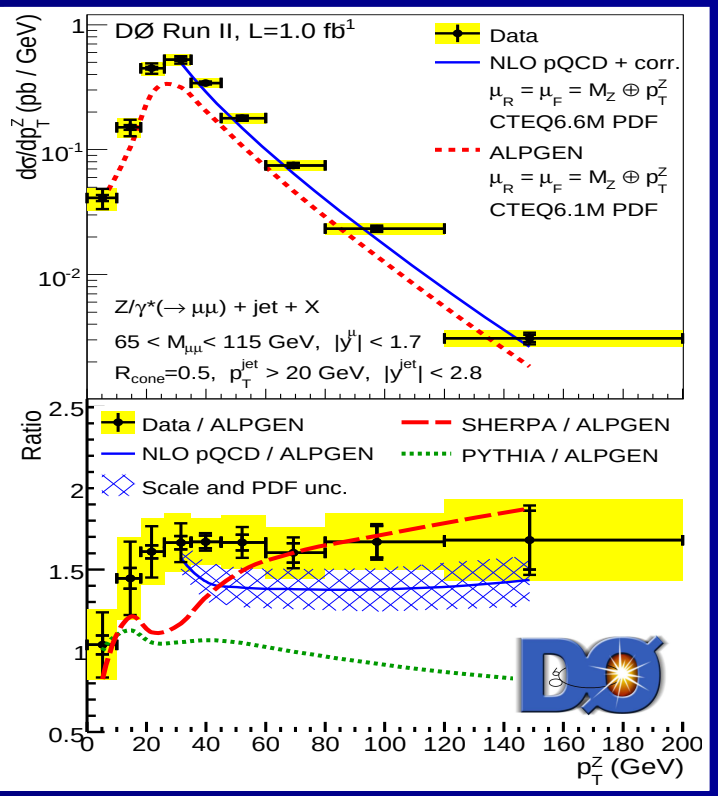
Z+jet production similar to γ+jet except that the scale is dominated by M_Z:

- tests NLO pQCD, ME+PS, and event generators
- sensitive to the gluon PDF
- important background in searches for new physics









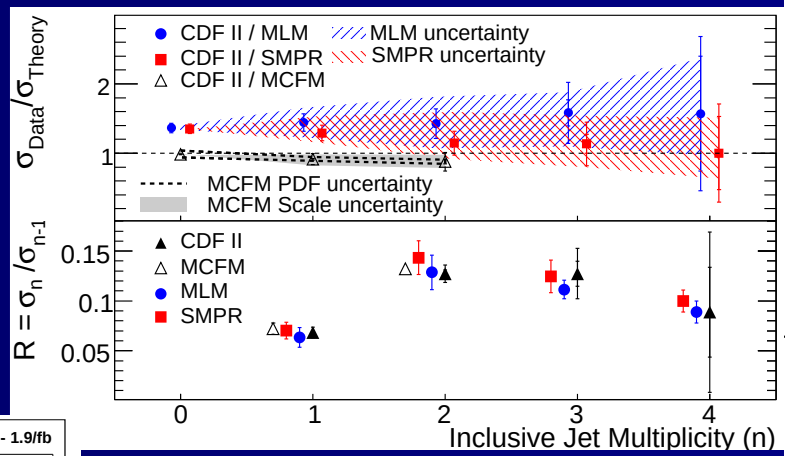
PRL 100, 102001 (2008) [CDF]

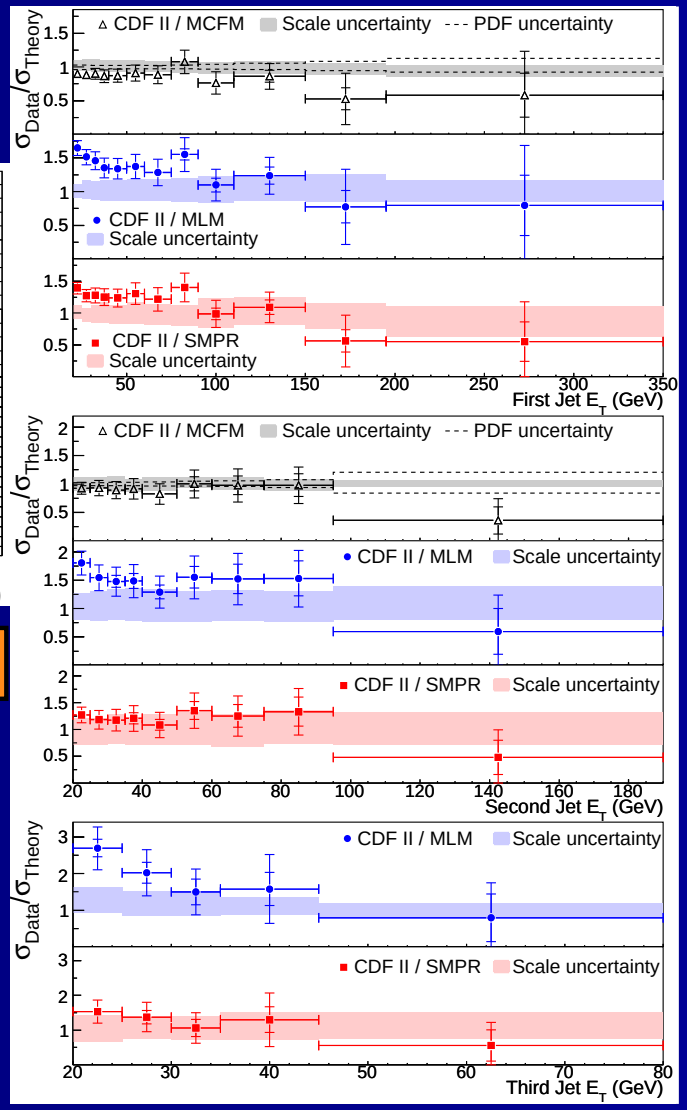
PLB 658, 112 (2008) [DØ]
PLB 669, 278 (2008) [DØ]

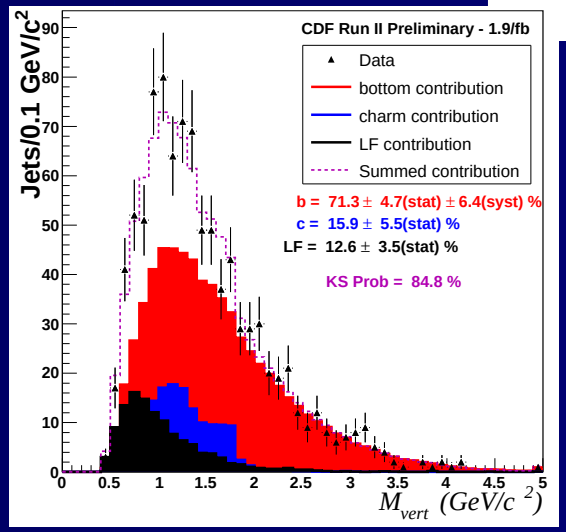
NLO pQCD agrees with data; ME+PS has different shape & norm.

$W+$Jet Production

$W+$jet production tests NLO pQCD and ME+PS, and is an important background for new physics searches.







PRD 77, 011108(R) (2008) [CDF]

Production of $W+bX$ is also important for searches and tests the $g \to b\bar{b}$ splitting function.

$$\sigma_{W+b} = 2.74 \pm 0.27 \pm 0.42\,\mathrm{pb}$$

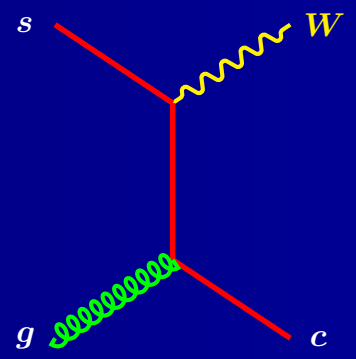
$$\mathrm{ALPGEN} = 0.78\,\mathrm{pb}$$

NLO pQCD agrees with data; ME+PS has diff. normalization

$W + c$ Production

$W + c$ jet production probes the strange PDF.

The jets are muon-tagged and the signal extracted from opposite-sign same-sign subtraction.

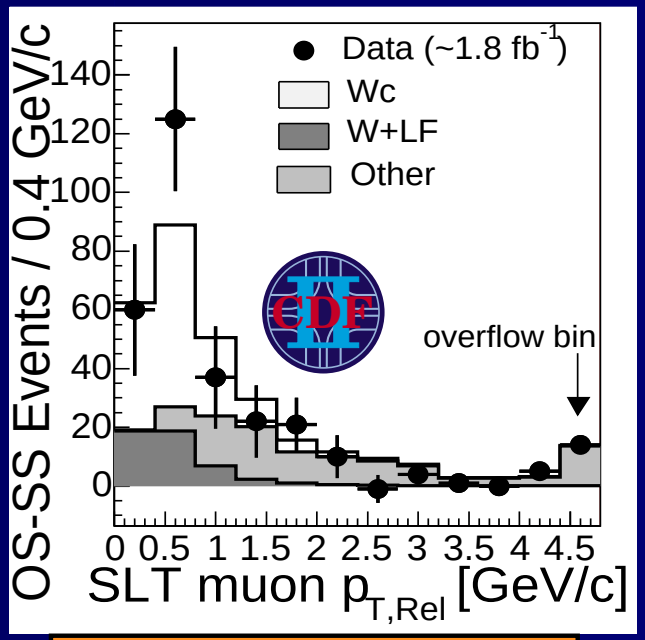


$$\sigma_{W+c} = 9.8 \pm 2.8^{+1.4}_{-1.8} \pm 0.6\ \mathrm{pb}$$

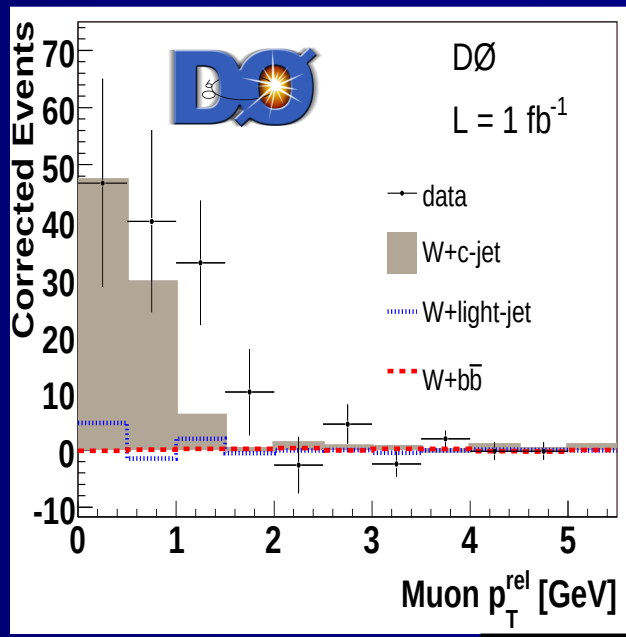
$$\mathrm{NLO} = 11^{+1.4}_{-3.0}\ \mathrm{pb}$$

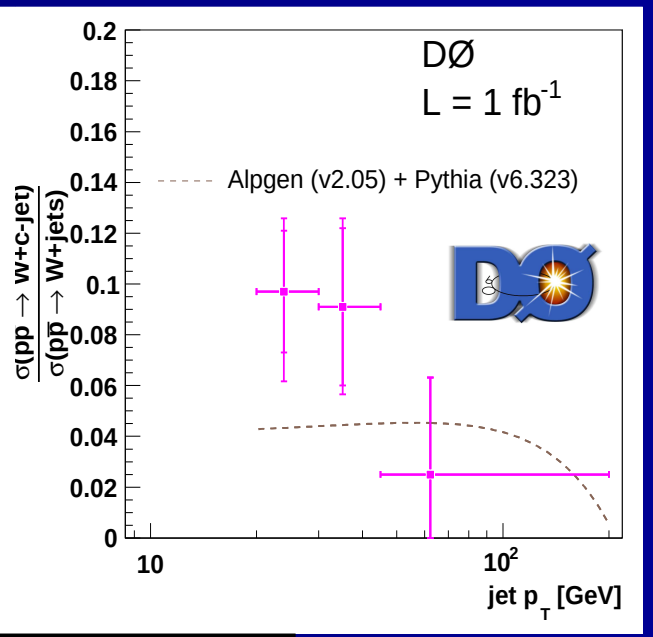
$$\frac{\sigma_{W+c}}{\sigma_{W+\mathrm{jet}}} = 0.074 \pm 0.019^{+0.012}_{-0.014}$$

$$\mathrm{ALPGEN} = 0.044 \pm 0.003$$



PRL 100, 091803 (2008) [CDF]



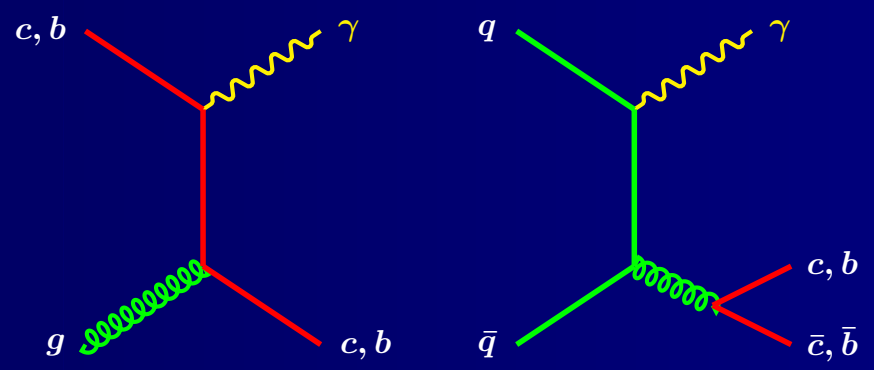


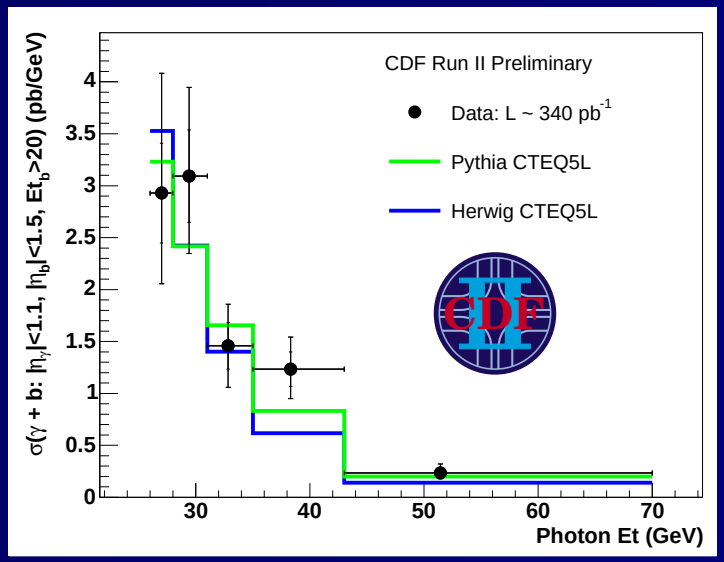
PLB 666, 23 (2008) [DØ]

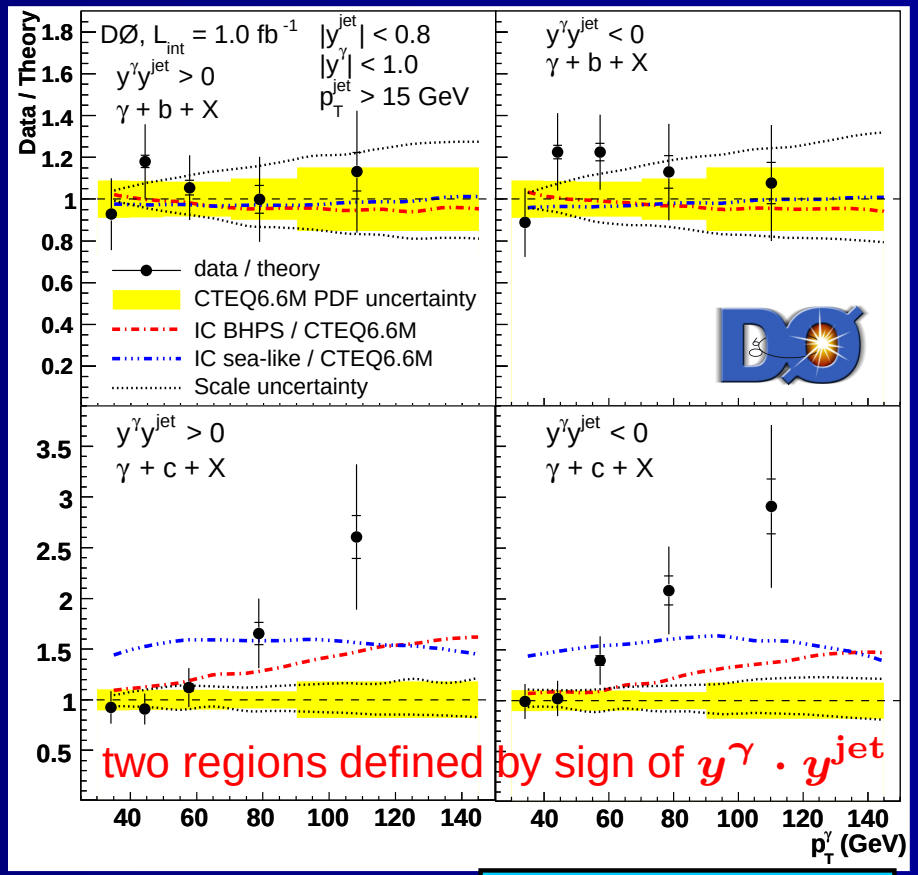
NLO pQCD agrees with data

$\gamma + c/b$ Production

The heavy-flavor content of the proton can be probed in γ+jet events where the jets are flavor tagged.







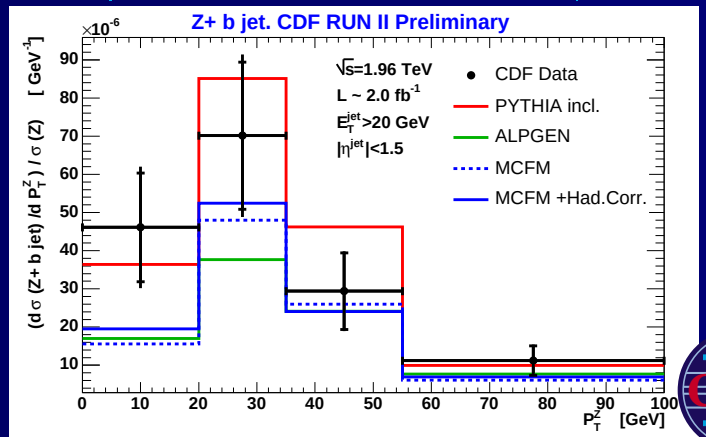
hep-ex/0901.0739 [DØ]

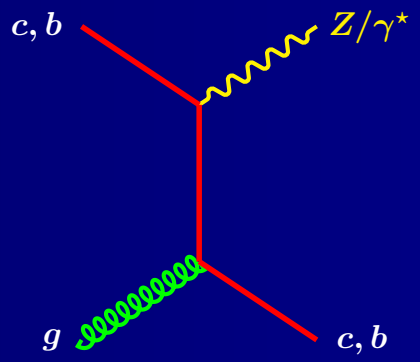
NLO pQCD agrees with $\gamma + b$ jet measurements, but $\gamma + c$ jet data exceeds expectation at high p_T.

$Z + b$ Production

$Z + b$ jet is also sensitive to the b PDF and is an important background in searches for new physics.

	Observable	Data	NLO	PYTHIA	ALPGEN	HERWIG
CDF	$\sigma(Z + b\,\text{jet})$	$0.86 \pm 0.14 \pm 0.12$ pb	0.53 ± 0.08 pb			
	$\sigma(Z + b\,\text{jet})/\sigma(Z)$	$(0.336 \pm 0.053 \pm 0.041)\%$	$(0.23 \pm 0.03)\%$	0.35%	0.21%	0.21%
	$\sigma(Z + b\,\text{jet})/\sigma(Z + \text{jet})$	$(2.11 \pm 0.33 \pm 0.34)\%$	$(1.77 \pm 0.27)\%$	2.18%	1.45%	1.24%
DØ	$\sigma(Z + b\,\text{jet})/\sigma(Z + \text{jet})$	$(2.3 \pm 0.4^{+0.2}_{-0.8})\%$	$(1.8 \pm 0.4)\%$			

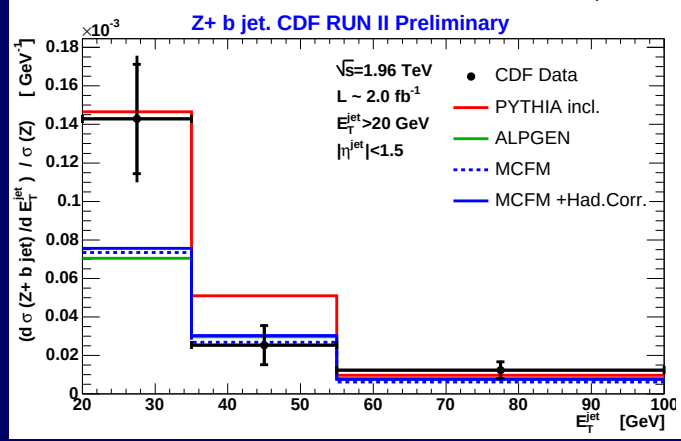


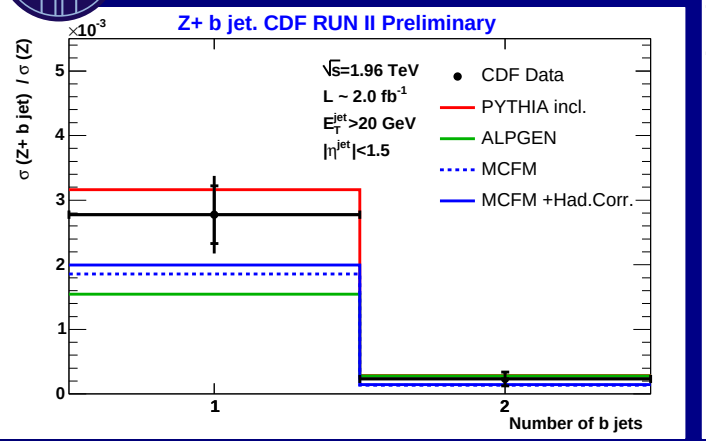


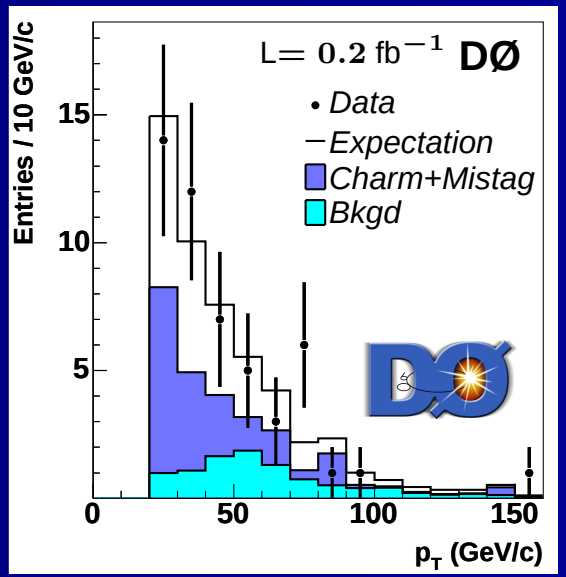
NLO pQCD slightly low compared to data

hep-ex/0812.4458 [CDF]

PRL 94, 161801 (2005) [DØ]

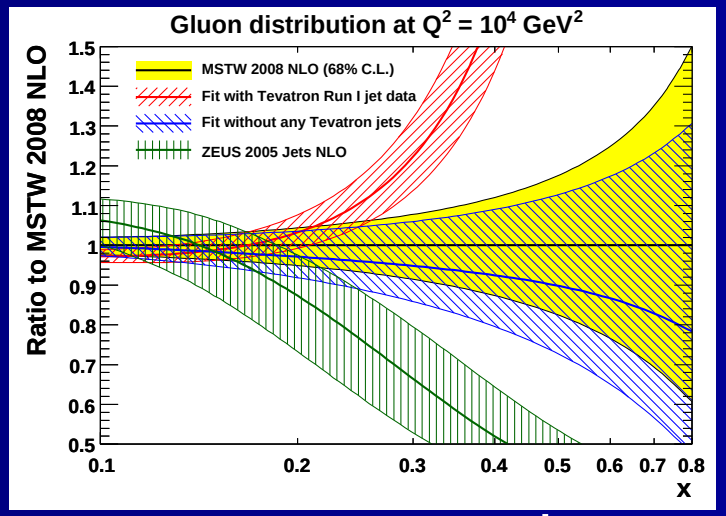






Conclusions

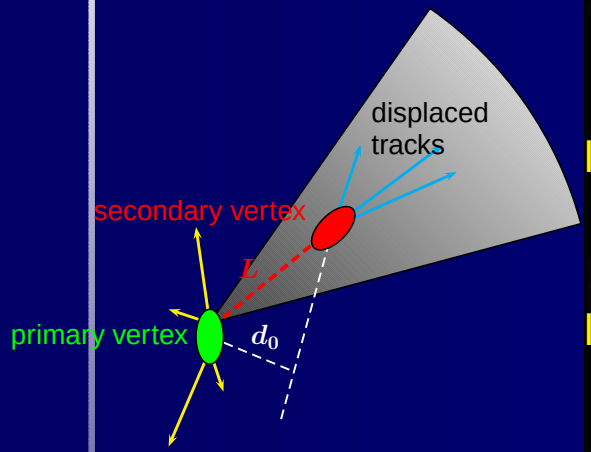
- The Tevatron program has a rich tapestry of hard QCD measurements — more than can be described in this talk.
- Tevatron jet measurements are currently being incorporated into the next generation of global PDF fits.
- We have not seen signs of new physical phenomena with jets.
- Direct photon results from the current Tevatron run show similar shapes with respect to theory as seen with earlier measurements at the Tevatron, SppS, ISR, . . .
- NLO pQCD agrees with $Z+$jet and $W+$jet measurements, however, ME+PS models disagree in both normalization and shape.
- The b content of the proton is well described by current PDF, however, theory disagrees with $\gamma + c$ jet data at high p_T.

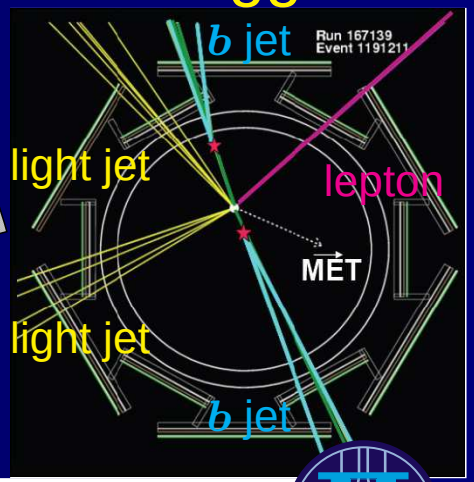


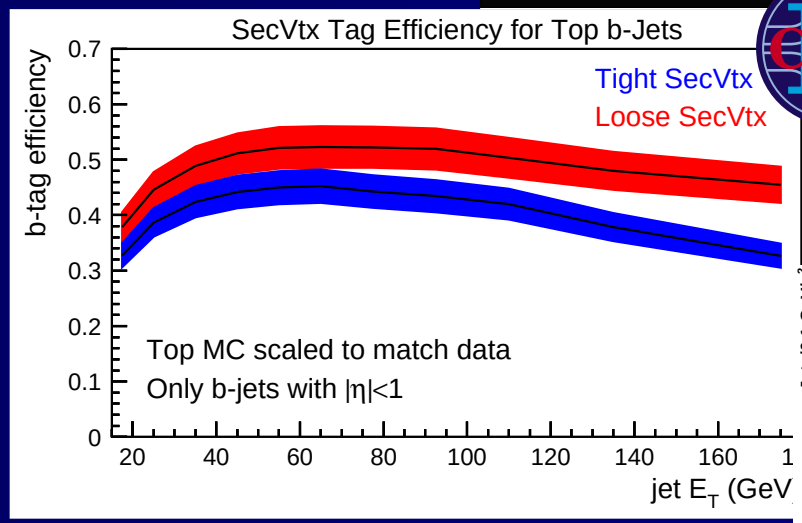
Backup

b Jet Identification

Secondary Vertex Tagger



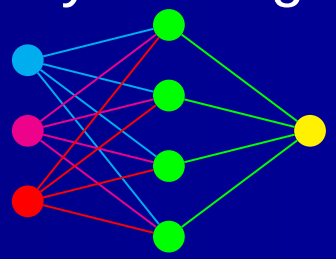


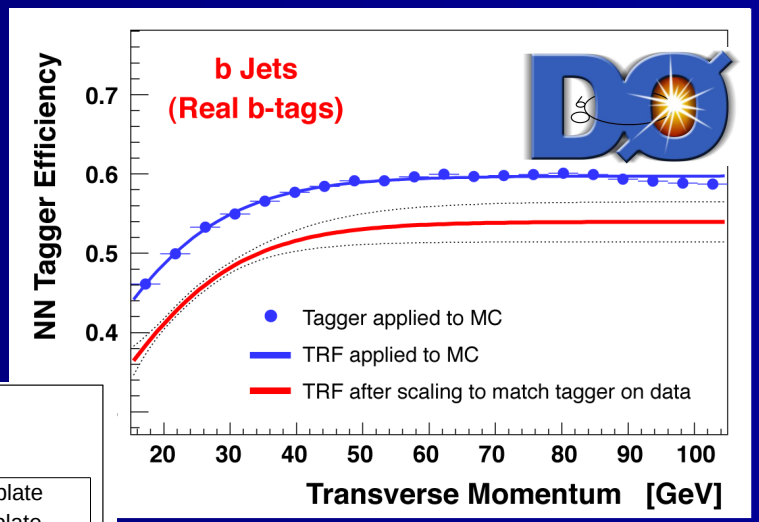


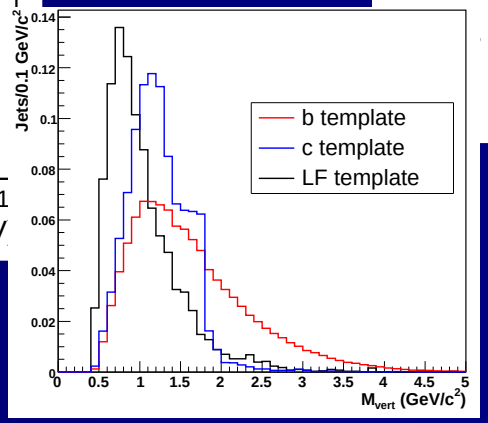
muons-in-jets identify semi-leptonic decays

Neural Network Tagger

improve efficiency by feeding secondary vertex and other information into a neural network





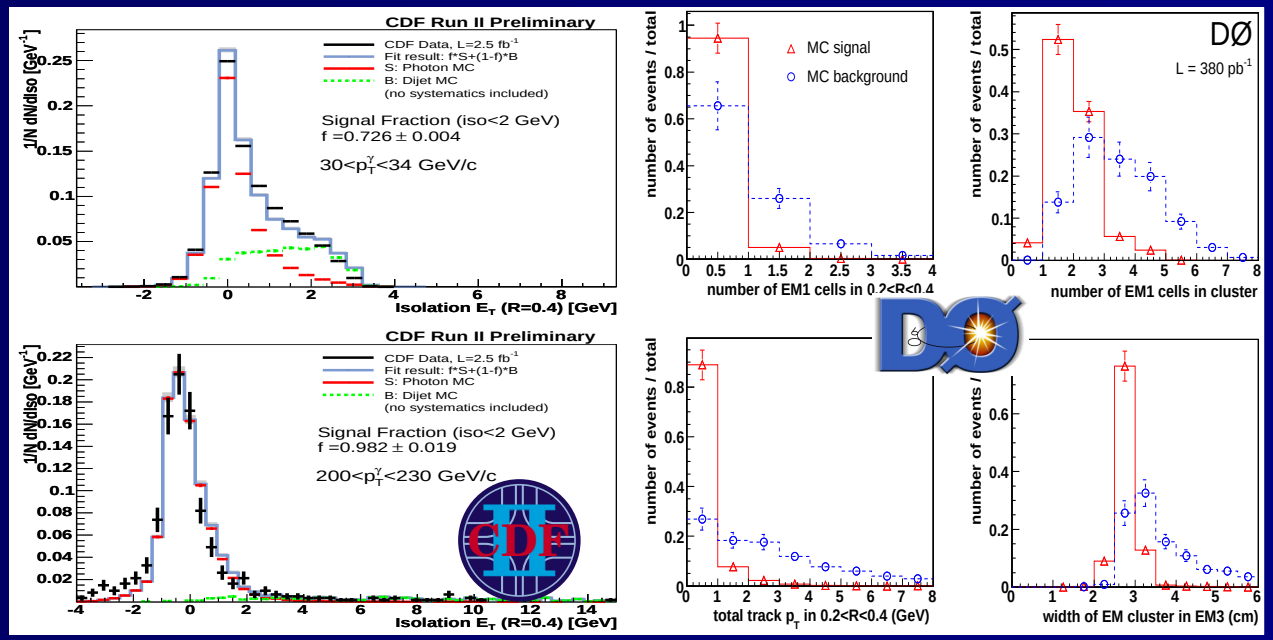


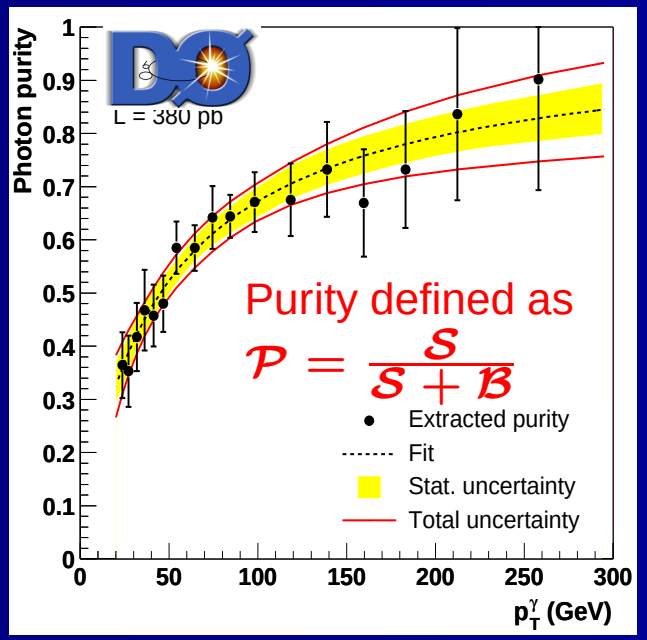
templates in the secondary vertex mass used to fit for c and b fractions

Direct Photon Analyses

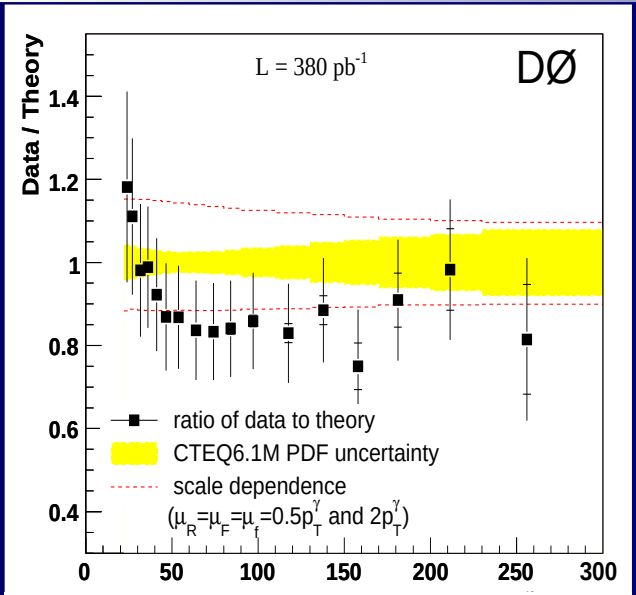
Measuring direct photon production is challenging since the signal is small compared to the potential backgrounds:

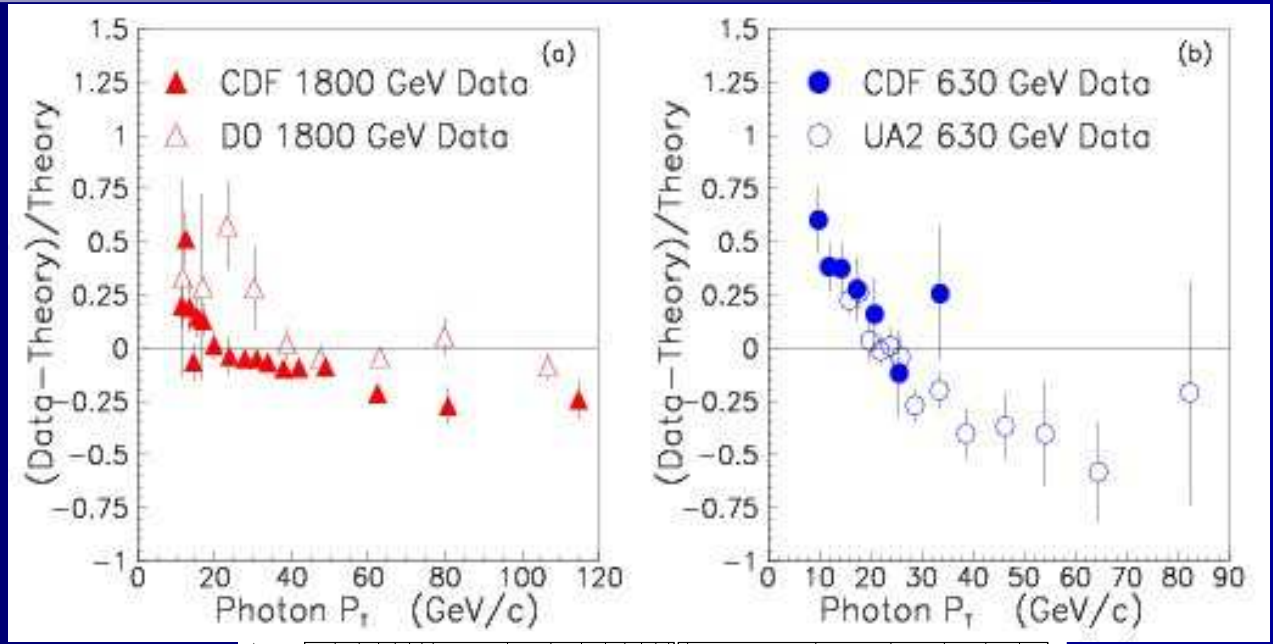
- dominant background are photons from the electromagnetic decay of particles such as π^0 and η mesons
- photon candidates are isolated to suppress background
- characteristics of the reconstructed shower are used to discriminate between signal and background

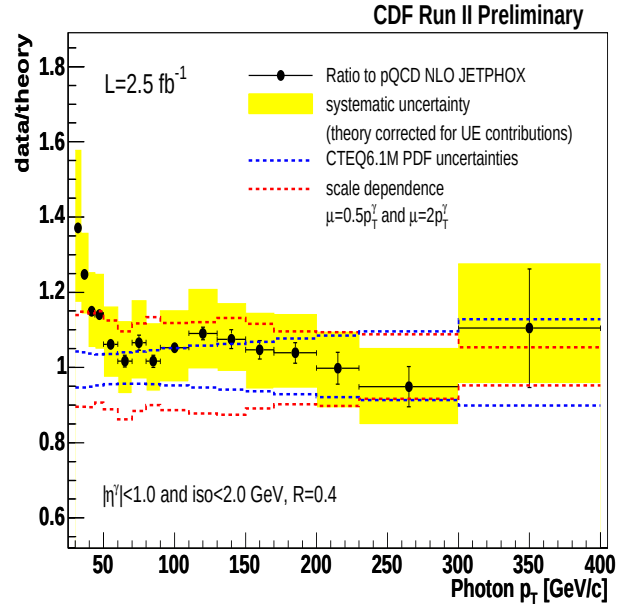


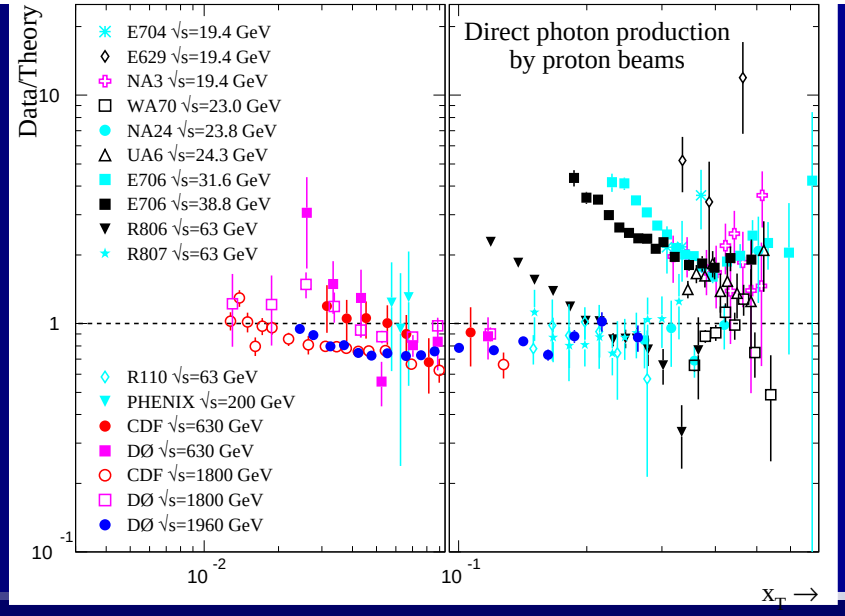


Direct Photon Production

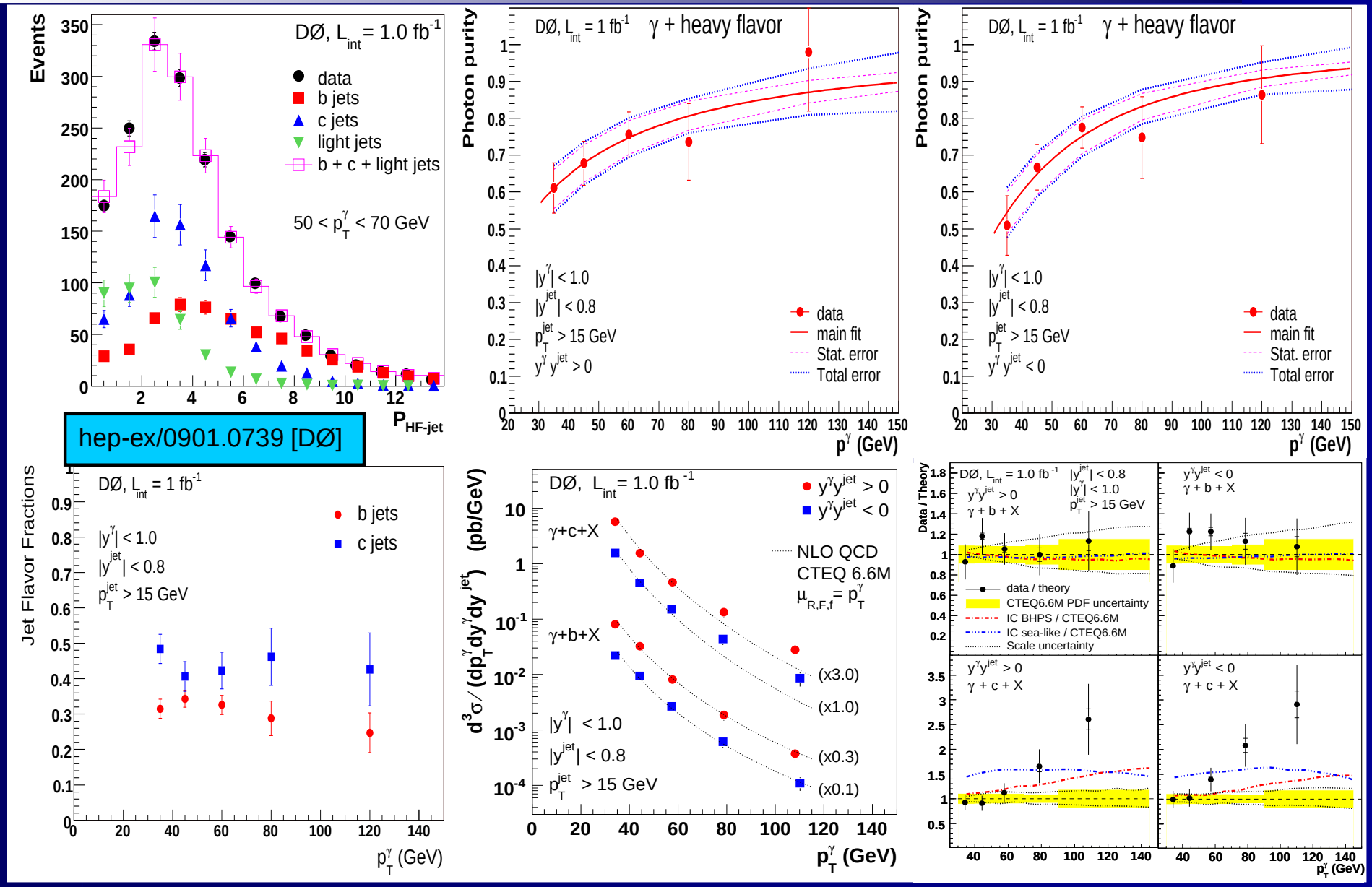






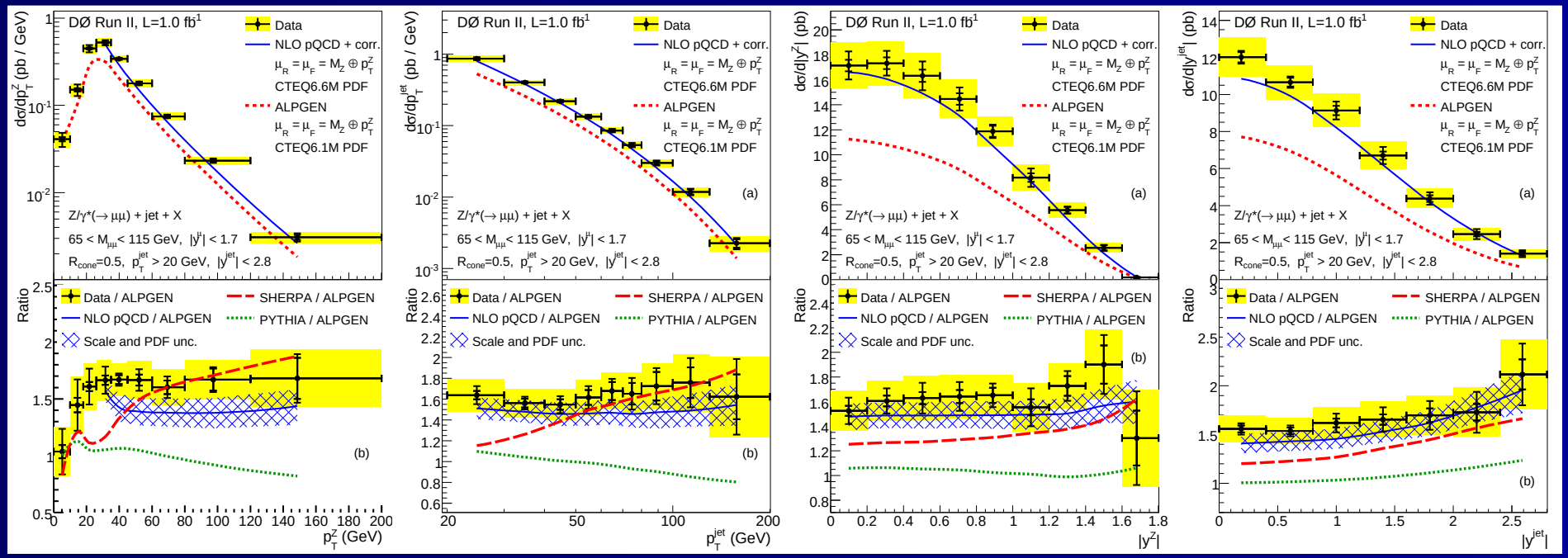


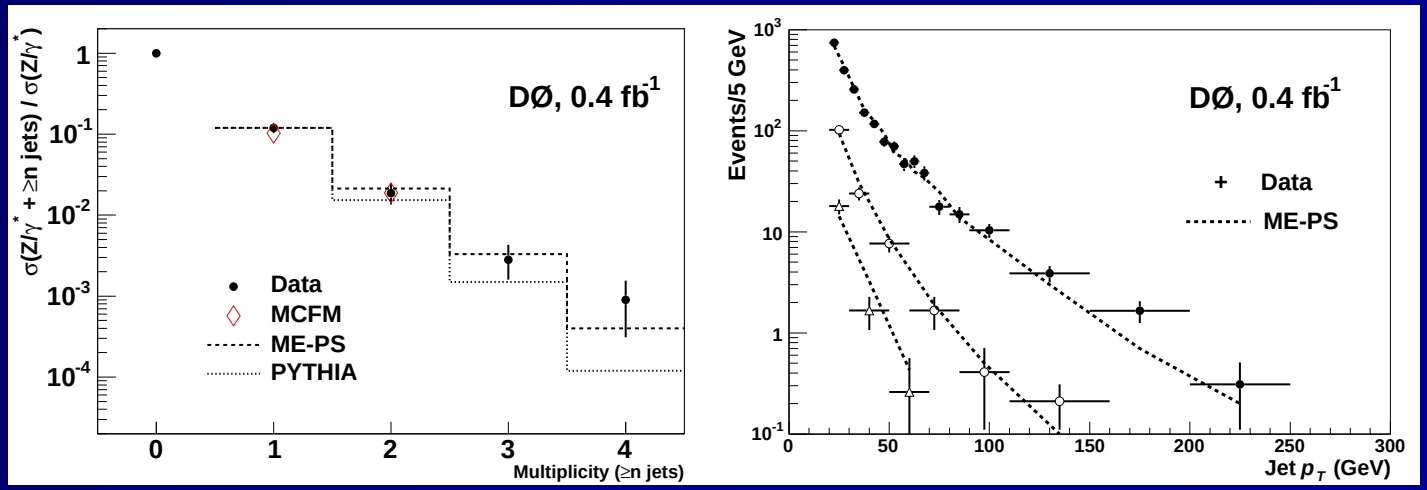
$\gamma + c/b$ Production



hep-ex/0901.0739 [DØ]

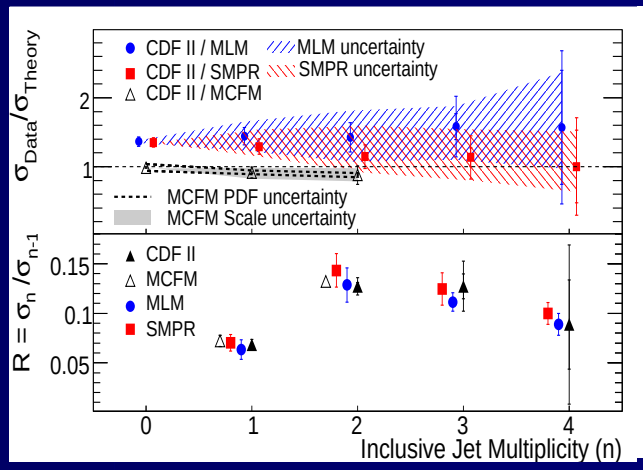
$Z+$Jet Production

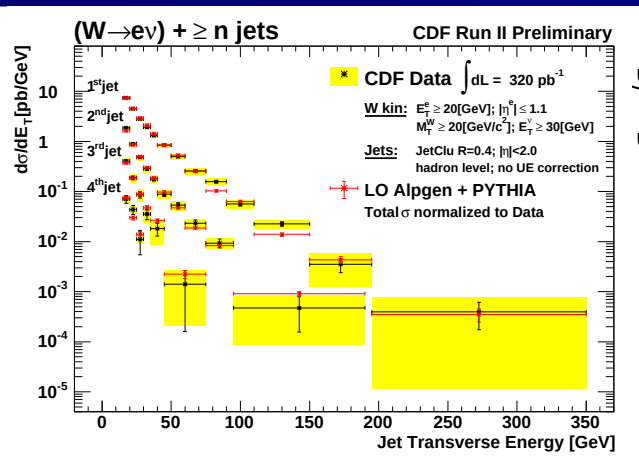


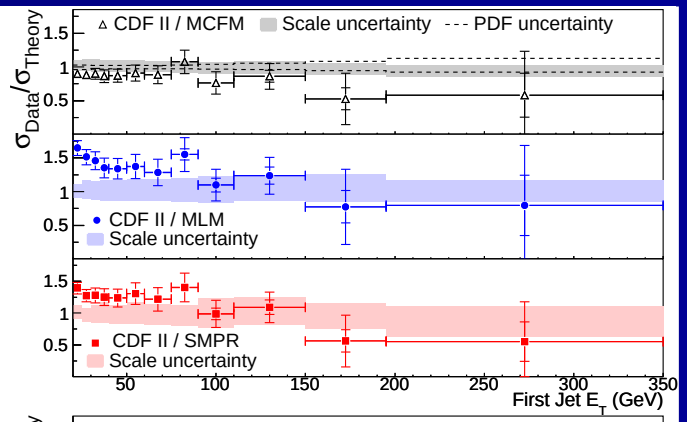
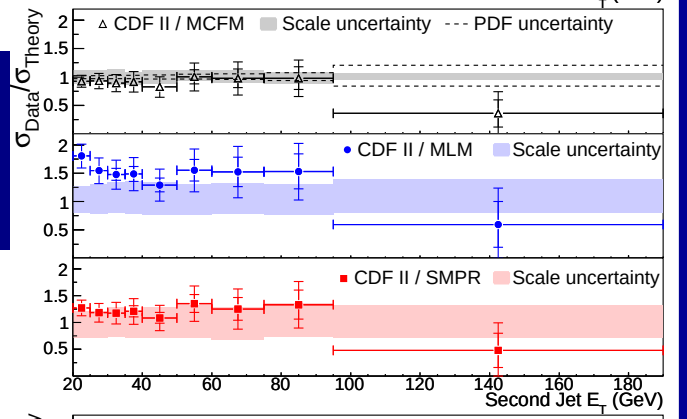
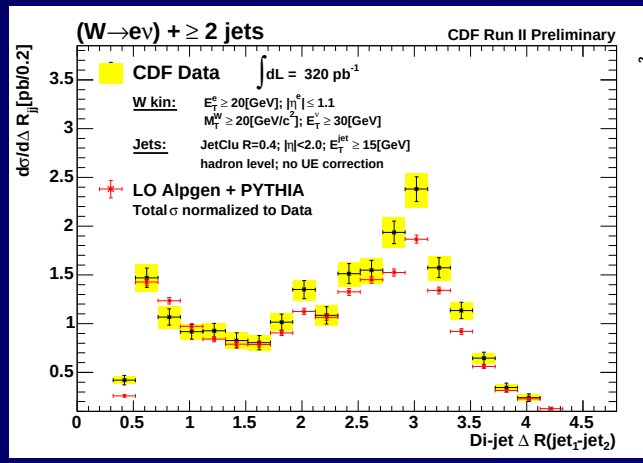
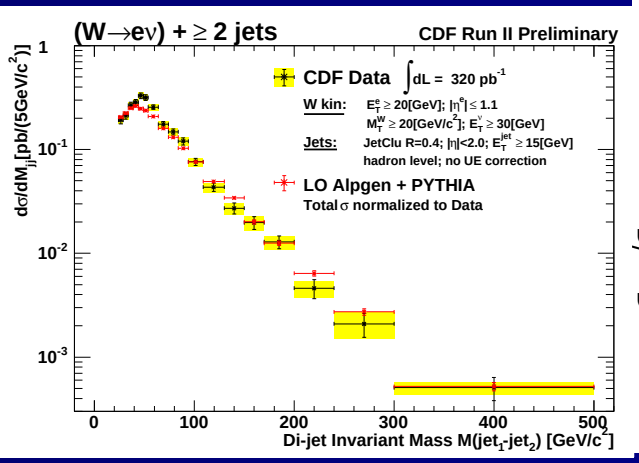
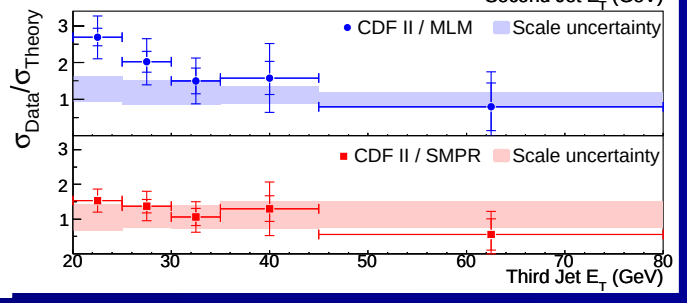


PLB 658, 112 (2008) [DØ]
PLB 669, 278 (2008) [DØ]

W+Jet Production







PRD 77, 011108(R) (2008) [CDF]