QCD Studies at the Tevatron

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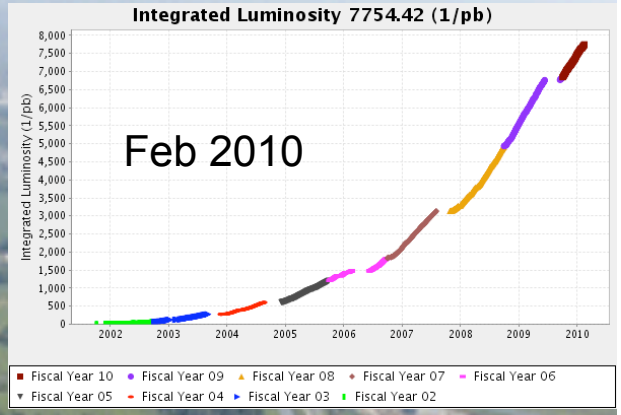
Introduction

The Tevatron is the world highest energy “proton-antiproton” collider ….

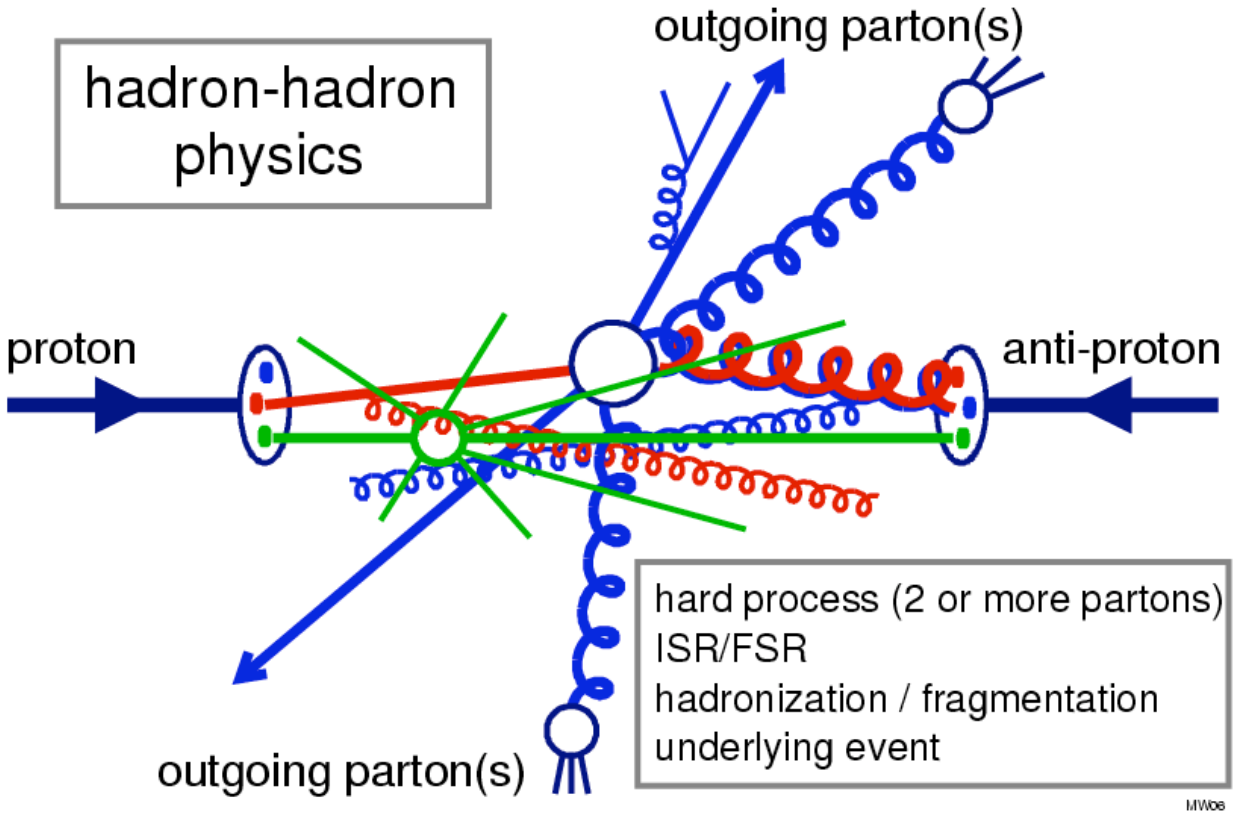
- Located about 30 miles west of Chicago, IL
  - 1.96 TeV in the C.M.
- Data are continuously recorded with very high efficiency (85-90%)
- The machine and the detectors (CDF and D0) are performing very well
  - Both experiments have collected already > 6 fb-1 on tape



- **Measurements are becoming very precise**
  - **Top quark mass known with precision < 2%**
- **New analyses are now looking for the needle in the hay stack**
  - **low cross section phenomena**
  - **The search for Higgs**
  - **Physics beyond the Standard Model**

Still, an hadron machine is the perfect place to test QCD!

QCD at Hadron Colliders

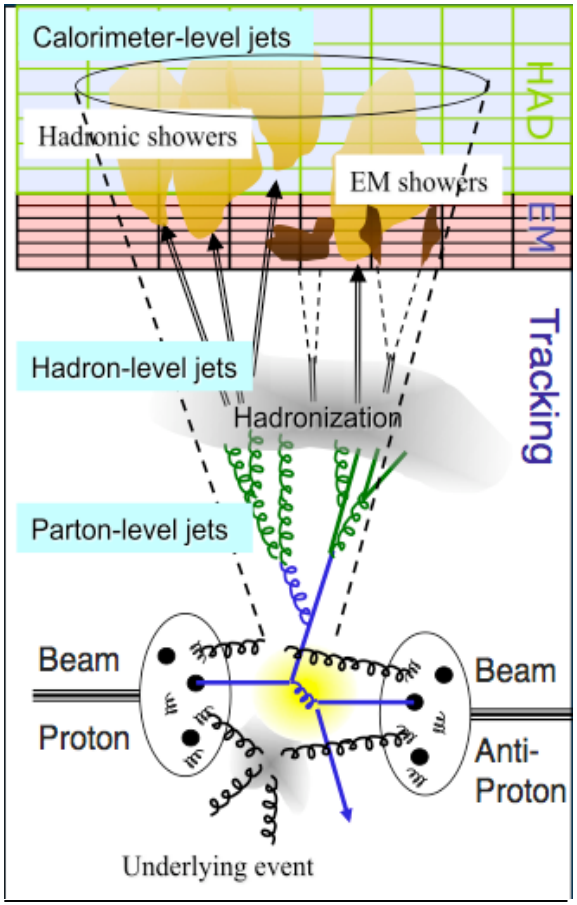


Test of the Standard Model (pQCD)
Search for new physics
Inform/check/tune Monte Carlo and theory predictions

The physics objects

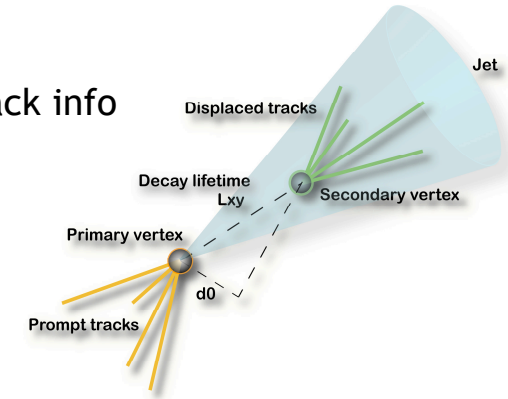
Hadronic jets are reconstructed using several algorithms: Cone,Midpoint, KT etc..

- From the calorimeter measurement to the parton-level jets, via several corrections
- Currently the jet energy scale is the major source of uncertainty (< 3% over the entire jet energy range)

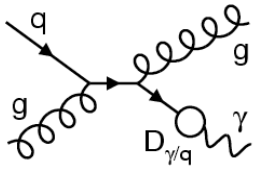


Heavy Flavor-jet identification is implemented via:

- Displaced vertices with L_{xy}/σ cut (CDF)
- Vertex mass separation (CDF)
- Vertex properties and displaced track info combined with NN algorithms



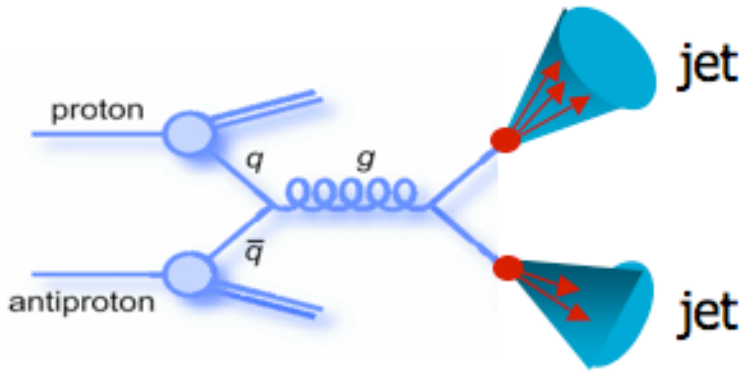
Photons are selected with stringent isolation criteria to minimize QCD fragmentation effects



In This Talk

- Selected topics
  - Jets and dijet inclusive production
    - PDF's constraint and measurement of the strong coupling constant
    - Search for quark substructure in dijet angular distribution
    - Search for new particles decaying into dijets
  - Photons final states
    - Inclusive photon cross section
    - Photon + jet(s)
  - Vector bosons + jet(s)
  - The future outlook: TeV vs LHC

Jets



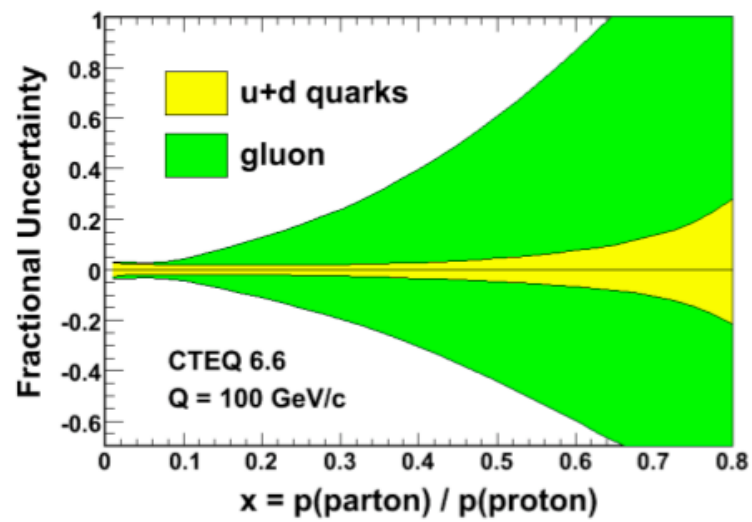
Collimated sprays of particles originating from quark and gluon fragmentation

Jets measurements probes the highest momentum transfer in particle collisions

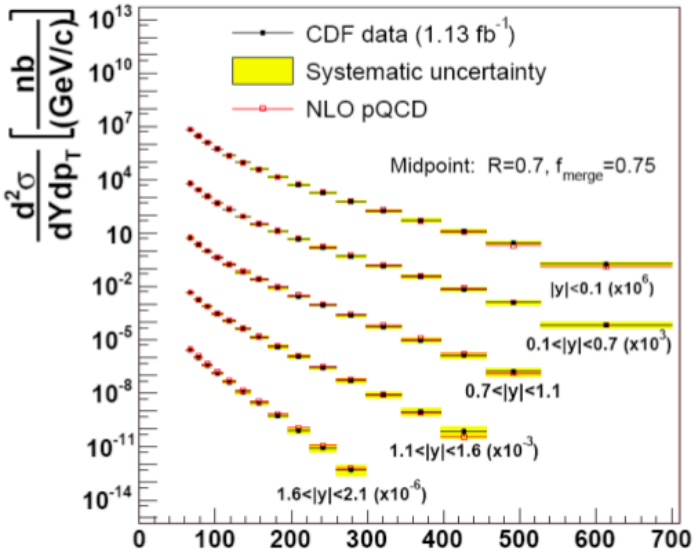
$$d\sigma_{jet} = \sum_a \sum_b \overbrace{f_{a/p}(x_1,\mu_F^2) f_{b/\bar{p}}(x_2,\mu_F^2)}^{\text{PDFs}} \otimes \underbrace{\hat{\sigma}_{a,b}(p_1,p_2,\alpha_s,Q^2/\mu_R^2,Q^2/\mu_F^2)}_{\text{Hard Scatter}}$$

Sensitive to:

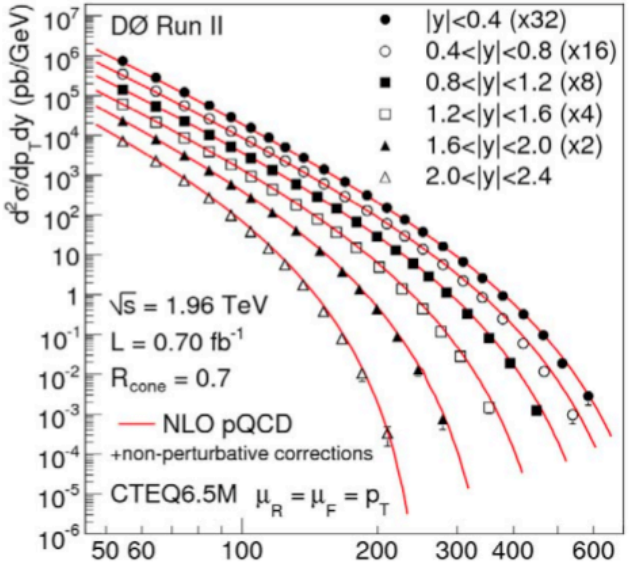
- Hard partonic scattering
- strong coupling constant
- proton's parton content
  → unique sensitivity to high-x gluon
- dynamics of interaction
  - validity of approximations (NLO, LLA, …)
  - QCD vs. new physical phenomena



Inclusive Jet Cross Section



Phys. Rev. D 78, 052006 (2008) p_T (GeV/c)



Phys. Rev. Lett. 101, 062001 (2008) p_T (GeV/c)

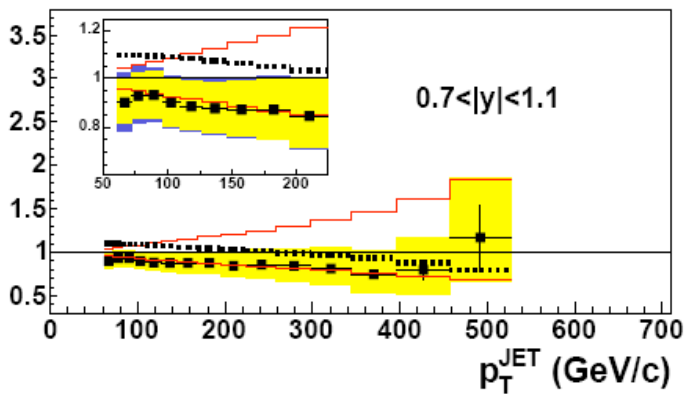
Measurements span over 8 order of magnitude in $d\sigma^2/dp_T dy$

Highest p_T^{jet} > 600 GeV/c

Jet energy calibration ± 1%

➔ ±(5 – 10)% central x-section
➔ ±(10 – 25)% forward x-section

Inclusive Jet Cross Section



CDF Data (1.13 fb^{-1}) / NLO
PDF Uncertainty
MRST 2004 / CTEQ6.1M
Systematic uncertainty
Including hadronization and UE

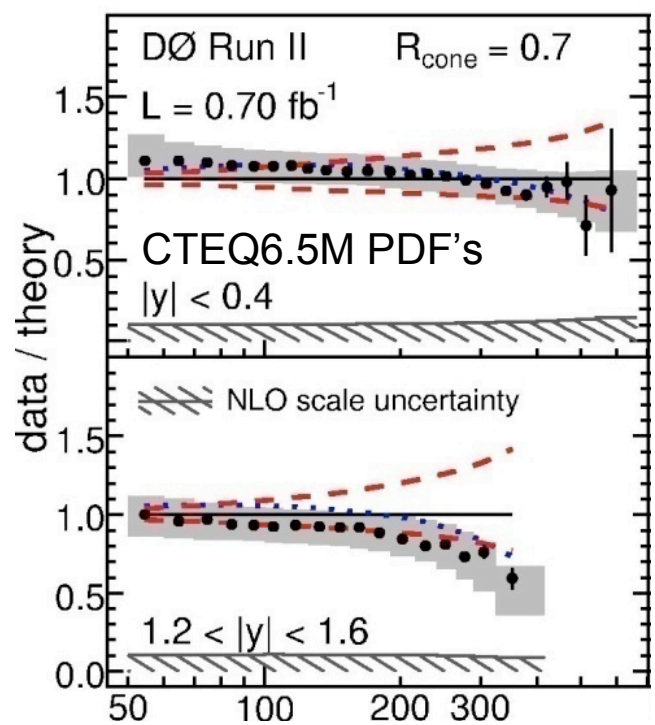
Midpoint: R=0.7, f_{merge}=0.75

Both CDF and D0 measurements are in very good agreement with NLO predictions

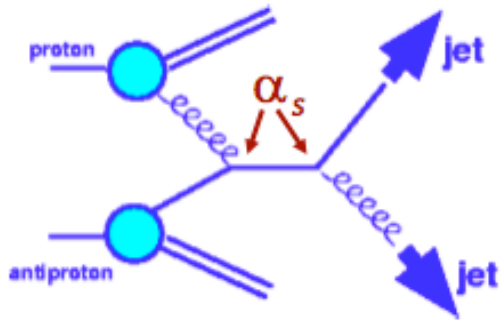
- Precision now exceeds that of PDF uncertainties
- Data can inform the PDF fits: suggestive of softer gluons at high-x

data are used in PDF fits:

- included in MSTW2008 PDFs
- at work: forthcoming CTEQ PDFs

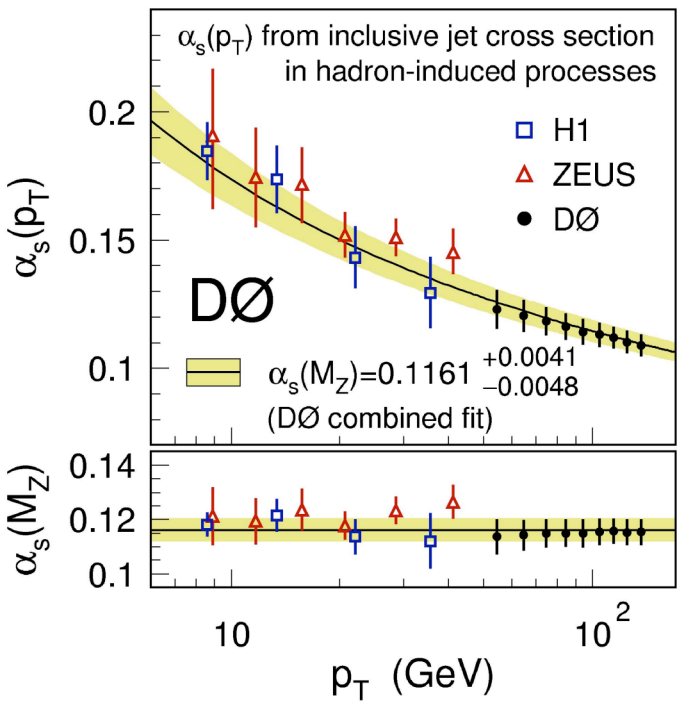


Strong Coupling Constant



Measurement uses the P_T dependence of the jet x-section

- χ^2 minimization of data/theory points
  - 22/110 points in the inclusive jet cross section used
    - $50 < P_T < 145$ GeV/c,
    - high points excluded to minimize PDF uncertainty correlations
- NLO+2 loop thresholds corrections
- MSTW2008NNLO PDF's



Phys. Rev. D 80, 111107 (2009)

$$\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$$

Most precise result at hadron-hadron collider

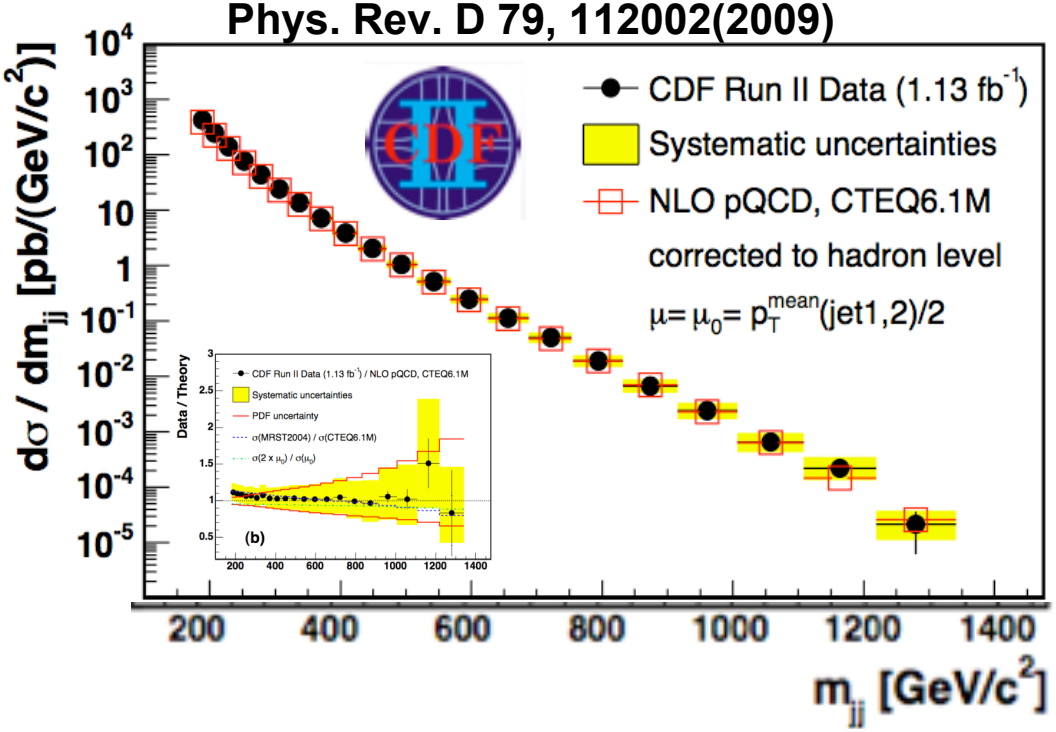
CDF results in Phys. Rev. Lett. 88, 042001

Dijet Mass Spectrum

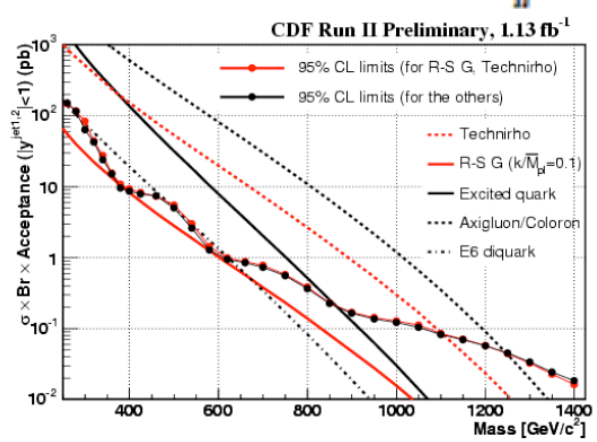
Old fashion mass bump hunt…

- Choose events with two high-p_T jets with rapidity less than 1.0. Look for an excess in the dijet mass spectrum for masses above 180 GeV
- Possible signals include excited quarks, W', Z', and Randall-Sundrum gravitons
- Find functional form of of dijet spectrum in pythia and herwig, fit to data. Look for "bumps" in the data minus fit plot

Phys. Rev. D 79, 112002(2009)



- No significant resonant structure is observed, so limits are set on various models
- Excludes (at 95% CL) excited quarks from 260-870 GeV, W' from 280-840 GeV, and Z' from 320-740 GeV

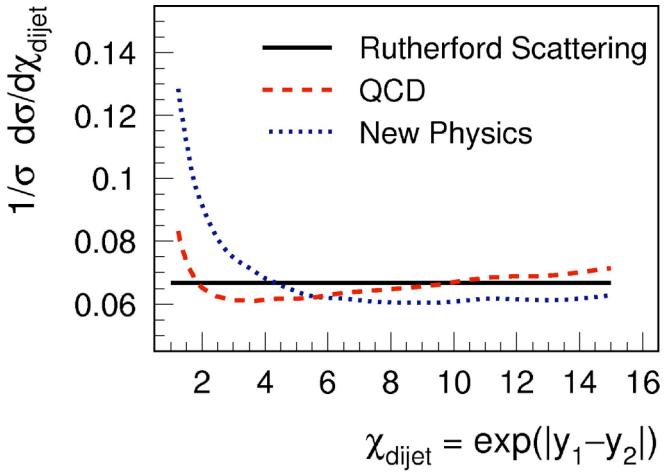


D0 has also a new result out (arxiv: 1002.4594)

Dijets Angular Distribution

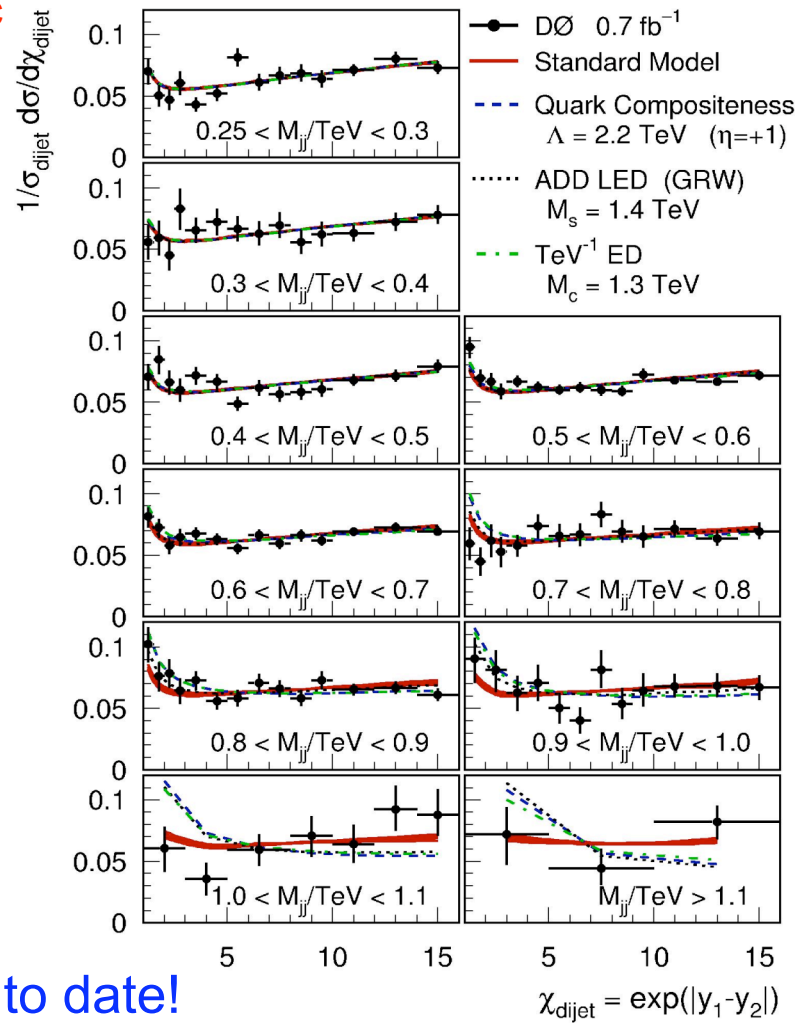
Dijet angular distributions is measured in bins of dijet mass:

- First differential cross section measurement at partonic energies >1 TeV!
- Small experimental and theoretical uncertainties.
- Sensitive to New Physics (95% CL limits)



Consistent with NLO pQCD

Phys. Rev. Lett. **103**, 191803 (2009)



Limits on Compositeness & LED

- Quark Compositeness Λ > 2.9TeV
- ADD LED (GRW) Ms > 1.6 TeV
- TeV-1 ED Mc > 1.6 TeV

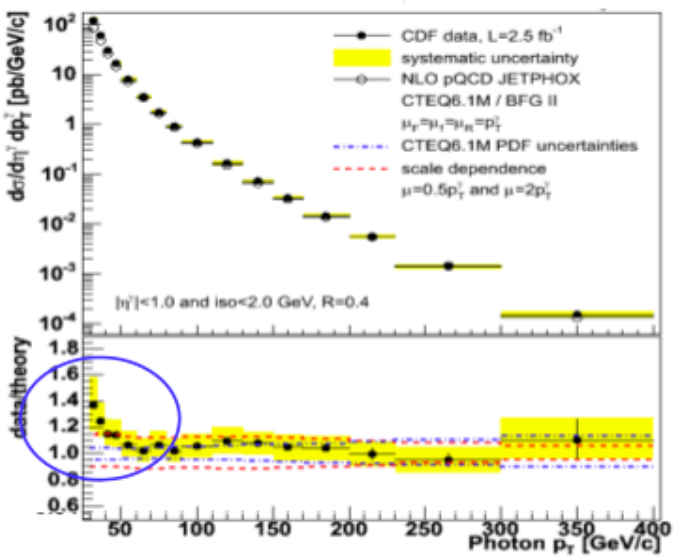
Most stringent limits to date!

Photons

- Inclusive photon cross section

direct photons emerge unaltered from the hard subprocess
→ direct probe of the hard scattering dynamics
→ sensitive to PDFs (gluon!) ...but only if theory works

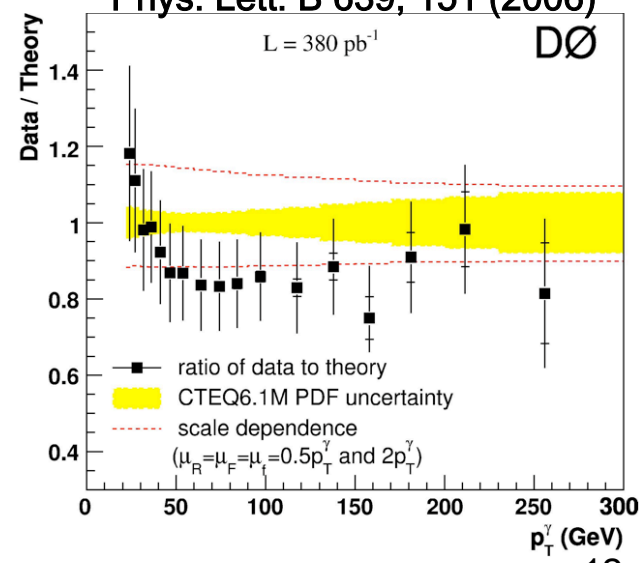
Phys. Rev. D80, 11106 (2009)



Data/pQCD in agreement at high PT
enhancement at low PT

Region where effects of resummation might be higher as well as fragmentation

Phys. Lett. B 639, 151 (2006)

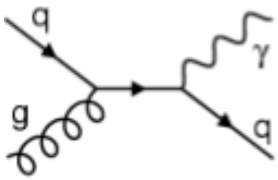


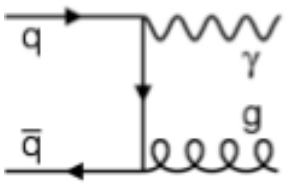
Not yet sensitive to PDF's: experimental and theoretical uncertainties still dominate

Photons

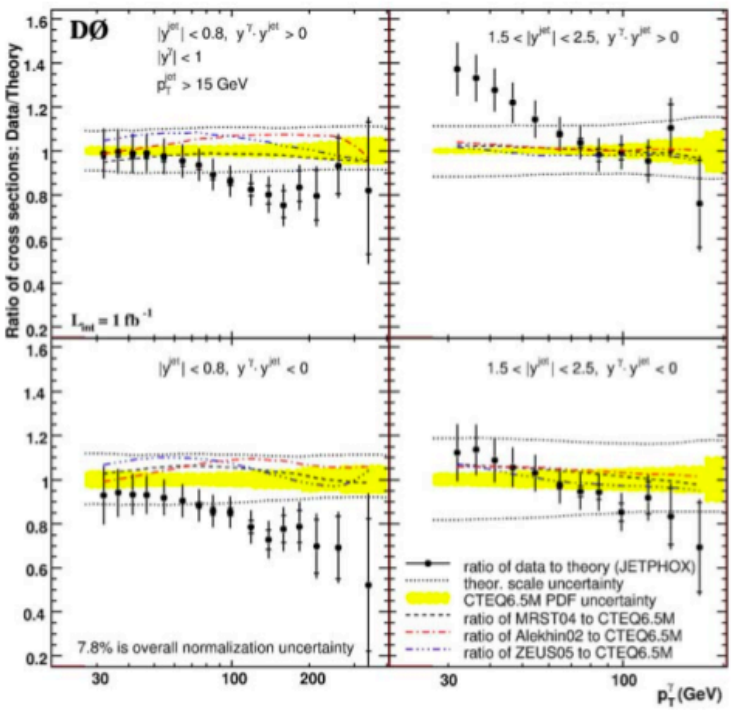
-Isolated Photon + jet

-Probe of the gluon pdf and of the dynamics of hard QCD over a wide range of x and Q^2





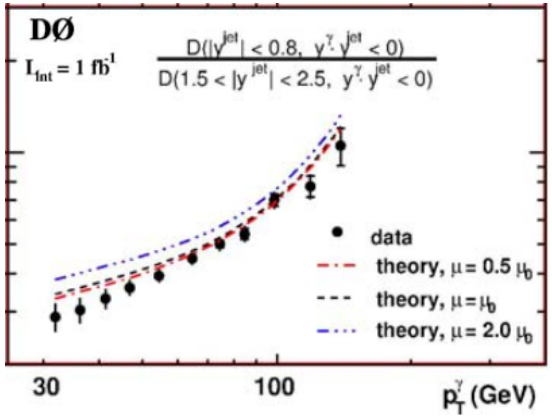
Central Forward



- NLO predictions do not describe the shape over the full range of P_T^{γ}
- Scale variations cannot describe normalization simultaneously for the 4 rapidity ranges
- Measuring ratios reduces some uncertainty, but disagreement still present

Phys. Lett. B 666, 435 (2008)

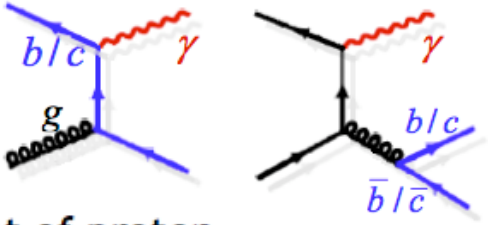
Need for an improved and consistent theory description of the process



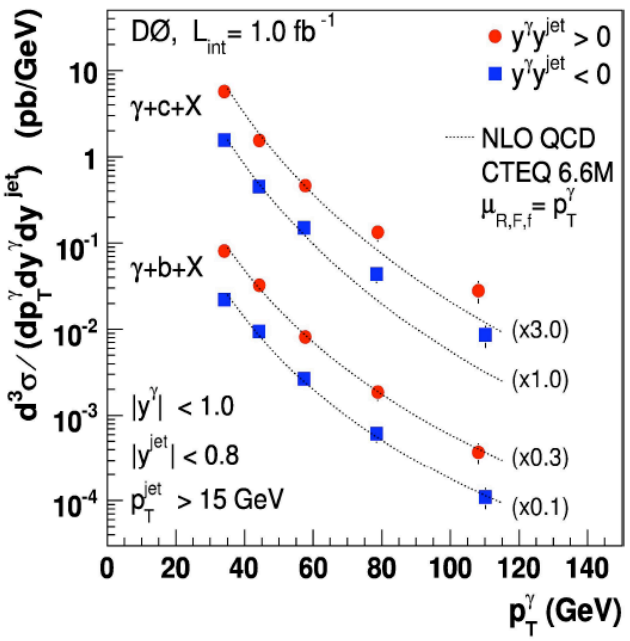
Theory:Aurenche et al. Nucl. Phys. B297, 661 (1988)
Aversa et al. Nucl.Phys.B327, 105 (1989) - JETPHOX

Photons

- Photons + heavy flavor production



Phys. Rev. Lett. **102**, 192002 (2009)



Photon p_T: 30 – 150 GeV/c
Rapidities: $|y^\gamma|<1.0$, $|y^{jet}|<0.8$

Theory: T.Stavreva, J.F.Owens, arXiv:0901.3791v1(2009) - phase space slicing

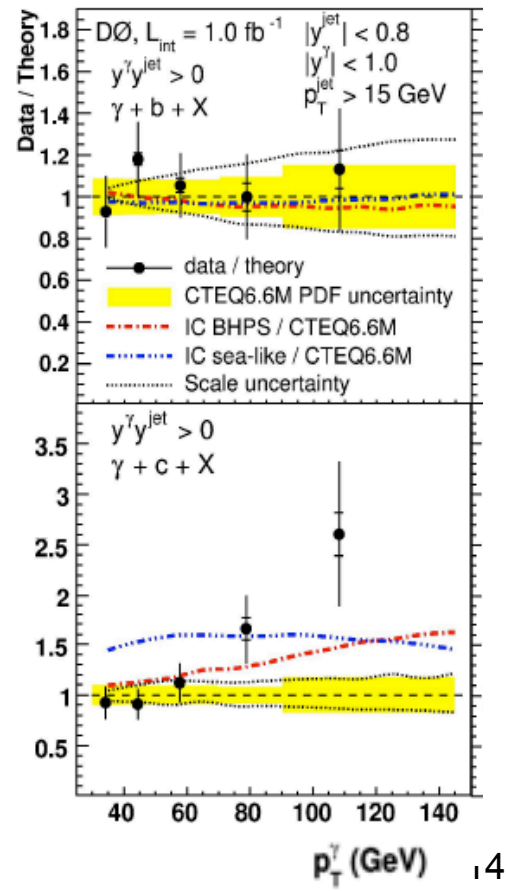
Sensitive to HF-content of proton
Bkgd for many BSMs

Photon + b

good agreement on all P_T range

Photon + c

agreement only up to P_T^γ < 50 GeV/c
increasing disagreement at higher P_T^γ
Using PDF intrinsic charm improves theory P_T dependence, but data disagreement still remains

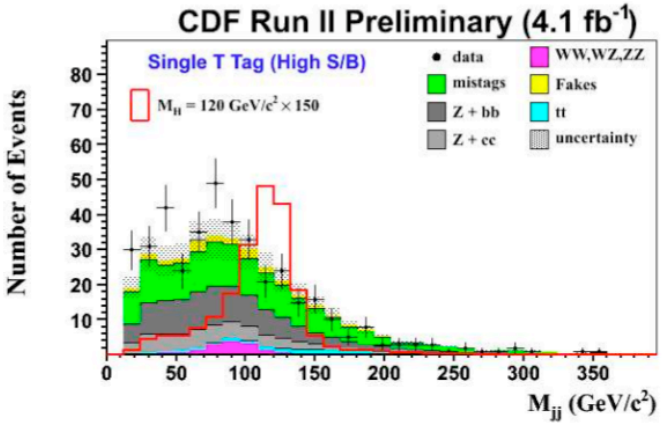


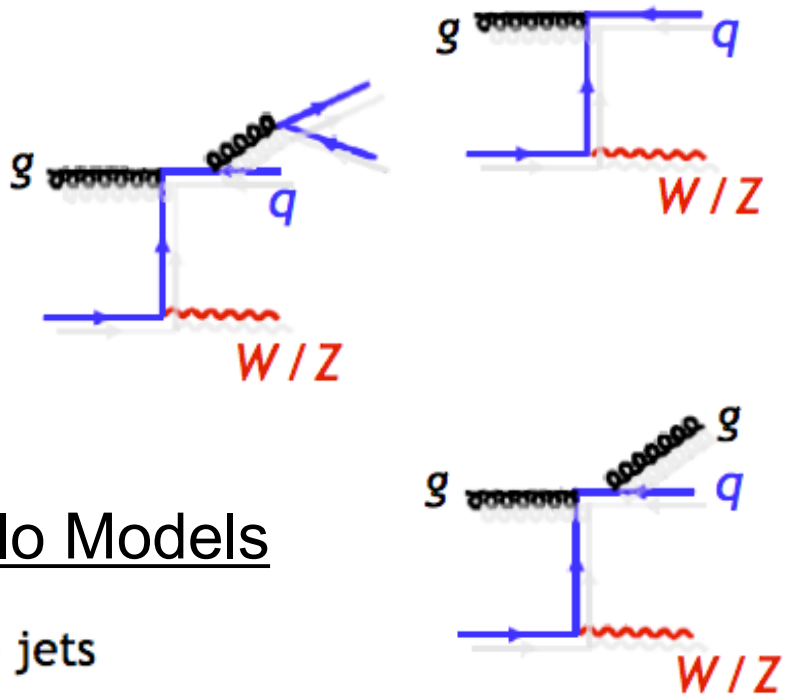
CDF has a recently submitted result with similar results for Photon + b
arXiv:0912.3453

Vector bosons + jets

Prerequisite for top, Higgs, SUSY, BSM

- major "universal" background





Test of pQCD and various Monte Carlo Models

NLO pQCD calculations are available up to 2(3) jets

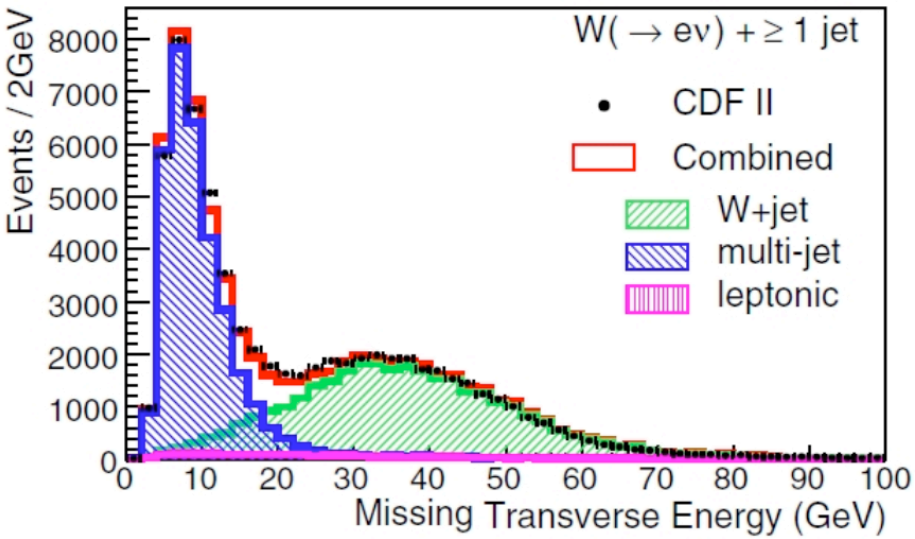
Many Monte Carlo tools are available

- LO + Parton shower Monte Carlo (Pythia, Herwig,)
- MC based on tree level matrix element + parton showers, matched to remove double counting: Alpgen, Sherpa, etc..

These calculations and tools need "validation" by experimental measurements

W + jets

Measure σ at hadron level as function of E_T^{jet} cf. LO, NLO predictions



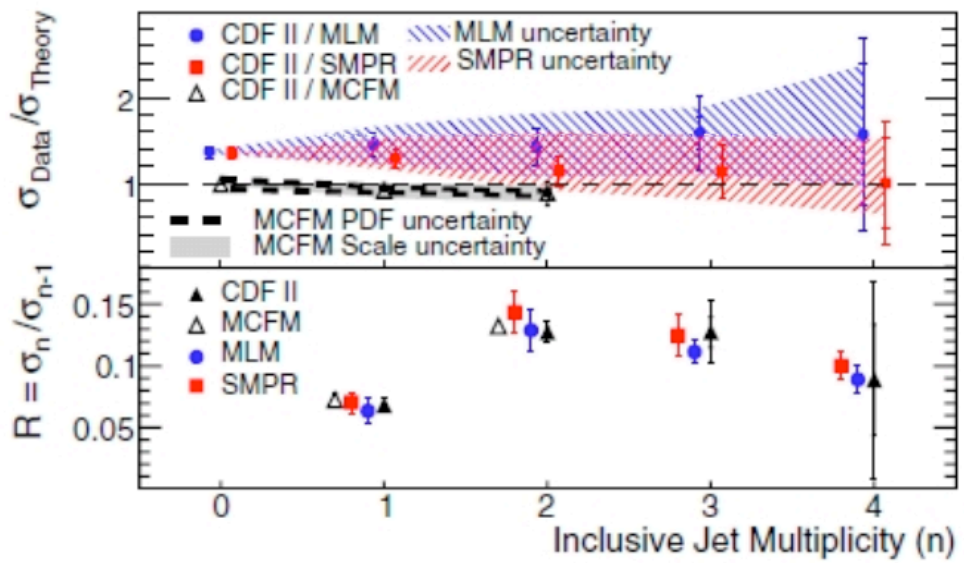
Phys. Rev. D 77, 011108(R) (2008)

NLO: MCFM (W + 1 and 2 jet available)

LO: ME+PS + nonpQCD correction:
SMPR: Madgraph, CTEQ6L, Pythia, S. Mrenna and P. Richardson, J. High Energy Phys. 05 (2004) 040.
MLM: Alpgen, CTEQ5L, Herwig, J. Alwall et al., arXiv:0706.2569.

Agreement with NLO good.

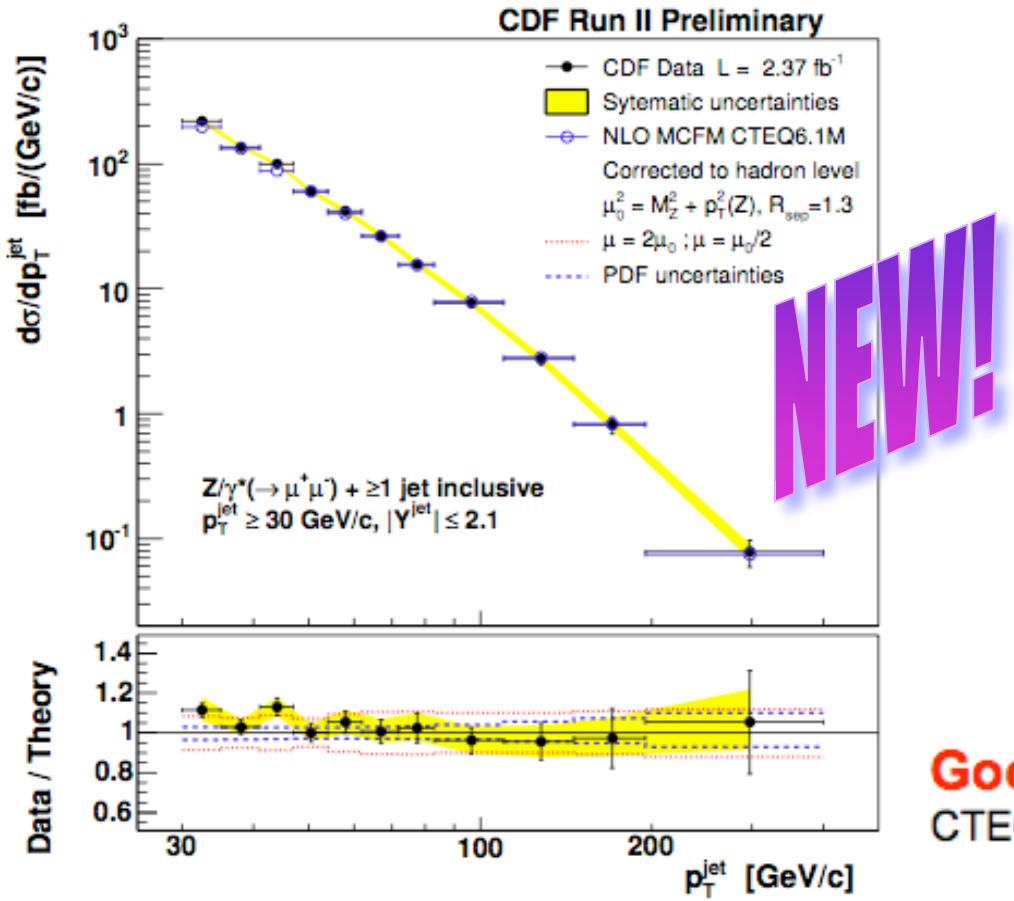
LO low.

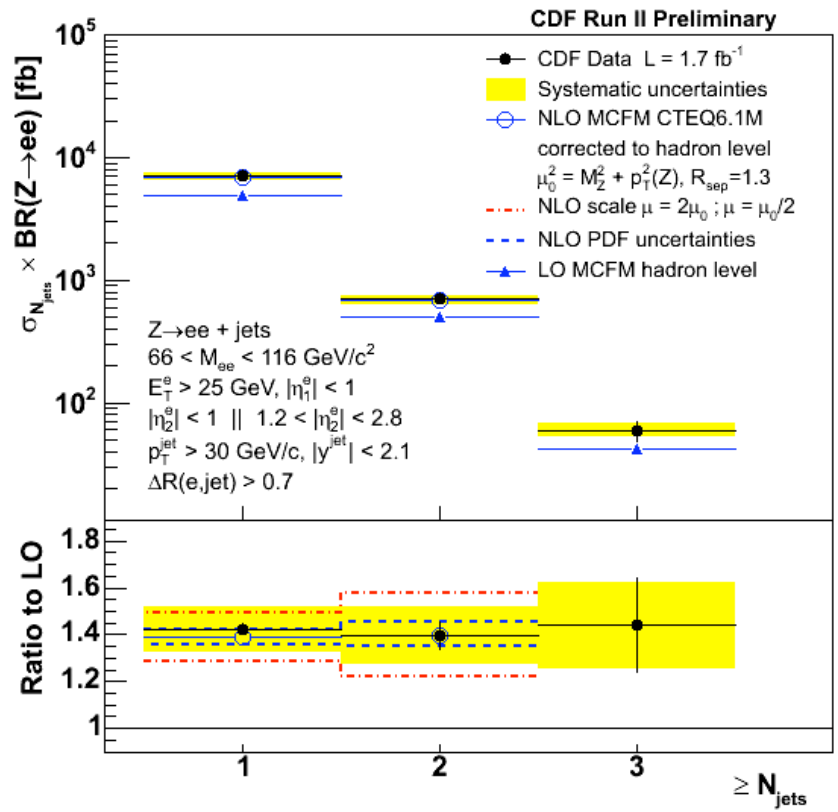


Z+jets

Phys. Rev. Lett 100, 102001 & update

Z→ee channel being updated and Z→μμ added

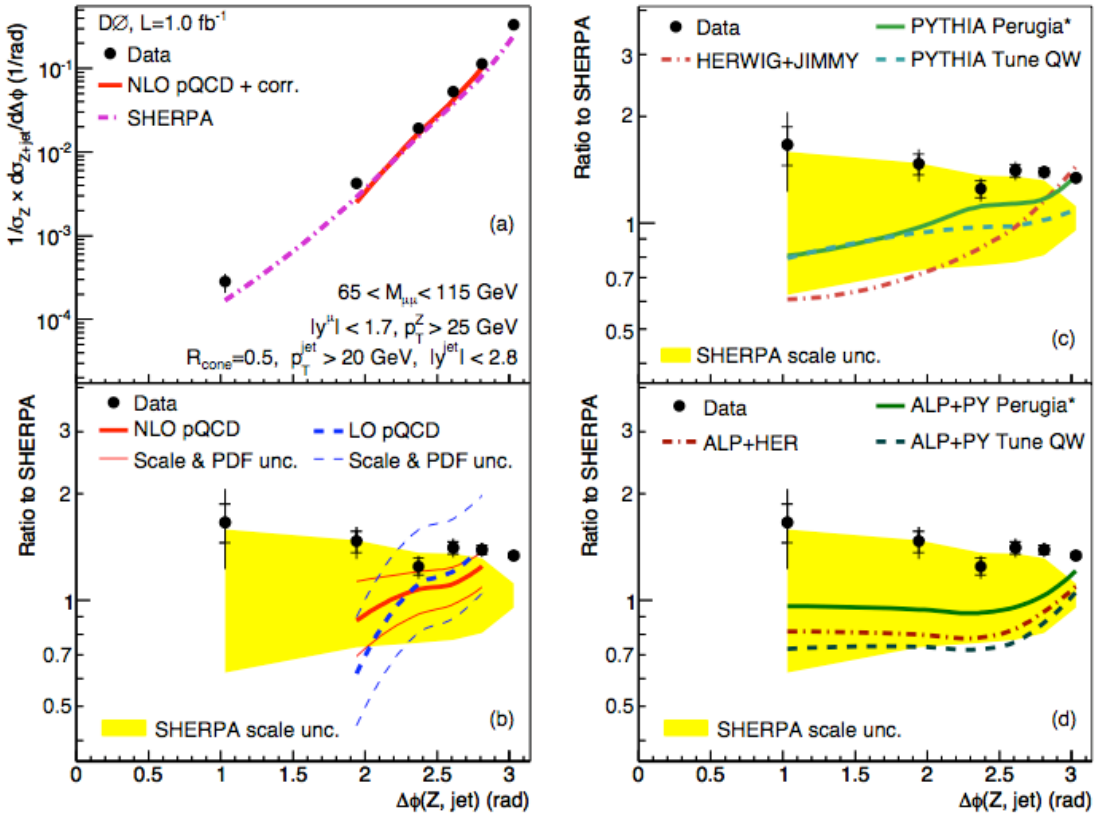




Good agreement with NLO (MCFM + CTEQ6M, corrected for UE, fragmentation)

Z+jets angular distributions

- Test of theory predictions (LO and NLO) and Monte Carlo generators
- These measurements test the best predictions for V+jet production at hadron colliders
- These measurements can be used as inputs in tuning event generators
- Sensitive to extra QCD radiation and its modeling ($\Delta\varphi$(Z-jet), Δy(Z-jet))
  - Does not require observation of extra jets



Sherpa is chosen as the common denominator for all ratios as it provides the best description of the shape of data in most distributions

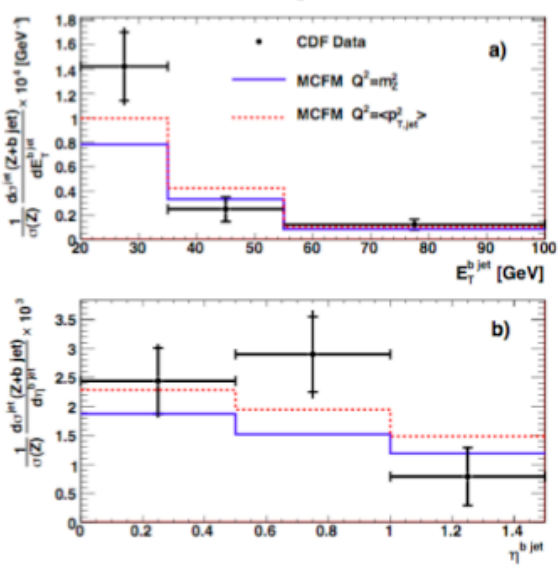
Phys.Lett.B682:370-380,2010

Z+b-jet

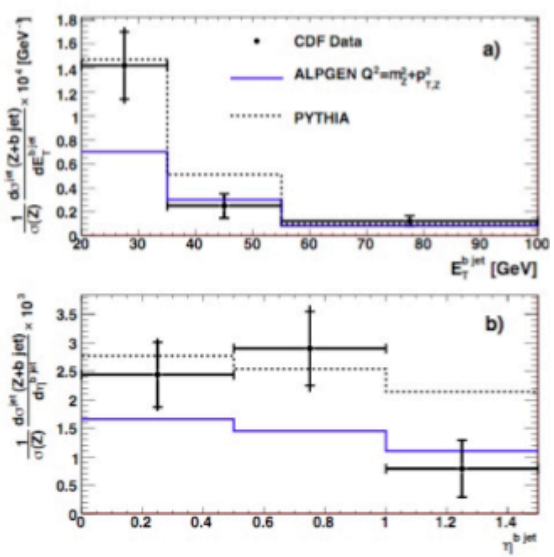
Z+b-jet is an important background to Higgs searches in ZH channel
Z+b-jet is sensitive to the b-content of the proton
Data are corrected to the hadron level and compared to predictions from PYTHIA, ALPGEN, HERWIG and NLO QCD.
Ratio of cross-section allows for several sources of uncertainties to cancel

	data	Alpgen	Pythia	MCFM ($Q^2=m_Z^2+p_{TZ}^2$)	MCFM ($Q^2=\langle p_{Tjet}\rangle^2$)
$\frac{\sigma(Z+b)}{\sigma(Z)}$	$(3.32 \pm 0.53 \pm 0.42)\times10^{-3}$	2.1×10^{-3}	3.5×10^{-3}	2.3×10^{-3}	2.8×10^{-3}
$\frac{\sigma(Z+b)}{\sigma(Z+j)}$	$(2.08 \pm 0.33 \pm 0.34)$ %	1.5 %	2.2 %	1.8 %	2.2 %

NLO



LO



PRD 79 052008 (2009)

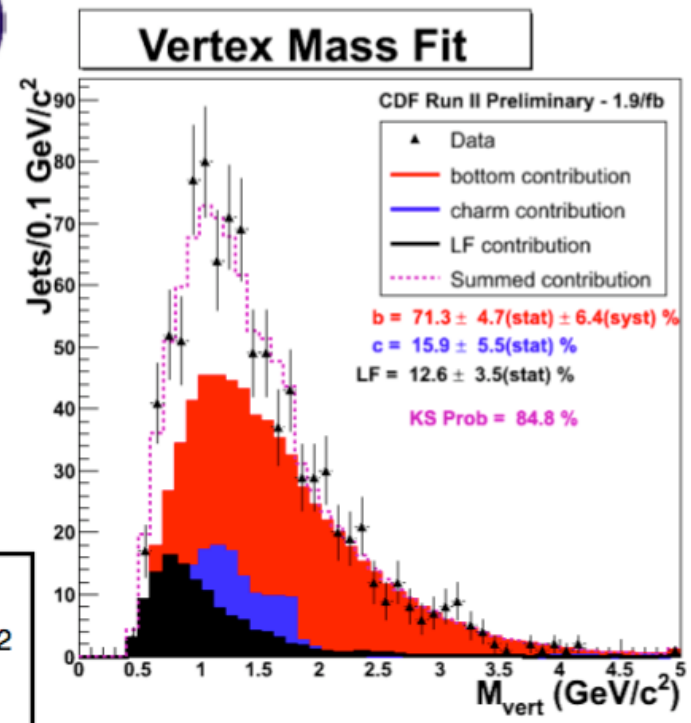
Several kinematical distributions show the level of (dis)agreement with theory prediction at LO and NLO

Awaiting for a complete NLO prediction(qqbar→Zbbar)

W+b-jet

data-driven measurement of a difficult-to-predict background for single top and Higgs searches.

Jets consistent with the decay of long-lived hadrons are selected by identifying a displaced decay vertex.
The invariant mass of the charged particle tracks associated with the vertex is sensitive to the flavor of the decaying hadron and is used to determine the fraction of jets from b-quark production.



Results:
in events with a $p_T > 20$ GeV/c, $|\eta| < 1.1$ electron or muon, a $p_T > 25$ GeV/c neutrino, and 1 or 2 $E_T > 20$ GeV, $|\eta| < 2.0$ jets regardless of species.

Data: $\sigma_{bjets}(W + b \text{ jets}) \times BR(W \rightarrow l\nu) = 2.74 \pm 0.27 \pm 0.42$ pb

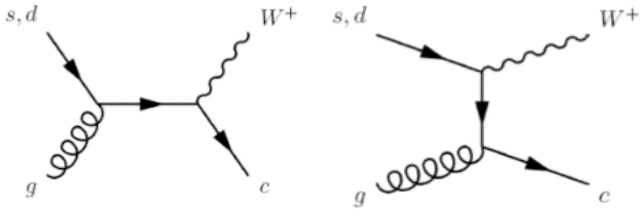
LO: ALPGEN: $\sigma \cdot BR = 0.78$ pb

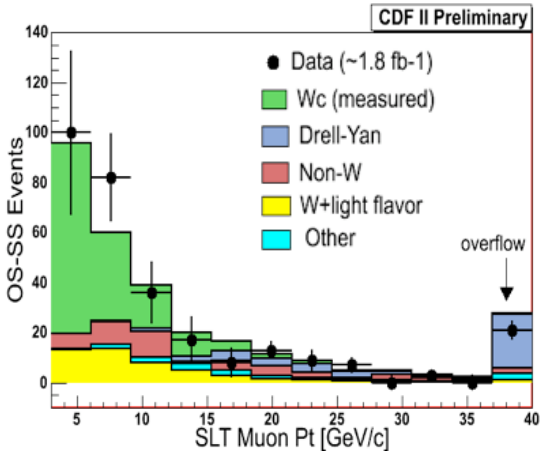
LO factor 3 low (nb. high scale)
- **awaiting NLO comparison.**

arXiv:0909.1505v2
(Submitted to PRL)

W+charm

s-quark initiated process (dg and bg heavily suppressed)
Charge correlation of the leptons used to identify events
Soft Lepton tagger used to identify charm-jet
and NN algorithms





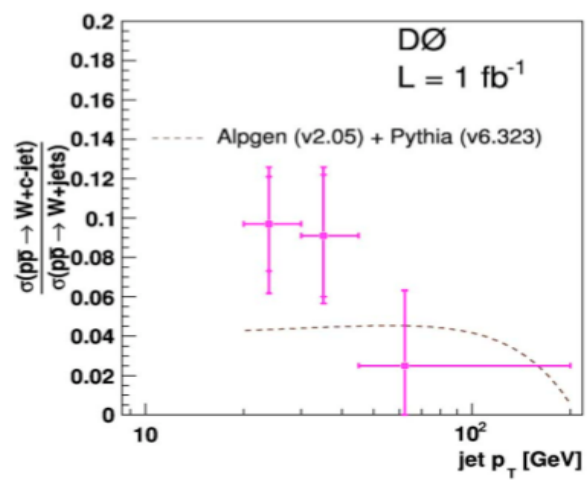
$$\sigma_{Wc} \cdot BR(W \rightarrow l\nu) = 9.8 \pm 3.2 \text{ pb}$$

Theory prediction: $11.0\ ^{+1.4}_{-3.0}$ @NLO (mcfm)

Phys. Rev. Lett. 100, 091803 (2008)

A new CDF measurement is in process

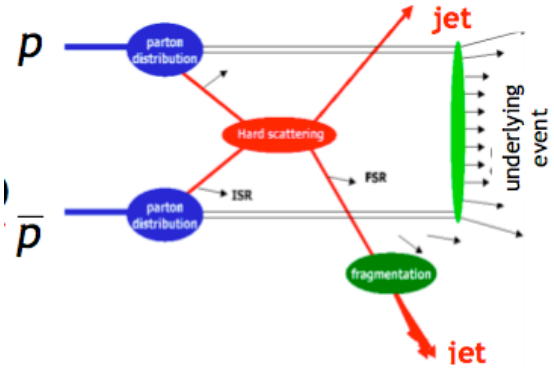
$$\frac{\sigma[W + c\text{-jet}]}{\sigma[W + \text{jets}]} = 0.074 \pm 0.019^{+0.012}_{-0.014}$$



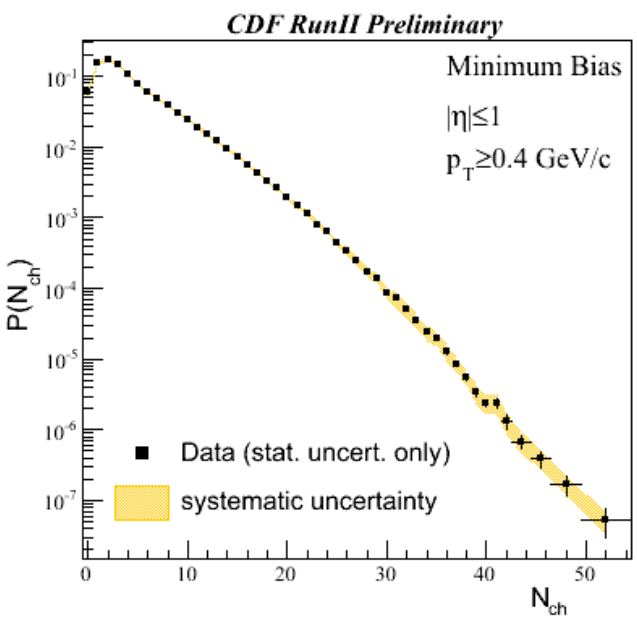
Theory: 0.044±0.003
Alpgen+Pythia

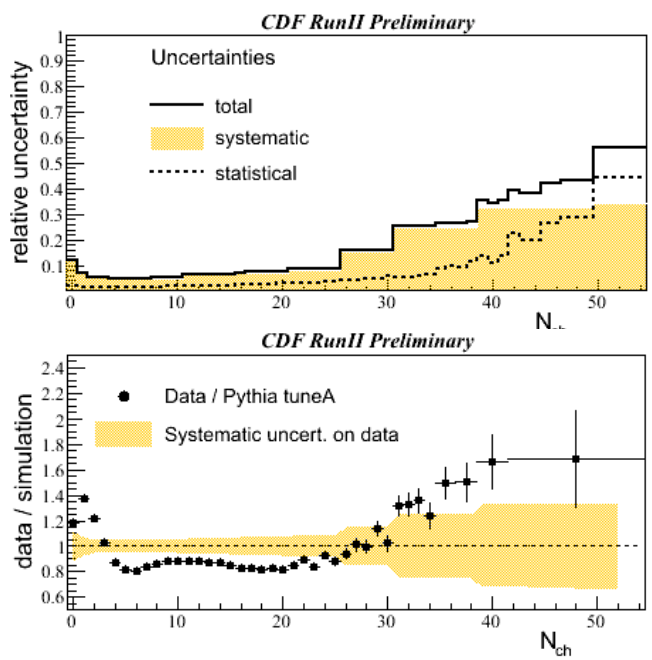
Phys. Lett. B 666, 23, July 2008

Underlying Events and Fragmentation



- The multiplicity distribution of charged particles is measured in inelastic non-diffractive collisions.
- The analysis is part of a systematic and detailed set of measurements of minimum-bias events.
- This data have the highest precision and the largest range extension ever reached in the pseudorapidity range $|\eta| \leq 1$.

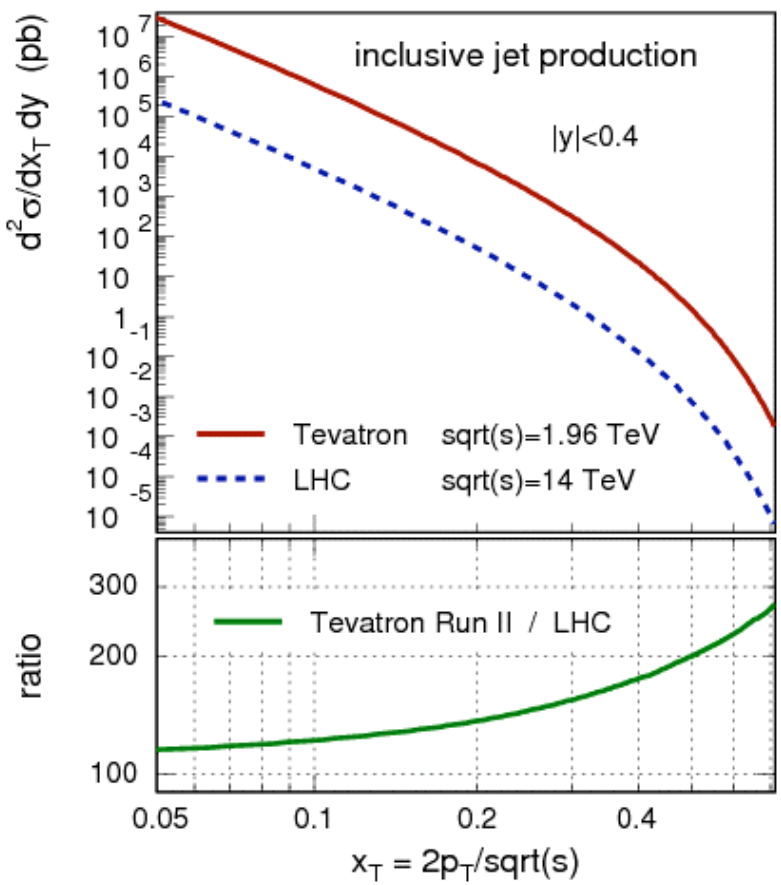




Important for MC tunings

- Complement the underlying event study in hard-scattering events
- Actively used for recent MC tunes

Future Outlook: Inclusive Jets



PDF sensitivity:

→ compare jet cross section at fixed
$x_T = 2\,p_T$ / sqrt(s)

Tevatron (ppbar)

>100x higher cross section @ all x_T

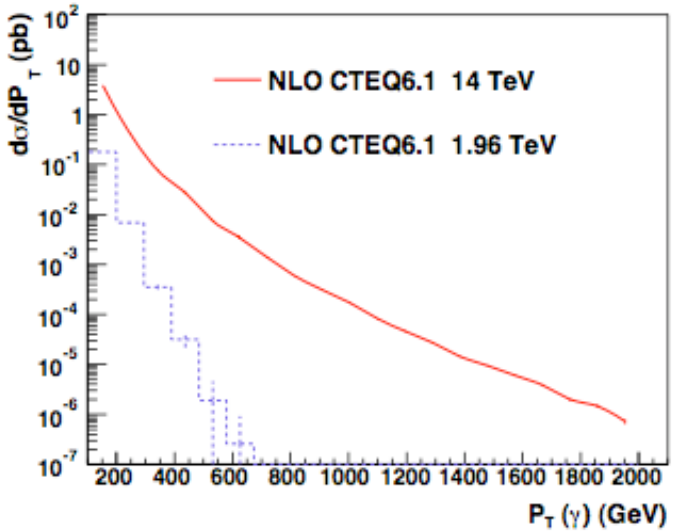
>200x higher cross section @ x_T >0.5

LHC (pp)

- need more than 2400 fb^{-1} luminosity to improve Tevatron@12 fb^{-1}
- more high-x gluon contributions
- but more steeply falling cross sect. at highest p_T (=larger uncertainties)
- Relatively high JES uncertainty in early data impact (5-10% for jets below 1TeV) might seriously limit the physics potential of the data (D. Clements, DIS 2007).

→ Tevatron results will dominate high-x gluon for some years

Future Outlook: Photons

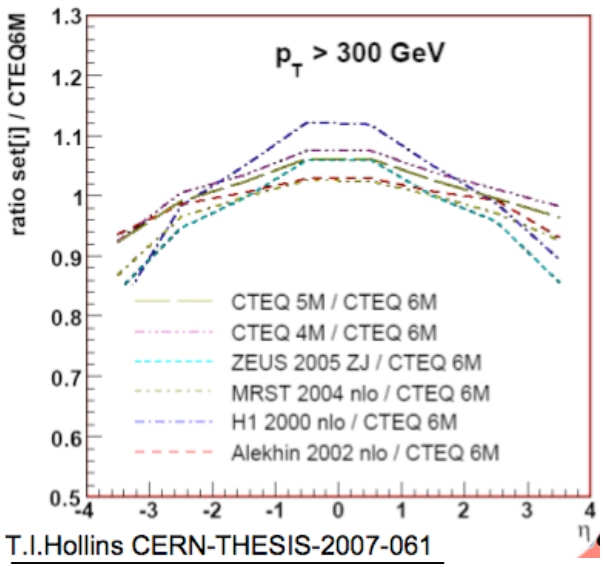


$P_T\gamma$ cross-section for γ+jet events predicted by NLO QCD for Tevatron and LHC kinematic range

Some experimental issues (ATLAS)

- Photon mis-identification
  low fake probability but high jet rate
- Large fraction of photons will convert before reaching the calorimeters (70%)
- Photon Purity (very high at the Tevatron)

- The jet energy scale does not apply to direct photon events so they will have a much smaller uncertainty
- This should allow the differences in the η spectrum of different PDF's (~10%) to be observed



T.I.Hollins CERN-THESIS-2007-061

Future Outlook: V+jets

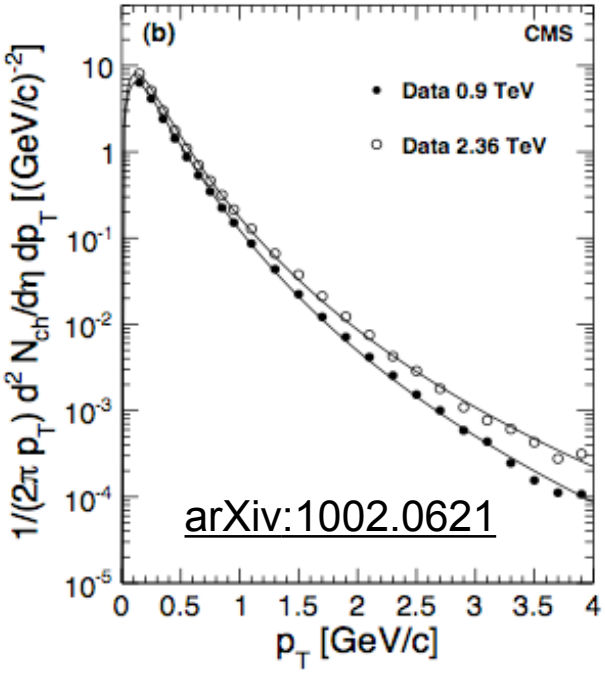
	Inclusive jets	B-jets	C-jets
Z-boson	Agree with MC or theory predictions so far	Discrepancies observed	No planned measurement so far
W-boson	Agree with MC or theory predictions so far	Discrepancies observed	Update in progress
Photon	D0 observes discrepancies	D0 results agrees with predictions Same diagrams as for Z+b (different Q^2)	D0 observes discrepancies. Provide information about c-pdf's

- Perform all V+jets analyses with full Run-2 dataset
  - All these processes are backgrounds to New Physics and Higgs
- Great interest in Tevatron measurements from theoretical community
  - They need our detailed results for tuning MC and checking calculations
- It will take considerable time for LHC measurements to compete with Tevatron results

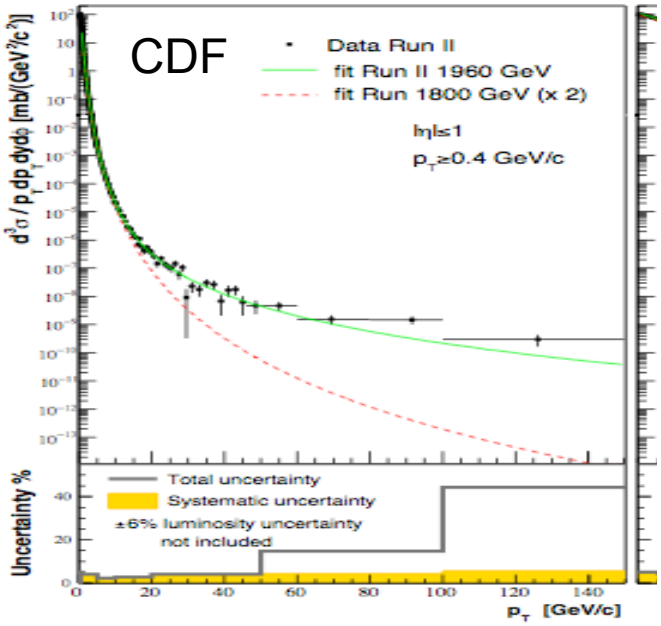
Future Outlook: soft physics

First results on Minimum Bias data(CMS)

measurements of inclusive charged-hadron transverse-momentum and pseudorapidity distributions



Still very low track P_T compared to the range measured at the Tevatron



Phys. Rev. D 79, 112005 (2009)

Might still need some time to perform more accurate measurements

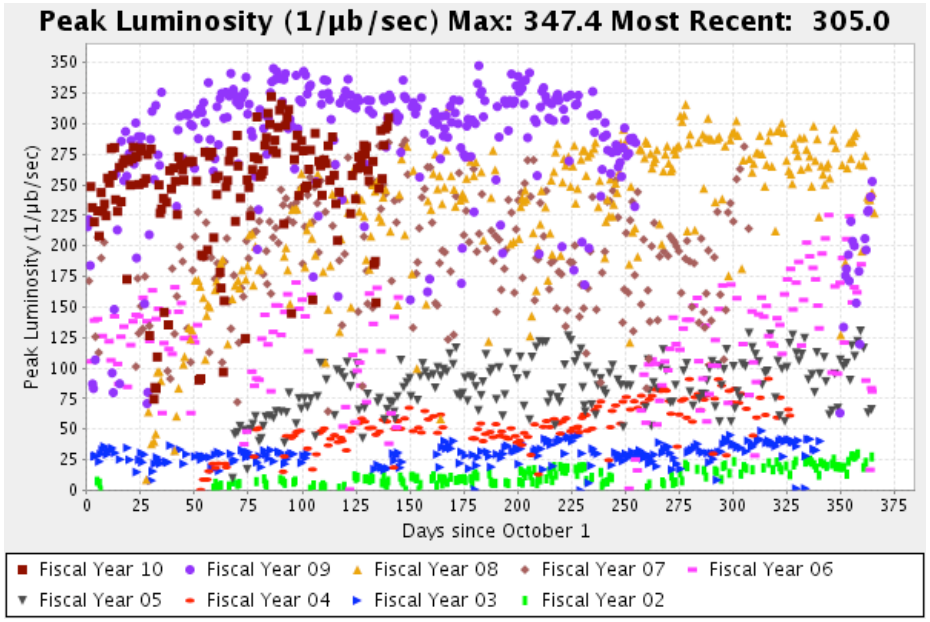
- Integrate all detector
- Accumulate enough luminosity to be in the cross-section reach
- Tune the simulation appropriately

Conclusions

- The Tevatron is providing for precision QCD physics
  - Consistency between CDF and D0 results
- Jet Production (inclusive, dijet mass, dijet angle)
  - Tests pQCD
    - PDF, α_s
  - constraints new physics,
- Photons and Photons + (heavy flavor) jets
  - Some disagreement (γ+jet) and need for more theory feedback
- Vector bosons + jets
  - Very active area, universal background to many other processes
    - W/Z + jets in very good agreement
    - W/Z+ b, W+charm
  - Testing of Monte Carlo tools and schema
- Underlying events and fragmentation studies
  - MC tuning
- Community looks forward to the re-discovery of QCD at LHC
  - But more to come from the Tevatron…

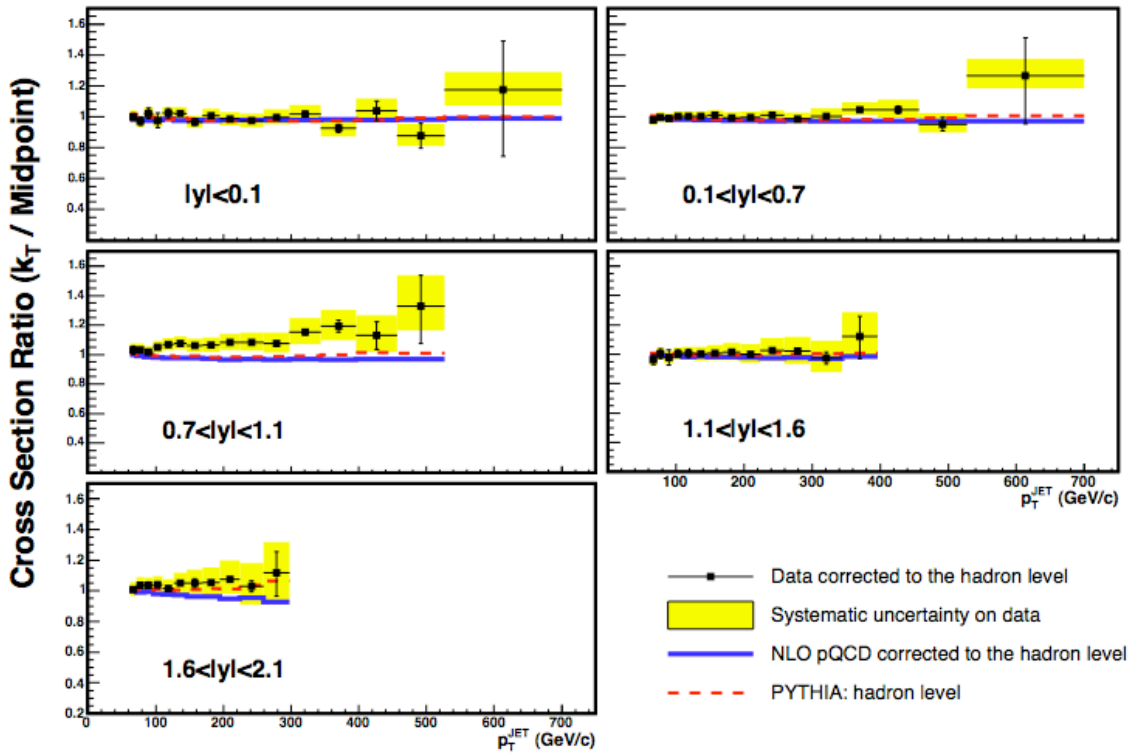
Backup: Peak Lumi

Tevatron Peak Luminosity



Backup: Jet Algs

Jet Algorithms: association of objects to cluster based on proximity in space coordinates (cone algorithms) or proximity in momentum space (K_T algorithms)



Comparison between midpoint and K_T results

Backup: Photon + Jets

-Photon + Jet

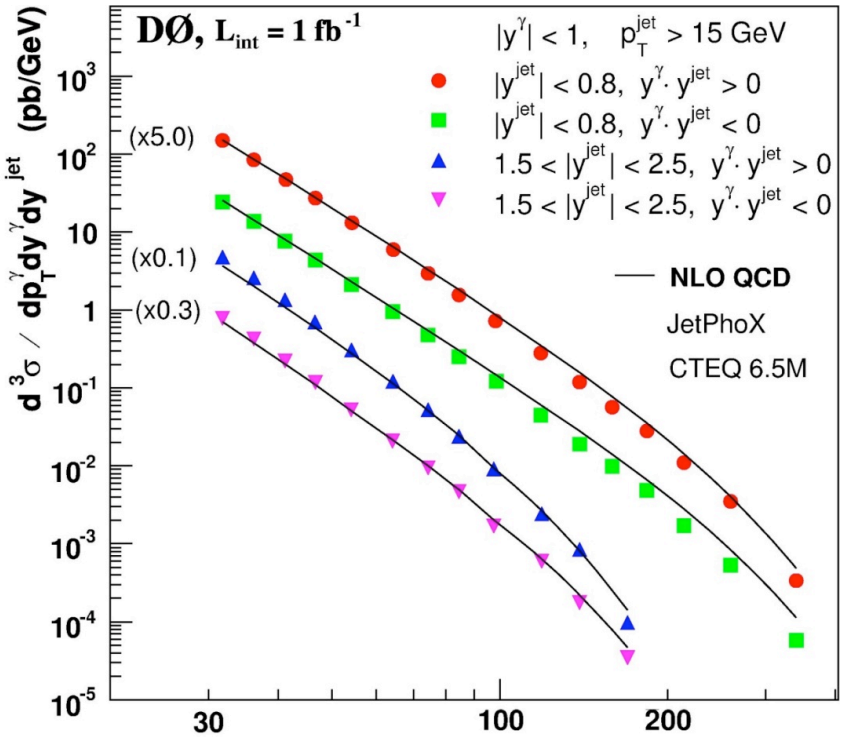
investigate source for disagreement in data/theory incl. photon pT shape:

measure more differential:

- tag **photon and jet**
  → reconstruct full event kinematics

- measure in 4 regions of y^{γ} / y^{jet}
  - photon: central
  - jet: central / forward
  - same side / opposite side

- different PDF sensitivity in different y^{γ} / y^{jet} regions

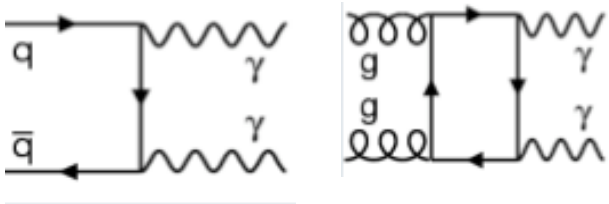


Need for an improved and consistent theoretical prediction

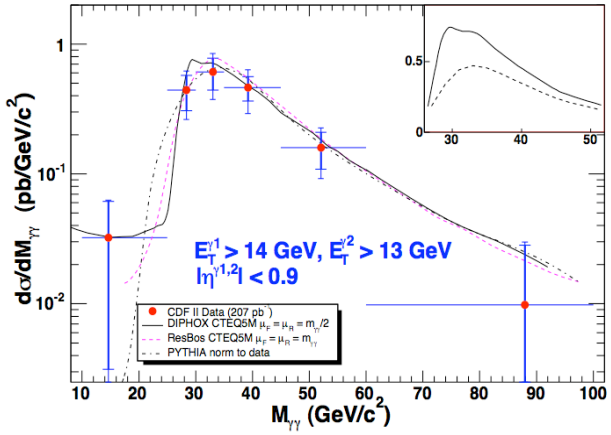
→ look at ratios for quantitative statement …

Backup:Photons

-DiPhotons

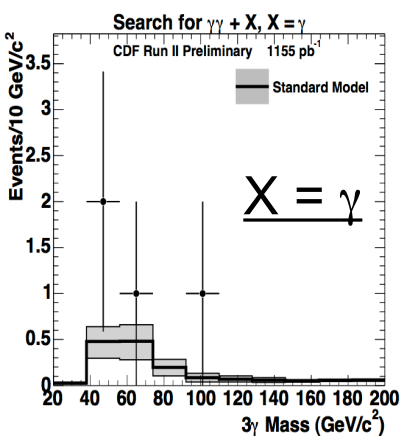


- Signature for very interesting physics processes
- Invariant mass distribution can be measured with good precision
-The direct measurement of the transverse momentum of the γ γ system (q_T) is sensitive to initial state soft gluon radiation

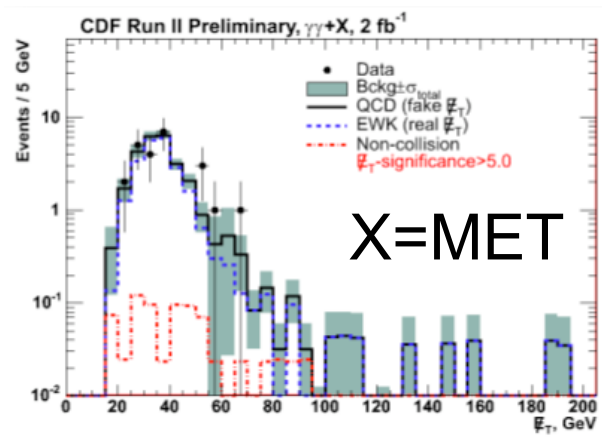


Phys.Rev Lett. **95,** 022003 (2005)

A window on new physics: diphoton + X as an example of model independent searches

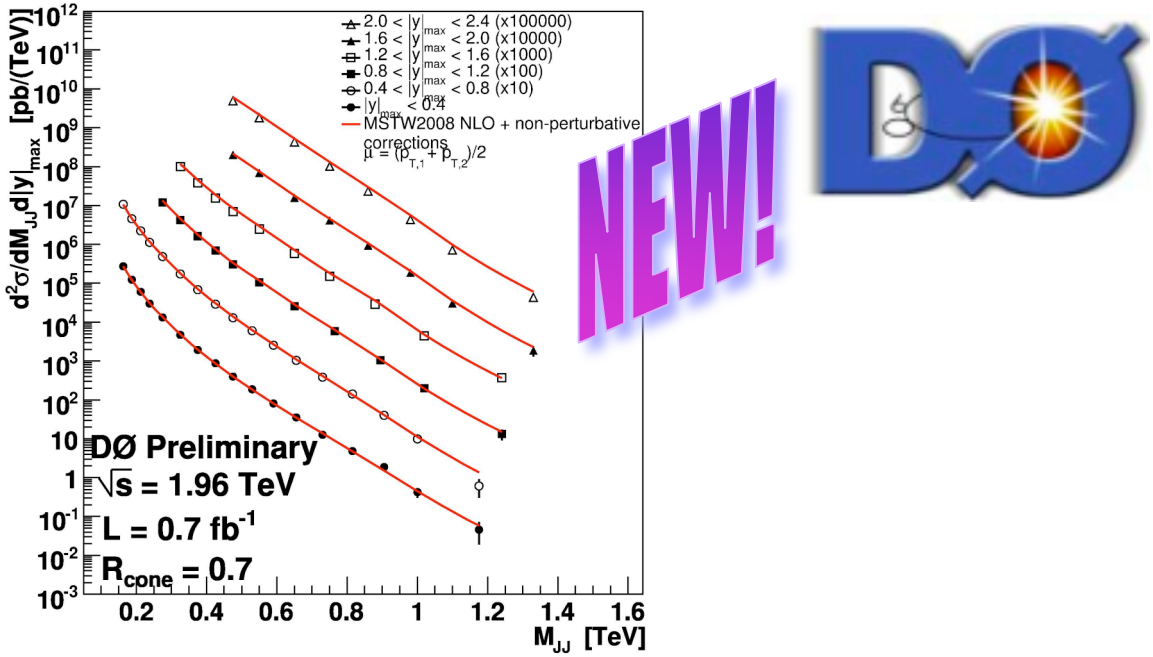


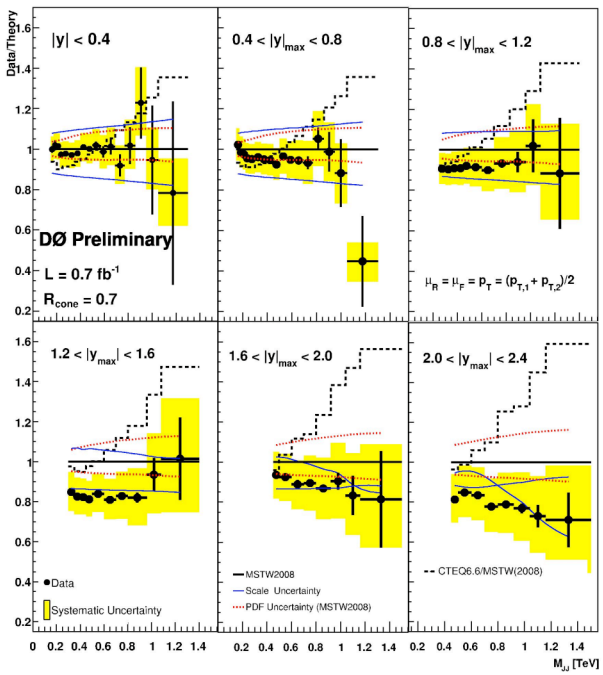
Nominal high E_T object identification and kinematic selections are used.
The observed event counts is reported as well as SM prediction for various kinematic distributions

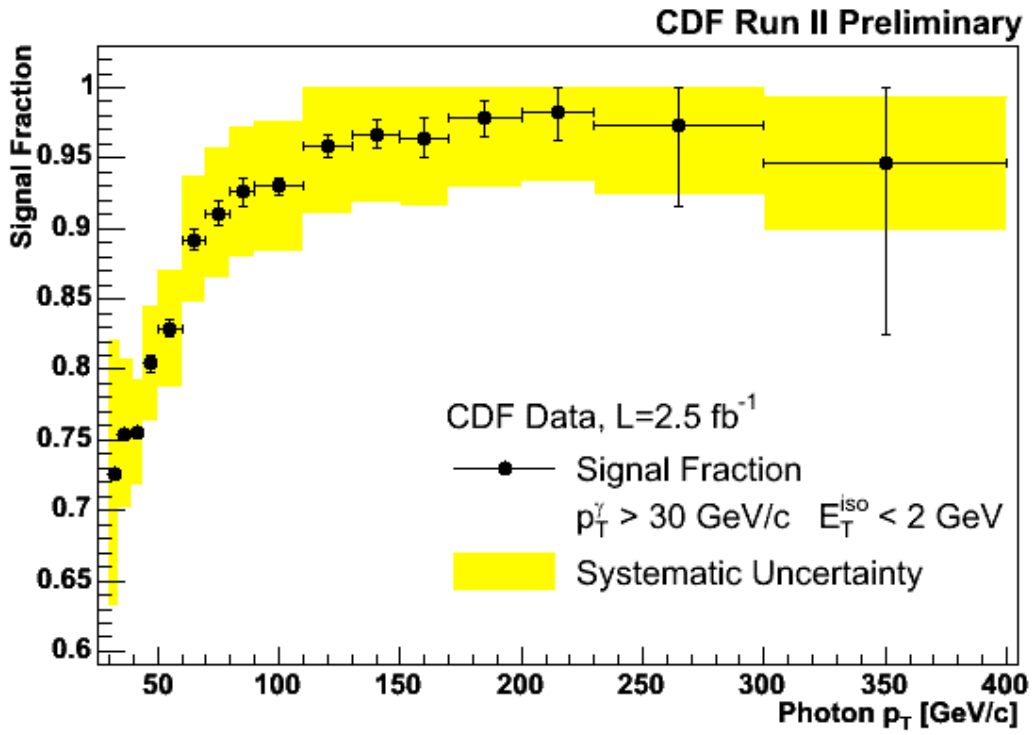


Backup:Dijet Mass spectrum

The dijet mass spectrum is measured in 6 different rapidity regions





Experimental uncertainties are similar in size to PDF and scale uncertainty, suggesting that the measurement might constraint future theoretical predictions

Backup: Photon Purity