QCD at the TeVatron

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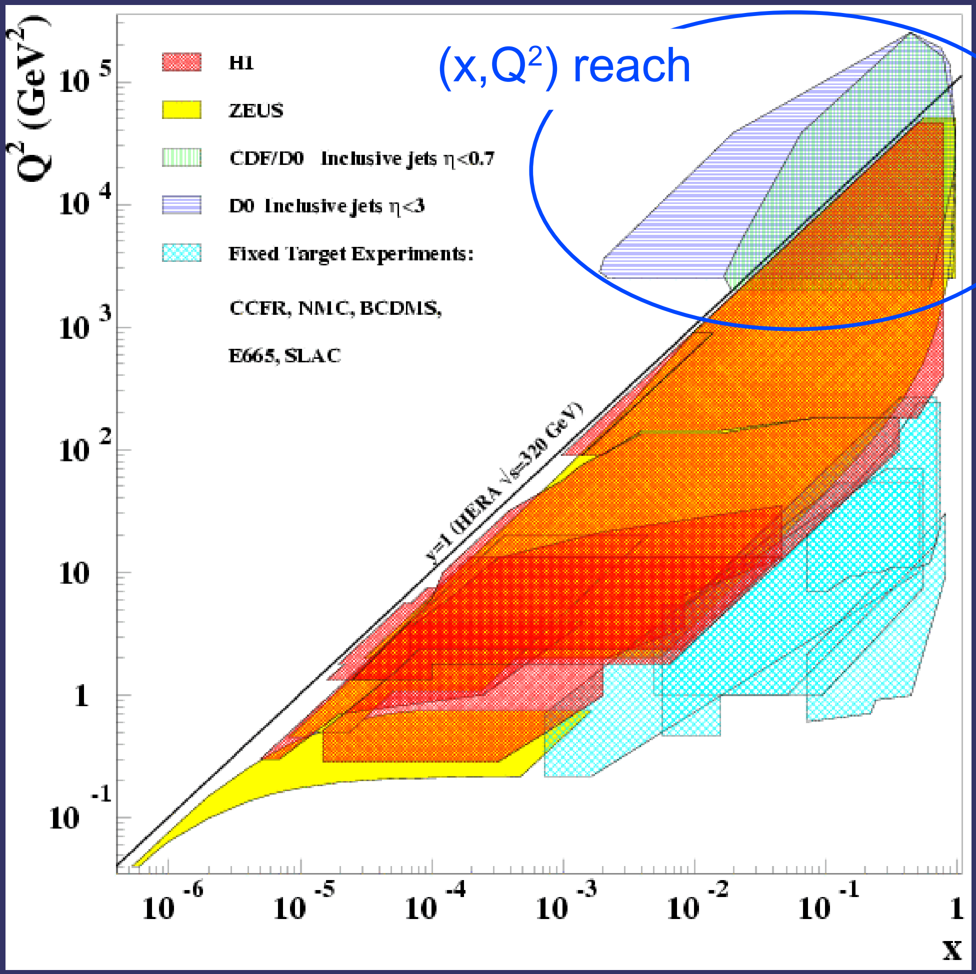
for the DØ and CDF Collaborations

- Hard QCD processes
  (high p_T, hard partonic processes)
  - Inclusive jet production
  - Dijets
  - V+jets (including heavy flavor)
- Non-perturbative effects
- Diffractive production
  - Exclusive final states, jets, W/Z production
- Underlying event / min-bias studies

Focus on updates from this year

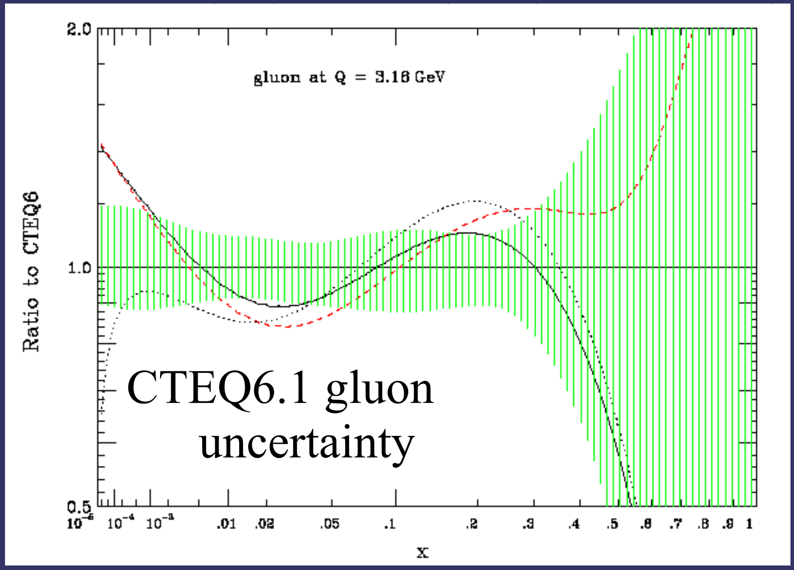
QCD with Jets

Tevatron data provide unique and increasingly precise inputs with...



...large kinematic reach...

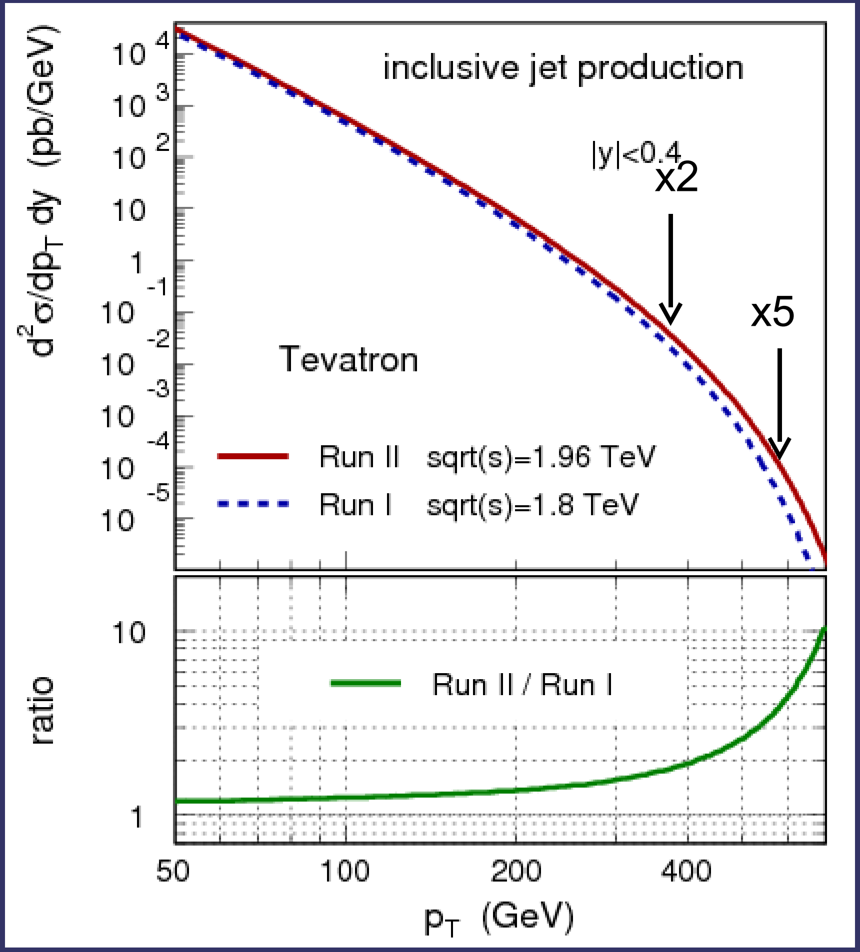
... into poorly constrained regions of pdf fits



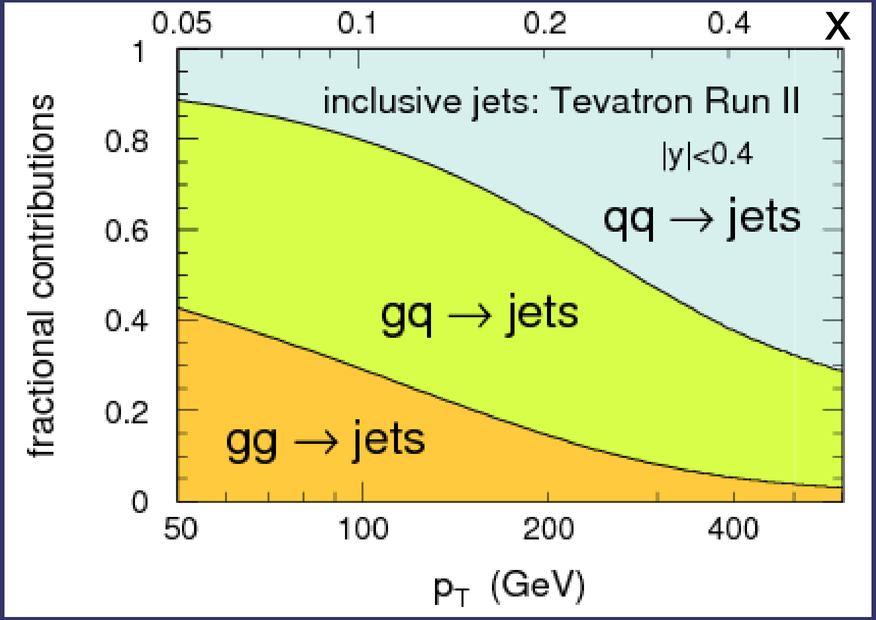
Access to hardest partonic subprocesses, approach limit: $\sqrt{\hat{s}} \approx \sqrt{s}$

High pT Jets

Large high p_T cross section
→ unique sensitivity



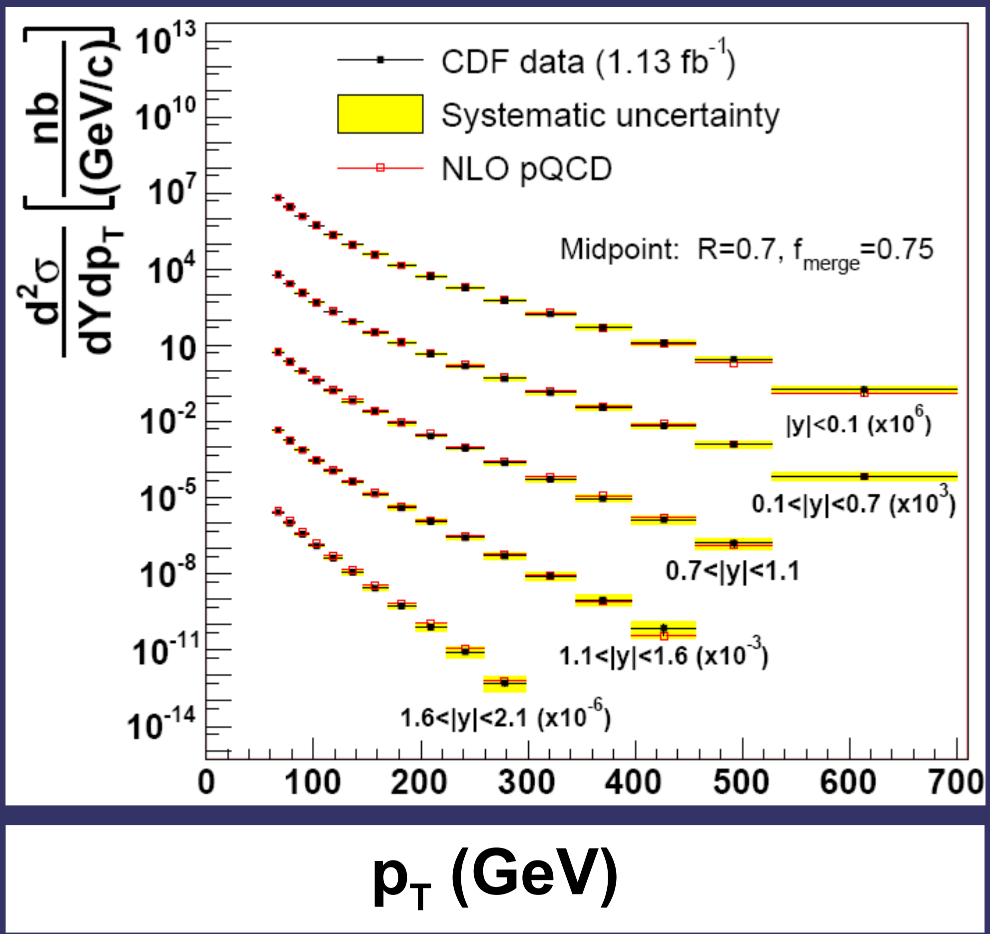
- Run II: σ^{jet} increased x5 at p_T= 600GeV
  - sensitive to new physics:
    quark compositeness,
    extra dimensions, …(?)…
- Theory @NLO is reliable (±10%)
  - sensitivity to PDFs, dynamics, α_s
  - unique reach for high-x gluon

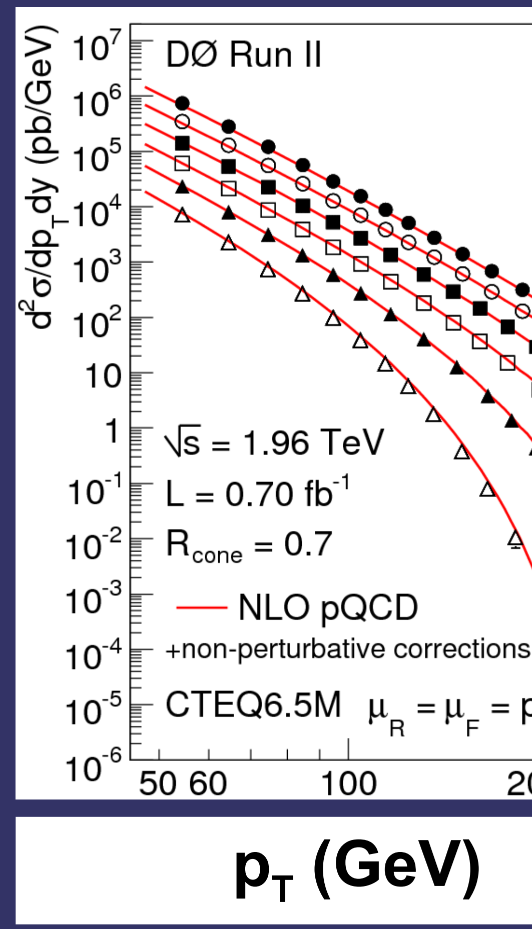


Phys. Rev. D 78, 052006 (2008)

PRL 101, 062001 (2008)

Inclusive Jet Production





~9 decades measurement!

Steeply falling p_T spectrum:

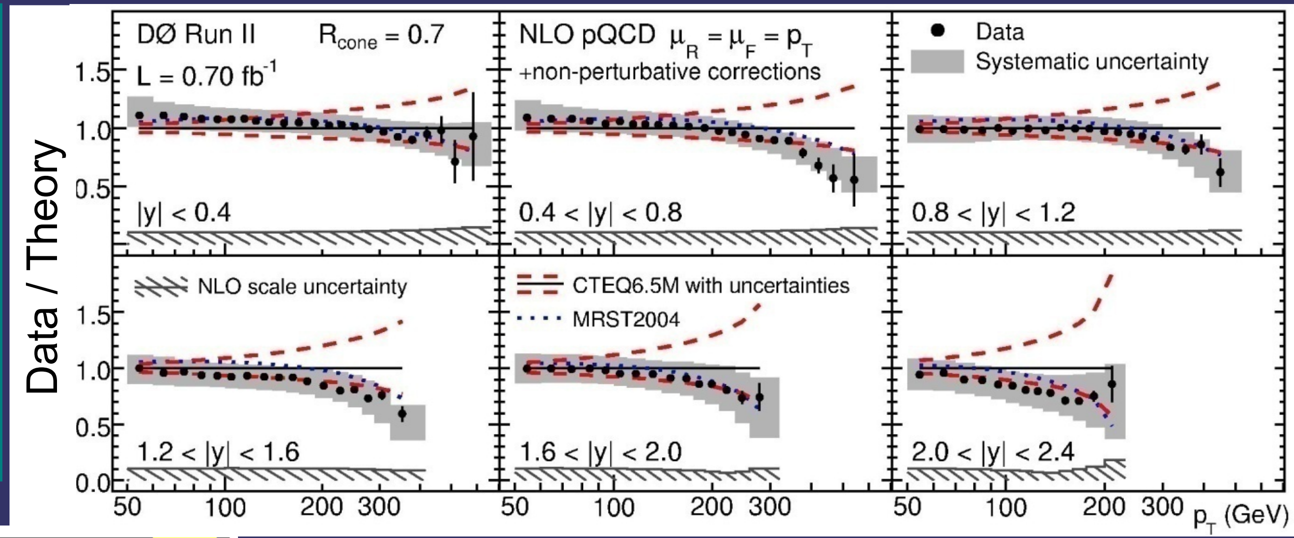
1% error in jet energy calibration
→ 5-10% (10-25%) error
central (forward) x-section

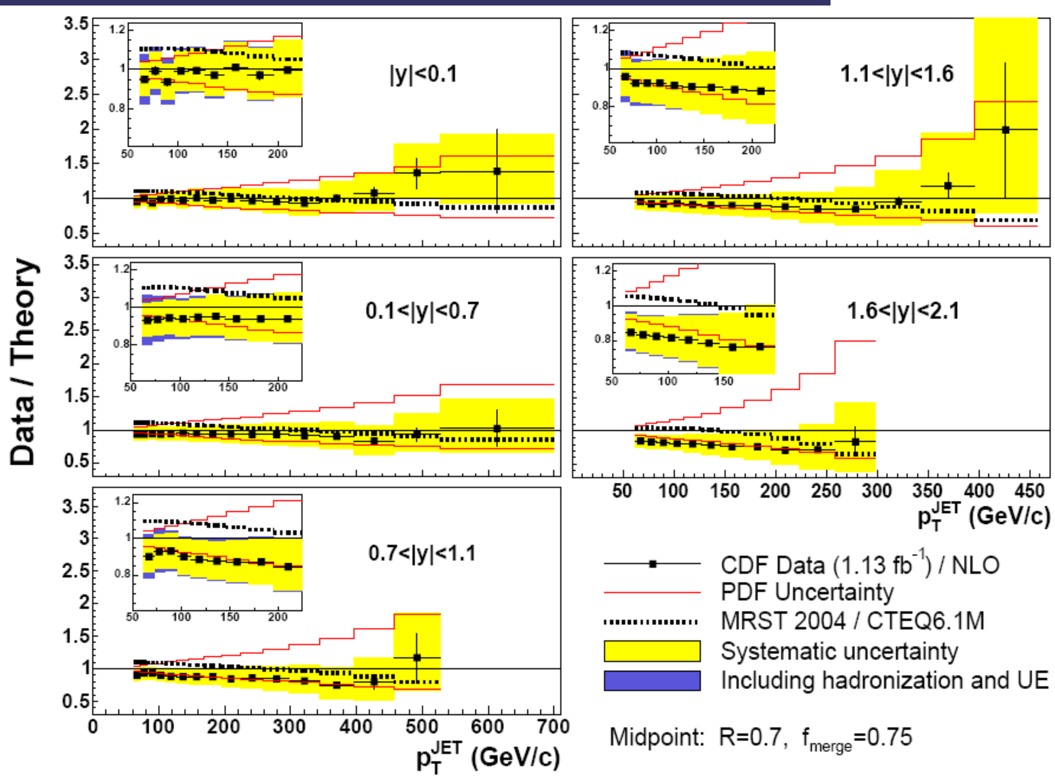
Benefit from:

- high luminosity in run II
- increased run II cm energy → high p_T
- **hard work on jet energy calibration**

Inclusive Jet Production

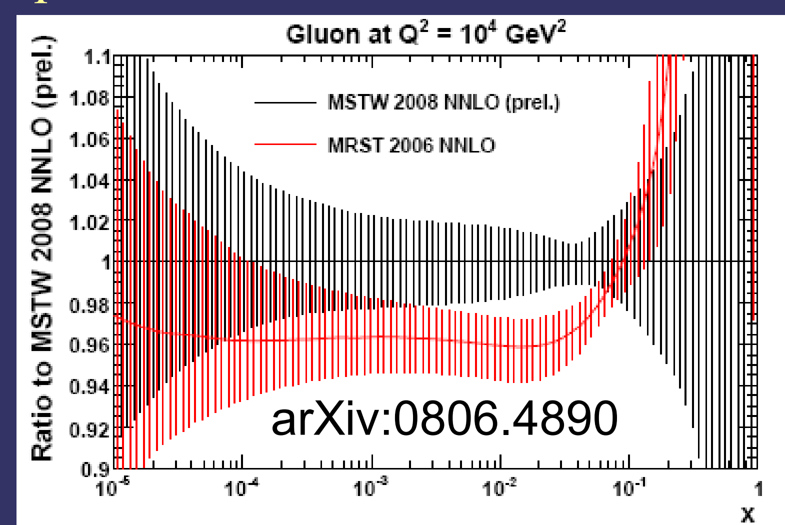
- CDF/DØ data are consistent
- well-described by NLO pQCD
- experimental uncertainties: < PDF uncertainties!
- data favor lower edge of CTEQ PDF uncertainties at high p_T



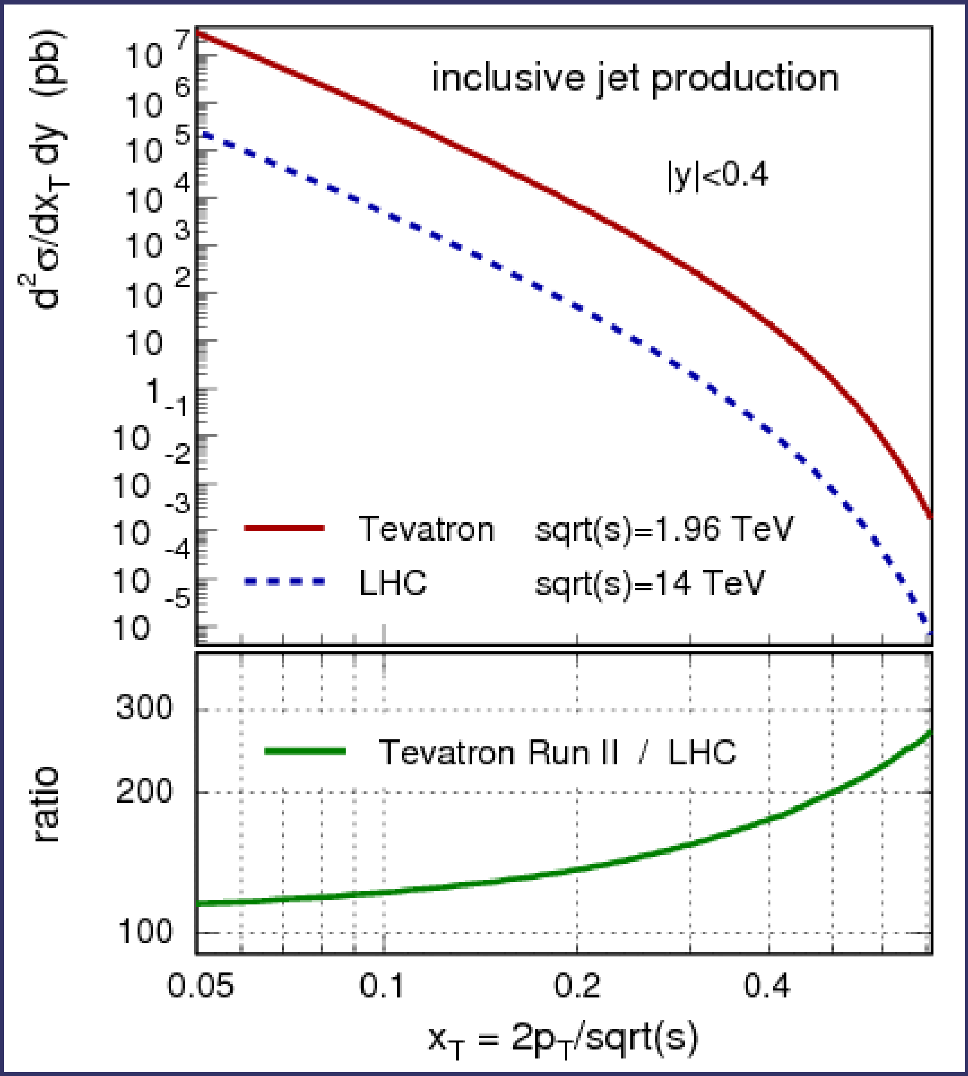


- shape well described by MRST2004

preview of precision DØ run II data in new fits...



Incl. Jets: TeVatron vs LHC



PDF sensitivity:

compare jet cross section at fixed

$x_T = 2p_T$ / sqrt(s)

Tevatron (ppbar)

>100x higher cross section @ all x_T

>200x higher cross section @ x_T>0.5

LHC (pp)

- need more than 1600fb^{-1} luminosity to compete with Tevatron @8fb^{-1}
- more high-x gluon contributions
- but more steeply falling cross sect. at highest p_T (=larger uncertainties)

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

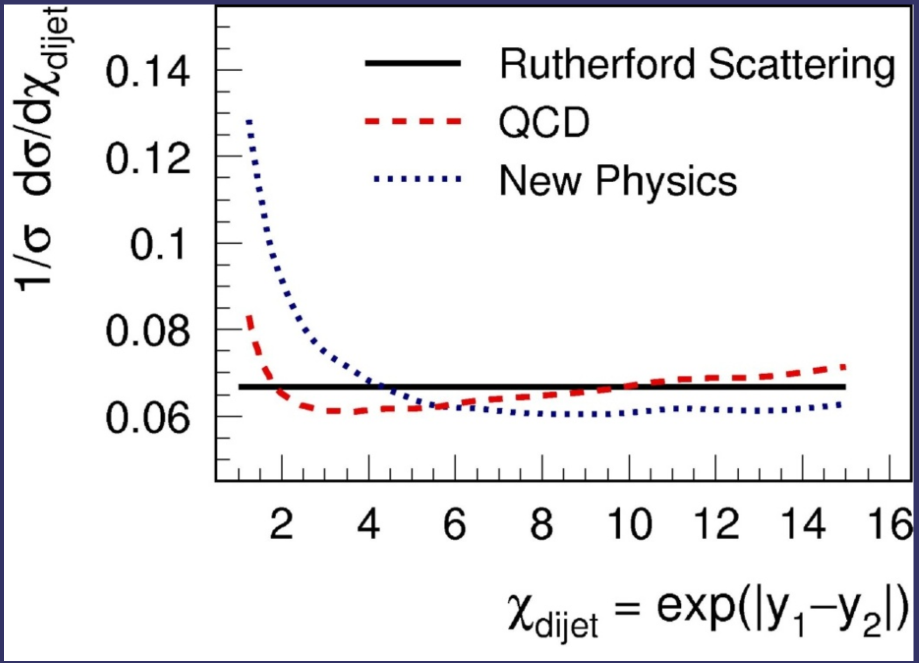
Dijet Angular Distribution

Analysis variable:

$$\chi_{\text{dijet}} = \exp(|y_1 - y_2|)$$

at LO, related to parton CM scattering angle

$$\chi_{\text{dijet}} = \frac{1+\cos\theta^*}{1-\cos\theta^*}$$



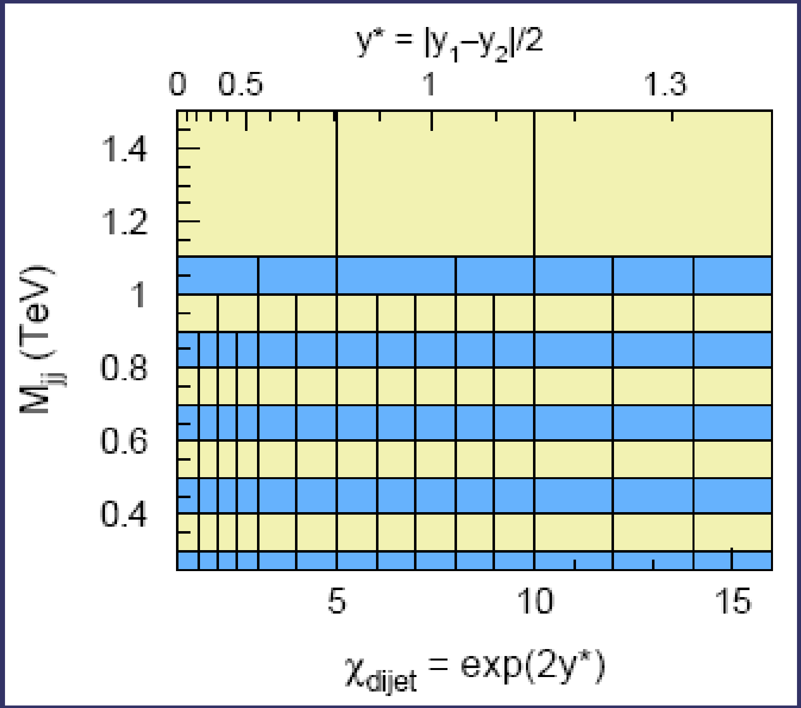
Large θ* Small θ*

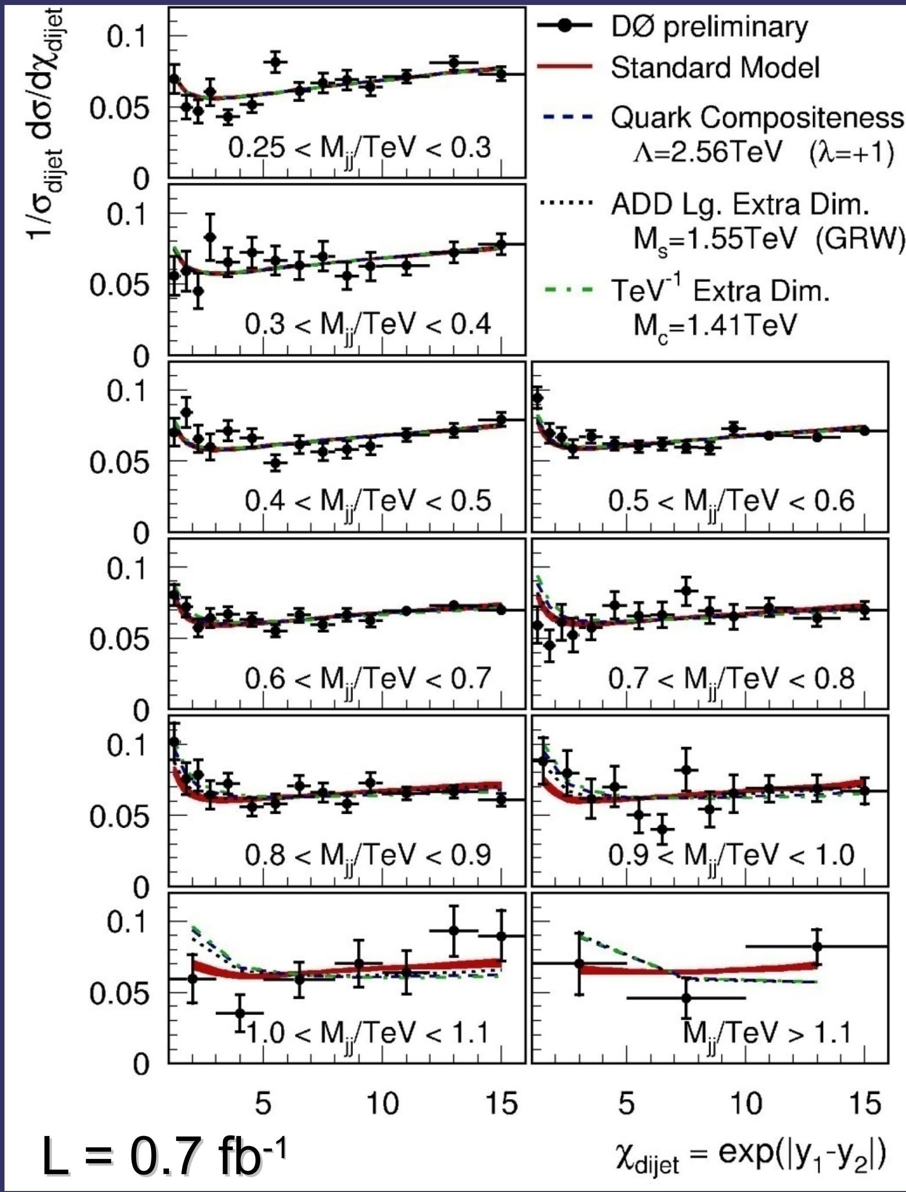
- flat for Rutherford scattering
- relatively flat shape in QCD
- small PDF dependence
- enhancement at low χ_{dijet} for new physics
  - quark compositeness
  - ADD large extra dimensions
  - TeV^{-1} extra dimensions

examine normalized distribution $\frac{1}{\sigma}\frac{d\sigma}{d\chi_{\text{dijet}}}$
to reduce experimental and theoretical uncertainties

Dijet Angular Distribution

- Take data with single trigger (avoid correlated trigger biases)
- Correct distributions to particle level
- Analyze data in ranges of dijet invariant mass





First measurement of angular distributions of a scattering process above 1 TeV

Good agreement w/ QCD, set limits on new physics models

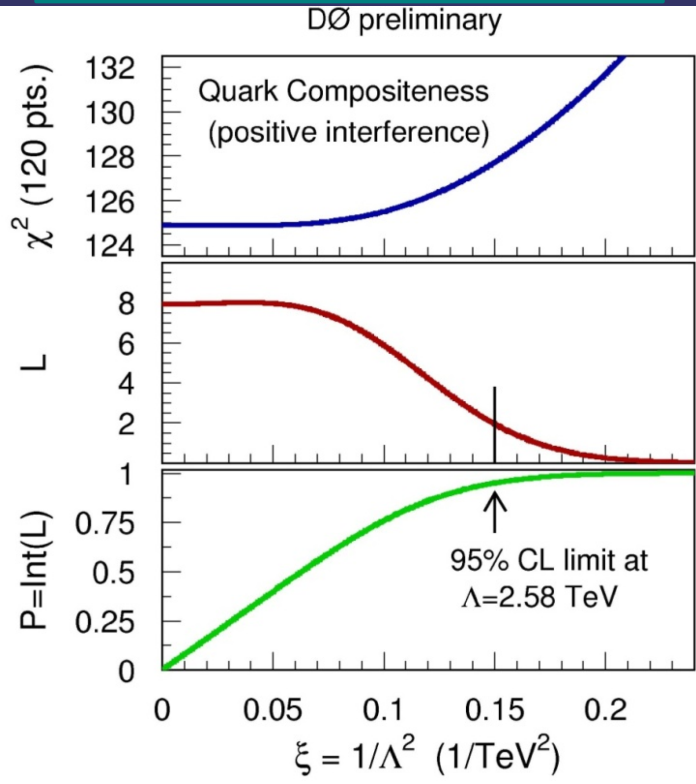
Exclusion limits on new physics models (95% CL)

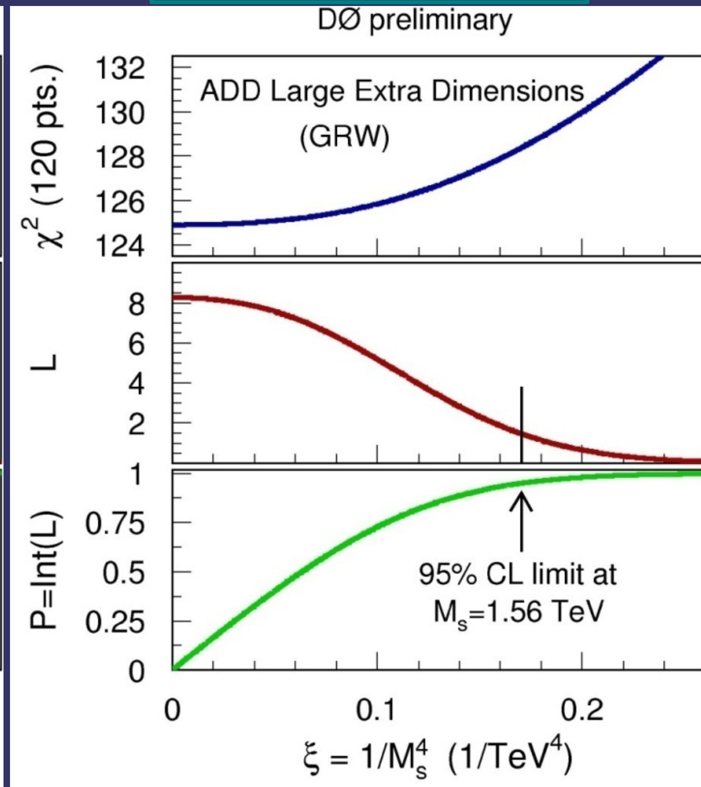
Dijet Angular Distribution

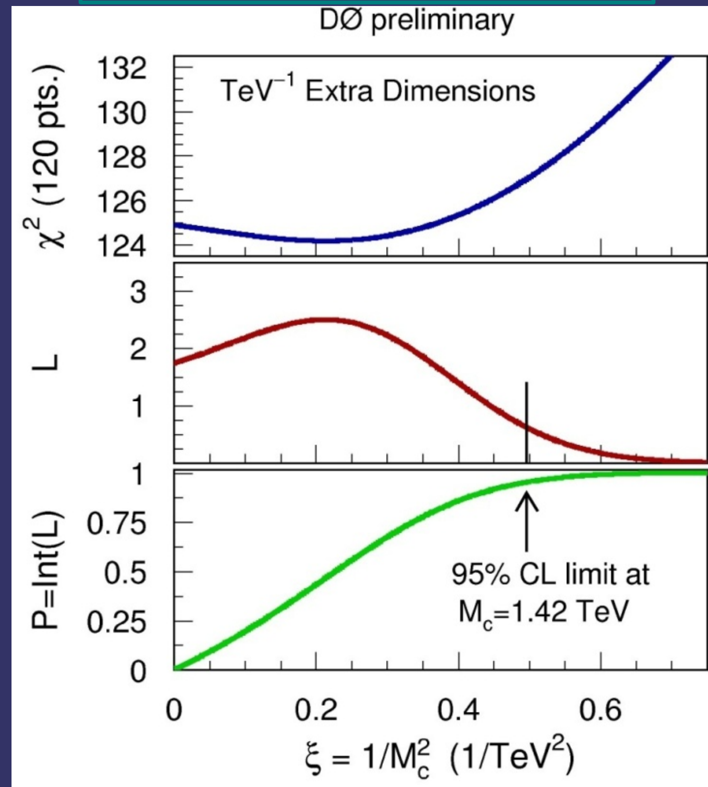
Quark Compositeness:
Λ=2.58 TeV

A.D.D. LEDs:
M_S=1.56 TeV

TeV^{-1} Extra Dims.:
M_C=1.42 TeV







Most stringent limit

Most stringent limit from single process at hadron collider

Strongest limit from a hadron collider

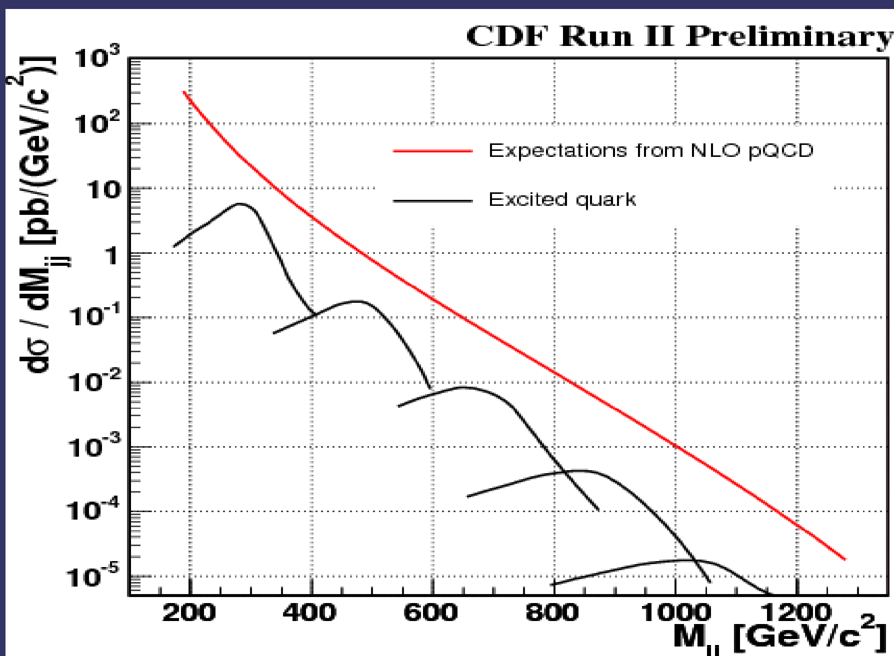
Bayesian limits shown

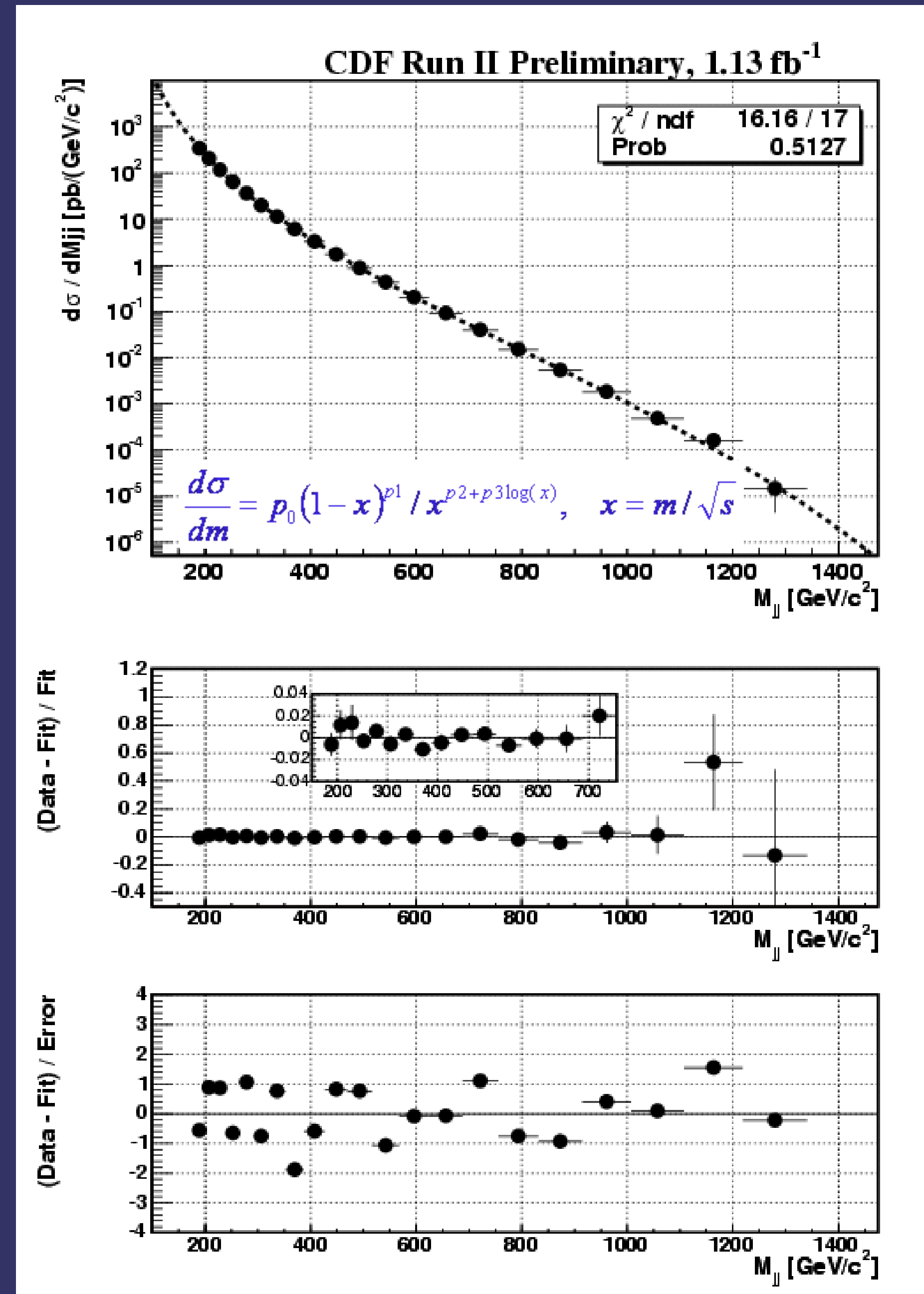
(2007)

Dijet Mass Distribution

Select jets w/in $|\eta|<1.0$
- midpoint cone, R=0.7
- M_{dijet} > 180 GeV

Fit spectrum with parameterized model shape





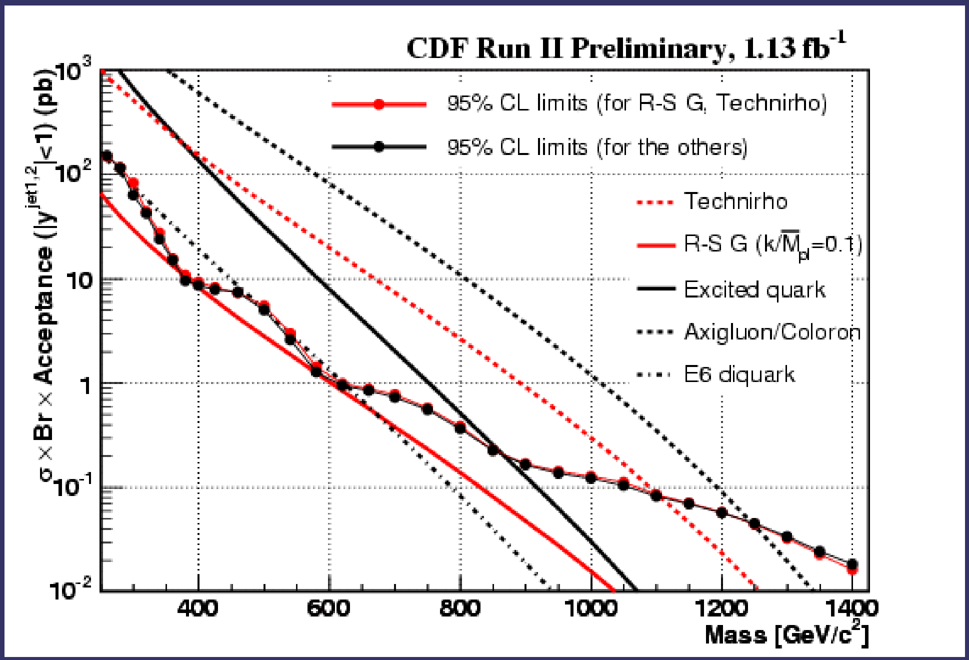
Data with Mjj > 1.2TeV!
Described by NLO pQCD

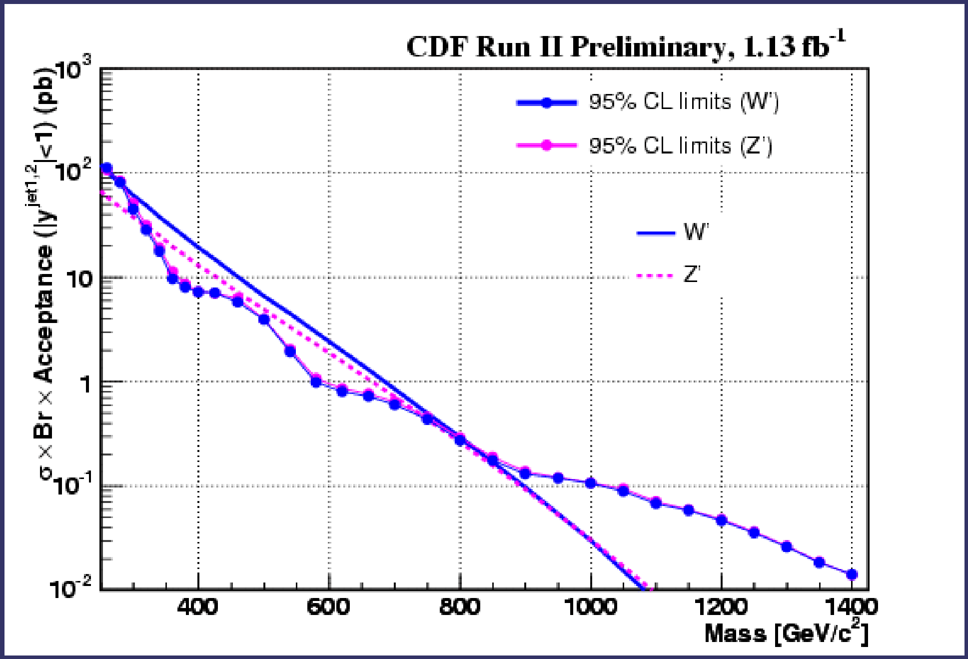
No indications for resonances

Set limits using Bayesian approach

(2007)

Dijet Mass Distribution

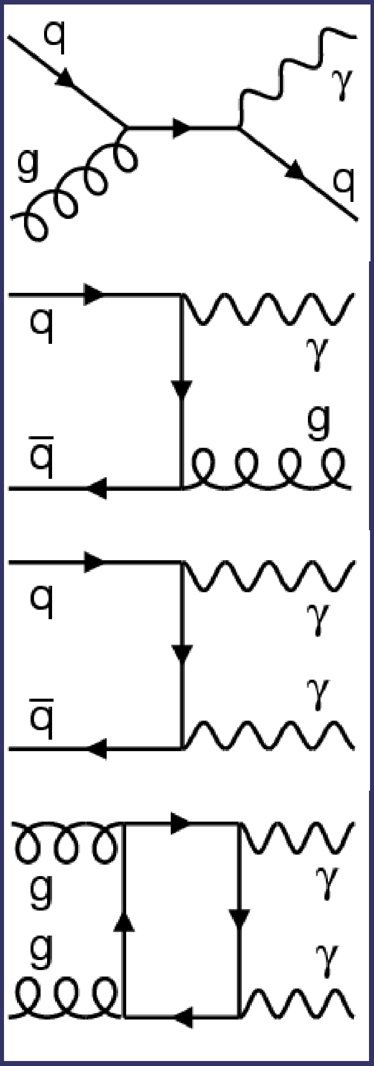




Observed Exclusion	Model
280 – 840 GeV	W′ (SM couplings)
320 – 740 GeV	Z′ (SM couplings)
260 – 870 GeV	Excited quark (SM couplings)
260 – 1100 GeV	Color-octet technirho
260 – 1250 GeV	Axigluon & flavor-universal coloron
290 – 630 GeV	E6 diquark

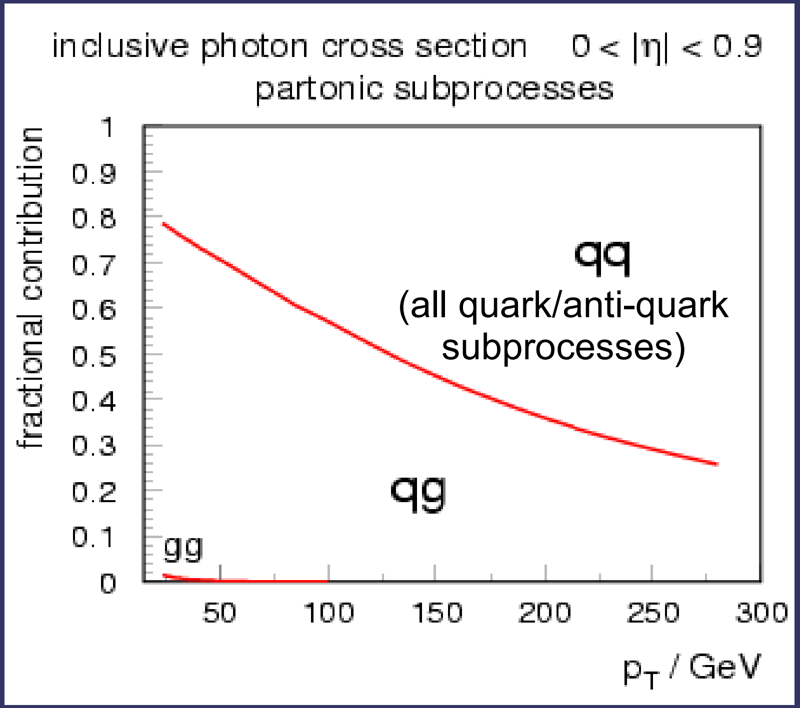
Most stringent limits except for W',Z'

Direct Photon Production

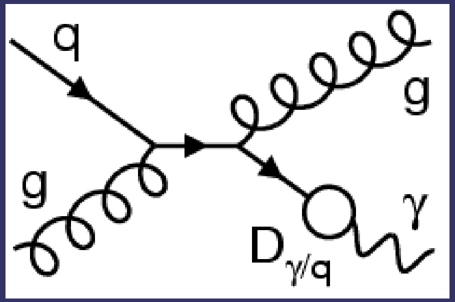


Direct photons come unaltered from the hard subprocess

- direct probe of the hard scattering dynamics
- sensitivity to PDFs (gluon!) …but only if theory works



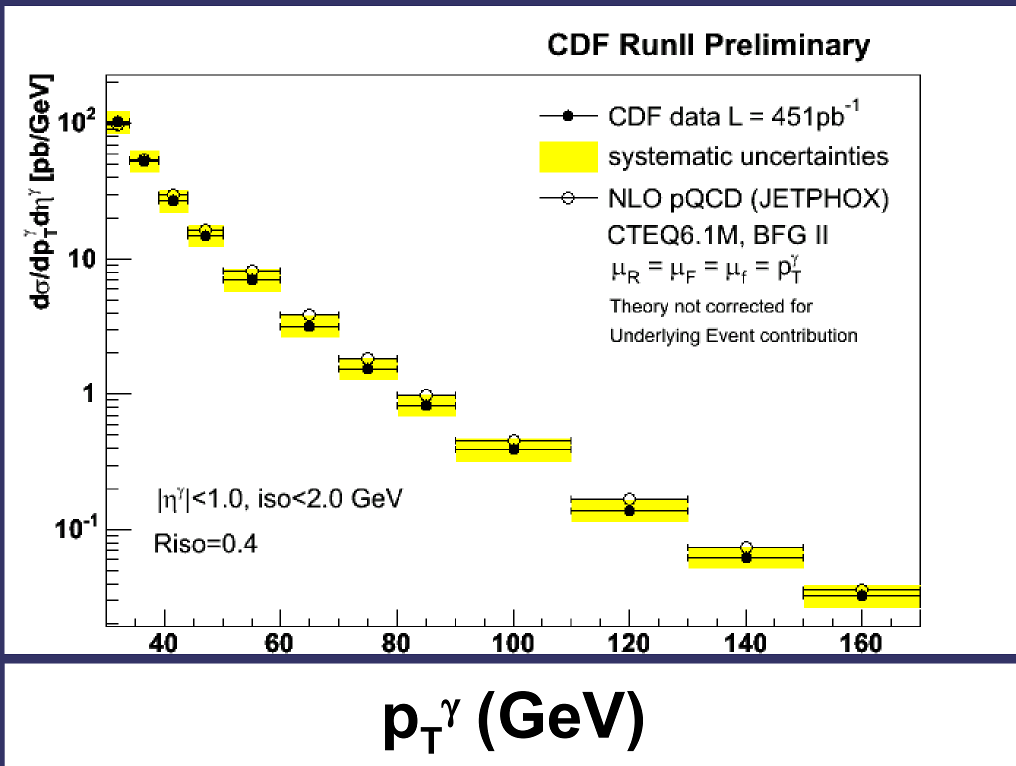
Also have fragmentation contributions...

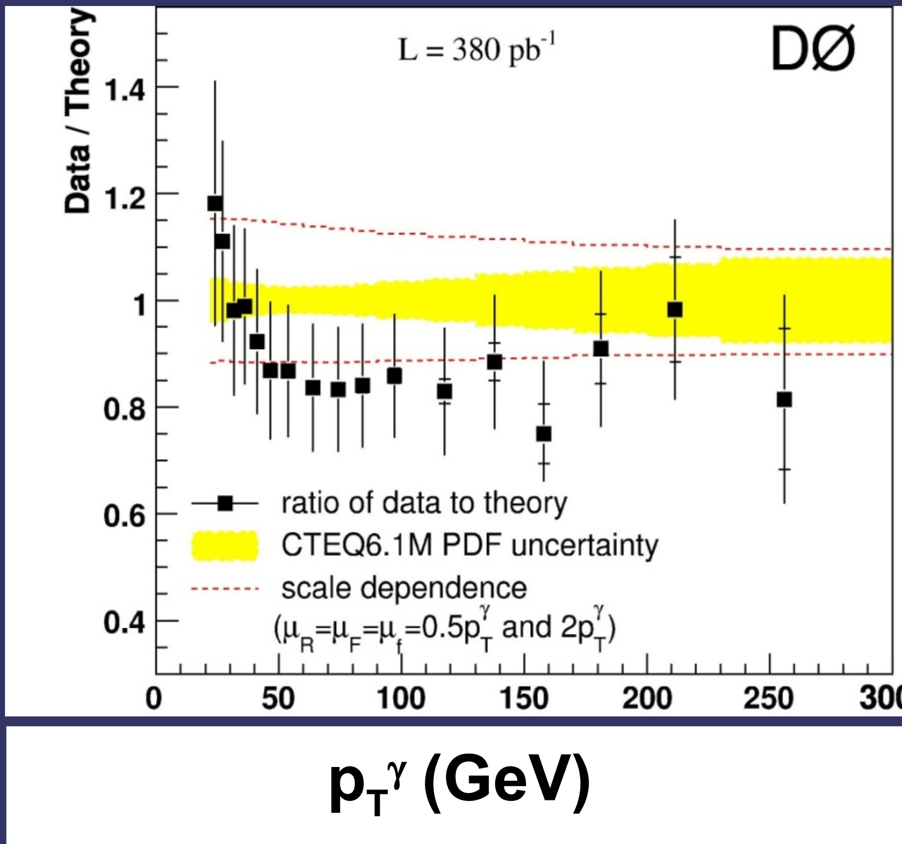


suppress by isolation criterion

observable: **isolated** photons

Direct Photon Production





- CDF and DØ measurements: $20<p_T<300$GeV in agreement
- data/theory: different shape at low p_T
- experimental and theory uncertainties > PDF uncertainty
  → no PDF sensitivity yet

  First/(still!) need to understand discrepancies in shape...

Photon + Jet

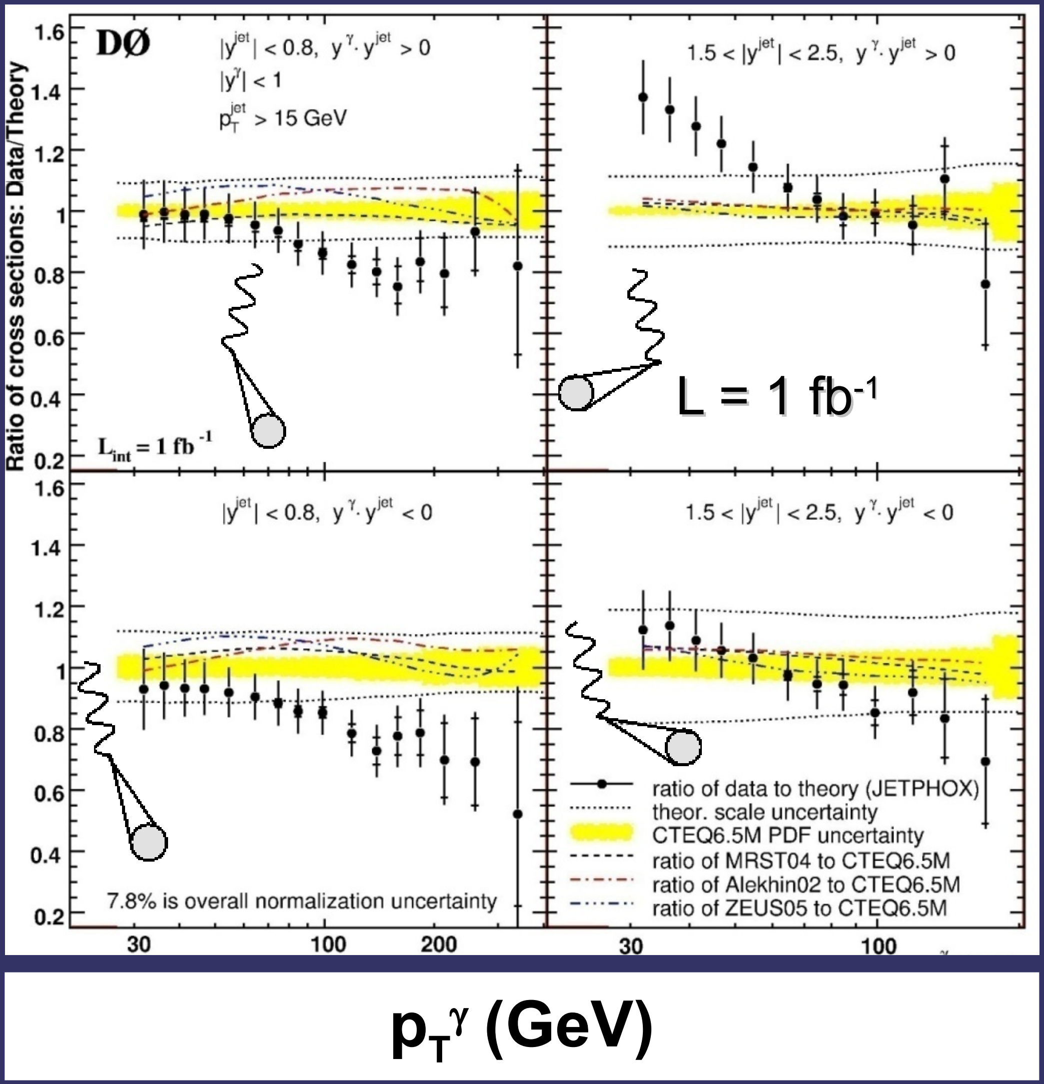
arXiv: 0804.1107

Investigate source(s) for disagreement
→ measure more differential distributions

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

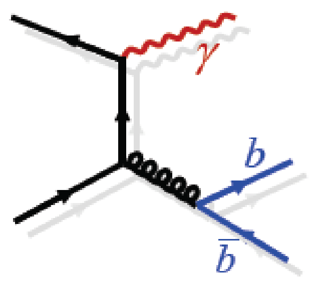
- measure in 4 regions of y^{γ}, y^{jet}
  photon: central
  - jet: central / forward
  - same side / opposite side

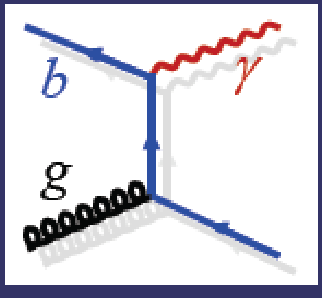
discrepancies in data/theory
→ figure out what is missing…
higher orders?
resummation?
…???

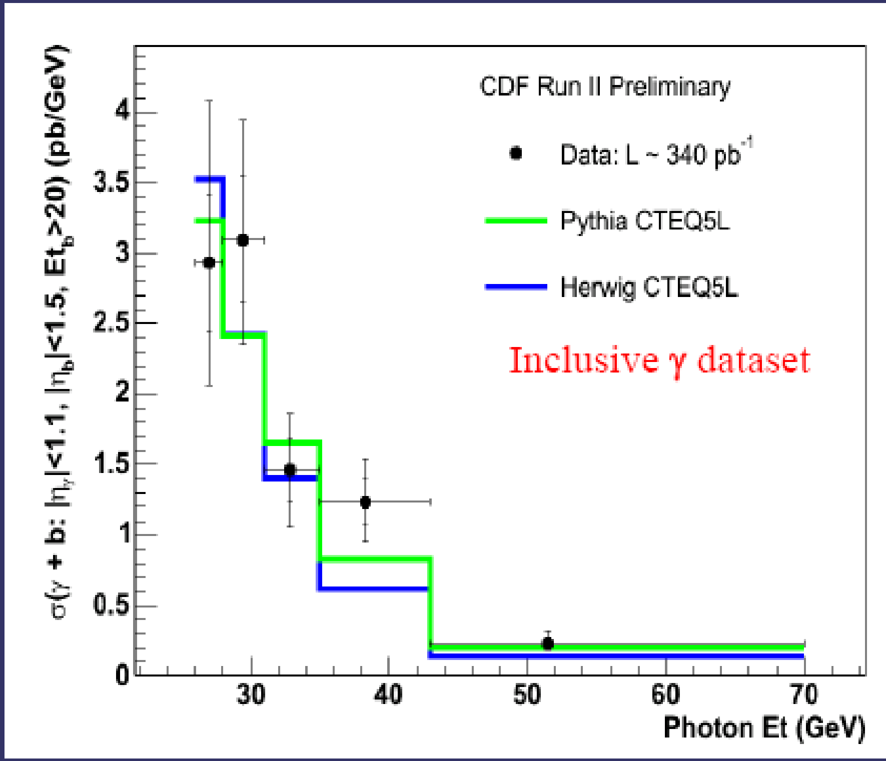


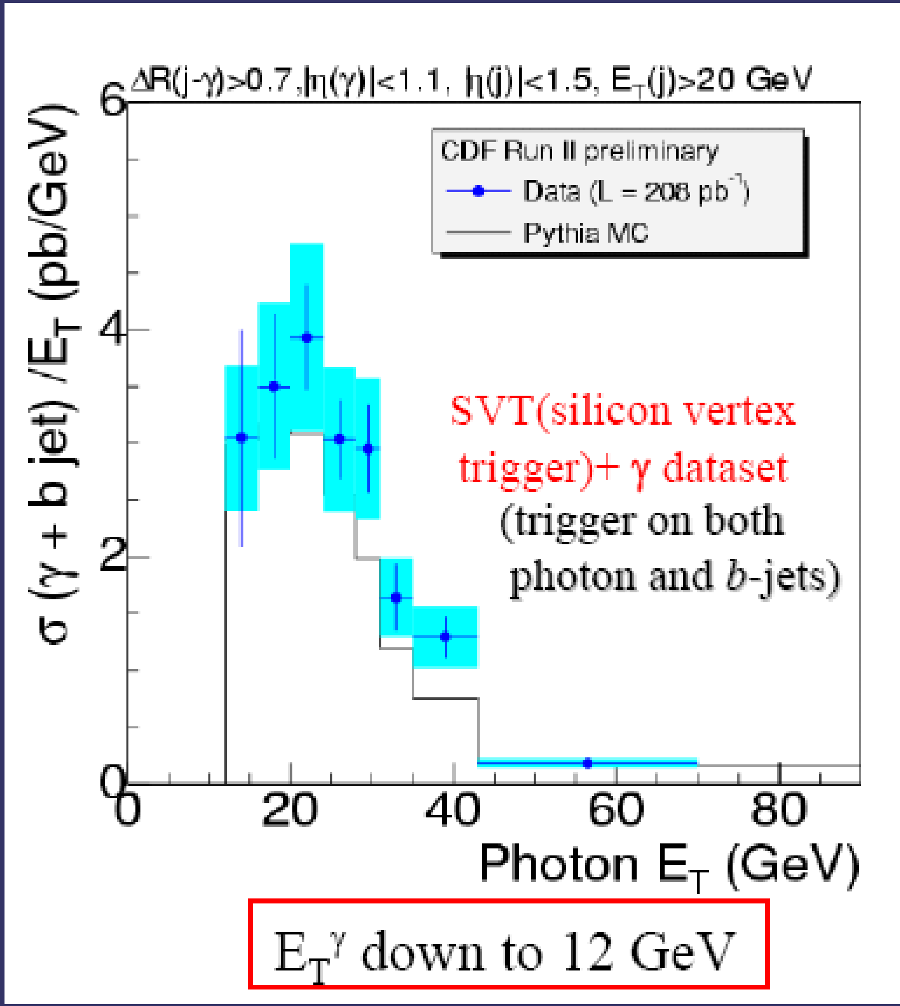
Photon + b Jets

Probe *b*-content of proton
Signature of various physics models
eg. Technicolor, SUSY,
4^{th} generation, excited *b*-quark





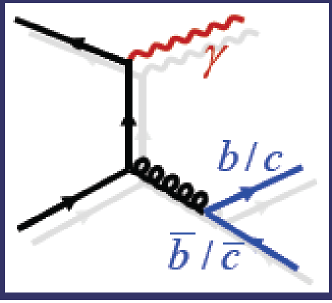


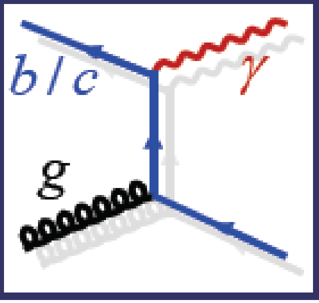


Reasonable agreement with PYTHIA (LO) predictions.
Waiting for NLO pQCD calculations for this process.

Photon + HF (b/c) Jets

Measure triple differential CS: $d^3\sigma/(dp_T^\gamma dy^\gamma dy^{jet})$





$y^\gamma<1.0, |y^{jet}|<0.8$

$y^\gamma \cdot y^{jet}>0$: $0.01<x_1<0.03$, $0.03<x_2<0.09$

$y^\gamma \cdot y^{jet}<0$: $0.02<x_1,x_2<0.06$

p_T^γ : 30 – 150 GeV/c

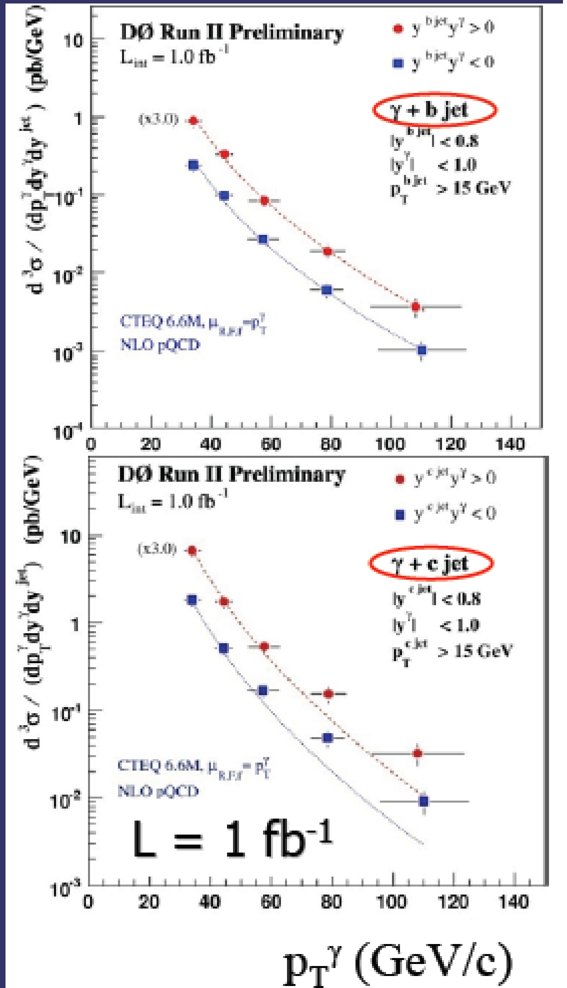
use template-based fit for components

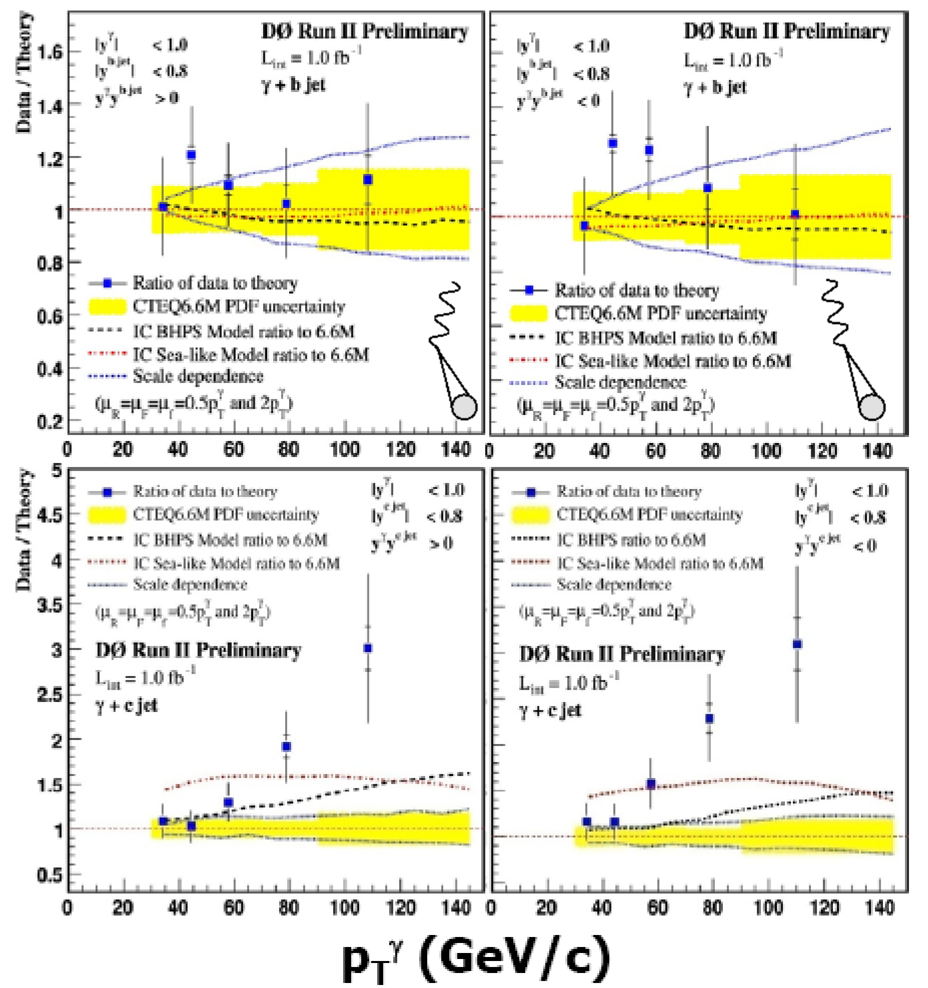
Photon+*b*: →

Agreement over full p_T^γ range: 30 – 150 GeV/c

Photon+*c*: →

- Agree only at $p_T^\gamma<50$ GeV/c
- Disagreement increases with photon p_T^γ.
- Using PDF including the intrinsic charm (IC) improves the p_T^γ dependence



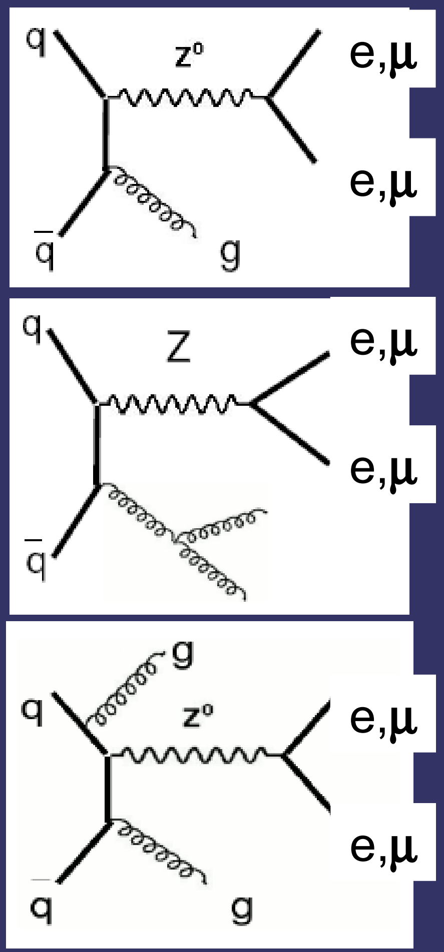


W/Z + Jets

W/Z gives clean measure of production dynamics
- constrain theoretical parameters
- provide data for tuning models

High PT and associated (in)exclusive final jet states
- probe pQCD models
- final state signatures, for much physics
  - top, H, W/Z+H
  - leptoquarks, SUSY, ...
- significant backgrounds to same!

Low P_T Z
- test models of gluon re-summation
- calibration for precision W mass measurement



W/Z + Jets

Understanding SM W/Z + jet production crucial!
W/ Z + 3, 4, 5 jets dominate over many signals: top, Higgs, SUSY, ...
...much more common at LHC

MCFM: NLO pQCD V + <=2 partons

Current event generators
Tree level matrix element + parton shower
matching schemes to avoid double counting jets from ME and PS

- MLM matching (Alpgen, MadEvent, Helac)
- CKKW scheme (Sherpa)
- Dipole Cascade (Ariadne)

Contain (~untuned) internal parameters (arXiv:0706.2569v1 hep-ph)

Alpgen is the main generator at CDF/DØ
Pythia or Herwig used for showering

Z + Jets Inclusive CS Update

Update to CDF Z+jets analysis

$Z \rightarrow ee$ channel, jet $p_T > 30$, $|y| < 2.1$

Differential cross sections in:

leading and second jet p_T, $|y|$

Published with 1.7 fb^{-1}

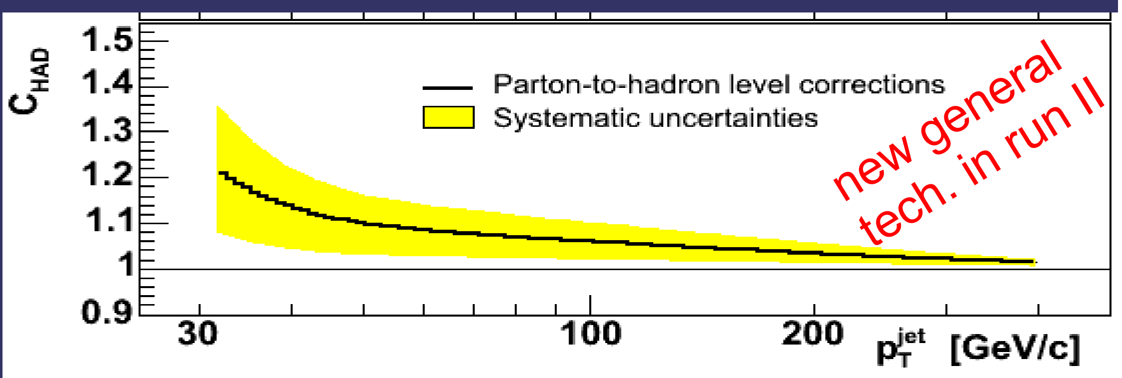
Updated with 2.5 fb^{-1}

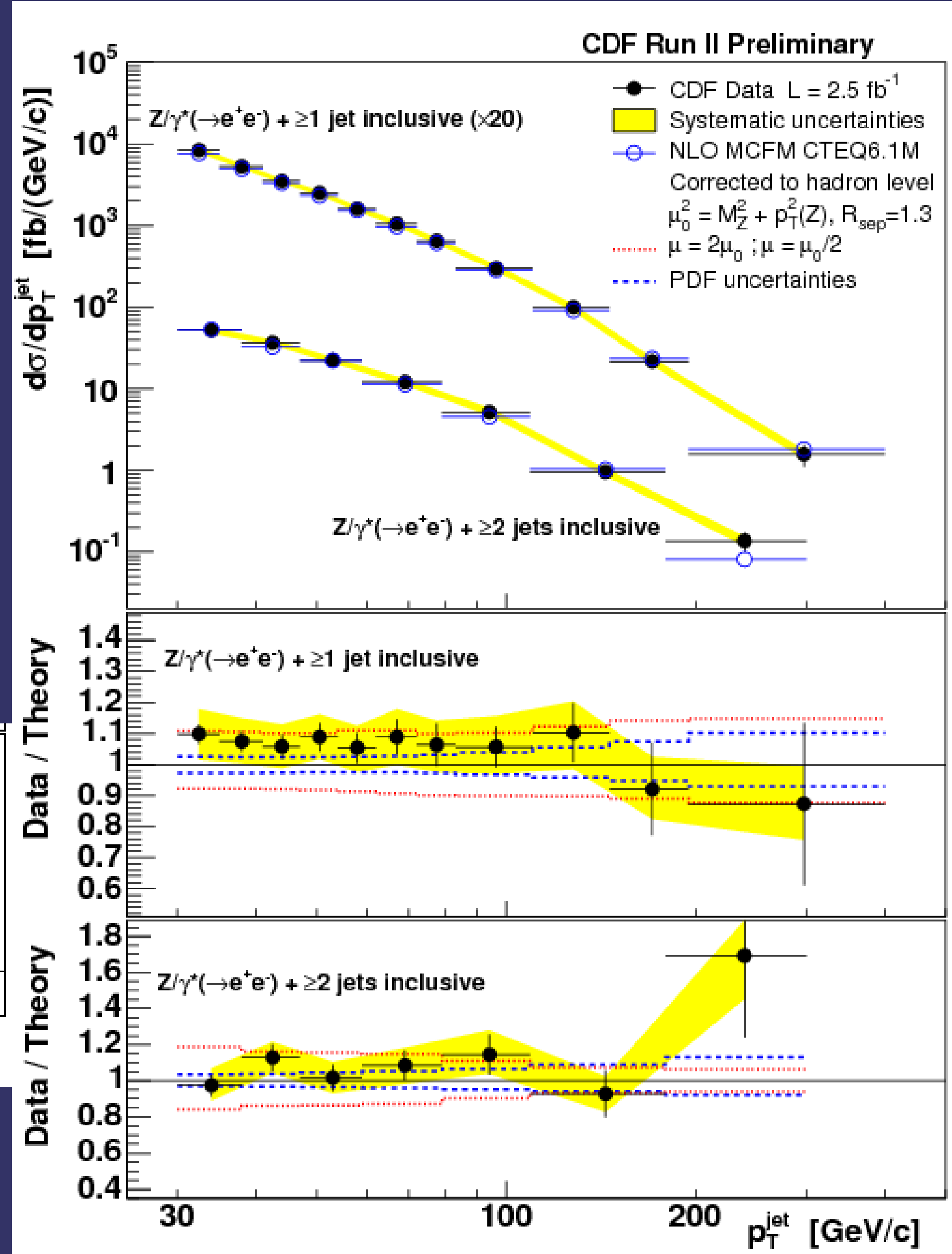
Improved result in high p_T tail

Compared to pQCD NLO prediction (MCFM)

derived corrections from Pythia:

nonperturbative effects, underlying event





NLO describes shapes well!
normalization agrees within uncertainties.

jet: $p_T > 20$ GeV/c,
mouns: $p_T > 15$ $|y|<1.7$

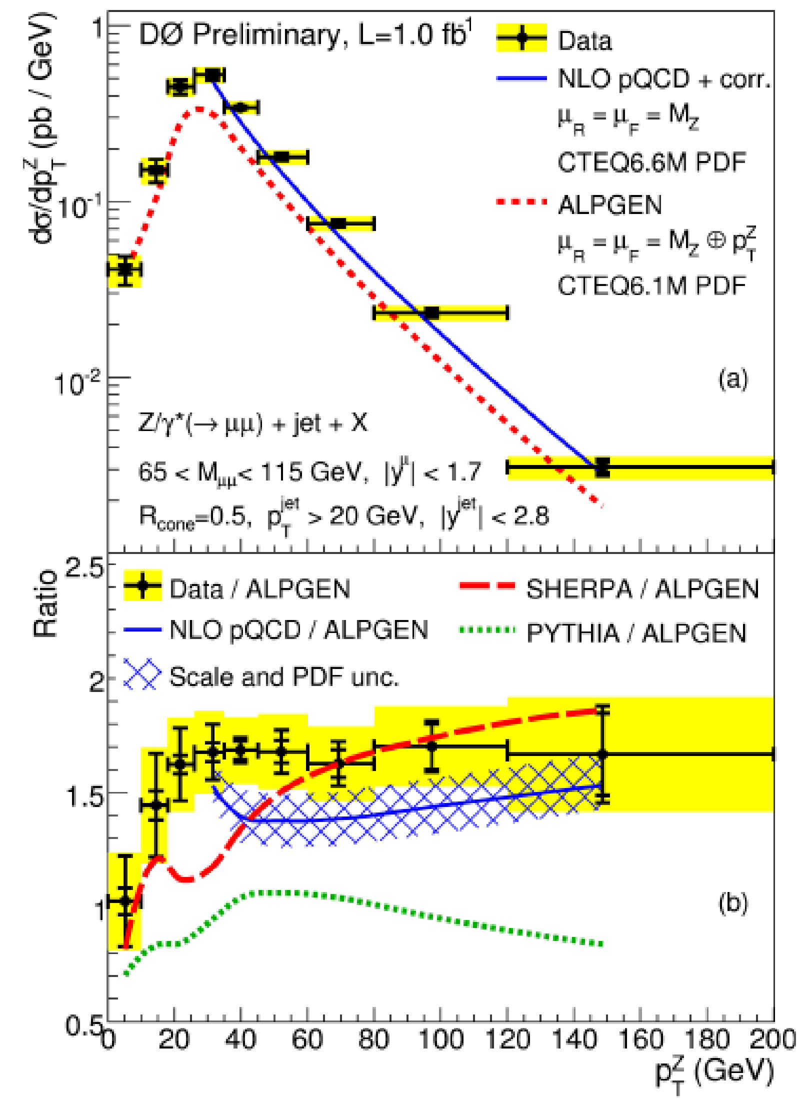
New in Z + Jets

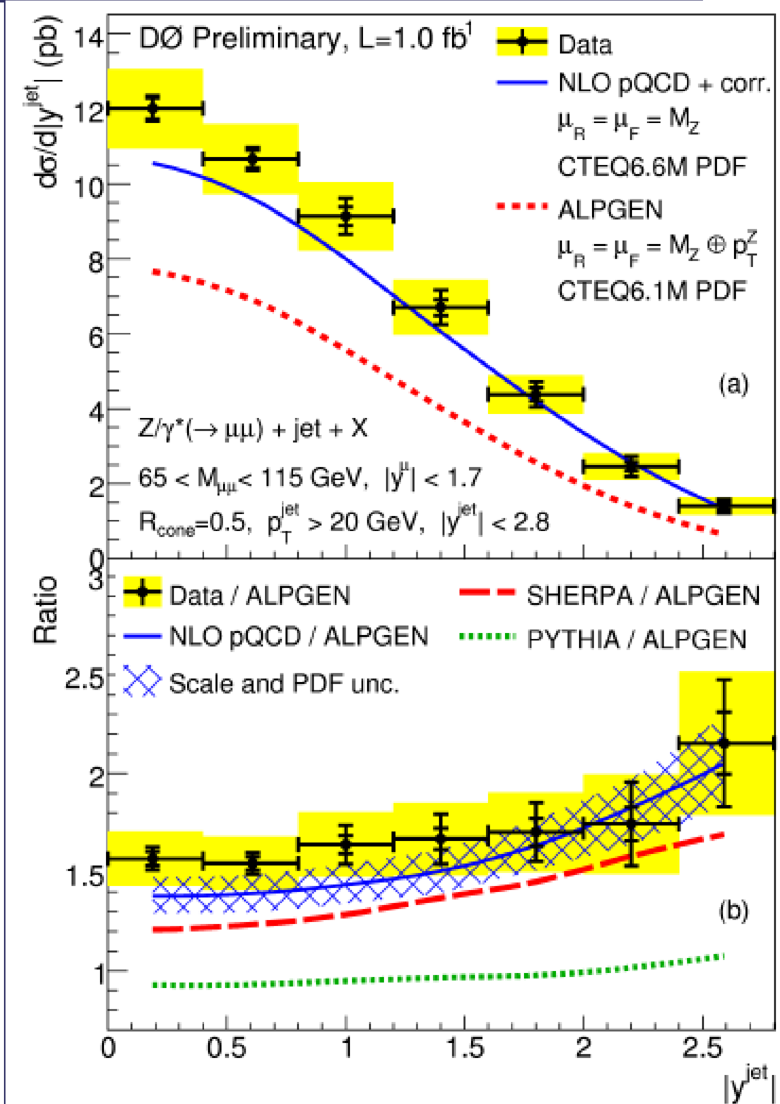
arXiv:0808.1296

New DØ analysis of $Z\to\mu\mu$ channel, 1 fb^{-1}

Differential CS in: p_T^{jet}, $|y^{jet}|$ & p_T^{Z}, $|y^Z|$

- comparisons to:
  - NLO pQCD + corrections
  - ME+PS ALPGEN
  - ME+PS SHERPA
  - PS PYTHIA





- Test best predictions for V+jet production at hadron colliders. → test/improve generators/models
- Shapes generally described by pQCD (low P_T region dominated by non-perturbative processes...)
- Total CS and shape differences in ALPGEN / PYTHIA / SHERPA

PRL 100, 102002 (2008)

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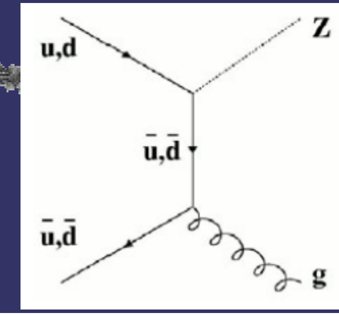
Z pT



High p_T dominated by hard parton emission, pQCD

Low Z p_T mainly from soft gluon emission: (pT <~30 GeV/c)
gluon re-summation, BLNY parameterization:

$$S_{NP}(b, Q^2) = [g_1 + g_2 \ln(\frac{Q}{2Q_0}) + g_1 g_3 \ln(100 x_i x_j)]b^2$$

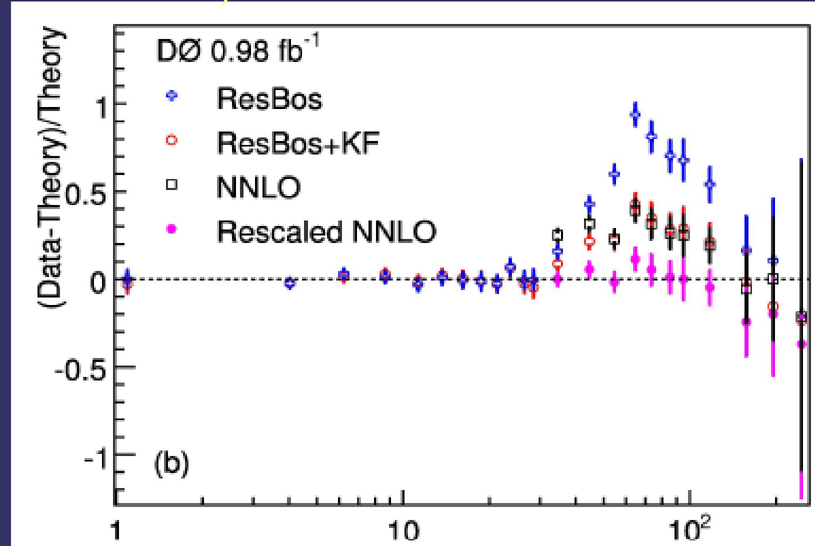
Implemented in RESBOS MC

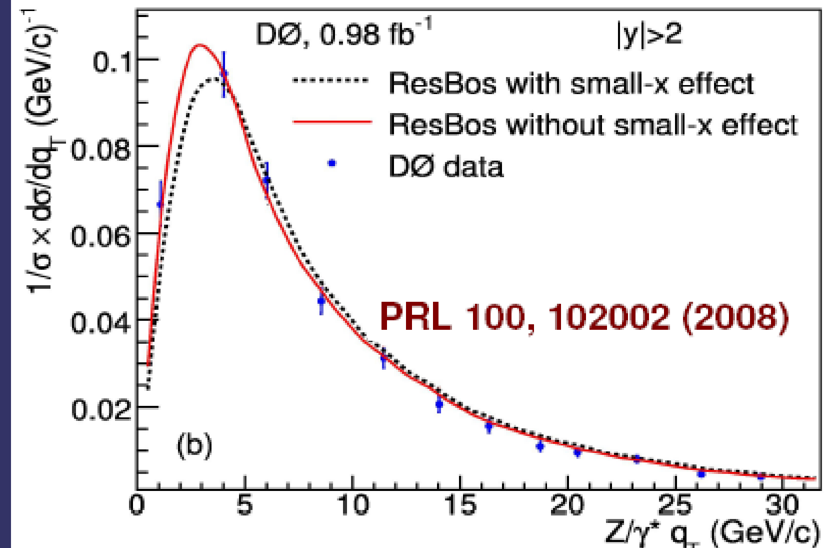
Measure at Tevatron in Z->ee over
full p_T range <260 GeV/c

- High p_T: Shape well described by pQCD, but needs +25% scale factor to correct normalization

- Low p_T: Well described by RESBOS

extract g_2=0.77±0.06 (World Average $0.68^{+0.02}_{-0.01}$)
Analysis limited by experimental resolution

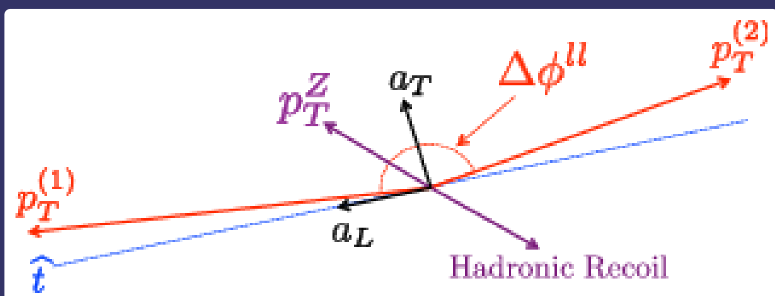




New Z pT

New DØ analysis
2fb^{-1}, combine ee/μμ channels

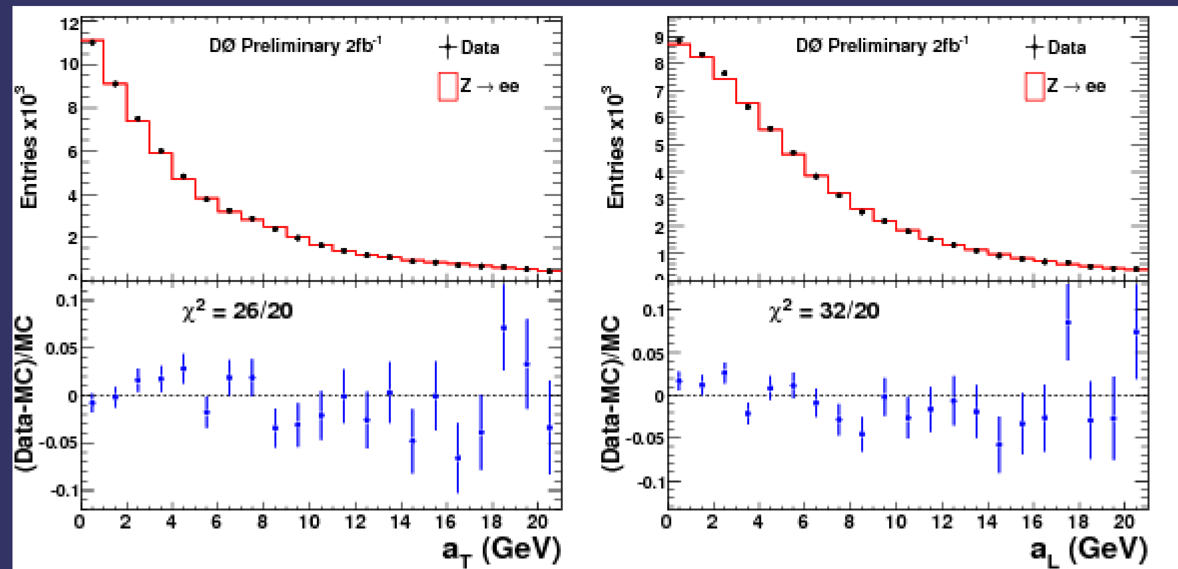
Increase sensitivity to g_2 by using new variable, a_T largely insensitive to experimental resolution

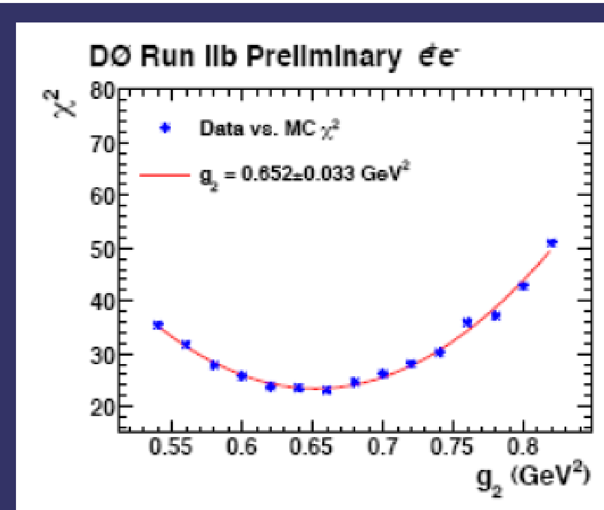


-RESPOS run w/ varying g_2 values
-re-weight PYTHA+detector sim
-fit PYTHIA samples to data

Statistics limited (~±4% stat)!

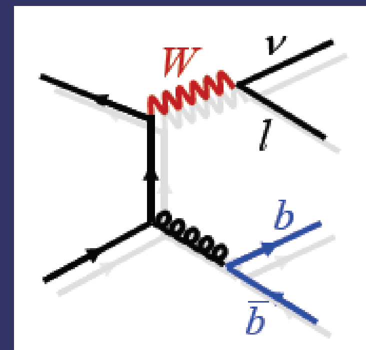
(Data not unfolded for prelim. result)

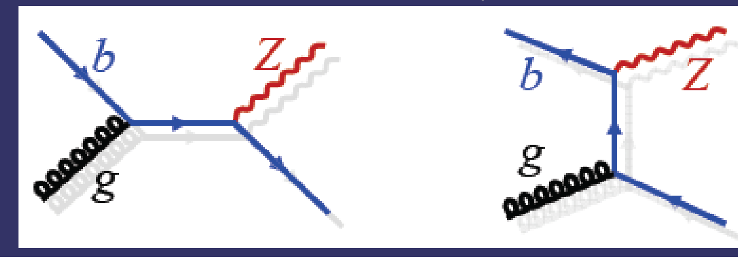


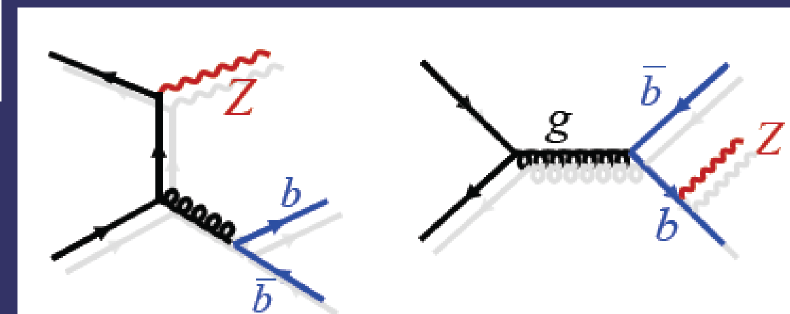


Result: g_2=0.63 ± 0.02 (exp) ± 0.03 (PDF)
Best single measure, comparable to World Average

W/Z + Heavy Flavor







<u>QCD</u>

- γ/W/Z provides direct probe of hard scattering dynamics
- for W/Z $q^2 \sim M_{W/Z} \rightarrow$ perturbative theory
- sensitivity to HF content of proton PDF

<u>Bkgd for many channels</u>

- W/Z+HF: ttbat, sngl top, Higgs, SUSY, Technicolor,...
- γ+HF: SUSY, Technicolor, new generations, q-compositeness, ...

Vector boson + HF jets important to overall physics program

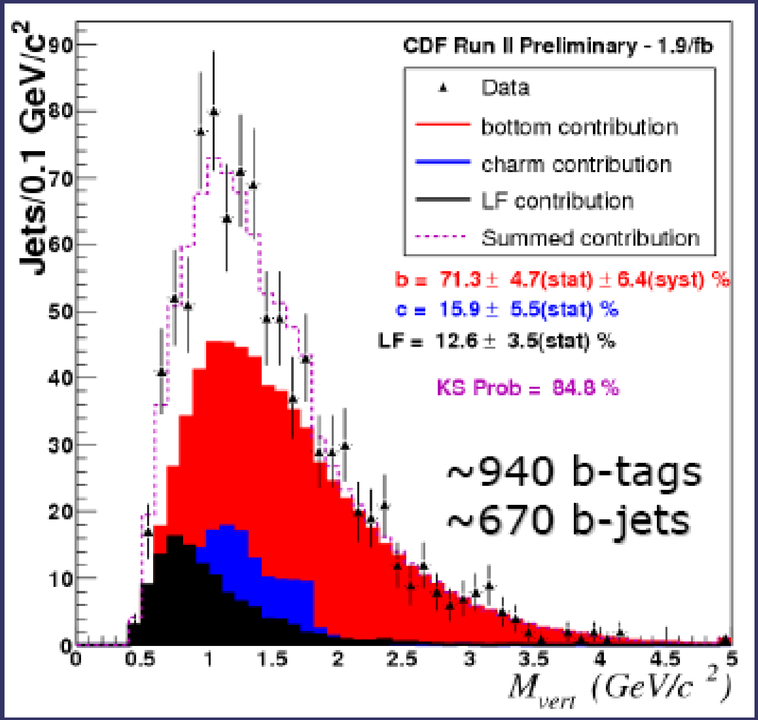
Must understand these processes to maximize physics potential

Major bkgd for SM Higgs (W/ZH, H->bbbar)

Measure of b-content of proton to model:
- sngl-top production : qb->q't, gb->Wt
- SUSY Higgs prod. : gb ->hb, bbar->h

W/Z + b

W+b



$p_T^{e,\mu} > 20$ GeV/c, $|\eta^{e\mu}| < 1.1$, $p_T^{\nu} > 25$ GeV/c

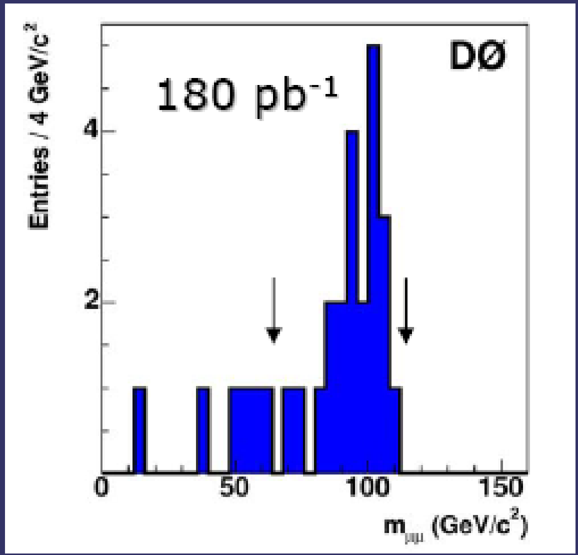
$E_T^{bjet} > 20$ GeV, $|\eta^{bjet}| < 2.0$ (tight b-tag)

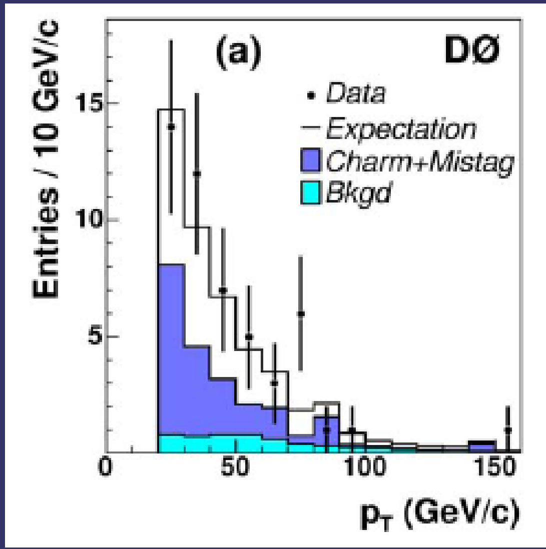
Measurement: $\sigma \cdot BR = 2.74 \pm 0.27 \pm 0.42$ pb

Alpgen (LO): $\sigma \cdot BR = 0.78$ pb

3.5X larger than ALPGEN prediction, waiting for other predictions (MCFM NLO, etc)

Z+b





Measure of ratio σ(Z+b jets)/(Z+jets) cancels many systematic uncertainties

$p_T^{jet} > 20$ GeV/c, $|\eta^{jet}| < 2.5$

Measurement: $2.1 \pm 0.4^{+0.2}_{-0.3}$ %

In agreement w/ NLO prediction: 1.8 ± 0.4 %

PRL 94, 161801

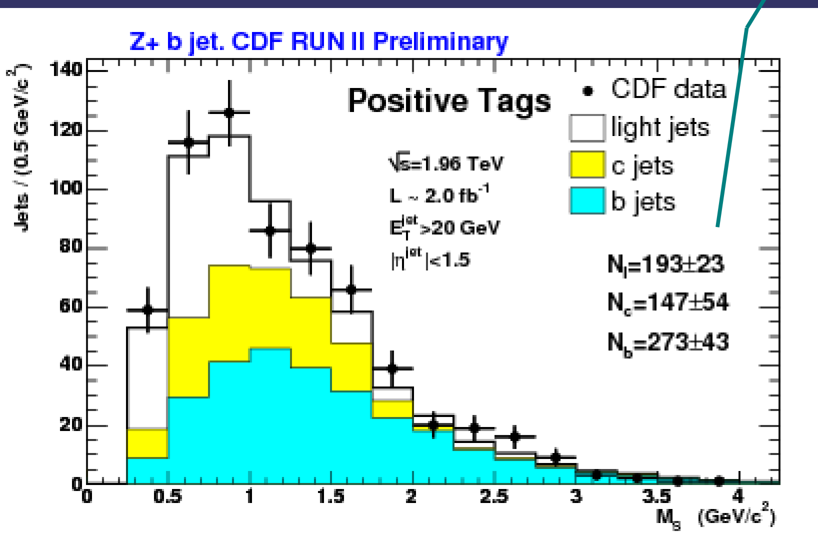
also CDF Phys. Rev. D 74, 032008

Z + b

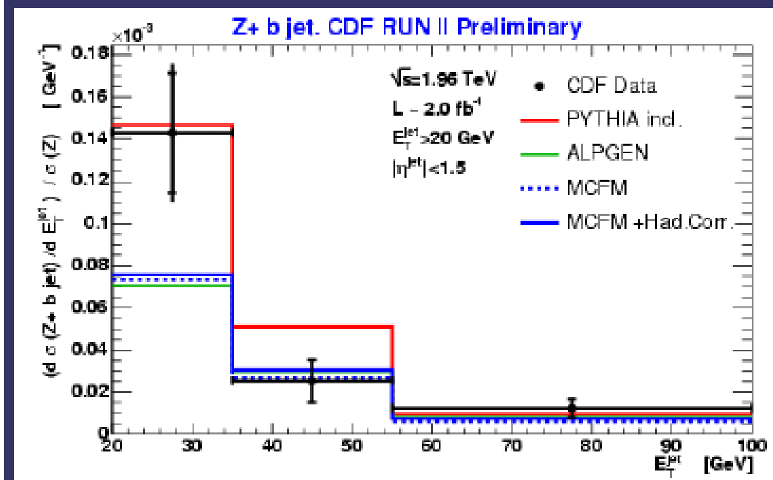
First measurement of differential distributions: p_T^Z, E_t^{jet}, $|\eta^{jet}|$, ...

$2fb^{-1}$, Z->ee/μμ
b-jet ID: Tight 2ndary vertex tagging

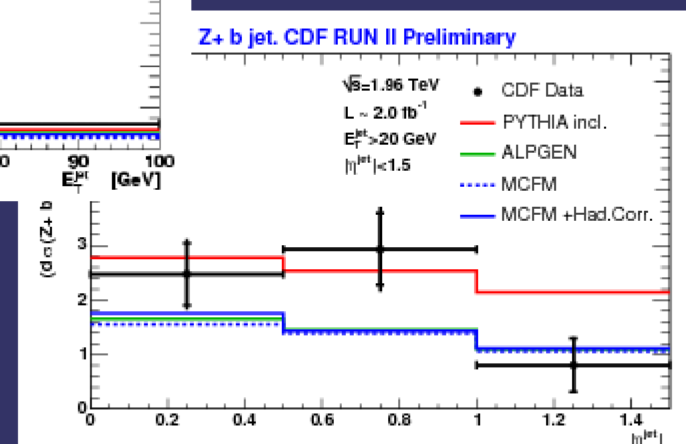
b, c and light fractions determined from template fit of secondary vertex mass distributions



Invariant mass of tracks at 2ndary vertex



E_t^{jet}



$|\eta^{jet}|$

Data somewhat higher than NLO predictions. PYTHIA (LO) reasonable in some kinematic regions NLO vs PYTHIA Differences not well understood yet.

$E_T^{jet}>20$ GeV, $\lvert\eta^{jet}\rvert<1.5$ $R_{jet}=0.7$	Measurement	PYTHIA	Alpgen	NLO	NLO + UE + hadr.
σ(Z+b-jet)	0.86 ± 0.14 ± 0.12 (pb)			0.51 pb	0.53(pb)
σ(Z+b-jet)/ σ(Z)	0. 336 ± 0.053 ± 0.041 %	0.35 %	0.21%	0.21 %	0.23 %
σ(Z+b-jet)/ σ(Z+jet)	2.11 ± 0.33 ± 0.34 %	2.18 %	1.45%	1.88 %	1.77 %

W + Single c Production

Probe s-content of proton at high Q2

- g+s ~ 90%, g+d ~ 10%

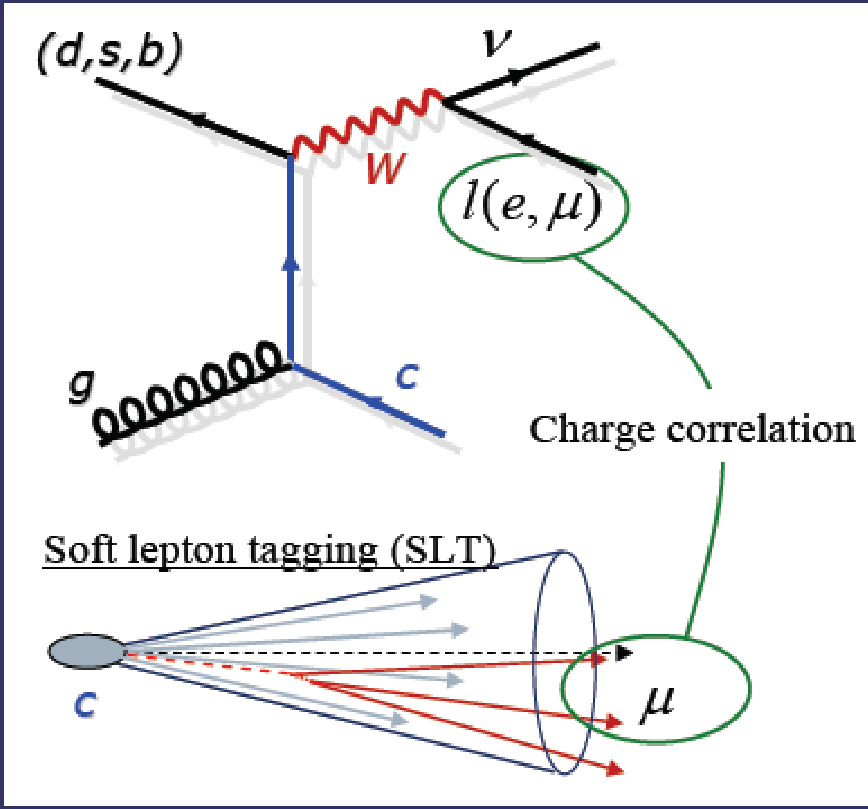
Important bkgd for top, Higgs, stop, ...

W→lν selected by high p_T (e,μ) + MET

Charm-jet ID by soft lepton (μ) tagging (SLT) algorithm

Use charge correlation between W lepton and SLT muon:

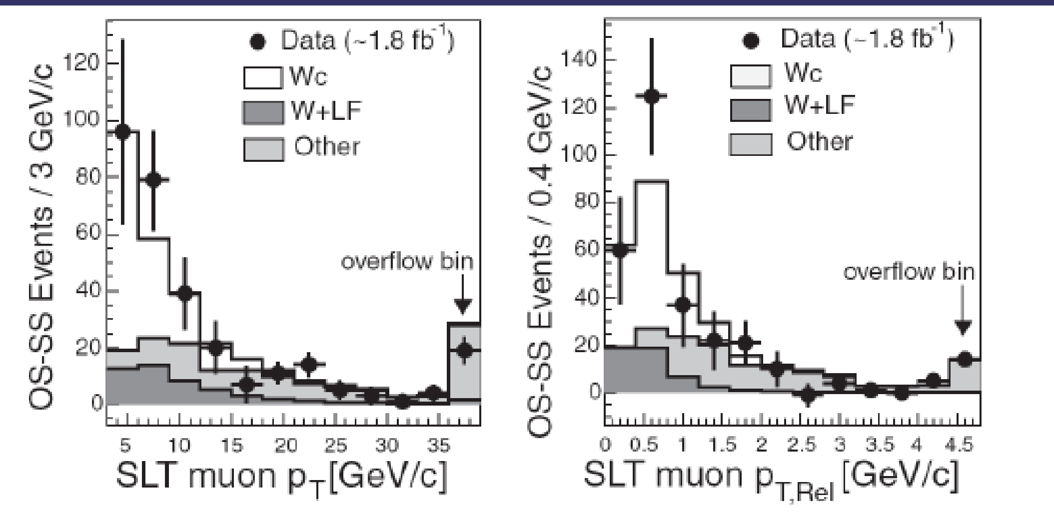
- In W+c : opposite sign (OS) > same sign (SS)
- In W+bb(cc) : OS ~ SS



Provides direct experimental evidence of the underlying partonic process qg → Wq', should dominate W boson production LHC

W + Single c Production

Phys. Lett. B 666 , 23 (2008)

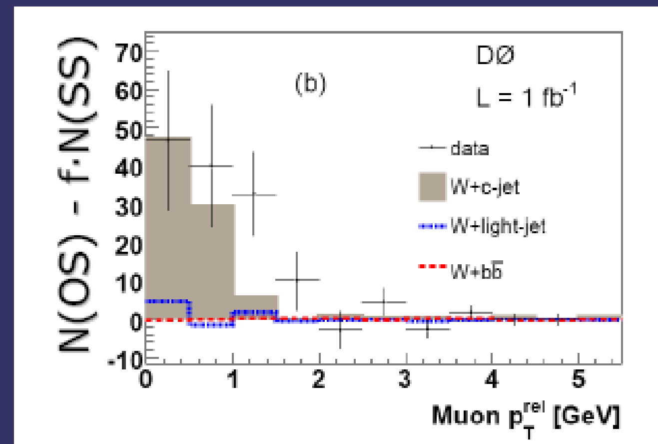


Total: 298 events, W+c = 149 ± 42 ± 15 events.

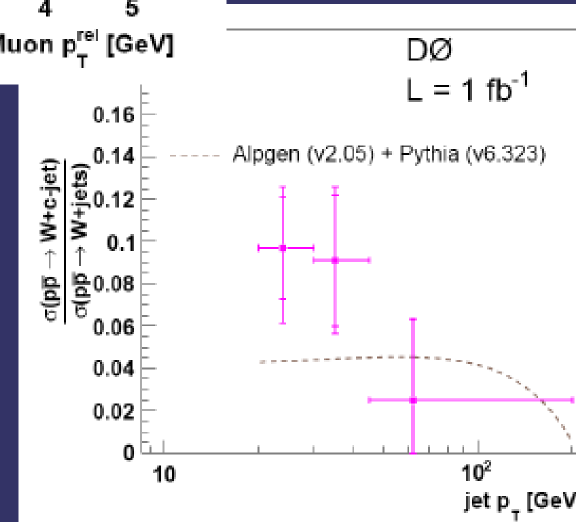
$p_T^c > 20$ GeV/c, $|\eta^c| < 1.5$

Measure of ratio σ(W+c jet)/(W+jets) cancels many systematic uncertainties

$p_T^{jet} > 20$ GeV/c, $|\eta^{jet}| < 2.5$



Measure as function of jet p_T



Measurement: $\sigma_{W+c} \cdot BR(W \to l\nu) =$
$9.8 \pm 1.8(stat)^{+1.4}_{-1.6}(sys) \pm 0.6$ (lum) pb

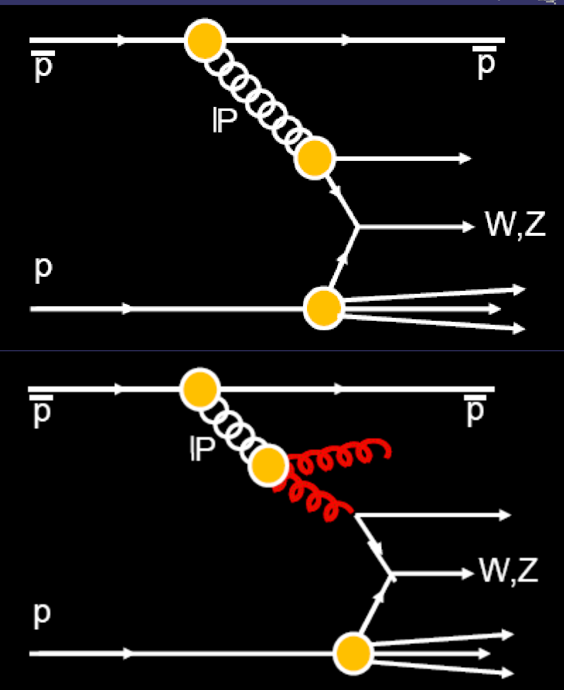
Good agreement w/
pQCD NLO: $11.0^{+1.4}_{-3.0}$ pb

PRL 100, 091803 (2008)

ALPGEN +PYTHIA: 0.040± 0.003 (PDF)

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

Diffractive W/Z Production



The study of diffractive W/Z production helps to determine the quark content of the pomeron

- To LO W/Z is produced by a quark in the pomeron
- Production by gluons suppressed by factor α_S, can be distinguished from q-production by additional jet

Use Roman Pots to get accurate ξ^{RP} measurement

$$\xi^{cal} = \sum_{towers} \frac{E_T}{\sqrt{s}} e^{-\eta}$$

As in diffractive dijet case, can calculate ξ^{CAL} from energy in calorimeter

Neutrino missing E yields $\xi^{CAL} < \xi^{RP}$, ξ^{RP}-ξ^{CAL} determines ν kinematics

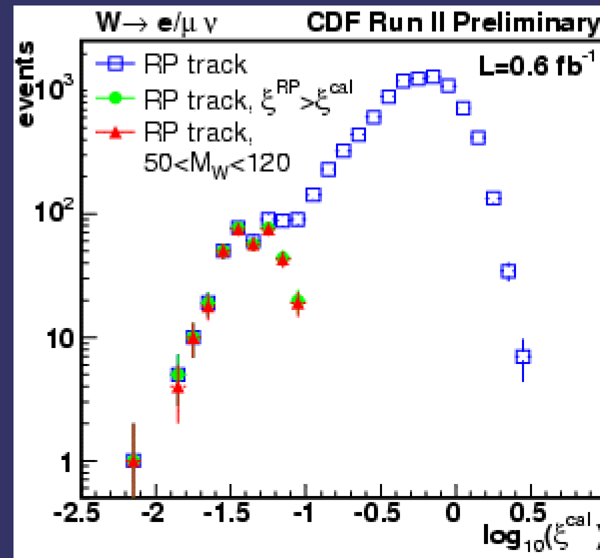
$$\xi^{RP} - \xi^{cal} = \frac{\not{E}_T}{\sqrt{s}} e^{-\eta_\nu}$$

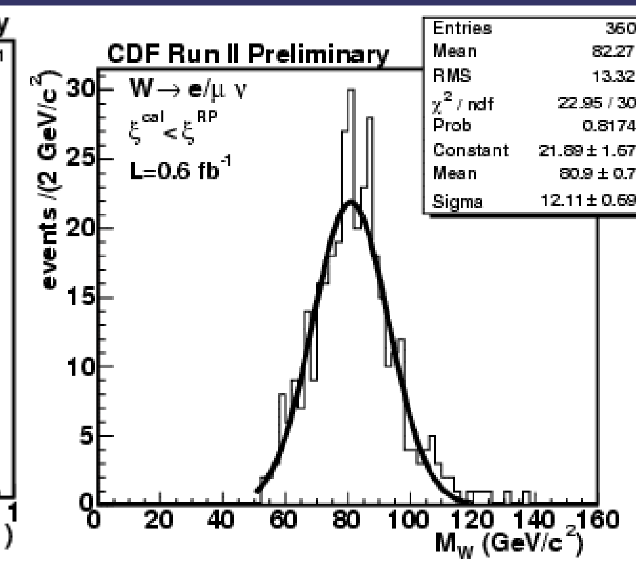
- Goal to determine structure function using diffractive W production
- Measurement of exclusive production (ee,$\gamma\gamma$,jets,W/Z) calibrate predictions for exclusive Higgs at LHC

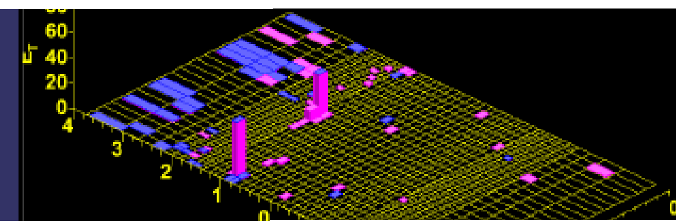
Diffractive W/Z Production

$\xi^{CAL} < \xi^{RP}$ requirement removes most multi-p-pbar events

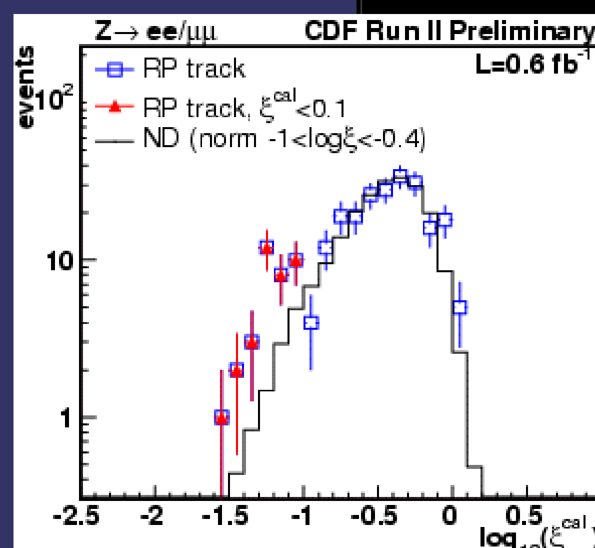
Fraction of W's from diffraction
R_W (0.03<ξ<0.10,|t|<1)
=[0.97±0.05±0.11]%
Consistent w/ Run1 results
(extrapolated to all ξ)

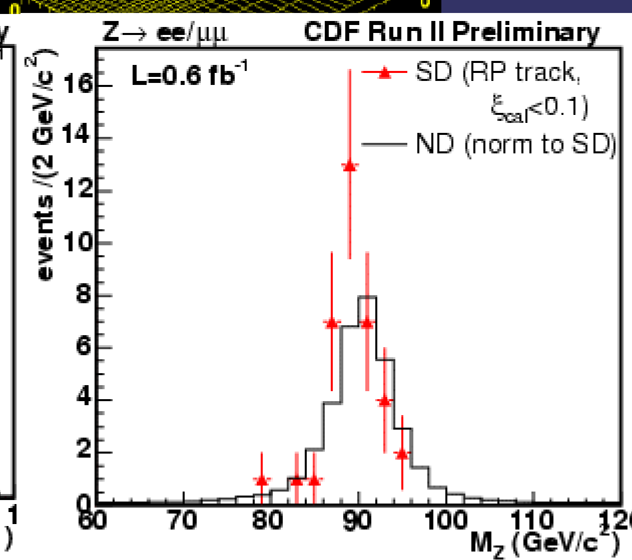






37 diffractive Z-> ee/mm
expected bkg from 11ND+SD overlap





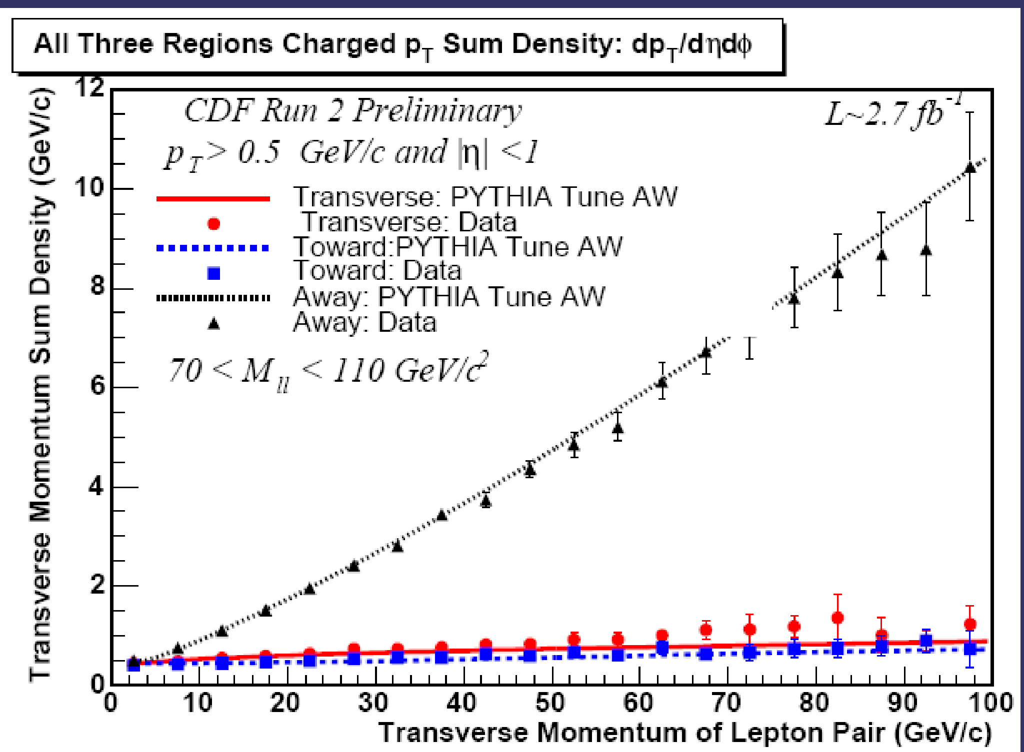
Fraction of Z's from diffraction
R_Z (0.03<ξ<0.10,|t|<1)
=[0.85±0.2±0.11]%

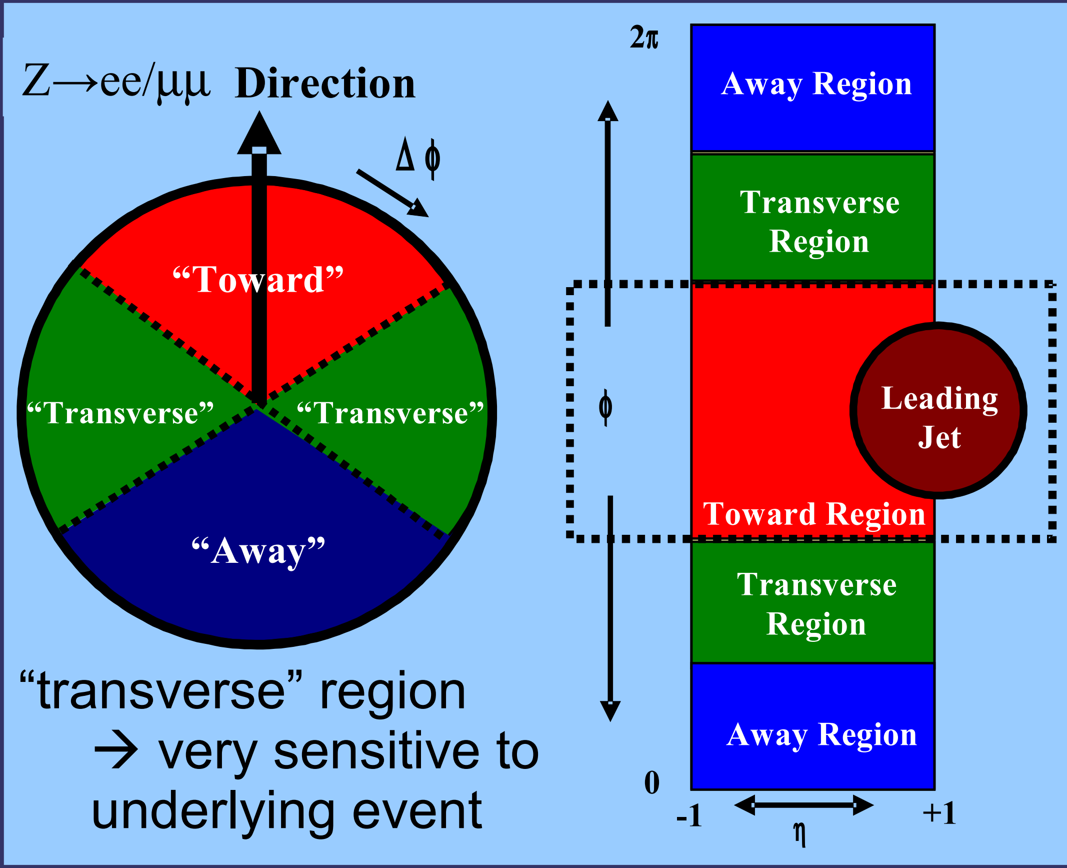
ULE in Drell-Yan + Jet Production

Goal: improve understanding and modeling of high energy collider events...

Study charged particle, p_T/E_T densities:

- "away" region: p_T density increases with lepton pair p_T
- "transverse", "toward" regions: p_T density flat with lepton pair p_T





Similar trend in "transverse" region between **jets and DY** tuned PYTHIA describes data

ULE in Drell-Yan + Jet Production

Goal: improve understanding and modeling of high energy collider events...

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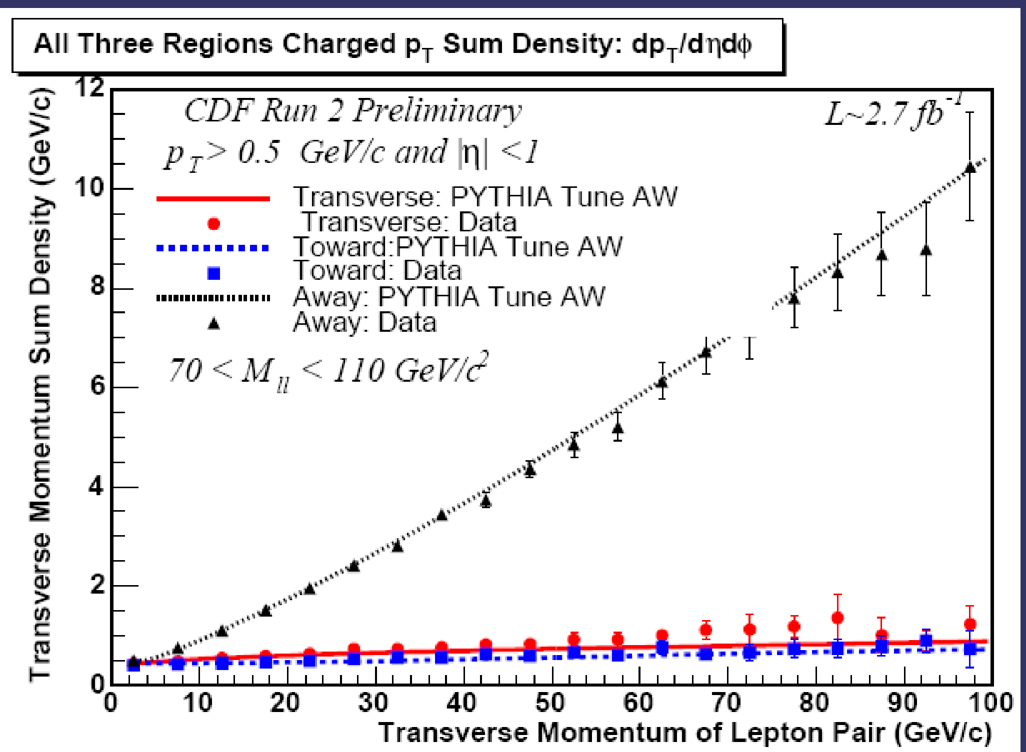

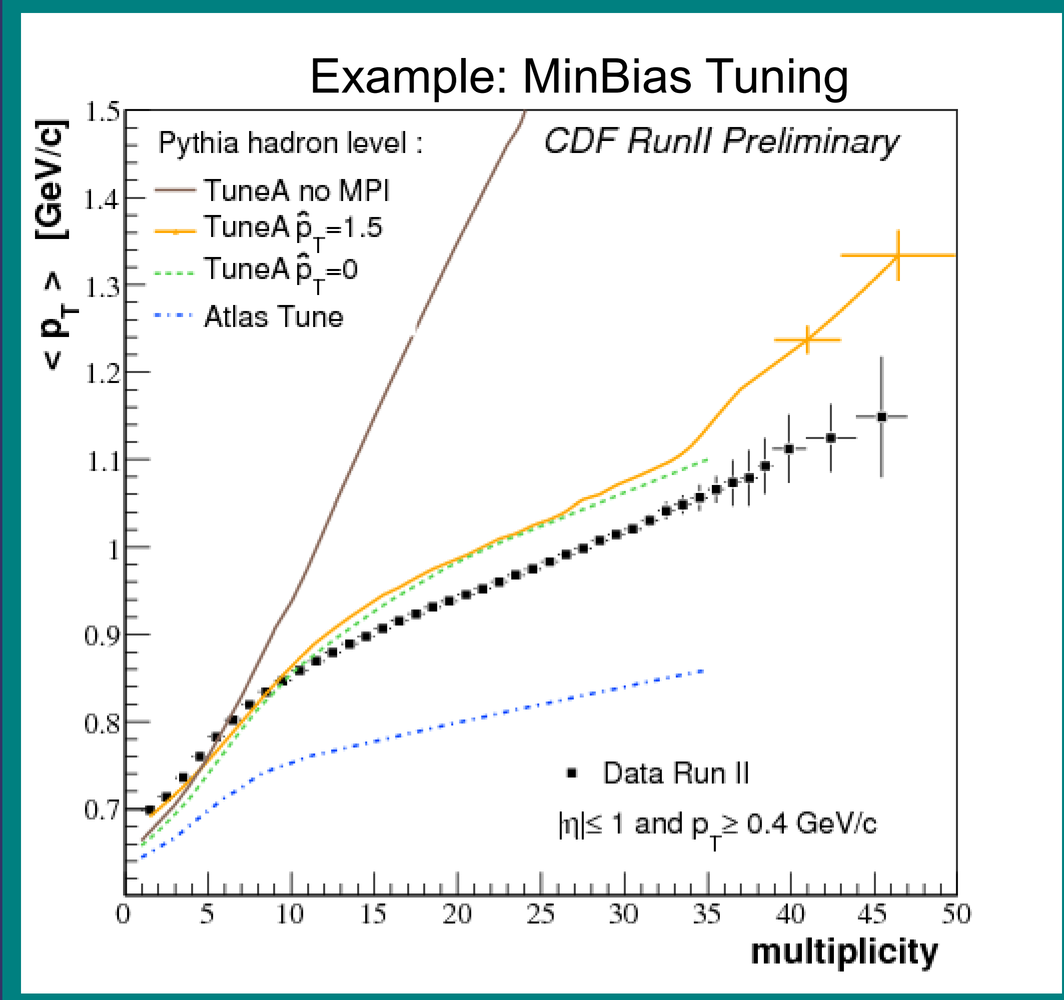

Outlook and Summary

QCD analyses are a broad component of CDF/DØ physics programs

- Analyses are providing fundamental insights into light & heavy flavor PDFs, perturbative & nonperturbative models; indicate "missing pieces" for photons
- Tevatron data will dominate high-x gluon for some time
- Jet data providing most stringent limit on numerous NP models until LHC is going, but comparisons w/ benchmark measurements from Tevatron will speed validation of any new physics signatures.
- V+jets data critical to sorting out major backgrounds to much new physics.
- Many analyses (eg. V+jets, X+HF jets, photons, highest Björken-x) still statistics limited – lot's of work ahead!

Full Tevatron data set will be 4-8x(?) higher than most results in this talk

We'll have much more to say about the Standard Model,
and if we're on the edge of something new...