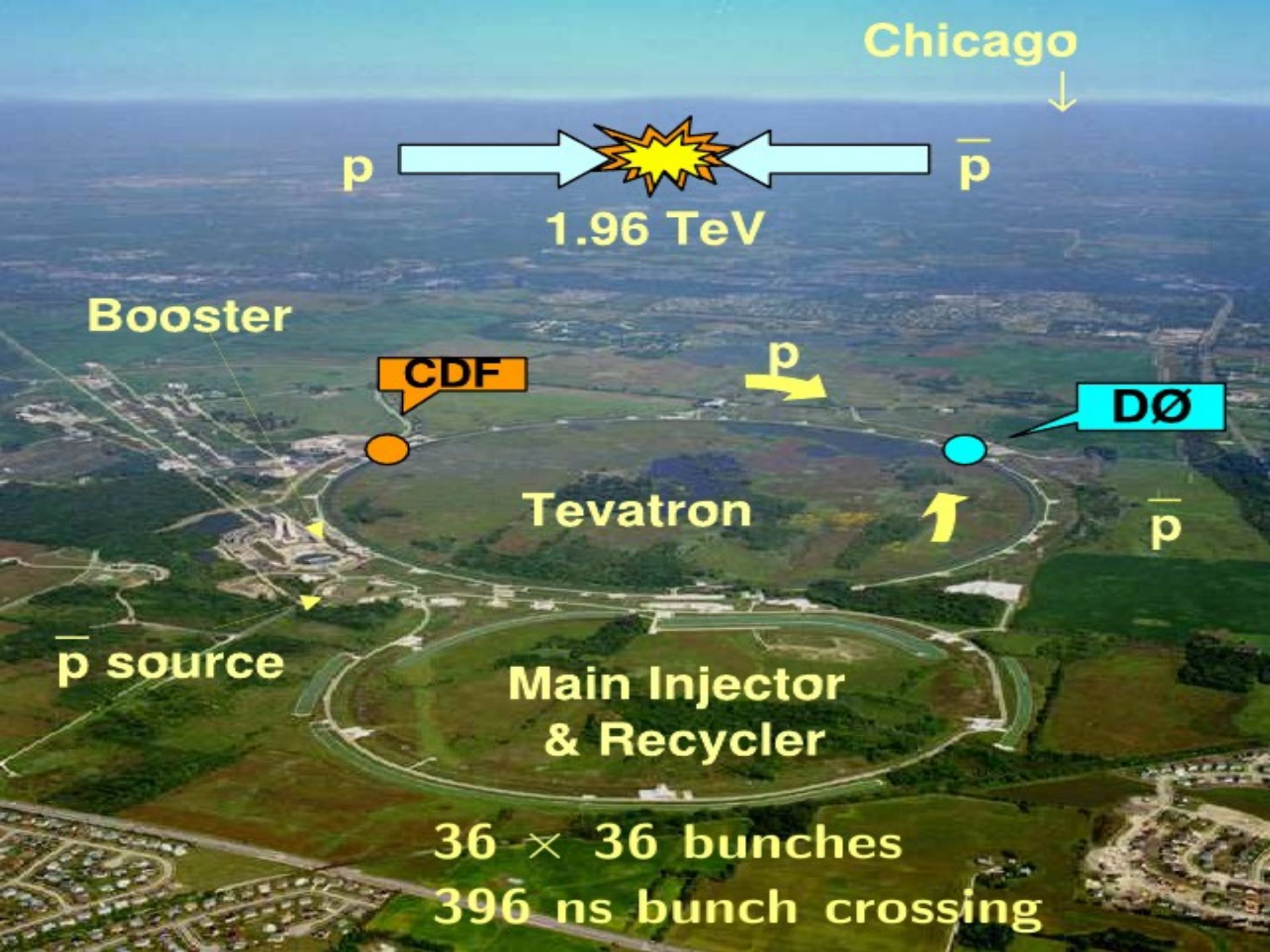
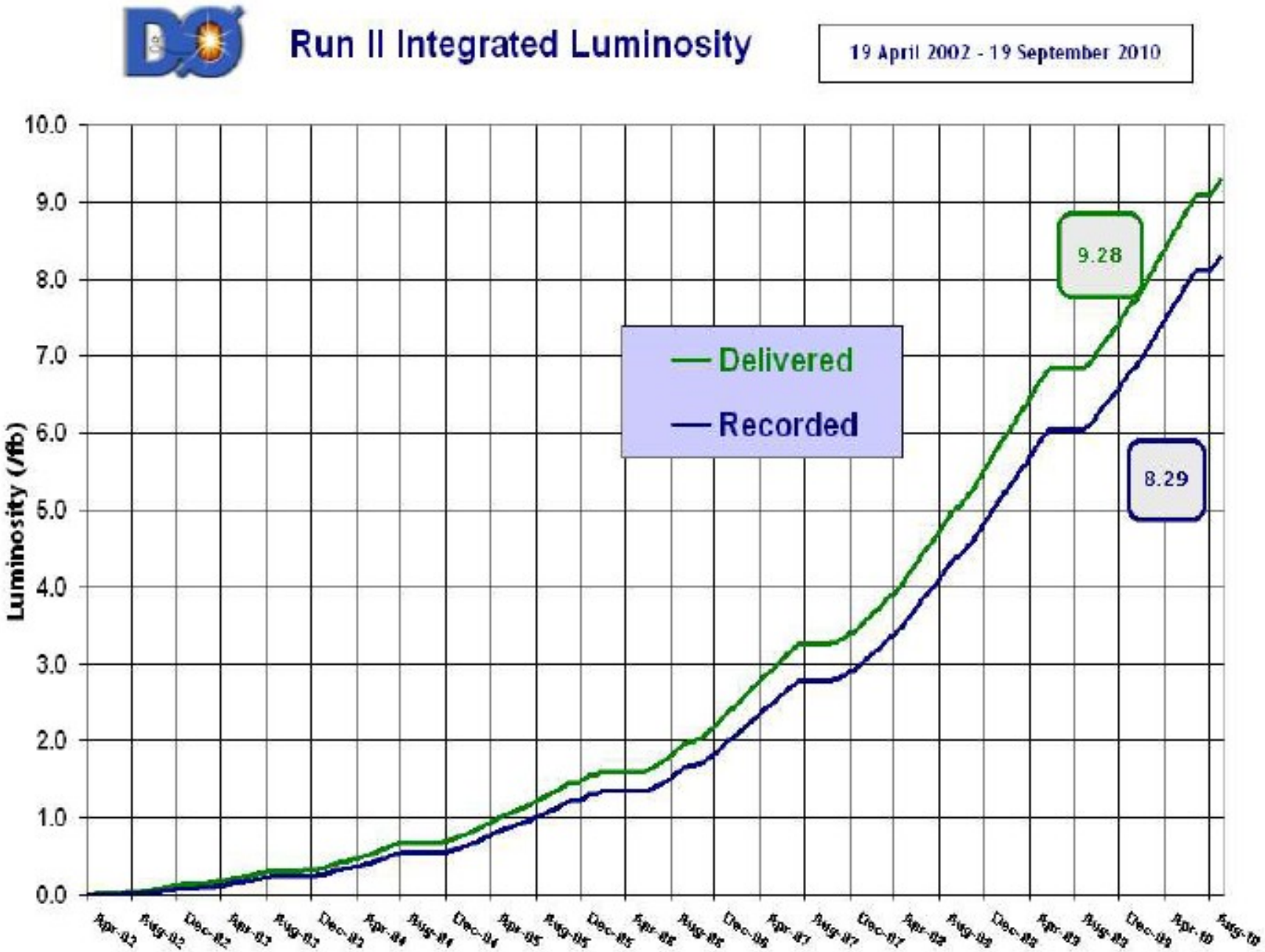
QCD at the Tevatron

N.Skachkov (JINR, Dubna)

On behalf of the **DØ and CDF** Collaborations


Chicago
p
p̄
1.96 TeV
Booster
CDF
p
DØ
Tevatron
p̄
p̄ source
Main Injector
& Recycler
36 × 36 bunches
396 ns bunch crossing


Run II Integrated Luminosity
19 April 2002 - 19 September 2010
Luminosity (/fb)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Delivered
Recorded
9.28
8.29
Apr-02
Aug-02
Dec-02
Apr-03
Aug-03
Dec-03
Apr-04
Aug-04
Dec-04
Apr-05
Aug-05
Dec-05
Apr-06
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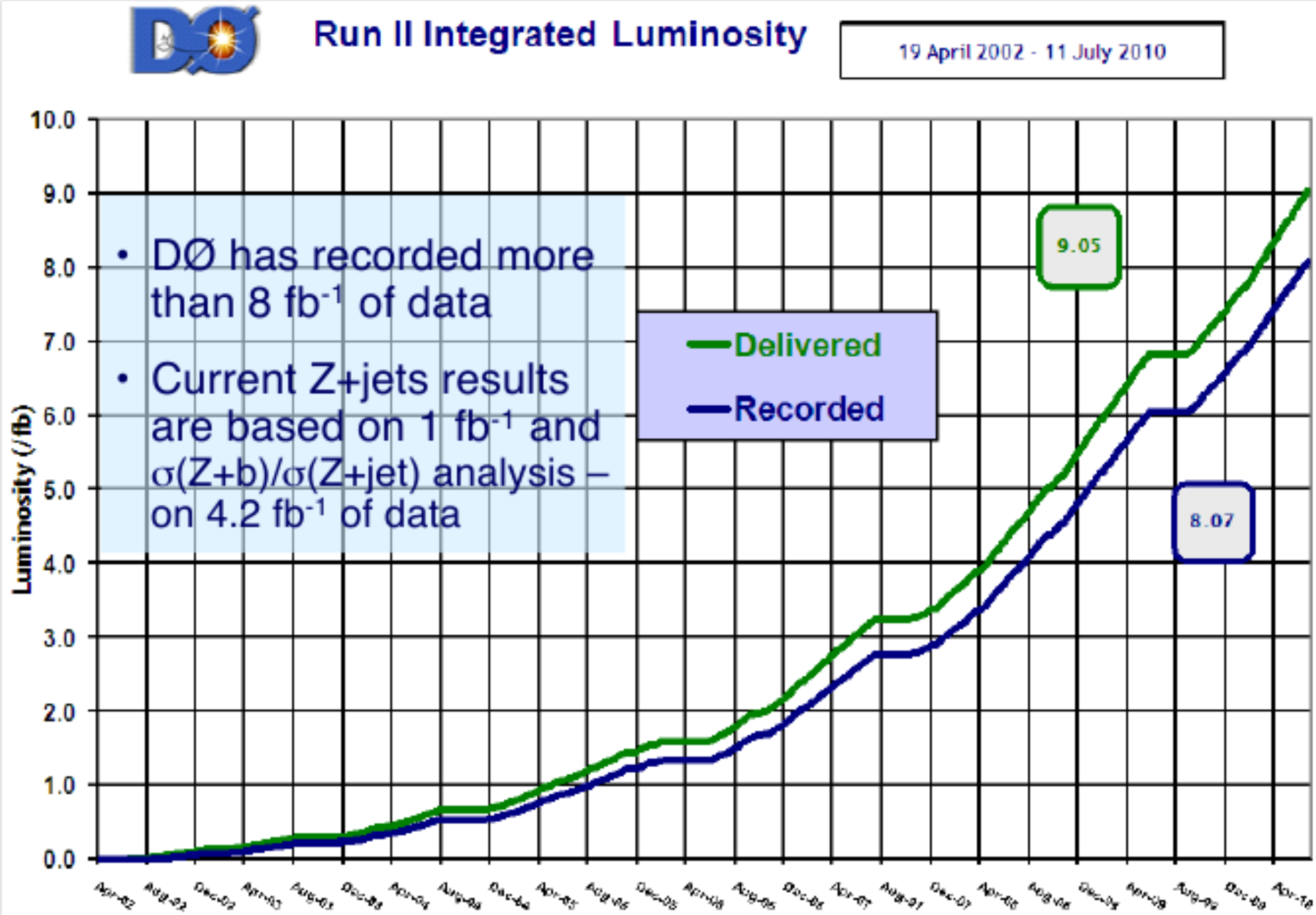
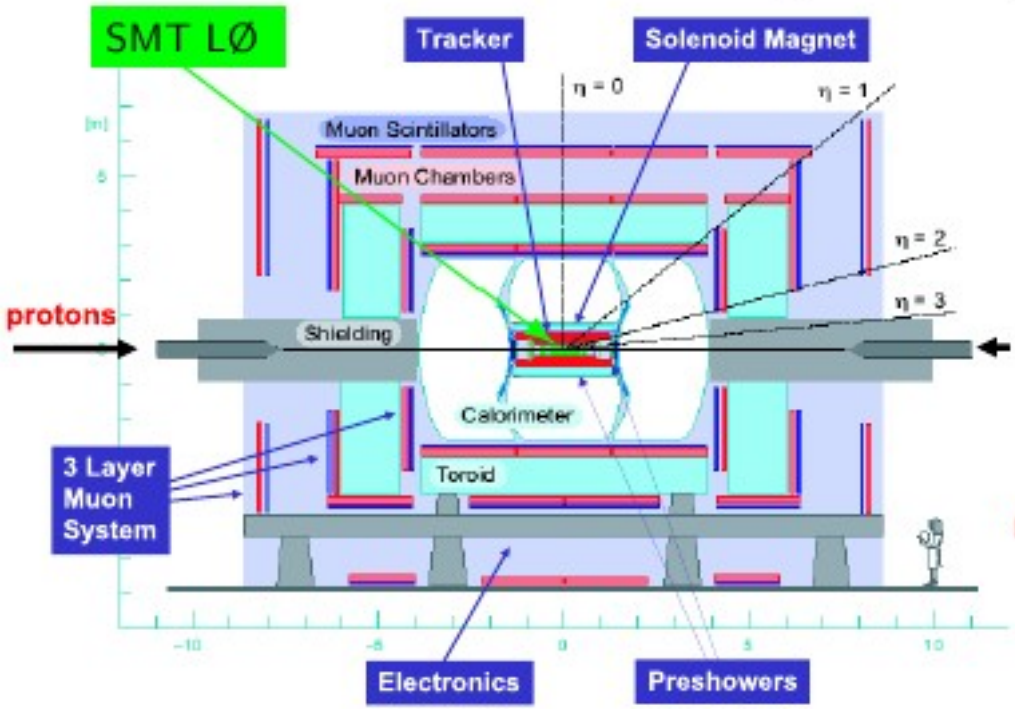
Apr-10
Aug-10

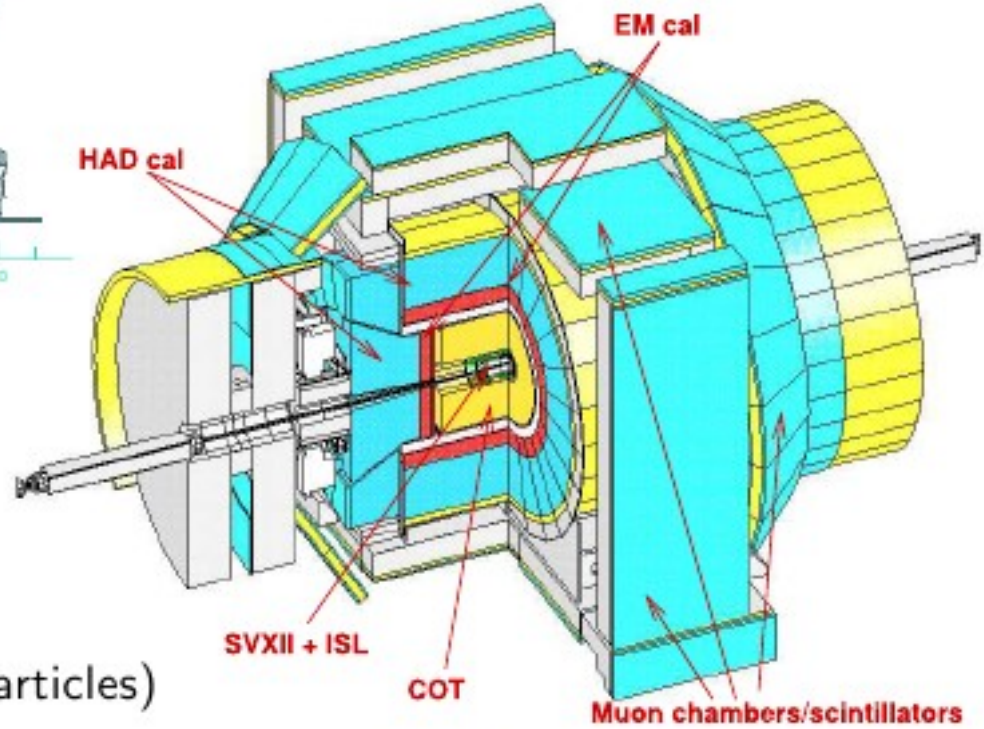

Run II Integrated Luminosity
19 April 2002 - 11 July 2010
• DØ has recorded more than 8 fb-1 of data
• Current Z+jets results are based on 1 fb-1 and σ(Z+b)/σ(Z+jet) analysis – on 4.2 fb-1 of data
Delivered
Recorded
9.05
8.07
Luminosity (/fb)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0

The DØ and CDF detectors

- Data taking efficiency (DØ & CDF) $\gtrsim$ 90%



- Multi purpose detectors with broad particle ID capabilities
- Stable detectors and triggers

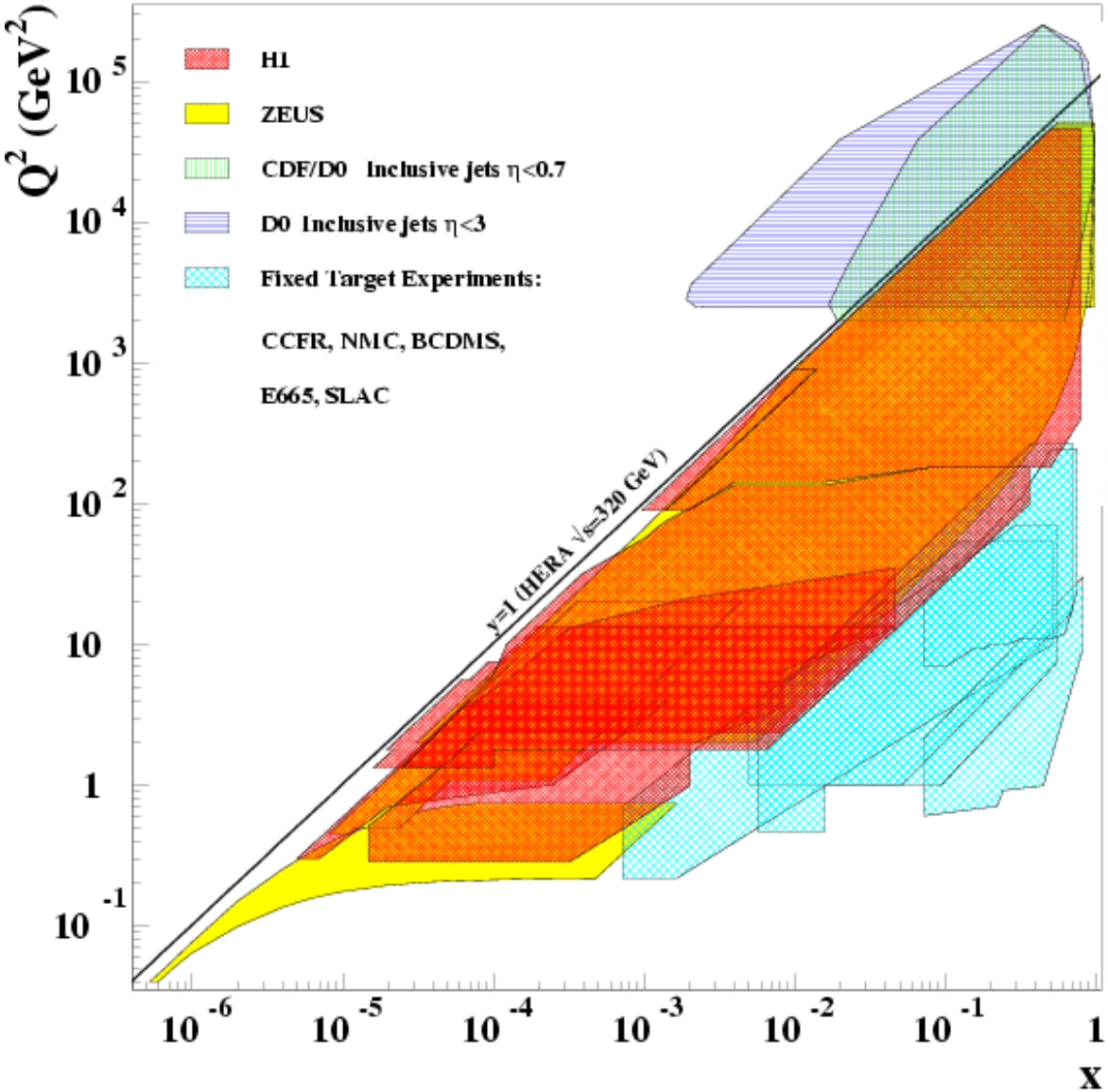


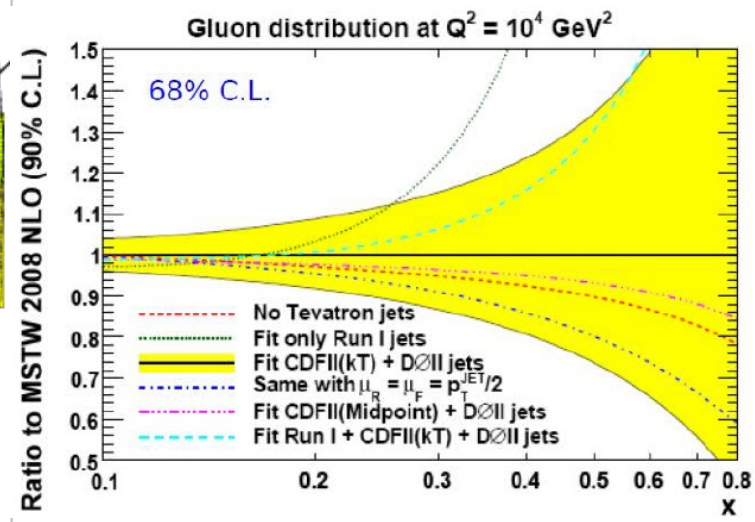
- Calorimeters ($\rightarrow$ jets, e, γ): Fine granularity and good energy resolution
  DØ: $\Delta\eta \times \Delta\phi \sim 0.1 \times 0.1$
  CDF: $\Delta\eta \times \Delta\phi \sim 0.1 \times 0.26$
- Central tracking systems ($\rightarrow$ charged particles)
- Muon spectrometers ($\rightarrow$ muons)

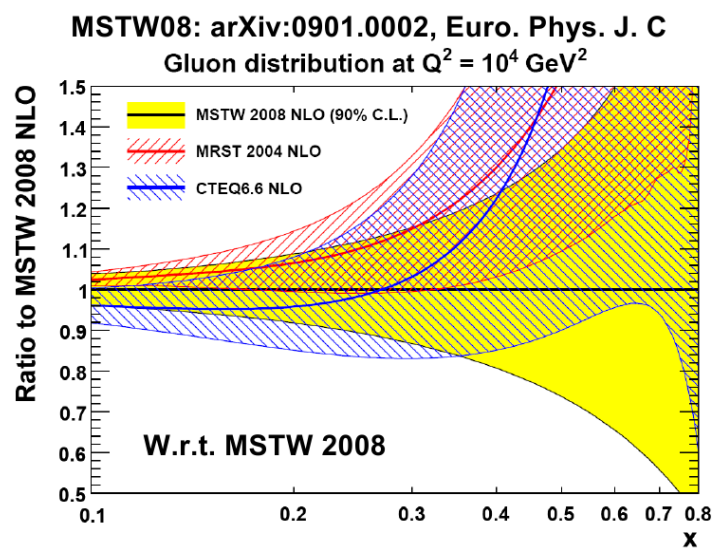
Outline

- **Jet Production**
- **a) Inclusive jets**
- **b) Dijets**
- **c) 3-jets**
- **Z/W + Jet(s)**
- **Photon Production (+ Jet)**
- **Double Parton Interactions**
- **Diphotons**
- **Hadron Production**
- **Underlying Event**

Kinematical regions in x - Q**2 plane



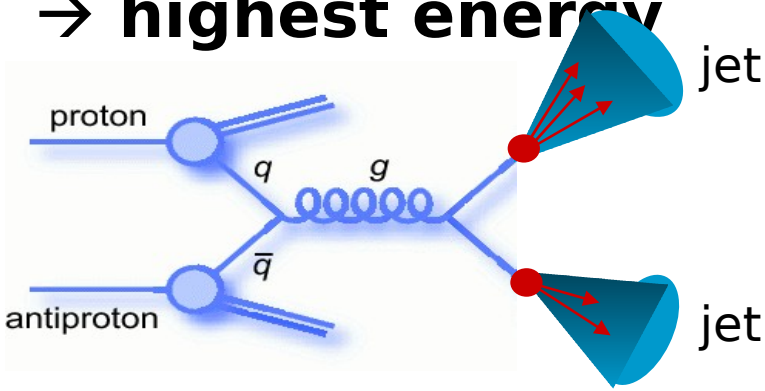




Jets and Parent Partons

largest high pT cross section
at a hadron collider

→ **highest energy**



Unique sensitivity to **new physics**:

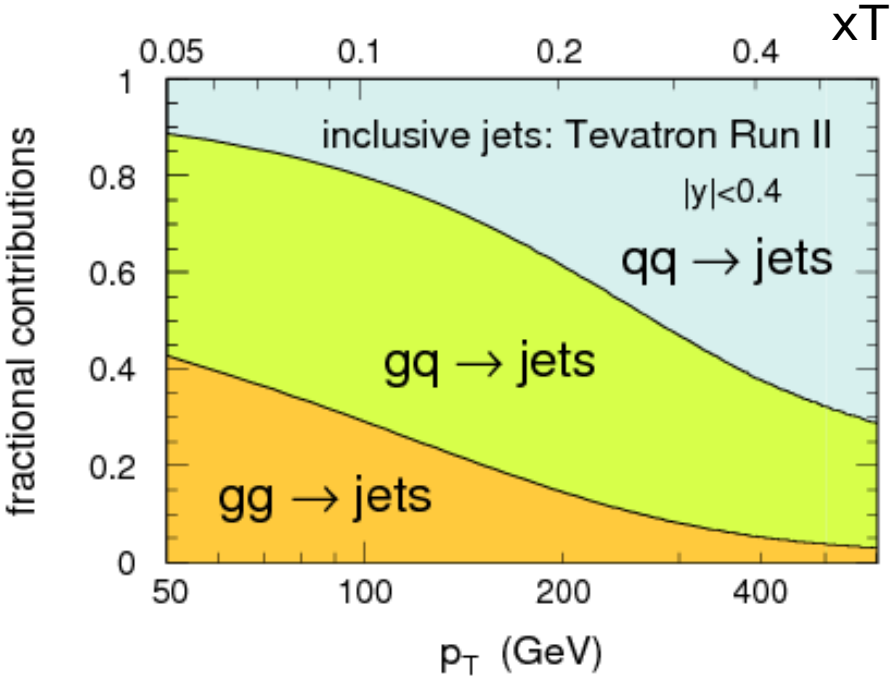
- new particles decaying to jets,
- quark compositeness,
- extra dimensions,
- …(?)…

In the absence of new physics:

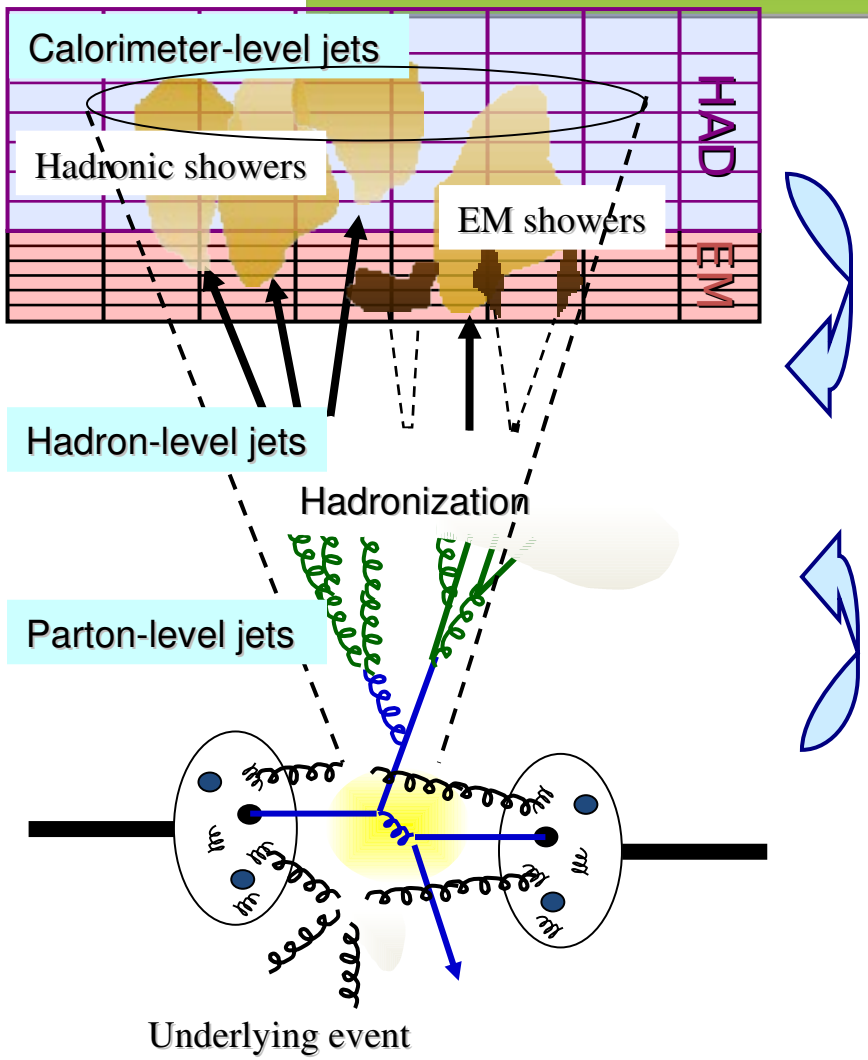
theory @NLO is reliable (±10%)

→ **Precision phenomenology**

- sensitivity to PDFs → high-x gluon
- sensitive to α_s



Inclusive jets Production



Unfold measurements to the hadron (particle) level

Correct parton-level theory for non-perturbative effects (hadronization & underlying event)

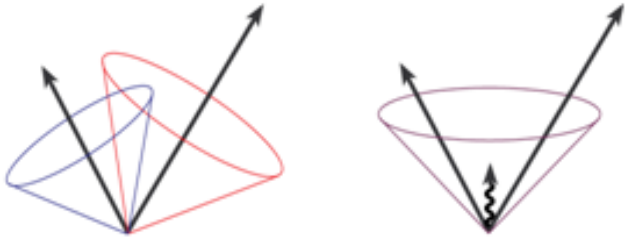
Jets are collimated spray of particles originating from parton fragmentation.
→ To be defined by an algorithm

Jet "Definitions" - Jet Algorithms

Midpoint cone-based algorithm

- Cluster objects based on their proximity in y-ϕ space
- Starting from seeds (calorimeter towers/particles above threshold), find stable cones (kinematic centroid = geometric center).
- Seeds necessary for speed, however source of infrared unsafety.
- In recent QCD studies, we use "Midpoint" algorithm, i.e. look for stable cones from middle points between two adjacent cones
- Stable cones sometime overlap
  → merge cones when p_T overlap > 75%

Infrared unsafety:
soft parton emission changes jet clustering



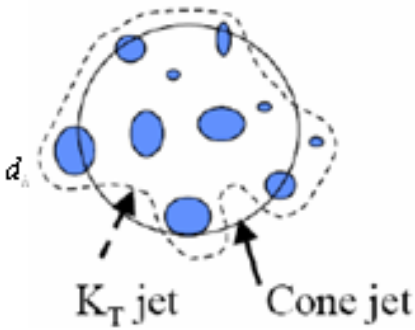
More advanced algorithm(s) available now, but negligible effects on this measurement.

Jet "Definitions" - Jet Algorithms

k_T algorithm

- Cluster objects in order of increasing their relative transverse momentum (k_T)
  - $d_{ii} = p_{T,i}^2, \quad d_{ij} = \min(p_{T,i}^2, p_{T,j}^2) \frac{\Delta R^2}{D^2}$

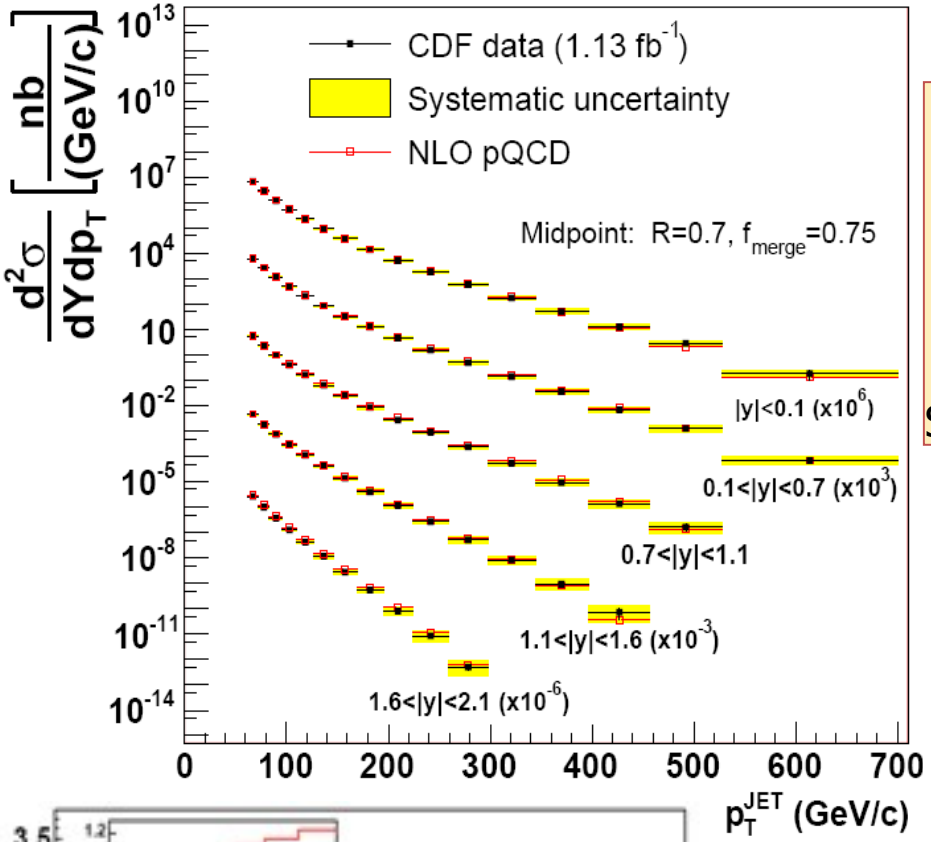
  until all objects become part of jets
- D parameter controls merging termination and characterizes size of resulting jets



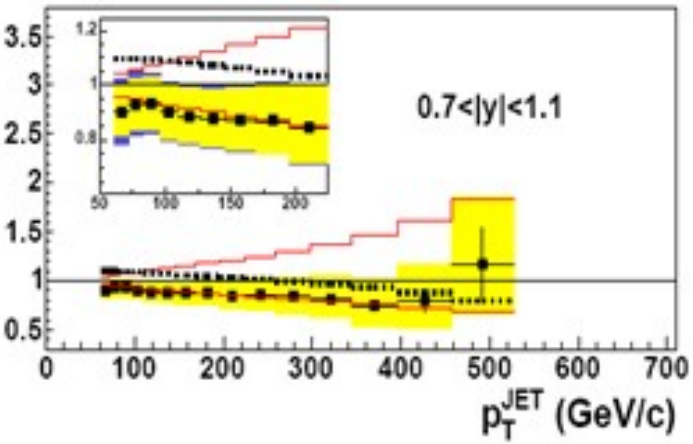
- No issue of splitting/merging. Infrared and collinear safe to all orders of QCD.
- Every object assigned to a jet: concerns about vacuuming up too many particles.
- Successful at LEP & HERA, but relatively new at the hadron colliders
  - More difficult environment (underlying event, multiple *pp* interactions...)

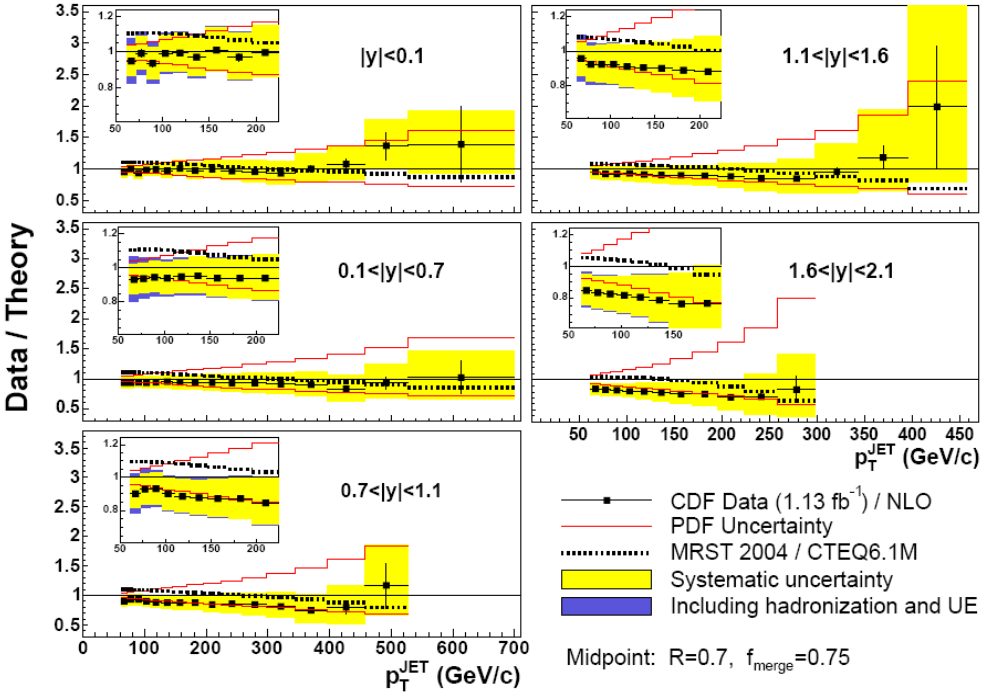
Inclusive jets , CDF

Phys. Rev. D 78, 052006 (2008)



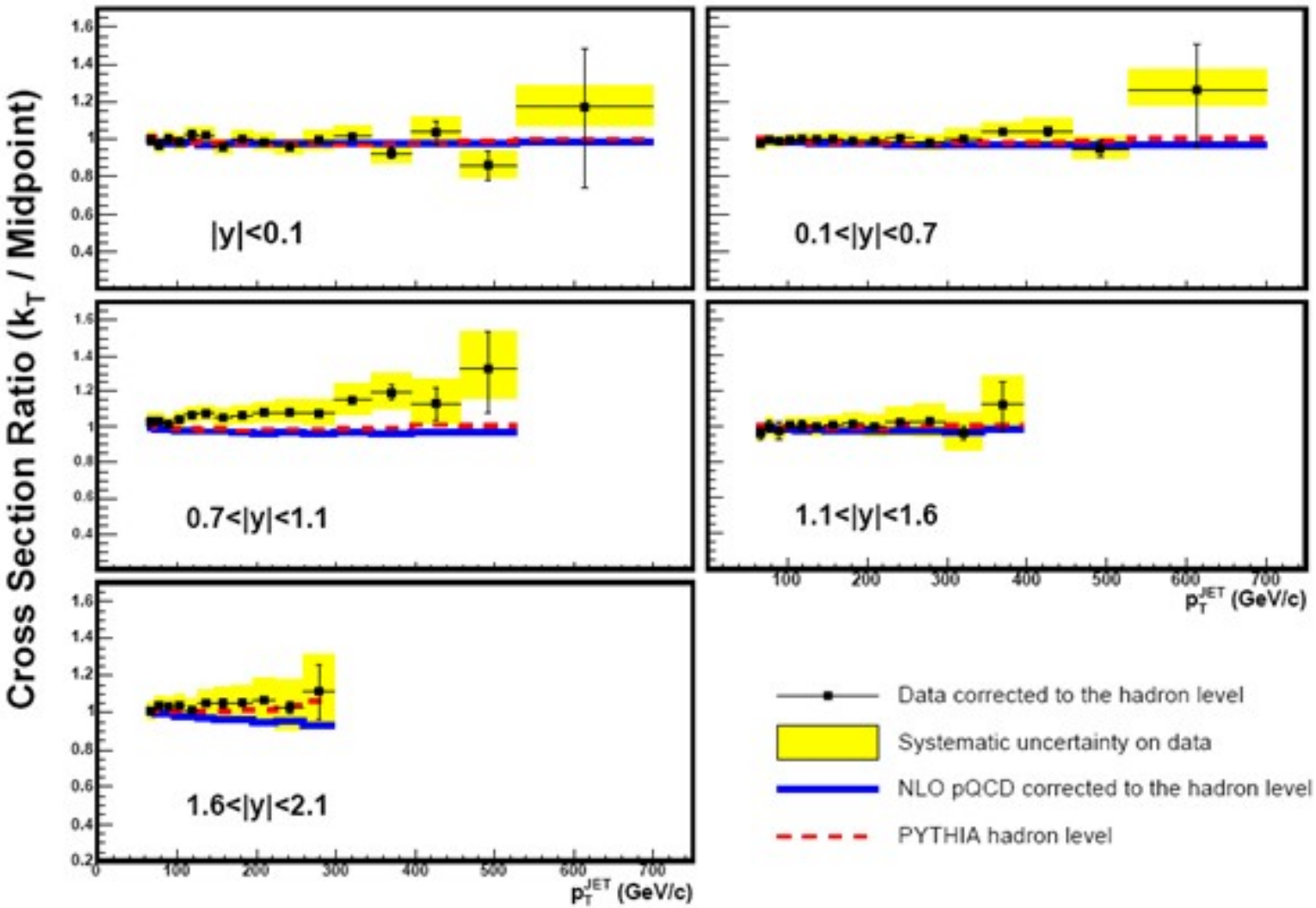
* 5 lyl intervals
* L = 1.13 fb-1
* CTEQ6.1 & MRST2004 comparison with 2 other jet clustering algorithms: k-t and SISCone➔reasonnable



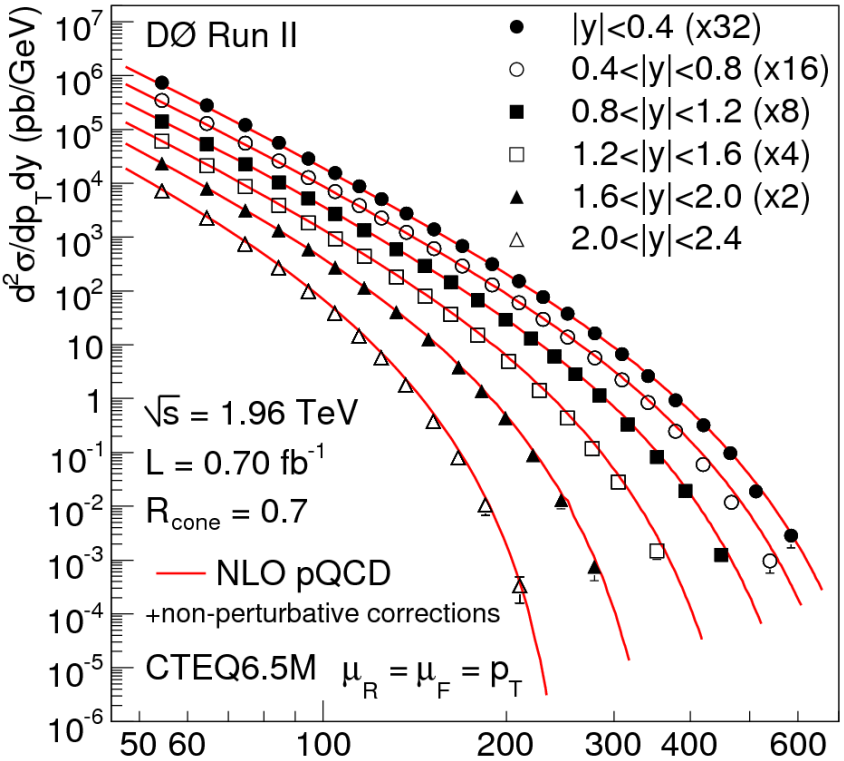


Inclusive jets , CDF

Midpoint Cone vs KT algorithm: good agreement over a large range of y and P_T



Inclusive jets , D0



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

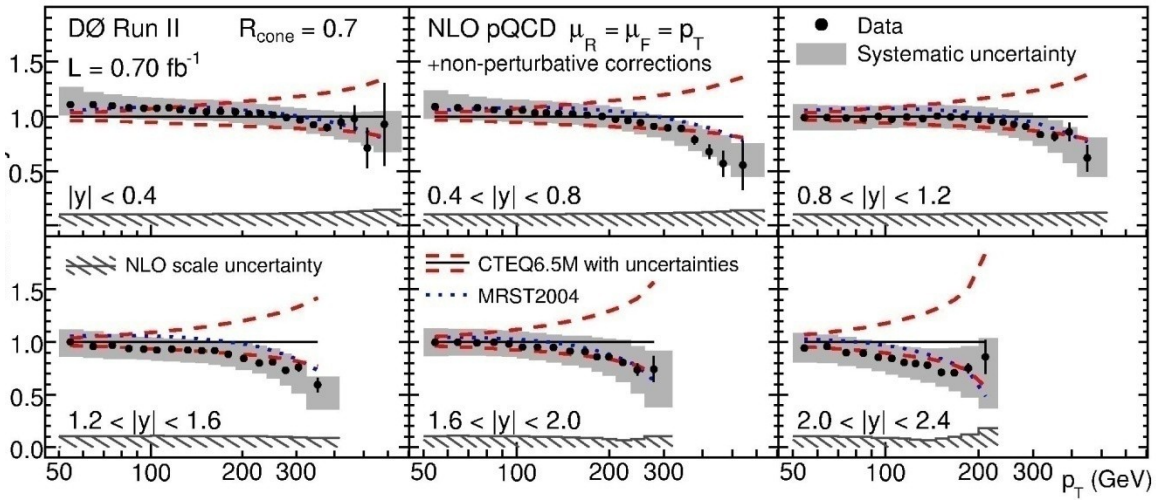
*6 lyl intervals with 110 data points

* L = 0.7 fb-1

*FASTNLO(based on NLOJET++) and the PDFs from the CTEQ6.5M are compared to the data

*correction for nonpertubative effects (underling events and hadronization) was done by PYTHIA

*8 orders of magnitude from PT=50 toPT>600GeV



data/theory (CTEQ6.5M)

- - - - CTEQ6.5 uncertainty

. . . . . MRST2004 predictions

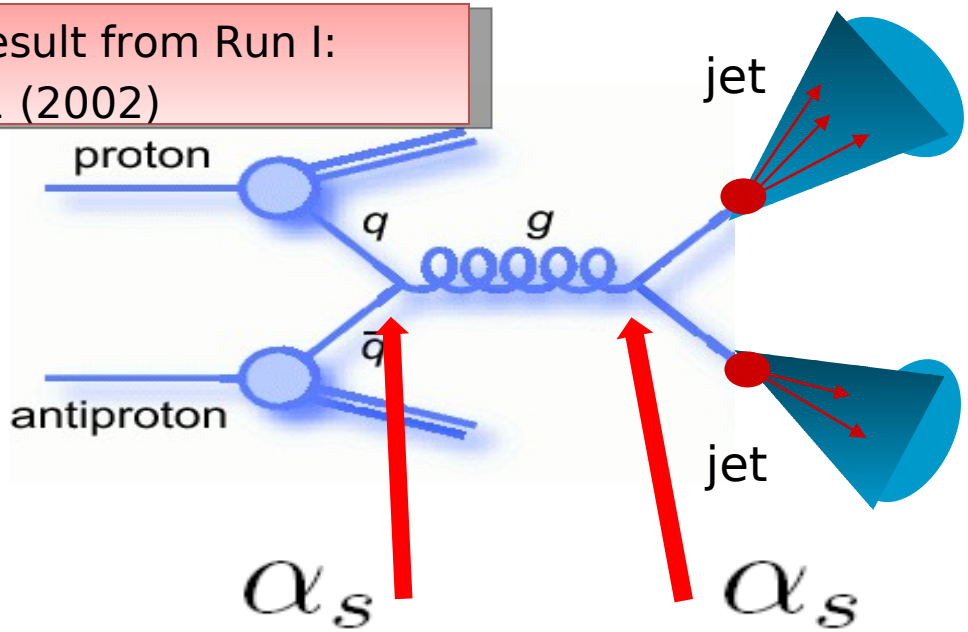
* factoriz. and renormaliz. scales uncertanties ~10% --15%

* the full systematic uncertainties are similare in size to PDF uncertanies.

Strong coupling constant from D0 inclusive jets data

inclusive jet cross section is sensitive to α_s

previous CDF result from Run I:
PRL88, 042001 (2002)



$$\sigma_{\text{pert}}(\alpha_s) = \left(\sum_n \alpha_s^n c_n\right) \otimes f_1(\alpha_s) \otimes f_2(\alpha_s)$$

$$\sigma_{\text{theory}}(\alpha_s(M_Z)) = \sigma_{\text{pert}}(\alpha_s(M_Z)) \cdot c_{\text{non-pert}}$$

Strong coupling constant from D0 inclusive jets data

22 (out of 110) inclusive jet Xsection data points at 50 < P_T < 145 GeV

Phys. Rev. D 80 111107(R) (2009)

NLO + 2-loop threshold corrections

The only Run II result on alfa_s

MSTW2008NNLO PDFs

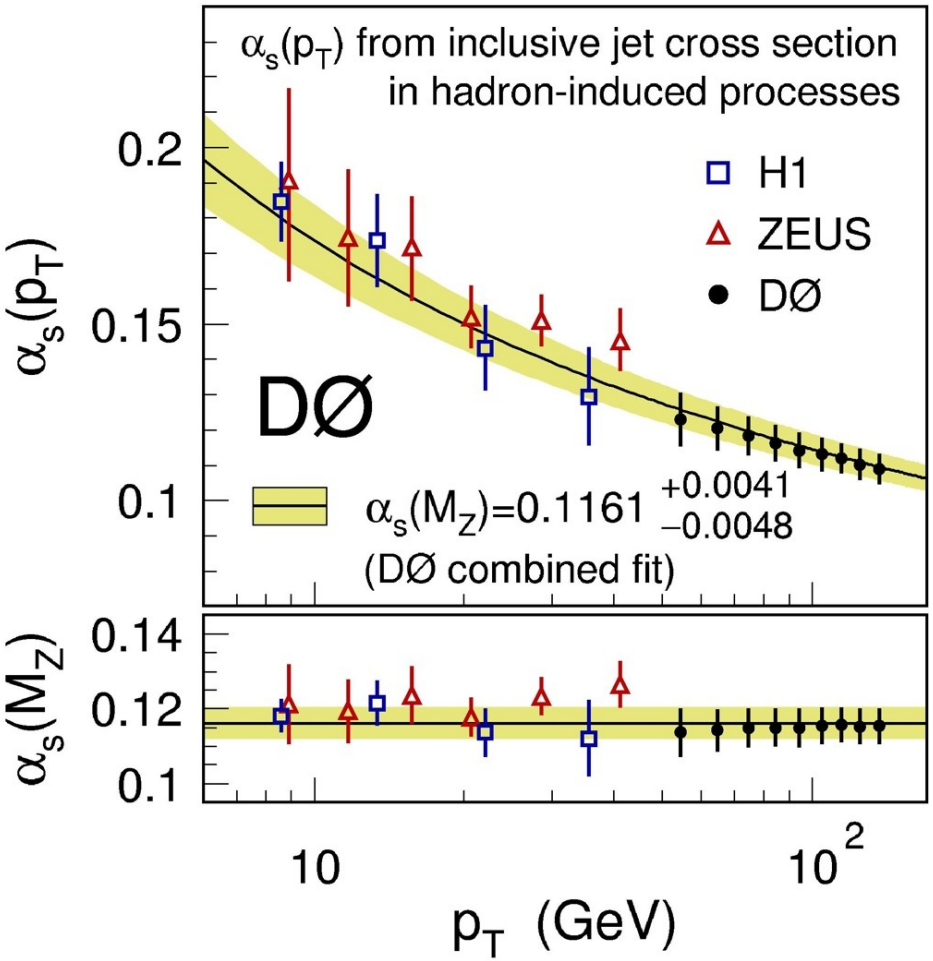
From combined HERA jet data: $\alpha_s(M_Z) =$ 0.1189 +/- 0.0032

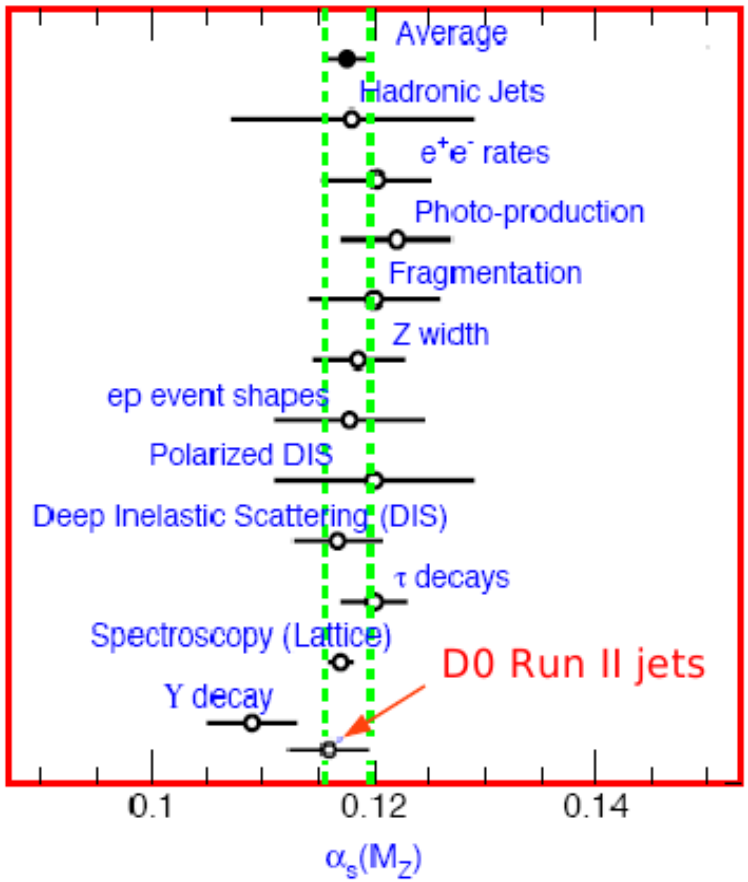
"World average": $\alpha_s(M_Z) =$ 0.1184 +/- 0.0007

D0: $\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0049}$

Strong coupling constant from D0 inclusive jets data

Review of Particle Physics 2008





Highest PT measurement of strong coupling constant to date

result	uncertainty contributions				
$\alpha_s(M_Z)$	stat.	exp. syst.	non-pert.	PDF	scale $\mu_{r,f}$
0.01161	$^{+0.0001}_{-0.0001}$	$^{+0.0034}_{-0.0029}$	$^{+0.0010}_{-0.0010}$	$^{+0.0012}_{-0.0011}$	$^{+0.0021}_{-0.0029}$

Combined α_s(Mz)

Based on 22 inclusive jet data points with x-test<0.15

Combined α_s(Mz):

$$\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$$ NLO + 2-loop threshold corrections

$$= 0.1202^{+0.0072}_{-0.0059}$$ NLO

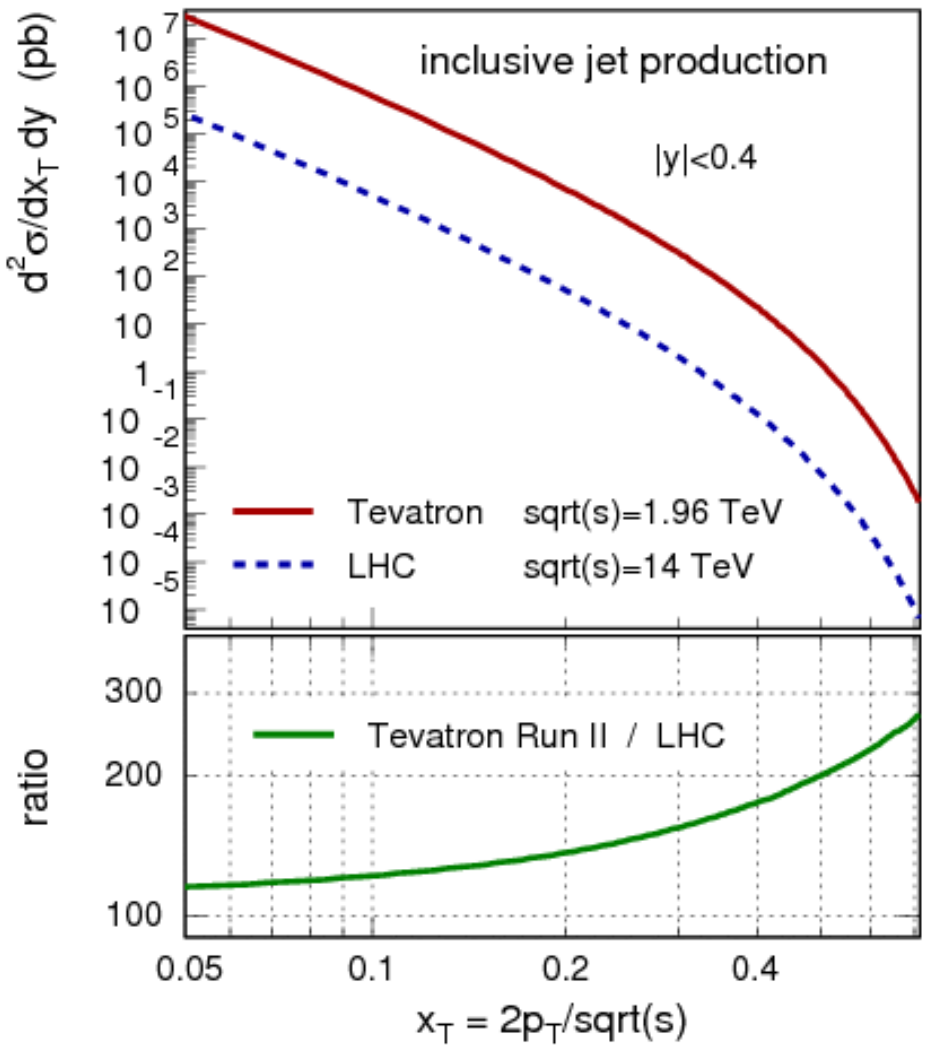
ABLE I: Central values and uncertainties due to different sources for the nine $\alpha_s(p_T)$ results and for the combined $\alpha_s(M_Z)$ esult (bottom). All uncertainties are multiplied by a factor of 10^3.

p_T range (GeV)	No. of data points	p_T (GeV)	$\alpha_s(p_T)$	total uncertainty	experimental uncorrelated	experimental correlated	non-perturb. correction	PDF uncertainty	$\mu_{r,f}$ variation
50 - 60	4	54.5	0.1229	$^{+7.6}_{-7.7}$	±0.4	$^{+4.8}_{-4.9}$	$^{+5.8}_{-5.6}$	$^{+0.4}_{-0.6}$	$^{+1.0}_{-1.9}$
60 - 70	4	64.5	0.1204	$^{+6.2}_{-6.3}$	±0.3	$^{+4.1}_{-4.3}$	$^{+4.5}_{-4.3}$	$^{+0.6}_{-0.5}$	$^{+1.3}_{-1.5}$
70 - 80	3	74.5	0.1184	$^{+5.6}_{-5.6}$	±0.3	$^{+3.8}_{-3.9}$	$^{+4.0}_{-3.9}$	$^{+0.6}_{-0.6}$	$^{+1.0}_{-0.9}$
80 - 90	3	84.5	0.1163	$^{+5.1}_{-5.1}$	±0.3	$^{+3.6}_{-3.7}$	$^{+3.5}_{-3.5}$	$^{+0.7}_{-0.7}$	$^{+0.9}_{-0.6}$
90 - 100	2	94.5	0.1142	$^{+5.1}_{-4.9}$	±0.3	$^{+3.5}_{-3.6}$	$^{+3.5}_{-3.3}$	$^{+0.8}_{-0.8}$	$^{+1.1}_{-0.6}$
00 - 110	2	104.5	0.1131	$^{+4.7}_{-4.7}$	±0.2	$^{+3.4}_{-3.5}$	$^{+3.1}_{-3.0}$	$^{+0.8}_{-0.8}$	$^{+1.1}_{-0.6}$
10 - 120	2	114.5	0.1121	$^{+4.2}_{-4.4}$	±0.2	$^{+3.1}_{-3.3}$	$^{+2.5}_{-2.7}$	$^{+0.7}_{-0.8}$	$^{+1.2}_{-0.7}$
20 - 130	1	124.5	0.1102	$^{+4.4}_{-4.4}$	±0.2	$^{+3.2}_{-3.4}$	$^{+2.6}_{-2.6}$	$^{+0.9}_{-0.9}$	$^{+1.4}_{-0.9}$
30 - 145	1	136.5	0.1090	$^{+4.2}_{-4.3}$	±0.3	$^{+3.1}_{-3.4}$	$^{+2.3}_{-2.4}$	$^{+0.9}_{-0.9}$	$^{+1.5}_{-0.9}$
50 - 145	22	M_Z	0.1161	$^{+4.1}_{-4.8}$	±0.1	$^{+3.4}_{-3.3}$	$^{+1.0}_{-1.6}$	$^{+1.1}_{-1.2}$	$^{+2.5}_{-2.9}$

Main correlated uncertainties: JES, pT-resolution, luminosity

Inclusive Jets: Tevatron vs. LHC

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



PDF sensitivity:

→ compare jet cross section at fixed

$x_T = 2\ p_T\ /\ \mathrm{sqrt}(s)$

Tevatron (ppbar)

>100x higher cross section @ all x_T

>200x higher cross section @ x_T >0.5

LHC (pp)

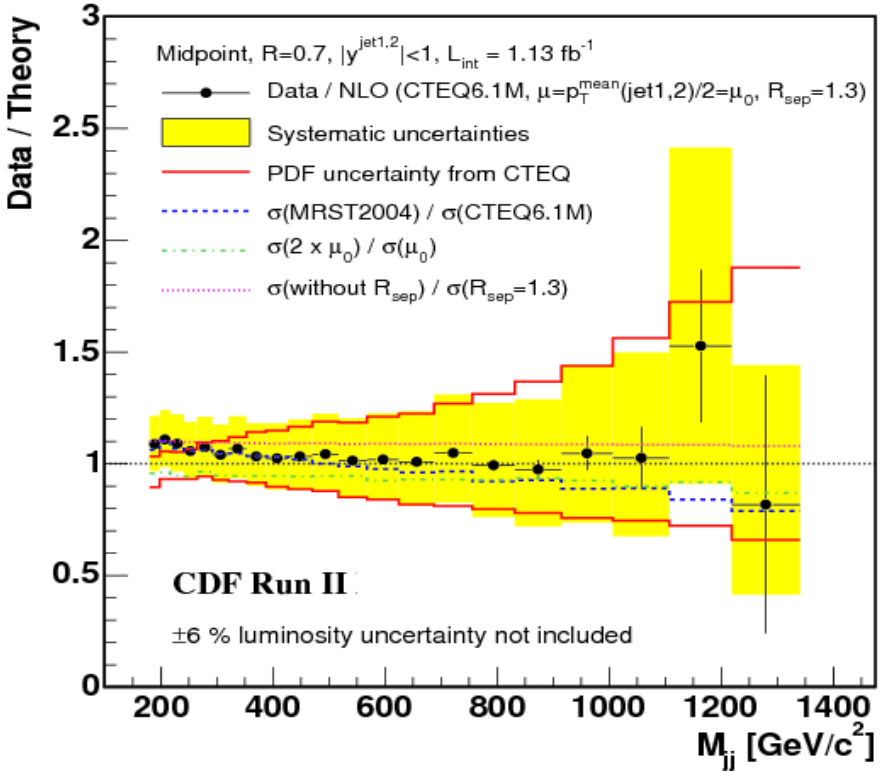
- need more than 2400 fb^{-1} luminosity to improve Tevatron@12 fb^{-1}
- more high-x gluon contributions
- but more steeply falling cross sect. at highest p_T (=larger uncertainties)

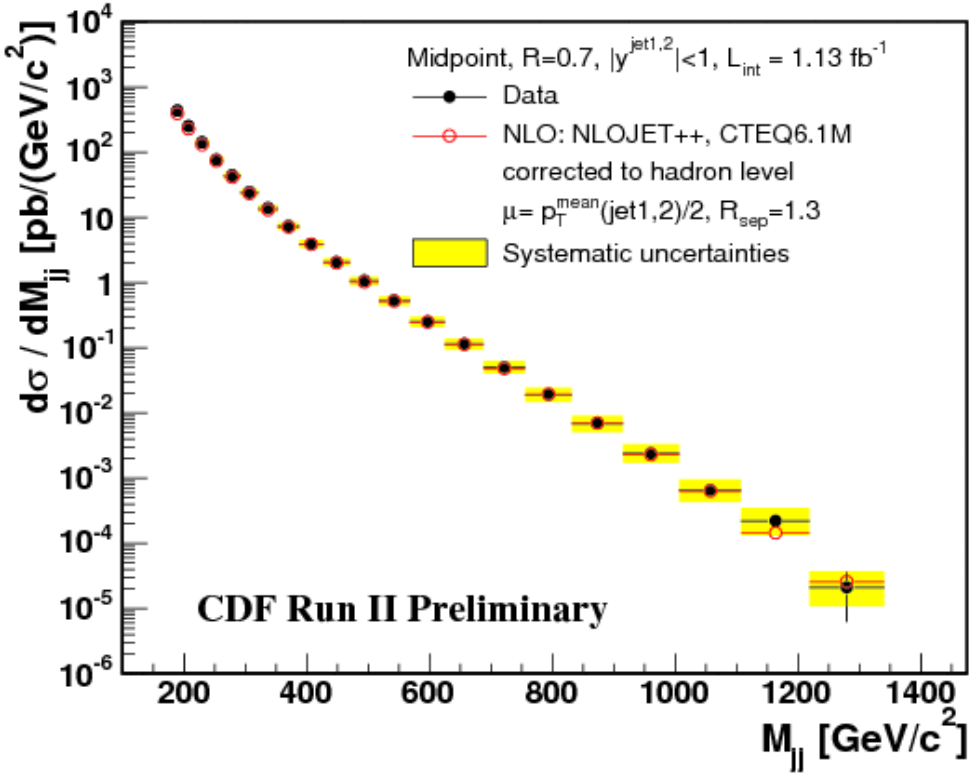
Dijet Mass Spectrum , CDF

Phys. Rev. D 79, 112002 (2009)

central dijet production |y|<1
test pQCD predictions

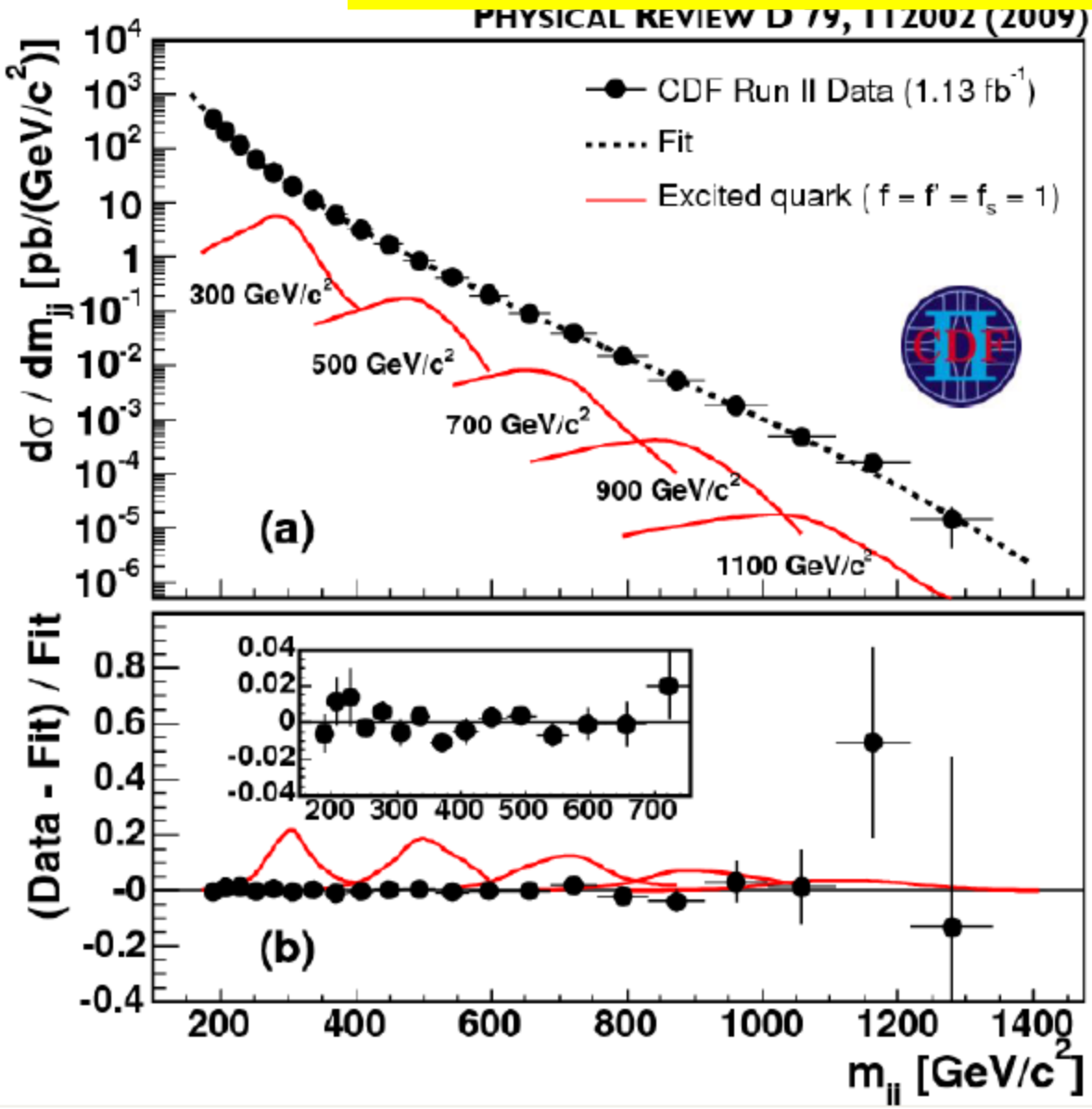
- **sensitive to new particles**
- **decaying into dijets:**
- **excited quarks, Z', W',**
- **Randall-Sundrum gravitons,**
- **color-octet, techni-rho, axigluons, colorons**





→ data with Mjj > 1.2 TeV!
→ all described by NLO pQCD
no indications for resonances
→ set limits on new particles

Dijet Mass Spectrum , CDF



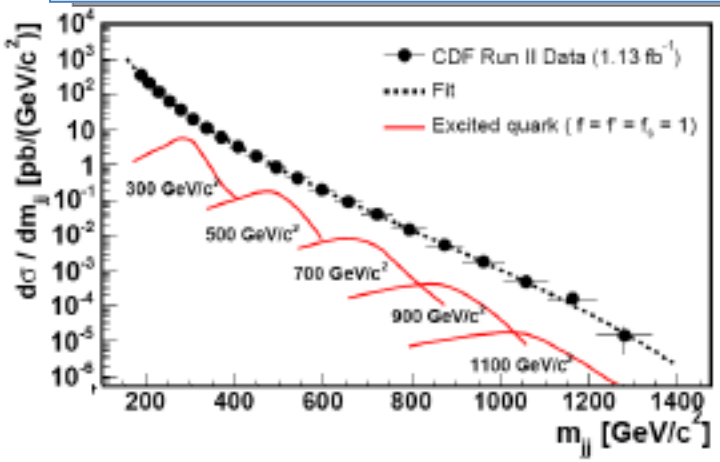
Phys. Rev. D 79, 112002(2009)

Compare data to predicted signal shapes, e.g. exited quarks

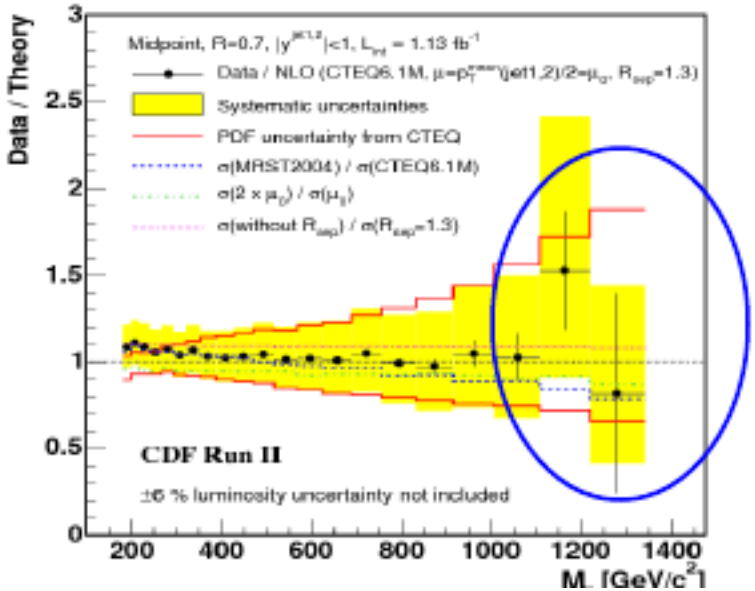
Dijet Mass Spectrum , CDF

Phys. Rev. D 79, 112002 (2009)

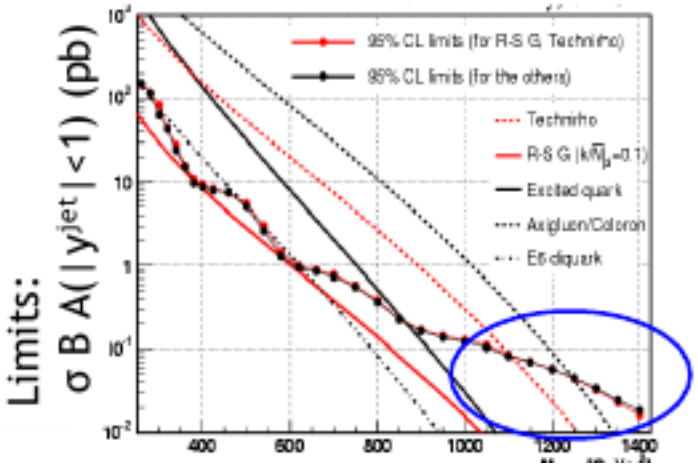
- Test pQCD predictions
- Sensitive to new particles decaying into dijets: excited quarks, heavy gluons, techni-ρ, etc



Dijets with jets $|y^{jet}|<1$



- Consistent with NLO pQCD
- Most stringent limits on many new heavy particles



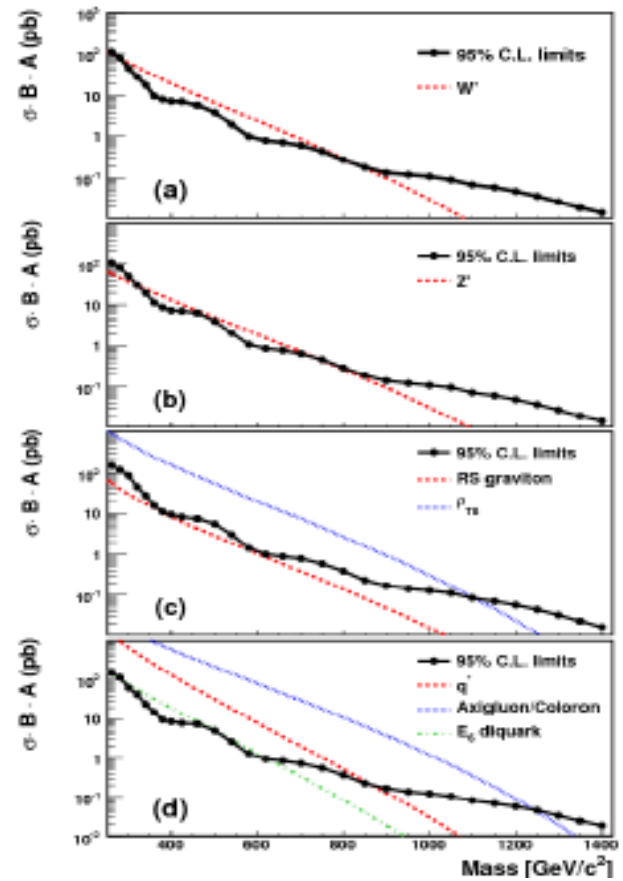
Dijet mass spectrum , CDF

is sensitive to new particles decaying into dijets: exited quarks, Z', W', Randail-Sundrum gravitons, coler-octet, techni-rho,axigluons, colorons

Results: the most stringent lower mass limits available on excited quark[1], axigluon[2], flavor-universal coloron[3], E_6 diquark[4], and color-octet techni-ρ[5].

Excluded mass limits (GeV):

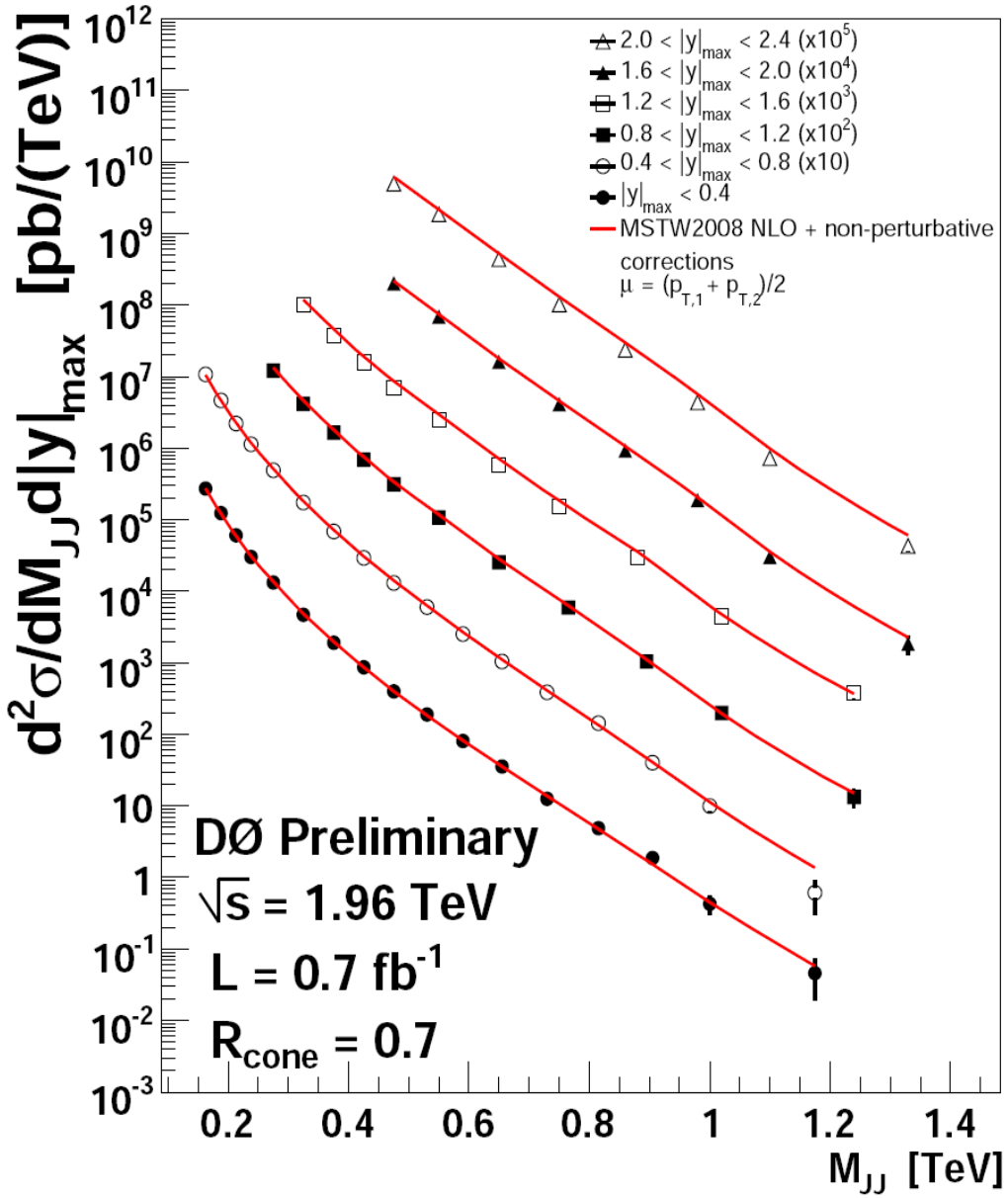
q*	260-870
axigluon, coloron	260-1250
E_6 diquark	290-630
ρ_{T8}	260-1100
W'[6]	280-840
Z'[6]	320-740



[1] PRD 42, 815 (1990).
[2] Phys. Lett. B 190, 157 (1987); PRD 37, 1188 (1988).
[3] Phys. Lett. B 380, 92 (1996); PRD 55, 1678 (1997).
[4] Phys. Rept. 183, 193 (1989).
[5] PRD 44, 2678 (1991); PRD 67, 115011 (2003).
[6] Rev. Mod. Phys. 56, 579 (1984); Rev. Mod. Phys. 58, 1065 (1986).

Dijet mass spectrum , D0

arXiv: 1002 .4594v1 [hep-ex] 24Feb 2010



* L = 0.7 fb-1
* 6 |y| - regions
* 0 < |y| < 2.4

Extend QCD test to forward region

NLOpQCD predictions (fastNLO, based on NLOJET++) using MSTW2008NLO

Data with Mjj described by NLO pQCD + non-Perturbative corrections

No indications for resonanses

Dijet mass spectrum , D0

Data to Theory Ratio

Ratio of data over theoretical prediction

(NLO pQCD + non-Perturbative)

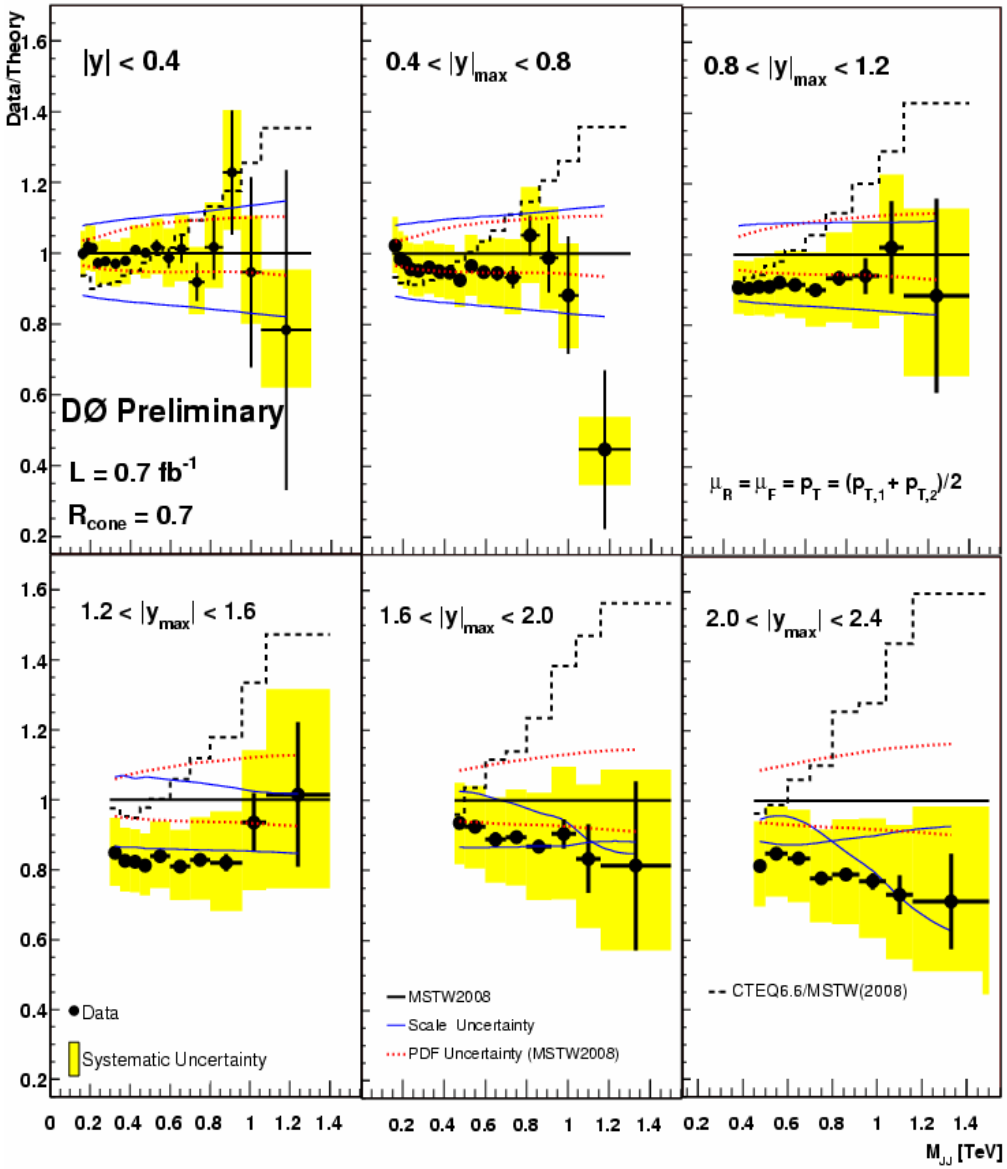
usung MSTW2008NLO PDFs

. . . . . CTEQ6.6 prediction too high

- - - - - PDF MSTW2008NLO uncertanty

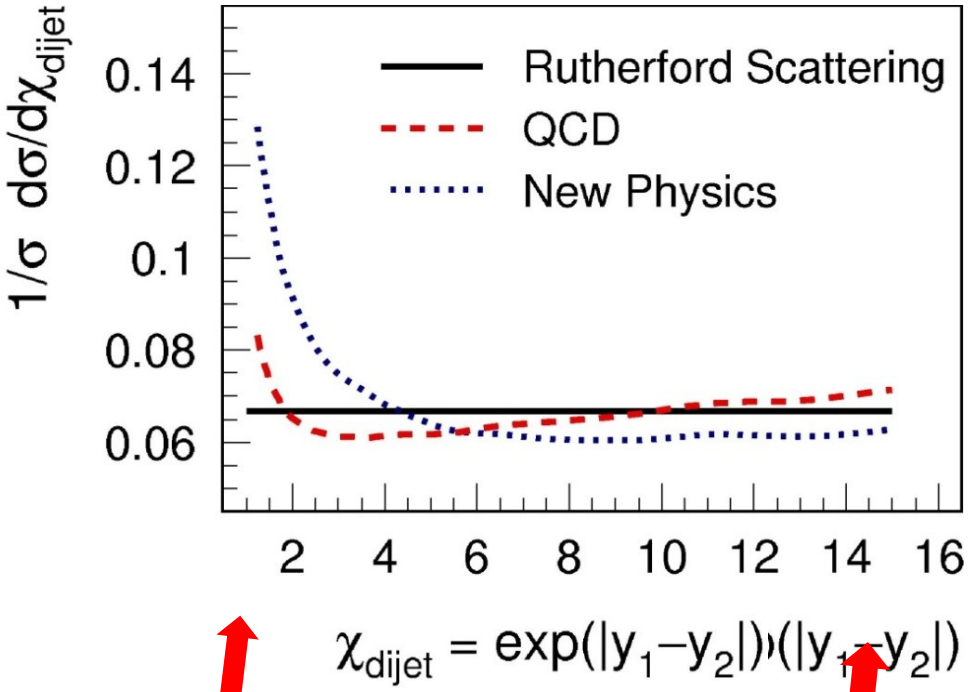
- - - - - scale uncertainty

Data are well described by NLO QCD predictions using MSTW2008NLO in all six rapidity regions.



Dijet angular distribution , D0

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



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

at LO related to CM scattering angle $\chi_{\rm dijet} = \frac{1+\cos\theta^*}{1-\cos\theta^*}$

- flat for Rutherford scattering
- slightly shaped in QCD
- new physics, like
  - quark compositeness
  - extra spatial dimensions

  → enhancements at low $\chi_{\rm dijet}$

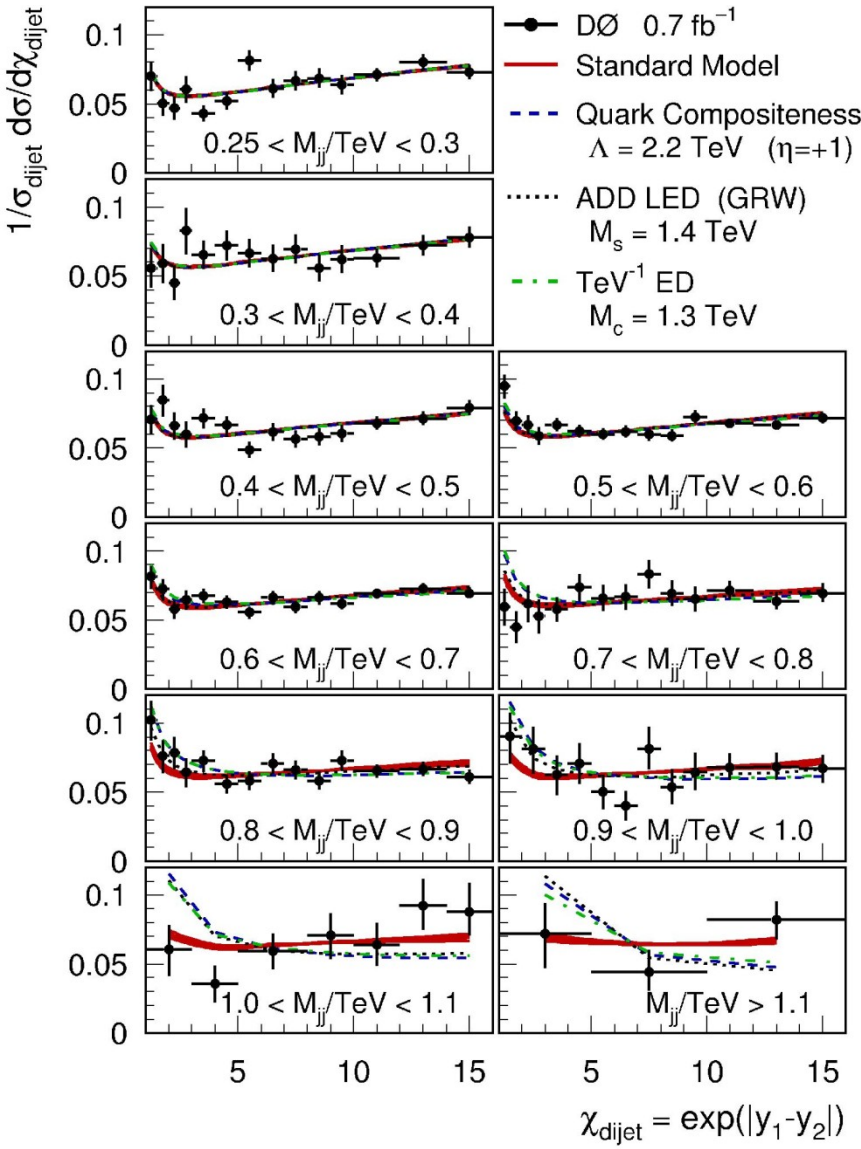
small Δy **large Δy**

Dijet angular distribution , D0

→ normalized distribution $\frac{1}{\sigma}\frac{d\sigma}{d\chi_{\mathrm{dijet}}}$

→ reduced experimental and theoretical uncertainties

Measurement for dijet masses from 0.25 TeV to >1.1 TeV



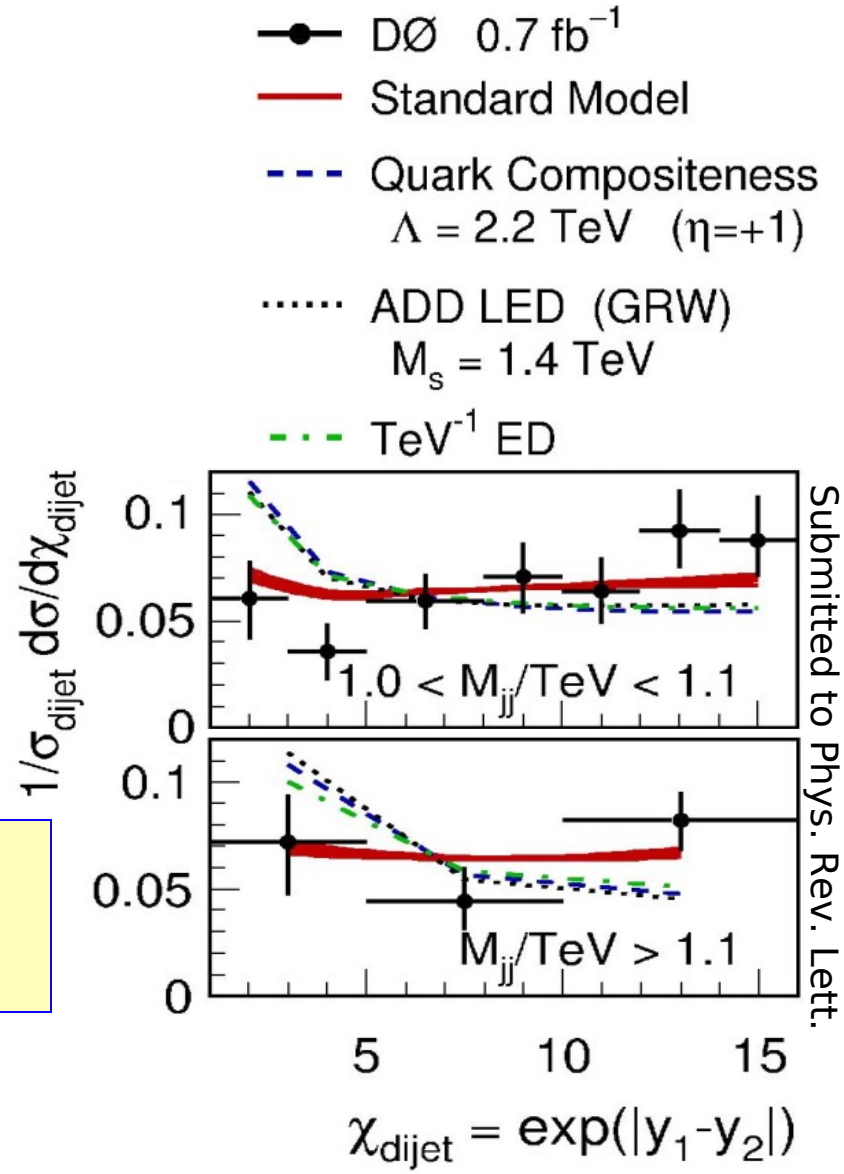
Dijet angular distribution , D0

→ normalized distribution $\frac{1}{\sigma}\frac{d\sigma}{d\chi_{\mathrm{dijet}}}$

→ reduced experimental
and theoretical uncertainties

Measurement for dijet masses
from 0.25 TeV to >1.1 TeV

First time:
Rutherford experiment above 1TeV



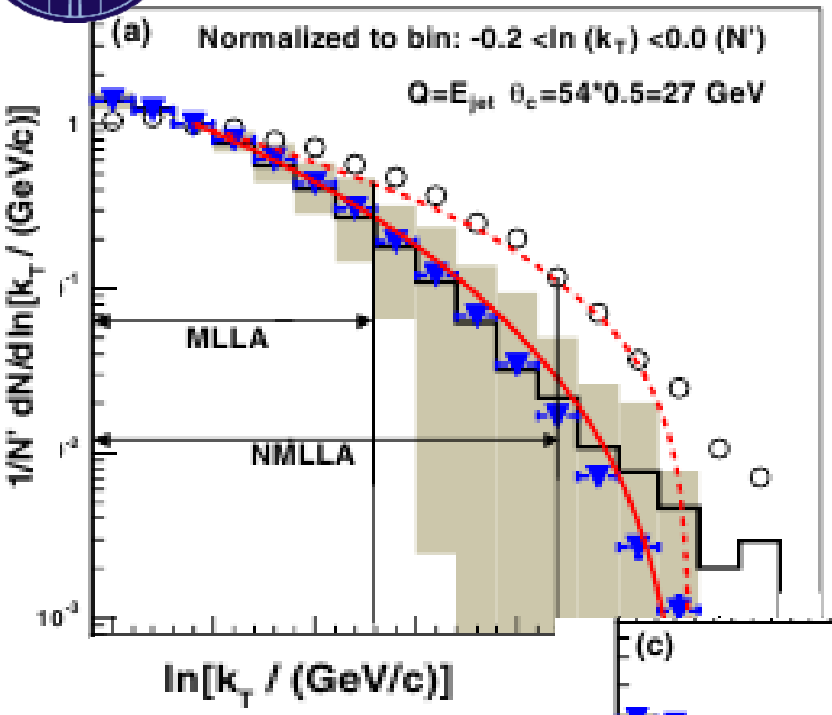
Dijet angular distribution , D0

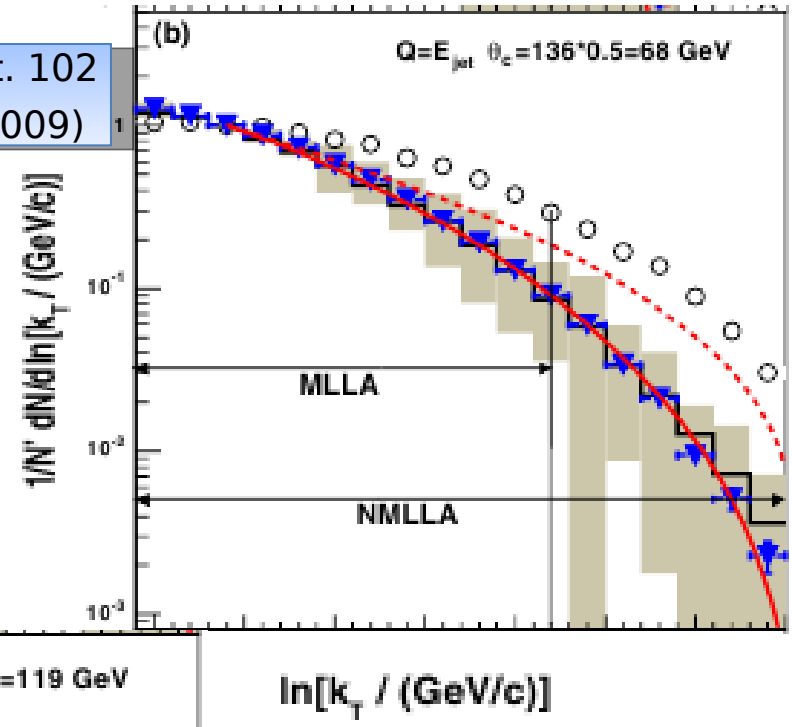
TABLE I: Expected and observed 95% C.L. limits in units of TeV on various new physics (NP) models for different Bayesian priors, and for the $\Delta\chi^2$ criterion.

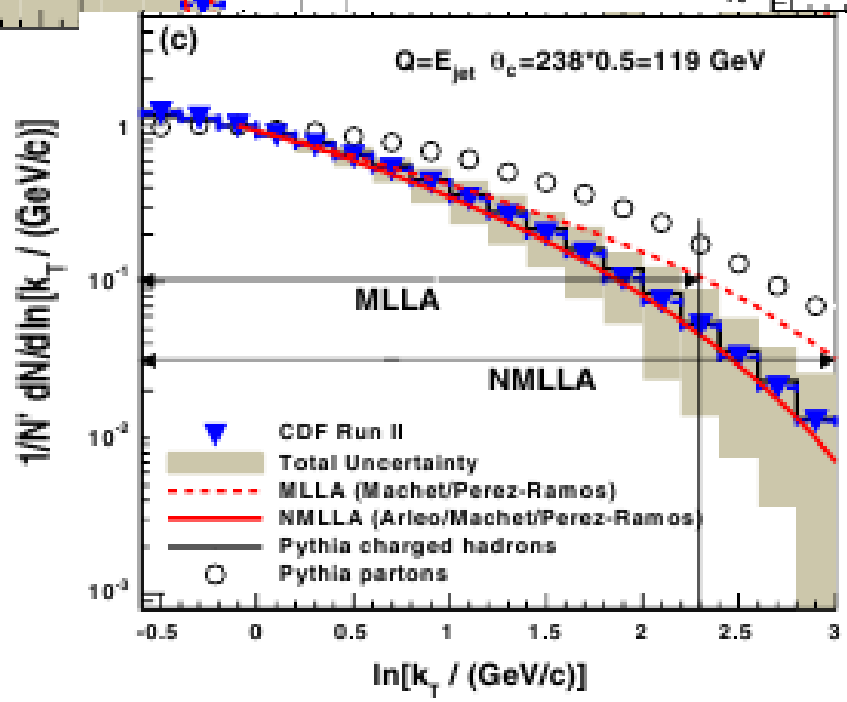
	Prior flat in NP Lagrang.		Prior flat in NP x-section		$\Delta\chi^2 = 3.84$ criterion	
Model (parameter)	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
Quark comp. (Λ)						
$\eta = +1$	2.91	3.06	2.76	2.84	2.80	2.92
$\eta = -1$	2.97	3.06	2.75	2.82	2.82	2.96
TeV^{-1} ED (M_C)	1.73	1.67	1.60	1.55	1.66	1.59
ADD LED (M_S)						
GRW	1.53	1.67	1.47	1.59	1.49	1.66
HLZ $n = 3$	1.81	1.98	1.75	1.89	1.77	1.97
HLZ $n = 4$	1.53	1.67	1.47	1.59	1.49	1.66
HLZ $n = 5$	1.38	1.51	1.33	1.43	1.35	1.50
HLZ $n = 6$	1.28	1.40	1.24	1.34	1.25	1.39
HLZ $n = 7$	1.21	1.33	1.17	1.26	1.19	1.32

K_t distribution of Particles in Jets , CDF

Phys.Rev. Lett. 102 232002 (2009)







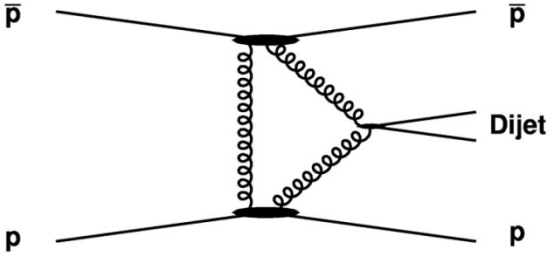
Modified Leading Log Approximation MLLA + local -hadron- parton Duality (LPHD)
Jet "hardness"
Q=E_jet x angle
? Pertubative hard or non-perturbative soft hadronization domina te?

Conclusion: parton shower dominates, hadronization effects are small, LPHD is supported; NMLLA describes data well over dijet mass range 66-737 GeV

Exclusive Dijet Production, D0

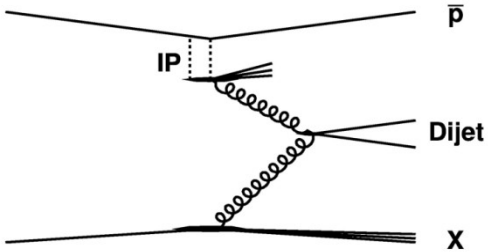
D0 Note 6042 - CONF (2010)

signal



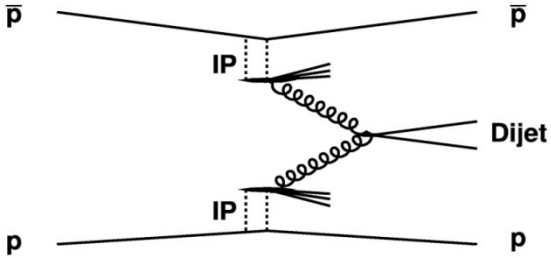
Exclusive diffractive dijet (EDP)

background



Single diffractive (SDS)

background



Inclusive double pomeron (IDP)

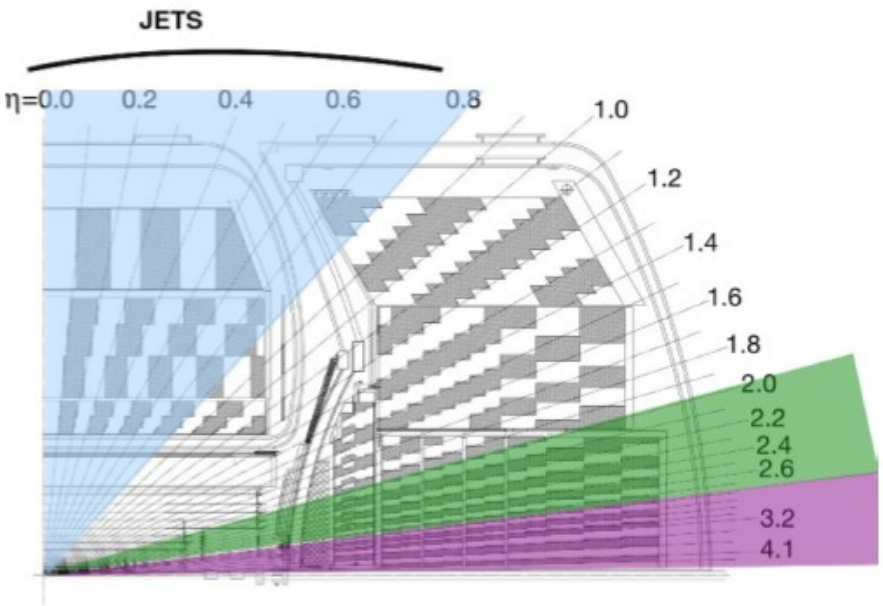
require 2 central jets, study forward region

Study mechanism of EDP production at high dijet mass

Discriminant: Δ=

$$\frac{1}{2}\exp\Big(-\sum_{20<|ieta|\leq 30} E_T\Big) + \frac{1}{2}\exp\Big(-\sum_{|ieta|>30} E_T\Big)$$

designed to discriminate against different bkgds simultaneously

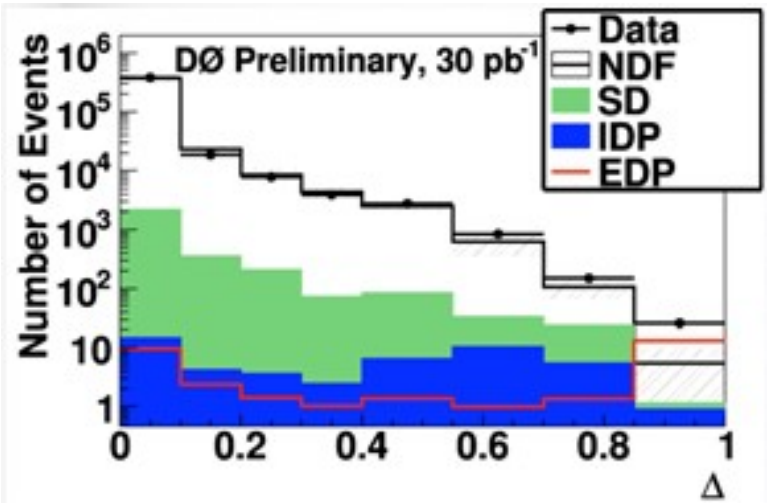


Discriminate against IDP

Discriminate against NDF

NDF=non-difractive

Exclusive Dijet Production, D0

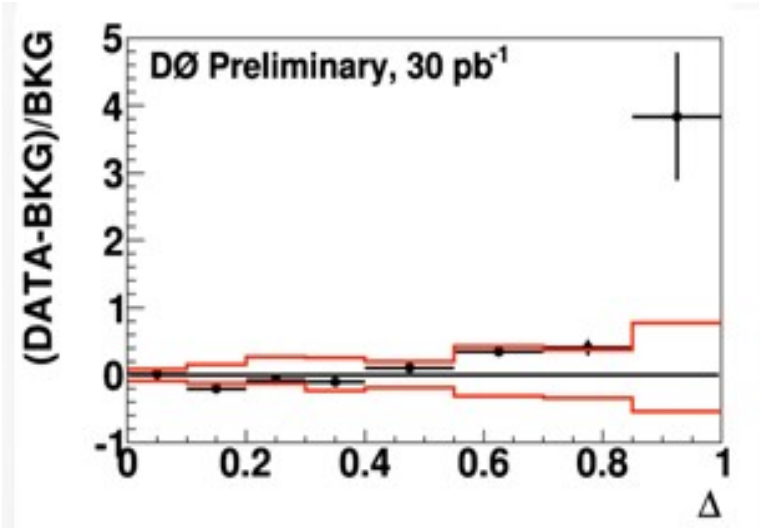


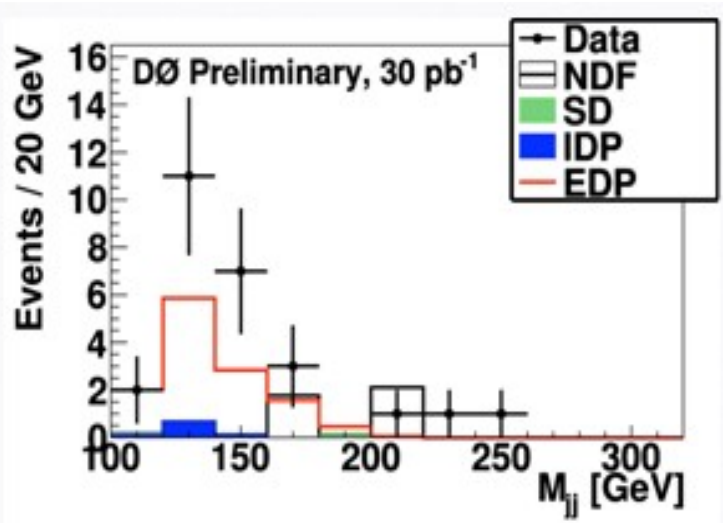
*Discriminant works well

*26 candidate events are observed in **Δ >.85** region,

* total bkgd prediction is of $5.4^{+4.2}_{-2.9}$ events

*4.1σ evidence of EDP at high dijet invariant mass Mjj > 100 GeV





3-jet mass cross section , D0

D0 Note 6043 --CONF (2010)

First Measurement of three-jet cross section at the Tevatron

→ First corrected 3-jet mass distribution

→ First comparison to NLO pQCD calculations for 3-jet cross sections

Strategy:

Measure cross sect. vs. invariant three-jet mass

- in different rapidity intervals $|y| < 0.8, 1.6, 2.4$

For the largest rapidity interval

- for different p_T requirements of the 3rd jet $p_T^{Jet3} > 40, 70, 100$ GeV

Data Set:

- 0.7 fb-1 inclusive jet triggers
- Require at least 3 reconstructed jets passing data quality and jet id criteria
  - Jet 1 $p_T > 150$ GeV
  - Jet 2, 3 $p_T > 40$ GeV
  - All jets separated by $\Delta R > 1.4 = 2*R_{cone}$

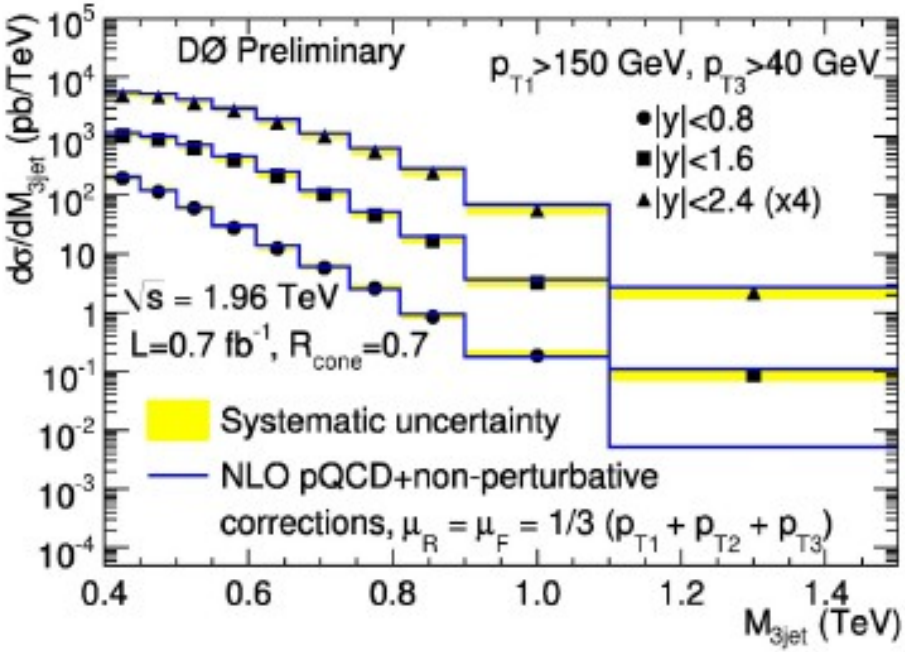
D0 Three-jet Mass Results

- First measurement at the Tevatron of corrected 3-jet mass distribution
- First comparison to NLO prediction for 3-jet cross-section

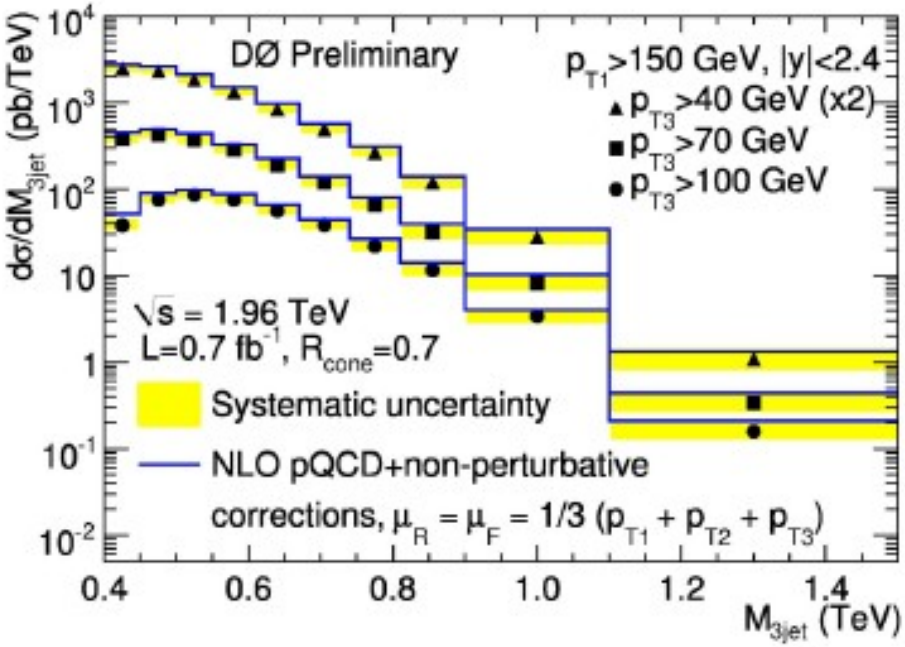
3-jet Mass Cross Section , D0

$$\frac{d\sigma}{dM_{3jet}} = \frac{1}{L \cdot \Delta M_{3jet}} \cdot \left(\sum_{i=1}^{N_{evt}} \frac{1}{\epsilon_v^i} \right) \cdot C_{unsmear}$$

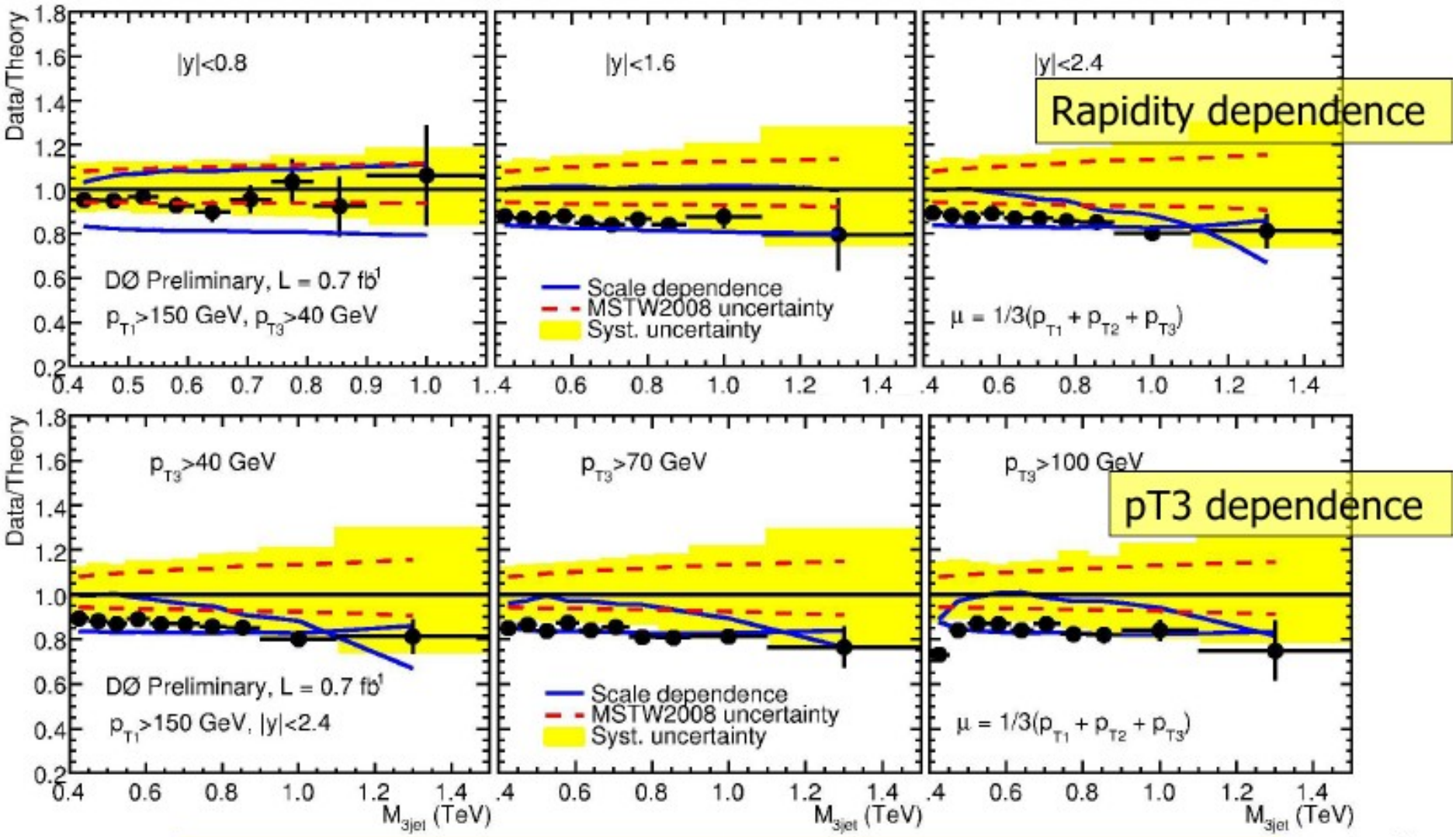
Rapidity dependence



p_T^{Jet3} dependence



3-jet mass cross section , D0



Well described by pQCD: 1st test 3-jet NLO cross section!

Ratios of Multi-Jet Cross Sections, R3/2 , D0

D0 Note 6032--CONF (2010)

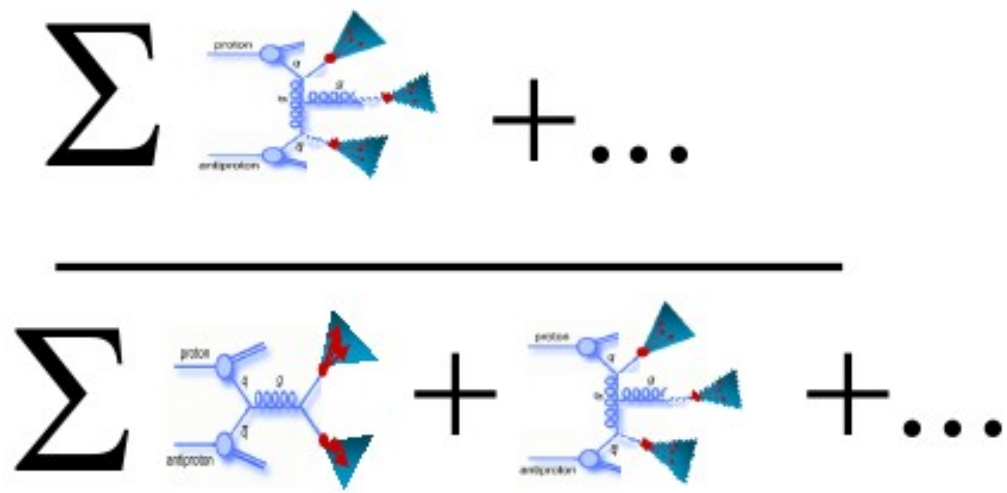
Goal: test pQCD (and α_s) independent of PDFs

Conditional probability:

$R_{3/2}$

$= P(3^{rd} \text{ jet} \mid 2 \text{ jets})$

$= \sigma_{3\text{-jet}} / \sigma_{2\text{-jet}}$



- Probability to find a third jet in an inclusive dijet event
- Sensitive to α_s (3-jets: α_s^3 / 2-jets: α_s^2)
- (almost) independent of PDFs

Ratios of Multi-Jet Cross Sections, $R_{3/2}$, D0

Measure as function of two momentum scales:

- p_{Tmax} : common scale for both $\sigma_{2\text{-}jet}$ and $\sigma_{3\text{-}jet}$
- p_{Tmin} : scale at which 3rd jet is resolved ($\sigma_{3\text{-}jet}$ only)

Sensitive to α_s at the scale p_{Tmax}

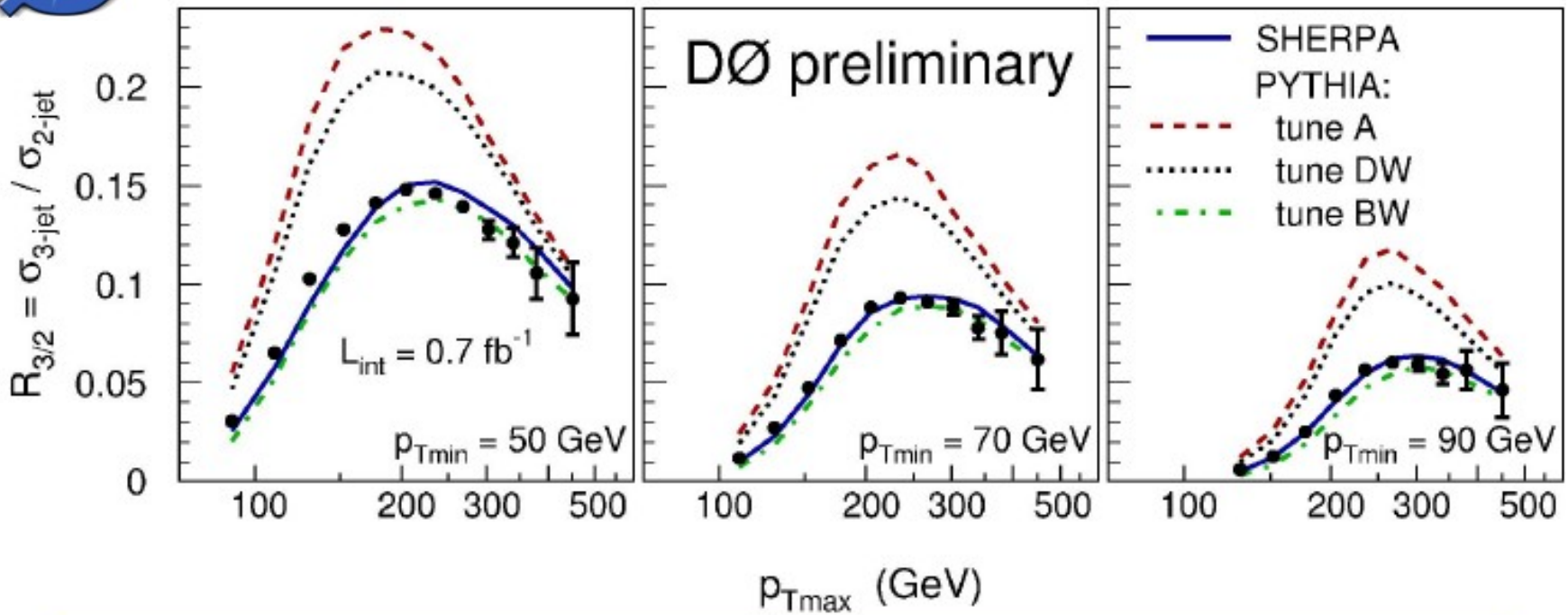
→ probe running of α_s in Tevatron energy regime → up to 500 GeV

Details:

- inclusive *n*-jet samples (*n*=3,2) with *n* (or more) jets above p_{Tmin}
- $|y|<2.4$ for all *n* leading p_T jets
- $\Delta R_{jet,jet} > 1.4$ (insensitive to overlapping jet cones)
- study p_{Tmax} dependence for different p_{Tmin} of 50, 70, 90 GeV

→ Measurement of $R_{3/2}(p_{Tmax} ; p_{Tmin})$

Ratios of Multi-Jet Cross Sections, R3/2, D0



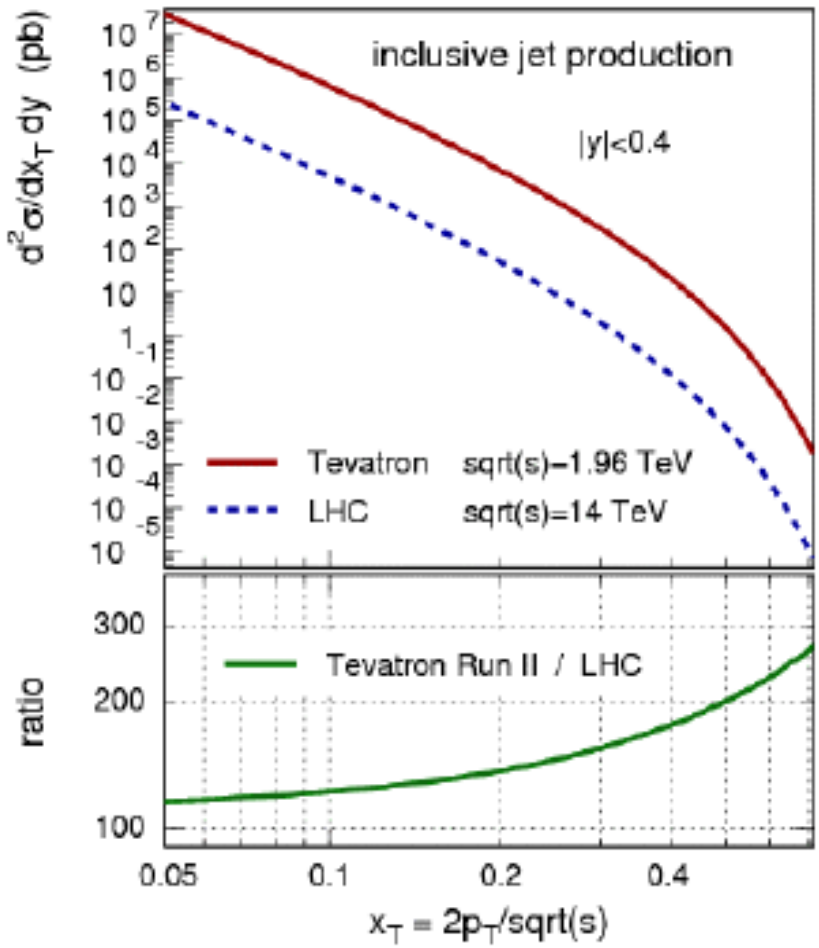
SHERPA: good description (default version w/ MSTW2008LO PDFs)

PYTHIA: huge dependence on tune

- Reasonable description by tune BW
- Popular tunes A, DW → totally off

D0 Multijet Ratios $R_{3/2}$ Results

- High precision test of pQCD
- Comparisons to NLO prediction underway
- Can be extended to other ratios ($R_{4/2}$, $R_{4/3}$, etc) & extraction of α_S.



PDF sensitivity:

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

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

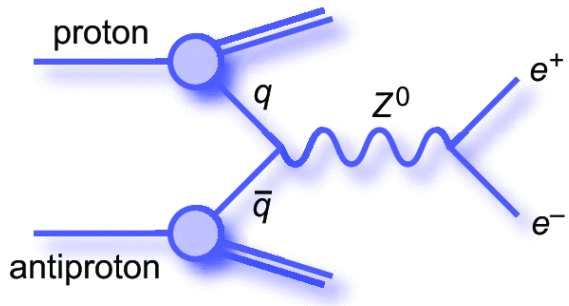
Z/W + Jets

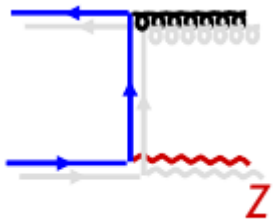
Fixed-order: NLO

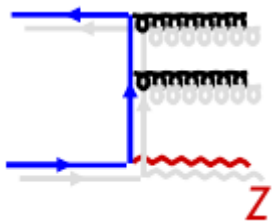
LO + Parton Shower

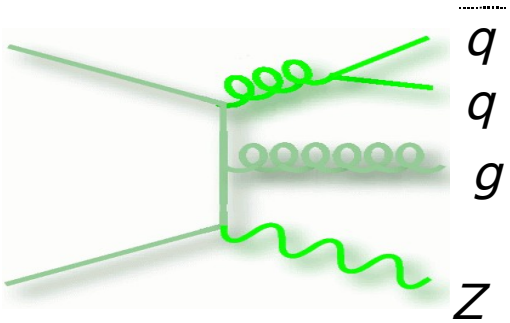
Backgrounds to New Physics

Vector Boson + Jets (Njet =1, 2, 3 ...)









- relevant to other high-multiplicity processes
- background to Higgs

Provide detailed measurements of p_T and angular distributions of vector boson and jet

→ test perturbative QCD calculations

→ testing and tuning of phenomenological models

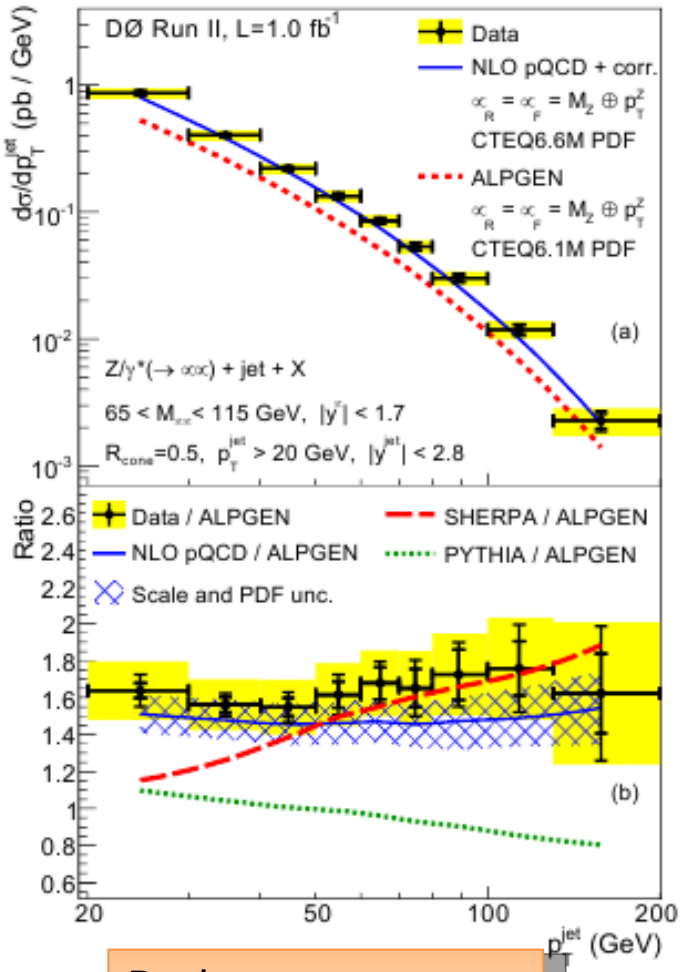
Differential Z/gamma + 1jet+ X cross section , D0

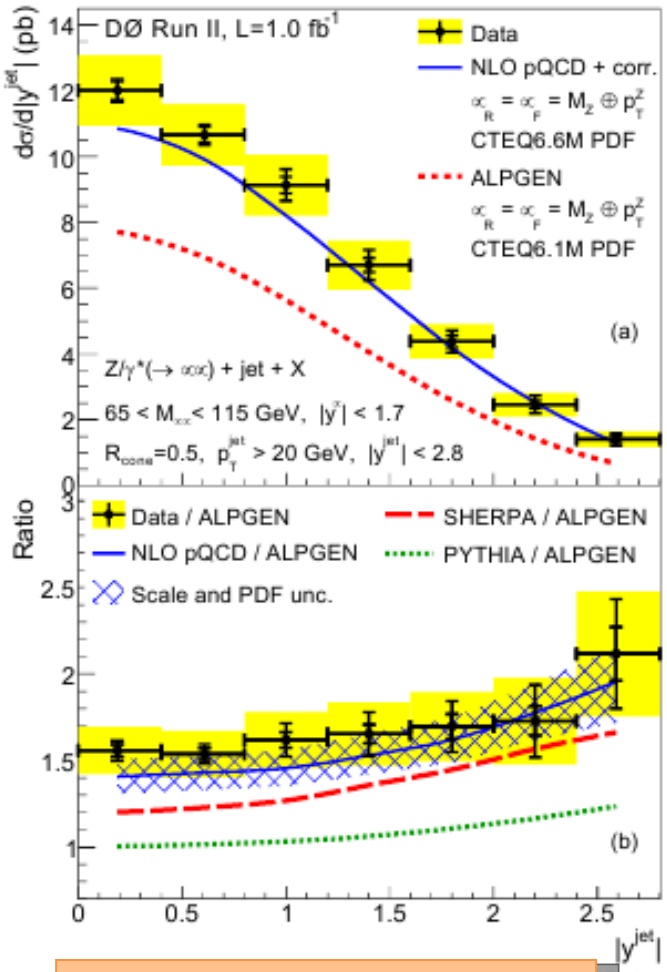
$Z/\gamma^*(\rightarrow \mu^+\mu^-)$

L= 1 fb-1

Phys.Lett. B, **669,** 278 (2008)

$65 < M_{\mu\mu} < 115$ GeV, $|y_\mu| < 1.7$, $p_T^{jet}(R=0.5) > 20$ GeV, $|y_{jet}| < 2.8$





NLO pQCD: MCFM v5.4
PDF: CTEQ6.6M
$\mu_r^2 = \mu_f^2 = M_Z^2 + p_{T,Z}^2$

PYTHIA 6.323,
ALPGEN 2.05,
SHERPA 1.1.1,
PDF: CTEQ6.1M

NLO pQCD prediction 5% below measured cross section.

For $p_T(Z) < 30$ GeV prediction sensitive to underlying event

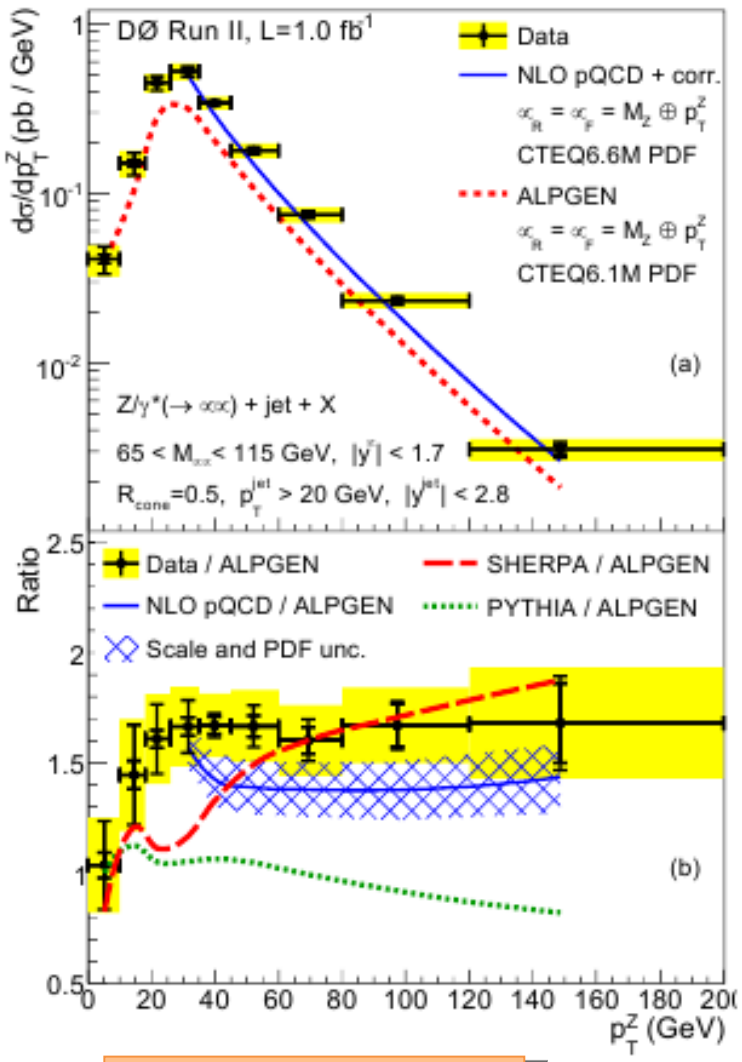
Total cross section prediction of ALPGEN and PYTHIA significantly below data

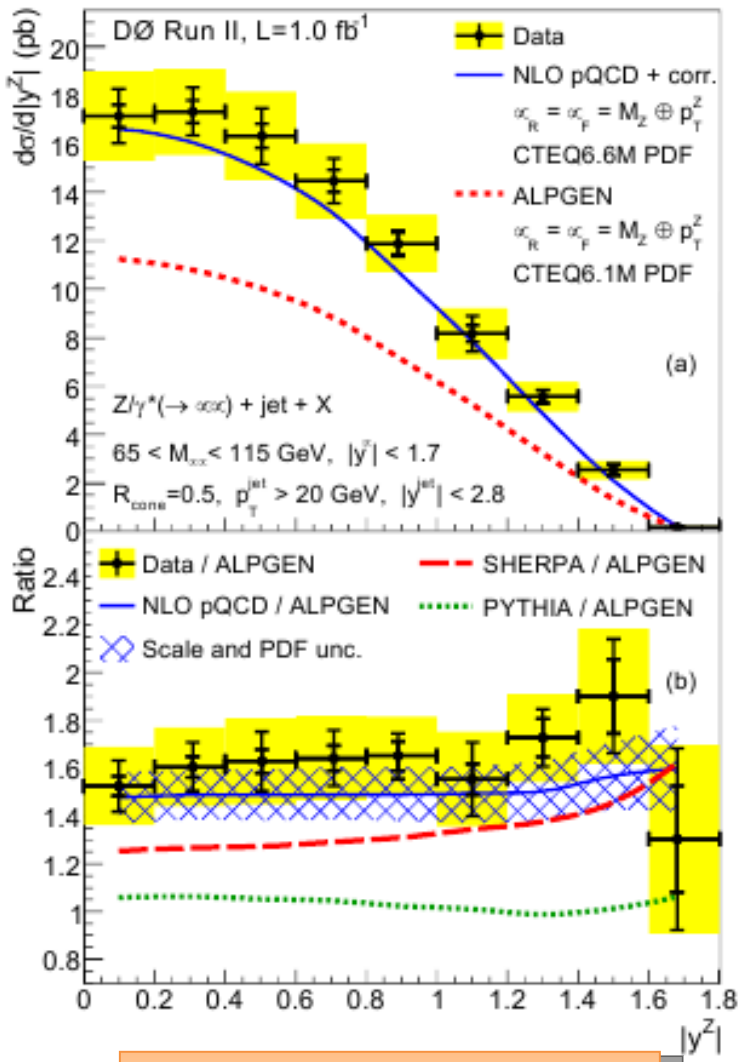
Pt- jet dependence

Jet- rapidity dependence

Differential Z/gamma + 1jet+ X cross section , D0

$\sigma(z/\gamma^*(\rightarrow \mu\mu)+\text{jet}+X) = 18.7 \pm 0.2(\text{stat.}) \pm 0.8(\text{syst.}) \pm 0.9(\text{muon}) \pm 1.1(\text{lumi.})$ pb





1.The shapes are well described by NLOpQCD

2.Cross section at lower Pt-Z is dominated by non -perturbative process.

Pt- Z dependence

Z- rapidity dependence

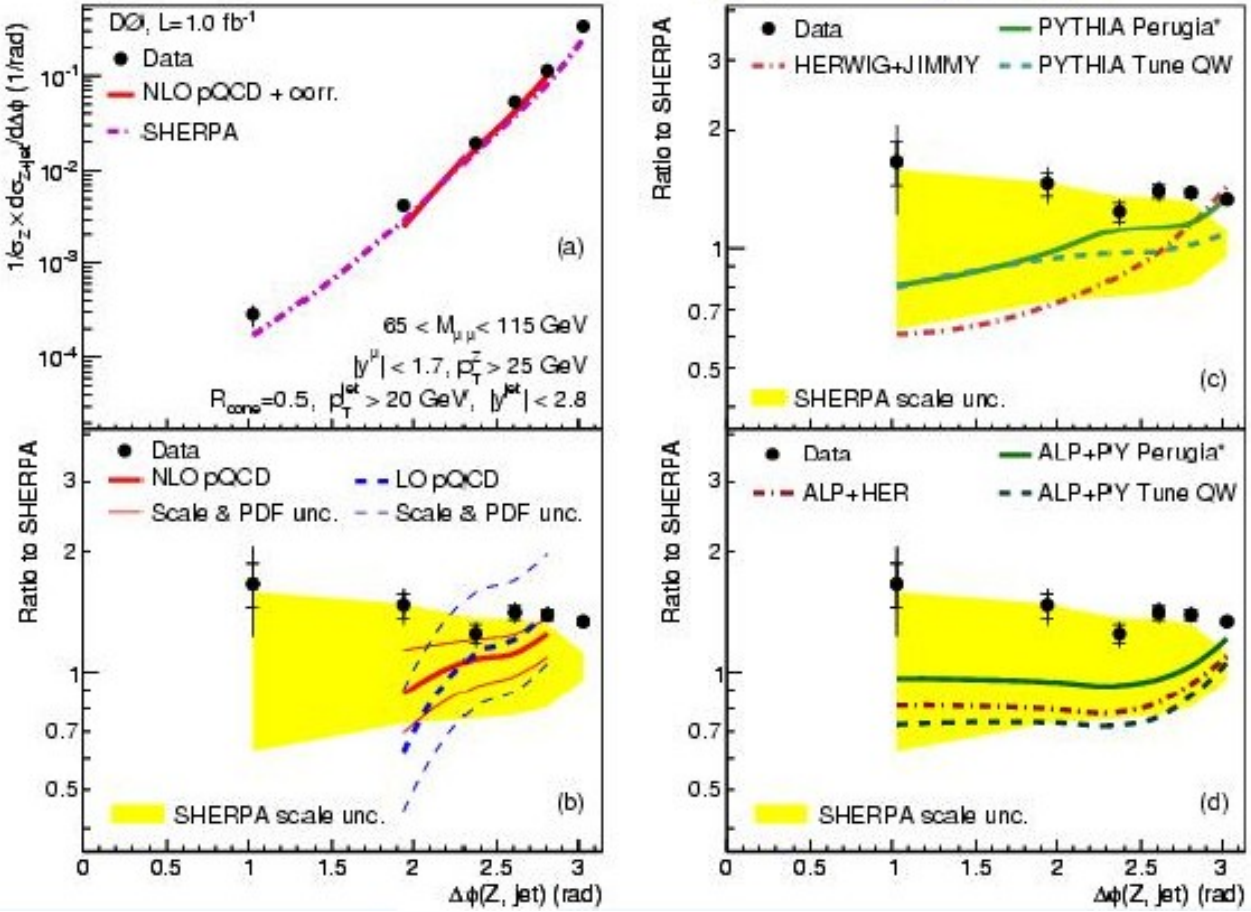
Differential Z/gamma + 1jet+ X angular distributions, D0

L= 1 fb-1

Phys.Lett. B, **682,** 370 (2010)

$Z/\gamma^*(\rightarrow\mu^+\mu^-)$ + jets: angular correlations

- Normalized diff. cross section in $\Delta\phi$(Z,leading jet), $p_T^Z > 25$ GeV

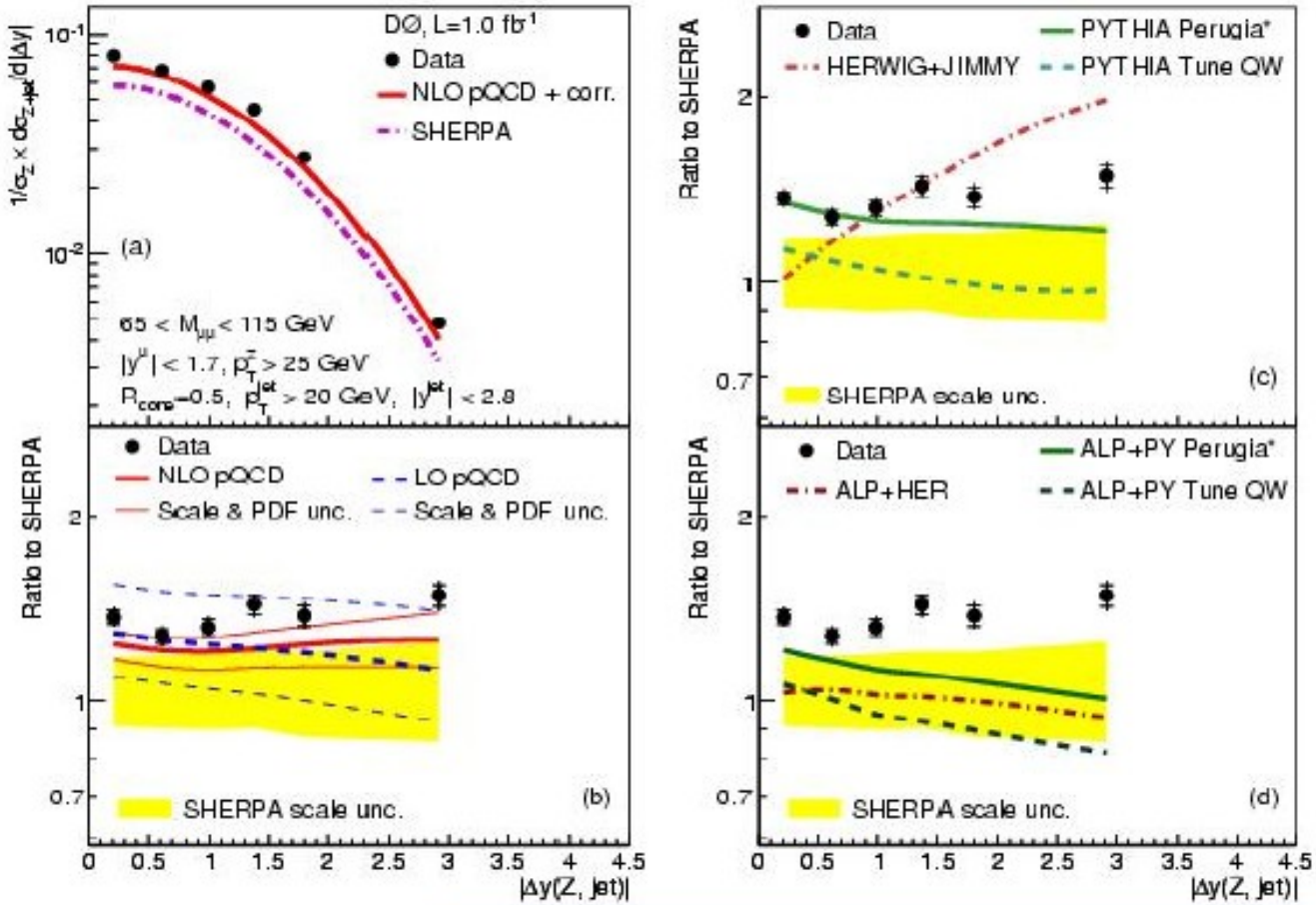


SHERPA is preferred by data

Differential Z/gamma + 1jet+ X angular distributions, D0

$Z/\gamma^*(\rightarrow\mu^+\mu^-)$ + jets: rapidity correlations

- Normalized diff. cross section in Δy(Z,leading jet) , $p_T^Z > 25$ GeV



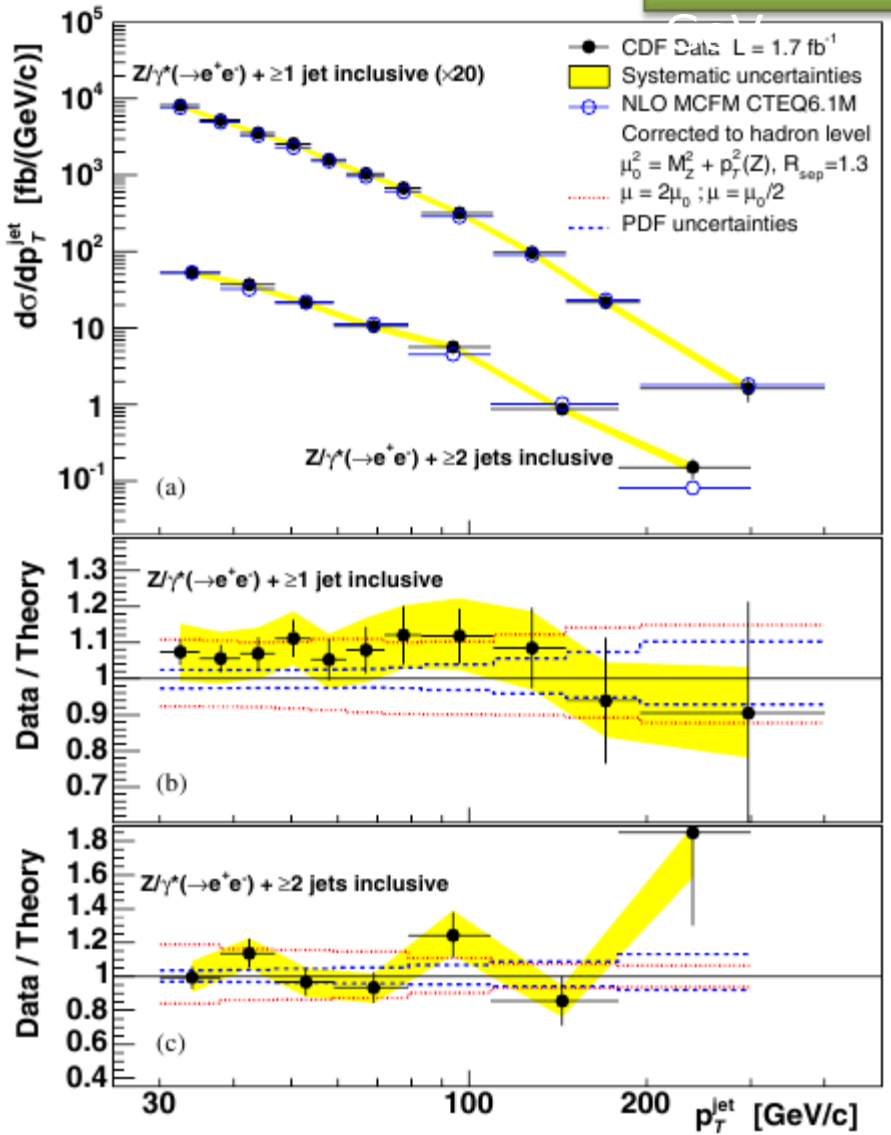
- NLO pQCD is preferred by data

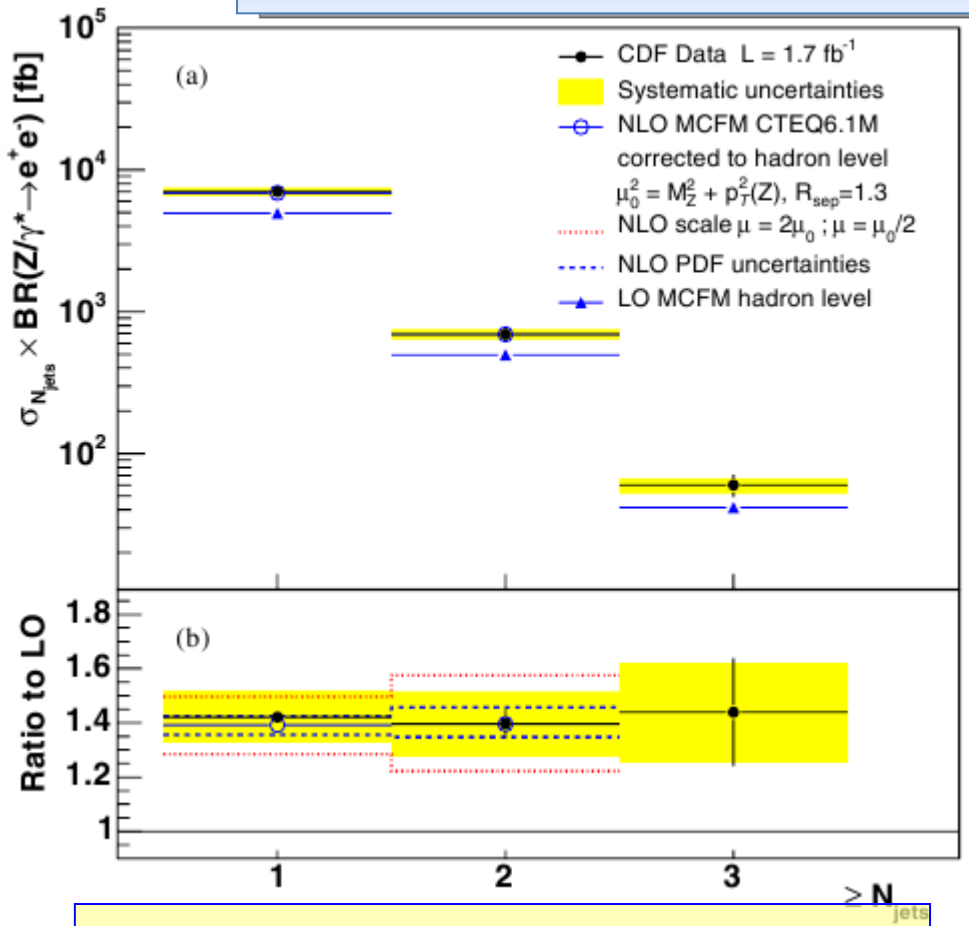
Inclusive Jet Cross Sections in Z/gamma(➔e+e-) + jets+ X Production , CDF

L= 1.7 fb-1

66< Mee <116

Phys. Rev. Lett. , **100,** 102001 (2008)





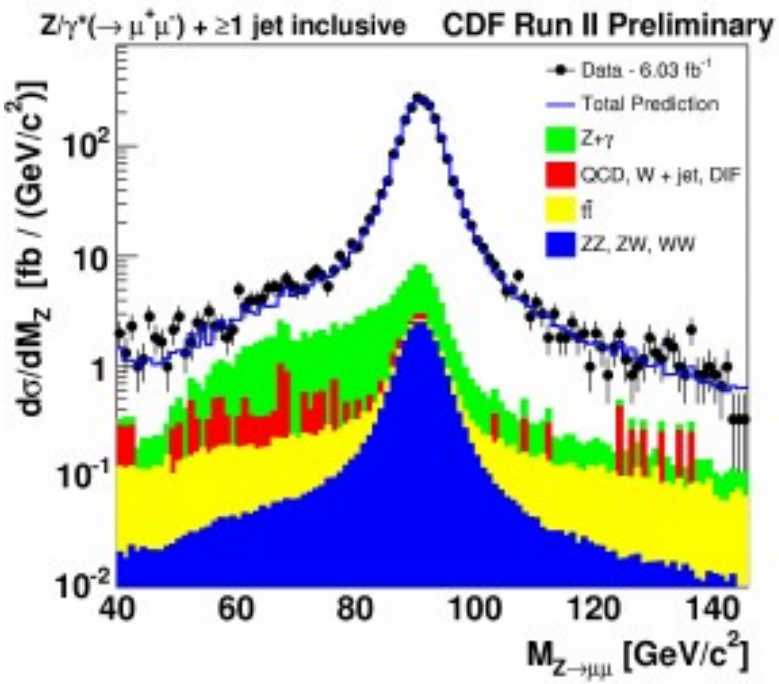
Measured cross sections are well described by NLOpQCD + non-pertubative

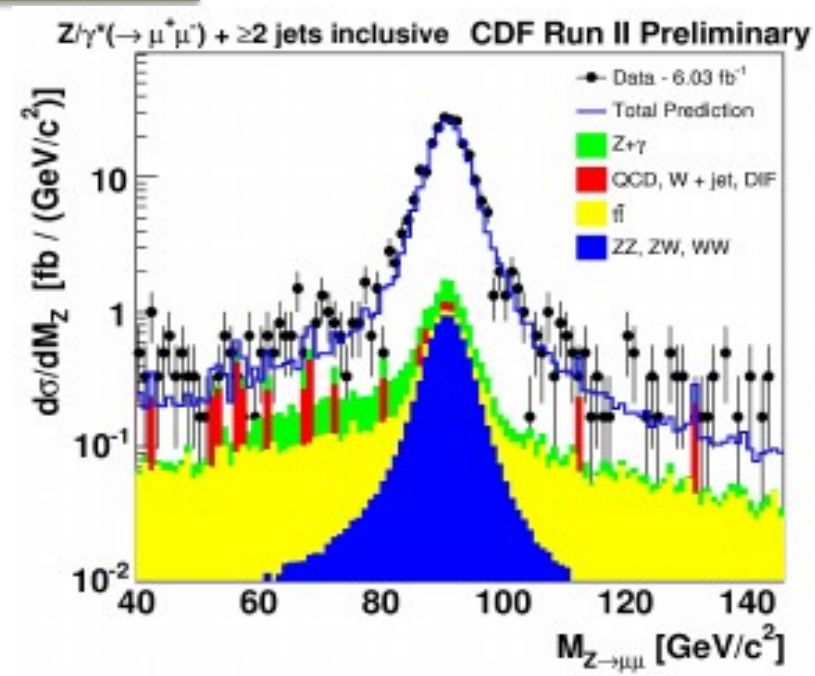
Inclusive Jet Cross Sections
Z/gamma(➔ μ+μ-) + jets+ X Production,

L= 6.0 fb-1

66 < Mmumu < 116

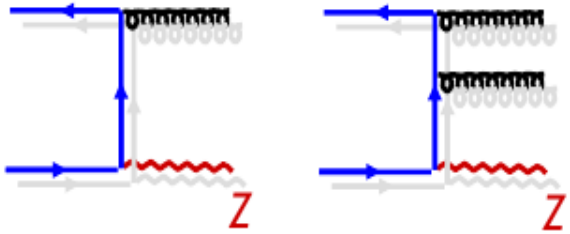
CDF note 10216, July 10 , 2010



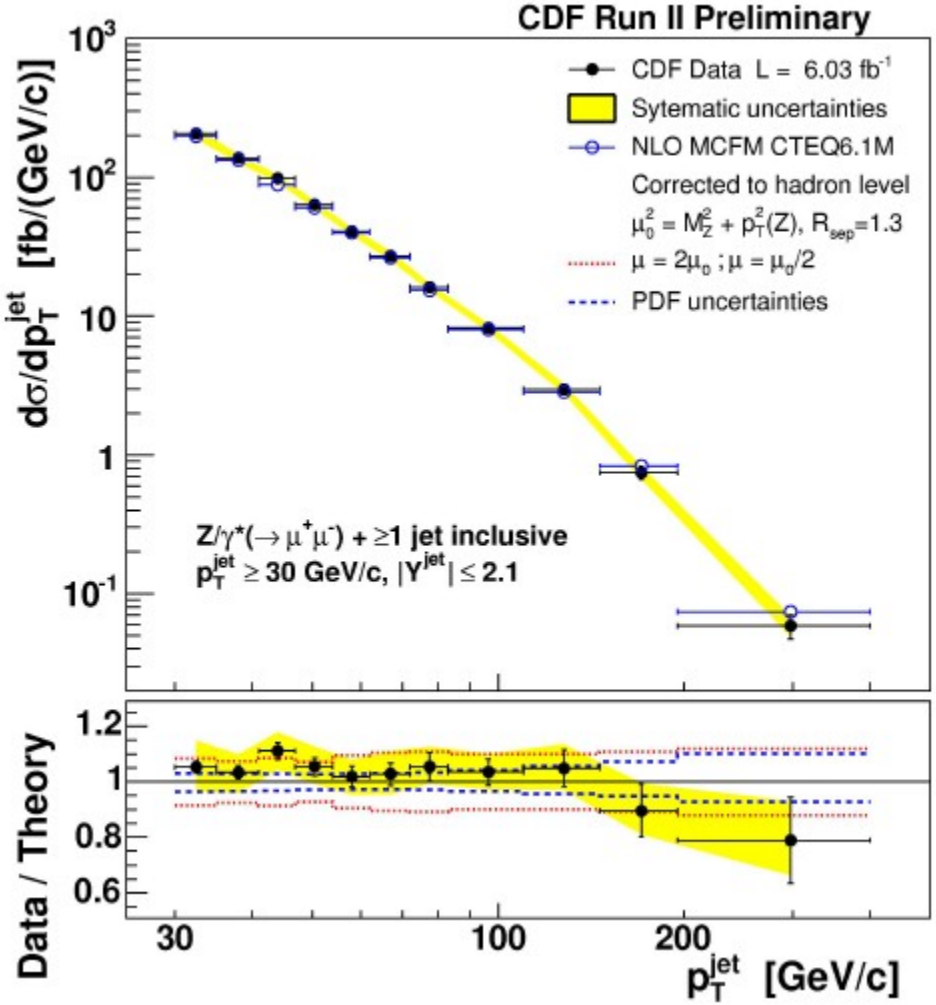


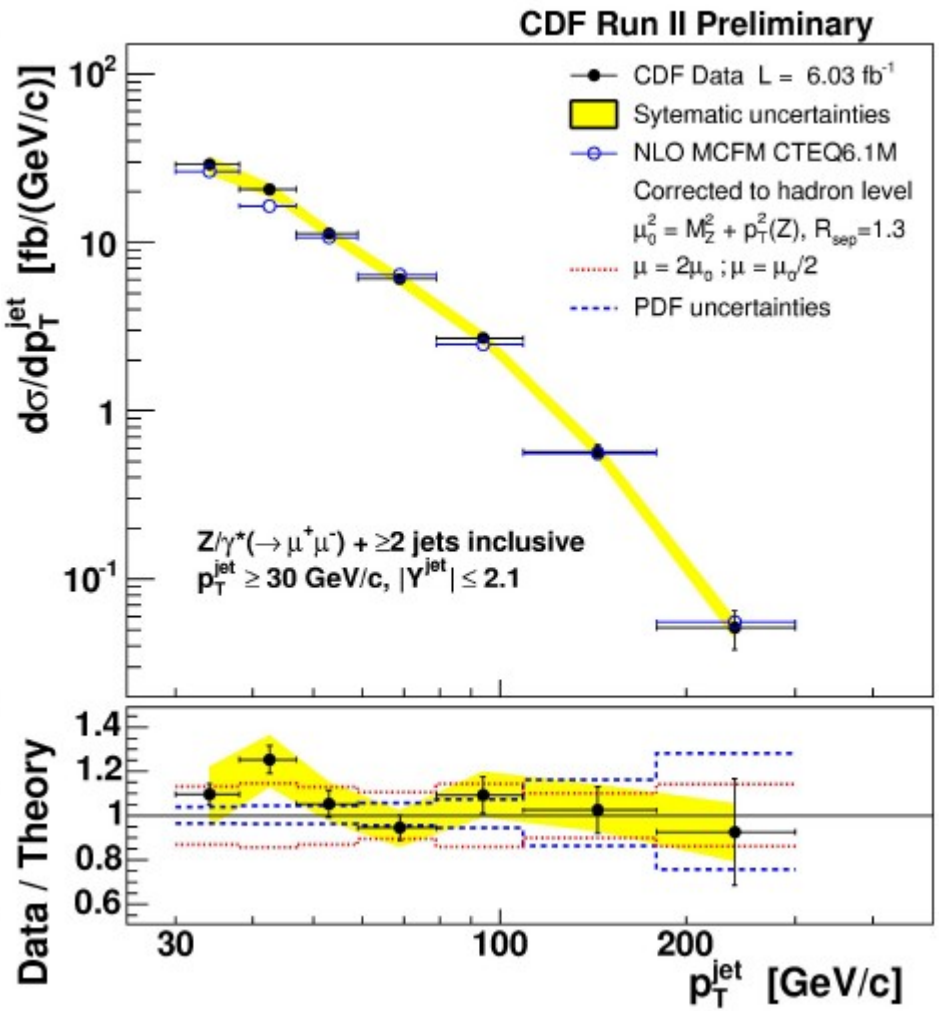
CDF II Preliminary

Backgrounds	Estimated events in 6.03 fb^{-1}		
	Z + ≥ 1 jet	Z + ≥ 2 jets	Z + ≥ 3 jets
$Z/\gamma^* \to \mu^+\mu^- + \gamma$	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
$Z \to \tau^+\tau^- +$ 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



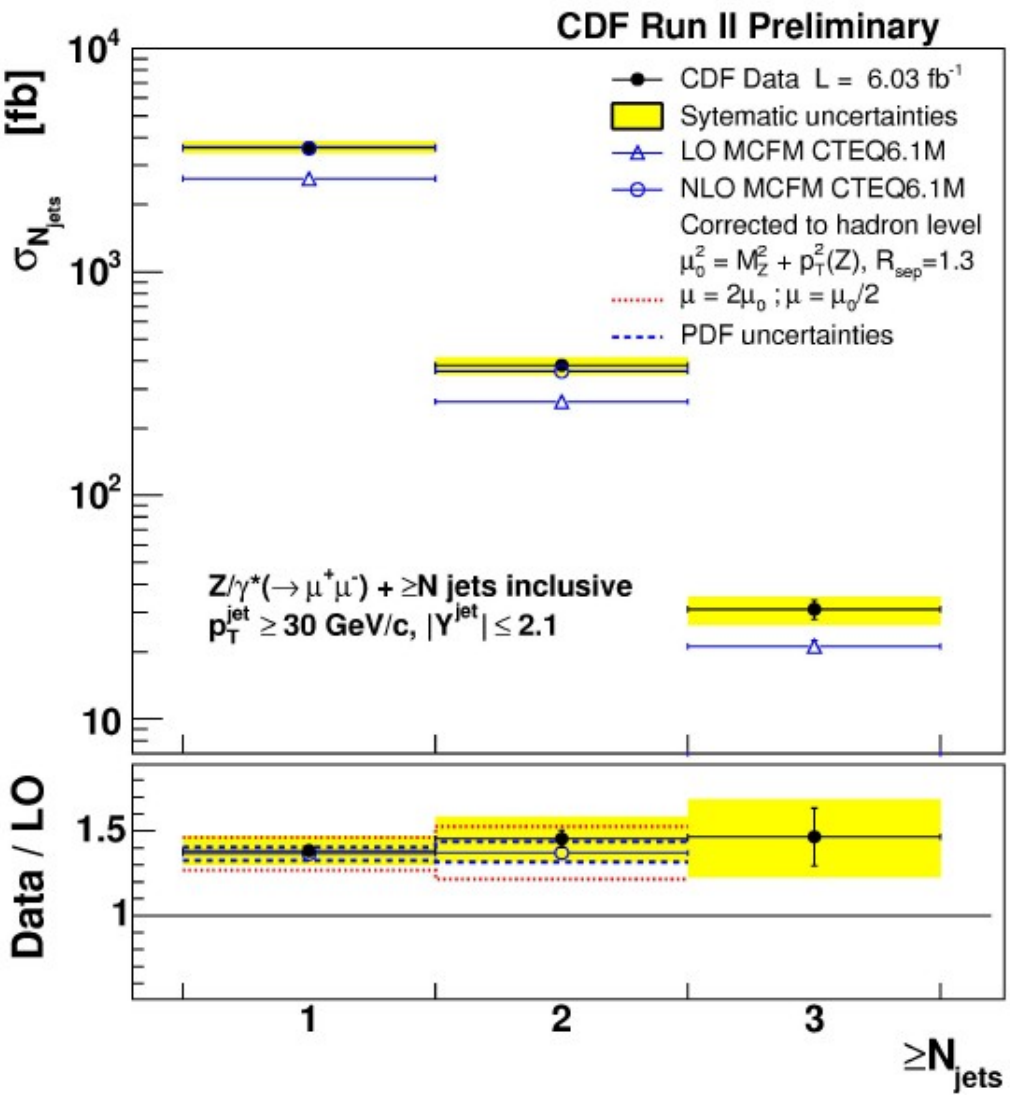
Inclusive Jet Cross Sections
Z/gamma(➔ μ+μ-) + jets+ X Production

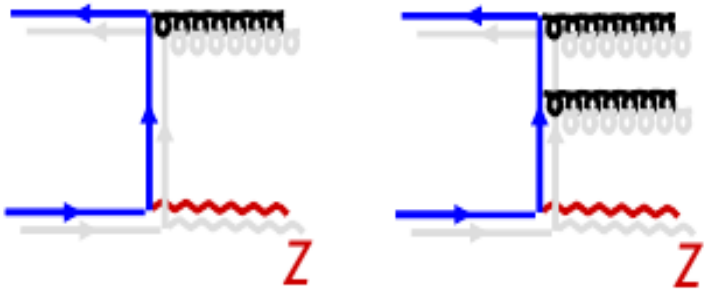




σ decrease by more than 3 orders of magnitude

Jets Multiplicity in Z/gamma(➔ μ+μ−) + jets+ X Production, CDF





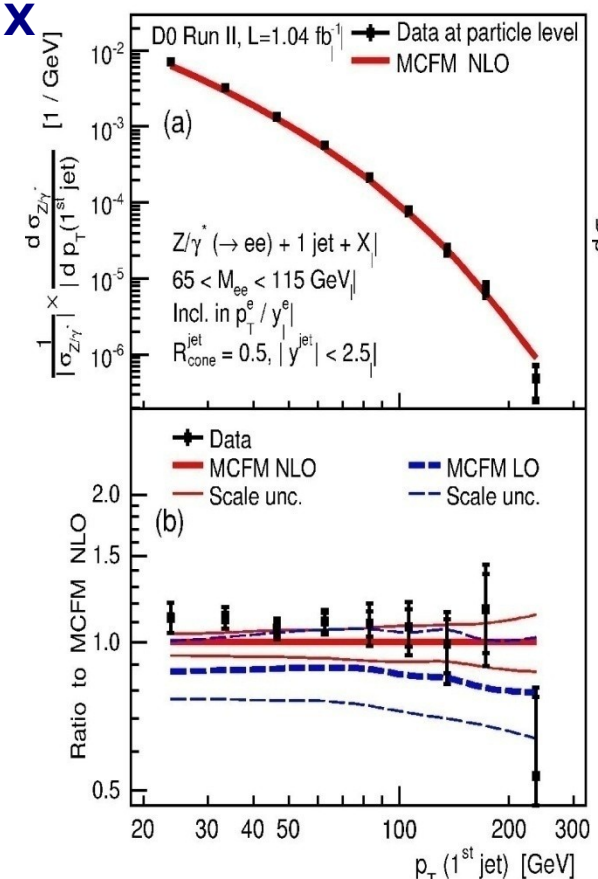
The measurements are well described by NLOpQCD + non-pertubative corrections which are estimated with PYHTIA-Tune A MC simulation

Cross Section for Z/gamma + jets (1,2,3) + X, D0

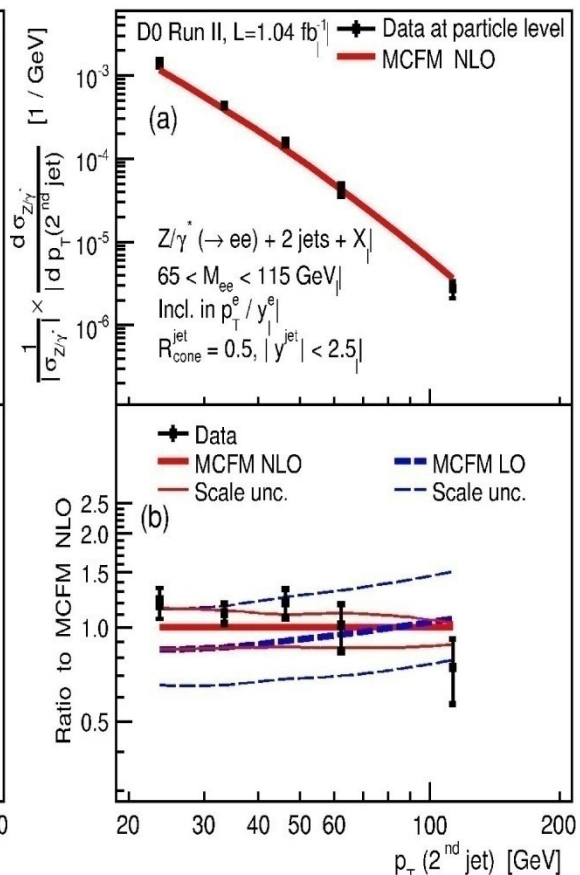
Measurement of 1st, 2nd and 3rd jet p_T in Z events:
→normalize to inclusive Z production (cancel some uncertainties) compare to pQCD @ LO / NLO

FERMILAB-PUB-09-066-E
arXiv:0903.1748v2 [hep-ex]
4Aug 2009

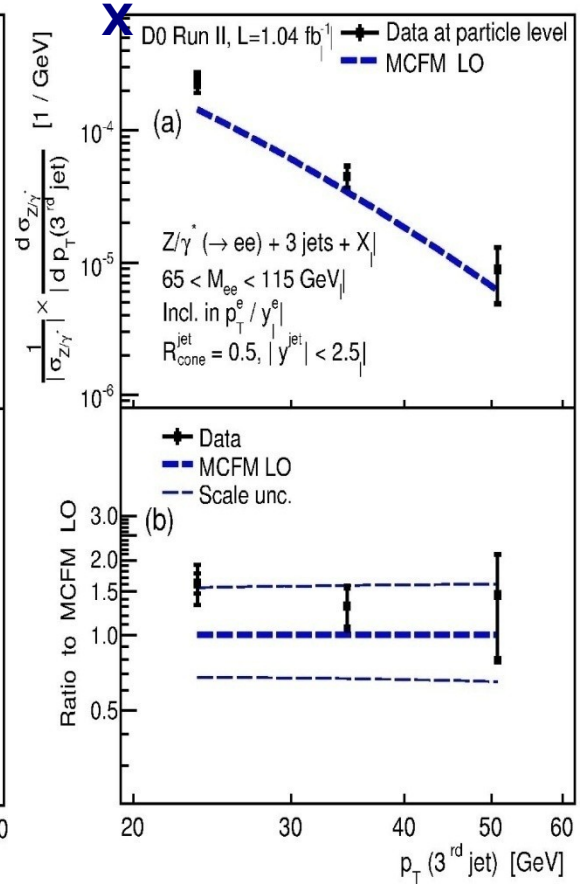
Leading jet in Z + jet + X



Second jet in Z + 2jet + X



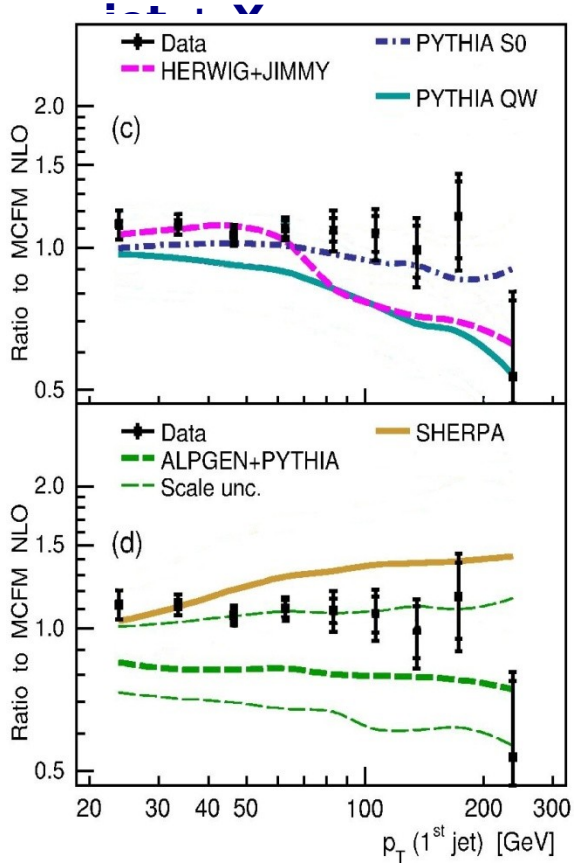
Third jet in Z + 3jet + X



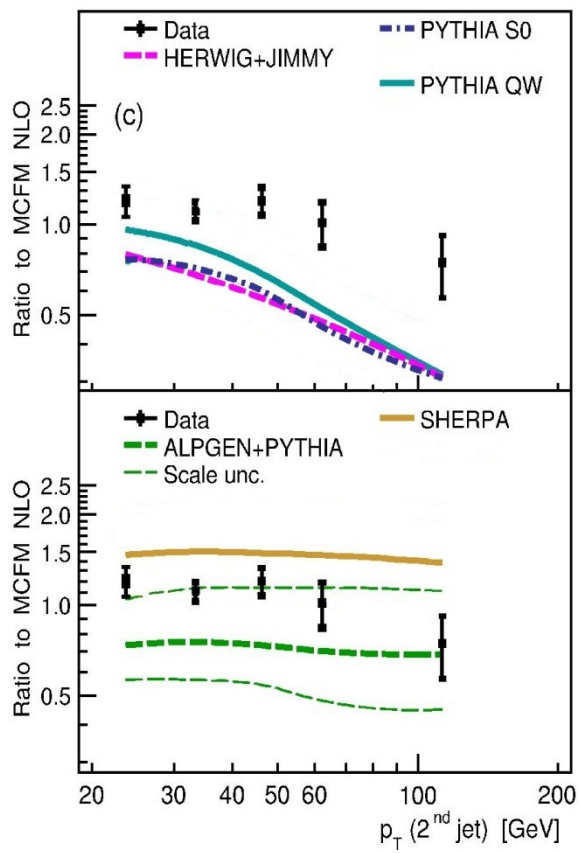
Cross Section for Z/gamma + jets (1,2,3) + X

Ratios of data and different MC generators → favor ALPGEN +PYTHIA w/ low scale
For "ALPGEN + PYTHA" (- - -) scales (factoriz. and renorm.) can be chosen so that a good, simultaneous agreement with data is achieved for all three leading jets .

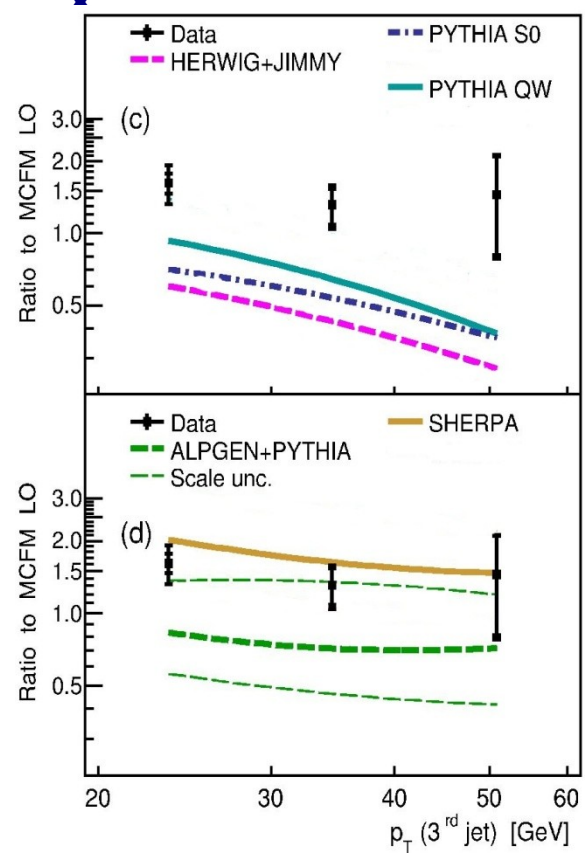
Leading jet in Z + jet + X



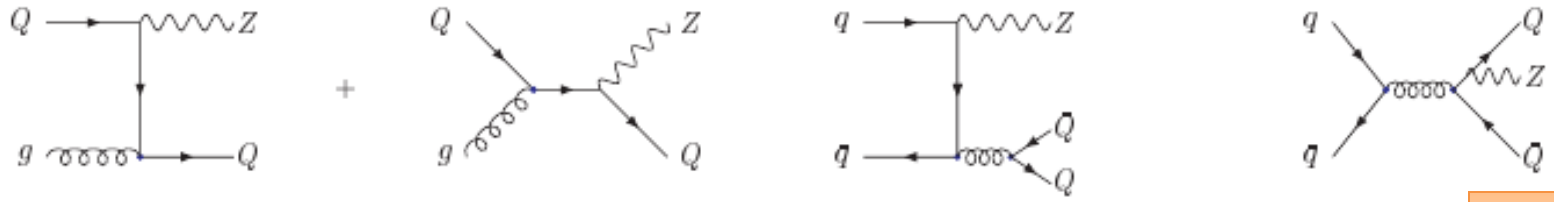
Second jet in Z + 2jet + X



Third jet in Z + 3jet + X



Ratio of Cross Sections Z + b-jet/Z+jet , D0



L= 180 pb-1

σ (Z + b-jet) / σ (Z +jet) = 0.021 $\pm$ 0.005

D0:
Phys. Rev. Lett.,
94, 161801 (2005)

σ (Z + b-jet) / σ (Z +jet) =0.208 $\pm$ 0.0033(stat.) $\pm$ 0.0034(syst.)

L= 2.0 fb-1

CDF : Phys. Rev., D, 79, 052008 (2009)

Ratio of Cross Sections Z + b-jet/Z+jet , D0

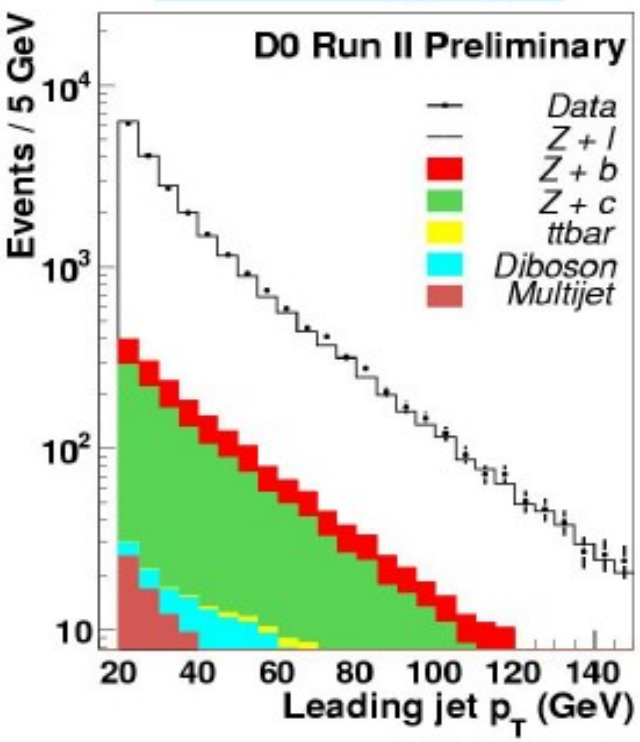
L= 4.2 fb-1

D0 Note 6053--CONF (2010)

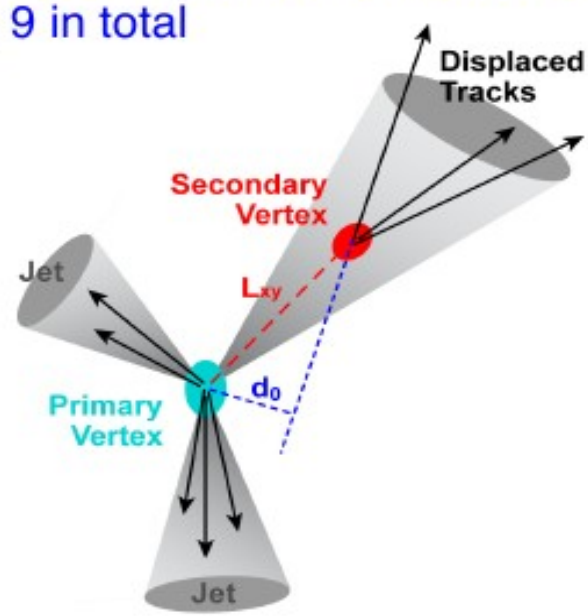
σ(Z+b)/σ(Z+jet) ratio measurement

- Event Selection
  - Dilepton mass 70≤M≤110 GeV
  - ≥ 1 jet: p_T> 20 GeV, |η|<1.1

Before tagging



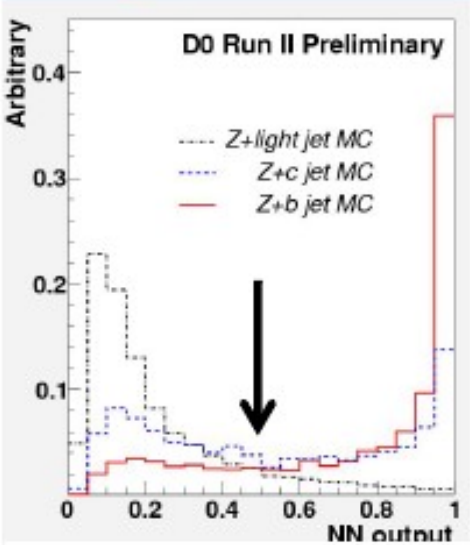
- Inputs for NN tagging algorithm
  - Decay length significance of sec. vtx
  - No. of tracks associated to sec. vtx.
  - Mass of the sec. vertex
  - (reduced) Jet Lifetime Probability, rJLIP: confidence level that all tracks in a jet originate from primary vertex
  - etc., 9 in total

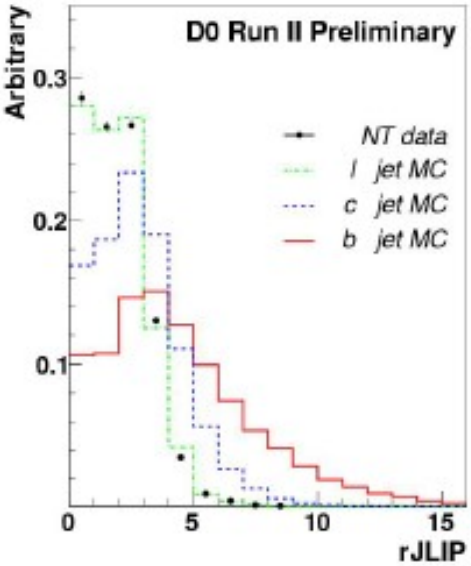


Ratio of Cross Sections Z + b-jet/Z+jet , D0

Separation of light, c and b jets

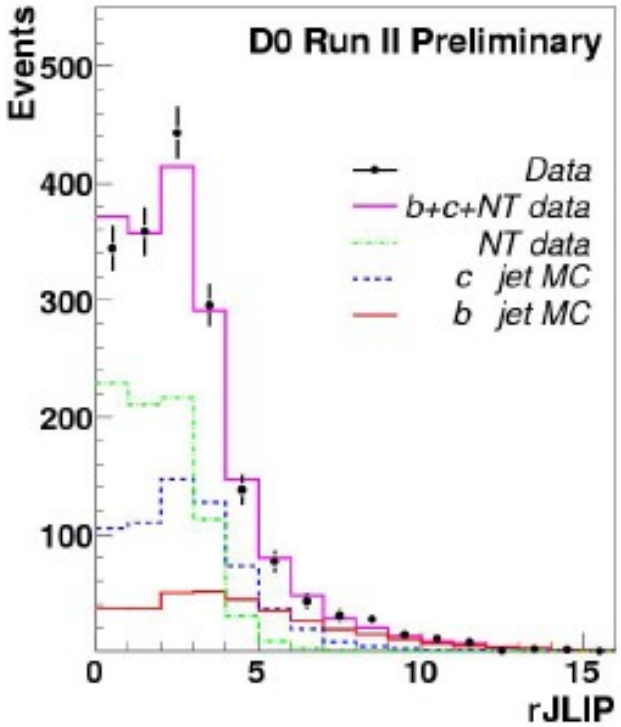
- Apply Neural Network tagging algorithm on jets to enrich b content
- Use rJLIP variable to discriminate between light, c and b jets
- Light jet template is derived from "Negatively Tagged" (NT) data
  - Jets are formed from tracks that have negative values for some of the inputs for the NN algorithm
- Use Alpgen+Pythia for b and c jet templates
- Use log likelihood fit to extract Z+b fraction from the preselected sample

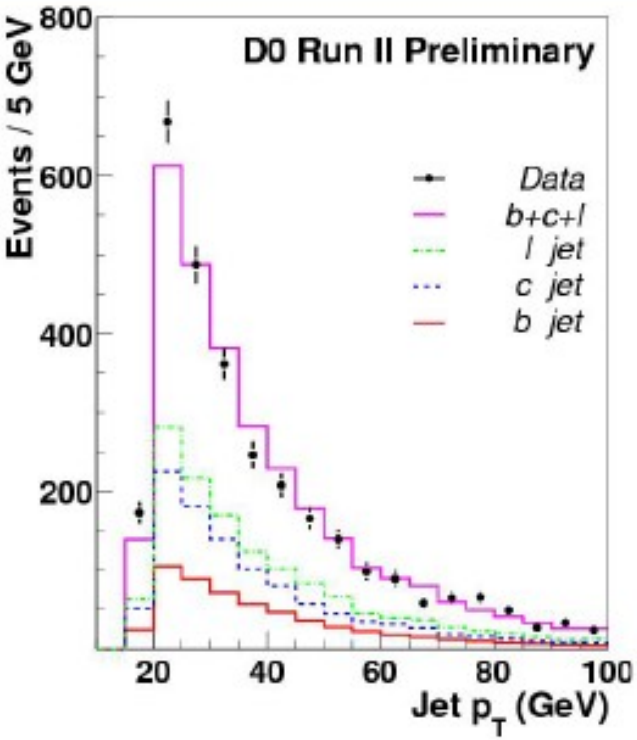




Ratio of Cross Sections Z + b-jet/Z+jet

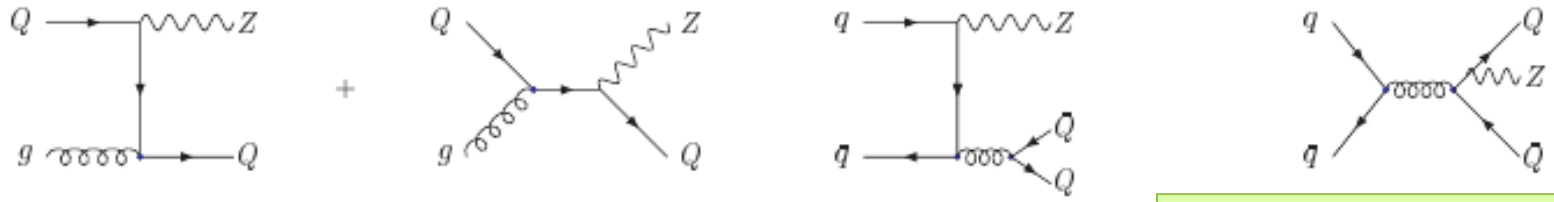
σ(Z+b)/σ(Z+jet): preliminary results





Z+b fraction	**0.191 ± 0.030**
Z+c fraction	0.384 ± 0.072
Z+light jet fraction	0.424 ± 0.054
σ(Z+b)/σ(Z+jet) NLO/MCFM	**0.0176 ± 0.0024 (stat) ± 0.0023 (syst)** 0.0184 ± 0.0022

Ratio of Cross Sections Z + b-jet/Z+jet , D0



L= 180 pb-1

D0: Phys. Rev. Lett., **94**, 161801 (2005)

σ (Z + b-jet) /σ (Z +jet) = 0.021 ± 0.005

σ (Z + b-jet) / σ (Z +jet) = 0.0208 ± 0.0033(stat.) ± 0.0034(syst.)

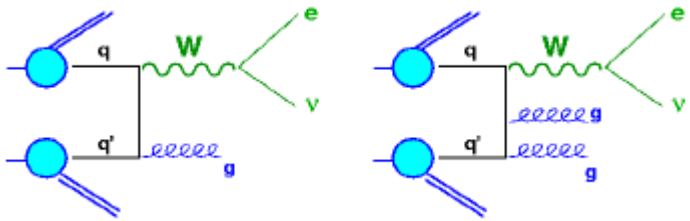
D0: L= 4.2 fb-1

CDF : Phys. Rev., D, 79, 052008 (2009)

L= 2.0 fb-1

σ(Z+b)/σ(Z+jet)	**0.0176 ± 0.0024 (stat) ± 0.0023 (syst)**
NLO/MCFM	0.0184 ± 0.0022

Cross Section for W + jets+ X Production, CDF



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

L= 320 pb-1

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

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

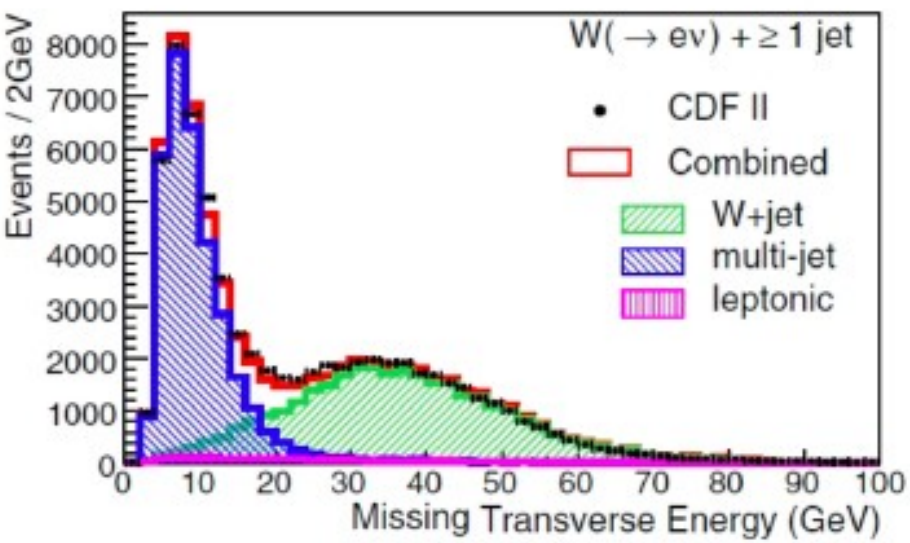
LO: ME+PS + nonpQCD correction:

SMPR: Madgraph, CTEQ6L, Pythia, S. Mrenna and P. Richardson, J. High Energy Phys. 05 (2004) 040.

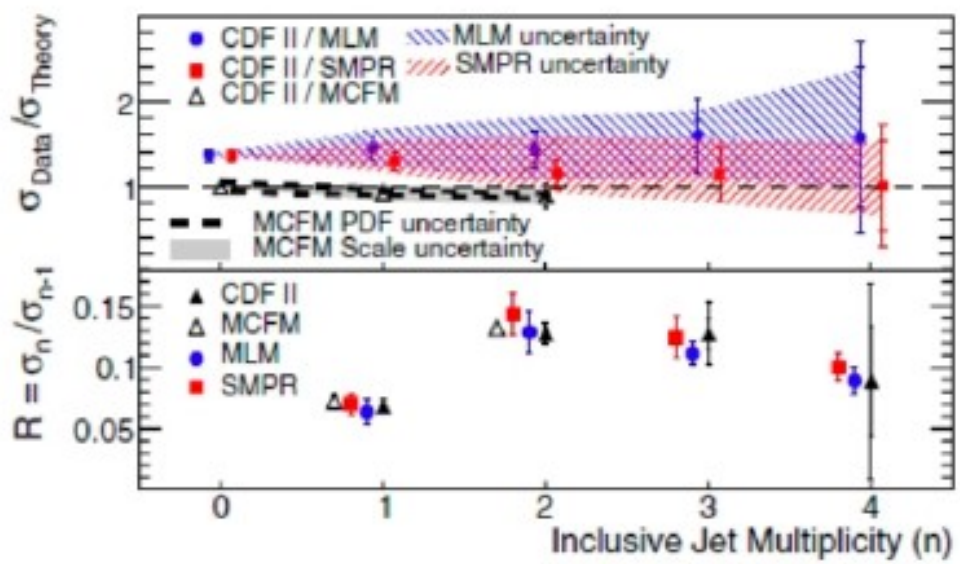
MLM: Alpgen, CTEQ5L, Herwig, J. Alwall et al., arXiv:0706.2569.

Agreement with NLO good.

LO low.



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

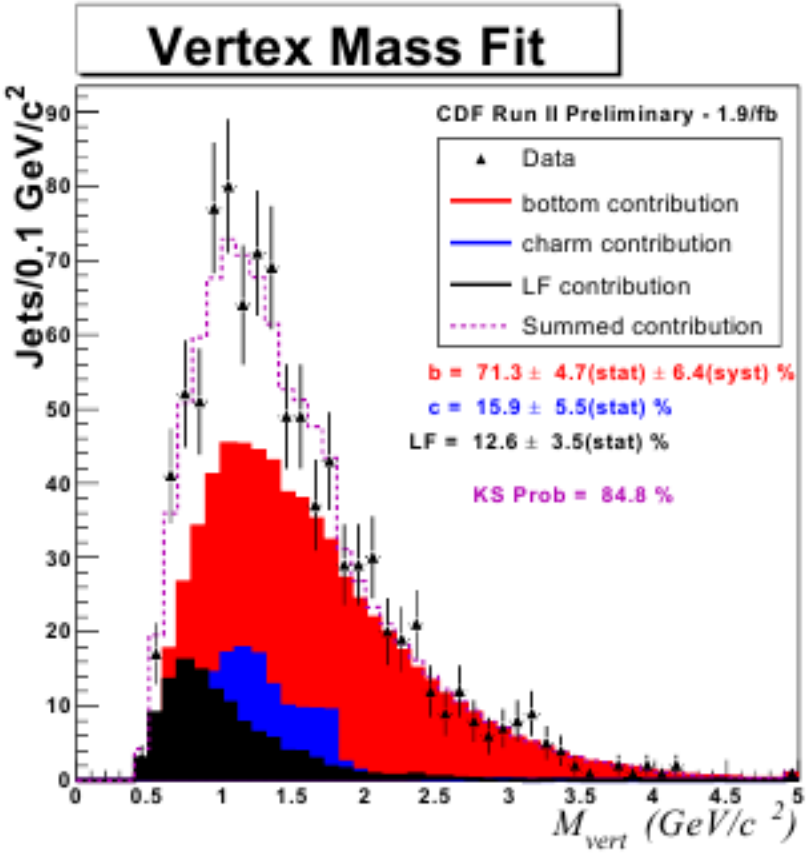


Cross Section for W + b-jet + X Production, CDF

L= 1.9 fb-1

Phys.Rev. Lett. **104,** 131801 (2010)

$p_T^{b\text{-jet}} > 20$ GeV, $|\eta_{b\text{-jet}}| < 2.0$, ($R_{\text{cone}} = 0.4$), $p_T^{\ell} > 20$ GeV, $|\eta_{\ell}| < 1.1$, $p_T^{V} > 25$ GeV



- $\sigma(W_{(\to \ell\nu)} + b) = \dfrac{N_{b\text{-tags}} \cdot f_{b\text{-jets}} - N_{\text{bkg}}^{b\text{-jets}}}{\mathcal{L} \times A \times \epsilon}$

Major *b*-jet backgrounds:

$t\bar{t}$ (40% of total background)
single top (30%)
Fake W (15%)
WZ (5%)

Measured cross section larger than ALPGEN and NLO predictions ($\sim 3\sigma$)

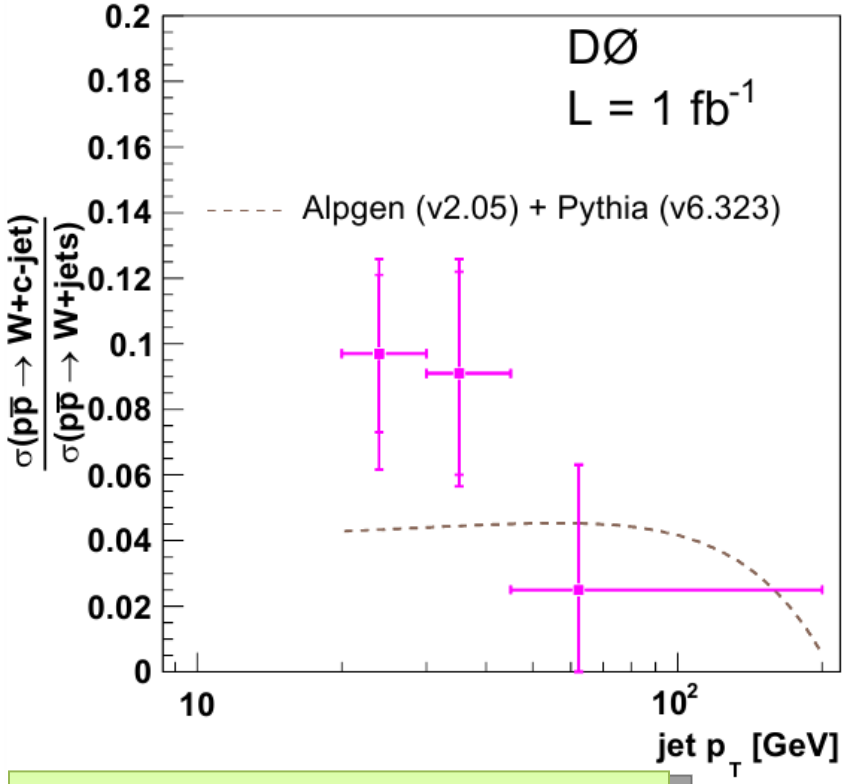
σ b-jets (W+b-jets) · BR(W → l ν) = 2.74 ± 0.27 (stat) ± 0.42(syst) pb

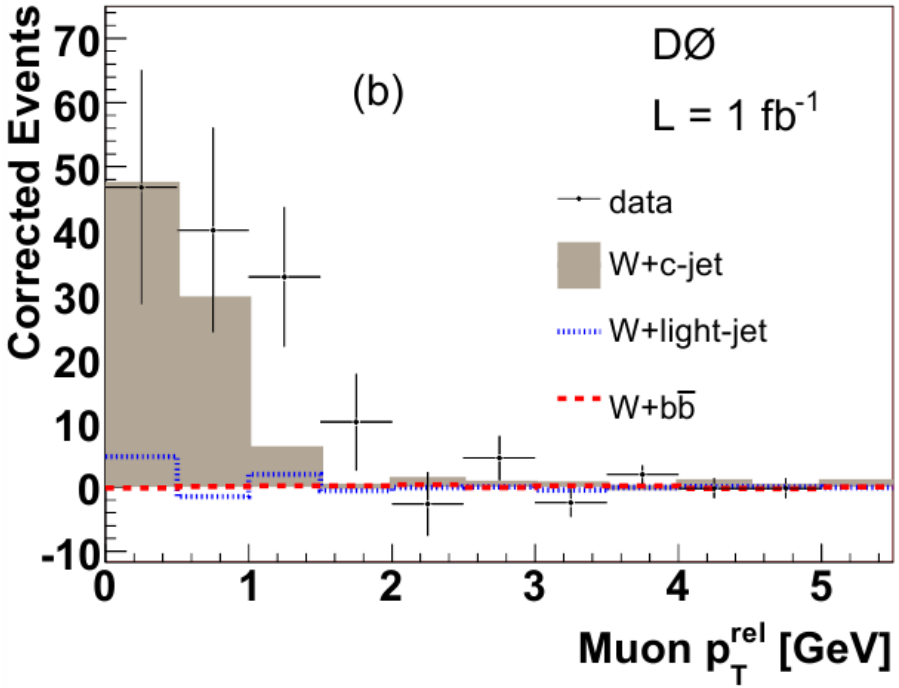
NLO prediction (J. Campbell *et al.*): $\sigma(W_{(\to \ell\nu)} + b) = 1.2 \pm 0.14$ pb

LO prediction (ALPGEN): $\sigma(W_{(\to \ell\nu)} + b) = 0.78$ pb

Ratio of the W+c-jet+X Cross Section to the W +jets+X Cross Section, D0

FERMILAB-PUB-08/062-E
arXiv:0803.2259v1 [hep-ex]
14 Mar 2008





Ratio is close to the prediction of Alpgen + PYTHIA

Relative transverse momentum of the jet-muon with respect to the jet axis, PT^{rel}, shows the consistency between data and the c-jet expectation.

Ratio of the W+c-jet+X Cross Section to the W +jets+X Cross Section, D0

The measured W+c-jet fractions integrated over $p_T >$ 20 GeV and $|\eta| < 2.5$ are

$$\frac{\sigma\left[W\left(\rightarrow e\nu\right)+c\text{-jet}\right]}{\sigma\left[W\left(\rightarrow e\nu\right)+\text{jets}\right]} = 0.073 \pm 0.023(\text{stat.})^{+0.012}_{-0.014}(\text{syst.}),$$

$$\frac{\sigma\left[W\left(\rightarrow \mu\nu\right)+c\text{-jet}\right]}{\sigma\left[W\left(\rightarrow \mu\nu\right)+\text{jets}\right]} = 0.075 \pm 0.031(\text{stat.})^{+0.015}_{-0.017}(\text{syst.}).$$

Since the $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ measurements are consistent with one another, and statistical uncertainties dominate, the two lepton channels are combined to yield

$$\frac{\sigma\left[W+c\text{-jet}\right]}{\sigma\left[W+\text{jets}\right]} = 0.074 \pm 0.019(\text{stat.})^{+0.012}_{-0.014}(\text{syst.}).$$

Photons

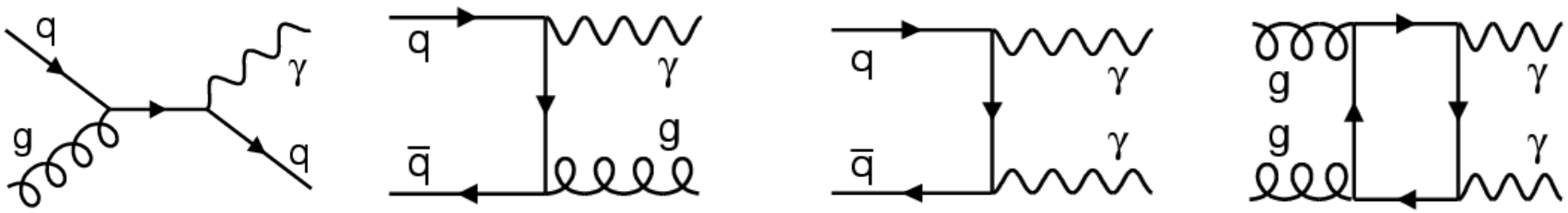
test theory

fixed order: NLO

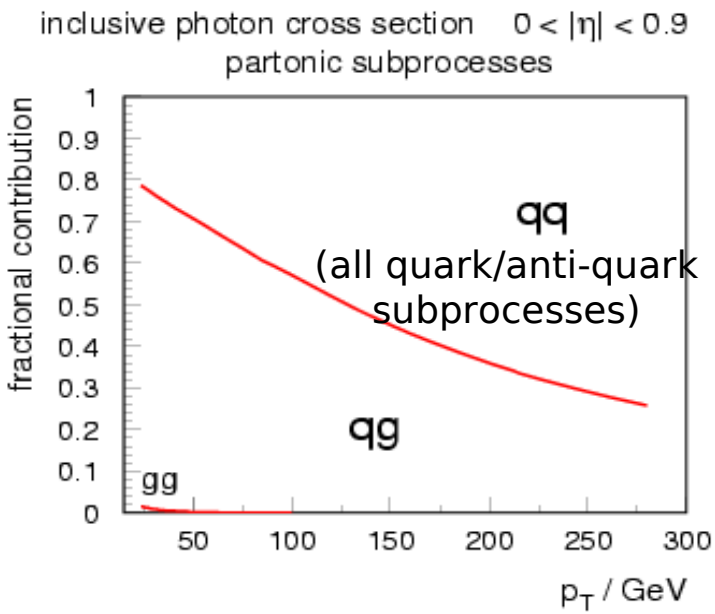
resummation

PDFs

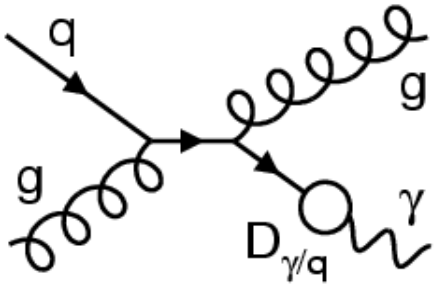
Direct Photon Production



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



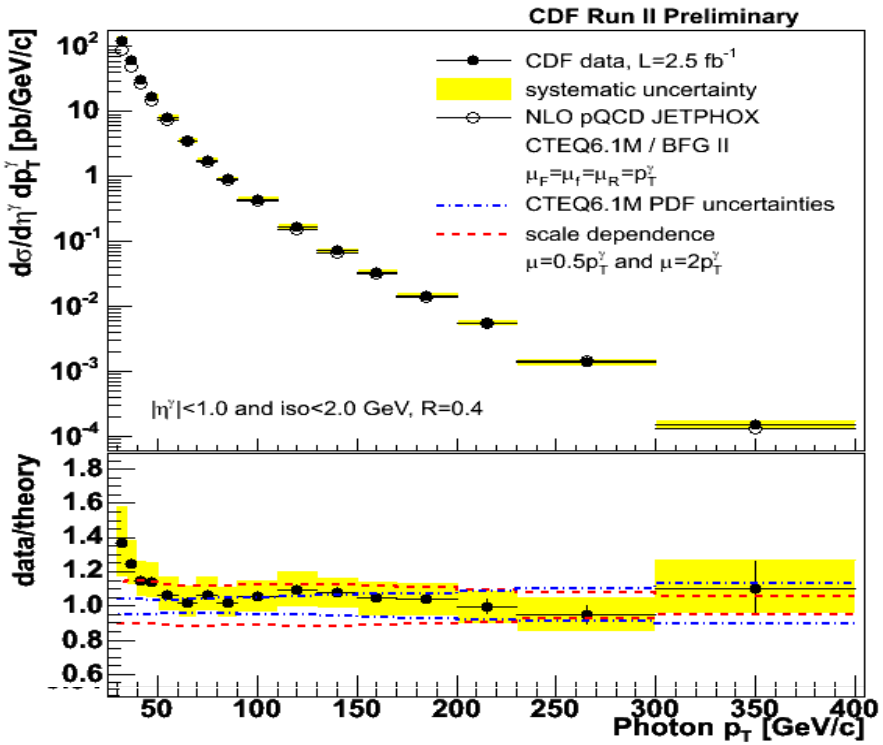
also fragmentation contributions:

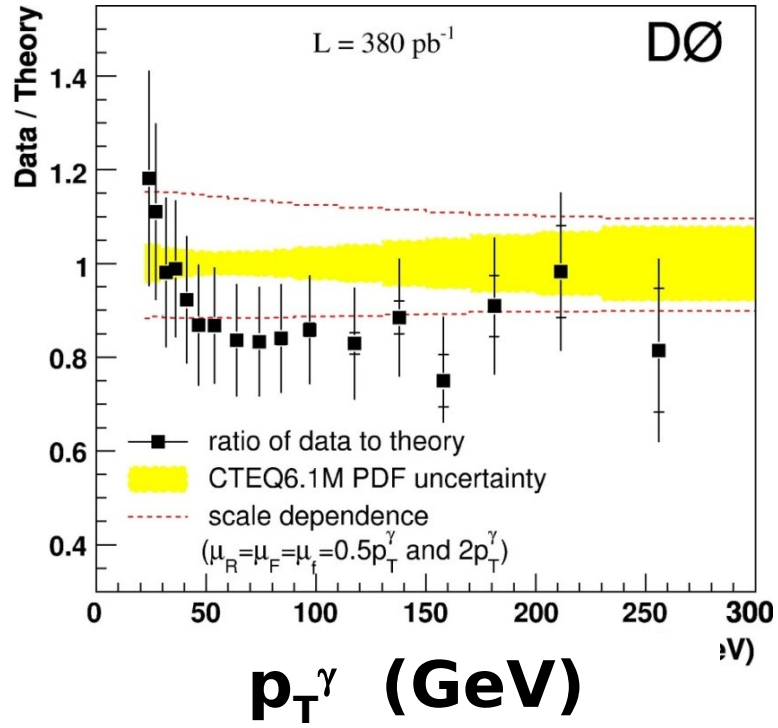


suppress by isolation criterion
→ observable: **isolated** photons

Inclusive Isolated Photons

Phys. Lett. B, **639**, 151 (2006), D0

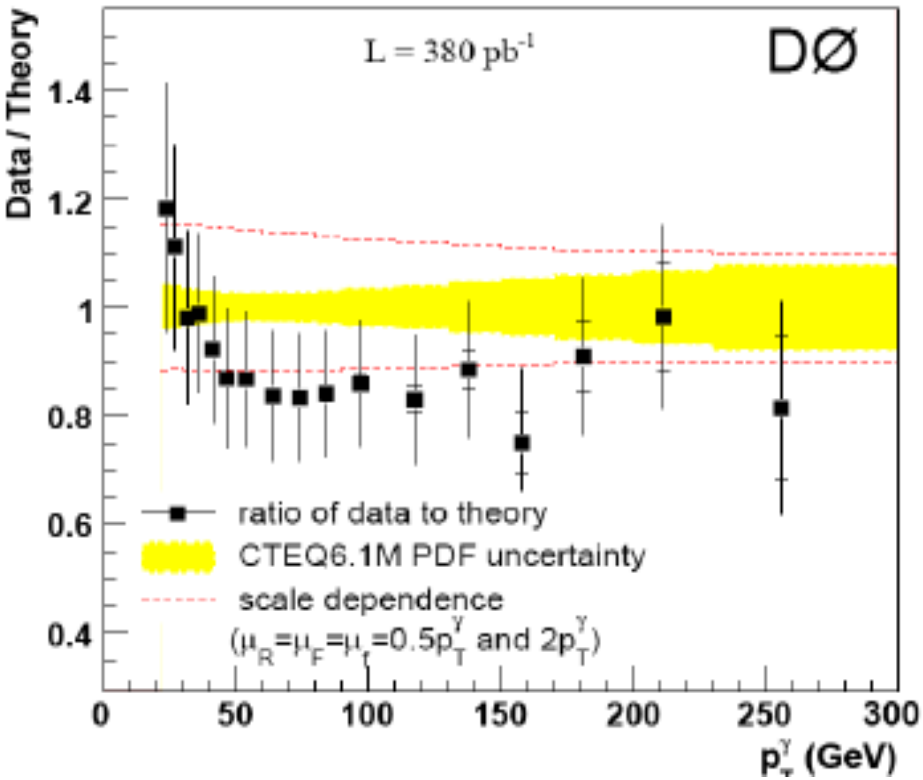




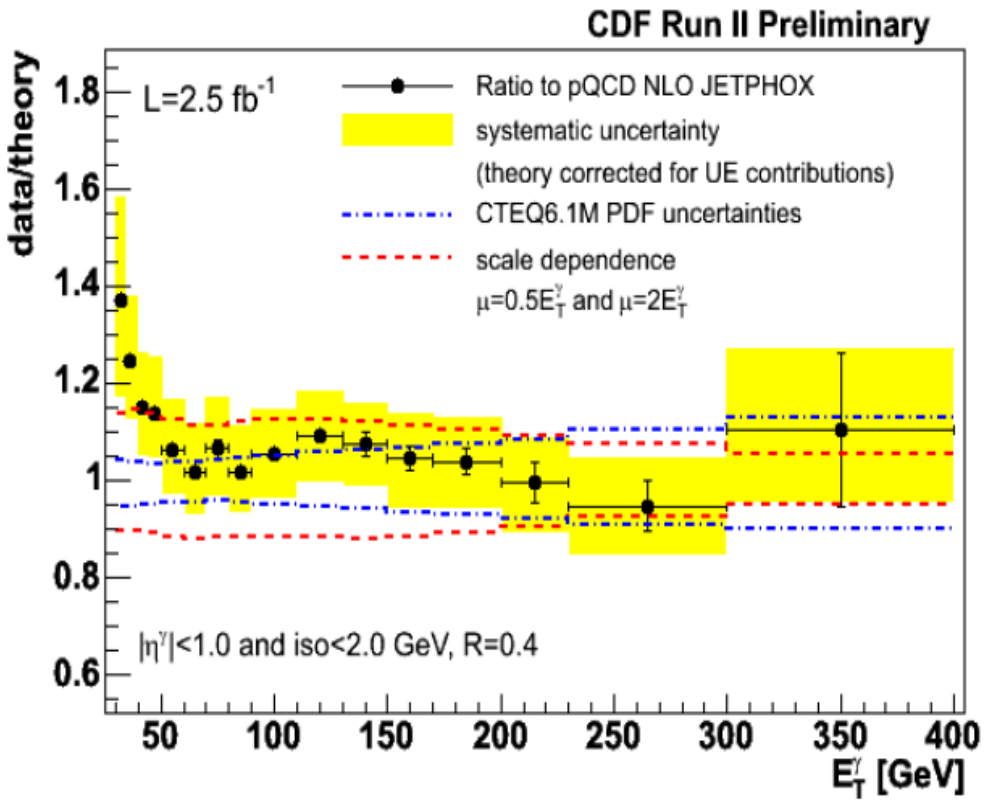
- CDF and D0 measurements: 20< p_T <400GeV → agreement
- data/theory: difference in low p_T shape
- experimental and theory uncertainties > PDF uncertainty
  → no PDF sensitivity yet
- first: need to understand discrepancies in shape

In D0 2006 publication on the prompt photons production the deviations from the corresponding pQCD predictions, previously founded in RunI data, are observed in a more wide kinematical region and with higher statistics. This result was confirmed by CDF measurement in 2009 (DIS09, Madrid).

D0 (2006) ratio data / QCD_NLO



CDF (2009) ratio data / QCD_NLO



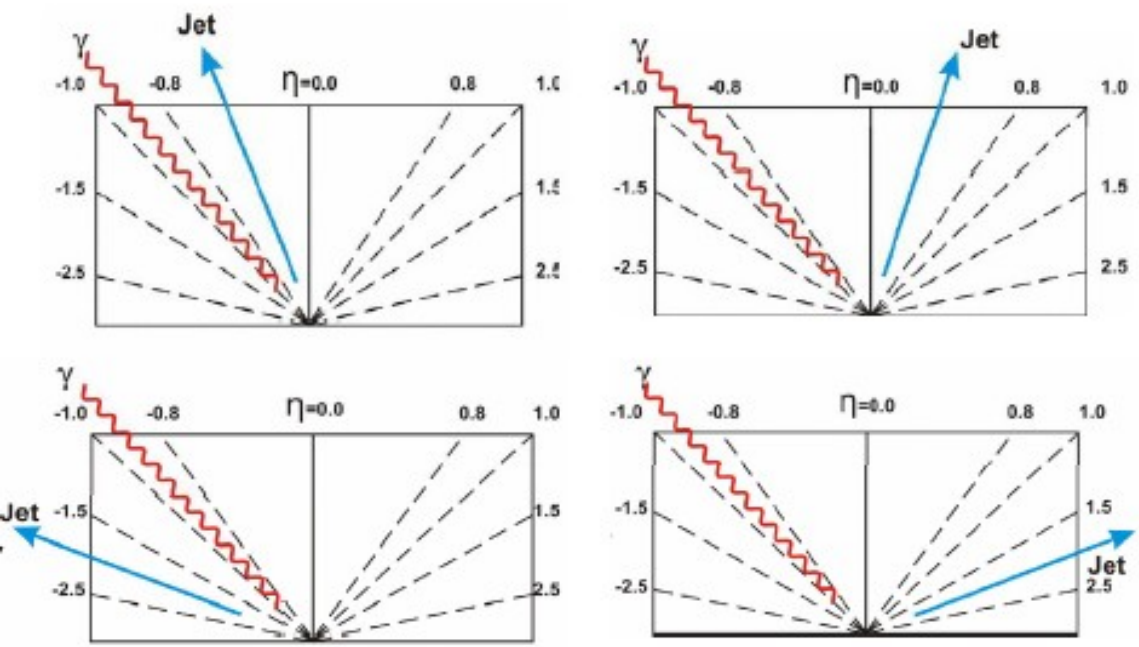
Inclusive photon+jet production

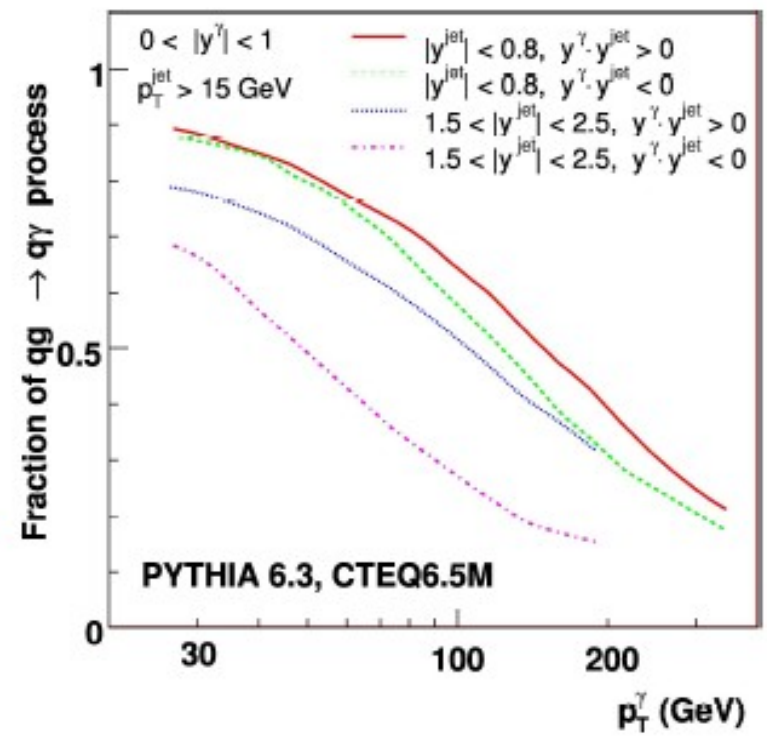
$$\frac{d^3\sigma}{dp_T^\gamma\, d\eta^\gamma\, d\eta^{jet}}$$

D0 Collab., Phys. Lett. B 666, 2435 (2008)

L = 1 fb^{-1}

- Tag photon and jet, ⇒ full control of the 2-body kinematics in the final state
- Measurement done in the four photon-jet rapidity regions
- Photons: $30 < p_T^\gamma < 400$ GeV with $|\eta| < 1.0$
- Jets (cone with R=0.7): pT > 15 GeV and $|\eta|<0.8$ or $1.5<|\eta|<2.5$
- Dominant production at $p_T^\gamma < 120$ GeV is through Compton scattering: $qg \to \gamma q$
- Various rapidity regions ⇒ various parton x and qg fractions.





Inclusive Isolated Photon + Jet

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

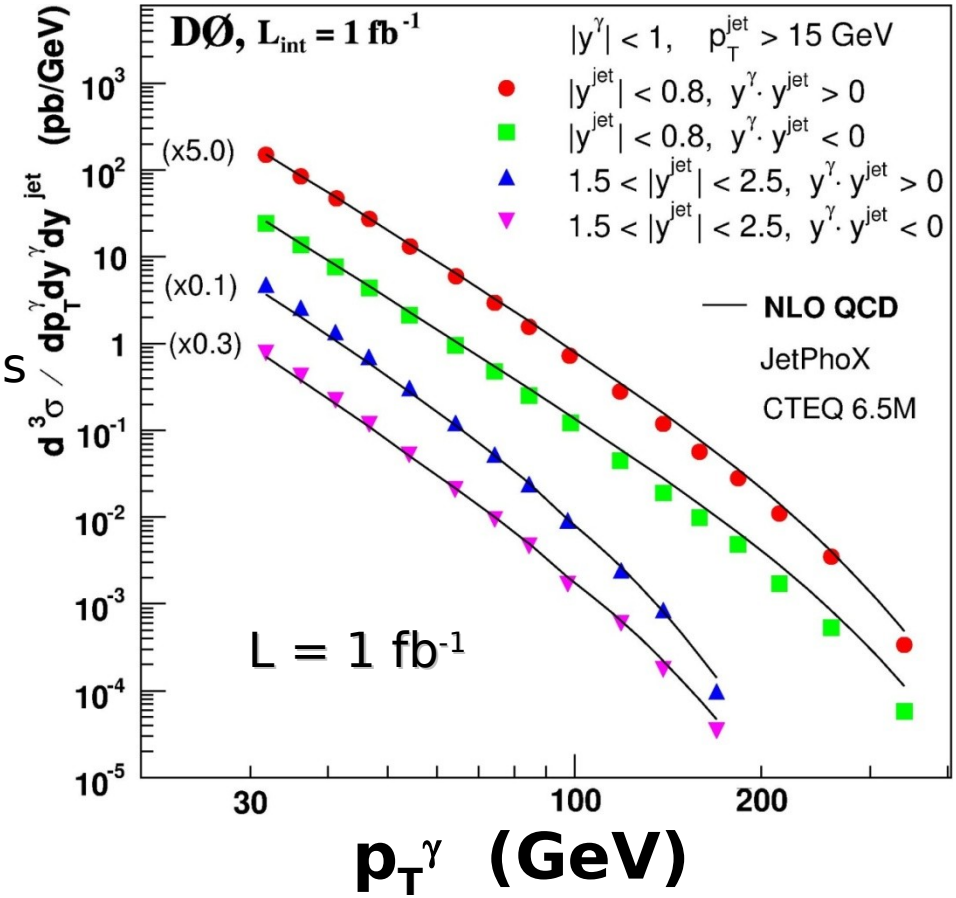
investigate source for disagreement in data/theory incl. photon pT shape:

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

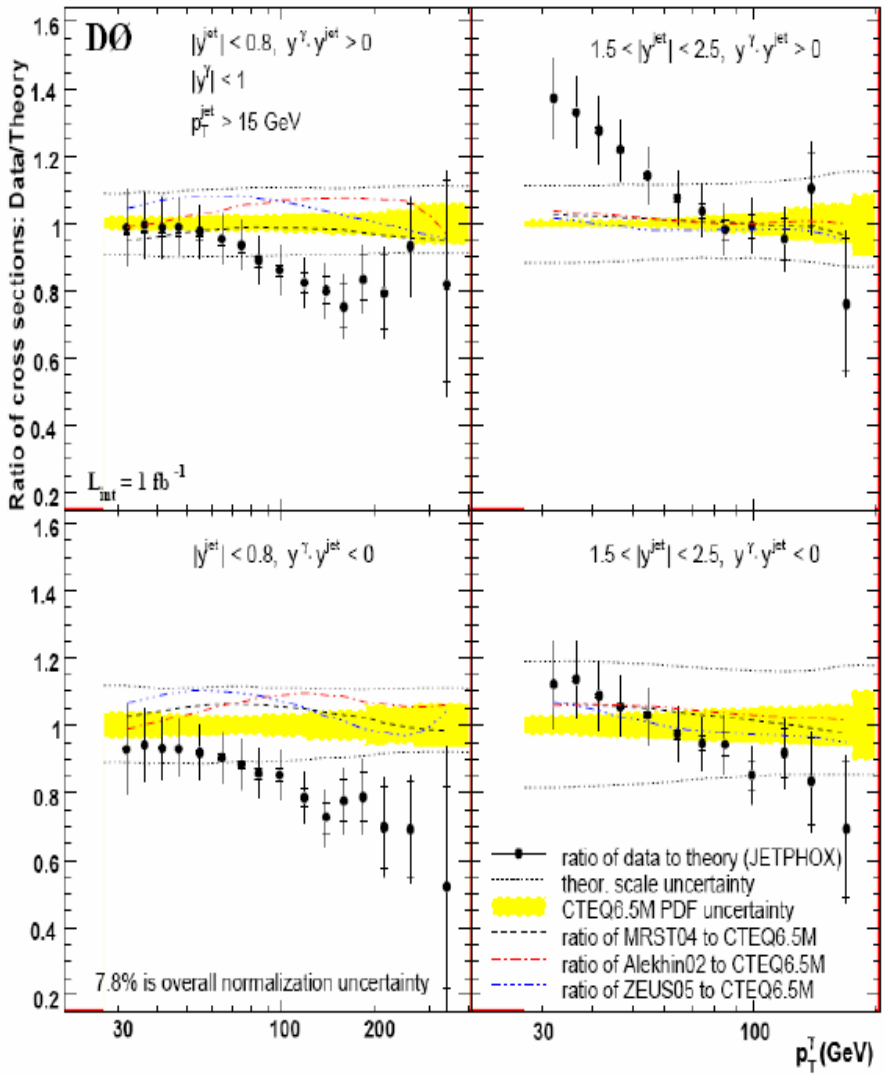


→ look at ratios for quantitative statement ...

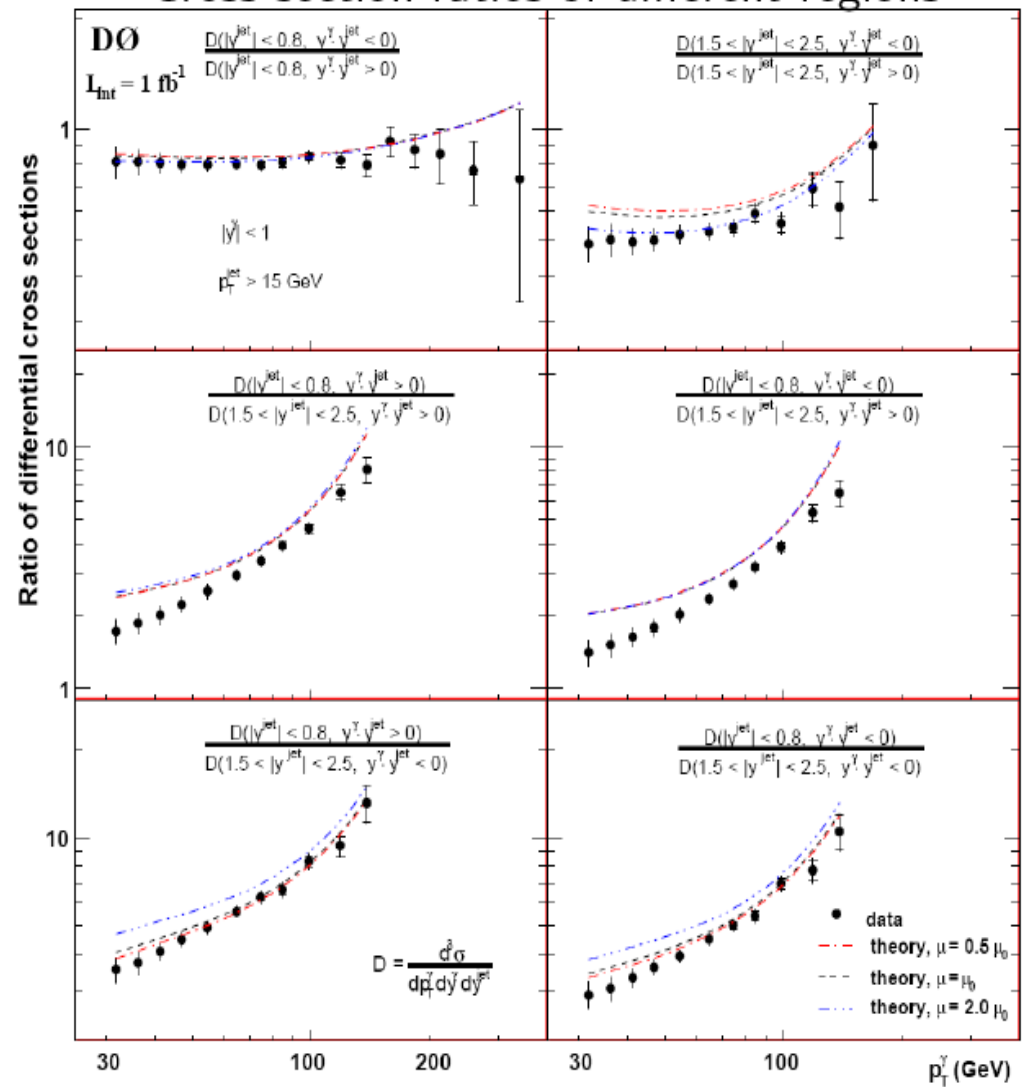
Inclusive Isolated Photon + Jet

Difference between **data** and **QCD predictions** for **cross sections** (left) and their **ratios** (right) **in 4 different rapidity** (y) **regions**

Data over theory comparison

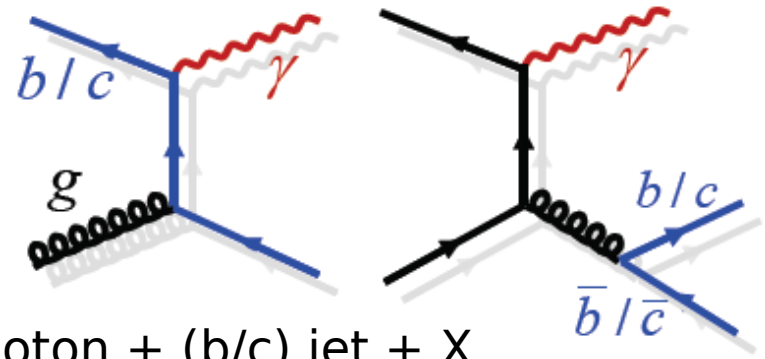


Cross section ratios of different regions



Isolated Photon + HF Jet

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



Photon + (b/c) jet + X

Photon p_T : 30-150 GeV

0.01<x<0.3 → b, c, gluon PDF

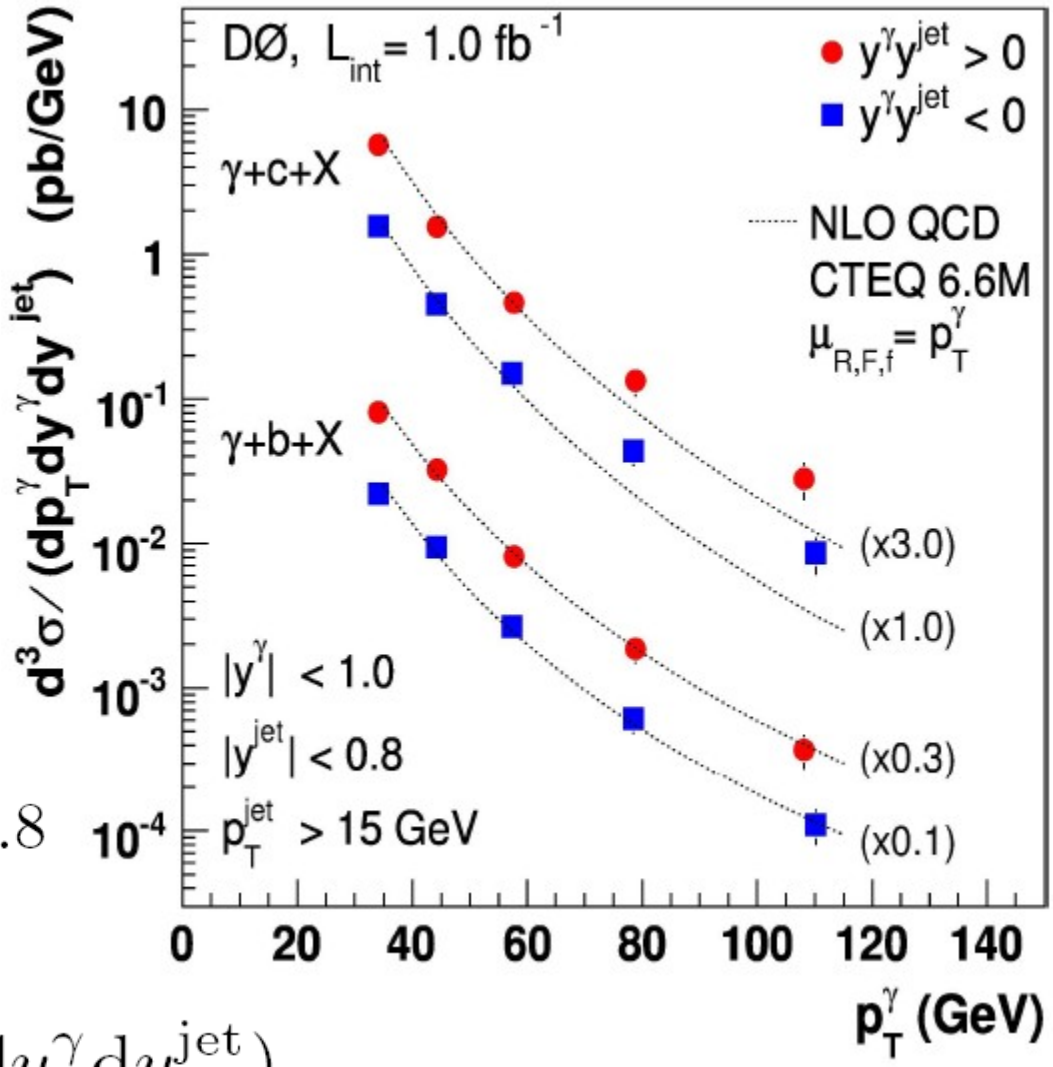
→ test gluon splitting contribution

tag **photon and jet**

Rapidities: $|y^\gamma| < 1.0 \quad |y^{\mathrm{jet}}| < 0.8$

→ triple differential

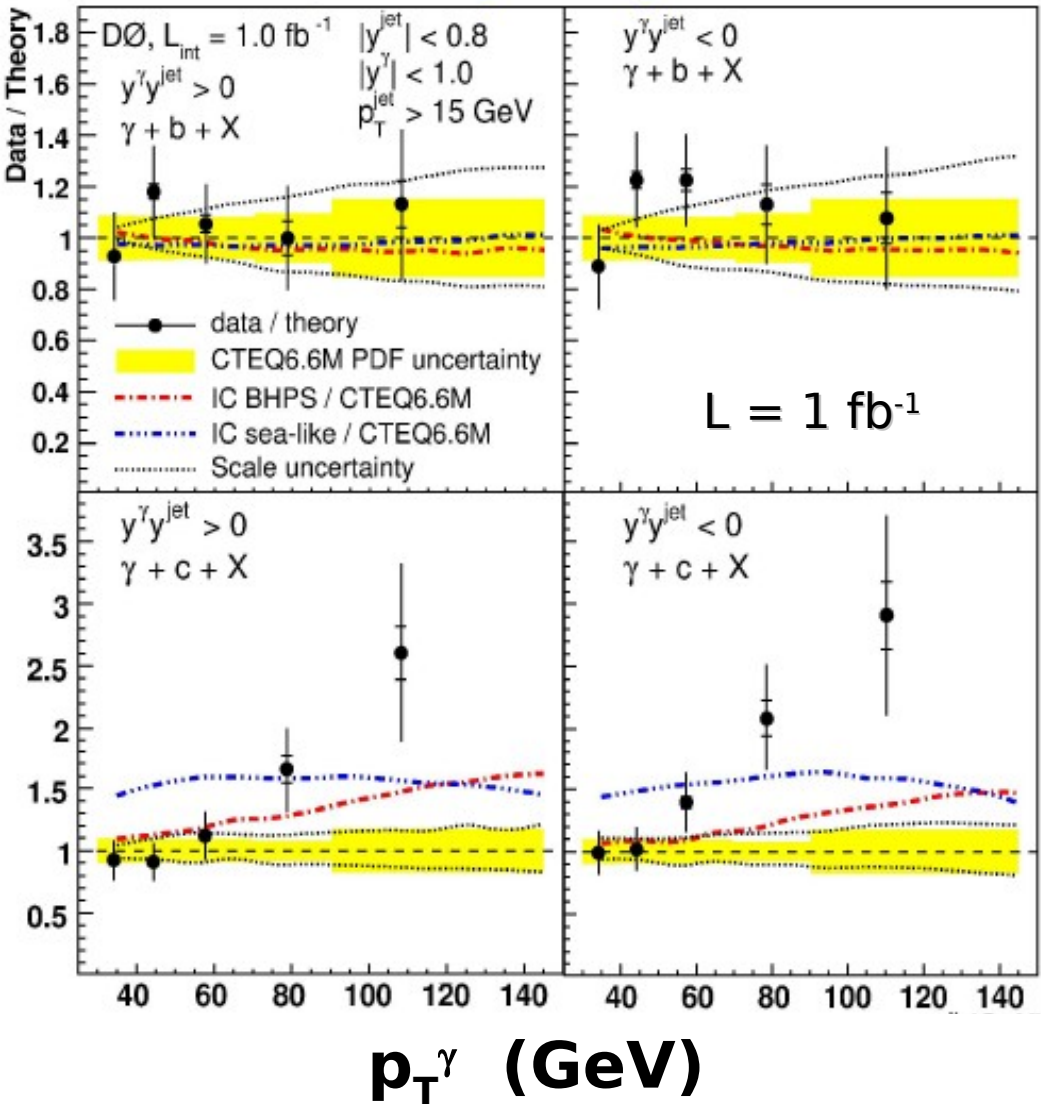
$$\mathrm{d}^3\sigma/(\mathrm{d}p_T^\gamma \mathrm{d}y^\gamma \mathrm{d}y^{\mathrm{jet}})$$



Isolated Photon + HF Jet

→ photon+b:
agreement over full pT range: 30-150 GeV
→ no PDF sensitivity

→ photon+c:
- agree only at pT<50GeV
- disagreement increases with photon p_T
- using PDF including intrinsic charm (IC) improves the theory p_T dependence

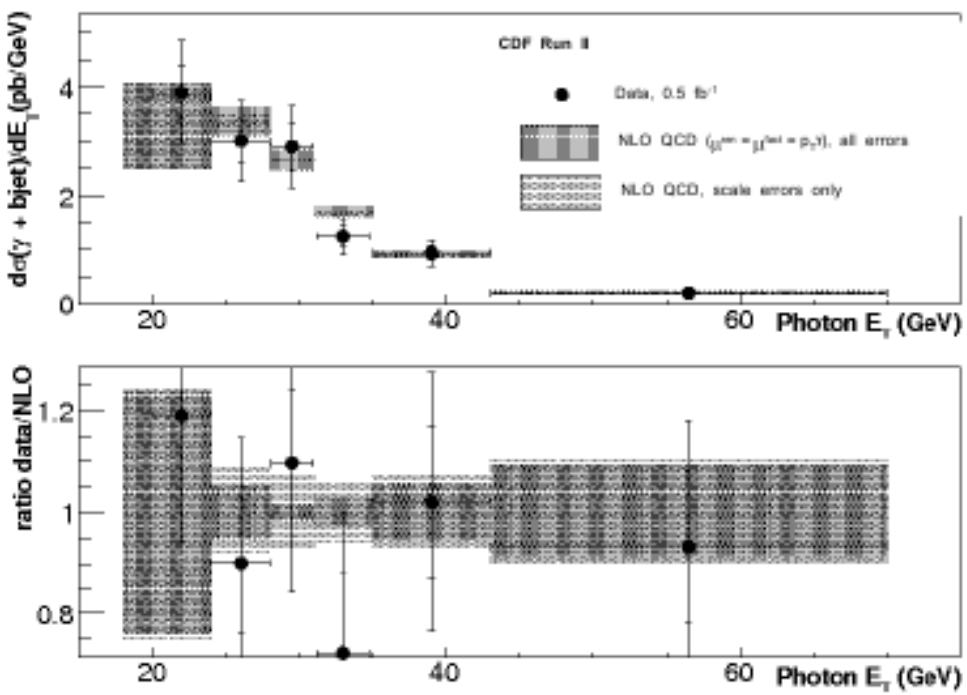


Isolated Photon + b-Jet Xsection, CDF

L= 0.5 fb-1

Phys. Rev. D. **81**, 052006 (2010)

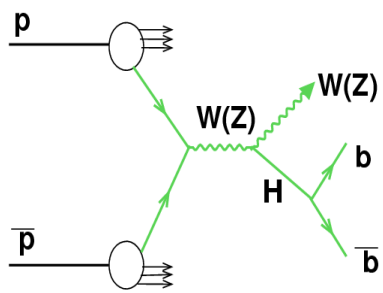
- Isolated γ's ($\Sigma E_T^{R=0.4} - E_T^{\gamma} < 2$ GeV) with $E_T^{\gamma} > 20$ GeV and $|y^{\gamma}| < 1.1$ selected from 0.5 fb^{-1} of data
- Background photons subtracted using **CPR and CES data**
- Central ($|y^{jet}| < 1.5$) jets with $E_T^{jet} > 20$ GeV selected, b jets identified using **secondary vertex displacement**
- γ+LF jet background subtracted by fitting **Pythia** γ+HF jet and γ+LF jet **templates** to the data
- Main source of systematic uncertainty in the data (~17%) is the **b jet purity**

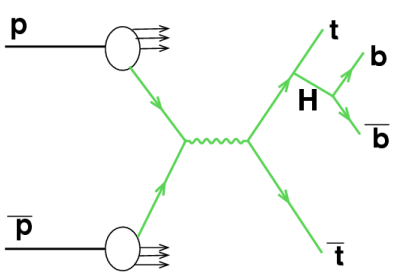


- The data are well described by NLO calculations [PRD **79**, 054017 (2009)]

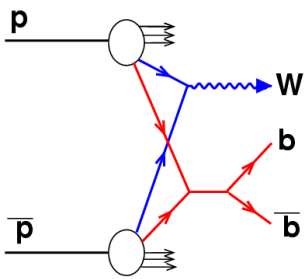
Double Parton Scattering

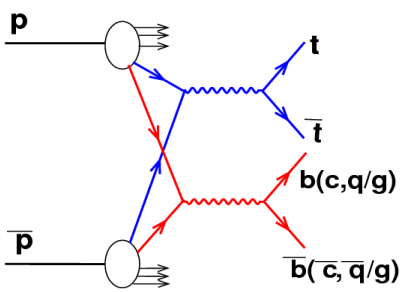
Signal





DP background

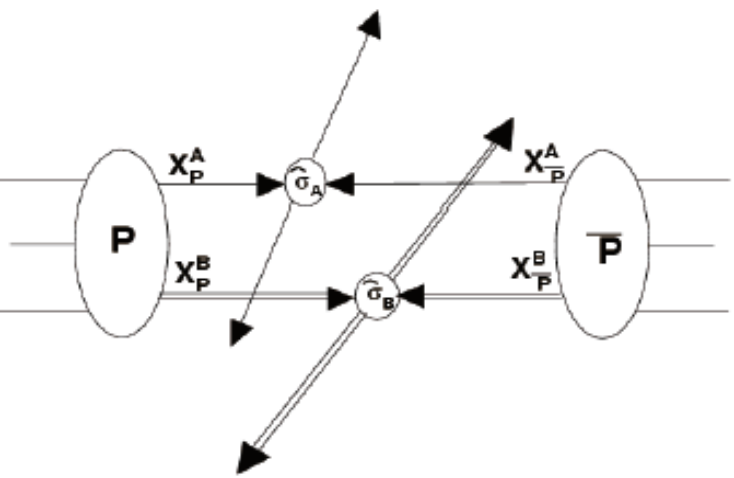




Double Parton Scattering in γ+3 jet events

Phys. Rev. D, **81**, 052012 (2010)

- Complementary information about proton structure: Spatial distribution of partons ⇒ Possible parton-parton correlations. Impact on PDFs?
- Needed for understanding many signal events and correct estimating backgrounds to many rare processes.
- Especially important at high luminosities due to additional pp(bar) interactions.



Selections: 60 < photon pT < 80 GeV, lead. jet pT > 25, other 2 jets with pT > 15 GeV

Main Background: Single Parton scattering

$$\sigma_{DP} = m \cdot \sigma_A \cdot \frac{\sigma_B}{2\sigma_{eff}}$$

σ_A, σ_B: cross sections of processes A, B

σ_{eff}: characterising size of effective interaction region

$\sigma_B/2\sigma_{eff}$: prob. of 2nd interaction, given 1st one

($m = 2(1)$ when A and B are (not) distinguishable)

History of measurements

- Theoretical discussion on DPS continues for many years (~ beginning of 1980's)
- Experimental problem is extracting DP signal from more probable double bremstr. background.

Typical experiments choose 4-jet sample motivated by a large di-jet cross section. Measuring σ_{eff} in 4-jet sample:

$$\sigma_{DP} = \frac{\sigma_{JJ}^2}{2\sigma_{eff}}$$

☞ Measure σ_{DP} but need then QCD calculations of σ_{jj} to get σ_{eff} And MC signal & background modeling.

CDF 1997: photon+3jet events. A new, data-driven, method developed:

☞ Use of Double interaction (two separate ppbar collisions) and DPS rates from a single ppbar collision rates to extract σ_{eff}, → reduce dependence on MC

	$\sqrt{s}$ (GeV)	final state	p_T^{min} (GeV/c)	η range	Result
AFS, 1986	63	$4jets$	$p_T^{jet} > 4$	$\lvert\eta^{jet}\rvert < 1$	$\sigma_{eff} \sim 5$ mb
UA2, 1991	630	$4jets$	$p_T^{jet} > 15$	$\lvert\eta^{jet}\rvert < 2$	$\sigma_{eff} > 8.3$ mb (95% C.L.)
CDF, 1993	1800	$4jets$	$p_T^{jet} > 25$	$\lvert\eta^{jet}\rvert < 3.5$	$\sigma_{eff} = 12.1^{+10.7}_{-5.4}$ mb
CDF, 1997	1800	$\gamma + 3jets$	$p_T^{jet} > 6$	$\lvert\eta^{jet}\rvert < 3.5$	
			$p_T^{\gamma} > 16$	$\lvert\eta^{\gamma}\rvert < 0.9$	$\sigma_{eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb

Double parton cross sections, D0

Different to CDF(1997) this analysis was done:

1. basing on higher RunII statistics :

$L_{CDF_1997} = 16\ pb^{-1} \implies L_{D0_2009} = 1.0\ fb^{-1}$

2. D0(2009) used "gamma + 3jets" events (Purity_gamma~60%)

CDF(1997) used "gamma/pi0 + 3jets" events .

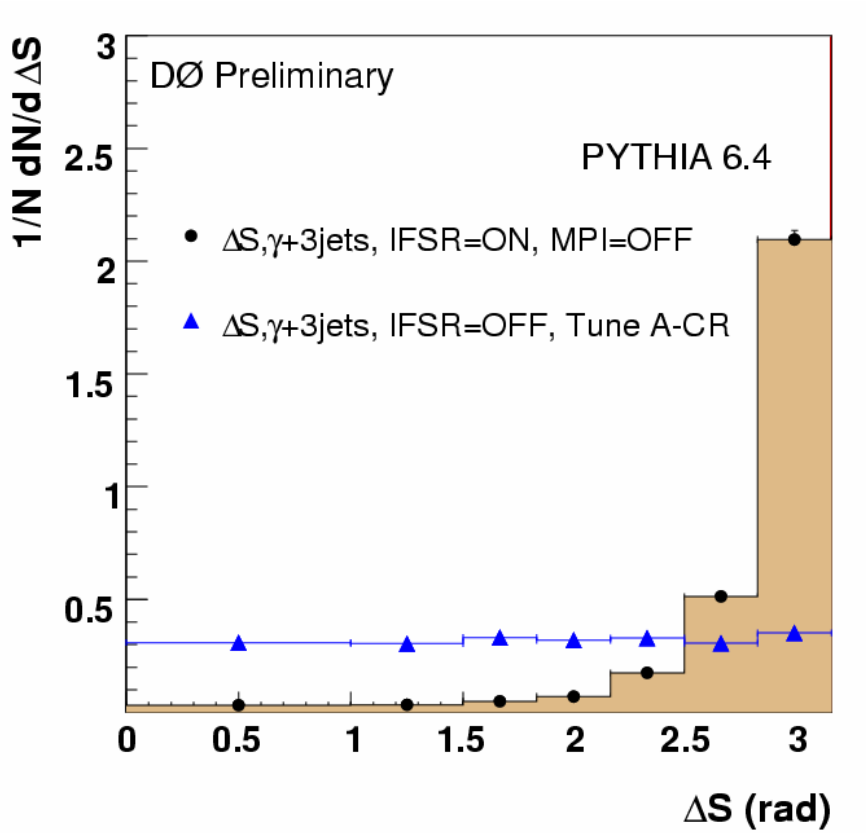
3. D0(2009) measured at 3 high $PT^{2nd\text{-}jet} > 15$ GeV regions

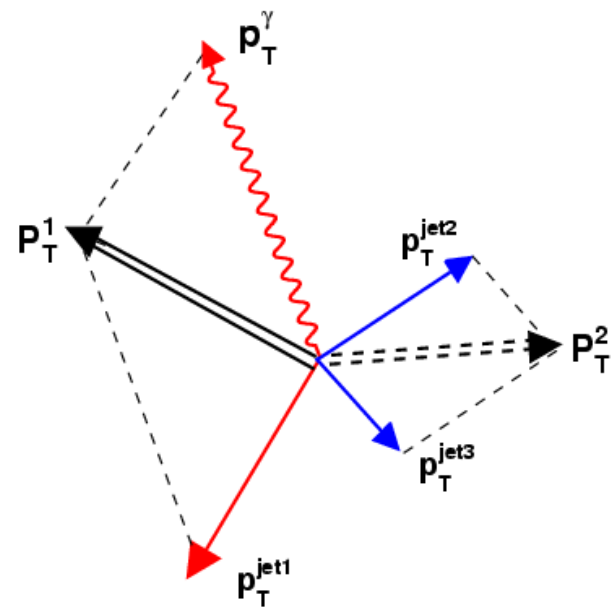
CDF(1997) meas. at 1 low PT region $5 < PT^{2nd\text{-}jet} < 7$ GeV

Double parton events selection, D0

Calculated for the pair that gives the minimum value of *S*:

$$\Delta S = \Delta\phi\left(\mathrm{p_T}^{\gamma,jet_i},\ \mathrm{p_T}^{jet_j,jet_k}\right)$$





$$S_{\phi} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{\Delta\phi(\gamma,i)}{\delta\phi(\gamma,i)}\right)^2 + \left(\frac{\Delta\phi(j,k)}{\delta\phi(j,k)}\right)^2}$$

$$S_{pT} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{|\vec{P}_T(\gamma,i)|}{\delta P_T(\gamma,i)}\right)^2 + \left(\frac{|\vec{P}_T(j,k)|}{\delta P_T(j,k)}\right)^2}$$

Double parton cross sections, D0

Measurement of σ_{eff}

At two hard scattering events:

$$P_{DI} = 2\left(\frac{\sigma^{\gamma j}}{\sigma_{hard}}\right)\left(\frac{\sigma^{jj}}{\sigma_{hard}}\right)$$

The number of DI events:

$$N_{DI} = 2\frac{\sigma^{\gamma j}}{\sigma_{hard}}\frac{\sigma^{jj}}{\sigma_{hard}} N_C(2) A_{DI}\epsilon_{DI}\epsilon_{2vtx}$$

At one hard interaction:

$$P_{DP} = \left(\frac{\sigma^{\gamma j}}{\sigma_{hard}}\right)\left(\frac{\sigma^{jj}}{\sigma_{eff}}\right)$$

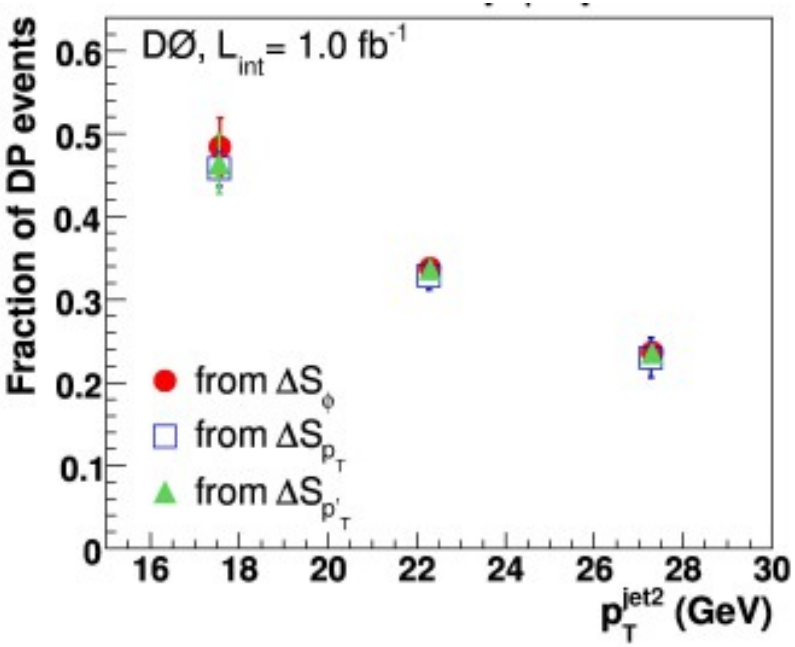
Then the number of DP events:

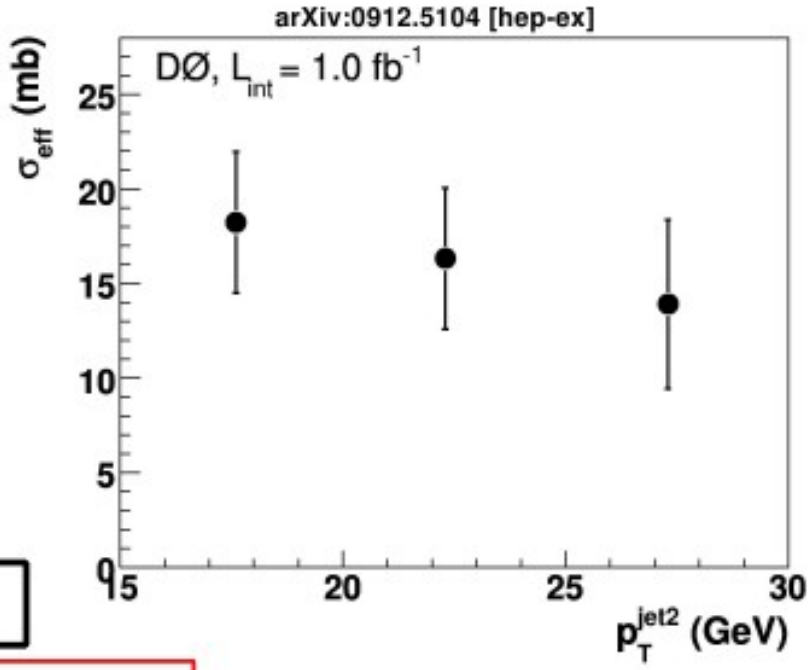
$$N_{DP} = \frac{\sigma^{\gamma j}}{\sigma_{hard}}\frac{\sigma^{jj}}{\sigma_{eff}} N_C(1) A_{DP}\epsilon_{DP}\epsilon_{1vtx}$$

Therefore one can extract:

$$\sigma_{eff} = \frac{N_{DI}}{N_{DP}}\frac{N_C(1)}{2N_C(2)}\frac{A_{DP}}{A_{DI}}\frac{\epsilon_{DP}}{\epsilon_{DI}}\frac{\epsilon_{1vtx}}{\epsilon_{2vtx}}\sigma_{hard}$$

Double parton cross sections, D0





Fraction of DP events decreases as expected.

$$\sigma_{eff}^{ave} = 16.4 \pm 0.3\,(stat) \pm 2.3\,(syst)\ mb$$

Effective cross section is approximately constant across pT bins, and it is in agreement with previous CDF measurement. → $14.5 \pm 1.7^{+1.7}_{-2.3}$ mb

Phys. Rev. Lett. 79, 584
Phys. Rev. D 56, 3811

Summary

In the current analysis we have measured:

- ***DP** fractions in three jet* pT *intervals: 15-20; 20-25; 25-30 GeV..*

  It drops from 0.46 at *15< pT < 20 GeV* to 0.22 at *25< pT <30 GeV.*

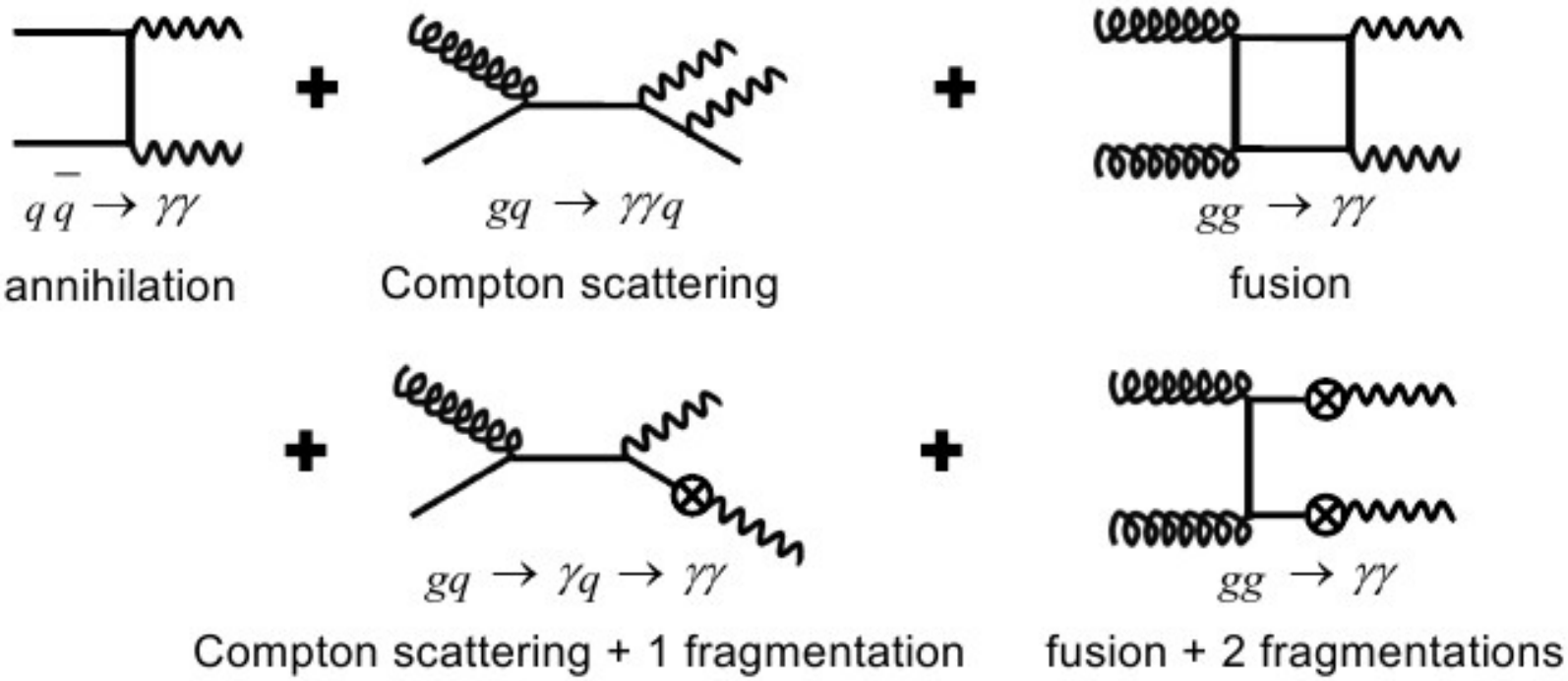
- *Effective cross section* σ*_eff has been measured in the same jet pT*

  bins and found to be stable within uncertainties.

- *Results are consistent with previous UA2 and two CDF measurements.*

Direct Photon Pair (DPP) Production

At the **Tevatron** DPP is strongly dominated (at high M_gam-gam) by qqbar, while at the **LHC** gg and qg will give the main contribution

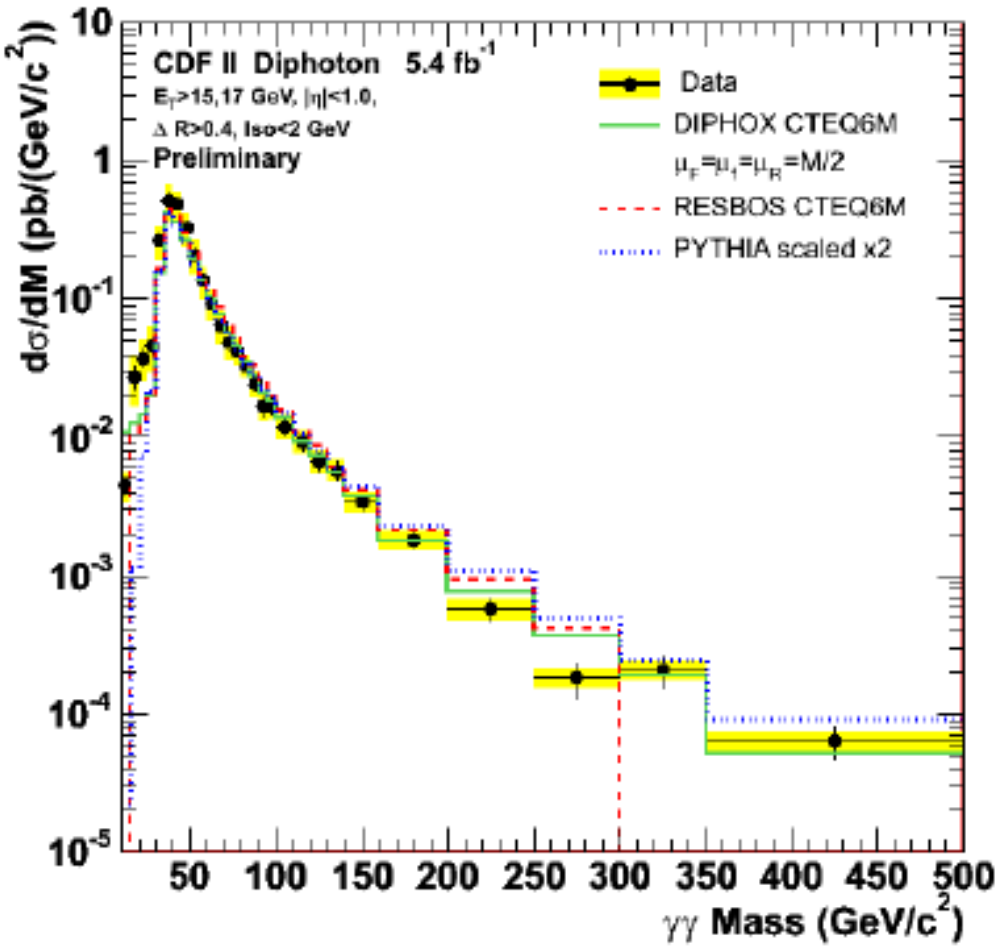


Direct Photon Pair Production, CDF

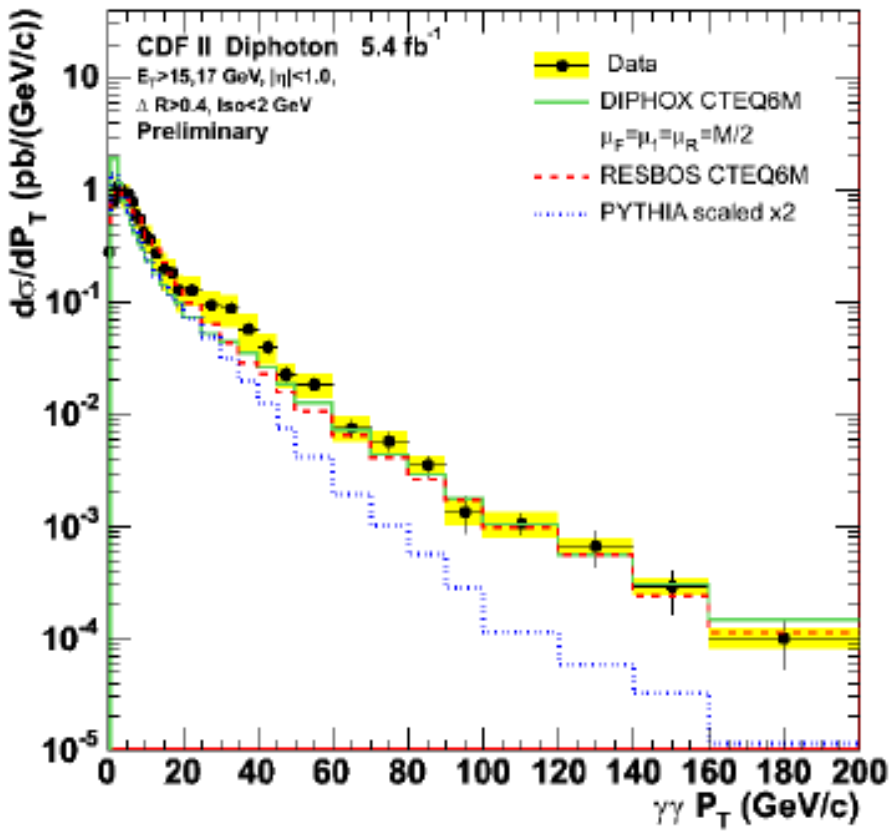
L= 5.4 fb-1

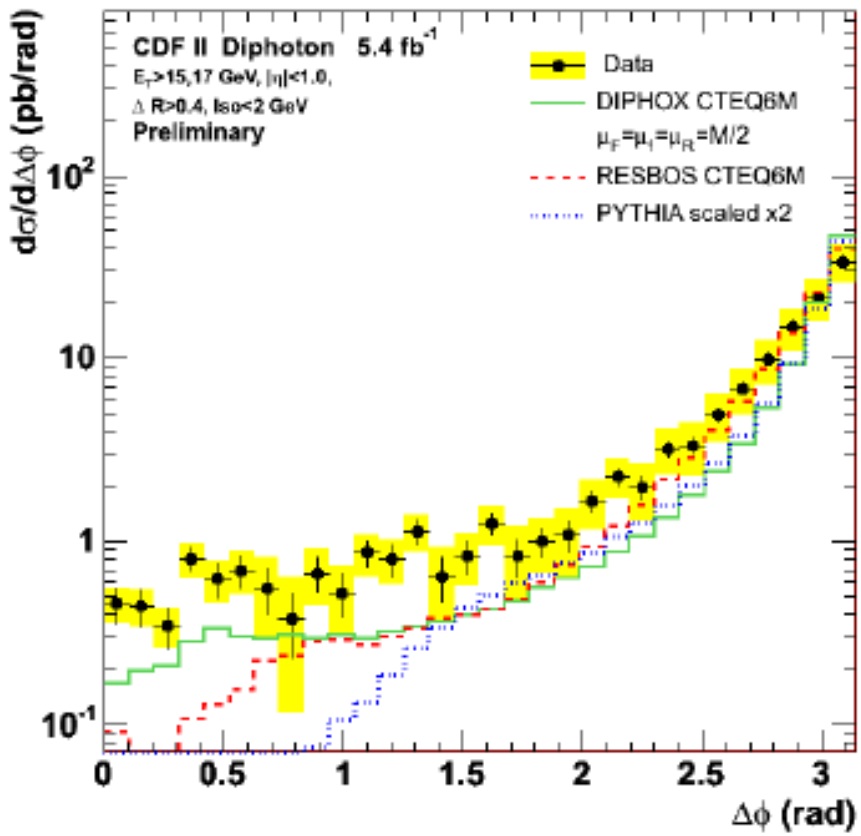
CDF note 10160, May 17 , 2010

- Isolated photons ($\Sigma E_T^{R=0.4} - E_T^{\gamma} <$ 2 GeV) with $E_T^{\gamma 1} > 17$ GeV, $E_T^{\gamma 2} >$ 15 GeV and $|y^{\gamma}| < 1$ selected from **5.4 fb^{-1} of data**
- Diphoton background subtracted with a 4×4 matrix technique using the **track isolation** ($\Sigma p_T^{R=0.4} - p_T^{\gamma}$) as the discriminant between signal and background photons
- Data are compared with calculations from **Pythia**, **Diphox** and **Resbos**



Direct Photon Pair Production, CDF

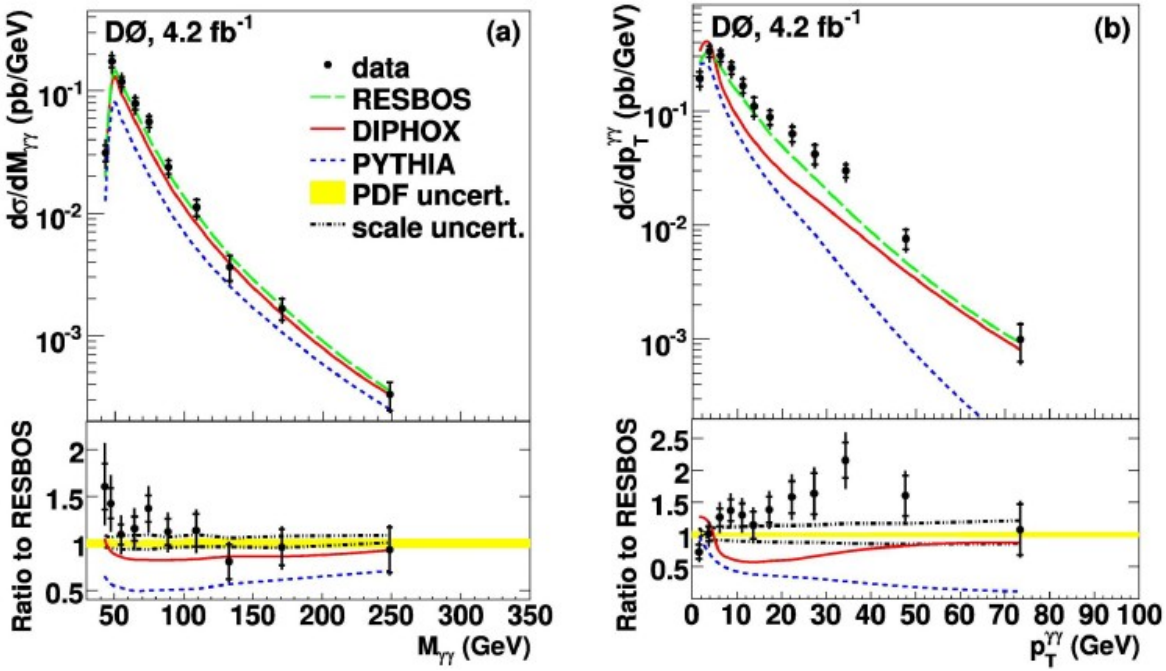


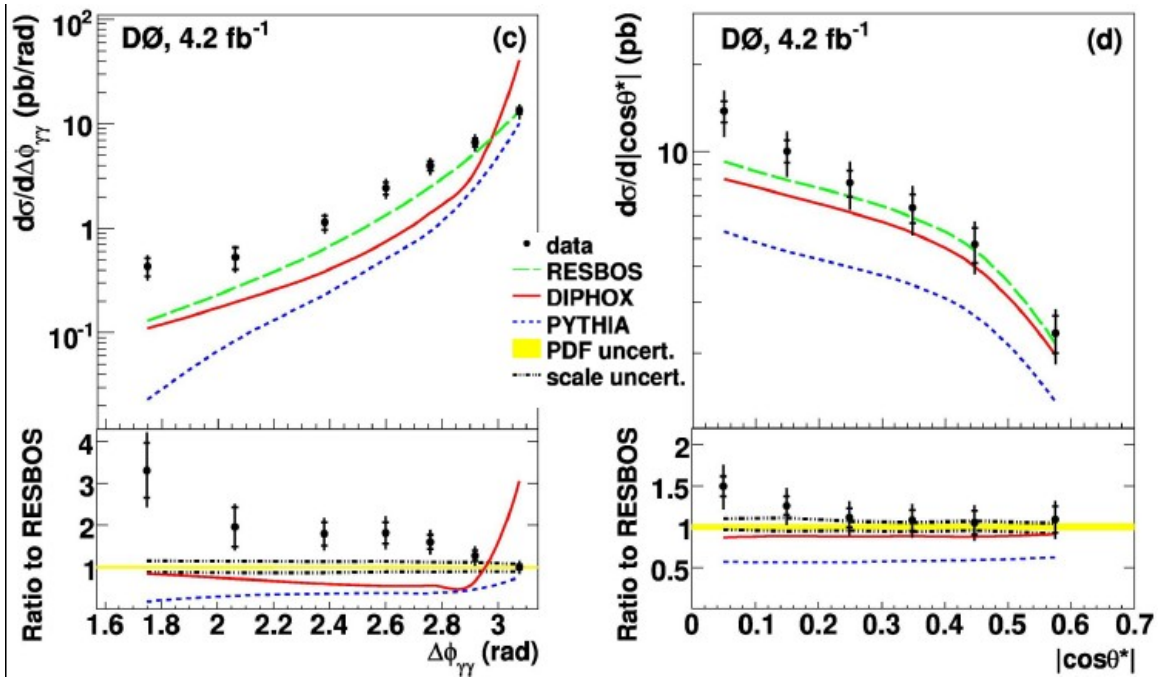


- **No model describes** the data well over the full kinematic ranges, in particular at **low $M_{\gamma\gamma}$** (< 60 GeV/c^2) and **low $\Delta\phi_{\gamma\gamma}$** (< 1.7 rad) where gluon scattering and fragmentations surviving the isolation cut are expected to contribute strongly

L= 4.2 fb-1

Direct Photon Pair (DPP) **Single differential** cross sections $d\sigma/dx$ (x=M,PT,angles)



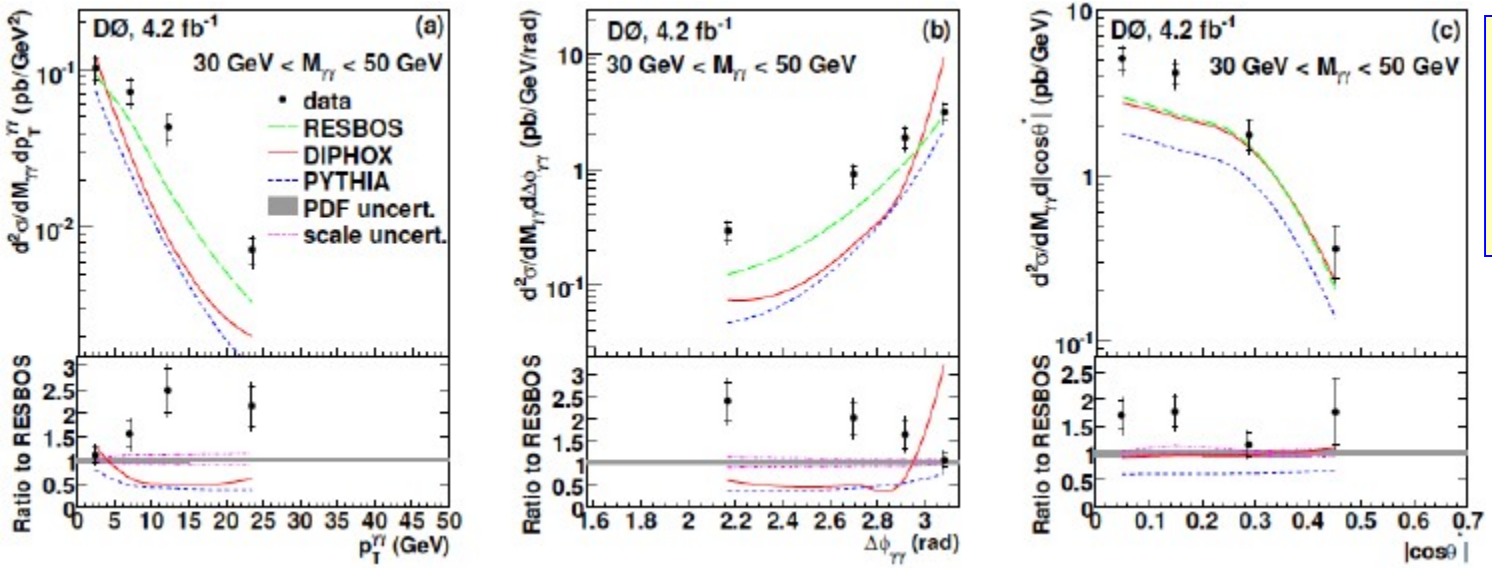


FERMILAB --PUB--10--039 (2010)

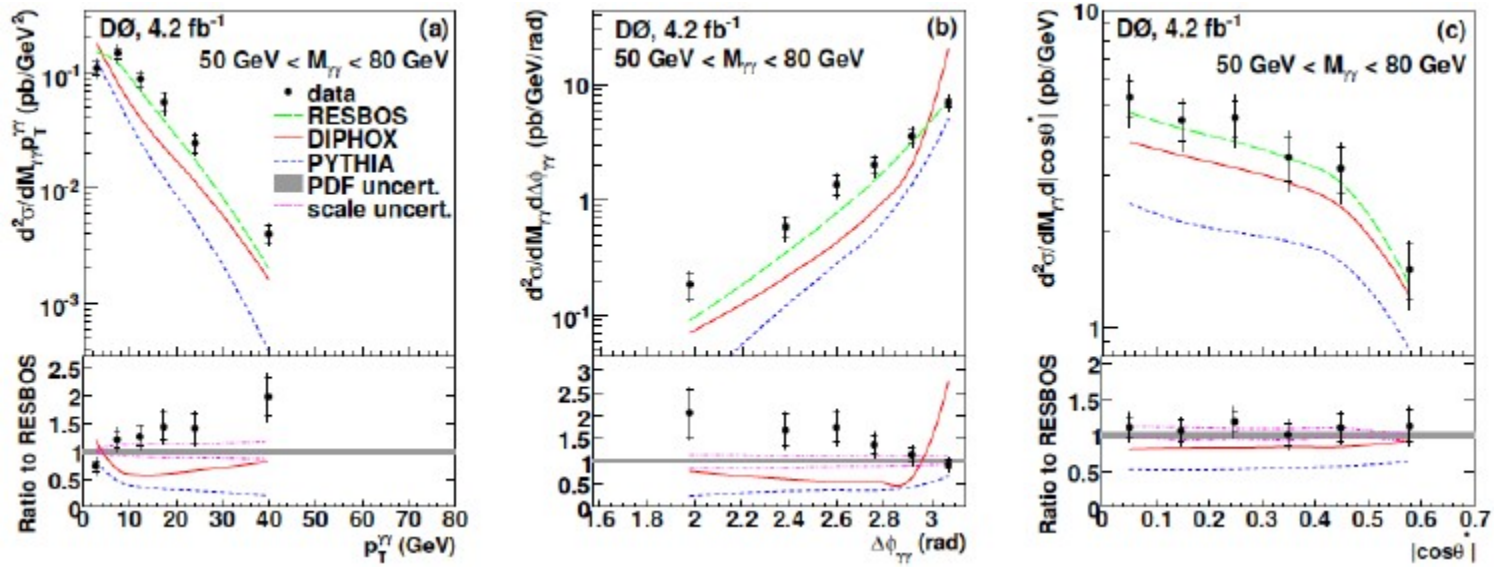
RESBOS **(- - - -)** shows the best agreement with data

High PT_gam-gam and **low D_phi** data discrepances

Direct Photon Pair **Double Differential** Xsections

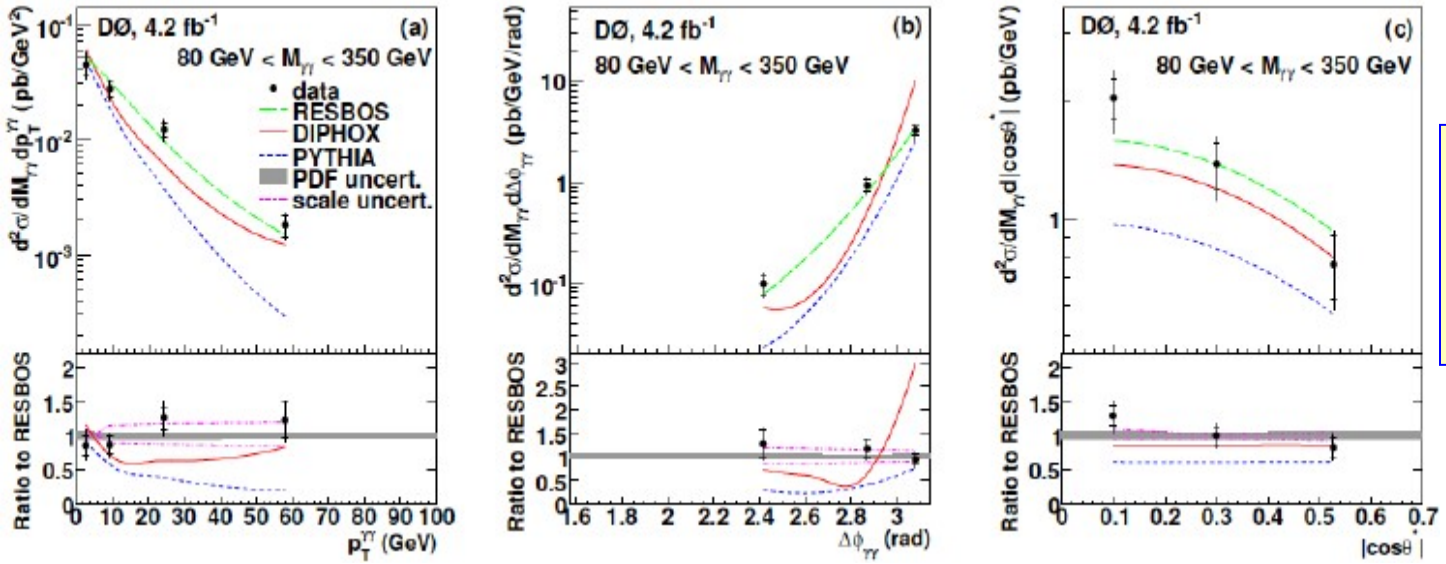


30 < M_gam-gam < < 50 GeV



50 < M_gam-gam < < 80 GeV

Direct Photon Pair **Double Differential** Xsections



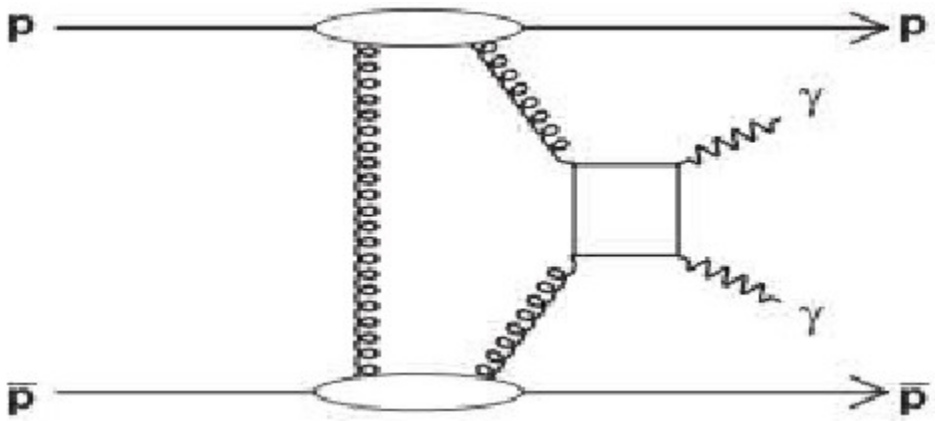
80 < M_gam-gam <
< 350 GeV

None of the theoretical predictions considered is able to describe the DPP data well in all kinematical regions of 4 variables. May be **N**NLO corrections to RESBOS will improve the description of the high PT_gam-gam (**low** D_phi) spectrum **at low M_gam-gam**?

Exclusive Photon Pair Production in ppbar, CDF

L= 532 pb-1

Phys. Rev. Lett. **99,** 242002 (2007)



The process is closely relatede to exclusive Higgs boson production at the LHC p + p ➔ p + H + p (gg fusion through a top quark loop)

Two electromagnetic showers with E_t > 5 GeV and |y| < 1.0 with no other particles detected in the event in the range |y| <7.4.

Three candidate events for exclusive gamma-gamma, pi0-pi0, or η η production are observed with the expected bkgd of 0.09 +/- 0.04 events

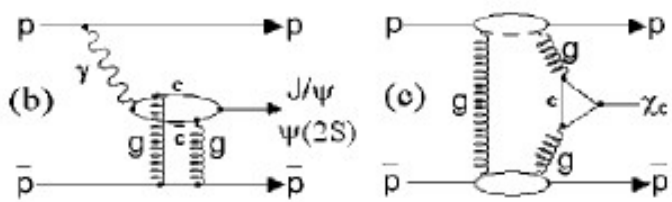
Exclusive J/Psi, Psi(2S) and Production in ppbar collisions, CDF

L= 1.48 fb-1

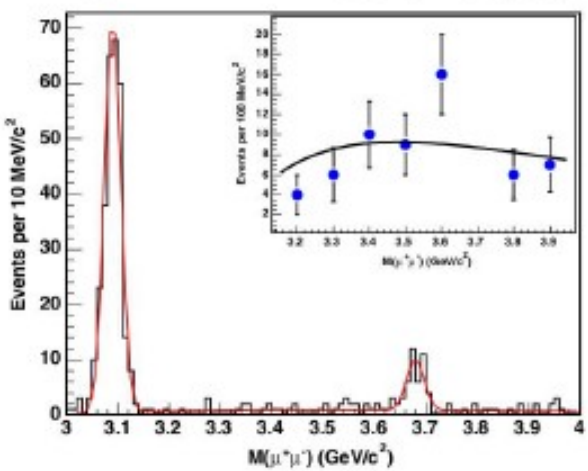
arXiv: 0902.1271, (2010)

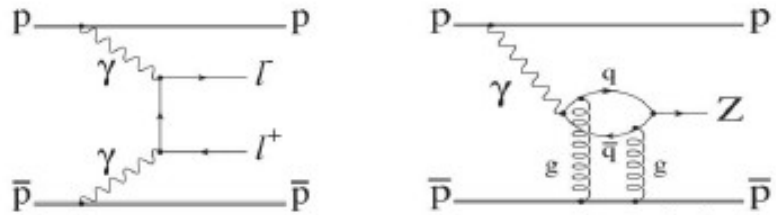
→ Exclusive production (EP) is a search channel for new physics / Higgs Boson.

→ Observed EP in the dijet, dielectron and charmonium channels.

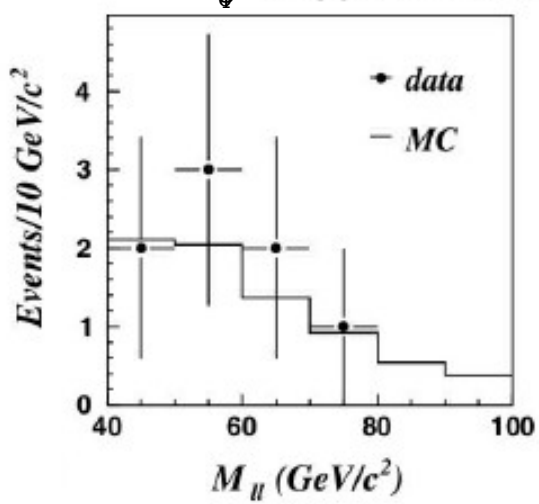


PHYSICAL REVIEW LETTERS 102, 242001 (2009)





PHYSICAL REVIEW LETTERS 102, 222002 (2009)



Not observed, but limits do not exclude SM calculation.

Analogous to HERA observations in ep, first time in hadron –hadron collisions.

Cross sections dsigma/dy/ y=0 are measured for the first time in hadron –hadron collisions.

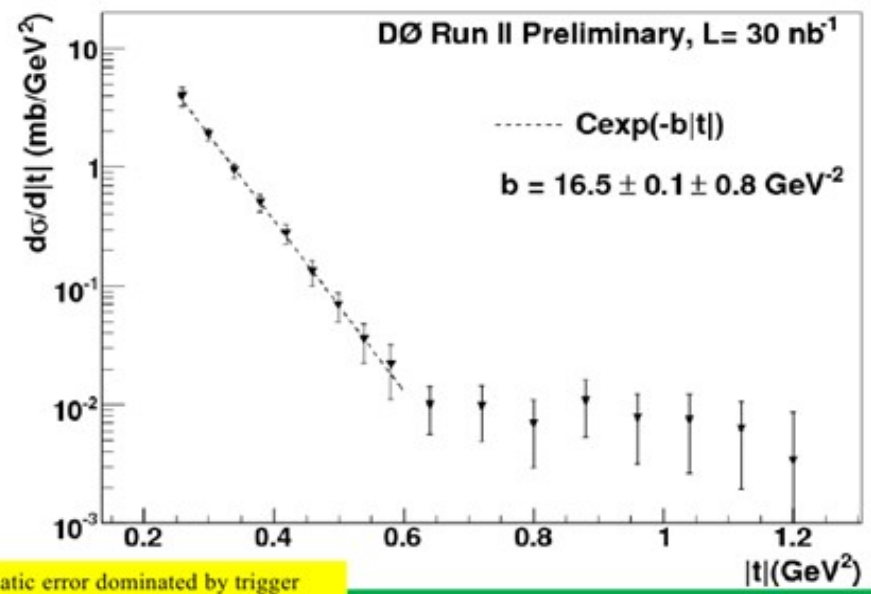
Differential Cross Section in elastic ppbar Scattering

Differential cross section of ppbar elastic Xsection

L= 30 nb-1

D0 note 6056--Conf, April, 2010

- $d\sigma/d|t|$ where $|t|$ 4-momentum transfer squared
  - $0.25 < |t| < 0.6$ GeV^2 and $0.6 < |t| 1.2$GeV^2
- Fit to form $d\sigma/d|t| = C \exp(-b|t|)$ in range $0.25 < |t| < 0.6$ GeV^2
  - $b = 16.54 \pm 0.10(\text{stat}) \pm 0.80(\text{syst})$ GeV^{-2}
- 14.3% luminosity uncertainty not included in plots
- Other important systematic detector positions and efficiencies, beam divergence, analysis function

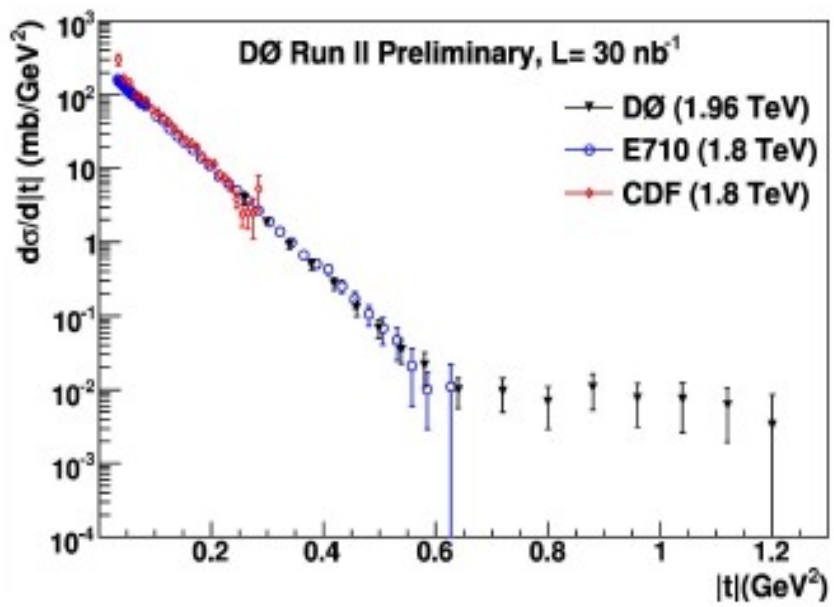


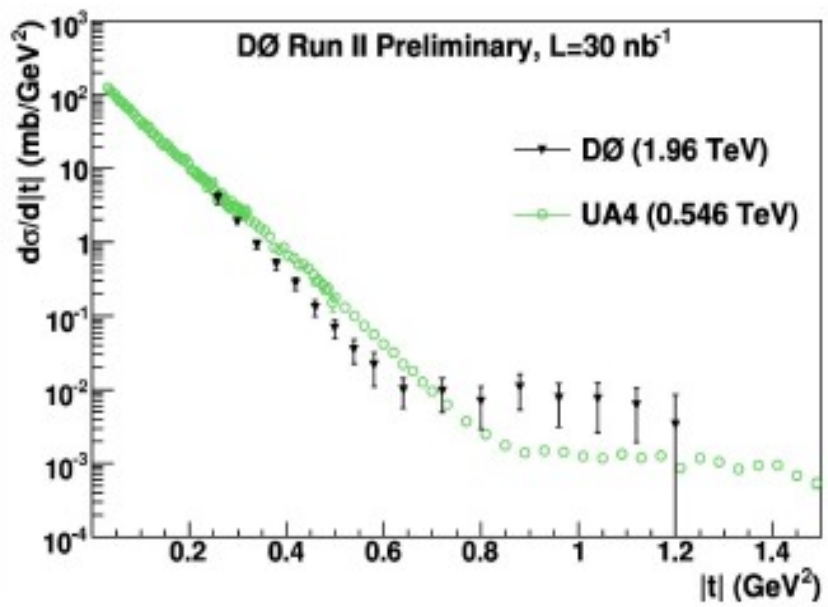
•Systematic error dominated by trigger efficiency correction
•Second biggest uncertainty (alignment) = ± 0.3 GeV^2

First measurement of b at $\sqrt{s}$=1.96 TeV

Differential cross section of ppbar elastic Xsection

- Comparison to other experiments
  - Slope parameters consistent with similar √s
  - Position of first diffraction minimum moves to lower values of |t| with increased collision energy

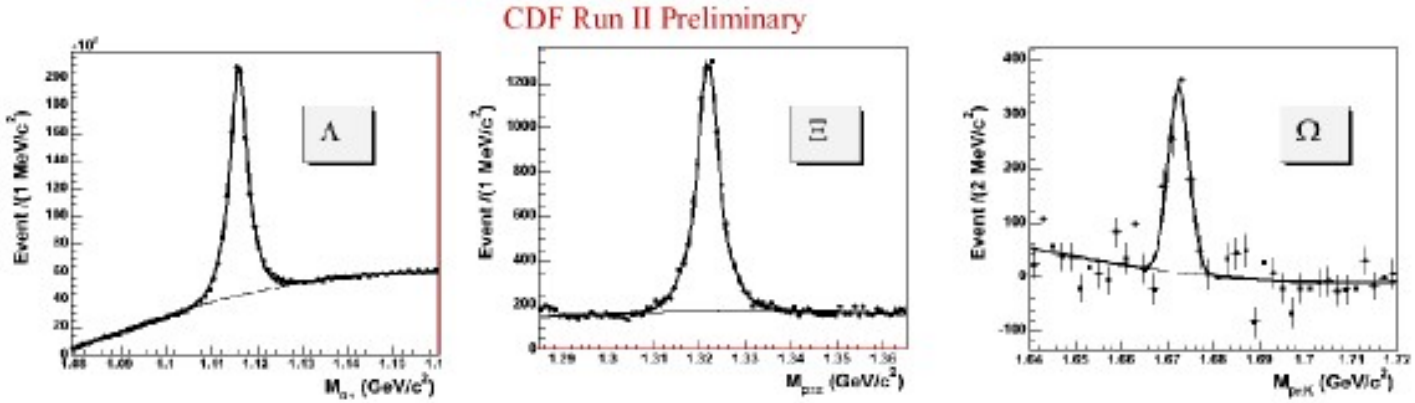


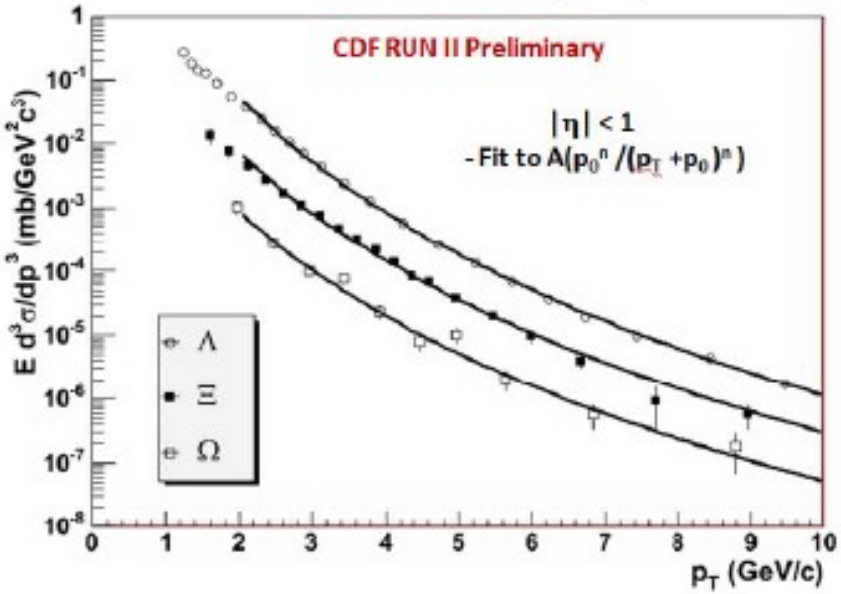


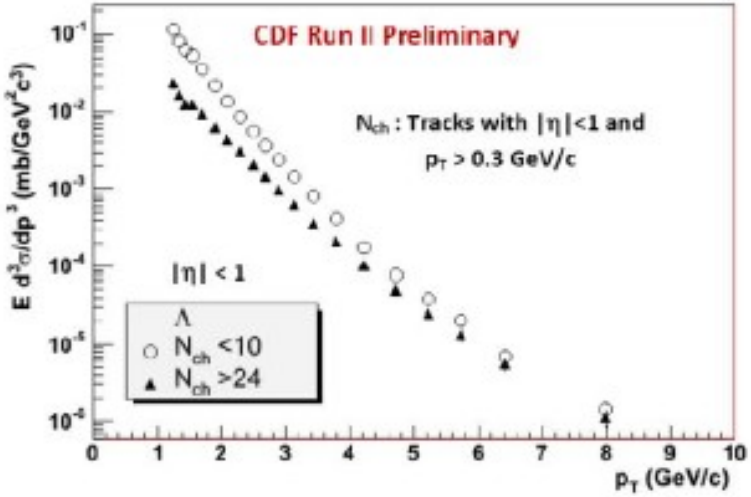
- **Hadron Production**

Differential cross section of ppbar elastic Xsection

→ Strange particle production can reveal mechanisms from the collision.







→ Cross sections are measured in pT bins, accessing previously unexplored high pT regions.

→ Cross sections are also measured in different multiplicity regions.

Underlying Event

↕

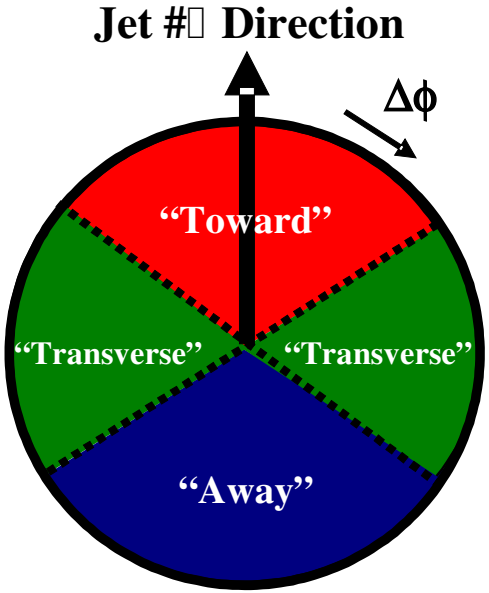
MC Generator Tuning

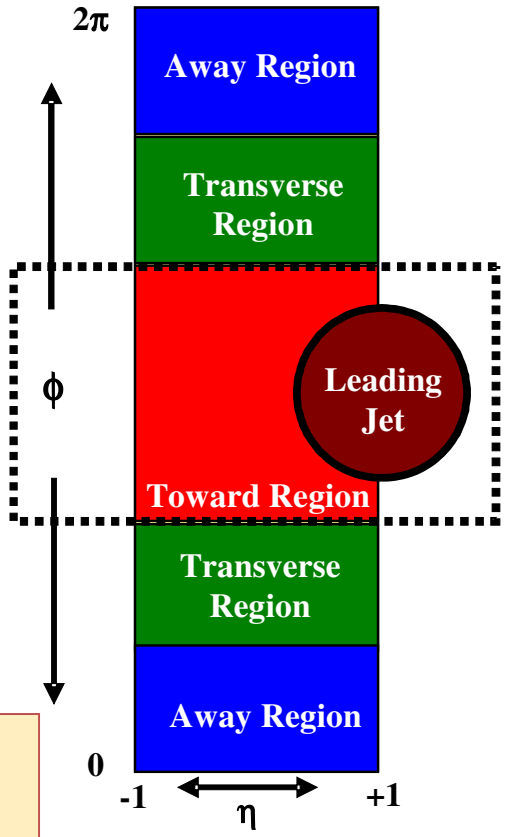
Underlying Event Studies

goal: improve understanding and modeling of high energy collider events

define 3 regions in an event, based on the leading jet

- "toward"
- "away"
- "transverse"





"transverse" region
→ very sensitive to underlying event

study (in all regions)

- charged particle density
- p_T sum density
- E_T sum density

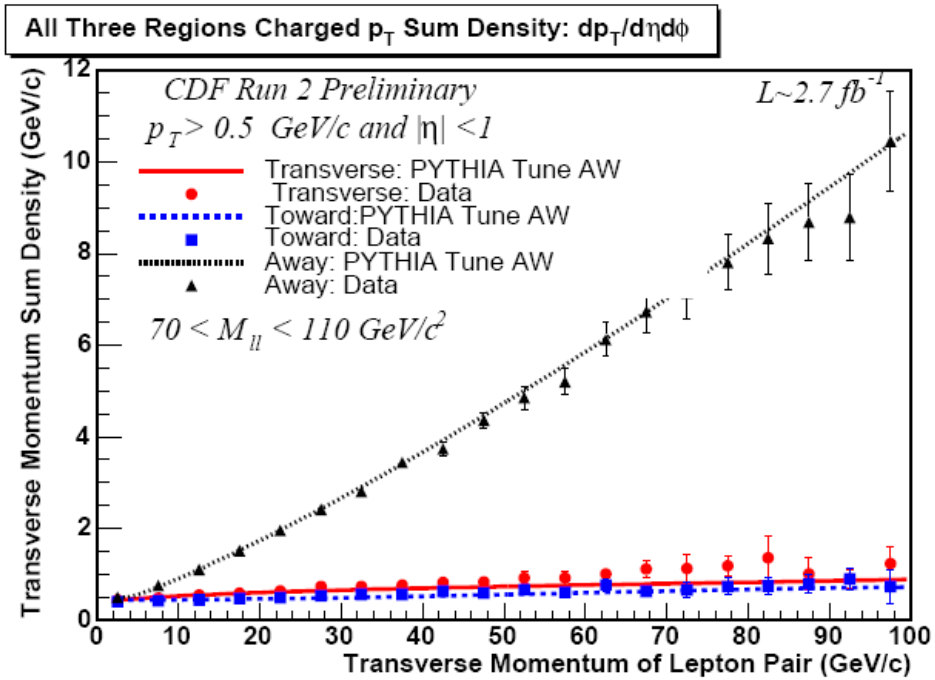
There should be a much higher professional talk on UE of R. Field (CDF)

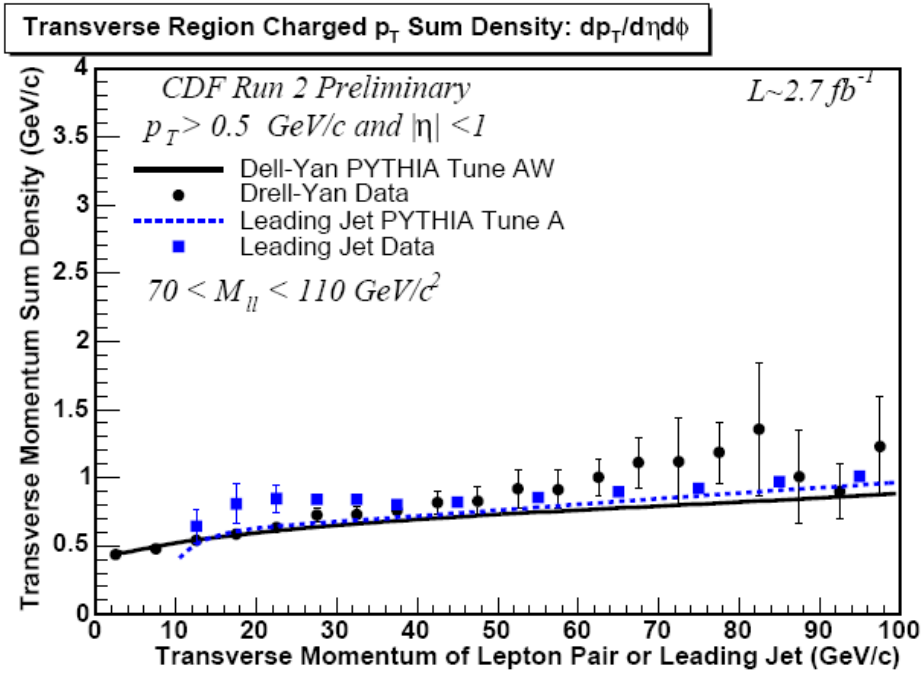
Underlying Event in Drell-Yan and Jet Production

→ charged p_T sum density

comparison of **three regions** in DY:

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





comparison of "transverse" region between **jets and DY**

- similar trend in both
- tuned PYTHIA describes data

Summary

- **New high precision results**
- **Consistency between experiments**

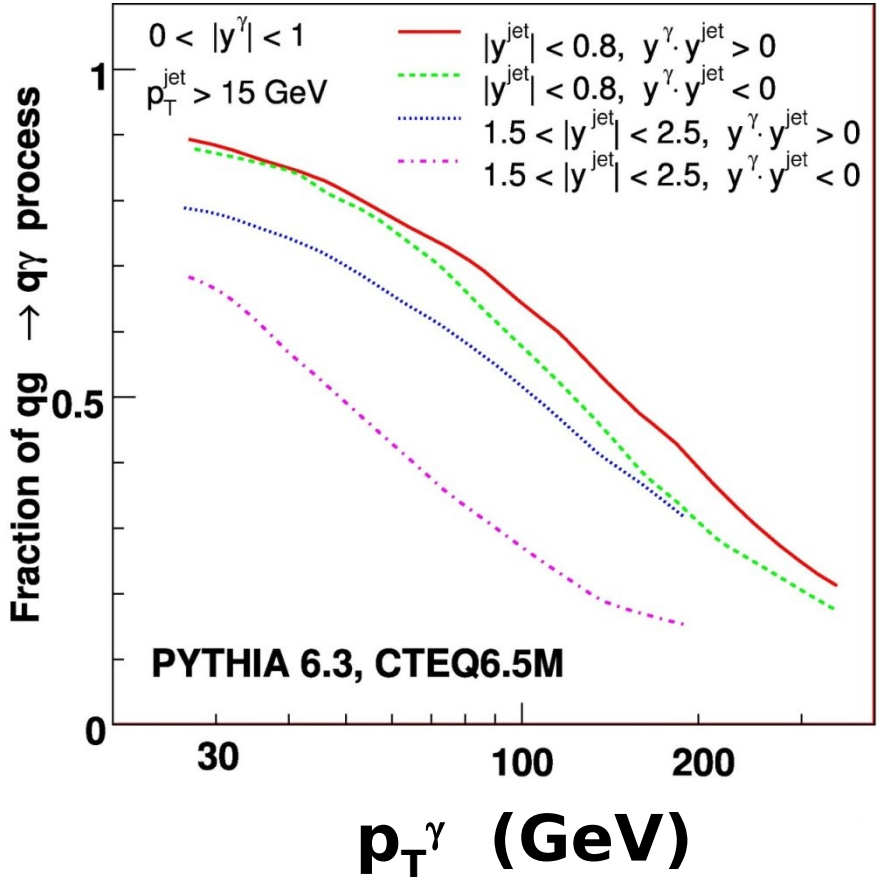
There are many things to do in the nearest future

Now we have the results with up to 4 fb^{-1}

Next year we expect about 12 fb-1

Backup

Isolated Photon + Jet



quark-gluon subprocess fraction in different rapidity regions versus pT