Measurement of Dijet Angular Distributions at D0

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- Motivation
- Theory and Experiment
- Analysis
- Experimental Results
- Limits on New Physics
- Summary

Motivation

Jet production at a hadron collider is sensitive to:

- Dynamics of interaction (QCD or "New Physics"?)
- Proton structure (PDFs)

Before we can use tevatron jet data in PDF fits based on QCD matrix elements, we need:

- Independent confirmation that jets are really produced by QCD

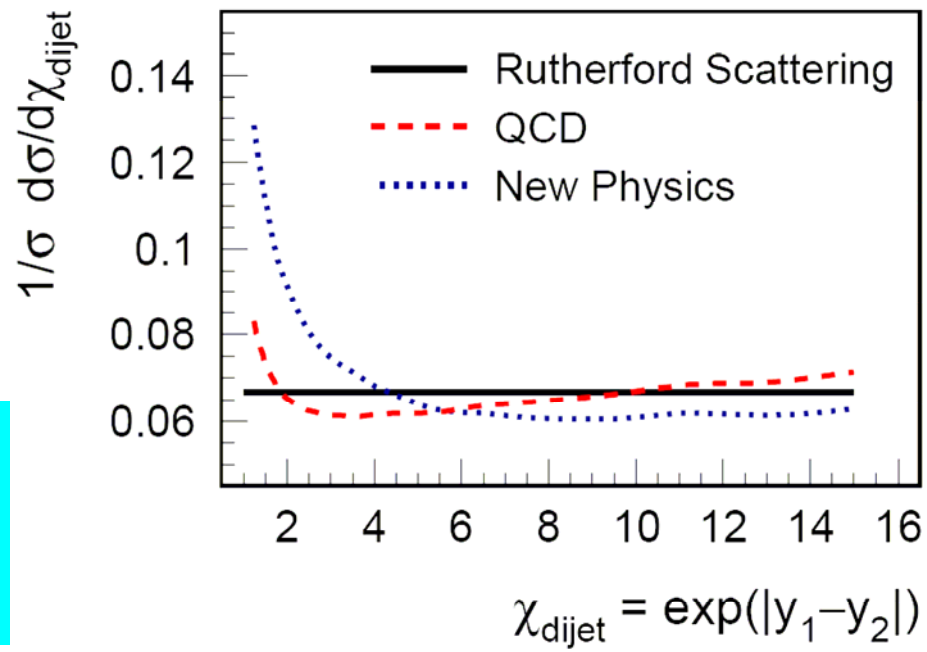
Ideal observable:

Dijet angular distribution

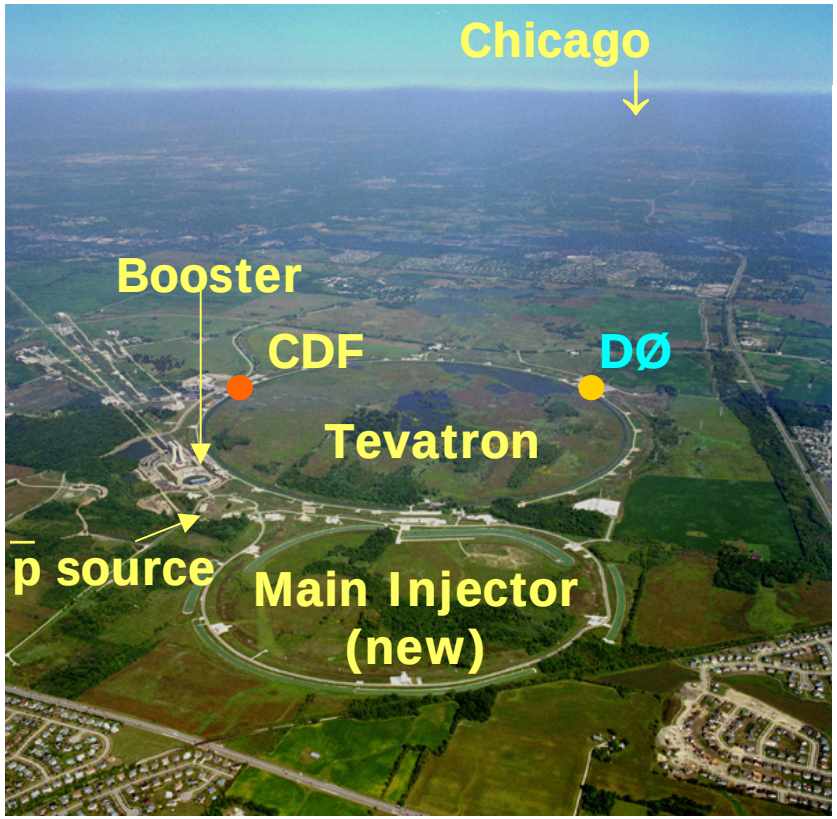
→ Disentangle QCD from "New Physics"

➢Normalized distributions

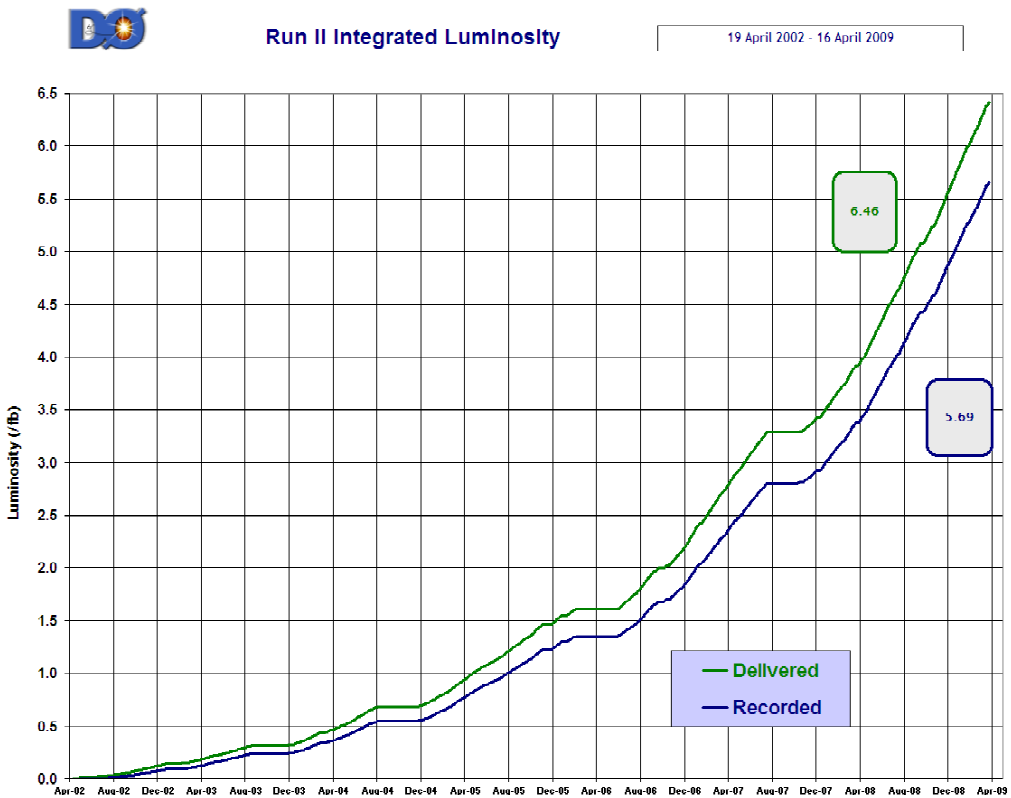
➢Reduction of experimental and theoretical uncertainties



The Run II Tevatron



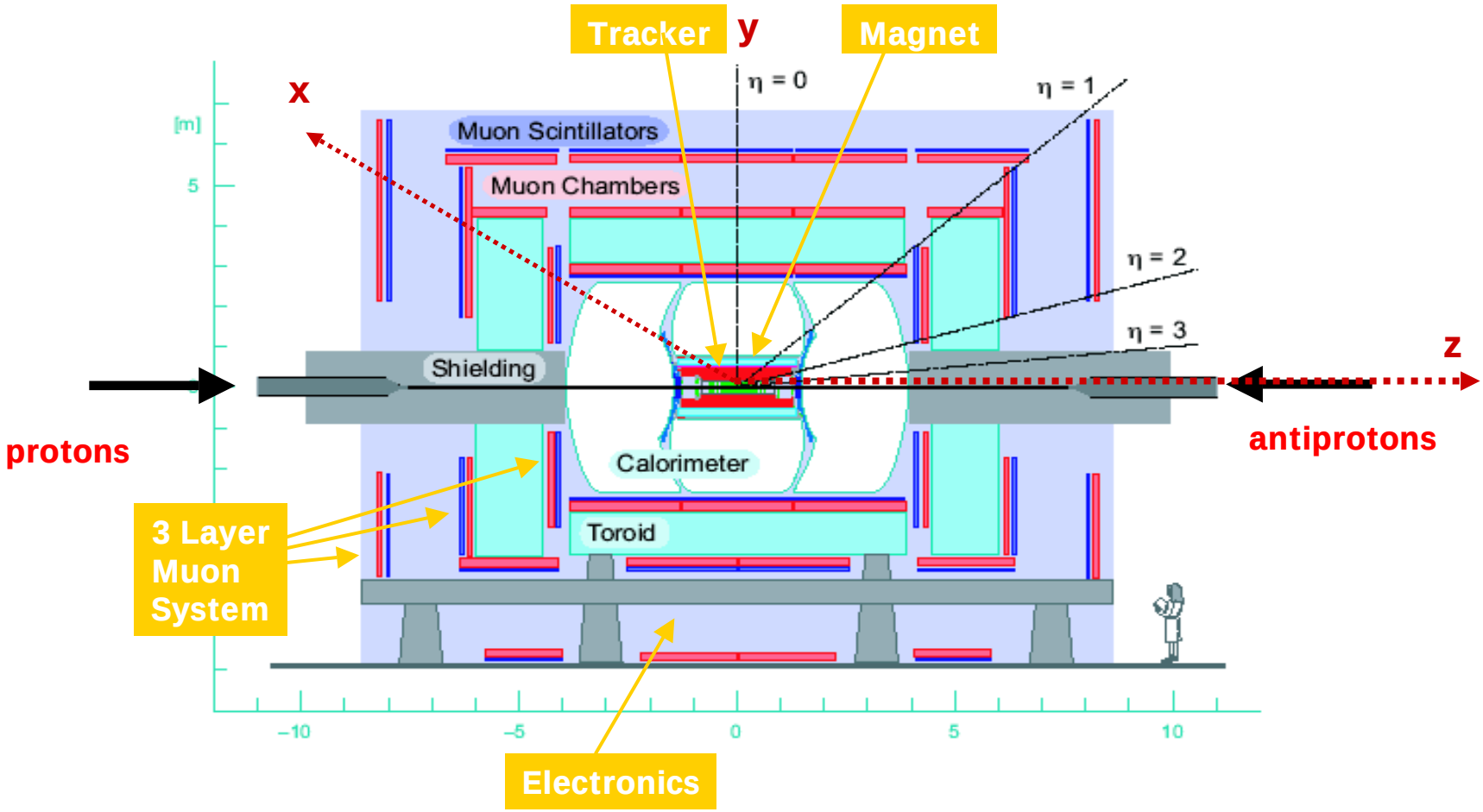
p p̲ collisions at $\sqrt{s} = 1.96\ TeV$



Analysis presented here uses up to 0.7 fb^{-1} of luminosity

More than 5 fb^{-1} of luminosity recorded

DØ Detector


Tracker
y
Magnet
x
η = 0
η = 1
η = 2
η = 3
[m]
5
Muon Scintillators
Muon Chambers
Shielding
z
protons
antiprotons
Calorimeter
Toroid
3 Layer Muon System
Electronics
−10
−5
0
5
10

Variables & Analysis Phase Space

Variables:

- $y^* = \frac{|y_1 - y_2|}{2}$ $\qquad \chi_{\text{dijet}} \equiv \exp(2y^*)$
- $y^{\text{boost}} = \frac{y_1 + y_2}{2}$
- Dijet Mass: M_{dijet}

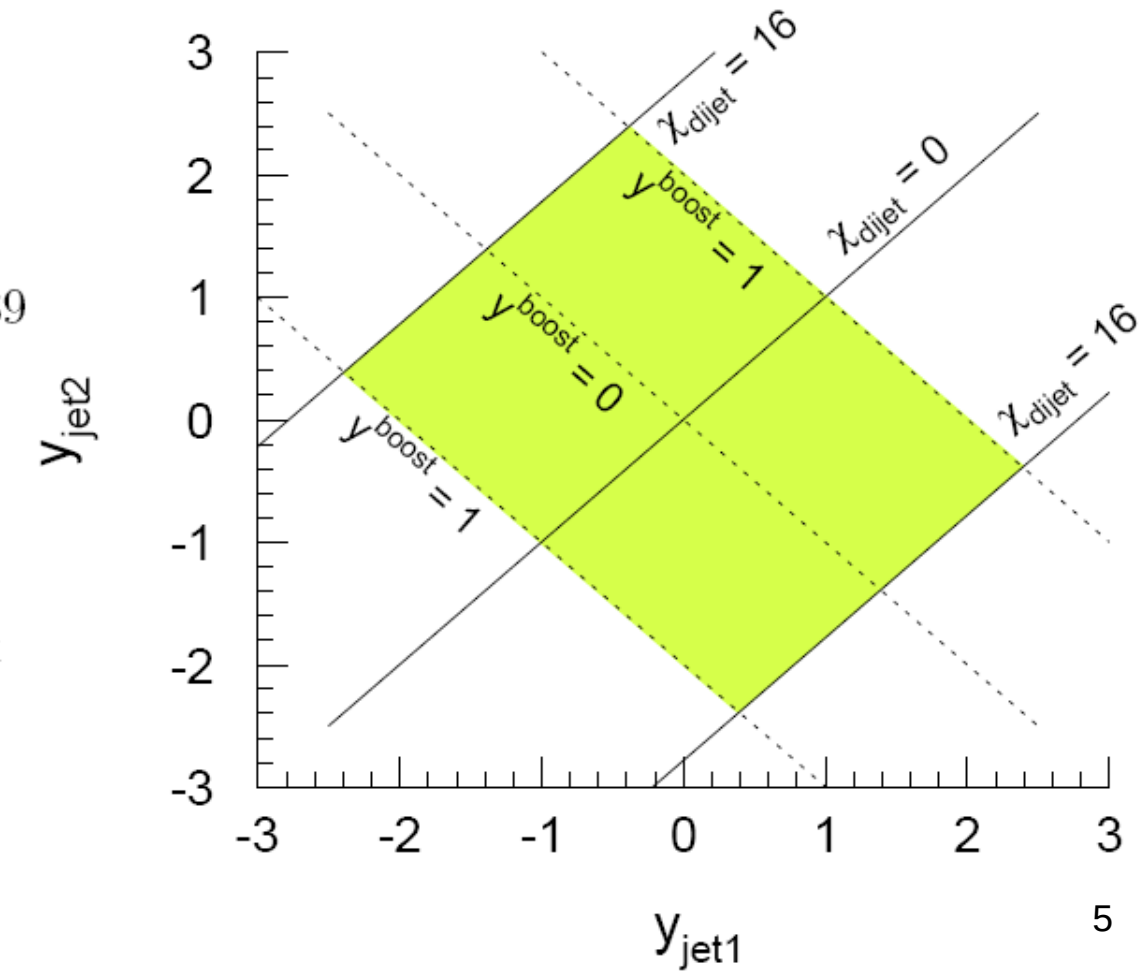
Phase Space Cuts:

- $\chi^{\max}_{\text{dijet}} = 16$ → $y^*_{\max} \simeq 1.39$
- $y^{\text{boost}}_{\max} < 1.0$

With:

$$|y|_{\max} = y^{\text{boost}}_{\max} + y^*_{\max}$$

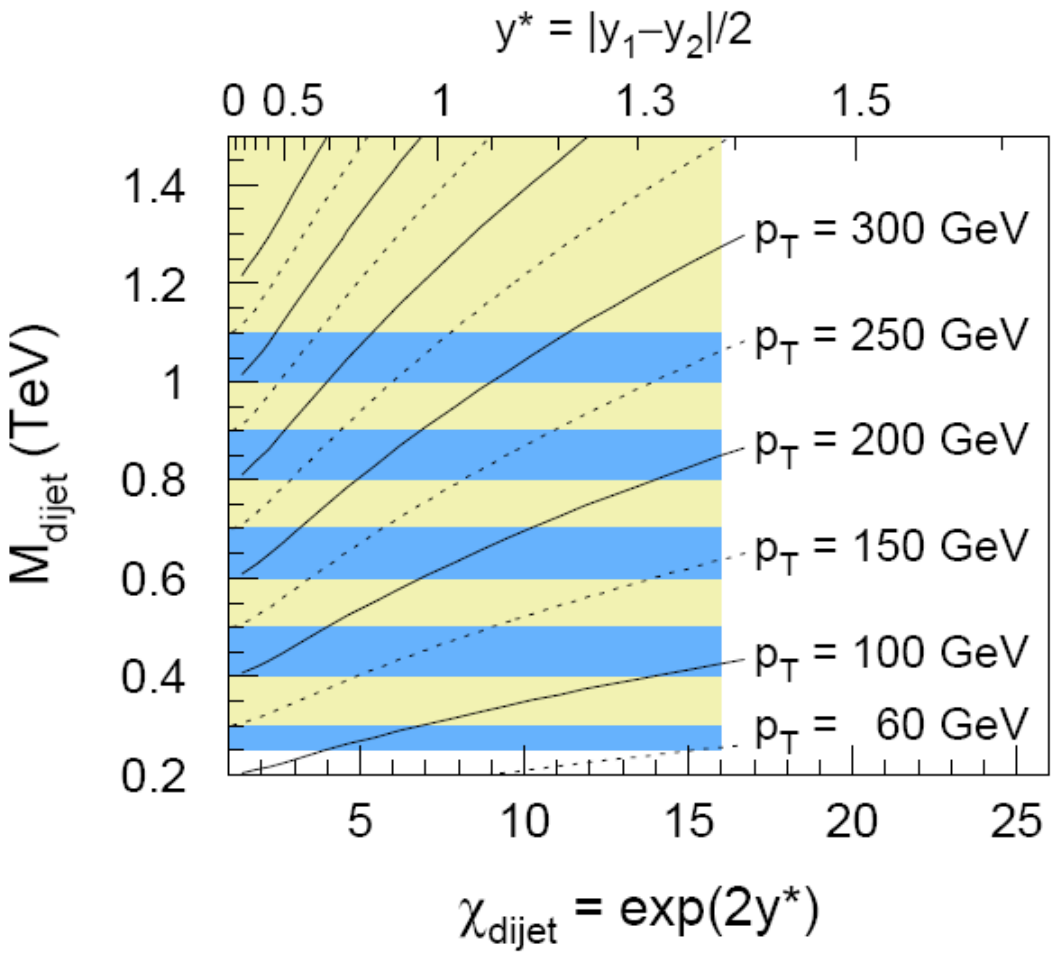
→ $|y|_{\max} < 2.39$



Phase Space

Relation: χ_{dijet}, M_{dijet}, p_T

→ justify choices of triggers

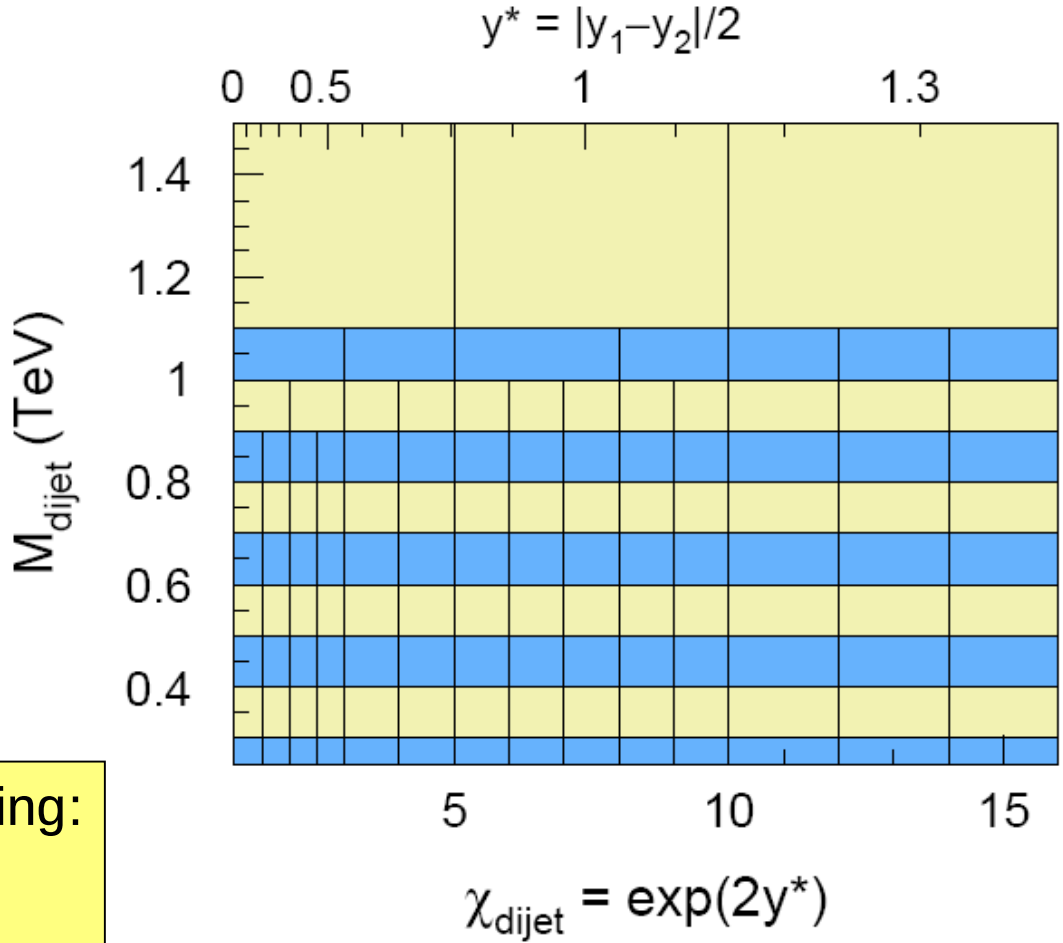


Analysis Bins

- 120 chi bins
- 72 y-boost bins

in 10 dijet mass regions
from 0.25TeV to sqrt(s)

→ Two χ_{dijet} regions beyond 1TeV!



→ criteria for (χ_{dijet} / M_{dijet}) binning:
- access highest M_{dijet}
- large range in χ_{dijet}

Data and Jet Selection

Data Set

~0.7 fb^{-1} of Luminosity is used by this analysis .

Triggers: For each invariant mass region we use a single jet trigger JT15, JT25, JT45, JT65, JT95, JT125

Event Selection Criteria

- Events when performance of detector was questionable were rejected
- Events with met/leading jet p_T> 0.7 (>0.5) for p_T <100 GeV (p_T>100 GeV) and were rejected
- |Z| > 50 cm were rejected
- Events where either leading or next to leading jets failed Jet identification cuts which were devised to reject noise jets, electron/photon overlap

Data Correction Procedure

Correction and the uncertainties are determined using MC

→ Using PYTHIA (tune QW) events – reweighted to match NLO (NLOJET++) and detector effects are parametrized.

- Jet pT resolutions
- Jet eta, phi resolutions
- Jet ID efficiencies
- JES uncertainties (49 eigenvectors, correlations are taken into account)
- Z-vertex distribution
- Muon/Neutrino corrections to jet energies
- Non-Perturbative corrections

Corrections

Corrections applied to jets in data:

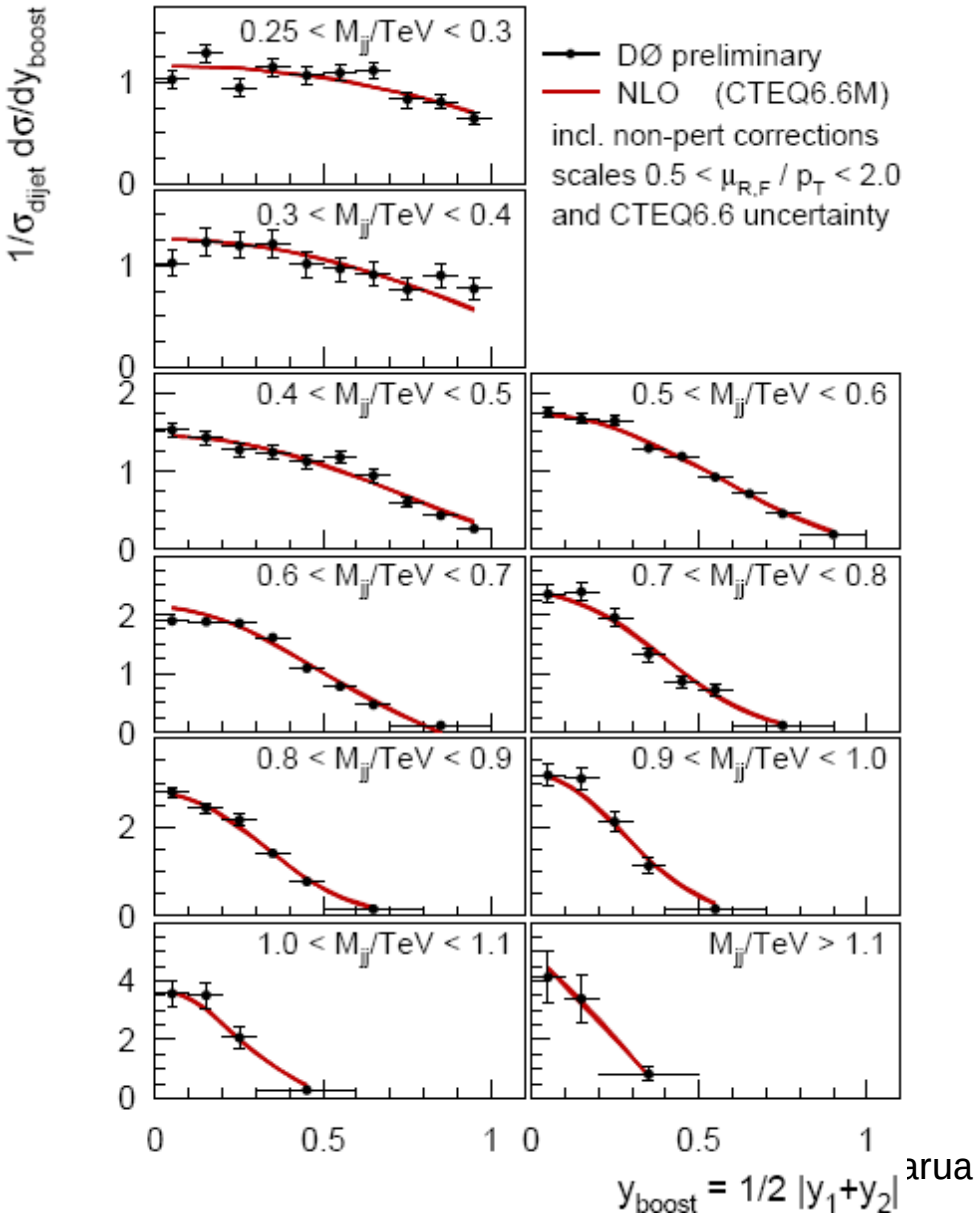
- JES (+ Rapidity Bias)

Corrections from simulations
(applied to MC distributions):

- pT resolution – dominant (upto 30%)
- eta-det resolution
- phi resolution
- Jet ID efficiency
- Misvertexing
- Muon/Neutrino energies in jets

Only JES uncertainty and jet pT resolution uncertainty are significant

Results – yboost vs. pQCD

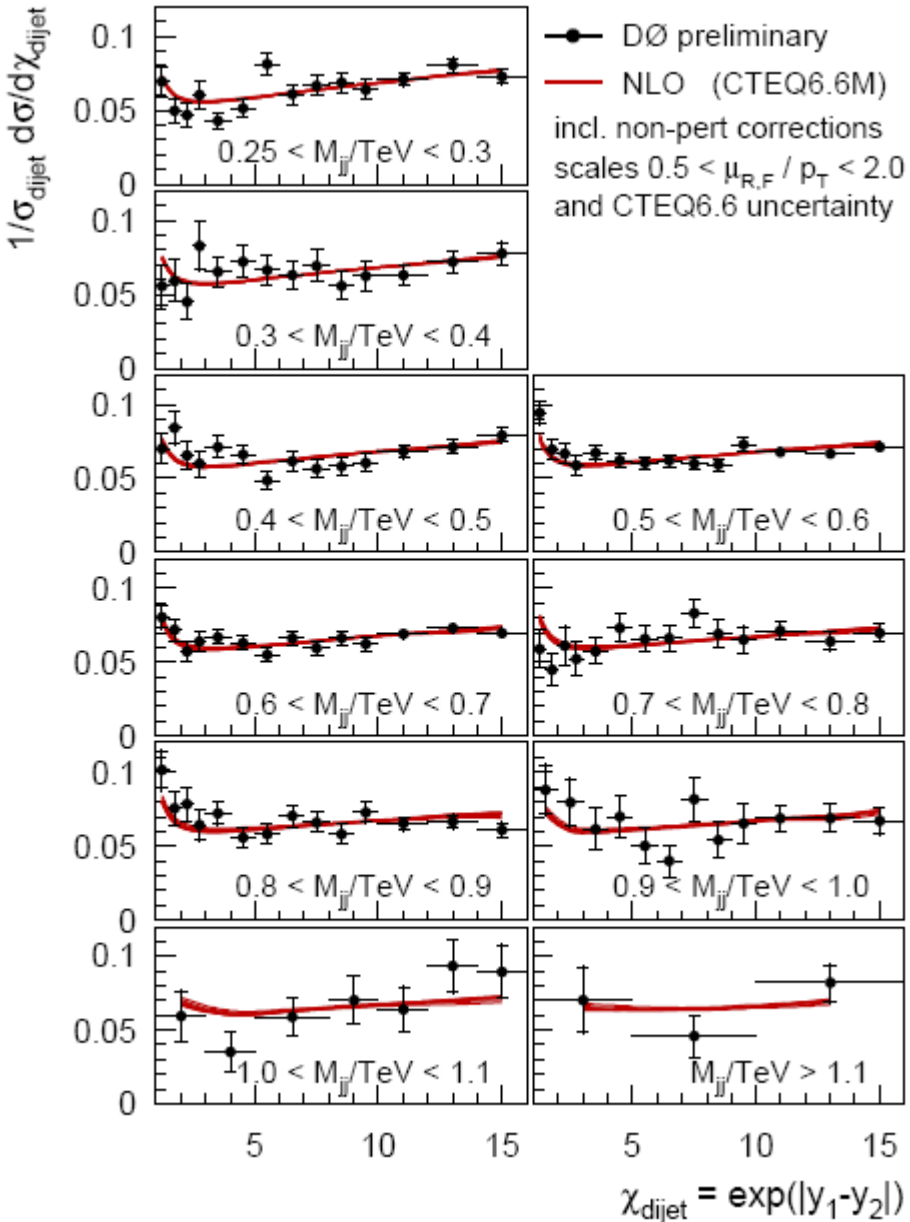


Data points include both stat and syst uncertainties

→ Data are well described by NLO pQCD

→ Theory uncertainties (PDFs and scales) are very small

Results – chi vs. pQCD



Data points include both stat and syst uncertainties

→ Data are well described by PQCD (χ^2 ~ 124)

→ Theory uncertainties (PDFs and scales) are very small

New Physics Models

Quark Compositeness:

Symmetries in groups of particles like atoms or hadrons have often been explained by substructure.

Hypothetically quarks could also be made of other particles.

Parameters : the energy Scale Λ, and interference term λ

ADD Large extra dimension:

This model assumes that extra dimensions exist in which gravity is allowed to propagate.

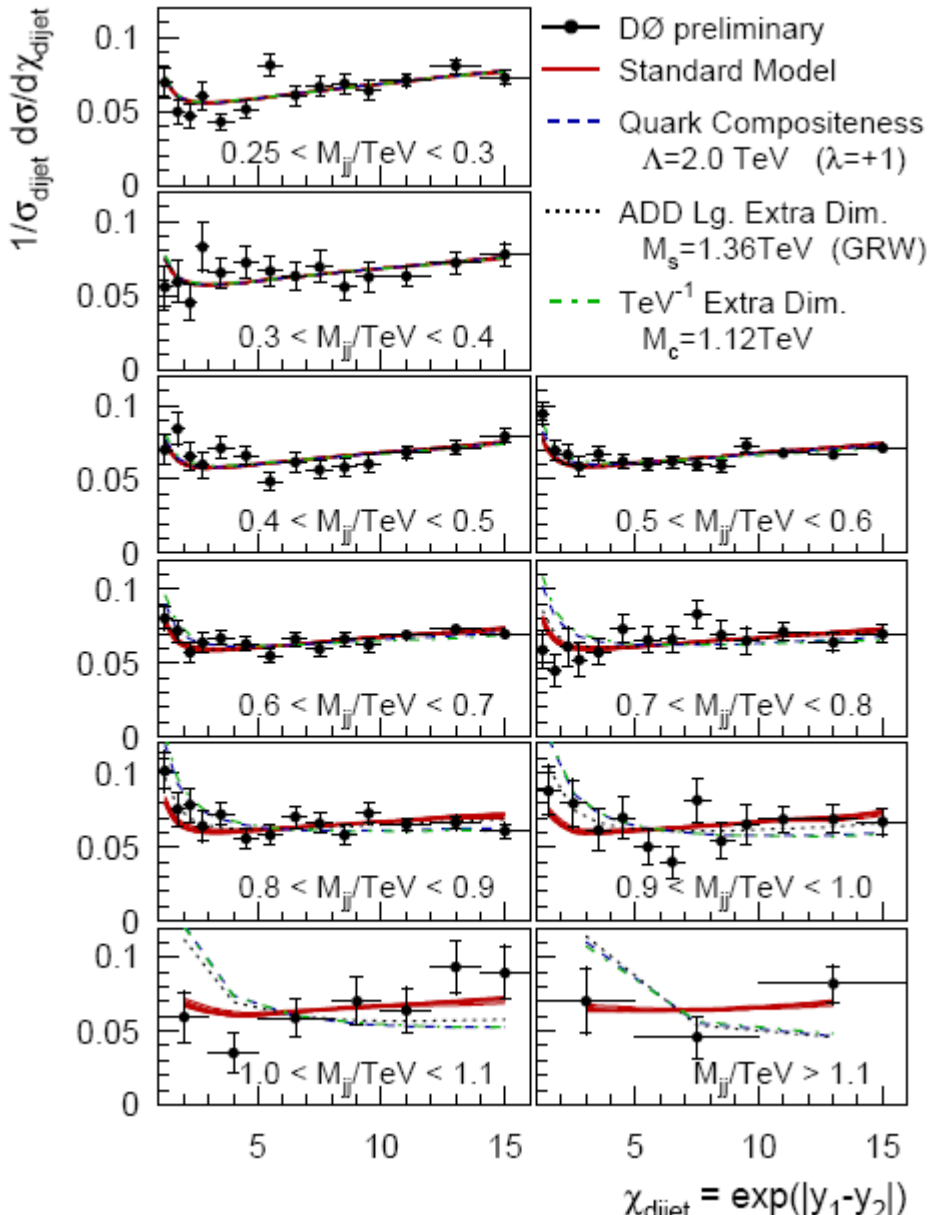
Parameter: Planck scale M_s and number n of large extra dimensions

TeV^{-1} Extra Dimensions:

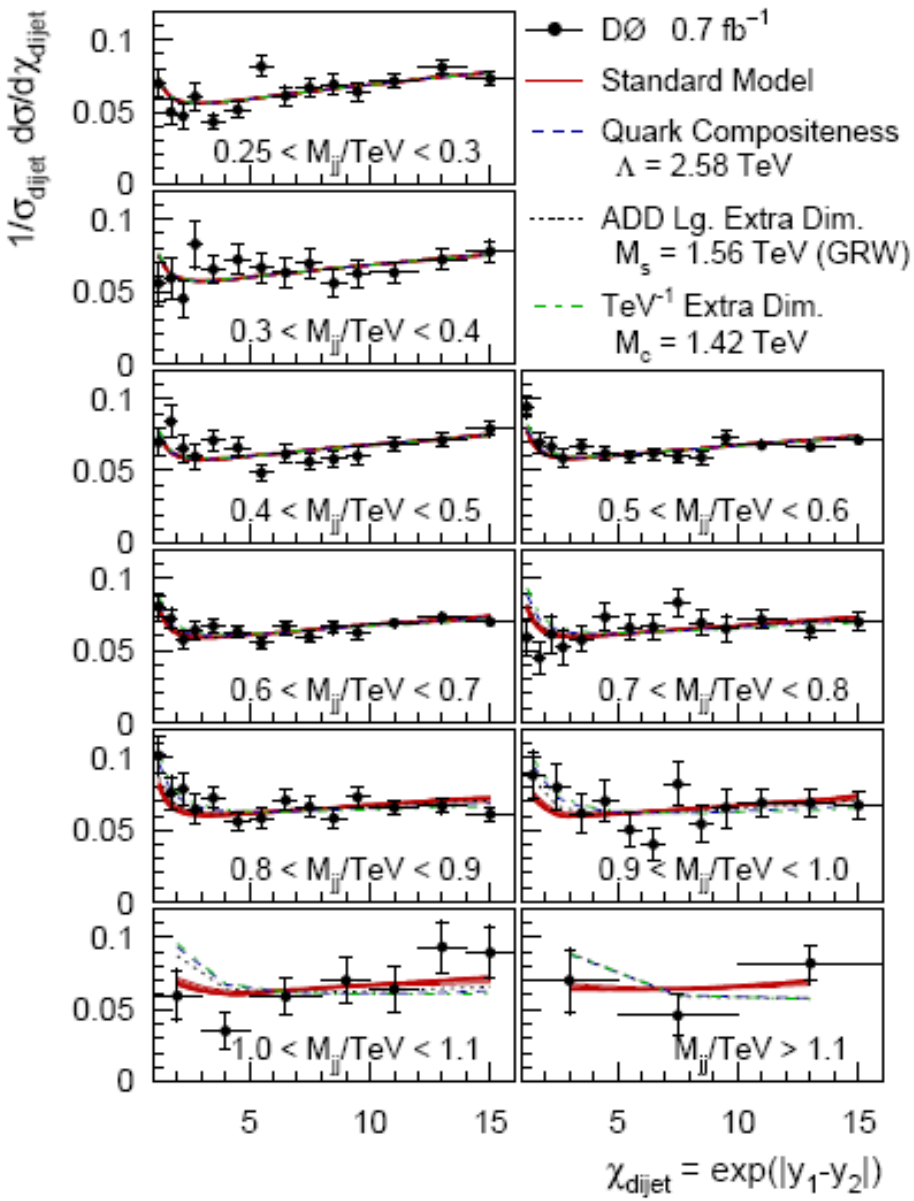
Instead of graviton exchange of virtual Kaluza-Klein excitations is considered

Parameter : compactification scale M_c

χ vs New Physics Models



Results: χ vs New Physics



→ New physics models change shape

→ Effects depends on dijet mass

Limits on New Physics

Set Limits to

- Quark Compositeness (scale Λ)
- ADD Large Extra Dimensions (scale Ms, n)
- TeV-1 Extra Dimensions (scale Mc)

Matrix Elements taken from following references

- Quark Compositeness – Contact Interactions
  P. Chiappetta, M. Perrottet, Phys. Lett. B 253: 489 (1991)
- ADD Large Extra Dimensions
  D. Atwood, S. Bar-Shalom, A. Soni, Phys. Rev. D 62 (2000)
- TeV-1 Extra Dimensions
  K. Cheung, G. Landsberg, Phys. Rev. D 65 (2002)

$$\sigma_{\rm NP}^{\rm NLO} = \sigma_{\rm QCD}^{\rm NLO} \cdot \frac{\sigma_{\rm NP}^{\rm LO}}{\sigma_{\rm QCD}^{\rm LO}} = \sigma_{\rm NP}^{\rm LO} \cdot \frac{\sigma_{\rm QCD}^{\rm NLO}}{\sigma_{\rm QCD}^{\rm LO}} .$$

Bayesian Limit Setting Procedure

Define χ^2 between data and theory and minimize it with respect to nuisance parameter

Define Likelihood: $$L(\xi) = \frac{1}{A} \exp\left(-\frac{1}{2}\chi^2\right)$$

Transform New Physics mass scale

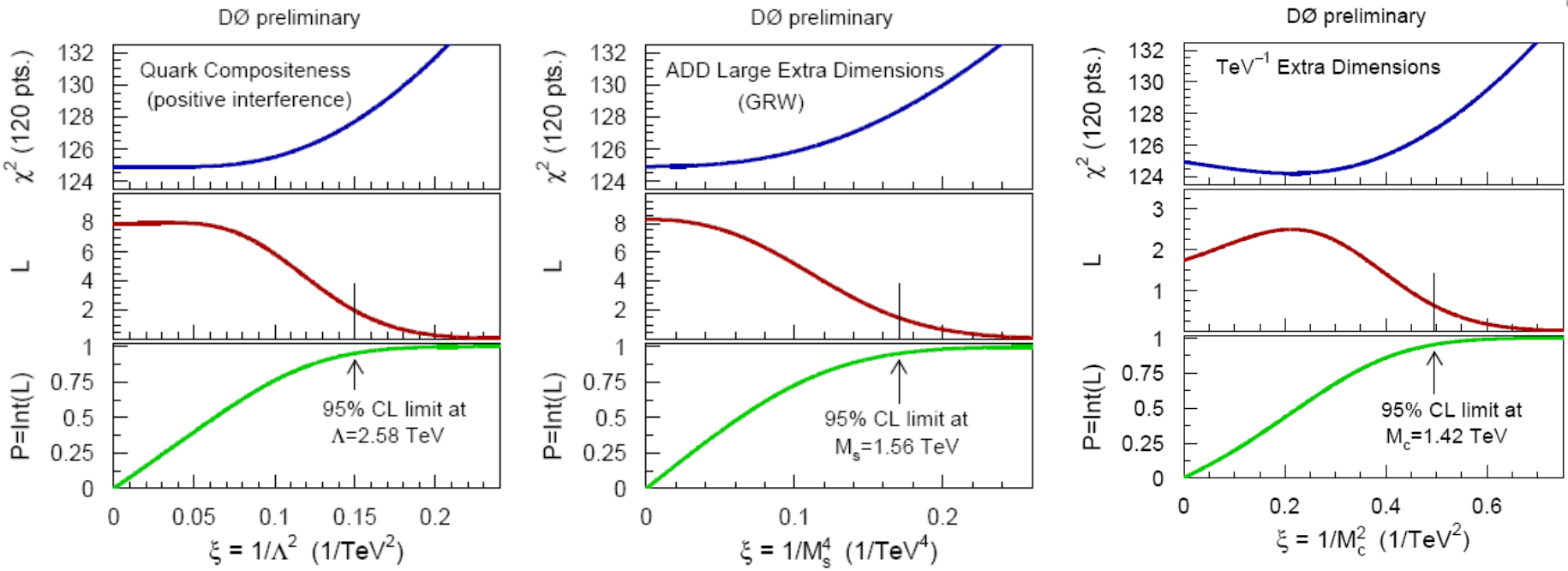
$$\xi = 1/\Lambda^2 \text{ (QC)},\ 1/M_S^4 \text{ (ADD LED)},\ 1/M_C^2 \text{ (TeV}^{-1}\text{ ED)}$$

Prior flat in transformed scale and other powers are tried

Compute Integral $$Q(\xi) = \int_0^{\xi} L(\xi')\, P(\xi)\, d\xi'$$

Define Limit $$Q(\xi_{\text{limit}}) = 0.95 \cdot Q(\infty)\,.$$

Limits on New Physics



Bayesian 95% C.L Limits:

(prior flat in ξ)	2.58	1.56	1.42
(prior flat in ξ^2)	2.39	1.48	1.33

Limits obtained using other methods fall in between Bayesian limits with two choices of prior

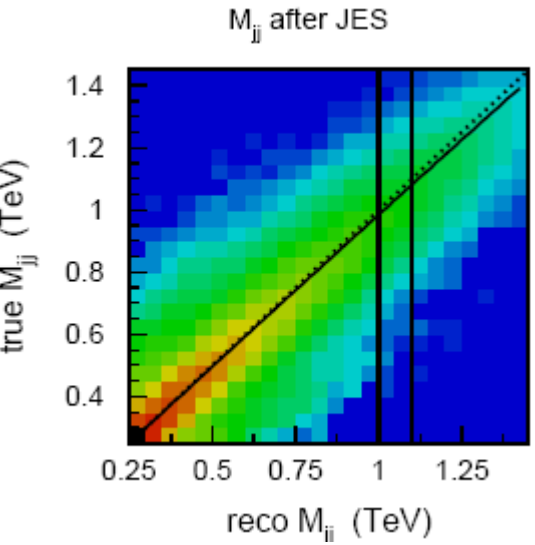
Summary and outlook

- Normalized y_{boost} and χ have been measured by the D0 detector in 10 mass bins using 0.7 fb^{-1} of data
- Very first such measurement at partonic cm energy above 1 TeV
- Result is in good agreement with QCD.
- Limits are set for several new physics model, some limits are most stringent limits.

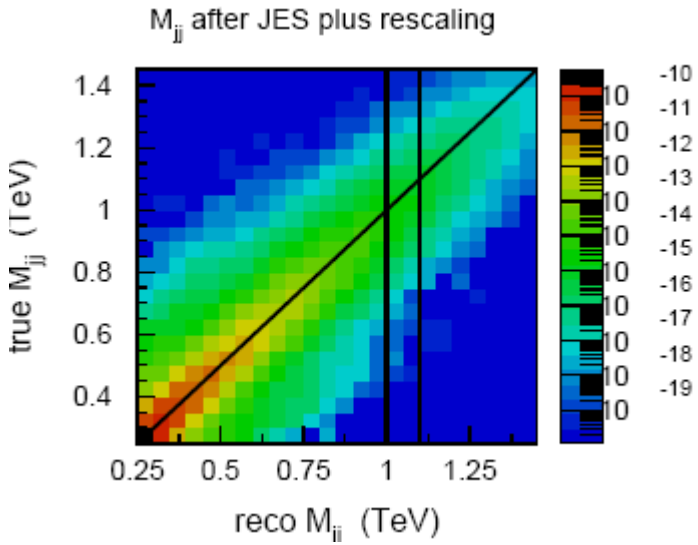
Extra

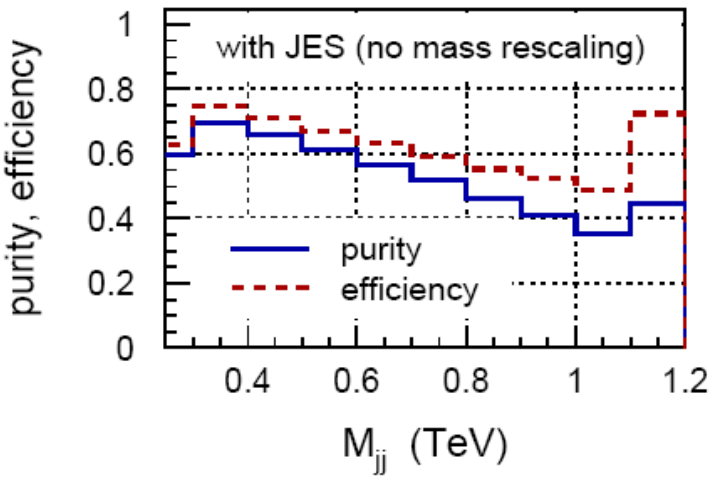
Rescaling of Dijet Mass

$$M_{\mathrm{jj}}^{\mathrm{rescaled}} = M_{\mathrm{jj}}^{\mathrm{reco}} - 0.001\,\mathrm{TeV} \cdot \left(\frac{M_{\mathrm{jj}}^{\mathrm{reco}}}{0.25\,\mathrm{TeV}}\right)^2$$

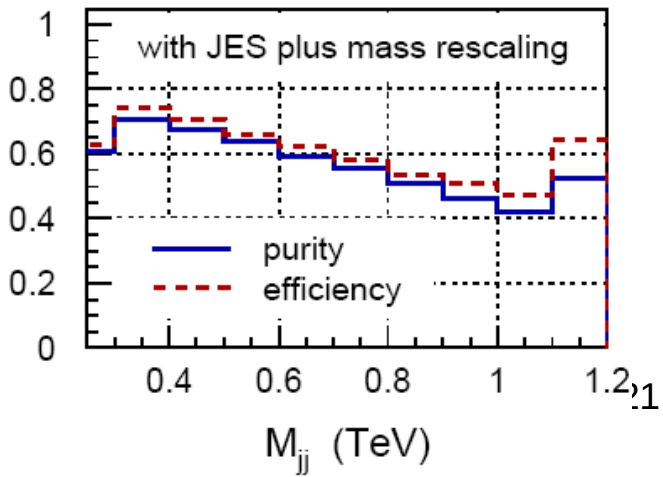


Improved correlation between truth vs reco

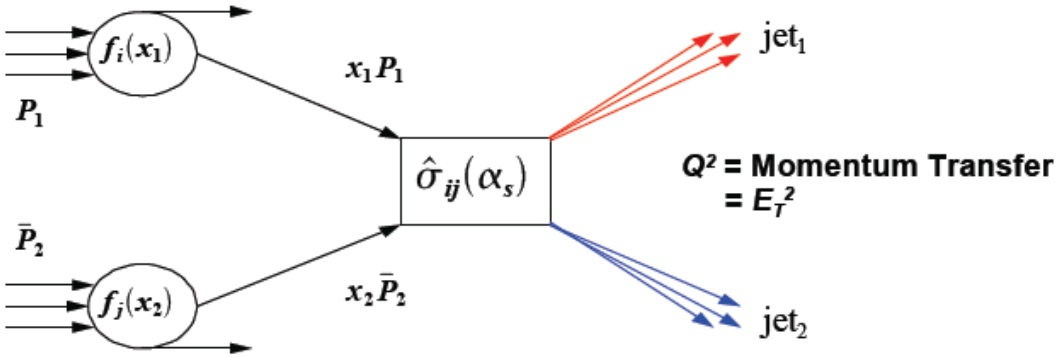




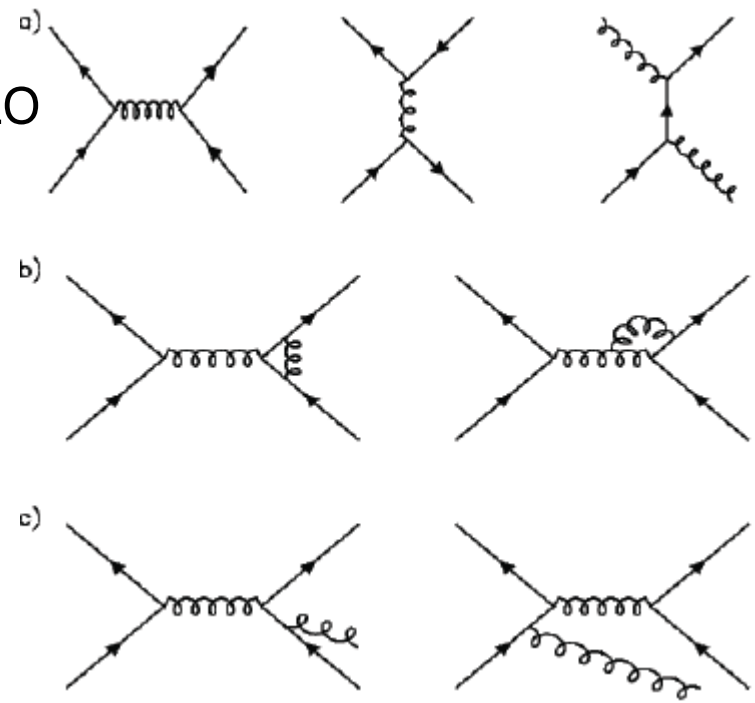
Improved Purity



Theory Calculation



LO



$$\sigma = \sum_{ij} \int dx_1\, dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2)\, \hat{\sigma}_{ij}\left(\alpha_s^m(\mu_R^2), \textit{elementary process}\right)$$

Parton distributions

Factorization scale

Elementary cross section

Order α_s^m

Renormalization scale

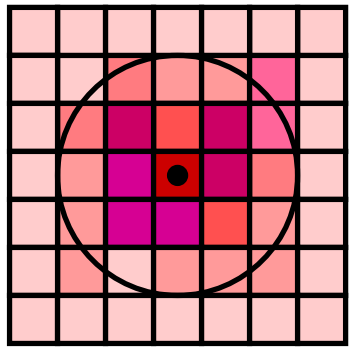
Data

dijet mass range	smallest $p_{T\,\mathrm{max}}$	trigger	lumi (pb^{-1})	$p_{T\,\mathrm{threshold}}$	No. events
$0.25 < M_{\mathrm{jj}} < 0.3\,\mathrm{TeV}$	55 GeV	JT15	0.0987	50 GeV	1354
$0.3 < M_{\mathrm{jj}} < 0.4\,\mathrm{TeV}$	75 GeV	JT15	0.0987	50 GeV	591
$0.4 < M_{\mathrm{jj}} < 0.5\,\mathrm{TeV}$	90 GeV	JT25	1.54	90 GeV	1434
$0.5 < M_{\mathrm{jj}} < 0.6\,\mathrm{TeV}$	110 GeV	JT45	17.2	110 GeV	3171
$0.6 < M_{\mathrm{jj}} < 0.7\,\mathrm{TeV}$	140 GeV	JT65	73.0	140 GeV	2957
$0.7 < M_{\mathrm{jj}} < 0.8\,\mathrm{TeV}$	160 GeV	JT65	73.0	140 GeV	759
$0.8 < M_{\mathrm{jj}} < 0.9\,\mathrm{TeV}$	190 GeV	JT95	508.	190 GeV	1297
$0.9 < M_{\mathrm{jj}} < 1.0\,\mathrm{TeV}$	200 GeV	JT95	508.	190 GeV	329
$1.0 < M_{\mathrm{jj}} < 1.1\,\mathrm{TeV}$	238 GeV	JT125	707.	240 GeV	111
$1.1 < M_{\mathrm{jj}} < 1.96\,\mathrm{TeV}$	280 GeV	JT125	707.	240 GeV	36

Jet Algorithms

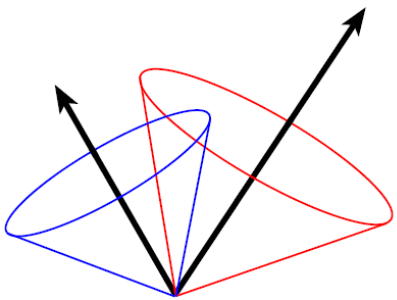
Run I cone algorithm

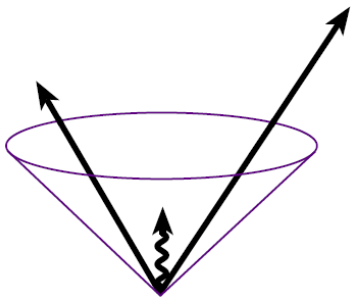
- **Draw a cone of fixed size around a seed (unit region with high energy deposit).**
- **Compute jet axis by E_T weighted mean and jet energy by summing over energies.**
- **Draw new cone around the new jet axis and recalculate axis and new energy.**
- **Iterate until stable.**



RunII midpoint cone algorithm used for analysis presented here

- Use 4 vector instead of E_T
- Add additional seed in the middle of two stable jets



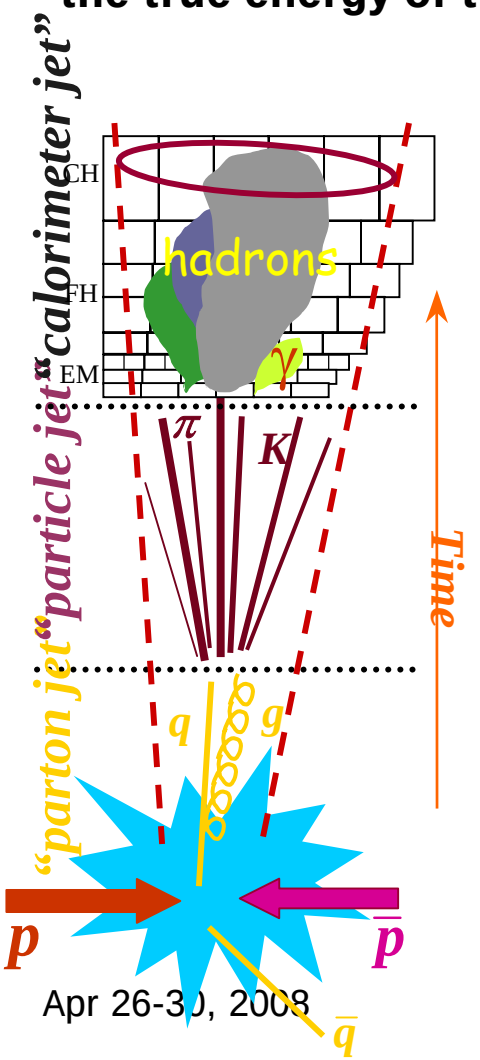


Use 0.7 cone in this analysis

http://theory.fnal.gov/people/ellis/QCDWB/YB/qcd_wz_run2_ch2.pdf

Jet Energy Scale

Aim is to go from measured energy in calorimeter using cone algorithm to the true energy of the particle jets



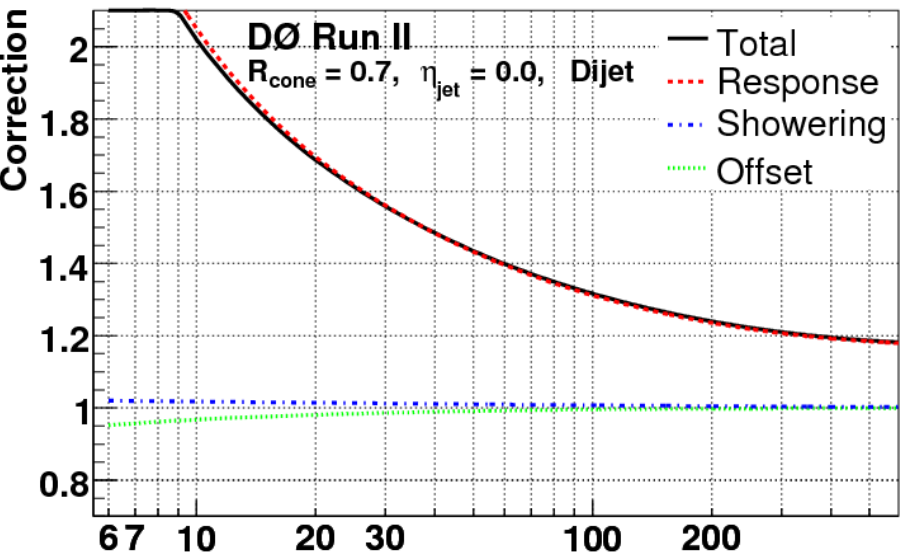
$$E_{ptcl} = \frac{E_{cal} - Offset}{(F_\eta \cdot R) \cdot S} \cdot k_{bias}$$

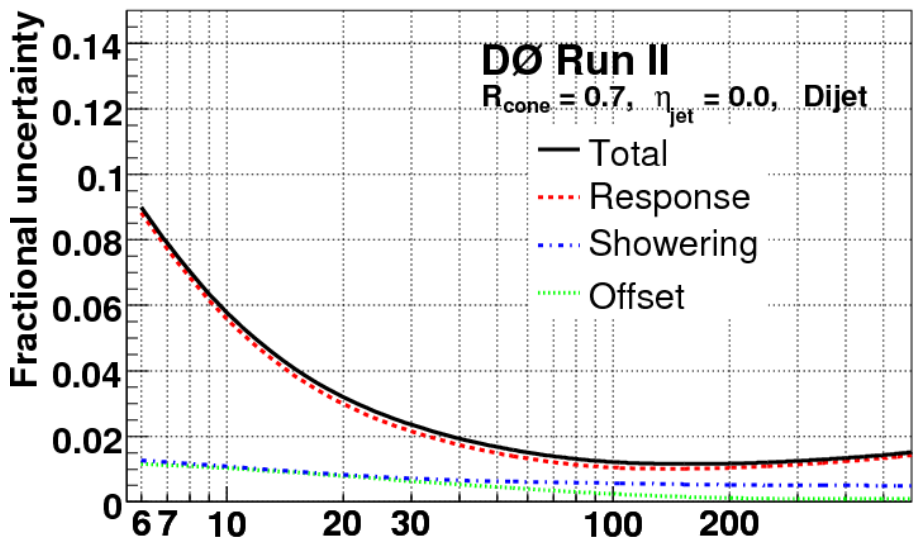
Offset correction takes into account electronic noise, pile-up, and multiple interaction

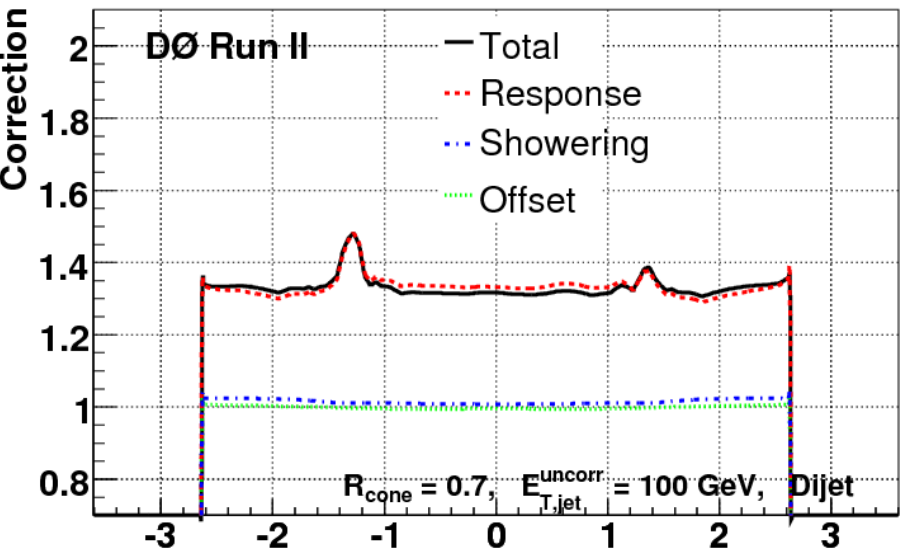
Response, R, is the calorimeter response to particle jets

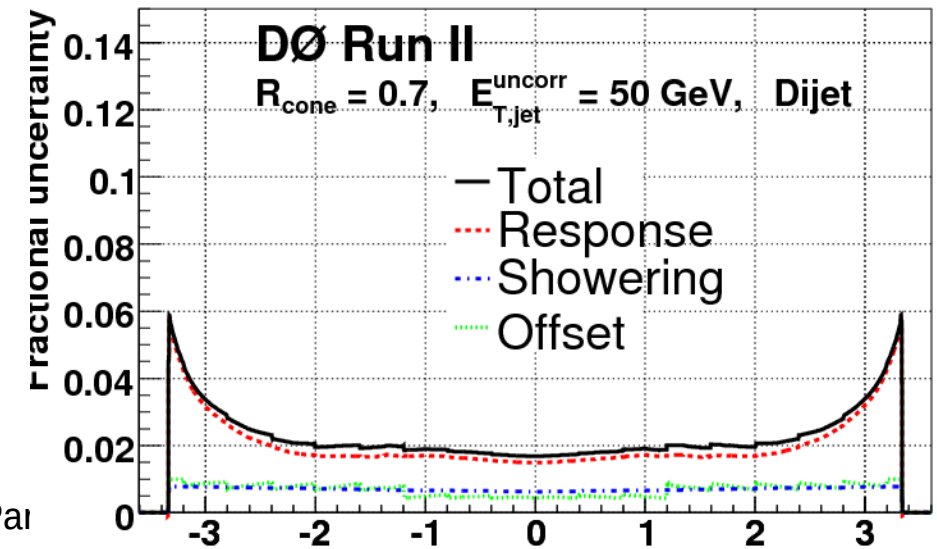
Showering correction is the fraction of the shower contained within the cone

Jet Energy Scale





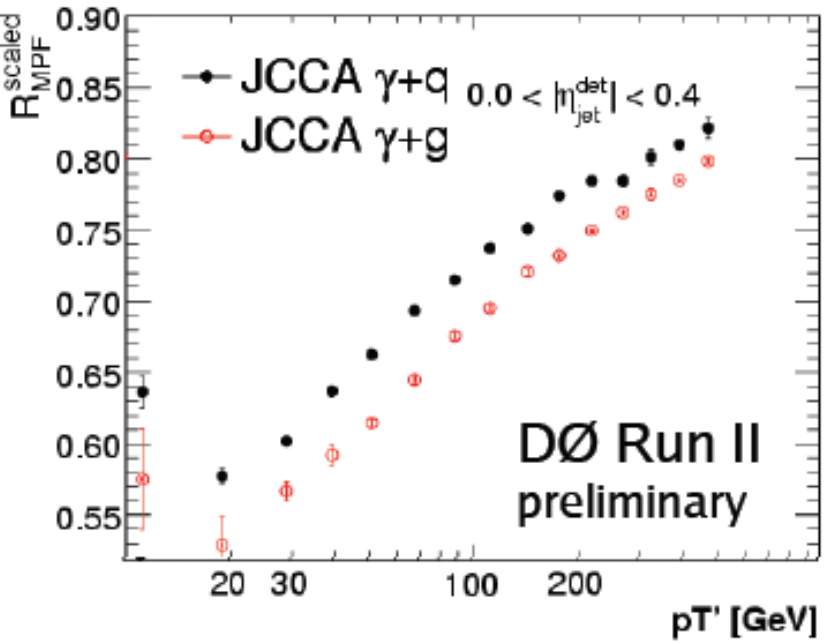


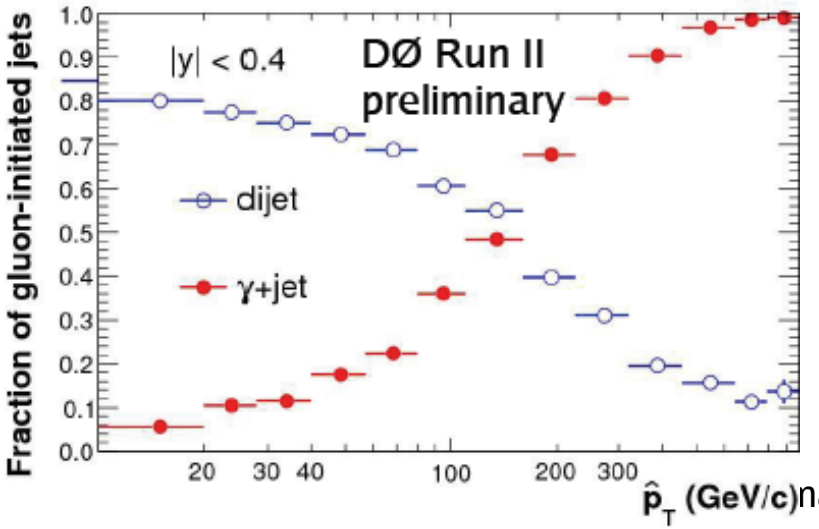


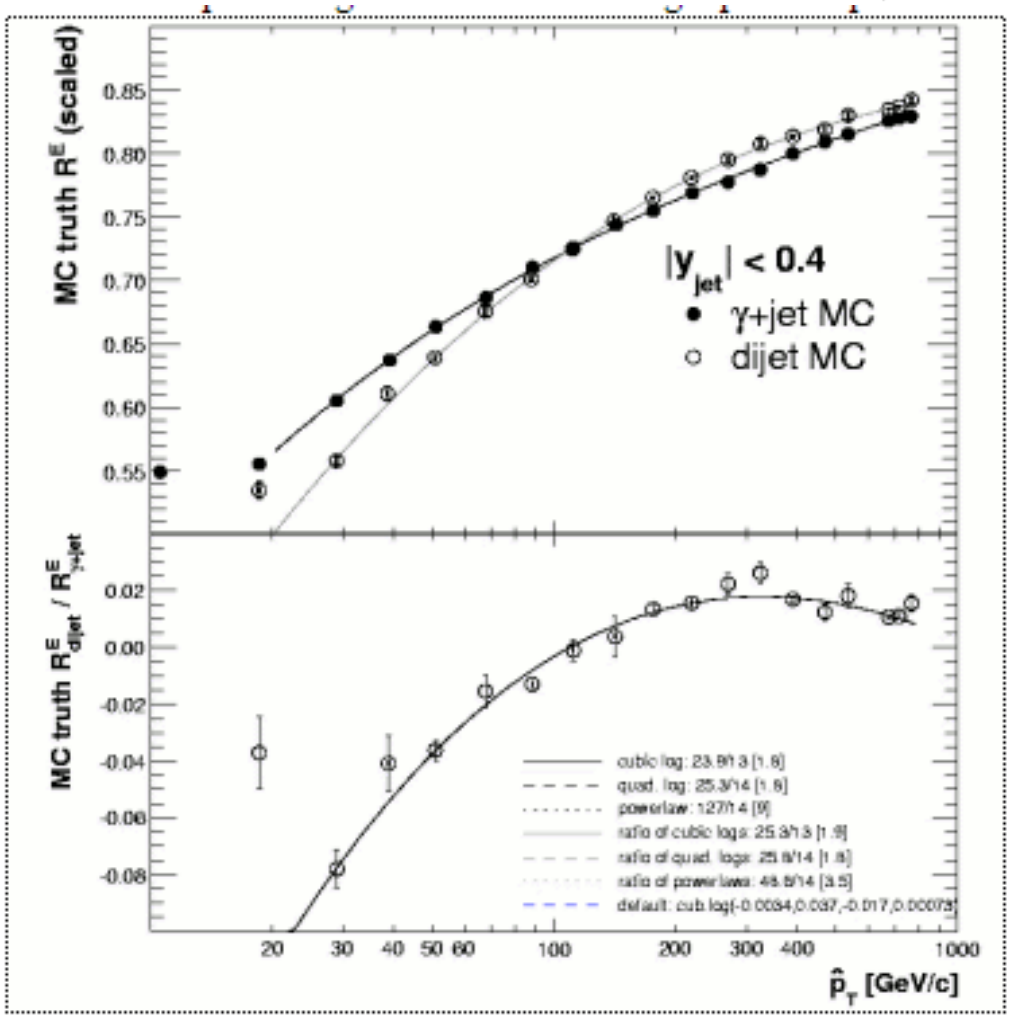
Limits on New Physics

	prior flat in NP Lagrangian		prior flat in NP cross section	
model (parameter)	expected	observed	expected	observed
Quark Comp. (Λ)				
pos. interfer.	$2.75\ ^{+0.43}_{-0.35}$	2.58	$2.58\ ^{+0.28}_{-0.29}$	2.39
neg. interfer.	$2.78\ ^{+0.36}_{-0.41}$	2.54	$2.55\ ^{+0.31}_{-0.33}$	2.35
TeV^{-1} ED (M_C)	$1.64\ ^{+0.23}_{-0.25}$	1.42	$1.51\ ^{+0.16}_{-0.19}$	1.33
ADD LED (M_S)				
GRW	$1.49\ ^{+0.12}_{-0.14}$	1.56	$1.44\ ^{+0.10}_{-0.10}$	1.48
HLZ n=3	$1.77\ ^{+0.14}_{-0.16}$	1.85	$1.71\ ^{+0.11}_{-0.12}$	1.76
HLZ n=4	$1.49\ ^{+0.12}_{-0.14}$	1.56	$1.44\ ^{+0.10}_{-0.10}$	1.48
HLZ n=5	$1.35\ ^{+0.11}_{-0.12}$	1.41	$1.30\ ^{+0.09}_{-0.09}$	1.34
HLZ n=6	$1.25\ ^{+0.11}_{-0.10}$	1.31	$1.21\ ^{+0.08}_{-0.09}$	1.25
HLZ n=7	$1.19\ ^{+0.09}_{-0.11}$	1.24	$1.14\ ^{+0.08}_{-0.08}$	1.18

More on JES


R^{scaled}_{MPF}
JCCA γ+q
JCCA γ+g
$0.0 < |\eta^{det}_{jet}| < 0.4$
DØ Run II
preliminary
pT' [GeV]


Fraction of gluon-initiated jets
|y| < 0.4
DØ Run II
preliminary
dijet
γ+jet
$\hat{p}_T$ (GeV/c)

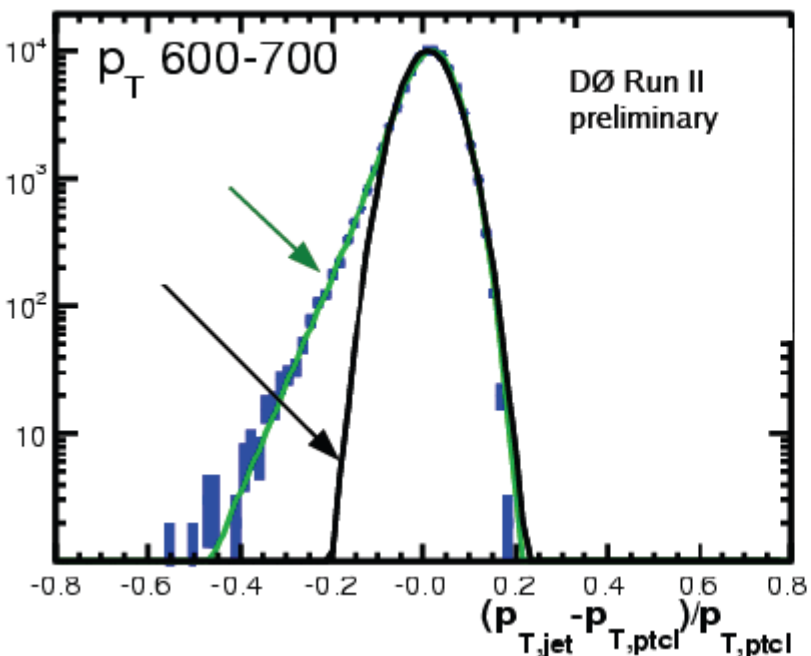

MC truth R^E (scaled)
$|y_{jet}| < 0.4$
γ+jet MC
dijet MC
MC truth $R^E_{dijet} / R^E_{\gamma+jet}$
$\hat{p}_T$ [GeV/c]

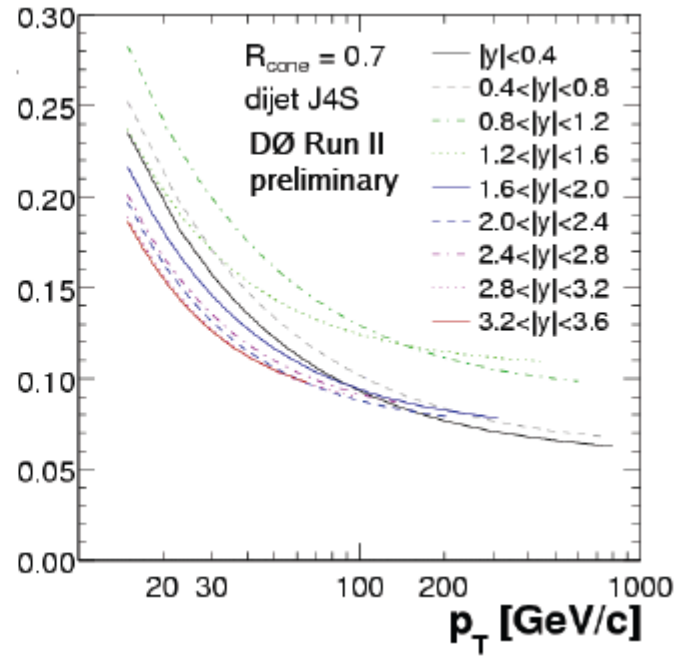
Jet PT resolution

P_T resolution is obtained from Dijet data using P_T asymmetry

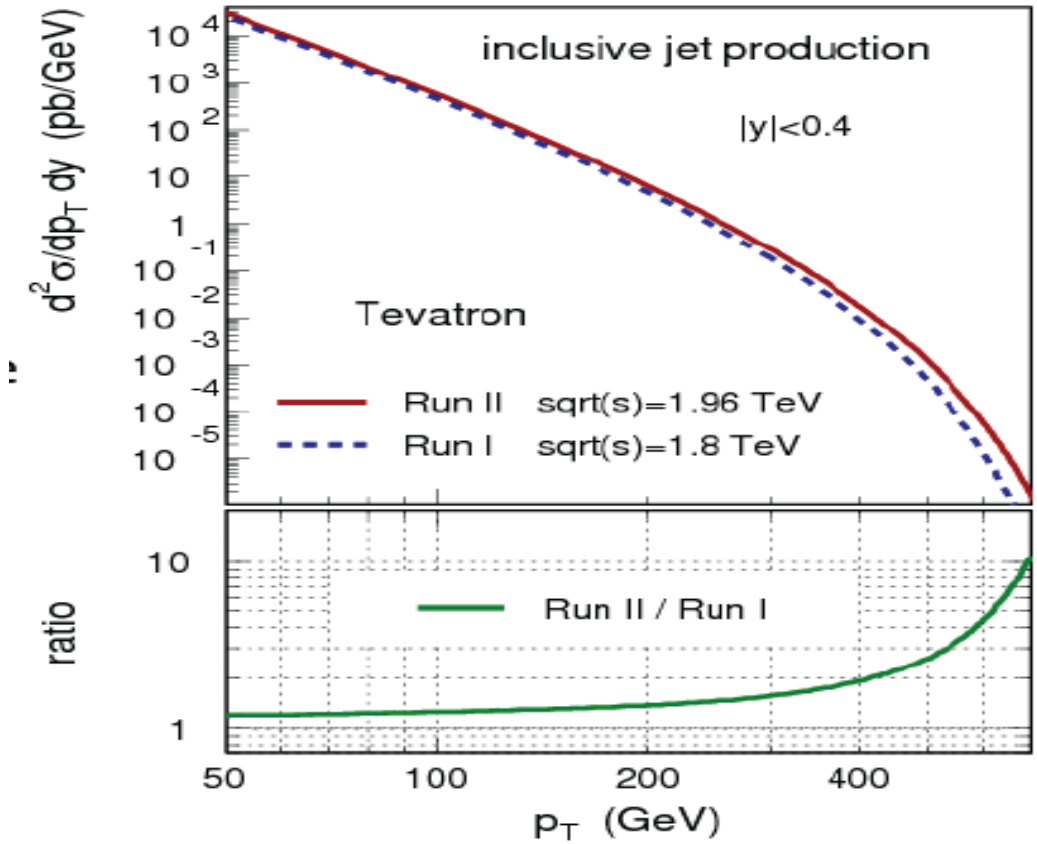
$$A = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \Rightarrow \frac{\sigma_{p_T}}{p_T} = \sqrt{2}\,\sigma_A$$

We took into account non-Gaussian tails for high P_T jets





QCD at Tevatron RunII



Cross-section 5 times higher at Pt > 600 GeV