Self-similarity of jet production & QCD

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JINR

Contents

- Introduction (motivation & goals)
- z-Scaling (ideas, definitions, properties,…)
- Tevatron, RHIC jet data & z presentation
- QCD test of z-scaling
- Conclusions

Motivations & goals

Development of a universal phenomenological description of inclusive cross sections of particles produced at high energies to search for:

- - new physics phenomena in elementary processes
  (quark compositeness, fractal space-time, extra dimensions, ...)
- - signatures of exotic state of nuclear matter
  (phase transitions, quark-gluon plasma, …)
- - complementary restrictions for theory
  (nonperturbative QCD effects, Standard Model, ...)

Analysis of new experimental data on jet production
at Tevatron and RHIC
to verify properties and QCD test of *z*-scaling.

Principles & Symmetries

- Relativity (special, general, scale,…)
- Gauge invariance (U(1), SU(2), SU(3),…)
- Self-similarity (hydro & aerodynamics, point explosions, critical phenomena,...)
- Fractality (scale dependence,…)
- Locality (constituent level of interactions,…)
- …….

Guiding principles to discover new laws in Nature at small scales

		$s^{1/2}$ (GeV)	p_T (GeV/c)	scale (fm)
RHIC	(pp, AA)	50-500	~50	$\sim 4\cdot 10^{-3}$
Tevatron	($\bar{p}p$)	1960	~500	$\sim 4\cdot 10^{-4}$
LHC	(pp, AA)	14000	~5000	$\sim 4\cdot 10^{-5}$

Scaling analysis in high energy interactions

Self-similarity parameter

Scaling variables

- $m_T = \sqrt{p_T^2 + m_0^2}$ — transverse mass
- $x_F = p^*_{\parallel}/p^*_{\parallel max}$ — Feynman variable
- $x_R = E^*/E^*_{max}$ — radial scaling variable
- $\alpha = k_+/p_+$ — light-cone variable
- $x_{Bj} = -q^2/2(Pq)$ — Bjorken variable
- $n/\langle n \rangle$ — KNO variable

➢ These scaling regularities have restricted range of validity

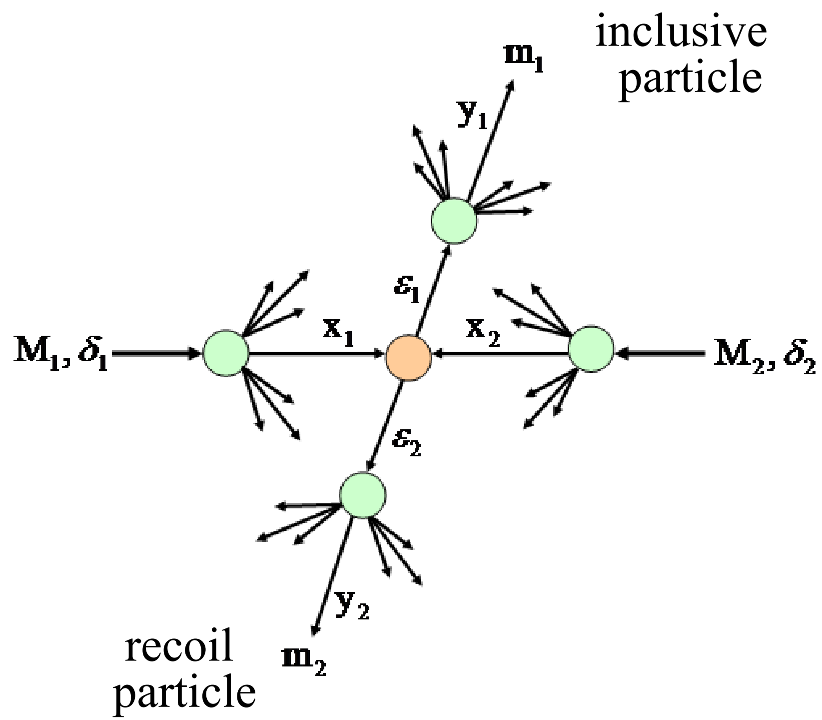
➢ Violation of the scaling laws can be indication of new physics

z-Scaling: it provides universal description of inclusive particle cross sections over a wide kinematical region

(central+fragmentation region, $p_T > 0.5$ GeV/c, $s^{1/2} > 20$ GeV)

Locality of hadron interactions

M.T. & I.Zborovský
Part.Nucl.Lett.312(2006)
PRD75,094008(2007)
Int.J.Mod.Phys.A24,1(2009)



Constituent subprocess

$$(x_1M_1) + (x_2M_2) \Rightarrow (m_1/y_1) + (x_1M_1+x_2M_2+m_2/y_2)$$

Kinematical condition (4-momentum conservation law):

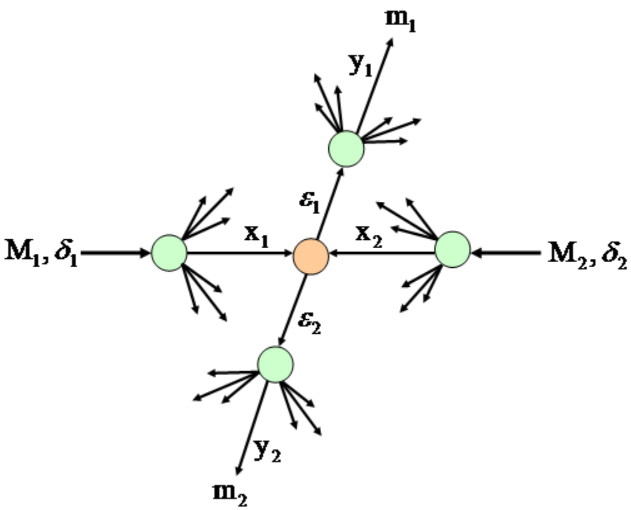
$$(x_1P_1+x_2P_2-p/y_1)^2 = M_X^2$$

Recoil mass: $M_X= x_1M_1+x_2M_2+m_2/y_2$

Scaling variable z

$$z = z_0 \cdot \Omega^{-1}$$

$$z_0 = \frac{s_\perp^{1/2}}{(dN_{ch}/d\eta|_0)^c m}$$



- Ω^{-1} is the minimal resolution at which a constituent subprocess can be singled out of the inclusive reaction
- $s_\perp^{1/2}$ is the transverse kinetic energy of the subprocess consumed on production of m_1 & m_2
- $dN_{ch}/d\eta|_0$ is the multiplicity density of charged particles at $\eta = 0$
- c is a parameter interpreted as a "specific heat" of created medium
- m is an arbitrary constant (fixed at the value of nucleon mass)

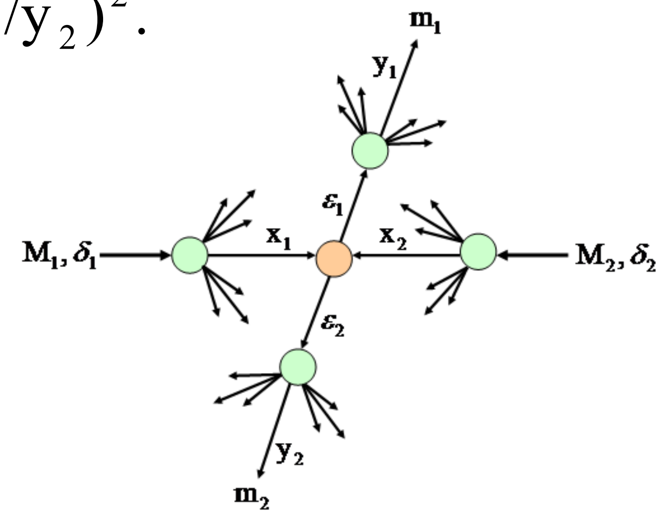
Resolution $\Omega^{-1}(x_1,x_2,y_1,y_2)$

$$\Omega = (1-x_1)^{\delta_1}(1-x_2)^{\delta_2}(1-y_1)^{\varepsilon_1}(1-y_2)^{\varepsilon_2}$$

$\delta_1,\delta_2,\varepsilon_1,\varepsilon_2$ - structural parameters

Principle of minimal resolution: The momentum fractions x_1, x_2 and y_1, y_2 are determined in a way to minimize the resolution Ω^{-1} of the fractal measure $z(\Omega)$ with respect to all constituent subprocesses taking into account the momentum conservation law

$$(x_1P_1+x_2P_2-p/y_1)^2 = (x_1M_1+x_2M_2+m_2/y_2)^2.$$



Extremum conditions:

$$\begin{cases} \partial\Omega/\partial x_1 \,|_{y_1=y_1(x_1,x_2,y_2)} = 0 \\ \partial\Omega/\partial x_2 \,|_{y_1=y_1(x_1,x_2,y_2)} = 0 \\ \partial\Omega/\partial y_2 \,|_{y_1=y_1(x_1,x_2,y_2)} = 0 \end{cases}$$

$pp/p\bar{p}$: $\delta_1=\delta_2\equiv\delta$, $\varepsilon_1=\varepsilon_2\equiv\varepsilon_F$, $m_1=m_2$

Self-similarity of hadron interactions

- The variable *z* is a specific dimensionless combination of quantities characterizing particle production in high energy inclusive reactions.

z is a self-similarity parameter

- The self-similarity is connected with dropping of certain dimensional quantities out of the description of physical phenomena.

- Self-similarity of hadron interactions reflects a property that hadron constituents, their interactions, and formation of the produced particles are similar.

- Multiple interaction of the constituents is an ensemble of mutually similar individual subprocesses.

- These properties are common to various interactions of hadrons and nuclei at high energies.

Fractality of hadron interactions

- Fractality is a specific feature connected with substructure of the interacting objects (hadrons and nuclei).
  It is connected with self-similarity of constituent interactions over a wide scale range.

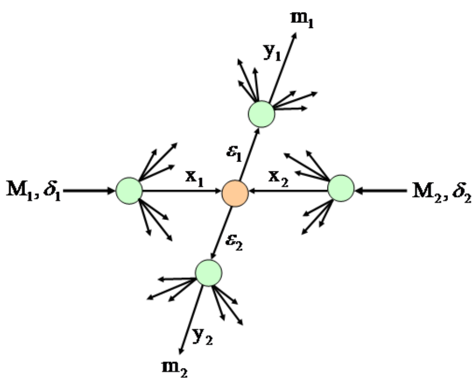
- Fractality of soft processes was investigated by A.Bialas, R.Peshchanski, I.Dremin, E.DeWolf,…

- Fractality of hard processes is reflected in the z-scaling via the variable z.

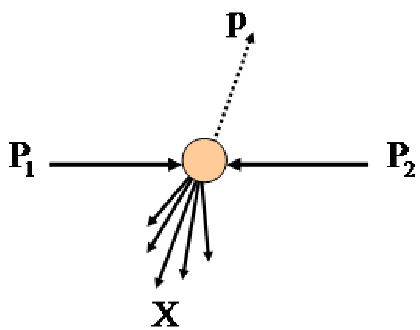
z is a fractal measure attributed to any inclusive reaction:

$$z(\Omega) \to \infty \quad \text{if} \quad \text{resolution} \;\; \Omega^{-1} \to \infty$$

Scaling function $\Psi(z)$



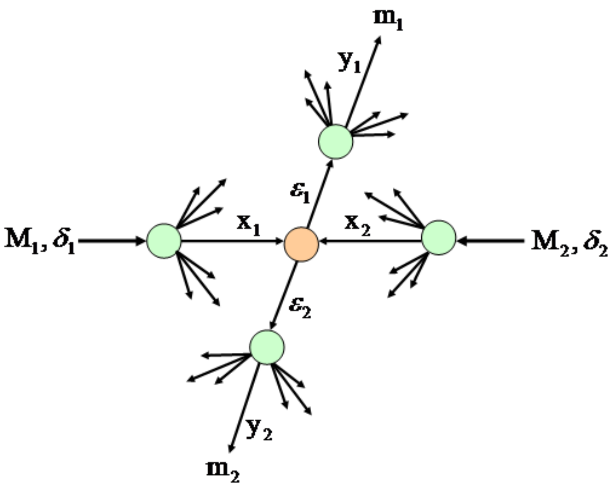
$$\Psi(z) = \frac{\pi}{(dN/d\eta)\cdot\sigma_{inel}} \cdot J^{-1} \cdot E\frac{d^3\sigma}{dp^3}$$



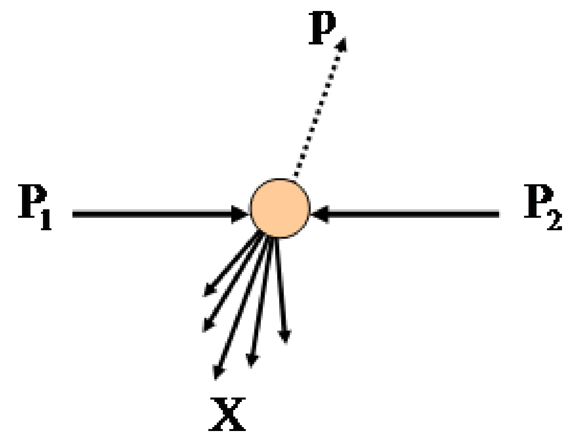
- $s^{1/2}$ is the collision energy.
- $dN/d\eta$ is the pseudorapidity multiplicity density at η.
- σ_{inel} is the inelastic cross section.
- $J(z,\eta; p_T^2, y)$ is the corresponding Jacobian (y-rapidity).
- $Ed^3\sigma/dp^3$ is the inclusive cross section.

The variable z and the function $\Psi(z)$ are expressed via momenta and masses of the colliding and produced particles, multiplicity density, and inclusive cross section.

Normalization of Ψ(z)



$$\int_0^\infty \Psi(z)dz = 1$$

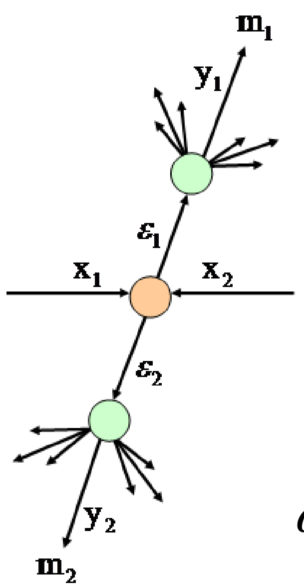


$$\Psi(z) = \frac{\pi \cdot s}{(dN/d\eta) \cdot \sigma_{inel}} \cdot J^{-1} \cdot E \frac{d^3\sigma}{dp^3} \quad \Longleftrightarrow \quad \int E \frac{d^3\sigma}{dp^3} dy d^2 p_\perp = \sigma_{inel} \cdot N$$

The scaling function Ψ(z) is probability density
to produce an inclusive particle
with the corresponding fractal measure z.

Transverse kinetic energy $s_{\perp}^{1/2}$

$$s_{\perp}^{1/2} = \underbrace{y_1(s_{\lambda}^{1/2} - M_1\lambda_1 - M_2\lambda_2) - m_1}_{\text{energy consumed for the inclusive particle } m_1} + \underbrace{y_2(s_{\chi}^{1/2} - M_1\chi_1 - M_2\chi_2) - m_2}_{\text{energy consumed for the recoil particle } m_2}$$



Decomposition: $x_{1,2} = \lambda_{1,2} + \chi_{1,2}$

$$\lambda_{1,2} = \kappa_{1,2}/y_1 + \nu_{1,2}/y_2$$

$$\kappa_{1,2} = \frac{(P_{2,1}p)}{(P_2P_1)}, \quad \nu_{1,2} = \frac{M_{2,1}m_2}{(P_2P_1)}$$

$$\chi_{1,2} = (\mu_{1,2}^2 + \omega_{1,2}^2)^{1/2} \mp \omega_{1,2}$$

$$\mu_{1,2}^2 = \alpha^{\pm 1}(\lambda_1\lambda_2 + \lambda_0)\frac{1 - \lambda_{1,2}}{1 - \lambda_{2,1}}$$

$$\omega_{1,2} = \mu_{1,2}U, \quad U = \frac{\alpha - 1}{2\sqrt{\alpha}}\xi, \quad \alpha = \frac{\delta_2}{\delta_1}$$

$$\lambda_0 = \bar{\nu}_0/y_2^2 - \nu_0/y_1^2$$

$$\xi^2 = (\lambda_1\lambda_2 + \lambda_0)/[(1-\lambda_1)(1-\lambda_2)]$$

$$\bar{\nu}_0 = \frac{0.5m_2^2}{(P_1P_2)}, \quad \nu_0 = \frac{0.5m_1^2}{(P_1P_2)}$$

$$s_{\lambda} = (\lambda_1 P_1 + \lambda_2 P_2)^2$$

$$s_{\chi} = (\chi_1 P_1 + \chi_2 P_2)^2$$

Properties of z-scaling

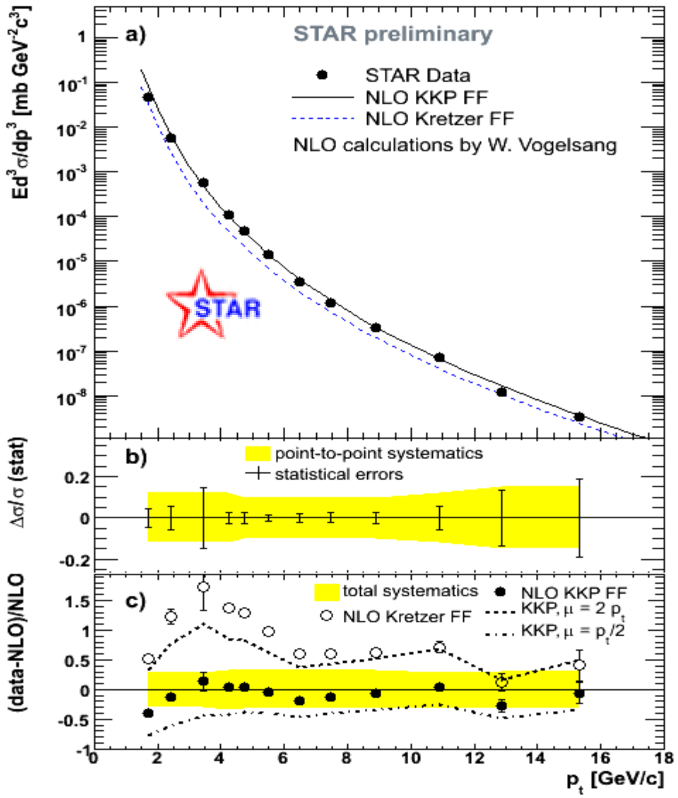
- Energy independence of $\Psi(z)$ ($s^{1/2} > 20$ GeV)
- Angular independence of $\Psi(z)$ ($\theta_{cms} = 3^0$-90^0)
- Multiplicity independence of $\Psi(z)$ ($dN_{ch}/d\eta=1.5$-$26.$)
- Power law, $\Psi(z) \sim z^{-\beta}$, at high z ($z > 4$)
- Flavor independence of $\Psi(z)$ (π,K,φ,Λ,..,D,J/ψ,B,†,…)
- Saturation of $\Psi(z)$ at low z ($z<0.1$)

These properties reflect self-similarity, locality,
and fractality of the hadron interaction at a constituent level.
It concerns the structure of the colliding objects, interactions
of their constituents, and fragmentation process.

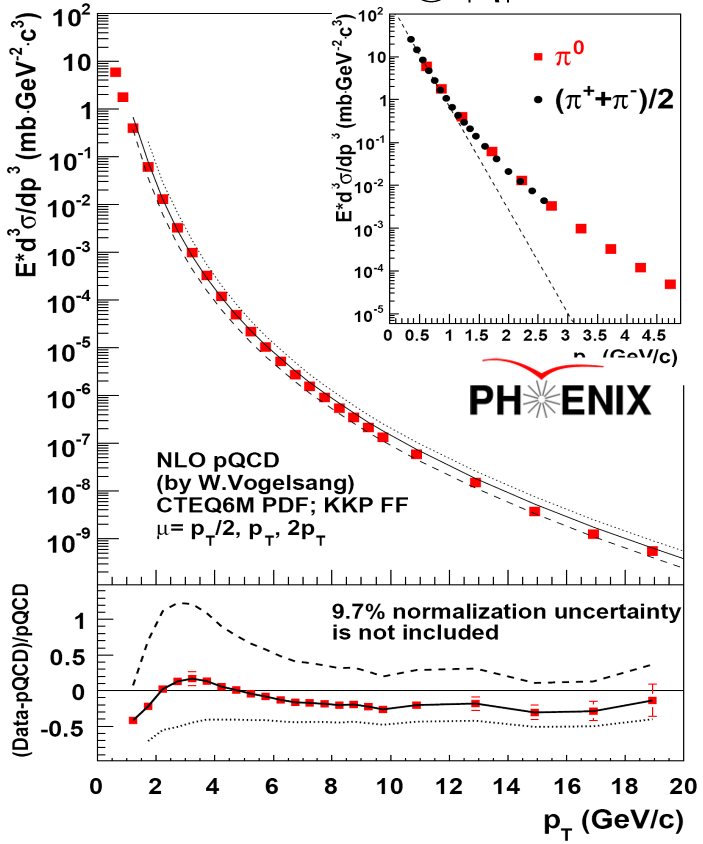
M.T. & I.Zborovský, Part.Nucl.Lett.312(2006); PRD75,094008(2007); Int.J.Mod.Phys.A24,1(2009)

Spectra of π^0 mesons in pp at RHIC

200 GeV @ |η|<1.



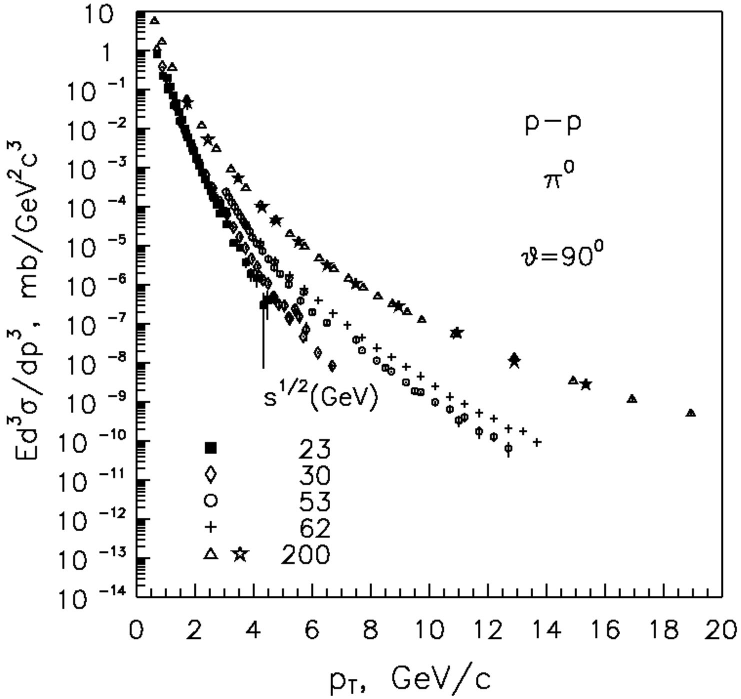
200 GeV @ |η|<0.35

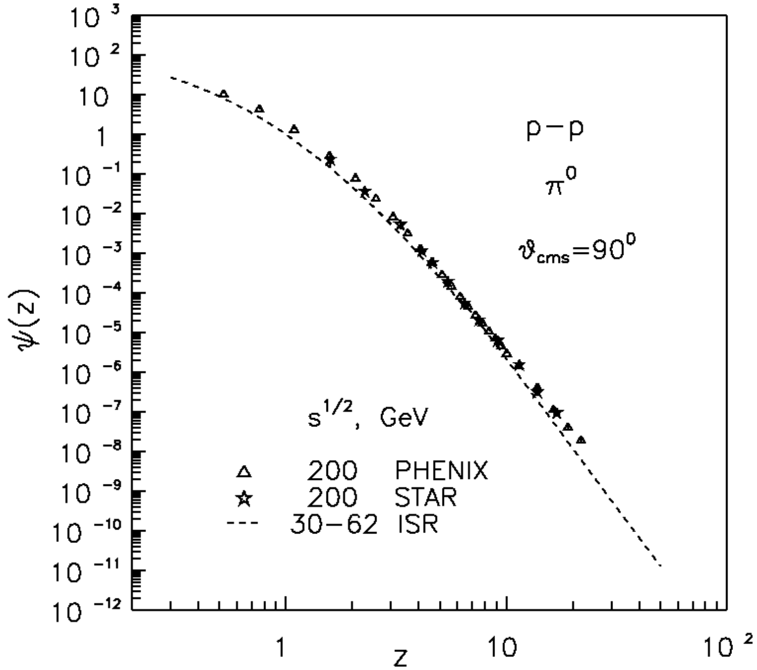


- Good agreement between NLO pQCD calculations and data
- Confirmation that pQCD can be used to extract PDFs from RHIC data

Spectra of π^0 mesons in pp at ISR & RHIC

M.T.
O.Rogachevsky
T.Dedovich
J. Phys. G26
1671 (2000)



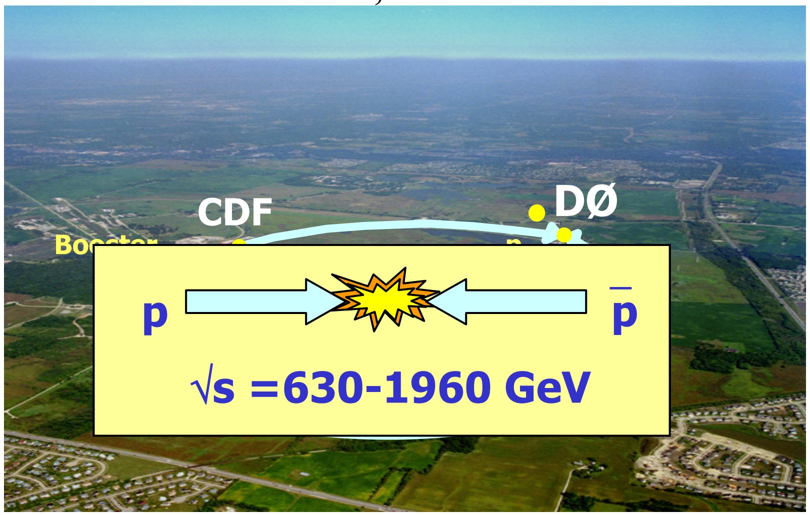


- Test of pQCD + phenomenology (PDFs, FFs, μ_R,…)
- Test of z-scaling + exp. uncertainties (σ_{in}, $dN_{ch}/d\eta$,...)

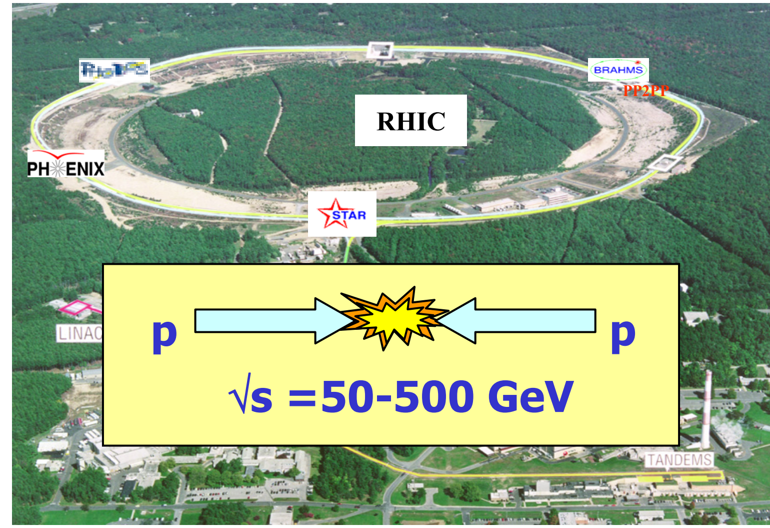
Self-similarity of hadron production in pp at high energies

Jets at Hadron Colliders

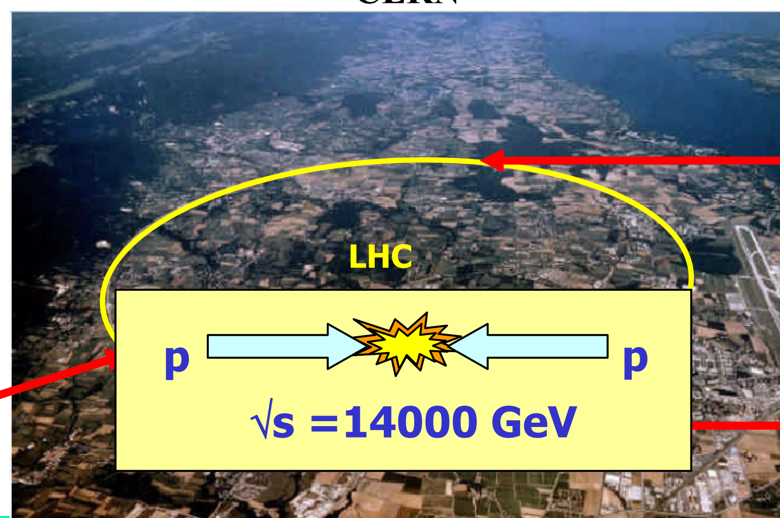
Batavia, Illinois



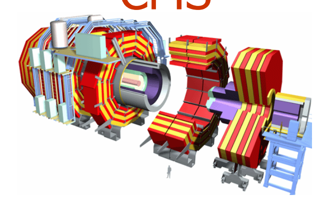
Upton, Long Island, New York



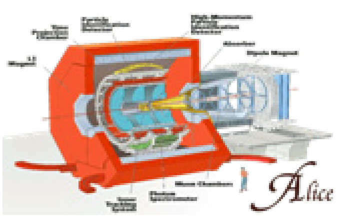
CERN



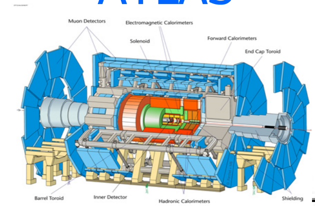
CMS



ALICE



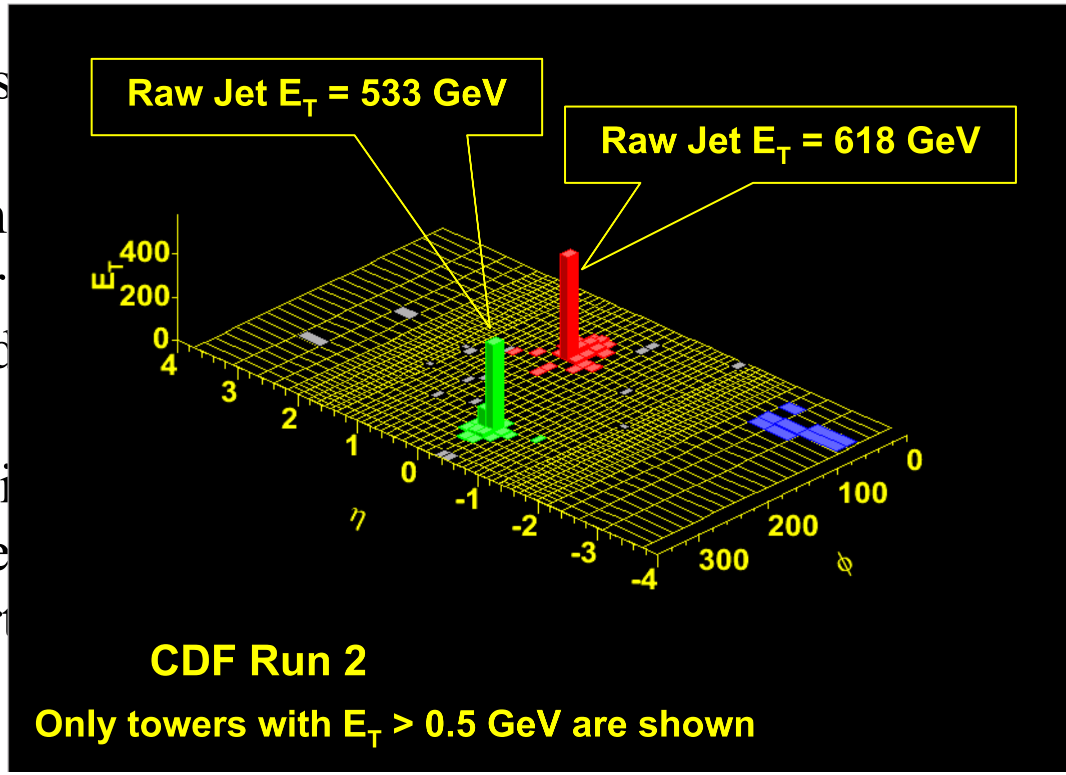
ATLAS



Era of QCD precision measurements at hadron colliders

What is jet ?

- Jet is ... ime.
- Jet is ... nts.
- Defin ... or under ... d gluon to had...
- QCD ... CCFM equati...
- Large ... due to uncert ... n function.

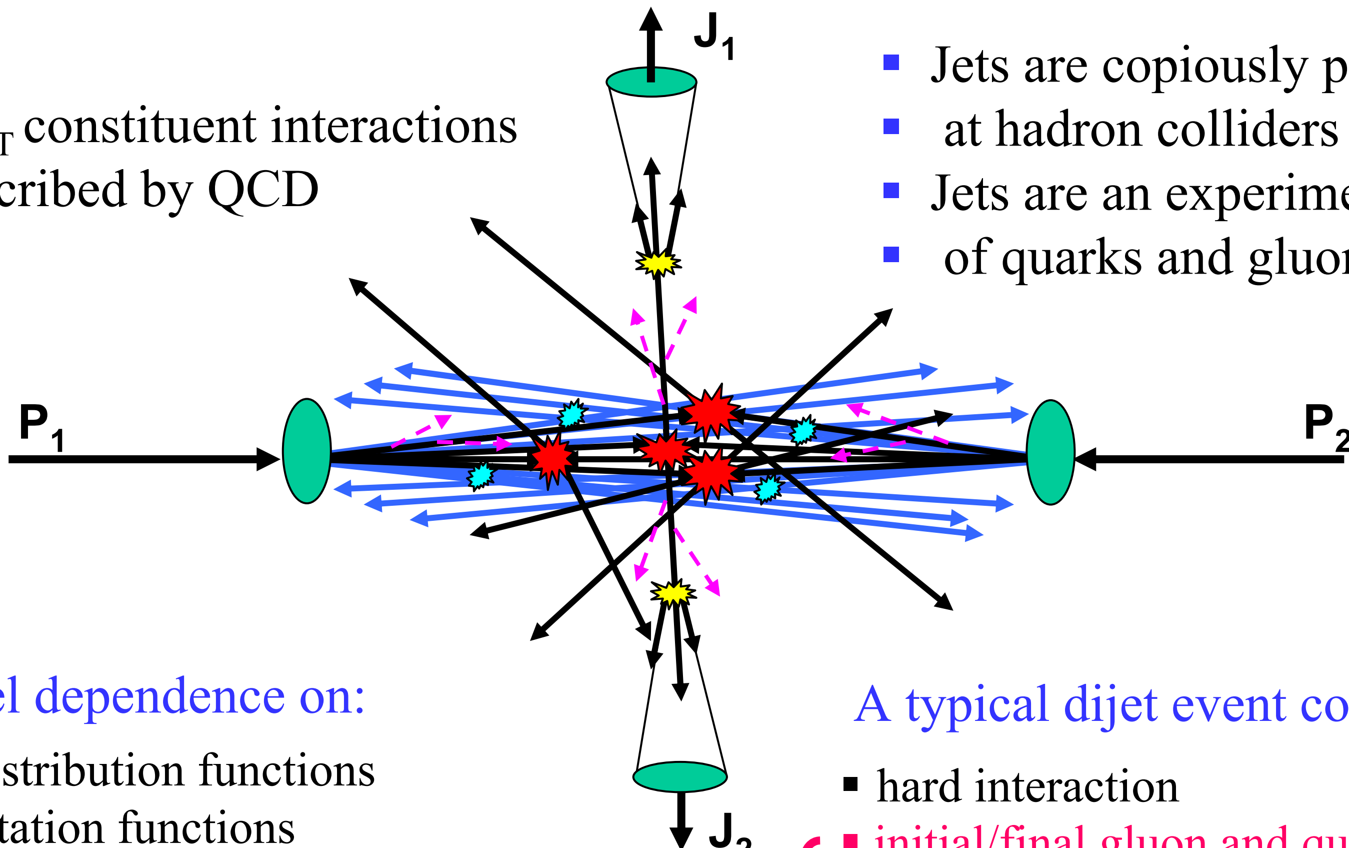


Experimental verification and QCD test of *z*-scaling of jet production in hadron collisions to search for new phenomena and establish new constraints (gluons, Q^2-evolution etc.) on theory.

Jet Topology

- High-p_T constituent interactions are described by QCD

- Jets are copiously produced
- at hadron colliders
- Jets are an experimental signature
- of quarks and gluons



Model dependence on:

- Parton distribution functions
- Fragmentation functions
- Higher order corrections
- Renormalization, factorization and fragmentation scales
- QCD evolution scheme

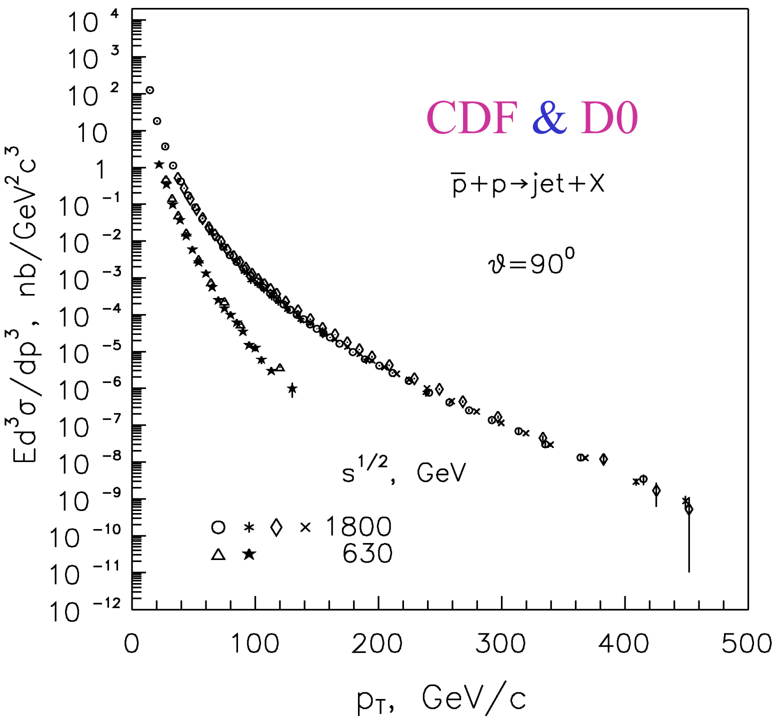
A typical dijet event consists of:

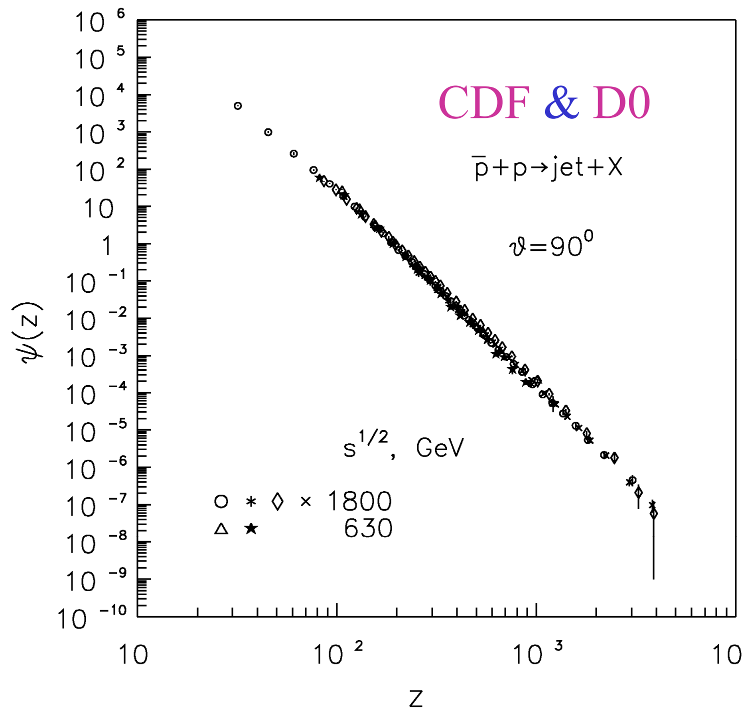
- hard interaction
- initial/final gluon and quark radiation
- secondary semi-hard interactions
- interaction between remnants
- hadronization
- jet formation

Underlying event

z-Scaling & Jets at Tevatron in Run I

Energy dependence of jet production in $\bar{p}p$ collisions





M. T.
T. Dedovich

Int. J. Mod. Phys. A15 (2000) 3495

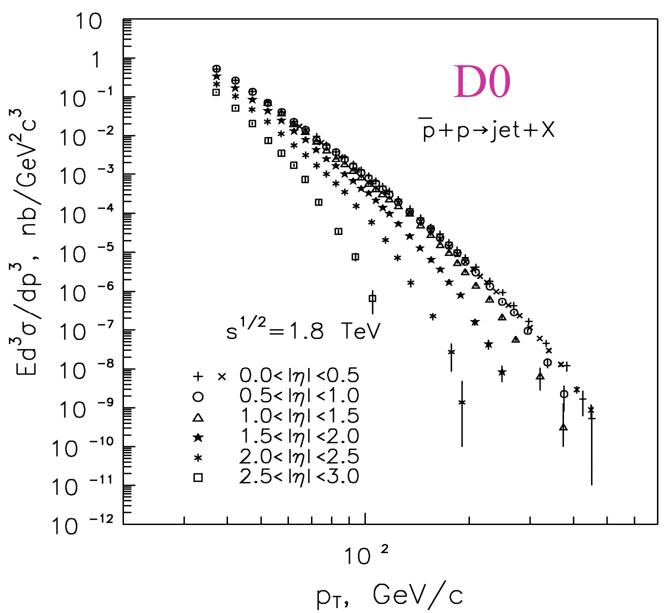
Data are in agreement with each other in the momentum range p_T =10 - 450 GeV/c.

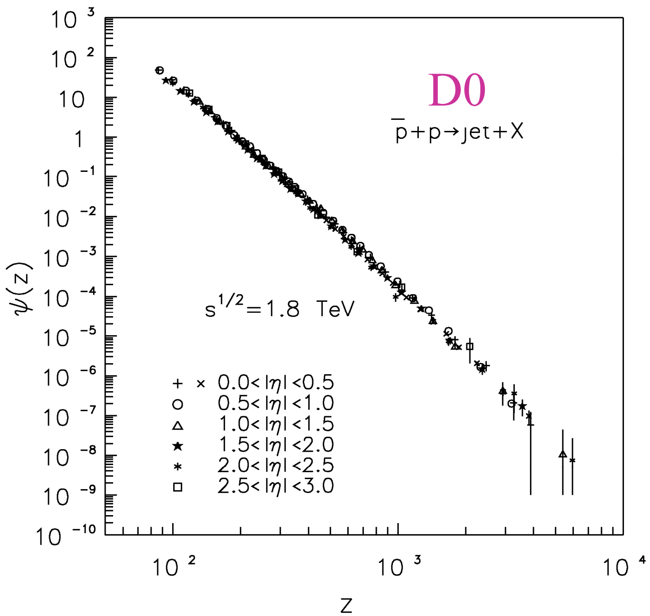
- Energy independence of $\Psi(z)$
- Power law, $\Psi(z) \sim z^{-\beta}$

Self-similarity of jet production in proton-antiproton collisions

z-Scaling & Jets at Tevatron in Run I

Angular dependence of jet production in $\bar{p}p$ collisions





M. T.
T. Dedovich
Int. J. Mod. Phys. A15 (2000) 3495

Phys.At. Nucl. 68, 404 (2005)

D.Elvira & D0 Collaboration

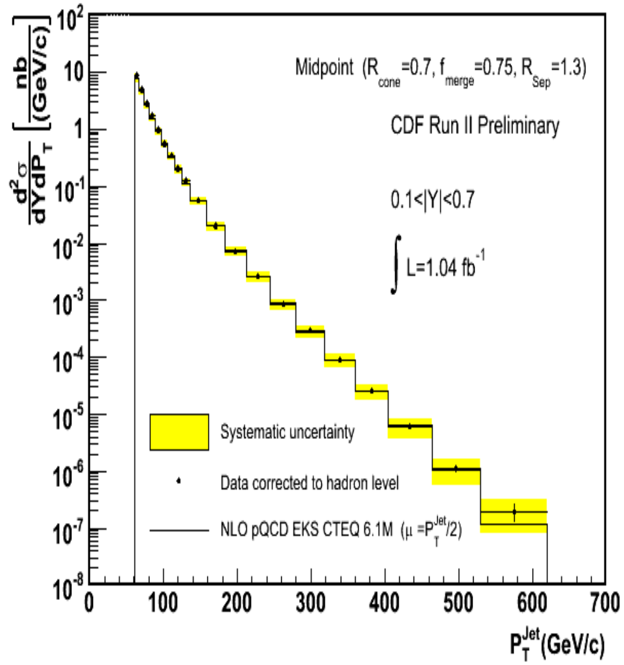
PhD Thesis, Universodad de Buenos Aires, Argentina (1995).

- Angular independence of $\Psi(z)$
- Power law, $\Psi(z) \sim z^{-\beta}$

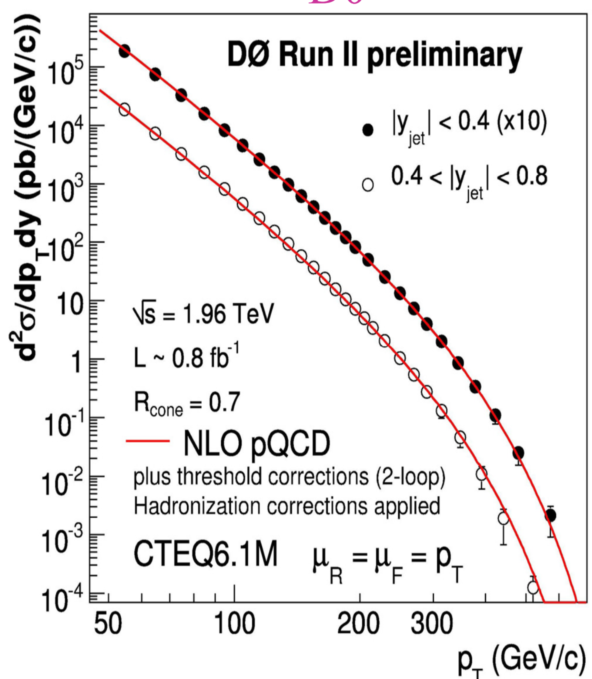
Self-similarity of jet production in proton-antiproton collisions

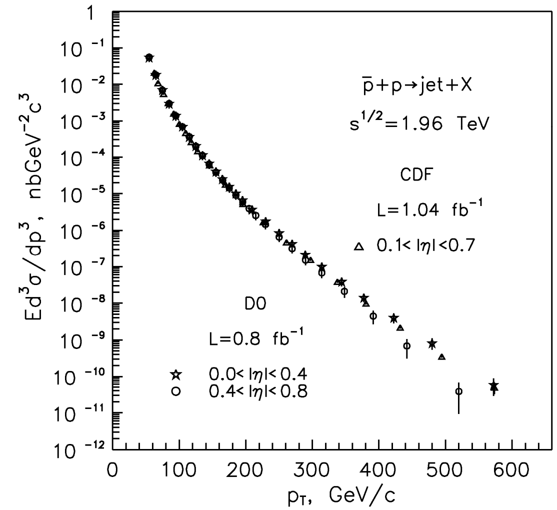
z-Scaling & Jets at Tevatron in Run II

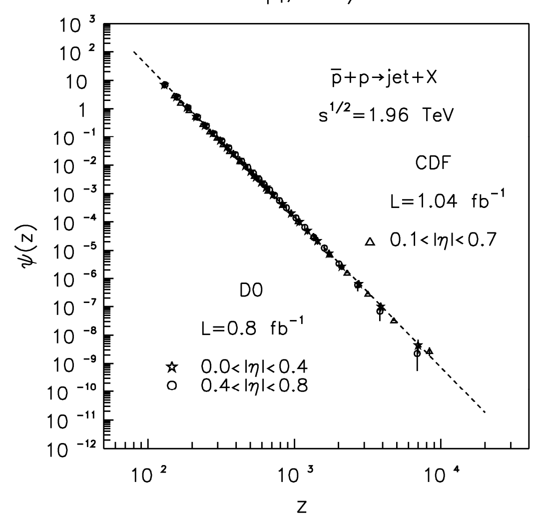
CDF



D0







- Spectra are measured up to 600 GeV/c !!!
- CDF & DØ data are described by NLO QCD
- CDF & DØ confirm z-scaling of jet production in $\bar{p}p$

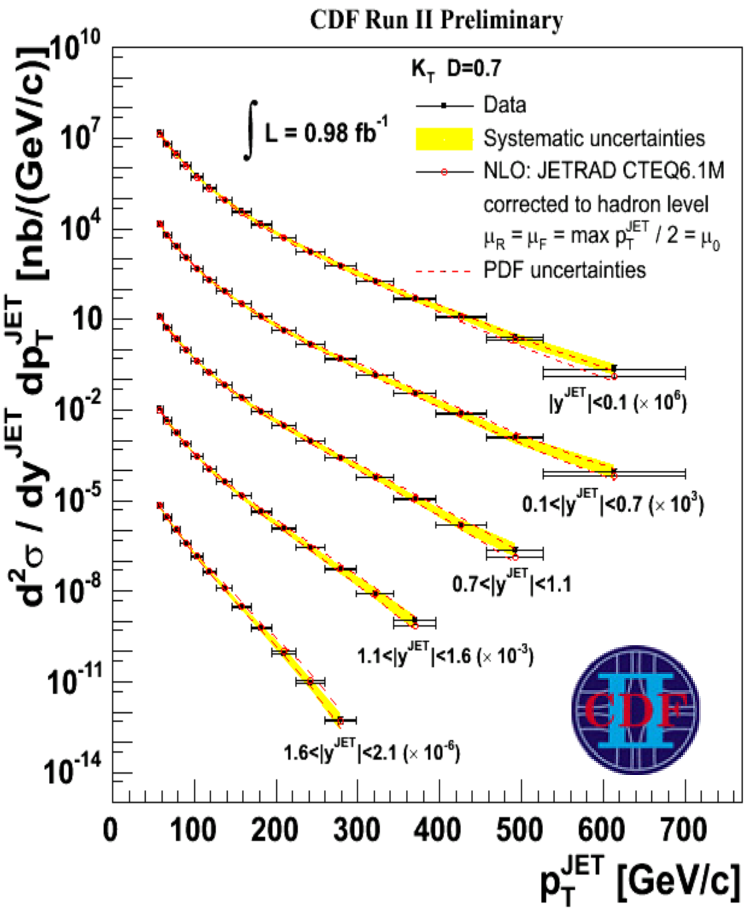
CDF Collaboration
A.Abulencia et al.,
Phys.Rev.Lett.96:122001,2006.

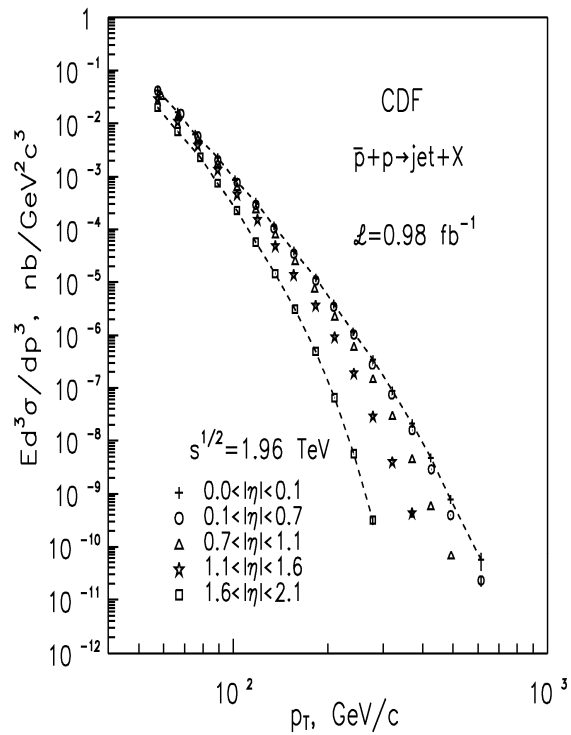
DØ Collaborations
J.Commin et al.,
DIS2007, April 16-20,
2007,Munich,Germany

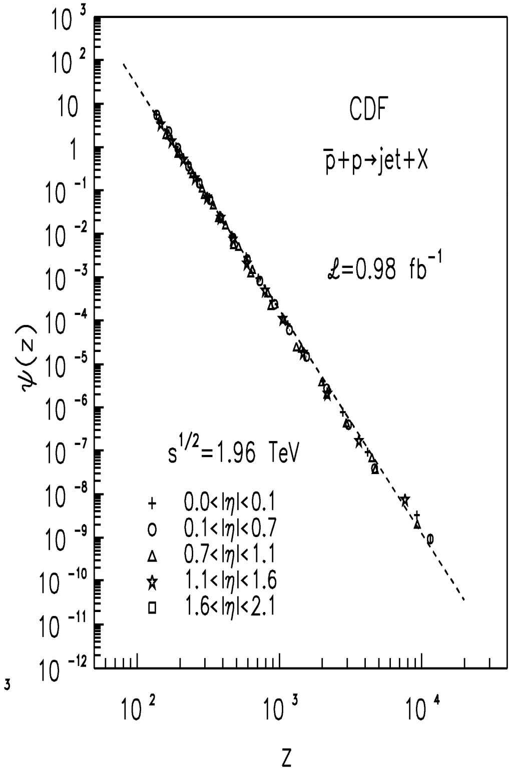
MT & T.Dedovich
Phys.At. Nucl. 68, 404 (2005)

JINR

z-Scaling & Jets at Tevatron in Run II





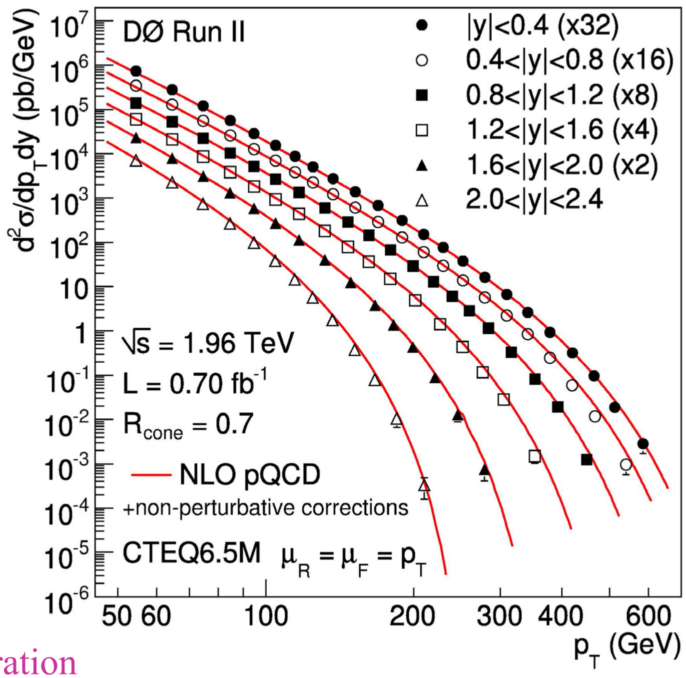


CDF collaboration
A.Abulencia et al.,
Phys.Rev.D75:092006,2007

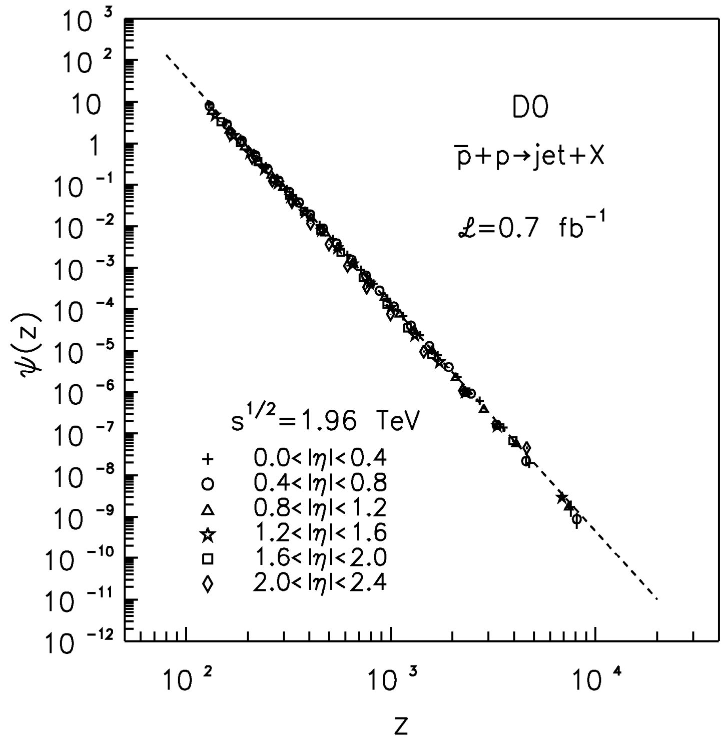
- Angular independence of $\Psi(z)$
- Power law, $\Psi(z) \sim z^{-\beta}$

Tevatron confirms properties of z-scaling in jet production in $\bar{p}p$

z-Scaling & Jets at Tevatron in Run II



D0 Collaboration
V.M.Abazov et al.,
Phys.Rev.Lett.101,062001(2008)



Jet transverse spectra are measured up to 600 GeV/c

- Angular independence of $\Psi(z)$
- Power law $\Psi(z) \sim z^{-\beta}$

Self-similarity of jet production in proton-antiproton collisions

First jets in pp at STAR

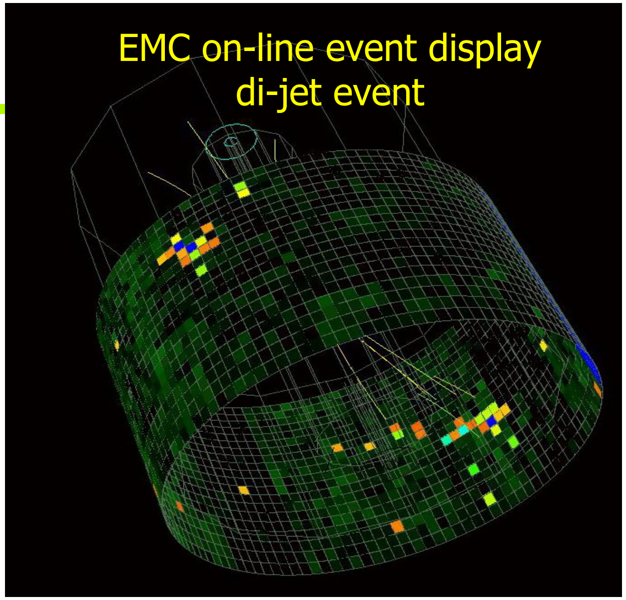
TPC for charged hadrons+EMC for e-m showers

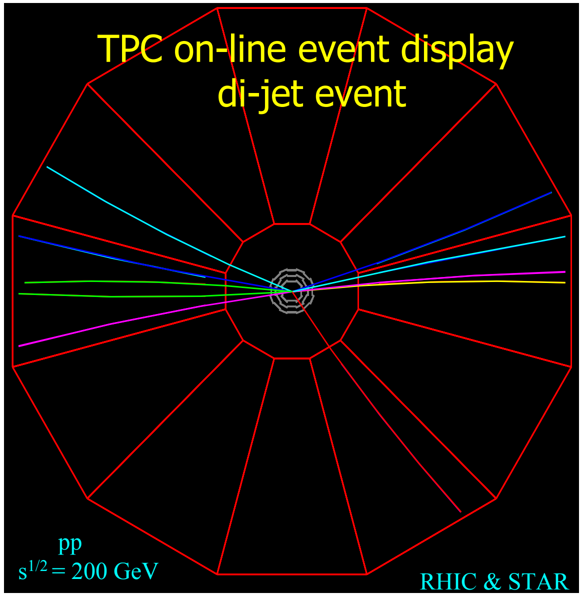
1) Jets reconstruction - midpoint cone algorithm (Tevatron II)
seed energy = 0.5 GeV, cone angle R = 0.4 in $\eta-\phi$
splitting/merging fraction f=0.5

2) Trigger used in this analysis - High Tower:
E_T > 2.4 GeV deposited in one tower ($\Delta\eta$ x $\Delta\phi$)=(0.05 x 0.05)
+ additional requirement of BBC coincidence.

3) Cuts on:

- charged tracks $|\eta| < 1.6$ and p_T >0.1 GeV/c
- jets: p_T jet > 5 GeV/c , 0.2< jet η (det) <0.8
- background: E_{jet}(neutral)/E_{jet}(total)< 0.9 (2004) and < 0.8 (2003)
- |z-vertex| < 75cm (2003) and < 60cm (2004)
- tower E_T>3.5 GeV software threshold (only 2004 cross section)



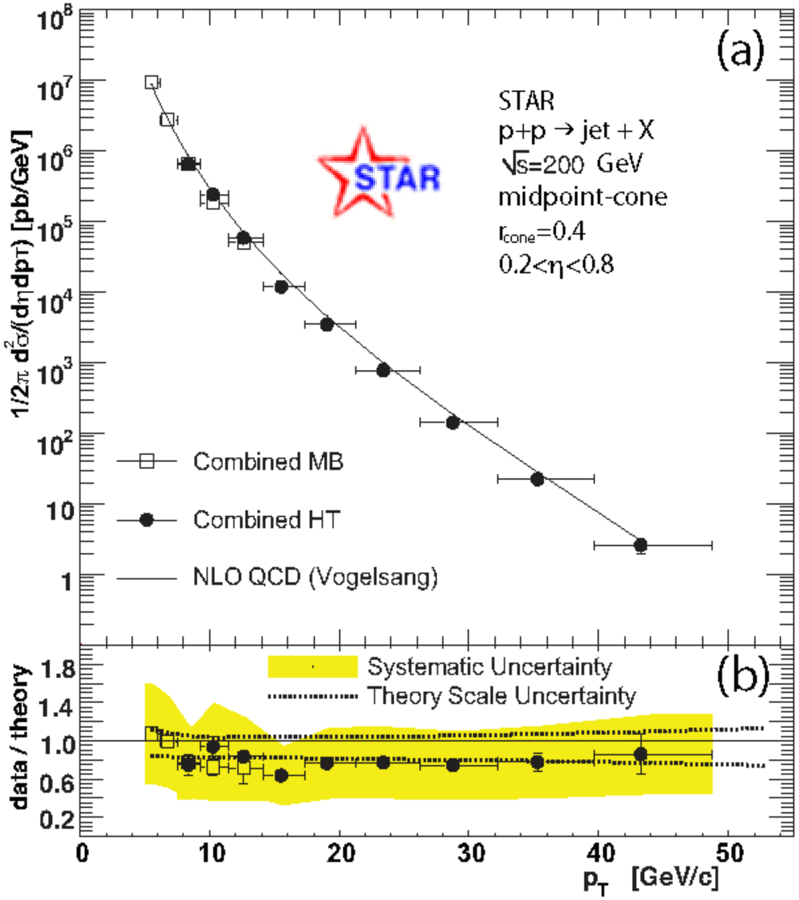


M.Miller, QM'05, NPD2005, PANIC'05, hep-ex/0604001

Hard scattering at RHIC and NLO pQCD

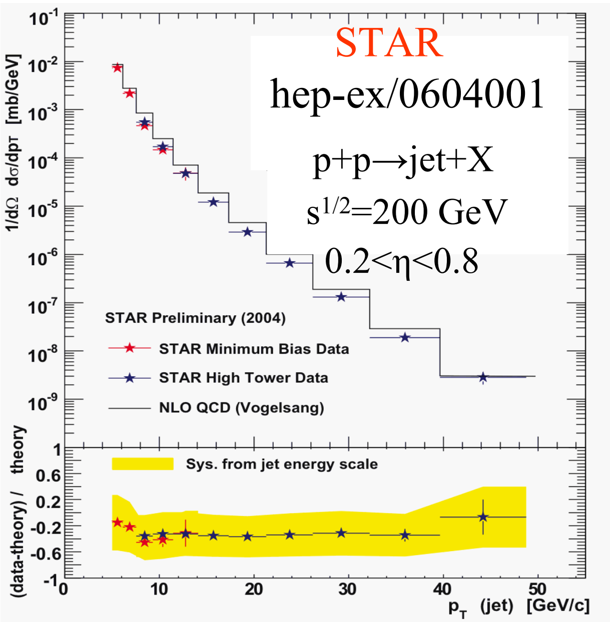
Jets at STAR

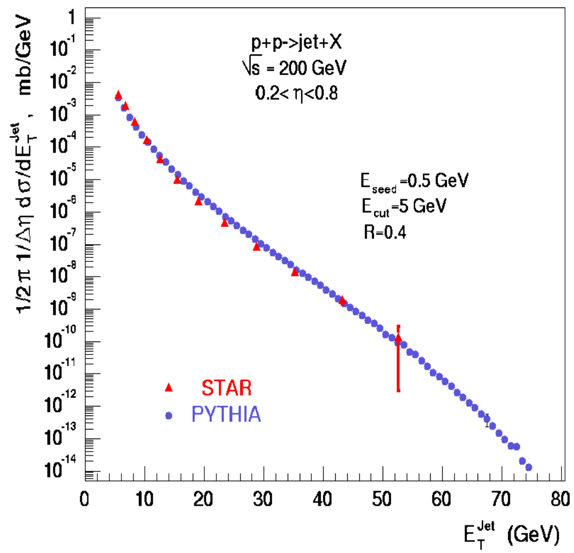
STAR Collab.,
B.I. Abelev et al.,
PRL97,252001(2006)
hep-ex/0608030

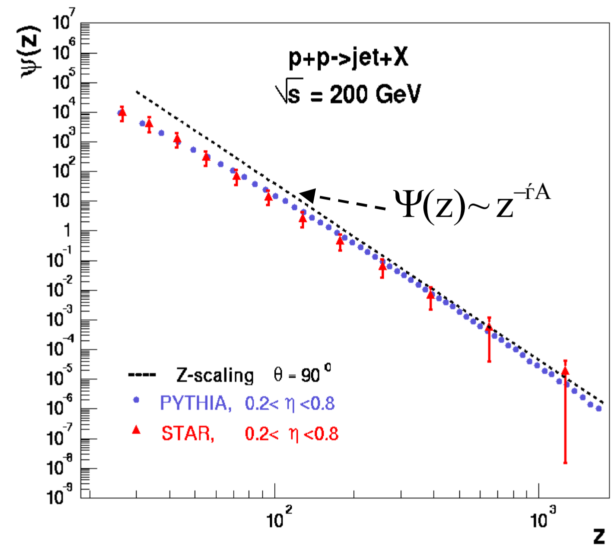


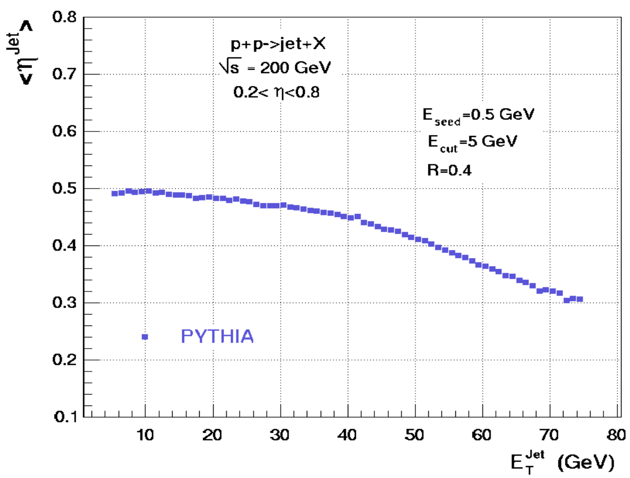
- Good agreement with NLO pQCD
- pQCD should be broadly applicable at RHIC

z-Scaling & Jets at RHIC









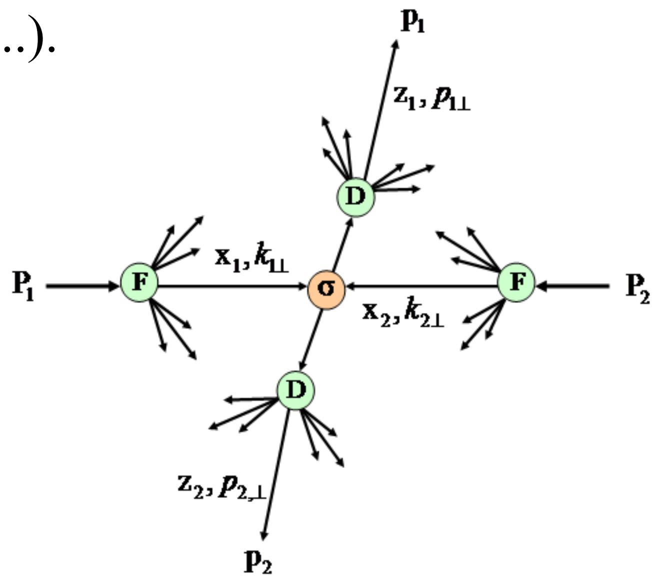
- MC results are in agreement with STAR data.
- Dependence of spectra on rapidity range ($0.2<\eta<0.8$ & $|\eta|<1.$).
- The slope parameter β of $\Psi(z)$ is found to be 6.01 ± 0.06 over the range $E_T^{Jet}=25\text{-}60$ GeV.
- Sensitivity of $\Psi(z)$ at high z to E_T^{Jet} (η^{Jet}).

T.Dedovich , PhD Thesis, JINR,Dubna, 2007

QCD test of z-scaling

- QCD is basic theory for calculations of hadron interactions in terms of quarks and gluons.
- Perturbative expansion is under control (LO, NLO, ...).
- Non-perturbative effects – PDFs, FFs, μ_R, μ_F, μ_H, are partially under control.
- Correct extrapolation in low and high (x,p_T) range is restricted by available data (e^+e^-, DIS,…).
- Additional constraints on PDFs and FFs are needed to confirm their universality (gluons, flavor, …).
- Soft regime (multiple interactions, …).

Hadron interaction at a constituent level



$$F_h^q(x_1, k_{1\perp}, \mu_F)$$
$$\sigma_{qq}(x_1, x_2, k_{1\perp}, k_{2\perp}, \mu_R)$$
$$D_q^h(z_1, p_{1\perp}, \mu_H)$$

- A lot of data are analyzed in framework of z–presentation.
- New confirmations from RHIC and Tevatron are obtained.
- Can NLO QCD describe z-scaling in soft and hard regime ?
- …..

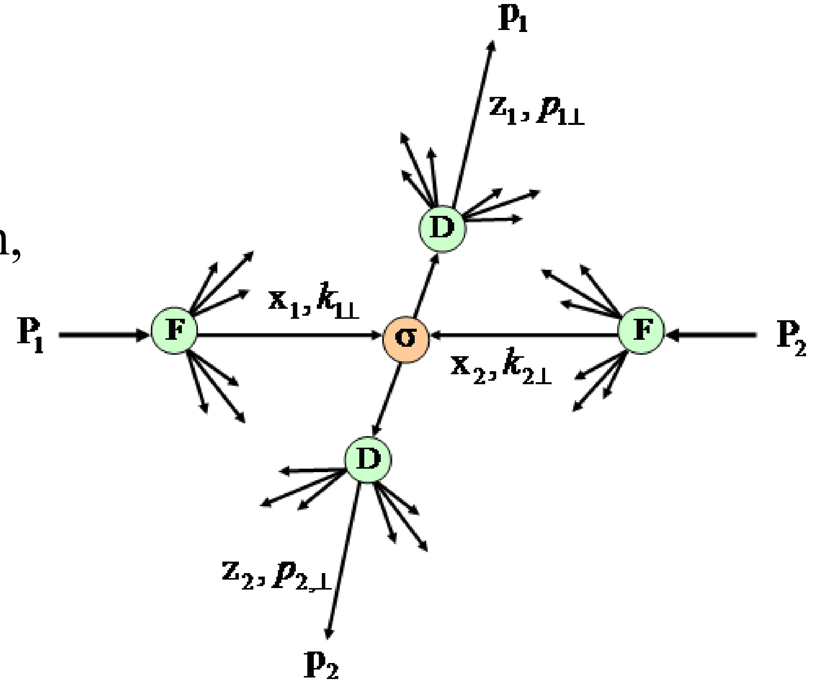
NLO QCD ingredients

- NLO QCD jet production code
  S.D.Ellis, Z.Kunszt, D.Soper
  PRD40,2188(1989); PRL69,1496(1992); PRD46,192 (1992)

- Parton Distribution Functions
  CTEQ6M – J.Pumplin, D.R.Stump, J.Huston, H.L.Lai, P.Nadolski, W.K.Tang
  JHEP 0207 (2002) 012
  MRST01 – A.D.Martin, R.G.Roberts, W.J.Stirling, R.S.Thorne
  Eur. Phys. J. C23 (2002) 73

- Scales $\mu = c \cdot p_T$, $c = 0.5, 1., 2.$
  – Renormalization μ_R
  – Factorization μ_F
  – Hadronization μ_H

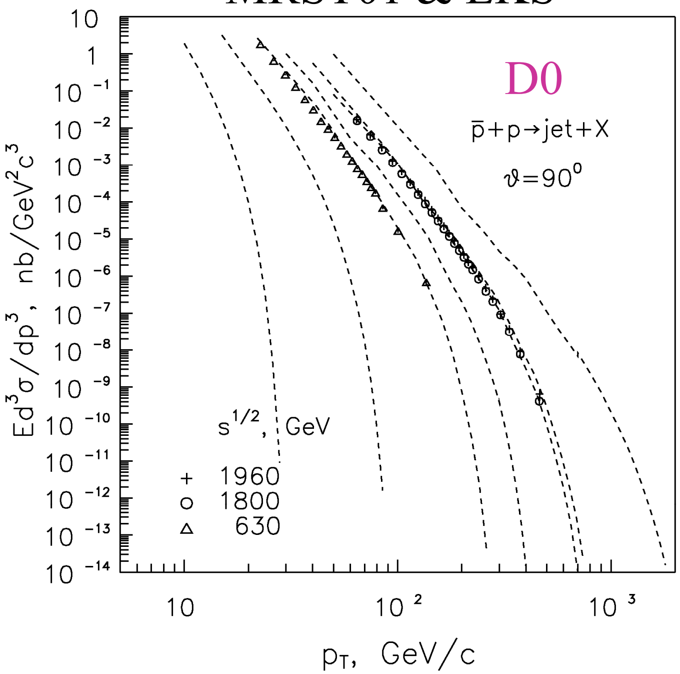
Hadron interaction at a constituent level

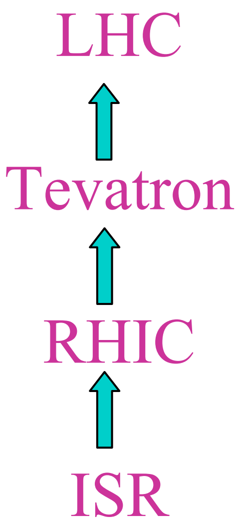


$$F_h^q(x_1, \mu_F)$$
$$\sigma_{qq}(x_1, x_2, k_{1\perp}, k_{2\perp}, \mu_R)$$
$$D_q^h(z_1, \mu_H)$$

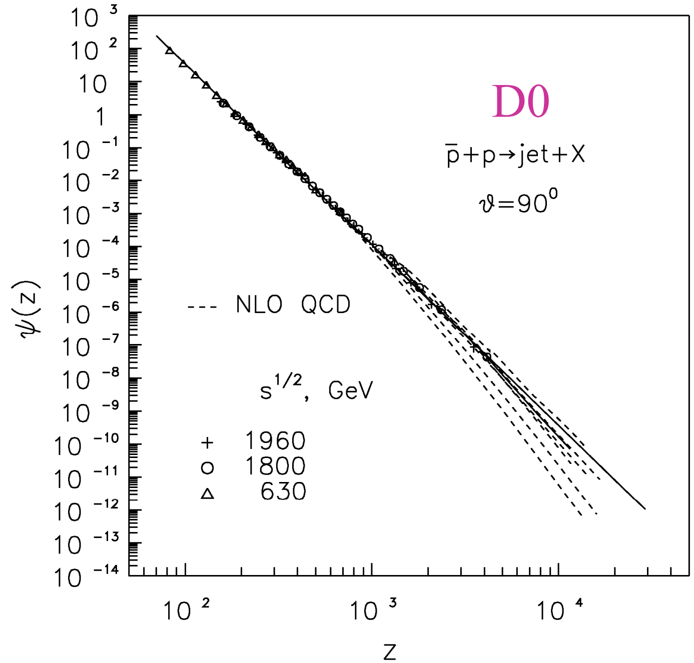
Jet NLO QCD spectra in $\bar{p}p$ & PDFs

MRST01 & EKS



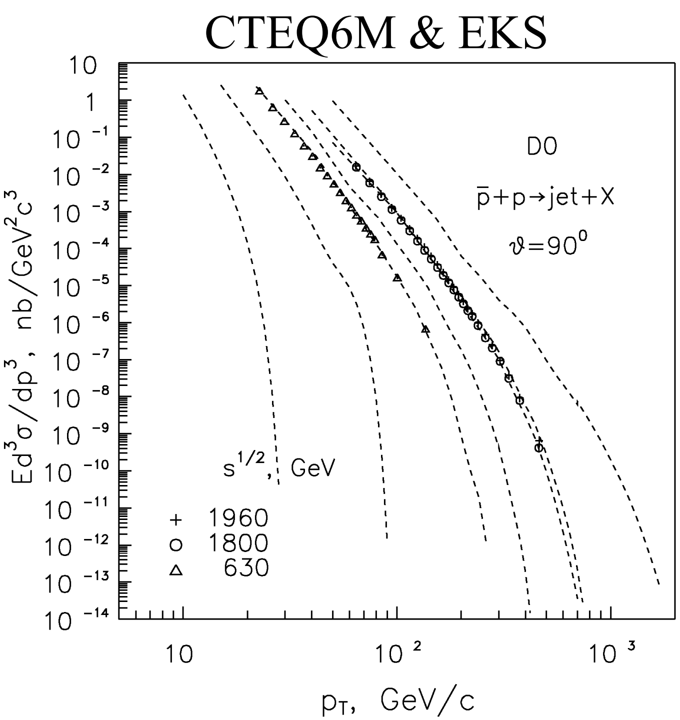


$s^{1/2}$=63-14000 GeV, |η|<0.5, R=0.7



- Strong dependence of spectra on energy $s^{1/2}$ at high p_T .
- Sensitivity to PDFs (MRST) & μ_R, μ_F, μ_H scales.
- NLO QCD calc. results are in agreement with available data.
- Different extrapolation of spectra predicted by NLO QCD and z-scaling for high transverse momenta.

Jet NLO QCD spectra in $\bar{p}p$ & PDFs



LHC

↑

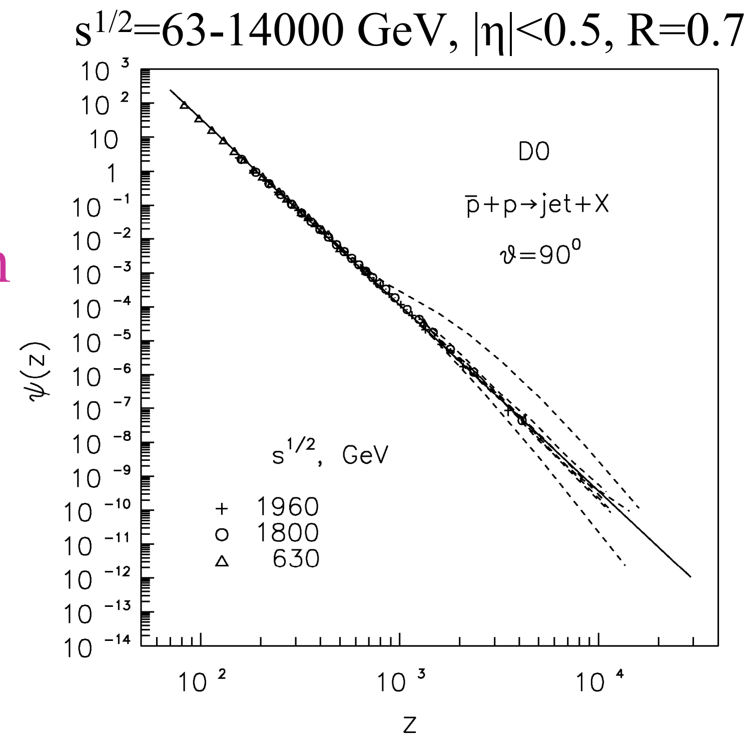
Tevatron

↑

RHIC

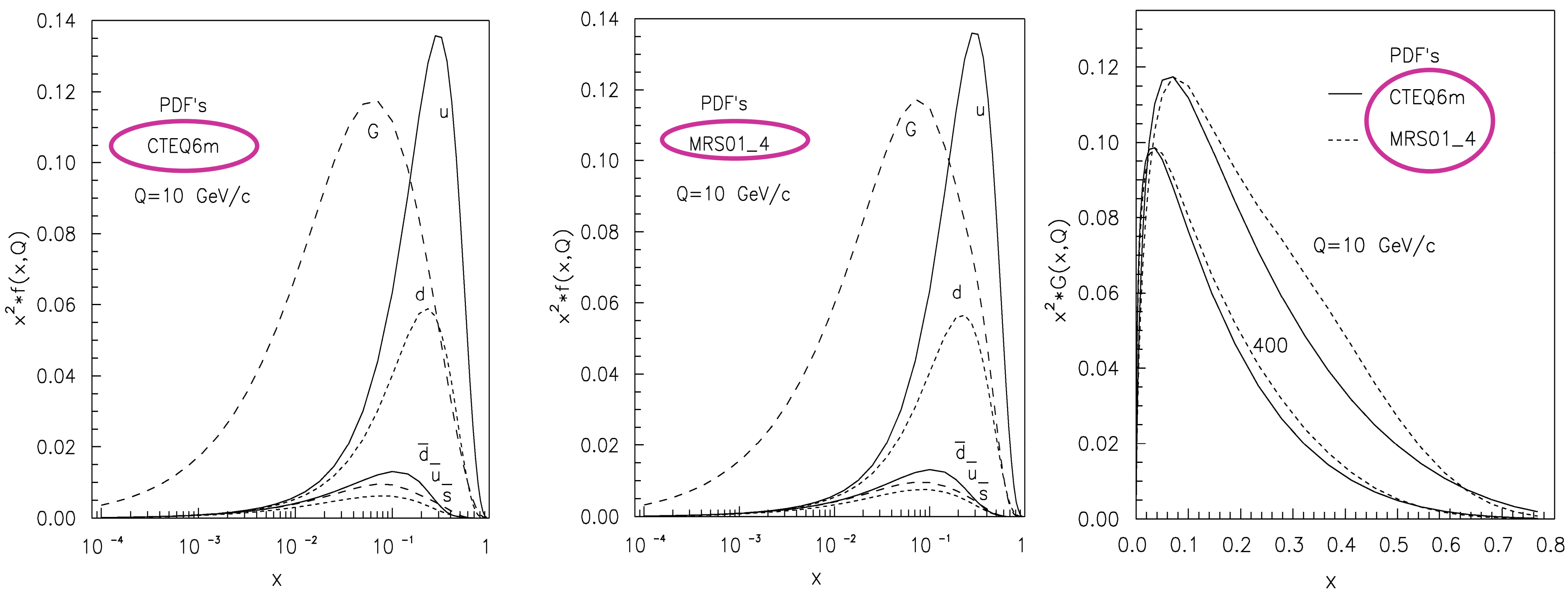
↑

ISR



- Strong dependence of spectra on energy $s^{1/2}$ at high p_T .
- Sensitivity to PDFs (CTEQ) & μ_R, μ_F, μ_H scales.
- NLO QCD calc. results are in agreement with available data.
- Different extrapolation of spectra predicted by NLO QCD and z-scaling for high transverse momenta.

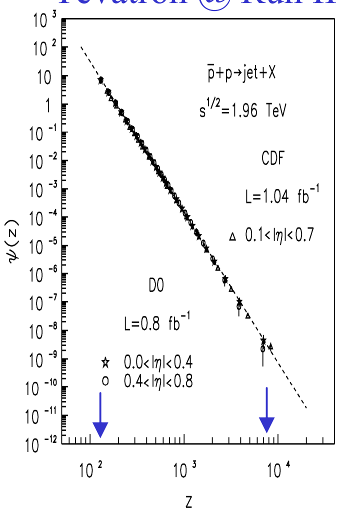
PDFs

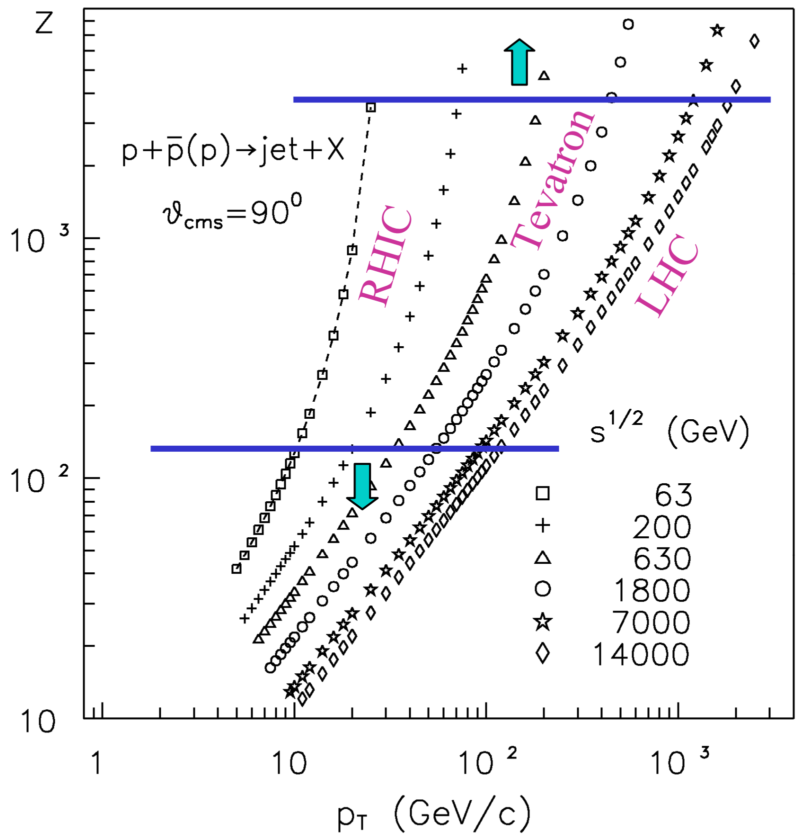


- PDFs (CTEQ, MRST) & scales (μ_R, μ_F, μ_H) are model dependent ingredients of QCD fit of exp. data.
- z-Scaling can give additional constraints on PDFs.

z-p_T plot for jet production

Tevatron @ Run II





Phenomena
due to constituent substructure
and space-time structure

Collective phenomena
due to multiple jet production

Kinematical regions are of more preferable
for searching for new physics at RHIC, Tevatron and LHC.

Conclusions

- Results of analysis of Tevatron and RHIC data on inclusive transverse spectra of jets produced in pp and $\bar{p}p$ collisions in z-presentation are presented.
- New confirmation of properties of z-scaling (energy and angular independence) are obtained.
- z-Scaling of jet production at high energies manifests self-similarity, locality and fractality of hadron interactions at a constituent level.
- QCD test of z-scaling is performed: z-scaling gives restriction on the asymptotic behavior of jet spectra in high-p_T region.
- The approach is useful for searching for new physics phenomena in particle production at RHIC, Tevatron, and LHC.

Thank You for Attention !