LBL-28789
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Submitted to Physics Letters B

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April 1990

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

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LBL-28789

Mini-jets and Multiplicity Fluctuation in Small Rapidity Intervals *

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Abstract

The multiplicity fluctuation of particles in small rapidity intervals from mini-jets in high-energy hadron-hadron collisions are considered and a power-law behavior is found. An increase of the observed factorial moments with P_T of the jets is expected. However, the fluctuation becomes smaller for larger total multiplicity due to the contributions from multiple mini-jets production.

*This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Since Białas and Peschanski[1] proposed a new way to analyse the particle density fluctuation in different rapidity intervals, experimentalists have found evidences of the so called intermittency, or the power-law behavior of the factorial moments as functions of the rapidity interval, in both hadron-hadron and nucleus-nucleus collisions[2]–[6]. When many conventional models in their present form failed to explain these phenomena quantitatively[2]–[6], the self-similar property[8] suggests a cascade process[1][9] for the multiparticle production. However, other interpretations in terms of phase transition[7], and short-range correlations[10] contributed more to the controversy on a possible new dynamical mechanism underling the observed power-law behavior. In this letter we explore another new contribution to the intermittency from mini-jet production and its implications in high-energy hadron-hadron collisions.

When colliding energy is increased beyond the ISR energy range both experiments[11] and theoretical estimations[12][13] show that the hard or semi-hard collisions between point-like partons become important and are responsible for many phenomena which pertain to high-energy hadronic interactions. One then naturally expects multiple jets production. The first estimations of the cross section of three or four jets production through multiple interaction were made in early 1980's[14]. Later, a probabilistic method was used to calculate the cross sections for multiple parton interaction and the average number of jets production in a *pp* collision[15]. It has also been shown[16][17] that many such hard collisions in an event give rise to large multiplicity so that KNO scaling of multiplicity distribution is violated. It is also estimated[18] that copious mini-jets could be produced in relativistic heavy-ion collisions. In the light of the discussion on intermittency, it is of interest to investigate the multiplicity fluctuation from mini-jets in different rapidity intervals.

A realistic model should contain soft and hard processes and a detailed treatment of jet fragmentation. Due to the limited length of this letter, we only investigate analytically the kinetic fluctuation of mini-jets and how they could contribute to what is observed in experiments before one can do some real simulations using programs such as Pythia[16]. We calculate the production of mini-jets in the framework of perturbative QCD and use the parametrized results of e^+e^- for the fragmentation. We hope the investigation here can serve as a guidance to search for the effects of mini-jets on multiplicity fluctuation.

By perturbative QCD the differential cross section of hard parton interaction or jet production is[19],

$$\begin{aligned}\frac{d\sigma_{jet}}{dP_T^2 dy_1 dy_2} &= \sum_{a,b} x_1 x_2 \Big[f_a(x_1, P_T^2) f_b(x_2, P_T^2) d\sigma^{ab}(\hat{s}, \hat{t}, \hat{u})/d\hat{t} \\ &\quad + f_b(x_1, P_T^2) f_a(x_2, P_T^2) d\sigma^{ab}(\hat{s}, \hat{u}, \hat{t})/d\hat{t} \Big] (1 - \frac{\delta_{a,b}}{2}), \qquad (1)\end{aligned}$$

where the summation runs over all parton species, x_1 and x_2 are the fractions of the momenta of the nucleons the partons carry, which are related to their final rapidities y_1, y_2, and transverse momentum P_T by $x_1 = x_T(e^{y_1} + e^{y_2})$, $x_2 = x_T(e^{-y_1} + e^{-y_2})$ and $x_T = 2P_T/\sqrt{s}$. The differential parton cross sections $d\sigma^{ab}/d\hat{t}$ are compiled in Ref. [20]. We use the Duke-Owens[21] parametrization of parton distribution functions with P_T as the hard scale and Λ=200 MeV. The inclusive cross section of jet production is then

$$\sigma_{jet}(s) = \int_{P_0^2}^{s/4} dP_T^2 dy_1 dy_2 \frac{1}{2} \frac{d\sigma_{jet}}{dP_T^2 dy_1 dy_2}, \qquad (2)$$

where P_0 is the low P_T cut-off . The value of P_0 can not be uniquely determined here. However, P_0=2 GeV is compatible with most of the calculations of the total cross section $\sigma_{tot}(s)$ of nucleon-nucleon collisions in the framework of eikonal formalism[13][15][17][22]. Now the multiplicity distribution for the charged particles in a rapidity interval δy_c from an inclusive hard process in the nucleon-nucleon collisions is,

$$P_n^{jet}(\delta y_c) = \frac{1}{\sigma_{jet}} \int_{P_0^2}^{s/4} dP_T^2 dy_1 dy_2\, p_n(\overline{n}_{jet}) \frac{1}{2} \frac{d\sigma_{jet}}{dP_T^2 dy_1 dy_2}, \tag{3}$$

where, $p_n(\overline{n}_{jet})$ is the distribution for a pair of jets with fixed P_T, y_1 and y_2. Note that $\overline{n}_{jet} \equiv \overline{n}_{jet}(y_1, y_2, \hat{s}, \delta y_c)$ depends on the rapidities and the center-of-mass enery $\hat{s} = x_1 x_2 s$ of the jet. Even though $p_n(\overline{n}_{jet})$ might be narrow, the final fluctuation of P_n^{jet} can be large due to the variation of the virtuality $\hat{s}$ and P_T of the jet.

The jets produced in nucleon-nucleon collisions can be either quark or gluon jets, though the gluon-gluon scatterings are dominant among other semihard subprocesses due to the rapid increase of gluon distribution function at small x. The solution to the evolution equations of the fragmentation functions[23] gives a gluon jet 9/4 times of the average multiplicity of a quark jet. However, studies in both $p\overline{p}$ and e^+e^- experiments[24][25] show little difference between the two, especially at low energies. Since we are only interested in mini-jets, we will approximate both gluon and quark jets with an effective one, which is assumed to have the same properties as the ones in e^+e^- annihilation, *e.g.*, the multiplicty and rapidity distributions of the charged particles.

We take a Poisson form, which fits the e^+e^- data well, as the multiplicity distribution for the charged particles from jet fragmentation,

$$p_n(\overline{n}_{jet}) = \frac{[\overline{n}_{jet}]^n}{n!} e^{-\overline{n}_{jet}}, \tag{4}$$

and extrapolate it to the cases of limited rapidity intervals. It is known[26] that the total average multiplicity of e^+e^- can be fitted by $2.18 s^{1/4}$. Therefore we assume the same for the jets in nucleon-nucleon collisions,

$$\overline{n}_{jet}(\hat{s}) = 2.18\hat{s}^{1/4}. \tag{5}$$

Similarly, a good parametrization of e^+e^- data[26] on the rapidity density along the jet's axis can be given by,

$$\frac{dn_{jet}}{dy} = \frac{\overline{n}_0(\hat{s})}{1 + e^{3(|y| - y_{max})}}, \tag{6}$$

where,

$$\overline{n}_0(\hat{s}) = 0.743 + 0.238 \ln \hat{s}, \tag{7}$$

is the height of the central plateau and y_{max} is the half-width of the plateau determined by $\overline{n}_{jet}(\hat{s}) = \int_{-\infty}^{\infty} (dn_{jet}/dy)dy$.

Suppose that a pair of jets in a nucleon-nucleon collision have rapidities y_1 and y_2, respectively. By a Lorentz boost with $y_b = (y_1 + y_2)/2$ respect to the original frame we consider the situation in the center-of-mass frame of the two colliding partons. The jets then have rapidities $\pm y^* = \pm(y_1 - y_2)/2$, and a particle with a rapidity y' along the jet's axis has

$$\sinh y = \frac{\sinh y' \sinh y^*}{\sqrt{\cosh^2 y^* + \sinh^2 y'}}, \tag{8}$$

where the intrinsic transverse momentum in the jet fragmentation has been ignored. Note that $|y| \leq |y^*|$. Therefore, the averaged number of particles which fall into a rapidity window δy_c is then,

$$\overline{n}_{jet}(y_1, y_2, \hat{s}, \delta y_c) = \int_{y_1'}^{y_2'} dy' \frac{dn_{jet}}{dy'}, \tag{9}$$

where dn_{jet}/dy' is given by Eq. 6 and y_1', y_2' are obtained from Eq. 8 by restricting

$$| y + y_b | \leq \delta y_c/2. \tag{10}$$

When $\delta y_c \to \infty$ or $\delta y_c \gg 2\ln(\sqrt{s}/P_0)$, $\overline{n}_{jet}(y_1, y_2, \hat{s}, \delta y_c)$ becomes the total average multiplicity $\overline{n}_{jet}(\hat{s})$ as given in Eq. 5. Using $\overline{n}_{jet}(y_1, y_2, \hat{s}, \delta y_c)$ in Eq. 3, we can calculate the charged multiplicity distribution $P_n^{jet}(\delta y_c)$ of the particles within the rapidity window δy_c from the jet fragmentation of a hard collision.

In Fig. 1, we show $P_n^{jet}(\delta y_c)$ (solid lines) at two energies with different rapidity intervals. Even though the Poisson distribution in Eq. 4 is narrow, it becomes very broad after being smeared over the transverse momentum and rapidities of the jets, due to the variation of the virtuality of the subprocess. The fluctuation of the distributions increases with smaller rapidity intervals. In these two plots, we also give the contributions from $2 \leq P_T \leq 4$ GeV region(dashed lines). The contributions from large transverse momentum jets with $P_T \geq 4$ GeV is significantly suppressed for large rapidity intervals. Most of the contributions come from those jets with small P_T which characterizes mini-jets or semihard collisions. However, for small rapidity intervals the contributions from large transverse momentum jets become dominant at high multiplicities. This is simply because the events with large n in a small rapidity interval mainly come from those jets with large P_T. Therefore, triggering on high multiplicities in restricted rapidity windows intrinsically biases the events toward larger P_T mini-jets.

Following Ref. [1], we calculate the normalized factorial moments of the multiplicity distribution $P_n^{jet}(\delta y_c)$,

$$F_i(\delta y_c) = \frac{\sum_{n=1}^{\infty} n(n-1)\cdots(n-i+1)P_n^{jet}(\delta y_c)}{\left[\sum_{n=1}^{\infty} nP_n^{jet}(\delta y_c)\right]^i}. \tag{11}$$

in order to see the variation of the fluctuation with δy_c. It is obvious from Eq. 11 that a Poisson distribution will give a constant value $F_i = 1$ for all i's. Any larger values indicate a broader distribution than Poisson. Using Eqs. 3, 4 and the property of Poisson distribution, we have

$$F_i(\delta y_c) = \widehat{n^i}(\delta y_c)/[\widehat{n}(\delta y_c)]^i, \tag{12}$$

where,

$$\widehat{n^i}(\delta y_c) = \frac{1}{\sigma_{jet}} \int_{P_0^2}^{s/4} dP_T^2 dy_1 dy_2 \overline{n}^i_{jet}(y_1, y_2, \hat{s}, \delta y_c) \frac{1}{2} \frac{d\sigma_{jet}}{dP_T^2 dy_1 dy_2}. \tag{13}$$

In Fig. 2, we show the calculated resluts at $\sqrt{s}$=900 GeV in a log-log plot. It is apparent that $\ln F_i(\delta y_c)$ becomes linear in $\ln \delta y_c$ when $\delta y_c \leq 1$. Therefore a power-law behavior

$$F_i(\delta y_c) \propto \delta y_c^{-a_i} \tag{14}$$

exists for all the mements for small rapidity intervals, where a_i which is the slope of the log-log plot is refered to as the index of the intermittency. To justify our speculation that the fluctuation is stronger when the jets with larger P_T are considered, we also include the linear portions of $\ln F_i$ for two different P_T ranges, $2 \leq P_T \leq 4$ GeV(dashed line) and $P_T \geq 8$ GeV (dot-dashed line). Indeed, both the factorial moments and the range of the linear sections increase with the transverse momentum of the jets which are considered. The indices a_i, especially for large i, are independent of P_T cuts. Thus, selecting events with a lower P_T cut-off can minimize the contribution to multiplicity fluctuation from jet production, while choosing large P_T jets would enhance the fluctuation. We have done the calculation at different energies and the results are more or less independent of the energy at small δy_c.

Since the parton density at small x is very high there could be multiple mini-jets production in high-energy nucleon-nucleon collisions. When many jets contribute to the multiplicity in a small rapidity interval at the same time, we would expect that the relative fluctuation from the mean is reduced. If there are j number of mini-jets production, the multiplicity distribution of particles from them is then,

$$P_n^{jet}(j, \delta y_c) = \sum_{n_1, \ldots, n_j} \prod_{i=1}^{j} P_{n_i}^{jet}(\delta y_c) \delta_{n, \Sigma n_i} \,. \tag{15}$$

The corresponding factorial moments can be obtained as,

$$F_2(j, \delta y_c) = \left[j F_2(\delta y_c) + j(j-1) \right] / j^2, \tag{16}$$

$$F_3(j, \delta y_c) = \left[j F_3(\delta y_c) + 3j(j-1) F_2(\delta y_c) + j(j-1)(j-2) \right] / j^3, \tag{17}$$

$$\begin{aligned} F_4(j, \delta y_c) &= \Big[j F_4(\delta y_c) + 4j(j-1) F_3(\delta y_c) + 3j(j-1) F_3^2(\delta y_c) \\ &\quad + 6j(j-1)(j-2) F_2(\delta y_c) + j(j-1)(j-2)(j-3) \Big] / j^4, \end{aligned} \tag{18}$$

$$\begin{aligned} F_5(j, \delta y_c) &= \big[j F_5(\delta y_c) + 5j(j-1) F_4(\delta y_c) + 10j(j-1) F_3(\delta y_c) F_2(\delta y_c) \\ &\quad + 10j(j-1)(j-2) F_3(\delta y_c) + 15j(j-1)(j-2) F_2^2(\delta y_c) \\ &\quad + 10j(j-1)(j-2)(j-3) F_2(\delta y_c) \\ &\quad + j(j-1)(j-2)(j-3)(j-4) \big] / j^5, \end{aligned} \tag{19}$$

where $F_i(\delta y_c)$ are given in Eq. 12. In Fig. 3 the indices a_i of the linear portions of the log-log plots of these calculated moments are shown for j=1(solid line), 2, 4, 8(dashed lines) number of jets production at $\sqrt{s}$ = 900 GeV. It is obvious that the degree of intermittency is reduced significantly when there are more jets contributing to the same small rapidity interval. Since it has been shown[16][17] that there could be many mini-jets production in the events of large multiplicities in high-energy nucleon-nucleon collisions, selecting such events could actually decrease the fluctuation in a limited rapidity window.

It has been estimated[15][17] that the average number of semi-hard interactions, at $\sqrt{s} = 900$ GeV for example, is about 1 and in a high multiplicity event there could be as many as 4 pairs of jets production. Therefore, the effect of jets on the factorial moments and its variation with the number of jets production should be observable at present collider energies.

In summary, we have considered the multiplicity fluctuation in small rapidity intervals from inclusive mini-jets production in high-energy nucleon-nucleon collisions. A power-law behavior is found. In practice, the intrinsic p_T distribution with respect to the jet's axis and the particles from soft processes will reduce the fluctuation due to the mini-jets. The final results will dependend on the balance between soft and hard components and the number of mini-jets produced. However, two qualitative conclusions can be drawn for the effects of mini-jets on multiplicity fluctuation:

(1) Since the fluctuation from mini-jets increases with their P_T, one would expect the observed moments to increase with p_{Tcut} if he only selects those particles with $p_T \geq p_{Tcut}$. Furthermore, by selecting high p_T tracks, one automatically biases the contributions toward those of particles from mini-jets.

(2) If one measures the fluctuation in different multiplicity intervals, the moments should decrease with the multiplicity. This is because that at higher energies the events with higher multiplicities are dominated by more mini-jets production and multiple mini-jets reduce the fluctuation from the mean in a small rapidity window.

Even though we can not make direct comparision with the data at this stage, we hope the investigation here can give some guidance to search for the effects of mini-jets in terms of intermittency. Most importantly, it provides a new source of multiplicity fluctuation in small rapidity intervals and the related power-law behavior.

I am grateful to M. Gyulassy and R. C. Hwa for their inspirations, encouragements and helpful discussions. I have benefitted from discussions with G. Gustafson and M. Markytan.

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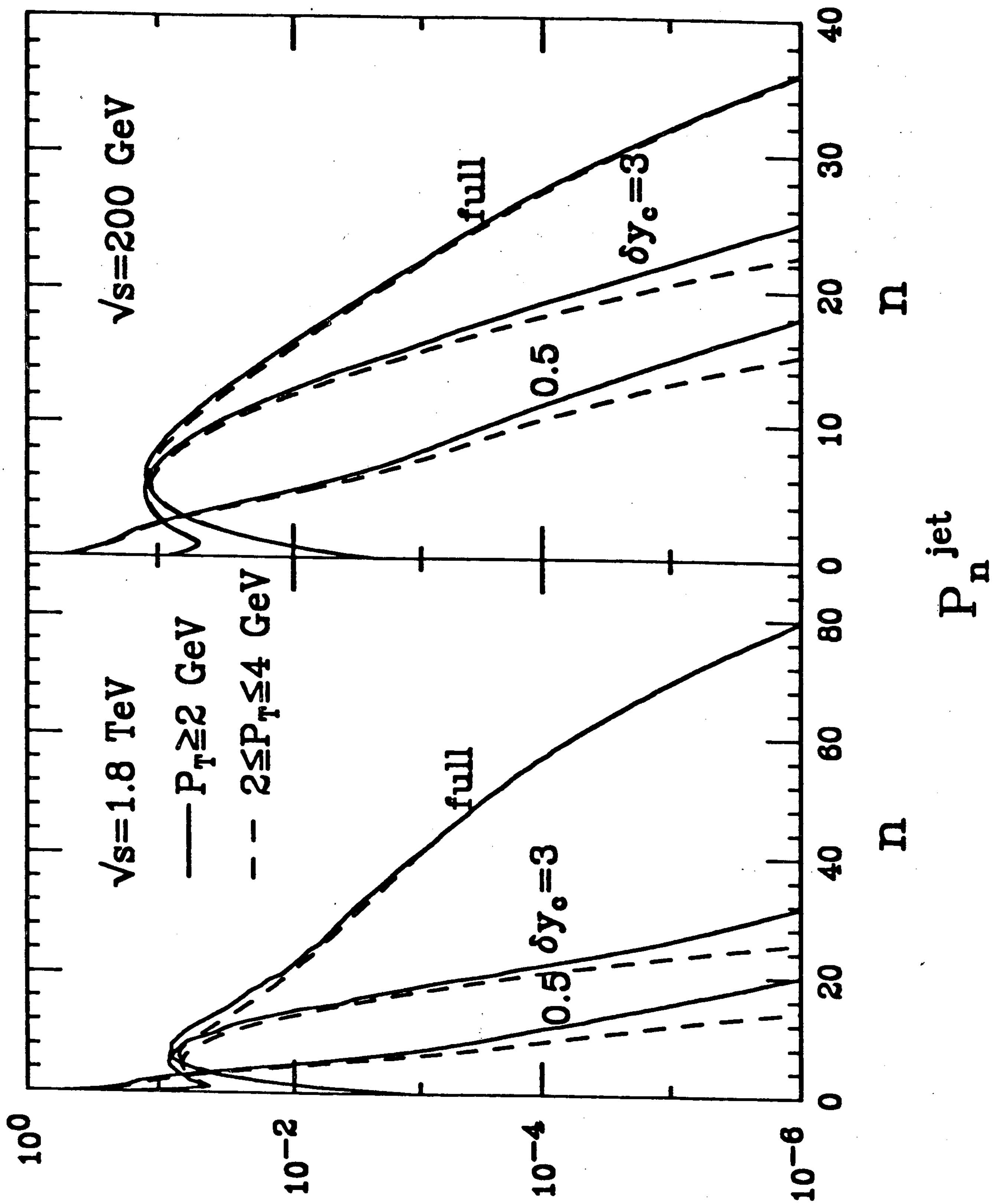
Figure Captions

Fig. 1 The multiplicity distributions of particles in different rapidity intervals δy_c from a jet production in nucleon-nucleon collisions at $\sqrt{s}$=200 GeV, and 1.8 TeV. The dashed lines are the contributions from jets with $2 \leq P_T \leq 4$ GeV.

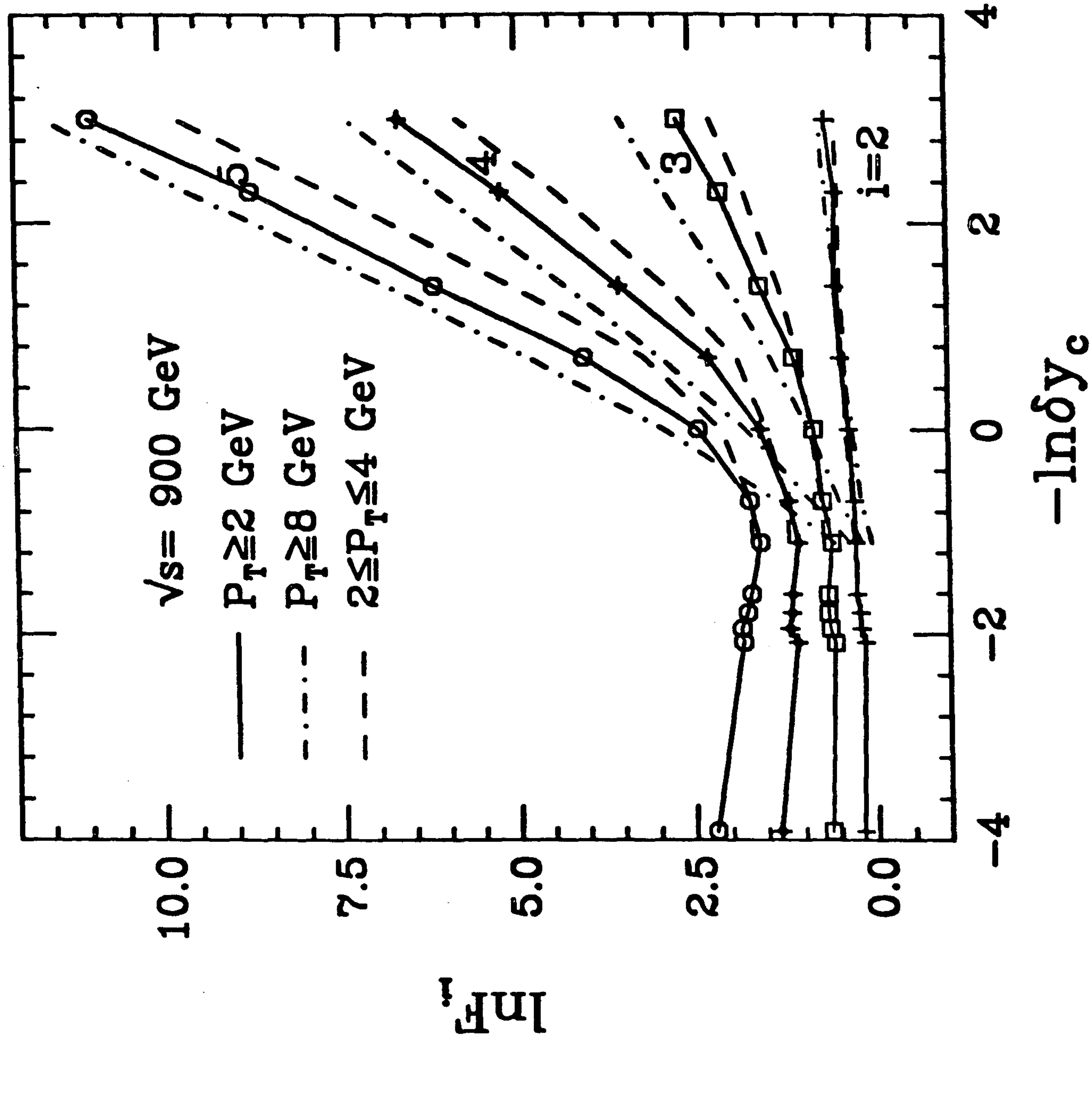
Fig. 2 $\ln F_i$ as functions of $-\ln \delta y_c$ at $\sqrt{s}$ =900 GeV for $P_T \geq$2 GeV(solid lines), $P_T \geq 8$ GeV(dot-dashed lines), and $2 \leq P_T \leq 4$ GeV(dashed lines).

Fig. 3 Slopes a_i of the linear portions of $\ln F_i(j, \delta y_c)$ vs $-\ln \delta y_c$ plots for j =1 (solid line), 2, 4, and 8(dashed lines) number of mini-jets production.



√s=200 GeV
full
δy_c=3
0.5
n
√s=1.8 TeV
P_T≧2 GeV
2≦P_T≦4 GeV
full
δy_c=3
0.5
n
P_n^jet
10^0
10^-2
10^-4
10^-6
0
20
40
60
80
0
10
20
30
40

Fig. 1



√s= 900 GeV
P_T≥2 GeV
P_T≥8 GeV
2≤P_T≤4 GeV
lnF_i
−lnδy_c
i=2
3
4
5
10.0
7.5
5.0
2.5
0.0
−4
−2
0
2
4

Fig. 2

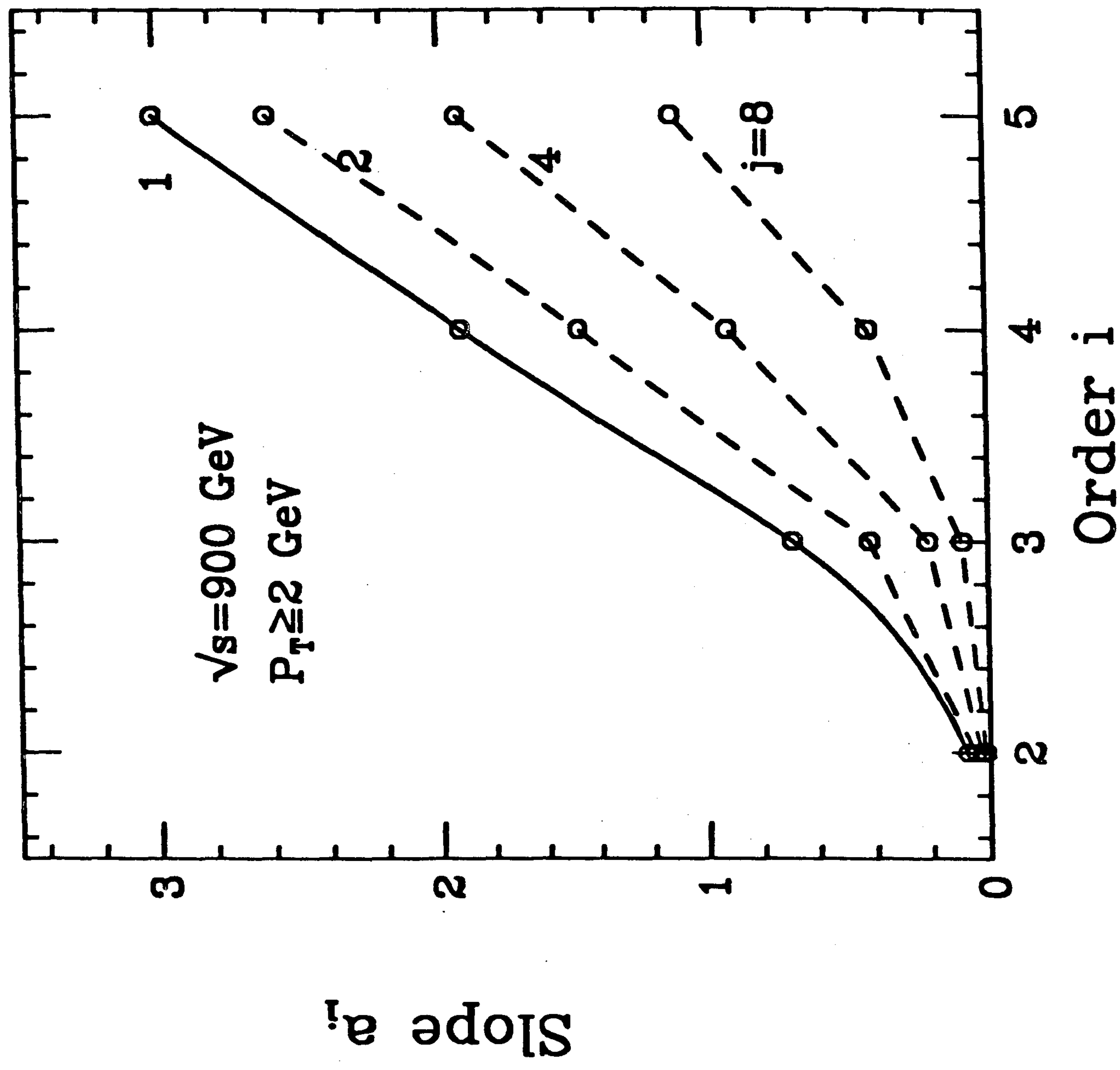


Fig. 3

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