Diffractive proton dissociation into three jets at LHC

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Outline

- **Motivations to measure hard exclusive three-jet production**

$$p + p \to jet + jet + jet + p$$

  in early LHC runs

- **Calculation in k_t factorization**

- **Results for LHC and Tevatron kinematics**

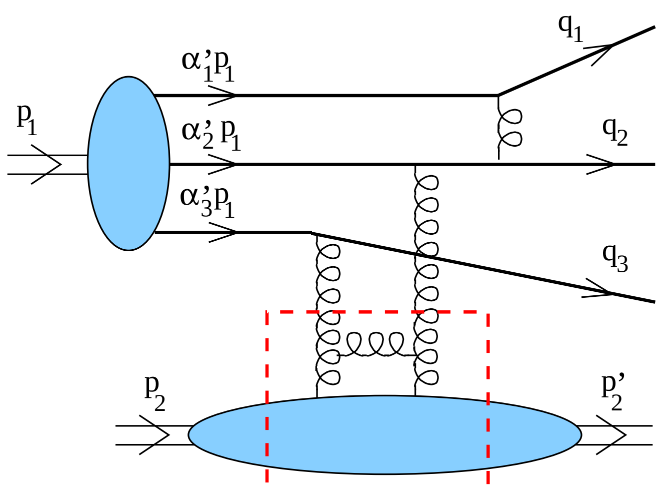
- **Conclusions**

Motivations

The physics potential of forward detectors at LHC, within and beyond the standard model, is attracting a lot of attention.

We suggest to observe hard exclusive diffractive dissociation of a proton into three hard jets

$$p(p_1) + p(p_2) \to jet(q_1) + jet(q_2) + jet(q_3) + p(p_2')$$



We are interested in *exclusive* three–jet production — a small fraction of the inclusive single diffraction cross section.

The exclusive and inclusive mechanisms have different final state topologies and can be distinguished experimentally. A characteristic quantity is e.g.

$$R_{jets} = \frac{M_{3j}}{M_X}$$

the ratio of the three-jet mass to the total invariant mass of the system produced in the diffractive interaction.
Exclusive production corresponds to $R_{jets} \to 1$.

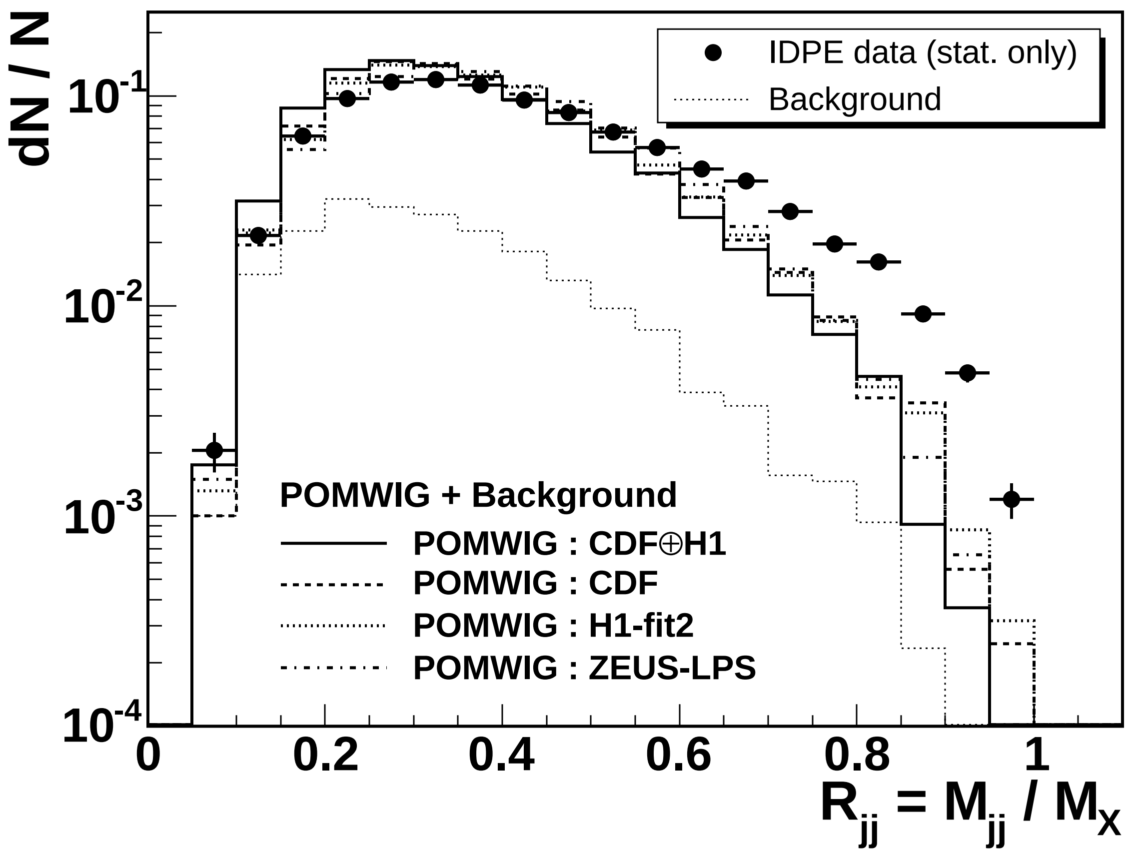
This strategy to separate exclusive events was used at the Tevatron [Phys.Rev.D. 2008] (Christina Mesropian talks), where central exclusive dijet production,

$$p\bar{p} \to p + jet + jet + \bar{p}$$

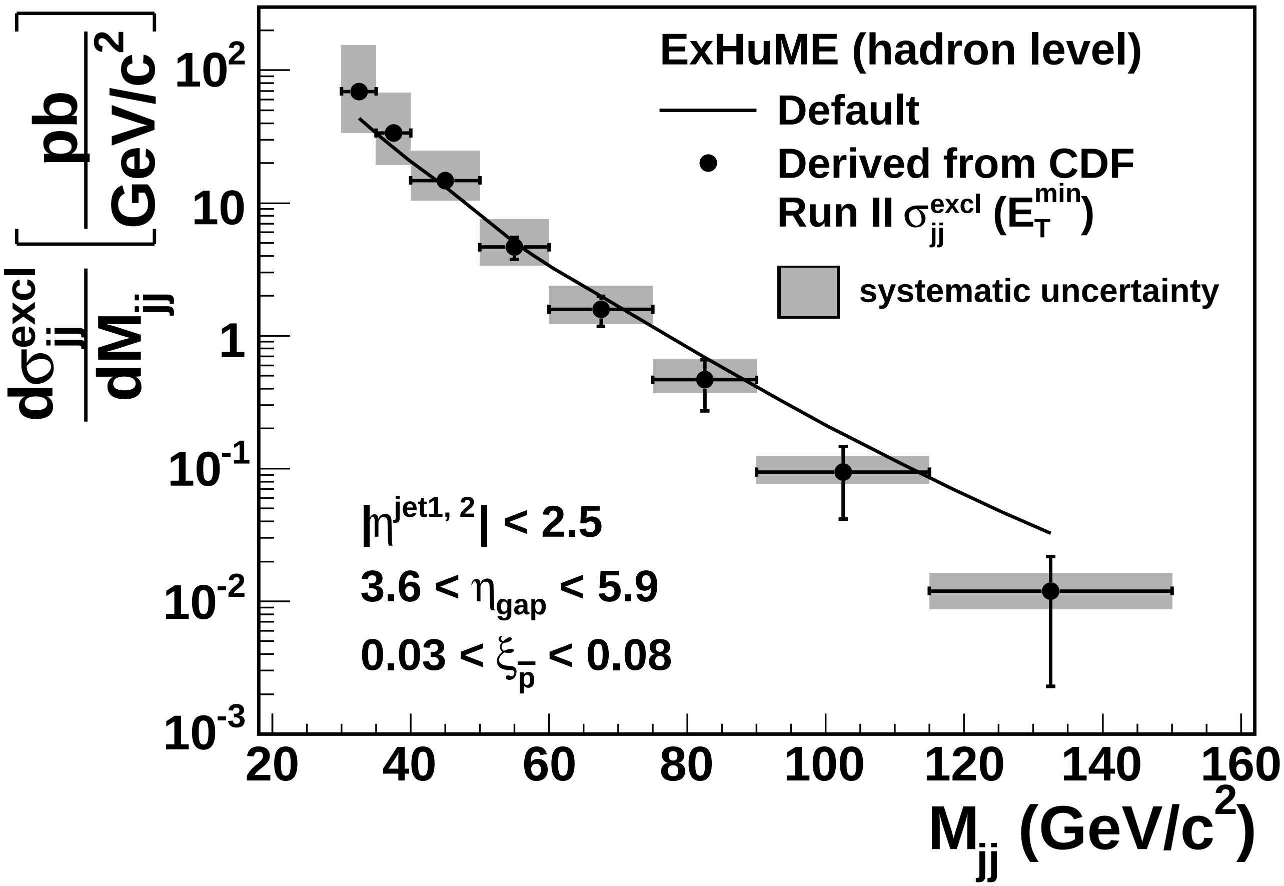
in double–Pomeron collisions was measured for the first time.

CDF run II data

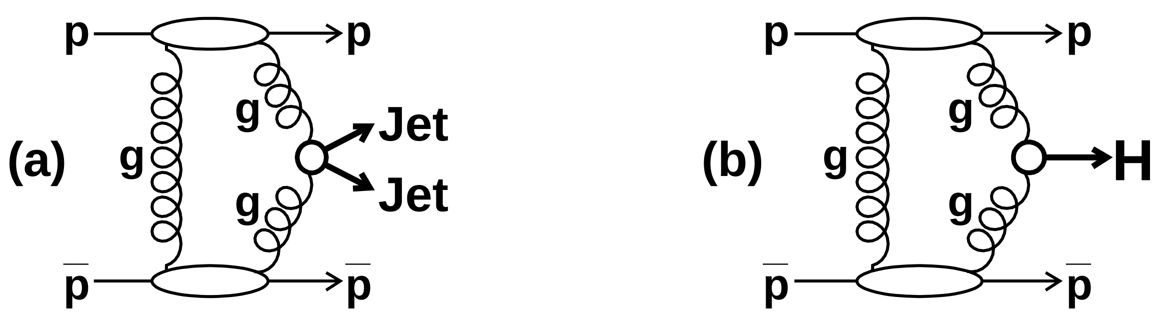
Separation of exclusive dijets:



CDF exclusive dijets cross section:



Exclusive dijet production in the central region has much in common with the exclusive Higgs boson production process



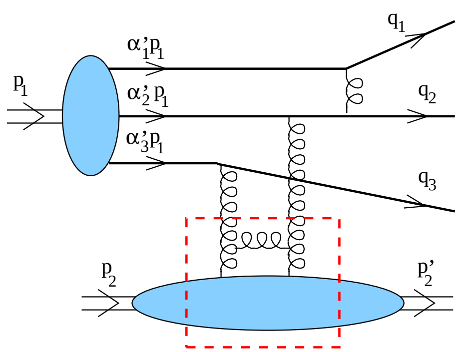
Khoze, Martin, Ryskin ’08 (Valery talk): studies of exclusive dijet and other diffractive processes at the early data runs of the LHC can provide valuable checks of the different components of the theory formalism:

- hard-soft factorization
- soft rescattering (gap survival probability)
- Sudakov logs in the hard part
- unintegrated gluon distribution

Indeed, this was the main motivation for Tevatron experiment.

Advantages of exclusive 3-jets production in single diffraction:

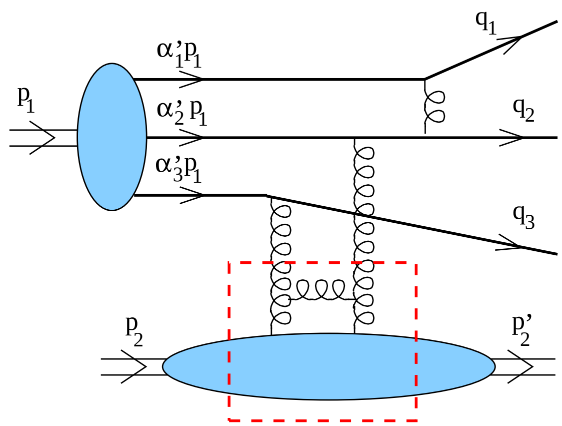
- **factorization of hard and soft interactions in this case is less complicated.**
- **underlining mechanism – the fluctuation of a proton projectile into a state with small transverse size. Suppression of secondary soft interactions that may fill the rapidity gap. (No gap survival effects!)**



- **an access to the gluon distribution at small x in a cleaner environment**
- **sensitive to the proton distribution amplitude**

Our approach derives from experience with coherent pion diffraction dissociation, $\pi A \to jet + jet + A$, measured by the E791 collaboration '01.

At leading order the jets are formed by the three valence quarks of the proton:



- **All three jets having large transverse momenta requires at least two hard gluon exchanges.**
- **One of them can be effectively included in the high-momentum component of the unintegrated gluon density,** $\mathcal{F}(x, k_\perp)$
- **the second one has to be added explicitly since the hard pomeron only couples to two of the three quarks of the proton.**
- **an additional hard gluon exchange makes calculation of proton diffraction dissociation more difficult as compared to the meson case.**

Our study of $\pi A \to jet + jet + A$, works of '01 and '02

- **collinear factorization is violated in dijet production due to pinching of singularities between soft gluon (and quark) interactions in the initial and final state.**
- **the nonfactorizable contribution is suppressed compared to the leading contribution by a logarithm of energy**
- **in the double logarithmic approximation $\ln q_\perp^2 \ln s/q_\perp^2$ collinear factorization is restored.**
- **to this accuracy hard gluon exchange can be "hidden" in the unintegrated gluon distribution $\mathcal{F}(x, q_\perp)$.**
- **In the true diffraction limit, for very large energies, hard exclusive dijet production can be considered as a probe of the hard component of the pomeron.**
  The same interpretation was suggested earlier in N. Nikolaev, W. Schaäfer, G. Schwiete '01 within the k_t factorization framework.

Based on the generalization of these ideas:
we present an estimate for the cross section for the exclusive $3jets$ in the double logarithmic approximation.

Kinematics

Sudakov decomposition for the jet momenta

$$q_k = \alpha_k p_1 + \beta_k p_2 + q_{k\perp} \,, \qquad k = 1, 2, 3 \tag{1}$$

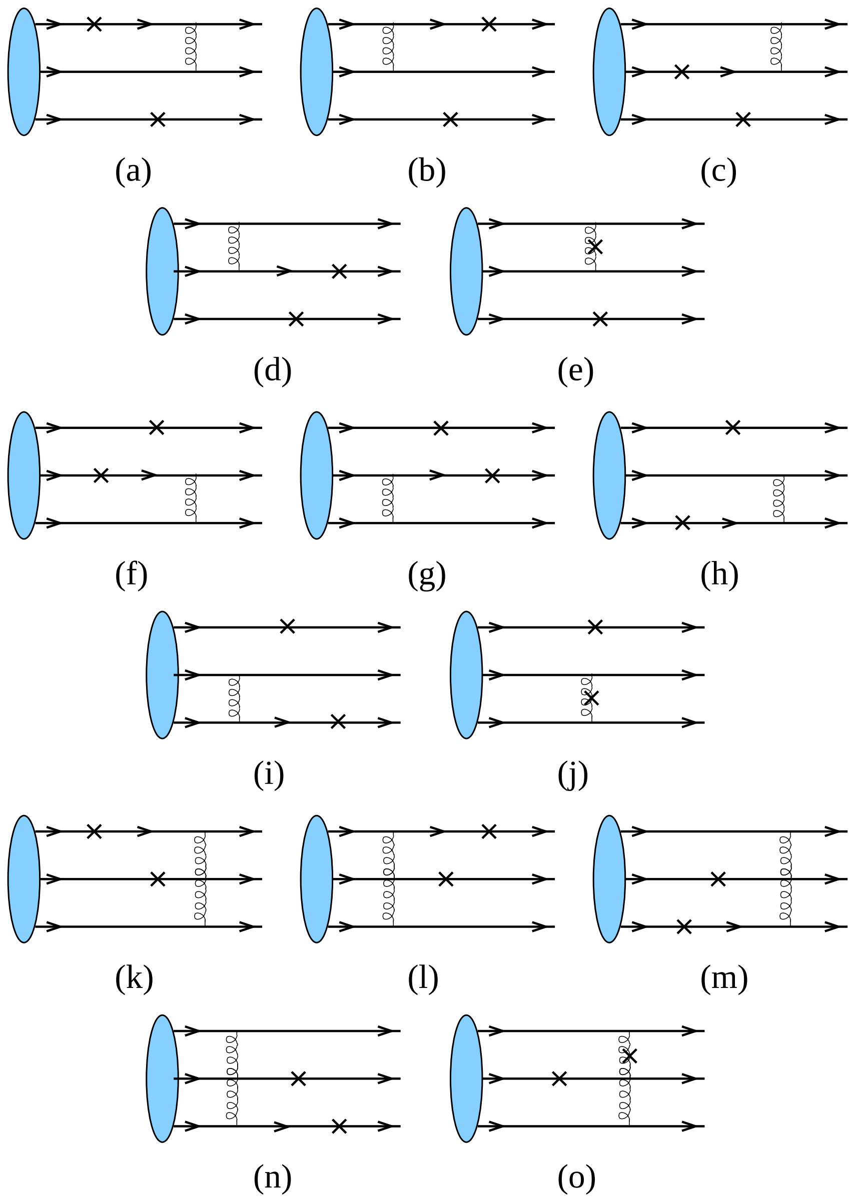
where high transverse momenta of jets are compensated

$$\vec{q}_{1\perp} + \vec{q}_{2\perp} + \vec{q}_{3\perp} = 0 \,, \qquad \alpha_1 + \alpha_2 + \alpha_3 = 1 \,, \qquad \beta_k = \vec{q}_{k\perp}^{\,2}/(\alpha_k s) \,, \tag{2}$$

The three–jet invariant mass is given by

$$M^2 = (q_1 + q_2 + q_3)^2 = \frac{\vec{q}_{1\perp}^{\,2}}{\alpha_1} + \frac{\vec{q}_{2\perp}^{\,2}}{\alpha_2} + \frac{\vec{q}_{3\perp}^{\,2}}{\alpha_3} \,, \qquad \zeta = \frac{M^2}{s} = \beta_1 + \beta_2 + \beta_3 \,. \tag{3}$$

$s = (p_1 + p_2)^2 = 2p_1 \cdot p_2$ **is the invariant energy. If the relevant jet transverse momenta are of the order of 5 GeV, at LHC** $\zeta \sim 10^{-6} \div 10^{-5}$**.**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There are three different contributions to the amplitude:

$$\mathcal{M} = -i\,2^7\pi^5\,s\,\alpha_s^2\left[\frac{e^{ijk}\left(\frac{1+N}{N}\right)^2}{4N!(N^2-1)}\right]\int D\alpha'$$

$$\times\left(\mathcal{L}_{f\div j}\frac{\delta(\alpha_1-\alpha_1')}{q_{1\perp}^4}\mathcal{F}(\zeta,q_{1\perp})+\mathcal{L}_{k\div o}\frac{\delta(\alpha_2-\alpha_2')}{q_{2\perp}^4}\mathcal{F}(\zeta,q_{2\perp})+\mathcal{L}_{a\div e}\frac{\delta(\alpha_3-\alpha_3')}{q_{3\perp}^4}\mathcal{F}(\zeta,q_{3\perp})\right),$$

where $\int D\alpha' = \int_0^1 d\alpha_1' d\alpha_2' d\alpha_3' \delta(1-\sum\alpha_i')$ **corresponds to the integration over the quark momentum fractions in the incident proton,** e^{ijk} **describes the color state of the final quarks,** $N=3$ **is the number of colors.**

$$\mathcal{L}_{f\div j} = [\mathcal{V}\,\bar{u}(q_1)\not{p}_1 v(q_2)\,\bar{u}(q_3)\not{p}_2\gamma_5 N(p_1) - \mathcal{A}\,\bar{u}(q_1)\not{p}_1\gamma_5 v(q_2)\,\bar{u}(q_3)\not{p}_2 N(p_1)]$$

$$\times\left(\frac{\alpha_1(\alpha_3+\alpha_3')}{[-\alpha_2'\alpha_3\beta_2 s^3][\alpha_3'(\beta_2+\beta_3)-\alpha_1\beta_1+i\epsilon]}+\frac{-\alpha_1(\alpha_3+\alpha_3')}{[-\alpha_3'\alpha_3\beta_3 s^3][\alpha_2'(\beta_2+\beta_3)-\alpha_1\beta_1+i\epsilon]}\right)$$

$$+\ldots$$

The functions $\mathcal{A}(\alpha_1', \alpha_2', \alpha_3')$, $\mathcal{V}(\alpha_1', \alpha_2', \alpha_3')$ and $\mathcal{T}(\alpha_1', \alpha_2', \alpha_3')$ are the leading-twist light-cone nucleon distribution amplitudes:

$$\langle 0|\epsilon^{ijk} u_\alpha^i(a_1 z) u_\beta^j(a_2 z) d_\gamma^k(a_3 z)|N(p_1)\rangle =$$

$$= \quad V\,(\not p_1 C)_{\alpha\beta}\,(\gamma_5 N(p_1))_\gamma + A\,(\not p_1 \gamma_5 C)_{\alpha\beta}\,(N(p_1))_\gamma + T\,\left(i\sigma_{\mu\nu} p_1^\nu C\right)_{\alpha\beta}\left(\gamma^\mu \gamma_5 N(p_1)\right)_\gamma \,,$$

where $z^2 = 0$ and $\sigma_{\mu\nu} = (i/2)[\gamma_\mu, \gamma_\nu]$.

V, A, T depends on the scalar products $a_i p_1 \cdot z$ and can be represented as the Fourier transform of the corresponding distribution amplitude, e.g.

$$V(a_i p_1 z) = \int D\alpha' e^{-ip_1\cdot z \sum_i \alpha_i' a_i} \mathcal{V}(\alpha_i')$$

The differential cross section:

$$d\sigma = \frac{|\mathcal{M}|^2}{2^5 (2\pi)^8 s^2} \frac{d\alpha_1 d\alpha_2 d\alpha_3 \delta(1-\alpha_1-\alpha_2-\alpha_3)}{\alpha_1\alpha_2\alpha_3} d^2\vec{q}_1 d^2\vec{q}_2 dt d\phi_t$$

where $t = (p_2 - p_2')^2$ is the Mandelstam t variable of the pp scattering.

Our numerical estimates:

- **we integrate differential cross section numerically**
- **t dependence: a simple exponential form, $d\sigma/dt \sim e^{bt}$, with $b \sim 4 \div 5\,\mathrm{GeV}^2$, a typical for hard exclusive processes at HERA.**
- **the nucleon distribution amplitude: the simplest, asymptotic form**

$$\mathcal{V}(\alpha_i') \;=\; \mathcal{T}(\alpha_i') \;=\; 120 f_N \alpha_1' \alpha_2' \alpha_3' \,, \qquad \mathcal{A}(\alpha_i') \;=\; 0\,.$$

The normalization parameter f_N is scale-dependent.

$$f_N(\mu) = f_N(\mu_0) \left(\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)} \right)^{\frac{2}{3\beta_0}} \,,$$

where $\beta_0 = 11/3N - 2/3n_f$. The existing QCD sum rule estimates

$$m_N f_N(\mu = 1\ \textbf{GeV}) = (5.0 \pm 0.3) \times 10^{-3}\,\mathrm{GeV}^3 \quad ,$$

- **unintegrated gluon: the simplest approach**

$$\mathcal{F}(x, q_\perp^2) = \frac{\partial}{\partial \ln q_\perp^2}\, x\, g(x, q_\perp^2)$$

The cuts for jets phase space:

$$0.1 \le \alpha_1, \alpha_2, \alpha_3 \le 0.8\,, \quad q_{1\perp}, q_{2\perp}, q_{3\perp} \ge q_0$$

to assure a clear three–jet event selection.

At the LHC energies we obtained:

$$\sigma_{3-jets}^{\rm LHC} = 4\,\textbf{pb}\cdot\left(\frac{f_N(q_0)}{4.7\cdot 10^{-3}\textbf{GeV}^2}\right)^2\left(\frac{\alpha_s(q_0)}{0.21}\right)^4\left(\frac{5\ \textbf{GeV}}{q_0}\right)^9 .$$

- **the integrated luminosity for the first LHC runs in the range 100 pb^{-1} to 1 fb^{-1}. An observation of this process at LHC seems to be feasible!**
- **The effective power $\sigma \sim 1/q_0^9$ (fitted in the $q_0 = 3 \div 8$ GeV range) is somewhat stronger than the naive power counting prediction $\sigma \sim 1/q_0^8$. This effect is due to the strong ζ dependence of the unintegrated gluon distribution.**
- **The sizeable cross section for $q_0 = 5$ GeV is an implication of the expected rise of the LO gluon distribution more than two times as ζ is decreasing by roughly a factor of 50 when going from Tevatron to LHC.**
- **The existing parameterizations of the gluon distribution at $\zeta \sim 10^{-6}$ differ from each other by $\sim 30\%$. A valuable constraint for the gluon distribution at small momentum fractions.**

A comparison of the three-jet exclusive production at LHC and the Tevatron can be especially illuminating for constraint of gluon since other uncertainties do not have significant impact on the energy dependence.

For Tevatron kinematics, our estimate for the cross section (fitted in the range $q_0 = 2 \div 4.5$ GeV):

$$\sigma^{\rm Tevatron}_{3-jets} = 50\,\textbf{pb}\,\cdot\left(\frac{f_N(q_0)}{4.7\cdot 10^{-3}\textbf{GeV}^2}\right)^2\left(\frac{\alpha_s(q_0)}{0.255}\right)^4\left(\frac{3\,\textbf{GeV}}{q_0}\right)^9 .$$

In this case $M^2 \sim 100\,\mathrm{GeV}^2$ and $\zeta \sim 10^{-5}\div 10^{-4}$ where the gluon distribution is much better known: The typical difference between existing parameterizations is of order $\sim 10\%$.

Jets longitudinal momentum distribution

Measurement of the valence quark momentum fraction distribution in a pion – the main motivation for the E791 experiment.

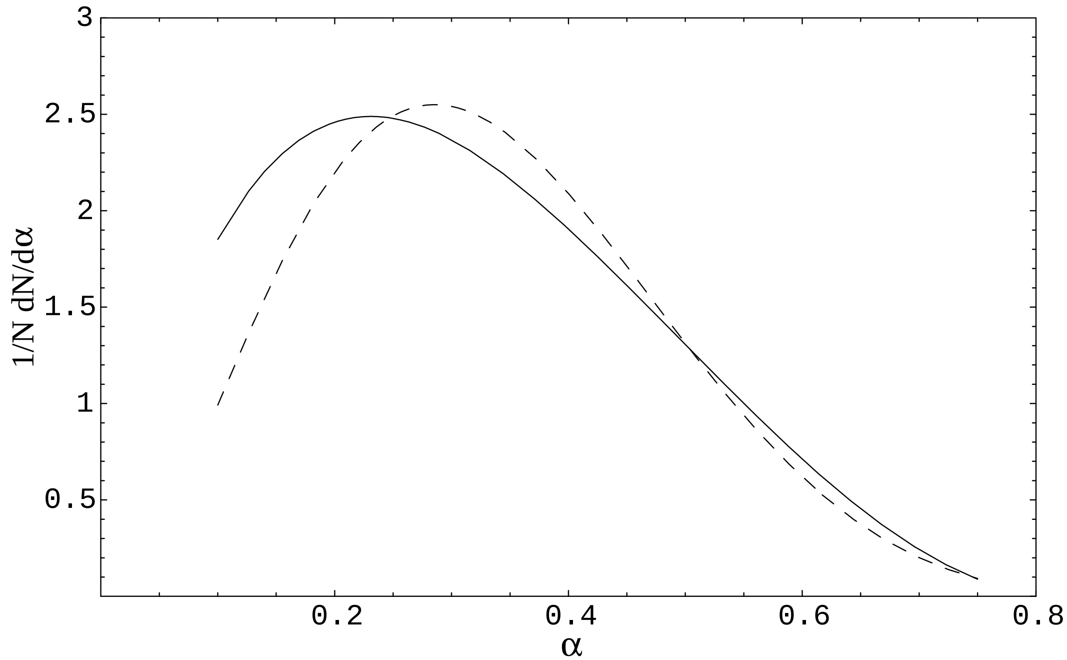
Naively, the longitudinal momentum fraction distribution of the jets is expected to follow that of the valence quarks in the proton: The momentum fraction distribution of a jet, arbitrary chosen in each event, is proportional to the proton distribution amplitude squared

$$\frac{d\sigma}{d\alpha} \sim \int D\alpha' \delta(\alpha - \alpha'_1) |\phi_N(\alpha')|^2 ,$$

where $\phi_N = \mathcal{V} - \mathcal{A}$.

In reality, a hard gluon exchange leads to a certain redistribution of the longitudinal momenta.

Calculated normalized jet momentum fraction distribution (averaged over quark flavors) and one "$\sim$ proton DA squared".



The two distributions are similar, but the one resulting from the QCD calculation is shifted towards lower momentum fractions.

Summary

- **Using k_t factorization we calculate exclusive three-jet production in single diffraction interaction.**
- **The process is sensitive to**
  - **the unintegrated gluon distribution at small x**
  - **leading twist proton distribution amplitudes**
- **observation of the process at LHC is feasible for jet transverse momenta $q_\perp \sim 5$ GeV.**
- **we give cross section estimates for Tevatron energy.**