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KRONOS: A Monte Carlo Event Generator for Higher Order QED Corrections at HERA – Status Report*

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Abstract

We report on the status of the Monte Carlo event generator KRONOS for deep inelastic lepton hadron scattering at HERA. KRONOS focusses on the description of electromagnetic corrections beyond the existing fixed order calculations.

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1 Introduction

At the new *ep* collider HERA a new kinematic range for deep inelastic lepton hadron scattering will be explored[1]. The electroweak corrections to deep inelastic *ep* scattering have been calculated completely to one loop order[2] and have been implemented in a Monte Carlo event generator[3]. The leading logarithms of the next order have also been calculated analytically[4].

On the other hand, radiative corrections become large at very high momentum transfers as well as in certain kinematical regions, and a partial summation of higher-order terms becomes mandatory for reliable predictions.

The leading contributions in processes involving the scattering of high energy electrons originate from logarithms of the form

$$\frac{\alpha}{\pi}\ln\left(\frac{Q^2}{m_e^2}\right) \approx 6.2\% \quad \text{for} \quad Q^2 \approx 10^5\ \text{GeV}^2 \tag{1}$$

where m_e is the mass of the electron.

These leading logarithmic corrections can be summed by using renormalization group techniques well-known from QCD. These methods are directly applicable to QED inclusive radiative corrections where the outgoing photons are not individually detected. In this approach the cross section with inclusive radiative corrections is obtained by folding the Born cross section with a so-called radiator $e(\xi, Q^2)$

$$\sigma(l) = \int_0^1 d\xi\, e(\xi, Q^2)\sigma_{Born}(\xi l) \tag{2}$$

where l is the momentum of the incoming electron, Q^2 is the characteristic momentum transfer in the process and ξ is the fraction of the initial electron momentum left after photon radiation. The radiator $e(\xi, Q^2)$ is obtained as the solution of the evolution equation

$$\begin{aligned} Q^2\frac{\partial}{\partial Q^2}e(\xi,Q^2) &= -\frac{\alpha}{2\pi}\left[\int_0^{1-\epsilon} d\zeta P(\zeta)\right]e(\xi,Q^2) \\ &+ \frac{\alpha}{2\pi}\int_\xi^{1-\epsilon}\frac{d\zeta}{\zeta}P(\zeta)e\left(\frac{\xi}{\zeta},Q^2\right) \end{aligned} \tag{3}$$

with the initial condition

$$e(\xi, m_e^2) = \delta(1-\xi)\ , \tag{4}$$

and the splitting function

$$P(\zeta) = \frac{1+\zeta^2}{1-\zeta}\ . \tag{5}$$

The infrared regulator $\epsilon \ll 1$ will drop out in the final results.

This method may also be extended to describe the inclusive radiative corrections due to emission of photons off the outgoing electron.

However, aiming at the construction of an event generator for the analysis of HERA experiments, it is necessary to describe the individual photons. Since the renormalization group sums the leading logarithms (1), arbitrarily high orders in α are involved and thus a corresponding event generator must be capable of generating multiphoton final states.

2 The Monte Carlo generator KRONOS

The Monte Carlo event generator **KRONOS** [5] simulates *ep* scattering at HERA energies including leading logarithmic QED corrections due to radiation off lepton lines summed to all orders in α. For the radiation of photons off the incoming lepton, **KRONOS** uses a cascade algorithm similar to space-like parton showers in QCD. The branching of the incoming electron is implemented in the following way. First the number of photons is generated according to a Poisson distribution with mean

$$\bar{n} = \frac{\alpha}{2\pi}\ln\left(\frac{Q^2}{m^2}\right)\int_0^{1-\epsilon} dz P(z). \tag{6}$$

The energies of the generated photons are determined according to the splitting function (5), while the transverse components of the photon momenta are determined by a probability distribution according to the pole in the electron propagator $1/2l\cdot k$.

The procedure is repeated as many times as the number of photons in the corresponding event, taking into account the appropriate ordering of virtualities to obtain the leading logarithmic contribution.

For the radiation of photons off the outgoing lepton the corresponding time-lik showering algorithm is used.

In **KRONOS** the leading contributions to the radiatively corrected cross section ar split into two channels with different Born cross sections. The first channel is the usua neutral current reaction

$$e + p \rightarrow e' + X \tag{7}$$

where X denotes some hadronic final state. The other channel takes into account the so-called Compton events

$$e + p \rightarrow e' + \gamma + X \tag{8}$$

which are characterized by a high p_T electron and photon with little hadronic activity. In the first reaction the large momentum transfer is given by the exchanged boson, while in the latter reaction the exchanged photon is close to its mass shell and the intermediate far off-shell electron sets the scale.

The radiative corrections due to photon emission are implemented as follows: Firstly, **KRONOS** generates the momenta of the radiated photons and the resulting electron momentum after initial state radiation. This electron momentum is used as input for the hard scattering process. After the hard scattering, the photons corresponding to final state radiation are generated and the final electron momentum is calculated.

The electromagnetic radiation from the incoming and outgoing quark can be treated in the same spirit. However, this contribution is significantly smaller, since the leading collinear QED singularity is to be absorbed into the parton distributions. Furthermore it can be separated in a gauge invariant way, therefore we will not consider it.

3 Features of KRONOS

Version 1.1 of **KRONOS** treats initial and final state radiation off the electron by the cascade algorithm described above.

The radiatively corrected cross section is split into two channels which may be switched on and off separately: the standard neutral current reaction and the Compton process.

The initial state proton is described in terms of quark distributions, for which the present release contains a set of commonly used parametrizations, or in terms of model independent structure functions F_i. In the latter case, no outgoing hadrons are generated.

KRONOS may also be forced to generate at most one photon, which is useful for comparisons with $O(\alpha)$-calculations as well as for estimates of the magnitude of the higher-order corrections.

4 Results from KRONOS

As a first example we consider the QED radiative corrections to the cross section expressed in terms of the so-called Jaquet-Blondel variables, which are obtained from a measurement of the outgoing hadrons. In this case the leading radiative corrections

are only due to emission of photons collinear to the incoming electron, while final st radiation does not influence the kinematics at the hadronic vertex. Therefore th variables are very inclusive with respect to corrections due to emission of the lept line.

Figure 1 shows the radiative corrections, defined by

$$\delta = \left(\frac{d^2\sigma}{dx_{\rm JB}\, dy_{\rm JB}} \Big/ \frac{d^2\sigma_0}{dx\, dy} \right) - 1 \, , \qquad (\,$$

as a function of $y_{\rm JB}$ for different fixed values of $x_{\rm JB}$. They are almost flat functions both $x_{\rm JB}$ and $y_{\rm JB}$ and become only large for $y_{\rm JB} \rightarrow 1$. The lowest-order correctior (open symbols) agree within statistical errors with the analytical calculation of [6]. Th higher-order corrections turn out to be quite small except in the kinematic region wher $y_{\rm JB}$ is close to 1, because this region is dominated by the emission of soft photons, an therefore the resummation of multiple photon emission becomes important.

Next we calculated the corrections in the usual Bjorken variables x and y. It is wel known that the QED corrections to neutral current ep scattering enhance the cross section for very small x and for $y \rightarrow 1$, while they decrease the cross section for $x \rightarrow$ and for $y \rightarrow 0$.

In figure 2 we plotted the ratio of the radiatively corrected cross section to the lowest order cross section in the bin $0.4 < x < 0.6$. The broken line denotes the result from the calculation where at most one photon is emitted, while the full line represents the **KRONOS** result to all orders. For small y this ratio is significantly smaller than 1 therefore the radiative corrections are large and negative; furthermore the higher-order corrections are large since this kinematic region is again dominated by the emission of multiple soft photons.

Figure 3 shows the same ratio in the bin $0.75 \cdot 10^{-3} < x < 1.25 \cdot 10^{-3}$. For compariso with $O(\alpha)$ calculations, we used the parton distributions of Duke and Owens. In the range of considered values of y, the corrections are positive. For small values of y the higher-order corrections are again sizable; the enhancement being due to multiple emission of collinear photons.

We now turn to more exclusive observables. In figure 4 we plotted the angular distribution of photons from radiative events satisfying

$$0.075 < x < 0.125 \quad \text{and} \quad 0.8 < x < 0.9 \tag{10}$$

with at least one photon above 0.5 GeV, which has already been discussed in [7] The cross section clearly shows three peaks which correspond to different kinematica situations: Firstly, the photons emitted at very small angles are almost collinear to the incoming electron. Secondly, the narrow peak around 150° corresponds to photons almost collinear to the outgoing electron. Thirdly, the photons in the broad peak around 70° originate from the so-called Compton events.

As a consequence of higher-order radiative corrections there are also final states with more than one photon. In order to estimate the experimental relevance of those events, we estimated the cross section for multiple resolved photons using a simplified model of the ZEUS and H1 detectors at HERA.

We required that we have a reconstructed electron with x and Q^2 in the range

$$10^{-3} < x < 10^{-1} \quad \text{and} \quad Q_e^2 > 100\ \mathrm{GeV}^2\ , \tag{11}$$

the photons are registered either in the main detector

$$150\,\mathrm{mrad} < \angle(\gamma, e^-\text{-beam}) < \pi - 100\,\mathrm{mrad} \tag{12}$$

or in the luminosity monitor

$$\begin{aligned} \angle(\gamma, e^-\text{-beam}) &< 0.5\,\mathrm{mrad} \quad \text{or} \\ \angle(\gamma, p\text{-beam}) &< 0.5\,\mathrm{mrad}, \end{aligned} \tag{13}$$

and the photons must be well separated from the scattered electron

$$\angle(\gamma, e^-) > 150\,\mathrm{mrad} \tag{14}$$

and from the hadronic jet

$$\angle(\gamma, \text{jet}) > 300\,\mathrm{mrad}\ . \tag{15}$$

Figure 5 shows the spectrum of the hardest photon (lightly filled histogram) and of the second hardest photon (darkly filled histogram) for events with at least two photons above 0.5 GeV. For comparison, the unfilled histogram shows the energy distribution of photons in events with exactly one photon above 0.5 GeV.

The photon multiplicity distribution is shown in figure 6 as a function of the minimal required photon energy. Even for a threshold of $E_{\gamma,min} = 3\,\mathrm{GeV}$, we find a cross section of 6-7 pb for events with two photons. Assuming an annual integrated luminosity of 100 pb^{-1}, we expect about 600-700 events of this type per year. The cross section for events with at least three bremsstrahlung photons is however negligible after application of the cuts mentioned above.

In approximately 50% of these two photon events *both* photons end up in the main detector, while less than 10% have both photons in the luminosity monitors.

5 Conclusions and outlook

We have calculated QED radiative corrections beyond $O(\alpha)$ using the Monte Carlo event generator **KRONOS**. The higher-order corrections to inclusive cross sections may become sizable for small y as well as for large y_{JB}. We also found that the cross section for two-photon events using semi-realistic cuts is of the order of 10 pb; therefore events of this type will be accessible at HERA, while events with three or more photons will hardly play any role for realistic energy resolutions.

Only minor internal changes have been implemented in the release 1.2 of **KRONOS**, which can be linked with the **HERWIG** Monte Carlo[8] via the interface code **KROWIG** [9]. This combination opens the possibility to study the effects of higher-order corrections on hadronic final states.

Future releases of **KRONOS** are expected to provide additional features which are currently under study: interfaces to other QCD parton shower and fragmentation Monte Carlos, higher-order corrections to charged current scattering, and the optional generation of suitably weighted event samples.

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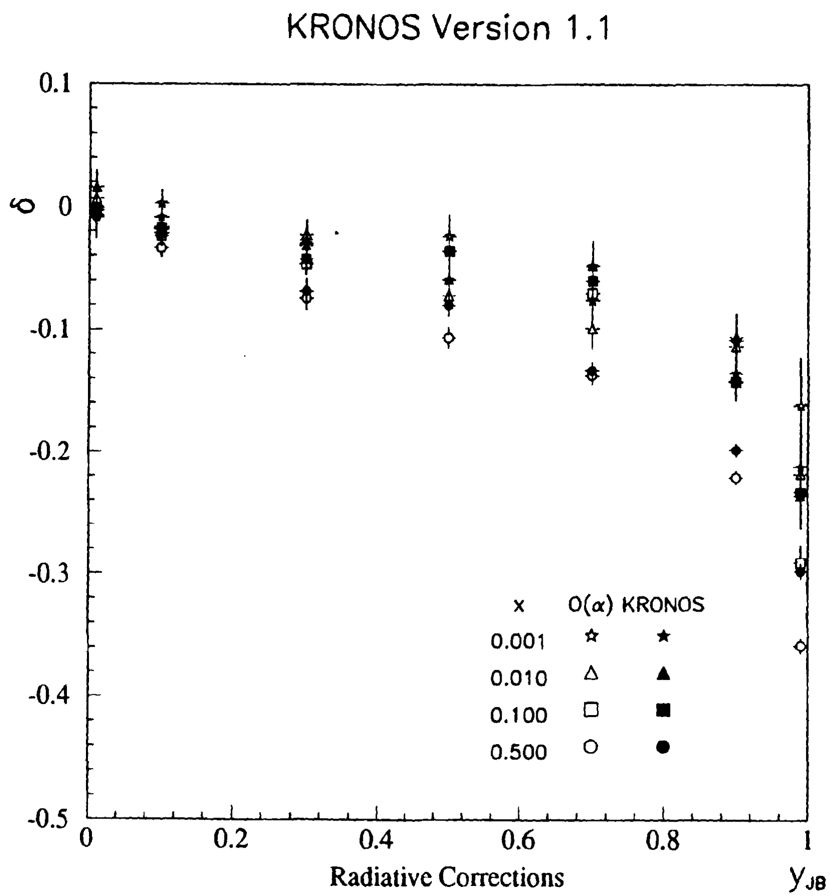

Figure 1: Radiative Corrections to Jaquet-Blondel variables.

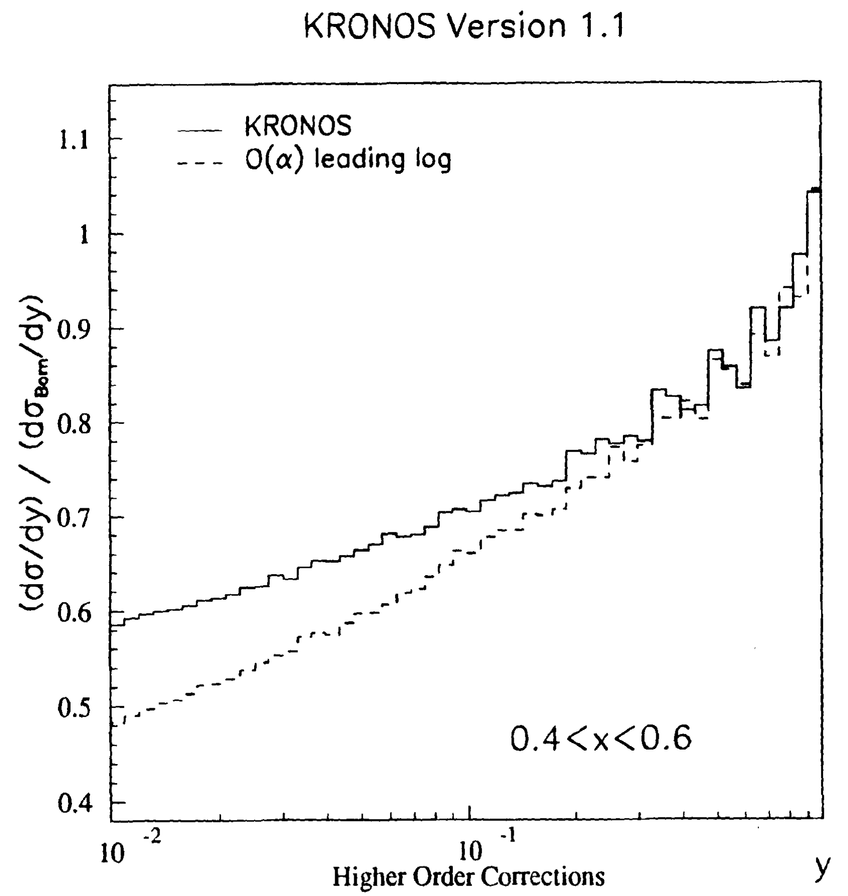

Figure 2: Ratio of the radiatively corrected cross section to the lowest order cross section at large x ($x \approx 0.5$). The broken line shows the leading-log corrections to $O(\alpha)$, the full line is the result from KRONOS.

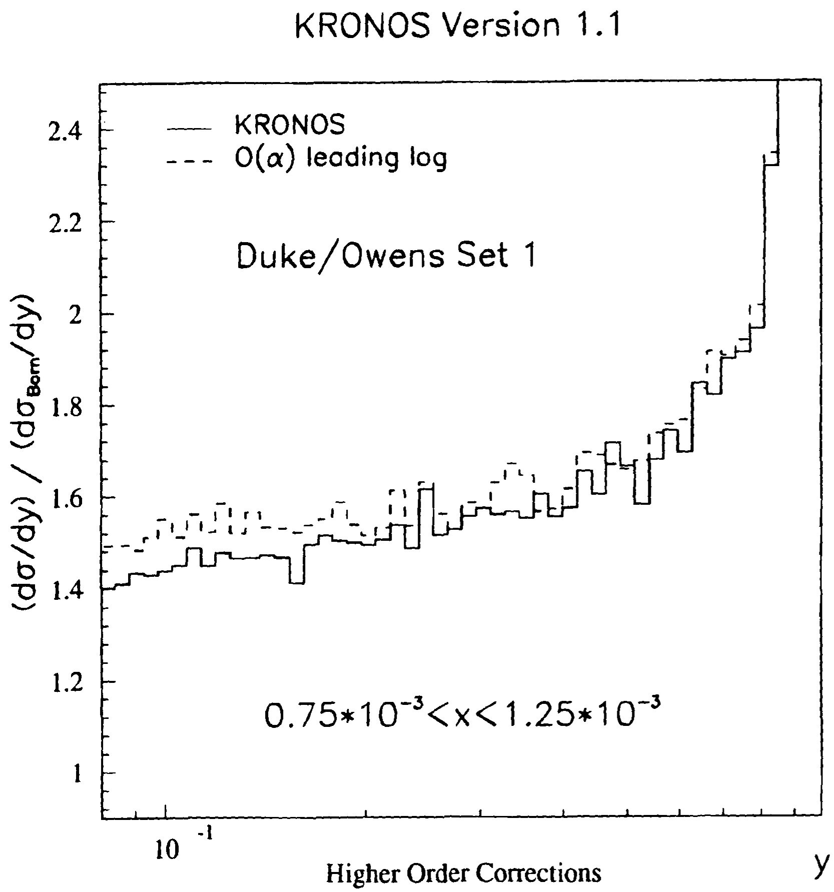

Figure 3: Ratio of the radiatively corrected cross section to the lowest order cross section at small x ($x \approx 10^{-3}$). The broken line shows the leading-log corrections to $O(\alpha)$, the full line is the result from **KRONOS**.

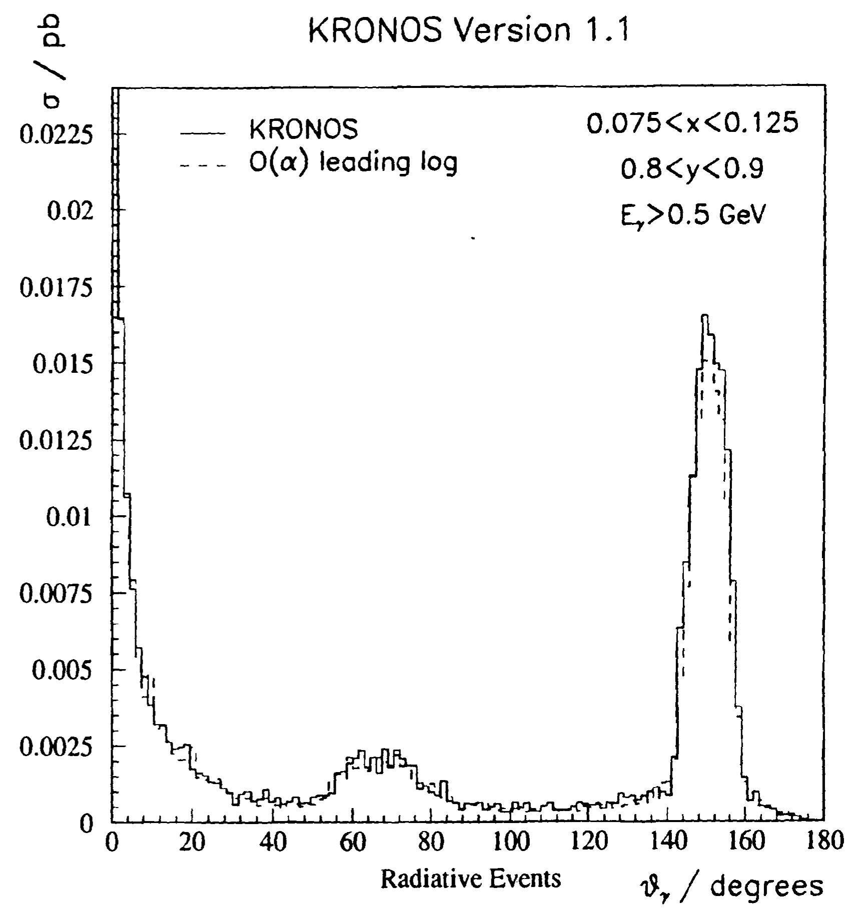

Figure 4: Angular distribution of photons in radiative events with at least one photon above 0.5 GeV.

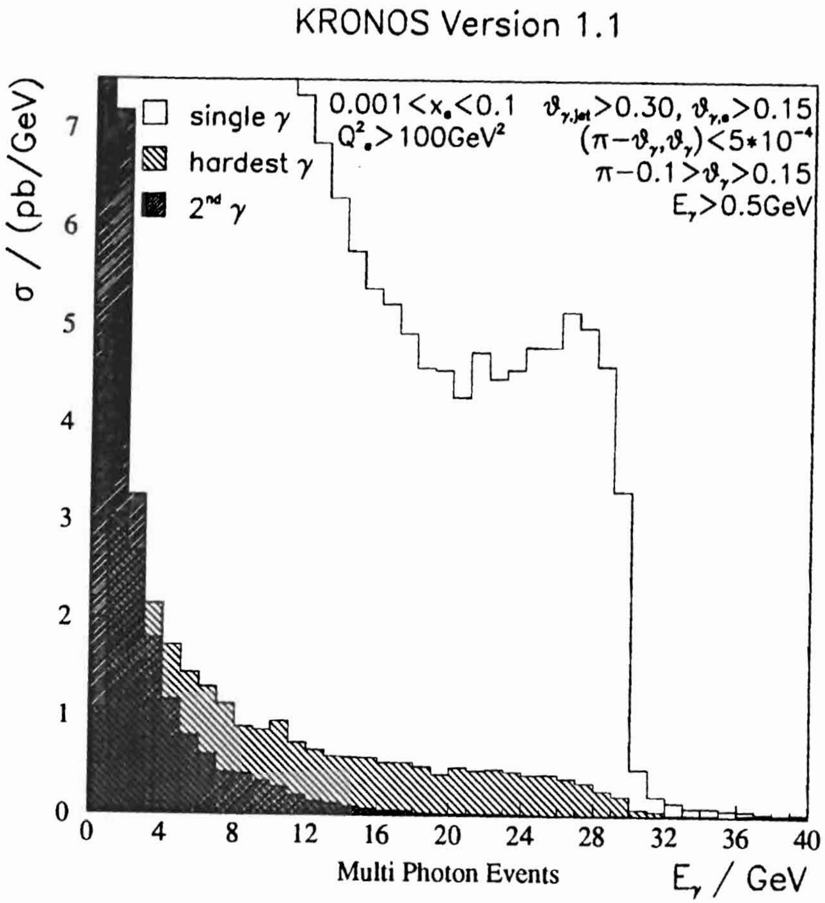

Figure 5: Energy distribution of the hardest and second hardest photon in multiphoton events.

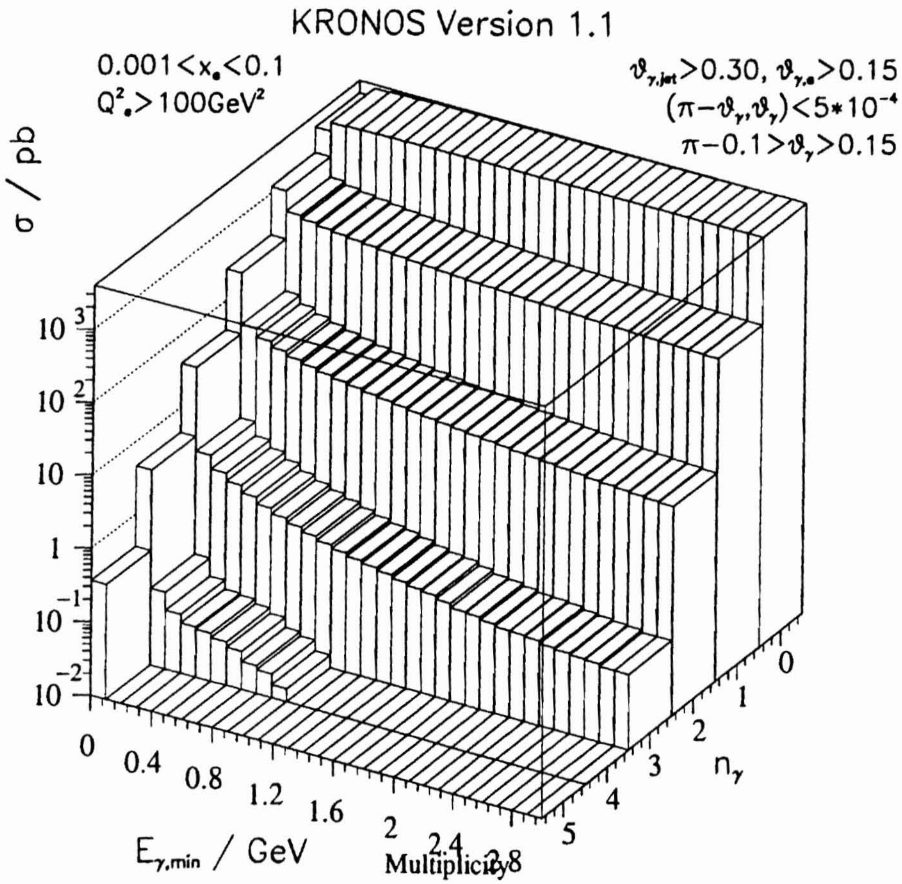

Figure 6: Photon multiplicity distribution vs. energy resolution.