Hard probes and the event generator EPOS

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Abstract. After a short presentation of the event generator EPOS, we discuss the production of heavy quarks and prompt photons which has been recently implemented. Whereas we have satisfying results for the charm, work on photons is still in progress.

1. Introduction

Today, there is a large amount of data from p-p, Pb-Pb and recently p-Pb collisions at the LHC which need to be interpreted. EPOS, based on 'Parton-based Gribov-Regge theory' [1], aims to reproduce a large range of LHC observables like jets, multiplicity or collective behavior. We will discuss the recent implementation of charm and prompt photons in this event generator. We want hard probes production to be under control for p-p collisions and then, use them for the study of the QGP.

First, we will quickly show the general features of EPOS. Then the charm production will be detailed and finally our projet on prompt photons will be exposed.

2. General presentation

Some important features of EPOS are :

- (i) Being a real event generator
- (ii) Multiple interactions based on a quantum formalism
- (iii) Perturbative calculation with resummation of collinear corrections at the order $\left(\alpha_s(Q^2)\ln(\frac{Q^2}{\mu^2})\right)^n$
- (iv) Core-corona separation
- (v) Hydrodynamics done event by event
- (vi) Hadronisation done using a string fragmentation model for the core

By "being a real event generator", we mean that one event in the LHC $\simeq$ one event in EPOS. The program will generate pions even if one is only interested in charm. All particles are registered in a table and, at the end, one has to select particles of interest.

Our model for multiple interactions is based on a marriage of Gribov-Regge theory [2, 3] and pQCD. It gives the possibility of a quantum treatment of multiple interactions. By "based on Gribov-Regge theory" we mean an assumption about the structure of the T matrix, expressed in terms of elementary objects called Pomerons (not the same object in EPOS and Gribov-Regge theory). The total cross section can be expressed as illustrated on figure 1.

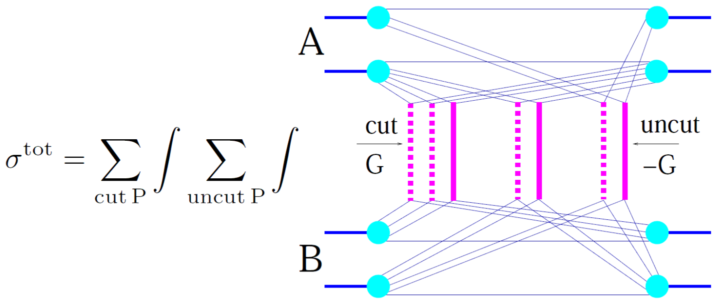

Figure 1. Pink lines : pomerons. A and B are nuclei. Small horizontal lines are remnants.

Partial summation provides exclusive cross sections. In Gribov-Regge theory, the elastic amplitude is given by :

$$A_{2\to 2}(s,t) = \sum_n A_n(s,t) \tag{1}$$

with $A_n(s,t)$ corresponding to the amplitude for n pomeron(s) exchange. Following the same idea, we can defined σ_m corresponding to the cross section for m cut pomerons. A cut pomeron, figure 6, is at the origin of particles production. The multiplicity is then, on the average, proportional to :

$$N \propto m \sum_m \sigma_m \tag{2}$$

The treatment is the same for p-p, p-A or A-A collisions.

The hydrodynamical evolution is done event by event. Initial conditions are given by the distribution of cut pomerons which correspond to color flux tubes, figure 2. Flux tubes fragment into string pieces which will later constitute particles. These flux tubes will constitute both bulk matter (if the energy density is high enough) and jets. "Matter" is defined by the region of high energy density flux tubes (the blue region figure 3). Then, there are 3 possibilities :

(i) The string piece (the red one) is formed outside the "matter". In that case, it simply escapes as a jet.

(ii) The string piece (the pink one) is formed inside the "matter" but has not enough energy to escape. It constitutes the "matter" and will evolve with the hydrodynamical code.

(iii) The string piece (the blue one) is formed inside the "matter" and has enough energy to escape (based on energy loss argument). It escapes as a jet which has interacted with the fluid.

For more details, see [4, 5].

With these prescriptions, we can reproduce the v_2 for identified particles or the ridge, even for p-Pb collisions (figure 4 and figure 5).

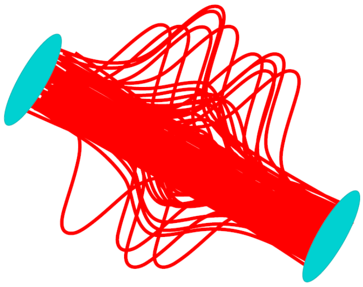

Figure 2. Cut pomerons form color flux tubes between the 2 nuclei.

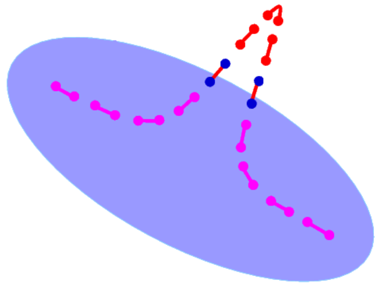

Figure 3. Color flux tubes fragment into string piece. The blue region is "matter" formed by high energy density flux tubes.

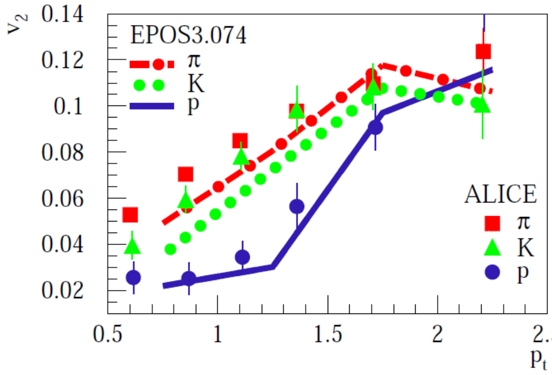

Figure 4. (Color online) Elliptical flow coefficients v2 for pi- ons, kaons, and protons. We show ALICE results (squares) and EPOS3 simulations (lines). Pions appear red, kaons green, protons blue.

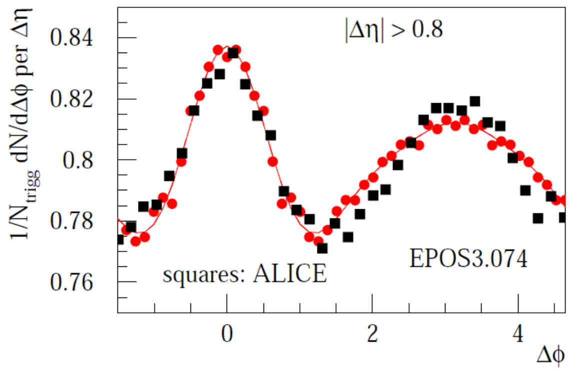

Figure 5. (Color online) Associated yield per trigger, pro- jected onto $\Delta\phi$, for $|\Delta\eta| > 0.8$. We show ALICE results (black squares) and EPOS3 simulations (red dots).

3. Charm production

A charm can be produced during the spacelike cascade, the born process, the timelike cascade (partonic shower) and the string fragmentation, see figures 6 and 7. Based on DGLAP formalism, spacelike and timelike cascades resumme collinear divergences.

During the spacelike cascade, a spacelike parton emits timelike particles until he reaches the born process. In the leading log approximation, virtualities are strongly ordered :

$$Q_1^2 \ll Q_2^2 \ll ... \ll Q_{born}^2 \tag{3}$$

We use the following probability distribution for variables Q^2 and x :

$$\frac{dP(Q_0^2, Q^2, x)}{dx dQ^2} \propto \frac{\alpha_s}{2\pi} \frac{p(x)}{Q^2} \Delta(Q_0^2, Q^2) \qquad Q_0^2 < Q^2 \tag{4}$$

where $p(x)$ are the appropriate splitting functions and x is the fraction of the parent parton light cone momentum k^+ :

$$k'^+ = x k^+ \tag{5}$$

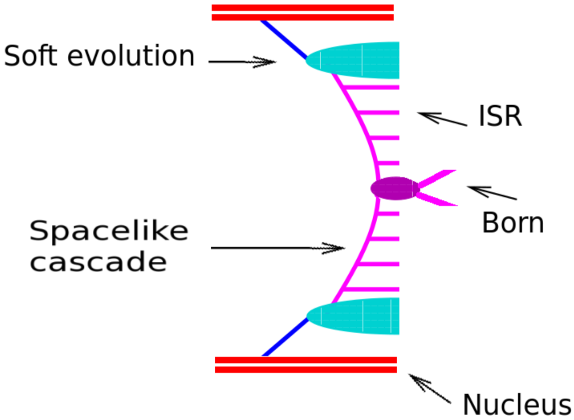

Figure 6. A cut pomeron. The center of the pomeron is a (pQCD) ladder diagram.

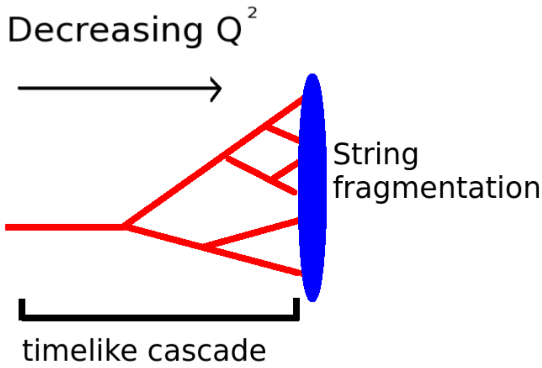

Figure 7. Partonic shower and hadronization by string fragmentation.

$\Delta(Q_0^2, Q^2)$, the Sudakov form factor, gives the probability for no resolvable emissions between Q_0^2 and Q^2. In text books one can find :

$$r^2 = \frac{(1-x)}{x} Q^2 - \frac{p_t^2}{x} \tag{6}$$

r being the 4-momentum of the emitted (timelike) parton and p_t its transverse momentum. Usually one takes $r^2 = 0$, but for heavy quarks we choose :

$$r^2 = m^2 \tag{7}$$

which implies :

$$x < \frac{Q^2}{Q^2 + m^2} \tag{8}$$

The phase space for radiating a heavy quark is smaller than the one for light partons.

The born process, in the center of the ladder, is nothing else that the leading order cross sections for α_s^2, $\alpha_s \alpha_{el}$ and α_{el}^2 processes.

Outgoing on-shell partons ($r^2 = 0$) is an approximation. Out-born partons and those emitted during the spacelike cascade have a finite virtuality :

$$Q_{max}^2 \sim p_t^2 + m^2 \tag{9}$$

During the timelike cascade (partonic shower) these partons will loose their virtuality by doing successive splittings. This cascade is stopped when $Q^2 \sim \Lambda_{QCD}^2$. The leading log approximation is used and angular ordering [6, 7] is implemented. The emission probability is :

$$\frac{dP(Q_0^2, Q^2, z)}{dx dQ^2} \propto \frac{\alpha_s}{2\pi} \frac{p(z)}{Q^2} \Delta(Q_0^2, Q^2) \qquad Q_0^2 > Q^2 \tag{10}$$

z being the splitting variable defined as :

$$z = E_{children}/E_{parent} \tag{11}$$

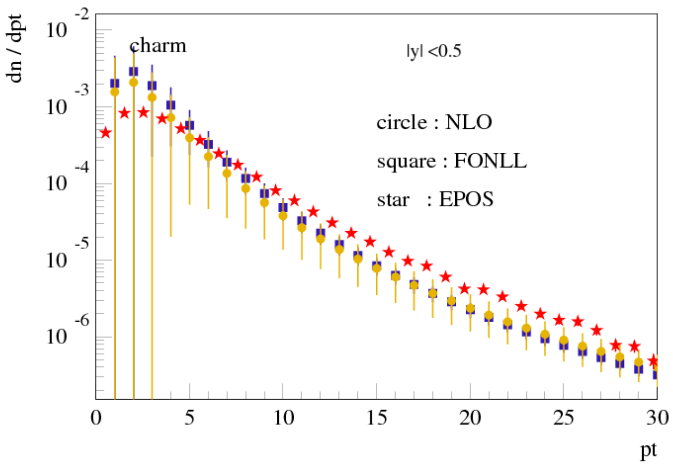

Figure 8. charm from Cacciari vs EPOS.

For the implementation of charm production, no parameters have been changed. Our first test is the comparison with FONLL calculations of M. Cacciari [8], figure 8. At high p_t the shape is the same but our central values are higher. Next, we test EPOS for $D+$ and $D0$ mesons, by comparing our results with the Alice experiment [9] and FONLL calculation, figure 9 and figure 10.

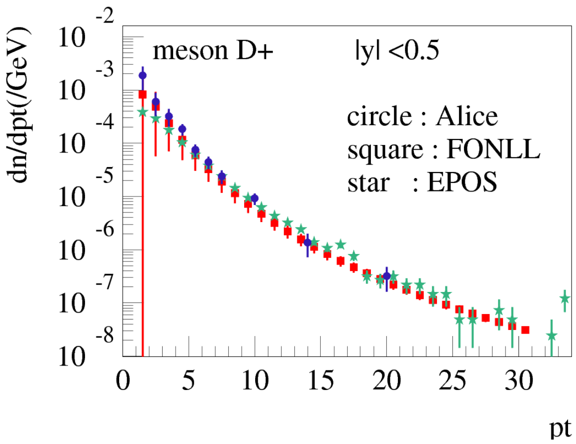

Figure 9. D+ yield from EPOS compare to FONLL calculation [8] and Alice experiment [9].

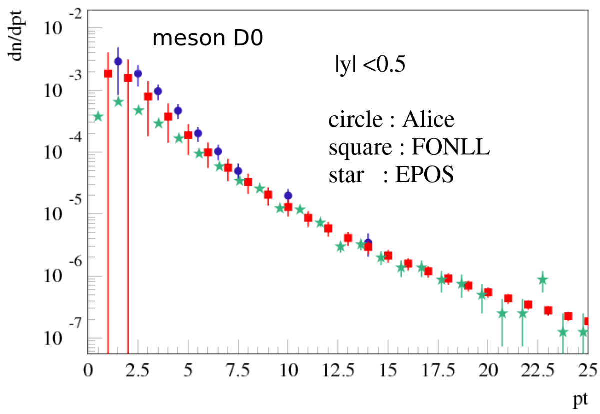

Figure 10. D0 yield from EPOS compare to FONLL calculation [8] and Alice experiment [9].

EPOS uncertainties account only for statistics and there is no charm production during the string fragmentation. Our results are globally in good agreement with Alice and FONLL. However, charm quarks are missing at very low p_t. The explanation could be that charm production during the timelike cascade is too small. In the game of fitting data, we can reproduce Alice results by allowing charm production in string fragmentation (one parameter is changed), figure 11.

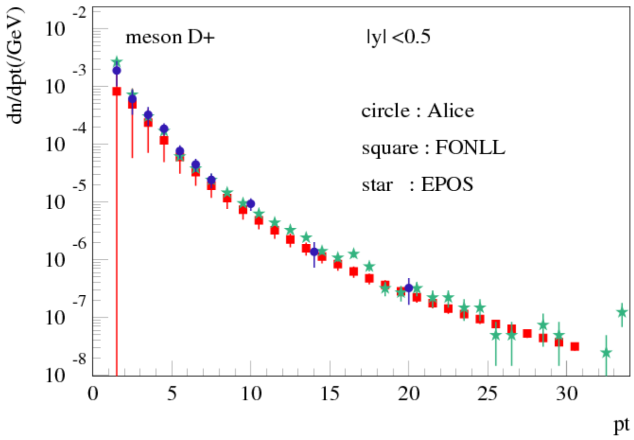

Figure 11. D+ from EPOS with $c\bar{c}$ creation during strings fragmentation.

4. Prompt photons

We want to :

(i) Study isolation criteria

(ii) Compare EPOS and Jetphox

(iii) Use EPOS for γ/jet and $\gamma/hadron$ correlations

Photons production in the born process was already implemented, but it was not the case for the spacelike and the timelike cascade. It has been done with the same formalism used for partons i.e based on the probability eq. 4. One needs to replace α_s by α_{el} and use the appropriate splitting function. The splitting of a photon into a pair of particle-antiparticle is neglected.

Like in experiments, we have an isolation condition on selected photons. Using the table where final particles are registered, we define a cone of radius R around the photon candidate. If the sum of transverse energy of particles in this cone is smaller than a given value (5 GeV for CMS [10]), then the photon is isolated. Here, the fact that EPOS is experiment like is important. In Jetphox, the addition of this isolation criteria gives a non-physical rise of the cross section with $1/R$ [11].

Work on photons is still in progress. Fragmentation photons are strongly suppressed due to isolation requirement, whereas $\sim 98\%$ of direct photons are isolated, table 1.

Comparison with CMS [10], figure 12, shows that our yield seems to be too low by approximately a factor of 1.5. Comparison with Jetphox will give precious information which, I hope, will allow us to improve our results for photons.

Table 1. Pourcentage of isolated direct photons as a function of transverse mometum for the isolation criteria used by CMS [10] ($R = 0.4$, $\sum p_t < 5$GeV).

p_t	# of isolated direct photons/# of direct photons
11	0.972
13	0.981
15	0.971
17	0.973
19	0.976
21	0.992
23	0.947
25	0.991
27	0.976
29	0.966
31	0.977
33	0.978
35	0.978

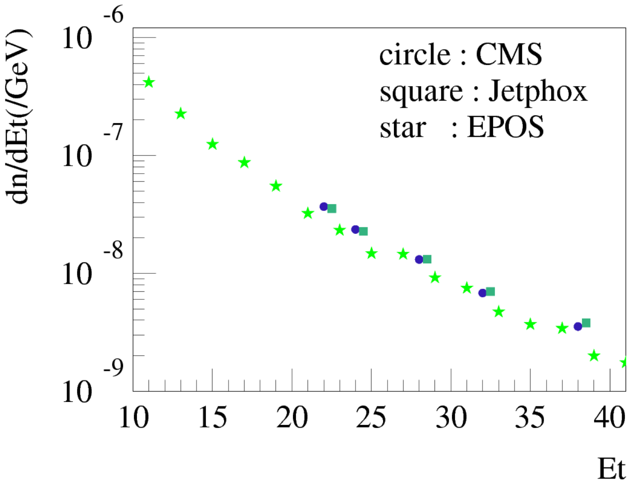

Figure 12. Isolated photons. For more clarity, a +0.5 shift (x axis) is used for Jetphox data.

5. Conclusion

A unified formalism in EPOS is one of its strengths. Heavy quarks and prompt photons production are based on the same equations with the same parameters. Whereas the work on charm is nearly finished, prompt photons physics still need to be improved. We already have very good results for flow [5, 12], and with the implementation of hard probes, EPOS could be an excellent tool for the study of the QGP.

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References

[1] Drescher H J, Hladik M, Ostapchenko S, Pierog T and Werner K 2001 *Phys. Rep.* **350** 93
[2] Gribov V N 1968 *Sov. Phys. JETP* **26** 414
[3] Werner K 1993 *Phys. Rep.* **232** 87

[4] Werner K, Karpenko I, Bleicher M, Pierog T and Porteboeuf-Houssais S 2012 *arXiv 1203.5704v2*
[5] Werner K, Bleicher M, Guiot B, Karpenko I and Pierog T 2013 *arXiv 1307.4379v1*
[6] Webber B R 1984 *Nuclear Physics B* **238** 492
[7] Marchesini G and Webber B R 1984 *Nuclear Physics B* **238** 1
[8] Cacciari M, Greco M and Nason P 1998 *arXiv hep-ph/9803400*
[9] Alice collaboration 2012 *arXiv 1111.1553v2*
[10] CMS collaboration 2011 *arXiv 1012.0799v2*
[11] Catani S, Fontannaz M, Guillet J Ph and Pilon E 2002 *arXiv hep-ph/0204023*
[12] Werner K, Guiot B, Karpenko I and Pierog T 2013 *arXiv 1312.1233*