New Developments in EPOS:
Parton Saturation

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Key elements of EPOS3 (model for pp, pA, AA)

Energy conserving multiple scattering

Parton ladders (multiple)

Off-shell (excited) remnants

Saturation (NEW)

3 dim viscous EbyE hydro (NEW) + hadronic afterburner
Energy conserving multiple scattering

Saturation
Energy conserving multiple scattering and saturation are very closely related, both necessary for a consistent multiple scattering scheme.
“Historical” result, showing need of better understanding of multiple scattering

\[ \text{pp@1800GeV} \]
\[ \text{data: CDF} \]

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many more
“multiple scattering” sensitive observables measured at the LHC
J / Psi yield versus charged multiplicity
(ALICE, CERN-PH-EP-2012-021)
Recent LHC pp publications (mainly ATLAS, CMS, LHCf) usually compare with

- Pythia tunes
- three “Cosmic ray models” including EPOS

EPOS works quite well, partly thanks to multiple scattering
What makes EPOS very different compared to models like Pythia?
Two fundamentally different approaches

(1) Starting from the factorization formula,

\[ \sigma_{\text{inclusive}} = f(x^+, M^2) + f(x^-, M^2) \]

one “reconstructs” multiple scattering such that factorization is reproduced;

PDFs f are input
(2) Starting from a Gribov-Regge multiple scattering Ansatz, one ends up (if things are done properly) with

factorization for $\sigma_{\text{inclusive}}$ (pp, AA)

binary scaling (AA, also pp)

PDFs are outcome, also $\sigma_{\text{tot}}, \sigma_{\text{el}}$ and much more
Some history of GRT:

  \( pp = \) multiple exchange of “Pomerons” (parametrized amplitudes)

- 1980-1990: pQCD processes added into GRT scheme (Capella)

- 1990: M.Braun, V.A.Abramovskii, G.G.Leptoukh: problem with energy conservation (not done consistently)

Multiple scatterings (in parallel !!)
in pp, pA, or AA

Single scattering
= hard elementary scattering including IS + FS radiation

\[ \sum x_i^\pm + x_{\text{remn}}^\pm = 1 \]

Multiple scatterings (in parallel!!) in pp, pA, or AA

Single scattering

= hard elementary scattering including IS + FS radiation

\[ \sum x_i^\pm + x_{\text{remn}}^\pm = 1 \]
Nice: pA and AA is a straightforward generalization of pp (at least concerning the initial stage)

one cannot separate pp, pA, AA (initial)
Picture is not yet complete (Clear from the beginning) in particular visible in pA, AA

- Introducing energy conservation (which is a must)

- one generates a violation of “binary scaling”,

\[ R_{AA} = \left. \frac{dn}{dp_t} \right|_{AA} / \left( N_{\text{coll}} \left. \frac{dn}{dp_t} \right|_{pp} \right) = 1 \]

in pA, AA (photons) at high pt (observed), and too little violation at low pt

We have a model for low and high pt!
NSD p+Pb 5.02 TeV  
data: ALICE  
charged particles
scaled parton distributions
( primary partons)

$p+Pb$
at 5.02TeV

centralities (in%): 0-5,10-20,20-30,30-40,40-50,50-60,60-70

$p p$

$1/N_{coll} \frac{dN}{dy} \frac{dp_t}{dp_t}$ (c/GeV)

transv. momentum $p_t$ (GeV/c)
Missing:

**nonlinear effects**

Already needed in pp: total cross section, \( \frac{dn}{dy(0)} \) explode at high energy.
First attempt to solve the problem (in EPOS1 and EPOS2)

Computed amplitude for parton ladder is multiplied by a factor

\[ \times (x^+)^{\epsilon_P} (x^-)^{\epsilon_T}, \]

\[ x^\pm : \text{light cone momenta of “outer” partons} \]
The exponents $\varepsilon$ depends on

- energy
- impact parameter
- the environment (nucleons around in AA)

Easy to implement, works to some extent, but at the end ...

despite introducing quite a few parameters, the “binary scaling problem” was not solved (clearly visible in pPb)
New solution
based on the saturation scale $Q_s$

L. McLerran, R. Venugopalan, Yu. Kovchegov,
J. Jalilian-Marian, A. Kovner, A. Leonidov, H. Weigert,
E. Iancu, D. Kharzeev, E. Levin, M. Nardi, ...
Nucleus-nucleus collisions:

For a parton ladder connected to projectile nucleon $i$ and target nucleon $j$, one defines the “participant number”

\[ N_{\text{part}}(i, j) = \max \left\{ N_{\text{part}}^{\text{targ}}(i), N_{\text{part}}^{\text{proj}}(j) \right\} \]

with

- $N_{\text{part}}^{\text{proj}}(j)$: number of proj nucleons “interacting” with $j$
- $N_{\text{part}}^{\text{targ}}(i)$: number of target nucleons “interacting” with $i$

(For a given Monte Carlo configuration)
The usual “soft” scale

\[ Q_0^2 = 4 \text{GeV}^2 \]

is replaced by

\[ Q_s^2 = Q_0^2 \left( 1 + B_{\text{satur}} N_{\text{part}}(i, j) \right) \]

So each parton ladder has “its own” saturation scale, depending on the number of connected participants

We will use \( B_{\text{satur}} = 0.6 \)
**Proton-proton:**

Number of scatterings depends on $b$

Centrality dependent saturation scale:

$$Q_s^2 = Q_0^2 \left(1 + B_{satur} n_{part}(b)\right)$$

with some “good guess” of the average number of “participating partons” $n_{part}(b)$.

**To have a unique procedure:**

In AB one still counts the participants, but each participant gets a “weight” $n_{part}(b)$ when computing of $N_{part}(i, j)$. 
We use

\[ n_{\text{part}}(b) = f(A_{\text{satur}} e^{-b^2/4\pi\lambda}), \]

where \( e^{-b^2/4\pi\lambda} \) is our “usual” \( b \)-dependence, and with

\[ f(x) = \frac{x}{1 - \exp(-x)}. \]
Results
PbPb with constant scale $Q_0$

scaled parton distributions
( primary partons )

Pb+Pb
at 2.76 TeV
centralities (in%):
0-5, 10-20, 20-30, 30-40, 40-50, 50-60, 60-70

$\frac{1}{N_{\text{coll}}} \frac{dN}{dy} \frac{d^2p_T}{dp_T^2} \text{ (c/GeV)}$

transv. momentum $p_T$ (GeV/c)
... with saturation scale

$1/N_{\text{coll}} \frac{d^2N}{dy dp_t} (c/GeV)$

-2
-3
-4

$\frac{dN}{dy dp_t} (c/GeV)$

pp

scaled parton distributions
(primary partons)

Pb+Pb
at 2.76 TeV

centralities (in%):
0-5, 10-20, 20-30,
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$Q_s$

transv. momentum $p_t$ (GeV/c)
pPb with constant scale $Q_0$

scaled parton distributions
(primary partons)

\[ \frac{1}{N_{\text{coll}}} \frac{dN}{dy} \frac{dp_t}{d\eta} \, (c/\text{GeV}) \]

$p+\text{Pb}$

at $5.02 \text{ TeV}$

centralities (in%): 0-5, 10-20, 20-30, 30-40, 40-50, 50-60, 60-70

transv. momentum $p_t$ (GeV/c)
... with saturation scale

**Graph:**

- **x-axis:** transv. momentum $p_t$ (GeV/c)
- **y-axis:** $1/N_{coll} \, dN/dy \, dp_t$ (c/GeV)

**Legend:**
- **pp**
- **scaled parton distributions** (primary partons)
- **p+Pb at 5.02 TeV**

**Centralities (in%):**
- 0-5, 10-20, 20-30, 30-40, 40-50, 50-60, 60-70, 70-80
Charged particle production in pPb

NSD pPb 5.02 TeV charged particles
EPOS3β no hydro

$|\eta| < 0.3$

data: ALICE

$Q_s$

$Q_0$ const

$R_{pPb}$

$p_t$ (GeV/c)
dependence of $p_t$ spectra in $p\bar{p}$

$$\frac{d^2N}{dp_t d\eta} (c/GeV)^2$$

NSD $p\bar{p}$ 5.02 TeV
charged particles

EPOS3$\beta$ no hydro

Data: ALICE

$|\eta| < 0.3$
$0.3 < \eta < 0.8$ (x4)
$0.8 < \eta < 1.3$ (x16)
dependence of $p_t$ spectra in pPb

\[
\frac{d^2n}{dp_t d\eta} (c/GeV)^2
\]

NSD pPb 5.02 TeV
charged particles
EPOS3$\beta$ no hydro
data: ALICE

hydro

?!?!
"binary scaling" in pp

scaled parton distributions
( primary partons)

$Q_s(Z_{\text{part}})$

saturation at small $p_t$

$1/N_{\text{scatt}} dn/ dy dp_t$ (c/GeV)

pp at 7 TeV

$N_{\text{scatt}}$ : 1 - 3 (solid)
4 - 7 (dashed)
8 - 11 (dotted)
Multiple scattering test in pp:

Correlate multiplicities of hard (D, J/Psi,...) and soft production (low pt pions, charged):

**Binary scaling** =>

$$n_{\text{hard}} \propto N_{\text{scatt}}$$

**Saturation** =>

$$n_{\text{soft}} \lesssim N_{\text{scatt}}$$

(but small effect)
\[ \frac{n_{\text{hard}}}{\langle n_{\text{hard}} \rangle} \]

\[ n_{\text{soft}} / \langle n_{\text{soft}} \rangle \]

Excess at high mult (saturation!!)

roughly linear

see E.G. Ferreiro, C. Pajares, arXiv:1203.5936
Remark concerning particle production in AA:

- At central rapidity, low and high pt particle production is governed by binary collisions.
- At low pt, saturation and energy conservation violate binary scaling, and makes it look like participant one.
- Remnants (wounded nucleons) only contribute at very forward / backward rapidity.

How can one possibly use a so-called “Glauber MC” (a wounded nucleon model) to initialize hydro???
Summary

■ We (finally) get a consistent multiple scattering picture,
  • when energy sharing among parton ladders is accompanied by individual saturation scales $Q_s(N_{\text{part}})$
  • restores binary scaling at high pt in AA, sufficient scale breaking at low pt!!

■ Good basis for studying hydro evolution in pPb, interaction between jets and matter in PbPb ...
Summary

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