String fusion mechanism and studies of correlations

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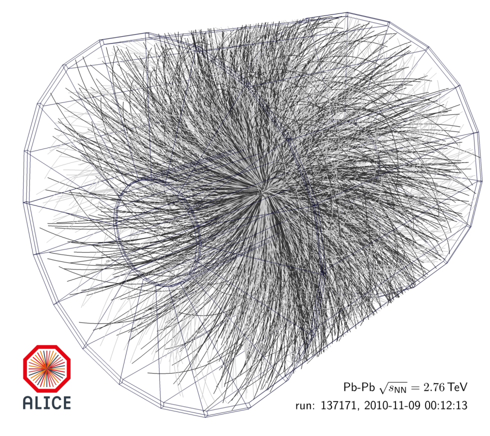
Outline

1. Colour quark-gluon strings as particle emitting sources
2. Monte-Carlo model development and tuning
3. Study of correlations: model results, ALICE data and PYTHIA simulations
4. Summary and outlook

Colour quark-gluon strings as particle emitting sources

Why?

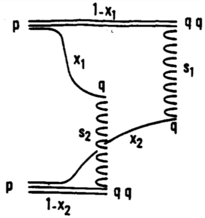


[https://cds.cern.ch/record/2032743]

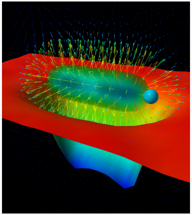
- soft processes predominate in hadron collisions
- impossible to conduct the calculations in perturbative QCD regime
- the largest uncertainties come from the initial stages of the collisions
- phenomenological colour strings approach can deal with it!

Basics

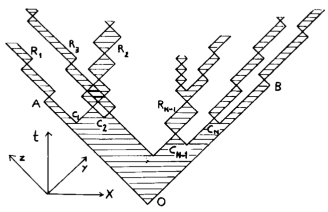
- non-perturbative Regge approach: a unitarity cut of the cylindrical Pomeron diagram → two-chain diagram ↔ two strings formed
- strings stretch between flying outwards wounded partons and are formed by the colour field lines gathered together (gluon self-interaction)
- colour field energy grows with the distance → string fragmentation starts
- strings' remnants: colourless hadrons or new strings that still break with the further expansion



A. Capella, Phys. Rep. **236**, 225 (1994)



P. Varilly, Thesis, MIT (2006).



X. Artru, Phys. Rep. **97**, 147 (1983)

Longitudinal strings dynamics

Initial strings ends' rapidities are defined by proton momentum fraction x_q (extracted from PDFs) carried by partons that form a string:

$$y_q = \text{arcsin}\left(x_q\sqrt{\frac{s}{4m_q^2} - 1}\right). \tag{1}$$

Afterwards, strings are shrinked in the longitudinal direction according to the averaged rapidity loss function:

$$\langle y_{\text{loss}}\rangle = A y_{\text{init}}^{\alpha_2}(\tanh y_{\text{init}})^{\alpha_1-\alpha_2}, \tag{2}$$

where $y_{\text{init}} = |y_1 - y_2|$, with y_1 and y_2 being string's left and right end initial rapidities y_q [C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)]. A, α_1 and α_2 we change while tuning the model to mimic the data.

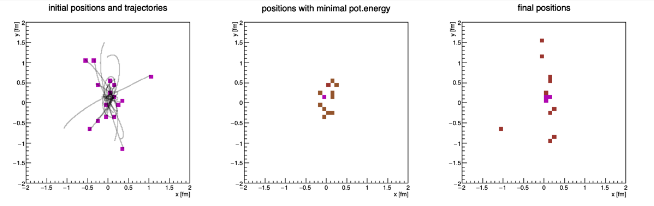
Transverse strings dynamics

We put strings in motion in transverse direction according to system of DE:

$$\ddot{\vec{r}}_i = \vec{f}_{ij} = \frac{\vec{r}_{ij}}{\sqrt{r_{ij}^2 + s_{string}^2}} (g_N \sigma_T) m_\sigma 2 K_1(m_\sigma \tilde{r}_{ij}), \quad (3)$$

where K_1 is a modified Bessel function [T. Kalaydzhyan, E. Shuryak, Phys. Rev. C 90(1), 014901 (2014)].

String evolution can be frozen at the conventional string fragmentation time $\tau = 1.5$ fm/c or at the moment $\tau_{deepest}$ with the global minimum of the potential energy of the system $\leftrightarrow$ fireball creation.



Example of 16 strings movement: left) initial positions and trajectories, middle) position at $\tau_{deepest}$, right) positions at $\tau = 1.5$ fm/c.

String fusion mechanism

Taking into account strings' density evolution in rapidity and transverse plane dimensions, we consider strings interaction in their final configuration:

- having finite size in the transverse plane strings can "overlap"
- their interaction changes the colour field density and modifies strings characteristics affecting particle production [M. A. Braun, C. Pajares, Inter. J. Mod. Phys. A 14, 2689 (1999)] :

$$\langle \mu \rangle_k = \mu_0 \sqrt{k}, \tag{4}$$

$$\langle p_T^2 \rangle_k = p_0^2 \sqrt{k}, \tag{5}$$

μ_0 - mean particle multiplicity per rapidity unit for an independent string, p_0 - mean transverse momentum of particles produced by it. Whereas $\langle \mu \rangle_k$ and $\langle p_T^2 \rangle_k$ correspond to the cluster of k fused strings.

Therefore, one expects lower multiplicity and higher p_T for interacting strings in comparison to the independent particle sources.

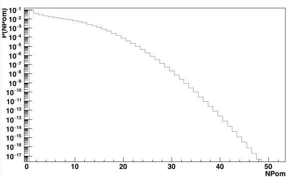
Monte-Carlo model development and tuning

Formation of colour strings

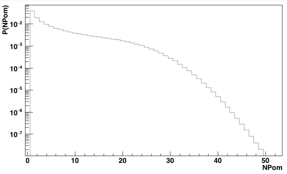
An event simulation starts with defining the number of colour strings as $N_{\mathrm{str}} = 2N_{\mathrm{pom}}$, N_{pom} comes from the pomeron number distribution function:

$$f(N_{\mathrm{pom}}) \sim \frac{1}{zN_{\mathrm{pom}}}\left(1 - e^{-z}\sum_{l=0}^{N_{\mathrm{pom}}-1}\frac{z^l}{l!}\right), \quad z = \frac{2C\gamma s_{NN}^{\Delta}}{R^2 + \alpha' \log(s_{NN})} \qquad (6)$$

[G.H. Arakelyan, A. Capella, A.B. Kaidalov, Yu.M. Shabelski, Eur. Phys. J. C26, 81 (2002)]



a)



b)

Example distribution of the number of pomerons for inelastic p+p interactions at $\sqrt{s_{NN}}$ = a) 900 GeV, b) 7000 GeV.

In our approach, $N_{\mathrm{partons}} = N_{\mathrm{str}}$ since we do not allow partons to escape the collision: all partons from two colliding protons should form strings.

Formation of colour strings

We prepare a large set of protons using PDFs to sample x_i [CT10nnlo set №1 by LHAPDF at $Q^2 = 1$ (GeV/c)^2] and demanding for each proton:

$$\sum_{i=0}^{N_{partons}} x_i < 1, \sum_{i=0}^{N_{partons}} e_i < 1 \quad (7)$$

where $x_i = \frac{p_i}{p_{\mathrm{proton}}}$ and $e_i = \sqrt{\frac{m_i^2}{m_{proton}^2 \cosh^2(y_{beam})} + x_i^2 \tanh^2(y_{beam})}$.

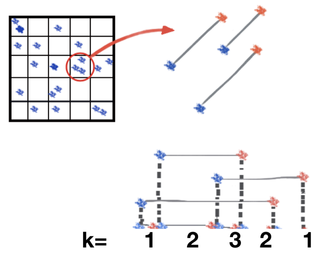
To meet these conditions, we exchange partons in two random protons asking for the largest possible sum of x_i and e_i. If, after all the combinations, it is still less then 1, we create a gluonic cloud with $x_{gcloud} = 1 - \sum_{i=0}^{N_{partons}} x_i$ and $e_{gcloud} = 1 - \sum_{i=0}^{N_{partons}} e_i$.

For each string from N_{str} we sample a pair of partons from two random prepared protons providing that $S_x \geq 2m_\pi$, where $S_x = \sqrt{s_{NN} x_1 x_2}$. All N_{str} should be formed from these two protons. When impossible, we look for another pair of random protons.

3-d fusion picture

We consider string fusion mechanism in the cellular version (in the transverse plane) for different slices of rapidity [V. V. Vechernin and R. S. Kolevatov, Vestn. SPbU Ser. 4, 11 (2004)].

If primary strings' centres lie in the same transverse cell, we do a projection in rapidity space to find the number of overlaps k. Thus, final strings become shorter but more "powerful".



Schematic picture of the string fusion procedure. As example: 3 primary strings with $k = 1, 1, 1$ lying in the same cell result in 5 strings with $k = 1, 2, 3, 2, 1$.

Event multiplicity:

- prepared strings are discretized in longitudinal direction into units of length ε with corresponding mean multiplicity $\langle N_\varepsilon \rangle = \mu_0 \varepsilon \sqrt{k}$
- actual multiplicity N_ε from this unit of string is sampled from the Poisson distribution with a given mean $\langle N_\varepsilon \rangle$
- string multiplicity $N^{\mathrm{str}} = \sum_\varepsilon N_\varepsilon$ and event multiplicity $N = \sum N^{\mathrm{str}}$

Particles' rapidities:

- for each of N_ε particles rapidity is sampled from Gauss distribution (mean = centre of the ε unit, variance = ε).

Particles' p_T is sampled from:

$$f(p_T) = \frac{\pi p_T}{2\langle p_T \rangle_k^2} \exp\left(- \frac{\pi p_T^2}{4\langle p_T \rangle_k^2} \right). \quad (8)$$

Selection of the model parameters

To fit the experimental data on the rapidity spectra for p+p inelastic interactions [http://mcplots-dev.cern.ch/?query=plots,ppppbar,mb-inelastic,etapp900, http://mcplots-dev.cern.ch/?query=plots,ppppbar,mb-inelastic,etapp7000], we change free model parameters that affect rapidity distribution via $\langle y_{\mathrm{loss}} \rangle$ parametrization and adjust μ_0 to catch the overall multiplicity.

$p + p$@/model parameters	A	α_1	α_2	σ_x	μ_0
900 GeV	1.1	0.2	0.05	0.1	0.45
7000 GeV	1.1	0.2	0.05	0.1	0.7

Values of model parameters found by tuning model to world data

Global model parameters:

- $g_N \sigma_T = 0.2$, $s_{string} = 0.176$ fm, $m_\sigma = 0.6$ GeV
  [T. Kalaydzhyan, E. Shuryak, Phys. Rev. C 90(1), 014901 (2014)]
- $\sigma_t = 0.5$, $p_{T0} = 0.3\ \mathrm{GeV}/c$ and $\varepsilon = 0.1$
  [D.P., V.N. Kovalenko, Phys. Part. Nucl. 51, 323 (2020)]
- $\Delta = 0.139$, $C = 1.5$, $\gamma = 1.77\ \mathrm{GeV}^{-2}$, $R^2 = 3.18\ \mathrm{GeV}^{-2}$, $\alpha^{'} = 0.21\ \mathrm{GeV}^{-2}$ [V. V. Vechernin, J.Phys.Conf.Ser. 1690 (2020) 1]

Study of correlations: model results, ALICE data and PYTHIA simulations

Quantities of interest

We study long-range correlations in terms of correlation coefficient that represents the slope of the correlation function defined in two rapidity intervals ("Forward" and "Backward") separated by $\Delta\eta$:

$$b_{B-F} = \left.\frac{df(F)}{dF}\right|_{\mathbf{F}=\langle \mathbf{F} \rangle} \tag{9}$$

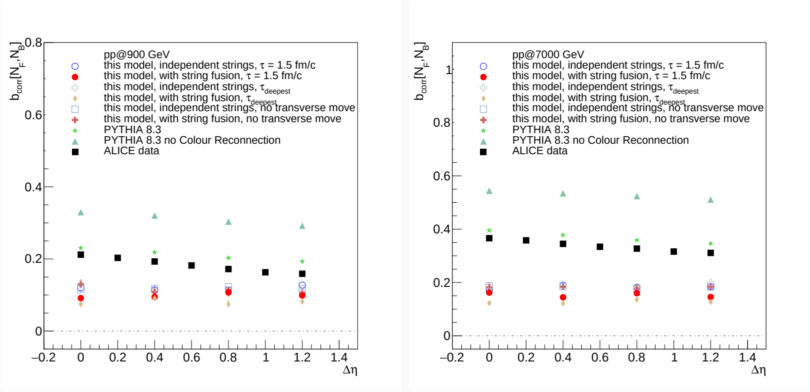
In normalised variables (to get rid of the experimental bias) for multiplicities N_F and N_B it becomes:

$$b_{corr}[N_F, N_B] = \frac{\langle N_F \rangle}{\langle N_B \rangle} \frac{d\langle N_B \rangle}{dN_F} \tag{10}$$

And in the case of linear correlation functions, it transforms into:

$$b_{corr}[N_F, N_B] = \frac{\langle N_F N_B \rangle - \langle N_F \rangle \langle N_B \rangle}{\langle N_B^2 \rangle - \langle N_B \rangle^2}. \tag{11}$$

Multiplicity correlations via $b_{corr}[N_F, N_B]$



a) b)

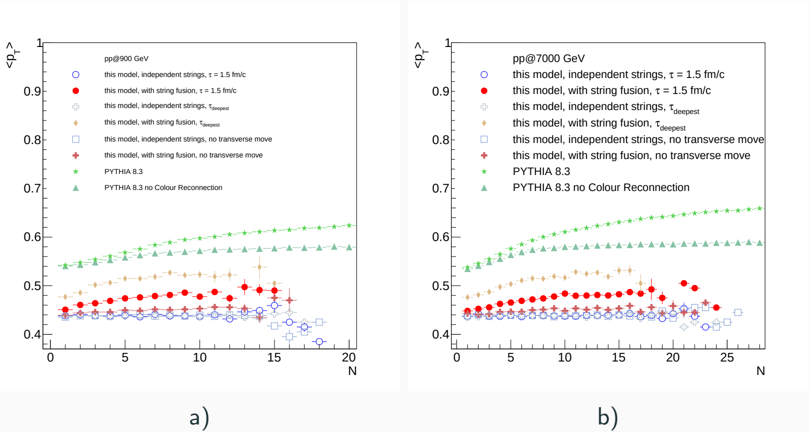
Results for $b_{corr}[N_F, N_B]$ as a function of the distance $\Delta\eta$ between Forward and Backward pseudorapidity acceptance intervals, where N_F and N_B multiplicities were calculated for inelastic p+p interactions at $\sqrt{s_{NN}}$ = a) 900 GeV, b) 7000 GeV. Particle selection: 0.3 GeV$/c < p_T < 1.5$ GeV$/c$

Multiplicity correlations via $b_{corr}[N_F, N_B]$: discussion

The conclusions below are correct for both considered energies

- there is almost no difference in $b_{corr}[N_F, N_B]$ for independent particle sources regardless the transverse strings dynamics
- model results for the highest density of strings lie a little bit below due to the lower multiplicity (the same for PYTHIA CR off and on)
- in the model, we observe almost a constant behaviour of $b_{corr}[N_F, N_B]$ as a function of $\Delta\eta$: it is a contribution of the long-range correlations (LRC)
- LRC are present at all $\Delta\eta$ and are defined by the fluctuations in the number of particle sources in F and B rapidity intervals
- our current results are far from ALICE and PYTHIA plots that contains also short-range correlations (SRC) coming from, e.g. resonance decays. We plan to implement it in the model in the nearest future.

$\langle p_T \rangle - N$ correlation functions



Results for $\langle p_T \rangle - N$ correlation function calculated in $|\eta| < 1$ pseudorapidity acceptance with 0.3 GeV/c $< p_T <$ 1.5 GeV/c for inelastic p+p interactions at $\sqrt{s_{NN}}$ = a) 900 GeV, b) 7000 GeV.

$\langle p_T \rangle - N$ correlation functions: discussion

The conclusions below are correct for both considered energies

- results for independent strings lie on each other and exhibit no dependence of $\langle p_T \rangle$ on N regardless the transverse strings dynamics
- $\langle p_T \rangle$ vs N with string fusion for fixed strings' positions in transverse plane shows a very slight (almost no) dependence $\leftrightarrow$ very rare fusion
- $\langle p_T \rangle$ - N correlation is weaker for string evolving till $\tau = 1.5$ fm/c in comparison to the one for the largest density of strings at $\tau_{deepest}$ $\leftrightarrow$ again fusion probability
- $\langle p_T \rangle$ - N result for $\tau_{deepest}$ is the closest one to PYTHIA plot, where colour reconnection plays the same role as our string fusion mechanism

Summary and outlook

Summary and outlook

In general:

- we address the problem of initial conditions in relativistic p+p collisions
- the Monte-Carlo model of interacting colour strings as particle emitting sources that has non-uniform strings density over rapidity was developed
- it has rich 3-d dynamics of strings and string fusion mechanism, what makes it useful in the study of correlations

In particular:

- results on multiplicity and transverse momentum correlations for p+p interactions at $\sqrt{s} = 900$ and $\sqrt{s} = 7000$ GeV are presented
- string fusion mechanism gives similar effect at b_{corr} as Colour Reconnection regime in PYTHIA 8.3
- long-range correlations are present in the model due to the fluctuation in the number of strings in F and B rapidity intervals, but there is no short-range correlations implemented **yet**

THANK YOU FOR YOUR ATTENTION!

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