String shoving effects on jets in pp collisions in PYTHIA8

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Questions to answer:

1. Explanation of possible collective effects in high multiplicity p-p collisions with string model

2. Is there any jet quenching in high multiplicity p-p events? Explanation in string model?

3. String model to study A-A systems

4. Quest for a unified model: from $e^+ - e^-$ to A-A collision systems
Angantyr and advancements

- Aspects of Angantyr:
  - A-A is treated as a collection of overlaid p-p collisions
  - Modifications needed when one nucleon in one nucleus collides with several nucleons in the other
  - No collective effects

The elliptic flow coefficient $v_2\{2\}$ at $\sqrt{s_{NN}} = 2.76\, TeV$, as measured by CMS (without $\Delta \eta$-gap) and ALICE (with $\Delta \eta = 1$), compared to the non-flow contribution calculated by Angantyr

Aspects of Angantyr:
✓ A-A is treated as a collection of overlaid p-p collisions
✓ Modifications needed when one nucleon in one nucleus collides with several nucleons in the other
✓ No collective effects

Signatures
Final-state collective effects
Jet quenching
Strangeness enhancement

Underlying mechanisms
String shoving
Colour reconnection
Rope hadronization*

Steps involved in implementing string shoving (for massless partons):

1. Symmetric topology for strings \(\rightarrow\) **Parallel frame**
2. Giving strings **width** \(\rightarrow\) calculate interaction force
3. **Push distribution among hadrons**
2. Interaction energy

1. A string of width $R$:

$$\text{Field } E(r_\perp) = C \exp \left( -\frac{r_\perp^2}{2R^2} \right)$$  \hspace{1cm} (1)

2. Force $f(d_\perp)$ per unit length:

$$f(d_\perp) = \frac{dE_{int}}{dd_\perp} = \frac{gKd_\perp}{R^2} \exp \left( -\frac{d_\perp^2(t)}{4R^2} \right)$$  \hspace{1cm} (2)

where $g$ is a tunable parameter.
1. Lorentz invariant frame - the parallel frame

Figure: 1,2,3,4 are partons (string-ends), $\theta = \text{opening angle}$, $\phi = \text{skew angle}$.

**Left**: view from above. **Right**: Schematic view of two strings in the parallel frame
Role of parallel frames in jets

- Jets $\rightarrow$ quarks and gluons

- Interaction with partons following rule of least string length $\rightarrow$ modifies jets
3. 'Push' distribution among hadrons

- $t_1$ is earliest and $t_5$ is the latest time
- String extends in the longitudinal direction along $x$ and the shoving kink is along $y$
- Kink extends over $t_i$
- String breaks following fragmentation function and the push is distributed following energy-momentum conservation
Parton vertices and hadronization

- Eg. a kink produced at $t_2$ will spread in a lightcone
- The hadrons produced in this lightcone will carry the $p_T$ push in a way such that they keep moving along their original pseudorapidity
PRELIMINARY RESULTS
Set 1: What are we looking at?

1. \( S_N = \frac{1}{N(N-1)} \frac{d^2 N^{signal}}{d \Delta \phi d \Delta \eta} \)

2. \( B_N = \frac{1}{N^2} \frac{d^2 N^{mixed}}{d \Delta \phi d \Delta \eta} \)

3. \( R(\phi) = \left\langle (\langle N \rangle - 1) \left( \frac{S_N}{B_N} - 1 \right) \right\rangle \)

   where \( \langle N \rangle \) is the number of tracks per event averaged over the multiplicity bin, and the final \( R(\Delta \eta, \Delta \phi) \) is found by averaging over multiplicity bins

Set 1: Di-hadron correlations in p-p at 7 TeV at minbias

0 0.5 1 1.5 2 2.5 3
-1 -0.5 0 0.5 1

N < 35, 1 < p⊥ < 2, 2.0 < ∆η < 4.8

90 < N < 110, 1 < p⊥ < 2, 2.0 < ∆η < 4.8

35 < N < 90, 1 < p⊥ < 2, 2.0 < ∆η < 4.8

110 < N, 1 < p⊥ < 2, 2.0 < ∆η < 4.8
Di-hadron correlations in p-p at 7 TeV at minbias

1. Pick charged hadron in $|\Delta \eta| < 2.4$ with $6 \text{ GeV} < p_T < 8 \text{ GeV}$

2. Pick associated charged hadron in $|\Delta \eta| < 2.4$ with $4 \text{ GeV} < p_T < 6 \text{ GeV}$

3. Calculate $\Delta \phi$ between high $p_T$ hadron and associated lower $p_T$ hadron

4. No background subtraction performed
Set 2: Charged hadron correlation in p-p at 7 TeV for $g=0.5$

No 'jet' suppression predicted in high-multiplicity p-p collisions
Set 2: Charged hadron correlation in p-p at 7 TeV for $g=5$

- $N < 35, -2.4 < \Delta \eta < 2.4$
- $35 < N < 90, -2.4 < \Delta \eta < 2.4$
- $90 < N < 110, -2.4 < \Delta \eta < 2.4$
- $110 < N, -2.4 < \Delta \eta < 2.4$
Set 2: Charged hadron correlation in p-p at 7 TeV for $g=5$

$g=5$ gives a feel about the shoving effects in jets in larger systems such as heavy-ion collisions even with $g=0.5$, hence shoving could contribute to some jet quenching effects.
Set 3: $v_2$ in Pb-Pb at 5.02 TeV

- Example case in Pb-Pb: initial state with long parallel strings
- Calculate force on a string cutting through such an environment
- Calculate $v_2$

*Christian Bierlich’s plenary talk on Wednesday*
Set 4: Two particle correlations in $e^+ - e^-$ at 91 GeV

- Applicable to all systems: the parallel frame allows shoving in $e^+e^-$ geometries
- Recent re-analysed ALEPH data is important for cross checks

- Possibility of dedicated predictions for more elaborate observables
- Opportunities for FCC-ee with more statistics
- **Wanted:** Rivet implementation of analyses with archived data
Conclusions

1. Summary:

- Parallel frame formalism extends the baseline to study jets including string interactions
- Space-time dependent string width gives better grip in calculation of interaction force
- Shoving gives an observable collective effect in high multiplicity p-p
- Two particle correlations in high-pT hadrons do not predict any suppression in jets in string interaction picture

2. Coming soon:

- Shoving in p-A and A-A systems
- Jet observable analysis for p-A and A-A systems
EXTRAS
Di-hadron correlations in p-p at 7 TeV

Di-hadron correlations in p-Pb

Di-hadron correlations in p-Pb

Rivet analysis used is for p-p!

Di-hadron correlations in p-Pb

Note: Rivet analysis used is for p-p!