Initial state fluctuations in PYTHIA 8

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- Mueller dipole formalism
- Monte Carlo implementation
- Eccentricities for pp, pA, AA
- Steps towards eA

Based on the following work:
Christian Bierlich, Christine O. Rasmussen: Probing the spatial structure of the proton at small and large scales, In preparation.
Motivation

- Take pQCD model with event-by-event initial-state fluctuations
- Neglect any final-state effects (no hydro, no interacting strings etc.)
- Can we describe observables related to geometry with model tuned only to cross sections?

ALICE arXiv:1903.01790[nucl-ex]

Mueller dipole formalism
Mueller dipole formalism describes evolution of a single dipole in rapidity.

- Defined by the dipole splitting probability,

$$\frac{dP}{d^2r_3dy} = \frac{3\alpha_S(Q^2)}{2\pi^2} \frac{r_{12}^2}{r_{13}^2 r_{23}^2},$$

- After evolution the two chains of dipoles are allowed to interact.
- Frame choice for collision not obvious, we use "center-of-rapidity", where both beams are evolved equally in rapidity.
• Interaction given by dipole-dipole scattering probability,

\[ f_{ij} = \frac{\alpha_s^2(Q^2)}{2} \log^2 \left[ \frac{r_{14}r_{23}}{r_{24}r_{13}} \right], \]

• Measurable quantities obtained from unitarized dipole-dipole scattering amplitude plus Good-Walker formalism,

\[
T(b) = 1 - \exp \left( - \sum_{i=1}^{N_A} \sum_{j=1}^{N_B} f_{ij} \right) = 1 - \exp(-F(b))
\]

\[
\sigma_{tot} = \int d^2b 2 \langle T(b) \rangle, \quad \sigma_{el} = \int d^2b \langle T(b) \rangle^2, \quad B_{el} = \frac{\int d^2b 3 \langle T(b) \rangle}{2 \int d^2b \langle T(b) \rangle}
\]
Monte Carlo implementation
Previous implementations includes

- Unpublished MC by Kovalenko (arXiv:1212.2590[nucl-th])
- DIPSY by Avsar et. al (arXiv:1103.4321 [hep-ph])

New implementation in Pythia 8

- Includes energy and momentum conservation ($k_+$ and $k_-$)
- Includes confinement effects by adding gluon mass
- Includes recoil effects when new dipoles are created
- Possibility for collisions with $\gamma^*$- and $p$-beams
- Larger systems described with Angantyr model
- Available in upcoming Pythia 8.3 release

C. Bierlich, COR in prep.
Framework requires assumption on initial dipole configuration

- Previous implementation showed reasonable agreement with data when using equilateral triangle
- Photon represented by single dipole with wavefunction using three lightest quarks,

\[ \sigma_{\text{tot}} = \int \, dz \int \, d^2 r \left( |\psi_L(z, r)|^2 + |\psi_T(z, r)|^2 \right) \int \, d^2 b \, 2 \langle T(z, r, b) \rangle \]
New model contains four tunable parameters

- Initial dipole size for protons: $r_0$
- Width of fluctuations around initial dipole size for protons: $r_{\text{width}}$
- Maximal dipole size used with confinement: $r_{\text{max}}$
- Fixed strong coupling: $\alpha_S$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>pp</th>
<th>γ*p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>unconfined</td>
<td>confined</td>
</tr>
<tr>
<td>$r_0$ [fm]</td>
<td>0.53</td>
<td>0.70</td>
</tr>
<tr>
<td>$r_{\text{max}}$ [fm]</td>
<td>-</td>
<td>3.00</td>
</tr>
<tr>
<td>$r_{\text{width}}$ [fm]</td>
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<td>0.27</td>
</tr>
<tr>
<td>$\alpha_S$</td>
<td>0.24</td>
<td>0.22</td>
</tr>
</tbody>
</table>
pp cross sections:

- Confined model consistent with data on $\sigma_{\text{tot}}$ for $\sqrt{s} \geq 10^2$ GeV
- Difficult to get both $\sigma_{\text{el}}$ and $B_{\text{el}}$ right w/o saturation
- $d\sigma/dt$ impossible w/o saturation effects
\gamma^* p \text{ total cross section:}

- Low $Q^2$: lacks vector meson contribution and light quark masses
- Intermediate $Q^2$: Good overall agreement
- Very high $Q^2$: overshoots data.
Model highlights:

- Dipole model describes energy dependence of total cross sections in $pp$ as well as energy dependence of elastic slope at $t = 0$
- Dipole model describes energy dependence of total cross section for $\gamma^*p$ well over a large range of virtualities
- Full space-time structure of partonic event comes for free with dipole model
- Use model to study collective effects in small and large systems
- Starting point for $\gamma^*A$ exclusive final states
Eccentricities
Space-time information used as input for \textsc{Pythia} 8 MPI model

- Default: MPs normal distributed around proton center – symmetric
- Dipole model gives transverse location of MPs – not symmetric
- Study effects of asymmetry in partonic eccentricities $\epsilon_n$ and normalised symmetric cumulants in $pp$, $pA$, $AA$

**Note:** Initial state is everything \textbf{before hadronization}

- Parton shower adds a small ($p_\perp$-dependent) non-flow effect
- No response function added as no final-state effects are included
Linear response function often assumed in AA: \( v_n = f(\epsilon_n) \approx a\epsilon_n \), with

\[
\epsilon_n = \sqrt{\langle r^n \cos(n\phi) \rangle^2 + \langle r^n \sin(n\phi) \rangle^2} / \langle r^n \rangle
\]

\[
NSC(n, m) = \frac{\langle v^2_n v^2_m \rangle - \langle v^2_n \rangle \langle v^2_m \rangle}{\langle v^2_n \rangle \langle v^2_m \rangle} \approx \frac{\langle \epsilon^2_n \epsilon^2_m \rangle - \langle \epsilon^2_n \rangle \langle \epsilon^2_m \rangle}{\langle \epsilon^2_n \rangle \langle \epsilon^2_m \rangle}
\]

Models for assigning coordinates to MPI vertices in transverse space:

- Glauber: MPIs moved to nucleon position
- Gaussian model: \( x, y \) chosen from gaussian with \( r_p = 0.7 \) and \( \nu_r = 0.1 \)
- Dipole model: \( x, y \) chosen w.r.t. dipole-dipole interaction strength \( f_{ij} \)
\( \epsilon_2 \{2\} \) as a function of average central multiplicity

\[
\epsilon_n = \sqrt{\langle r^2 \cos(n\phi) \rangle^2 + \langle r^2 \sin(n\phi) \rangle^2}
\]

- Asymmetry gives rise to more eccentricity
- Initial state fluctuations important in AA at low multiplicity
- If response function for pA equals that of pp at same average multiplicity, then
  - Eccentricity ratio should be comparable to flow ratios measured in data
  - Dipole model predicts flat pA/pp ratio also seen in data
\( \epsilon_3 \{2\} \) and NSC(2, 3) as a function of average central multiplicity

\[
\epsilon_n = \sqrt{\langle r^2 \cos(n\phi) \rangle^2 + \langle r^2 \sin(n\phi) \rangle^2 / \langle r^2 \rangle}
\]

- \( \epsilon_3 \) related to initial geometry
- Initial geometry not distinguishable in \( \text{NSC}(3, 2) \) for pp
- Very different behaviour in pA for symmetric and asymmetric initial states
Ratios of higher order eccentricities: CMS $\sqrt{s_{NN}} = 8.16$ TeV.
Eccentricities highlights:

- Not possible to describe flow coefficients with current implementation
- We can describe ratios, where response function does not appear
- Good agreement with $pA/pp$ ratio from ALICE
- Good agreement with higher order eccentricities from CMS
- Dipole model is distinguishable wrt. symmetric model and pure glauber (initial states matter!)
Steps towards eA
First steps towards $\gamma^* A$ and $eA$ in **PYTHIA 8**:

- Use Glauber-Gribov to calculate number of interacting nucleons
- Event-by-event colour fluctuations on total $\gamma^* p$ cross section with dipole model
- Wounded nucleon model for particle production
- GG: Colour fluctuations studies with projectile frozen in some state $k$ while target configuration is averaged

$\sigma_{\gamma^*p}^{\text{tot}} = \int dz \int d^2r (|\psi_L(z, r)|^2 + |\psi_T(z, r)|^2) \int d^2b 2 \langle T(z, r, b) \rangle_t$

- Photon is a **superposition** of all $(z, r)$
- At first interaction wavefunction collapses to specific dipole with a given $(z_1, r_1)$
- Dipole is then frozen in this state
- Secondary interactions described as **dipole-proton interactions**
• 'Frozen': Secondaries found from dipole-proton cross sections
• Black disk: Full photon wavefunction used for both primary and secondary interactions
Conclusions and outlook
• New model for dipole evolution and dipole-dipole scatterings implemented in Pythia 8

• Promising results when comparing to integrated cross sections in \( pp \) and \( \gamma^*p \)

• Asymmetric initial state show overall trends in eccentricities and normalised symmetric cumulants measured at ALICE

• First results presented for \( \gamma^*A \) exclusive final states

Future work:

• Running strong coupling, new initial proton configurations and saturation to go in next

• Extension to low-\( Q^2 \) photons (VMD contribution and quark masses)

• Combination with final-state effects expected using string-string interaction models
Thank you!
Backup slides
Eccentricities:

\[ \varepsilon_n = \sqrt{\frac{(r^2 \cos(n\phi))^2 + (r^2 \sin(n\phi))^2}{r^4}} \]

\[ n = r^2 \cos^2(n\phi) + r^2 \sin^2(n\phi) \]
Eccentricities:

\[ \epsilon_n = \sqrt{\left\langle r^2 \cos(n\phi) \right\rangle^2 + \left\langle r^2 \sin(n\phi) \right\rangle^2} / \left\langle r^2 \right\rangle \]

\[ \langle dN_{ch}/d\eta \rangle |_{|\eta|<0.8} \]

- pp-gauss-7TeV
- pp-dipole-7TeV
- pA-glauber
- pA-gauss
- pA-dipole
- AA-glauber
- AA-gauss
- AA-dipole
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- \( \epsilon_3 \{6\} \)
- pp-gauss-7TeV
- pp-dipole-7TeV
- pA-glauber
- pA-gauss
- pA-dipole
- AA-glauber
- AA-gauss
- AA-dipole

\[ \langle dN_{ch} / d\eta \rangle |_{|\eta|<0.8} \]
Eccentricities:

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\[ \langle dN_{ch}/d\eta \rangle \big|_{|\eta|<0.8} \]

Christine O. Rasmussen — Initial state fluctuations in PYTHIA 8 — June 26 2019
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Normalised symmetric cumulants:

\[ \epsilon_n = \frac{\sqrt{\langle r^2 \cos(n\phi)\rangle^2 + \langle r^2 \sin(n\phi)\rangle^2}}{\langle r^2 \rangle} \]
Saturation

Dipoles in PY8: cannot describe $d\sigma/dt$ w/o saturation, but DIPSY MC can (w/ dipole swing)