Particle Production via Strings and Baryon Stopping in a Hadronic Transport Approach

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Investigate regions with high $\mu_B$ to search for a phase transition and a critical point.
Baryon Stopping

- Net proton number $N^p - \bar{p}$ to measure stopped protons from initial nuclei

- Shape of $dN^p - \bar{p} / dy$ is strongly energy dependent

- $\sqrt{s_{NN}} \approx 5$ GeV: Baryons are stopped around mid rapidity

- $\sqrt{s_{NN}} > 60$ GeV: Nuclei pass through each other

- First nucleon-nucleon interactions play most important role

C. Shen, B. Schenke, 10.1103/PhysRevC.97.024907
Transport Model SMASH

- Hadronic degrees of freedom
- Geometric collision criterion:
  \[ d_{\text{trans}} < \sqrt{\frac{\sigma_{\text{tot}}}{\pi}} \]
- Established hadrons from PDG up to \( m \approx 2 \text{ GeV} \)
- Effectively solving relativistic Boltzmann equation
  J.Tindall et al. 10.1016/j.physletb.2017.04.080
- Inelastic processes via resonances, soft strings or Pythia directly, depending on energy
  J.Weil et al. 10.1103/PhysRevC.94.054905

Code available at https://smash-transport.github.io

Lead-lead collision at \( \sqrt{s_{\text{NN}}} = 17.3 \text{ GeV} \) in SMASH

J.Weil et al. 10.1103/PhysRevC.94.054905
String Model

- Massless quarks with momentum $p_1$, $p_2$ and position $x_1$, $x_2$
- Motion according to:

$$H = |p_1| + |p_2| + \kappa |x_1 - x_2|$$

- $\kappa \approx 1$ GeV/fm: String tension
- New $q\bar{q}$ pairs are produced
- String fragments into hadrons
- Hadrons are formed around a constant proper time

B. Anderson et al. 10.1016/0370-1573(83)90080-7
Strings in SMASH

**Hard processes:**
- Dominate for high $\sqrt{s}$
- Pythia to excite and fragment strings
- Map colliding hadron species to nucleons and pions

**Soft processes:**
- Dominate at intermediate $\sqrt{s}$
- Excite strings and call Pythia only for fragmentation
- Contains single diffractive, double diffractive and non-diffractive processes
Calculations for Proton-Proton Collisions
Fragmentation Function for Leading Baryons

- Fragmentation function for sampling light cone momentum fraction for each string fragment
- Use a different fragmentation function for leading baryons to increase longitudinal momentum of protons

$$p \sqrt{\frac{s_{NN}}{s_{NN}}} = 17.27 \text{GeV}$$

- Green curve: use Lund fragmentation function everywhere
- Blue curve: use Gaussian with $\mu = 1$ and $\sigma = 0.6$ for leading Baryons
- Slightly better agreement with data for longitudinal momentum

$$x_F = \frac{p_z}{p_{z,\text{beam}}}$$
Slightly worse agreement when using separate fragmentation function for leading baryons
Proton Mean Transverse Mass

\[ p + p \rightarrow p + X \]

\[ \langle m_T \rangle - m_p \text{ [GeV]} \]

- Transverse momentum underestimated at mid rapidity as shown before
- Energy dependence looks reasonable
Overview p+p Rapidity Spectra

Fragmentation function, strangeness suppression and diquark suppression tuned to data
Overview p+p mean $p_T$

- Transverse momentum transfer and transverse momentum production from string fragmentation tuned to data
Calculations for Heavy Ion Collisions
Formation Times

- String fragments need time to form
- Formation times are distributed around constant proper time
  \[ \langle \tau_{\text{form}} \rangle = \frac{\sqrt{2m}}{\kappa} \]
- Assume mass dependent formation times

B. Anderson et al. 10.1016/0370-1573(83)90080-7
Formation Times

\[ \text{Pb} + \text{Pb}, \sqrt{s_{NN}} = 17.27 \text{GeV} \]

- Multiply formation times by a constant factor \( b_{\text{form}} \)
- Equivalent to changing string tension \( \kappa \)
- Short formation times reproduce shape best
- How does changing the formation time affect pions?
Formation Times

\[ \text{Pb} + \text{Pb}, \sqrt{s_{NN}} = 17.27 \text{GeV} \]

- Pion multiplicity increases with longer formation times
- Use \( b_{\text{form}} = 1 \) to obtain a reasonable agreement for pions and protons
Cross Section Scaling Factors

- During formation time cross section is scaled down by factor $f_\sigma$
- By default use a Heavyside function in time for $f_\sigma$
- One can also have $f_\sigma$ grow with a given power $\alpha$ in time

Cross Section Scaling Factors

\( \text{Pb} + \text{Pb}, \sqrt{s_{NN}} = 8.765 \text{GeV} \)

- Vary power \( \alpha \) with which the cross section grows in time
- \( \alpha = -1 \) stands for using a Heavyside function
- If the cross section grows too fast the dip cannot be reproduced at intermediate SPS energy
Heavy Ion Collisions

![Graph of dN/dy vs y for proton Pb+Pb collisions at different energies](image)

- Good agreement with measured proton rapidity spectrum high SPS energies
- Overshoot proton multiplicity at low SPS energies but shape is reproduced

Heavy Ion Collisions

$\pi^-, \text{Pb} + \text{Pb}$

- $\sqrt{s_{NN}} = 17.27 \text{ GeV}$
- $\sqrt{s_{NN}} = 8.765 \text{ GeV}$
- $\sqrt{s_{NN}} = 6.27 \text{ GeV}$

SMASH
UrQMD v.2.3
NA49 data

- Overall reasonable agreement with measurement for pion production
- Slightly underestimate pion production at top SPS energies
- Overestimate pion production at low SPS energies

Conclusions and Outlook

Conclusions:
▶ String model matches NA49 and NA61 p+p data for produced hadrons
▶ Rapidity and transverse momentum distribution of protons difficult to reproduce in p+p collisions
▶ Stopping of protons and pion production in heavy ion collisions is reasonably well described

Outlook:
▶ Use SMASH to calculate initial state of a heavy ion collision
  ▶ Event by event initial condition with full phase space information for all charges
Backup
Soft String Processes in SMASH

**Single diffractive:** \( A + B \rightarrow A + X \) or \( A + B \rightarrow X + B \)

- Two hadrons collide, exchange momentum and **one** of the hadrons is excited to a string
- Mass \( M_X \) of the string and transferred transverse momentum \( p_T \) are sampled according to:

\[
\frac{d^3N}{dM_X^2 d^2p_T} \propto \frac{1}{M_X^2} \exp \left(-\frac{p_T^2}{\sigma_T^2}\right)
\]

G. Ingelman and P. E. Schlein 10.1016/0370-2693(85)91181-5

**Double diffractive:** \( A + B \rightarrow X + X \)

- Two hadrons exchange a pomeron and are **both** excited to a string
- Light-cone momentum fraction \( x \) of gluons exchanging a pomeron is sampled from PDF:

\[
\text{PDF} \propto \frac{1}{x}(1 - x)^{\beta+1}
\]

Soft String Processes in SMASH

Non-diffractive:
- Two hadrons exchange a valence quark and are excited to strings
- Light cone momentum fraction of quarks sampled from PDF:
  \[ \text{PDF} \propto x^{\alpha - 1}(1 - x)^{\beta - 1} \]
- Transverse momentum sampled from Gaussian

Subprocess selection:
- From experimental \( \sigma_{\text{tot}} \) and \( \sigma_{\text{el}} \)
  \[ \sigma_{\text{inel}} = \sigma_{\text{tot}} - \sigma_{\text{el}} \]
- With parametrization of \( \sigma_{\text{SD}} \) and \( \sigma_{\text{DD}} \) from Pythia
  \[ \sigma_{\text{ND}} = \sigma_{\text{inel}} - \sigma_{\text{SD}} - \sigma_{\text{DD}} \]