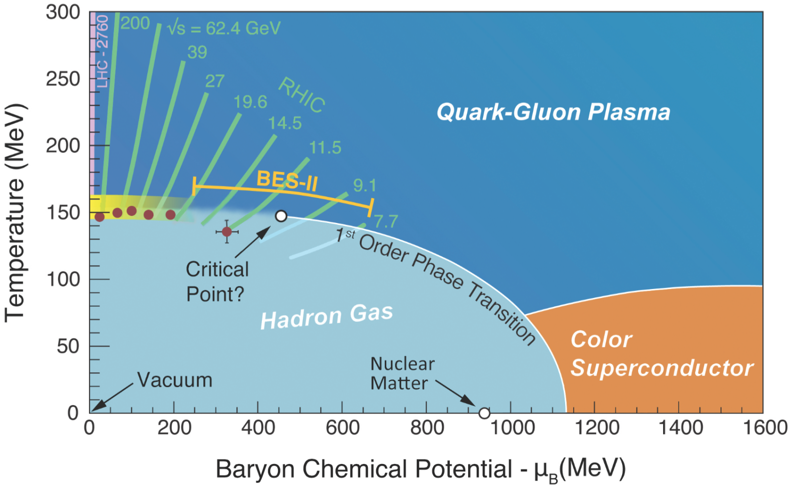
Particle Production via Strings and Baryon Stopping in a Hadronic Transport Approach

Justin Mohs,
Sangwook Ryu and Hannah Elfner

Hirschegg, January 17, 2019

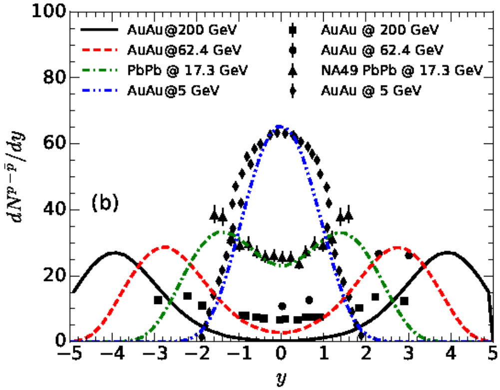
Exploring the QCD Phase Diagram



- Investigate regions with high μ_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



C. Shen, B. Schenke, 10.1103/PhysRevC.97.024907

- Shape of $dN^{p-\bar{p}}/dy$ is strongly energy dependent
- $\sqrt{s_{NN}} \approx 5\,\mathrm{GeV}$: Baryons are stopped around mid rapidity
- $\sqrt{s_{NN}} > 60\,\mathrm{GeV}$: Nuclei pass through each other

- First nucleon-nucleon interactions play most important role

Transport Model SMASH

- Hadronic degrees of freedom
- Geometric collision criterion:

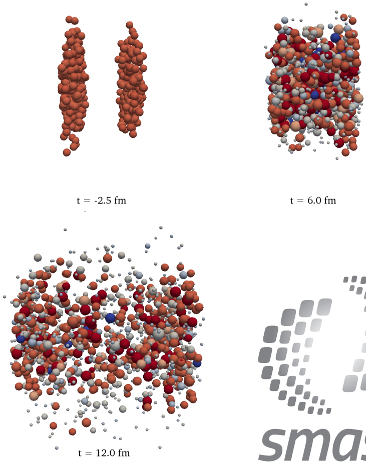
$$d_{\text{trans}} < \sqrt{\frac{\sigma_{\text{tot}}}{\pi}}$$

- 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

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



Lead-lead collision at $\sqrt{s_{NN}} = 17.3$ GeV In SMASH

J.Weil et al. 10.1103/PhysRevC.94.054905

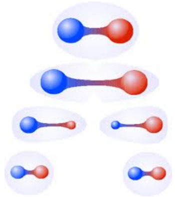
String Model

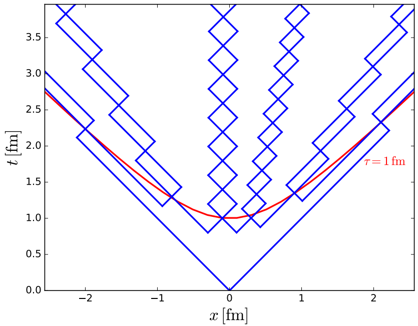
- Massless quarks with momentum p_1, p_2 and position x_1, x_2
- Motion according to:

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

- $\kappa \approx 1$ 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

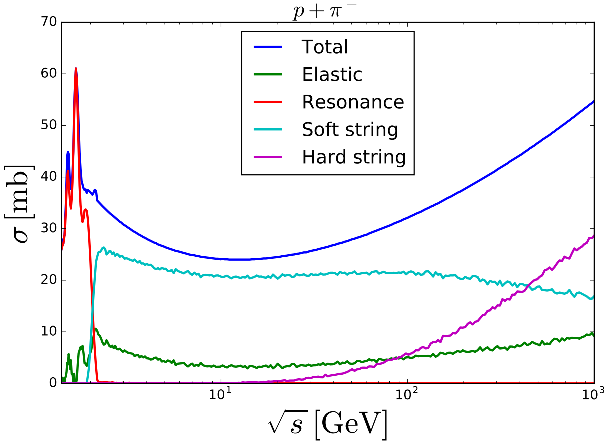




Strings in SMASH

Hard processes:

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



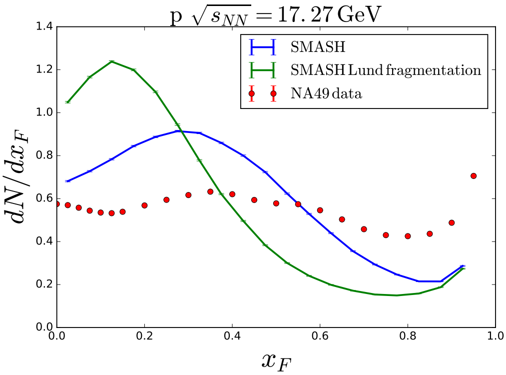
Soft processes:

- 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

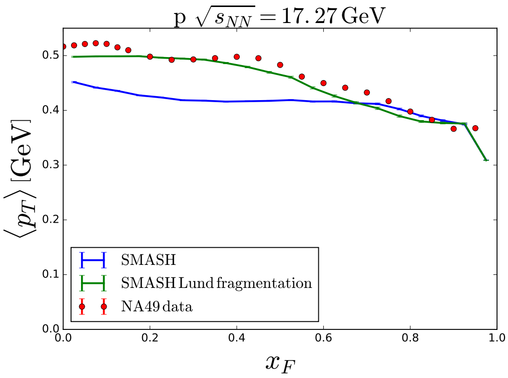
- Fragmentation function for sampling light cone momentum fraction for each string fragment
- Use a different fragmentation function for leading baryons to increase longitudinal momentum of protons

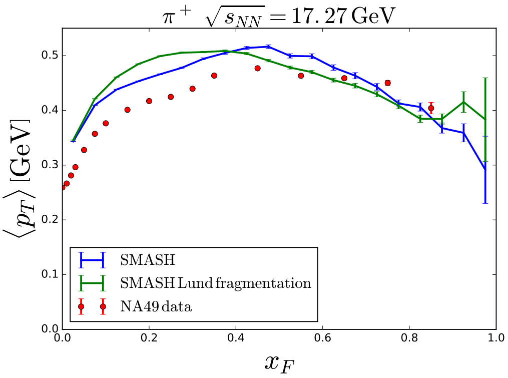


- Green curve: use Lund fragmentation function everywhere
- Blue curve: use Gaussian with $\mu = 1$ and $\sigma = 0.6$ for leading Baryons
- Slightly better agreement with data for longitudinal momentum

$$x_F = \frac{p_z}{p_{z,\mathrm{beam}}}$$

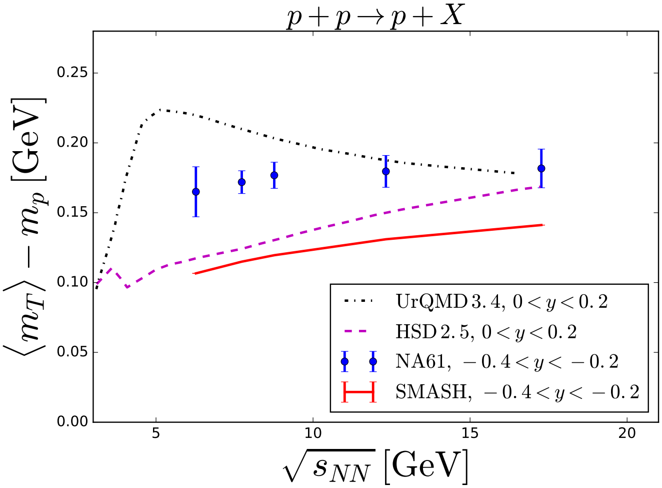
Transverse Momentum





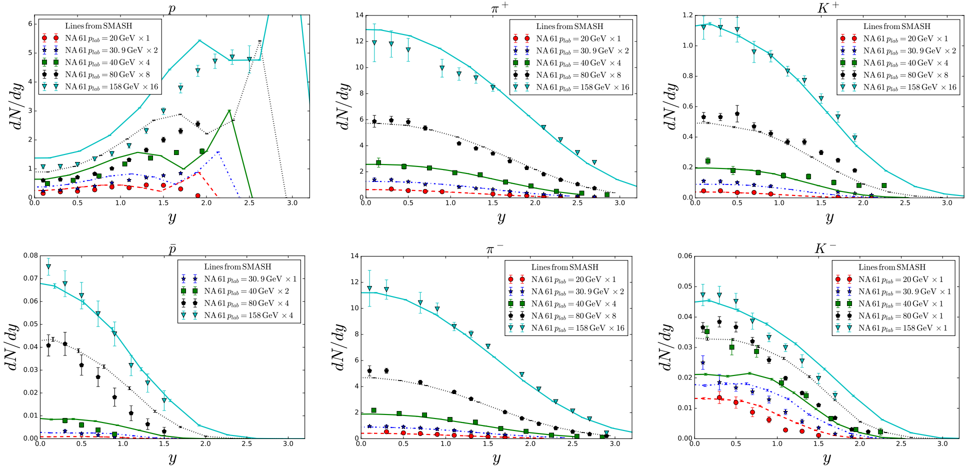
- Slightly worse agreement when using separate fragmentation function for leading baryons

Proton Mean Transverse Mass



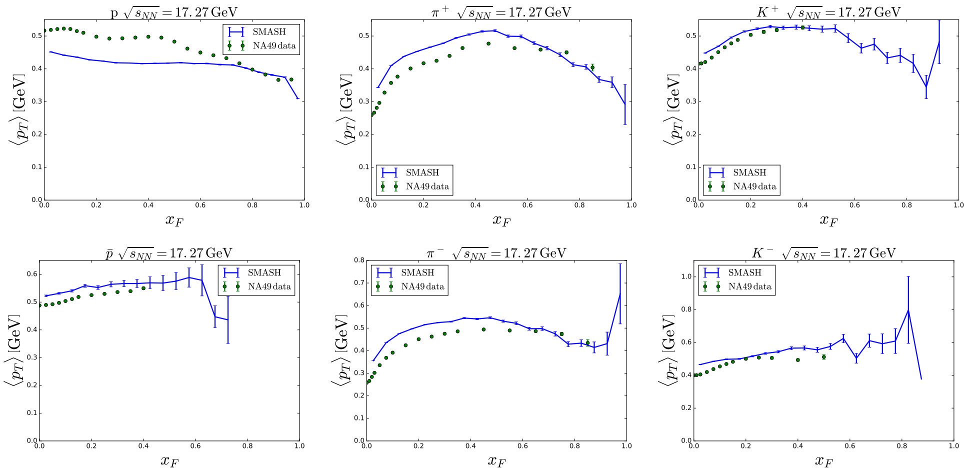
- Transverse momentum underestimated at mid rapidity as shown before
- Energy dependence looks reasonable

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

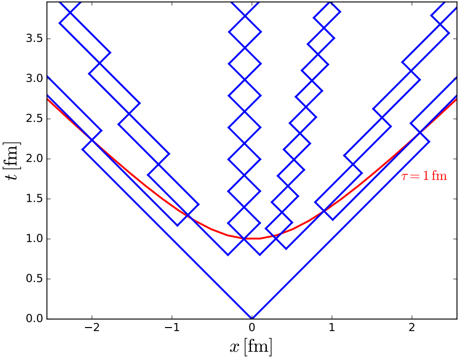
Formation Times

- String fragments need time to form
- Formation times are distributed around constant proper time

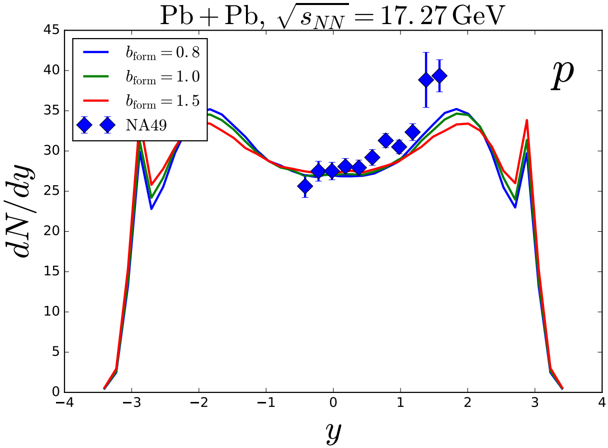
$$\langle \tau_{\text{form}} \rangle = \frac{\sqrt{2}m}{\kappa}$$

B. Andersson et al. 10.1016/0370-1573(83)90080-7

- Assume mass dependent formation times

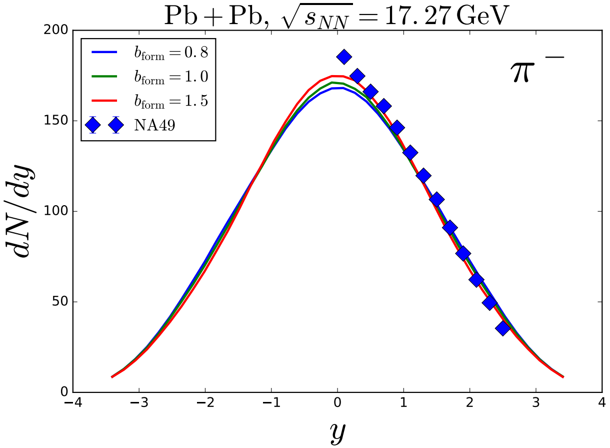


Formation Times



- Multiply formation times by a constant factor b_{form}
- Equivalent to changing string tension κ
- Short formation times reproduce shape best
- How does changing the formation time affect pions?

Formation Times

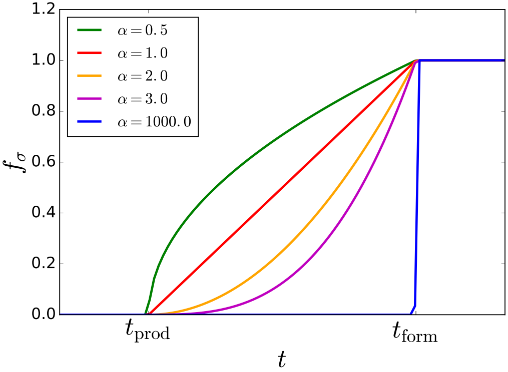


- Pion multiplicity increases with longer formation times
- Use $b_{form} = 1$ to obtain a reasonable agreement for pions and protons

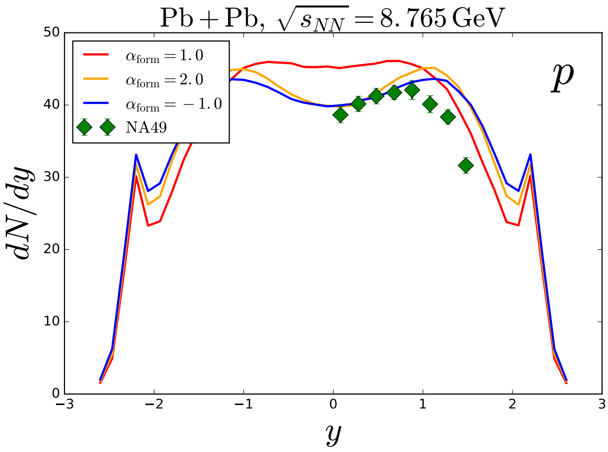
Cross Section Scaling Factors

- During formation time cross section is scaled down by factor f_σ
- By default use a Heavyside function in time for f_σ
- One can also have f_σ grow with a given power α in time

K. Gallmeister U. Mosel 10.1016/j.nuclphysa.2007.12.009

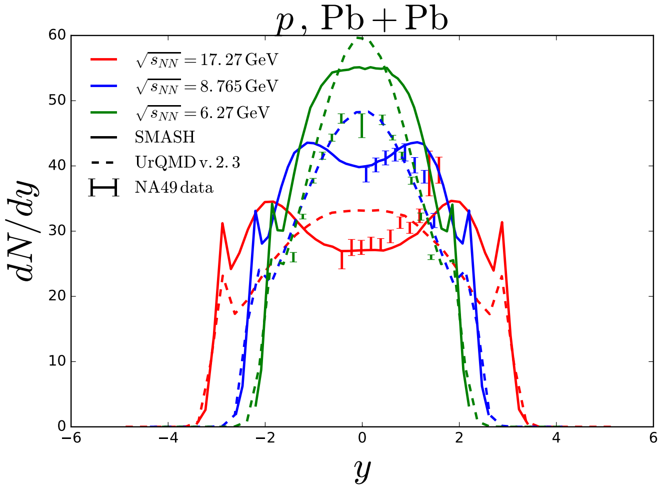


Cross Section Scaling Factors



- Vary power α 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

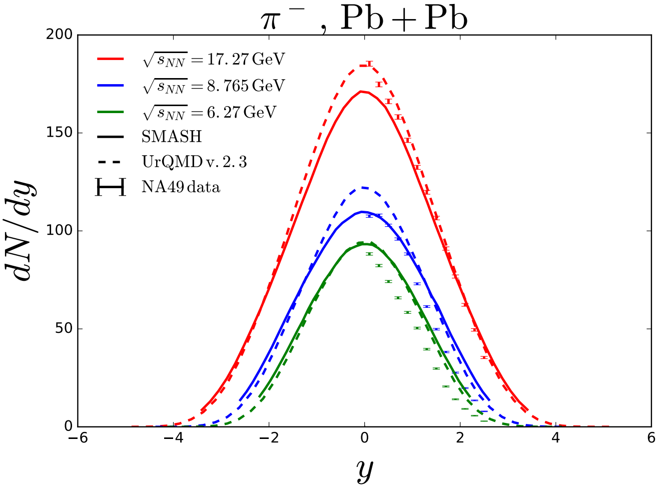
Heavy Ion Collisions



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

H. Petersen et al. arXiv:0805.0567 [hep-ph]

Heavy Ion Collisions



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

H. Petersen et al. arXiv:0805.0567 [hep-ph]

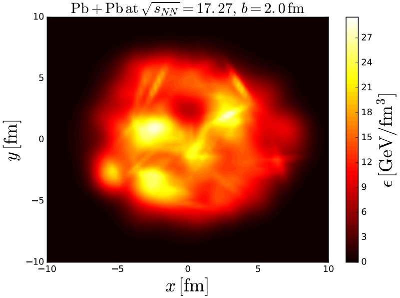
Conclusions and Outlook

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: $A + B \to A + X$ or $A + B \to X + B$

- 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:

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

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

Double diffractive: $A + B \to X + X$

- 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:

$$\mathrm{PDF} \propto \frac{1}{x}(1-x)^{\beta+1}$$

S.Bass et al. arXiv:nucl-th/9803035

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:

$$\mathrm{PDF} \propto x^{\alpha-1}(1-x)^{\beta-1}$$

- Transverse momentum sampled from Gaussian

A.Capella et al. 10.1016/0370-2693(79)90718-4

Subprocess selection:

- From experimental σ_{tot} and σ_{el}

$$\sigma_{\mathrm{inel}} = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{el}}$$

- With parametrization of σ_{SD} and σ_{DD} from Pythia

$$\sigma_{\mathrm{ND}} = \sigma_{\mathrm{inel}} - \sigma_{\mathrm{SD}} - \sigma_{\mathrm{DD}}$$

G. A. Schuler and T. Sjostrand 10.1103/PhysRevD.49.2257