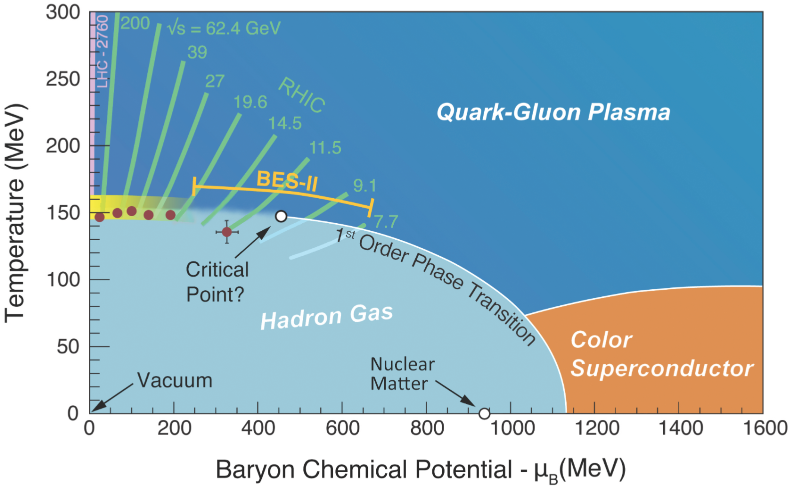
Can Baryon Stopping be understood within the String Model

Justin Mohs,
Sangwook Ryu and Hannah Elfner

Goethe University Frankfurt

Hot Quarks
September 11, 2018

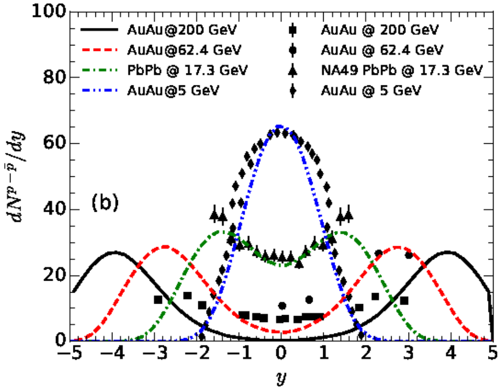
Exploring the QCD Phase Diagram



- 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

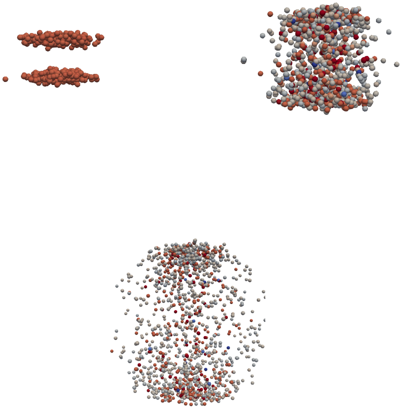
- Hadronic degrees of freedom
- Geometric collision criterion:

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

- 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



Gold-gold collision at $\sqrt{s_{NN}} = 10$ GeV In SMASH

J.Weil et al. 10.1103/PhysRevC.94.054905

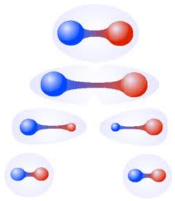
String Model

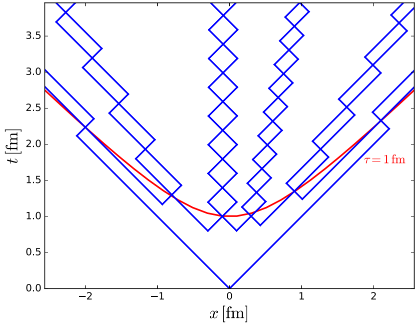
- Massless quarks with momentum p_1, p_2 and position x_1, x_2
- Motion according to:

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

- $\kappa \approx 1$ 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





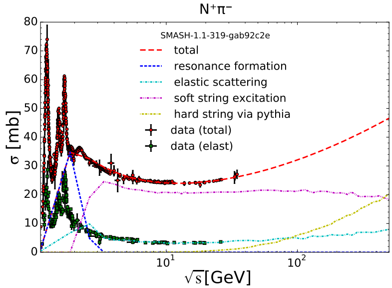
Strings in SMASH

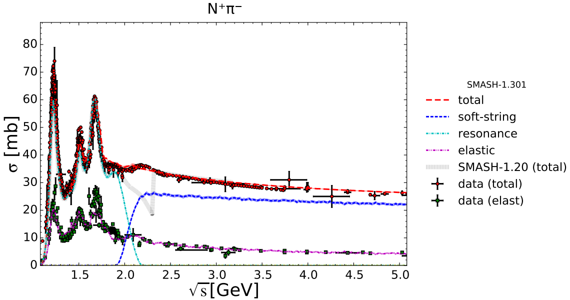
Hard processes:

- 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
- Includes single diffractive, double diffractive and non-diffractive subprocesses



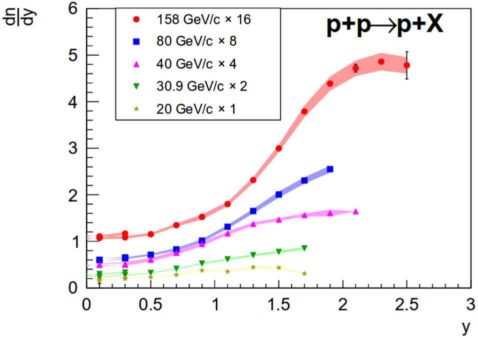


System and Observables

- Reproduce experimental p+p data before investigating baryon stopping in larger systems

- Most important are dynamics of string fragments and initial protons
- Particle multiplicities
- Rapidity spectra
- $\langle p_T \rangle$ as function of x_F

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

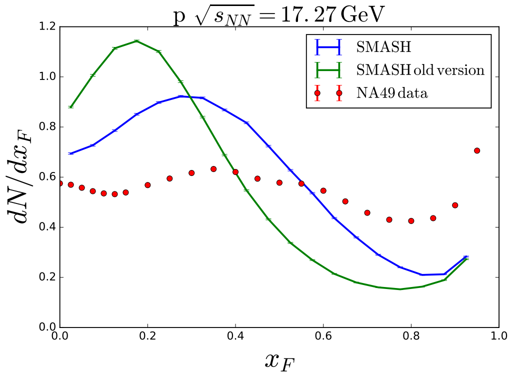


NA61 10.1140/epjc/s10052-017-5260-4

- Which results are influenced by string parameters and how?

Fragmentation Function for Leading Baryons

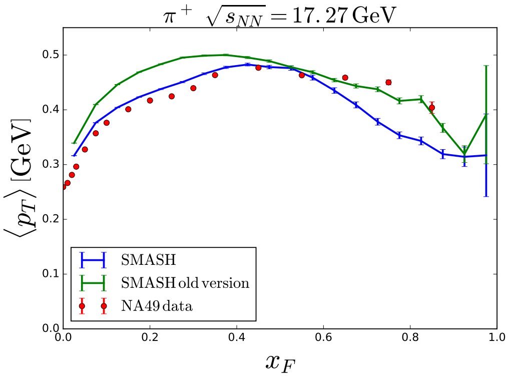
- Fragmentation function for sampling light cone momentum fraction for each string fragment
- Use a different fragmentation function for leading baryons to increase longitudinal momentum of protons

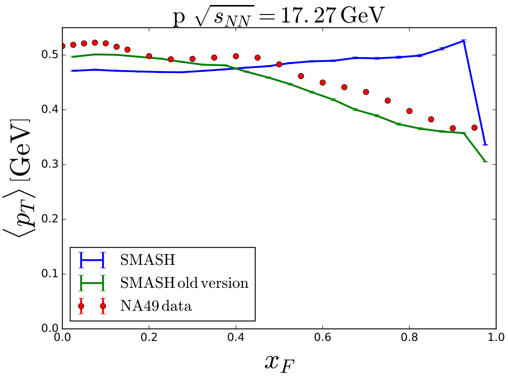


- Old version: use Lund fragmentation function consistently
- New version: use Gaussian with $\mu = 1$ and $\sigma = 0.6$ for leading Baryons
- Slightly better agreement with data for longitudinal momentum

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

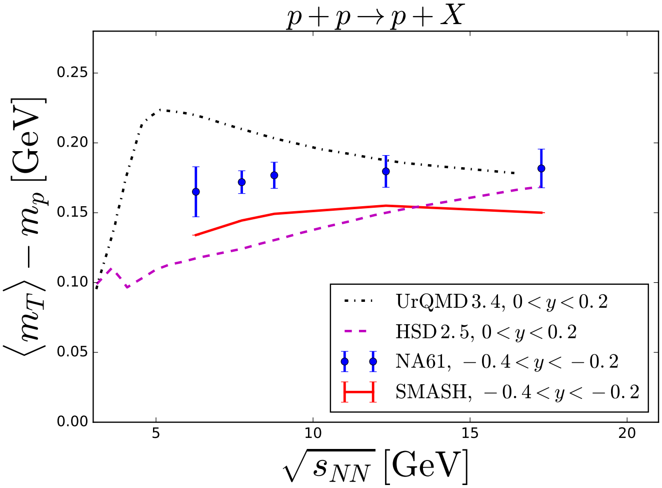
Transverse Momentum





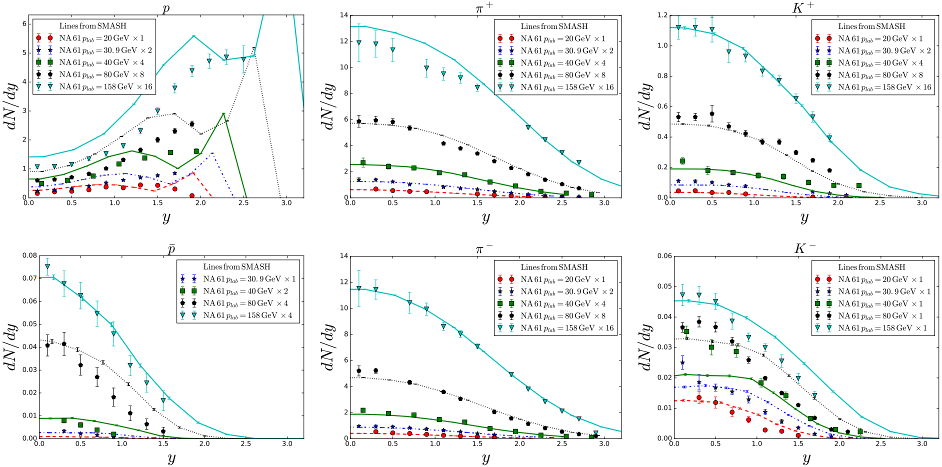
- Reasonable agreement for transverse momentum using only symmetric Lund fragmentation function

Proton Mean Transverse Mass



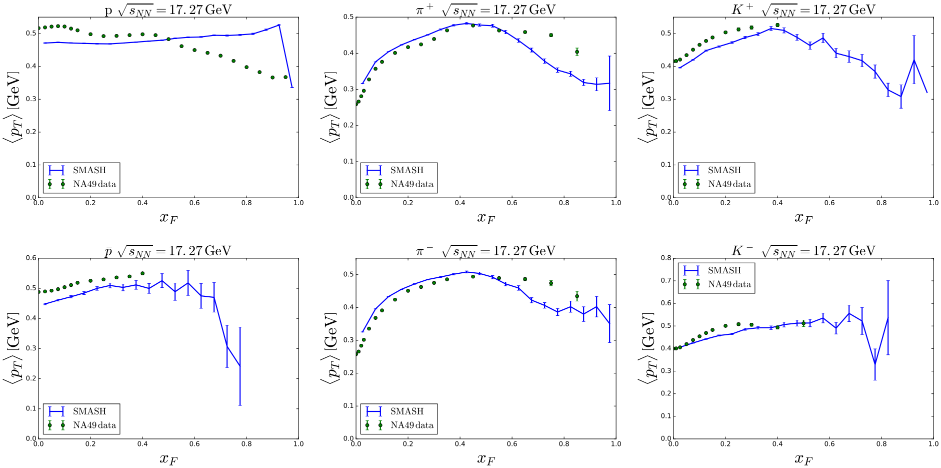
- Transverse momentum underestimated at mid rapidity as shown before
- Energy dependence looks reasonable

Overview p+p Rapidity Spectra



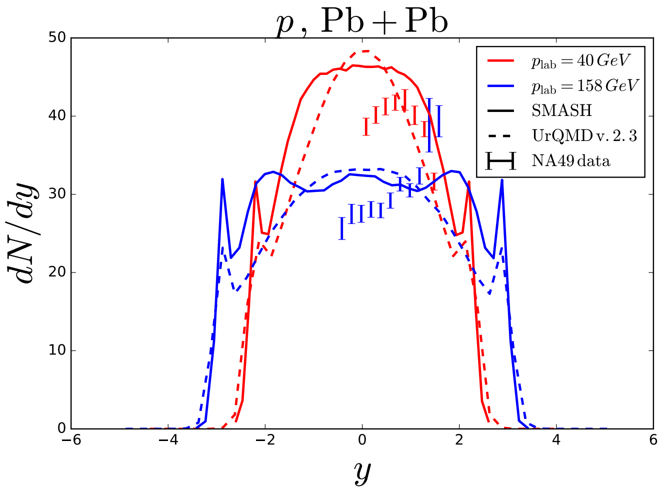
- Fragmentation function, strangeness suppression and diquark suppression tuned to data

Overview p+p mean p_T



- Transverse momentum transfer and transverse momentum production from string fragmentation tuned to data

Heavy Ion Collisions



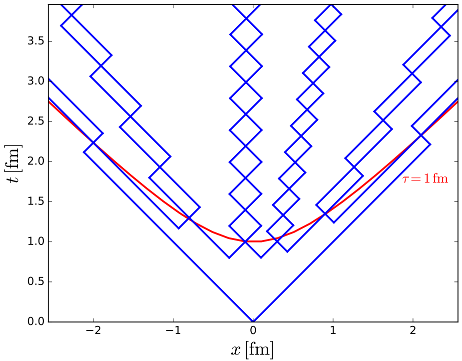
- First calculation for heavy ions after tuning to p+p data
- Protons are stopped too much but less than in UrQMD
- Understand interaction of string fragments

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

Formation Times

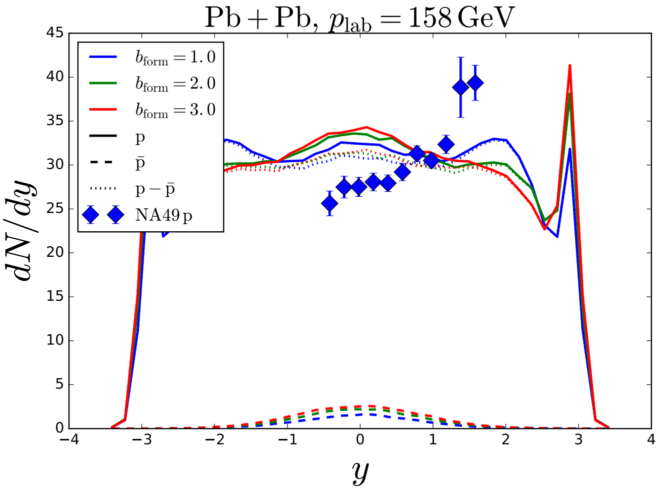
- String fragments need time to form
- Formation times are distributed around constant proper time
- Calculate formation times from yoyo-formalism

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



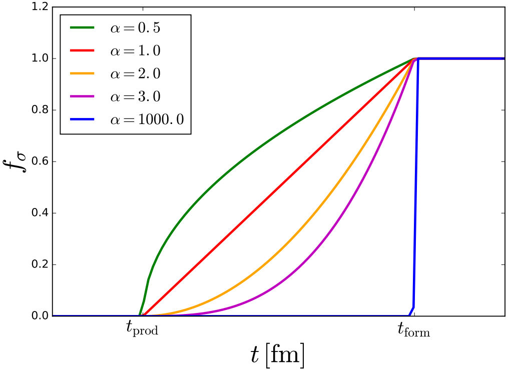
Effect of Formation Times

- Multiply formation time from yoyo-formalism with factor b_{form}
- Protons stopped more at mid rapidity for larger formation times
- Unexpected since larger formation times means less interactions
- Need to study time dependence of collision number and rapidity distribution



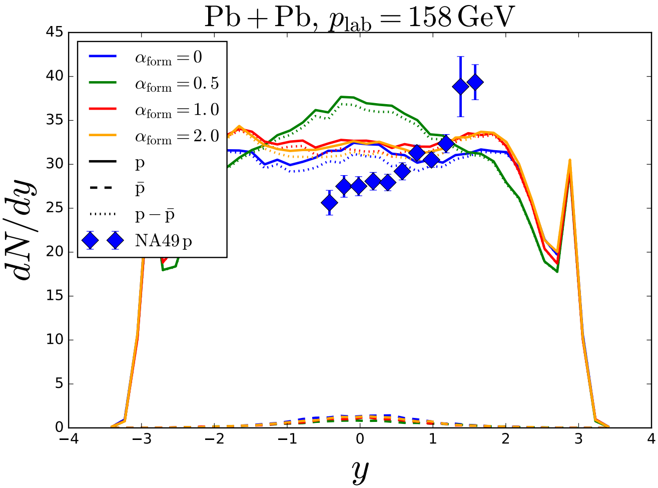
Cross Section Scaling Factors

- 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

Results for Different Powers α



- Lines labeled $\alpha = 0$ use a step function
- Large impact on dN/dy when going to $\alpha = 0.5$
- Very short time after initial collision most important
- Steady increase of scaling factor dissolves bump at mid rapidity

Summary

- String model parameters tuned to p+p data at SPS energies
- p+p results agree with experimental data for produced hadrons
- Proton y or x_F improved but still needs investigation
- Calculation for heavy ion collisions show slightly too much stopping
- Insights on the role of formation times and cross section scaling factors for baryon stopping gained

Outlook

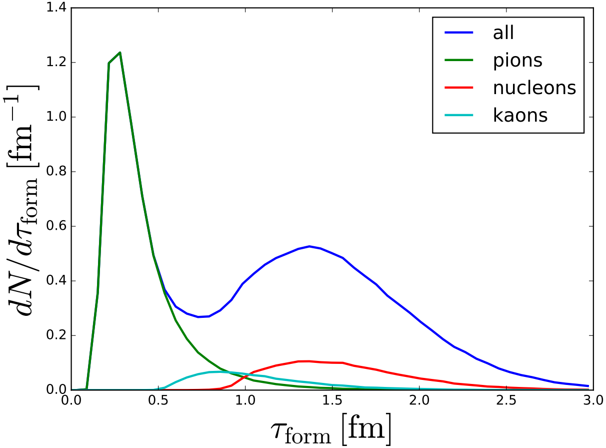
- Experimental p+p and Pb+Pb proton rapidity spectra look similar
  $\rightarrow$ Turn off all secondary collisions

- Understand which kind of reactions are responsible for stopping

- More rigorous study of parameter dependencies in fragmentation functions to match p+p data

- Investigate interplay of formation times and cross-section scaling factors

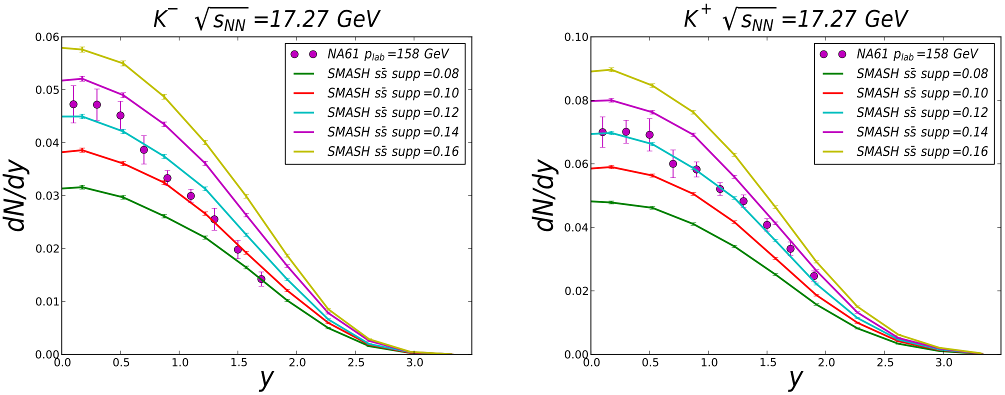
Backup: Formation Time Distribution



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

Backup: Strangeness Suppression

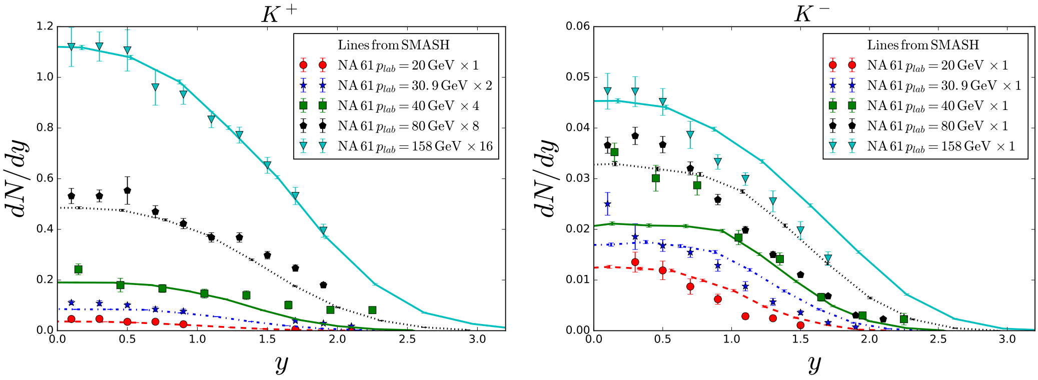
- Pythia parameter to define the probability to produce an $s\bar{s}$ relative to $u\bar{u}$ or $d\bar{d}$



- Non-strange hadrons are also slightly affected
- Strangeness suppression set to 0.12

Backup: Strangeness Suppression

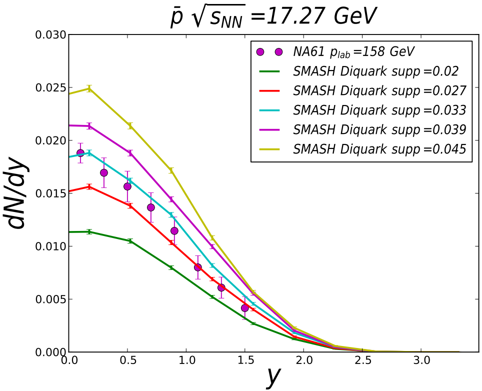
- Energy dependence of Kaon yields hard to reproduce for all species simultaneously

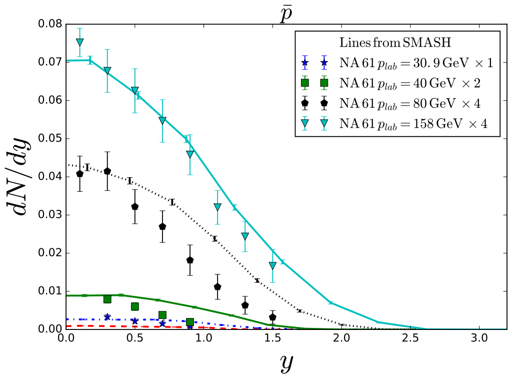


- Strangeness suppression not energy dependent in SMASH

Backup: Diquark Suppression

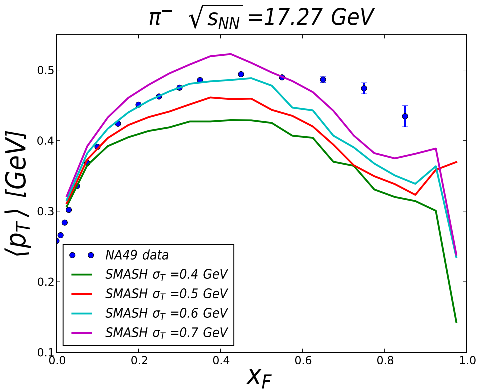
- Pythia parameter to define probability to produce $qq\bar{q}\bar{q}$ relative to $q\bar{q}$
- Antiprotons sensitive to diquark suppression

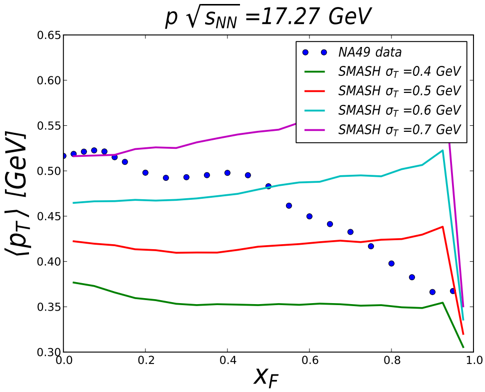




- Reasonable agreement with data for a value of 0.042

Backup: Transverse Momentum Transfer



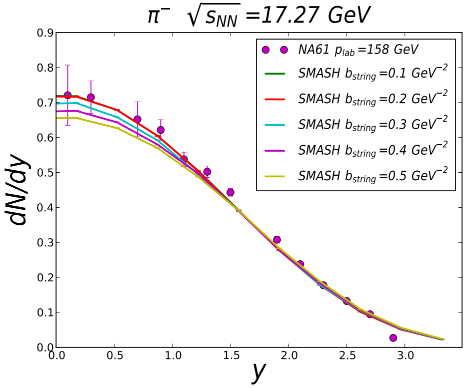


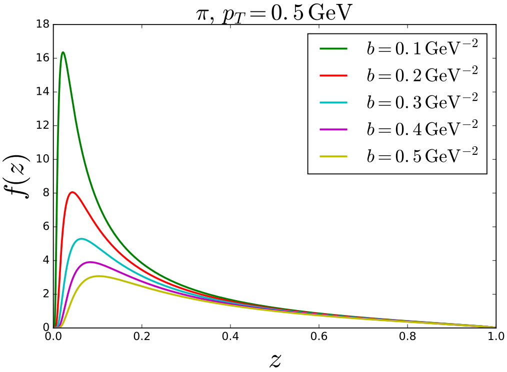
- Varying the width σ_T in Gaussian to sample transverse momentum transfer
- Allowing more transverse momentum transfer increases $\langle p_T \rangle$
- Protons and other mesons not simultaneously reproducible

Backup: Fragmentation Function

- Fragmentation function used in PYTHIA:

$$f(z) = \frac{1}{z}(1-z)^a \exp\left(-b\frac{m_T^2}{z}\right)$$





- Sample light cone momentum fraction z for each string fragment
- Is tuned to the shape of pion dN/dy

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:

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

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:

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

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

Backup: 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

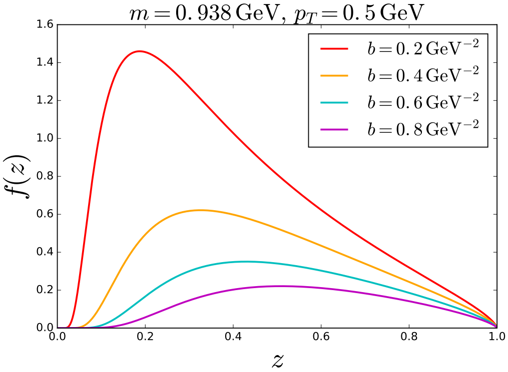
$$\sigma_{\mathrm{ND}} = \sigma_{\mathrm{inel}} - \sigma_{\mathrm{SD}} - \sigma_{\mathrm{DD}}$$

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

Backup: Fragmentation Function

- Symmetric Lund fragmentation function used in PYTHIA

$$f(z) = \frac{1}{z}(1-z)^a \exp\left(-b\frac{m_T^2}{z}\right)$$



- Fragmentation function for leading baryons

$$f_{\text{leading}}(z) \propto \exp\left(-\frac{(z-1.0)^2}{0.6^2}\right)$$