Effects of hadronic reinteraction on jet fragmentation from small to large systems

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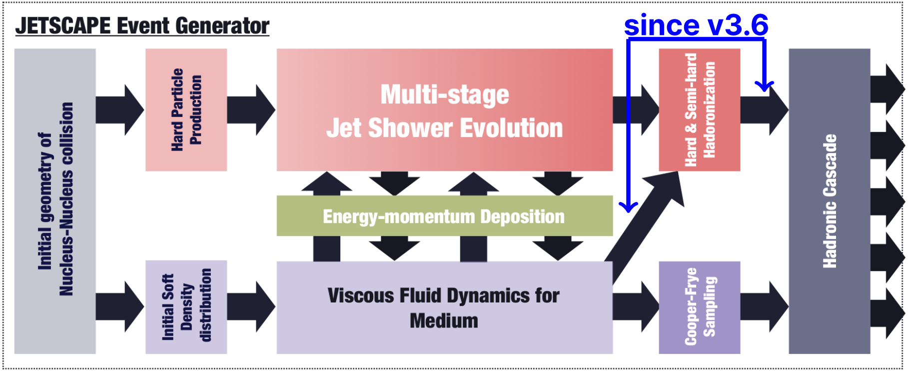
WAYNE STATE UNIVERSITY JETSCAPE

HP2024 NAGASAKI

The JETSCAPE Framework

- Modular framework for jet and bulk dynamics studies in HIC
- Latest version **JETSCAPE 3.6.5**: `github.com/JETSCAPE`



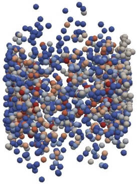
- New connection: study effects of hard hadrons in the afterburner phase

Figure from Y. Tachibana

SMASH - Simulating Many Accelerated Strongly-interacting Hadrons

- Dynamical non-equilibrium description of HIC at low beam energies (GSI/FAIR) and late stage rescattering at high beam energies (RHIC/LHC)
- PDG(2018) hadrons up to $m \approx 2.35$ GeV

Weil et al., Phys. Rev. C 94 (2016)



SMASH Setup

- Effective solution to the relativistic Boltzmann equation

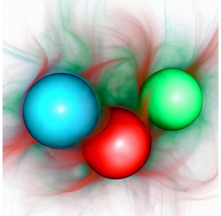
$$p^\mu \partial_\mu f_i(t,\vec{x},\vec{p}) + m_i F^\alpha \partial^p_\alpha f_i(t,\vec{x},\vec{p}) = \mathcal{C}^i_{\text{coll}}\left[f_i(t,\vec{x},\vec{p})\right]$$

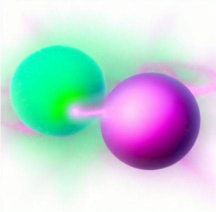
- Geometric collision criterion

$$d_{\text{trans}} < d_{\text{int}} = \sqrt{\frac{\sigma_{\text{tot}}}{\pi}}, \quad d^2_{\text{trans}} = (\vec{r}_a - \vec{r}_b)^2 - \frac{[(\vec{r}_a - \vec{r}_b)\cdot(\vec{p}_a - \vec{p}_b)]^2}{(\vec{p}_a - \vec{p}_b)^2}$$

Hybrid Hadronization

- Interpolates between: ✎Han, Fries, Ko. (2016)
  - String fragmentation → dilute systems
  - Quark recombination → dense systems
- How to interpolate between the two models?
  - Physics criterion: Recombination probability vanishes for large phase-space distances
- Advantages:
  - Hadronizes all systems from $e^+ + e^-$, $p + p$ to $A + A$
  - Full phase space information of the partons / hadrons ⇒ Input for SMASH
  - Can hadronize “negative hadrons” when a medium is present
- New features of Hybrid Hadronization since JETSCAPE 3.6:
  - Complete treatment of systems with medium (brick, 2+1d, 3+1d), more precise position determination along strings/junctions, ...



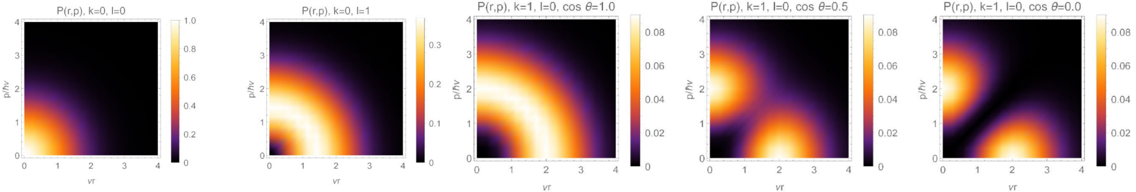


Talk: Rainer Fries, Wed 10:50

Poster: Rainer Fries, Tue 16:35

How To Hadronize Jets

- Dilute part (string fragmentation) → PYTHIA 8
- Solving the recombination problem:
  - (Anti-)quarks are Gaussian wave packets in phase space around $(\vec{r}_i, \vec{p}_i)$ with width δ, color + spin information might be available (otherwise set statistically)
  - Short range correlation: isotropic harmonic oscillator potential (width $1/\nu$)
  - Wigner formalism in phase space (need angular momentum eigenstates)
- Example with mesons:
  - Sum over magnetic quantum number m (not tracking spin polarization)
  - Probabilities depend on relative coordinates r, p in phase space $(\theta = \angle(r, p))$



Plots from R. J. Fries

How To Hadronize Jets

- Probabilities depend on two variables: total phase-space distance squared v and total angular momentum squared t

$$v = \frac{\nu^2 r^2}{2} + \frac{p^2}{2\hbar^2\nu^2}, \quad t = \frac{1}{\hbar^2}\left[p^2r^2 - (\vec{p}\cdot\vec{r})^2\right] = \frac{1}{\hbar^2}L^2$$

- t connects the relative angular momentum of the quarks to the quantum number l of the bound state
- Total recombination probability takes quark spins (statistically) and color into account
- Color factors are determined by color tags, thermal partons and shower partons with random color have tag 0

$$\mathcal{P}_{00} = e^{-v}$$

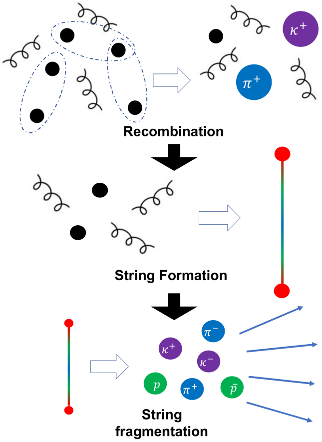
$$\mathcal{P}_{01} = e^{-v}v$$

$$\mathcal{P}_{02} = \frac{1}{2}e^{-v}\left(\frac{2}{3}v^2 + \frac{1}{3}t\right)$$

$$\mathcal{P}_{10} = \frac{1}{2}e^{-v}\left(\frac{1}{3}v^2 - \frac{1}{3}t\right)$$

Hybrid Hadronization Workflow

- Input:
  - Partons with virtualities below a cutoff, with space-time information and color tags
- Recombination Step:
  - Decay gluons into $q\bar{q}$ and sample recombination probabilities (w/ Wigner functions) for all $q\bar{q}$ and qqq bound states (in medium → thermal partons from hypersurface)
- Intermediate Step:
  - String system of recombined hadrons and remnant partons (in medium → thermal partons in remnant strings), only color singlets removed
- Fragmentation:
  - Remnant partons tend to be further apart in phase space → Hadronize remnant strings in PYTHIA 8



QM23 Poster, Cameron Parker

Setup - Vacuum Systems

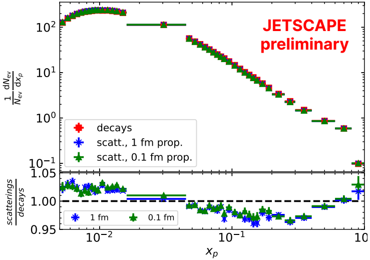
Initial state $e^+ + e^- / p + p$ PYTHIA → **Energy loss** Matter → **Hadronization** Recombination + String fragmentation → **Afterburner** SMASH

- Consider two vacuum systems:
  - $e^+ + e^-$ at $\sqrt{s_{\mathrm{NN}}} = 91.2$ GeV
  - $p + p$ at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV
- Simulation setup:
  - Only decays in SMASH
  - 1 fm/c free-streaming phase before SMASH (including scatterings)
  - 0.1 fm/c free-streaming phase before SMASH (including scatterings)

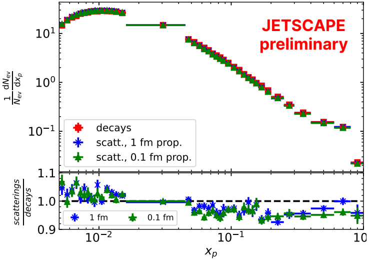
$e^+ + e^-$

$$x_p \equiv \frac{2|\vec{p}|}{\sqrt{s_{\mathrm{NN}}}}$$

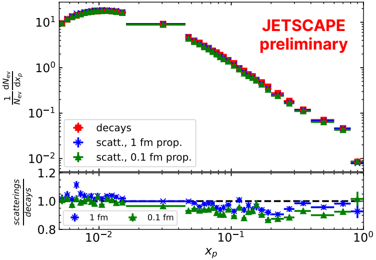
Pions:



Kaons:



Protons:

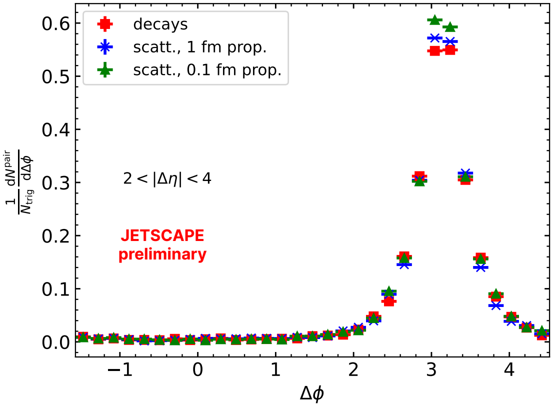


- Transverse momenta are reshuffled to smaller values caused by interactions
- Larger effect for heavier hadrons (known from afterburner studies in heavy-ion simulations)

Dihadron Correlations

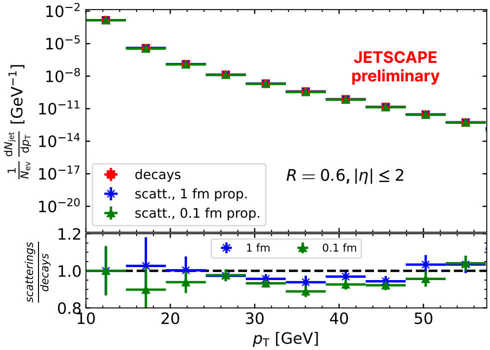
- Analysis similar to CMS (2011) , CMS (2012) :

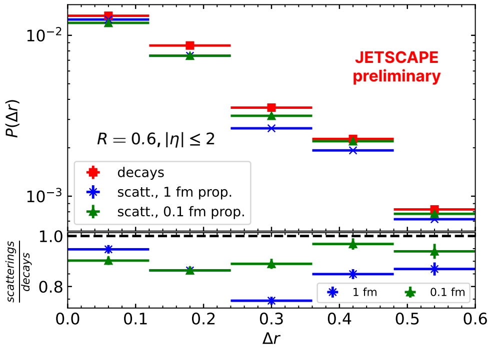
$$\frac{1}{N_{\text{trig}}}\frac{d^2N^{\text{pair}}}{d\Delta\phi} = \frac{1}{\Delta\eta_{\max} - \Delta\eta_{\min}} \int_{\Delta\eta_{\min}}^{\Delta\eta_{\max}} \frac{1}{N_{\text{trig}}}\frac{d^2N^{\text{pair}}}{d\Delta\eta d\Delta\phi}\, d\Delta\eta$$



- Enhancement of long-range correlations with more rescatterings in the afterburner

$p + p$

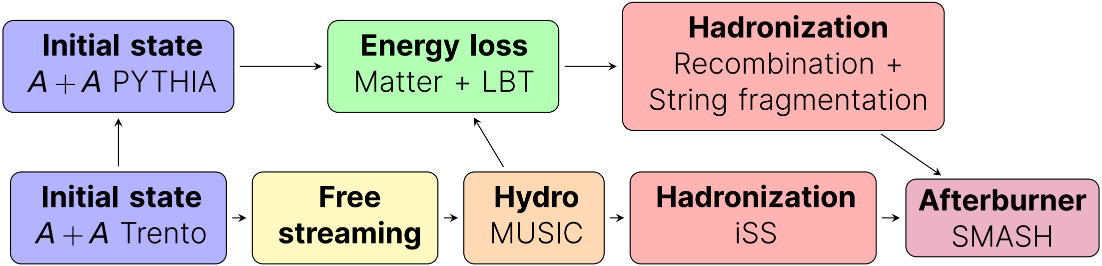




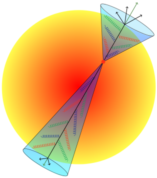
- In the jets we see a diffusion of momentum
- Diffusion of hadrons away from the jet center
- $p + p$ hadron spectra $p_T \leq 15$ GeV no significant differences
- Next: $p + p$ with more statistics and high multiplicity cut

$$P(\Delta r) = \frac{1}{N_{\text{jet}}} \frac{\mathrm{d}\sum_i p_T^i}{\mathrm{d}\Delta r}, \quad \Delta r \equiv \sqrt{(\eta - \eta_{\text{jet}})^2 + (\phi - \phi_{\text{jet}})^2}$$

Outlook - Medium Systems



- Particles from the hard and soft sectors can rescatter
- Expectation: Effects in the p_T region between $\approx 5 - 20$ GeV



Summary

- Modernized Hybrid Hadronization module for all systems ($e^+ + e^-$, $p + p$, $A + A$)
- New connection between Hybrid Hadronization and SMASH → study jet modification in hadronic matter
- First results in vacuum systems show (expected) small effects in the redistribution of hadron momenta

Outlook

- Next steps:
  - Use optimized $e^+ + e^-$, $p + p$ parameters from Bayesian analysis + more statistics
    Poster: Rainer Fries, Tue 16:35
  - Look at $A + A$, where we expect even larger effects

Analysis performed with SPARKX (v1.3.0) - Software Package for Analyzing Relativistic Kinematics in Collision eXperiments:

GitHub: smash-transport/sparkx
10.5281/zenodo.12821236

Götz, Roch, Sass (2024)

Documentation:

`smash-transport.github.io/sparkx/`

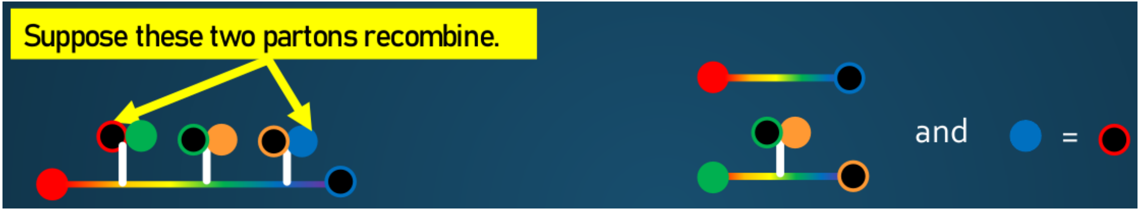
Other JETSCAPE presentations

- Peter Jacobs: *Multi-Observable Analysis of Jet Quenching Using Bayesian Inference*, **Monday 15:40**
- Yasiki Tachibana: *Extraction of jet-medium interaction details through jet substructure for inclusive and gamma-tagged jets*, **Monday 17:50**
- Yayun He: *Energy-energy correlators of inclusive jets in heavy-ion collisions*, **Tuesday 9:40**
- Abhijit Majumder: *Correlations between hard probes and bulk dynamics in small systems*, **Tuesday 16:15**
- Chathuranga Sirimanna: *Interplay of prompt and non-prompt photons in photon-triggered jet observables*, **Wednesday 9:40**
- Rainer Fries: *X-SCAPE as a universal Event Generator for e+p, e+e- and pp collisions*, **Poster session**

Backup Slides

Hybrid Hadronization At Work - String Repair

- 1 quick example:

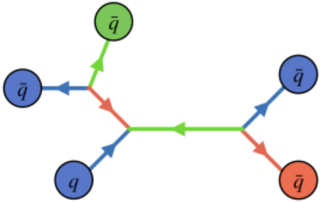


Picture shamelessly stolen from R. J. Fries

- Recombination removes color singlets, remaining strings "snap together" the right way automatically

Hybrid Hadronization At Work - String Repair

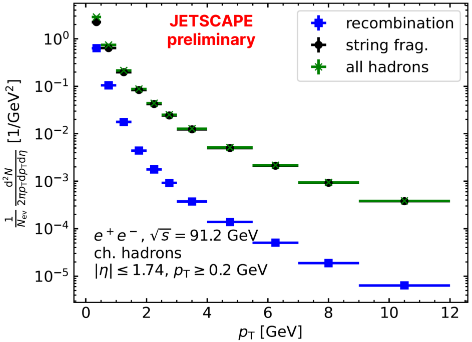
- Remnant partons with color tag 0 (e.g. from LBT) are used in strings
- Unused gluons are restored
- If the initial system was not a color singlet: introduce extra partons to balance color
    - Beam partons
    - Thermal partons
    - Fake partons with zero momentum
- Prepare junctions for PYTHIA: many systems have a too complicated junction topology → cut them into single- and di-junctions



Hybrid Hadronization At Work - Fragmentation

- Remaining string system handled by PYTHIA
- Decays of excited hadron states can be handled via PYTHIA or by using SMASH
- Positions of fragmentation hadrons are determined by placing them along the strings and junction legs

- Remanant partons tend to have a larger distance in phase space:



Dihadron Correlations

- Analysis similar to ✎CMS (2011) , ✎CMS (2012) :

$$\frac{1}{N_{\text{trig}}}\frac{\mathrm{d}^2N^{\text{pair}}}{\mathrm{d}\Delta\eta\mathrm{d}\Delta\phi} = B(0,0)\times\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

$$S(\Delta\eta,\Delta\phi) = \frac{1}{N_{\text{trig}}}\frac{\mathrm{d}^2N^{\text{same}}}{\mathrm{d}\Delta\eta\mathrm{d}\Delta\phi}$$

$$B(\Delta\eta,\Delta\phi) = \frac{1}{N_{\text{trig}}}\frac{\mathrm{d}^2N^{\text{mix}}}{\mathrm{d}\Delta\eta\mathrm{d}\Delta\phi}$$

- $p^{\text{trig}} \in [4,6]$ GeV, $p^{\text{assoc}} \in [2,4]$ GeV
- Integrate out $\Delta\eta$ dependence:

$$\frac{1}{N_{\text{trig}}}\frac{\mathrm{d}^2N^{\text{pair}}}{\mathrm{d}\Delta\phi} = \frac{1}{\Delta\eta_{\text{max}}-\Delta\eta_{\text{min}}}\int_{\Delta\eta_{\text{min}}}^{\Delta\eta_{\text{max}}}\frac{1}{N_{\text{trig}}}\frac{\mathrm{d}^2N^{\text{pair}}}{\mathrm{d}\Delta\eta\mathrm{d}\Delta\phi}\,\mathrm{d}\Delta\eta$$