Effects of jet fragmentation hadrons in the hadronic afterburner phase from small to large systems

Hendrik Roch with Hannah Elfner & Rainer J. Fries
FIAS / Wayne State University
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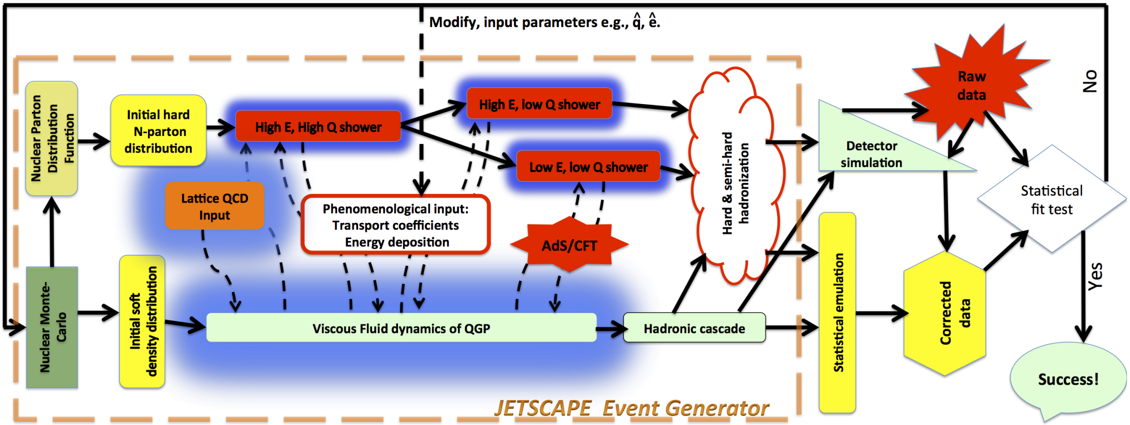
STRONG-HFHF-2023, Sicily

The JETSCAPE Framework

- Modular framework for jet and bulk dynamics studies in HIC
- Latest version **JETSCAPE 3.6**: `github.com/JETSCAPE` (released last Tuesday)



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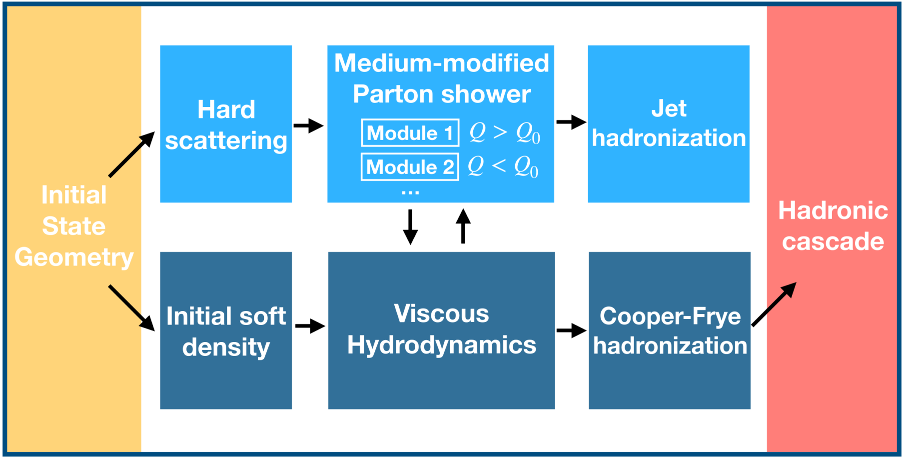
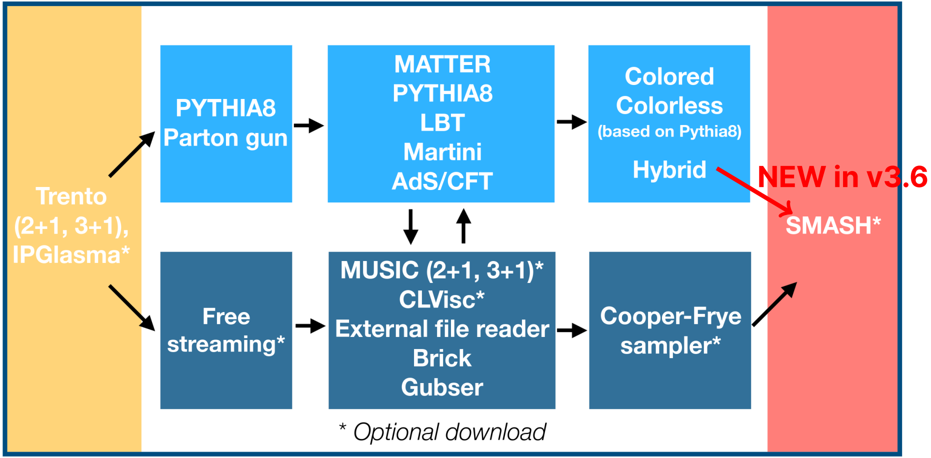
Simplified Setup - Physics



✎JETSCAPE Summer School 2023, Joern Putschke

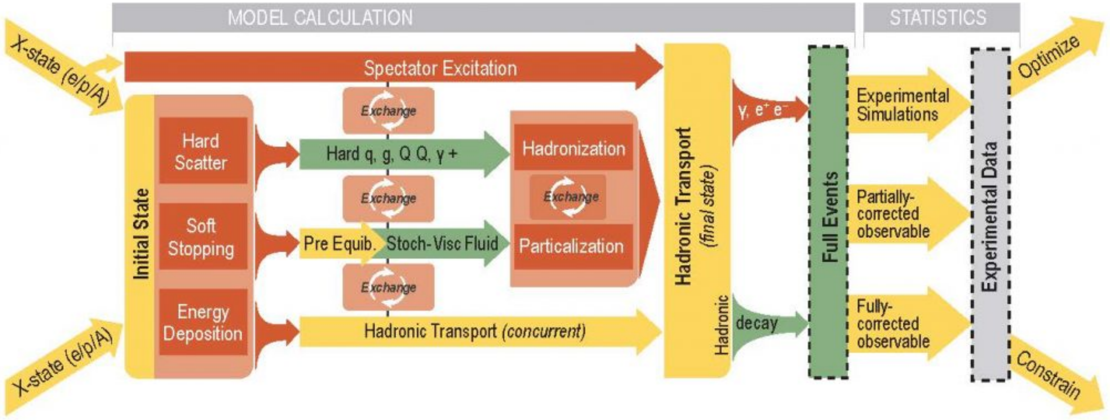
Simplified Setup - Modules



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

JETSCAPE Summer School 2023, Joern Putschke

The X-SCAPE Framework



- Full backwards compatibility with JETSCAPE, more flexibility for information flow, concept of time ⇒ Low beam energy physics

JETSCAPE

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)
- Hadrons from PDG(2018) up to $m \approx 2.35$ GeV are included

✎Weil et al., Phys. Rev. C 94 (2016)

SMASH Setup

- Effective solution to the relativistic Boltzmann equation

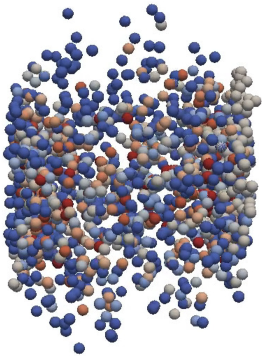
$$p^\mu \partial_\mu f_i(t,\vec{x},\vec{p}) + m_i F^\alpha \partial^p_\alpha f_i(t,\vec{x},\vec{p}) = \mathcal{C}^i_{\text{coll}}\left[f_i(t,\vec{x},\vec{p})\right]$$

- Geometric collision criterion

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

- Test particle method: $\sigma \rightarrow \sigma \cdot N^{-1}_{\text{test}}$, $N \rightarrow N \cdot N_{\text{test}}$

SMASH - Simulating Many Accelerated Strongly-interacting Hadrons



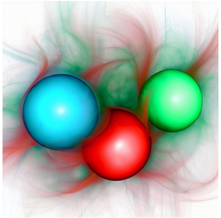
✎SMASH

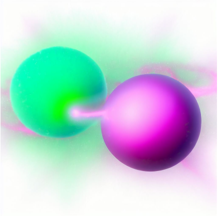
SMASH Modi

- **IC** Initial condition generator for hydrodynamic models
- **Collider** Elementary or AA reactions
- **Box** Infinite matter simulations
- **Afterburner** Hadronic rescatterings after hydrodynamic evolution
- **Library** Use SMASH as library in third party codes
  → Implementation in JETSCAPE framework
- ⇒ **Output** OSCAR, Binary, HepMC, YODA (Rivet), ROOT, VTK, ...

Hybrid Hadronization

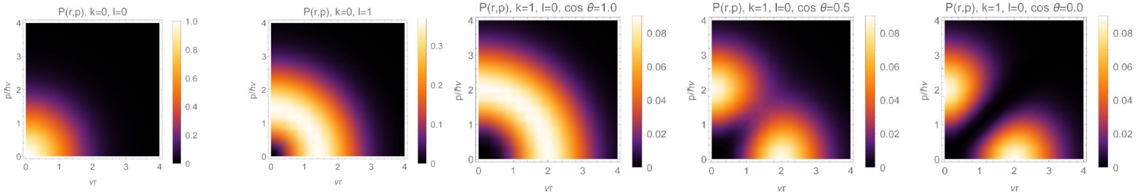
- Interpolates between: ✎Han, Fries, Ko. (2016)
  - String fragmentation → dilute systems
  - Quark recombination → dense systems
- How to interpolate between the two models?
  - Use physics criterion: Probability for recombination vanishes for large phase-space distances
- Advantages:
  - Can handle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





How To Hadronize Jets

- Dilute part (string fragmentation) → PYTHIA
- 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

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

- 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

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

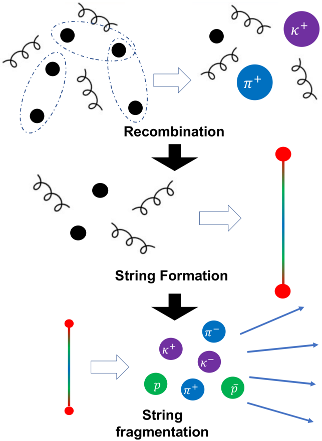
$$\mathcal{P}_{01} = e^{-v} v$$

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

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

Hybrid Hadronization Workflow

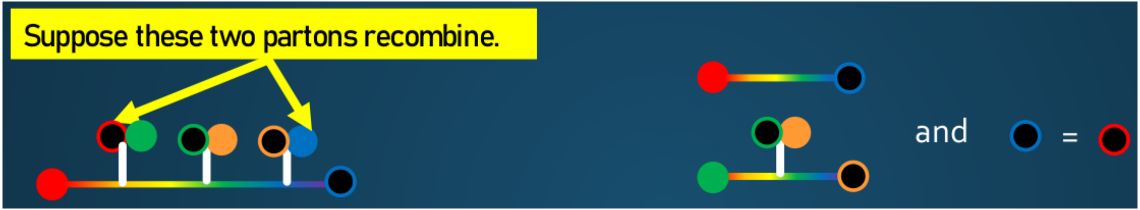
- Input:
  - Partons with virtualities below a cutoff, with space-time information and color tags
- Recombination Step:
  - Decay gluons into $q\bar{q}$ and sample recombination probabilities (w/ Wigner functions) for all $q\bar{q}$ and qqq bound states (in medium → thermal partons from hypersurface)
- 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 string systems in PYTHIA



QM23 Poster, Cameron Parker

Hybrid Hadronization At Work

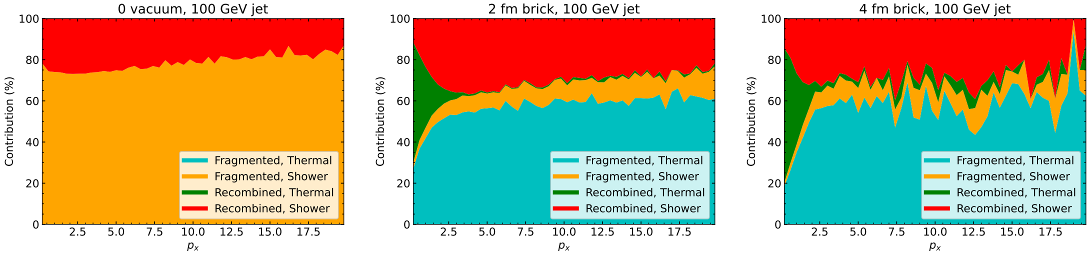
- 1 quick example:



Picture shamelessly stolen from R. J. Fries

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

Hybrid Hadronization At Work



- pGun + MATTER + Hybrid Hadronization
- String fragmentation dominant

- pGun + MATTER + LBT + Hybrid Hadronization
- In medium systems with thermal partons the thermal recombination becomes a strong contribution at low and intermediate momenta growing with the medium size (event stronger when the medium has flow)

(4 fm brick has 10 times less statistics)

Setup - Vacuum Systems

Initial state
$e^+ + e^- / p + p$
PYTHIA

→

Energy loss
Matter

→

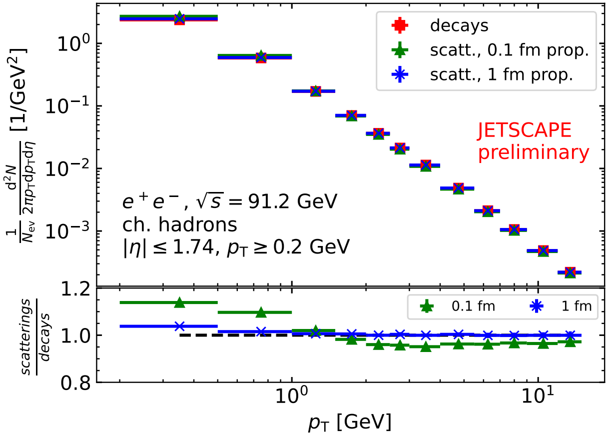
Hadronization
Recombination +
String fragmentation

→

Afterburner
SMASH

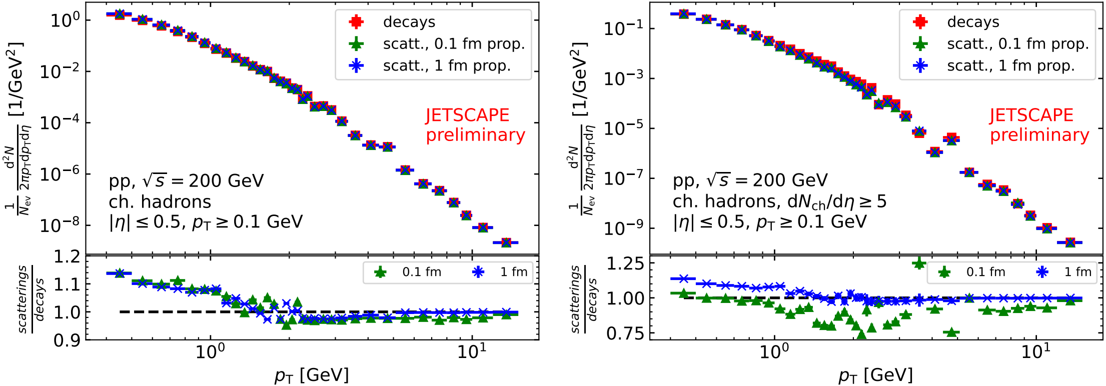
$e^+ + e^-$ - Very Preliminary Results

- Charged hadrons at $\sqrt{s} = 91.2$ GeV: Hybrid Hadronization + SMASH
- Three runs: SMASH decays only, SMASH rescatterings with two different durations of the hadronization process (in hadron rest frame)
- 5-15% effects depending on the density of the system (explored with the different times)

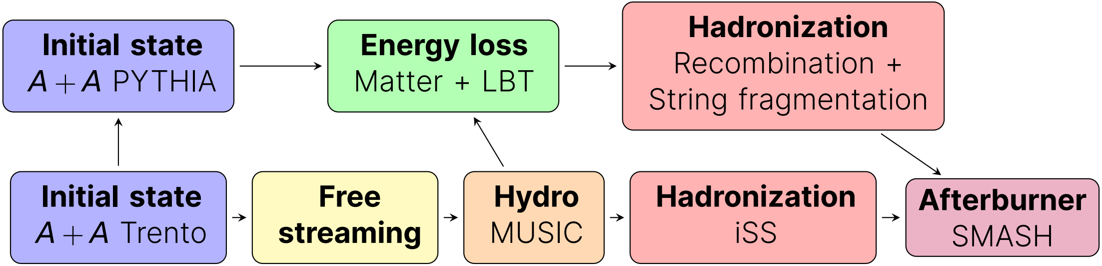


$p+p$ - Very Preliminary Results

- Charged hadrons at $\sqrt{s} = 200$ GeV with and without multiplicity cut
- Up to $\approx 15\%$ effect at low p_T even for the long hadronization time

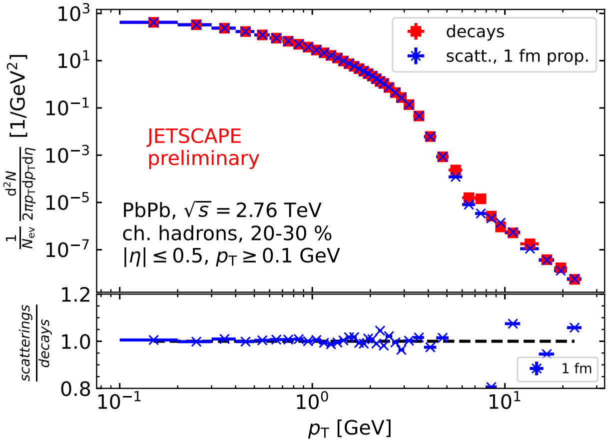


Setup - Medium Systems



$\mathbf{Pb} + \mathbf{Pb}$ - Very Preliminary Results

- Charged hadrons at $\sqrt{s} = \mathbf{2.76}$ **TeV** (very low statistics)
- Hadronic rescatterings in SMASH are always done for the soft particles, blue points add jet hadrons to SMASH evolution
- Soft hadrons dominate region up to $\approx$ **4 GeV**, statistics above is not sufficient for clear statement



Summary

- New interesting modules (& physics) implemented in JETSCAPE 3.6
- First study of jet hadron rescatterings in the afterburner shows interesting effects

Outlook

- Next steps:
  - Use optimized $e^+ + e^-$, $p + p$ parameters from Bayesian analysis, more statistics
  - Look at different jet observables and correlations