Completing the Picture of Partonic Interactions in the Quark–Gluon Plasma

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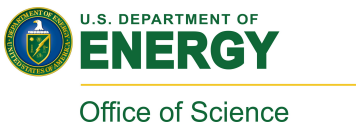
March 27, 2026



Outline

Motivation

- Majority of HIC simulations only consider soft-soft and hard-soft partonic interactions
- Parton cascade model (PCM) developed in the early 1990's considered hard-hard and hard-soft interactions
- Early popularity of the model was suppressed due to the success of hydro simulations:
  - PCM failed to describe bulk properties: no soft-soft interactions
  - Partonic energy loss + hydro: full realistic simulations
- Hard-hard interactions: less important in smaller systems

Goal: Complete the picture of partonic interactions by including the hard-hard interactions in JETSCAPE

Historical Overview

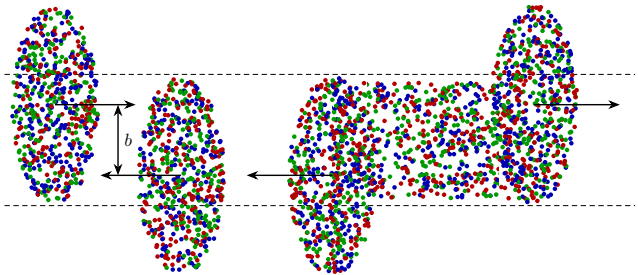
- Understanding QCD matter under extreme conditions
- Heavy-ion collisions: creation of deconfined quark–gluon plasma (QGP)
- Need a transport model for full description of collision dynamics
- **PCM** bridges perturbative QCD and macroscopic evolution
- Developed by K. Geiger and B. Müller (Nucl.Phys.B369:600-654,1992)
- Newly revised and improved implementation was developed by S. A. Bass, B. Müller, and D. K. Srivastava in early 2000's
- Inspired modern transport codes like **BAMPS, AMPT, PHSD**

Parton Cascade Model (PCM)

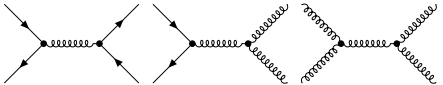
- PCM is a microscopic transport model based on Boltzmann Equation:

$$\left[\frac{\partial}{\partial t}\frac{\vec{p}}{E}\cdot\frac{\partial}{\partial \vec{r}}\right] f_1(\vec{p},\vec{r},t) = \sum_{processes} C(\vec{p},\vec{r},t)$$

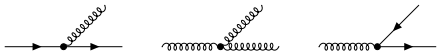
- Full time-evolution of a system of partons at high density and temperature
- Ideally suited for the interaction of jets with medium and medium response



- Binary cross sections in LO pQCD



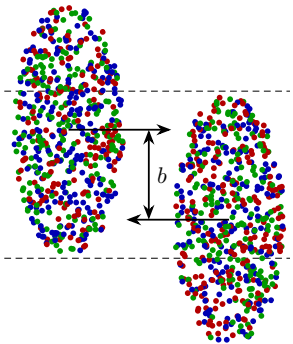
- Radiative processes (full DGLAP)



Construction in PCM

Initial State:

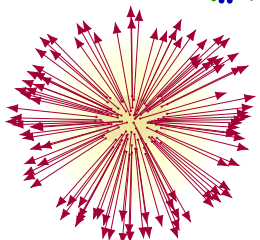
- PDF-based parton sampling: flavor, color tag, momentum fraction x
- Intrinsic transverse momentum by Gaussian smearing
- Spatial distribution of nucleons and partons from Woods–Saxon density



Classical Parton Trajectories after Collision

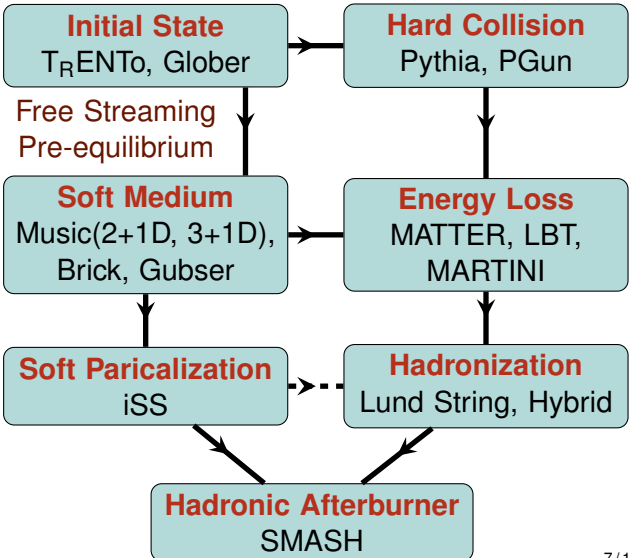
- Interaction criterion based on geometric interpretation of cross section:

$$d_{min} \leq \sqrt{\frac{\sigma_{tot}}{\pi}} \qquad \sigma_{tot} = \sum_{final\ states} \frac{d\sigma(\hat{s}, \hat{t}, \hat{u})}{d\hat{t}} d\hat{t}$$



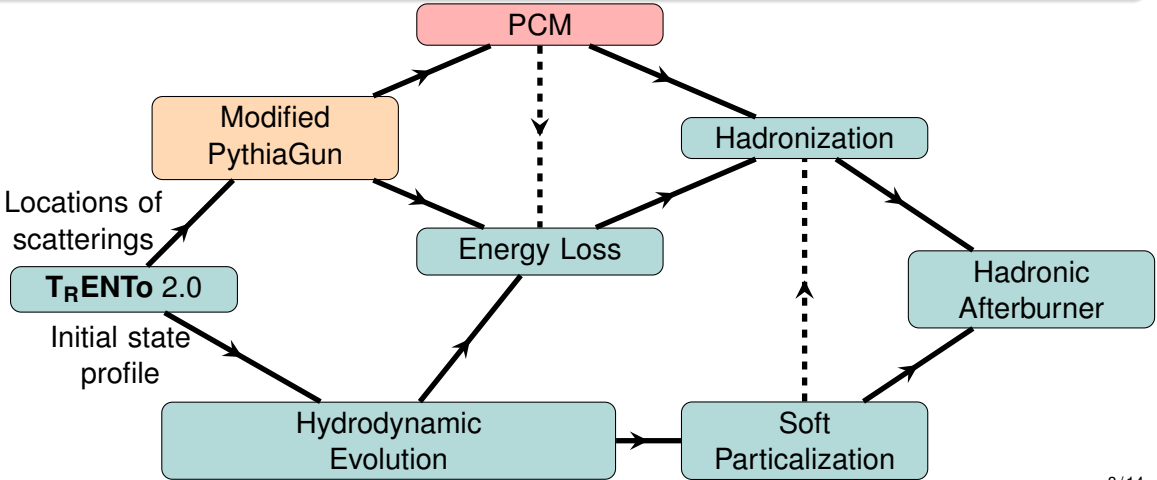
JETSCAPE framework

- JETSCAPE is a general, modular, extensive framework to simulate HIC
- Modularity of the framework allow us to combine multiple code bases for different stages of HIC: realistic simulation
- Multi-stage jet evolution: different stages depending on the virtuality, Q and energy, E of the partons



JETSCAPE Implementation

Motivation: Adding hard-hard partonic interactions to JETSCAPE framework



SMASH

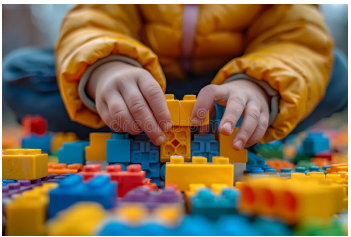
- SMASH: Simulating Many Accelerated Strongly-interacting Hadrons
- Microscopic hadronic transport model with hadrons and resonances as active degrees of freedom
- Dynamics based on a Boltzmann-type evolution:

$$p^{\mu}\partial_{\mu}f_i(x,p) = C_i[f]$$

  where $C_i[f]$ includes scattering, resonance formation, and decays
- Well suited for the dilute hadronic phase where mean free paths become sizable

Modified SMASH

- SMASH uses hadronic interaction cross sections
- Partonic interactions: partonic scattering cross sections
- Radiations are not included: handled by other energy loss modules
- Partonic cross sections:
  - Need kinemetics of outgoing partons
  - Same incoming partons can have multiple processes
  - Eg. $q\bar{q} \to q\bar{q}$, $q\bar{q} \to gg$, $q\bar{q} \to \gamma\gamma$, etc.
  - Diverge at the boundaries
  - Variable change: increases the accuracy of the integration
- Define $\frac{dt}{d\xi}$ and ξ: $\frac{d\sigma}{dt} \Rightarrow \frac{d\sigma}{d\xi}$

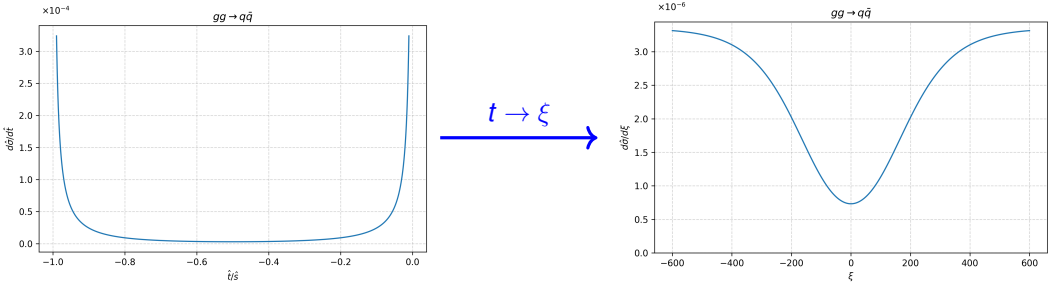


Partonic Cross Sections and Variable Transformation

Process	$\frac{d\sigma}{dt}$	$\frac{dt}{d\xi}$	ξ
$q\bar{q} \to q\bar{q}$	$\frac{\pi\alpha_s^2}{s^2}\frac{4}{9}\left(\frac{s^2+u^2}{t^2} - \frac{2}{3}\frac{u^2}{st}\right)$	$\frac{t^2}{s^2}$	$\frac{-s^2}{t}$
$q_i q_i \to q_i q_i$	$\frac{\pi\alpha_s^2}{s^2}\frac{4}{9}\left(\frac{s^2+u^2}{t^2} + \frac{s^2+t^2}{u^2} - \frac{2}{3}\frac{s^2}{ut}\right)$	$\frac{t^2u^2}{s^3}$	$2\log\left(\frac{u}{t}\right) - \frac{s}{t} + \frac{s}{u}$
$q\bar{q} \to gg$	$\frac{\pi\alpha_s^2}{s^2}\frac{32}{27}\left(\frac{u}{t} + \frac{t}{u} - \frac{9}{4}\frac{u^2+t^2}{s^2}\right)$	$\frac{tu}{s^2}$	$s(\log(s+t) - \log(-t))$
$qg \to qg$	$\frac{\pi\alpha_s^2}{s^2}\frac{4}{9}\left(\frac{9}{4}\frac{s^2+u^2}{t^2} - \frac{s}{u} - \frac{u}{s}\right)$	$\frac{t^2u}{s^3}$	$s\left(\frac{s}{t} + \log\left(\frac{t}{u}\right)\right)$
$gg \to q\bar{q}$	$\frac{\pi\alpha_s^2}{s^2}\frac{1}{6}\left(\frac{u}{t} + \frac{t}{u} - \frac{9}{4}\frac{u^2+t^2}{s^2}\right)$	$\frac{tu}{s^2}$	$s(\log(s+t) - \log(-t))$
$gg \to gg$	$\frac{\pi\alpha_s^2}{s^2}\frac{9}{4}\left(3 + \frac{s^2+u^2}{t^2} + \frac{u^2+t^2}{s^2} + \frac{s^2+t^2}{u^2}\right)$	$\frac{t^2u^2}{s^3}$	$2\log\left(\frac{s+t}{-t}\right) - \frac{s}{t} - \frac{s}{s+t}$

Integrating Differential Cross Sections

- Partonic cross sections diverge at the boundaries
- Modified cross sections by variable change
  - No divergences: more accurate integrations
  - Similar transformation is used in Pythia
- Modified Newton-Raphson method is used as root finding algorithem to identify processes and kinematics after sampling



Towards the First Results

Current Status:

- SMASH implementation and preliminary tests completed
- Initial implementation on JETSCAPE is completed
- Ongoing tests on JETSCAPE

Next Steps:

- Understanding the effect from hard-hard interactions within JETSCAPE simulations
- Realistic simulations to data comparison

Summary

- PCM: Microscopic description of parton dynamics using perturbative QCD
  - Modeling initial conditions and QGP formation
  - Insight into jet quenching and energy loss
  - Foundation for modern hybrid models
  - Replaced due to modern development of Hydrodynamic and Hybrid models
- Hard-hard interactions are not implemented in most modern day simulations
- Modified SMASH is used to implement hard-hard interactions in the JETSCAPE framework
- Completed partonic interaction picture can give insight into both bulk and jet observables
- Stay tuned for the results!