PYQUEN

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1. PYQUEN
    - Energy loss
2. Physics frameworks of the model
    - Collisional energy loss
    - Radiative energy loss
    - Model
3. Simulation procedure
    - Internal model parameters
4. RHIC

PYQUEN*

- The method to simulate the rescattering and energy loss of hard partons in ultrarelativistic heavy ion collisions.
- The full heavy ion event is obtained as a superposition of a soft hydro-type state and hard multi-jets.

The gluon radiation being associated with each parton scattering in the expanding medium and includes the interference effect using the modified radiation spectrum dE/dl as a function of decreasing temperature T.

- Collisional energy loss Elastic scattering with high-momentum transfer
- Radiative energy loss BDMS formalism (Baier-Dokshitzer-Muller-Schiff)

*I. P. Lokhtin and A. M.Snigirev, Eur. Phys. J. C **21**, 155 (2001)

Energy loss

The basic kinetic integral equation for the energy loss ΔE as a function of initial energy E and path length L has the form

$$\Delta E(L,E) = \int_0^L dl \frac{dP(l)}{dl} \lambda(l) \frac{dE(l,E)}{dl}, \quad \frac{dP(l)}{dl} = \frac{1}{\lambda(l)} \exp\left(-l/\lambda(l)\right) \qquad (1)$$

- l is the current transverse coordinate of a parton
- dP/dl is the scattering probability density
- dE/dl is the energy loss per unit length
- $\lambda = 1/(\sigma\rho)$ is in-medium mean free path
- $\rho \propto T^3$ is the medium density at the temperature T

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Collisional energy loss

The collisional energy loss due to elastic scattering with high-momentum transfer

$$\frac{dE}{dl}^{col} = \frac{1}{4T\lambda\sigma} \int_{\mu_D^2}^{t_{\max}} dt \frac{d\sigma}{dt} t \ , \qquad (2)$$

$$\frac{d\sigma}{dt} \cong C \frac{2\pi\alpha_s^2(t)}{t^2} \frac{E^2}{E^2 - m_p^2} \ , \qquad \alpha_s = \frac{12\pi}{(33 - 2N_f) \ln (t/\Lambda_{QCD}^2)} \qquad (3)$$

- $C = 9/4, 1, 4/9$ for gg, gq and qq scatterings respectively
- α_s is the QCD running coupling constant for N_f active quark flavors
- Λ_{QCD} is the QCD scale parameter which is of the order of the critical temperature, $\Lambda_{QCD} \simeq T_c \simeq 200$ MeV.

Radiative energy loss

In the BDMS* frameworks, the strength of multiple scattering is characterized by the transport coefficient $\hat{q} = \mu_D^2/\lambda_g$ (λ_g is the gluon mean free path) wich describe the average transverse momentum transfer squred per unit distance.

$$\Delta E = \frac{\alpha_s N_c}{4} \hat{q} L^2 \tag{4}$$

*R. Baier, Yuri L. Dokshitzer, Alfred H. Mueller and D. Schiff. Phys. Rev. C **60**, 064902 (1999)

Model

1. The medium is treated as a boost-invariant longitudinally expanding quark-gluon fluid, and partons as being produced on a hyper-surface of equal proper time
2. Omit the transverse expansion and viscosity of the fluid using scaling solution obtained by Bjorken for a temperature and density of QGP at $T > T_c \simeq 200$ MeV

$$\varepsilon(\tau)\tau^{4/3} = \varepsilon_0\tau_0^{4/3}, \quad T(\tau)\tau^{1/3} = T_0\tau_0^{1/3}, \quad \rho(\tau)\tau = \rho_0\tau_0. \tag{5}$$

3. Angular spectrum of in-medium gluon radiation.

$$\frac{dN^g}{d\theta} \propto \sin\theta \exp\left(-\frac{(\theta-\theta_0)^2}{2\theta_0^2}\right), \tag{6}$$

where θ_0 is the emission angle

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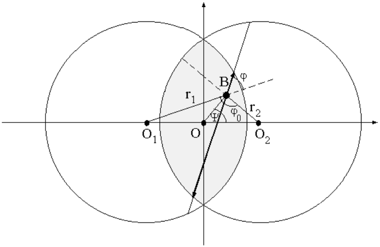
Simulation procedure

- Generation of the initial parton spectra with PYTHIA
- Generation of the jet production vertex at the impact parameter b according to the distribution

$$\frac{dN^{\mathrm{jet}}}{d\psi dr}(b) = \frac{T_A(r_1)T_A(r_2)}{T_{AA}(b)} \tag{7}$$

$$T_{AA}(b) = \int_0^{2\pi} d\psi \int_0^{r_{max}} rdrT_A(r_1)T_A(r_2)\ , \tag{8}$$



- $r_{1,2}(b, r, \psi)$ are the distances between the nucleus centers and the jet production vertex
- $V(r\cos\psi, r\sin\psi)$; $r_{max}(b, \psi) \leq R_A$ is the maximum possible transverse distance r from the nuclear collision axis to V;
- R_A is the radius of the nucleus A
- $T_A(\mathbf{r}) = A\int \rho_A(\mathbf{r}, z)dz$ is the nuclear thickness function with nucleon density distribution $\rho_A(\mathbf{r}, z)$
- $T_{AA}(b)$ nuclear overlap function

*I. P. Lokhtin and A. M.Snigirev, Eur. Phys. J. C **16**, 527 (2000)

Simulation procedure

- Calculation of scattering cross section
- Generation of the displacement between i-th and $(i+1)$-th scatterings and calculation of the corresponding transverse distance $l_i p_T/E$ and the parton energy by collisional and radiative loss per each i-th scattering
- Calculation of the parton transverse momentum kick due to elastic scattering i:

$$\Delta k_{t,i}^2 = (E - \frac{t_i}{2m_{0i}})^2 - (p - \frac{E}{p}\frac{t_i}{2m_{0i}} - \frac{t_i}{2p})^2 - m_p^2. \qquad (9)$$

- Formation of the additional (in-medium emitted) gluon with the energy ω_i and the emission angle θ_i relative to the parent parton

Simulation procedure

- Halting the rescattering if:
    1. The parton escapes the dense zone
    2. QGP cools down to $T_c = 200$ MeV
    3. The parton loses so much energy that its $p_T(\tau)$ drops below $2T(\tau)$.
- At the end of each event, adding new (in-medium emitted) gluons to the PYTHIA parton list and rearrangement of partons to update string formation.
- Formation of the final state particles by PYTHIA

Internal model parameters

1. Medium-induced partonic energy loss (**ienglu**)

   ienglu=0 - radiative and collisional loss

   ienglu=1 - radiative loss, **ienglu=2** - collisional loss
2. Initial temparature of quark-gluon plasma ($\mathbf{T}_0$)
   $0.2\ \mathrm{GeV} < T_0 < 2\ \mathrm{GeV}$
3. Proper time of quark-gluon plasma formation (τ_0)
   $0.01 < \tau_0 < 10$ fm/c
4. Number of active quark flavours in quark-gluon plasma ($\mathbf{n}_f$)
   $\mathbf{n}_f = 0, 1, 2$ or 3
5. Angular distribution of emitted gluons (**ianglu**)
   small-angular=0, wide-angular=1, collinear=2

RHIC: ienglu=0, T_0=500MeV, τ_0=0.4fm/c, n_f=2, ianglu =0
LHC: ienglu=0, T_0=1GeV, τ_0=0.1fm/c, n_f=0, ianglu =0

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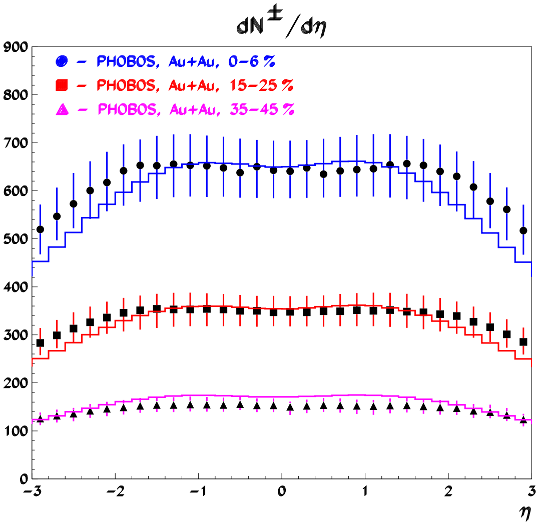
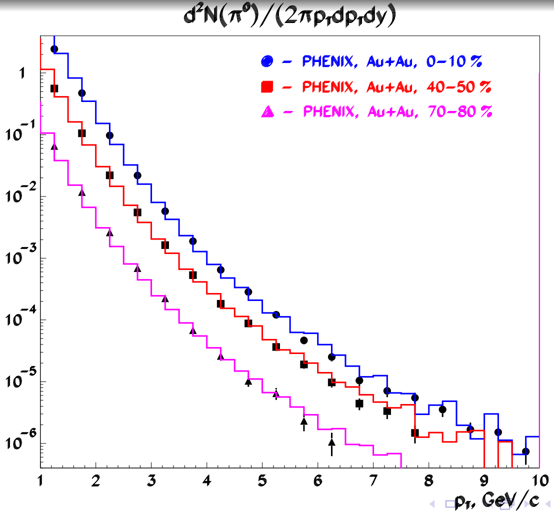
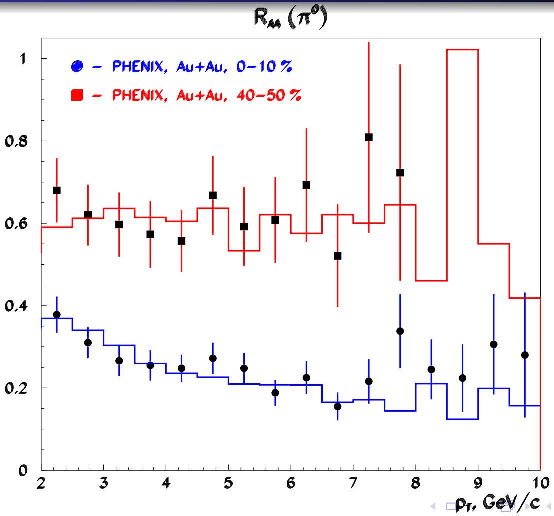
Pseudorapidity distribution of charged hadrons in Au+Au



Transverse momentum distribution of neutral pions in Au+Au collisions



Nuclear modification factor R_{AA} for neutral pions in Au+Au



Azimuthal two-particle correlation function for *pp* and for central Au+Au collisions