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HYDJET++ model
for the ultra-relativistic heavy-ion collisions:
new results and developments
HYDJET and HYDJET++
relativistic heavy ion event generators

HYDJET
(HYDrodynamics + JETs)
event generator to simulate heavy ion event as merging of two independent components (soft hydro-type part + hard multi-partonic state)

http://cern.ch/lokhtin/hydro/hydjet.html
(latest version 1.9)

HYDJET++
continuation of HYDJET
(improved soft component including full set of thermal resonance production + identical to HYDJET hard component)

http://cern.ch/lokhtin/hydjet++
(latest version 2.3)
HYDJET++ soft component

Soft (hydro) part of HYDJET++ is based on the adapted FAST MC model


- Fast HYDJET-inspired MC procedure for soft hadron generation;
- multiplicities are determined assuming thermal equilibrium;
- hadrons are produced on the hypersurface represented by a parameterization of relativistic hydrodynamics with given freeze-out conditions;
- chemical and kinetic freeze-outs are separated;
- decays of hadronic resonances are taken into account (360 particles from SHARE data table) with “home-made" decayer;
- written within ROOT framework (C++);
- contains 16 free parameters (can be reduced to 9).
HYDJET++ hard component

PYQUEN  (PYthia QUENched)
http://lokhtin.web.cern.ch/lokhtin/pyquen/
(latest version 1.5.1)

Initial parton configuration
PYTHIA6.4  w/o hadronization: mstp(111)=0

Parton rescattering & energy loss (collisional, radiative) + emitted gluons
PYQUEN rearranges partons to update number of strings

Parton hadronization and final particle formation
PYTHIA6.4  with hadronization: call PYEXEC

Three model parameters: initial maximal QGP temperature \( T_0 \),
QGP formation time \( \tau_0 \) and number of active quark flavors in QGP \( N_f \)
(\( + \) minimal \( p_T \) of hard process \( Ptmin \) to specify the number of hard NN collisions)
Charged multiplicity vs. centrality and pseudorapidity with HYDJET++ at LHC


\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

Tuned HYDJET++ reproduces multiplicity vs. event centrality down to very peripheral events, as well as approximately flat pseudorapidity distribution.

Open points:
ALICE  PRL 106 (2011) 032301

Closed points:
CMS  JHEP 1108 (2011) 141

Histograms:
HYDJET++ simulation
HYDJET++ reproduces $p_T$-spectrum and $R_{AA}$ of inclusive charged hadrons for central PbPb collisions in mid-rapidity up to $p_T \sim 100$ GeV/c.
HYDJET++ reproduces \( p_T \)-spectrum of pions, kaons and (anti-)protons.
Anisotropic flow generation in HYDJET++ (soft component)

**Elliptic flow** $v_2$

- Spatial modulation of freeze-out surface;
- Fluid velocity modulation.

Spatial anisotropy

$$\varepsilon(b) = \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2}$$

Momentum anisotropy

$$\tan \phi_u = \frac{1 - \delta(b)}{1 + \delta(b)} \tan \phi$$

$R(b)$ – surface radius

$\phi_u$ - azimuthal angle of fluid velocity

$\phi$ - spatial azimuthal angle

**Triangular flow** $v_3$

Spatial modulation of freeze-out surface as $\cos(3\phi)$ with independent phase $\Psi_3$ and parameter $\varepsilon_3$

$$R(b, \phi) = R_f(b) \frac{\sqrt{1 - \varepsilon_3^2(b)}}{\sqrt{1 + \varepsilon(b) \cos 2\phi}} [1 + \varepsilon_3(b) \cos 3(\phi - \Psi_3^{RP})]$$

Three parameters $\varepsilon(b_0)$, $\varepsilon_3(b_0)$ и $\delta(b_0)$ are tuned to fit the data.

The simple modification of the HYDJET++ via introducing the distribution over spatial anisotropy parameters permits model to reproduce both elliptic and triangular flow fluctuations in heavy ion collisions at the LHC energy.
Anisotropic flow generation in HYDJET++ (hard component)

Some anisotropic flow for hard component (elliptic flow and higher even harmonics at high transverse momenta) is generated due to partonic rescattering and energy loss in azimuthally asymmetric volume of the medium.
Elliptic flow in HYDJET++ vs. LHC data


Points: CMS data v2\{4\} PRC 87 (2013) 014902
histograms: HYDJET++ “true” $v_2(\psi_2)$, dashed line (soft), dotted line (hard)

Sergey Petrushanko      HYDJET++ model...  모스크바 주립 대학
Triangular flow in HYDJET++ vs. LHC data


Closed circles and squares: CMS data $v_3\{2\} \& v_3\{EP\}$ PRC 89 (2014) 044906

histograms and open circles: HYDJET++ “true” $v_3(\psi_3)$ and $v_3\{EP\}$
Interplay of hydrodynamics and jets

Hydrodynamics gives mass ordering of $v_3$.

The model possesses crossing of baryon and meson branches.

The reason for the mass ordering break at 2 GeV/c is traced to hard processes (jets).
The probability density distributions of elliptic flow


The top/bottom row: the model results with/without the additional smearing of spatial anisotropy parameters. Dashed and solid histograms: HYDJET++ before and after the unfolding procedure.
The top/bottom row: the model results with/without the additional smearing of spatial anisotropy parameters. Dashed and solid histograms: HYDJET++ before and after the unfolding procedure.
Dihadron angular correlations ("ridge") in HYDJET++

Interplay of elliptic and triangular flows in HYDJET++ yields long-range two-particle azimuthal correlations (*ridge effect*), but centrality dependence of the correlation strength seems to be a bit stronger.
Charm production in HYDJET++

1) Thermal charm production in HYDJET++ (soft component)

$$N_D = \gamma_c N_D^{\text{th}} (I_1 (\gamma_c N_D^{\text{th}}) / I_0 (\gamma_c N_D^{\text{th}})), \quad N_{J/\psi} = \gamma_c^2 N_{J/\psi}^{\text{th}}$$

$\gamma_c$ - charm enhancement factor, which may be treated as a free model parameter, or (as an option) may be obtained from the equation:

$$N_{cc} = 0.5 \gamma_c N_D^{\text{th}} (I_1 (\gamma_c N_D^{\text{th}}) / I_0 (\gamma_c N_D^{\text{th}})) + \gamma_c^2 N_{J/\psi}^{\text{th}}$$

where number of $c$-quark pairs $N_{cc}$ is calculated with PYTHIA (the factor $K \sim 2$ is applied to take into account NLO pQCD corrections) and multiplied by the number of NN sub-collisions for given centrality.

2) Non-thermal charm production in HYDJET++ (hard component)
Non-thermal charmed hadrons are generated within PYTHIA/PYQUEN taking into account medium-induced rescattering and energy loss of heavy quarks ($b$, $c$).
J/ψ meson $p_T$-spectrum and elliptic flow


histograms: HYDJET++

HYDJET++ reproduces $p_T$-spectrum & $v_2(p_T)$ of D-mesons with the same freeze-out parameters as for inclusive hadrons ⇒ significant part of D-mesons (thermal component) is in the kinetic equilibrium with the medium; non-thermal component is important at high $p_T$.
Elliptic flow of D-mesons


HYDJET++ reproduces $p_T$-spectrum & $v_2(p_T)$ of D-mesons with the same freeze-out parameters as for inclusive hadrons ⇒ significant part of D-mesons (thermal component) is in the kinetic equilibrium with the medium; non-thermal component is important at high $p_T$. 

HYDJET++ model...
The contributions of nuclear shadowing and jet quenching into B-meson suppression are comparable at $p_T \sim 10$ GeV/c; the relative contribution of jet quenching gets stronger with increasing $p_T$, and totally dominates at $p_T > 30$ GeV/c.

B-meson $R_{AA}$ due to jet quenching (nuclear shadowing) decreases (increases) with $p_T$; the interplay between two effects results in a weak (roughly constant) $p_T$ dependence of $R_{AA}$.

Thus HYDJET++ reproduces the trend seen in the data if both mechanisms (jet quenching & nuclear shadowing) are taken into account.
Dynamical vs. geometric anisotropy


“Dynamical vs. geometric anisotropy in relativistic heavy-ion collisions: Which one prevails?”

Elliptic flow and femtoscopic radii oscillations w.r.t. $\Psi_2$

Only SPATIAL anisotropy

Only DYNAMICAL anisotropy

Either flow or radii oscillations are reproduced

Correct $v_2$ and oscillation phases

Triangular flow and femtoscopic radii oscillations w.r.t. $\Psi_3$

Only SPATIAL anisotropy

Only DYNAMICAL anisotropy

Again, either flow or radii oscillations are reproduced

Correct $v_3$ and oscillation phases

Decays of resonances provide significant increase of the emitting areas and make the radii oscillations but do not change the phases.

Decays of resonances provide significant increase of the emitting areas and make the radii oscillations but do not change the phases.

Dynamical vs. geometric anisotropy

- Elliptic or triangular spatial anisotropy alone cannot reproduce simultaneously the correct phase of the radii oscillations and the correct sign of the corresponding flow harmonics.

- Dynamical flow anisotropy provides correct qualitative description of both $p_T$-dependence of $v_2$ and $v_3$ and the phases of the femtoscopic radii oscillations.

- Decays of resonances provide significant increase of the emitting areas and make the radii oscillations more pronounced. However, they do not change the phases of the oscillations.

Both spatial and dynamical anisotropies are needed for the quantitative description of both signals.

List of the main publications (2012 – 2018)


HYDJET++ model combines the description of soft processes with the treatment of hard partons propagating hot and dense nuclear medium. The model is widely used by the theoreticians and experimentalists.

The model is employed for the analysis of PbPb collisions at LHC energies. The basic input parameters of the model have been tuned to reproduce the data on charged particle multiplicity, $p_T$-spectrum and flow.

The simple modification of the model via introducing the distribution over spatial anisotropy parameters permits HYDJET++ to reproduce both $v_2$ and $v_3$ fluctuations and related to it eccentricity fluctuations of the initial state. The cross-talk of elliptic and triangular flow in the model generates both even and odd harmonics of higher order, as well as long-range azimuthal dihadron correlations ("ridge" structure).

The data on momentum spectra and elliptic flow of charmed mesons are reproduced by HYDJET++ including thermal and non-thermal charm production mechanisms. The experimentally observed weak momentum dependence of B-meson suppression factor is reproduced by HYDJET++ taking into account both jet quenching and nuclear shadowing effects.

Second- and third-order oscillations of the femtoscopic radii in PbPb collisions were studied together with the differential elliptic and triangular flow.
BACK UP
The Block Structure of HYDJET++

- **particles.data, tabledecay.txt** (particle properties)
- **RunInputHydjet** (input model parameters)
- **RunHadronSource.cxx** (generate events and create trees)
- **RunOutput.root** (particle output information for each event and global output parameters)
- Tree “td” (particle output)
- **ROOT macros** (to produce histograms)
- **ROOT**
- **Histograms**
HYDJET++ (soft): input parameters

1-5. Thermodynamic parameters at chemical freeze-out: $T_{\text{ch}}$, $\{\mu_B, \mu_S, \mu_C, \mu_Q\}$ (option to calculate $T_{\text{ch}}$, $\mu_B$ and $\mu_s$ using phenomenological parameterization $\mu_B(\sqrt{s})$, $T_{\text{ch}}(\mu_B)$ is foreseen).

6-7. Strangeness suppression factor $\gamma_S \leq 1$ and charm enhancement factor $\gamma_c \geq 1$ (options to use phenomenological parameterization $\gamma_S (T_{\text{ch}}, \mu_B)$ and to calculate $\gamma_c$ are foreseen).

8-9. Thermodynamical parameters at thermal freeze-out: $T_{\text{th}}$, and $\mu_\pi$ - effective chemical potential of positively charged pions.

10-12. Volume parameters at thermal freeze-out: proper time $\tau_f$, its standard deviation (emission duration) $\Delta\tau_f$, maximal transverse radius $R_f$.

13. Maximal transverse flow rapidity at thermal freeze-out $\rho_u^{\text{max}}$.

14. Maximal longitudinal flow rapidity at thermal freeze-out $\eta^{\text{max}}$.

15. Flow anisotropy parameter: $\delta(b) \rightarrow u^\mu = u^\mu (\delta(b), \phi)$

16. Coordinate anisotropy:

$$\varepsilon(b) \rightarrow R_f(b) = R_f(0) \left[ V_{\text{eff}}(\varepsilon(0), \delta(0)) / V_{\text{eff}}(\varepsilon(b), \delta(b)) \right]^{1/2} \left[ N_{\text{part}}(b) / N_{\text{part}}(0) \right]^{1/3}$$

For impact parameter range $b_{\text{min}}$-$b_{\text{max}}$:

$$V_{\text{eff}}(b) = V_{\text{eff}}(0) N_{\text{part}}(b) / N_{\text{part}}(0), \quad \tau_f(b) = \tau_f(0) \left[ N_{\text{part}}(b) / N_{\text{part}}(0) \right]^{1/3}$$
Monte-Carlo simulation of hard component (including nuclear shadowing) in HYDJET/HYD Ji ET++

- Calculating the number of hard NN sub-collisions \( N_{\text{jet}} (b, P_{\text{tmin}}, \sqrt{s}) \) with \( P_t > P_{\text{tmin}} \) around its mean value according to the binomial distribution.
- Selecting the type (for each of \( N_{\text{jet}} \)) of hard NN sub-collisions (\( pp, np \) or \( nn \)) depending on number of protons (\( Z \)) and neutrons (\( A-Z \)) in nucleus \( A \) according to the formula: \( Z = A/(1.98 + 0.015A^{2/3}) \).
- Generating the hard component by calling PYQUEN \( n_{\text{jet}} \) times.
- Correcting the PDF in nucleus by the accepting/rejecting procedure for each of \( N_{\text{jet}} \) hard NN sub-collisions: comparison of random number generated uniformly in the interval [0,1] with shadowing factor \( S(r_1,r_2,x_1,x_2,Q_2) \leq 1 \) taken from the adapted impact parameter dependent parameterization based on Glauber-Gribov theory (K. Tywoniuk et al., Phys. Lett. B 657 (2007) 170).
HYDJET++ (soft): main physics assumptions

A hydrodynamic expansion of the fireball is supposed ends by a sudden system breakup at given T and chemical potentials. Momentum distribution of produced hadrons keeps the thermal character of the equilibrium distribution.

Cooper-Frye formula:
\[ p^0 \frac{d^3 N_i}{d^3 p} = \int d^3 \sigma(x) p^\mu f_i^{eq}(p^\nu u_\mu(x); T, \mu_i) \]

HYDJET++ avoids straightforward 6-dimensional integration by using the special simulation procedure (like HYDJET): momentum generation in the rest frame of fluid element, then Lorentz transformation in the global frame → uniform weights → effective von-Neumann rejection-acceptance procedure.

Freeze-out surface parameterizations

1. The Bjorken model with hypersurface
\[ \tau = \left( t^2 - z^2 \right)^{1/2} = \text{const} \]
2. Linear transverse flow rapidity profile
\[ \rho_u = \frac{r}{R} \rho_u^{\text{max}} \]
3. The total effective volume for particle production at
\[ V_{\text{eff}} = \int_{\sigma(x)} d^3 \sigma(x) u_\mu(x) = \tau \int_0^R \int_0^{2\pi} \int_{\eta_{\text{min}}}^{\eta_{\text{max}}} \left( \frac{R}{\rho_u^{\text{max}}} \right)^2 (\rho_u^{\text{max}} \sinh \rho_u^{\text{max}} - \cosh \rho_u^{\text{max}} + 1) \]
HYDJET++ (soft): hadron multiplicities

1. The hadronic matter created in heavy-ion collisions is considered as a hydrodynamically expanding fireball with EOS of an ideal hadron gas.

2. “Concept of effective volume” $T=$const and $\mu=$const: the total yield of particle species is

$$N_i = \rho_i(T, \mu_i)V_{\text{eff}}$$

3. Chemical freeze-out: $T, \mu_i = \mu_B B_i + \mu_S S_i + \mu_C C_i + \mu_Q Q_i$; $T, \mu_B$ –can be fixed by particle ratios, or by phenomenological formulas

$$T(\mu_B) = a - b\mu_B - c\mu_B^4, \mu_B(\sqrt{s_{NN}}) = \frac{d}{1 + e\sqrt{s_{NN}}}$$

4. Chemical freeze-out: all macroscopic characteristics of particle system are determined via a set of equilibrium distribution functions in the fluid element rest frame:

$$f_{i}^{eq}(p^0; T, \mu_i) = \frac{1}{(2\pi)^3} \frac{g_i}{\exp([p^0 - \mu_i]/T) \pm 1}$$

$$\rho_{i}^{eq}(T, \mu_i) = \int_0^\infty d^3 \vec{p}^* f_{i}^{eq}(p^0; T(x^*), \mu(x^*)) = 4\pi \int_0^\infty dp^* p^{*2} f_{i}^{eq}(p^0; T, \mu_i)$$
HYDJET++ (soft): thermal and chemical freeze-outs

1. The particle densities at the chemical freeze-out stage are too high to consider particles as free streaming and to associate this stage with the thermal freeze-out.

2. Within the concept of chemically frozen evolution, assumption of the conservation of the particle number ratios from the chemical to thermal freeze-out:

\[
\frac{\rho_i^{eq}(T^{ch}, \mu_i^{ch})}{\rho_\pi^{eq}(T^{ch}, \mu_\pi^{ch})} = \frac{\rho_i^{eq}(T^{th}, \mu_i^{th})}{\rho_\pi^{eq}(T^{th}, \mu_\pi^{th})}
\]

3. The absolute values \( \rho_i^{eq}(T^{th}, \mu_i^{th}) \) are determined by the choice of the free parameter of the model: effective pion chemical potential \( \mu_{\pi}^{eff,th} \) at \( T^{th} \).

Assuming for the other particles (heavier than pions) the Boltzmann approximation:

\[
\mu_i^{th} = T^{th} \ln \left( \frac{\rho_i^{eq}(T^{ch}, \mu_i^{ch})}{\rho_i^{eq}(T^{th}, \mu_i = 0)} \frac{\rho_\pi^{eq}(T^{th}, \mu_\pi^{eff,th})}{\rho_\pi^{eq}(T^{ch}, \mu_\pi^{ch})} \right)
\]

Particle momentum spectra are generated on the thermal freeze-out hypersurface, the hadronic composition at this stage is defined by the parameters of the system at chemical freeze-out.
PYQUEN: Physics Frames

General kinetic integral equation:

$$\Delta E(L, E) = \int_{0}^{L} dx \frac{dP}{dx}(x) \lambda(x) \frac{dE}{dx}(x, E), \quad \frac{dP}{dx}(x) = \frac{1}{\lambda(x)} \exp\left(-x/\lambda(x)\right)$$

1. Collisional loss and elastic scattering cross section:

$$\frac{dE}{dx} = \frac{1}{4T \lambda \sigma} \int_{t_{max}} \frac{d\sigma}{dt} dt \frac{d\sigma}{dt} \approx C \frac{2\pi \alpha_s^2(t)}{t^2}, \quad \alpha_s = \frac{12\pi}{(33 - 2N_f) \ln(t/\Lambda_{QCD}^2)}, \quad C = 9/4 (gg), 1 (gq), 4/9 (qq)$$

2. Radiative loss (BDMPS):

$$\frac{dE}{dx}(m_q = 0) = \frac{2\alpha_s C_F}{\pi \tau_L} \int_{E_{p_0}} E d\omega \left[ 1 - y + \frac{y^2}{2} \right] \ln|\cos(\omega_1 \tau_1)|, \quad \omega_1 = \sqrt{i \left(1 - y + \frac{C_F}{3} y^2\right) \ln \frac{16}{k}}, \quad k = \frac{\mu_D \lambda_g}{\omega(1-y)}, \quad \tau_1 = \frac{\tau_L}{2 \lambda_g}, \quad y = \frac{\omega}{E}, \quad C_F = \frac{4}{3}$$

“dead cone” approximation for massive quarks:

$$\frac{dE}{dx}(m_q \neq 0) = \frac{1}{\left(1 + (l \omega)^{3/2}\right)^2} \frac{dE}{dx}(m_q = 0), \quad l = \left(\frac{\lambda}{\mu_D^2}\right)^{1/3} \left(\frac{m_q}{E}\right)^{4/3}$$
Calculating the number of hard NN sub-collisions $N_{\text{jet}} (b, P_{\text{tmin}}, \sqrt{s})$ with $P_t > P_{\text{tmin}}$ around its mean value according to the binomial distribution.

Selecting the type (for each of $N_{\text{jet}}$) of hard NN sub-collisions ($pp$, $np$ or $nn$) depending on number of protons ($Z$) and neutrons ($A-Z$) in nucleus $A$ according to the formula: $Z = A / (1.98 + 0.015A^{2/3})$.

Generating the hard component by calling PYQUEN $n_{\text{jet}}$ times.

Correcting the PDF in nucleus by the accepting/rejecting procedure for each of $N_{\text{jet}}$ hard NN sub-collisions: comparision of random number generated uniformly in the interval $[0,1]$ with shadowing factor $S(r_1, r_2, x_1, x_2, Q^2) \leq 1$ taken from the adapted impact parameter dependent parameterization based on Glauber-Gribov theory ($K.\ Tywoniuk$ et al., Phys. Lett. B 657 (2007) 170).
Correlation between elliptic and triangular flows and fluctuations


HYDJET++ reproduces the correlation between elliptic and triangular flows.

Closed circles: ATLAS data Phys. Rev. C 92, 034903
asterisks: HYDJET simulation
Quadrangular flow in HYDJET++ vs. LHC data


Closed circles and squares: CMS data $v_4 \{2\} \ & v_4 \{LYZ\} \ PRC 89 (2014) 044906$

histograms and open circles: HYDJET++ “true” $v_4(\psi_2)$ and $v_4\{EP\}$

Sergey Petrushanko  HYDJET++ model... 모스크바 주립 대학
Pentagonal flow in HYDJET++ vs. LHC data


Closed circles and squares: CMS data $v_5\{2\}$ & $v_5\{EP\}$ PRC 89 (2014) 044906
histograms and open circles: HYDJET++ “true” $v_5(\psi_3)$ and $v_5\{EP\}$
Hexagonal flow in HYDJET++ vs. LHC data


Closed circles and squares: CMS data $v_6\{2\}$ \& $v_6\{LYZ\}$ PRC 89 (2014) 044906 histograms and open circles: HYDJET++ “true” $v_6(\psi_2)$
Number of constituent quark scaling $v_2$


Resonance decay kinematics works towards the scaling (prediction 2009 for LHC).
Number of constituent quark scaling $v_3$


Sergey Petrushanko  HYDJET++ model...  모스크바 주립 대학
$v_3$ in HYDJET++ vs. ALICE


ALICE: arXiv:1606.06057

Sergey Petushanko  HYDJET++ model...
Femtoscopic momentum correlations
(pion pairs)

\[ CF = 1 + \lambda \exp\left(-R_{o}^2 q_{o}^2 - R_{s}^2 q_{s}^2 - R_{l}^2 q_{l}^2 - 2R_{o}q_{o}q_{l}\right) \]


Points: ALICE data PLB 696 (2011) 328, histograms: HYDJET++

Sergey Petrushanko  HYDJET++ model... 모스크바 주립 대학
Charm production in HYDJET++


The most important parameters for our current consideration are the chemical and thermal freeze-out temperatures, $T_{ch} = 165$ MeV and $T_{th} = 105$ MeV, maximal longitudinal and transverse flow rapidities, $Y^\text{max}\_L = 4.5$ and $Y^\text{max}\_T = 1.265$, minimal transverse momentum transfer of initial hard scatterings $p^\text{min}\_T = 8.2$ GeV/c, and initial maximal temperature of quark-gluon fluid $T^\text{max}\_0 = 1$ GeV.

two sets of input parameters:

1) as for inclusive hadrons (listed above), and 2) for early thermal freeze-out ($T_{ch} = T_{th} = 165$ MeV, $Y^\text{max}\_L = 2.3$, $Y^\text{max}\_T = 0.6$, $p^\text{min}\_T = 3.0$ GeV/c). The fugacity value $\gamma_c = 11.5$ was fixed from absolute $J/\psi$ yields.
HYDJET++ reproduces $p_T$-spectrum & $v_2(p_T)$ of D-mesons with the same freeze-out parameters as for inclusive hadrons $\Rightarrow$ significant part of D-mesons (thermal component) is in the kinetic equilibrium with the medium; non-thermal component is important at high $p_T$. 
HYDJET++ reproduces $R_{AA}(p_T)$ of D-mesons up to very high $p_T \Rightarrow$ treatment of heavy quark energy loss in hard component of HYDJET++ (PYQUEN) seems quite successful.
Angular structure of energy loss in PYQUEN

Radiative loss, three options (simple parametrizations) for angular distribution of in-medium emitted gluons:

Collinear radiation \[ \theta = 0 \]

Small-angular radiation \[ \frac{dN^g}{d\theta} \propto \sin \theta \exp\left(\frac{-(\theta - \theta_0)^2}{2 \theta_0^2}\right), \quad \theta_0 \sim 5^\circ \]

Wide-angular radiation \[ \frac{dN^g}{d\theta} \propto \frac{1}{\theta} \]

Collisional loss always “out-of-cone” (energy is absorbed by medium)
Suppression factor of inclusive jets vs. \( p_T \) in ATLAS and PYQUEN


PYQUEN simulation results for \( R_{AA} \) are close to the data within statistical and systematic experimental uncertainties.
Suppression factor of b-jets vs. $p_T$ in CMS and PYQUEN

$\sqrt{s_{NN}} = 2.76$ TeV

Reproduced well by PYQUEN

ICHEP2018 SEOUL

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The modification of radial jet profile ($E_T^{jet}>100$ GeV, $R=0.3$): excess at large radii; suppression at intermediate radii; core is unchanged. Reproduced well by PYQUEN with wide-angle radiative + collisional partonic energy loss.
The modification of longitudinal jet profile ($E_T^{jet} > 100$ GeV, $R=0.3$): excess at low $p_T$; suppression at intermediate $p_T$; high $p_T$ is slightly enhanced. Reproduced well by PYQUEN with wide-angle radiative + collisional partonic energy loss.