12 years of HYDJET++ generator: history and the latest results

5th International Conference on Particle Physics and Astrophysics
VIRTUAL in MOSCOW
5 - 9 October 2020
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 2.4)*

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 $P_{tmin}$ 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

Histories:
HYDJET++ simulation
HYDJET++ soft
HYDJET++ hard
(~30% at mid-rap. with central PbPb)

Sergey Petrushanko et al.  12 years of HYDJET++ generator...
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/$c$. 

Sergey Petrushanko et al. 12 years of HYDJET++ generator...
\( p_T \)-spectra of identified hadrons


HYDJET++ reproduces \( p_T \)-spectrum of pions, kaons and (anti-)protons.


HYDJET++ reproduces \( p_T \)-spectrum of pions, kaons and (anti-)protons.

Sergey Petrushanko et al. 12 years of HYDJET++ generator...
Anisotropic flow generation in HYDJET++
(soft component)

Elliptic flow $v_2$
- Spatial modulation of freeze-out surface;
- Fluid velocity modulation.

Spatial anisotropy

$$
\varepsilon(b) = \frac{R^2_y - R^2_x}{R^2_y + R^2_x}
$$

Momentum anisotropy

$$
\tan \varphi_u = \sqrt{\frac{1 - \delta(b)}{1 + \delta(b)}} \tan \varphi
$$

$R(b)$ – surface radius
$\varphi_u$ - azimuthal angle of fluid velocity
$\varphi$ - spatial azimuthal angle

Triangular flow $v_3$

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

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

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.

Sergey Petrushanko et al. 12 years of HYDJET++ generator...
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 et al. 12 years of HYDJET++ generator...
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)

Sergey Petrushanko et al. 12 years of HYDJET++ generator...
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.

Sergey Petrushanko et al. 12 years of HYDJET++ generator...
The probability density distributions of triangular 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.

Sergey Petrushanko et al. 12 years of HYDJET++ generator...
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)

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

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

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

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 ($b, c$).
HYDJET++ reproduces $p_T$-spectrum & $v_2(p_T)$ of $J/\psi$ with another freeze-out parameters then for inclusive hadrons ⇒ thermal freeze-out of $J/\psi$-mesons happens before thermal freeze-out of light hadrons.
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 $p_T$. 

Points: ALICE data, JHEP 1209 (2012) 112 histograms: HYDJET++

Sergey Petrushanko et al. 12 years of HYDJET++ generator...
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 $p_T$.
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


Sergey Petrushanko et al. 12 years of HYDJET++ generator...
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


Sergey Petrushanko et al. 12 years of HYDJET++ generator...
Decays of resonances provide significant increase of the emitting areas and make the radii oscillations but do not change the phases.

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Sergey Petrushanko et al. 12 years of HYDJET++ generator...
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.

Mechanisms of forward–backward (FB) correlations in the multiplicity of particles

HYDJET++ model reproduces quite well the experimentally observed dependence of the strength of FB correlations in the multiplicity of charged particles on the centrality. FB correlations for the hard jet component are stronger than those for the soft hydrodynamic components and, in the most central collisions, they are determined mainly by the hard component. However, both components should be taken into account simultaneously in order to reproduce the correct dependence of the strength of correlations on the centrality of nucleus–nucleus collisions.

Journal of Experimental and Theoretical Physics, 130(5) (2020) 660

Sergey Petrushanko et al. 12 years of HYDJET++ generator...
HYDJET++ model reproduces quite well multiplicity and $p_T$ spectrum of identified charged hadrons ($\pi$, $K$, $p$) in central $Au+Au$ collisions at $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV (STAR data). We have started to use HYDJET++ for model analysis of some physical observables at NICA energies.
List of the main publications


SUMMARY

It has been dozen years since HYDJET++ Monte-Carlo event generator for the simulation of relativistic heavy ion collisions was developed. Now the generator is widely used for the simulation of nucleus-nucleus interactions from NICA to LHC energies. The model calculations on soft and hard probes of quark-gluon plasma (including collective flow, different kinds of particle correlations, jets, D and B mesons, etc.) agree well with the experimental data.
THANK YOU!

СПАСИБО!
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: $T_{ch}$, $\{\mu_B, \mu_S, \mu_C, \mu_Q\}$ (option to calculate $T_{ch}$, $\mu_B$ and $\mu_s$ using phenomenological parameterization $\mu_B(\sqrt{s})$, $T_{ch}(\mu_B)$ is foreseen).

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

8-9. Thermodynamical parameters at thermal freeze-out: $T_{th}$, 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: 

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

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

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

- 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 ($K.\text{Tywoniuk et al., Phys. Lett. B 657 (2007) 170}$).
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:

$$p^0 \frac{d^3 N_i}{d^3 p} = \int_{\sigma(x)} d^3 \sigma \mu(x) p^\mu f_i^{eq}(p^\gamma u_\mu(x); T, \mu_i)$$

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

$$\tau = (t^2 - z^2)^{1/2} = \text{const}$$

2. Linear transverse flow rapidity profile

$$\rho_u = \frac{r}{R} \rho_u^{\text{max}}$$

3. The total effective volume for particle production at

$$V_{\text{eff}} = \int_{\sigma(x)} d^3 \sigma \mu(x) u_\mu(x) = \tau \int_0^R \gamma_r rdr \int_0^{2\pi} d\phi \int_{\eta_{\text{min}}}^{\eta_{\text{max}}} d\eta = 2\pi \tau \Delta \eta \left( \frac{R}{\rho_u^{\text{max}}} \right)^2 (\rho_u^{\text{max}} \sinh \rho_u^{\text{max}} - \cosh \rho_u^{\text{max}} + 1)$$
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” $T=\text{const}$ and $\mu=\text{const}$: 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

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

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:

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

$$\rho_i^{eq}(T, \mu_i) = \int_0^\infty d^3 \vec{p}^* f_i^{eq}(p^{0*}; T(x^*), \mu(x^*)_i) = 4\pi \int_0^\infty dp^* p^{*2} f_i^{eq}(p^{0*}; T, \mu_i)$$

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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:

\[
\frac{dE}{dx} = \frac{1}{4T \lambda \sigma} \int_0^{t_{\text{max}}} dt \frac{d\sigma}{dt} t, \quad \frac{d\sigma}{dt} \approx C \frac{2\pi \alpha_s^2(t)}{t^2}, \quad \alpha_s = \frac{12\pi}{(33 - 2N_f) \ln(t/\Lambda_{\text{QCD}}^2)}, \quad C = \frac{9}{4}(gg), \frac{1}{4}(gq), \frac{4}{9}(qq)
\]

2. Radiative loss (BDMPS):

\[
\frac{dE}{dx}(m_q = 0) = \frac{2\alpha_s C_F}{\pi \tau_L} \int_E^{E_{\text{max}}} d\omega \left[1 - y + \frac{y^2}{2}\right] \ln|\cos(\omega_1 \tau_1)|, \quad \omega_1 = \sqrt{i_1 \left(1 - y + \frac{C_F}{3} y^2\right) \ln \frac{16}{k}, \quad \bar{k} = \frac{\mu_D^2 \lambda_g}{\omega (1 - y), \quad \tau_1 = \frac{2\lambda_g}{\omega}, \quad y = \frac{E}{\bar{k}}, \quad C_F = \frac{4}{3}}
\]

“dead cone” approximation for massive quarks:

\[
\frac{dE}{dx}(m_q \neq 0) = \frac{1}{1 + (l \omega)^{3/2}} \frac{dE}{dx}(m_q = 0), \quad l = \left(\frac{\lambda}{\mu_D^2}\right)^{1/3} \left(\frac{m_q}{E}\right)^{4/3}
\]

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Monte-Carlo simulation of hard component (including nuclear shadowing) in HYDJET/HYDJET++

- 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 $S(r1,r2,x1,x2,Q2) \leq 1$ taken from the adapted impact parameter dependent parameterization based on Glauber-Gribov theory ($K.\text{Tywoniuk et al.}, \text{Phys. Lett. B} \ 657 \ (2007) \ 170$).
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

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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 $v_4\{EP\}$

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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}

Sergey Petrushanko et al. 12 years of HYDJET++ generator...
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” $v_6(\psi_2)$

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Number of constituent quark scaling $v_2$


Resonance decay kinematics works towards the scaling (prediction 2009 for LHC).

Sergey Petrushanko et al.      12 years of HYDJET++ generator...
Number of constituent quark scaling

$v_3$


Sergey Petrushanko et al. 12 years of HYDJET++ generator...
$v_3$ in HYDJET++ vs. ALICE


Sergey Petrushanko et al. 12 years of HYDJET++ generator...
Femtoscopic momentum correlations (pion pairs)

$$CF = 1 + \lambda \exp(-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2 - 2 R_o^2 q_o q_l)$$

Charm production in HYDJET++


The most important parameters for our current consideration are the chemical and thermal freeze-out temperatures, \( T_{ch} = 165 \text{ MeV} \) and \( T_{th} = 105 \text{ MeV} \), maximal longitudinal and transverse flow rapidities, \( Y_{L}^{\text{max}} = 4.5 \) and \( Y_{T}^{\text{max}} = 1.265 \), minimal transverse momentum transfer of initial hard scatterings \( p_{T}^{\text{min}} = 8.2 \text{ GeV/c} \), and initial maximal temperature of quark-gluon fluid \( T_{0}^{\text{max}} = 1 \text{ GeV} \).

Two sets of input parameters:

1) as for inclusive hadrons (listed above), and 2) for early thermal freeze-out \( (T_{ch} = T_{th} = 165 \text{ MeV}, Y_{L}^{\text{max}} = 2.3, Y_{T}^{\text{max}} = 0.6, p_{T}^{\text{min}} = 3.0 \text{ GeV/c}) \). 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 ⇒ significant part of D-mesons (thermal component) is in the kinetic equilibrium with the medium; non-thermal component is important at high $p_T$. 

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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.

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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.

Sergey Petrushanko et al. 12 years of HYDJET++ generator...
Suppression factor of b-jets vs. $p_T$ in CMS and PYQUEN


Reproduced well by PYQUEN

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

CMS (PLB 730 (2014) 243)

PYQUEN (small-angle radiation)

PYQUEN (wide-angle radiation)

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Jet shapes
PYQUEN vs. CMS data

The modification of radial jet profile ($E_T^{\text{jet}}>100$ 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.

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Jet fragmentation function
PYQUEN vs. CMS data


\[ \xi = -\ln z = -\ln \frac{p_{T}^{\text{track}}}{p_{T}^{\text{jet}}} \]

The modification of longitudinal jet profile \((E_{T}^{\text{jet}} > 100 \text{ GeV}, R=0.3)\): 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.

Sergey Petrushanko et al.      12 years of HYDJET++ generator...