



PYQUEEN event generator

Igor Lokhtin



PYQUEEN team: I.Lokhtin, A.Snigirev (SINP MSU)

**HYDJET team: I.Lokhtin, A.Snigirev,(SINP MSU), K.Tywoniuk
(Universidad de Santiago de Compostela)**

**HYDJET++ team: I.Lokhtin, L.Malinina, A.Snigirev, S.V.Petrushanko
(SINP MSU), I.Arsene (Oslo University),K.Tywoniuk (Universidad de
Santiago de Compostela)**



PYQUEN and HYDJET/HYDJET++

PYQUEN - medium-induced partonic energy loss model
(modifies PYTHIA6.4 jet event), latest version 1.5 (2007)

<http://cern.ch/lokhtin/pyquen>

HYDJET - merging two independent components: soft hydro-type part and hard multi-parton part generated with **PYQUEN**, latest version 1.6 (2009) <http://cern.ch/lokhtin/hydro/hydjet.html>

I. Lokhtin, A. Snigirev, Eur. Phys. J. C 46 (2006) 211

HYDJET++ - continuation of HYDJET (more detailed treatment of soft part including resonance decays and separate treatment of chemical & thermal freeze-outs), first version 2.0 (2008), version 2.1 is about completed (2009)
<http://cern.ch/lokhtin/hydjet++>

I.Lokhtin, L.Malinina, S.Petrushanko, A.Snigirev, I.Arsene, K.Tywoniuk, CPC 180 (2009) 779



Medium-induced partonic energy loss in PYQUEN

General kinetic integral equation:

$$\Delta E(L, E) = \int_0^L dx \frac{dP}{dx}(x) \lambda(x) \frac{dE}{dx}(x, E), \quad \frac{dP}{dx}(x) = \frac{1}{\lambda(x)} \exp(-x/\lambda(x))$$

1. Collisional loss and elastic scattering cross section:

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

2. Radiative loss (BDMS):

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

“dead cone” approximation for massive quarks:

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



Angular spectrum of gluon radiation

Three option for angular distribution of in-medium emitted gluons:

Collinear radiation

$$\theta = 0$$

Small-angular radiation
(default)

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

Broad-angular radiation

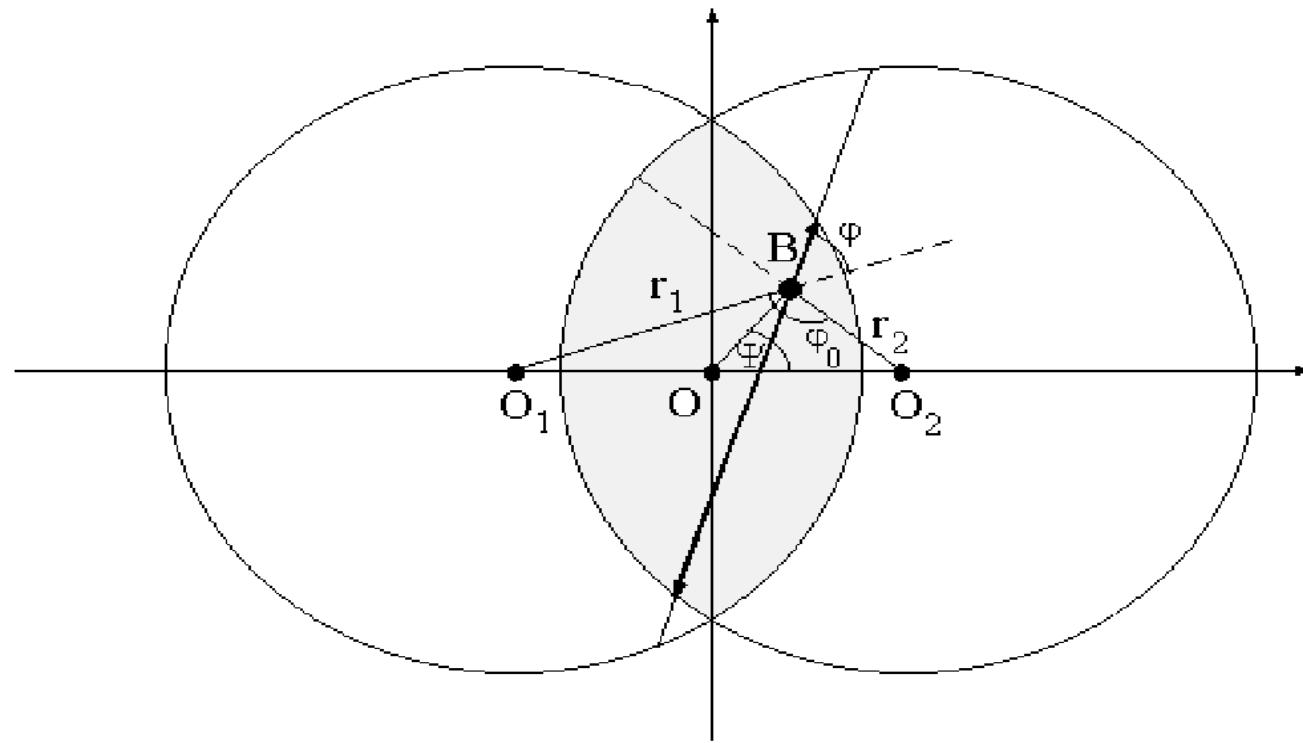
$$\frac{dN^g}{d\theta} \propto \frac{1}{\theta}$$



Nuclear geometry and QGP evolution

impact parameter $b \equiv |O_1 O_2|$ - transverse distance between nucleus centers

$$\varepsilon(r_1, r_2) \propto T_A(r_1) * T_A(r_2) \quad (T_A(b) - \text{nuclear thickness function})$$



Space-time evolution of QGP, created in region of initial overlapping of colliding nuclei, is described by Lorenz-invariant Bjorken's hydrodynamics J.D. Bjorken, PRD 27 (1983) 140



Monte-Carlo simulation of parton rescattering and energy loss in PYQUEN

Distribution over jet production vertex $V(r \cos\psi, r \sin\psi)$ at im.p. b

$$\frac{dN}{d\psi dr}(b) = \frac{T_A(r_1)T_A(r_2)}{\int_0^{2\pi} d\psi \int_0^{r_{max}} r dr T_A(r_1)T_A(r_2)}$$

Transverse distance between parton scatterings $l_i = (\tau_{i+1} - \tau_i) E/p_T$

$$\frac{dP}{dl_i} = \lambda^{-1}(\tau_{i+1}) \exp\left(-\int_0^{l_i} \lambda^{-1}(\tau_i + s) ds\right), \quad \lambda^{-1} = \sigma \rho$$

Radiative and collisional energy loss per scattering

$$\Delta E_{tot,i} = \Delta E_{rad,i} + \Delta E_{col,i}$$

Transverse momentum kick per scattering

$$\Delta k_{t,i}^2 = \left(E - \frac{t_i}{2m_{0i}} \right)^2 - \left(p - \frac{E}{p} \frac{t_i}{2m_{0i}} - \frac{t_i}{2p} \right)^2 - m_q^2$$



PYQUEN (PYthia QUENched)

Initial parton configuration

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



Parton rescattering & energy loss (collisional, radiative) + emitted g
PYQUEN rearranges partons to update ns strings: ns call PYJOIN



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

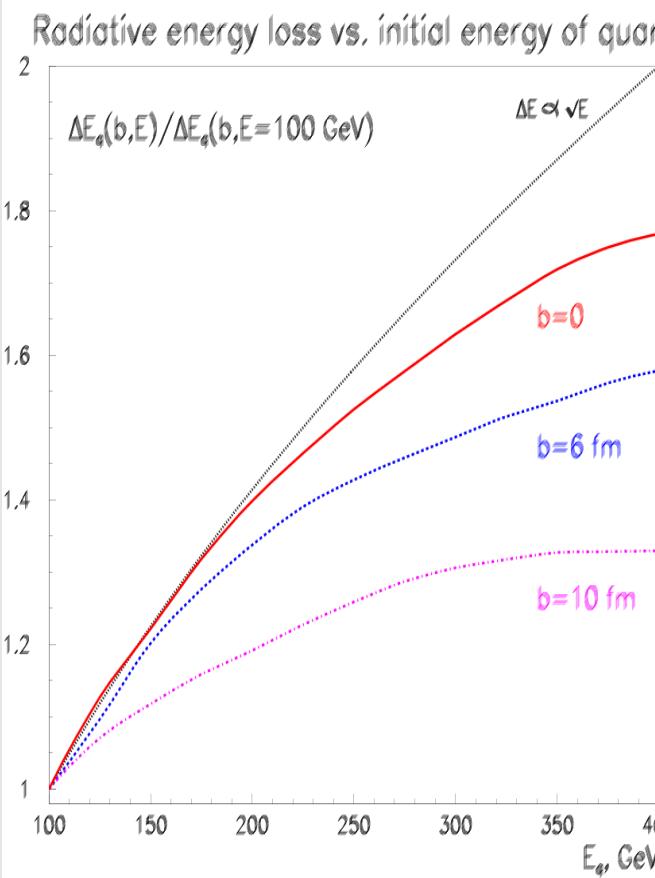
Three model parameters: initial QGP temperature T_0 , QGP formation time τ_0
and number of active quark flavors in QGP N_f (in central Pb+Pb)
(+ minimal p_T of hard process Ptmin and other PYTHIA parameters)



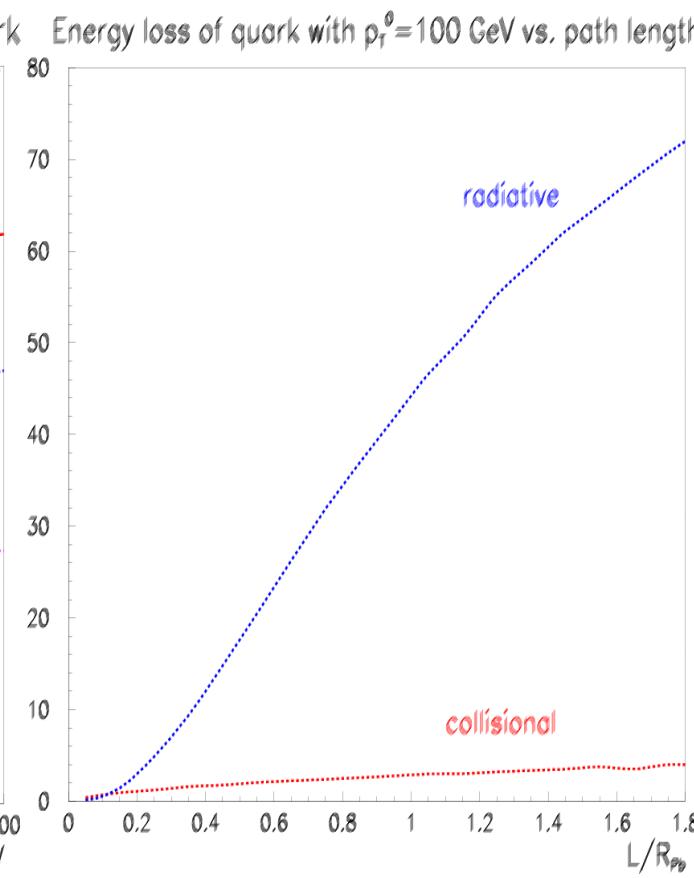
PYQUEN: mean energy loss

($\sqrt{s}=5.5 \text{ A TeV, Pb+Pb, } T_{0, \text{QGP}}(b=0) = 1 \text{ GeV, } \tau_0 = 0.1 \text{ fm/c}$)

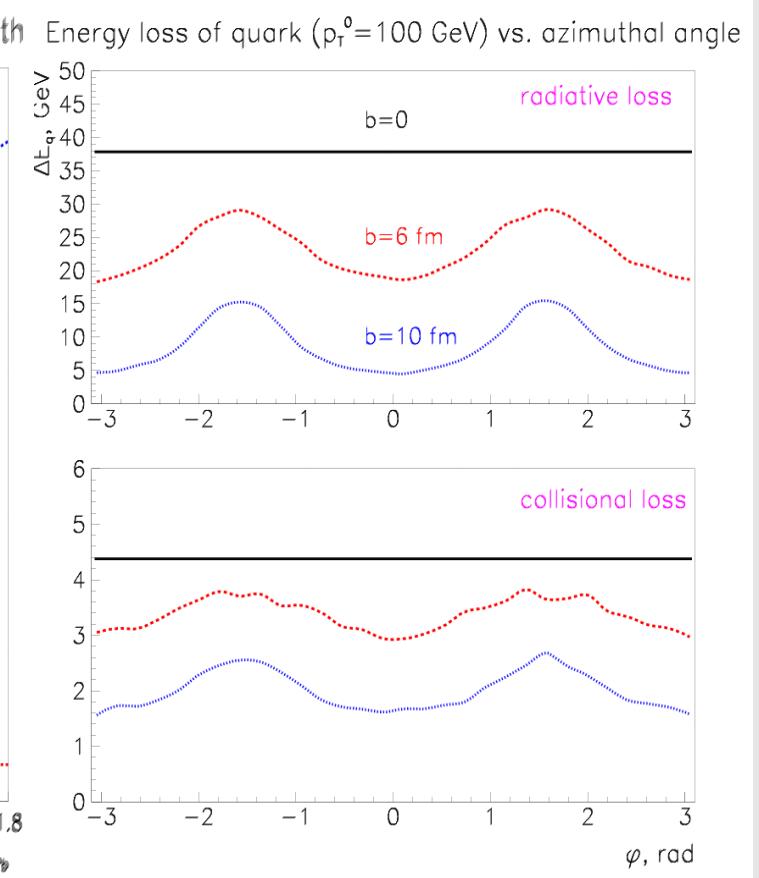
E-dependence



L-dependence



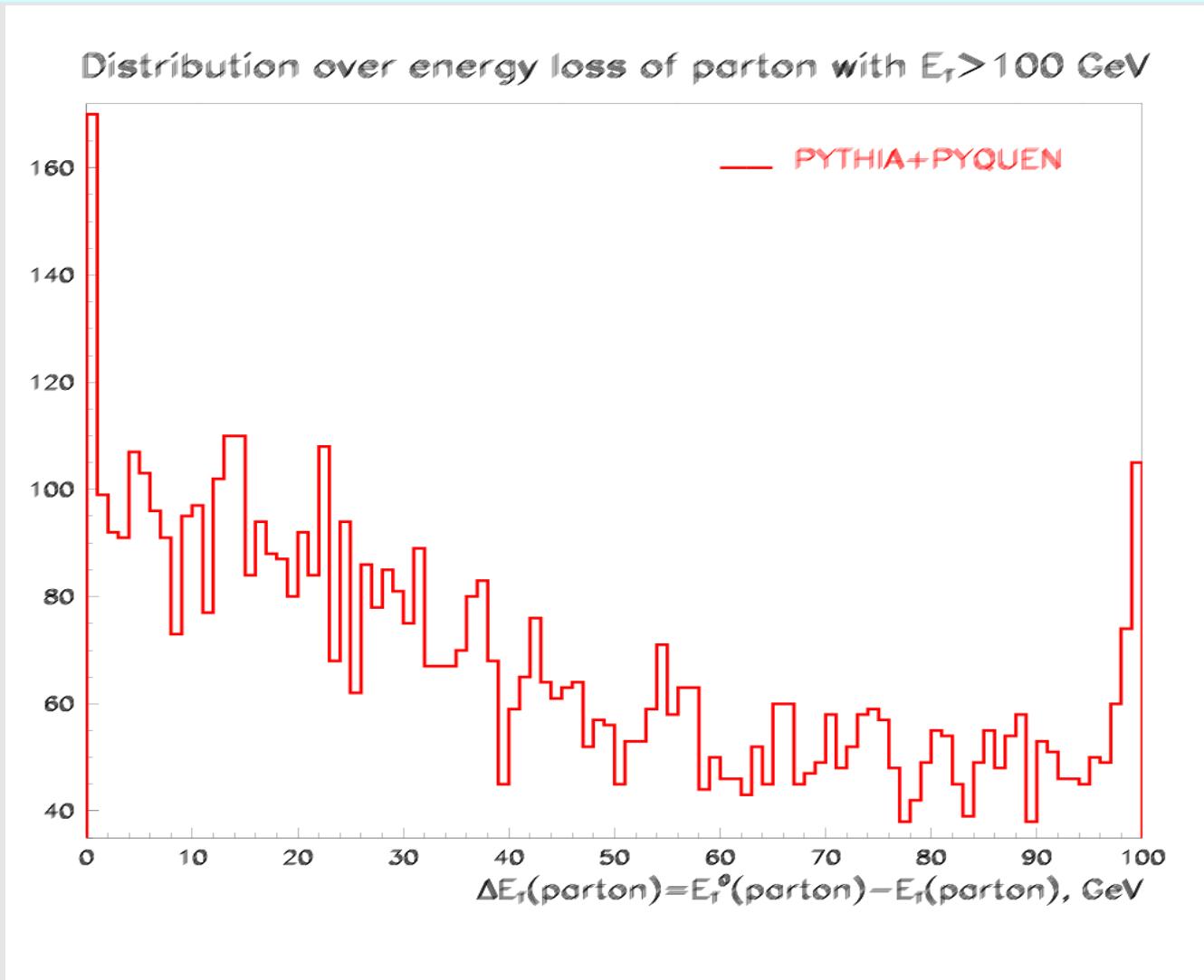
φ -dependence





PYQUEN: energy loss fluctuations

($\sqrt{s}=5.5 \text{ A TeV}$, Pb+Pb, $T_{0, \text{QGP}}(b=0) = 1 \text{ GeV}$, $\tau_0 = 0.1 \text{ fm/c}$)



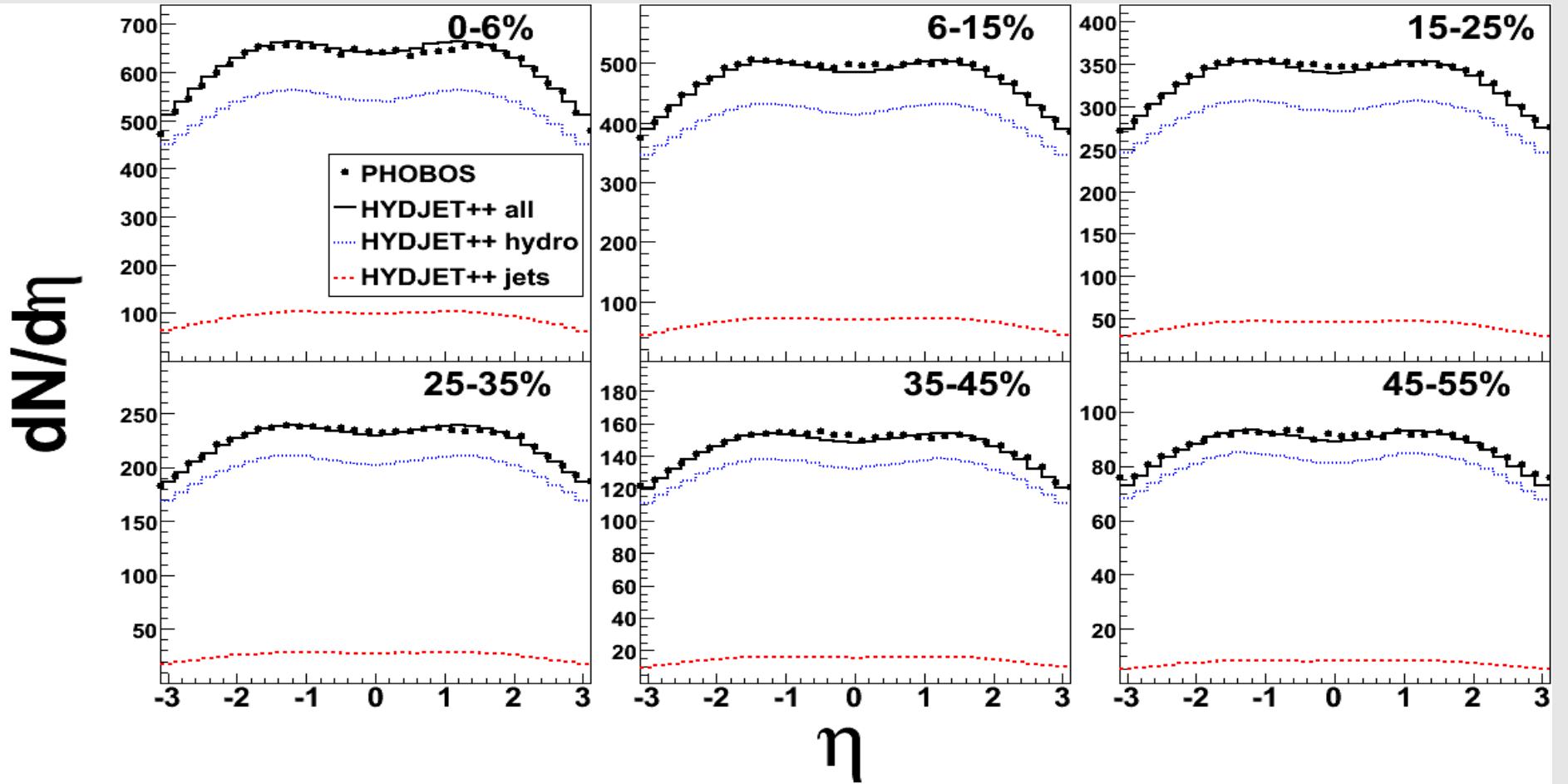


HYDJET & HYDJET++ (HYDrodynamics + JETs)

Calculating the number of hard NN sub-collisions **Njet** (**b**, **Ptmin**, \sqrt{s}) with **Pt>Ptmin** around its mean value according to the binomial distr.
Selecting the type (for each of **Njet**) 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 part by calling PYTHIA/PYQUEN **njet** times
If nuclear shadowing is switched on, the correction for PDF in nucleus is done by the accepting/rejecting procedure for each of **Njet** hard NN sub-collisions: by comparision of random number generated uniformly in the interval [0,1] with shadowing factor **S ≤ 1**, which is taken from the adapted impact parameter dependent parameterization based on Glauber-Gribov theory (*K.Tyroniuk et al., Phys. Lett. B 657 (2007) 170*).
Generating the soft part according to the corresponding “thermal” model (for **b≠0** mean **multiplicity** is proportional to # of N-participants)
Junction of two independent event outputs (hard & soft) to **event record**



HYDJET++: rapidity spectra vs. event centrality at RHIC



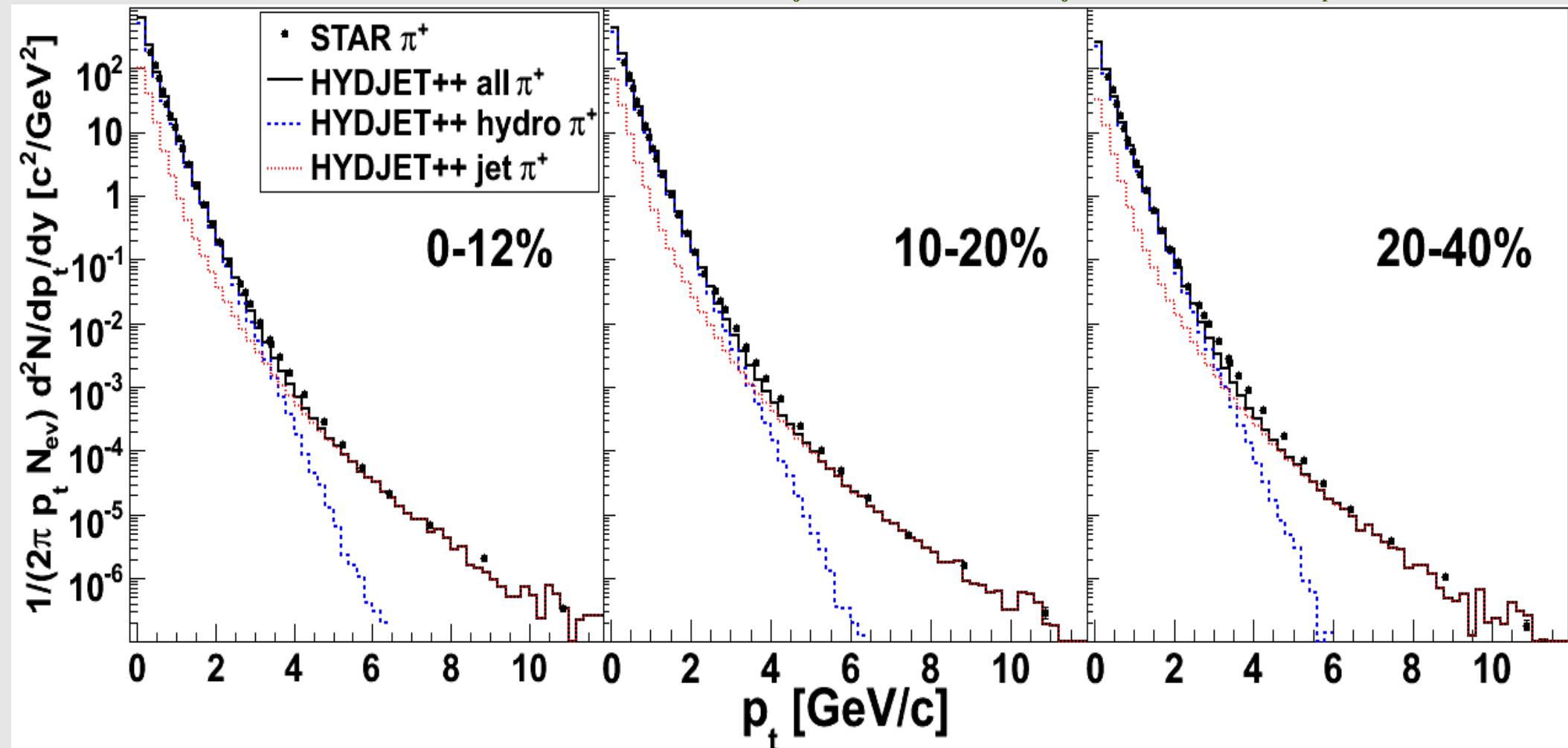
Width of the spectra allows one to fix $\eta^{\max} = 3.3$,

Centrality dependence of multiplicity allows one to fix $pt\min = 3.4 \text{ GeV}/c$



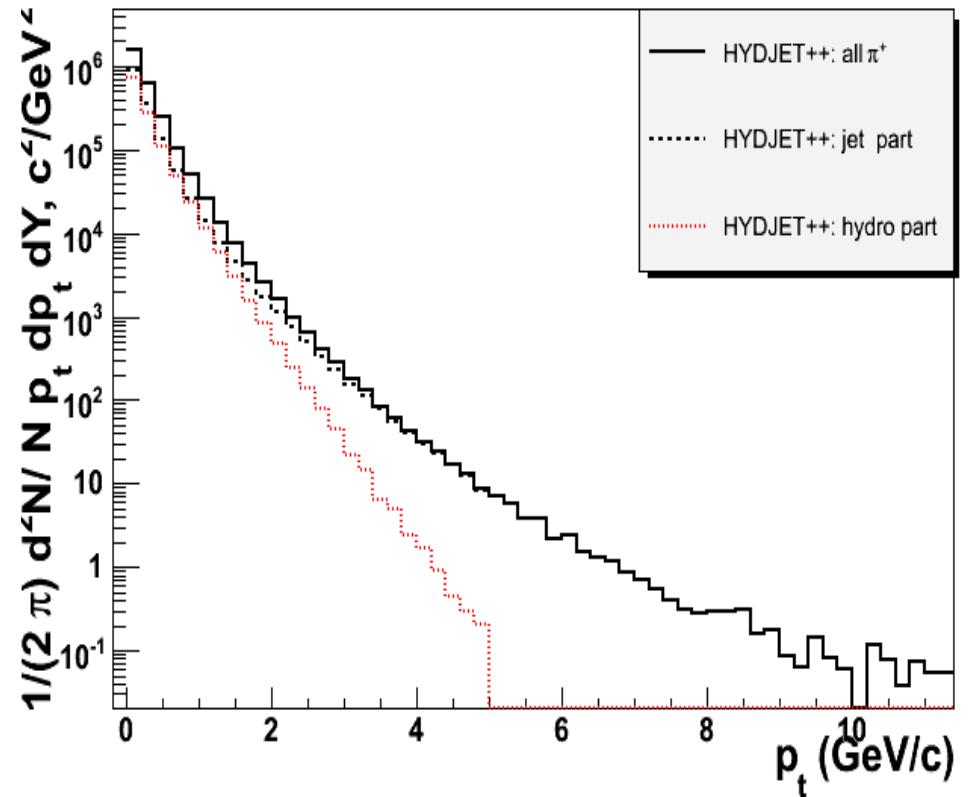
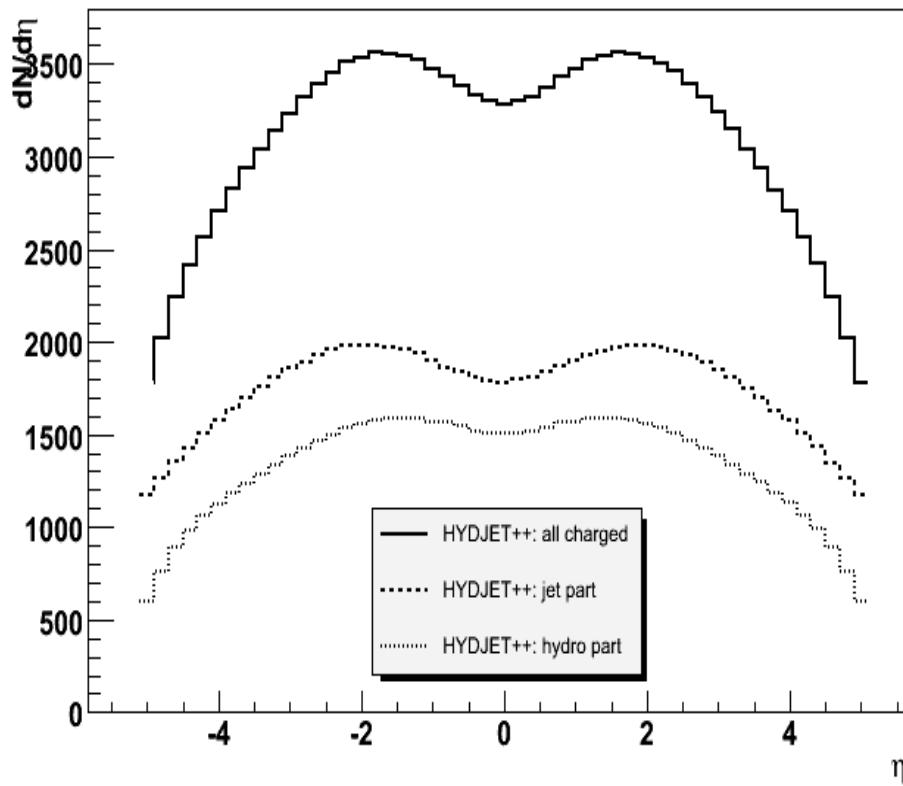
HYDJET++: transverse momentum spectra at RHIC

PYQUEN energy loss model parameters: $T_0(\text{QGP})=300 \text{ MeV}$, $\tau_0(\text{QGP})=0.4 \text{ fm/c}$, $N_f=2$





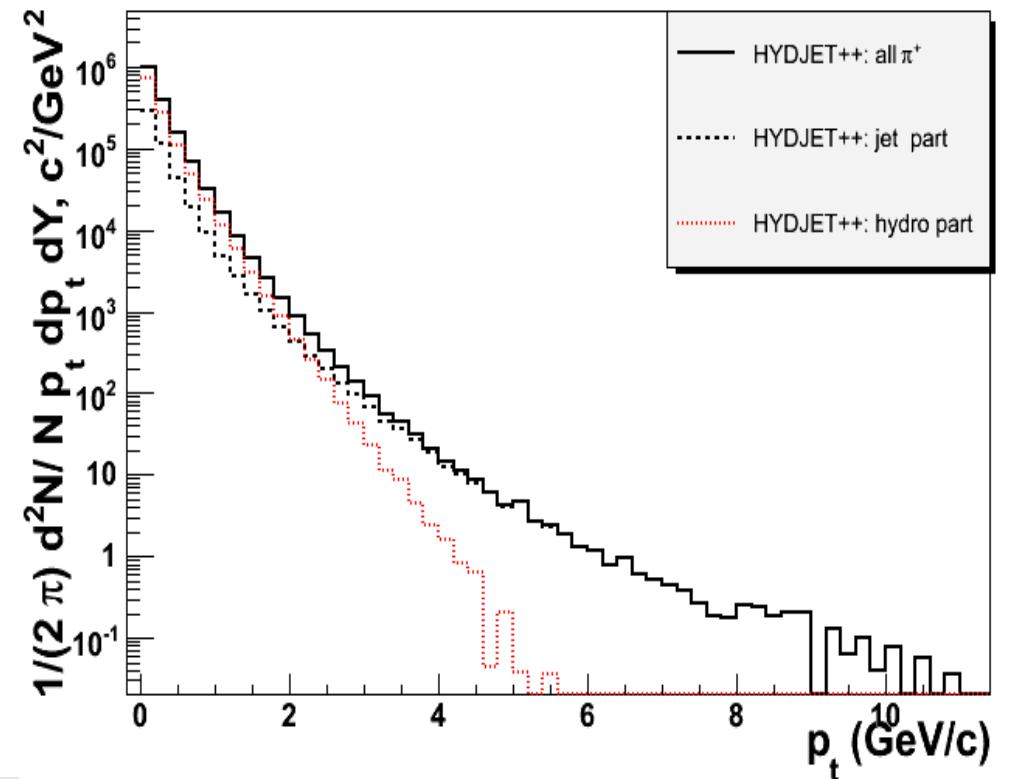
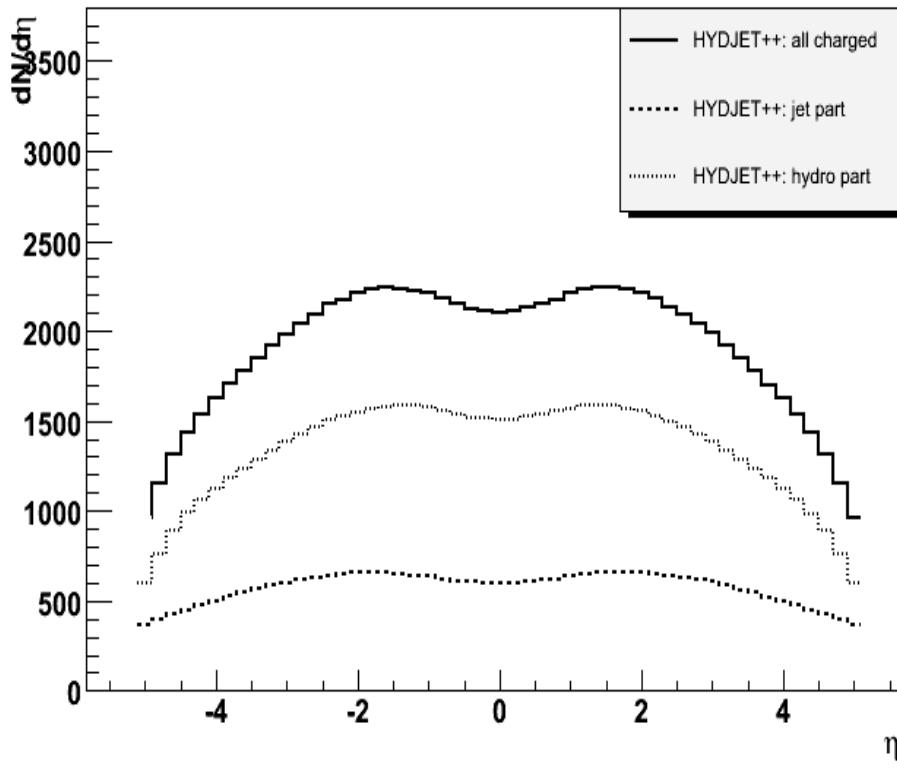
HYDJET++: hadron spectra at LHC



1000 events Pb+Pb (0-5 % centrality) at $\sqrt{s}=5.5 \text{ A TeV}$
(*default parameters, ptmin=7 GeV/c*)



HYDJET++: hadron spectra at LHC

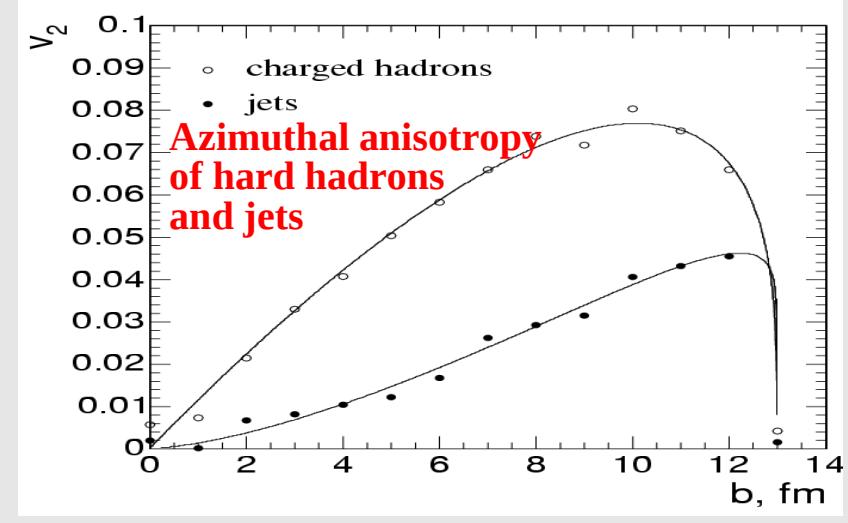
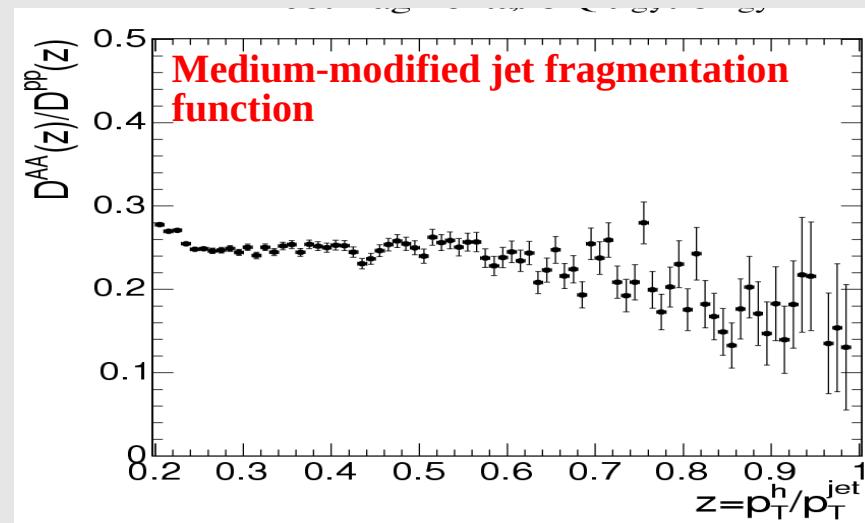
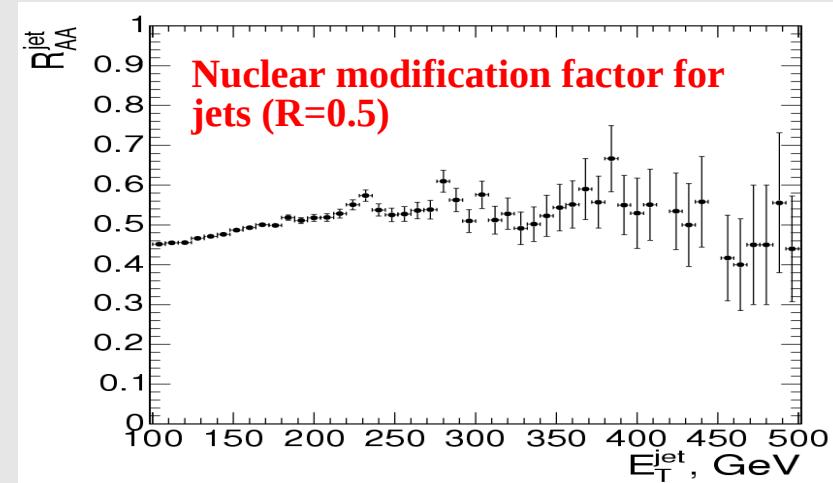
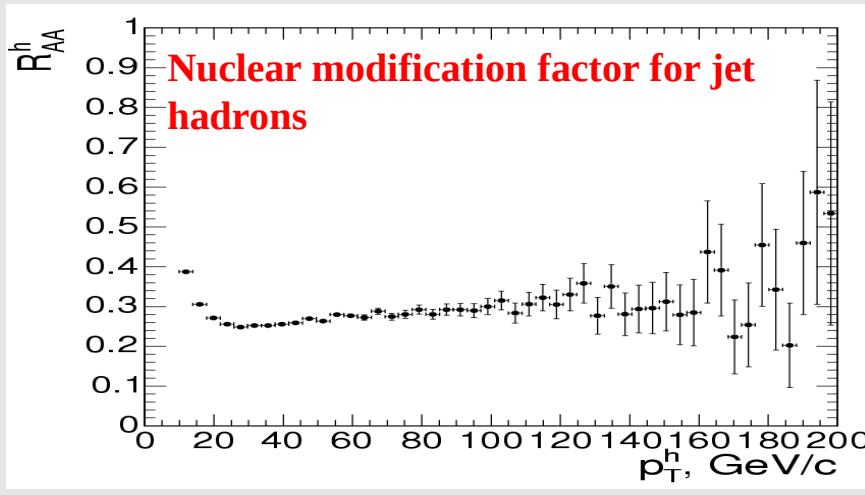


1000 events Pb+Pb (0-5 % centrality) at $\sqrt{s}=5.5 \text{ A TeV}$
(default parameters, $ptmin=10 \text{ GeV}/c$)



Examples of jet quenching observables at the LHC (PYQUEN, Pb+Pb)

~ 10^6 events with jet energy $E_T^{\text{jet}} > 100$ GeV per «1 year» (10^6 sec) at the integral luminosity $L=0.5 \text{ nb}^{-1}$





Summary

- Partonic energy loss MC model PYQUEN (**PYthia QUENched**) is available via Internet: <http://cern.ch/lokhtin/pyquen>
Corresponding code versioning is provided (latest version is 1.5)
- PYQUEN is incorporated in “full” heavy ion event generators HYDJET and HYDJET++ (HYDrodynamics plus JETs; superposition of two independent components: hard multi-parton fragmentation and soft hydro-type state)
<http://cern.ch/lokhtin/hydro/hydjet.html>
<http://cern.ch/lokhtin/hydjet++>
Corresponding code versioning is provided (latest versions are HYDJET_1.6 and HYDJET++_2.0; v. 2.1 is about completed).



BACKUP SLIDES



HYDJET: simple (but fast) model for soft hadroproduction

The final hadron spectrum (π, K, p) are given by the superposition of thermal distribution and collective flow assuming Bjorken's scaling.

1. Thermal distribution of produced hadron in rest frame of fluid element

$$f(E_0) \propto E_0 \sqrt{E_0^2 - m^2} \exp(-E_0/T_f), \quad -1 < \cos \theta_0 < 1, \quad 0 < \phi_0 < 2\pi$$

2. Space position r and local 4-velocity u_μ

$$f(r) = 2r/R_f^2(R_A, b, \Phi) (0 < r < R_f), \quad f(\eta) \propto e^{-\frac{-(\eta - Y_L^{max})^2}{2(Y_L^{max})^2}}, \quad 0 < \Phi < 2\pi$$

$$u_r = \sinh Y_T^{max} \cdot r / \sqrt{R_{eff}(R_A, b) \cdot R_A}, \quad u_t = \sqrt{1 + u_r^2} \cosh \eta, \quad u_z = \sqrt{1 + u_r^2} \sinh \eta$$

3. Boost of hadron 4-momentum p^μ in c.m. frame of the event

$$p_x = p_0 \sin \theta_0 \cos \phi_0 + u_r \cos \Phi [E_0 + (u^i p_0^i)/(u_t + 1)],$$

$$p_y = p_0 \sin \theta_0 \sin \phi_0 + u_r \sin \Phi [E_0 + (u^i p_0^i)/(u_t + 1)],$$

$$p_z = p_0 \cos \theta_0 + u_z [E_0 + (u^i p_0^i)/(u_t + 1)],$$

$$E = E_0 u_t + (u^i p_0^i), \quad (u^i p_0^i) = u_r p_0 \sin \theta_0 \cos(\Phi - \phi_0) + u_z p_0 \cos \theta_0$$



HYDJET: output information

Output particle information:

event record in PYTHIA/JETSET format

(common block HYJETS, #150000)

copy of event record in adopted for high multiplicites JETSET arrays

(common block LUJETS, #150000)

Output global event characteristics:

bgen - generated value of impact parameter

nbcoll - mean # of NN subcollisions at given bgen

npart - mean # of nucleon participants at given bgen

npyt - multiplicity of jet-induced particles in the event

nhyd - multiplicity of HYDRO-induced particles in the event

njet - number of hard parton-parton scatterings with $pt > ptmin$ in event

sigin - total inelastic NN cross section at given c.m.s. energy

sigjet - hard scattering NN cross section at given ptmin and energy



HYDJET: model parameters

External input

beam and target nucleus atomic weight ($A=B$)

c.m.s. energy per nucleon pair

impact parameter (fixed or distributed)

total mean multiplicity of soft part in central Pb+Pb events (multiplicity for other centralities and atomic weights is calculated automatically)

Parameter can be varied by user

ytfl - maximum transverse collective rapidity, controls slope of low-pt spectra
($0.01 < \text{ytfl} < 3.0$, default value is $\text{ytfl}=1.5$)

ylfl - maximum longitudinal collective rapidity, controls width of η -spectra
($0.01 < \text{ylfl} < 7.0$, default value is $\text{ylfl}=4.$)

Tf – hadron freeze-out temperature ($0.08 < \text{Tf} < 0.2$, $\text{Tf}(\text{default})=0.1$ GeV)

fpart - fraction of multiplicity proportional to # of participants;
($1.-\text{fpart}$) - fraction of multiplicity proportional to # of NN
subcollisions ($0.0 < \text{fpart} < 1.0$, default value is $\text{fpart}=1.$)

some parameters and flags of parton energy loss model PYQUEN

flags to switch on/off jet production, jet quenching and nuclear shadowing

ptmin=ckin(3) - minimal pt of parton-parton scattering in PYTHIA

Internal sets for soft part

poison multiplicity distribution

thermal particle ratios (π , K and p only)



HYDJET++: more detailed (and still fast) model for soft hadroproduction

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

Part I: N.S.Amelin, R.Lednisky, T.A.Pocheptsov, I.P.Lokhtin, L.V.Malinina,
A.M.Snigirev, Yu.A.Karpenko, Yu.M.Sinyukov, Phys. Rev. C 74 (2006) 064901

Part II: N.S.Amelin, R.Lednisky, I.P.Lokhtin, L.V.Malinina, A.M.Snigirev,
Yu.A.Karpenko, Yu.M.Sinyukov, I.C.Arsene, L.Bravina, Phys. Rev. C 77 (2008) 014903

fast (but realistic) 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 15 free parameters (but this number may be reduced to 9)



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} , μ_B and μ_s using phenomenological parameterization $\mu_B(\sqrt{s})$, $T^{ch}(\mu_B)$ is foreseen).
6. Strangeness suppression factor $\gamma_s \leq 1$ (the option to use phenomenological parameterization $\gamma_s(T^{ch}, \mu_B)$ is foreseen).
- 7-8. Thermodynamical parameters at thermal freeze-out: T^{th} , and μ_π - effective chemical potential of positively charged pions.
- 9-11. Volume parameters at thermal freeze-out: proper time τ_f , its standard deviation (emission duration) $\Delta\tau_f$, maximal transverse radius R_f .
12. Maximal transverse flow rapidity at thermal freeze-out ρ_u^{\max} .
13. Maximal longitudinal flow rapidity at thermal freeze-out η^{\max} .
14. Flow anisotropy parameter: $\delta(b) \rightarrow u^\mu = u^\mu(\delta(b), \varphi)$
15. Coordinate anisotropy: $\epsilon(b) \rightarrow R_f(b) = R_f(0)[V_{eff}(\epsilon(0), \delta(0))/V_{eff}(\epsilon(b), \delta(b))]^{1/2}[N_{part}(b)/N_{part}(0)]^{1/3}$

For impact parameter range bmin-bmax: $V_{eff}(b) = V_{eff}(0)N_{part}(b)/N_{part}(0)$, $\tau_f(b) = \tau_f(0)[N_{part}(b)/N_{part}(0)]^{1/3}$



HYDJET++: elliptic flow at RHIC

$$\frac{dN}{d^2 p_t dy} = \frac{dN}{2\pi p_t dp_t dy} (1 + v_2 \cos 2\phi + 2v_4 \cos 4\phi + \dots)$$

