Influence of jets on femtoscopic correlation radii in ultrarelativistic heavy ion collisions

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- HYDJET++ heavy ion event generator: physics frames
- Hadron production and correlation radii at RHIC
- Hadron production and correlation radii at LHC
- Outlook

HYDJET++ Monte-Carlo model for relativistic heavy ion collisions

HYDJET++ - event generator to simulate heavy ion event as merging two independent components (continuation of HYDJET):
soft hydro-type part (adapted FAST MC code) +
hard multi-parton part (PYQUEN partonic energy loss model, medium-modified PYTHIA)
first version 2.0 (September 2008)
latest version 2.1 (September 2009)

http://cern.ch/lokhtin/hydjet++

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

HYDJET & HYDJET++ (HYDrodynamics + JETs)

Calculating the number of hard NN sub-collisions Njet (b, Ptmin, √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 $S \leq 1$, which is taken from the adapted impact parameter dependent parameterization based on Glauber-Gribov theory (*K.Tywoniuk et al.,, Phys. Lett. B 657 (2007) 170*).

Generating the soft part according to the corresponding "thermal" model (for b≠0 mean multiplicty is proportional to # of N-participants)

Junction of two independent event outputs (hard & soft) to event record

HYDJET++ (hard):
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 (+ minimal p_T of hard process Ptmin)

I.P.Lokhtin, A.M.Snigirev, Eur. Phys. J. 45 (2006) 211

HYDJET++ (hard): physics frames

General kinetic integral equation:

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

1. Collisional loss and elastic scattering cross section:

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

2. Radiative loss (BDMS):

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

“dead cone” approximation for massive quarks:

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

HYDJET++ (hard):
partonic energy loss MC procedure

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

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

HYDJET++ (soft): physics frames

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 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): 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:

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

- FAST MC 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-acception procedure.

Freeze-out surface parameterizations

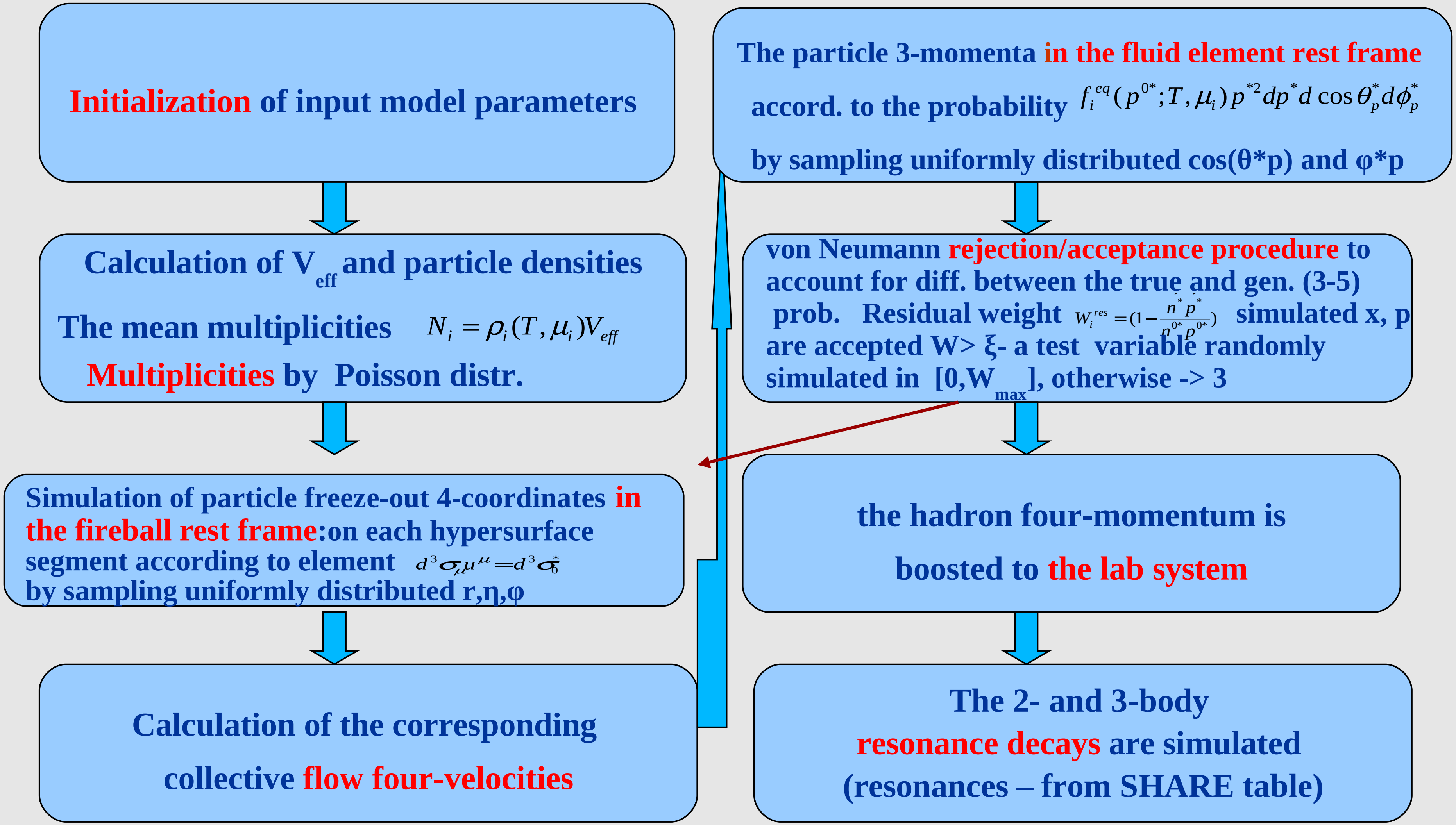
1. The Bjorken model with hypersurface $\tau = (t^2 - z^2)^{1/2} = const$

2. Linear transverse flow rapidity profile $\rho_u = \frac{r}{R}\rho_u^{\max}$

3. The total effective volume for particle production at

$$- \quad V_{eff} = \int_{\sigma(x)} d^3\sigma_\mu(x) u^\mu(x) = \tau \int_0^R \gamma_r r\,dr \int_0^{2\pi} d\phi \int_{\eta_{\min}}^{\eta_{\max}} d\eta = 2\pi\tau\Delta\eta \left(\frac{R}{\rho_u^{\max}}\right)^2 (\rho_u^{\max}\sinh\rho_u^{\max} - \cosh\rho_u^{\max} + 1)$$

HYDJET++ (soft): hadron generation MC procedure



Initialization of input model parameters

Calculation of V_{eff} and particle densities

The mean multiplicities $N_i = \rho_i(T, \mu_i) V_{eff}$

Multiplicities by Poisson distr.

Simulation of particle freeze-out 4-coordinates in the fireball rest frame: on each hypersurface segment according to element $d^3\sigma_\mu u^\mu = d^3\sigma_0^*$ **by sampling uniformly distributed r,η,φ**

Calculation of the corresponding collective flow four-velocities

The particle 3-momenta in the fluid element rest frame accord. to the probability $f_i^{eq}(p^{0*}; T, \mu_i) p^{*2} dp^* d\cos\theta_p^* d\phi_p^*$ **by sampling uniformly distributed cos(θ*p) and φ*p**

von Neumann rejection/acceptance procedure to account for diff. between the true and gen. (3-5) prob. Residual weight $W_i^{res} = (1 - \frac{n^* p^*}{n^{0*} p^{0*}})$ **simulated x, p are accepted W> ξ- a test variable randomly simulated in [0,W_{max}], otherwise -> 3**

the hadron four-momentum is boosted to the lab system

The 2- and 3-body resonance decays are simulated (resonances – from SHARE table)

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 then pions) the Botzmann approximation :

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

Particles (stable, resonances) 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

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}.

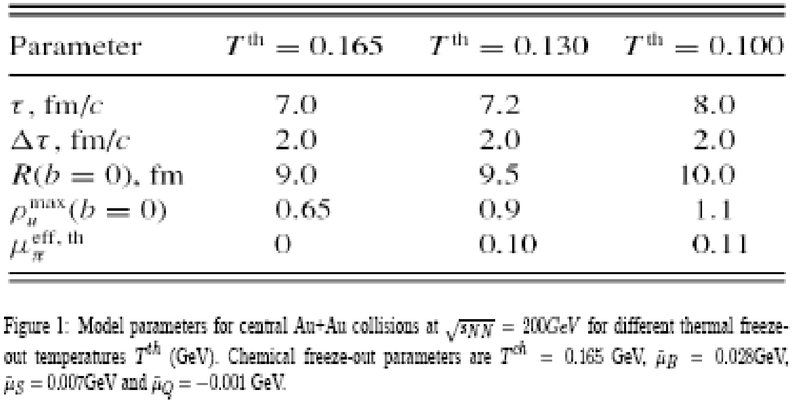
13. Maximal longitudinal flow rapidity at thermal freeze-out η^{max}.

14. Flow anisotropy parameter: $\delta(b)$ → $u^\mu = u^\mu(\delta(b),\varphi)$

15. Coordinate anisotropy: $\varepsilon(b)$ → $R_f(b)=R_f(0)[V_{eff}(\varepsilon(0),\delta(0))/V_{eff}(\varepsilon(b),\delta(b))]^{1/2}[N_{part}(b)/N_{part}(0)]^{1/3}$

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++ : particle ratios at RHIC



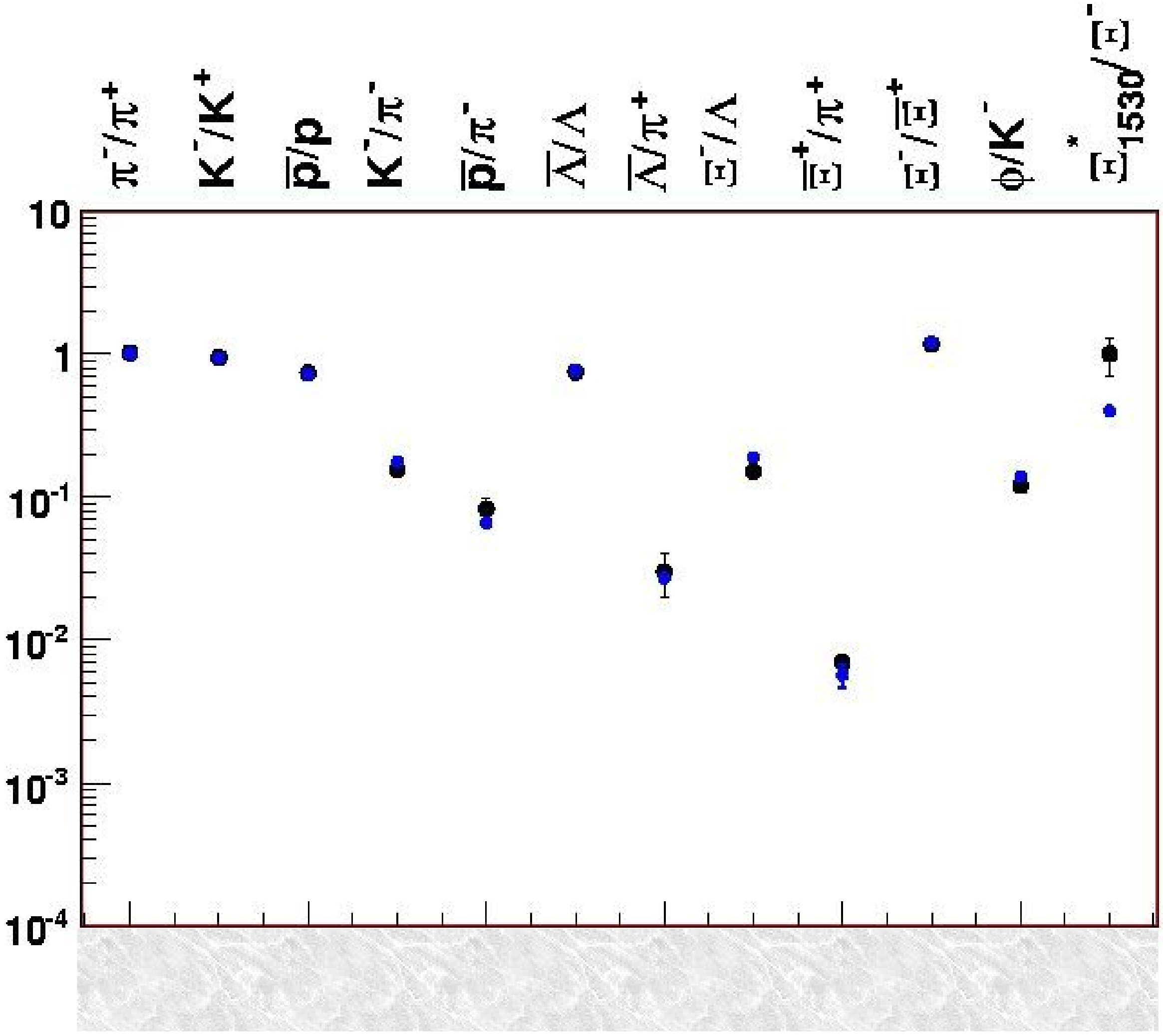
Parameter	$T^{\rm th} = 0.165$	$T^{\rm th} = 0.130$	$T^{\rm th} = 0.100$
τ, fm/c	7.0	7.2	8.0
$\Delta\tau$, fm/c	2.0	2.0	2.0
$R(b=0)$, fm	9.0	9.5	10.0
$\rho_u^{\rm max}(b=0)$	0.65	0.9	1.1
$\mu_\pi^{\rm eff,\,th}$	0	0.10	0.11

Figure 1: Model parameters for central Au+Au collisions at $\sqrt{s_{NN}} = 200GeV$ for different thermal freeze-out temperatures T^{th} (GeV). Chemical freeze-out parameters are $T^{ch} = 0.165$ GeV, $\tilde{\mu}_B = 0.028$GeV, $\tilde{\mu}_S = 0.007$GeV and $\tilde{\mu}_Q = -0.001$ GeV.

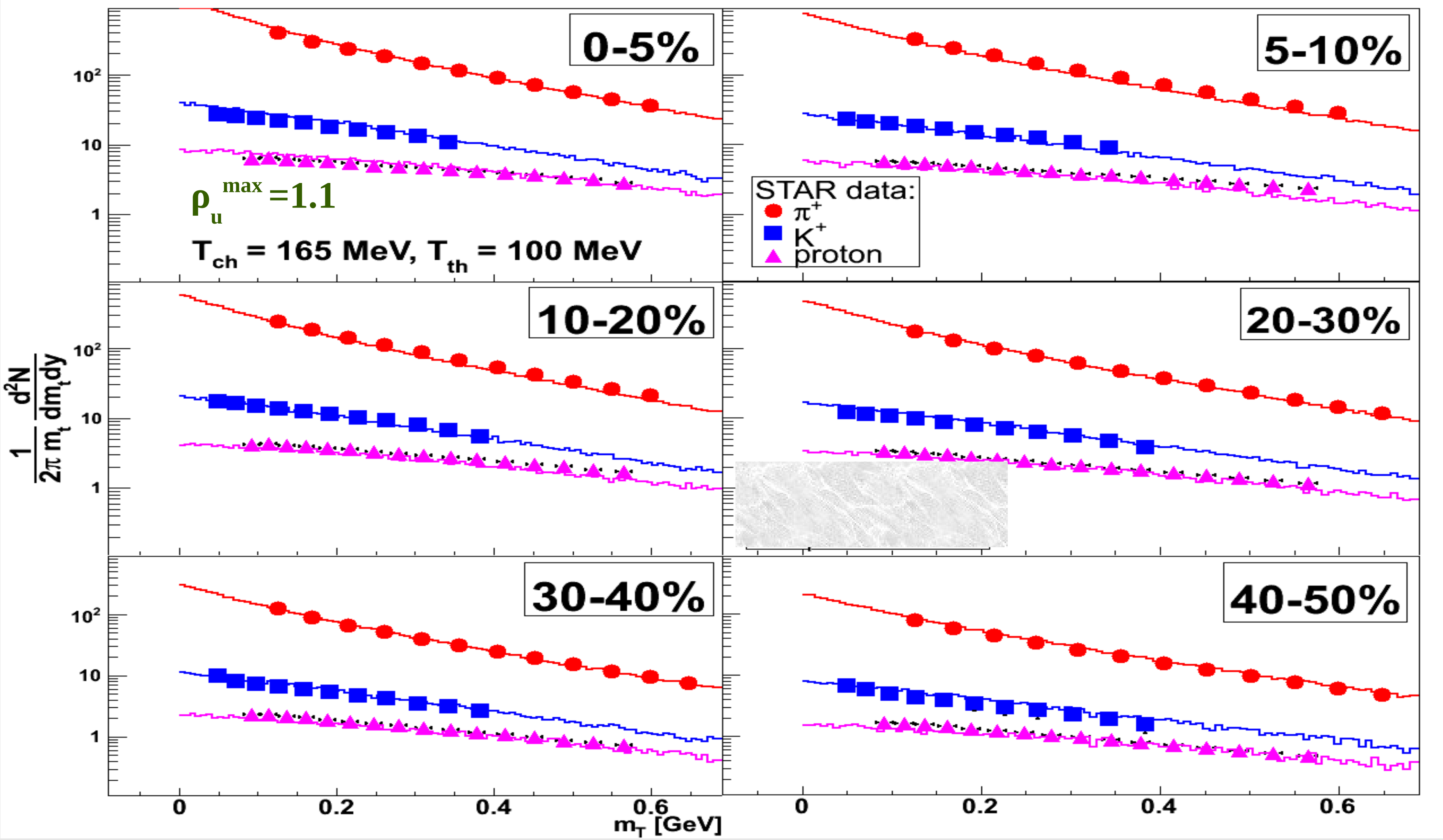
T^{ch}=0.165 GeV, μ_B=0.028 GeV, μ_S=0.007 GeV, μ_Q=-0.001 GeV

T^{th}=0.100, 0.130, 0.165 GeV

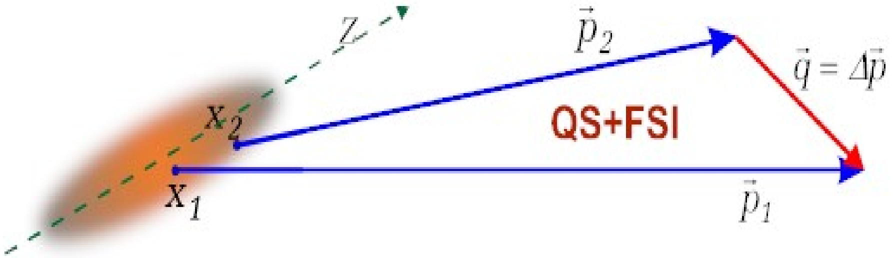
Particle number ratios near mid-rapidity in central Au Au collisions



HYDJET++: radial flow at RHIC

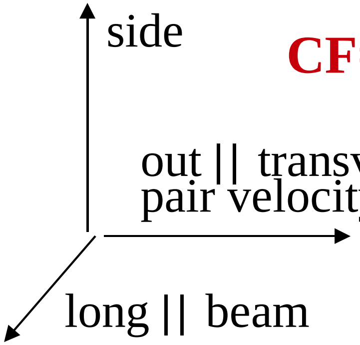


HYDJET++: correlation radii at RHIC



$$C(q)=\frac{N_2(k_1,k_2)}{N_1(k_1)N_2(k_2)} \rightarrow CF = N\,\frac{S(Q_{inv})}{B(Q_{inv})}$$

Weights for QS only: $P_{12}=C(q)=1+\langle\cos q\Delta x\rangle$



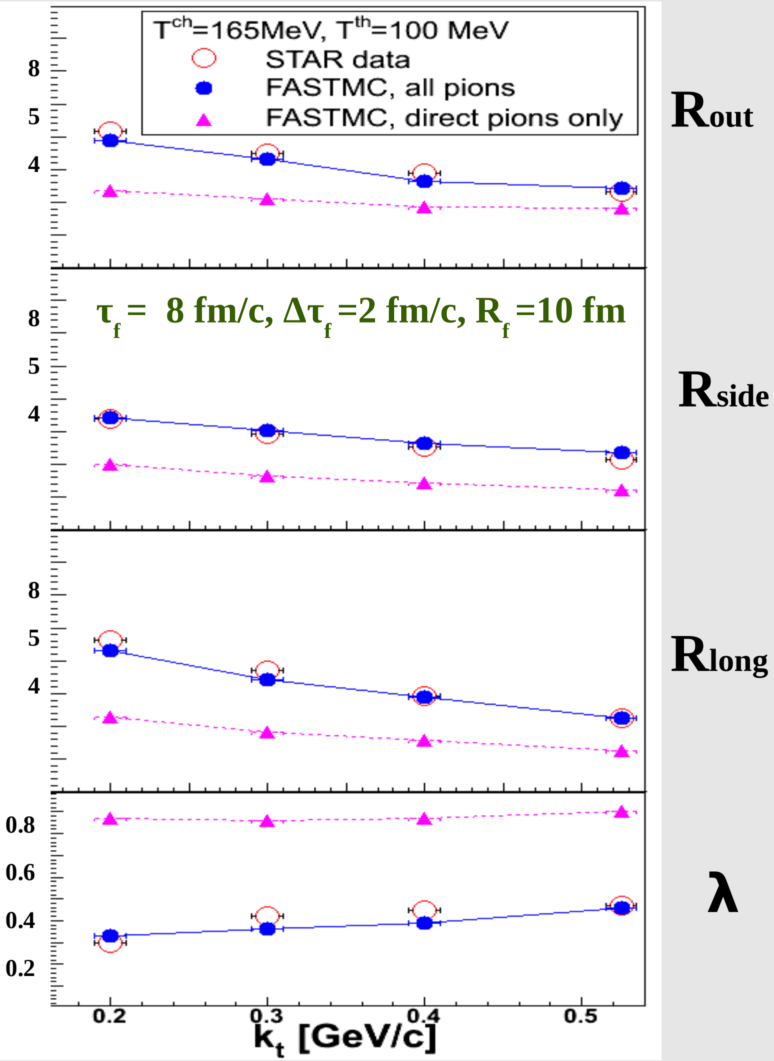
side

out || transverse pair velocity v_t

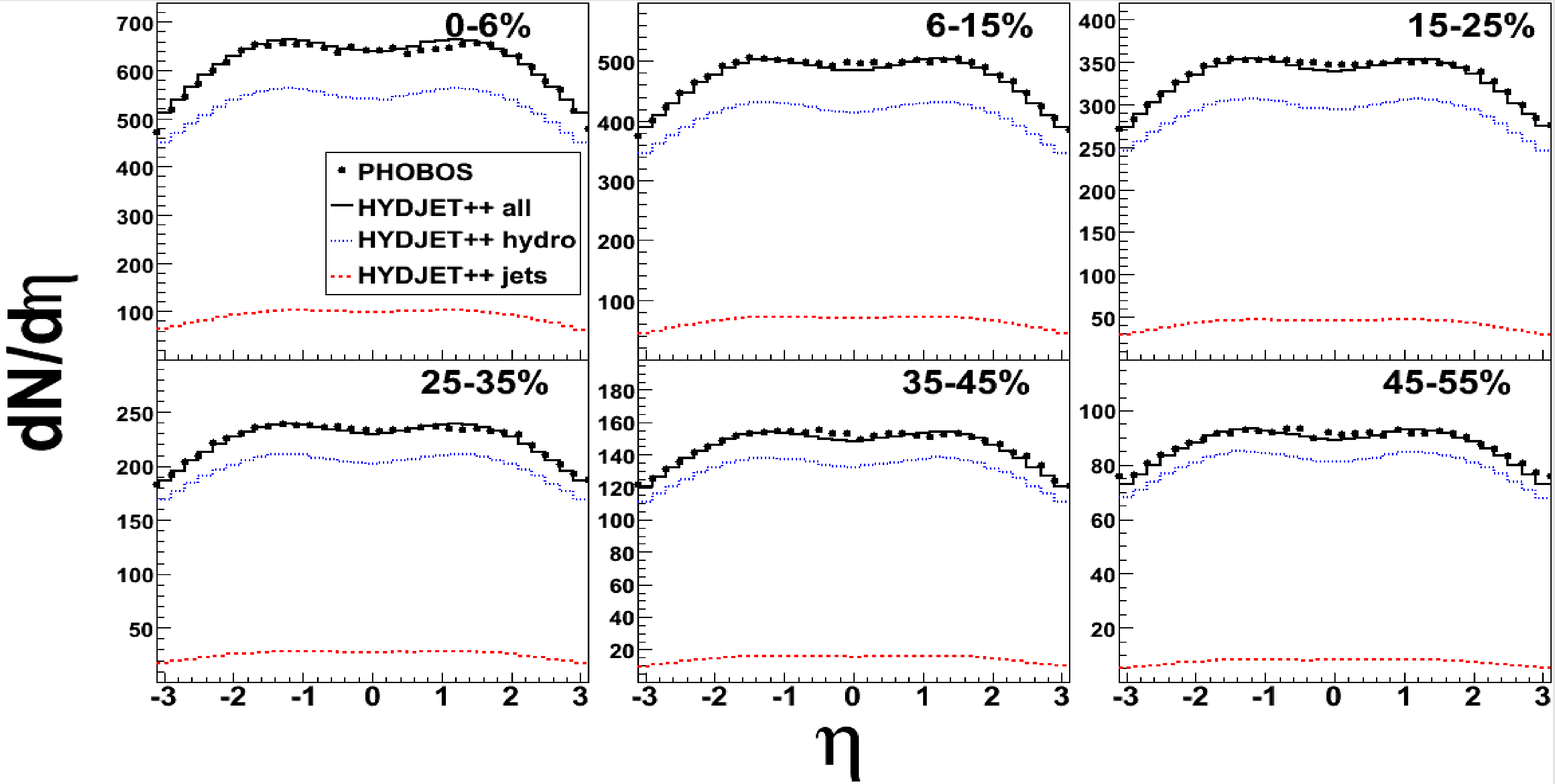
long || beam

$$CF=1+\lambda\exp(-R_o^2q_o^2-R_s^2q_s^2-R_l^2q_l^2-2R_{ol}^2q_o\,q_l)$$

The corresponding correlation widths are parameterized in terms of the Gaussian correlation radii R_i



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

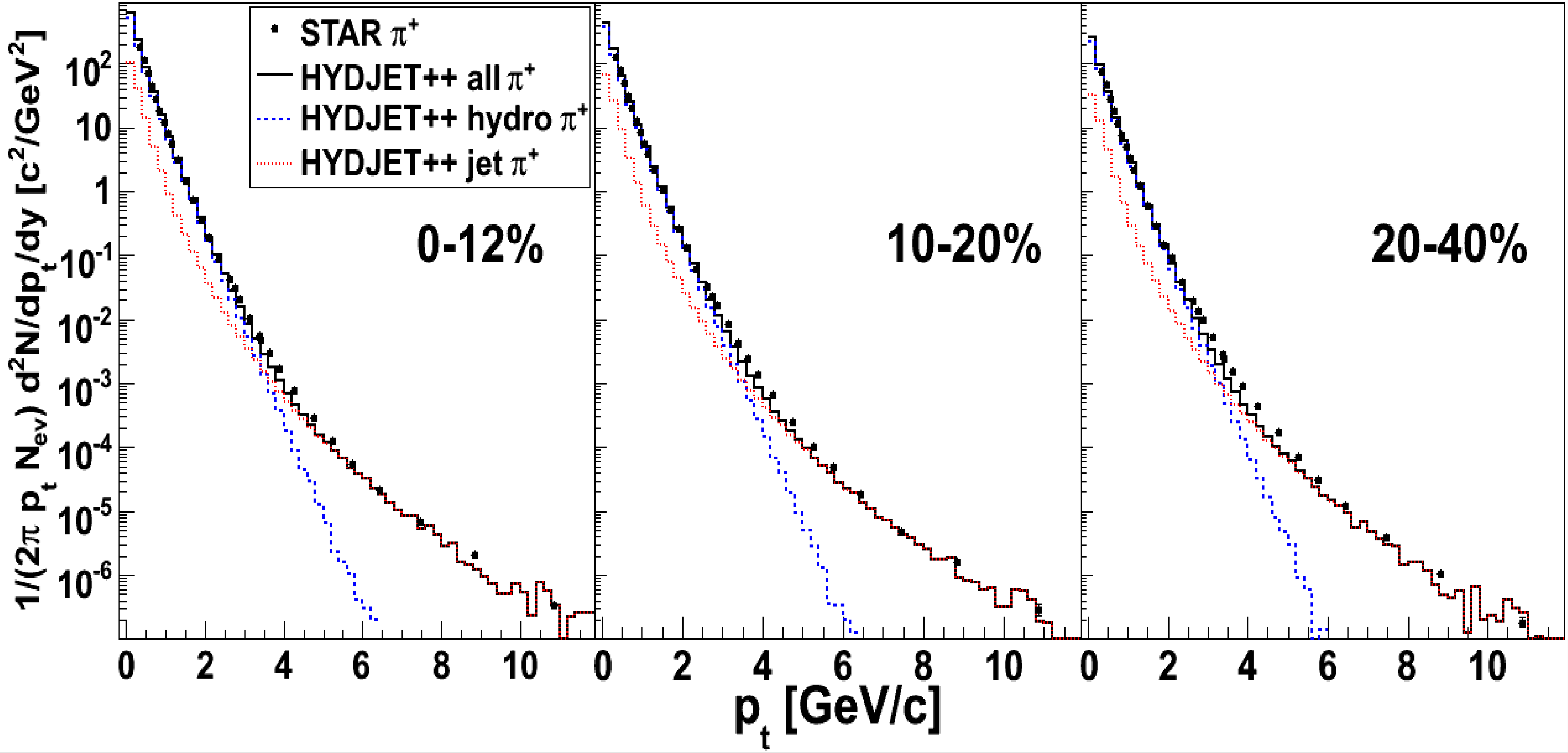


Width of the spectra allows one to fix η^{max}=3.3,

Centrality dependence of multiplicity allows one to fix ptmin=3.4 GeV/c and μ_π=0.06

HYDJET++: transverse momentum spectra at RHIC

PYQUEN energy loss model parameters: T_0(QGP)=300 MeV, τ_0(QGP)=0.4 fm/c, N_f=2



The coordinate information for “jet-induced” particles in HYDJET++

$$x_j = rCos(\phi) + x_{NN}$$

$$y_j = rSin(\phi) + y_{NN}$$

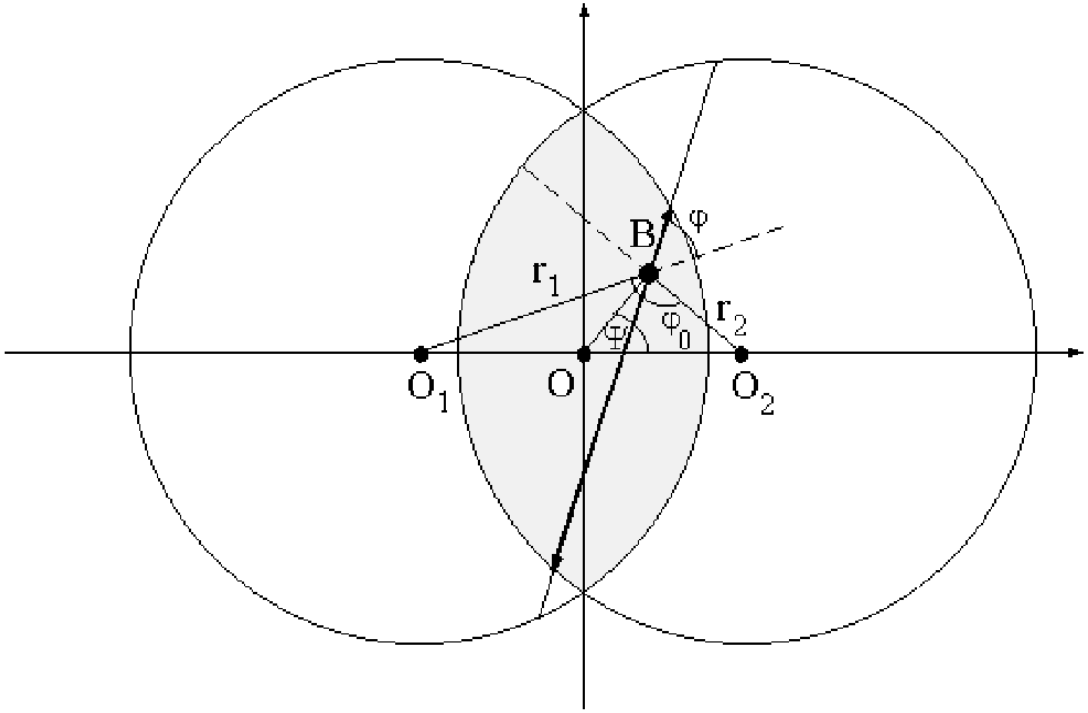
Transverse coordinate smearing of hadron formation in NN (X_{NN}, Y_{NN}) << than in HI and can be neglected as a first approximation

(optionally one can randomize positions around the jet origin Xj, Yj with radius 1 fm);

$$z_h = \tau_{hard\_process} Sinh(\eta_h)$$

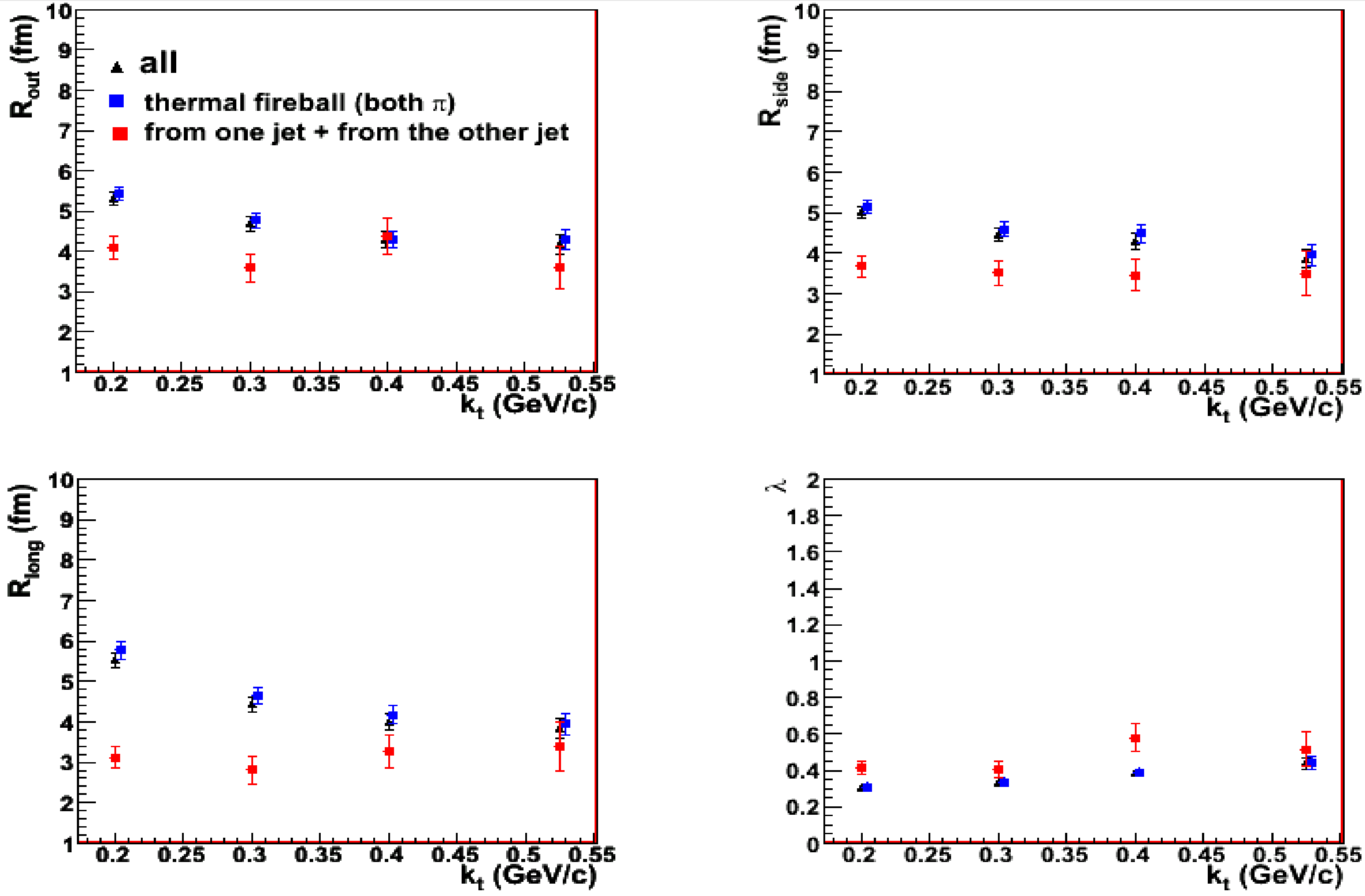
$$t_h = \tau_{hard\_process} Cosh(\eta_h)$$

$$\tau_{hard\_process} = 1/Q$$



x, y, z & t with assumption space rapidity = coordinate rapidity – rather “toy” estimation.

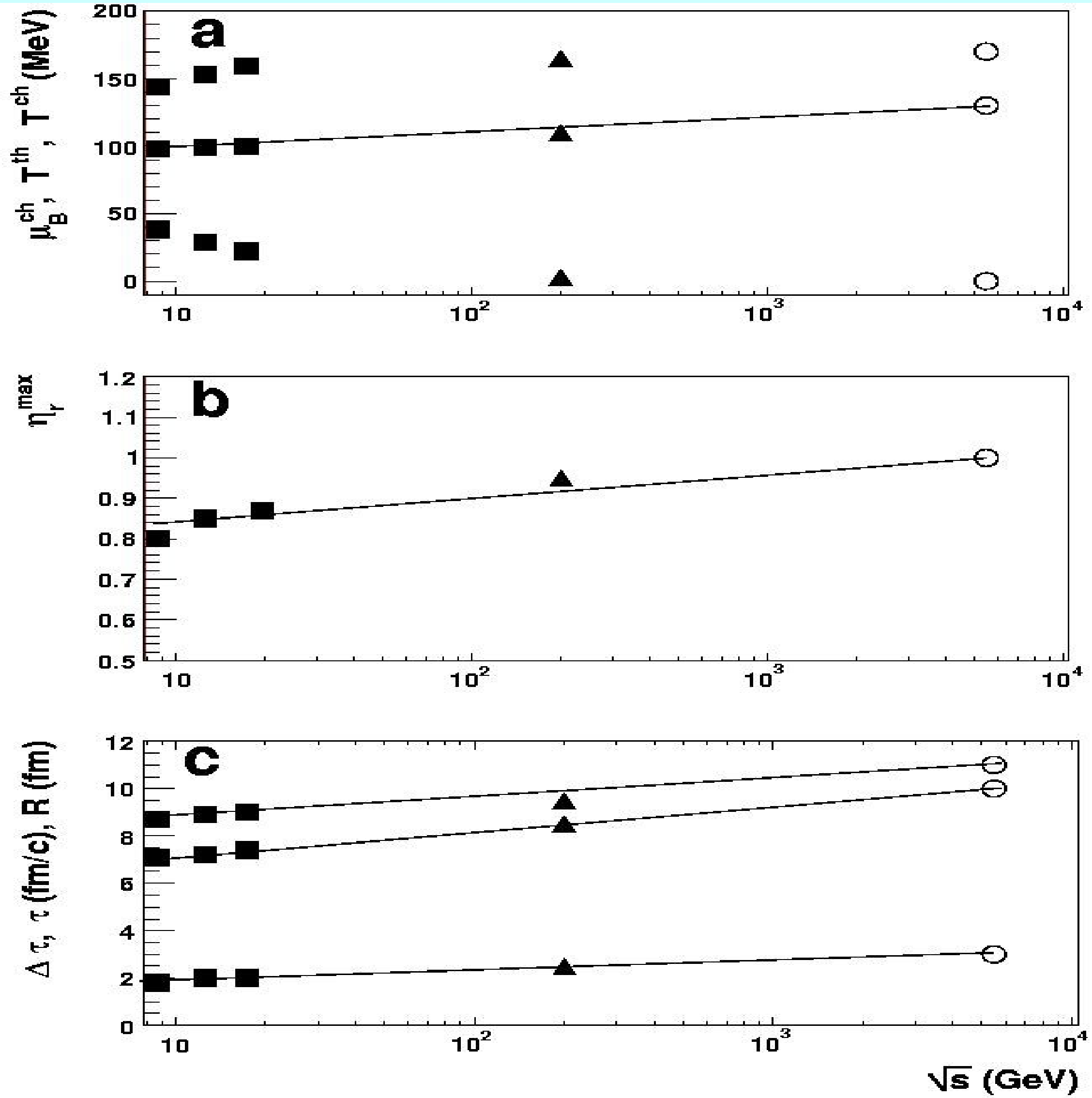
Influence of jet fragmentation on correlation radii at RHIC



At RHIC the contribution of jet part to total multiplicity is ~ 15%.

Influence of jets on CFs is neglidgible.

Extrapolation of HYDJET++ parameters for soft hydro-part to LHC



- ■ SPS ($\sqrt{s_{NN}}$ = 8.7 - 17.3 GeV)
- ▲ RHIC ($\sqrt{s_{NN}}$ = 200 GeV)
- ○ LHC ($\sqrt{s_{NN}}$ = 5500 GeV)

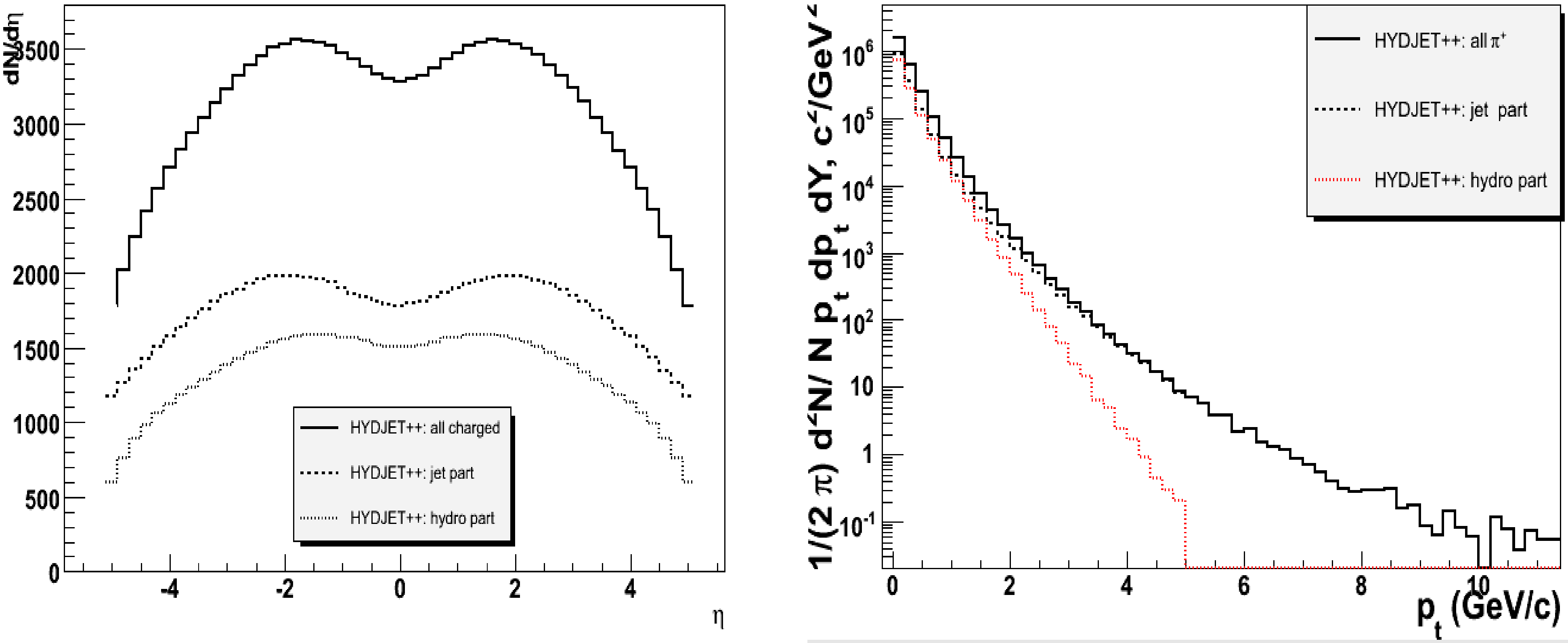
The extrapolated values :

$R \sim 11$ fm,
$\tau \sim 10$ fm/c,
$\Delta\tau \sim 3.0$ fm/c,

$\rho_u^{max} \sim 1.1$,
$T_{th} \sim 130$ MeV.

$T_{ch}=170$ MeV,
$\mu_B=0$, $\mu_S=0$, $\mu_Q=0$ MeV

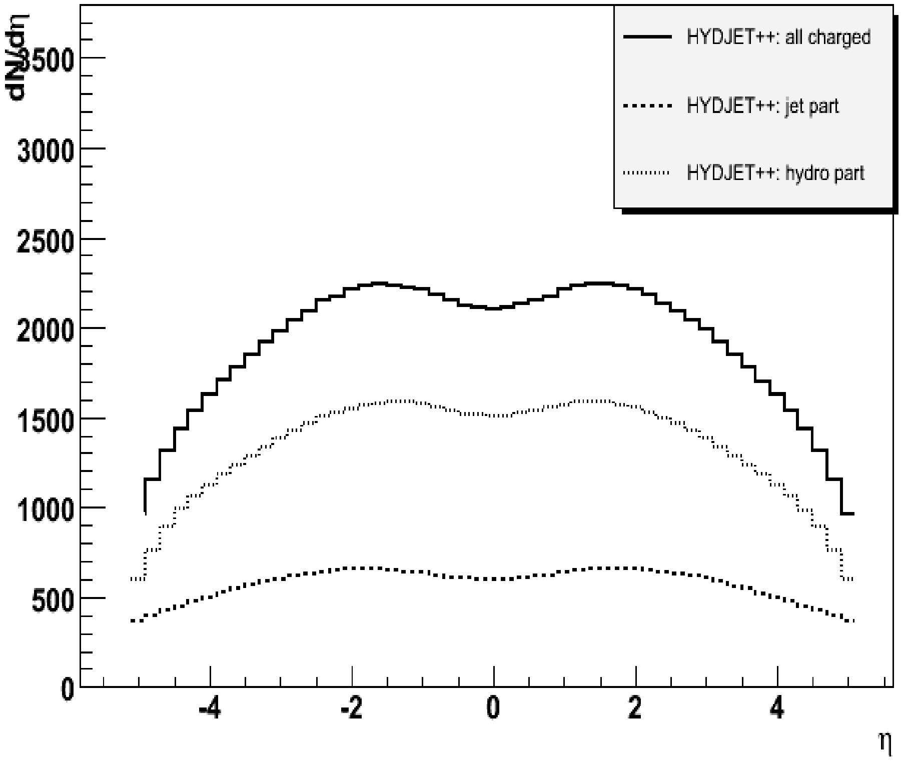
HYDJET++: hadron spectra at LHC

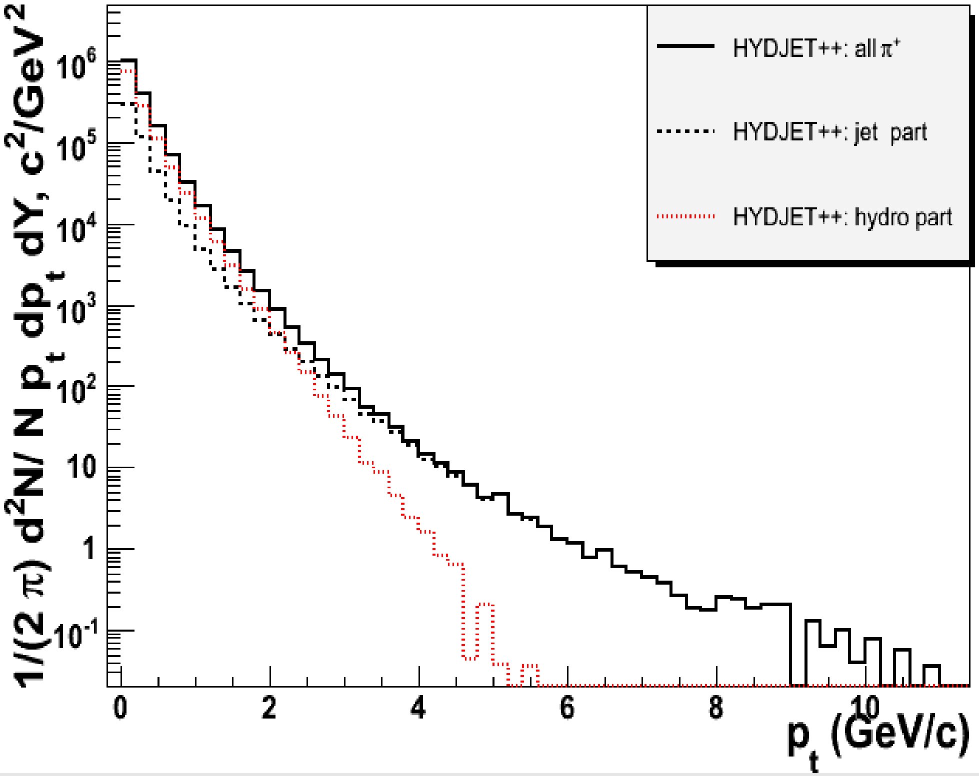


1000 events Pb+Pb (0-5 % centrality) at √s=5.5 A TeV

(default parameters, ptmin=7 GeV/c: ~55% jet contribution)

HYDJET++: hadron spectra at LHC

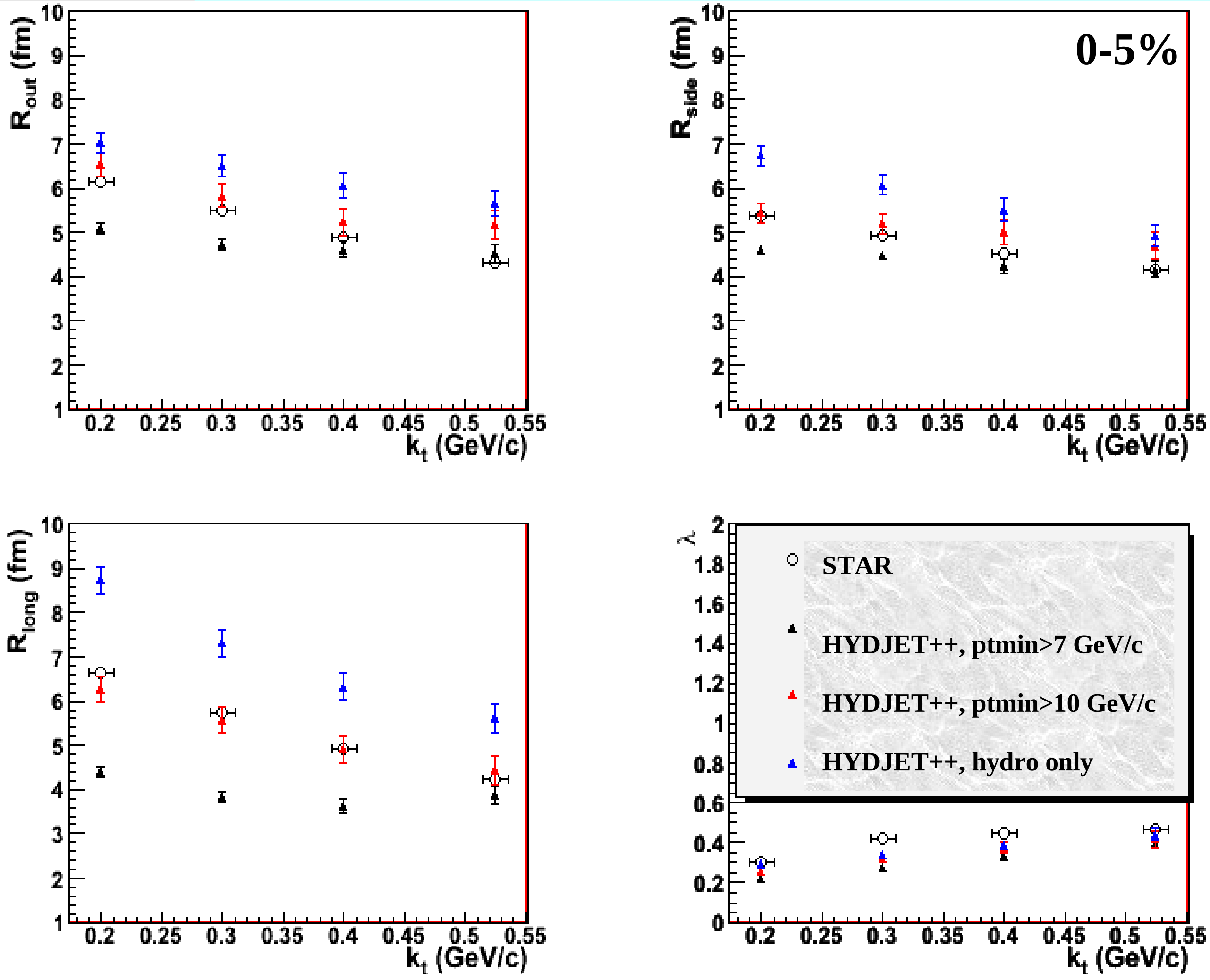




1000 events Pb+Pb (0-5 % centrality) at $\sqrt{s}$=5.5 A TeV

(default parameters, ptmin=10 GeV/c: ~25% jet contribution)

Influence of jet fragmentation on correlation radii at LHC



Pure hydro (no jets):
R(LHC) > R(RHIC)
Ptmin=10 GeV/c
(~25% jet contribution):
R(LHC) ~ R(RHIC)
Ptmin=7 GeV/c
(~55% jet contribution):
R(LHC) < R(RHIC)!
(especially R_{long})

due to the significant influence of “jet-induced” hadrons, which are emitted on shorter space-time scales than soft hadrons.

It seems quite non-trivial prediction…

I.P.Lokhtin, “Influence of jets on femtoscopic correlation radii in ultra-relativistic heavy ion collisions”

Outlook: jets.femtoscopy@LHC

- ***Influence of jet quenching:*** **softening the hadron spectra (mostly from partons coming from the center of the nuclear overlapping region, but much less for partons coming from peripheral regions) -** ***"surface emission" at relatively high p_T - can we see it on correlation radii?***
- ***Influence of nuclear shadowing:*** **hardening the hadron spectra (since shadowing factor *S* depends on the jet production vertex *r*, parton production in the nuclear centre is more suppressed then in periphery; but the dependence *S(r)* is rather weak as compared with the r-dependence of quenching) -** ***imitation of partial "surface emission" at intermediate p_T - can we see it on correlation radii?***

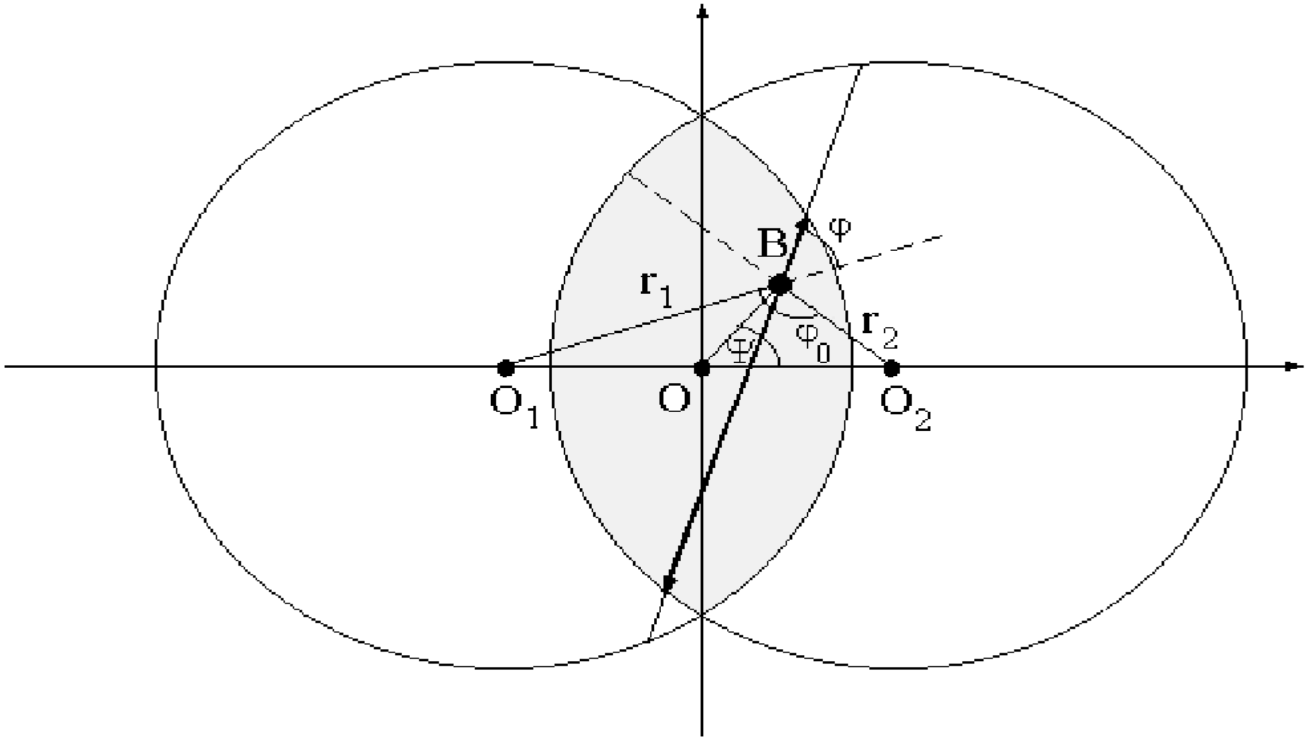
Note. **In our best knowledge, the first study of the influence of hard processes on momentum correlations:** ***G.Paic, P.K. Skowronski and B. Tomasik, Nucleonica 49 (2004) S89***

BACKUP SLIDES

Nuclear geometry and QGP evolution

impact parameter b≡ $|O_1O_2|$ - transverse distance between nucleus centers

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



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

Angular spectrum of gluon radiation

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

Collinear radiation

$$\theta = 0$$

Small-angular radiation **(default)**

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

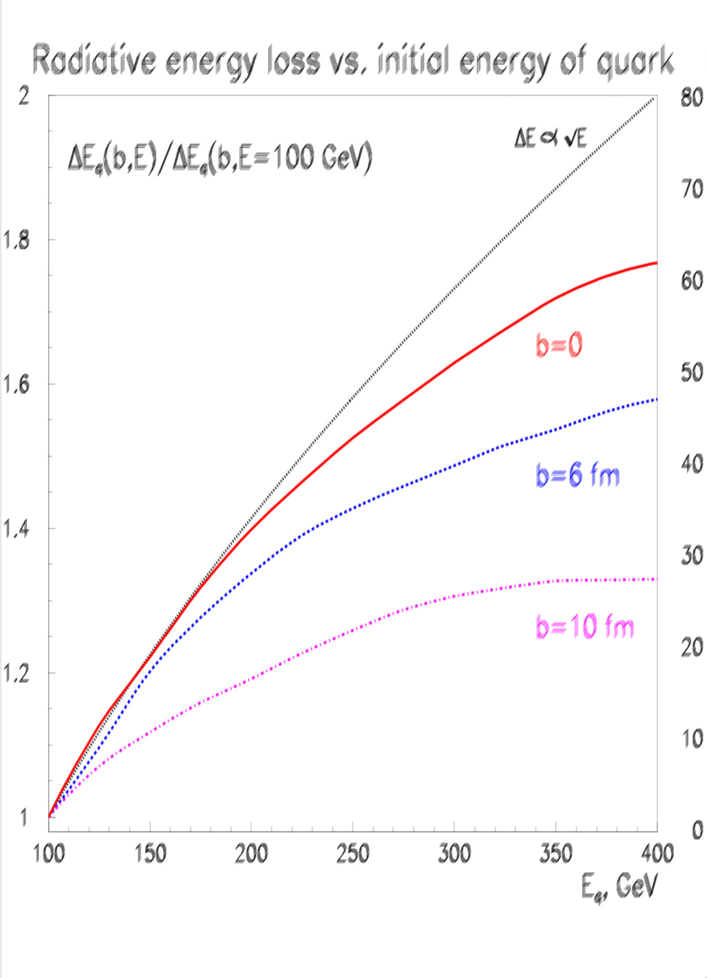
Broad-angular radiation

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

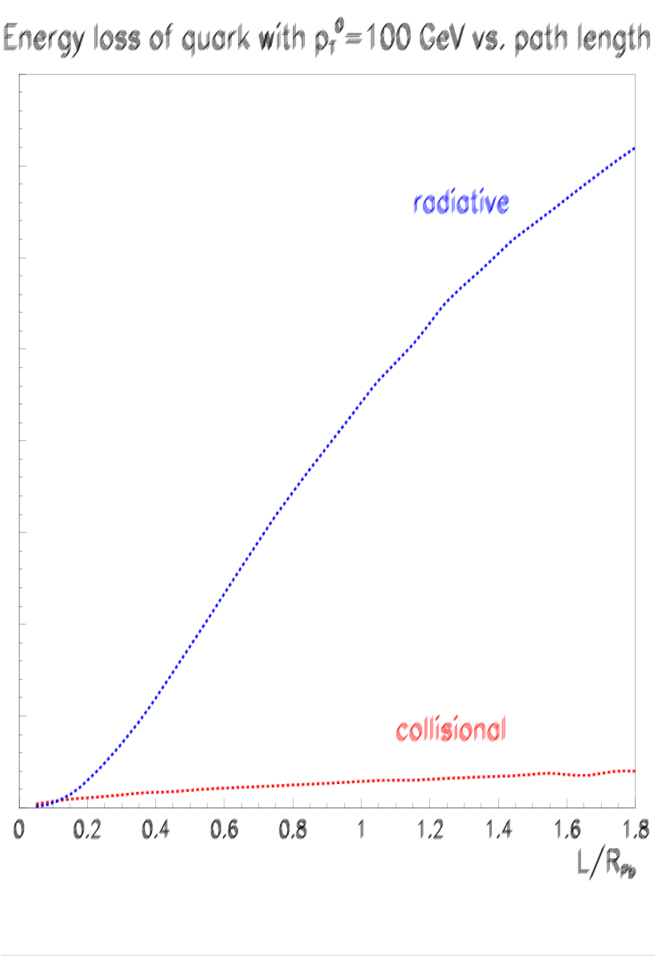
PYQUEN: mean energy loss

($\sqrt{s}$=5.5 A TeV, Pb+Pb, $T_{0,\,QGP}$ (b=0) = 1 GeV, τ_0=0.1 fm/c)

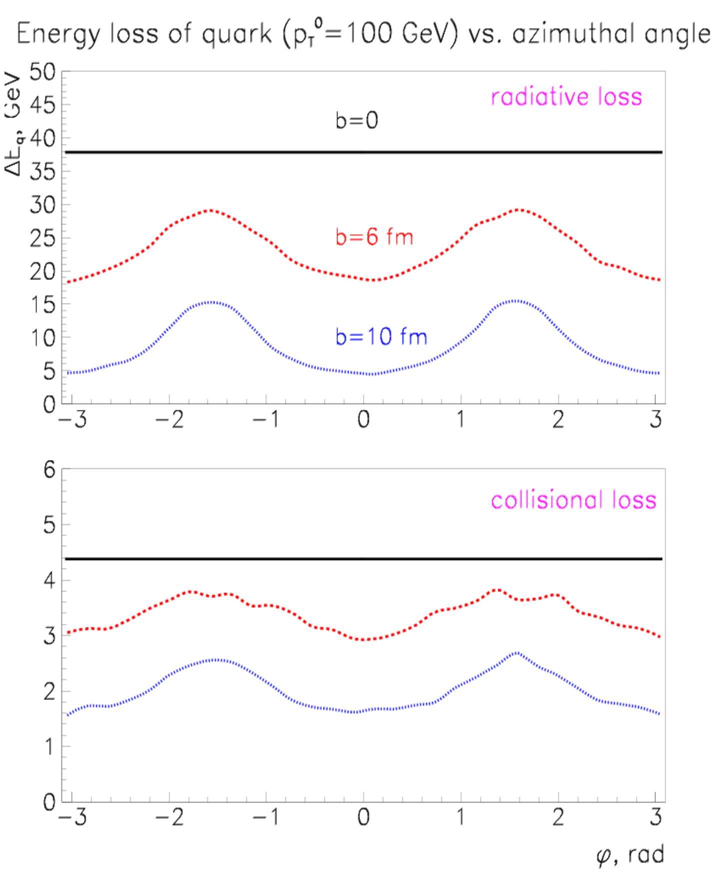
E-dependence



L-dependence

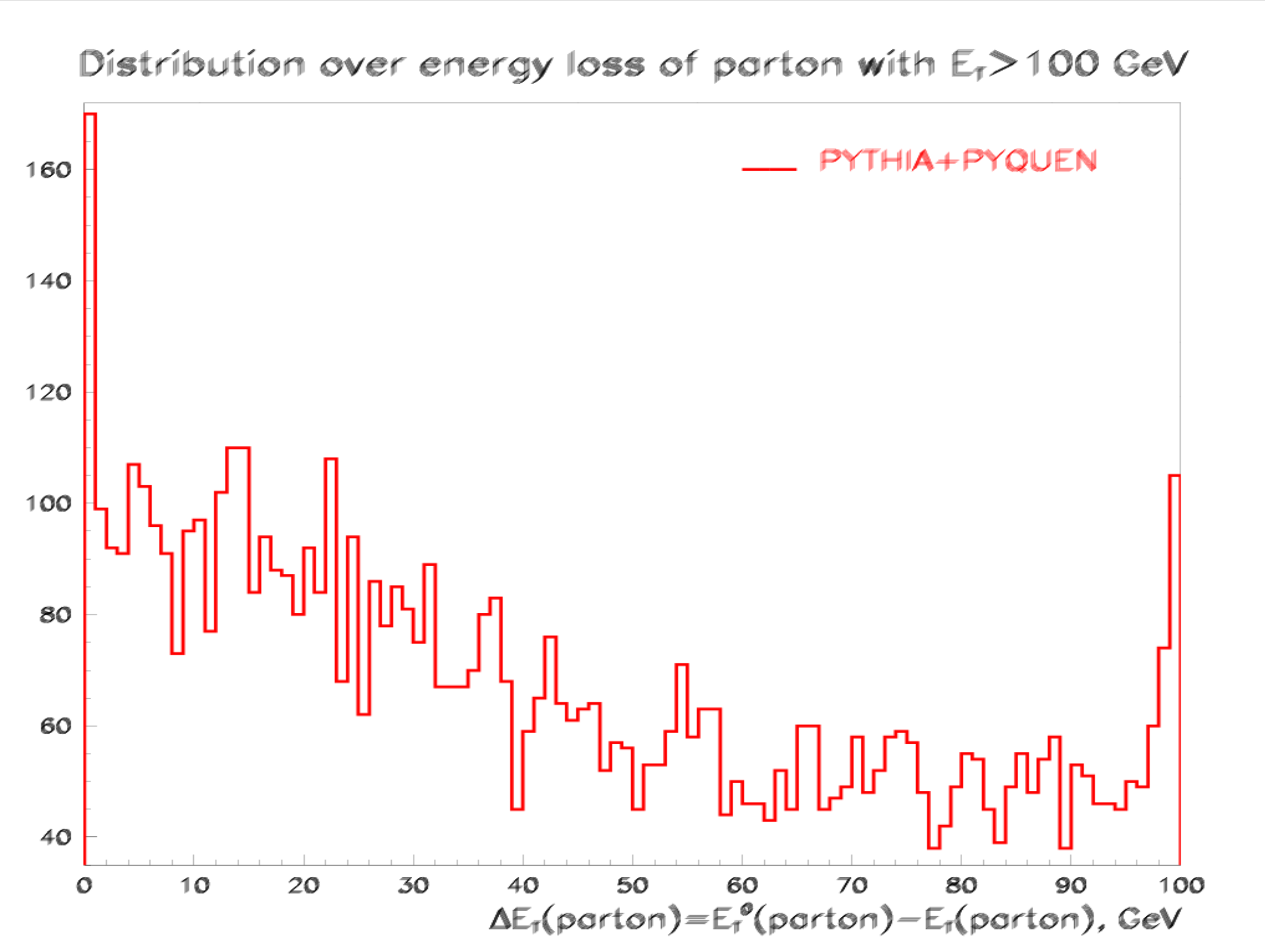


φ-dependence



PYQUEN: energy loss fluctuations

($\sqrt{s}$=5.5 A TeV, Pb+Pb, $T_{0,\,QGP}$(b=0) = 1 GeV, τ_0=0.1 fm/c)



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 μ=const: the total yield of particle species is $N_i = \rho_i(T,\mu_i)V_{eff}$ **.**

3. Chemical freeze-out : T, $\mu_i = \mu_B B_i + \mu_S S_i + \mu_c C_i + \mu_Q Q_i$; T, μ_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:

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

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

HYDJET++ (soft): thermal charm production

Thermal charmed mesons J/ψ, D^0, $\bar{D}^0$, D^+, D^-, D_s^+, D_s^-, Λ_c^+, Λ_c^- are generated within the statistical hadronization model

(feed-down corrections and meson 2- and 3- body decays are performed)

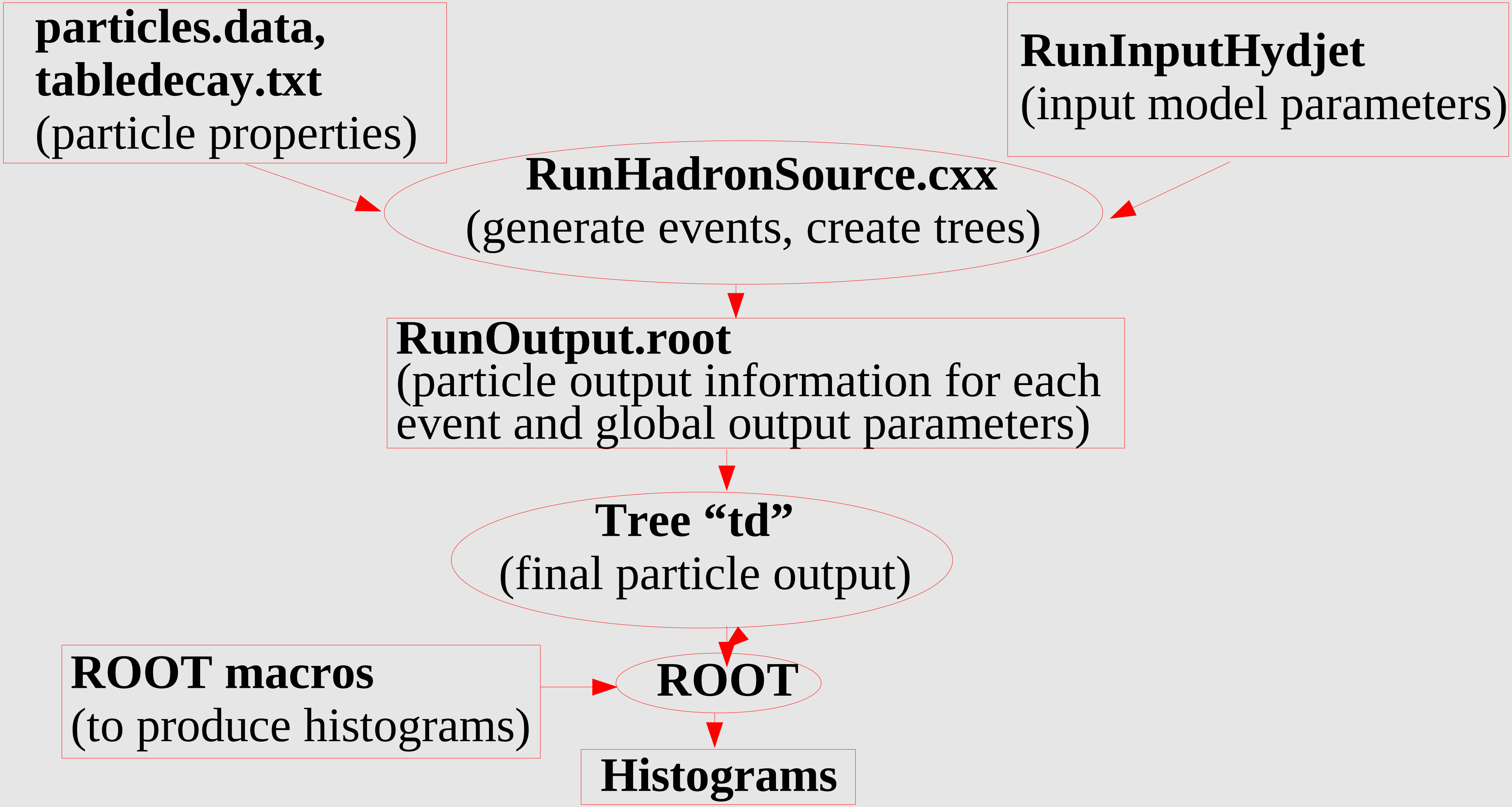
$$N_D=\gamma_c N_D^{th}(I_1(\gamma_c N_D^{th})/I_0(\gamma_c N_D^{th})), \qquad N_{J/\psi}=\gamma_c^2 N_{J/\psi}^{th}$$

γ_c - charm enhancement factor 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=2 is applied to take into account NLO pQCD corrections)

The block structure of HYDJET++



particles.data,
tabledecay.txt
(particle properties)

RunInputHydjet
(input model parameters)

RunHadronSource.cxx
(generate events, create trees)

RunOutput.root
(particle output information for each event and global output parameters)

Tree "td"
(final particle output)

ROOT macros
(to produce histograms)

ROOT

Histograms

RunInputHydjetRHIC200

(input parameter file for Au+Au collisions at RHIC, *default*)

```
Number of events to generate
10
C.m.s. energy per nucleon pair, fSqrtS [GeV]
200.
Atomic weigth of nuclei, fAw
197.
Flag of type of centrality generation, fBfix (=0 is fixed by fBfix, >0 distributed [fBfmin, fBmax])
1
Minimum impact parameter in units of nuclear radius, fBmin
0.
Maximum impact parameter in units of nuclear radius, fBmax
0.55
Fixed impact parameter in units of nuclear radius, fBfix
0.
Parameter to set random number seed, fSeed (=0 the current time is used, >0 the value fSeed is used)
0
Temperature at chemical freeze-out, fT [GeV]
0.165
Chemical baryon potential per unit charge, fMuB [GeV]
0.0285
Chemical strangeness potential per unit charge, fMuS [GeV]
0.007
Chemical charm potential per unit charge, fMuC [GeV] (used if charm production is turned on)
0.
Chemical isospin potential per unit charge, fMuI3 [GeV]
-0.001
Temperature at thermal freeze-out, fTthFO [GeV]
0.1
Chemical potential of pi+ at thermal freeze-out, fMu_th_pip [GeV]
0.06
Proper time proper at thermal freeze-out for central collisions, fTau [fm/c]
8.
Duration of emission at thermal freeze-out for central collisions, fSigmaTau [fm/c]
2.
Maximal transverse radius at thermal freeze-out for central collisions, fR [fm]
10.
Maximal longitudinal flow rapidity at thermal freeze-out, fYlmax
3.3
Maximal transverse flow rapidity at thermal freeze-out for central collisions, fUmax
1.1
Momentum azimuthal anizotropy parameter at thermal freeze-out, fDelta
0.1
Spatial azimuthal anisotropy parameter at thermal freeze-out, fEpsilon
0.05
Flag to specify fDelta and fEpsilon values, fIfDeltaEpsilon (=0 user's ones, >=1 calculated)
0.
Flag to switch on/off hadron decays, fDecay (=0 decays off, >=1 decays on)
1.
Low decay width threshold fWeakDecay[GeV]: width<fWeakDecay decay off, width>=fDecayWidth decay on; can be used to switch off weak decays
0.
Flag to choose rapidity distribution, fEtaType (=0 uniform, >0 Gaussian with the dispersion Ylmax)
1.
Flag to use calculated T_ch, mu_B and mu_S as a function of fSqrtS, fTMuType (=0 user's ones, >0 calculated)
0.
Strangeness supression factor gamma_s with fCorrS value (0<fCorrS <=1, if fCorrS <= 0., then it will be calculated)
1.
Flag to include statistical charm productio, fIcharm (=0 no charm production, >=1 charm production)
0
Flag to include jet (J)/jet quenching (JQ) and hydro (H) state production, fNhsel (0 H on & J off, 1 H/J on & JQ off, 2 H/J/HQ on, 3 J on & H/JQ off, 4 H off & J/JQ on)
2
Flag to suppress the output of particle history from PYTHIA, fIedit (=1 only final state particles; =0 full particle history from PYTHIA)
1
Flag to switch on/off nuclear shadowing, fIshad (0 shadowing off, 1 shadowing on)
1
Minimal pt of parton-parton scattering in PYTHIA event, fPtmin [GeV/c]
3.4
Initial QGP temperature for central Pb+Pb collisions in mid-rapidity, fT0 [GeV]
0.3
Proper QGP formation time in fm/c, fTau0 (0.01<fTau0<10)
0.4
Number of active quark flavours in QGP, fNf (0, 1, 2 or 3)
2
Flag to fix type of partonic energy loss, fIenglu (0 radiative and collisional loss, 1 radiative loss only, 2 collisional loss only)
0
Flag to fix type of angular distribution of in-medium emitted gluons, fIanglu (0 small-angular, 1 wide-angular, 2 collinear).
0
```

7 input parameters;
19 free model parameters
(may be reduced to 13) +
PYTHIA parameters;
12 flags.

RunInputHydjetLHC5500

(input parameter file for Pb+Pb collisions at LHC, *default*)

```
Number of events to generate
10
C.m.s. energy per nucleon pair, fSqrtS [GeV]
5500.
Atomic weigth of nuclei, fAw
207.
Flag of type of centrality generation, fBfix (=0 is fixed by fBfix, >0 distributed [fBfmin, fBmax])
1
Minimum impact parameter in units of nuclear radius, fBmin
0.
Maximum impact parameter in units of nuclear radius, fBmax
0.57
Fixed impact parameter in units of nuclear radius, fBfix
0.
Parameter to set random number seed, fSeed (=0 the current time is used, >0 the value fSeed is used)
0
Temperature at chemical freeze-out, fT [GeV]
0.170
Chemical baryon potential per unit charge, fMuB [GeV]
0.
Chemical strangeness potential per unit charge, fMuS [GeV]
0.
Chemical charm potential per unit charge, fMuC [GeV] (used if charm production is turned on)
0.
Chemical isospin potential per unit charge, fMuI3 [GeV]
0.
Temperature at thermal freeze-out, fTthFO [GeV]
0.13
Chemical potential of pi+ at thermal freeze-out, fMu_th_pip [GeV]
0.
Proper time proper at thermal freeze-out for central collisions, fTau [fm/c]
10.
Duration of emission at thermal freeze-out for central collisions, fSigmaTau [fm/c]
3.
Maximal transverse radius at thermal freeze-out for central collisions, fR [fm]
11.
Maximal longitudinal flow rapidity at thermal freeze-out, fYlmax
4.
Maximal transverse flow rapidity at thermal freeze-out for central collisions, fUmax
1.1
Momentum azimuthal anizotropy parameter at thermal freeze-out, fDelta
0.1
Spatial azimuthal anisotropy parameter at thermal freeze-out, fEpsilon
0.05
Flag to specify fDelta and fEpsilon values, fIfDeltaEpsilon (=0 user's ones, >=1 calculated)
0.
Flag to switch on/off hadron decays, fDecay (=0 decays off, >=1 decays on)
1.
Low decay width threshold fWeakDecay[GeV]: width<fWeakDecay decay off, width>=fDecayWidth decay on; can be used to switch off weak decays
0.
Flag to choose rapidity distribution, fEtaType (=0 uniform, >0 Gaussian with the dispersion Ylmax)
1.
Flag to use calculated T_ch, mu_B and mu_S as a function of fSqrtS, fTMuType (=0 user's ones, >0 calculated)
0.
Strangeness supression factor gamma_s with fCorrS value (0<fCorrS <=1, if fCorrS <= 0., then it will be calculated)
1.
Flag to include thermal charm production, fIcharm (=0 no charm production, >=1 charm production)
0.
Flag to include jet (J)/jet quenching (JQ) and hydro (H) state production, fNhsel (0 H on & J off, 1 H/J on & JQ off, 2 H/J/HQ on, 3 J on & H/JQ off, 4 H off & J/JQ on)
2
Flag to suppress the output of particle history from PYTHIA, fIedit (=1 only final state particles; =0 full particle history from PYTHIA)
1
Flag to switch on/off nuclear shadowing, fIshad (0 shadowing off, 1 shadowing on)
1
Minimal pt of parton-parton scattering in PYTHIA event, fPtmin [GeV/c]
7.
Initial QGP temperature for central Pb+Pb collisions in mid-rapidity, fT0 [GeV]
0.8
Proper QGP formation time in fm/c, fTau0 (0.01<fTau0<10)
0.1
Number of active quark flavours in QGP, fNf (0, 1, 2 or 3)
0
Flag to fixe type of partonic energy loss, fIenglu (0 radiative and collisional loss, 1 radiative loss only, 2 collisional loss only)
0
Flag to fix type of angular distribution of in-medium emitted gluons, fIanglu (0 small-angular, 1 wide-angular, 2 collinear).
0
```

7 input parameters;
19 free model parameters
(may be reduced to 13) +
PYTHIA parameters;
12 flags.

RunOutput.root

(tree structure)

```
td->Branch("nev",&nev,"nev/I");                     // event number
td->Branch("Bgen",&Bgen,"Bgen/F");                  // generated impact parameter
td->Branch("Sigin",&Sigin,"Sigin/F");               // total inelastic NN cross section
td->Branch("Sigjet",&Sigjet,"Sigjet/F");            // hard scattering NN cross section
td->Branch("Ntot",&Ntot,"Ntot/I");                  // total event multiplicity
td->Branch("Nhyd",&Nhyd,"Nhyd/I");                  // multiplicity of hydro-induced particles
td->Branch("Npyt",&Npyt,"Npyt/I");                  // multiplicity of jet-induced particles
td->Branch("Njet",&Njet,"Njet/I");                  // number of hard parton-parton scatterings
td->Branch("Nbcol",&Nbcol,"Nbcol/I");               // mean number of NN sub-collisions
td->Branch("Npart",&Npart,"Npart/I");               // mean number of nucleon-participants
td->Branch("Px",&Px[0],"Px[npart]/F");              // x-component of the momentum, in GeV/c
td->Branch("Py",&Py[0],"Py[npart]/F");              // y-component of the momentum, in GeV/c
td->Branch("Pz",&Pz[0],"Pz[npart]/F");              // z-component of the momentum, in GeV/c
td->Branch("E",&E[0],"E[npart]/F");                 // energy, in GeV
td->Branch("X",&X[0],"X[npart]/F");                 // x-coordinate at emission point, in fm
td->Branch("Y",&Y[0],"Y[npart]/F");                 // y-coordinate at emission point, in fm
td->Branch("Z",&Z[0],"Z[npart]/F");                 // z-coordinate at emission point, in fm
td->Branch("T",&T[0],"T[npart]/F");                 // proper time of particle emission, in fm/c
td->Branch("pdg",&pdg[0],"pdg[npart]/I");           // Geant particle code
td->Branch("Mpdg",&Mpdg[0],"Mpdg[npart]/I"); // Geant code of mothers  (-1 for primordials)
td->Branch("type",&type[0],"type[npart]/I")            // particle origin (=0 – from hydro,  >0 – jets)
td->Branch("Index",&Index[0],"Index[Ntot]/I");      // unique zero based index of the particle
td->Branch("MotherIndex",&MotherIndex[0],"MotherIndex[Ntot]/I");   // index of mother (-1 for primordials)
td->Branch("NDaughters",&NDaughters[0],"NDaughters[Ntot]/I"); // number of daughters
td->Branch("FirstDaughterIndex",&FirstDaughterIndex[0],"FirstDaughterIndex[Ntot]/I"); // index of first daughter
td->Branch("LastDaughterIndex",&LastDaughterIndex[0],"LastDaughterIndex[Ntot]/I"); // index of last daughter
td->Branch("pythiaStatus",&pythiaStatus[0],"pythiaStatus[Ntot]/I");  // PYTHIA status code (-1 for hydro)
td->Branch("final",&final[0],"final[Ntot]/I");  // an integer branch: =1 for final particles, =0 for decayed particles
```

HYDJET++ version 2.1 (update note)

Version 2.1 is completed in September 2009

1. Option to get output from full particle history for PYTHIA/PYQUEN generated particles (including partons and strings) is introduced.
It is controlled by the new flag:
fIedit=1 - only final state particles are presented in event output,
fIedit=0 - full particle history from PYTHIA/PYQUEN is produced.
By default the full particle history is not produced, fIedit(D=1).

2. Option to produce thermal charmed particles (J/ψ and D mesons) is introduced. Total number of c-quarks is calculated with PYTHIA, and then thermal charmed hadrons are generated within the statistical hadronization model.
It is controlled by the new flag:
fIcharm=0 - thermal charm production is switched off,
fIcharm>=1 - thermal charm production is switched on),
By default thermal charmed particle production is switched off fIcharm(D=1).
The new input parameter fMuC (chemical charm potential) is introduced.

3. A number of technical improvements and bug fixing are implemented.

HYDJET++: elliptic flow at RHIC

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