Recent developments on HYDJET and PYQUEN event generators and novel jet quenching observables at the LHC

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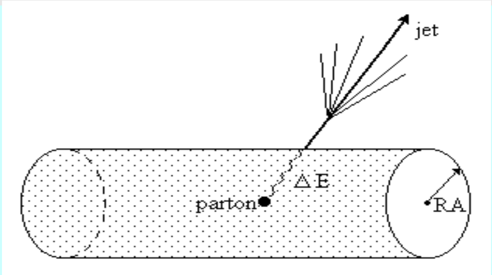
- Current status and versioning of PYQUEN and HYDJET
- Recent progress on simulating soft hadron spectra (FAST MC), its validation at RHIC
- Examples of novel jet quenching observables in heavy ion collisons at LHC with HYDJET/PYQUEN
- Summary and outlook

Jet quenching: medium tomography



Collisional loss

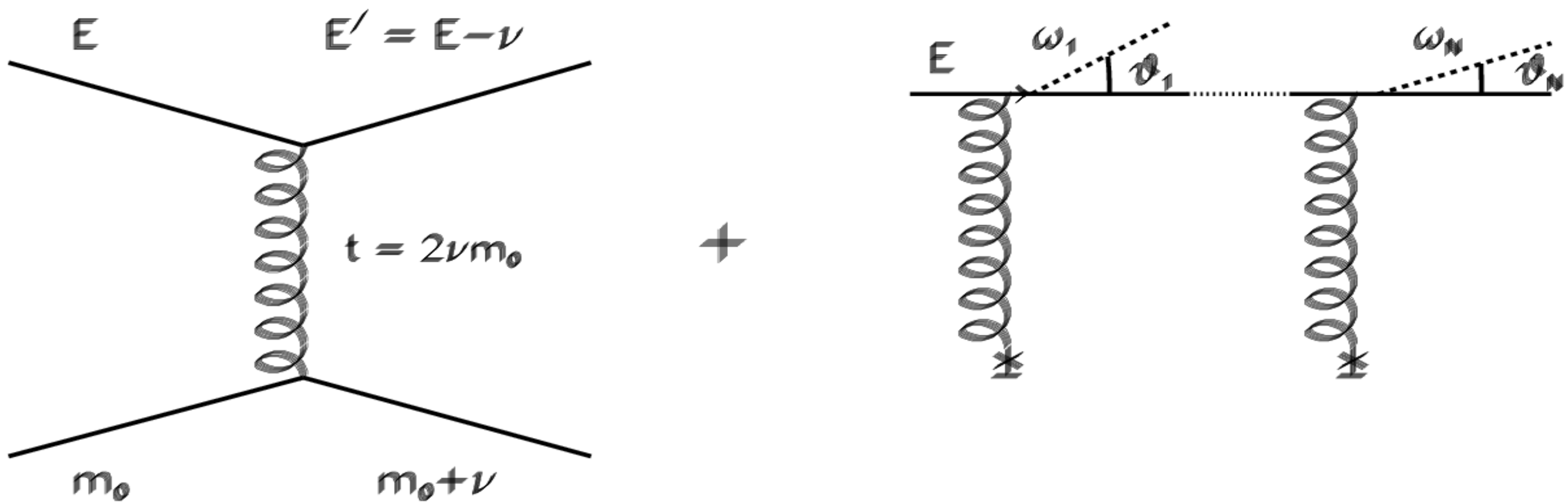
(incoherent sum over scatterings?)

Bjorken; Mrowzinski; Thoma; Markov; Mustafa et al...

Radiation loss

(coherent LPM interference)

Gylassy-Wang; BDMPS; GLV; Zakharov; ASW; AdS CFT,...



Current status of PYQUEN and HYDJET

- PYQUEN - medium-induced partonic energy loss model (modifies PYTHIA6.4 jet event), http://cern.ch/lokhtin/pyquen
- HYDJET - merging soft part (nuclear collective flow phenomena) and multijets generated with PYQUEN, http://cern.ch/lokhtin/hydro/hydjet.html

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HYDJET reproduces RHIC data on high-p_T hadron spectra and can be used for LHC energies.

HYDJET/PYQUEN are included in common LHC generator database GENSER. At this moment HYDJET/PYQUEN are basic MC tools for HI analysis in CMS. As far as I know, they are also included in software of ALICE and ATLAS.

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):

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

“dead cone” approximation for massive quarks:

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

Angular spectrum of gluon radiation

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

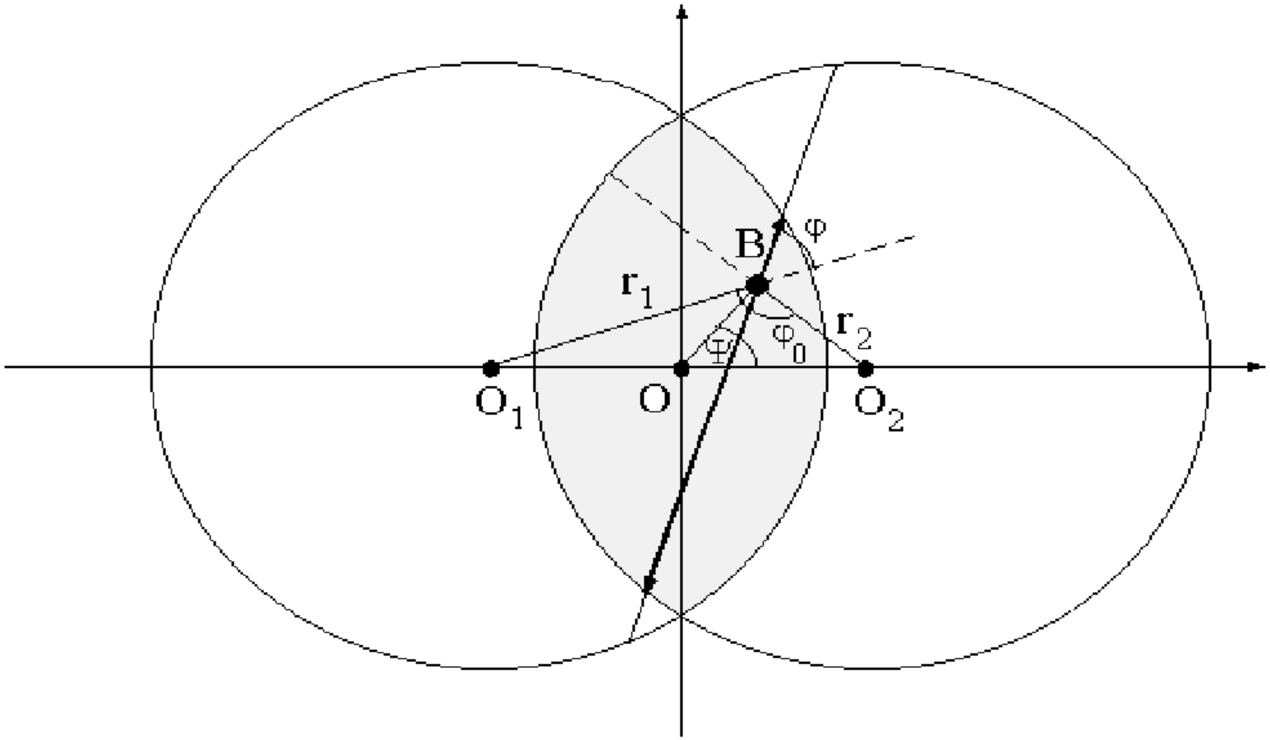
Collinear radiation $\theta = 0$

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

Nuclear geometry and QGP evolution

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



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

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

$$\frac{dN}{d\psi\, dr}(b)=\frac{T_A(r_1)T_A(r_2)}{\int\limits_0^{2\pi} d\psi \int\limits_0^{r_{max}} r dr T_A(r_1)T_A(r_2)}$$

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

$$\frac{dP}{dl_i}=\lambda^{-1}(\tau_{i+1})\exp(-\int\limits_0^{l_i}\lambda^{-1}(\tau_i+s)\,ds), \quad \lambda^{-1}=\sigma\rho$$

- Radiative and collisional energy loss per scattering

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

- Transverse momentum kick per scattering

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

PYQUEN (PYthia QUENched)

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

↓

Hard parton rescattering and energy loss + emitted gluons
PYQUEN rearranges partons to update ns strings: ns call PYJOIN

↓

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

Simple (but fast) model for HYDRO flow

The final hadron spectrum 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

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

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

3. Boost of hadron 4-momentum p_μ in c.m. frame of the event

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

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

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

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

HYDJET (HYDrodynamics + JETs)

generates njet (b, ptmin) NN subcollisions and formation of jet-induced state by calling (PYTHIA+PYQUEN) njet times

↓

filling HYJETS arrays with npyt lines (hard event part)

↓

generation of HYDRO-induced particles (soft part) with multiplicity nhyd, and adding new particles in HYJETS arrays (n=nhyd+npyt)

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<ytfl<3.0, default value is ytfl=1.5)
- ylfl - maximum longitudinal collective rapidity, controls width of η-spectra (0.01<ylfl<7.0, default value is ylfl=4.)
- Tf – hadron freeze-out temperature (0.08 <Tf < 0.2, Tf(default)=0.1 GeV)
- fpart - fraction of multiplicity proportional to # of participants; (1.-fpart) - fraction of multiplicity proportional to # of NN subcollisions (0.0<fpart<1.0, default value is 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 - minimal pt of parton-parton scattering in PYTHIA

Internal sets for soft part

- poison multiplicty distribution
- thermal particle ratios

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
- nbcol - 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/PYQUEN versioning (1.2)

PYQUEN v.1.2 / HYDJET v. 1.2 completed in June 2007.

1) PYQUEN and HYDJET can be used for different beam energies now
(introducing input paramer "energy")

2) Initial parameters of QGP and some energy loss model settings can be specified by user now
(common block "pyqpar")

3) New subroutine HYINIT has been created for HYDJET initialization:

- *PYTHIA initialization at given c.m.s. energy per nucleon pair;*
- *calculation of total inelastic NN cross section at given energy;*
- *calculation of hard scattering NN cross section at given ptmin and energy;*
- *calculation of number of participants & binary collisions at Pb+Pb (b=0).*

HYDJET/PYQUEN versioning (1.3)

PYQUEN v.1.3 / HYDJET v. 1.3 completed in the October 2007.

1) New physics feature of HYDJET1_3: nuclear shadowing correction for parton distributions (important at LHC!)

Impact-parameter dependent parameterization of NS (K.Tywoniuk, I.Arsene, L.Bravina, A.Kaidalov and E.Zabrodin, Phys. Lett. B 657 (2007) 170) is provided by Konrad Tywoniuk from Oslo University. It based on Glauber-Gribov theory for NS (Pomeron diagram sum). Estimated reducing in "hard" multiplicty for central PbPb at 5.5 A TeV up to ~50% due to NS

2) Another physics update: introducing the isospin effect

The probability to have pp, pn or nn hard sub-collision depends on number of protons (Z) and neutrons (A-Z) in the stable nucleus A:

$$Z=A/(1.98+0.015A^{2/3})$$

3) Plus a few technical improvements and bug fixing

HYDJET/PYQUEN versioning (1.4)

PYQUEN v.1.4 / HYDJET v. 1.4 completed in the October 2007.

1) New physics feature of HYDJET1_4 and PYQUEN1_4:
Wood-Saxon nucleon distribution instead of simple hard sphere *(similar results for central AA collisions, some difference for non-central)*

$$\rho(r)=\rho_0(1+\exp((r-R_A))/d)^{-1}, \quad \rho_0=3/((4\pi R_A^3(1+(\pi d/R_A)^2)), \quad d=0.54 \text{ fm}$$

Tabulation of impact parameter dependences of nuclear thickness $T_A(b)$ and nuclear overlap $T_{AA}(b)$ functions is performed in HYINIT & PYQUEN.
The radial profile of energy density in PYQUEN: $\varepsilon(r_1,r_2) \propto T_A(r_1) * T_A(r_2)$
HYDJET1_4: *effect on Npart(b) and Nbcol(b); and also on $\sigma_{in}^{AA}(b)$ for ifb=1*
PYQUEN1_4: *effect on medium-induced v_2; and also on $\sigma_{jet}^{AA}(b)$ for ifb=1*

2) Main technical improvement in HYDJET1_4: transition to "double precision" for all calculations. *One exception is still hold: JETSET arrays in common block LUJETS with output particle information (contains "REAL" copy of original "DP" event record from common block HYJETS). Such copy allows the user to perform easily some useful manipulations with the event record using standard JETSET subroutines and functions (to exclude unstable particles, to list an event, to provide various event data, etc.).*

HYDJET/PYQUEN versioning (1.5)

PYQUEN v.1.5 / HYDJET v. 1.5 completed in the December 2007.

1) *The treatment of hadronization of in-medium emitted gluons in frames of PYTHIA string fragmentation scheme is improved by additional re-ordering of colour connections of such gluons along the string. The appearance of small rapidity asymmetry of hadroproduction coming from PYQUEN-rearranged strings is avoided by such a way.*
   Increasing low-pt hadron multiplicity due to in-medium radiation reduces in this case, but high-pt spectra remain the same.

2) ***The previous sharp rapidity dependence of initial energy density in nuclear overlapping zone is replaced by the smooth (Gaussian-like) distribution. The input parameter T0 has now meaning of the effective initial temperature in central Pb-Pb collisions at mid-rapidity (y=0).***

HYDJET: developments in progress

HYDJET++ (HYDJET&FAST MC) (impact on soft physics)

At this moment, the "private" test version exists. Detailed hydro-type model for soft particle production (including resonance decays, thermal & chemical freeze-outs, etc.) was written in C++ within ROOT framework, and merged with hard part of HYDJET. But different structures of standard (Fortran written) HYDJET and HYDJET++ do not allow one to use both generators by the same way. For hard hadroproduction HYDJET is OK. For soft hadroproduction studies HYDJET++ is preferable, but new way of implementation in LHC software (GENSER) is needed.

Web-page with the first version and documentation to be created soon (hopefully).

FAST MC: fast hadron freeze-out generator

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
- hypersurface represented by a parameterization (Bjorken- or Hubble-like) or a numerical solution of relativistic hydrodynamics
- chemical and kinetic freeze-out temperatures are input model parameters
- decays of hadronic resonances are taken into account
- written within ROOT framework (C++), avaiable for public use at http://uhkm.jinr.ru/
- the model reproduces soft hadroproduction features at RHIC (flows, HBT)

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

- 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

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

FAST MC – input parameters for central collisions

1. Thermodynamic parameters at chemical freeze-out: T^{ch}, $\{\mu_B, \mu_S, \mu_Q\}$.

2. If thermal freeze-out is considered: T^{th}, and μ_π-effective chemical potential of pions at thermal freeze-out (=0 for single freeze-out). .

3. As an option, strangeness suppression $\gamma_S < 1$ (the possibility to use phenomenological parameterization $\gamma_S(T, \mu_B)$ is foreseen).

4. Volume parameters: the freeze-out proper time τ_f and its standard deviation (emission duration) $\Delta\tau_f$, firebal transverse radius R_f.

5. Maximal transverse flow rapidity for Bjorken-like parametrization ρ_u^{max}.

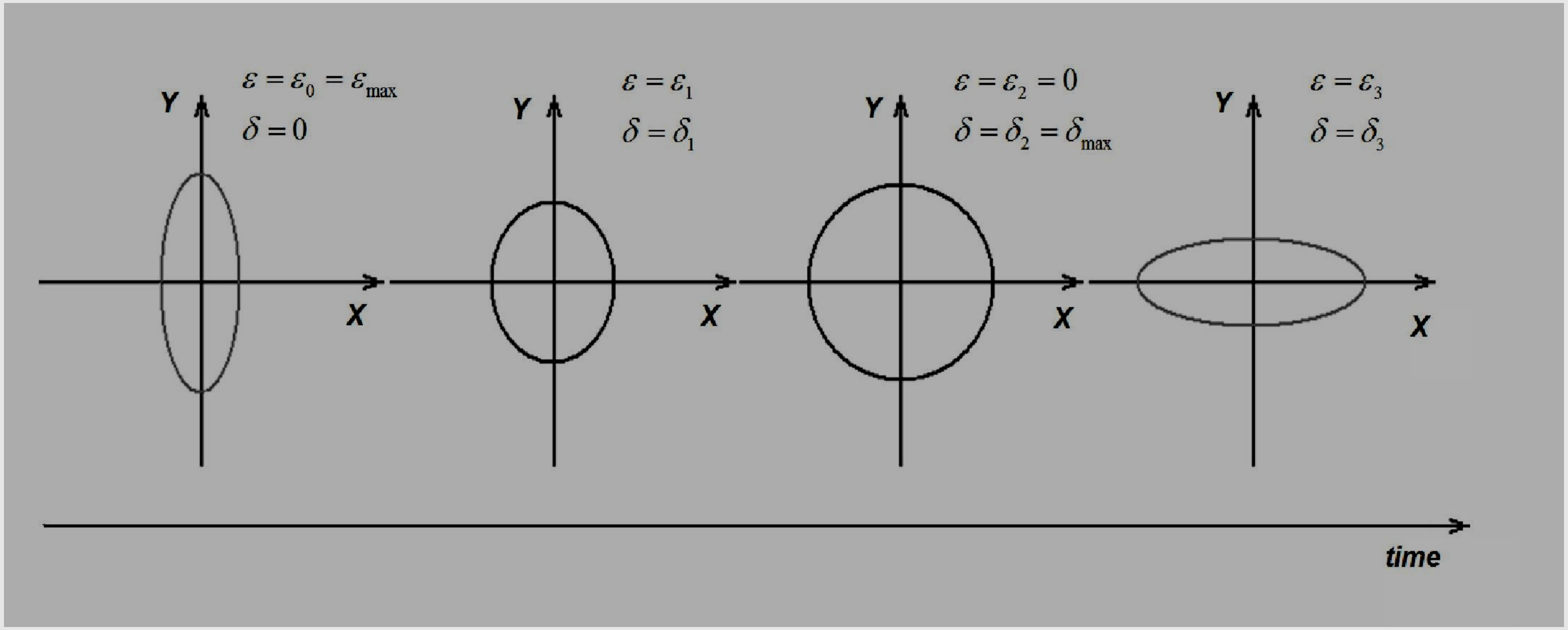
6. Maximal space-time longitudinal flow rapidity η_u^{max}.

7. Option to calculate T and μ_B using phenomenological parameterization $\mu_B(\sqrt{s})$, $T(\mu_B)$ is foreseen.

FAST MC – additional input parameters for non-central collisions

The SAME parameters which are used to simulate central collisions, are used for noncentral collisions at different centralities.
Only two additional parameters are needed for noncentral collisions.

For the impact parameter range: (bmin , bmax)
8. Flow anisotropy parameter: δ(b)
9. Coordinate anisotropy parameter: ε(b)



FAST MC - hadron generation procedure

Initialization of input model parameters

Calculation of Veff 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 accord. 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 two-body, three-body and many-body resonance decays are simulated (resonances – from SHARE table)

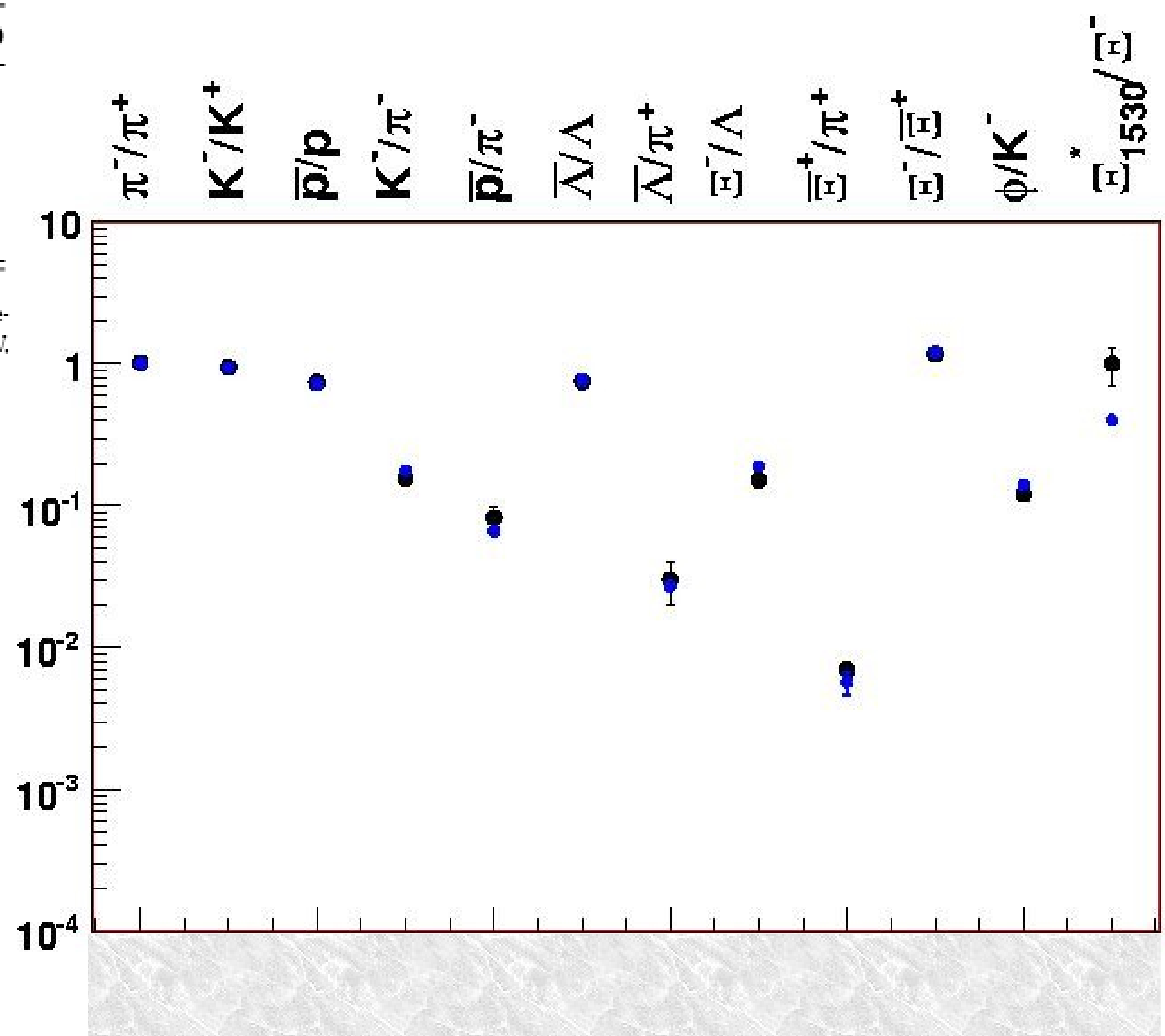
FAST MC – particle ratios at RHIC

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
$\rho_u^{\max}(b=0)$	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 $\sqrt{s_{NN}} = 200 GeV$ for different thermal freeze-out temperatures T^{th} (GeV). Chemical freeze-out parameters are T^{ch} = 0.165 GeV, $\tilde{\mu}_B$ = 0.028GeV, $\tilde{\mu}_S$ = 0.007GeV and $\tilde{\mu}_Q$ = −0.001 GeV.

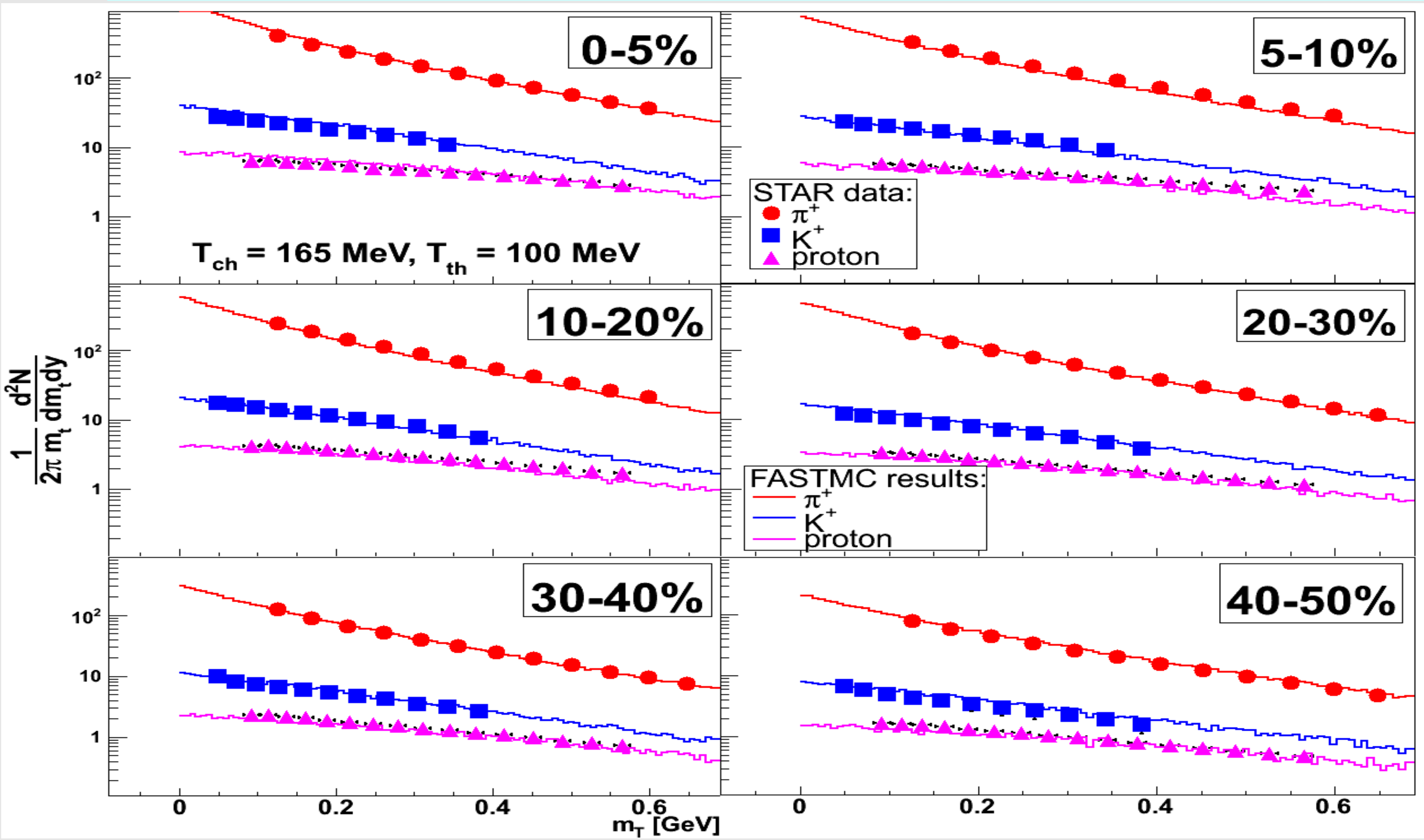
T^{ch}=0.165 GeV μ_B=0.028, μ_S=0.007, μ_Q=-0.001GeV

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



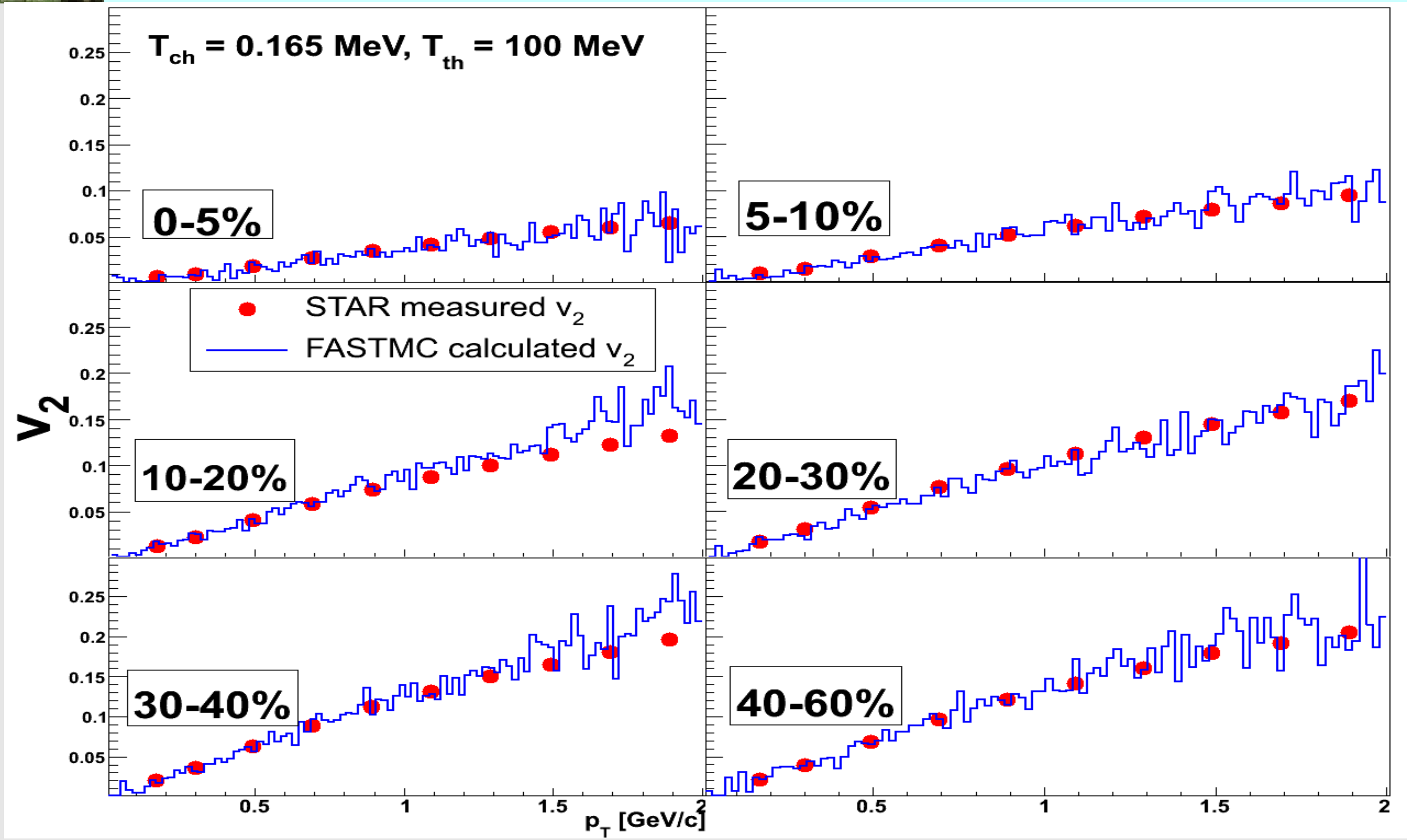
Particle number ratios near mid-rapidity in central Au Au collisions

FAST MC: radial flow at RHIC



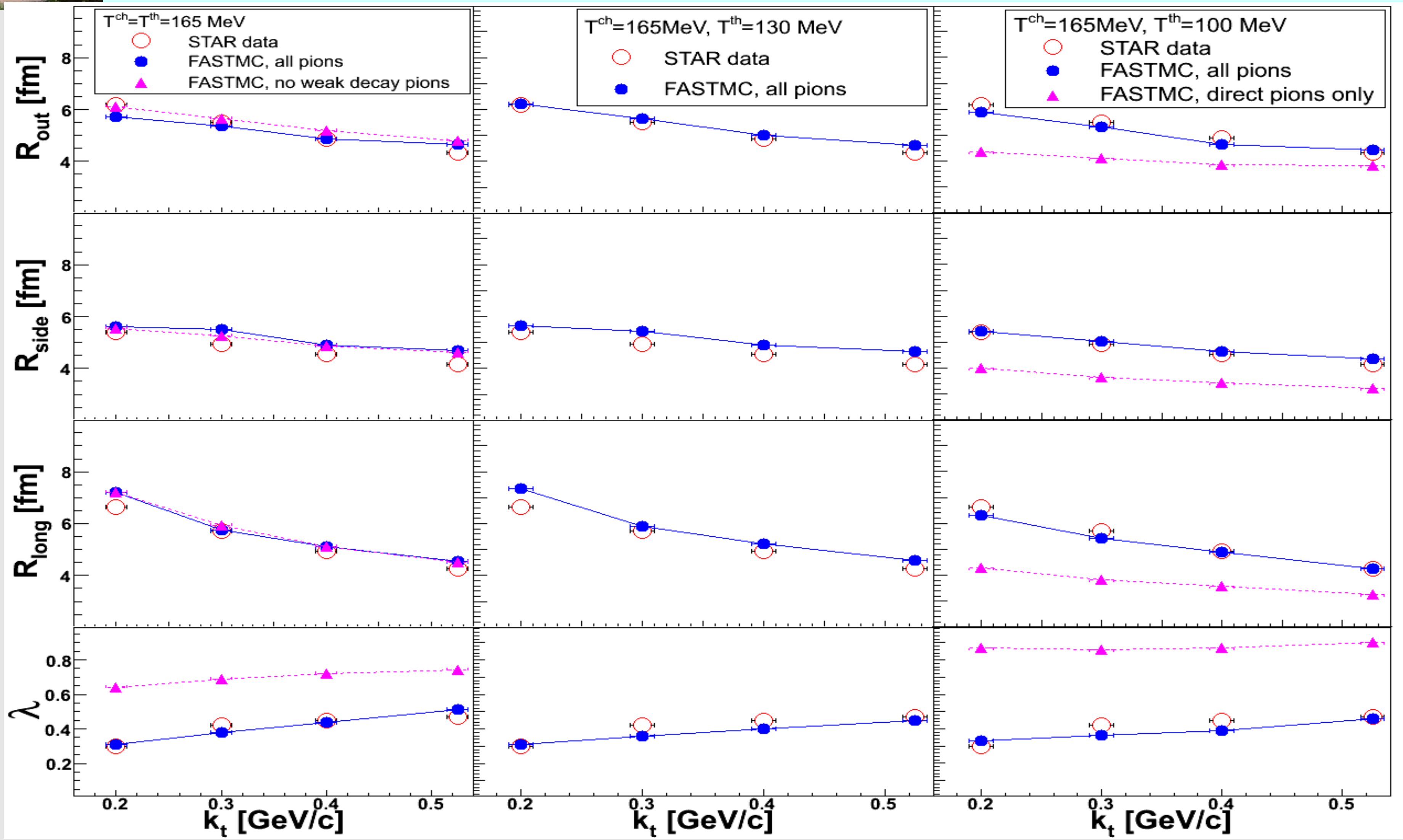
FAST MC: elliptic flow at RHIC

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



FAST MC: momentum correlations

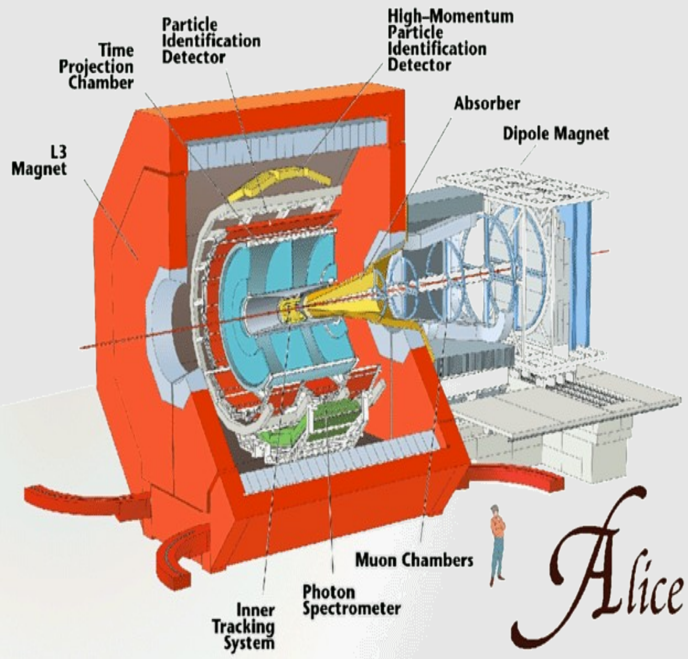
$$CF(p_1, p_2) = 1 + \lambda(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2 - 2R_{out,long}^2 q_{out} q_{long})$$

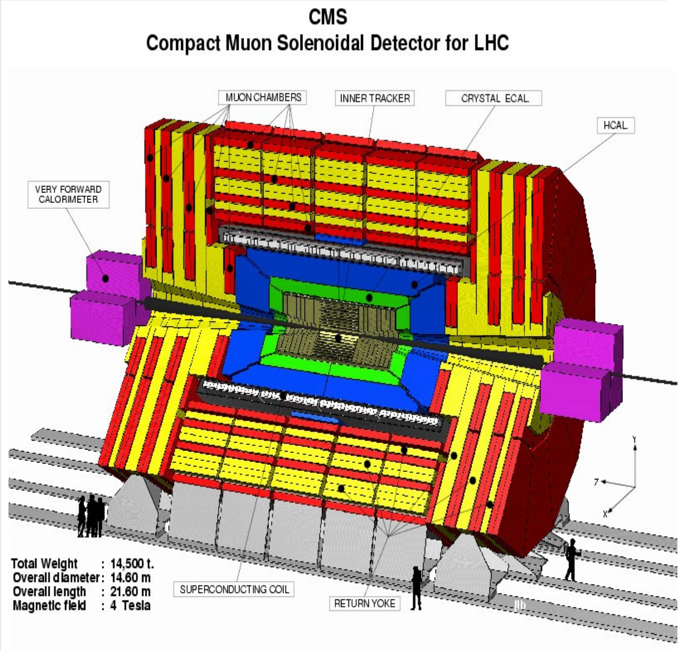


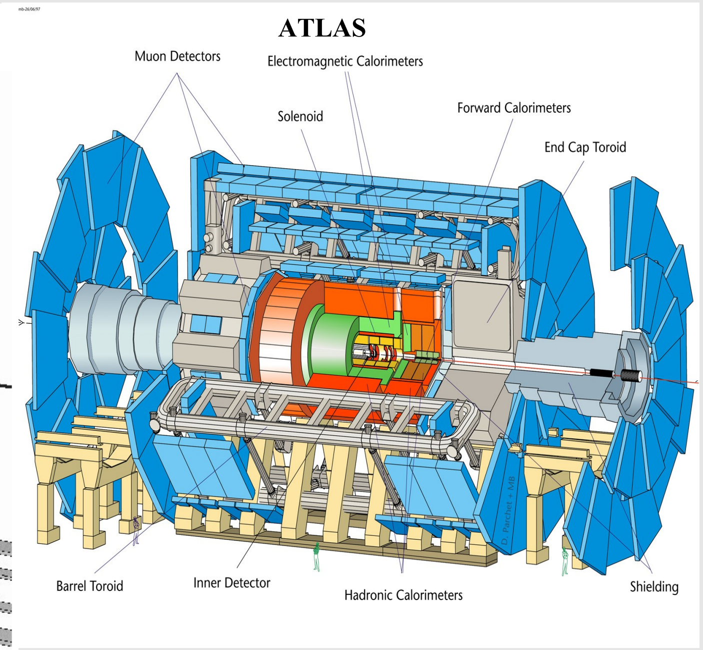
Potential of jet physics at CERN-LHC (Pb+Pb, $\sqrt{s}$ = 5500 A GeV)

New regime of HI physics where hard and semi-hard QCD production dominates over soft "background" and probes hot and long lived QGP

complementary measurements from ALICE & CMS/ATLAS







ALICE (low-pt particle tracking & ID, forward μ (J/ψ, Υ), γ multiplicity,...)
soft probes + selected hard probes

CMS/ATLAS (high-pt particle tracking, central μ (J/ψ, Υ, Z), jets with calorimetry & tracker,...)
hard probes + selected soft probes

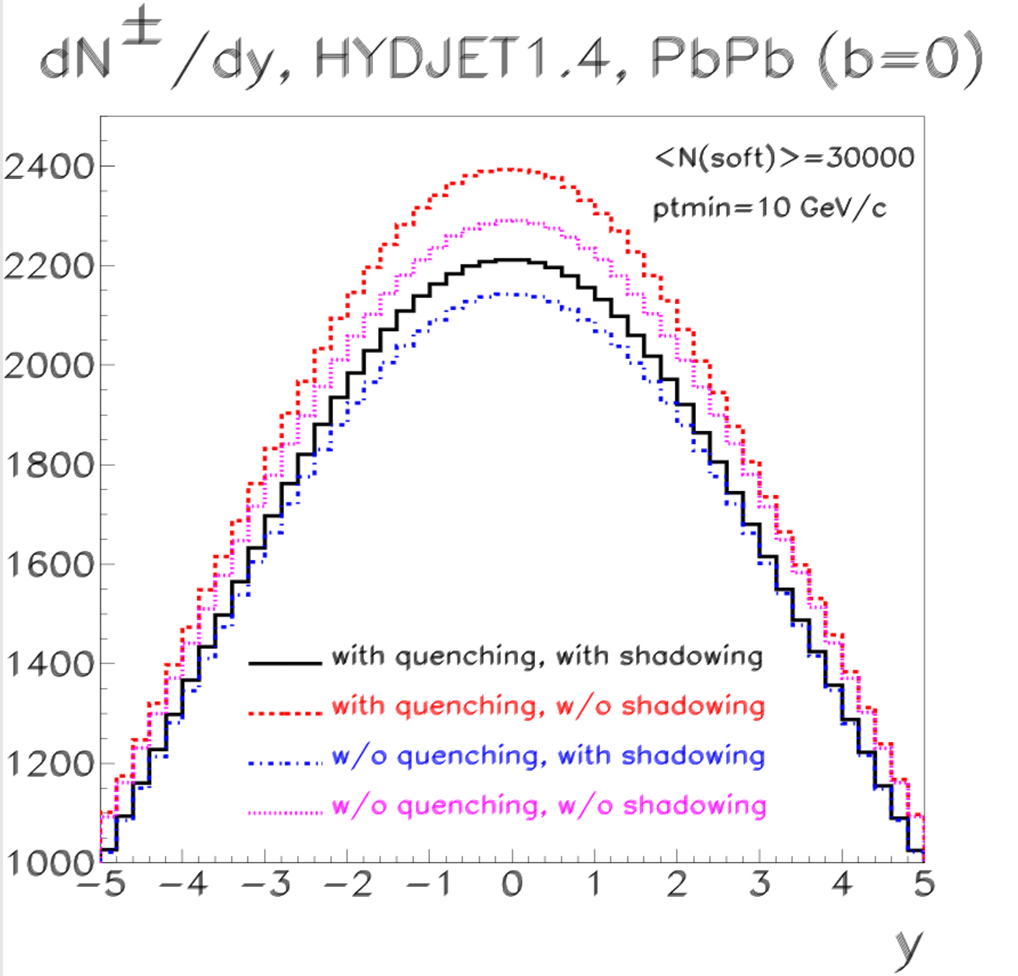
Jet quenching studies at the LHC

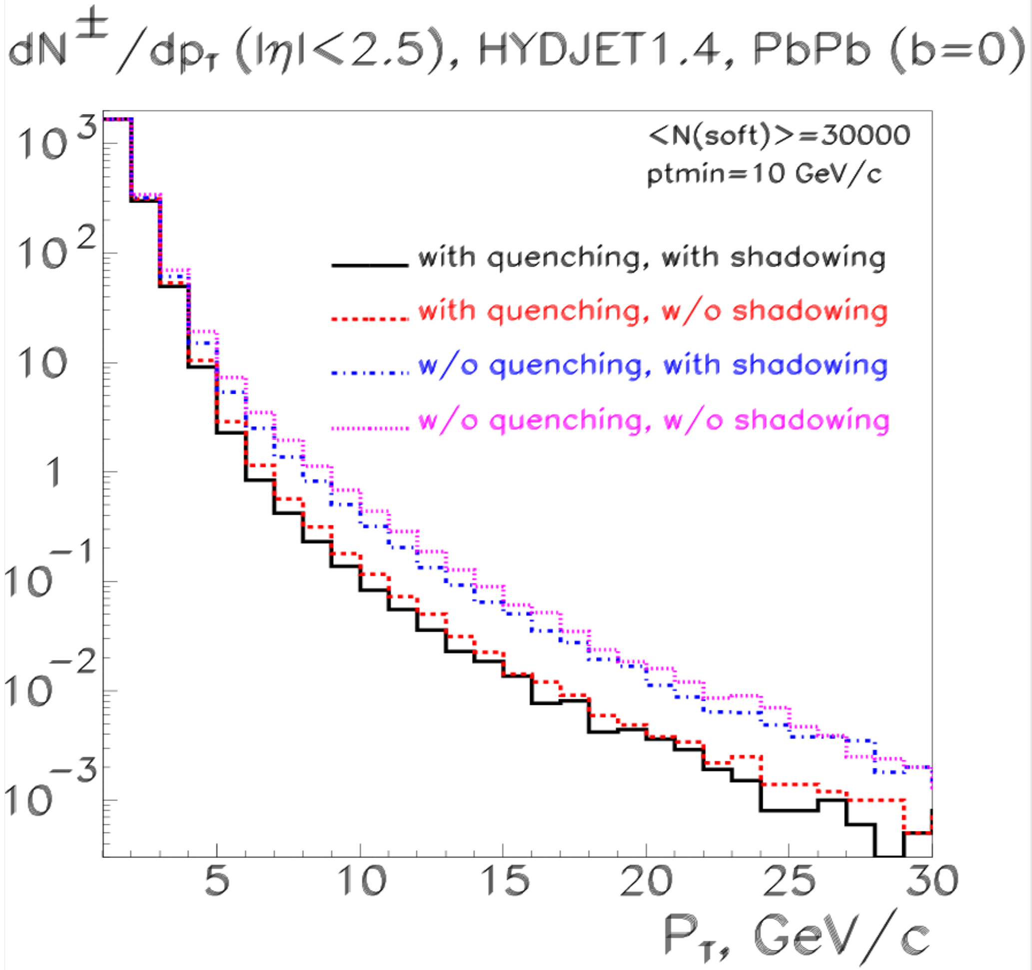
- high-E_T QCD jets
- jets tagged by leading $h^{\pm}, \pi^0$
- B-jets tagged by leading μ
- γ+jet, $\gamma^*/Z(\rightarrow \mu^+\mu^-, e^+e^-)$+jet
- BB, DD $\rightarrow \mu^+\mu^-, e^+e^-$
- high-p_T hadron spectra
- energy flow
- ...

Requires adequate reconstruction:

- jets
- γ/π^0
- charged particle tracking in jets
- muons
- event centrality, event plane
- ...

HYDJET: effect of jet quenching and nuclear shadowing on hadron spectra

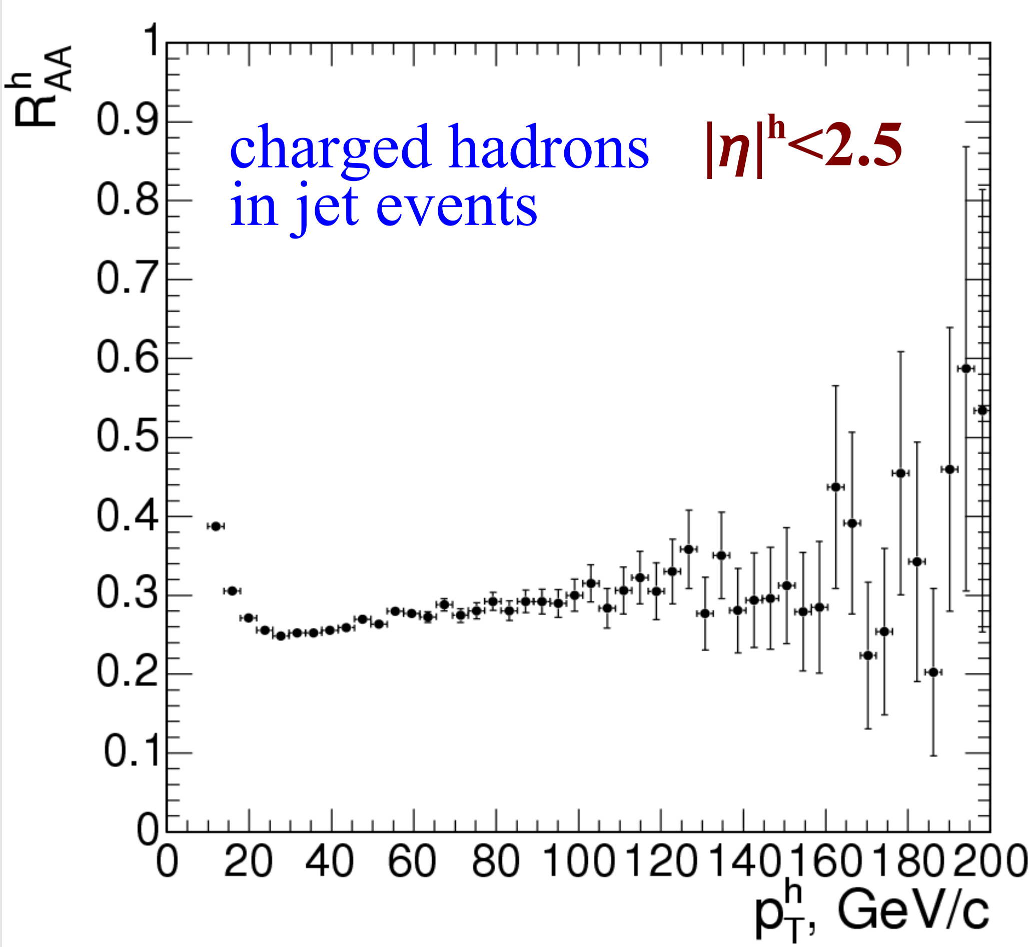


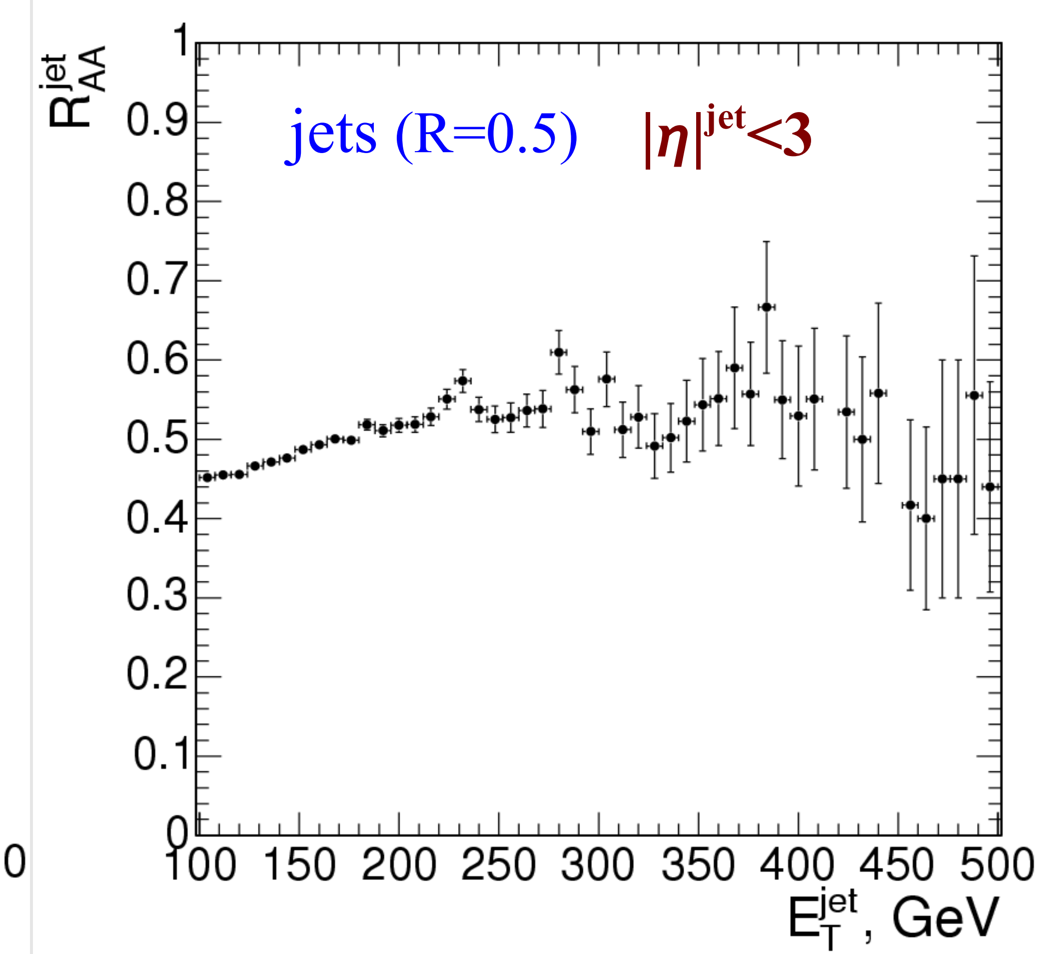


Jet quenching at LHC (example I): jet nuclear modification factor

PYQUEN, Pb+Pb (b=0), $\sqrt{s}$=5.5 A TeV (T_0=1 GeV, τ_0=0.1 fm/c, n_f=0)

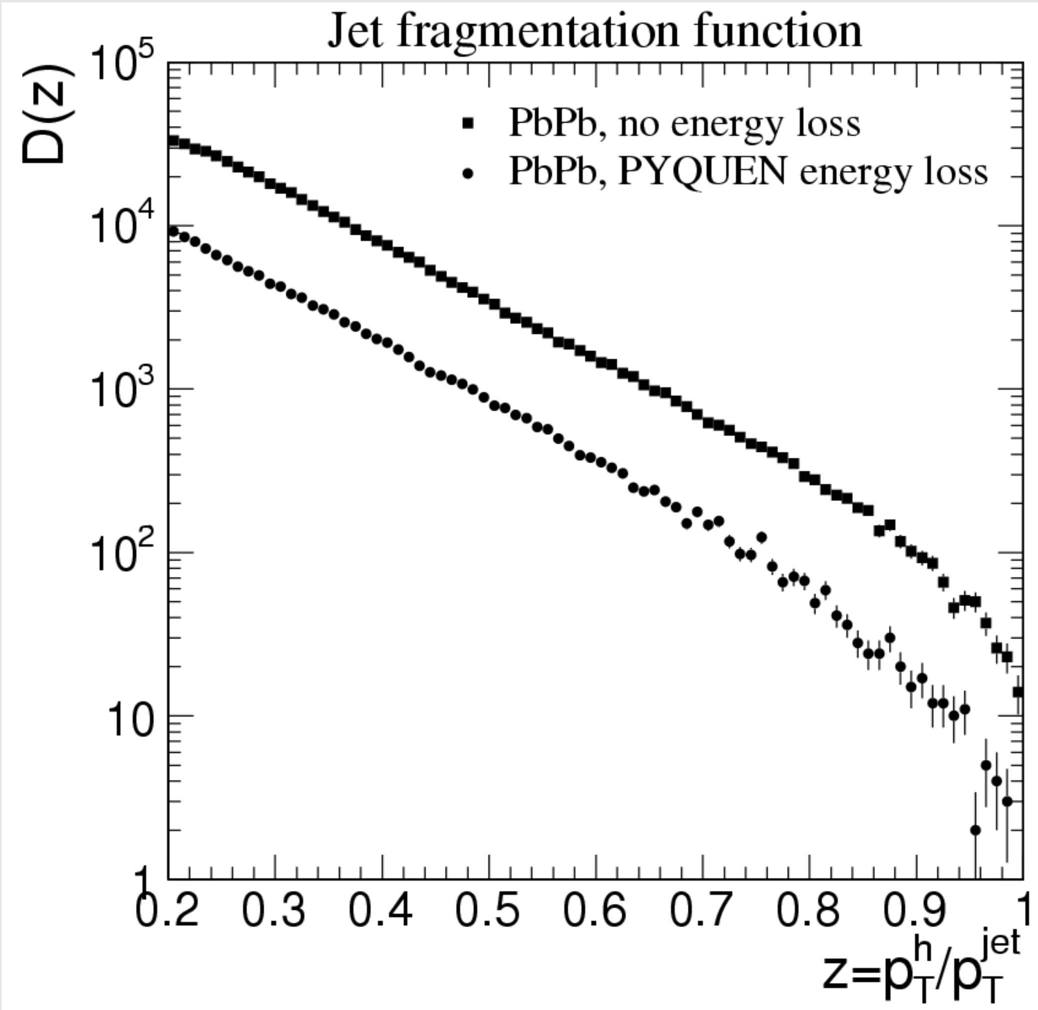
(~10^6 events with E_T^{jet} > 100 GeV is expected for 1 month LHC run, L=0.5 nb^{-1})

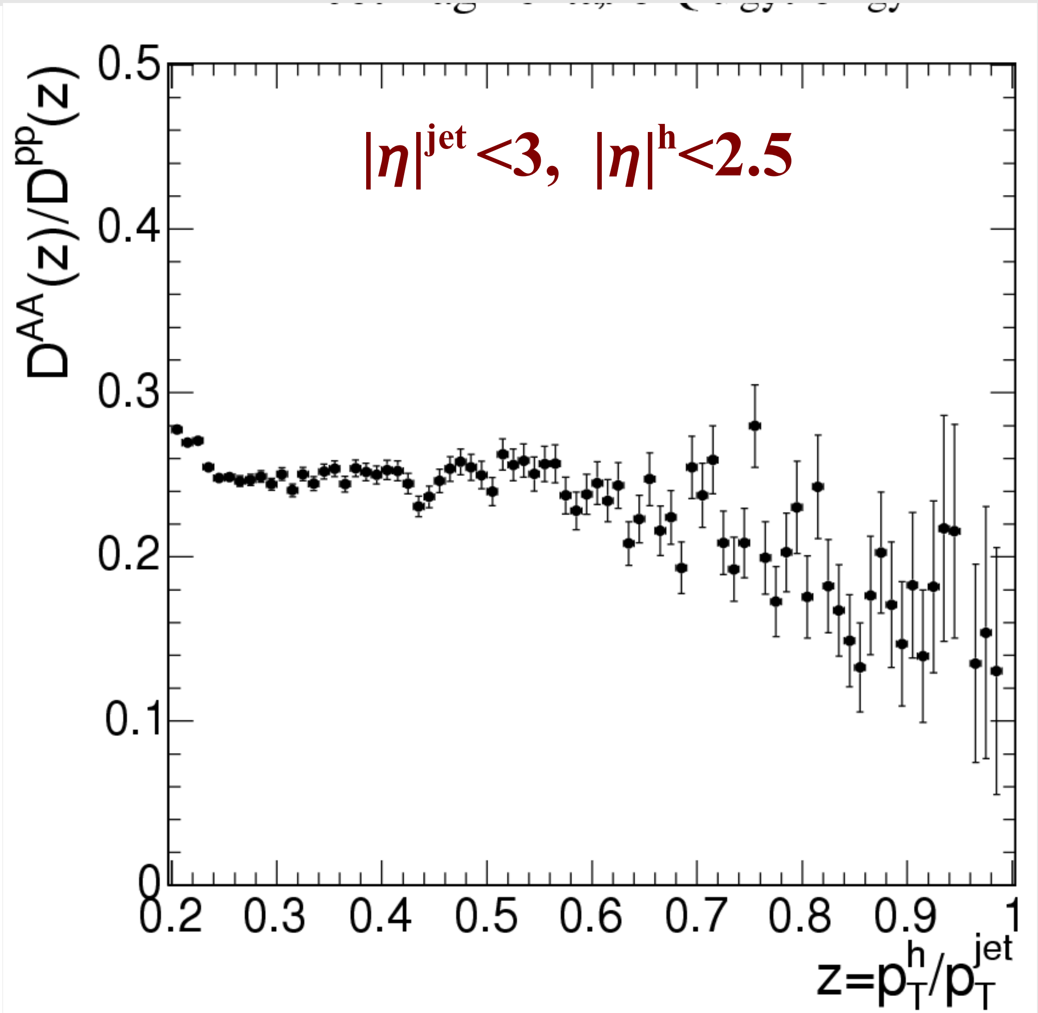




Jet quenching at LHC (example II): jet fragmentation function with leading $h^{\pm,0}$

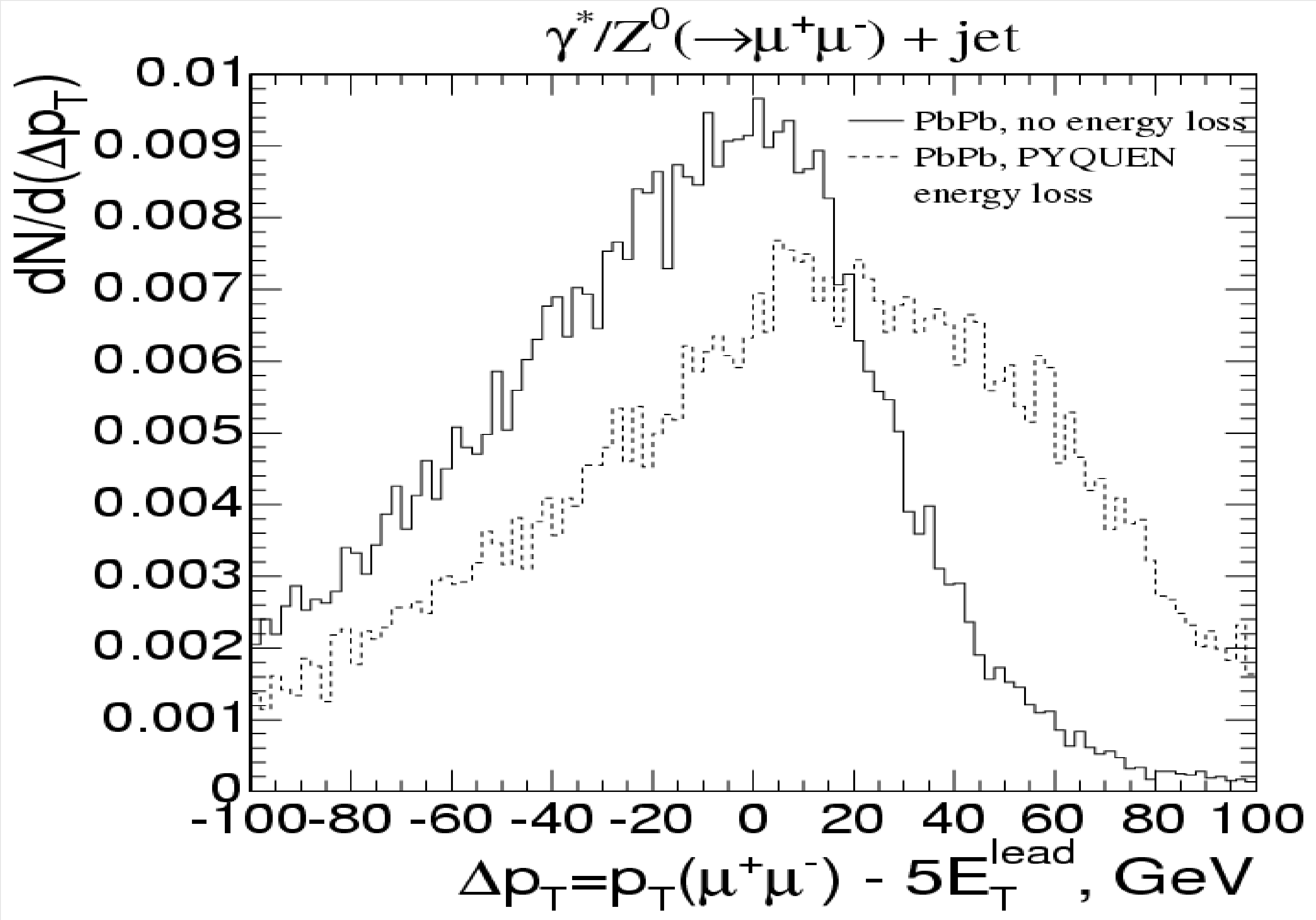
Pb+Pb (b=0), √s=5.5 A TeV, E_T^{jet} > 100 GeV (~0.6 millions unquenched jets with z>0.2 for 1 month LHC run)





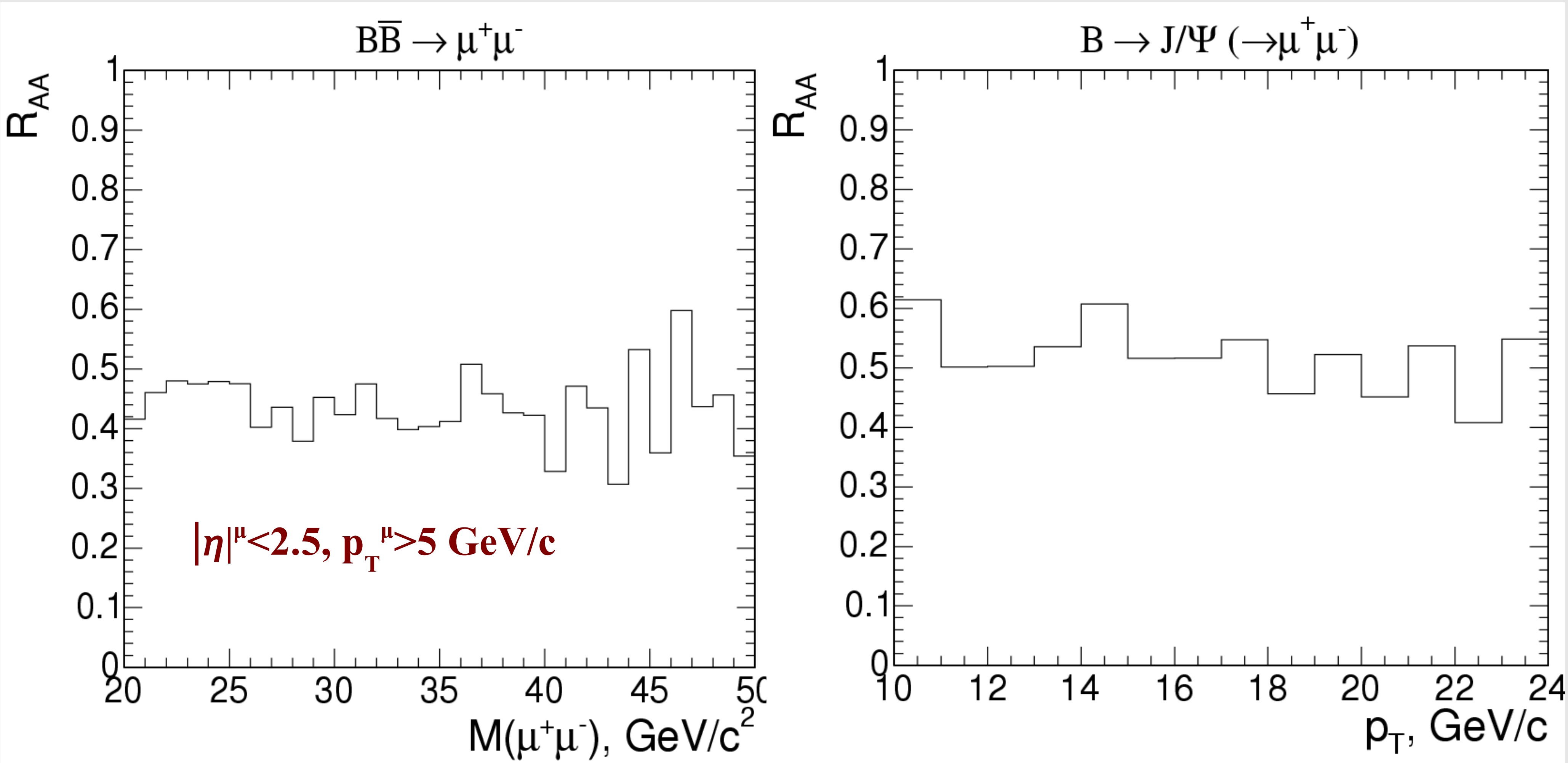
Jet quenching at LHC (example III): p_T-imbalance in $\gamma^*/Z(\rightarrow\mu^+\mu^-)$+jet channel

minimum bias Pb+Pb, $\sqrt{s}$=5.5 A TeV, E_T^{jet},$P_T^{\mu\mu}$>50 GeV (~500 events for 1 month LHC run)

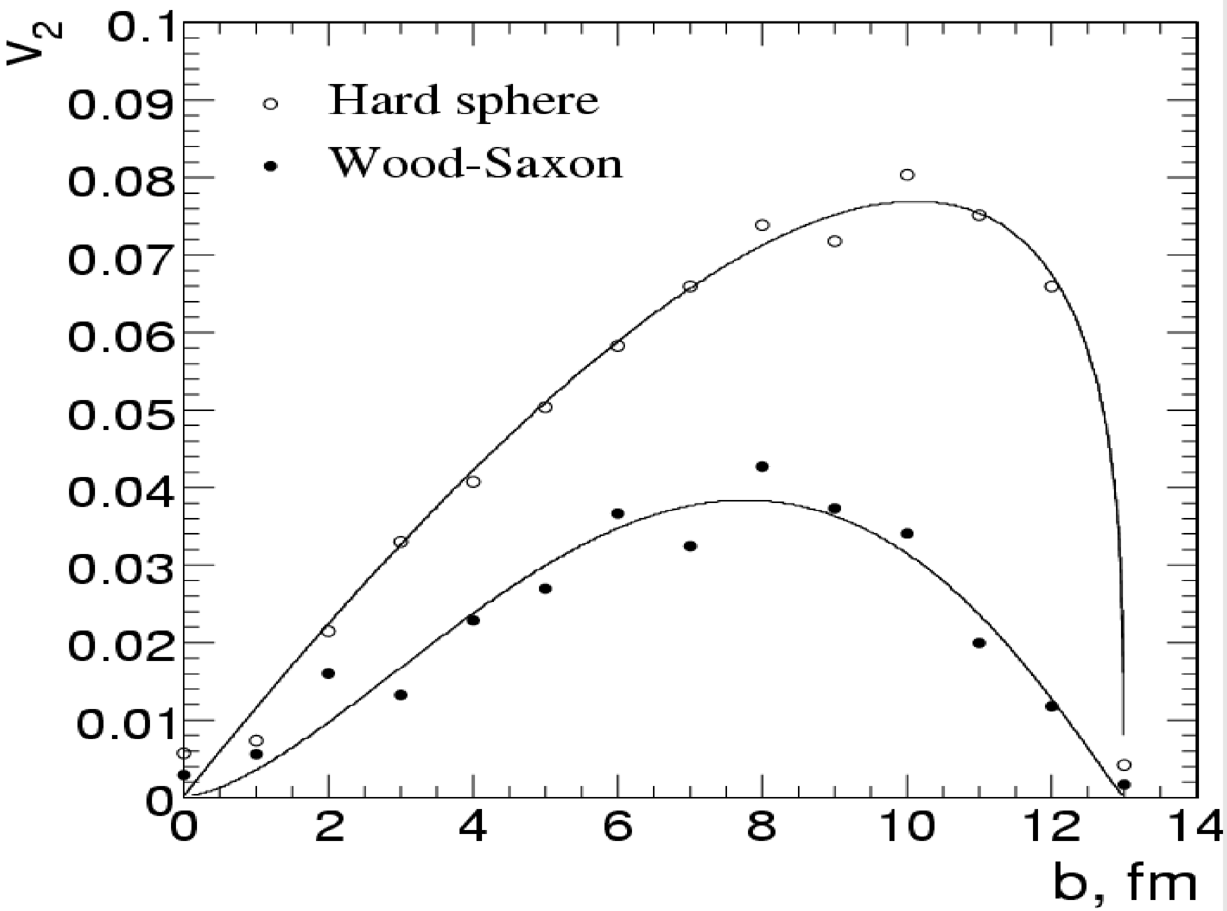


Jet quenching at LHC (example IV): nuclear modification factors for high-mass dimuons and secondary J/ψ

~5x10^4 events for each unquenched channels is expected for 1 month LHC run (with showering b-bbar production)



Jet quenching at LHC (example V): high-p_T azimuthal anisotropy in jet events



Introducing Wood-Saxon nucleon distribution in PYQUEN partonic energy loss model almost does not change azimuthally integrated hadron spectra, but reduces azimuthal anisotropy of high-P_T hadron yield (appearing due to jet quenching).

Impact parameter dependence of elliptic flow coefficient, v_2=<cos(2φ)>, for charged hadrons with p_T>20 GeV/c in jet-triggered PbPb collisions at $\sqrt{s}$=5.5 A TeV.

Summary and outlook

Among other heavy ion event generators (HIJING, DPMJET, PSM, UrQMD, AMPT, THERMINATOR, QGSM, etc.), HYDJET/PYQUEN are concentrated on detailed simulation of jet quenching effect, and also reproducing main features of nuclear collective dynamic (radial and elliptic flow) by fast and simple way. So the final hadron state in HYDJET represents the superposition of hard multi-parton state and soft hydro-type part. The model is capable of reproducing main features of the jet quenching pattern at RHIC and applying to probe dense QCD-matter by jet quenching in various novel channels at LHC.

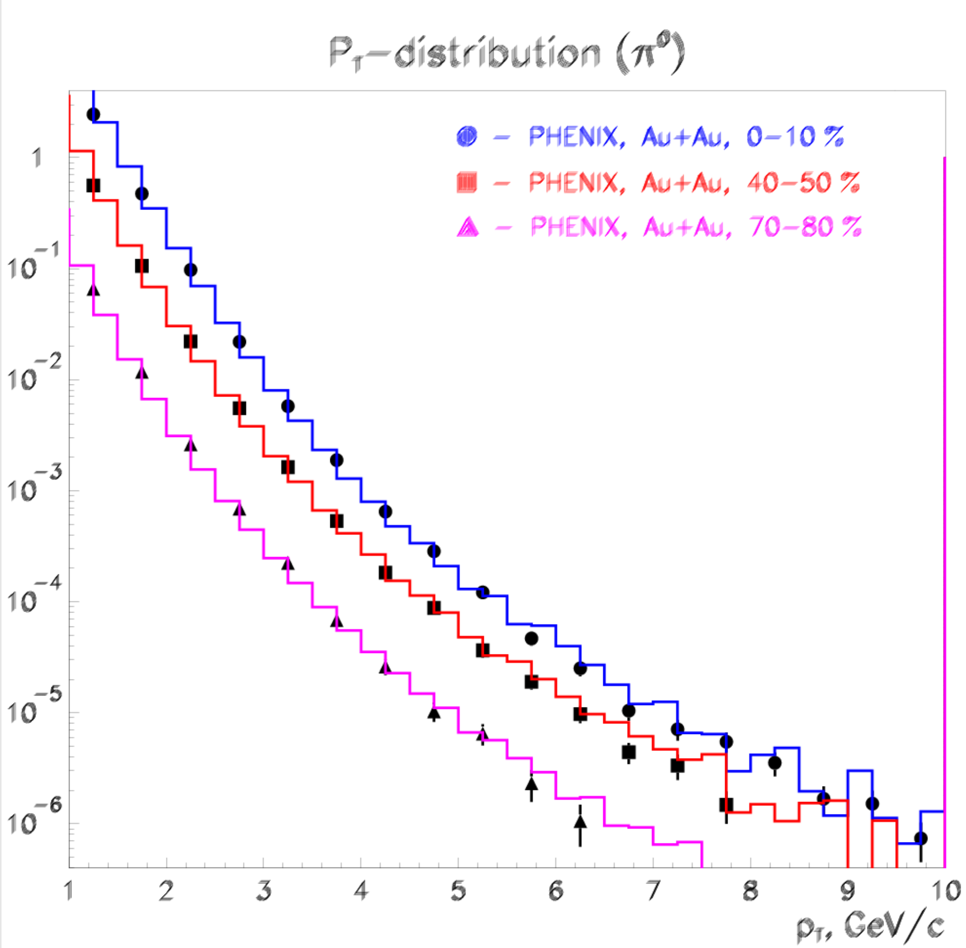
Detailed HYDJET-inspired hydro-type event generator FAST MC for soft hadroproduction (including resonance decays, thermal & chemical freeze-outs, etc.) has been created. It describes well bulk properties of multi-particle system created in HIC at RHIC (particle spectra and ratios, radial and elliptic flow, HBT-correlation). Merging of FAST MC and HYDJET is under way.

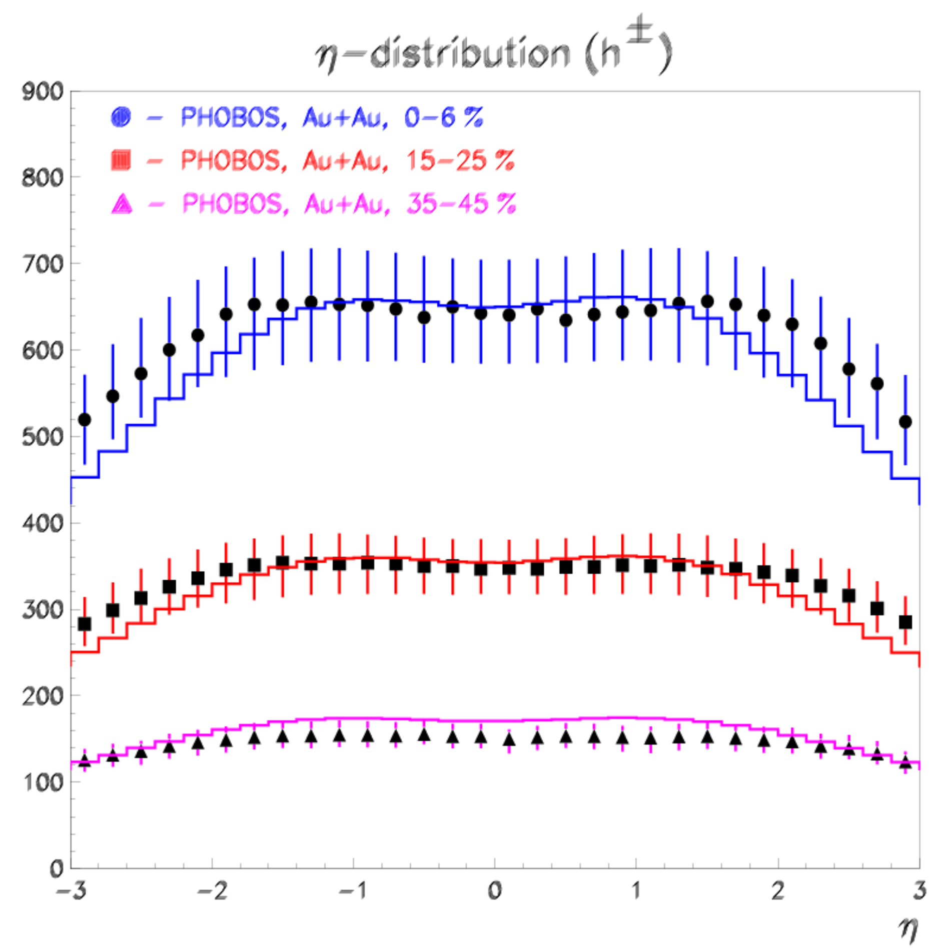
BACKUP SLIDES

Fit RHIC spectra with HYDJET

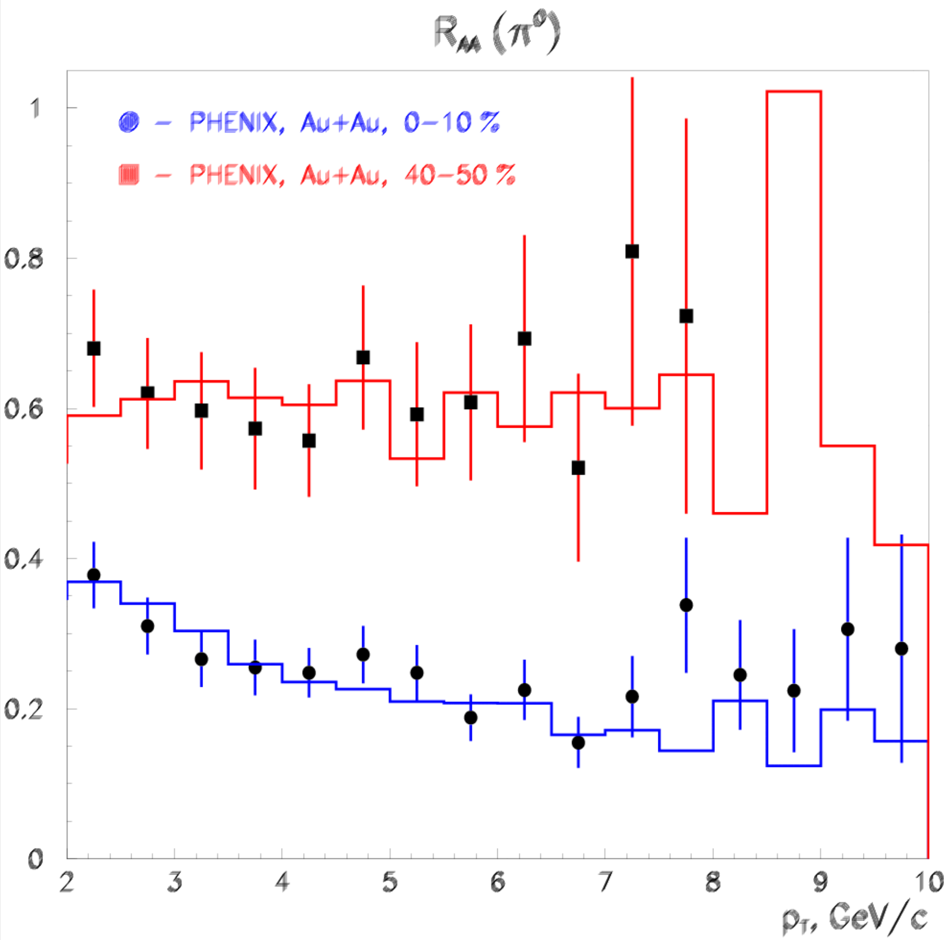
- Fixing multiplicity and Y_l^{max}=3.5 from PHOBOS η-spectra (no K-factor requested for PYTHIA6.4)
- Fixing T_f=100 MeV, Y_T^{max}=1.3 and p_T^{min}=2.6 GeV/c from PHENIX p_T-spectra
- Fixing initial QGP conditions from high-p_T part: T_0=500 MeV, τ_0=0.4 fm/c and n_f=2
- Calculating nuclear modification factor R_{AA} and azimuthal correlation function $C(\Delta\varphi)$

Fit RHIC spectra with HYDJET

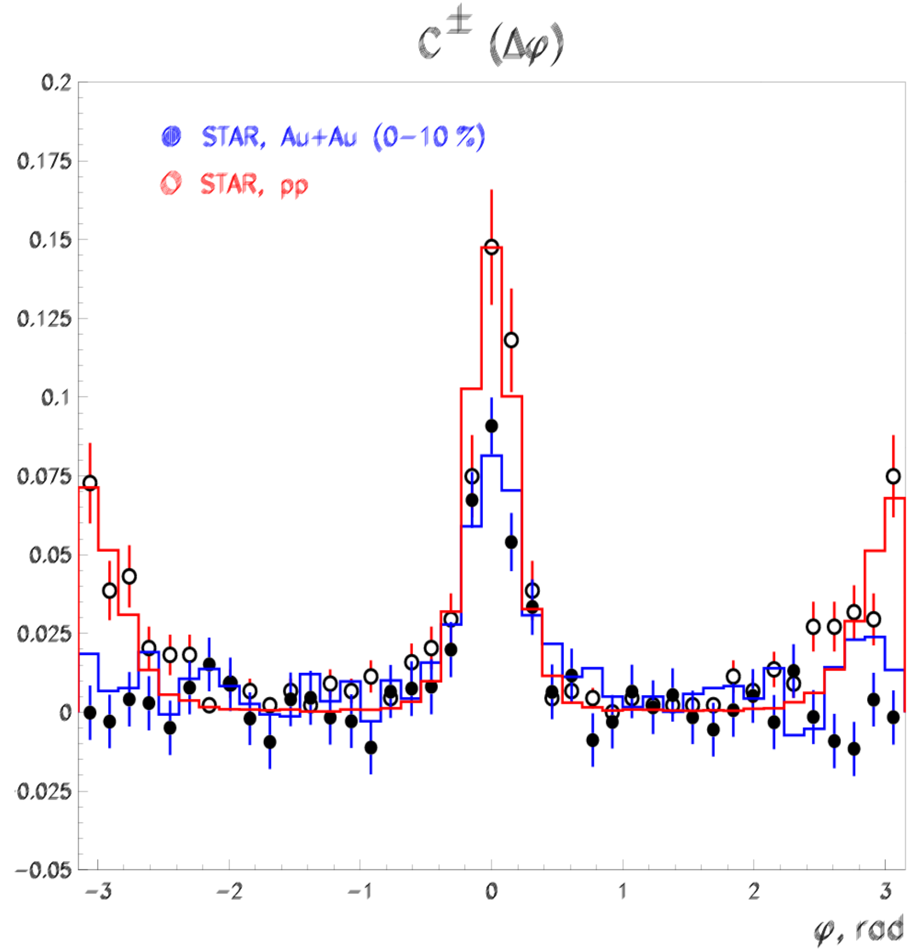




Reproducing jet quenching pattern at RHIC with HYJDET



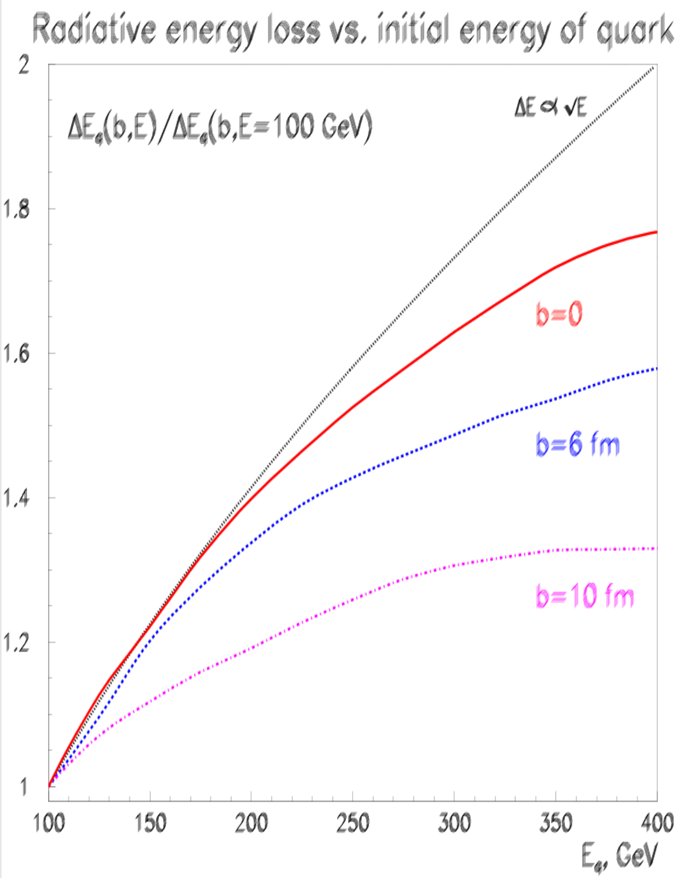
Nuclear modification factor



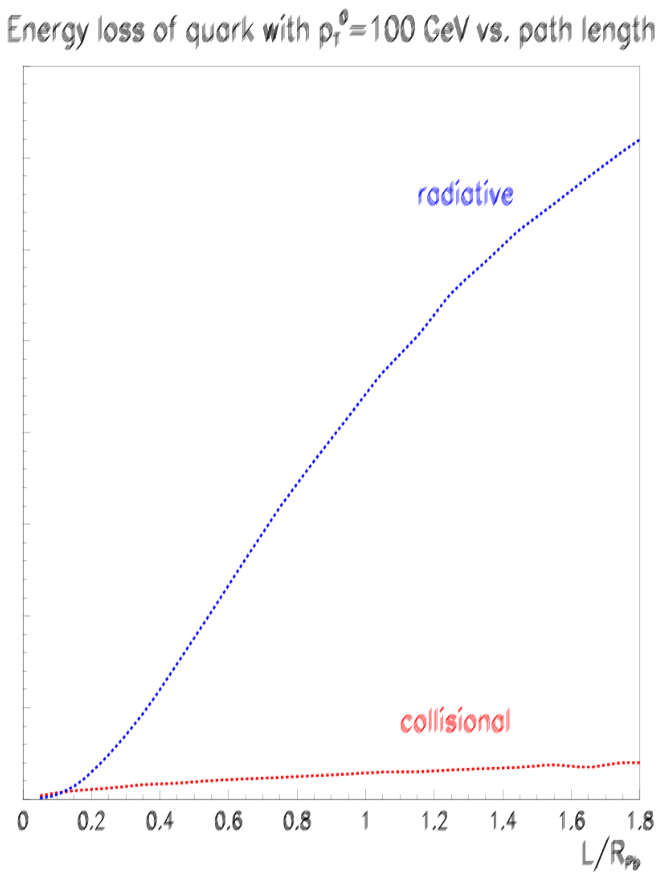
Azimuthal back-to-back correlations

PYQUEN: mean energy loss dependences (LHC, Pb+Pb, $T_{0,\,QGP}$ (b=0) = 1 GeV, τ_0=0.1 fm/c)

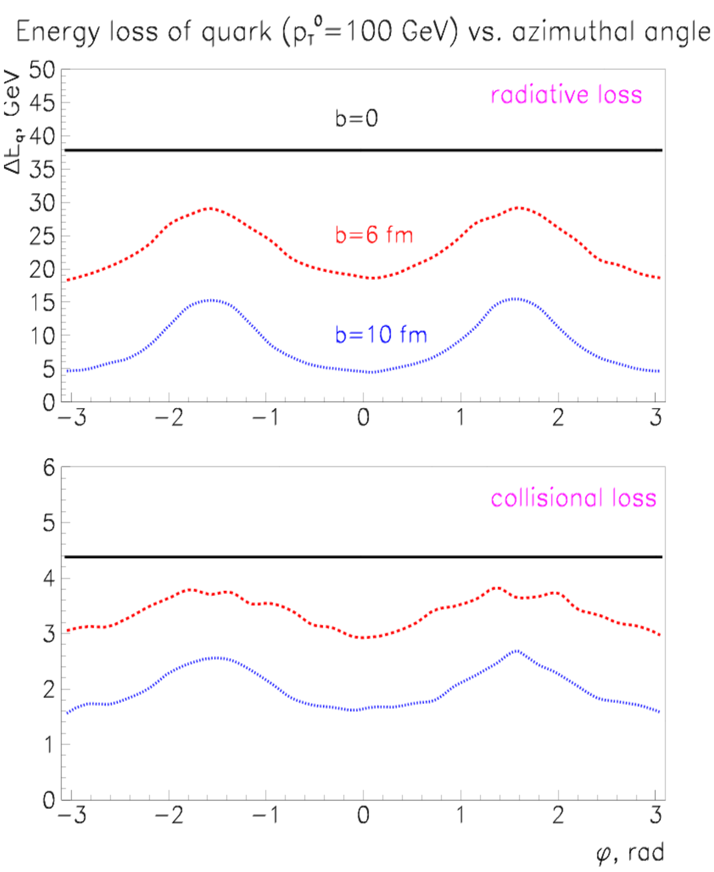
E-dependence



L-dependence



φ-dependence



FAST MC physical frameworks: 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 : $T, \mu_i = \mu_B B_i + \mu_S S_i + \mu_Q Q_i$; 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:

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

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

FAST MC physical frameworks: thermal freeze-out

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

Jet quenching at LHC (example VI): jet shape broadening

It can be characterized by the special transverse energy-energy correlator in the vicinity of maximum energy deposition of the event

$$\frac{d\Sigma_T}{d\eta} = \frac{1}{N_{\rm event}} \sum_{\rm event} \frac{1}{\Delta\eta} \sum_{kl} \frac{E_{Tk} \quad E_{Tl}}{(E_T^{\rm vis})^2 - \sum_j E_{Tj}^2} \delta(k-l-m)$$

$$E_T^{\rm vis} = \sum_{j=-M}^{M} E_{Tj} \qquad m = [\eta/\Delta\eta]$$

Measured dependence (or independence) of this correlator on pseudorapidity can serve as a sensitive test of different types of partonic energy loss models

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