

Monte-Carlo simulation of jet quenching and high transverse momentum observables in heavy ion collisions at the LHC

I.P. Lokhtin, L.I. Sarycheva, A.M. Snigirev,
S.V. Petrushanko, C.Yu. Teplov
(SINP MSU, Moscow, Russia)

- PYQUEN - model of jet quenching in heavy ion collisions
- Validation of PYQUEN at RHIC
- Examples of jet quenching observables at LHC:
 1. Nuclear modification factors for jets and high transverse momentum hadrons
 2. Jet fragmentation function measured by leading hadrons
 3. Transverse momentum imbalance in dimuon tagged jet events
 4. High-mass dimuon and secondary charmonium spectra
 5. Azimuthal anisotropy of jet quenching
 6. Jet shape broadening and quenching versus rapidity
- Conclusions and outlook

Monte-Carlo models to simulate jet quenching and flow effects in HIC

- PYQUEN - fast code to simulate jet quenching (modify PYTHIA6.4 jet event), <http://cern.ch/lokhtin/pyquen>
- HYDJET - merging soft part (with including flow effects) and multijets generated with PYQUEN
<http://cern.ch/lokhtin/hydro/hydjet.html>

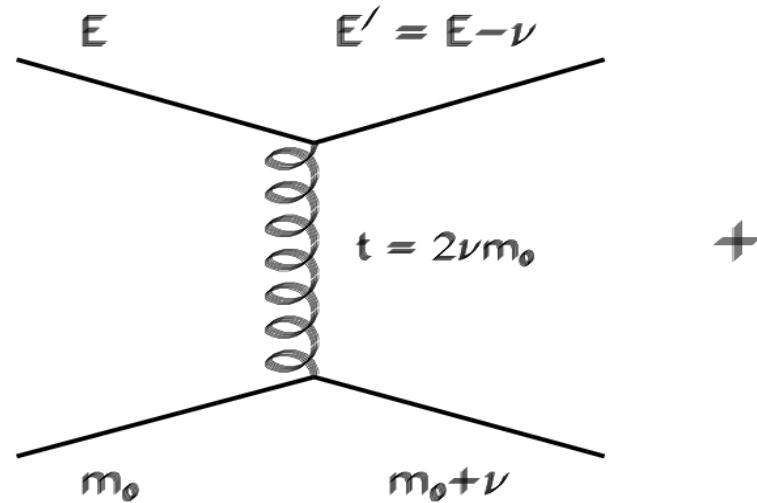
HydjetRHIC and PyquenRHIC are also available by web

The codes are included in LHC generator database GENSET
(*HYDJET1_1 and PYQUEN 1_1 are latest versions*)

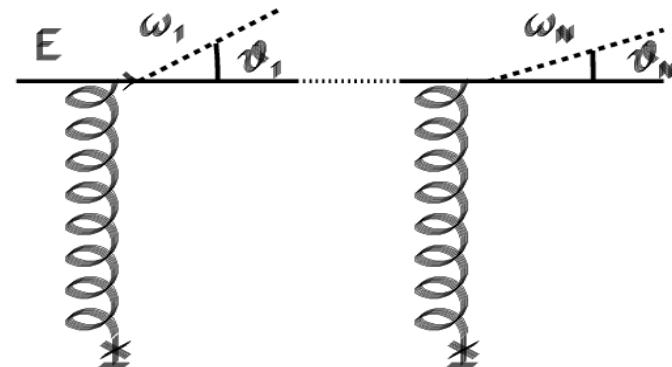
I. Lokhtin, A. Snigirev, Eur. Phys. J. C 46 (2006) 211

Medium-induced partonic energy loss

Collisional loss
(incoherent sum over scatterings)
Bjorken; Mrowzinski; Thoma;
Markov; Mustafa et al...



Radiation loss
(coherent LPM interference)
Gylassy-Wang; BDMPS; GLV;
Zakharov; Wiedemann...



Medium-induced partonic energy loss

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):

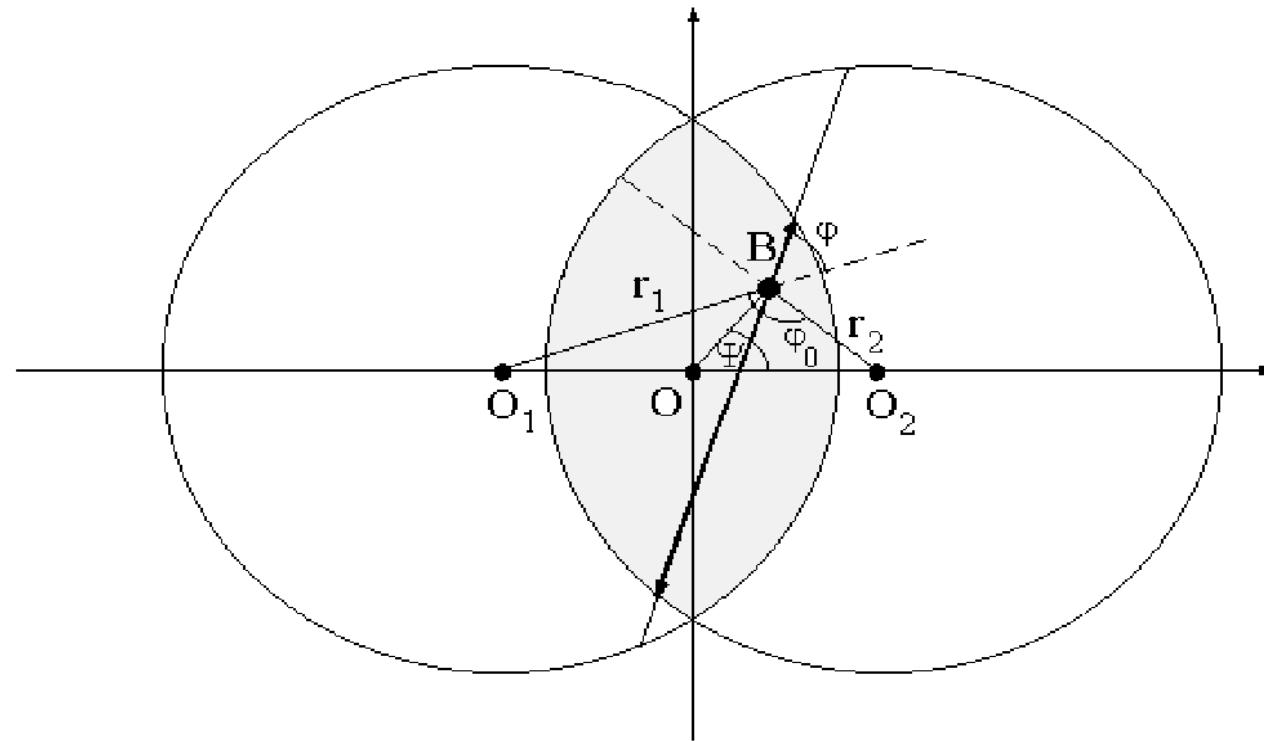
$$\frac{dE}{dx}(m_q=0) = \frac{2\alpha_s C_F}{\pi\tau_L} \int_{E_{max} \sim \lambda_g \mu_n^2}^E d\omega \left[1 - y + \frac{y^2}{2} \right] \ln |\cos(\omega_1 \tau_1)|, \quad \omega_1 = \sqrt{i \left(1 - y + \frac{C_F}{3} y^2 \right) \bar{k} \ln \frac{16}{\bar{k}}}, \quad \bar{k} = \frac{\mu_D^2 \lambda_g}{\omega(1-y)},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

“dead cone” approximation for massive quarks:

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

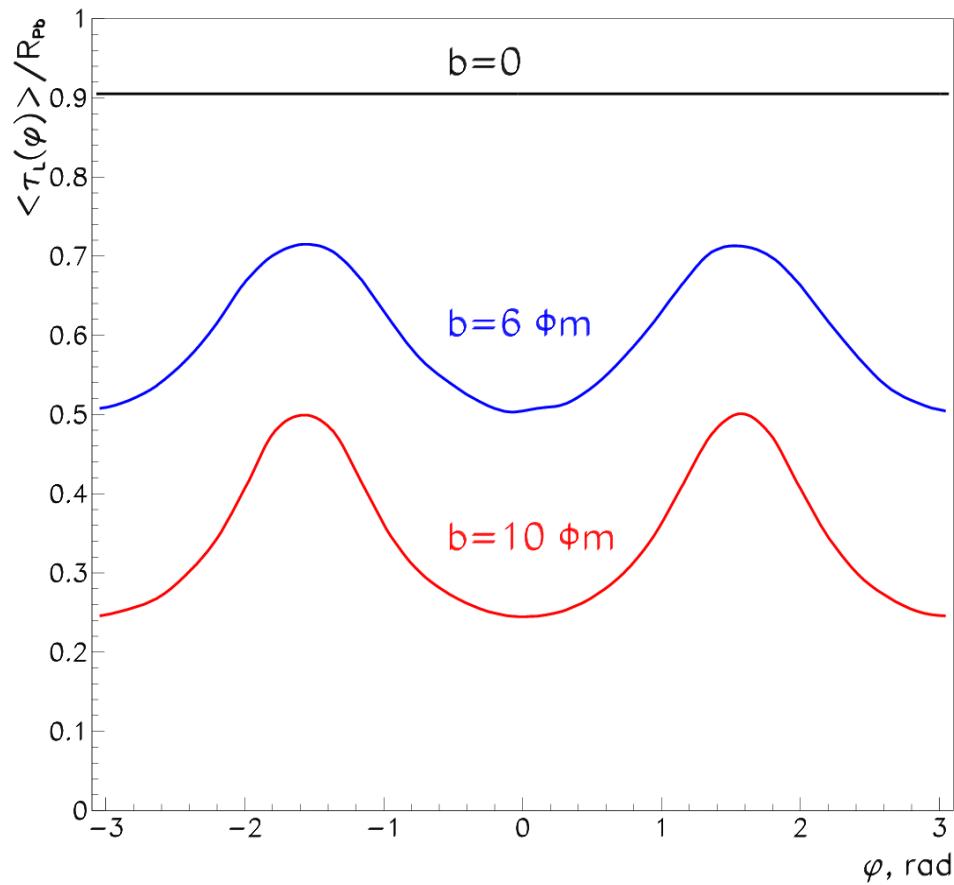
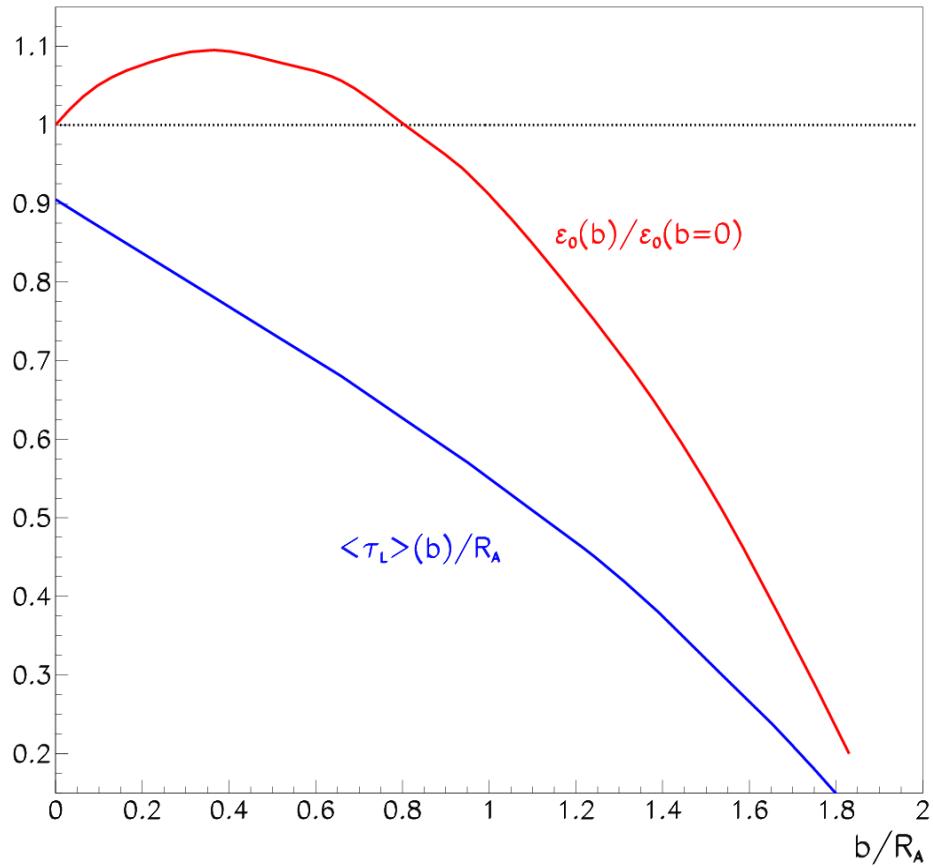
Nuclear geometry and QGP evolution

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



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

Dependence of geometry and interaction dynamics on event centrality



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

- 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

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

Angular spectrum of gluon radiation

Medium-modified jet fragmentation depends on fraction of partonic energy loss falling outside the jet cone

But full treatment of angular spectrum of emitted gluons is sophisticated and model-dependent

Two simple parameterizations of gluon angular distribution:

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

Broad-angular radiation: $\frac{dN^g}{d\theta} \propto \frac{1}{\theta}$

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: mstp(111)=1, call PYEXEC

More details on PYQUEN physics can be found in:

I.Lokhtin, A.Snigirev, EPJ C45 (2006) 211; ; and references therein.

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

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

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

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 (HYDrodynamics + JETs)

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



start filling JETSET arrays with **npyt** lines and HYDJET arrays with **nl** (corresponding to **nl** partons) lines



calculation of multiplicity of HYDRO-induced particles, **nhyd=n-npyt**, and adding new particles in JETSET arrays

We are working on improvement of soft part generation:

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

HYDJET: model parameters

External input

- beam and target nucleus atomic weight ($A=B$)
- impact parameter (fixed or distributed)
- total mean multiplicity in central Pb+Pb or Au+Au 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 $\text{ytfl}=1.$)
- **ylfl** - maximum longitudinal collective rapidity, controls width of η -spectra
($0.01 < \text{ylfl} < 7.0$, default value is $\text{ylfl}=5.$)
- **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 $\text{fpart}=1.$)
- **ptmin** - minimal pt of hard parton-parton scattering in PYTHIA
($5 \text{ GeV} < \text{ptmin} < 500 \text{ GeV}$ for LHC, $2 \text{ GeV} < \text{ptmin} < 70 \text{ GeV}$ for RHIC)

Internal sets

- poison multiplicity distribution
- thermal particle ratios and freeze-out at $T_f=100 \text{ MeV}$

HYDJET: output information

Output particle information:

- final hadronic state of the event in JETSET format
(common block LUJETS, #150000)
- parton history of the event in JETSET format
(common block HYJETS, #150000)

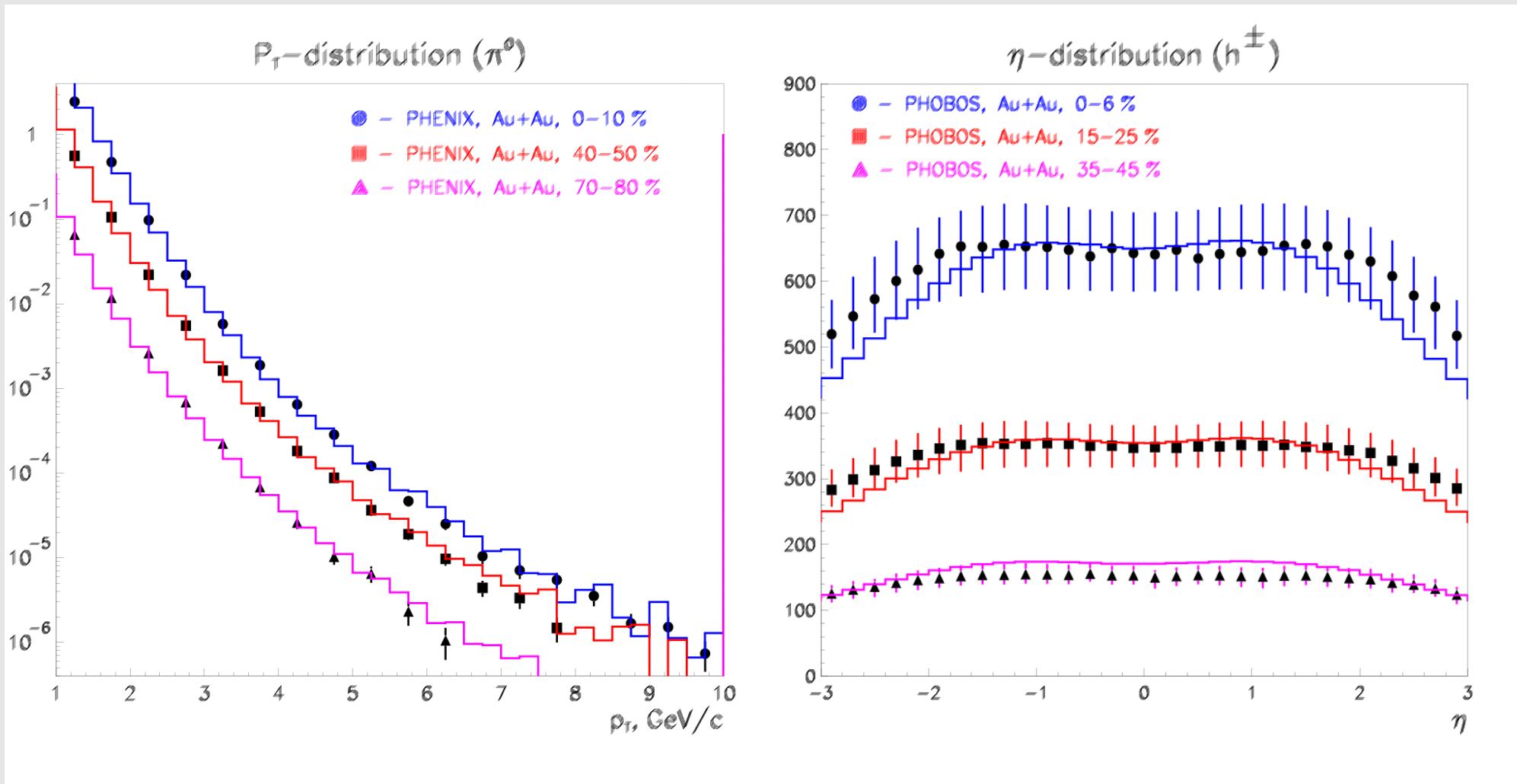
Output global event characteristics:

- **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

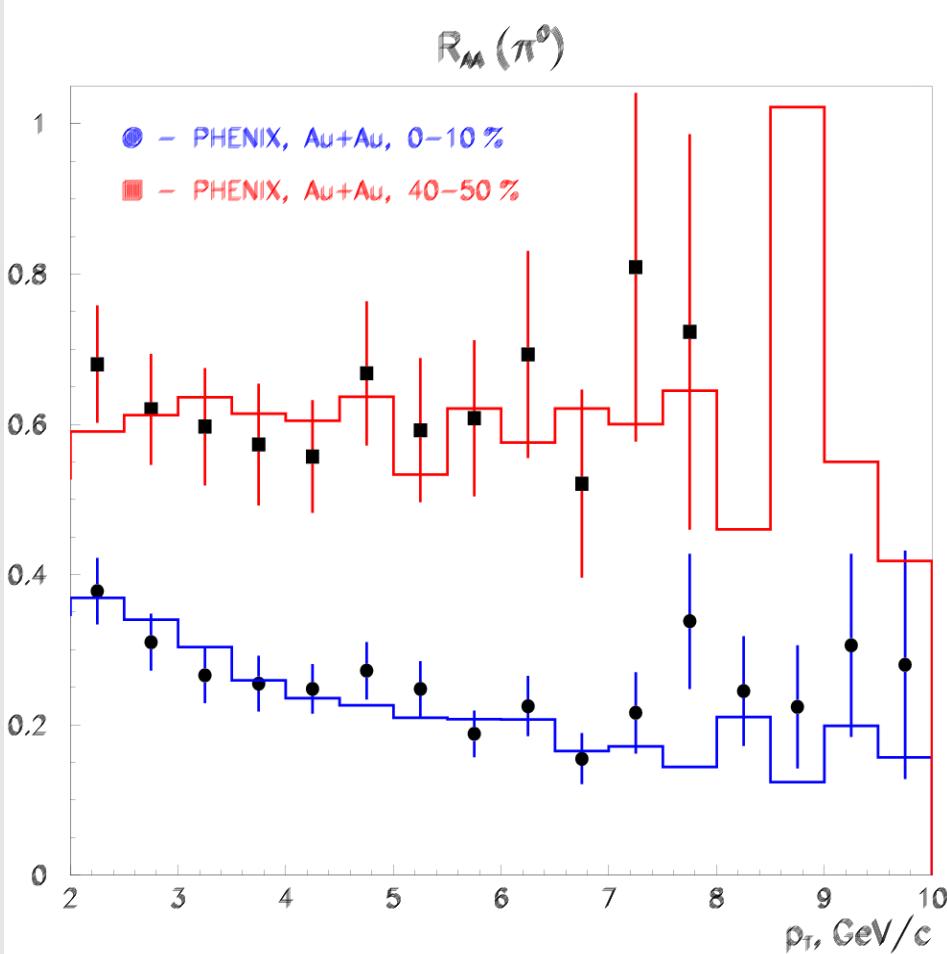
Fit RHIC hadron spectra with HYDJET

- Fixing multiplicity and $Y_1^{\max}=3.5$ from PHOBOS η -spectra (no K-factor requested for PYTHIA6.4)
- Fixing $T_f=100 \text{ MeV}$, $Y_T^{\max}=1.3$ and $p_T^{\min}=2.6 \text{ GeV/c}$ from PHENIX p_T -spectra
- Fixing initial QGP conditions from high- p_T part:
 $T_0=500 \text{ MeV}$, $\tau_0=0.4 \text{ fm/c}$ and $n_f=2$
- Calculating nuclear modification factor R_{AA} and azimuthal correlation function $C(\Delta\varphi)$

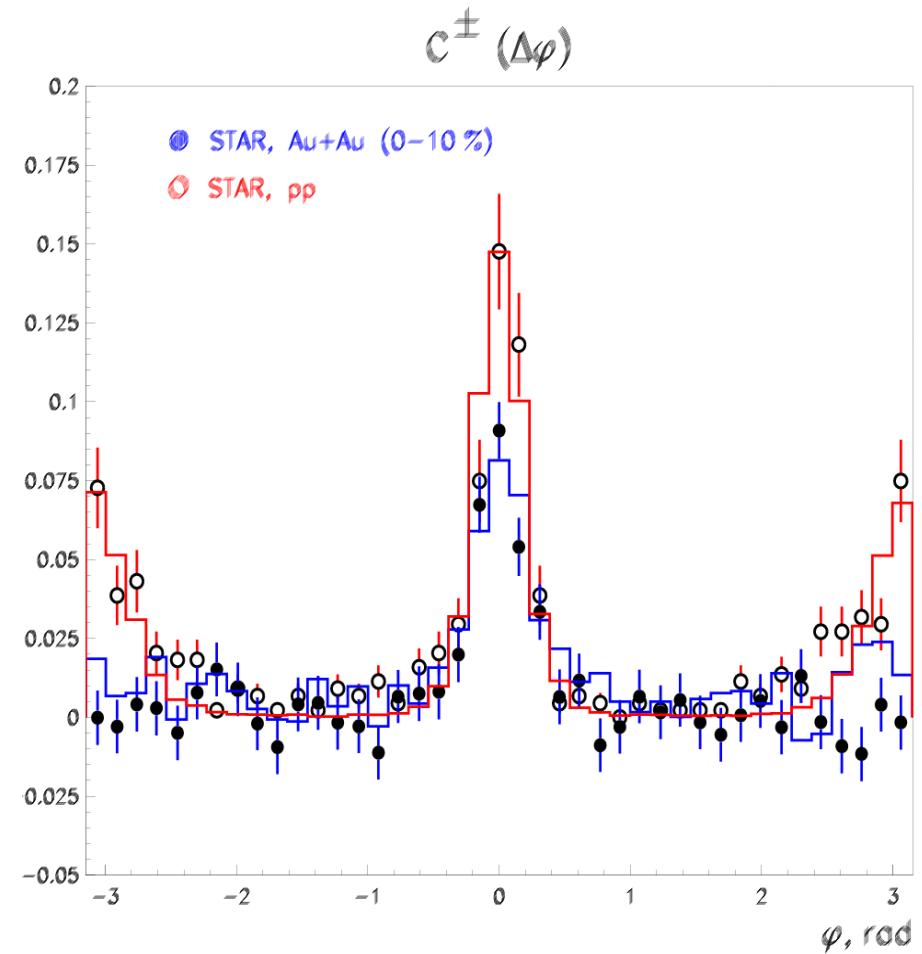
Fit RHIC spectra with HYDJET



Reproducing jet quenching pattern at RHIC with HYDJET



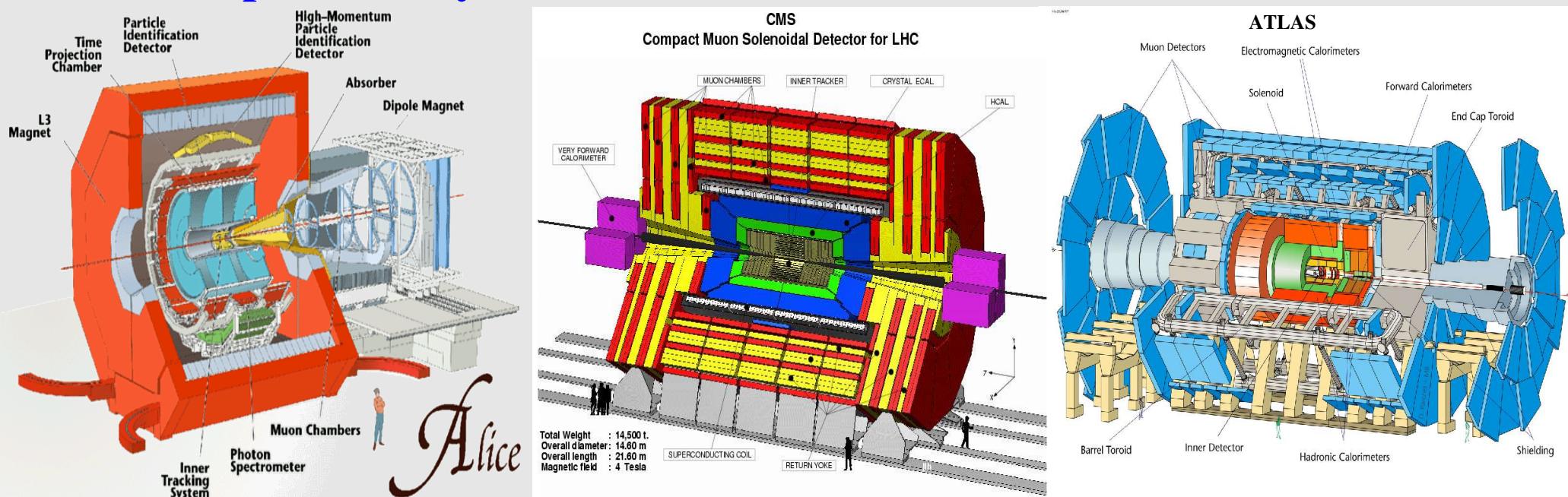
Nuclear modification factor



Azimuthal back-to-back correlations

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

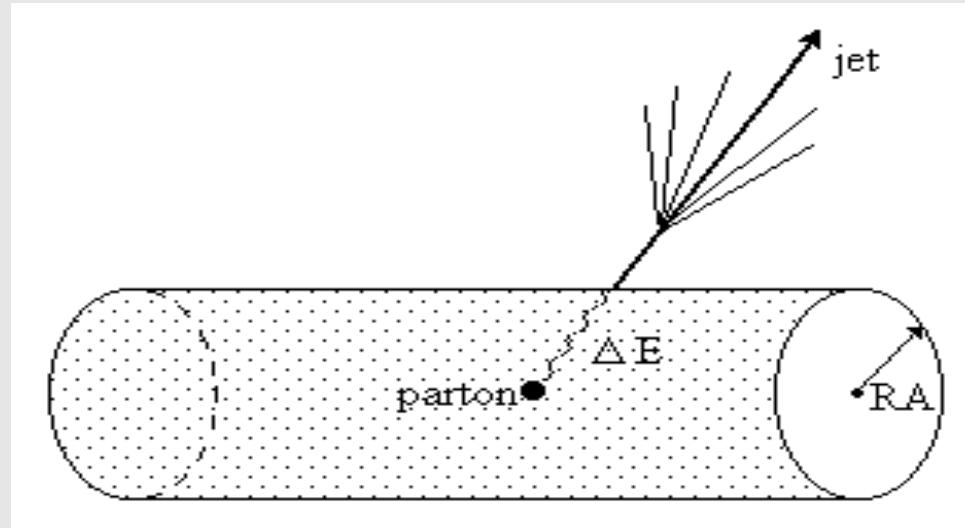
New regime of HI physics where hard and semi-hard QCD production dominates over soft “background” and probes hot and long lived QGP complementary measurements from ALICE & CMS/ATLAS



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 in heavy ion collisions at the LHC



$\Delta E \propto T_0^3$ (temperature), g (number degrees of freedom) $\Rightarrow \Delta E_{\text{QGP}} \gg \Delta E_{\text{HG}}$
LHC, central Pb+Pb:

$$T_{0, \text{QGP}} \sim 1 \text{ GeV} \gg T_{0, \text{HG}}^{\text{max}} \sim 0.2 \text{ GeV},$$

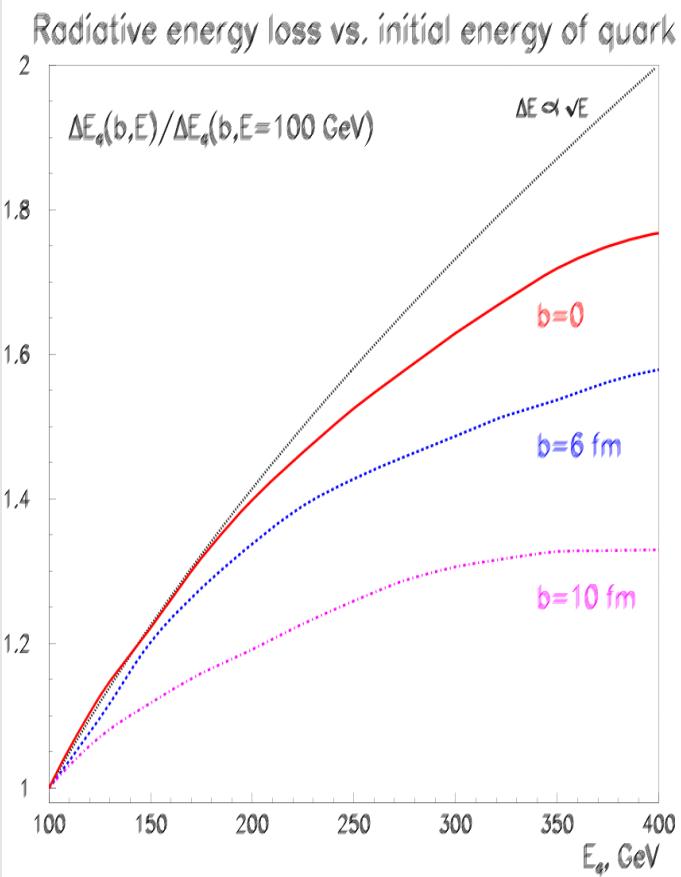
$$g_{\text{QGP}} > g_{\text{HG}}$$

↓

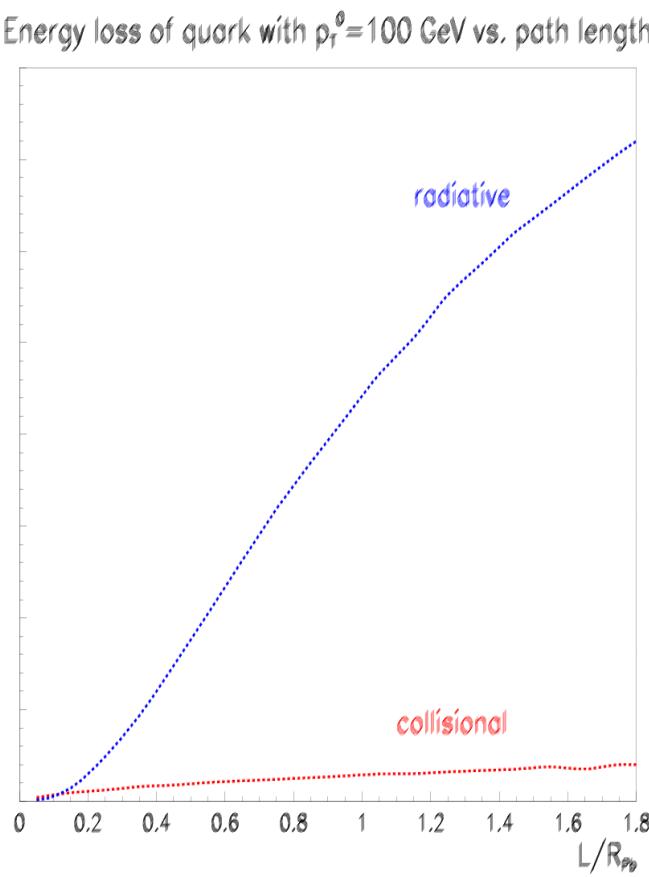
$$\Delta E_{\text{QGP}} / \Delta E_{\text{HG}} \geq (1 \text{ GeV} / 0.2 \text{ GeV})^3 \sim 10^2$$

PYQUEN: mean energy loss dependences (LHC, Pb+Pb, $T_{0, \text{QGP}}(b=0) = 1 \text{ GeV}$, $\tau_0 = 0.1 \text{ fm/c}$)

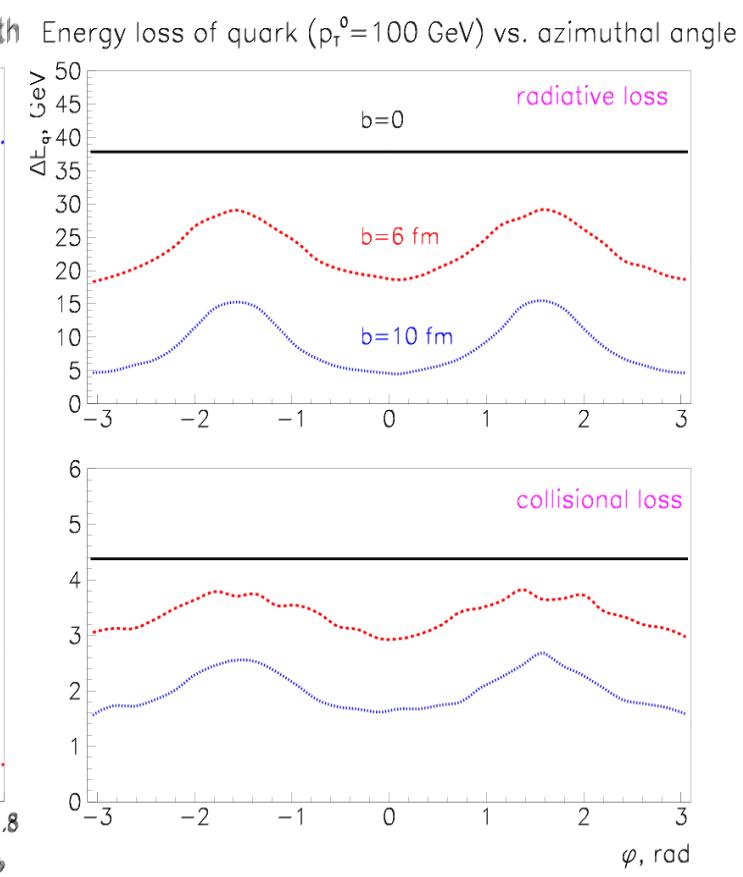
E-dependence



L-dependence



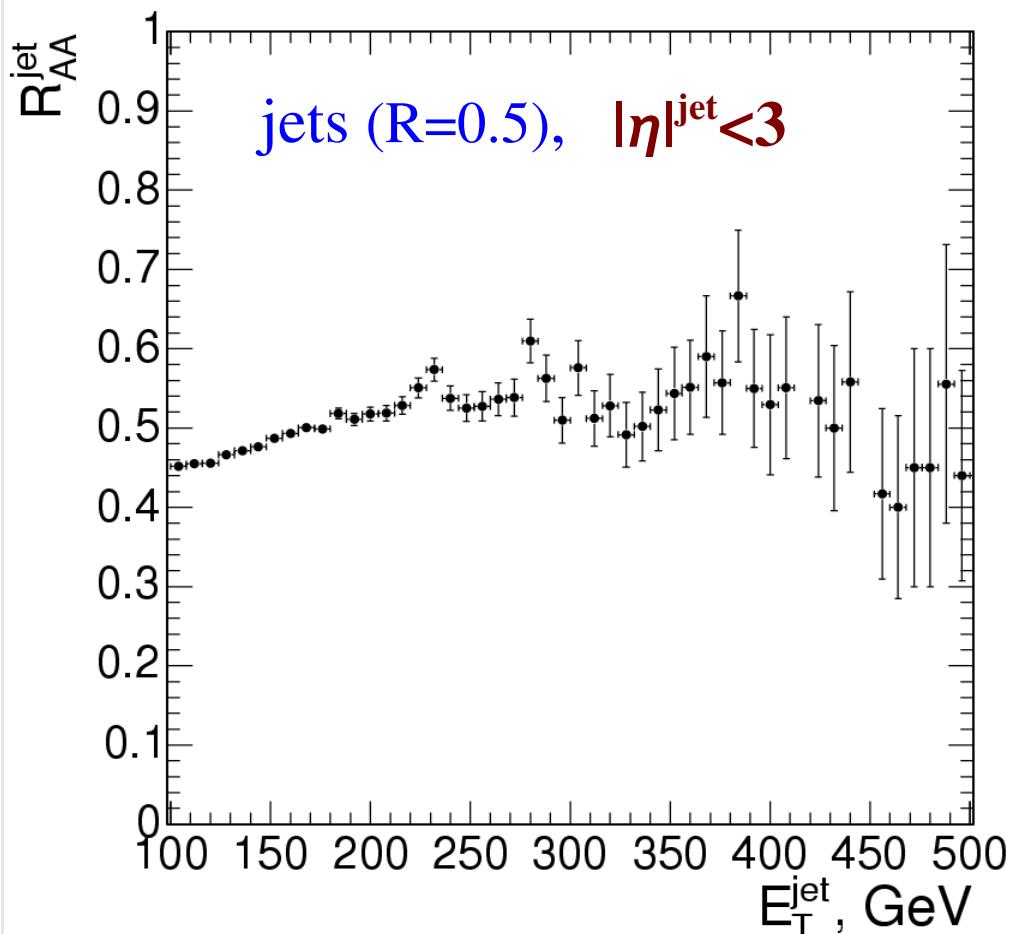
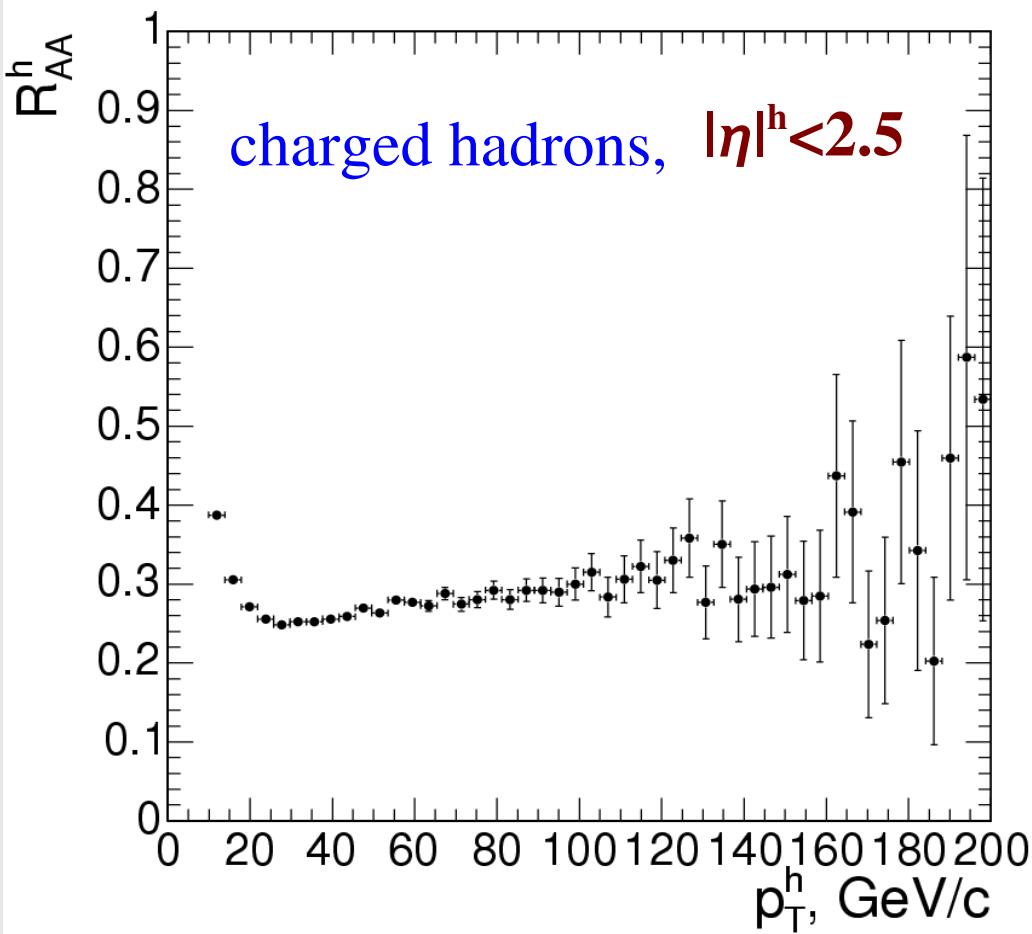
φ -dependence



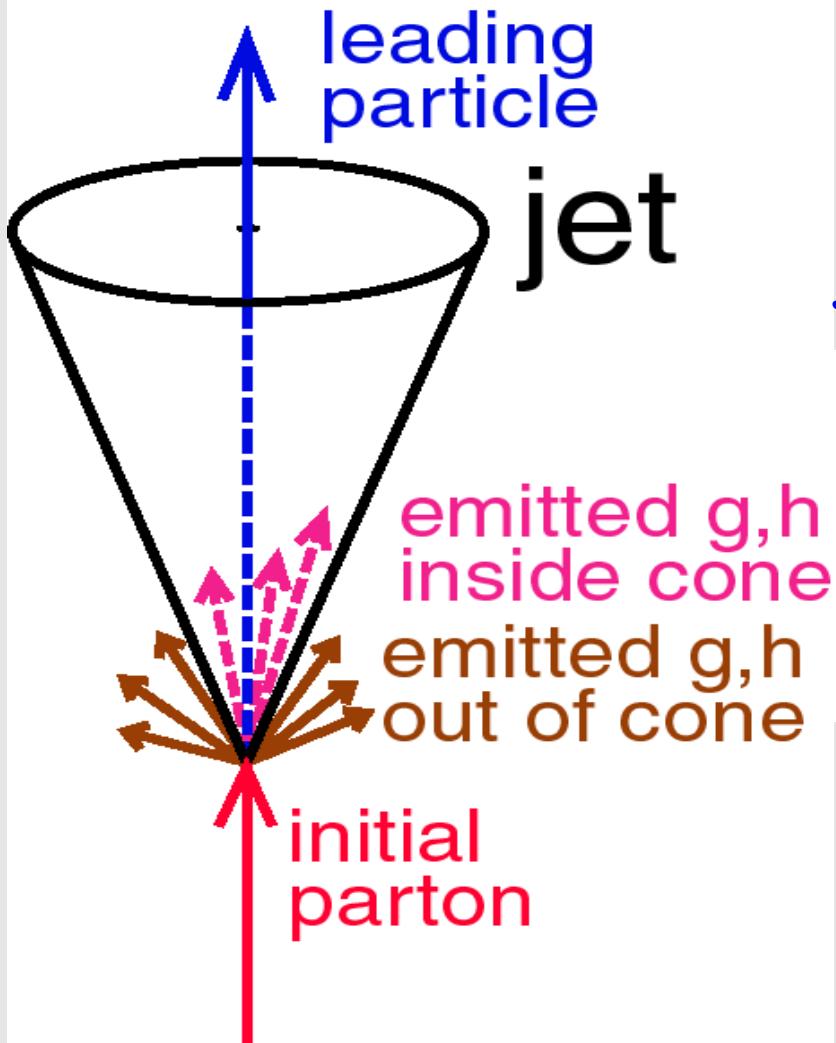
Jet quenching at LHC (I): jet nuclear modification factors

PYQUEN, Pb+Pb ($b=0$), $\sqrt{s}=5.5\text{A}$ TeV ($T_0=1$ GeV, $\tau_0=0.1$ fm/c, $n_f=0$)

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



Jet quenching at LHC (II): jet fragmentation function



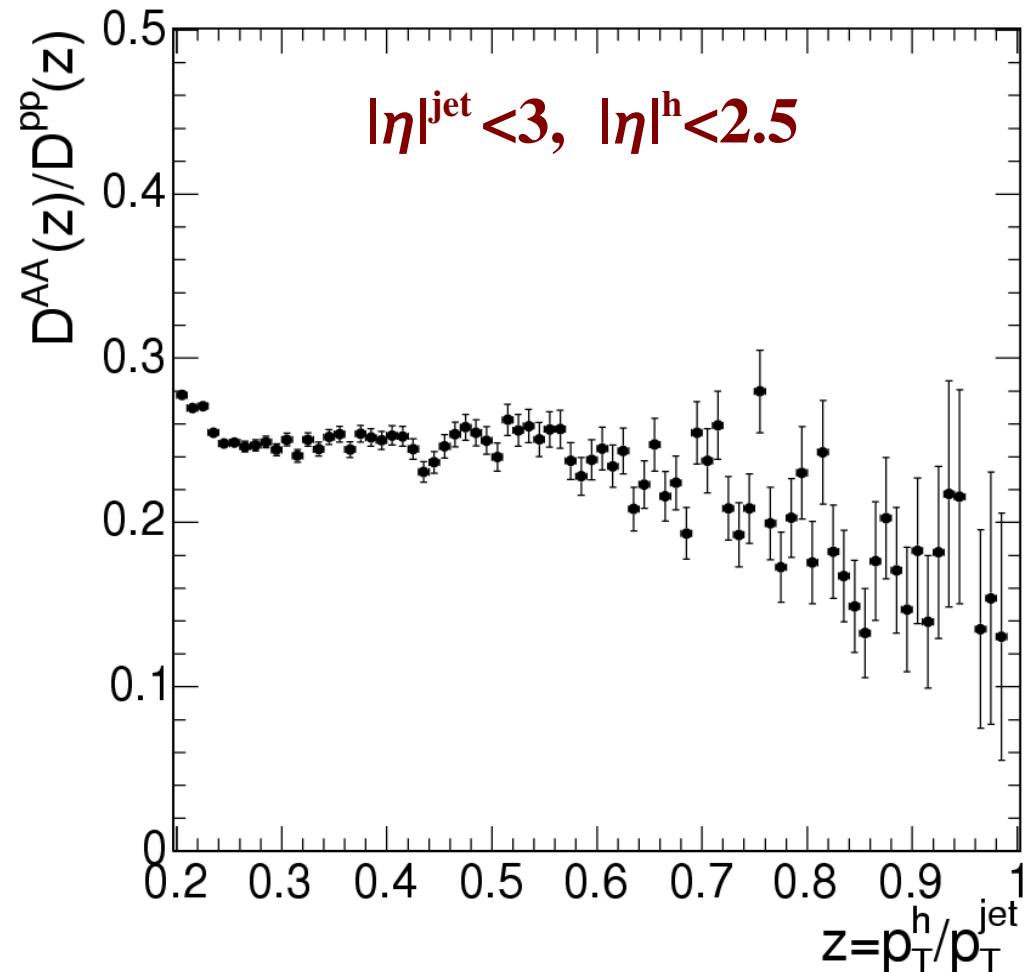
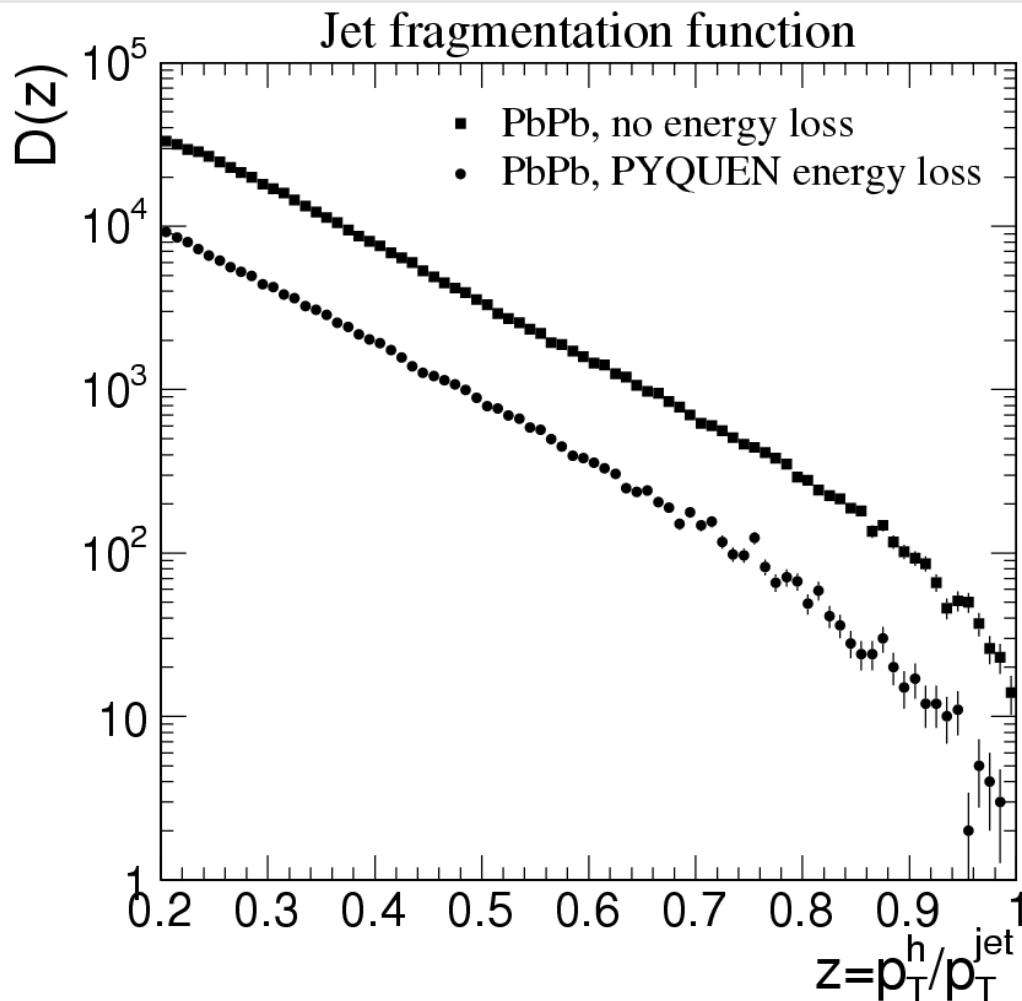
Jet fragmentation function $D(z)$:
probability distribution for leading hadron
in the jet to carry fraction $z(\equiv p_T^h/p_T^{jet})$ of
jet transverse momentum:

$$D(z) = \int_{\frac{z p_T^{jet}}{p_T^{min}}} d(p_T^h)^2 dy dz' \frac{dN_{AA}^h}{d(p_T^h)^2 dy dz'} \delta(z - p_T^h/p_T^{jet}) / \int_{p_T^{min}} d(p_T^{jet})^2 dy \frac{dN_{AA}^{jet}}{d(p_T^{jet})^2 dy}$$

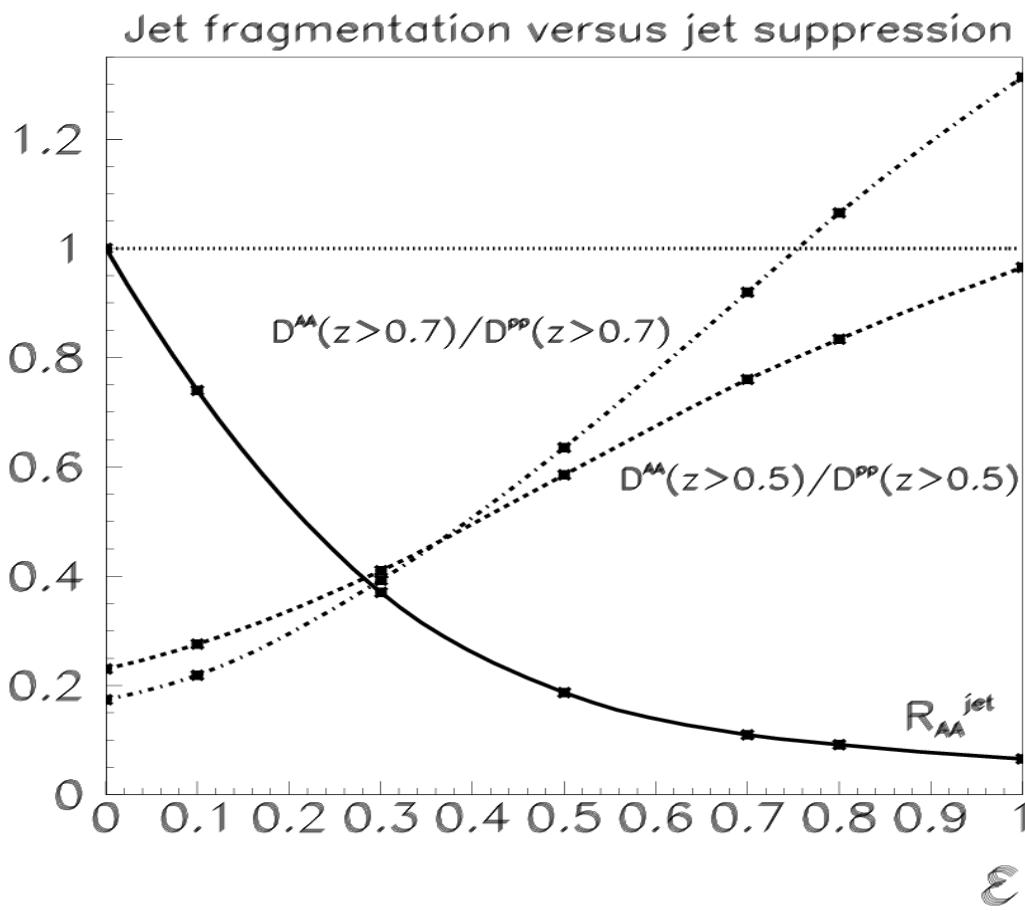
In the jet induced by heavy quark, the
energetic muon can be produced
("b-tagging")

Medium-modified jet fragmentation function measured with leading h^\pm, h^0

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



JFF softening vs. jet rate suppression



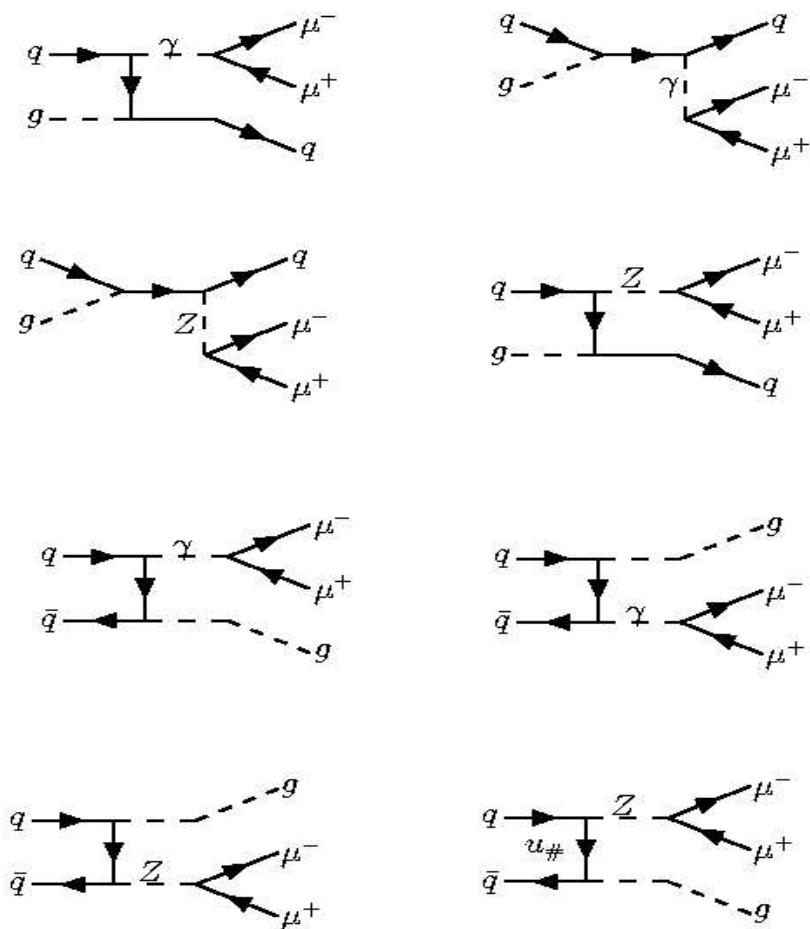
Medium-modified JFF softening and jet rate suppression depends on the fraction ϵ of jet energy loss falling outside the jet cone

The anti-correlation between two effects can be carried out in order to differentiate between various energy loss mechanisms (small-angular radiation vs. wide-angular radiation and collisional loss).

I.P.Lokhtin and A.M.Snigirev,
Phys.Lett. B567 (2003) 39

Jet quenching at LHC (III): $\gamma^*/Z(\rightarrow\mu^+\mu^-)$ +jet production

COMHEP + PYTHIA



$|\eta|^\mu < 2.5, p_T^\mu > 5 \text{ GeV}/c$

$|\eta|^{\text{jet}} < 3, E_T^{\text{jet}}, P_T^{\mu\mu} > 50 \text{ GeV}$

$\sqrt{s}=5.5 \text{ A TeV}:$

$\sigma(pp \rightarrow \mu^+\mu^- + \text{jet}) \approx 18 \text{ pb},$

$\sigma(Pb+Pb \rightarrow \mu^+\mu^- + \text{jet}) \approx 0.8 \mu b$

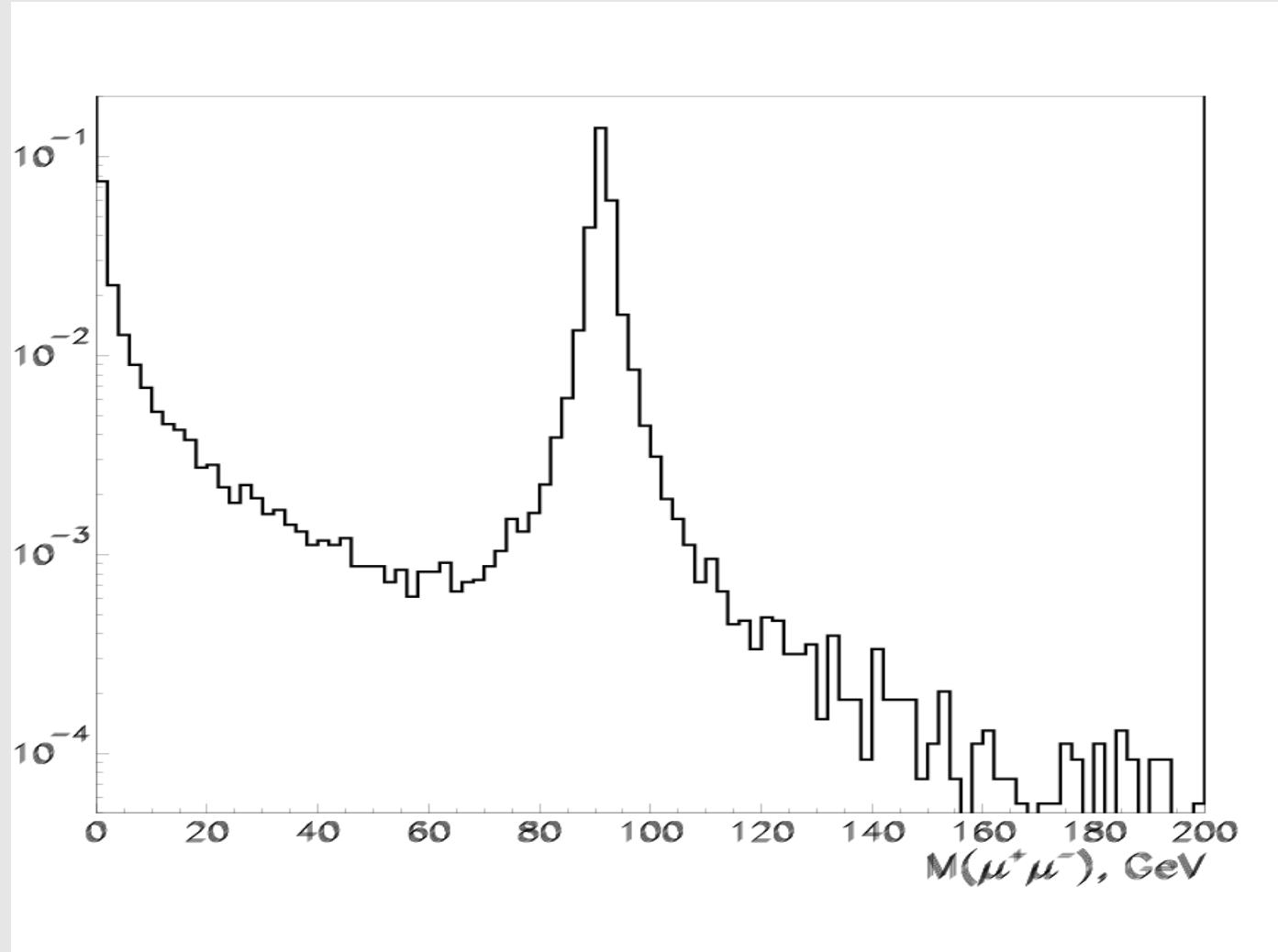
Events per 1 month:

($T=1.3 \times 10^6 \text{ s}$, $L=4.2 \times 10^{26} \text{ sm}^{-2}\text{s}^{-1}$)

$T \times L \times \sigma(Pb+Pb \rightarrow \mu^+\mu^- + \text{jet}) \sim 500$

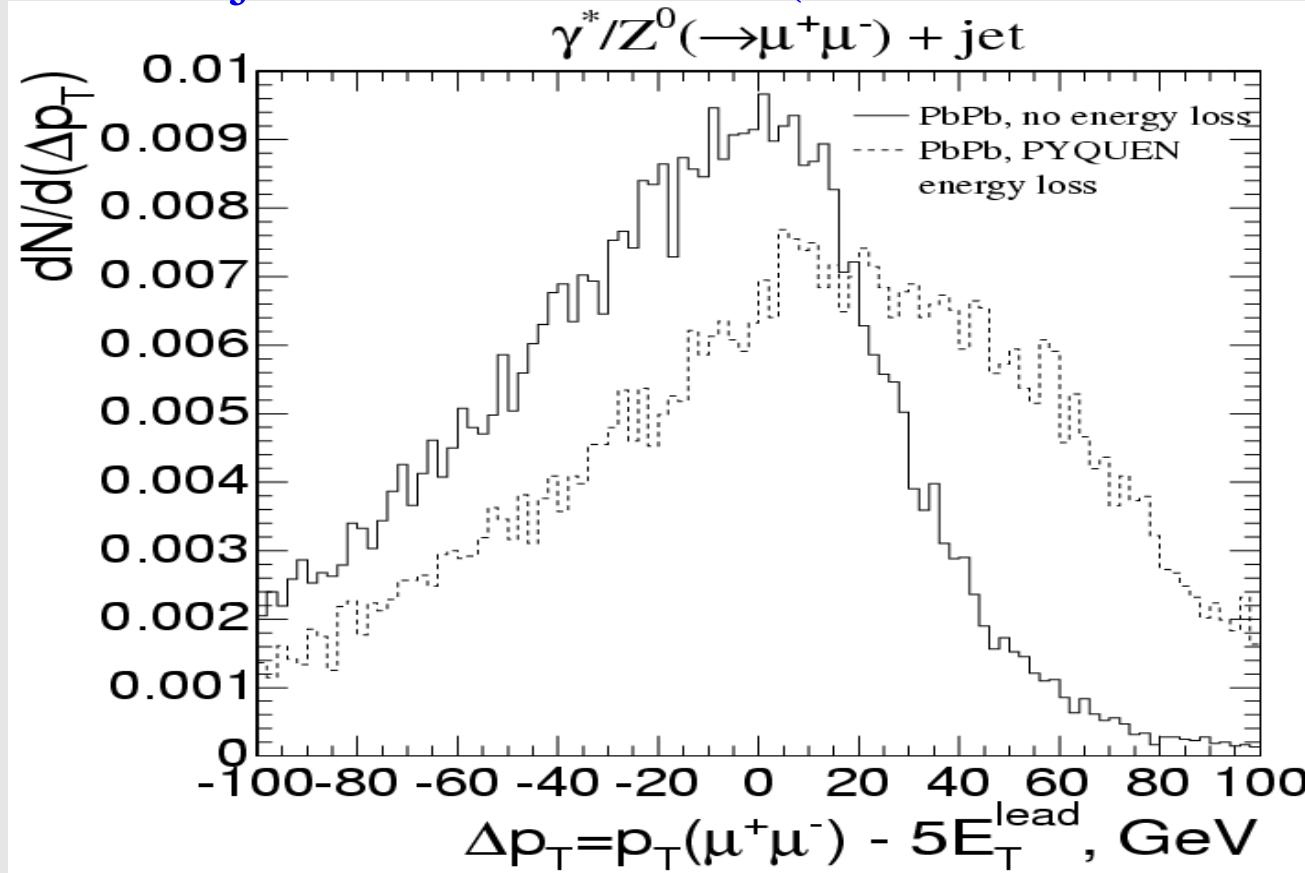
I. Lokhtin, A. Sherstnev, A. Snigirev,
 Phys. Lett. B 599 (260) 2004

Invariant mass spectrum of $\mu^+\mu^-$ -pairs from $\gamma^*/Z + \text{jet}$ production



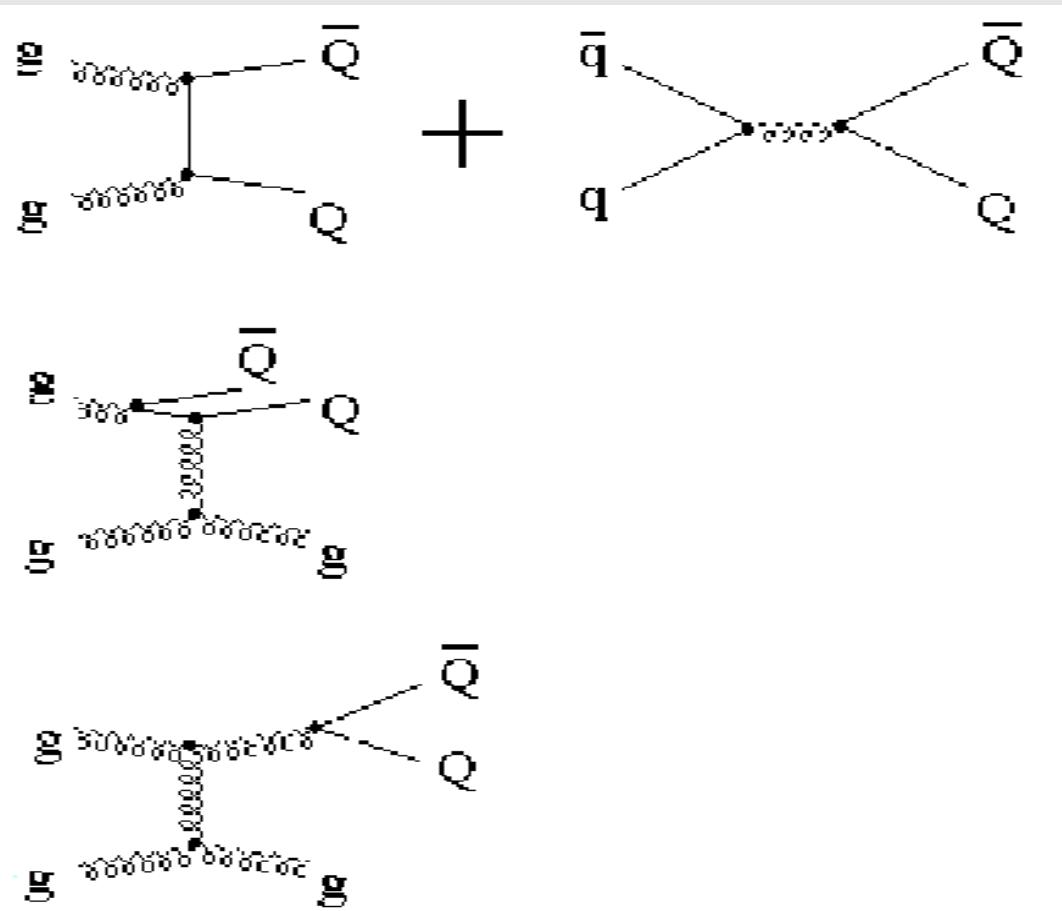
Imbalance of transverse momentum in $\gamma^*/Z(\rightarrow\mu^+\mu^-) + \text{jet}$ channel in HIC

Dimuon-jet leader correlation (minimum bias PbPb)



Advantage in using P_T -imbalance between leading hadron in a jet (but not jet itself) and muon pair:
weak dependence on dispersion of jet energy determination

Jet quenching at LHC (IV): heavy quark production to dileptons

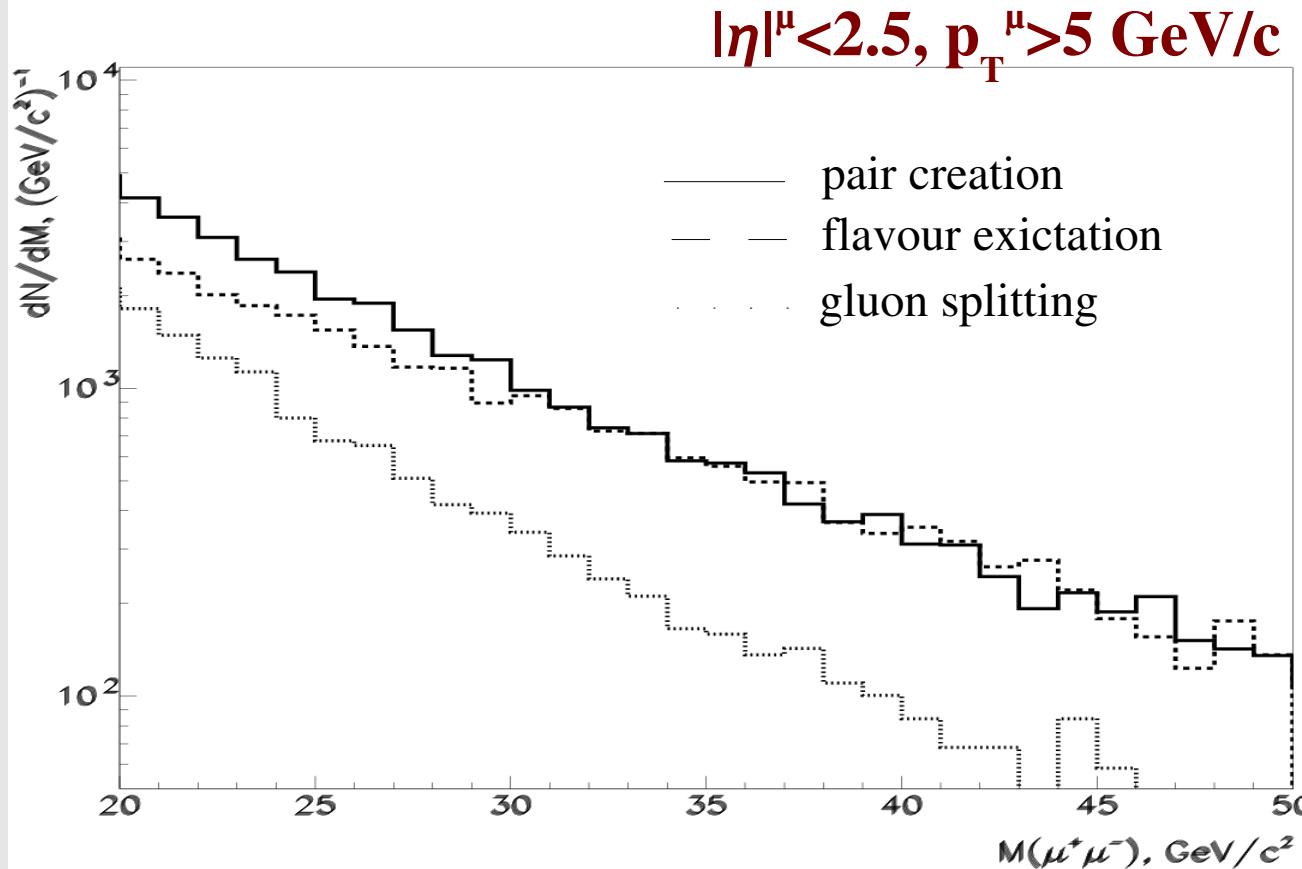


Pair creation

Flavour excitation

Gluon splitting

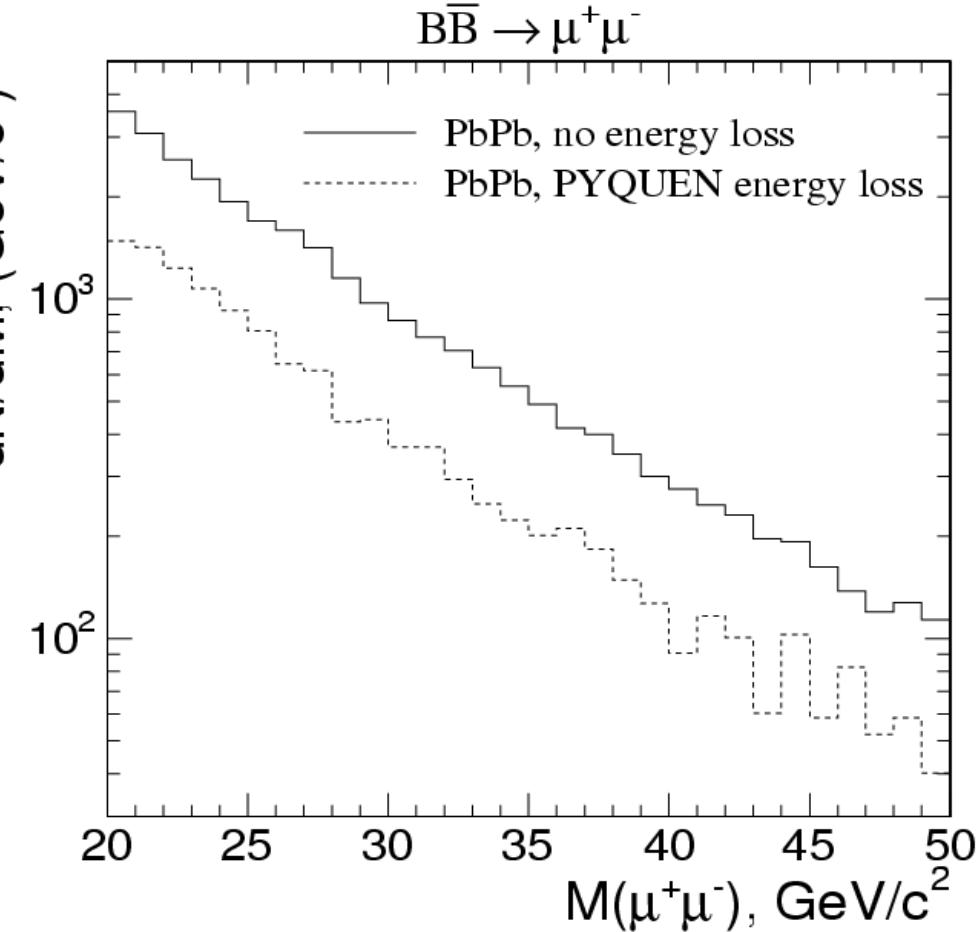
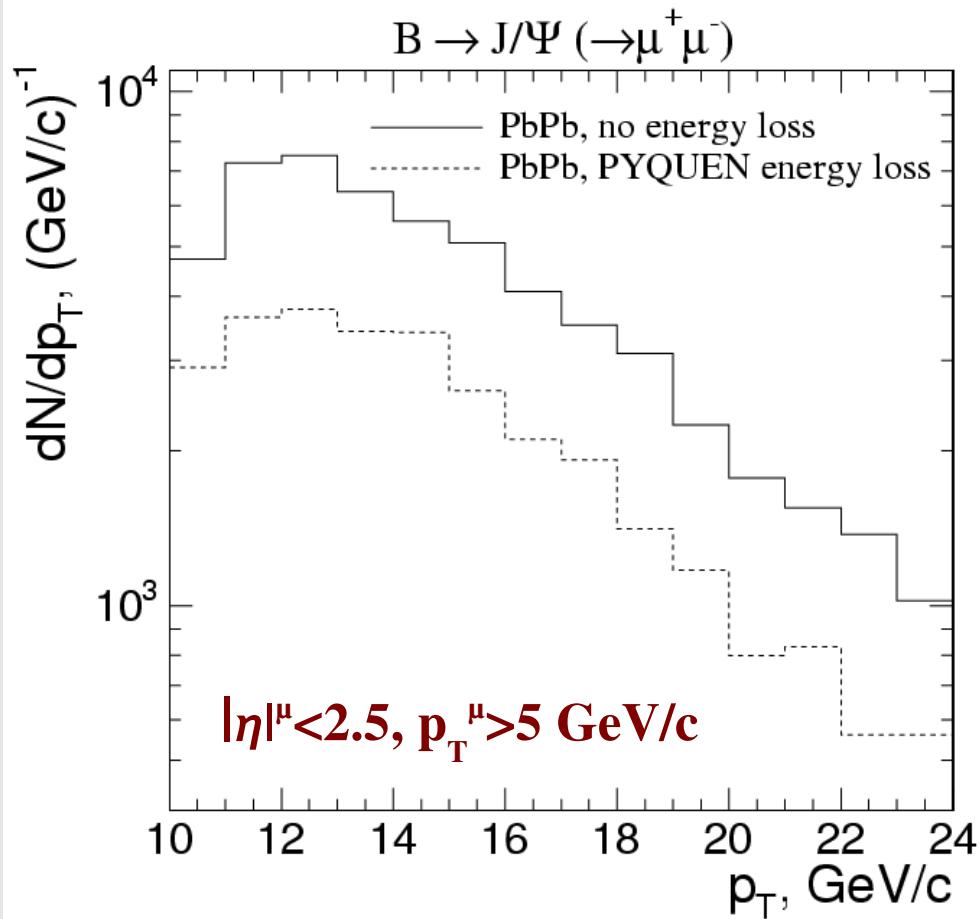
Spectrum of $\mu^+\mu^-$ - pairs of high invariant mass from BB decays



Contribution of showering b-quarks in $\text{BB} \rightarrow \mu^+\mu^-$ is comparable with pair creation
Contribution of showering b-quarks in $\text{B} \rightarrow \text{J}/\psi \rightarrow \mu^+\mu^-$ is dominant (~80%)

Medium-modified high-mass dimuons and secondary J/ ψ spectra

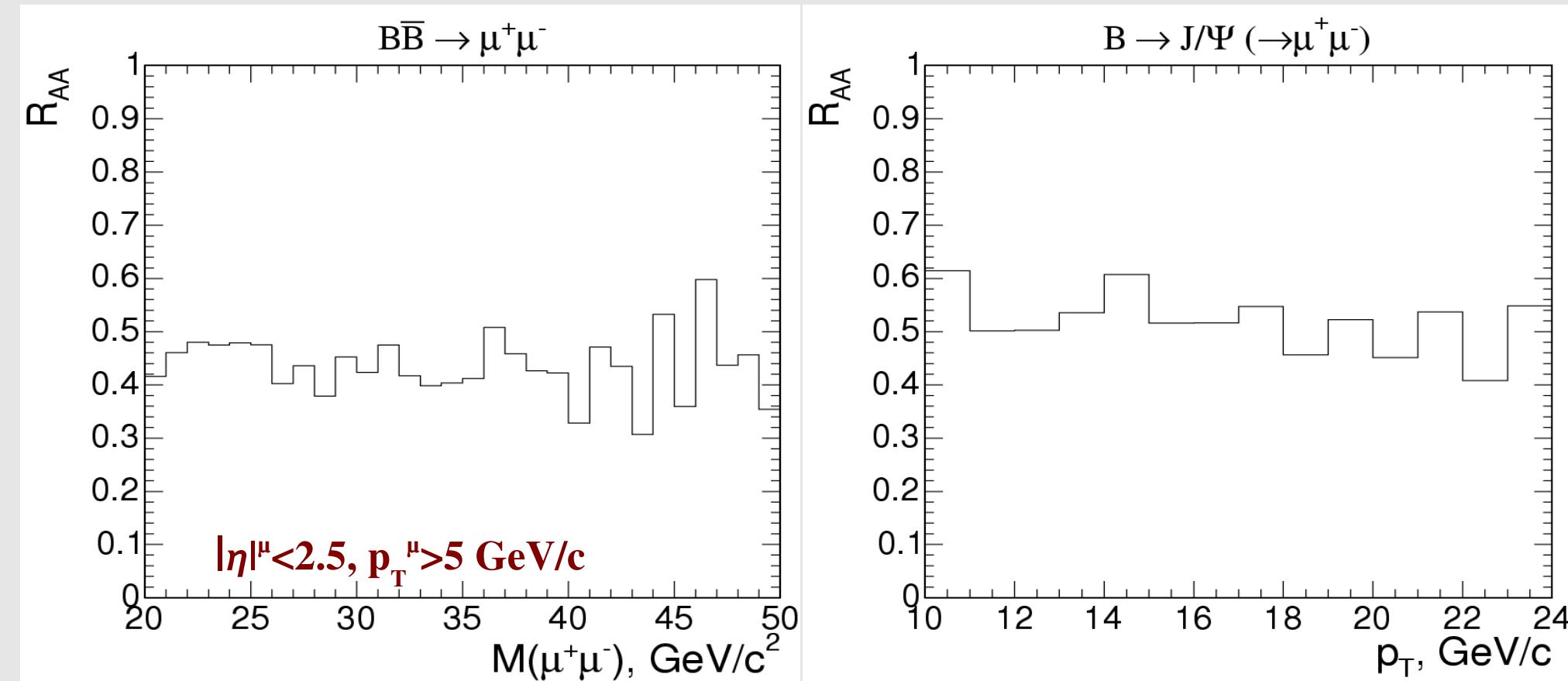
$\sim 5 \times 10^4$ events for each unquenched channels is expected for 1 month LHC run (with showering b-bbar production)



In-medium energy loss of b-quark (collisional+radiative) affects significantly the dimuon spectra

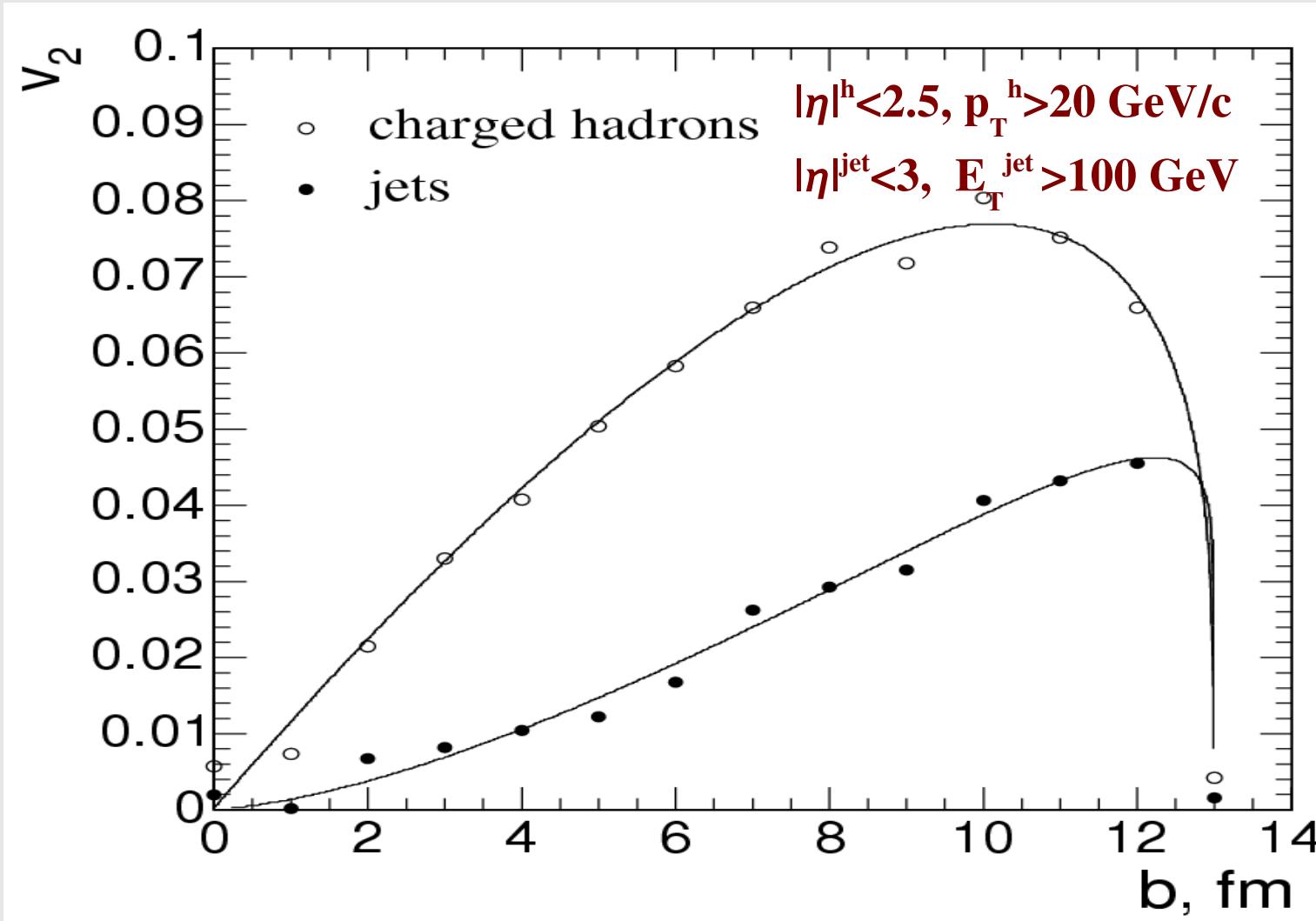
Nuclear modification factors for high-mass dimuons and secondary J/ ψ

~ 5×10^4 events for each unquenched channels is expected for 1 month LHC run (with showering b-bbar production)



Nuclear modifications factors are slightly dependent on kinematics and above EKS shadowing (~15%)

Jet quenching at LHC (V): jet azimuthal anisotropy



Jet quenching at LHC (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

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

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

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

**I.P Lokhtin, S.V. Petrushanko, L.I. Sarycheva, A. Snigirev,
Phys. Rev. C 73 (2006) 064905; Phys. Atom. Nucl. 69 (2006) 1609**

Summary and outlook

The method to simulate jet quenching in heavy ion collisions has been developed. The model is the fast Monte-Carlo tool implemented to modify a standard PYTHIA jet event. The full heavy ion event is obtained as a superposition of a soft hydro-type state and hard jets.

The model is capable of reproducing main features of the jet quenching pattern at RHIC (the momentum dependence of the nuclear modification factor and the suppression of azimuthal back-to-back correlations).

The model was applied to probe jet quenching in various novel channels at LHC: jet nuclear modification factor, jet fragmentation function measured with leading particles, dilepton-jet correlations, high-mass dimuons and secondary J/ψ , jet azimuthal anisotropy and jet shapes.

The further development of the model focusing on a more detailed description of low transverse momentum particle production and merging new soft and hard parts are in the progress.

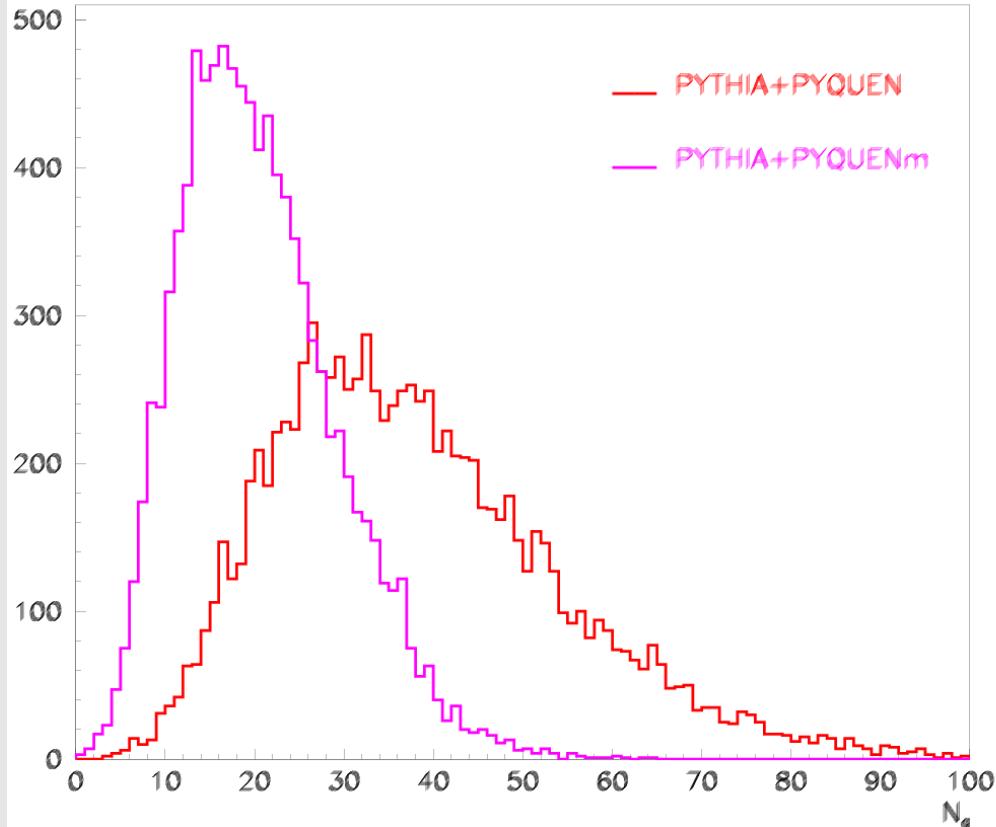
BACKUP SLIDES

PYQUEN: gluon radiation spectrum (LHC, central Pb+Pb, $T_{0, \text{QGP}} = 1 \text{ GeV}$)

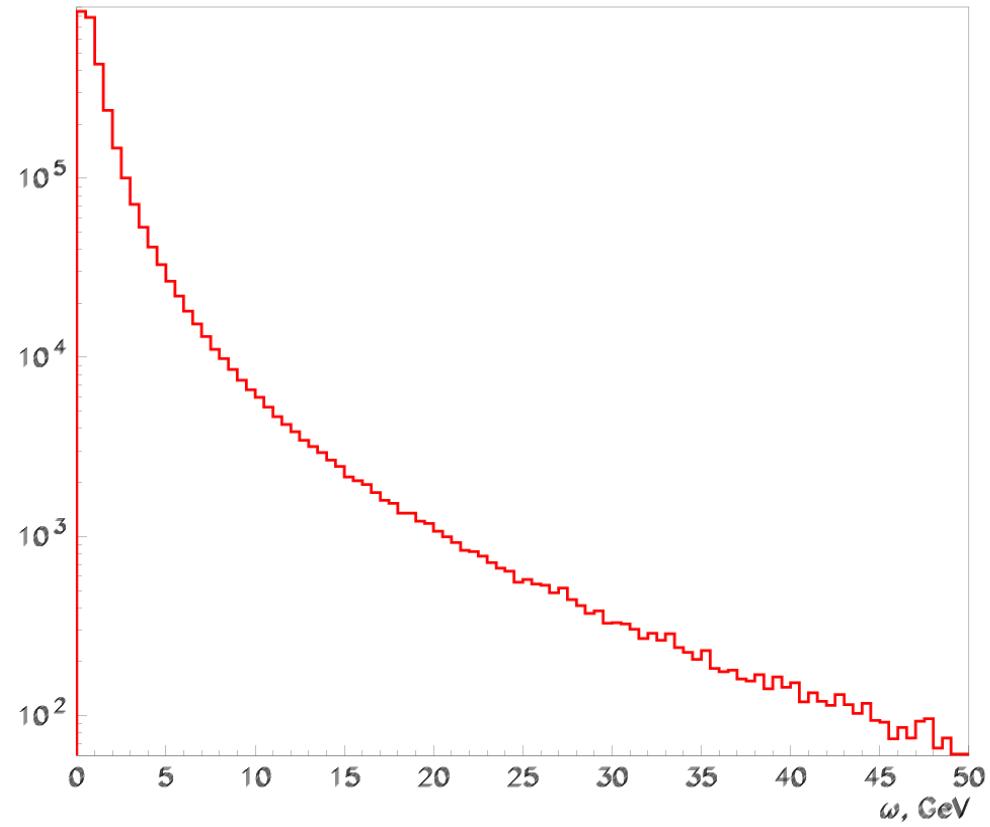
Number of gluons

Gluon energy

Distribution over number of in-medium emitted gluons per jet



Energy spectrum of in-medium emitted gluons



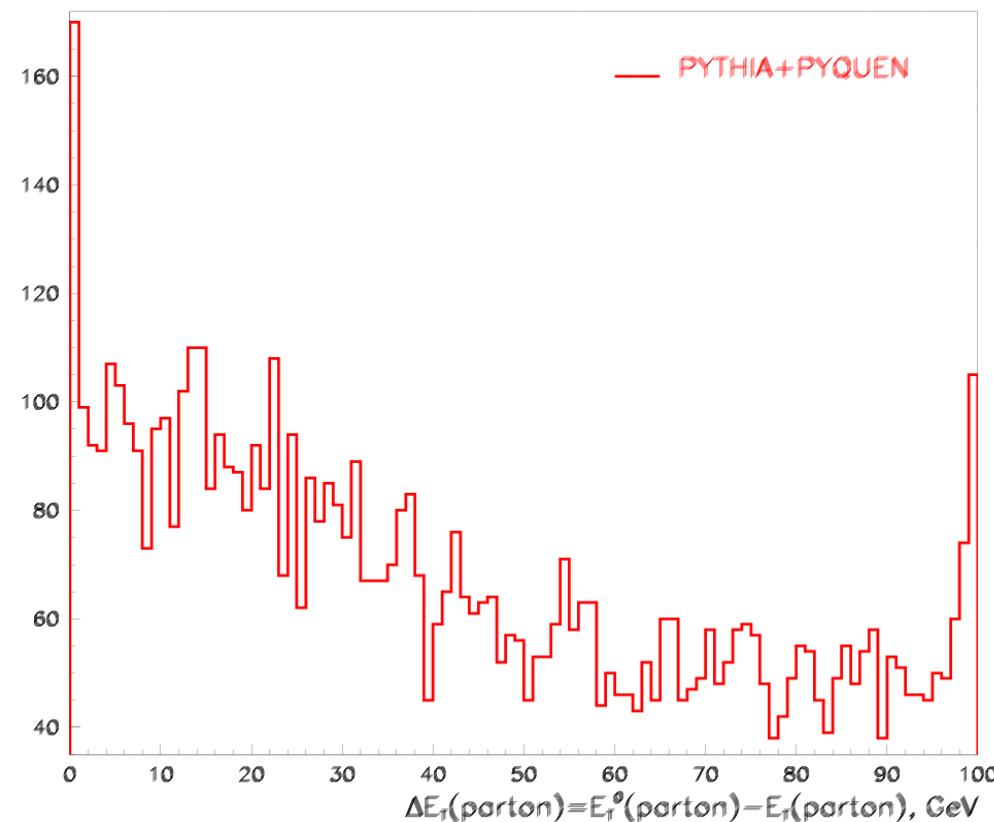
PYQUEN - # of gluons per partonic jet, PYQUENm - # of gluons per leading parton

PYQUEN: energy loss fluctuations

(LHC, central Pb+Pb, $T_{0, \text{QGP}} = 1 \text{ GeV}$)

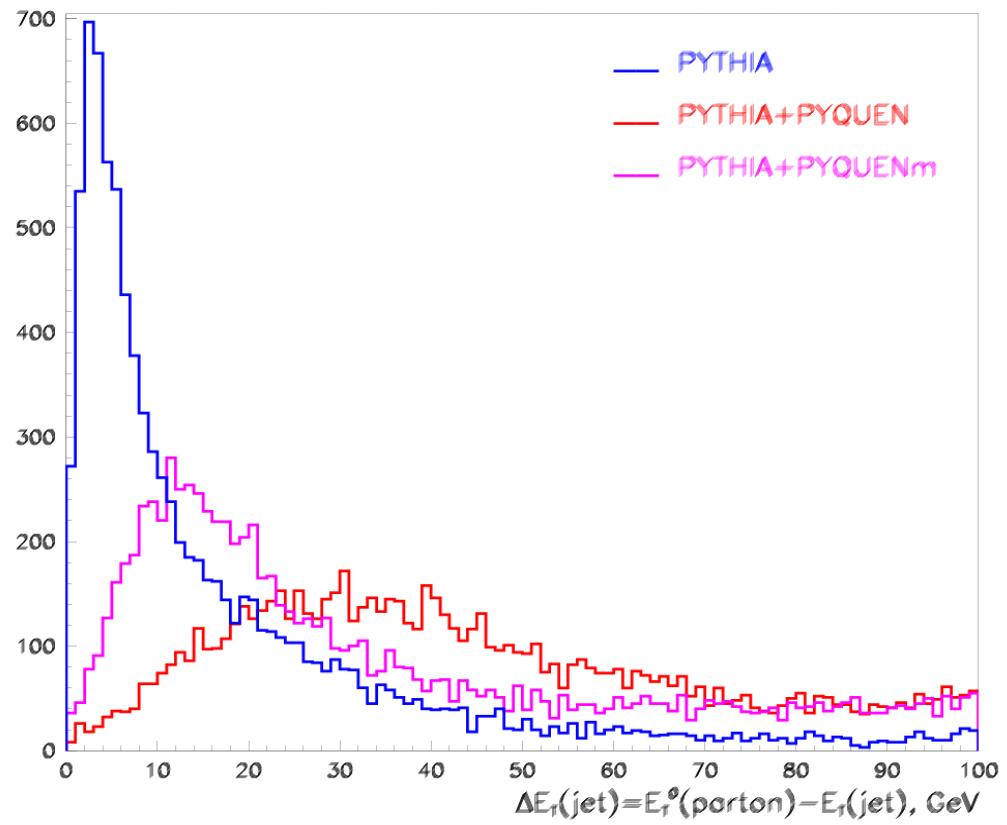
Single parton loss

Distribution over energy loss of parton with $E_t > 100 \text{ GeV}$



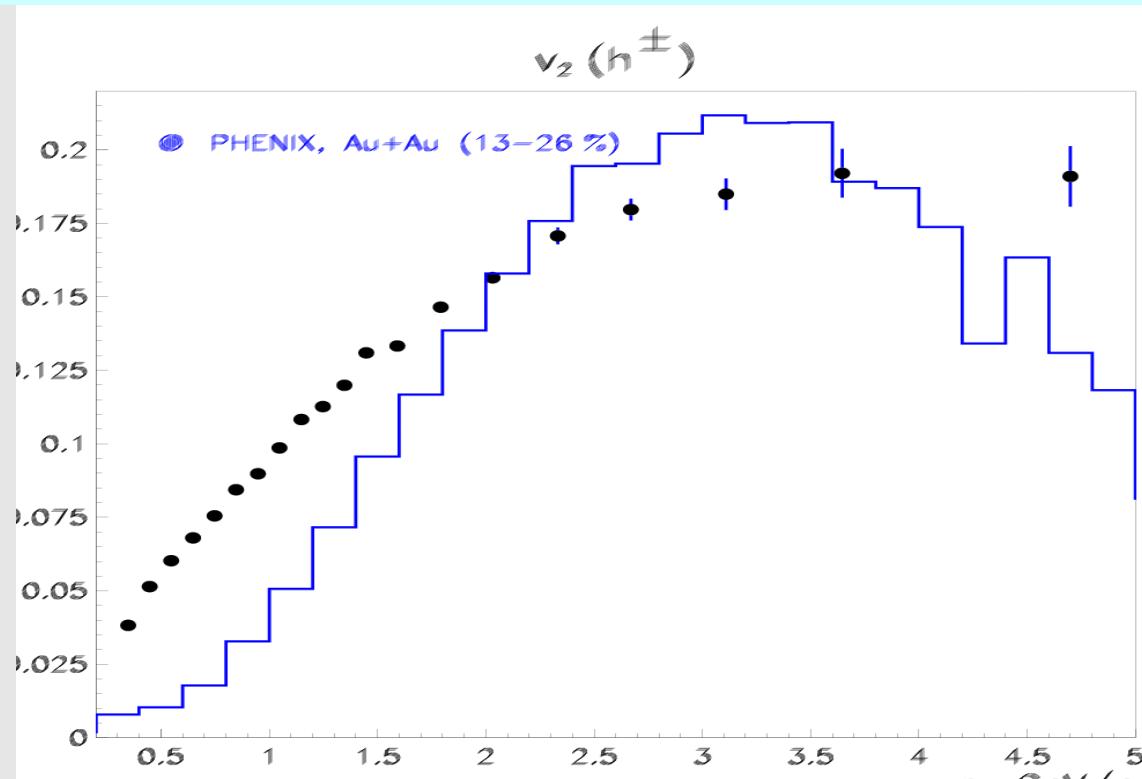
Partonic jet loss ($R_{\text{jet}} = 0.5$)

Distribution over jet energy loss, $E_t^\theta(\text{parton}) > 100 \text{ GeV}$



PYQUEN (PYQUENm) - vacuum shower **before (after)** in-medium radiation

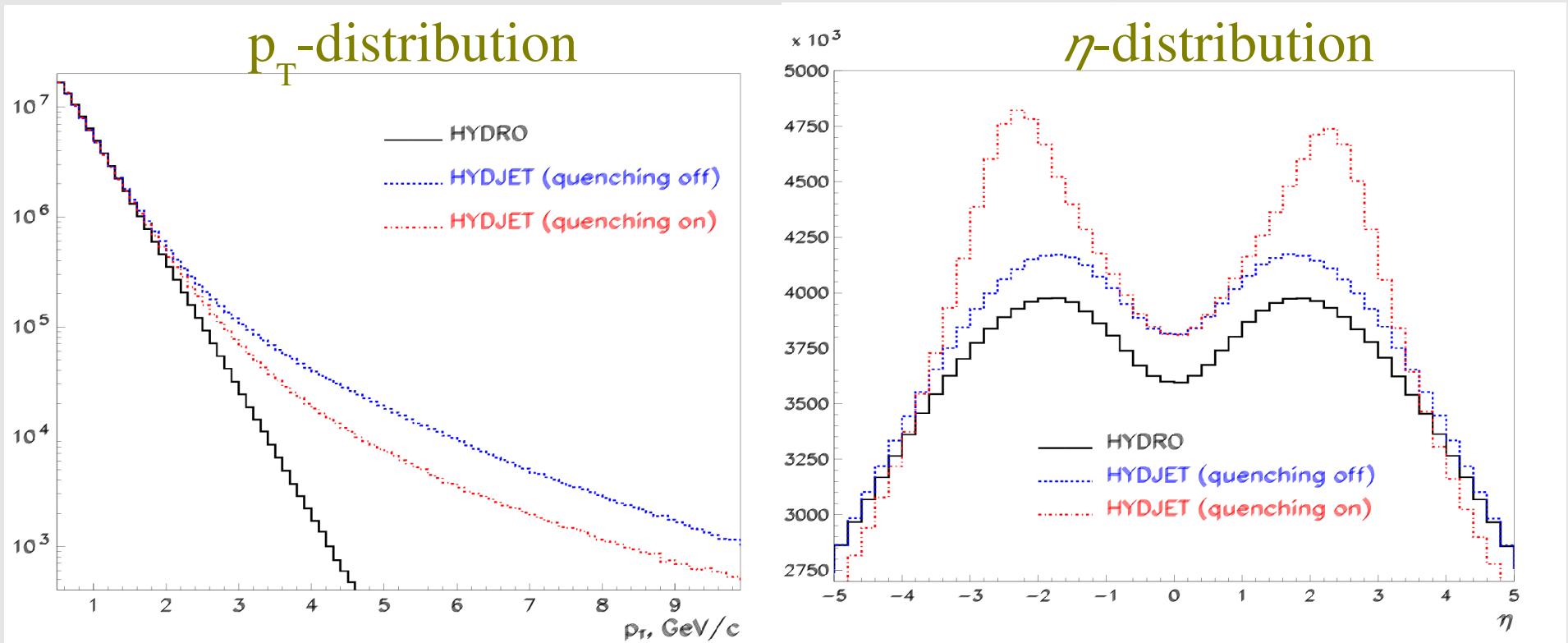
Elliptic flow at RHIC with HYJDET



Underestimation at $p_T < 2$ GeV/c due to large contribution of h^\mp from in-medium emitted “non-perturbative” gluons (at low p_T HYDRO w/o jets describes better).
Increasing p_T^{\min} remove discrepancy (LHC case)

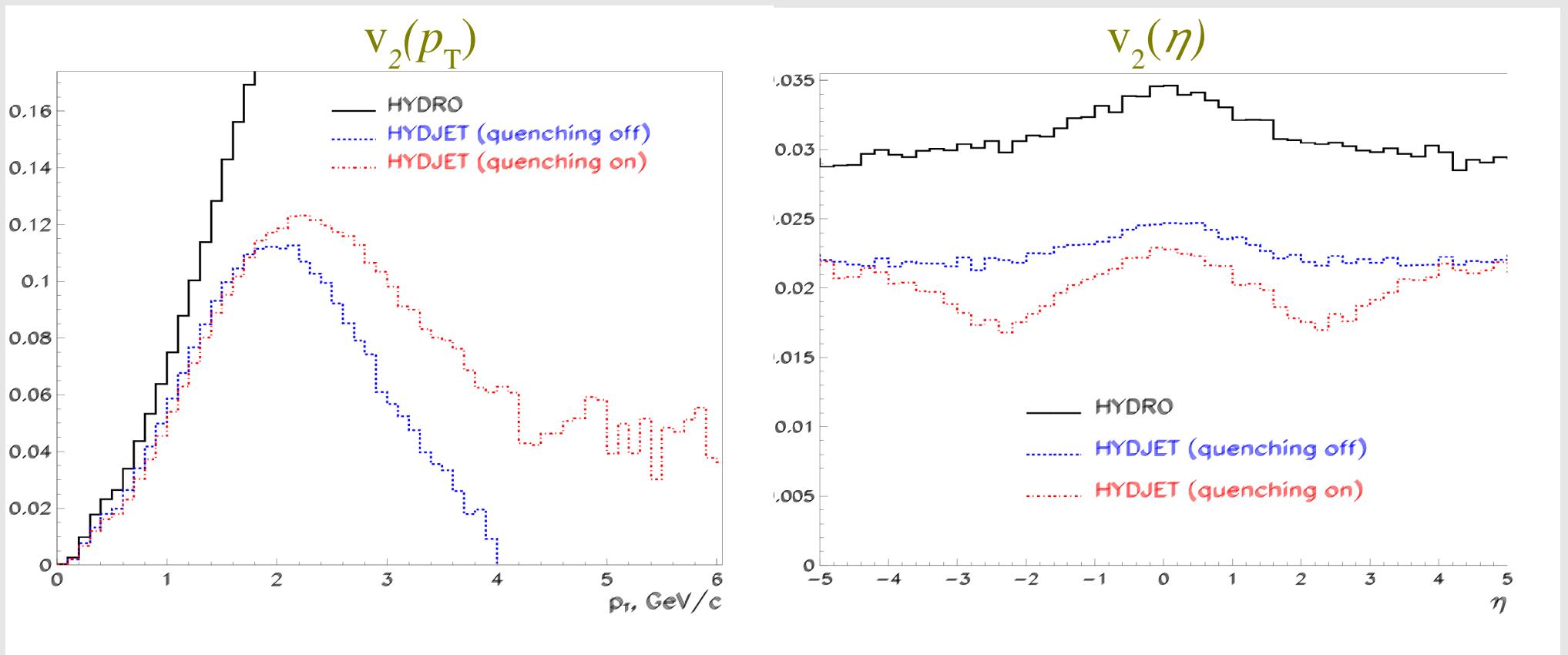
HYDJET: quenching of particle spectra

30,000 minimum bias Pb+Pb events, $\sqrt{s}=5.5\text{A TeV}$ ($p_{T, \text{min}}=10\text{ GeV}$, $n_{\text{tot}}=30000$)



p_T -spectra: strong hardening due to jets and softening due to jet quenching
 η -spectra: some broadening due to jets and narrowing due to jet quenching

HYDJET: elliptic flow



$v_2(p_T > 2 \text{ GeV})$: sharp drop due to jets and additional v_2 due to jet quenching
 $v_2(\eta)$: ~30%-reduction due to jets and small influence due to jet quenching