Статус моделей
PYQUEN, HYDJET и HYDJET++

Latest PYQUEN paper:

I.P. Lokhtin, A.V. Belyaev, A.M. Snigirev, "Jet quenching pattern at LHC in PYQUEN model", *Eur. Phys. J. C 71 (2011) 1650*

Latest HYDJET++ paper:

I.P. Lokhtin, A.V. Belyaev, L.V. Malinina, S.V. Petrushanko, E.P. Rogochaya, A.M. Snigirev, "Hadron spectra, flow and correlations in PbPb collisions at the LHC: interplay between soft and hard physics", *Eur. Phys. J. C 72 (2012) 2045*

HYDJET

Works in the frames of CMS Heavy Ion Physics Analysis Group

HYDJET and HYDJET++ relativistic heavy ion event generators

HYDJET (HYDrodynamics + JETs) - event generator to simulate heavy ion event as merging of two independent components (soft hydro-type part + hard multi-partonic state, the latter is based on PYQUEN - PYthia QUENched).

http://cern.ch/lokhtin/hydro/hydjet.html *(latest version 1.8)*

Original paper: I.Lokhtin, A.Snigirev, Eur. Phys. J. C 46 (2006) 2011

HYDJET++ (HYDJET v.2.*) – continuation of HYDJET (identical hard component + improved soft component including full set of thermal resonance production).

http://cern.ch/lokhtin/hydjet++ *(latest version 2.1)*

Original paper: I.Lokhtin, L.Malinina, S.Petrushanko, A.Snigirev, I.Arsene, K.Tywoniuk, Comp. Phys. Comm. 180 (2009) 779

HYDJET/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

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 (latest version 1.5.1)

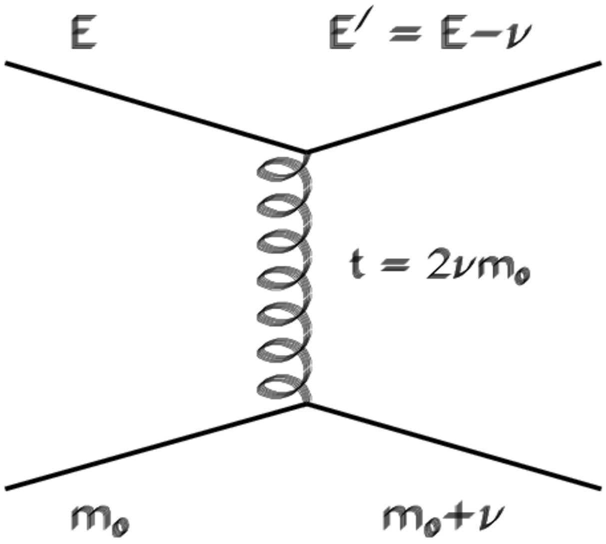
Перерассеяние и потери энергии партонов в среде («jet quenching»)

Collisional loss

(high momentum transfer approximation)

Radiative loss

(BDMS model, coherent radiation)



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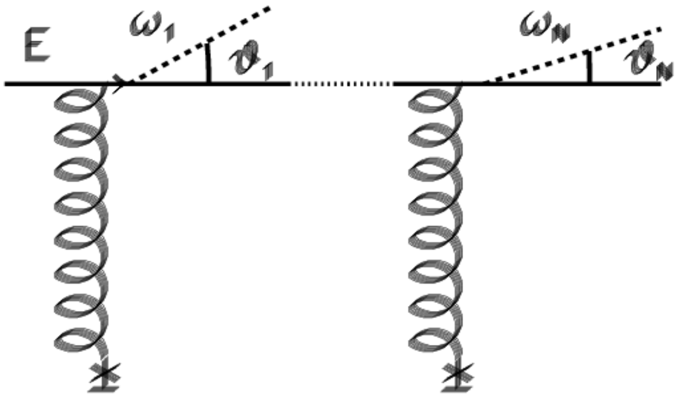


Strength of e-loss in PYQUEN is determined mainly by initial maximal temperature T0 of hot matter in central (b=0) PbPb collisions (depends also on formation time τ_0 and # of quark flavors N_f)

PYQUEN: physics frames

General kinetic integral equation:

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

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:

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

Angular structure of energy loss in PYQUEN

Radiative loss, three options (simple parametrizations) for angular distribution of in-medium emitted gluons:

Collinear radiation $\theta=0$

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

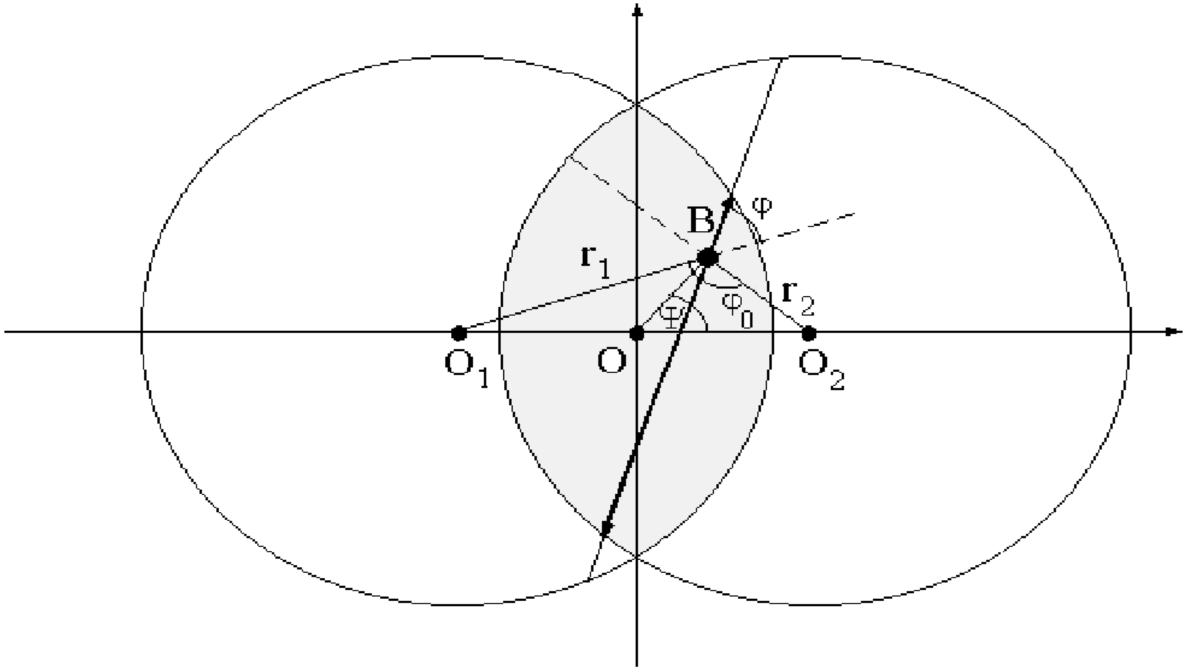
Wide-angular radiation $\frac{dN^g}{d\theta} \propto \frac{1}{\theta}$

Collisional loss always “out-of-cone” (energy is absorbed by medium)

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

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*

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

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

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

- Radiative and collisional energy loss per scattering

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

- Transverse momentum kick per scattering

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

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

- Calculating the number of hard NN sub-collisions Njet (b, Ptmin, √s) with Pt>Ptmin around its mean value according to the binomial distribution.
- 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 component by calling PYQUEN njet times.
- Correcting the PDF in nucleus by the accepting/rejecting procedure for each of Njet hard NN sub-collisions: comparision of random number generated uniformly in the interval [0,1] with shadowing factor $S(r1,r2,x1,x2,Q2) \leq 1$ taken from the adapted impact parameter dependent parameterization based on Glauber-Gribov theory *(K.Tywoniuk et al.,, Phys. Lett. B 657 (2007) 170).*

HYDJET(soft): physics frames & simulation procedure

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

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

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

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

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

HYDJET: model parameters

Minimal external input

A - beam and target nucleus atomic weight;

energy - c.m.s. energy per nucleon pair;

ifb, bmin, bmax, bfix – parameters to fix event centrality selection;

nh- total mean multiplicity of primary hadrons for soft component (PbPb, b=0); (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;

ylfl - maximum longitudinal collective rapidity, controls width of $\bar{ƒ}$-spectra;

Tf – hadron thermal freeze-out temperature;

fpart - fraction of soft multiplicity proportional to # of participants (fpart(D)=1);

sigin – inelastic NN cross-section (calculated by PYTHIA by default);

ptmin - minimal transverse momentum of “non-thermalized” initial parton-parton scatterings (=*ckin(3)* in PYTHIA; other PYTHIA parameters also can be varied);

T0, tau0, nf, ienglu, ianglu – PYQUEN parameters;

nhsel - flag to switch on/off jet production and jet quenching;

ishad - flag to switch on/off nuclear shadowing.

Internal sets for soft component

poison multiplicty distribution; thermal particle ratios.

HYDJET (soft): «post-LHC» updates

HYDJET1.8 (July 2011)

1. The set of basic resonances (ρ, ω, η, η', ϕ, K*, Λ) for the soft component is implemented. The ratios between primary hadrons are taken from the thermal model. Previously, only final π, K, p and n were considered for the soft component.

HYDJET1.7 (April 2011)

1. The additional von Neumann rejection/acceptance procedure generating hadron spectra of soft component in accordance with the Cooper-Frye freeze-out prescription is introduced.
2. The hydro-inspired parametrization for the momentum and spatial anisotropy of soft hadron emission source is implemented.

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

- HYDJET++ avoids straightforward 6-dimensional integration by using the special simulation procedure (like HYDJET): momentum generation in the rest frame of fluid element, then Lorentz transformation in the global frame → uniform weights → effective von-Neumann rejection-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

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

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 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 :

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

Particle momentum spectra are generated on the thermal freeze-out hypersurface, the hadronic composition at this stage is defined by the parameters of the system at chemical freeze-out

HYDJET++ (soft): thermal charm production

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

(A.Andronic, P.Braun-Munzinger, K.Redlich, J.Stachel,

Phys.Lett. B 571 (2003) 36; Nucl. Phys. A 789 (2007) 334)

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

γ_c - charm enhancement factor can be obtained from the equation:

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

where number of c-quark pairs N_{cc} is calculated with PYTHIA

(the factor K~2 is applied to take into account NLO pQCD corrections)

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).

6-7. Strangeness suppression factor $\gamma_S \le 1$ and charm enchancement factor $\gamma_c \ge 1$ (options to use phenomenological parameterization $\gamma_S (T^{ch}, \mu_B)$ and to calculate γ_c are foreseen).

8-9. Thermodynamical parameters at thermal freeze-out: T^{th} , and μ_π- effective chemical potential of positively charged pions.

10-12. Volume parameters at thermal freeze-out: proper time τ_f, its standard deviation (emission duration) $\Delta\tau_f$, maximal transverse radius R_f.

13. Maximal transverse flow rapidity at thermal freeze-out ρ_u^{max}.

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

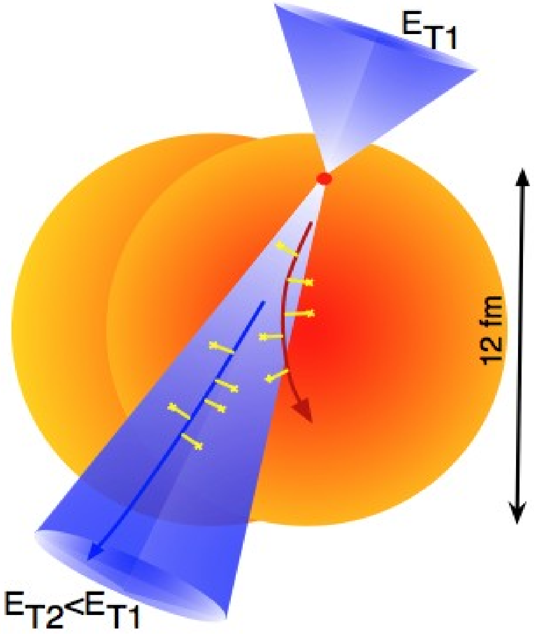
15. Flow anisotropy parameter: $\delta(b) \rightarrow u^\mu = u^\mu (\delta(b),\varphi)$

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

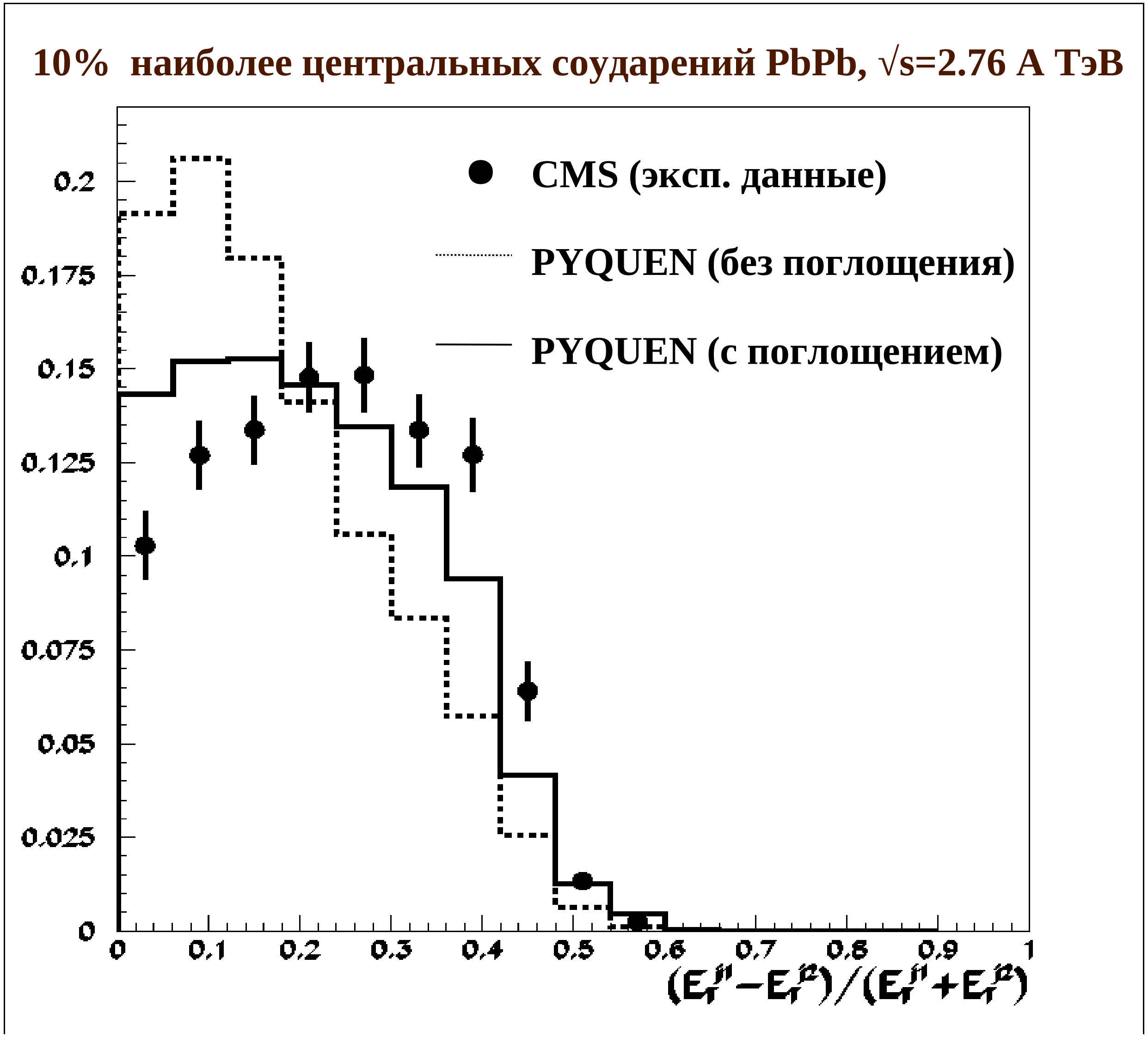
For impact parameter range bmin-bmax:

$V_{eff}(b)=V_{eff}(0)N_{part}(b)/N_{part}(0)$, $\tau_f(b)=\tau_f(0)[N_{part}(b)/N_{part}(0)]^{1/3}$

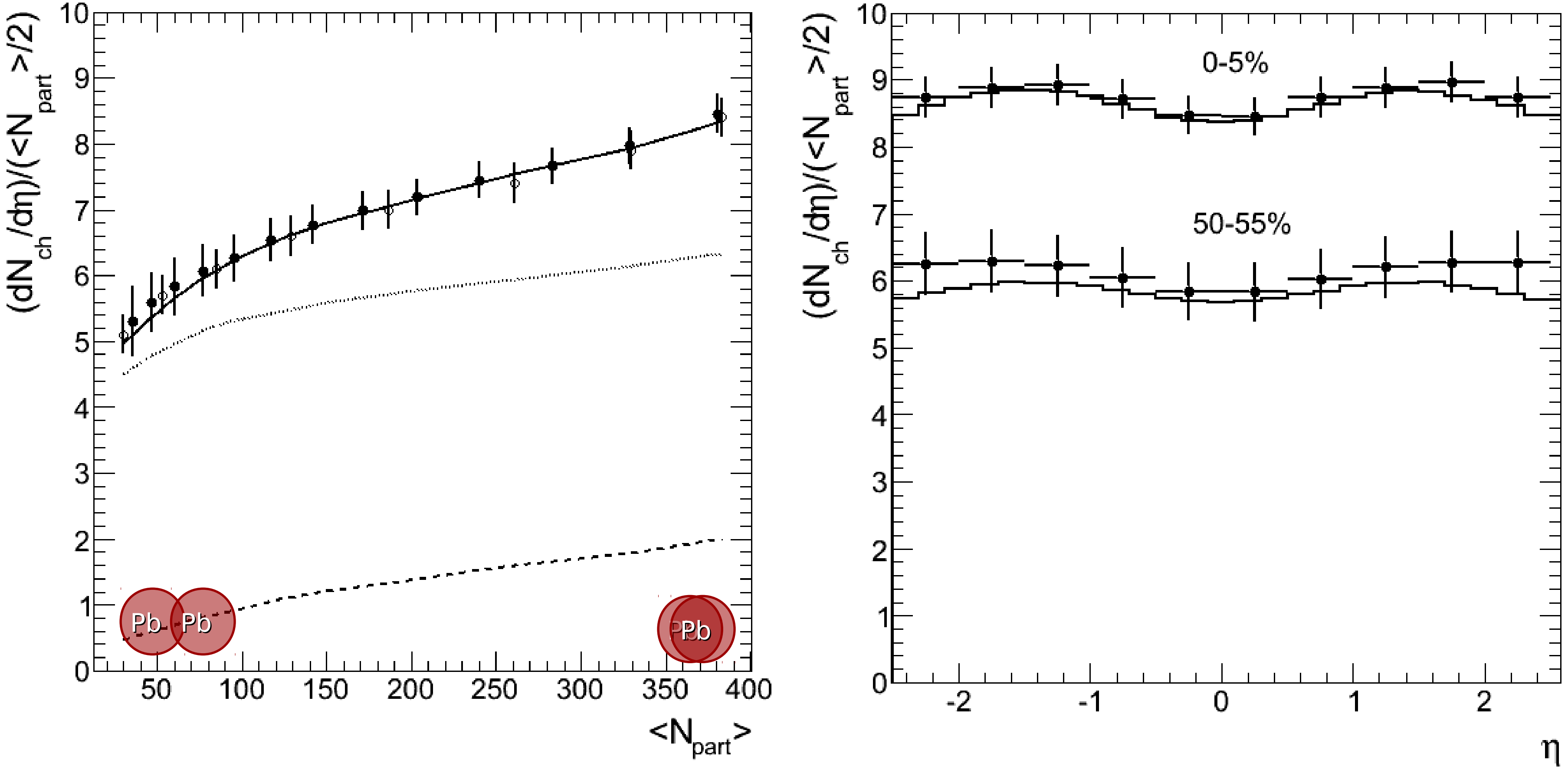
Одним из первых новых результатов LHC в соударениях ионов свинца при √s=2.76 А ТэВ стало наблюдение асимметрии поперечной энергии пар струй в центральных соударениях PbPb, указывающее на поглощение партонных струй в высокотемпературной кварк-глюонной материи.



$$A_J = \frac{E_T^{j1} - E_T^{j2}}{E_T^{j1} + E_T^{j2}}$$


10% наиболее центральных соударений PbPb, √s=2.76 А ТэВ

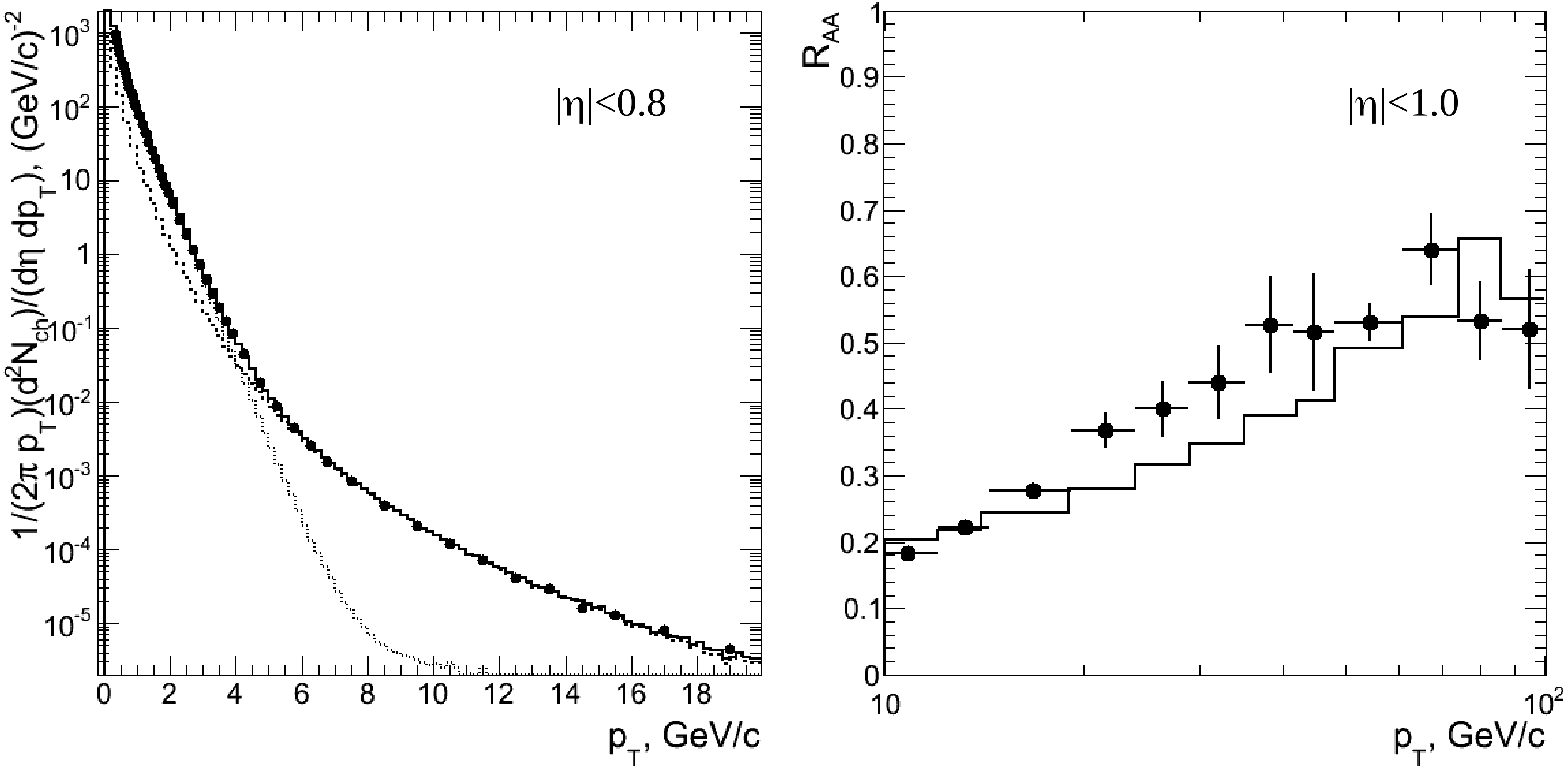
Multiplicity vs. centrality and pseudorapidity



Open points: ALICE data *(PRL 106 (2011) 032301)*, closed points: CMS data (*JHEP 1108 (2011) 141*), histograms: HYDJET++ (the similar for HYDJET).

Tuned HYDJET & HYDJET++ reproduce multiplicity vs. event centrality (down to very peripheral events) with contribution of hard component to multiplicity in mid-rapidity for central PbPb ~25%(~30%), as well as approximately flat pseudorapidity distribution.

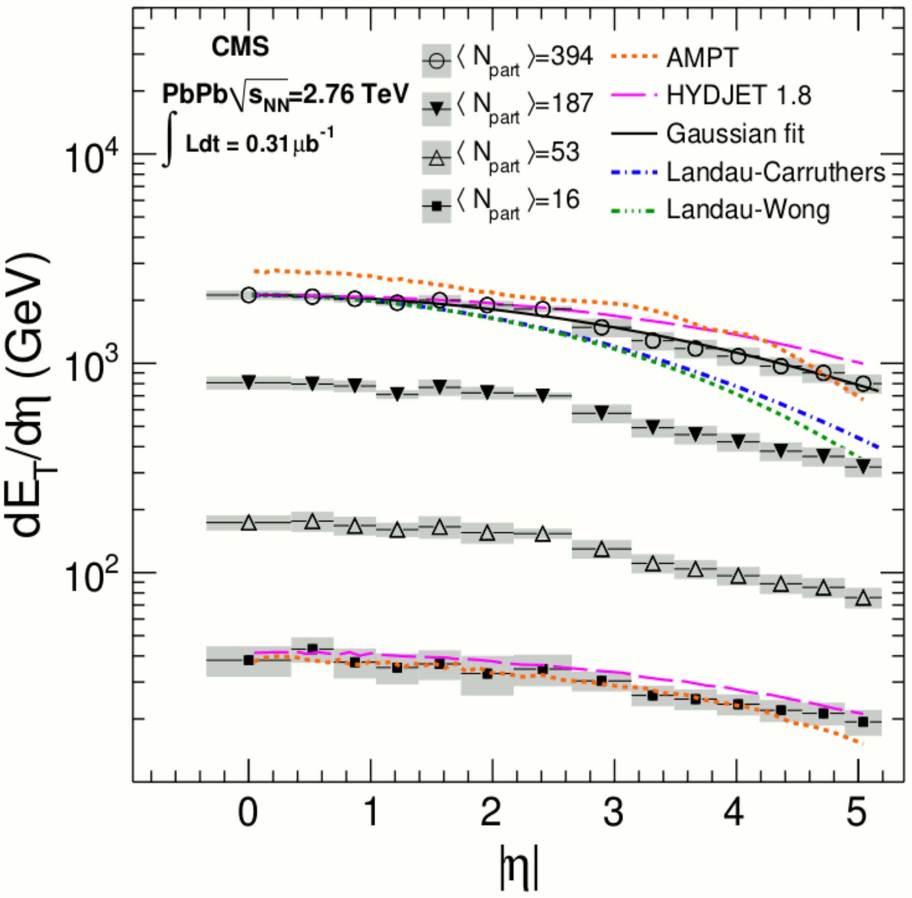
P_T-spectrum and nuclear modification factor R_{AA}

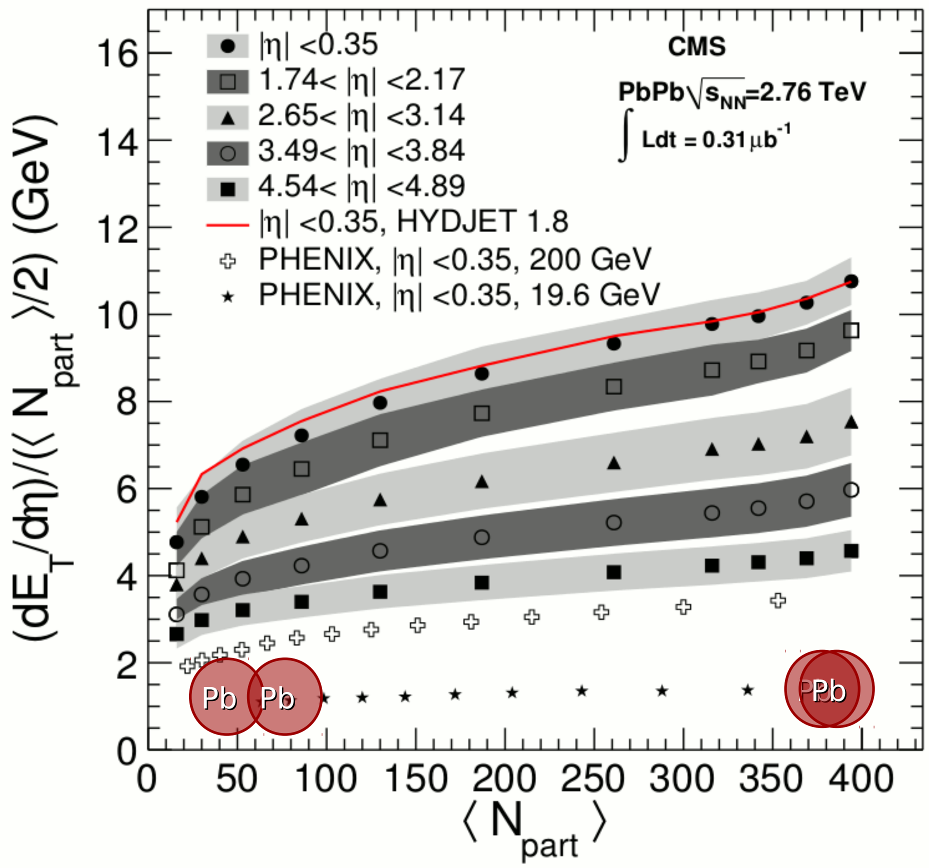


Points: ALICE (left) *(PL 696(2011) 30)* & CMS (right) (*EPJ C 72 (2012) 1945*) data,
histograms: HYDJET++ (the same for HYDJET).

HYDJET & HYDJET++ reproduce p_T-spectrum of charged particle and nuclear modification factor for central PbPb in mid-rapidity up to p_T~100 GeV/c

Energy density vs. η and centrality





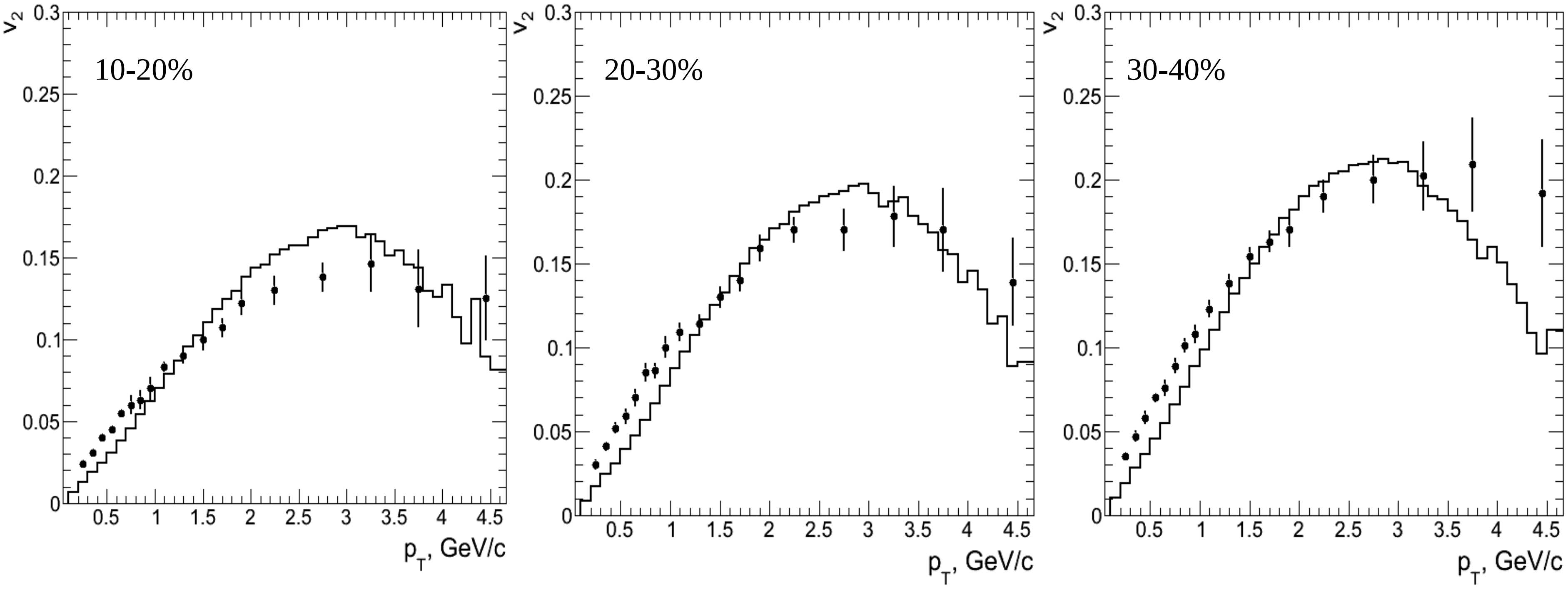
CMS Collab., Phys.Rev.Lett. 109 (2012) 152303

Hadron ratios

	ALICE data	HYDJET	HYDJET++
	(JPG 38 (2011) 124025)	PbPb, 0-5%, |η|<0.5	
$K^{\pm}/\pi^{\pm}$	0.155 ± 0.012	0.171	0.153
$p^{\pm}/\pi^{\pm}$	0.0456 ± 0.0036	0.040	0.065

Not perfect (K/π better for HYDJET++, p/ π – for HYDJET),
but depends on treatment of weak decays (off in the models).

Elliptic flow

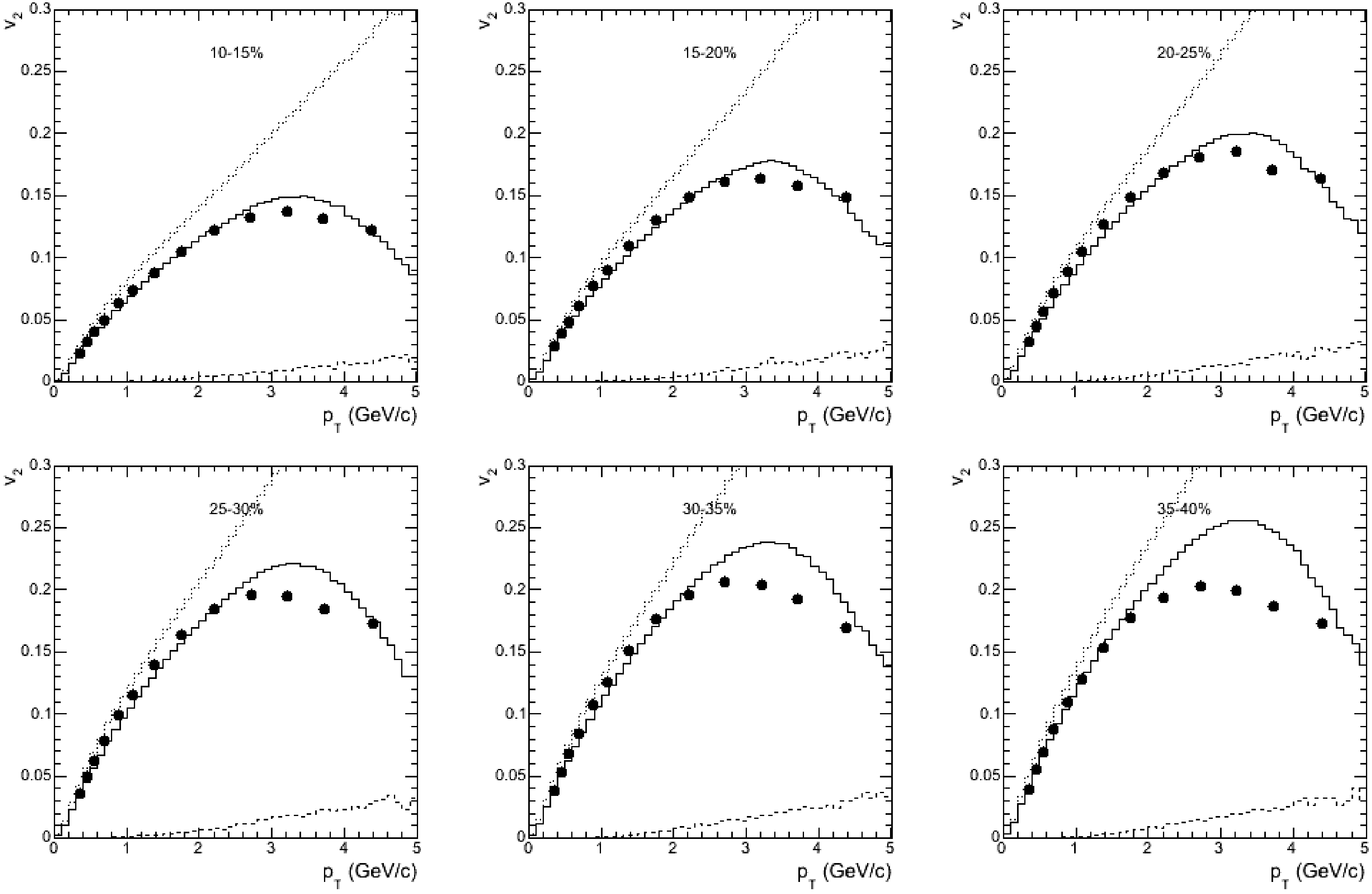


Points: ALICE data v_2\{4\} *(PRL 105(2010) 252302),*

histograms: HYDJET

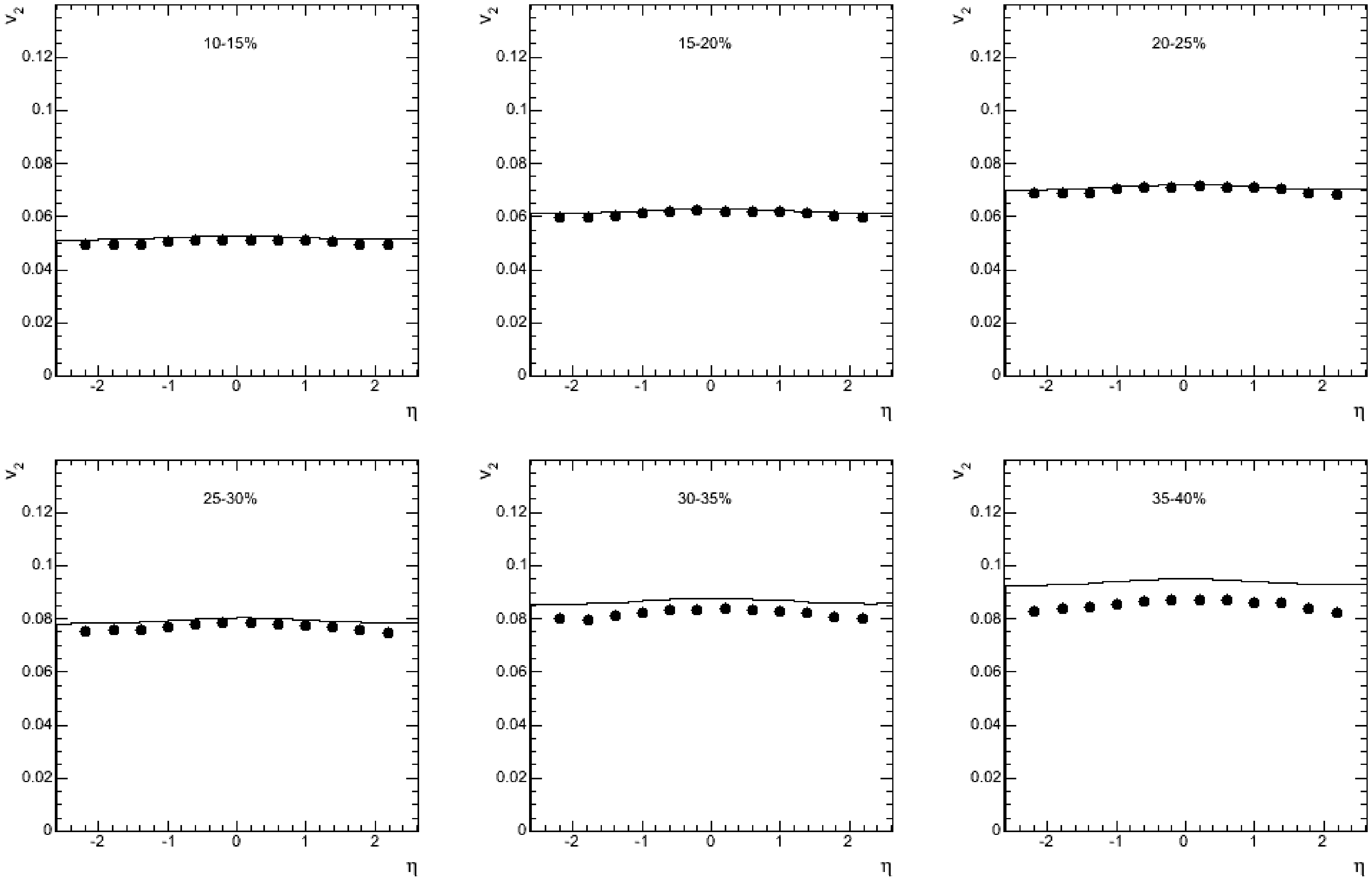
HYDJET & HYDJET++ reproduce elliptic flow coefficient v_2 up to p_T~5 GeV/c and 40% PbPb centrality

Elliptic flow



Points: CMS data $v_2\{4\}$ *(archiv:1204.1409)*, histograms: HYDJET++

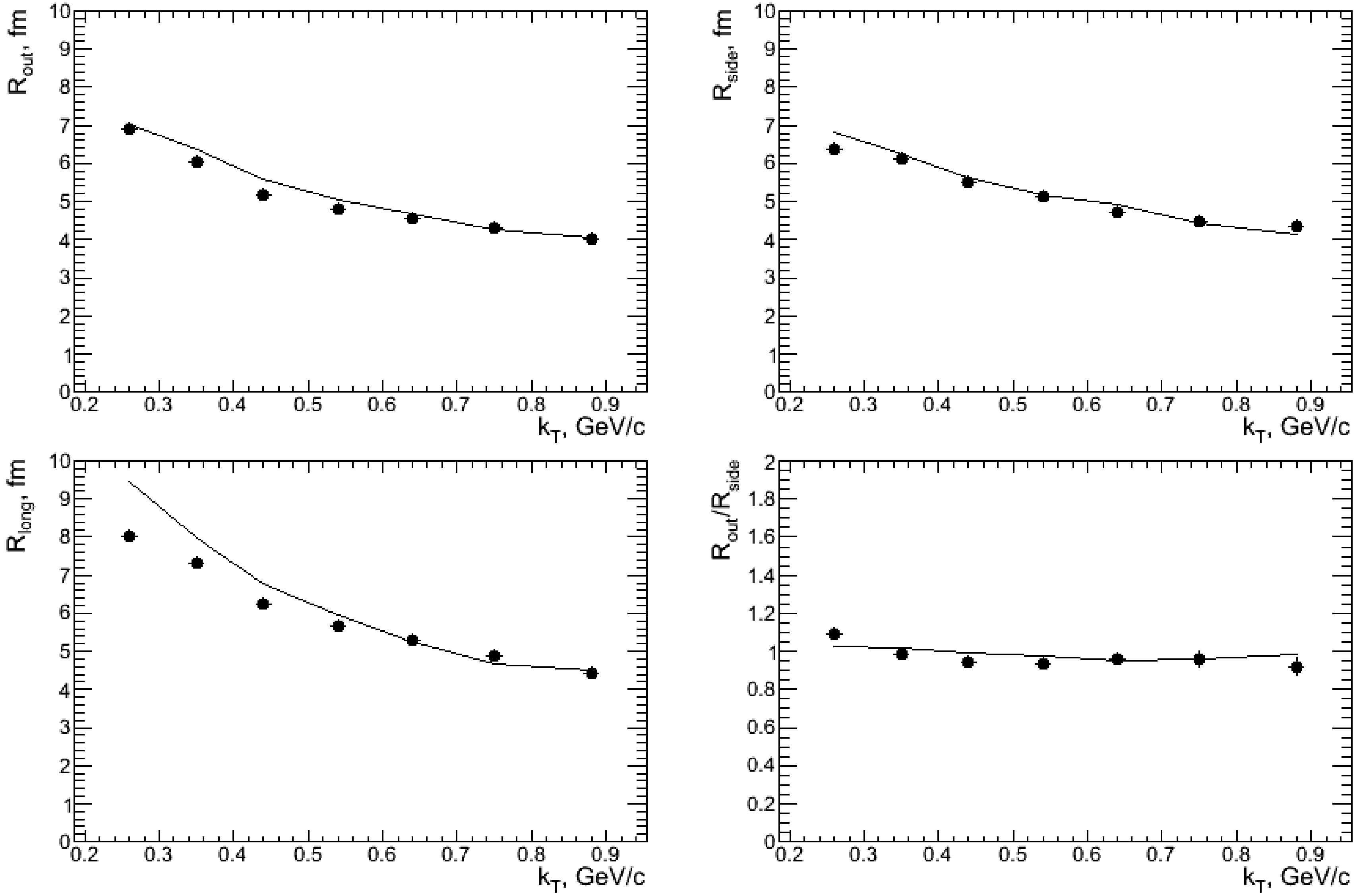
Elliptic flow



Points: CMS data $v_2\{4\}$ *(archiv:1204.1409)*, histograms: HYDJET++

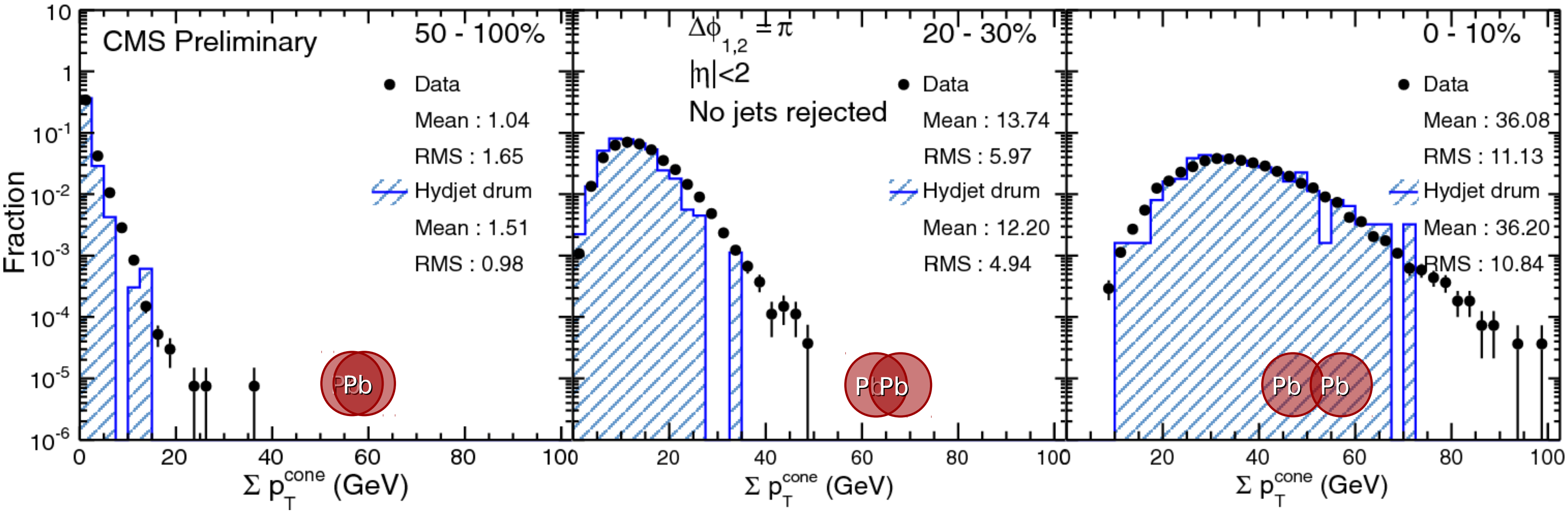
Femtoscopic momentum correlations

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



Points: ALICE data *(PLB 696 (2011) 328)*, histograms: HYDJET++

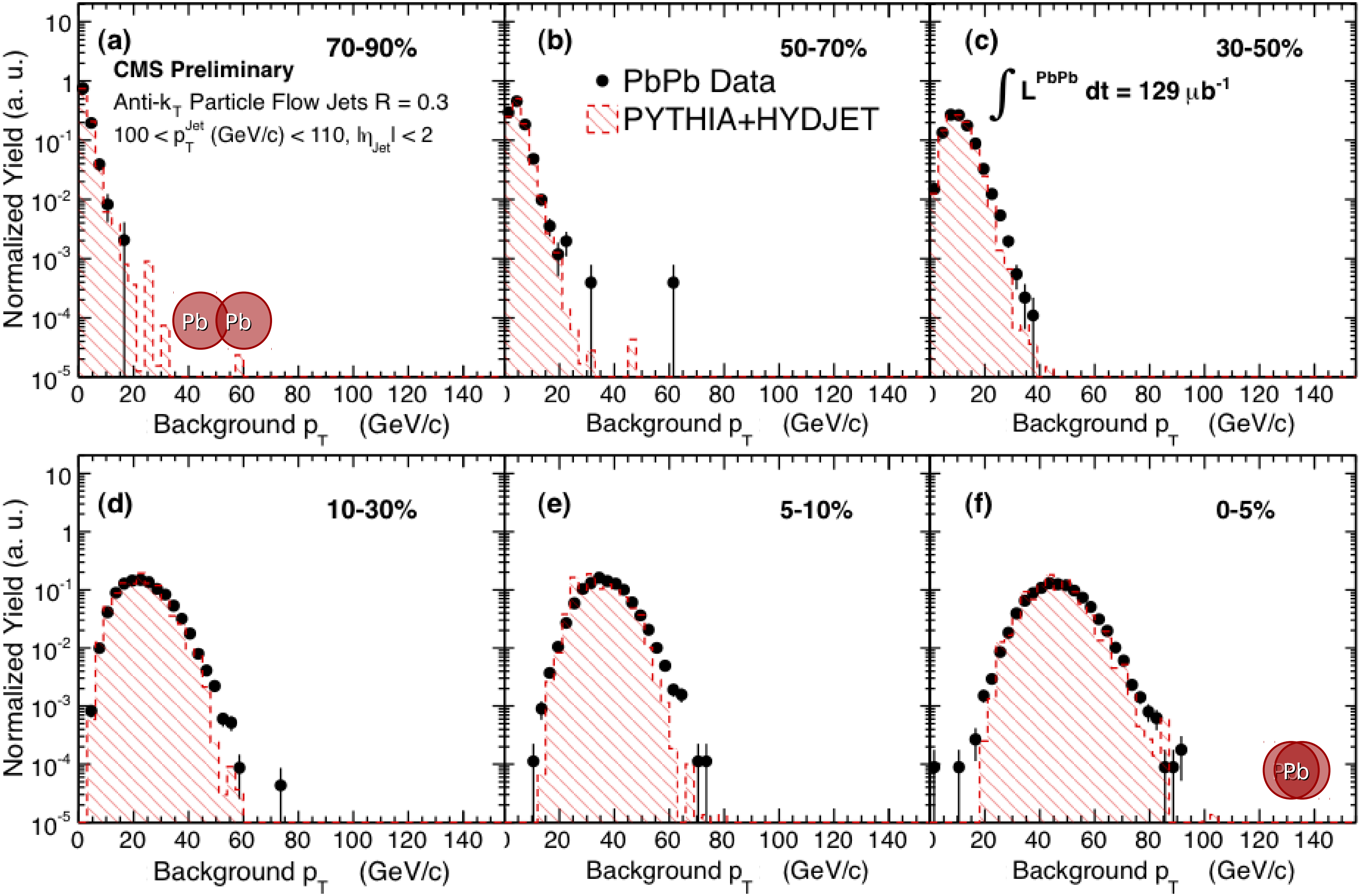
Jet background fluctuations



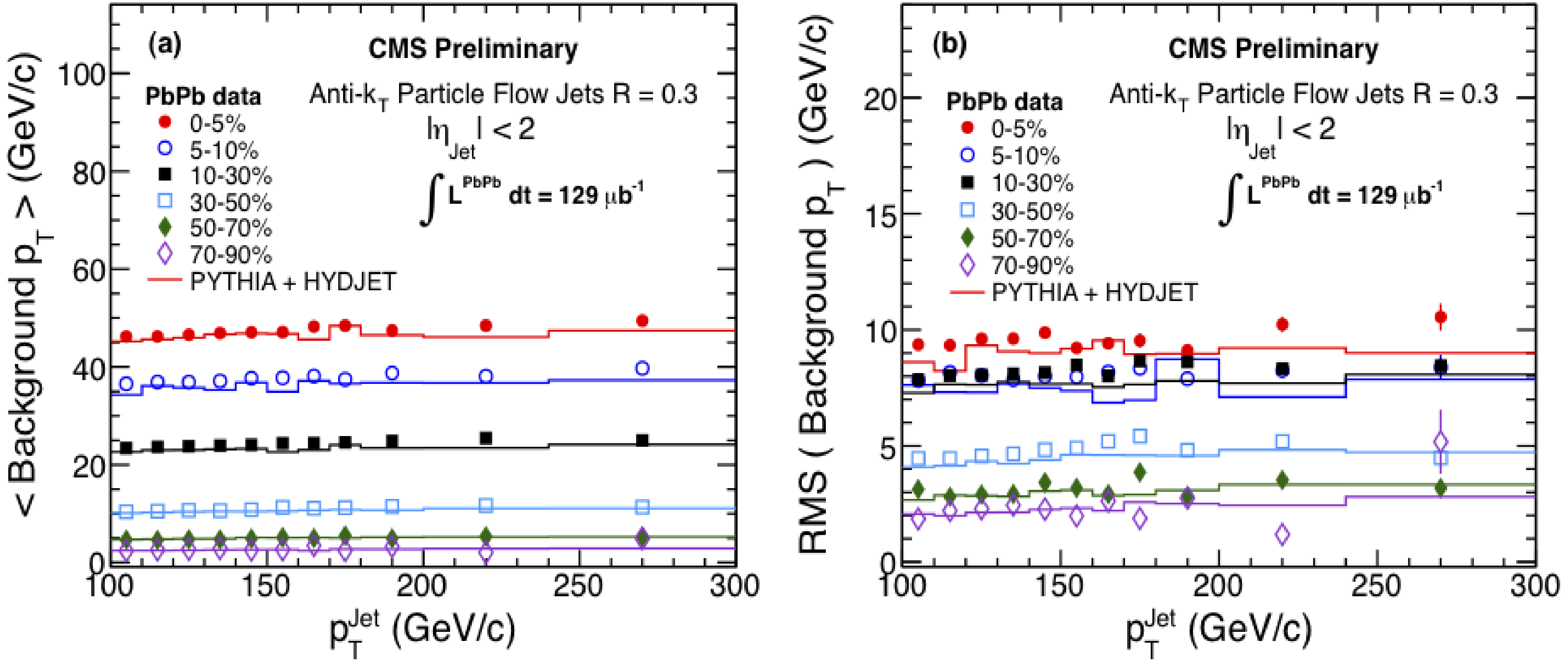
Tuned HYDJET event generator reproduces jet background fluctuations, that allows us to use it as the reference for jet quenching analysis in PbPb collisions

- Use PYTHIA and N_{coll} scaling for unquenched reference
- Embed in HYDJET (underlying event)

Validation of background

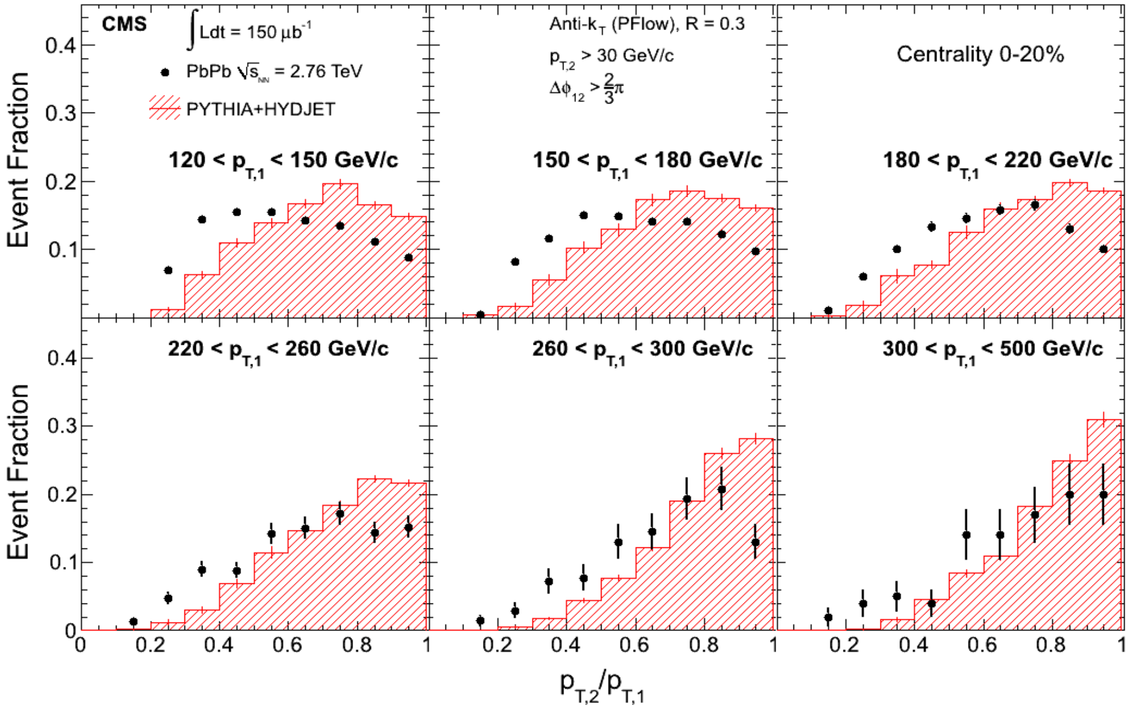


Validation of background



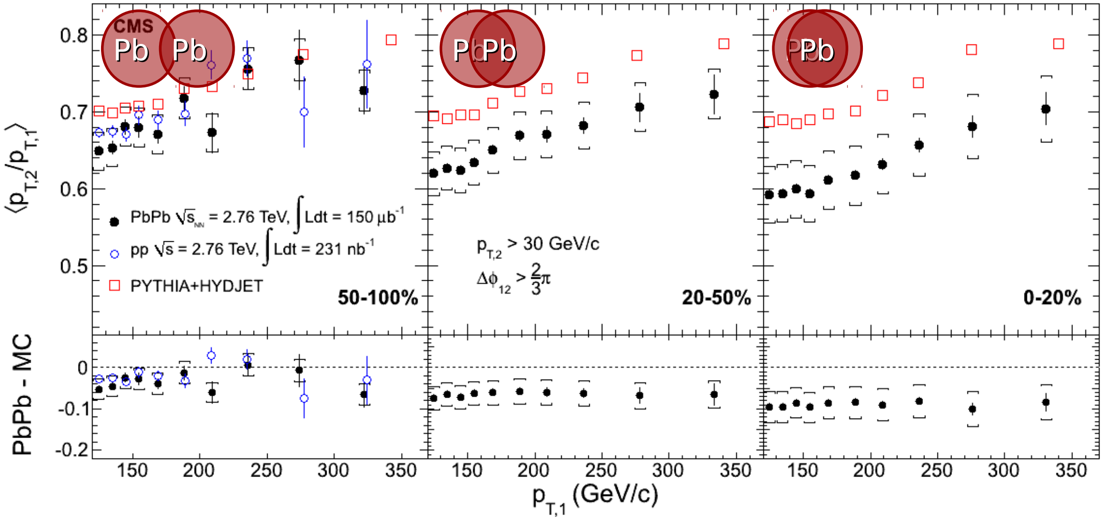
Jet momentum dependence of jet quenching

A significantly lower average dijet momentum ratio $p_{T,2}/p_{T,1}$ in central PbPb collisions than in pp and peripheral PbPb collisions, and in the dijet embedded MC simulations



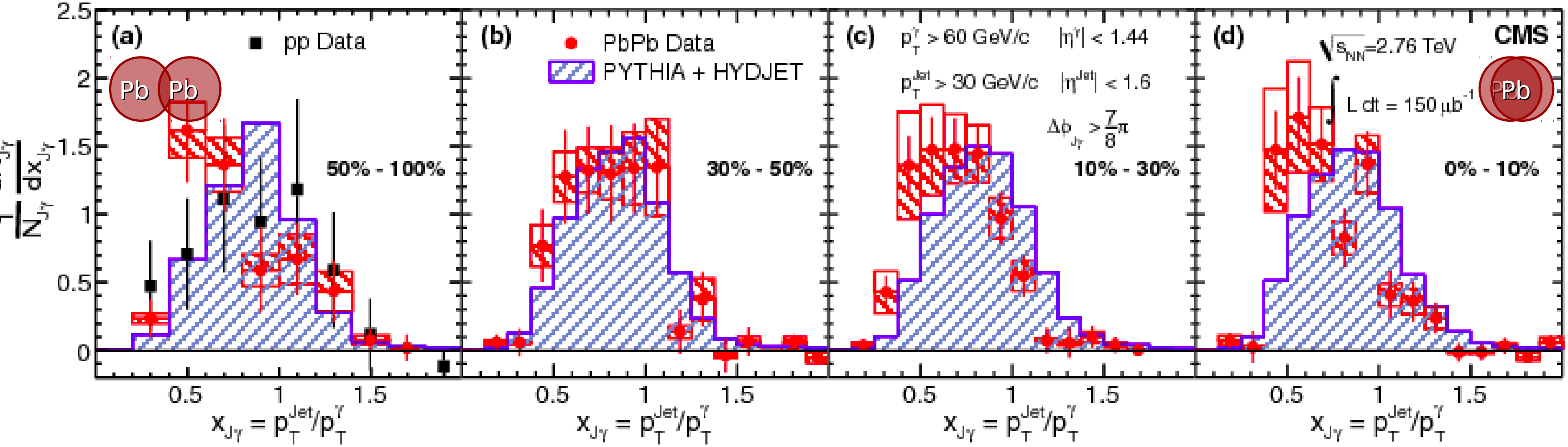
CMS Collab.,
Phys.Lett. B712 (2012) 176

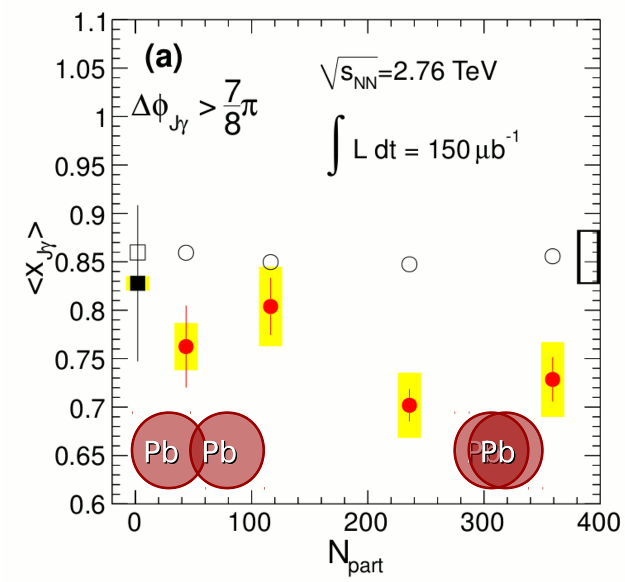
The fraction of the energy that a jet loses increases monotonically with increasing collision centrality, and does not dramatically change with jet p_T



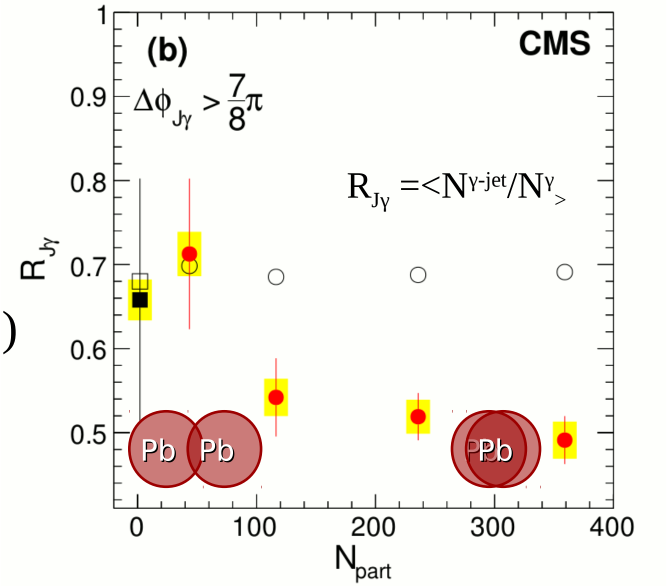
$\Delta E_{jet} \sim 0.1 E_{jet}$?

Photon+jet correlation





CMS Collab.,
Phys.Lett. B718 (2013)



A significant *shift of jet–photon p_T-ratio (~15%)* and *reducing the fraction of isolated photons with associated partner jet (~20%)* in central PbPb collisions as compared with pp and peripheral PbPb events, and MC simulations ⇒ jet quenching in hot QCD-matter