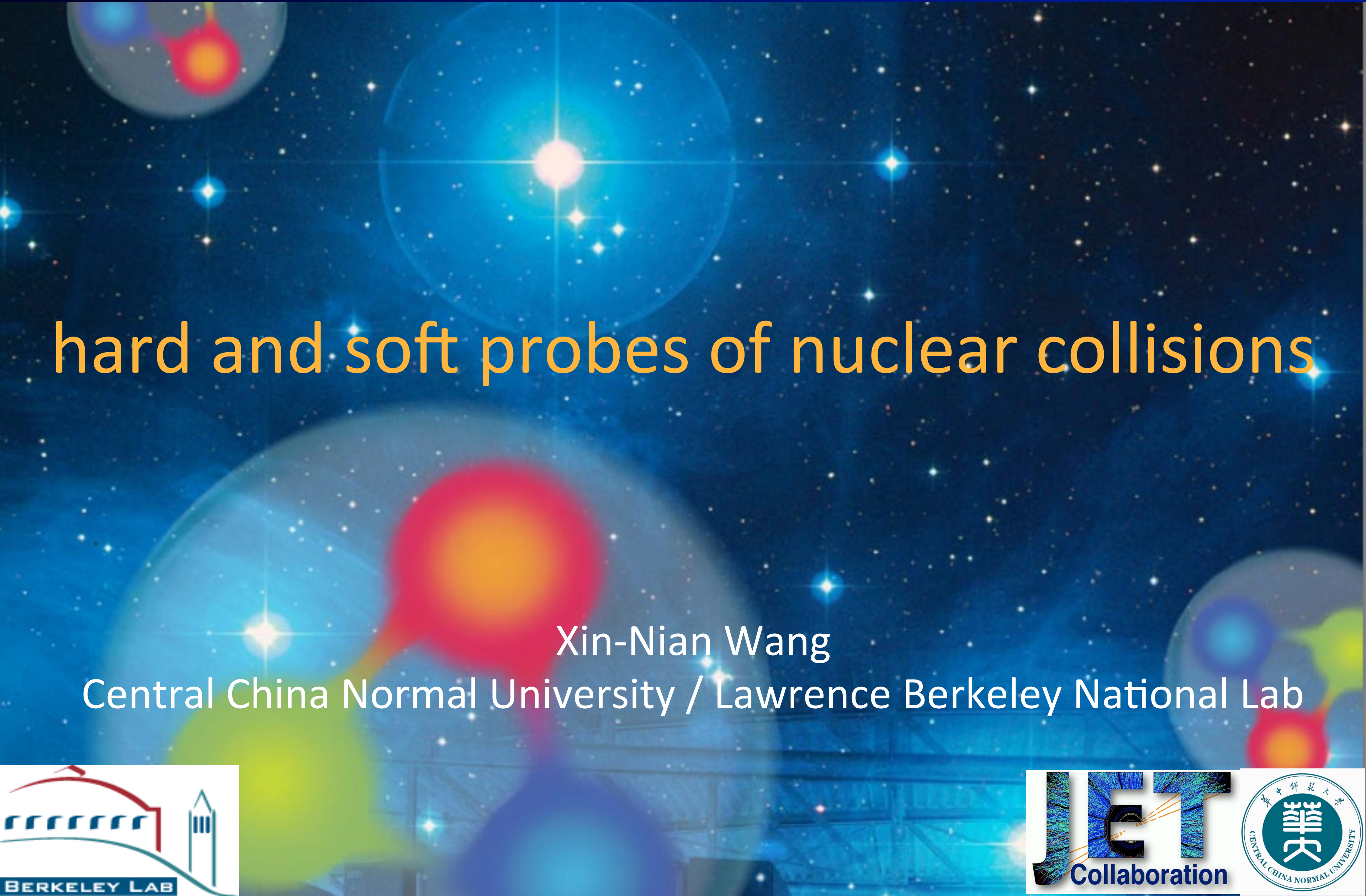
STAR Collaboration meeting, Berkeley, 10.14.2013

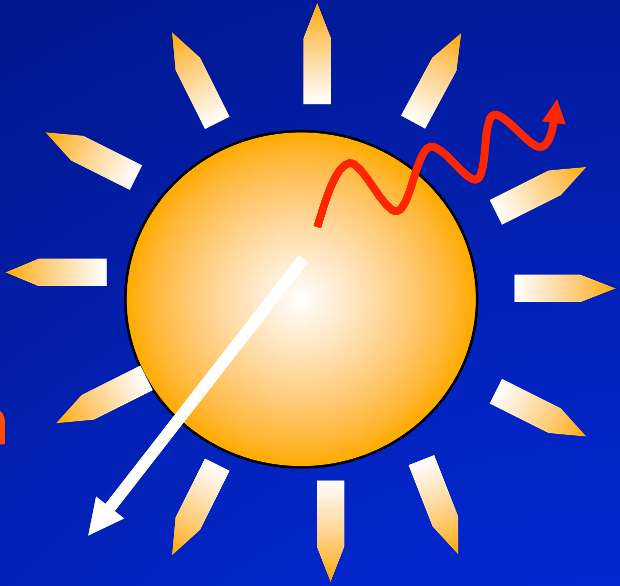


hard and soft probes of nuclear collisions

Xin-Nian Wang
Central China Normal University / Lawrence Berkeley National Lab

Properties of QGP in A+A Collisions

Dynamic System:



- EM emission: Medium response
to EM interaction

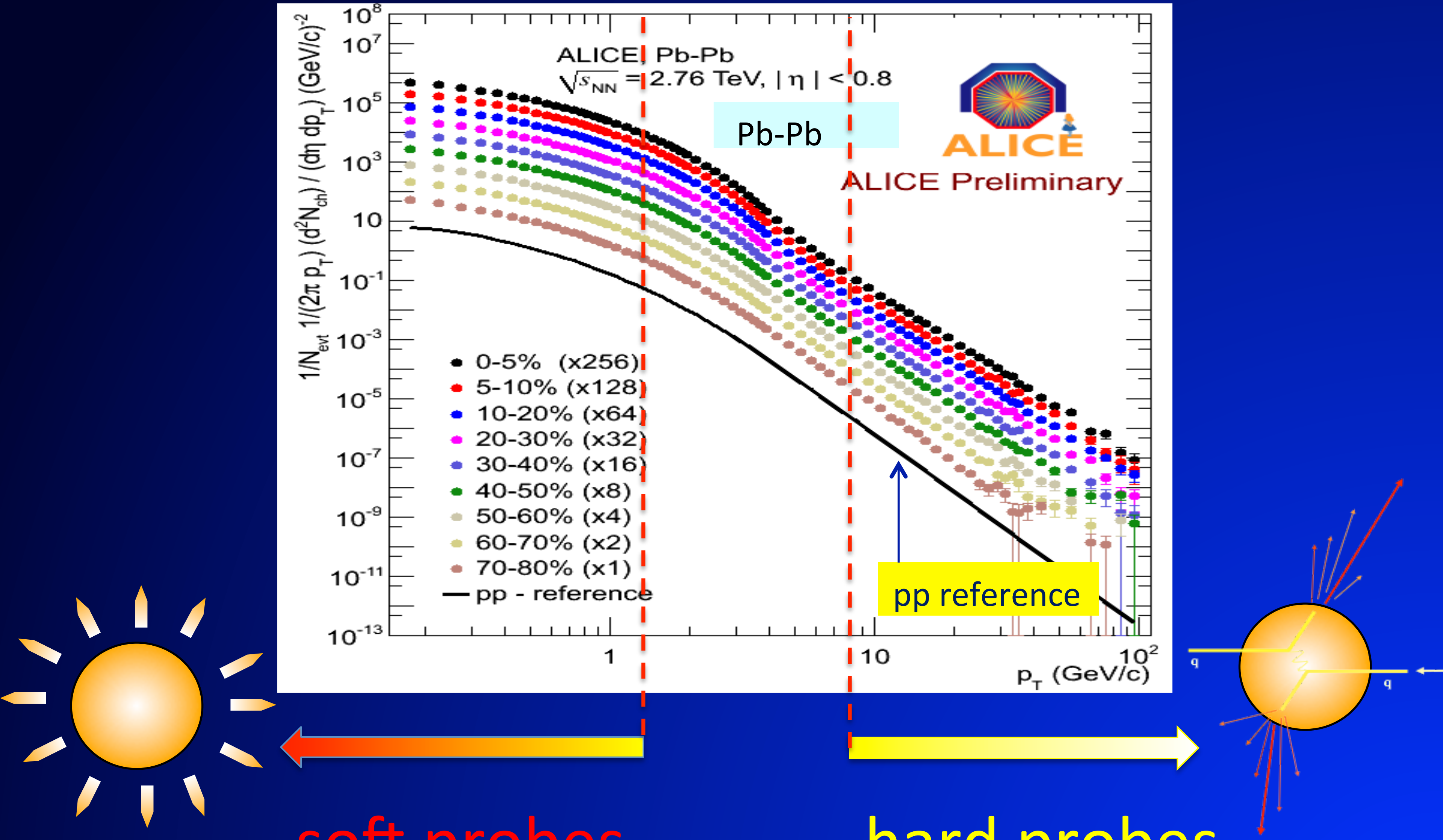
γ production, J/Ψ suppression

- Hard probes: Medium response to strong interaction

Jet quenching

- Soft probes: Bulk properties of medium
collective flow

Hard and soft probes



soft probes

hard probes

Hydro description of A+A Collisions

- Hydrodynamic: $\partial_\mu T^{\mu\nu} = 0$

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \Delta T^{\mu\nu}$$

$$\Delta T^{\mu\nu} = \eta(\Delta^\mu u^\nu + \Delta^\nu u^\mu) + (\frac{2}{3}\eta - \zeta)H^{\mu\nu}\partial_\rho u^\rho$$

  - a low-momentum effective theory
  - Inputs from first principle QCD (lattice QCD) EoS $p(\varepsilon)$, transport coefficients $\xi(T)$, $\zeta(T)$
  - Initial condition: parton prod. & thermalization

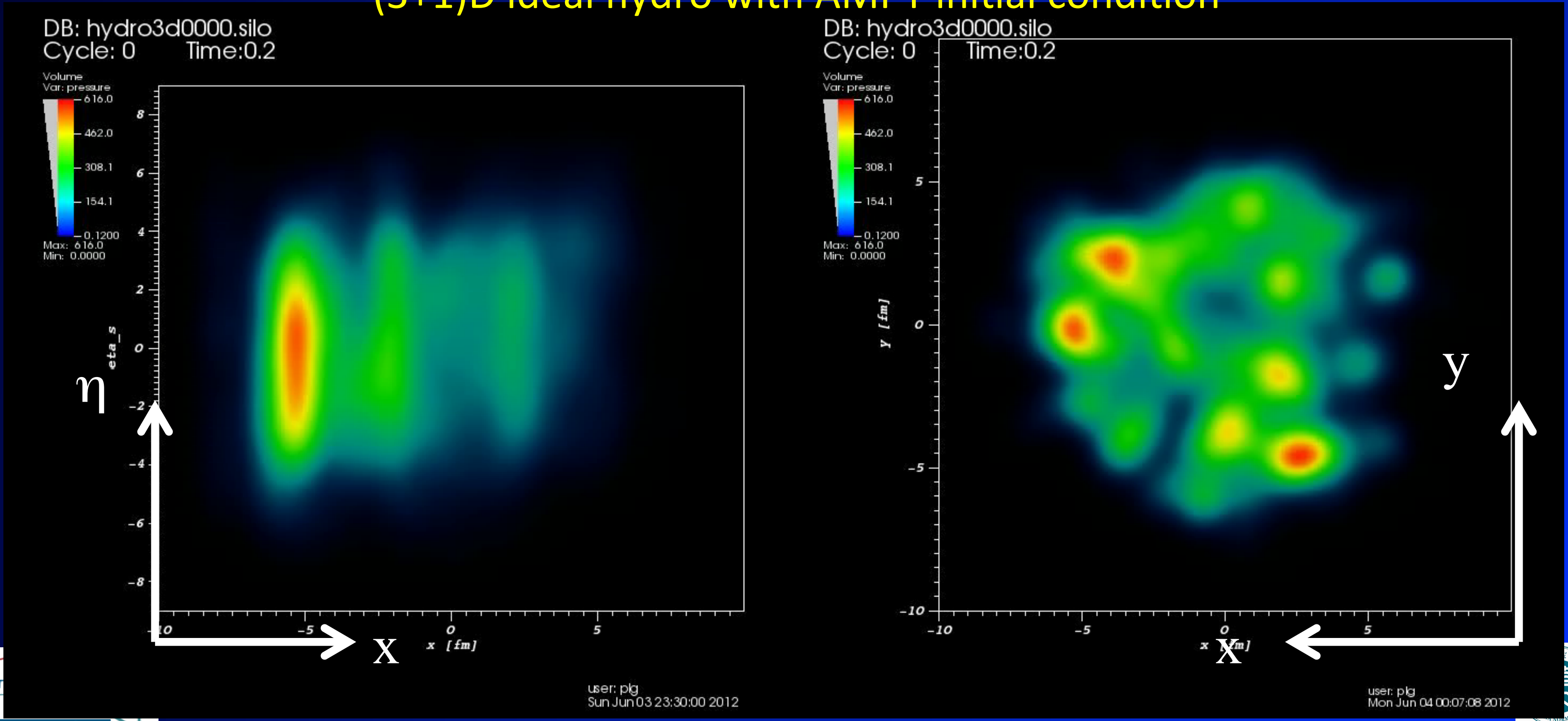
Initial conditions for hydro

2D fluctuating geometry: MC- Glauber, MC-KLN

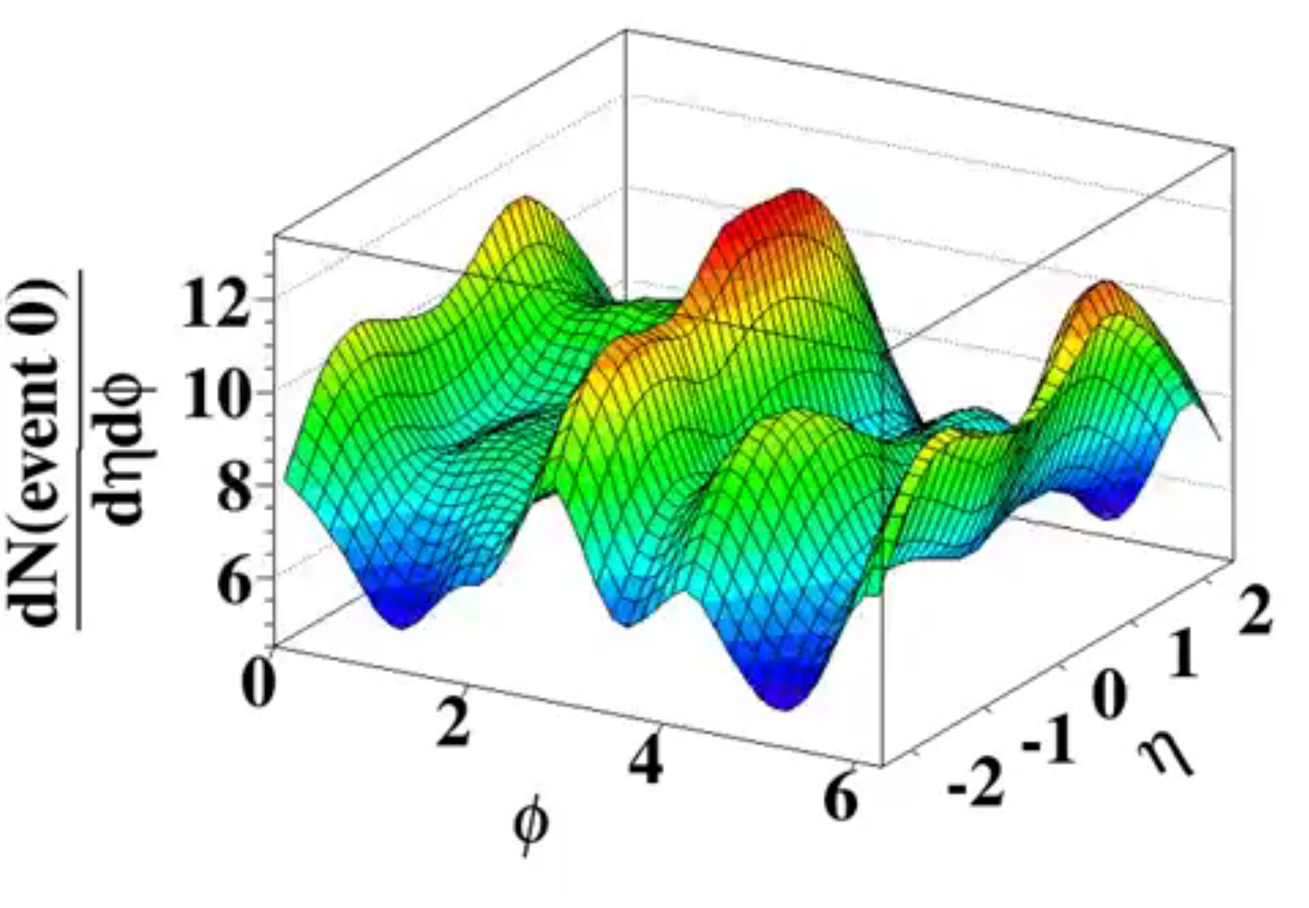
2D fluctuating geometry + QM: IP-Glasma

3D fluctuating geometry +QM: HIJING, AMPT, NeXus, UrQMD

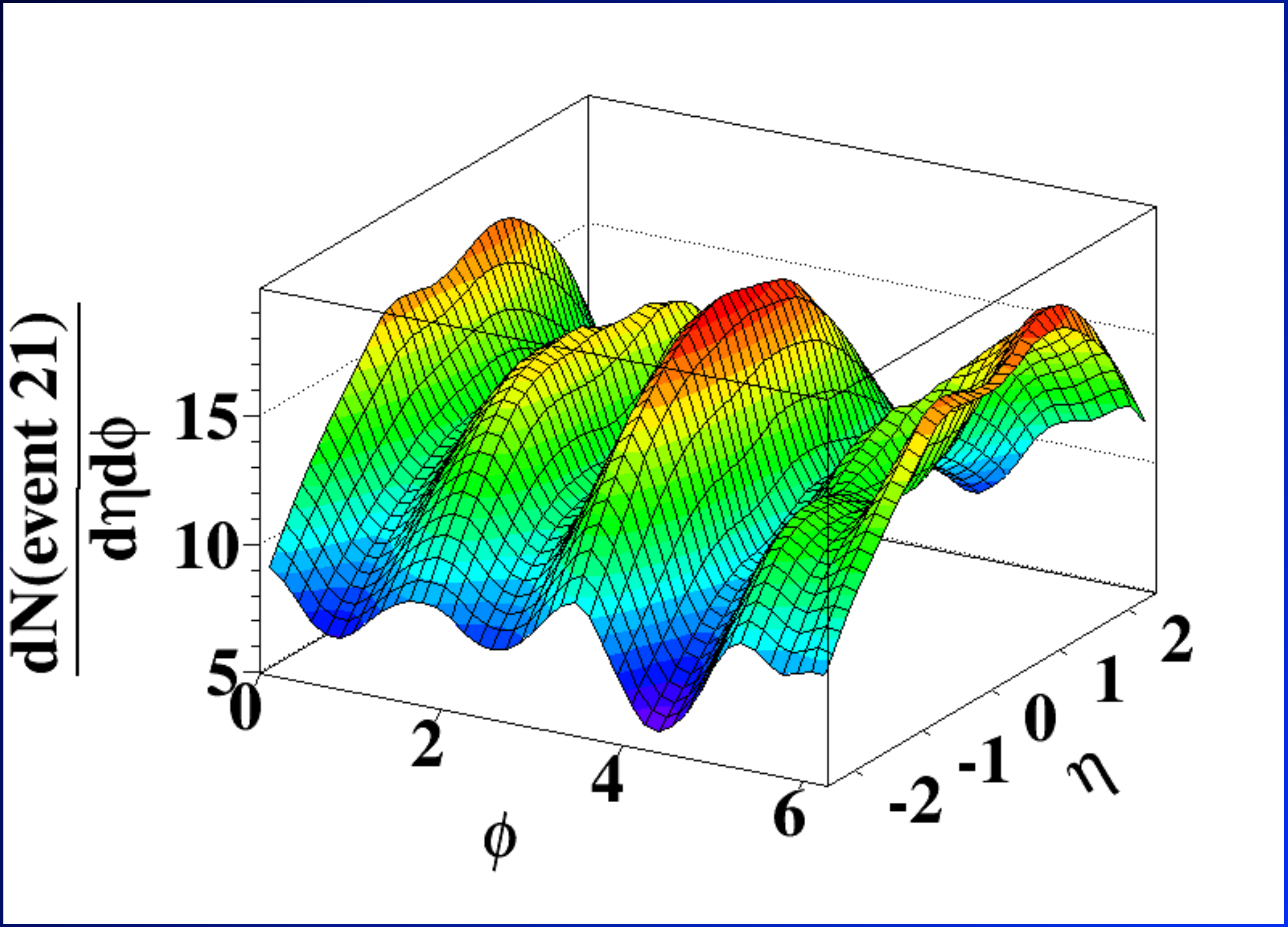
(3+1)D ideal hydro with AMPT initial condition



Event-by-event hadron distributions

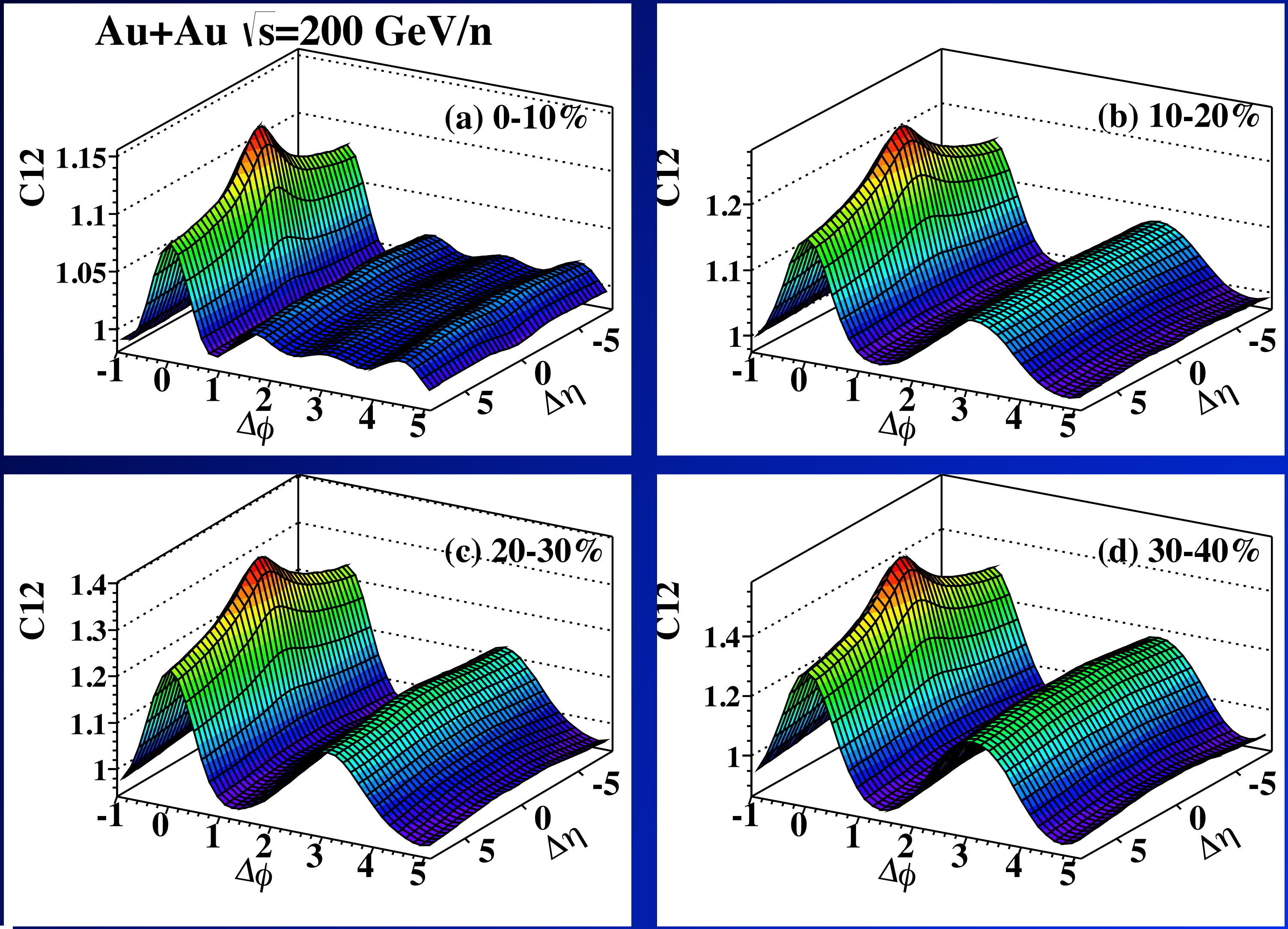


Event-by-event hadron distributions



Dihadron correlation

Pang, Wang & XNW 2013

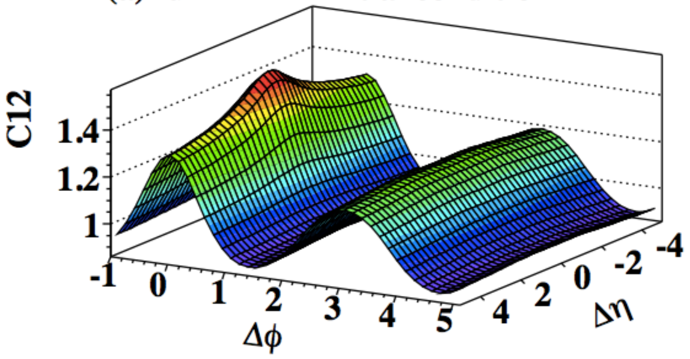


Effects of tran. & long. fluctuations

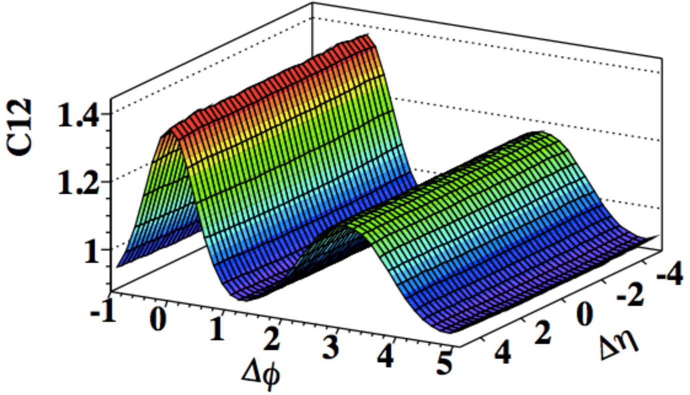
Pang , Wang and XNW PRC 81 (2012) 031903

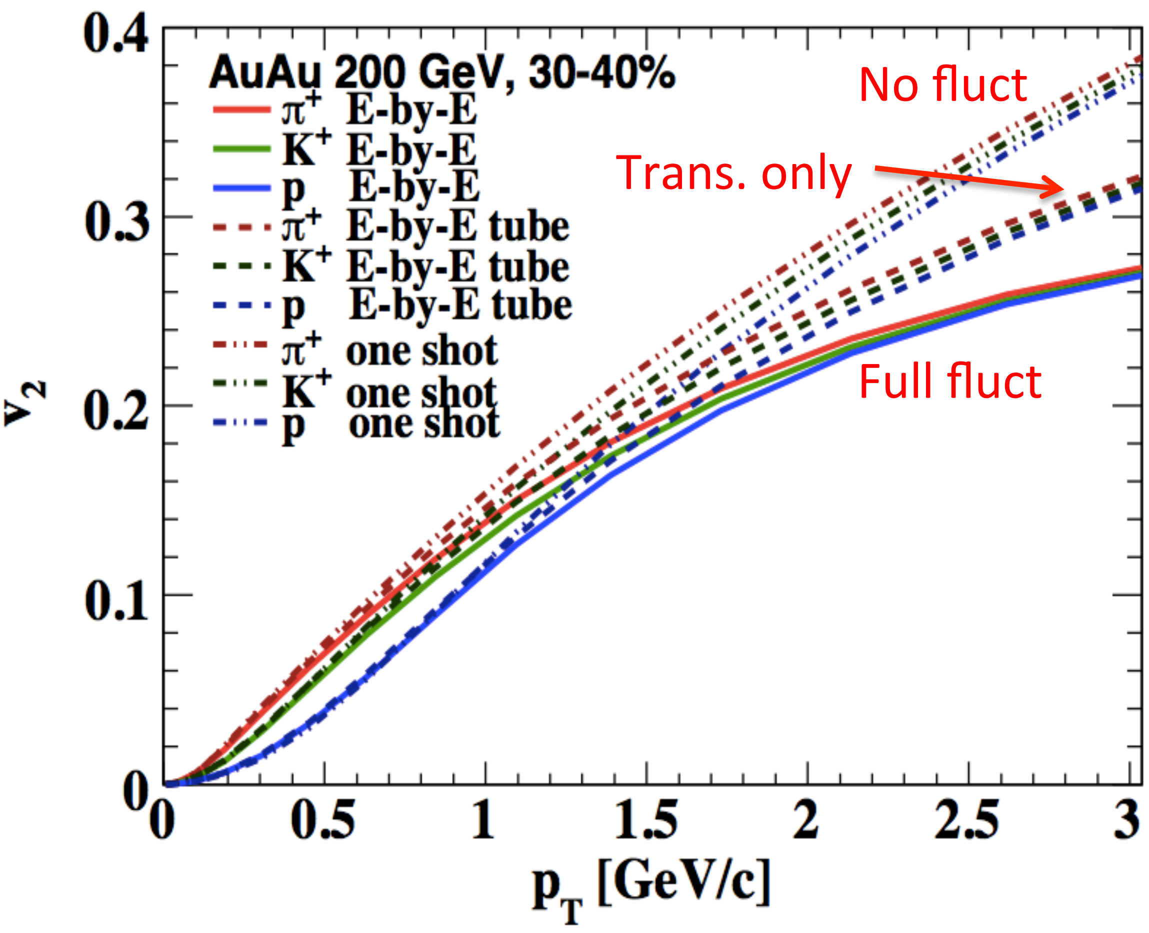
Au+Au (30-40%) √s=200 GeV/n

(a)Full AMPT initial condition



(b)Tube-like initial condition





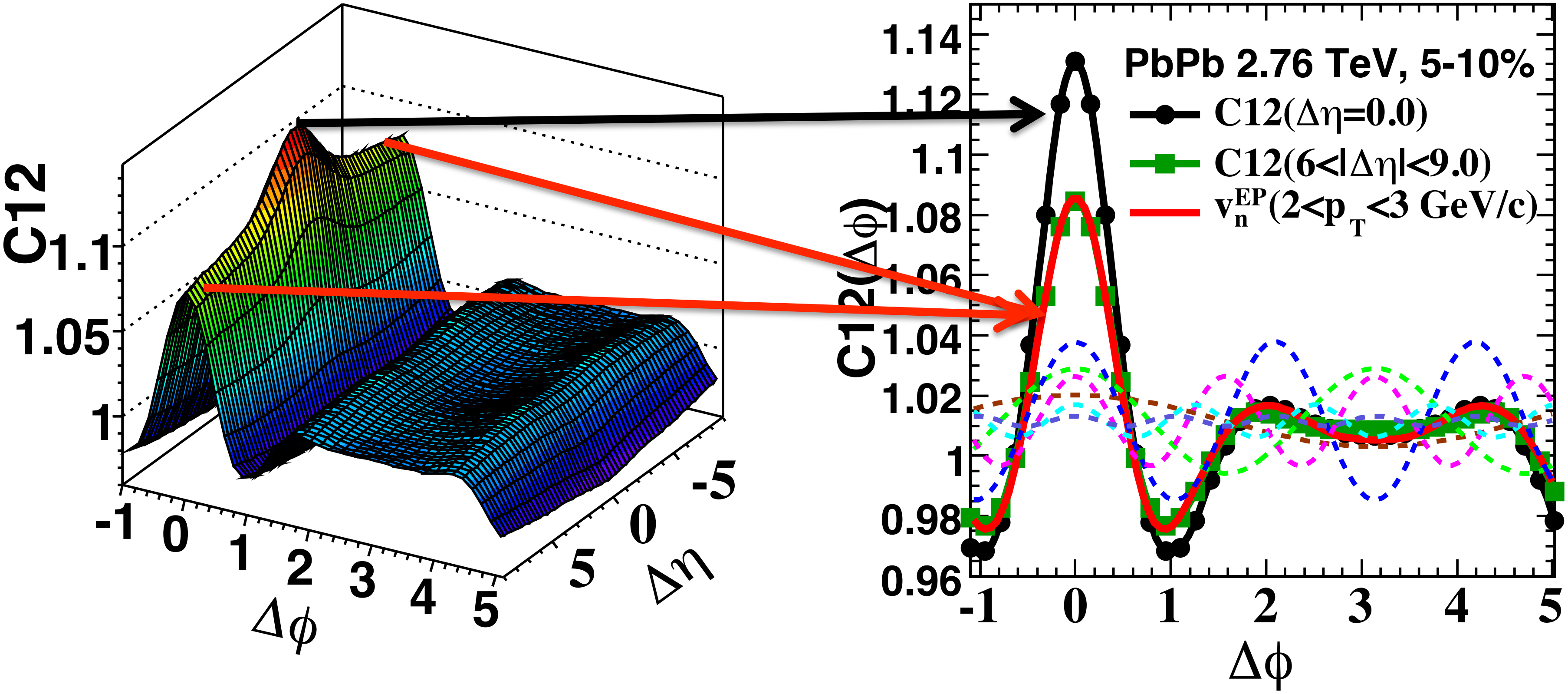
No fluct

Trans. only

Full fluct

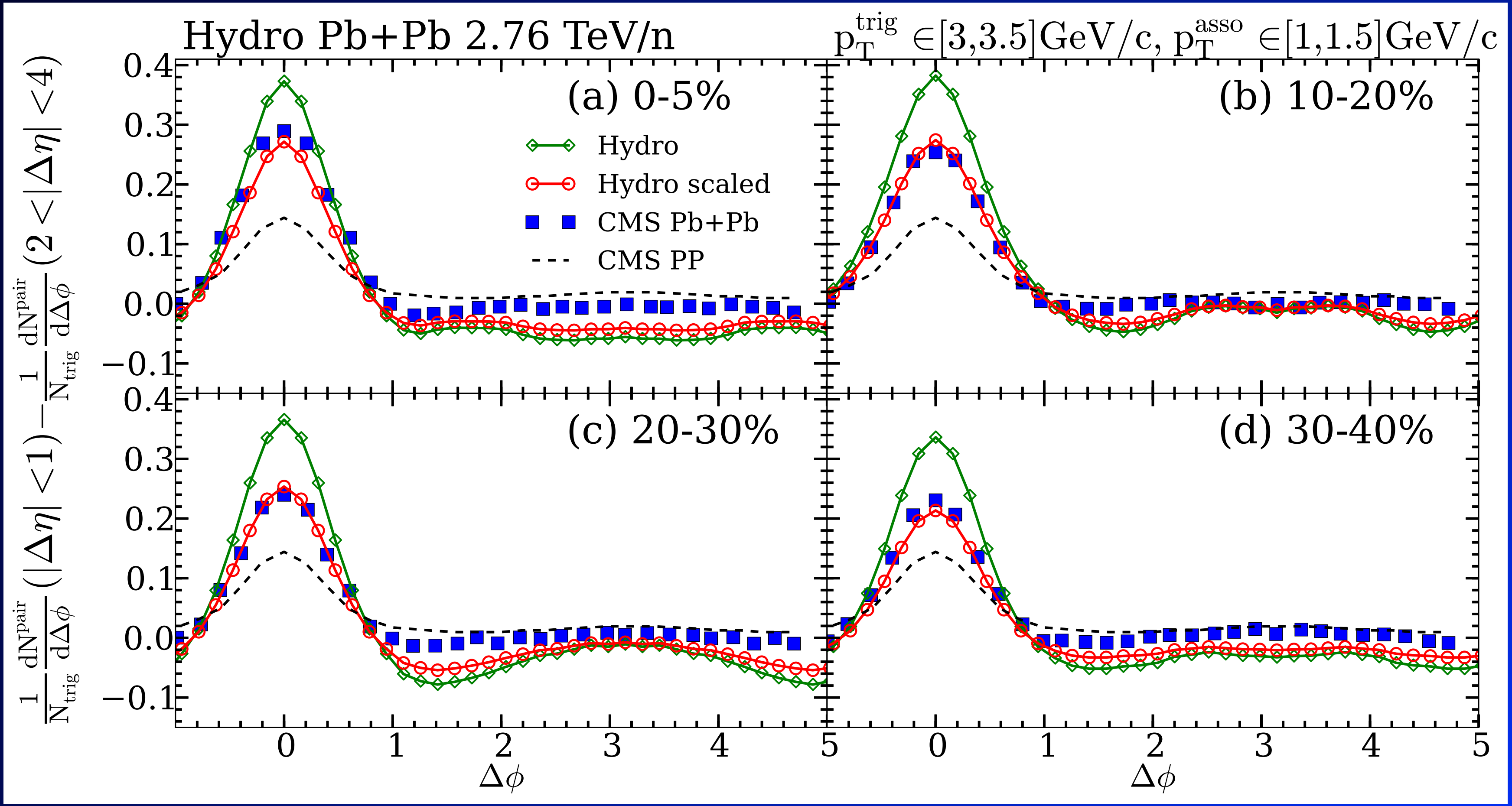
Anisotropic flow & relics of minijets

Pang, Wang & XNW 2013



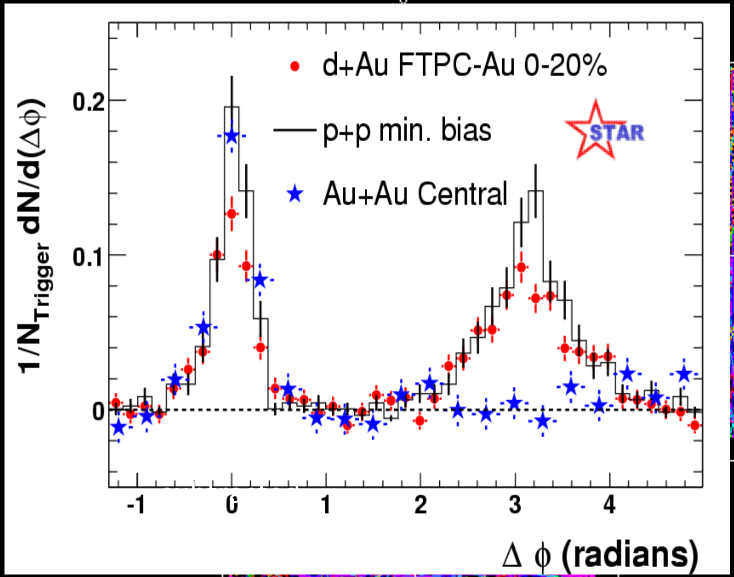
Anisotropic flow & relics of minijets

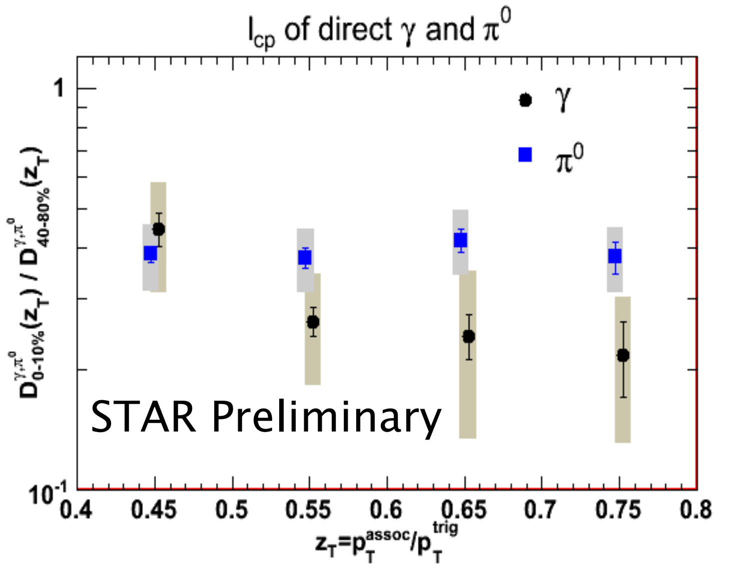
$$[C_{12}(\Delta\eta = 0) - C_{12}(\Delta\eta = 2.5)]\, B(0,0)$$

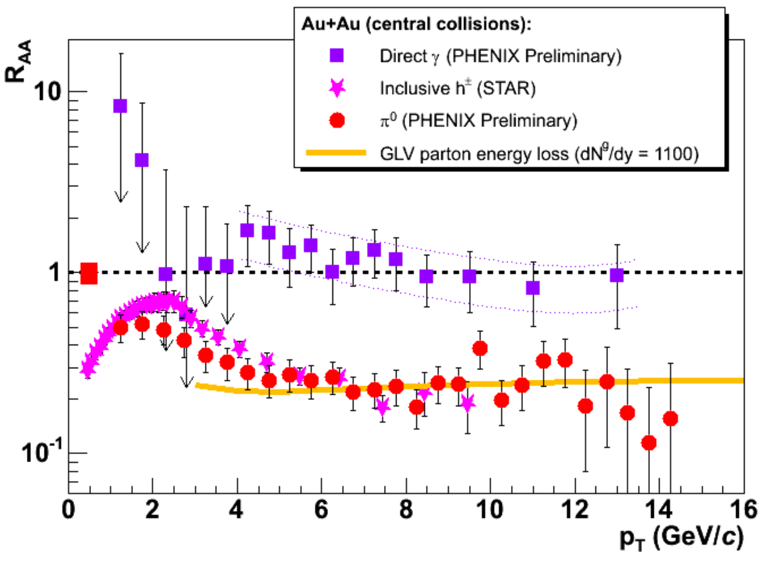


Pang, Wang & XNW 2013

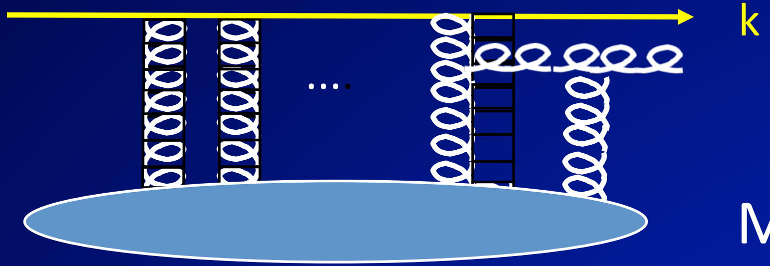
Jet Quenching phenomena at RHIC







Parton Transport in Medium



Liang, Zhou & XNW 2008

Color Lorentz force

Multiple scattering

Transverse momentum broadening:

$$\langle \Delta k_T^2 \rangle = \int dy \hat{q}(y)$$

Jet radiative energy loss:

$$\frac{\Delta E}{E} = \frac{2\alpha_s N_c}{\pi} \int \frac{d\ell_T^2}{\ell_\perp^4} dz[1+(1-z)^2] \int d\xi^- \hat{q}(\xi) \sin^2(x_L p^+ \xi^-)$$

Guo & XNW'00
Zhang, Wang, XNW'03

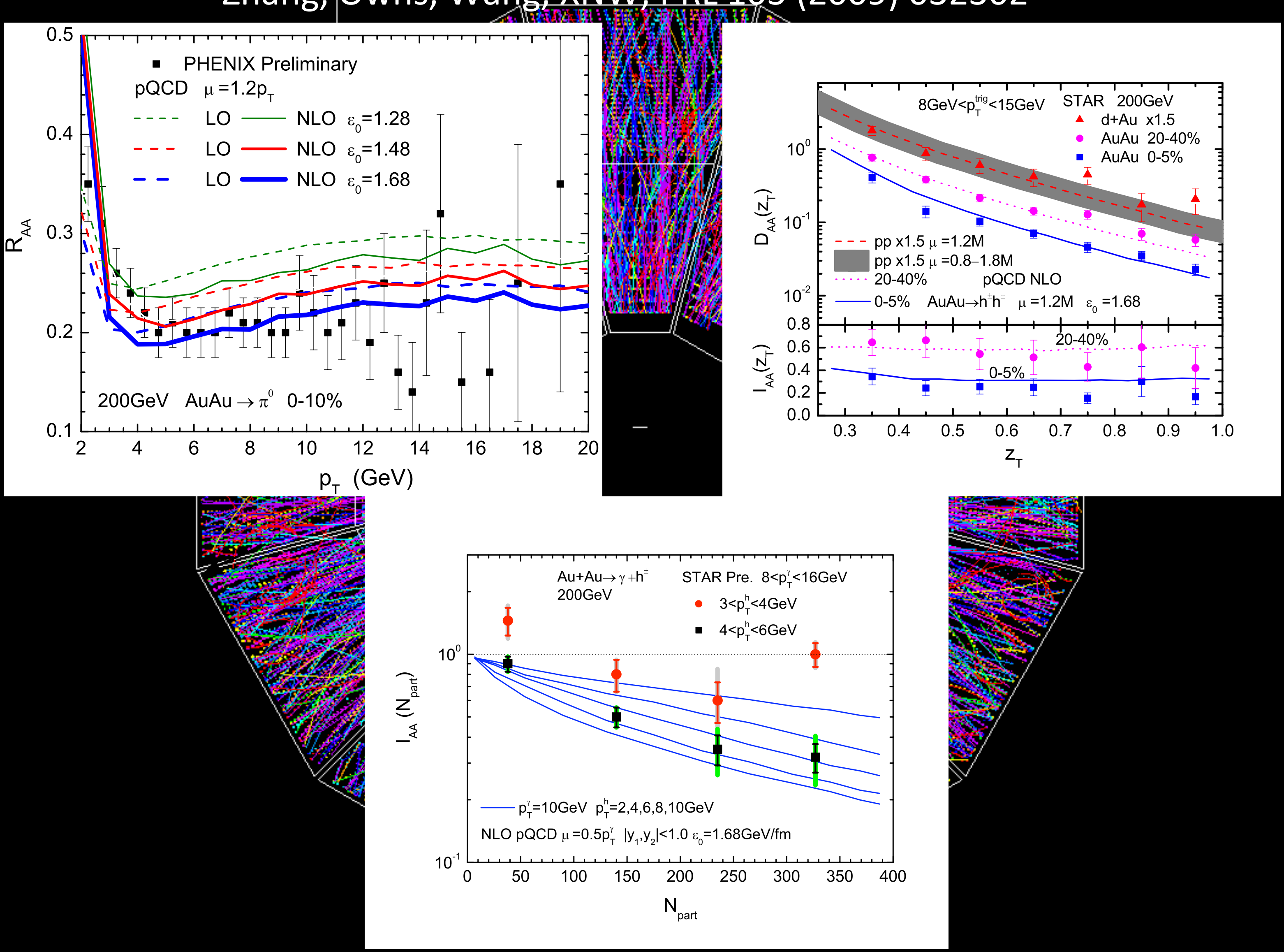
Jet transport coefficient:

$$\hat{q}(y) = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \rho(y) x G(x)|_{x\approx 0}$$

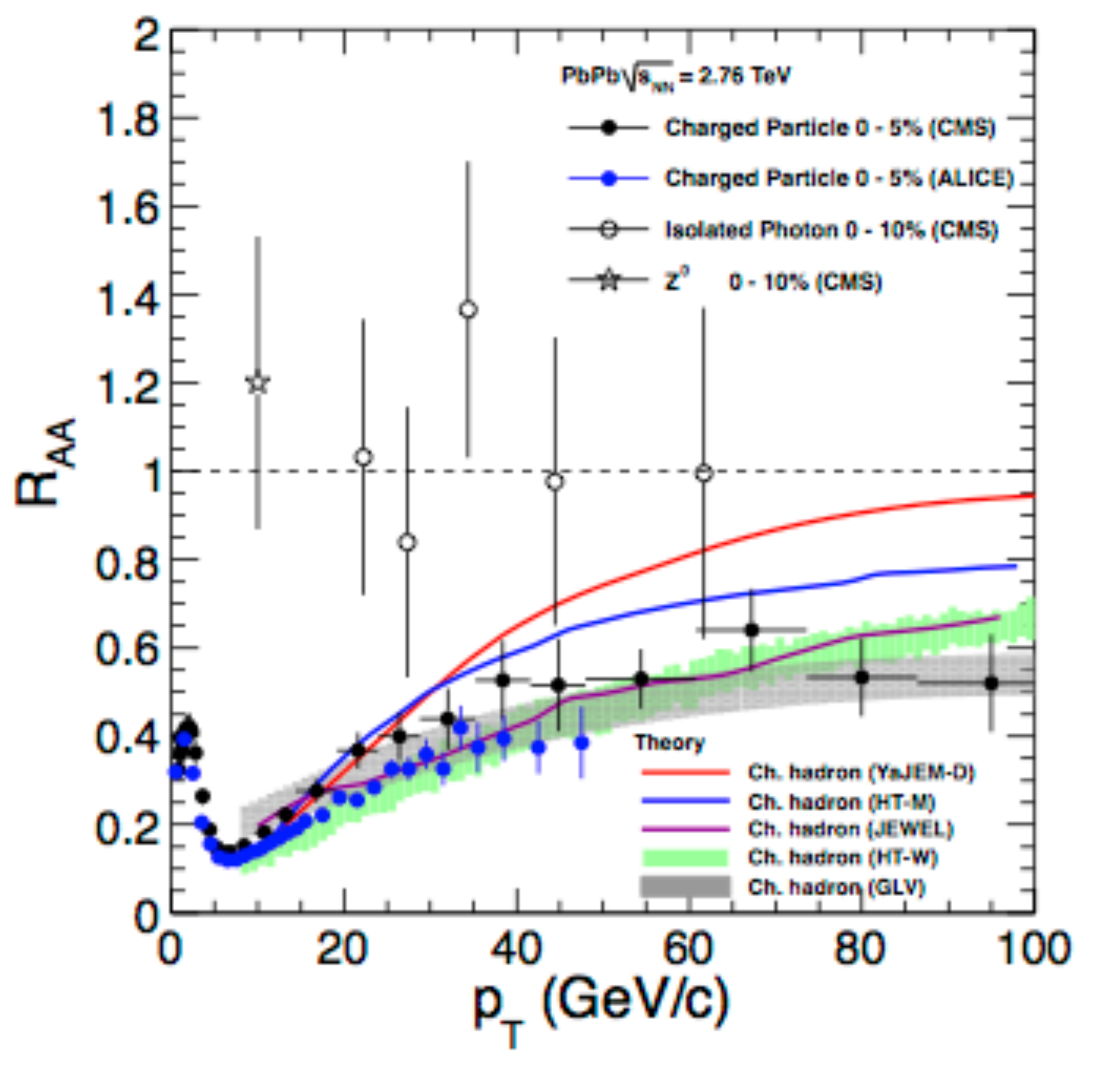
pQCD (BDMPS'96)
AdS/CFT (Liu, Rajagopal & Wideman'06)
lattice QCD (Majumder'12)

Jet Quenching phenomena at RHIC

Zhang, Owns, Wang, XNW, PRL 98 (2007) 212301
Zhang, Owns, Wang, XNW, PRL 103 (2009) 032302

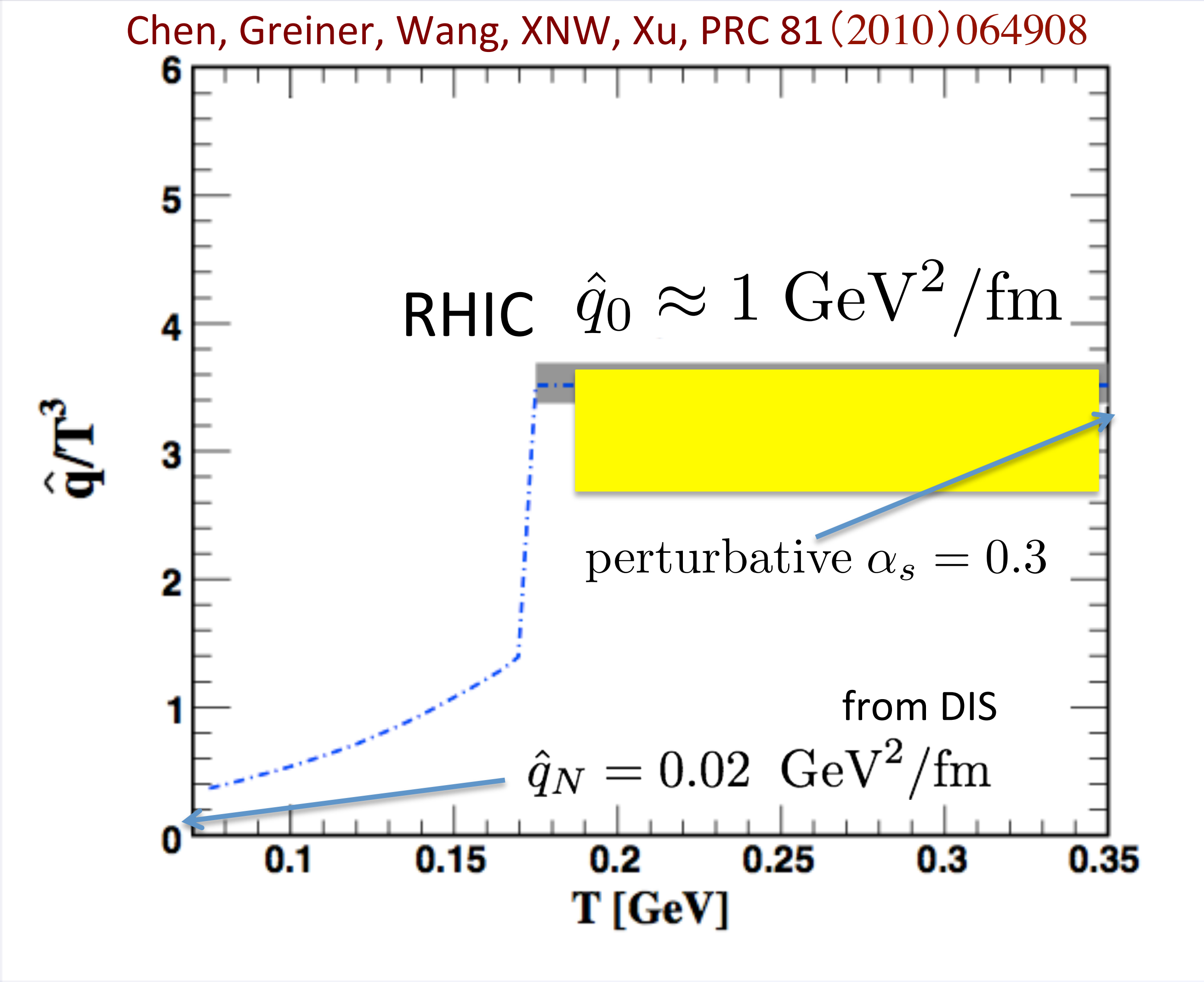


Jet quenching at LHC



Muller, Schukfrat & Wyslouch 2012

Jet transport coefficient



Chen, Greiner, Wang, XNW, Xu, PRC 81（2010）064908

RHIC $\hat{q}_0 \approx 1\ \mathrm{GeV}^2/\mathrm{fm}$

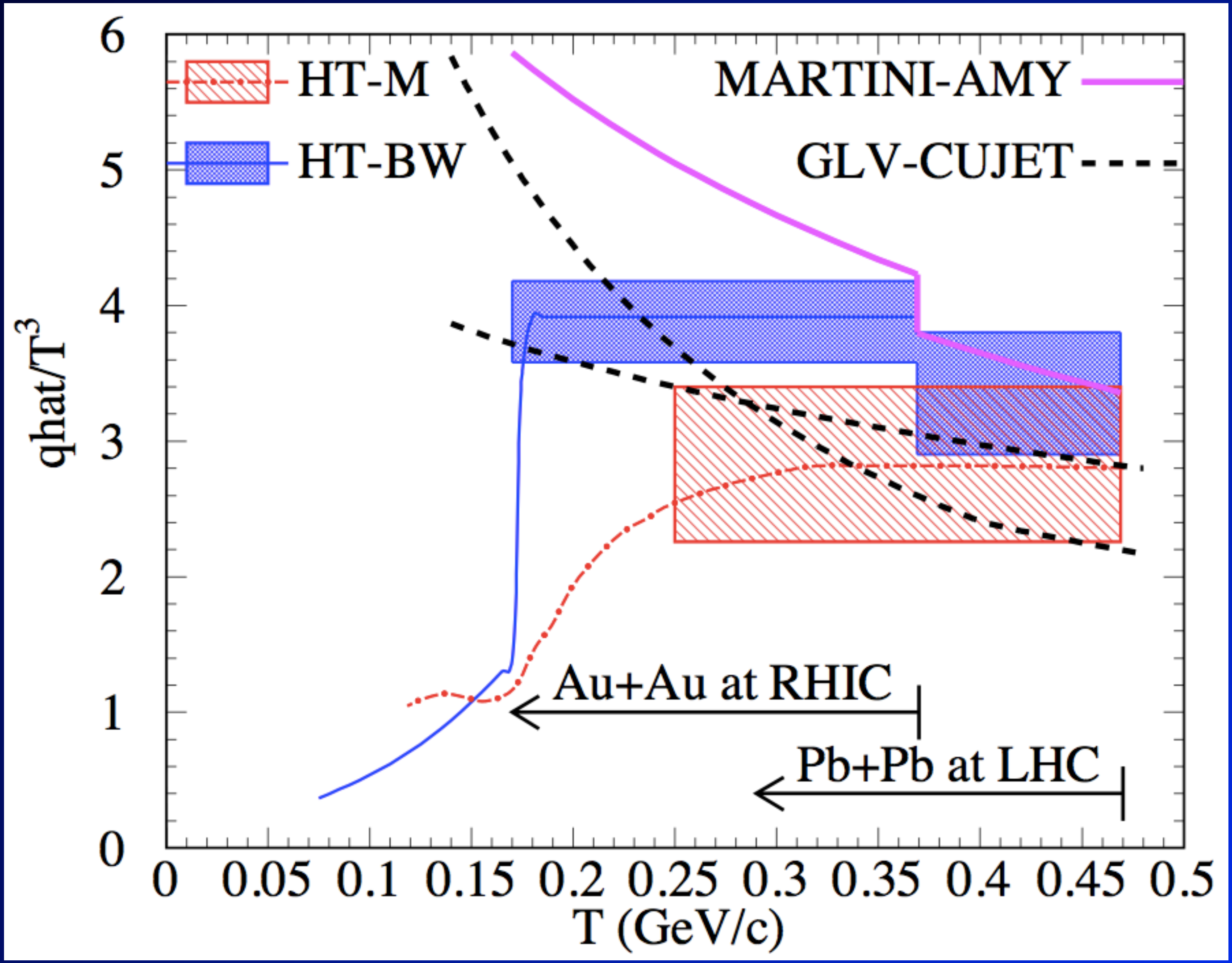
perturbative $\alpha_s = 0.3$

from DIS

$\hat{q}_N = 0.02\ \ \mathrm{GeV}^2/\mathrm{fm}$

Deng & XNW PRC 81 (2010) 024902

Jet transport coefficient



JET Collaboration (to be published)

MC approach to jet medium interaction

JET Collaboration

3+1D hydro + Jet transport + Hadronization

Berkeley-Wuhan Hybrid MC

3+1D hydro + Linear Boltzmann Jet Transport

Jet-induced medium excitation & anisotropic flow
Jet quenching in an anisotropic/expanding medum

Linear Boltzmann jet transport

$$p_1 \cdot \partial f_1(p_1) \quad = \quad -\int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4) \left|M_{12\to 34}\right|^2 (2\pi)^4 \delta^4(\sum_i p_i),$$

$$f_i(p) = (2\pi)^3 \delta^3(\vec{p}_i - \vec{p}_0)\delta^3(\vec{x} - \vec{x}_0 - t\vec{v}_i)[i = 1, 3]$$

$$f_i(p_i) = \frac{1}{e^{p_i \cdot u/T} \pm 1}(i = 2, 4)$$

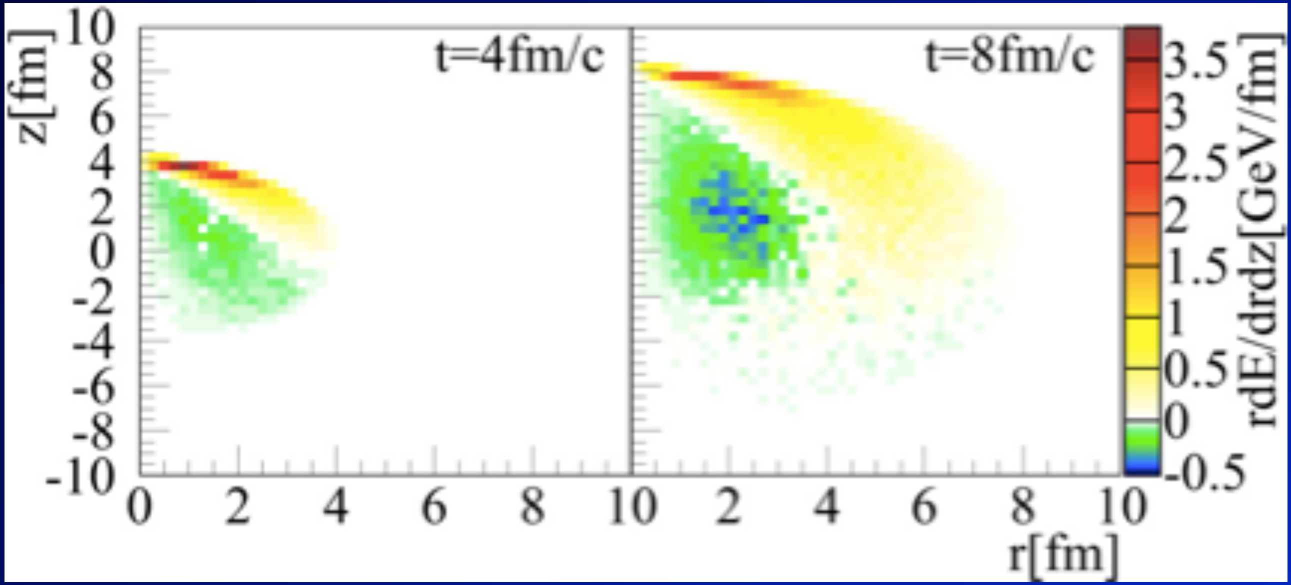
$$\frac{d\sigma}{dt} = |M_{12\to 34}|/16\pi^2 s^2$$

$$\mu_D^2 = (\frac{3}{2})4\pi\alpha_s T^2$$

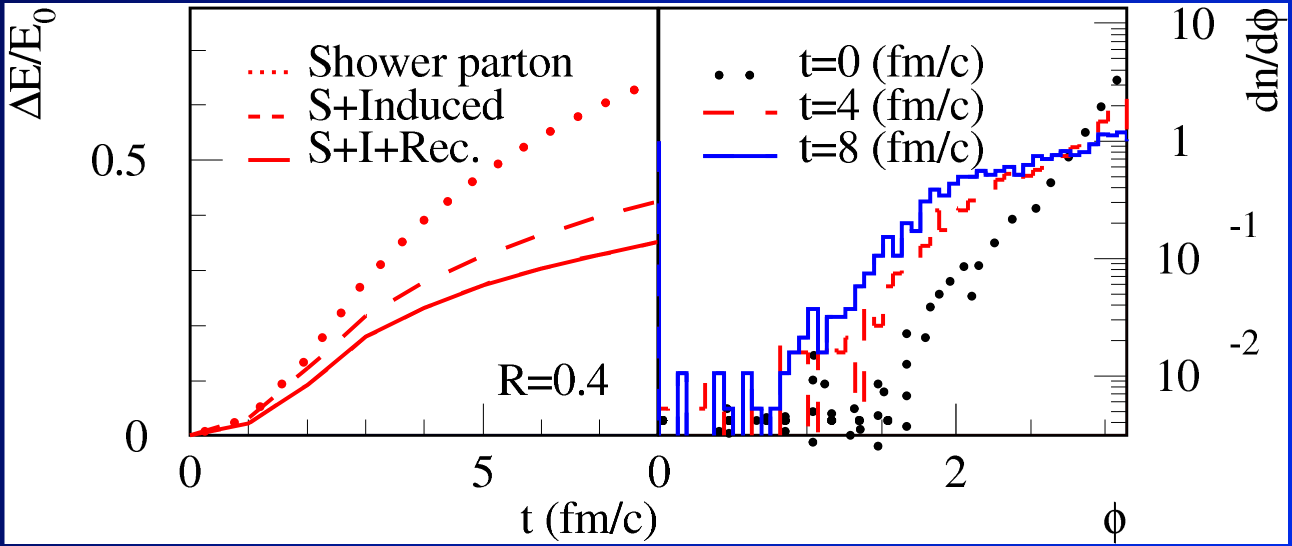
Induced radiation $$\frac{dN_g}{dz d^2k_\perp dt} = \frac{2\alpha_s N_c}{\pi k_\perp^4} P(z)(\hat{p} \cdot u)\hat{q} \sin^2(\frac{t - t_0}{2\tau_f})$$

Li, Liu, Ma, XNW and Zhu, PRL 106（2010）012301
XNW and Zhu, PRL 111 (2013) 062301

Jet-induced medium excitation

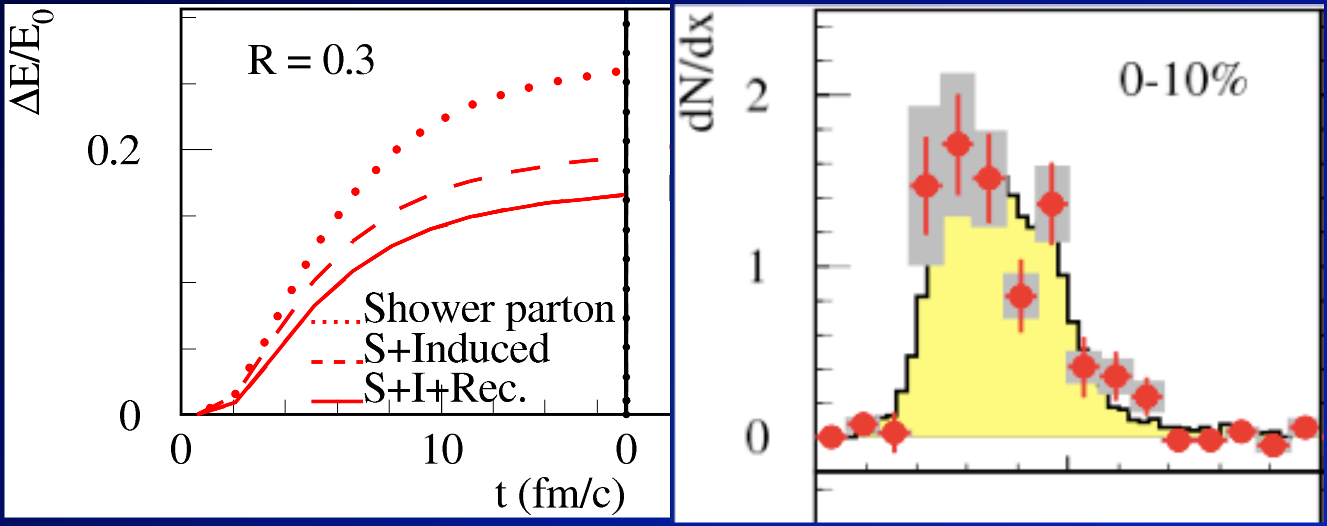


Jet propagation in a uniform medium



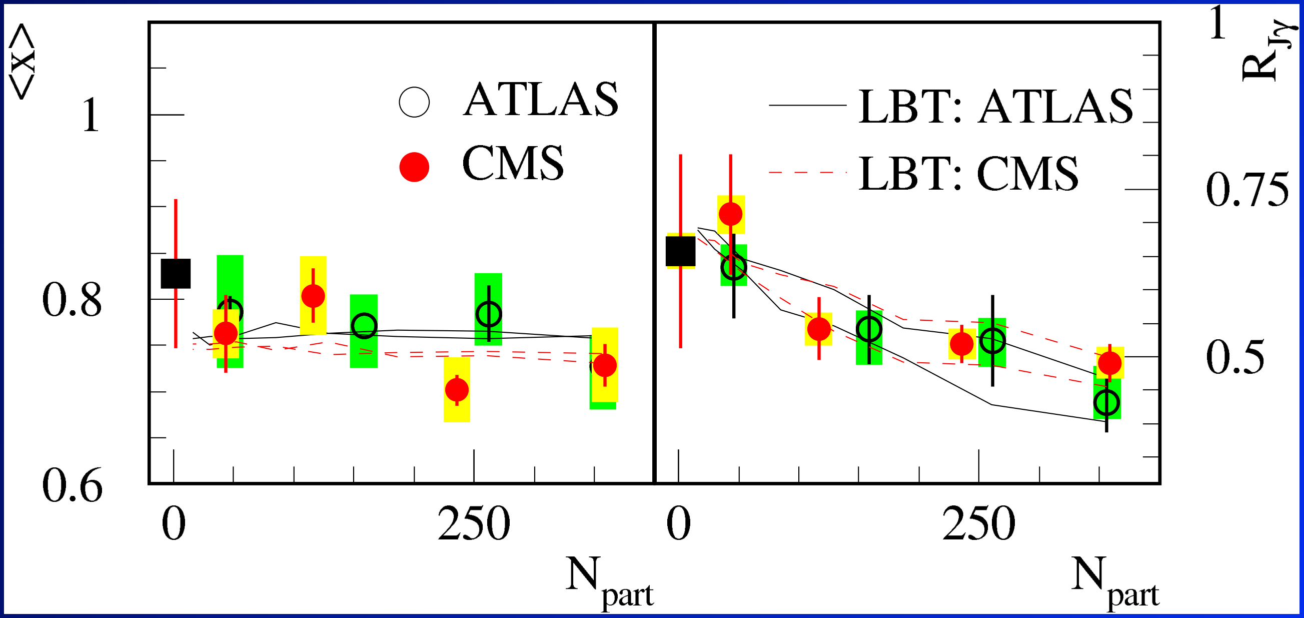
γ-jets in an expanding medium

Similar results by Dai, Vitev and Zhang, PRL 110 (2013) 032302



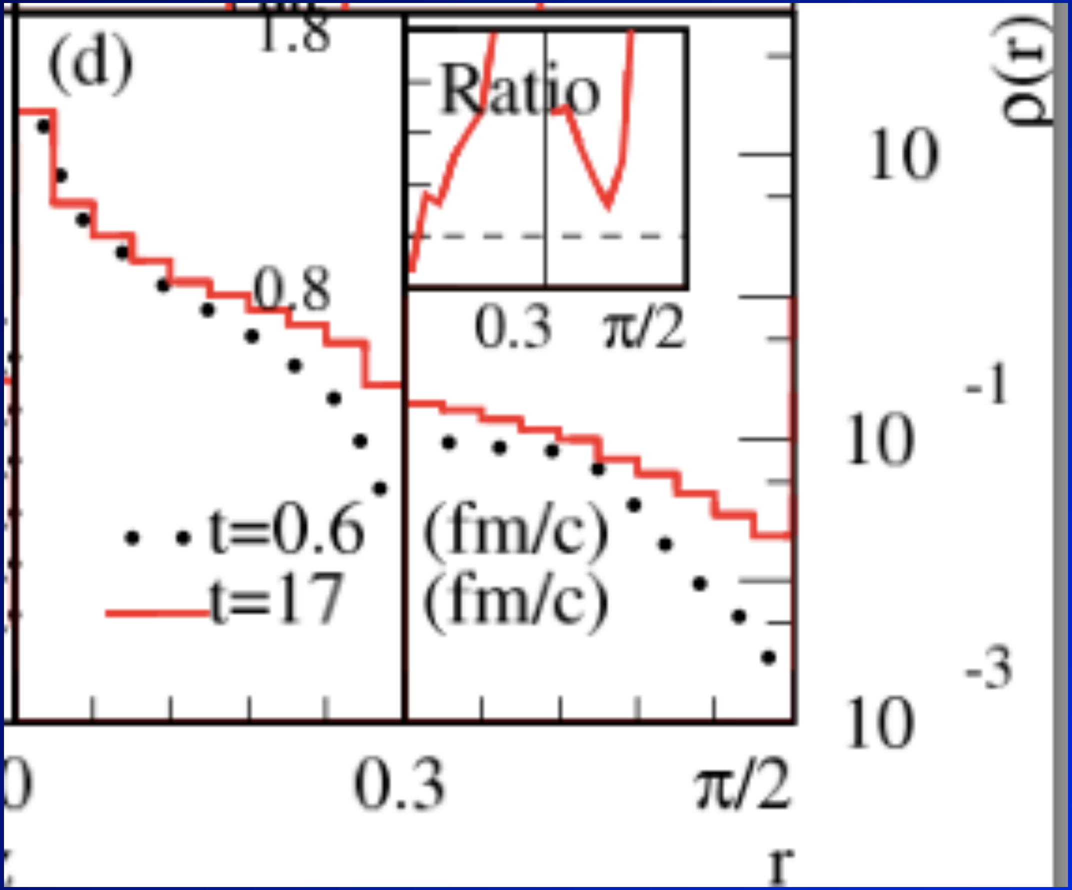
XNW and Zhu, PRL 111 (2013) 062301

$$x = \frac{P_T}{P_T^\gamma}$$



Broadening of jet transv. profile

$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N^{\text{jet}}}\sum_{\text{jets}}\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)},$$

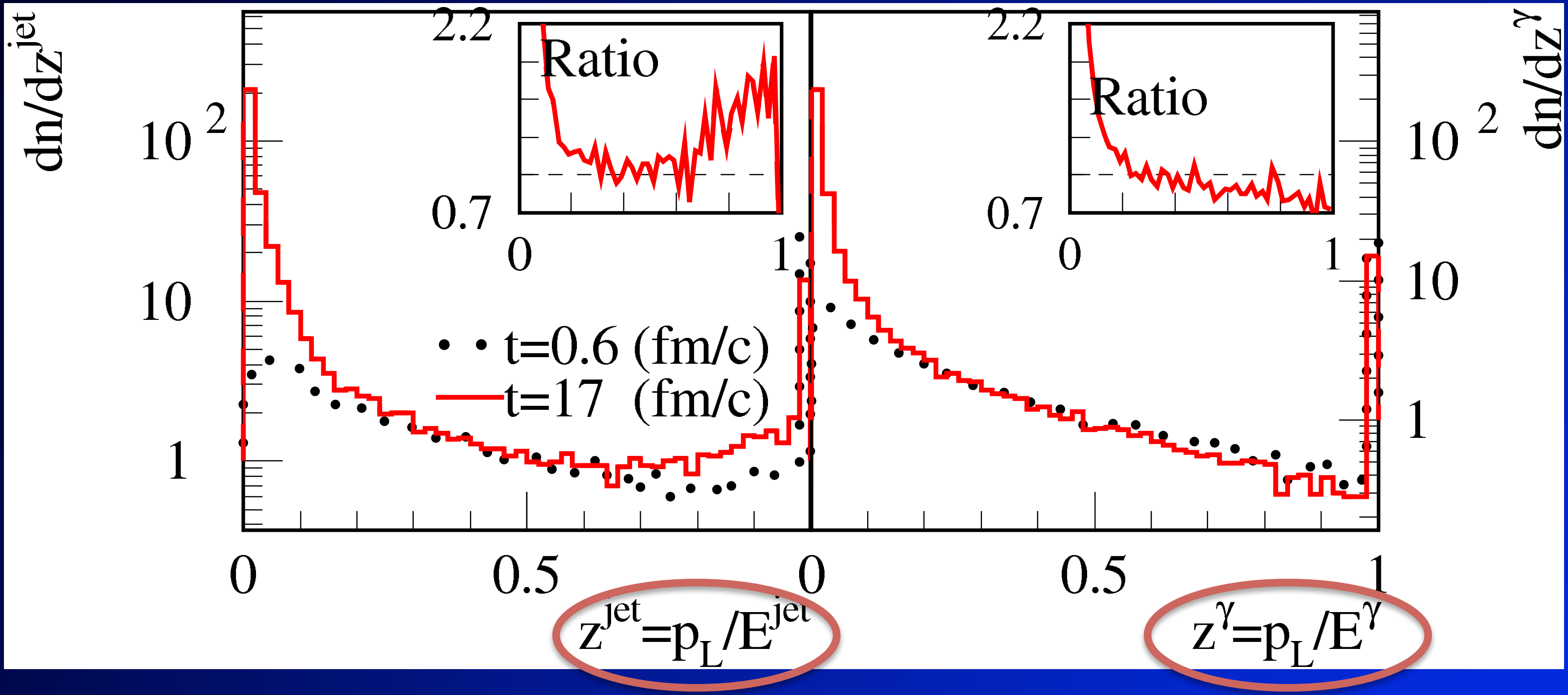


R=0.3

Medium mod. of frag function

Seen in CMS & ATLAS single jets

XNW and Zhu, PRL 111(2013)062301



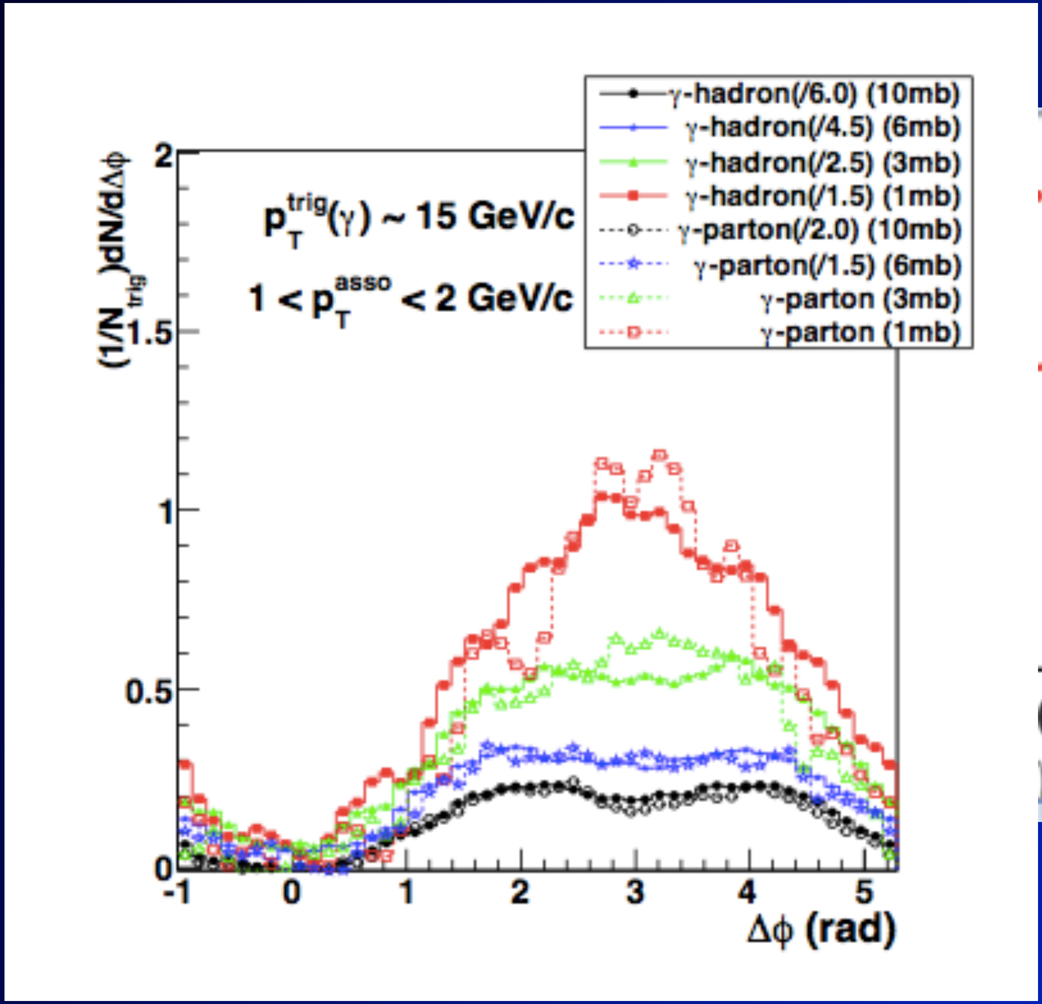
XNW, Huang & Sarcevic (1996)

Energy of reconstructed jet dominated by leading particle

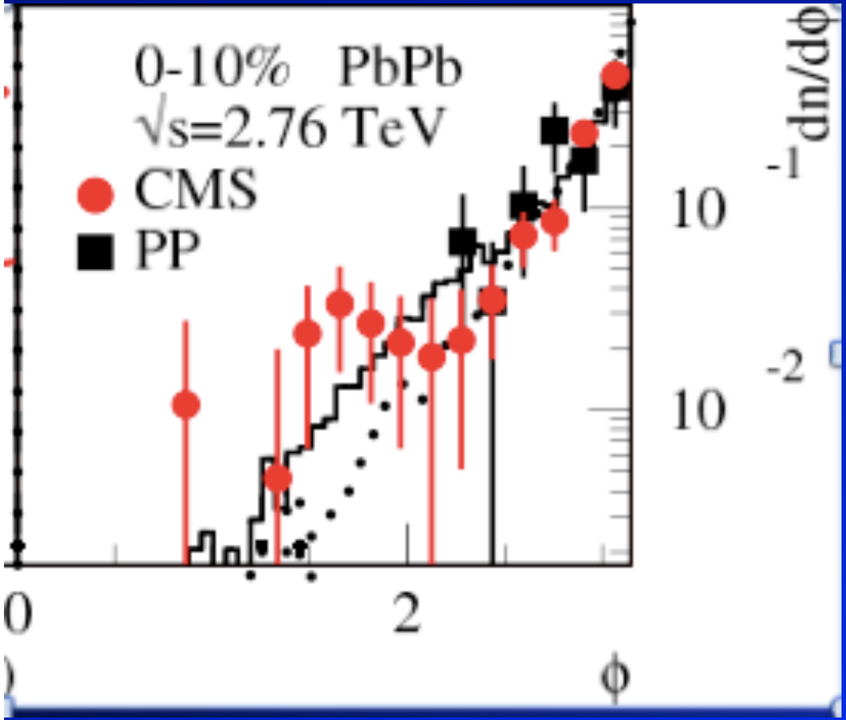
Suppression of fragmentation functions relative to initial energy

Broadening of γ-hadron correlation

γ-hadron from AMPT calculation



γ-jet from LBT



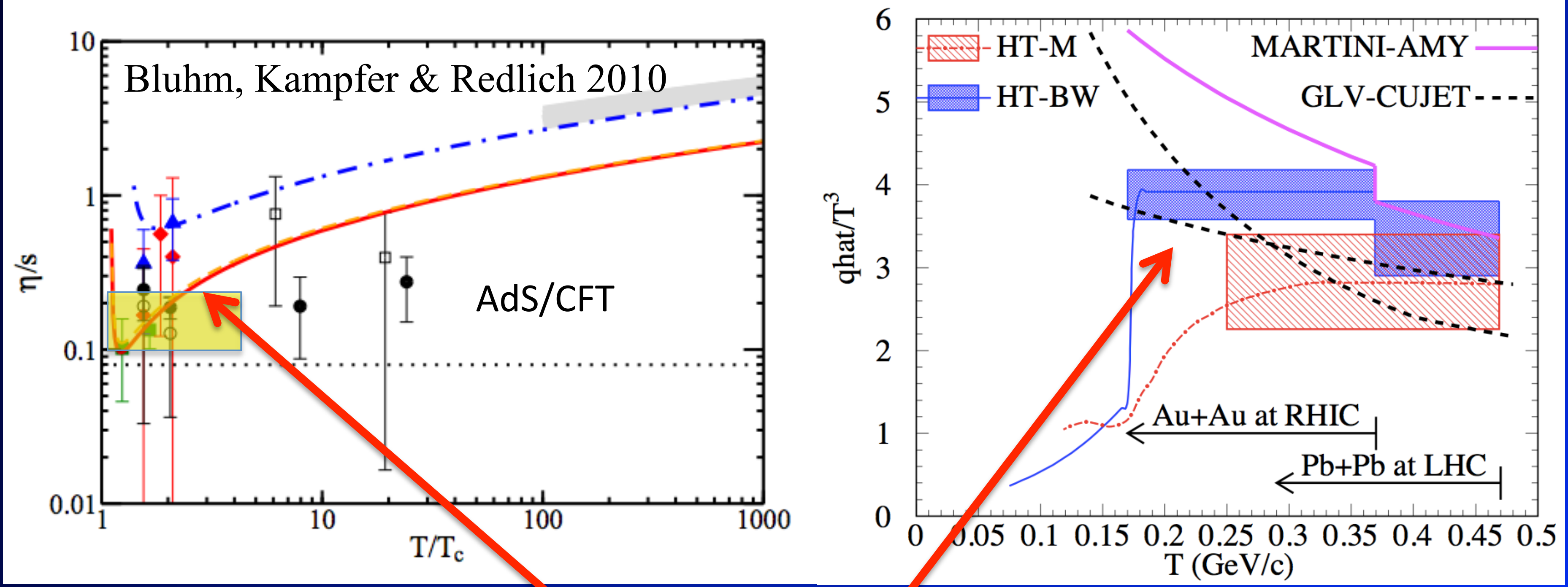
Jet azimuthal angle broadening is smaller but still finite

Li, Liu, Ma, XNW and Zhu, PRL 106（2010）012301
Ma and XNW, PRL 106 (2011) 162301

Summary

Hard probes and anisotropic flows provide unprecedented constraints on the transport properties of the sQGP in A+A

Future: mapping out T-dependence at RHIC & LHC



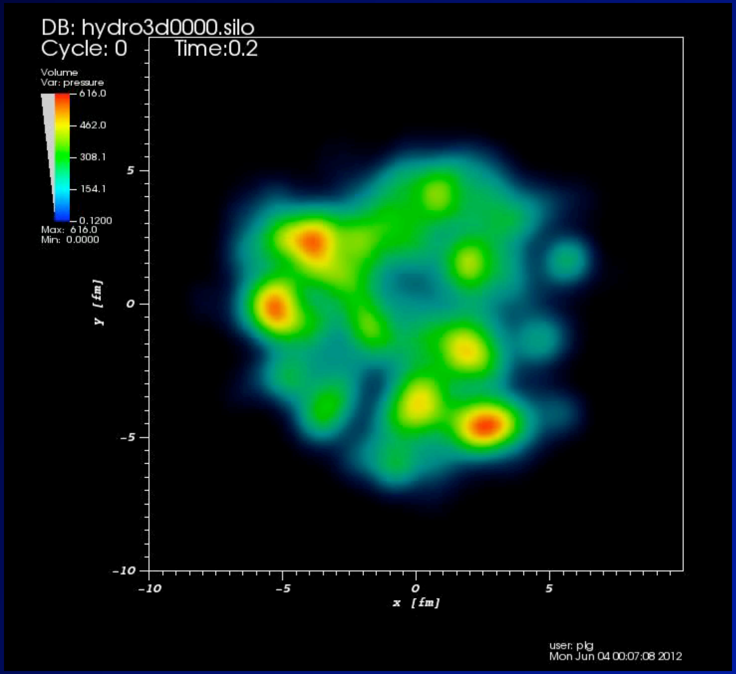
Bluhm, Kampfer & Redlich 2010

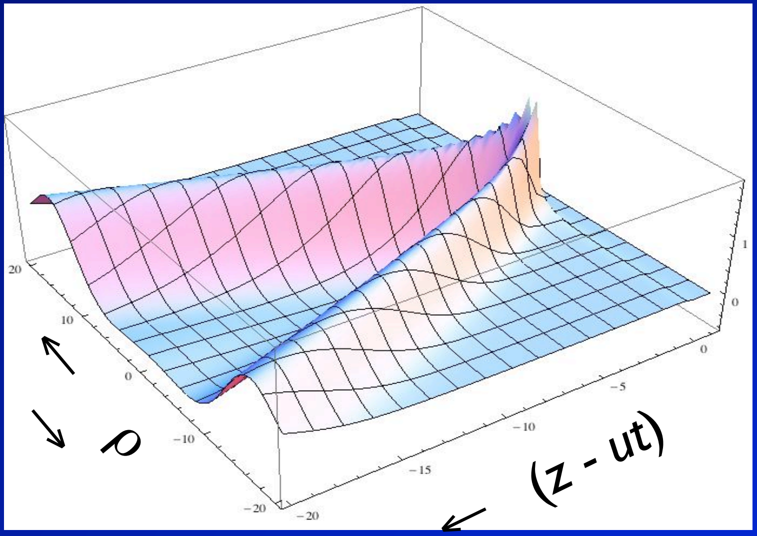
$$\frac{\eta}{s} \geq \frac{3T^3}{2\hat{q}}$$

Majumder, Muller & XNW 2007

Hydro dynamics of dense matter

$$\partial_\mu T^{\mu\nu} = j^\nu$$

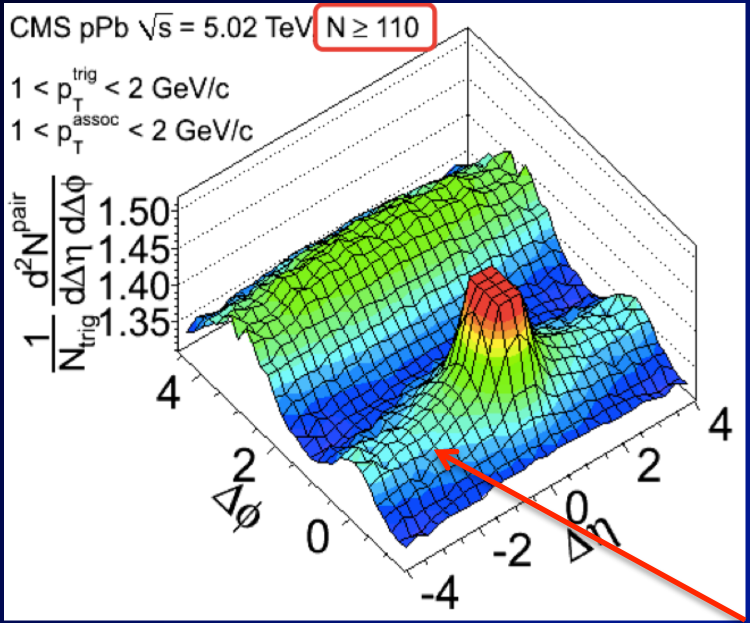


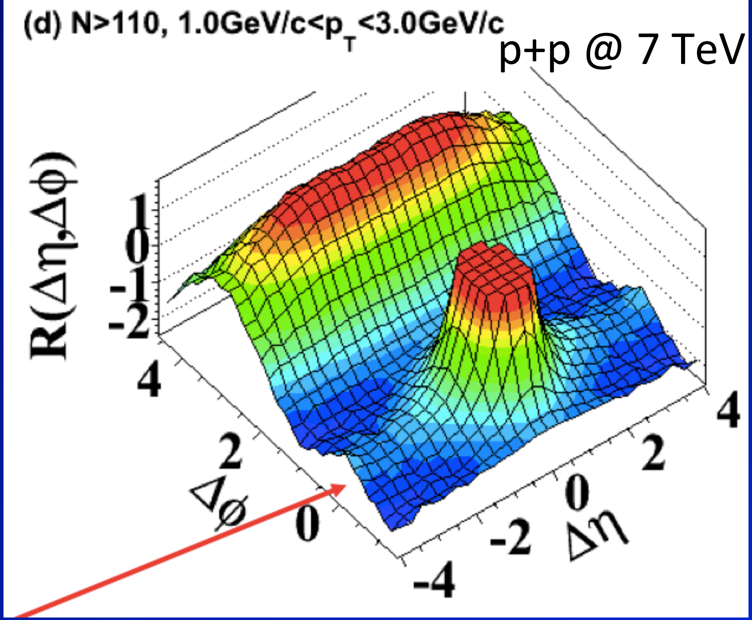


c_S

EOS of QGP

QGP in p+p & p+A collisions?





Collective flow in high multiplicity events of p+p & pA?

But no jet quenching! Werner et al ‘12, Bozek & Broniowski’13

Maybe from initial state: glasma? Venugapalan & Dusling et al, ‘12

But large values of v3!

See talks by Roland (G1)

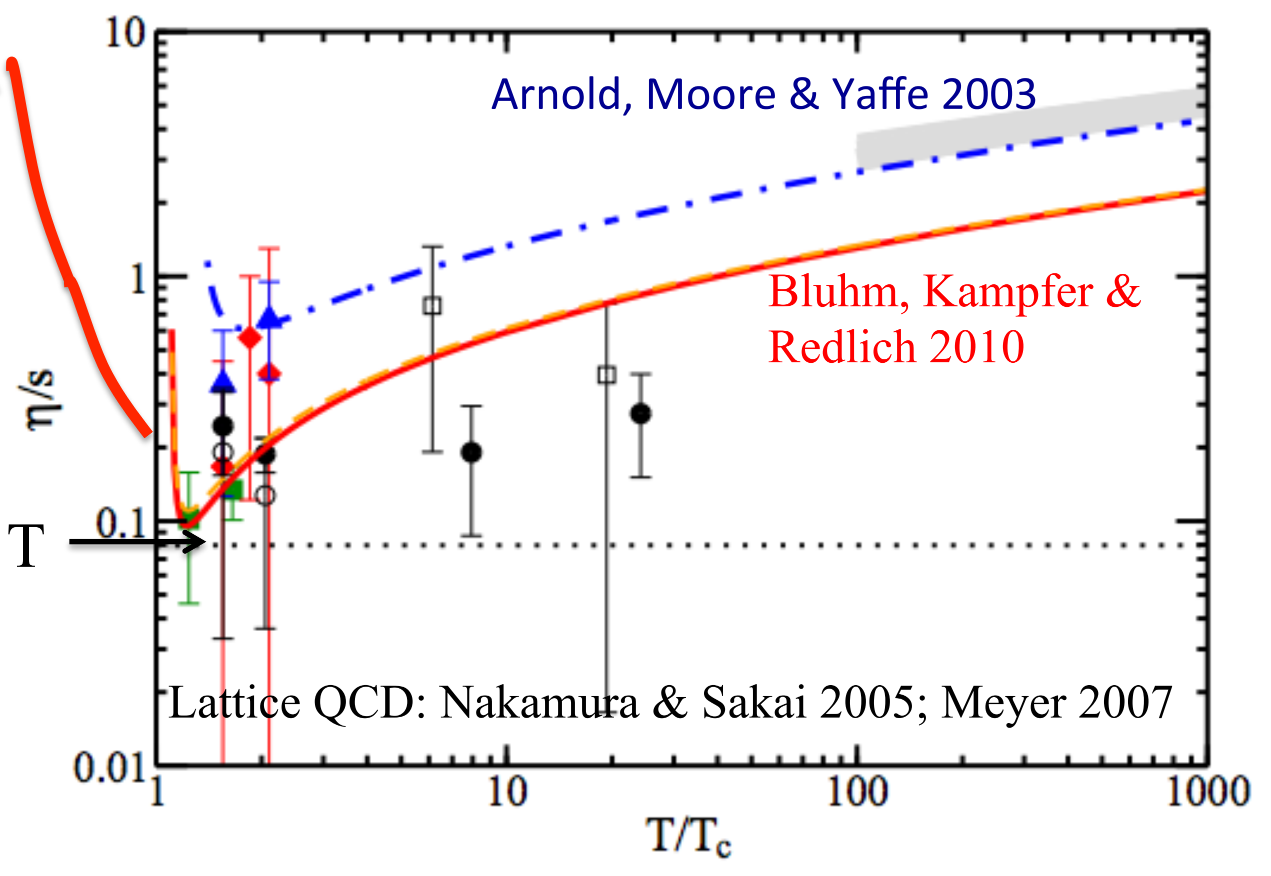
Transport properties of QCD matter

$$\eta = \lim_{\omega\to 0}\frac{1}{2\omega}\int dtdx\, e^{i\omega t}\langle[T^{ij}(x,t),T^{ij}(0,0)]\rangle$$

$$\frac{\eta}{s}=\frac{15}{16\pi}\frac{f_\pi^4}{T^4}$$

pion gas
Prakash'93

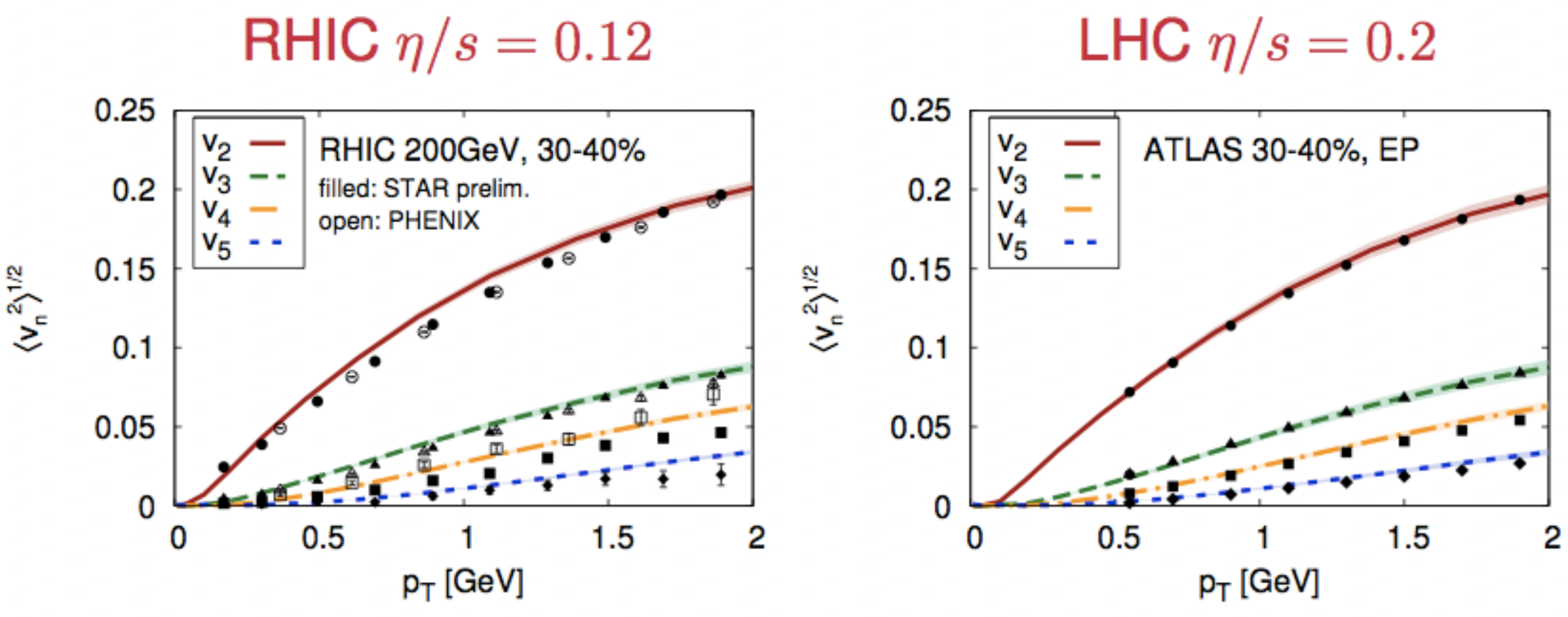
AdS/CFT



Viscosity of QGP in A+A collisions

Heinz & Song 2010

Gale, Jeon, Schenke, Tribedy & Venugopalan 2013

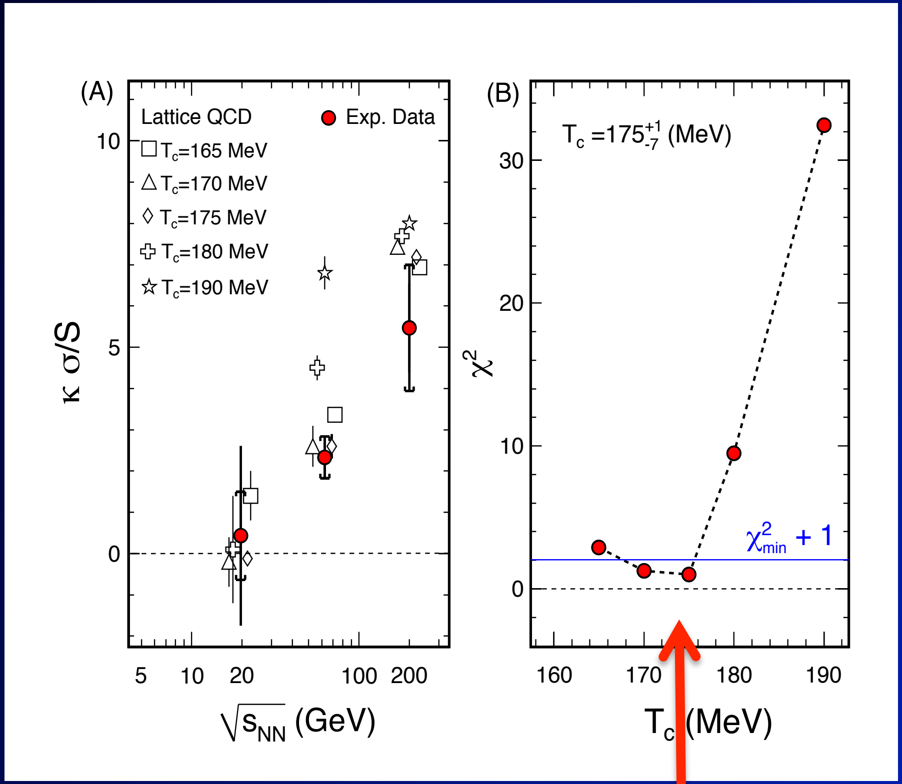


Fluctuation + viscous hydro required to fit all v_n

Viscosity at LHC is larger than at RHIC

See talk by Schenke (Wednesday, IUPAP prize)

Phase structure of QCD matter



$$[\mathbf{B^n}] = \mathbf{V T^{n-1}} \chi_{\mathbf{B}}^{(\mathbf{n})}\left(\frac{\mathbf{T}}{\mathbf{T_c}}, \frac{\mu_{\mathbf{B}}}{\mathbf{T}}\right)$$

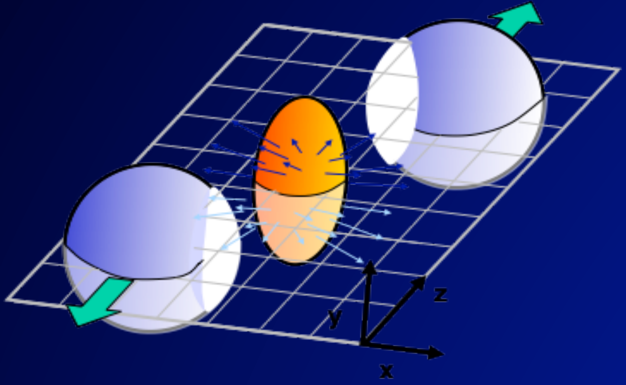
Fluctuation and T_c

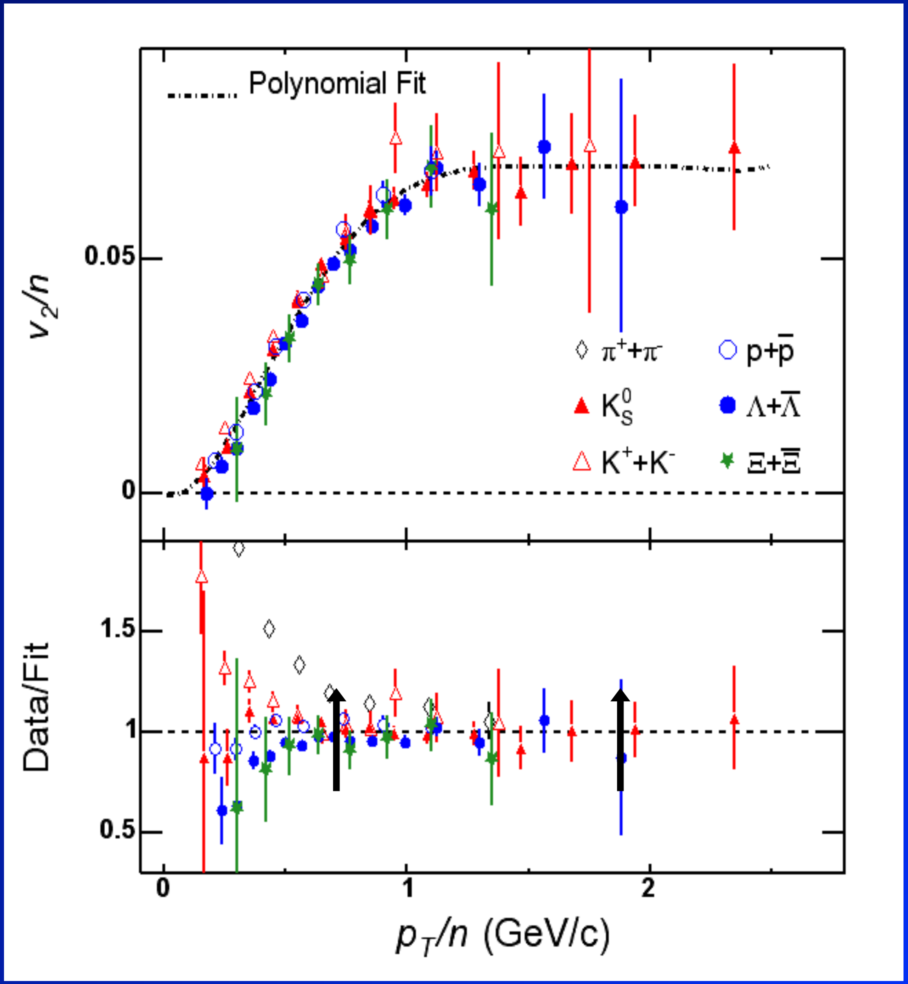
$$T_c = 175\ \mathrm{MeV} \approx 2 \times 10^{14}\ \mathrm{K}$$

Quark number scaling of v2

STAR: Phys. Rev. Lett. **92**, 052302(04)

Anisotropic flow





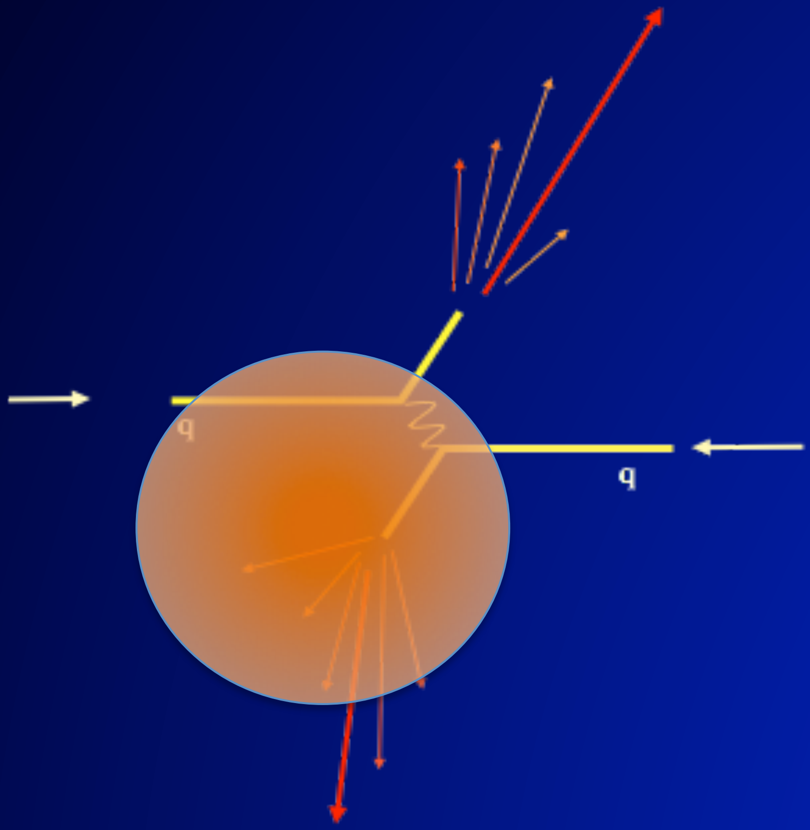
n: valence quark

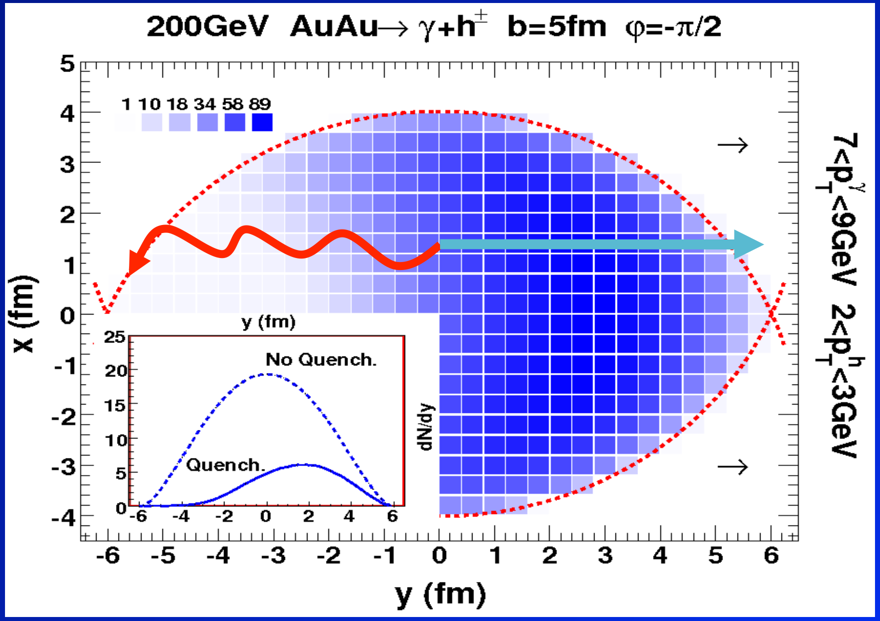
$$\frac{v_2(p_T/n)}{n}$$

Hard probes of dense matter

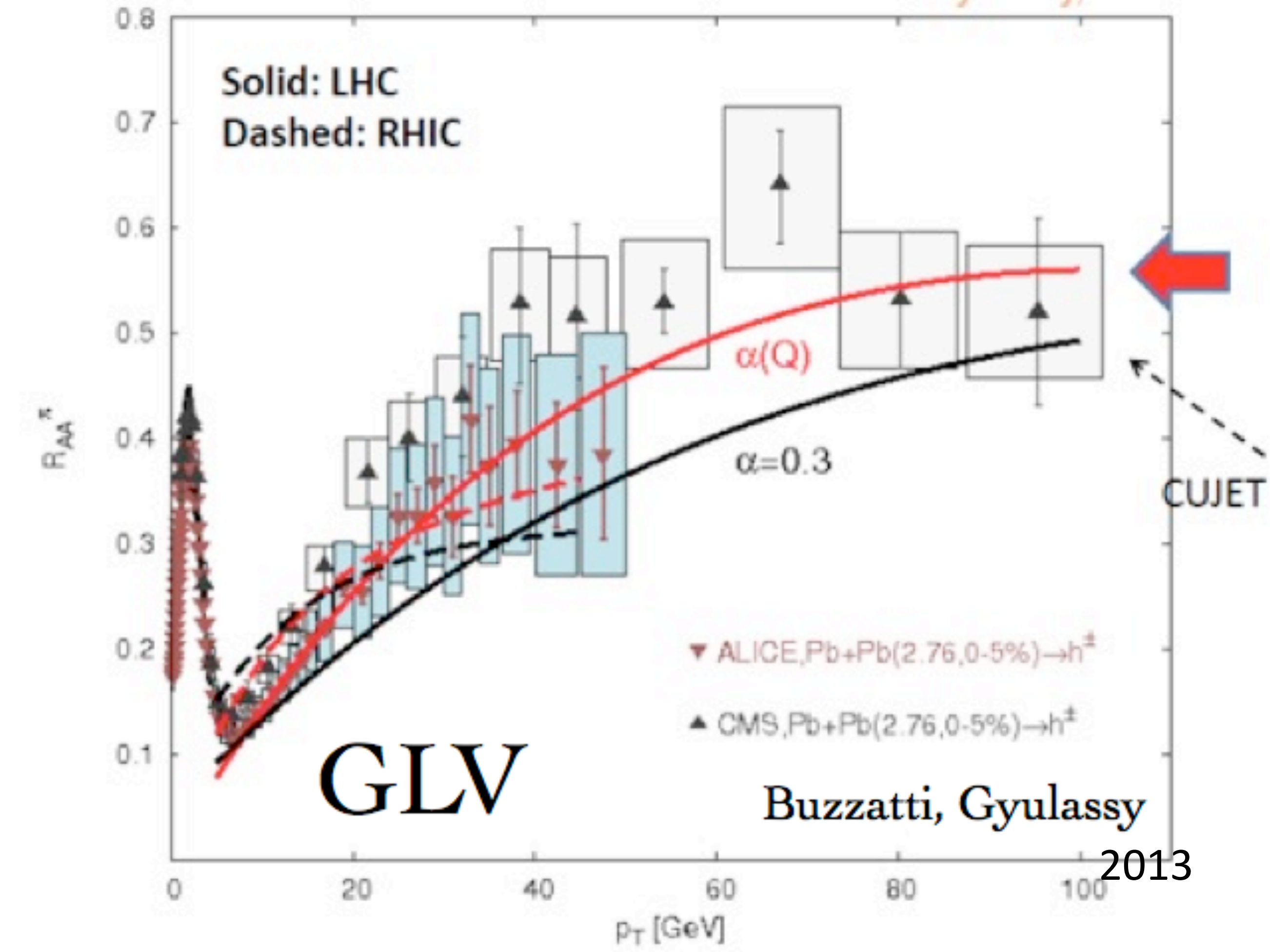
Jet quenching via parton energy loss

$$\boxed{\frac{dE}{dx} \sim \rho(x)}$$

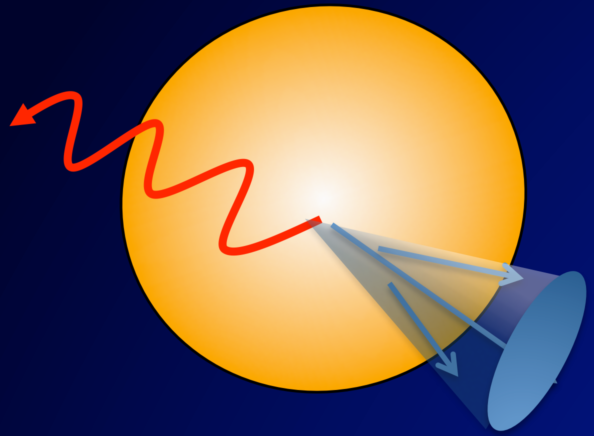


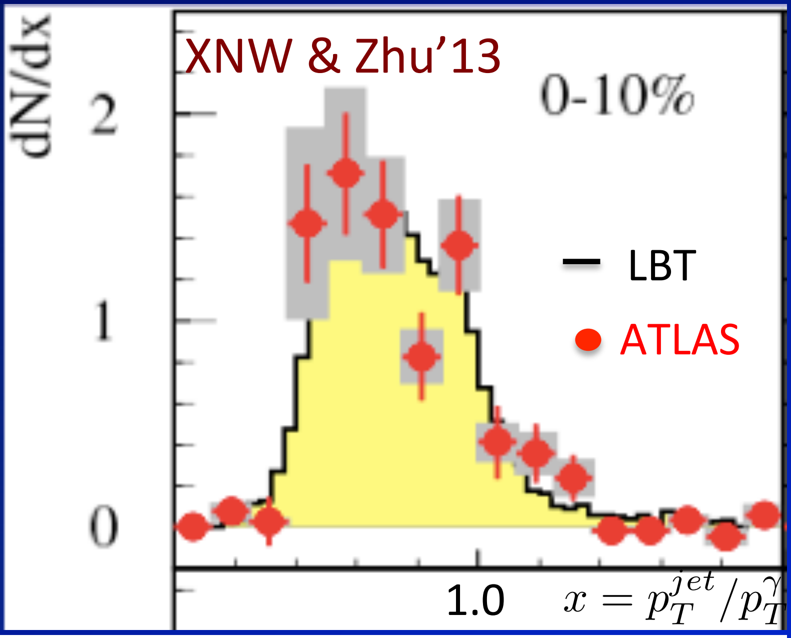


Running coupling in jet quenching



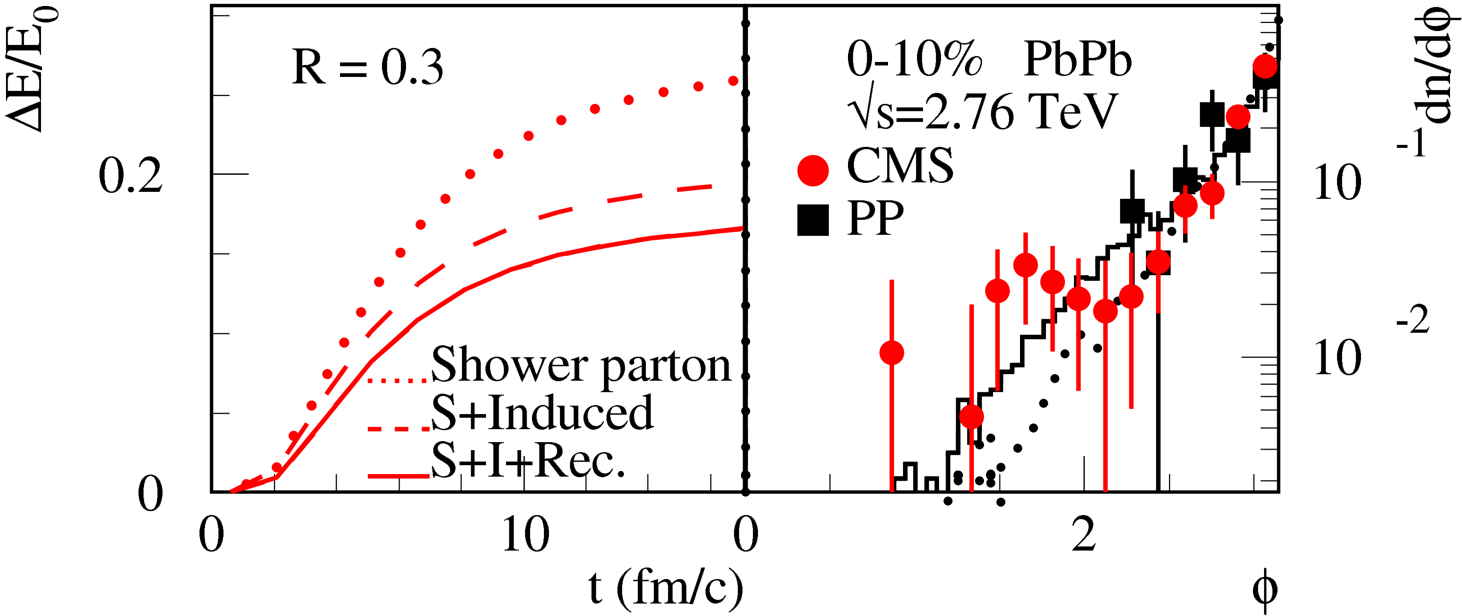
Gamma-jet asymmetry





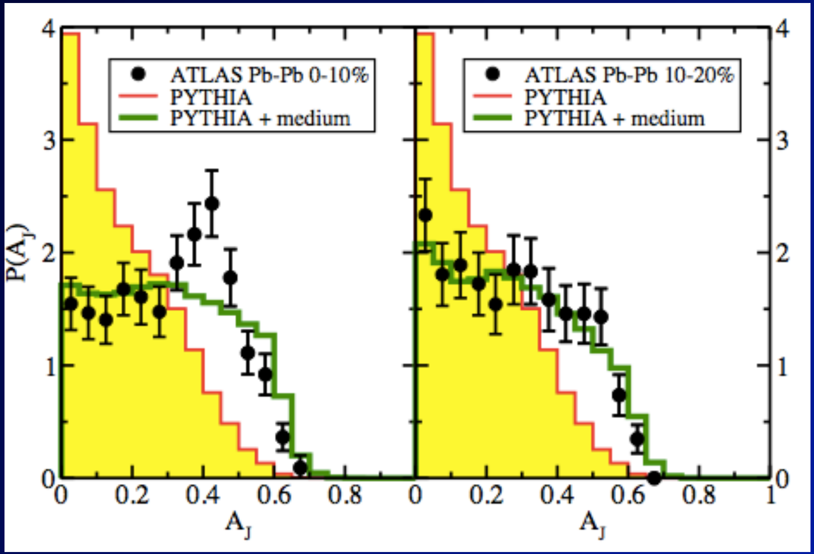
$$\Delta E/E \approx 15\%$$

Rapid expansion & recoiled parton

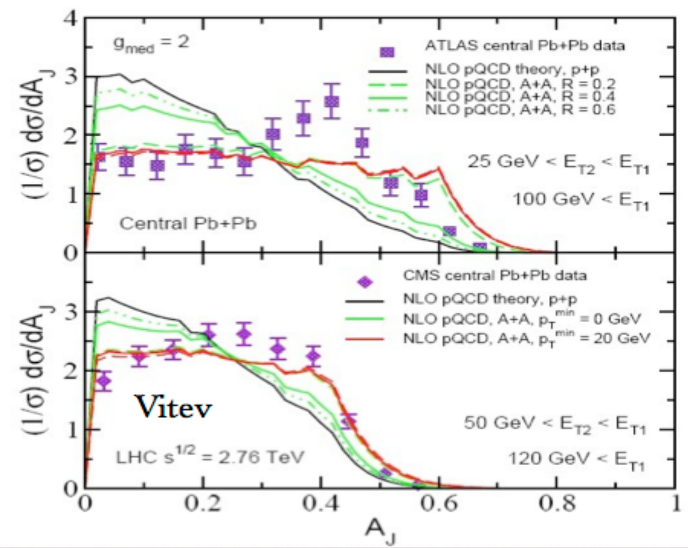


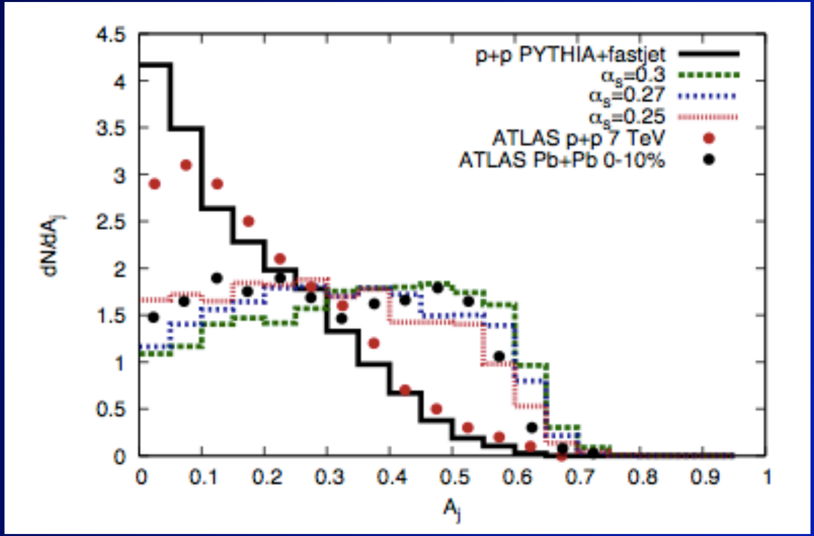
Dijet asymmetry at LHC

Qin & Muller' 2012

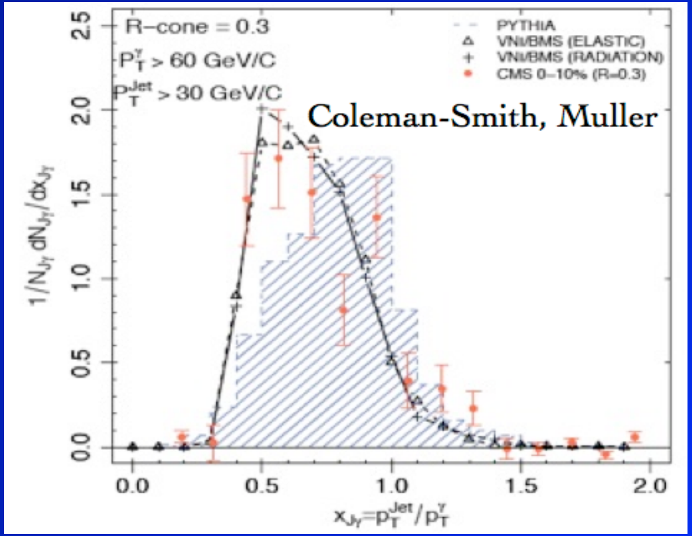


He, Vitev & Zhang' 2012



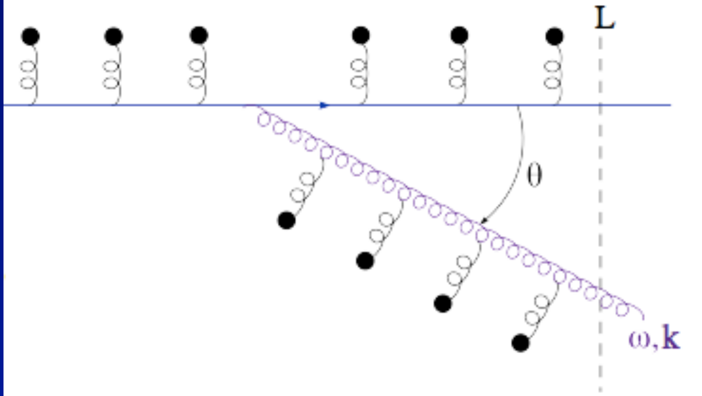


Young, Schenke, Jeon & Gale, 2012



Multiple scattering & angular ordering

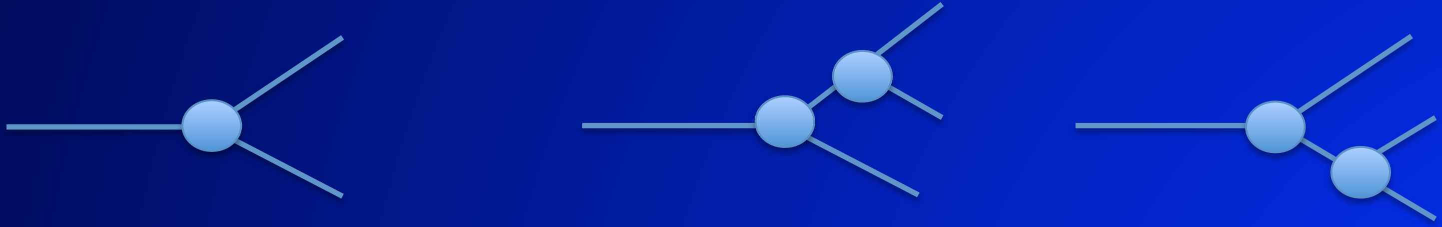
Formation time $$\frac{1}{\tau_f} \sim \frac{k_T^2}{2\omega}$$



$$\tau_f(\omega) \sim \sqrt{\frac{2\omega}{\hat{q}}} \qquad \theta \sim k_T/\omega \sim (\hat{q}/\omega^3)^{1/4}$$

Color coherence is rapidly lost in medium, independent emission is enhanced by L/τ_f

Blaizot, Dominguez, Iancu, Mehtar-Tani' 12
Mehta-Tani, Salgado, Tywoniuk'10



Multi-scattering → Many-body int. → Hydrodynamics

JET Collaboration

Hard QCD Physics @ CCNU

- Jet physics:
  - W^2Z^2: Enke Wang, XNW, Benwei Zhang, Hanzhong Zhang – High-twist approach to parton energy loss
  - Bowen Xiao – hard processes at small x
  - Guangyou Qin – AMY jet quenching, and flow
  - Defu Hou – jet quenching in AdS/CFT
  - Chunbin Yang – Oregon-Wuhan (Hwa-Yang) recombination
  - Fuming Liu -- Direct photons
- Experiments:
  - ALICE@LHC, STAR@RHIC
- Lattice QCD
  - Hengtong Ding