Jet and Flow

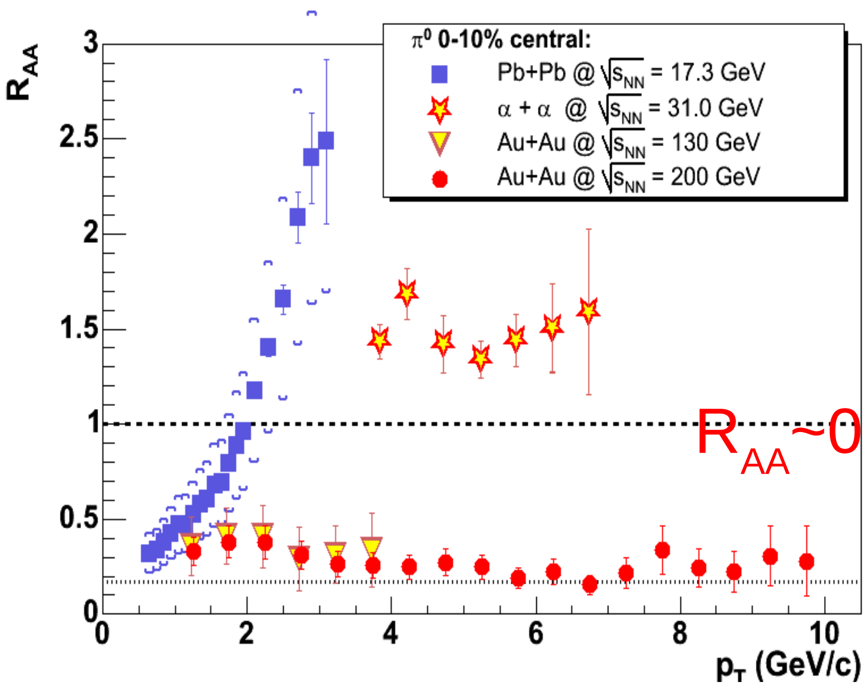
Yasushi Nara (Akita International Univ.)

- Jet quenching
- V2 and R_AA
- Jet energy loss near the Tc?
- Jet energy loss in the Glasma?
- Fluctuations in bulk matter
- Summary

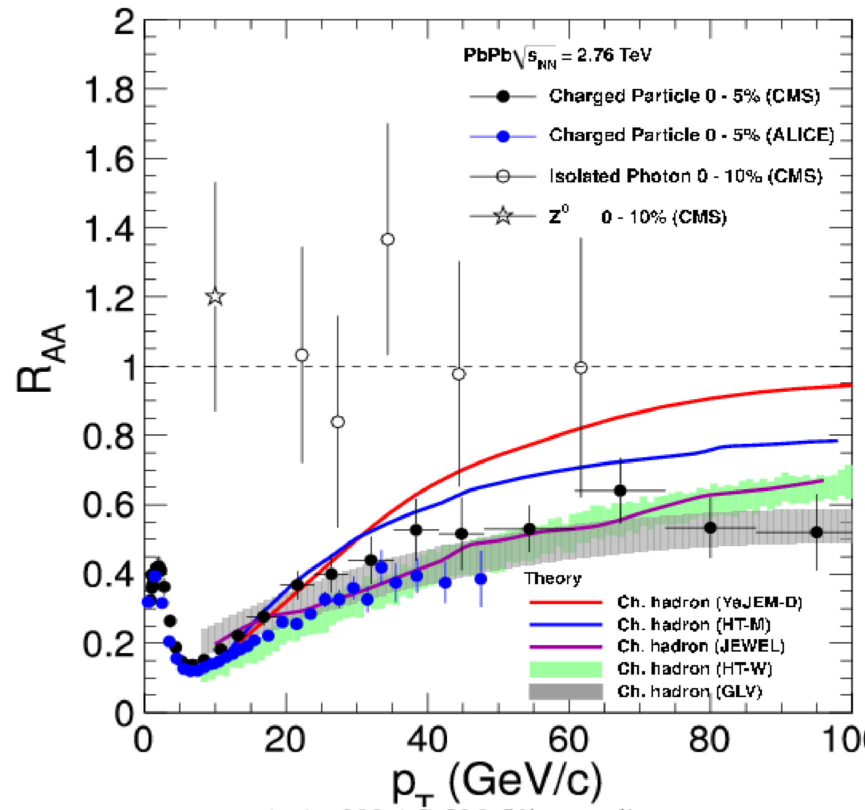
PHENIX Workshop on Physics Prospects with Detector and Accelerator Upgrades 2013/7/29-8/2

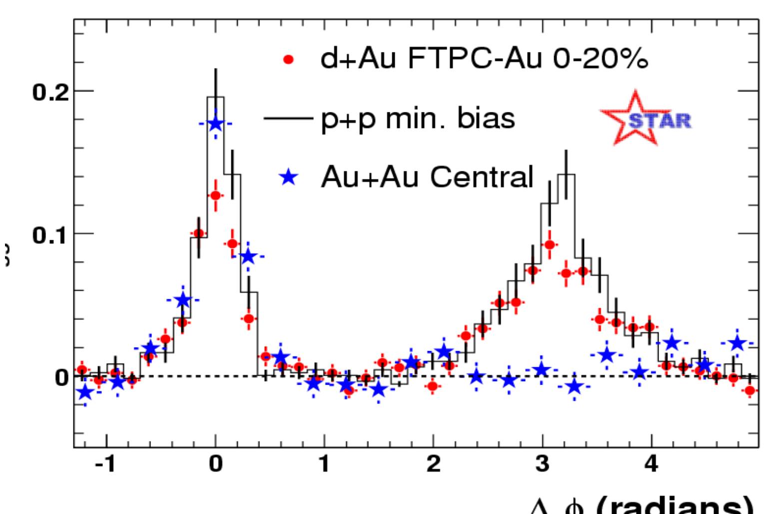
Jet quenching

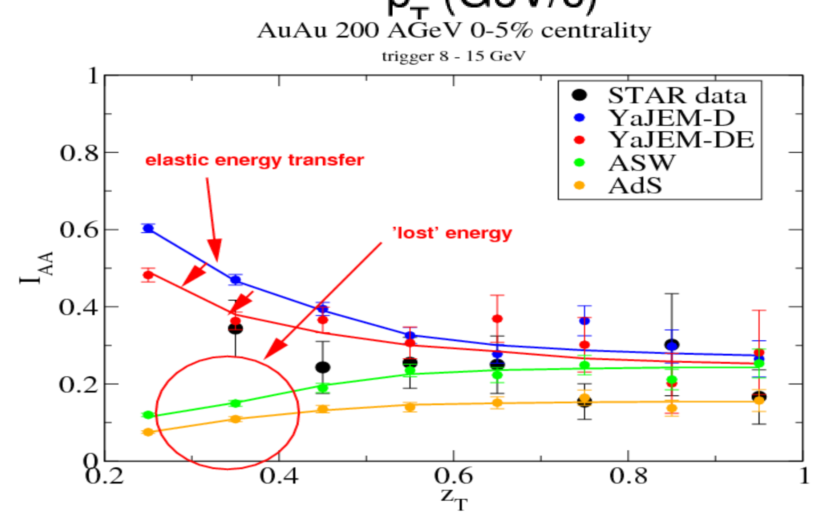
$$R_{AA}(p_T) = \frac{dN^{AA}/d^2 p_T d\eta}{\langle N_{coll}\rangle dN^{NN}/d^2 p_T d\eta}$$



Adams *et al.*, Phys. Rev. Lett. 91 (2003)







Monte Carlo Implementations based on
BDMSPS-Z/ASW, GLV, HT (Higher twist), AMY

- Q-PYTHIA (Armesto, Cunqueiro, Salgado, Xiang):
  Monte Carlo implementation of ASW scheme
- MARTINI Monte Carlo for AMY scheme
- MATTER++ Monte-Carlo based on HT
- YaJEM Renk:
  medium increases virtuality of partons during evolution
- PYQUEN (Lokhtin, Snigirev):
  PYTHIA afterburner,
  reduces energy of final state partons and adds radiated gluons according to BDMPS expectations
- PQM (Dainese, Loizides, Paic):
  Monte Carlo implementation of BDMPS quenching weights
- JEWEL (Jet Evolution With Energy Loss)
  K.Zapp, Stachel, Wiedemann

Realistic density evolution is important

Density profile from hydrodynamics

T.Hirano and Y.N. PRC66(2002)041901

T.Renk, J.Ruppert, C. Nonaka, and S.A.Bass, PRC75(2007)031902(R)
A.Majunder, C. Nonaka and S.A.Bass, PRC76(2007)041902(R)

Thorsten Renk, Hannu Holopainen, Jussi Auvinen, and Kari Eskola

MARITINI+MUSIC: B.Shenke, C.Gale, S.Jeon

Jet quenching measurements

- Nuclear modification factor R_{AA} (Centrality and Pt dep.) for charged particles, pions, charm
- γ - hadron correlation
- Dihadron away side correlation strength I_{AA}
- Dijet energy imbalance A_J or ratio ET2/ET1
- Elliptic flow at high pt

Can we have coherent picture of jet-medium interaction?

Do we have coherent picture?

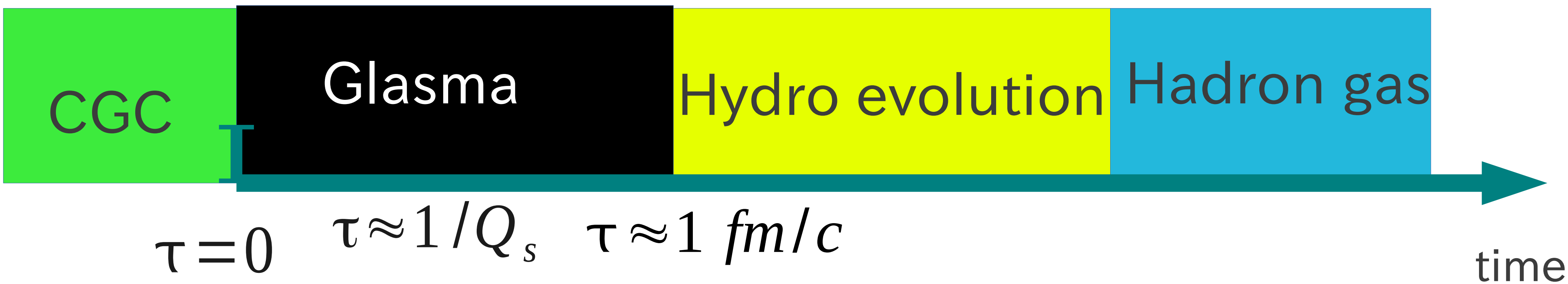
Parton energy loss with QGP phase

	$R_{AA}(\phi)$@RHIC	R_{AA}@LHC (P_T)	I_{AA}@RHIC	I_{AA}@LHC	A_J	$E_{T2}/E_{T1}(E_{trig})$
elastic	fails	works	fails	fails	works	fails
elMC	fails	fails	fails	not tested	not tested	not tested
ASW	works	fails	marginal	works	N/A	N/A
AdS	works	fails	marginal	works	N/A	N/A
YaJEM	fails	fails	fails	fails	works	works
YaJEM-D	works	works	marginal	marginal	works	works
YaJEM-DE	works	works	works	works	works	works

T. Renk, arXiv:1207.4885

High energy heavy ion collisions

Jet productions and interaction with media



- Jet modification in non-equilibrium state.
- Interaction between jet parton and medium
  modification by jets.
- Interaction between hadron jet and soft hadrons

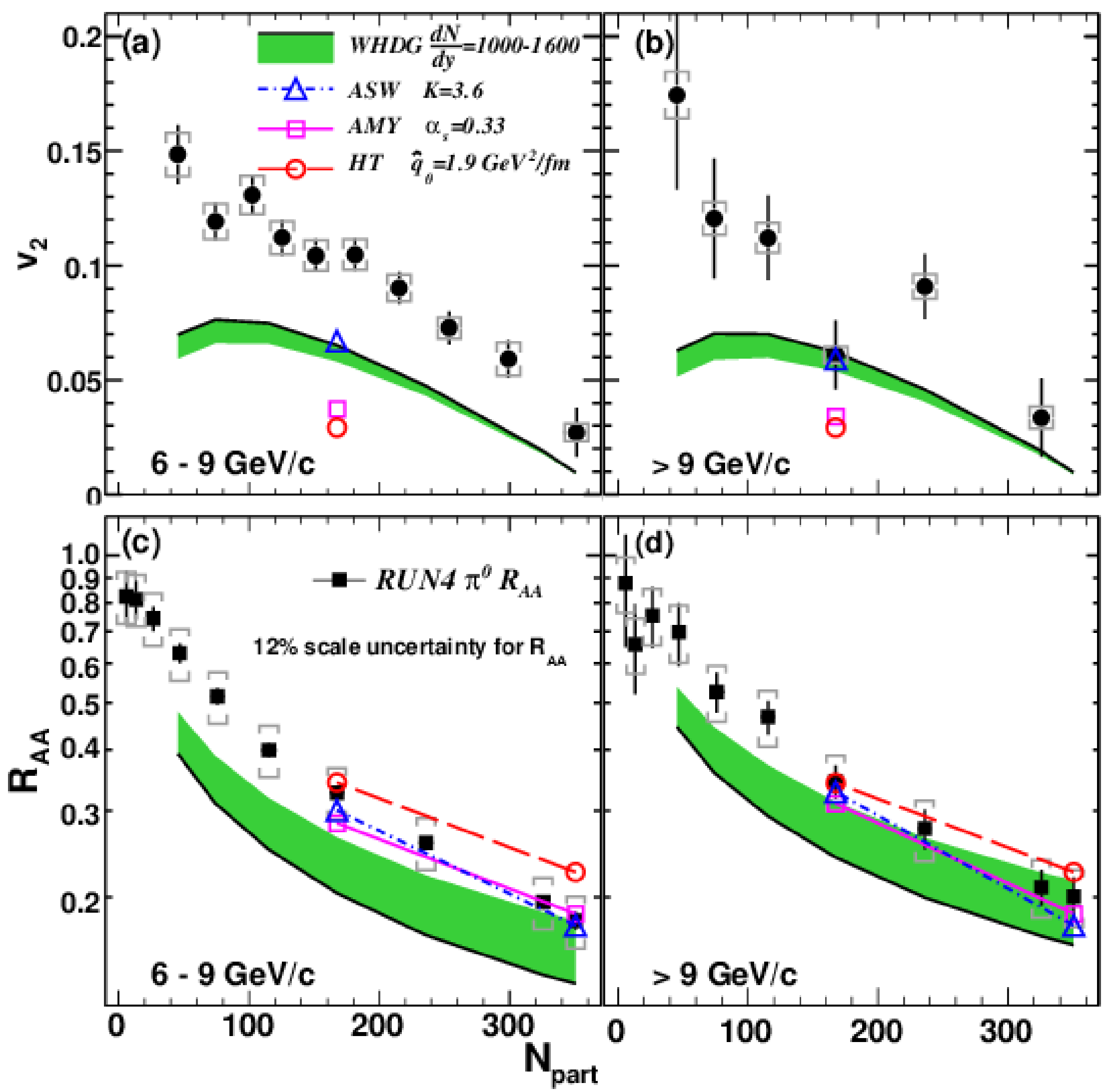
In most calculations, jets interact with thermalized matter (hydro).

Jet modification in the Glasma?
Jet modification during hadron gas stage?

Integrated dynamical approach is needed

Jet elliptic flow and R_AA

PHENIX Phys. Lev.Lett 105.142301 (2010)



Path-length dependence of Eloss?

$$E_{\rm elastic} \sim L,$$
$$E_{rad} \sim L^2,$$
$$E_{AdS/CFT} \sim L^3$$

Matter profile from CGC?

Initial transverse geometry for hydro initial conditions

Glauber model

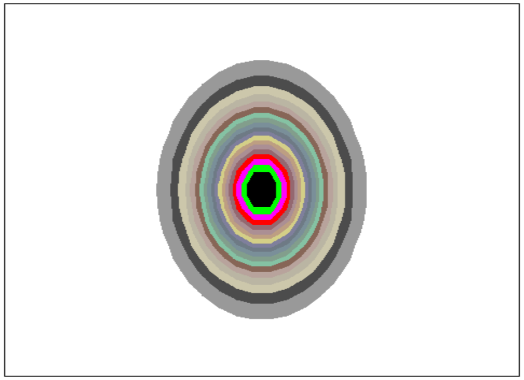
$$\frac{dN}{d^2 \boldsymbol{x}_\perp dy} \sim N_{part,1}(\boldsymbol{x}_\perp) + N_{part,2}(\boldsymbol{x}_\perp)$$

CGC

$$\frac{dN}{d^2 \boldsymbol{x}_\perp dy} \sim \min\{N_{part,1}(\boldsymbol{x}_\perp), N_{part,2}(\boldsymbol{x}_\perp)\}$$

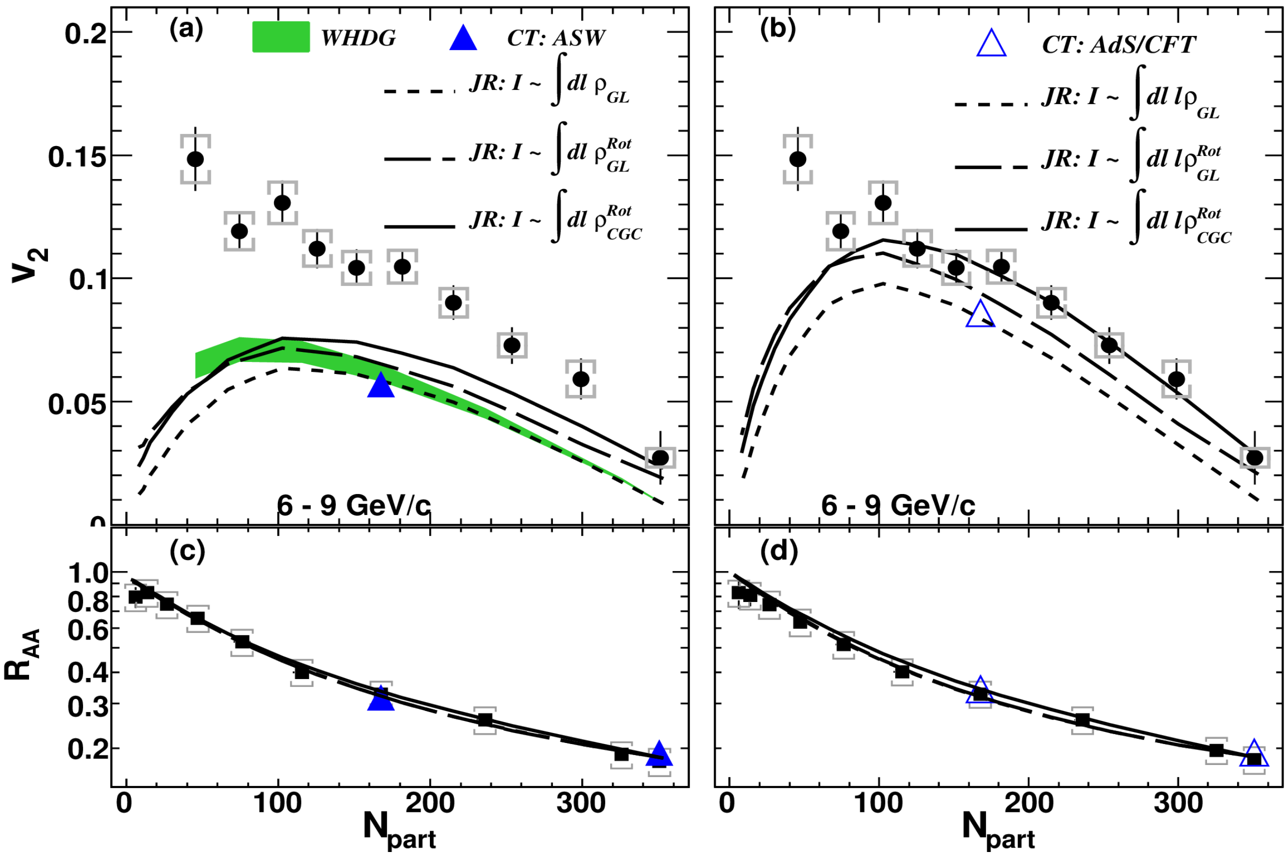
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle x^2 + y^2 \rangle}$$

$$\varepsilon_{CGC} > \varepsilon_{Glauber}$$



Path-length dependence

PHENIX Phys. Lev.Lett 105.142301 (2010)



CT:ASW
CT:AdS/CFT:
C.Marquet and T.Renk,
Phys.Lett.B685(2010)270

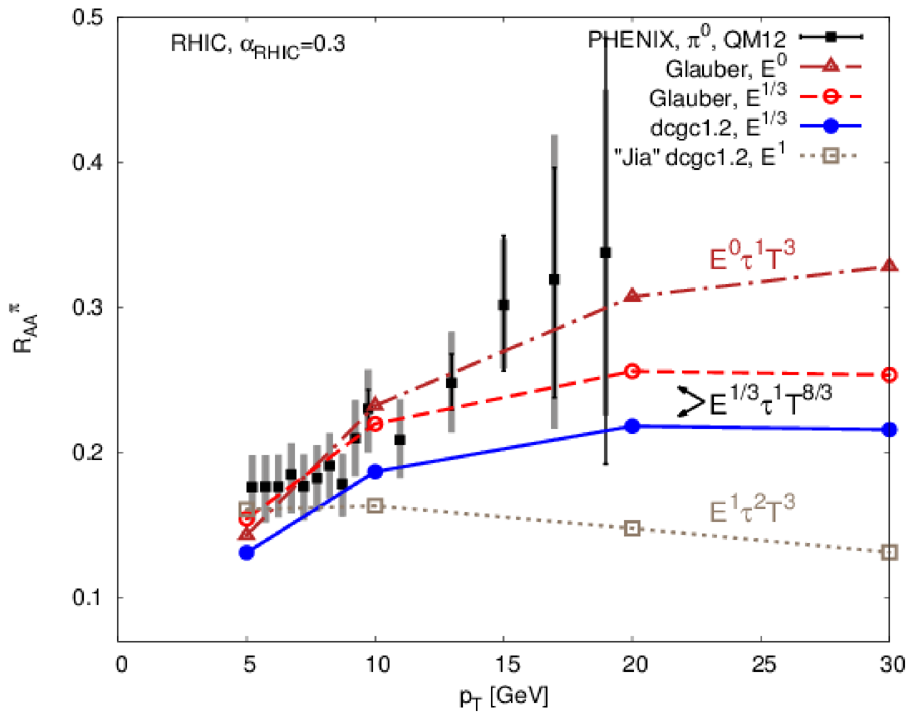
JR model:
A.Drees, H.Feng and J.Jia,
Phys. Rev.C71(2005)034909
J.Jia and R.Wei,
Phys.Rev.C82(2010)024902

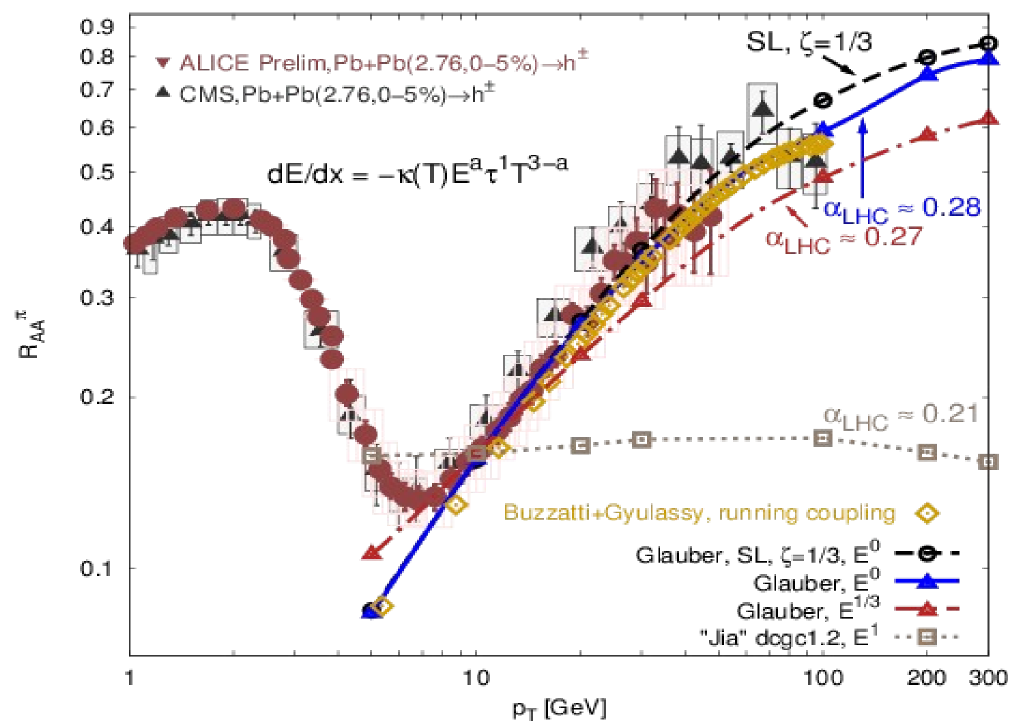
AdS/CFT:
S.S.Gubser, et.al, JHEPhys10
(2008)052,
P.M<.Chesler,et.al PRD79
(2009)025021
Predict L^3 dependence.

A.Ficnar, PRD86(2012)046010: AdS/CFT predicts the same L dependence as pQCD; L

Pt dependence of R_AA

B.Betz and M. Gyulassy, QM2012 , NPA904(2013)717c



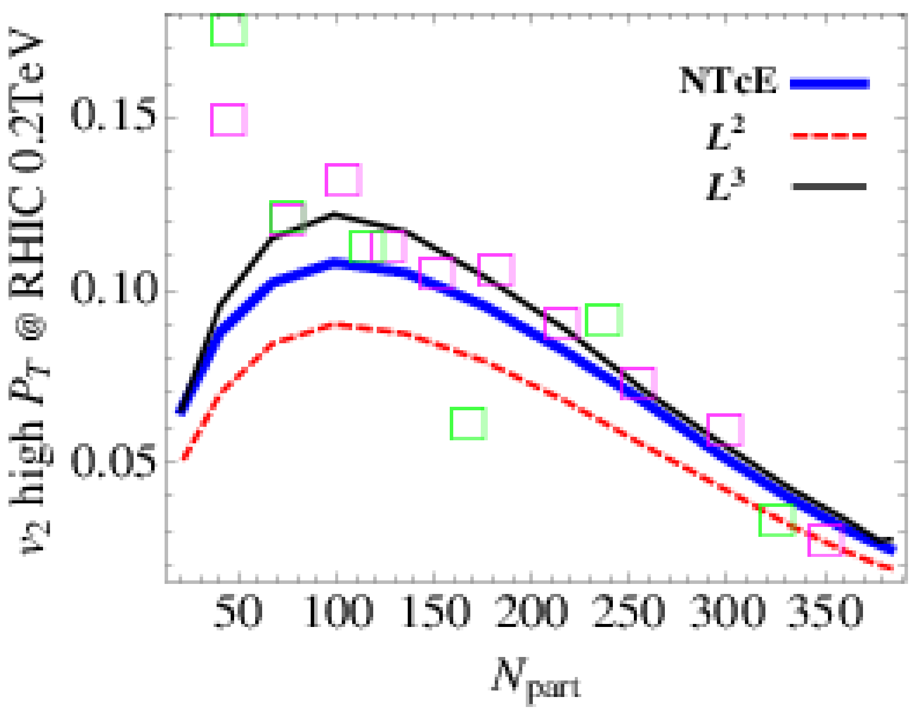


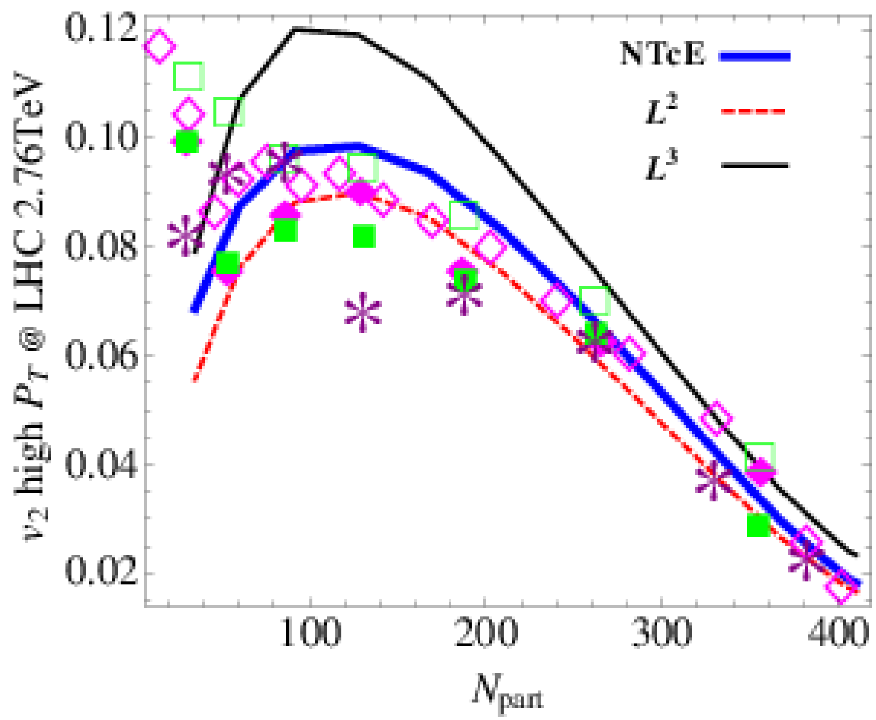
L^3 dependence is inconsistent with the transverse momentum dependence of R_AA

V2 from NTcE model

Near Tc enhancement (NtcE) model introduces a strong jet quenching in the vicinity of phase transition temperature Tc.

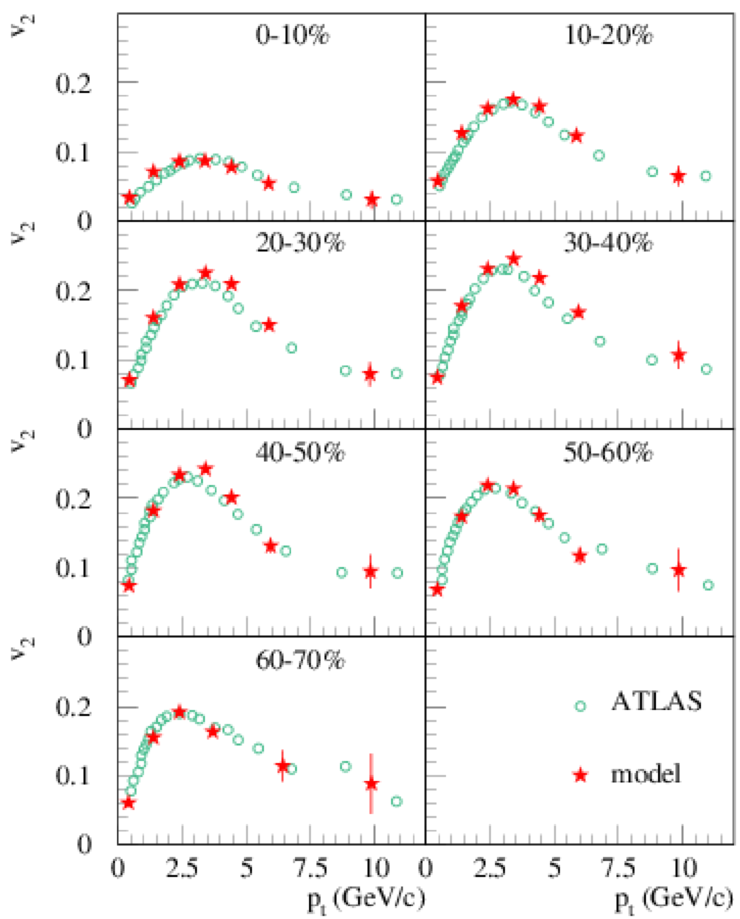
Nucl-th1208.6361, X. Zhang and J. Liao

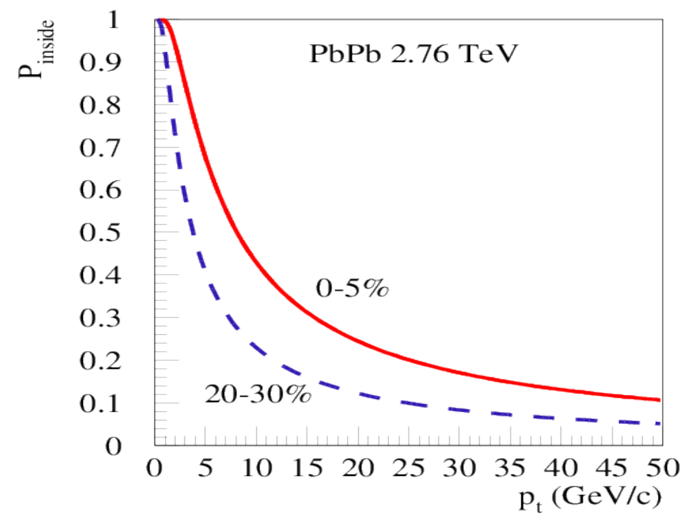


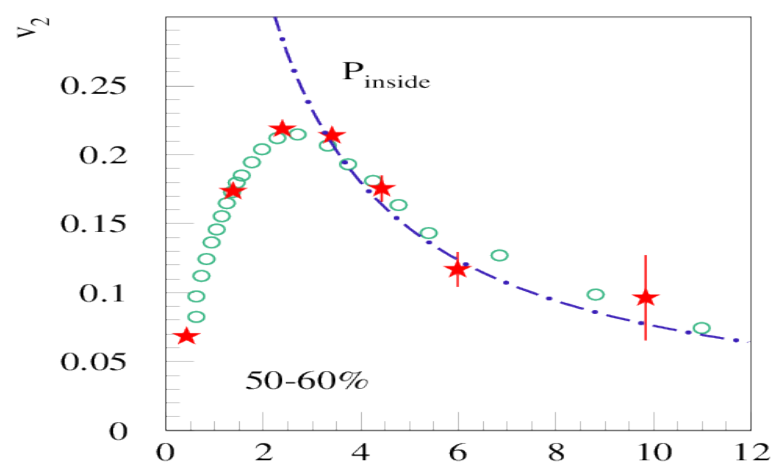


Epos + hydro prediction

V2 is proportional to the fluid-jet interaction prob. P_{inside}



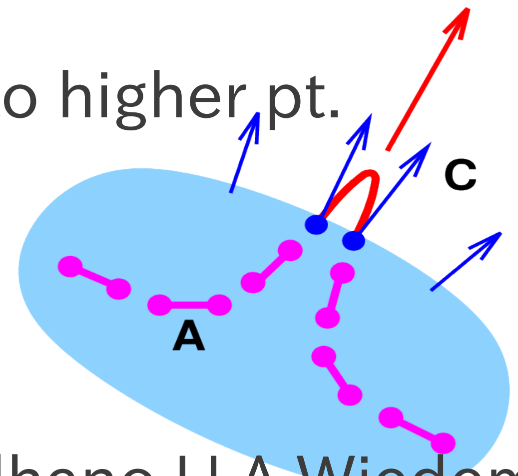




K. Werner, I..Karpenko, M. Bleicher, T. Pierog and S. Porteboeuf-Houssais, Phys. Rev. C85, 064907 (2012)

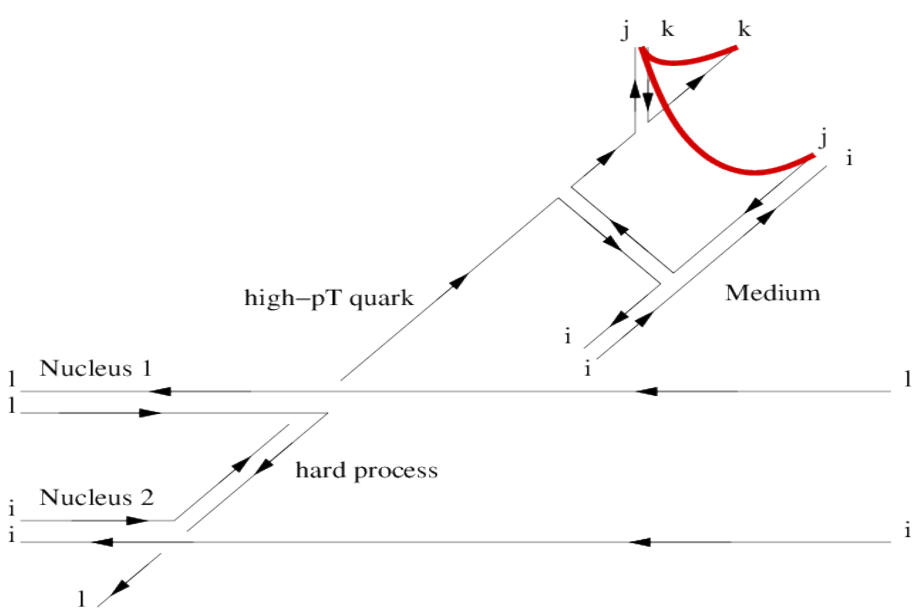
Bigger effects near Tc?

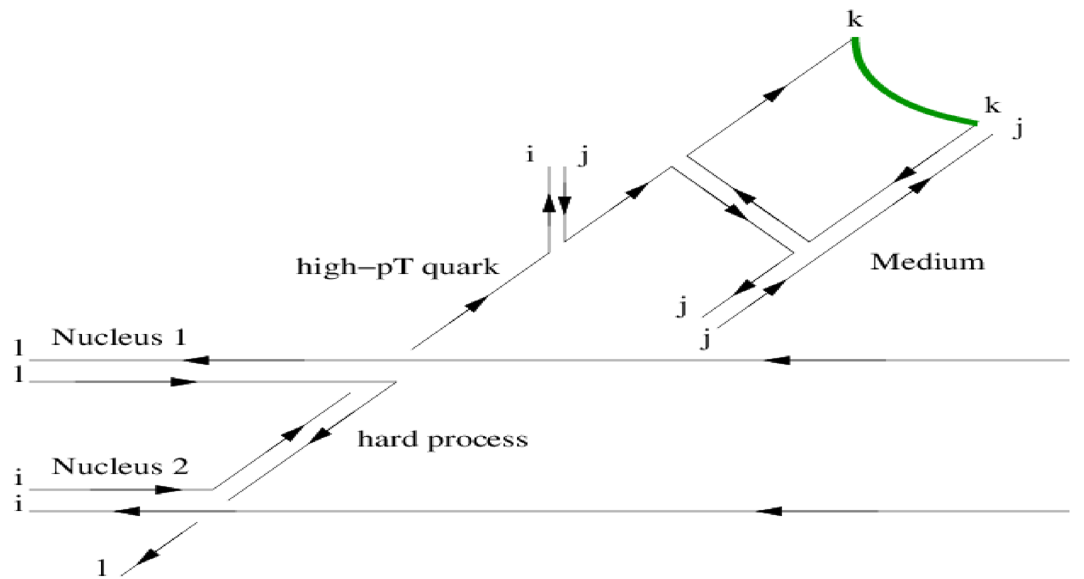
Fluid-jet interaction (eops+hydro):
Pushing the jet hadrons at intermediate pt to higher pt.



The near-Tc enhancement (NtcE)
Strong energy loss near Tc

Medium modified color flow (A.Beraudo,J.G.Milhano,U.A.Wiedemann
Softening of hadronic spectra for the color modified channels.





Out of medium or in medium hadronization?

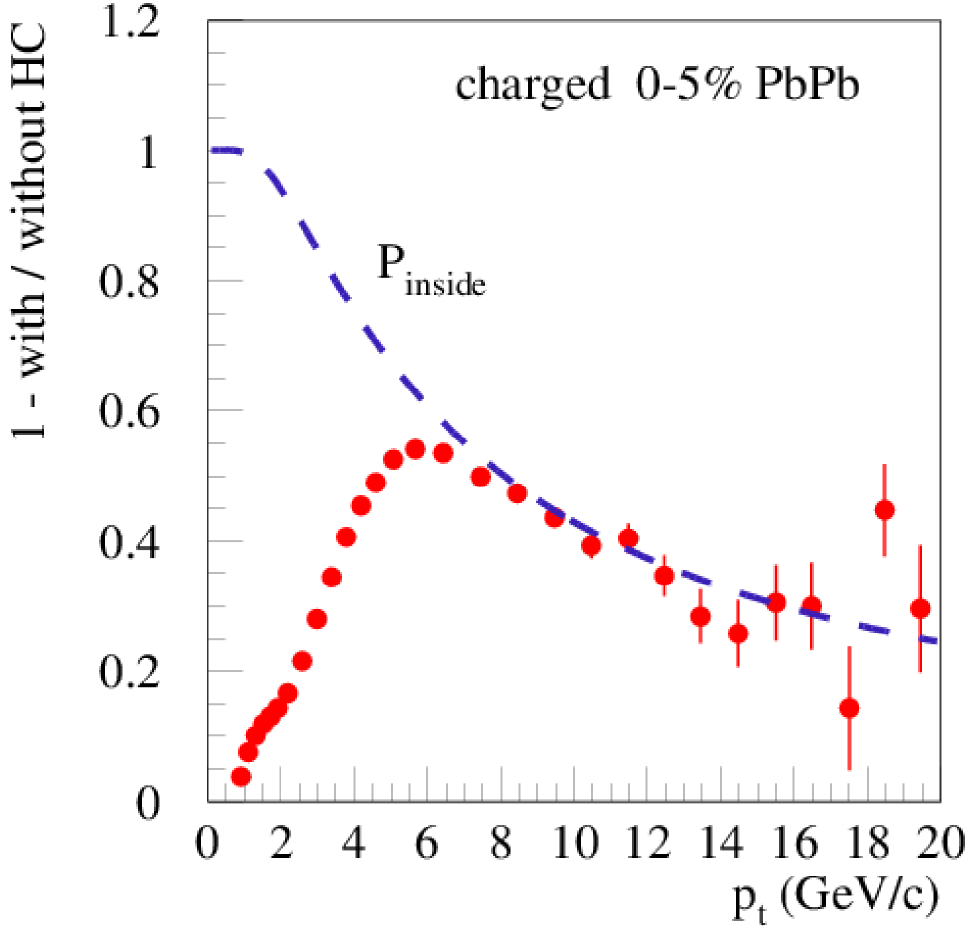
J. Casalderrey-Solana, J. G. Milhano and P. Q. Arias,
``Out of Medium Fragmentation from Long-Lived Jet Showers,"
Phys. Lett. B710, 175 (2012) [arXiv:1111.0310 [hep-ph]].

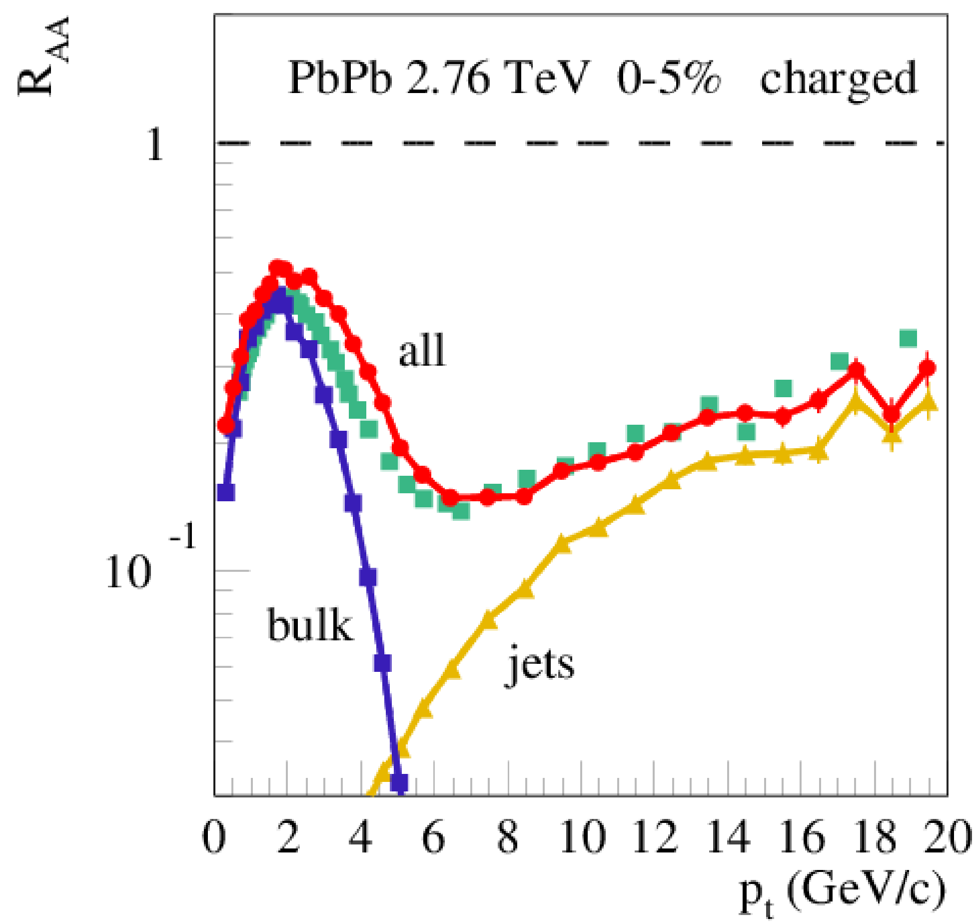
R. Bellwied and C.Markert,
``In-medium hadronization in the deconfined matter at RHIC and LHC,
Phys. Lett. B691, 208 (2010) [arXiv:1005.5416 [nucl-th]].

Effect of hadronic scattering

Epos + 3D ideal hydro + UrQMD

Jet-soft interaction is important up to 20GeV/





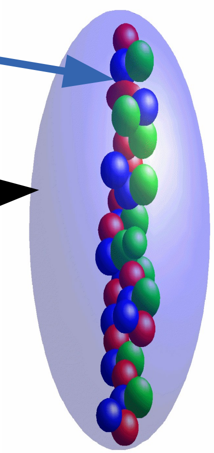
K. Werner, I..Karpenko, M. Bleicher, T. Pierog and S. Porteboeuf-Houssais,
Phys. Rev. C85, 064907 (2012)

Gauge field in the MV model

The gluon distribution is large:

Suggests the use of the semi-classical methods

$$D_\nu F^{\nu\mu} = J^\mu$$



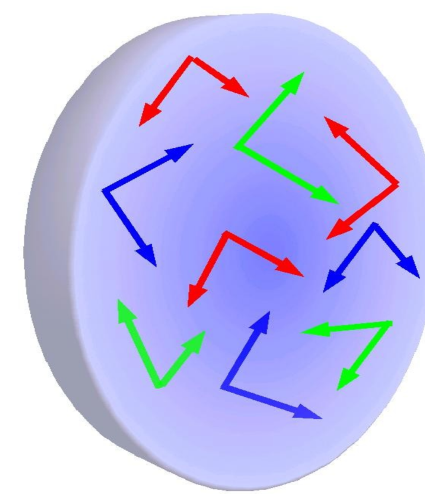
In the light-cone gauge: $A^+ = 0$,
a solution can be

$$A^- = 0,\ A^i = \frac{i}{g} U \partial^i U^\dagger,$$

$$U = P\exp\left[ig\int \Lambda\, dz^-\right], \quad -\Delta_\perp \Lambda = \rho$$

$\Lambda = A^+$
in covariant gauge

Color Glass Condensate



Non-abelian Weiszacker-Williams filed

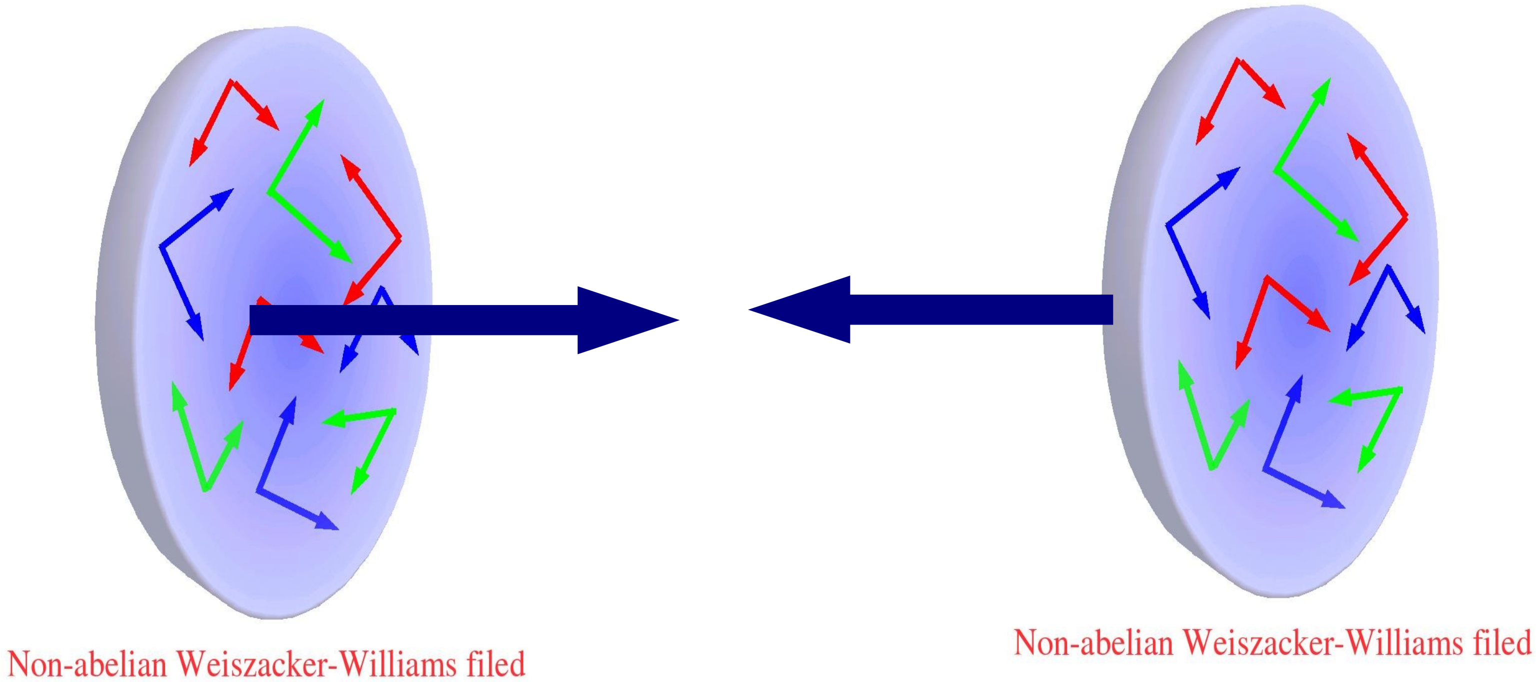
transverse component:
gauge transformation of vacuum $F^{ij} = 0$

The only non-zero component of the field strength: $F^{+i} \neq 0$

$$\boldsymbol{B}\cdot\boldsymbol{E} = 0,\ \boldsymbol{B}_z = \boldsymbol{E}_z = 0$$

$\tau \leq 0$:Before collision

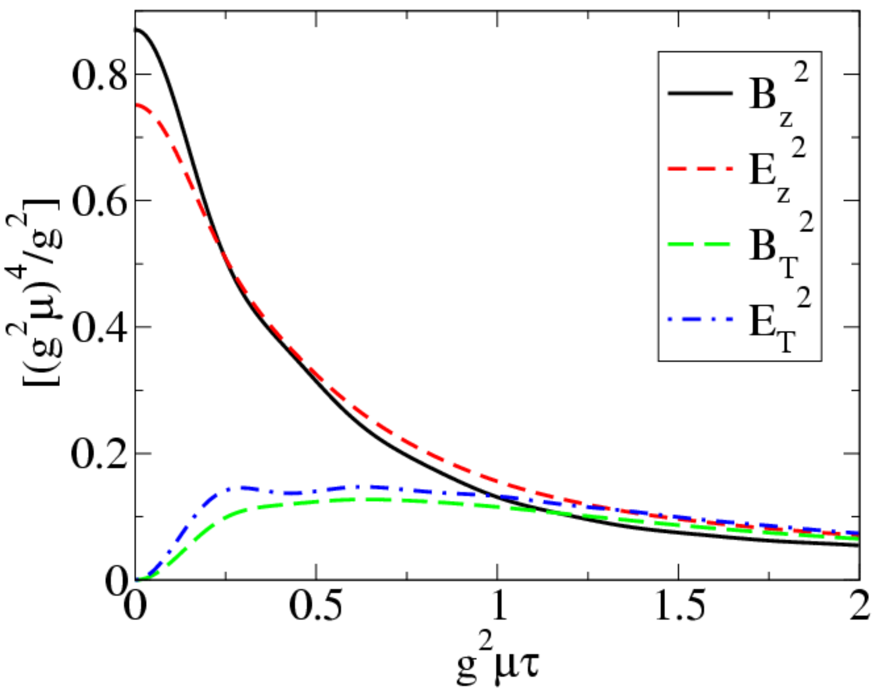
Color glass condensate



$\tau < 1/Q_s$: Yang-Mills field dynamics

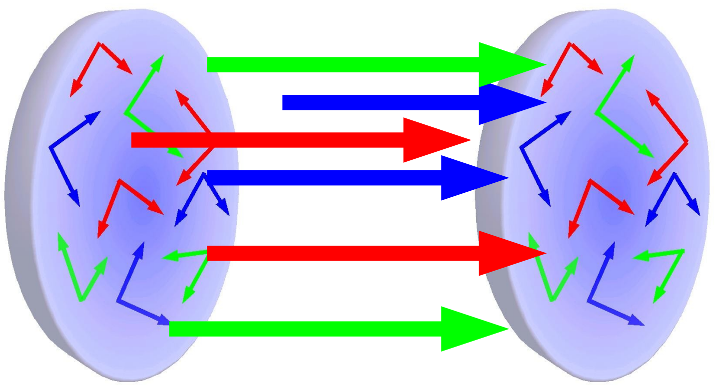
Real time evolution of the Classical Yang-Mills

T.Lappi, L. McLerran, N.P.A772



Similar to Lund string model picture but produce both color electric and magnetic fields.

Production of longitudinal color EM fields.



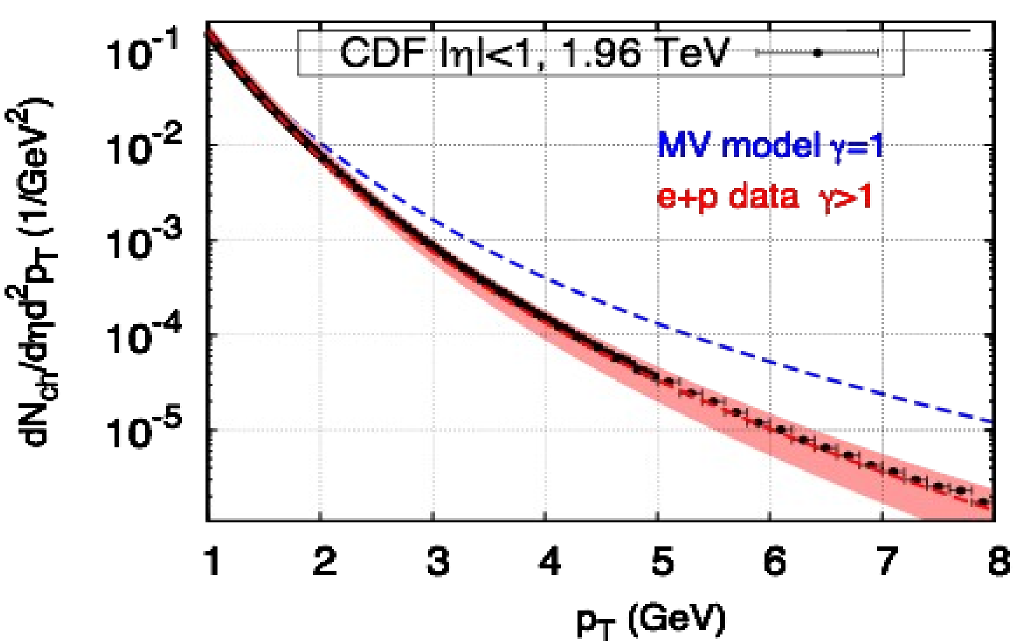
Instabilities of Yang-Mills field :
P.Romatschke, R.Venugopalan,K.Fukushima, Gelis, McLerran, A.Iwazaki

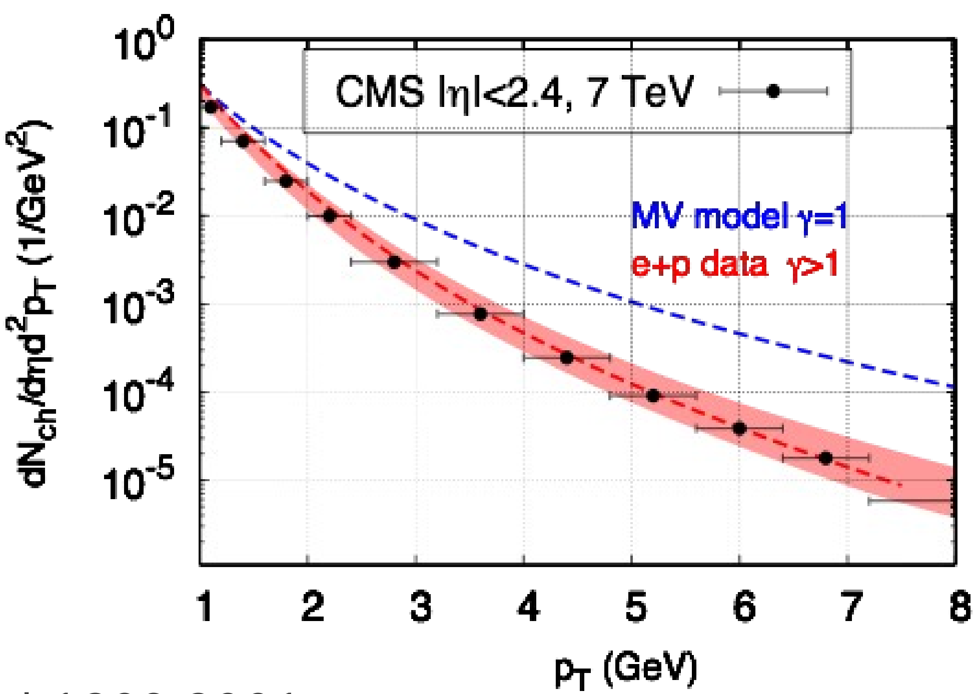
Comparison to LHC data with kt-factorization formula + rcBK

Strong constrain to the initial condition.

$\gamma > 1$ → evolution slow down

CGC prediction is consistent with data up to 8 GeV





J.L.Albacete, A. Dumitru, H. Fujii, Y.N. Hep-ph1209.2001

Parton energy loss in the Glasma

E.V. Shuryak and I. Zahed, PRD67(2003)039903.

A. Majumder, B. Muller and S.Mrowczynski,
``Momentum Broadening of a Fast Parton in a Perturbative Quark-Gluon Plasma,''
Phys. Rev. D80, 125020 (2009).

A. Dbeyssi, D.A.Dirani and H.Zaraket, PRD84 (2011)105033

P.~Aurenche and B.~G.~Zakharov,
``Parton energy loss in glasma," Phys. Lett. B718, 937 (2013)
[arXiv:1205.6462 [hep-ph]].

The contribution of the energy loss in the Glasma state is much smaller than the radiative energy loss in the QGP phase.

Beyond linear approximation (HL)

solving full Vlasov equation for gluons, i.e. dynamics of fields and particles.

$$p^{\mu}\left(\frac{\partial}{\partial x^{\mu}} - g f^{abc} A_{\mu}^{b} Q^{c} \frac{\partial}{\partial Q^{a}} - g Q_{a} F_{\mu\nu}^{a} \frac{\partial}{\partial p_{\nu}}\right) f(x, p, Q) = 0$$

$$D_{\mu} F^{\mu\nu} = J^{\nu}$$

- non-linear effects: saturation of instabilities.
- study isotropization of the system (particles and field) by interactions between particles and field.
- Extreme anisotropies (back reaction important)
- weak and strong initial field.

Particle in cell simulation for colored particles (CPIC)

Test particle method:

$$f(\boldsymbol{x},\boldsymbol{p},Q)=\frac{1}{N_{\text{test}}}\sum_i \delta(\boldsymbol{x}-\boldsymbol{x_i}(t))\delta(\boldsymbol{p}-\boldsymbol{p_i}(t))\delta(Q-Q_i(t))$$

Wong-Yang-Mills equation:

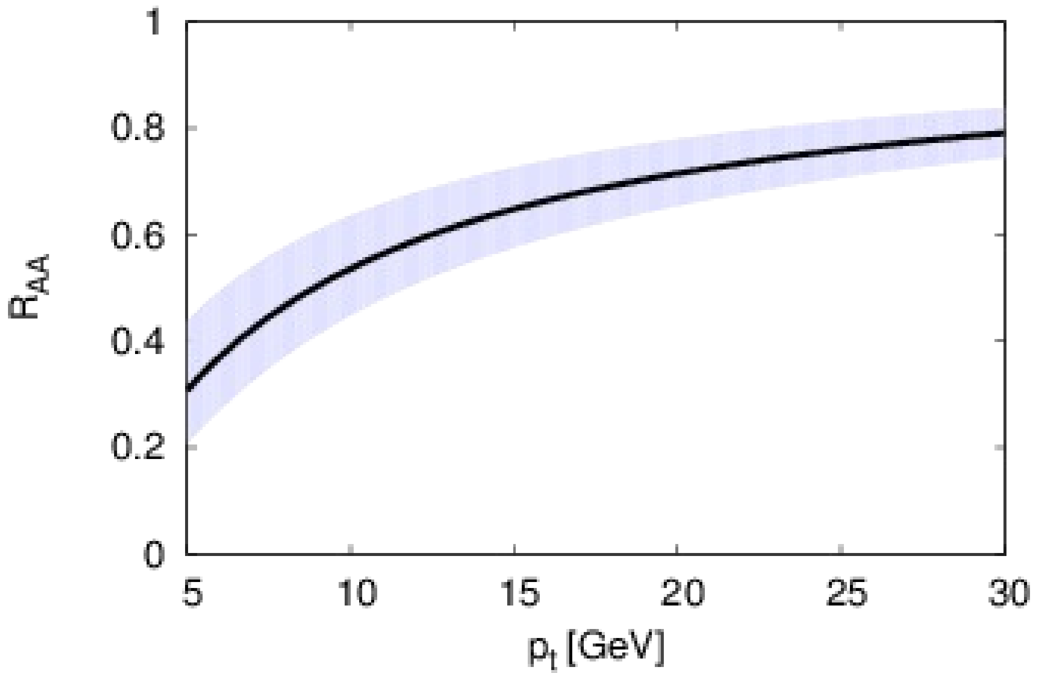
$$\frac{d\,\boldsymbol{x}_i}{dt}=\boldsymbol{v}_i,\quad \frac{d\,\boldsymbol{p}_i}{dt}=gQ_i^a(\boldsymbol{E}_i^a+v_i\times\boldsymbol{B}_i^a),\quad \frac{d\boldsymbol{Q}_i}{dt}=igv_i^\mu[A_\mu,Q_i].$$

$$D_\mu F^{\mu\nu}=J^\nu=g\sum Q v^\mu\delta(x-x_i(t))$$

Elastic collisions among hard particles are also included.

Nuclear Modification factor from classical YM field

Contribution of energy loss before thermalization is significant.

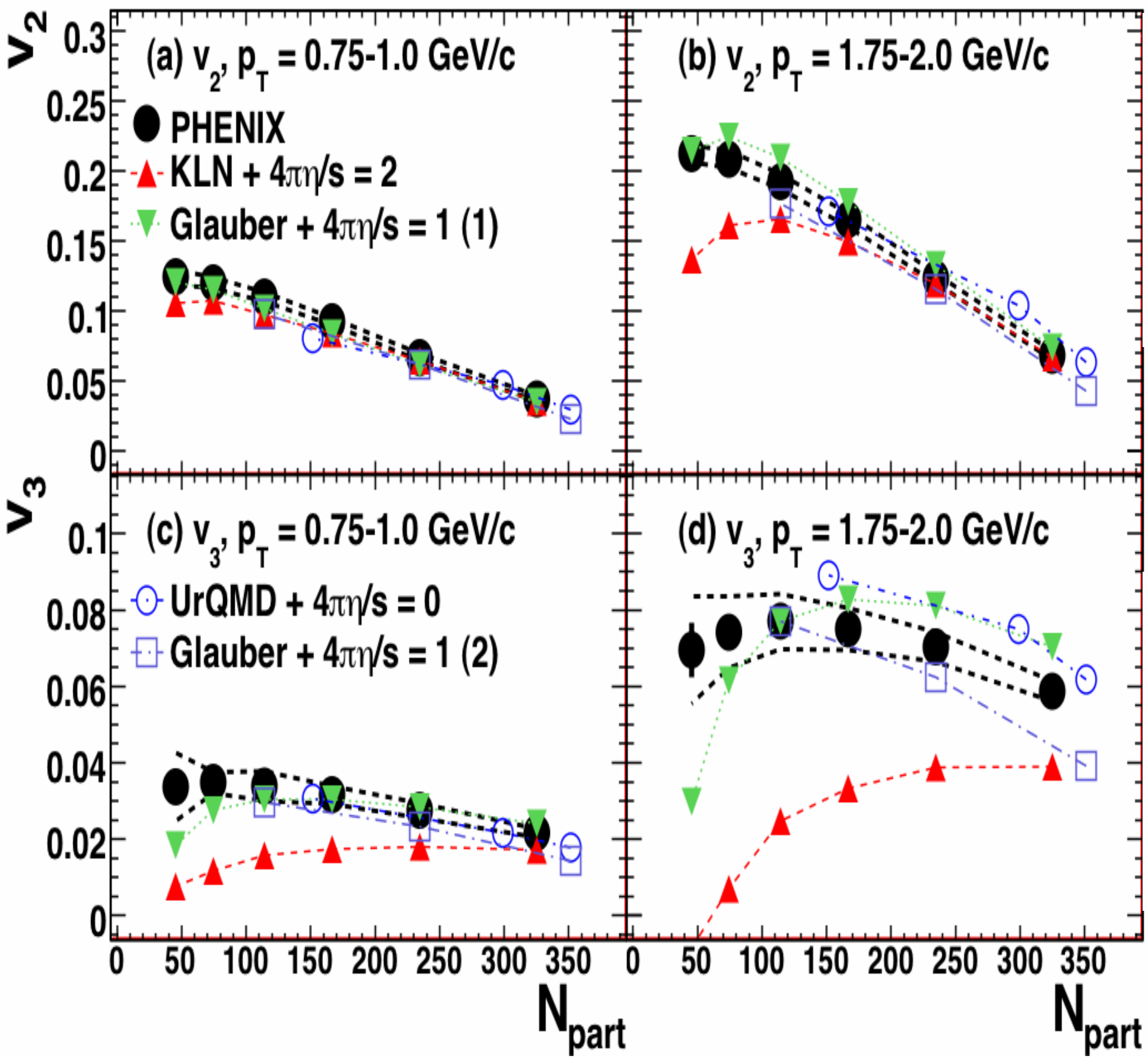


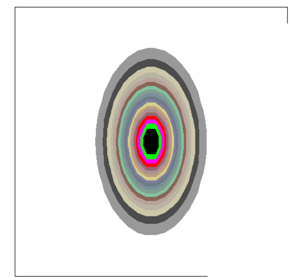
B. Schenke, M. Strickland, A. Dumitru, Y. N. and C. Greiner, Phys. Rev. C79, 034903 (2009)

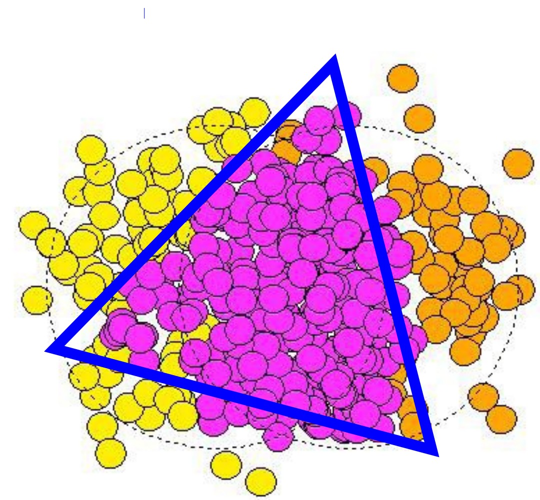
V_2 and V_3 data from PHENIX

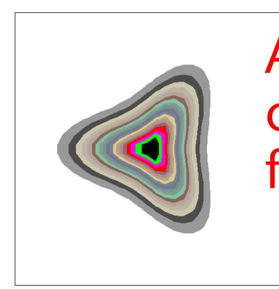
A. Adare et al. [PHENIX Collaboration],
Phys. Rev. Lett. 107, 252301 (2011).

Z.Qiu, C.Shen, U.W.Heinz,
Phys. Lett. B707, 151 (2012)
For analysis of ALICE data.





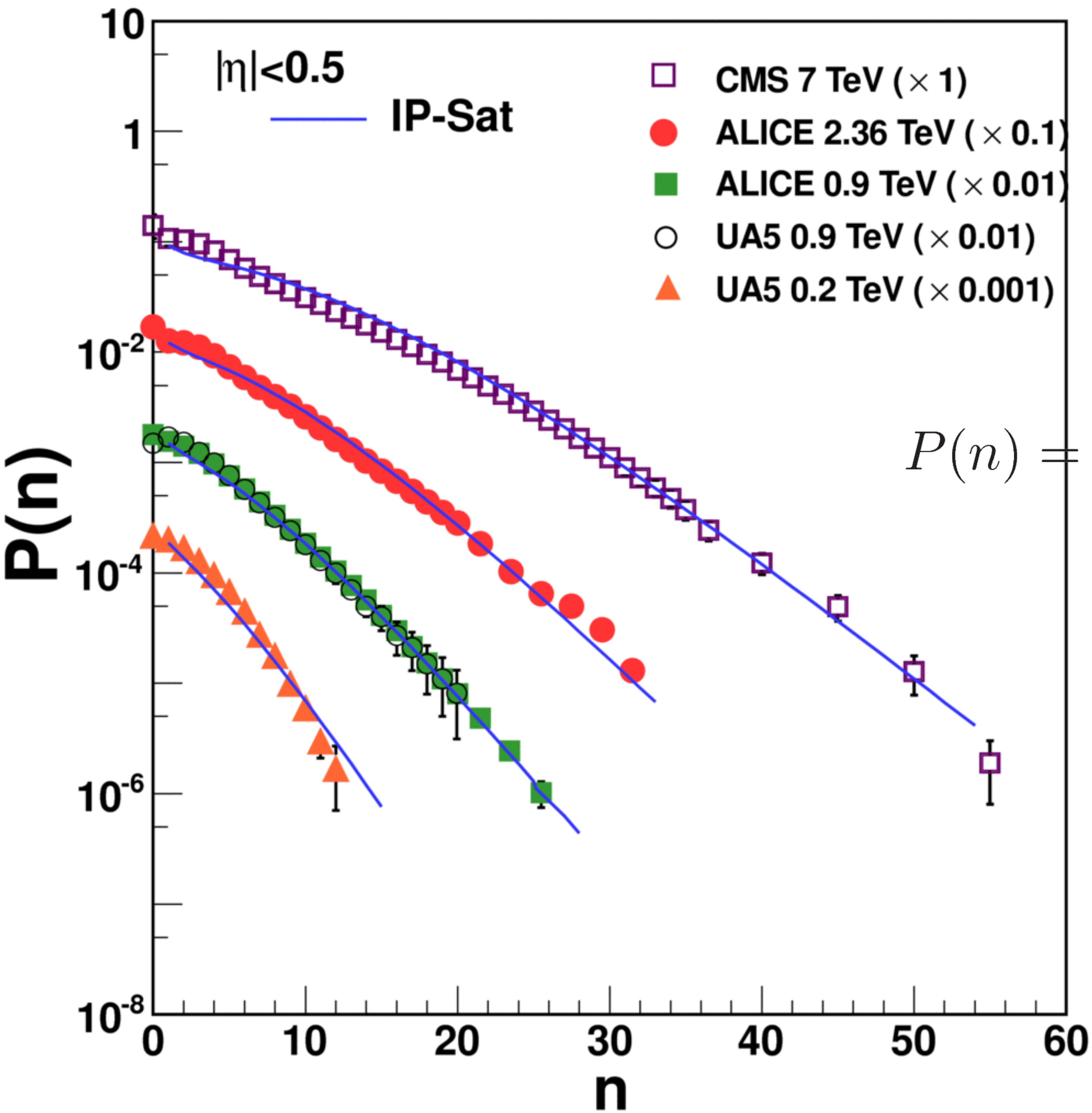




All theoretical approaches only include fluctuations from nucleon position.

B. Alver et. al., Phys. Rev. C82, 034913(2010).
B. Schenke et. al., Phys. Rev. Lett. 106, 042301(2011).
H. Petersen et. al., Phys. Rev. C82, 041901(2010).

Multiplicity distributions in *pp* collisions



Gelis, Lappi, McLerran:
Nucl.Phys.A828:149-160,2009

Glasma → Negative binomial

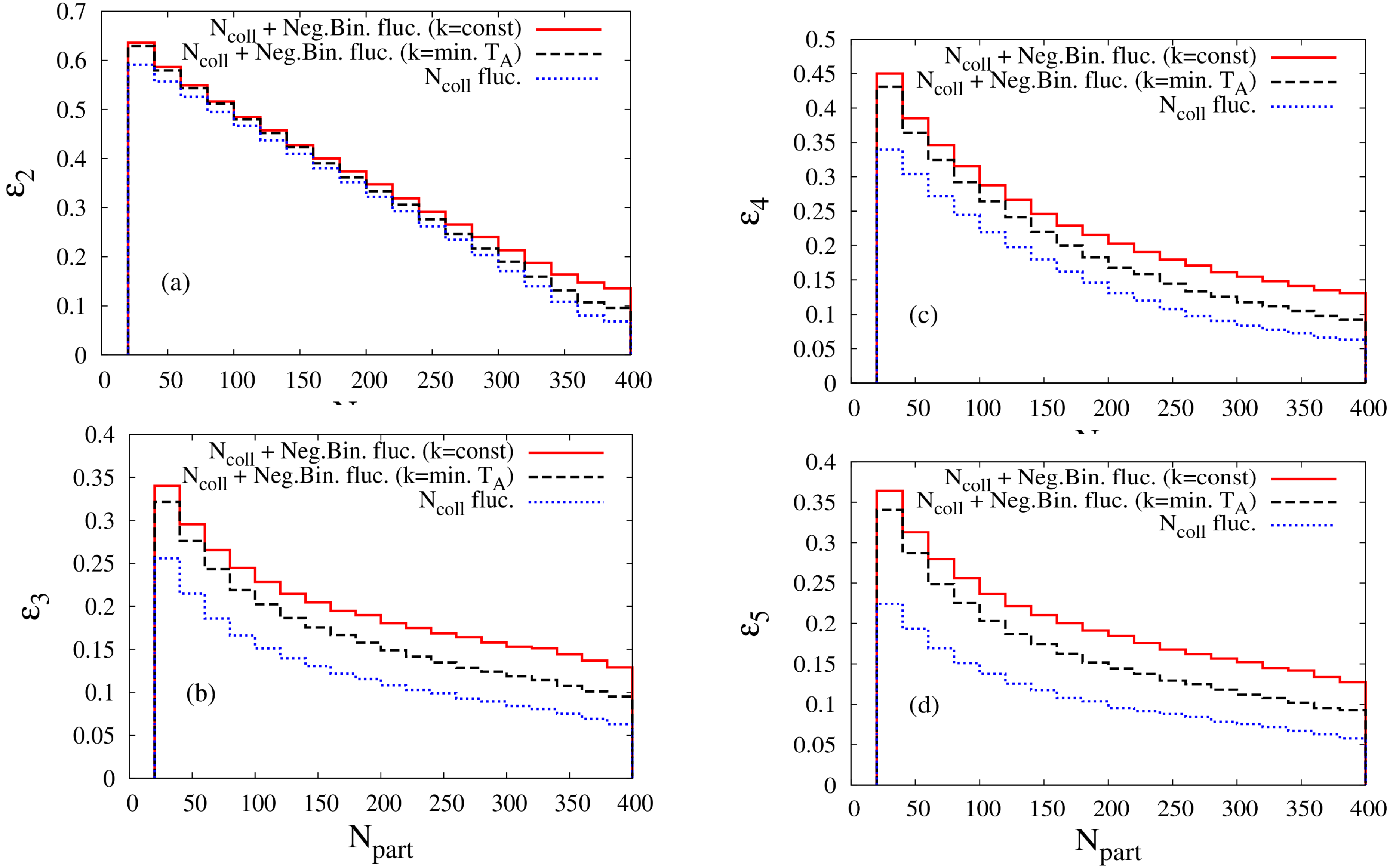
$$P(n) = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)} \frac{\langle n \rangle^n k^k}{(\langle n \rangle + k)^{n+k}}$$

Effects of fluctuations
in the particle production
on the eccentricities?

Tribedy & Venugopalan: arXiv:1112.2445

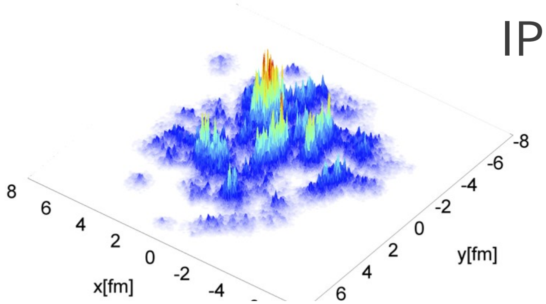
Eccentricities with N.B. dist.

epslion_2 stays the same but higher order ecc.s become larger!

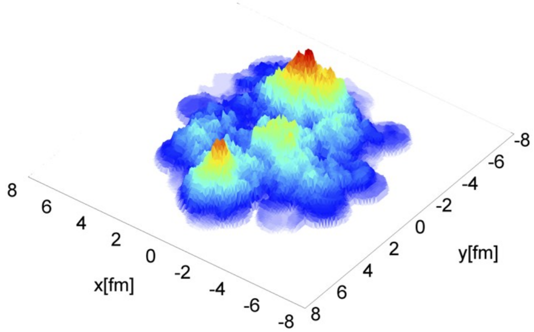


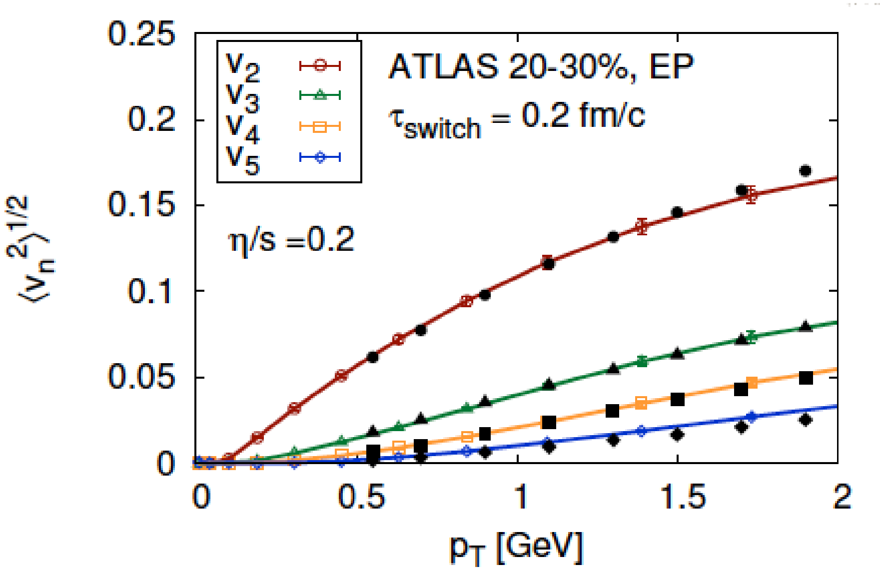
IP-sat Classical YM

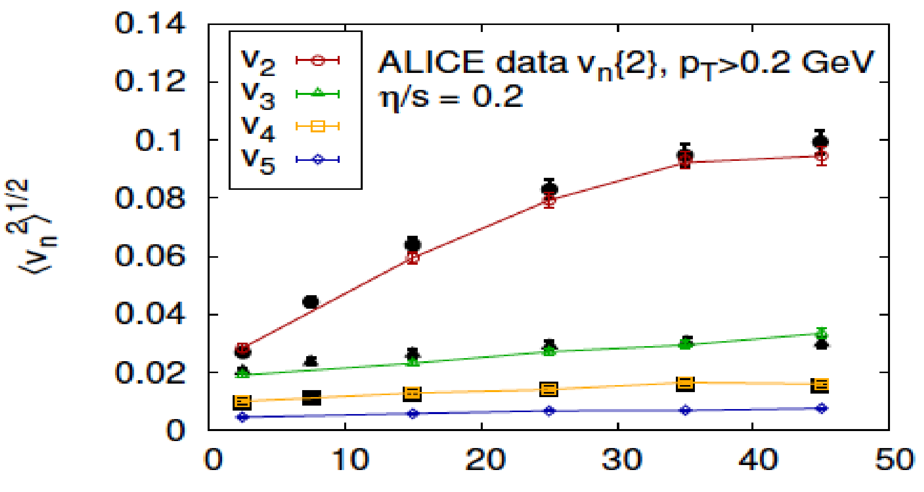
IP-sat



KLN







B.Schenke, P.Tribedy and R.Venugopalan,
Phys. Rev. Lett.108, 252301 (2012)

Summary

- There is no theoretical model which describes
  the jet quenching data systematically.

- Energy loss data may give an important information on
  the physics near the Tc.

- Realistic model for energy loss in the Glasma is needed.