Theoretical Review on Heavy Ion Physics at LHC Energies

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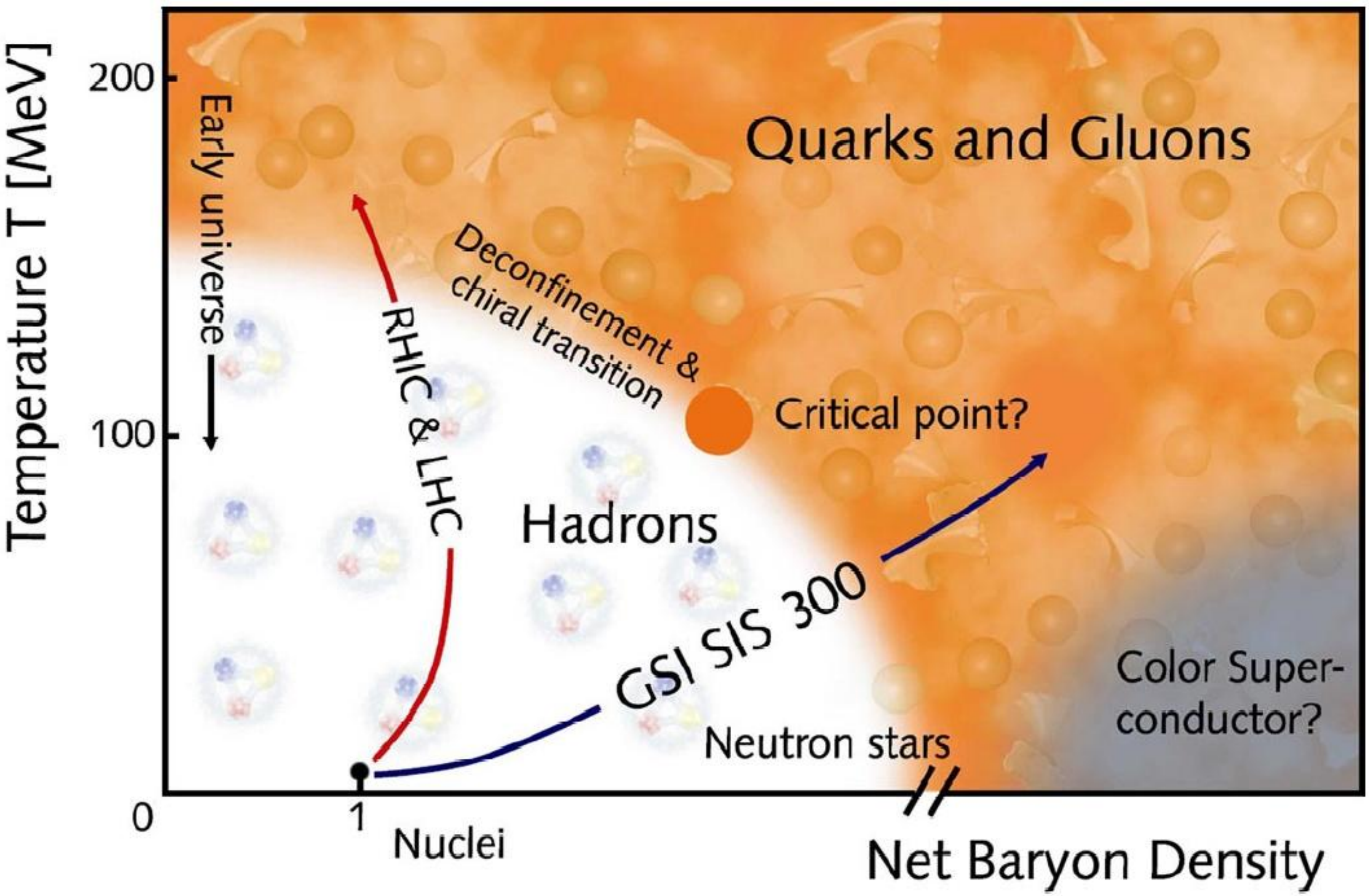
Outline

- Bulk properties of QGP system at LHC
- Energy Loss and jet production
- Direct photon production
- CGC and small-x physics
- Summary

QCD Phase Diagram

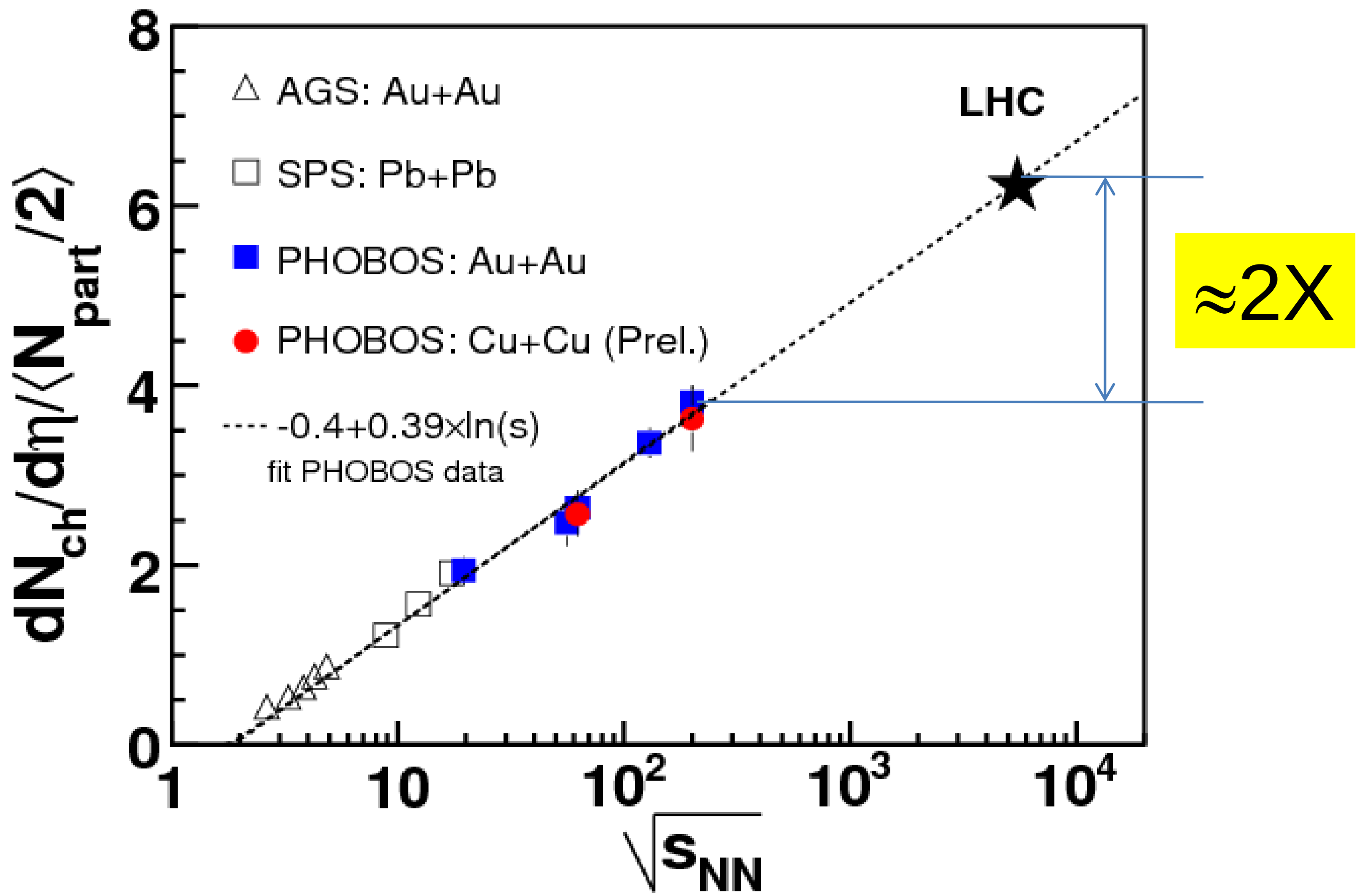


Bulk properties of QGP

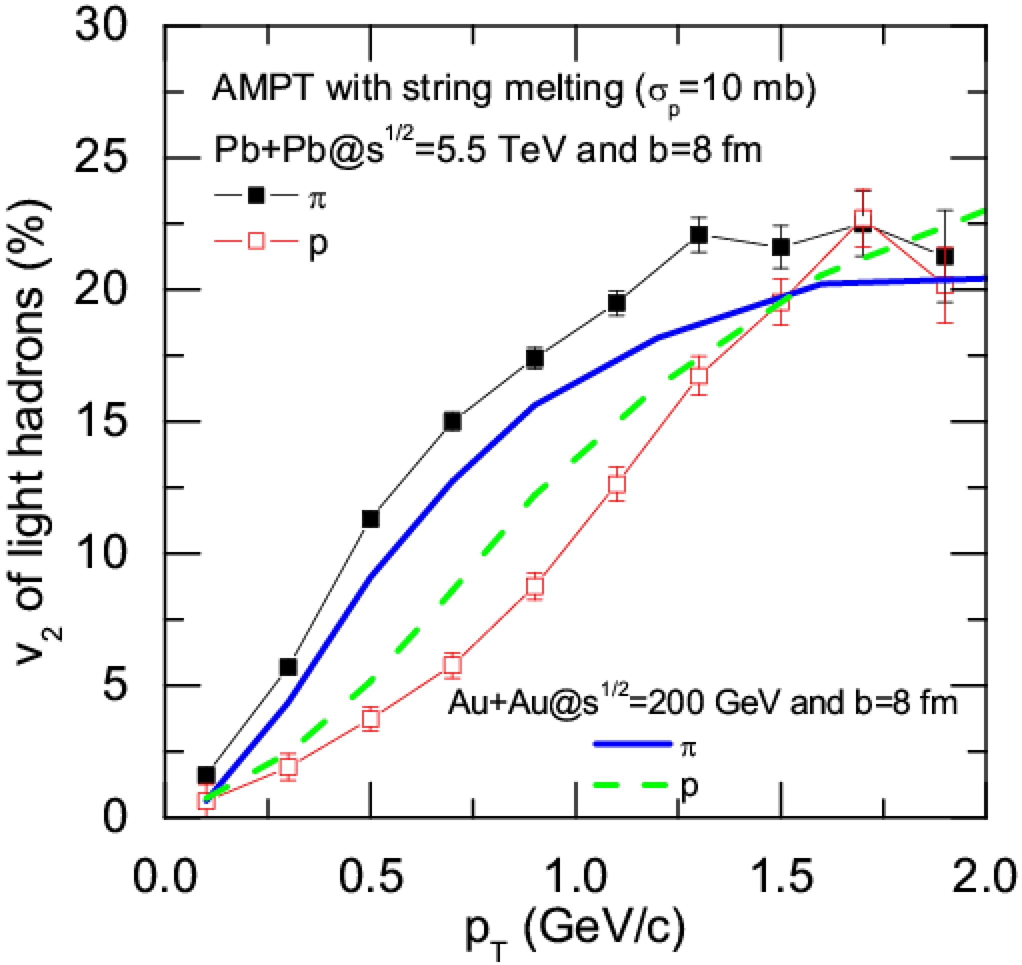
Comparing ALICE with RHIC

- Higher initial energy density $\varepsilon_0 \geq 10\varepsilon_c$
- Higher initial temperature $T_0 \geq 2T_c$
- Larger lifetime and freeze-out volume
- Nearly net baryon free
- More likely to be ideal parton gas

Mid-rapidity Densities



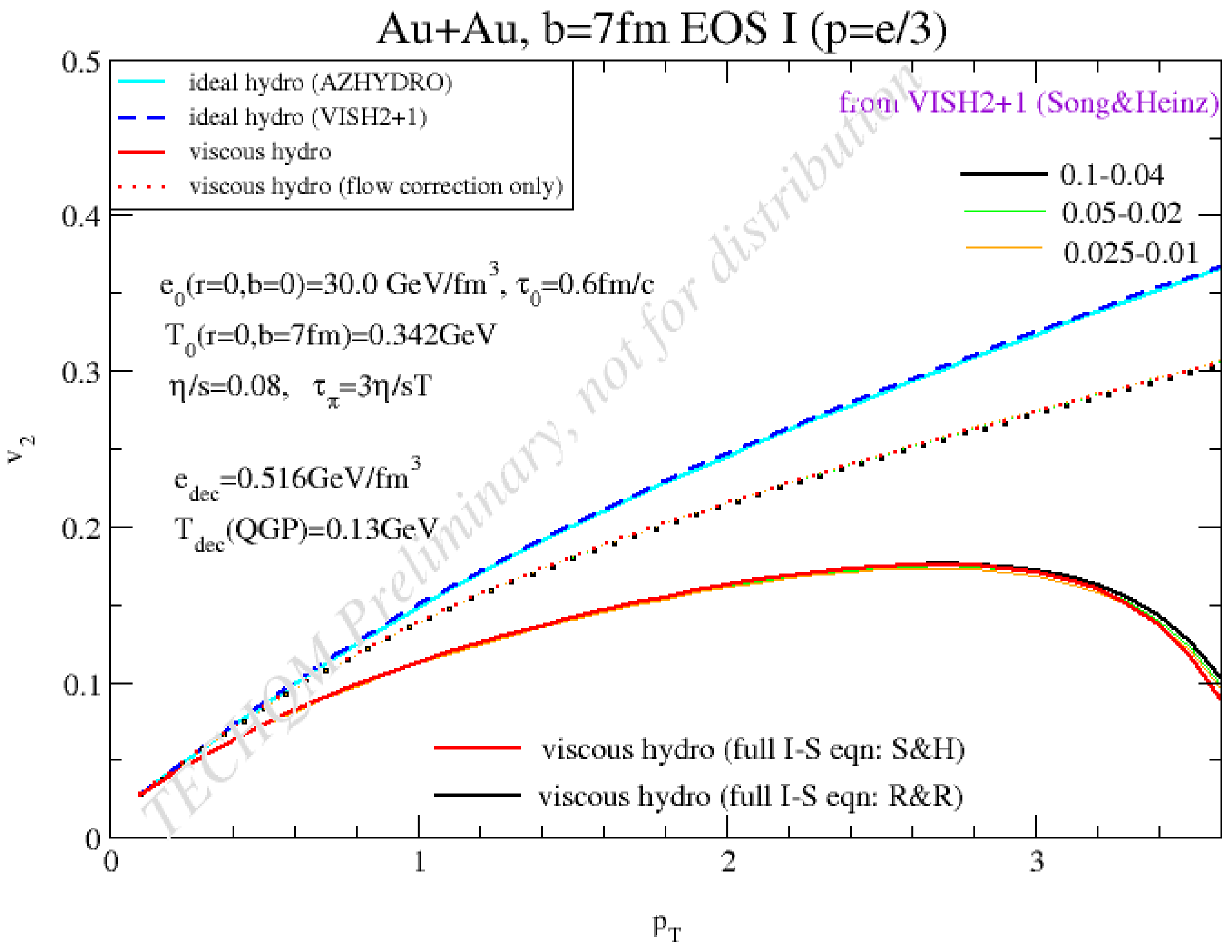
at LHC, $dN/d\eta \approx 1000 - 3000$



Elliptic flow is larger for pions but smaller for protons at LHC than at RHIC

Quark number scaling of v_2 no longer valid

Elliptic flow is sensitive to viscosity



Viscosity: Bounds from theory

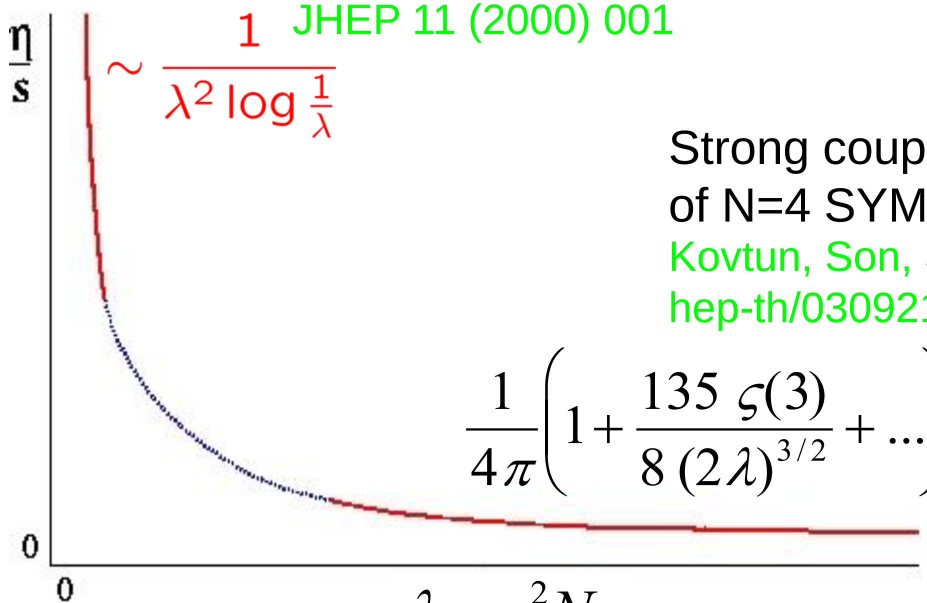
- Viscosity η controls entropy s increase

$$\frac{d(\tau s)}{d\tau} = \frac{\frac{4}{3}\eta}{\tau T}$$

- Hydrodynamics is valid, if

$$\frac{\eta}{\tau T}\frac{1}{s} \ll 1$$

- Constraint from string theory



$\sim \frac{1}{\lambda^2 \log \frac{1}{\lambda}}$

Arnold, Moore, Yaffe, JHEP 11 (2000) 001

Strong coupling limit of N=4 SYM

Kovtun, Son, Starinets, hep-th/0309213

$$\frac{1}{4\pi}\left(1 + \frac{135\,\varsigma(3)}{8\,(2\lambda)^{3/2}} + \ldots\right)$$

$$\frac{\eta}{s} > \frac{1}{4\pi}$$

$$\lambda \equiv g^2 N_c$$

Viscosity of QGP

Theoretical lowest bound is: $\frac{\eta}{s} \geq \frac{1}{4\pi}$

RHIC showed: η cannot exceed the lowest bound by a factor of 2, smaller than any other substance

How large is η at LHC?

AdS/CFT now being applied to Heavy ion physics

- Viscosity, η/s. (D.T. Son)
- Jet quenching (H. Liu)
- Heavy quarkonium

Defu Hou , Hai-cang Ren, JHEP0801:029(2008)

- ``Sound" waves
- Photon production
- Friction …
- Hardron spectrum (ADS/QCD)

LHC: the richness of hard probes

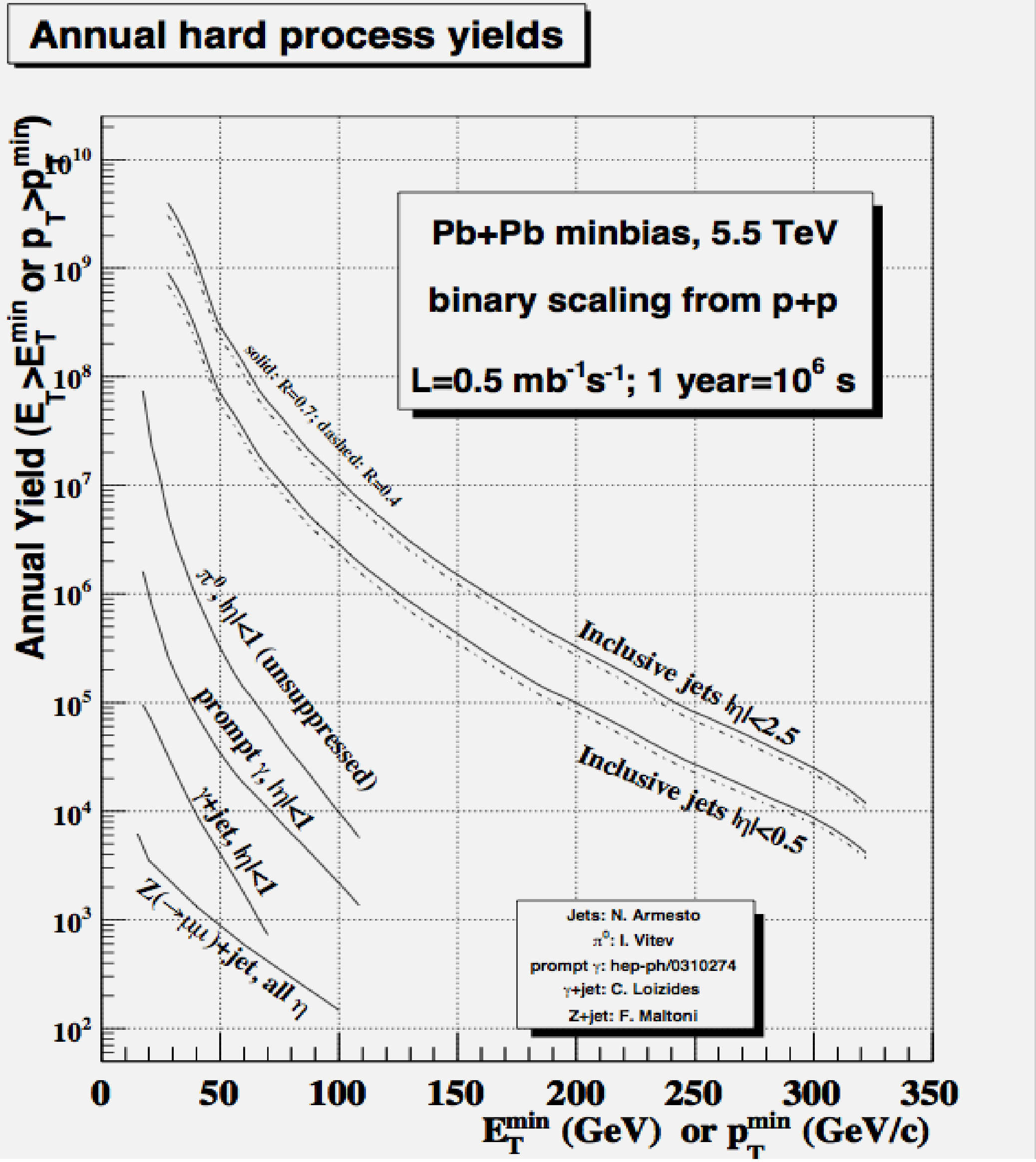
The probes:

- Jets
- identified hadron specta
- D-,B-mesons
- Quarkonia
- Photons
- Z-boson tags

The range:

Q^2 ,x, A, luminosity

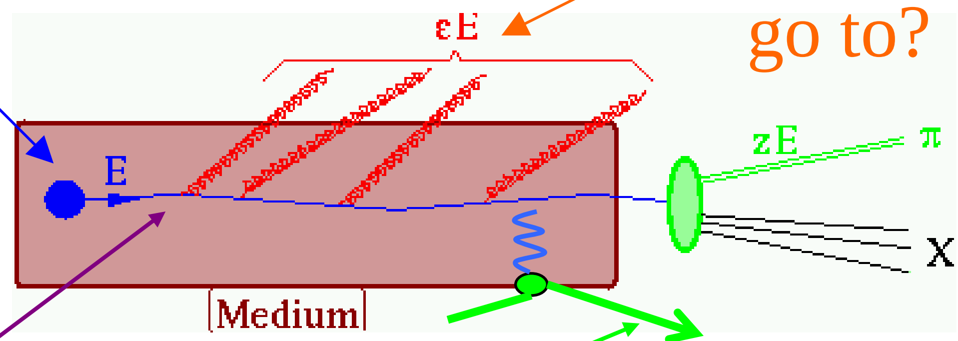
Abundant yield
of hard probes
+ robust signal
(medium sensitivity
>> uncertainties)
= detailed understanding
of dense QCD matter



How does a hard probe interact in the medium?

How does this parton thermalize?

Where does this associated radiation go to?



The dependence on parton identity?

$$\Delta E_{gluon} > \Delta E_{quark, m=0} > \Delta E_{quark, m>0}$$

Characterize Recoil: What is kicked in the medium?

$$\Delta E \propto L^2$$

Jet multiparticle final states provide qualitatively novel characterizations of the medium

Jet production at LHC

- Copious production of jets in Pb+Pb collisions at LHC
- Energy loss from radiation & collision about equally important, L dependence different
- Energy loss decreases with parton mass
- Jet shape and spectra influenced by medium

Correlations in jet

Many jets may overlap

Traditional jet analysis may fail

Correlation analysis should be used

Correlations in jets

- Near- & away-side correlations
  - Ridge+jet on the near side
  - Mach-cone + jet on the away side?
  - Universal distribution in ridge and Mach-cone?
  - System size dependence?
  - Trigger momentum dependence?

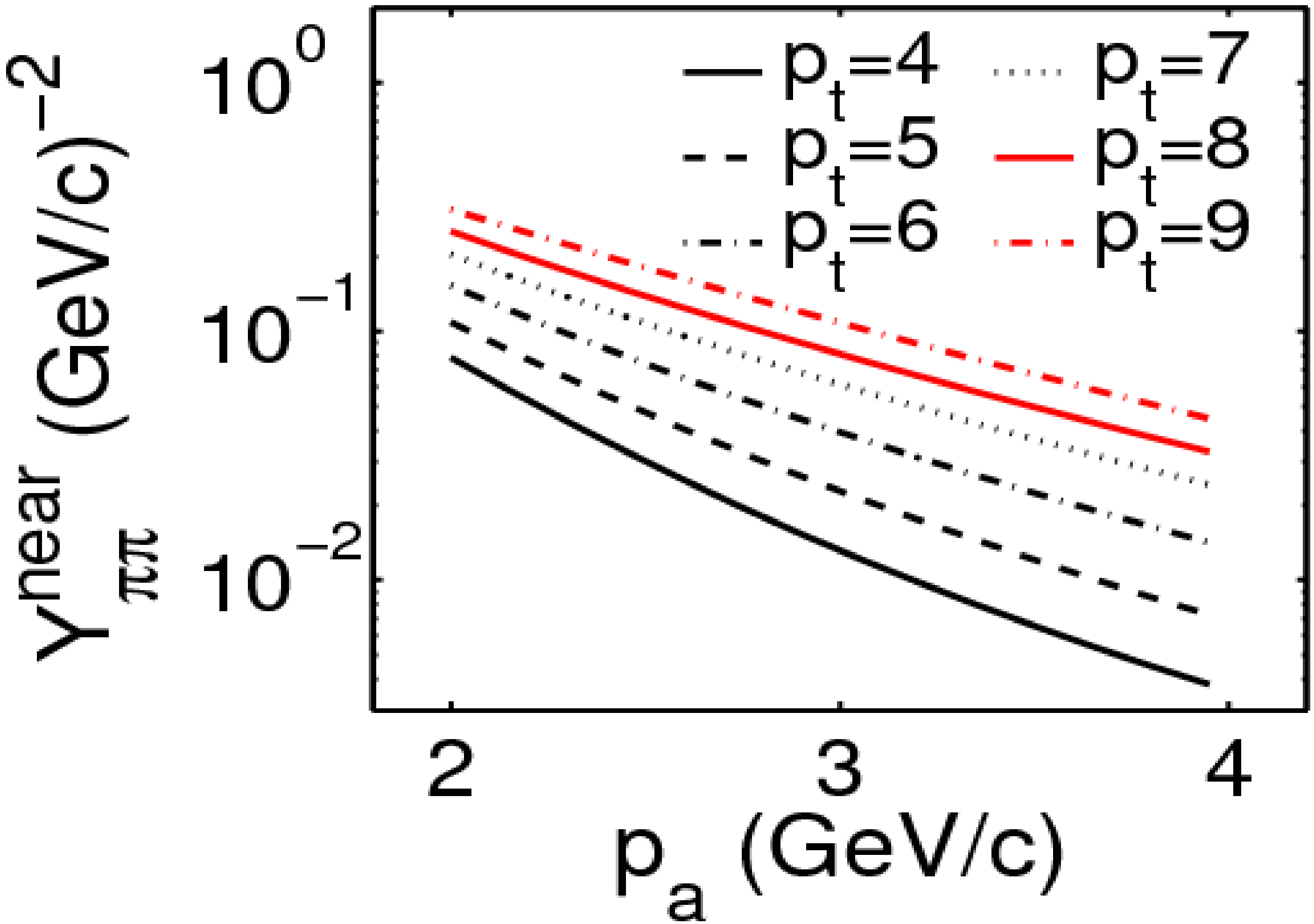
Correlations in jets

Jet yields

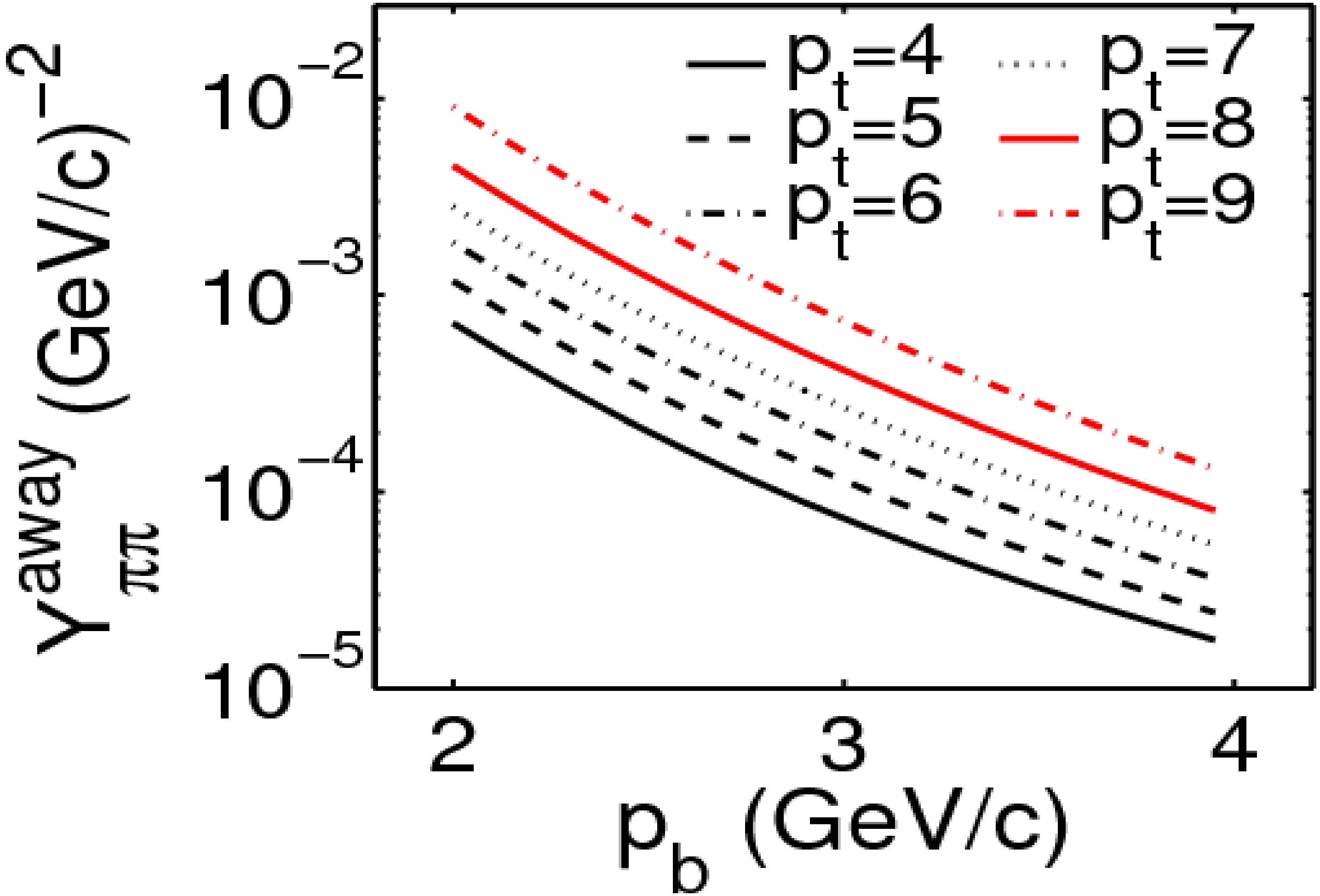
$$Y_{\pi\pi}^{\text{near}}(p_t, p_a) = \frac{1}{N_{\text{trig}}} \frac{dN_{\pi\pi}}{p_a dp_a}(p_t, p_a)$$
$$= \int_{\Delta p_t} dp_t \frac{dN_{\pi\pi}}{p_a dp_t dp_a} \Big/ \int_{\Delta p_t} dp_t \frac{dN_\pi}{dp_t}$$

$$Y_{\pi\pi}^{\text{away}}(p_t, p_b) = \frac{1}{N_{\text{trig}}} \frac{dN_{\pi\pi}}{p_b dp_b}(p_t, p_b)$$
$$= \int_{\Delta p_t} dp_t \frac{dN_{\pi\pi}}{p_b dp_t dp_b} \Big/ \int_{\Delta p_t} dp_t \frac{dN_\pi}{dp_t}$$

Correlations in jets



Correlations in jets



Correlations in jets

Trigger bias

- Very weak centrality dependence on near side
- Slope for associate particle distribution increases with $p_T^{trigger}$

- Strong centrality dependence on the away side
- Slope for the distribution≈for the inclusive one

Hadron-triggered FF

$$D^{h_1 h_2}\left(z_T, p_T^{\mathrm{trig}}\right) = p_T^{\mathrm{trig}} \frac{d\sigma_{AA}^{h_1 h_2}/dp_T^{\mathrm{trig}}\, dp_T}{d\sigma_{AA}^{h_1}/dp_T^{\mathrm{trig}}}$$

$$z_T = p_T \,/\, p_T^{Trig}$$

For pure fragmentation, $D^{h_1 h_2}(z_T, p_T^{trig})$ independent of p_T^{trig}

Hadron-triggered FF

When thermal medium exists, interactions of jet with medium change the behavior of

$$D^{\pi\pi}(z_T, p_T^{trig})$$

Recombination model predictions:

SS+TS dominates: $\propto p_T^{trig}$

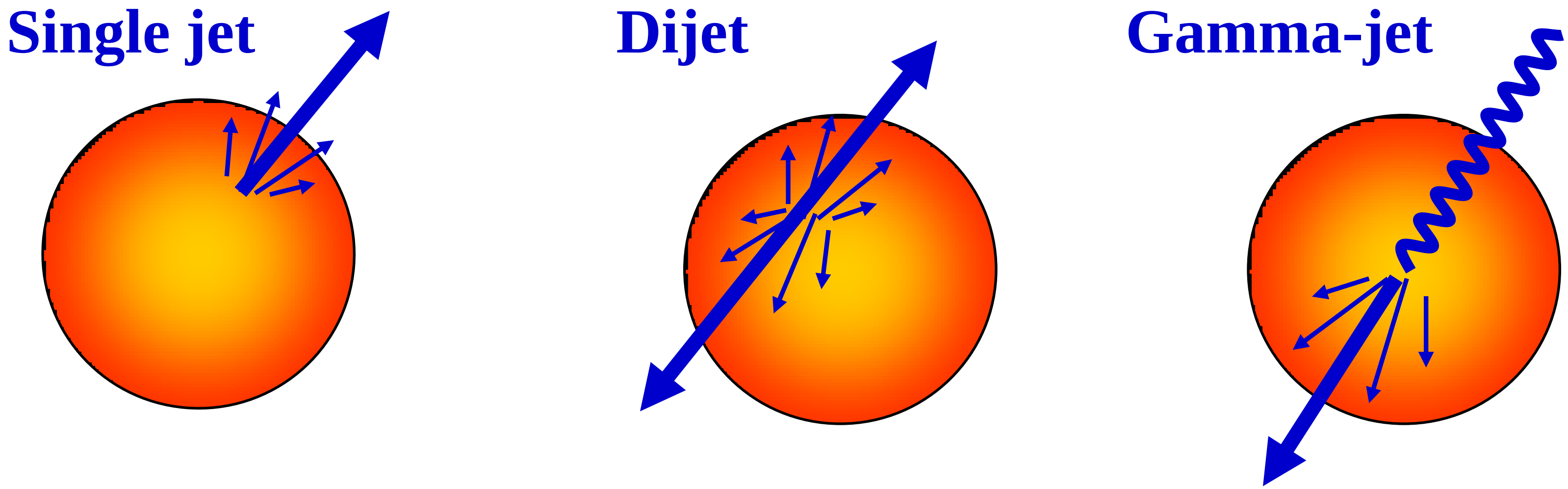
TS+TS dominates: $\propto p_T^{trig}$

SS+SS dominates: independent of p_T^{trig}

Jet Tomography

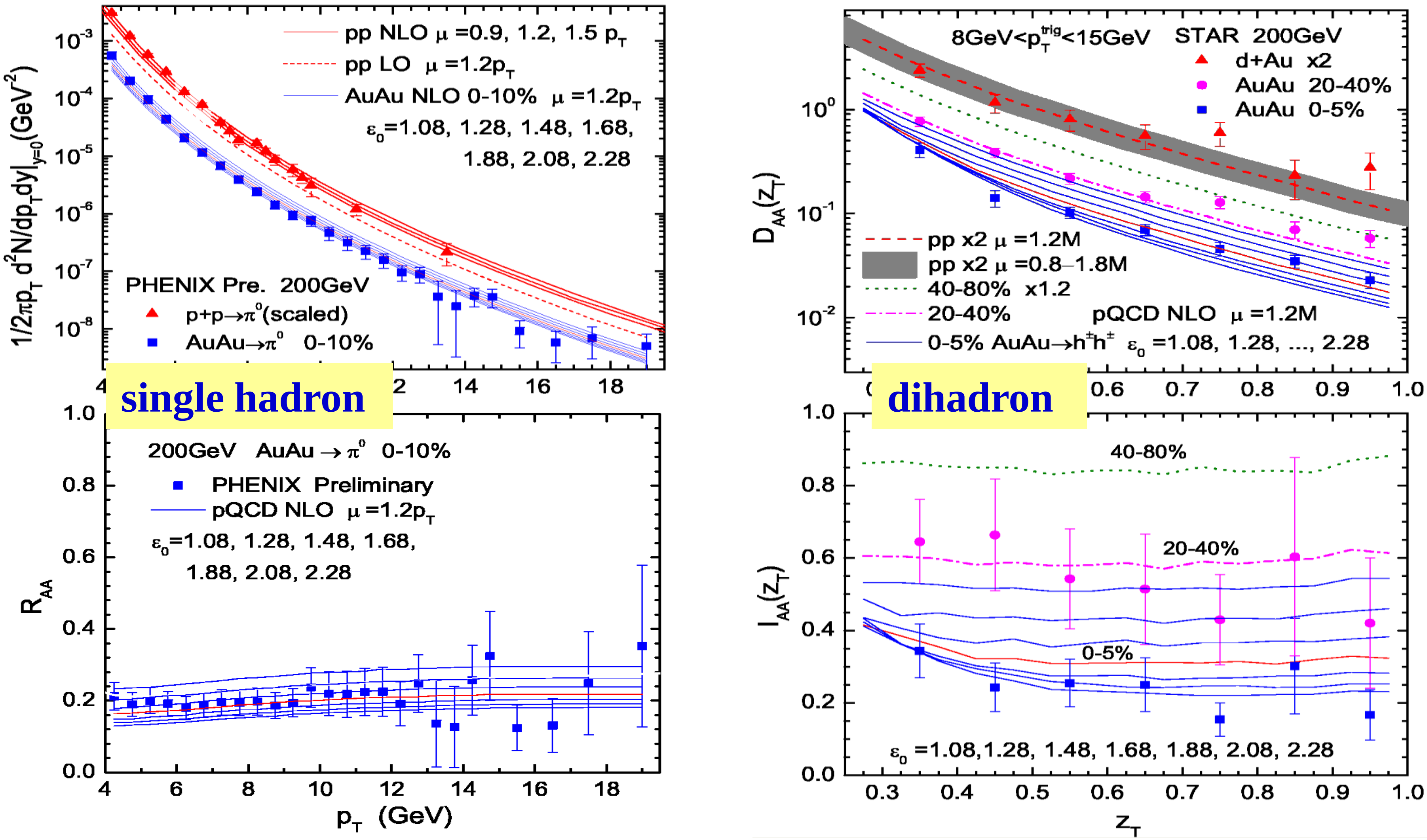
Three kinds of hard probes of QGP

1) **Single jet → Single hadron spectra**
2) **Dijet → Hadron-triggered away-side hadron spectra**
3) **Gamma-jet → Photon-triggered away-side hadron spectra**



1) H.Z. Zhang, J.F. Owens, E. Wang and X.-N. Wang , PRL 98(2007)212301
2) H.Z. Zhang, J.F. Owens, E. Wang and X.-N. Wang , arXiv:0902.4000

Simultaneous fits of single/dihadron productions



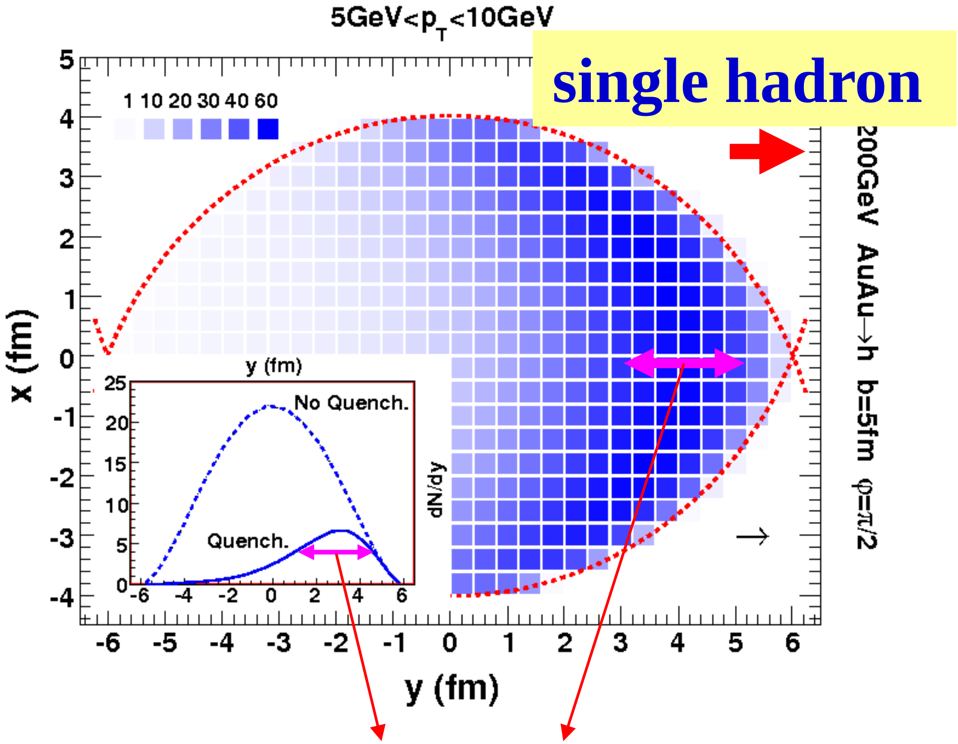
Tomography by single jets and dijets

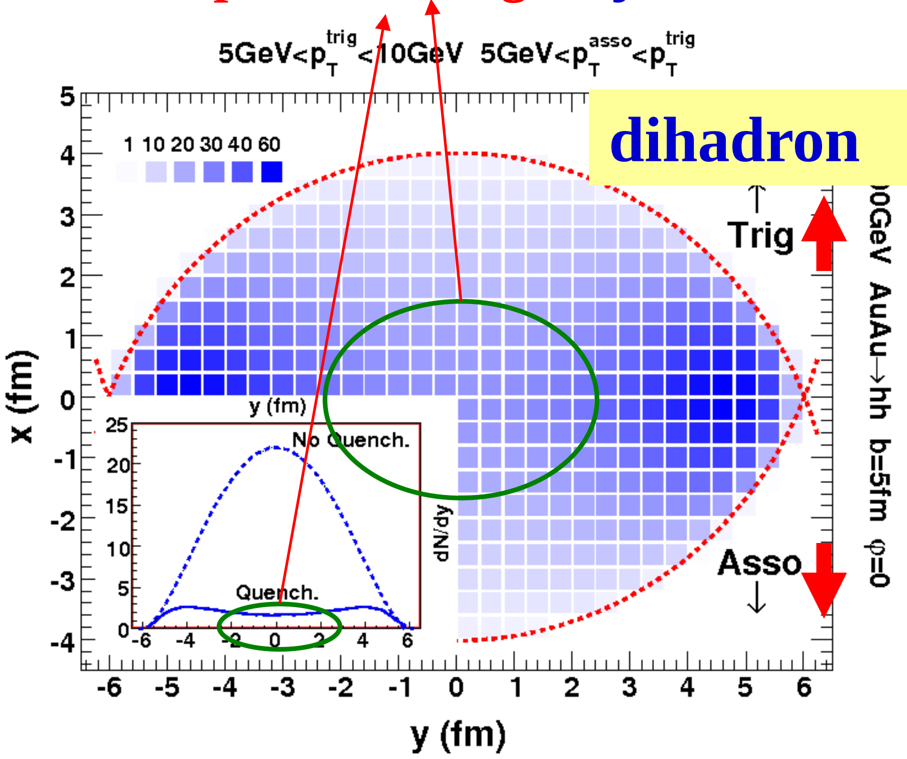
Spatial transverse distribution of the initial parton production points that contribute to the single and dihadron along a given direction

Color strength: single/dihadron yield from the jets originating from the square

Dominated by jets close and perpendicular to the surface

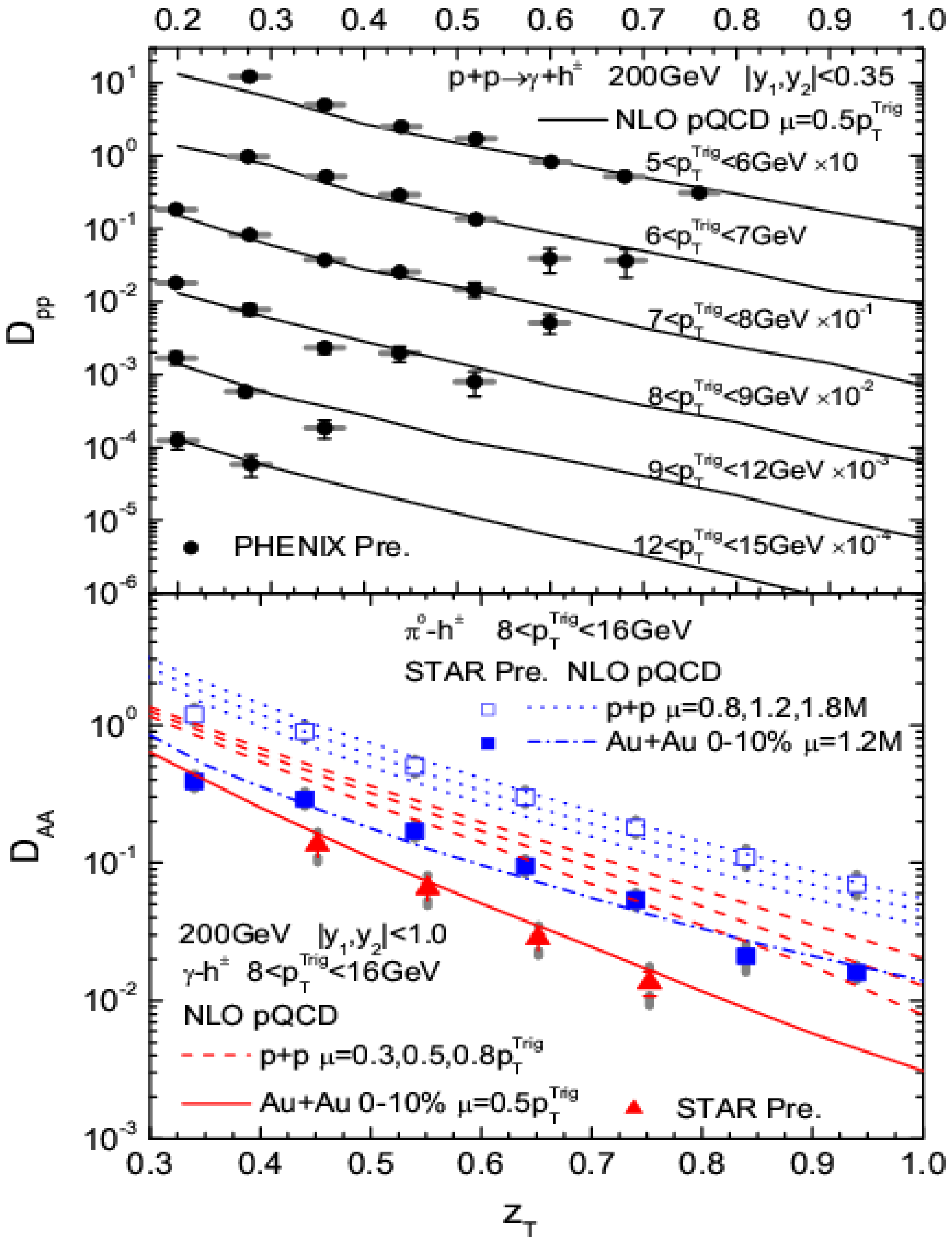
Dominated by dijets close and tangential to the surface and the punch-through dijets





Thickness of the outer corona

25% contribution



Gamma-triggered hadron spectra

H.Z. Zhang, J.F. Owens, E. Wang and X.-N. Wang , arXiv:0902.4000

1) Fit data well in pp/AA. Within the energy loss formalism same as that in our previous studies on single/dihadron spectra in A+A collisions.
2) Uncertainty due to scale
3) Hadron-triggered FF's > Photon-triggered FF's. Main reason?

Photon Production (Nantes and Wuhan)

In 1999, Fuming Liu started her joint PhD between Subatech and IOPP.

Since then, Klaus Werner (Nantes) and Fuming LIU (Wuhan)

have cooperated on 25 papers:

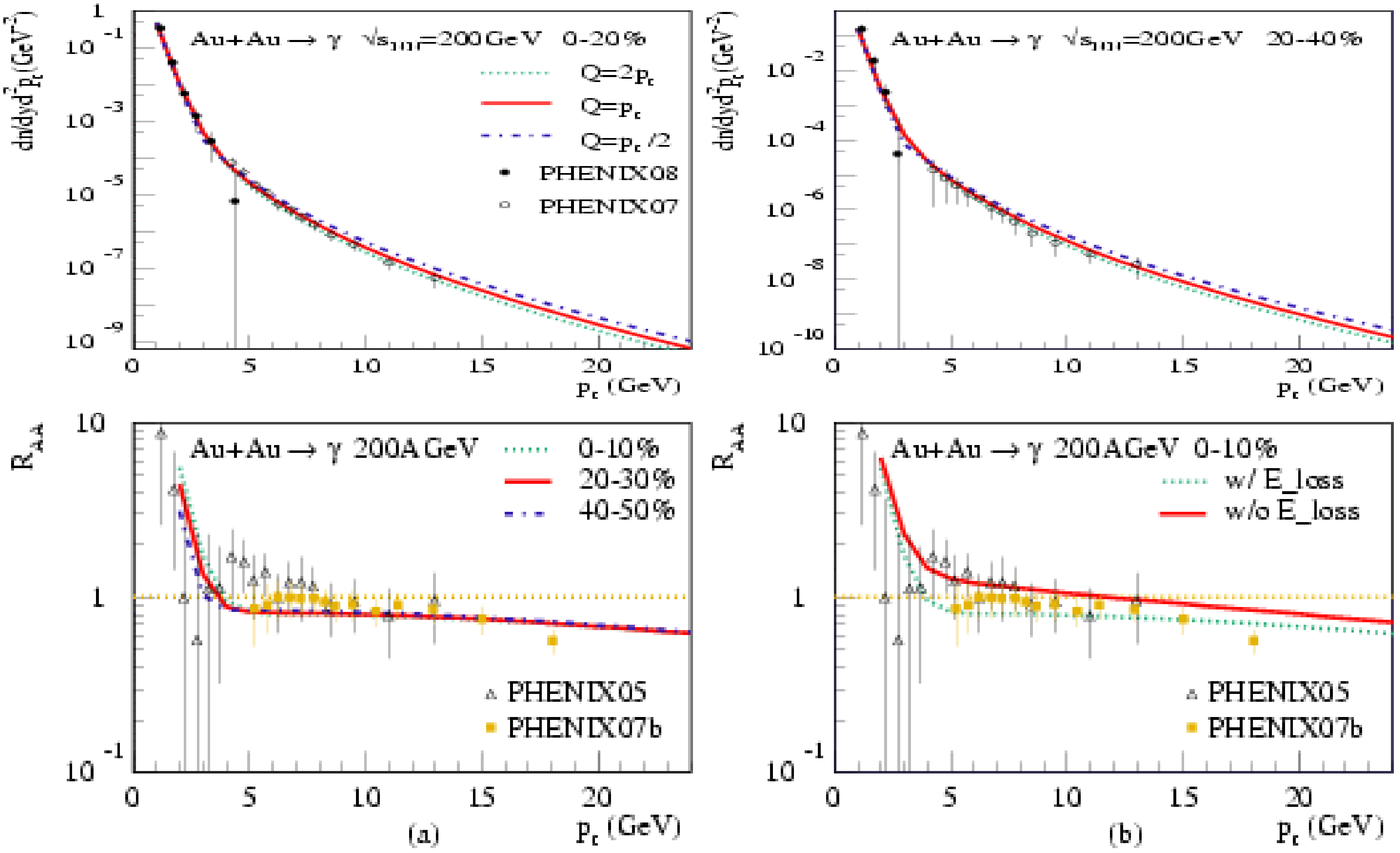
1. FML, T.Hirano, KW, Y. Zhu Phys. Rev. C **79**,014905 (2009).
2. FML, KW, J. Phys. G: Nucl. Part. Phys. 36 (2009) 035101
3. KW, FML, Tanguy Pierog, Phys. Rev. C 74, 044902 (2006)
4. FML, KW, Phys.Rev.D74:034024,(2006)

…..

24. F.M. Liu, … and K. Werner, Phys. Rev. D67, 034011 (2003)
25. M. Bleicher, F. M. Liu, … K. Werner, Phys.Rev.Lett.88:202501,(2002)

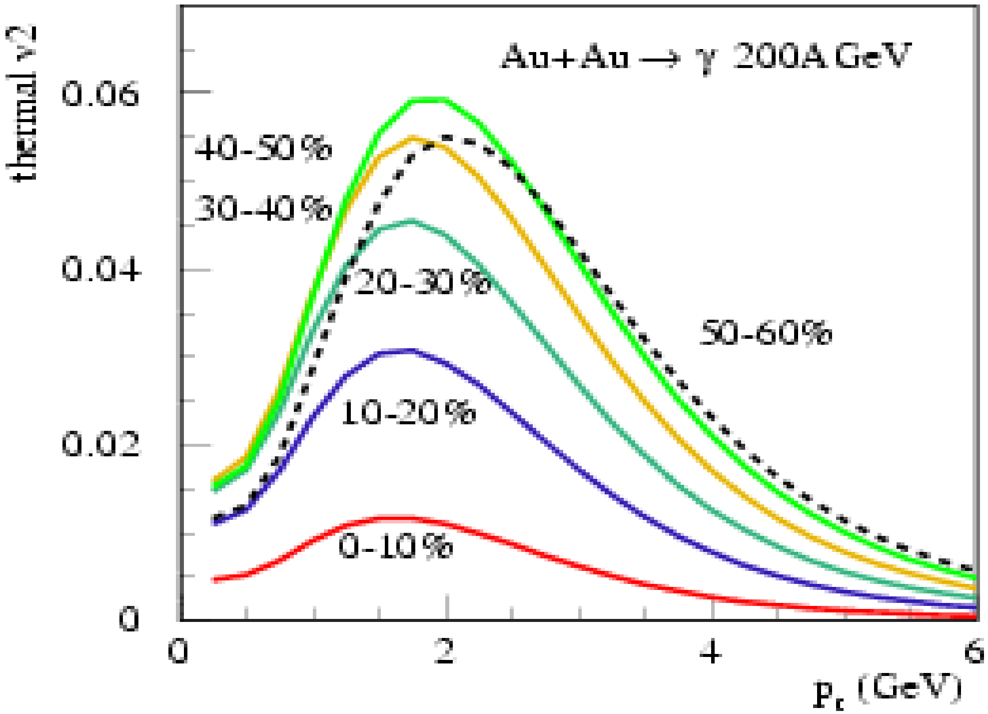
Pt spectra of direct photons

FML, T.Hirano, KW, Y. Zhu Phys. Rev. C **79**,014905 (2009).



V_2 of thermal photons

FML, T.Hirano, KW, Y. Zhu, e-Print: **arXiv:0902.1303**



Future project:

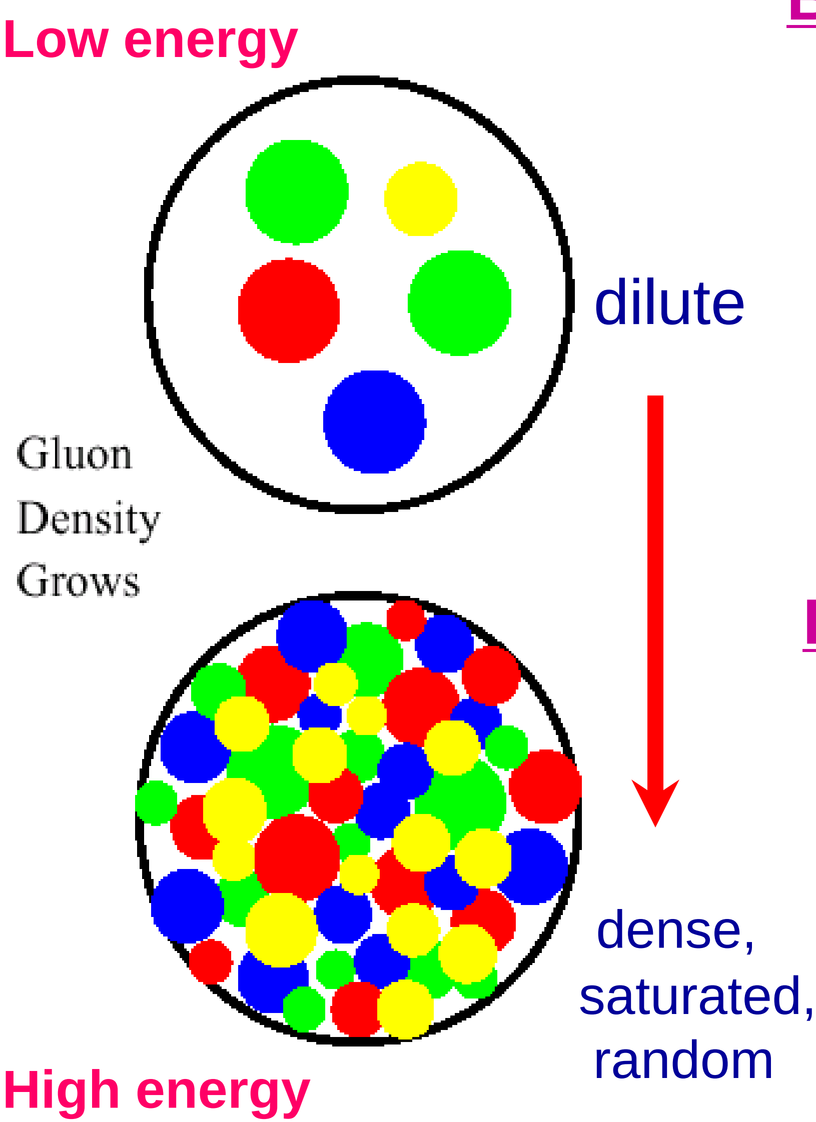
Signals from hadrons (Nantes) and direct photons (Wuhan) will be compared in a wider range.

Predictions for LHC should be ready soon.

Contrary to hadronic v_2 (ideal hydro predicted increase monotonically), the elliptic flow of thermal photons decrease at high pt!

Information for the earlier evolution of the plasma can be provided by direct photons.

Saturation & Quantum Evolution



BFKL eq. [Balitsky, Fadin,Kraev,Lipatov '78]

$$\frac{\partial}{\partial \tau} N_\tau = \bar{\alpha}_s \mathcal{K}_{\mathrm{BFKL}} \otimes N_\tau$$

N : scattering amp. ~ gluon number
τ : rapidity $\tau = \ln 1/x \sim \ln s$

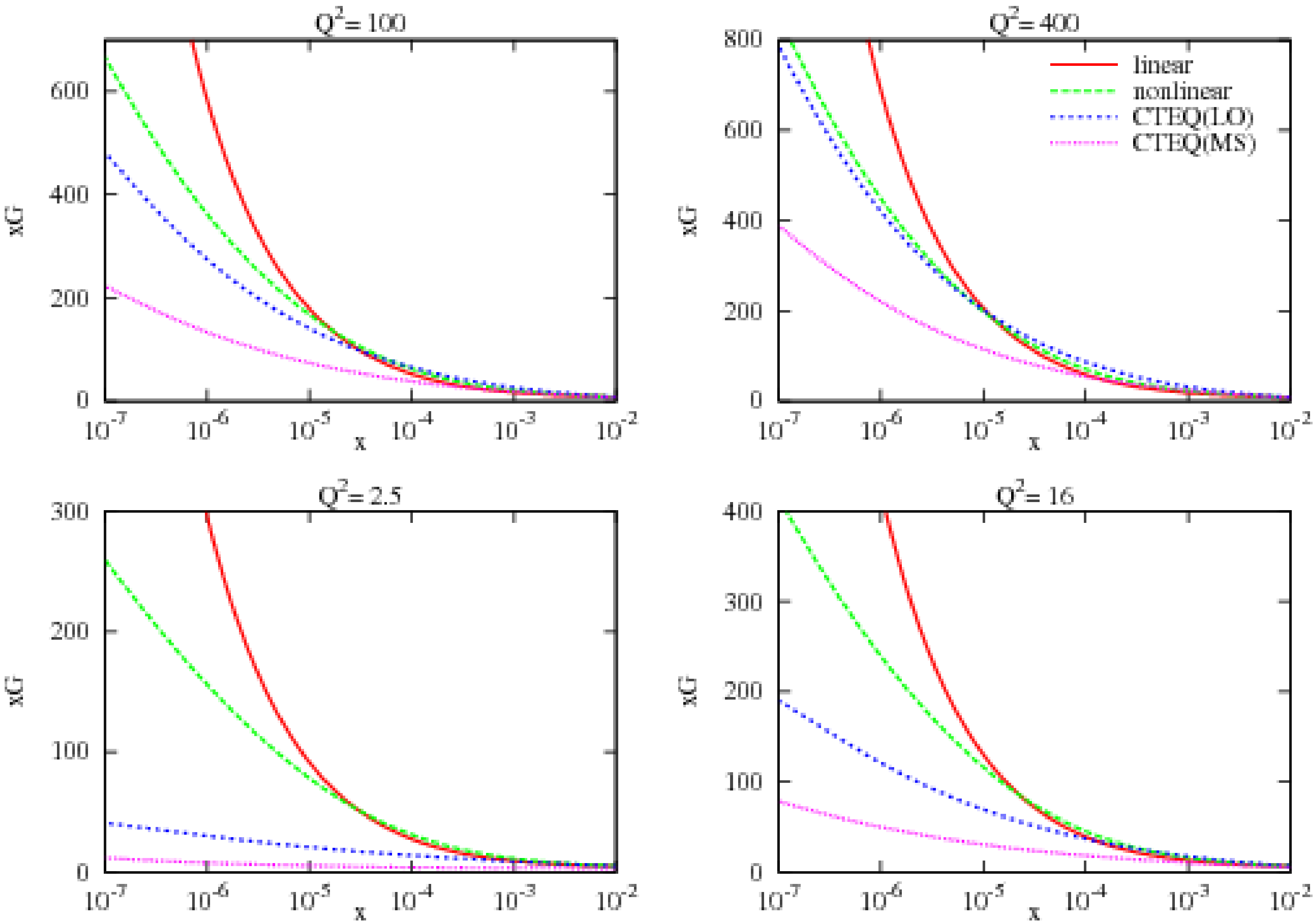
exponential growth of gluon number
→ violation of unitarity

Balitsky-Kovchegov eq. [Balitsky '96, Kovchegov '99]

$$\frac{\partial}{\partial \tau} N_\tau = \bar{\alpha}_s \mathcal{K}_{\mathrm{BFKL}} \otimes (N_\tau - N_\tau^2)$$

Gluon recombination
→ nonlinearity → saturation,
unitarization,
universality

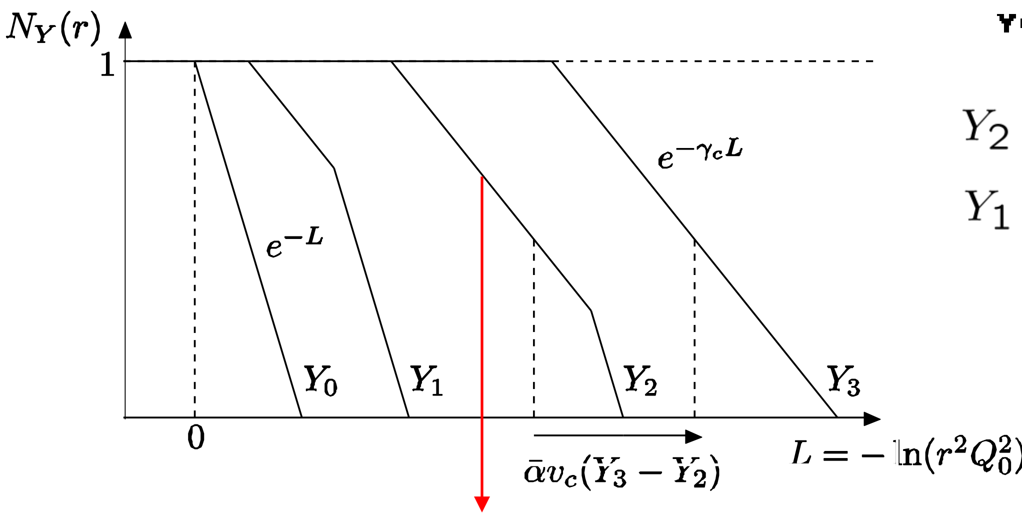
Saturation and small-x physics

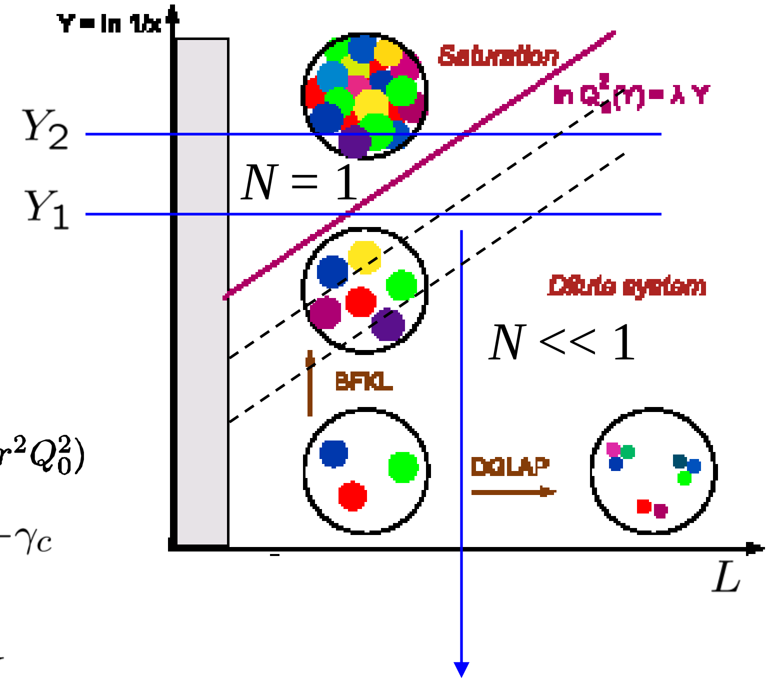


Geometric scaling from BK

- what we learned about the transition to saturation:

the dipole scattering amplitude $\langle T_{\mathbf{xy}} \rangle_Y = N_Y(r = |\mathbf{x} - \mathbf{y}|)$





$$N_Y(r) \propto e^{-\gamma_c (L - v_c \bar{\alpha} Y)} = \left(r^2 Q_s^2(Y)\right)^{-\gamma_c}$$

the saturation scale: $Q_s^2(Y) = Q_0^2 \; e^{v_c \bar{\alpha} Y}$

$$N_Y(r) = N[r^2 Q_s^2(Y)]$$

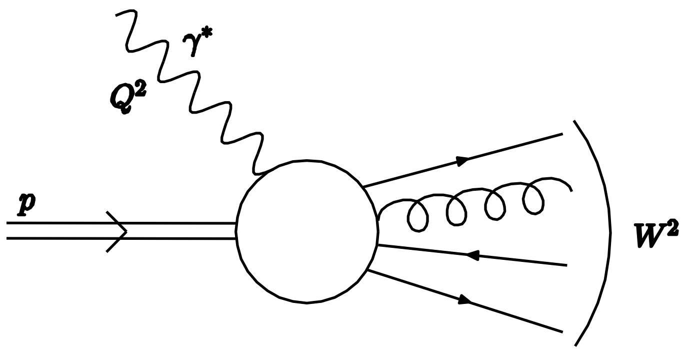
traveling wave solutions $\Rightarrow$ geometric scaling

the amplitude is invariant along any line parallel to the saturation line

When is saturation relevant ?

in processes that are sensitive to the small-*x* part of the hadron wavefunction

- deep inelastic scattering at small x_{Bj} :



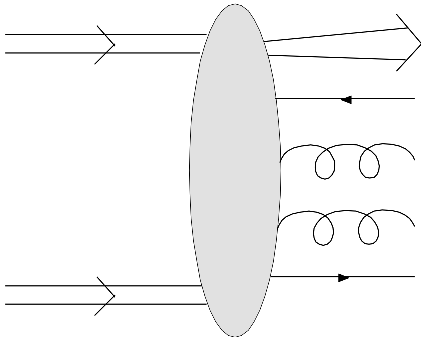
$$x_{Bj} = \frac{Q^2}{W^2 + Q^2}$$

at HERA, x_{Bj} ~10^{-4} for $Q^2 = 10$ GeV²

in DIS small *x* corresponds to high energy

saturation relevant for inclusive, diffractive, exclusive events

- particle production at forward rapidities *y* :



p_T, y

$$x_1 \sqrt{s} = p_T\ e^{y}$$

$$x_2 \sqrt{s} = p_T\ e^{-y}$$

at RHIC, x_2 ~10^{-4} for $p_T^{\,2} = 10$ GeV²

in particle production, small *x* corresponds to high energy and forward rapidities

saturation relevant for the production of jets, pions, heavy flavors, photons

Summary

- LHC offers a unique opportunity to study the properties of QGP system quantitatively
- Different interaction processes of jet+medium can be investigated at ALICE
- Hydrodynamics and recombination models can be testified at ALICE
- Physics in very small-x region can be studied

Thank you!