High-Density Systems: Introduction

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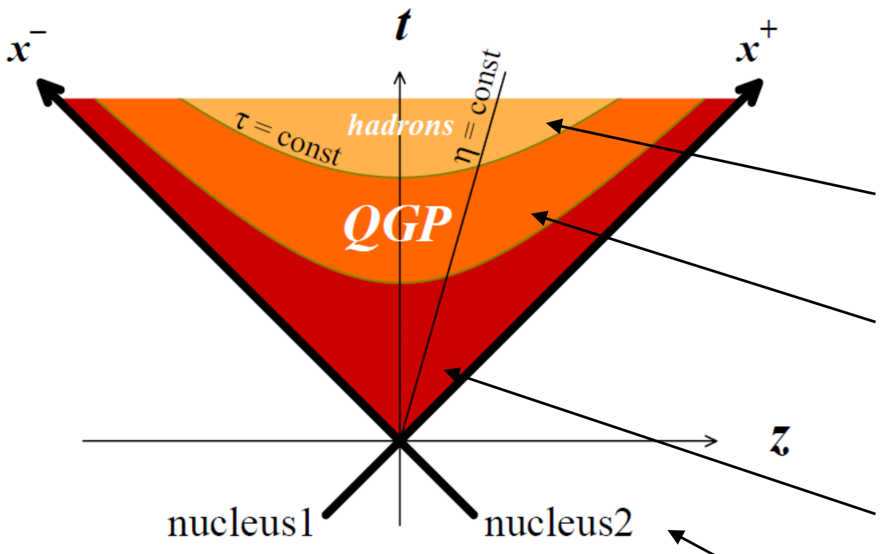
Relativistic Heavy-Ion Collisions

main goal: produce and study the quark-gluon-plasma



space-time picture of heavy-ion collisions

5. Individual hadrons

freeze out

4. Hadron gas

cooling with expansion

3. Quark Gluon Plasma

thermalization,
expansion

2. Pre-equilibrium state

collision

1. Nuclei (initial condition)

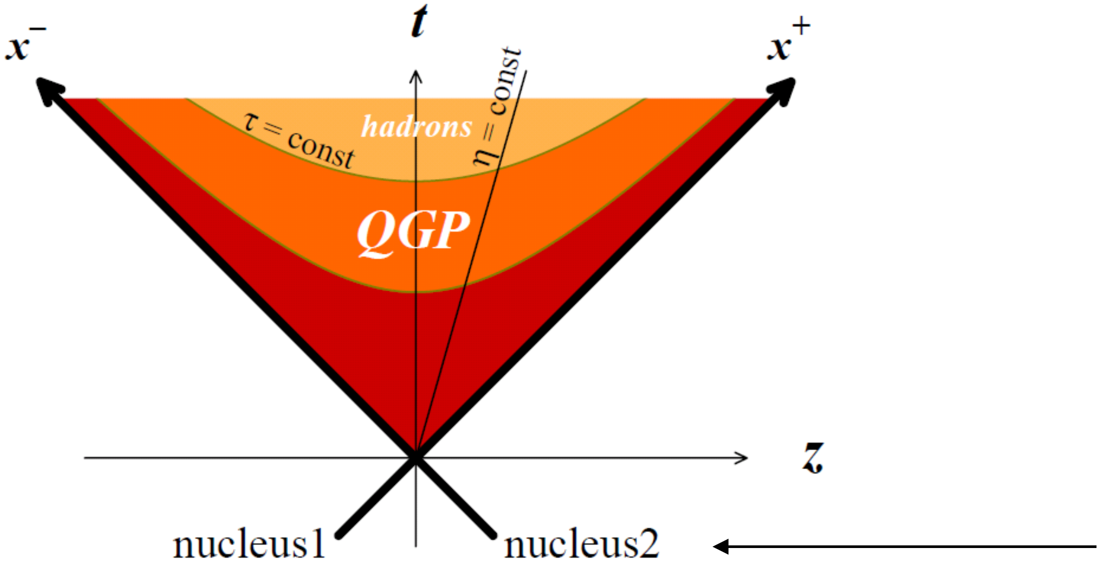
however, one observes the system after it has gone through
a complicated evolution involving different aspect of QCD

to understand each stage and the transition between them has been challenging

Outline

- The Color Glass Condensate
  an approximation of QCD to describe the nuclear wave function at small-x, using classical fields
- The Glasma
  the pre-equilibrium phase, resulting of the collisions of two CGCs, during which classical fields decay into a particles
- Finite temperature lattice QCD
  a laboratory to study the transition from the deconfined phase into the hadronic phase, and to explore the QCD phase diagram
- Bulk observables
  properties of the collective behavior of the (thermalized ?) low-p_T particles (quarks/gluons then hadrons) composing the plasma
- Hard Probes
  rare high-p_T particles created at early times that have propagated through the evolving plasma

The Color Glass Condensate



Color Glass Condensate

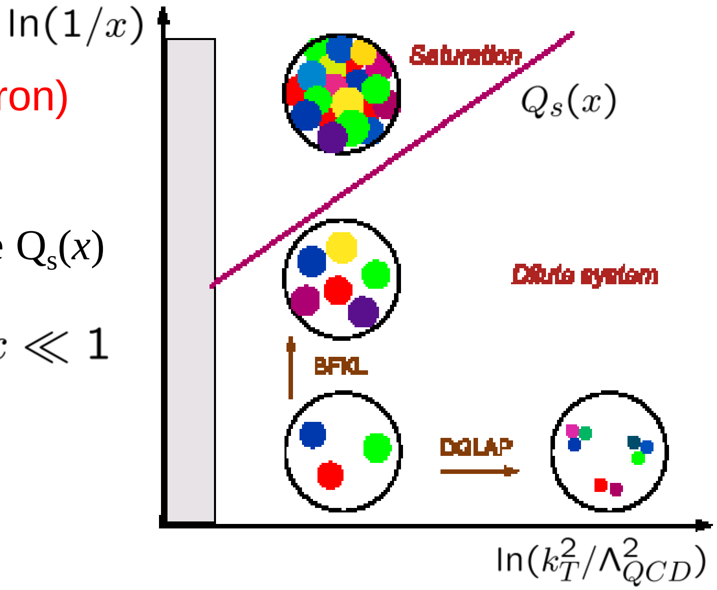
Parton saturation

- a regime of the hadronic/nuclear wave function predicted in QCD

x : parton longitudinal momentum fraction

k_T : parton transverse momentum

the distribution of partons as a function of x and k_T :



QCD linear evolutions: $k_T \gg Q_s$

DGLAP evolution to larger k_T (and a more dilute hadron)

BFKL evolution to smaller x (and denser hadron)

dilute/dense separation characterized by the saturation scale $Q_s(x)$

QCD non-linear evolution: $k_T \sim Q_s$ meaning $x \ll 1$

$\rho \sim \frac{xf(x,k_\perp^2)}{\pi R^2}$ gluon density per unit area

it grows with decreasing x

$\sigma_{rec} \sim \alpha_s/k^2$ recombination cross-section

recombinations important when $\rho\ \sigma_{rec} > 1$

the saturation regime: for $k^2 < Q_s^2$ with $Q_s^2 = \frac{\alpha_s x f(x,Q_s^2)}{\pi R^2}$

this regime is non-linear

yet weakly coupled

$\alpha_s(Q_s^2) \ll 1$

The Color Glass Condensate

- the CGC: an effective theory to describe the saturation regime

McLerran and Venugopalan (1994)

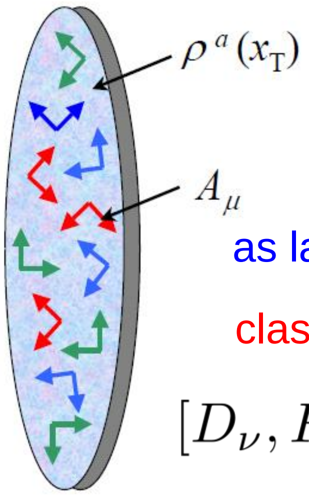
lifetime of the fluctuations
in the wave function ~ $xP^+/k_\perp^2$ $\Rightarrow$ $\left\{ \begin{array}{l} \text{high-x partons} \equiv \text{static sources } \rho \\ \text{low-x partons} \equiv \text{dynamical fields } \mathcal{A} \end{array} \right.$

short-lived fluctuations

$$|\text{hadron}\rangle = |qqq\rangle + |qqqg\rangle + \ldots + |qqq \ldots\ldots ggggg\rangle \Rightarrow |\text{hadron}\rangle = \int D\rho\, \Phi_x[\rho] |\rho\rangle \equiv |\text{CGC}\rangle$$

effective wave function
for the dressed hadron

separation between
the long-lived high-x partons
and the short-lived low-x gluons



valence partons
as static random
color source

small x gluons
as large classical fields

classical Yang-Mills equations

$$[D_\nu, F^{\nu\mu}]^a = \delta^{\mu+}\delta(x^-)\rho^a(x_\perp)$$

the evolution of $|\Phi_x[\rho]|^2$ with x is a
renormalization group
which sums both $\left\{ \begin{array}{l} \alpha_s^n \ln^n(1/x) \\ g_s^n \mathcal{A}^n \end{array} \right.$

this effective description of the hadronic wave function applies only to the small-x part

Probing the CGC in p+A collisions

we would like to extract from data the only parameter in the theory, Qs_0

we want to find out at what value of *x* one should one stop using nuclear pdfs to describe the nuclear wave function and use the CGC instead

- typical values of *x* being probed at forward rapidities (y~3)

RHIC $x_d \simeq 0.5 \quad x_A \simeq 5.10^{-3}$

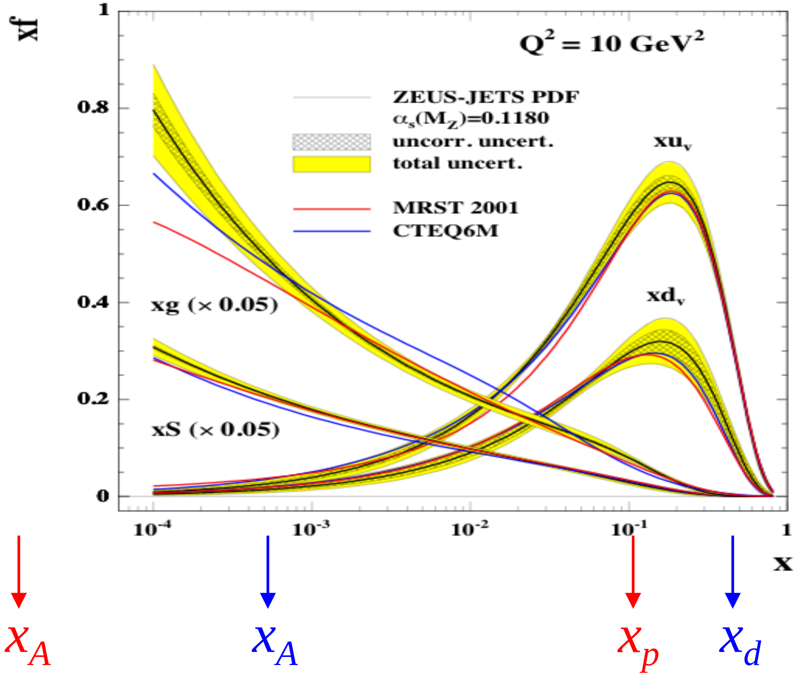
deuteron dominated by valence quarks

nucleus dominated by early CGC evolution

LHC $x_p \simeq 0.1 \quad x_A \simeq 10^{-5}$

the proton description should include both quarks and gluons

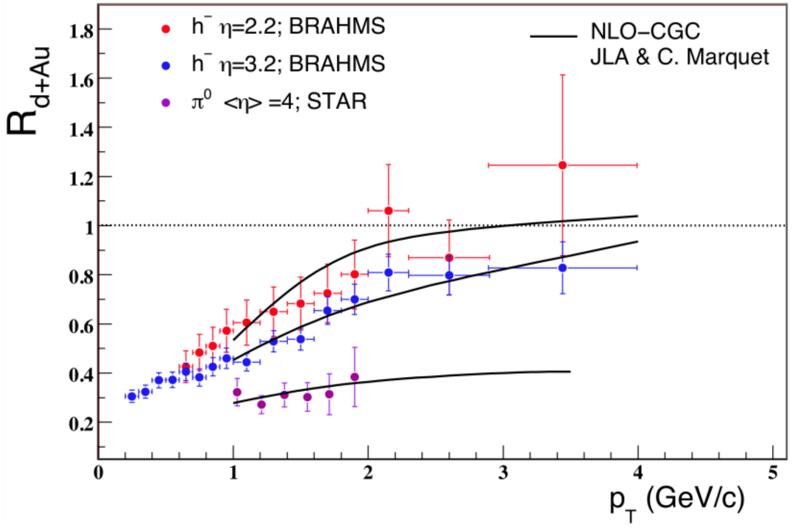
on the nucleus side, the CGC picture would be better tested



The suppression of R_{dA}

- the suppression of R_{dA} was predicted

$$R_{dA} = \frac{1}{N_{coll}} \frac{\frac{dN^{dA \to hX}}{d^2kdy}}{\frac{dN^{pp \to hX}}{d^2kdy}}$$

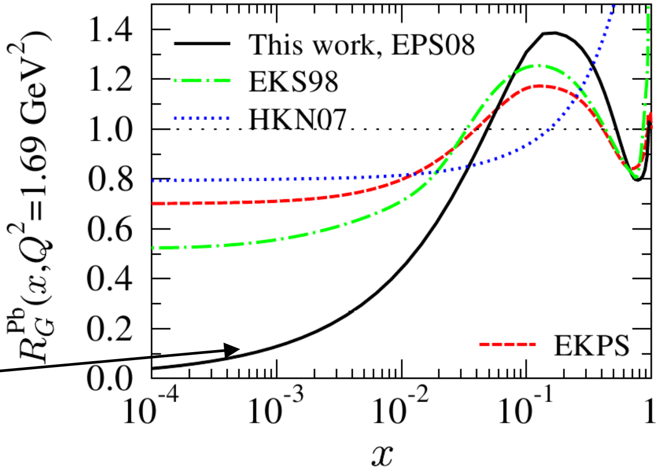


$R_{dA} = 1$ in the absence of nuclear effects, i.e. if the gluons in the nucleus interact incoherently as in A protons

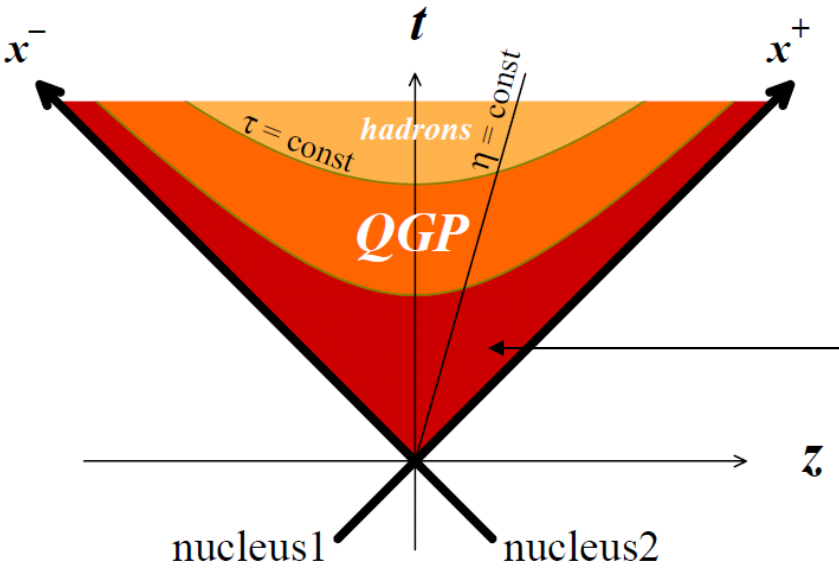
- what we learned

forward rapidities are needed to see the suppression $Q_s^2(0.01, Au) \sim 1\ \text{GeV}^2$

if forward rapidity data are included in npdfs fit, the resulting gluon distribution is over suppressed



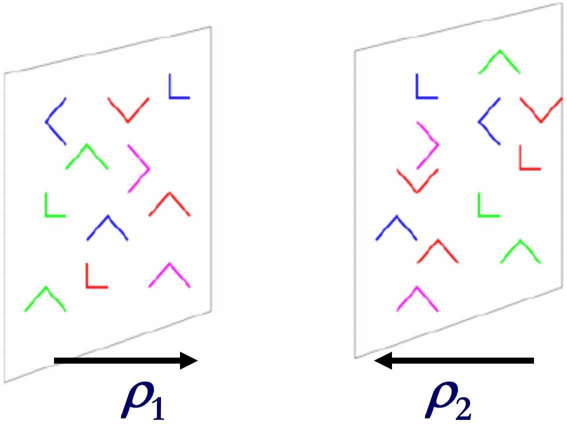
The Glasma



Glasma

Collision of two CGCs

- the initial condition for the time evolution in heavy-ion collisions



before the collision:

$$J^{\mu} = \delta^{\mu +}\delta(x^{-})\rho_1(x_{\perp}) + \delta^{\mu -}\delta(x^{+})\rho_2(x_{\perp})$$

the distributions of ρ contain the small-x evolution of the nuclear wave function

$$|\Phi_{x_1}[\rho_1]|^2 \qquad |\Phi_{x_2}[\rho_2]|^2$$

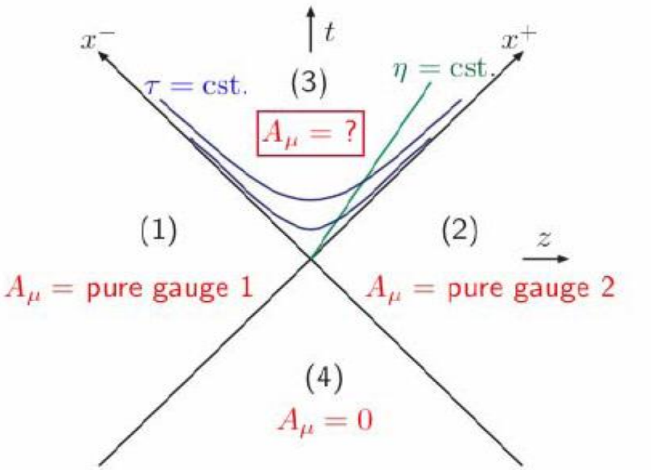
- after the collision

compute the gluon field in the forward light-cone

$$[D_\mu, F^{\mu\nu}] = J^\nu \quad \longrightarrow \quad \mathcal{A}_\mu[\rho_1, \rho_2]$$

the gluon field is a complicated function of the two classical color sources

the fields decay, once they are not strong (classical) anymore, a particle description is again appropriate



The field/particle composition

- the field after the collision is non trivial

Lappi and McLerran (2006)

it has a strong component $A^\mu \sim 1/g_s$, a particle-like component $A^\mu \sim 1$ and components of any strength in between

- the decay of the Glasma

right after the collision, the strong component contains all modes

then modes with $p_T > 1/\tau$ are not part of the strong component anymore

- thermalization is still an outstanding problem?

AdS/CFT ?

glasma: $T^{\mu\nu} = \frac{1}{4} g^{\mu\nu} F^{\lambda\sigma} F_{\lambda\sigma} - F^{\mu\lambda} F^{\nu}_{\lambda}$

$$T^{\mu\nu}(\tau = 0^+) = \begin{pmatrix} \epsilon & & & \\ & \epsilon & & \\ & & \epsilon & \\ & & & -\epsilon \end{pmatrix} \qquad T^{\mu\nu}_{hydro} = \begin{pmatrix} \epsilon & & & \\ & p & & \\ & & p & \\ & & & p \end{pmatrix}$$

how does the transition happens ? in a scalar theory:

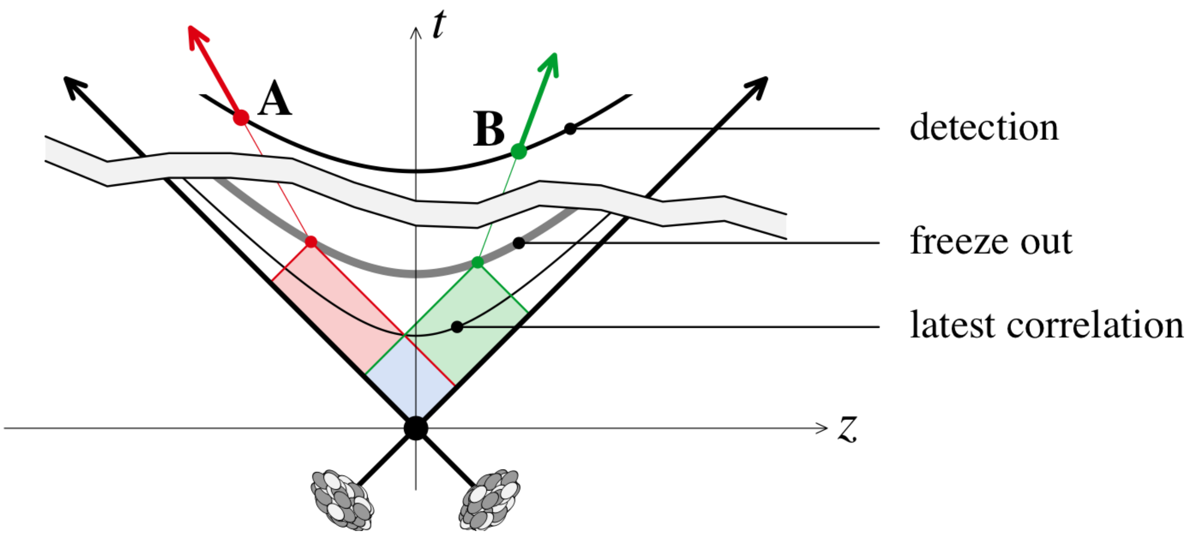
Dusling et al (2010)

Probing features of the Glasma

- possible with long-range rapidity correlations

in general, the following phases (QGP, …) destroy the information coming from the initial CGC collisions, heavy-ion collisions are not great probes of parton saturation

nevertheless, some observables are still sensitive to the physics of the early stages



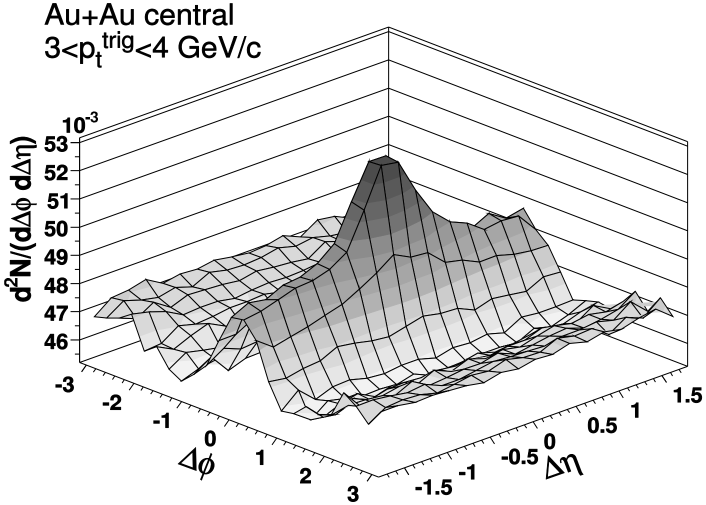
$$\tau < \tau_{\text{freezeout}} \quad \exp(-\Delta\eta/2)$$

The ridge in A+A collisions

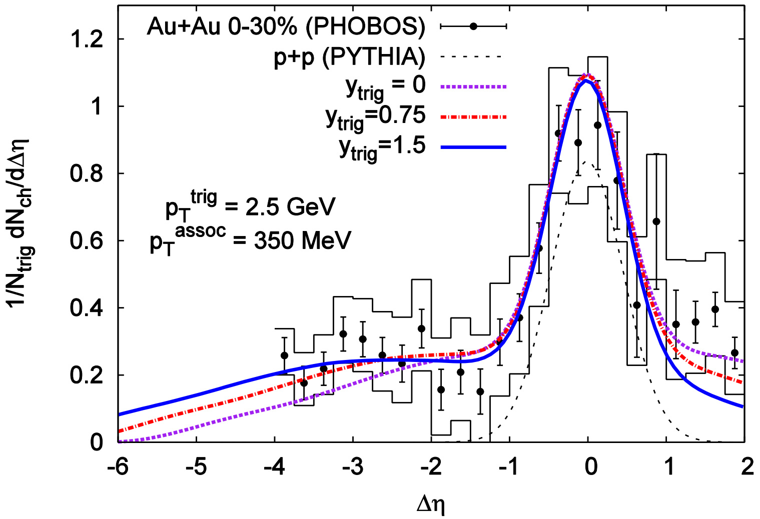
- the ridge is qualitatively understood within the CGC framework

if it is very extended in rapidity, the ridge is a manifestation of early-time phenomena: $\tau < \tau_{\text{freezeout}} \quad \exp(-\Delta\eta/2)$

STAR data (2009)



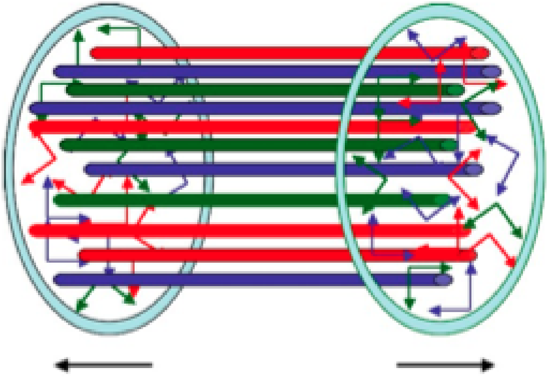
Dusling, Gelis, Lappi and Venugopalan (2009)



- quantitative calculations are underway

P- and CP-odd effects

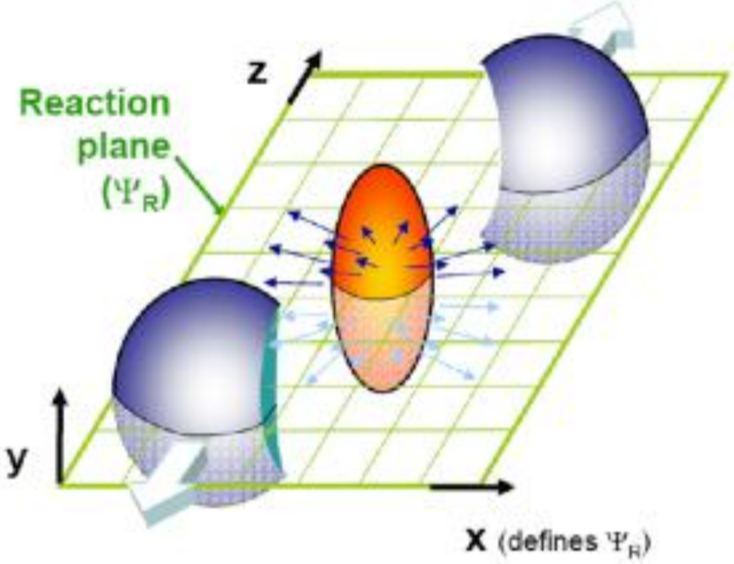
- topological charge fluctuations in the Glasma



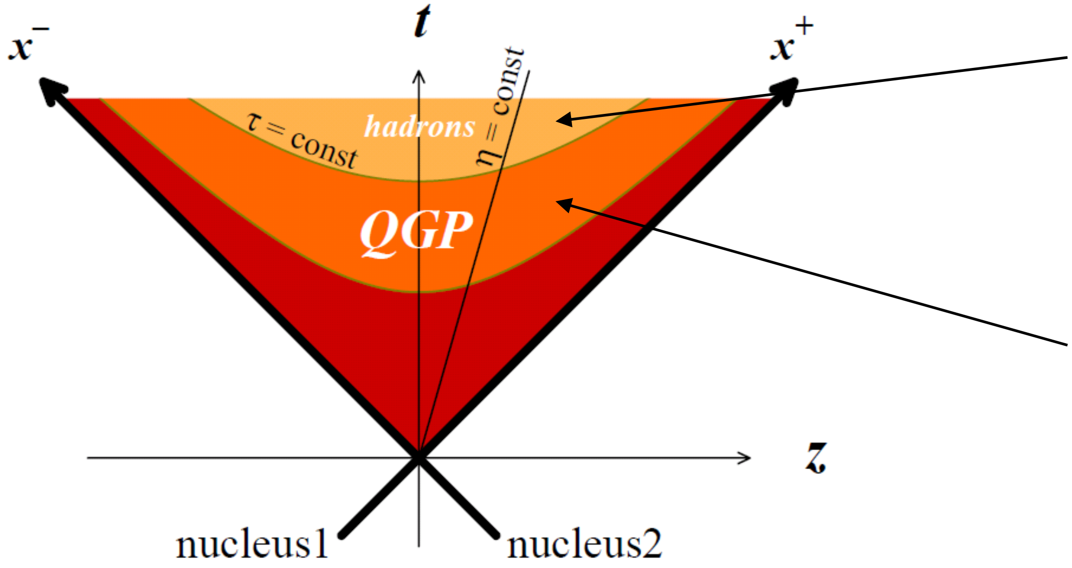
longitudinal E and B fields in
the flux tubes with non-zero E.B
Chern-Simons term

consequence: fluctuating charge asymmetry
with respect to reaction plane (although this
is not the only possible mechanism)

Kharzeev, McLerran and Warringa (2008)



Finite temperature lattice QCD

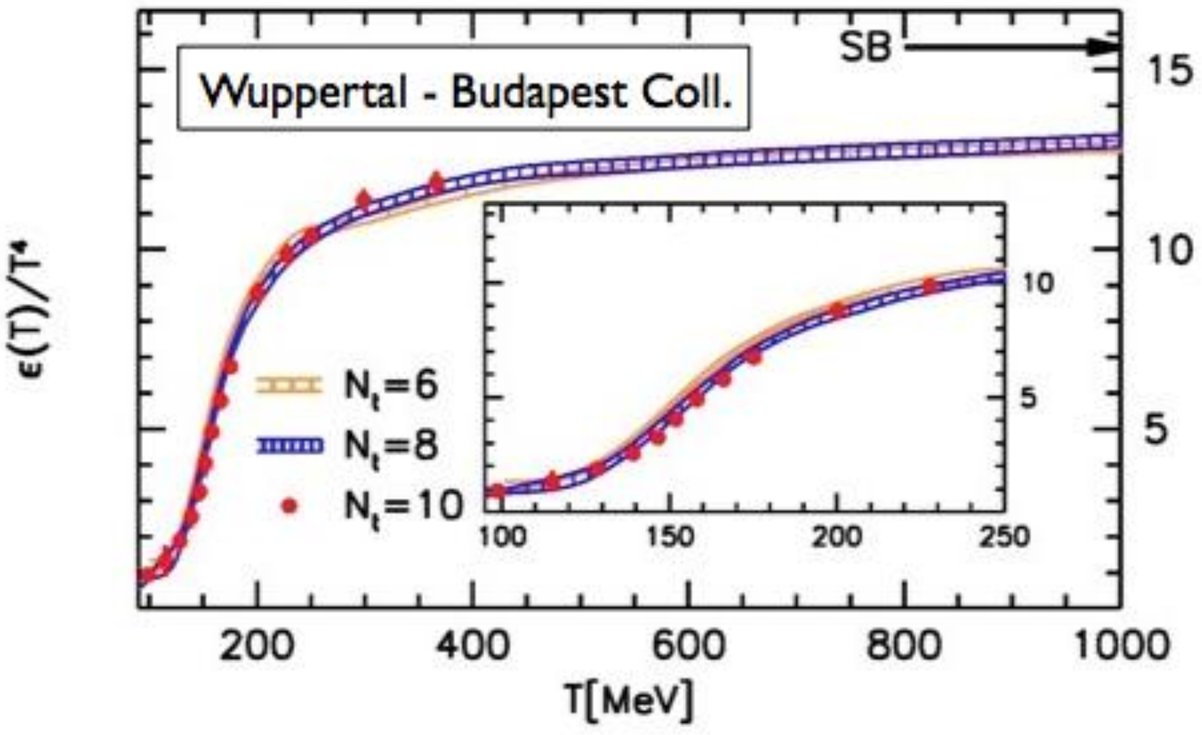


Hadron Gas

Quark-Gluon Plasma

Recent results

- for some quantities, it is now possible to use a realistic pion mass



lattice QCD deals with a simpler QGP compared to heavy-ion collisions:
it is static, fully-thermalized and baryon-less

Reproducing lattice results

- except around *Tc*, we know how to approximate QCD well enough

Hadron Resonance Gas

model works until 0.9 *Tc*

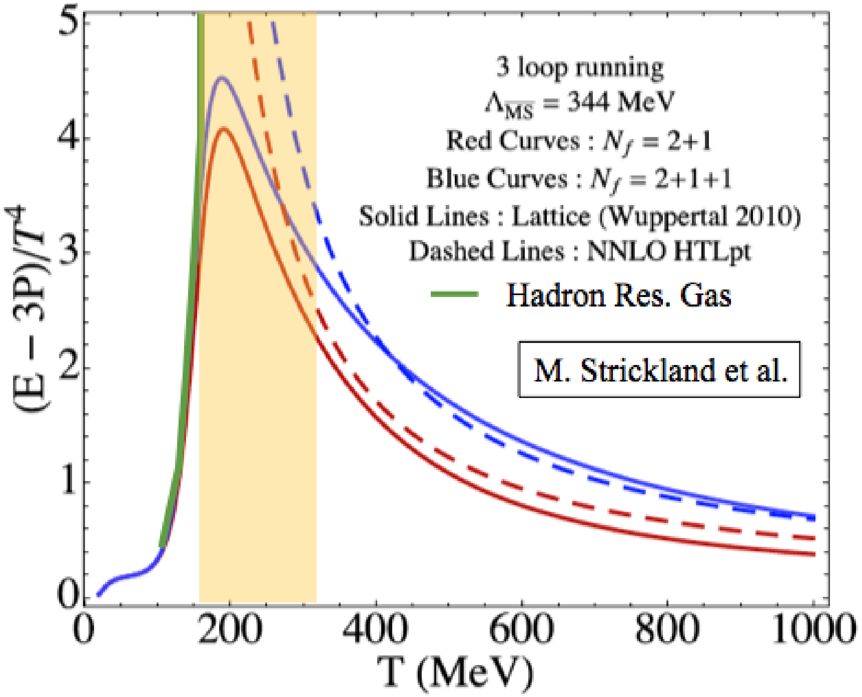
Hard-Thermal-Loop

QGP works above 2 *Tc*

can one build a model in which the transition between two regimes is smooth ?

with/without AdS/CFT ?

Andersen, Su and Strickland (2010)

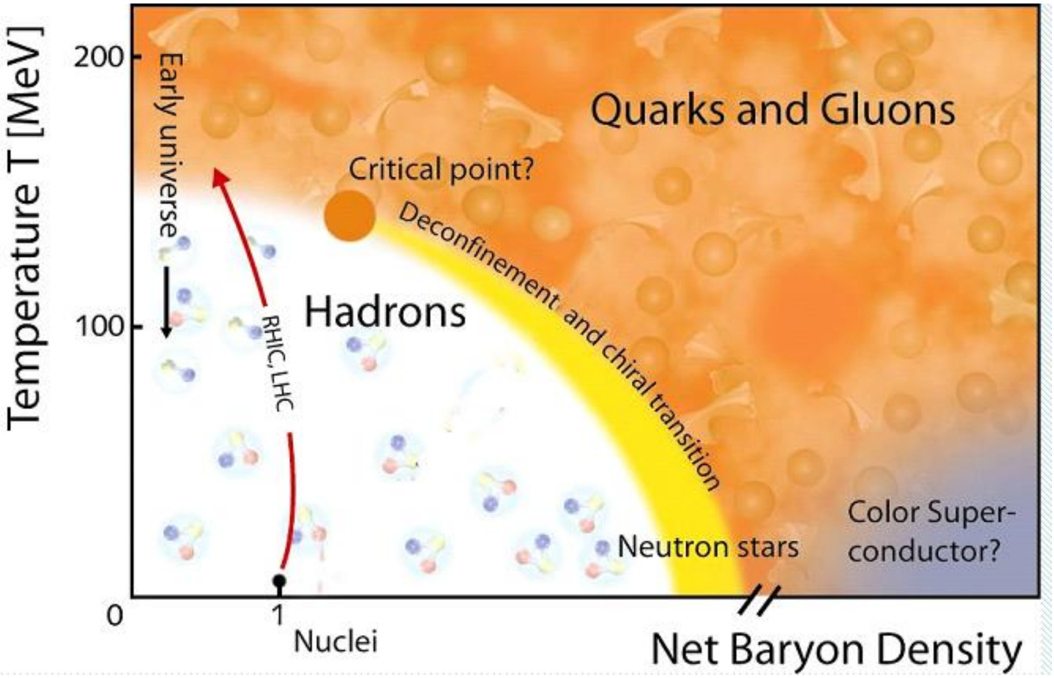


in actual RHIC, the medium is a dynamic fireball,

with a deconfined core and a hadronic corona

The QCD phase diagram

lattice QCD is successfully applied of zero baryon density

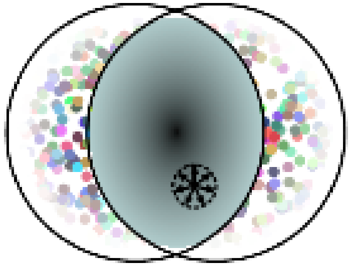


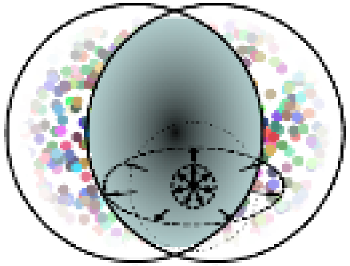
the chemical potential direction is also extensively studied:
deconfinement phase transition, chiral symmetry restoration
critical point, color superconductivity, …

Bulk Properties

The plasma flows like a fluid

the initial momentum distribution is isotropic





strong interactions induce pressure gradients

the expansion turns the space anisotropy

into a momentum anisotropy

a complete causal formulation of relativistic viscous hydro was developed

viscous corrections are necessary for a quantitative data description

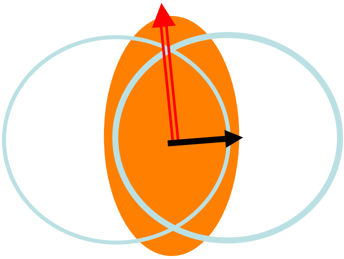
it was checked that they are small enough to validate the hydro approach

recently, the first 3+1d viscous hydro study was performed

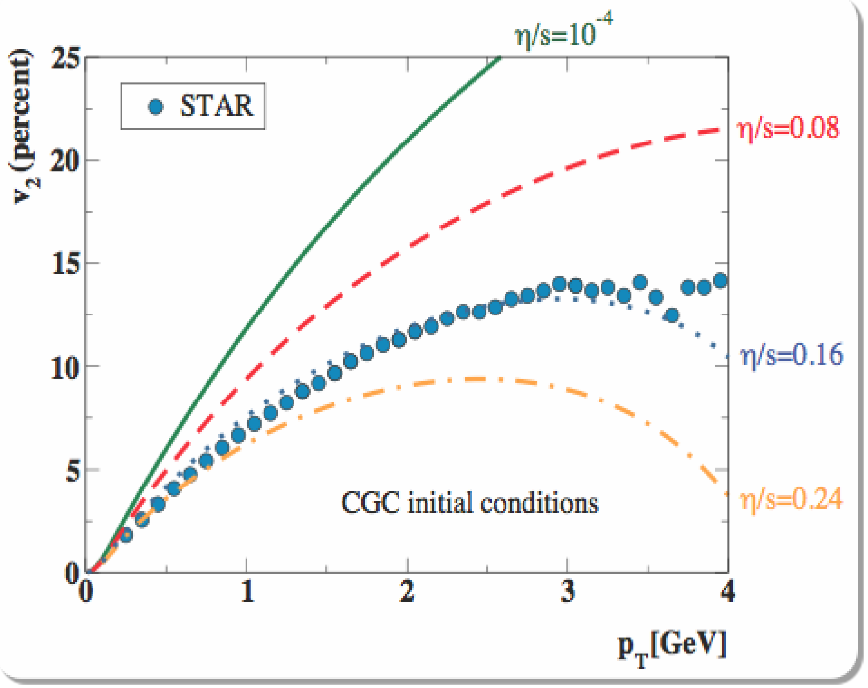
Schenke, Jeon and Gale (2010)

however, to describe the hadronic phase, transport models are needed, a hybrid approach is necessary to realistically describe the bulk medium (core/corona)

Elliptic flow



$$v_2(p_T,b) = \frac{\int d\phi \cos(2\phi)\ d\sigma_{AA}/d^2p_Td^2b}{\int d\phi\ d\sigma_{AA}/d^2p_Td^2b}$$



Luzum and Romatschke (2008)

a measure of the viscosity

viscous hydro calculations using CGC initial eccentricity describe the centrality and p_T dependence using η/s = 2/4π

but:

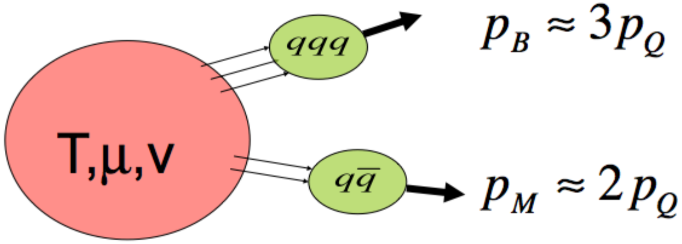
contribution from hadronic corona ?

uncertainties in initial conditions ?

….

AdS/CFT bound: $\frac{\eta}{s} > \frac{1}{4\pi}$

Quark recombination



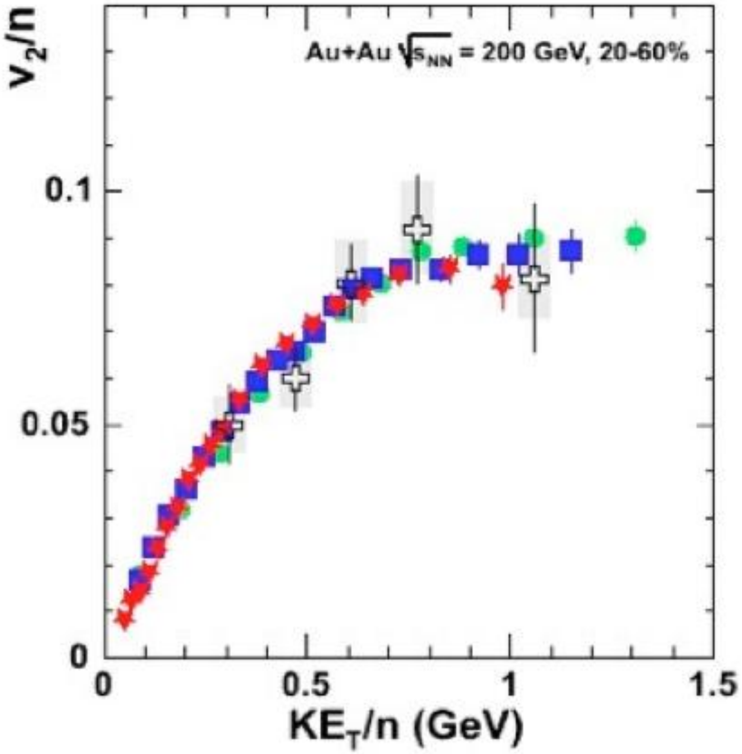
$p_B \approx 3p_Q$

$p_M \approx 2p_Q$

quark-number scaling of v_2

$$\frac{1}{2}v_2^M(p_T) = v_2^q\left(\frac{p_T}{2}\right)$$

$$\frac{1}{3}v_2^B(p_T) = v_2^q\left(\frac{p_T}{3}\right)$$

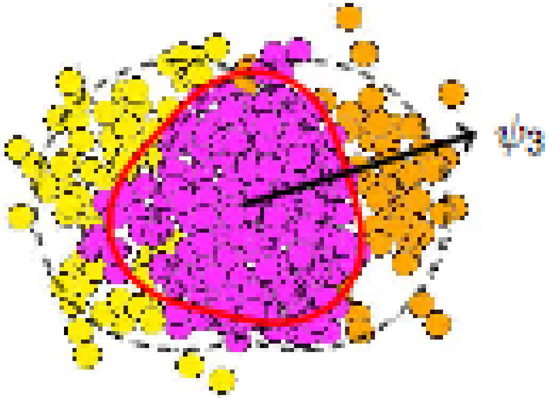


data for different mesons and baryons lie on a universal curve

Triangular flow

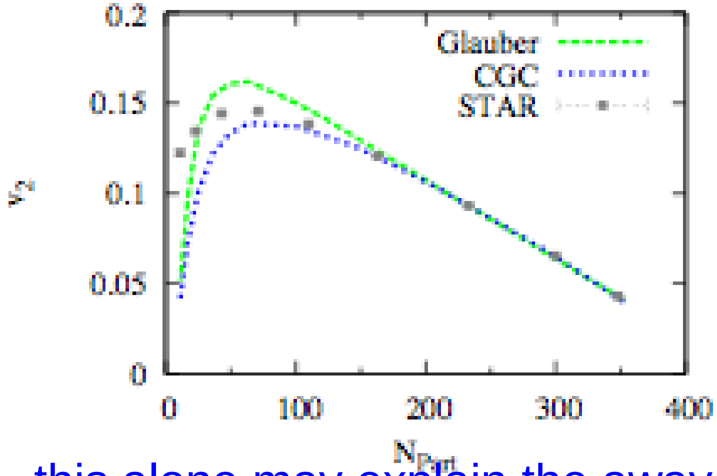
v_2 has two components, a geometric one and one due to fluctuations (the geometric component vanishes in central collisions)

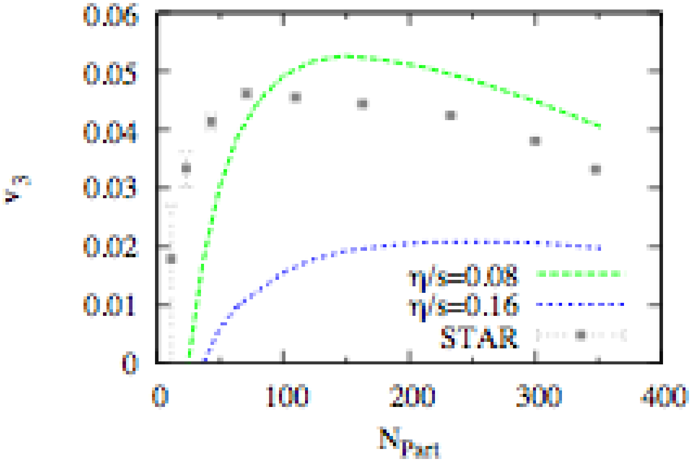
v_3 is only due to fluctuations



2+1d viscous hydro compared with data extracted from two-particle correlation measurements

Alver, Gombeaud, Luzum and Ollitrault (2010)

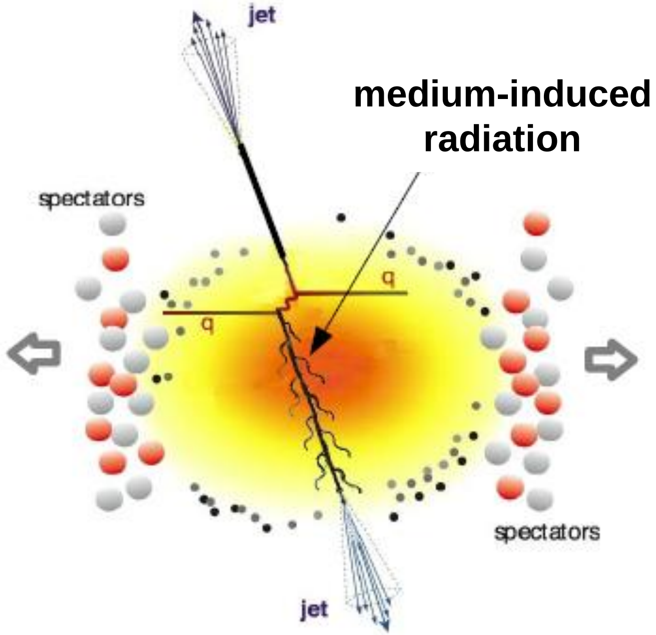




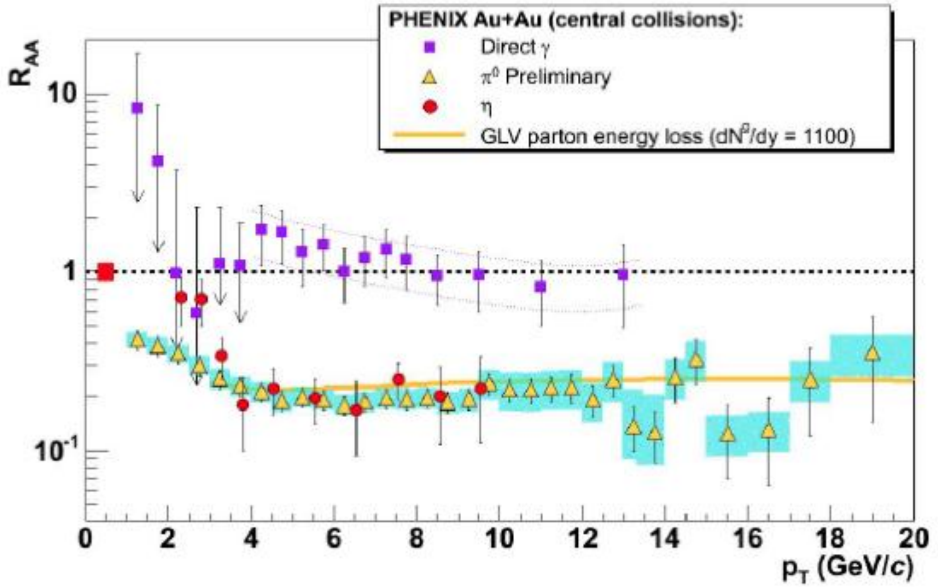
this alone may explain the away-side shoulder and perhaps even the ridge …

Hard Probes

Nuclear modification factor

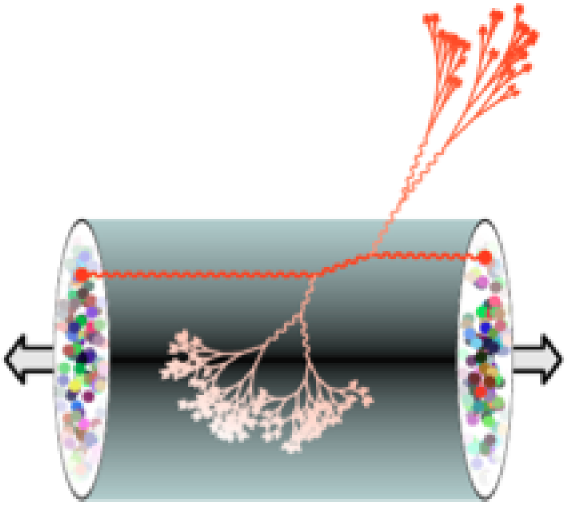


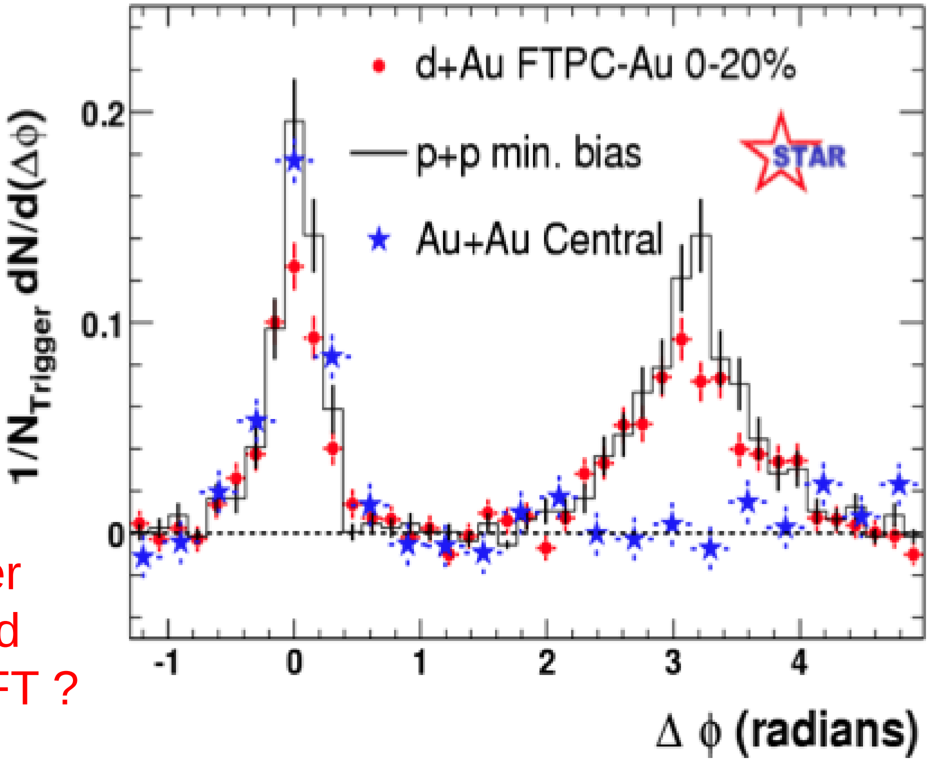
$$R_{AA}(p_T, b) = \frac{d\sigma_{AA}/dp_T d^2 b}{T_{AA}(b) d\sigma_{pp}/dp_T}$$



status of pQCD calculations: 4 main groups (WHDG, ASW, AMY, HT) obtain results using different assumptions

The plasma is opaque





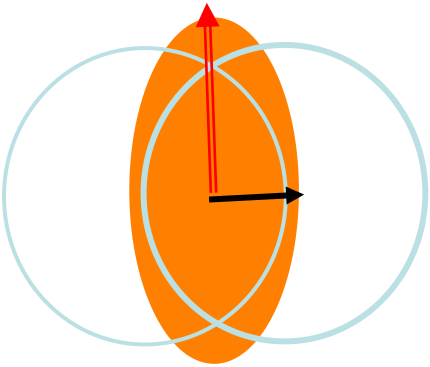
can such a strong stopping power happen in pQCD ? or do we need strong-coupling dynamics ? AdS/CFT ?

there is no compelling extraction of $\hat{q}$ from the data

(first the different jet-quenching calculations have to converge)

but still $\hat{q} \simeq \mathrm{a\ few\ GeV^2/fm}$ ($\Delta E \propto \hat{q} L^2$)

High-p_T azimuthal asymmetry



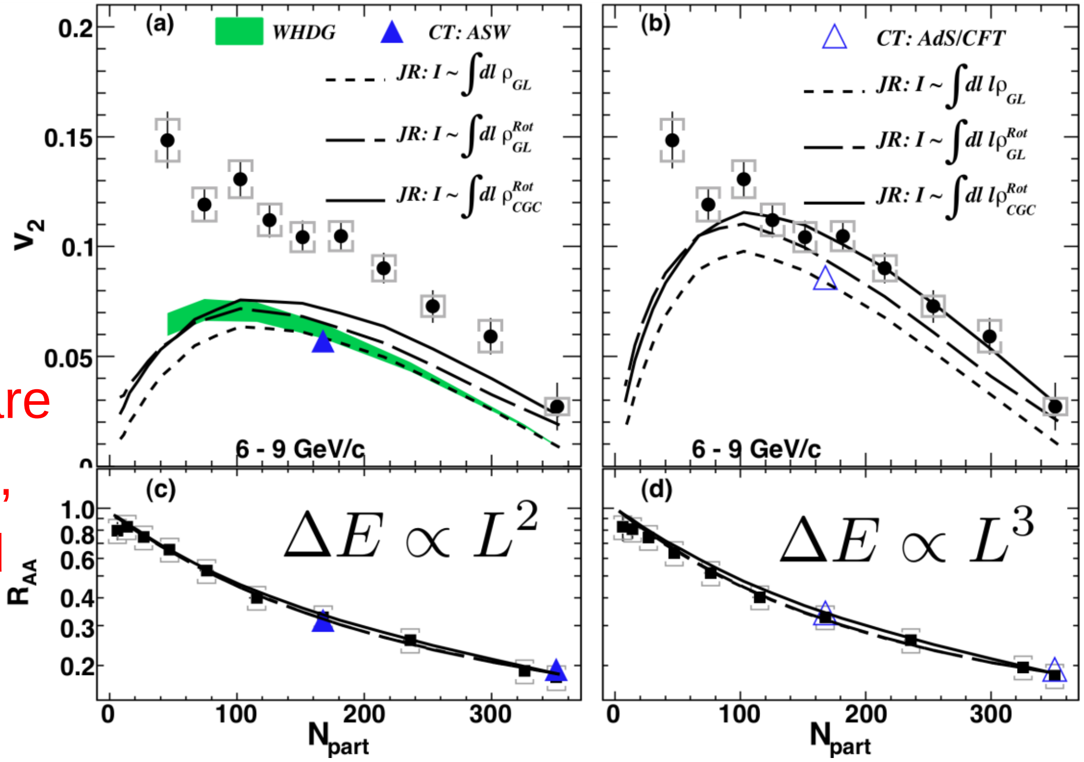
$$v_2(p_T, b) = \frac{\int d\phi \cos(2\phi)\ d\sigma_{AA}/d^2p_T d^2b}{\int d\phi\ d\sigma_{AA}/d^2p_T d^2b}$$

● **in-plane**

● **out-of-plane**

pQCD: once parameters are adjusted to describe R_{AA}, v_2 cannot be reproduced

PHENIX collaboration



pQCD model

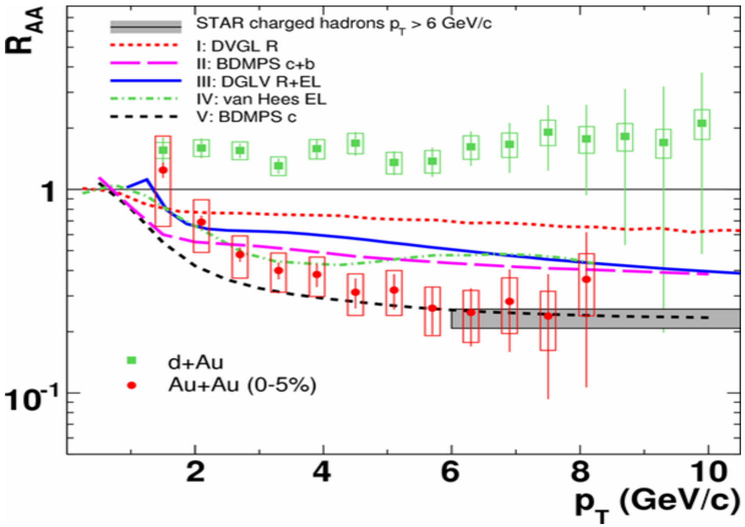
pQCD + AdS/CFT

Heavy-quark energy loss

- it is also unclear if the perturbative QCD approach works

high-p_T electrons from c and b decays indicate similar suppression for light and heavy quarks, but the dead-cone effect in pQCD implies a weaker suppression for heavier quarks

STAR data (2007)



trend: models underestimate the suppression

the measurements do not distinguish the charm and bottom quark contributions

in the future, separating the contributions from charm and bottom quarks will be helpful

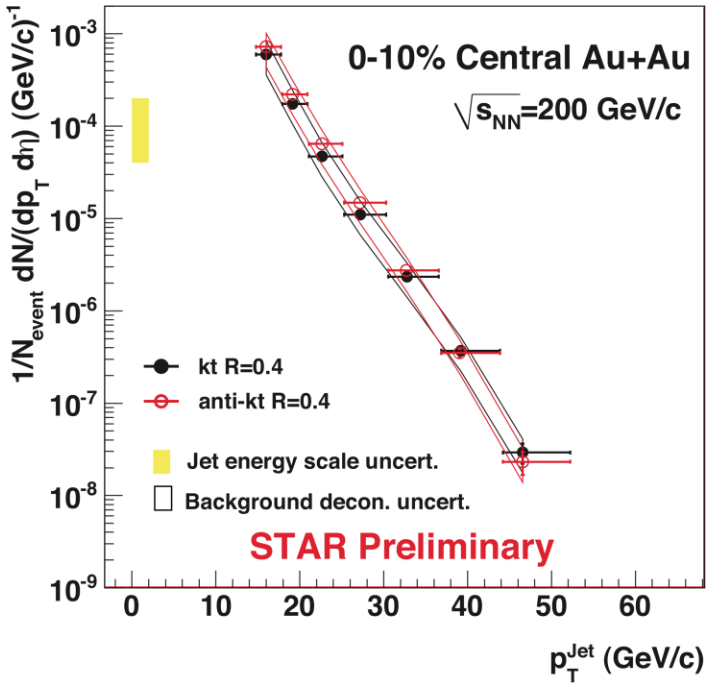
note that there are complications with heavy quarks:

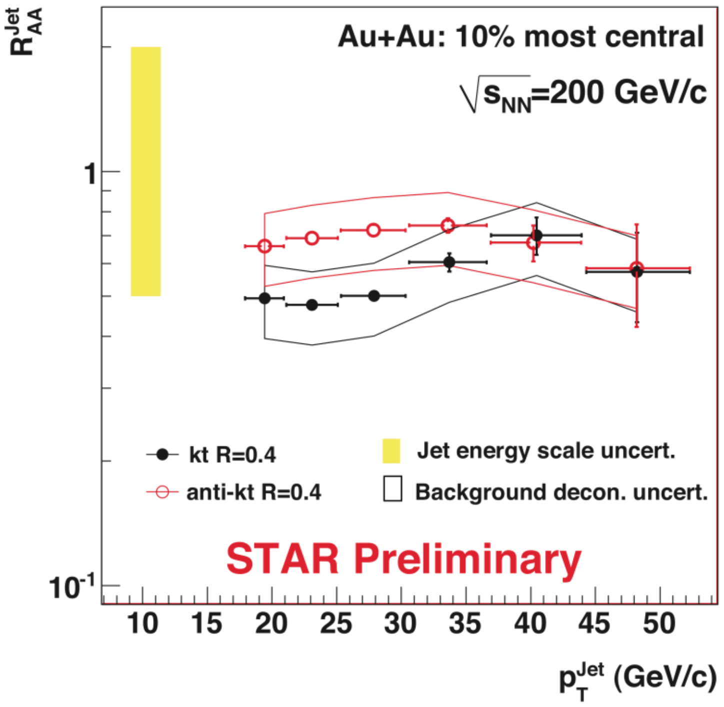
in-medium hadronization and dissociation, collisionnal energy loss, …

Jets in heavy-ion collisions

- a new sub-field which will appear with the LHC

tools are already being developed in the context of RHIC





they will be needed at the LHC

Conclusions

- there are many topics I didn't mention:

electromagnetic probes
strangeness
quarkonia
baryon production
chemical equilibrium
statistical hadronization
HBT radii
…

- there will be 15 talks in the session, some explaining (and correcting) what I said, some covering the missing topics

and I am sure the speakers will answer your questions