RHIC & *e*RHIC

The Symbiotic Relationship Between Heavy-Ion Physics & DIS

Thomas Ullrich (BNL)
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BROOKHAVEN
NATIONAL LABORATORY

The “Nearly” Perfect Theory: QCD

QCD is the “nearly perfect” fundamental theory of the strong interactions
F. Wilczek, hep-ph/9907340

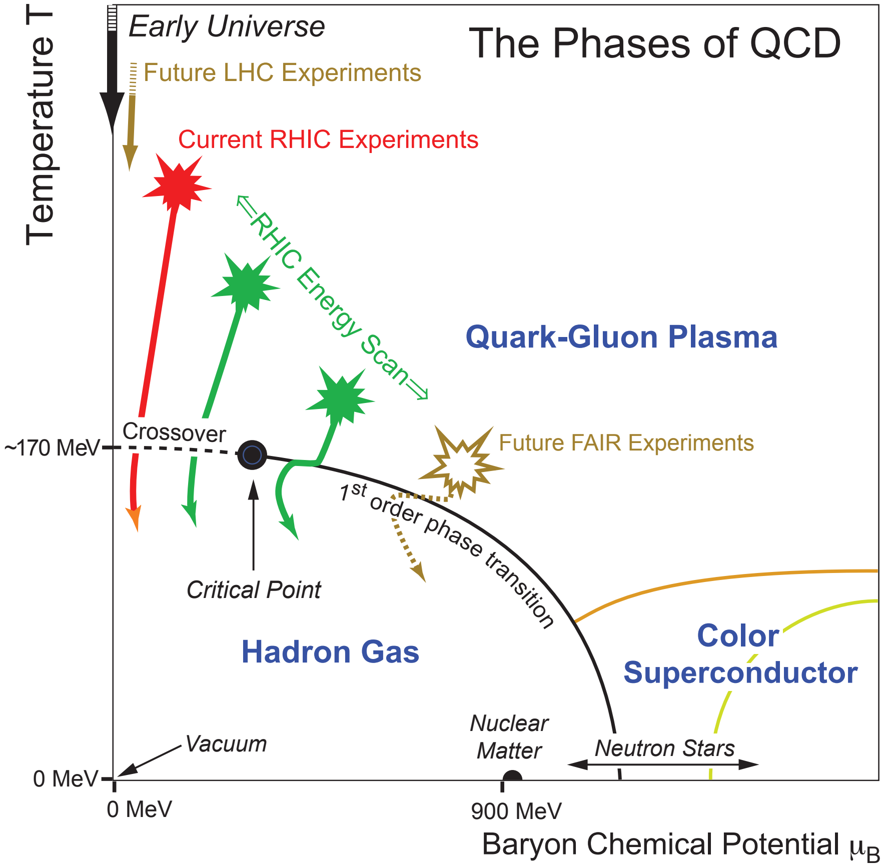
$$L_{QCD} = \bar{q}(i\gamma^\mu \partial_\mu - m)q - g(\bar{q}\gamma^\mu T_a q)A^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

- “Emergent” Phenomena not evident from Lagrangian
  - Asymptotic Freedom & Color Confinement
  - QCD under “extreme conditions” (high T, ρ | low-x, low-Q^2)
  - RHIC: QCD Phase Diagram
  - EIC: non-linear QCD @ low-x/Q^2

} non-perturbative

⇒ Requires *fundamental* investigation via *experiment: (e)RHIC*

The Phases of QCD



$T \gg \Lambda_{QCD}$: 'weak' coupling $\alpha_s(Q^2, T)$

⇒ deconfined phase

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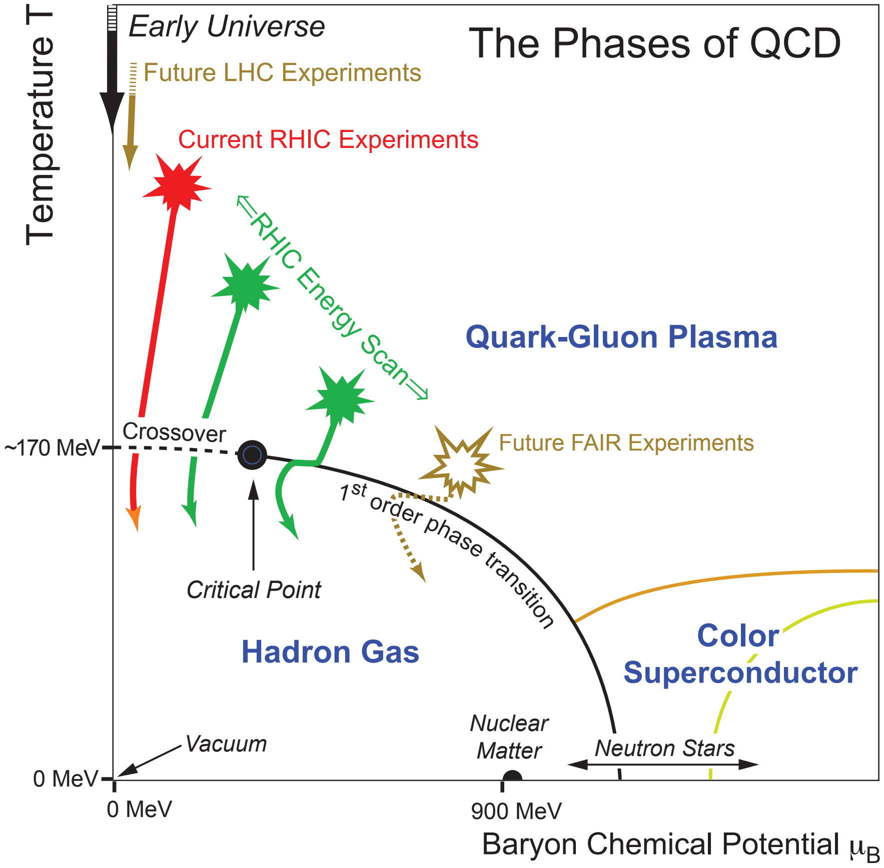
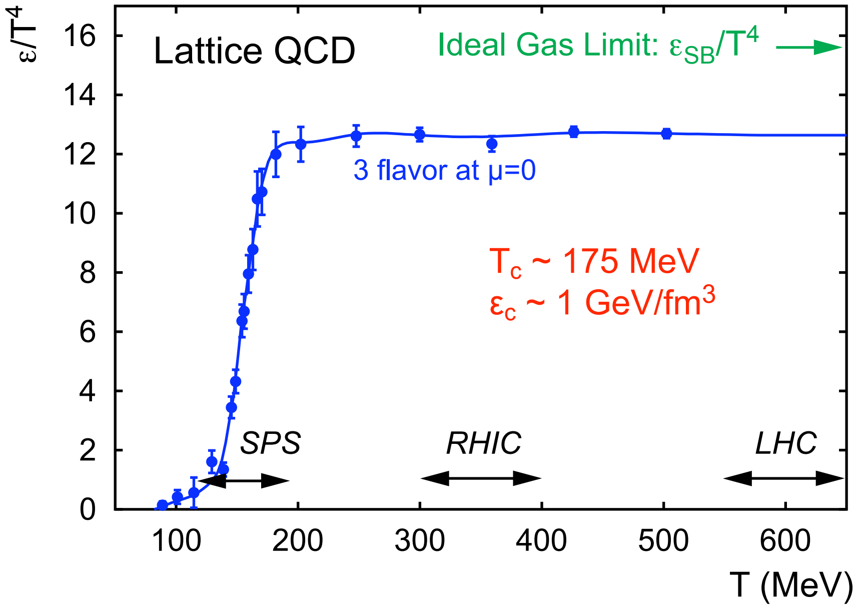
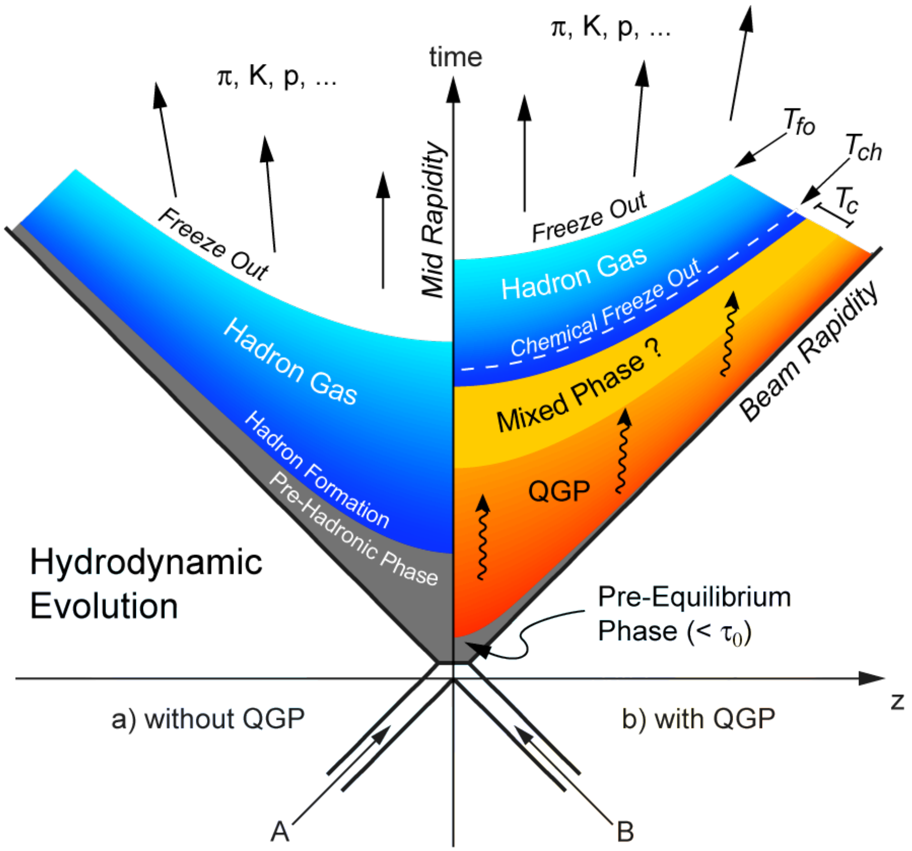




- Need experiments to explore the phase diagram of QCD
  - guidance by lattice for $\mu_B = 0$, substantial uncertainties
- Heavy Ion Collisions at RHIC and LHC create conditions sufficient to “melt” matter into a quark gluon plasma

QCD Phase Transition in the Laboratory



5. Individual hadrons

freeze out

4. Hadron gas

cooling with expansion

3. Quark Gluon Plasma

thermalization, expansion

2. Pre-equilibrium state

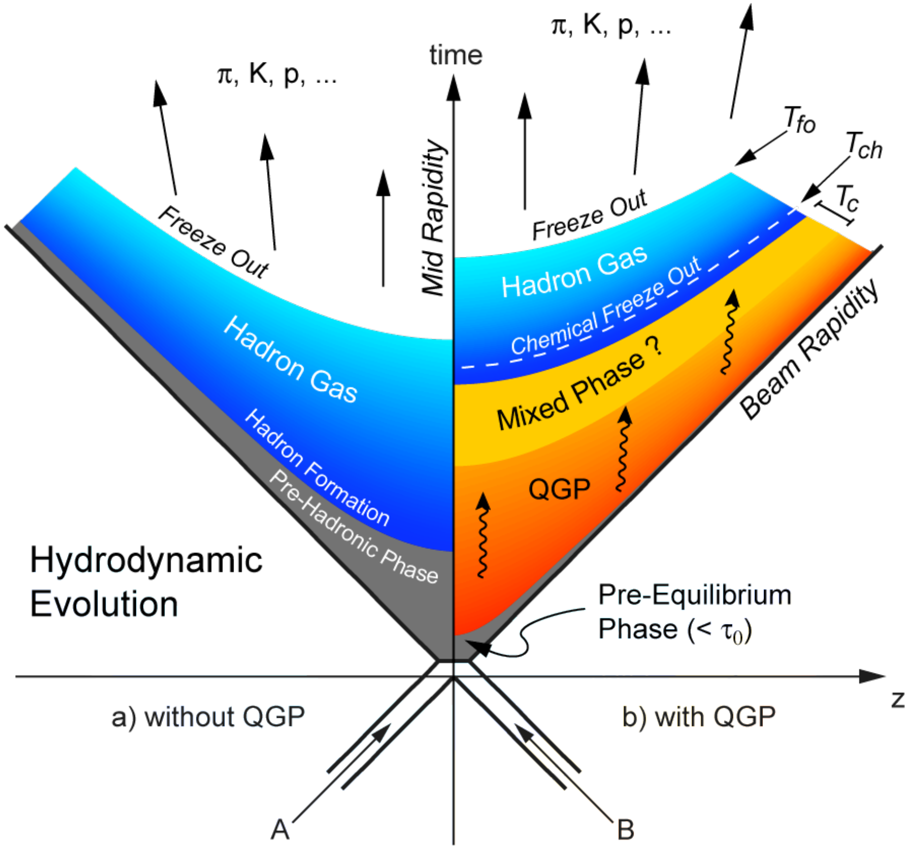
collision

1. Nuclei (initial condition)

Role of QCD:

- Not possible to describe all the steps within 1st principle calculation

QCD Phase Transition in the Laboratory



5. Individual hadrons ← Statistical Thermal Models
freeze out

4. Hadron gas ← Fragmentation
cooling with expansion

3. Quark Gluon Plasma ← Hydro
thermalization, expansion

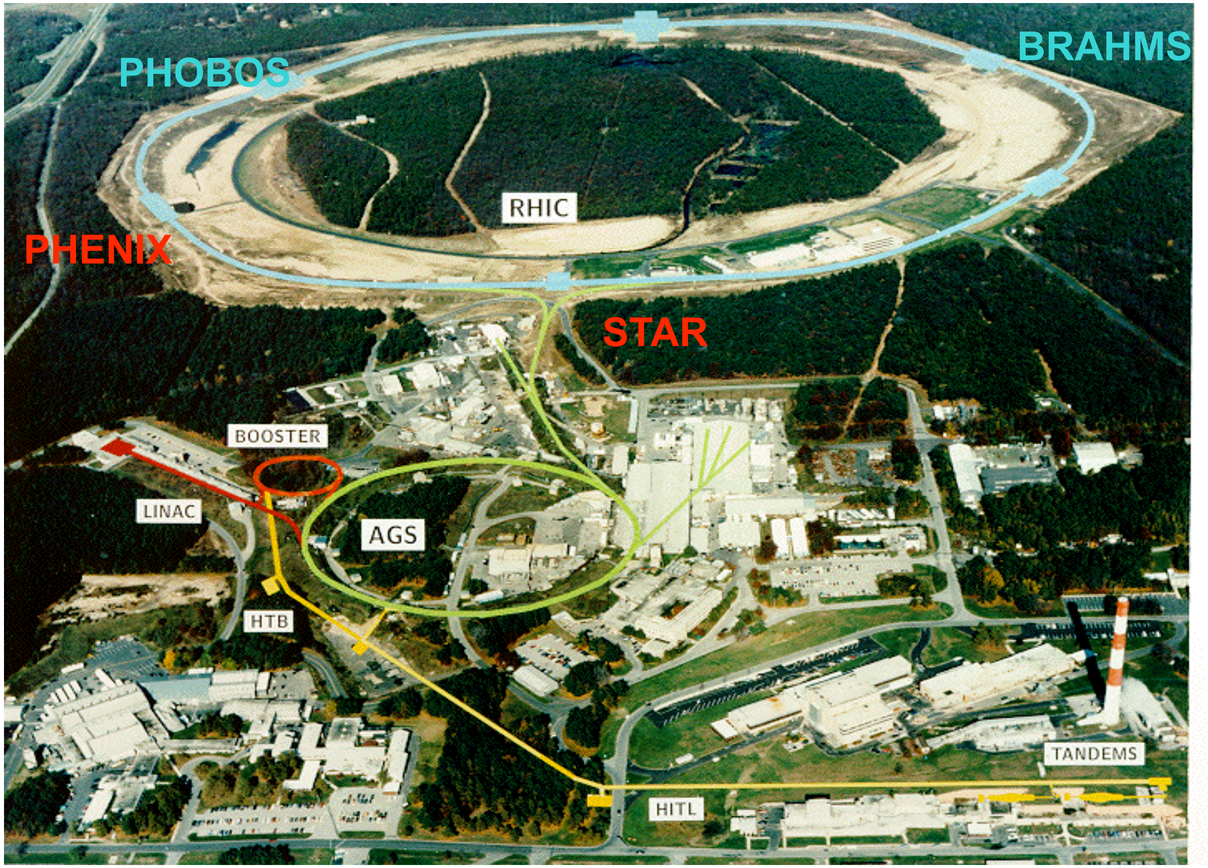
2. Pre-equilibrium state ← Glasma
collision ← pQCD

1. Nuclei (initial condition) ← CGC

Role of QCD:

- Not possible to describe all the steps within 1st principle calculation
- Platora of approaches specific to energy/density/time ranges: CGC, Glasma, pQCD (hard scatter), Hydrodynamics, AdS/CFT, Hadronic Transport Models, Statistical Thermal Models

Relativistic Heavy Ion Collider - RHIC



3.83 km circumference

Two *independent* rings

Capable of colliding
~any nuclear species
on
~any other species

i.e., from p to Au (U)

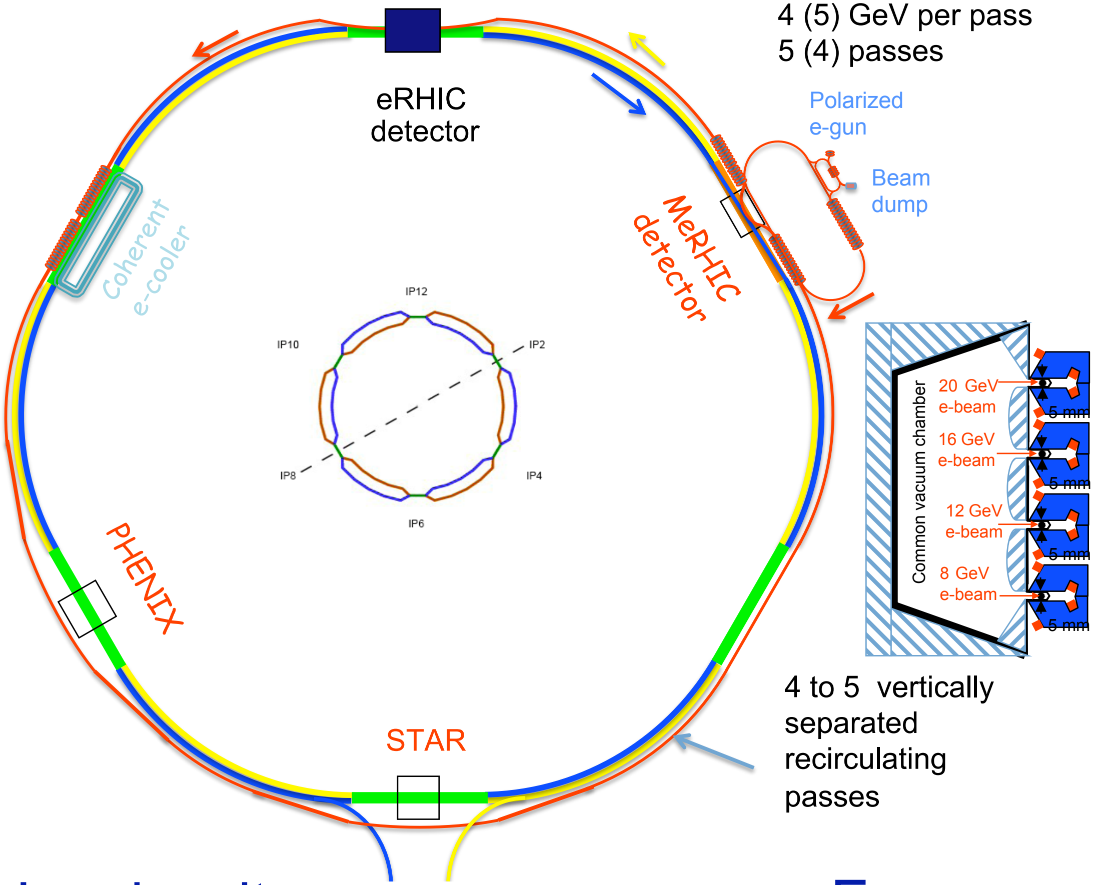
Energy √s:

- 0.5 TeV for p-p (polarized)
- 8-200 GeV for Au-Au
  (per N-N collision)

Luminosity

- Au-Au: 6 x $2\cdot10^{26}$ cm^{-2} s^{-1}
- p-p : 4 x $2\cdot10^{32}$ cm^{-2} s^{-1}
  (*polarized*)

Electron Ion Collider (EIC) - eRHIC



2 x 200 m SRF linac
4 (5) GeV per pass
5 (4) passes

4 to 5 vertically separated recirculating passes

eRHIC: add ERL to existing RHIC

- 10 GeV electron design energy
- 5 recirculation passes (4 of them in the RHIC tunnel)
- Full polarization at all energies for the electron beam
- Transverse cooling of the hadron beams

Luminosity

- ep: ~$3 \cdot 10^{33}$ $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
- $L_{\mathrm{eRHIC}} \approx 100 \times L_{\mathrm{Hera}}$

Energy options:

w/o HI experiments (no DX magnets):
e+p: 10-20 GeV e + 325 GeV p
e+A:10-20 GeV e + 130 GeV/u Au
possibility of 30 GeV e @ low current

See talk by V. Litvinenko

Discoveries at RHIC ...

- **Strong Elliptic Flow**
  - Collective flow of created matter
  - Constituent quark number degrees of freedom apparent in scaling laws of elliptic flow
- **Jet Quenching**
  - Energy loss of high-p_T partons traversing the hot and dense matter
- **“Black Body” Radiation**
  - Thermalized hot matter emits EM radiation $\Rightarrow T_i = 300\text{-}600$ MeV
- **Particle Production** through recombination/coalescence dominates over fragmentation at medium p_T

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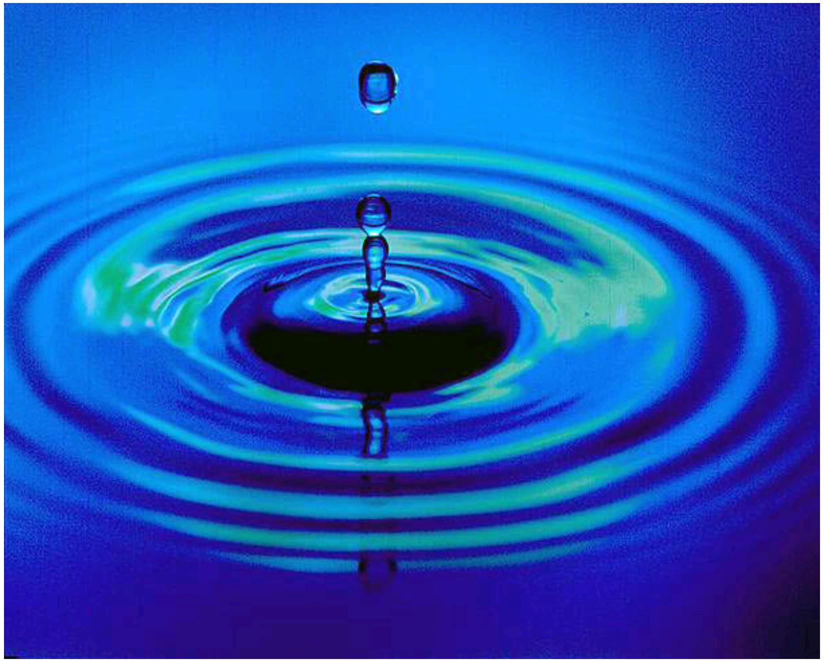


⇐ these and comparisons to models led to the "perfect fluid" hypothesis

Paradigm shift:

strongly coupled QGP = sQGP

... and Open Questions

Many open question will be answered in the future via detailed studies of AA collisions at RHIC and/or LHC

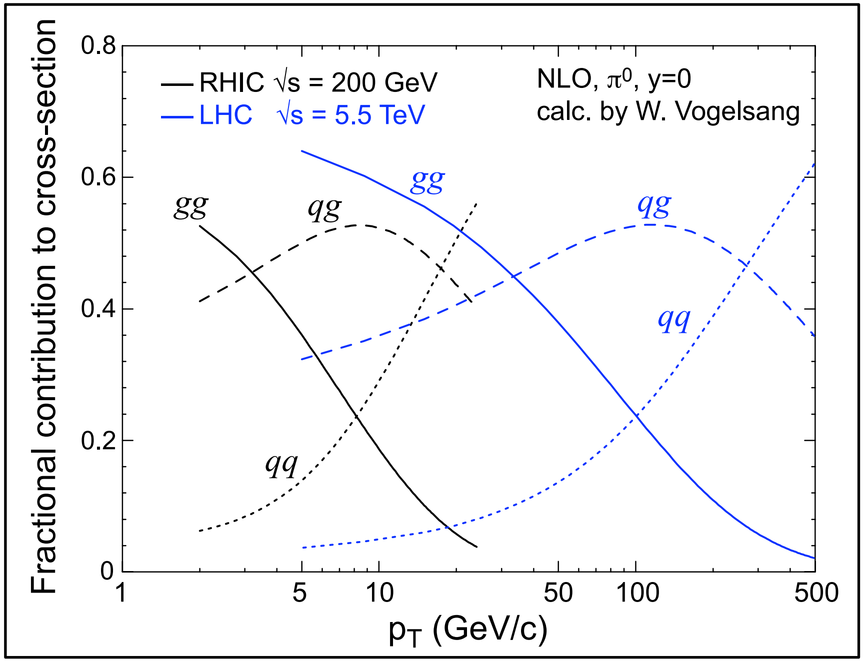
Some we cannot solve in AA, pA, or pp

⇒ will need massive input from elsewhere (eRHIC!)

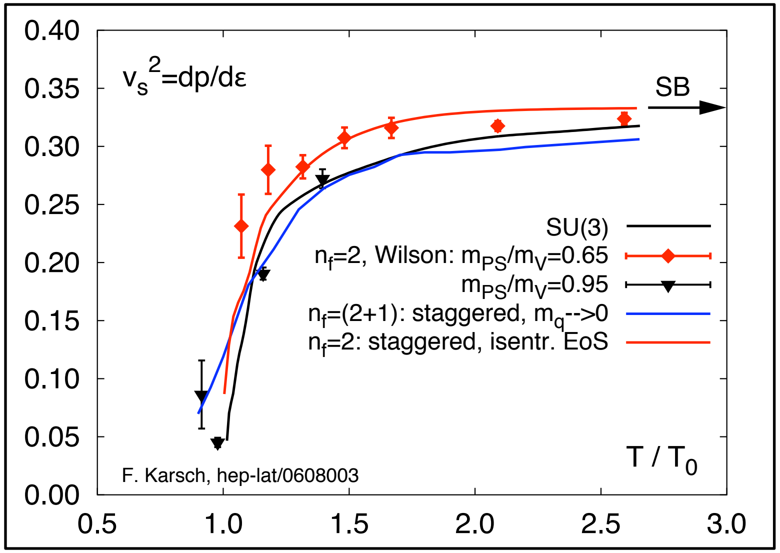
- What are the initial conditions that lead to thermalization?
- How does the matter thermalize so fast ($\tau \sim 0.6$ fm)?
  - What's the dynamics of thermalization?
- How perfect is the "perfect" liquid?
  - How close is η/s to the conjectured quantum limit $1/4\pi$?
- What's the role of gluon saturation in our observations?
- How do nuclear effects (e.g. (anti-)shadowing impact the findings at RHIC & LHC?

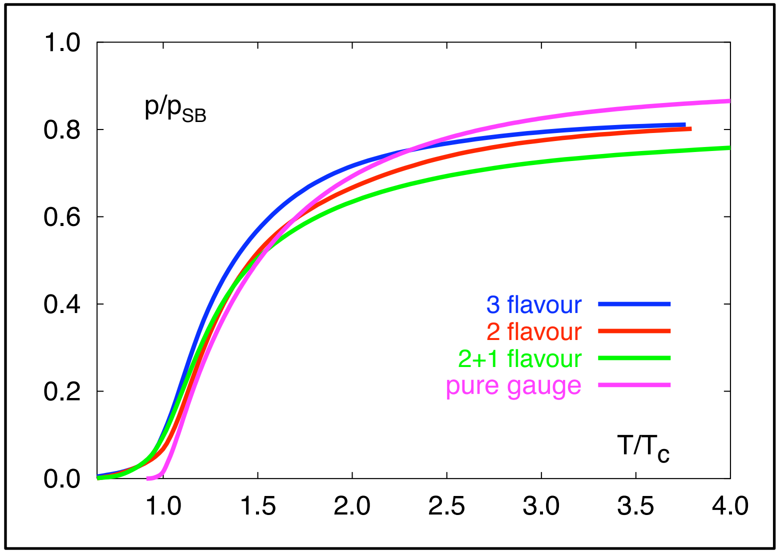
Role of Glue in Heavy-Ion Collisions

Jets (π^0) Production

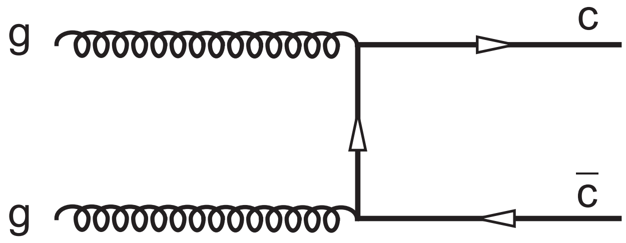


Lattice





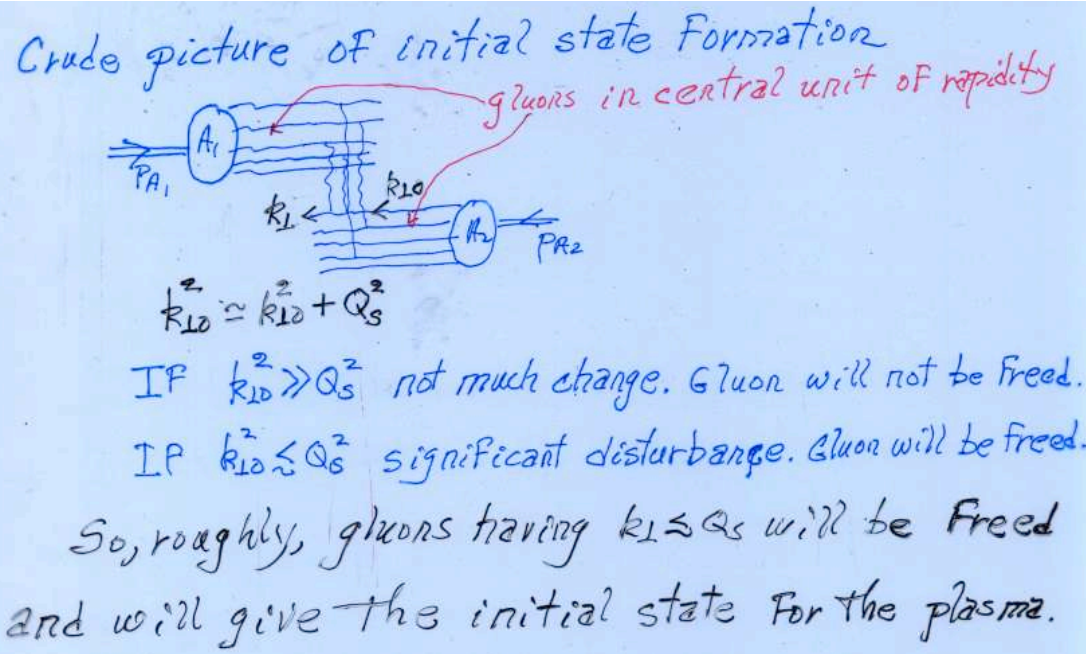
Heavy Flavor Production



Thermalization

Models that describe the early phase of the collision (EOS?!) conclude that matter at RHIC thermalizes rapidly ($\tau < 1$ fm)

- We don’t know why and how?
- At present no first principle understanding of thermalization in QCD



Crude picture of initial state Formation

$$k_{\perp 0}^2 \simeq k_{\perp 0}^2 + Q_s^2$$

IF $k_{\perp 0}^2 \gg Q_s^2$ not much change. Gluon will not be Freed.

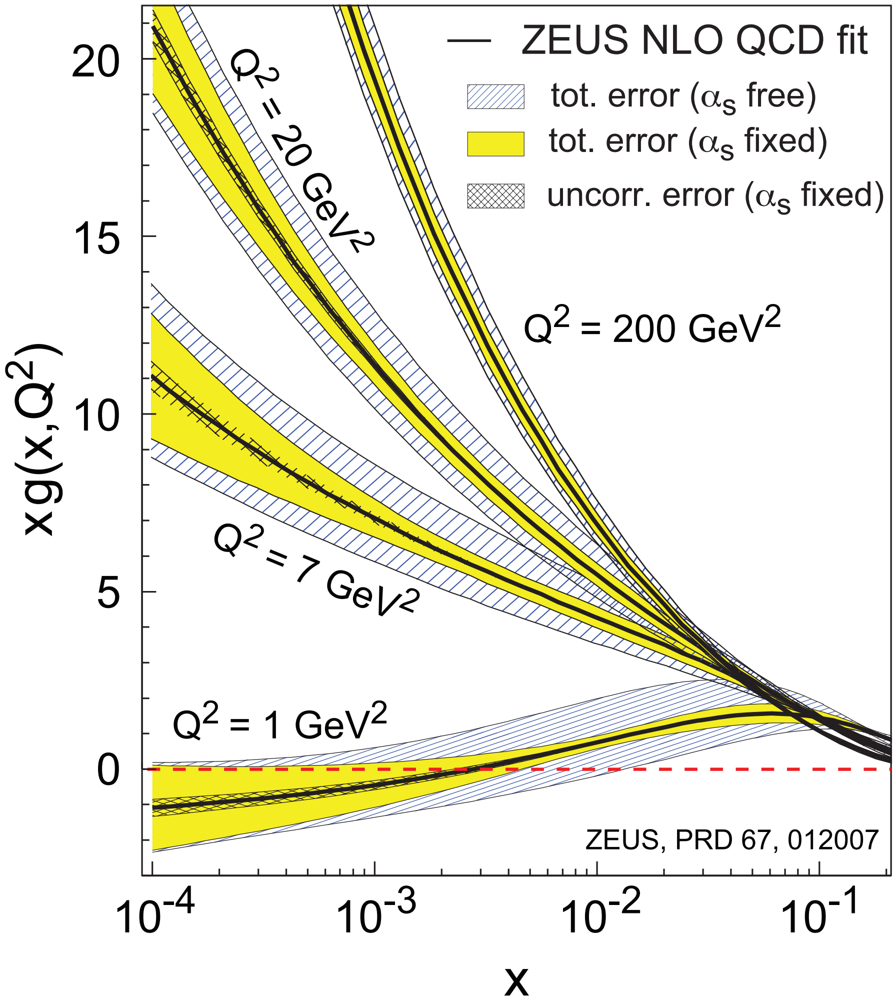
IF $k_{\perp 0}^2 \lesssim Q_s^2$ significant disturbance. Gluon will be freed.

So, roughly, gluons having $k_\perp \lesssim Q_s$ will be Freed and will give the initial state For the plasma.

Al Mueller (2007)

- pQCD attempts (e.g. gg→ggg Xu, Greiner) questionable
- CGC → Glasma → QGP
- In any case need $G(x,Q^2)$

Uncertainties in $G(x,Q^2)$ - DIS



Hera: Scaling violation:

$dF_2/dlnQ^2$ & linear DGLAP

$\Rightarrow G(x,Q^2)$ see Fabrizio's talk

Linear DGLAP evolution scheme

- Weird behavior of xG and F_L from HERA at small x and Q^2
- $G(x,Q^2) < Q_{sea}(x,Q^2)$?
- Unexpectedly large diffractive cross-section
- built in high energy "catastrophe"
  - xG rapid rise violates unitary bound

Linear BFKL Evolution

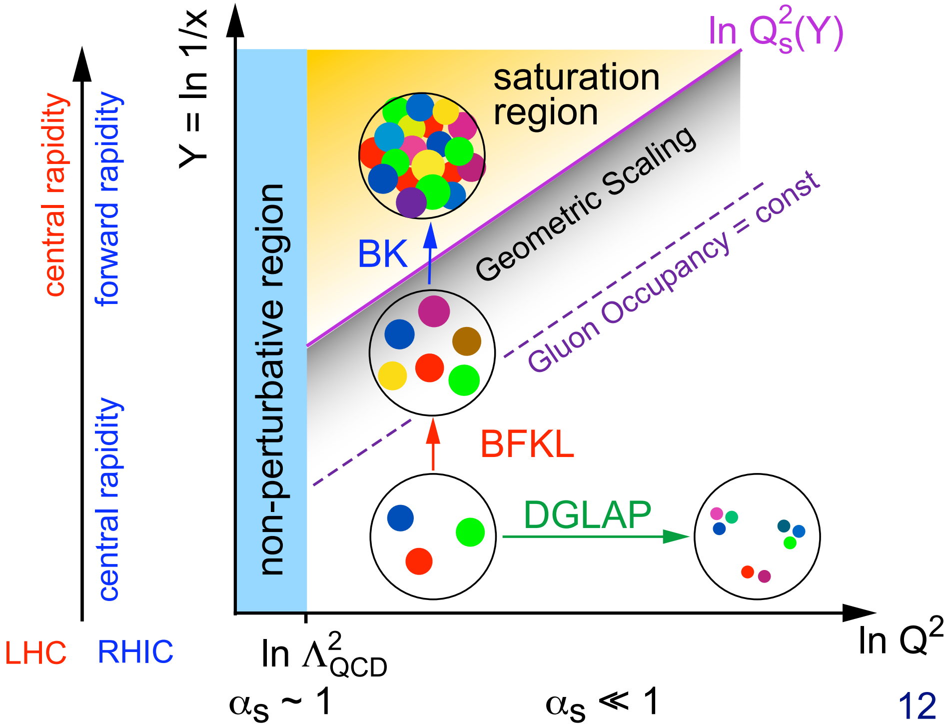
- Density along with σ grows as a power of energy: $N \sim s^\Delta$
- Can densities & cross-section rise forever?
- Black disk limit: $\sigma_{total} \leq 2 \pi R^2$

Saturation/Color Glass Condensate

McLerran-Venugopalan Model: & Non-Linear Evolution:

- At very high energy: recombination compensates gluon splitting
- Cross sections reach unitarity limit
- BK/JIMWLK: non-linear effects ⇒ saturation characterized by $Q_s(x,A)$
  - Wave function is Color Glass Condensate in IMF description
- Weak coupling description of the wave function
- Gluon field $A_\mu \sim 1/g$ ⇒ gluon fields are strong classical fields!

Verification/Clarification of saturation and the validity of CGC approach one of the fundamental outstanding problems in QCD



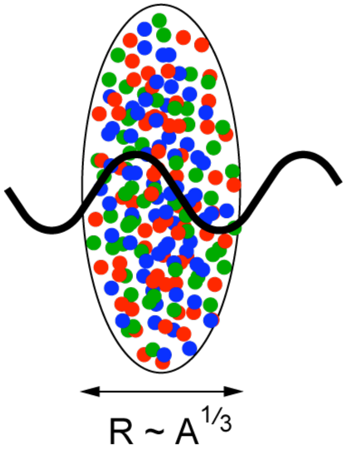
Raison d'être for *e*+A

Scattering of electrons off nuclei:

Probes interact over distances $L \sim (2m_N x)^{-1}$

For $L > 2\,R_A \sim A^{1/3}$ probe cannot distinguish between nucleons in front or back of nucleon

Probe interacts *coherently* with all nucleons



$$Q_s^2 \sim \frac{\alpha_s\, xG(x,Q_s^2)}{\pi R_A^2} \qquad \text{HERA}: \; xG \sim \frac{1}{x^{0.3}} \qquad \text{A dependence}: \; xG_A \sim A$$

"Expected"
Nuclear Enhancement Factor
(Pocket Formula):

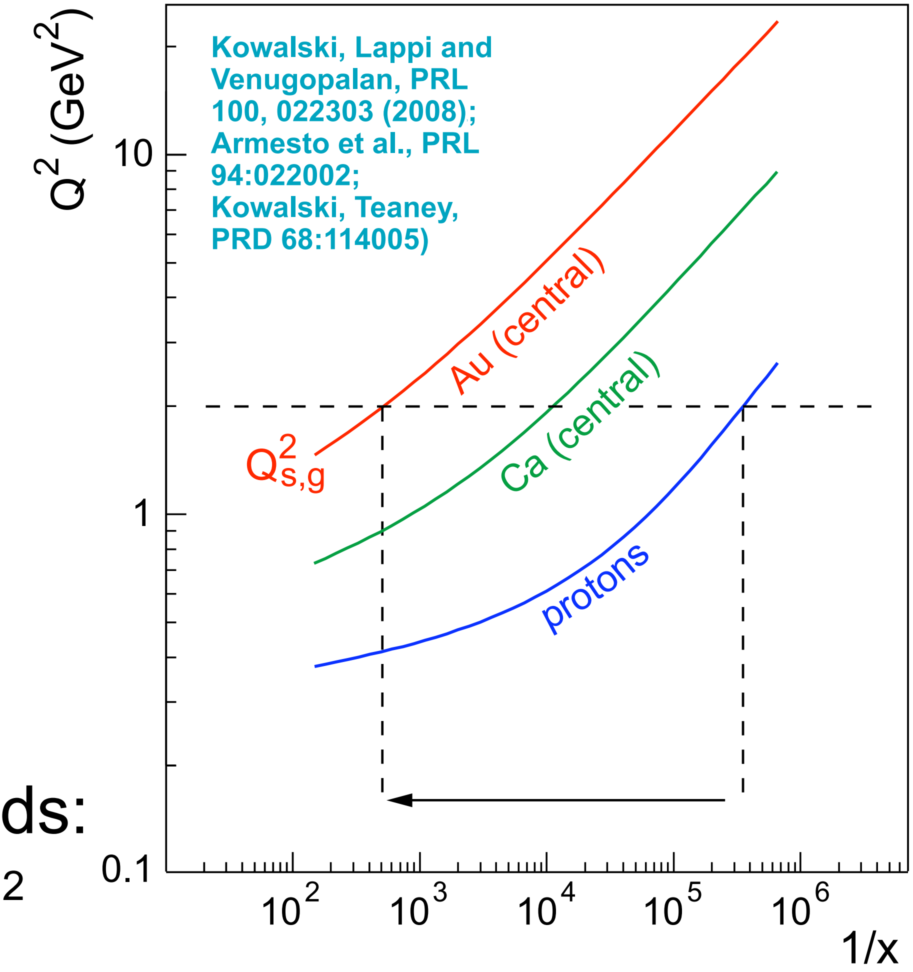
$$\boxed{(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}}$$

Enhancement of Q_S with A ⇒ non-linear QCD regime reached at significantly lower energy in A than in proton

Testing Saturation in e+A

Electron-Ion Collider (eA)

- Instead extending x, Q reach $\Rightarrow$ increase Q_s
- More sophisticated analyses (constraint by NMC data) confirm pocket formula but it neglects b dependence
- Still enough uncertainty to worry (N_{ch} at LHC will help)



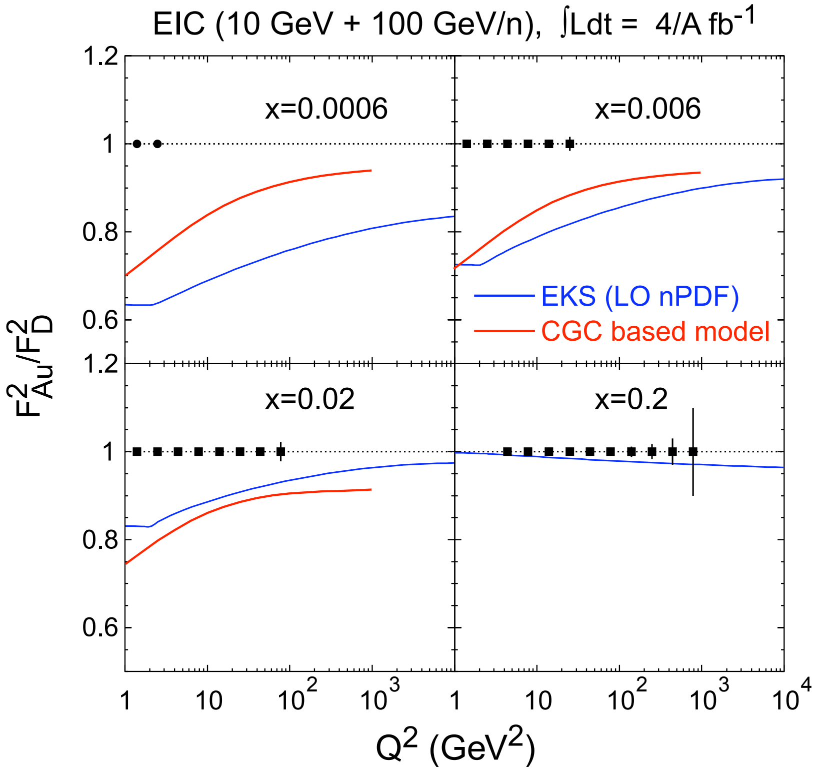
Gluon distribution $G(x,Q^2)$

- Various complementary methods:
  - Scaling violation in F_2: $\delta F_2/\delta \ln Q^2$
  - $F_L \sim xG(x,Q^2)$
  - 2+1 jet rates
  - Diffractive vector meson production $\sim [xG(x,Q^2)]^2$

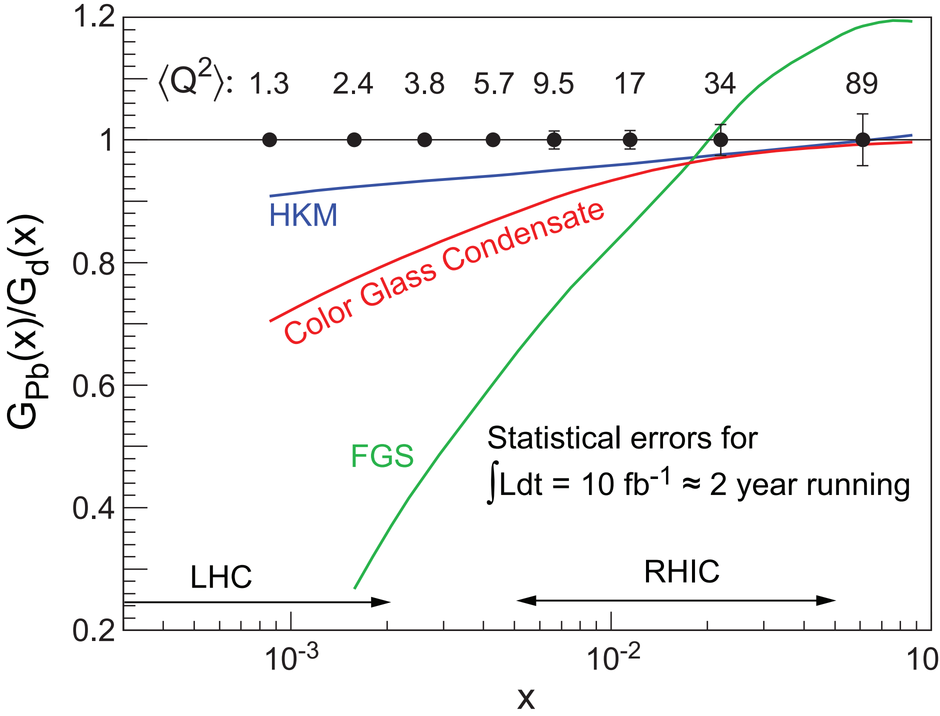
Key Measurement: F_2, $F_L \Rightarrow G(x,Q^2)$

Simulations to demonstrate the quality of EIC/eRHIC measurements

$$\frac{d^2\sigma^{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2)-\frac{y^2}{2}F_L(x,Q^2)\right]$$



Folded with eRHIC acceptance



Statistical errors for
∫Ldt = 10 fb^{-1} ≈ 2 year running

Assume:

L = 3.8 10^{33} cm^{-2} s^{-1} (100x Hera),

T = 4 weeks, duty cycle: 50%

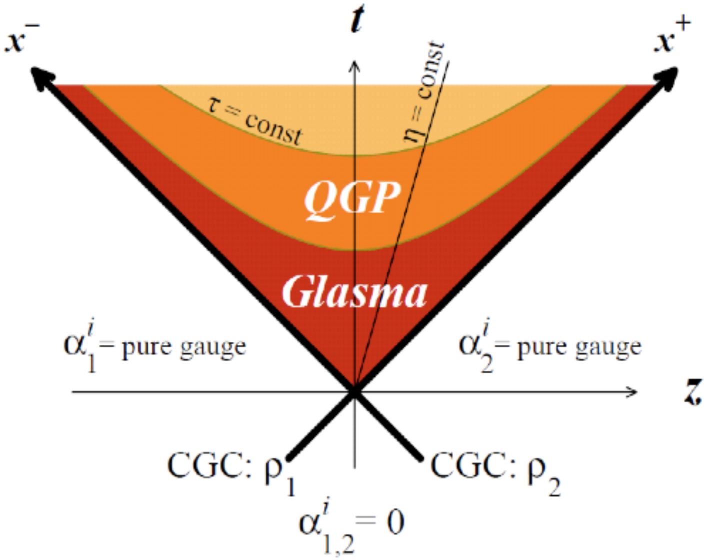
$F_L \sim \alpha_s\, G(x,Q^2)$ requires √s scan

Here: 10+100, 10+50, 5+50 GeV

Glasma

Definition:

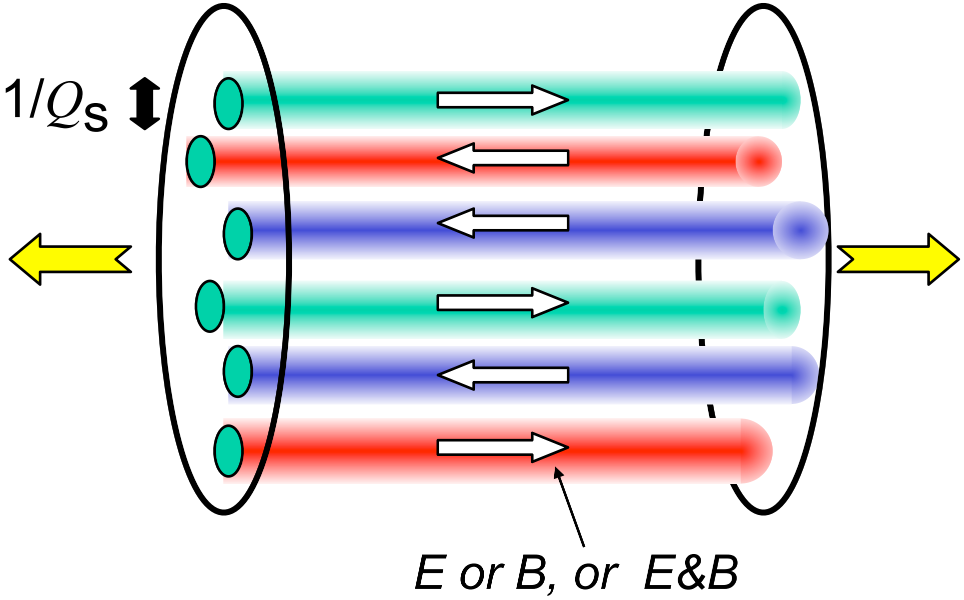
Non-equilibrium state between Color Glass Condensate and Quark Gluon Plasma which is created in high-energy heavy-ion collisions.



Considerable success describing:

1) rapid thermalization
2) Long-range rapidity correlations (ridge)
3) Baryon stopping

Expanding Flux Tubes



Boost invariant Glasma (without rapidity dependence) cannot thermalize

Need to violate the boost invariance !!!

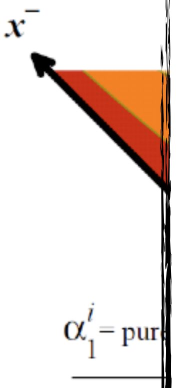
⇒ origin: fluctuation

Glasma

Definition:

Non-

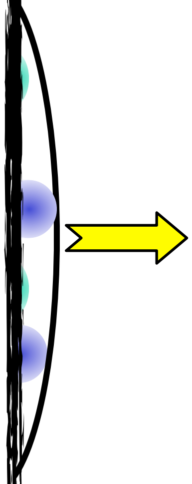
Plasm



Initial conditions and the earliest dynamics of the high-energy heavy-ion collisions can be understood within the framework of CGC and Glasma

However, I doubt that it can be tested/verified in either eA or in AA
(QGP wipes most traces out & hard to distinguish the source of correlations $\tau_{\text{Glasma}} < 1$ fm/c)

CGC approach be clarified in eA ⇒ hints for validity of Glasma ?



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1) ra

2) Lo

correlations (ridge)

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Need to violate the boost invariance !!!

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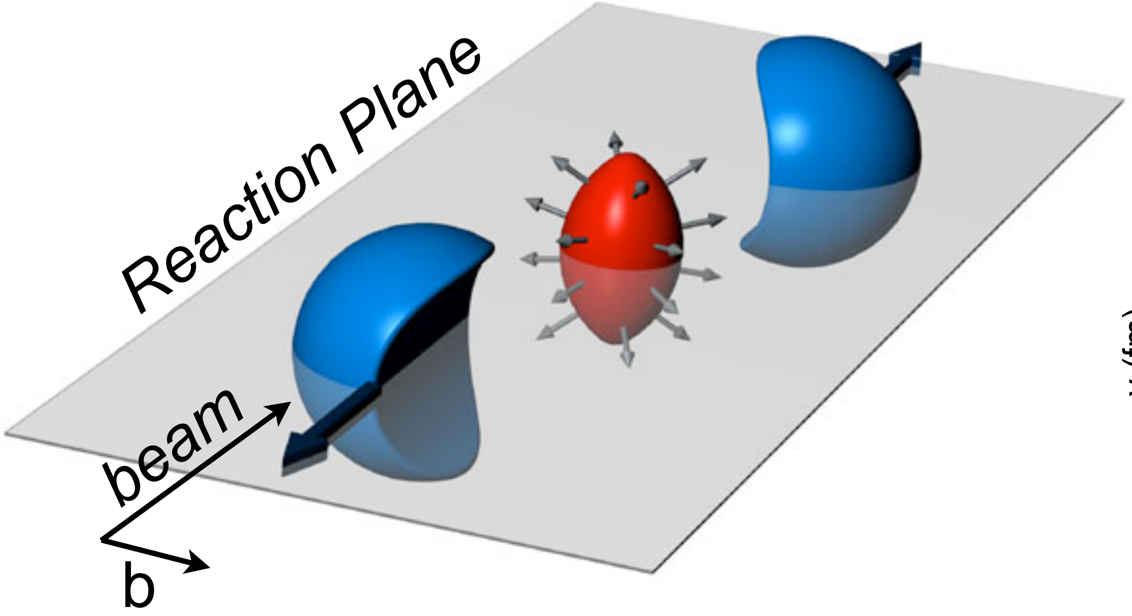
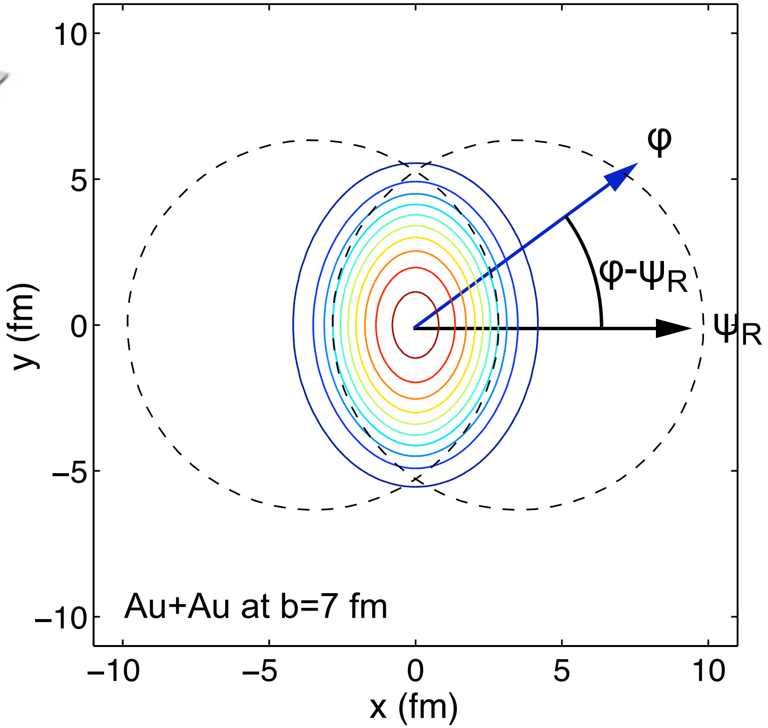
Elliptic Flow – Indicator for Early Thermalization





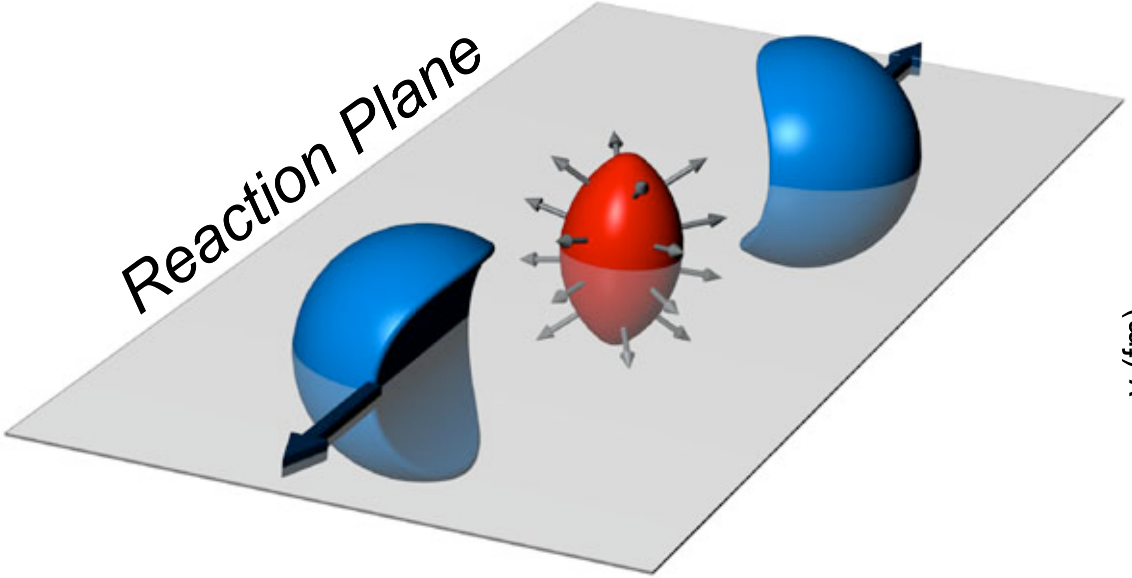
Initial spatial anisotropy → Interactions → Final state anisotropy in momentum space

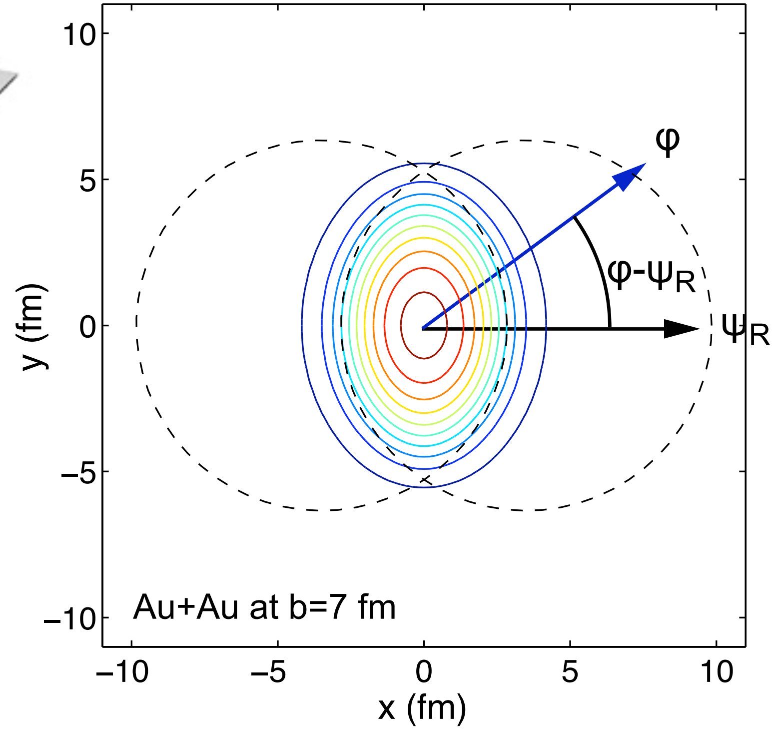
Use a Fourier expansion to describe the angular dependence of the particle density

$$\frac{dN}{d\varphi} \propto 1 + 2v_2 \cos[2(\varphi - \psi_R)] + \dots$$

$$v_2 = \langle \cos[2(\varphi - \psi_R)] \rangle$$

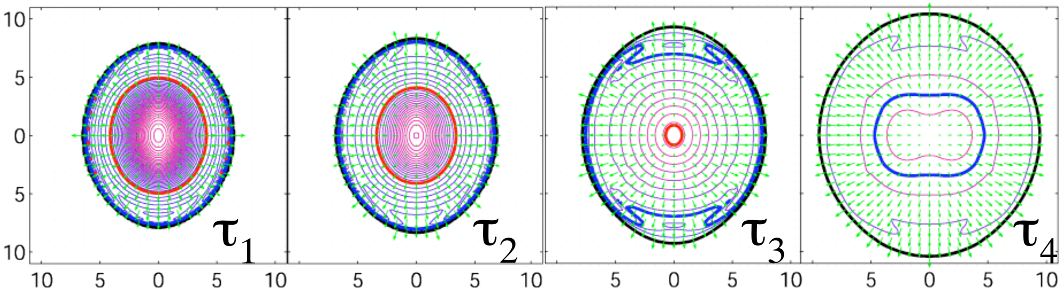
Elliptic Flow – Indicator for Early Thermalization





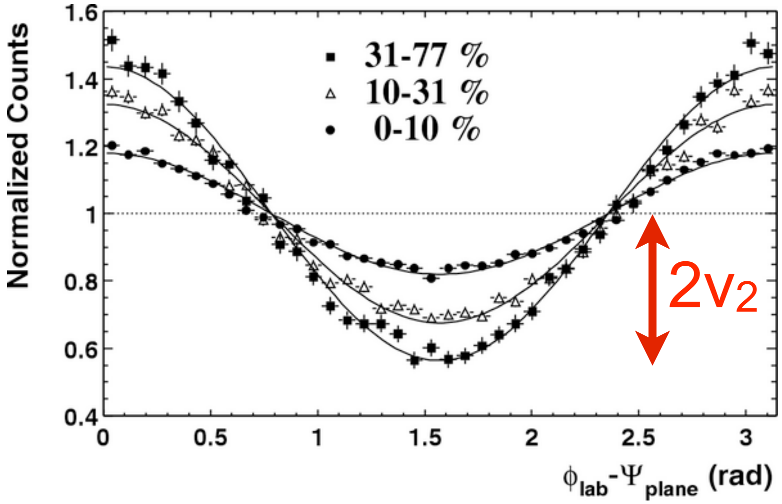
Au+Au at b=7 fm

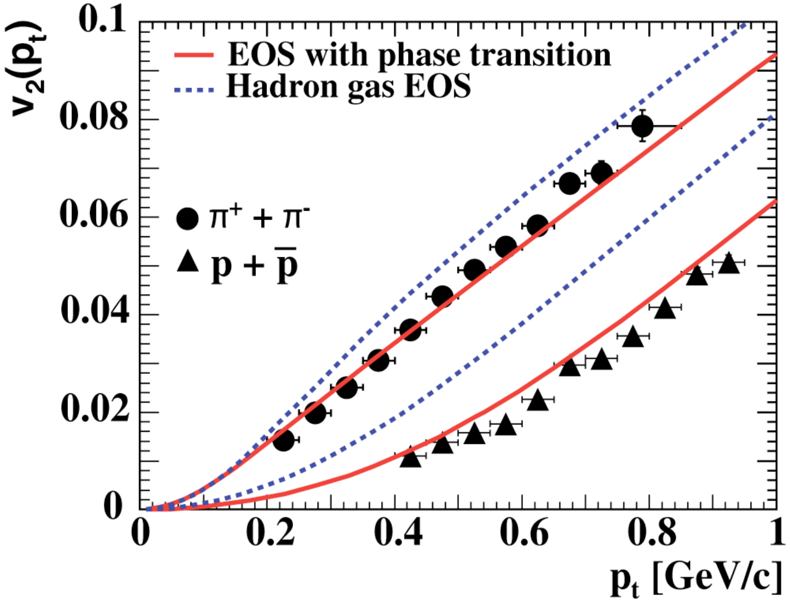
P. Kolb, J. Sollfrank, and U. Heinz



- ➢ driving spatial anisotropy vanishes ⇒ self quenching
- ➢ v_2 → sensitive to **early** interactions and pressure gradients

The Flow is $\approx$ Perfect





- Huge asymmetry found at RHIC
  - massive effect in azimuthal distribution w.r.t reaction plane
- "Fine structure" $v_2(p_T)$ for different mass particles
  - good agreement with ideal (zero viscosity η, $\lambda=0$) hydrodynamics
  - small $\eta \Rightarrow$ large $\sigma \Rightarrow$ strong coupling $\Rightarrow$ "perfect liquid"
- Conjectured quantum limit:
  - Kovtun, Son, Starinets, PRL.94:111601, motivated by AdS/CFT correspondence

$$\eta \geq \frac{\hbar}{4\pi}(Entropy\ Density) \equiv \frac{\hbar}{4\pi}s$$

Turns out RHIC is very close to this limit - how close?

Evaluating η/s

Ideal hydrodynamics $v_2 \propto$ spatial eccentricity ε:

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

v_2/ε versus particle density is sensitive gauge to test if system approaches ideal hydrodynamic

$$\frac{v_2}{\epsilon} = \frac{h}{1 + B/(\frac{1}{S}\frac{dN}{dy})}$$

Bhalerao, Blaizot, Borghini and Ollitrault,
Phys. Lett. B 627 (2005) 49
Luzum and Romatschke, Phys. Rev. C 78, 034915

S is the transverse area of the collision region, h corresponds to the ideal hydro limit of v_2/ε and $B \propto \eta/s$

The question is what is ε?

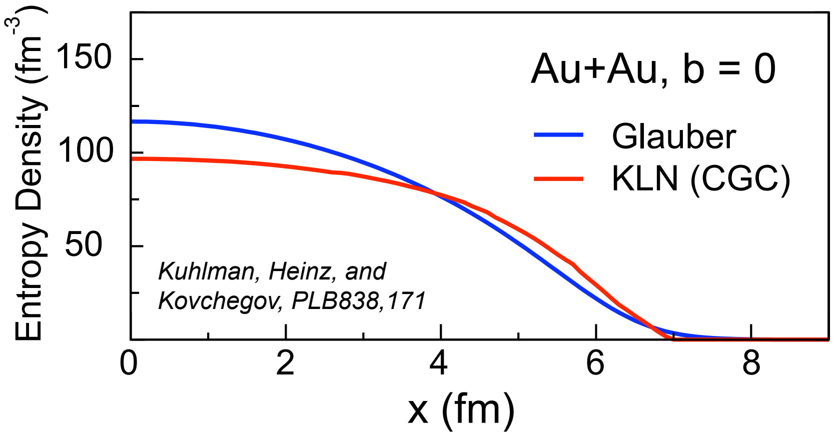
RHIC & LHC: low-p_T realm driven almost entirely by glue

⇒ spatial distribution of glue in nuclei?

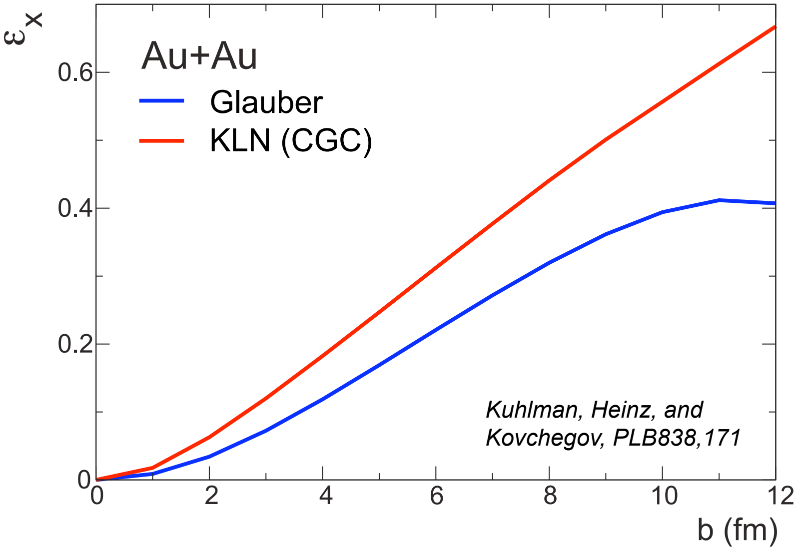
Two methods for ε:

Glauber (non-saturated) or CGC (saturated) approach ?

Eccentricity: Saturated Profile or Not?



Kuhlman, Heinz, and Kovchegov, PLB838,171



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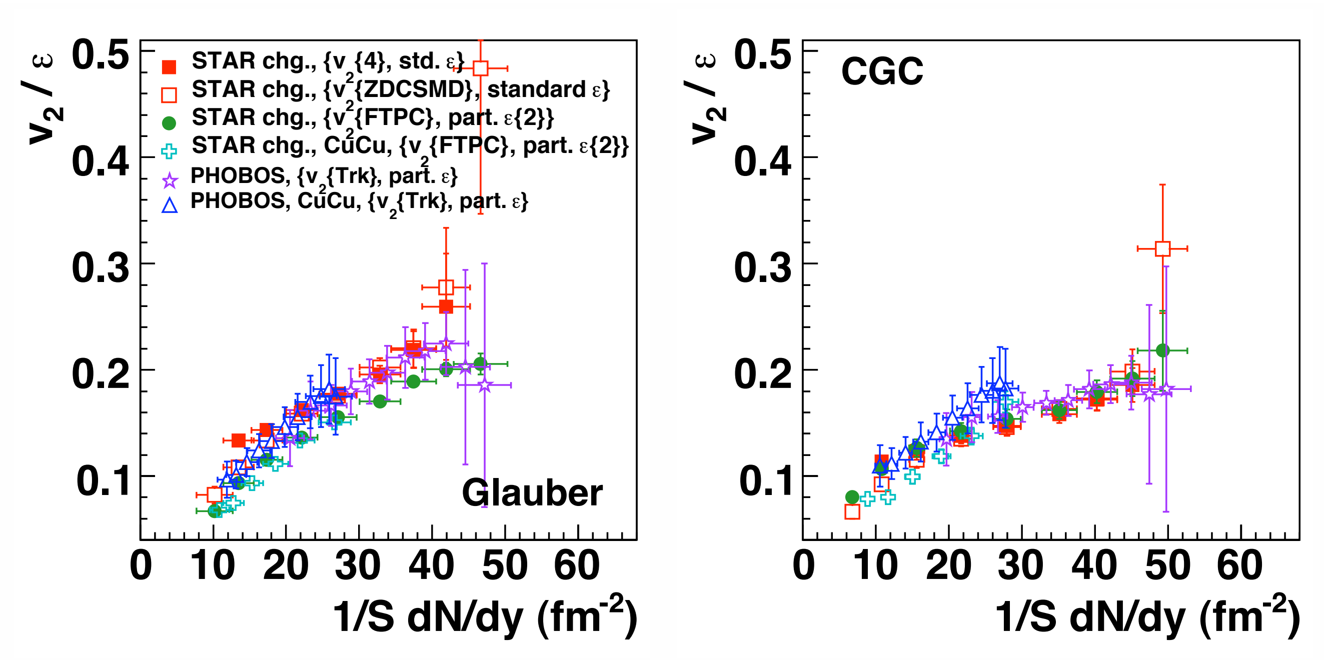
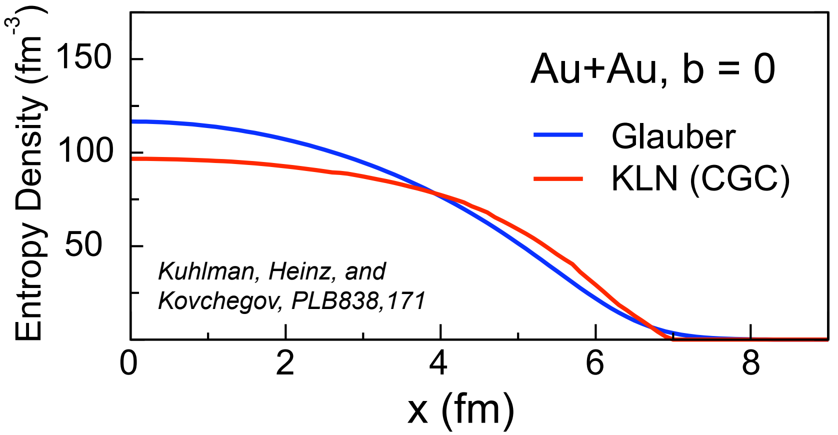
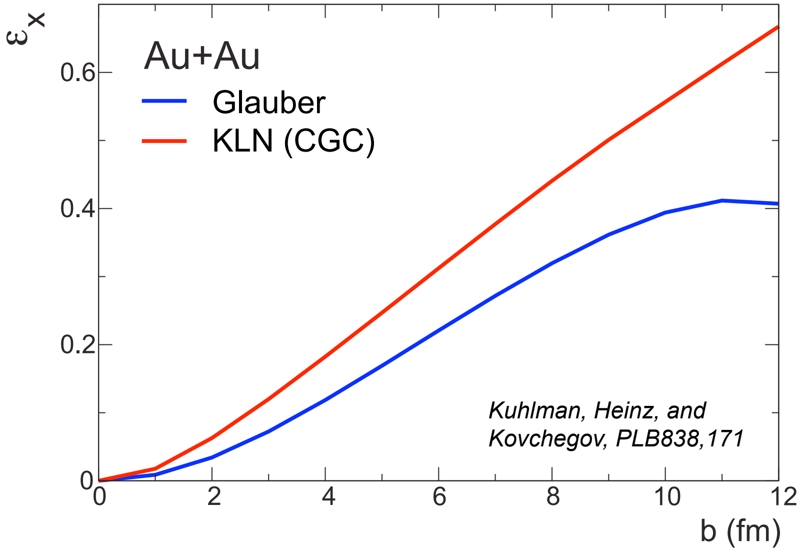
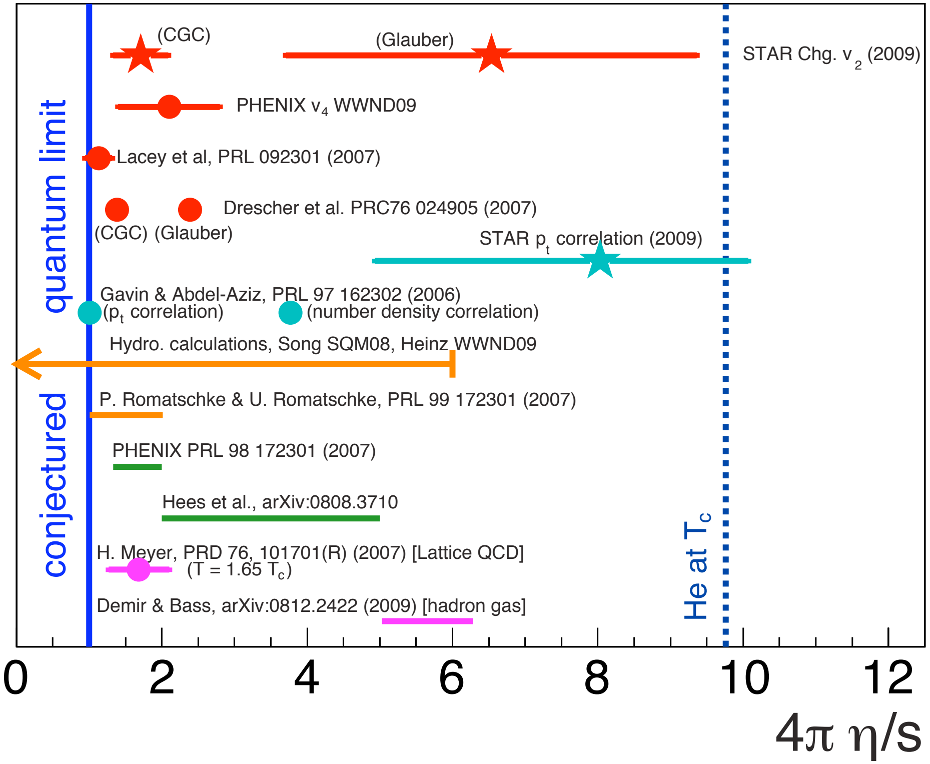


$\varepsilon_{CGC} > \varepsilon_{Glauber}$

Eccentricity: Saturated Profile or Not?







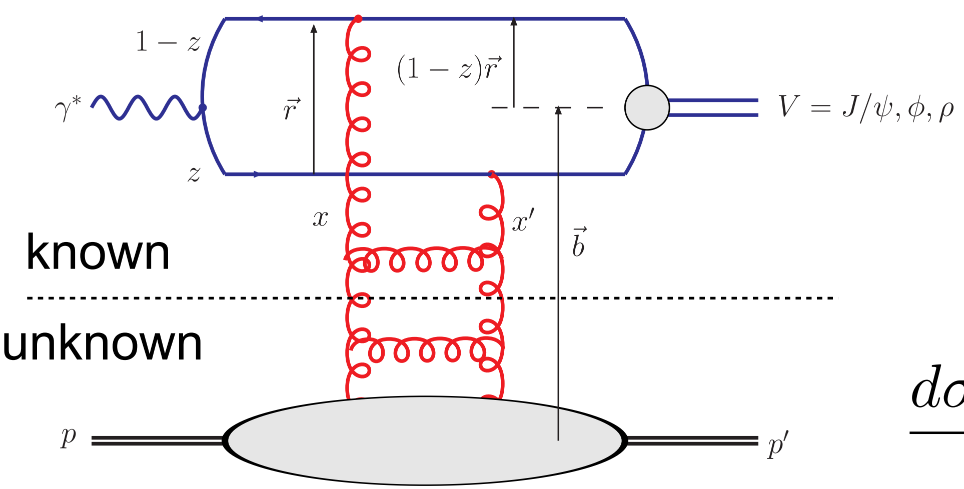
$\varepsilon_{CGC} > \varepsilon_{Glauber}$

(Viscous) Hydro is most convincing approach to determine η/s

No way to determine ε in AA collisions ⇒ eA

J/ψ as Probe of Gluonic Nuclear Structure

dipole life time ~ $1/m_p x$ ⇒ 20 to 2000 fm, for x^{-2} to x^{-4}



$$d\sigma^{\gamma^* p}_{tot} = \int \Psi^* \sigma_{q\bar{q}} \Psi$$

↑

Optical Theorem

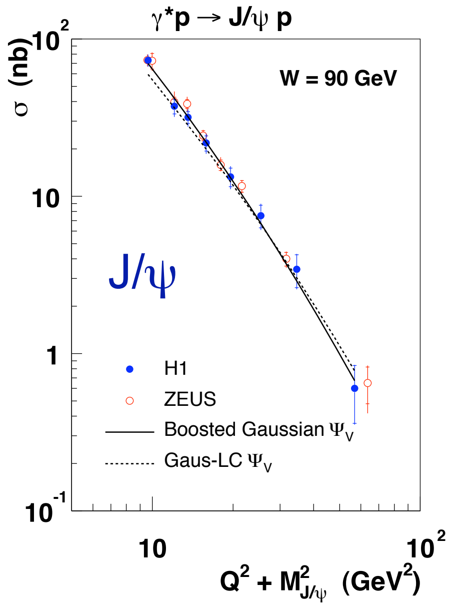
↓

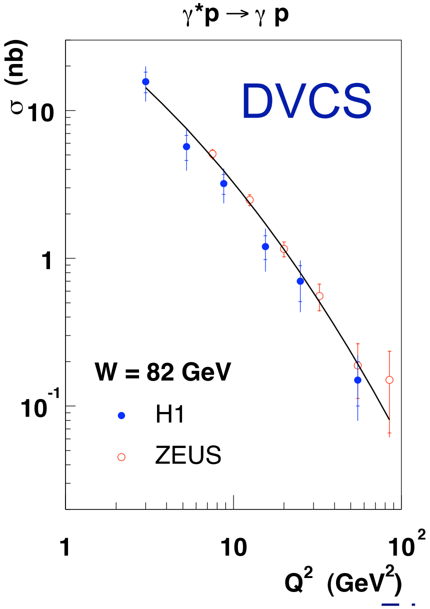
$$\frac{d\sigma^{\gamma^* p \to pV}}{dt} \sim \left| \int \Psi_V^* \frac{d\sigma_{q\bar{q}}}{d^2 b} \Psi e^{-ib\Delta} \right|^2$$

$$\frac{d\sigma_{q\bar{q}}}{d^2\vec{b}} \sim r^2 \alpha_s x g(x, \mu^2) T(b)$$

The same, universal, gluon density describes the properties of many reactions measured at HERA (Kowalski et al, PRD74:074016):

F_2, inclusive diffraction, exclusive J/ψ, φ and ρ production, DVCS, diffractive jets





Probing Gluonic Structure of Nuclear Forces

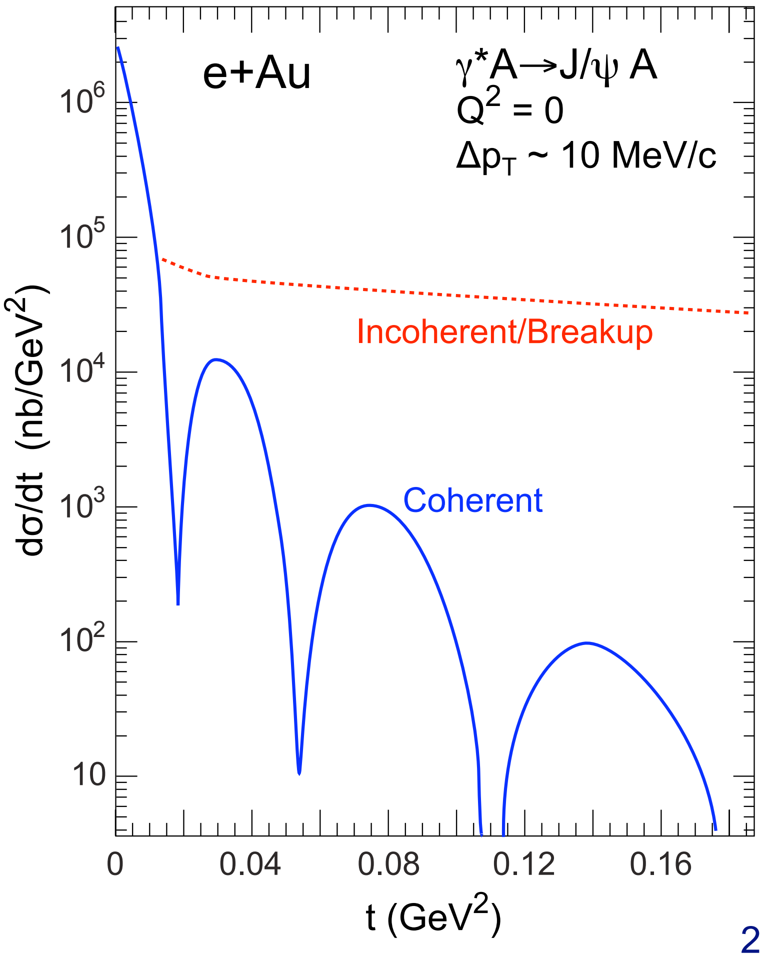
Simplified assumption for proof of principle:

- Random and uncorrelated distribution of nucleons within the nucleus
- Shape of the nucleus given by the Woods-Saxon distribution
- Average (sum) over all configurations
- Fourier transform the average ⇒ $d\sigma_A/dt$

Assumption clearly too simple:
Strong correlations between nucleons
but a promising method to measure
gluon form factor F_g in nuclei

This would provide valuable (decisive) input into the ε issue and hence the η/s question

H. Kowalski, private comm.



See Henri’s talk later

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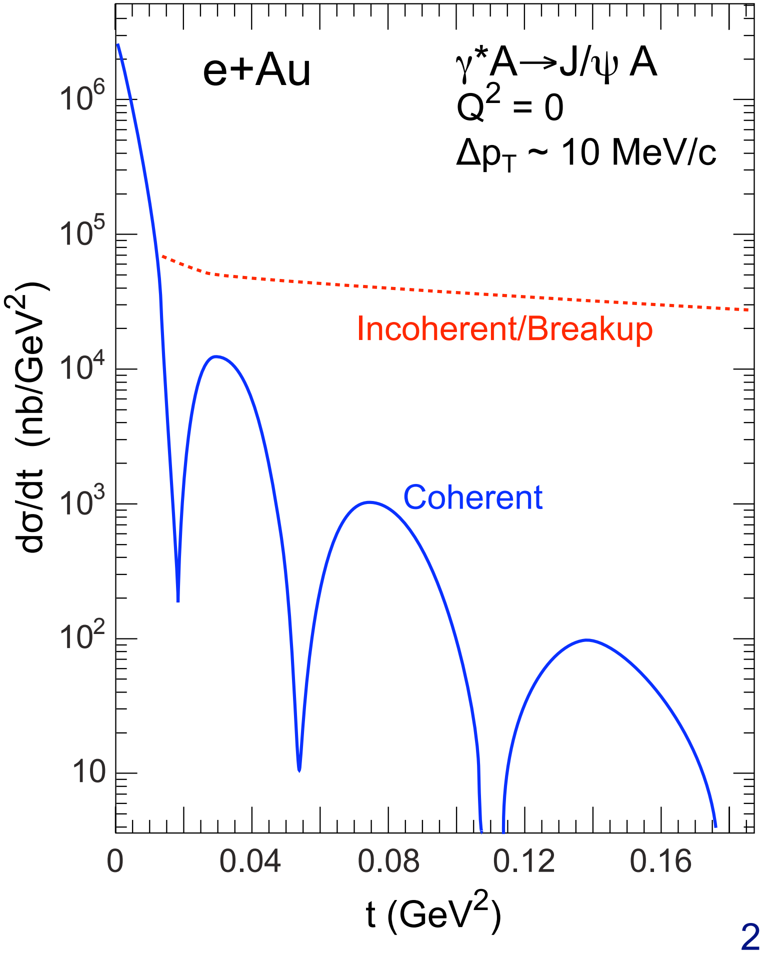
Experimental Aspects:

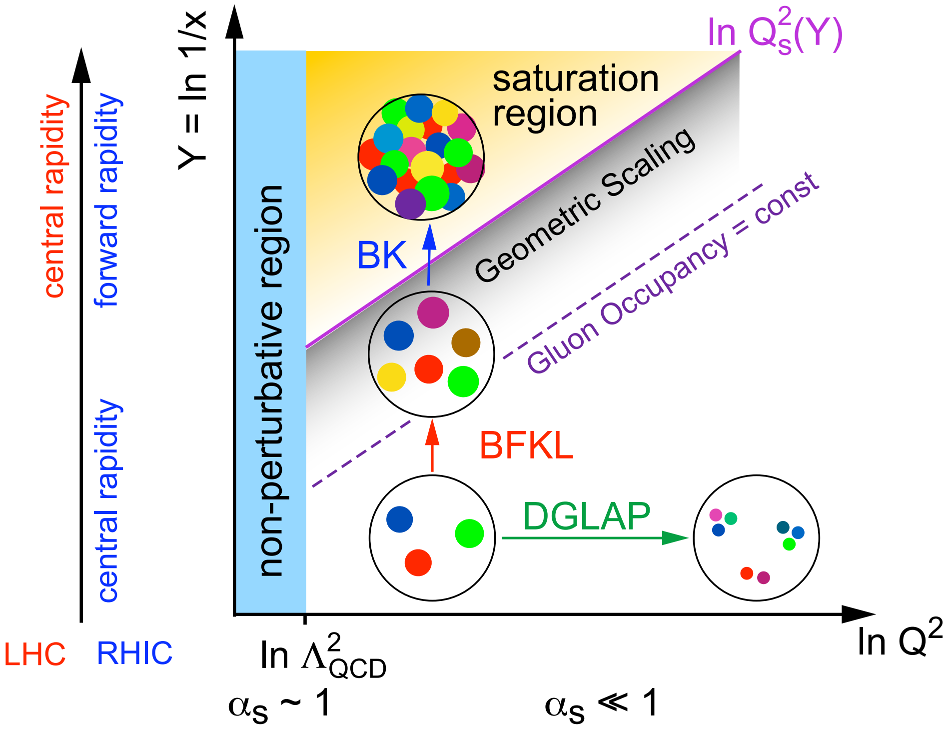
- Photo-production cross section large
- J/ψ easy detection well separated from background
- J/ψ dipole interacts only by 2g exchange at low x
  - process is well understood in QCD
- crucial: detecting breakup of nuclei

H. Kowalski, private comm.

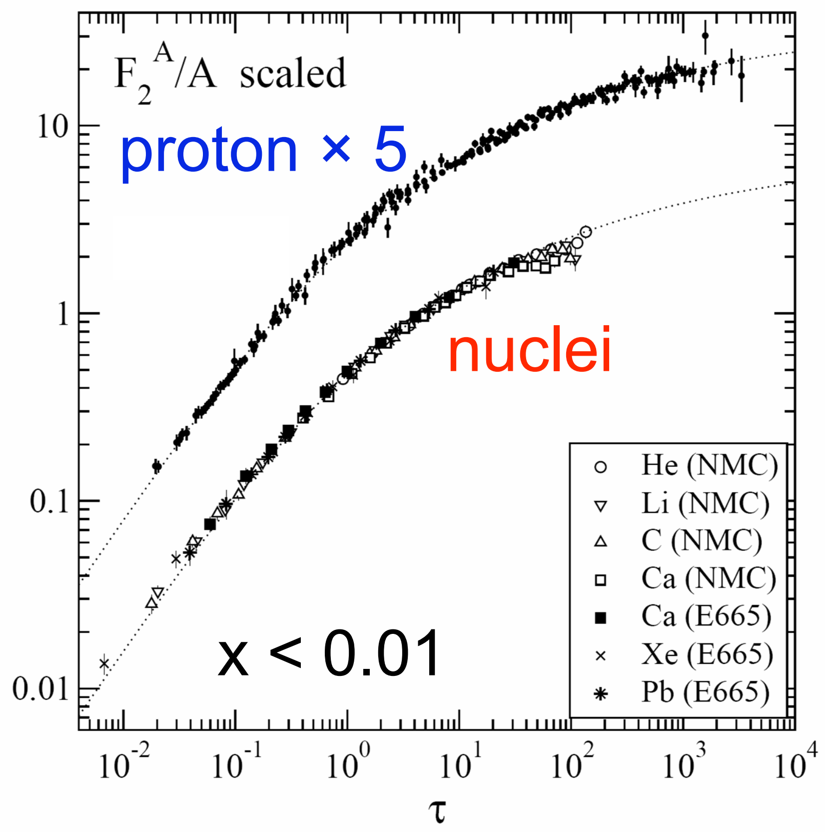


See Henri's talk later

Hints for Saturation in Nuclei



Geometrical scaling



Crucial consequence of non-linear evolution towards saturation:

- Physics invariant along trajectories parallel to saturation regime (lines of constant gluon occupancy)
- Scale with $\tau = Q^2/Q^2_s(x)$ instead of x and Q^2 separately
- Works for ep & eA !

Multiplicities in AA and Saturation

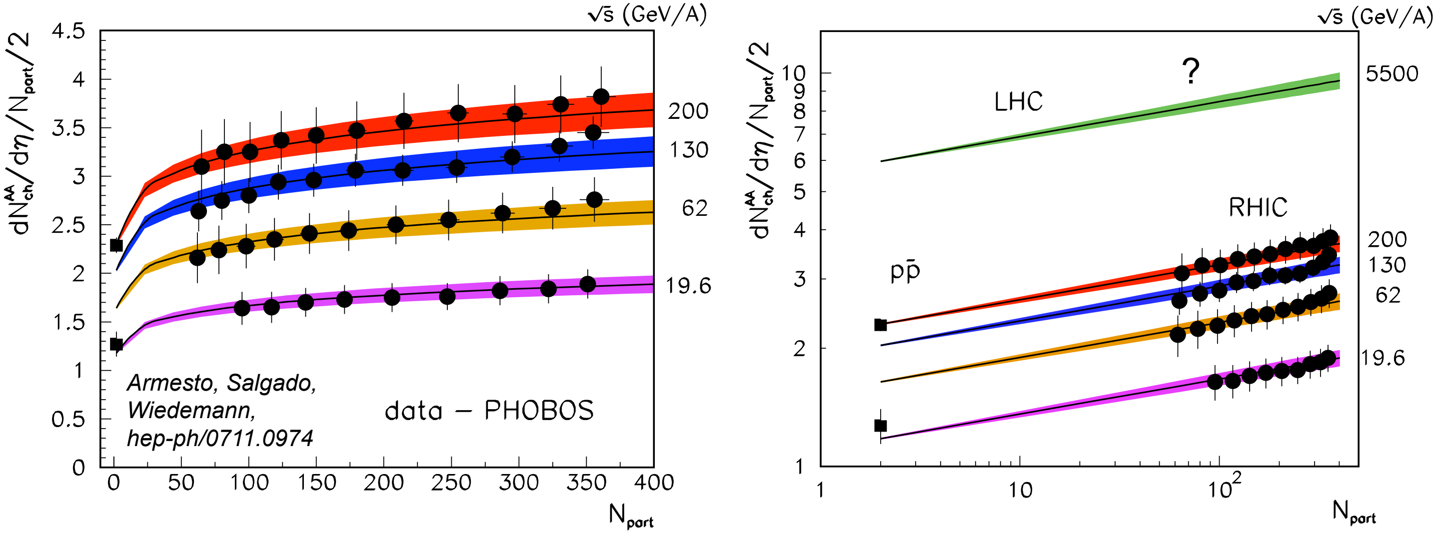
CGC predicts very simple dependence of multiplicity (using parton-hadron duality) on atomic number A / N_{part}

$$Q^2_{s,A} \propto x^{-\lambda} A^{1/(3\delta)} \text{ where } \lambda \sim 1/3,\ \delta \sim 0.8$$

Nuclear Oomph

$$\frac{2}{N_{part}} \frac{dN^{AA}}{d\eta}\Bigg|_{\eta=0} = N_0 \cdot (s/\mathrm{GeV}^2)^{\lambda/2} \cdot N_{part}^{(1-\delta)/\delta}$$

Kharzeev, Levin, Nardi
2002, 2004



Armesto, Salgado, Wiedemann, hep-ph/0711.0974

data – PHOBOS

- Connects slope of G (λ) directly to N_{ch} in A+A
- Works amazingly (too well at $\sqrt{s}$= 19.6 GeV (x large))
- N_{ch} at LHC might tell us if assumed Q_s scaling is correct

Saturation at Forward Rapidities

Compare Au+Au with p+p Collisions ⇒ R_{AA}

Nuclear Modification Factor:

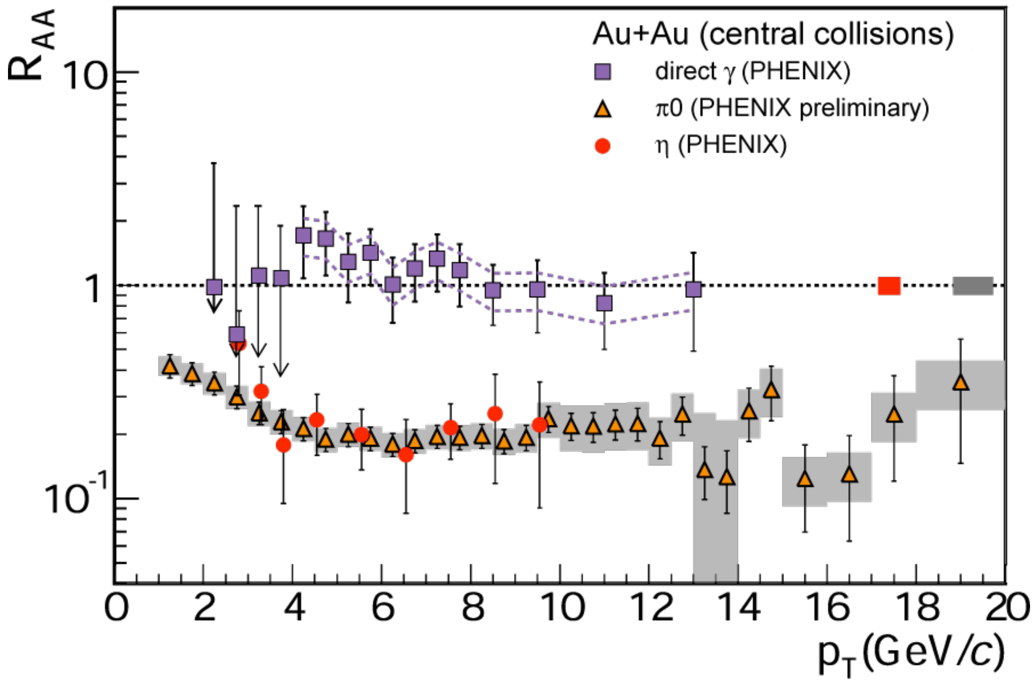
$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p)\times\langle N_{coll}\rangle}$$

RHIC: AuAu y=0

- Factor 5 suppression
- Source: induced gluon radiotion of partons traversing the medium

RHIC: dAu y=0

- RdAu ~ 1
- Small Cronin enhancement



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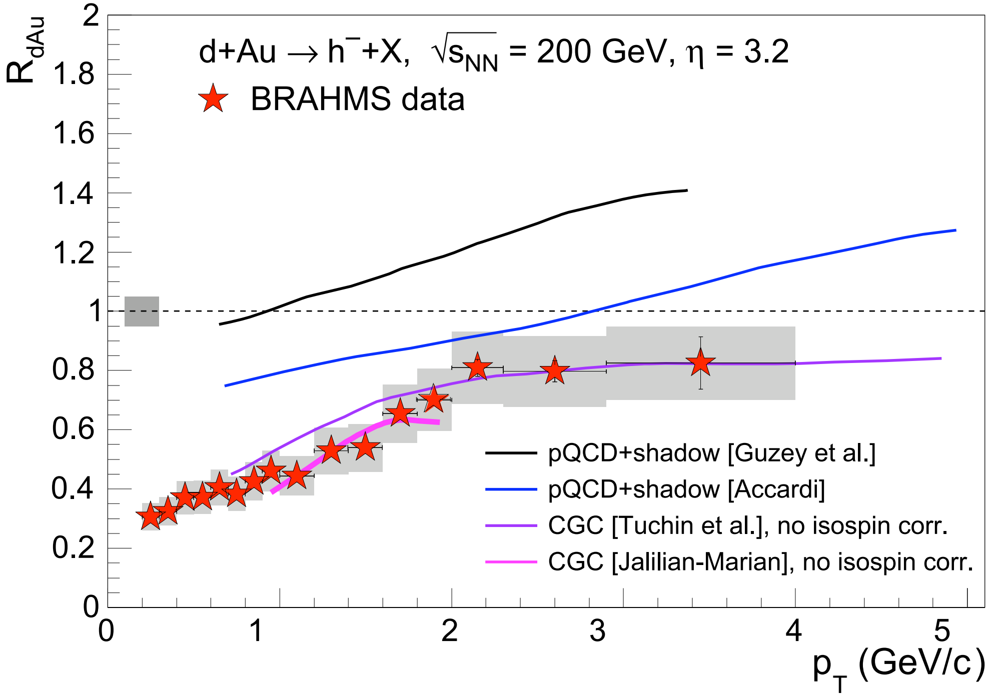
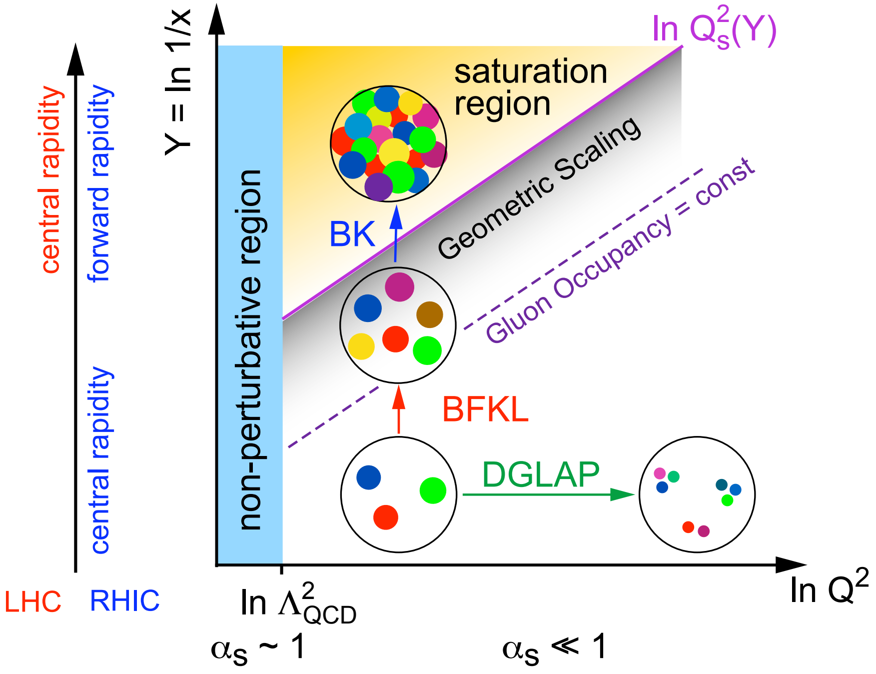
RHIC: dAu y>3

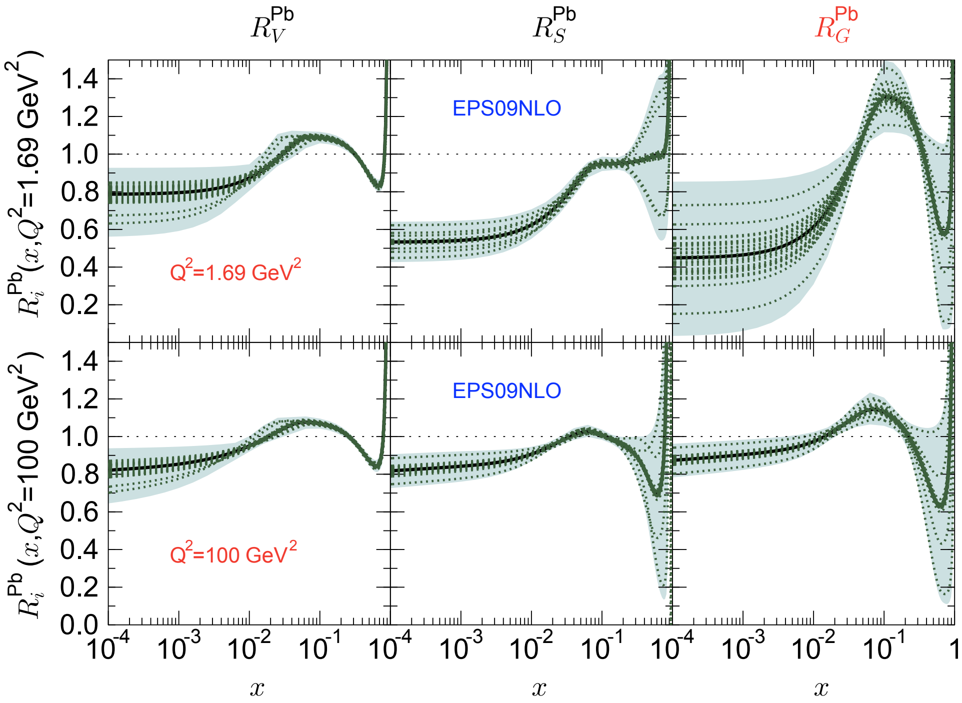
- RdAu < 1

Seen by many as indication for saturation effects at RHIC



A+A at LHC?





y=0: Q_s^2 ~ 1-2 GeV^2 (RHIC) 3 - 5 GeV^2 (LHC)

y = 3: Q_s^2 ~ 3 GeV^2 (RHIC) ~10 GeV^2 (LHC)

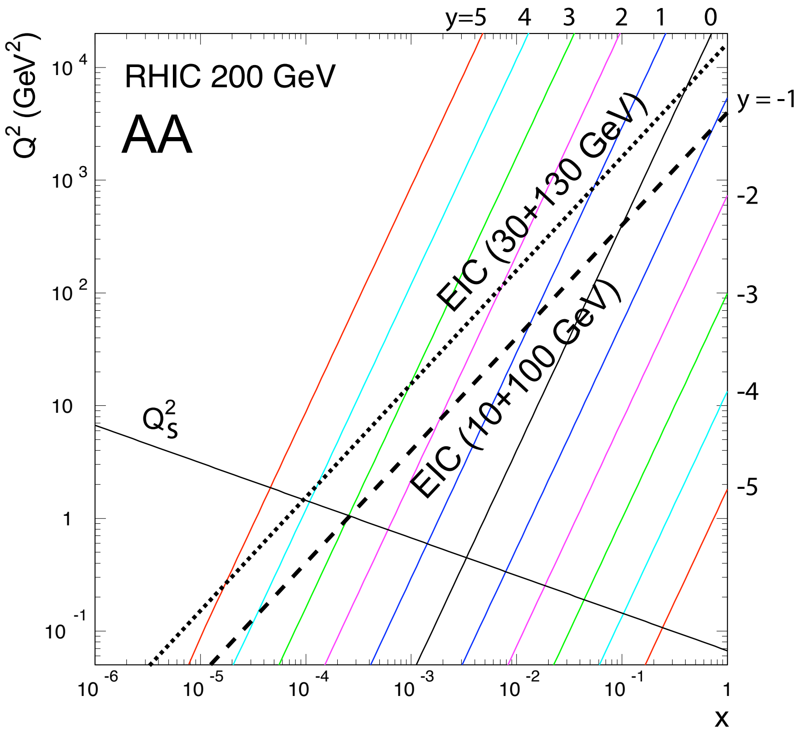
LHC:

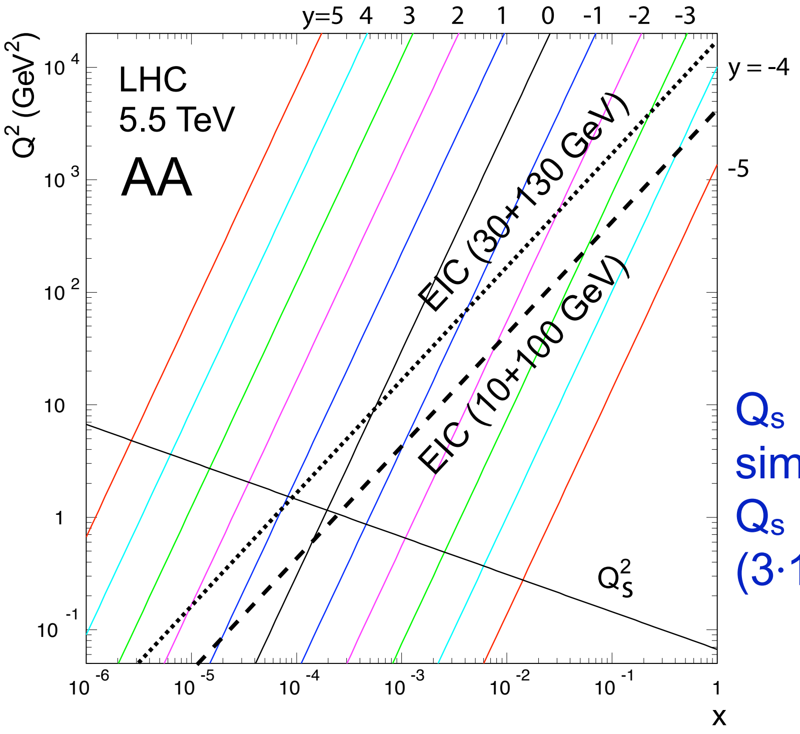
Saturation/nuclear effects become important for bulk at y=0

EMC even at high Q^2 ?

Understanding of AA at LHC limited by knowledge of $G(x,Q_2)$ and nPDF ⇒ eRHIC can provide that in the relevant x-range

x, Q^2 Plane: RHIC/LHC/EIC





Q_s here simply:
$Q_s = (3 \cdot 10^{-4}/x)^{1/3}$

2→2 process
$$x_1 = \frac{Q}{\sqrt{s}} e^{y}$$
$$x_2 = \frac{Q}{\sqrt{s}} e^{-y}$$

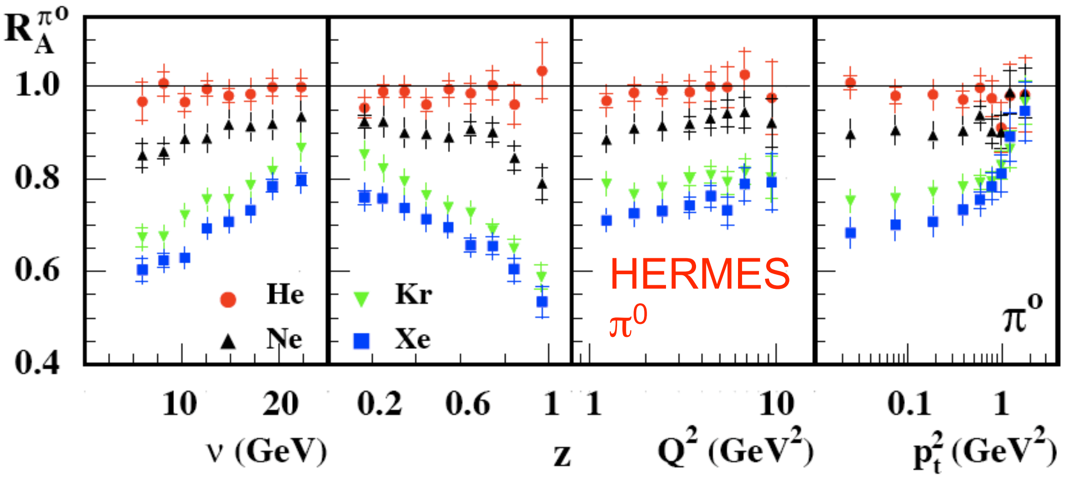
RHIC: need overlap with forward physics (y=4)
LHC: need overlap with central region (y=0)

Parton Interactions in Cold Nuclear Matter

nDIS:

- Suppression of high-p_T hadrons analogous but weaker than at RHIC
- Clean measurement in ‘cold’ nuclear matter
- Important control for Jet Quenching at RHIC & LHC

Hadron attenuation|Eloss in cold matter



Fundamental question:
When do colored partons get neutralized?
Parton energy loss vs. (pre)hadron absorption

JLAB (CLAS) sees massive final state broadening

Energy transfer in lab rest frame
EIC: 10 < ν < 1600 GeV (= LHC range)   HERMES: 2-25 GeV
EIC: *heavy flavor* CM effects!

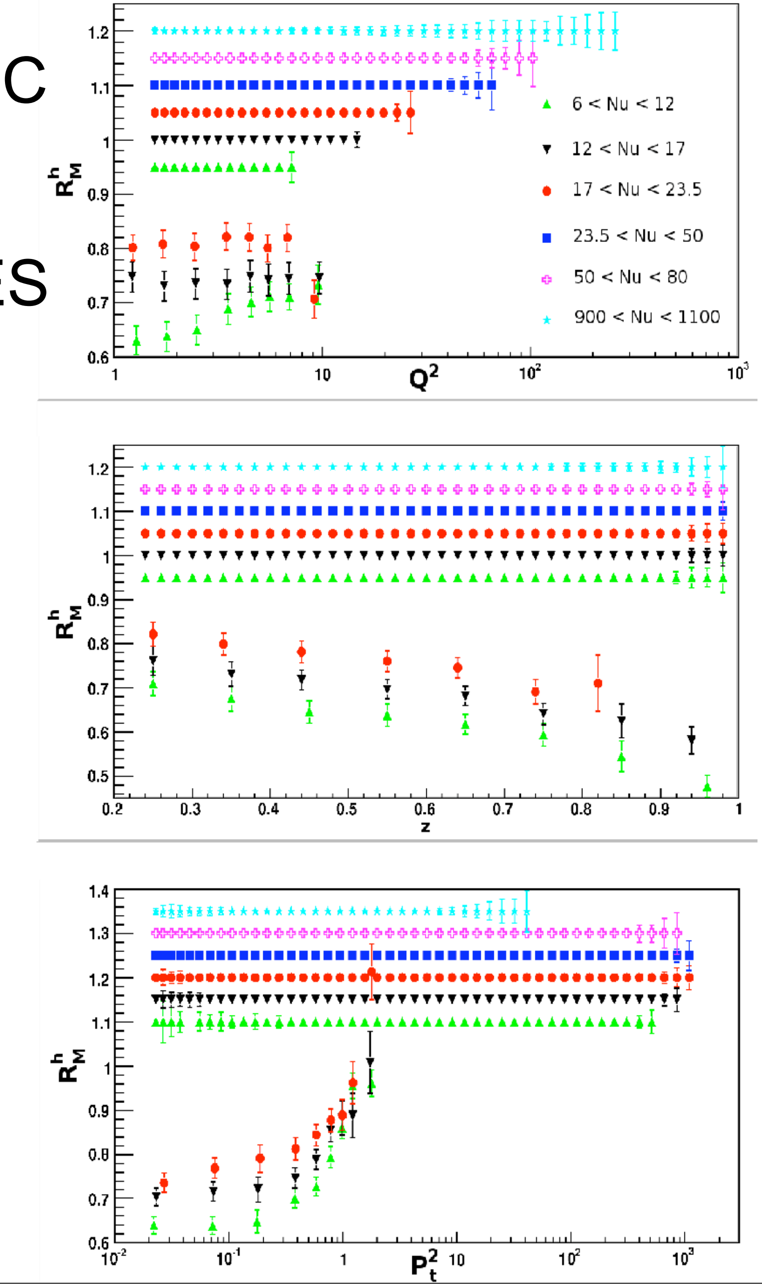
Parton Propagation and Fragmentation

A. Accardi for EIC (10-100 GeV)

$$R_M^h(z) = \frac{\frac{1}{N_A^{DIS}}\frac{dN_A^h(z)}{dz}}{\frac{1}{N_D^{DIS}}\frac{dN_D^h(z)}{dz}}$$

EIC

HERMES



- Simulation with PYTHIA 6.4.19
  - isoscalar nucleus target
  - no nuclear effect yet
  - 10 weeks of beam at eRHIC
    - High statistics:
      - from 2 to 5-dim distributions
- Large reach in Q^2 and p_T
- small ν - hadronization inside A
- large ν - precision tests of QCD
  - parton energy loss
  - DGLAP evolution and showers

Summary: eRHIC & RHIC

The primary goals of RHIC’s A+A and eRHIC’s e+A programs are the study of QCD (“QCD Lab”)

- In a regime in which physics is not described by “ordinary” pQCD
  - RHIC: Phases of QCD
  - eRHIC: Saturation, non-linear QCD, Strong Color Fields

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EIC/eRHIC will provide unique insight crucial to improving our understanding of RHIC and LHC heavy ion measurements

- Initial Conditions (saturation/CGC?)
    - impact on understanding of QGP properties (e.g. η/s)
- Thermalization (Glasma)
- Energy Loss (baseline/control) & Fragmentation
- Saturation & Multiplicity
- Understanding nuclear effects ((anti)-shadowing, EMC)

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Necessary cross-fertilization requires start of EIC program *before* termination of RHIC, LHC heavy ion programs

- much can be done already at staged eRHIC option (MeRHIC)