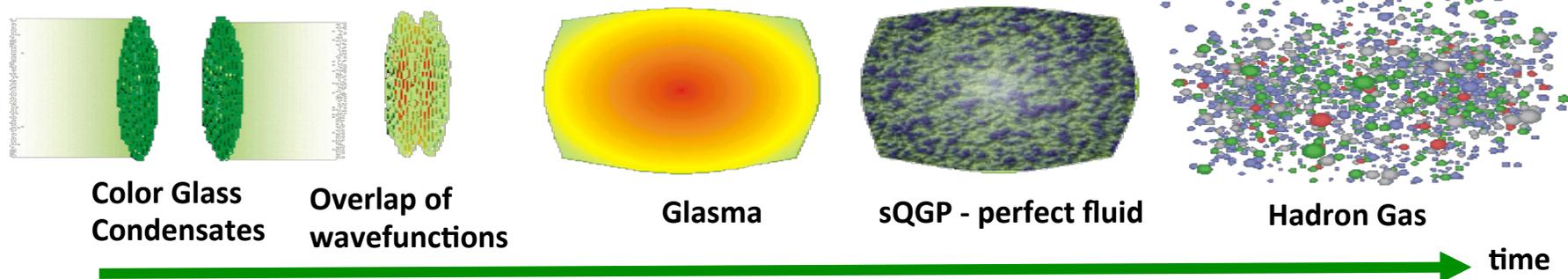
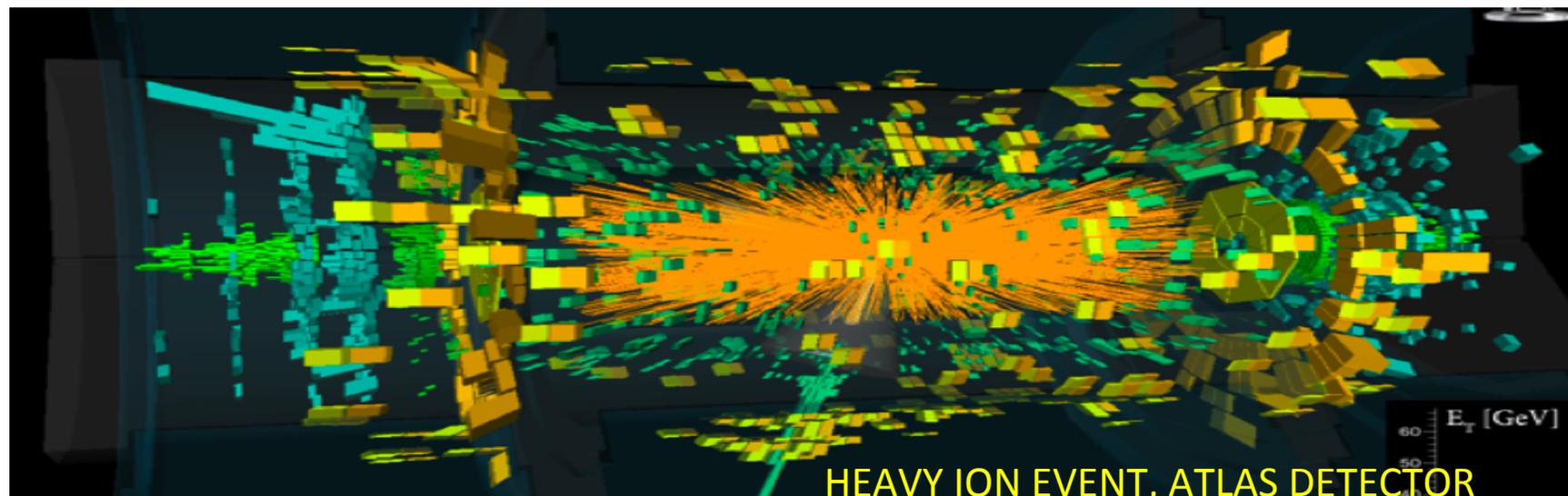


The initial state, its non-equilibrium evolution and Hard Probes

Raju Venugopalan
Brookhaven National Laboratory



Hard Probes Conference , Wuhan, September 23-27, 2016

Ab initio approaches to early time dynamics

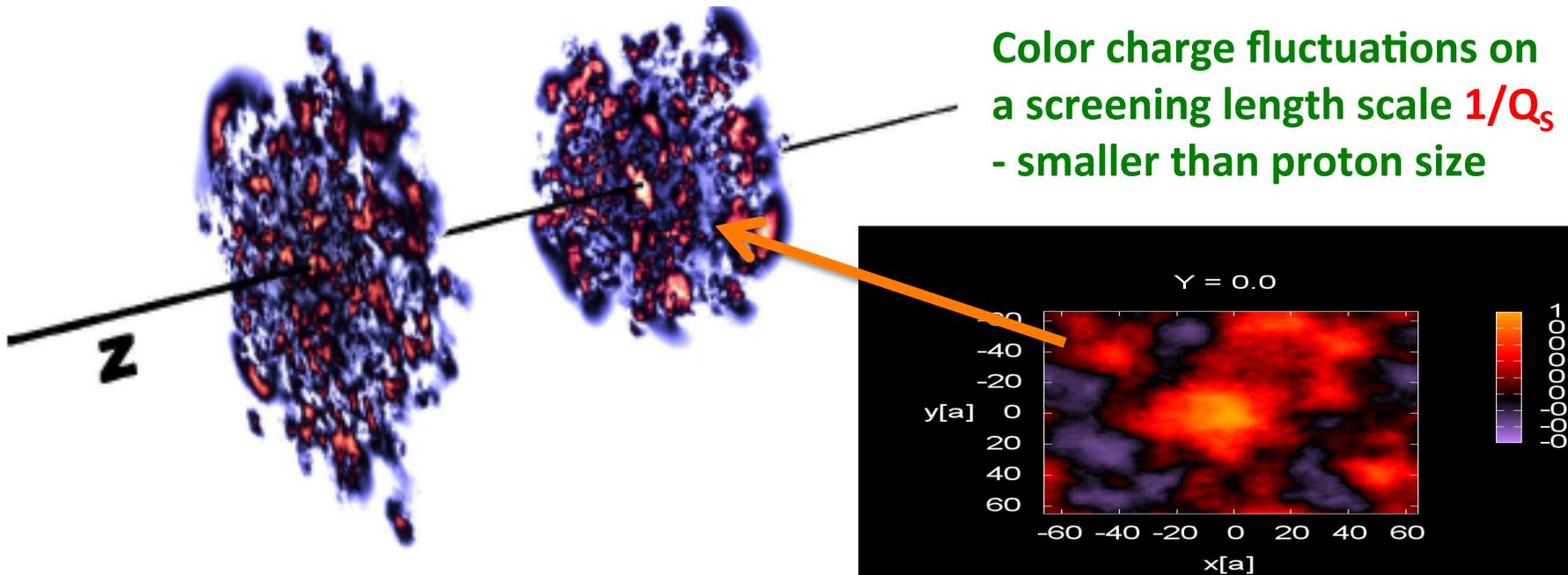
Two “clean” theoretical limits:

◆ Holographic thermalization (based on duality of strongly coupled $(g^2 N_c \rightarrow \infty; N_c \rightarrow \infty)$ N=4 SUSY YM to classical gravity in $AdS_5 \times S_5$)

◆ Highly occupied QCD at weak coupling
($g^2 \rightarrow 0; g^2 f \sim 1$)

Our focus: strongly correlated gluodynamics of the Initial state and early time dynamics in weak coupling

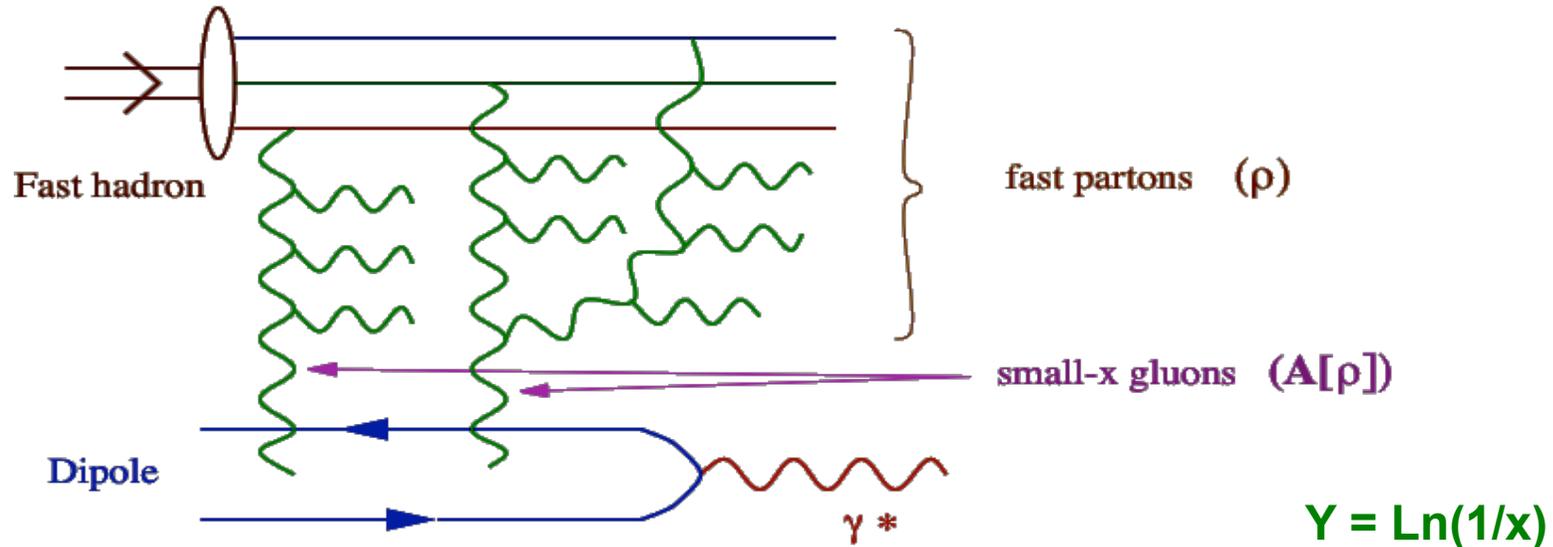
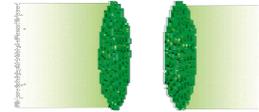
The initial state: a strongly correlated lumpy, gluon shock wave at high energies



Color charge fluctuations on a screening length scale $1/Q_s$ - smaller than proton size

Dumitru, Jalilian-Marian, Lappi, Schenke, Venugopalan
PLB706 (2011)219

Quantum evolution of CGC wavefunction



$$\frac{\partial}{\partial Y} \langle O[\alpha] \rangle_Y = \langle \frac{1}{2} \int_{x,y} \frac{\delta}{\delta \alpha_Y^a(x)} \chi_{x,y}^{ab} \frac{\delta}{\delta \alpha_Y^b(y)} O[\alpha] \rangle_Y$$

“time”

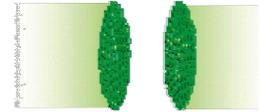
“diffusion coefficient”

Balitsky-JIMWLK “Fokker-Planck” hierarchy describes QCD evolution of n-point parton correlation functions

Balitsky (1996)

JIMWLK: Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner (1997-2001)

Quantum evolution of CGC: state of the art



- ◆ State of the theory art: resummations of gluon ladders to next-to-leading logarithmic accuracy: “NLO JIMWLK”

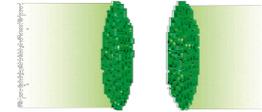
Balitsky, Chirilli, arXiv:1309.7644
Kovner, Lublinsky, Mulian, 1310.0378

See plenary talk by Guillaume Beuf for detailed discussion of theory status

- ◆ Practical applications in DIS and hadron-hadron collisions use
 - i) The running coupling Balitsky-Kovchegov (BK) eqn.
-- describes 2-point correlators in the JIMWLK hierarchy)
 - ii) The IP-Sat dipole model – evolution of Q_s from fits to HERA data

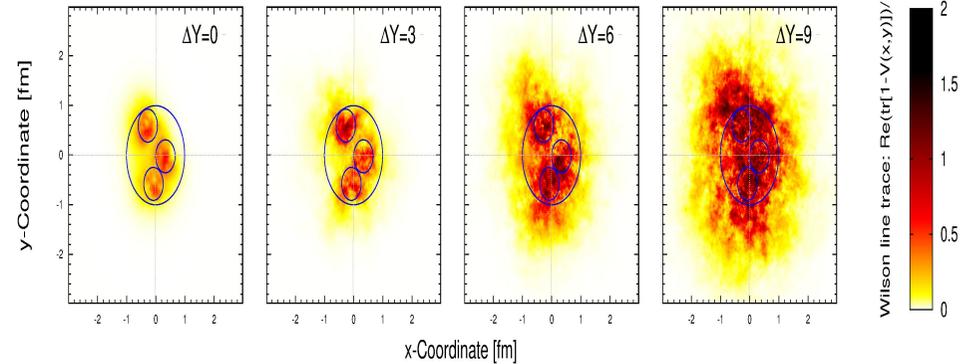
See parallel session talk by Tuomas Lappi
on numerical solutions of the NLO BK equation

Quantum evolution of CGC: state of the art



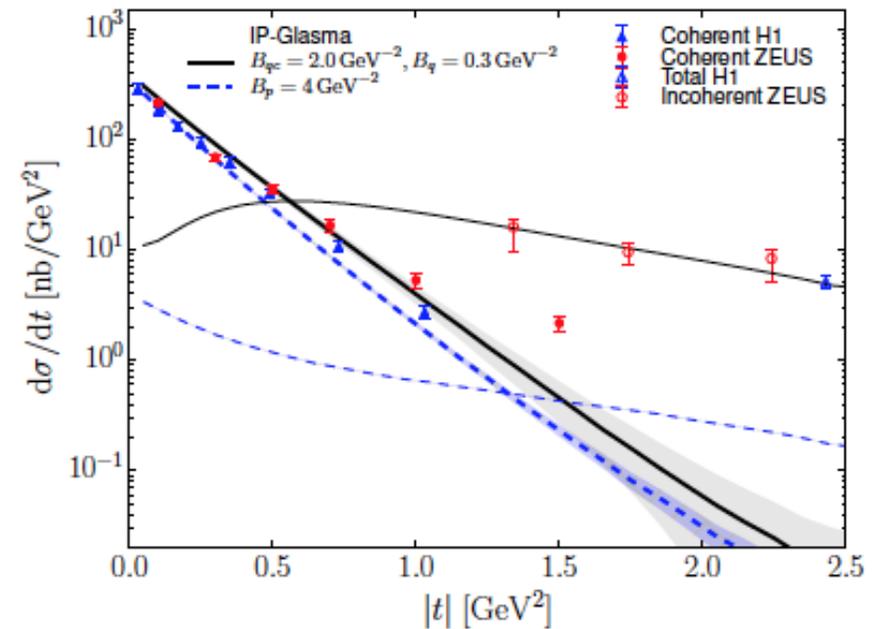
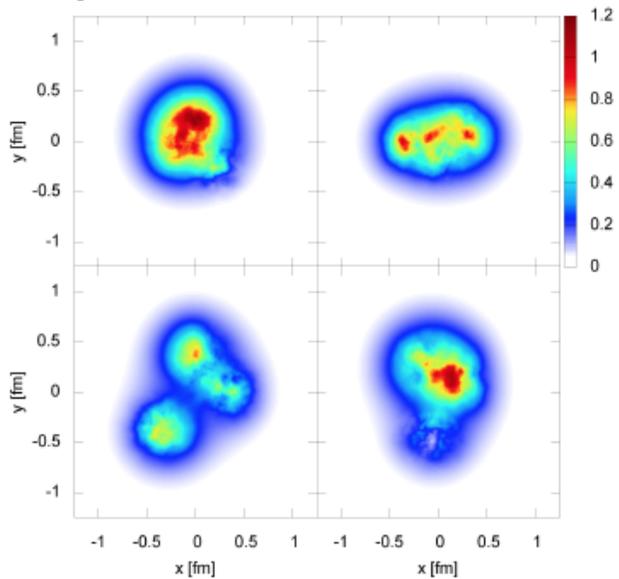
Schenke, Schlichting, arXiv:1407.8458

A recent development:
color fluctuations of
proton shape / Q_s in
IP-Glasma model/JIMWLK



Explains DIS HERA data on incoherent diffractive J/ψ production

Mantysaari, Schenke, arXiv:1603.04349



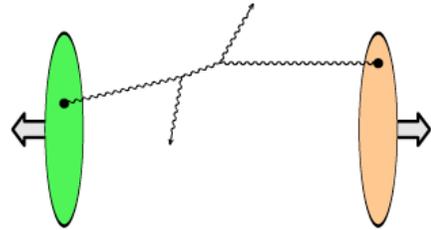
IP-Glasma: IP-sat color dist.+YM fields

Schenke, Tribedy, RV, arXiv:1202.6646

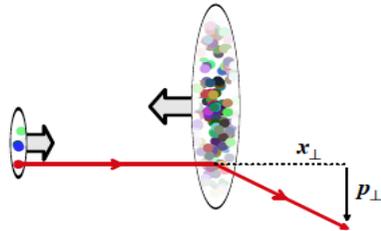
Colliding gluon shock waves

CGC power counting:

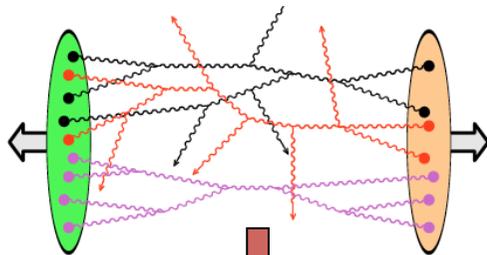
Review: Gelis,Lappi,RV arXiv:0708.0047



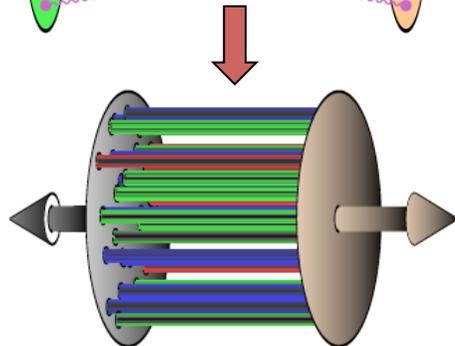
Dilute-Dilute: $Q_{S,A}^2/k_{T,A}^2 \ll 1$ and $Q_{S,B}^2/k_{T,B}^2 \ll 1$
 --match to pQCD computation of hard processes at small x



Dilute-Dense: $Q_{S,A}^2/k_{T,A}^2 \ll 1$ and $Q_{S,B}^2/k_{T,B}^2 \sim 1$
 -- “hybrid” pQCD/CGC description

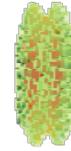


Dense-Dense: $Q_{S,A}^2/k_{T,A}^2 \sim 1$ and $Q_{S,B}^2/k_{T,B}^2 \sim 1$
 -- solve classical Yang-Mills eqns. (CYM) in 2+1-D/3+1-D with quantum (“stochastic”) initial conditions

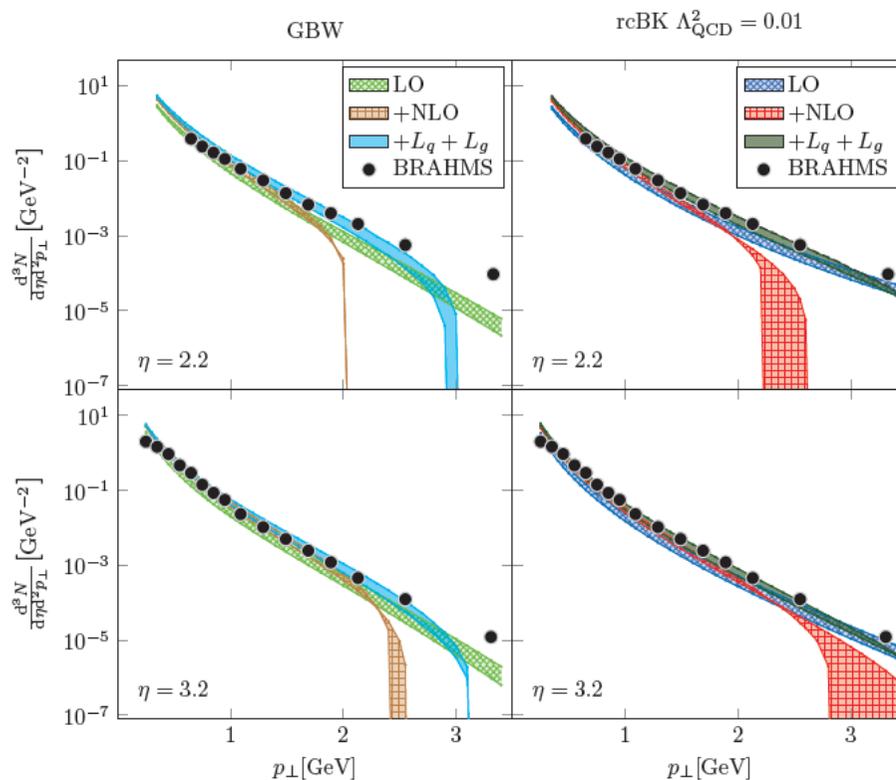


CGC paradigm: all these regimes are found in p+p/p+A/A+A depending on \sqrt{s} , centrality, rapidity, k_T

Single inclusive hadron production



Single inclusive hadron computations in the “hybrid” dilute-dense framework are now available to NLO accuracy



Kinematical constraints become increasingly important when matching to the high p_T collinear regime -- differing factorization schemes in rapidity

Chirilli,Xiao,Yuan,arXiv:1112.1061

Altinoluk,Armesto,Beuf,Kovner,Lublinsky,arXiv:1411.2869

Iancu,Mueller,Triantafyllopoulos,arXiv:1608.05293

Watanabe,Xiao,Yuan,Zaslavsky,arXiv:1505.05183

Review: Stasto,Zaslavsky, 1608.02285

Parallel talk by Yan Zhu

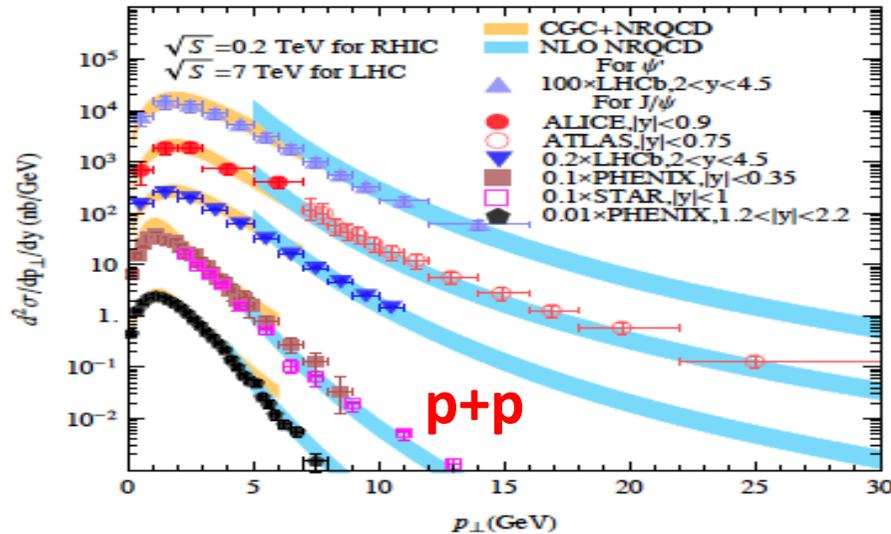
Onia in p+p and p+A collisions



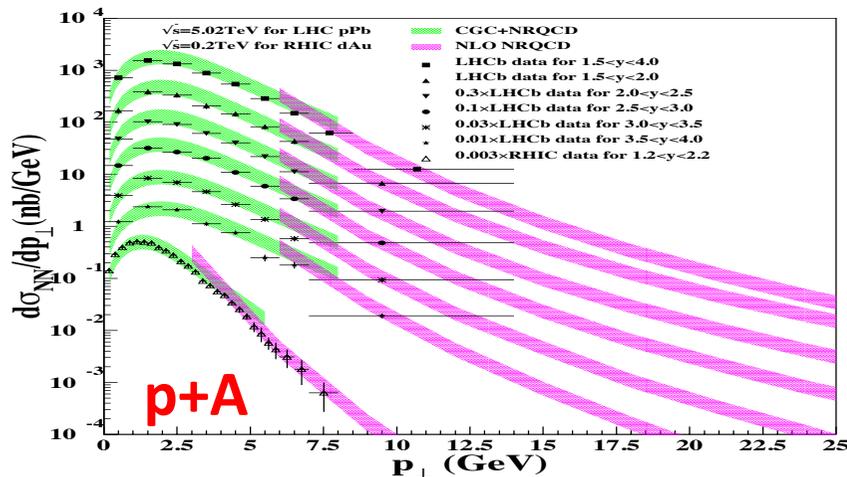
CGC/pQCD +NRQCD formalism

Kang, Ma, RV, JHEP1401 (2014) 056
Also, Qiu, Sun, Xiao, Yuan, PRD89 (2014)

Ma, RV, PRL113 (2014) 192301



Ma, RV, Zhang, 1503.07772

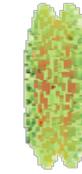


Similar framework for direct photon production in p+A – less sensitive to hadronization

Benic, Fukushima, Garcia-Montero, RV, in preparation

See parallel talk by Benic

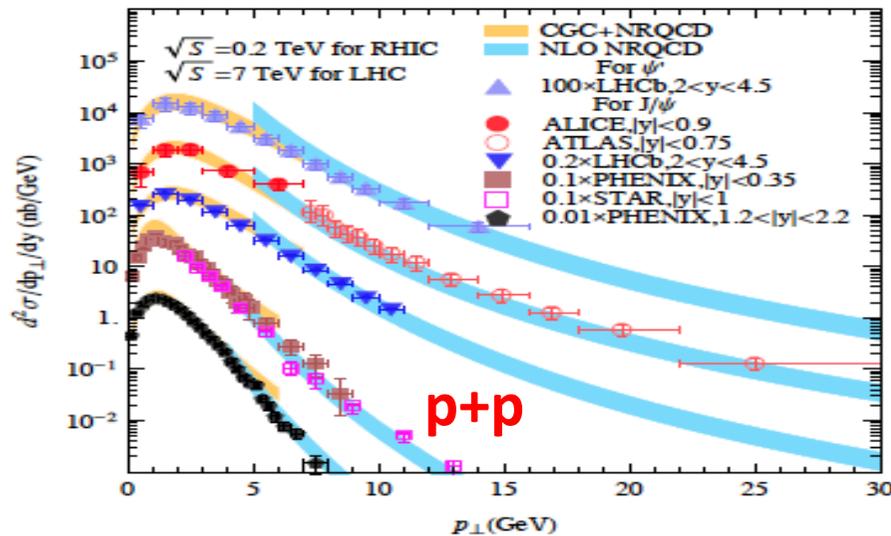
Onia in p+p and p+A collisions



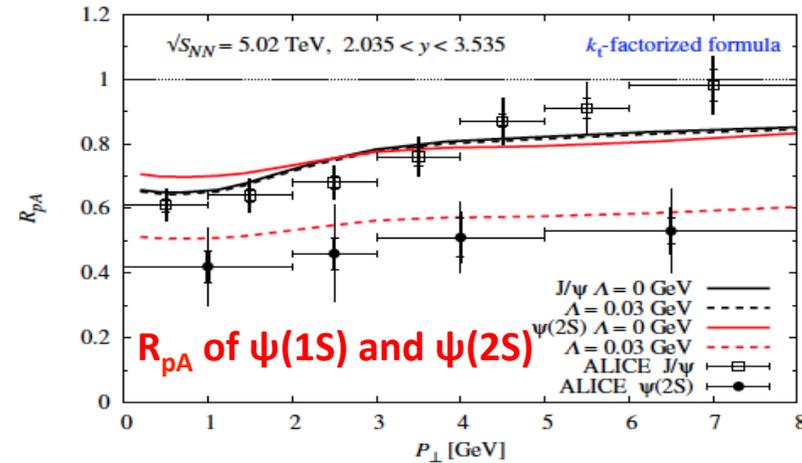
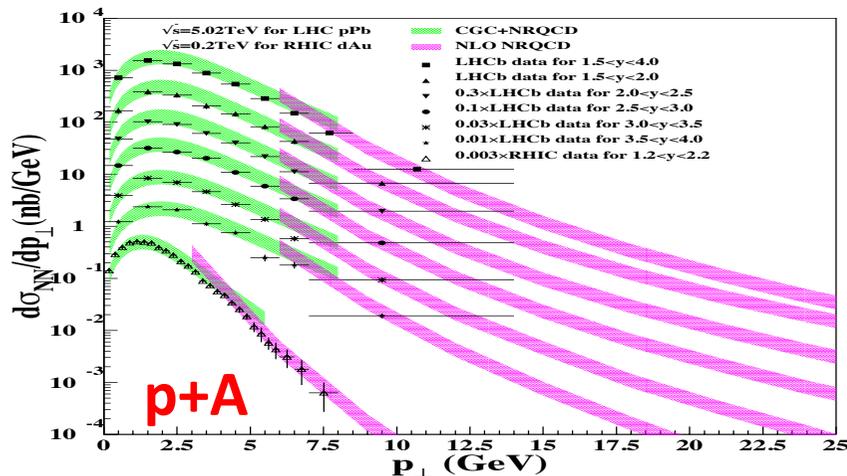
CGC/pQCD +NRQCD formalism

Kang, Ma, RV, JHEP1401 (2014) 056
Also, Qiu, Sun, Xiao, Yuan, PRD89 (2014)

Ma, RV, PRL113 (2014) 192301



Ma, RV, Zhang, 1503.07772



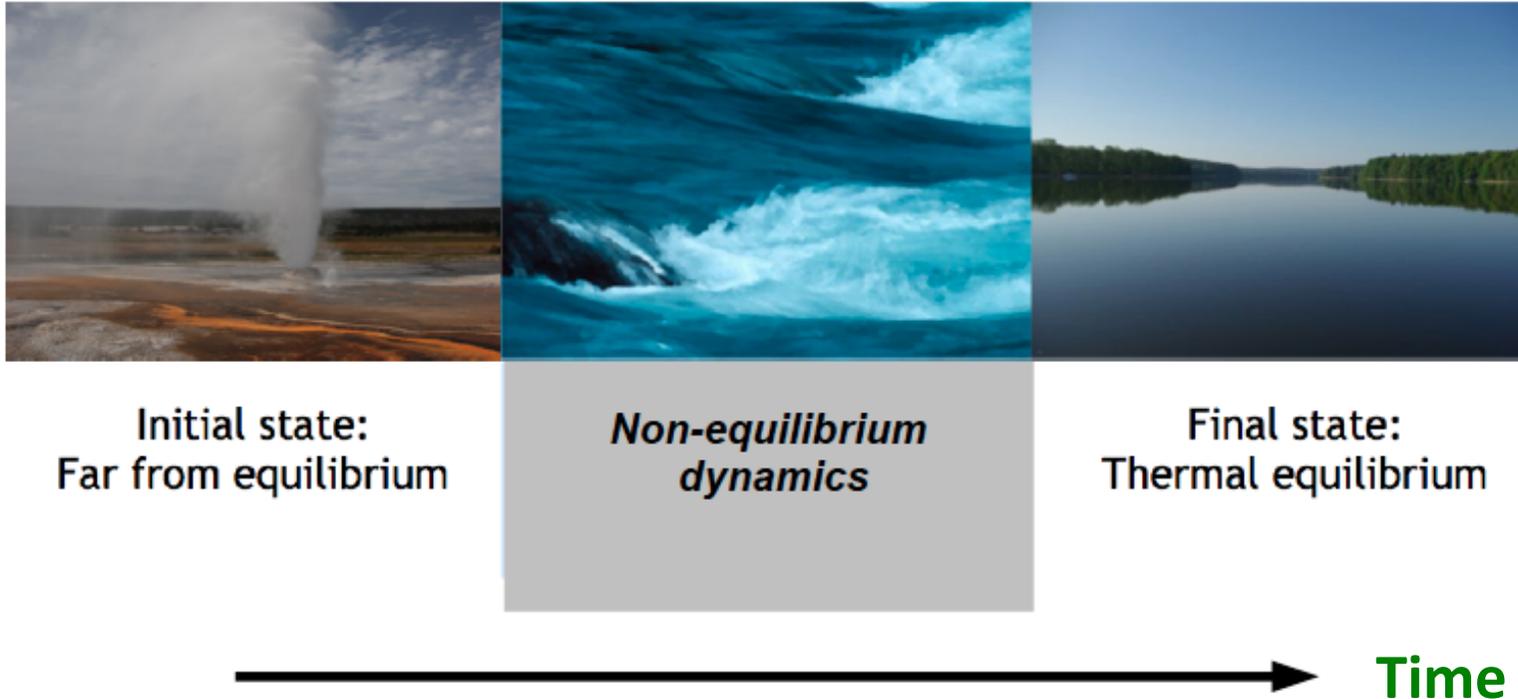
Slight modification of CEM hadronization model explains $\Psi(2S)/\psi(1S)$ suppression

$$\frac{d\sigma_H}{d^2 P_\perp dy} = F_H \int_{(2m_c)^2}^{(2m_D - \Lambda)^2} dM^2 \frac{d\sigma_{c\bar{c}}}{dM^2 d^2 P_\perp dY}$$

$\Lambda \sim 30 \text{ MeV}$ Ma, RV, Watanabe, Zhang, in preparation

Parallel talk: Ducloue on CGC+CEM model

Glasma: the non-equilibrium QGP

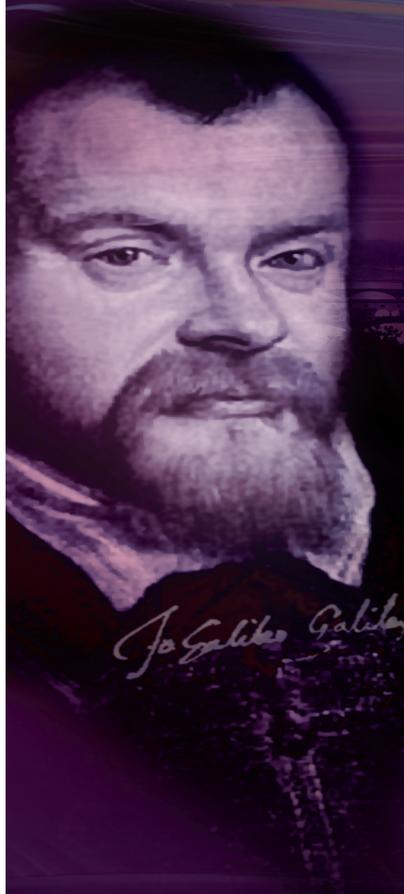


- ◆ How does one explain the “unreasonable effectiveness” of hydrodynamics in describing the dynamics of such small systems?
- ◆ What are the smallest systems to which hydrodynamics is applicable?

Can explore systematically in the CGC “dense-dense” framework



The Galileo Galilei Institute for Theoretical Physics
Arcetri, Florence



Advances in Nonequilibrium Statistical Mechanics: large deviations and long-range correlations, extreme value statistics, anomalous transport and long-range interactions

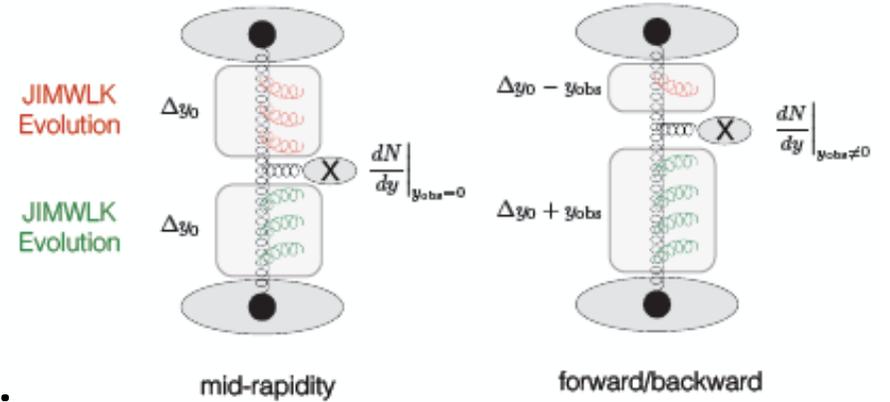
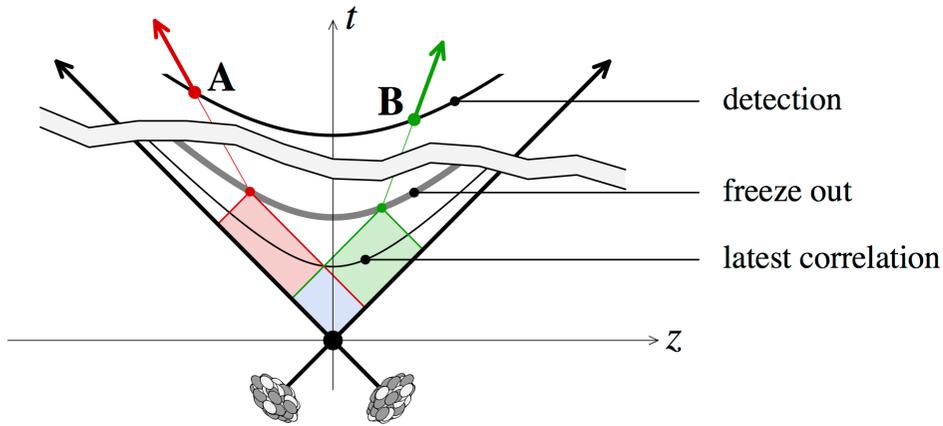
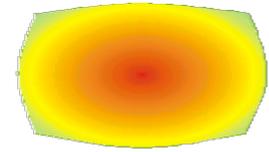
May 5, 2014 - July 4, 2014

The main topics of the workshop include:

- Large deviations
- Fluctuation and work relations
- Statistics of extreme events
- Anomalous transport
- Long-range correlations and interactions

The aim of the workshop is to bring together leading researchers, young scientists and PhD students working in different areas of nonequilibrium statistical mechanics. This workshop aims at strengthening the interaction among different communities in this field and at exploring open problems and new directions of research. Let us mention: the characterization of many-body probability distributions relying on what has been done for simple exclusion or zero range processes; the study of long-range correlations that determine a variety of collective phenomena; the derivation of universal current distributions in driven diffusive systems and novel universal distributions for extreme values of correlated random variables; the relevance of ensemble inequivalence observed in systems with long-range interactions for driven nonequilibrium systems; the study of anomalous transport processes in kinetic and dynamical models in one and two spatial dimensions.

Long range rapidity correlations

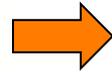
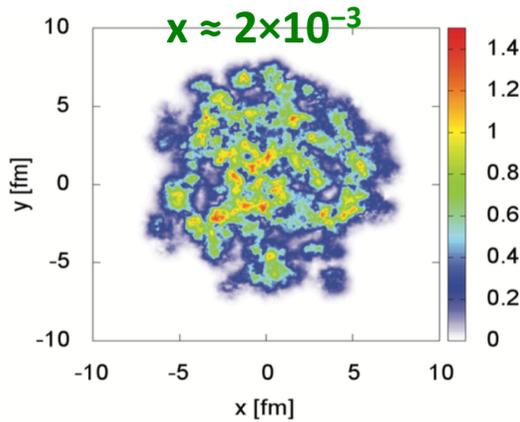


LR correlations sensitive to early time dynamics

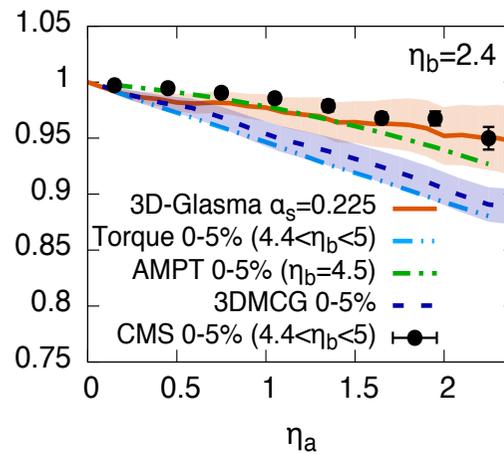
Dumitru, Gelis, McLerran, RV, arXiv:0804.3858
 Dusling, Gelis, Lappi, RV, arXiv:0911.2720

JIMWLK + 2+1-D Classical Yang-Mills evolution

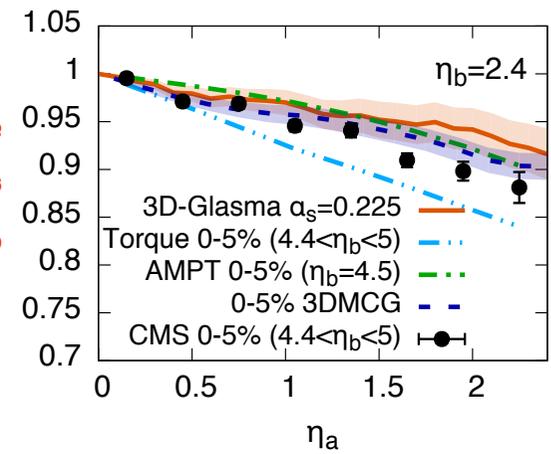
Schenke, Schlichting, arXiv:1605.07158



$r_2(\eta_a, \eta_b)$

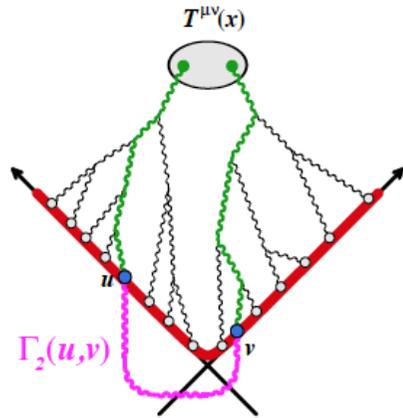
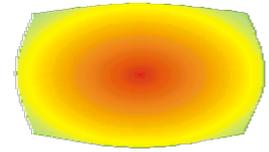


$r_3(\eta_a, \eta_b)$



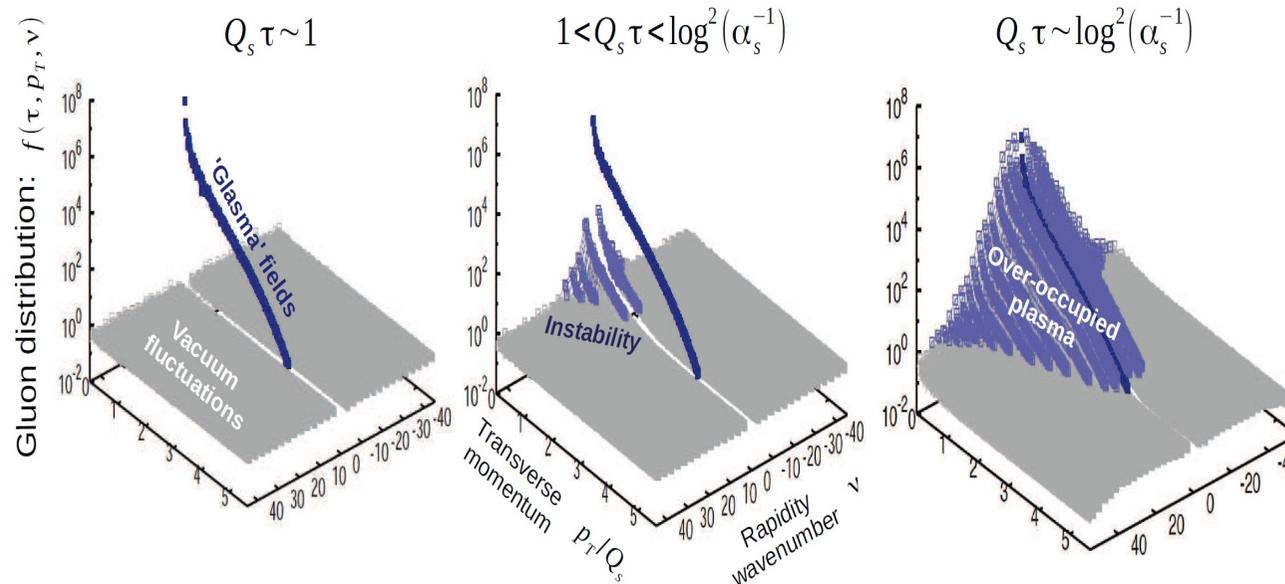
Decorrelation of initial spatial eccentricities in relative rapidity

Quantum fluctuations + 3+1-D Yang-Mills



Classical-statistical framework: 3+1-D CYM
evolution of stochastic (quantum) initial conditions

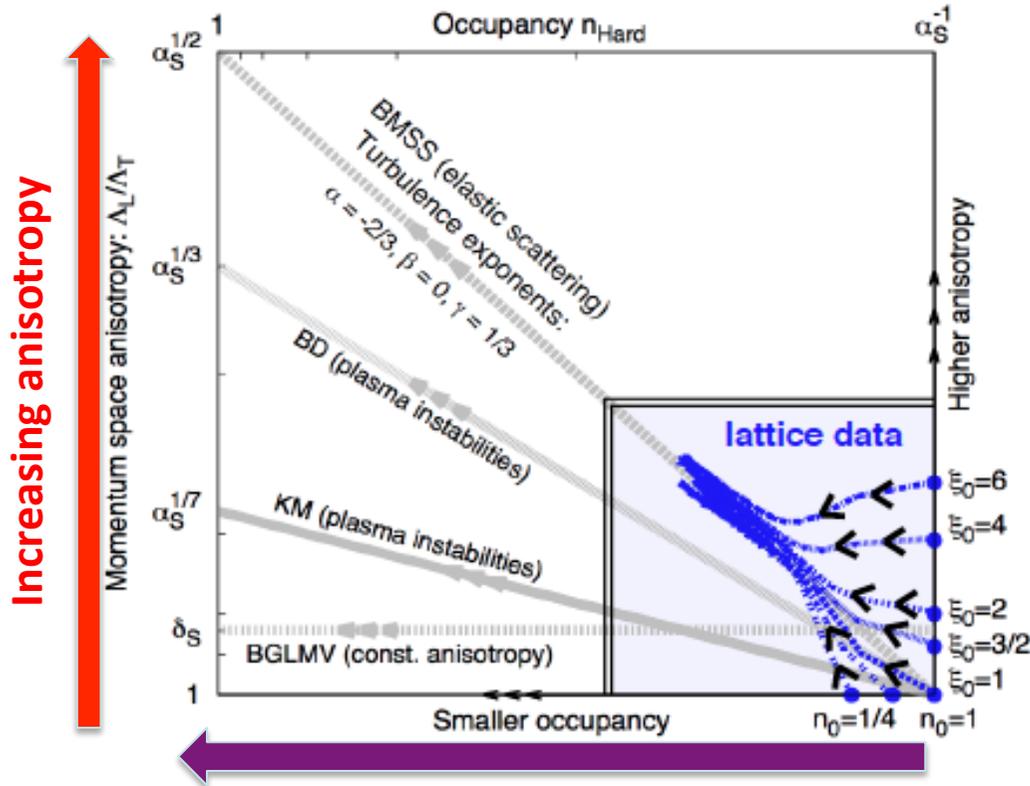
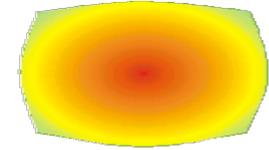
Berges, Scheffler, Sexty, arXiv:0712.3514
Dusling, Gelis, RV, arXiv:1106.3927
Epelbaum, Gelis, arXiv:1307.1765
Jeon, arXiv:1308.0263



Berges, Schenke, Schlichting, RV, NPA 931 (2014) 348

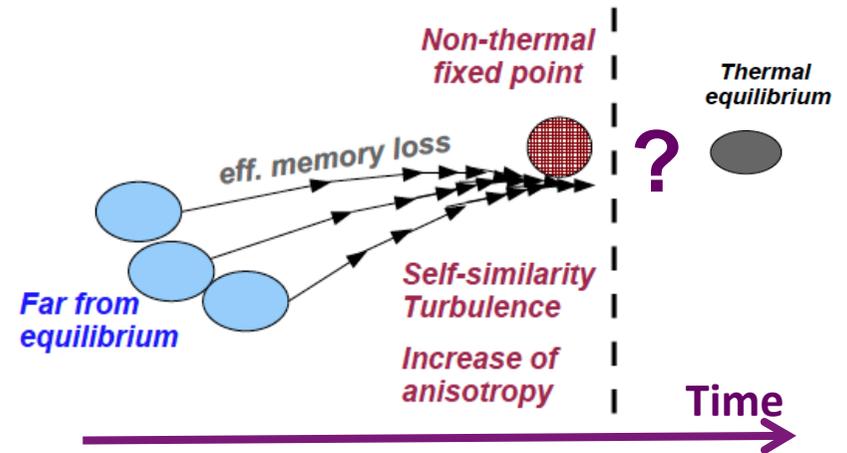
Real time numerical lattice simulations of an expanding gauge theory generate overpopulated gluons in a very short time after collision

Simulations identify kinetic approach



Decreasing occupancy with expansion

$$f(p_z, p_T, \tau) = (Q_S \tau)^\alpha f_S((Q_S \tau)^\beta p_T, (Q_S \tau)^\gamma p_z)$$

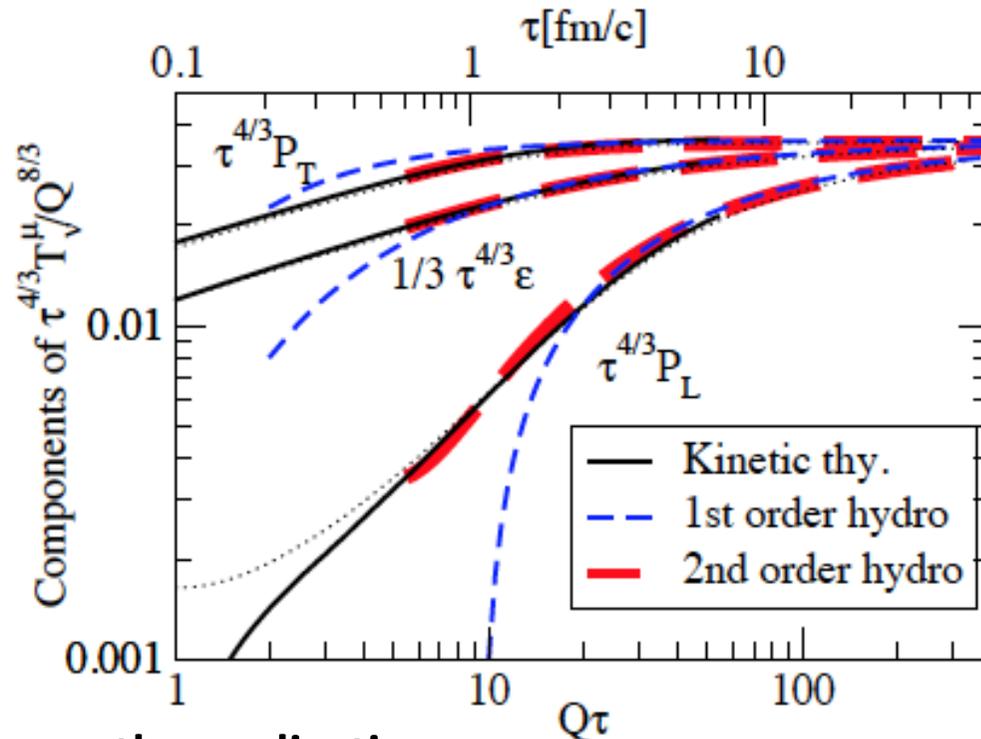


Berges, Boguslavski, Schlichting, RV:
arXiv: 1303.5650, 1311.3005, 1408.1679, 1508.03073

The kinetic theory that interpolates between the classical overoccupied regime and hydrodynamics is the “**bottom up**” **thermalization** scenario of Baier et al (BMSS)

Baier, Mueller, Schiff, Son, hep-ph/0009237

From nuts to soup: thermalization *ab initio*



Kurkela,Zhu,arXiv:1506.06647

See also Keegan,Kurkela,
Mazeliaukas,Teaney, arXiv1605.04287

Bottom-up thermalization

$1 < Q_s \tau < \ln(1/\alpha_s)$: Early time instabilities decohere classical YM fields

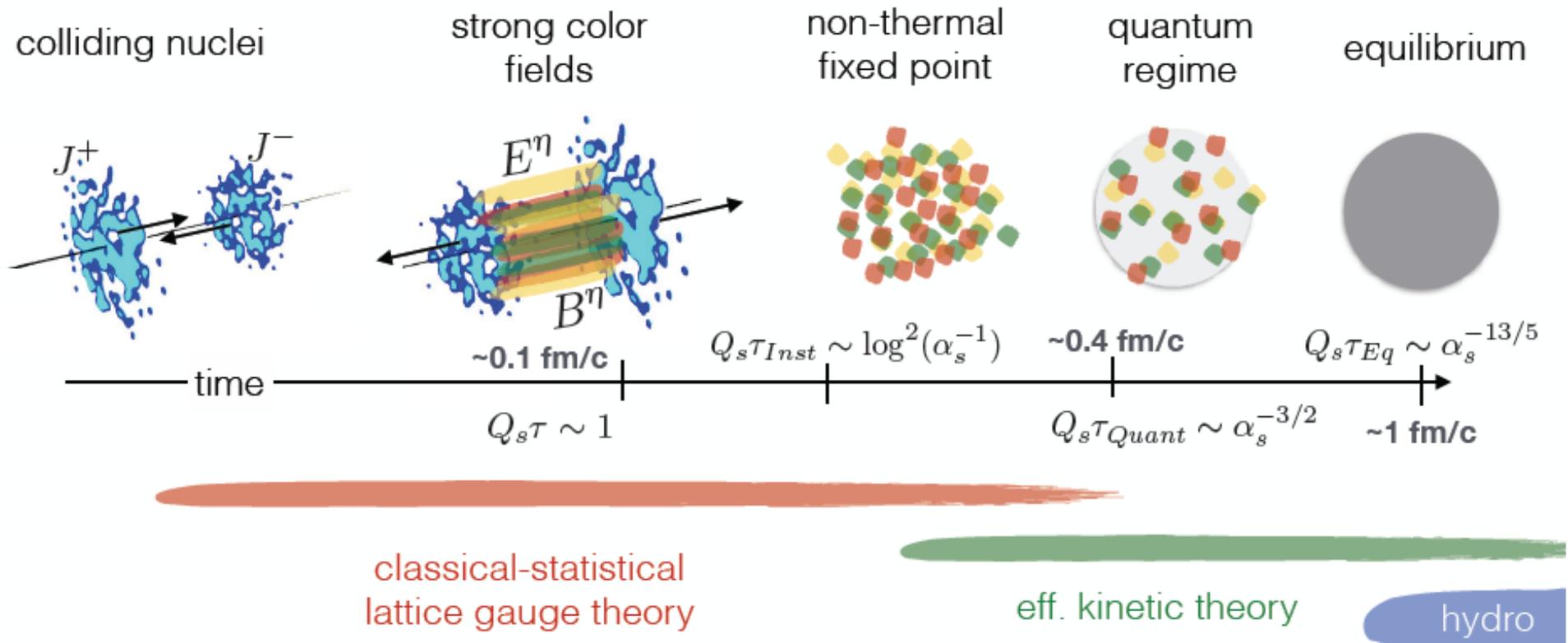
$1 \ll Q_s \tau < \alpha_s^{-3/2}$: Hard gluons scatter elastically and inelastically

$\alpha_s^{-3/2} < Q_s \tau < \alpha_s^{-5/2}$: Gluon radiation significant – “soft” sector thermalizes

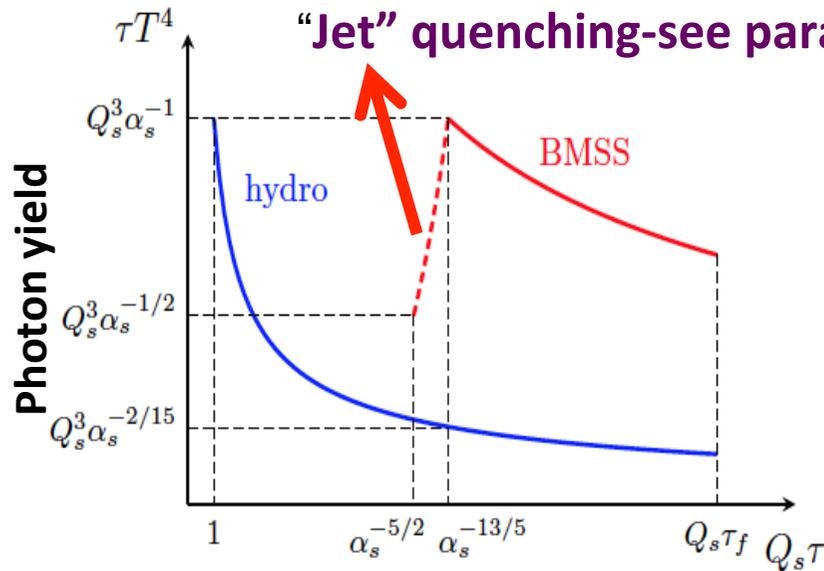
$\alpha_s^{-5/2} < Q_s \tau < \alpha_s^{-13/5}$: Hard gluons at scale Q_s are *quenched* – lose energy to bath

For further discussions of stage 1 in CYM, see talks by Fries and McDonald

From nuts to soup: thermalization *ab initio*



Consequences for photon production?



Berges, Reygers, Tanji, RV, in preparation

In hydro, can push thermal radiation to early times -delicate balance of yield and v_2

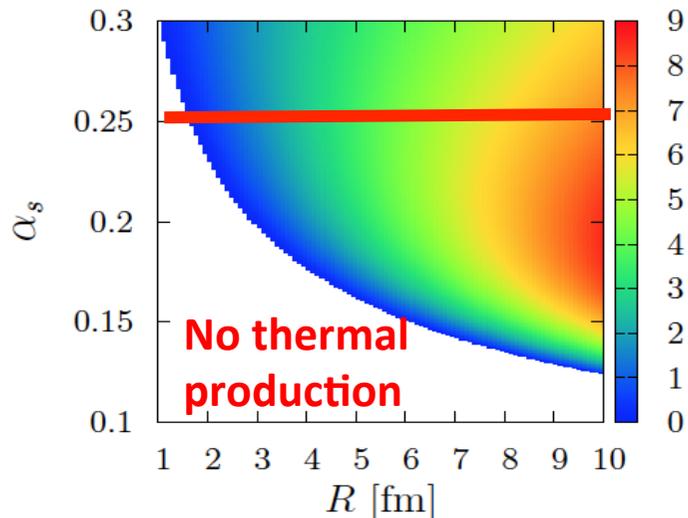
Paquet et al, arXiv:1509.06738

In bottom-up, thermalization occurs > 1 fm:

i) photons produced in quenching of “hard” quarks to heat bath more sensitive to v_2

ii) pre-equilibrium photons generate more yield but less v_2

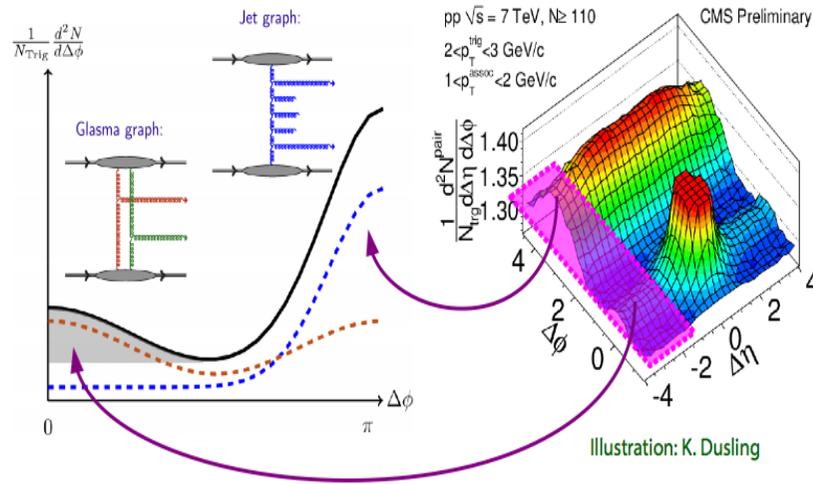
Parallel talk by Marco Ruggeri



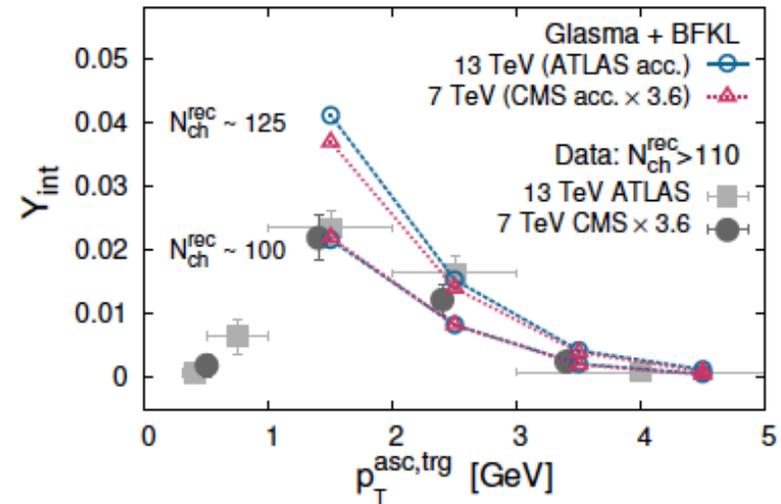
For smaller systems, in bottom up scenario, pre-equilibrium photons may be more significant

Parallel talk by Chun Shen

Collectivity in small systems: the role of mini-jets?

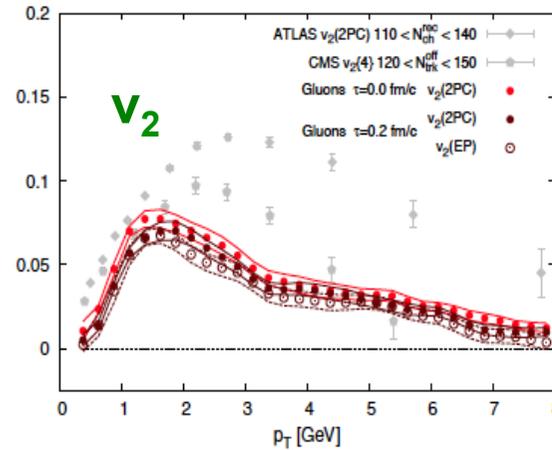
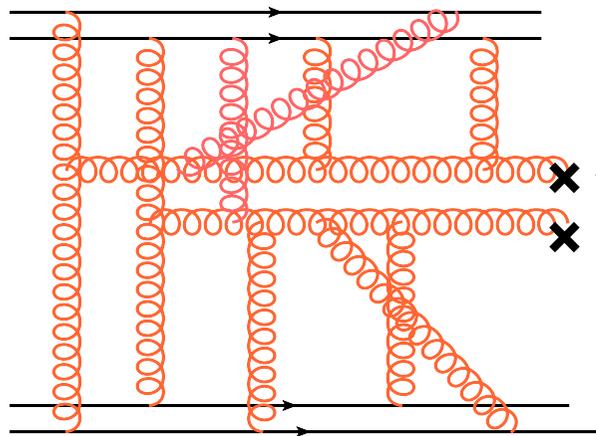


Dusling, Tribedy, RV, arXiv:1509.04410

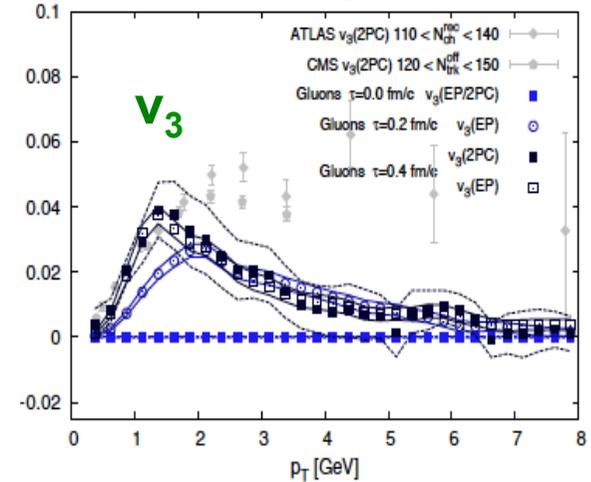


In initial state frameworks, copious production of mini-jets
 -- their theoretical treatment and “subtraction” is not fully understood

Collectivity in small systems: the role of mini-jets?

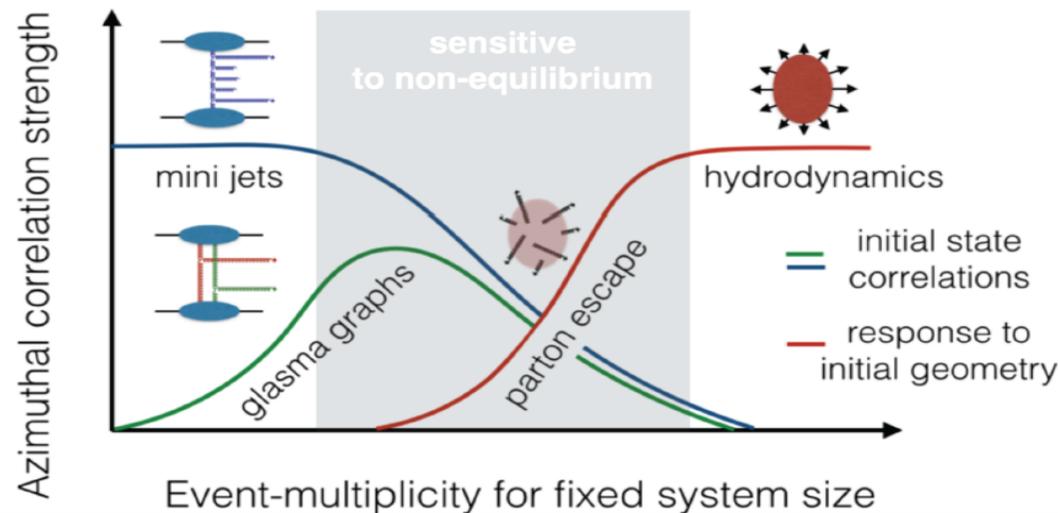


Schenke, Schlichting, RV, 1502.01331

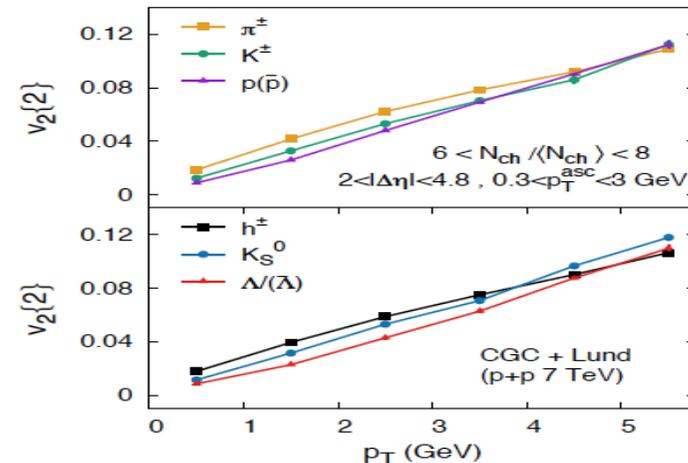
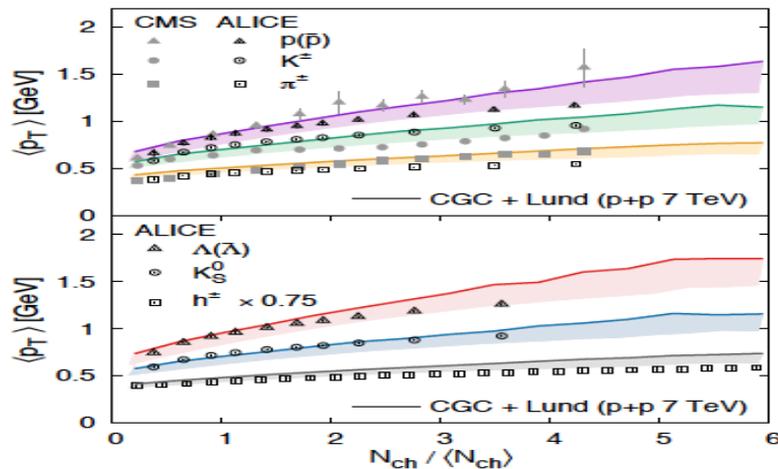
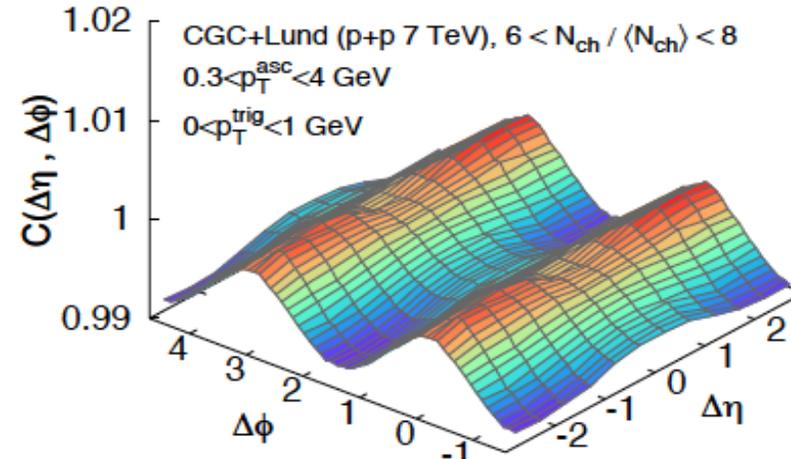
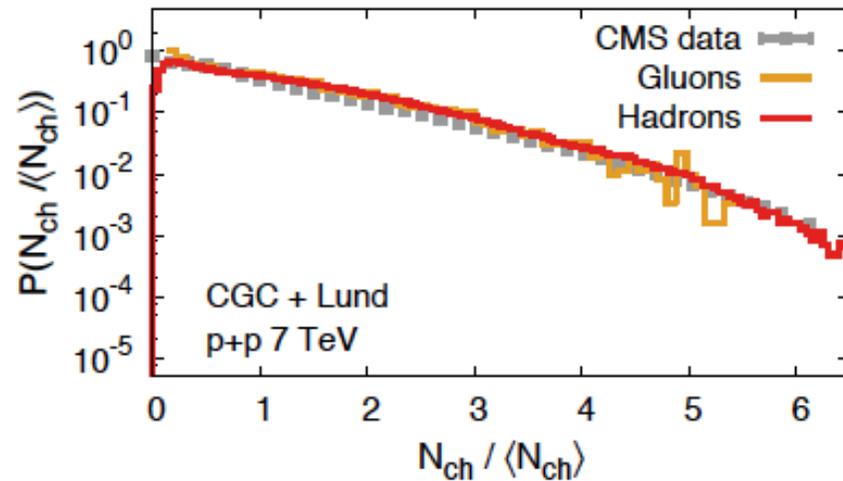


Coherent 2+1-D Classical YM gives trend in v_2, v_3
 -- but source of collectivity depends on size
 and distribution of color domains

Kovner, Lublinsky, arXiv:1109.0347,
 Dumitru, McLerran, Skokov, arXiv: 1410.4844
 Lappi, Schenke, Schlichting, RV, arXiv:1509.03499



Collectivity in small systems: CGC+PYTHIA



Schenke, Schlichting, Tribedy, RV, arXiv:1607.02496

CGC+PYTHIA connects strings to gluons produced from CYM evolution

-- reproduces systematics of multiplicity dist., $\langle p_T \rangle$ and v_2 mass ordering

-- useful tool in determining if collectivity is Glasma or hydro with increasing N_{ch}

Summary

Lots of progress in initial state and pre-equilibrium dynamics since McGill – emerging consensus in weak coupling approaches

The consequences of detailed thermalization scenarios for hard probes need to be fleshed out more

Hard & EM probes in small systems are particularly sensitive to the interplay of initial/final state dynamics

Several interesting talks on related topics I was unable to cover and hope to attend...look forward to the rest of the conference!

Back up