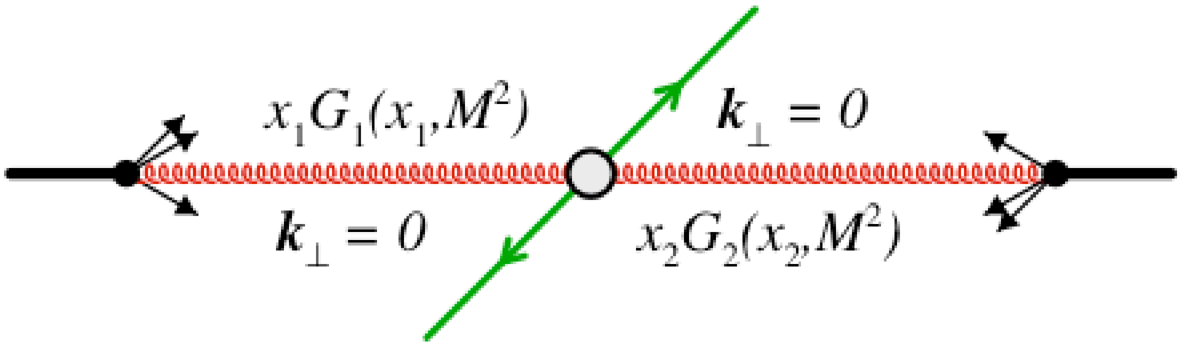
High energy factorization, long range rapidity correlations and a ridge in A+A collisions

Raju Venugopalan
Brookhaven National Laboratory

Talk, SC4 Conference, May 22 2009

Well known universal pdfs in pQCD collinear factorization:



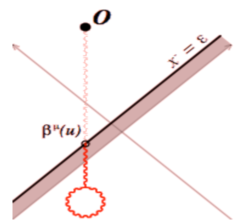
pdfs interpreted as parton densities in IMF and Light Cone Gauge.
State of the art for computing rare (high p_T) processes

X

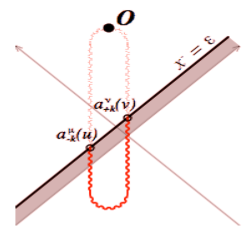
Formalism not designed *ab initio* to treat shadowing, multiple scattering, diffraction, energy loss, impact parameter dependence, thermalization…

JIMWLK RG evolution for a single nucleus:

$$\mathcal{O}_{\rm NLO} = \Bigg($$



+



$\chi(x_\perp, y_\perp)$

$$\Bigg)\, \mathcal{O}_{\rm LO}$$

$$= \ln\left(\frac{\Lambda^+}{p^+}\right) \mathcal{H}\, \mathcal{O}_{\rm LO}$$

(keeping leading log divergences)

$$\langle \mathcal{O}_{\rm LO} + \mathcal{O}_{\rm NLO} \rangle = \int [d\tilde{\rho}] W[\tilde{\rho}]\, [\mathcal{O}_{\rm LO} + \mathcal{O}_{\rm NLO}]$$

$$= \int [d\tilde{\rho}] \left\{ \left[1 + \ln\left(\frac{\Lambda^+}{p^+}\right) \mathcal{H} \right] W_{\Lambda^+} \right\} \mathcal{O}_{\rm LO}$$

LHS independent of Λ^+ =>

$$\frac{\partial W[\tilde{\rho}]}{\partial Y} = \mathcal{H}\, W[\tilde{\rho}]$$

JIMWLK eqn.

Jalilian-Marian,Iancu,McLerran,Weigert,Leonidov,Kovner

Correlation Functions

$$\langle O[\rho]\rangle_Y = \int [d\rho] O[\rho] W_Y[\rho]$$

Brownian motion in functional space: Fokker-Planck equation!

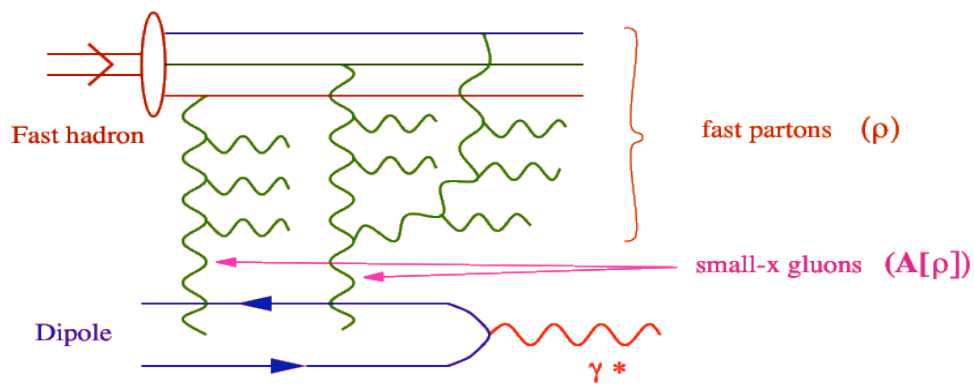
"diffusion coefficient"

$$=> \frac{\partial}{\partial Y} < O[\alpha] >_Y = < \underbrace{\frac{1}{2}\int_{x,y} \frac{\delta}{\delta \alpha_Y^a(x)} \chi_{x,y}^{ab} \frac{\delta}{\delta \alpha_Y^b(y)}}_{\mathcal{H}_{\mathrm{JIMWLK}}} O[\alpha] >_Y$$

"time"

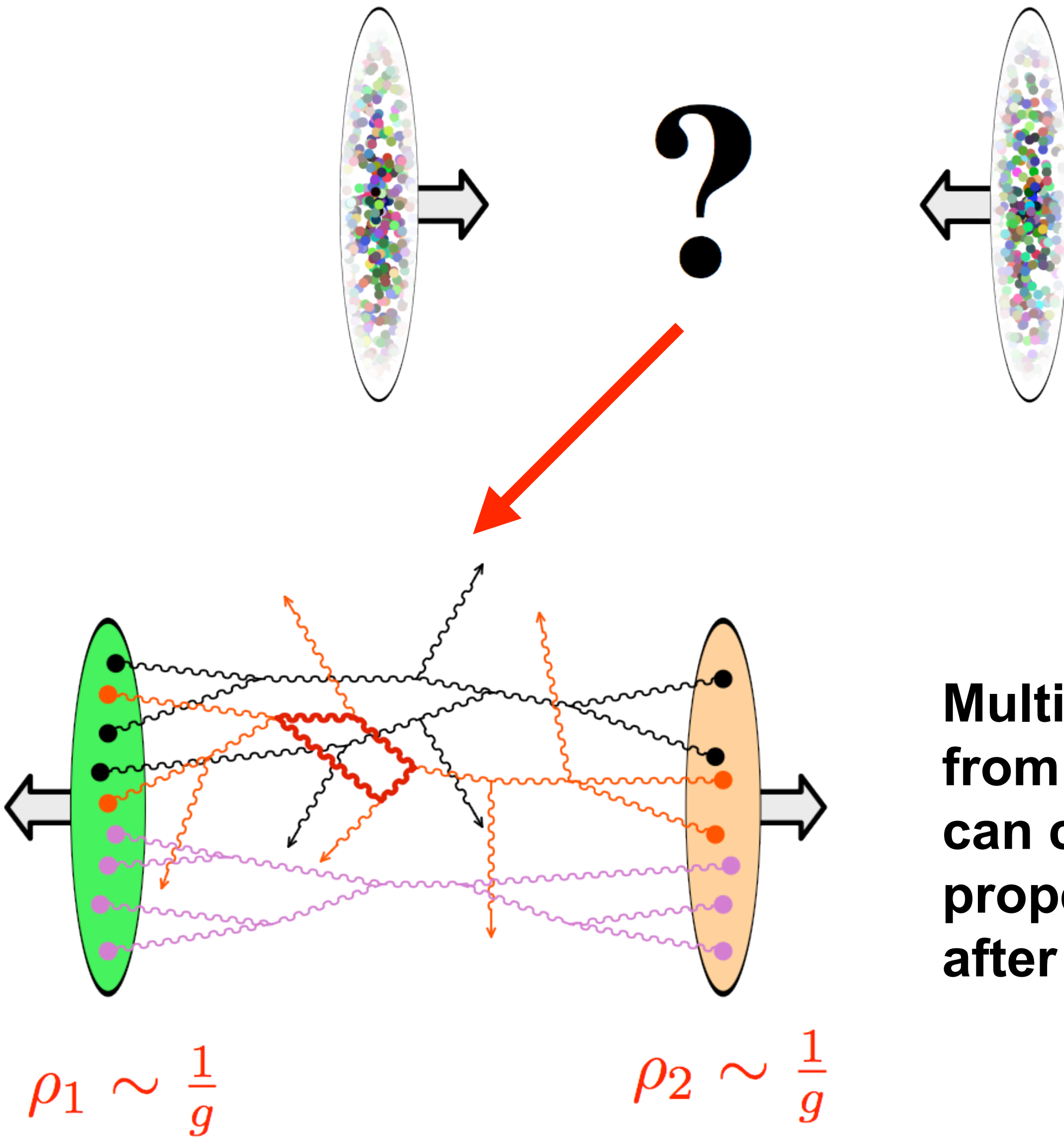
$$\alpha = \frac{\tilde{\rho}}{\nabla_\perp^2}$$

Mean field soln. (A>> 1, N_c >>1) for 2 pt. Wilson line (dipole) correlators= BK (Balitsky-Kovchegov) eqn.



Saturation scale $Q_S(Y)$ separates linear QCD evol. from saturation dynamics in BK

Nuclear Collisions: Glasma from melting CGCs



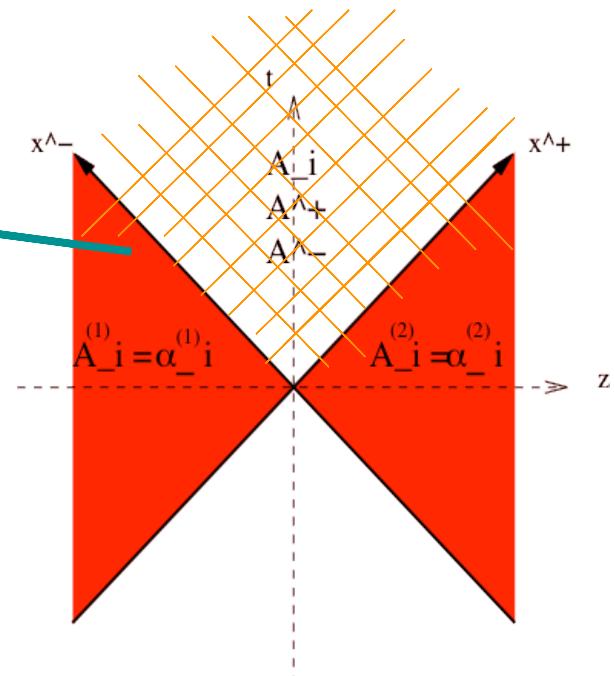
Multi-particle production from strong CGC fields: can compute *systematically* properties of Glasma fields after collision

The Glasma at LO:Yang-Mills eqns. for two nuclei

$(=O(1/g^2)$ and all orders in $(g\rho)^n$)

$$D_\mu F^{\mu\nu,a} = \delta^{\nu+}\rho_1^a(x_\perp)\delta(x^-) + \delta^{\nu-}\rho_2^a(x_\perp)\delta(x^+)$$

Glasma initial conditions from matching classical CGC wave-fns on light cone

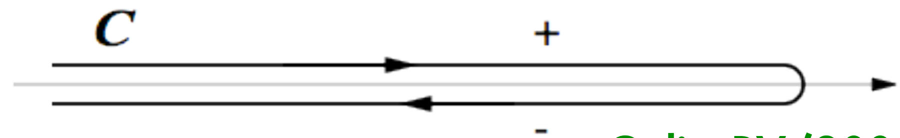


Kovner, McLerran, Weigert

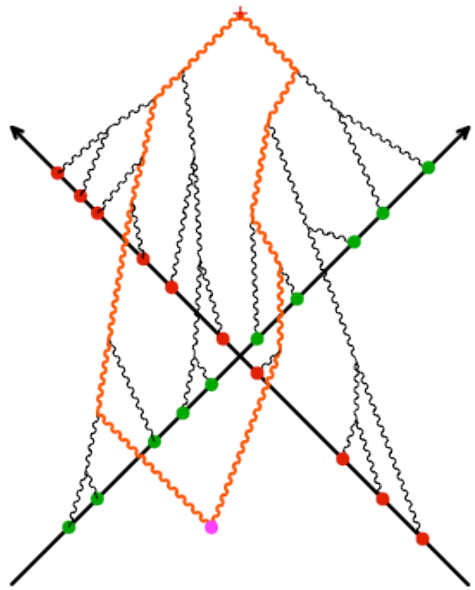
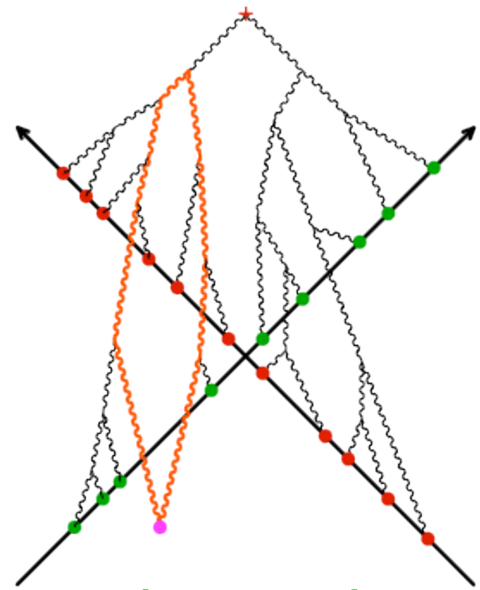
Sources become *time dependent* after collision:
field theory formalism--
particle production in strong external fields
(e.g., Schwinger mechanism of e+e- production in strong QED fields).

Multiplicity to NLO (=O(1) in g and all orders in $(g\rho)^n$)

Schwinger-Keldysh formalism



Gelis, RV (2006)

$$\langle n \rangle_{\rm NLO} =$$  + 

Gluon pair production

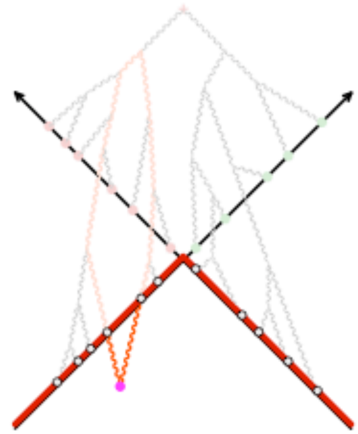
One loop contribution to classical field

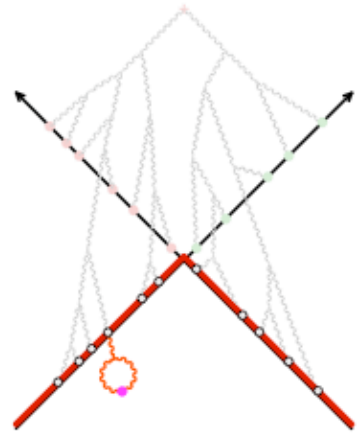
Initial value problem **with retarded boundary conditions**
- can be solved on a lattice in real time

(*a la* Gelis,Kajantie,Lappi for Fermion pair production)

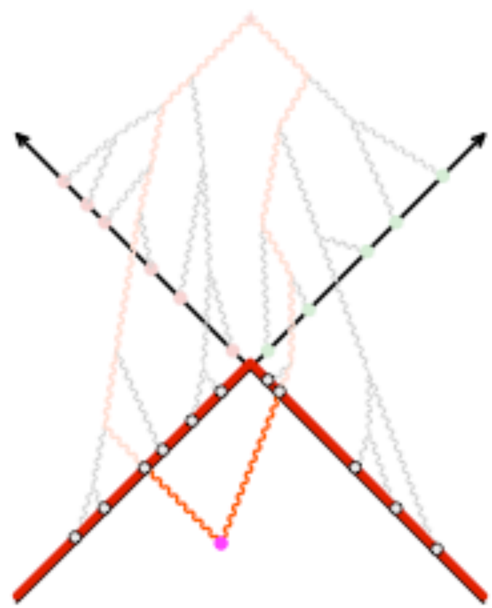
RG evolution for 2 nuclei

Log divergent contributions crossing nucleus 1 or 2:





Contributions across both nuclei are finite-no log divergences

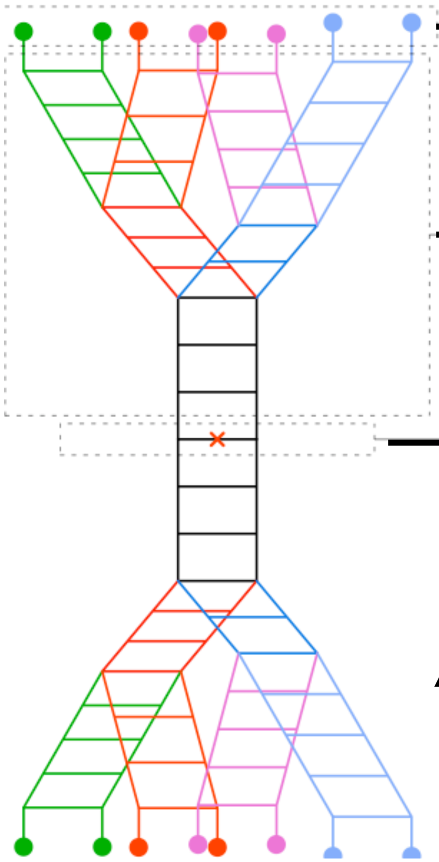


=> factorization

High energy factorization for inclusive multi-gluon production in A+A collisions

Gelis,Lappi,RV
arXiv:0804.2630 [hep-ph];
arXiv:0807.1306 [hep-ph]
arXiv:0810.4829 [hep-ph]

Multiplicity distribution



Initial configuration of sources for nucleus 1

JIMWLK evolution for nucleus 1

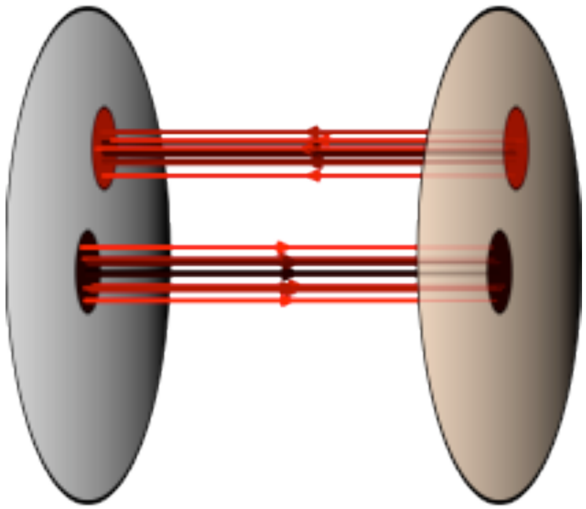
$$\frac{dN_{\rm LO}}{d^3p}$$ Computed from Yang-Mills Glasma field solns. for fixed dist. of sources

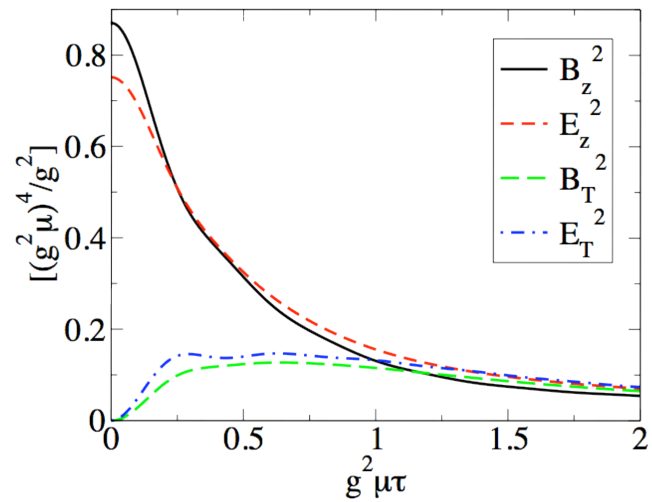
Identical evol. for nucleus 2

Mutiplicities for RHIC & LHC computed in simplified versions of this formalism

Krasnitz, Nara, RV; Lappi

Numerical solns: Glasma flux tubes

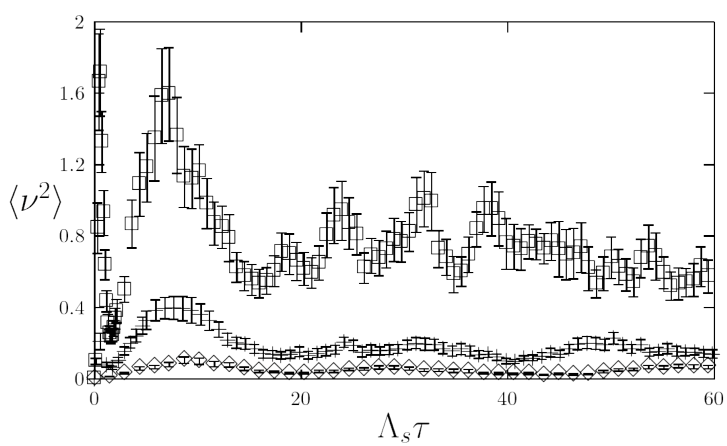




Flux tubes of size $1/Q_S$ with parallel color E & B fields
- generate Chern-Simons charge

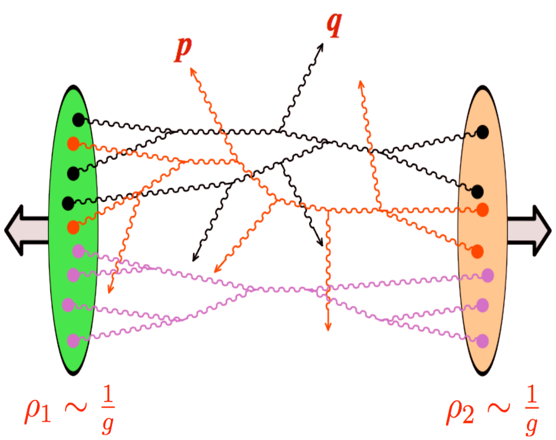
$$\nabla \cdot E = \rho_{\text{electric}}$$
$$\nabla \cdot B = \rho_{\text{magnetic}}$$

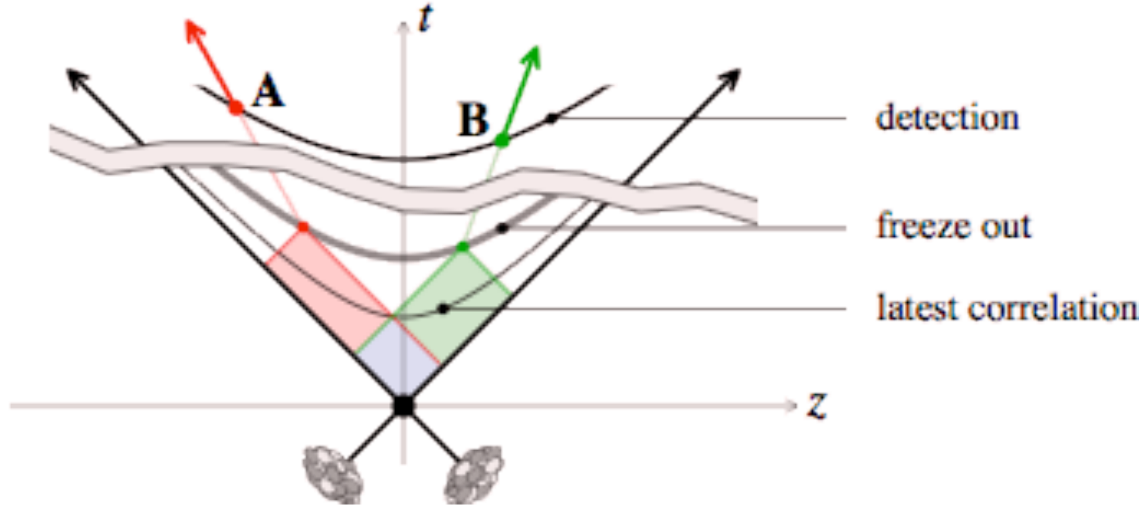
$$\rho_{\text{electric}} = ig[A^i, E^i]$$
$$\rho_{\text{magnetic}} = ig[A^i, B^i]$$



Kharzeev, Krasnitz, RV, Phys. Lett. B545 (2002)

Imaging the Glasma: two particle correlations and the near side Ridge





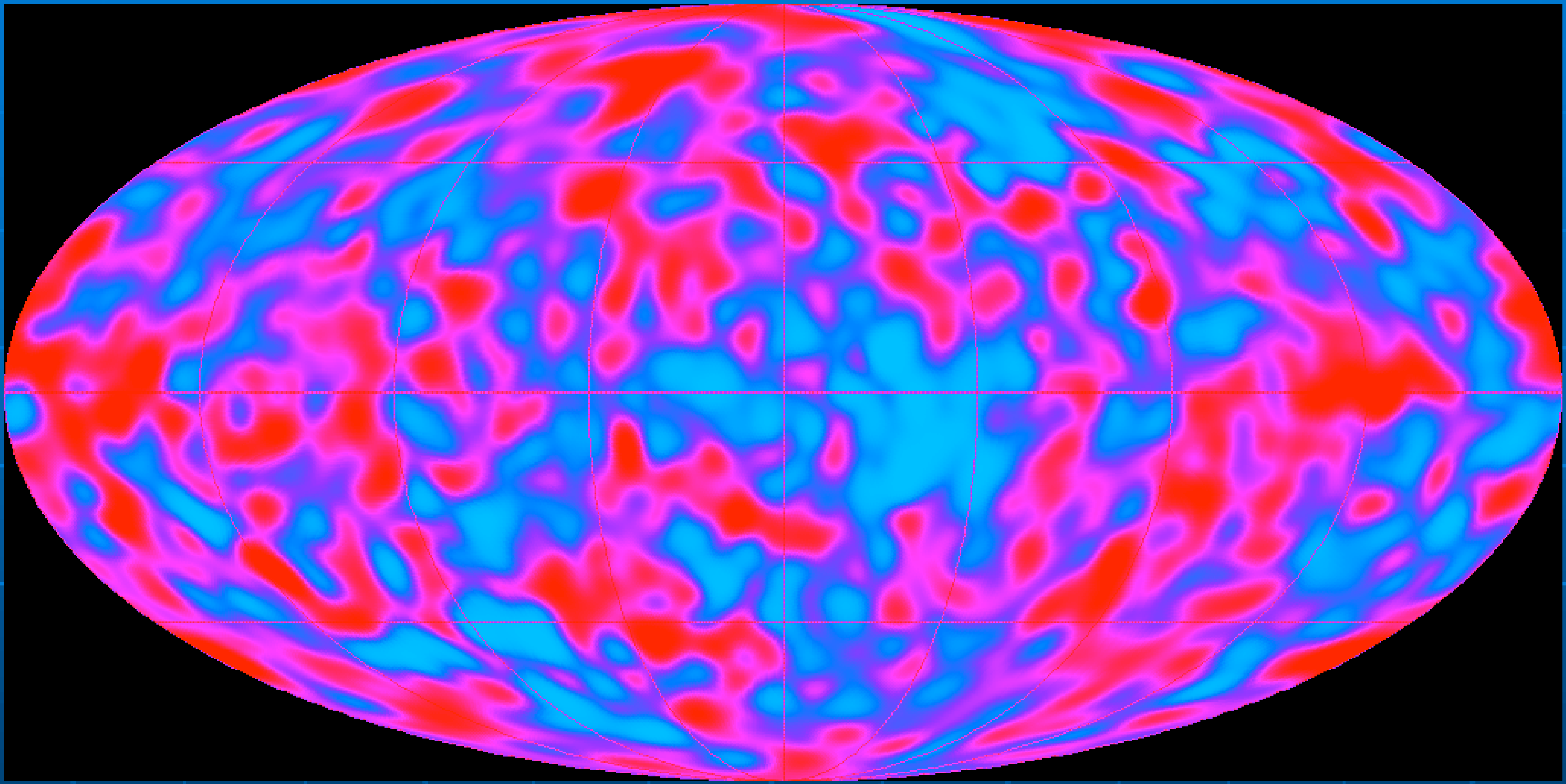
For particles to have been emitted from the same Event Horizon, causality dictates that

$$\tau \leq \tau_{\text{freeze-out}} \exp\left(-\frac{1}{2}|y_A - y_B|\right)$$

τ < 1 fm for Δy > 4

An example of a small fluctuation spectrum…

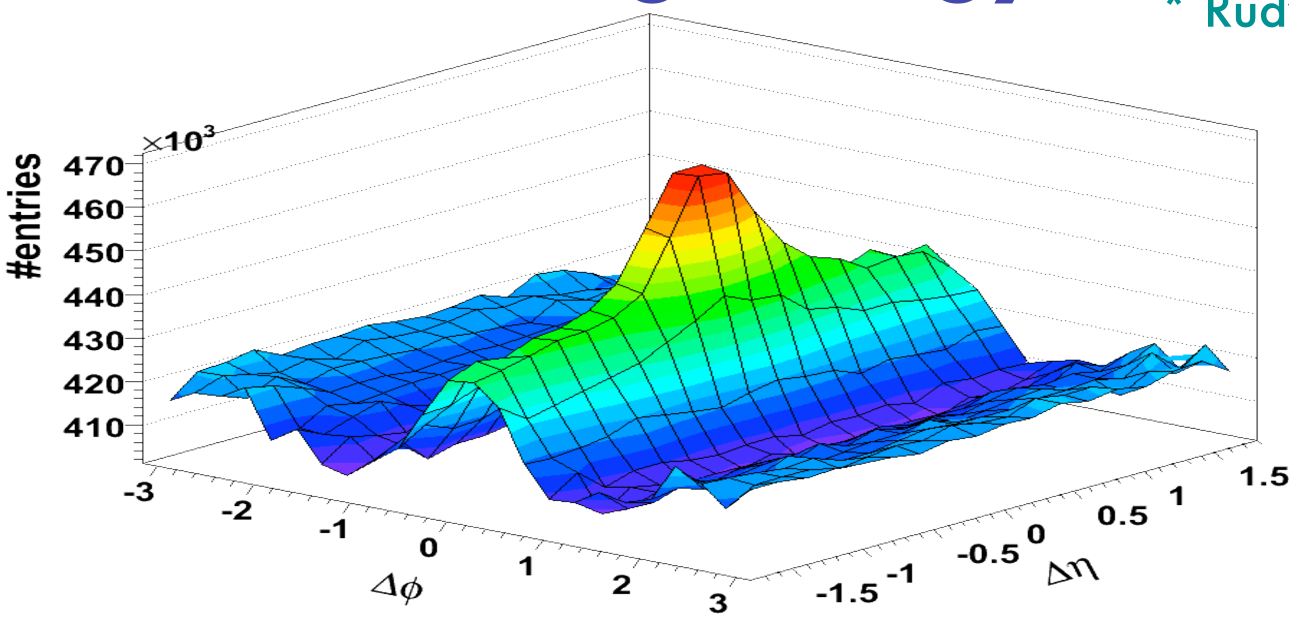
COBE Fluctuations



$\delta t/t < 10^{-5}$, i.e. much smoother than a baby's bottom!

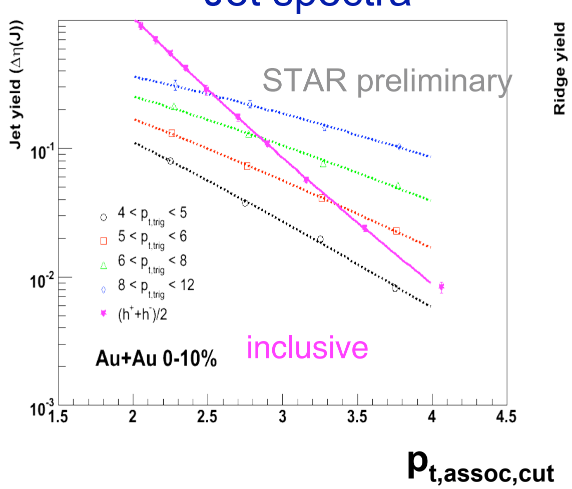
Ridgeology*

* Rudy Hwa

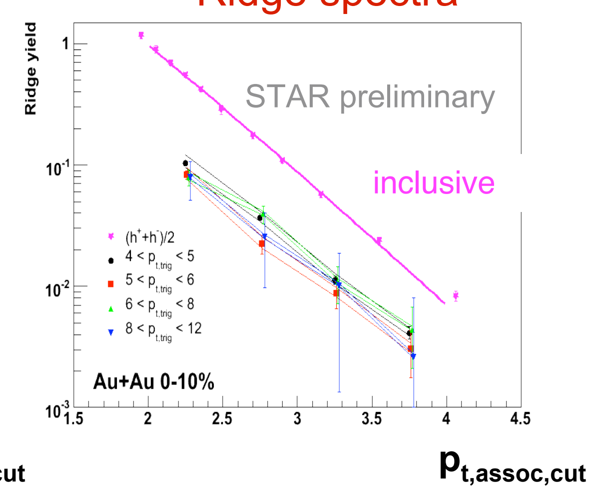


Near side peak+ ridge **(from talk by J. Putschke,STAR collaboration)**

Jet spectra

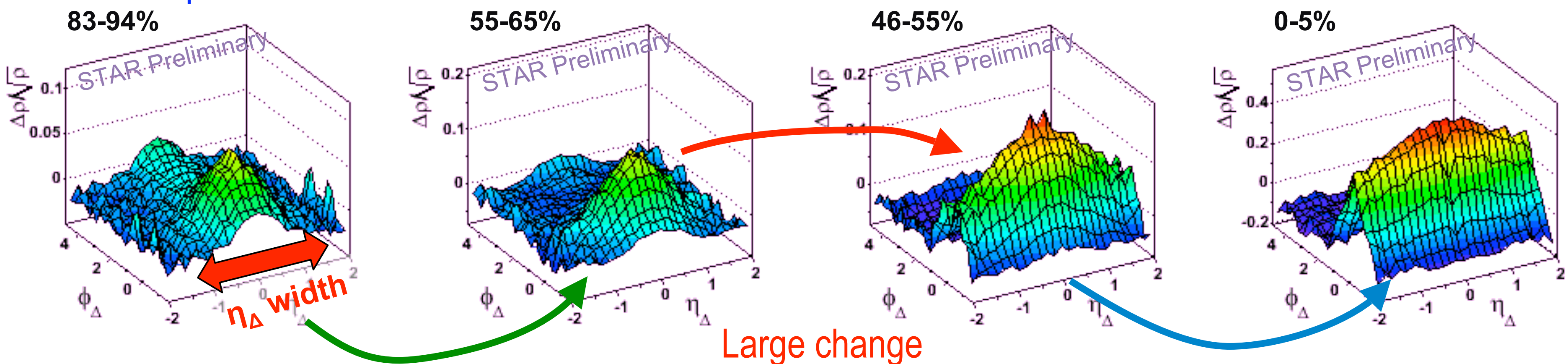


Ridge spectra



Evolution of mini-jet with centrality

Same-side peak



Little shape change from peripheral to 55% centrality

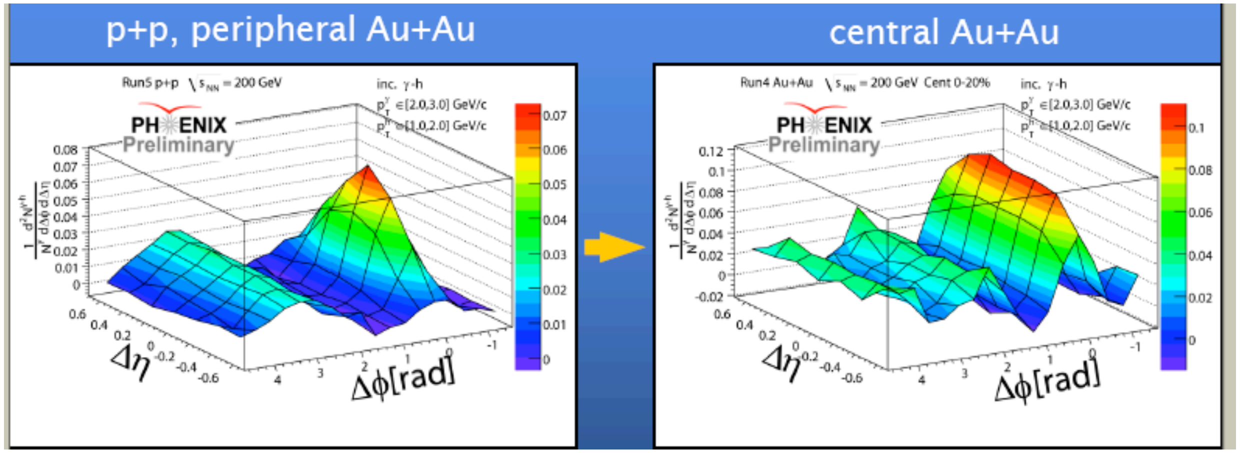
Large change within ~10% centrality

Smaller change from transition to most central

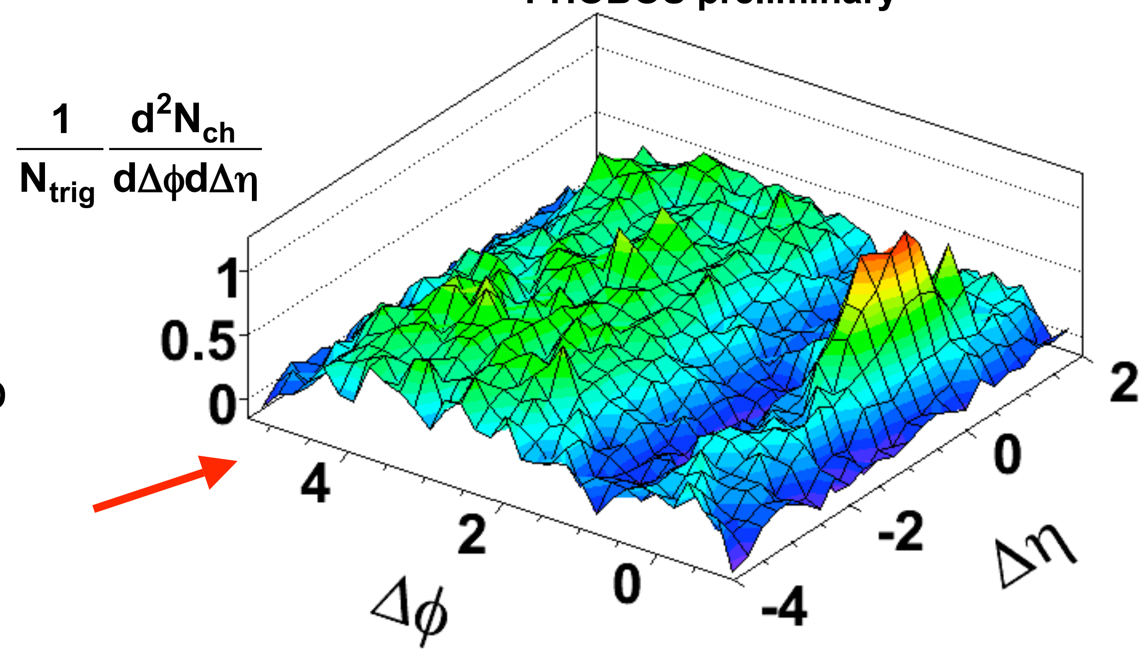
Binary scaling reference followed until sharp transition at ρ ~ 2.5
~30% of the hadrons in central Au+Au participate in the same-side correlation

M. Daugherty Session IX, QM2008

Update: the ridge comes into its own



PHENIX: sees a ridge

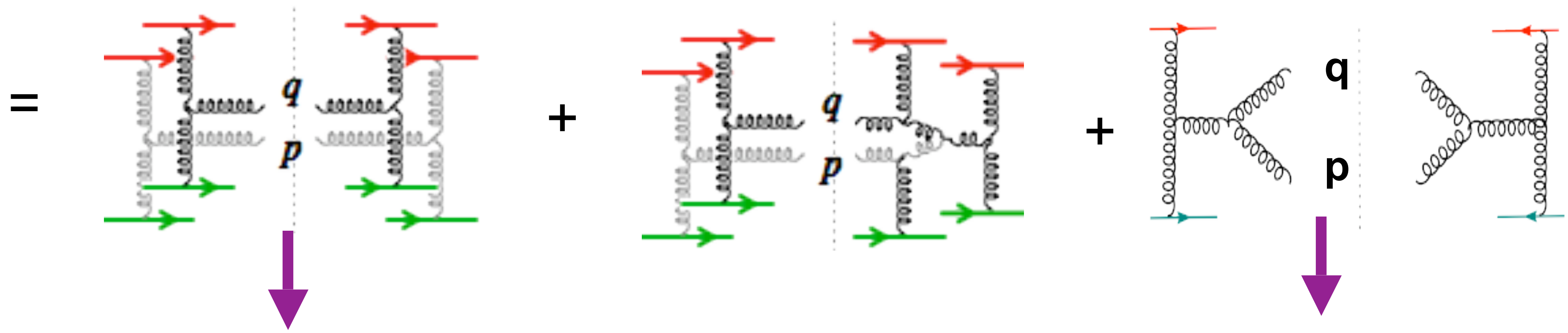


PHOBOS: the ridge extends to very high rapidity

2 particle correlations in the Glasma (I)

Dumitru, Gelis ,McLerran, RV, arXiv:0804.3858[hep-ph]

$$C(\mathbf{p},\mathbf{q}) = \left\langle \frac{dN_2}{dy_p\, d^2\mathbf{p}_\perp\, dy_q\, d^2\mathbf{q}_\perp} \right\rangle - \left\langle \frac{dN}{dy_p\, d^2\mathbf{p}_\perp} \right\rangle \left\langle \frac{dN}{dy_q\, d^2\mathbf{q}_\perp} \right\rangle$$



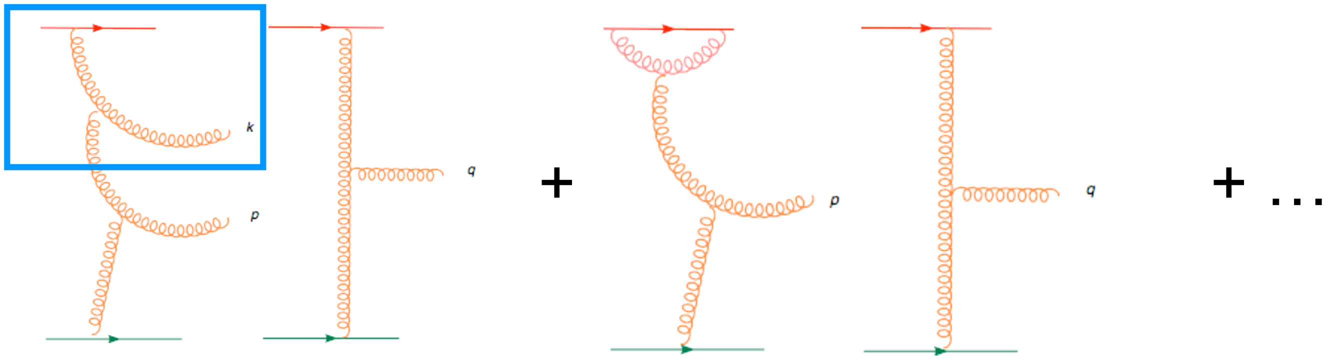
Leading (classical) contribution
- from disconnected QCD graphs

"pQCD" graphs

2 particle correlations in the Glasma (II)

RG evolution:

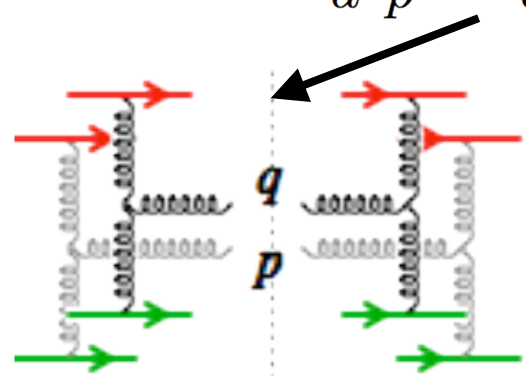
Gelis, Lappi, RV, arXiv: 0807.1306



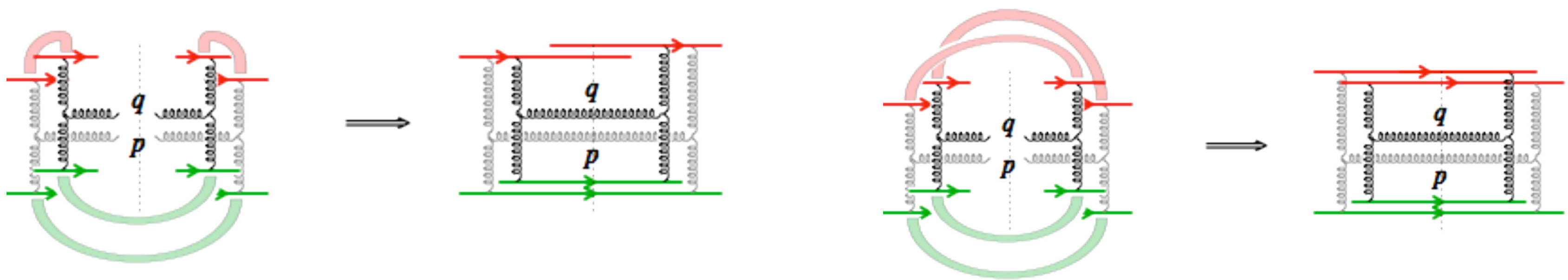
Keeping leading logs to all orders (NLO+NNLO+…)
2-particle spectrum can be written as

$$\langle \frac{dN_2}{d^3p\, d^3q} \rangle_{\mathrm{LLogs}} = \int [d\rho_1][d\rho_2] W_{Y_1}[\rho_1]\, W_{Y_2}[\rho_2]\, \frac{dN}{d^3p}|_{\mathrm{LO}}\, \frac{dN}{d^3q}|_{\mathrm{LO}}$$

= LO graph with evolved sources
Glasma flux tubes



2 particle correlations in the Glasma (III)



Simple "Geometrical" result:

$$\frac{C(\mathbf{p},\mathbf{q})}{\left\langle \frac{dN}{dy_p\, d^2\mathbf{p}_\perp} \right\rangle \left\langle \frac{dN}{dy_q\, d^2\mathbf{q}_\perp} \right\rangle} = \frac{\kappa}{S_\perp Q_S^2}$$

Ratio of transverse area of flux tube to nuclear area

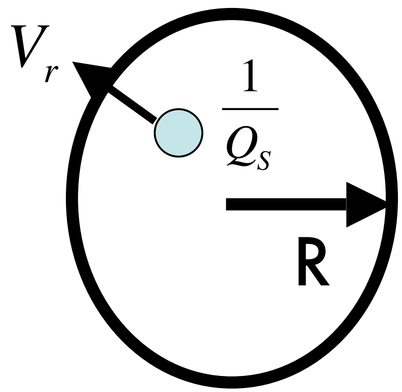
$$\frac{\Delta\rho}{\sqrt{\rho_{\rm ref}}} = \left\langle \frac{dN}{dy} \right\rangle \frac{C(\mathbf{p},\mathbf{q})}{\left\langle \frac{dN}{dy_p\, d^2\mathbf{p}_\perp} \right\rangle \left\langle \frac{dN}{dy_q\, d^2\mathbf{q}_\perp} \right\rangle} = \frac{K_N}{\alpha_S(Q_S)}$$

2 particle spectrum (IV)

Not the whole story… particle emission from the Glasma tubes is isotropic in the azimuth

Pairs correlated by transverse "Hubble flow" in final state - experience same boost

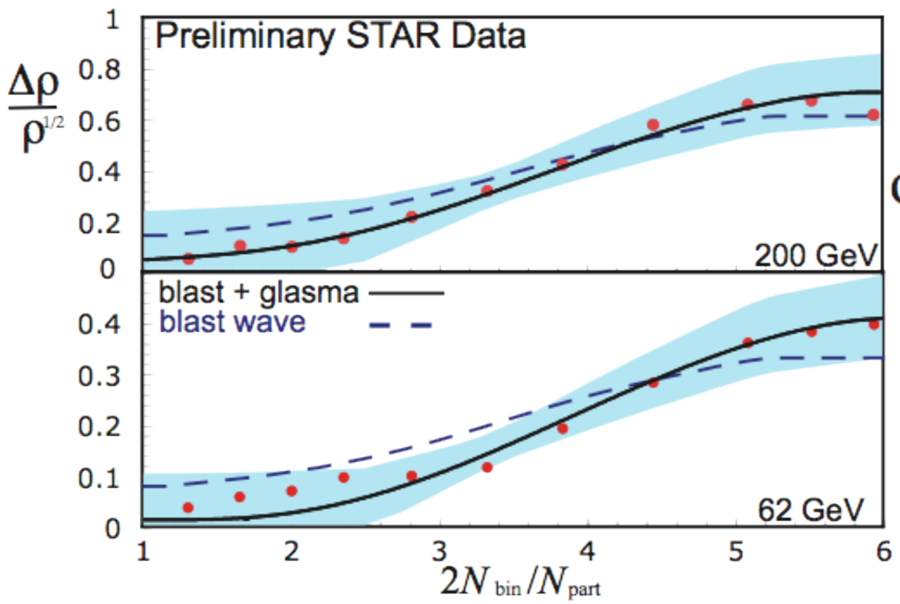
Voloshin, Shuryak
Gavin, Pruneau, Voloshin



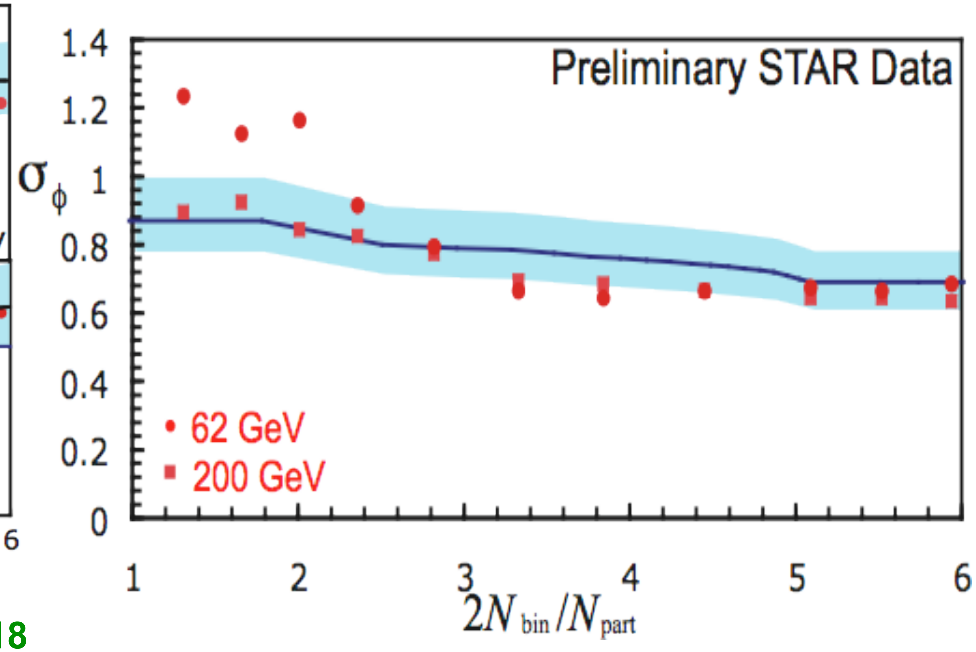
$$\gamma_B = \cosh \zeta_B$$

$$\int d\Phi \frac{\Delta\rho}{\sqrt{\rho_{\rm ref}}}(\Phi, \Delta\phi, y_p, y_q) = \frac{K_N}{\alpha_S(Q_S)} \frac{2\pi \cosh \zeta_B}{\cosh^2 \zeta_B - \sinh^2 \zeta_B \cos^2 \Delta\frac{\phi}{2}}$$

Ridge from flowing flux tubes



Gavin,McLerran,Moschelli, arXiv:0806.4718



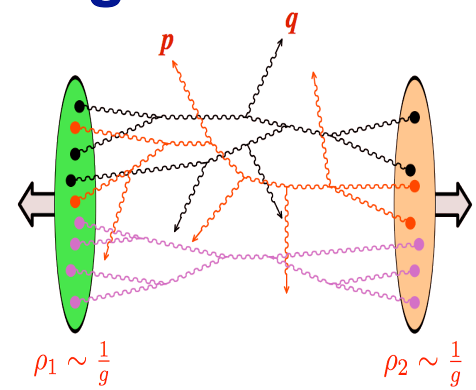
Glasma flux tubes get additional qualitative features right:

i) Same flavor composition as bulk matter

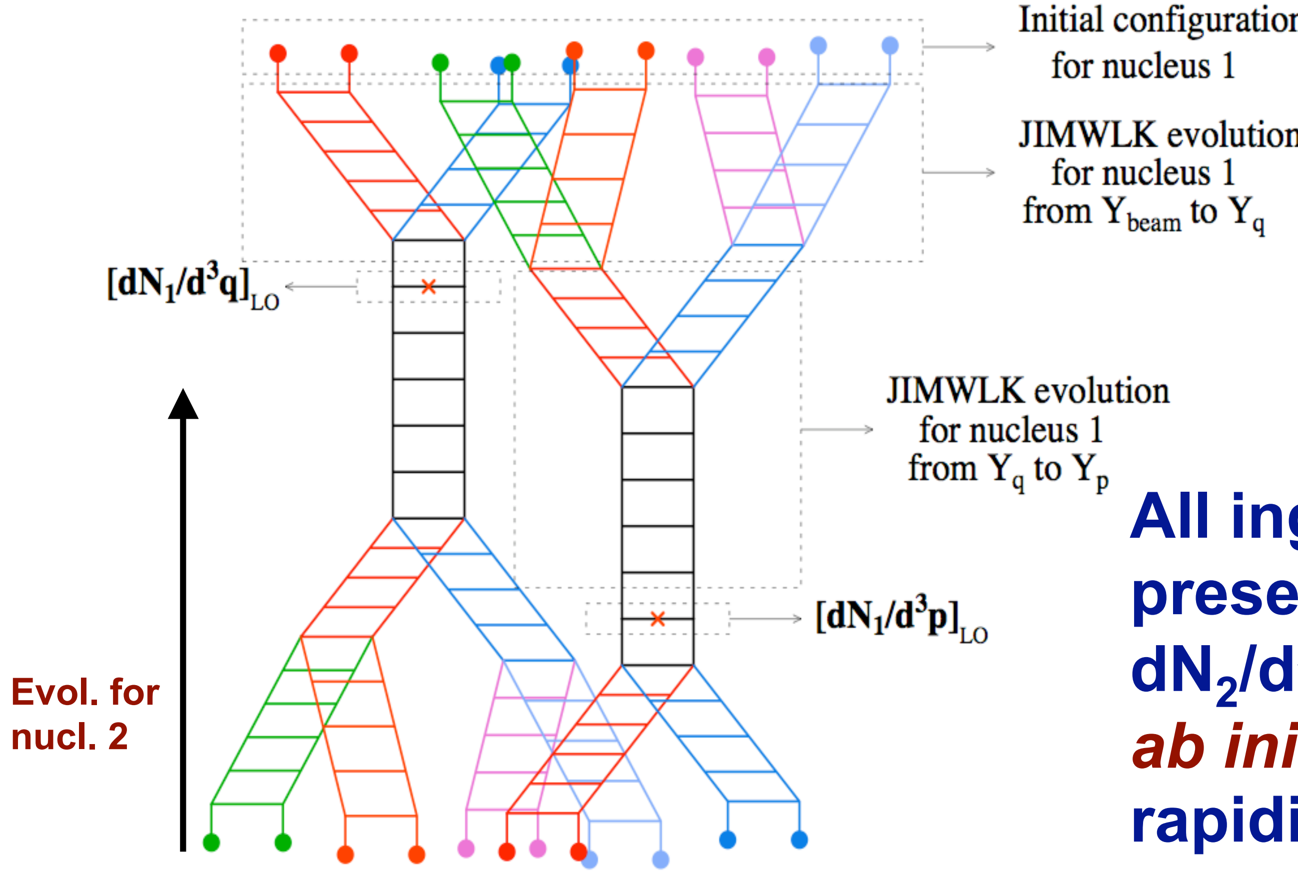
ii) Ridge independent of trigger p_T-geometrical effect

iii) Signal for like and unlike sign pairs the same at large $\Delta\eta$

High energy factorization for inclusive multi-gluon production in A+A collisions



Two particle inclusive dist.:



All ingredients present to compute $dN_2/d^3p\, d^3q$ *ab initio* for <u>arbitrary</u> rapidity separation ΔY_{pq}

Dusling, Gelis, Lappi, RV

Three particle Glasma correlations

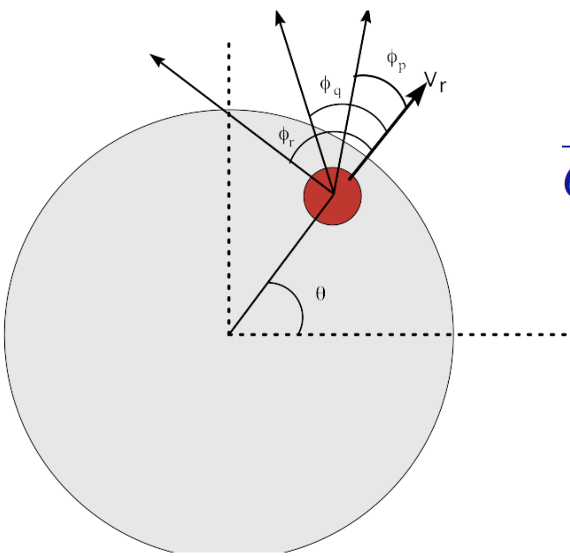
Dusling, Fernandez-Fraile, RV, arXiv:0902.4435 [nucl-th]

Three particle cumulant can be expressed as

$$C(\mathbf{p},\mathbf{q},\mathbf{r}) = \kappa_3 \underbrace{\frac{1}{S_\perp^2 Q_S^4}} \left\langle \frac{dN}{dy_p d^2\mathbf{p}_\perp} \right\rangle \left\langle \frac{dN}{dy_q d^2\mathbf{q}_\perp} \right\rangle \left\langle \frac{dN}{dy_r d^2\mathbf{r}_\perp} \right\rangle$$

$$\propto 1/N_{\mathrm{part.}}^2$$

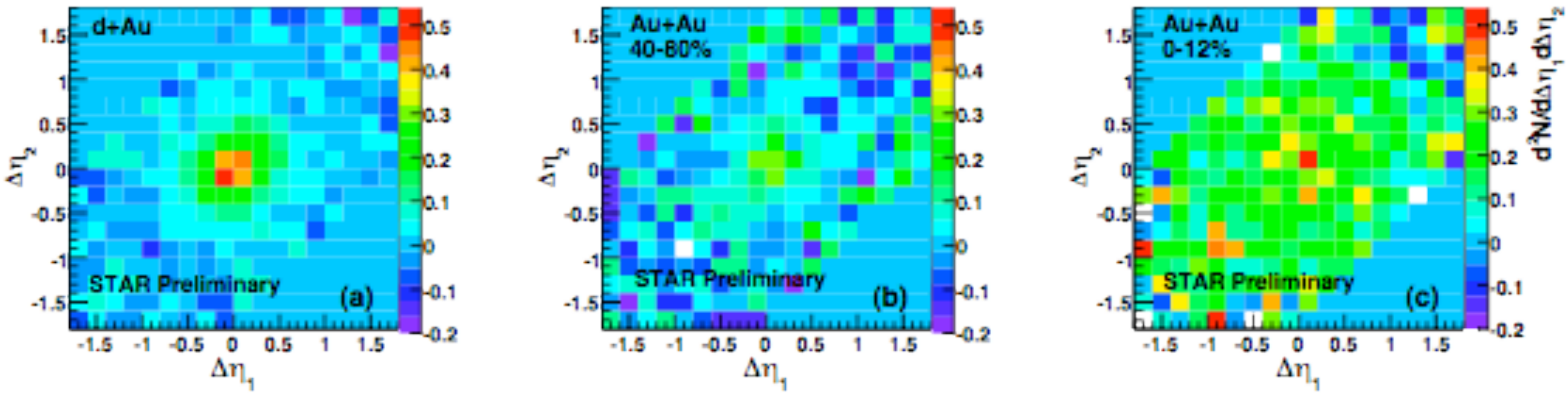
Distributions are radially boosted…



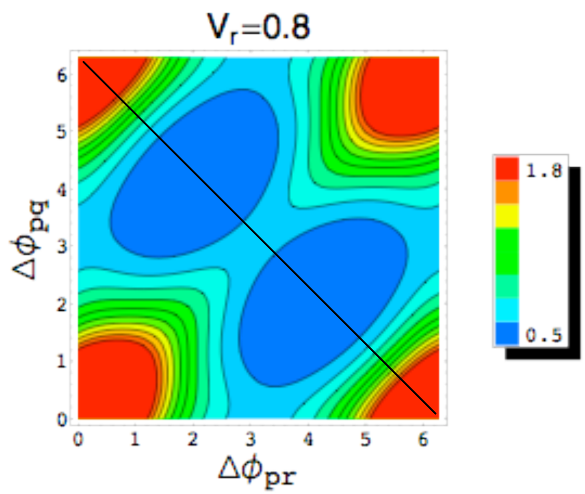
$$\frac{\tilde{C}_3(\Delta\phi_{pq},\Delta\phi_{pr})}{C_1C_1C_1(\Delta\phi_{pq},\Delta\phi_{pr}} = \frac{\kappa_3}{S_\perp^2 Q_S^4}\mathcal{A}(\Delta\phi_{pq},\Delta\phi_{pr},\zeta_B)$$

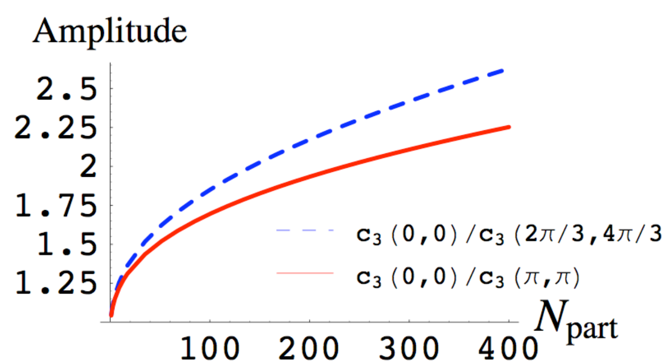
Radial Boost parameter

Three particle correlations uniform in $\Delta\eta_1 - \Delta\eta_2$



Prediction: angular collimation of three particle correlations - max. at (0,0) and min. at (2π/3, 4π/3)

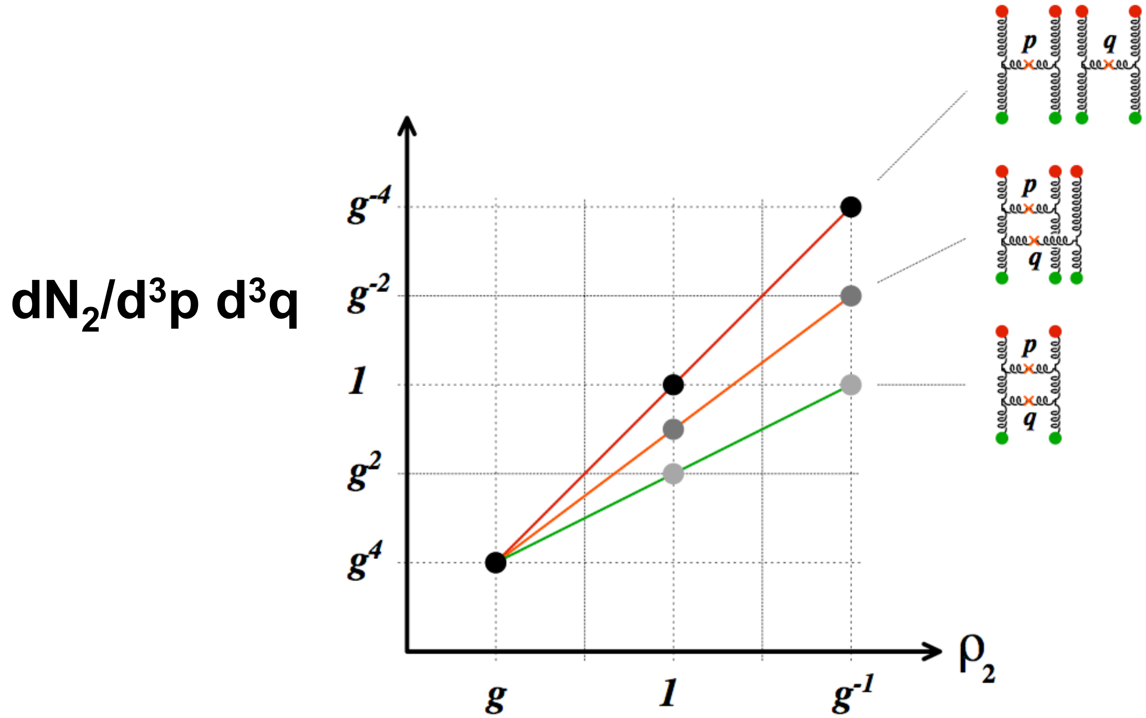




Ratio independent of α_S, κ_3 *and* N_{part}.

A+A collisions are simpler for n>1 correlations

Gelis,Lappi,RV



AA: $\rho_1 \sim \frac{1}{g}\,;\; \rho_2 \sim \frac{1}{g}$ **pA:** $\rho_1 \sim \frac{1}{g}\,;\; \rho_2 \sim g$

More diagrams even at LO in pA relative to AA
At NLO: AA has only "pomeron merging" contributions
pA has both merging + splitting contributions

pLoops: Jalilian-Marian, Kovchegov; Iancu, Triantafyllopolous; Mueller, Shoshi,Wong; Kovner,Lublinsky,…

Summary

- Novel high energy factorization formalism to compute multi-gluon correlations in the Glasma

- Long range rapidity correlations- a "chronometer" of strong color field dynamics; large window at the LHC will provide powerful diagnostic of multi-parton correlations.

- Angular correlations provide insight into the development of radial flow

- Multi-parton dynamics "simpler" in A+A than p+A; correlation measurements varying rapidities of tagged hadrons enable study of "pomeron splitting" dynamics in QCD