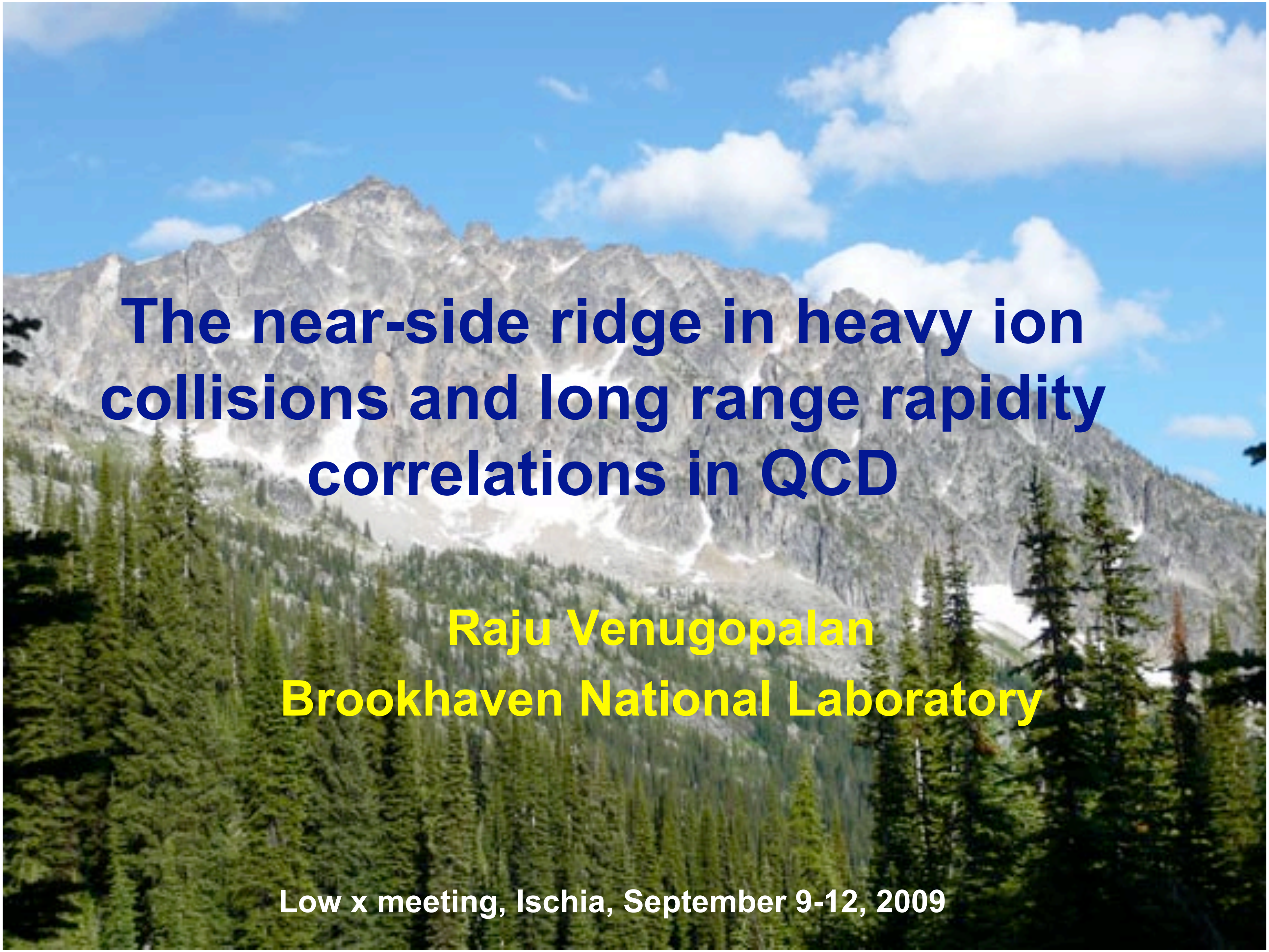


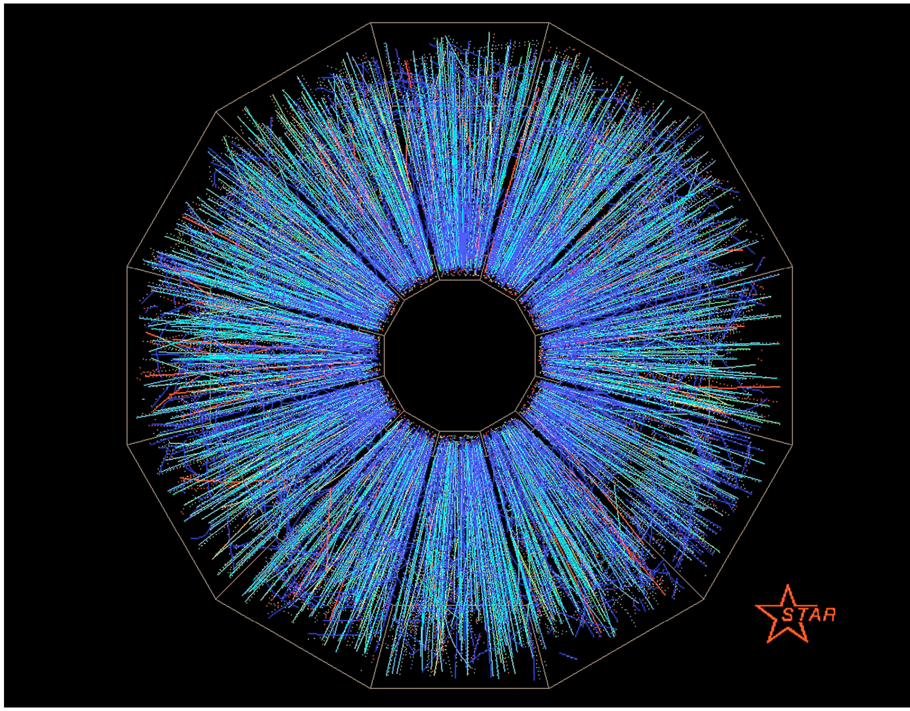
The near-side ridge in heavy ion collisions and long range rapidity correlations in QCD

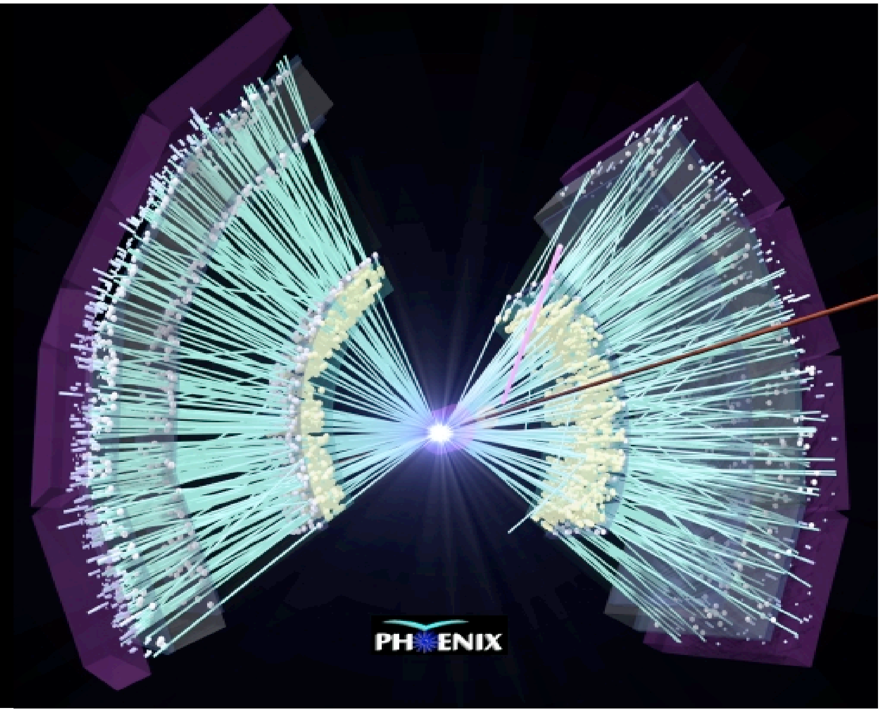
Raju Venugopalan

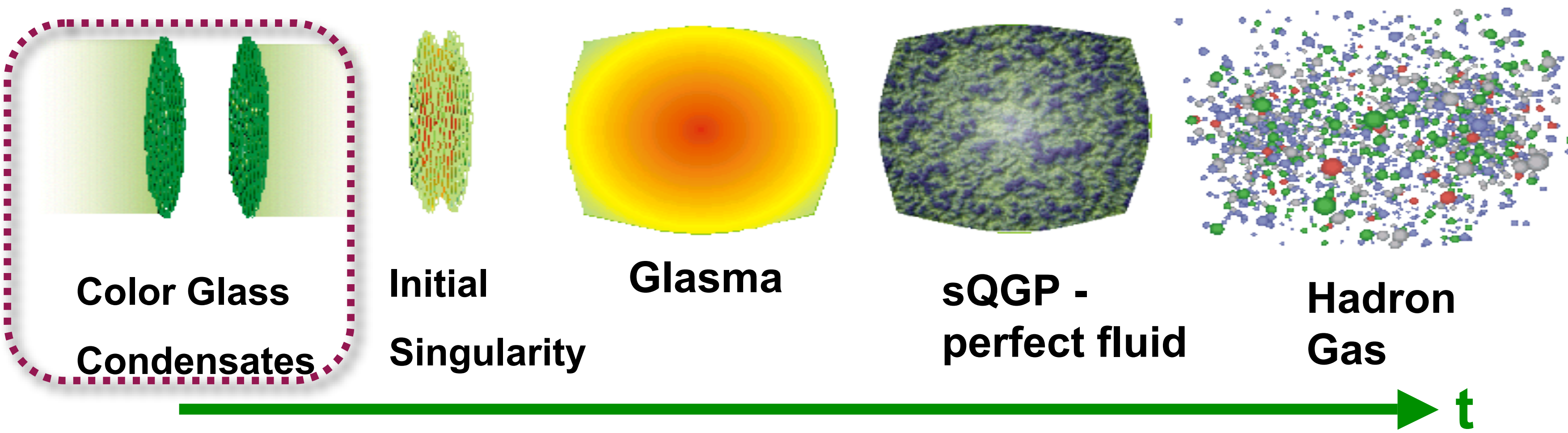
Brookhaven National Laboratory

Low x meeting, Ischia, September 9-12, 2009

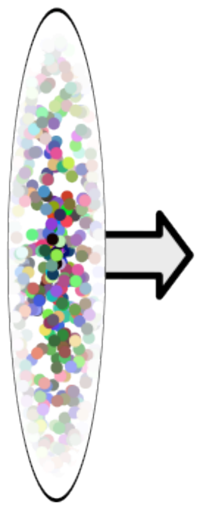
What does a heavy ion collision look like ?

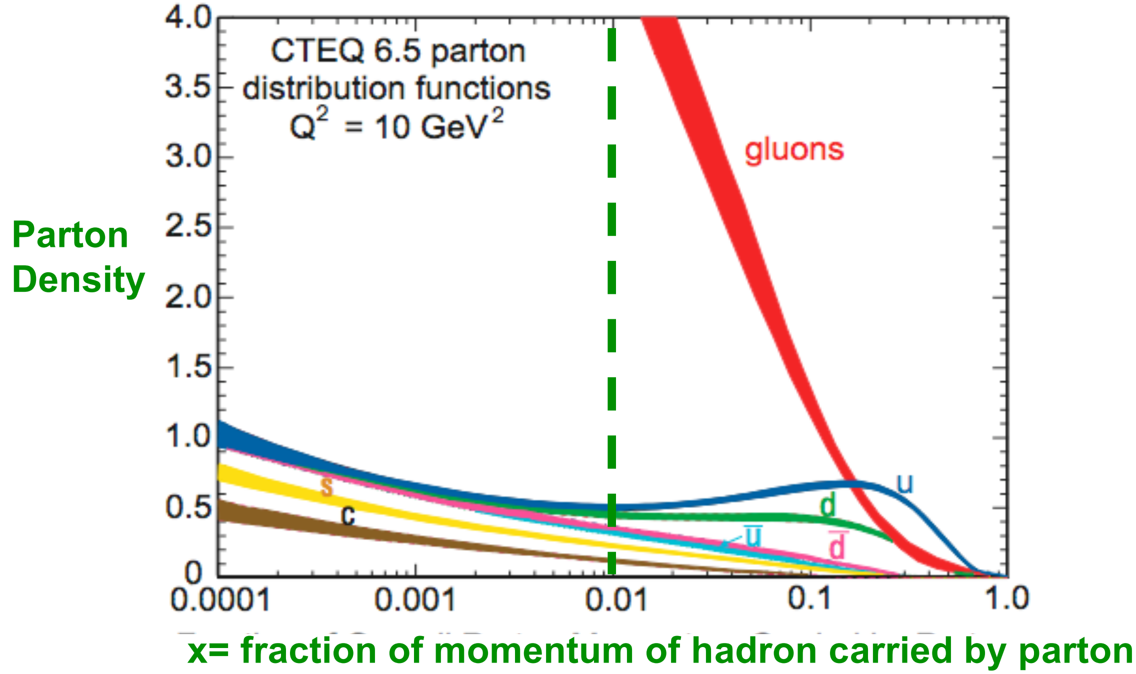






The nuclear wavefunction at high energies

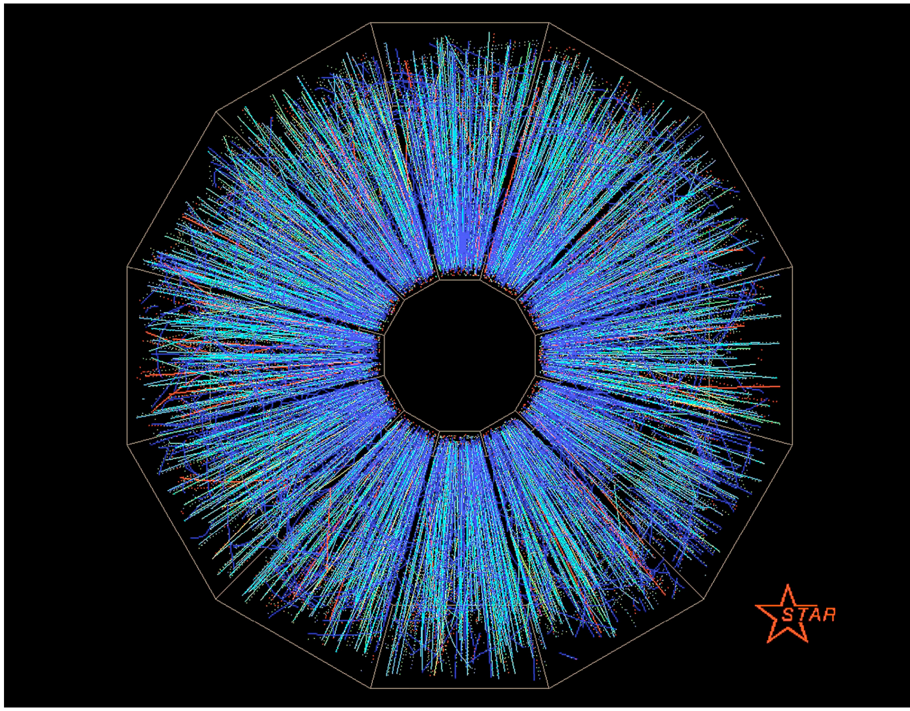


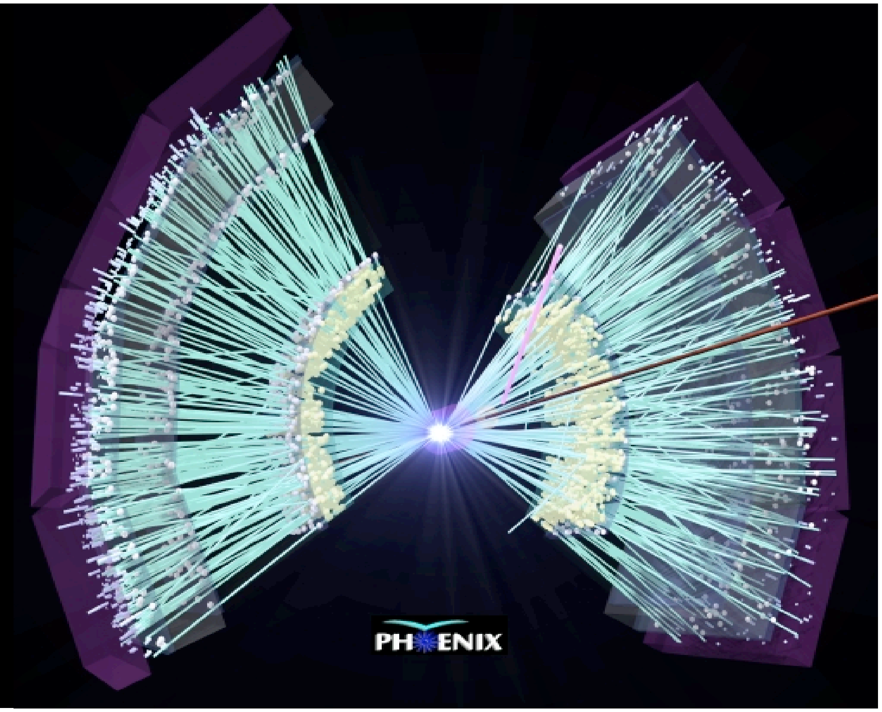


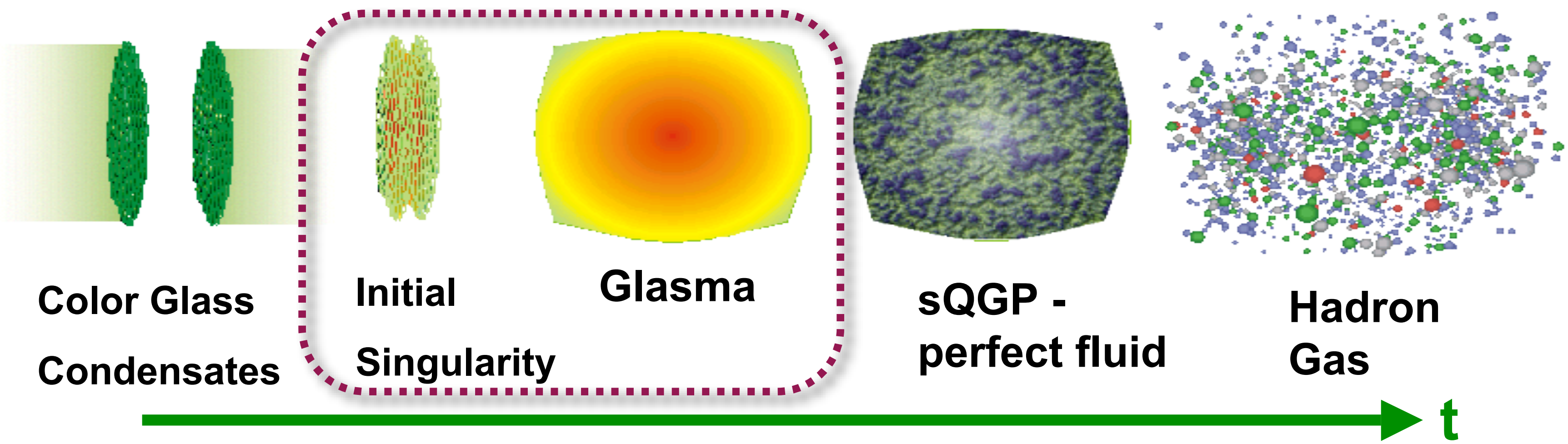
At RHIC typical x ~ 0.01 . At the LHC, x ~ 5 * 10^{-4} → Glue rules!

Nuclear wave function at high energies is a
Color Glass Condensate

What does a heavy ion collision look like ?







Forming a Glasma in the little Bang

Glasma (\Glahs-maa\): *Noun:* non-equilibrium matter between Color Glass Condensate (CGC)& Quark Gluon Plasma (QGP)

Lappi, McLerran

Forming a Glasma in the little Bang

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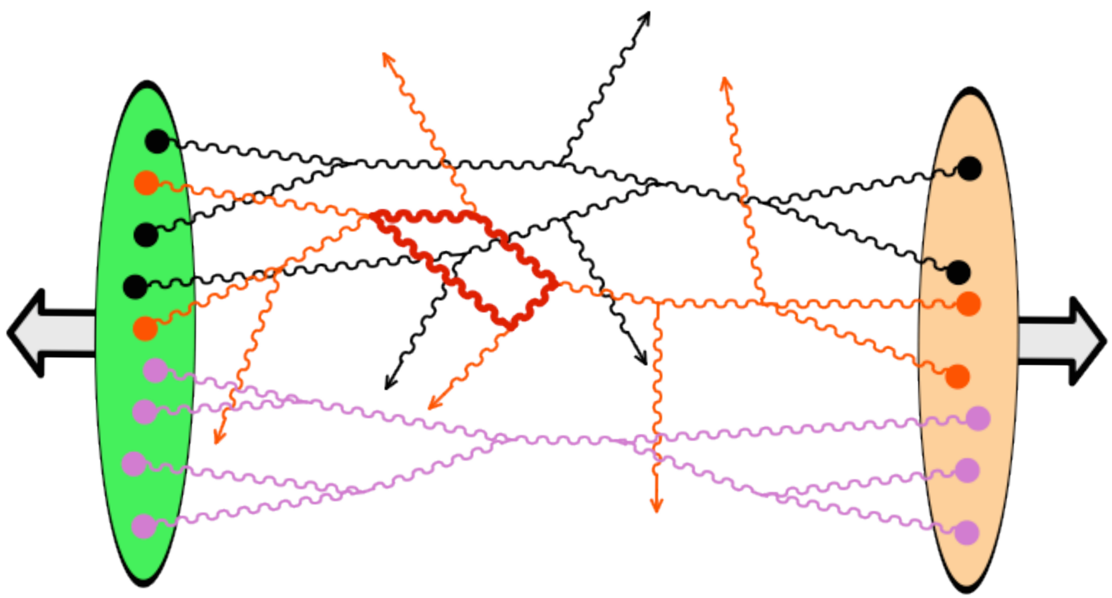
Lappi, McLerran



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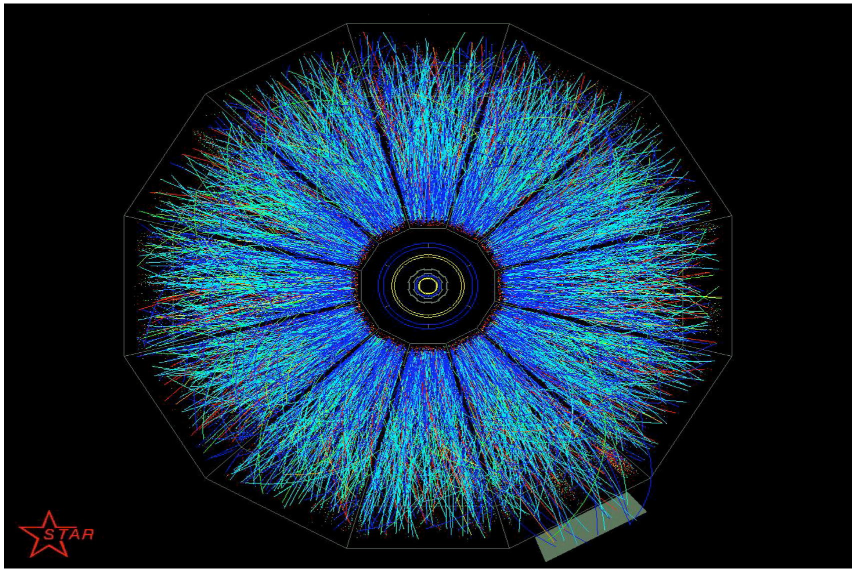

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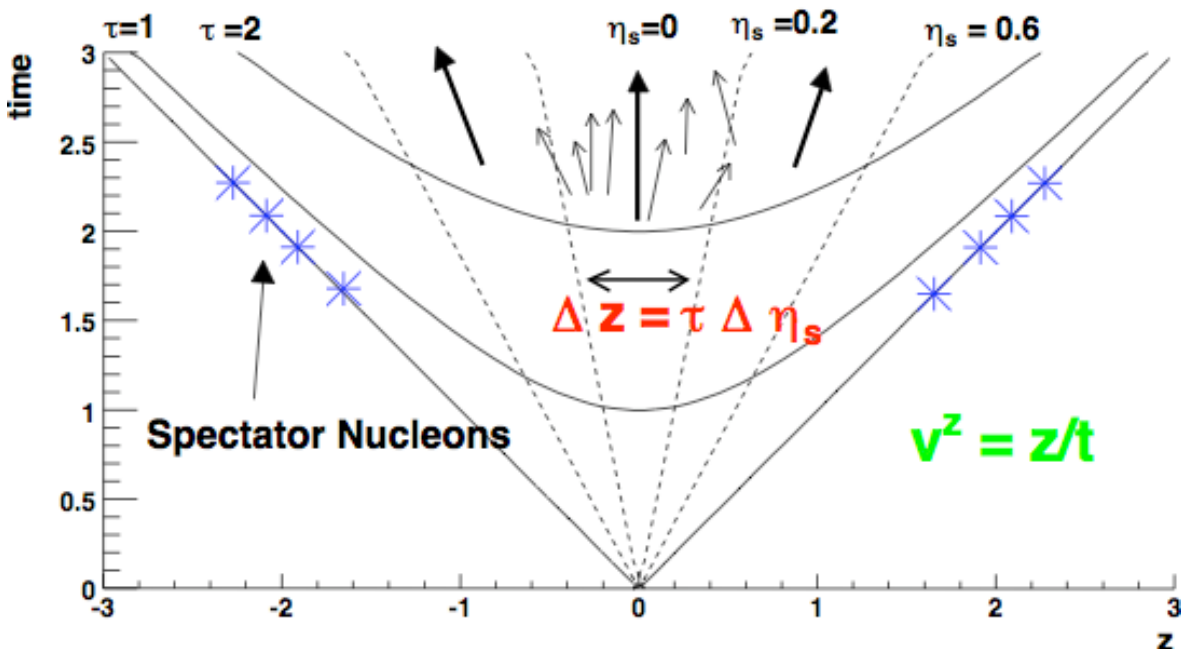
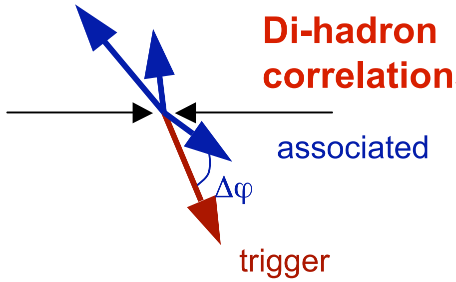
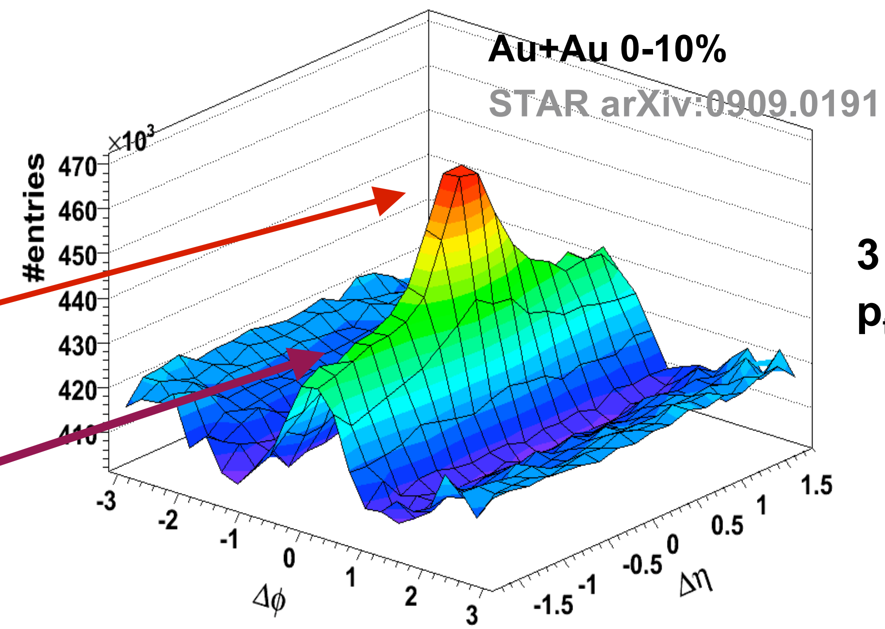


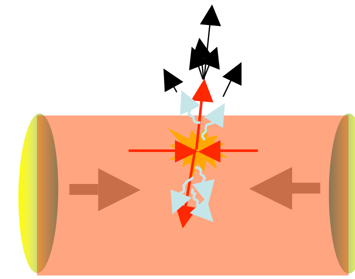
- **Problem: Compute particle production in QCD with *strong time dependent* sources** Gelis, RV, arXiv:hep-ph/ 0601209; 0605246
- **Solution: for early times ($t \leq 1/Q_S$) -- n-gluon production computed in A+A to all orders in pert. theory to leading log accuracy**
  Gelis, Lappi, RV; arXiv : 0804.2630, 0807.1306, 0810.4829

The near-side ridge

Di-hadron correlations





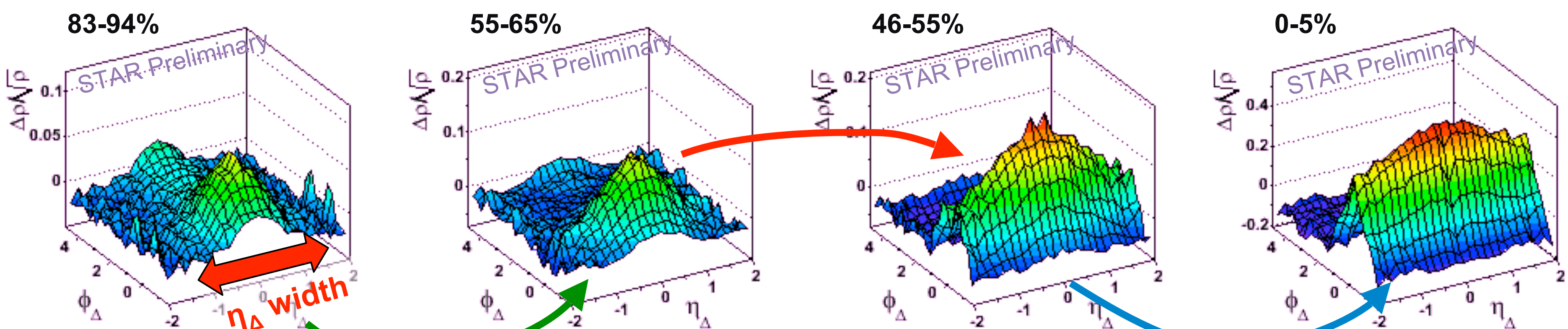


$3 < p_{t,trigger} < 4$ GeV

$p_{t,assoc.} > 2$ GeV

Near-side jet peak comparable to d+Au

Near-side Δη independent ridge

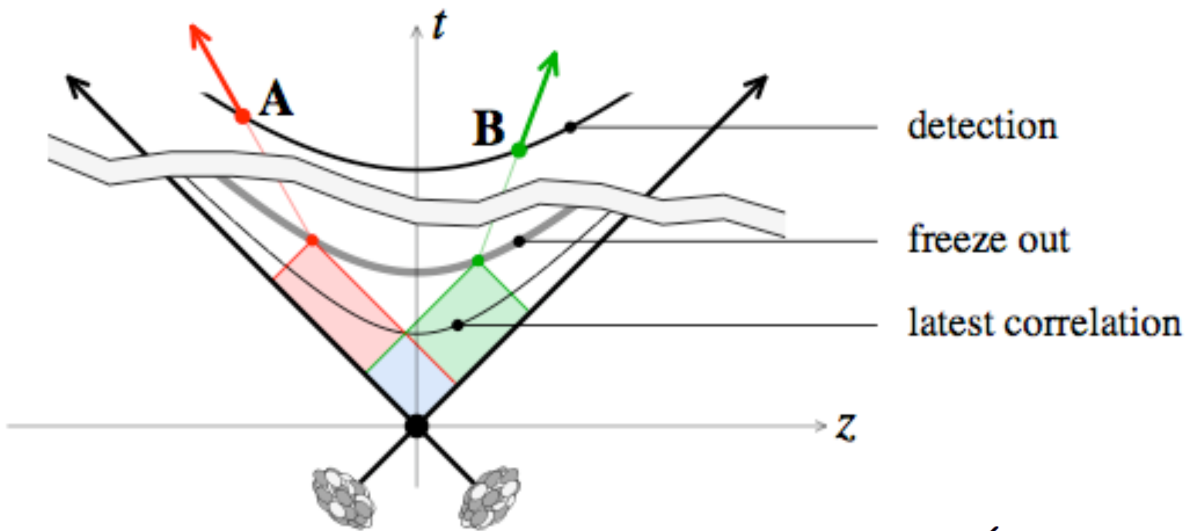


Little shape change from peripheral to 55% centrality

Large change within ~10% centrality

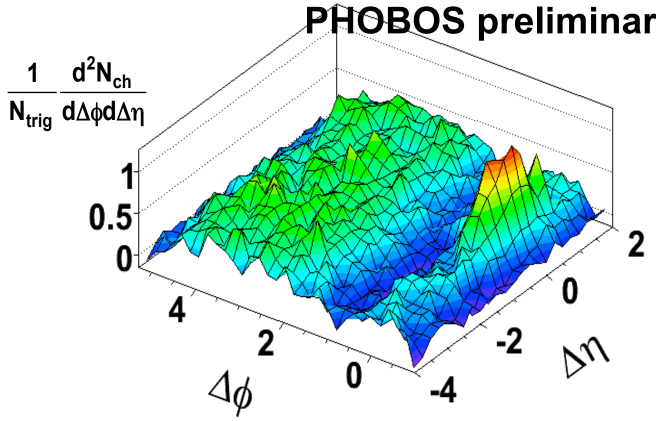
Smaller change from transition to most central

Imagining the Glasma



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

Au+Au 200 GeV, 0 - 30%
PHOBOS preliminary

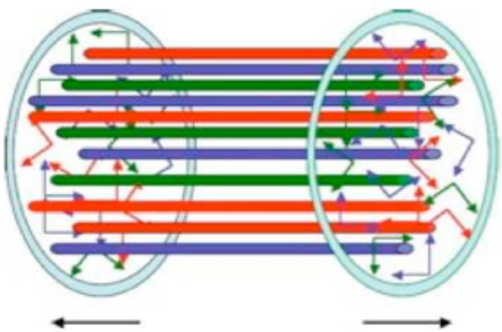


τ < 1 fm for Δy > 4

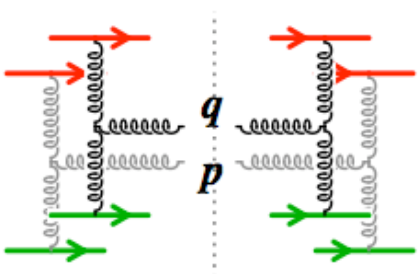
These correlations likely occur at early times…

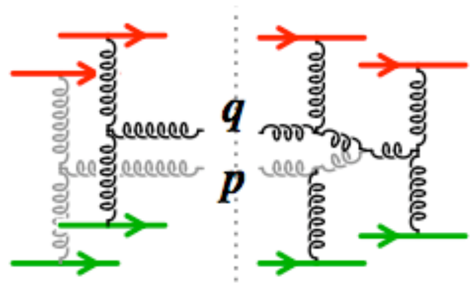
2 particle correlations in the Glasma: flux tubes

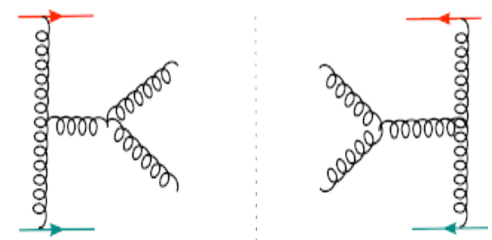
Dumitru, Gelis ,McLerran, RV, arXiv:0804.3858[hep-ph]



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







Independent gluon emission
from Glasma flux tube (near-side LRC)

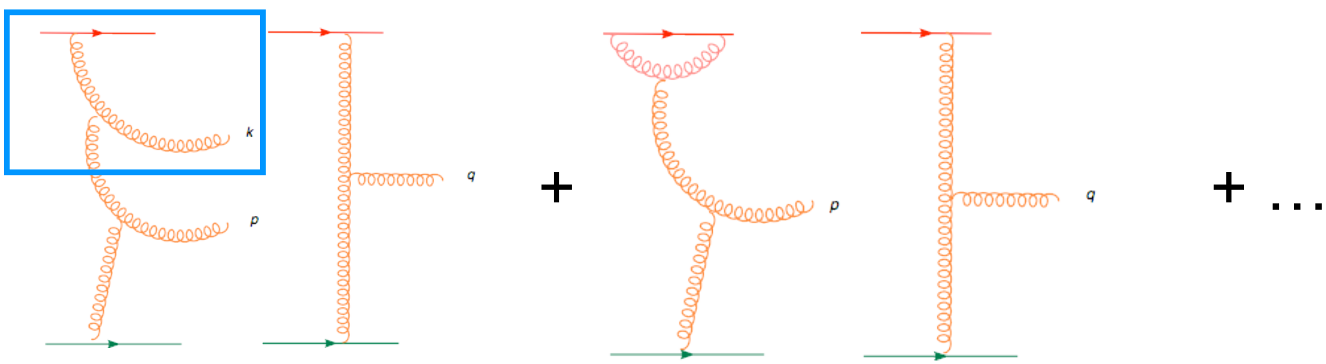
"pQCD" graphs
(near-side SRC)

- For Strong Color Sources (high energy/large nuclei/central collisions)
  Flux Tube Emission dominates "pQCD" by $1 / \alpha_s^2$

2 particle correlations in the Glasma (II)

RG evolution:

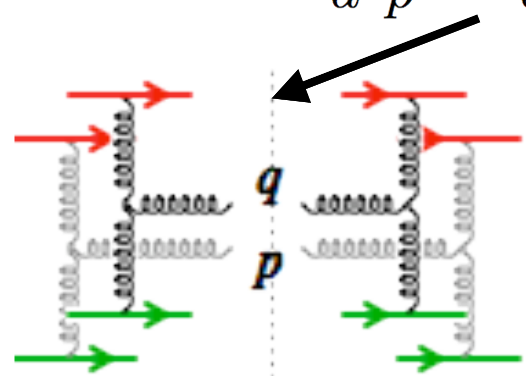
Gelis, Lappi, RV, arXiv: 0807.1306



Keeping leading logs to all orders (NLO+NNLO+…)
2-particle spectrum (for $\Delta y < 1/\alpha_S$) can be written as

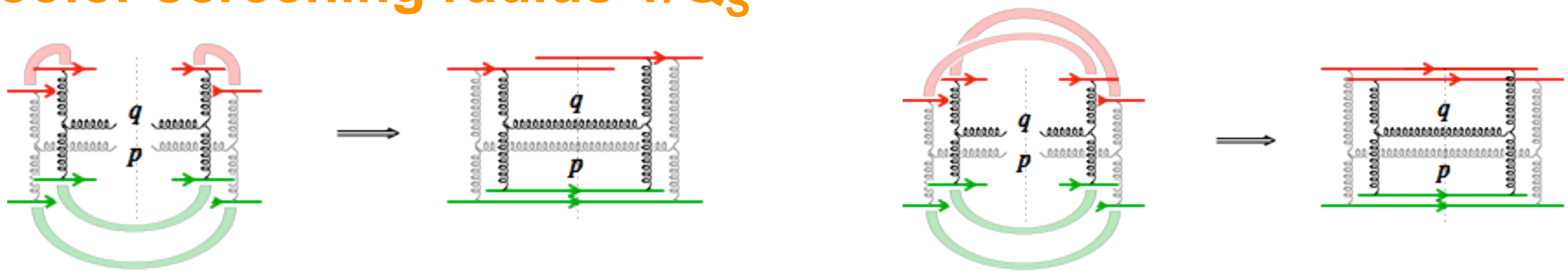
$$\langle \frac{dN_2}{d^3p\, d^3q} \rangle_{\rm LLogs} = \int [d\rho_1][d\rho_2] W_{Y_1}[\rho_1]\, W_{Y_2}[\rho_2]\, \frac{dN}{d^3p}|_{\rm LO}\, \frac{dN}{d^3q}|_{\rm LO}$$

= LO graph with evolved sources
Glasma flux tubes



2 particle correlations in the Glasma (III)

Correlations are induced by color fluctuations that vary event to event - these are local transversely and have color screening radius $1/Q_S$

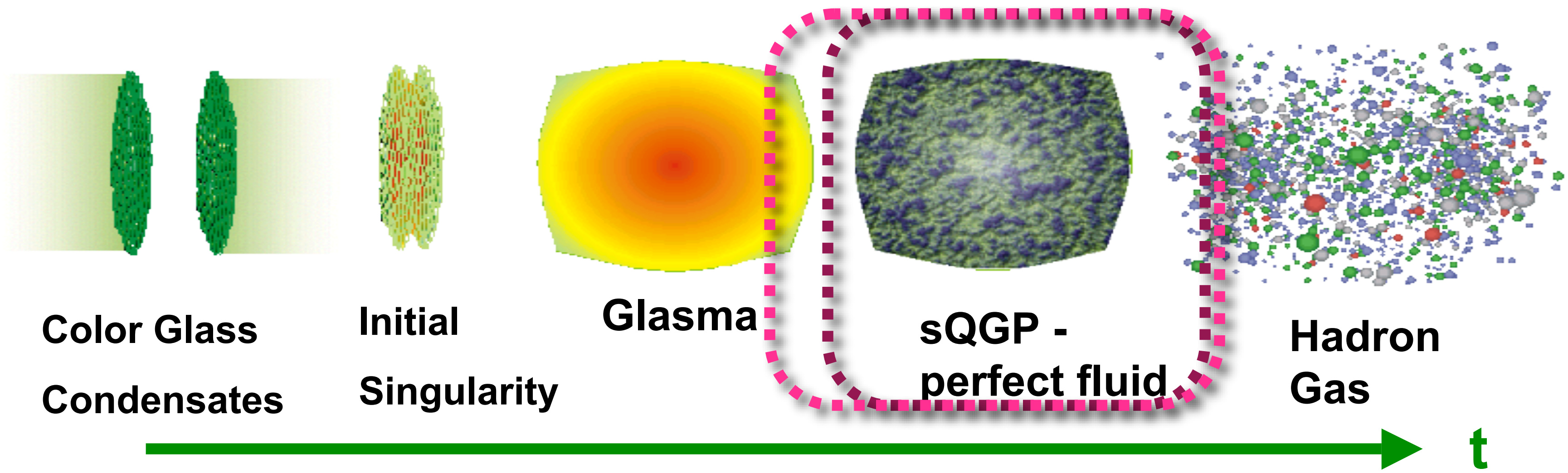


$$\frac{C(\mathbf{p},\mathbf{q})}{\left\langle \frac{dN}{dy_p\, d^2\mathbf{p}_\perp} \right\rangle \left\langle \frac{dN}{dy_q\, d^2\mathbf{q}_\perp} \right\rangle} = \frac{\kappa}{S_\perp Q_S^2}$$

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

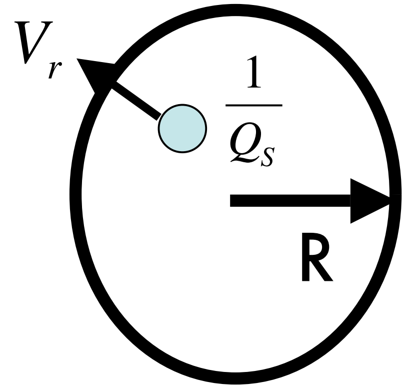
Simple "Geometrical" result:
strength of correlation
= area of flux tube / transverse area of nucleus

The Ridge and Glasma Flux tubes
- where theory meets model



The evolution of Glasma into the perfect fluid is not understood. Initial condition for hydro evolution requires modelling…

Soft Ridge = Glasma flux tubes + Radial flow



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

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

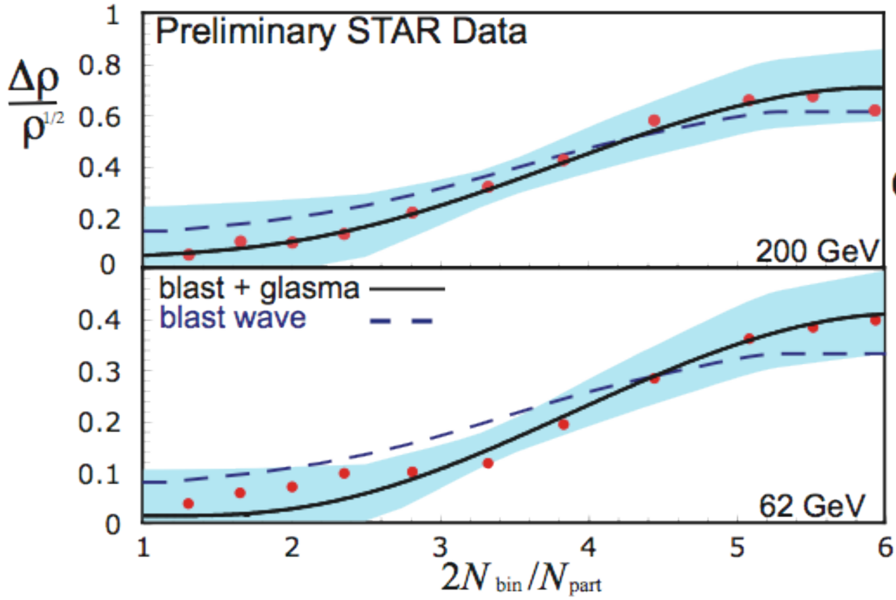
Can be computed non-perturbatively from numerical lattice simulations

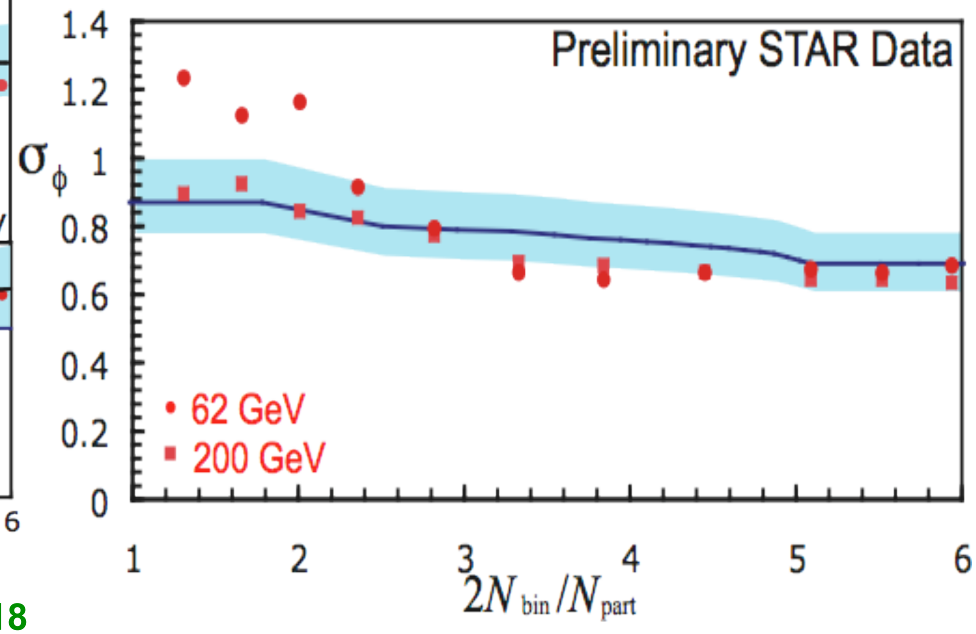
Srednyak,Lappi,RV

$\gamma_B = \cosh\zeta_B$ **from blast wave fits to spectra**

Q_S from centrality dependence of inclusive spectra

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 $\Delta\eta$

See also Lindenbaum and Longacre, arXiv:0809.3601, 0809.2286

Three particle Glasma correlations

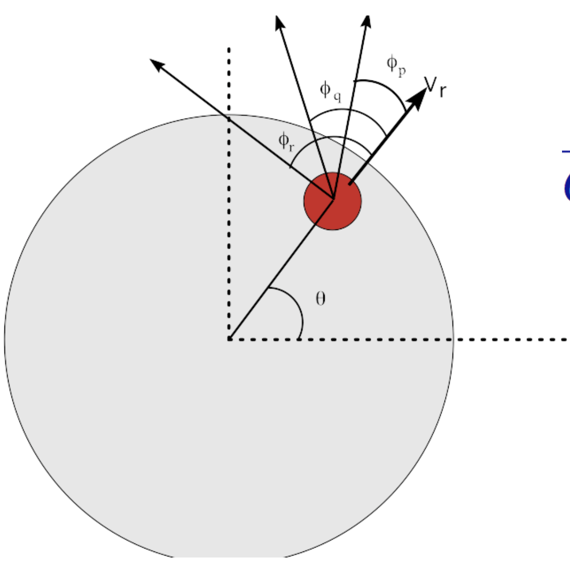
Dusling, Fernandez-Fraile, RV, arXiv:0902.4435 [nucl-th]

Three particle cumulant can be expressed as

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

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

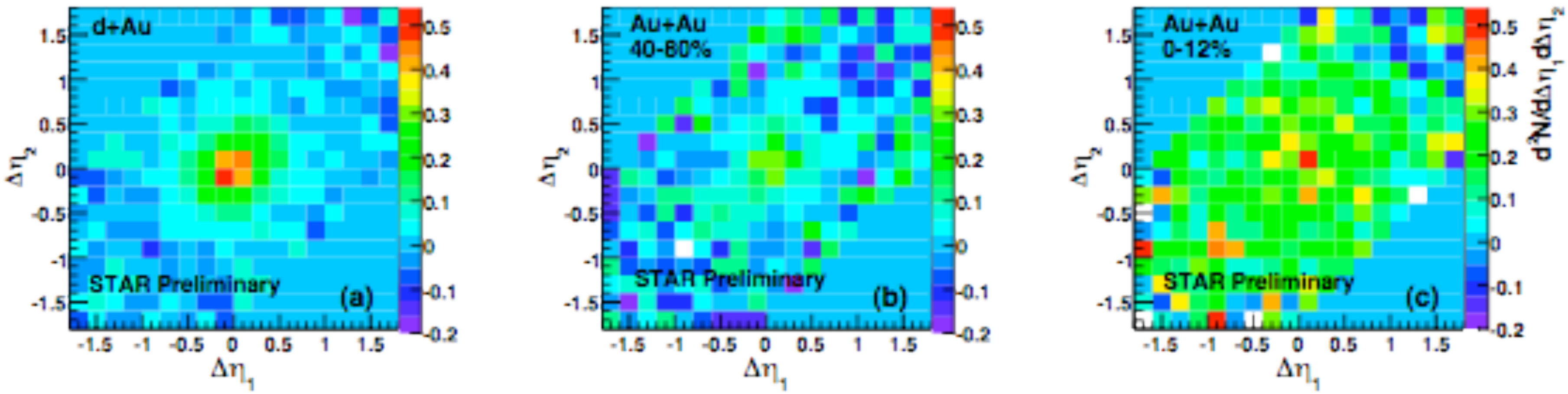
Distributions are radially boosted…



$$\frac{\tilde{C}_3(\Delta\phi_{pq},\Delta\phi_{pr})}{C_1 C_1 C_1(\Delta\phi_{pq},\Delta\phi_{pr}} = \frac{\kappa_3}{S_\perp^2 Q_S^4} \mathcal{A}(\Delta\phi_{pq},\Delta\phi_{pr},\zeta_B)$$

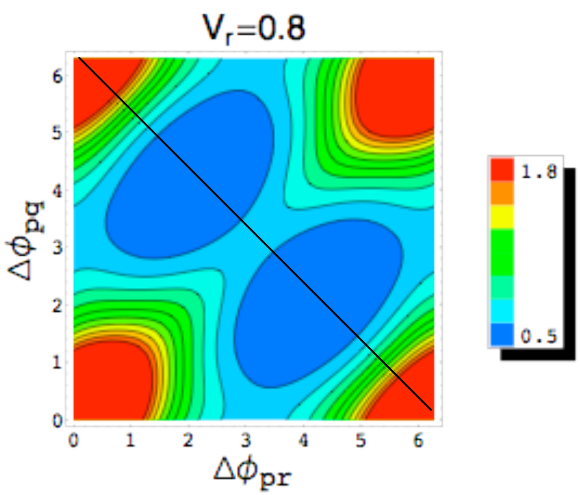
Radial Boost parameter

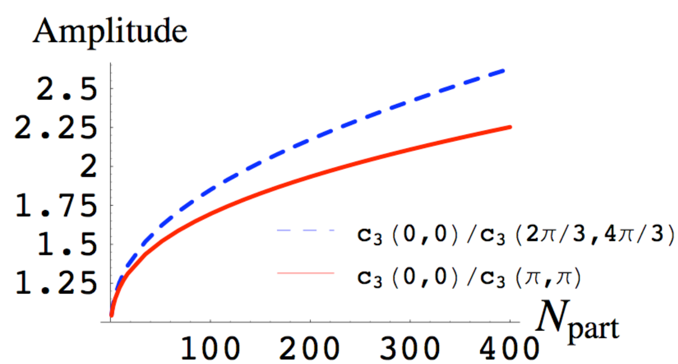
Three particle correlations uniform in $\Delta\eta_1 - \Delta\eta_2$



STAR, PRL 102:052302 (2009)

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 $N_{part.}$

"Glittering" Glasmas

Gelis,Lappi,McLerran, arXiv:0905.3234

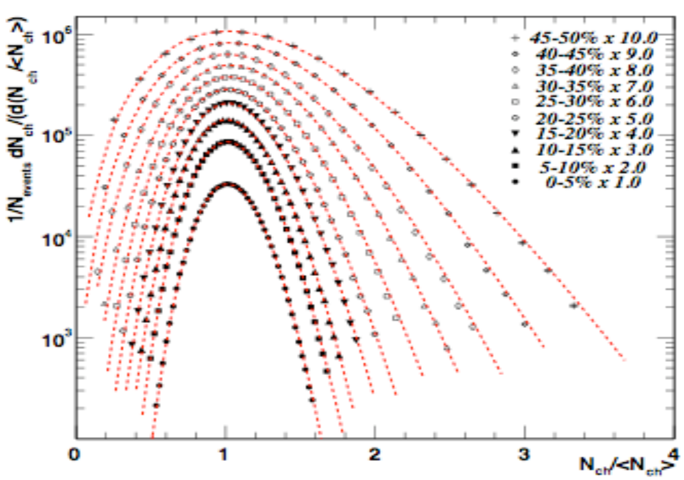
n-particle correlation can be expressed as

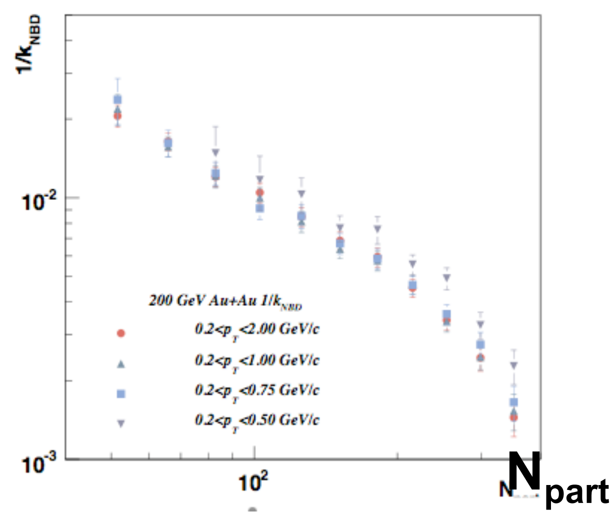
$$\left\langle \frac{d^n N}{dy_1 d^2\mathbf{p}_{\perp 1}\cdots dy_n d^2\mathbf{p}_{\perp n}} \right\rangle = \frac{(n-1)!}{k^{n-1}} \left\langle \frac{dN}{dy_1 d^2\mathbf{p}_{\perp 1}} \right\rangle \cdots \left\langle \frac{dN}{dy_n d^2\mathbf{p}_{\perp n}} \right\rangle$$

with $k = \zeta_n \frac{(N_c^2-1)Q_S^2 S_\perp}{2\pi}$

For k = 1, Bose-Einstein dist.
For k= ∞, Poisson Dist.

This is a negative binomial distribution which is known to describe well multiplicity distributions in hadronic and nuclear collisions

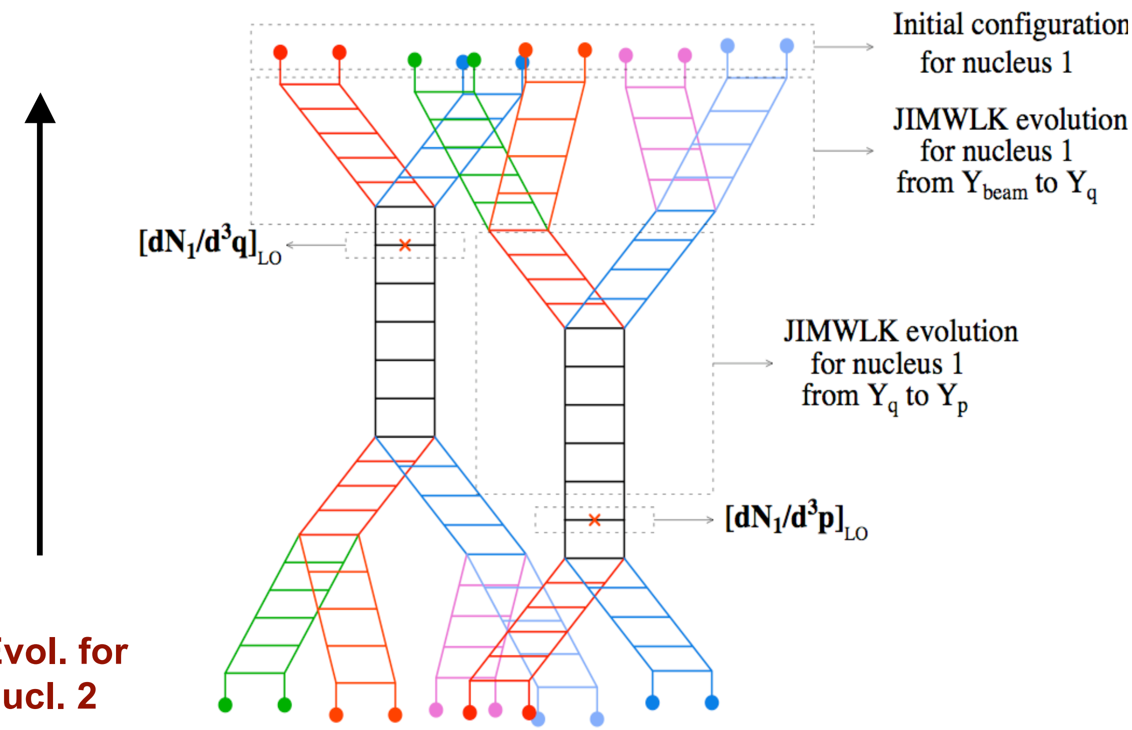




$$\sigma^2 = \bar{n} + \frac{\bar{n}^2}{k}$$

PHENIX
arXiv:0805.1521

Beyond boost inv. - Δη dependence of 2 Part. Corr.



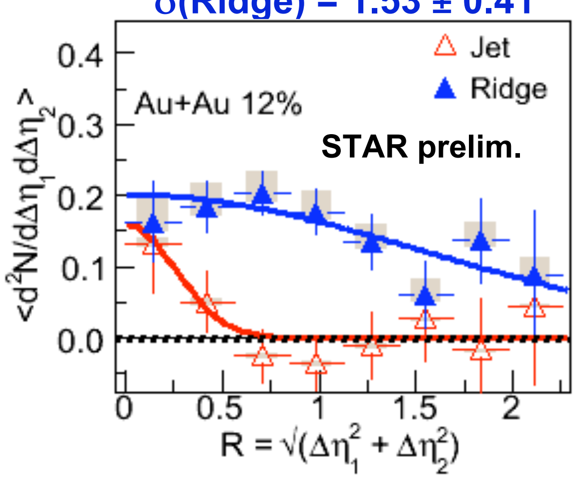
Evol. for nucl. 2

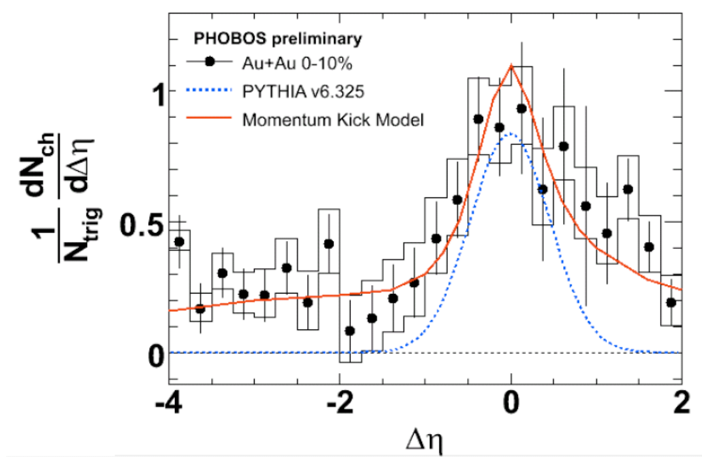
Formalism to compute $dN_2/d^3p\, d^3q$ *ab initio* for <u>arbitrary</u> rapidity separation ΔY_{pq}

Gelis,Lappi,RV arXiv:0810.4829

σ(Jet) = 0.25 ± 0.09

σ(Ridge) = 1.53 ± 0.41





Model comparison coming soon…

Dusling,Gelis,Lappi,RV

Piecing it all together

Remarkable features of RHIC data

- the presence of long range correlations strikingly seen in the ridge
- topological fluctuations and charge separation
- early “isotropization” and strong flow

are sensitive to the early time strong color field (Glasma) dynamics.

Glasma flux tubes may provide a unifying explanation of all these features

These ideas will be further tested and refined in future RHIC runs and at the LHC

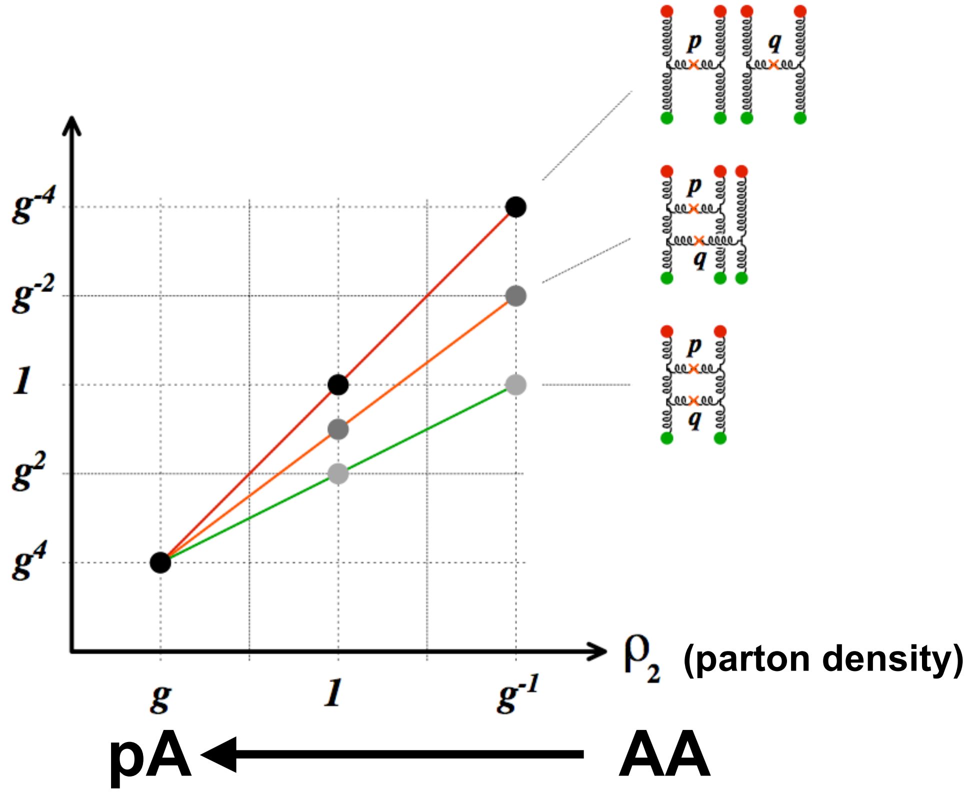
EXTRA SLIDES

The Long and the Short of LRC and SRC

Gelis,Lappi,RV

Strength of correlation

$dN_2/d^3p\, d^3q$



❖ For $p_\perp >> Q_S$ (1 GeV) expect SRC to dominate and LRC to diminish
However, because jet correlations die off so quickly,
phase space dominance extends naïve regime of validity
of LRC to large $p_\perp$

-- this argument can and should be quantified further.

Comparison of models by Nagle, QM09

i) "Causation" models: purely final state models

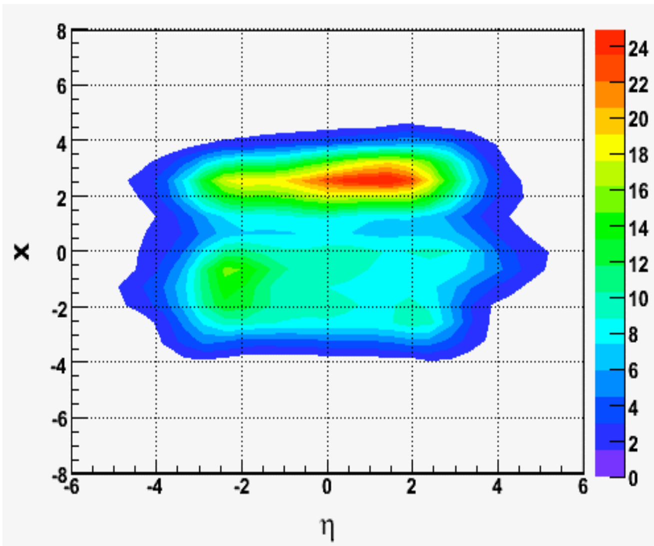
Longitudinal collective flow, Momentum kick, Broadening in turbulent color fields,…

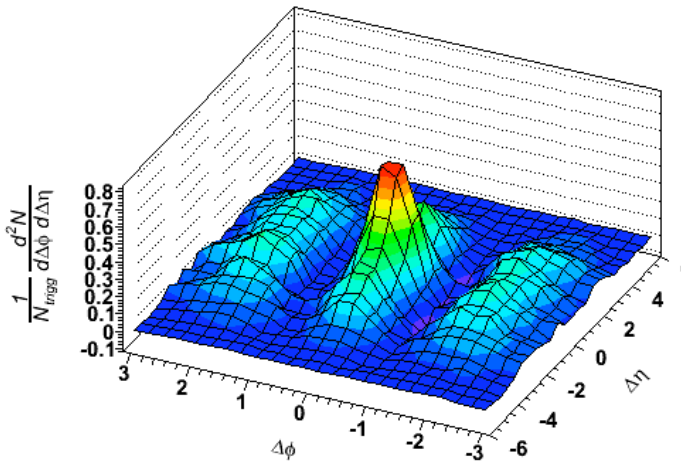
Difficult to get independence of trigger, width in $\Delta\eta$
Momentum kick model gets it but perhaps too wide in $\Delta\phi$

ii) "Auto-correlation" models: LRC from initial state and collimation in azimuth from boosted flow

Glasma flux tube, Parton Bubble, see also related model by Shuryak

Improving the Glasma flux tube model





Jun Takahashi et al.
arXiv:0902.4870

~~NEXUS initial condition~~ Glasma flux tube initial condition

+ SPHERIO hydro evolution

+ Cooper-Frye freezeout