The CMS ridge and a many body theory of wee glue

Raju Venugopalan

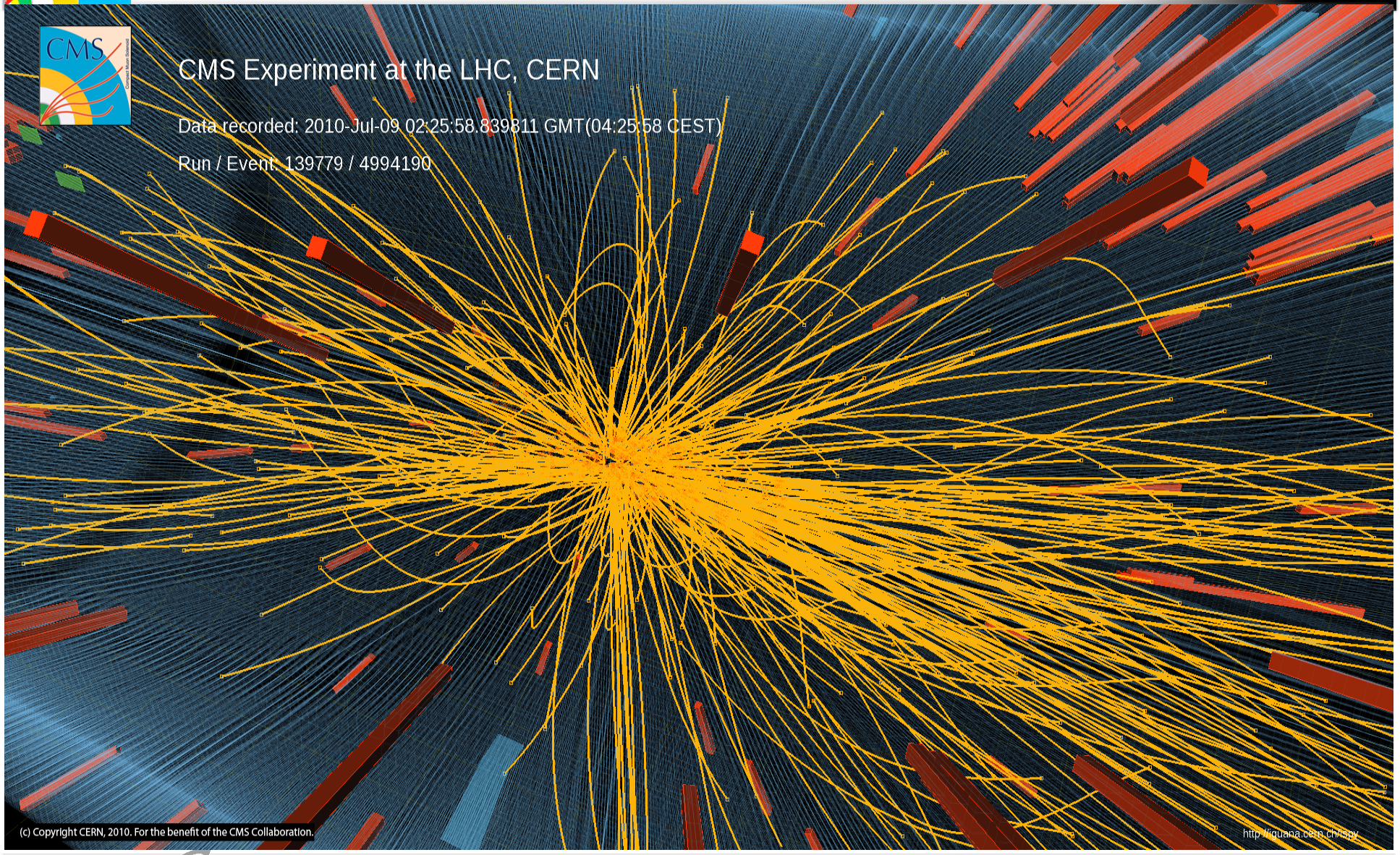
Brookhaven National Laboratory

Aspen Winter Workshop, February 12-18, 2011

Talk Outline

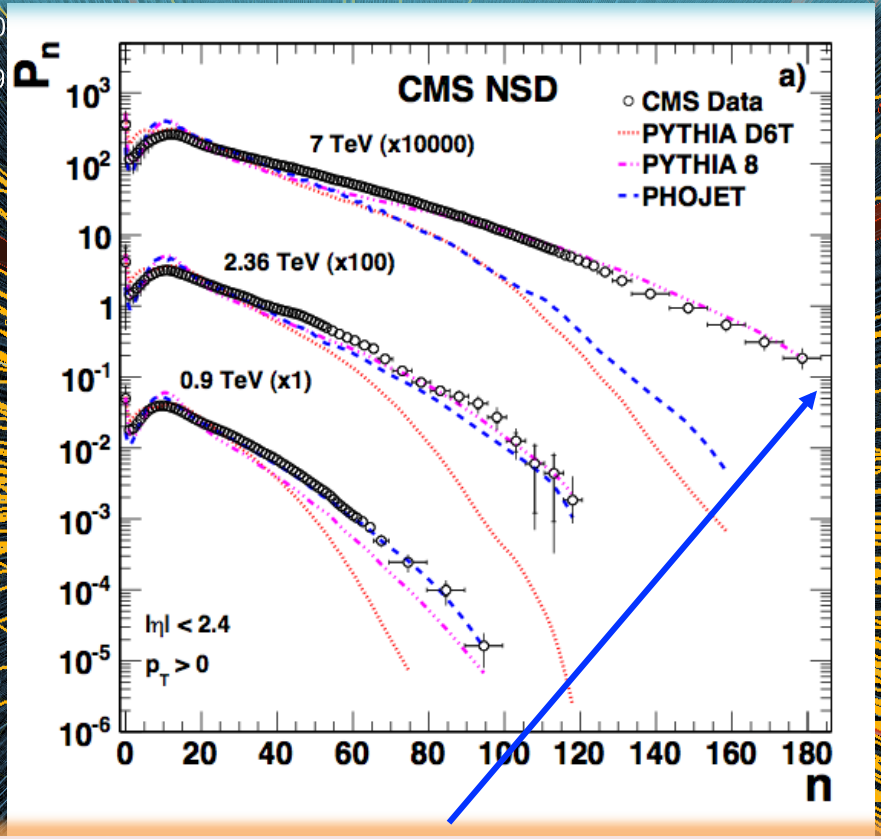
- The CMS ridge
- Parton saturation & Color Glass Condensate
  in Regge-Gribov asymptotics $\left(Q^2 >> \Lambda^2_{\rm QCD} \equiv \text{fixed}; s \to \infty, x \to 0\right)$
- Explanation of the ridge in the CGC EFT
- The ridge and early time dynamics in heavy ion collisions
  at RHIC and LHC

High Multiplicity pp collisions



High Multiplicity pp collisions

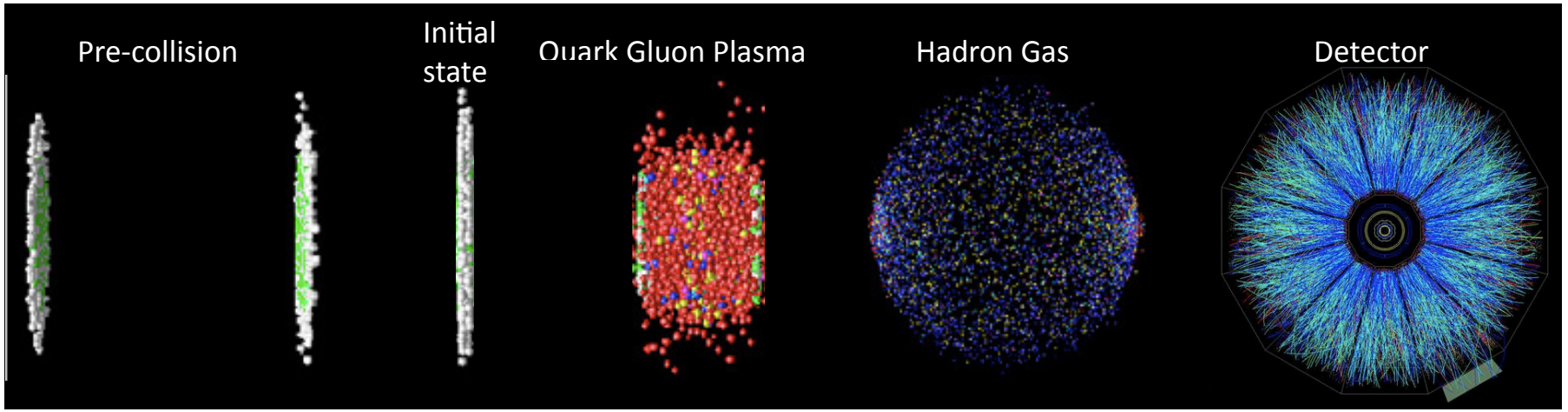
High Multiplicity events are rare in nature



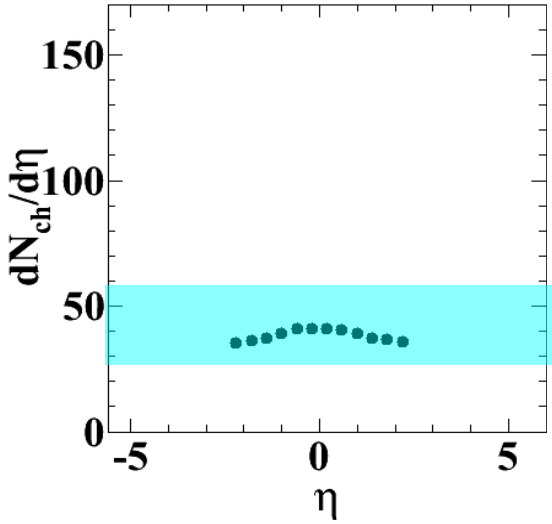
Very high particle density regime

Is there anything peculiar happening there?

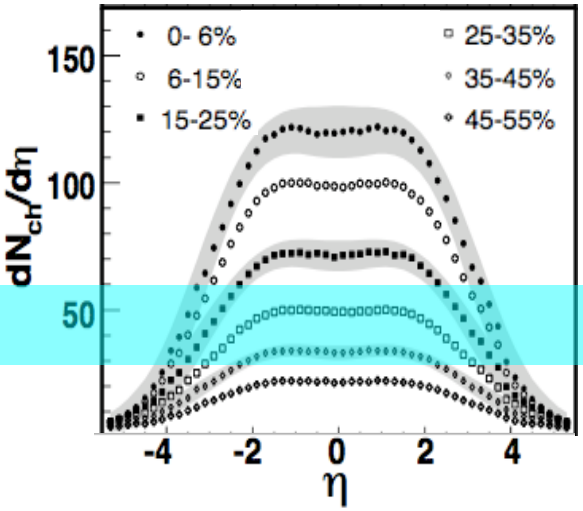
Relativistic Heavy Ion Collisions



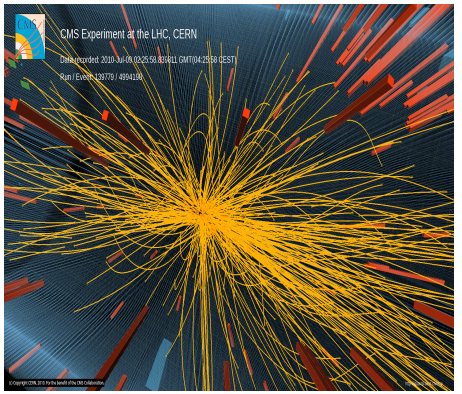
CMS pp 7TeV, N>110



PHOBOS CuCu 62.4GeV



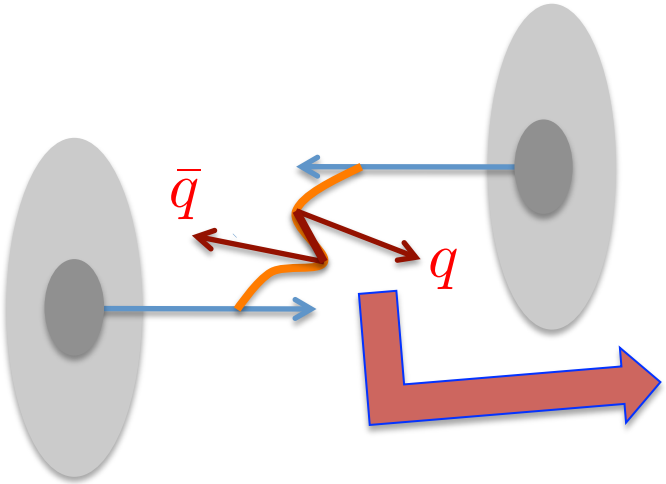
?



The p+p ridge

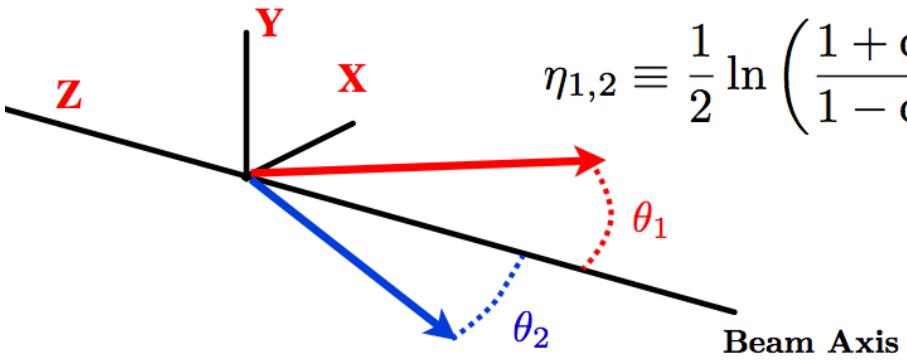
CMS reports a remarkable structure seen in two particle correlation spectrum as a function of angular variables Δη, ΔΦ in very high multiplicity p+p collisions

CMS, arXiv:1009.4122

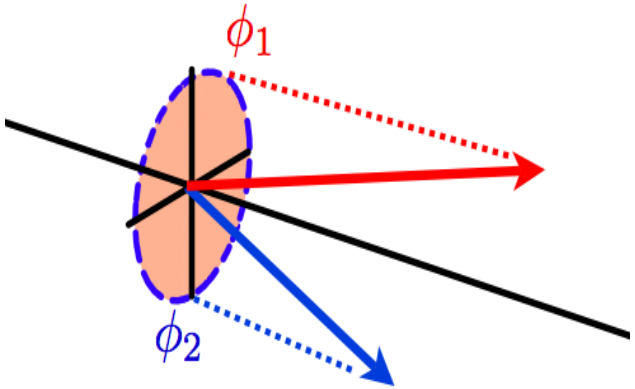


Back to back jet correlation in p+p

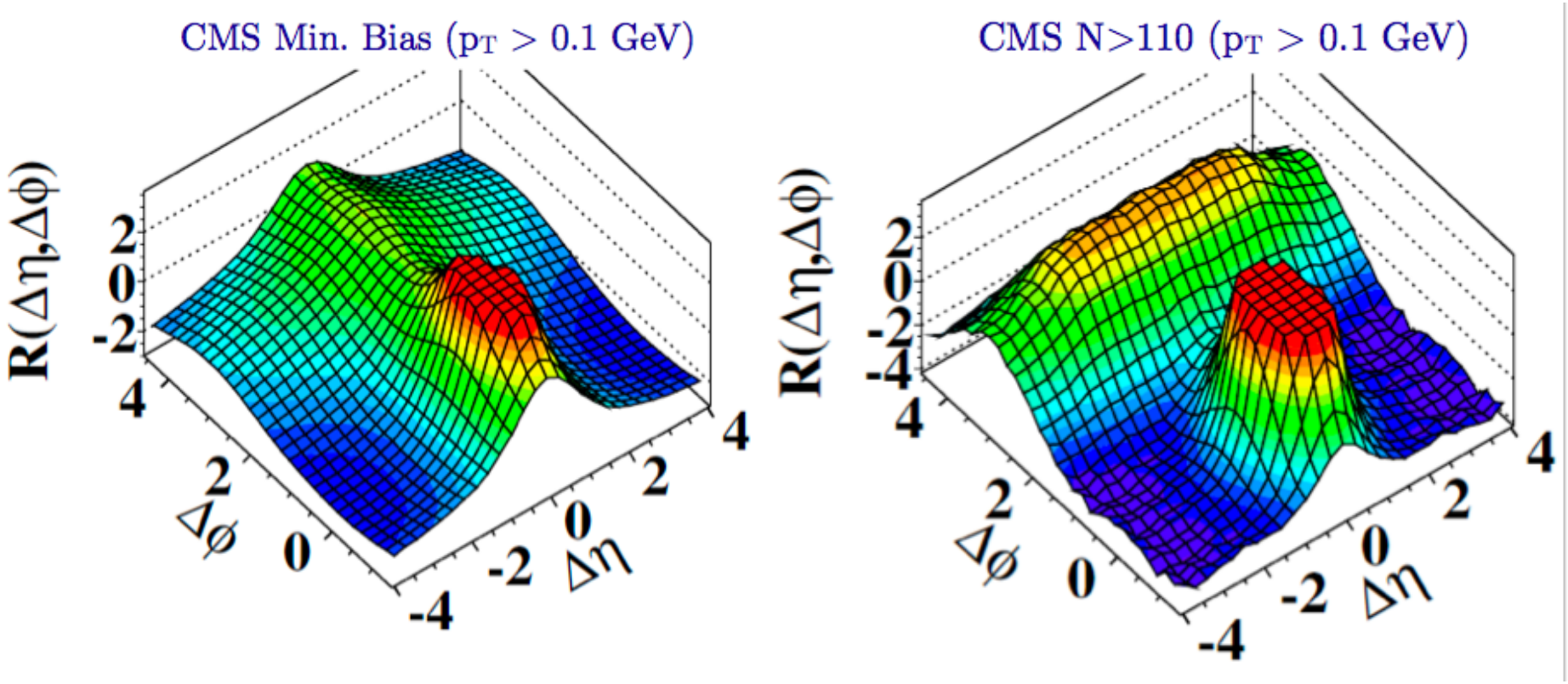
Collision Geometry:



$$\eta_{1,2} \equiv \frac{1}{2} \ln \left(\frac{1 + \cos\theta_{1,2}}{1 - \cos\theta_{1,2}} \right)$$

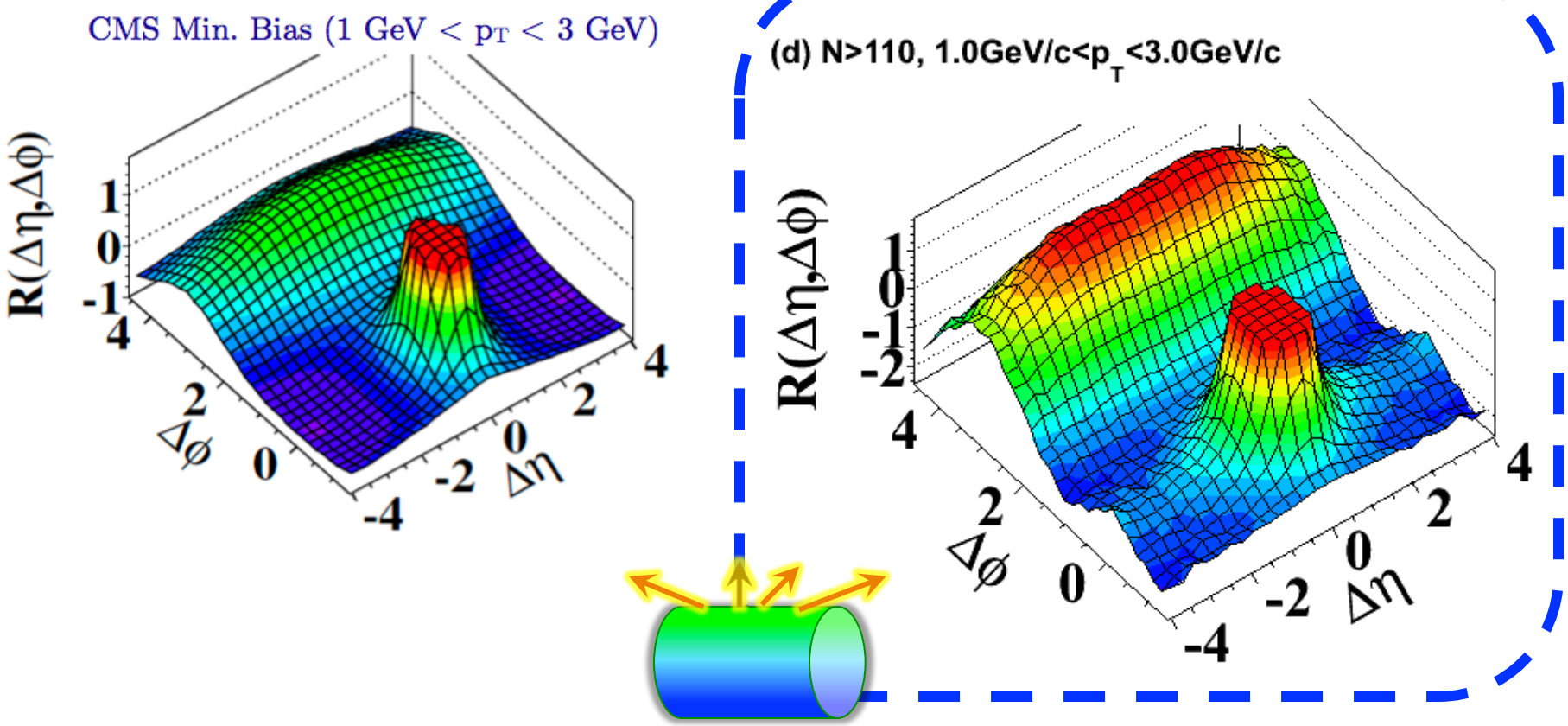


Two particle correlations: CMS results



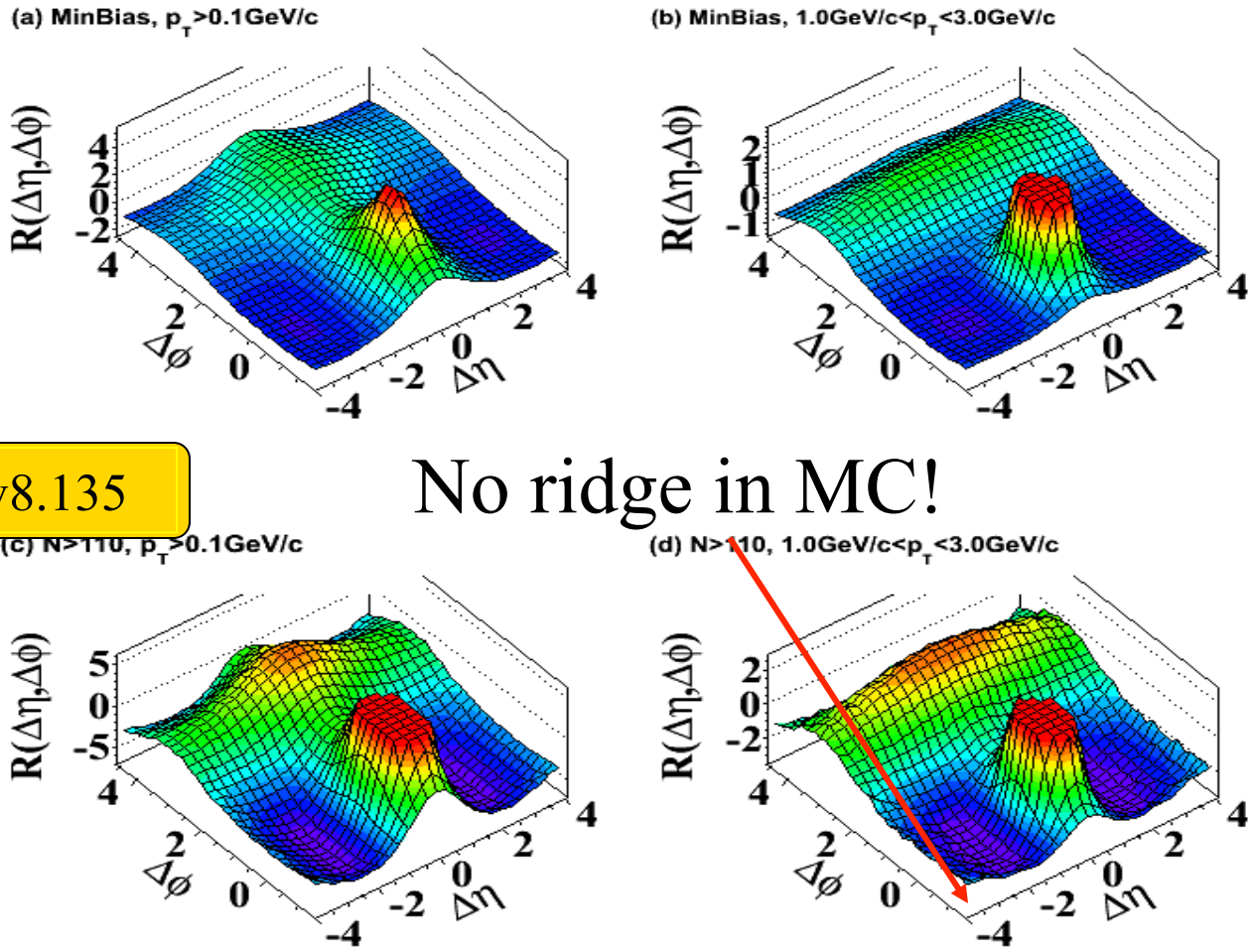
Two particle correlations: CMS results

"Discovery"



- **Ridge: Distinct long range correlation in η collimated around ΔΦ≈ 0 for two hadrons in the intermediate $1 < p_T, q_T < 3$ GeV**

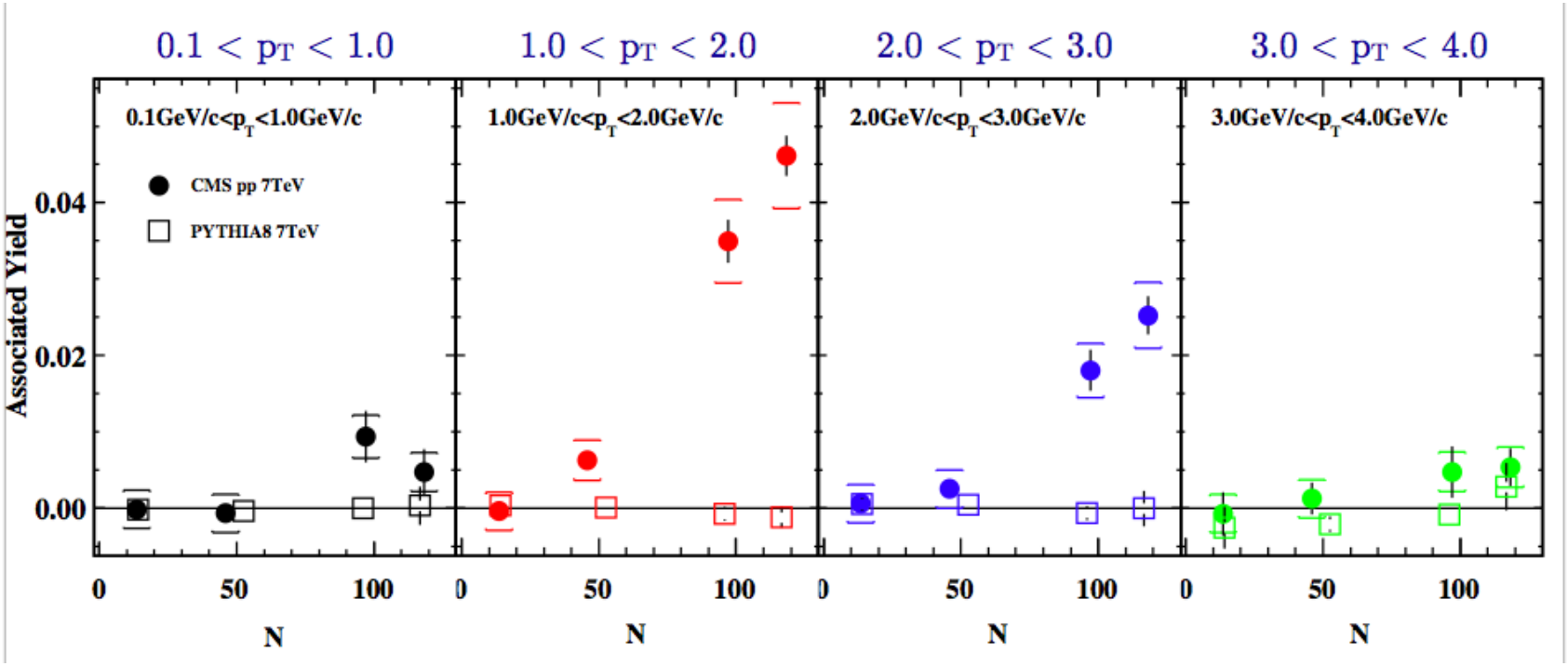
Comparing to MC models



PYTHIA8, v8.135

No ridge in MC!

Two particle correlations: p_T systematics



- Signal not present for p_T, q_T > 3 GeV

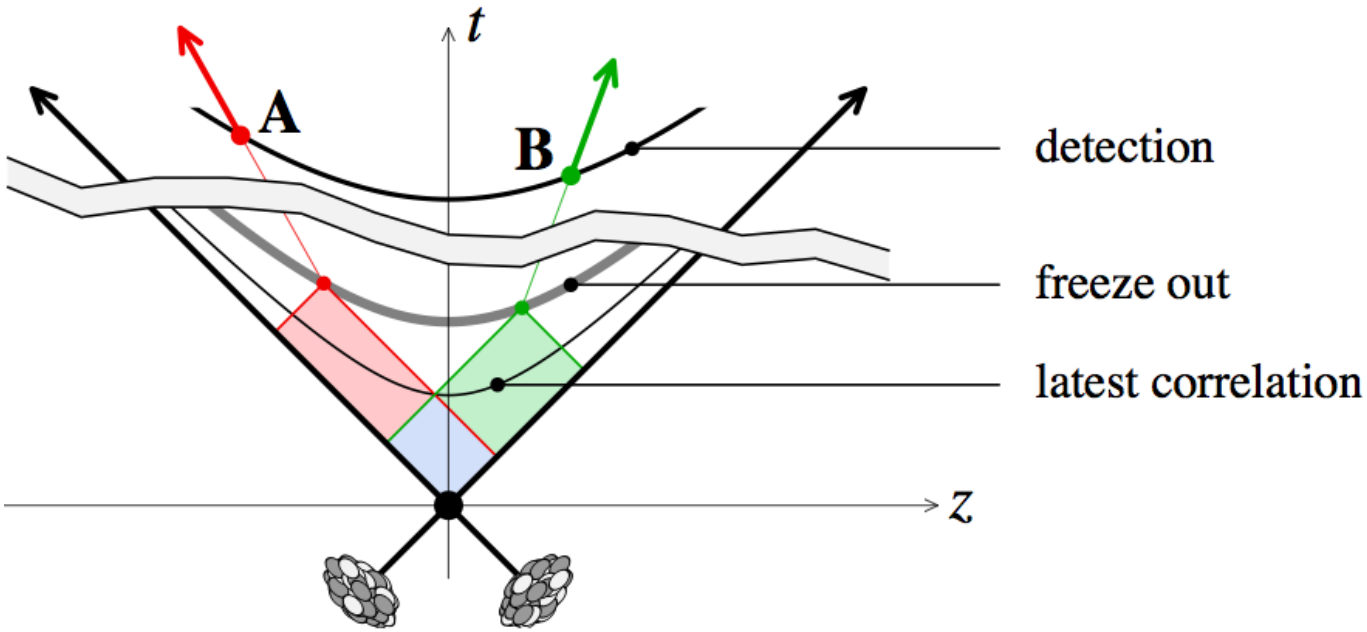
What's the underlying dynamics?

- Large number of models with a range of speculations

- A similar ridge was seen in heavy ion collisions @ RHIC (and now in HI collisions @ LHC) -is it hydrodynamic flow ?

- I will argue that the p+p ridge is an intrinsic QCD effect - providing a snapshot of frozen wee (small x) multi-parton correlations in the proton wave function

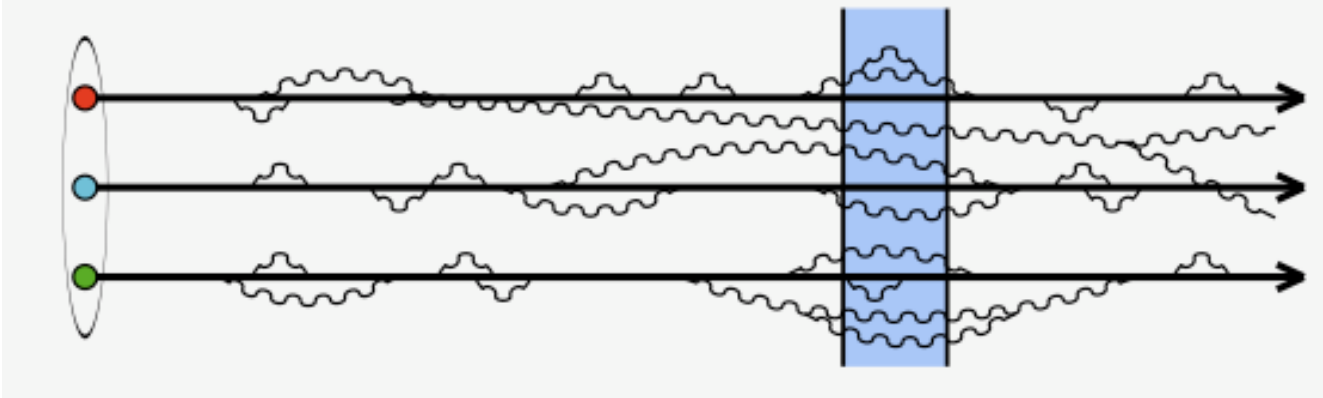
Long range rapidity correlations as a chronometer



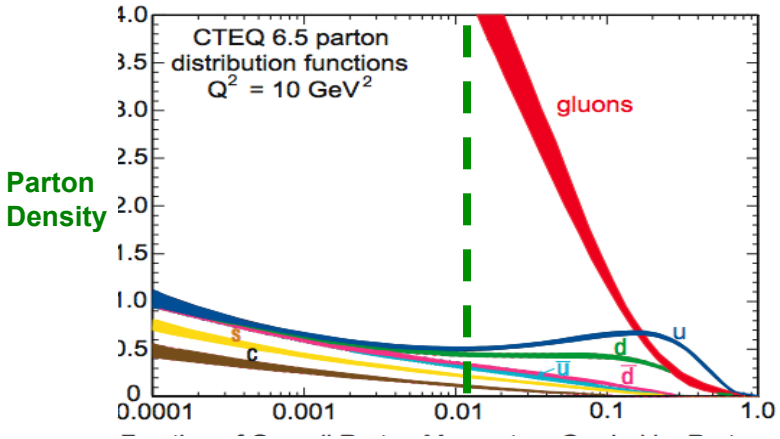
$$\tau \leq \tau_{\text{frz-out}} \exp\left(-\frac{1}{2}|y_A - y_B|\right)$$

- Long range correlations sensitive to very early time (fractions of a femtometer ~ 10^{-24} seconds) dynamics in collisions

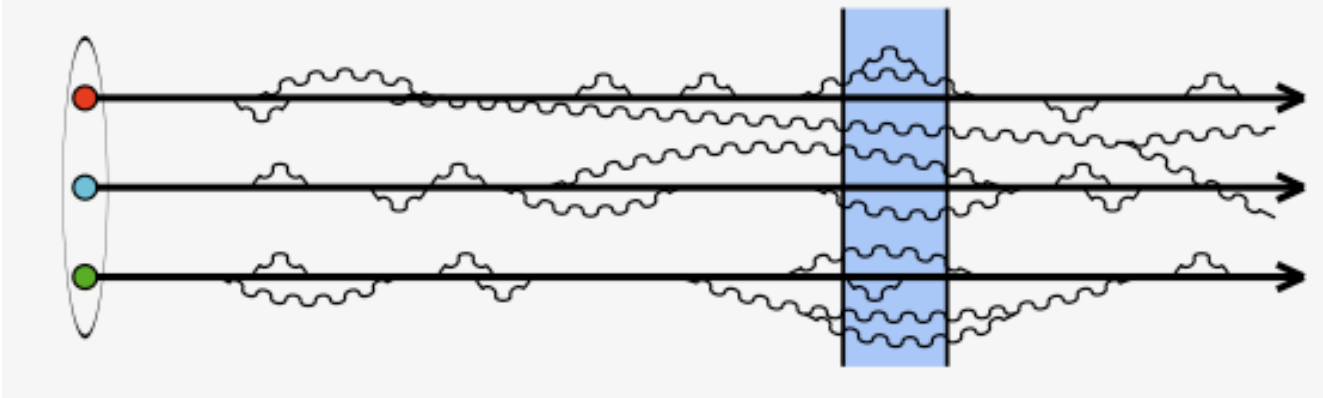
Gluon Saturation in a nucleus: classical coherence from quantum fluctuations



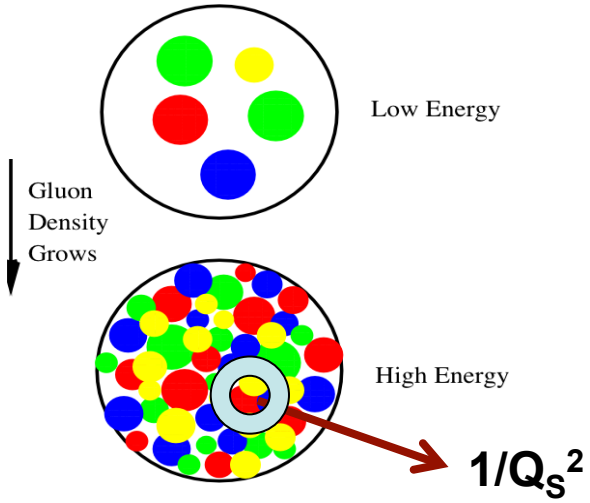
Wee parton fluctuations time dilated on strong interaction time scales



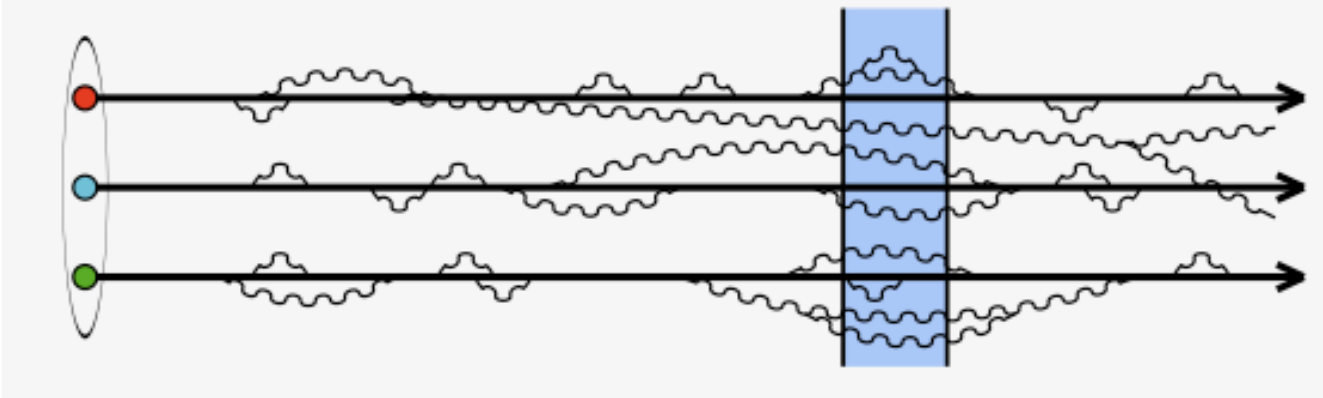
Gluon Saturation in a nucleus: classical coherence from quantum fluctuations



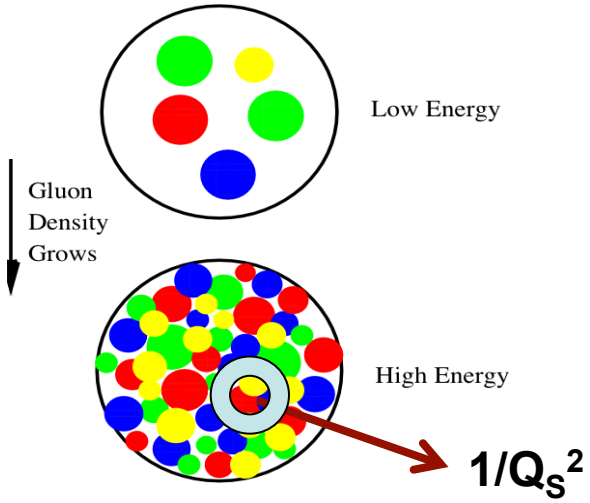
Wee parton fluctuations time dilated on strong interaction time scales



Gluon Saturation in a nucleus: classical coherence from quantum fluctuations



Wee parton fluctuations time dilated on strong interaction time scales



The gluon density saturates at a maximal value of ~ $1/\alpha_S$

➔ **gluon saturation**

Large occupation # => classical color fields

Many-body high energy QCD: The Color Glass Condensate

Gelis,Iancu,Jalilian-Marian,RV:
Ann. Rev. Nucl. Part. Sci. (2010), arXiv: 1002.0333

- QCD light front EFT framework of static light front color sources ρ^a and dynamical gauge fields A^a_μ

$$\langle \mathcal{O} \rangle_Y = \int [d\rho] W_Y[\rho]\, \mathcal{O}$$

- Functional RG from requiring observables be independent of separation of fast (large x) and slow (small x) degrees of freedom

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

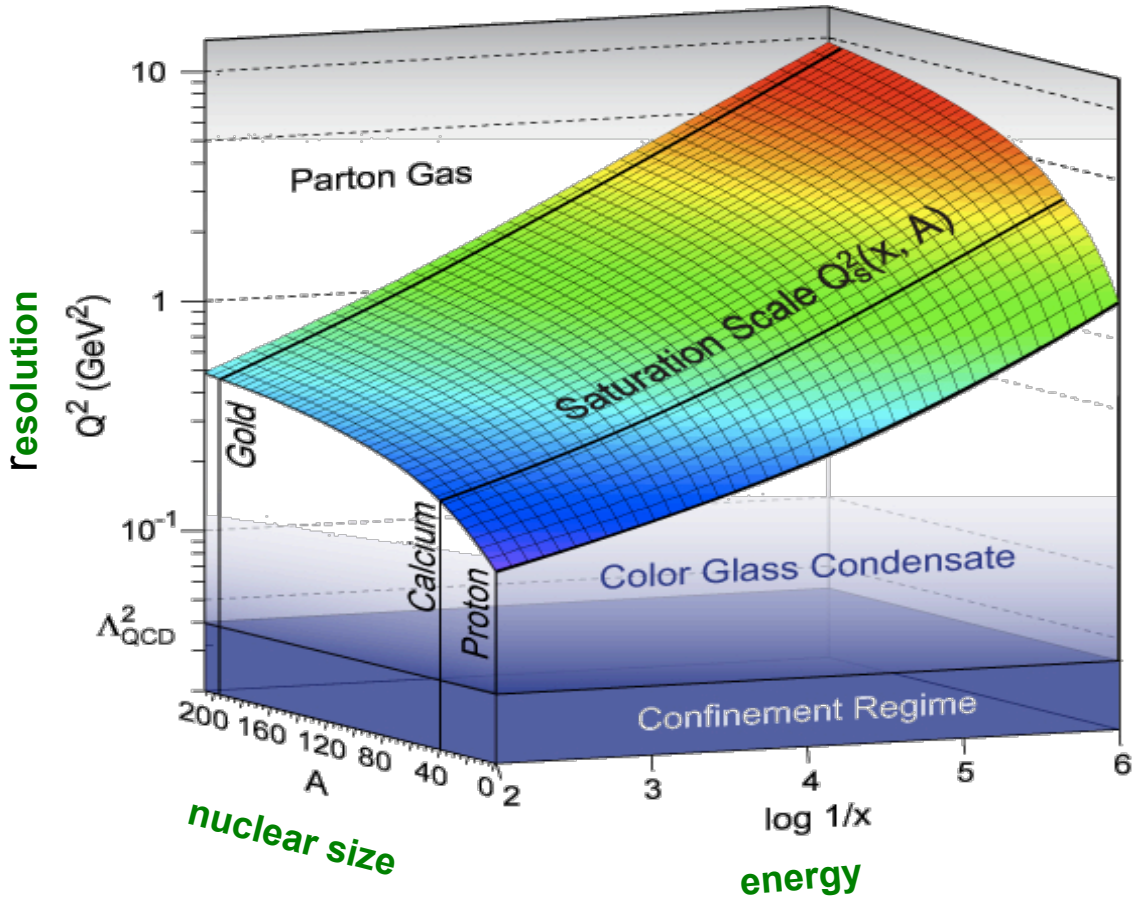
- JIMWLK Hamiltonian-describes "Fokker-Planck" –like evolution of multi-parton (Wilson line) correlators

- Factorization theorems--valid for inclusive observables to $(g^2 \ln(x))^n$ and $(g\rho)^n$ accuracy for W's

Gelis,Lappi,RV, PRD (2008,2009)

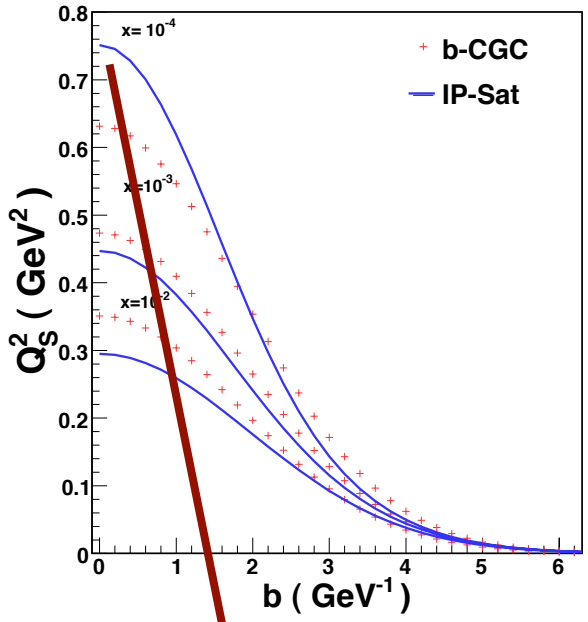
Many-body high energy QCD: The Color Glass Condensate

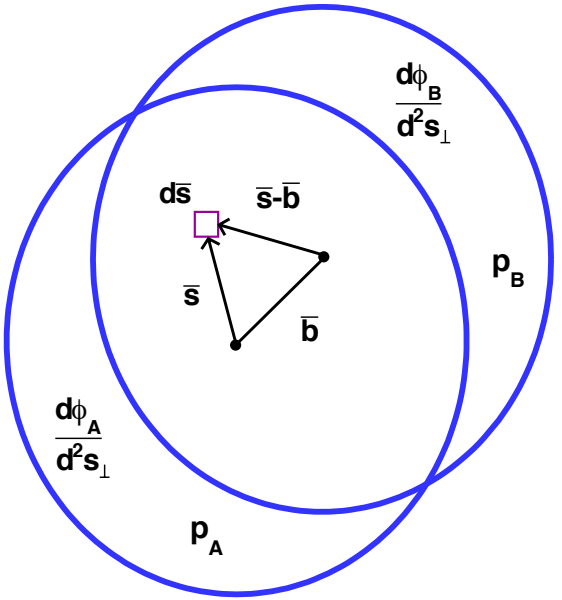
Gelis,Iancu,Jalilian-Marian,RV:
Ann. Rev. Nucl. Part. Sci. (2010), arXiv: 1002.0333

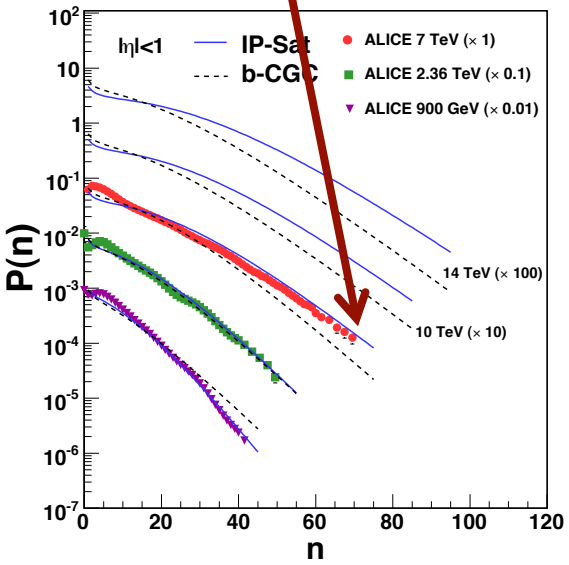


Dynamically generated semi-hard "saturation scale" opens window for systematic weak coupling study of non-perturbative dynamics

High multiplicity events in p+p



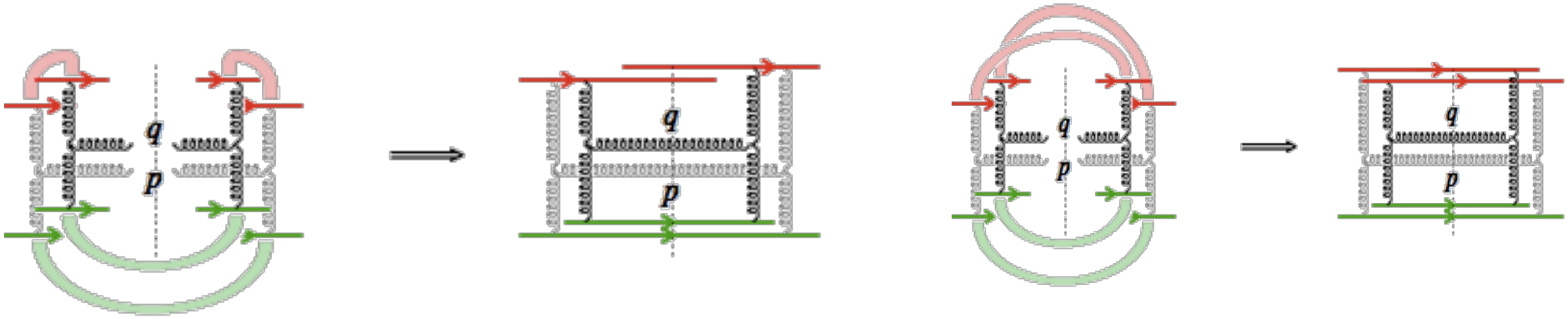




High multiplicity events likely correspond to high occupation numbers ($1/\alpha_S$) in the proton wave functions for $p_T \leq Q_S$

The saturated proton: two particle correlations

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



These graphs (called "Glasma graphs"), which generate long range rapidity correlations, are highly suppressed for $Q_S << p_T$

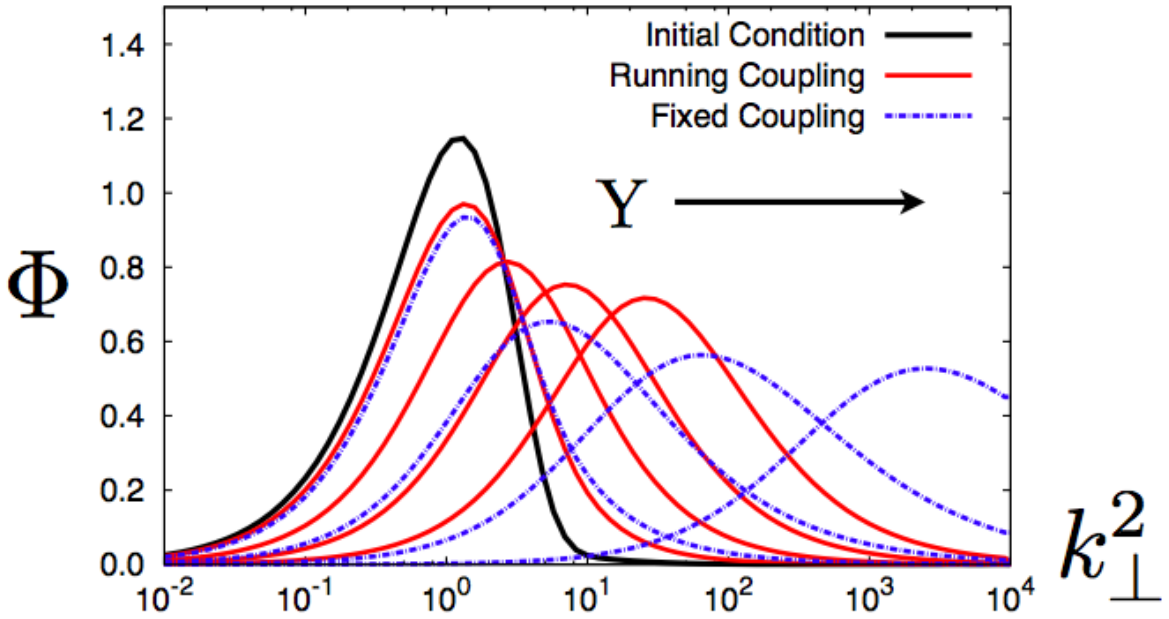
However, effective coupling of sources to fields with $k_T \leq Q_S = 1/g$ ("saturation")

Power counting changes for high multiplicity events by α_S^8
These graphs become competitive with usual short range (in $\Delta\eta$) pQCD graphs

The saturated proton: two particle correlations

RG evolution of two particle correlations (in mean field approx) expressed in terms of "unintegrated gluon distributions"

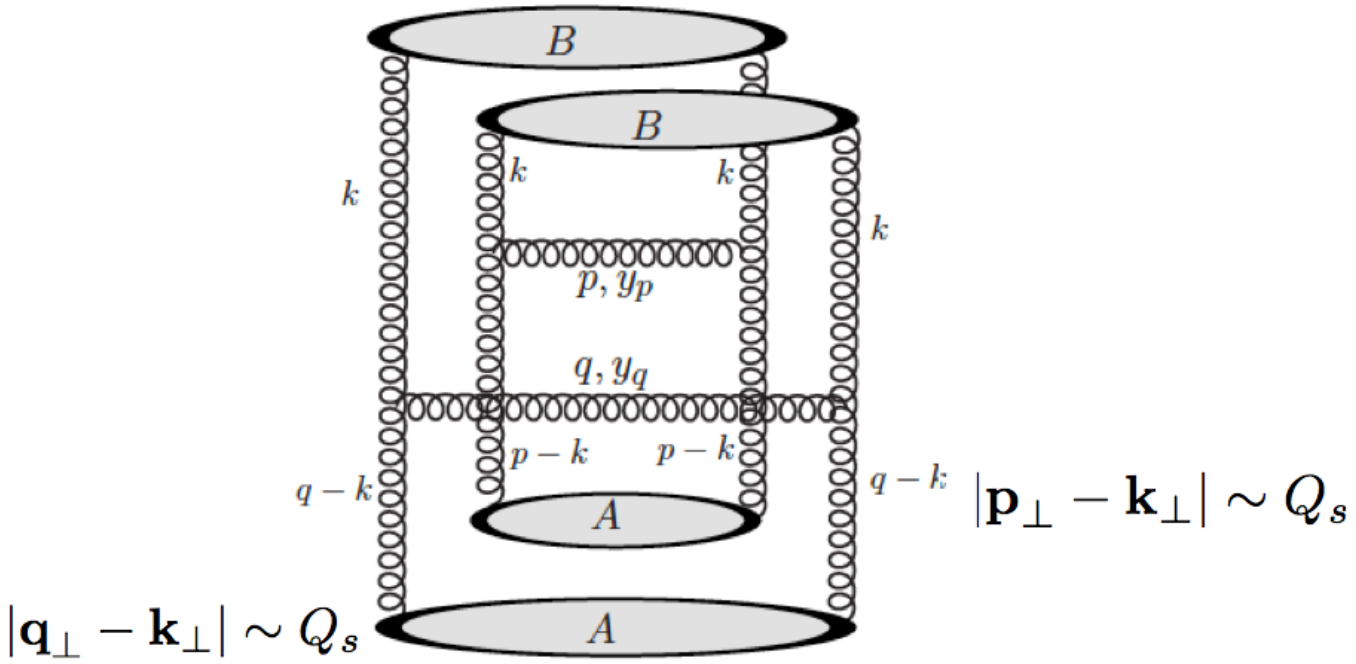
$$C(\mathbf{p},\mathbf{q}) \propto \frac{g^4}{\mathbf{p}_\perp^2\mathbf{q}_\perp^2}\int \mathrm{d}^2\mathbf{k}_{1\perp}\,\Phi^2_{A_1}(y_p,\mathbf{k}_{1\perp})\Phi_{A_2}(y_p,\mathbf{p}_\perp-\mathbf{k}_{1\perp})\Phi_{A_2}(y_q,\mathbf{q}_\perp-\mathbf{k}_{1\perp}) + \text{permutations}$$



Caveat: Contribution of higher 4-pt. Wilson line correlators not included

Dumitru, Jalilian-Marian; Kovner, Lublinsky (2011)

The saturated proton: azimuthal correlation

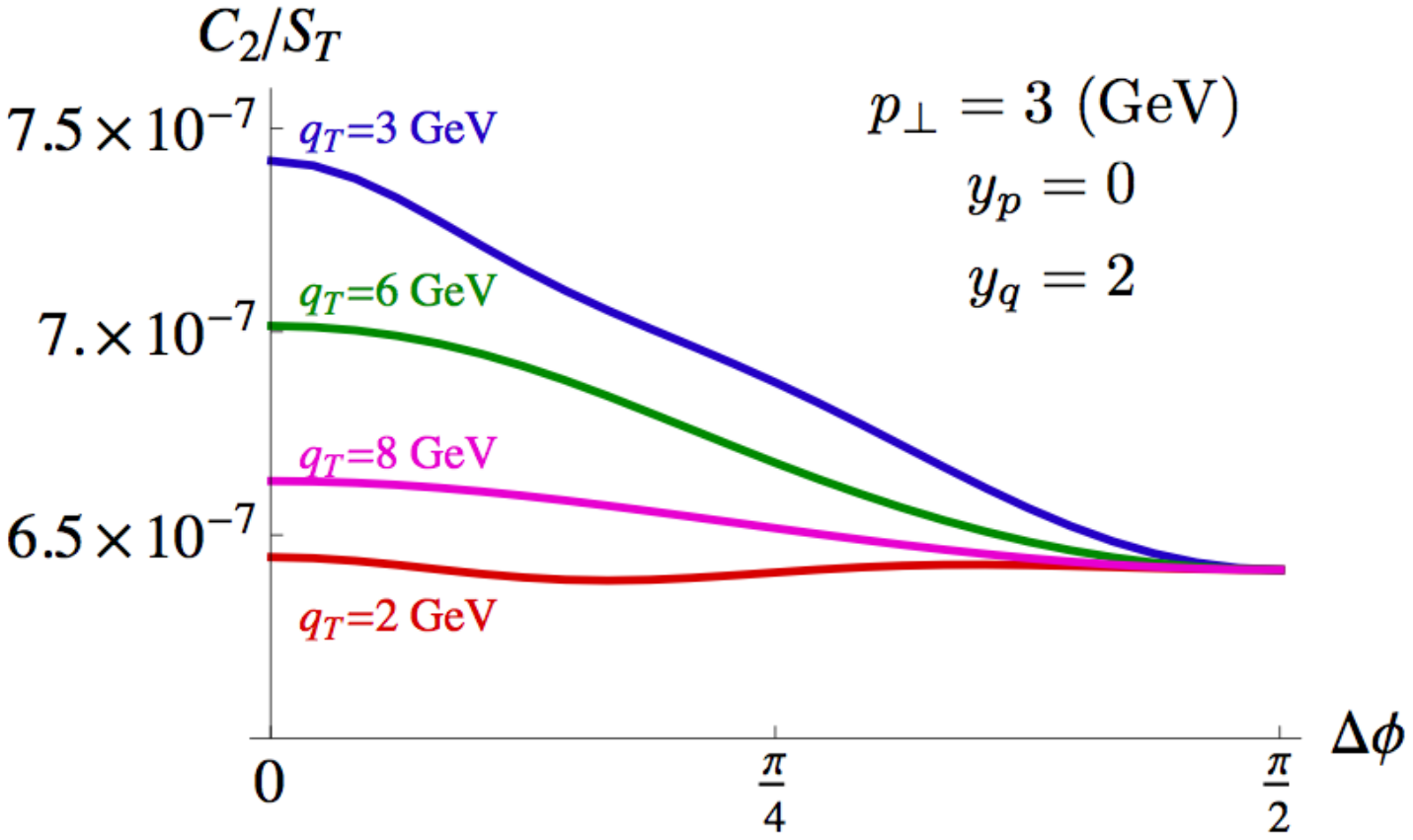


For $p_T = q_T$, the largest contribution to two particle correlation is from $\Delta\Phi \approx 0$

Simple explanation: In lab frame, fluctuation of projectile with widely separated (in rapidity) partons, gets same instantaneous momentum kick from strong color field strength in target

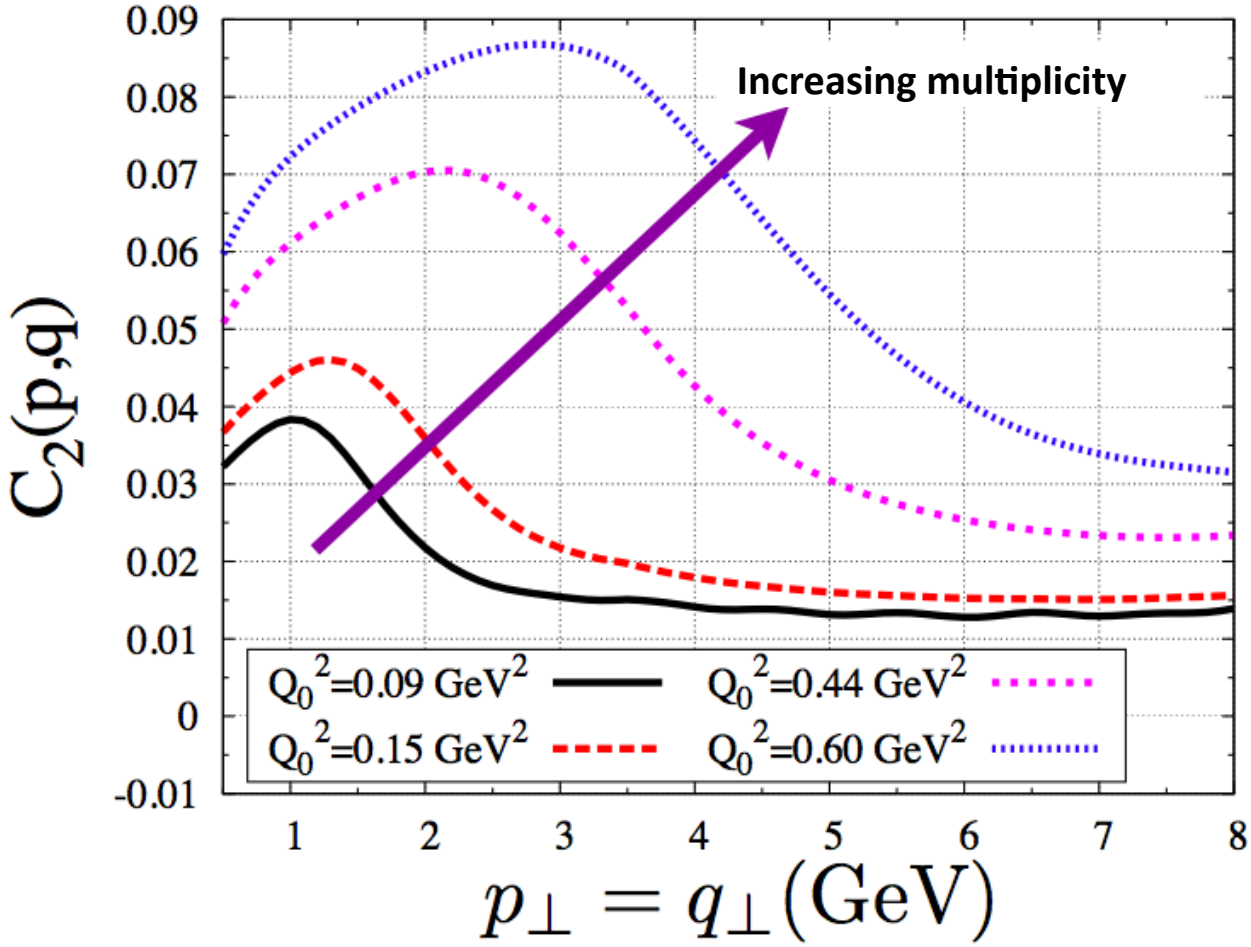
Systematics of the correlation

Dumitru,Dusling,Gelis,Jalilian-Marian,Lappi,RV, Phys. Lett. B697:21 (2011)
Dusling, RV, in preparation

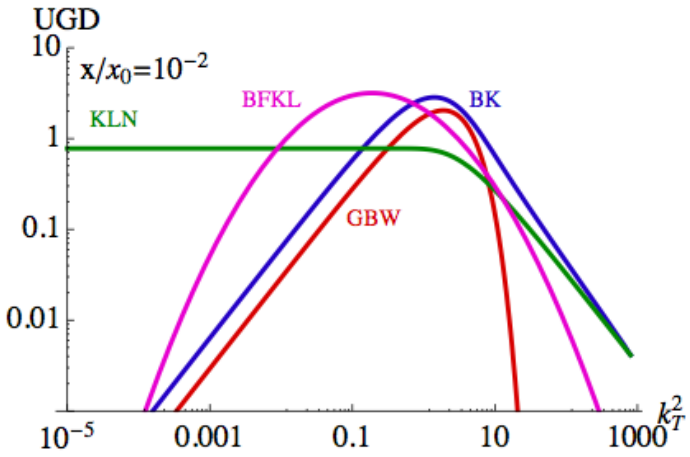


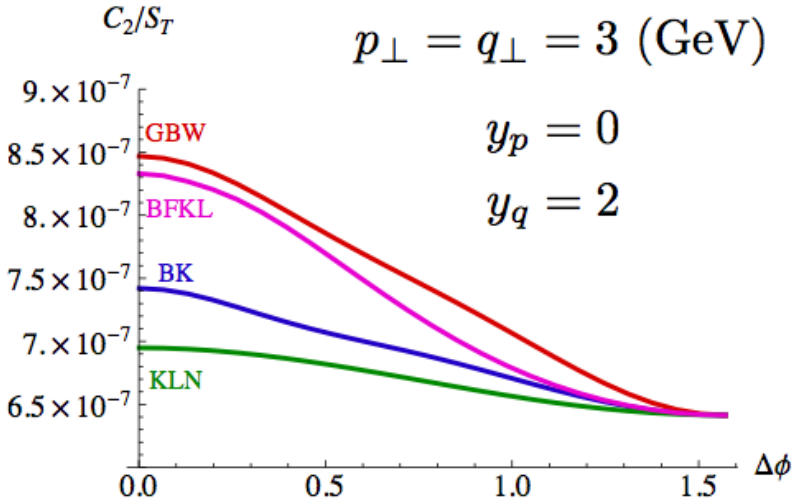
Ridge goes away for $p_T \neq q_T$

Systematics of the correlation



Systematics of the correlation





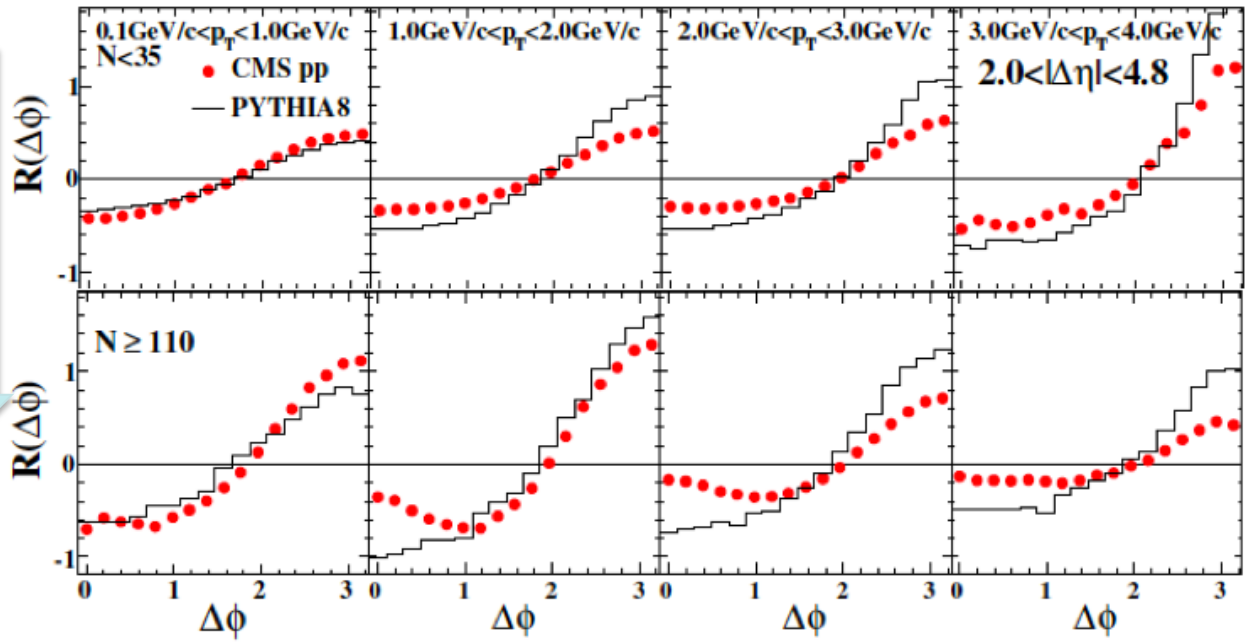
- **Near-side correlation sensitive to diffuseness of wavefunction**

p+p ridge: Getting more quantitative

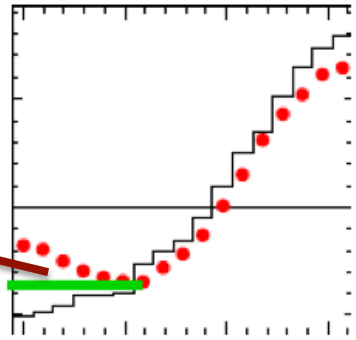
Dusling, RV: in preparation
(thanks to Wei Li)

p_T

Centrality

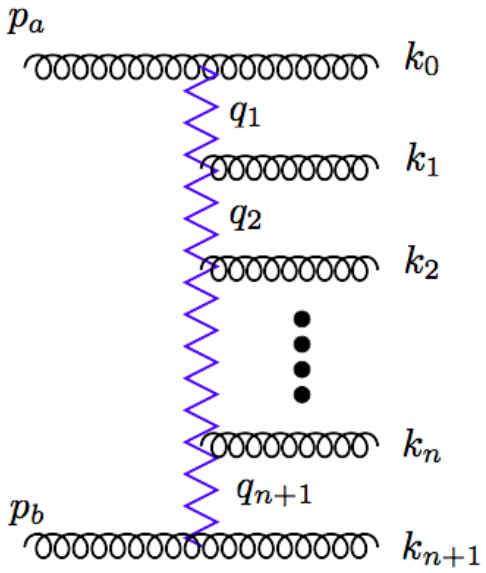


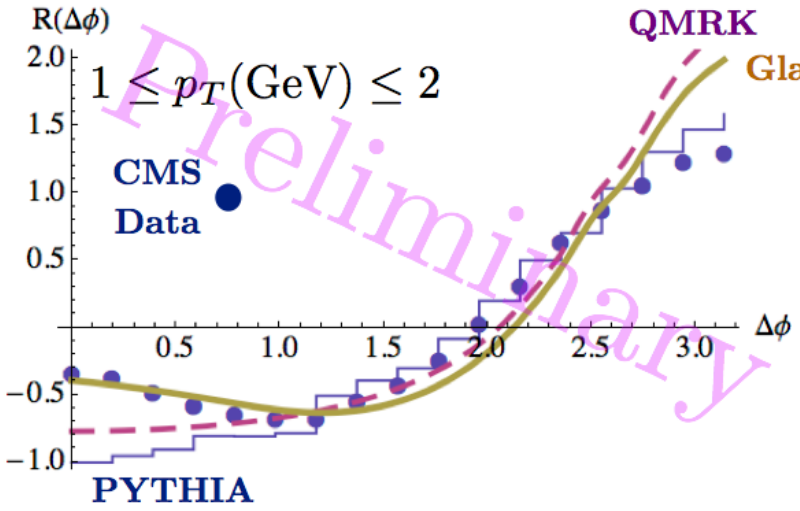
Associated yield from integrating over excess ("ZYAM")



Getting more quantitative

Have to get away-side large Δη contribution right -- "multi-Rege" kinematics for proper relative normalization

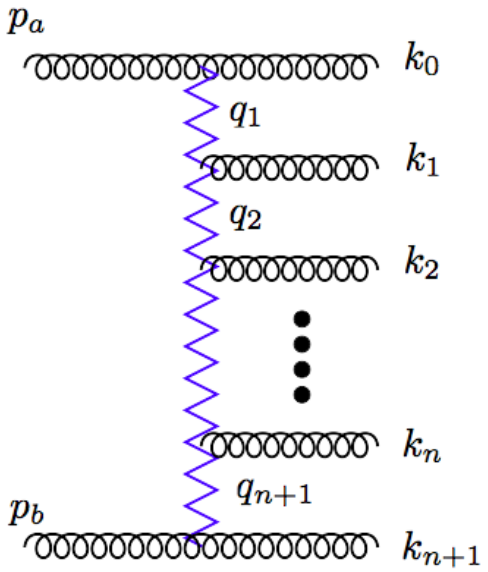


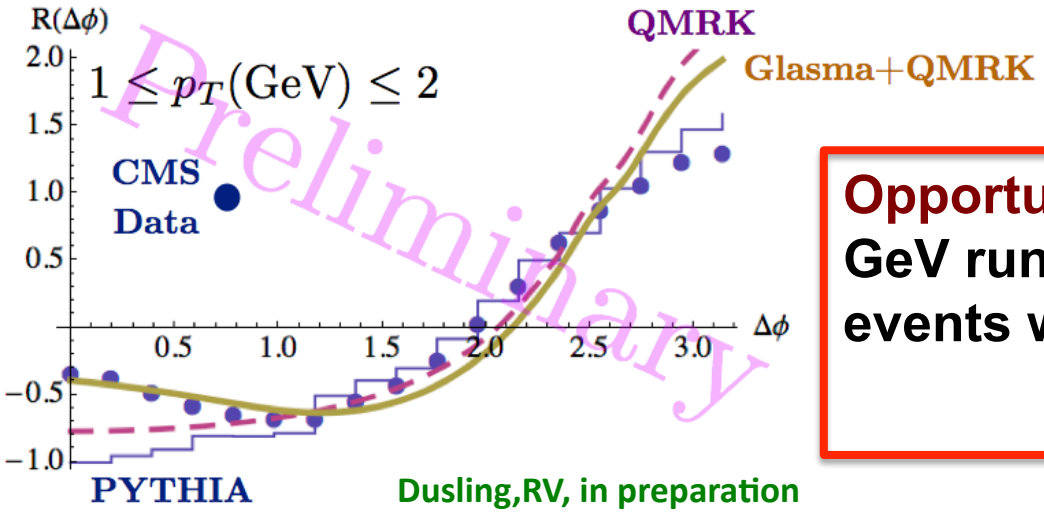


Dusling,RV, in preparation

Getting more quantitative

Have to get away-side large Δη contribution right for proper relative normalization
-- "multi-Regge" kinematics



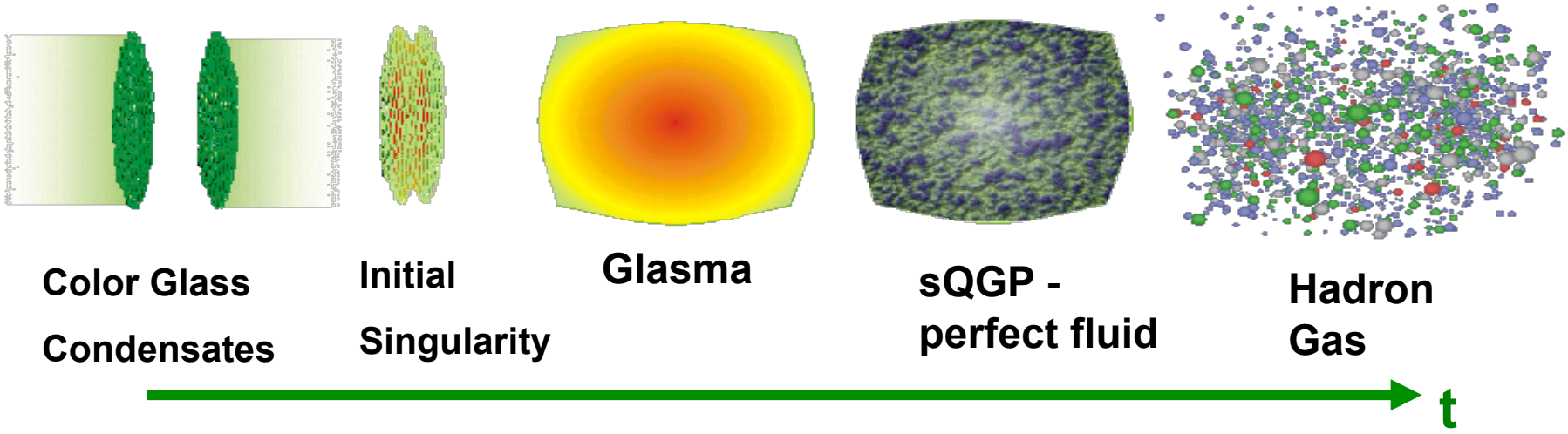


Dusling,RV, in preparation

Opportunity: look for ridge in p+p 500 GeV run @ RHIC. Estimate > 10^6 events with n_{ch} > 60!

Standard model of HI Collisions

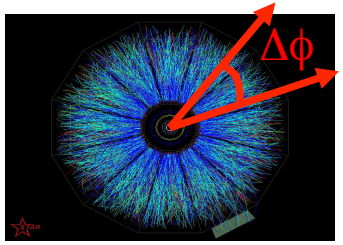
RV, ICHEP talk, arXiv:1012.4699

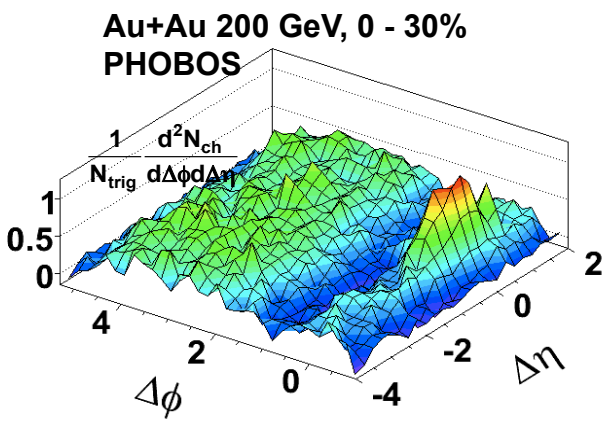


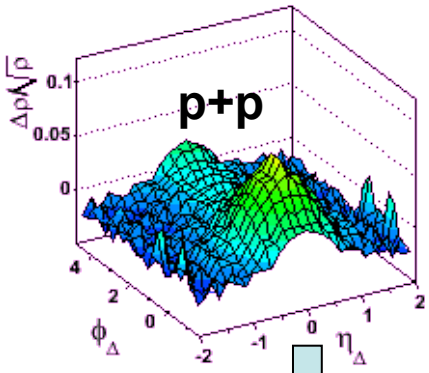
Understanding the ridge is very important for computing the early time dynamics (the spectrum of initial fluctuations) in the "little bang"

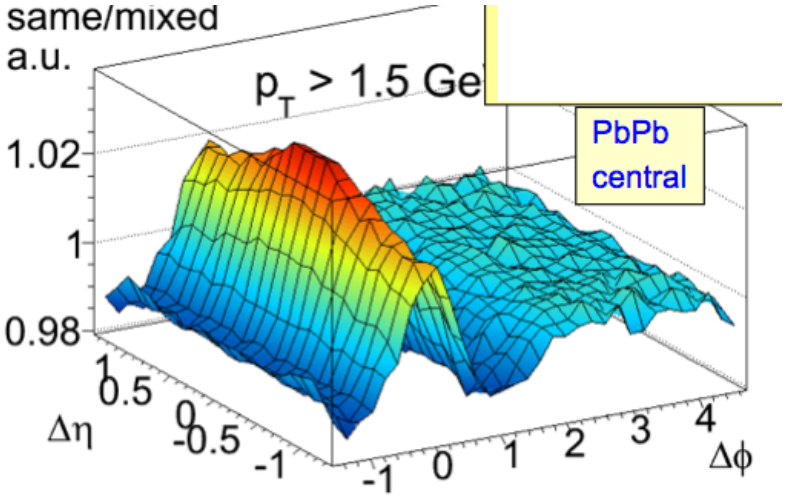
Address interesting issues such as thermalization of strong color fields and collective flow of quark-gluon matter

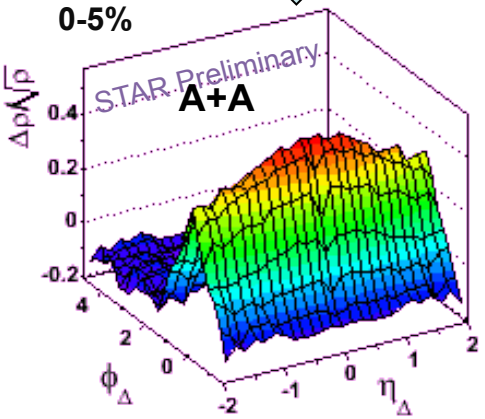
Heavy Ion Ridge: Glasma flux tubes+ Radial flow





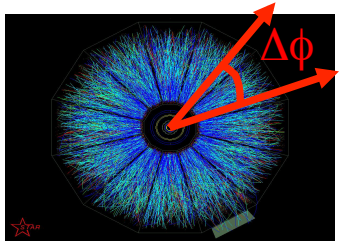


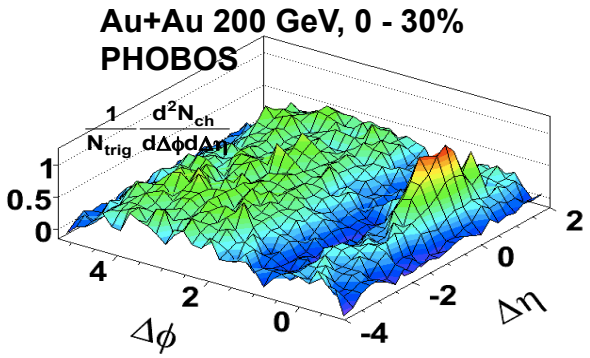


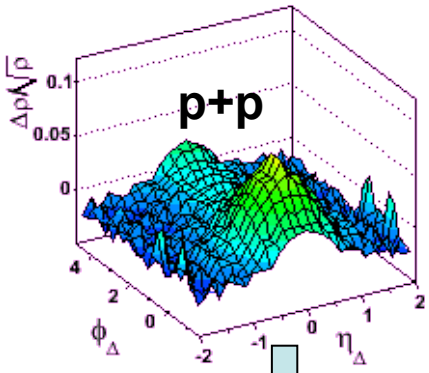


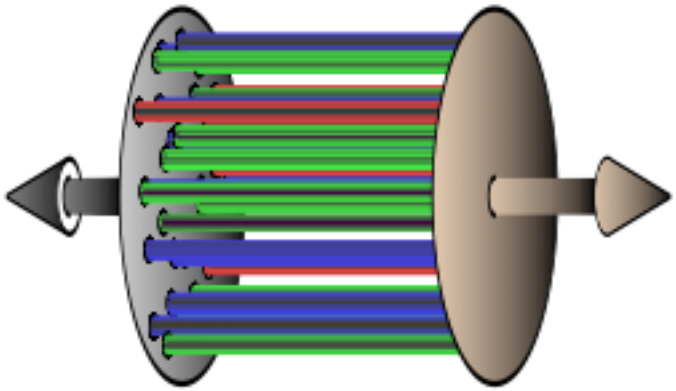
ALICE preliminary

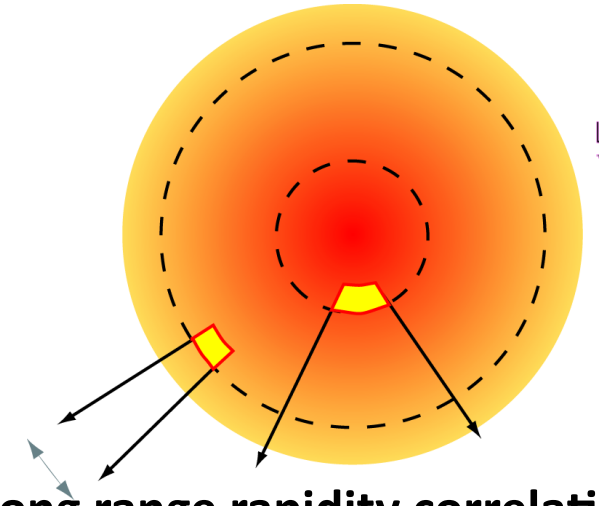
The Ridge: Glasma flux tubes+ Radial flow

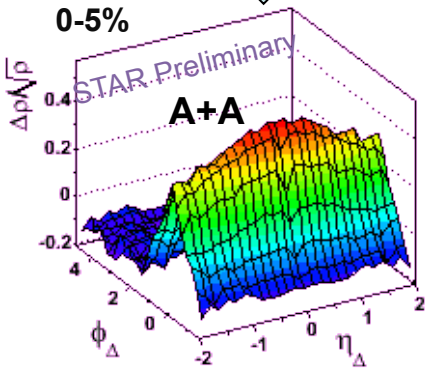












Glasma flux tubes provide the long range rapidity correlation

Dumitru, Gelis, McLerran, RV; Gavin, McLerran, Moschelli

Radial ("Hubble") flow of the tubes provides the azimuthal collimation

Voloshin; Shuryak

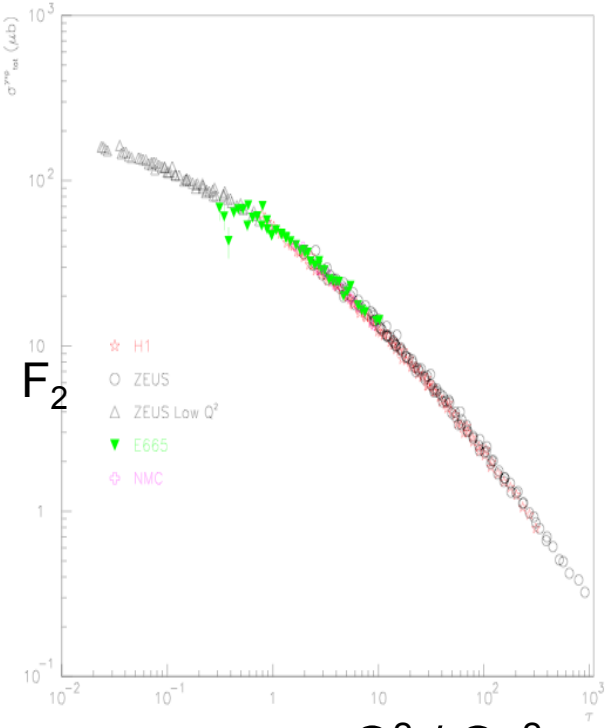
Outlook

- Ridge in high multiplicity events at LHC: new window into many body wee dynamics in the proton wave-function. More experimental systematics can strongly constrain models.

- Same dynamical origin as the ridge in A+A collisions:
  again, systematics from RHIC -> LHC can provide great insight into early time collective dynamics of A+A collisions

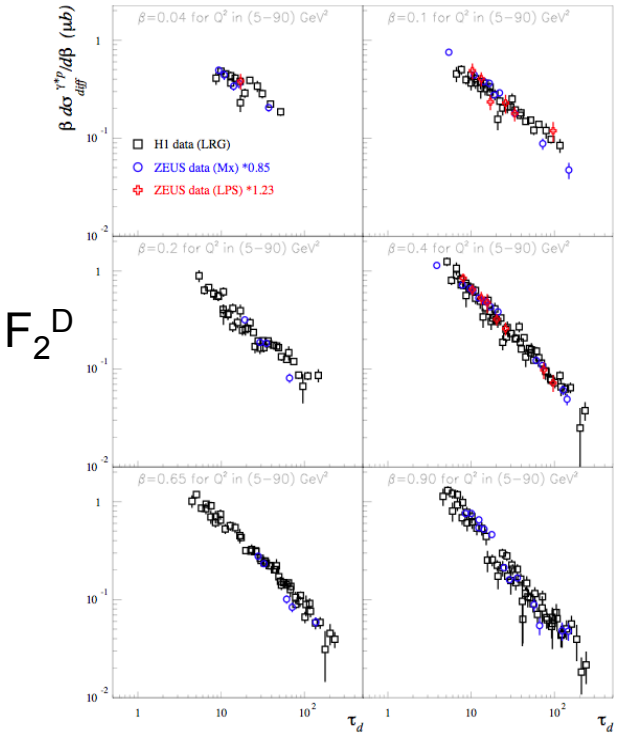
Semi-hard scale in the proton? geometrical scaling

Golec-Biernat, Stasto,Kwiecinski



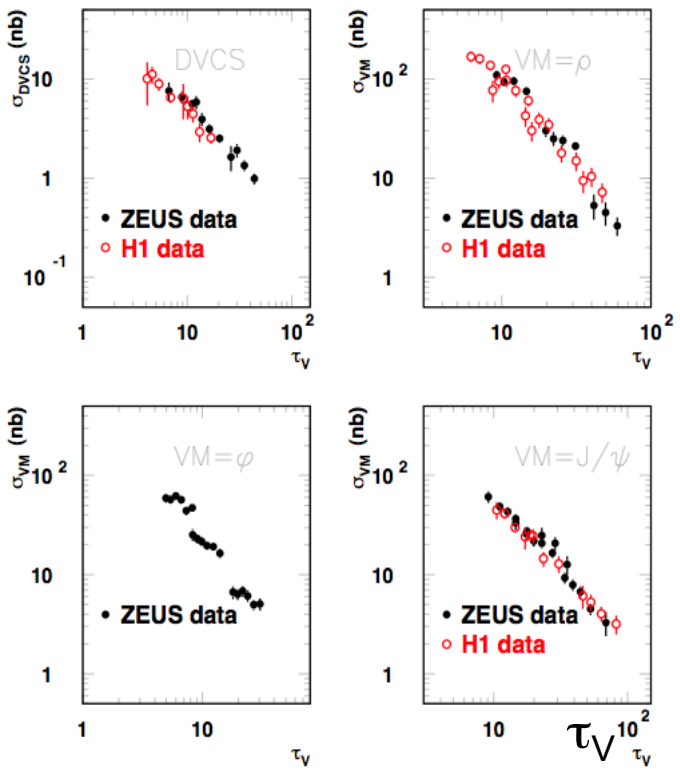
F_2

$\tau = Q^2 / Q_S^2$



F_2^D

τ_D



VM, DVCS

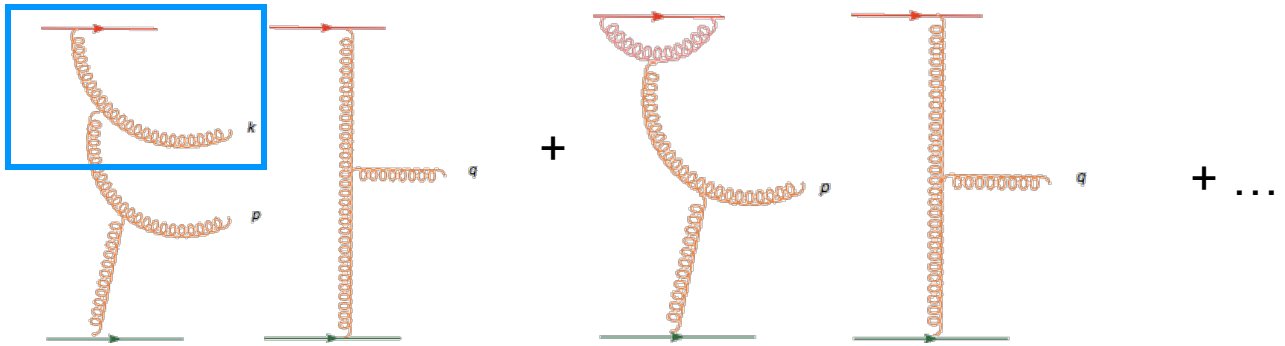
Marquet, Schoeffel hep-ph/0606079

High energy e+p scattering data from the HERA collider is very suggestive

The saturated proton: Glasma graphs -I

RG evolution:

Gelis, Lappi, RV, arXiv: 0807.1306



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

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

= LO graph with evolved sources

avg. over sources in each event and over all events gives correlation