Building bridges with ridges

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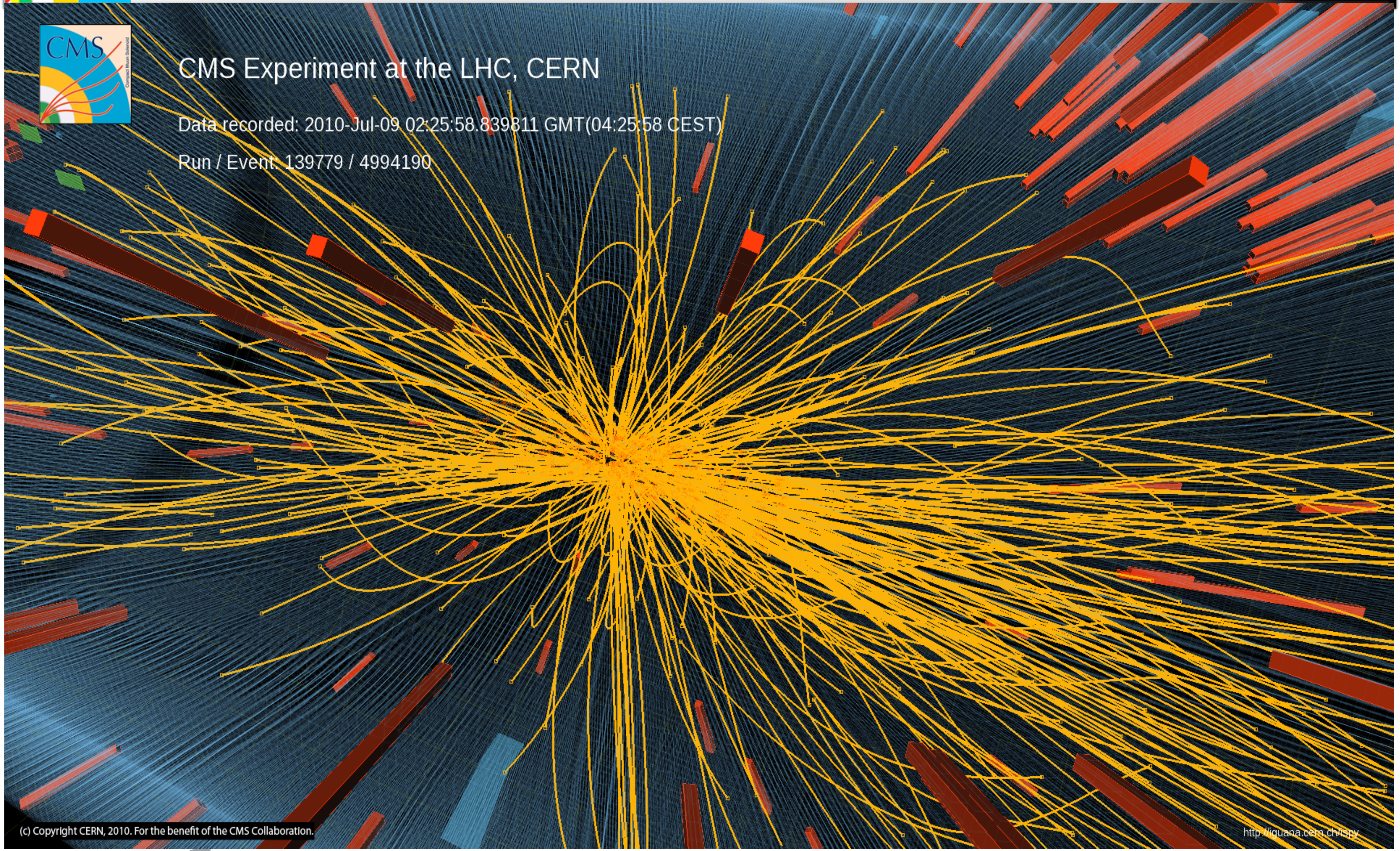
Brookhaven National Laboratory

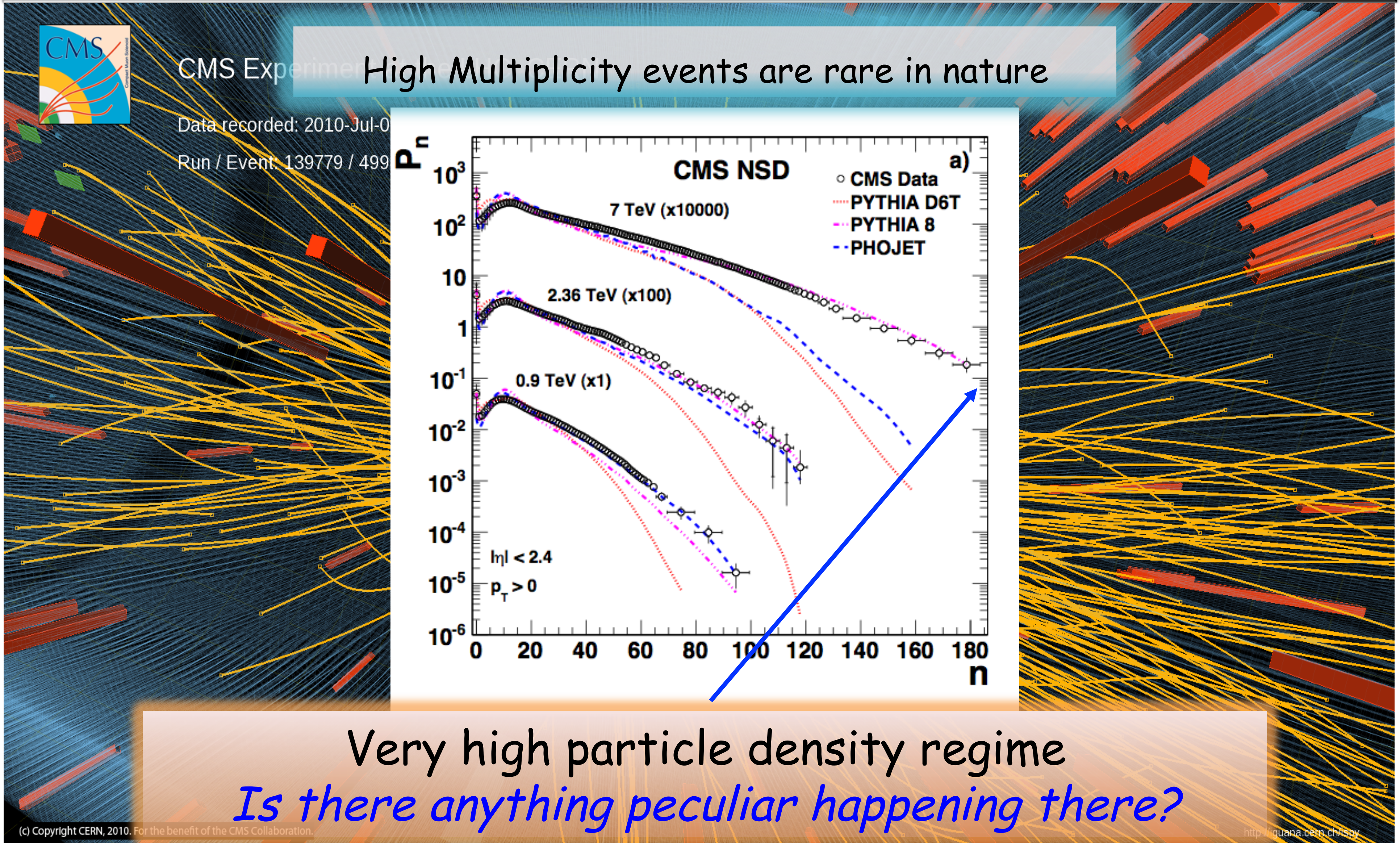
EIC workshop, STIAS, Stellenbosch U, Feb. 3rd, 2012

High Multiplicity pp collisions



High Multiplicity pp collisions

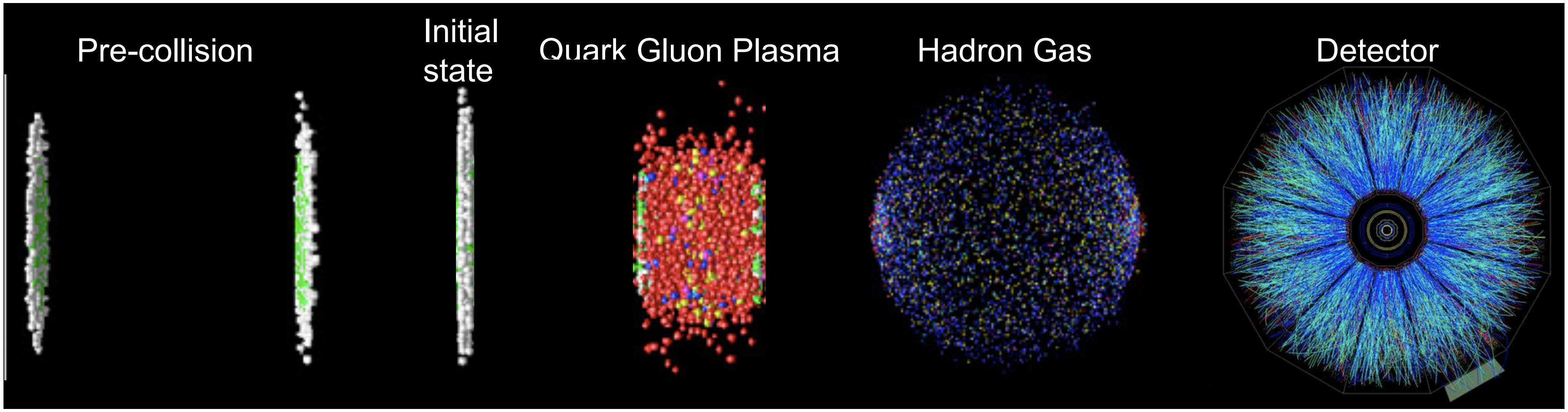
High Multiplicity events are rare in nature



Very high particle density regime

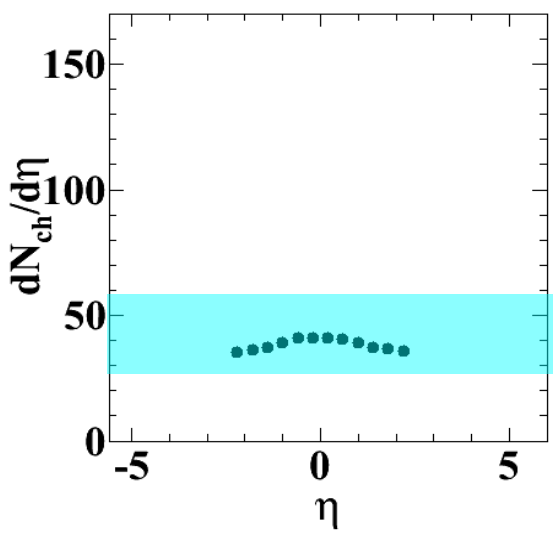
Is there anything peculiar happening there?

Relativistic Heavy Ion Collisions

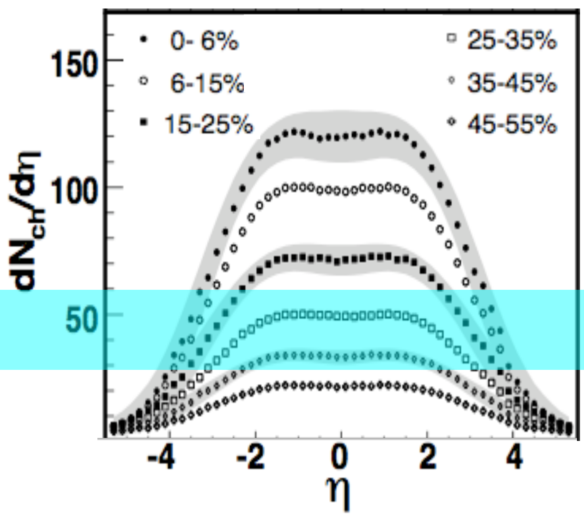


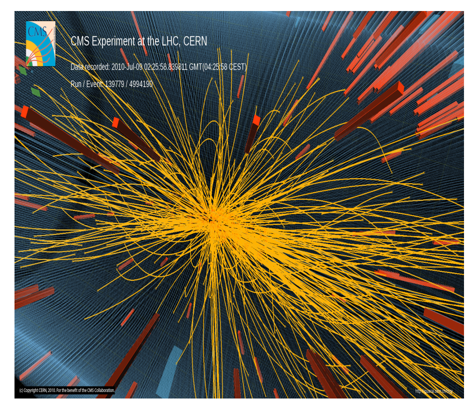
?

CMS pp 7TeV, N>110



PHOBOS CuCu 62.4GeV

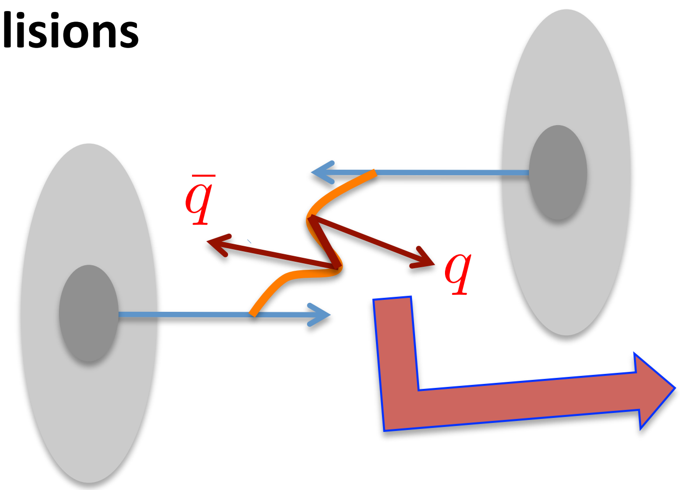




The p+p ridge

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

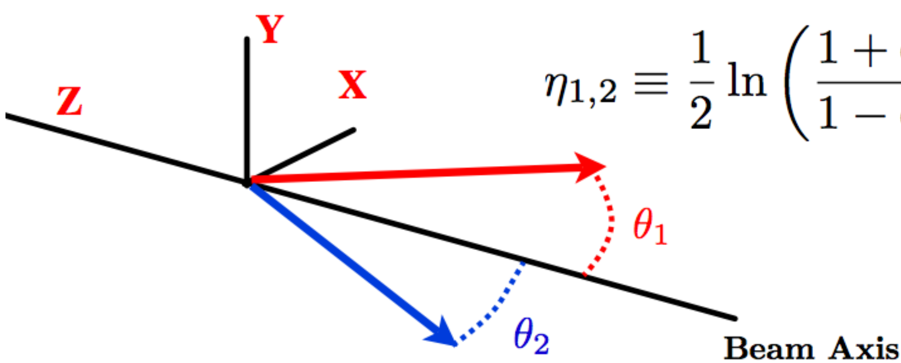
CMS, arXiv:1009.4122

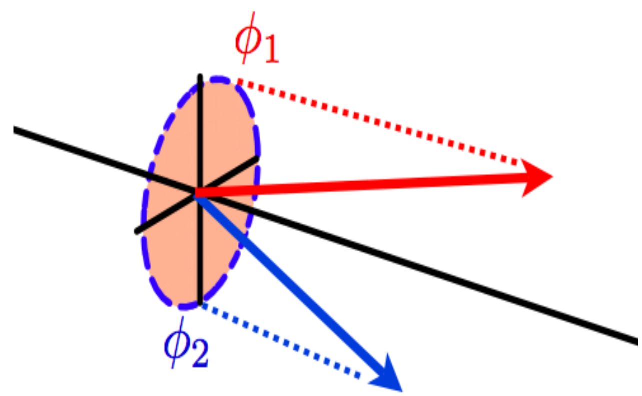


Back to back jet correlation in p+p

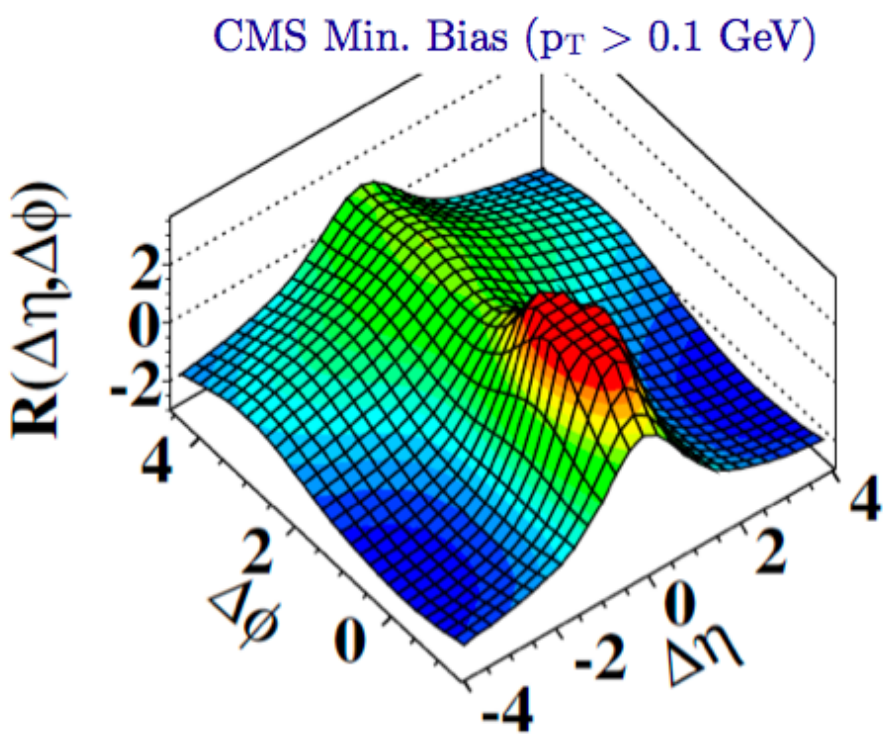
Collision Geometry:

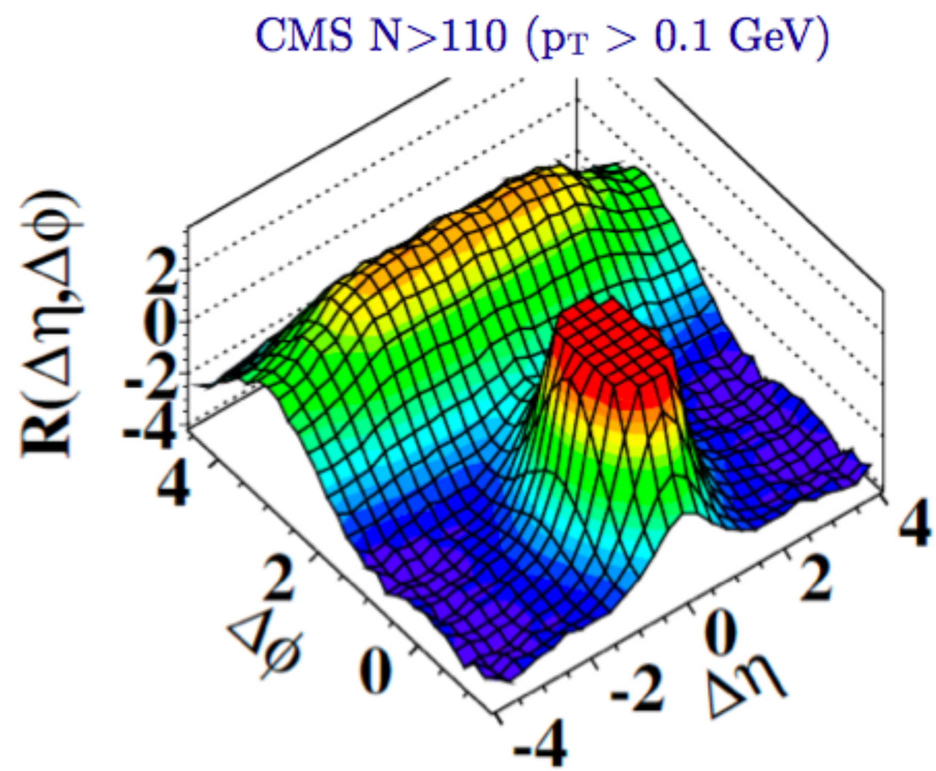
$$\eta_{1,2} \equiv \frac{1}{2} \ln \left(\frac{1 + \cos\theta_{1,2}}{1 - \cos\theta_{1,2}} \right)$$



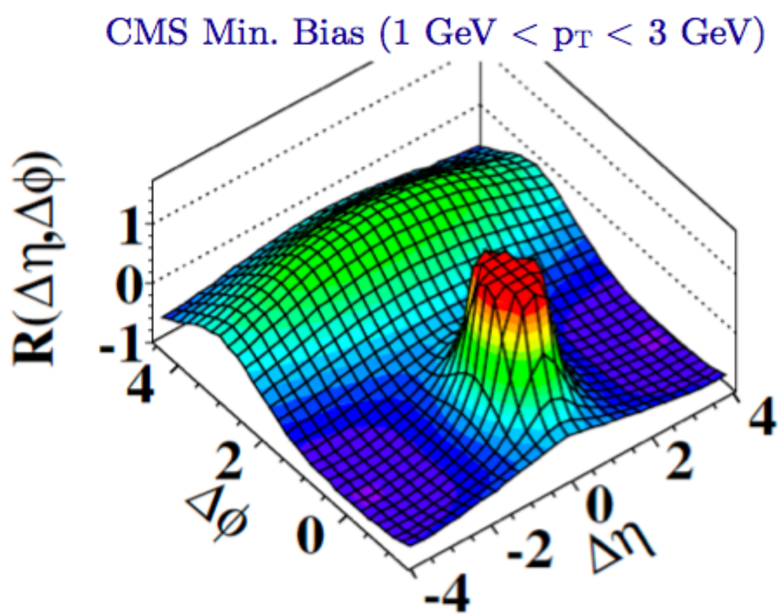


Two particle correlations: CMS results

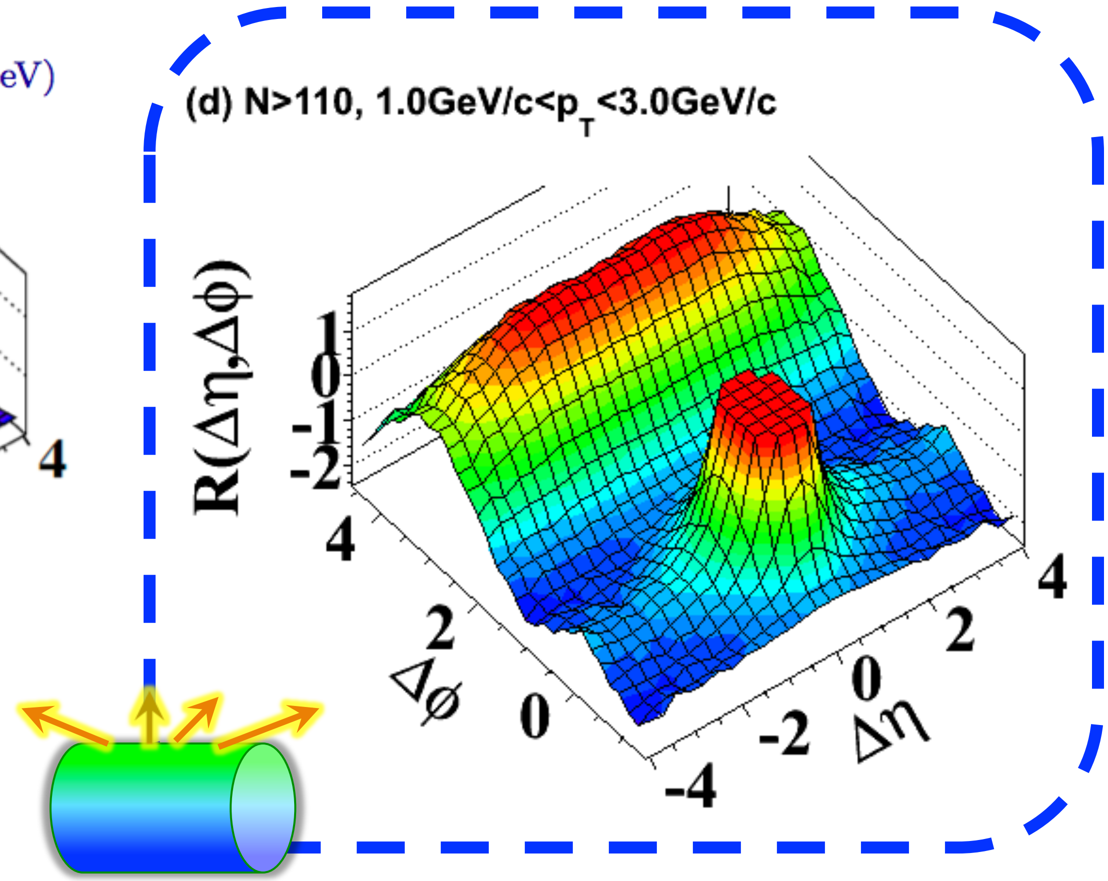




Two particle correlations: CMS results



"Discovery"

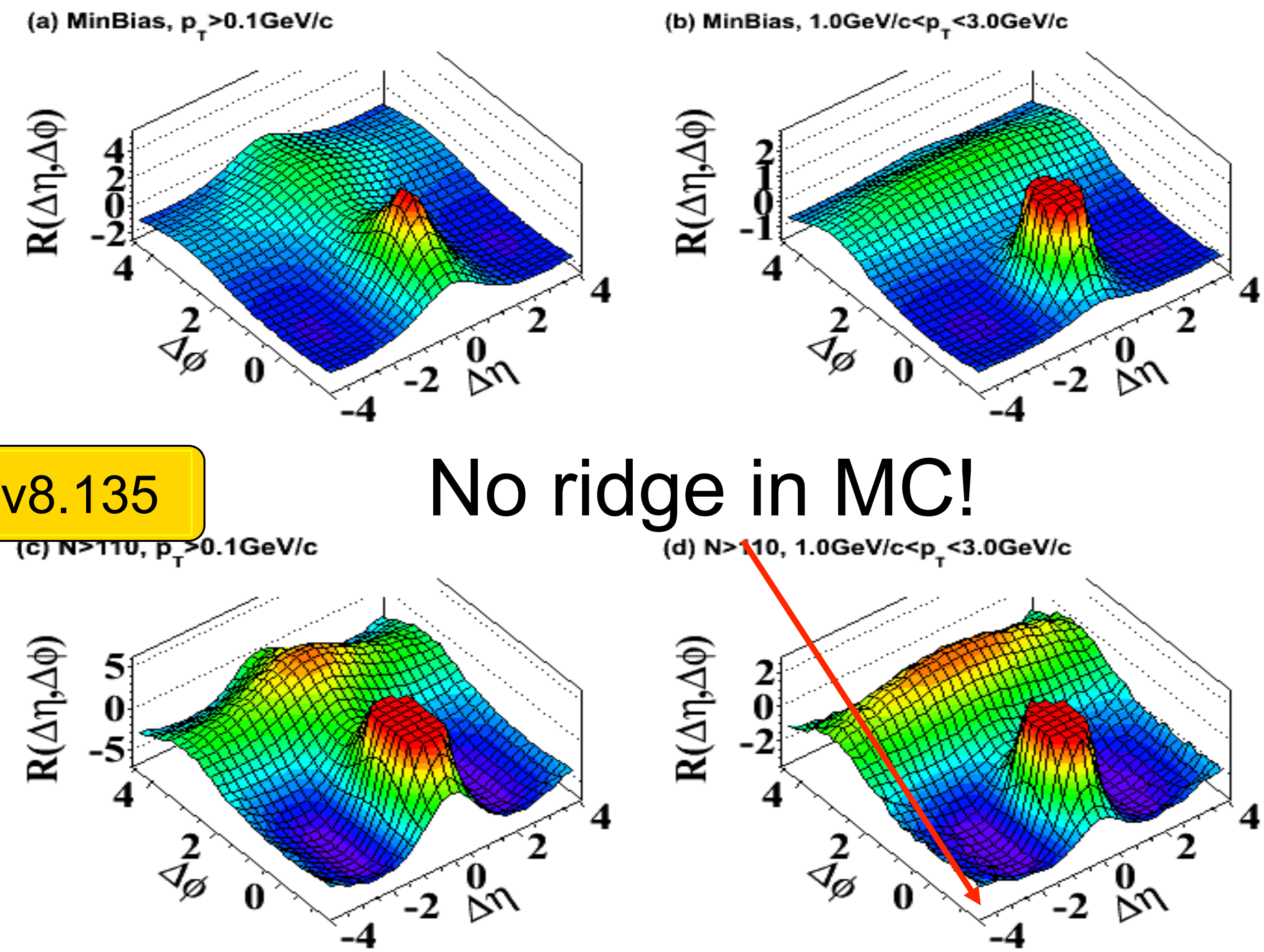


- **Ridge: Distinct long range correlation in η collimated around ΔΦ≈ 0 for two hadrons in the intermediate 1 < p_T, q_T < 3 GeV**

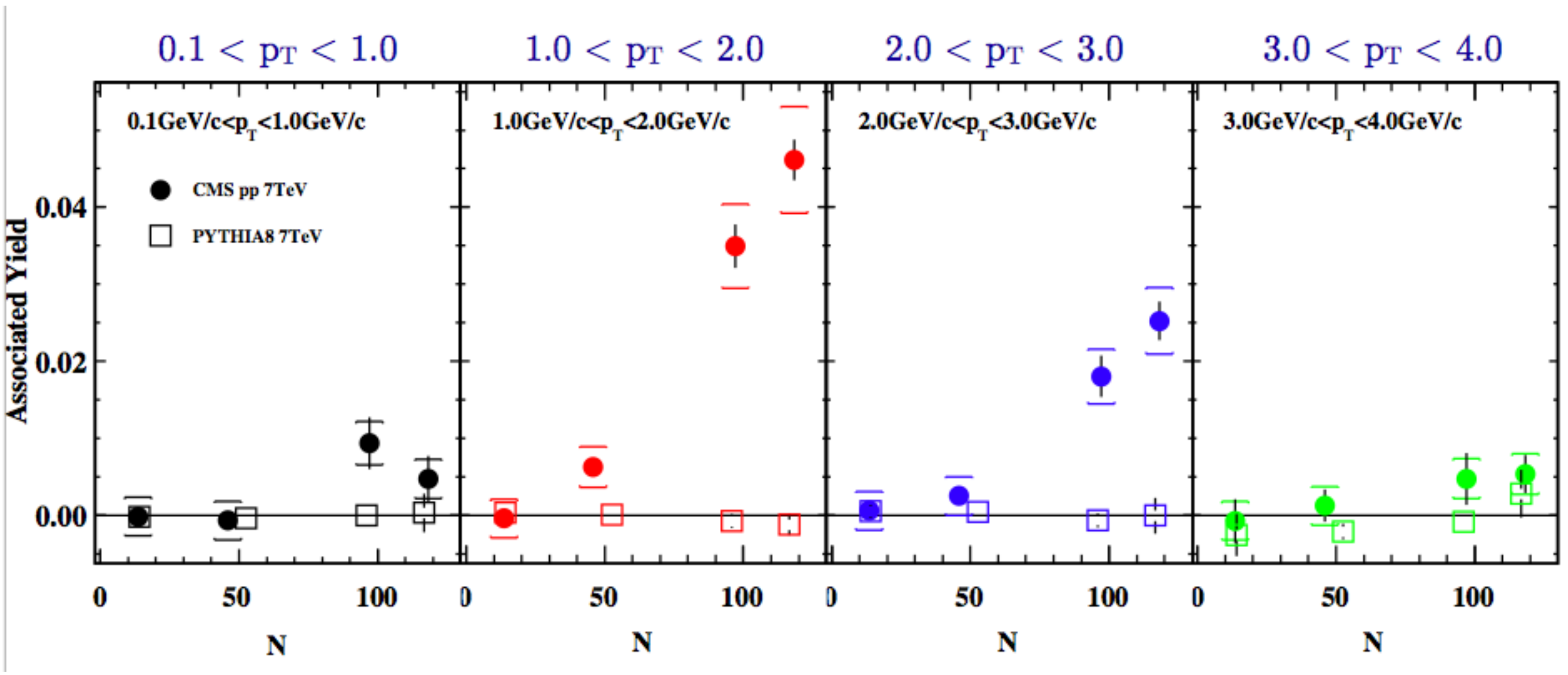
Comparing to MC models

PYTHIA8, v8.135

No ridge in MC!



Two particle correlations: p_T systematics



- Signal not present for p_T, q_T > 3 GeV

Particles That Flock: Strange Synchronization Behavior at the Large Hadron Collider

Scientists at the Large Hadron Collider are trying to solve a puzzle of their own making: why particles sometimes fly in sync

Scientific American, February (2011)

The high-energy collisions of protons in the LHC may be uncovering "a new deep internal structure of the initial protons," says Frank Wilczek of the Massachusetts Institute of Technology, winner of a Nobel Prize

"At these higher energies [of the LHC], one is taking a snapshot of the proton with higher spatial and time resolution than ever before"

What's the underlying dynamics?

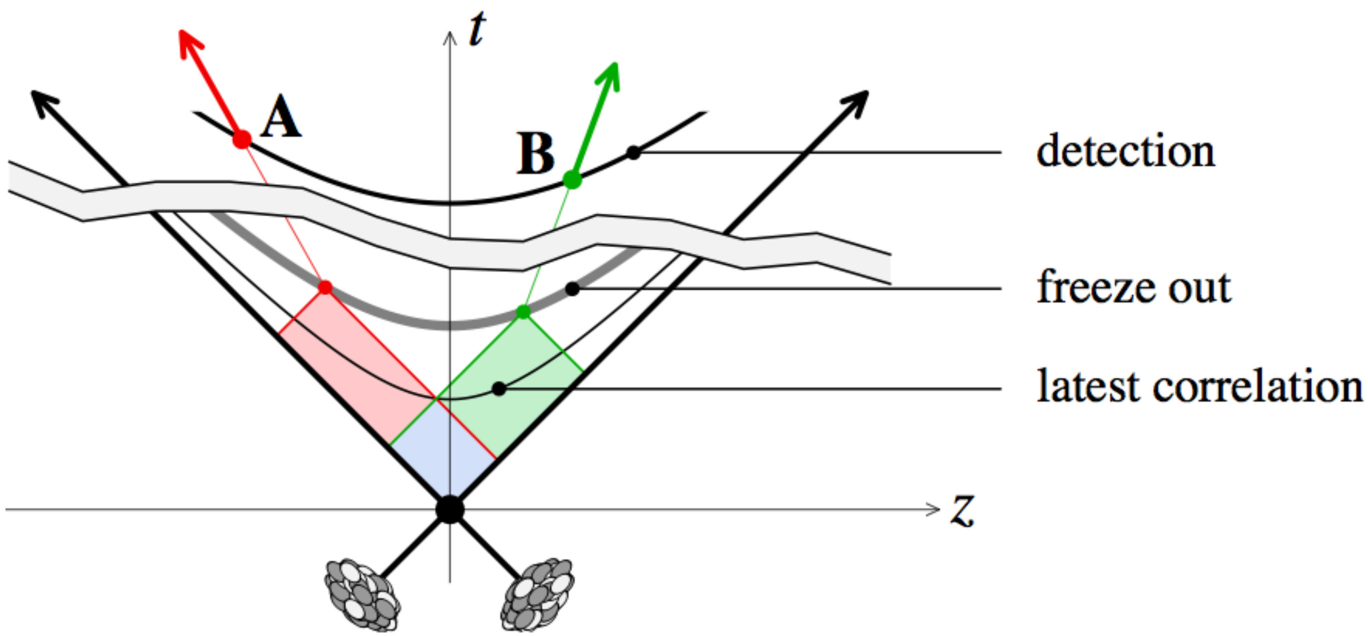
- Large number of models with a range of speculations

- 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

- In contrast, the A+A ridge is entirely due to hydrodynamic flow…

Long range rapidity correlations as a chronometer

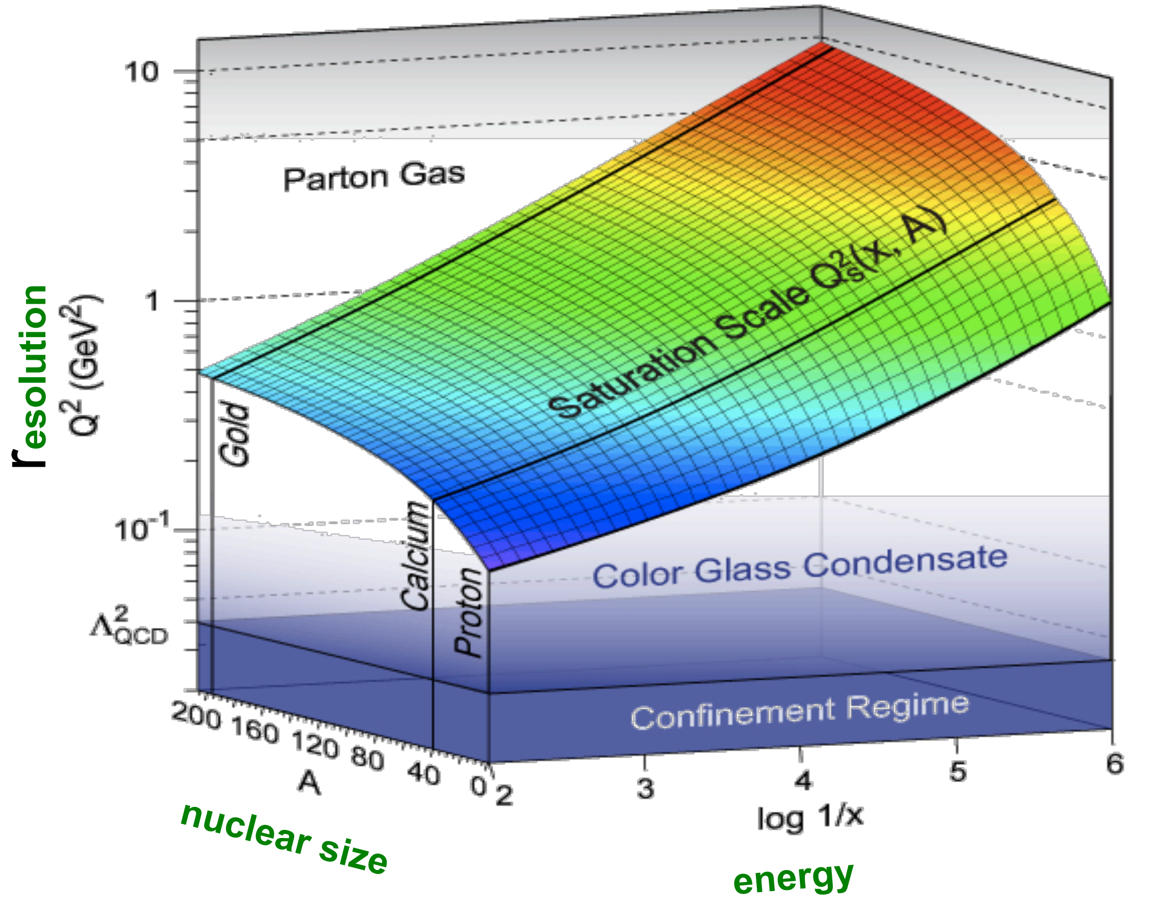


$$\tau \leq \tau_{\text{frz-out}} \exp\left(-\frac{1}{2}|y_A - y_B|\right)$$

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

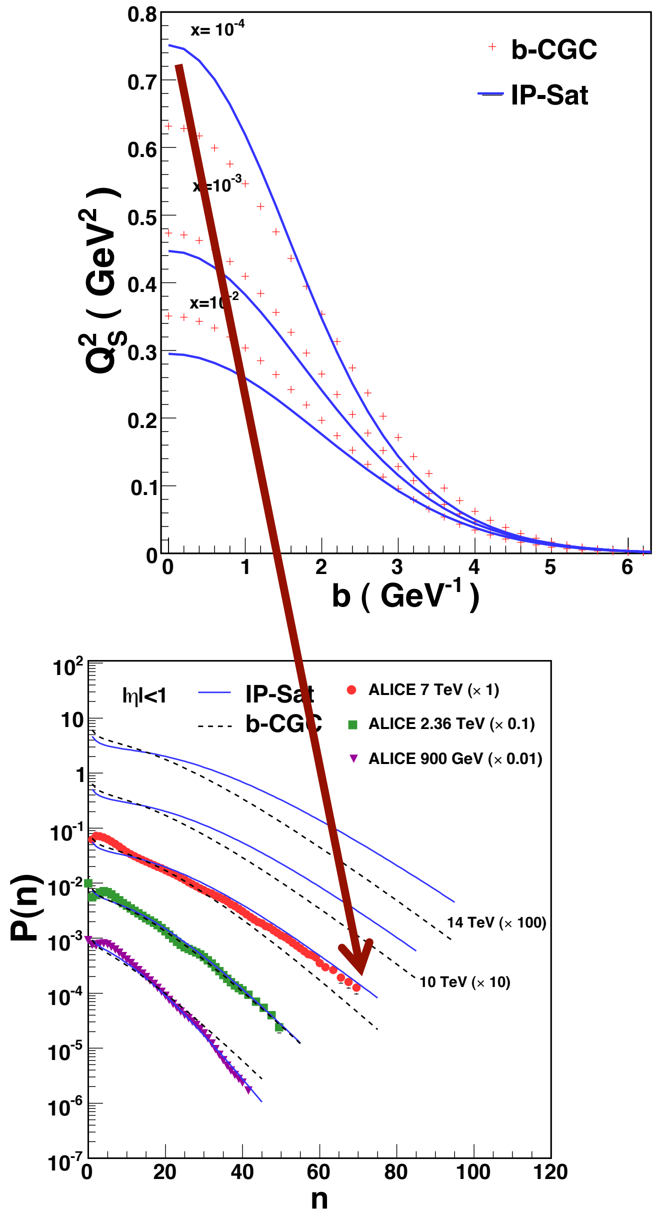
Nuclear wavefunction in high energy QCD:
The Color Glass Condensate

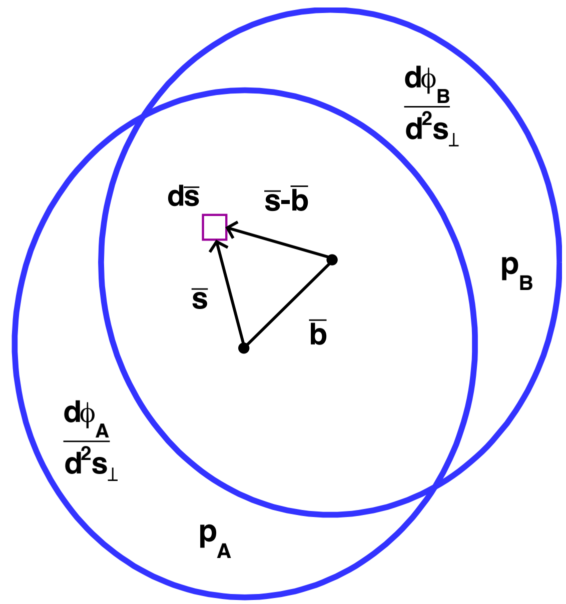
Gelis,Iancu,Jalilian-Marian,RV:
Ann. Rev. Nucl. Part. Sci. (2010), arXiv: 1002.0333



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

High multiplicity events in p+p



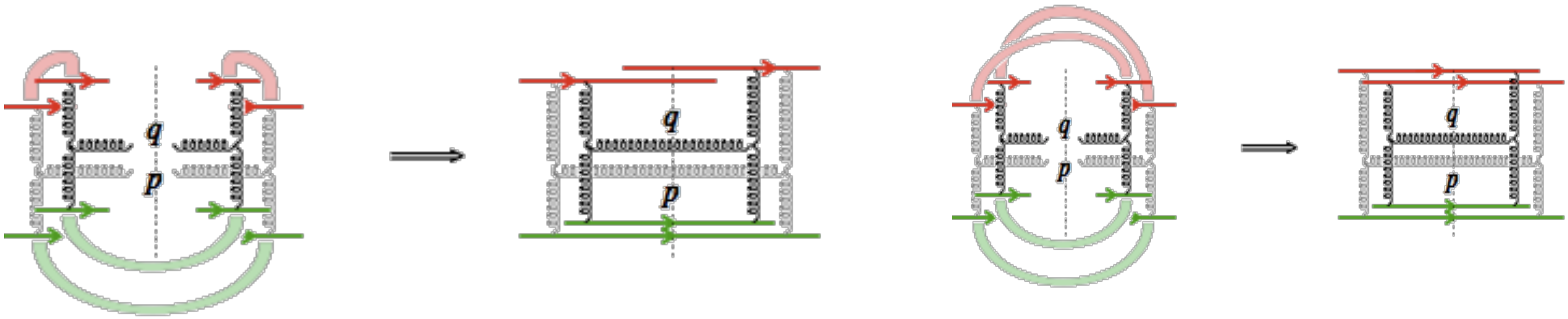


High multiplicity events likely correspond to high occupation numbers ($1/\alpha_S$) in the proton wave functions for $p_T \leq Q_S$

I will emphasize this point further shortly

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 ~ $1/Q_S$



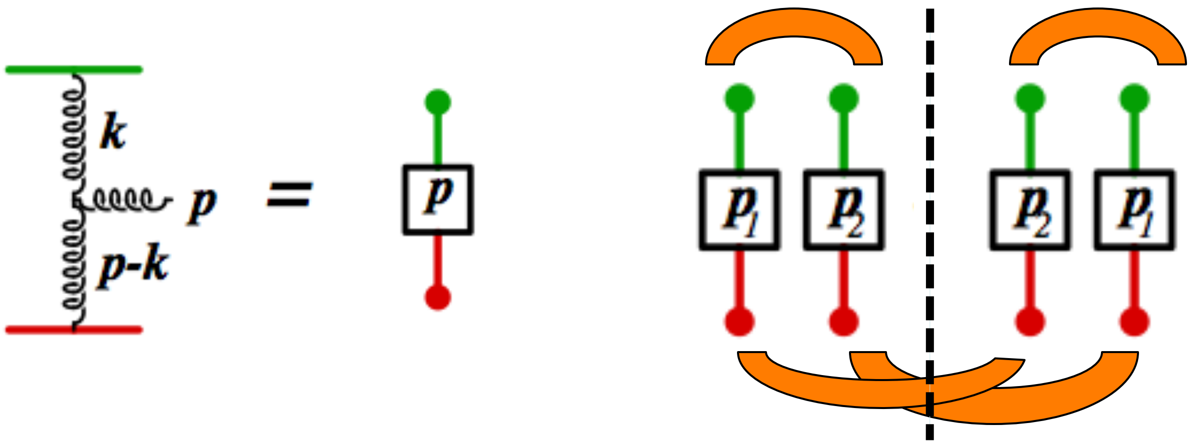
These graphs (called "Glasma graphs"), which generate long range rapidity correlations, are highly suppressed for $Q_S << p_T$

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 pQCD graphs

2-particle ➡ n-particle correlations

Dumitru,Gelis,McLerran,RV
Dusling,Fernandez-Fraile,RV

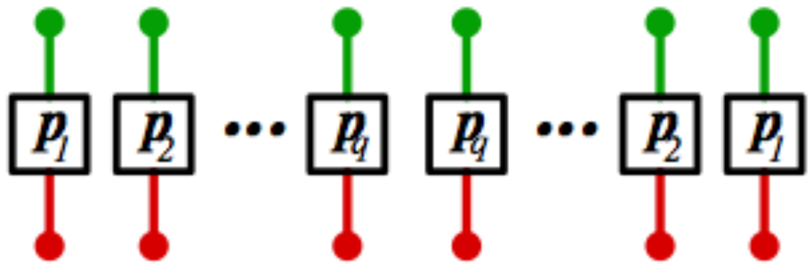


Glasma flux tube picture: two particle correlations proportional to ratio $1/Q_S^2 / S_T$

Only certain color combinations of "dimers" give leading contributions
…iterating combinatorics for 2, 3, n…gives

2-particle → n-particle correlations

Gelis, Lappi, McLerran



Multiplicity distribution: Leading combinatorics of dimers gives the negative binomial distribution

$$P_n^{\mathrm{N.B.}}(\bar{n},k) = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)}\,\frac{\bar{n}^n k^k}{(\bar{n}+k)^{n+k}}$$

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

k = 1 : Bose-Einstein

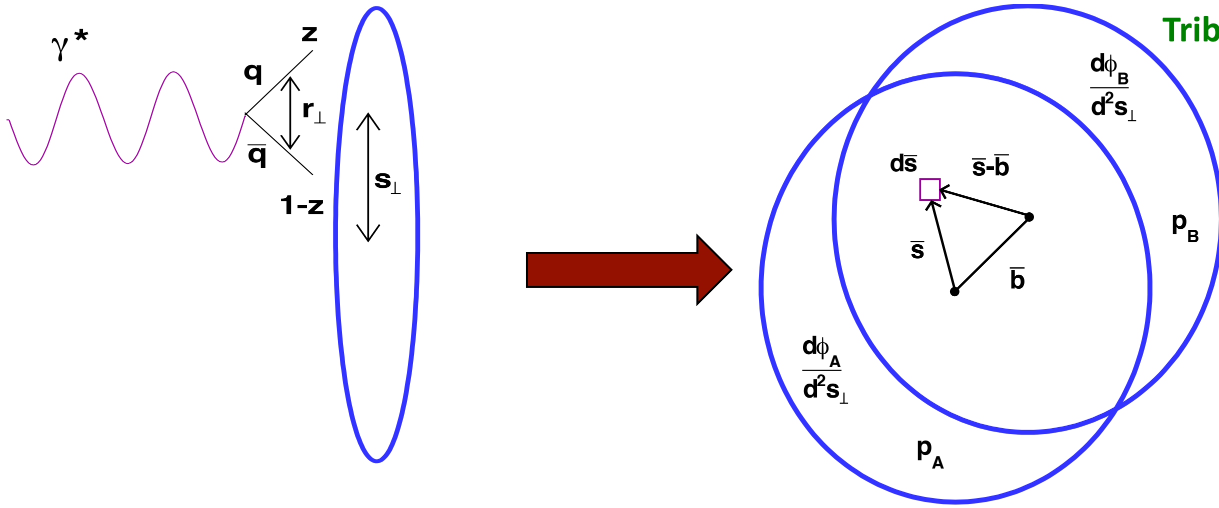
k = ∞ : Poisson

Yang-Mills computation shows picture is robust for 2 part. Corr. and gives ζ ~ 1/3 – 3/2 … O(1)

Lappi, Srednyak, RV

Saturation models: from HERA to RHIC/LHC

Levin,Rezaiean, arXiv:1005.0631
Tribedy,RV, 1011.1895



Unintegrated gluon dist. from dipole cross-section:

$$\frac{d\phi(x,k_\perp|s_\perp)}{d^2s_\perp} = \frac{k_\perp^2\,N_c}{4\,\alpha_s}\int_0^\infty d^2r_\perp\,e^{ik_\perp\cdot r_\perp}\left[1-\frac{1}{2}\,\frac{d\sigma^p_{\rm dip.}}{d^2s_\perp}(r_\perp,x,s_\perp)\right]^2$$

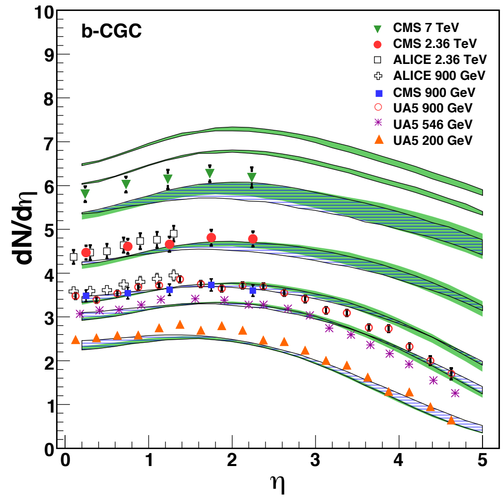
k_T factorization to compute inclusive gluon dist. at a given impact parameter:

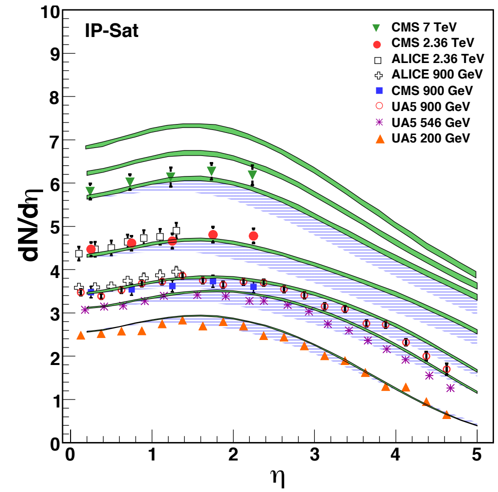
$$\frac{dN_g(b_\perp)}{dy\,d^2p_\perp} = \frac{16\,\alpha_s}{\pi C_F}\,\frac{1}{p_\perp^2}\int\frac{d^2k_\perp}{(2\pi)^5}\int d^2s_\perp\,\frac{d\phi_A(x,k_\perp|s_\perp)}{d^2s_\perp}\,\frac{d\phi_B(x,p_\perp-k_\perp|s_\perp-b_\perp)}{d^2s_\perp}$$

Saturation models: fits to RHIC/LHC incl. p+p data

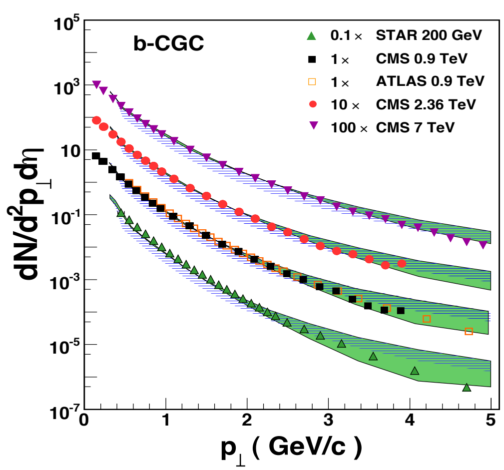
Kowalski, Motyka, Watt

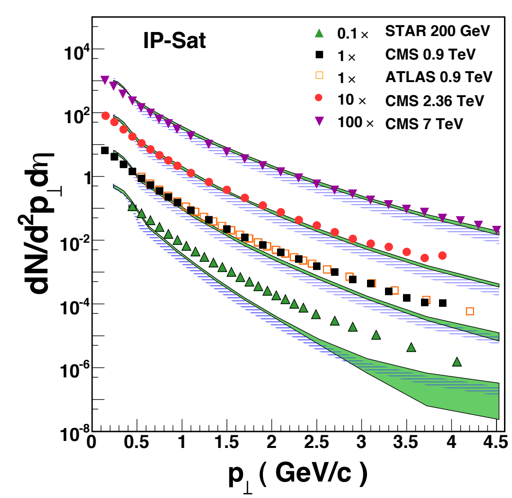
Rapidity dists.





p_T dists.



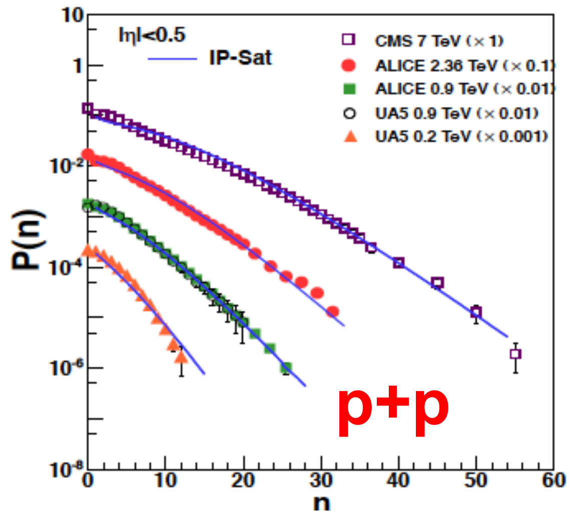


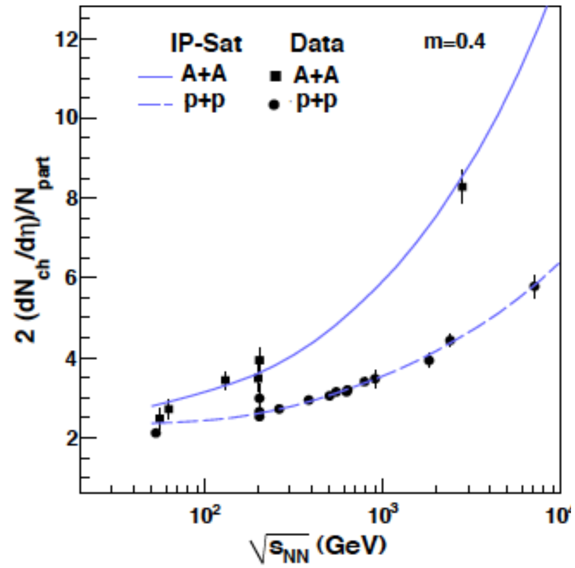
e+p constrained fits give good description of hadron data

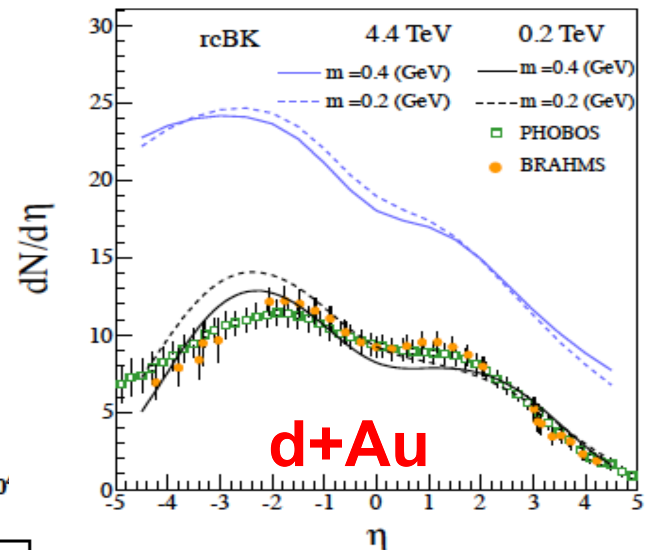
Tribedy,RV

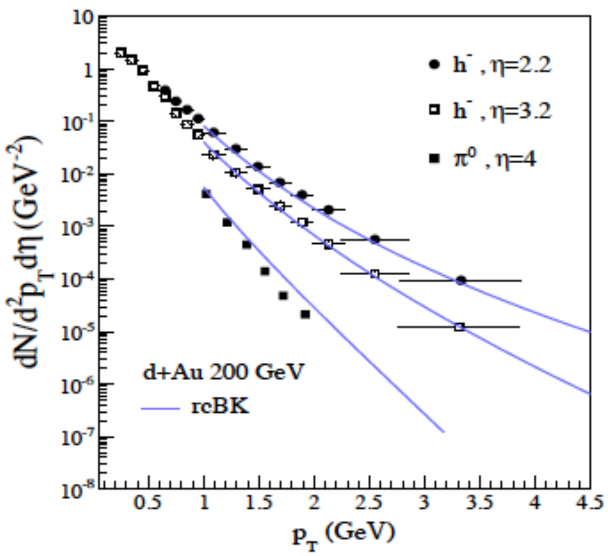
“Global analysis” of bulk distributions

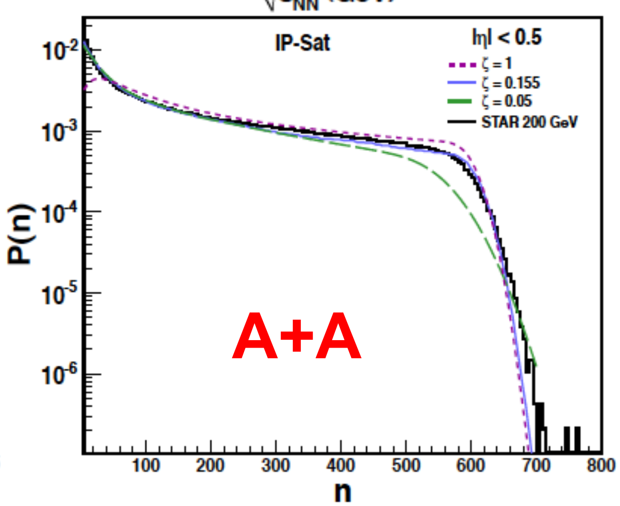
Tribedy,RV, 1112.2445









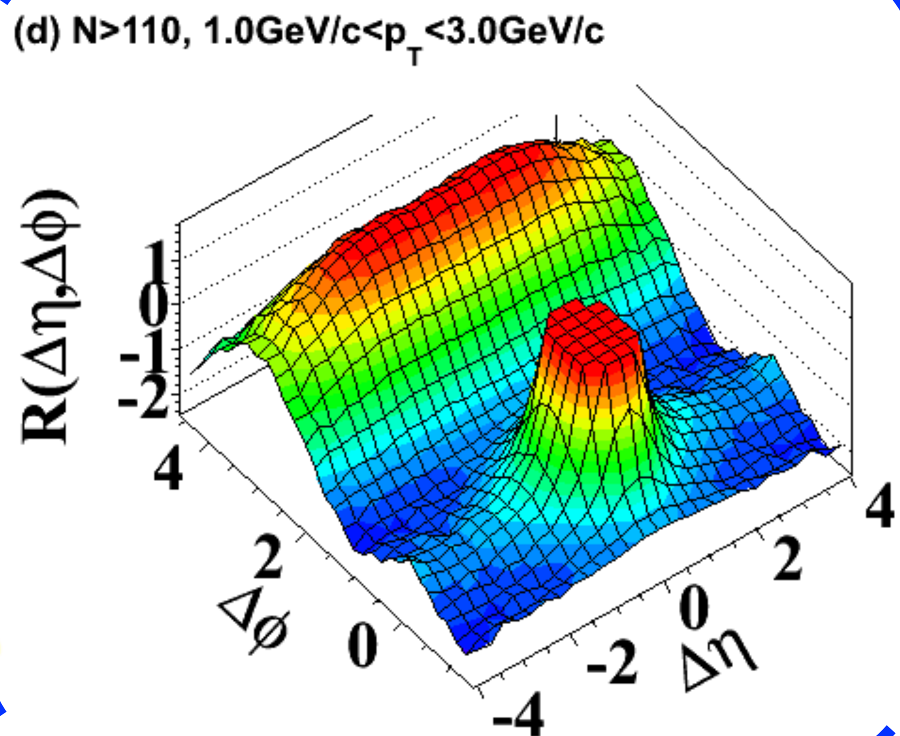


ζ = 1/6 for both

p+p and A+A

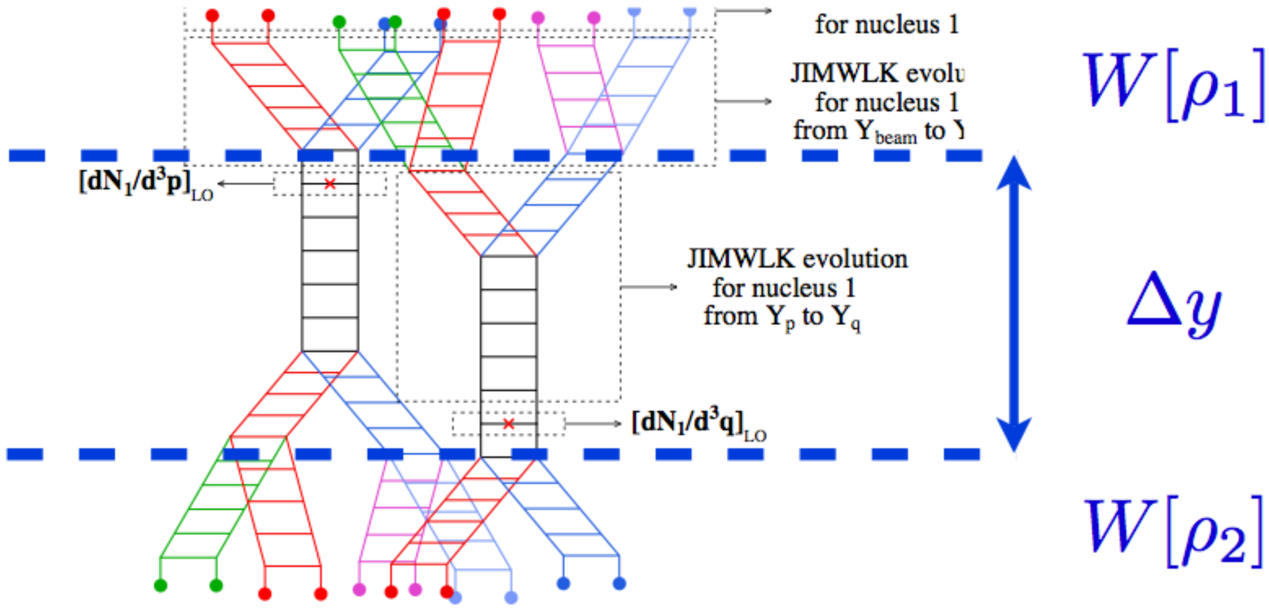
Back to the near side ridge in high multiplicity p+p collisions

"Discovery"

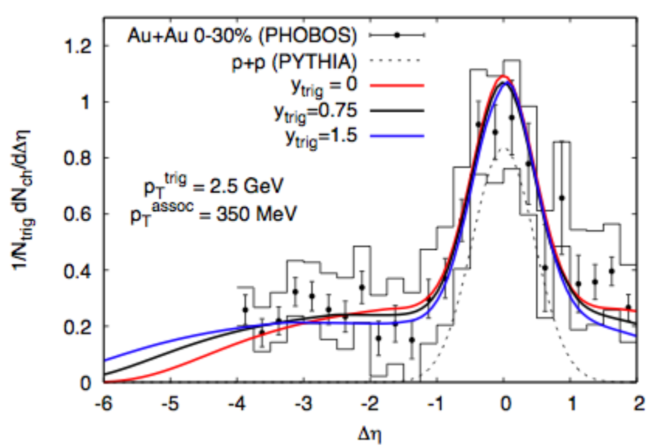


Long range di-hadron correlations

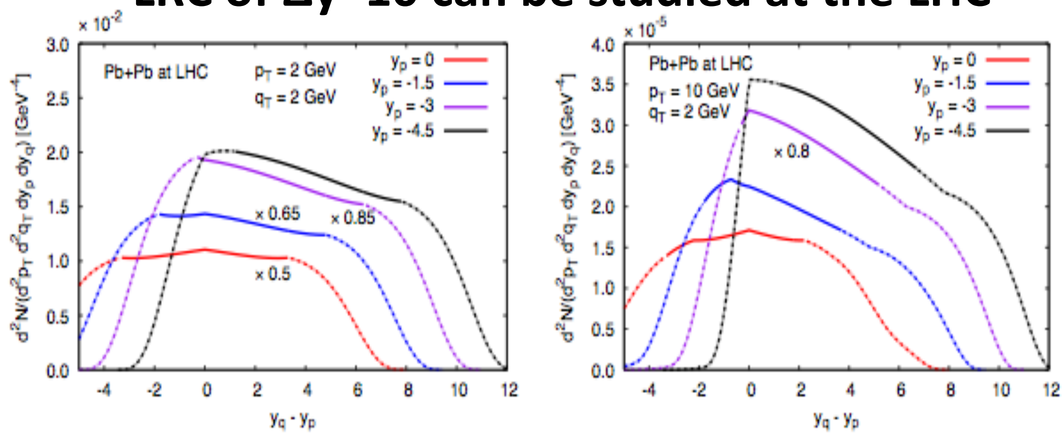
Gelis,Lappi,RV (2009)



Dusling,Gelis,Lappi,RV, arXiv:0911.2720



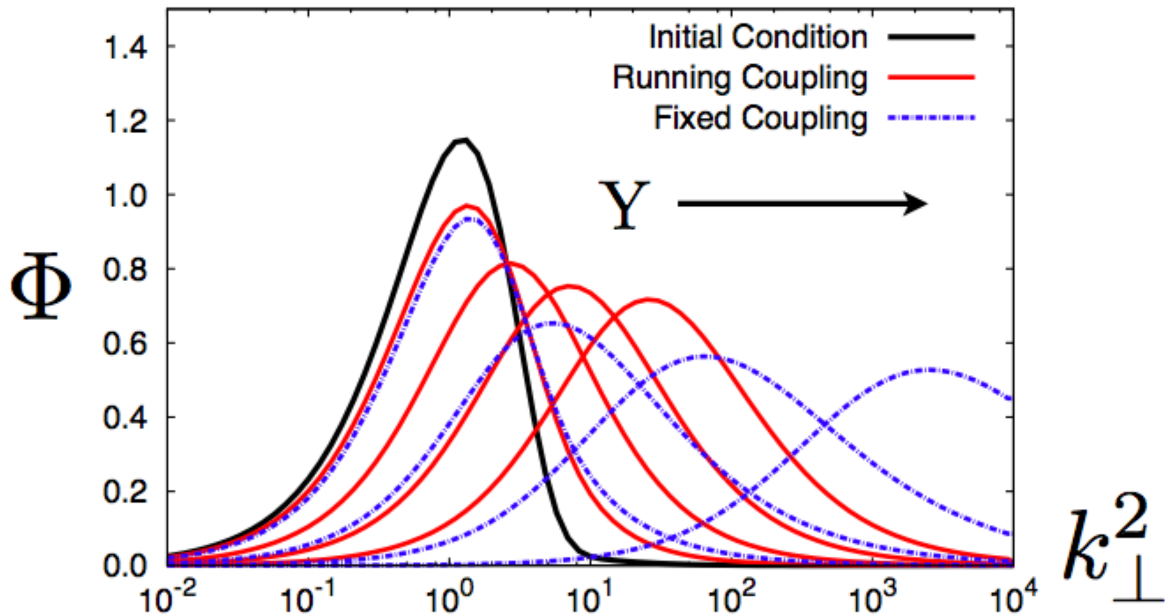
LRC of Δy~10 can be studied at the LHC



Long range di-hadron correlations

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

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

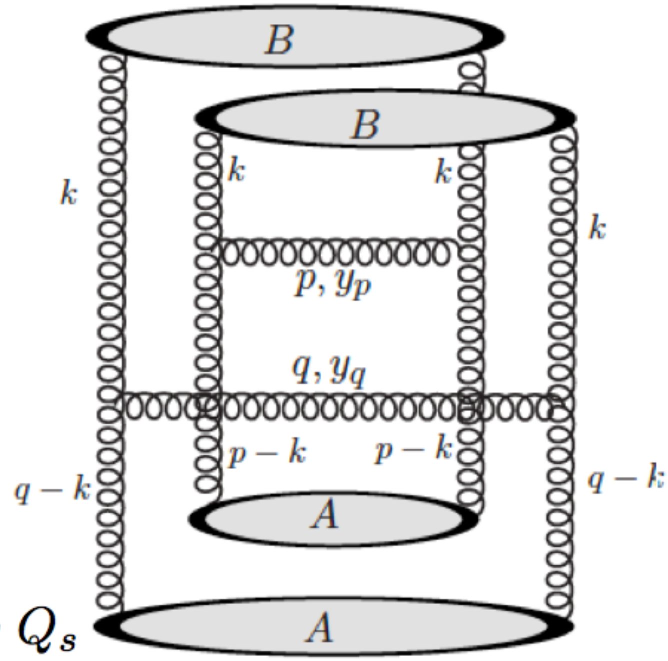


Caveat: Contribution of higher 4-pt. Wilson line correlators not included

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

The p+p ridge: azimuthal corr. from Glasma graphs

Dumitru; Dumitru,Dusling,Gelis,Jalilian-Marian,Lappi,RV



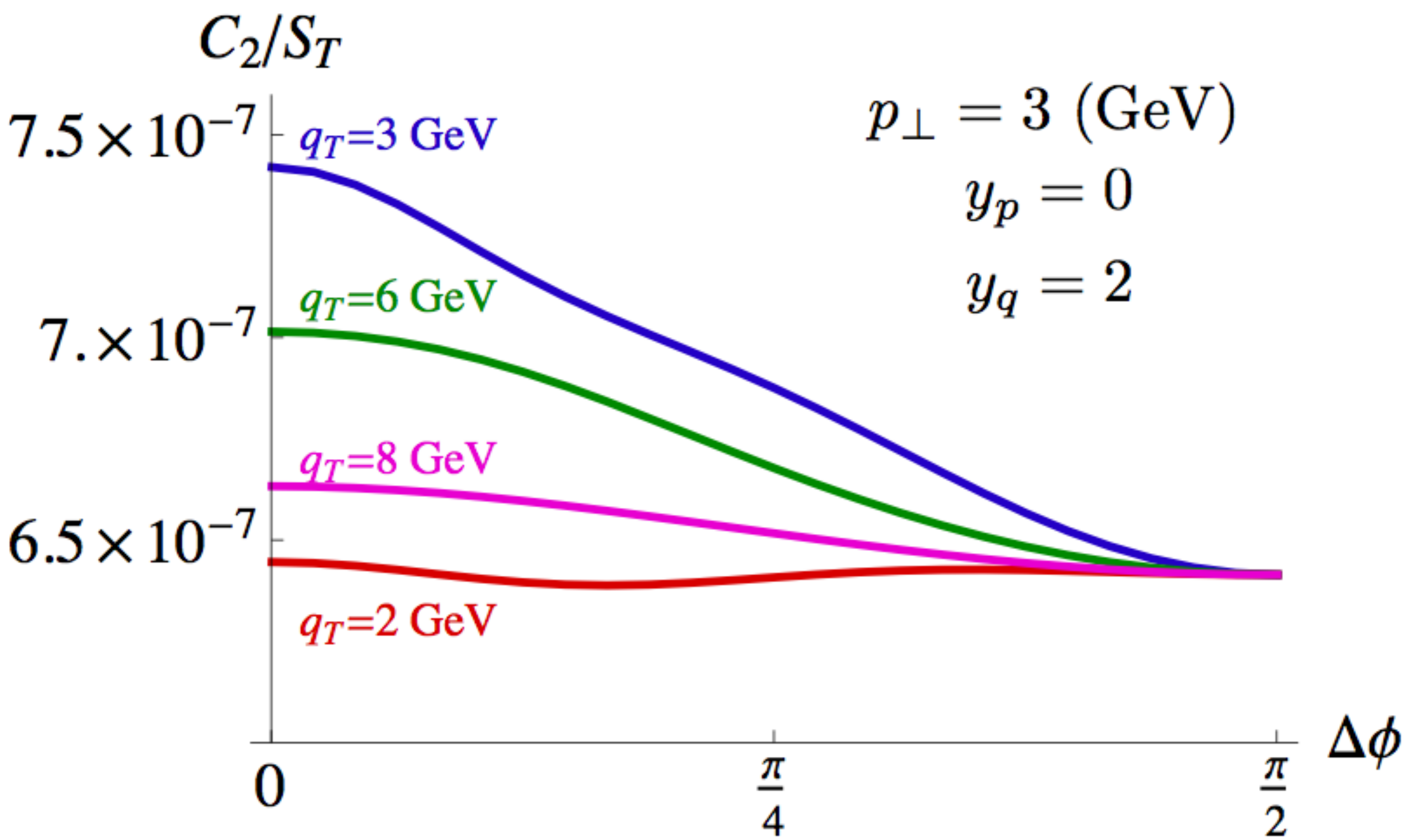
$|\mathbf{p}_\perp - \mathbf{k}_\perp| \sim Q_s$

$|\mathbf{q}_\perp - \mathbf{k}_\perp| \sim Q_s$

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

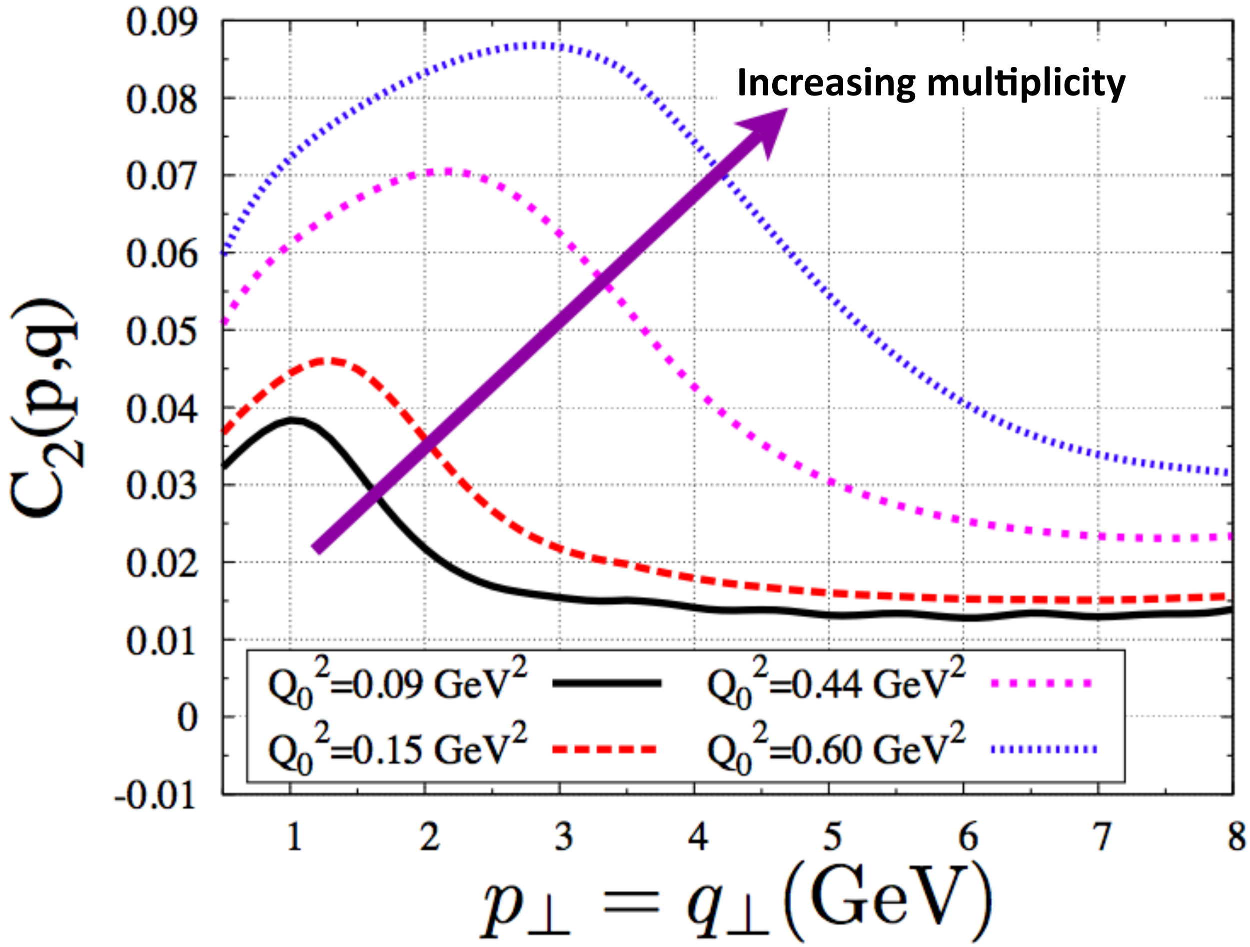
Systematics of the correlation

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



Ridge goes away for $p_T \neq q_T$

Systematics of the correlation



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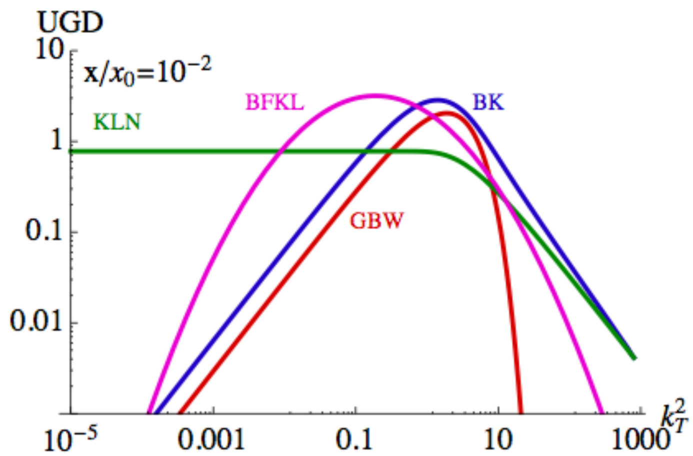
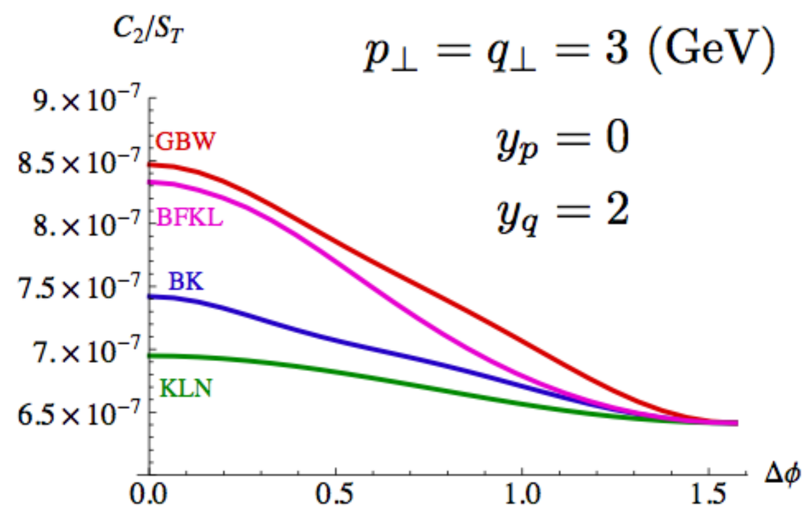




- Near-side correlation sensitive to diffuseness of wavefunction

Quantitative description of pp ridge

Dusling,RV, 1201.2658

$$\frac{d^2N}{d\Delta\phi} = K\int_{-2.4}^{+2.4} d\eta_p\, d\eta_q\ \mathcal{A}(\eta_p,\eta_q)$$
$$\times \int_{p_T^{\min}}^{p_T^{\max}} \frac{dp_T^2}{2} \int_{q_T^{\min}}^{q_T^{\max}} \frac{dq_T^2}{2} \int d\phi_p \int d\phi_q\ \delta(\phi_p - \phi_q - \Delta\phi)$$
$$\times \int_0^1 dz_1 dz_2 \frac{D(z_1)}{z_1^2}\frac{D(z_2)}{z_2^2}\frac{d^2N^{\rm corr.}_{\rm Glasma}}{d^2\mathbf{p}_T d^2\mathbf{q}_T d\eta_p d\eta_q}\left(\frac{p_T}{z_1},\frac{q_T}{z_2},\Delta\phi\right)$$

$$\mathcal{A}(\eta_p,\eta_q) = \theta(|\eta_p-\eta_q|-\Delta\eta_{\min})\,\theta(\Delta\eta_{\max}-|\eta_p-\eta_q|)$$

Try soft and hard fragmentation functions:

$D_1 = 3(1-x)^2 / x$
$D_2 = 2(1-x) / x$

$$N_{\rm trig} = \int_{-2.4}^{+2.4} d\eta \int_{p_T^{\min}}^{p_T^{\max}} d^2\mathbf{p}_T \int_0^1 dz \frac{D(z)}{z^2}\frac{dN}{d\eta\, d^2\mathbf{p}_T}\left(\frac{p_T}{z}\right)$$

Only parameter fit to yield data is K =2.3

$$\text{Assoc. Yield} = \frac{1}{N_{\rm trig}}\int_0^{\Delta\phi_{\rm min.}} d\Delta\phi \frac{d^2N}{d\Delta\phi} - \left.\frac{d^2N}{d\Delta\phi}\right|_{\Delta\phi_{\rm min.}}$$

Dependence on transverse area cancels in ratio…

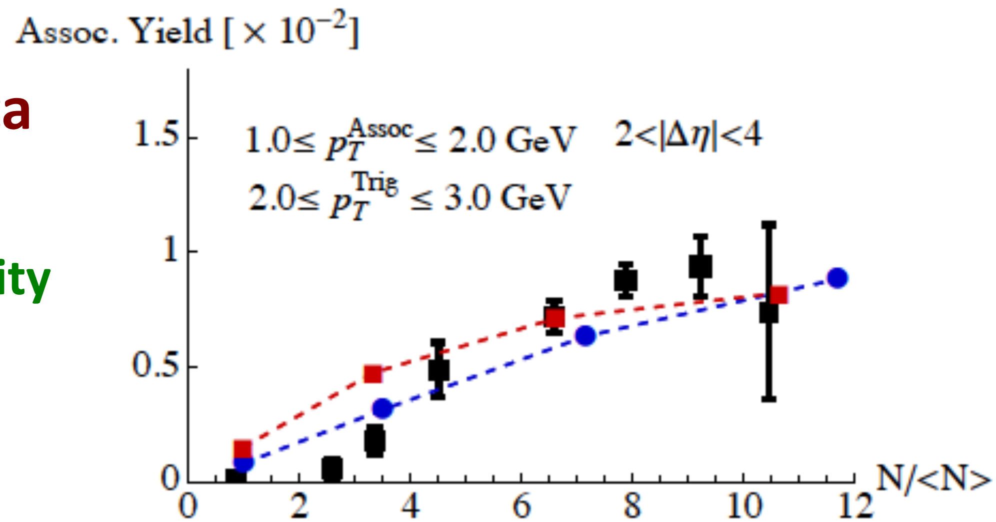
Subtracts any pedestal "phi-independent" correlation

Quantitative description of pp ridge

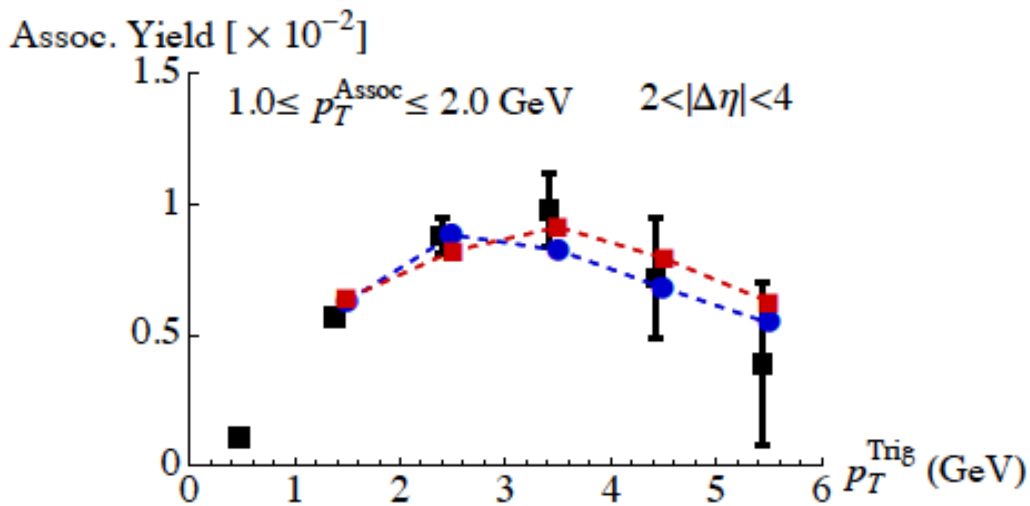
Dusling,RV, 1201.2658

CMS preliminary data

Assoc. yield with centrality



Assoc. yield with p_T^{Trig}

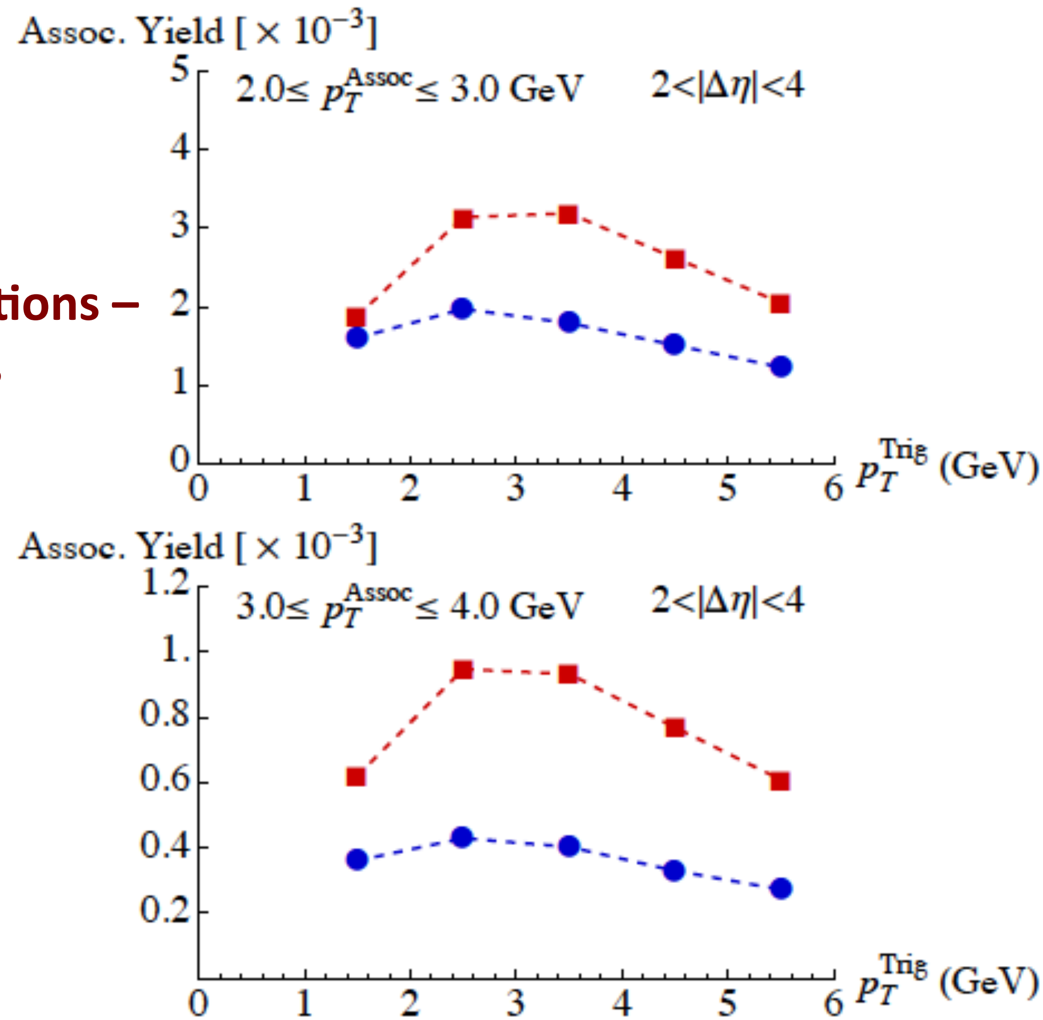


Quantitative description of pp ridge

Dusling,RV, 1201.2658

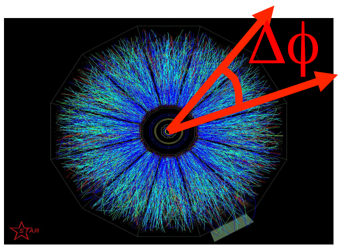
Predictions:

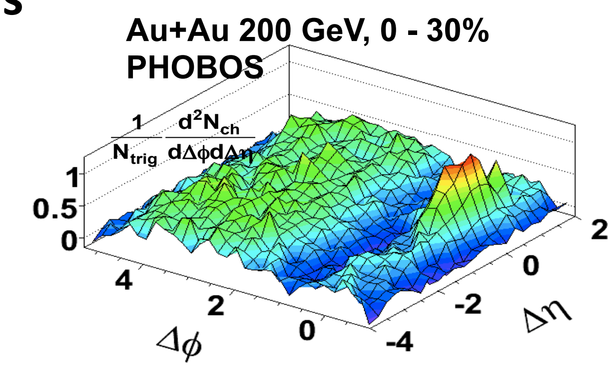
Yields for higher $p_T^{Assoc.}$ are sensitive to fragmentation functions – not known at forward rapidities

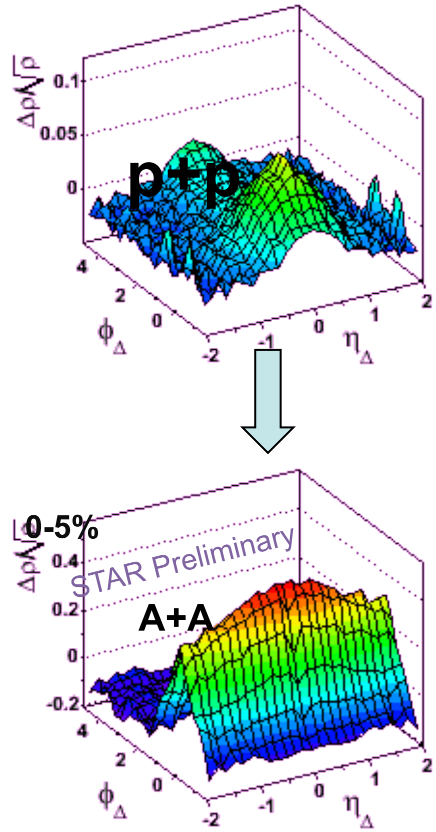


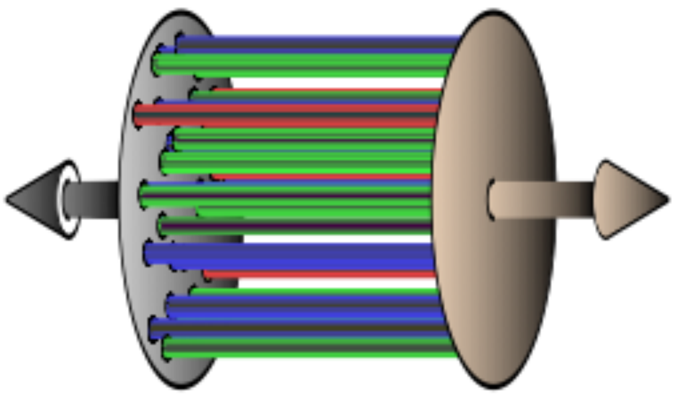
What about flow in p+p ?

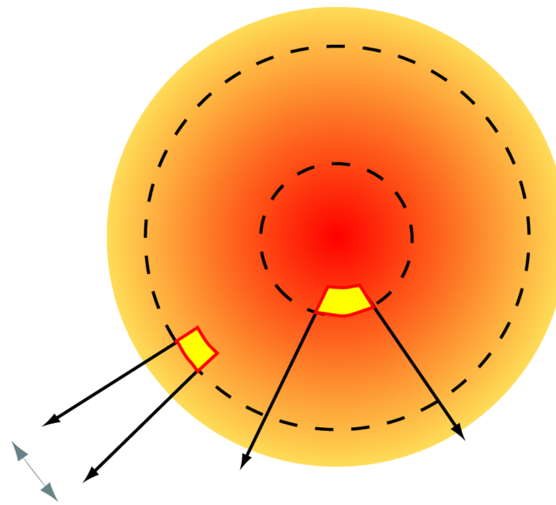
In heavy ion collisions











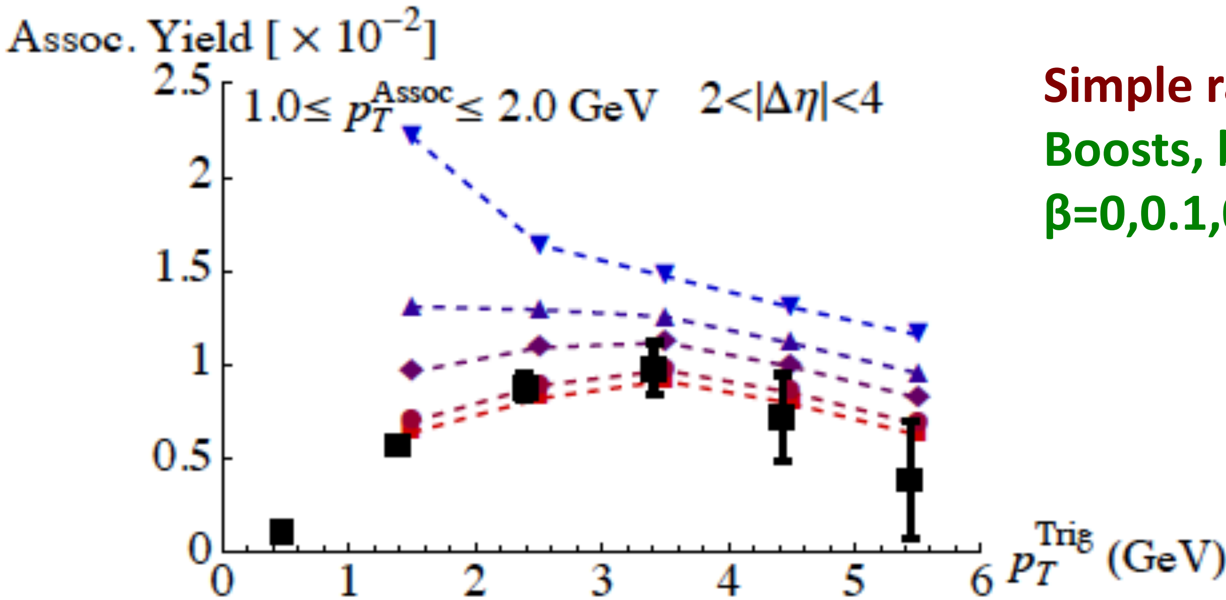
Glasma flux tubes provide the long range rapidity correlation

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

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

Voloshin; Shuryak

What about flow in p+p ?



Simple radial flow model result:

Boosts, bottom to top,

β=0,0.1,0.2,0.25,0.3

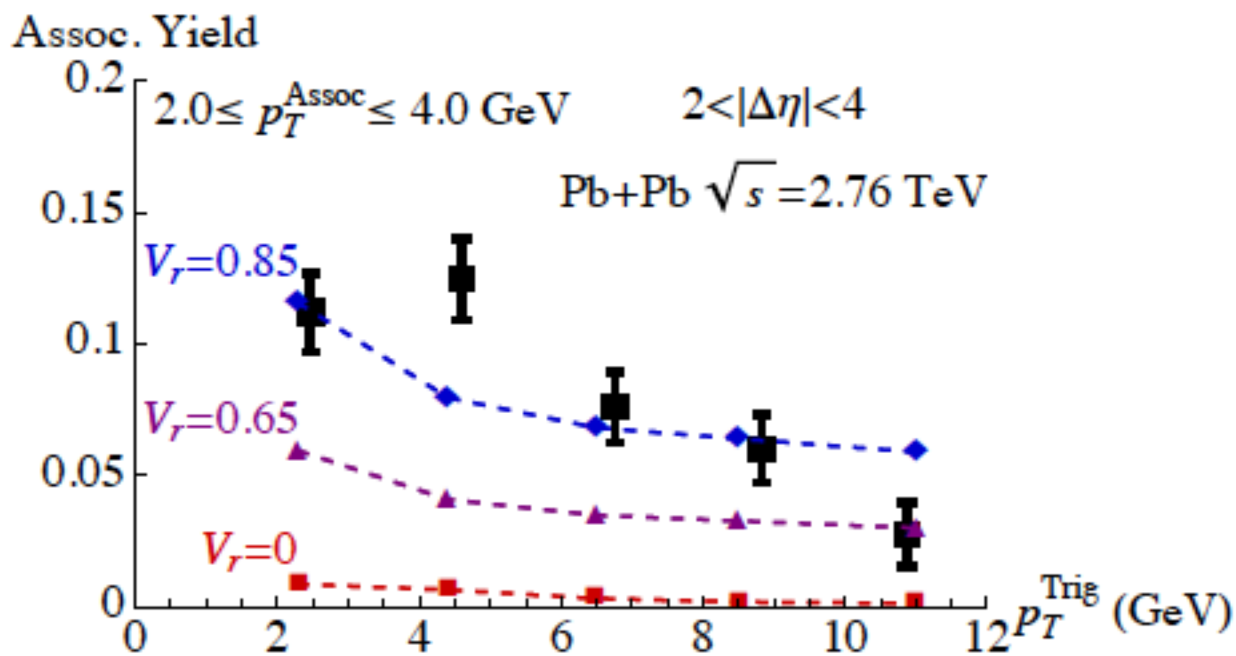
With increasing flow, the pedestal gets collimated

Associated yield reflects the p_T dependence of the Glasma pedestal

Can accommodate only very small re-scattering / flow contribution

A+A ridge is all flow

Preliminary CMS data



Theory issues

- Collimation in Glasma graphs is from N_c^2 suppressed graphs.
  Intrinsic leading N_c four point correlators give no collimation (Dumitru,Jalilian-Marian,Petreska) ?? – pomeron loop effects ? (Kovner talk)

- Multiple-scattering and evolution of two-gluon correlations can be computed for dense-dense sources systematically
  (Gelis,Lappi,RV; Lappi,Schenke,RV, in progress)

- More systematic "global" analysis of single (and double ?) inclusive distributions can constrain even simpler models

Experimental issues

- Current experiments (especially at the LHC) can strongly constrain theory
- Need fragmentation functions at forward rapidities
- Need more data on yield for wider p_T^{Trig}, p_T^{Assoc} and $N_{ch,}$, three particle corr.
- Compute correlation with $\Delta\eta$ for triggered η_p

Summary: bridges from ridges

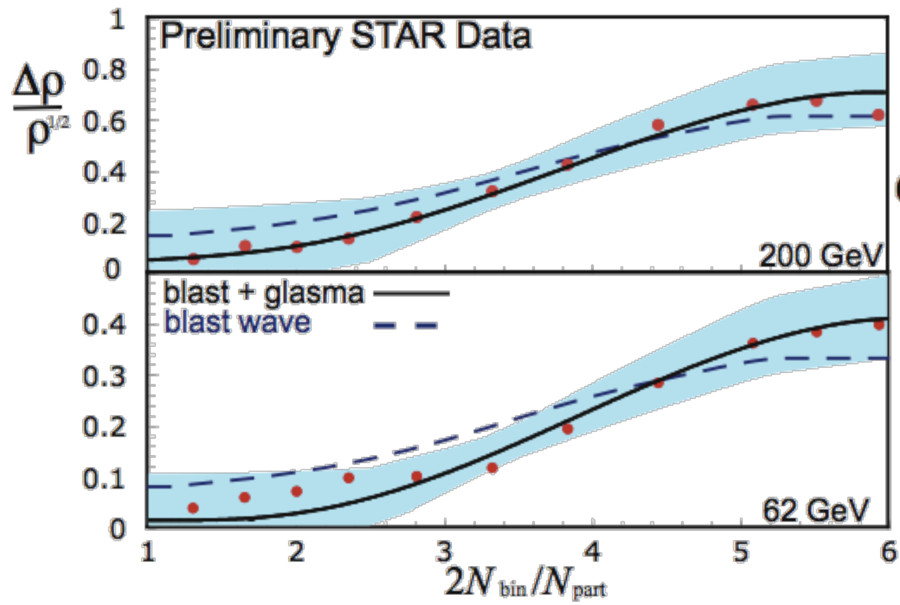
Ridges (and their pedestals) carry important dynamical information necessary to construct a successful theory of multi-particle production in QCD

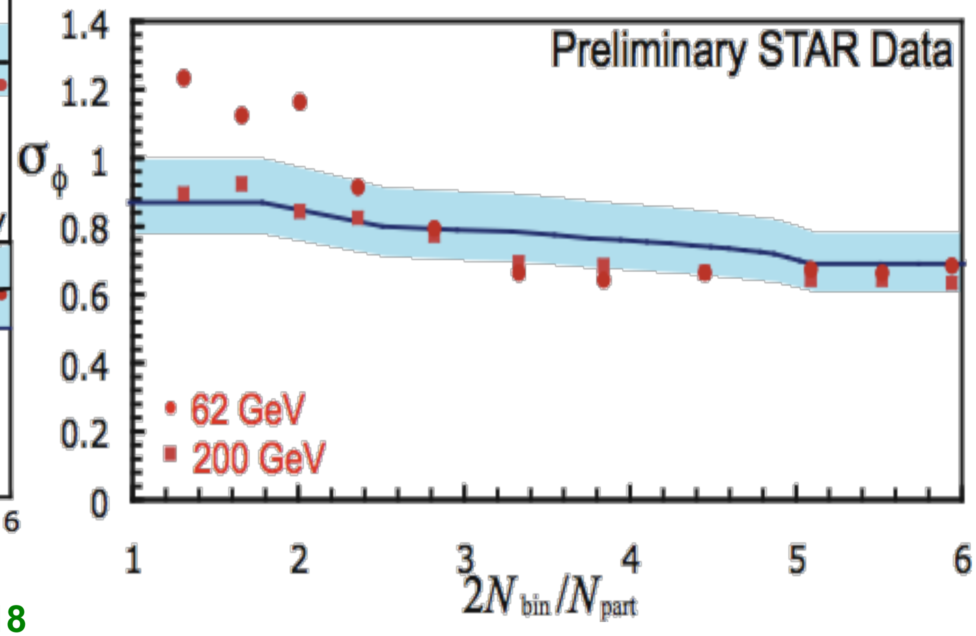
They provide key insight into the formation and evolution of strong color fields in heavy ion collisions


The nearly perfect ridge ?
Ridge
Jet

EXTRA SLIDES

Ridge from flowing flux tubes





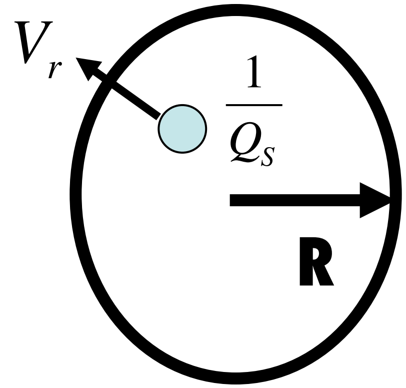
Gavin,McLerran,Moschelli, arXiv:0806.4718

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

Soft Ridge = Glasma flux tubes + Radial flow



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

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

Can be computed non-perturbatively from numerical lattice simulations

Srednyak,Lappi,RV

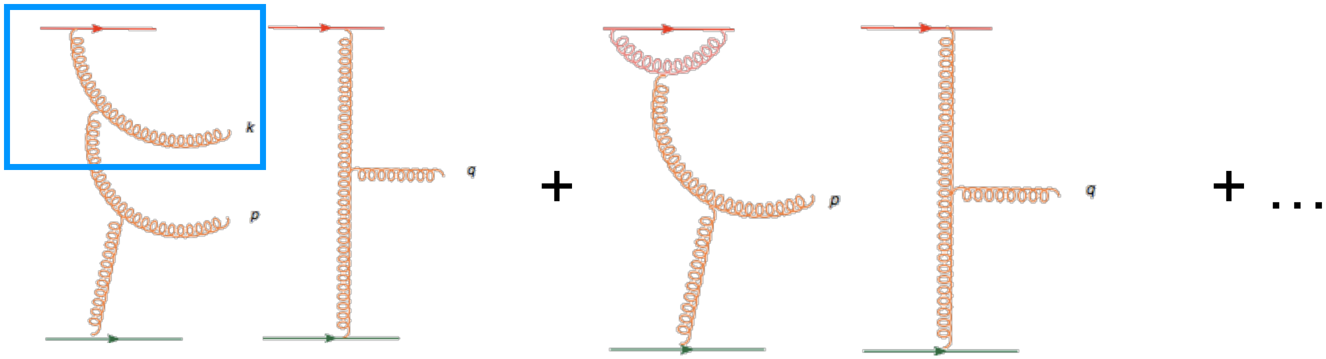
$\gamma_B = \cosh\zeta_B$ **from blast wave fits to spectra**

Q_s from centrality dependence of inclusive spectra

2 particle correlations in the Glasma (II)

Gelis, Lappi, RV, arXiv: 0807.1306

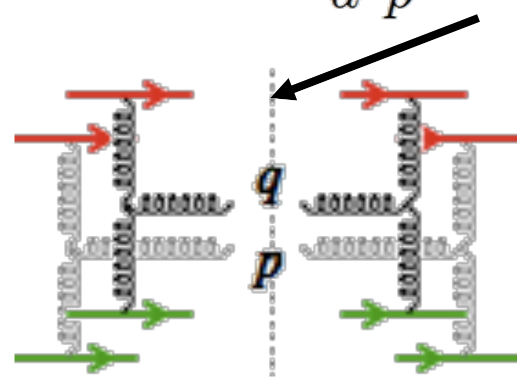
RG evolution:



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

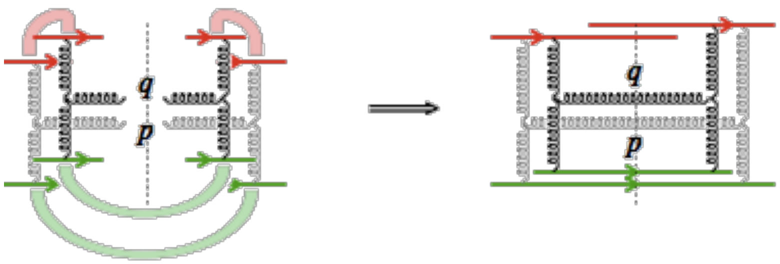
$$\langle \frac{dN_2}{d^3p\, d^3q} \rangle_{\rm LLogs} = \int [d\rho_1][d\rho_2] W_{Y_1}[\rho_1]\, W_{Y_2}[\rho_2]\, \frac{dN}{d^3p}|_{\rm LO}\, \frac{dN}{d^3q}|_{\rm LO}$$

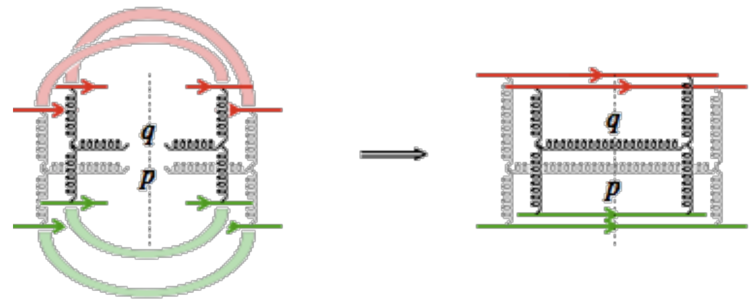
= LO graph with evolved sources
Glasma flux tubes



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