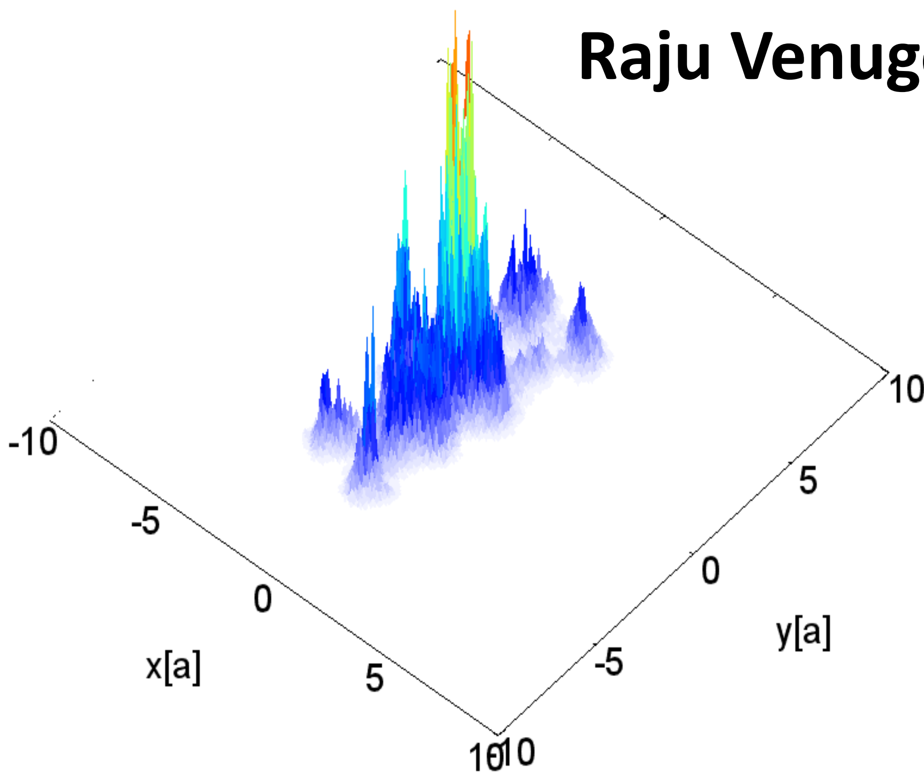
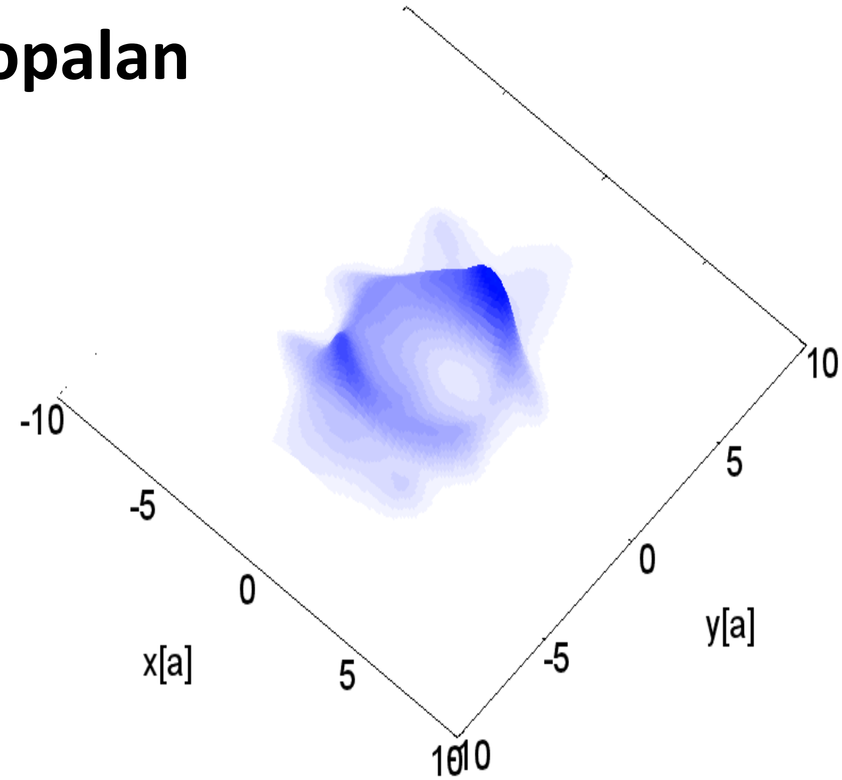
The Glasma: coherence, evolution, correlations

Raju Venugopalan





Lecture II, JET school, June 2012

Outline of lectures

- **Lecture I: Gluon Saturation and the Color Glass Condensate**

- **Lecture II: Quantum field theory in strong fields. Factorization. the Glasma and long range correlations**

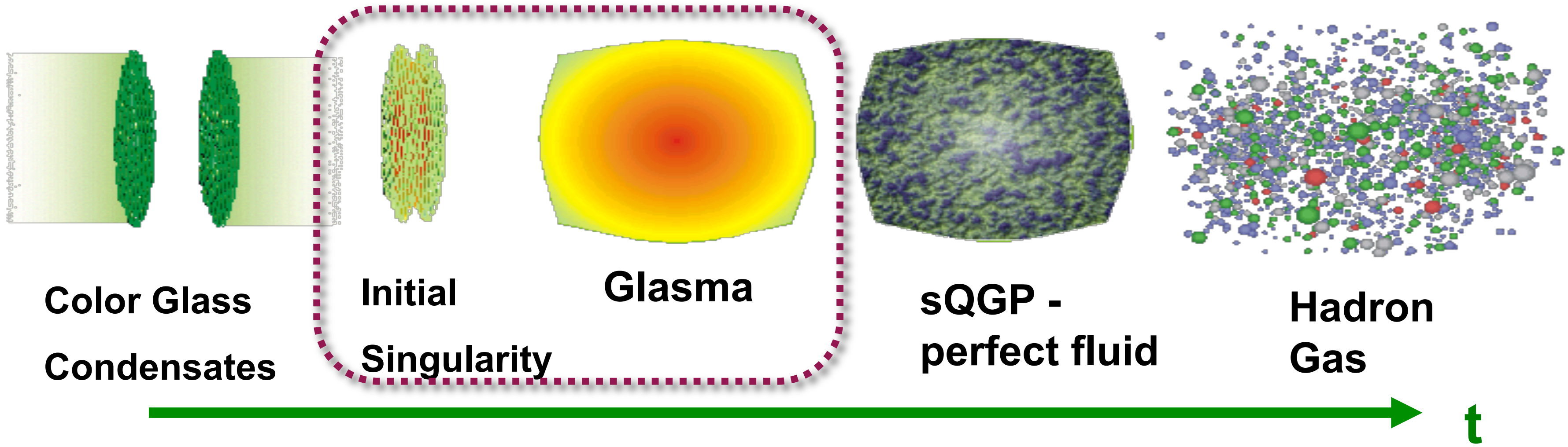
- **Lecture III: Quantum field theory in strong fields.**
  Instabilities, spectrum of initial quantum fluctuations, decoherence, hydrodynamics, B-Einstein condensation & thermalization

Traditional picture of heavy ion collisions

***@$#! on *@$#!**

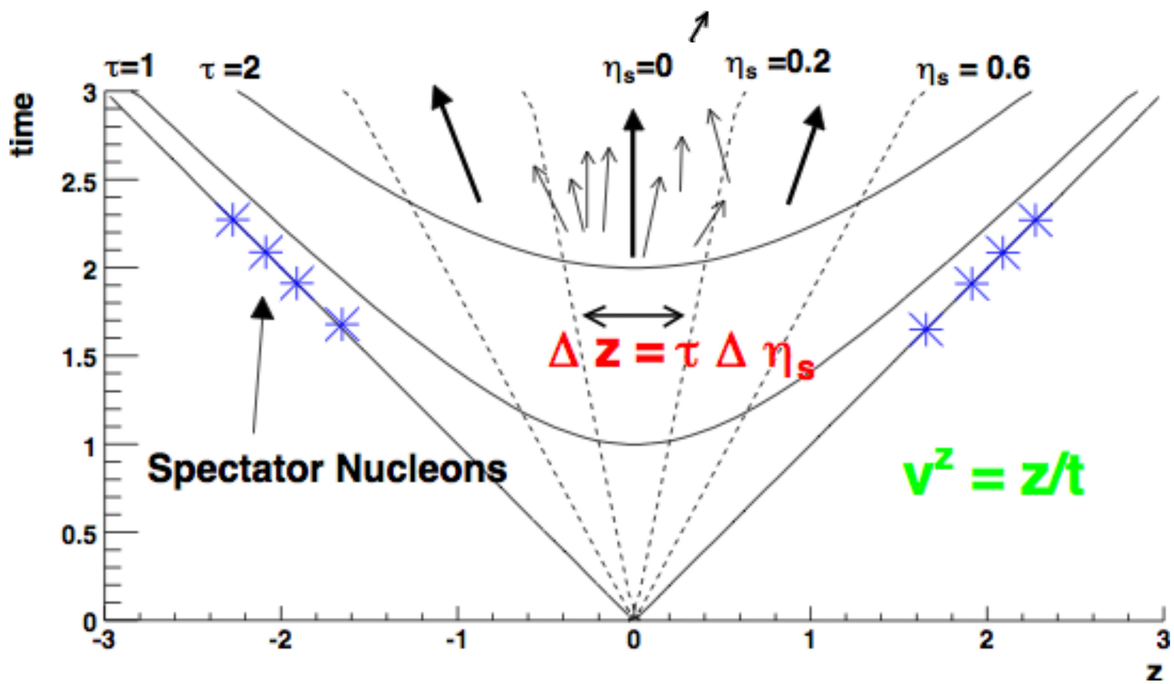
Well known physicist (circa early 1980s)

Standard model of HI Collisions



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

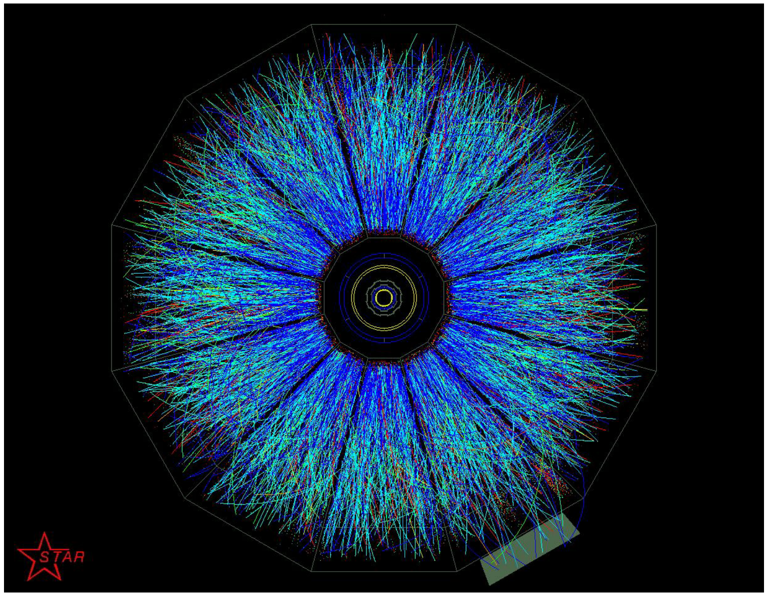
Forming a Glasma in the little Bang



- **Problem: Compute particle production in QCD with** ***strong time dependent*** **sources**
- **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 LITTLE BANG



How can we compute multiparticle production *ab initio* in HI collisions ?

-~~*perturbative VS non-perturbative,*~~

Always non-perturbative for questions of interest in this talk!

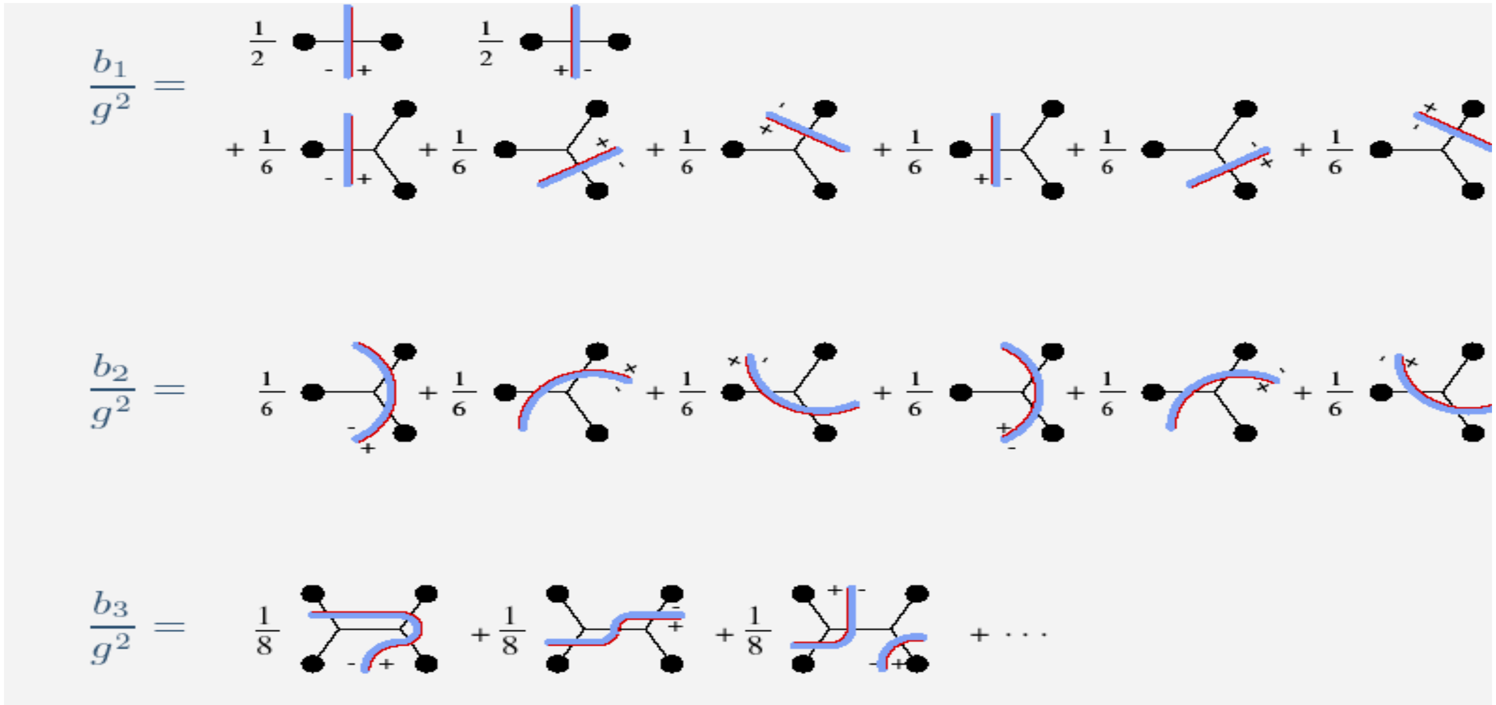
strong coupling VS weak coupling

↓

AdS/CFT ? Interesting set of issues… not discussed here

Multiparticle production for strong time dependent sources:

Gelis, RV ; NPA776 (2006)



$$P_n = e^{-\frac{1}{g^2}\sum_r b_r} \sum_{p=1}^{n} \frac{1}{p!} \sum_{\alpha_1+\cdots+\alpha_p=n} \frac{b_{\alpha_1}\cdots b_{\alpha_p}}{g^{2p}}$$

b_r - **probability of vacuum-vacuum diagrams with r cuts**

“combinants”

Observations:

I) **P_n is non-perturbative for any n and for coupling g << 1 - no simple power counting in g**

II) **Even at tree level, P_n is *not a Poisson dist.***

III) ***However, vacuum-vacuum contributions cancel for inclusive quantitites ($\langle n^p \rangle = \Sigma\, n^p P_n / \Sigma\, P_n$) and one has systematic power counting for these…***

Power counting

LO: $1/g^2$, all orders in sources $(g\rho_{1,2})^n$

NLO: O(1), all orders in $(g\rho_{1,2})^n$

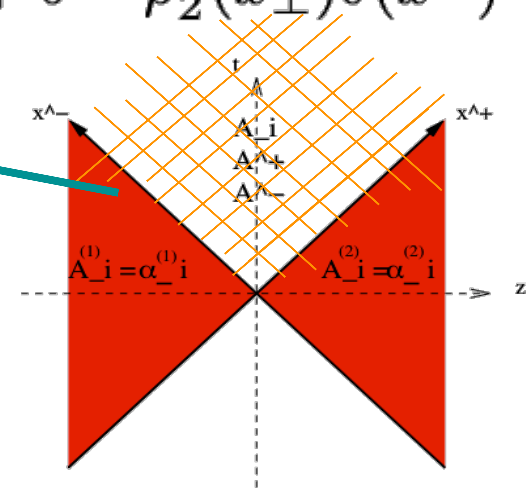
At NLO, large logs : $g^2 \ln(1/x_{1,2})$ – can be resummed to all orders and factorized into evolution of wave functions

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

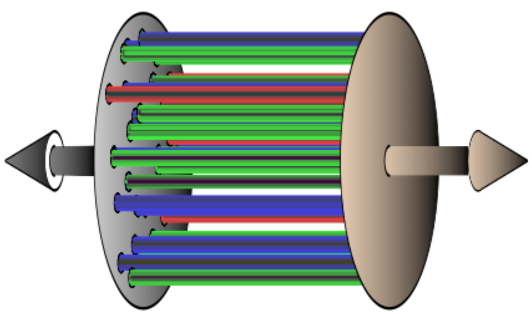
O(1/g^2) and all orders in (gρ)^n

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

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



Kovner,McLerran,Weigert; Krasnitz, RV; Lappi
Lappi,Srednyak,RV (2010)



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

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

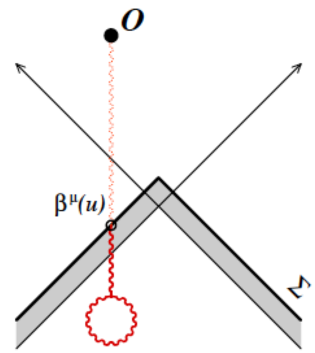
Boost invariant flux tubes of size with || color E & B fields- generate Chern-Simons charge

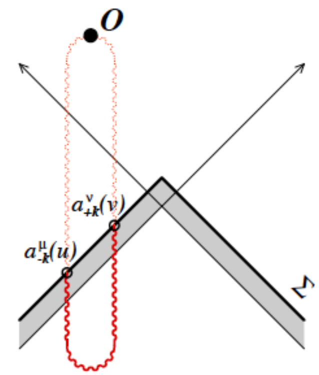
However, this results in very anisotropic ($P_T >> P_L$) pressure for τ ~ $1/Q_S$

RG evolution for 2 nuclei

Gelis,Lappi,RV (2008)

Log divergent contributions crossing nucleus 1 or 2:



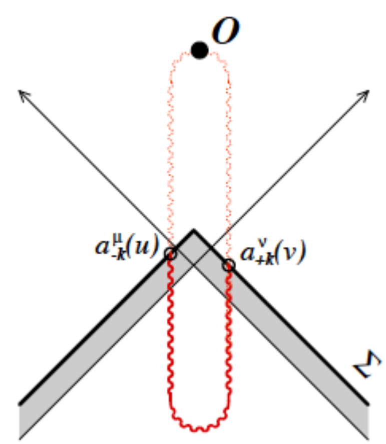


$$\mathcal{O}_{\rm NLO} = \left[\frac{1}{2} \int_{\vec{u},\vec{v}} \mathcal{G}(\vec{u},\vec{v})\ \mathcal{T}_u \mathcal{T}_v + \int_{\vec{u}} \beta(\vec{u})\ \mathcal{T}_u \right] \mathcal{O}_{\rm LO}$$

$\mathcal{G}(\vec{u},\vec{v})$ **and** $\beta(\vec{u})$ **can be computed on the initial Cauchy surface**

$\mathcal{T}_u = \frac{\delta}{\delta A(\vec{u})}$ **linear operator on initial surface**

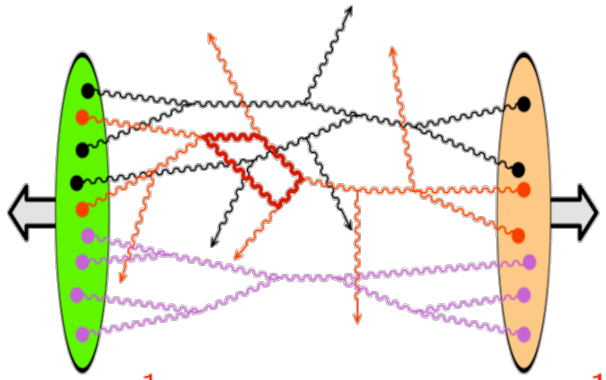
Contributions across both nuclei are finite-no log divergences => factorization



$$\mathcal{O}_{\rm NLO} = \left[\ln\left(\frac{\Lambda^+}{p^+}\right) \mathcal{H}_1 + \ln\left(\frac{\Lambda^-}{p^-}\right) \mathcal{H}_2 \right] \mathcal{O}_{\rm LO}$$

Factorization + temporal evolution in the Glasma

$$T^{\mu\nu}_{\rm LO} = \frac{1}{4} g^{\mu\nu} F^{\lambda\delta} F_{\lambda\delta} - F^{\mu\lambda} F^{\nu}_{\lambda} \qquad {\rm O}\left(\frac{Q_S^4}{g^2}\right)$$



ε=20-40 GeV/fm³ for τ=0.3 fm @ RHIC

NLO terms are as large as LO for $\alpha_S \ln(1/x)$:
small x (leading logs) and strong field (gρ) resummation

Gelis,Lappi,RV (2008)

$$\langle T^{\mu\nu}(\tau, \underline{\eta}, x_\perp)\rangle_{\rm LLog} = \int [D\rho_1 d\rho_2]\, W_{Y_1}[\rho_1]\, W_{Y_2}[\rho_2]\, T^{\mu\nu}_{\rm LO}(\tau, x_\perp)$$

$$Y_1 = Y_{\rm beam} - \eta\,;\; Y_2 = Y_{\rm beam} + \eta$$

Glasma factorization => universal “density matrices W” ⊗ “matrix element”

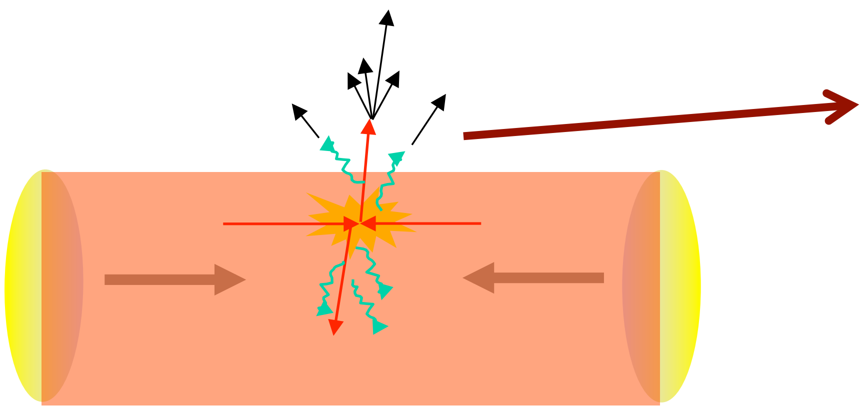
Some consequences of the Glasma flux tube picture

- **Compute long range rapidity correlations (the ridge in p+p and A+A)**

- **Compute n-particle distributions, incorporate these along with geometrical fluctuations in event-by-event hydro models**

Long range rapidity correlations

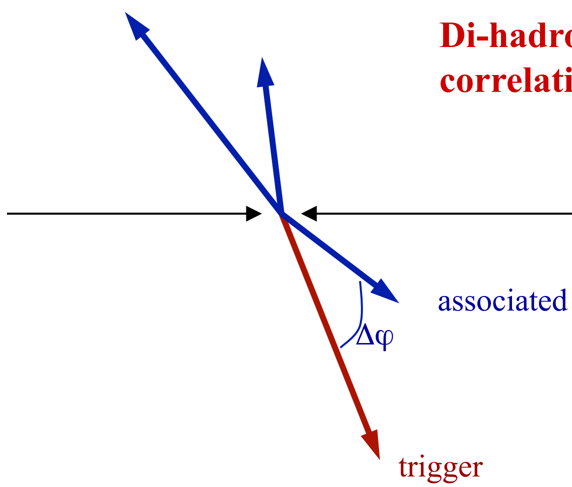
Some notation: Δη-ΔΦ



Rapidity: a measure of velocity (denoted by y or η) additive under Lorentz boost

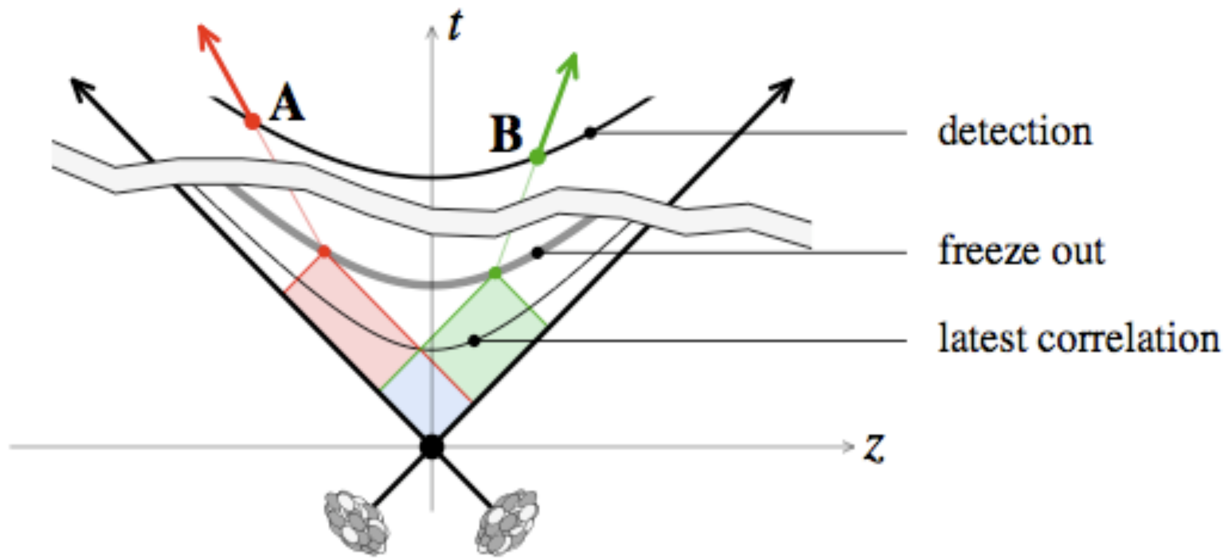
Δη – measure of angular separation along beam direction

Large Δη means particles are flying off in opposite directions along beam axis



Di-hadron correlations

Long range rapidity correlations as chronometer

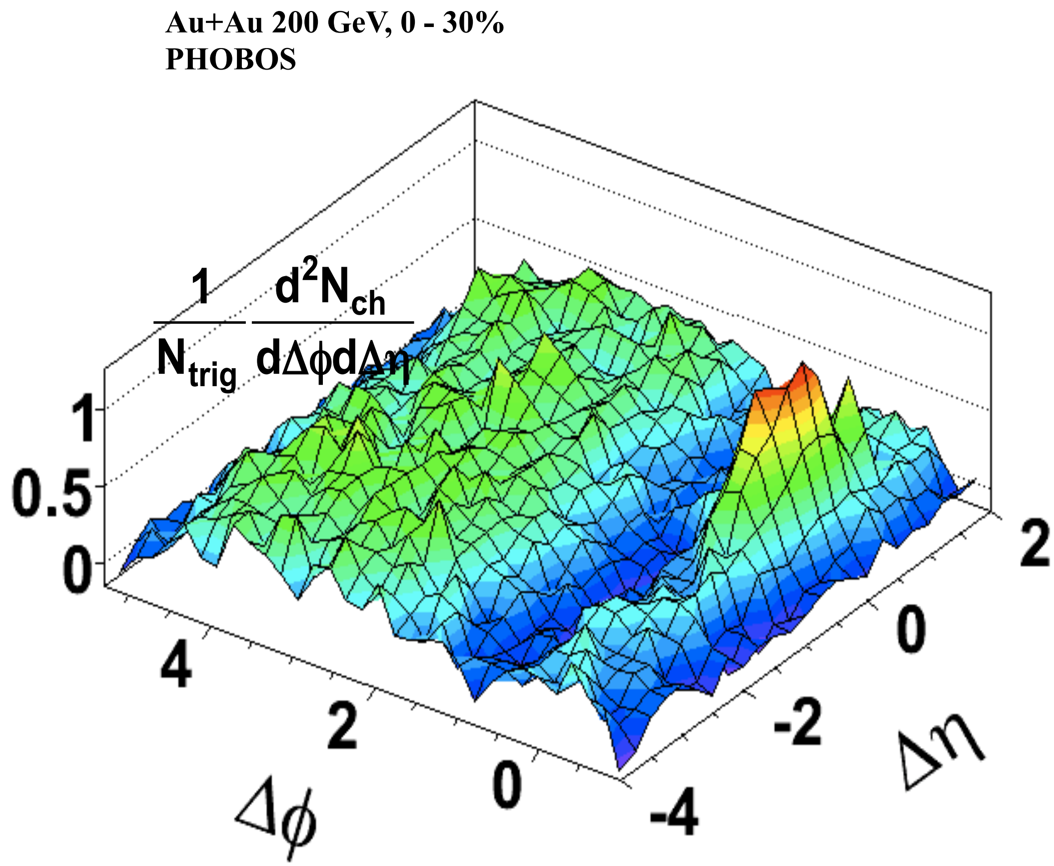


$$\tau \leq \tau_{\text{freeze-out}} \exp\left(-\frac{1}{2}|y_A - y_B|\right)$$

Long range rapidity correlations are sensitive to Glasma dynamics at early times

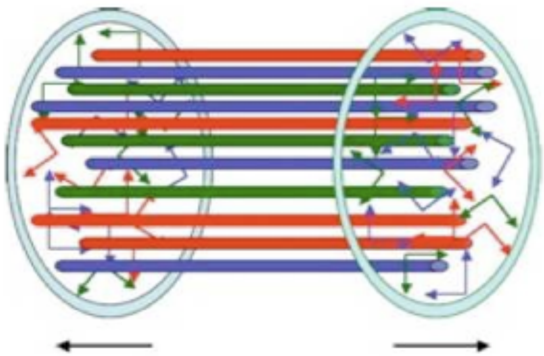
Dumitru, Gelis, McLerran, RV, arXiv 0804.3858

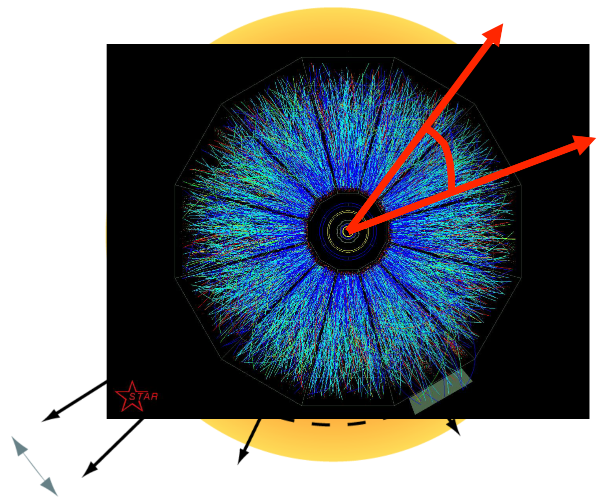
Really long range correlations



These structures reflect dynamics of strong gluon fields at times < 3•10^{-24} seconds

The Ridge: Glasma flux tubes+ Radial flow





Glasma flux tubes provide the long range rapidity correlation

Dumitru, Gelis, McLerran, RV; Gavin, McLerran, Moschelli
Lappi, Srednyak, RV (2010)

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

Voloshin; Shuryak

See Inside

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

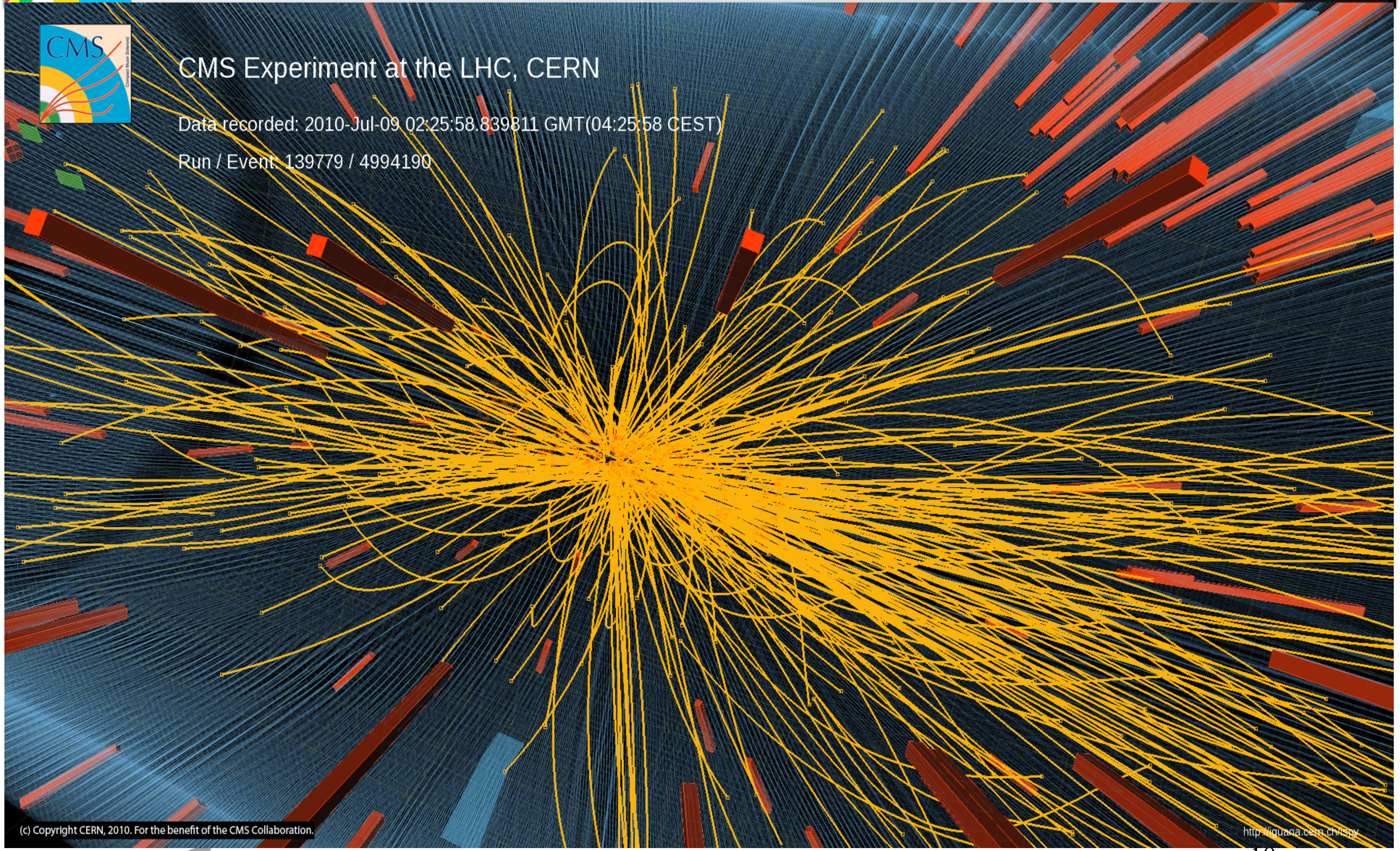
Scientists at the Large Hadron Collider are trying to solve a puzzle of their own making: why particles sometimes fly in sync

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"

A ridge in high multiplicity pp collisions



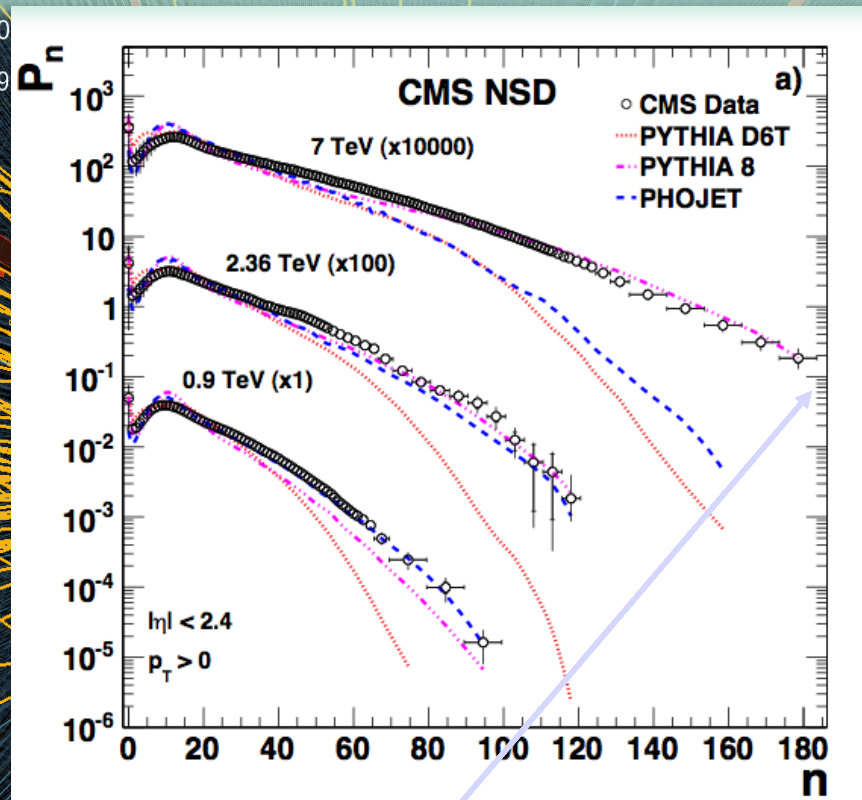
High Multiplicity pp collisions

CMS Experiment

Data recorded: 2010-Jul-0

Run / Event: 139779 / 499

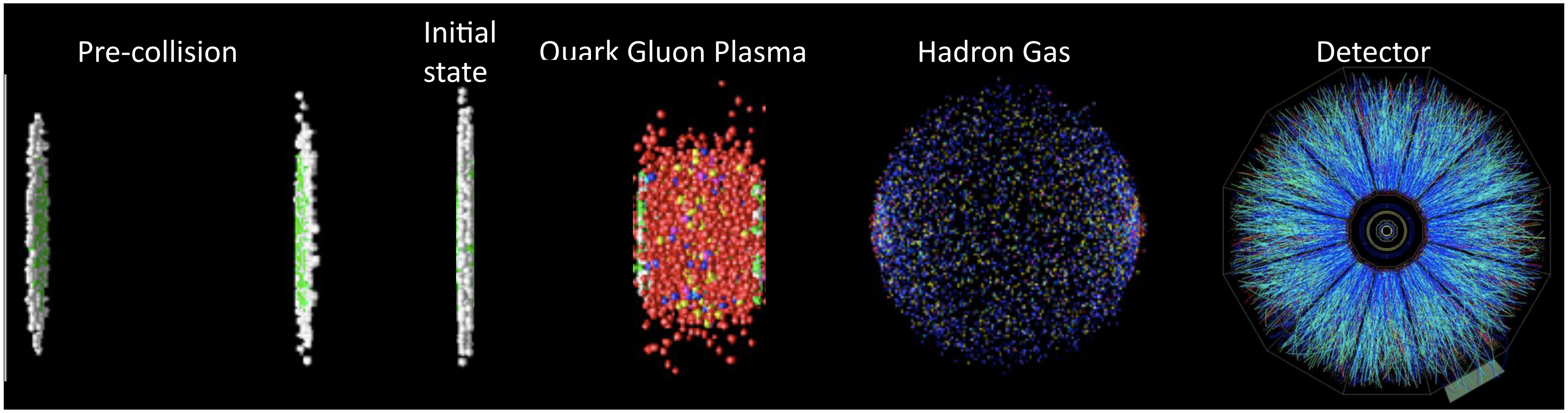
High Multiplicity events are rare in nature



Very high particle density regime

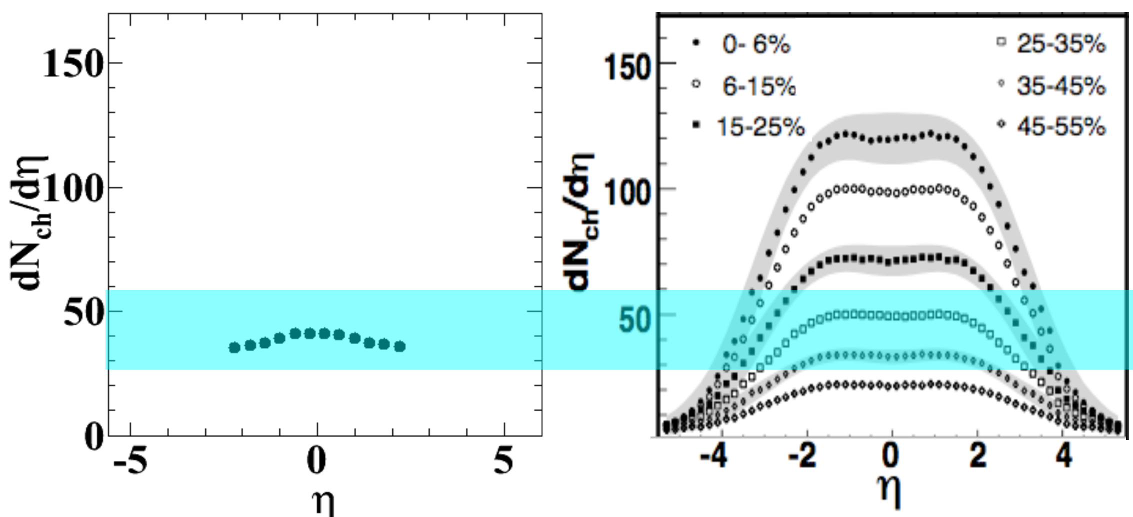
Is there anything peculiar happening there?

Relativistic Heavy Ion Collisions



CMS pp 7TeV, N>110

PHOBOS CuCu 62.4GeV



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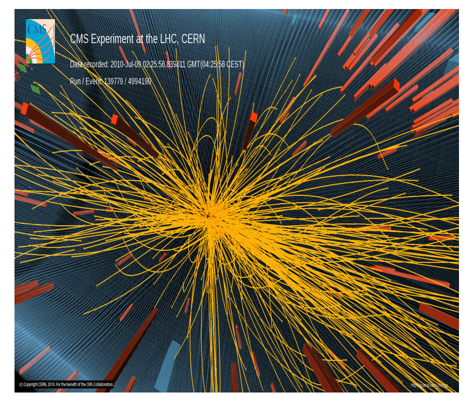
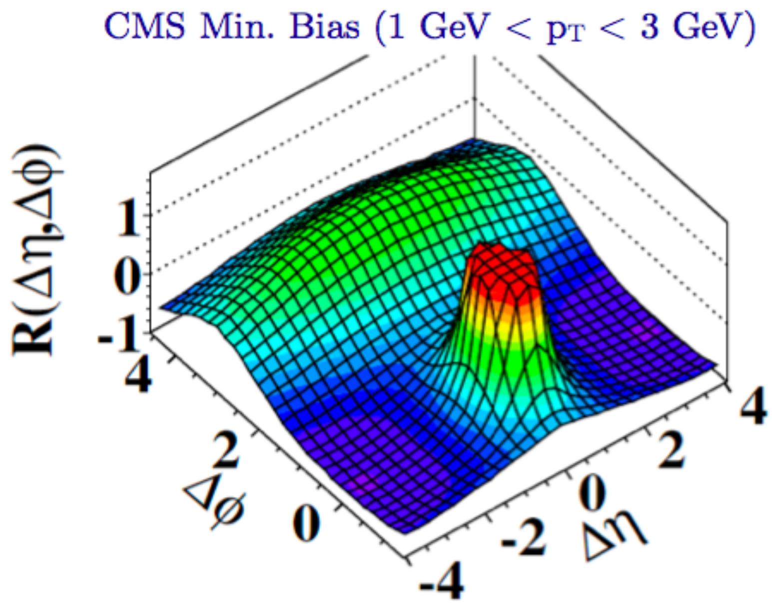
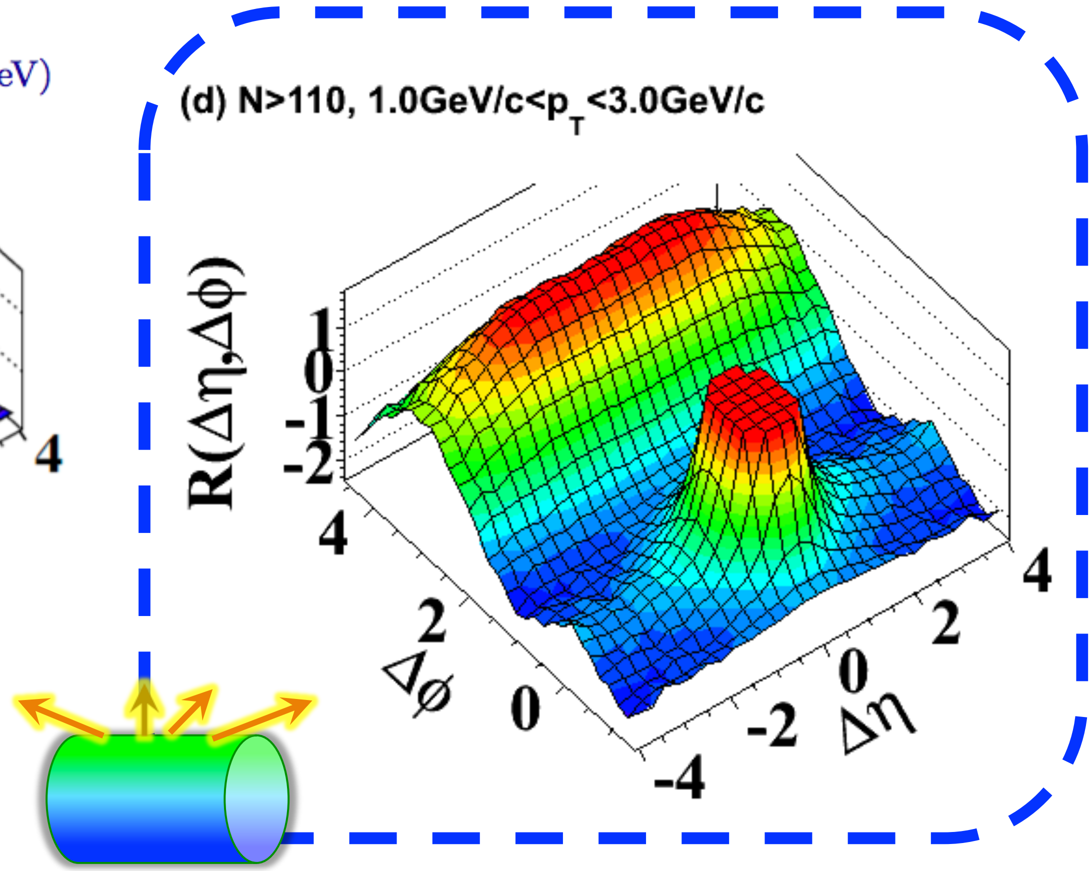


Two particle correlations: CMS results

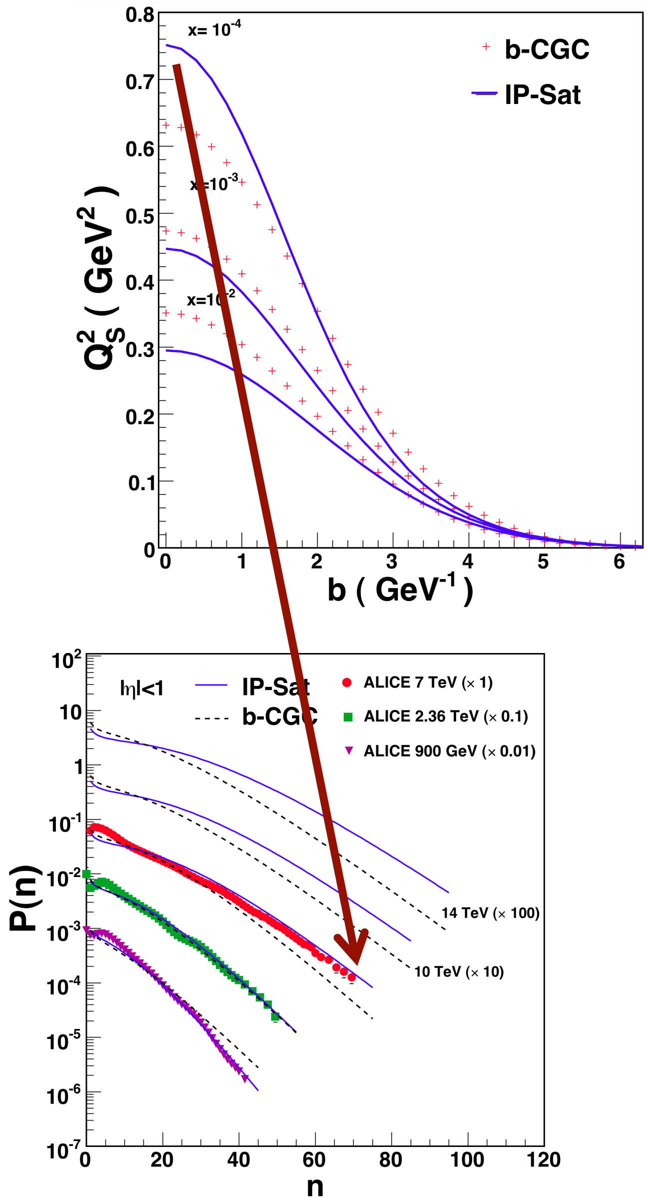
"Discovery"

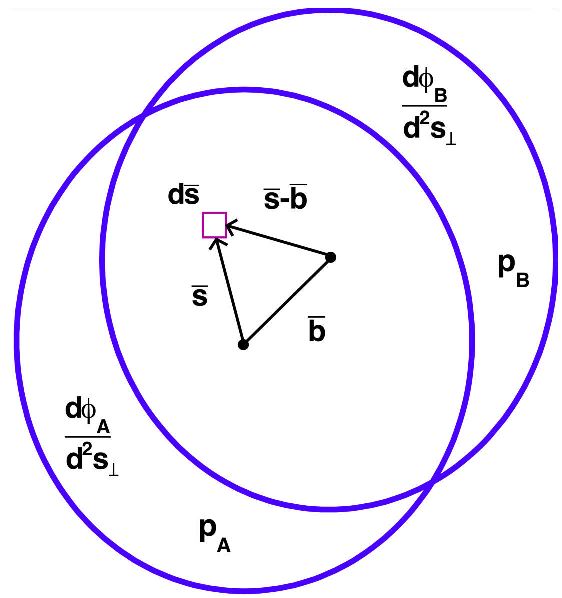




- Ridge: Distinct long range correlation in η collimated around ΔΦ≈ 0 for two hadrons in the intermediate $1 < p_T, q_T < 3$ GeV

High multiplicity events in p+p



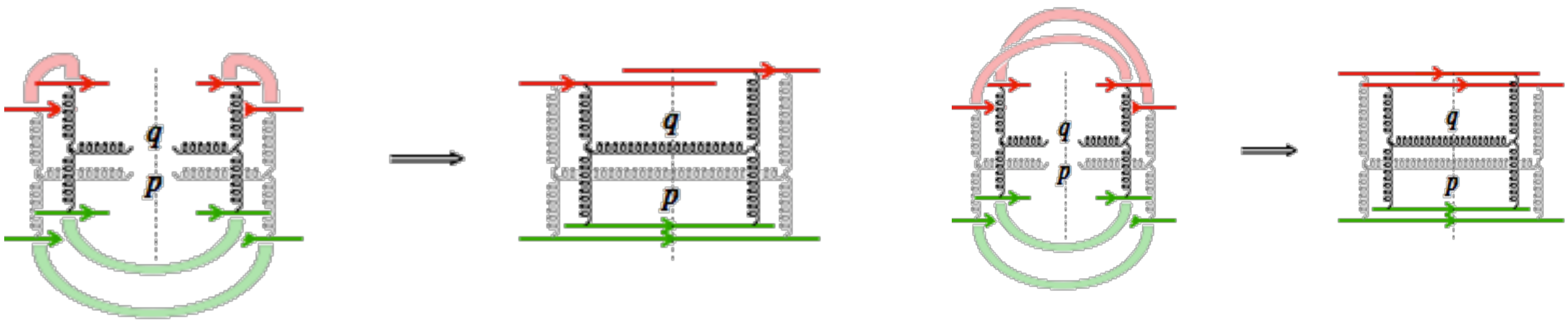


High multiplicity events likely correspond to high occupation numbers ($1/\alpha_S$) in the proton wave functions for $p_T \leq Q_S$

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 ~ $1/Q_S$



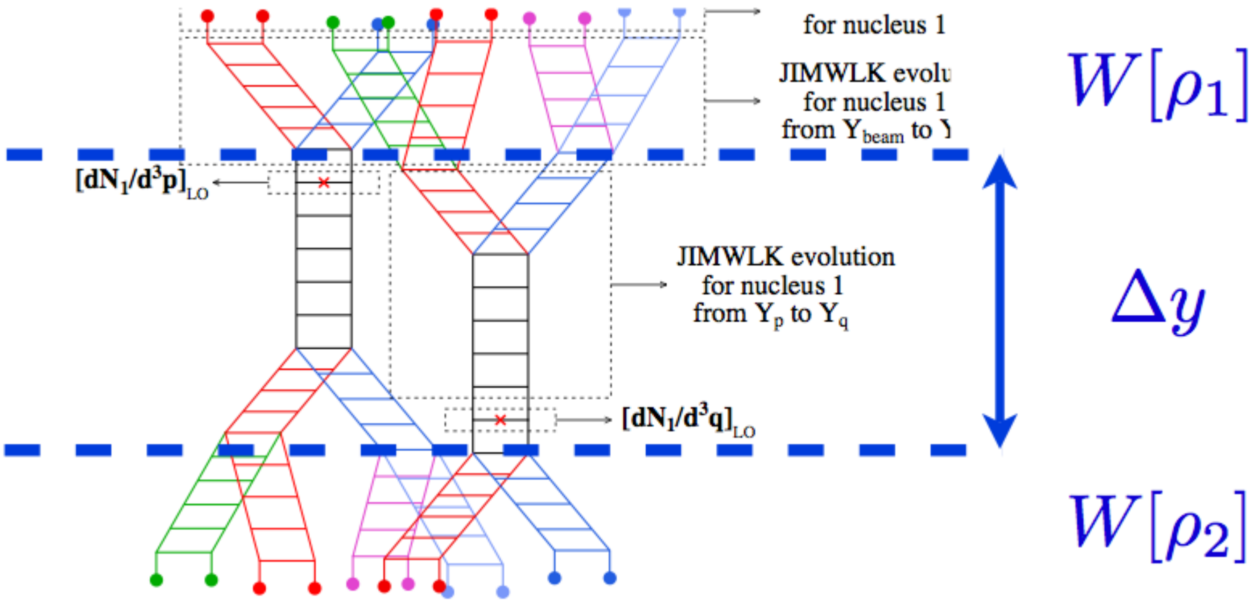
These graphs (called "Glasma graphs"), which generate long range rapidity correlations, are highly suppressed for $Q_S << p_T$

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

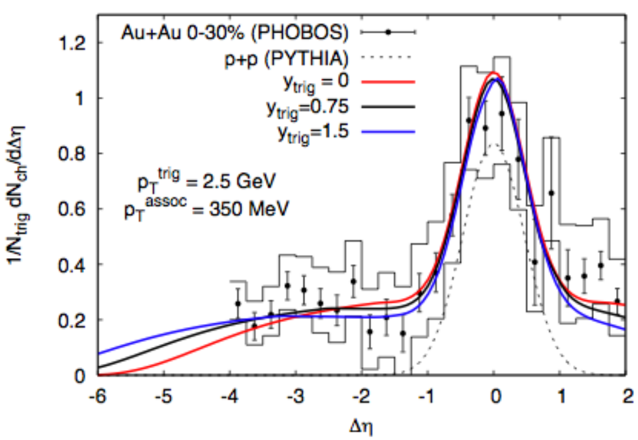
Power counting changes for high multiplicity events by α_S^8 !
These graphs become competitive with usual pQCD graphs

Long range di-hadron correlations

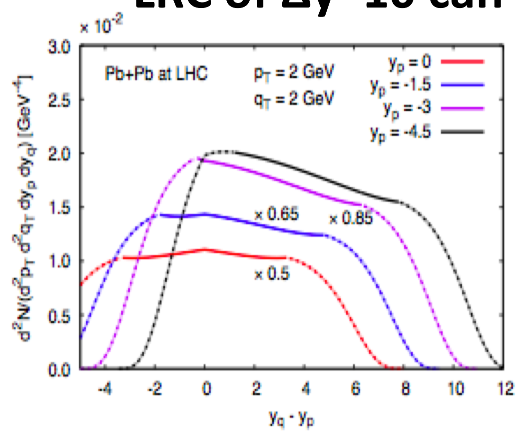
Gelis,Lappi,RV (2009)

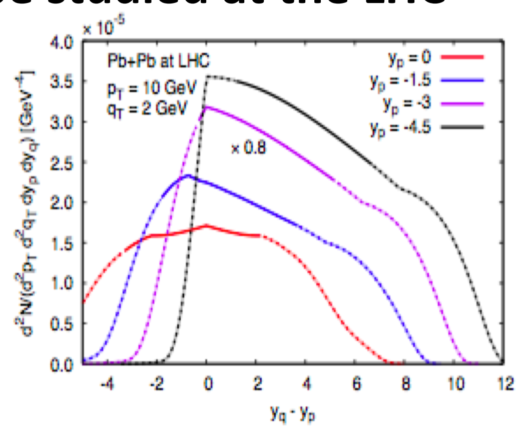


Dusling,Gelis,Lappi,RV, arXiv:0911.2720



LRC of Δy~10 can be studied at the LHC

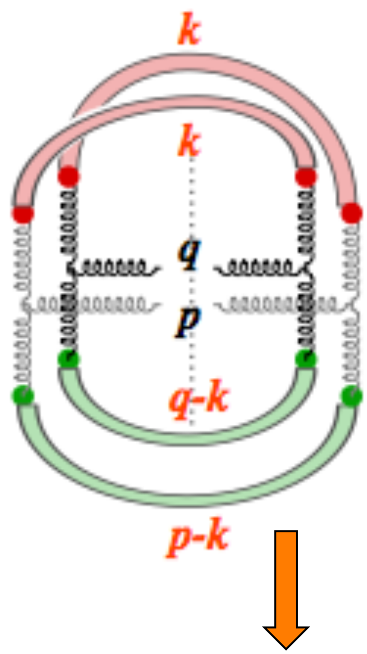


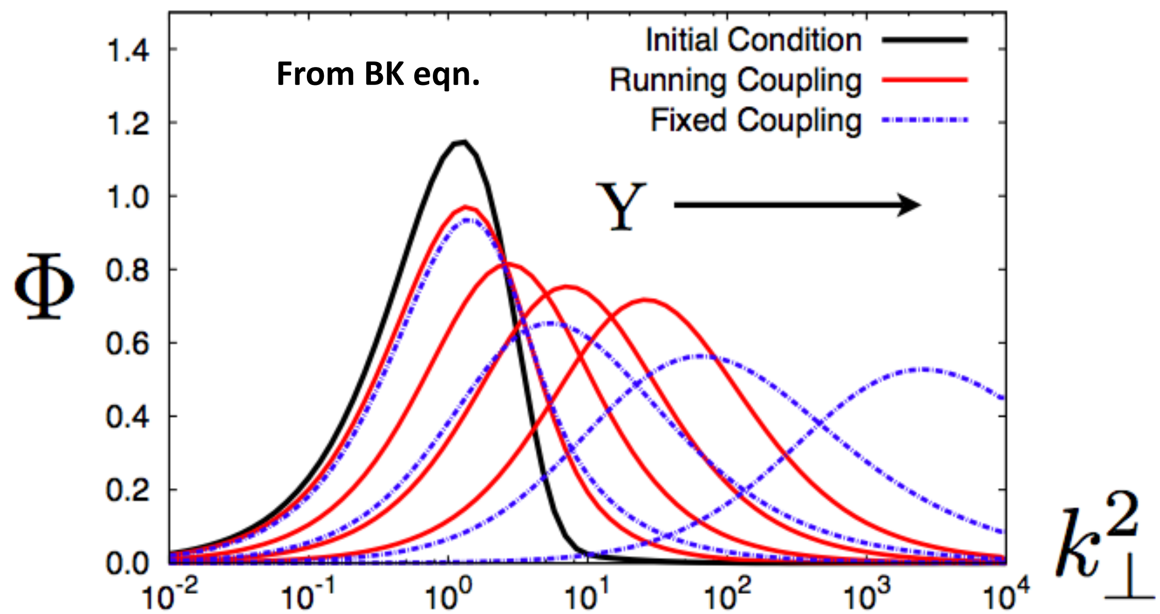


Long range di-hadron correlations

RG evolution of two particle correlations (in mean field approx) expressed in terms of "unintegrated gluon distributions" Dusling,Gelis,Lappi,RV (2009

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





Such "Glasma flux tube" graphs are enhanced by α_S^{-8} at high parton densities…

Dumitru,Dusling,Gelis,Jalilian-Marian,Lappi,RV, arXiv:1009.5295

Quantitative description of pp ridge

Dusling,RV, 1201.2658

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

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

Try soft and hard fragmentation functions:

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

$D_2 = 2(1-x) / x$

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

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…

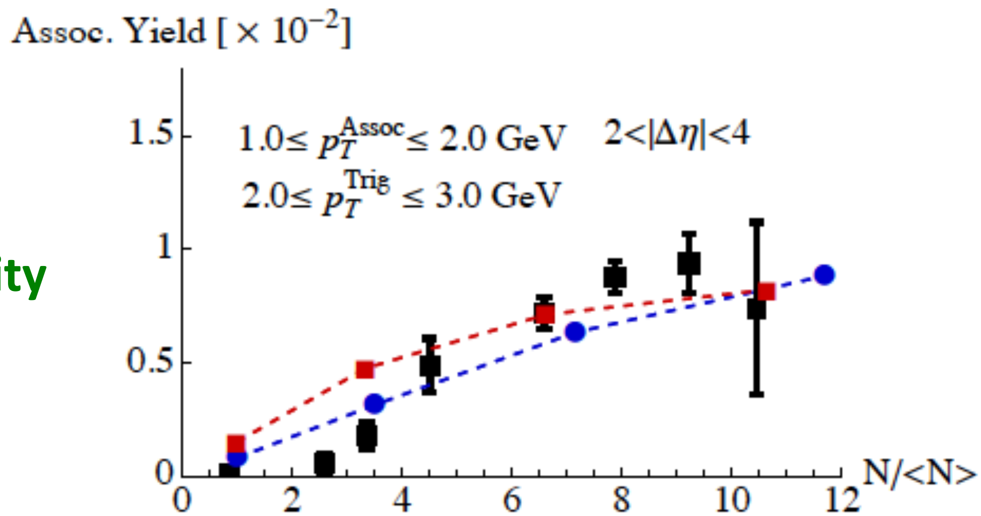
Subtracts any pedestal “phi-independent” correlation

Quantitative description of pp ridge

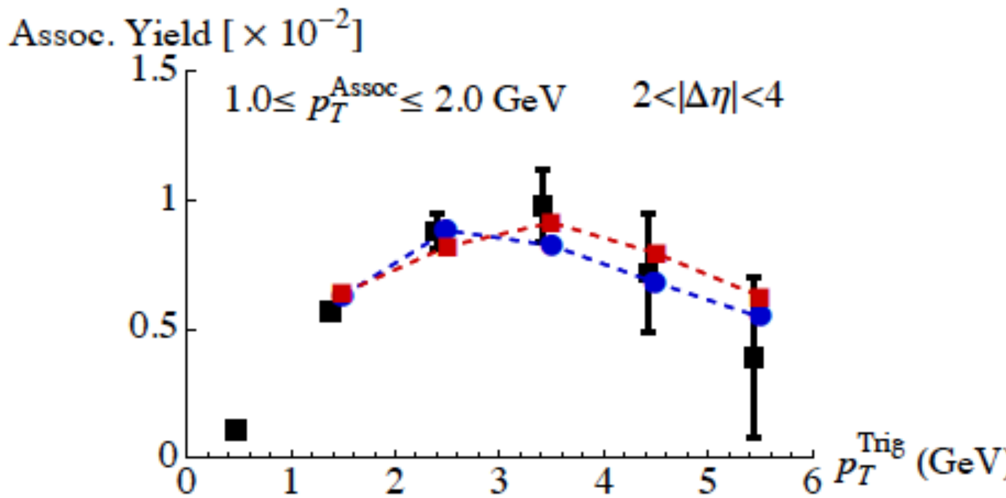
Dusling,RV, 1201.2658, PRL, in press

CMS preliminary data

Assoc. yield with centrality



Assoc. yield with p_T^{Trig}

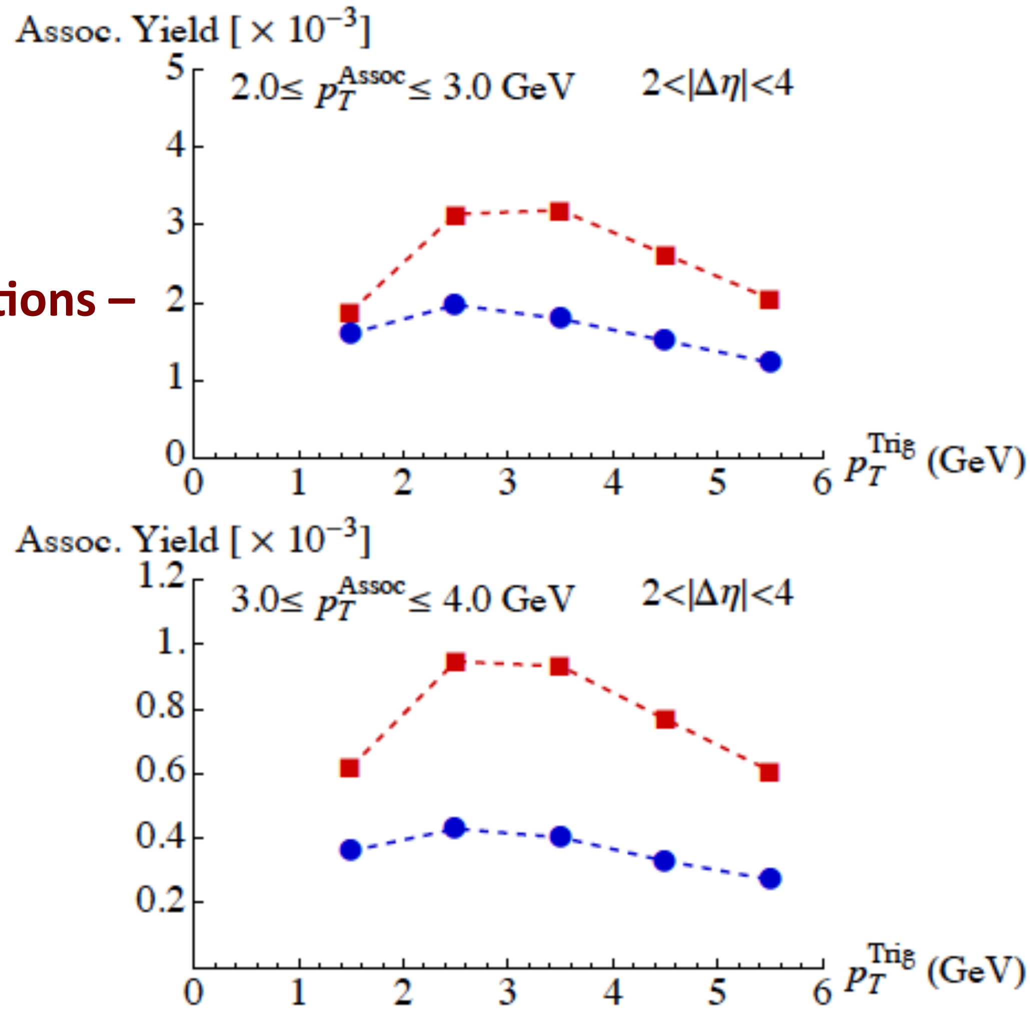


Quantitative description of pp ridge

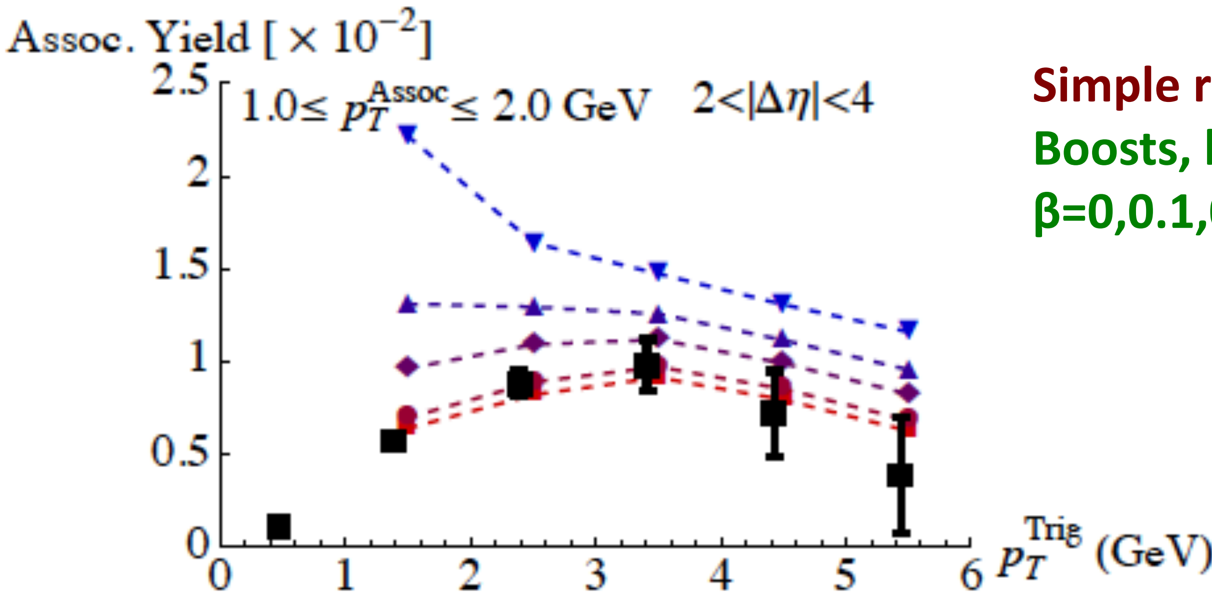
Dusling,RV, 1201.2658

Predictions:

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



What about flow in p+p ?



Simple radial flow model result:
Boosts, bottom to top,
β=0,0.1,0.2,0.25,0.3

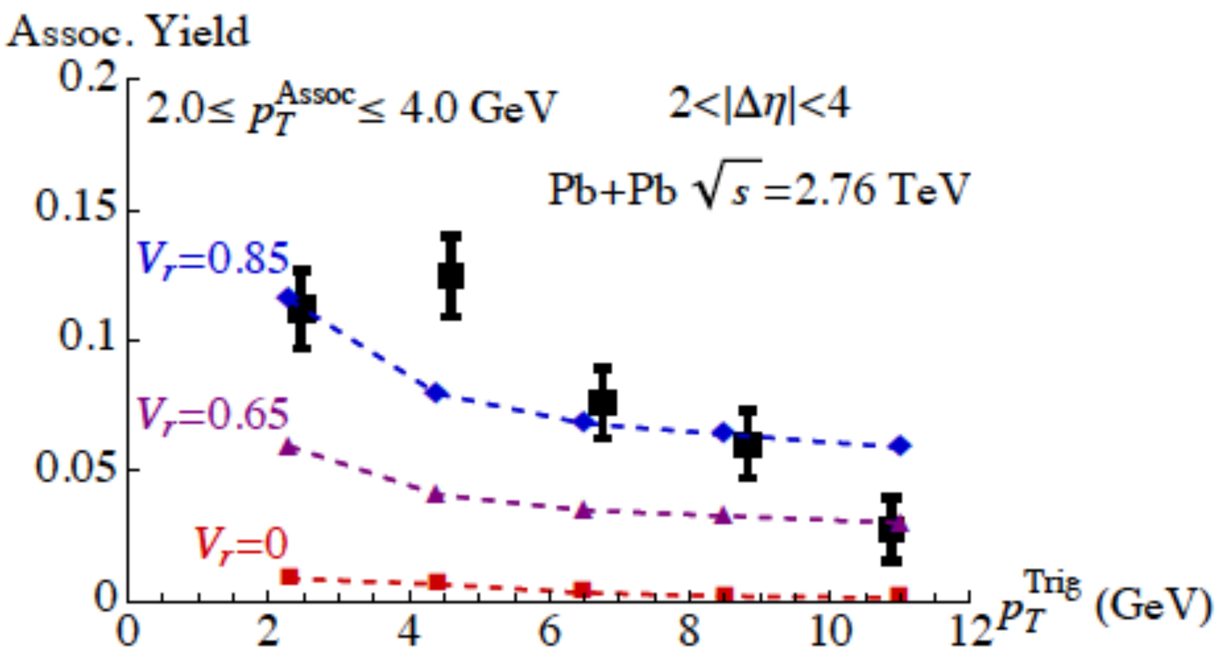
With increasing flow, the pedestal gets collimated

Associated yield reflects the p_T dependence of the Glasma pedestal

Can accommodate only very small re-scattering / flow contribution

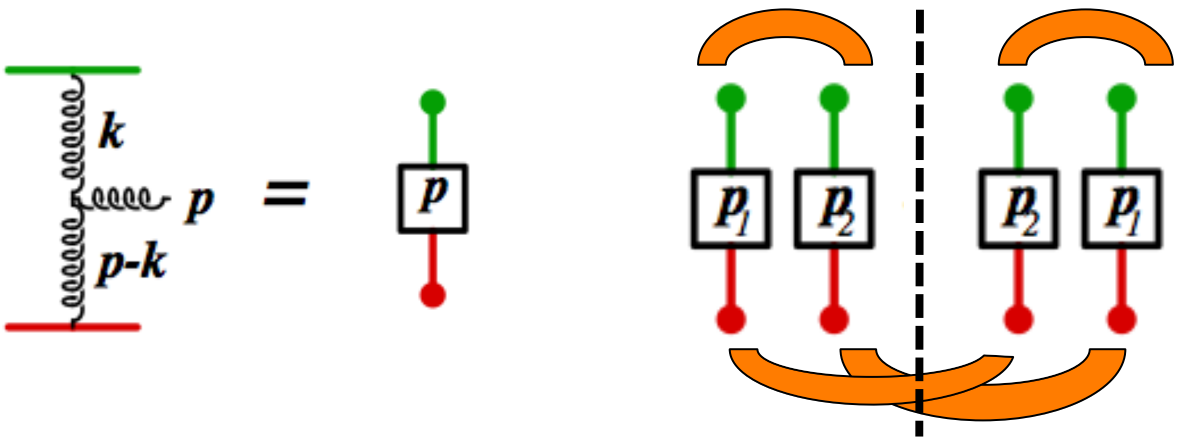
A+A ridge is all flow

Preliminary CMS data



2-particle ➡ n-particle correlations

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

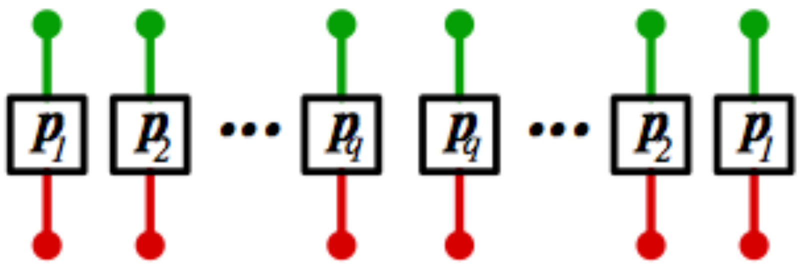


Glasma flux tube picture: two particle correlations proportional to ratio $1/Q_S^2 / S_T$

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

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

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

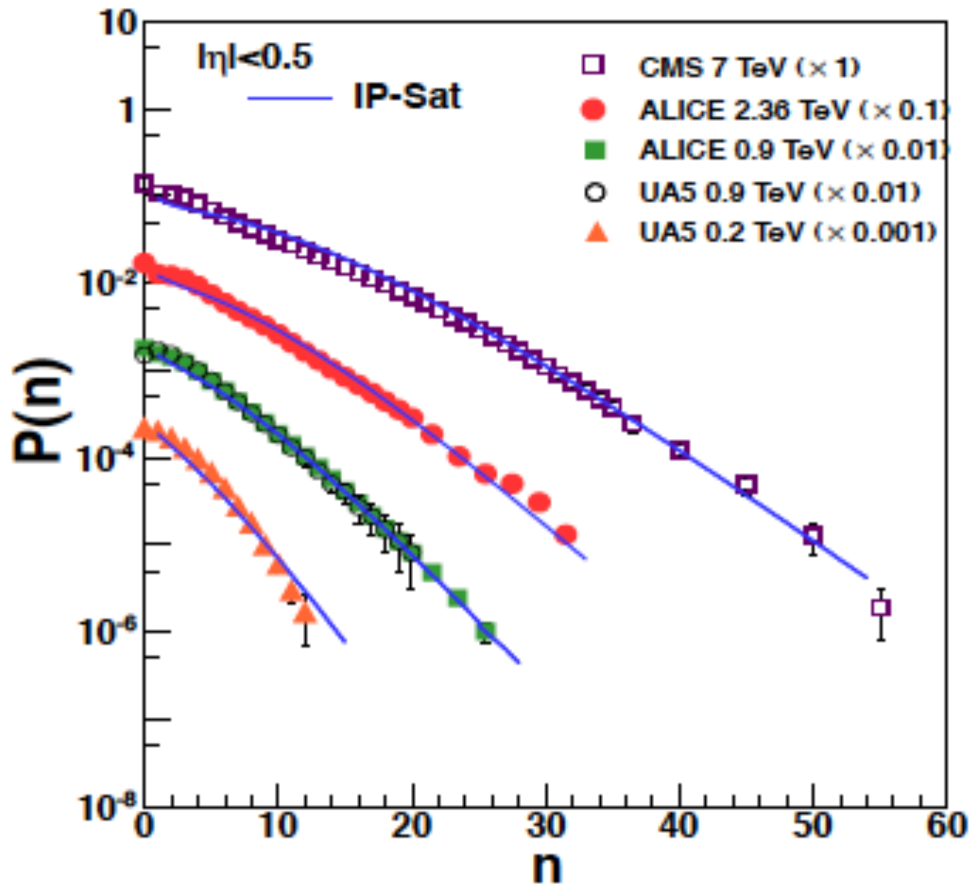
k = 1 : Bose-Einstein

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

Convolution of NBDs describes LHC p+p data



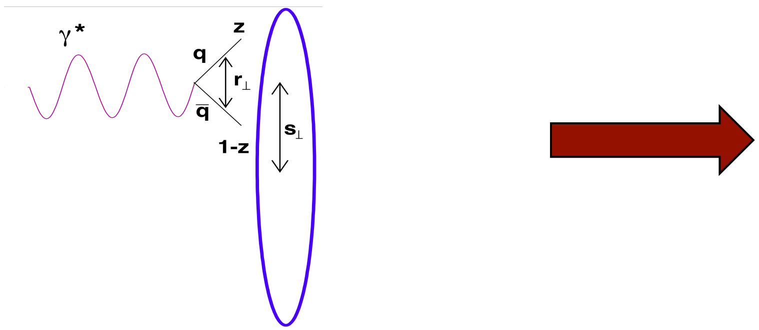
Tribedy, RV
1112.2445

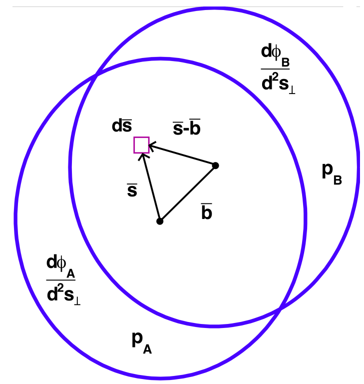
Dynamical quantum fluctuations in energy/# of gluons event-by-event

From nuts to soup: I. constraining initial conditions

First understand e+p and p+p:

Global analysis of HERA data thus far performed only in the IP-Sat, b-CGC and rcBK saturation models - more detailed JIMWLK analysis is desirable and likely





Unintegrated proton 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: compute inclusive dist. of produced gluons at given impact par. :

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

The IP-Sat model

Bartels,Golec-Biernat,Kowalski
Kowalski,Teaney
Kowalski,Motyka,Watt

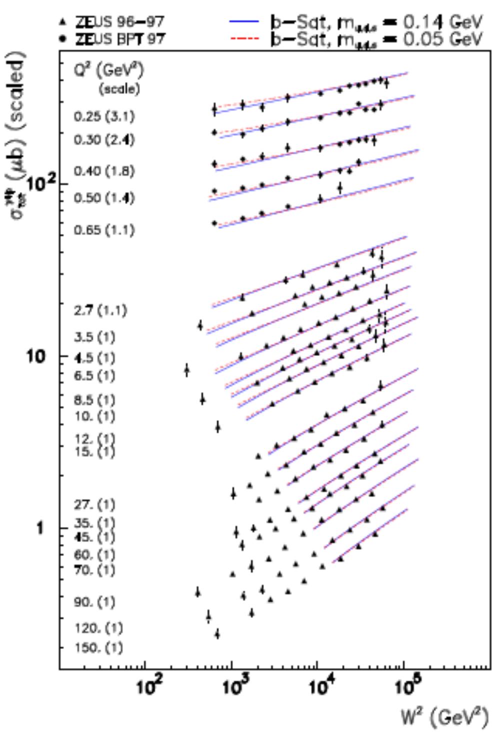
$$\frac{d\sigma^{p}_{dip}}{d^2\mathbf{b}_\perp}(\mathbf{r}_\perp, x, \mathbf{b}_\perp) = 2\mathcal{N}(\mathbf{r}_\perp, x, \mathbf{b}_\perp) = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c}\mathbf{r}_\perp{}^2\alpha_s(\tilde{\mu}^2)xg(x,\tilde{\mu}^2)T_p(\mathbf{b}_\perp)\right)\right]$$

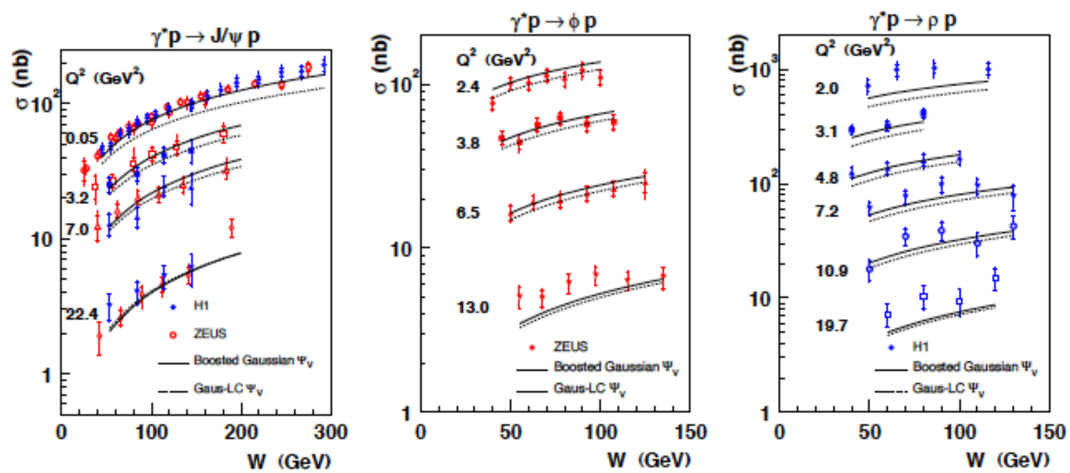
MV model extended to small x + impact parameter dependence

$$\tilde{\mu}^2 = \mu_0^2 + \frac{4}{r_\perp}^2$$

$$T_p(b_\perp) = e^{-\frac{b_\perp^2}{2B_G}}$$

Average gluon radius of the proton extracted from HERA diffractive data



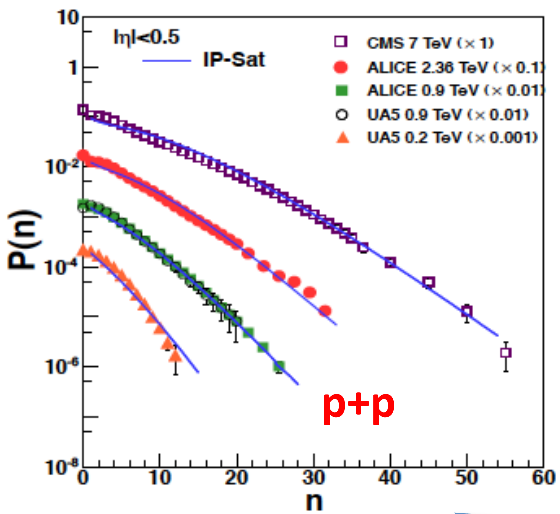


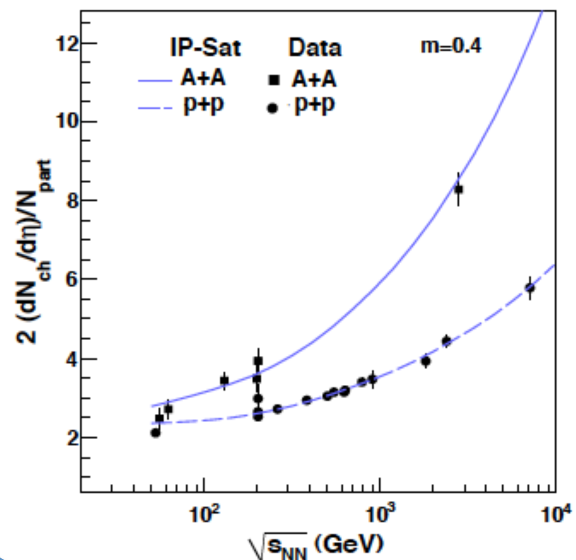
X^2 ~ 1 fits to HERA inclusive,diffractive and exclusive small x data with few parameters

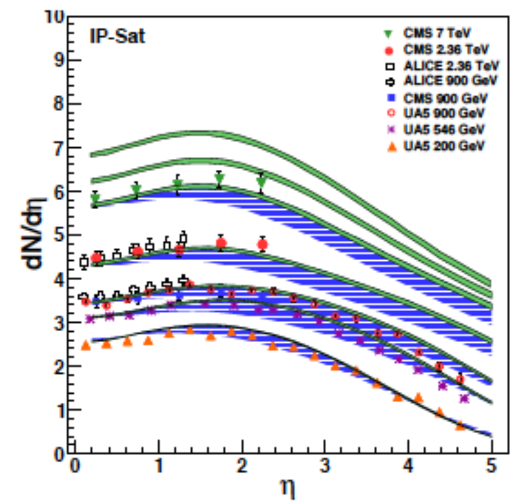
IP-Sat: from HERA to RHIC/LHC

Levin,Rezaiean
Tribedy, RV: 1011.1895, 1112.2445

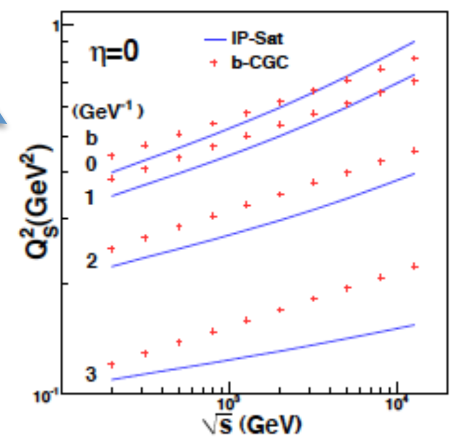
e+p constrained fits give good description of p+p data

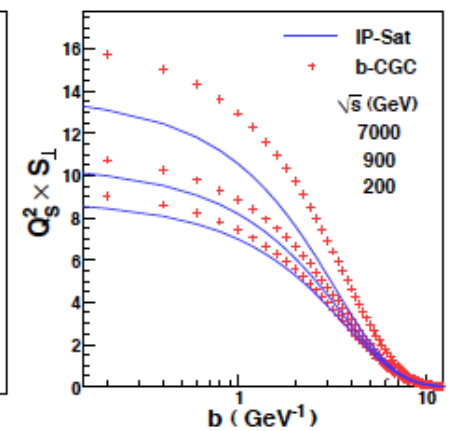






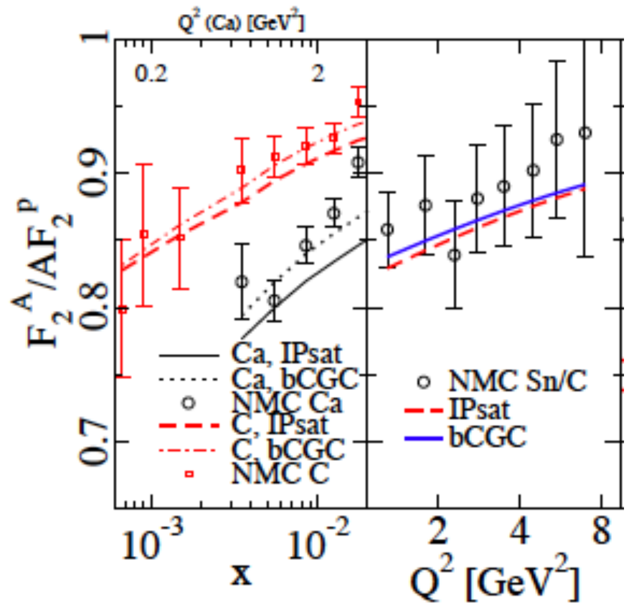
Impact parameter dependence (constrained by HERA diffractive data) important for good agreement with data

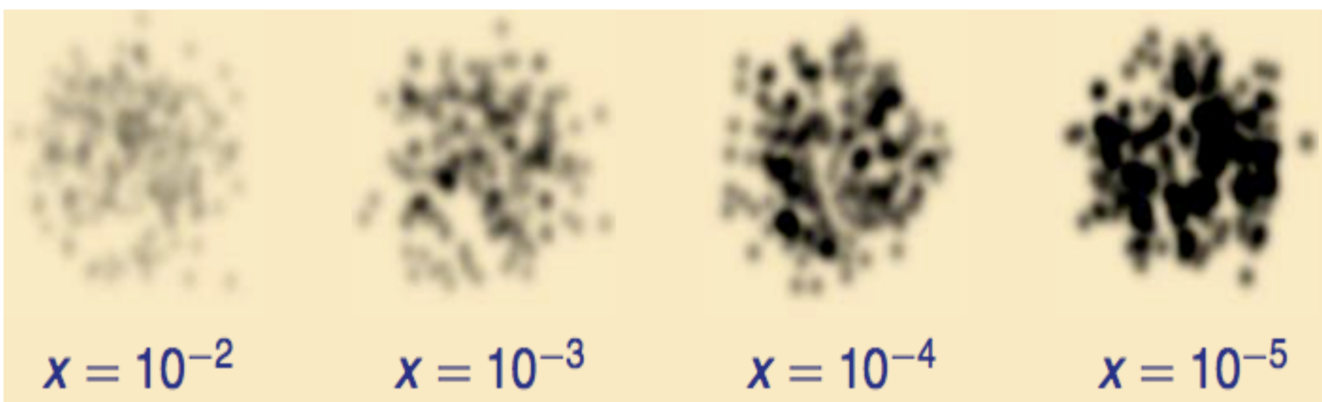




Lumpy nuclei: constrained by (limited) DIS data

Kowalski, Lappi, RV (2008)





From nuts to soup: II. the IP-Glasma model

Schenke,Tribedy,RV:1202.6646, PRL, in press

A. Construct color charge distributions, event-by-event:

- Positions of nucleons sampled from the Woods-Saxon distribution of each nucleus A and B

- IP-Sat provides $Q_S^2(x,b_T)$ for each nucleon – proportional to color charge squared per unit area $g^2\mu_p^2$ (details, see T. Lappi, arXiv:0711.3039)

- Add all $g^2\mu_p^2(x_T)$ to obtain $g^2\mu_A^2(x_T)$ and $g^2\mu_B^2(x_T)$

- Sample $\rho_{A,B}^a$ from local Gaussian distribution for each nucleus:

$$\langle \rho_k^a(x_\perp)\rho_l^b(y_\perp)\rangle = \delta_{kl}\delta^{ab}\delta^{(2)}(x_\perp - y_\perp)g^2\mu_{A,B}^2(x_\perp)$$

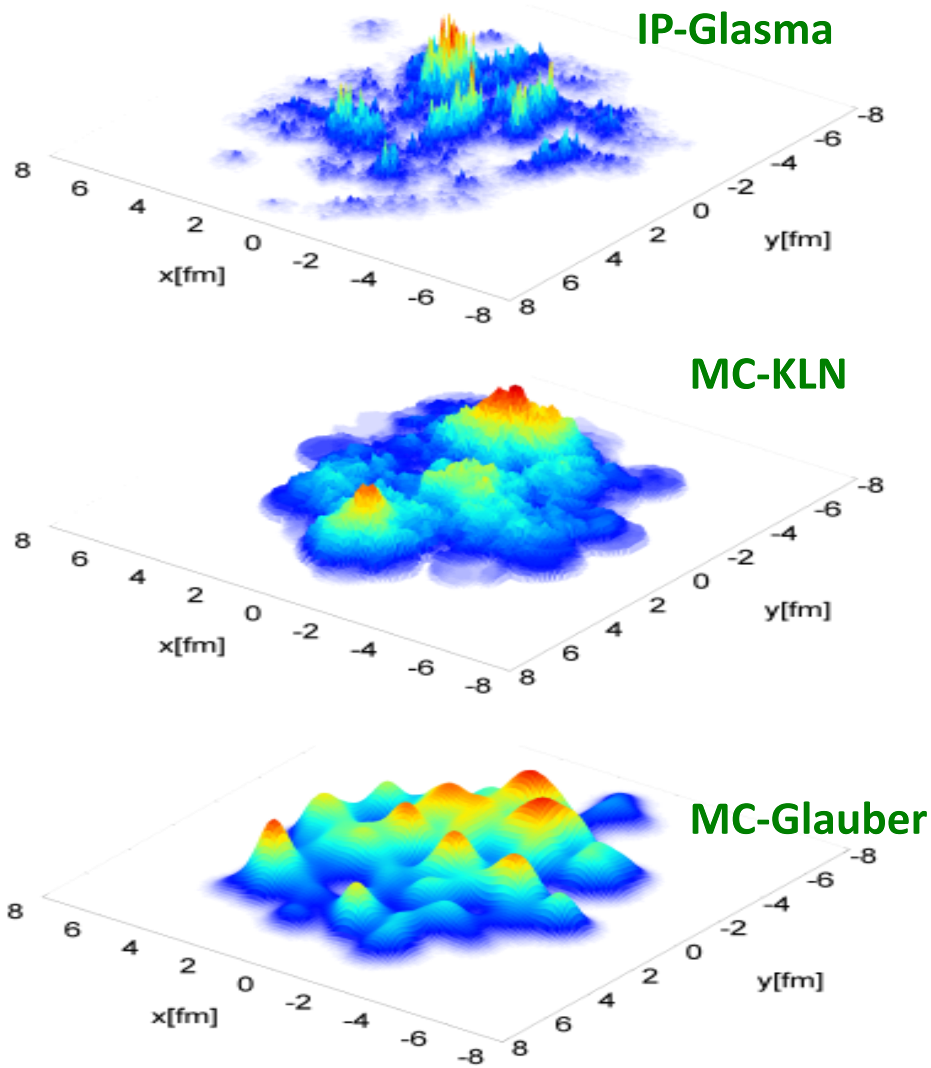
This gives the random static source distribution for event-by-event multi-particle production

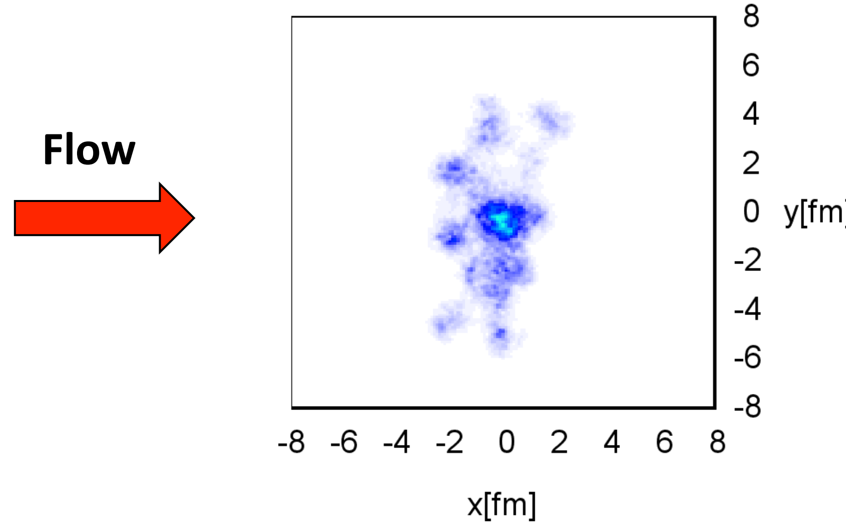
Some "hydro initial conditions" in the literature

- original KLN:
  - uses k_T-factorization
  - $(Q_s^A)^2(\mathbf{x}_\perp) \propto N_{\mathrm{part,A}}(\mathbf{x}_\perp)$.
  - Saturation scales are not universal: $N_{\mathrm{part,A}}(\mathbf{x}_\perp)$ depends on nucleus B.
  - The energy density ($\epsilon \propto Q_{s,\mathrm{larger}} Q^2_{s,\mathrm{smaller}}$) is suppressed in the edge region along the impact parameter direction $\rightarrow$ larger eccentricity.
- fKLN:
  - uses k_T-factorization
  - Different definition of unintegrated gluon distribution (correct limit: where there is one nulceon at the edge the uGDF is that of one nucleon - not so in KLN)
  - Universal saturation scales in nucleus A and B. (Important at the edges of the nuclei)
- MC-KLN: Monte-Carlo implementation of fKLN with fluctuating positions of the nucleons
- IP-Glasma (CYM):
  - Does not use k_T-factorization (because it is strictly not valid in A+A collisions - at least one source has to be dilute)
  - $Q_s(\mathbf{x}_\perp)$ universal and constrained by HERA data.
  - No utilization of the nucleon-nucleon cross section.
  - Takes into account non-linearities.
  - Includes fluctuations of color charges within a nucleon.

Compilation by B. Schenke

Granularity of initial distributions



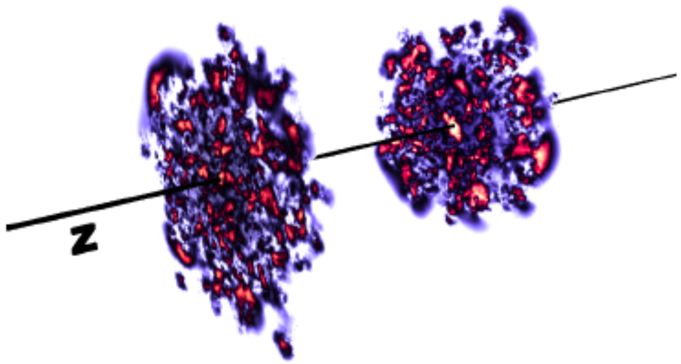


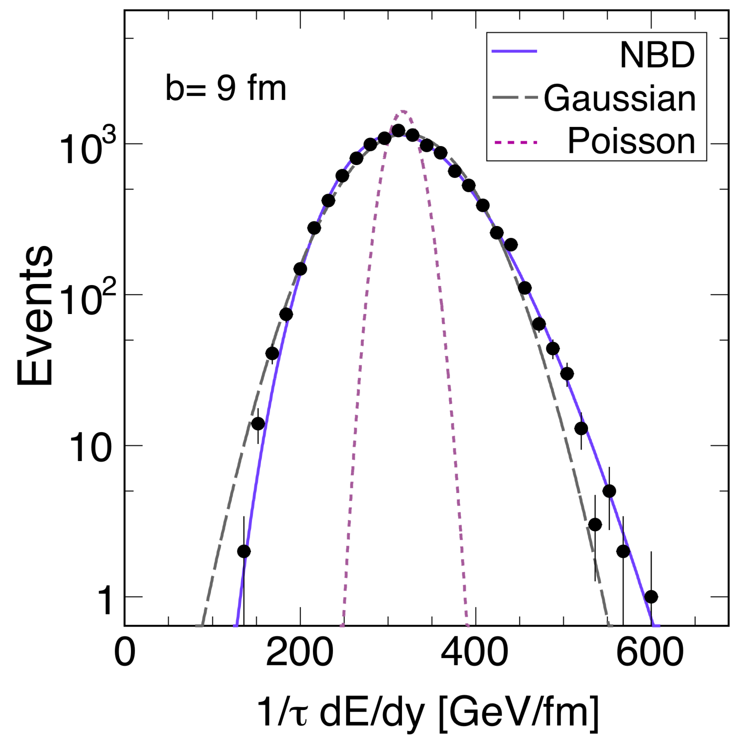
These models do not include KNO/NBD multiplicity fluctuations

Dumitru,Nara

Fluctuating energy distributions from event-by-event solutions of Yang-Mills eqns.

Schenke,Tribedy, RV, arXiv:1202.6646

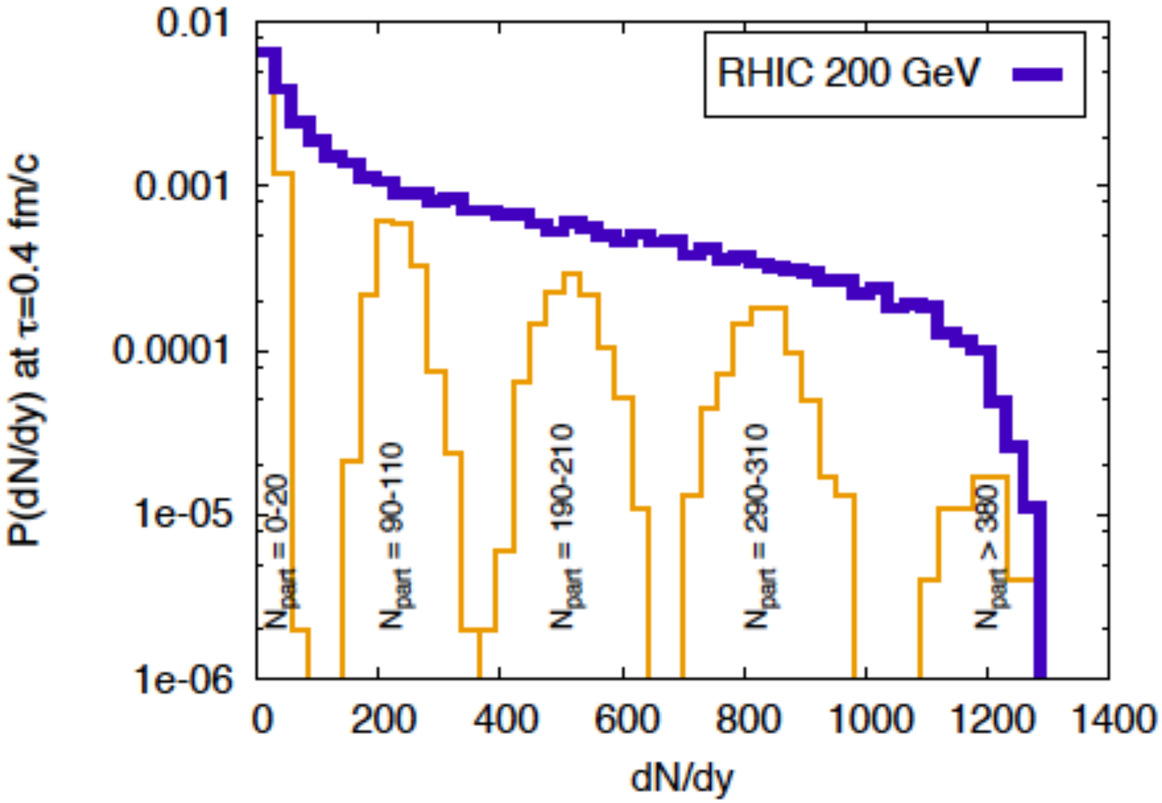




Dynamical quantum fluctuations in energy/# of gluons event-by-event

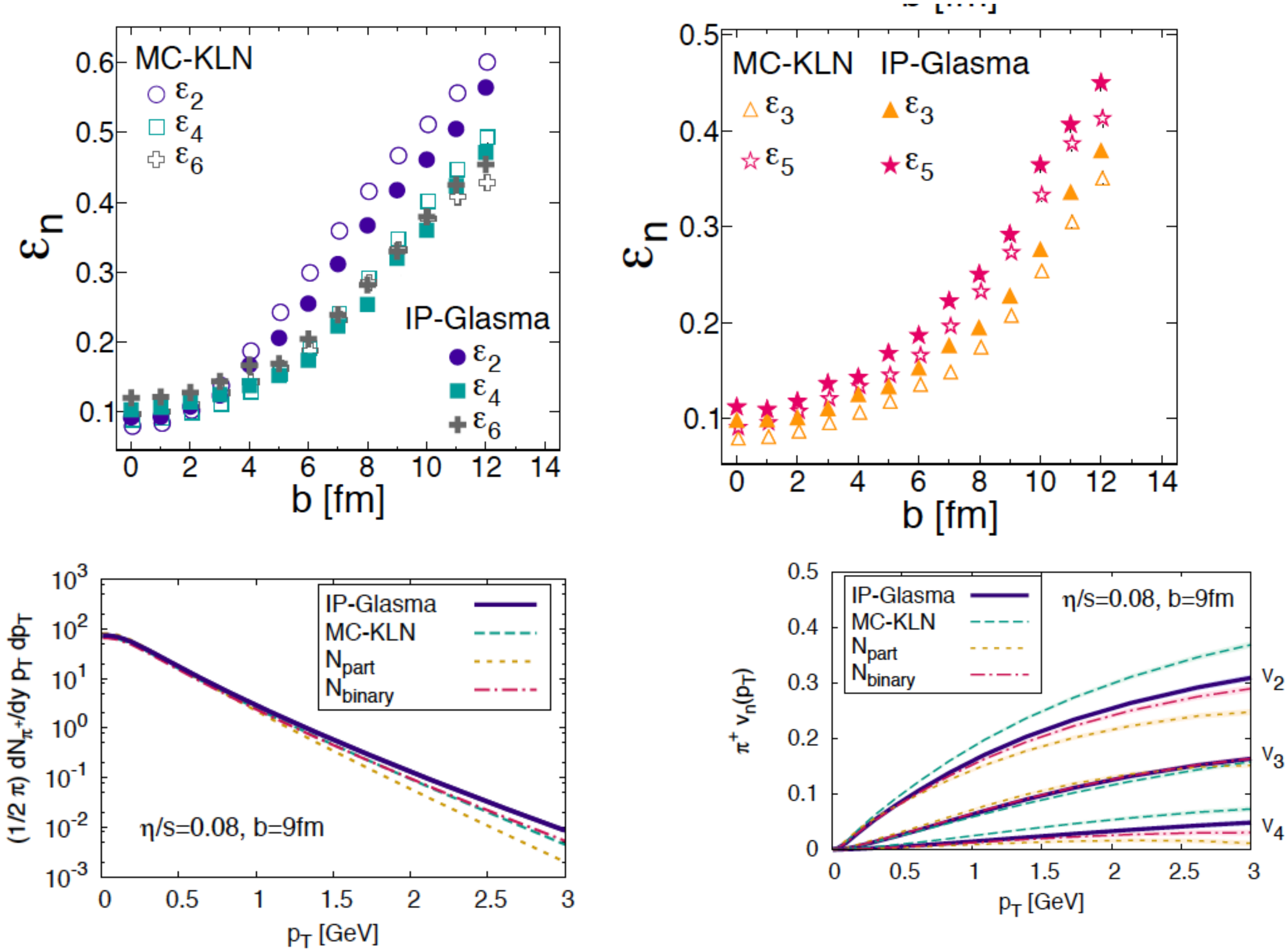
Gelis,Lappi,McLerran,arXiv: 0905.3234
Lappi, Srednyak, RV, arXiv: 0911.2068

Construct nuclear mult. distributions from NBDs



Flow distributions

Schenke,Tribedy, RV, arXiv:1202.6646



First study: may be feasible extract essential physics on how quantum field fluctuations generate flow