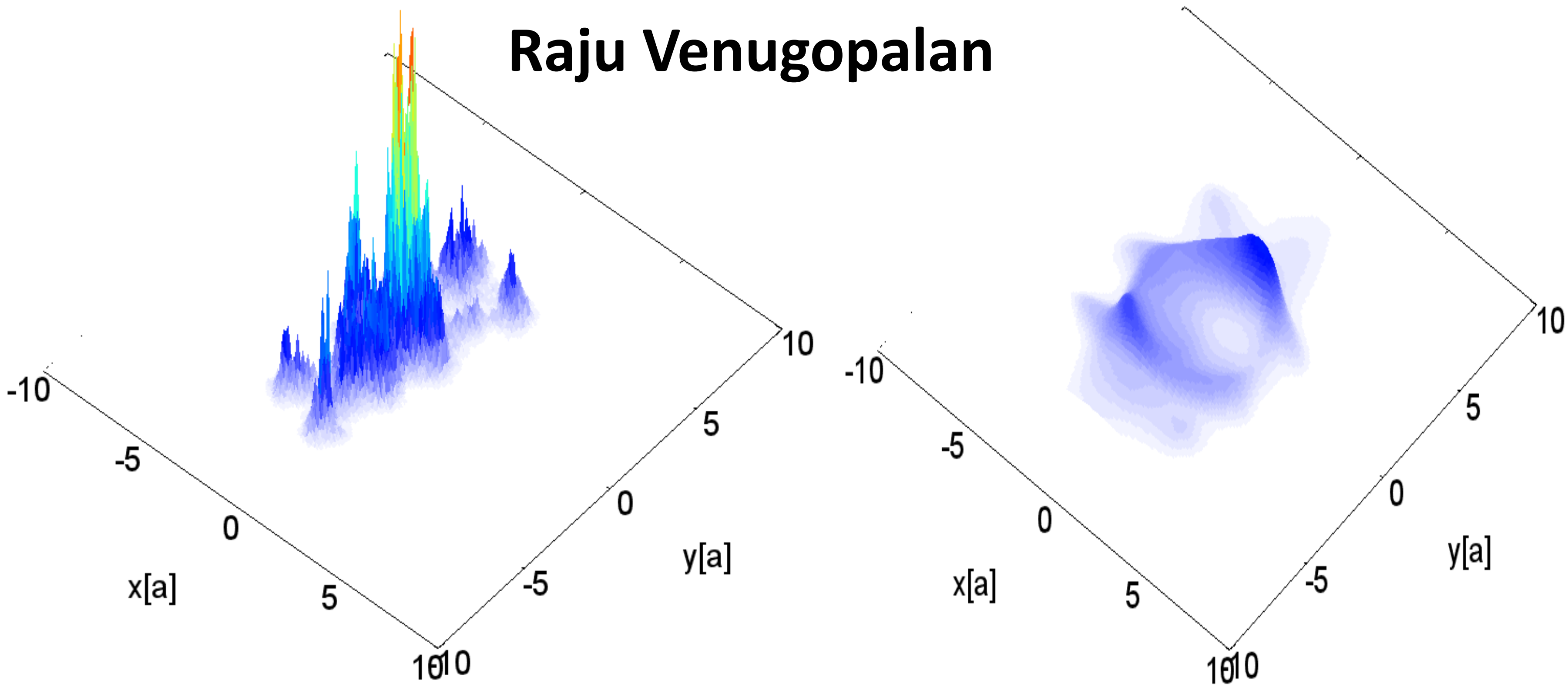
The Glasma: coherence, evolution, correlations

Raju Venugopalan



Lecture III, UCT, February 2012

Outline of lectures

- Lecture I: QCD and the Quark-Gluon Plasma
- Lecture II: Gluon Saturation and the Color Glass Condensate
- Lecture III: Quantum field theory in strong fields. Factorization. the Glasma and long range correlations
- Lecture IV: Quantum field theory in strong fields. Instabilities and the spectrum of initial quantum fluctuations
- Lecture V: Quantum field theory in strong fields. Decoherence, hydrodynamics, Bose-Einstein Condensation and thermalization
- Lecture VI: Future prospects: RHIC, LHC and the EIC

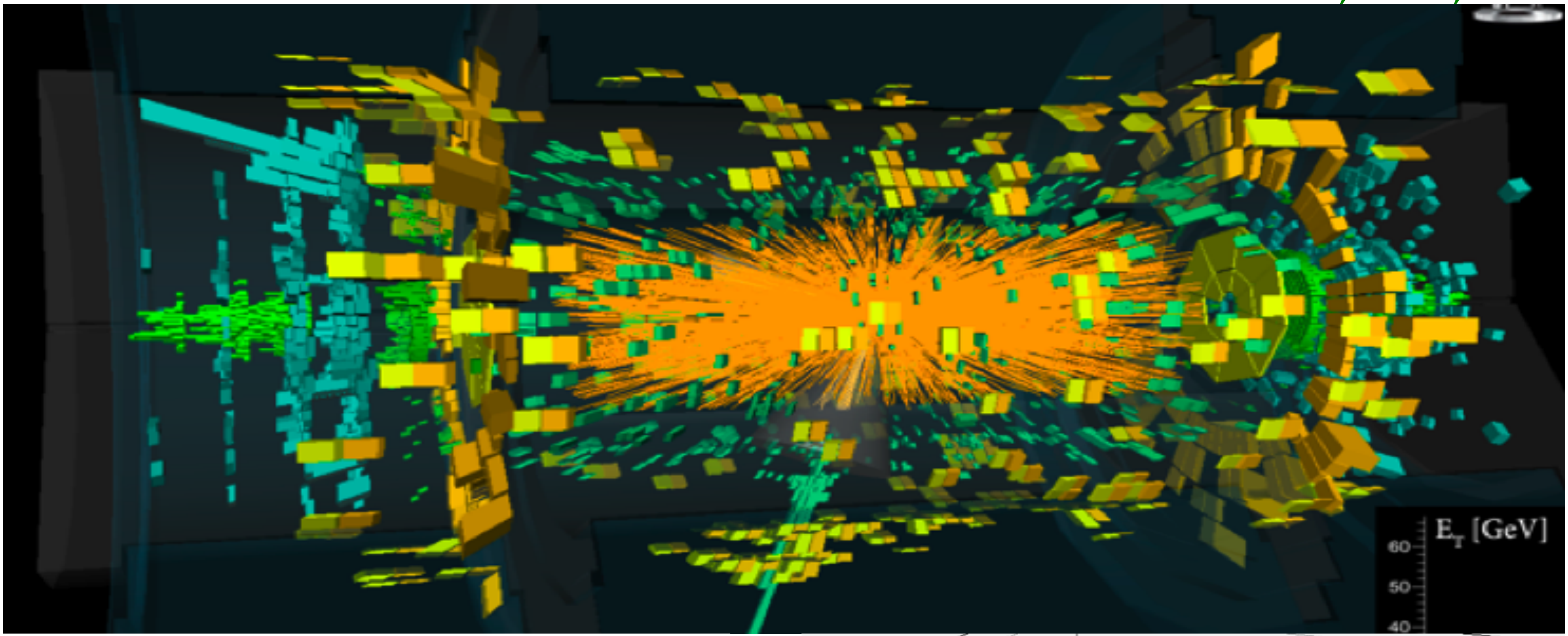
Traditional picture of heavy ion collisions

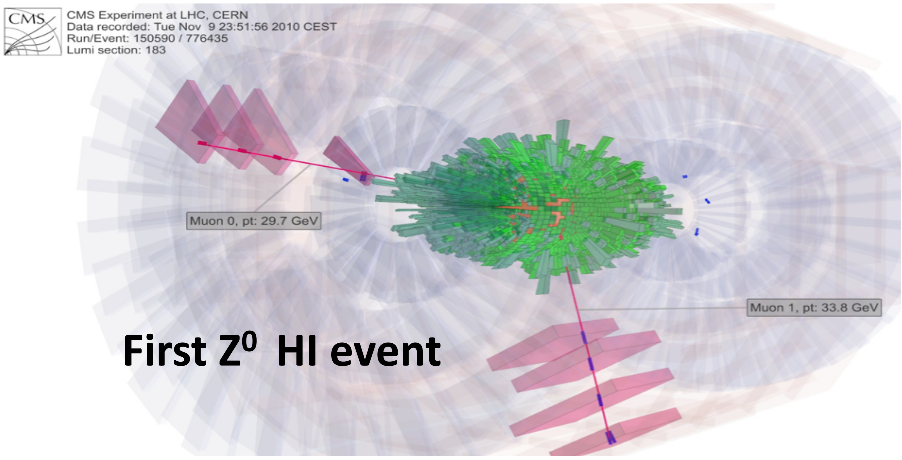
***@$#! on *@$#!**

Well known physicist (circa early 1980s)

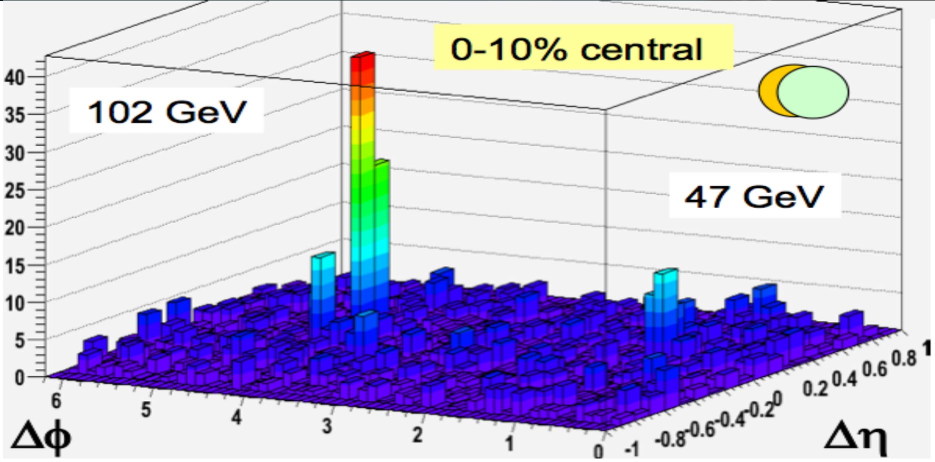
A contemporary view

CERN seminar, Dec. 2^{nd}, 2010

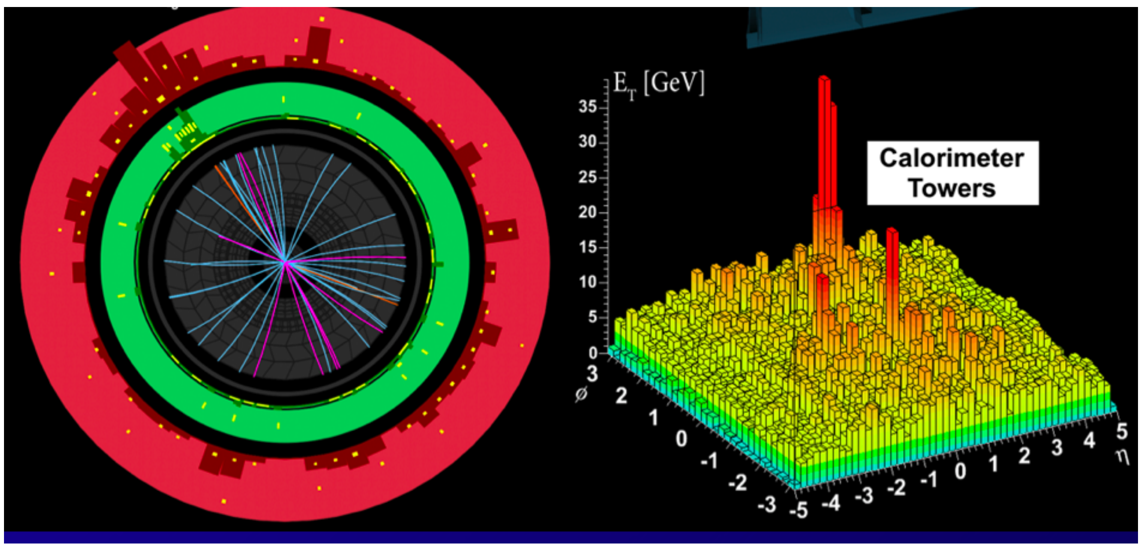




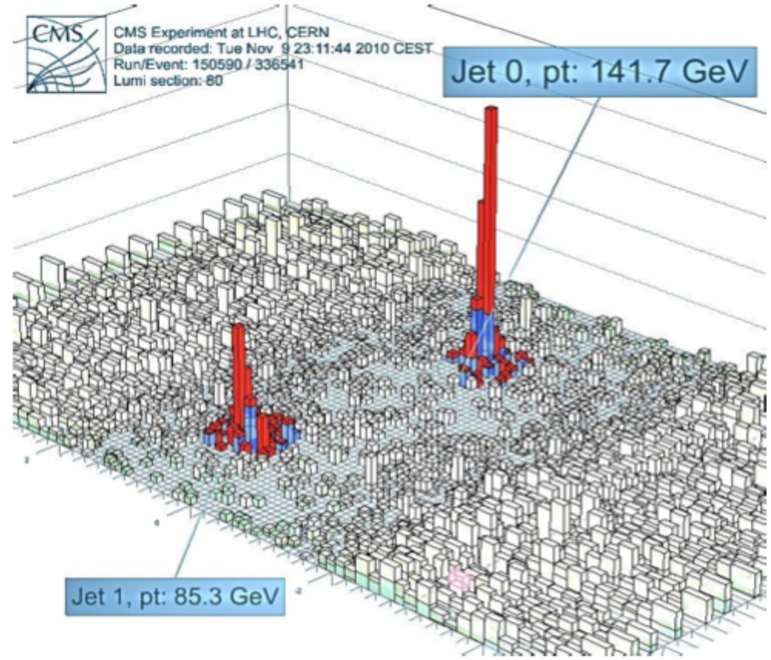
First Z^0 HI event



LHC jets!

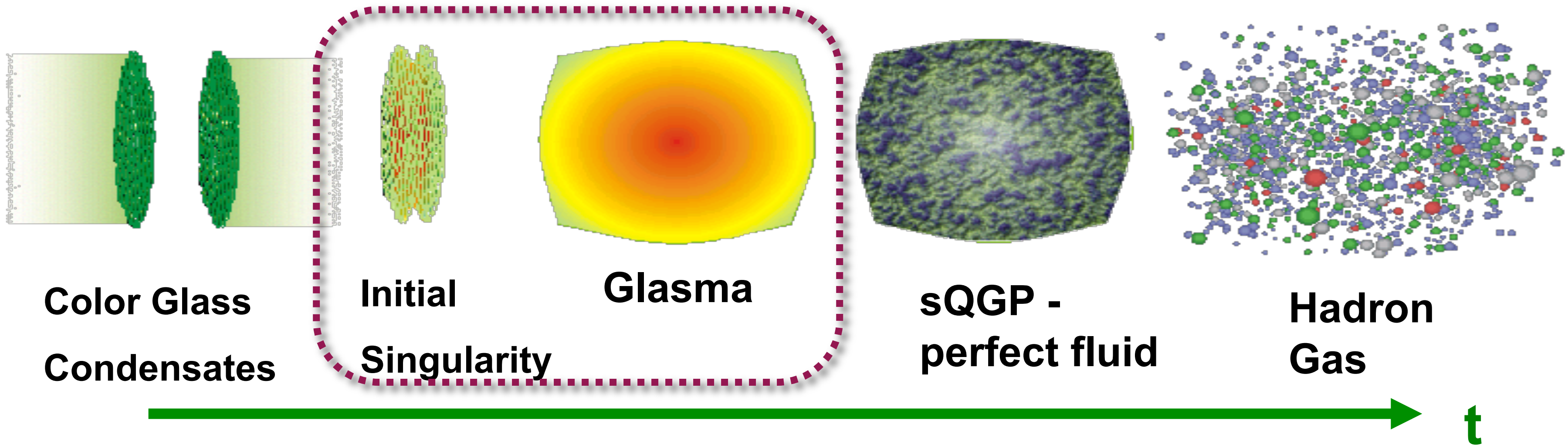


E_T [GeV]
Calorimeter Towers
ø
η



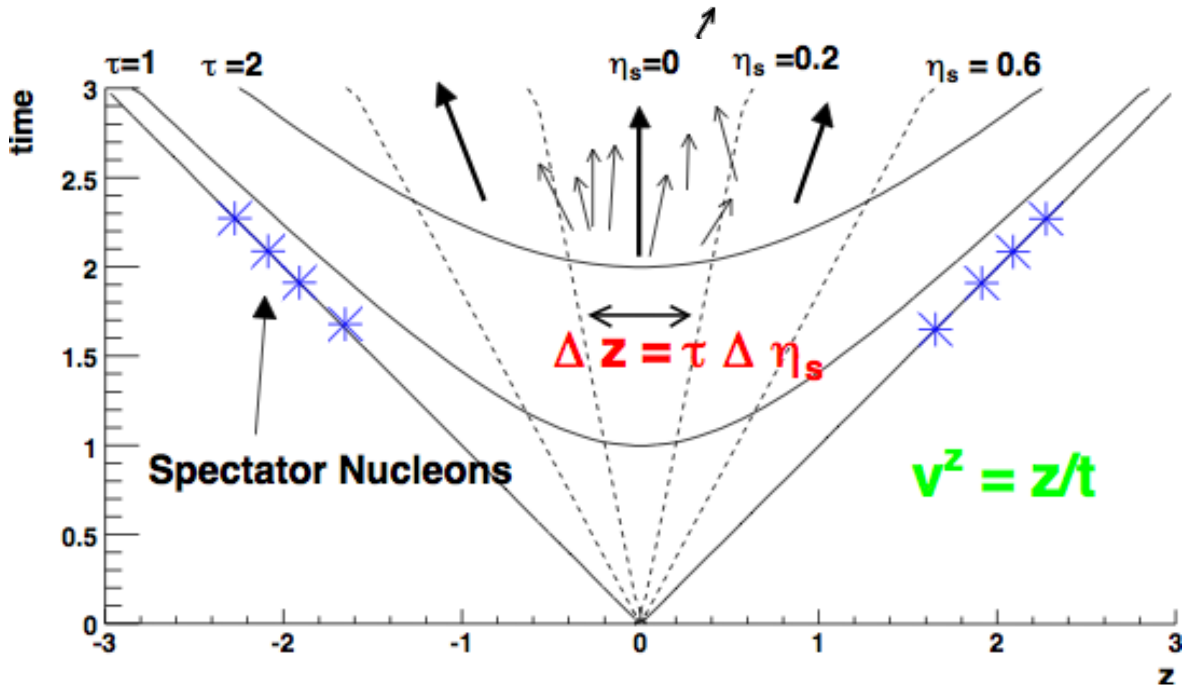
CMS
CMS Experiment at LHC, CERN
Data recorded: Tue Nov 9 23:11:44 2010 CEST
Run/Event: 150590 / 336541
Lumi section: 80
Jet 0, pt: 141.7 GeV
Jet 1, pt: 85.3 GeV

Standard model of HI Collisions



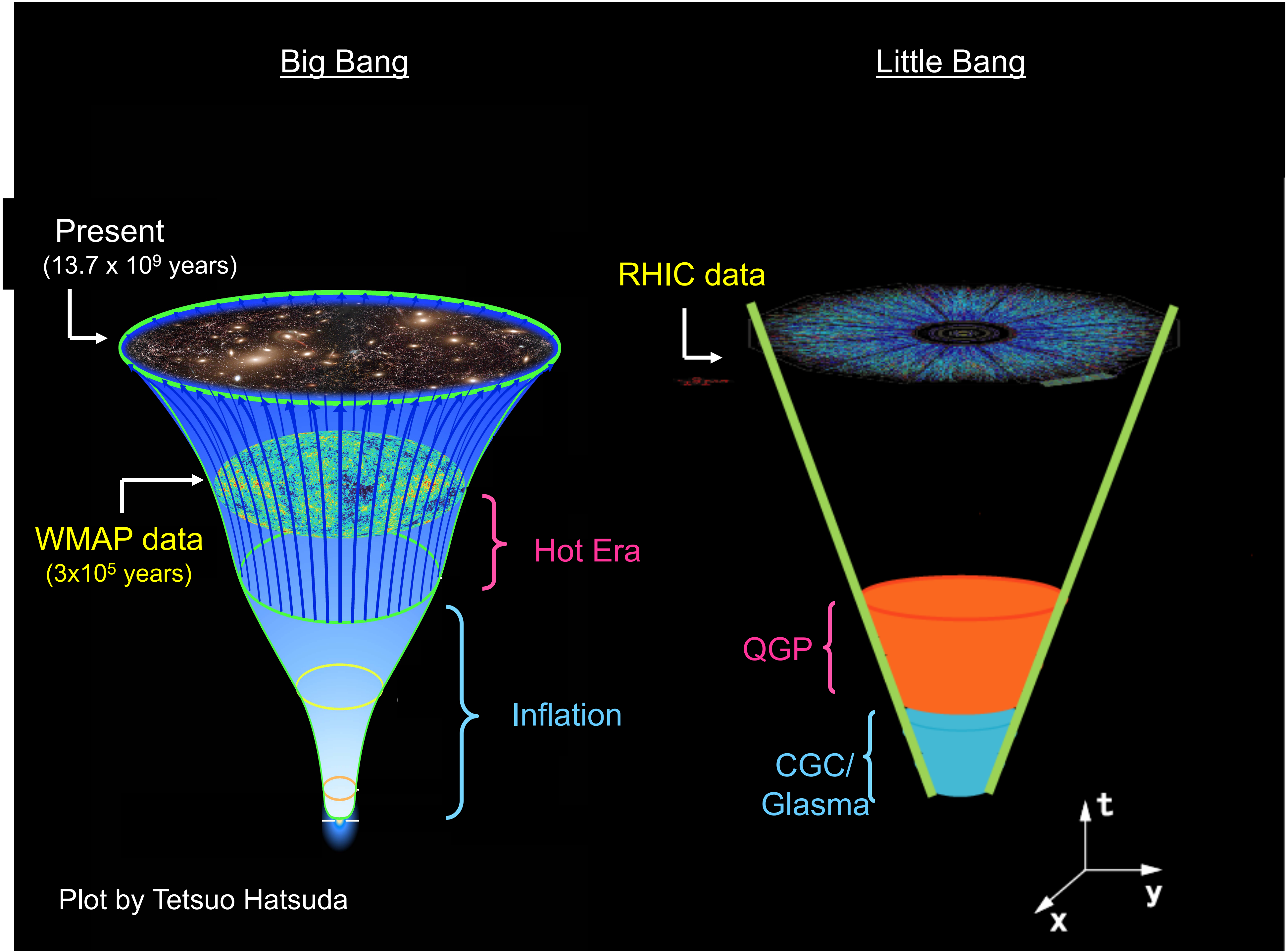
Glasma (\Glahs-maa\): ***Noun:*** non-equilibrium matter between Color Glass Condensate (CGC)& Quark Gluon Plasma (QGP)

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


Big Bang
Little Bang
Present
(13.7 x 10⁹ years)
WMAP data
(3x10⁵ years)
Hot Era
Inflation
RHIC data
QGP
CGC/
Glasma
t
y
x
Plot by Tetsuo Hatsuda

Big Bang vs. Little Bang

Decaying Inflaton
with occupation # $1/g^2$

↔

Decaying Glasma
with occupation # $1/g^2$

Explosive amplification
of low mom. small
fluctuations (preheating)

↔

Explosive amplification
of low mom. small fluct.
(Weibel instabilities)

Int. of fluctutations/inflaton
-> thermalization ?

↔

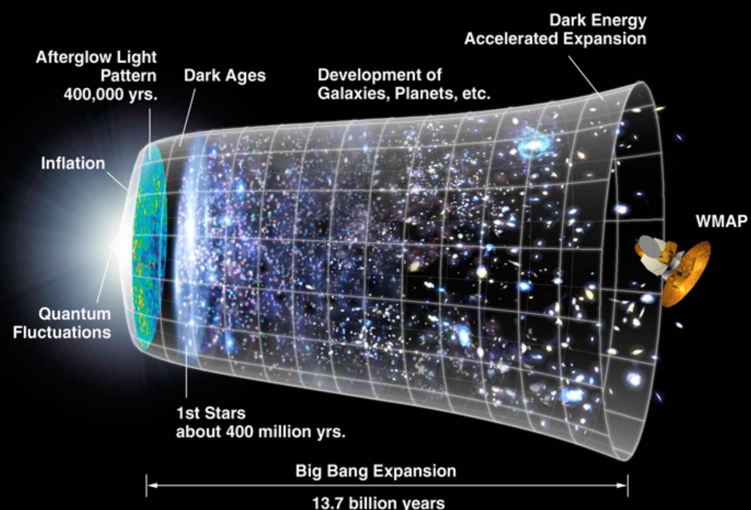
Int. of fluctutations/Glasma
-> thermalization ?

Other common features: topological defects, turbulence ?

Another Analogy with the Early Universe

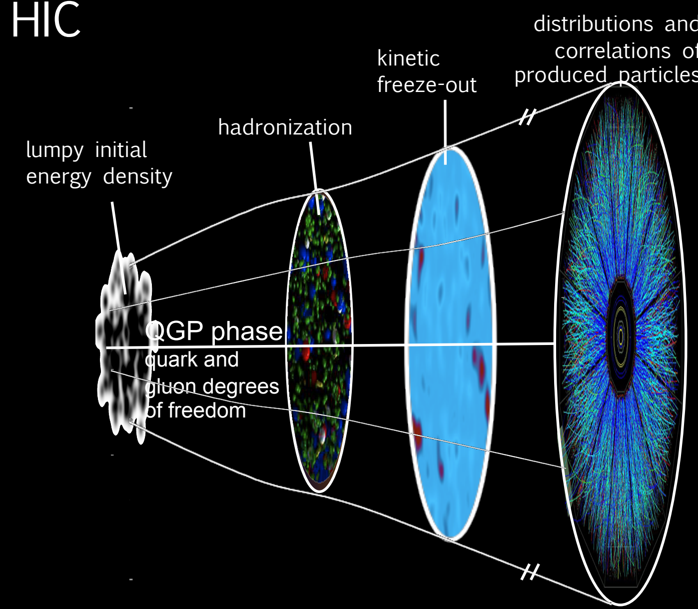
Mishra et al; Mocsy- Sorensen

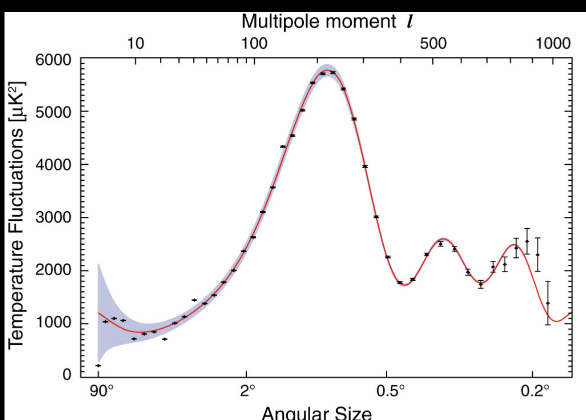
The Universe



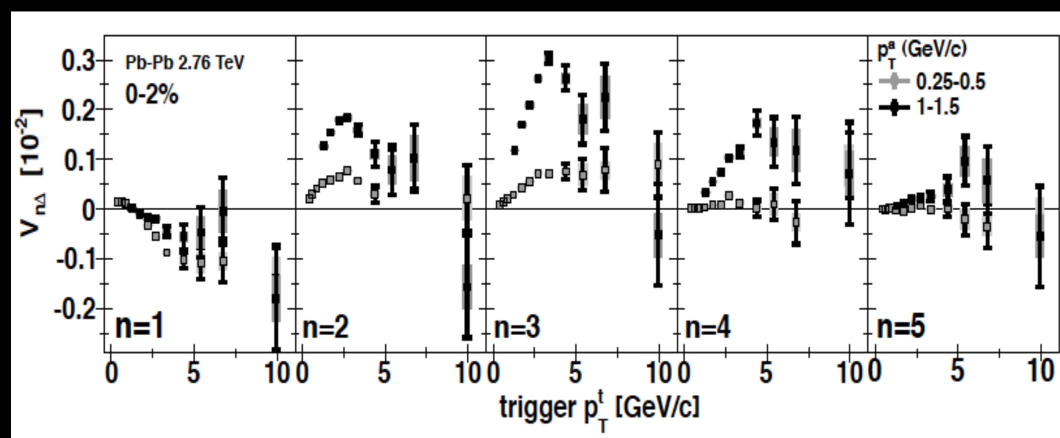
Credit: NASA

HIC



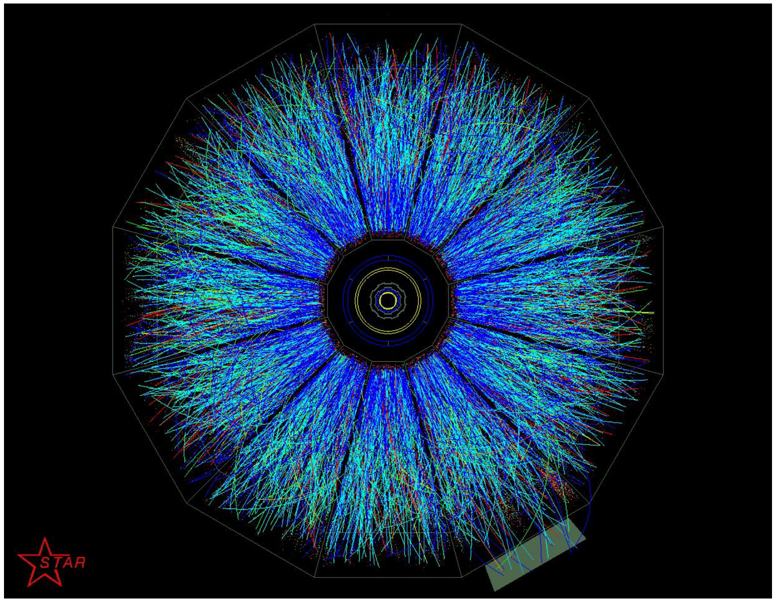


WMAP



HIC-ALICE

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!

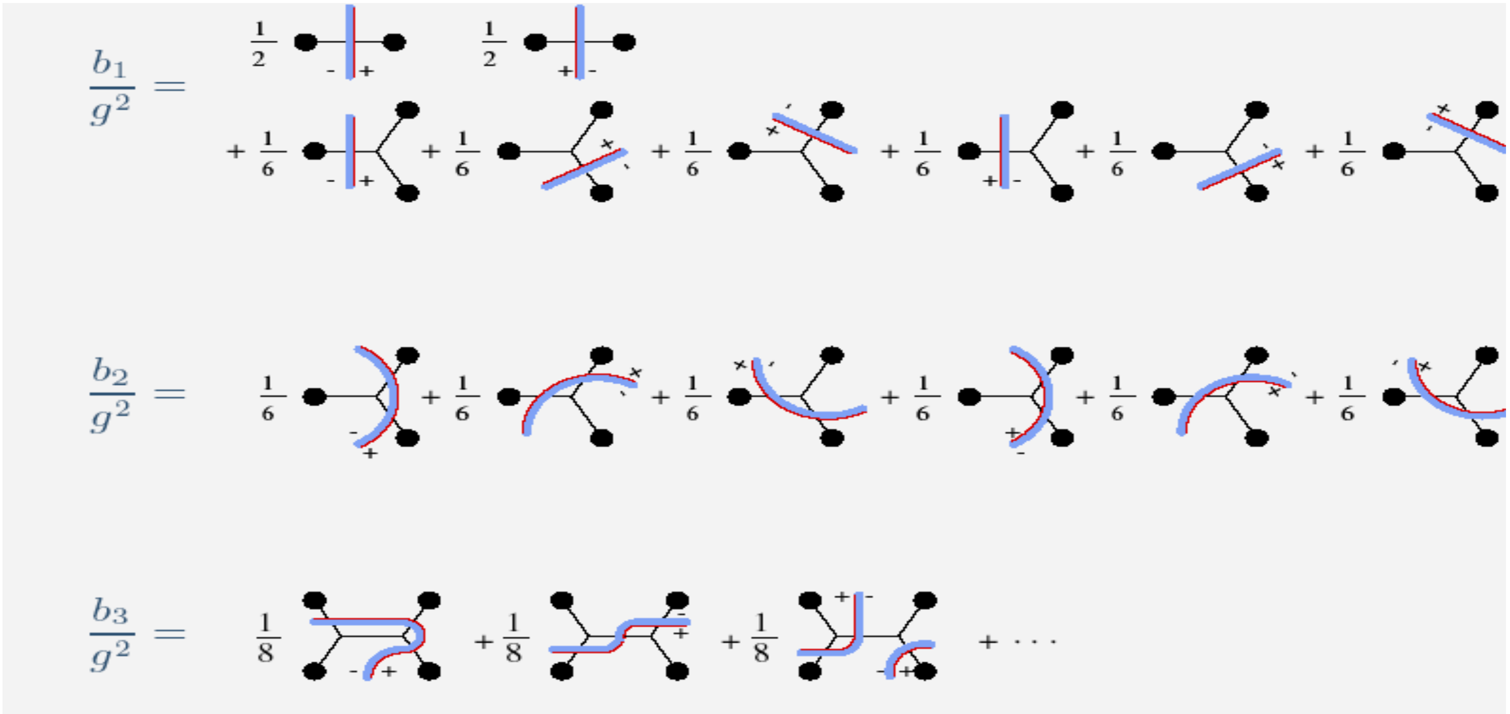
strong coupling VS weak coupling

↓

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…

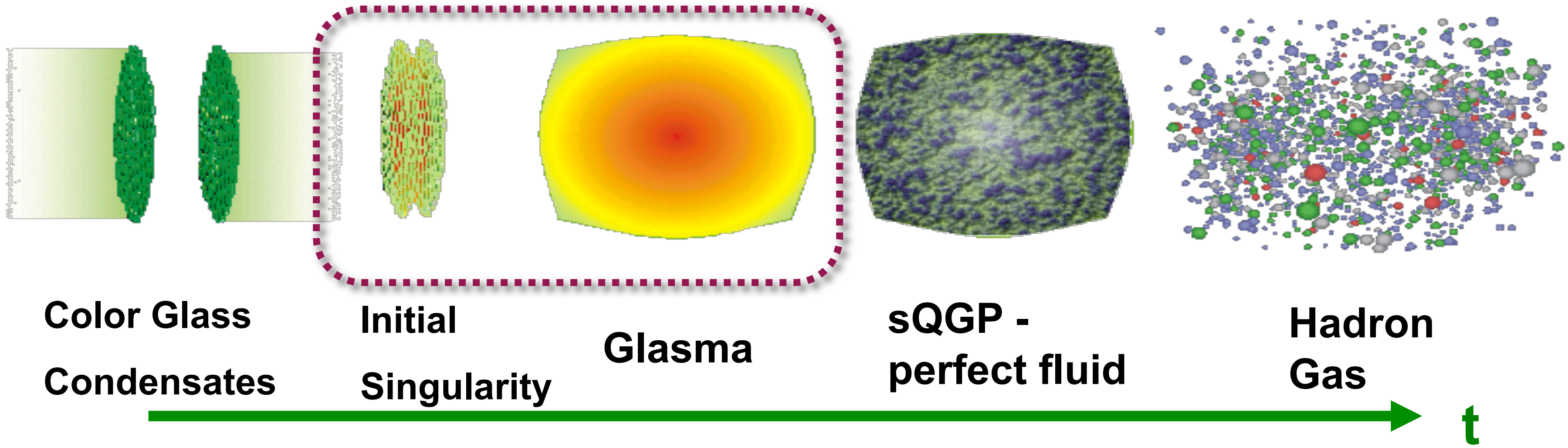
Power counting

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

Quantum decoherence from classical coherence



Computational framework

Schwinger-Keldysh: for strong time dependent sources (ρ ~ 1/g) ,
initial value problem for inclusive quantities

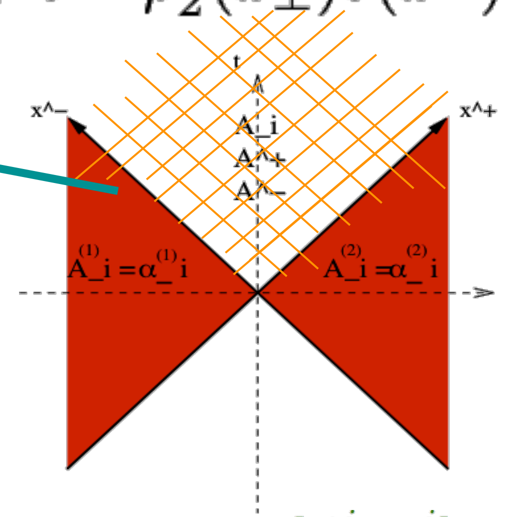
For eg., Schwinger mechanism for pair production, Hawking radiation, …

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

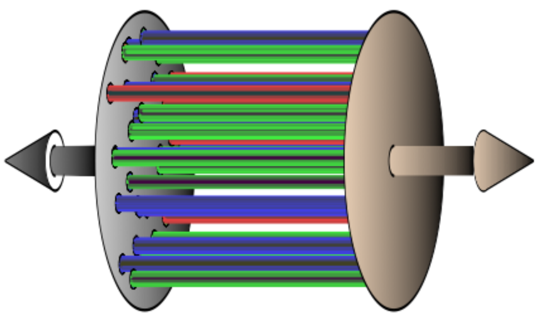
$O(1/g^2)$ and all orders in $(g\rho)^n$

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

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



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



$$\begin{aligned} \nabla \cdot E &= \rho_{\text{electric}} \\ \nabla \cdot B &= \rho_{\text{magnetic}} \end{aligned}$$

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

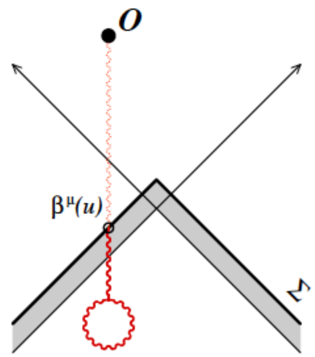
Boost invariant flux tubes of size with || color E & B fields- generate Chern-Simons charge

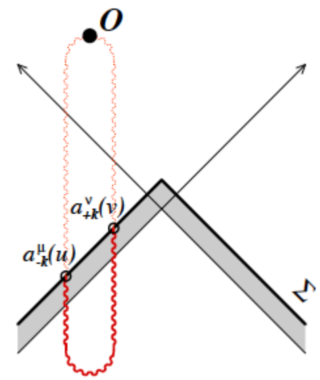
However, this results in very anisotropic ($P_T >> P_L$) pressure for $\tau \sim 1/Q_S$

RG evolution for 2 nuclei

Gelis,Lappi,RV (2008)

Log divergent contributions crossing nucleus 1 or 2:



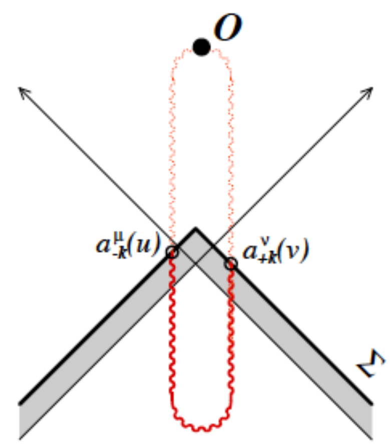


$$\mathcal{O}_{\rm NLO} = \left[\frac{1}{2}\int_{\vec{u},\vec{v}} \mathcal{G}(\vec{u},\vec{v})\ \mathcal{T}_u\mathcal{T}_v + \int_{\vec{u}} \beta(\vec{u})\ \mathcal{T}_u\right]\mathcal{O}_{\rm LO}$$

$\mathcal{G}(\vec{u},\vec{v})$ 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

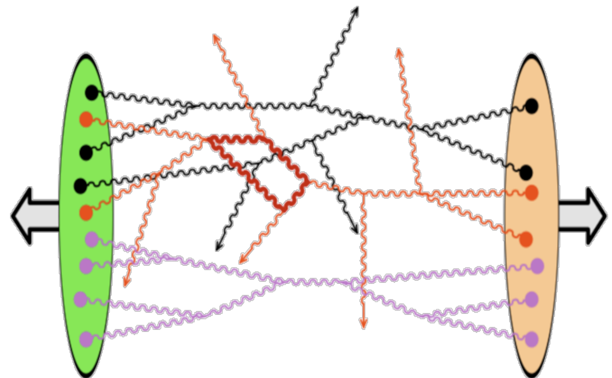


$$\mathcal{O}_{\rm NLO} = \left[\ln\left(\frac{\Lambda^+}{p^+}\right)\mathcal{H}_1 + \ln\left(\frac{\Lambda^-}{p^-}\right)\mathcal{H}_2\right]\mathcal{O}_{\rm LO}$$

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 α_s ln(1/x):
small x (leading logs) and strong field (gρ) resummation

Gelis,Lappi,RV (2008)

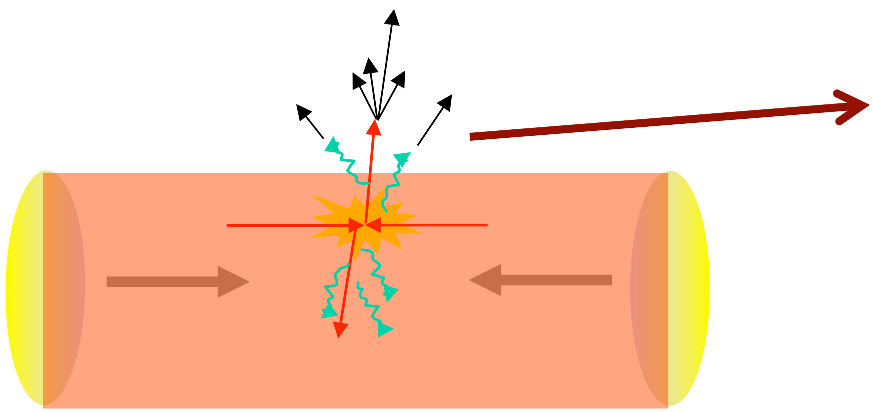
$$\langle T^{\mu\nu}(\tau, \underline{\eta}, x_\perp)\rangle_{\rm LLog} = \int [D\rho_1 d\rho_2]\, W_{Y_1}[\rho_1]\, W_{Y_2}[\rho_2]\, T^{\mu\nu}_{\rm LO}(\tau, x_\perp)$$

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

Glasma factorization => universal "density matrices W" ⊗ "matrix element"

Long range rapidity correlations

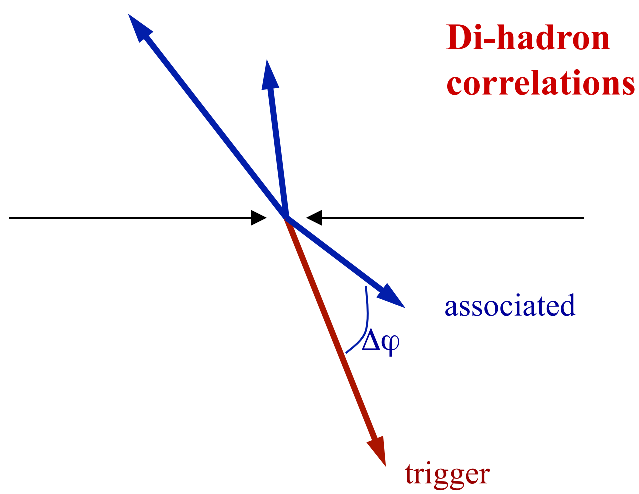
Some notation: Δη-ΔΦ



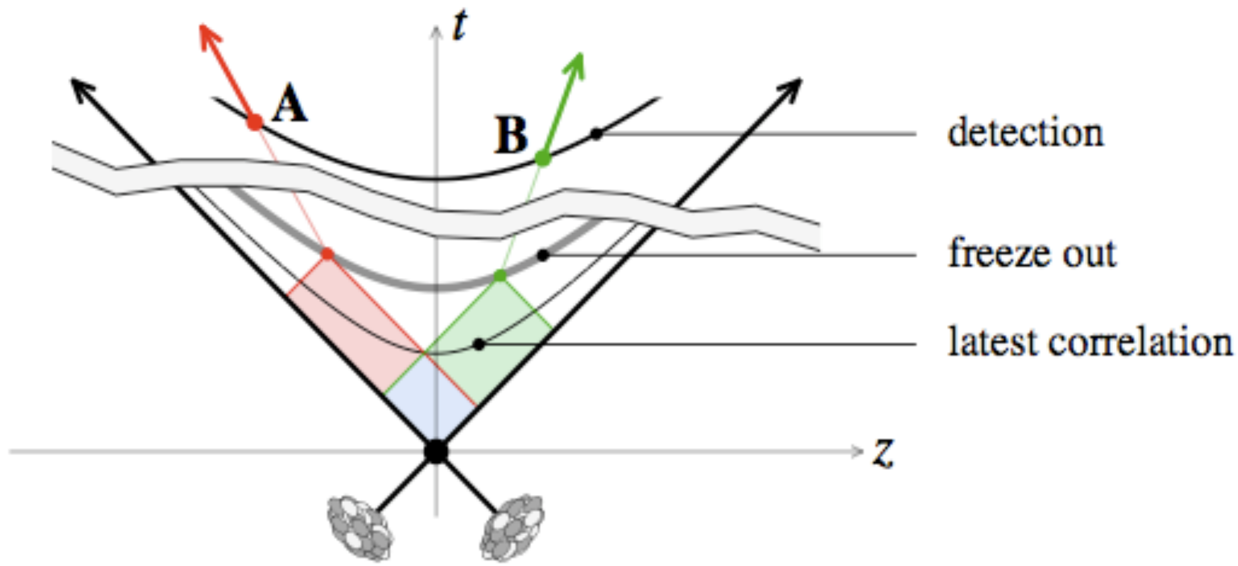
Rapidity: a measure of velocity (denoted by y or η) additive under Lorentz boost

Δη – measure of angular separation along beam direction

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



Long range rapidity correlations as chronometer

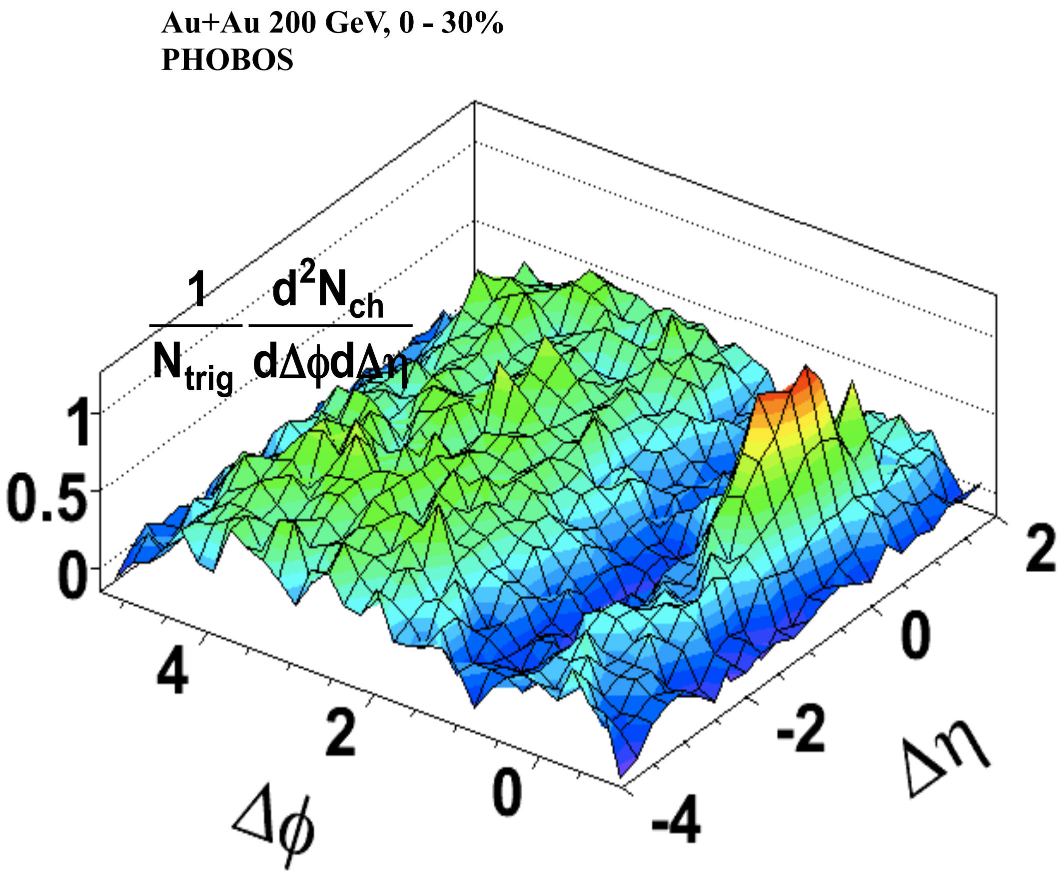


$$\tau \leq \tau_{\text{freeze-out}} \exp\left(-\frac{1}{2}|y_A - y_B|\right)$$

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

Dumitru, Gelis, McLerran, RV, arXiv 0804.3858

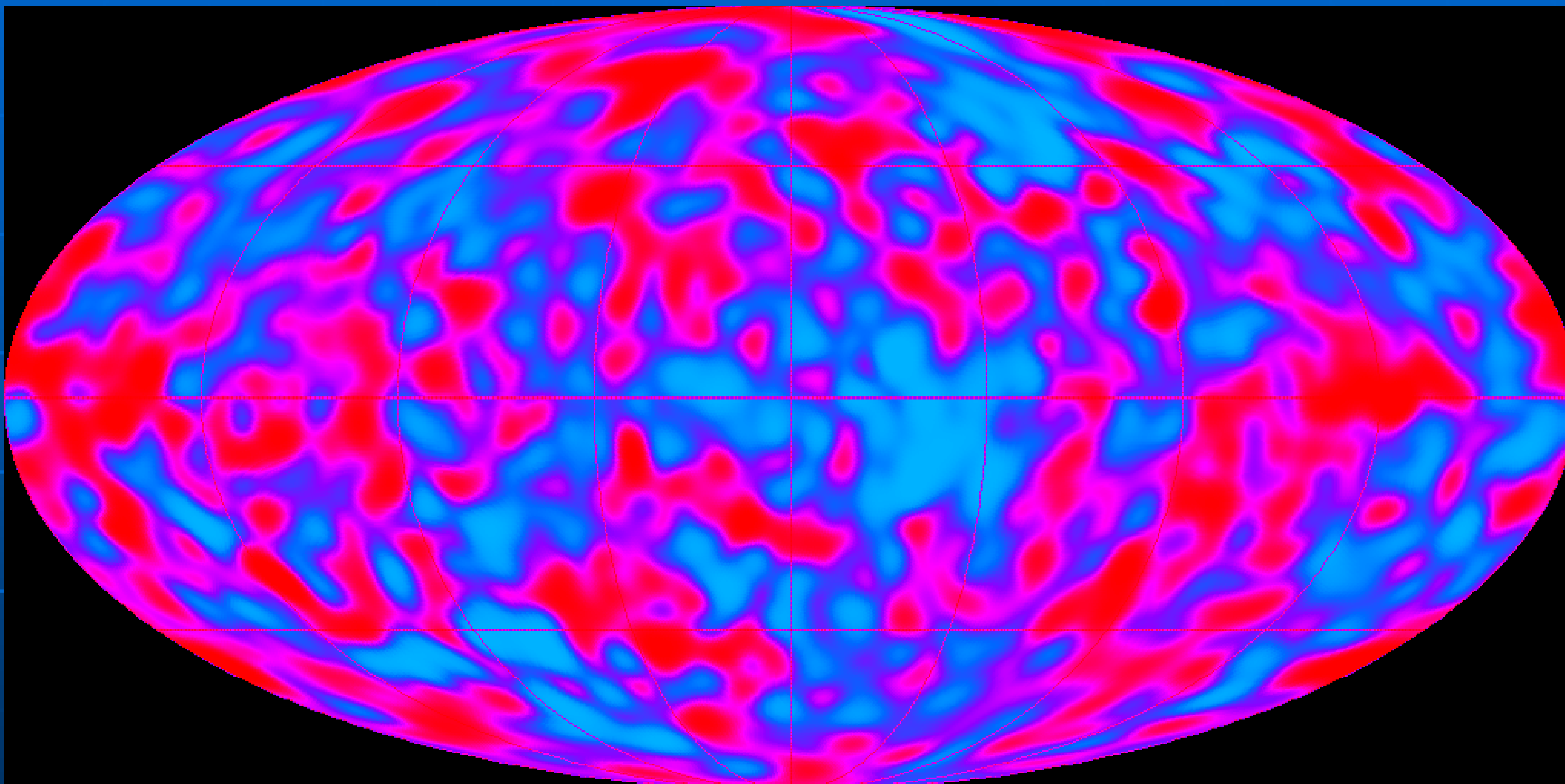
Really long range correlations



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

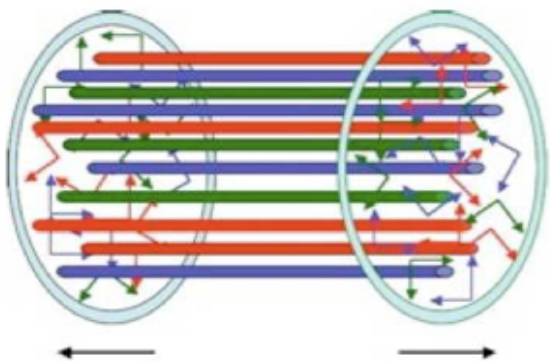
An example of a small fluctuation spectrum…

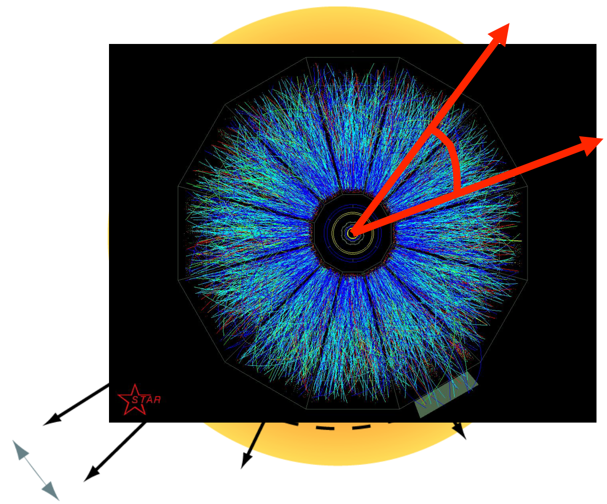
COBE Fluctuations



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

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

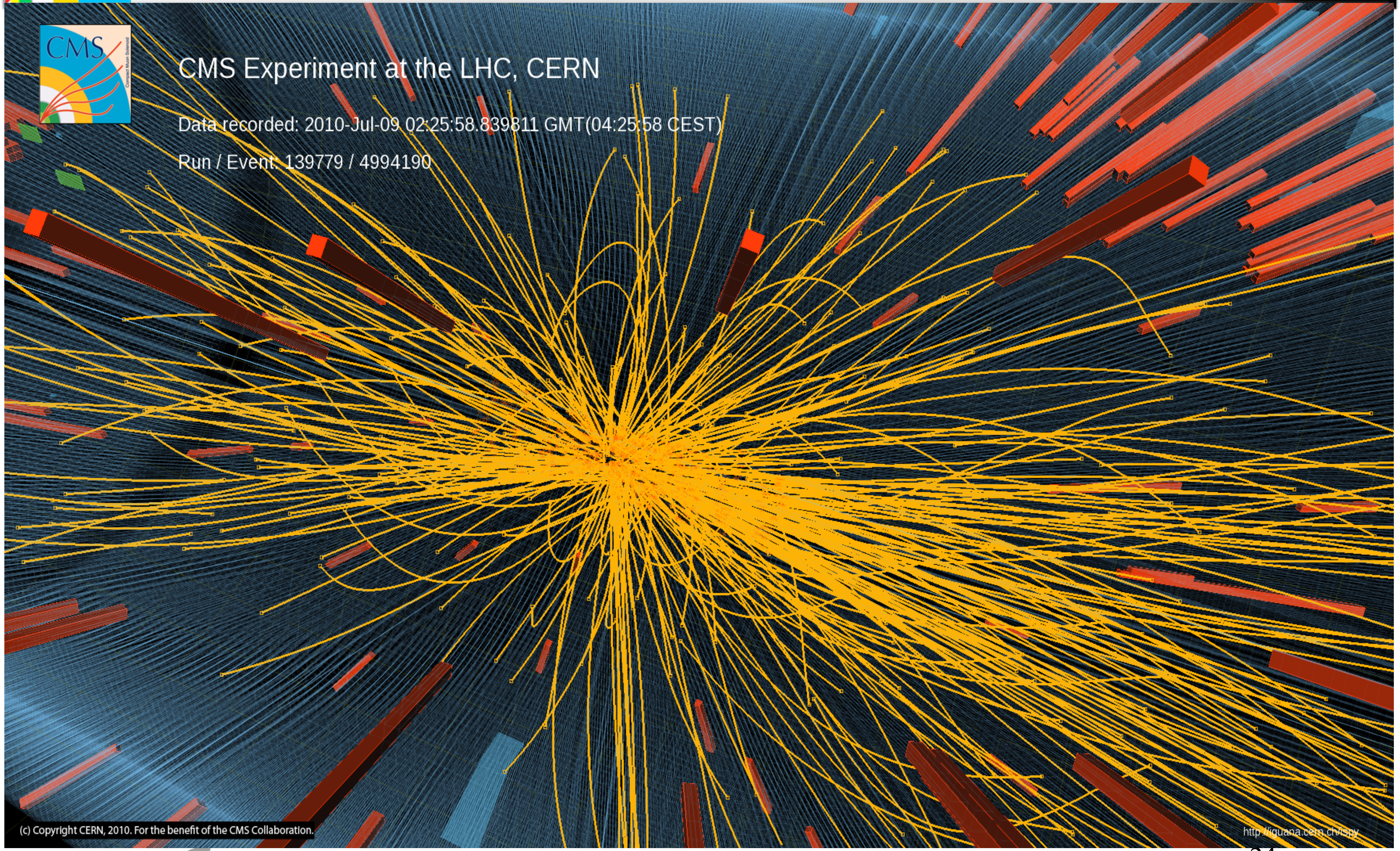
Scientists at the Large Hadron Collider are trying to solve a puzzle of their own making: why particles sometimes fly in sync

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

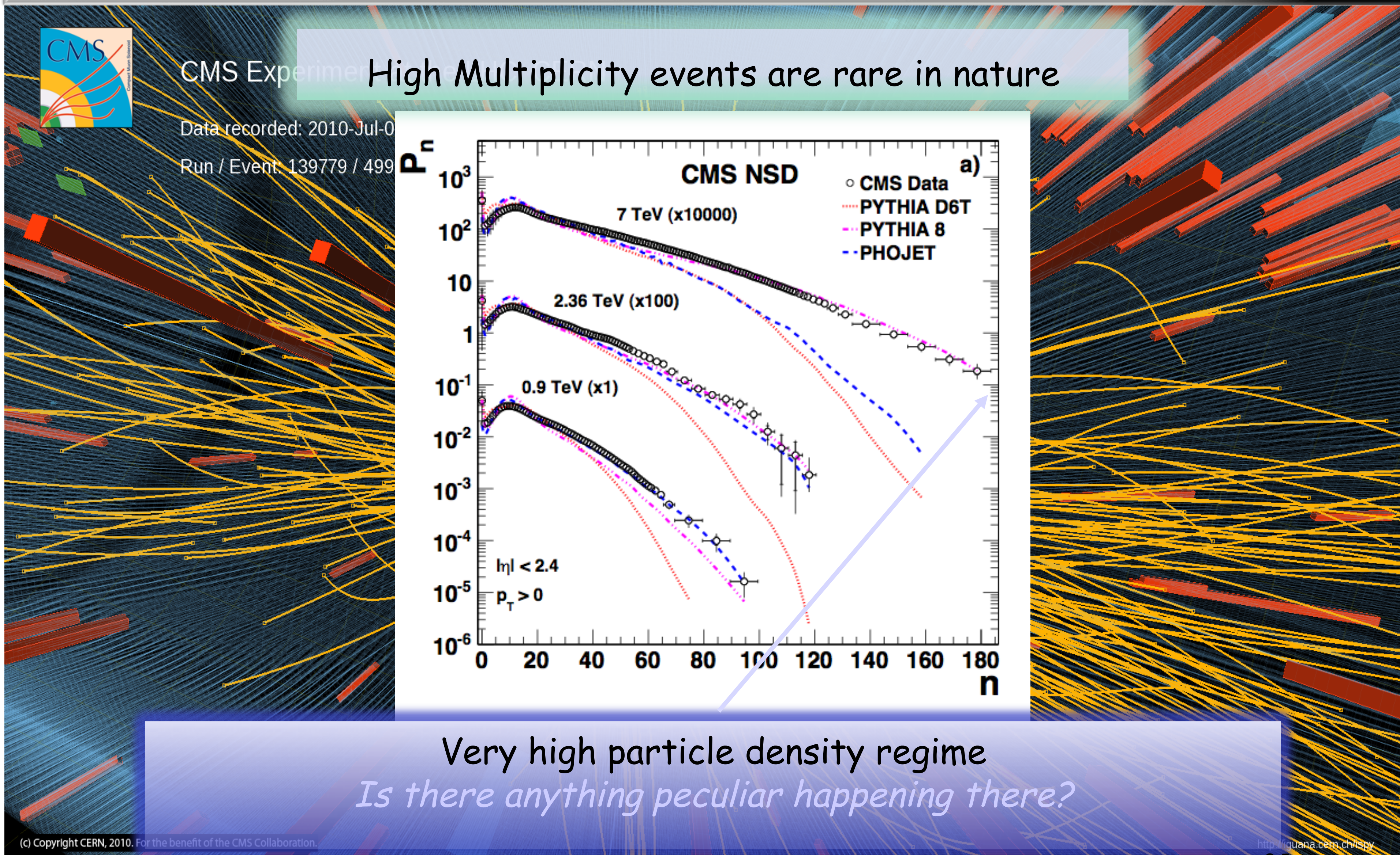
"At these higher energies [of the LHC], one is taking a snapshot of the proton with higher spatial and time resolution than ever before"

A ridge in high multiplicity pp collisions



High Multiplicity pp collisions

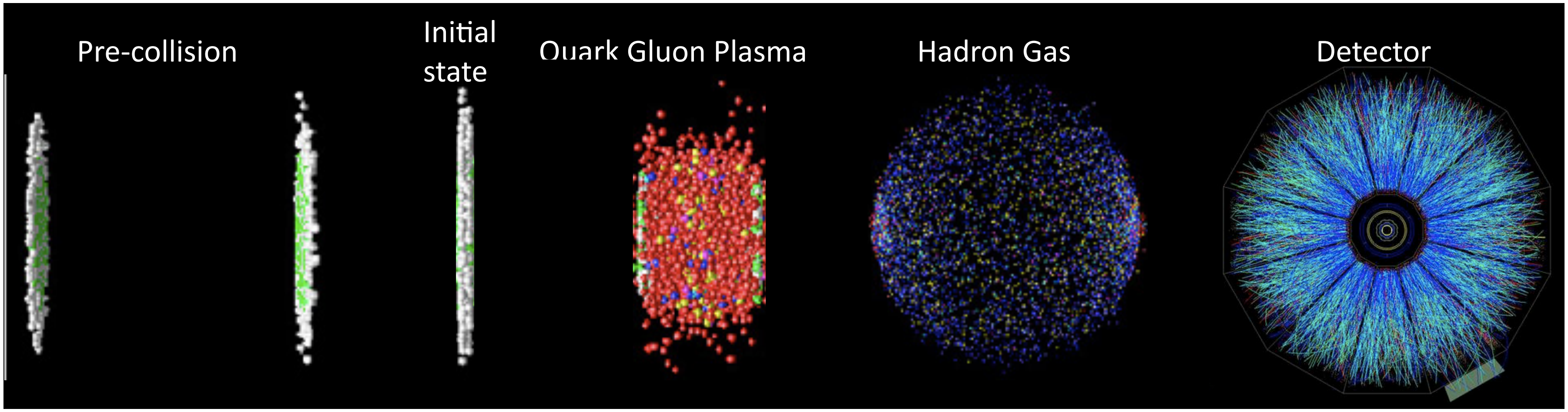
High Multiplicity events are rare in nature

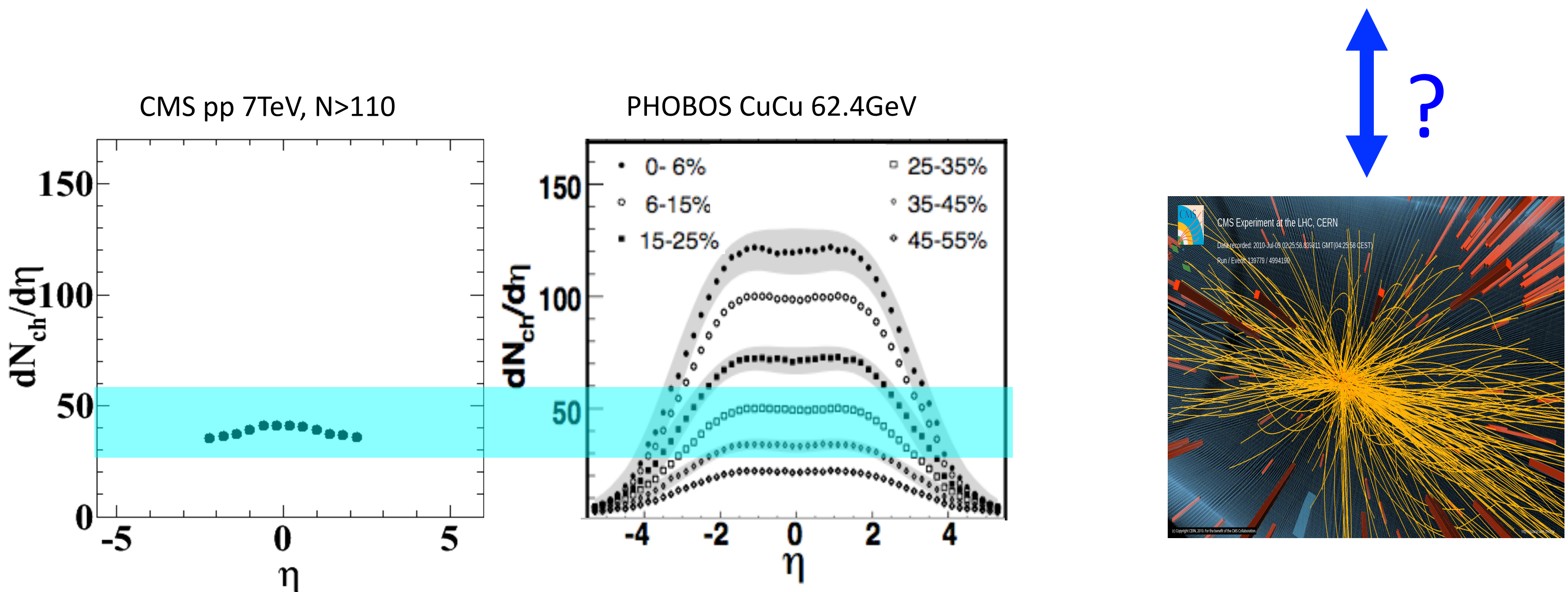


Very high particle density regime

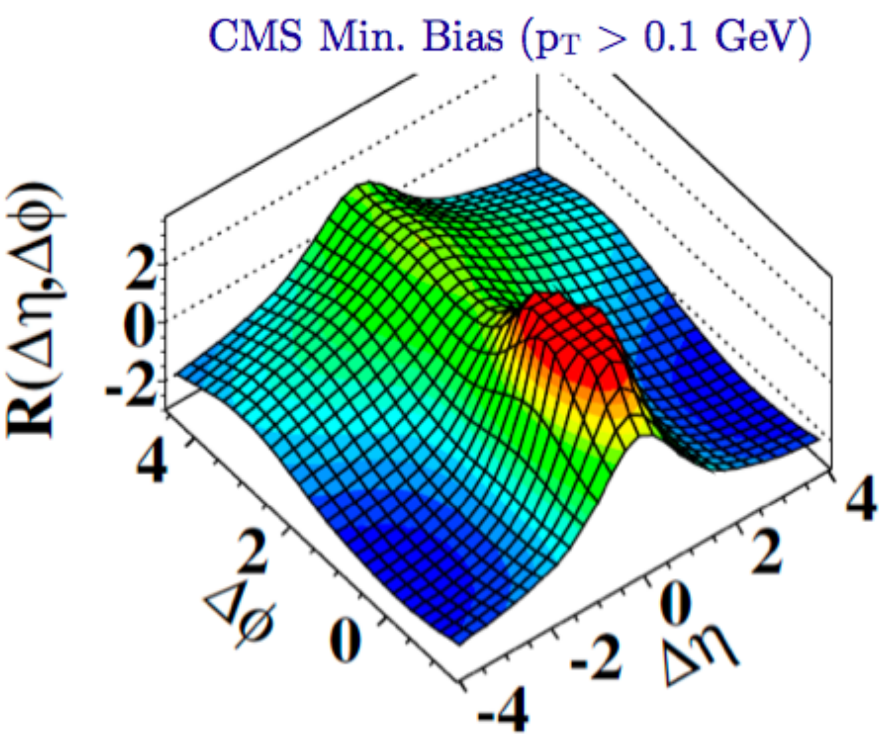
Is there anything peculiar happening there?

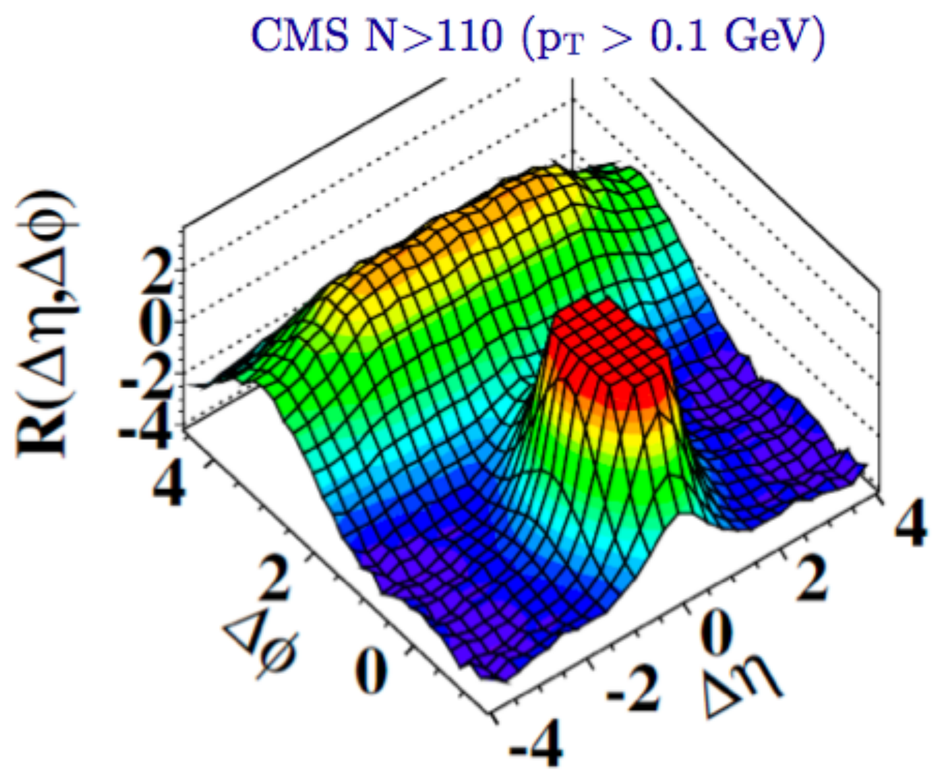
Relativistic Heavy Ion Collisions



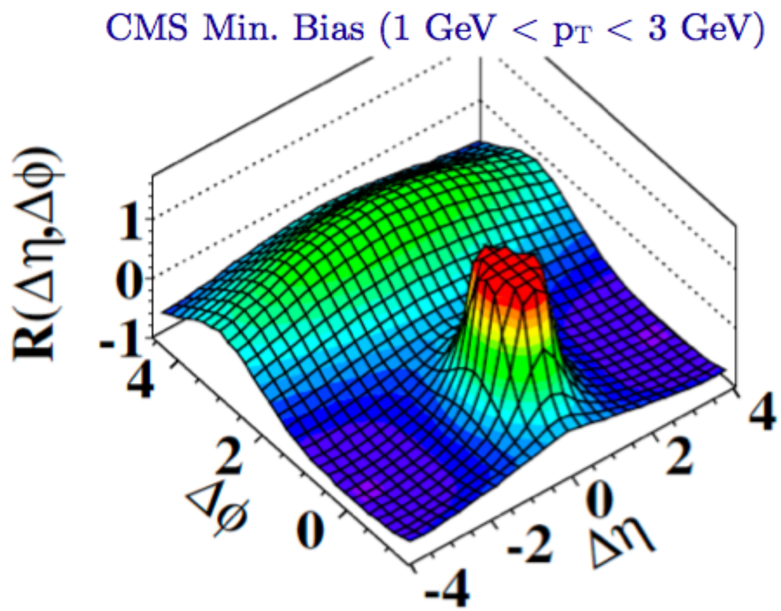


Two particle correlations: CMS results

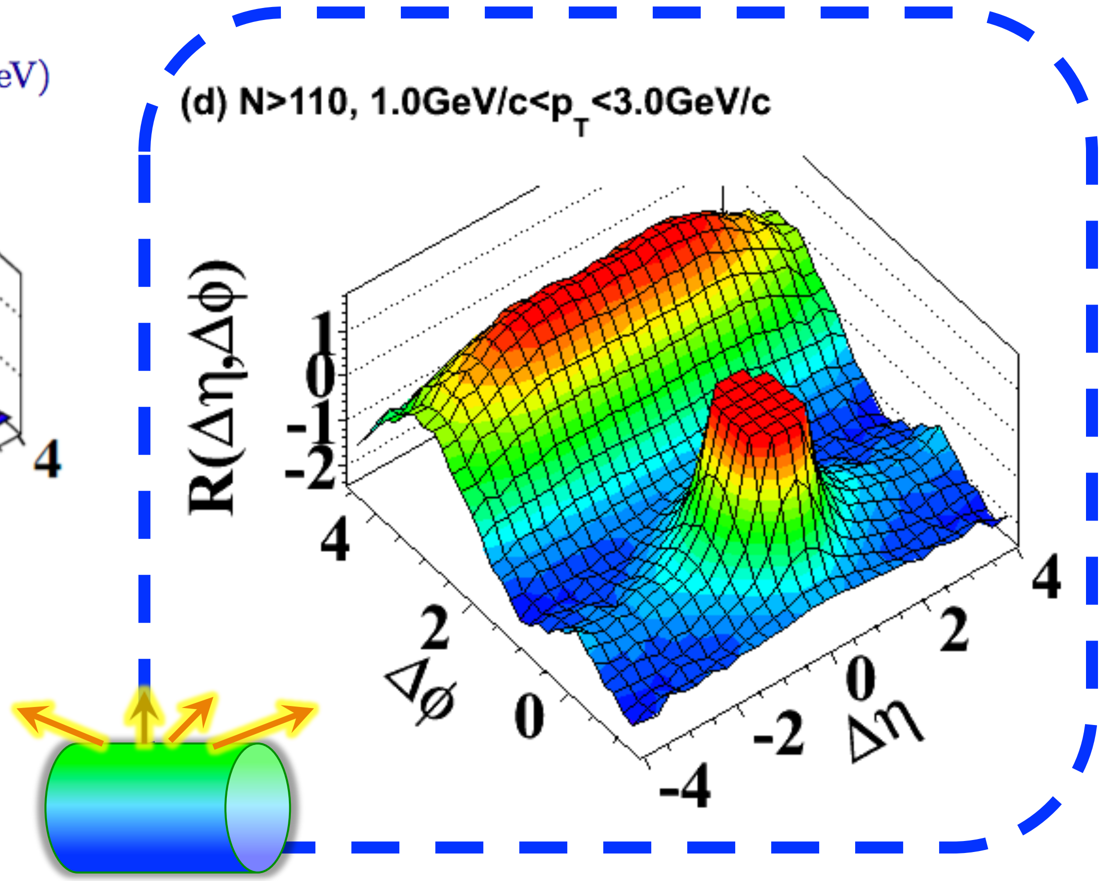




Two particle correlations: CMS results

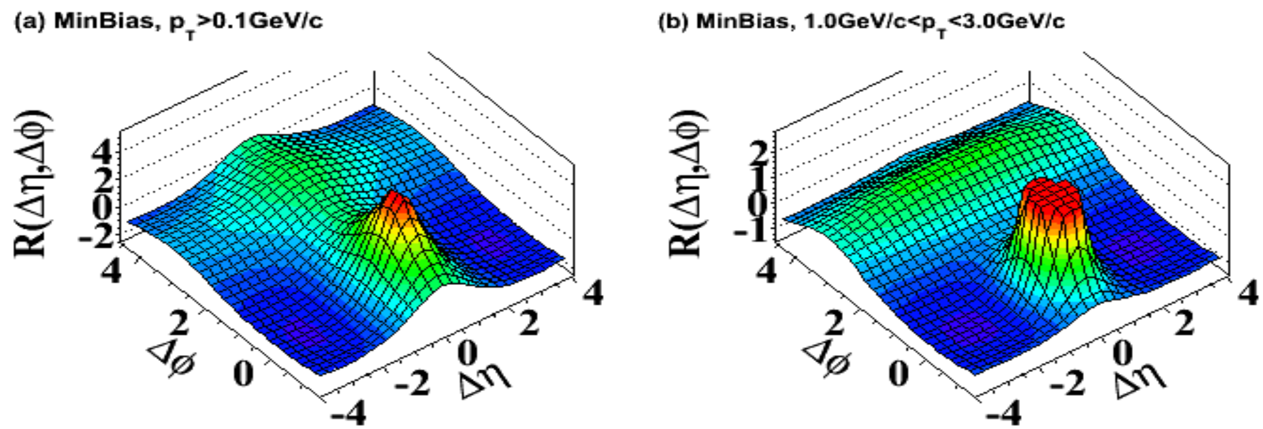


"Discovery"



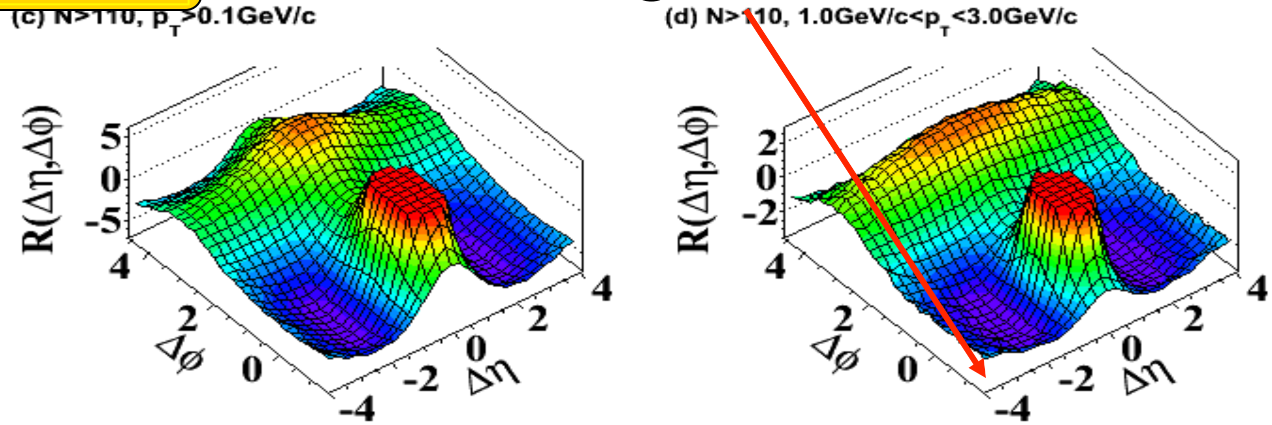
- **Ridge: Distinct long range correlation in η collimated around ΔΦ≈ 0 for two hadrons in the intermediate 1 < p_T, q_T < 3 GeV**

Comparing to MC models

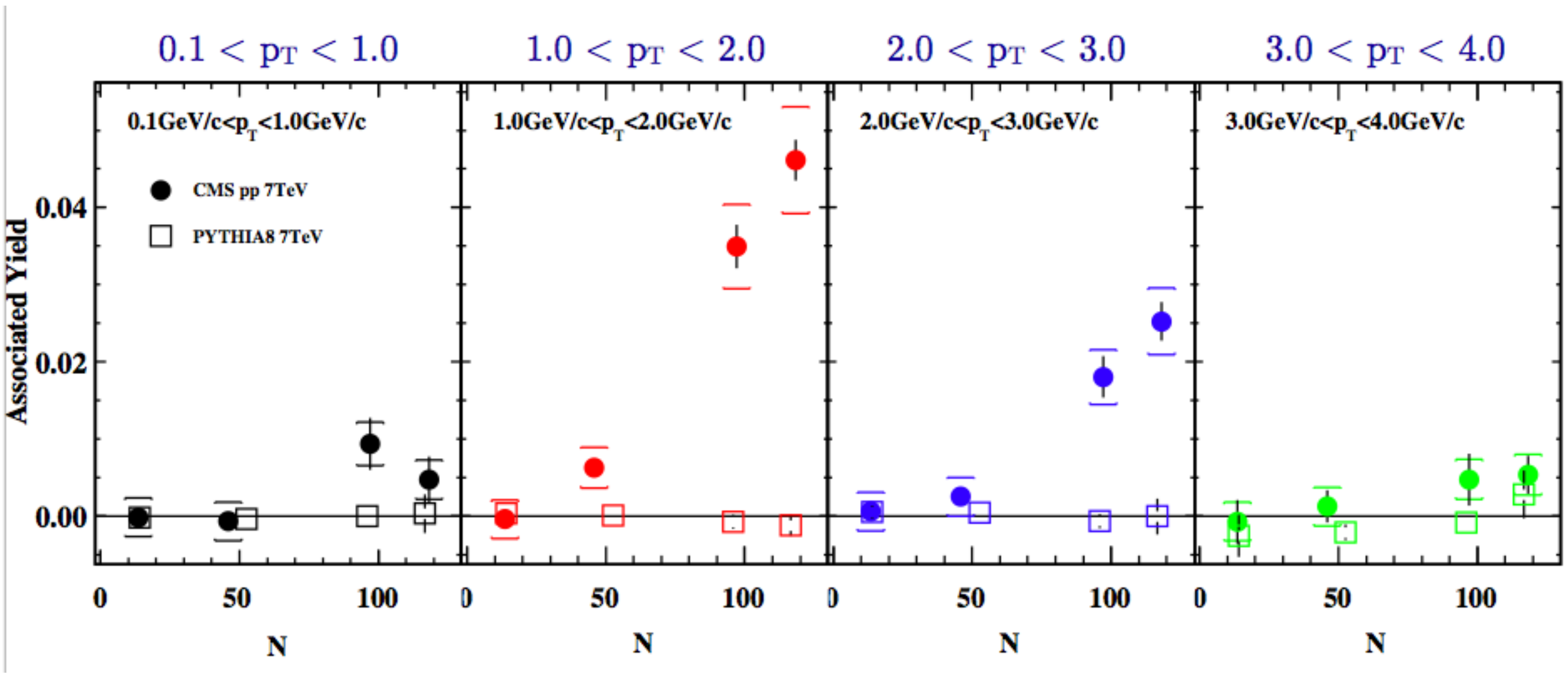


PYTHIA8, v8.135

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?

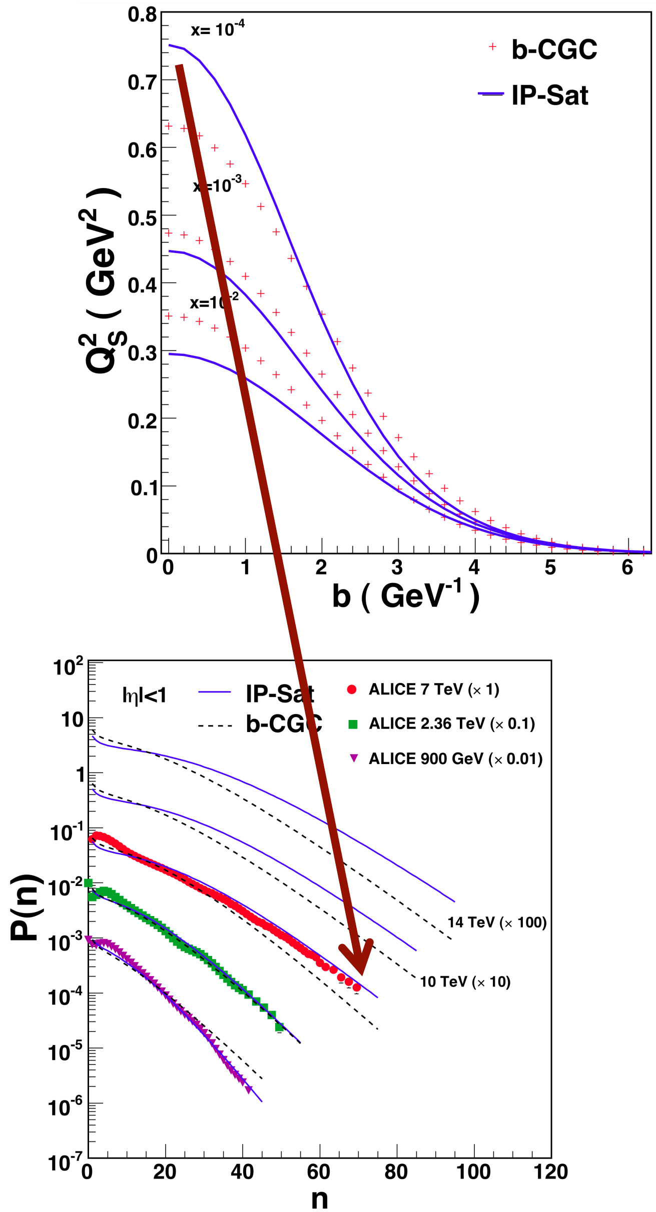
- Large number of models with a range of speculations

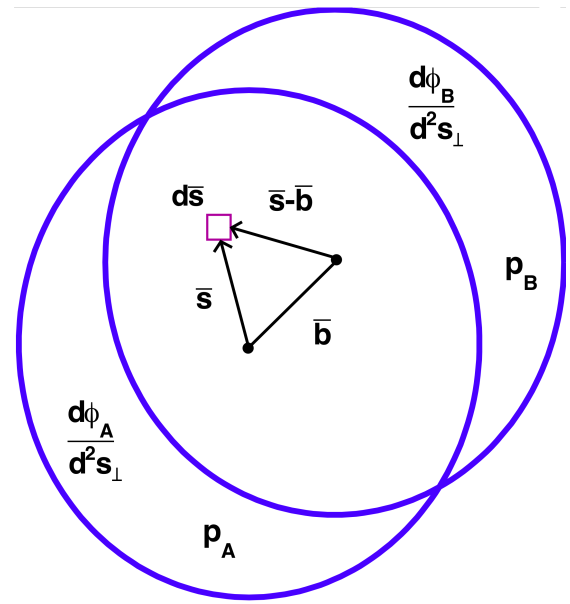
- A similar ridge was seen in heavy ion collisions @ RHIC (and now in HI collisions @ LHC) -is it hydrodynamic flow ?

- 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

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

High multiplicity events in p+p



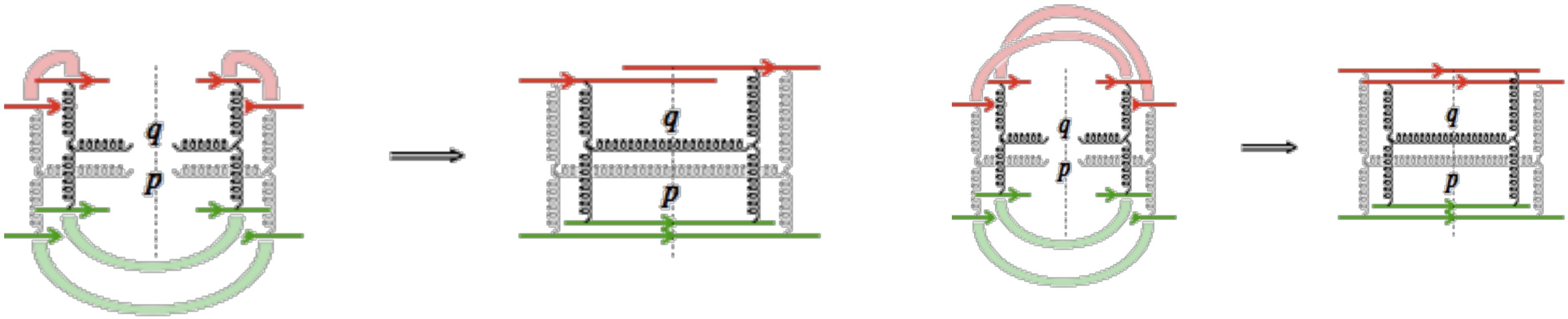


High multiplicity events likely correspond to high occupation numbers ($1/\alpha_S$) in the proton wave functions for $p_T \leq Q_S$

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 ~ $1/Q_S$



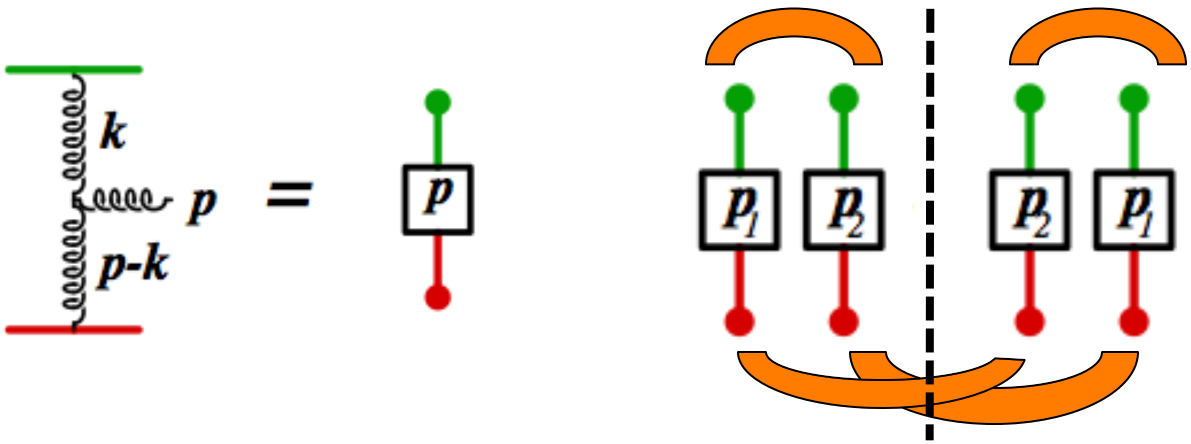
These graphs (called "Glasma graphs"), which generate long
range rapidity correlations, are highly suppressed for $Q_S << p_T$

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

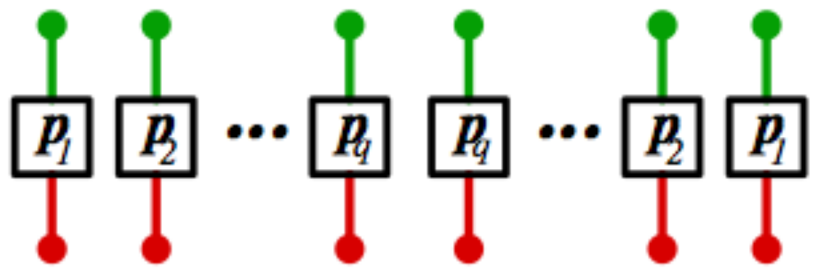


Glasma flux tube picture: two particle correlations proportional to ratio $1/Q_S^2 / S_T$

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

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

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

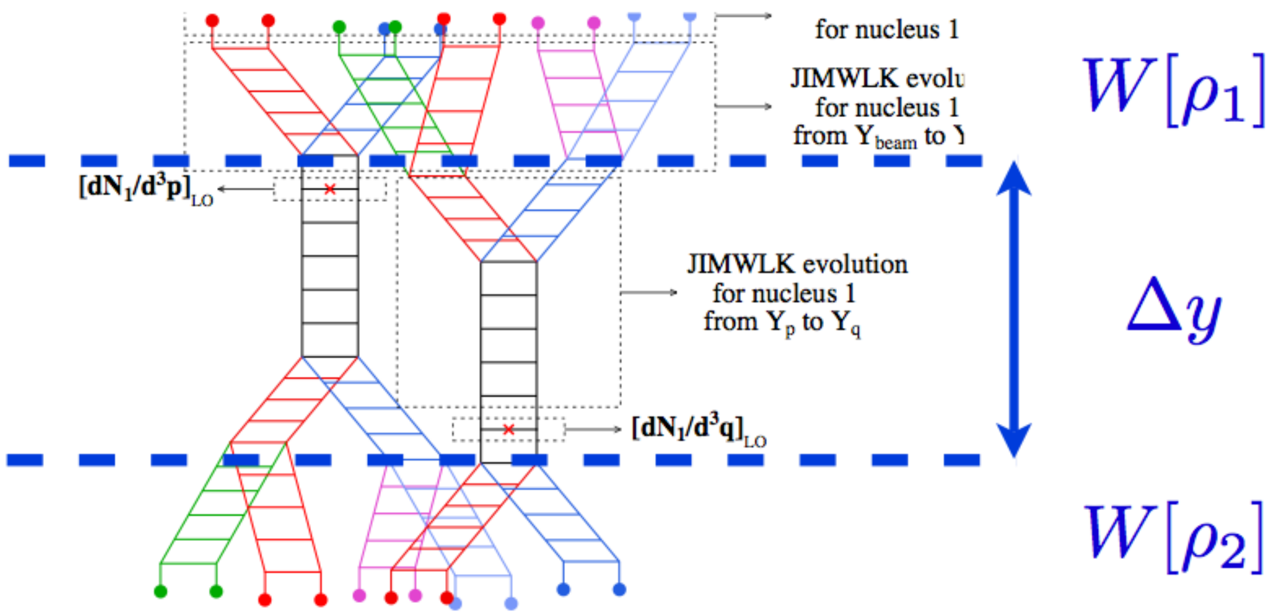
k = 1 : Bose-Einstein
k = ∞ : Poisson

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

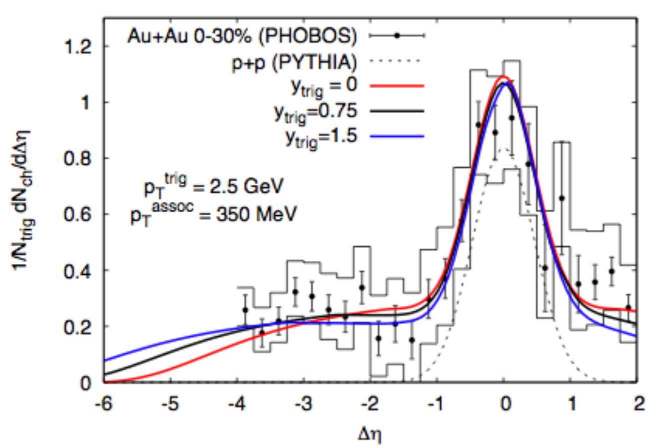
Lappi,Srednyak,RV

Long range di-hadron correlations

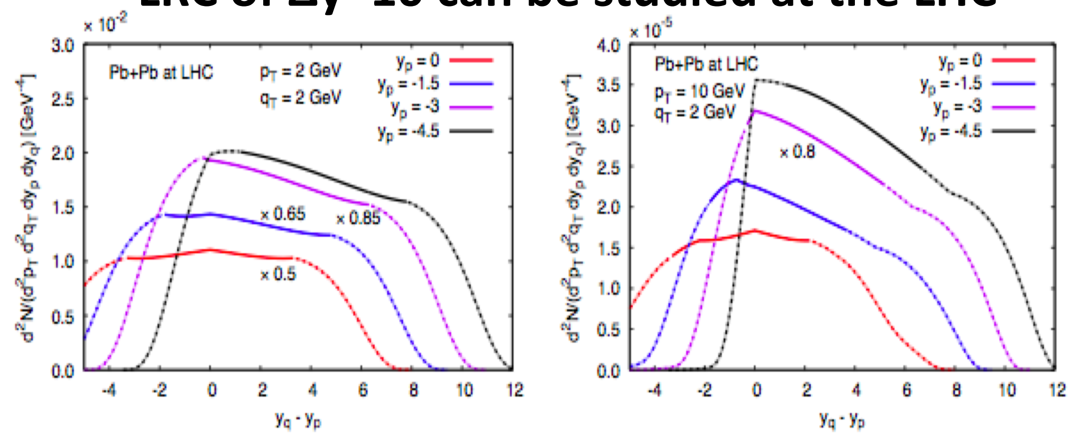
Gelis,Lappi,RV (2009)



Dusling,Gelis,Lappi,RV, arXiv:0911.2720



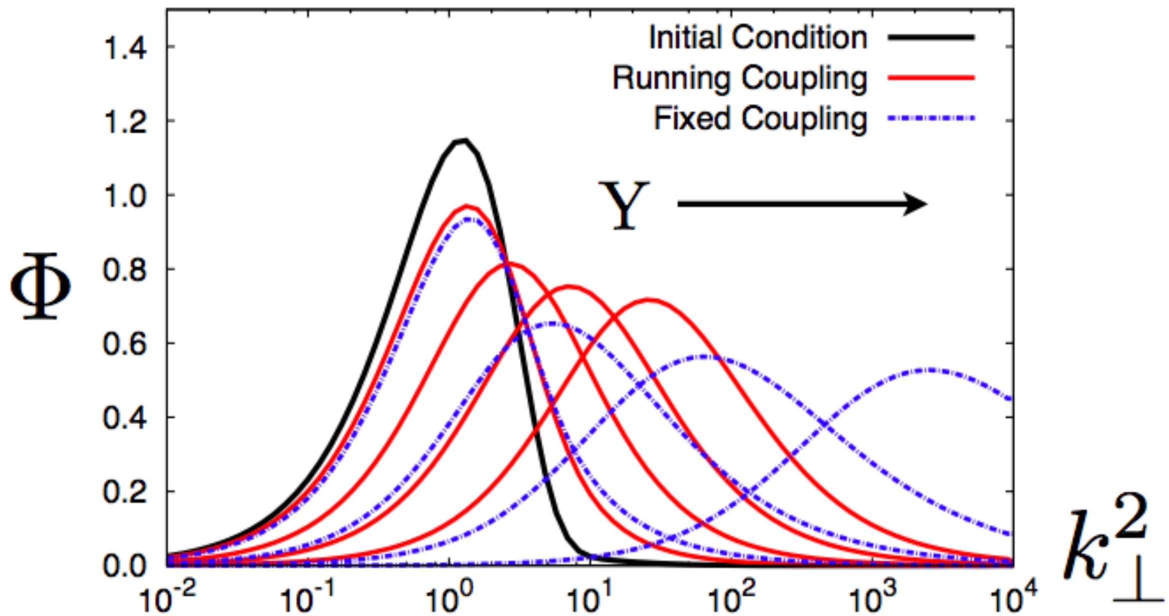
LRC of Δy~10 can be studied at the LHC



Long range di-hadron correlations

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

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

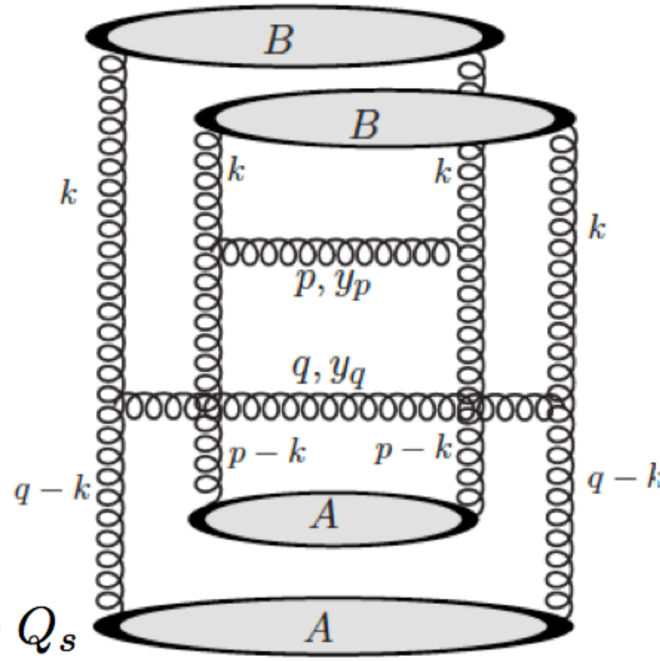


Caveat: Contribution of higher 4-pt. Wilson line correlators not included

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

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

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

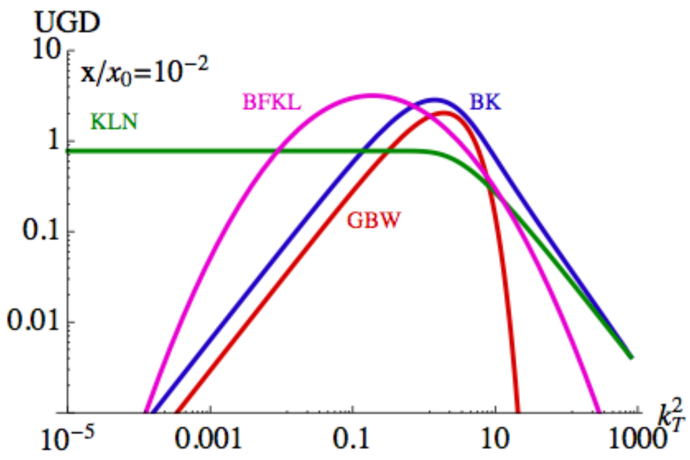


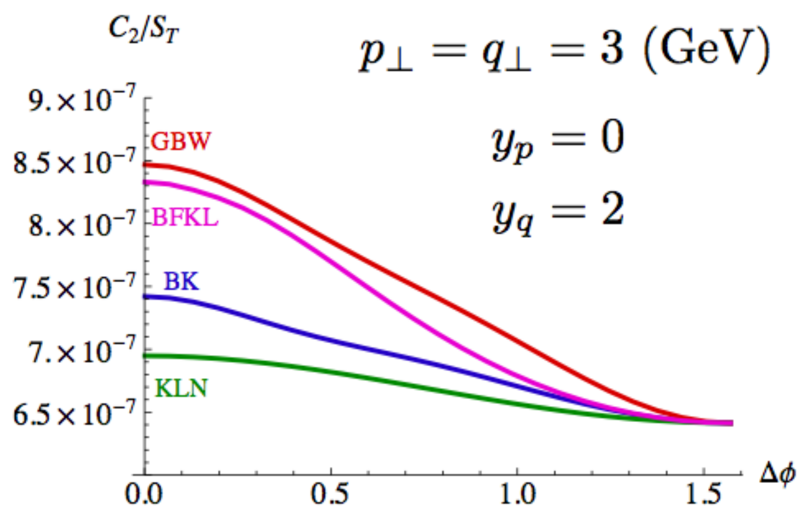
$|\mathbf{p}_\perp - \mathbf{k}_\perp| \sim Q_s$

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

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

Systematics of the correlation





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

Quantitative description of pp ridge

Dusling,RV, 1201.2658

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

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

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

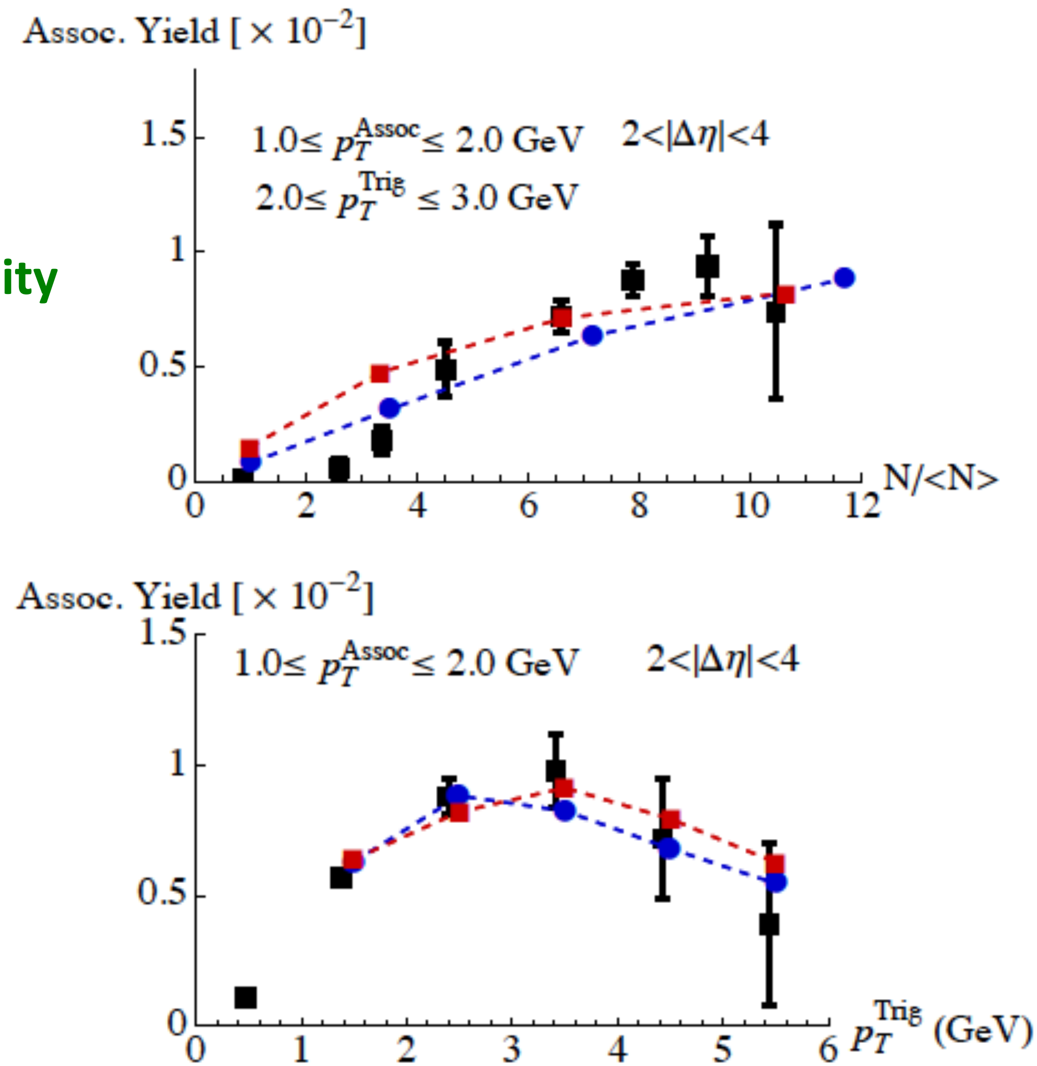
Quantitative description of pp ridge

Dusling,RV, 1201.2658

CMS preliminary data

Assoc. yield with centrality

Assoc. yield with p_T^{Trig}

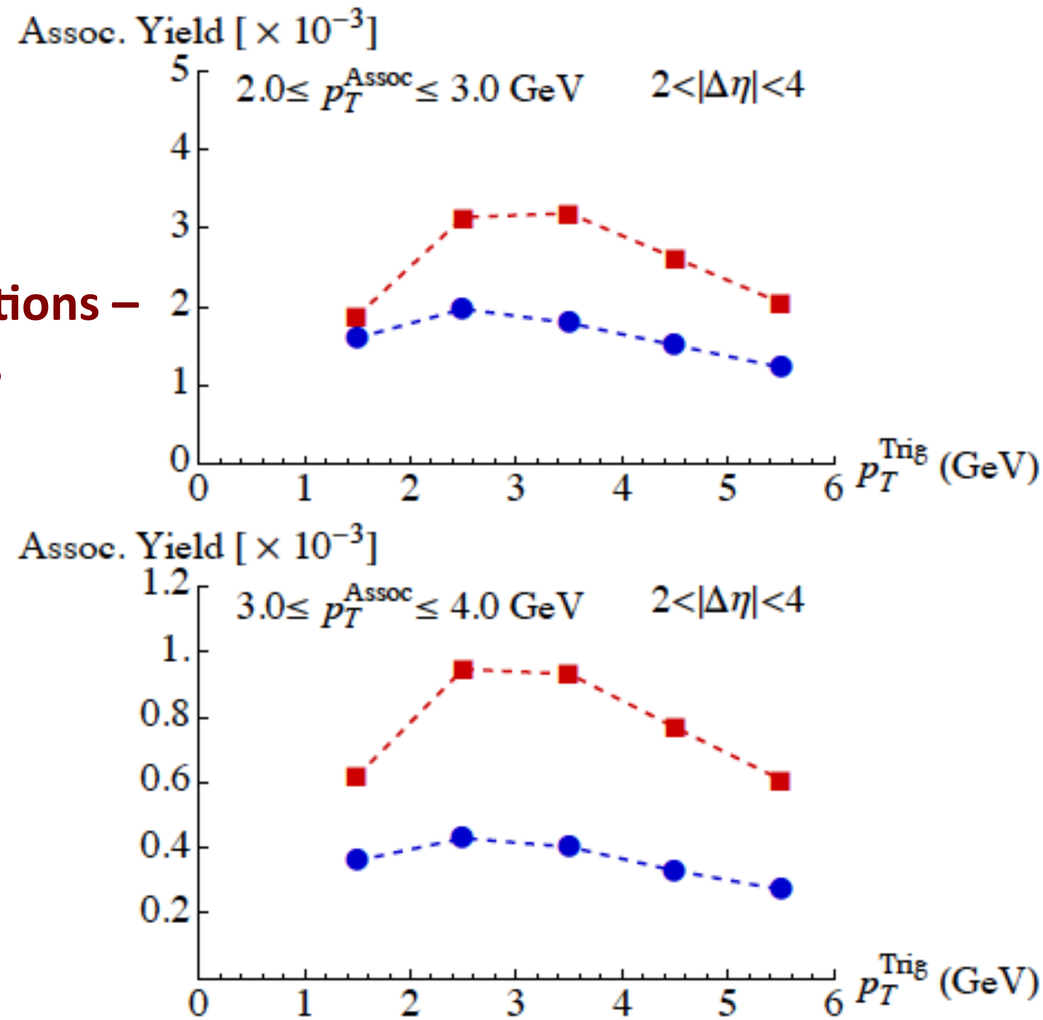


Quantitative description of pp ridge

Dusling,RV, 1201.2658

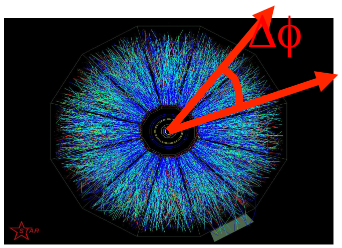
Predictions:

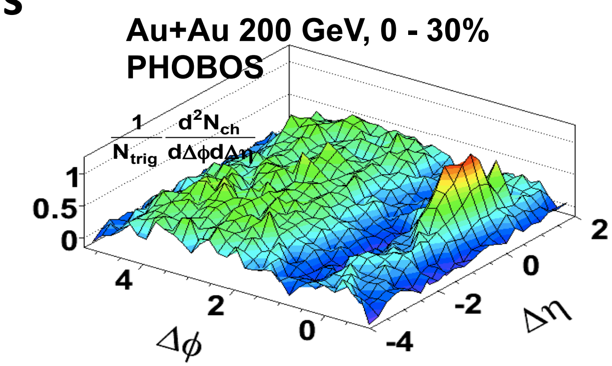
Yields for higher $p_T^{Assoc.}$ are sensitive to fragmentation functions – not known at forward rapidities

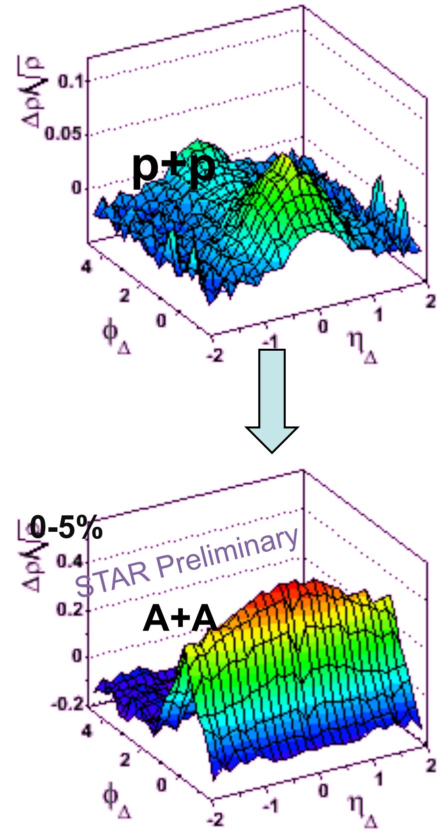


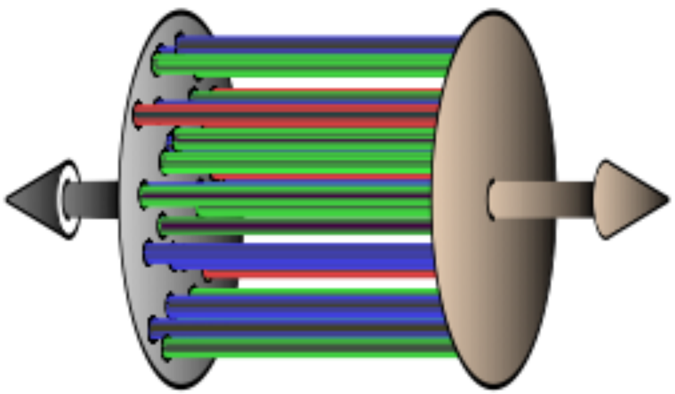
What about flow in p+p ?

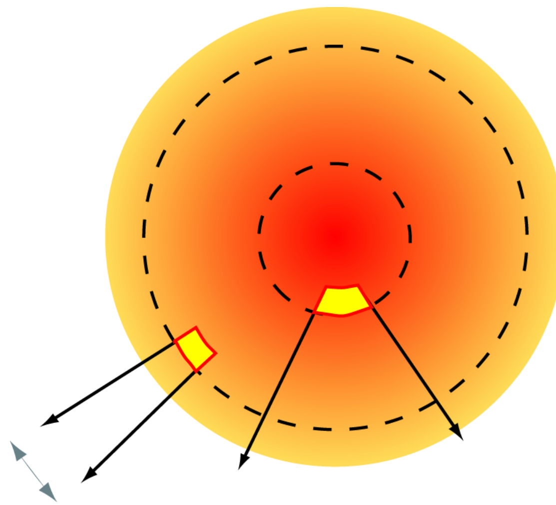
In heavy ion collisions











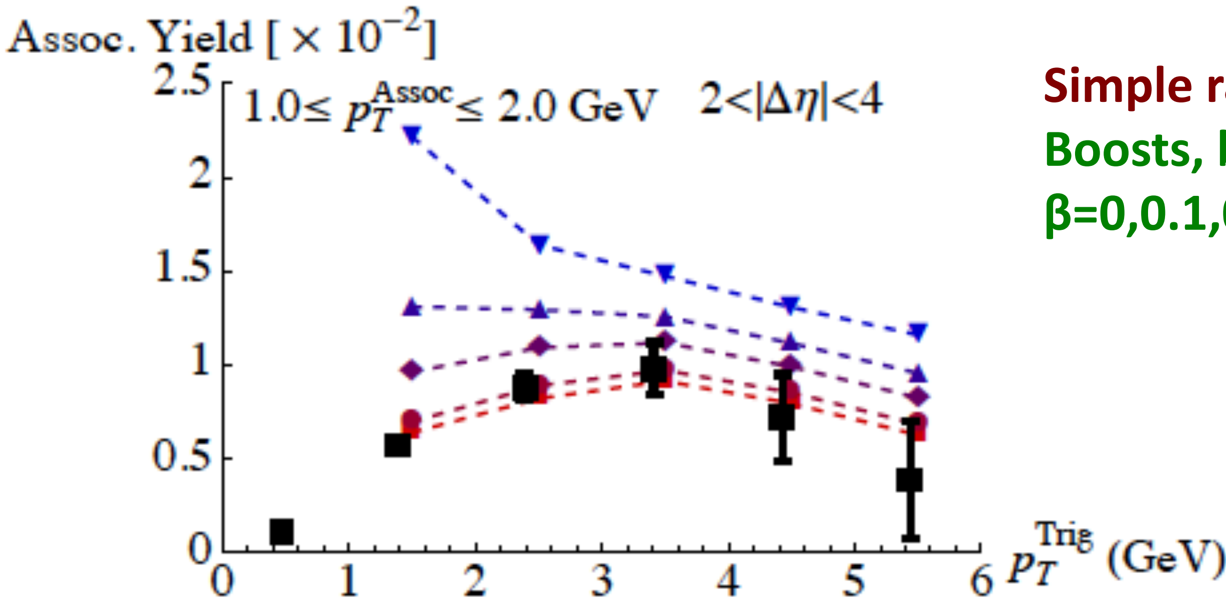
Glasma flux tubes provide the long range rapidity correlation

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

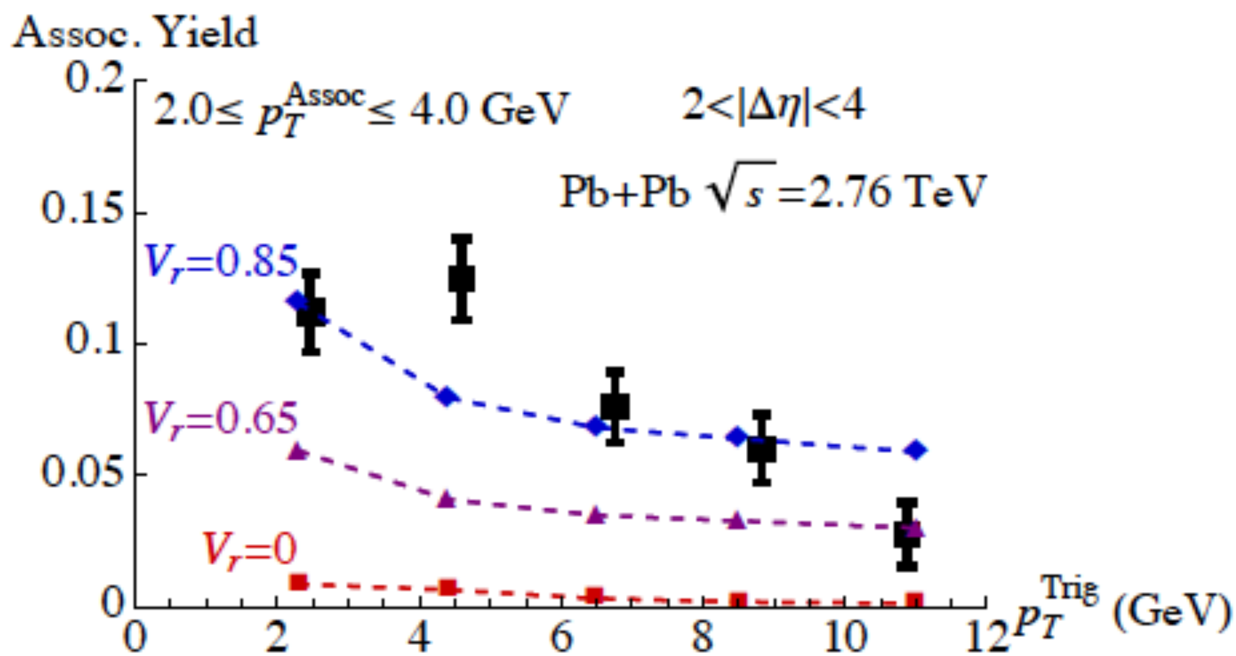
With increasing flow, the pedestal gets collimated

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-Lublinsky)

- 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