Building bridges with ridges: a peculiar quantum entanglement at the LHC & the structure of matter

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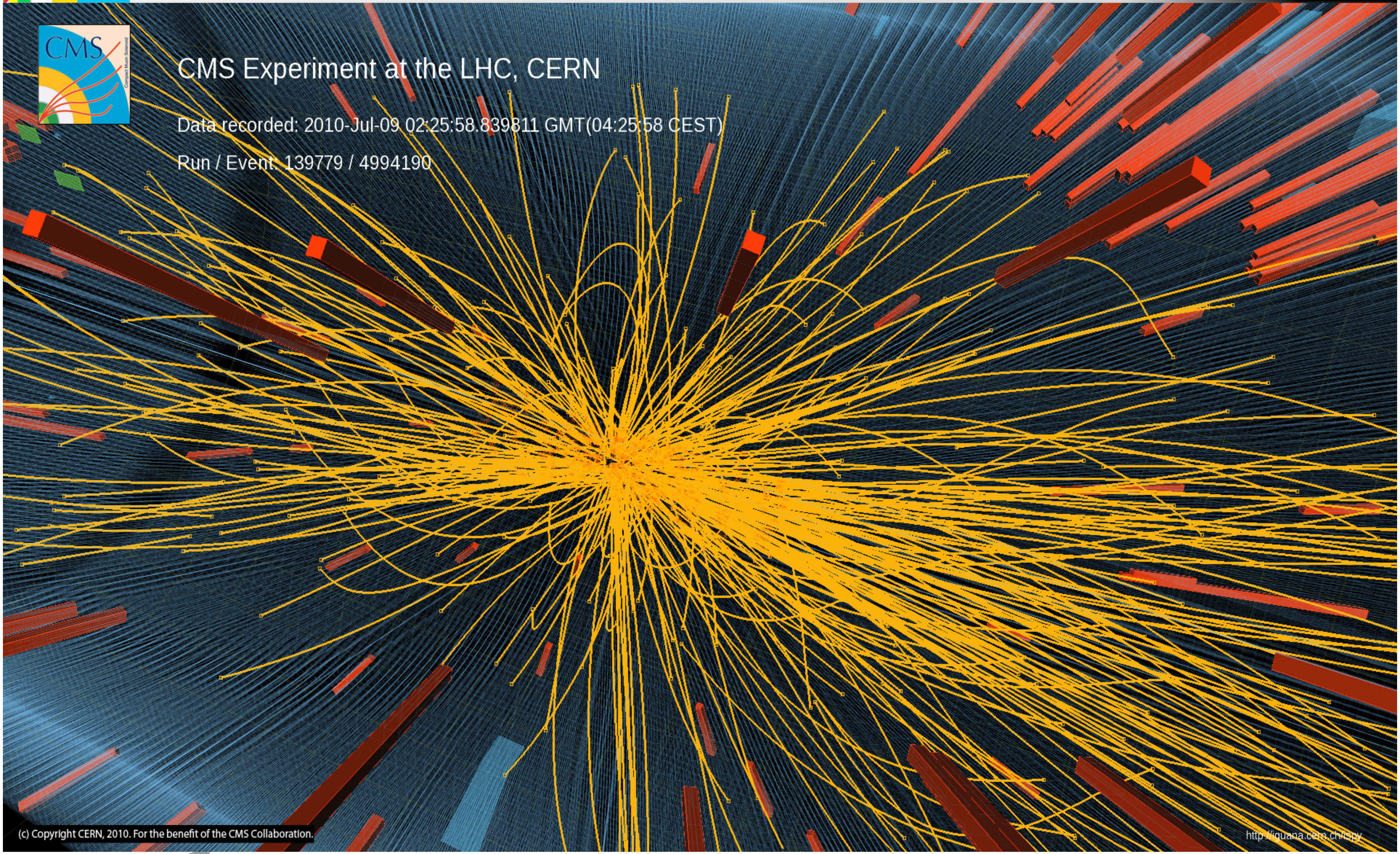
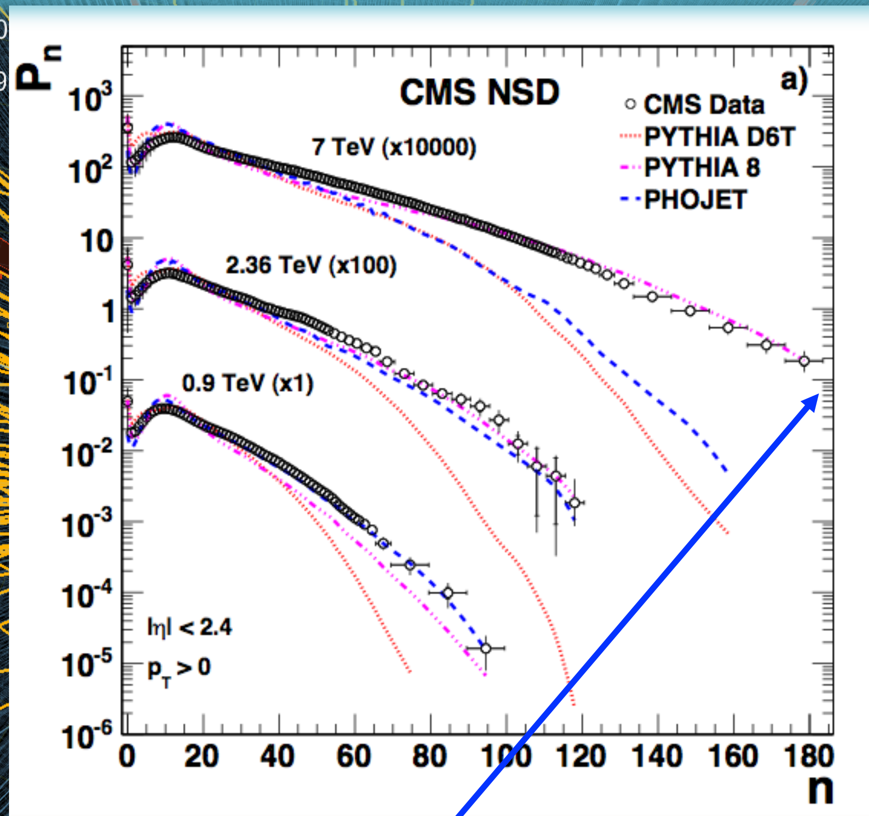
POETIC 3, March 4-8, 2013

High Multiplicity pp collisions



High Multiplicity pp collisions

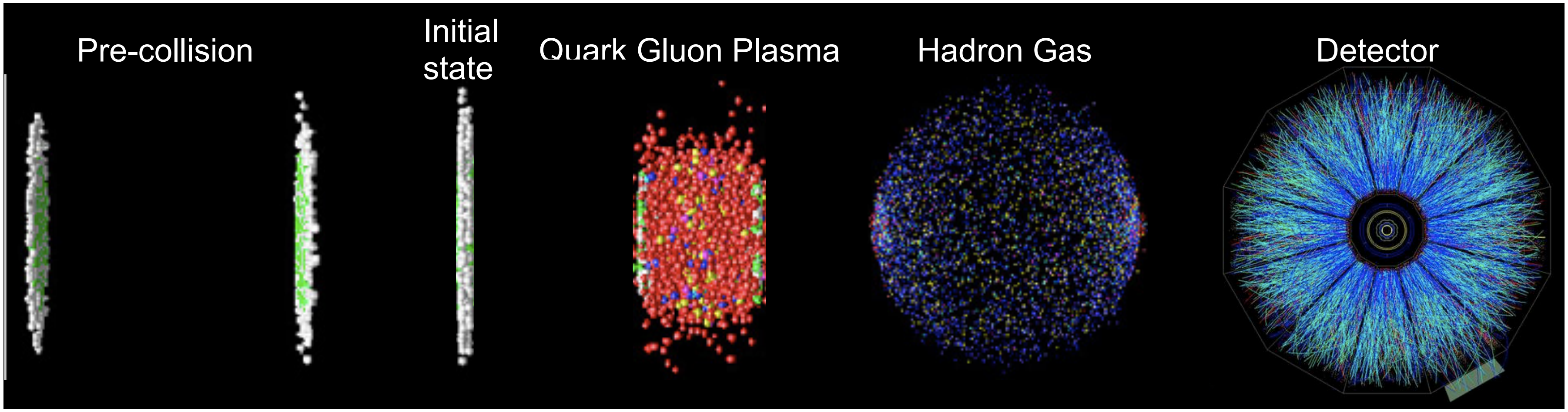
High Multiplicity events are rare in nature



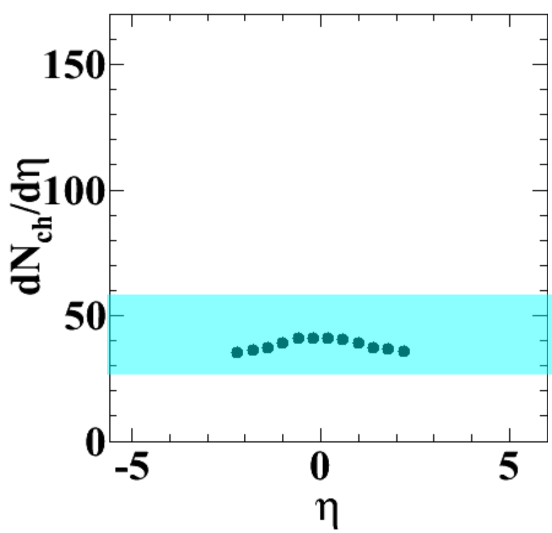
Very high particle density regime

Is there anything peculiar happening there?

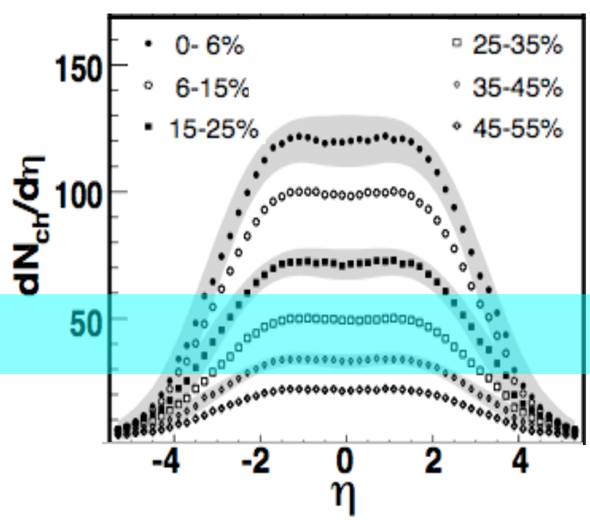
Relativistic Heavy Ion Collisions

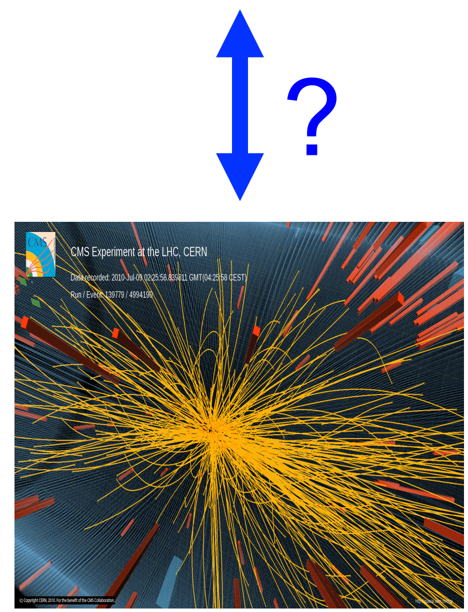


CMS pp 7TeV, N>110



PHOBOS CuCu 62.4GeV

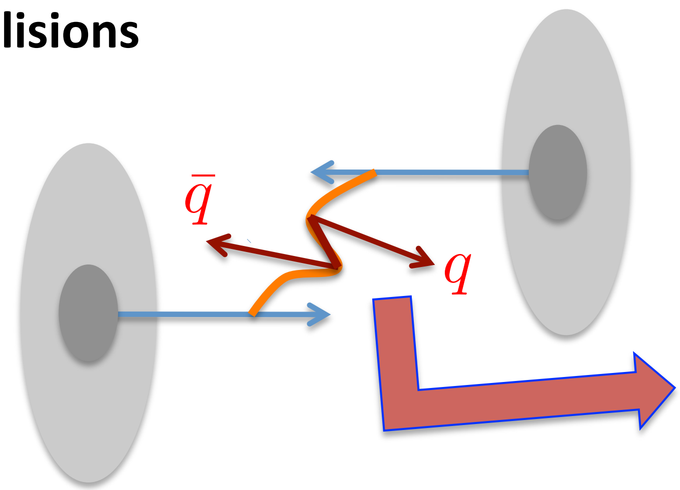




The p+p ridge

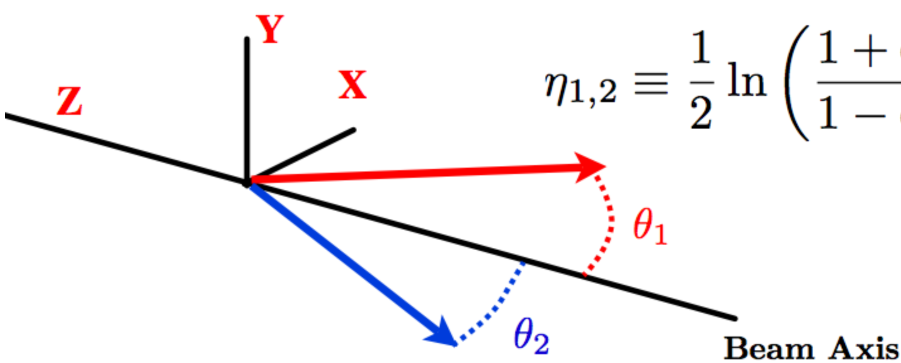
CMS reported a remarkable structure seen in two particle correlation spectrum as a function of angular variables Δη, ΔΦ in very high multiplicity p+p collisions

CMS, arXiv:1009.4122

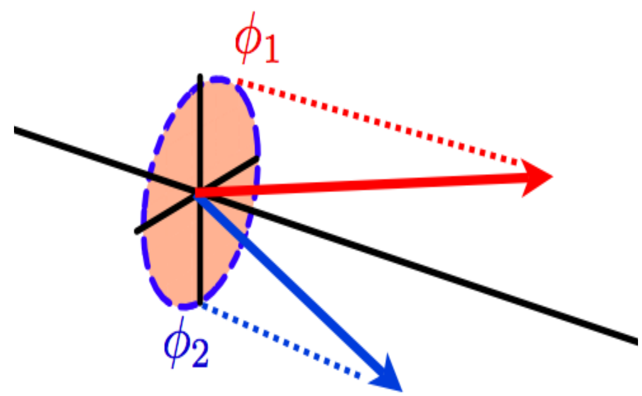


Back to back jet correlation in p+p

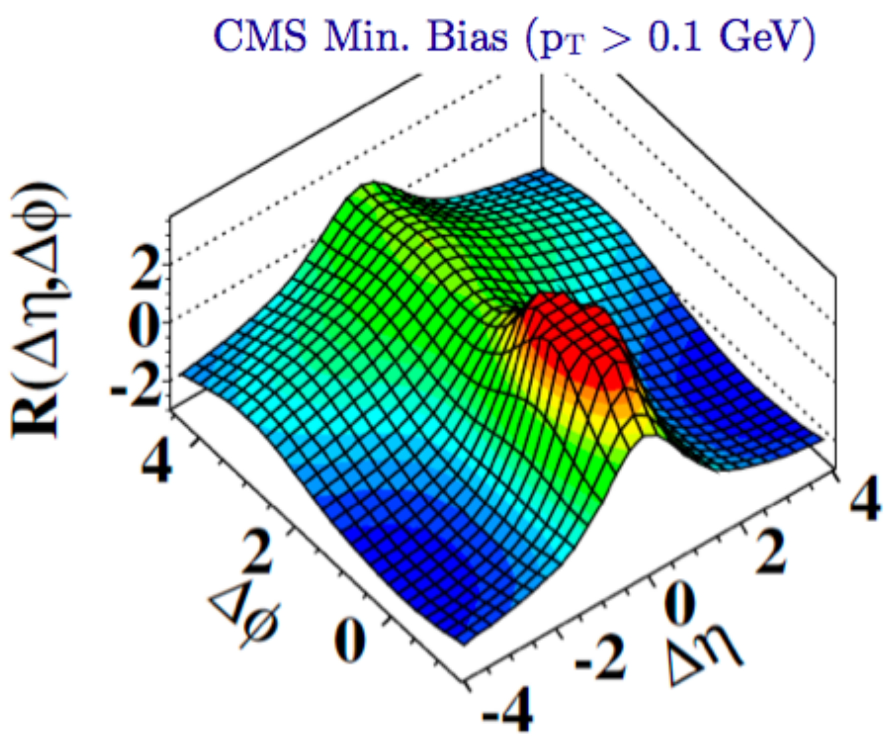
Collision Geometry:

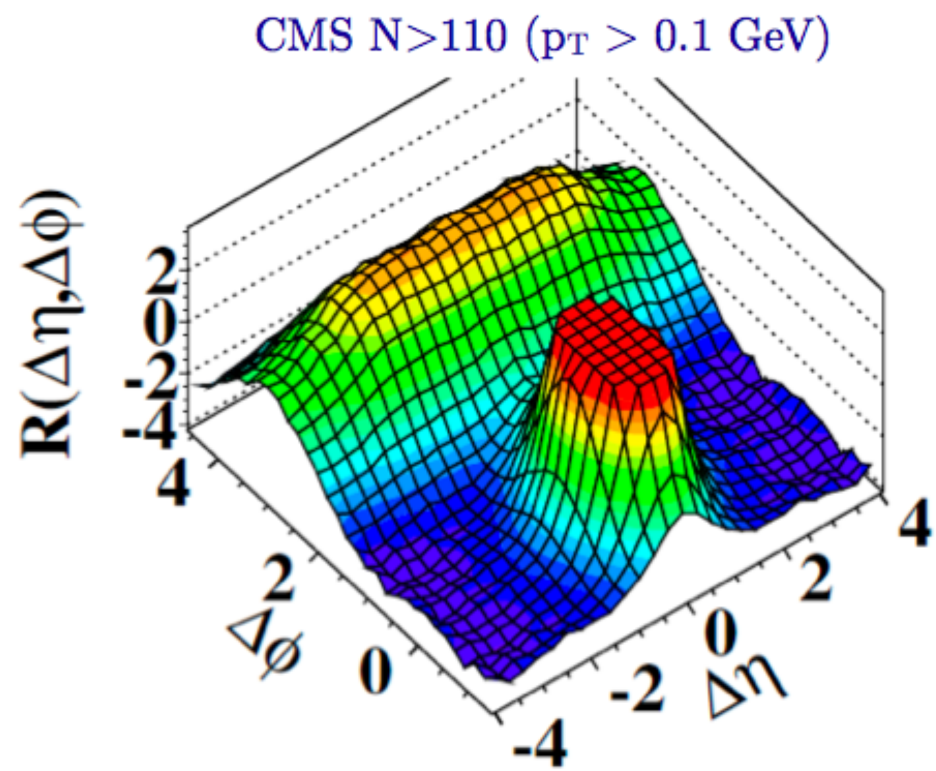


$$\eta_{1,2} \equiv \frac{1}{2} \ln \left(\frac{1 + \cos \theta_{1,2}}{1 - \cos \theta_{1,2}} \right)$$

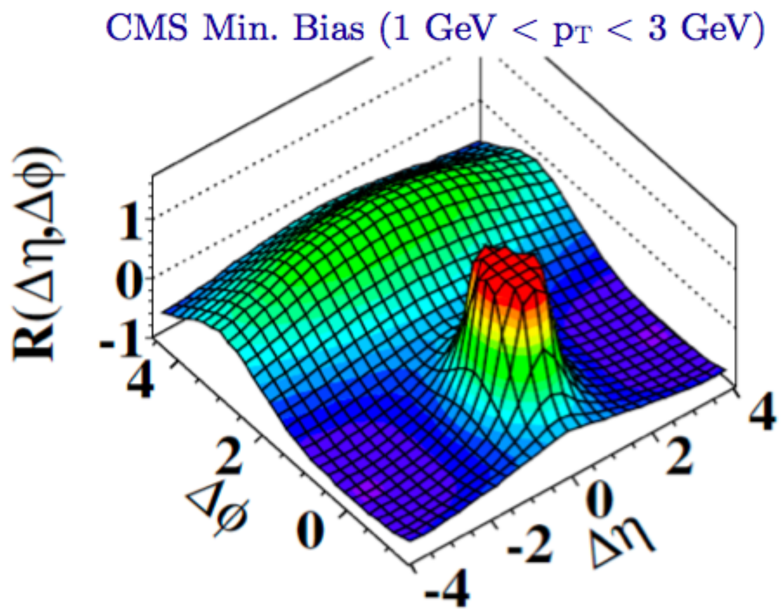


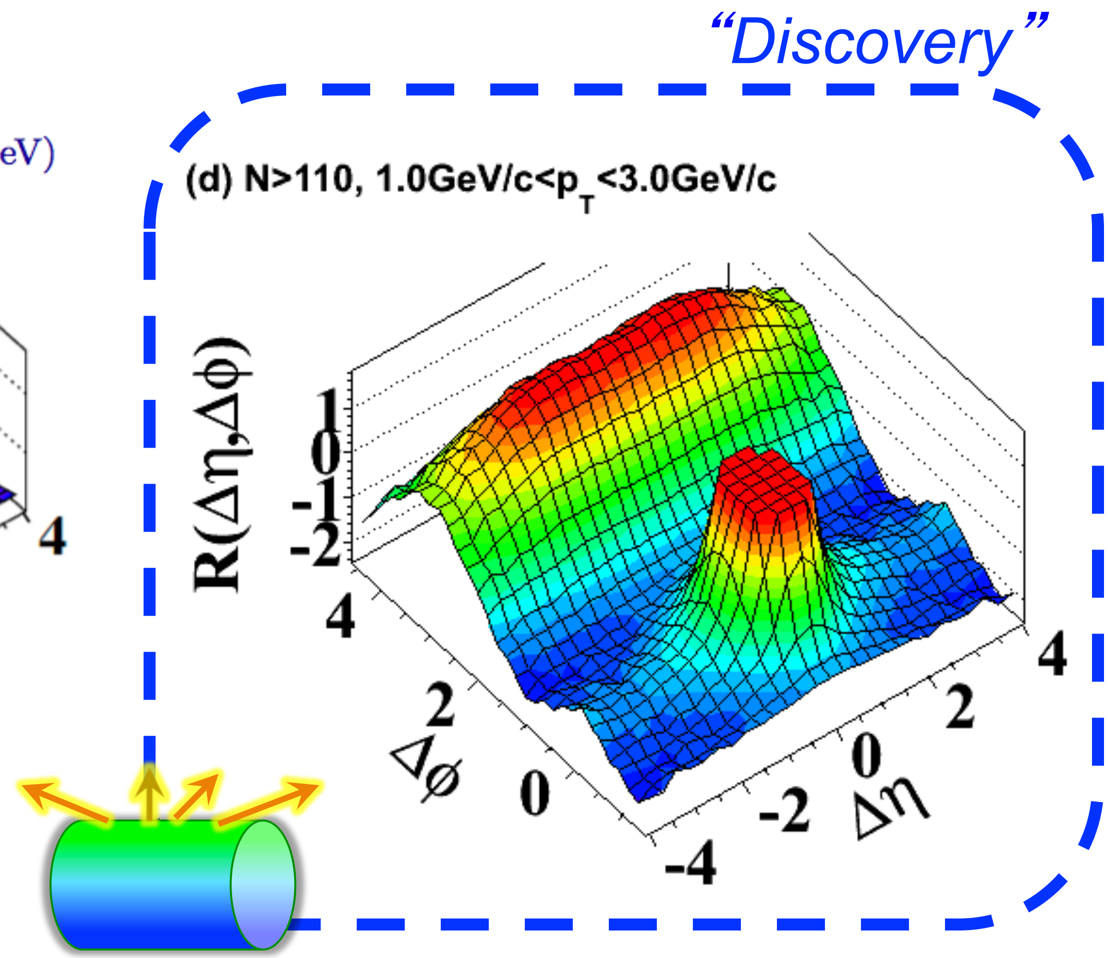
Two particle correlations: CMS results





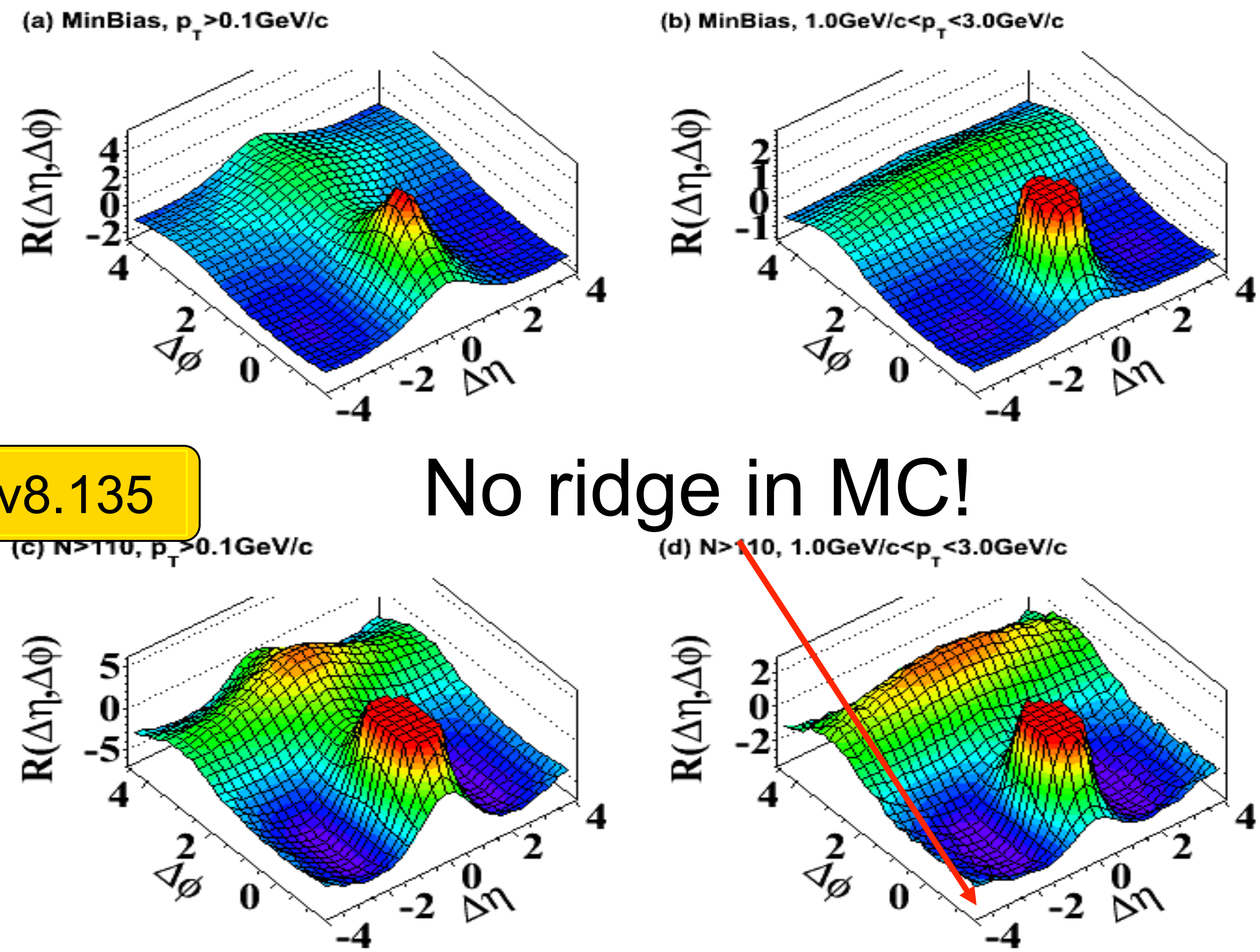
Two particle correlations: CMS results





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

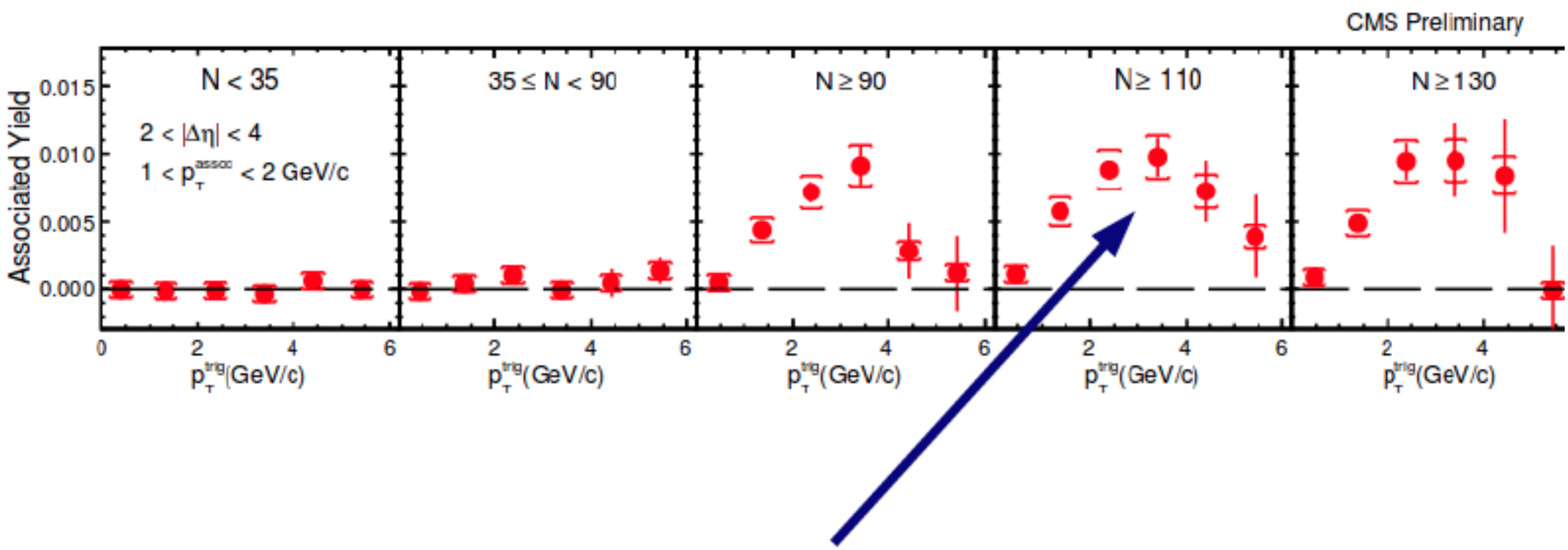
Comparing to MC models



PYTHIA8, v8.135

No ridge in MC!

The ridge



Evidence of a semi-hard scale in the data ?

See Inside

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

Scientific American, February (2011)

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

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"

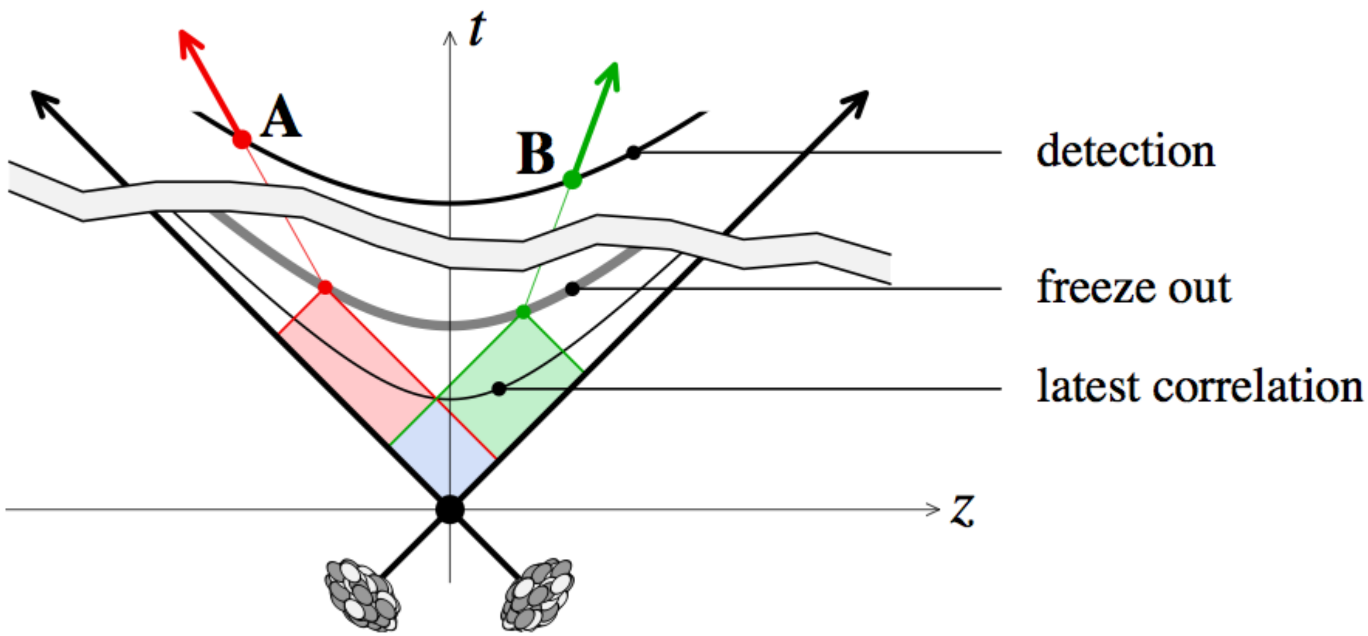
What's the underlying dynamics?

- 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 possibly a smoking gun for a fundamental feature of QCD -- gluon saturation

- In contrast, the A+A ridge is (nearly) entirely due to hydrodynamic flow of a nearly perfect fluid …

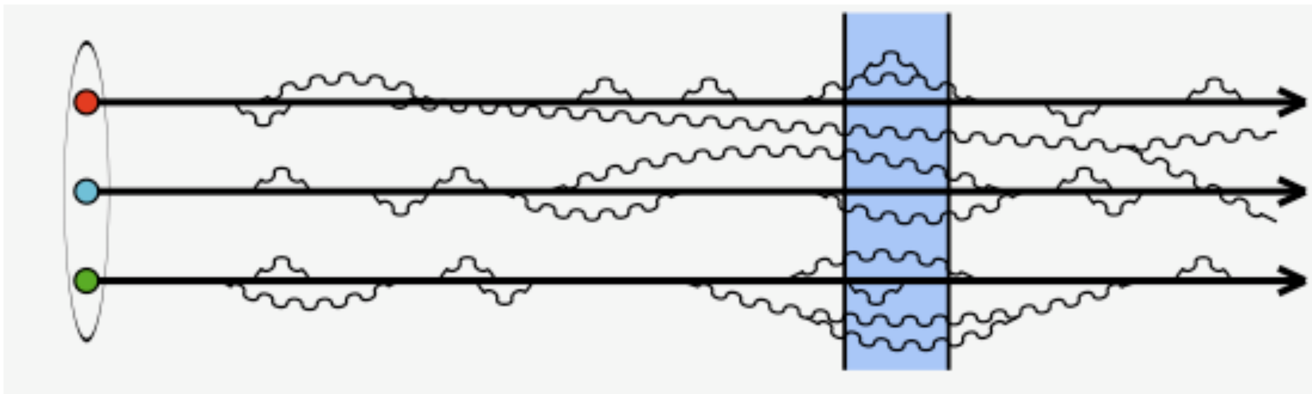
Long range rapidity correlations as a chronometer



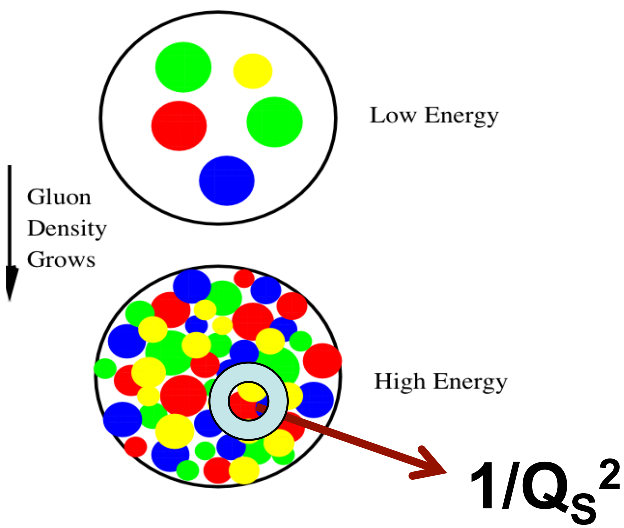
$$\tau \leq \tau_{\text{frz-out}} \exp\left(-\frac{1}{2}|y_A - y_B|\right)$$

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

Gluon Saturation in large nuclei: 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

|P>_pert ⟶ |P>_classical

"Gribov-Regge" limit of QCD

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

Wee parton correlations

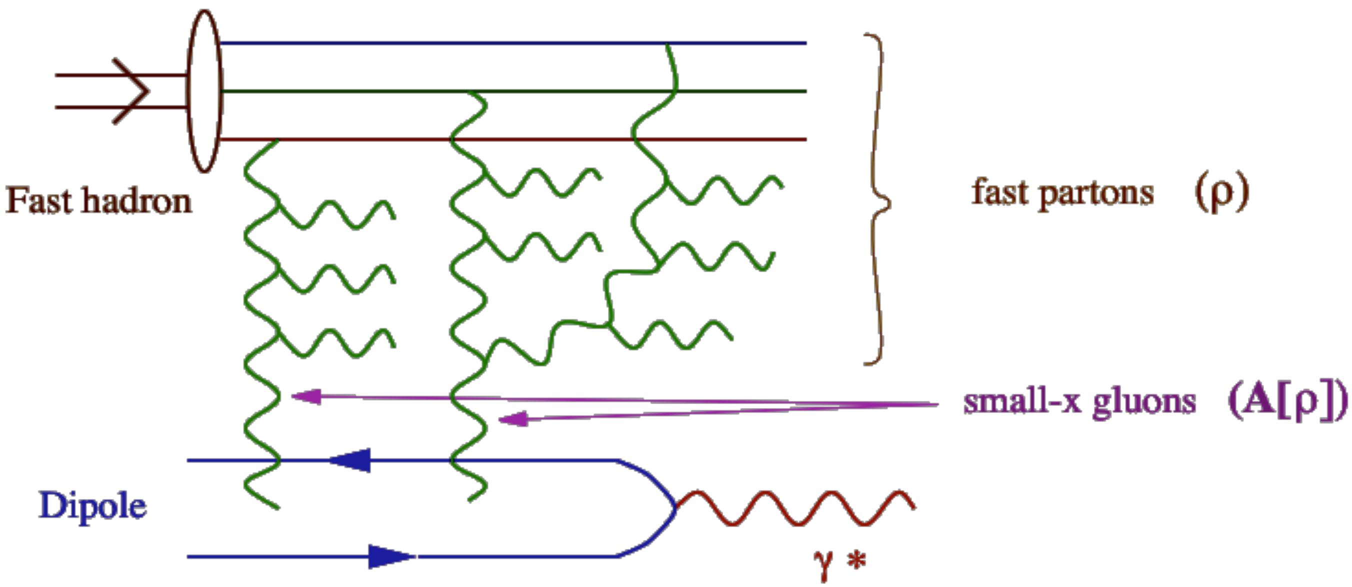
Brownian motion in functional space

"diffusion coefficient"

$$\frac{\partial W[\tilde{\rho}]}{\partial Y} = \mathcal{H}\, W[\tilde{\rho}] \qquad => \frac{\partial}{\partial Y} < O[\alpha] >_Y = \underbrace{< \frac{1}{2}\int_{x,y} \frac{\delta}{\delta \alpha_Y^a(x)} \chi_{x,y}^{ab} \frac{\delta}{\delta \alpha_Y^b(y)} O[\alpha] >_Y}_{\mathcal{H}_{\rm JIMWLK}}$$

"time"

$$\alpha = \frac{\tilde{\rho}}{\nabla_\perp^2}$$



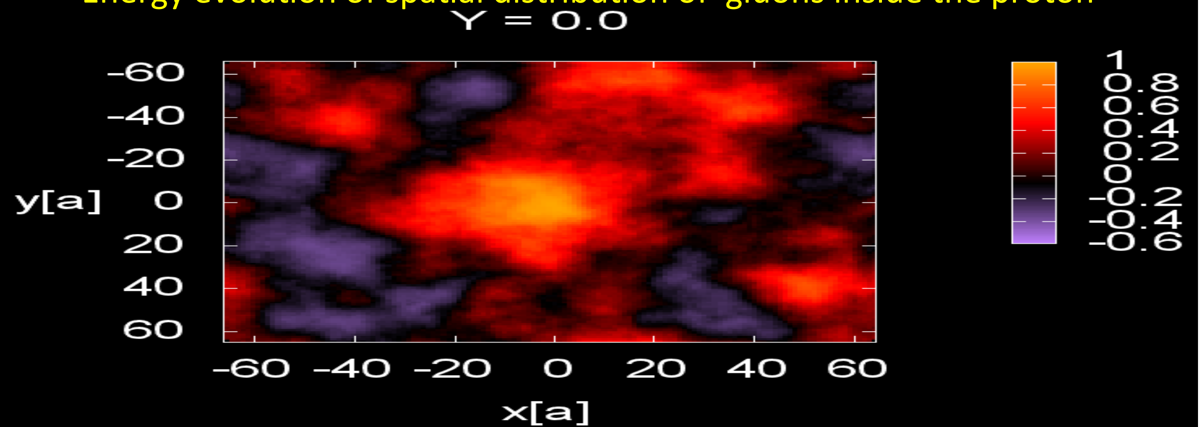
CGC Effective Theory: B-JIMWLK hierarchy of correlators

$$\frac{\partial}{\partial Y} < O[\alpha] >_Y = < \frac{1}{2} \int_{x,y} \frac{\delta}{\delta \alpha_Y^a(x)} \chi_{x,y}^{ab} \frac{\delta}{\delta \alpha_Y^b(y)} O[\alpha] >_Y$$

"time"

"diffusion coefficient"

Energy evolution of spatial distribution of gluons inside the proton



Dipole correlator of Light-like Wilson lines Tr(V(0,0)V^dagger (x,y))

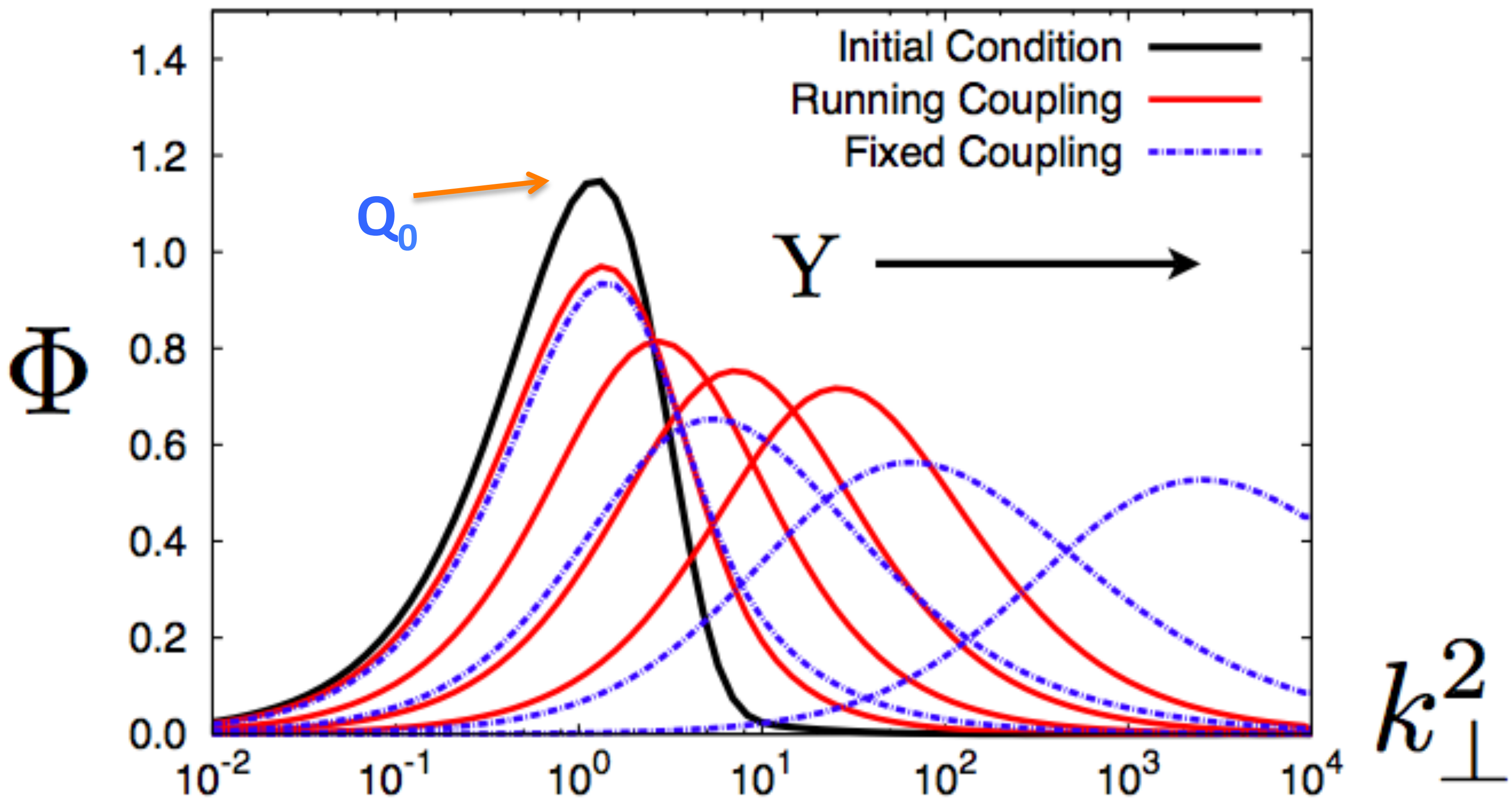
Rummukainen,Weigert (2003)

Dumitru,Jalilian-Marian,Lappi, Schenke,RV, PLB706 (2011)219

B-JIMWLK eqn. for dipole correlator – universal quantity whose (very good) mean field solution is the BK equation

$$\frac{\partial}{\partial Y} \langle \mathrm{Tr}(V_x V_y^\dagger) \rangle_Y = -\frac{\alpha_S N_c}{2\pi^2} \int_{z_\perp} \frac{(x_\perp - y_\perp)^2}{(x_\perp - z_\perp)^2 (z_\perp - y_\perp)^2} \langle \mathrm{Tr}(V_x V_y^\dagger) - \frac{1}{N_c} \mathrm{Tr}(V_x V_z^\dagger)\ \mathrm{Tr}(V_z V_y^\dagger) \rangle_Y$$

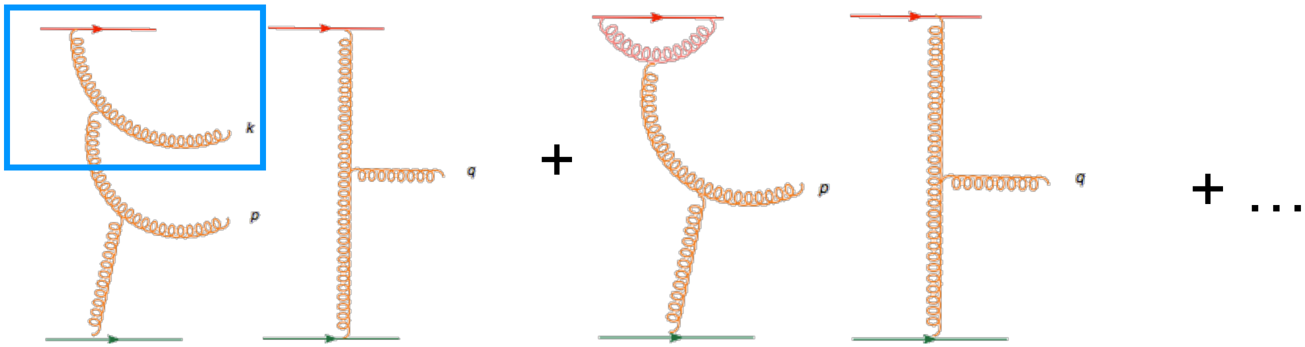
Solution of the Balitsky-Kovchegov equation



The saturated proton: Glasma graphs -I

Gelis, Lappi, RV, arXiv: 0807.1306

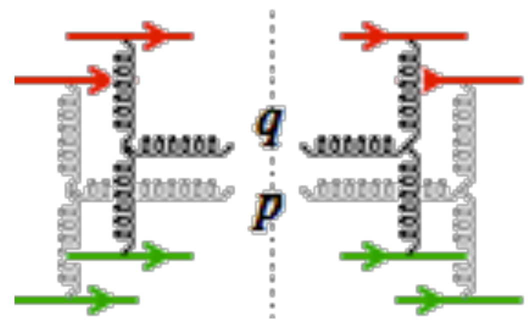
RG evolution:



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

= LO graph with evolved sources

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

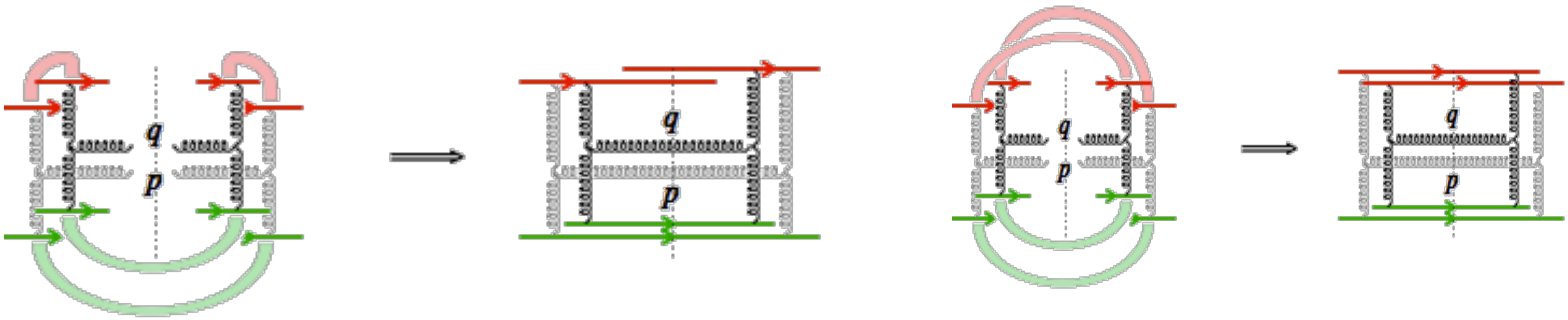


$$\langle \frac{dN_2}{d^3p\, d^3q} \rangle_{\rm LLogs} = \int [d\rho_1][d\rho_2] W_{Y_1}[\rho_1]\, W_{Y_2}[\rho_2]\, \frac{dN}{d^3p}\Big|_{\rm LO} \frac{dN}{d^3q}\Big|_{\rm LO}$$

From solns. Of Yang-Mills eqns.with two light cone sources
Includes all mult. scat. contributions $(g\rho_1)^n$ and $(g\rho_2)^n$

The saturated proton: two particle correlations

Correlations are induced by color fluctuations that vary event to event –
for Gaussian weight functionals in ρ, have color screening radius ~ $1/Q_S$



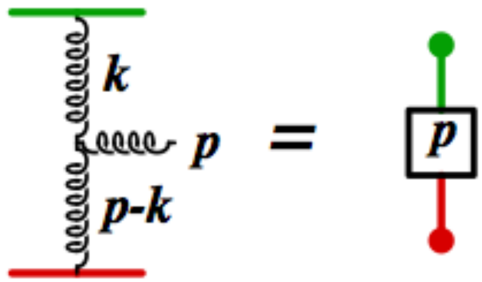
"Glasma graphs" : generate long range rapidity correlations, are suppressed for $Q_S \ll p_T$ -- high p_T, large x or large impact parameters.

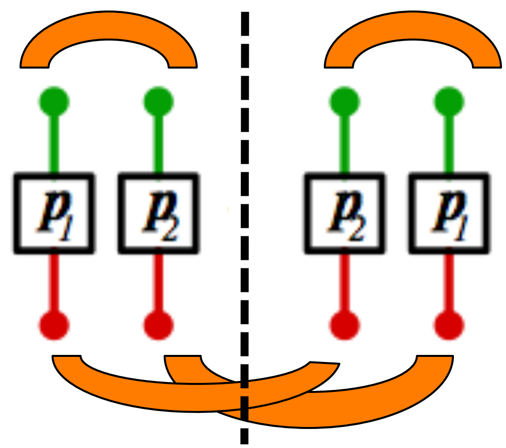
Effective coupling of sources to fields with $k_T \leq Q_S$ = 1/g ("saturation")
- changes from g to 1/g for high occupancy fields

Glasma graphs enhanced 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



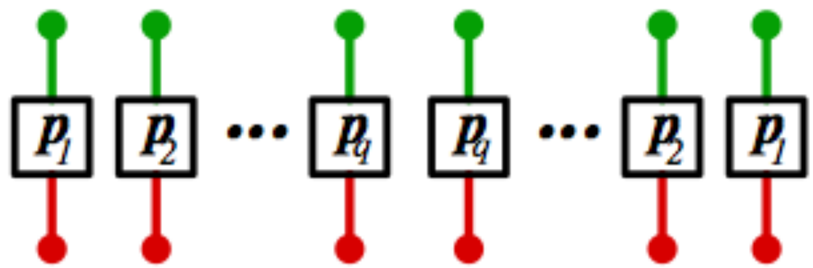


Glasma flux tube picture: two particle correlations proportional to ratio $1/Q_S^2$ / S_T

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

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

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

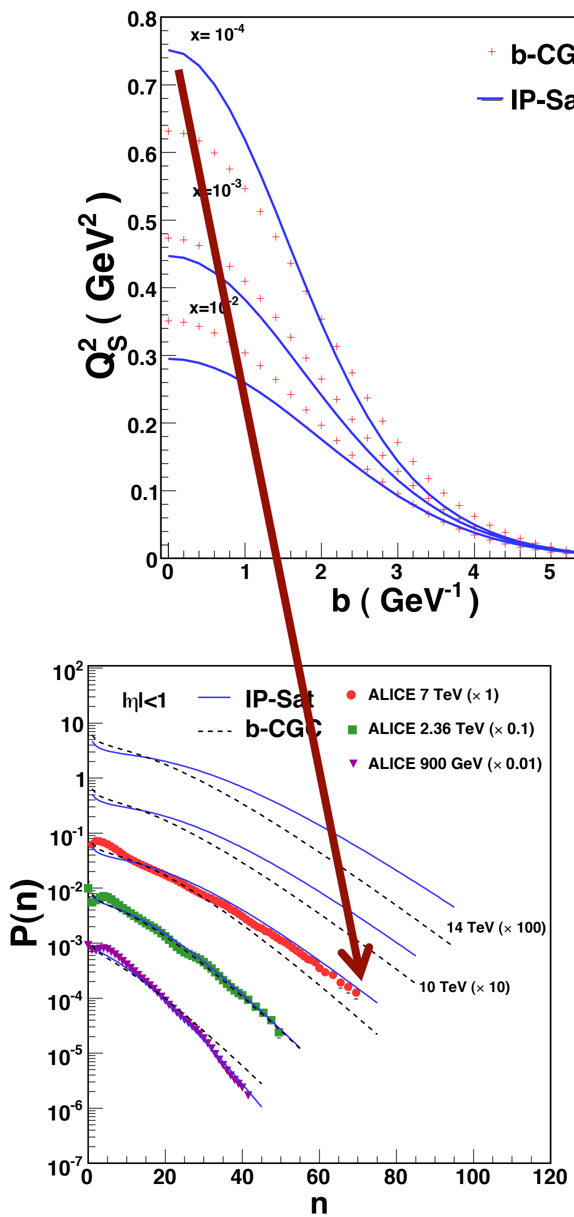
k = 1 : Bose-Einstein

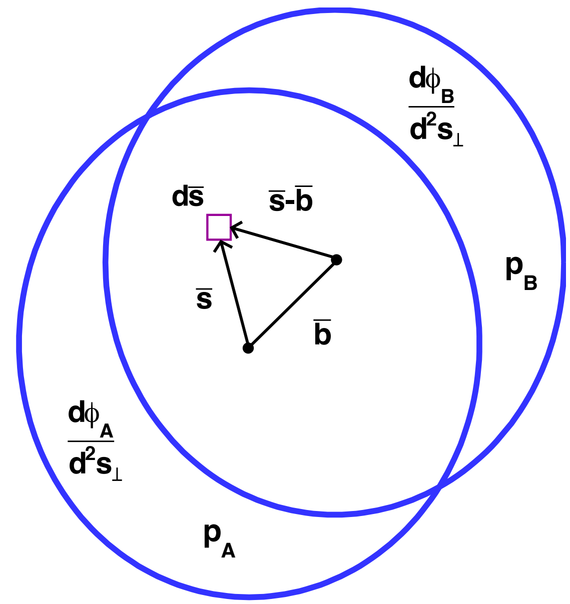
k = ∞ : Poisson

Yang-Mills computation shows picture is robust for 2 part. Corr. and gives ζ ~ 1/6

Lappi, Srednyak, RV, 0911.2068
Schenke, Tribedy, RV, 1206.6805

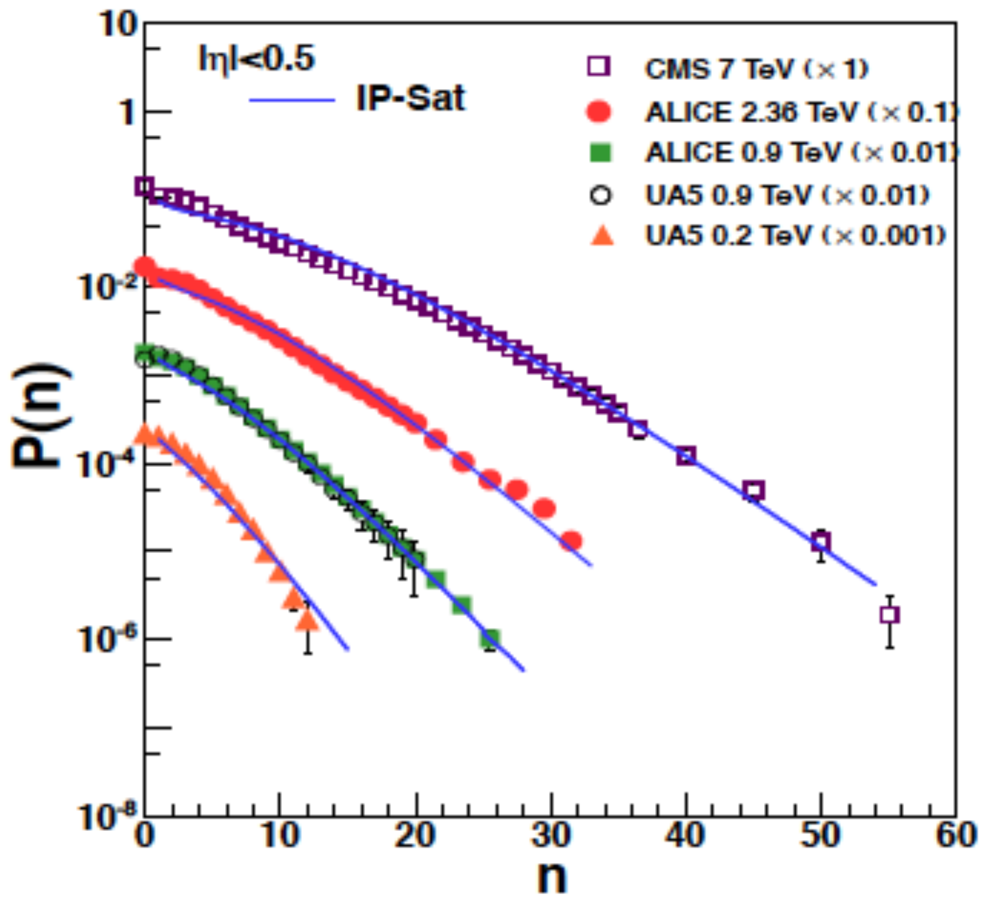
High multiplicity events in p+p





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

N-particle Glasma correlations describe LHC multiplicity data

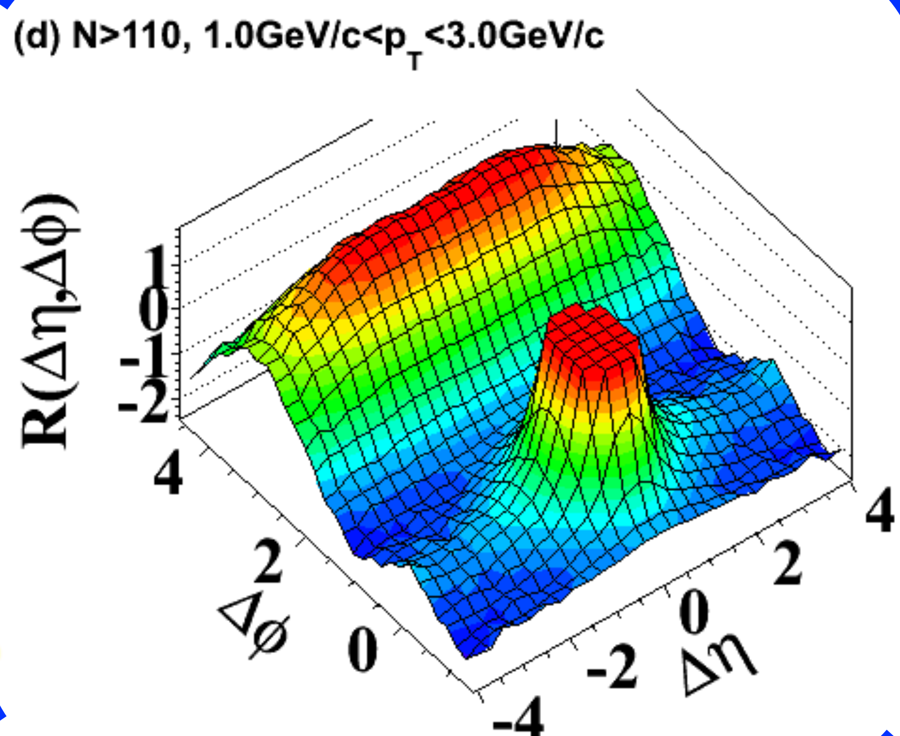


Tribedy, RV
1112.2445

Approx: k_T factorization; more detailed YM treatment in progress

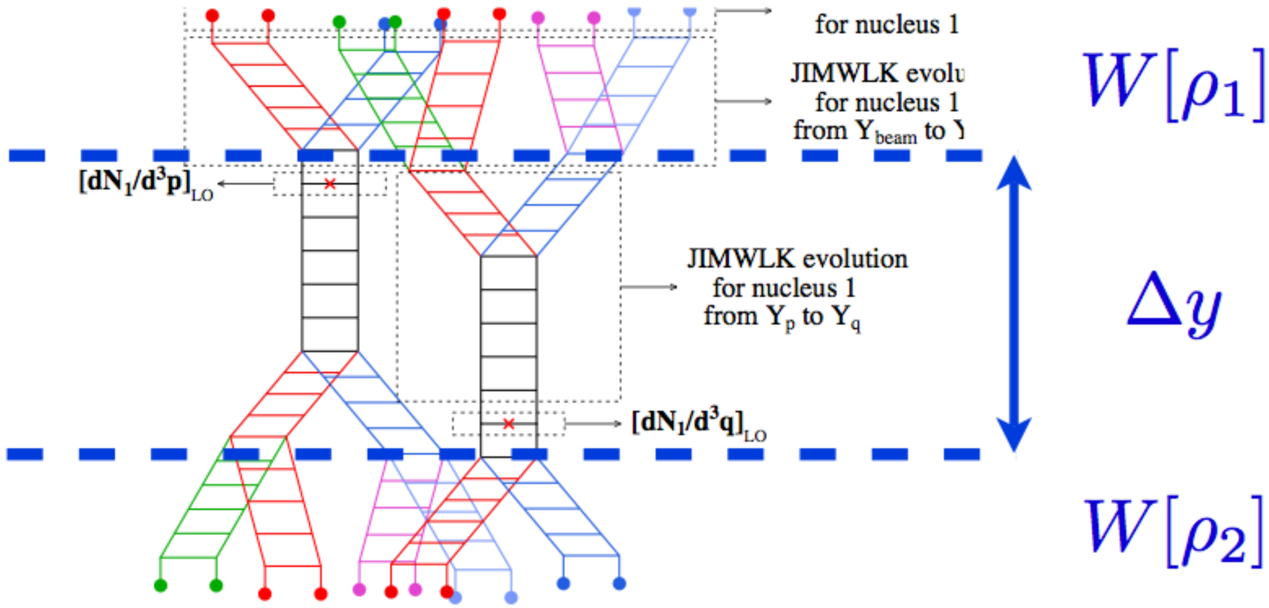
Back to the near side ridge in high multiplicity p+p collisions

"Discovery"



Long range di-hadron correlations

Gelis,Lappi,RV (2009)



$$\left\langle \frac{dN_2}{d^2\mathbf{p}_\perp dy_p d^2\mathbf{q}_\perp dy_q} \right\rangle_{\rm LLog} = \int [D\rho_1^p(\mathbf{x}_\perp) D\rho_2^p(\mathbf{x}_\perp) D\rho_1^q(\mathbf{x}_\perp) D\rho_2^q(\mathbf{x}_\perp)]$$

$$\times Z_{y_p}[\rho_1^p]\, G_{y_p,y_q}[\rho_1^p,\rho_1^q]\, Z_{y_q}[\rho_2^q]\, G_{y_q,y_p}[\rho_2^q,\rho_2^p]$$

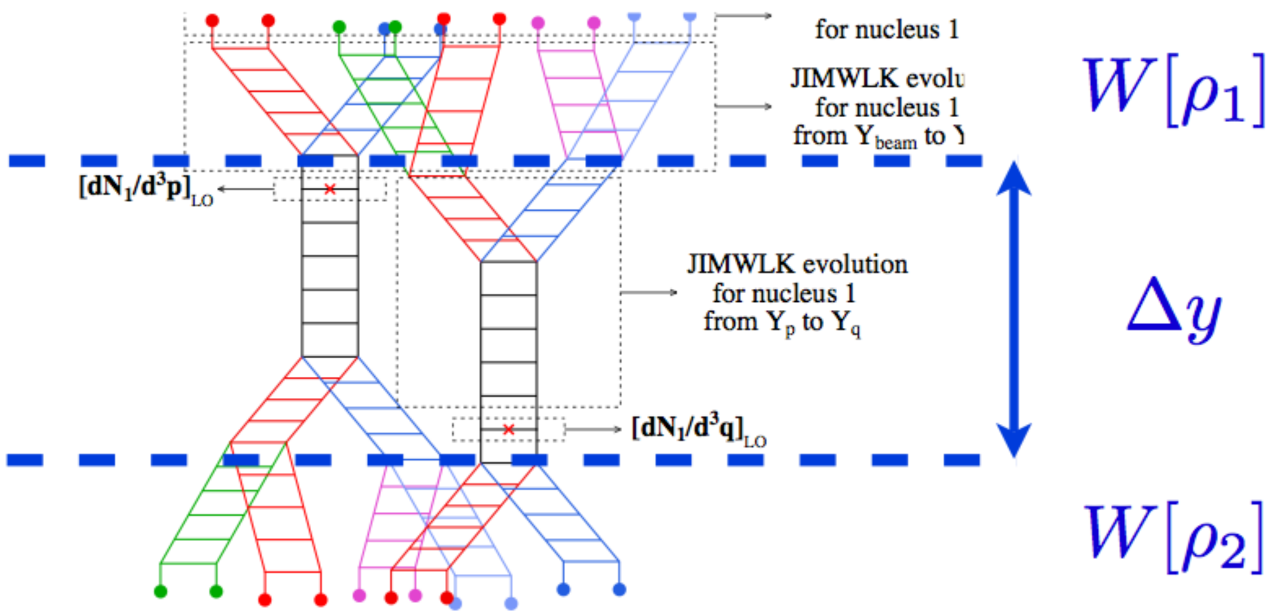
$$\times \left. \frac{dN_1\,[\rho_1^p,\rho_2^p]}{d^2\mathbf{p}_\perp dy_p}\right|_{\rm LO} \left. \frac{dN_1\,[\rho_1^q,\rho_2^q]}{d^2\mathbf{q}_\perp dy_q}\right|_{\rm LO} .$$

Simplify using "Gaussian truncation" approximation to JIMWLK

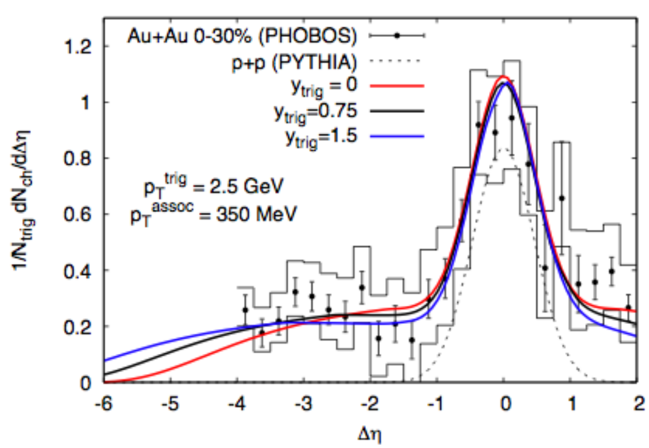
Dusling,Gelis,Lappi,RV:0911.2720

Long range di-hadron correlations

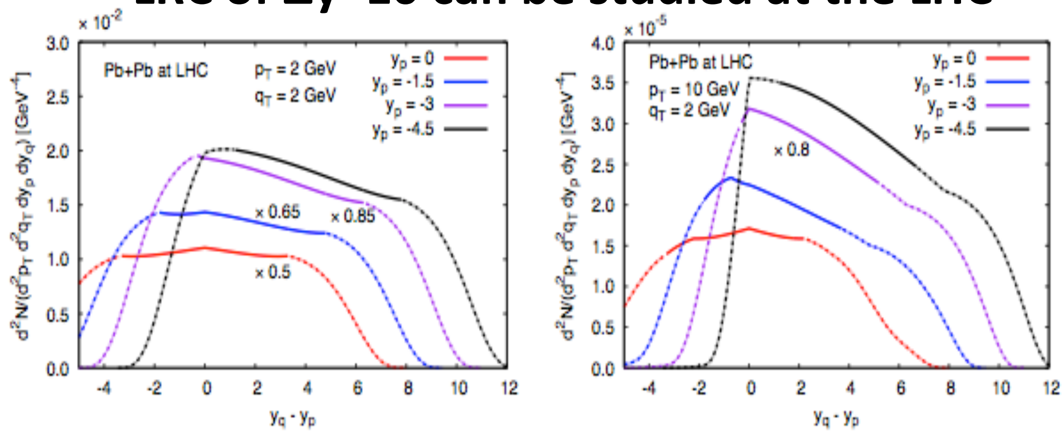
Gelis,Lappi,RV (2009)



Dusling,Gelis,Lappi,RV, arXiv:0911.2720



LRC of Δy~10 can be studied at the LHC



Nearside long range di-hadron correlations

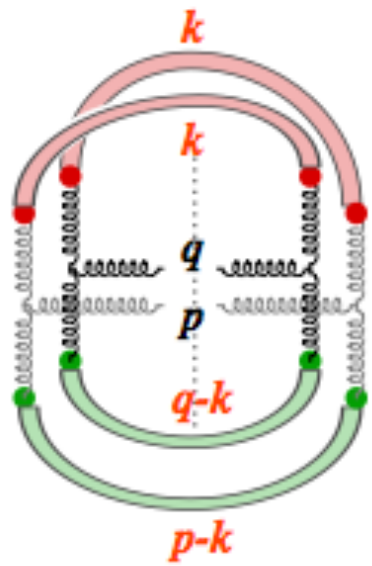
Dumitru,Dusling,Gelis,Jalilian-Marian,Lappi,RV, arXiv:1009.5295

RG evolution of two particle correlations C(p,q) expressed in terms of "unintegrated gluon distributions" in the proton

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

Proton 1

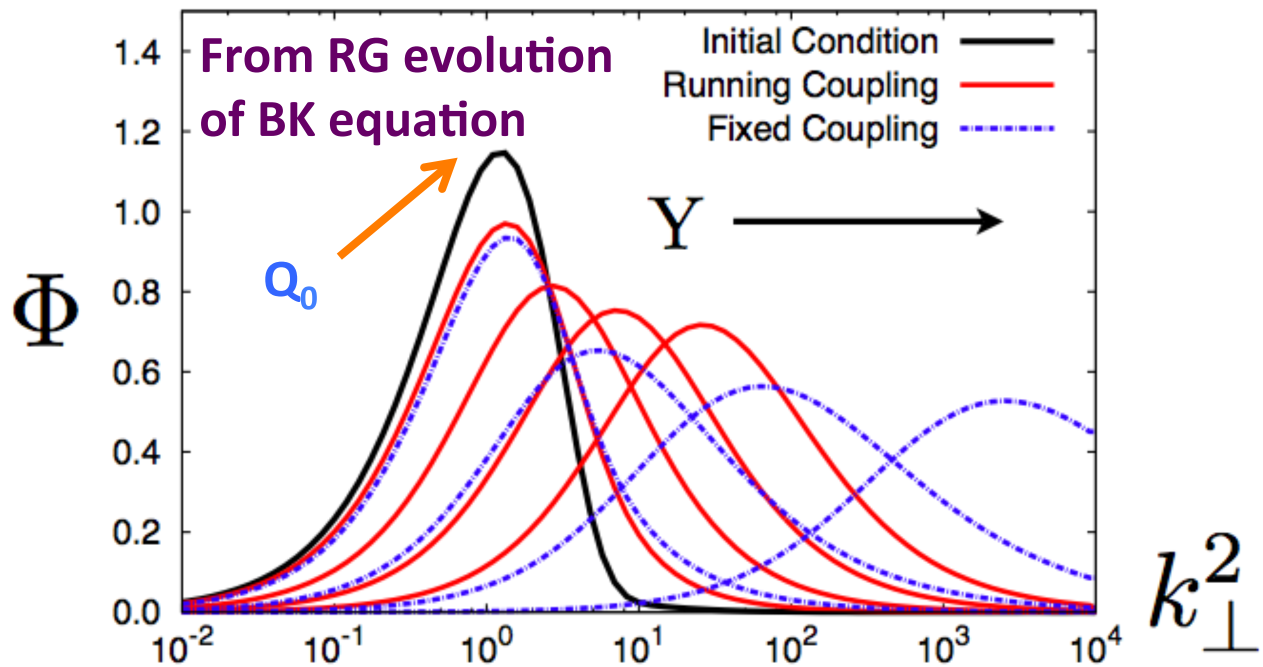
Proton 2



These contributions are of order α_S^6/N_c^2 in min. bias events- in high multiplicity events power counting changes to $1/\alpha_S^2\, N_c^2$

Collimated yield ?

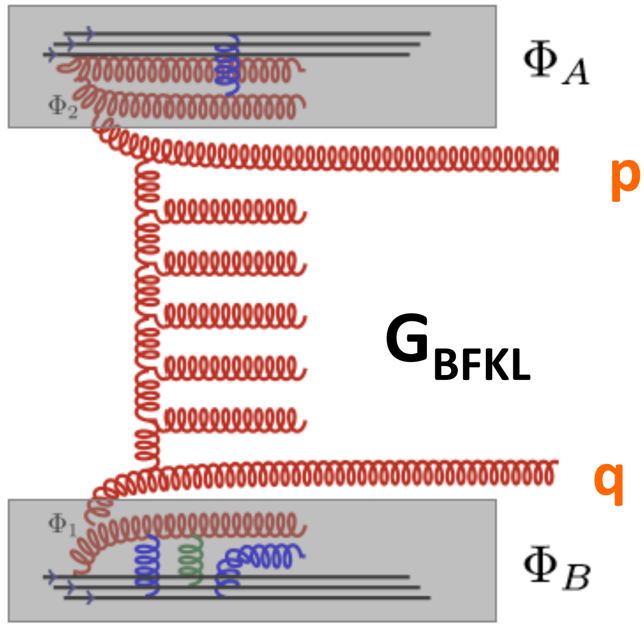
$$C(\mathbf{p},\mathbf{q}) \propto \frac{g^4}{\mathbf{p}_\perp^2\mathbf{q}_\perp^2}\int d^2\mathbf{k}_{1\perp}\,\Phi^2_{A_1}(y_p,\mathbf{k}_{1\perp})\Phi_{A_2}(y_p,\mathbf{p}_\perp-\mathbf{k}_{1\perp})\Phi_{A_2}(y_q,\mathbf{q}_\perp-\mathbf{k}_{1\perp})$$
$$+ \quad \text{permutations}$$



Dominant contribution from $|p_T-k_T| \sim |q_T-k_T| \sim |k_T| \sim Q_S$

This gives a collimation for $\Delta\Phi \approx 0$ and π

Angular structure from (mini-) Jet radiation



$$C_{\rm dijet}(\mathbf{p},\mathbf{q}) \propto \Phi_A \otimes \Phi_B \otimes G_{\rm BFKL}$$

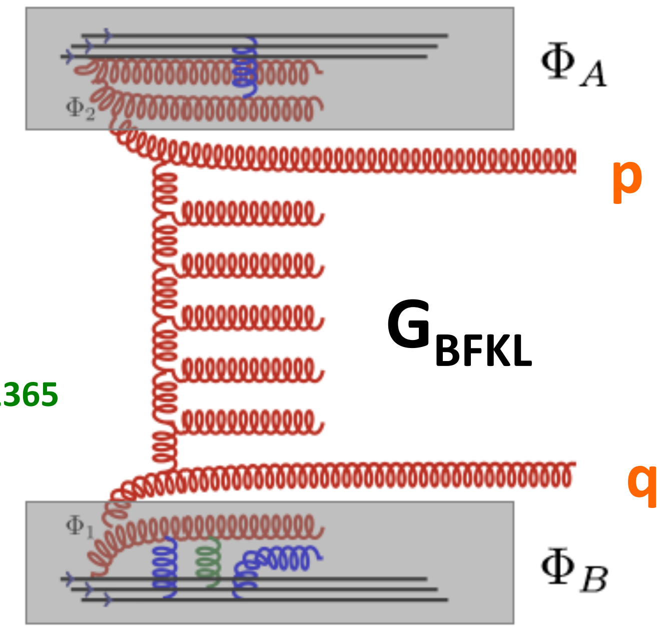
Mini-jets: O (1) in high multiplicity events
- give an angular collimation, albeit only at $\Delta\Phi \cong \pi$

CMS results also test the structure of bremsstrahlung radiation between jets

Angular structure from (mini-) Jet radiation

Structure seen at NLLx

Colferai,Schwennsen,Szymanowski,Wallon, 1002.1365
Caporale,Ivanov,Murdaca,Papa, 1209.6233



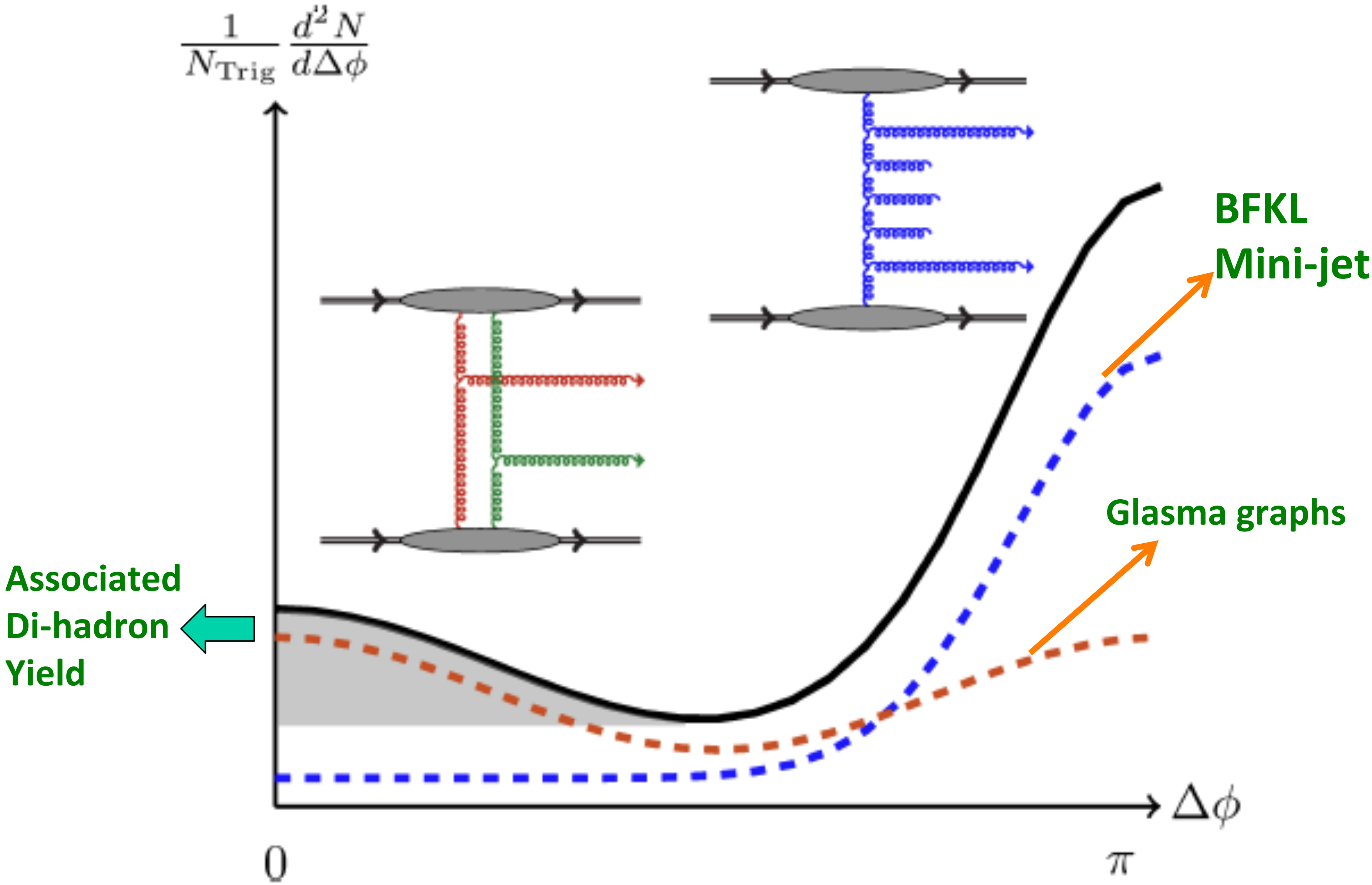
$$C_{\rm dijet}(\mathbf{p},\mathbf{q}) \propto \Phi_A \otimes \Phi_B \otimes G_{\rm BFKL}$$

from BK

LLx BFKL+r.c

NLLx BFKL corrections for <cos(Δϕ)> and <cos(2 Δϕ)> are 10-30%

Anatomy of long range di-hadron collimation



Quantitative description of pp ridge

Dusling,RV, 1201.2658, PRL

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

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

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

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

Dependence on transverse area cancels in ratio…

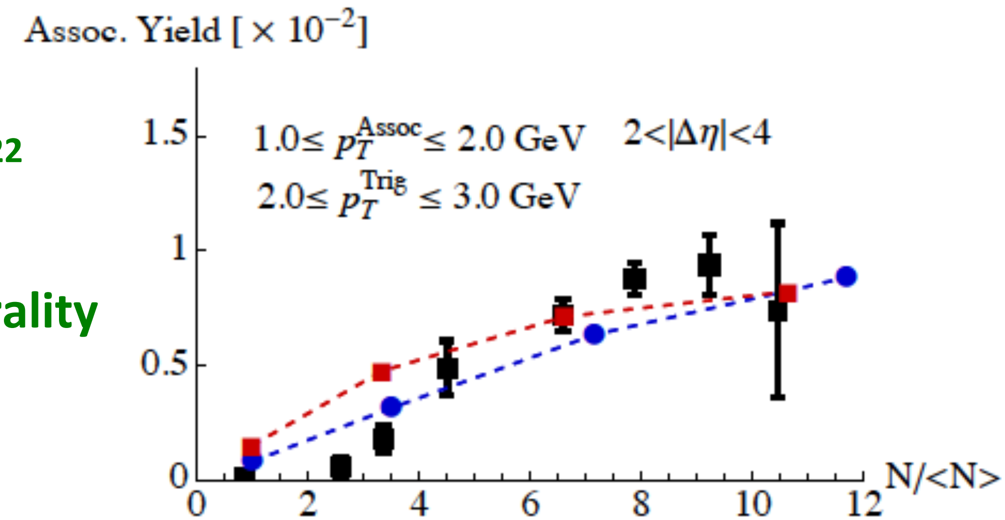
Subtracts any pedestal "phi-independent" correlation

Quantitative description of pp ridge

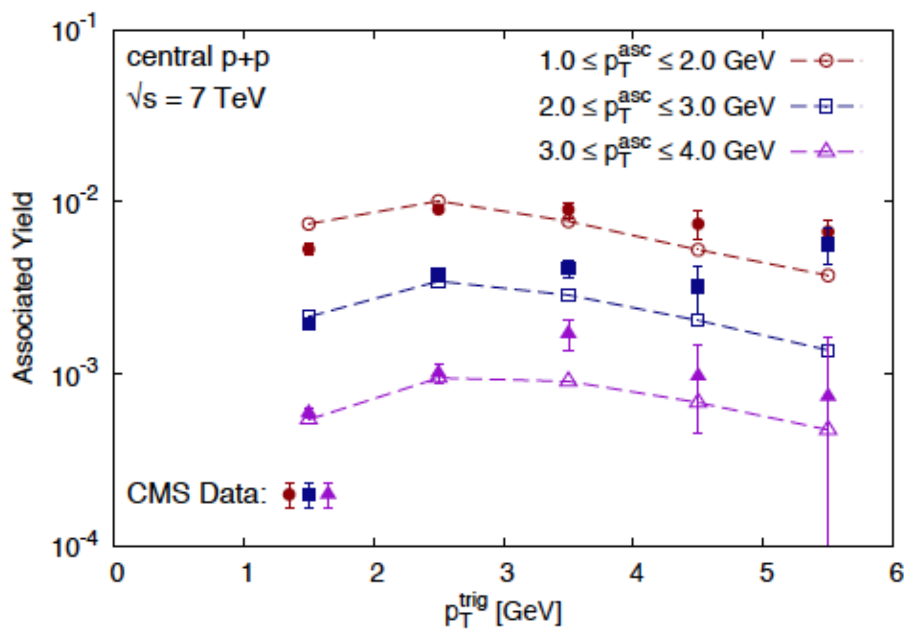
Dusling,RV, PRL 108 (2012)26201
& 1210.3890

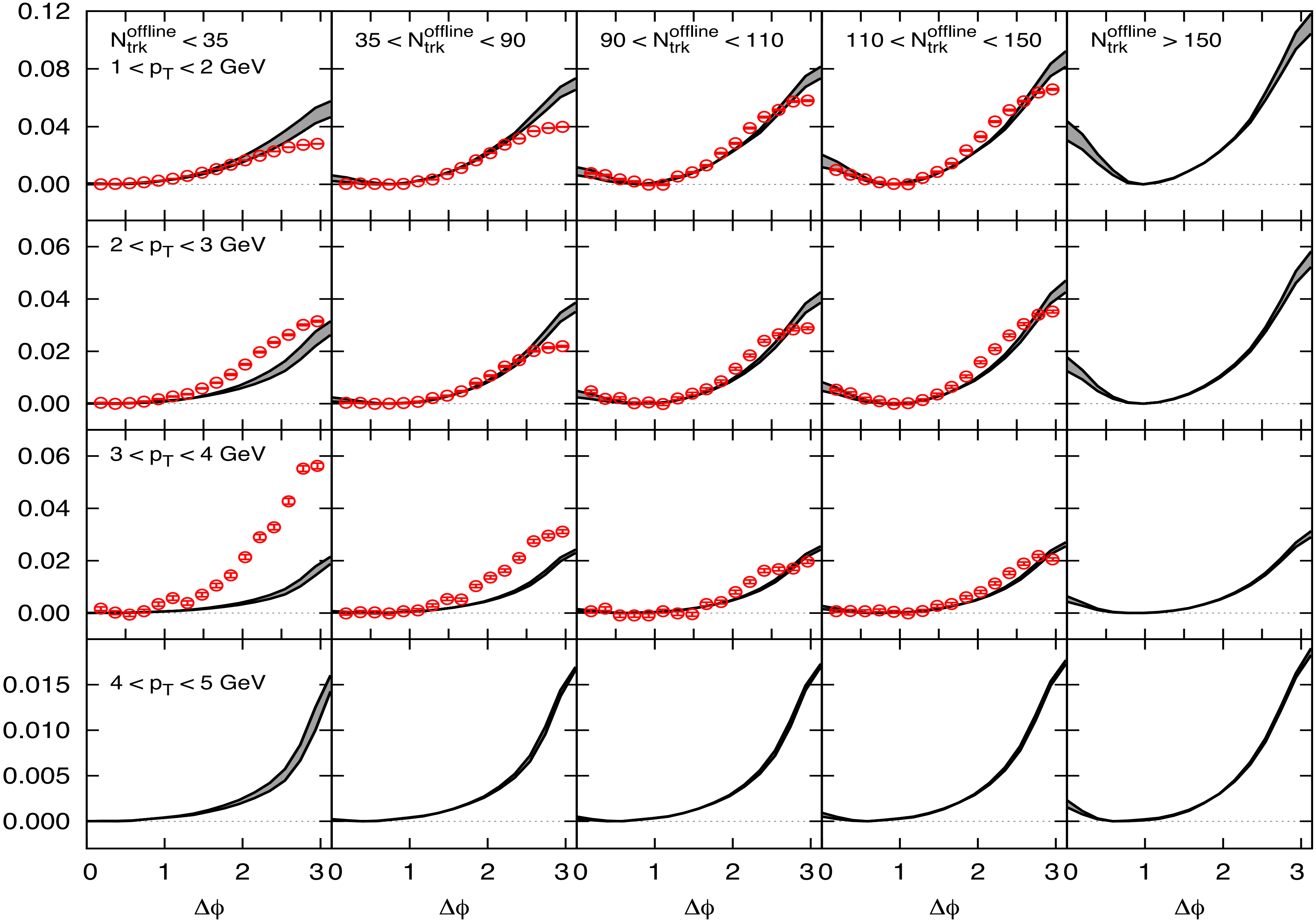
CMS data arXiv:1009.4122

Assoc. yield with centrality

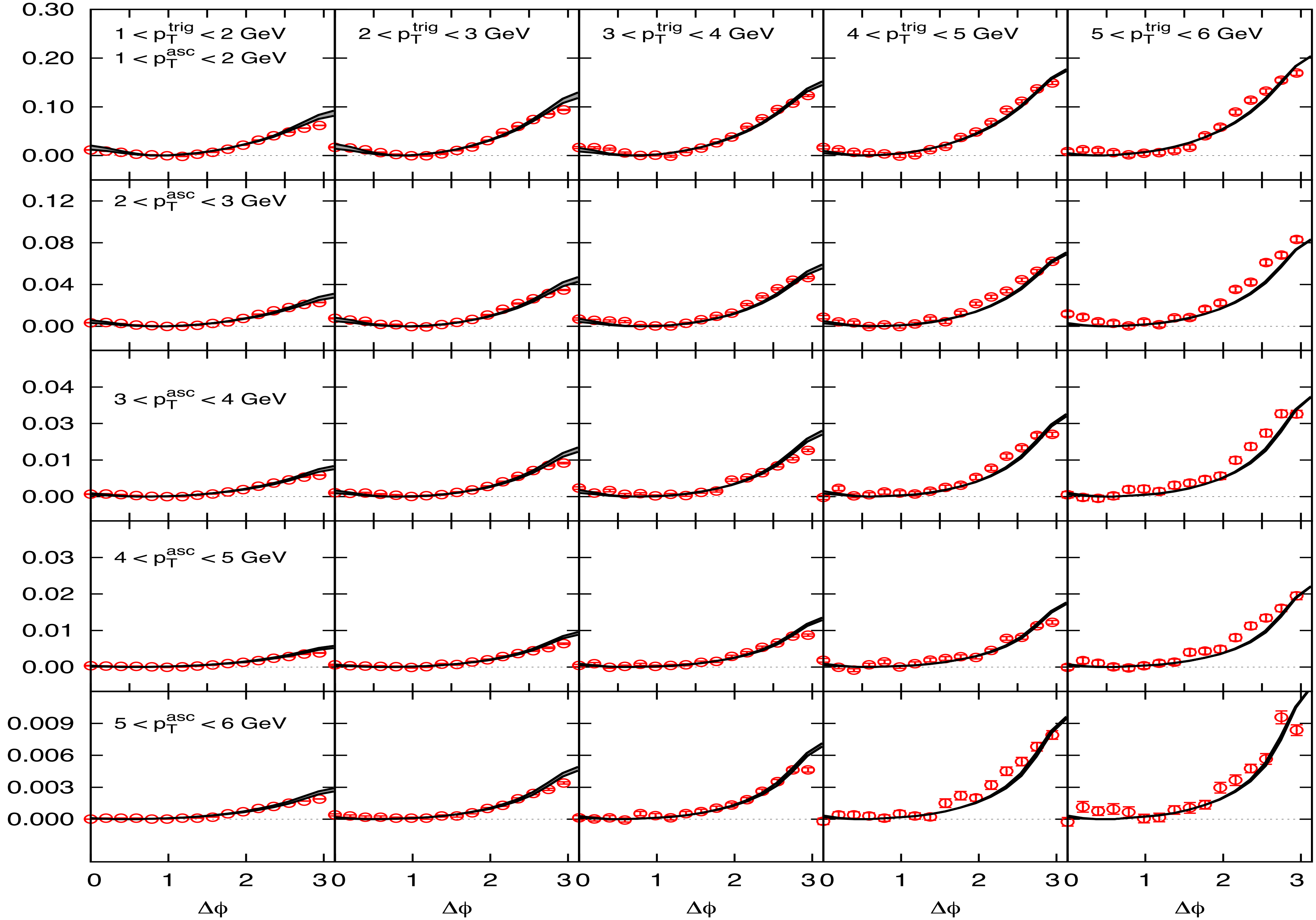


Assoc. yield with p_T^{Trig}

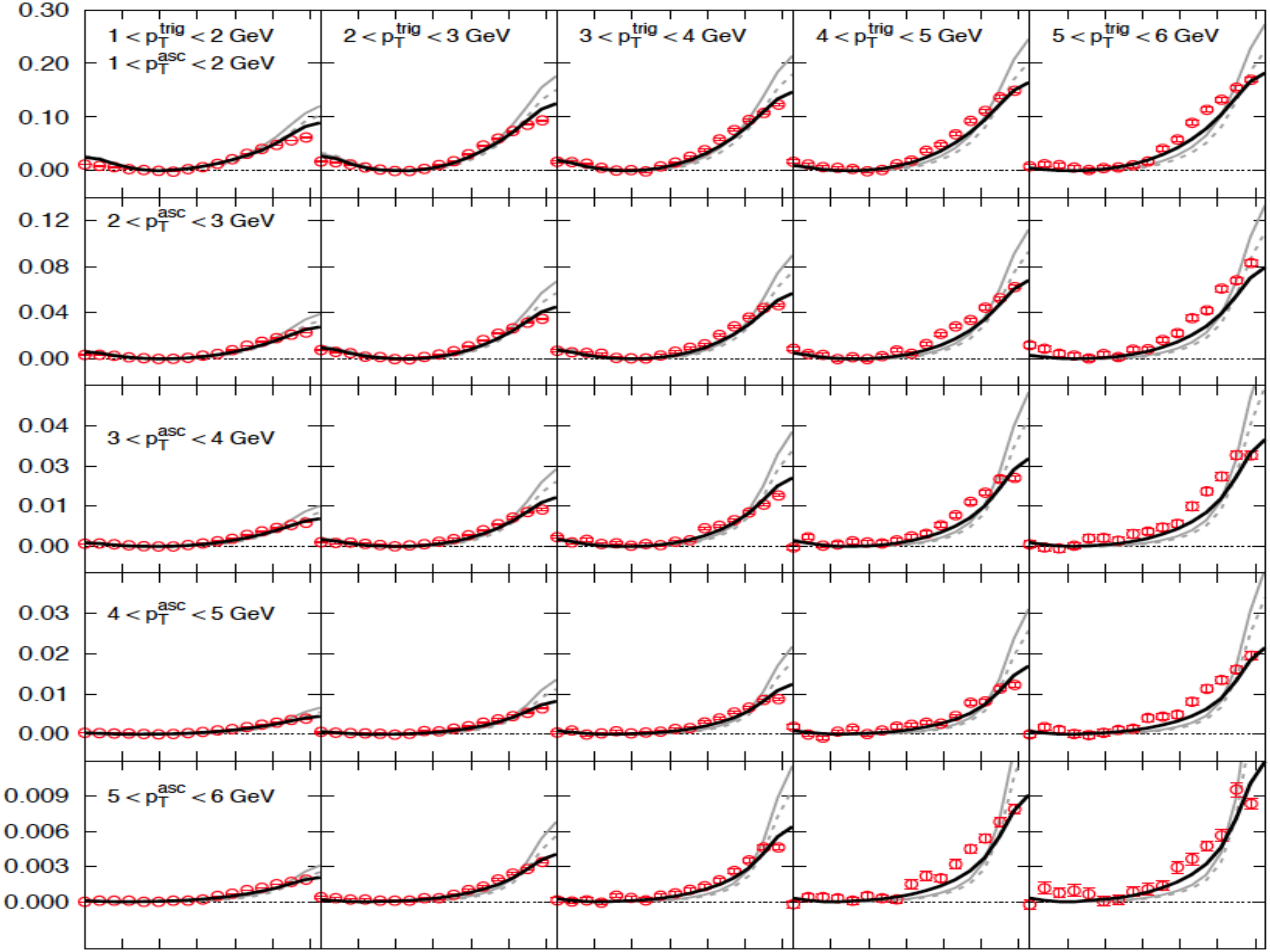




$N_{trk}^{offline} < 35$
$35 < N_{trk}^{offline} < 90$
$90 < N_{trk}^{offline} < 110$
$110 < N_{trk}^{offline} < 150$
$N_{trk}^{offline} > 150$
$1 < p_T < 2$ GeV
$2 < p_T < 3$ GeV
$3 < p_T < 4$ GeV
$4 < p_T < 5$ GeV
$\Delta\phi$



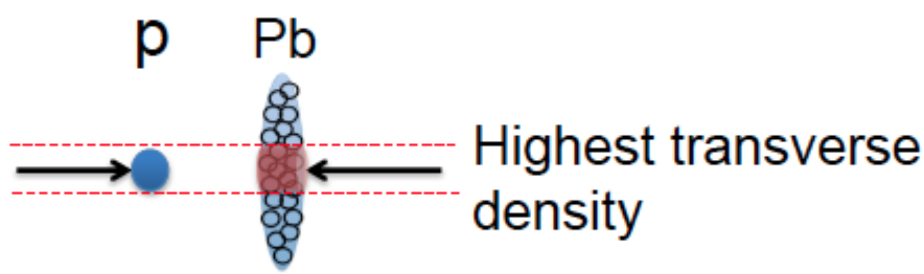
1 < p_T^trig < 2 GeV
1 < p_T^asc < 2 GeV
2 < p_T^trig < 3 GeV
3 < p_T^trig < 4 GeV
4 < p_T^trig < 5 GeV
5 < p_T^trig < 6 GeV
2 < p_T^asc < 3 GeV
3 < p_T^asc < 4 GeV
4 < p_T^asc < 5 GeV
5 < p_T^asc < 6 GeV
0.30
0.20
0.10
0.00
0.12
0.08
0.04
0.00
0.04
0.03
0.01
0.00
0.03
0.02
0.01
0.00
0.009
0.006
0.003
0.000
0
1
2
3
Δφ

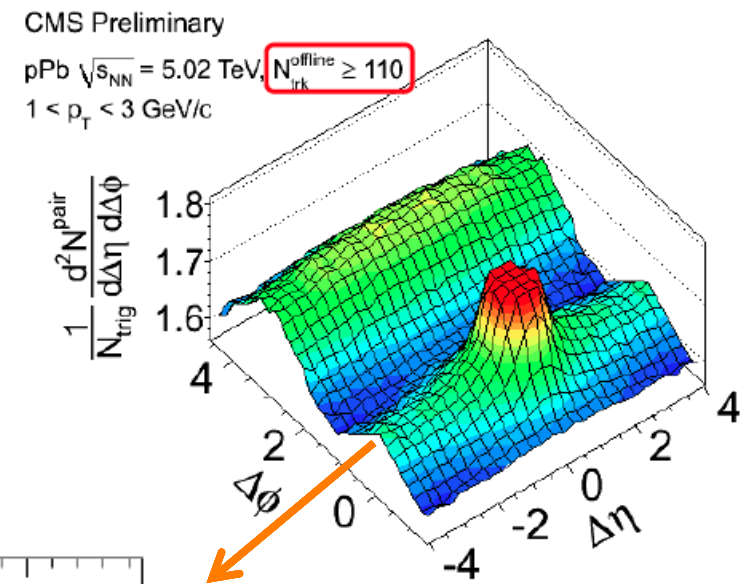


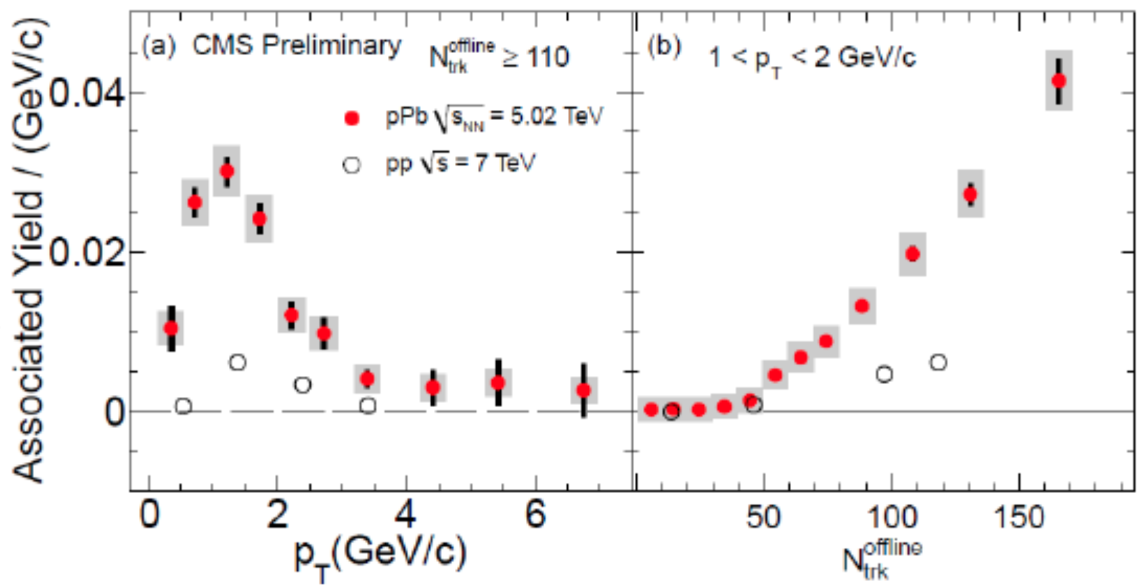
0.30
0.20
0.10
0.00
0.12
0.08
0.04
0.00
0.04
0.03
0.01
0.00
0.03
0.02
0.01
0.00
0.009
0.006
0.003
0.000
$1 < p_T^{trig} < 2$ GeV
$1 < p_T^{asc} < 2$ GeV
$2 < p_T^{trig} < 3$ GeV
$3 < p_T^{trig} < 4$ GeV
$4 < p_T^{trig} < 5$ GeV
$5 < p_T^{trig} < 6$ GeV
$2 < p_T^{asc} < 3$ GeV
$3 < p_T^{asc} < 4$ GeV
$4 < p_T^{asc} < 5$ GeV
$5 < p_T^{asc} < 6$ GeV

Exciting results from CMS on proton lead collisions

CMS coll. arXiv:1210.5482, Phys. Lett. B

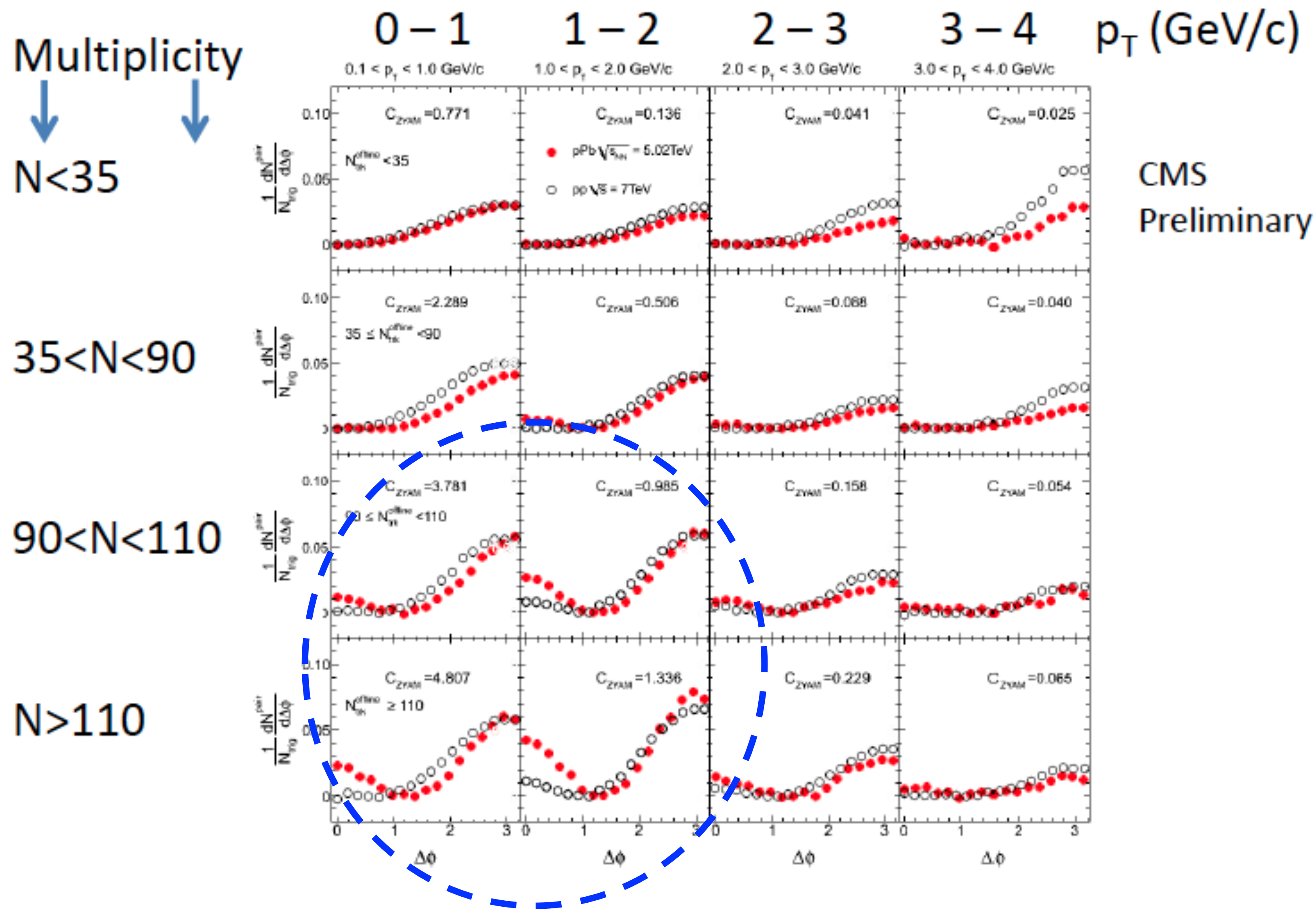






Ridge much bigger than p+p for the same multiplicity !

Exciting results from CMS on proton lead collisions

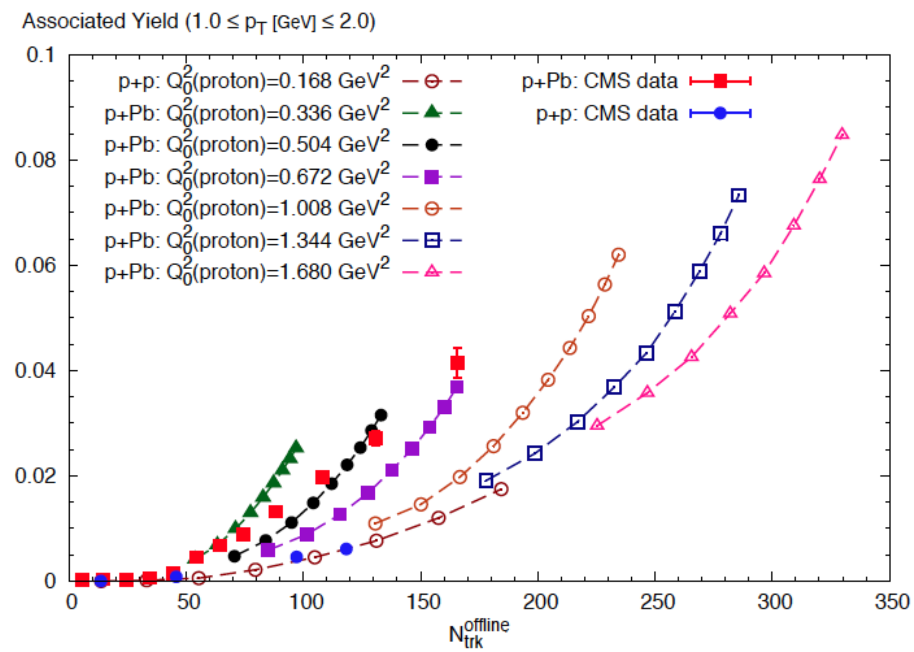


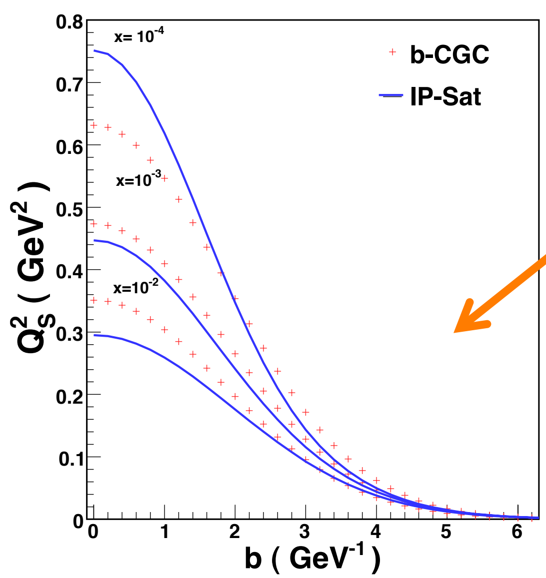
CMS p+Pb data explained

Dusling, RV: 1302.7018

$Q_0^2(\text{lead})=N_{Part}^{Pb} * Q_0^2(\text{proton})$

of "wounded" nucleons in Lead nucleus





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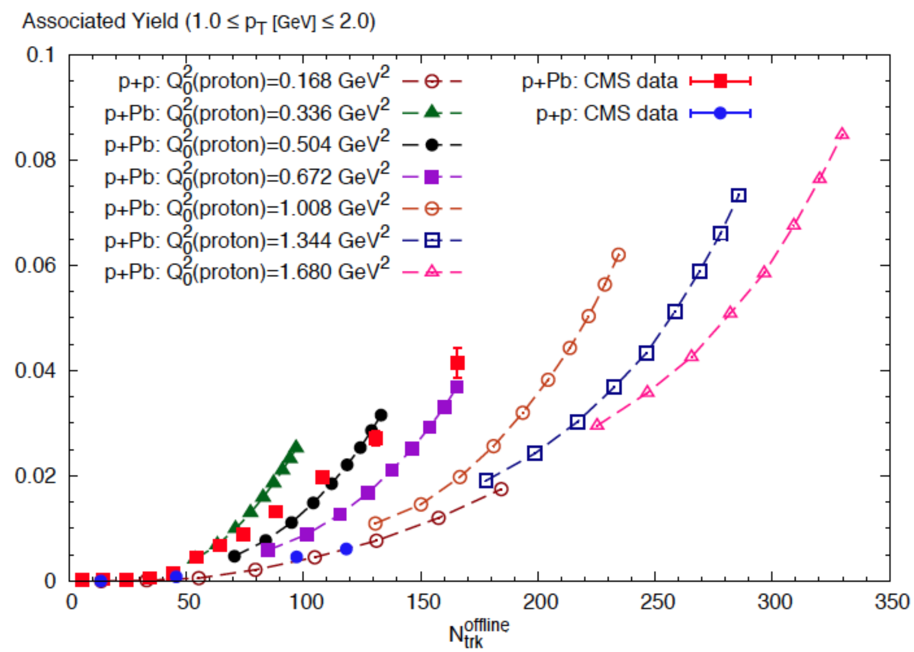
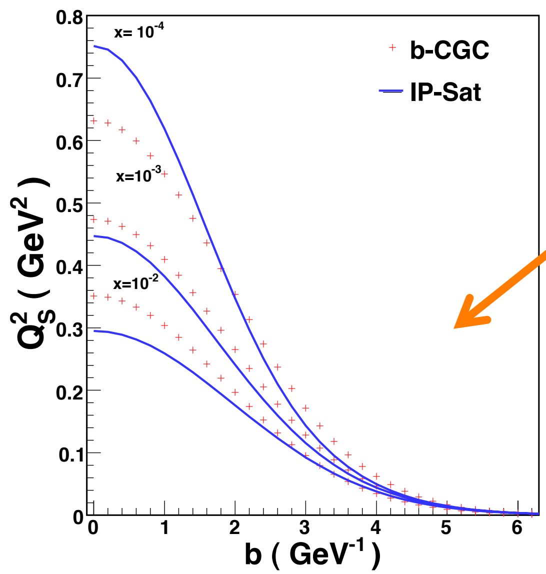


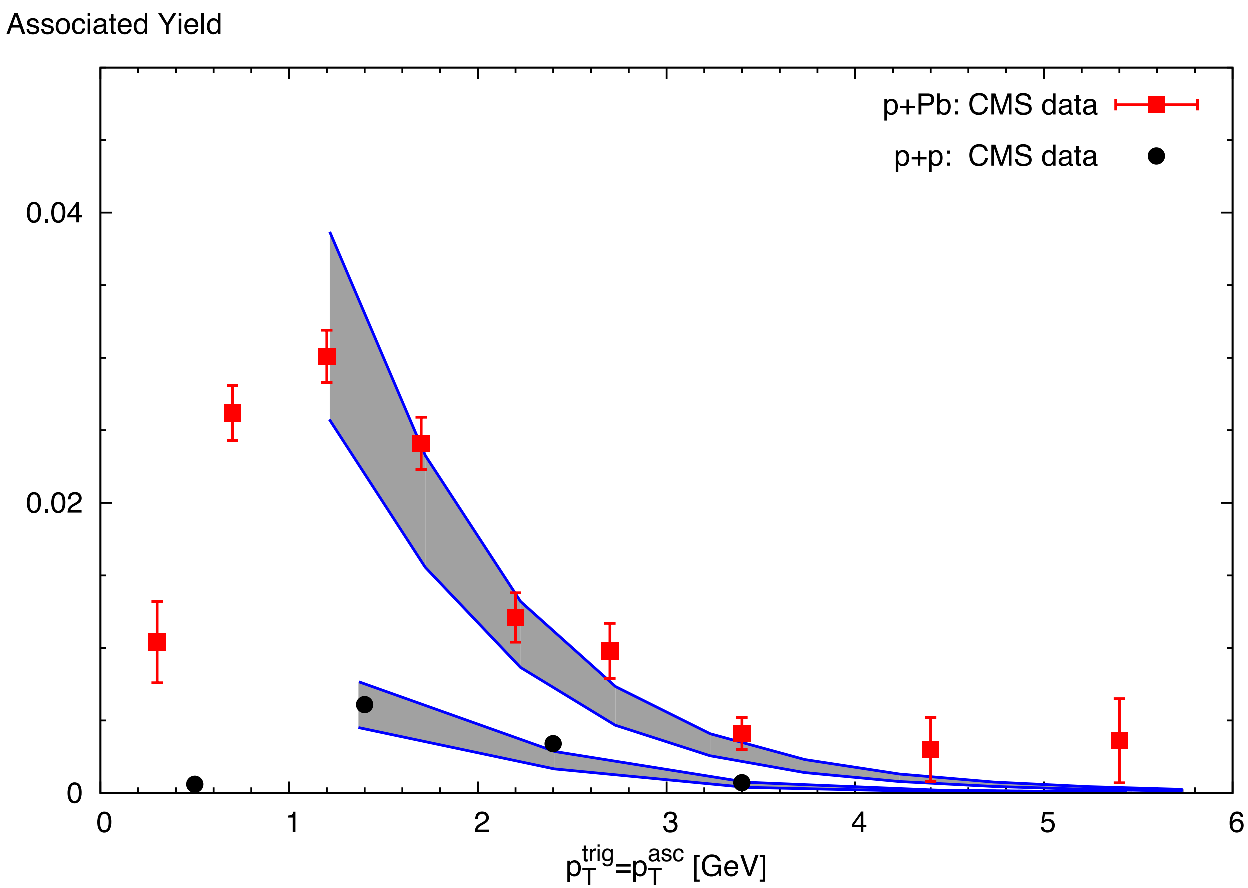


Large "ridge" seen by varying saturation scale in proton and # of wounded nucleons

--rarer and rarer Fock configurations probed in both proton and nucleus

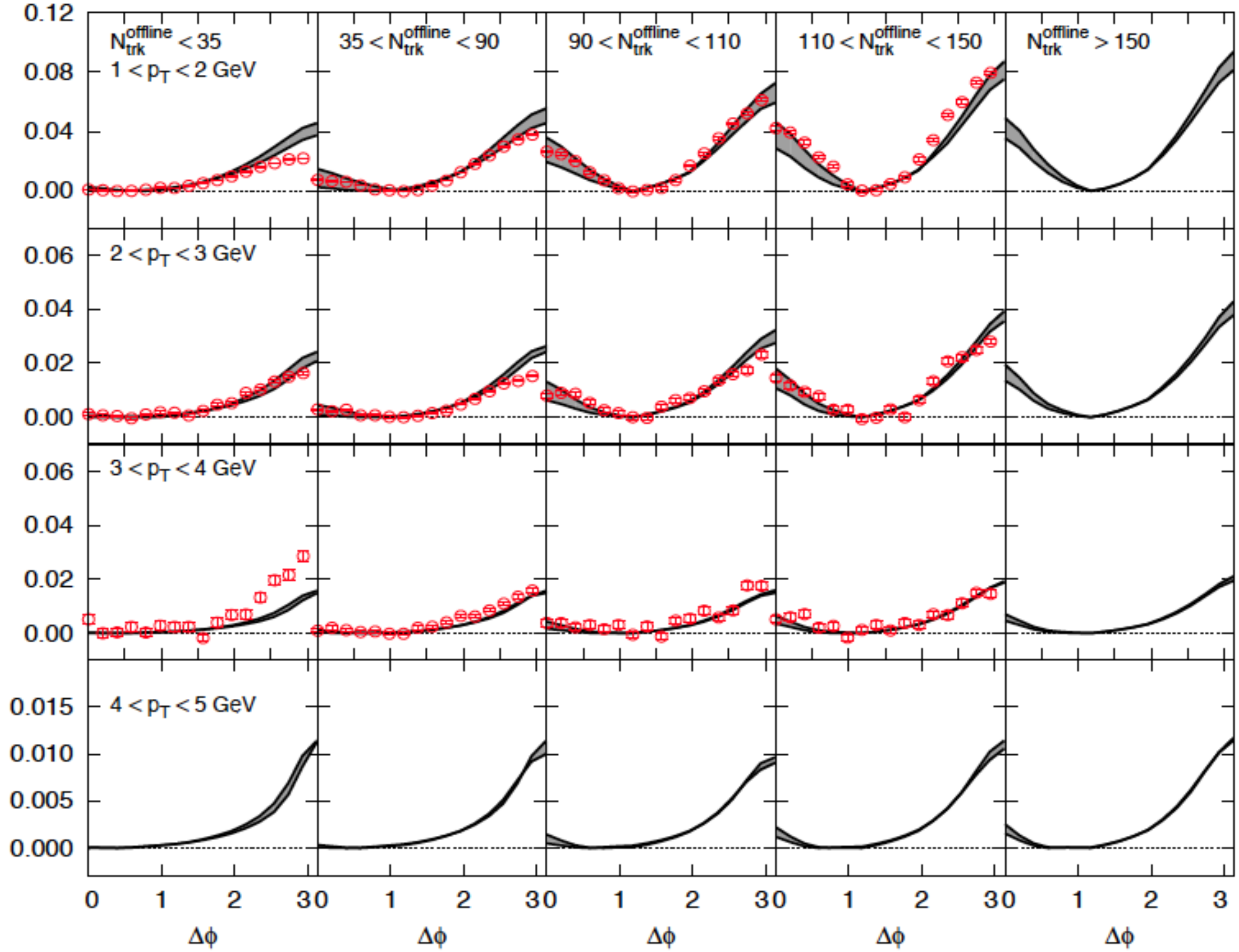
CMS p+Pb data explained

Dusling, RV: 1211.3701
1302.7018



CMS p+Pb data explained

Dusling, RV: 1211.3701
1302.7018



Smoking gun for gluon saturation and BFKL dynamics ?

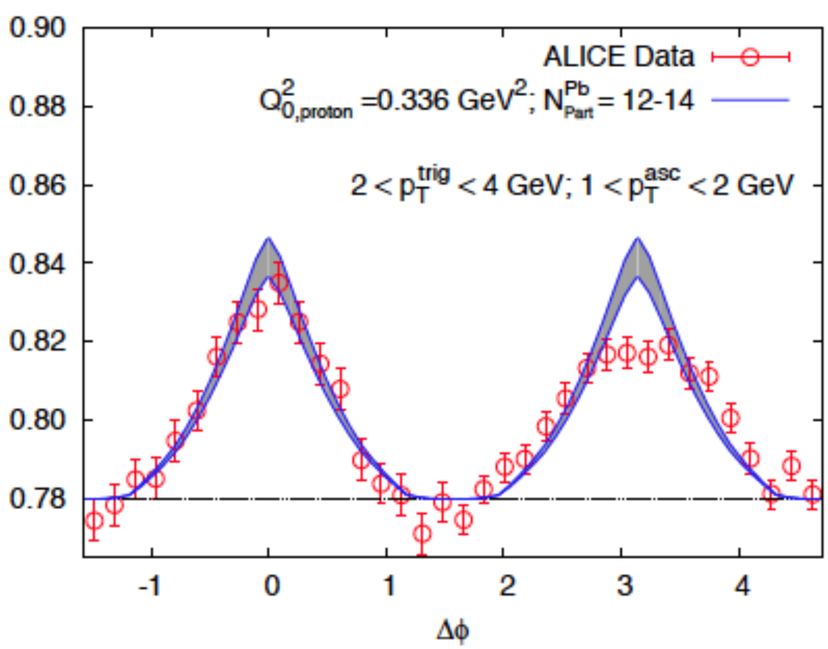
ALICE data on the p+Pb ridge

ALICE coll. arXiv:1212.2001

Different acceptance ($|\Delta\eta| < 1.8$) than CMS ($2 < |\eta| < 4$) and ATLAS ($2 < |\eta| < 5$).

ALICE subtracts away-side "jet" contribution at 40-60% centrality from most central events

–this gives dipole shape of correlation



Different analysis technique from CMS/ATLAS

-- same normalization as for CMS/ATLAS

Curves for $Q_{0,proton}^2$ =0.336 GeV^2 & N_{part}^{Pb} = 12 - 14

ALICE data on the p+Pb ridge

ALICE coll. arXiv:1212.2001

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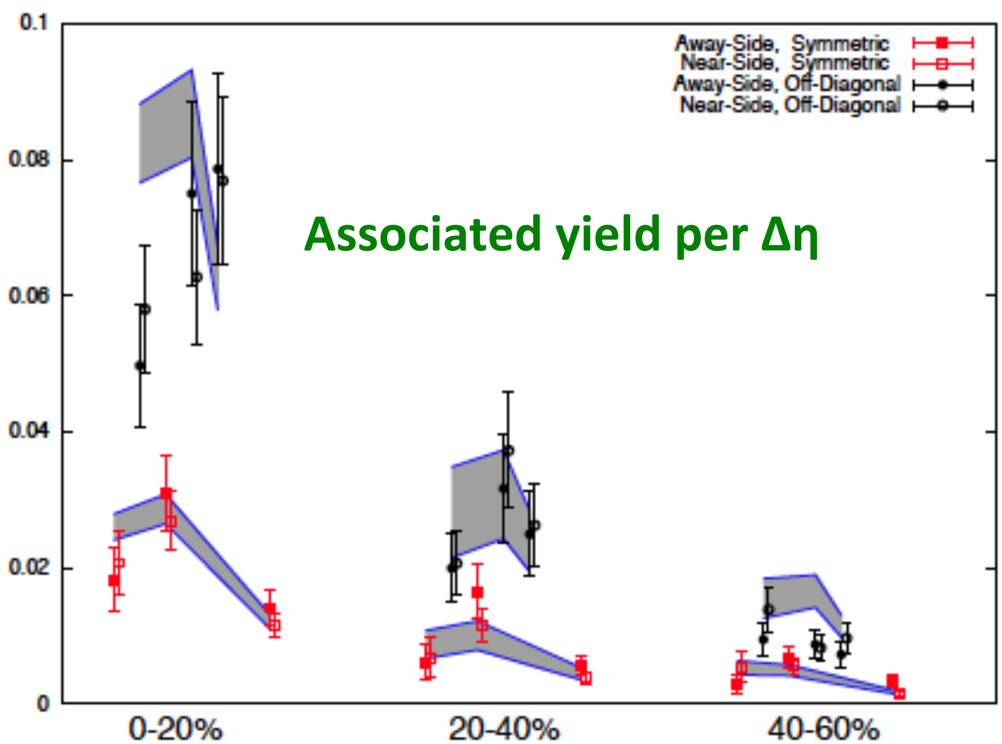


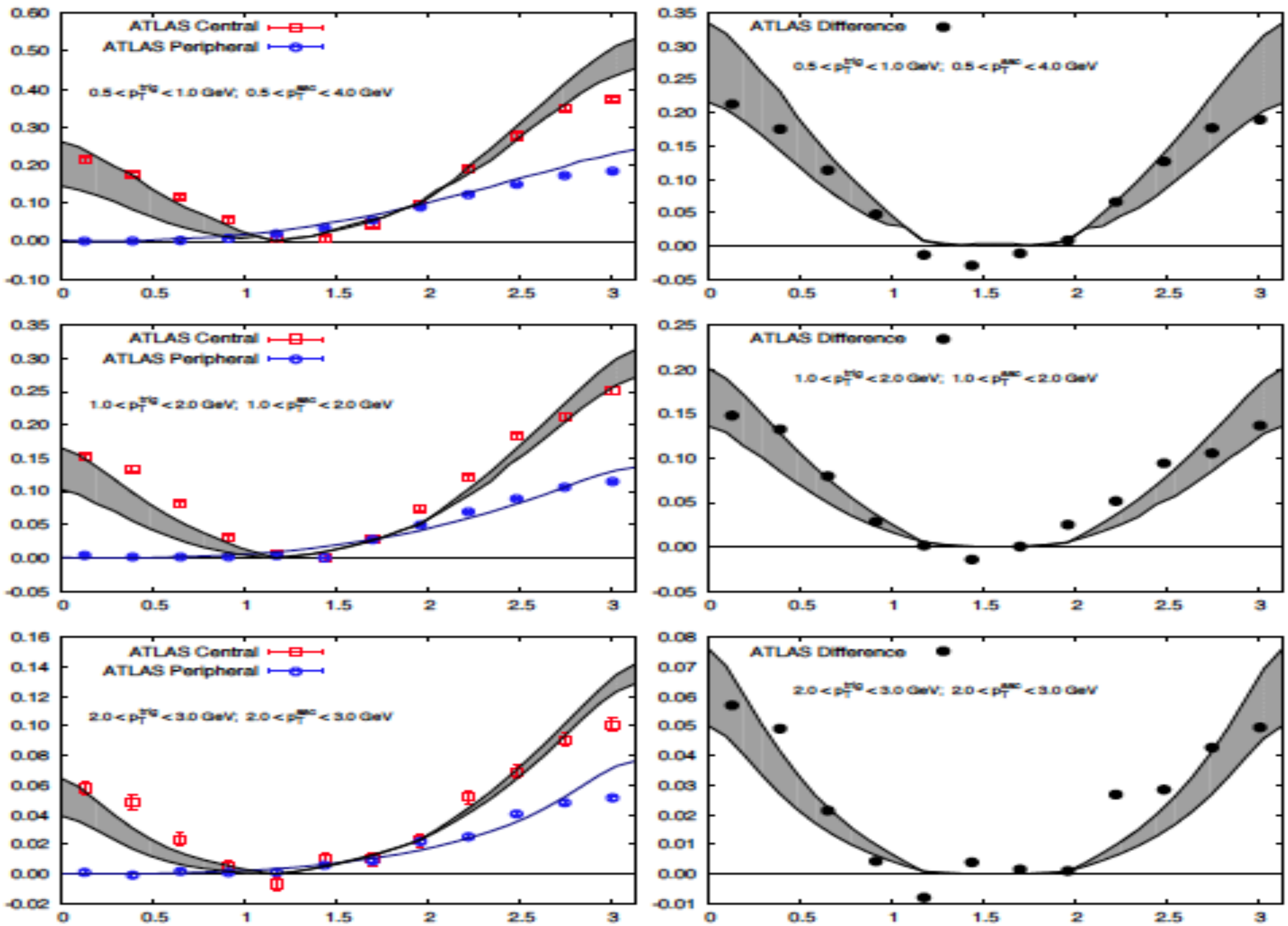
0-20% : $Q_{0,proton}^{\ 2} = 0.336\ \text{GeV}^2$ & $N_{part}^{Pb} = 12 - 14$

20-40% : $Q_{0,proton}^{\ 2} = 0.336\ \text{GeV}^2$ & $N_{part}^{Pb} = 4 - 6$

40-60%: $Q_{0,proton}^{\ 2} = 0.168\ \text{GeV}^2$ & $N_{part}^{Pb} = 3\text{-}4$

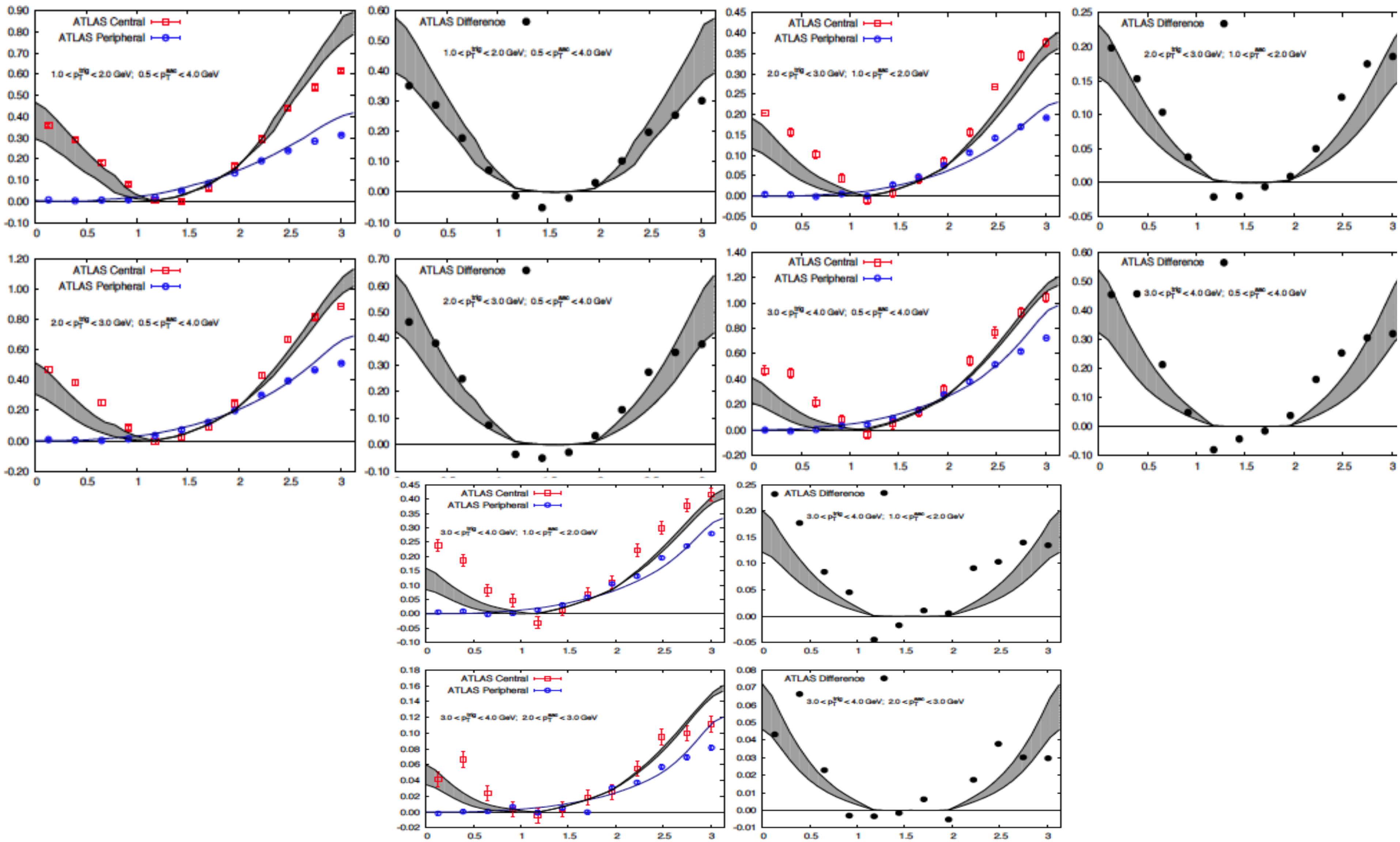
Comparison to ATLAS p+Pb ridge

ATLAS coll. arXiv: 1212.5198



Comparison to ATLAS p+Pb ridge

ATLAS coll. arXiv: 1212.5198



Physics underlying systematics of the ridge

For Glasma graphs

$$d^2N \propto \int d^2k_T \; \Phi_A^2(k_T) \; \Phi_B(|p_T - k_T|) \; \Phi_B(|q_T - k_T|)$$

For $|p_T| = |q_T|$, from the Cauchy-Schwarz inequality:

$$\int d^2k_T \; \Phi_A^2(k_T) \; \Phi_B(|p_T - k_T|) \; \Phi_B(|q_T - k_T|) \leq \int d^2k_T \; \Phi_A^2(k_T) \Phi_B^2(|p_T - k_T|)$$

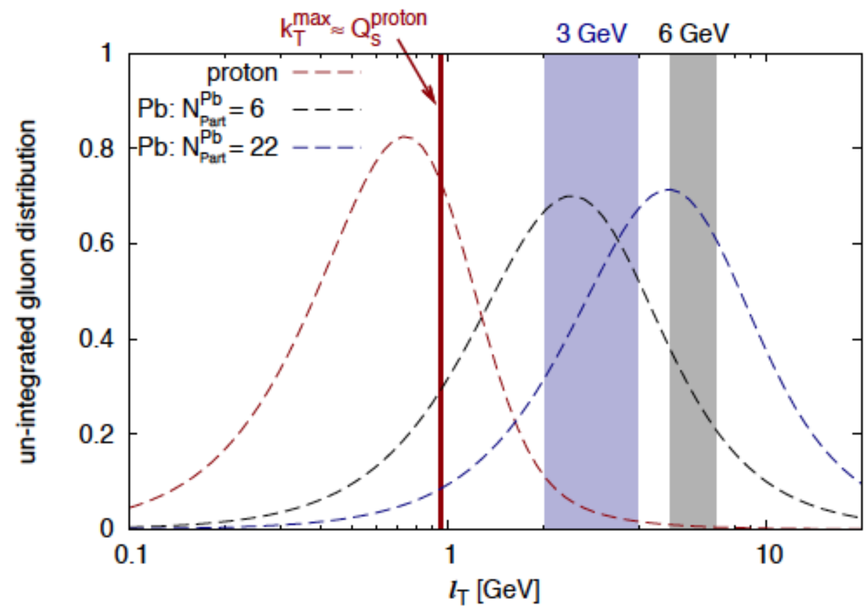
Equality implies no collimation; satisfied only iff $\Phi_B(|p_T - k_T|) \propto \Phi_B(|q_T - k_T|)$

True only if Φ is flat in k_T - for above fns. Else, there must be a collimation

Physics underlying the ridge

Look at ratio of yield at $\Delta\phi_{pq} = 0$ to $\Delta\phi_{pq}=\pi$ for $|p_T|=|q_T|$

$$\mathrm{CY} \propto \frac{\int d^2k_T\ \Phi_A^2(k_T)\ \Phi_B^2(|p_T - k_T)}{\int d^2k_T\ \Phi_A^2(k_T)\ \Phi_B(|p_T - k_T|)\Phi_B(|p_T + k_T|)}$$

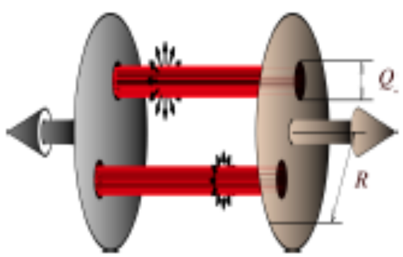


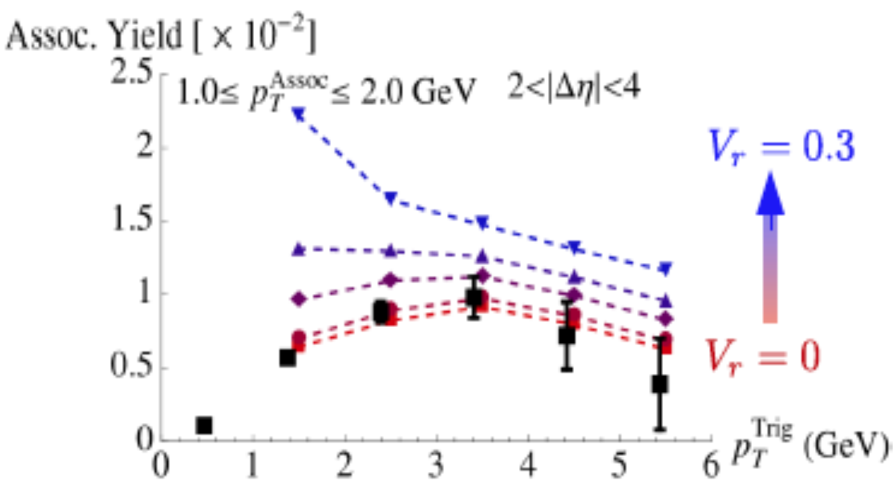
$$\mathrm{CY} \propto \frac{\Phi_B(Q_B)}{\Phi_B(\sqrt{2p_T^2 + 2Q_A^2 - Q_B^2})} \propto 1 + \frac{(Q_B - Q_A)^2}{Q_A^2} \sim N_{\mathrm{part}}$$

As seen in the LHC p+Pb data…

p+p vs A+A

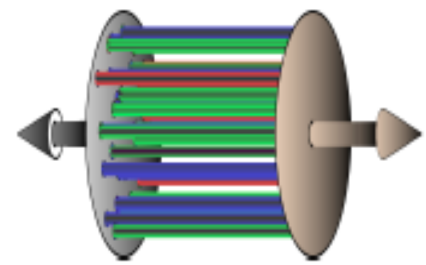
In p+p we are seeing the intrinsic collimation from a single flux tube

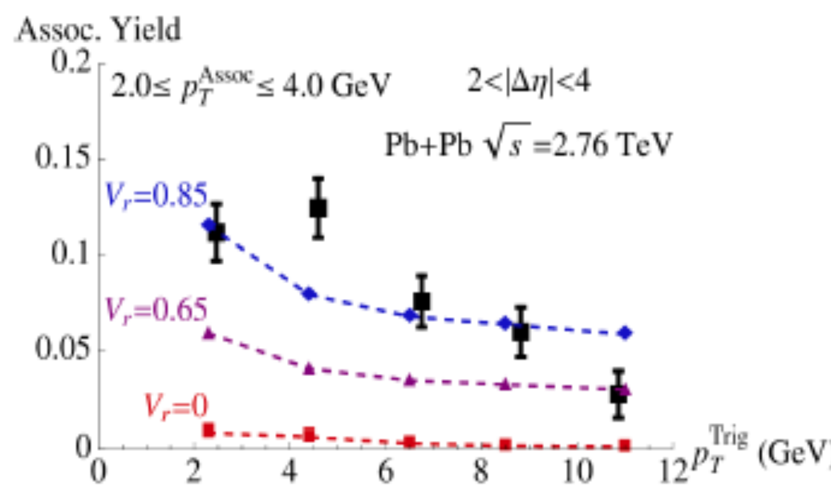




Increasing transverse flow in p+p creates a discrepancy with data.

In A+A there are many such tubes each with an intrinsic correlation enhanced by flow





Yet, transverse flow is needed to explain identical measurements in Pb+Pb

Conclusions

- **The remarkable discovery of an azimuthal collimation among particles flying in different directions in proton-proton and proton-lead collisions is a smoking gun for a universal gluon saturation in proton/nuclear wavefunctions**

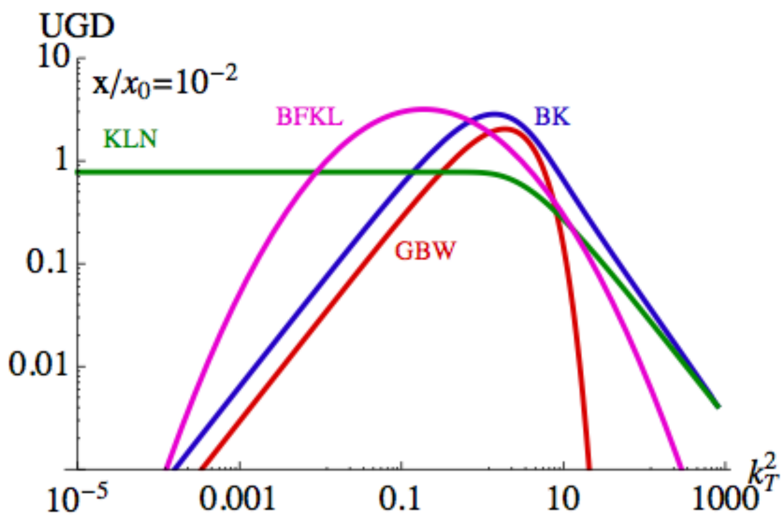
- **A similar ridge in A+A collisions is due to the hydrodynamic flow of quark-gluon matter. The underlying theory behind the p+p ridge however may also help constrain the transport properties of this nearly perfect fluid**

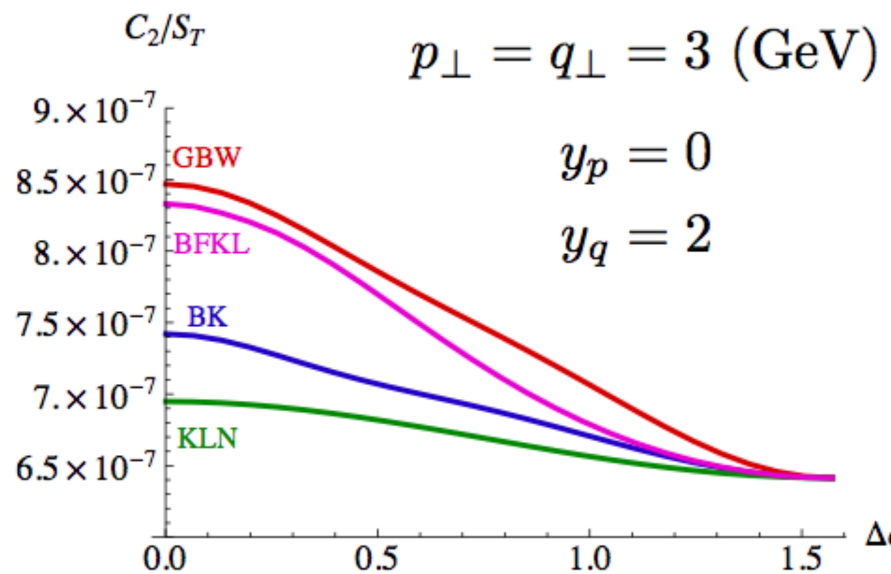
Thank you for your attention !


The nearly perfect ridge ?
Ridge
Jet

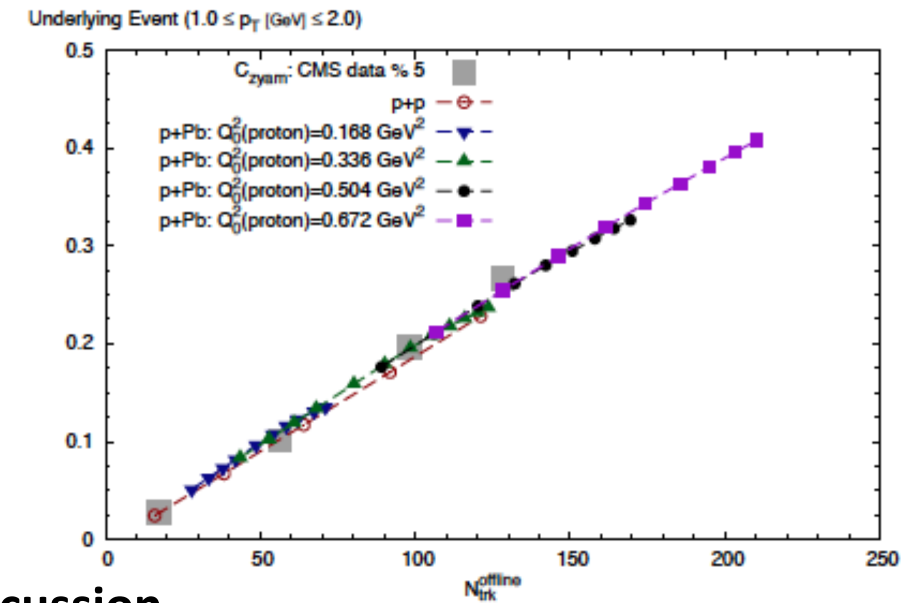
EXTRA SLIDES

Physics underlying the ridge





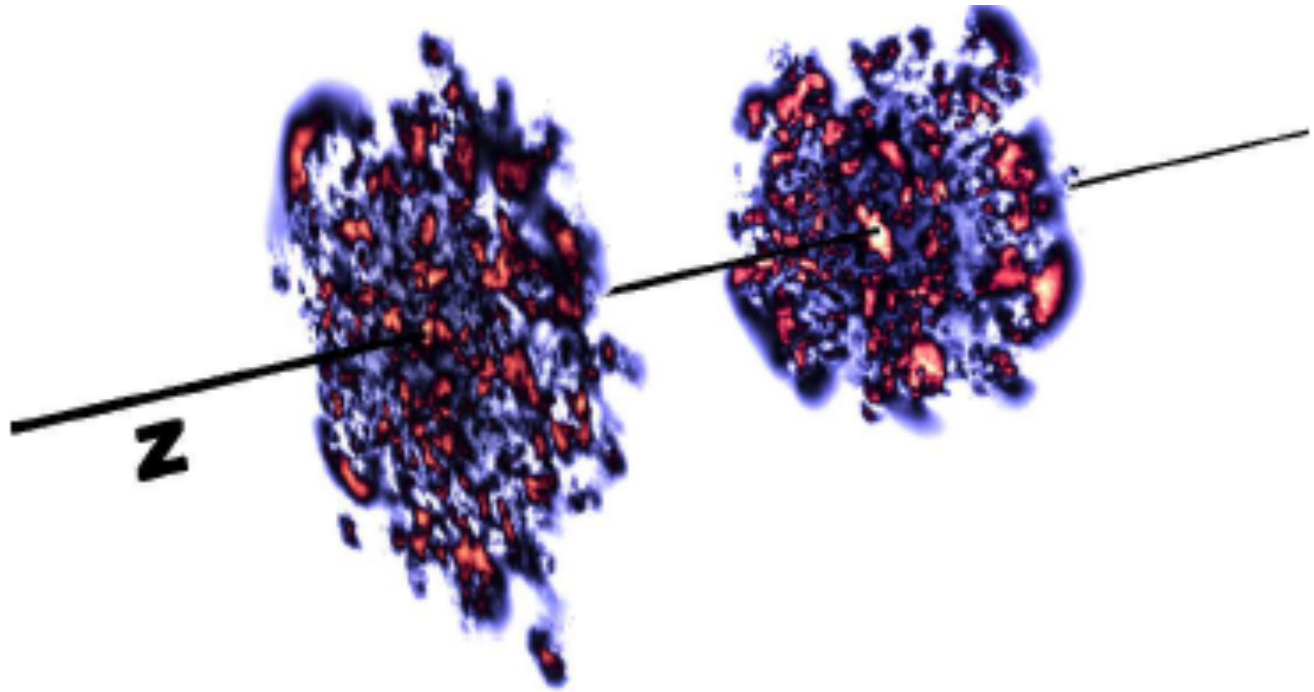
Physics underlying the ridge



From previous discussion

$$\text{UE} \propto \frac{\int d^2k_T\ \Phi_A^2(k_T)\ \Phi_B^2(|p_T - k_T)}{\int d^2k_T\ \Phi_A(k_T)\ \Phi_B(|p_T - k_T|)} \propto N_{\text{track}}$$

A+A initial state: saturated wave-functions

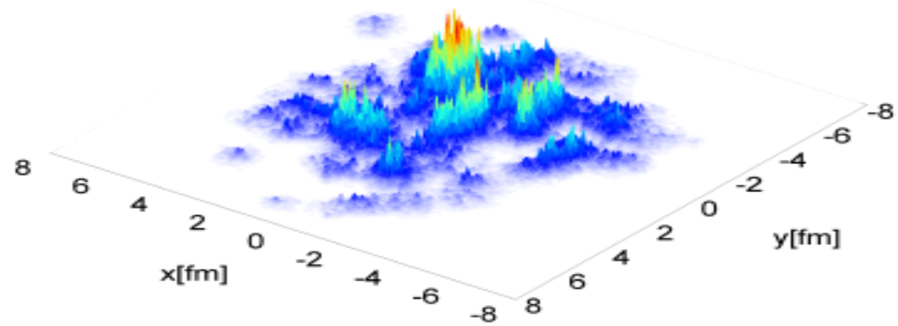


Incoming nuclei are Color Glass Condensates:

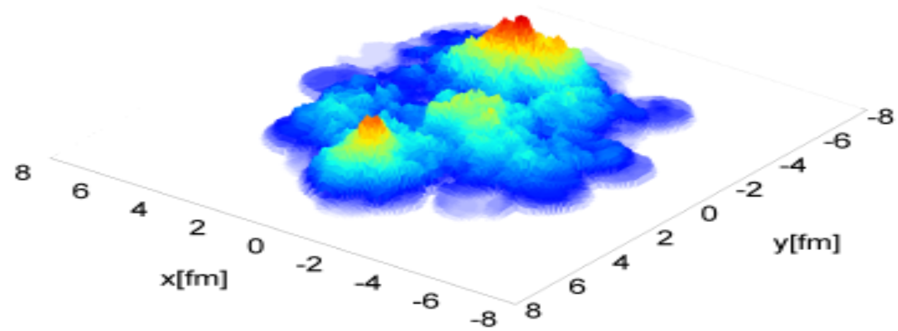
A Glasma / Quark-Gluon plasma is created.

Conjecture: matter produced is a nearly ideal perfect fluid with viscosity/entropy density, $\eta/s \geq 1 / 4\pi$, a universal bound

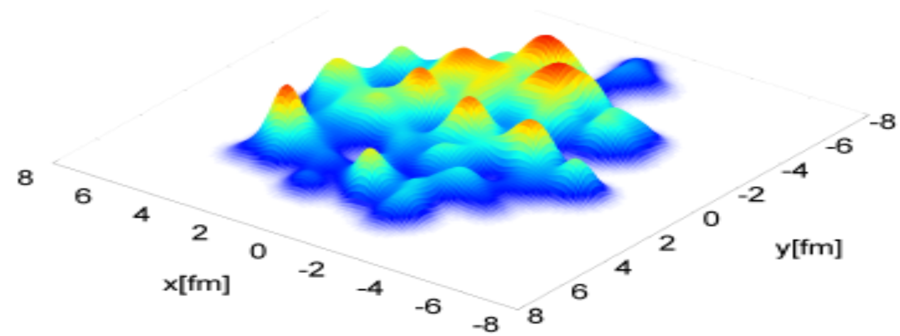
Granularity of initial distributions



IP-Glasma

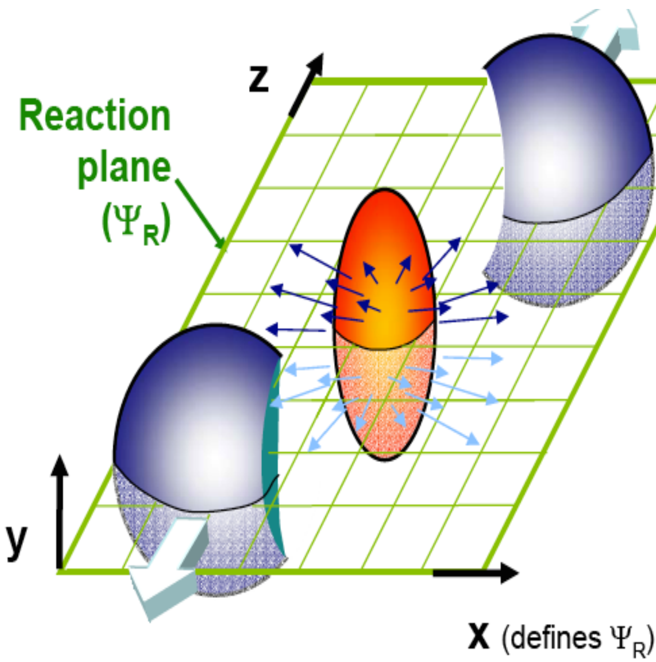


MC-KLN



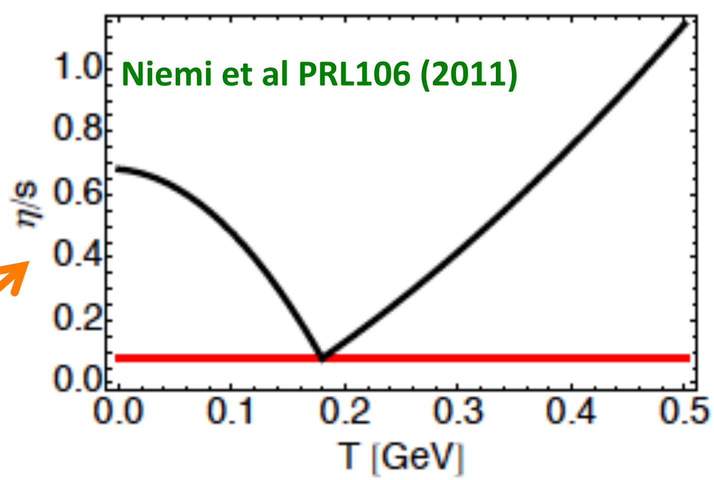
MC-Glauber

Transport coefficients from Anisotropic Flow



$$v_n = \langle \cos(n(\phi - \psi_n)) \rangle$$

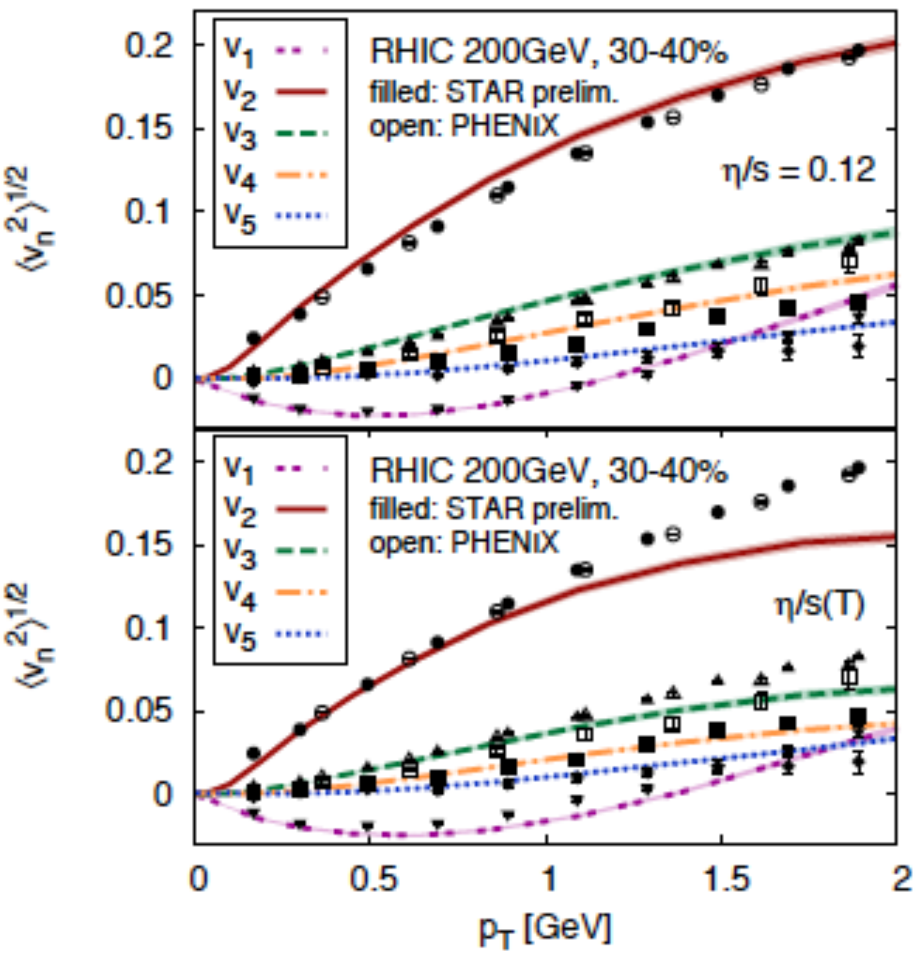
$$\psi_n = \frac{1}{n} \arctan \frac{\langle \sin(n\phi) \rangle}{\langle \cos(n\phi) \rangle}$$

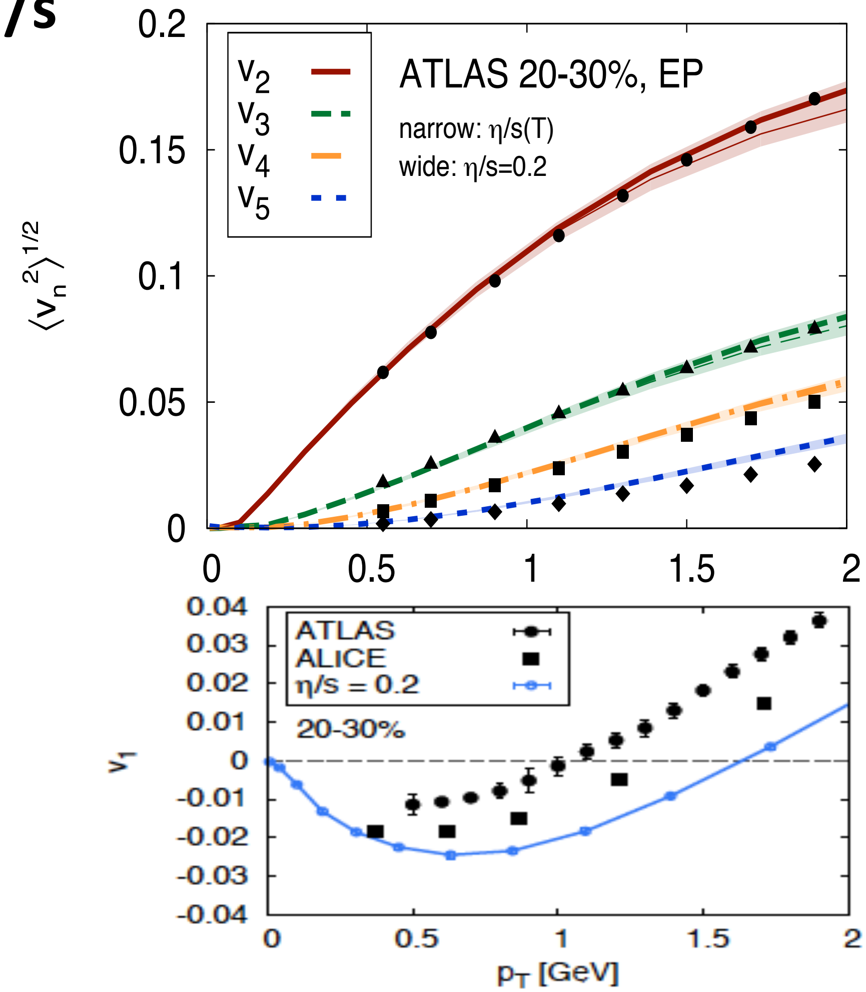


Learn about η/s from flow coefficients v_n

IP-Glasma + viscous hydro model model

Fixed vs temperature dependent η/s





RHIC and LHC have ~ 70% different η/s

IP-Glasma + vscous hydro model

Gale,Jeon,Schenke,Tribedy,RV, 1209.6330, PRL (in press)

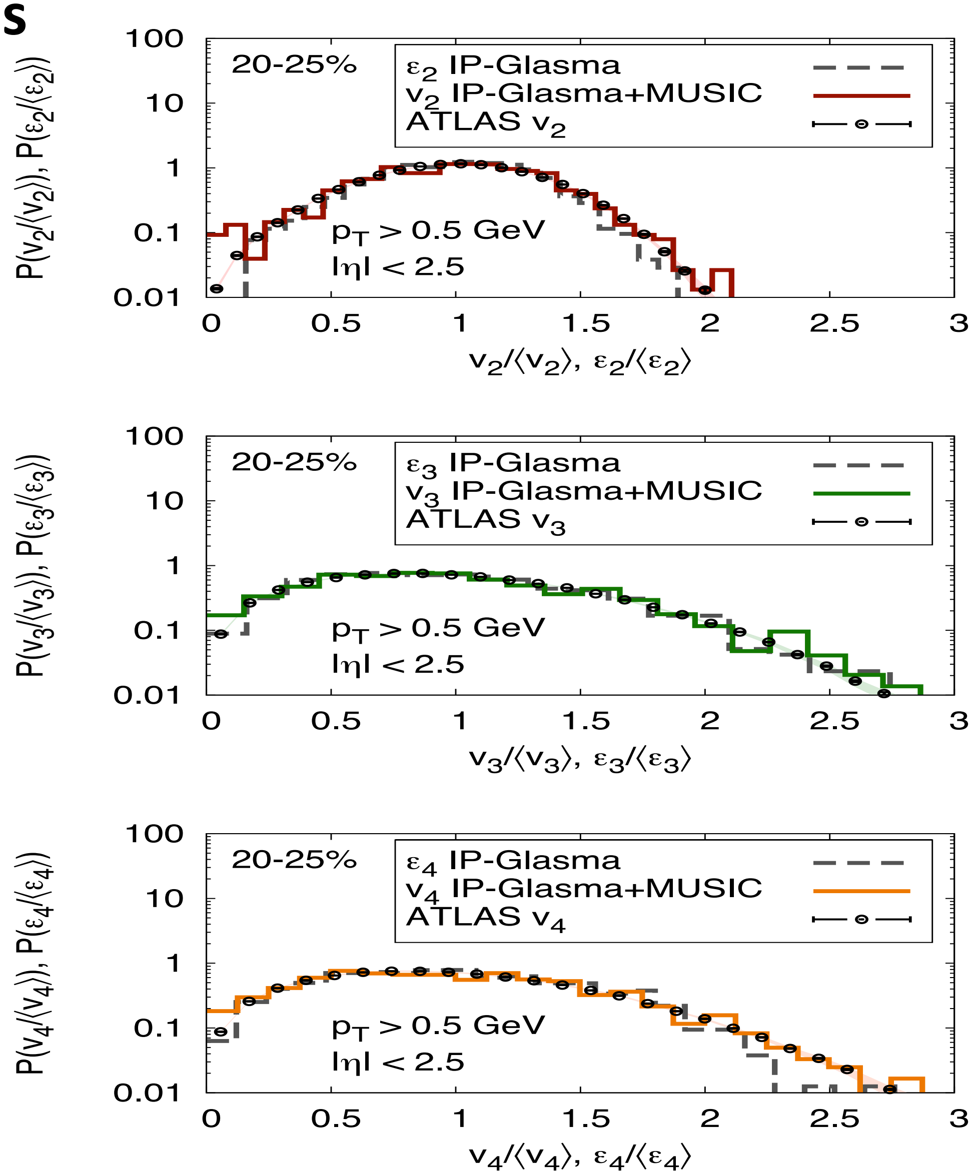
Event-by-event flow distributions

v_n distributions track eccentricities ε_n

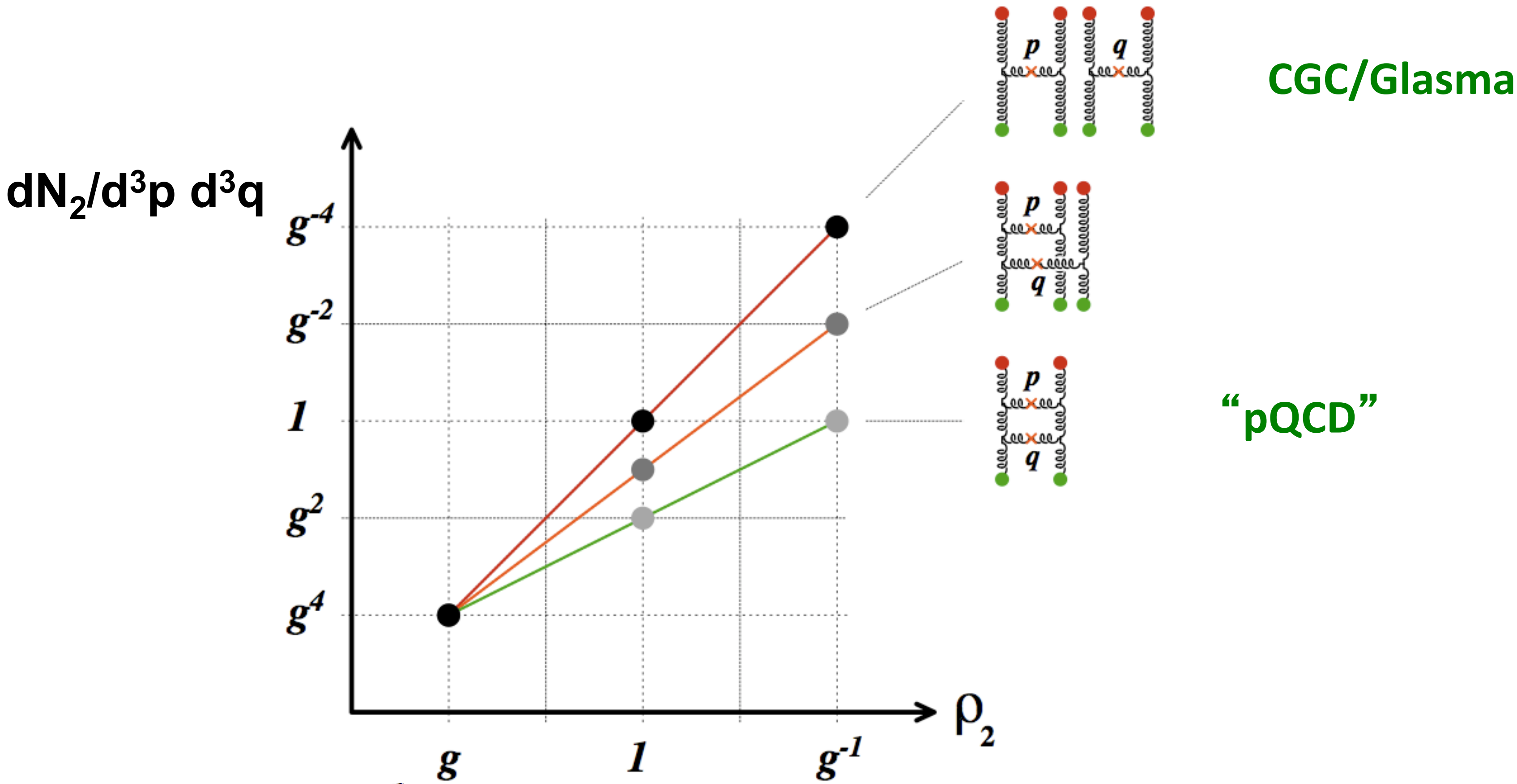
spatial fluctuations

efficiency => perfect fluidity

momentum anisotropies



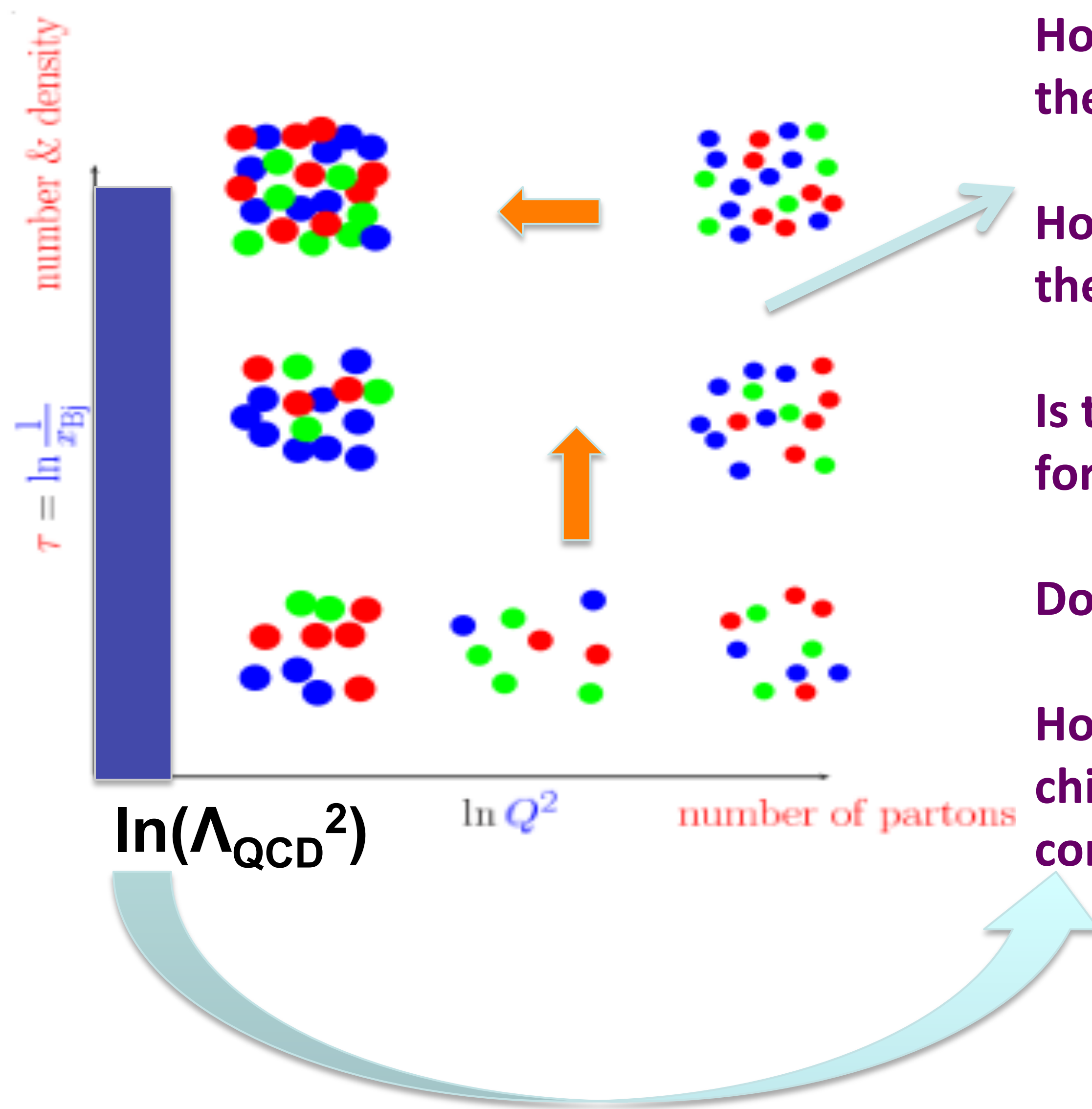
Power counting at high parton densities



$\rho_1 \sim \frac{1}{g}\,;\ \rho_2 \sim g$ $\qquad$ $\rho_1 \sim \frac{1}{g}\,;\ \rho_2 \sim \frac{1}{g}$

When ρ_1, $\rho_2 \sim g$, "dilute limit", CGC contribution is g^{12} – power counting changes from "dense limit" by $\alpha_S^{\,8}$!

Many-body dynamics of universal gluonic matter



How does this happen ? What are the right degrees of freedom ?

How do correlation functions of these evolve ?

Is there a universal fixed point for the RG evolution of d.o.f

Does the coupling run with Q_s^2 ?

How does saturation transition to chiral symmetry breaking and confinement