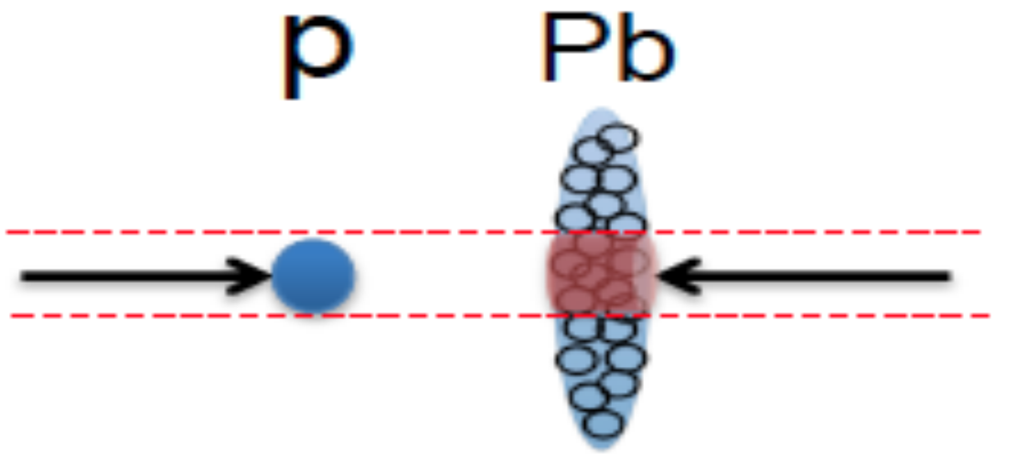


Collider p/d+A experiments: a new era in QCD at high parton densities

Raju Venugopalan
Brookhaven National Laboratory

Joint BNL-LANL-RBRC workshop, January 7-9, 2013

Exciting times !

- ✧ **LHC will start long awaited ~ 3 week p+A run at 5.02 TeV/n in a week !**

  4 hour "pilot" run past fall was extremely successful

- ✧ **Prospect of ↑p+A collisions at RHIC – significant extension of first collider studies – performed at RHIC - on light-heavy systems**

Talk outline

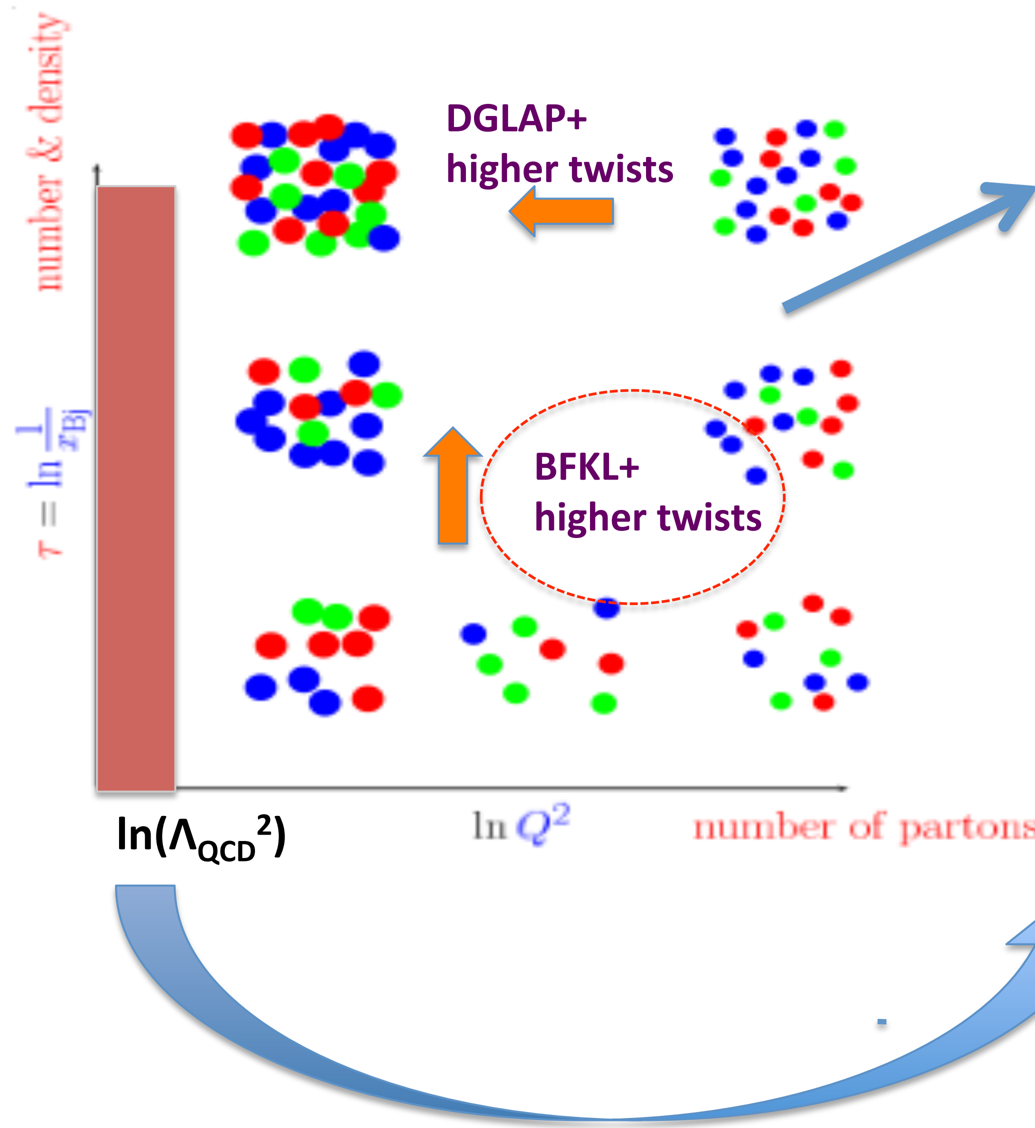
- ✧ Universal many-body parton dynamics at high energies
  --- saturation from DIS to hadron-hadron collisions

- ✧ Multiplicities and single inclusive distributions

- ✧ Di-hadron correlations at RHIC – the ridge in p+p & p+A collisions

- ✧ Initial state many-body parton dynamics in A+A collisions – the IP-Glasma model

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 ?

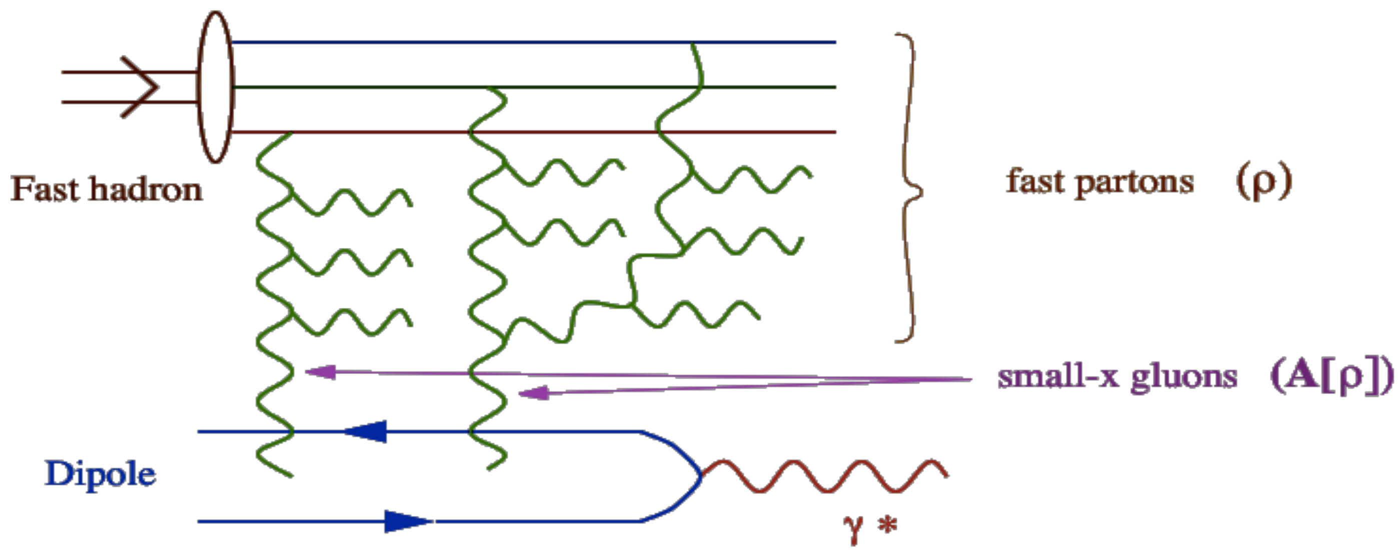
How does saturation transition to chiral symmetry breaking and confinement

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"



At high energies, the d.o.f that describe the frozen many-body gluon configurations are novel objects: dipoles, quadrupoles, …

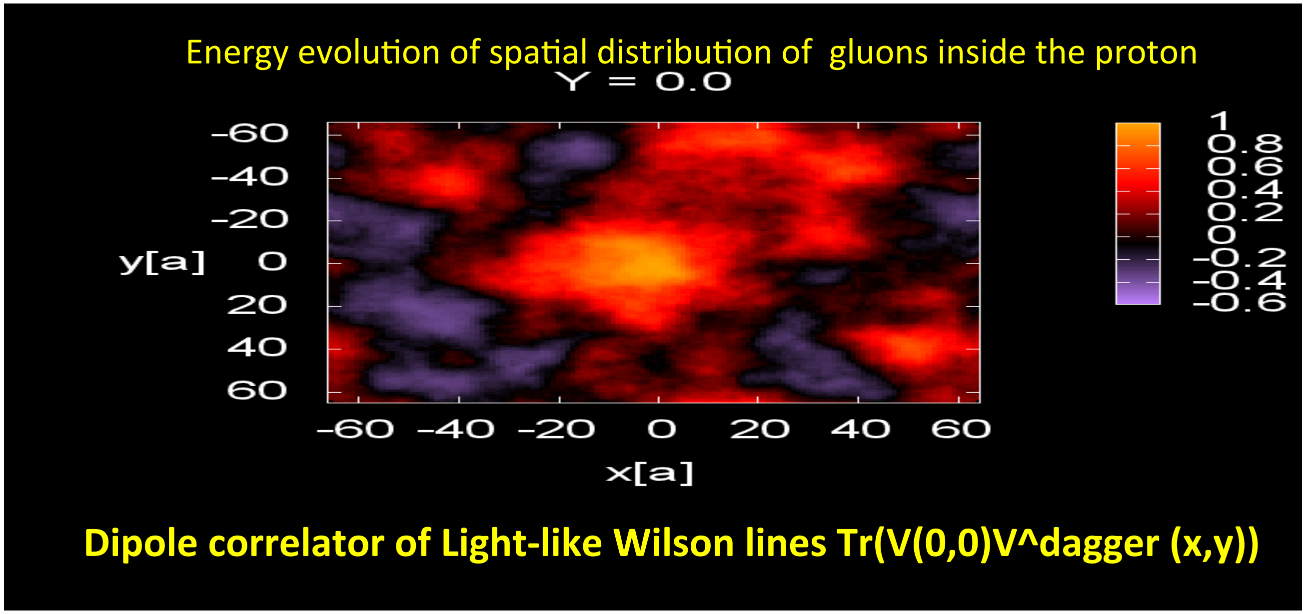
Universal – appear in a number of processes in p+A and e+A; how do these evolve with energy ?

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"



Rummukainen,Weigert (2003)

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

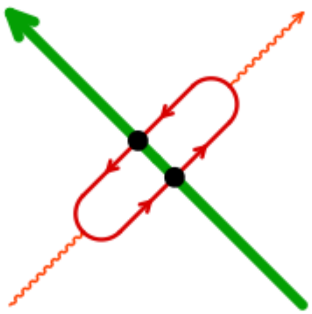
B-JIMWLK eqn. for dipole correlator – universal quantity whose (very good) mean field solution is the BK equation

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

Inclusive DIS: dipole evolution

Photon wave function

$$\sigma_{\gamma^* T} = \int_0^1 dz \int d^2 r_\perp \, |\psi(z, r_\perp)|^2 \sigma_{\text{dipole}}(x, r_\perp)$$



$$\sigma_{\text{dipole}}(x, r_\perp) = 2 \int d^2 b \int [D\rho] \, W_{\Lambda^+}[\rho] \, T(b + \frac{r_\perp}{2}, b - \frac{r_\perp}{2})$$

$$1 - \frac{1}{N_c} \text{Tr}\left(V\left(b + \frac{r_\perp}{2}\right) V^\dagger \left(b - \frac{r_\perp}{2}\right)\right)$$

Two dipole saturation models:

i) rcBK –higher twist corrections to pQCD BFKL small x evolution

Albacete,Kovchegov

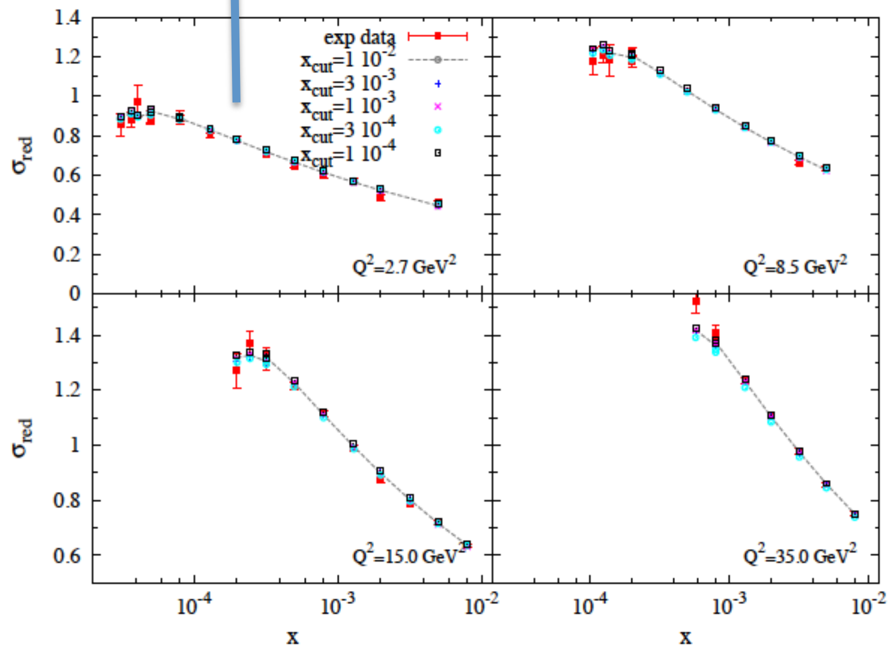
ii) IP-Sat based on eikonalized treatment of DGLAP higher twists – form same as MV model

$$\frac{d\sigma_{\text{dipole}}}{d^2 b_\perp} = 2\left(1 - \exp\left(-\frac{\pi^2 r_\perp^2}{2N_c} \alpha_S(\mu^2) \, xg(x, \mu^2) \, T_G(b_\perp)\right)\right)$$

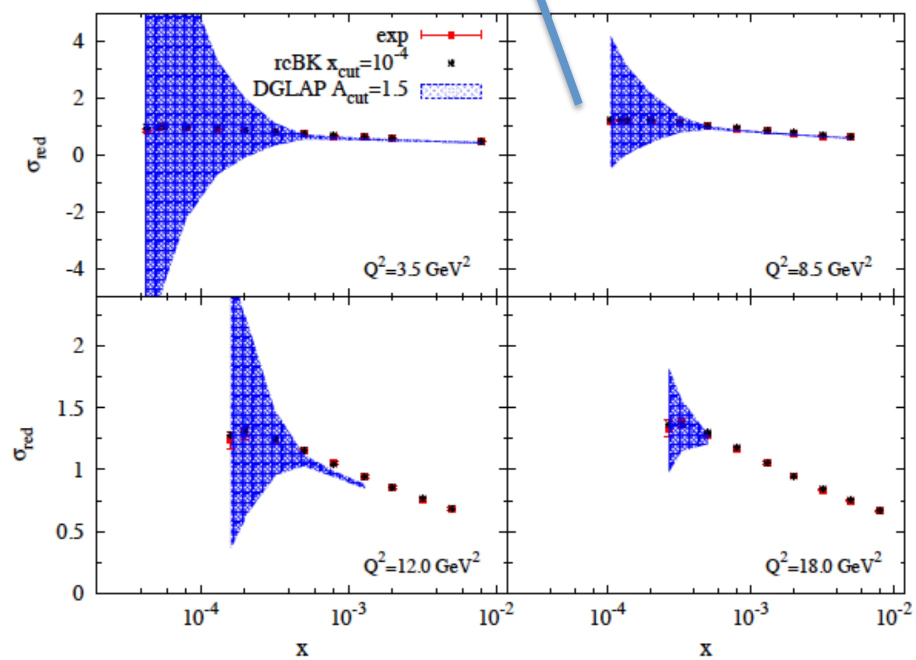
Bartels,Golec-Biernat,Kowalski
Kowalski, Teaney;
Kowalski, Motyka, Watt

Inclusive DIS: dipole evolution a la BK

Comparison of running coupling rcBK eqn. with precision small x combined HERA data

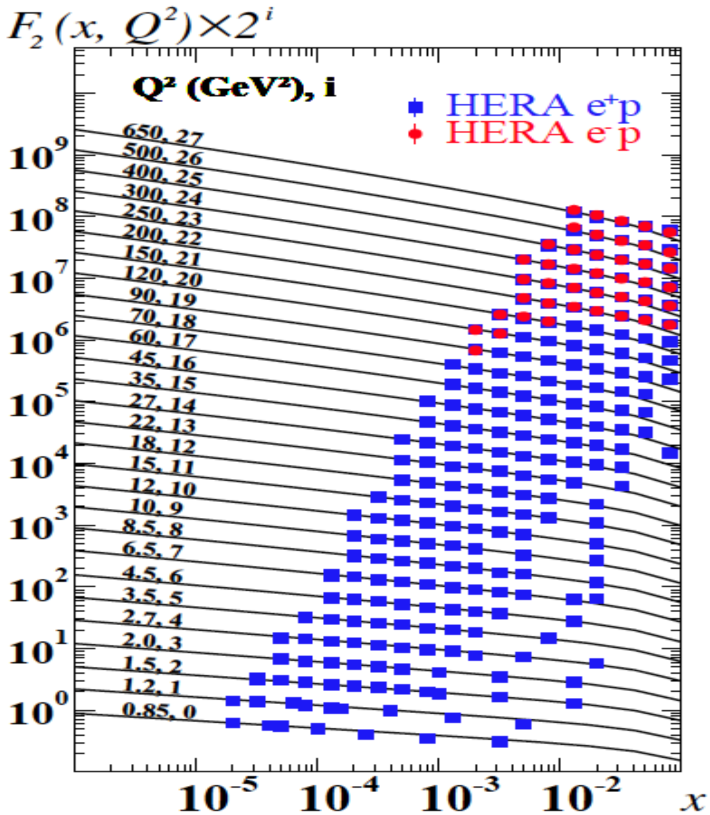


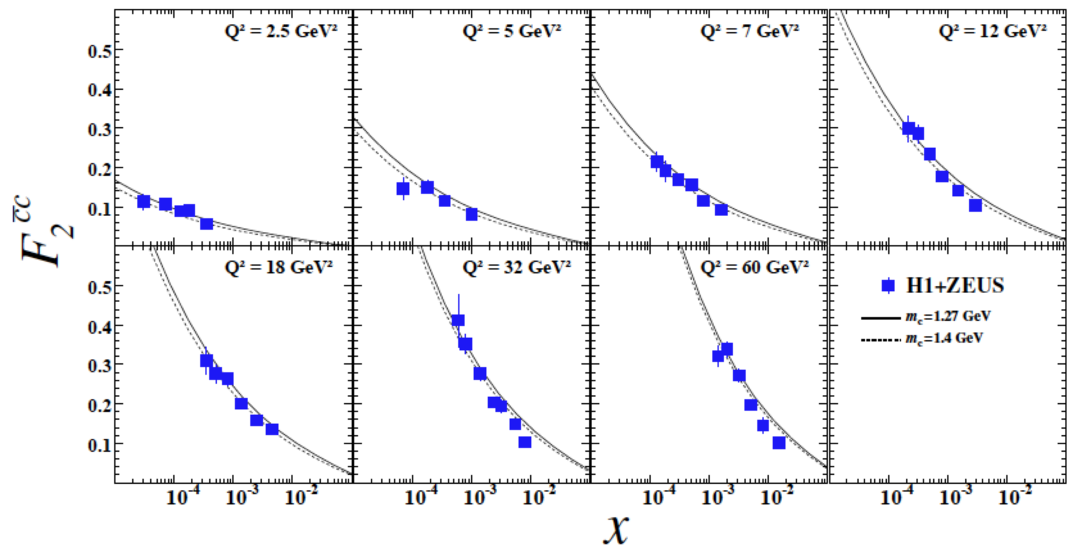
Relative comparison of rc BK to DGLAP fits-bands denote pdf uncertainties

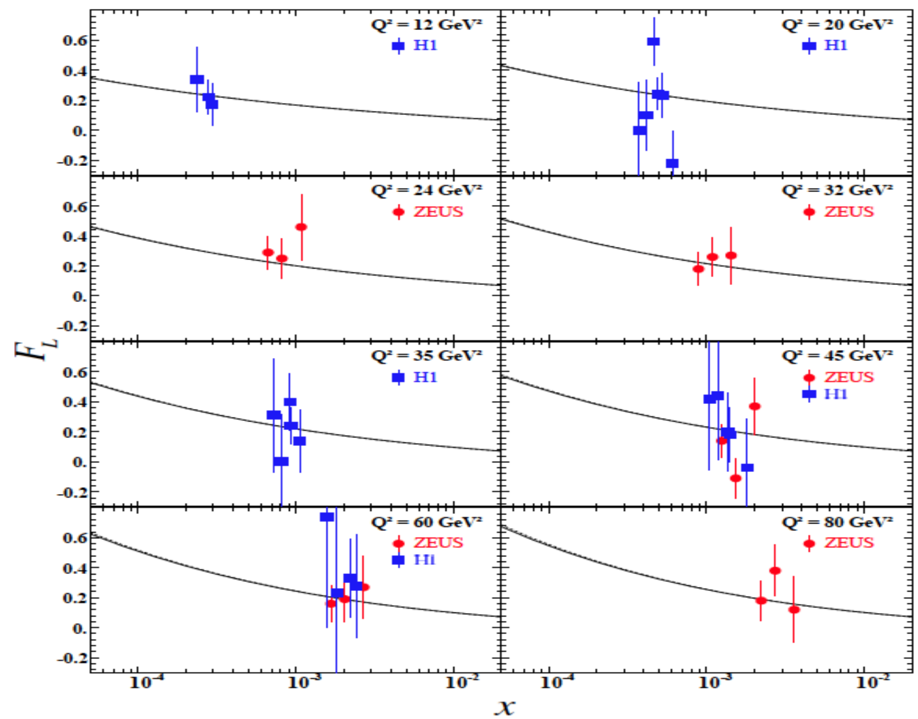


Albacete,Milhano,Quiroga-Arias,Rojo, arXiv:1203.1043

Inclusive DIS: dipole evolution a la IP-Sat





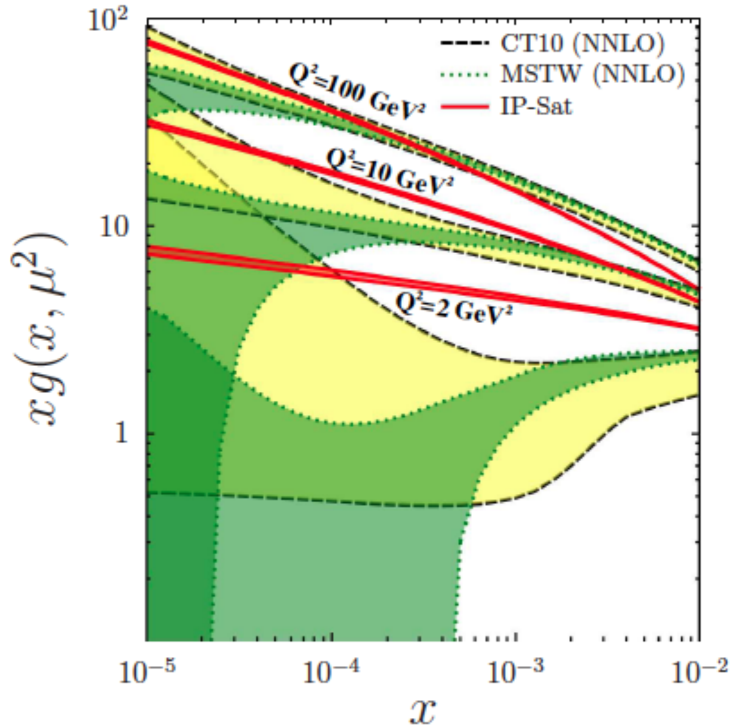


(Few) parameters fixed by χ-sq ~ 1 fit to combined (H1+Zeus) reduced cross-section

Rezaiean,Siddikov,Van de Klundert,RV: 1212.2974

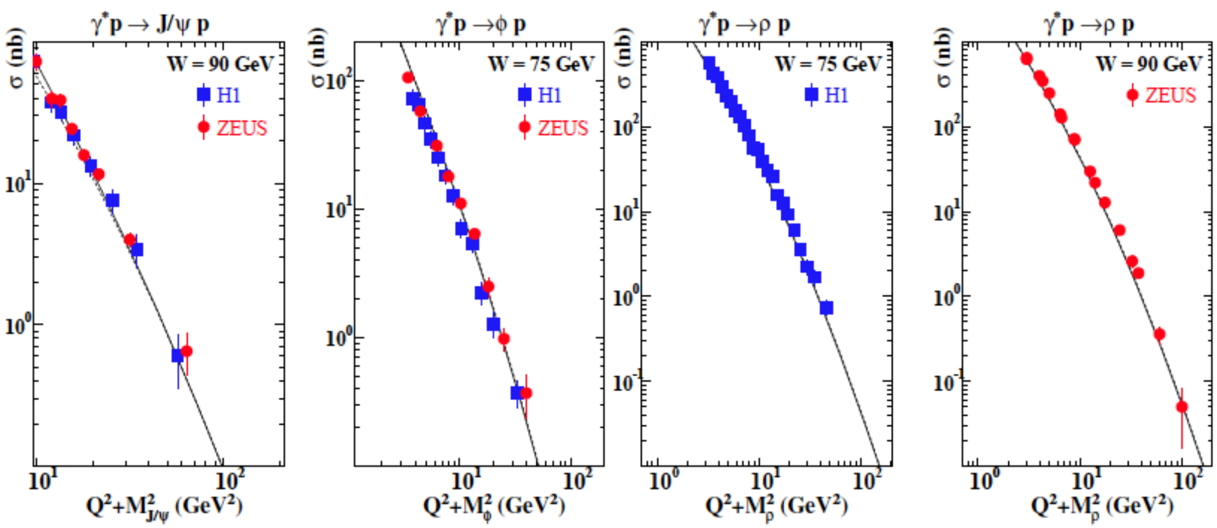
Inclusive DIS: dipole evolution a la IP-Sat

Rezaiean,Siddikov,Van de Klundert,RV: 1212.2974



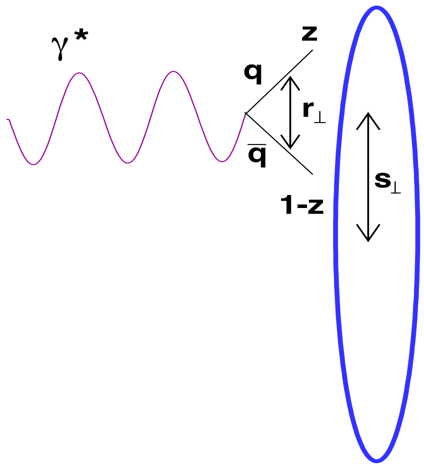
More stable gluon dist. at small x relative to NNLO pdf fits

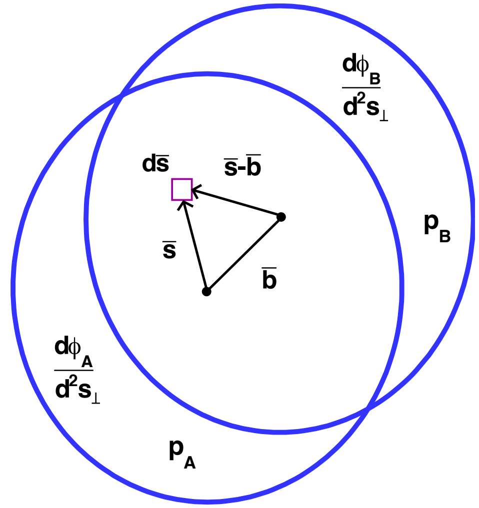
Exclusive VM production:



Comparable quality fits for energy (W) and t-distributions

Saturation models: from HERA to RHIC & LHC





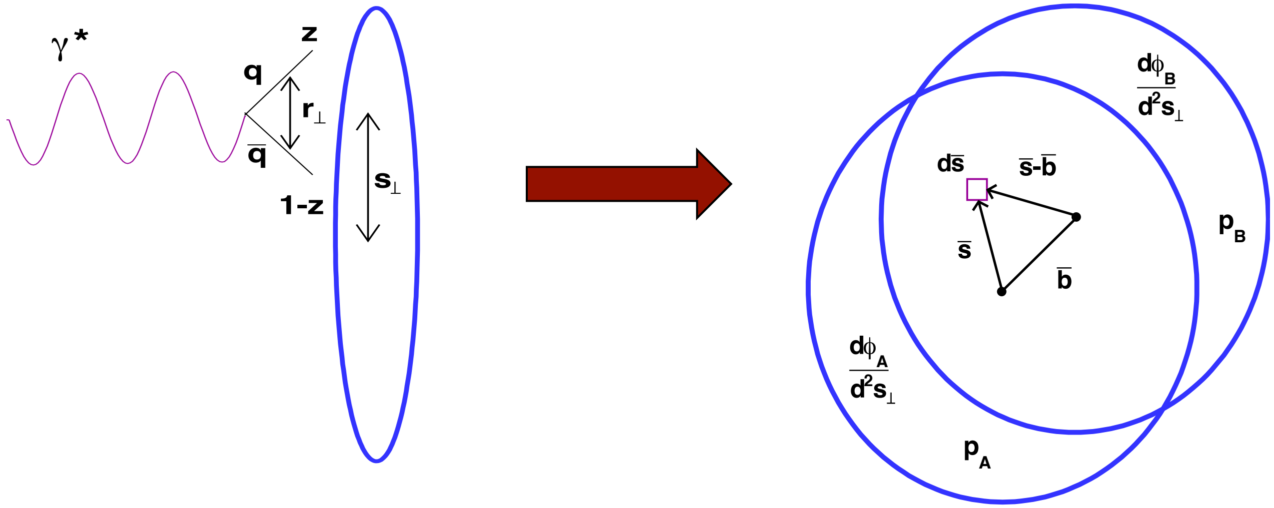
Unintegrated gluon dist. from dipole cross-section:

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

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

$$\frac{dN_g(b_\perp)}{dy d^2p_\perp} = \frac{4\alpha_S}{\pi C_F}\frac{1}{p_\perp^2}\int\frac{d^2k_\perp}{(2\pi)^5}\int d^2s_\perp \frac{d\phi_A(x,k_\perp|s_\perp)}{d^2s_\perp}\frac{d\phi_B(x,p_\perp-k_\perp|s_\perp-b_\perp)}{d^2s_\perp}$$

Saturation models: from HERA to RHIC & LHC



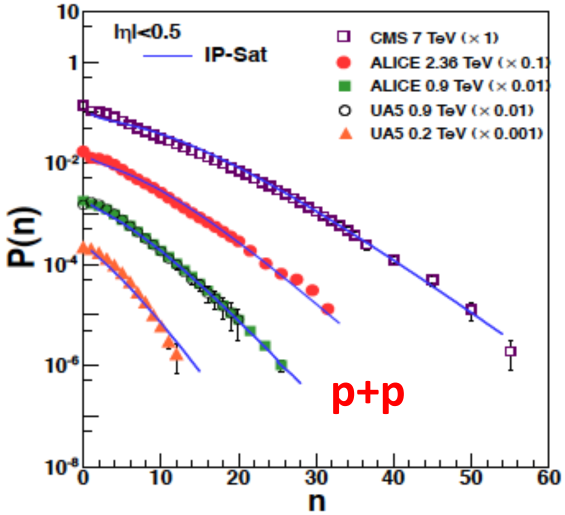
k_T factorization is an approximation valid for $Q_S < k_T$

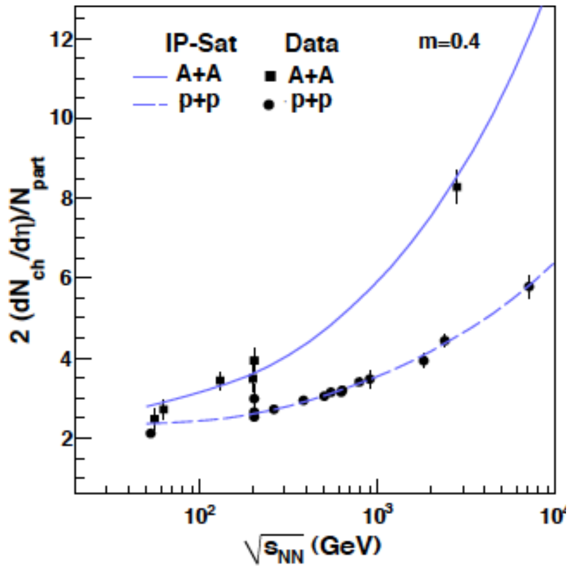
– in general need to solve classical Yang-Mills eqns when parton densities in both projectile and target are large…

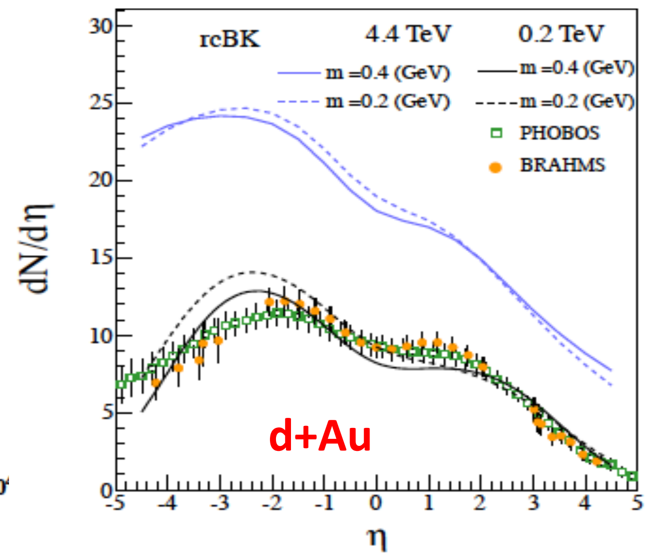
Gelis,Lappi,RV:0804.2630

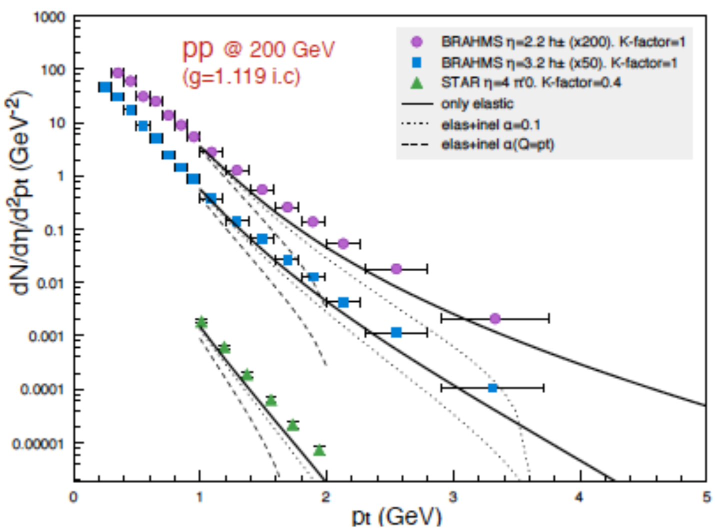
“Global analysis” of bulk distributions

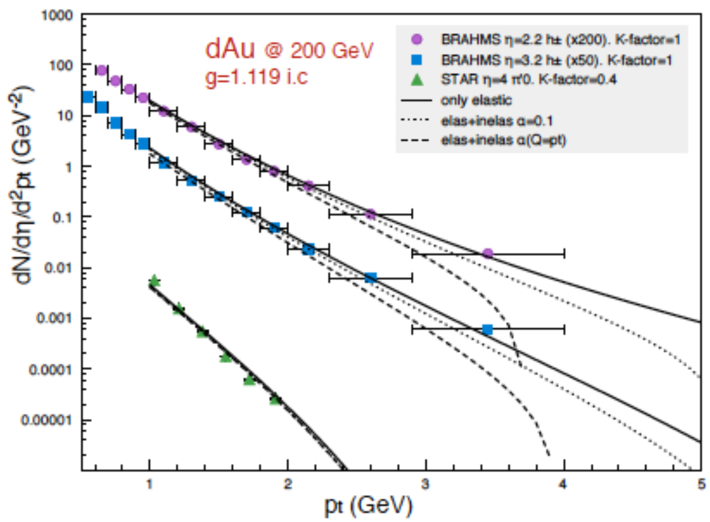
Tribedy,RV, 1112.2445











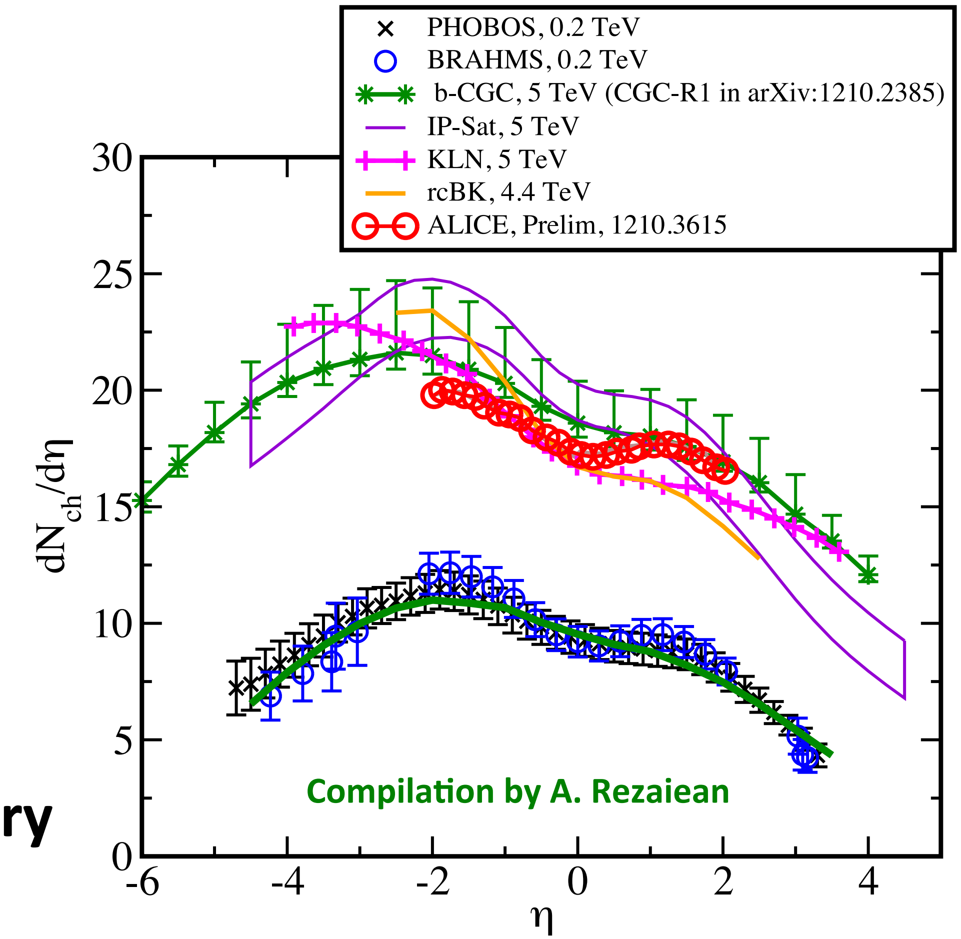
Albacete,Dumitru,Fujii,Nara,1209.2001

How do these models do with p+A at the LHC ?

In saturation models

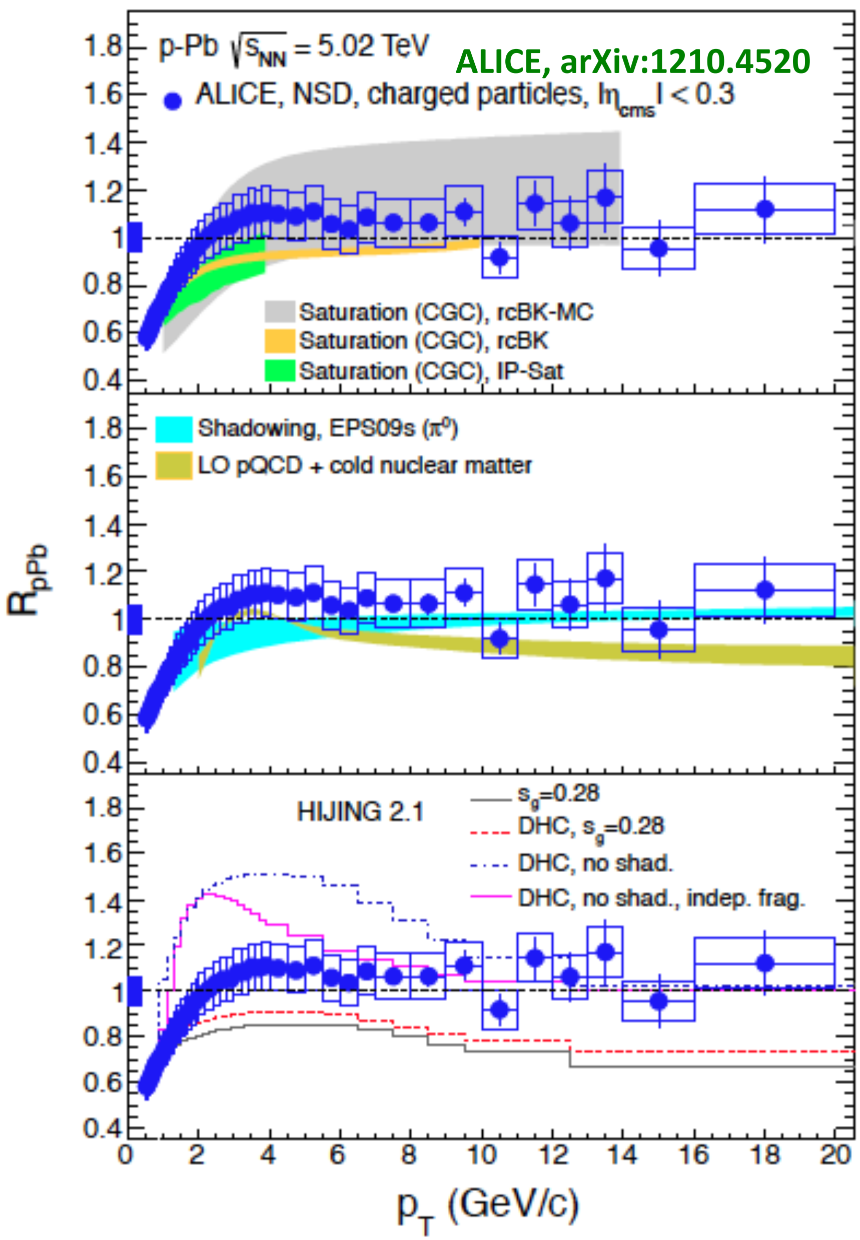
$$\frac{dN}{d\eta} \propto \frac{Q_S^2\, S_\perp}{\alpha_S(Q_S)}$$

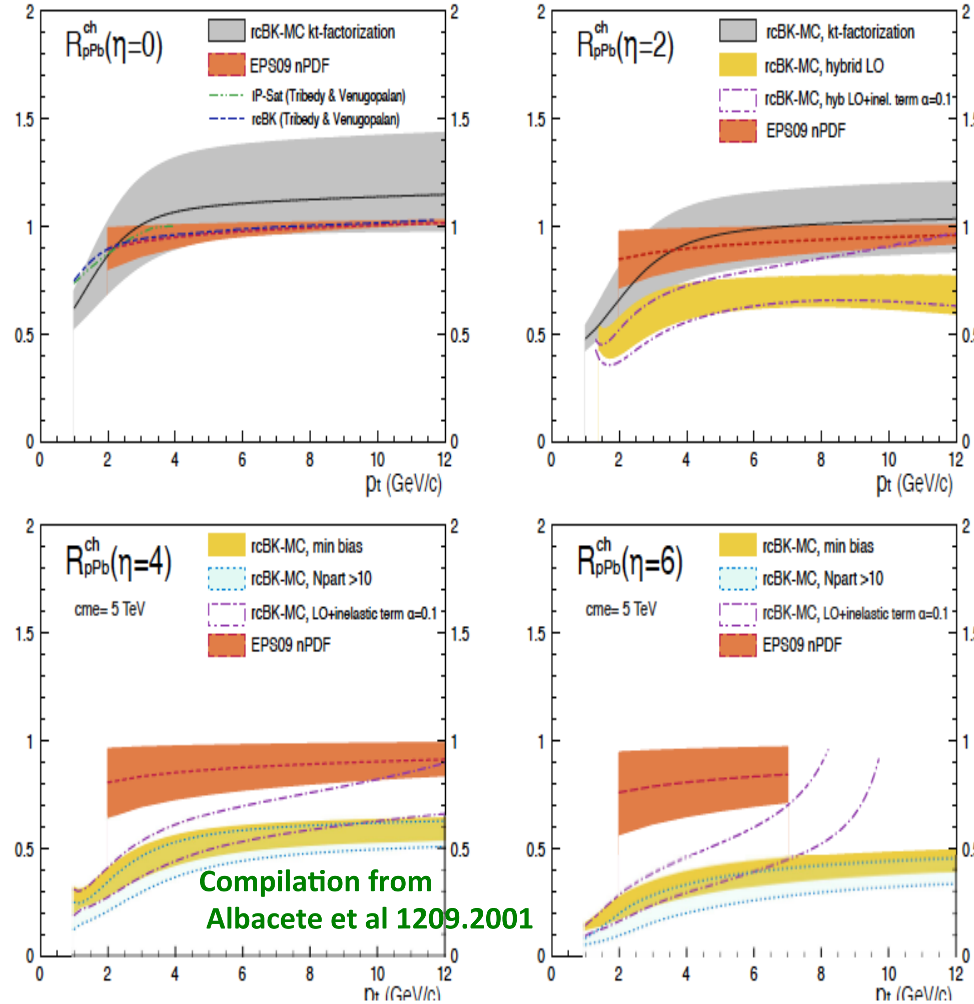
Multiplicities have some sensitivity to "infrared" non-pert. physics/geometry



Other model comparisons, see arXiv:1210.3615
-likely in Helen's talk…?

How do these models do with p+A at the LHC ?

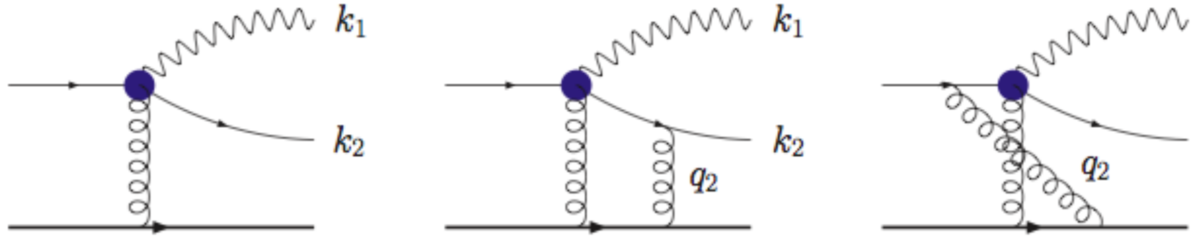




p+Pb run will add clarity

Di-hadrons in p/d-A collisions

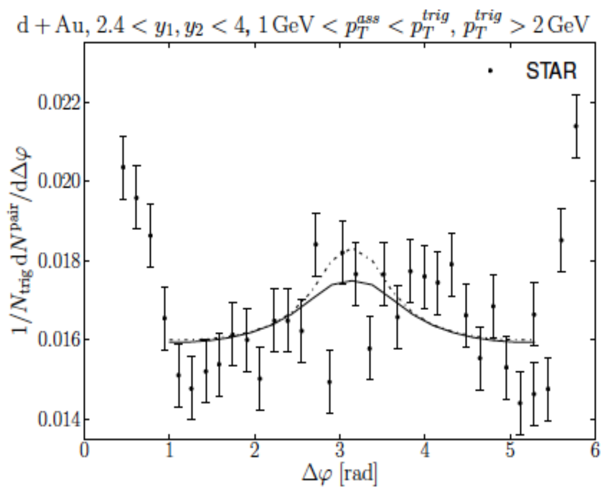
Jalilian-Marian, Kovchegov (2004)
Marquet (2007), Tuchin (2010)
Dominguez,Marquet,Xiao,Yuan (2011)
Strikman,Vogelsang (2010)

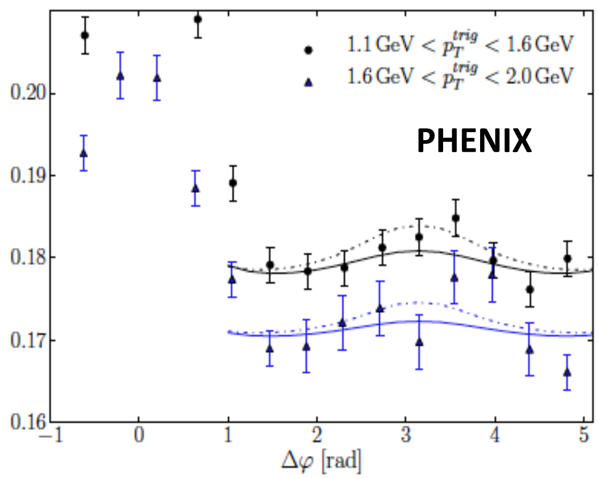


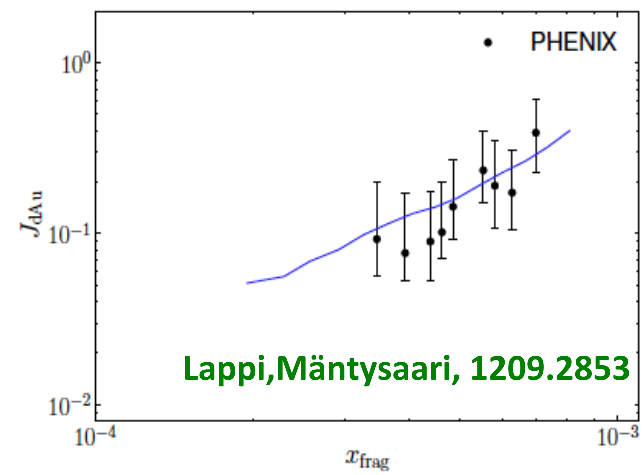
$$\frac{d\sigma^{qA\to qgX}}{d^3k_1 d^3k_2} \propto \int_{x,y,\bar{x},\bar{y}} e^{ik_{1\perp}\cdot(x-\bar{x})} e^{ik_{2\perp}\cdot(y-\bar{y})} \left[S_6(x,y,\bar{x},\bar{y}) - S_4(x,y,v) - \ldots\right]$$

$$\frac{N_c}{2\,C_F}\left\langle Q(x,y\,\bar{y},\bar{x})D(y,\bar{y}) - \frac{D(x,\bar{x})}{N_c}\right\rangle \quad \frac{N_c}{2\,C_F}\left\langle D(x,y)D(\bar{y},\bar{x}) - \frac{D(x,\bar{x})}{N_c}\right\rangle$$

Forward-forward di-hadrons sensitive to both dipole and quadrupole correlators

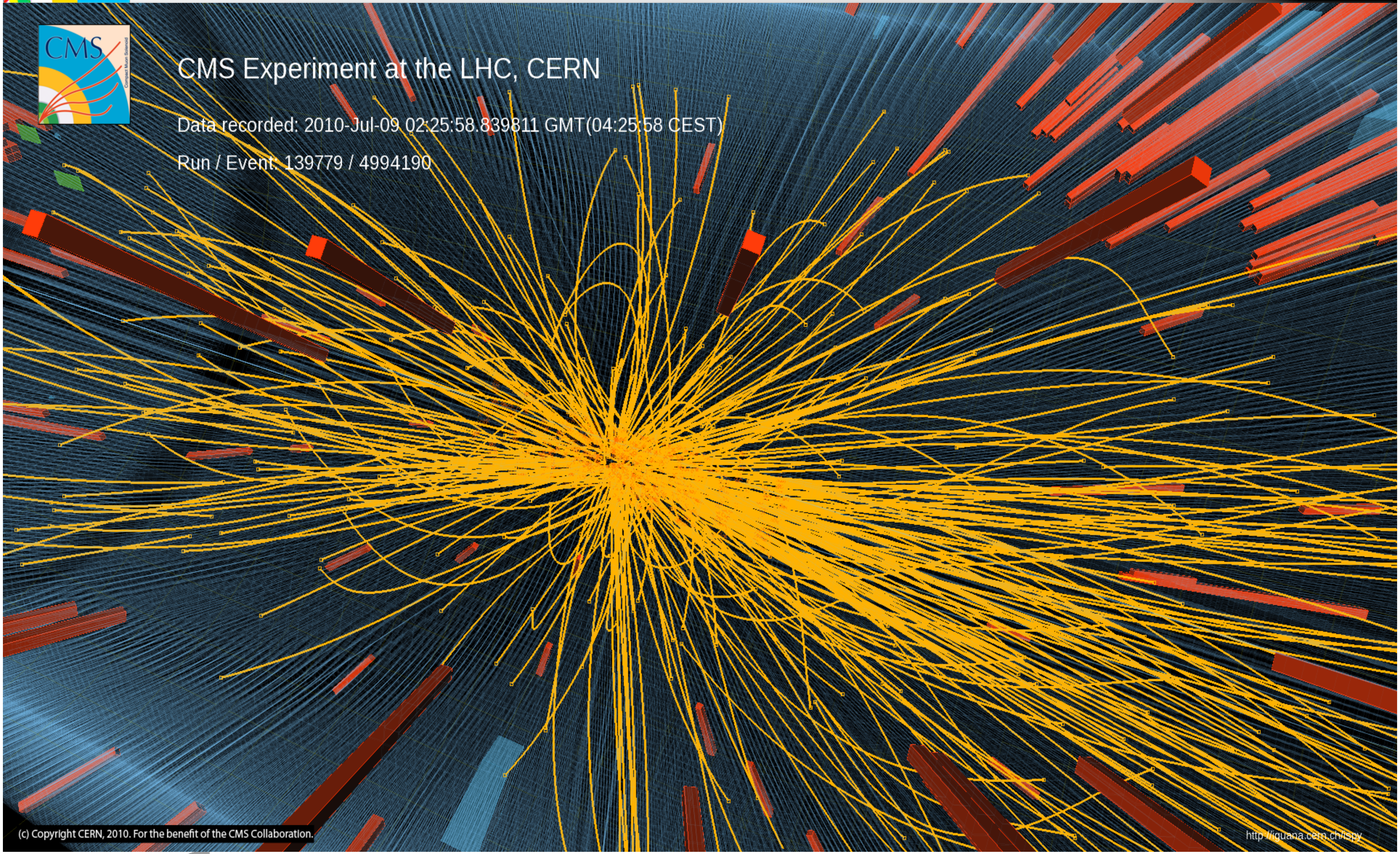






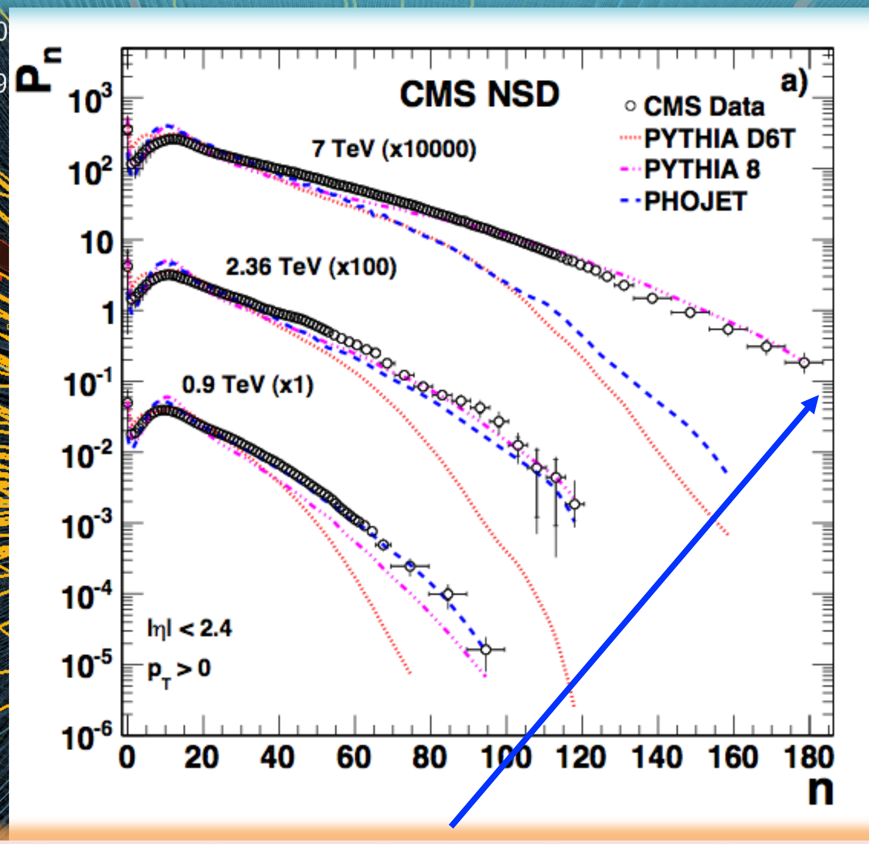
Recent computations (Stasto,Xiao,Yuan + Lappi,Mäntysaari) include Pedestal, Shadowing (color screening) and Broadening (multiple scattering) effects in CGC

High Multiplicity pp collisions



High Multiplicity pp collisions

High Multiplicity events are rare in nature



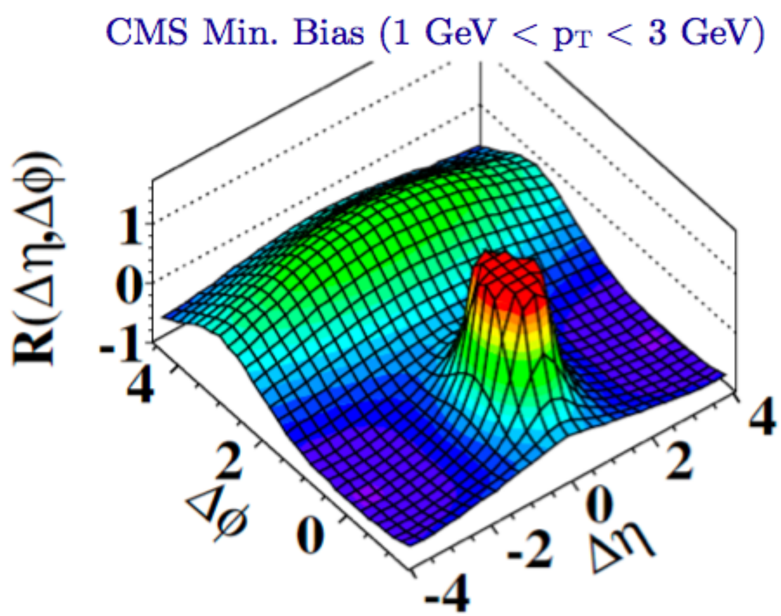
Very high particle density regime

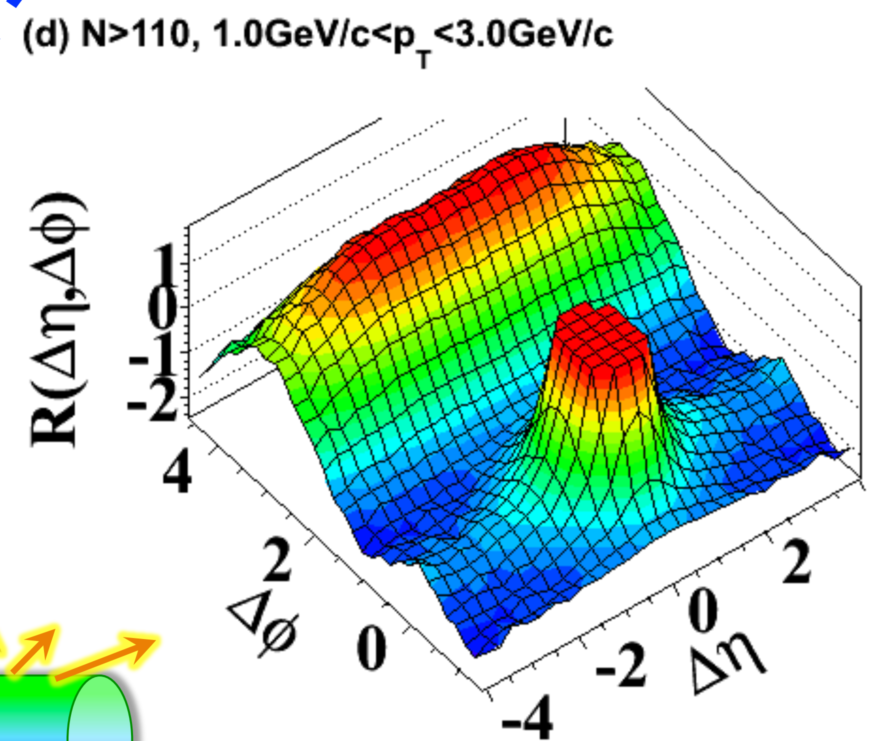
Is there anything peculiar happening there?

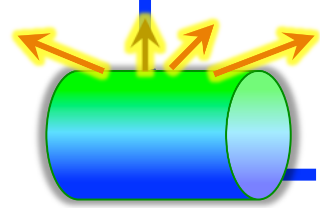
Two particle correlations in high mult. p+p

CMS 1009.4122

"Discovery"

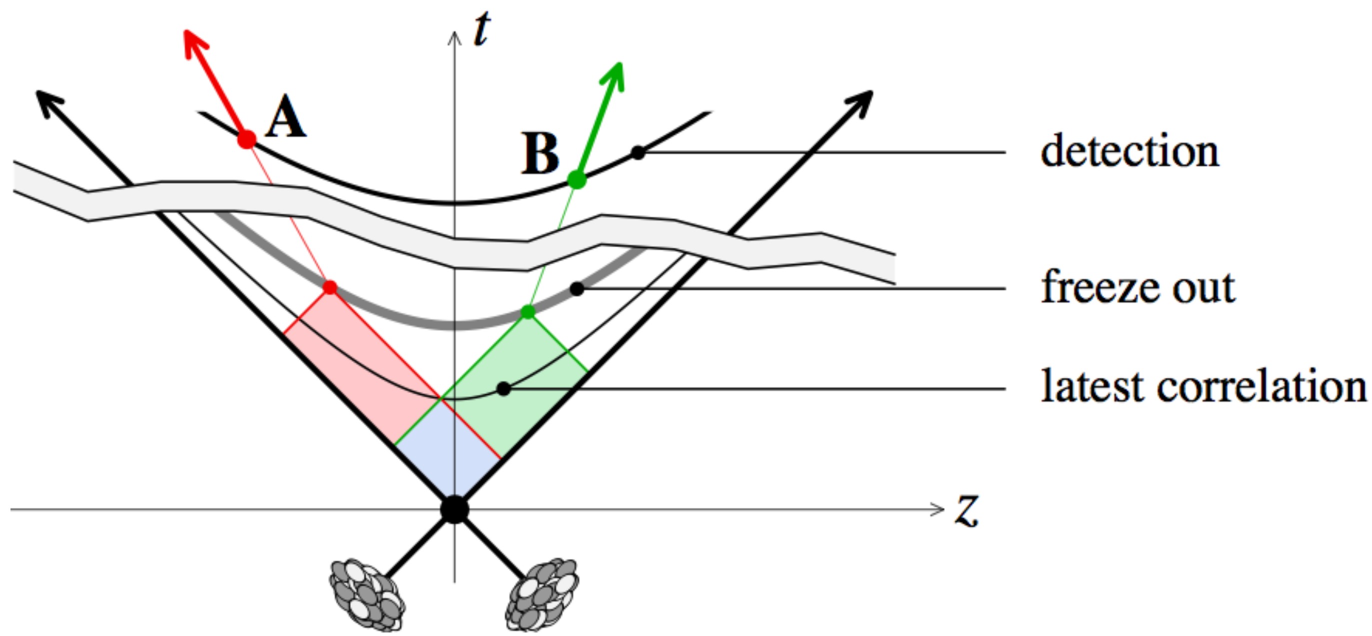






- **Ridge: Distinct long range correlation in η collimated around ΔΦ≈ 0 for two hadrons in the intermediate 1 < p_T, q_T < 3 GeV**

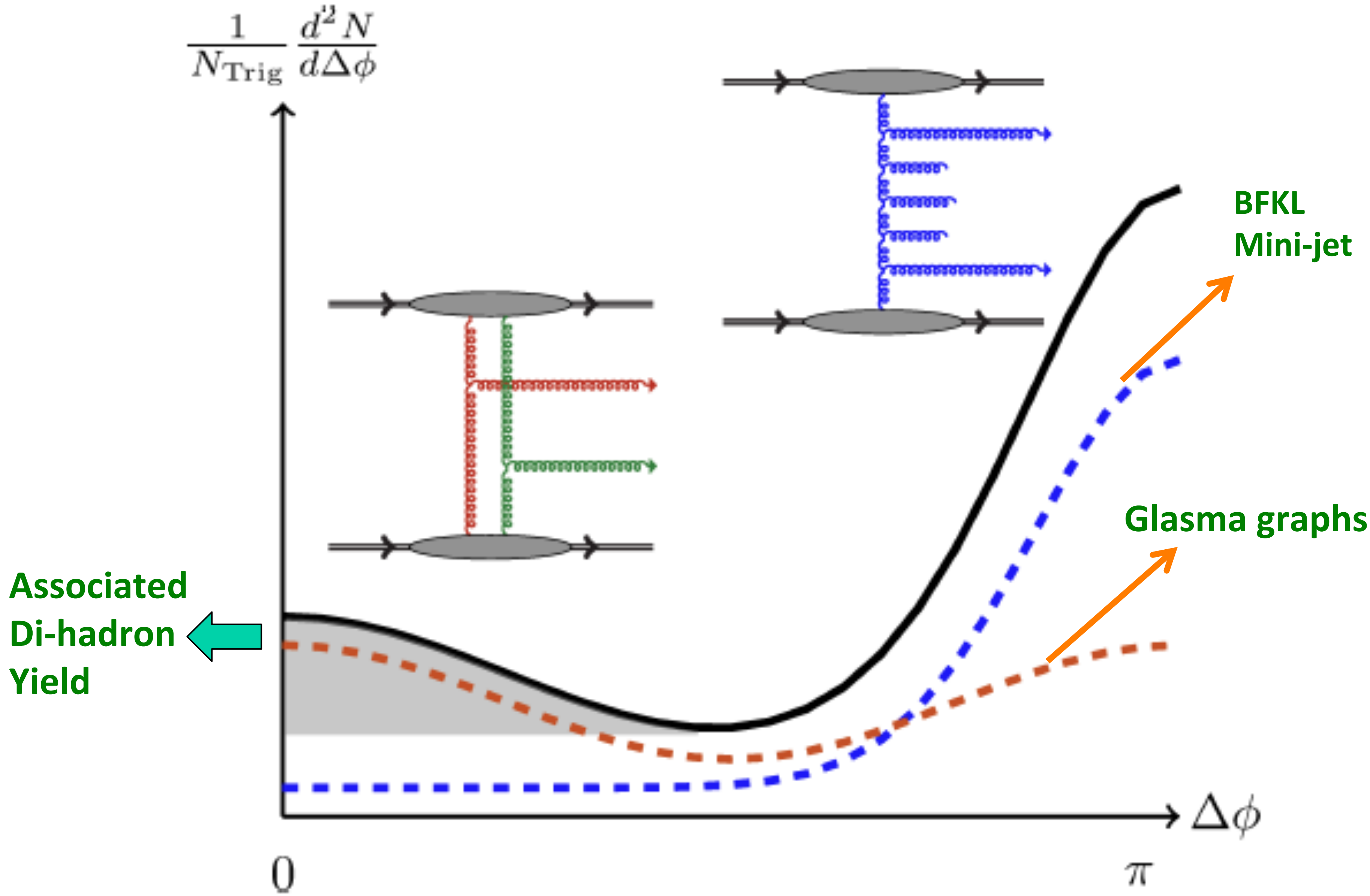
Long range rapidity correlations as a chronometer



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

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

Anatomy of long range di-hadron collimation

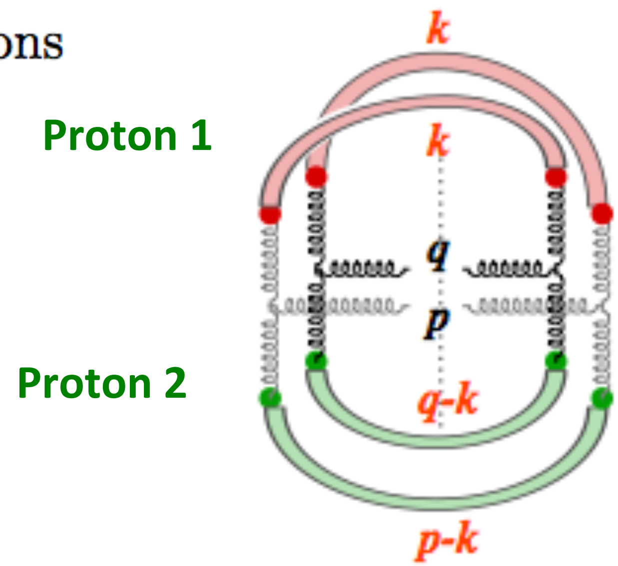


Long range di-hadron correlations

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

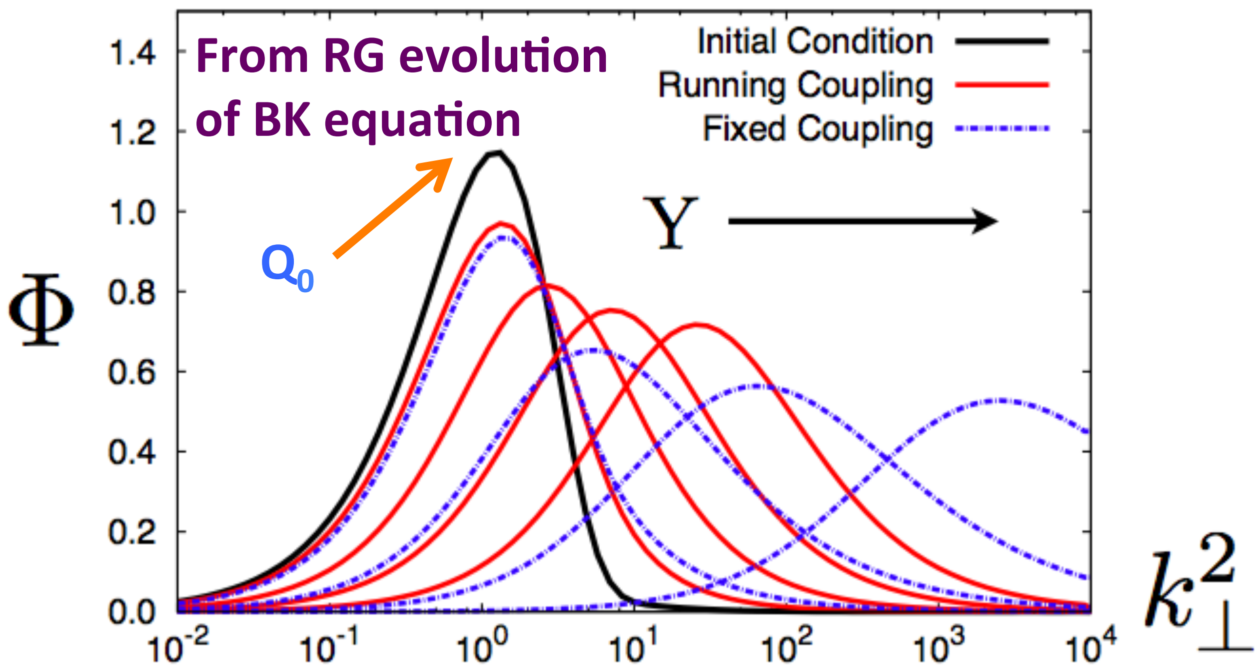
$$C(\mathbf{p},\mathbf{q}) \quad \propto \quad \frac{g^4}{\mathbf{p}_\perp^2\mathbf{q}_\perp^2}\int \mathrm{d}^2\mathbf{k}_{1\perp}\ \Phi_{A_1}^2(y_p,\mathbf{k}_{1\perp})\Phi_{A_2}(y_p,\mathbf{p}_\perp-\mathbf{k}_{1\perp})\Phi_{A_2}(y_q,\mathbf{q}_\perp-\mathbf{k}_{1\perp})$$
$$+ \quad \text{permutations}$$



Contribution ~ α_S^6/N_c^2 in min. bias, High mult. -> $1/\alpha_S^2\, N_c^2$
– enhancement of $1/\alpha_S^8$ ~ factor of 10^5 !

Collimated yield ?

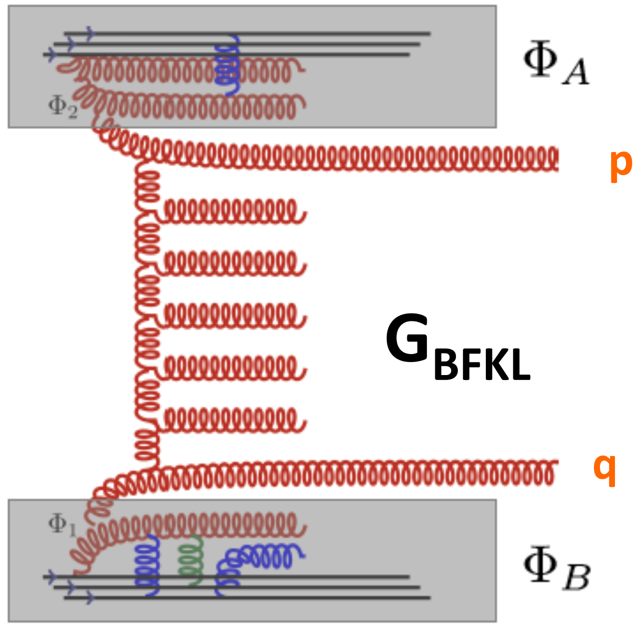
$$C(\mathbf{p},\mathbf{q}) \propto \frac{g^4}{\mathbf{p}_\perp^2 \mathbf{q}_\perp^2} \int d^2\mathbf{k}_{1\perp}\, \Phi^2_{A_1}(y_p,\mathbf{k}_{1\perp}) \Phi_{A_2}(y_p,\mathbf{p}_\perp - \mathbf{k}_{1\perp}) \Phi_{A_2}(y_q,\mathbf{q}_\perp - \mathbf{k}_{1\perp})$$
$$+ \quad \text{permutations}$$



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

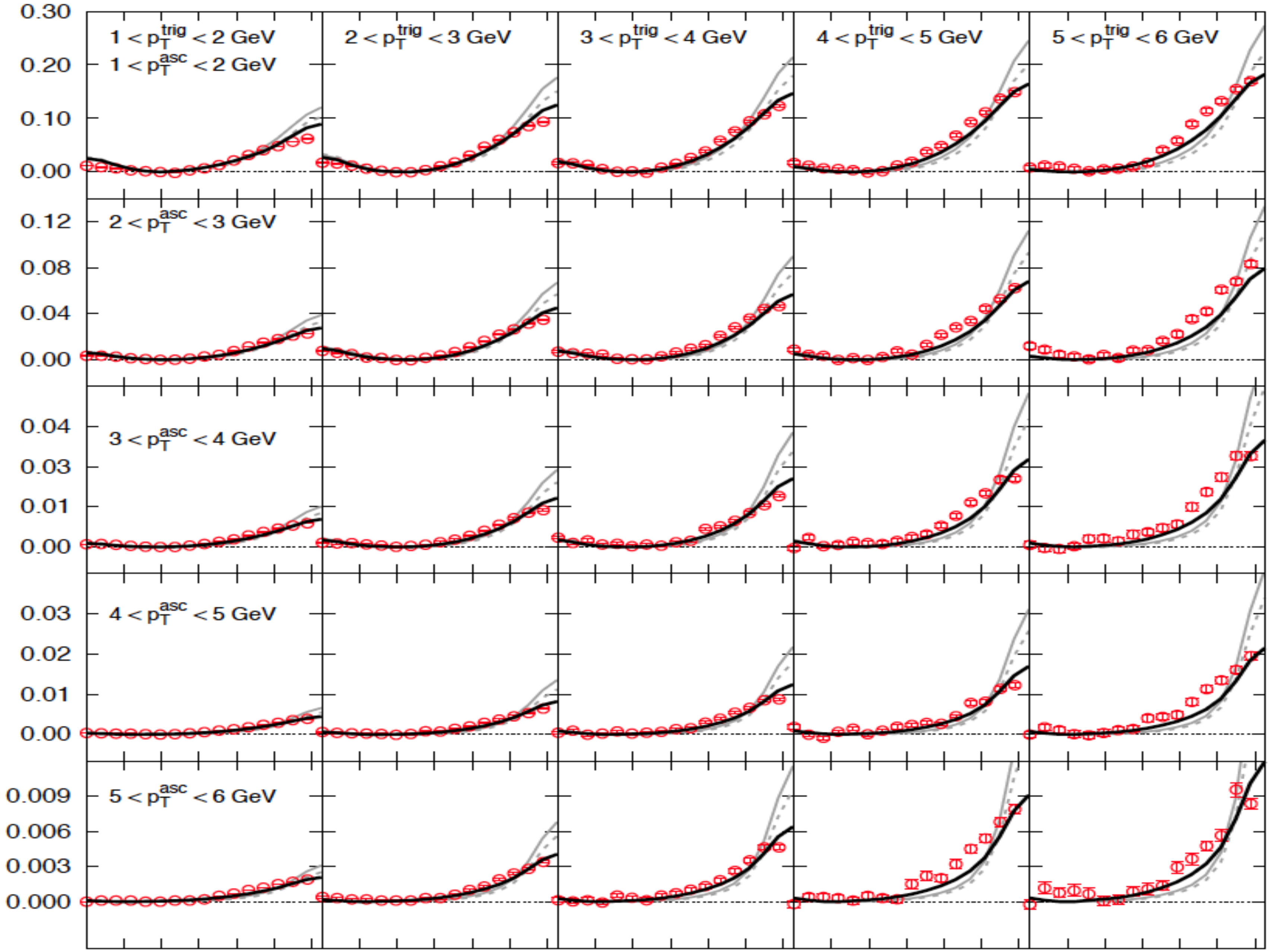


$$C_{\mathrm{BFKL}}(\mathbf{p},\mathbf{q}) \propto \Phi_A \otimes \Phi_B \otimes G_{\mathrm{BFKL}}$$

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

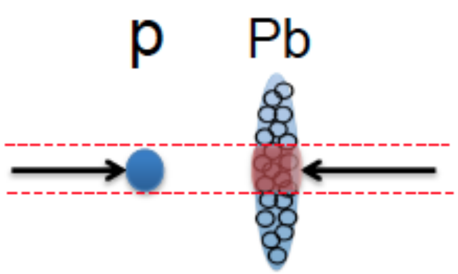
LHC results also test the structure of bremsstrahlung radiation between jets

Dusling, RV: 1201.2658
1210.3890

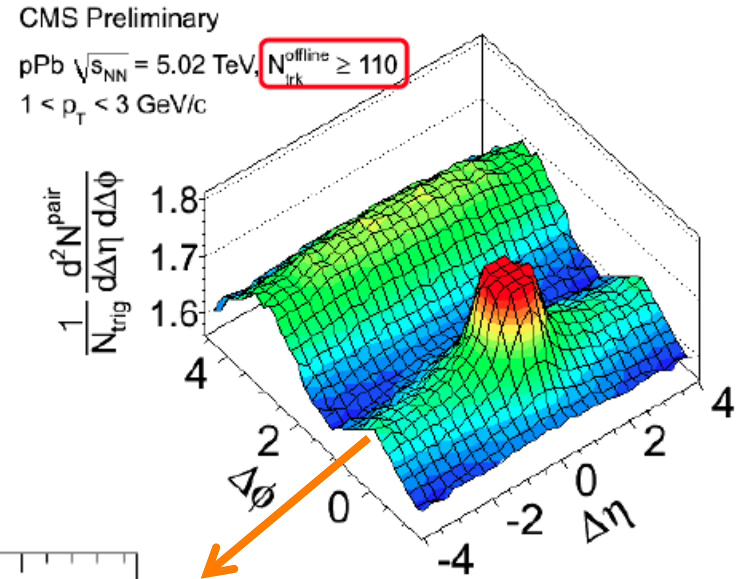


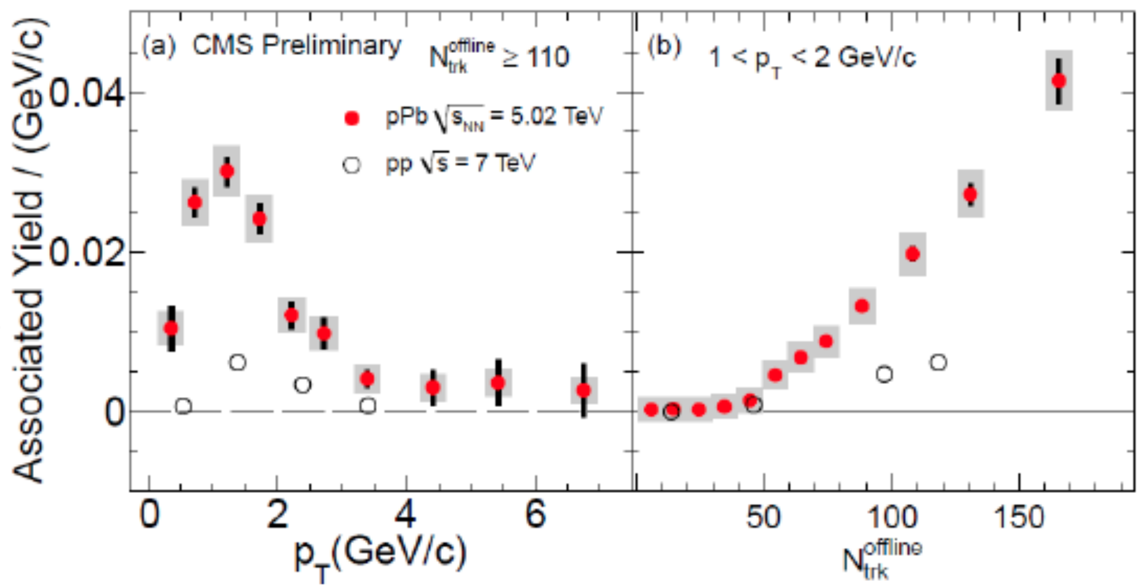
Exciting first results on proton lead collisions

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



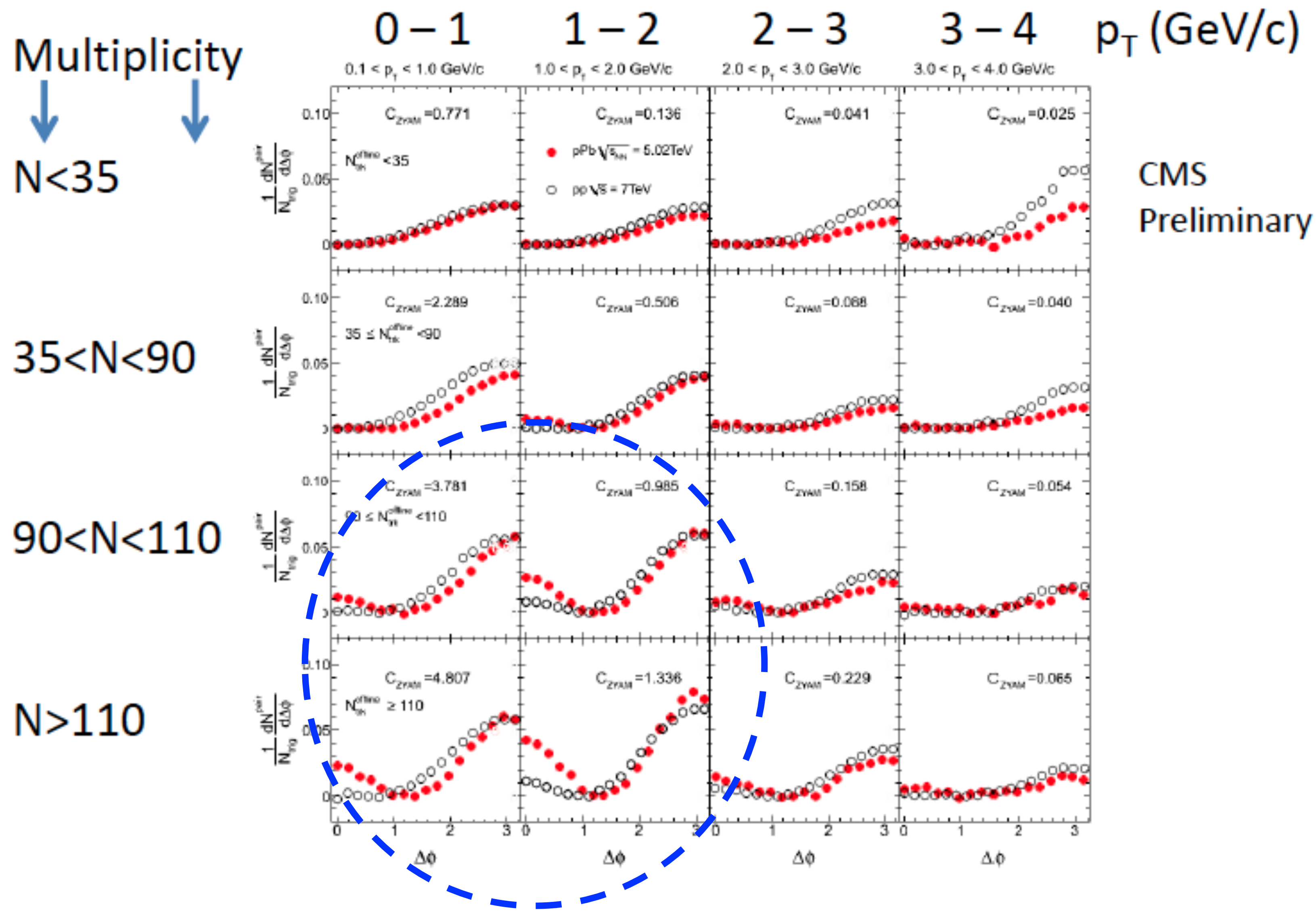
Highest transverse density





Key observation: Ridge much bigger than p+p for the *same* multiplicity !

Exciting results on proton lead collisions

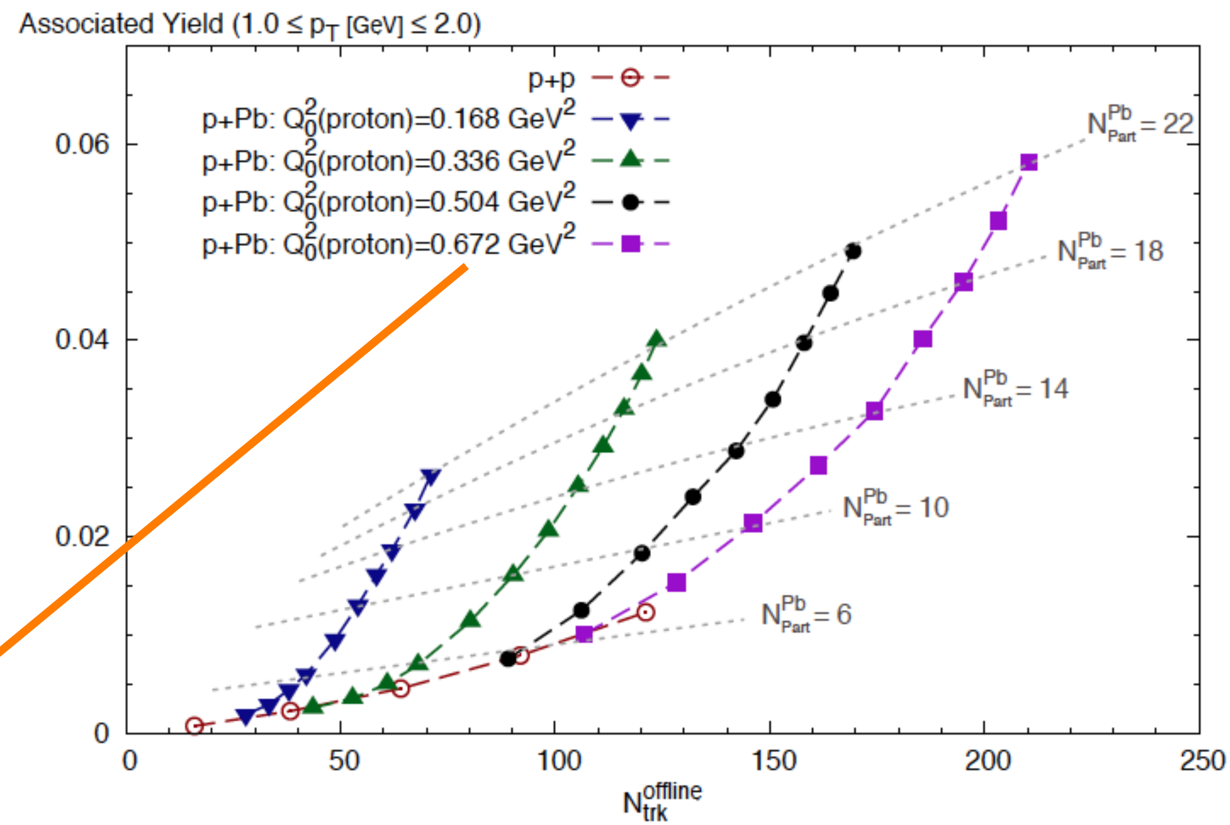


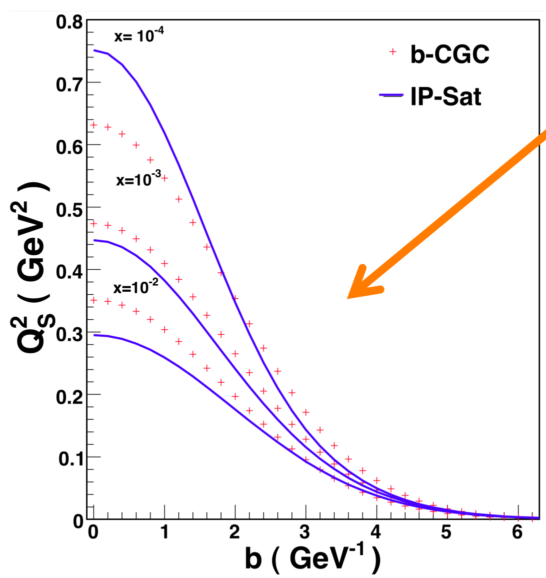
Systematics of p+Pb data explained

Dusling, RV: 1211.3701

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

of “wounded” nucleons in Lead nucleus





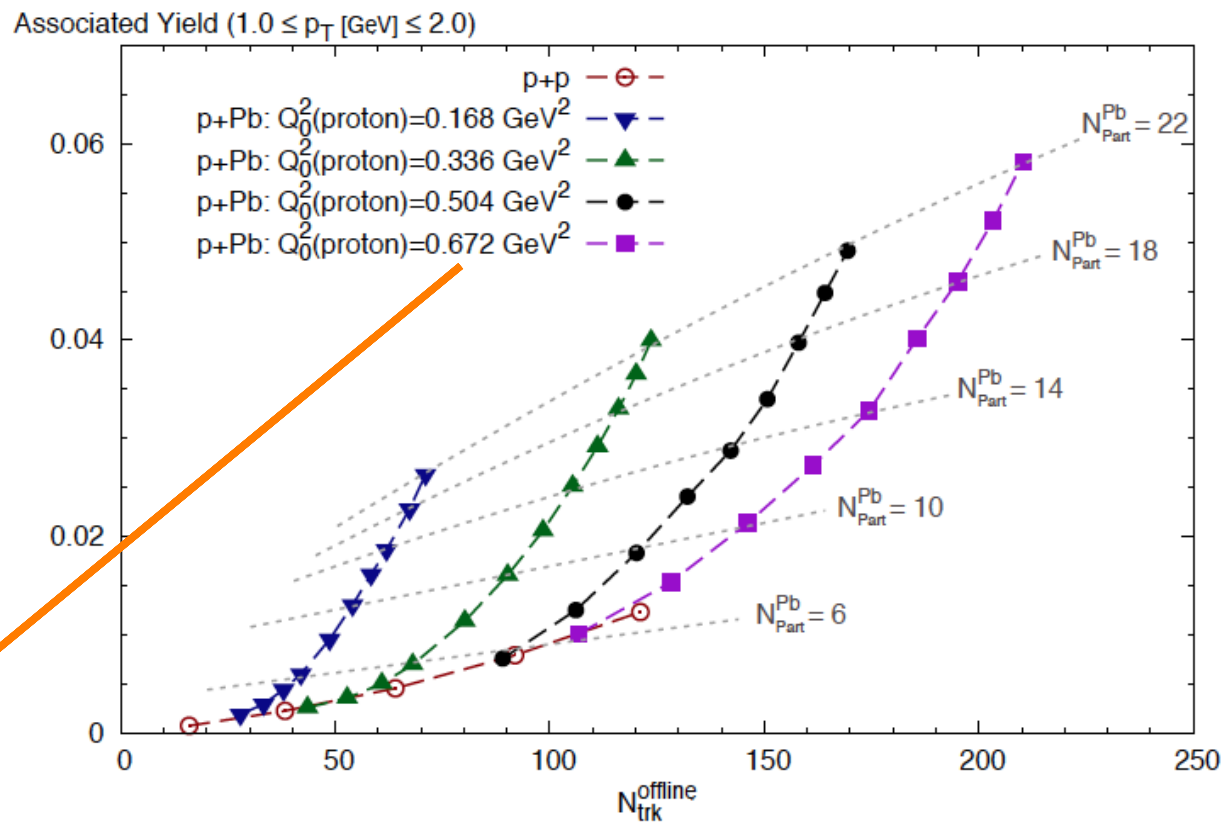
Glasma signal is ~ $N_{part} * N_{track}$

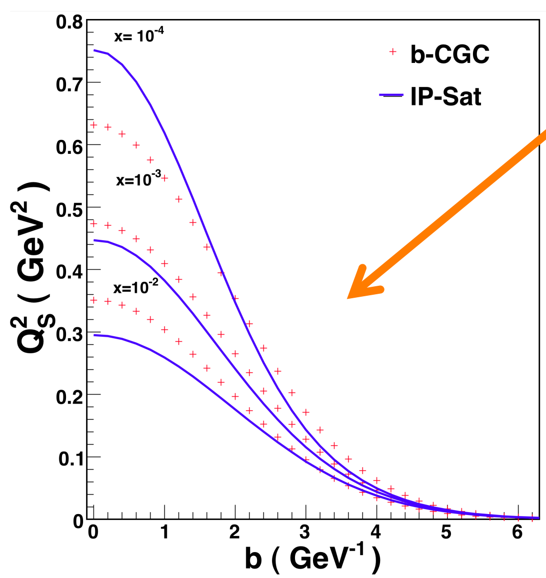
p+Pb data explained

Dusling, RV: 1211.3701

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

of "wounded" nucleons in Lead nucleus

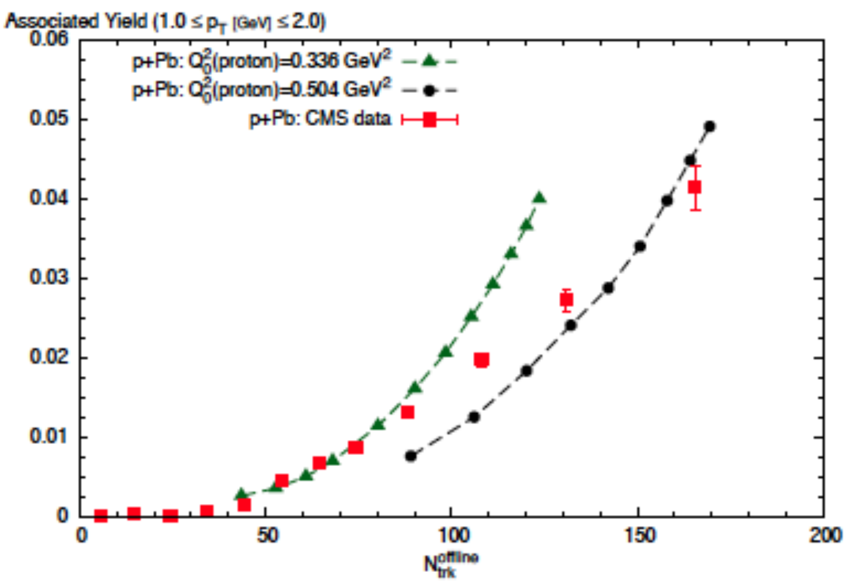


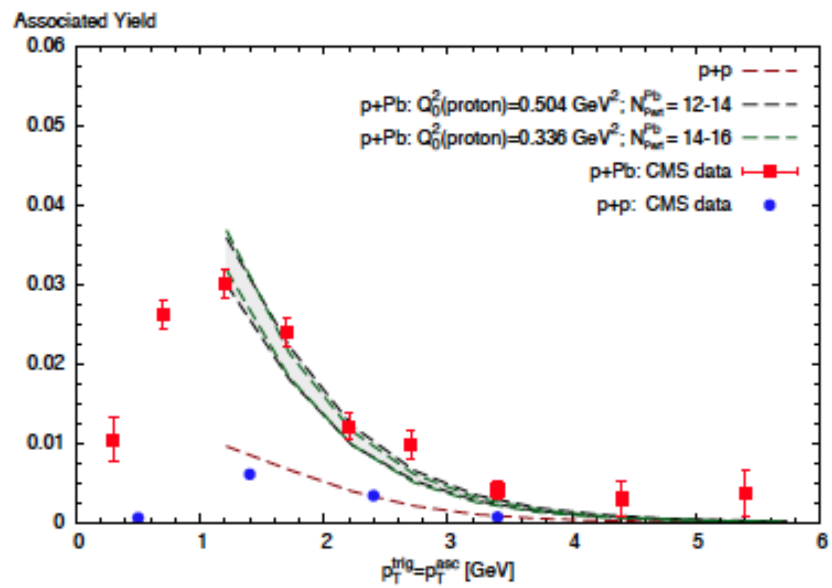


Large "ridge" seen in Color Glass Condensate by varying saturation scale in proton and # of wounded nucleons

CMS p+Pb data explained

Dusling, RV: 1211.3701



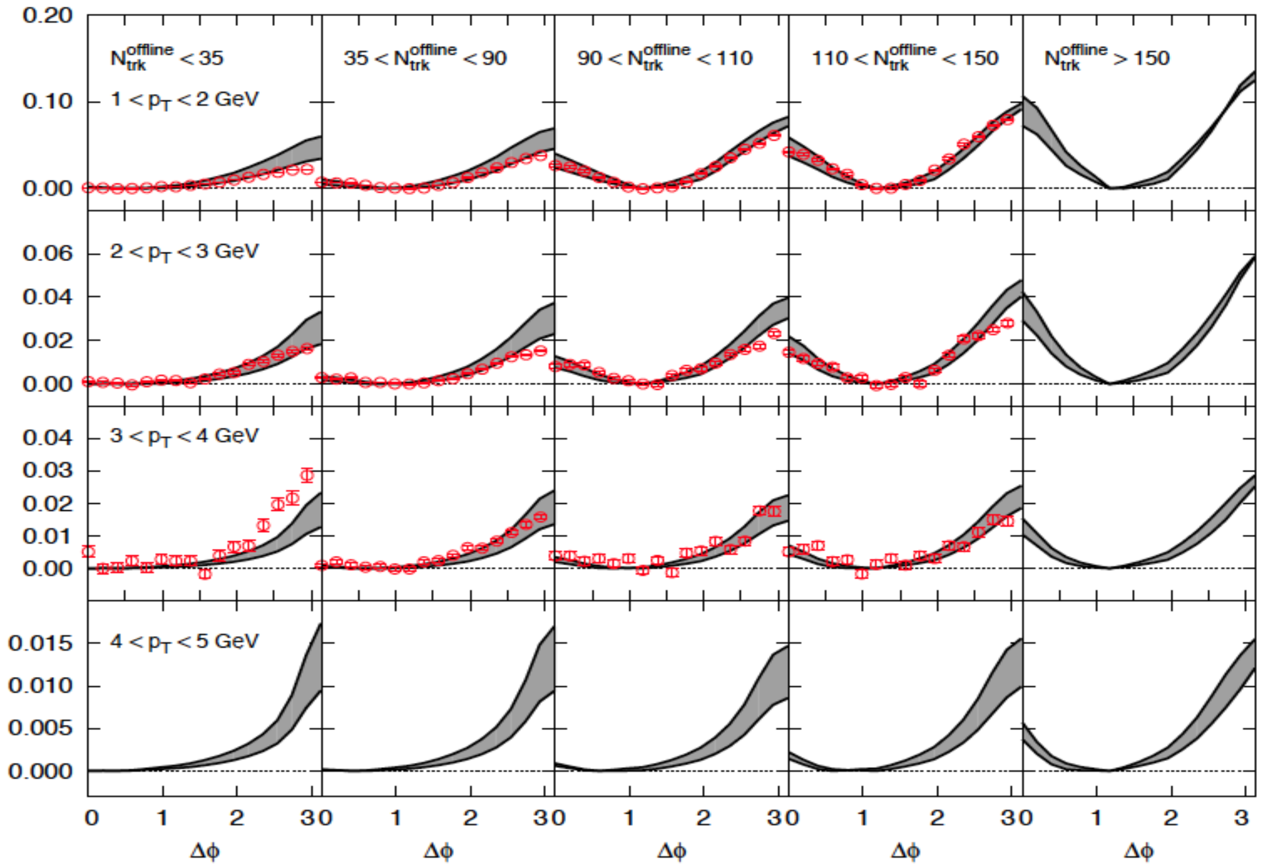


Same parameters as in p+p

- gives larger ridge when saturation scales are varied

CMS p+Pb data explained

Dusling, RV: 1211.3701



Smoking gun for gluon saturation and BFKL dynamics ?

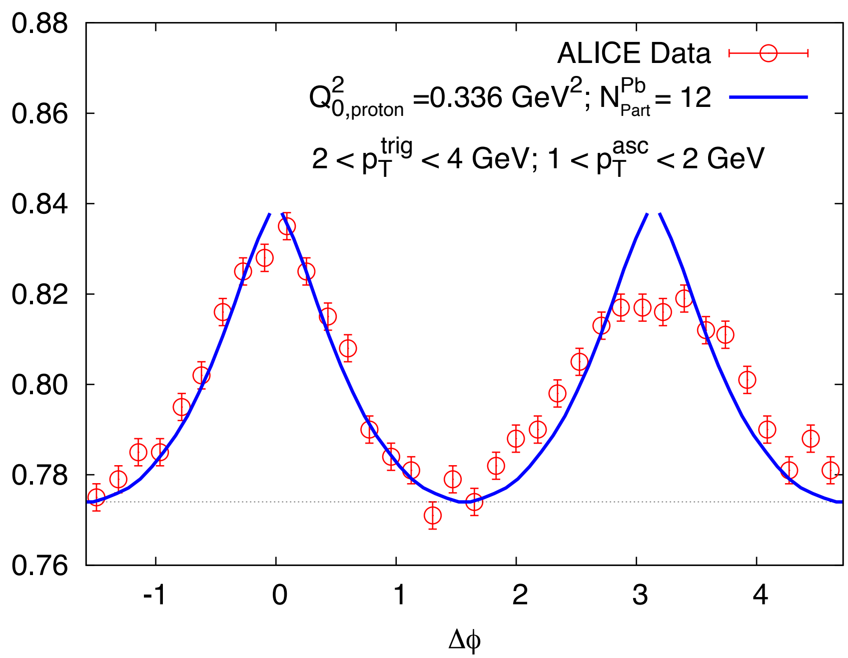
ALICE data on the p+Pb ridge

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



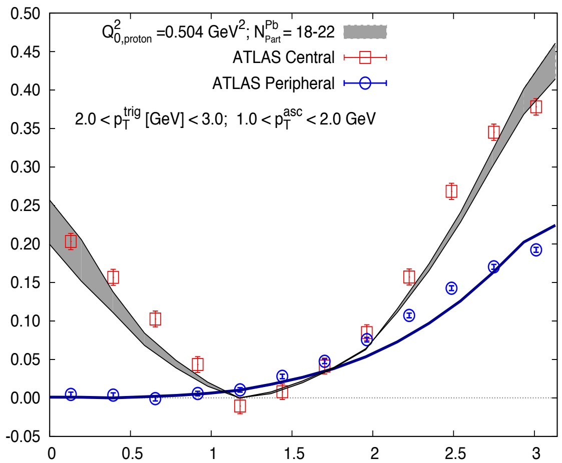
Different analysis technique from CMS/ATLAS

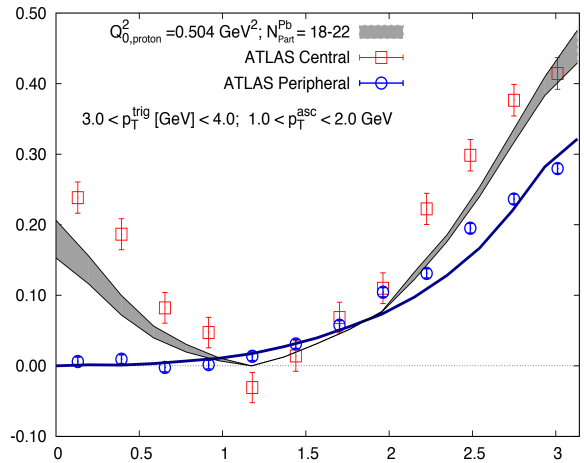
-- our fit here is with arbitrary normalization

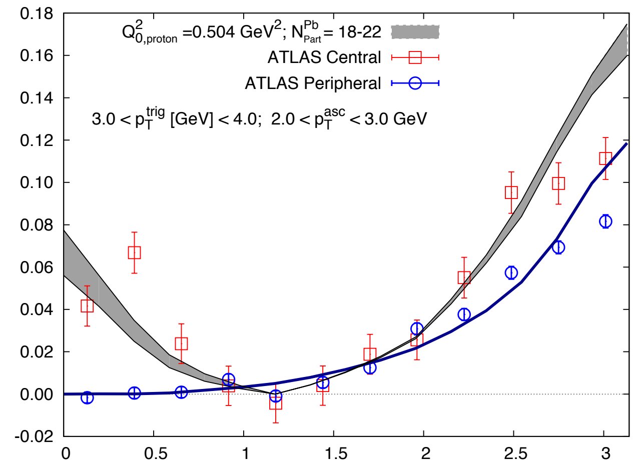
Comparison to ATLAS p+Pb ridge

ATLAS coll. arXiv: 1212.5198

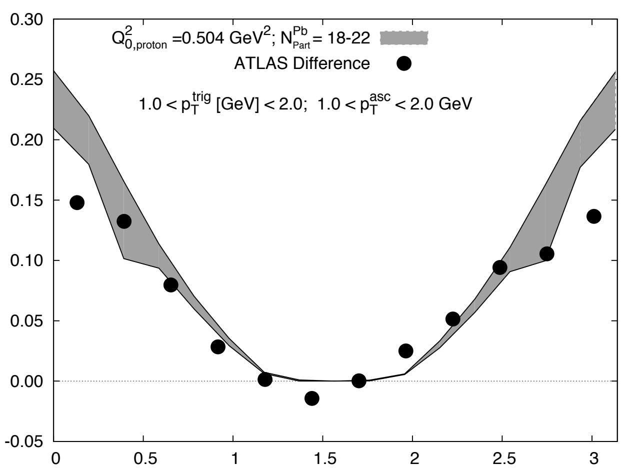
ATLAS yields in asymmetric p_T windows compared to Glasma + BFKL: K_{BFKL}=1 and K_{glasma}=4/3

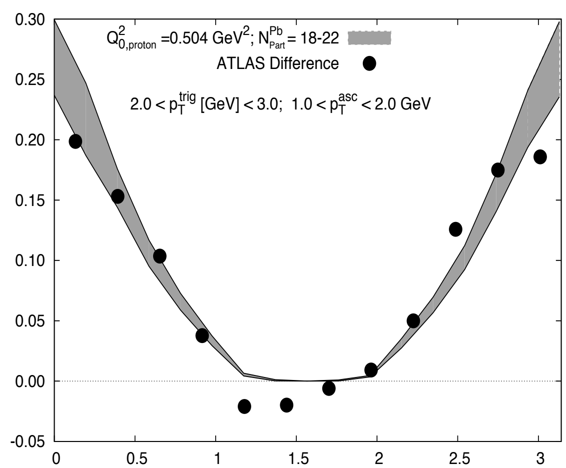


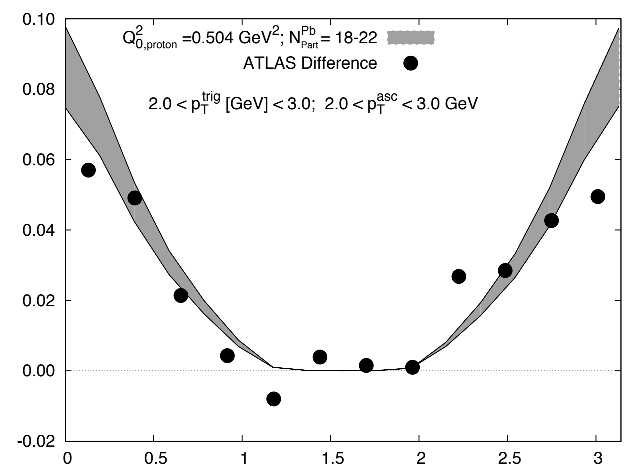




Glasma graph contributions compared to ATLAS central – ATLAS peripheral

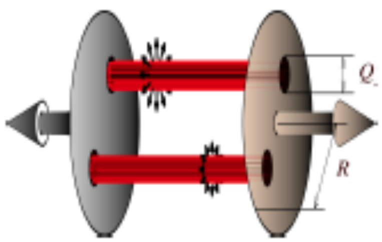


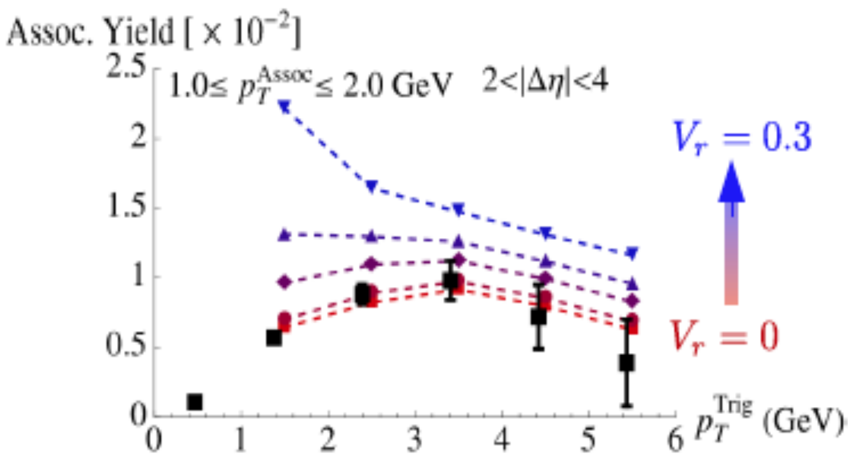




p+p vs A+A

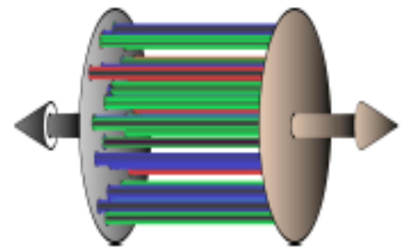
In p+p we are seeing the intrinsic collimation from a single flux tube

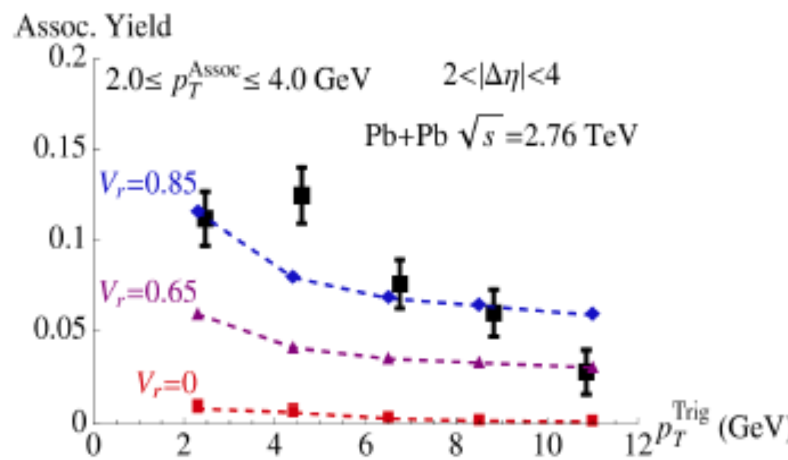




Increasing transverse flow in p+p creates a discrepancy with data.

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

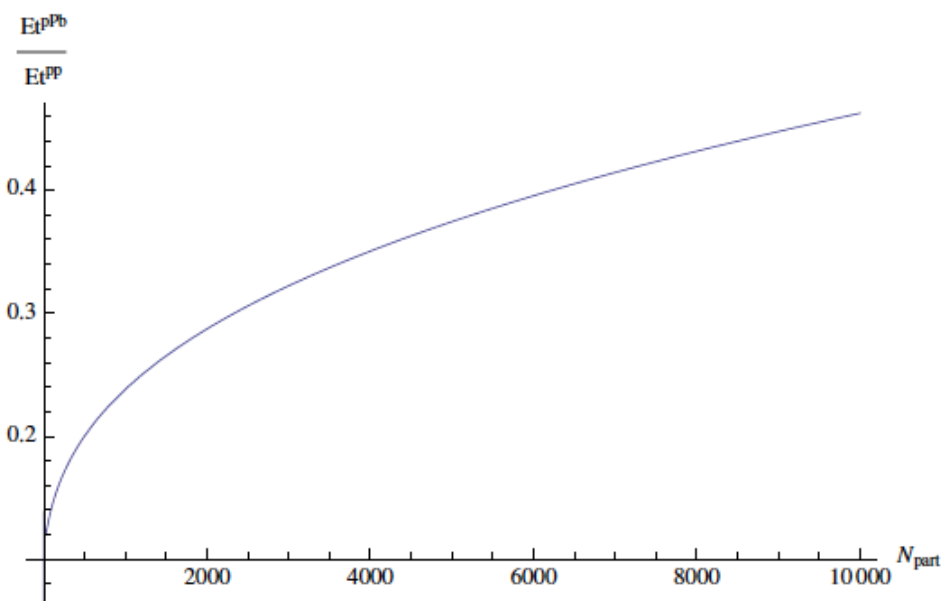
IP-Glasma + MUSIC model

Can flow in p+A explain the ridge ?

In a thermal picture, for same transverse overlap area, $\varepsilon_{pp} \approx \varepsilon_{pA}$ when $N_{track}^{pp} = N_{track}^{pA}$

For same energy densities, expect same flow dynamics but pA yield is ~ 6 times larger than pp

In CGC picture, $\varepsilon_{pA} < \varepsilon_{pp}$ for same N_{track} until very large N_{part}



Flow explanation unlikely based on this simple argument
+
questions about applicability to small size systems for large transverse momenta

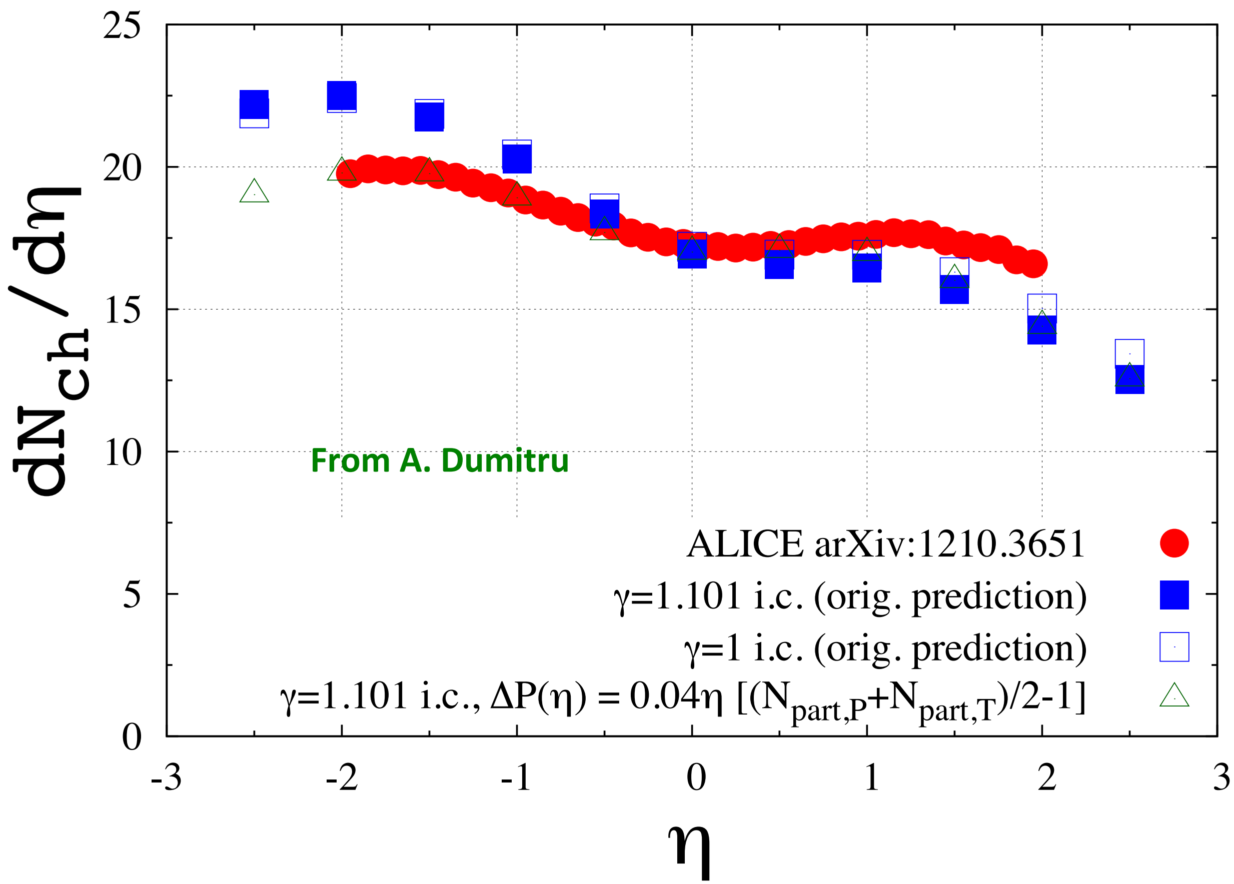
Summary

✧ **Have not covered many interesting channels: quarkonia, jets, photons that carry unique information about high parton densities**

✧ **Exciting year for such studies and much to look forward to @ RHIC ↑pA and EIC**

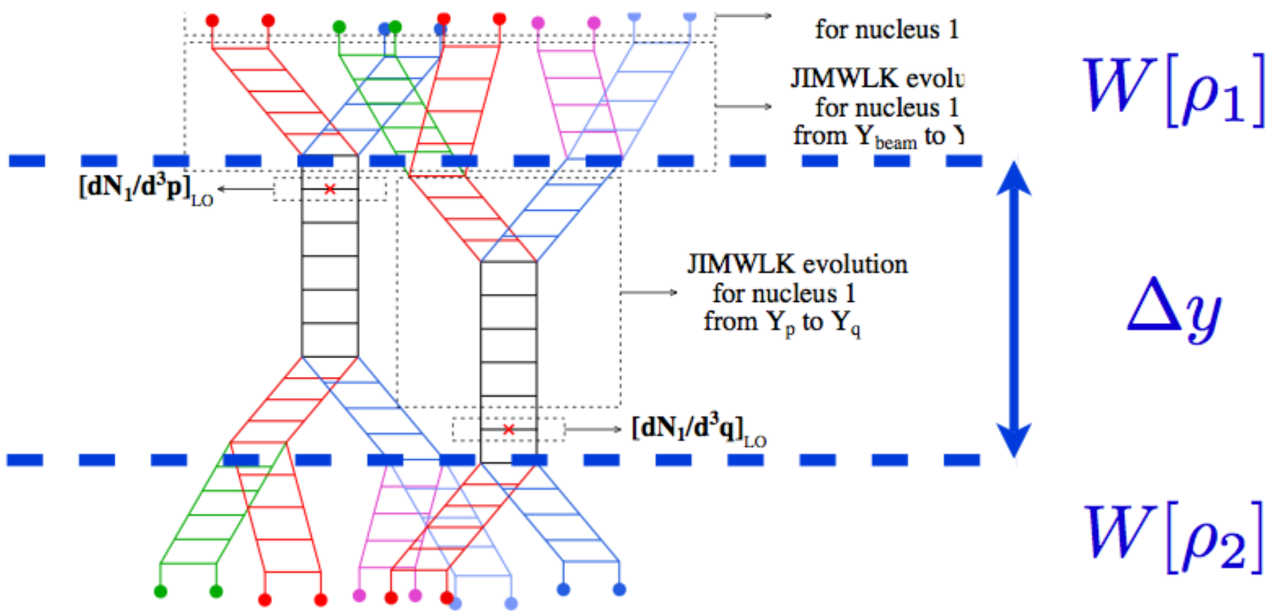
EXTRA SLIDES

MC rc BK LHC pseudo-rapidity dist. With different y -> η Jacobian

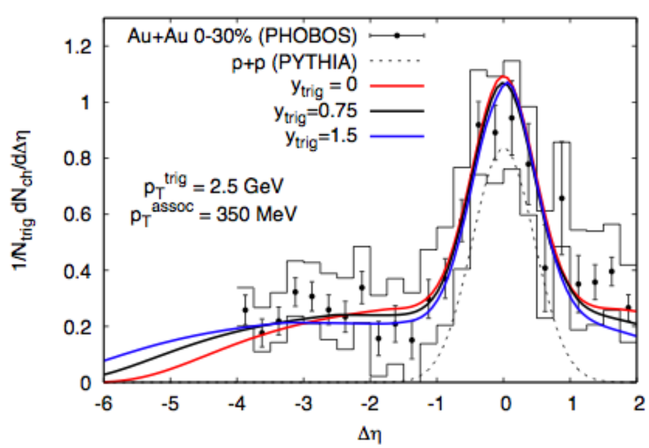


Long range di-hadron correlations

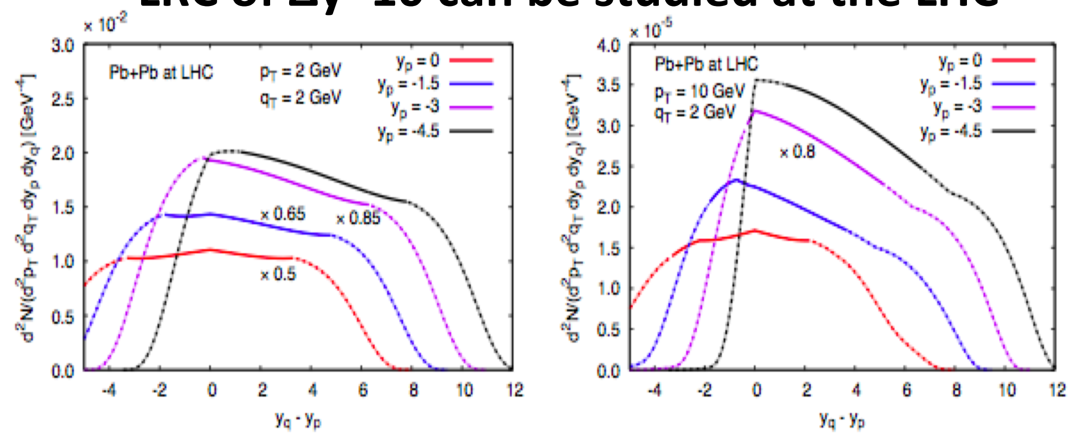
Gelis,Lappi,RV, arXiv:0810.4829



Dusling,Gelis,Lappi,RV, arXiv:0911.2720



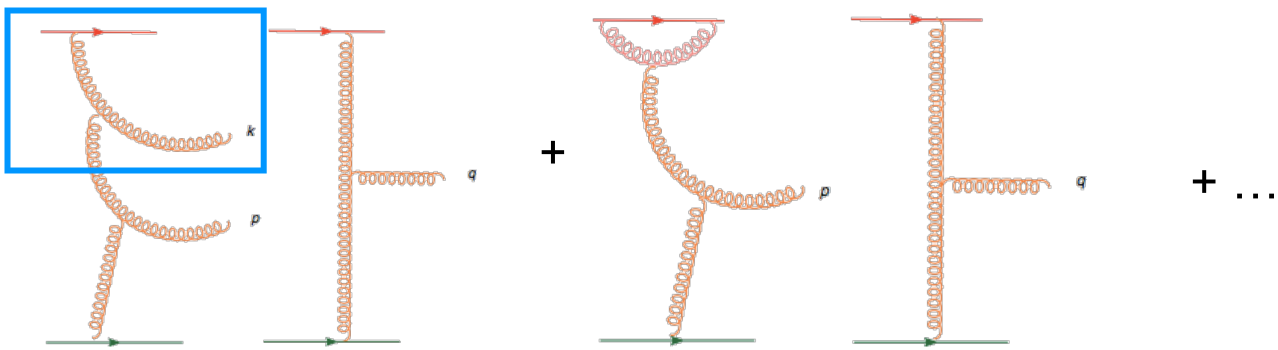
LRC of Δy~10 can be studied at the LHC



The saturated proton: Glasma graphs -I

RG evolution:

Gelis, Lappi, RV, arXiv: 0807.1306

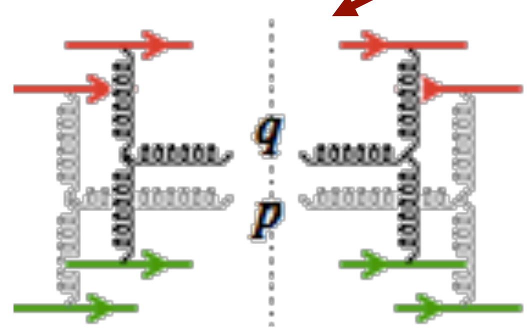


Keeping leading logs to all orders (NLO+NNLO+…) 2-particle spectrum (for $\Delta y < 1/\alpha_S$)

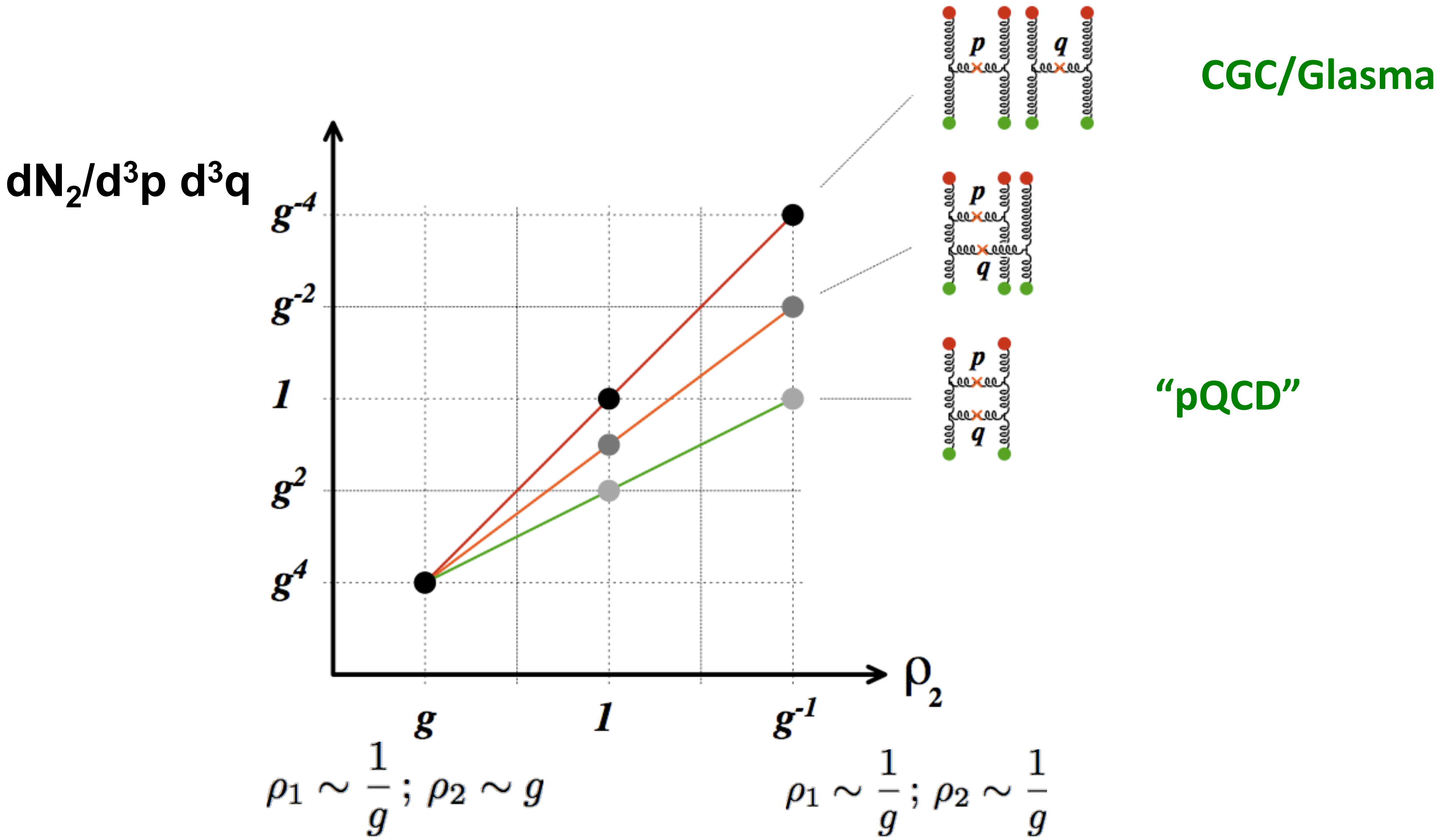
$$\langle \frac{dN_2}{d^3p\, d^3q} \rangle_{\rm LLogs} = \int [d\rho_1][d\rho_2] W_{Y_1}[\rho_1]\, W_{Y_2}[\rho_2]\, \frac{dN}{d^3p}|_{\rm LO}\, \frac{dN}{d^3q}|_{\rm LO}$$

= LO graph with evolved sources

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

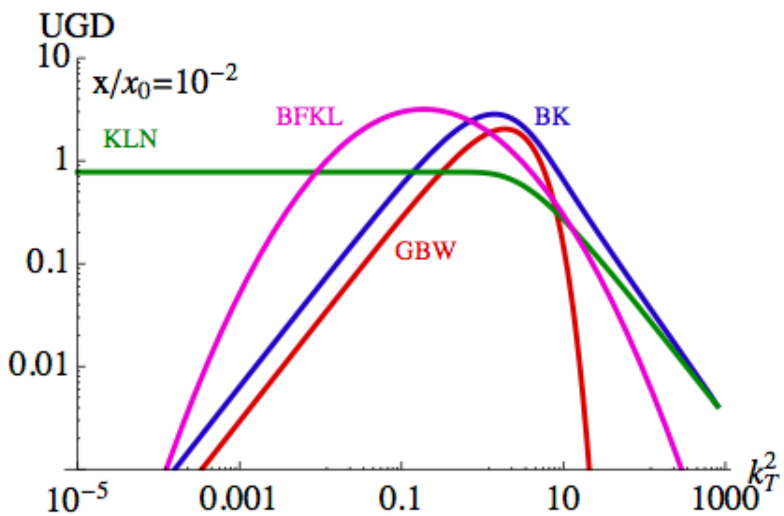


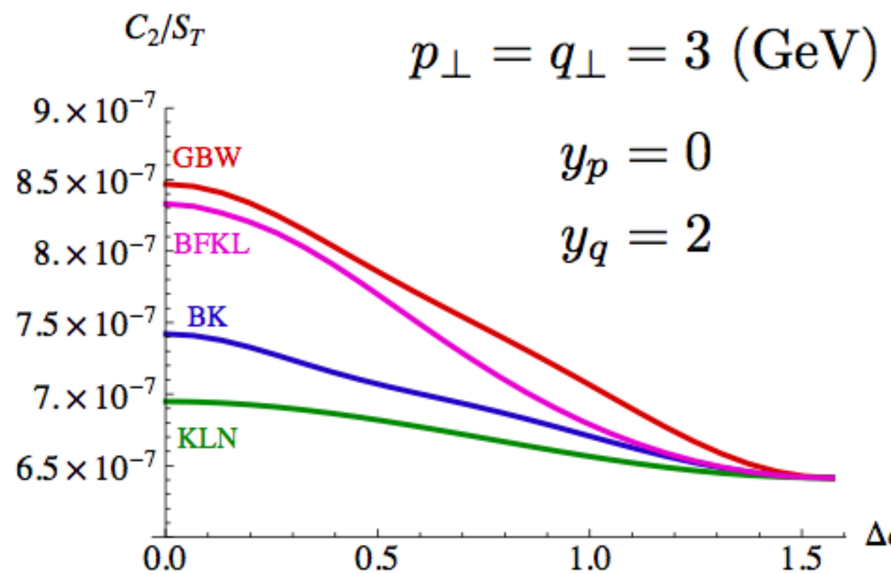
Power counting at high parton densities



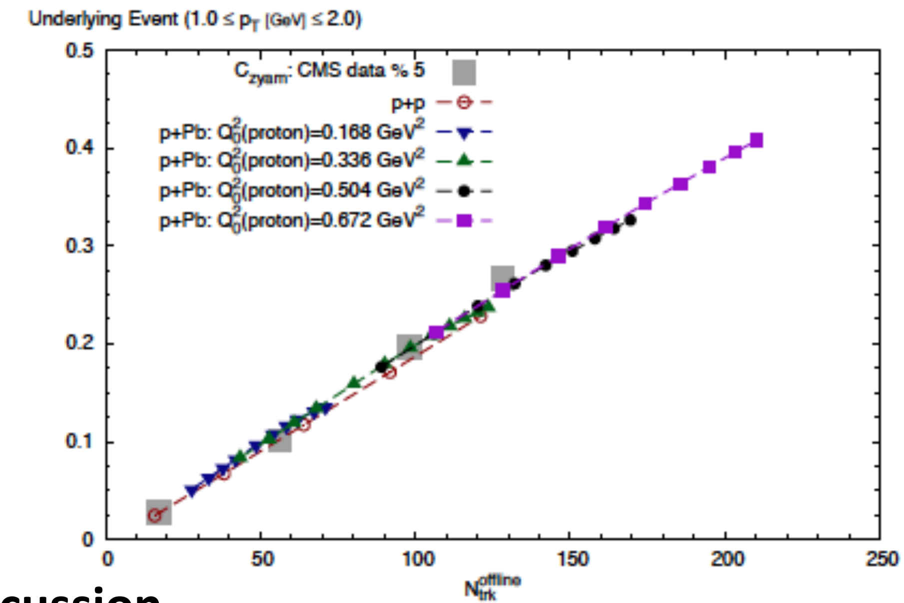
When ρ_1, ρ_2 ~ g, "dilute limit", CGC contribution is g^{12} – power counting changes from "dense limit" by $\alpha_S^{\ 8}$!

Physics underlying the ridge





Physics underlying the ridge



From previous discussion

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

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:

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

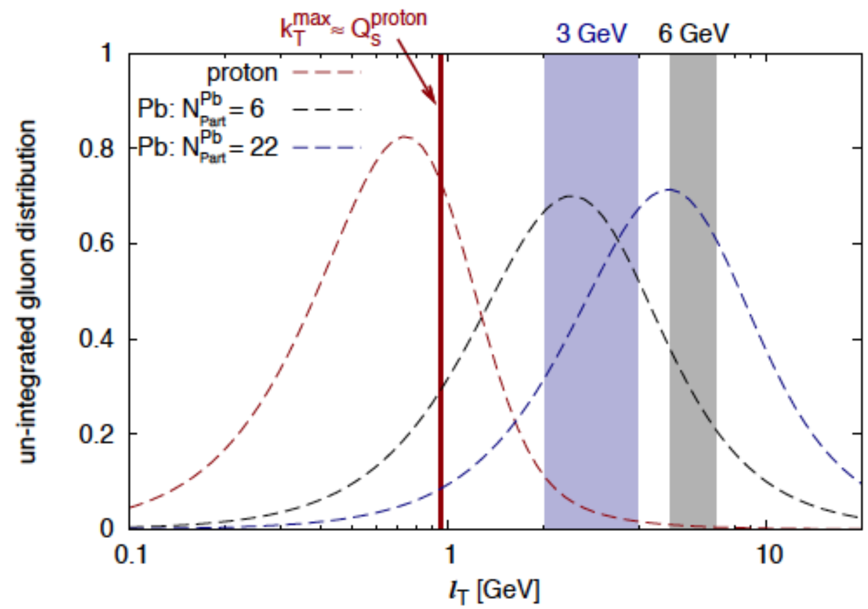
Equality implies no collimation; satisfied only iff $\Phi_B(|p_T - k_T|) \propto \Phi_B(|q_T - k_T|)$

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 $|p_T|=|q_T|$

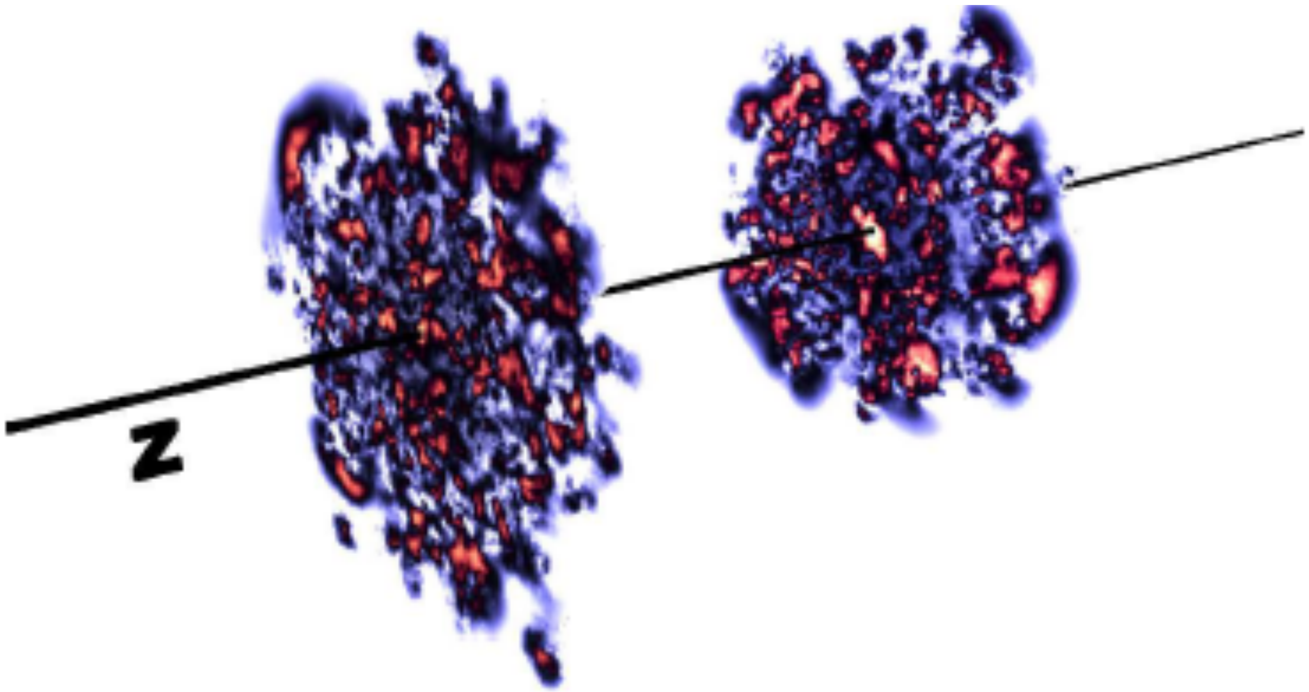
$$\mathrm{CY} \propto \frac{\int d^2k_T\ \Phi_A^2(k_T)\ \Phi_B^2(|p_T - k_T)}{\int d^2k_T\ \Phi_A^2(k_T)\ \Phi_B(|p_T - k_T|)\Phi_B(|p_T + k_T|)}$$



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

As seen in the p+Pb data…

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

IP-Glasma + vscous hydro model

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

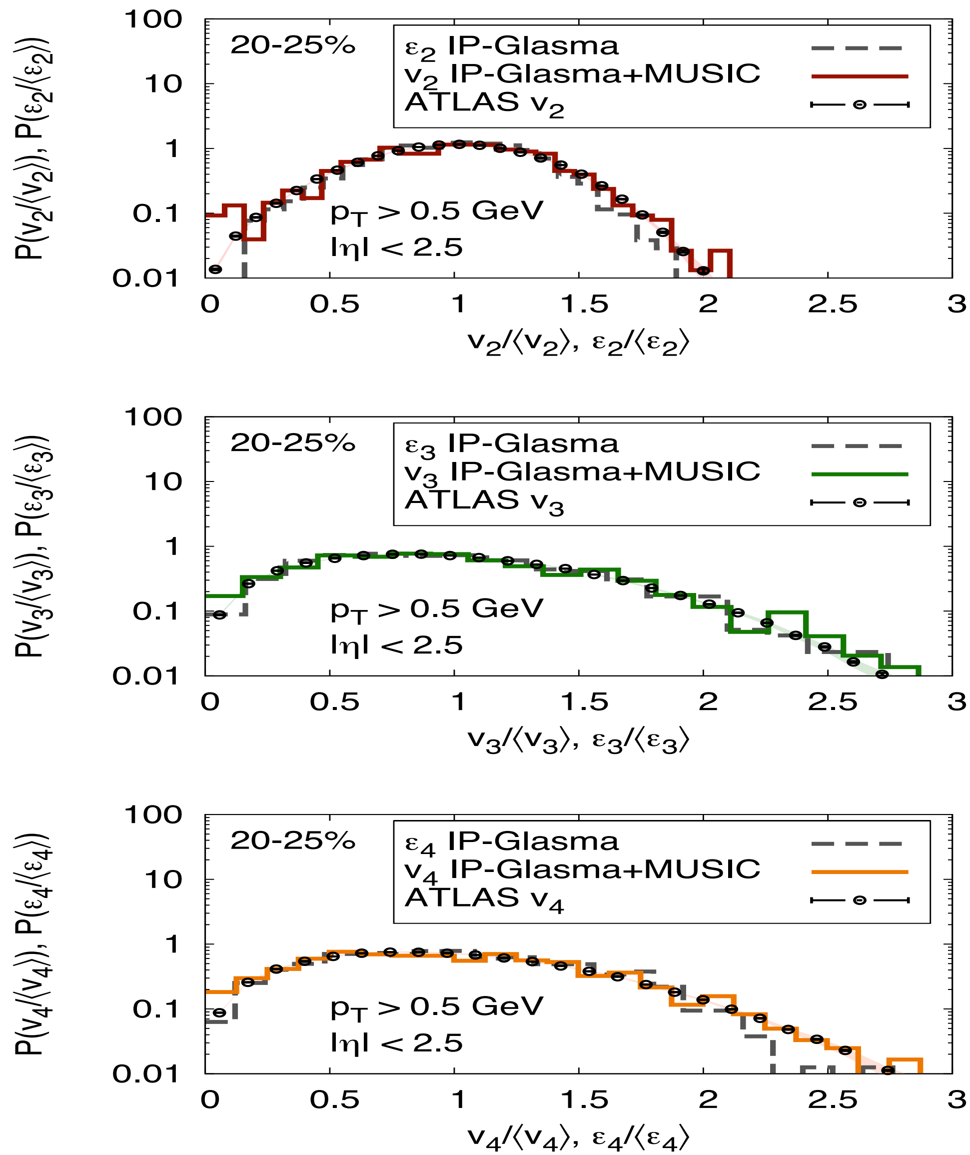
Event-by-event flow distributions

v_n distributions track eccentricities ε_n

spatial fluctuations

efficiency => perfect fluidity

momentum anisotropies

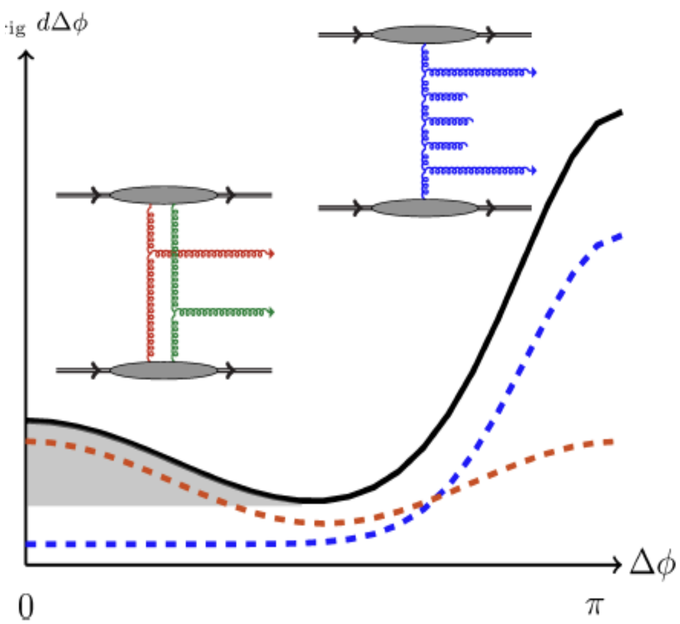


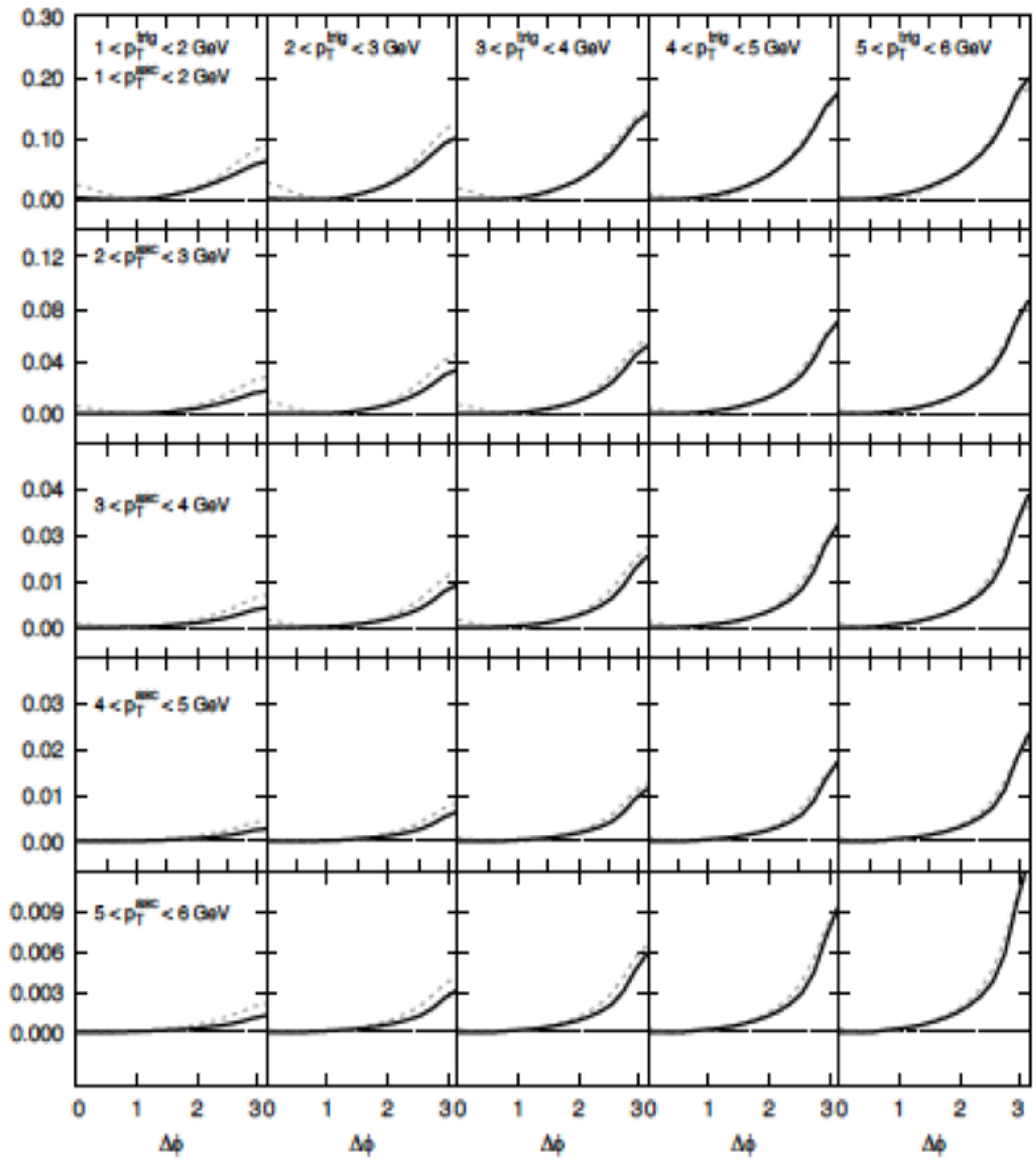
From our paper
1210.3890v3

BFKL has very
weak centrality dependence

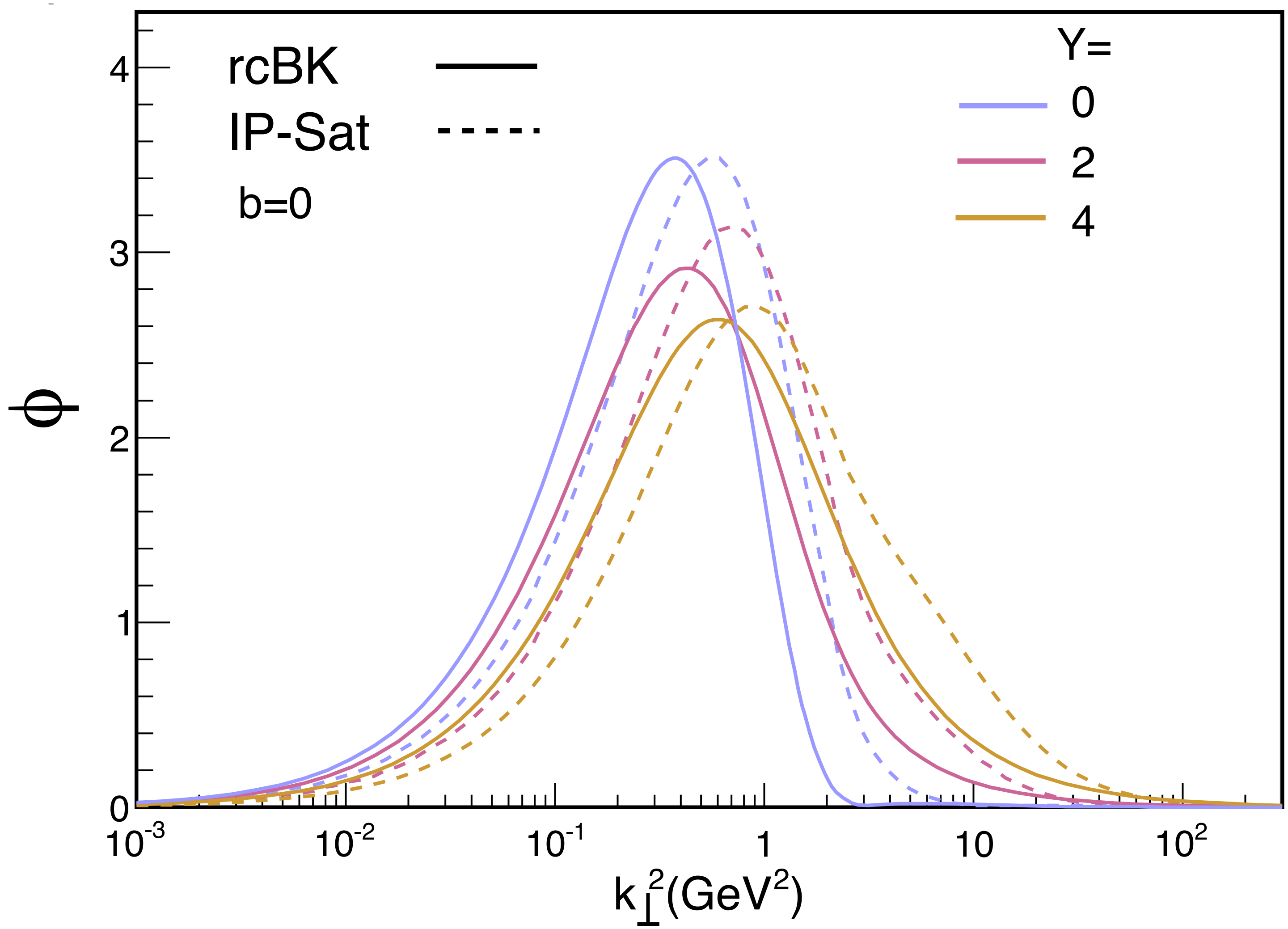
Subtracting 40-60%
gets rid of di-jet leaving only
dipole Glasma contribution

ALICE result consistent
with our expectations





rcBK vs IP-Sat evolution



Quantitative description of pp ridge

Dusling,RV, 1201.2658, PRL

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

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

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

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

Dependence on transverse area cancels in ratio…

Subtracts any pedestal "phi-independent" correlation