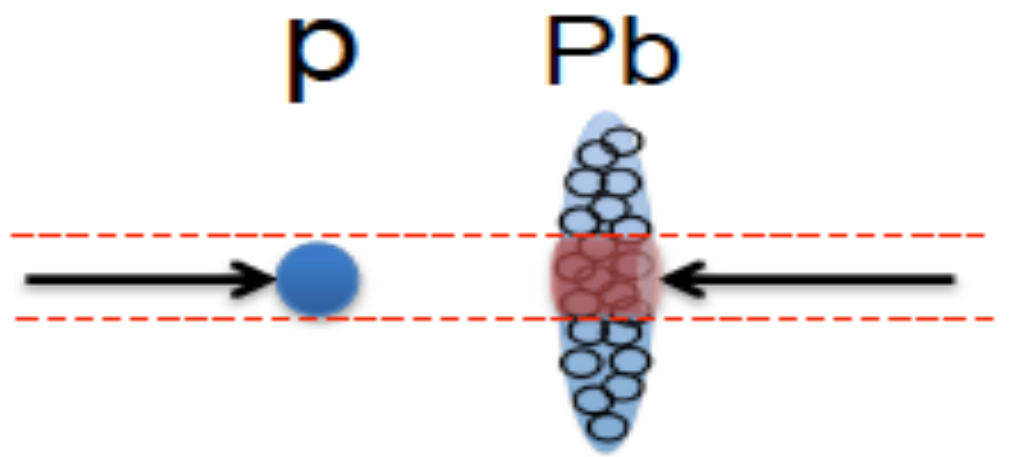


Large ridges in small systems: gluon entanglement in the Glasma

Raju Venugopalan
Brookhaven National Laboratory

RBRC jet quenching workshop, BNL, April 15, 2013

Talk outline

- Multi-particle dynamics in dense-dense systems:
  an ab initio CGC EFT approach

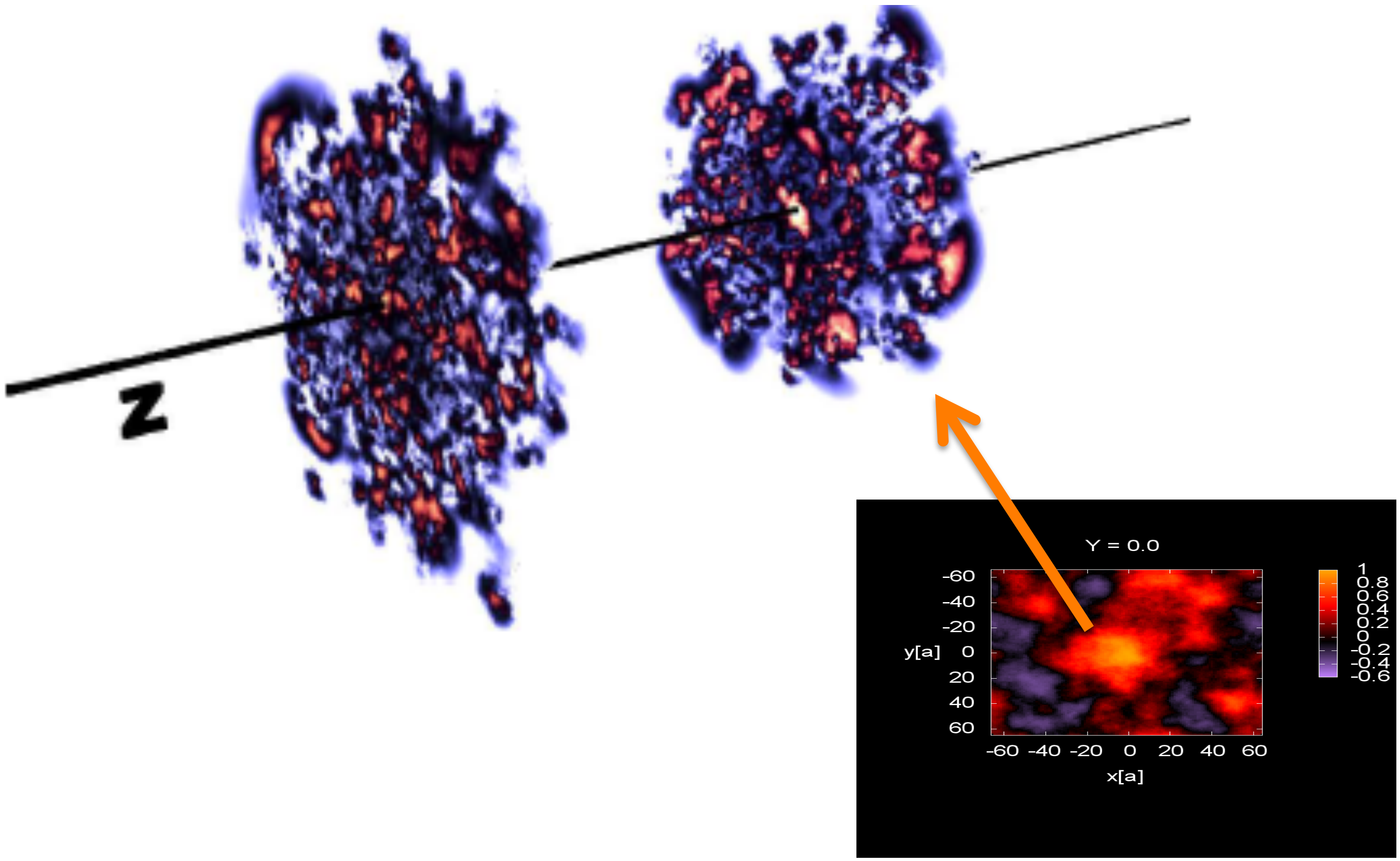
- The ridge in p+p collisions: Glasma + BFKL - QCD contributions

- The ridge in A+A collisions: the dominance of flow
  generated from the Glasma pedestal (IP-Glasma model)

- The ridge in p/d+A: like p+p or A+A ?
  Relative role of Glasma + flow contributions

High multiplicity events:

"dense-dense" hadron-hadron collisions



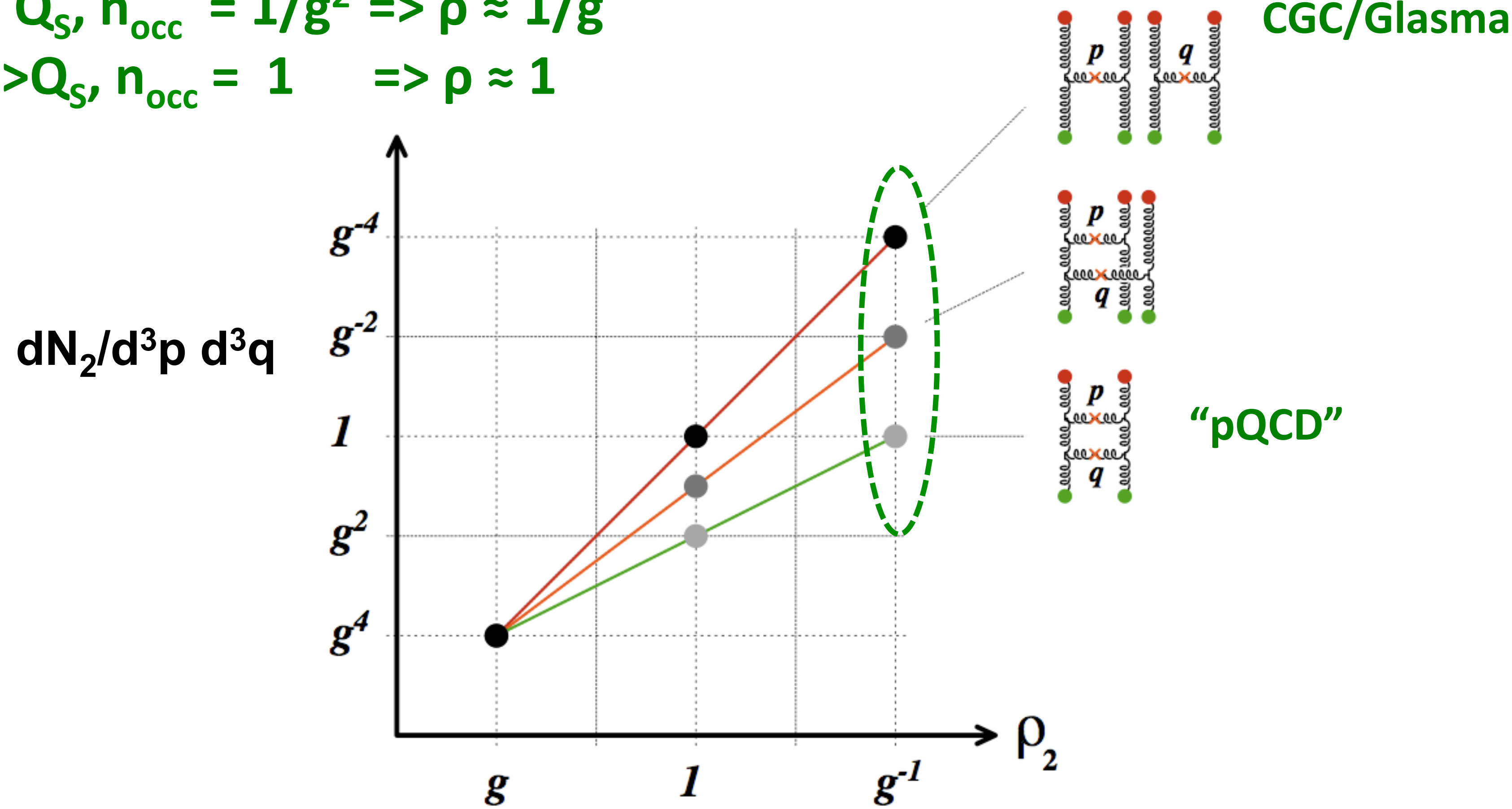
Incoming nuclei are Color Glass Condensates: Highly occupied gluon states with maximal occupancy allowed in QCD

High parton densities: multi-particle production

Counting powers of "effective" color charge density $\rho = g\, n_{occ}$

$k_T \leq Q_S$, $n_{occ} = 1/g^2 \Rightarrow \rho \approx 1/g$

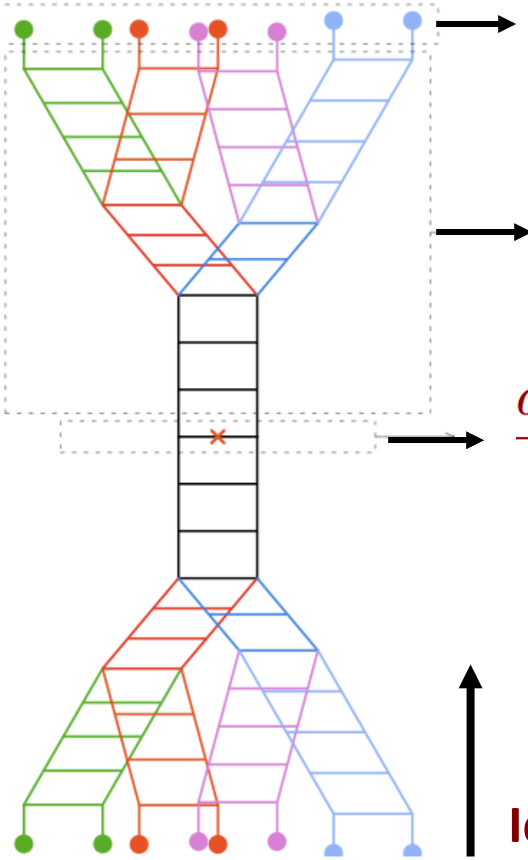
$k_T \gg Q_S$, $n_{occ} = 1 \Rightarrow \rho \approx 1$



"Dense-dense" limit relevant for high multiplicity events: $\rho_1, \rho_2 \sim 1/g$

High multiplicity events: single inclusive production

Gelis,Lappi,RV
arXiv:0804.2630 [hep-ph];
arXiv:0807.1306 [hep-ph]
arXiv:0810.4829 [hep-ph]



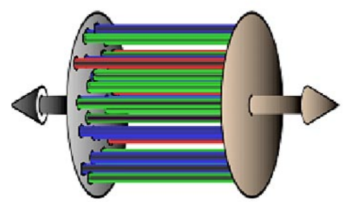
Initial configuration of sources for nucleus 1

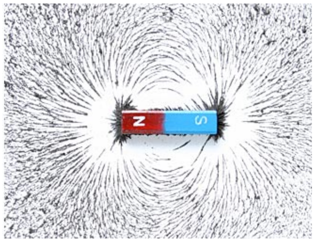
BK/JIMWLK evolution for nucleus 1

$$\frac{dN_{\mathrm{LO}}}{d^3p}$$

Computed from Yang-Mills Glasma gluon fields

Krasnitz, Nara, RV; Lappi

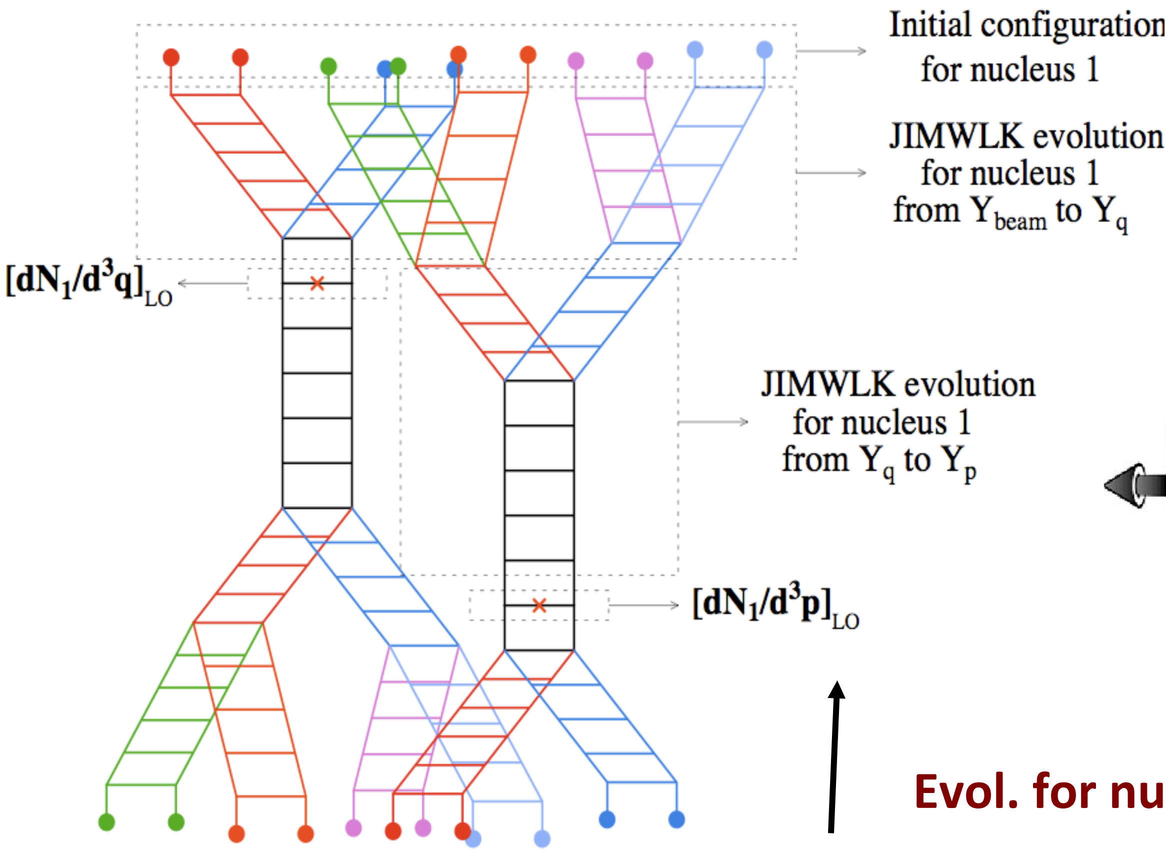




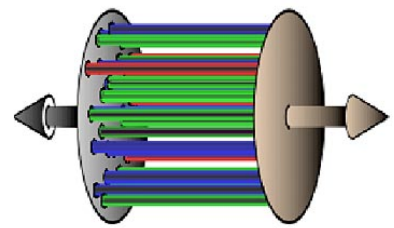
Identical evol. for nucleus 2

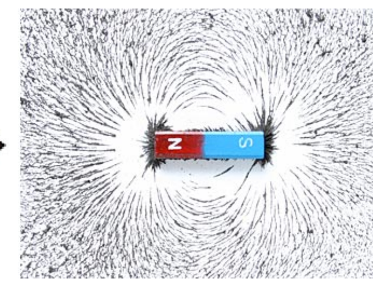
- Full JIMWLK+YM evolution feasible Lappi, PLB 703 (2011)209
- In practice: approximations of varying rigor

High multiplicity events: two particle correlations



Evol. for nucl. 2





- Full YM+JIMWLK evolution – not available yet   Lappi,Schenke,RV in progress

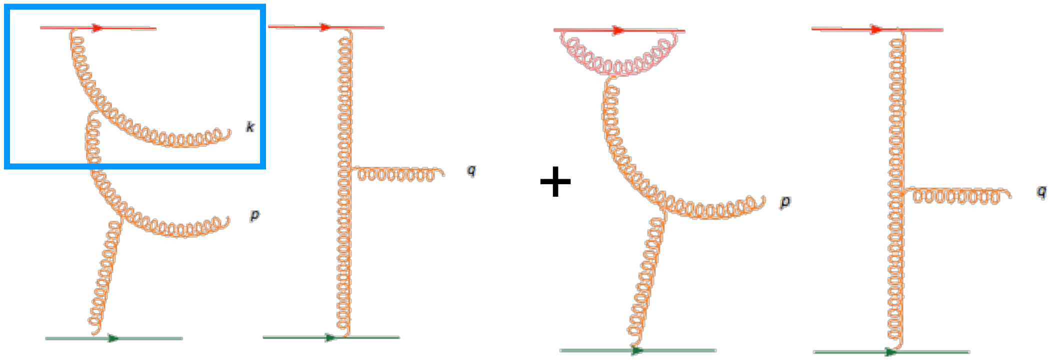
- Approximations: BK Gaussian truncation approximation for $k_T \geq Q_S$; YM results for MV model available for all k_T

Dusling,Gelis,Lappi,RV:0911.2720; Lappi,Srednyak,RV:0911.2068; Kovchegov,Wertepny: 1212.1195

The saturated hadron: Glasma graphs -I

Dumitru,Gelis,McLerran,RV: 0804.3858
Gelis, Lappi, RV, arXiv: 0807.1306

RG evolution:

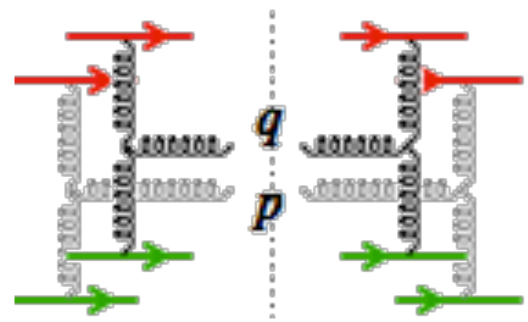


\+ . . .

Keeping leading logs to all orders (NLO+NNLO+…)

= LO graph with evolved sources

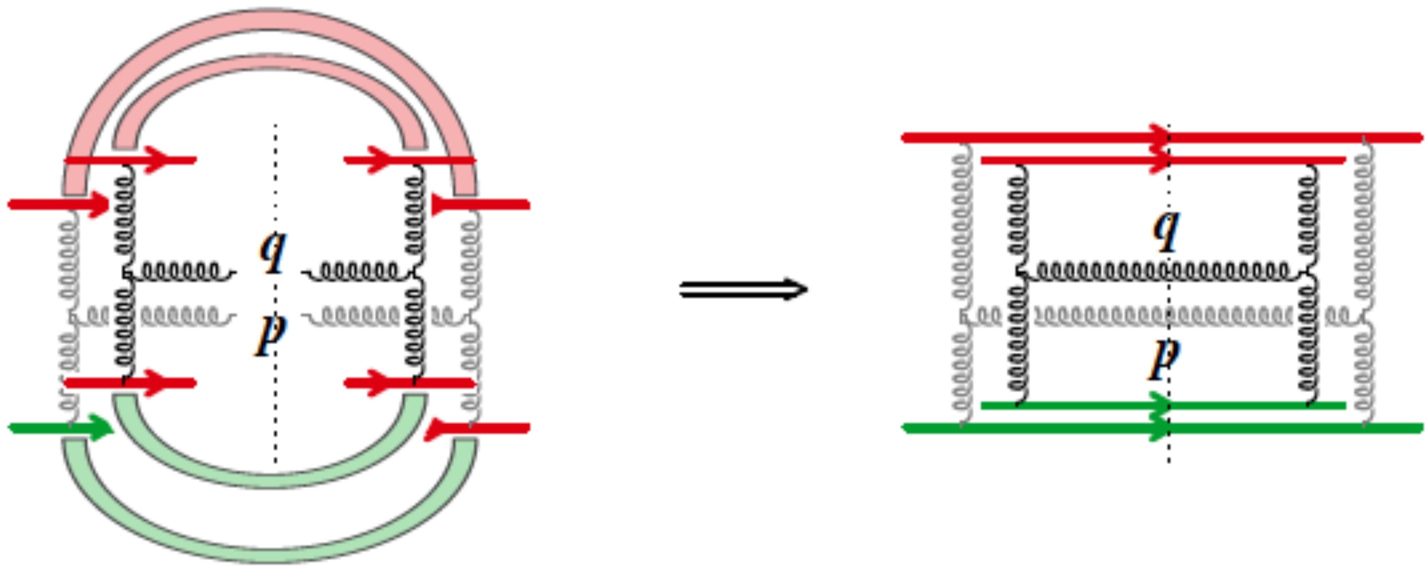
avg. over sources in each event
and over all events gives correlation



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

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 hadron: Glasma graphs -II



Disconnected graphs: $d^2N_{pedestal} \approx N_{incl.} \times N_{incl.}$

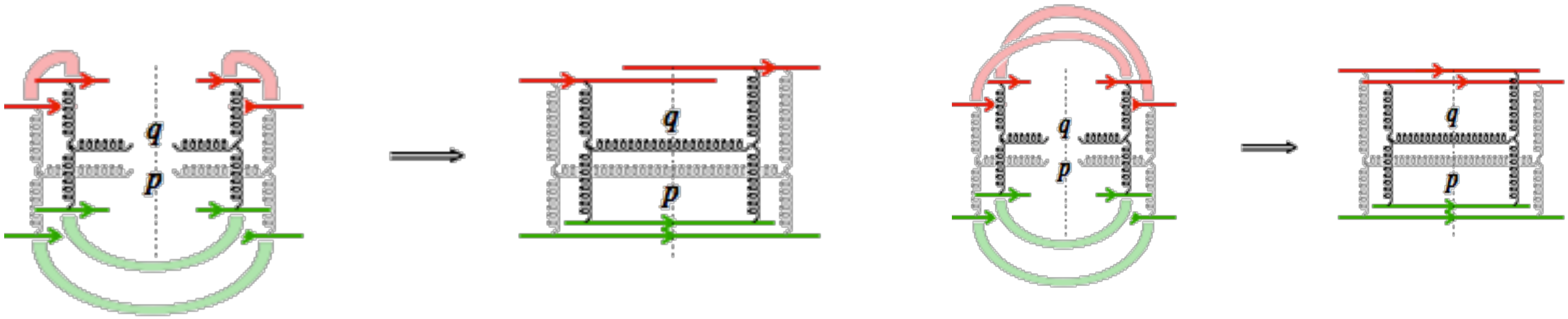
Dominant contribution to the "uncollimated" pedestal

Other sources in CGC EFT – 4 particle correlations

Kovner, Lublinsky, 1211:1298

The saturated hadron: Glasma graphs-III

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

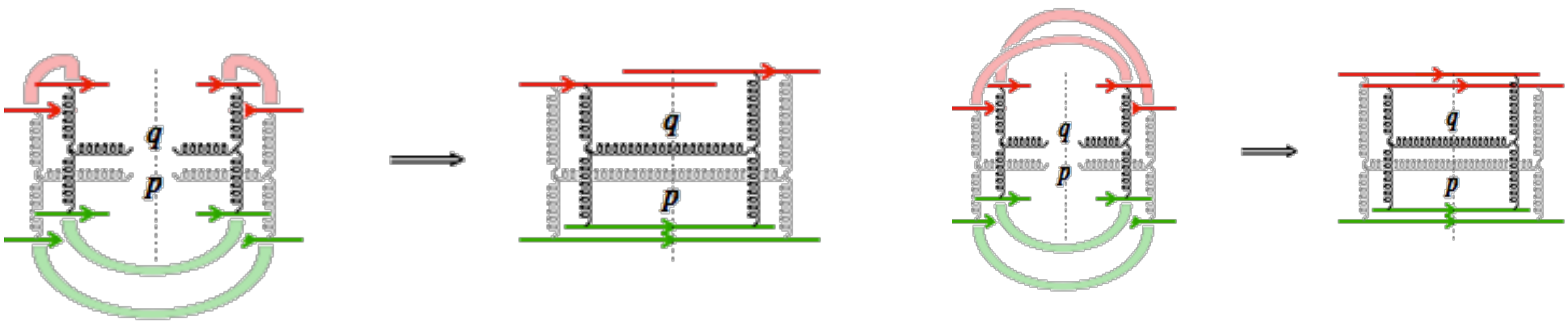


Glasma graphs generate long range rapidity correlations, are suppressed for $Q_S << p_T$ by powers of α_S AND N_C
(At high p_T, large x or large impact parameters)

However recall: coupling of sources to fields with $k_T \leq Q_S$ = 1/g not g for high occupancy fields
(central impact parameters, small x, low p_T, large nuclei)

The saturated hadron: Glasma graphs-III

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

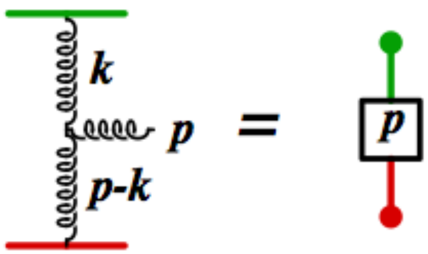


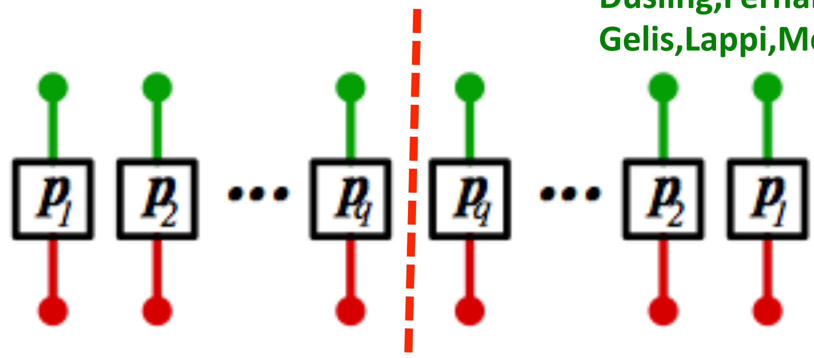
- **Glasma graphs enhanced for high multiplicity events by α_S^{-8} -- a factor of 10^5 !**

- **Collimated contributions competitive with pQCD back-to-back graphs for high multiplicity events**

2-particle → n-particle correlations

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





Multiplicity distribution: Leading combinatorics -> negative binomial dist.

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

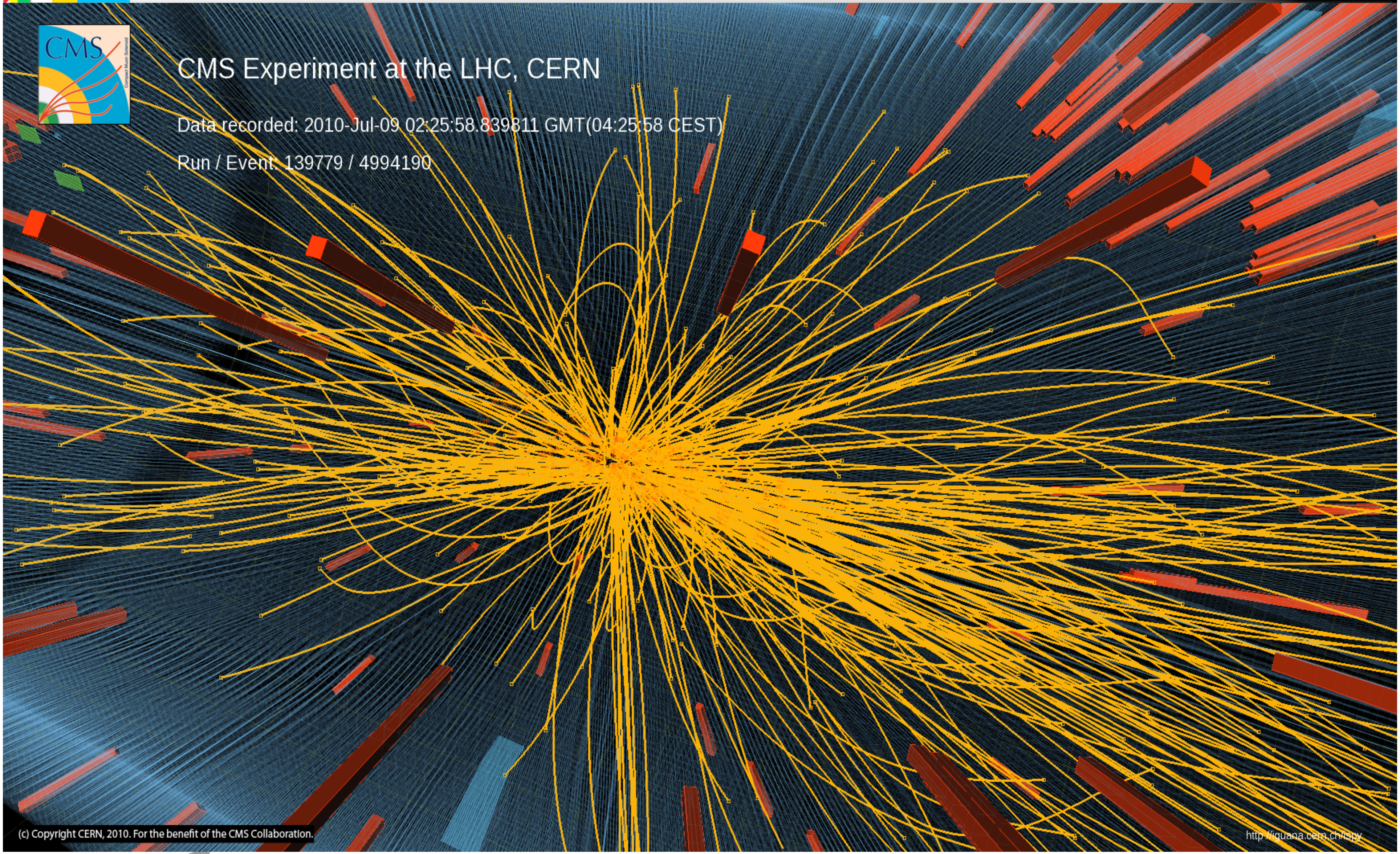
$$k = \zeta \frac{(N_c^2-1) Q_S^2 S_\perp}{2\pi}$$

From Yang-Mills: $\zeta \sim 1/6$

k = 1 : Bose-Einstein
k = ∞ : Poisson

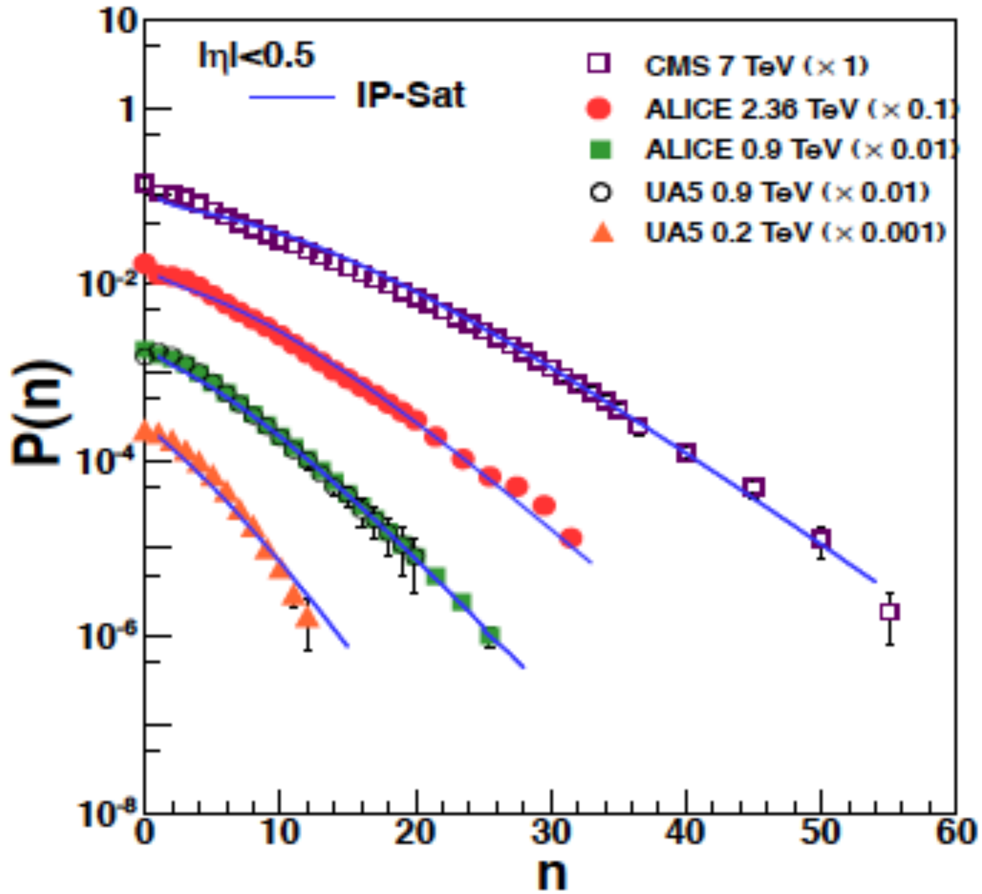
Lappi, Srednyak, RV, 0911.2068
Schenke, Tribedy, RV, 1206.6805

High Multiplicity pp collisions



n-particle Glasma correlations describe p+p multiplicity dist.

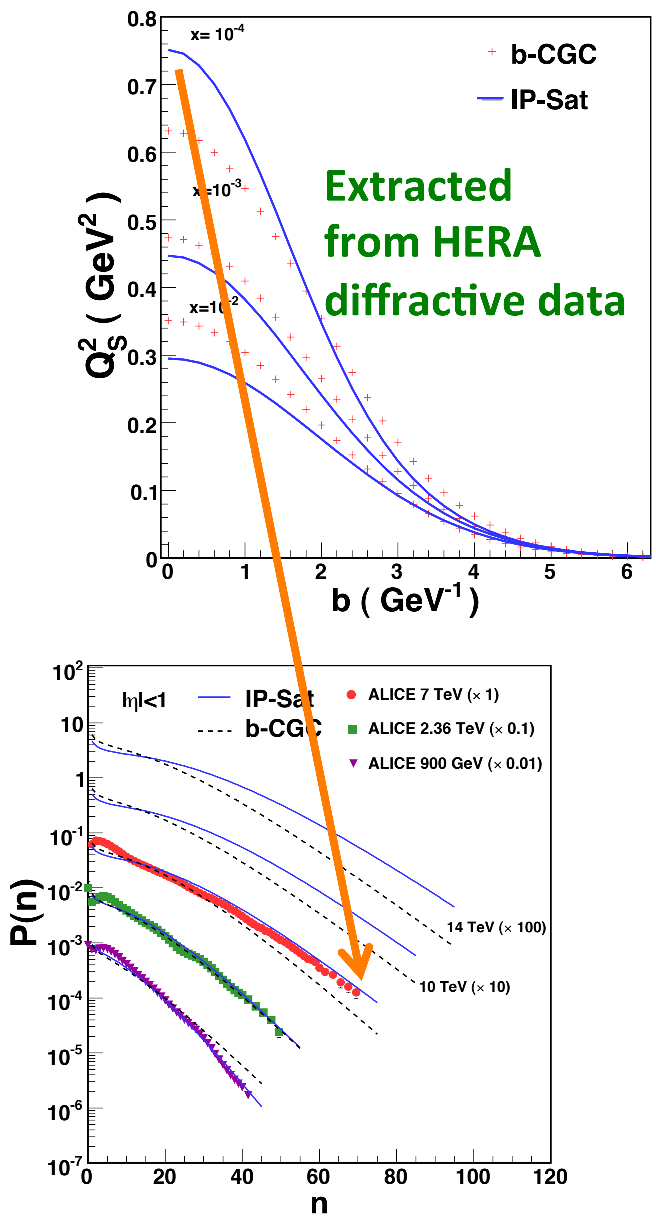
Tribedy, RV
1112.2445

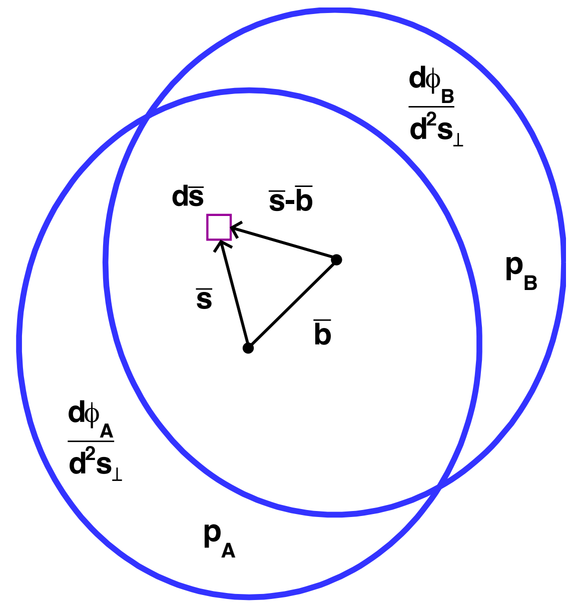


Approx: k_T factorization; more detailed YM treatment in progress

Schenke,Tribedy,RV

High multiplicity events in p+p





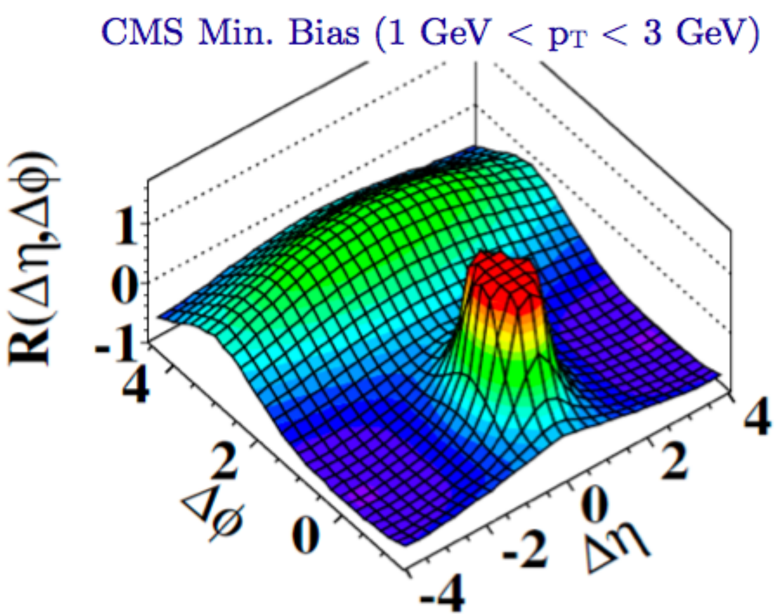
High multiplicity events likely correspond to high occupation numbers ($1/\alpha_S$) in the proton wave functions

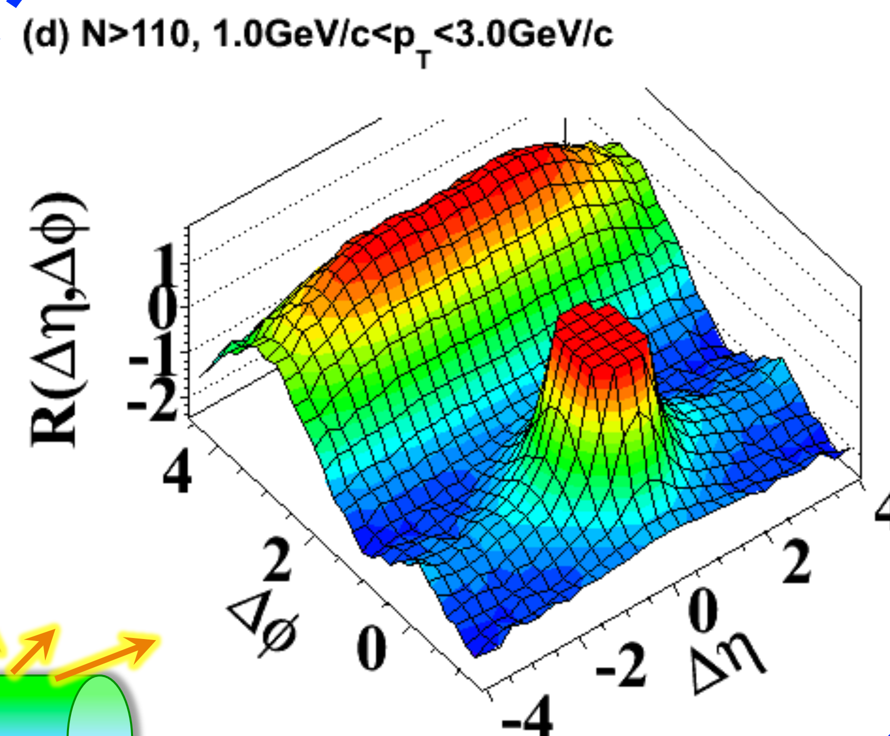
-- use "dense-dense" EFT framework

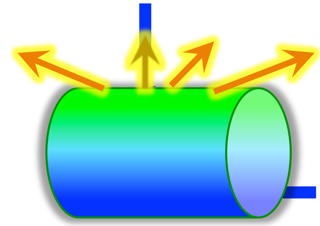
The ridge in high mult. p+p collisions

CMS 1009.4122

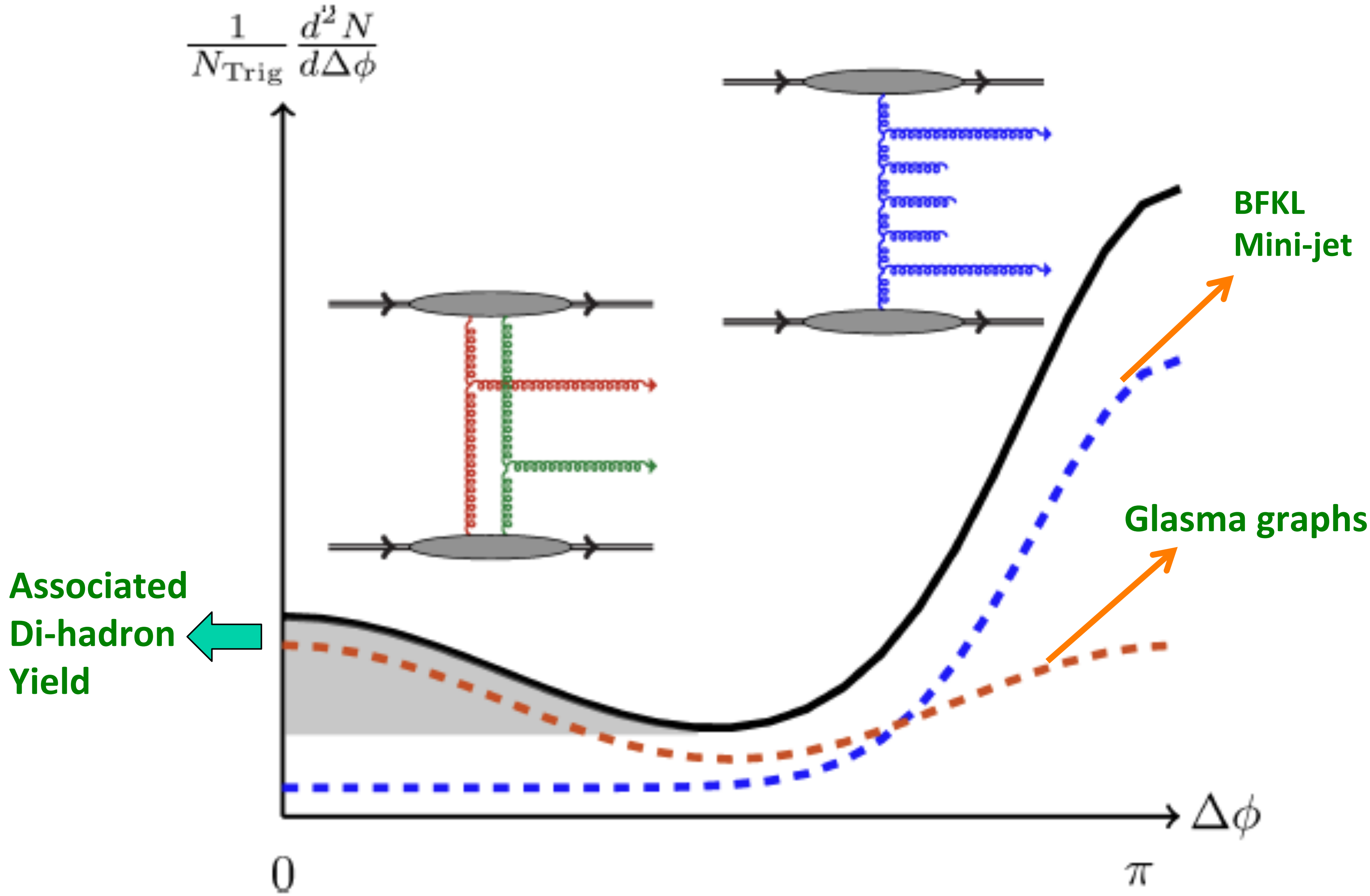
"Discovery"





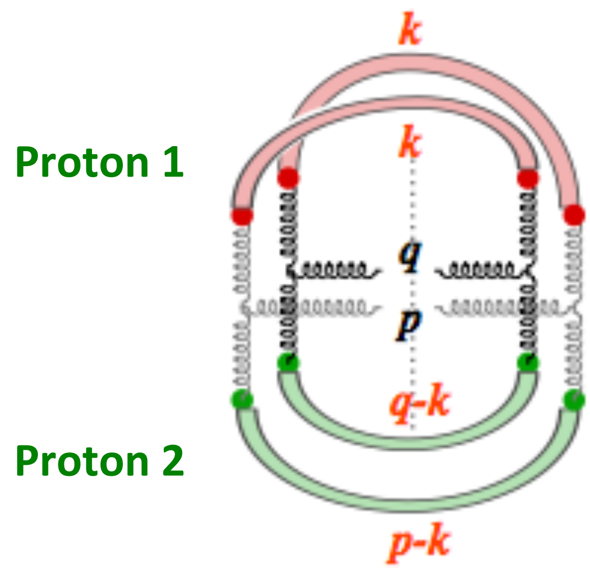


Anatomy of long range di-hadron collimation



Long range di-hadron Glasma correlations

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

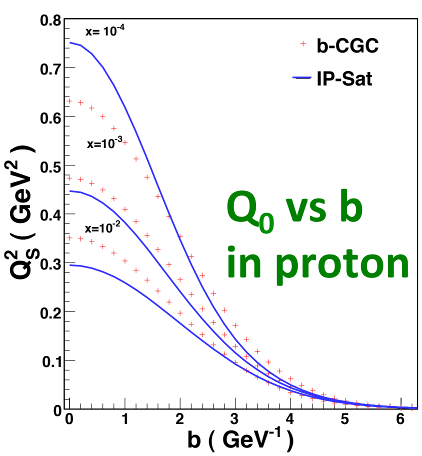


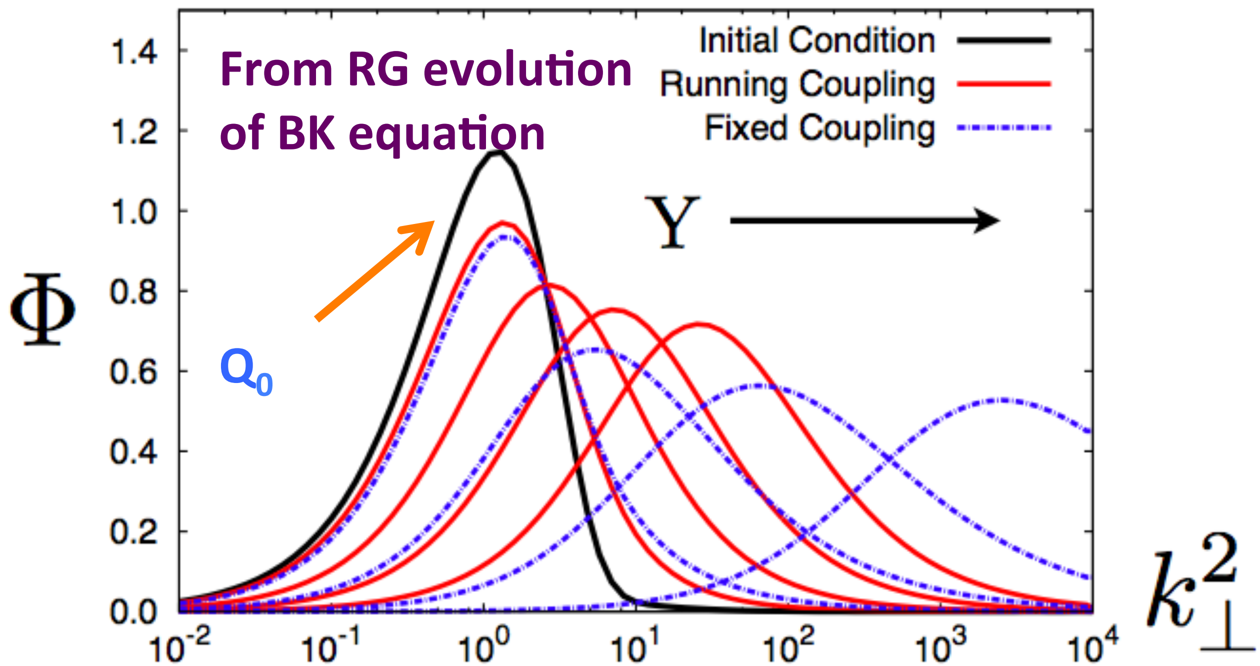
$$C(\mathbf{p},\mathbf{q}) \propto \frac{g^4}{\mathbf{p}_\perp^2 \mathbf{q}_\perp^2} \int d^2\mathbf{k}_{1\perp}\, \Phi_{A_1}^2(y_p,\mathbf{k}_{1\perp}) \Phi_{A_2}(y_p,\mathbf{p}_\perp - \mathbf{k}_{1\perp}) \Phi_{A_2}(y_q,\mathbf{q}_\perp - \mathbf{k}_{1\perp})$$
$$+ \quad \text{permutations}$$

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

Collimated Glasma yield

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

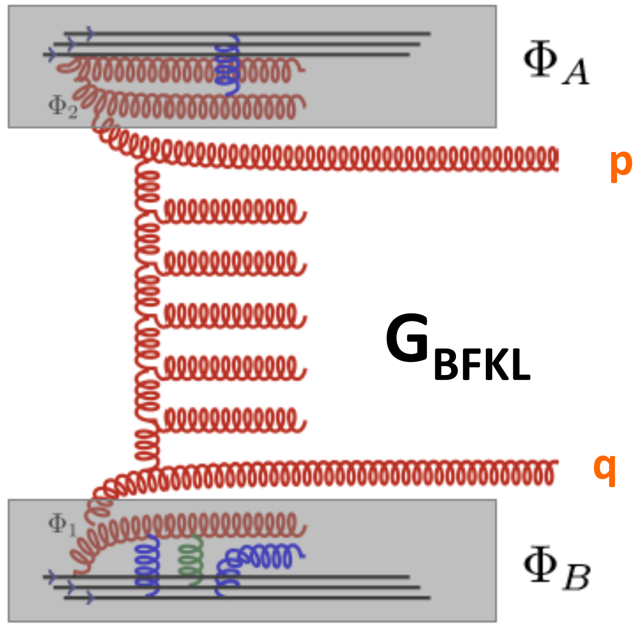




Dominant contribution from $|p_T\text{-}k_T| \sim |q_T\text{-}k_T| \sim |k_T| \sim Q_S$

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 at $\Delta\Phi \cong \pi$

LHC results also test the structure of bremsstrahlung radiation between jets

Quantitative description of ridge

Dusling,RV:PRL108 (2012)262001

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

(6

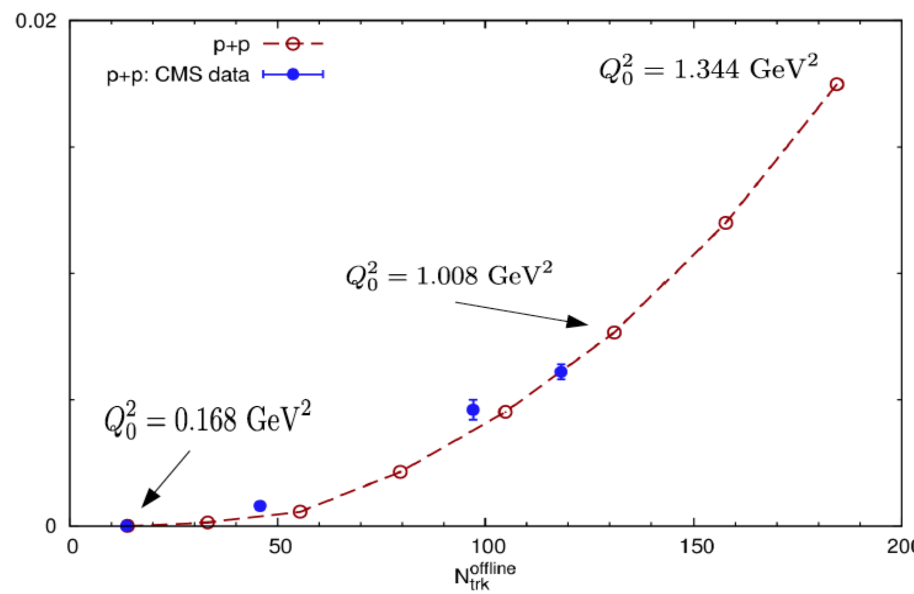
$$\mathcal{A}(\eta_p,\eta_q) = \theta(|\eta_p-\eta_q|-\Delta\eta_{\min})\,\theta(\Delta\eta_{\max}-|\eta_p-\eta_q|)$$

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

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

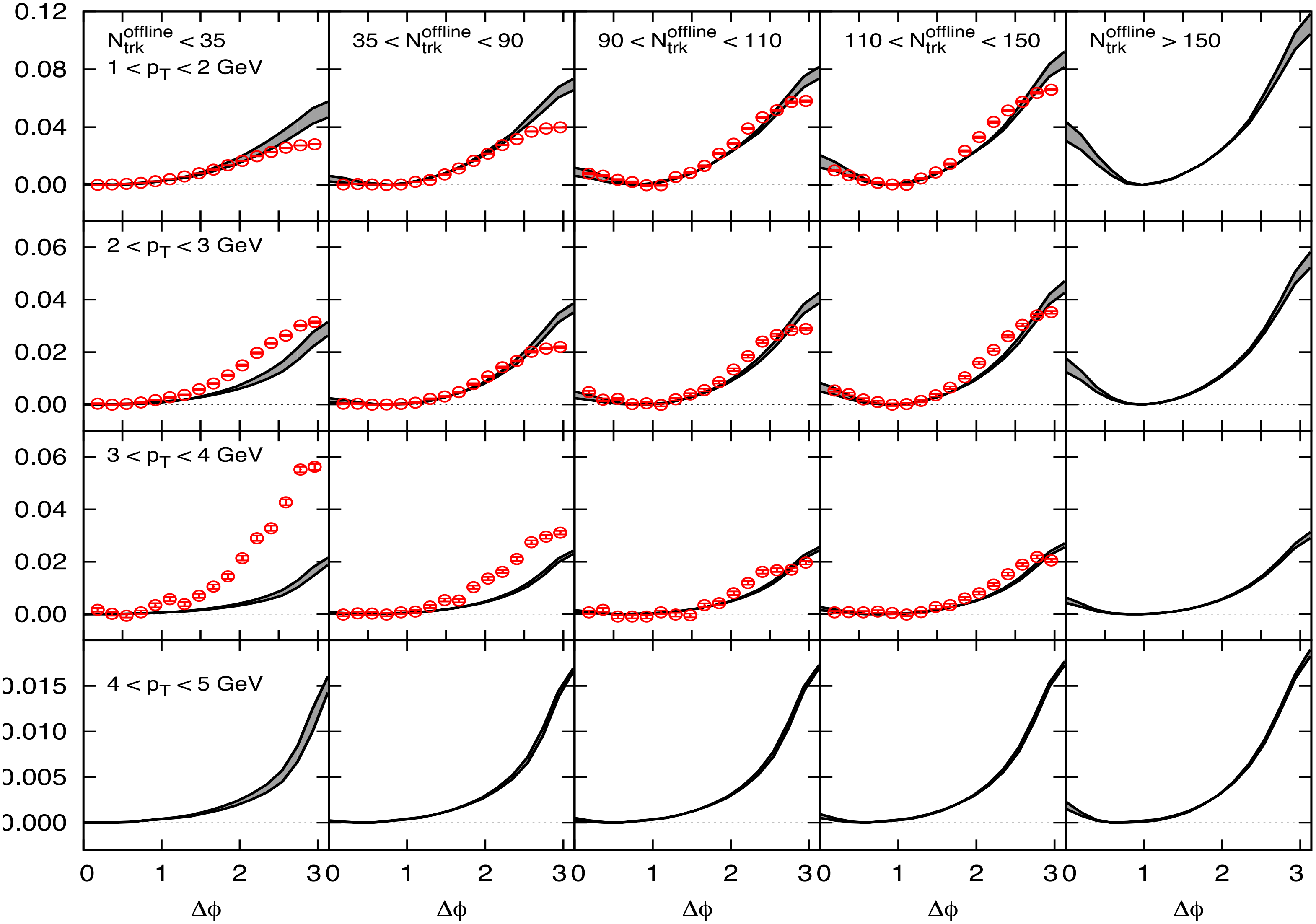
Dependence on transverse area cancels in ratio…

Rarer and rarer gluon configurations probed In the proton



CMS data: JHEP 1009, 091 (2010); PLB 718, 795 (2013)

Assoc. yield per. trig.

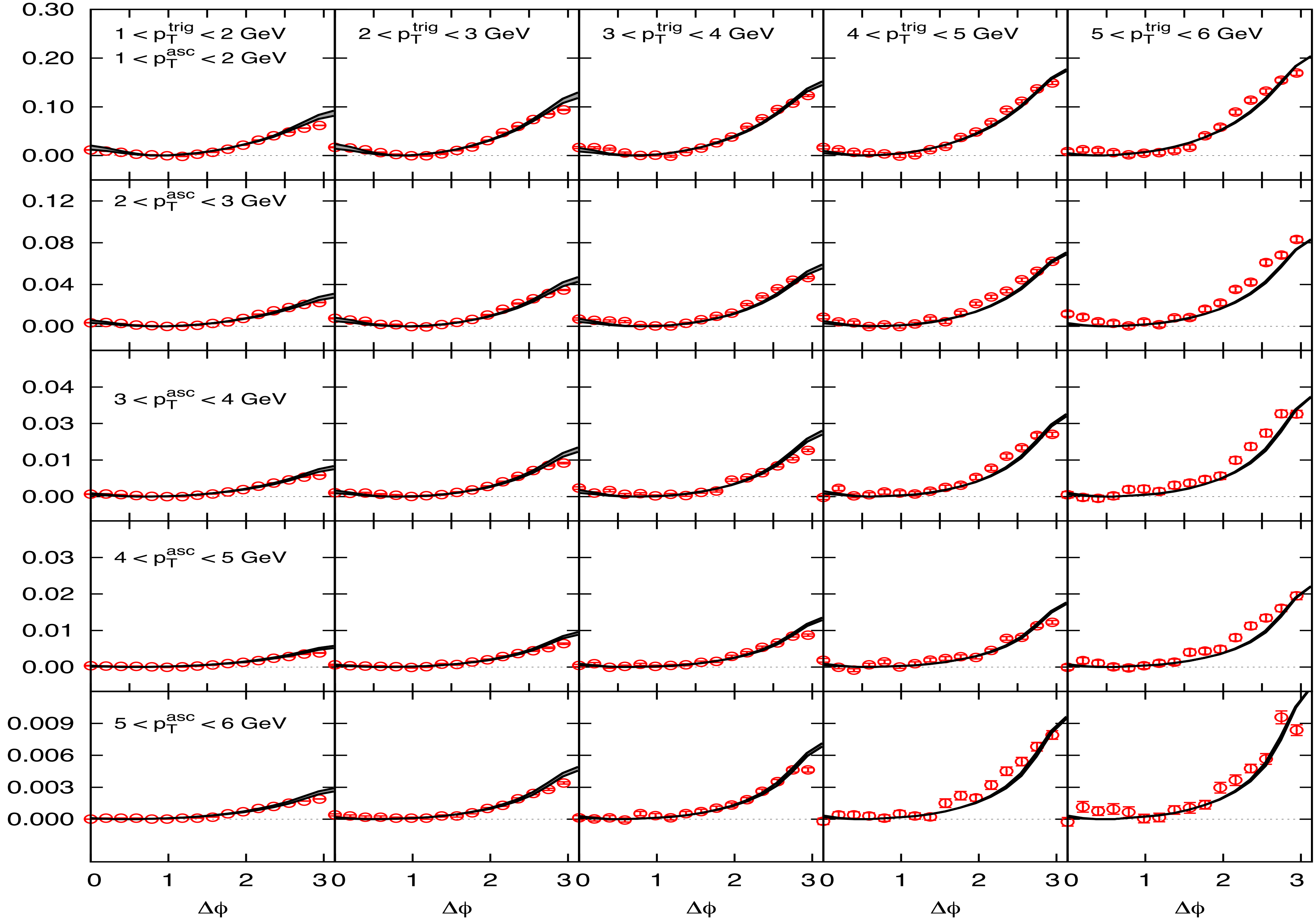


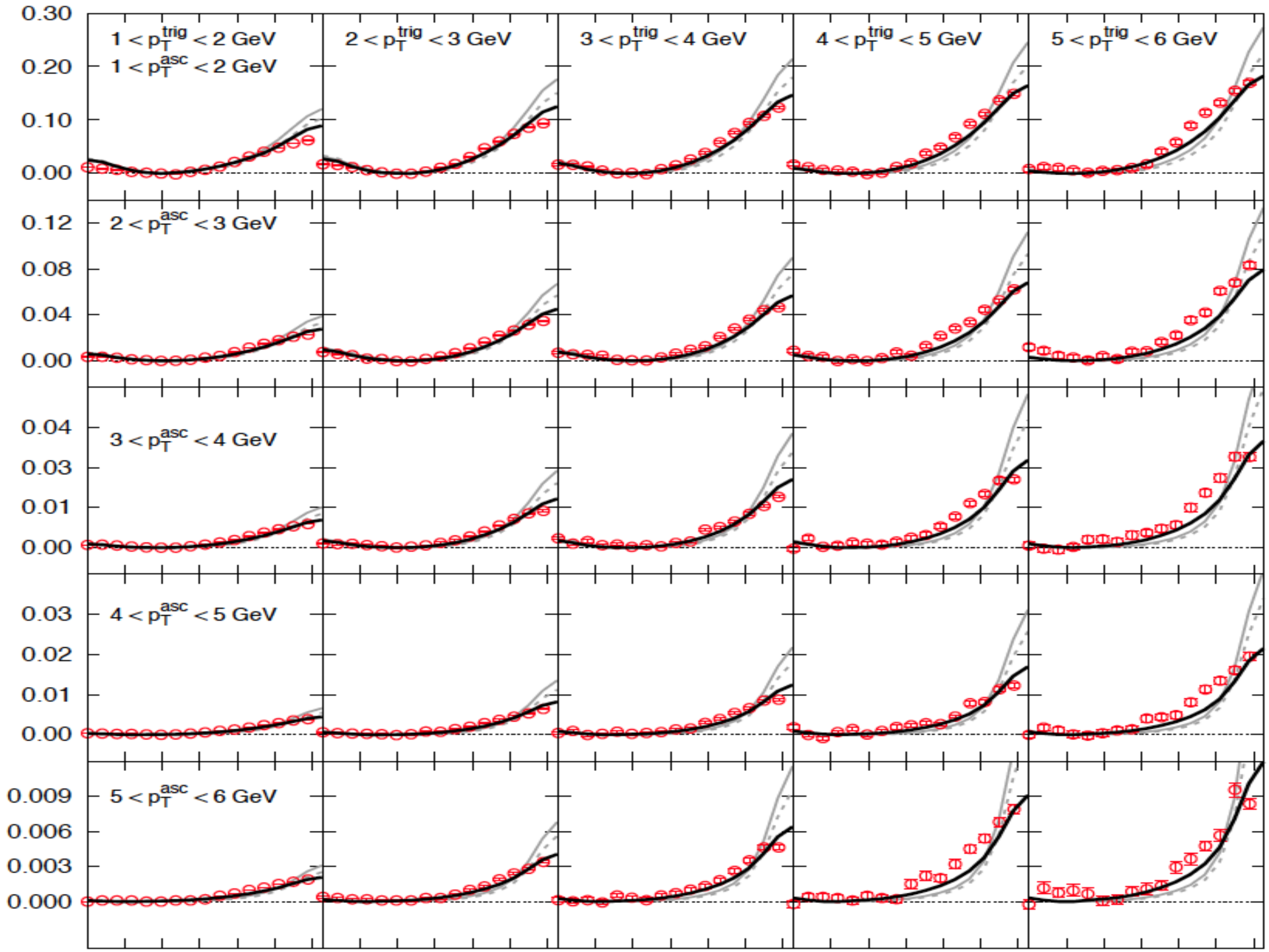
$K_{BFKL}=K_{Glasma}= 1$

KKP fragmentation

Dusling,RV, PRD 87, 051502 (R) (2013); arXiv:1302.7018

Dusling,RV, PRD 87, 051502 (R) (2013); arXiv:1302.7018

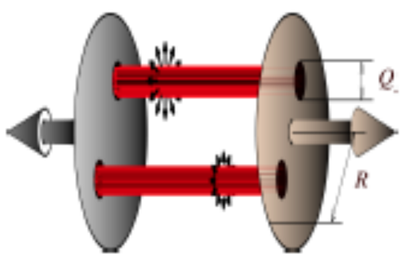


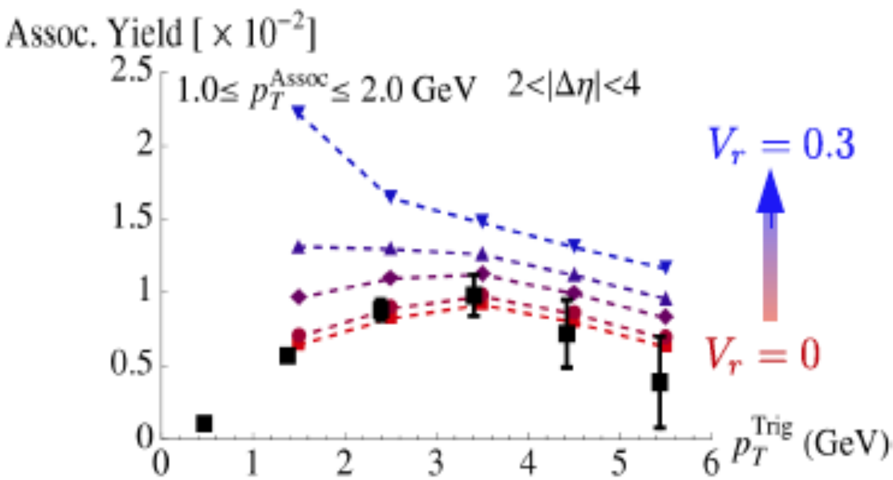


Grey curves: 2 -> 4 QCD (Multi-Regge) QCD results
– no emission in Δη between jets

p+p vs A+A

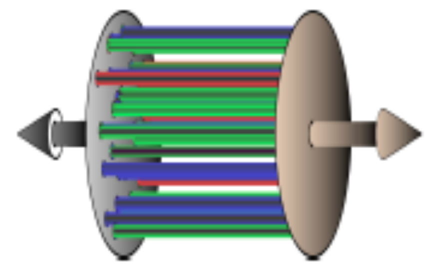
In p+p we are seeing the intrinsic collimation from a single flux tube

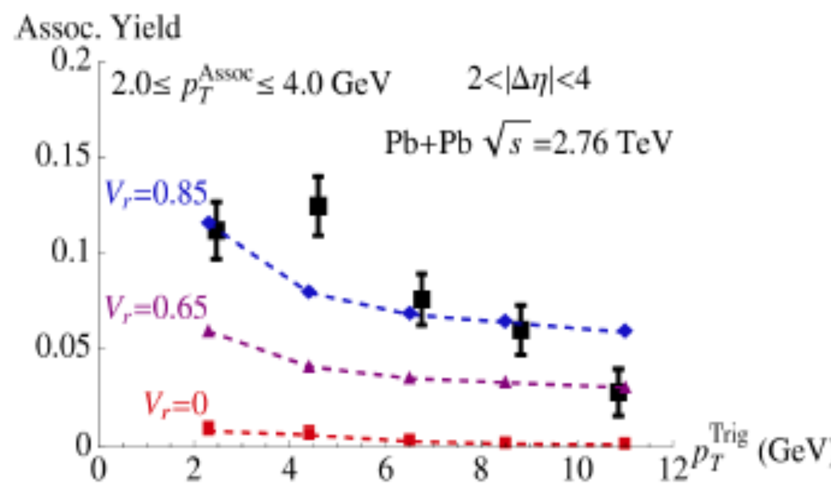




Increasing transverse flow in p+p creates a discrepancy with data.

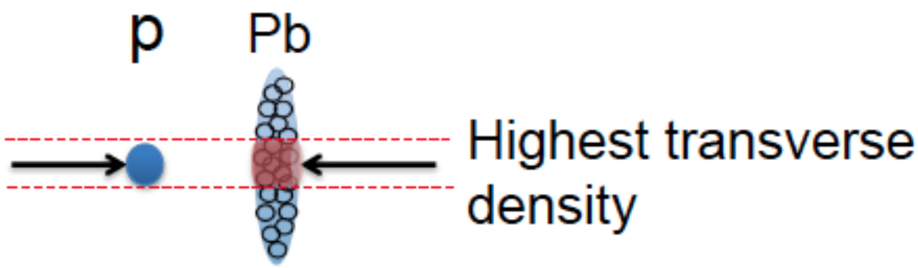
In A+A there are many such tubes each with an intrinsic correlation enhanced by flow

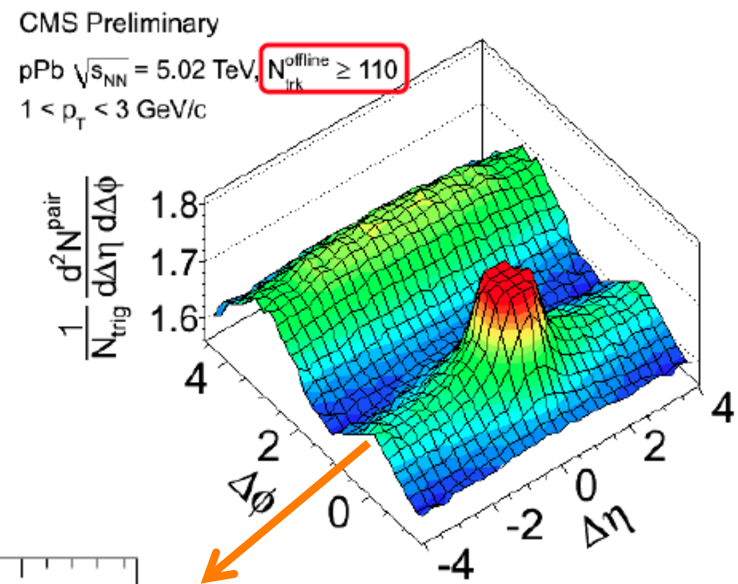


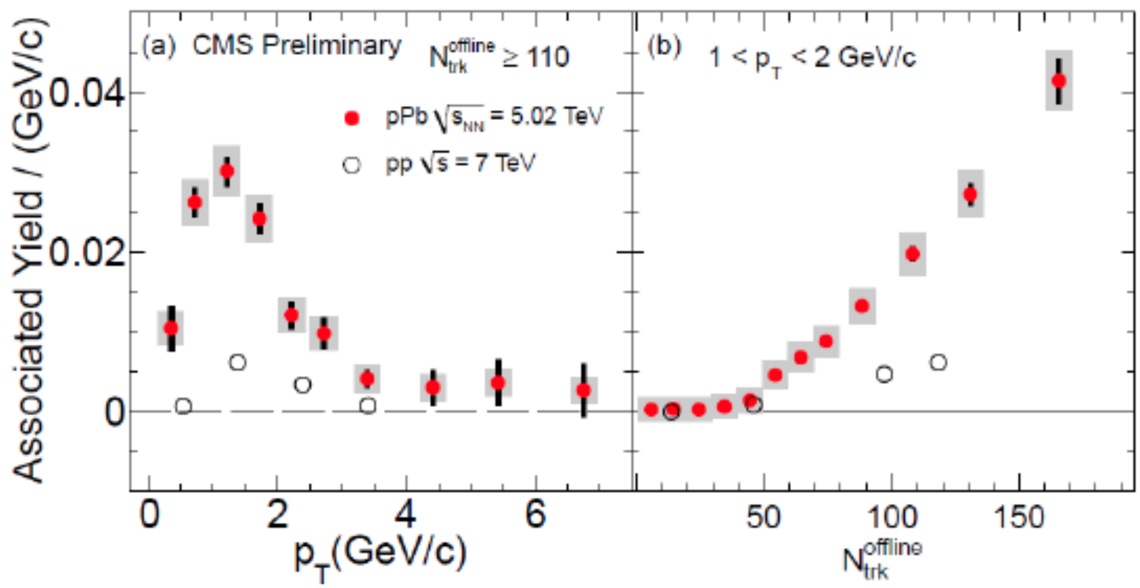


Yet, transverse flow is needed to explain identical measurements in Pb+Pb

Analysis of "pilot run" on proton lead collisions







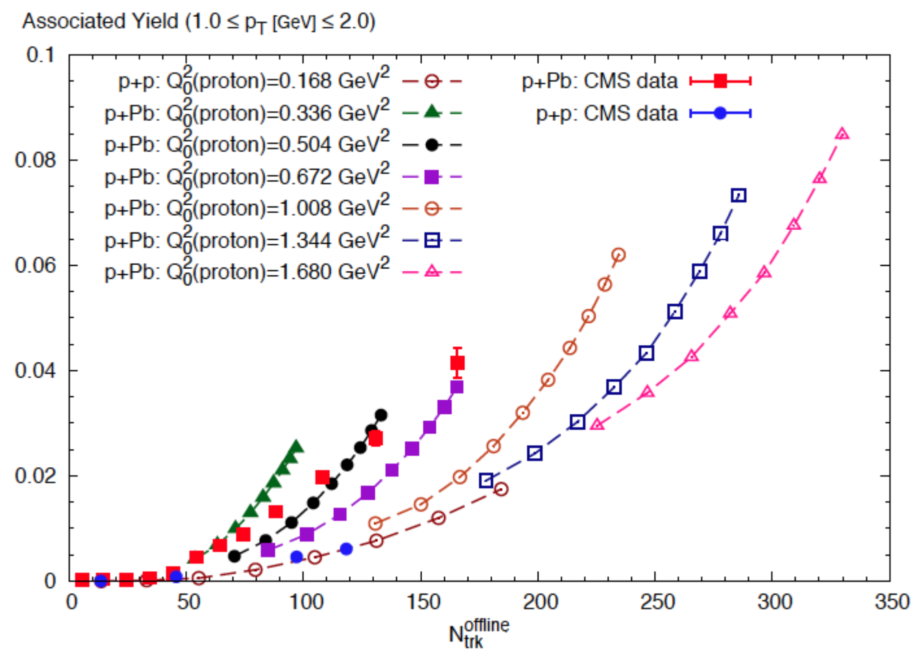
Ridge much bigger than p+p for the same multiplicity !

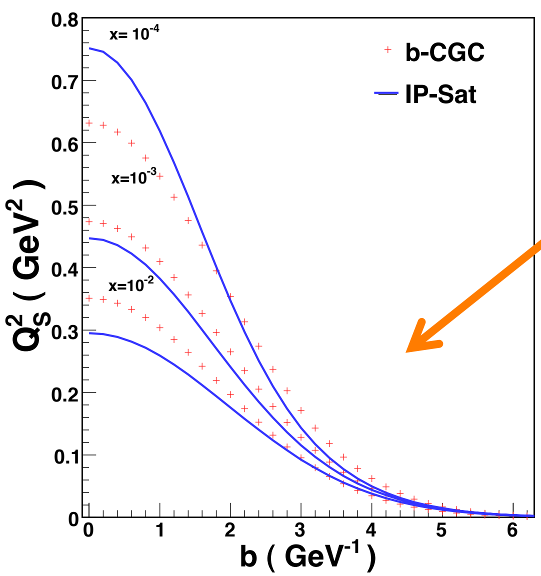
CMS p+Pb nearside per trigger yield-I

Dusling, RV: PRD87, 054014 (2013); arXiv:1302.7018

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

of "wounded" nucleons in Lead nucleus



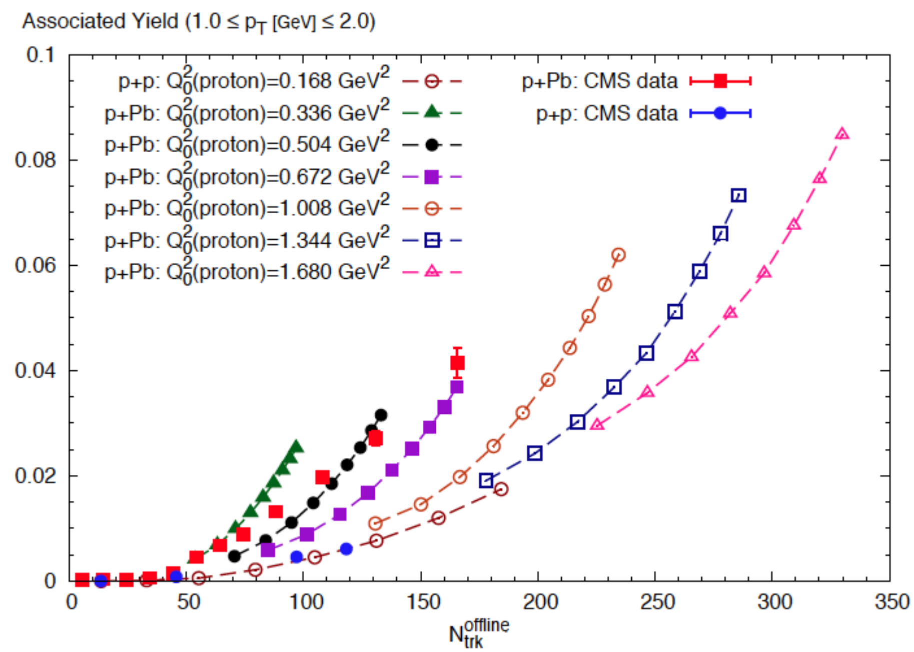


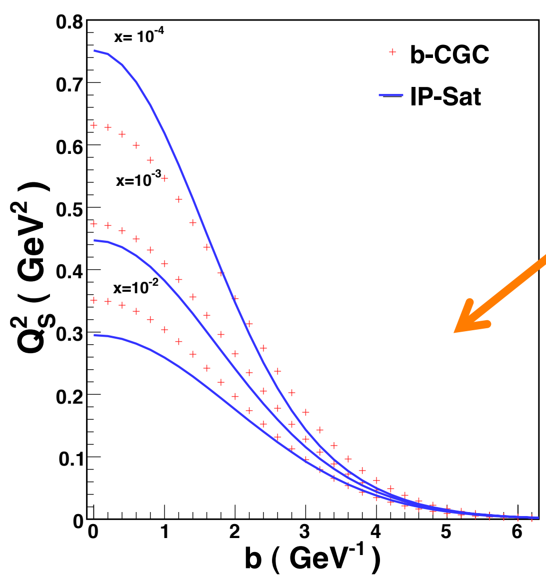
CMS p+Pb nearside yield per trigger-II

Dusling, RV: 1302.7018

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

of "wounded" nucleons in Lead nucleus



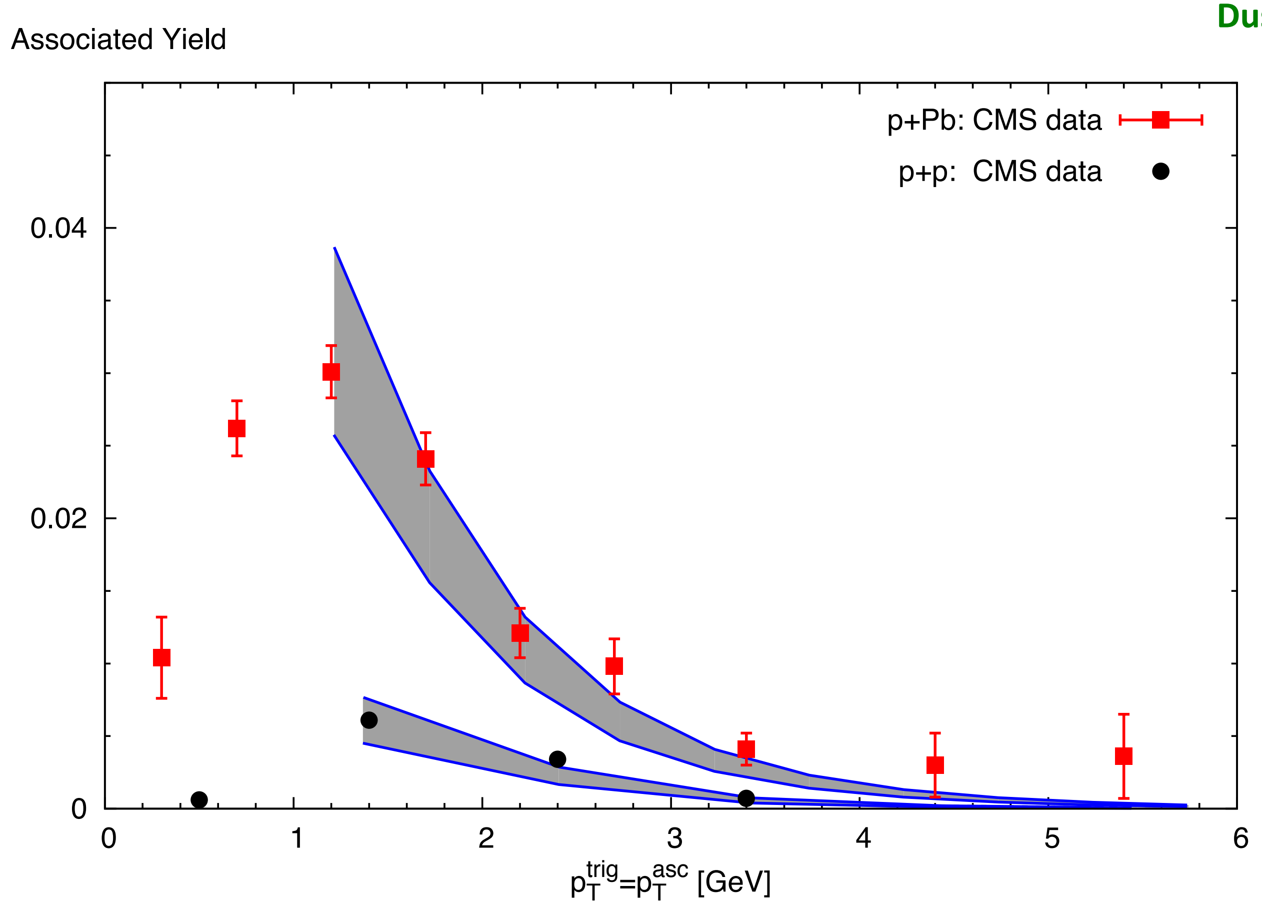


Large "ridge" seen by varying saturation scale in proton and # of wounded nucleons

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

CMS p+Pb nearside yield per trigger-III

Dusling, RV: 1211.3701
1302.7018



N_{trk} > 110

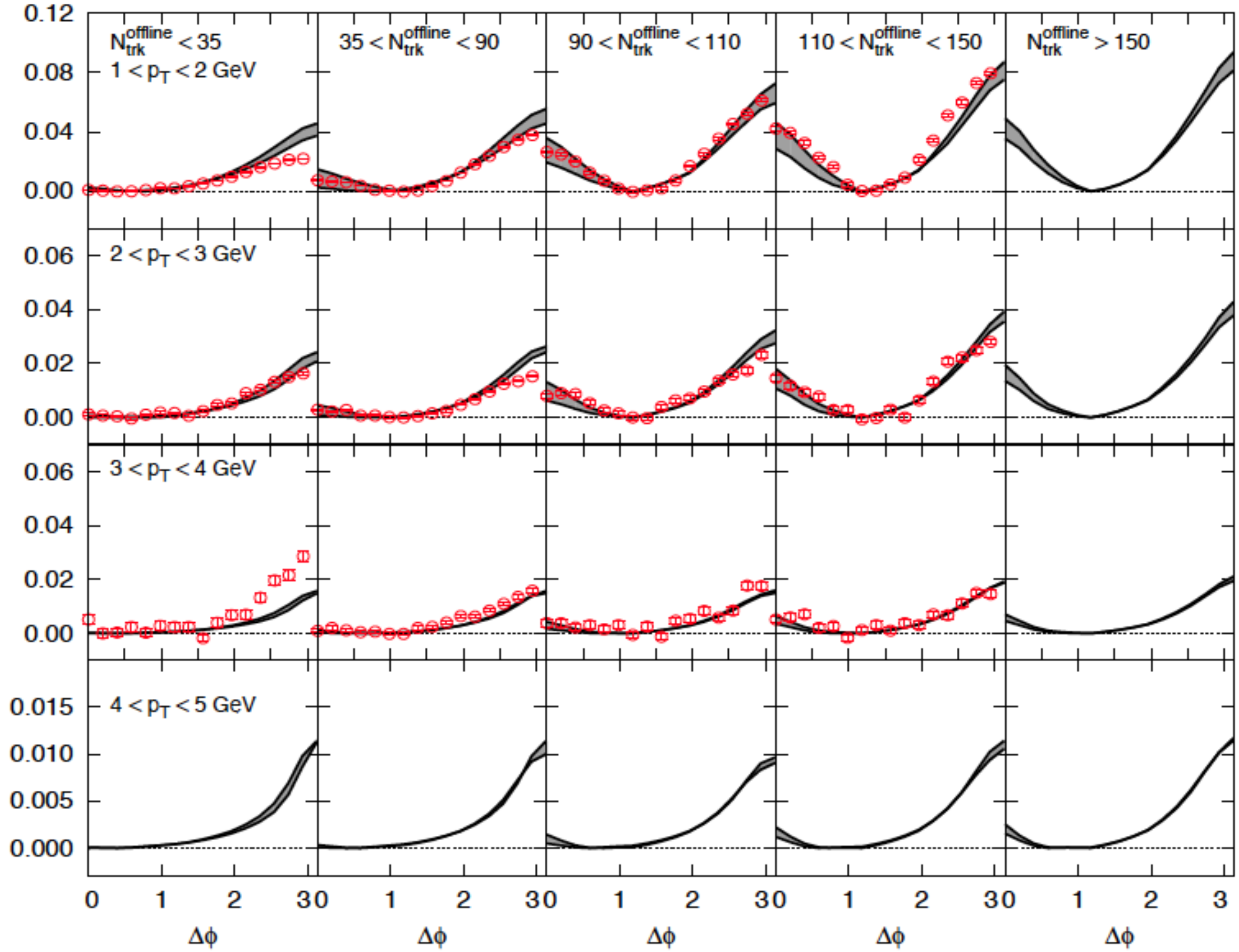
p+Pb Upper curve: (Np^{Part}, N_A^{Part}) = (3,22)

p+Pb Lower curve: (Np^{Part},N_A^{Part})=(4,14)

p+p N_{part} = 5,6

CMS p+Pb yield compared to Glasma + BFKL

Dusling, RV: 1211.3701
1302.7018



Smoking gun for gluon saturation and BFKL dynamics ?

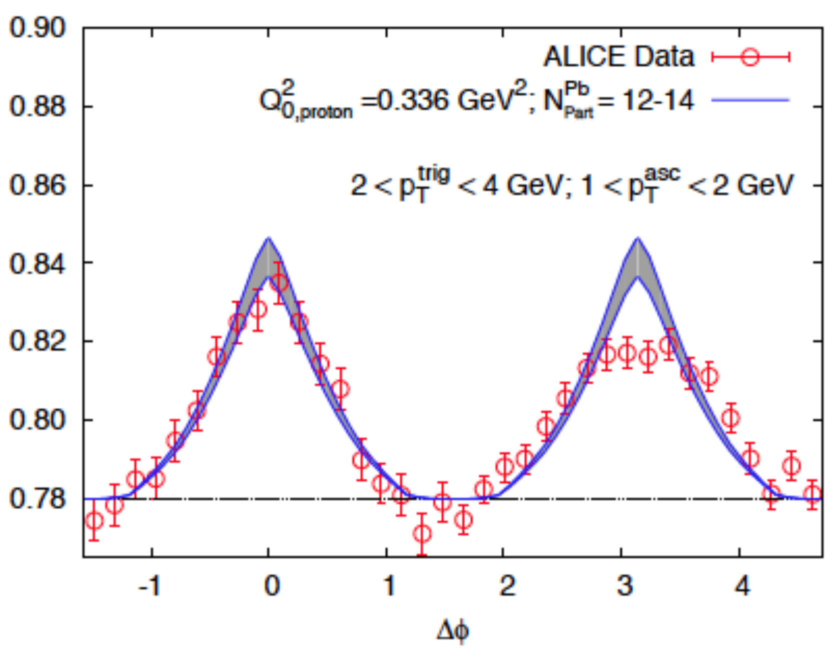
ALICE data on the p+Pb ridge

ALICE coll. PLB 719, 29 (2013)

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 –can interpret as v_2

–this gives symmetric "dipole" shape of correlation – expected for Glasma contribution



Dusling, RV: 1302.7018

Different analysis technique from CMS/ATLAS

-- same normalization as for CMS/ATLAS

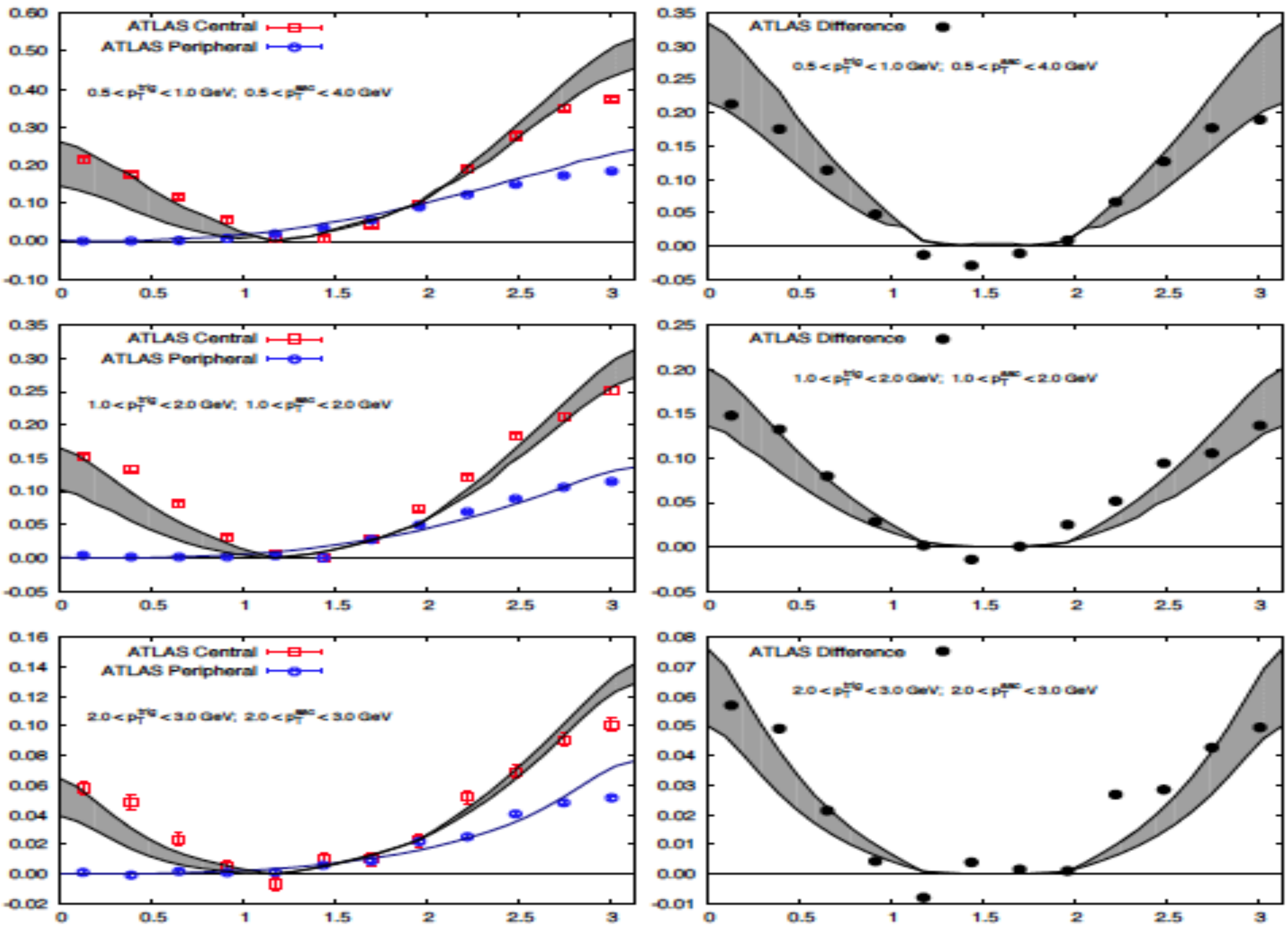
Curves for $Q_{0,proton}^2$ =0.336 GeV^2 & N_{part}^{Pb} = 12 - 14

Comparison to ATLAS p+Pb ridge

ATLAS coll. arXiv: 1212.5198, PRL in press

p+A centralities (N_{part}^{P},N_{part}^{A})

= (3,22) upper
= (4,14) lower



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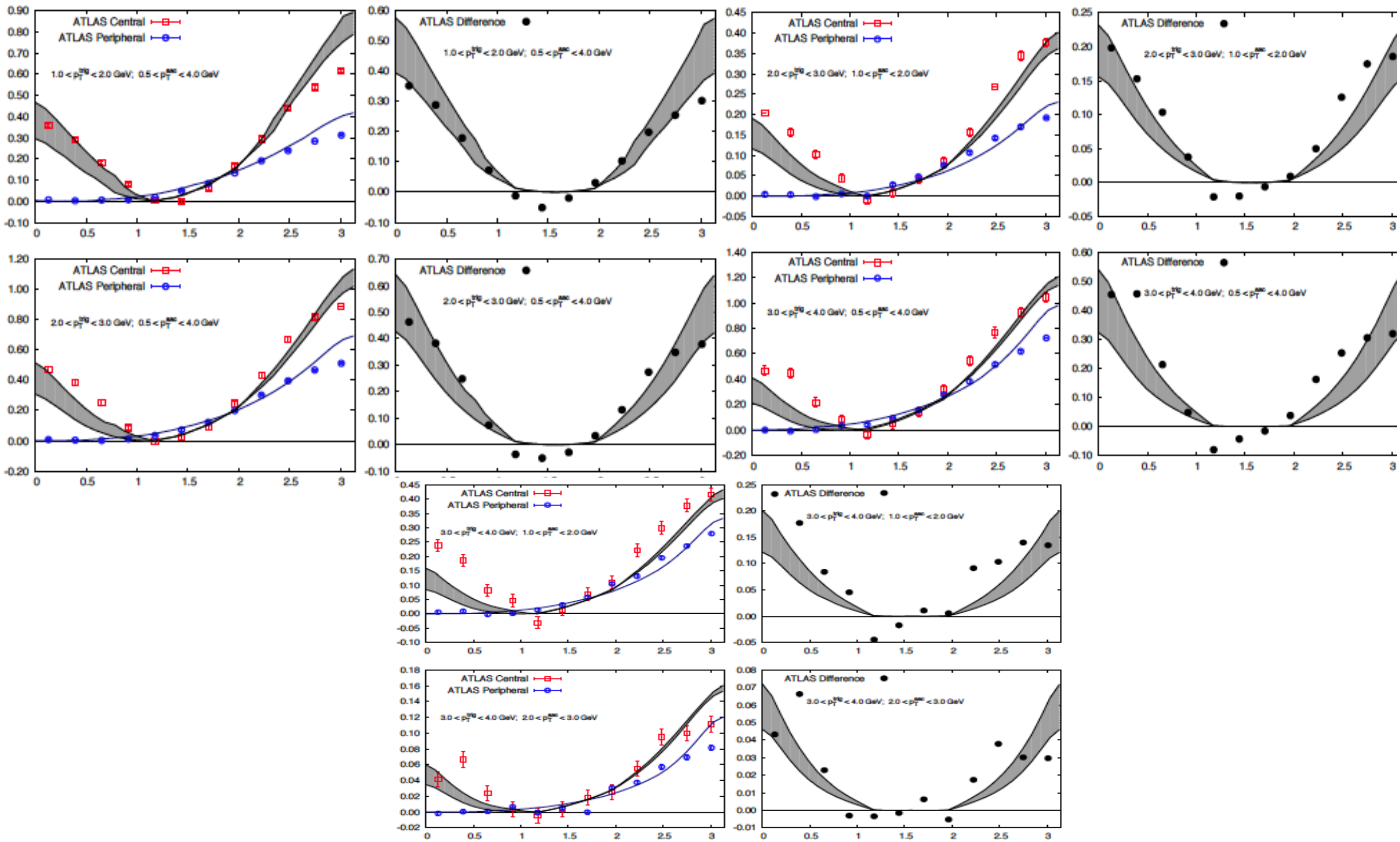
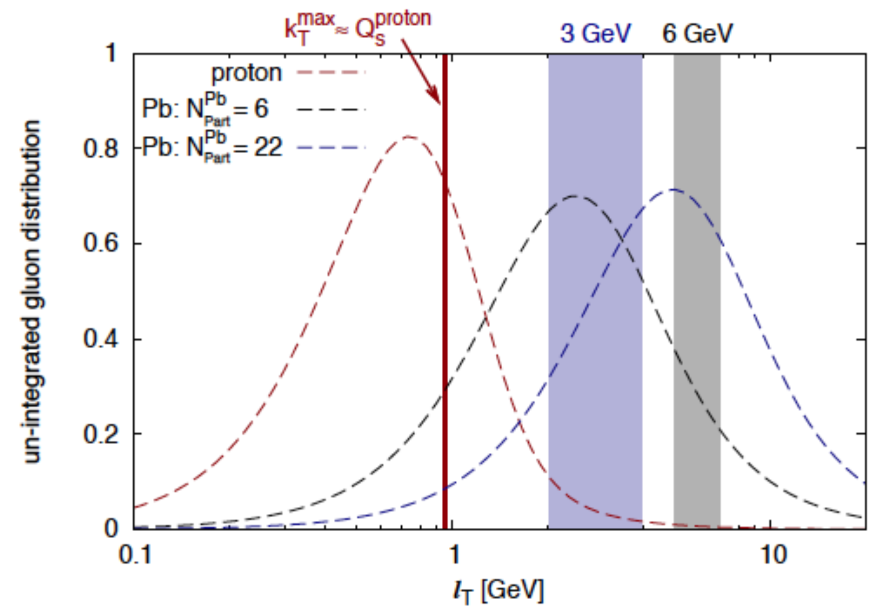


Physics underlying the ridge

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

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

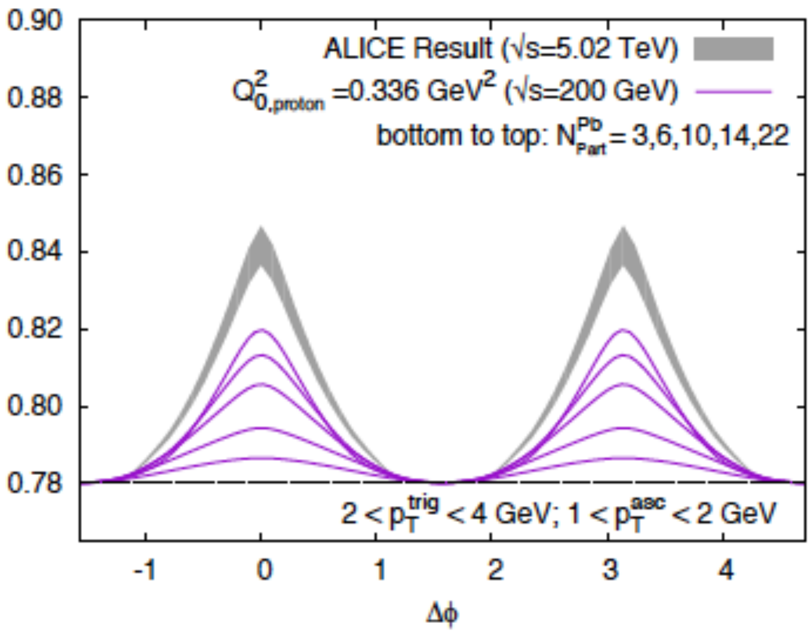


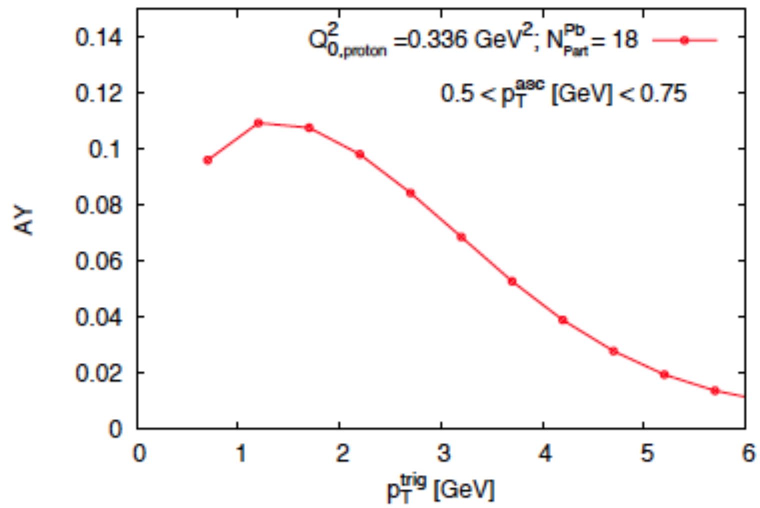
$$\mathrm{CY} \propto \frac{\Phi_B(Q_B)}{\Phi_B(\sqrt{2p_T^2 + 2Q_A^2 - Q_B^2})} \propto 1 + \frac{(Q_B - Q_A)^2}{Q_A^2} \sim N_{\mathrm{part}}$$

As seen in the LHC p+Pb data…

RHIC d+Au data

Dusling,RV: 1302.7018





PHENIX has measured large v2 in 0-5% d+Au collisions: arXiv:1303.1794

We compute correlated yield

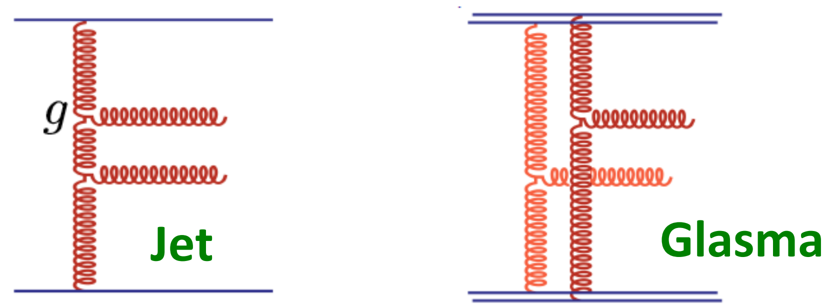
$d^2N_{corr} \approx d^2N_{pedestal}\, v_2^{\,2}$

Strong function of p_T^a, p_T^b – larger at LHC

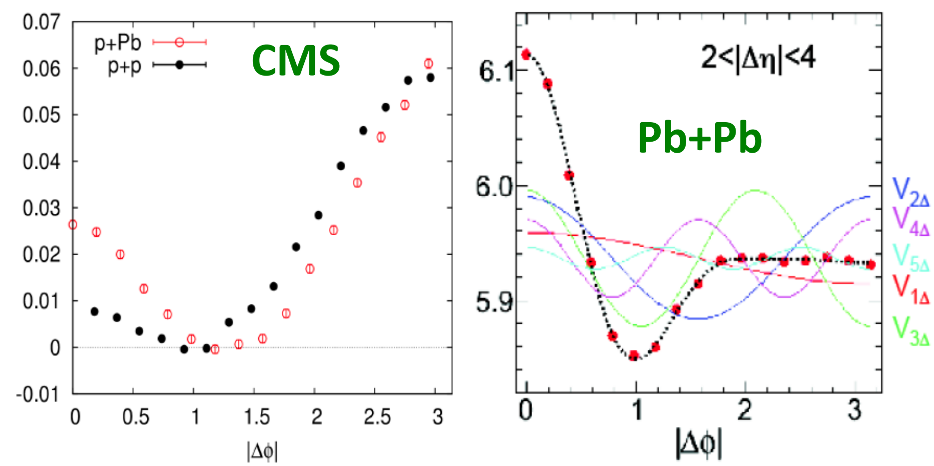
Extraction of d^2N_{corr} would allow quantitative study in our framework

Are there signficant final state effects ?

Why is jet unmodified while Glasma graph (which generates the v_2) is ?



Appears quite different in p+p and p/A versus A+A



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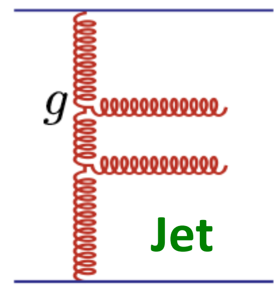

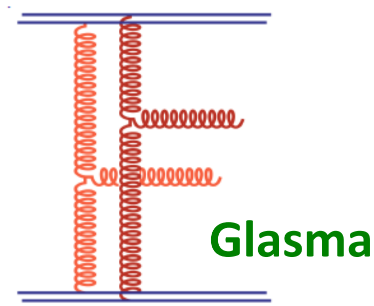

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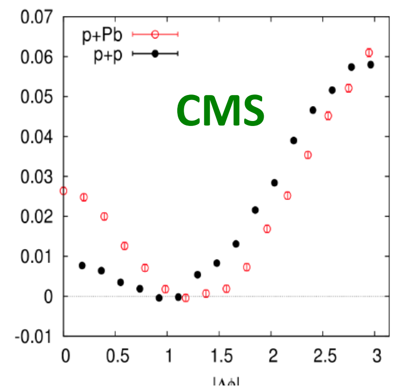
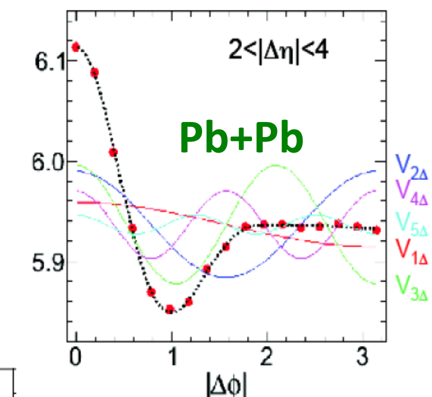
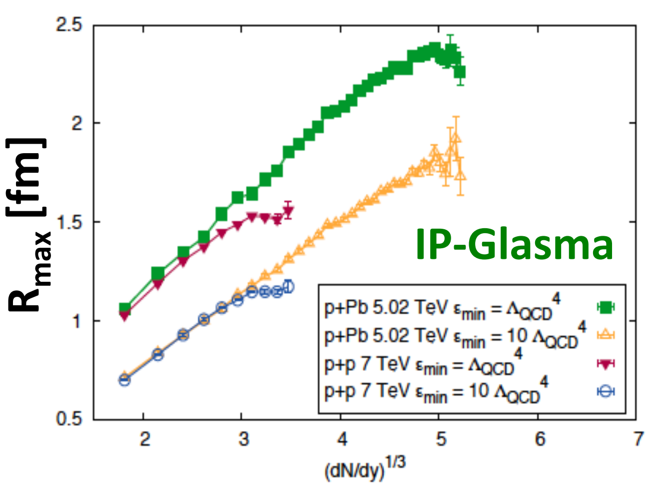
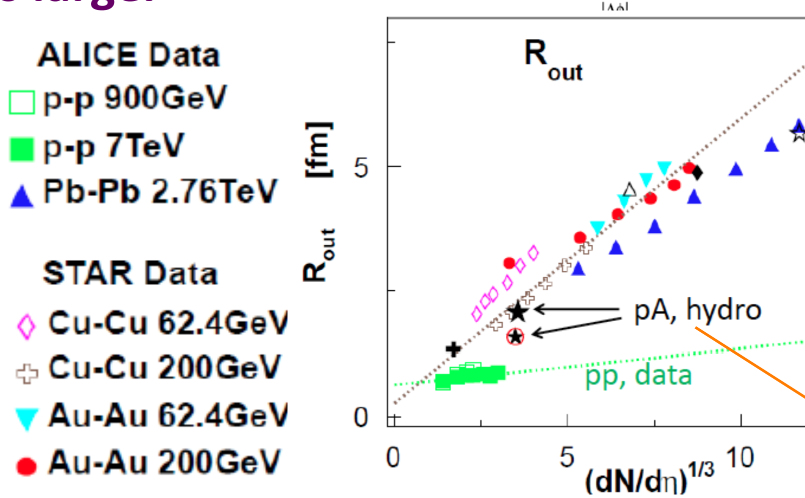




Sizes are the same in p+p and p+Pb whose ``v_2'' is ~ 4 times larger





HBT radii in p+A will be very helpful !

Bozek,Broniowski, PLB 720 (2013) 250

Role of flow in p+p, p/d+A

- ✧ Is there room for flow in these systems ? See next talk by Piotr Bozek

- ✧ Our view: hydro results very sensitive to initial conditions

  -- significant differences seen between IP-Glasma and MC-Glauber models

  -- flow in p+p is small and at most 50% less than p+A even for "nearly ideal" flow simulations

  -- large viscous corrections in small size systems

  -- talk on Wednesday by Bjoern Schenke   Bzdak,Schenke,Tribedy,RV, arXiv:1304.3403

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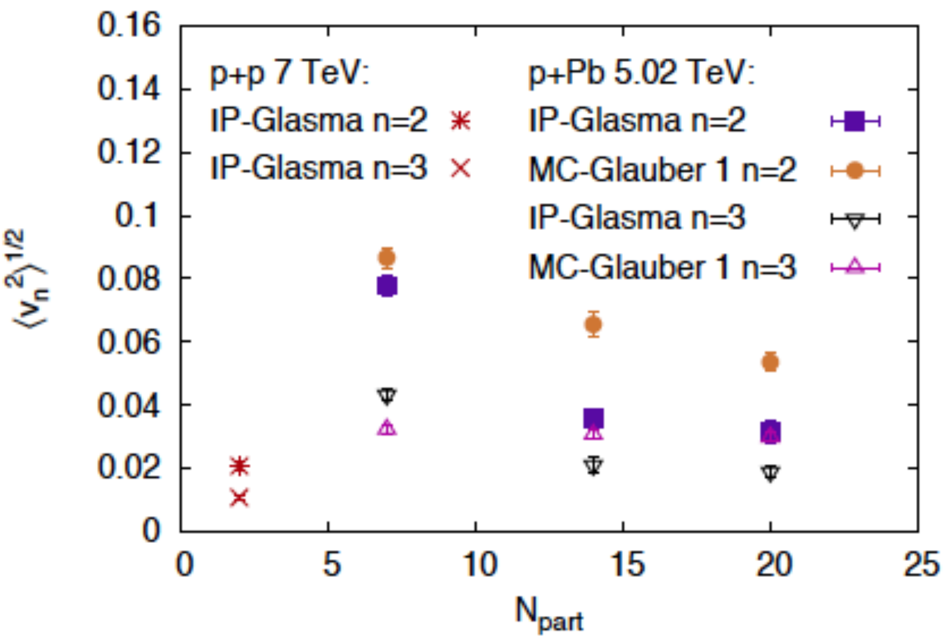
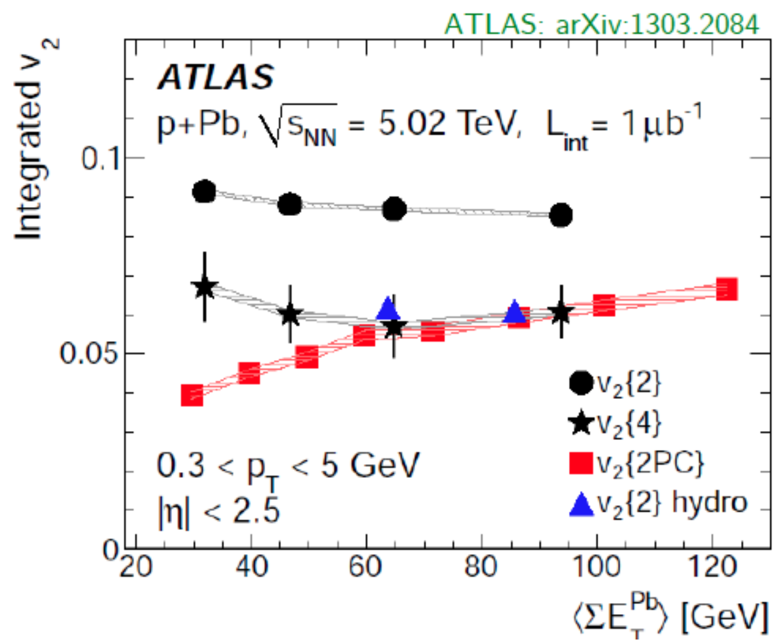
- ✧ **Trend/magnitude of flow different from p+Pb data – note Glasma η/s=0.08 !**



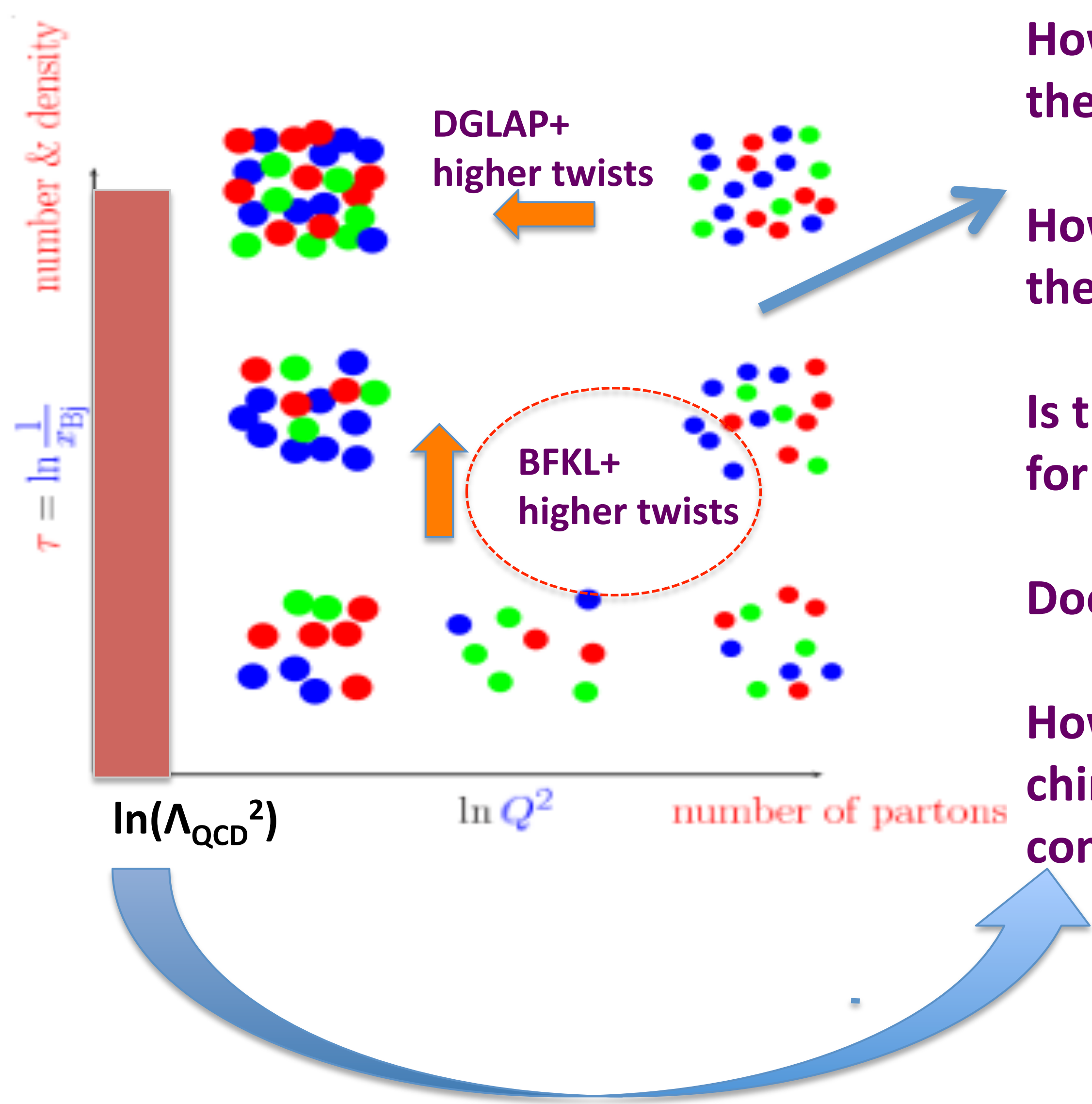


Conclusions

- The Glasma framework provides a systematic description of multi-particle production in p+p, p+A and A+A collisions
- The p+p ridge can be quantitatively understood from gluon saturation enhanced quantum interference Glasma graphs + BFKL graphs
- The A+A ridge and v_n moments are quantitatively described by IP-Glasma initial conditions + flow
- The p/d+A ridge situation is not completely clear yet
  - but will be clarified soon. 2-part corr. data presented thus far are quantitatively described by Glasma+BFKL dynamics

EXTRA SLIDES

The big picture: many-body universal gluodynamics



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

Physics underlying systematics of the ridge

For Glasma graphs

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

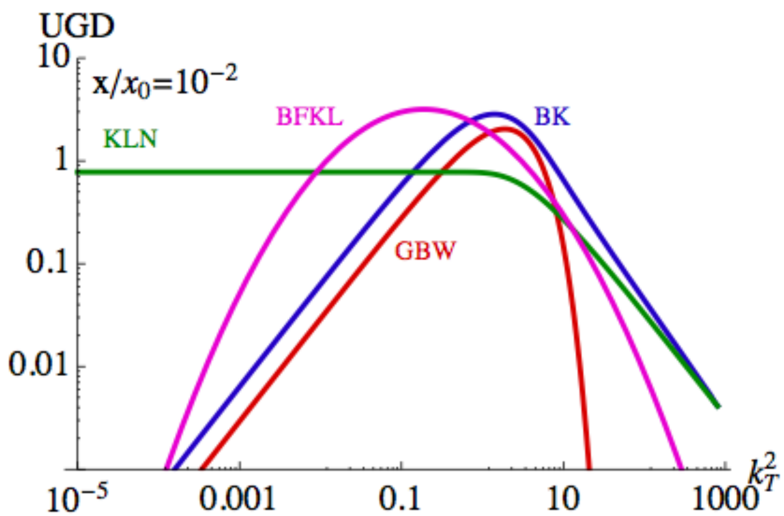
For $|p_T| = |q_T|$, from the Cauchy-Schwarz inequality:

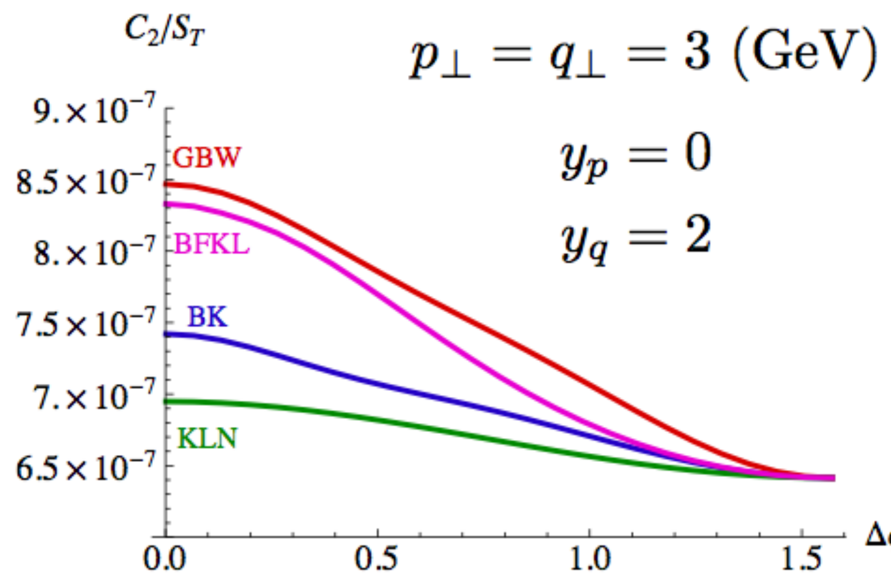
$$\int d^2k_T\ \Phi_A^2(k_T)\ \Phi_B(|p_T - k_T|)\ \Phi_B(|q_T - k_T|) \le \int d^2k_T\ \Phi_A^2(k_T)\Phi_B^2(|p_T - k_T|)$$

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





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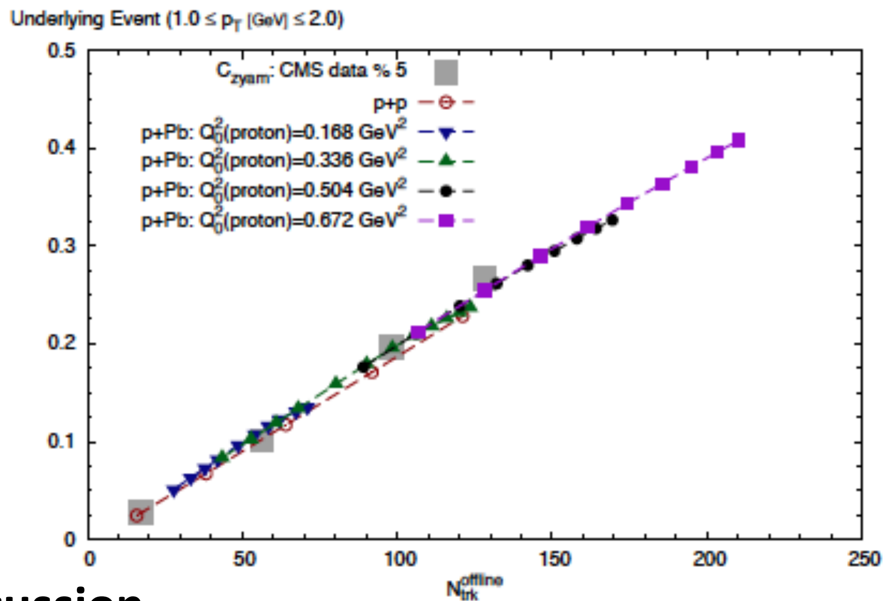

From previous discussion

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

rcBK vs IP-Sat evolution