CGC and Initial Conditions for Heavy Ion Collisions

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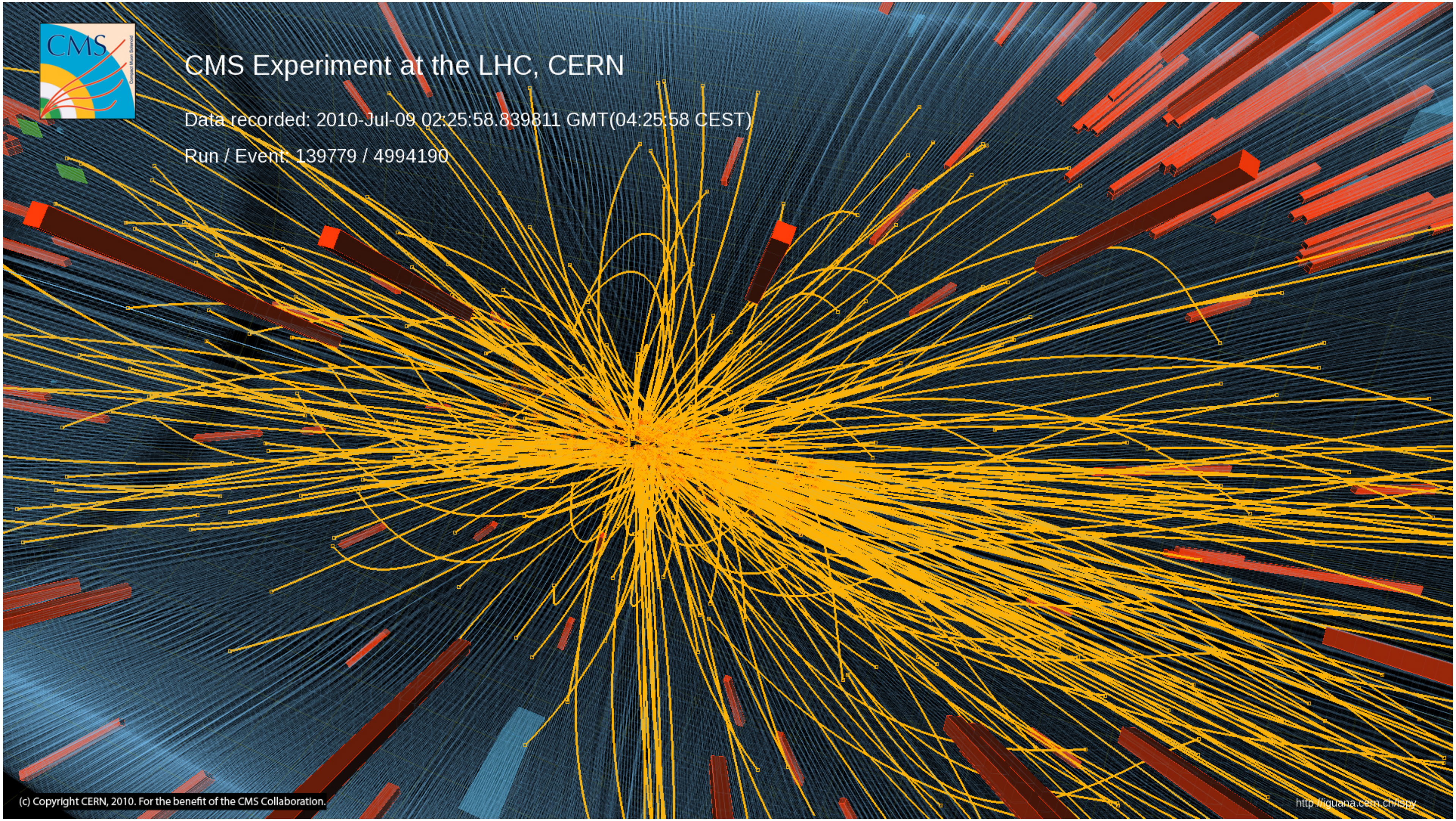
Two particle correlations in p+p collisions

1. Evidence for saturation dynamics (the p+p near-side Ridge)

2. Evidence for BFKL evolution (mini-jet decorrelation)

3. Prospects for p+Pb @ LHC

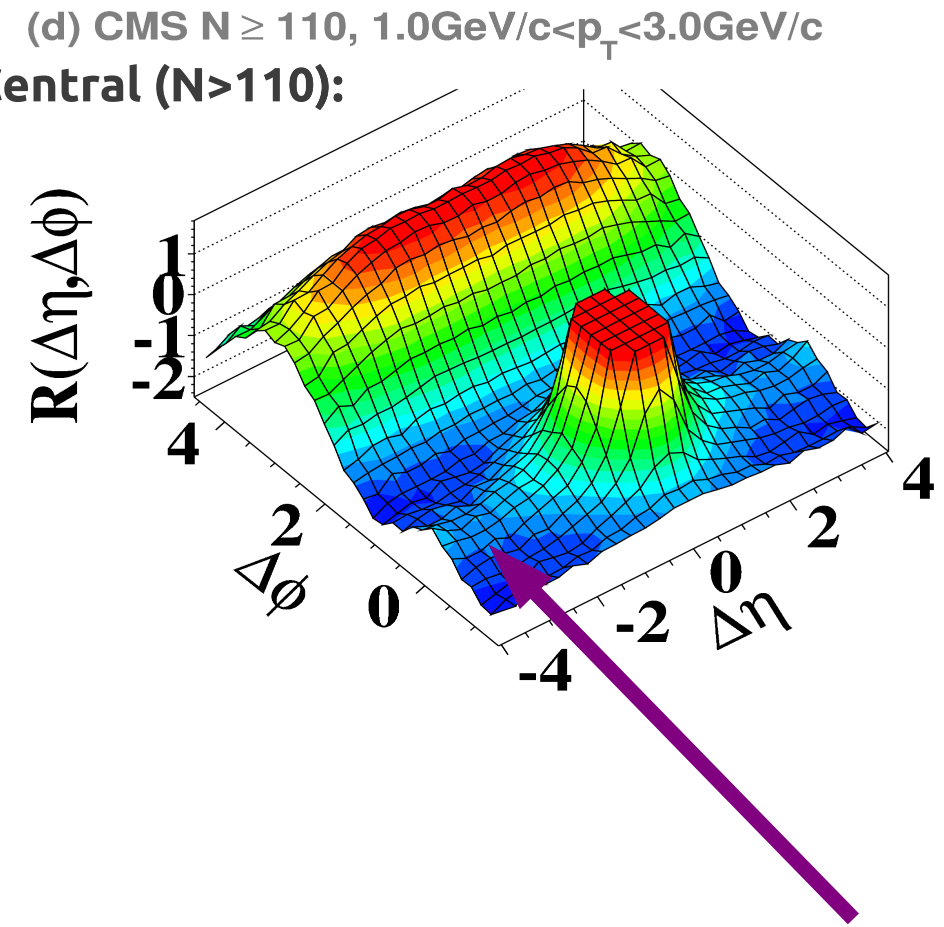
Part 1: the p+p near side ridge



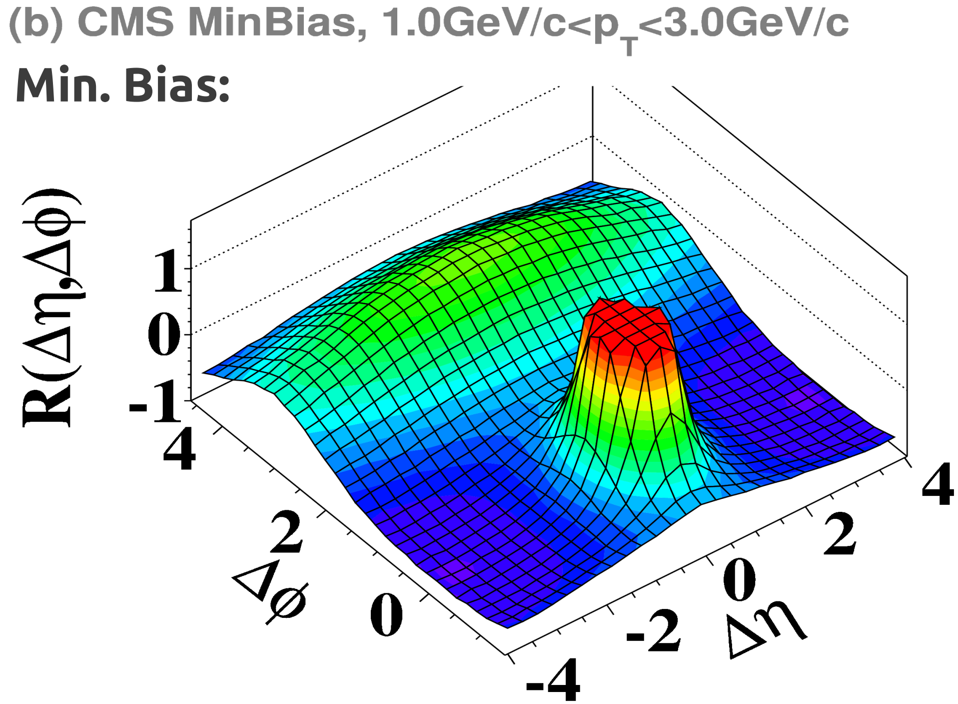
More than 200 charged particles!

$$1.0 < p_T[\text{GeV}] < 3.0$$

Central (N>110):

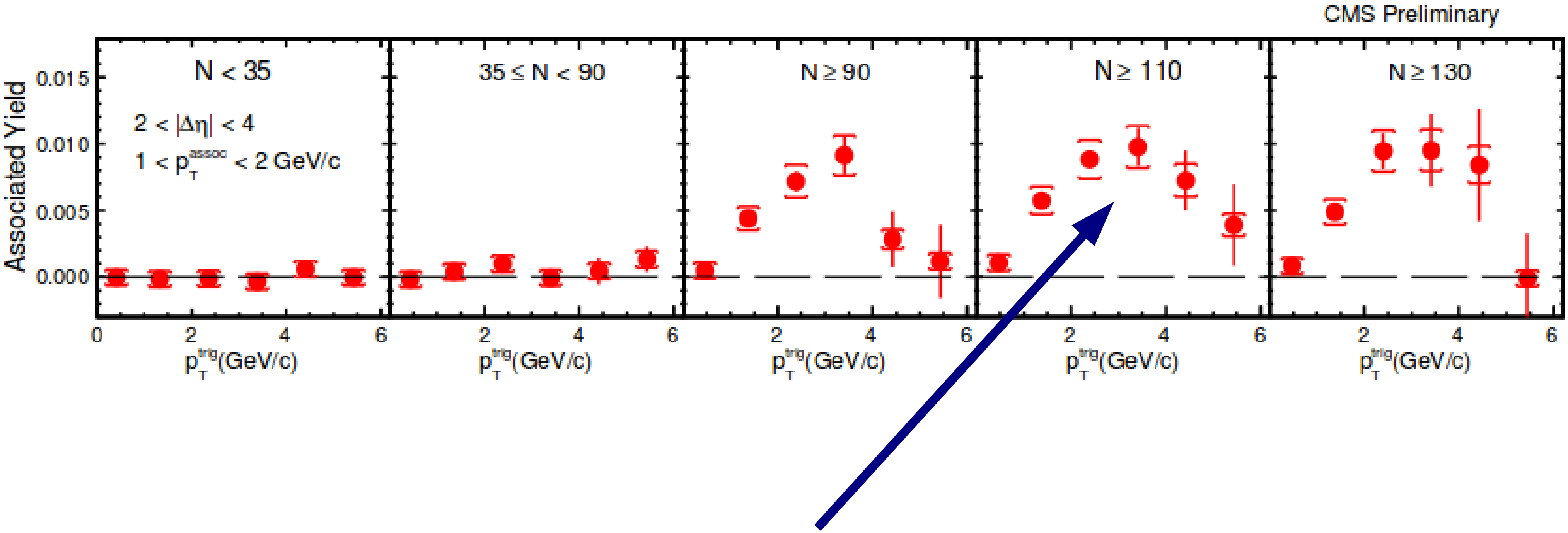


Min. Bias:



Novel structure seen in highest multiplicity events

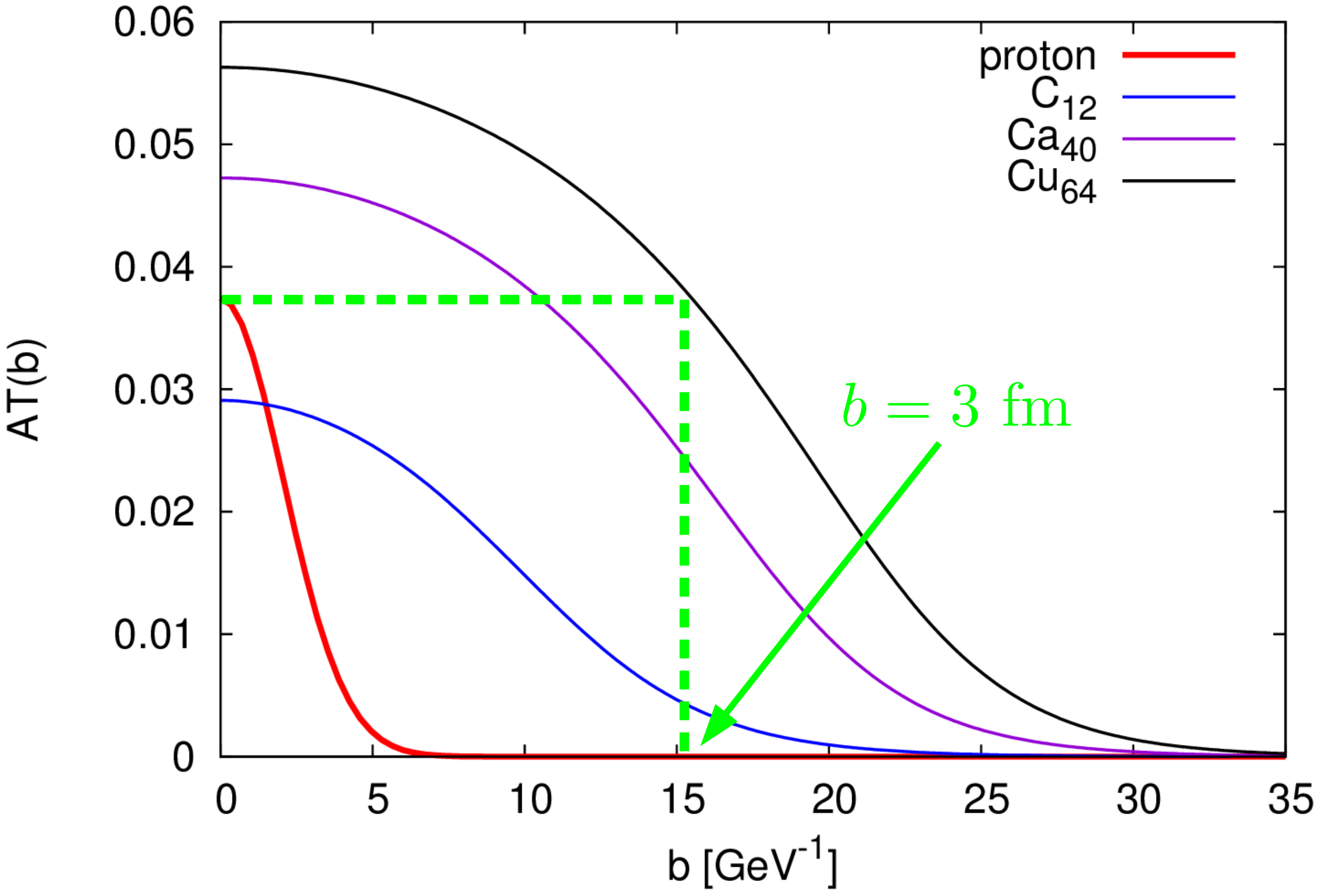
The Ridge



1. There is a clear scale in the data

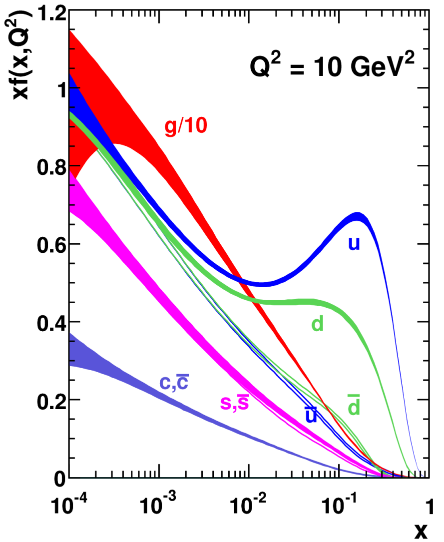
2. It is semi-hard and will be argued to be related to Q_s

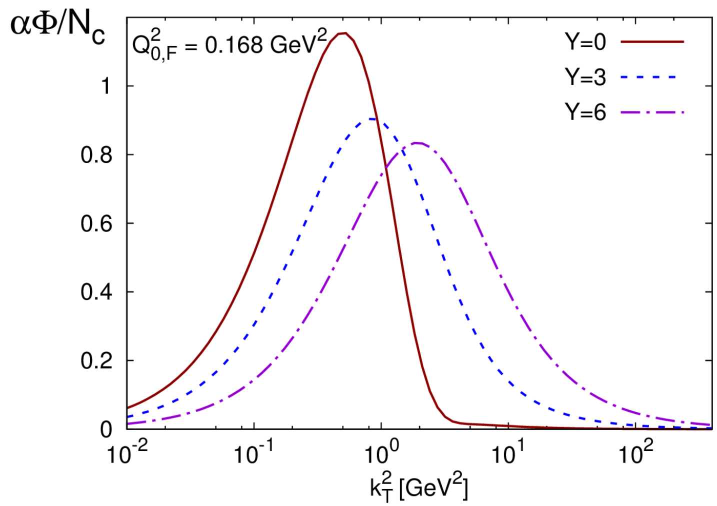
Multiplicity the same as in Cu+Cu !



The proton pre-collision

Our field has a good understanding of the proton wave-function:

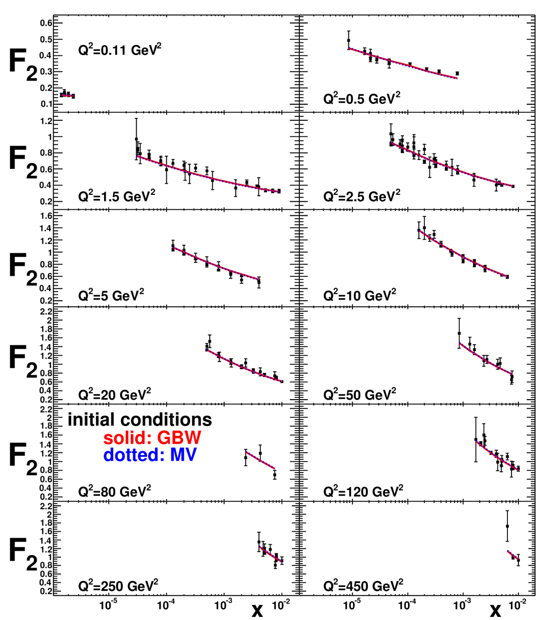


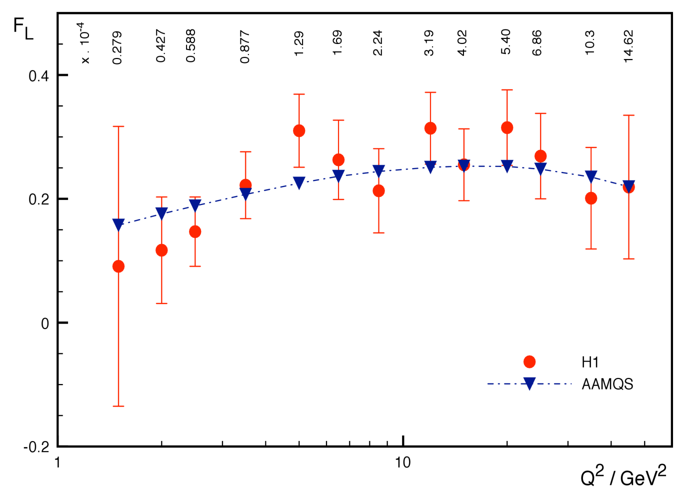


NLO DGLAP fits:
http://mstwpdf.hepforge.org/

NLO-BK:
Balitsky, Chirilli PRD 77 014019
Kovchegov, Weigert NPA 784 188
Albacete, Kovchegov PRD 75 125021

15 years of HERA data support this picture:



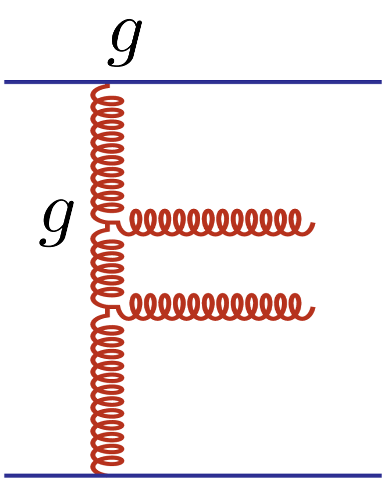


Albacete, Milhano, Quiroga-Arias ,Rojo,
arXiv:1203.1043 (2012).
Quiroga-Arias, Albacete, Armesto, Milhano, Salgado,
J.Phys.G G38 (2011) 124124.
Albacete, Armesto, Milhano, Salgado,
PRD80 (2009) 034031.

Power counting in QCD: multiparticle production

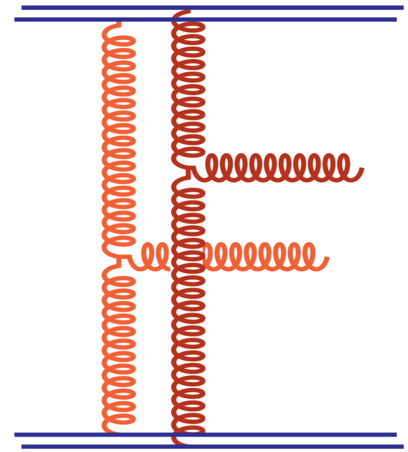
Low color charge density (min bias):

Jet graph:



$$\mathcal{O}\left(\alpha_s^4\right)$$

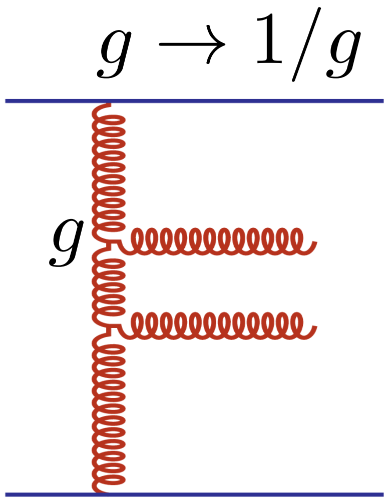
Glasma graph:



$$\mathcal{O}\left(\alpha_s^6\right)$$

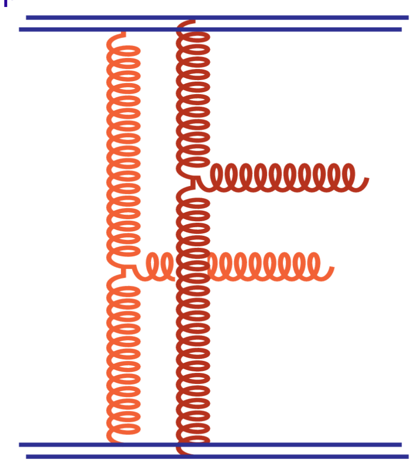
High color charge density (central):

Jet graph:



$$\mathcal{O}\left(1\right)$$

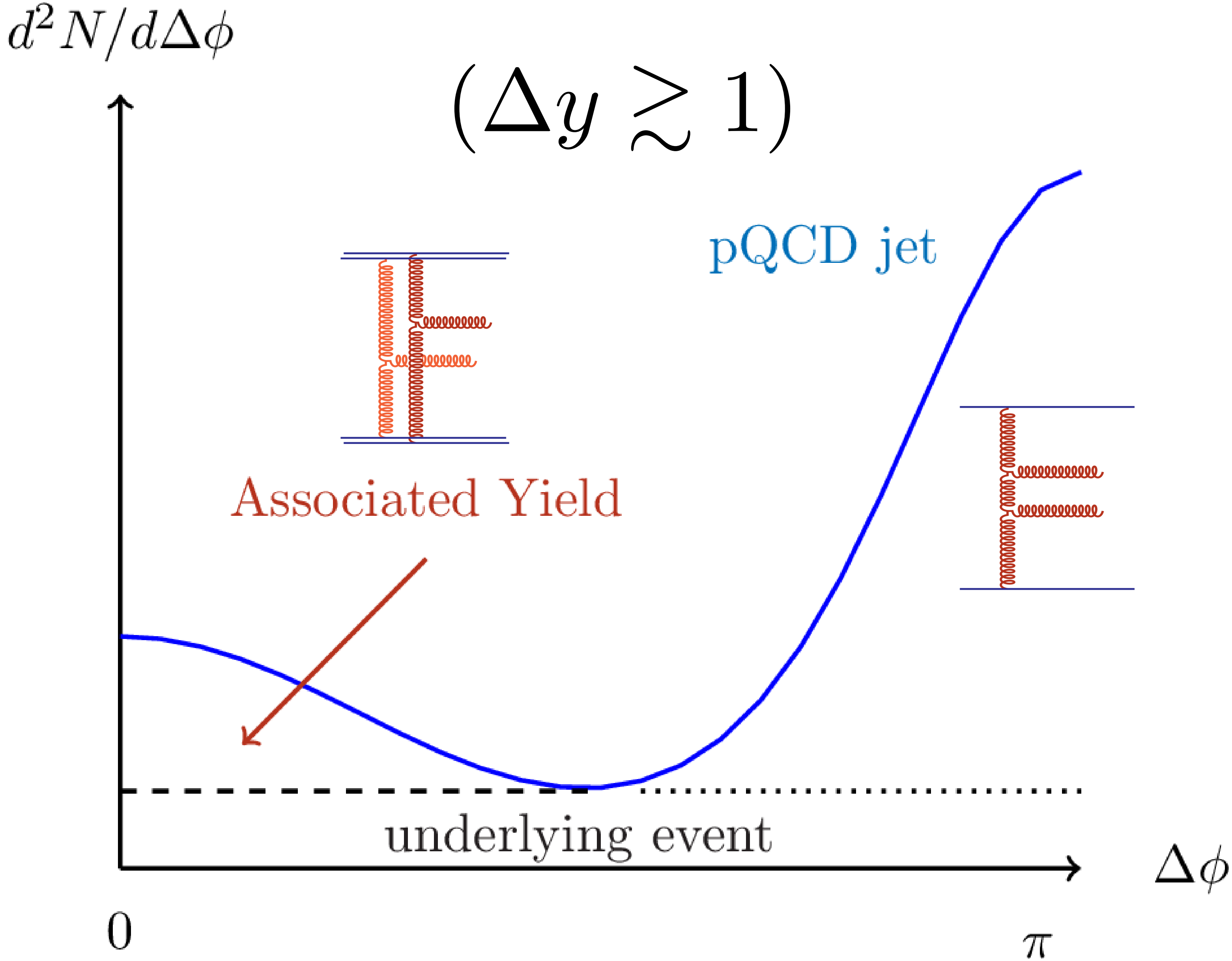
Glasma graph:



$$\mathcal{O}\left(\alpha_s^{-2}\right)$$

Expect $\alpha_{\mathbf{s}}^{\mathbf{8}}$ enhancement of "Glasma" graph! Is this seen in the data?

Forward jet structure



$\mathrm{k_T}$ factorization: double gluon production

$$\left\langle \frac{\mathrm{d}N_2}{\mathrm{d}^2\mathbf{p}_\perp \mathrm{d}y_p \mathrm{d}^2\mathbf{q}_\perp \mathrm{d}y_q} \right\rangle_{\mathrm{LLog}} = \frac{32\alpha_s(\mathbf{p}_\perp)\alpha_s(\mathbf{q}_\perp)}{(2\pi)^{10} N_c C_F^3 \zeta} \frac{1}{\mathbf{p}_\perp^2 \mathbf{q}_\perp^2}$$

$$\times \left\{ \int \mathrm{d}^2\mathbf{k}_{1\perp} \Phi_{A_1}^2(y_p, \mathbf{k}_{1\perp}) \Phi_{A_2}(y_p, \mathbf{p}_\perp - \mathbf{k}_{1\perp}) \Phi_{A_2}(y_q, \mathbf{q}_\perp + \mathbf{k}_{1\perp}) \right.$$

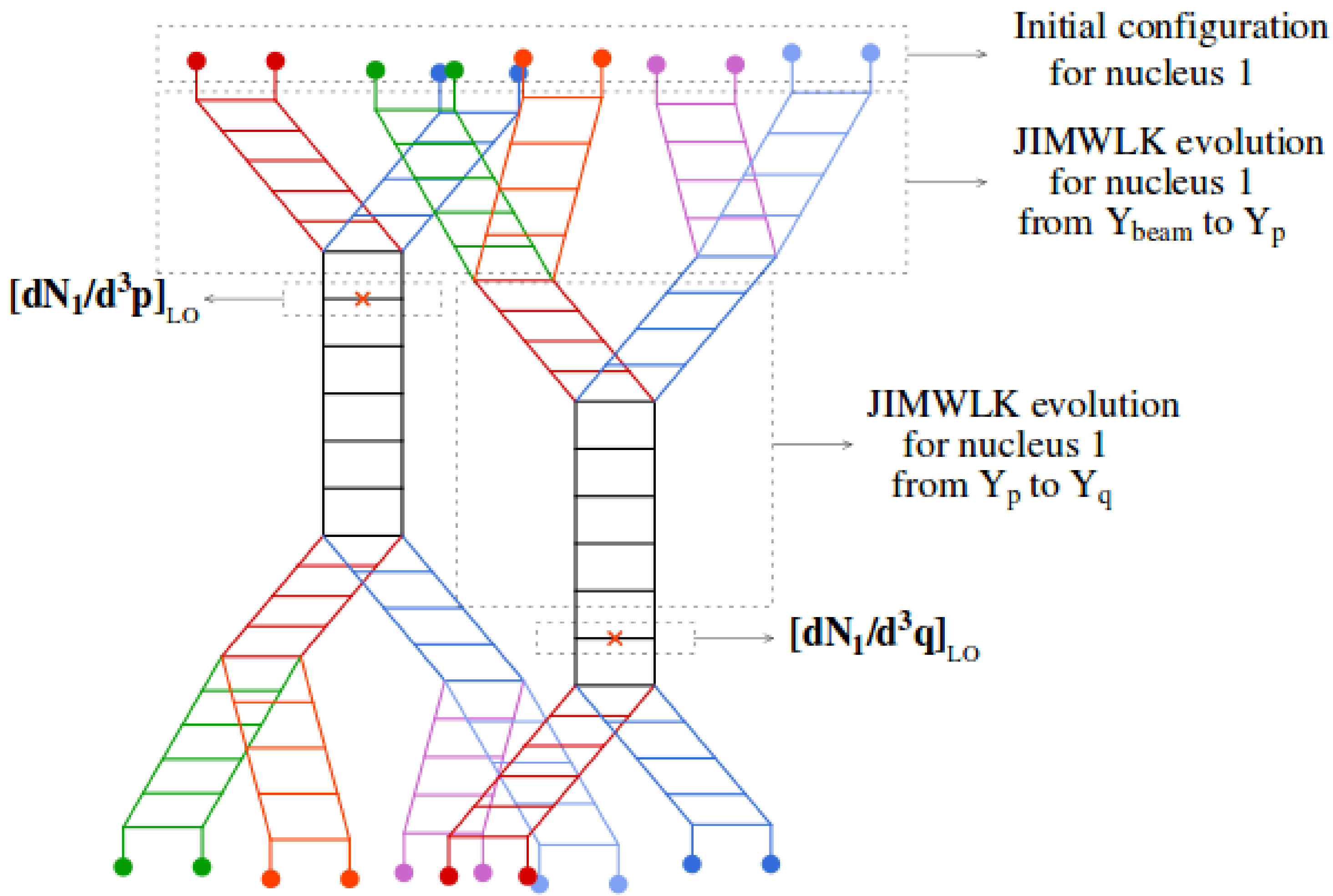
$$+ \int \mathrm{d}^2\mathbf{k}_{1\perp} \Phi_{A_1}^2(y_p, \mathbf{k}_{1\perp}) \Phi_{A_2}(y_p, \mathbf{p}_\perp - \mathbf{k}_{1\perp}) \Phi_{A_2}(y_q, \mathbf{q}_\perp - \mathbf{k}_{1\perp})$$

$$+ \int \mathrm{d}^2\mathbf{k}_{1\perp} \Phi_{A_2}^2(y_q, \mathbf{k}_{1\perp}) \Phi_{A_1}(y_p, \mathbf{p}_\perp - \mathbf{k}_{1\perp}) \Phi_{A_1}(y_q, \mathbf{q}_\perp + \mathbf{k}_{1\perp})$$

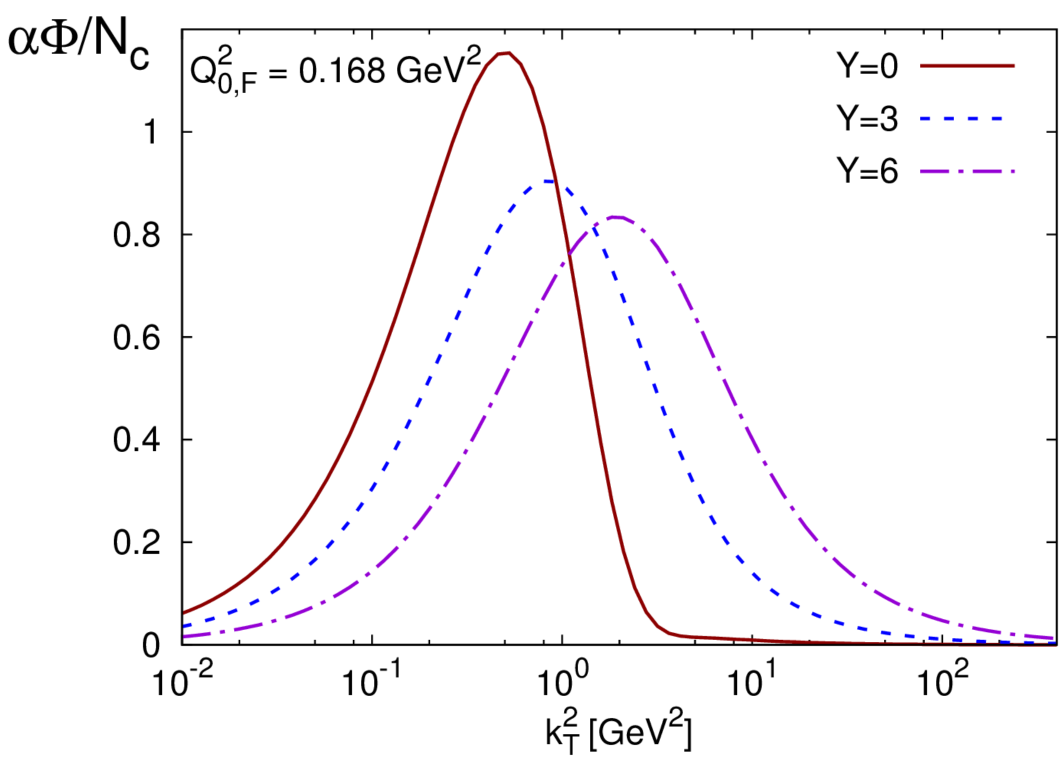
$$\left. + \int \mathrm{d}^2\mathbf{k}_{1\perp} \Phi_{A_2}^2(y_q, \mathbf{k}_{1\perp}) \Phi_{A_1}(y_p, \mathbf{p}_\perp - \mathbf{k}_{1\perp}) \Phi_{A_1}(y_q, \mathbf{q}_\perp - \mathbf{k}_{1\perp}) \right\}$$

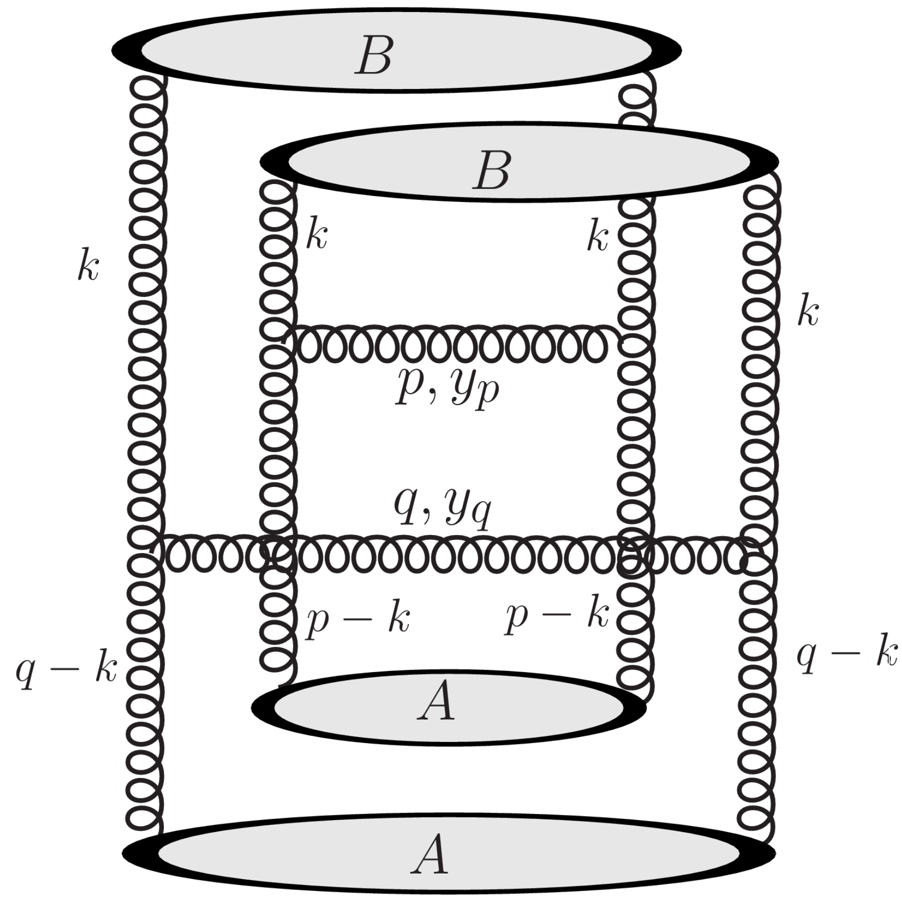
Gelis, Lappi, Venugopalan, PRD78, 050419 (2008).
PRD78, 054020 (2008).
PRD79, 094017 (2009).
Dusling, Gelis, Lappi, Venugopalan, NPA 836 159-182 (2010).

k_T factorization: double gluon production



Angular Structure



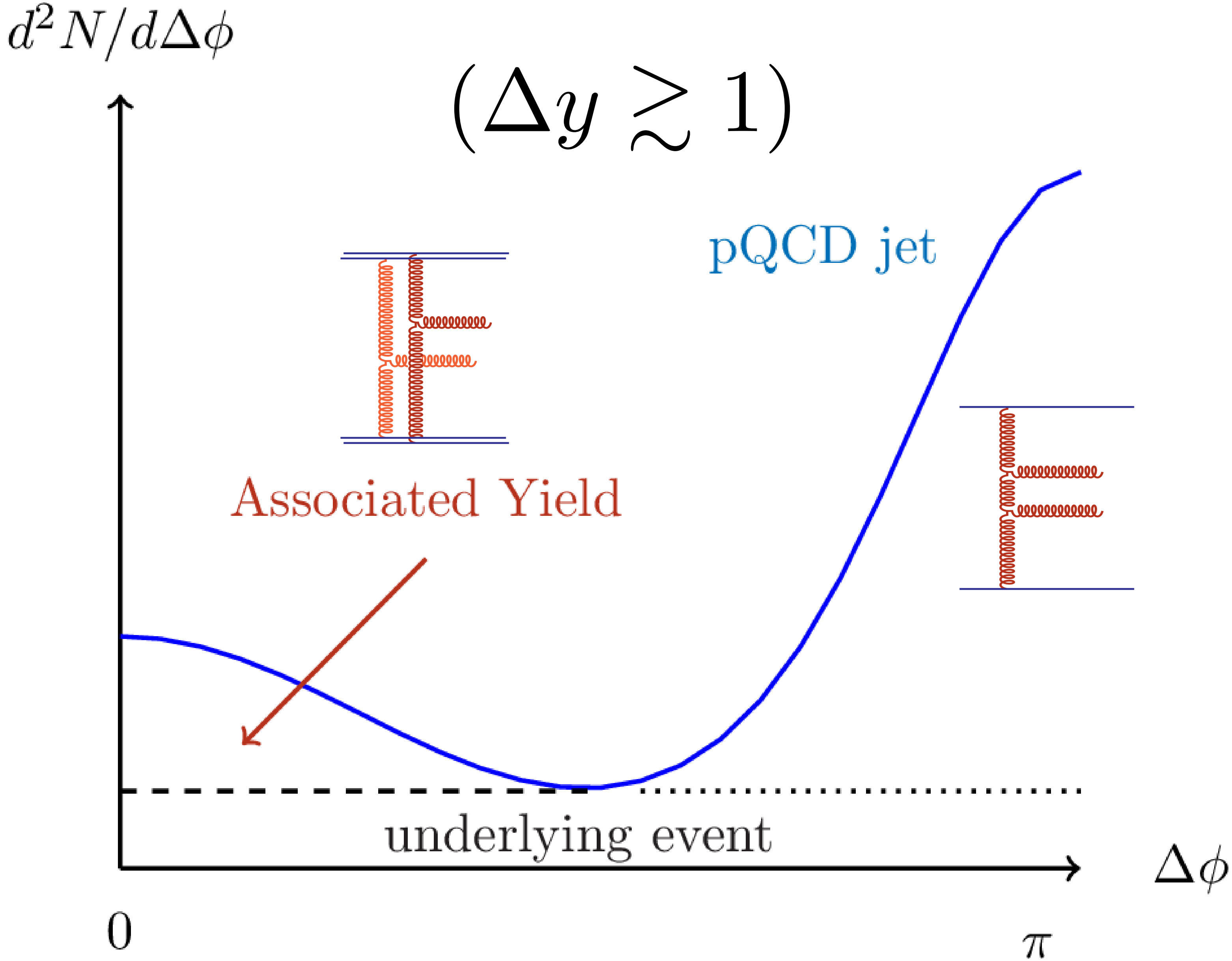


Condition for Ridge (Qualitatively):

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

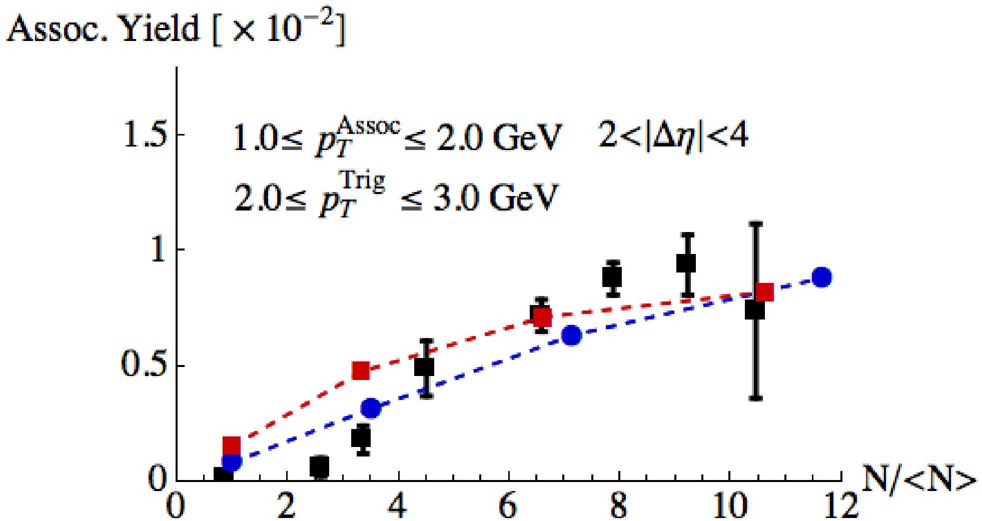
Dumitru, Dusling, Gelis, Lalilian-Marion, Lappi, Venugopalan, PLB 697 12-25 (2011).

Forward jet structure



Ridge in p+p collisions

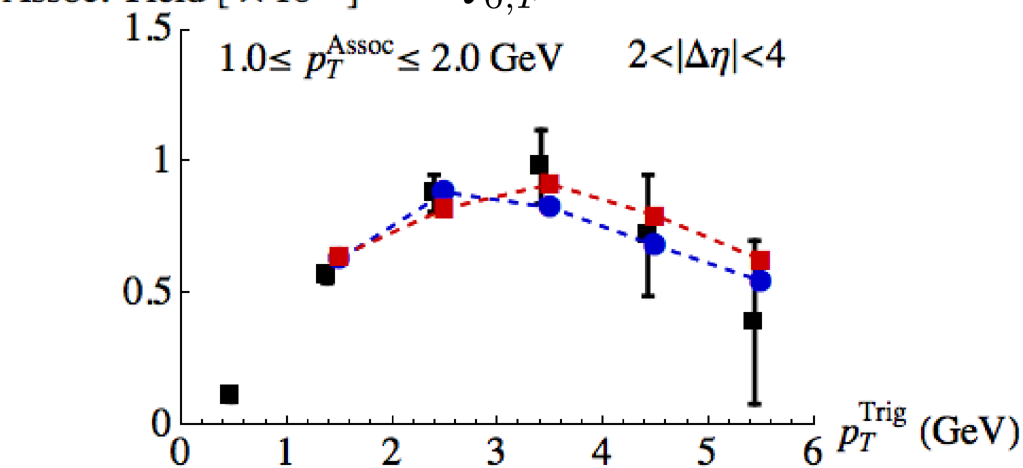
Centrality Dependence:



$$Q^2_{0,F}(x_0 = 0.01) = 0.15, 0.3, 0.45, 0.6 \text{ GeV}^2$$

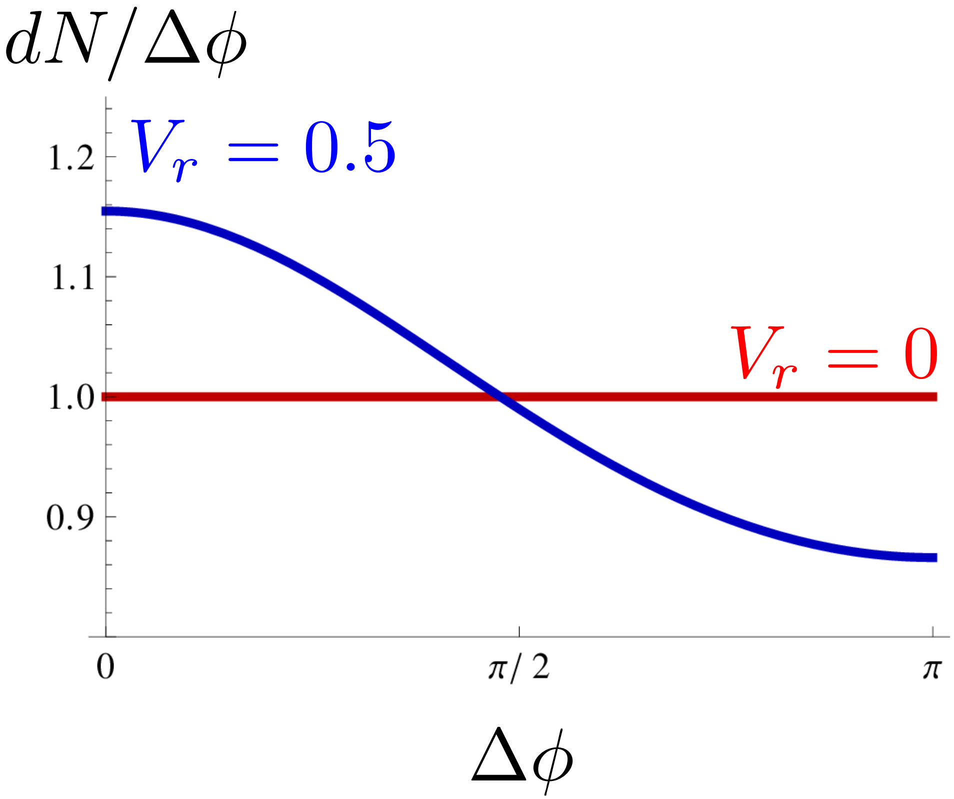
Trigger Dependence:

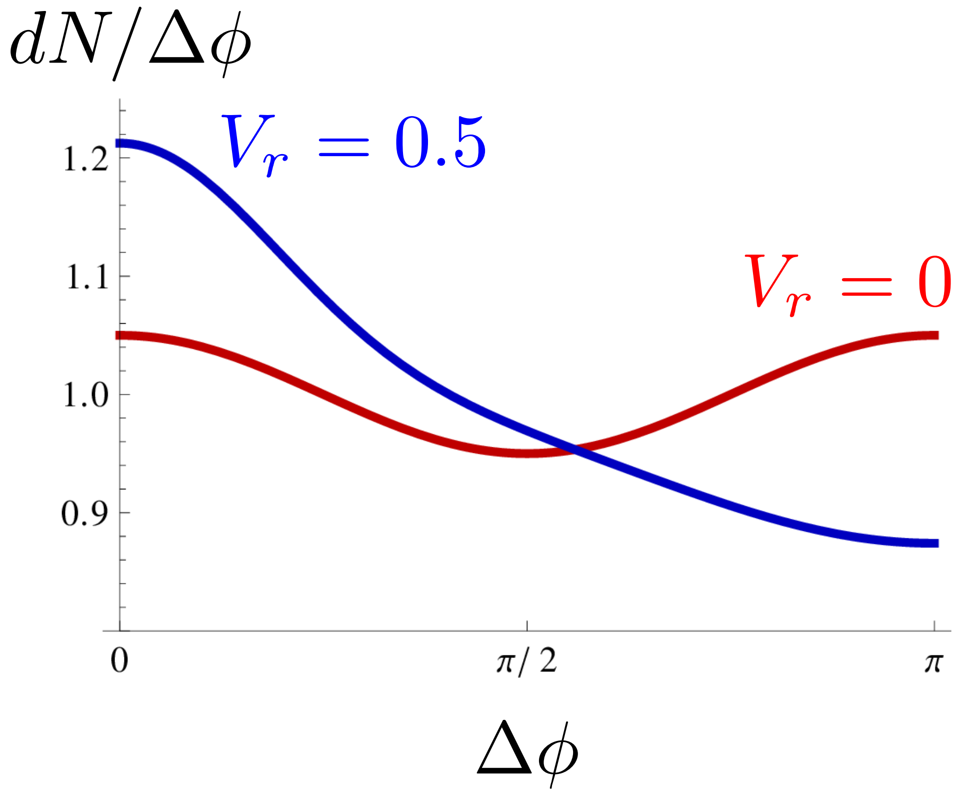
$Q^2_{0,F} = 0.6 \text{ GeV}^2$



Dusling, Venugopalan, PRL 108, 262001 (2012).
Dumitru, Dusling, Gelis, Jalilian-Marian, Lappi, Venugopalan, PLB 697 12-25 (2011).

Role played by transverse flow





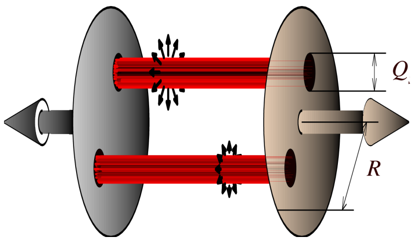
Left: No intrinsic correlation in Δφ followed by radial boost.

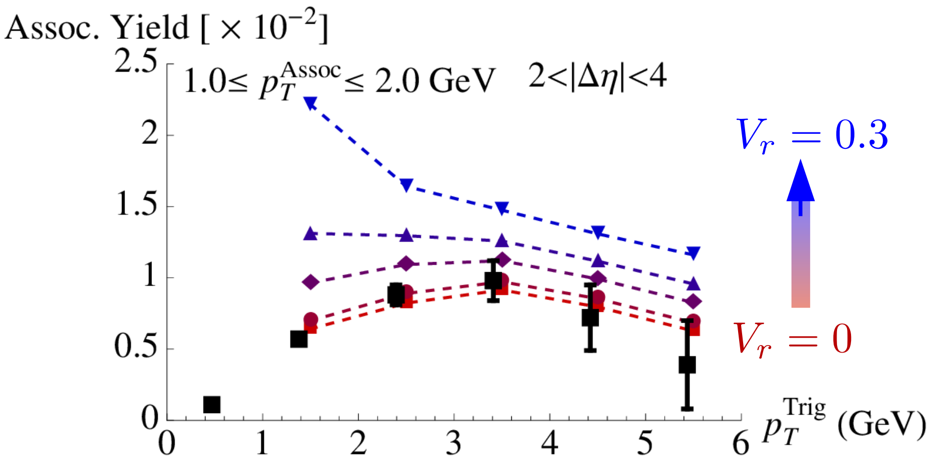
Right: Intrinsic azimuthal correlation followed by boost.

Transverse flow increases near side collimation; but is it seen in the data?

p+p vs A+A

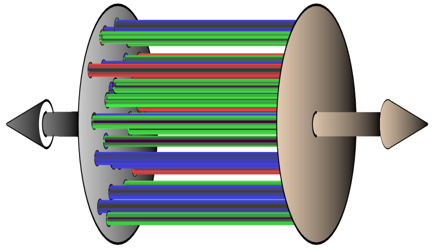
In p+p we are seeing the intrinsic collimation from a single flux tube

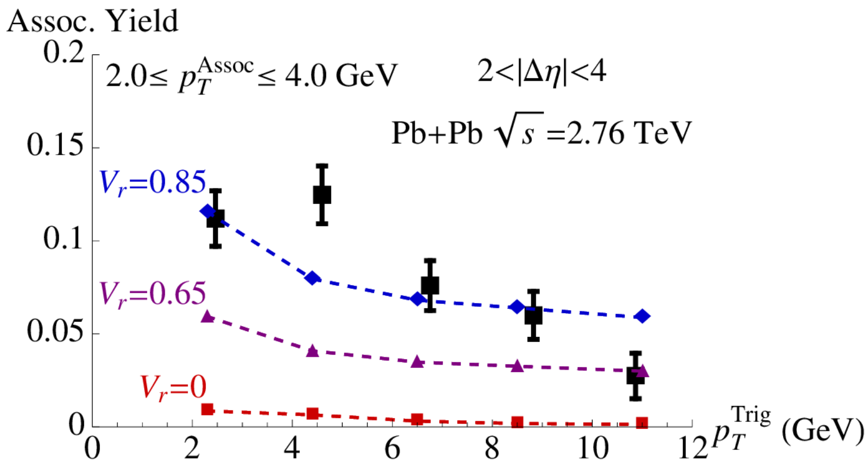




Increasing transverse flow in p+p creates a discrepancy with data.

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



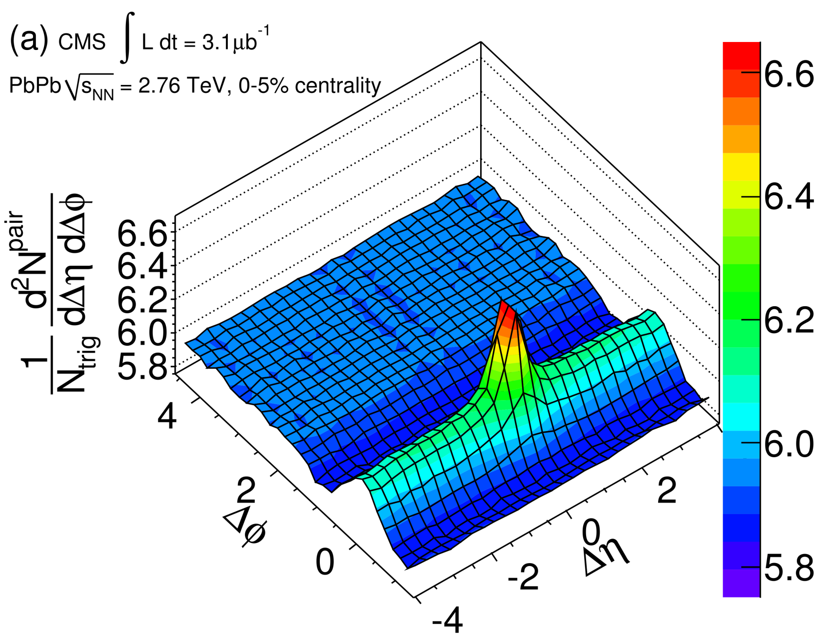


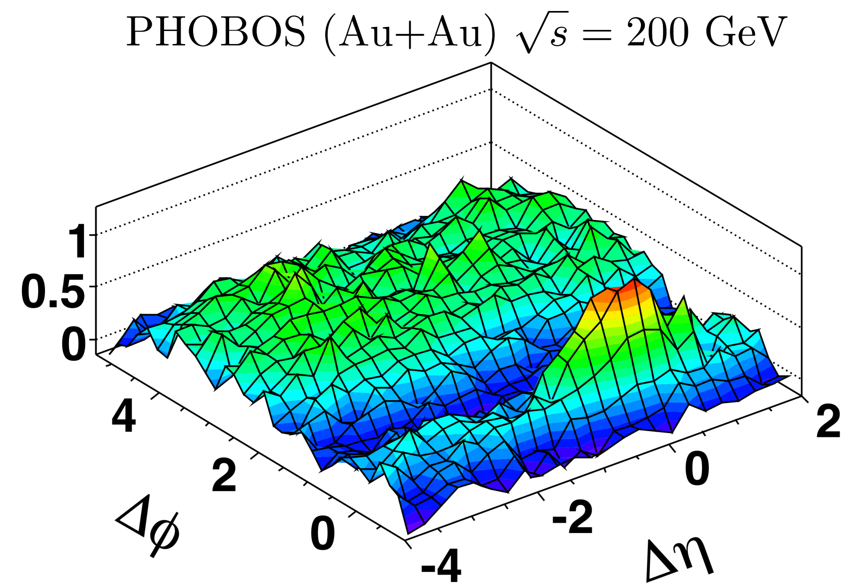
Yet, transverse flow is needed to explain identical measurements in Pb+Pb

Are we sure the A+A ridge is probing the nuclear wavefunction?

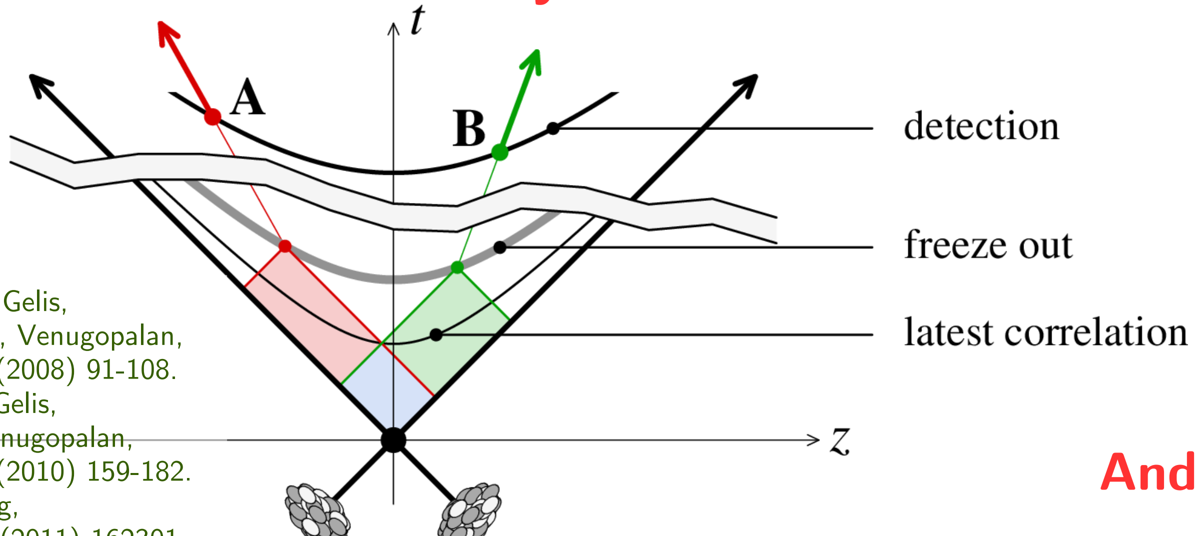
Dusling, Venugopalan, PRL 108, 262001 (2012).

Heavy-Ion Ridge





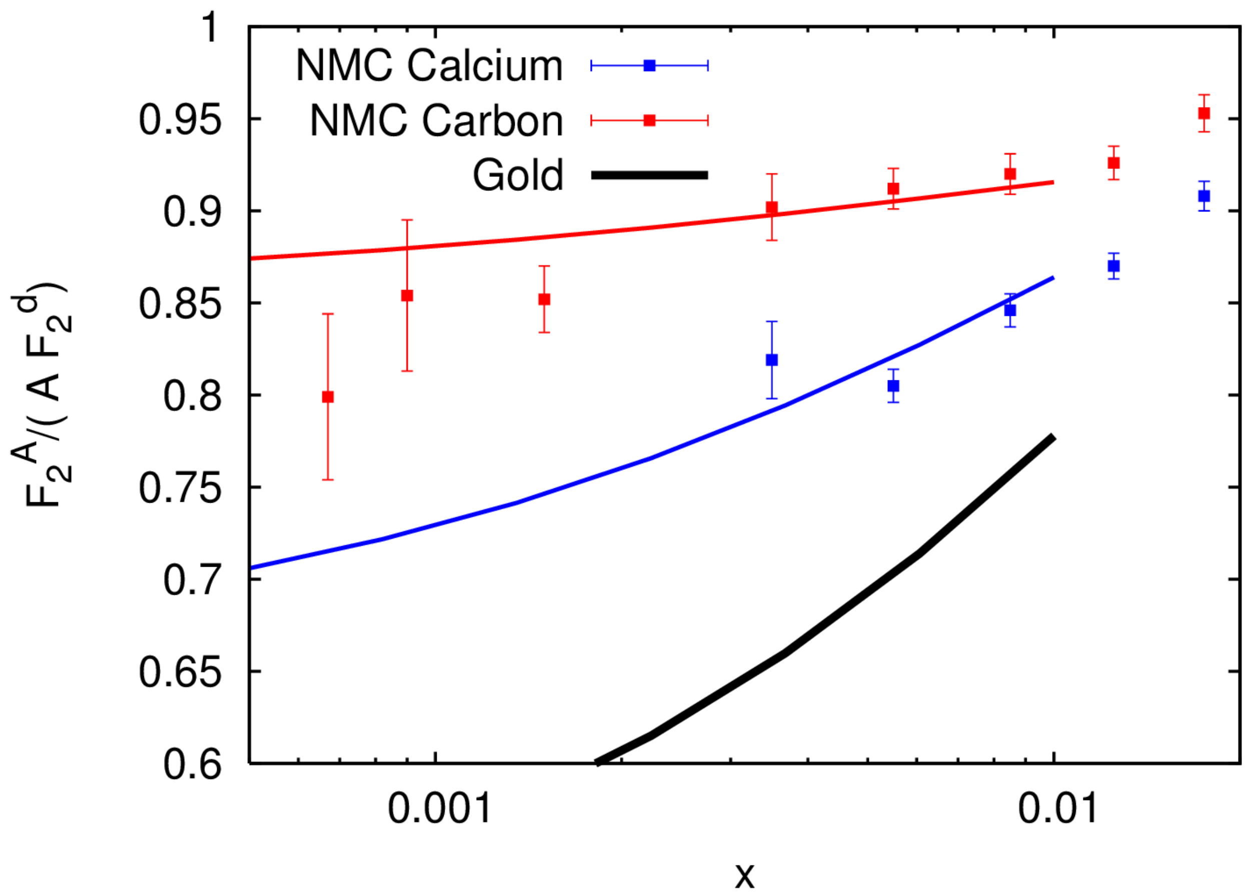
The correlation is long range in rapidity.
Causality dictates the correlation formed early.



Dumitru, Gelis, McLerran, Venugopalan, NPA810 (2008) 91-108.
Dusling, Gelis, Lappi, Venugopalan, NPA836 (2010) 159-182.
Ma, Wang, PRL 106 (2011) 162301.

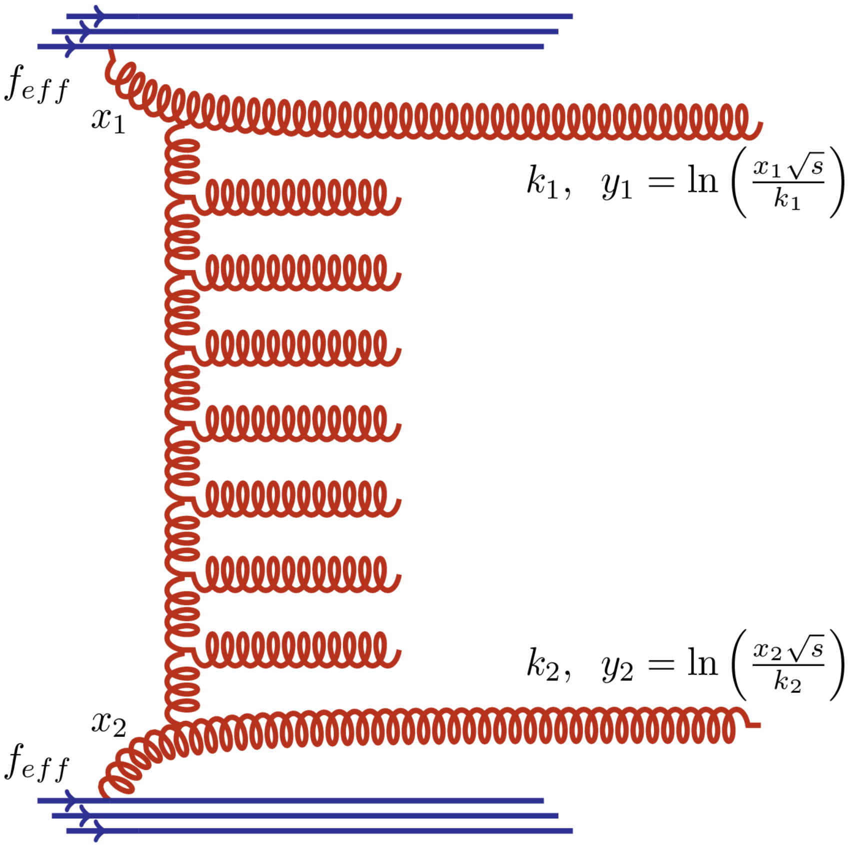
And it persists to the final state:

Need for EIC:



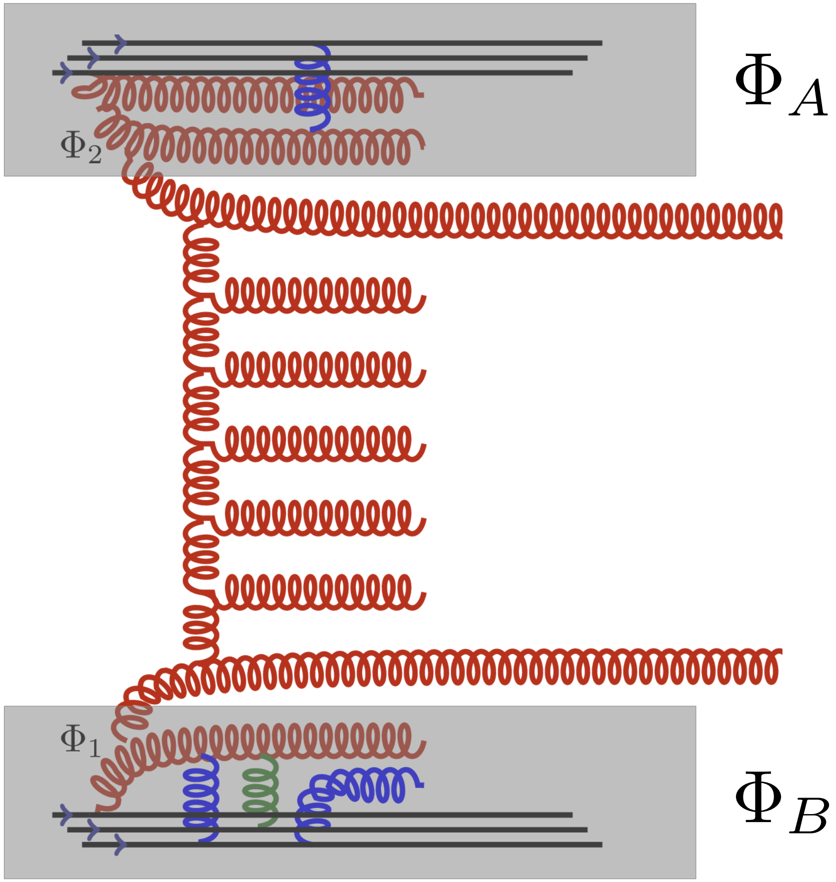
World collection of small x ($x \leq 0.01$) data for DIS on nuclei.

Part II: Jet Decorrelation



One can look for the growth in cross section with larger rapidity gaps as first suggested by Muller and Navelet.

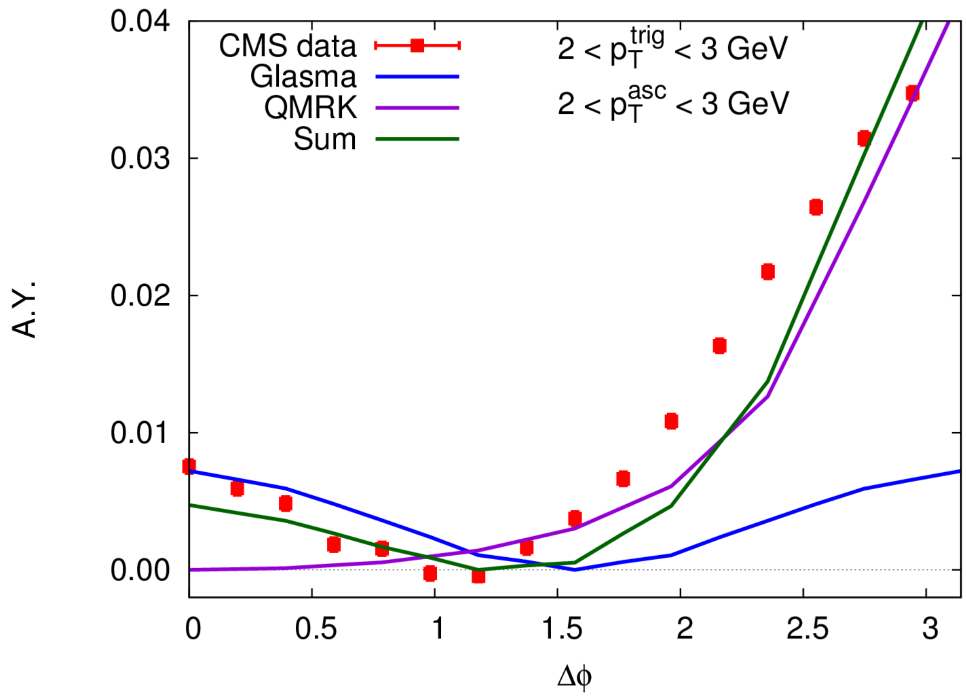
Mini jets in k_T factorization

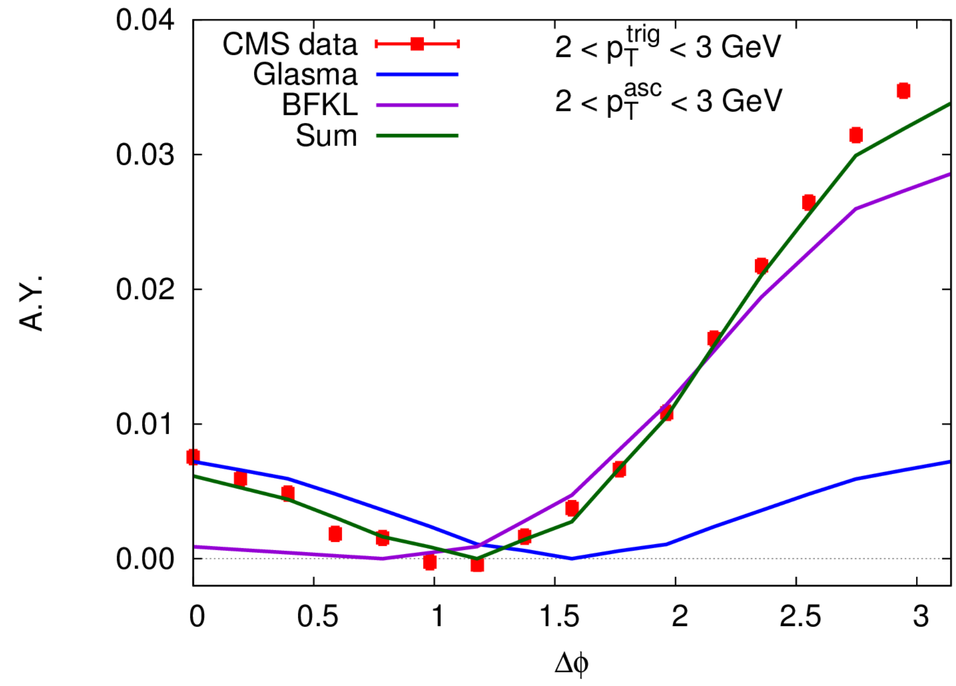


$$\frac{d^2 N_{AB}}{d^2\mathbf{p}_\perp d^2\mathbf{q}_\perp dy_p dy_q} = \frac{32 N_c \alpha_s(\mathbf{p}_\perp)\alpha_s(\mathbf{q}_\perp)}{(2\pi)^8 C_F} \frac{1}{\mathbf{p}_\perp^2 \mathbf{q}_\perp^2}$$

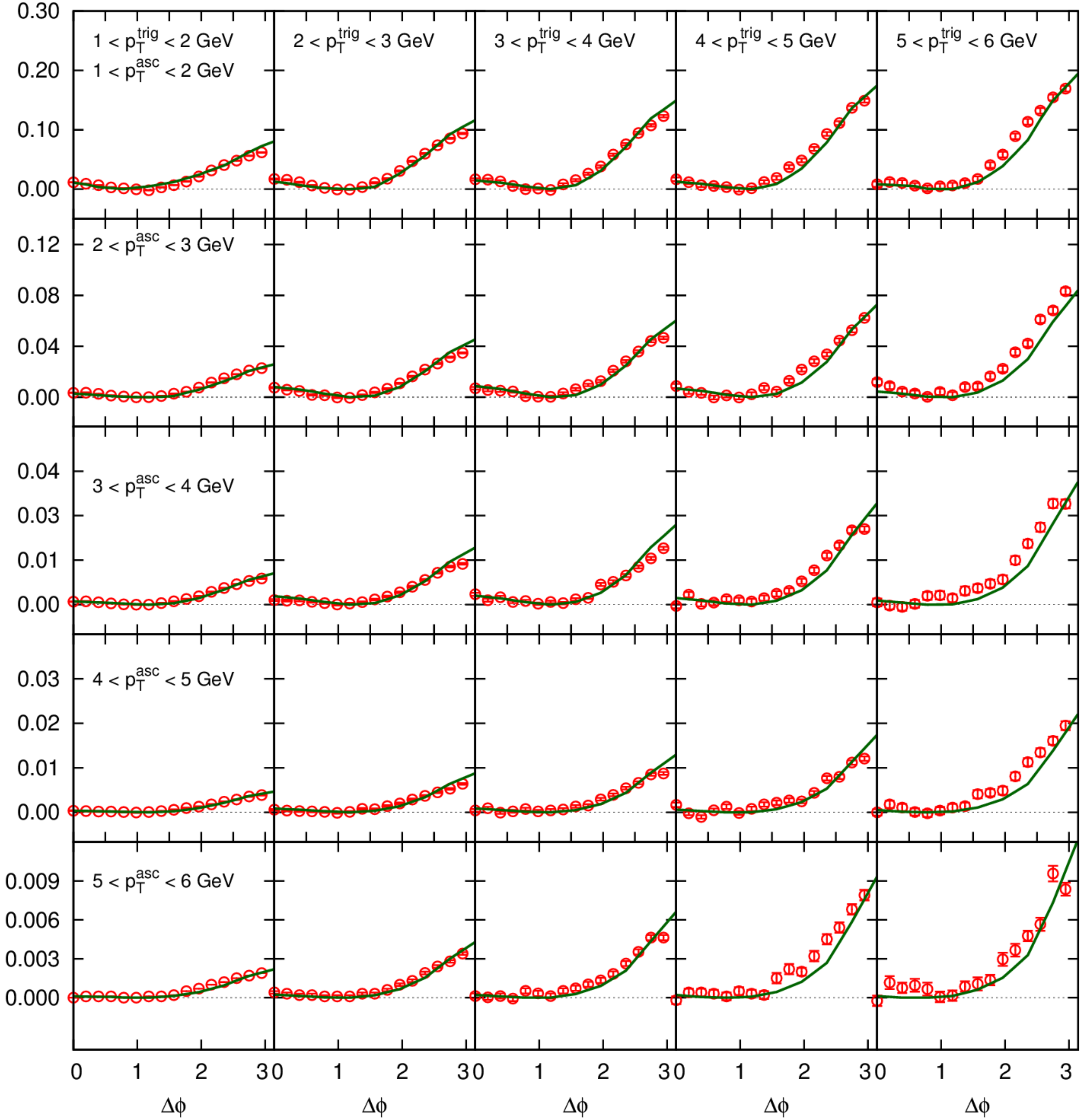
$$\times \int d^2\mathbf{k}_{0\perp} \int d^2\mathbf{k}_{3\perp} \Phi_A(x_1, \mathbf{k}_{0\perp}) \Phi_B(x_2, \mathbf{k}_{3\perp}) \mathcal{G}(\mathbf{k}_{0\perp} - \mathbf{p}_\perp, \mathbf{k}_{3\perp} + \mathbf{q}_\perp, y_p - y_q)$$

Evidence for BFKL evolution





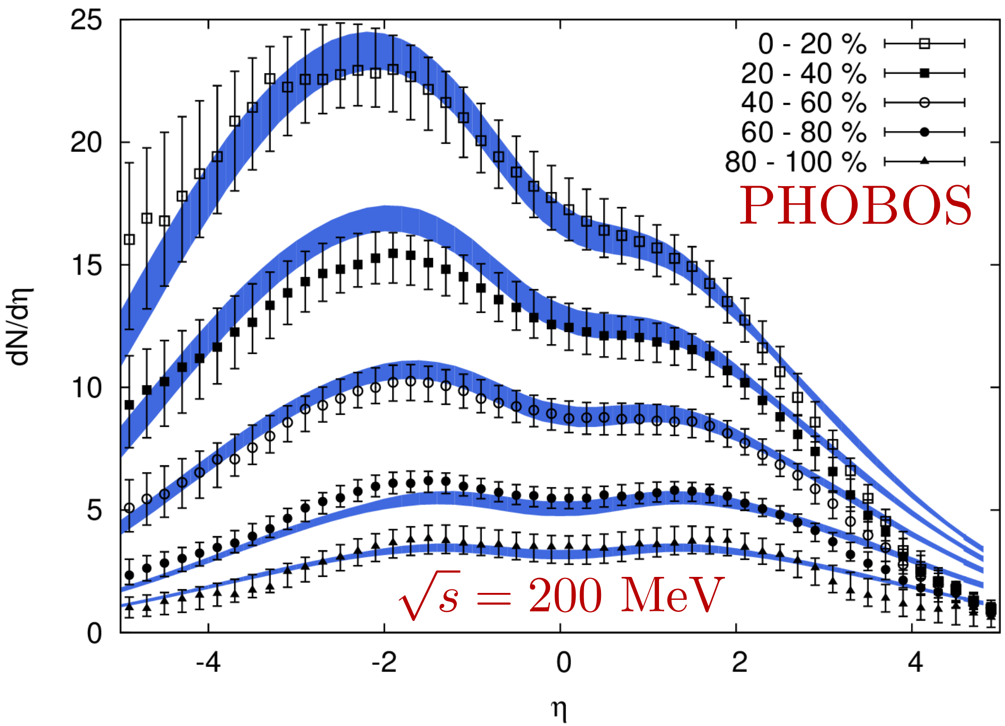
There is a clear need for evolution between the triggered particles (even for a rapidity gap as small as 2-4 units)



1 < p_T^{trig} < 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
1 < p_T^{asc} < 2 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
$\Delta\phi$

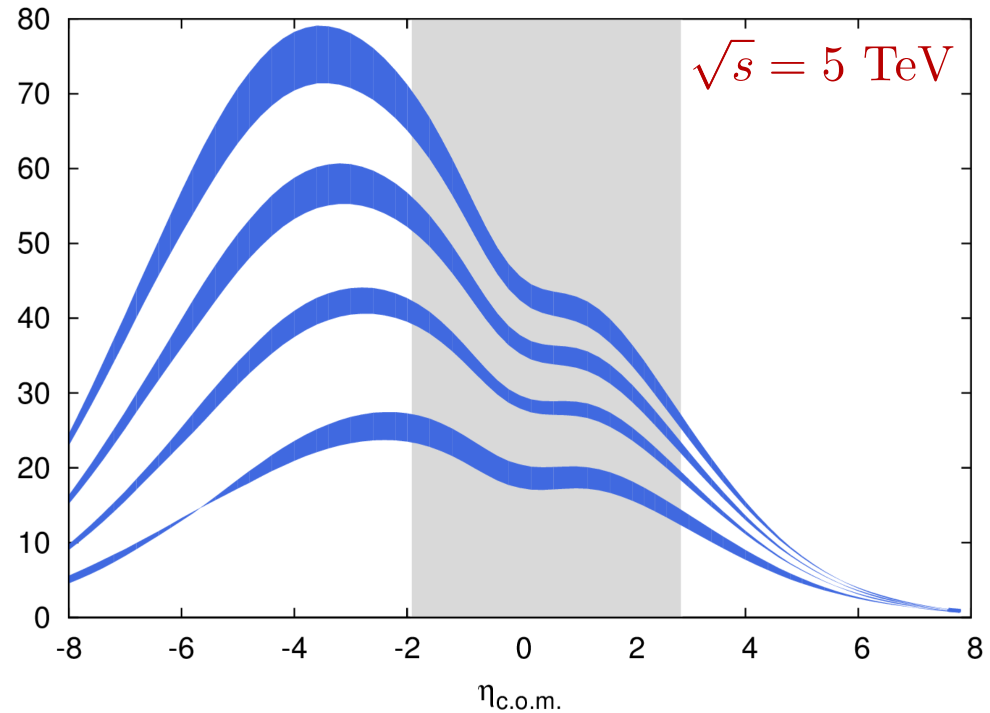
Part 3: Prospects for p+Pb

$Q^2_{0,\mathrm{Au}} = 0.336, 0.336, 0.504, 0.672, 0.840\ \mathrm{GeV}^2$



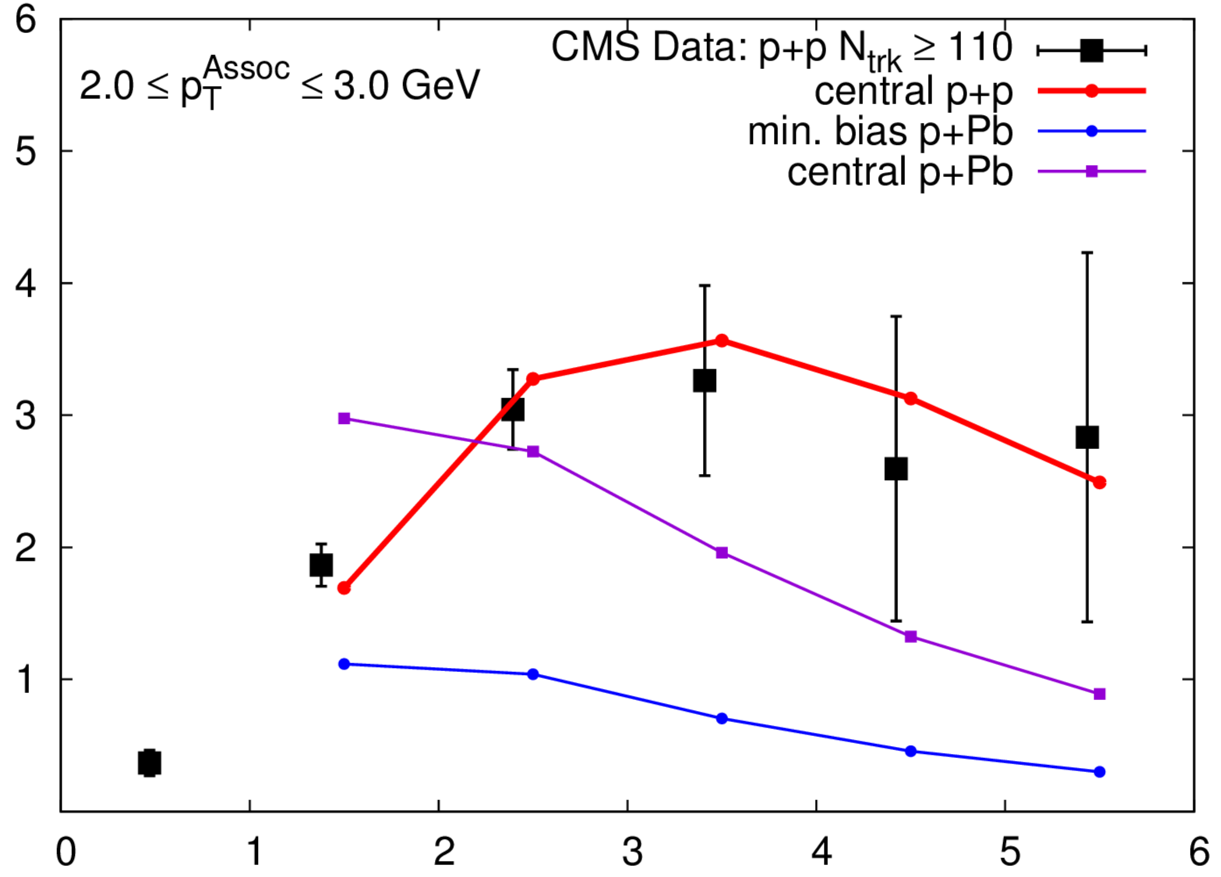
$Q^2_{0,\mathrm{d}} = 0.336\ \mathrm{GeV}^2$

$Q^2_{0,\mathrm{Pb}} = 0.504, 0.672, 0.840, 1.008\ \mathrm{GeV}^2$



$Q^2_{0,\mathrm{p}} = 0.168\ \mathrm{GeV}^2$

Ridge in p+Pb



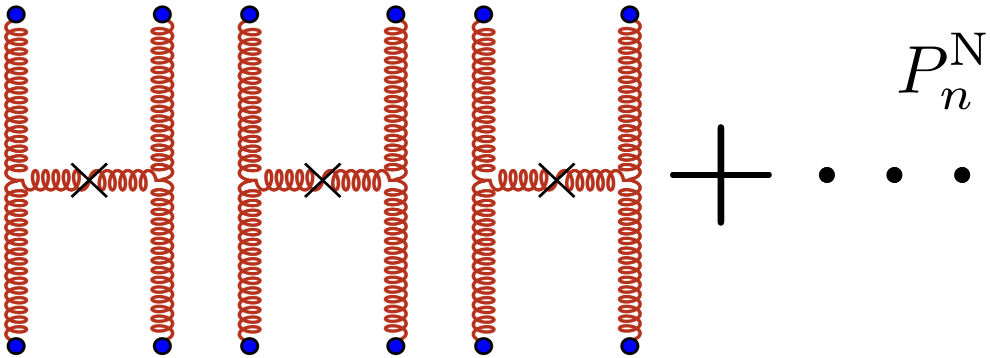
Ridge in p+Pb is smaller than in p+p for CMS acceptance.
Signal will also have to be pulled from a larger background.

Summary

- Strong color sources lead to α_s^8 enhancement of QCD diagram responsible for near-side enhancement
- Near side collimation is a clear signature of saturation dynamics
- Clear evidence for BFKL evolution in CMS dijet measurments

Backup

High multiplicity are b=0 collisions



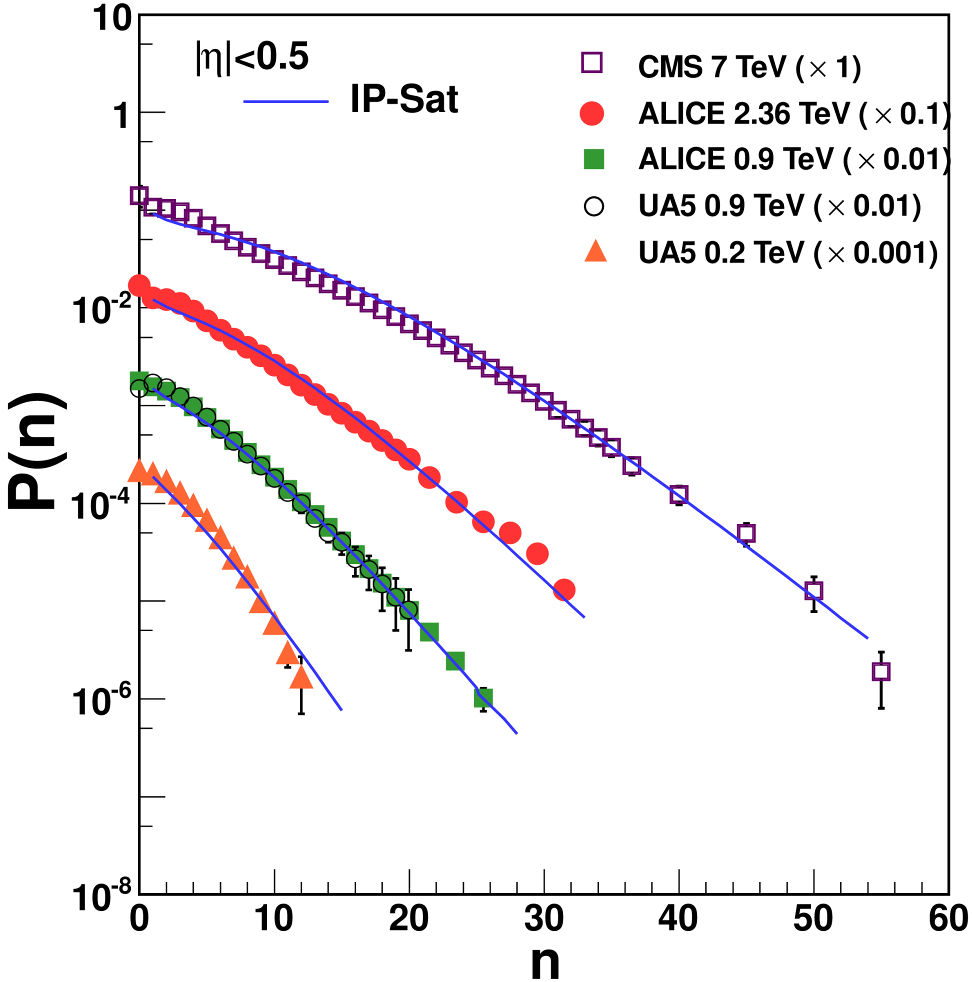
$$P_n^{\mathrm{NB}}(\overline{n}, k) = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)} \frac{\overline{n}^n k^k}{(\overline{n}+k)^{n+k}}$$

Dumitru, Gelis, McLerran, Venugopalan, NPA810 91-108 (2008).
Dusling, Fernandez-Fraile, Venugopalan NPA828 (2009) 161-177.
Gelis, Lappi, McLerran, NPA828 (2009) 149-160.

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

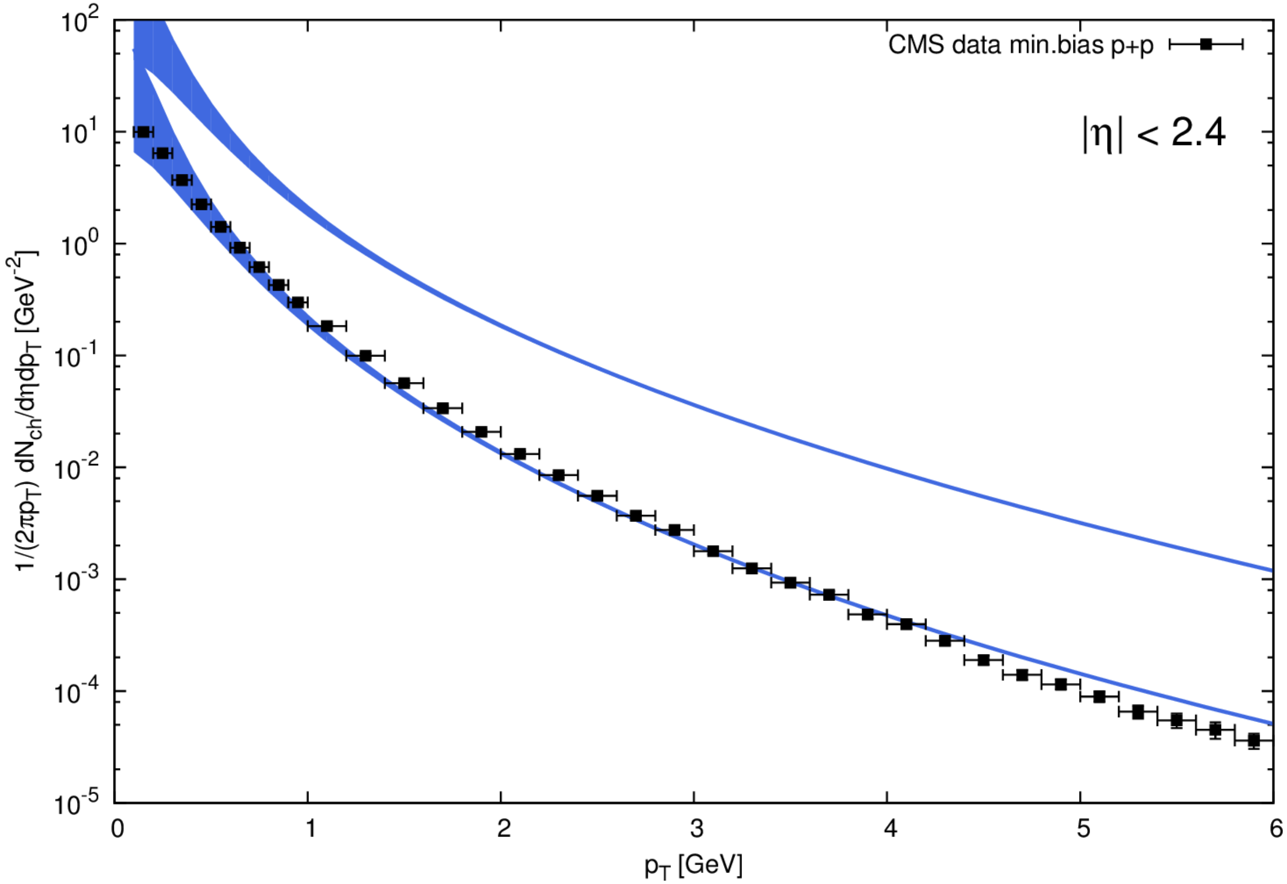
$$\zeta = 0.155 \ \text{[Empirical]}$$

$$\zeta = 0.2 - 1.5 \ \text{[Lattice]}$$

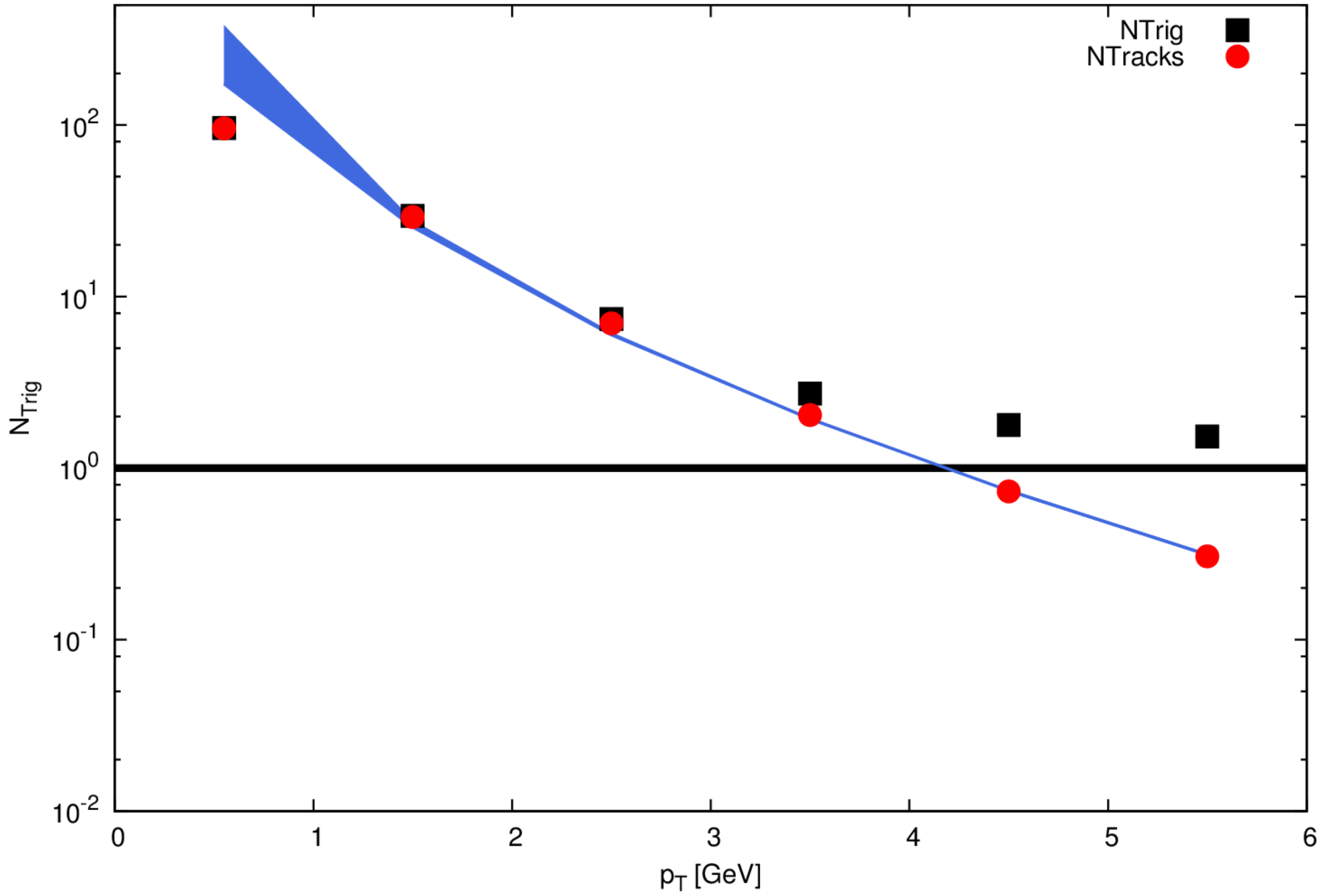


Emprical: Tribedy, Venugopalan, NPA850 (2011) 136-156.
Lattice (CYM): Lappi, Srednyak, Venugopalan, JHEP01 (2010) 066.
Schenke, Tribedy, Venugopalan, arXiv:1206.6805

p+p p_T distribution



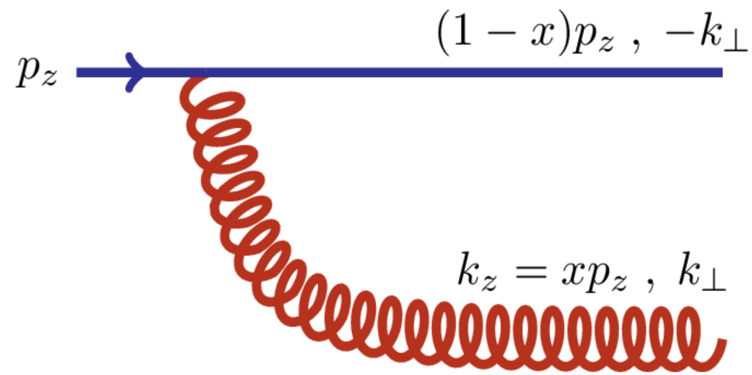
CMS Acceptance



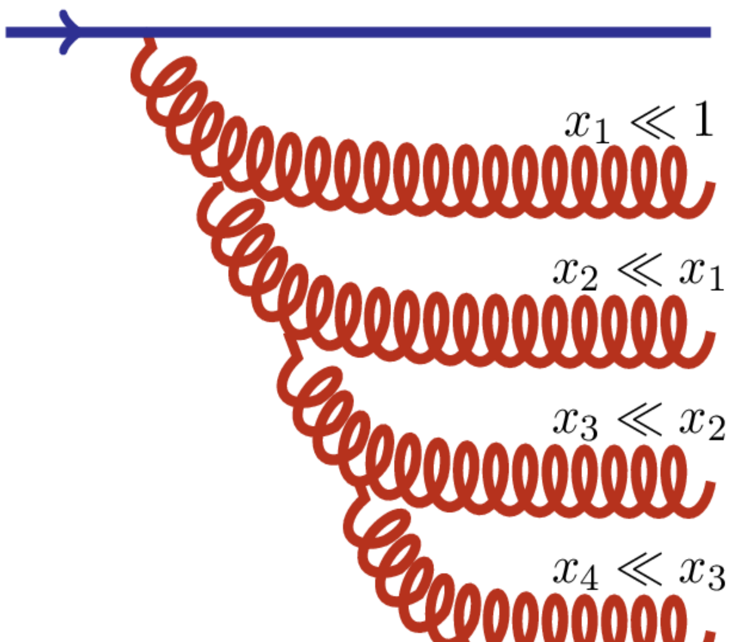
Gluon radiation

As the energy is increased new gluons are emitted with probability

$$\mathrm{d}P_{\mathrm{Brem}} \sim C_R \frac{\alpha_s}{\pi^2} \frac{\mathrm{d}^2 k_\perp}{k_\perp^2} \frac{\mathrm{d}x}{x}$$



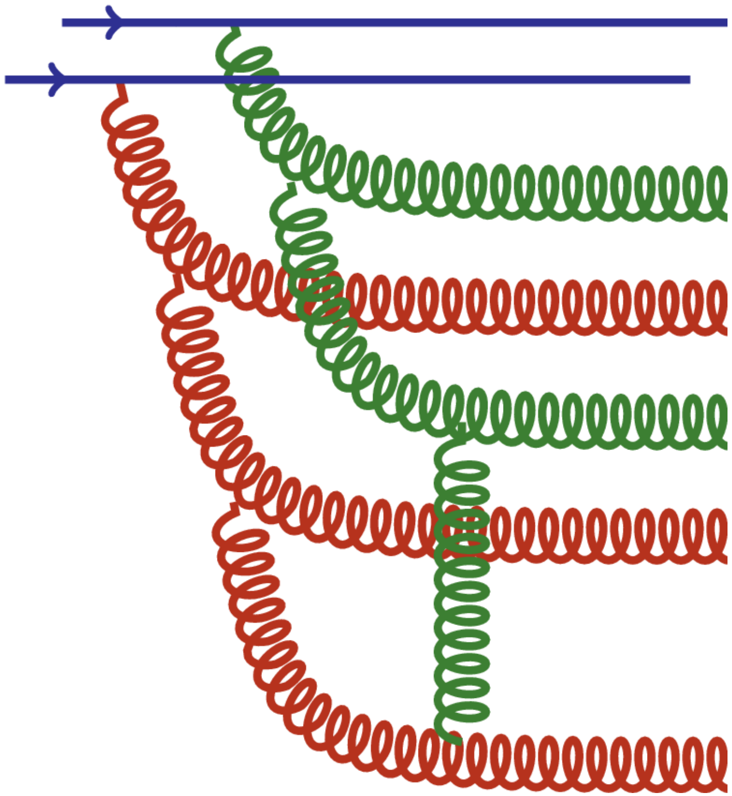
And as long as the density remains low the evolution is linear



$$\frac{\partial T(\mathbf{r}_\perp, Y)}{\partial Y} = \frac{\alpha_s N_c}{2\pi^2} \int \mathrm{d}\mathbf{r}_1 \, \frac{\mathbf{r}_\perp^2}{\mathbf{r}_1^2 \left(\mathbf{r}_\perp - \mathbf{r}_1\right)^2} \times$$
$$[T(\mathbf{r}_1, Y) + T(\mathbf{r}_\perp - \mathbf{r}_1, Y) - T(\mathbf{r}_\perp, Y)]$$

Kuraev, Lipatov, Fadin, Sov.Phys.JETP44 443-450 (1976).
Sov.Phys.JETP45 199-204 (1977).
Balitsky, Lipatov, Sov.J.Nucl.Phys 28 822-829 (1978).

BK Evolution Equation



Balitsky, NPB 463, 99 (1996).
Kovchegov, PRD 60, 034008 (1999).

Jalilian-Marian, Kovner, McLerran, Weigert, PRD 55 5414 (1997).
Jalilian-Marian, Kovner, Leonidov, Weigert, NPB 504 415 (1997), PRD 59 014014 (1999).

$$\frac{\partial T(\mathbf{r}_\perp, Y)}{\partial Y} = \frac{\alpha_s N_c}{2\pi^2} \int d\mathbf{r}_1 \, \frac{\mathbf{r}_\perp^2}{\mathbf{r}_1^2 \left(\mathbf{r}_\perp - \mathbf{r}_1\right)^2} \times$$

$$\left[T(\mathbf{r}_1, Y) + T(\mathbf{r}_\perp - \mathbf{r}_1, Y) - T(\mathbf{r}_\perp, Y) - T(\mathbf{r}_1, Y) T(\mathbf{r}_\perp - \mathbf{r}_1, Y)\right]$$

NLO BK Equation

$$\frac{\partial T(\mathbf{r}_\perp, Y)}{\partial Y} = \int \mathrm{d}\mathbf{r}_1 \mathcal{K}_{\mathrm{Bal.}}(\mathbf{r}_\perp, \mathbf{r}_1, \mathbf{r}_\perp - \mathbf{r}_1) \times$$
$$[T(\mathbf{r}_1, Y) + T(\mathbf{r}_\perp - \mathbf{r}_1, Y) - T(\mathbf{r}_\perp, Y) - T(\mathbf{r}_1, Y) T(\mathbf{r}_\perp - \mathbf{r}_1, Y)]$$

$$\mathcal{K}_{\mathrm{Bal.}}(\mathbf{r}_, \mathbf{r}_1, \mathbf{r}_2) = \frac{\alpha_s(\mathbf{r}) N_c}{\pi} \left[\frac{\mathbf{r}^2}{\mathbf{r}_1^2 \mathbf{r}_2^2} + \frac{1}{\mathbf{r}_1^2} \left(\frac{\alpha_s(\mathbf{r}_1^2)}{\alpha_s(\mathbf{r}_2^2)} - 1 \right) + \frac{1}{\mathbf{r}_2^2} \left(\frac{\alpha_s(\mathbf{r}_2^2)}{\alpha_s(\mathbf{r}_1^2)} - 1 \right) \right]$$

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Blast Wave Model

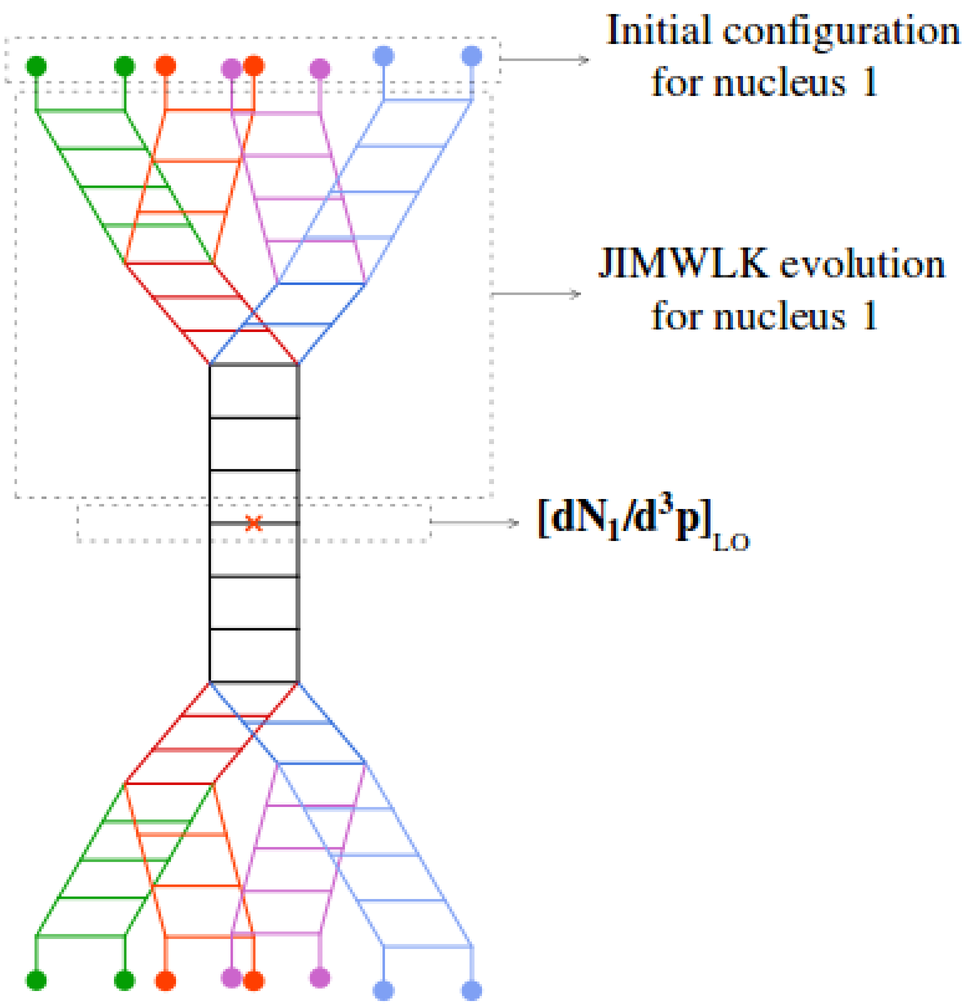
$$\frac{d^2N}{d\Delta\phi} = \int_{-\pi}^{\pi} d\Psi \mathcal{J}\left(\Psi, \Delta\phi\right) \frac{d^2N}{d\Delta\tilde{\phi}} \left(\Delta\tilde{\phi}\left(\Psi, \Delta\phi\right)\right)$$

$$2\sin^2\left(\frac{\Delta\tilde{\phi}}{2}\right) =$$

$$\frac{\sqrt{1-\beta^2}\left(1-\cos\left(\Delta\phi\right)\right)}{1-2\beta\cos\Psi\cos\left(\frac{\Delta\phi}{2}\right)+\frac{\beta^2}{2}\left(\cos\left(\Delta\phi\right)+\cos\left(2\Psi\right)\right)} \, .$$

$$\mathcal{J} = \frac{1-\beta^2}{\left(1-\beta\cos\left(\Psi+\Delta\phi/2\right)\right)\left(1-\beta\cos\left(\Psi-\Delta\phi/2\right)\right)} \, ,$$

k_T factorization: single gluon production



$$\left\langle \frac{\mathrm{d}N_1}{\mathrm{d}^2\mathbf{p}_\perp \mathrm{d}y_p} \right\rangle_{\mathrm{LLog}} = \frac{8\alpha_s(p_\perp)S_\perp}{C_F(2\pi)^4}\frac{1}{\mathbf{p}_\perp^2}\int \frac{\mathrm{d}^2k_\perp}{(2\pi)^2}\Phi_{A_1}(y_p,k_\perp)\Phi_{A_2}(y_p,p_\perp - k_\perp)$$

BFKL Formalism

$$\mathcal{G}(a,b,\Delta y) = \frac{1}{(2\pi)^2}\frac{1}{(a^2 b^2)^{1/2}}\sum_n e^{in\overline{\phi}}\int_{-\infty}^{+\infty} d\nu \; e^{\omega(\nu,n)\Delta y} e^{i\nu\ln\left(a^2/b^2\right)}$$

$$\omega(\nu,n) = -2\overline{\alpha}_s \mathrm{Re}\left[\Psi\left(\frac{|n|+1}{2}+i\nu\right) - \Psi(1)\right]$$

$$\overline{\alpha}_s \equiv \frac{N_c \alpha_s\left(\sqrt{ab}\right)}{\pi}$$

$$\overline{\phi} \equiv \arccos\left(\frac{a\cdot b}{|a|\;|b|}\right)$$