HIGHER HARMONICS FROM INTRINSIC MULTI-PARTICLE PRODUCTION

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QUARK
MATTER
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Physical Review Letters

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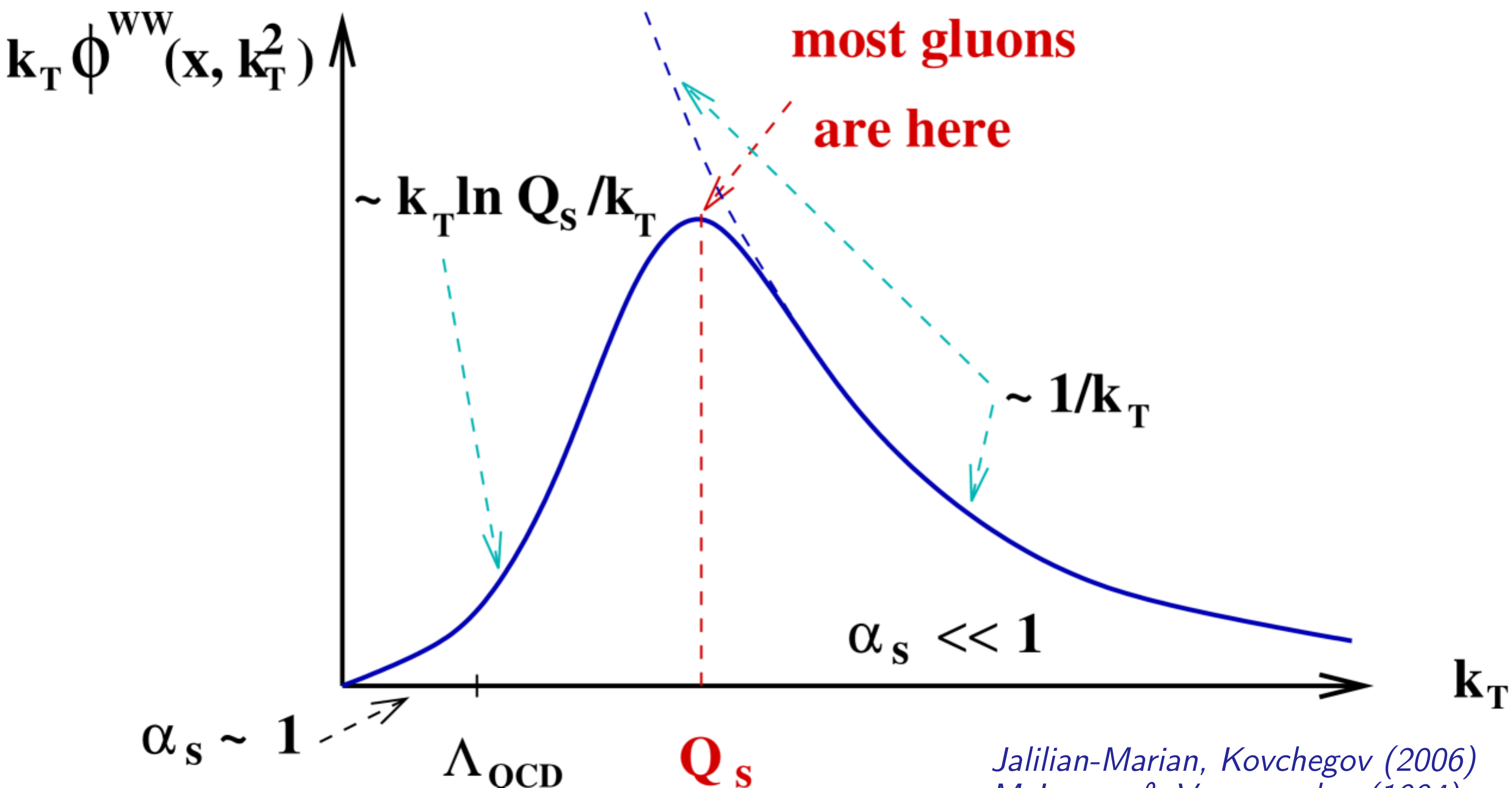
Gluon Saturation

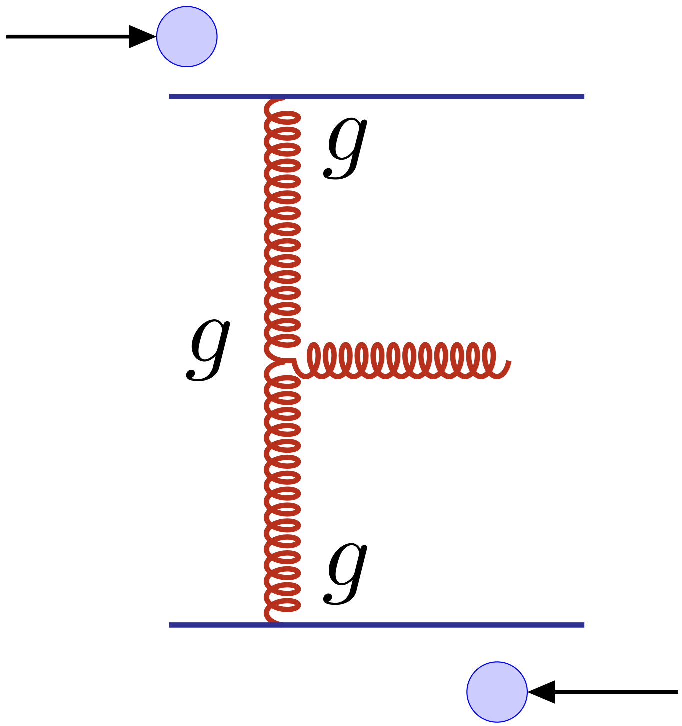
A large nucleus, $A \gg 1$ *, results in a high occupation of gluons,* $\rho \sim A^{1/3}$ *and therefore the gluon-field can be treated classically.*



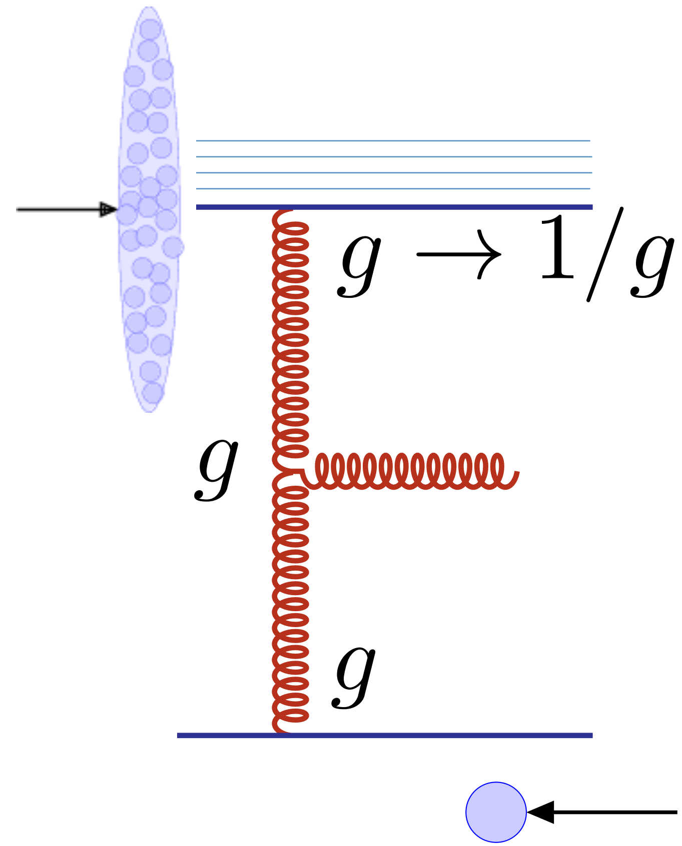
Jalilian-Marian, Kovchegov (2006)
McLerran & Venugopalan (1994)

Power counting changes considerably ...

Power counting in p+A



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



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

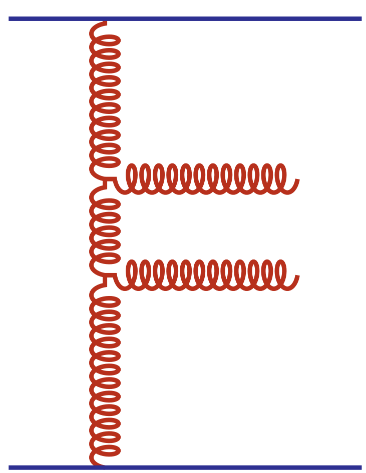
Can obtain saturation by large A, small x or high energy

Power counting in QCD: multiparticle production

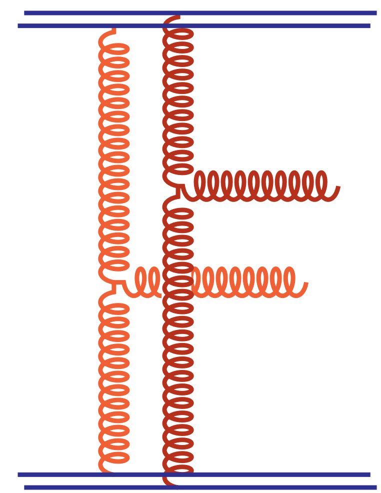
"jet" graph

"glasma" graph

Low color density
(min. bias events)

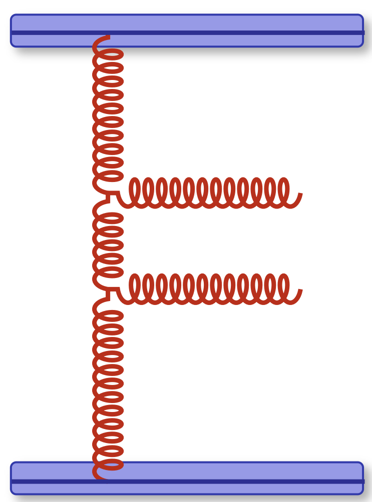


$\mathcal{O}\left(g^{8}\right)$

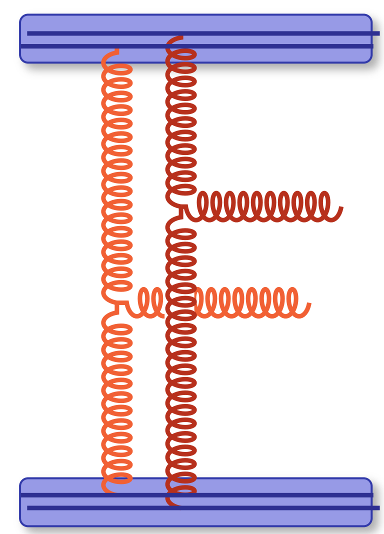


$\mathcal{O}\left(g^{12}\right)$

High color density
("central" events)

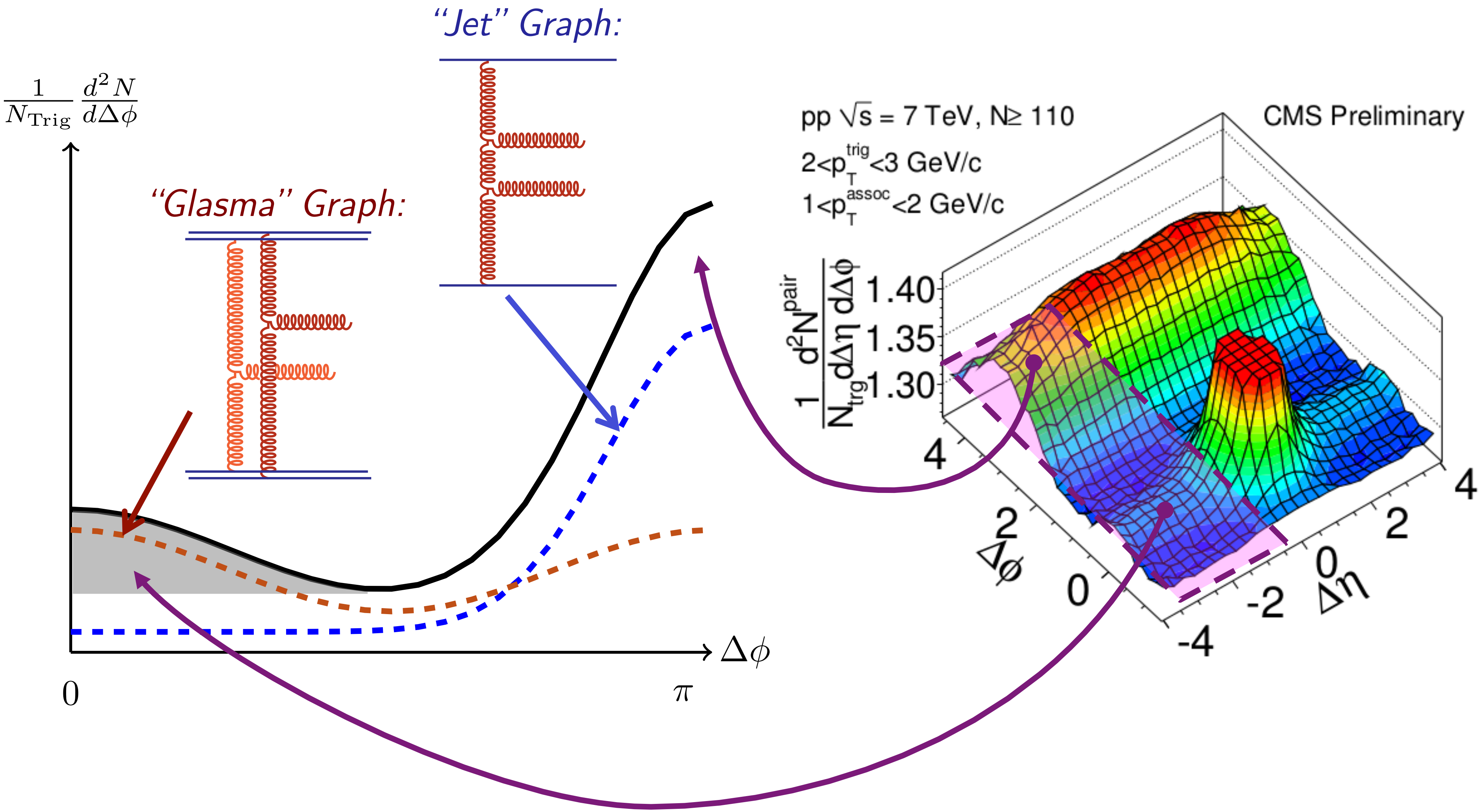


$\mathcal{O}\left(g^{0}\right)$



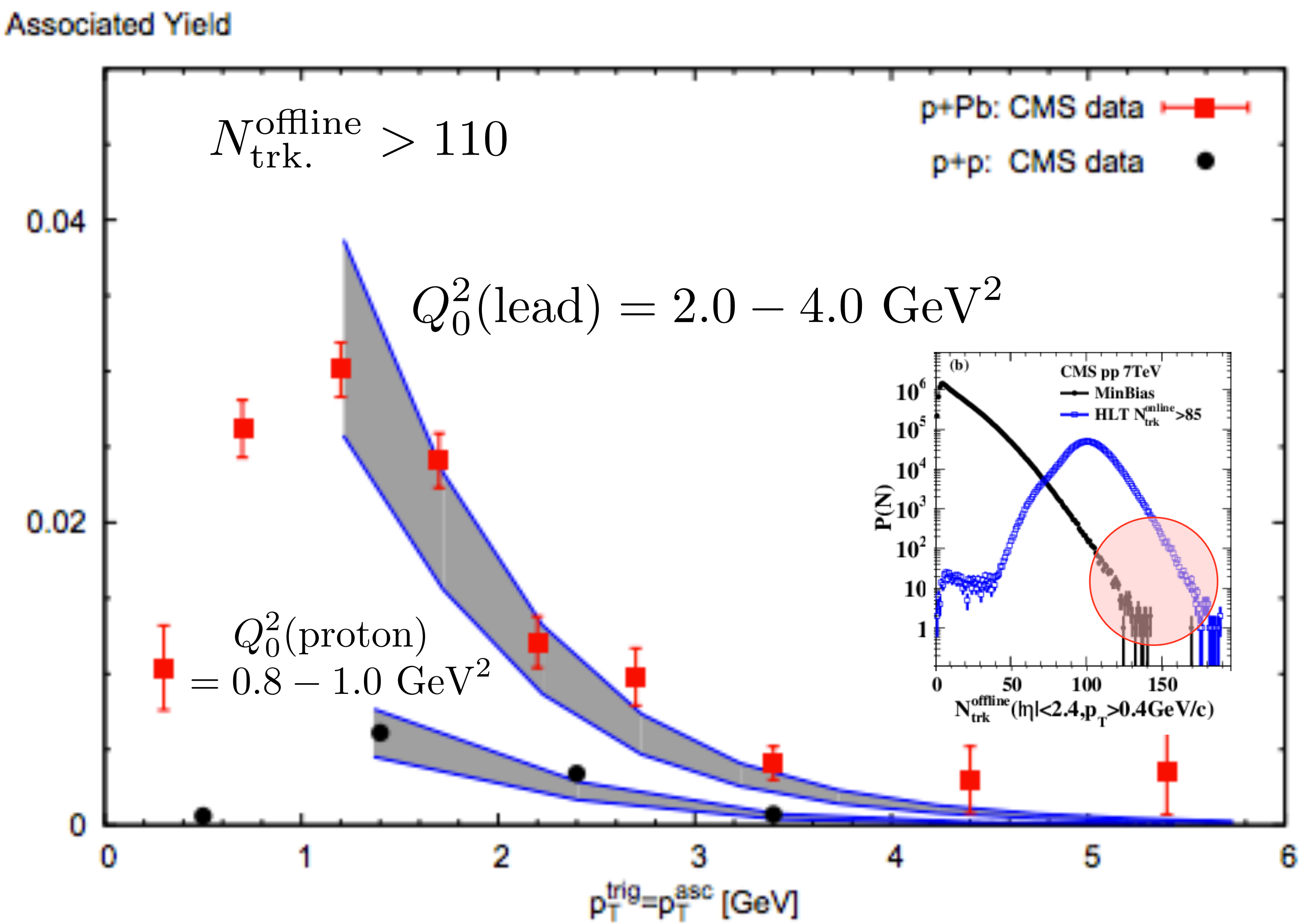
$\mathcal{O}\left(1/g^{4}\right)$

Expect $1/g^{16}$ enhancement of glasma graph! How can this be seen?



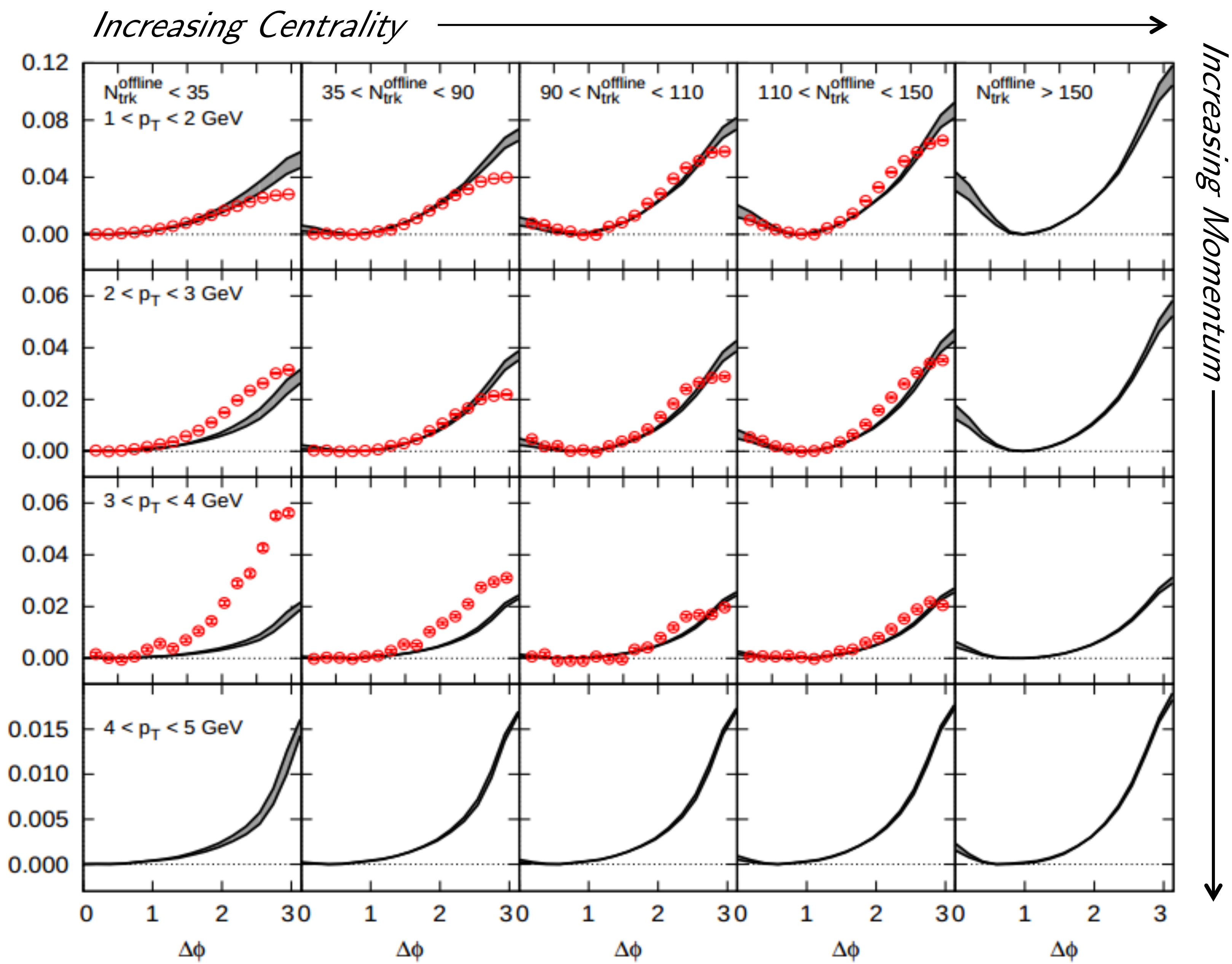
Anatomy of a proton-proton collision

Associated yield in rare events

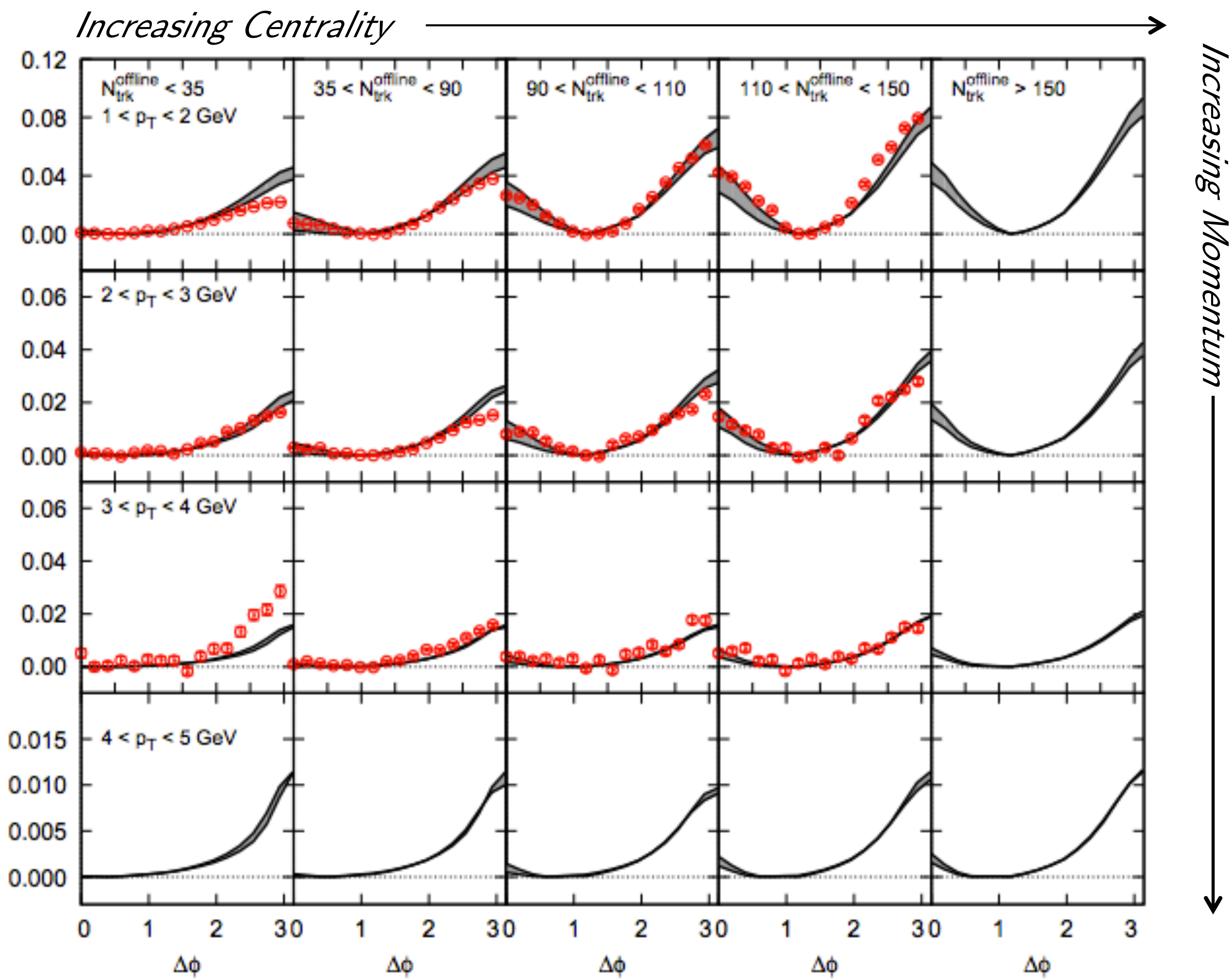


Dusling, Venugopalan, Phys.Rev. D87 (2013) 094034, arXiv:1302.7018

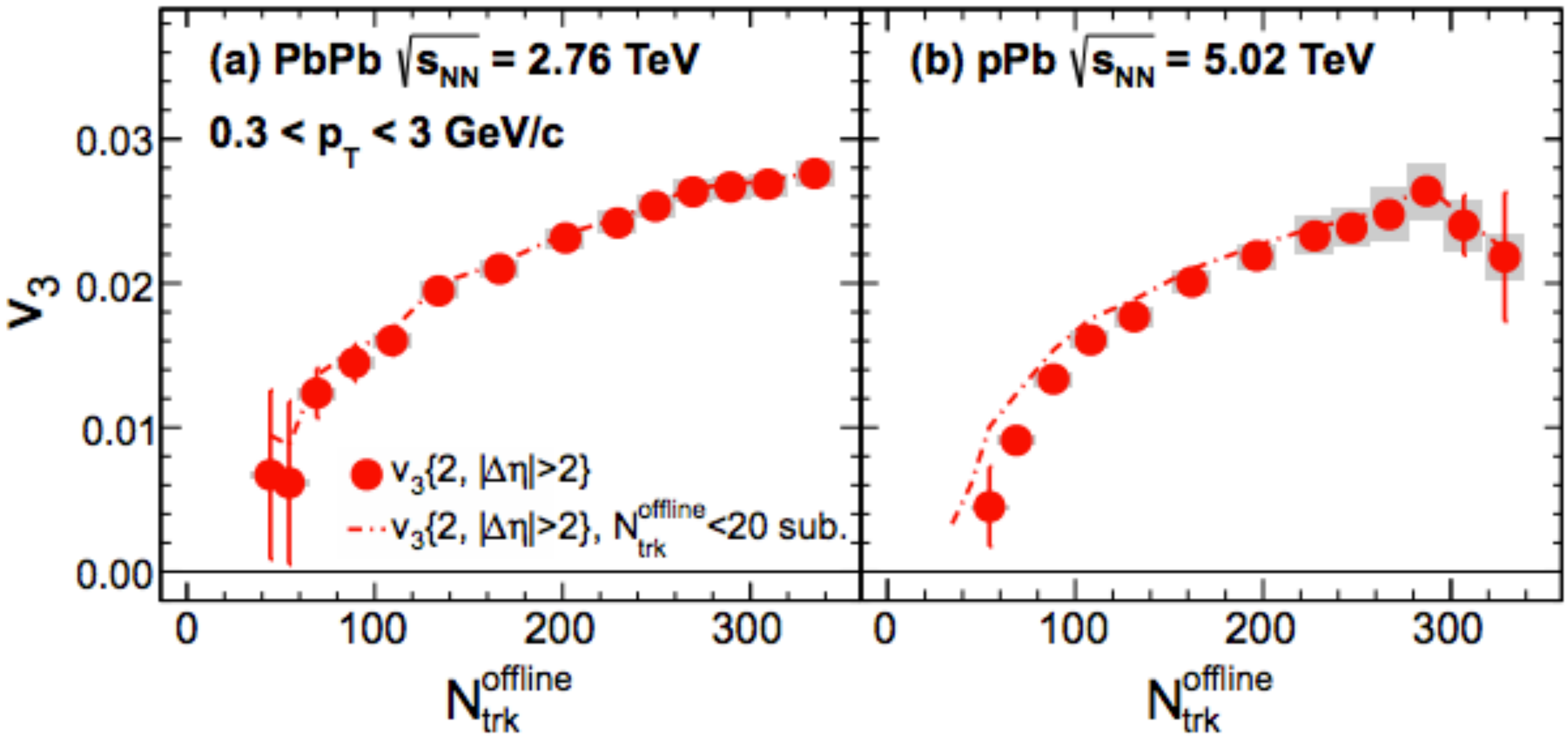
Proton-Proton systematics



Proton-Lead systematics



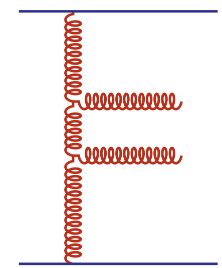
Part II: The v3 puzzle



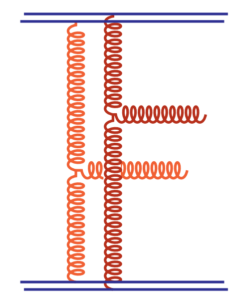
CMS Collaboration, Phys.Lett. B724 (2013) 213-240

v_3 from di-hadron production

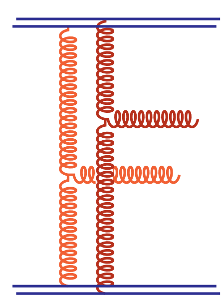
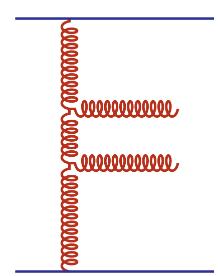
The "jet" produces a small negative v_3 :

|  |^2

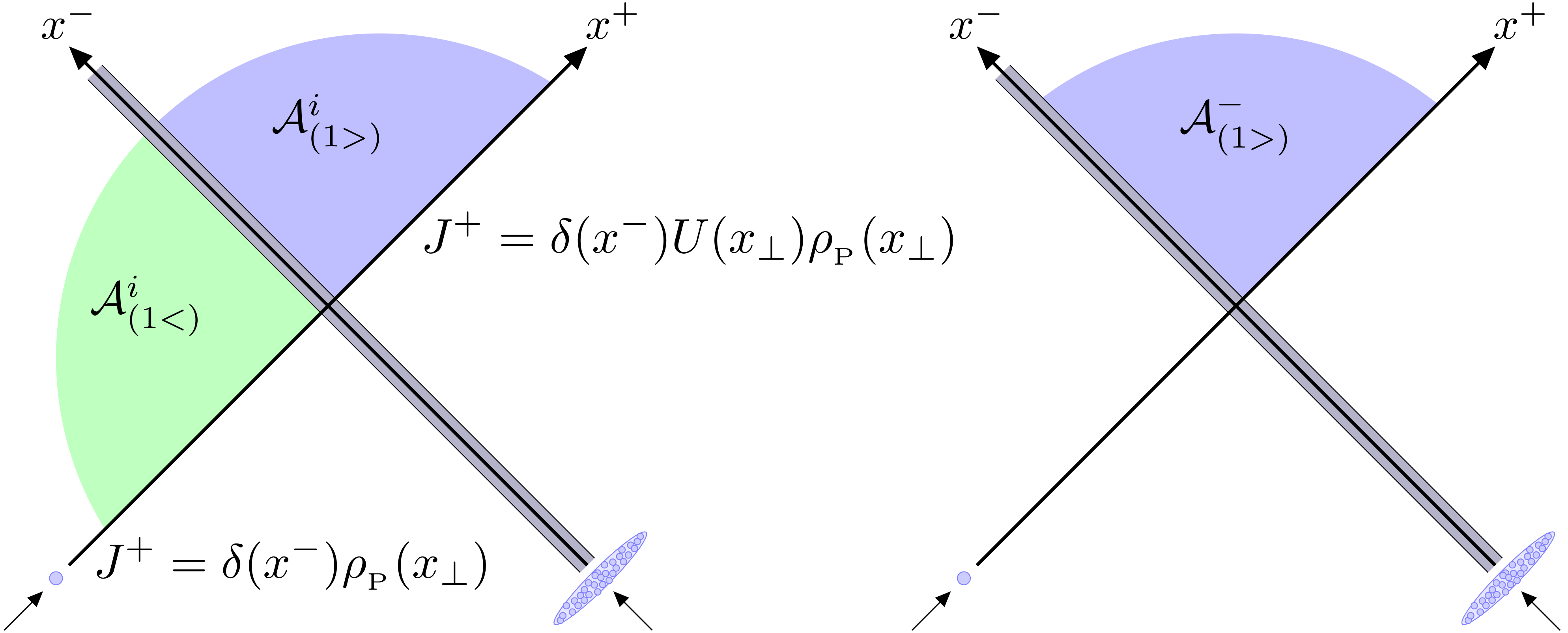
The "glasma" graphs have zero v_3 :

|  |^2

What about the interference term?

2Re {  ×  * }

Fields after collision



$$U(x_\perp) \equiv \mathcal{P}_{x^+} \exp\left[ig\int_{0^-}^{0^+} dx^+ \mathcal{A}^-_{(0)}\right]$$

F. Gelis and Y. Mehtar-Tani, PRD 73, 034019 (2006).

Background field propagator

The gluon propagator in a classical background field satisfies

$$-i\left[g^{\mu\nu}D^{ac}_{\rho}D^{\rho}_{cb} - D^{\mu}_{ac}D^{\nu}_{cb} + 2gf^{acb}F^{\mu\nu}_{c} - \frac{1}{\lambda}n^{\mu}n^{\nu}\delta^{ab}\right]_{x}\mathcal{G}^{bd}_{\nu\lambda}(x,y) = g^{\mu}_{\lambda}\delta^{ad}\delta^{(4)}(x-y)$$

This can be expanded to first order in the proton charge density (single scattering Born approx.)

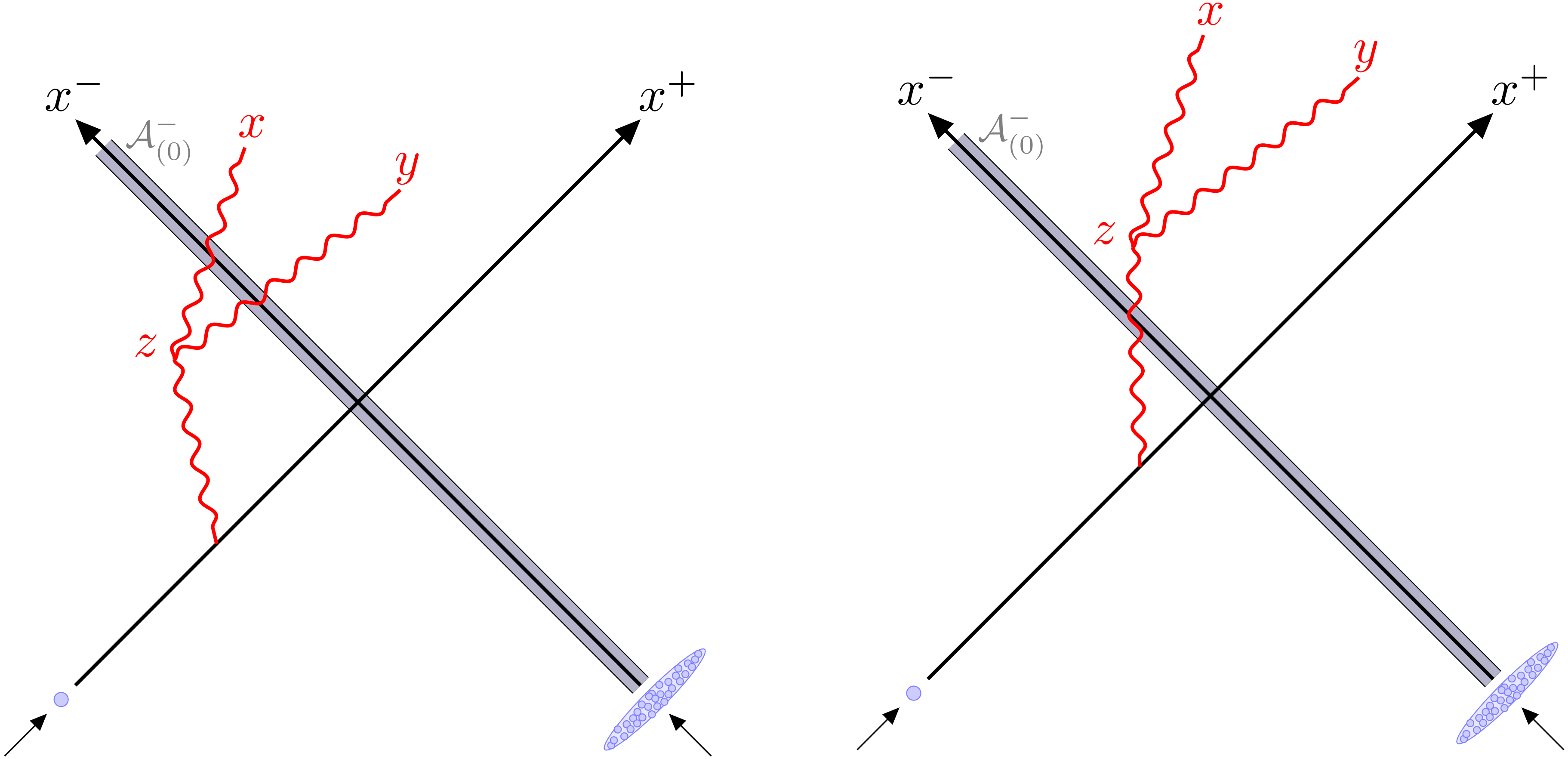
$$\delta\mathcal{G}^{\mu\nu}(x,y) \equiv \mathcal{G}^{\mu\nu}(x,y) - \mathcal{G}^{\mu\nu}_{(0)}(x,y) = +i\int d^4z\,\mathcal{G}^{\mu\lambda}_{(0)}(x,z)\delta\Gamma^{(3)}_{\lambda\sigma}(z)\mathcal{G}^{\sigma\nu}_{(0)}(z,y)$$

where we defined the triple-gluon vertex

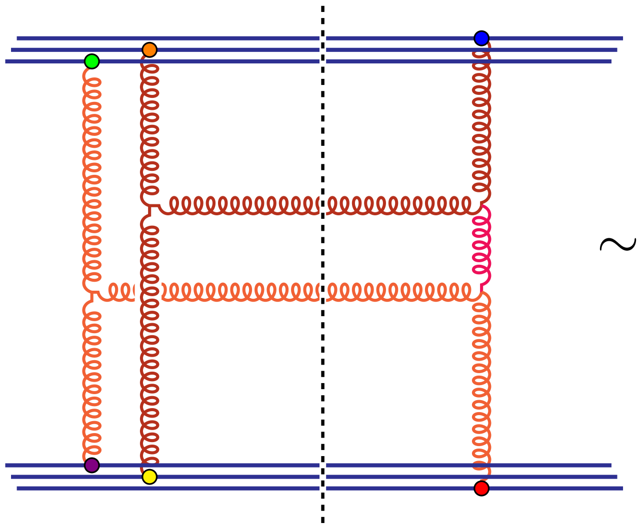
$$\delta\Gamma^{(3)}_{\mu\nu} = -ig\left\{\left[\partial_\lambda\mathcal{A}^{\lambda}_{(1)} + 2\mathcal{A}^{\lambda}_{(1)}\partial_\lambda\right]g_{\mu\nu} + \partial_\mu\mathcal{A}_{(1)\nu} - 2\partial_\nu\mathcal{A}_{(1)\mu} - \mathcal{A}_{(1)\mu}\partial_\nu - \mathcal{A}_{(1)\nu}\partial_\mu\right\}$$

K. Fukushima, Y. Hidaka, Nucl. Phys. A813 (2008) 171-197

Di-jet Amplitude

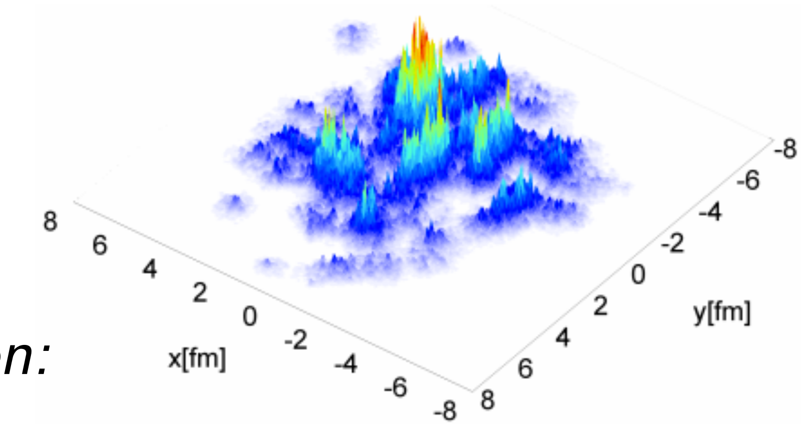


non-Gaussian color fluctuations



$$\sim \left\langle \int_{\mathbf{x},\mathbf{y},\mathbf{z}} \sin\left(\mathbf{k}_{1\perp}\cdot\mathbf{x}+\mathbf{k}_{2\perp}\cdot\mathbf{y}+\mathbf{k}_{3\perp}\cdot\mathbf{z}\right)\left\langle \rho^a(\mathbf{x})\rho^b(\mathbf{y})\rho^c(\mathbf{z})\right\rangle \right\rangle$$

Result vanishes for an even (reflection symmetric) source density
- Doug Wertepny, Yuri Kovchegov



We make an ansatz for the three-point function:

$$\left\langle \int_{\mathbf{x},\mathbf{y},\mathbf{z}} \sin\left(\mathbf{k}_{1\perp}\cdot\mathbf{x}+\mathbf{k}_{2\perp}\cdot\mathbf{y}+\mathbf{k}_{3\perp}\cdot\mathbf{z}\right)\left\langle \rho^a(\mathbf{x})\rho^b(\mathbf{y})\rho^c(\mathbf{z})\right\rangle \right\rangle$$

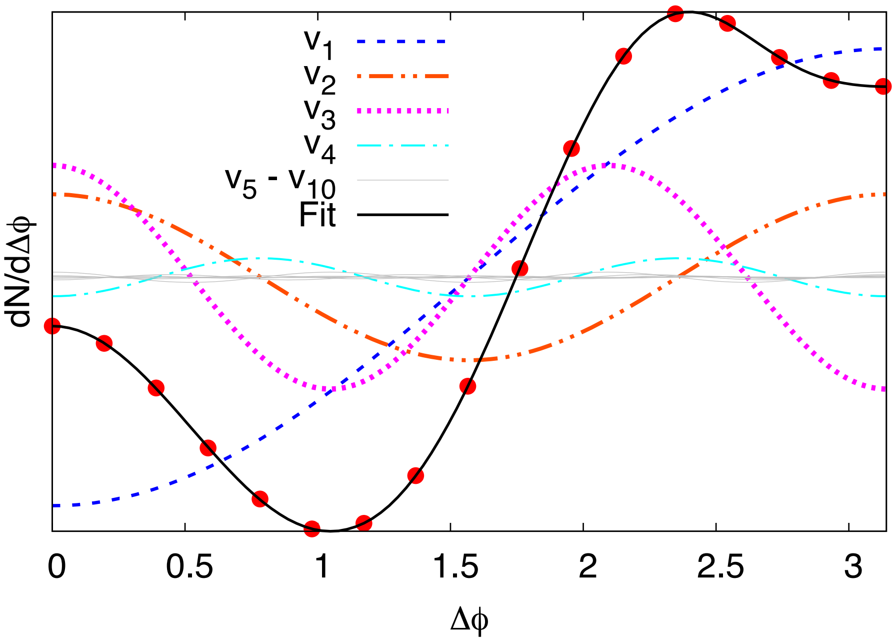
$$\approx \kappa_3 d^{abc}\delta^2(\mathbf{k}_{1\perp}+\mathbf{k}_{2\perp}+\mathbf{k}_{3\perp})\mathbf{k}_{1\perp}^2\Phi(\mathbf{k}_{1\perp})\mathbf{k}_{2\perp}^2\Phi(\mathbf{k}_{2\perp})\mathbf{k}_{3\perp}^2\Phi(\mathbf{k}_{3\perp})$$

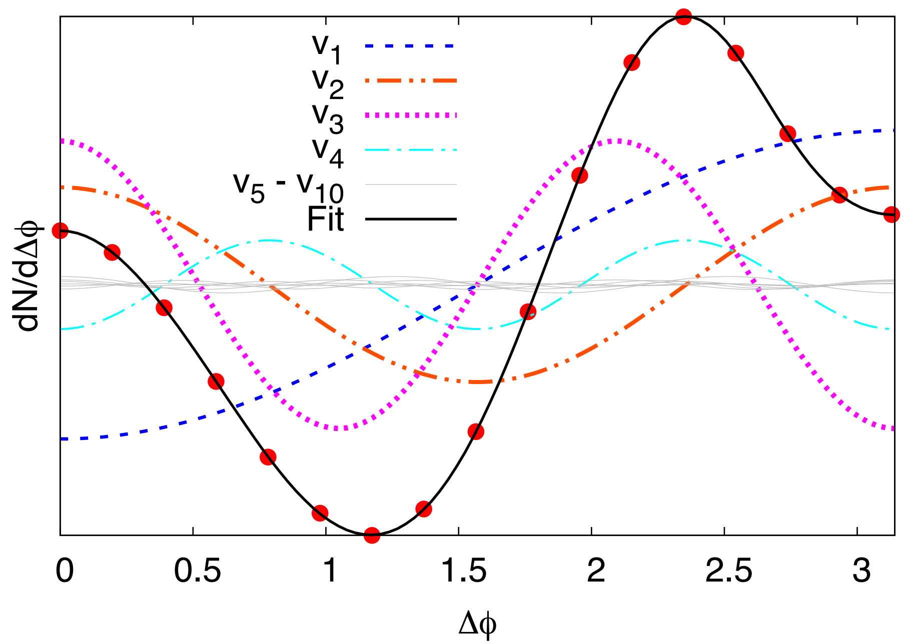
Result for interference diagram

$$\frac{d^2N}{d^2\mathbf{p}_T dy_p d^2\mathbf{q}_T dy_q} = \alpha_s^2 S_\perp \kappa_{3(P)}\kappa_{3(T)}$$

$$\times \int_{\mathbf{k}_{1\perp},\mathbf{k}_{2\perp}} \mathbf{k}_{2\perp}^2(\mathbf{k}_{1\perp}-\mathbf{k}_{2\perp})^2 \left[\frac{\mathbf{p}_T^i}{\mathbf{p}_T^2} - \frac{(\mathbf{k}_{1\perp}-\mathbf{q}_T)^i}{(\mathbf{k}_{1\perp}-\mathbf{q}_T)^2}\right]\cdot\left[\frac{\mathbf{p}_T^i}{\mathbf{p}_T^2} - \frac{\mathbf{k}_{2\perp}^i}{\mathbf{k}_{2\perp}^2}\right]\left[\frac{(\mathbf{k}_{1\perp}-\mathbf{k}_{2\perp})^j}{(\mathbf{k}_{1\perp}-\mathbf{k}_{2\perp})^2} - \frac{\mathbf{q}_T^j}{\mathbf{q}_T^2}\right]\cdot\mathbf{k}_{1\perp}^j$$

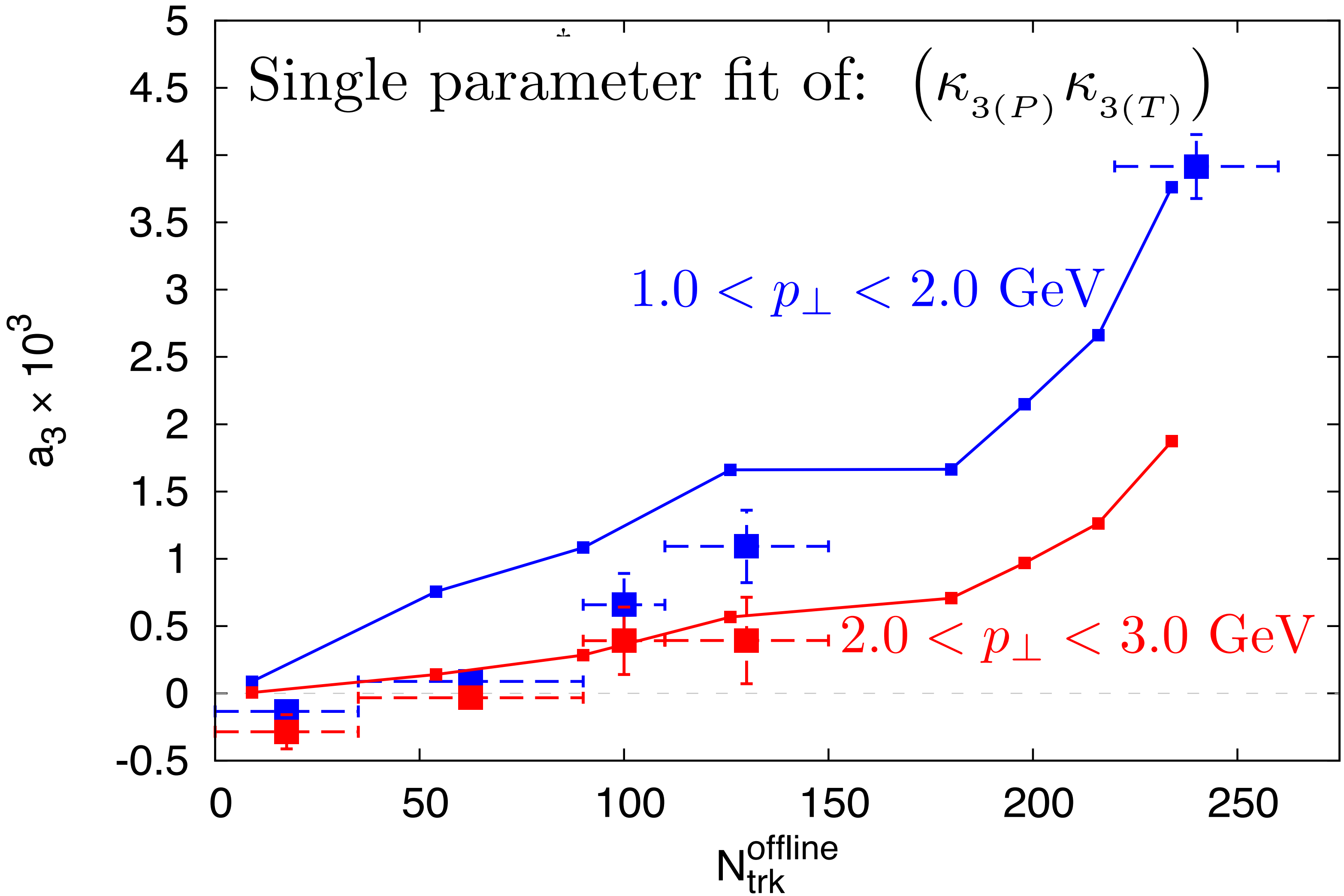
$$\times\, \Phi_{\rm P}(\mathbf{k}_{1\perp})\Phi_{\rm P}(\mathbf{k}_{2\perp})\Phi_{\rm P}(\mathbf{k}_{1\perp}-\mathbf{k}_{2\perp})\Phi_{\rm T}(\mathbf{p}_T-\mathbf{k}_{2\perp})\Phi_{\rm T}(\mathbf{q}_T+\mathbf{p}_T-\mathbf{k}_{1\perp})\Phi_{\rm T}(\mathbf{q}_T+\mathbf{k}_{2\perp}-\mathbf{k}_{1\perp})$$





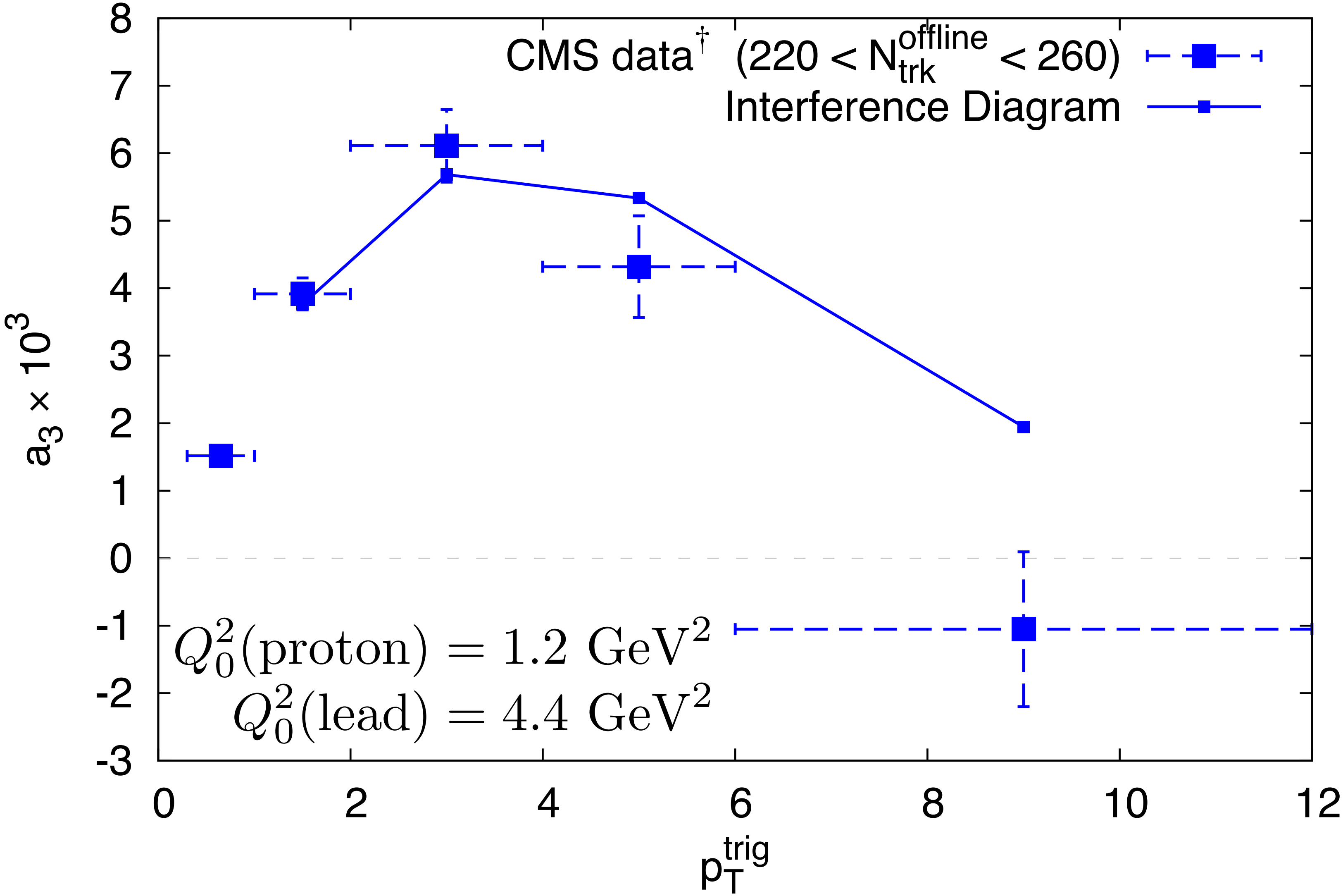
V_3 systematics

$$\frac{1}{N_{\text{trig}}}\frac{d^2N}{d\Delta\phi} = a_0 + 2\sum_{n=1} a_n \cos(n\Delta\phi)$$



Centrality dependence of Q_0^2(proton), Q_0^2(lead) taken from fit to a_2

V_3 systematics



Conclusions

Higher harmonics are naturally present in the CGC framework for multi-particle production

Interference between jet and glasma graphs may yield v_3 with correct systematics

The result is sensitive to the rotational symmetry breaking induced by event-by-event color charge fluctuations