Multi-particle production in small systems from CGC

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BROOKHAVEN NATIONAL LABORATORY

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The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy

The Abdus Salam International Centre for Theoretical Physics

U.S. DEPARTMENT OF ENERGY | Office of Science

outline

- Introduction
- Framework of color glass condensate
- Phenomenology of high multiplicity events
- Combining CGC with PYTHIA

Based on the work done in collaboration with :
K. Dusling, L. McLerran, B. Schenke, S. Schlichting & R. Venugopalan

Multi-particle production at high energies

Goal : Study correlated production of particles

$$\left\langle \frac{\mathrm{d}N}{\mathrm{d}y_1\,\mathrm{d}^2\mathbf{p}_{\perp 1}\ldots\mathrm{d}y_q\,\mathrm{d}^2\mathbf{p}_{\perp q}} \right\rangle \Longleftrightarrow \left\langle \frac{\mathrm{d}N}{\mathrm{d}y_1\,\mathrm{d}^2\mathbf{p}_{\perp 1}} \right\rangle \cdots \left\langle \frac{\mathrm{d}N}{\mathrm{d}y_q\,\mathrm{d}^2\mathbf{p}_{\perp q}} \right\rangle$$

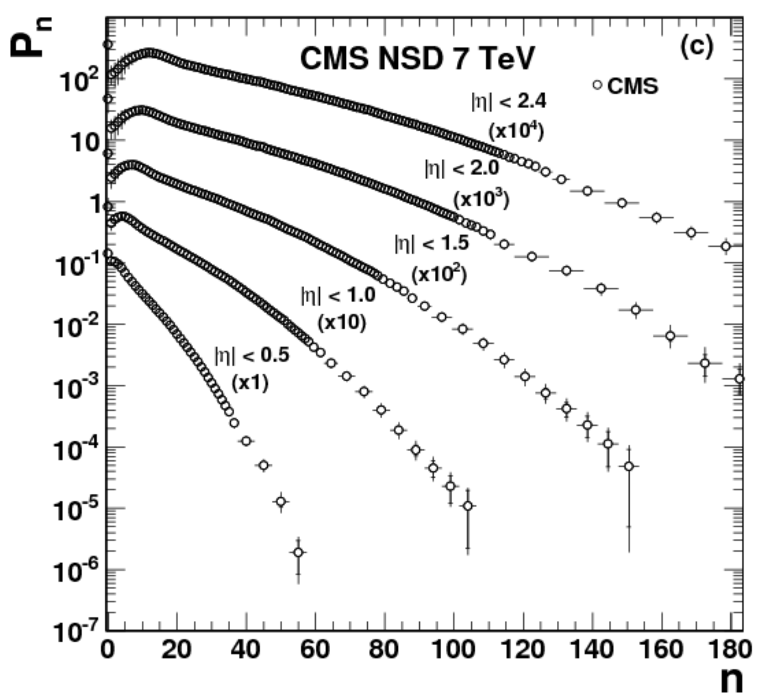
Focus : Collisions of small systems p+p and p+Pb are interesting as final state effects are minimal

We need :

- An *ab-initio* framework of particle production
- Full treatment of different sources of fluctuations
- State-of-the art treatment of fragmentation

Phenomena we want to describe

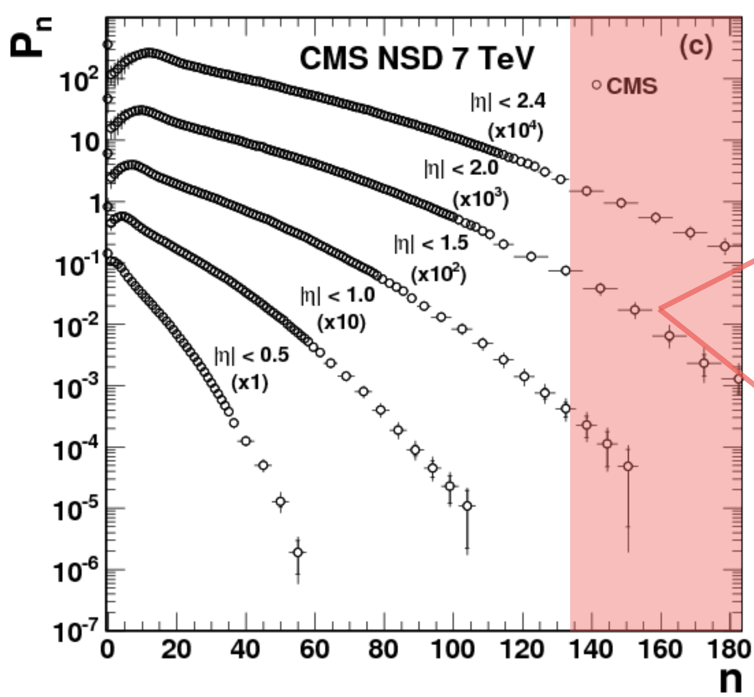
arXiv: 1011.5531



Origin of high multiplicity events

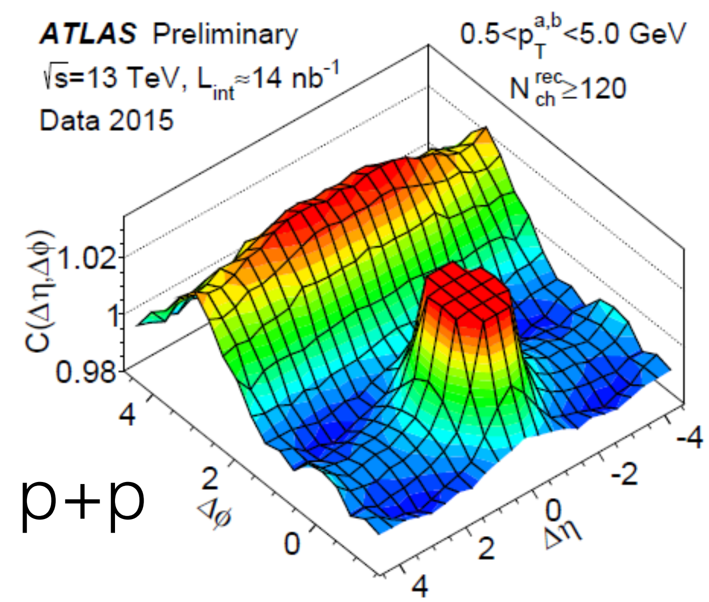
Phenomena we want to describe

arXiv: 1011.5531

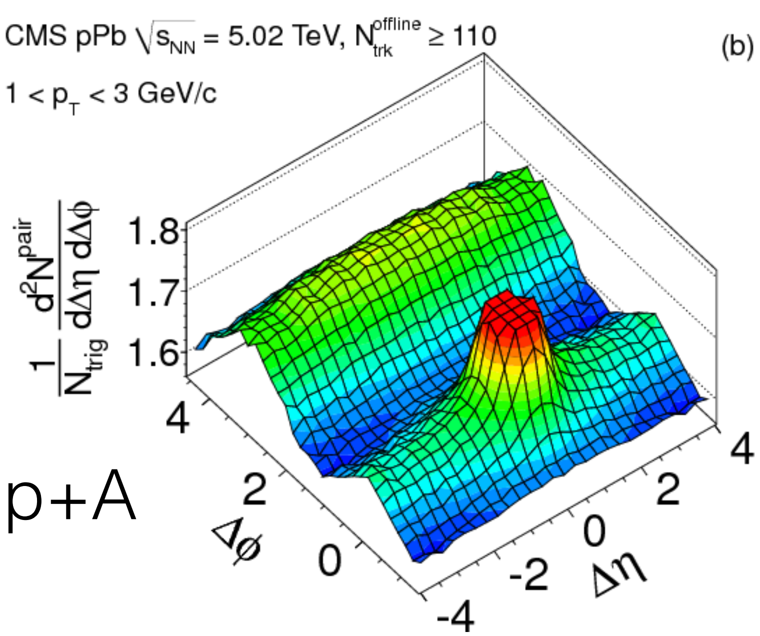


Origin of high multiplicity events

arXiv: 1509.04776, 1210.5482

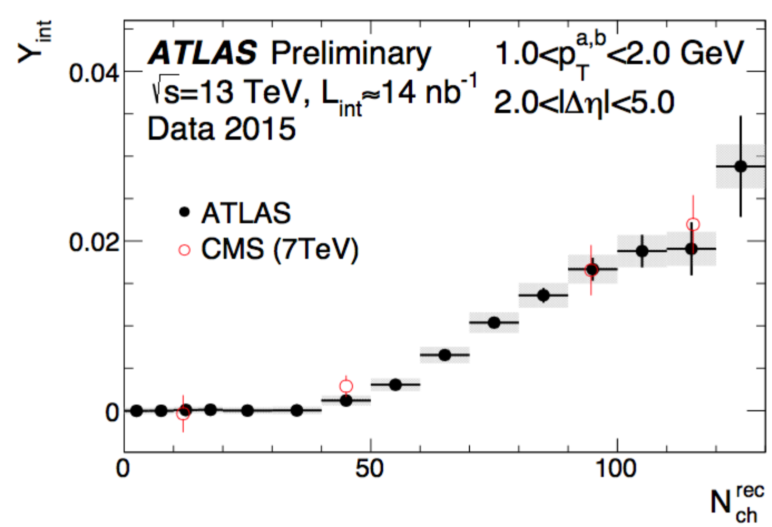


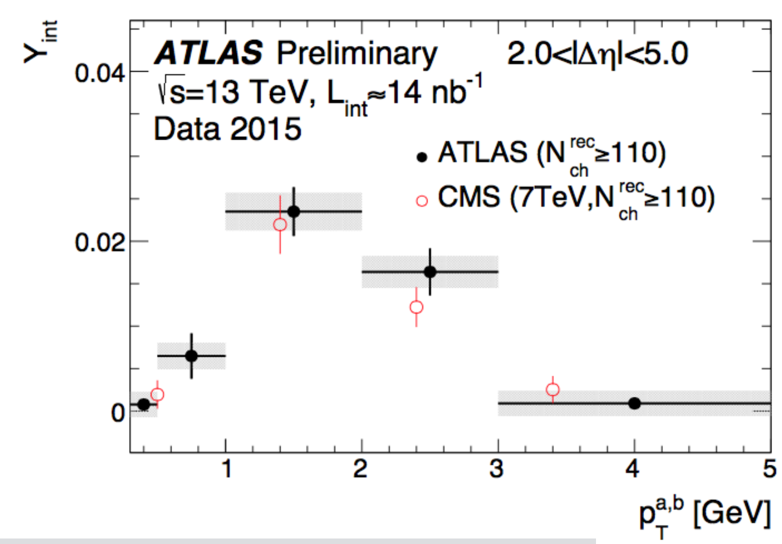
p+p



p+A

Systematics of Δη-Δφ correlations





Energy dependence of ridge in p+p

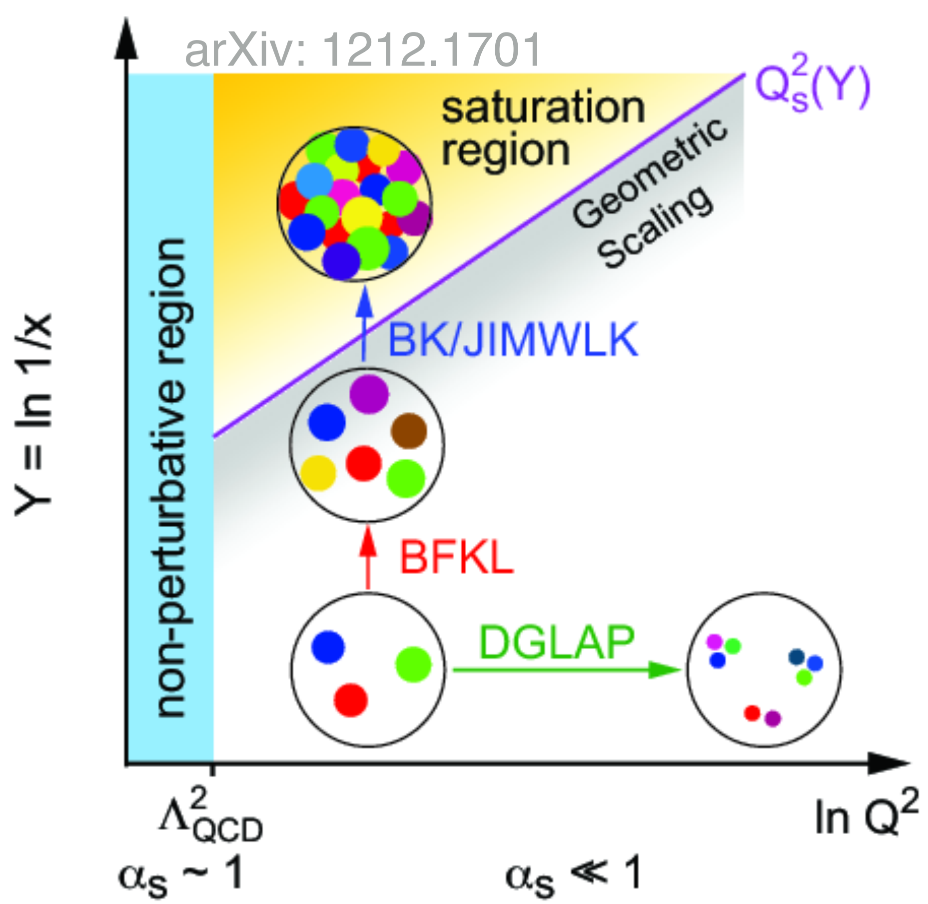
Similar underlying dynamics must drive these phenomenon

Particle production at high energies

Multi-particle production at high energies in **Regge Gribov limit** ($x \to 0$)

Colliding hadrons/nuclei :

- Saturation : Non-linear process strops growth of gluons, **semi-hard saturation scale** $Q_s(x) > \Lambda_{QCD}$

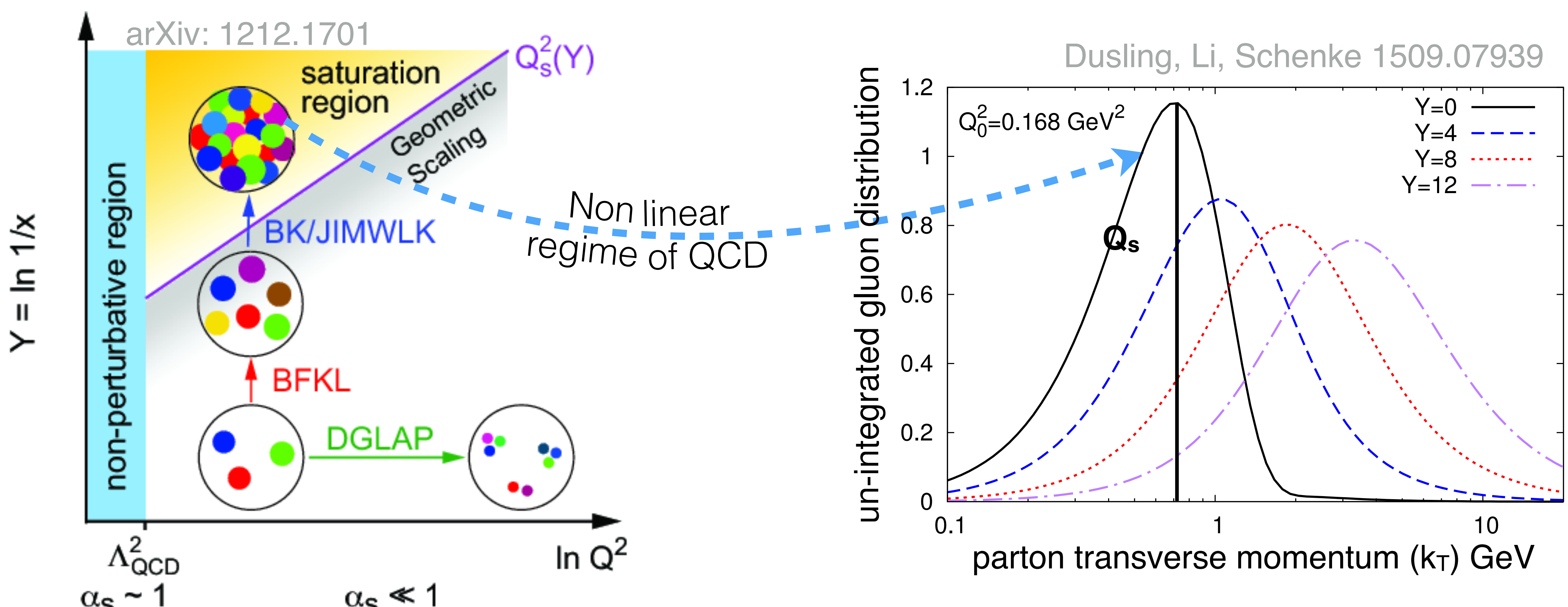


Particle production at high energies

Multi-particle production at high energies in **Regge Gribov limit** (x→0)

Colliding hadrons/nuclei :

- Saturation : Non-linear process strops growth of gluons, **semi-hard saturation scale** $Q_s(x) > \Lambda_{QCD}$
- **Gluon dominated wave function**, peaked at $Q_s(x \sim x_0 e^{-Y})$

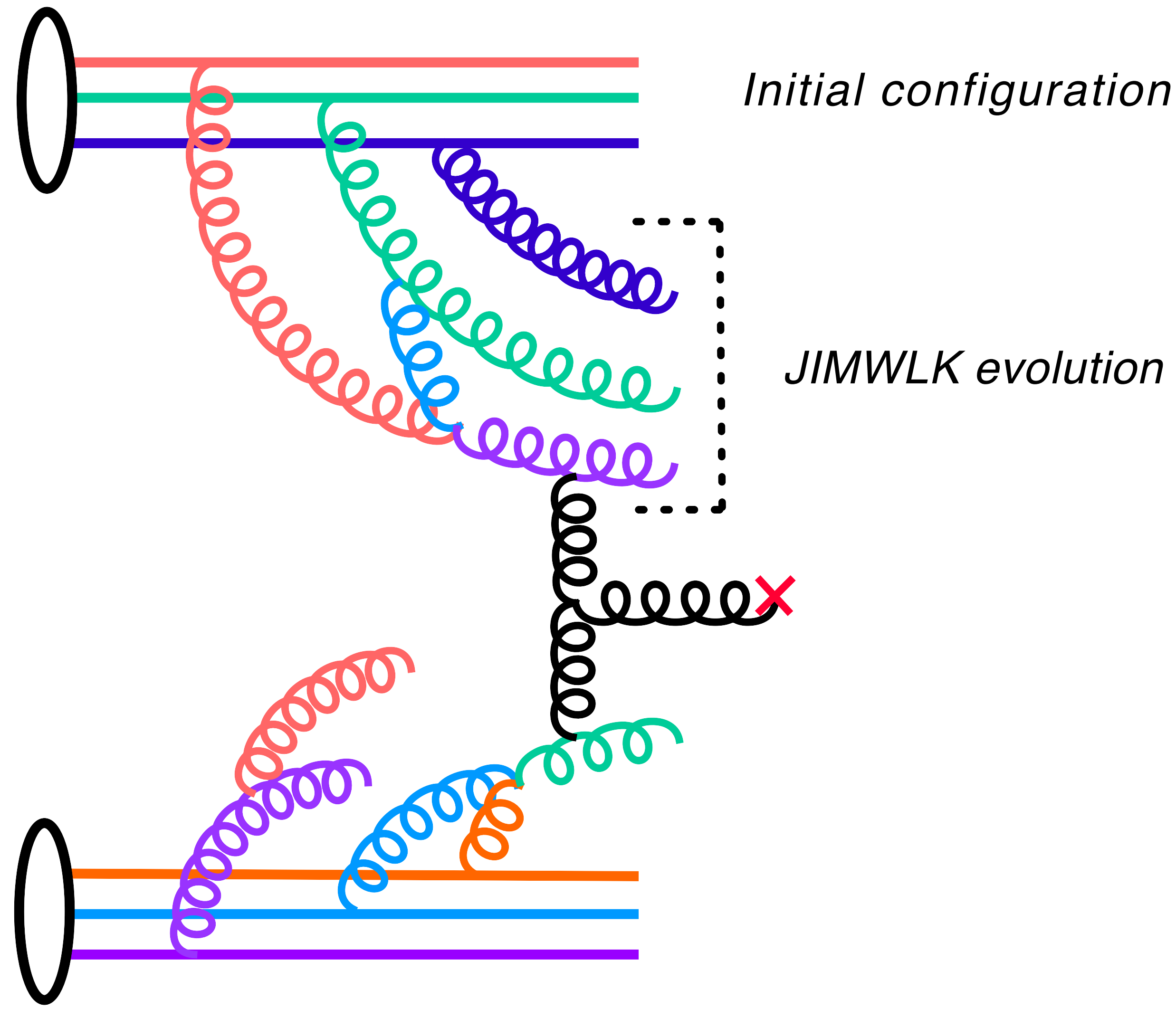


Particle production at high energies

Multi-particle production at high energies in **Regge Gribov limit** (x→0)

Particle production :

- t-channel exchange of ladder like emissions of gluons,



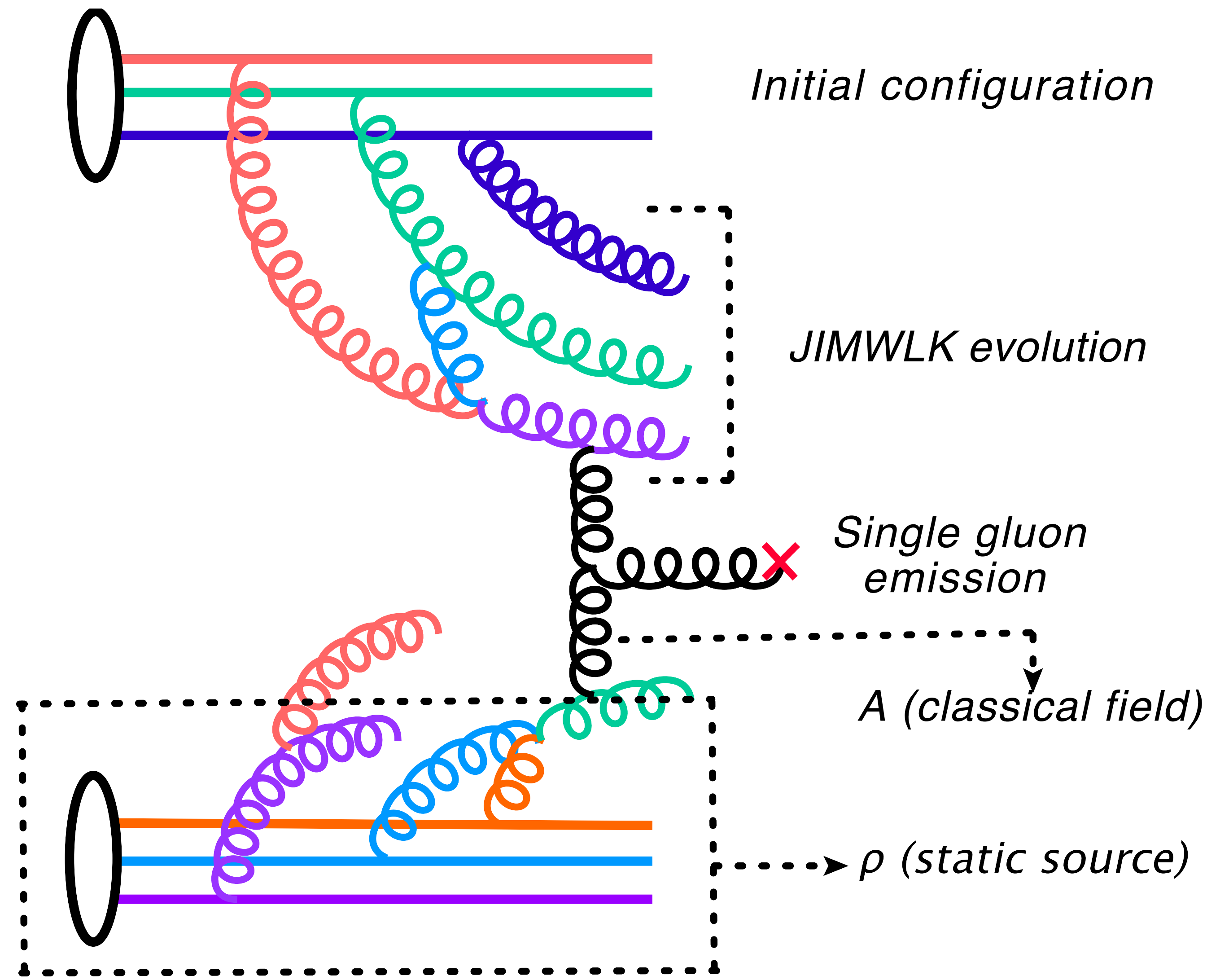
Particle production at high energies

Multi-particle production at high energies in **Regge Gribov limit** (x→0)

Particle production :

- t-channel exchange of ladder like emissions of gluons,
- Strong color fields, weak coupling, ***high occupancy of gluonic states*** *~1/g²*

(classical approximation)



McLerran, Venugopalan hep-ph/9309289

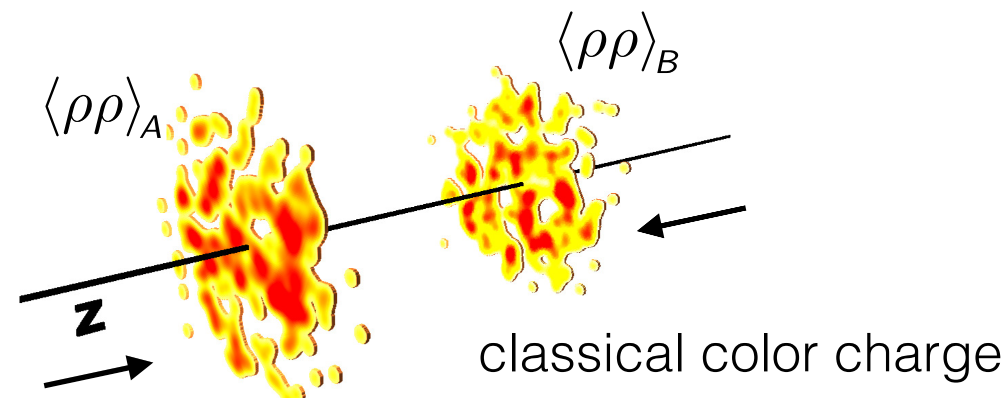
Color Glass condensate effective field theory → *ab-inito* framework to this problem

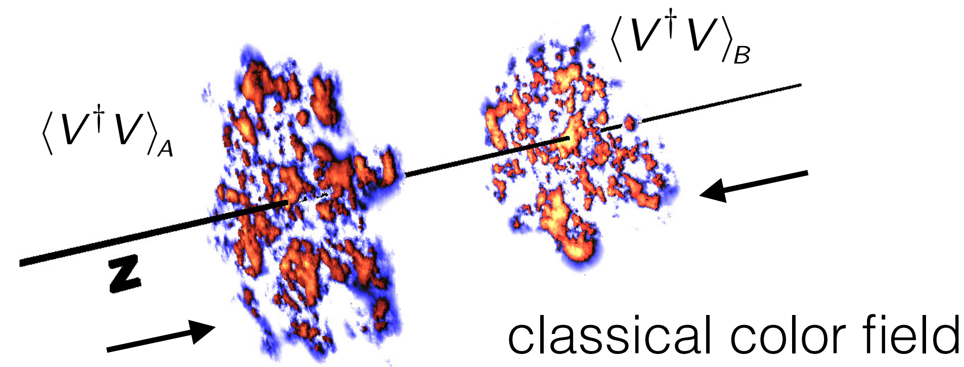
Details of CGC the framework

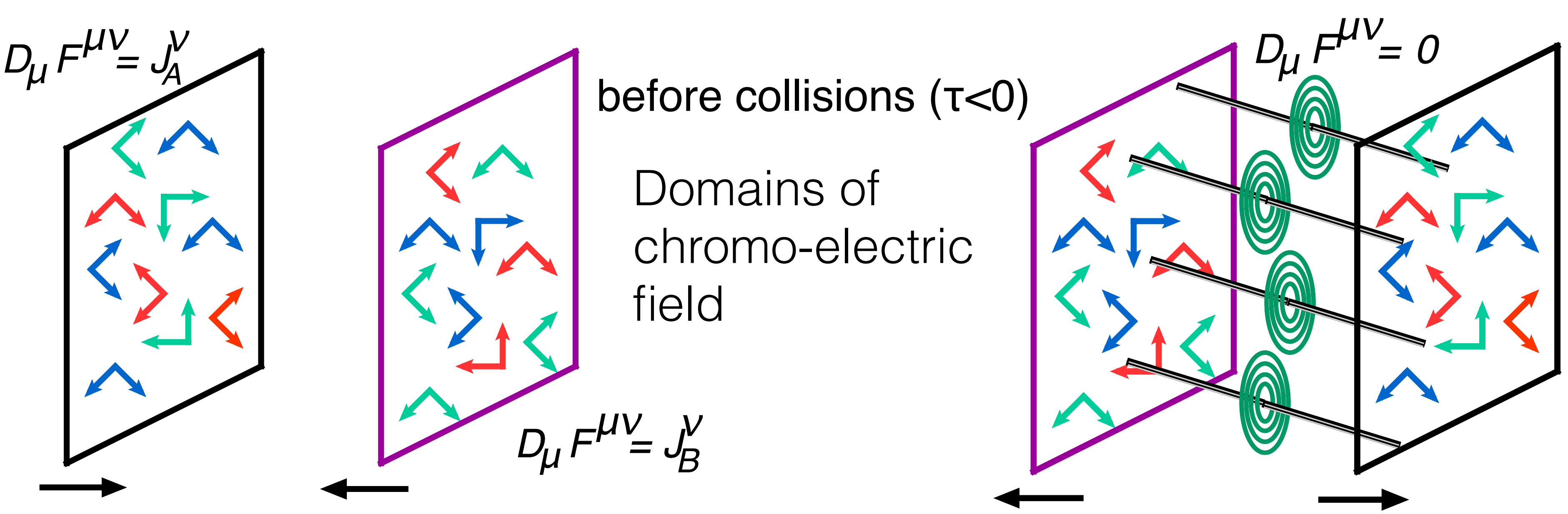
- Fundamental objects are Color Charge density matrices $\rho^a(x_\perp, Y)$
  Local Gaussian distribution $W[\rho]$
  (MV-Model)

$$\left\langle \rho^a(\mathbf{x}_\perp)\rho^b(\mathbf{y}_\perp)\right\rangle = \delta^{ab}\delta^2(\mathbf{x}_\perp - \mathbf{y}_\perp)g^2\mu^2(\mathbf{x}_\perp)$$

- Color field before collisions : solving Yang Mills equations $[D_\mu, F_{\mu\nu}] = J_\nu$ for each configuration of source $\rho(x_\perp)$







after collisions (τ>0)

Glasma flux tubes —> free streaming gluons

hep-ph/9809433,
hep-ph/0303076,
arXiv: 1206.6805
arXiv: 1202.6646

Details of the CGC framework

Input is constrained by dipole-cross sections in e+p/A collisions

Perturbative approach

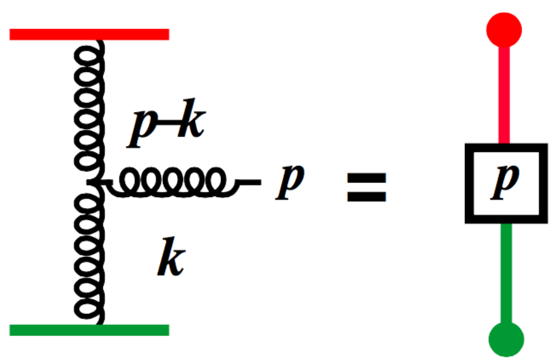
- Employ **k_T-factorization** ($p_T > Q_s$), dilute-dilute/dense systems

Non-perturbative approach

- Full solutions of CYM on 2+1D lattice : **IP-Glasma** Monte-Carlo model of initial conditions

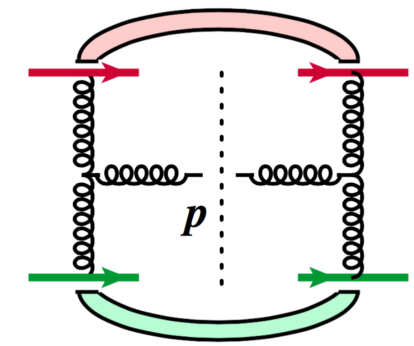
Multi-particle productions

Single-Inclusive



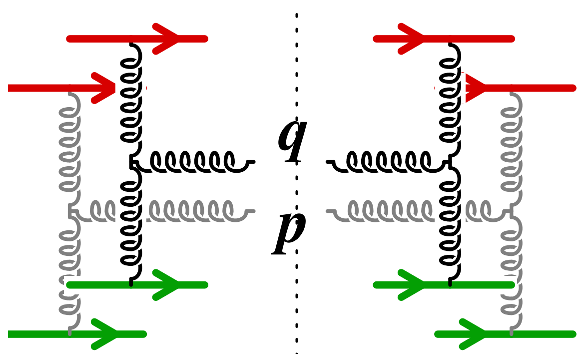
Color Averaging

$$\mathcal{M} \sim \frac{\rho_1(\mathbf{k}_\perp)}{\mathbf{k}_\perp{}^2}\,\frac{\rho_2(\mathbf{p}_\perp-\mathbf{k}_\perp)}{(\mathbf{p}_\perp-\mathbf{k}_\perp)^2}\, L^\gamma(\mathbf{p},\mathbf{k}_\perp)$$



$$\left\langle \frac{dN}{dy_p\, d^2\mathbf{p}_\perp}\right\rangle \sim \langle|\mathcal{M}|^2\rangle \sim \langle \rho_1^*\rho_1\rho_2^*\rho_2\rangle$$

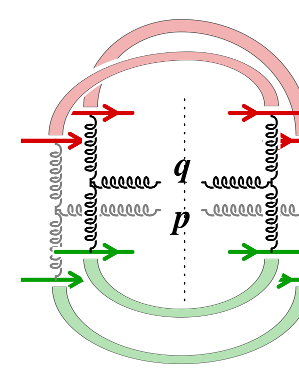
Double-Inclusive



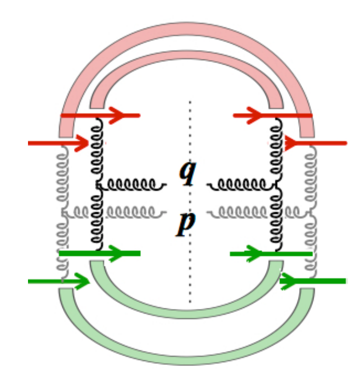
$$\langle|\mathcal{M}|^2\rangle \to \langle \rho_1^*\rho_1^*\rho_1\rho_1\rho_2^*\rho_2^*\rho_2\rho_2\rangle$$

$$C_2(\mathbf{p},\mathbf{q}) \equiv \left\langle \frac{dN_2}{dy_p\, d^2\mathbf{p}_\perp\, dy_q\, d^2\mathbf{q}_\perp}\right\rangle - \left\langle \frac{dN}{dy_p\, d^2\mathbf{p}_\perp}\right\rangle \left\langle \frac{dN}{dy_q\, d^2\mathbf{q}_\perp}\right\rangle$$

↓ ↓



8 topologies

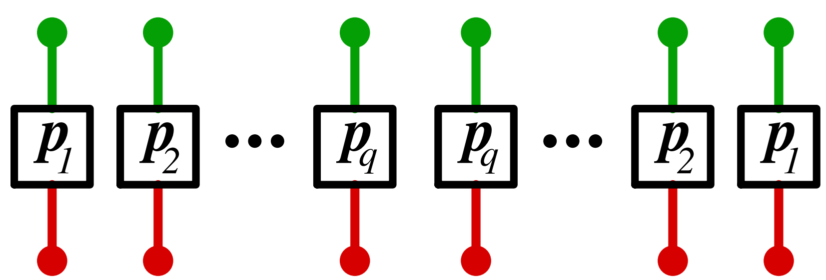


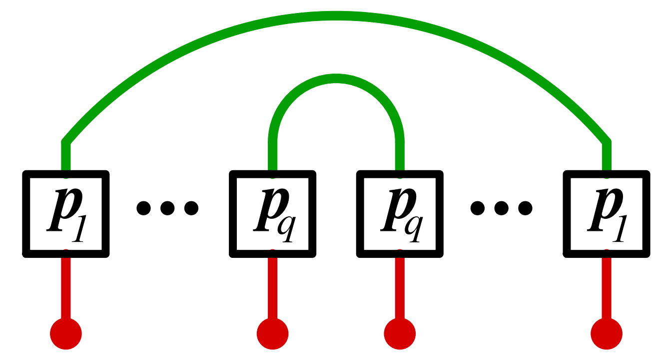
1 topology

Dumitru, Gelis, McLerran, Venugopalan 0804.3858

n-particle correlations

CGC framework is extendable to n-particle correlations





$2^n(n-1)!$ topologies

Naturally generates Negative Binomial distribution probability distribution

$$P_n^{\rm NB} = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)} \frac{\bar{n}^n k^k}{(\bar{n}+k)^{n+k}}$$

$$k = \kappa \frac{({N_{\rm c}}^2-1){Q_{\rm s}}^2 S_\perp}{2\pi}$$

High-multiplicity events —> originate from correlated production of n-particles
—> Highly non-perturbative

Gelis, Lappi, McLerran 0905.3234

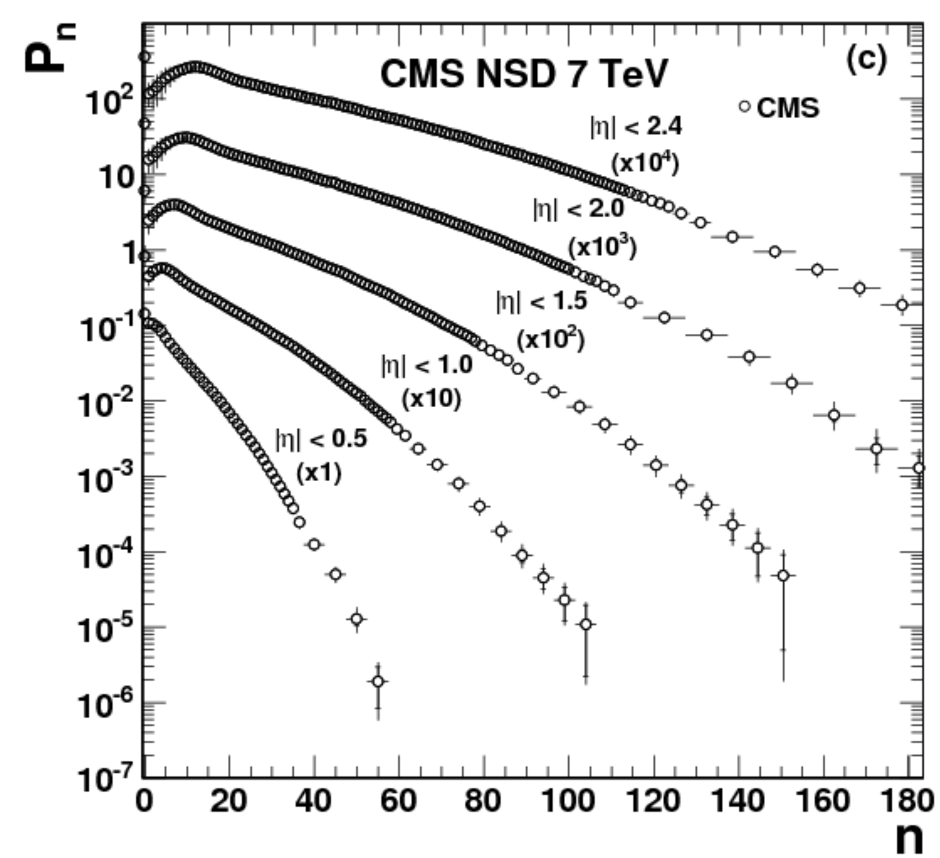
Description of Multiplicity distribution/ high multiplicity events

IP-Glasma model : combines CGC framework & different sources of initial state fluctuations

1. Collision geometry and impact parameter

2. Color charge

3. Rare Fock-Space configurations



(I) Fluctuation of collision geometry

- Collision geometry is not calculable from first principle
- Eikonal model with thickness profile from HERA data

Schenke, Tribedy, Venugopalan 1311.3636

Proton profile

$$T_p(\mathbf{s}_\perp) = \frac{1}{2\pi B_G} \exp\left(\frac{-\mathbf{s}_\perp{}^2}{2B_G}\right)$$

Overlap function

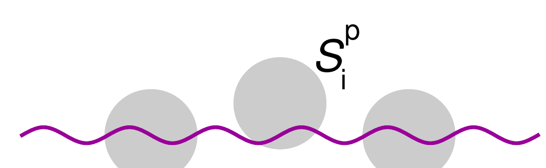
$$T_{pp}(b) = \int \mathrm{d}^2\mathbf{s}_\perp\, T_p^A(\mathbf{s}_\perp)\, T_p^B(\mathbf{s}_\perp - \mathbf{b}_\perp).$$

Impact parameter distribution

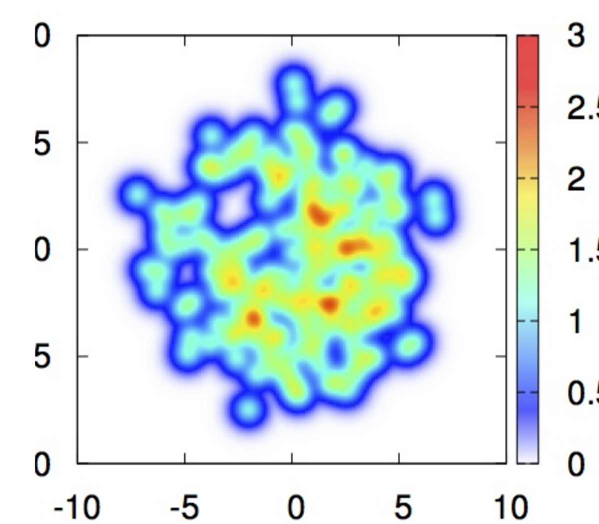
$$\frac{dP}{d^2b}(b) = \frac{1 - e^{-\sigma_{\mathrm{gg}} N_g^2 T_{pp}(b)}}{\int \mathrm{d}^2 b \left(1 - e^{-\sigma_{\mathrm{gg}} N_g^2 T_{pp}(b)}\right)}$$

Making Nucleus out of proton scattering

$$S^A_{\mathrm{dip}}(\mathbf{r}_\perp, x, \mathbf{b}_\perp) = \prod_{i=0}^{A} S^p_{\mathrm{dip}}(\mathbf{r}_\perp, x, \mathbf{b}_\perp)$$



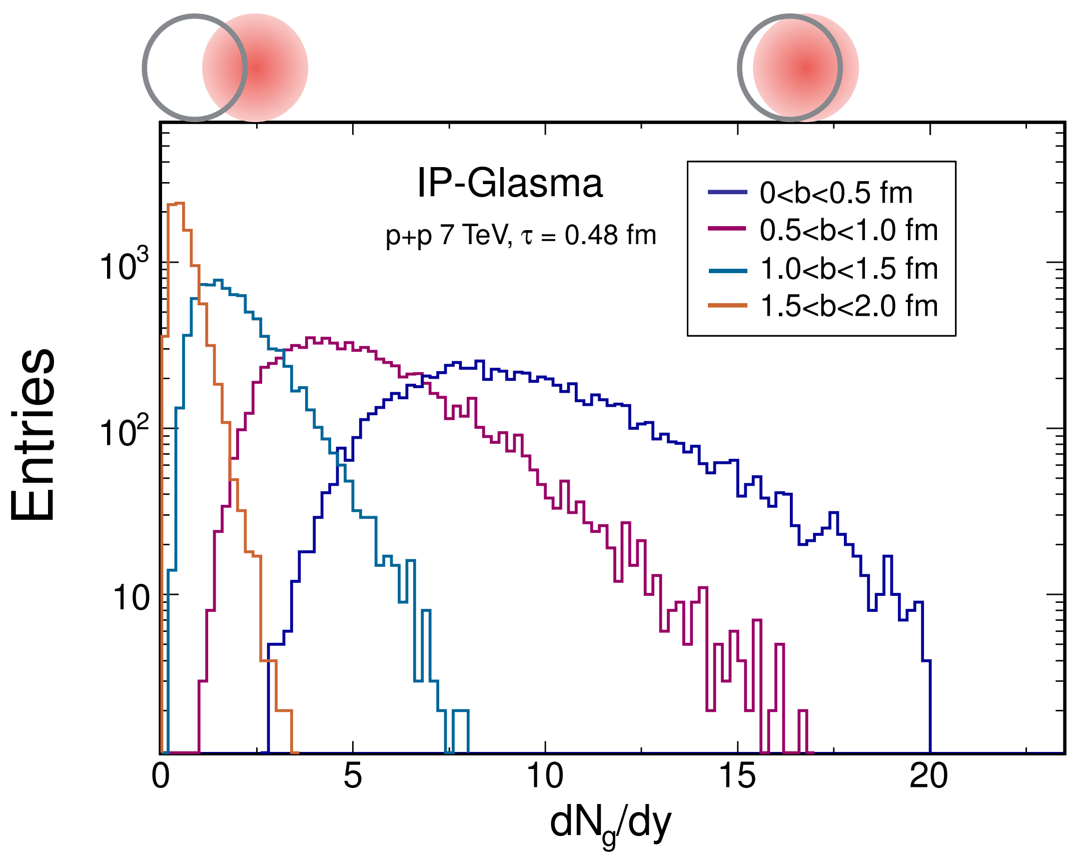
Nuclear saturation scale : $Q^2_{\mathrm{sA}} \sim A^{1/3} Q^2_{\mathrm{sp}}$



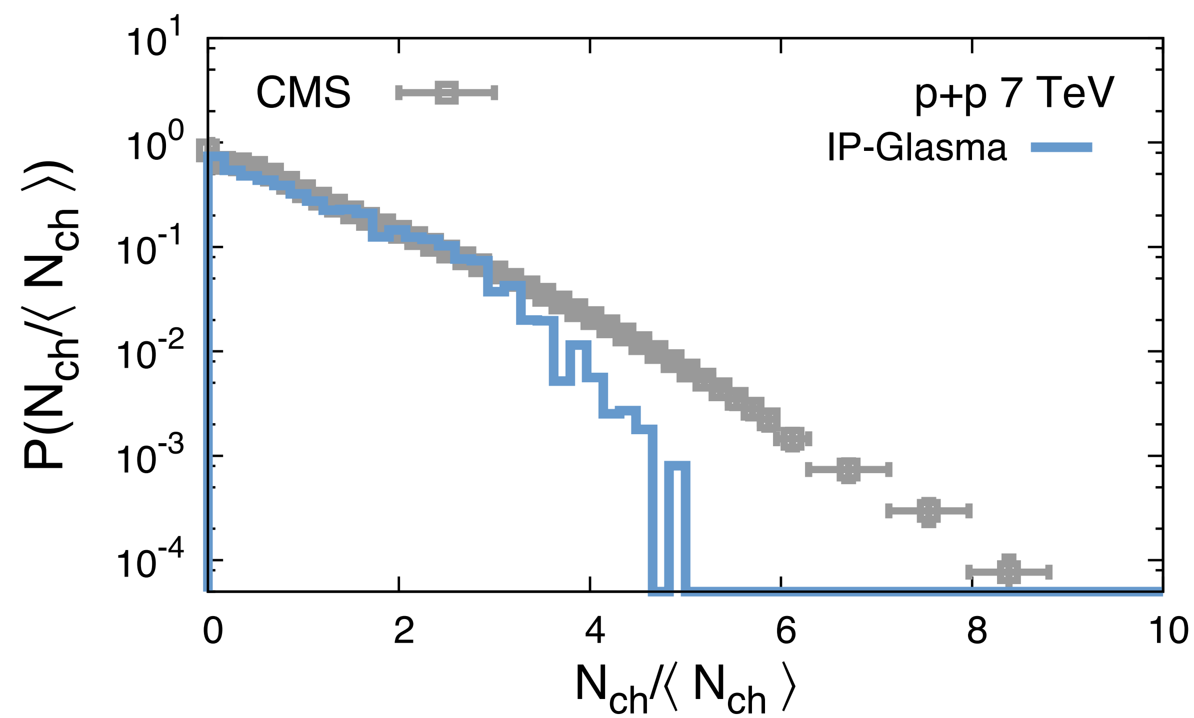
color charge distribution in nucleus

(II) Fluctuation of color charge

For a given geometry fluctuations of color charge
—> Negative Binomial distribution at each impact parameter



Convolution of many NBDs



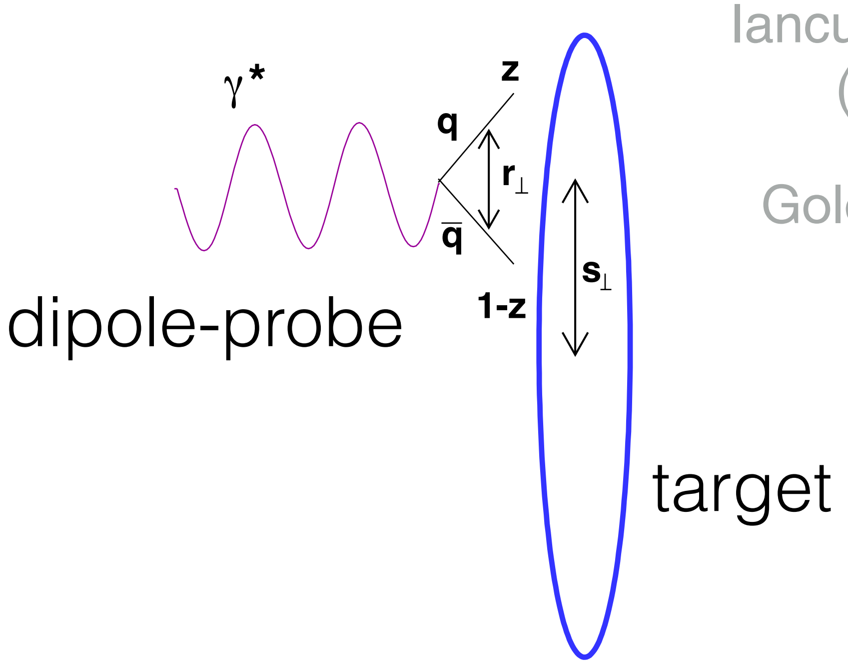
However the distribution is not wide enough to describe data

Some sources of fluctuation missing

(III) Intrinsic fluctuations of saturation scale

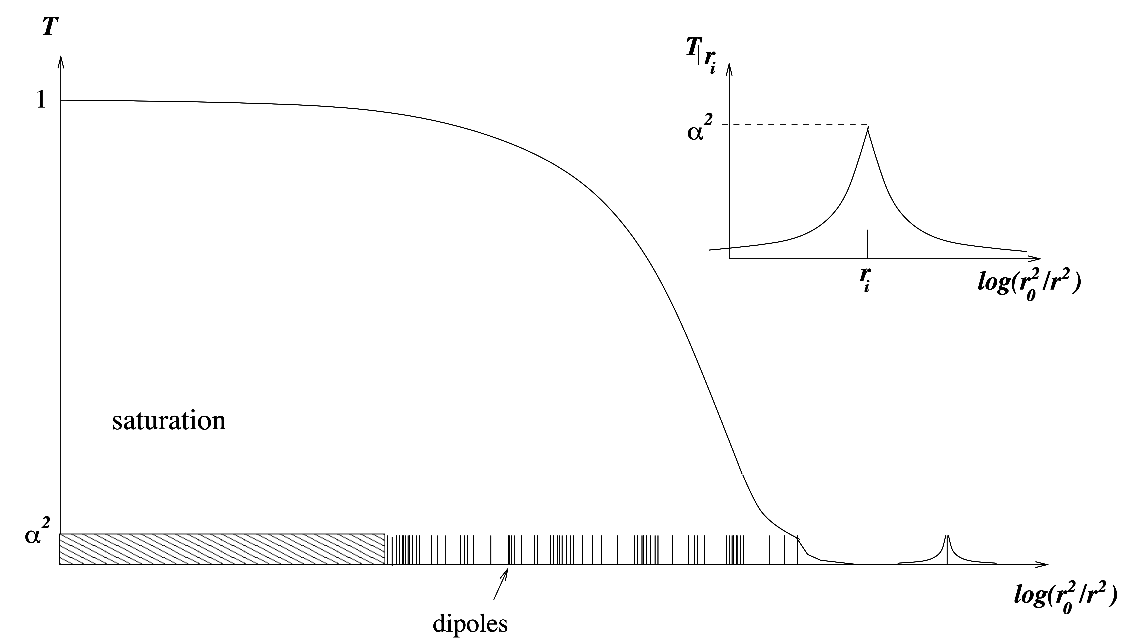
Input to CGC framework —> dipole cross section e+p/A

Color dipole picture : distribution of partons —> dist. of color dipoles



Iancu, Mueller, Munier (hep-ph/0410018)

Golec-Biernat, Wusthoff hep-ph/9807513

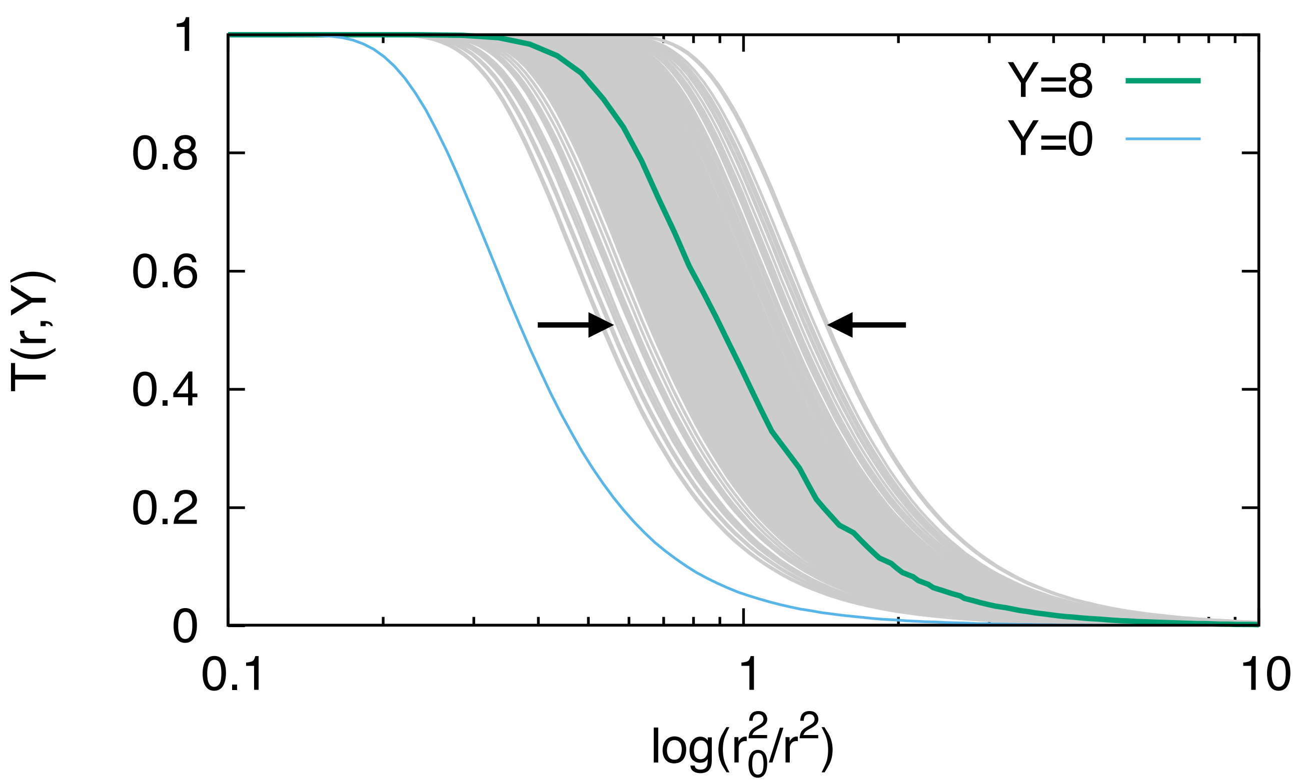


With evolution of rapidity each dipole split with probability ~ α_S dY
—> dipole splitting is however stochastic

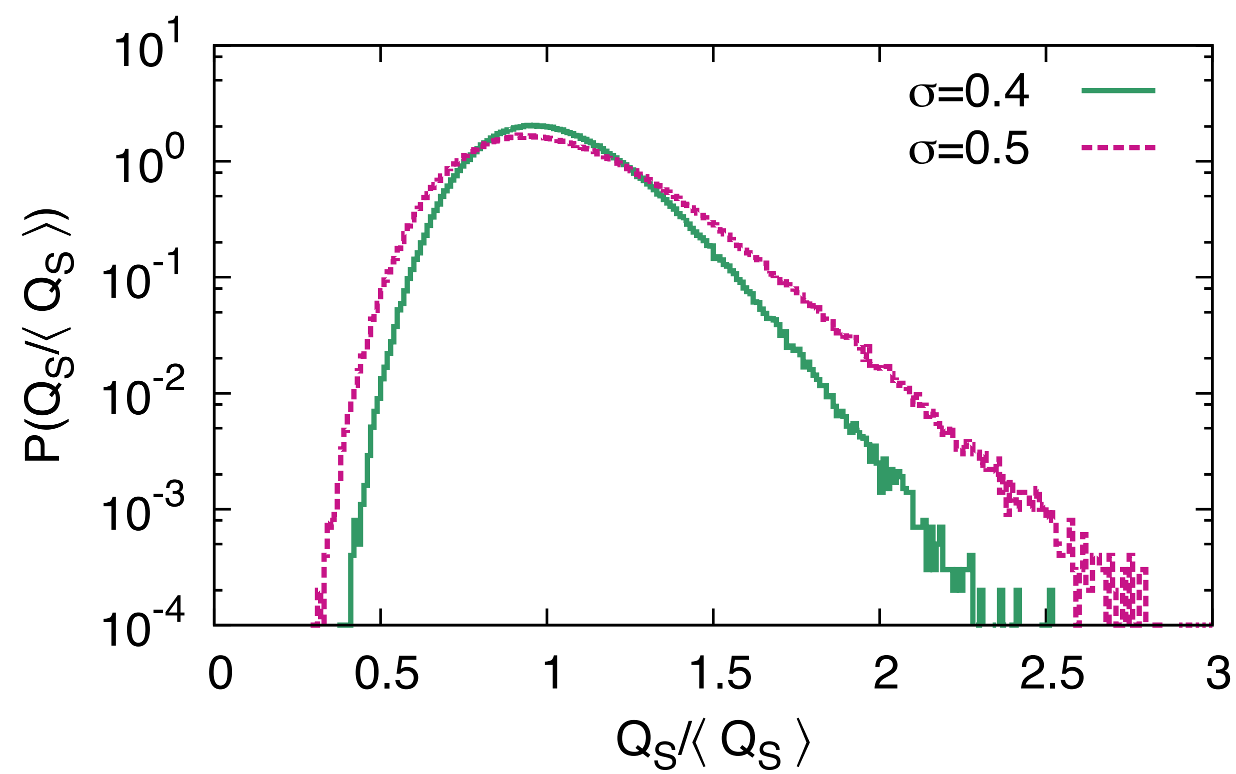
Stochastic dipole splitting —> not present in BK/JIMWLK —>beyond CGC

Intrinsic fluctuations of saturation momentum of a proton/nuclei

Dipole amplitude



Saturation scale



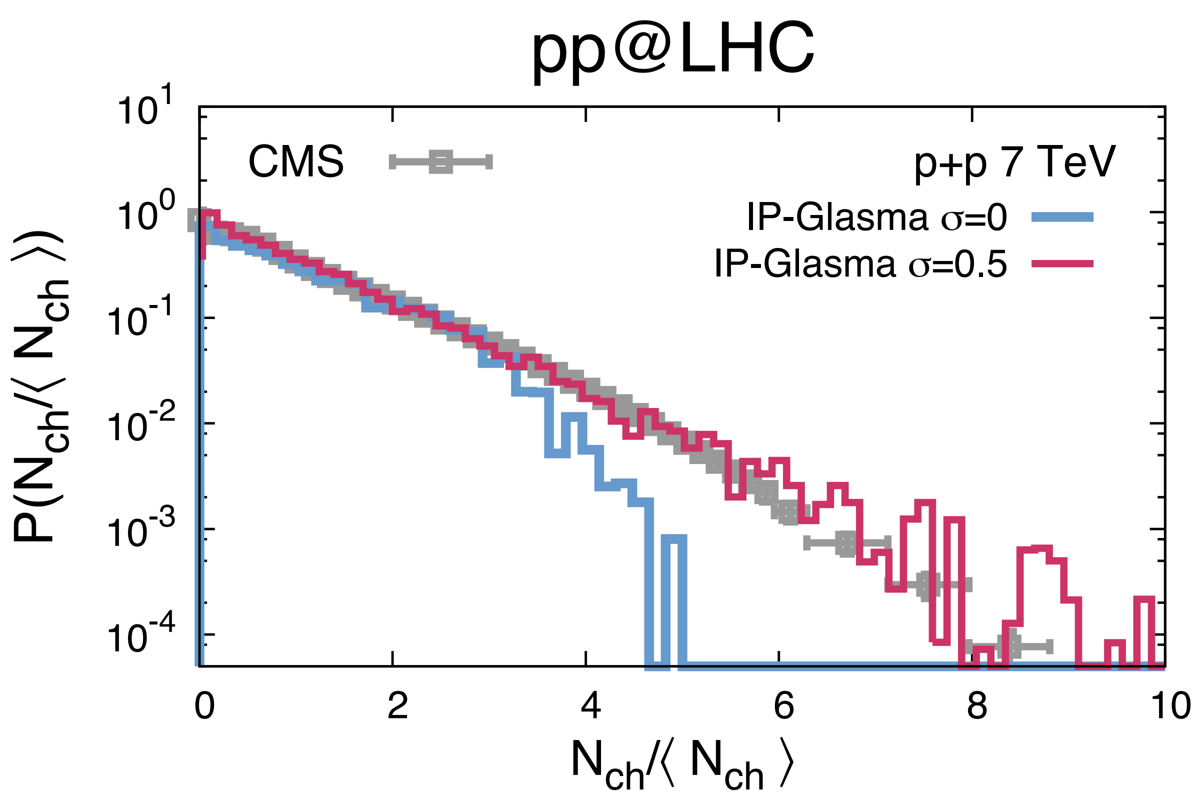
Marquet, Soyez, Xiao hep-ph/0606233

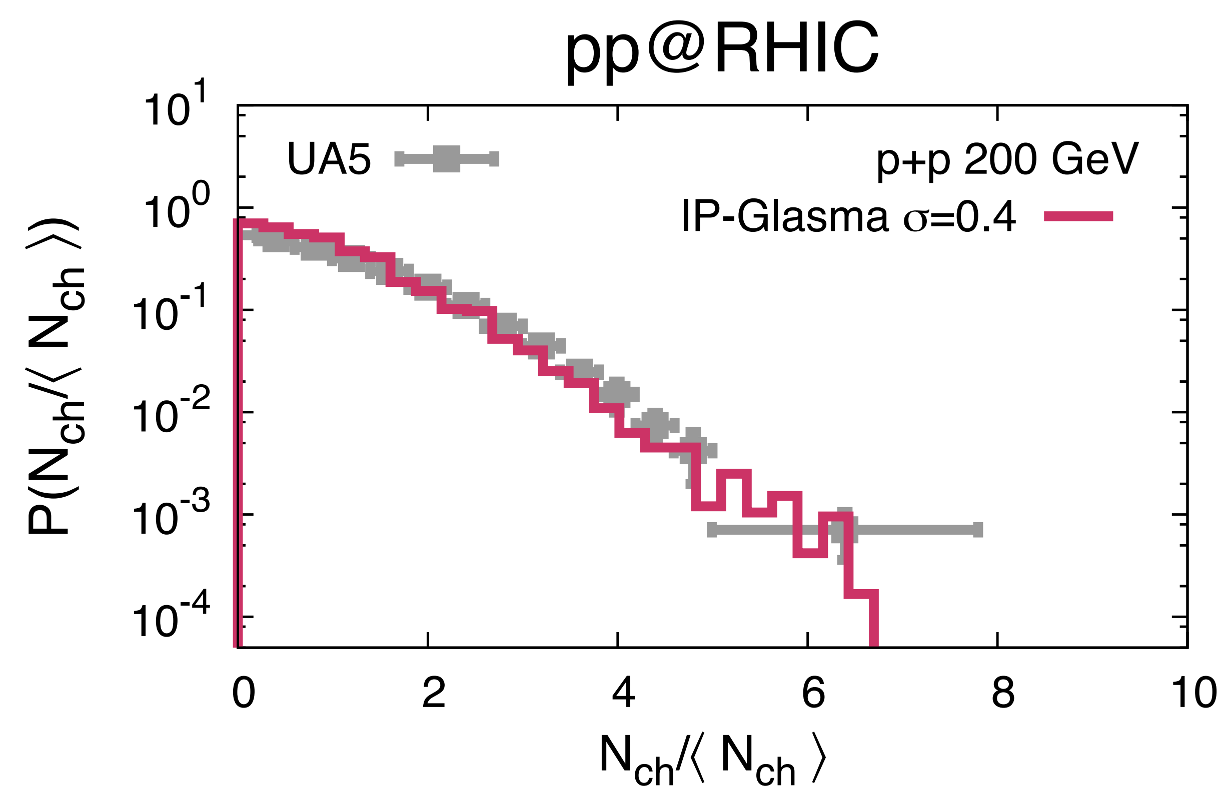
Stochastic splitting of dipole leads to a distribution of Qs

$$P(\ln(Q_S^2/\langle Q_S^2\rangle)) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{\ln^2(Q_S^2(\mathbf{s}_\perp)/\langle Q_S^2(\mathbf{s}_\perp)\rangle)}{2\sigma^2}\right) \qquad \sigma^2(Y) = \sigma_0^2(Y_0) + \sigma_1^2(Y - Y_0)$$

Distribution of multiplicity

McLerran, Tribedy 1508.03292



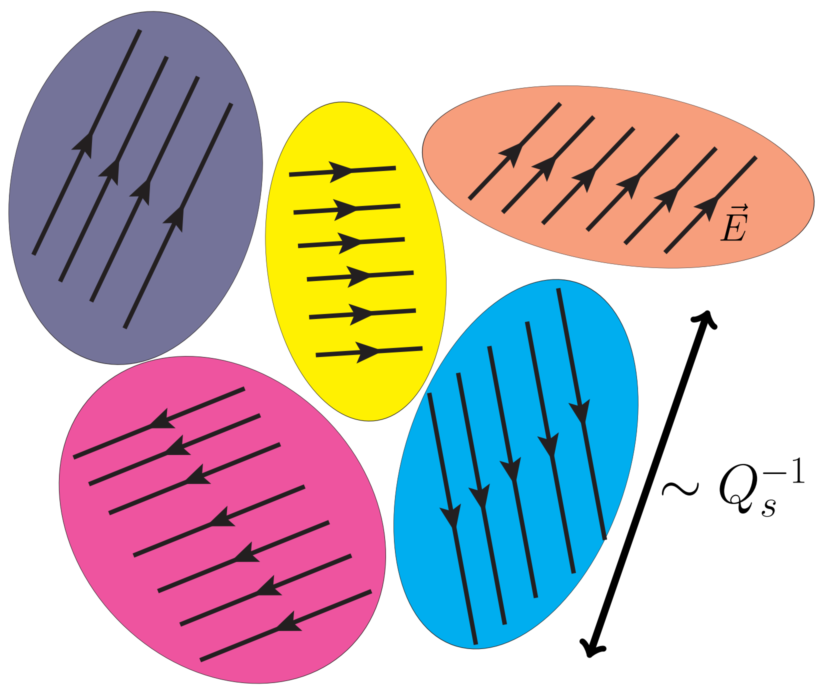


Origin of High multiplicity events (Tail of distributions)

High multiplicity events —> rare configuration of high color charge density ($1/g^2$)

Azimuthal Correlations in CGC

- Intrinsic momentum space correlation from initial state
- Originate probe scattering off a color domain
- Suppressed by number of color sources/domains

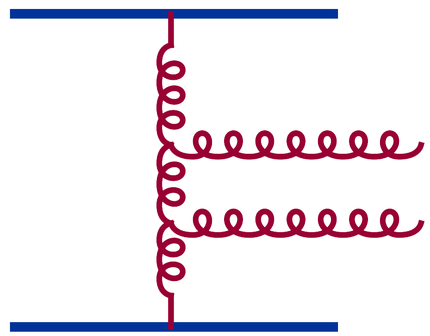


Dumitru, Dusling, Gelis, Jalilian-Marian, Lappi, Venugopalan 1009.5295
Kovner, Lublinsky 1012.3398
Dusling, Venugopalan 1201.2658
Kovchegov, Wertepny 1212.1195
Dumitru, Giannini 1406.5781
Lappi, Schenke, Schlichting, Venugopalan 1509.03499

Very distinct from Hydrodynamic flow (driven by geometry)

Two particle correlation in CGC

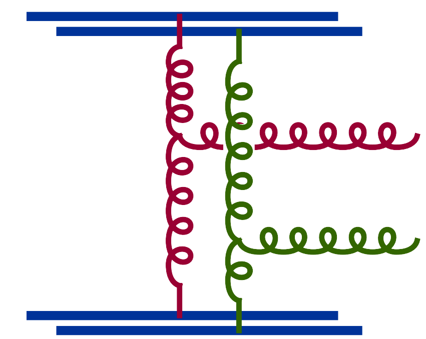
Jet Graph



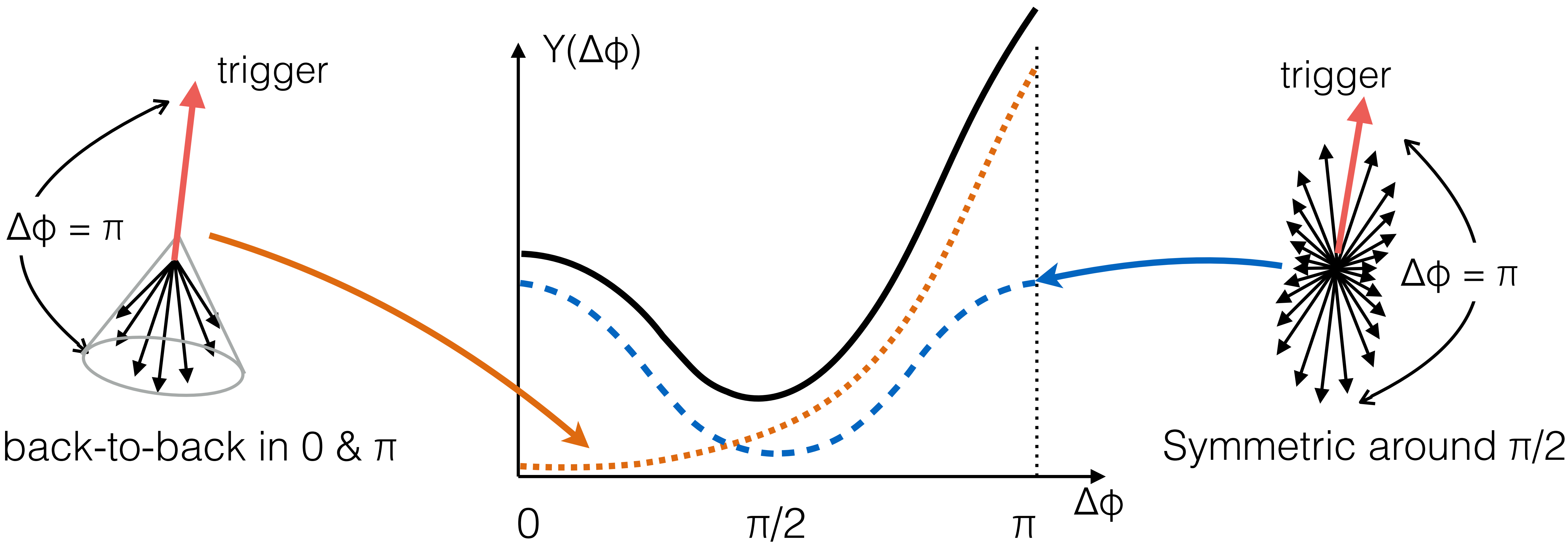
Kinematically constrained (back-to-back)

Dusling, Venugopalan
1201.2658, 1210.3890

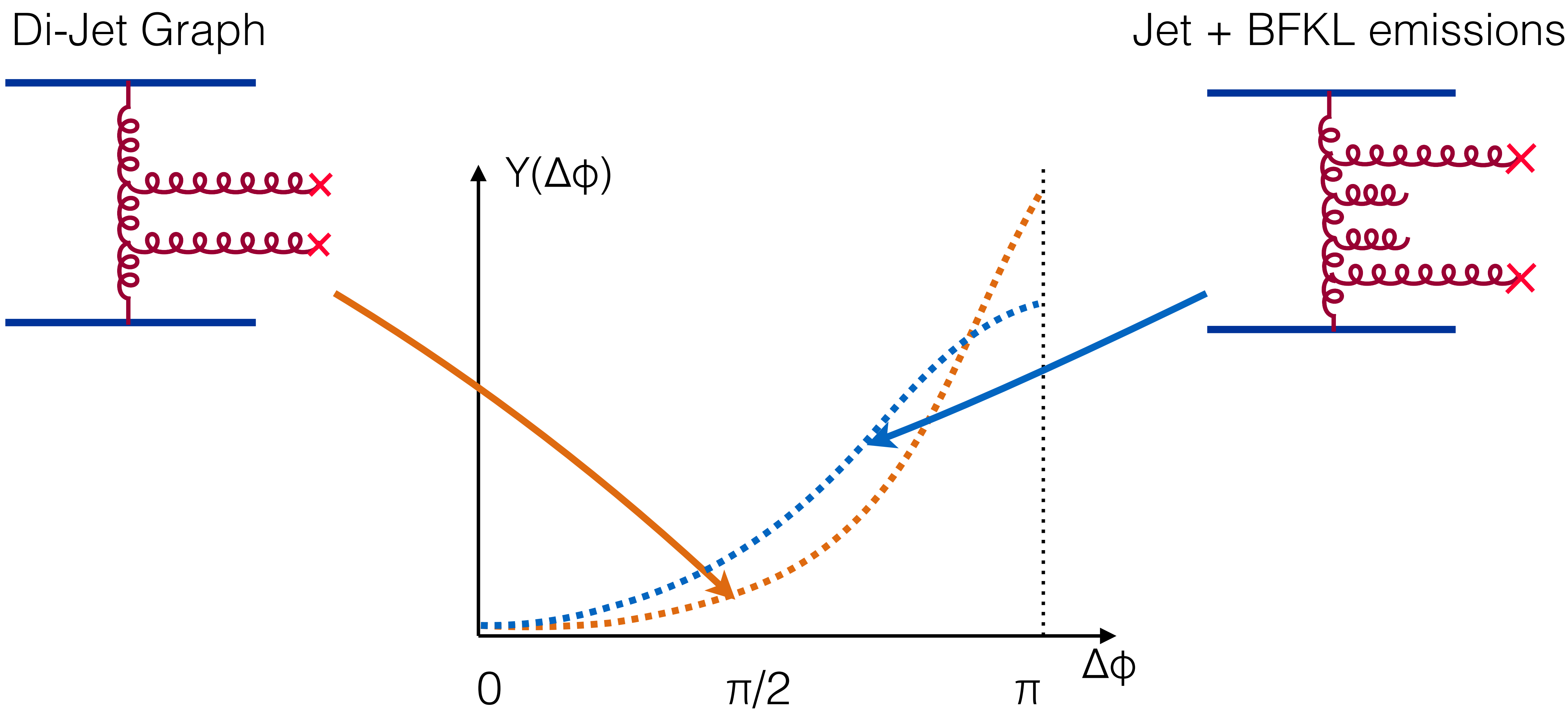
Glasma Graph



Not kinematically constrained

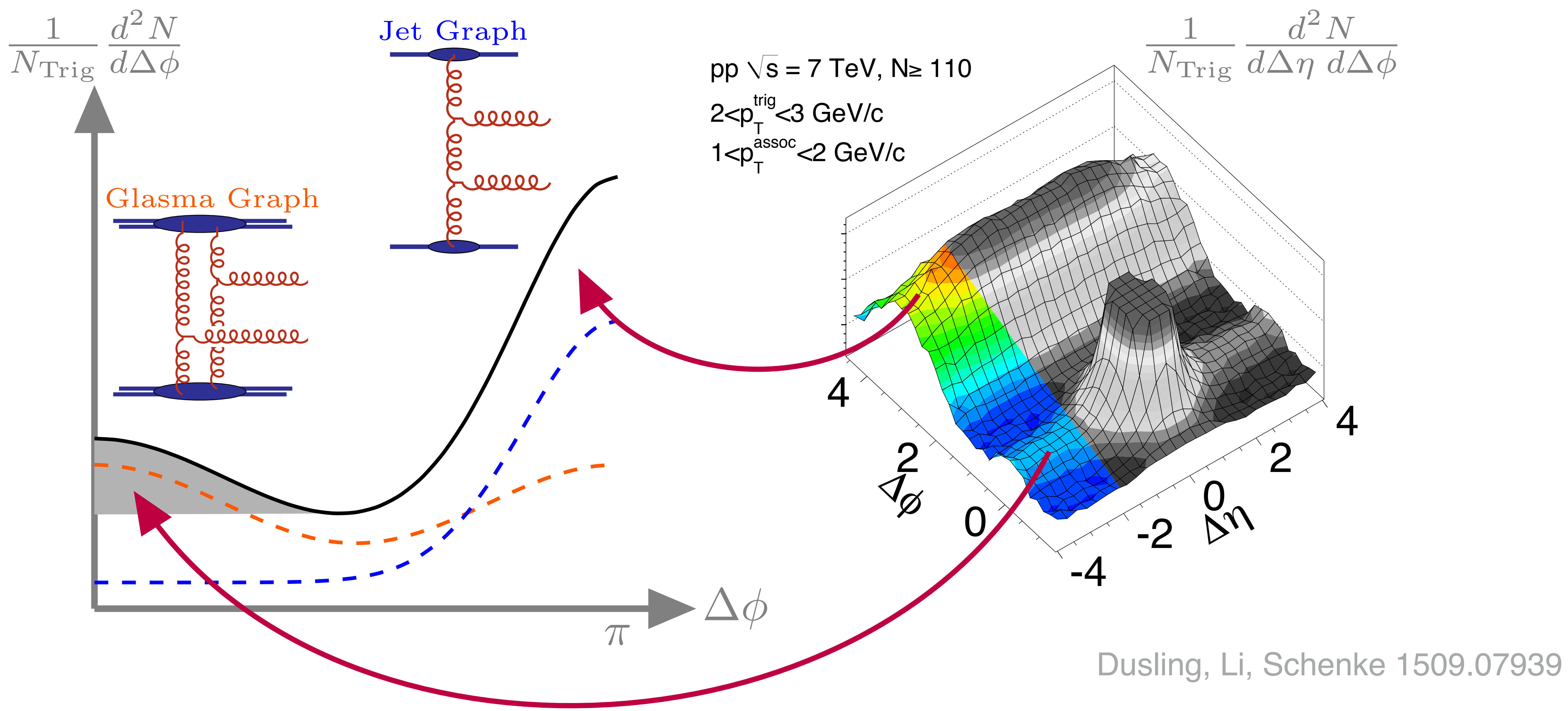


Two particle correlation in CGC



gluon emissions between two triggered hadrons—> broadening of the away side (de-correlation)

Origin of ridge-like correlations



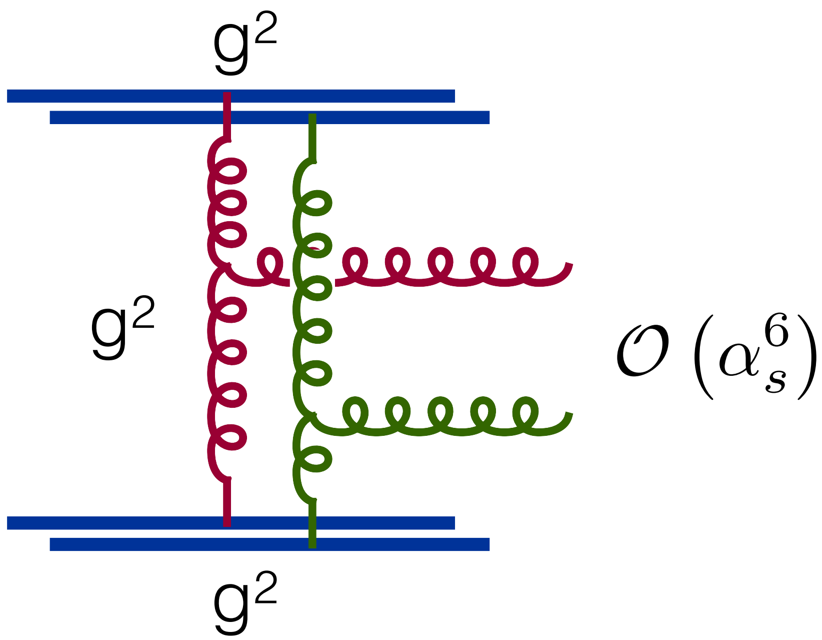
Dusling, Li, Schenke 1509.07939

But why ridge appears in high multiplicity events ?

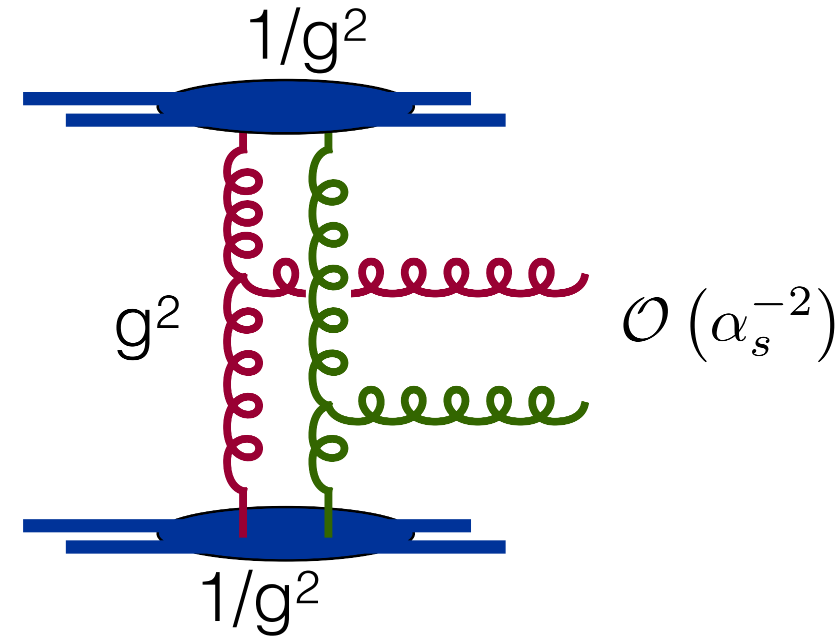
In CGC, high occupancy ~1/g² —> effective coupling 1/g² x g = 1/g

Picture in high multiplicity events

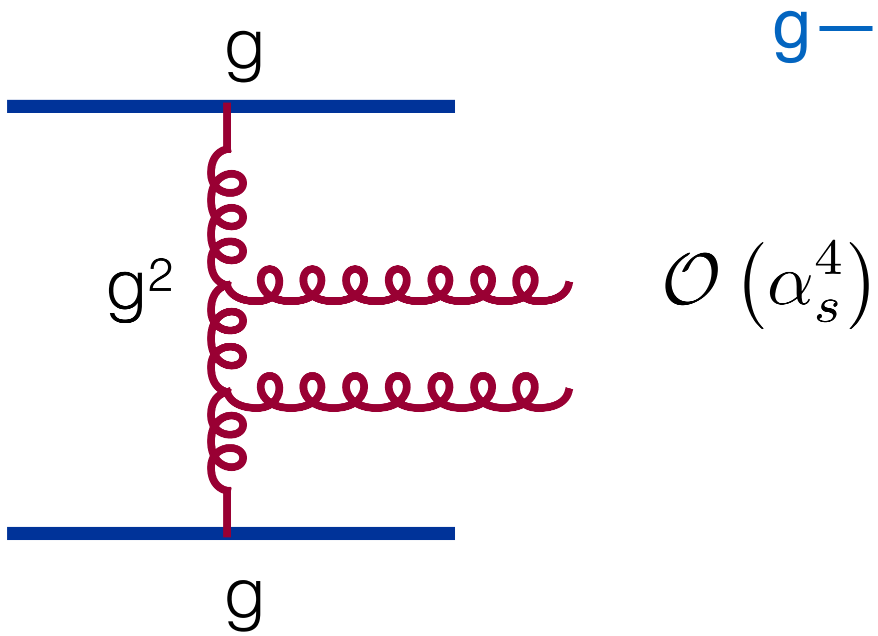
low density (min-bias events)

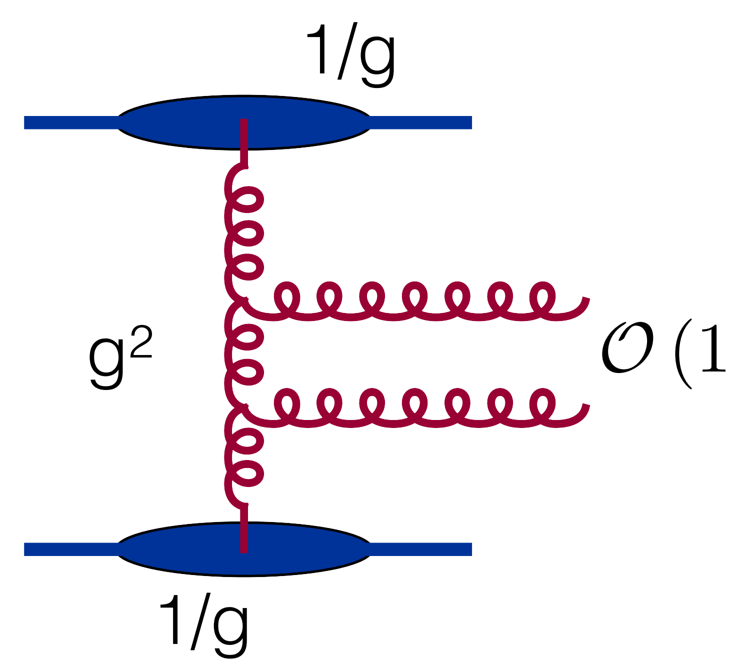


high density (high multiplicity events)



strong color field in CGC
g—> ρg~1/g² g~1/g





Comparison to data

p+p

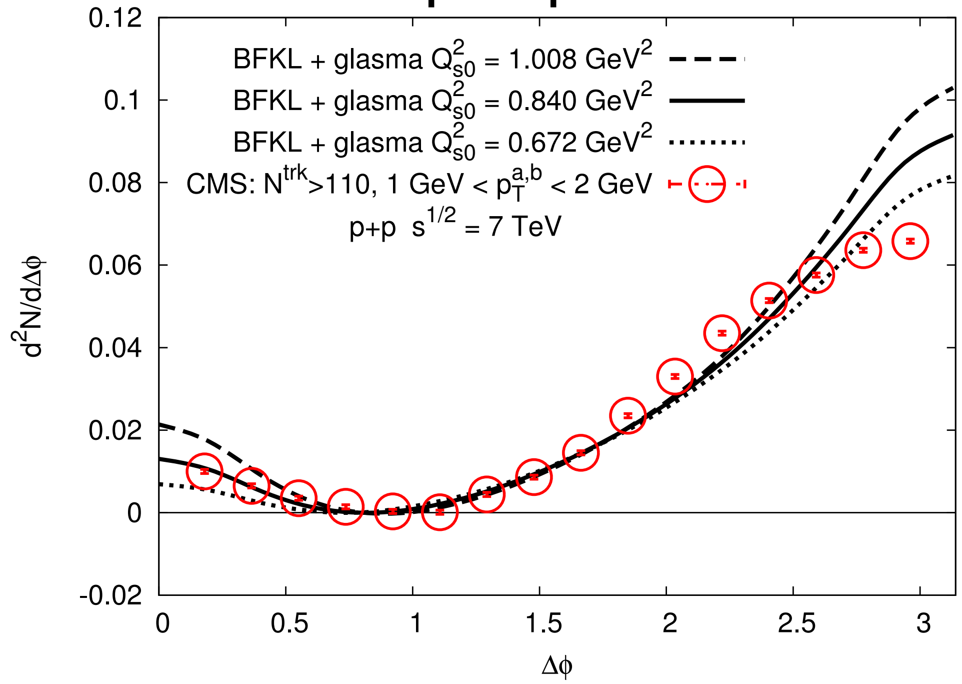
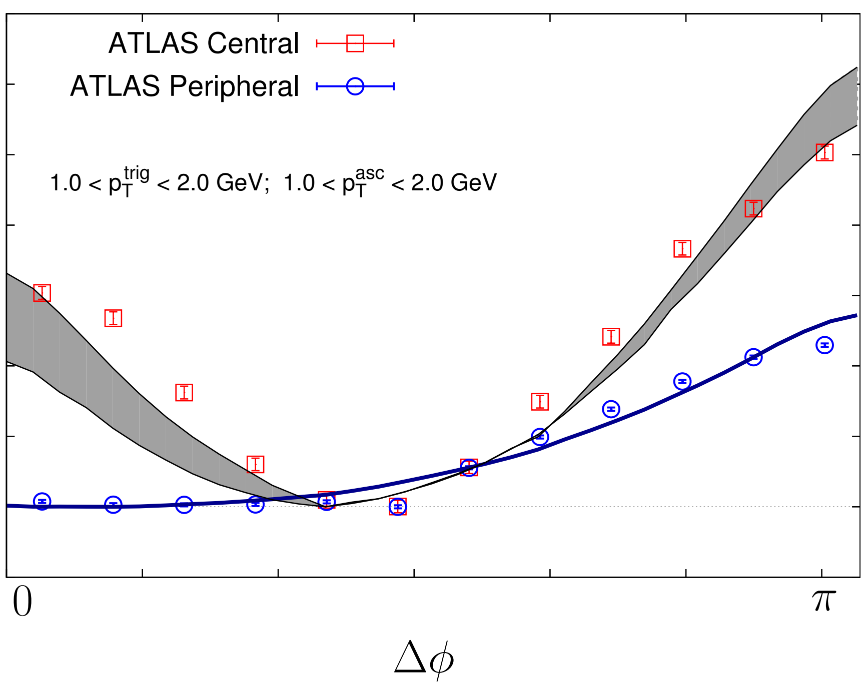


figure: Dusling, Li, Schenke 1509.07939

p+Pb

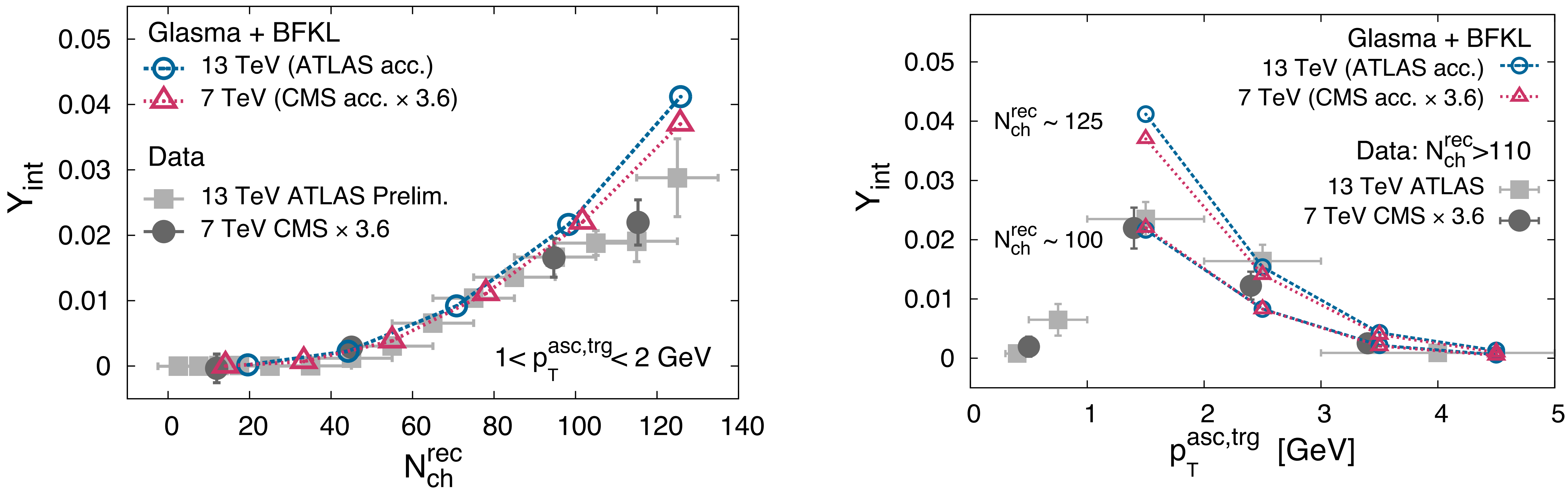


Dusling, Venugopalan 1201.2658, 1210.3890, 1211.3701, 1302.7018

Consistent explanation in the CGC picture

Energy independence of Ridge

Dusling, Tribedy, Venugopalan 1509.04410

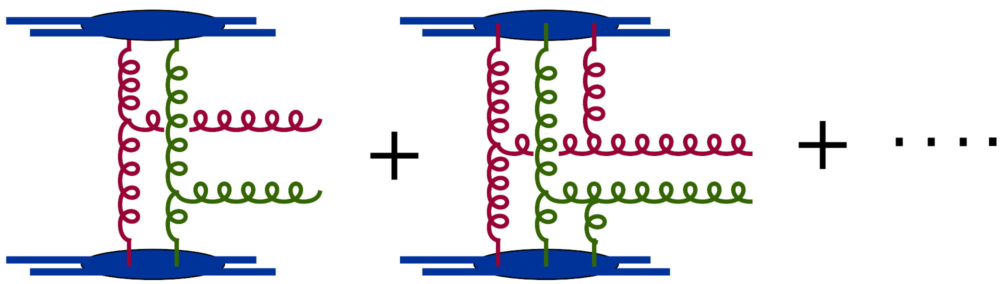


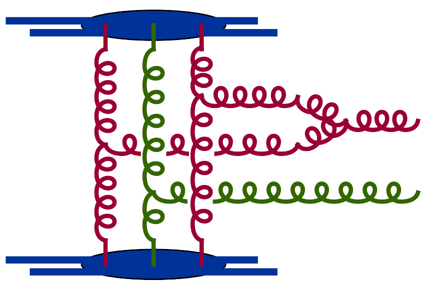
$$N_{\rm ch}^{\rm rec}(\sqrt{s}) = N_{\rm ch}^{\rm rec}({Q_{\rm s}}^2)\,,\ Y_{\rm int}(\sqrt{s}) = Y_{\rm int}({Q_{\rm s}}^2)$$

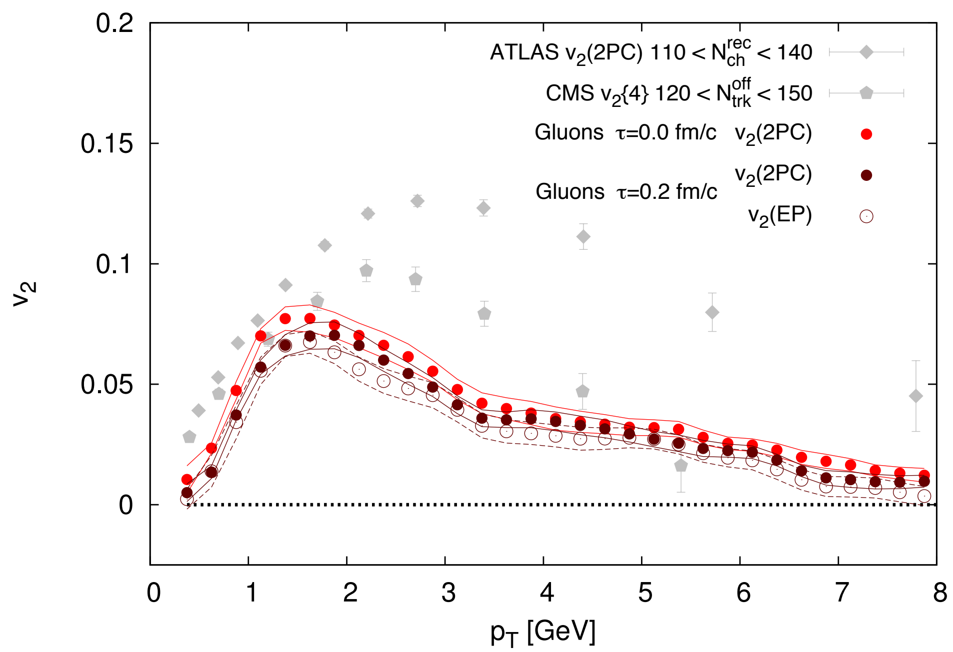
Energy dependence enters only though the saturation scale (only scale in problem) : Scaling of near side yield is natural in CGC approach

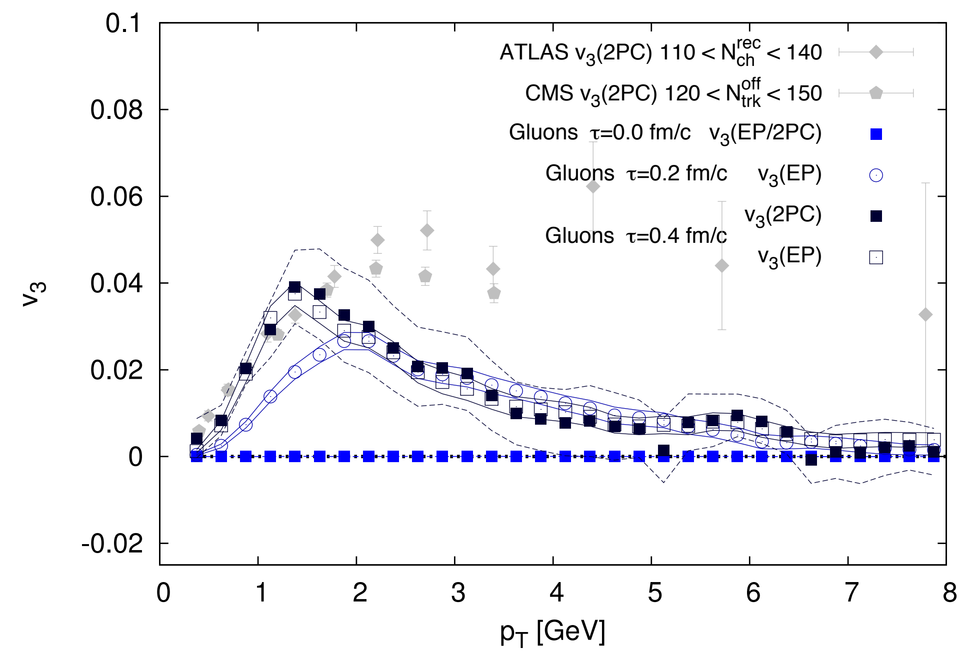
Harmonics of azimuthal correlations

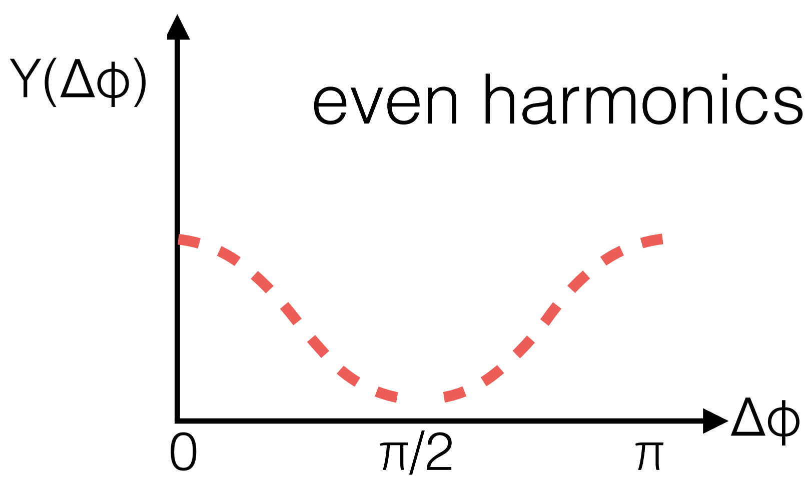
Schenke, Schlichting, Venugopalan 1502.01331

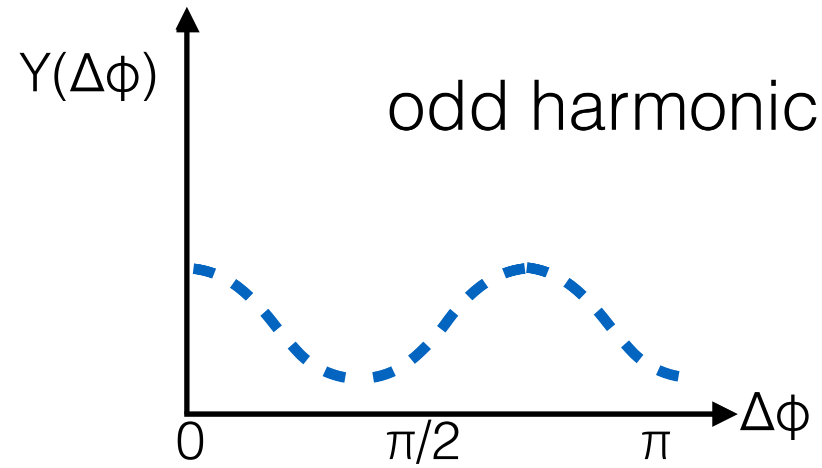






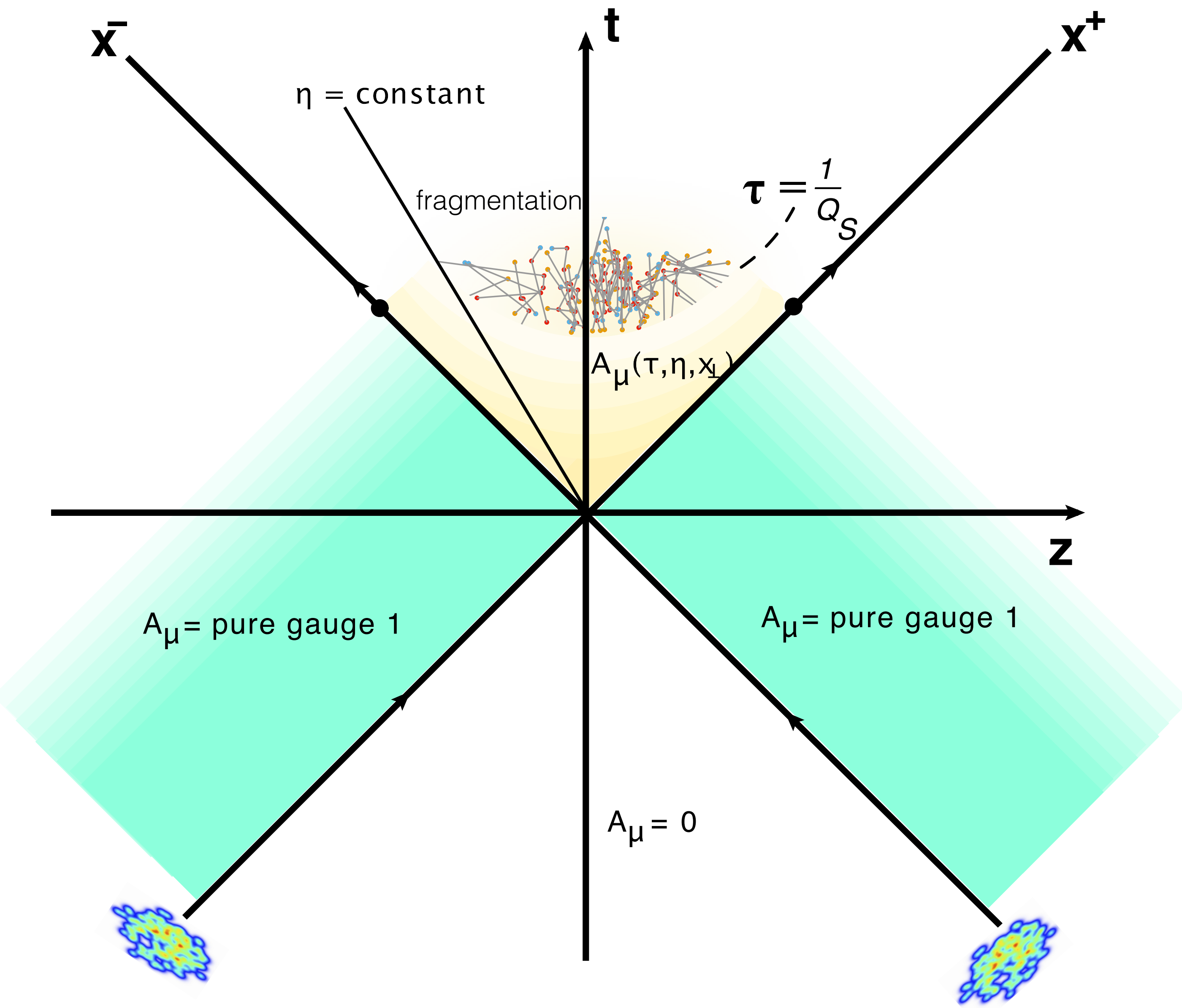






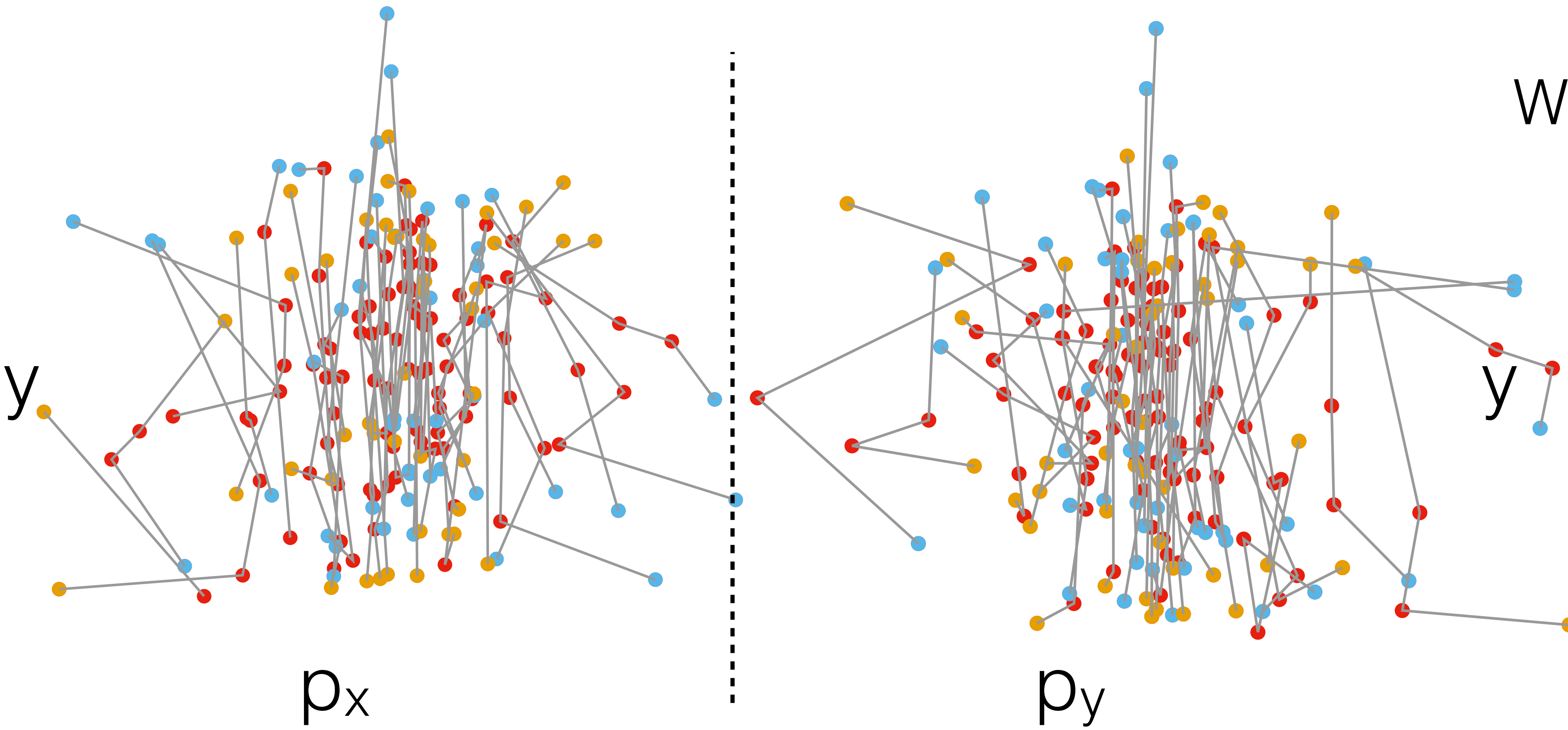
Combining CGC and PYTHIA

- Output distribution of Gluons from CGC
- Sample gluons in momentum space
- Connect the gluons close in phase space to color neutral strings
- Input to PYTHIA and fragment into final particles

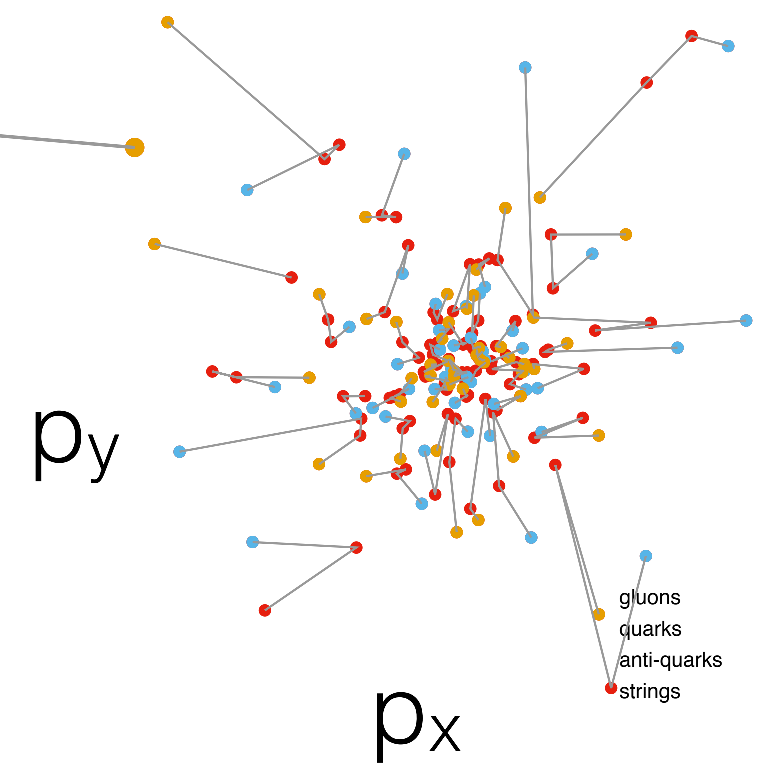


Implementing PYTHIA Strings

Work in progress

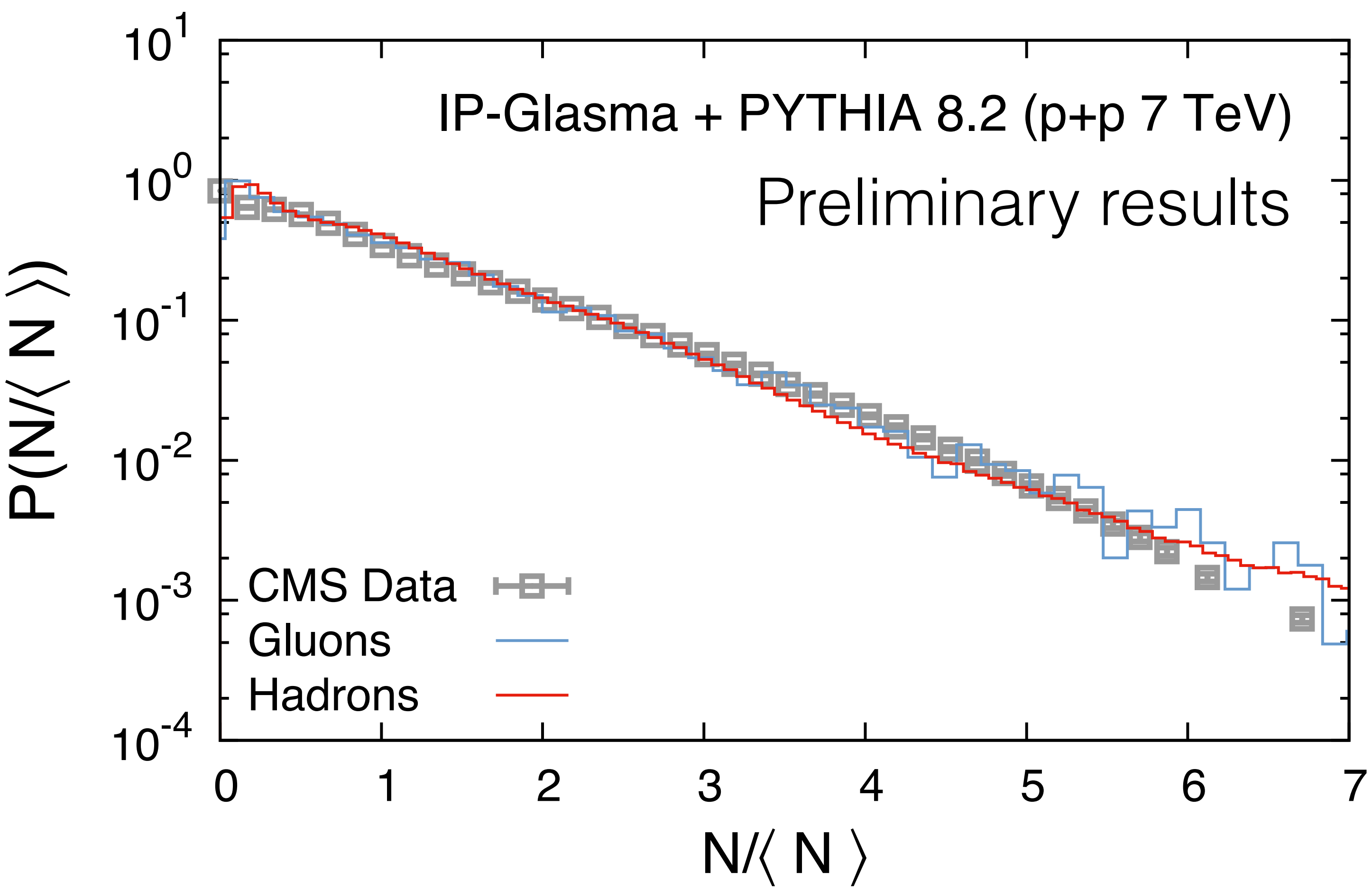


gluons
quarks
anti-quarks
strings



Connect the gluons close in phase space to color neutral strings

Combining CGC and PYTHIA



- Promising results on multiplicity distributions
- Angular correlations, more observables are to be studied

Outlook

- Including diffractive process
- Full 3+1D with JIMWLK rapidity evolutions
- Implement color-reconnection in PYTHIA
- Comparison to more data from LHC

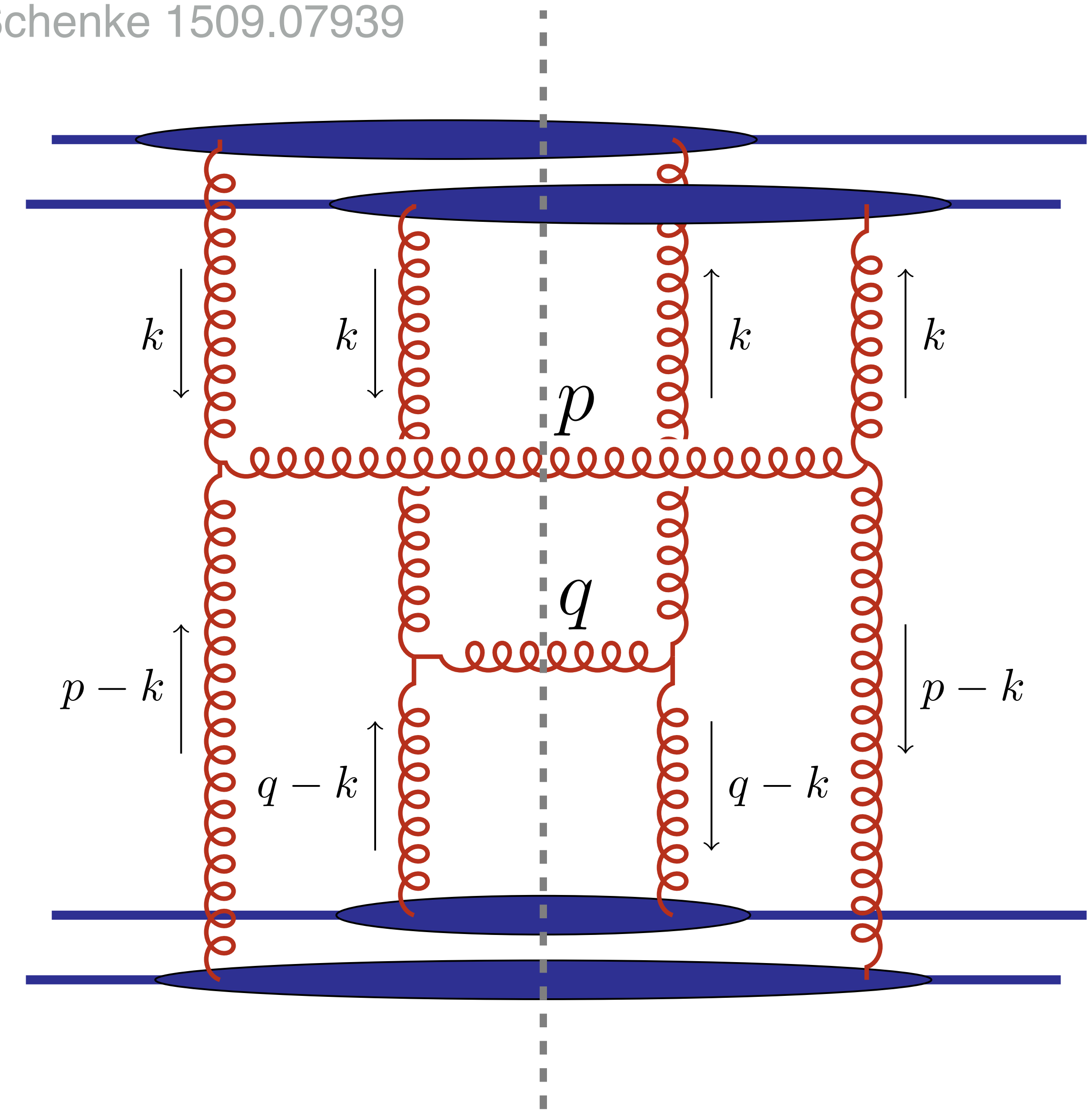
Summary

The *ab-initio* framework of CGC constrained by HERA DIS data provide successful description of the phenomena seen in high multiplicity events at LHC

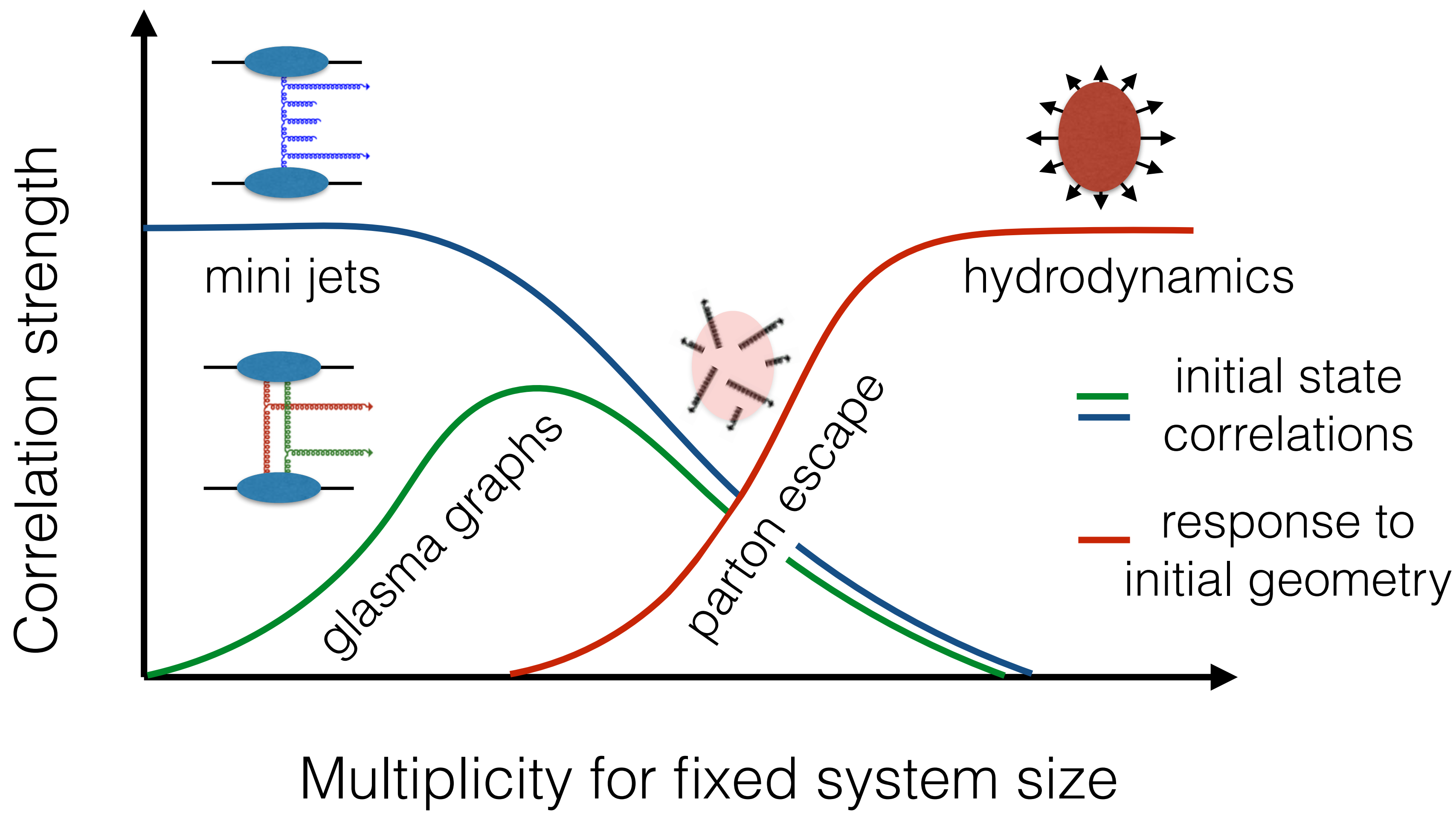
back-up

Momentum flow in Glasma graph (origin of ridge-like correlation)

Dusling, Li, Schenke 1509.07939



Qualitative picture of correlations in small systems



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Quark Matter 2015