Bulk observables in small colliding systems combining CGC and PYTHIA

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BROOKHAVEN NATIONAL LABORATORY

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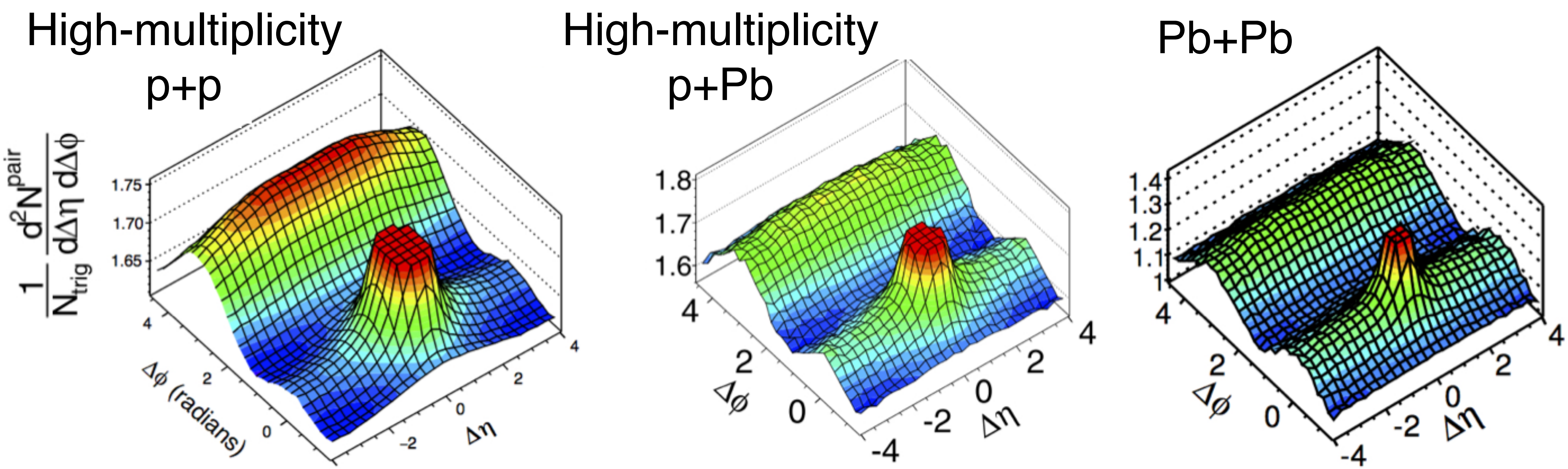
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline



Observation in high-multiplicity p+p & p+A events → similar to A+A

(Often regarded as signature of collectivity)

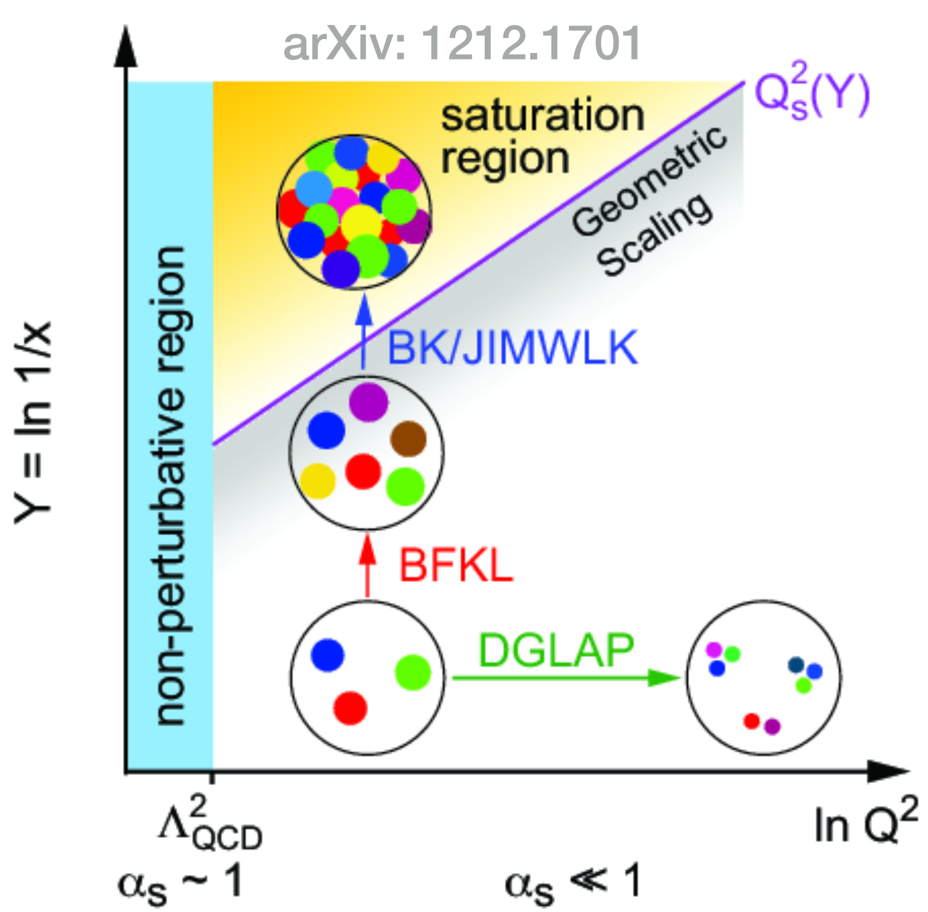
Goal : Model multi-particle production in p+p and p+A

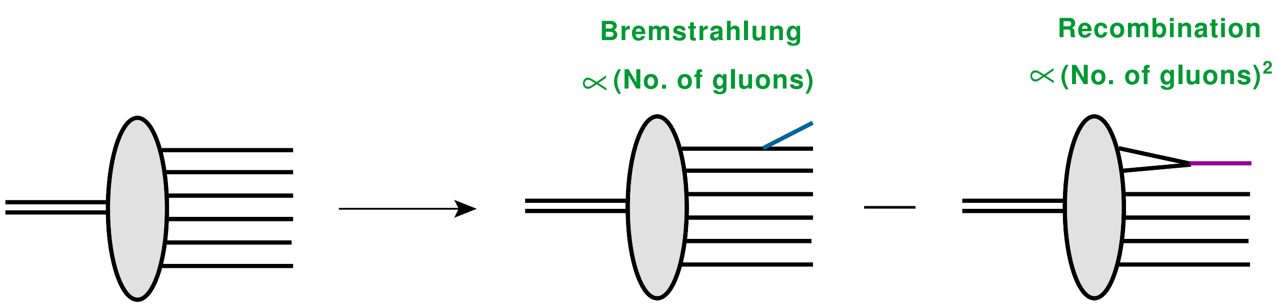
- A framework of particle production at high $\sqrt{s}$
- State-of-the art treatment of hadronization

Hadrons at high energies : gluon saturation

High energies ➞ **Regge Gribov limit** $\sqrt{s} \to \infty, x \to 0:$ gluon saturation

- Non-linear processes stop growth of gluons,
  emergence of saturation scale $Q_S(x) > \Lambda_{QCD}$



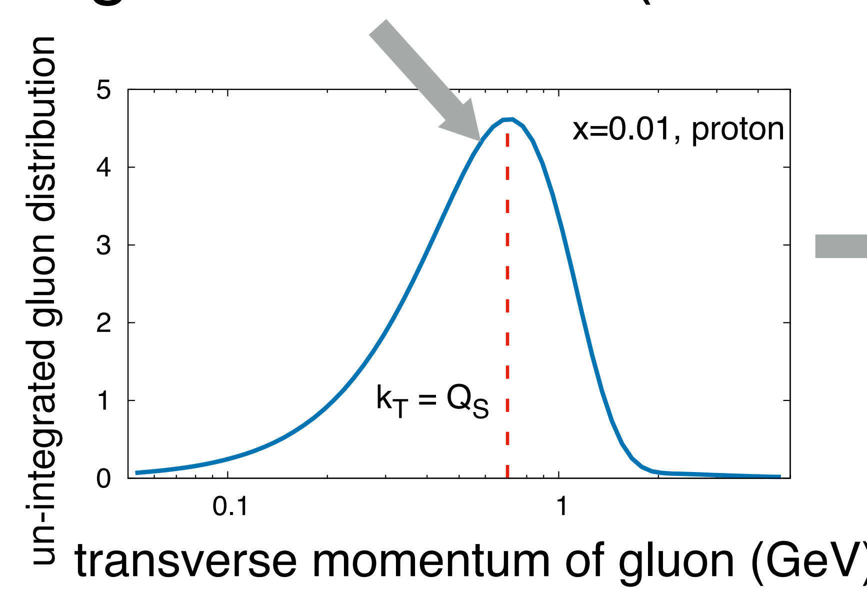


Hadrons at high energies : gluon saturation

High energies ➞ **Regge Gribov limit** $\sqrt{s} \to \infty, x \to 0$: gluon saturation

- Non-linear processes stop growth of gluons, emergence of saturation scale $Q_S(x) > \Lambda_{QCD}$
- Gluon dominated wave function, high occupancy $\sim \dfrac{1}{\alpha_S}$ peaked at $Q_S(x)$

most gluons are here (near Q_S)



from HERA DIS e+p data

CGC : particle production at high energies

Multi particle production → Color Glass condensate effective field theory

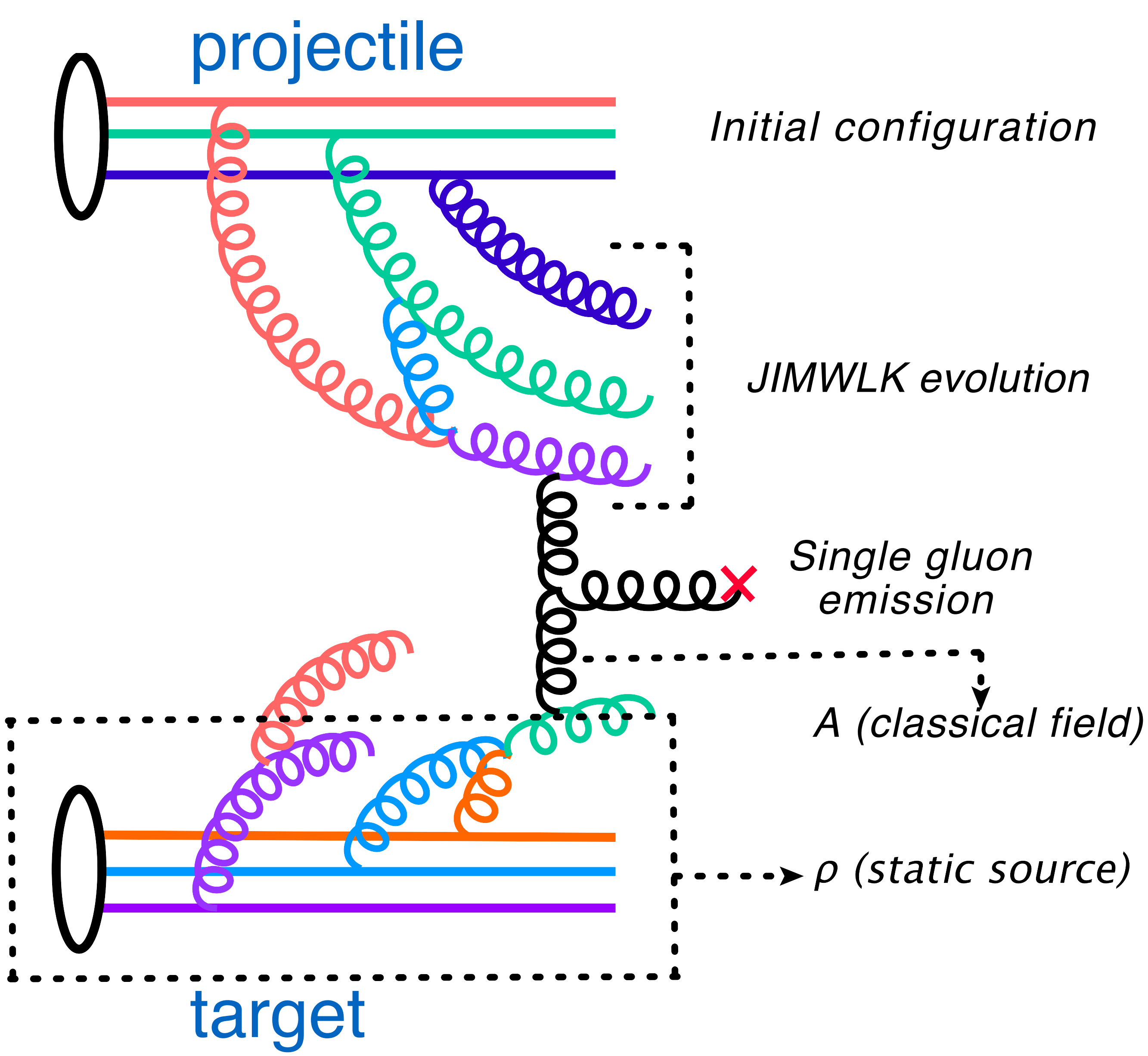
McLerran, Venugopalan hep-ph/9309289

Weak coupling effective theory:

- Fast (large-x) partons : classical color source ρ
- Slow (small-x) partons : classical color field $\mathcal{A}^{\mu}$

(classical approximation)

$\sim \mathcal{O}(\frac{1}{\alpha_s})$



CGC : particle production at high energies

Multi particle production

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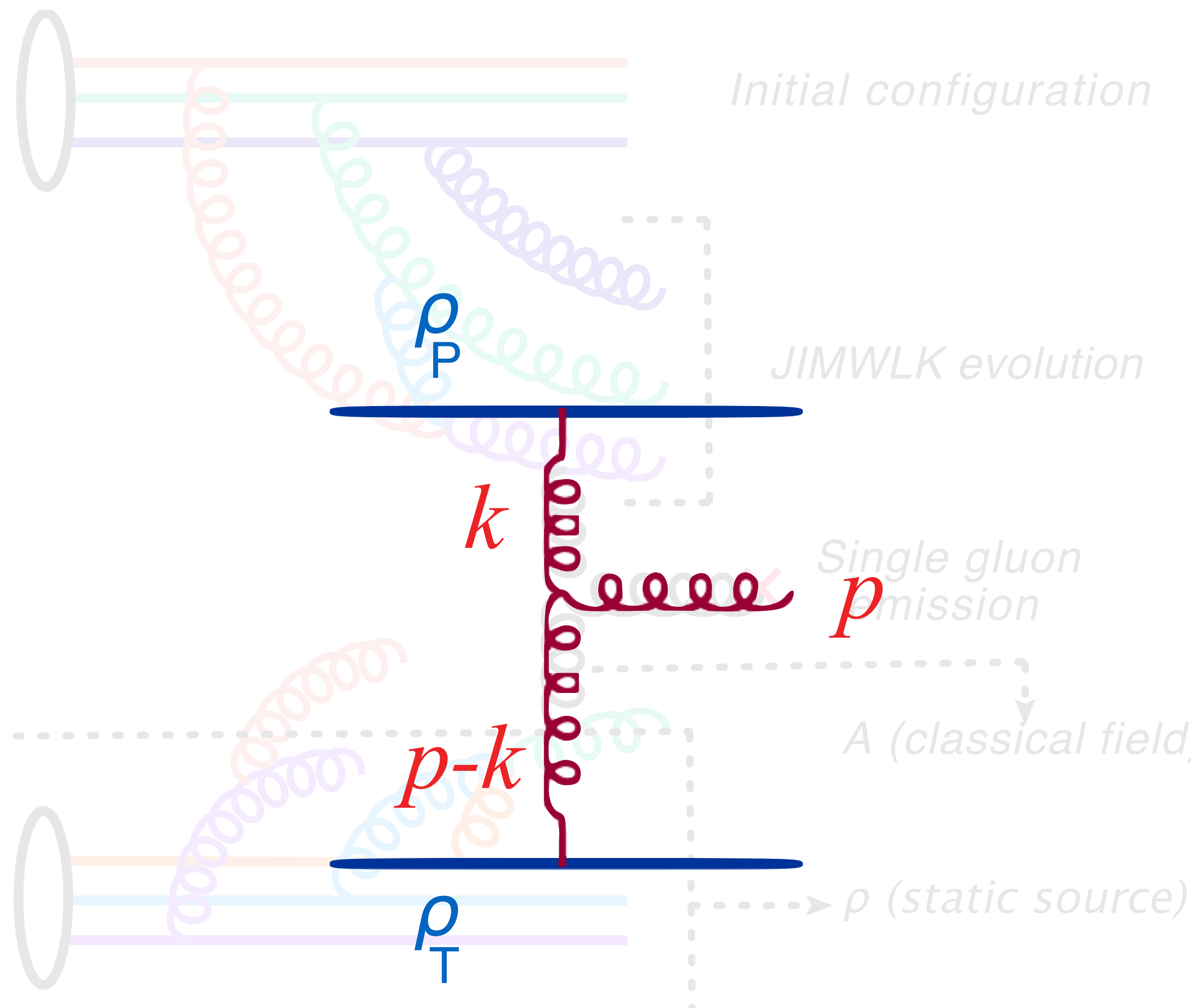


Weak coupling effective theory:

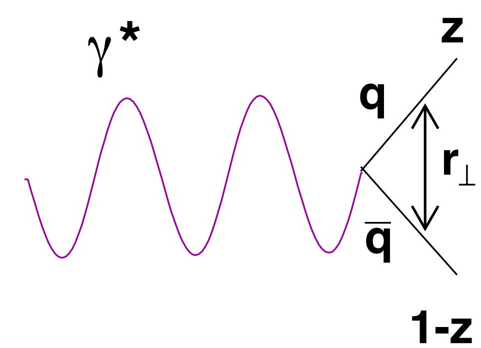
- Fast (large-x) partons : classical color source ρ
- Slow (small-x) partons : classical color field A^μ

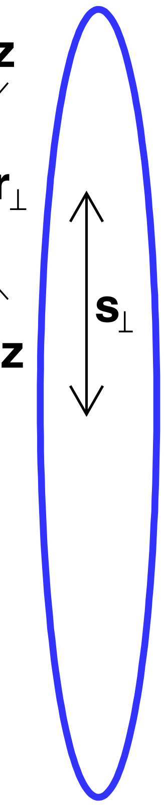
(classical approximation) → $\sim \mathcal{O}(\frac{1}{\alpha_s})$

Distribution of color charge $\rho(\mathbf{x}_\perp)$ → Input to the theory

Constraining color charge density

- IP-Sat model —> distribution of color charge density of colliding hadrons : constrained by HERA DIS e-p data

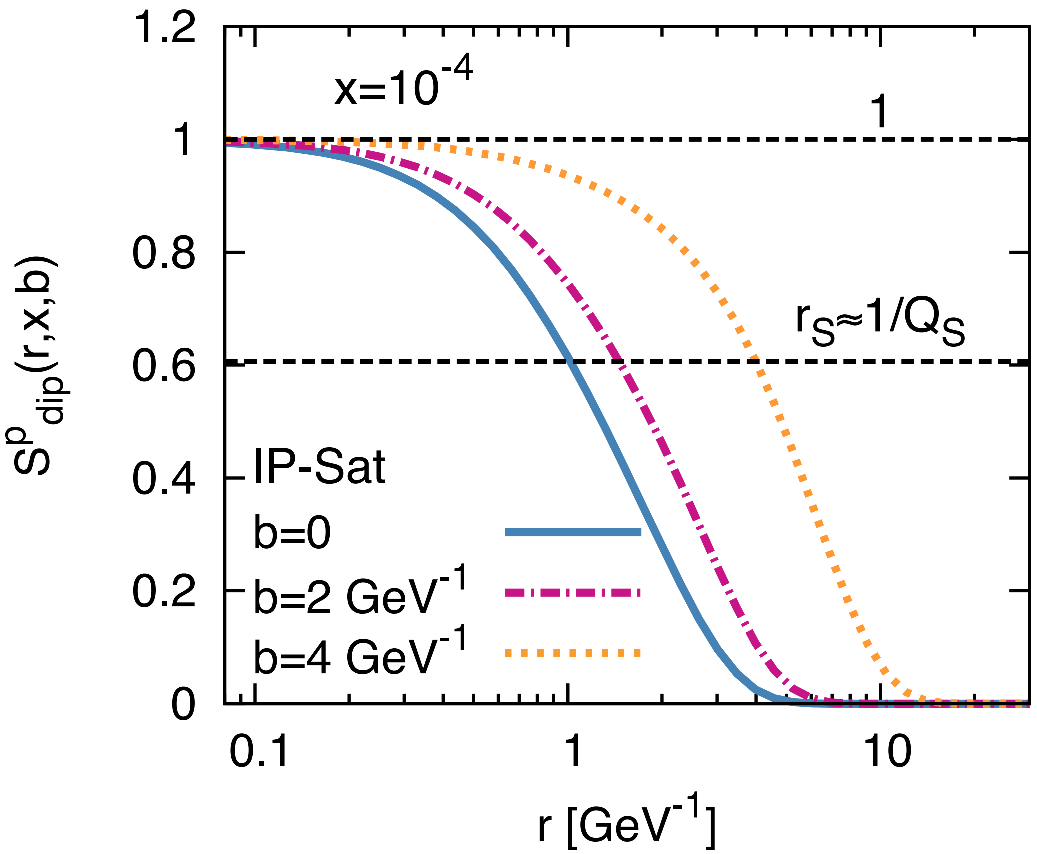


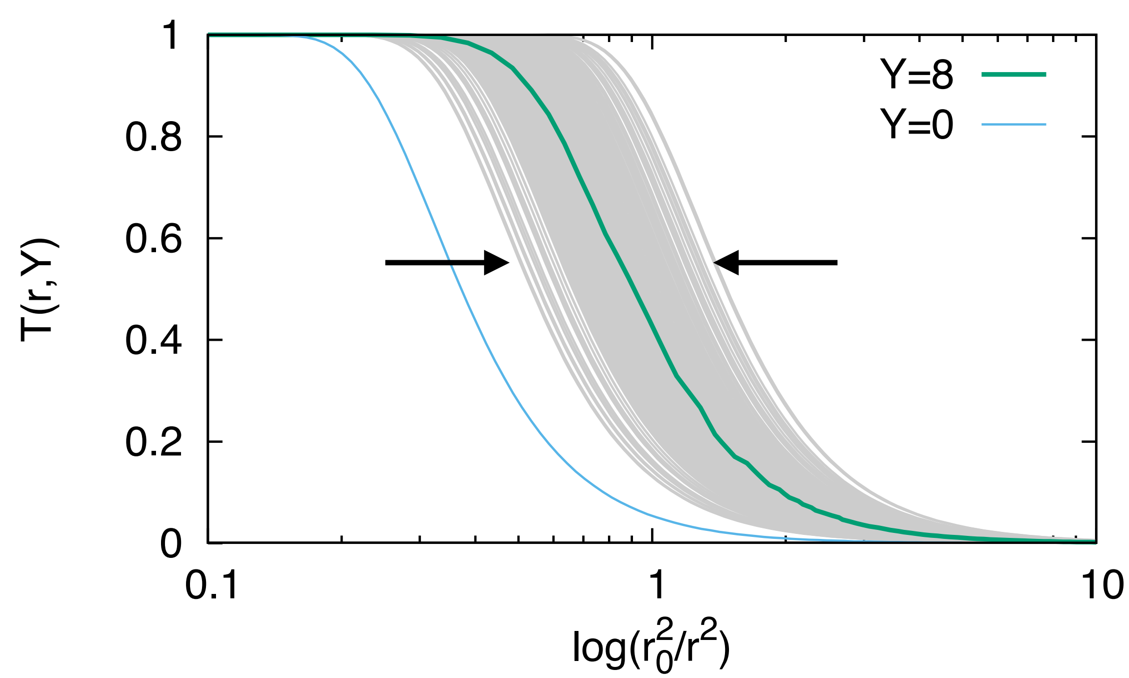


$$S^{p}_{\rm dip}(\mathbf{r}_\perp, x, \mathbf{b}_\perp) = \exp\left(-r^2 Q_S(x,b)^2\right)$$

In CGC (MV model) :

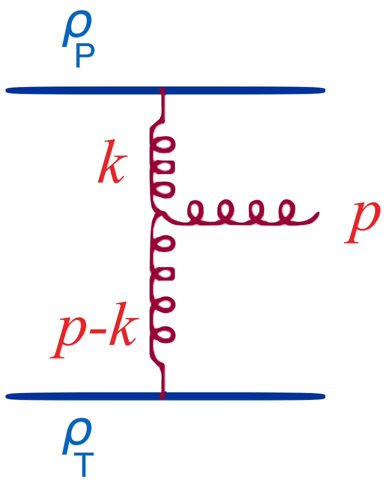
$$\langle \rho\rho \rangle \sim Q_S^2$$

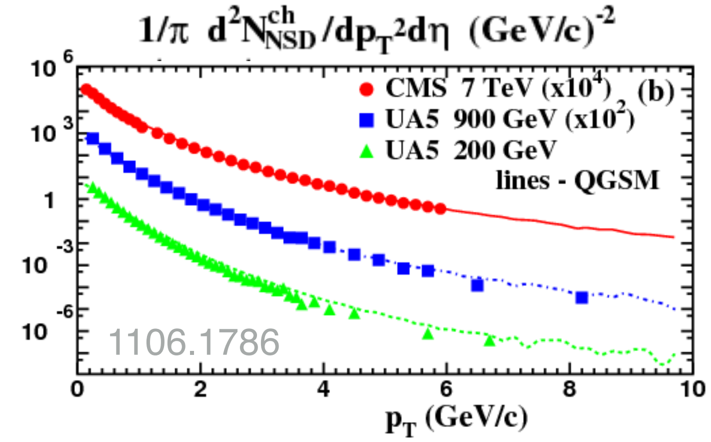




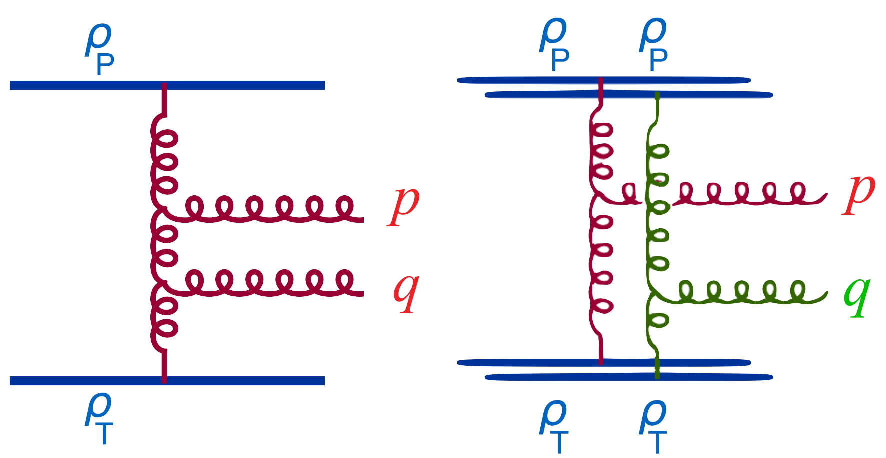
Quantities of experimental interests

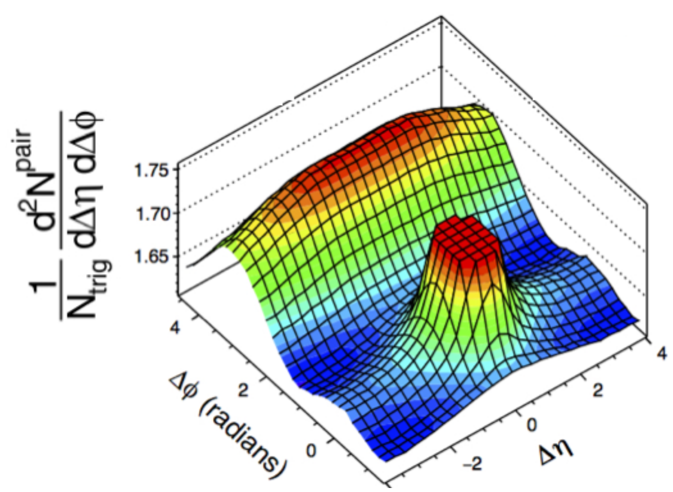
First-principle approach of n-gluon production



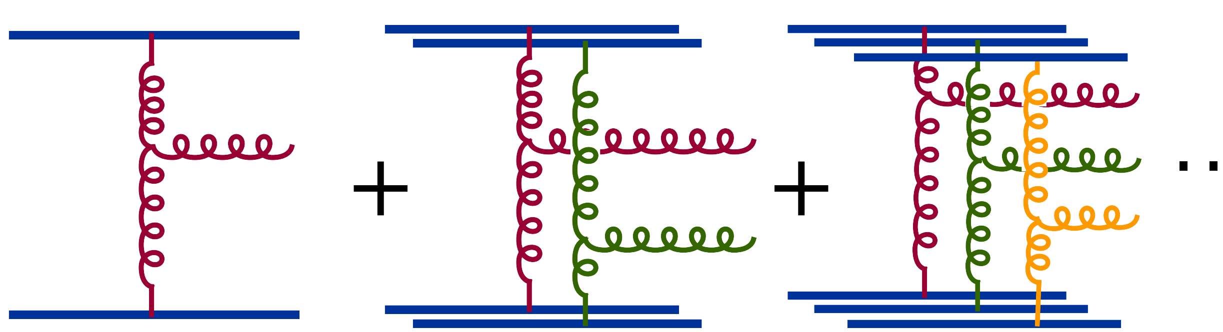


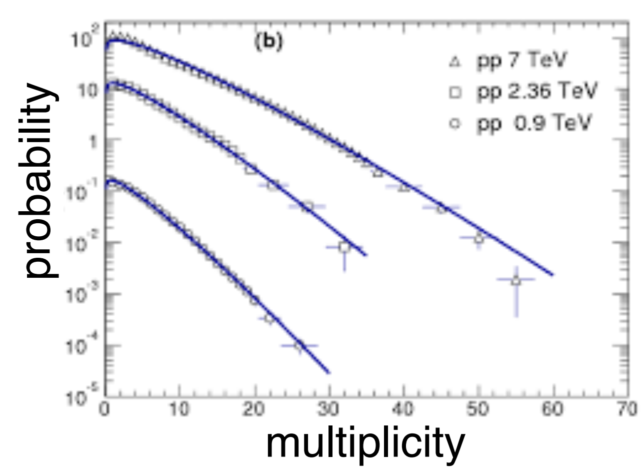
Single-particle production





Two-particle production





Multi-particle production

The IP-Glasma model

- Colliding nuclei generate color current

$$J^\nu = \delta^{\nu\pm}\rho_{A(B)}(x^\mp, \mathbf{x}_\perp)$$

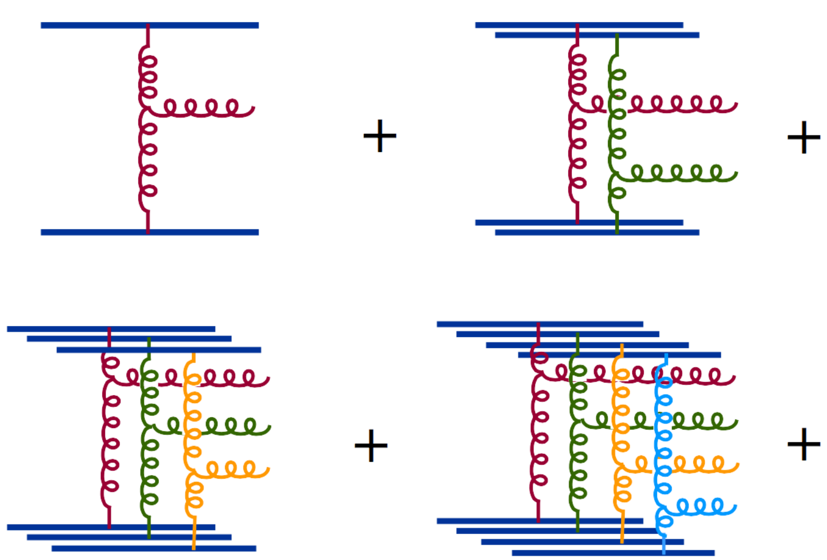
- The field is obtained by solving

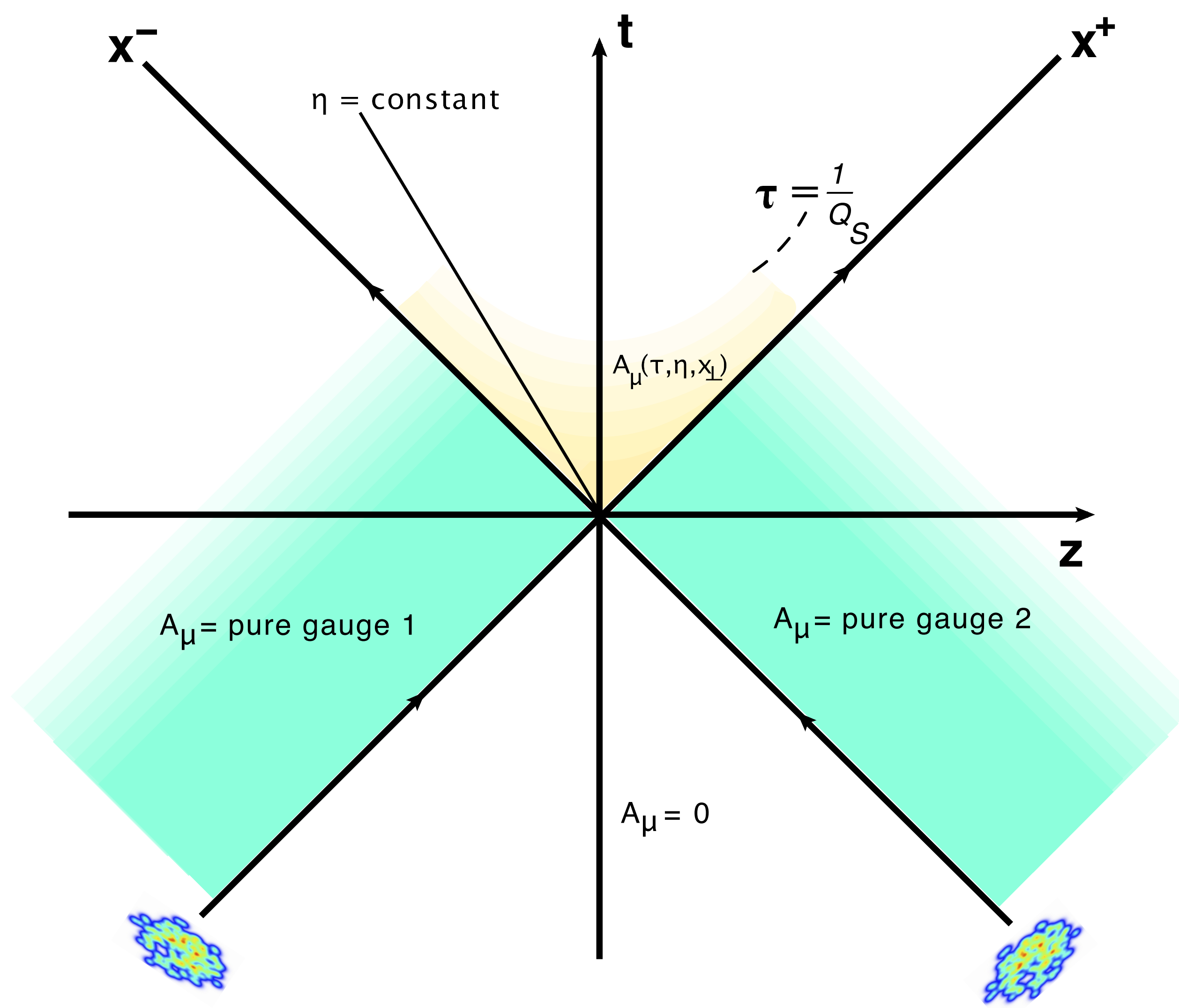
$$[D_\mu, F_{\mu\nu}] = J_\nu$$

- The fields after collisions →
  (in terms of incoming fields)

$$A^i = A^i_{(A)} + A^i_{(B)} \qquad A^\eta = \frac{ig}{2}\left[A^i_{(A)}, A^i_{(B)}\right]$$

$$|||$$





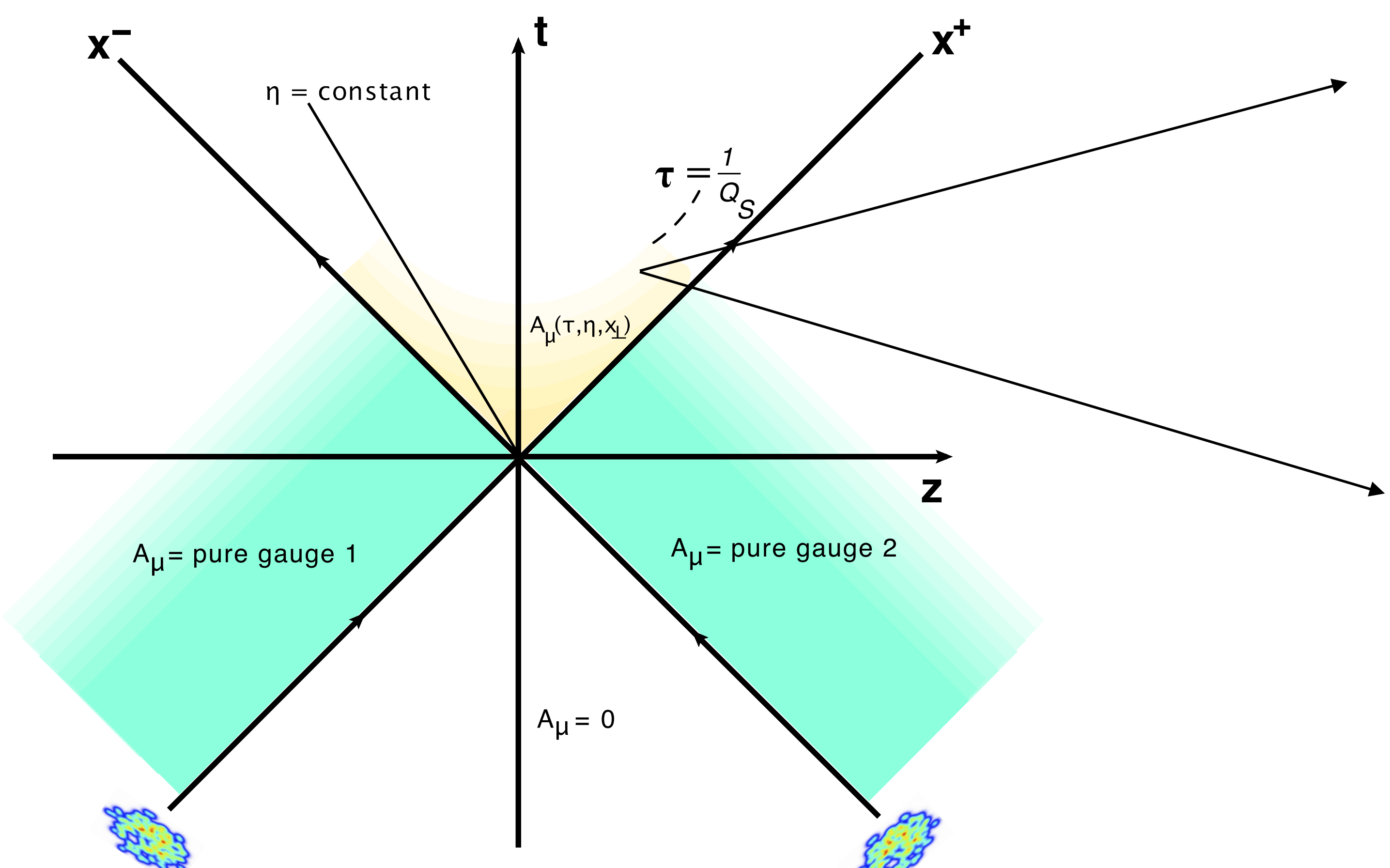
Schenke, PT, Venugopalan Phys. Rev. Lett. 108 (2012) 252301

The IP-Glasma model

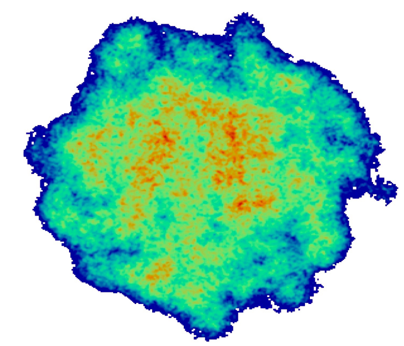
Schenke, PT, Venugopalan Phys. Rev. Lett. 108 (2012) 252301

Fields after collisions provide :

- The Stress-Energy Tensor (co-ordinate space information)
- The gluon spectra (momentum space information)

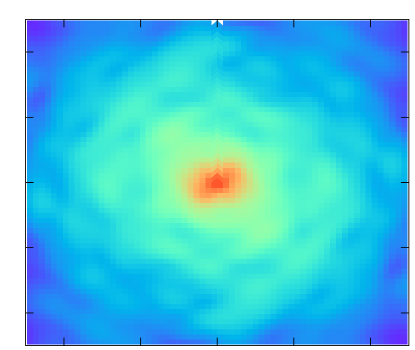


$$T_{\mu,\nu}(\tau, x_\perp, \eta)$$



Input for hydro, A+A collisions

$$\frac{dN}{d\mathbf{k}_T dy}$$



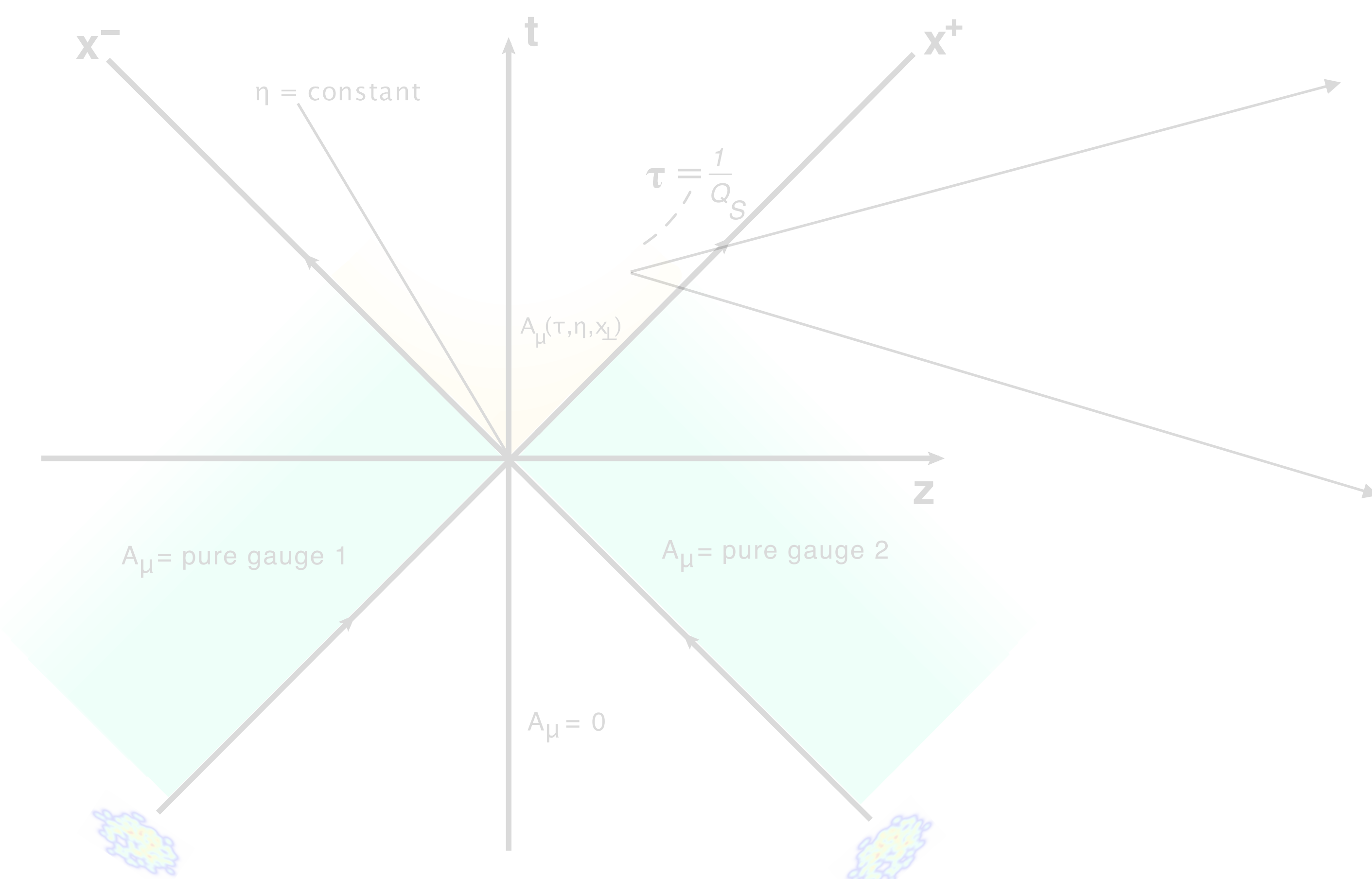
Input for PYTHIA, p+p collisions

The IP-Glasma model

Schenke, PT, Venugopalan Phys. Rev. Lett. 108 (2012) 252301

Fields after collisions provide :

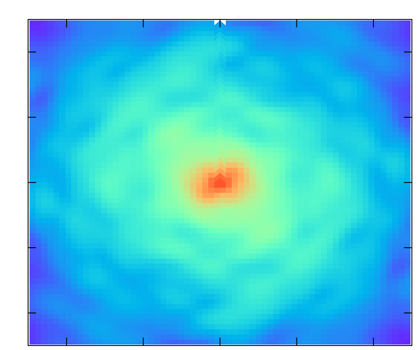
- The Stress-Energy Tensor (co-ordinate space information)
- The gluon spectra (momentum space information)



$$T_{\mu,\nu}(\tau, x_\perp, \eta)$$

Input for hydro,

$$\frac{dN}{d\mathbf{k}_T dy}$$

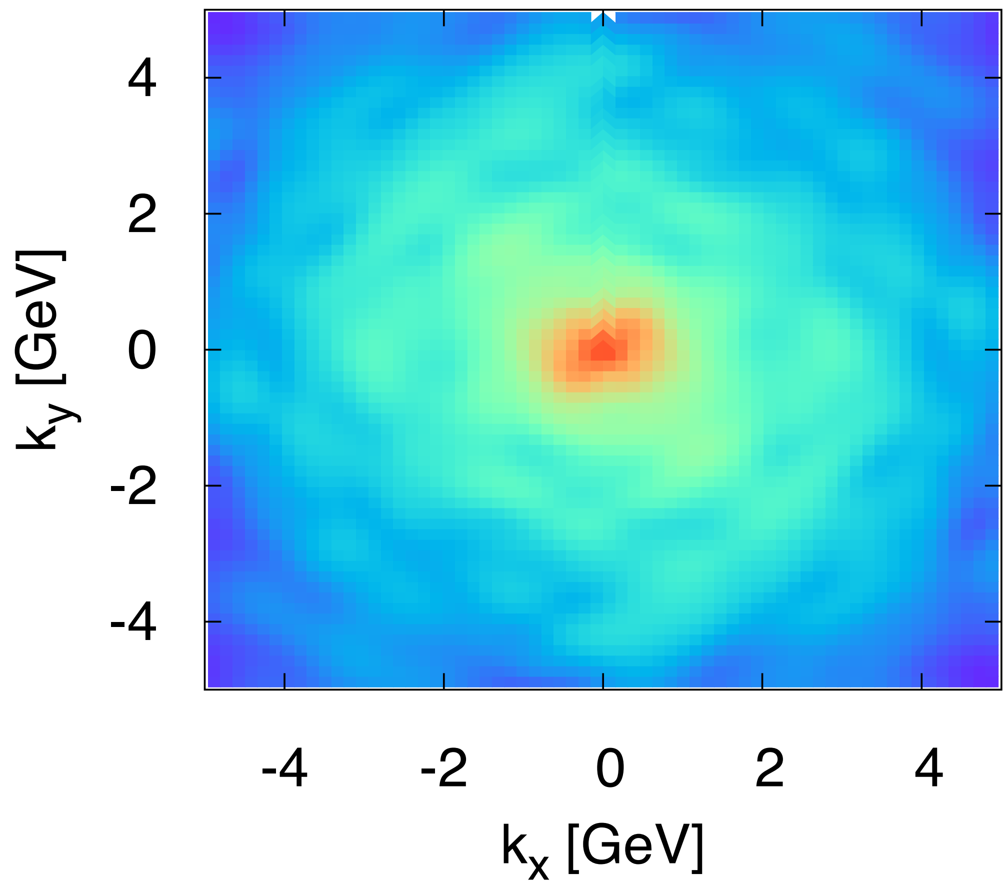


Input for PYTHIA, p+p collisions

IP-Glasma gluon dist→ Sampling gluons → Strings → Hadronization

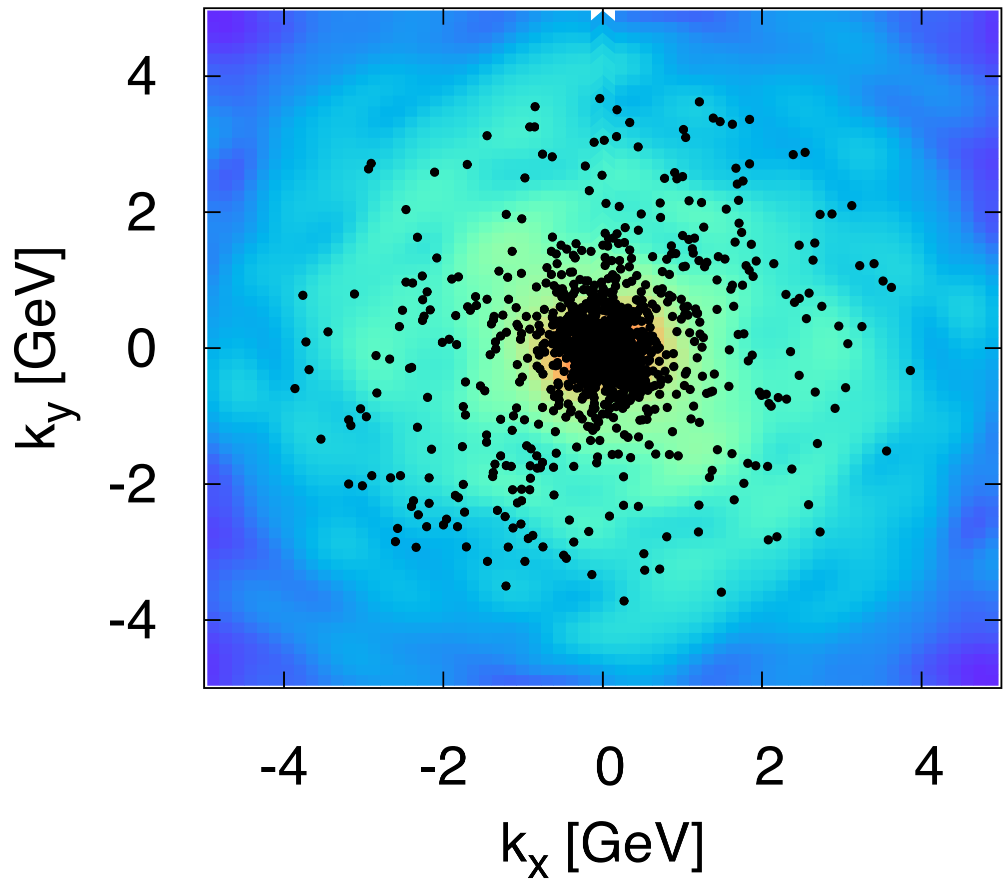
IP-Glasma : momentum distribution of gluons

$$\frac{dN}{d\mathbf{k}_T dy}$$



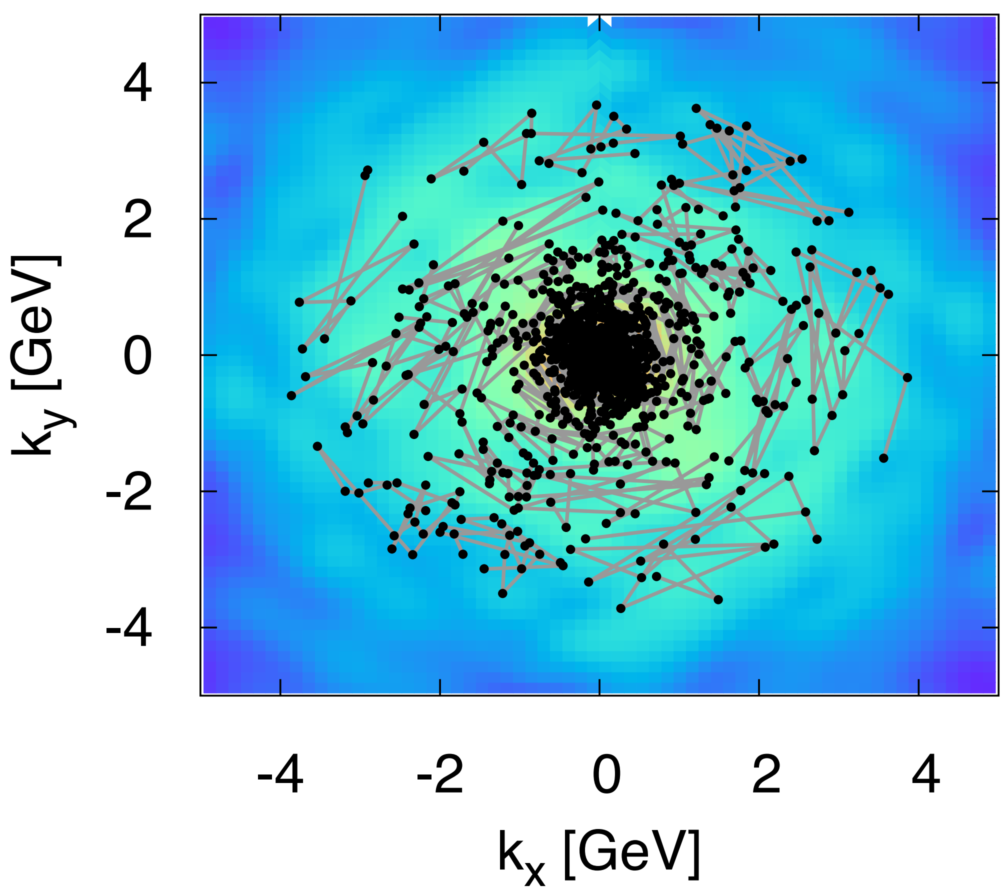
IP-Glasma : momentum distribution of gluons

$$\frac{dN}{d\mathbf{k}_T dy}$$

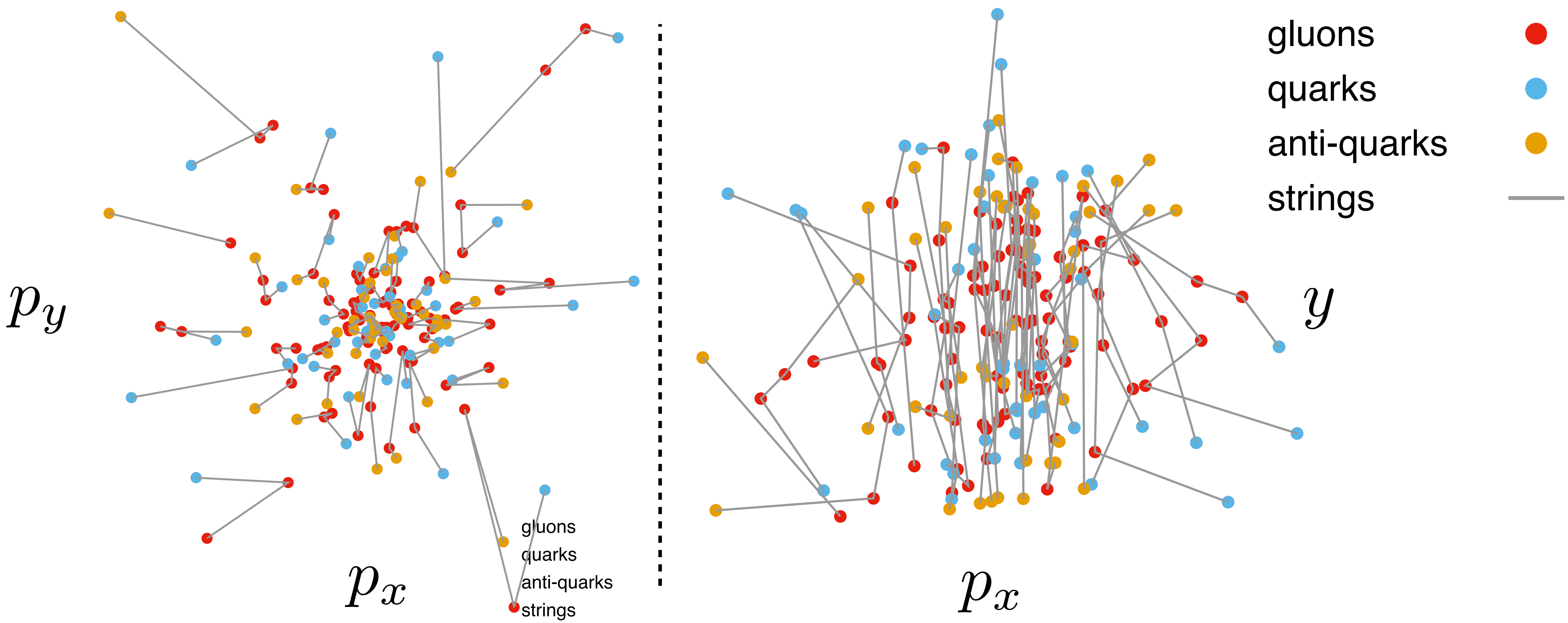


CGC + Lund : IP-Glasma input to PYTHIA

$$\frac{dN}{d\mathbf{k}_T dy}$$



CGC + Lund : Implementing strings

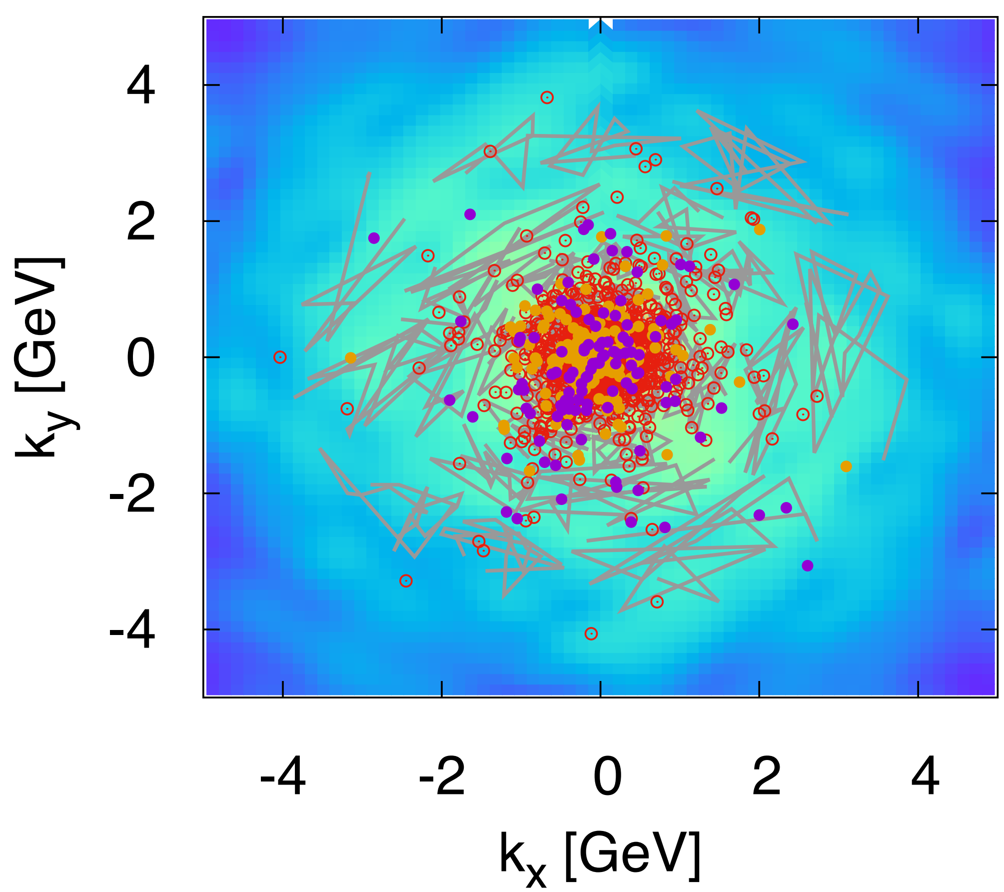


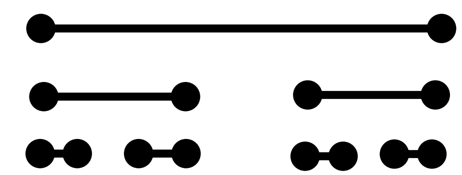
Connect the gluons close in momentum to strings with ~
No. of gluons per strings : $N_{\mathrm{gs}} = N_g / \langle Q_S^2 S_\perp \rangle$

PYTHIA → only for fragmentation, the MPI is replaced by IP-Glasma

CGC + Lund : Fragmentation of strings

$$\boxed{\frac{dN}{d\mathbf{k}_T dy}}$$



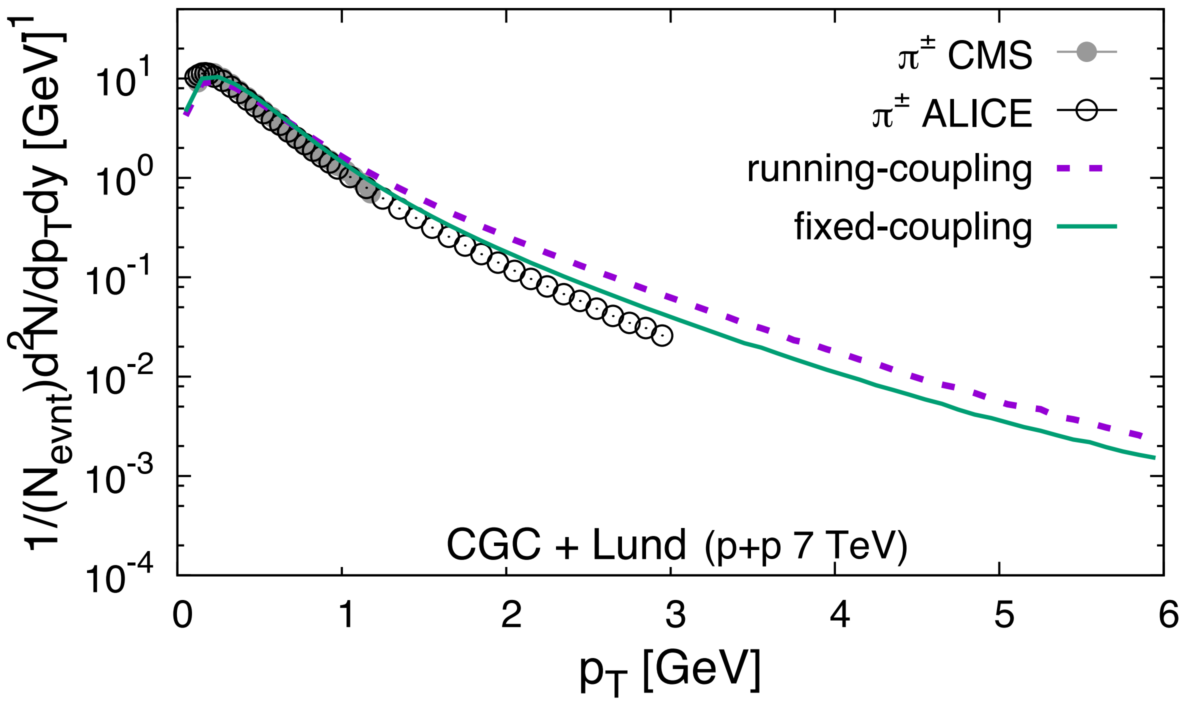


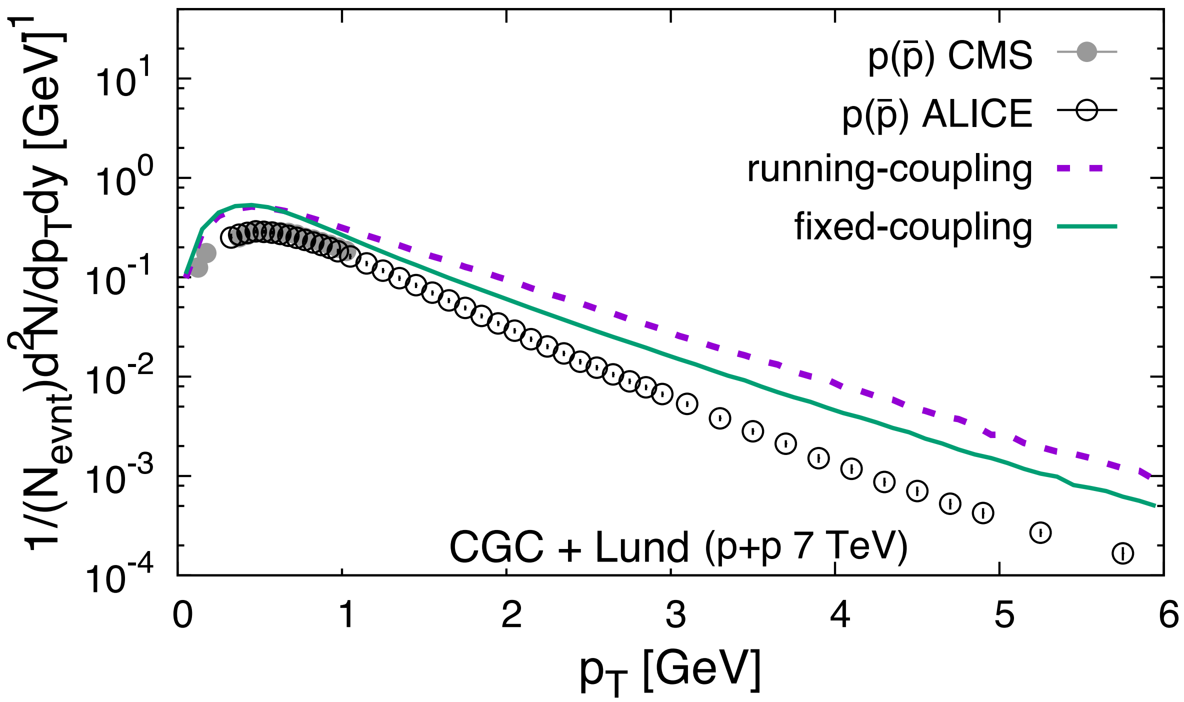
$$f(z, m_T) = \frac{1}{z}(1-z)^a \exp\left(-\frac{b\, {m_T}^2}{z}\right)$$

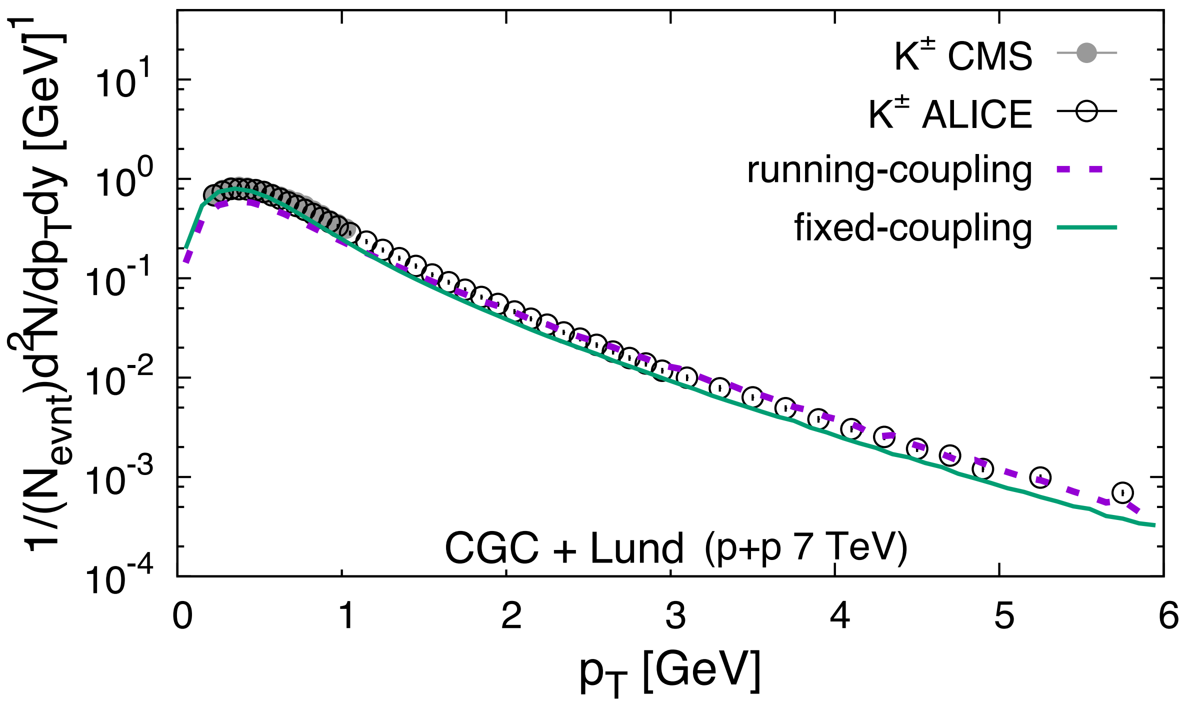
Lund String Fragmentation

A new Monte-Carlo event generator : CGC-Lund (CGC-PYTHIA)

Single Inclusive distributions

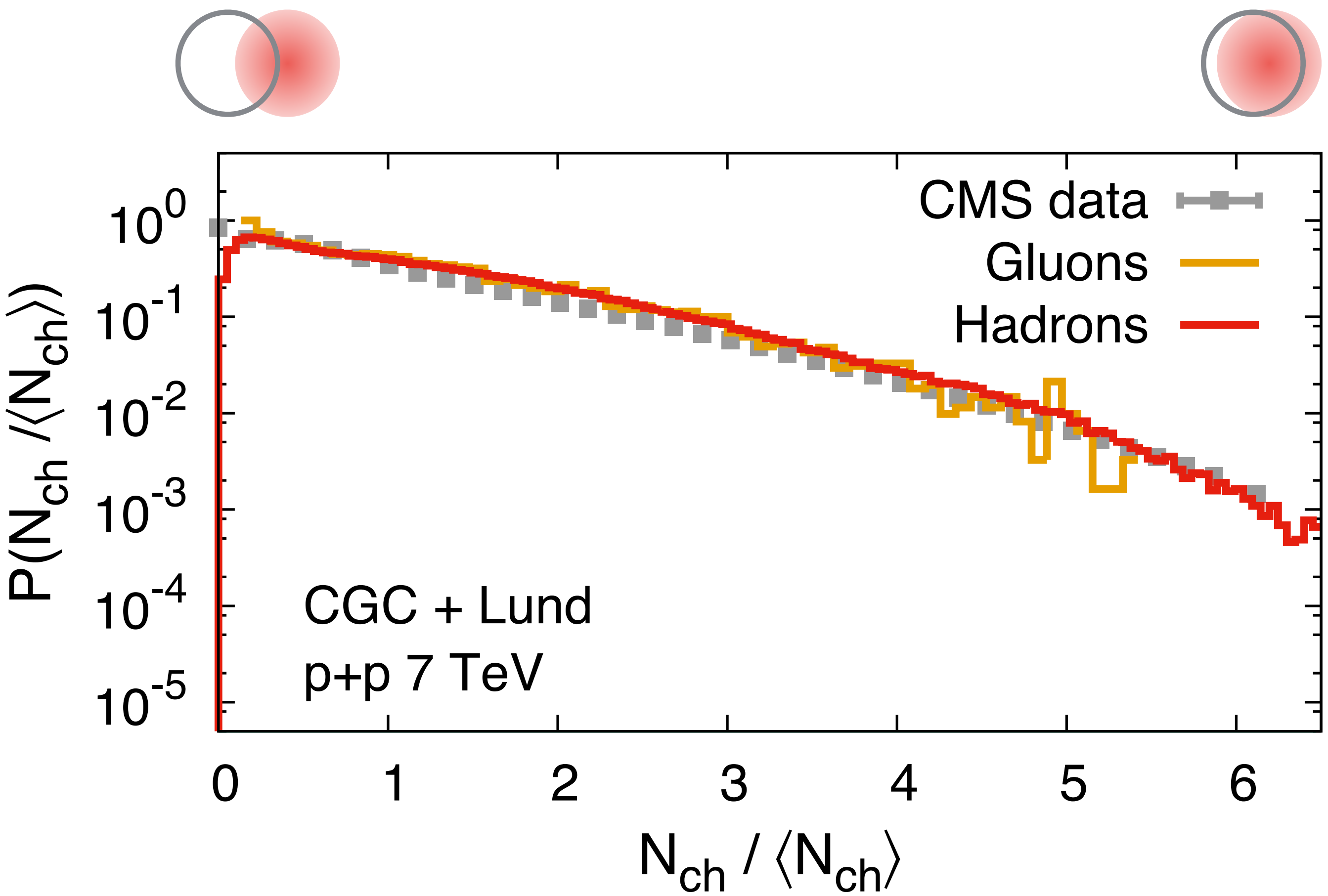


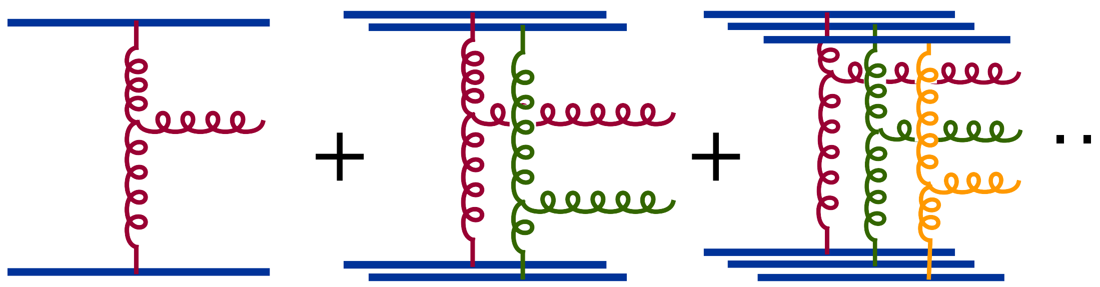




Reasonable agreement without any tuning

Multiplicity distribution



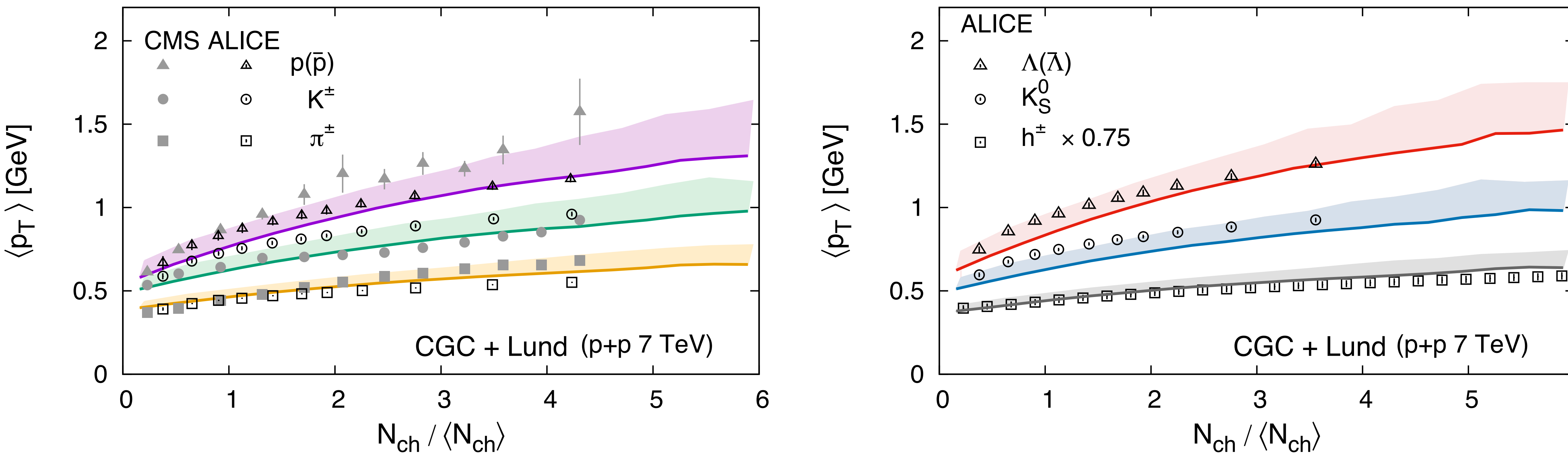


Multi-particle production in CGC Negative binomial distribution (NBD)

Collision geometry and impact parameter → convolution of NBDs

Mass ordering of $\langle p_T \rangle$

Data :1604.06736



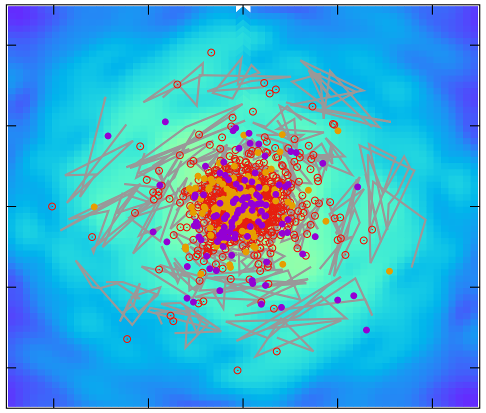
Mass ordering of average transverse momentum

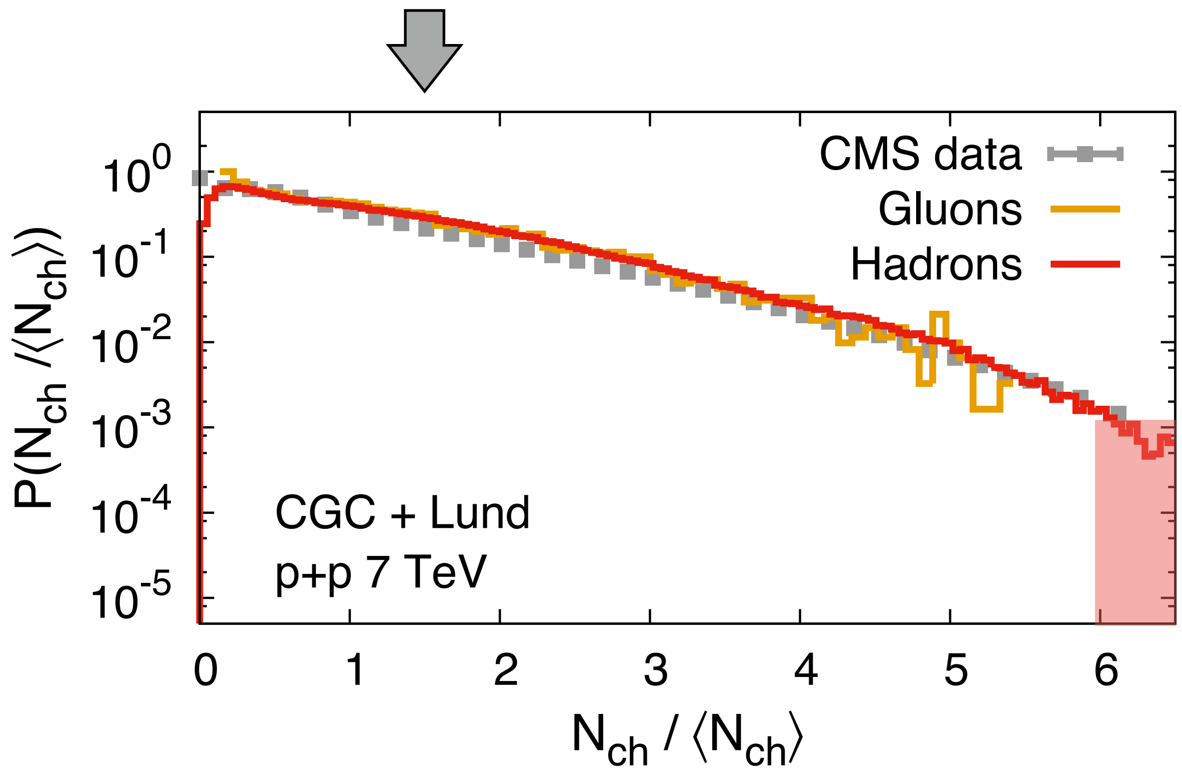
→ naturally reproduced in this framework

$$N_g \sim Q_S^2 S_\perp \,,\ \langle p_T \rangle \sim Q_S \ \rightarrow \langle p_T \rangle \sim \sqrt{N_g / S_\perp}$$

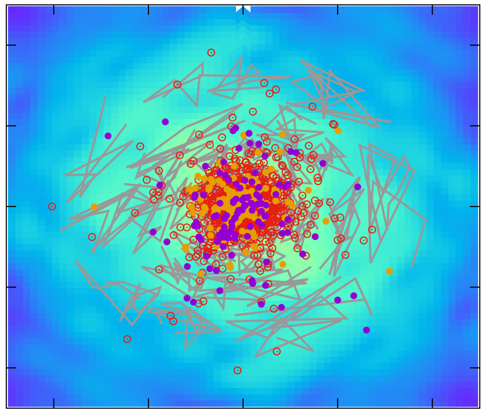
CGC→ effects like MPI & color reconnection is already built-in

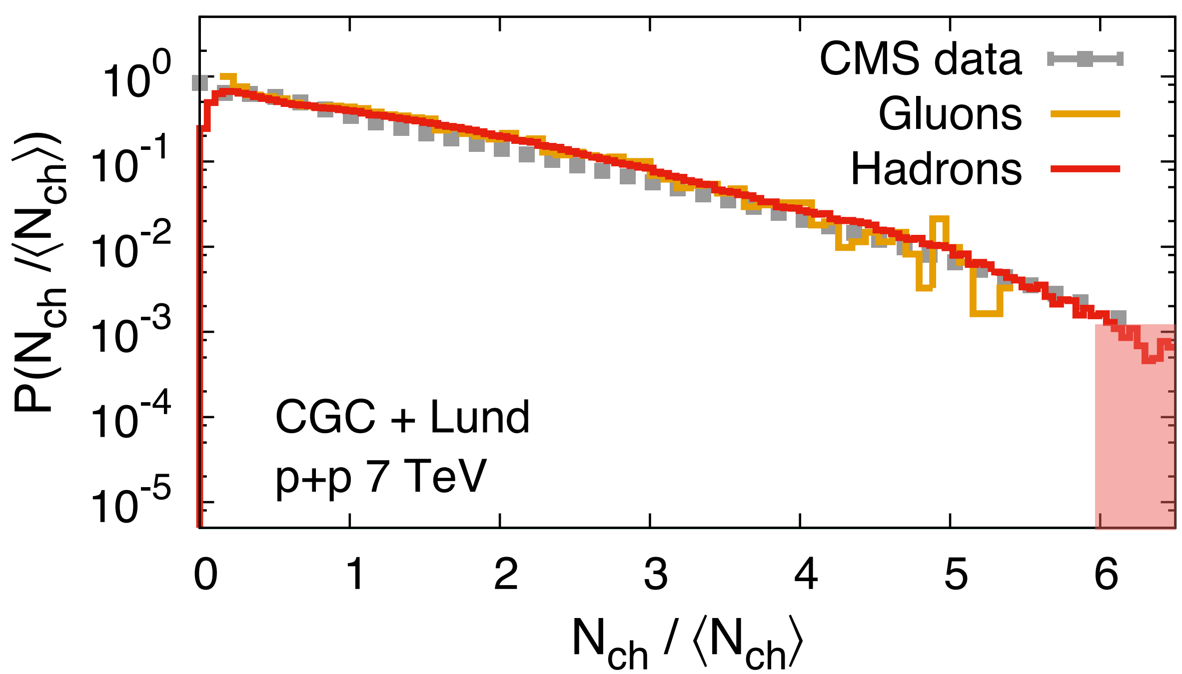
Di-hadron correlations

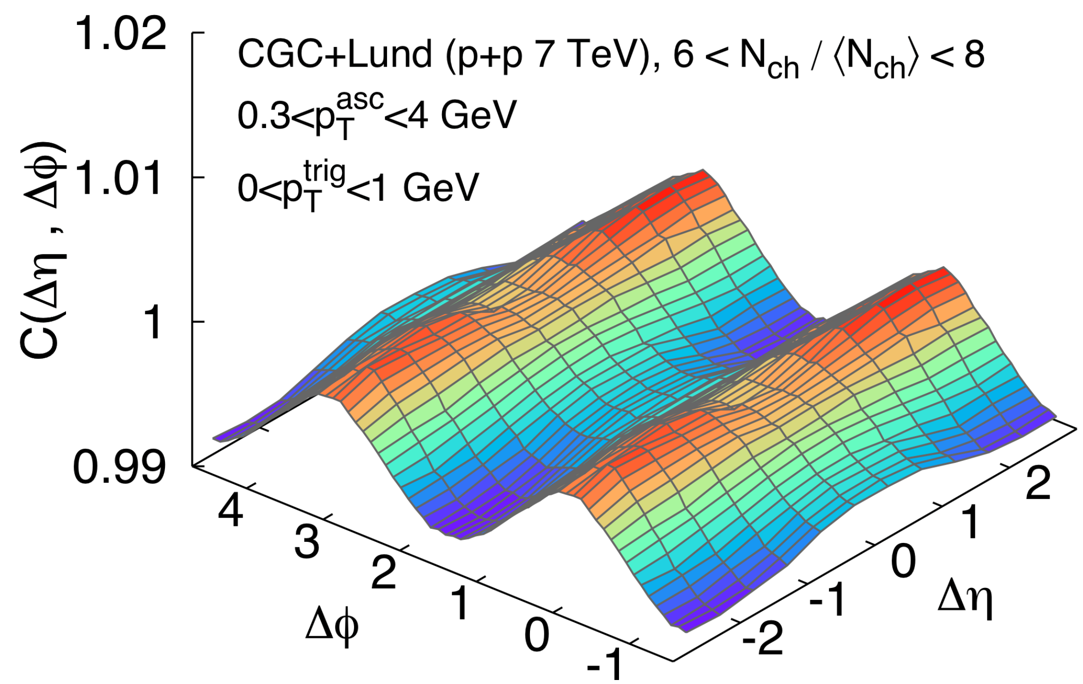




Di-hadron correlations

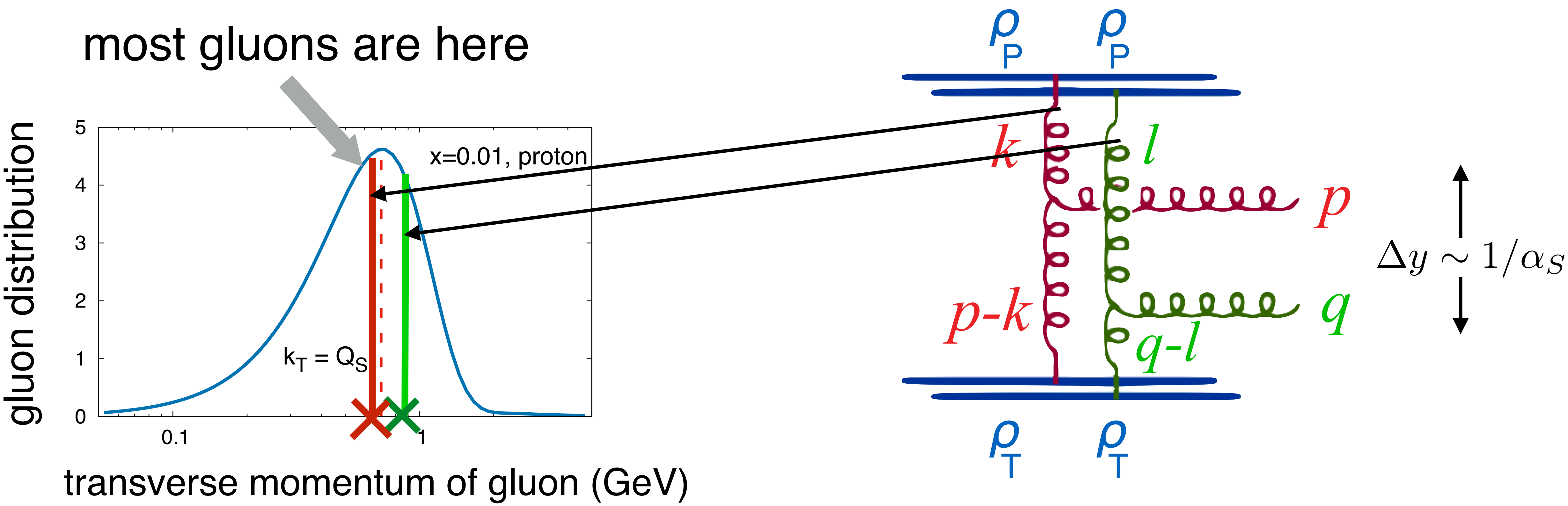




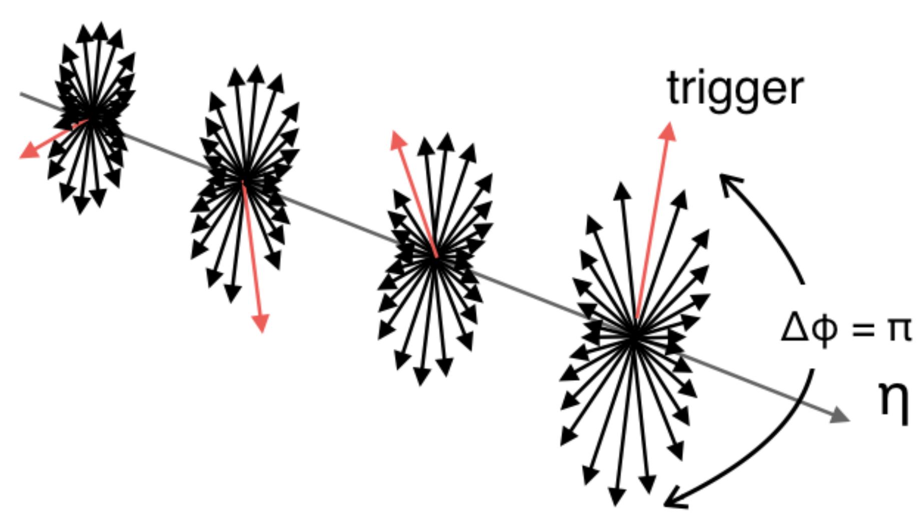


Purely momentum space correlations of gluons produce ridge after fragmentation

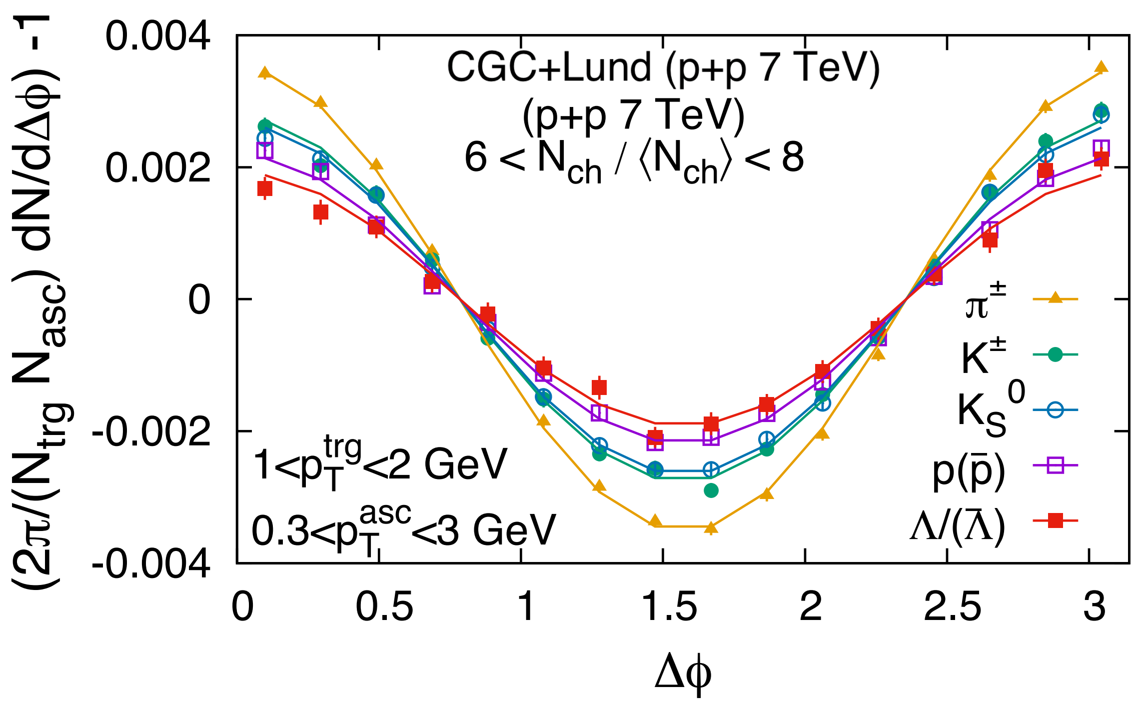
Origin of ridge

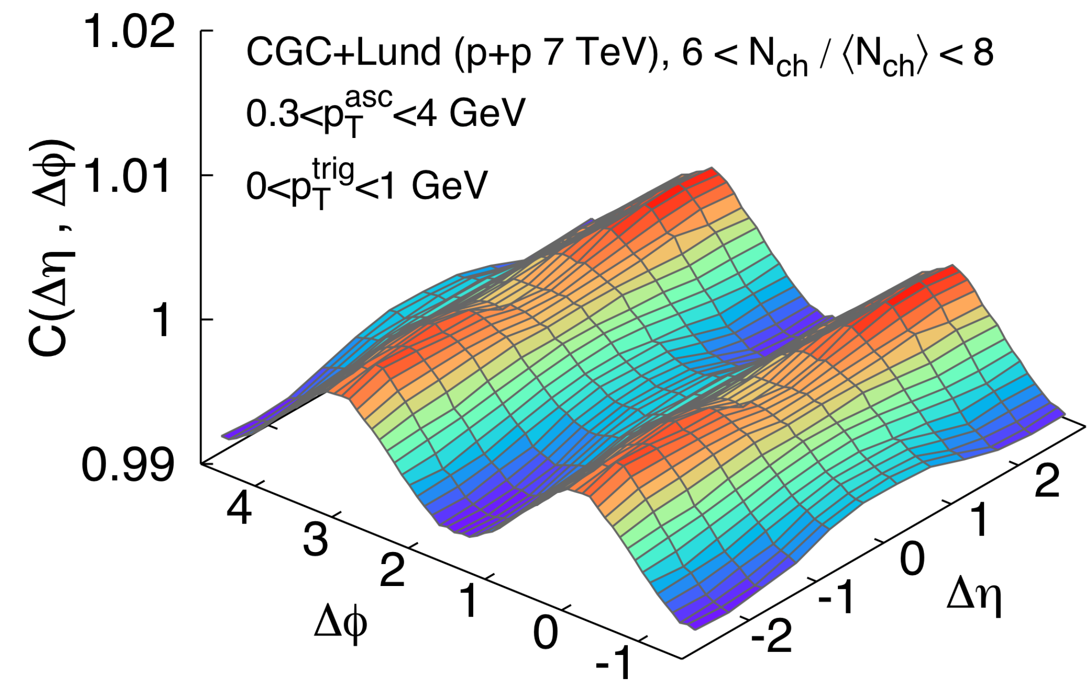


Intrinsic momentum space correlations
→ nature of the wave function



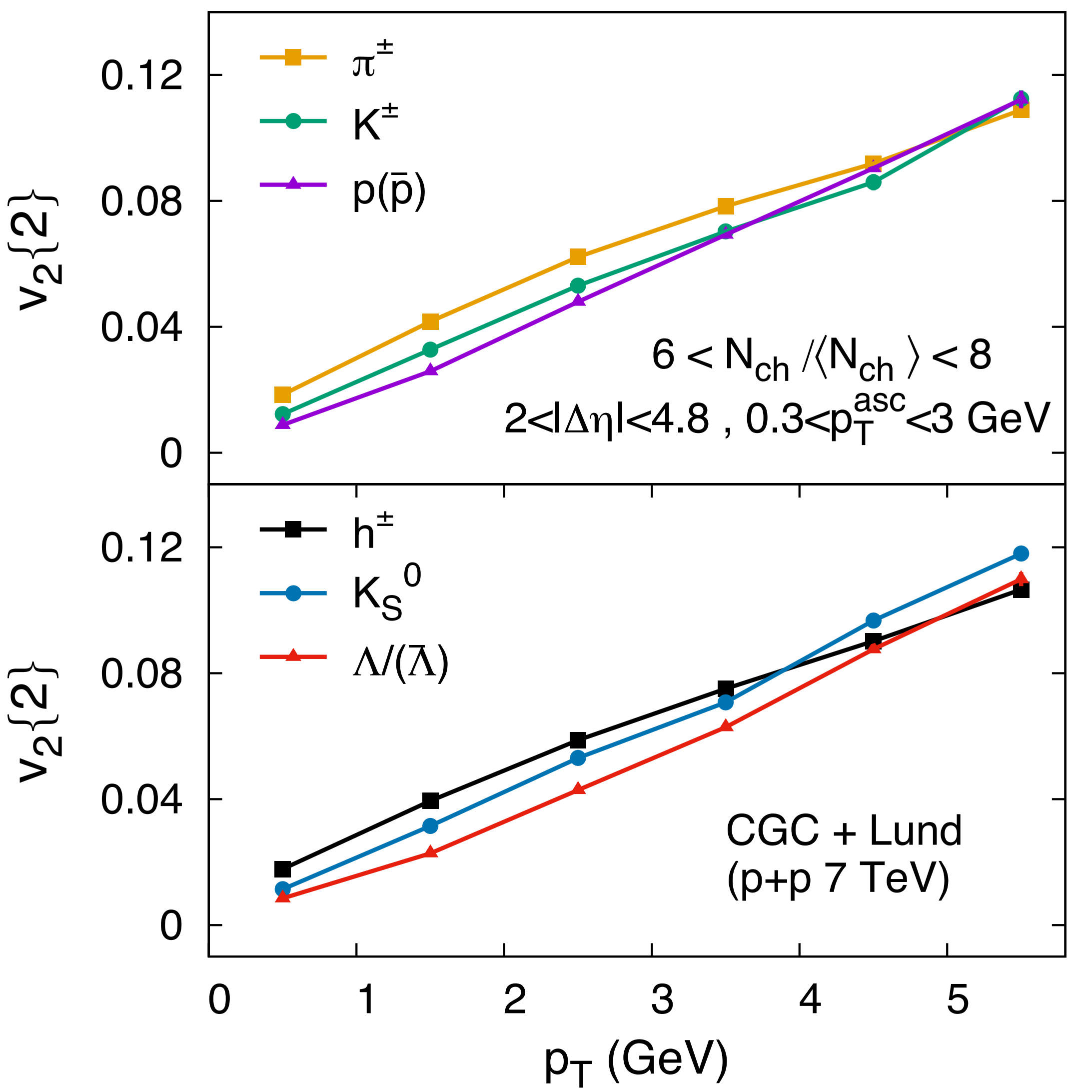
Mass ordering of di-hadron correlations

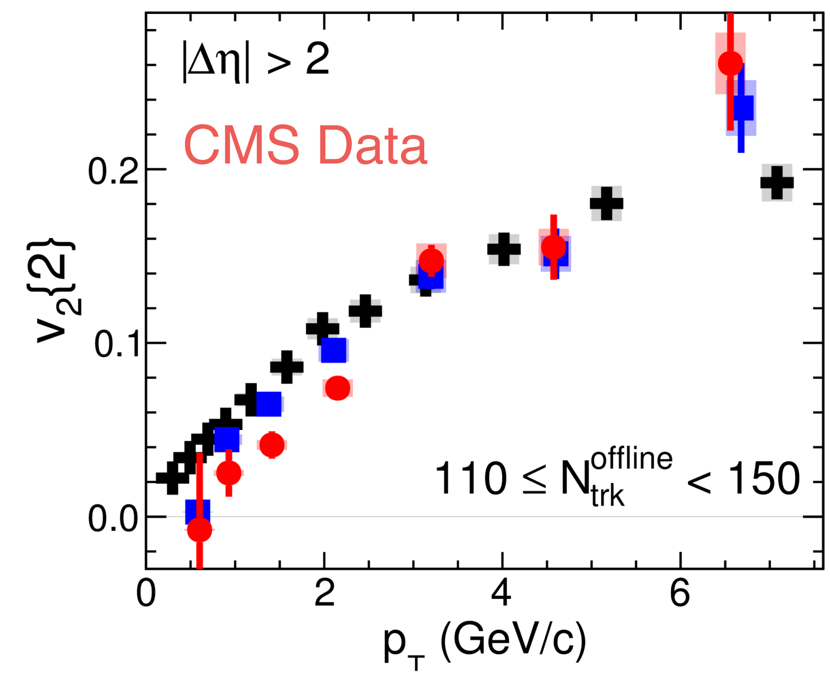




Strong species dependence of azimuthal correlations

Mass ordering of di-hadron correlations



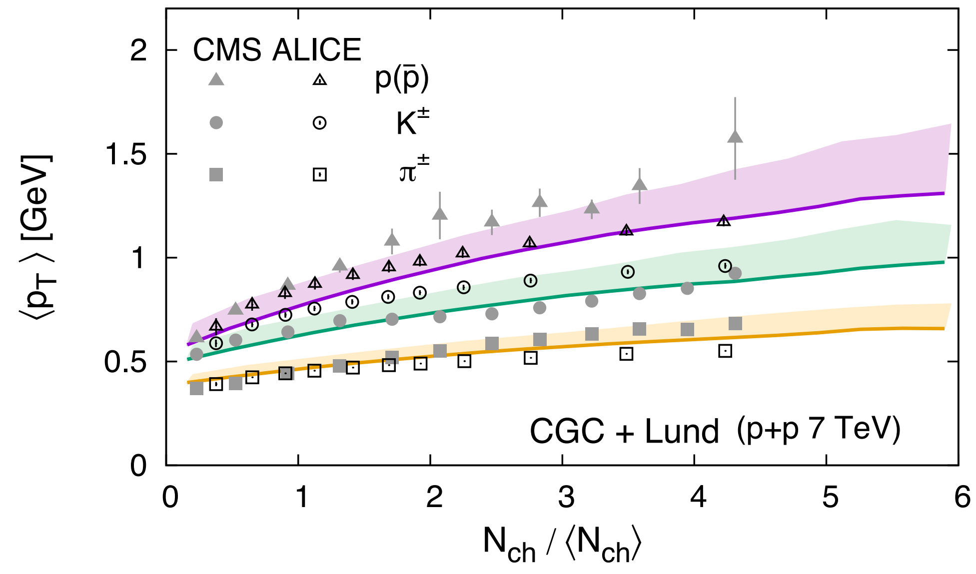


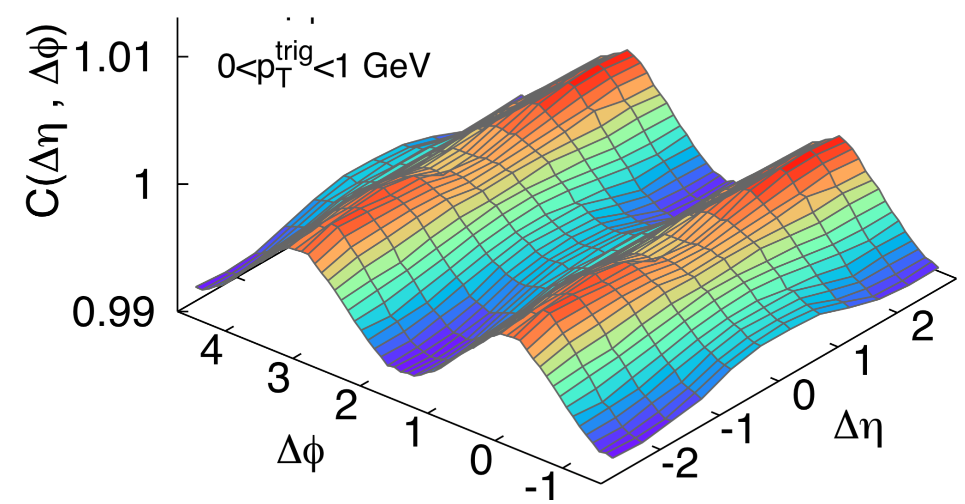
Mass ordering of v_2 → initial state correlations + fragmentations

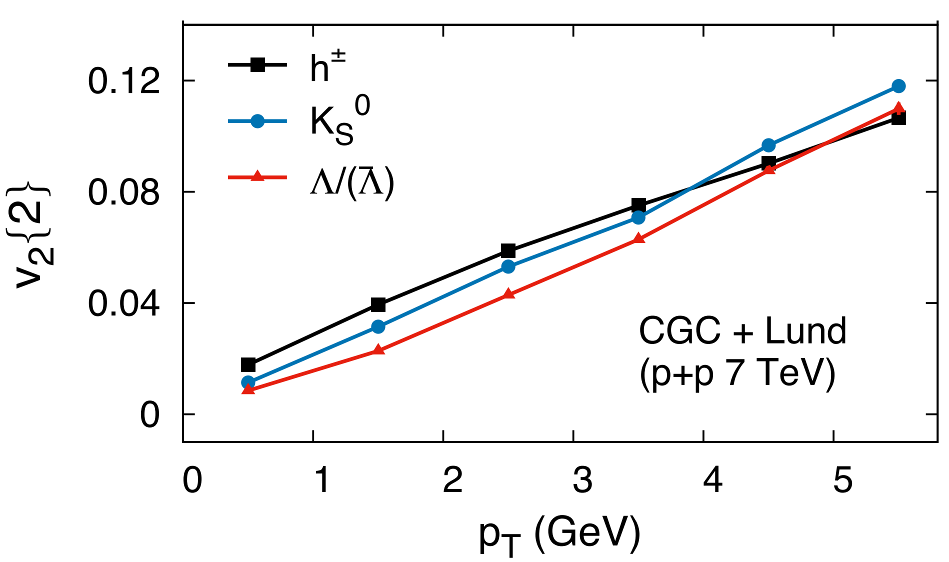
Summary and Takehome

- Very first attempt to combine CGC & PYTHIA
- Described ridge in HM events
- Observed mass ordering of <p_T> and v_2

Overall description of bulk observables based on initial state dynamics in p+p collisions looks promising



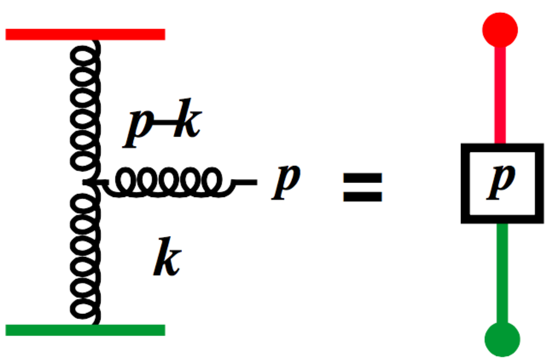




Backup slides

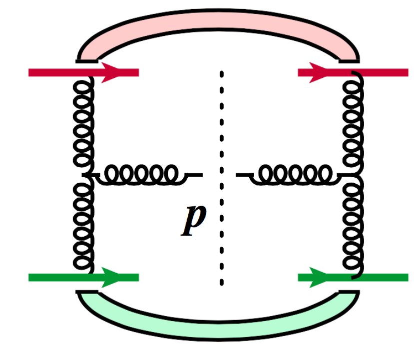
Multi-particle productions

Single-Inclusive



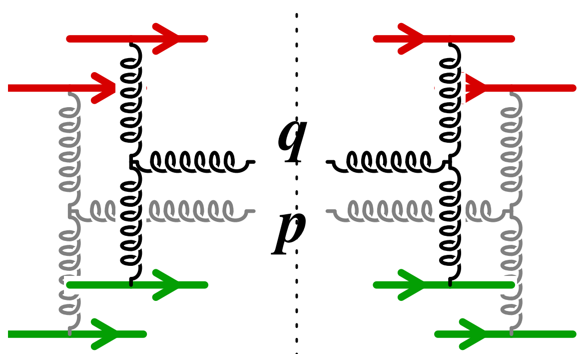
Color Averaging

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



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

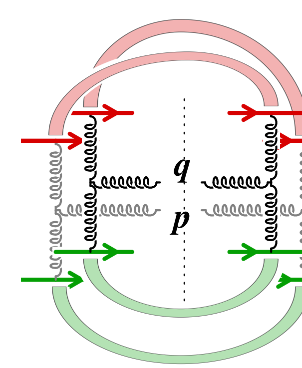
Double-Inclusive



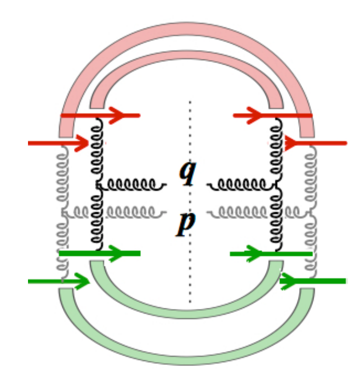
$$\langle |\mathcal{M}|^2 \rangle \rightarrow \langle \rho_1^* \rho_1^* \rho_1 \rho_1 \rho_2^* \rho_2^* \rho_2 \rho_2 \rangle$$

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

$\downarrow$ $\downarrow$



8 topologies

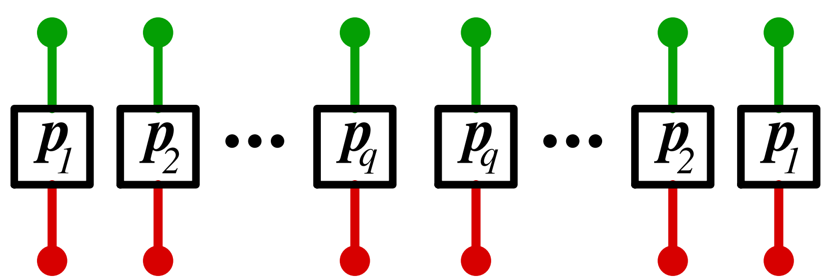


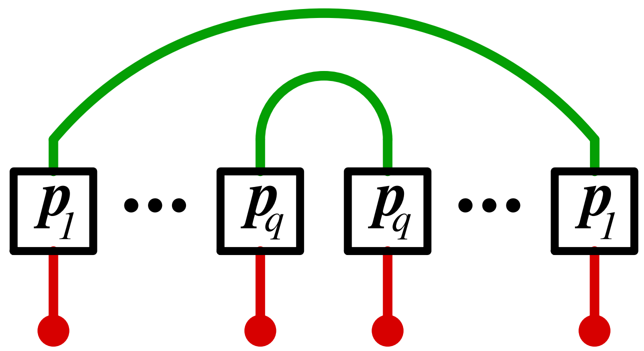
1 topology

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

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

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

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

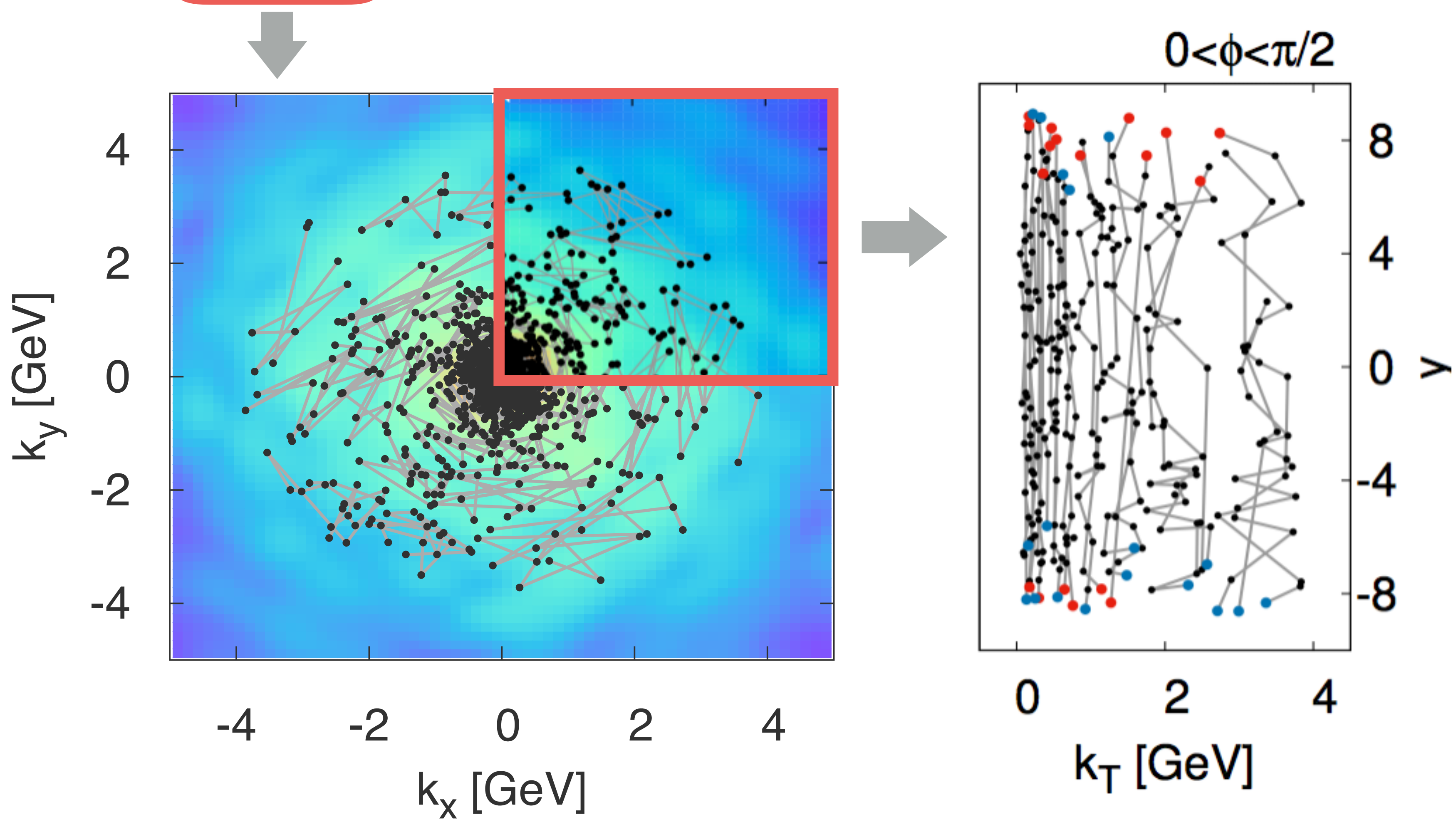
—> Highly non-perturbative

Gelis, Lappi, McLerran 0905.3234

CGC + Lund : IP-Glasma input to PYTHIA

Schenke, Schlichting, Tribedy, Venugopalan, Phys.Rev.Lett. 117 (2016) no.16, 162301

$$\boxed{\frac{dN}{d\mathbf{k}_T dy}}$$



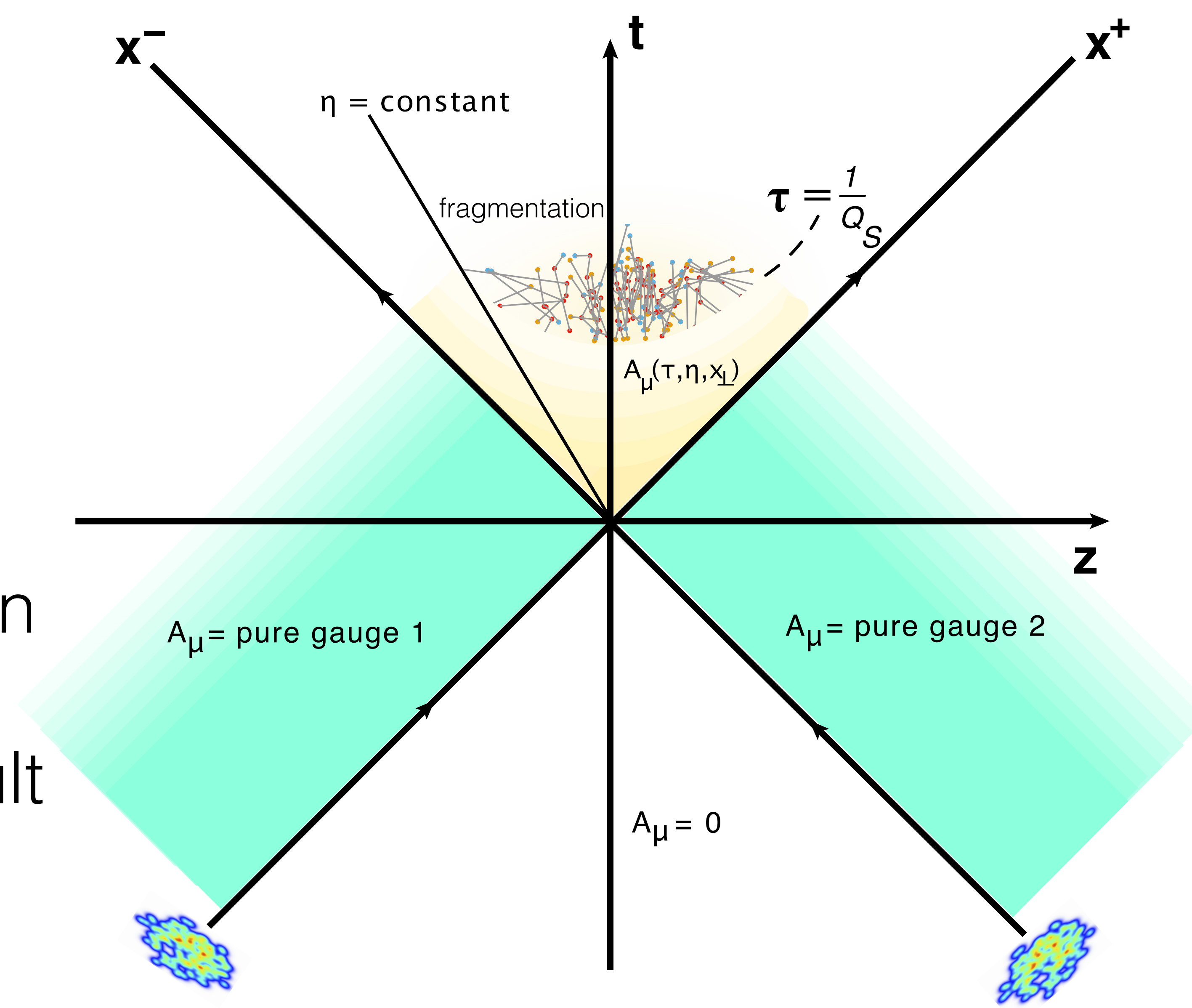
Hadronizations : combining CGC & PYTHIA

- Full solutions of CYM on 2+1D lattice : IP-Glasma Monte-Carlo model of initial conditions : constrained by HIC data

Schenke, PT, Venugopalan 1202.6646

- Lund model of fragmentation in PYTHIA to produce particles from gluons: default parameters to avoid tuning

Sjostrand, Mrenna, Skands hep-ph/0603175



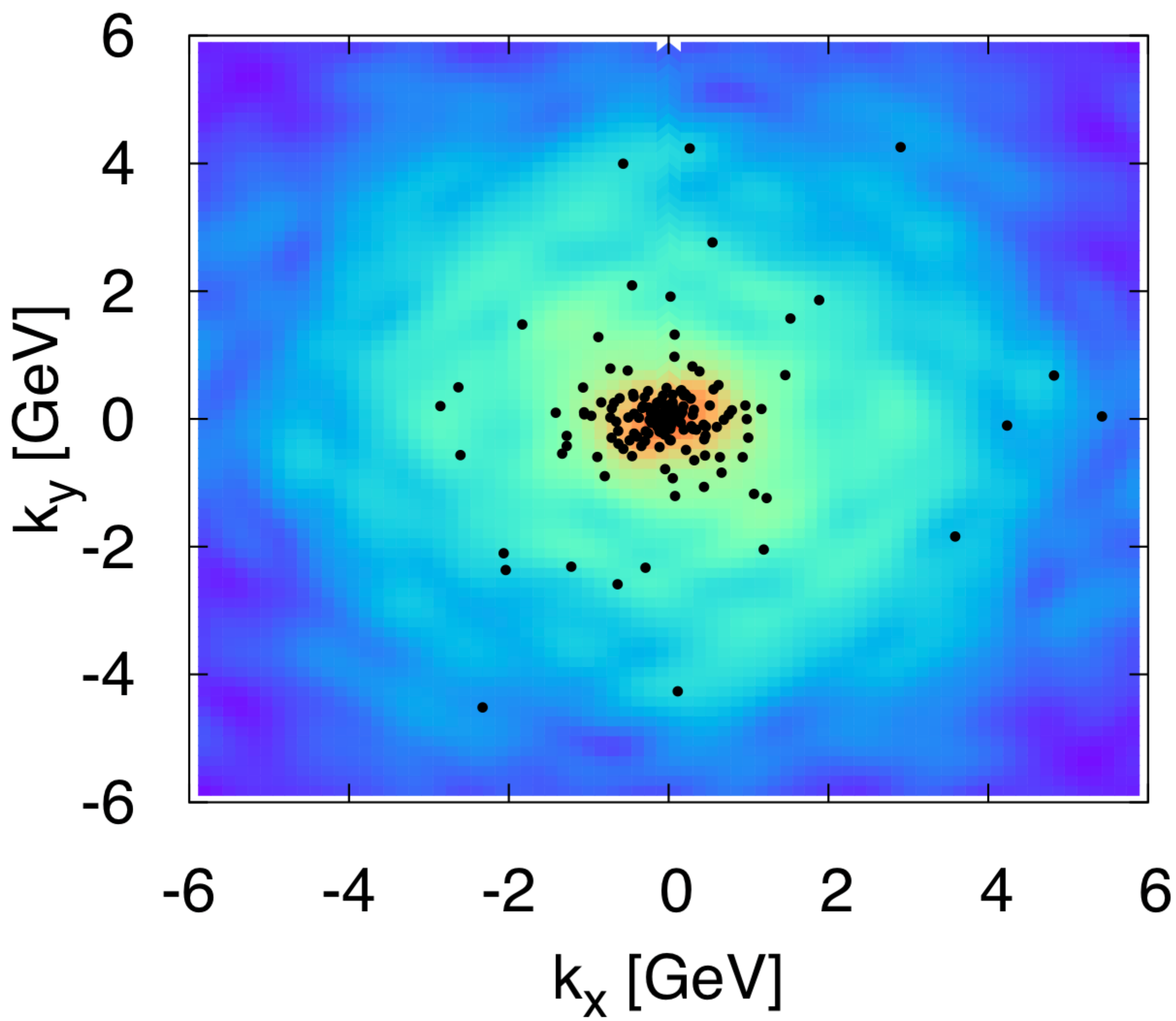
Step-I : sample gluons from IP-Glasma

Perform e-by-e classical Yang-Mills evolution till time $\tau \sim 1/Q_s$

$$\frac{dN_g}{dy d^2k_T} = \frac{2}{N^2}\frac{1}{\tilde{k}_T}\left[\frac{g^2}{\tau}\mathrm{tr}\left(E_i(\mathbf{k}_\perp)E_i(-\mathbf{k}_\perp)\right) + \tau\,\mathrm{tr}\left(\pi(\mathbf{k}_\perp)\pi(-\mathbf{k}_\perp)\right)\right]$$

Sample gluons in momentum space in the range :

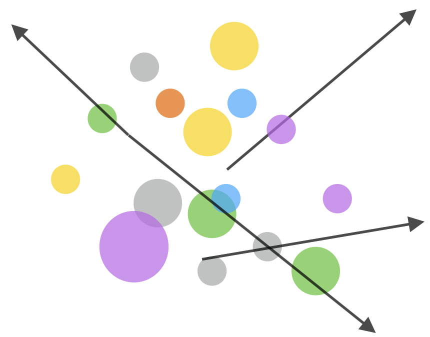
$$0 < |y_{\max}| < \log(\sqrt{s}/2m_p)$$



Glasma distribution is boost invariant :
Distribution of Gluons —> uniform in rapidity

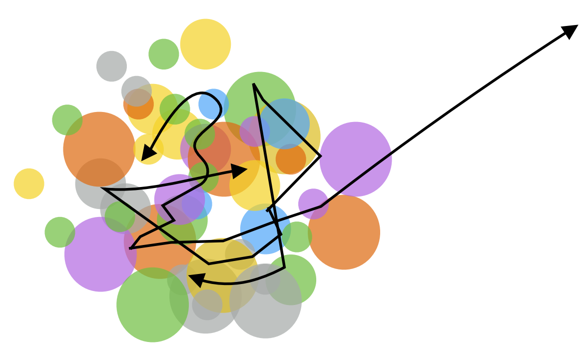
Qualitative Picture : Small systems

low multiplicity events



mini-jets escape

high multiplicity events



mini-jets quenched

A Phase Diagram of Correlation

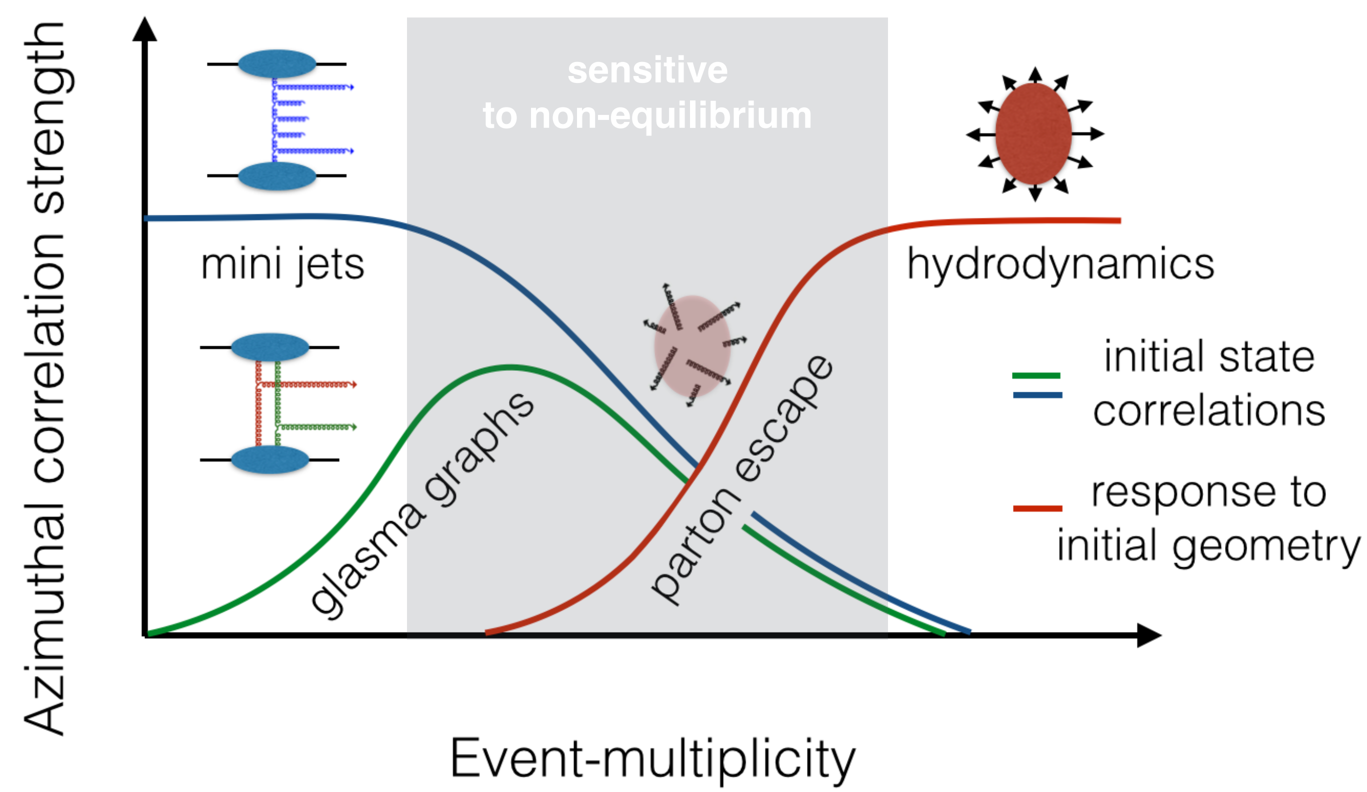
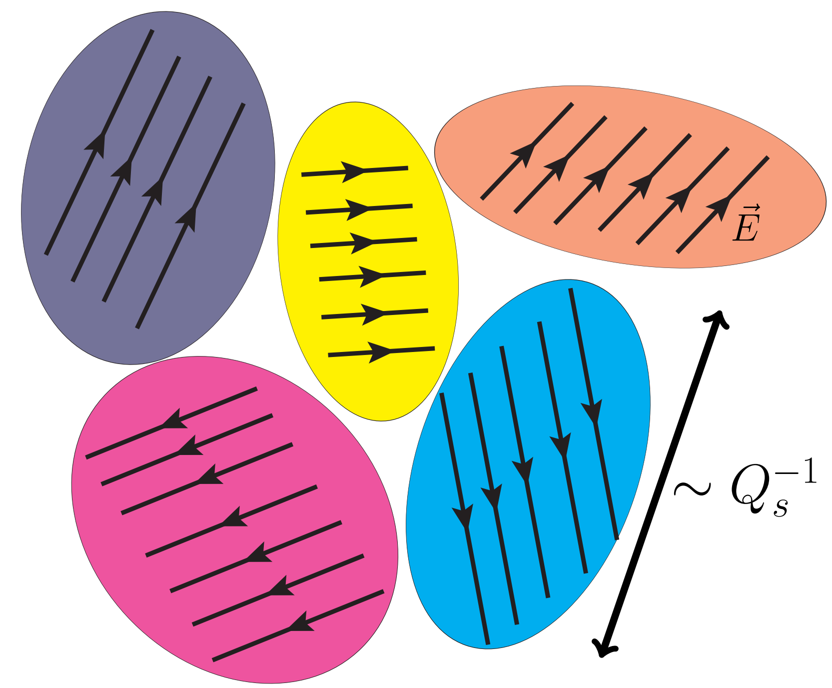


fig: S. Schlichting (QM'2015)

Azimuthal Correlations in CGC

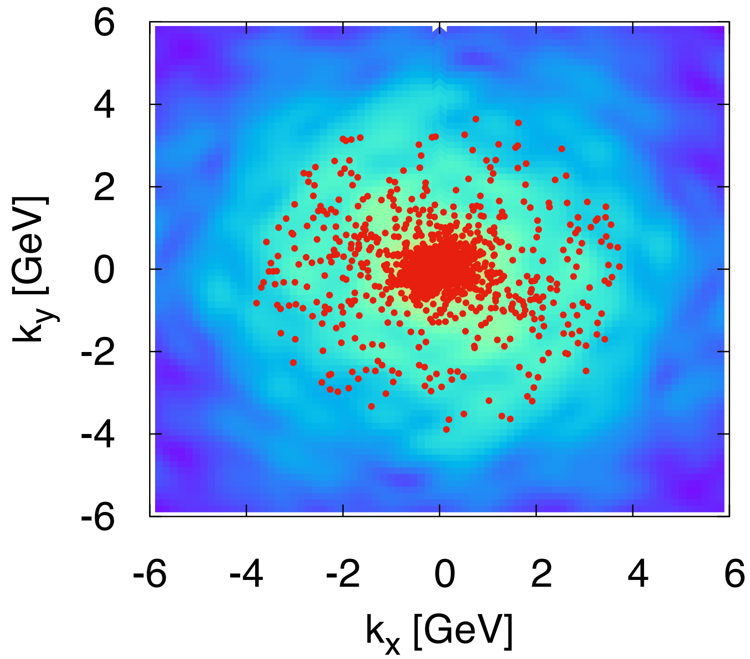
- Intrinsic momentum space correlation from initial state
- Originate from partons (probe) scattering off a color domain (target)
- Suppressed by number of color sources / domains



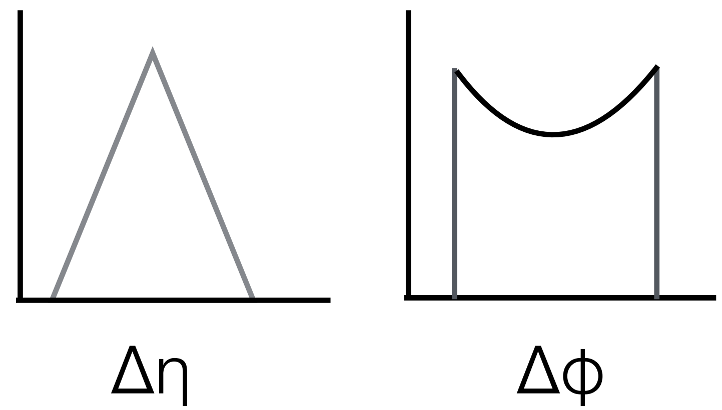
Dumitru, Dusling, Gelis, Jalilian-Marian, Lappi, Venugopalan 1009.5295
Kovner, Lublinsky 1012.3398
Dusling, Venugopalan 1201.2658
Kovchegov, Wertepny 1212.1195
Dumitru, Giannini 1406.5781
Lappi, Schenke, Schlichting, Venugopalan 1509.03499

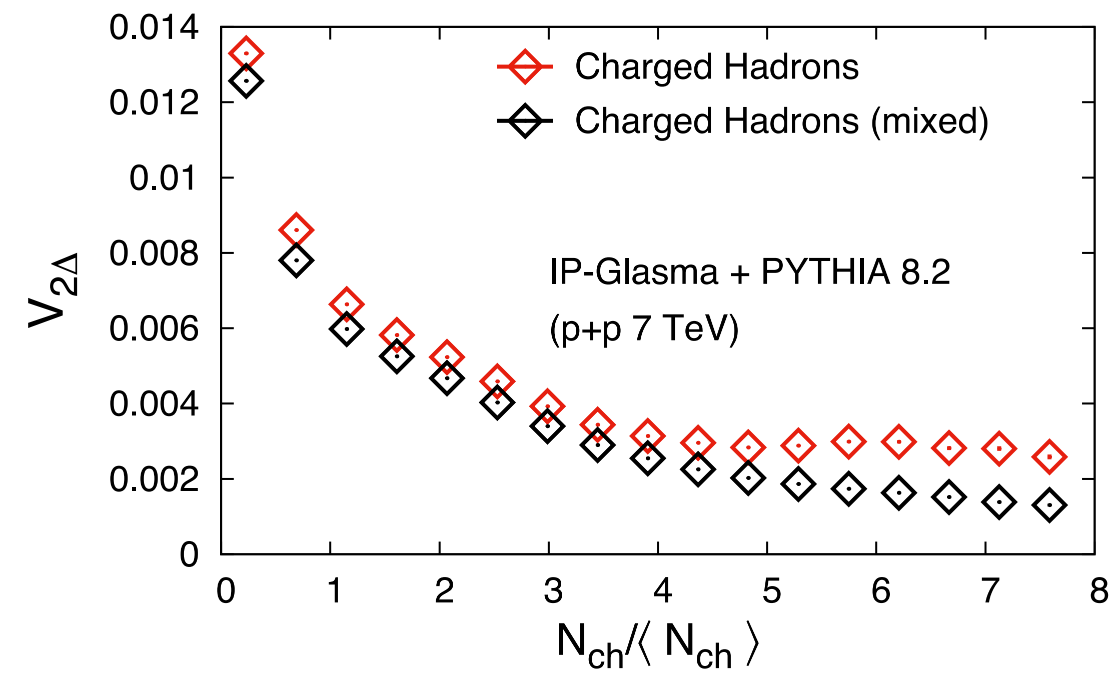
Very distinct from Hydrodynamic flow (driven by geometry)

Azimuthal correlations (after fragmentation)

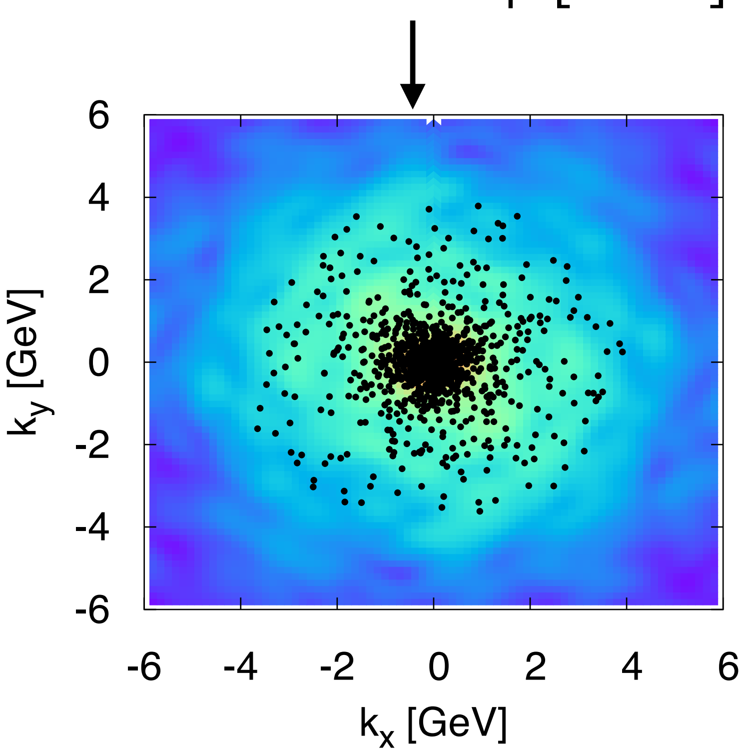


Real events





randomize φ [0-2π]



Mixed events