Hadronic observables in small collisions systems from classical Yang-Mills dynamics + Lund string fragmentation

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BROOKHAVEN NATIONAL LABORATORY

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Based on work done in collaboration with Bjoern Schenke, Soeren Schlichting & Raju Venugopalan

Venezia 2018 Quark Matter

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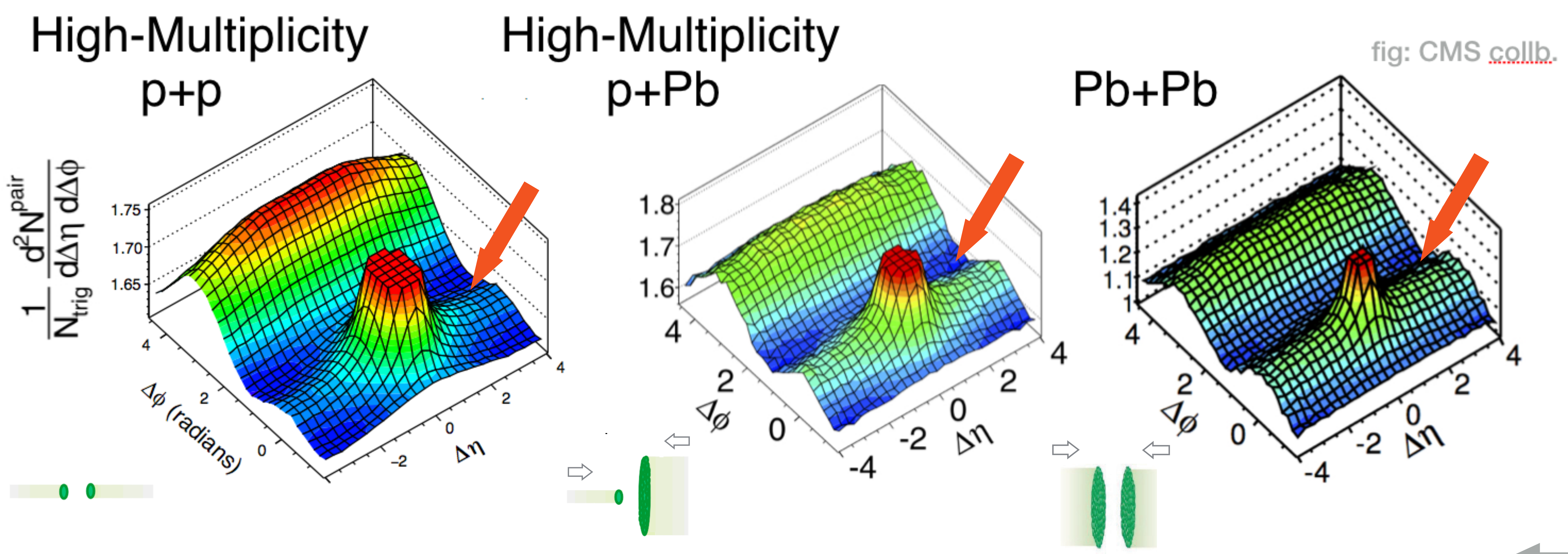
Multiparticle production in different systems



Microscopic approach :
Multiparton interaction

Challenges/uncertainties :

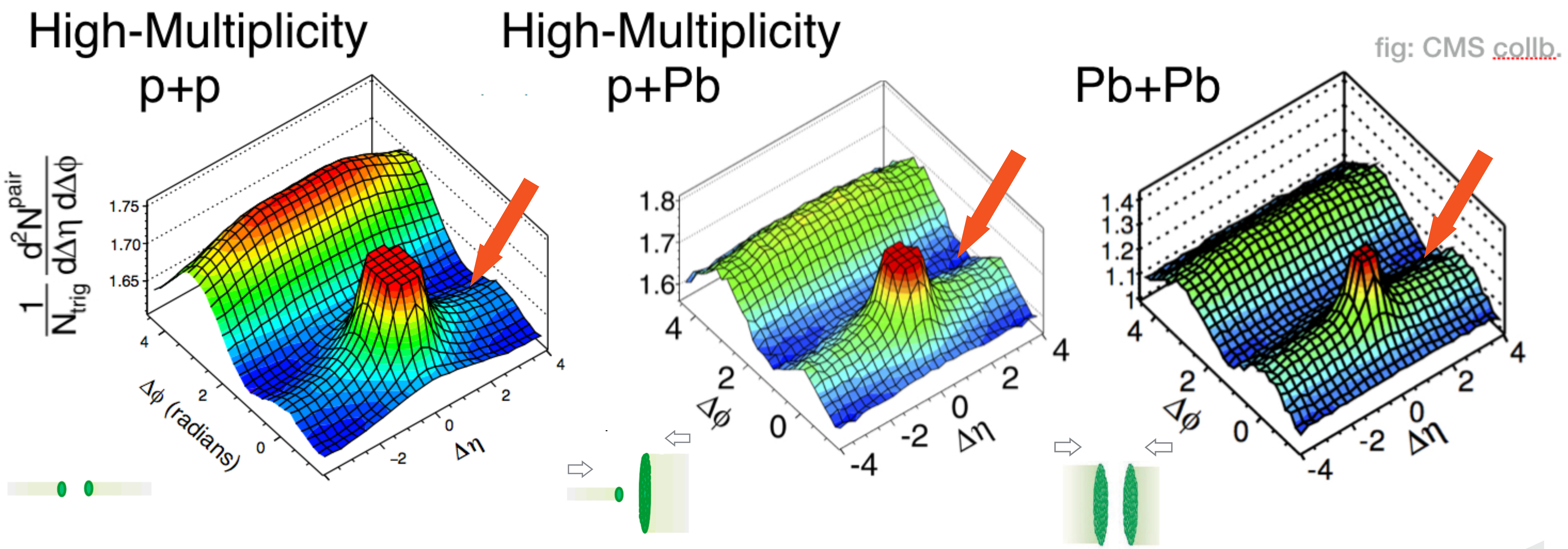
Highly nonperturbative nature of the multiparton interaction & hadronization

Macroscopic approach
Fluid-dynamic evolution

Challenges/uncertainties :

Initial conditions, viscous effects, thermalization, hadronization

Multiparticle production in different systems



Microscopic approach :
Multi-parton interaction

Challenges/uncertainties :

Highly nonperturbative nature of multiparton interaction & hadronization

This talk

Macroscopic approach
Fluid-dynamic evolution

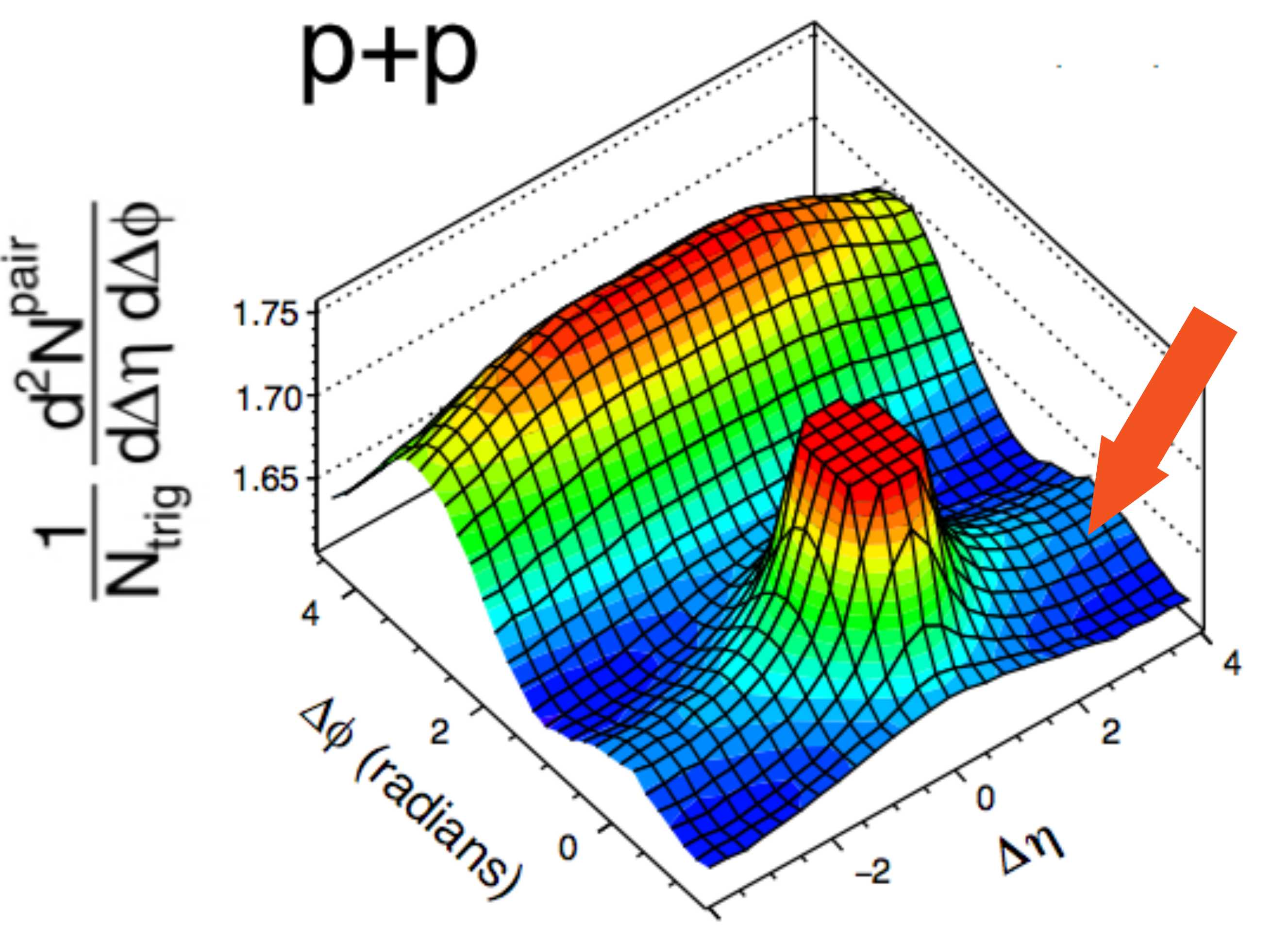
Challenges/uncertainties :

Initial conditions, viscous effects, thermalization, hadronization

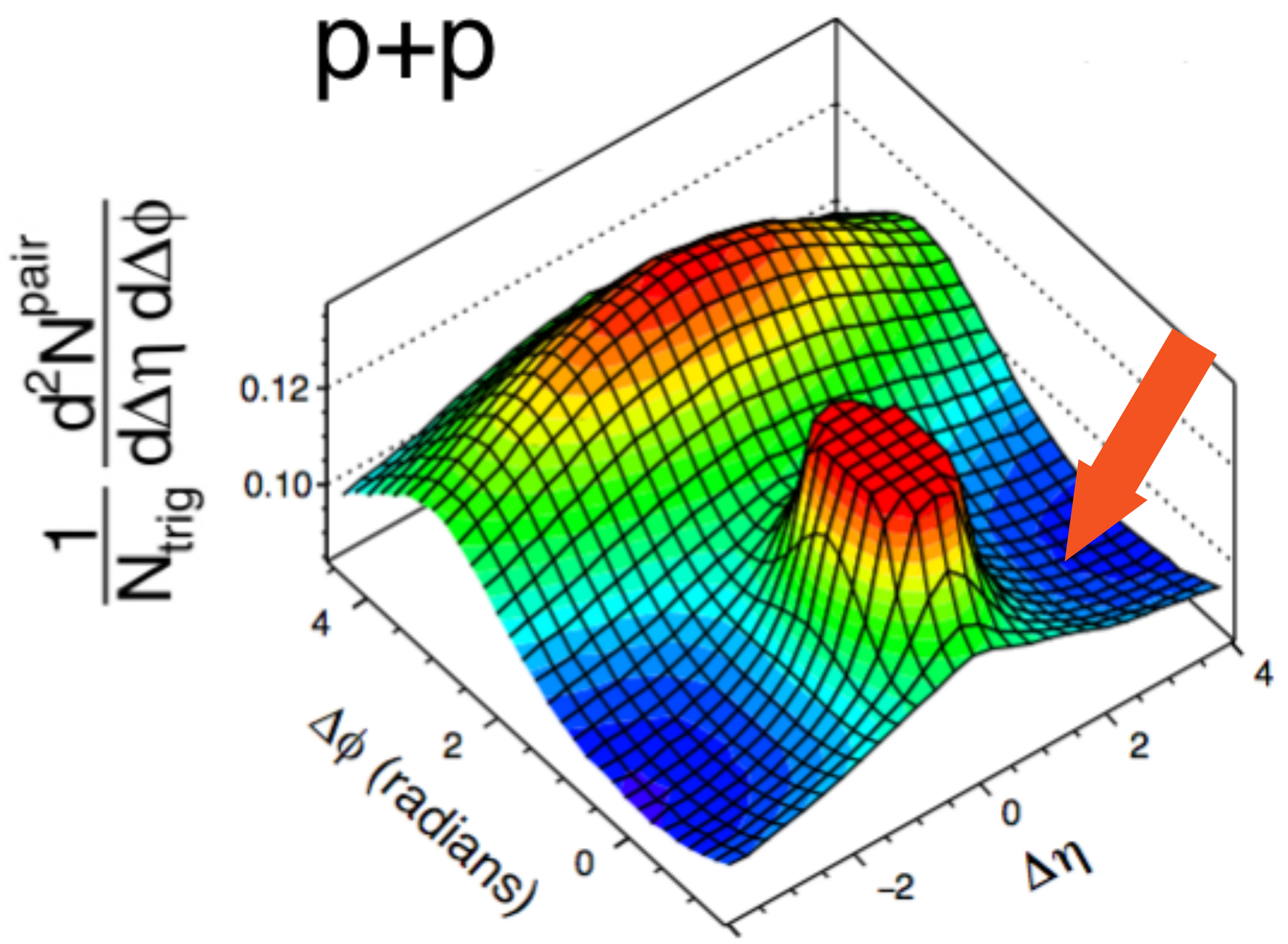
Conventional microscopic approaches/models

High-multiplicity (Data)

CMS collab : 1606.06198

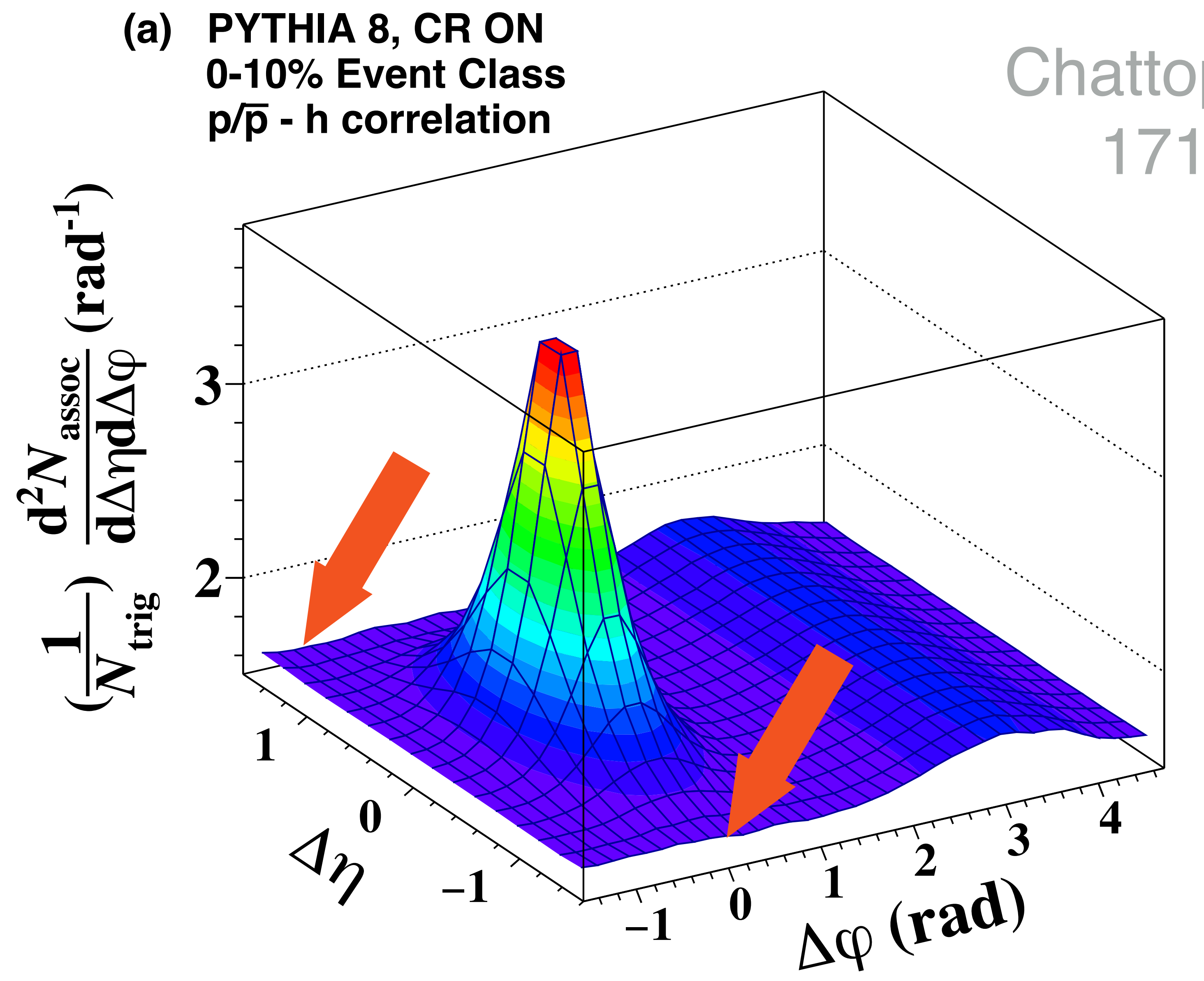


Low-multiplicity (Data)



High-multiplicity p+p (PYTHIA)

Sarkar, Chattopadhyay 1710.09785



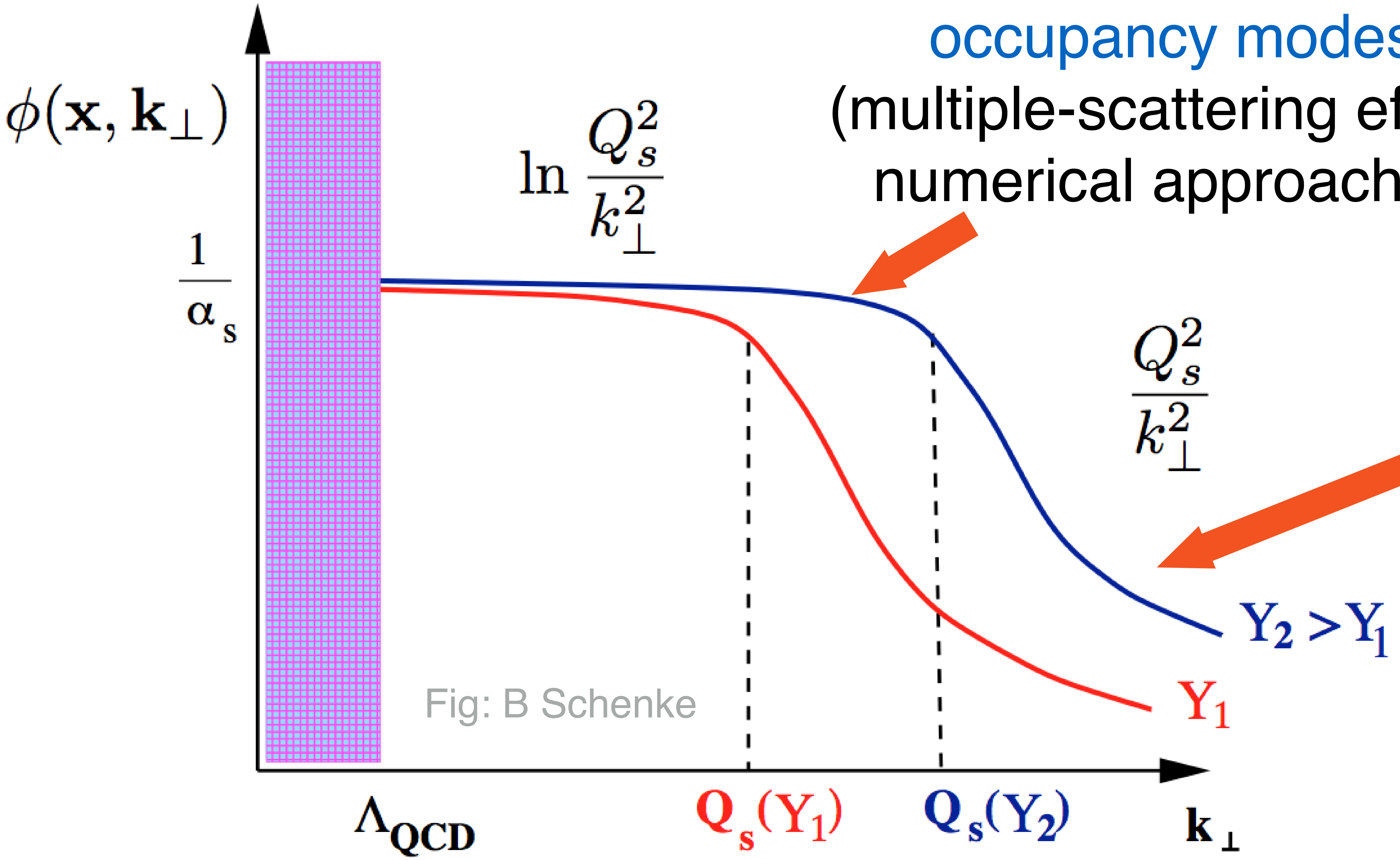
Only some of the non-perturbative aspects of bulk particle production are captured in conventional Monte-Carlo Models like PYTHIA

Includes a state-of-the art fragmentation,
Recent developments, talk by T. Sjostrand

The color glass condensate effective theory

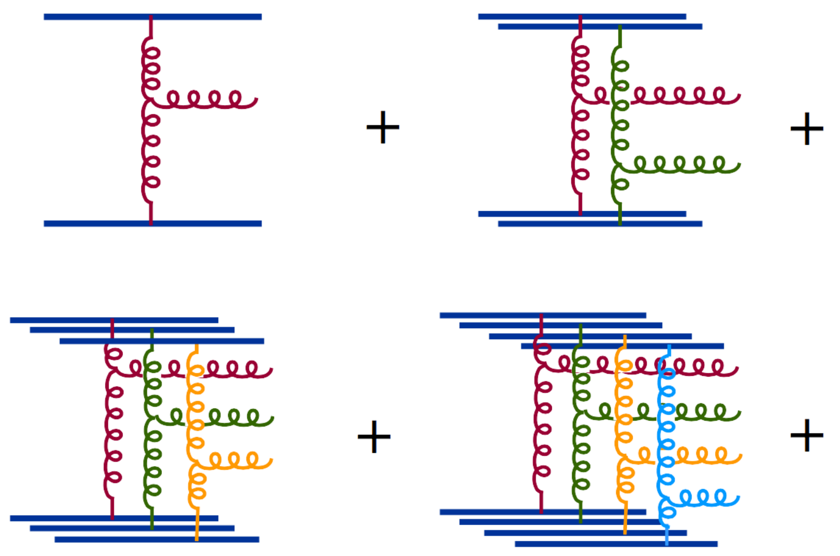
Makes use of the saturated target/projectile wave functions at sufficiently high energy, small-x,
→ a systematic treatment of non-perturbative aspects of multi particle productions

Semi-hard high occupancy modes
(multiple-scattering effects, numerical approaches)



Perturbative tails

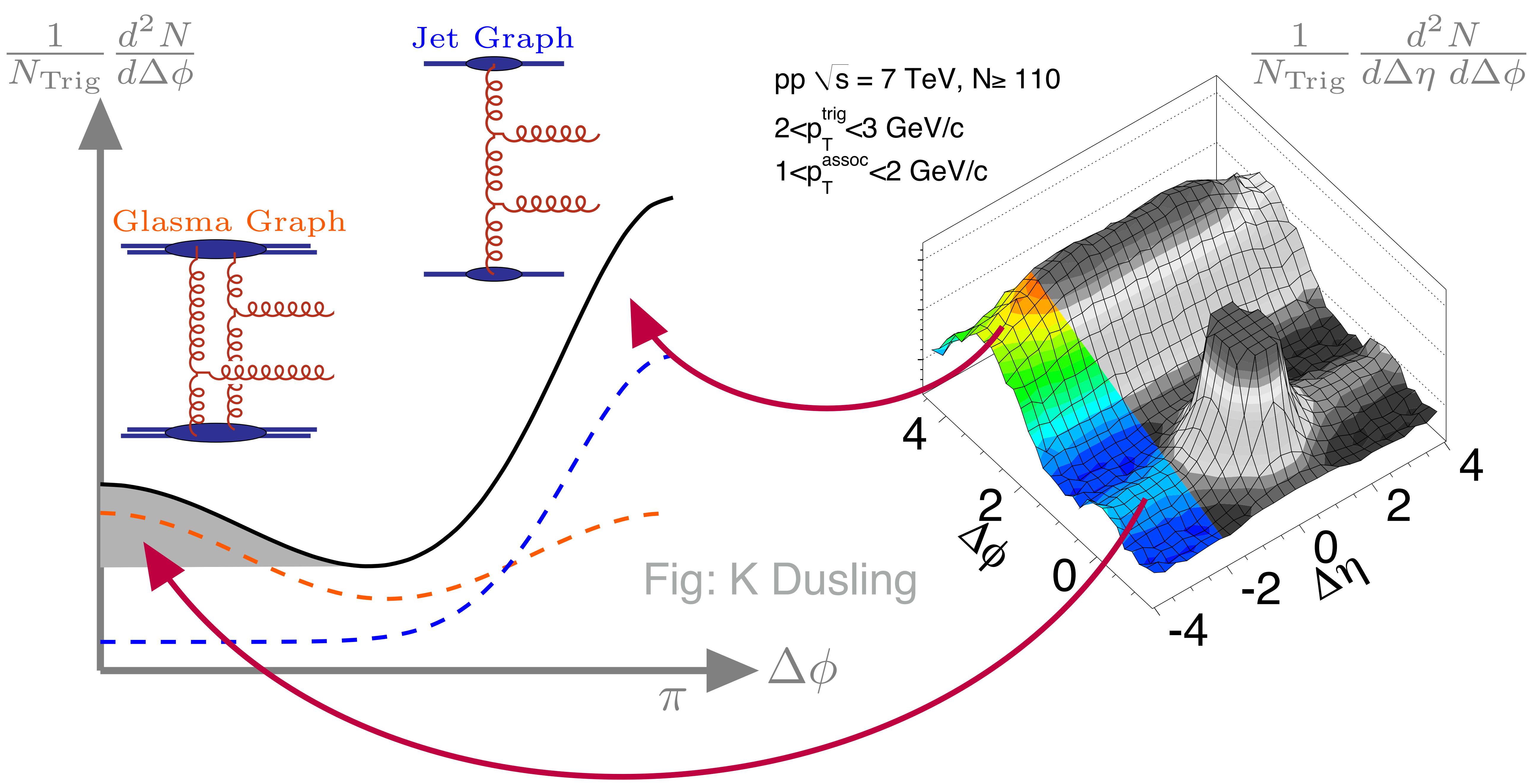
(kT- factorization, Glasma-Graphs dilute-dense approaches)



Needs a consistent treatment of hadronization for bulk multi particle production (dominated by low p_T)

Perturbative CGC computations explain ridge systematics

Under different perturbative approximation schemes CGC provides a natural explanation of : 1) origin of high multiplicity events 2) the appearance of ridge in high multiplicity events



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

Dumitru, McLerran, Skokov 1410.4844

Lappi, Schenke, Schlichting, Venugopalan 1509.03499

Saturation enhances correlated emission of gluons over a wide phase space

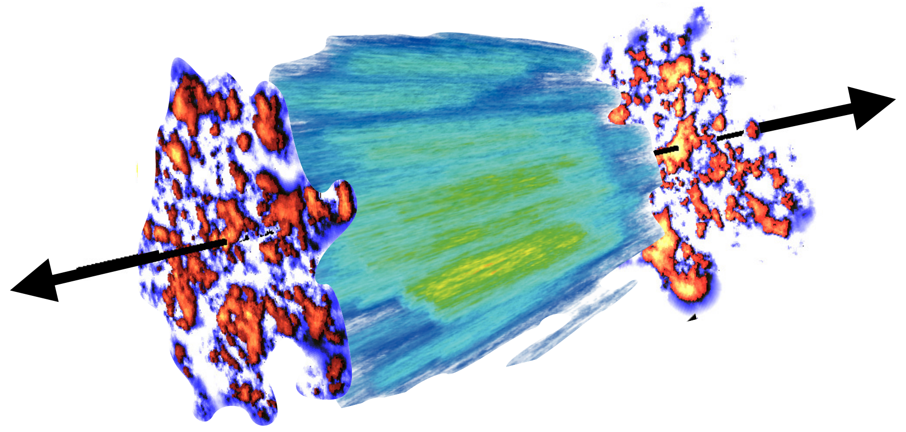
Conventional fragmentation schemes are used for phenomenology high p_T ⇨

$$\int_{z_0}^{1} dz_1 dz_2 \frac{D(z_1)}{z_1^2}\frac{D(z_2)}{z_2^2}\frac{d^2N_g^{\rm corr.}}{d^2\mathbf{p}_T d^2\mathbf{q}_T d\eta_p d\eta_q}\left(\frac{p_T}{z_1},\frac{q_T}{z_2}\right)$$

Beyond perturbative computations : the IP-Glasma model

Schenke, PT, Venugopalan
PRL108 (25), 252301

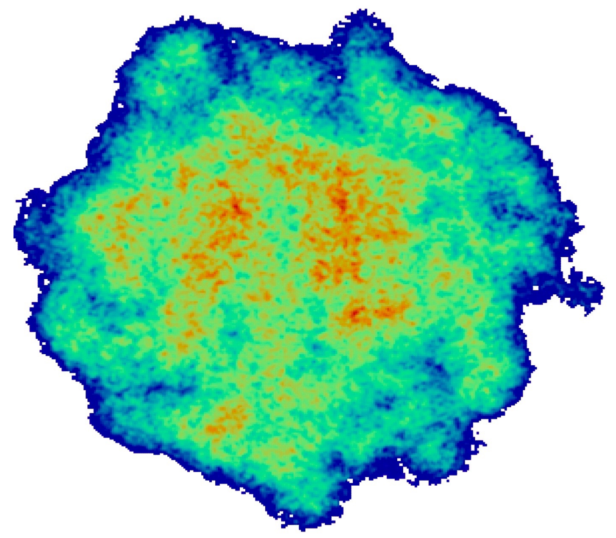
Light-cone gauge-fields



$$U(\mathbf{x}_T) = \mathbb{P}\exp\left\{ig\int dx^- A^+(x^-,\mathbf{x}_T)\right\}$$

Stress-Energy Tensor (Position space)

$$T^{\mu\nu} = -g^{\gamma\delta}F^{\mu}_{\ \gamma}F^{\nu}_{\ \delta} + \frac{1}{4}g^{\mu\nu}F^{\gamma}_{\ \delta}F_{\gamma}^{\ \delta}$$

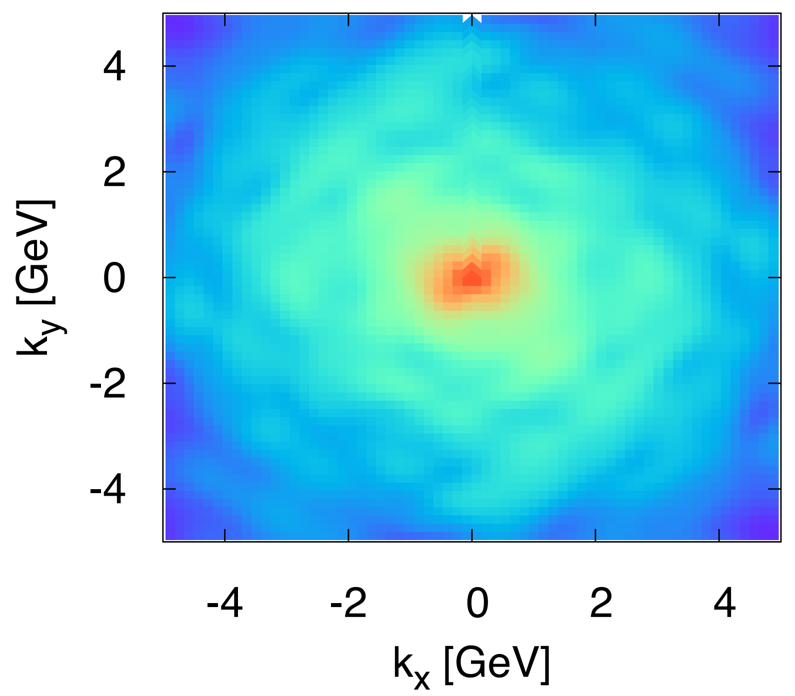


Input to hydro, transport, p+p, p+A, A+A collisions
→ Cooper-Frye prescription handles hadronization

Very successful phenomenology

Gluon density distribution (Momentum space)

$$\left.\frac{dN}{d^2k_t dy}\right|_{\tau} = \frac{1}{(2\pi)^2}\sum_{\lambda,a}\left|\tau g^{\mu\nu}\left(\xi_{\mu}^{\lambda,k_t *}(\tau)\overleftrightarrow{\partial_\tau}A_{\nu}^{a}(\tau,k_t)\right)\right|^2$$



Bulk particle production in p+p/A collisions → Needs a hadronization scheme for low p_T for better phenomenology

CGC meets Lund String fragmentation of PYTHIA

CGC + PYTHIA : A new approach to simulate p+p & p+A collisions

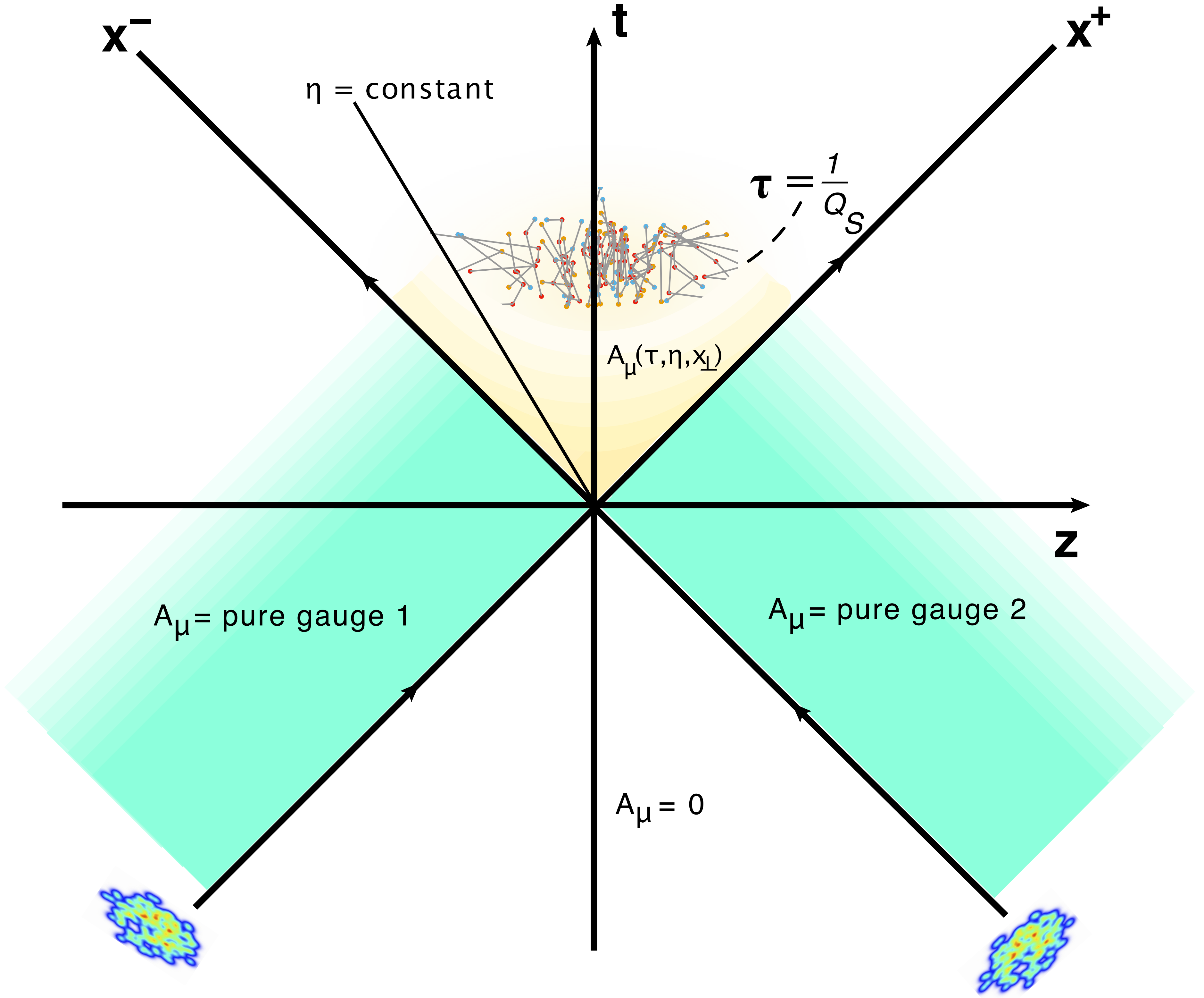
Schenke, PT, Venugopalan Phys. Rev. Lett. 108 (2012) 252301

1) Output distribution of Gluons from CGC based **IP-Glasma** model

2) Sample gluons in momentum space

3) Connect the gluons close in phase space to color neutral strings

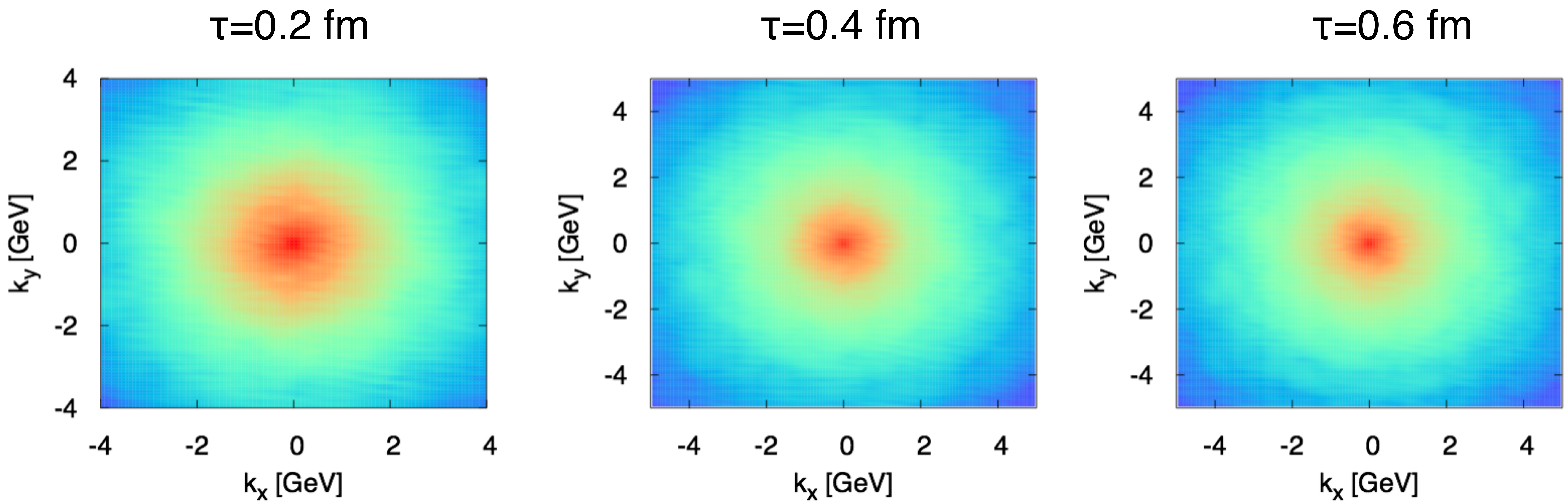
4) Input to **PYTHIA** and fragment into final particles



PYTHIA (realistic mechanism of hadronization) → partonic correlations from initial state dynamics → correlated production of final-state particles

Step-I : compute gluon distributions in momentum space

$\frac{dN}{d\mathbf{k}_T dy}$ at different times (k_x, k_y) plane, boost invariant in the rapidity direction from IP-Glasma



These distributions are boost invariant & extend in rapidity

Early time (regime of strong fields) → Yang-Mills evolution ~τ >1/Qs → on-shell gluon distributions

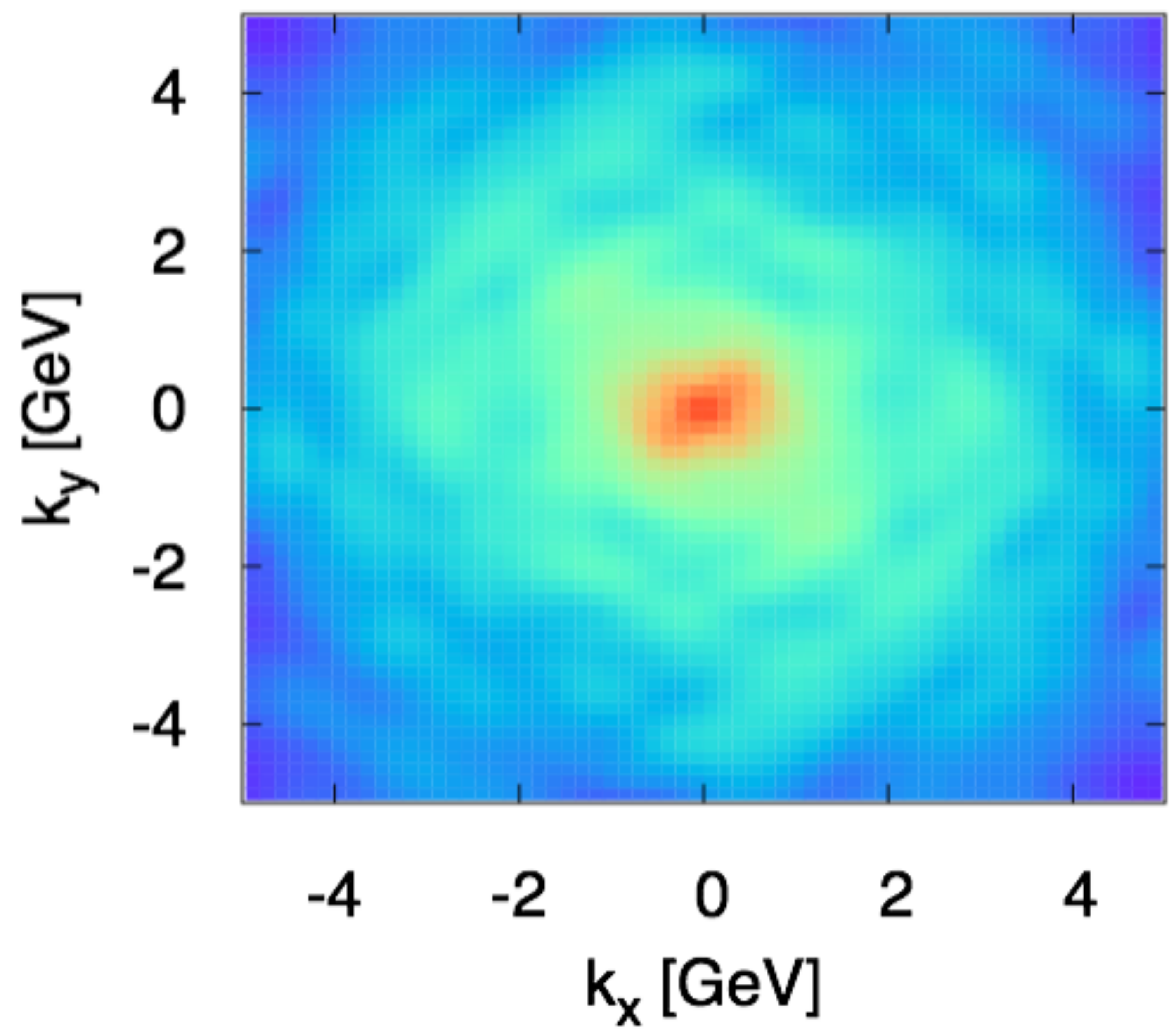
Step-II : sample gluons & form PYTHIA strings

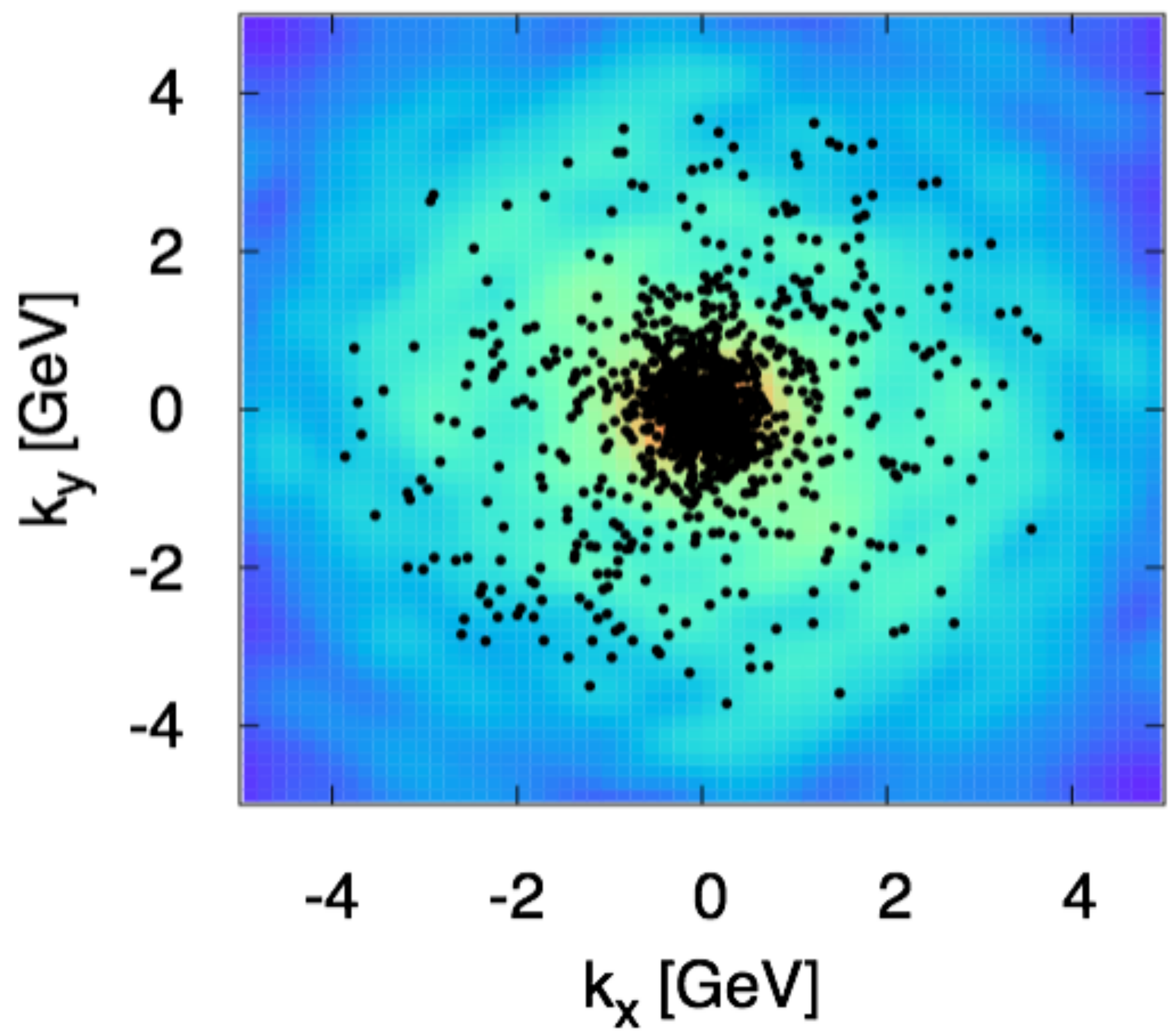
IP-Glasma gluon dist → Sample N_g gluons → Connect N_{gs} gluons to a string

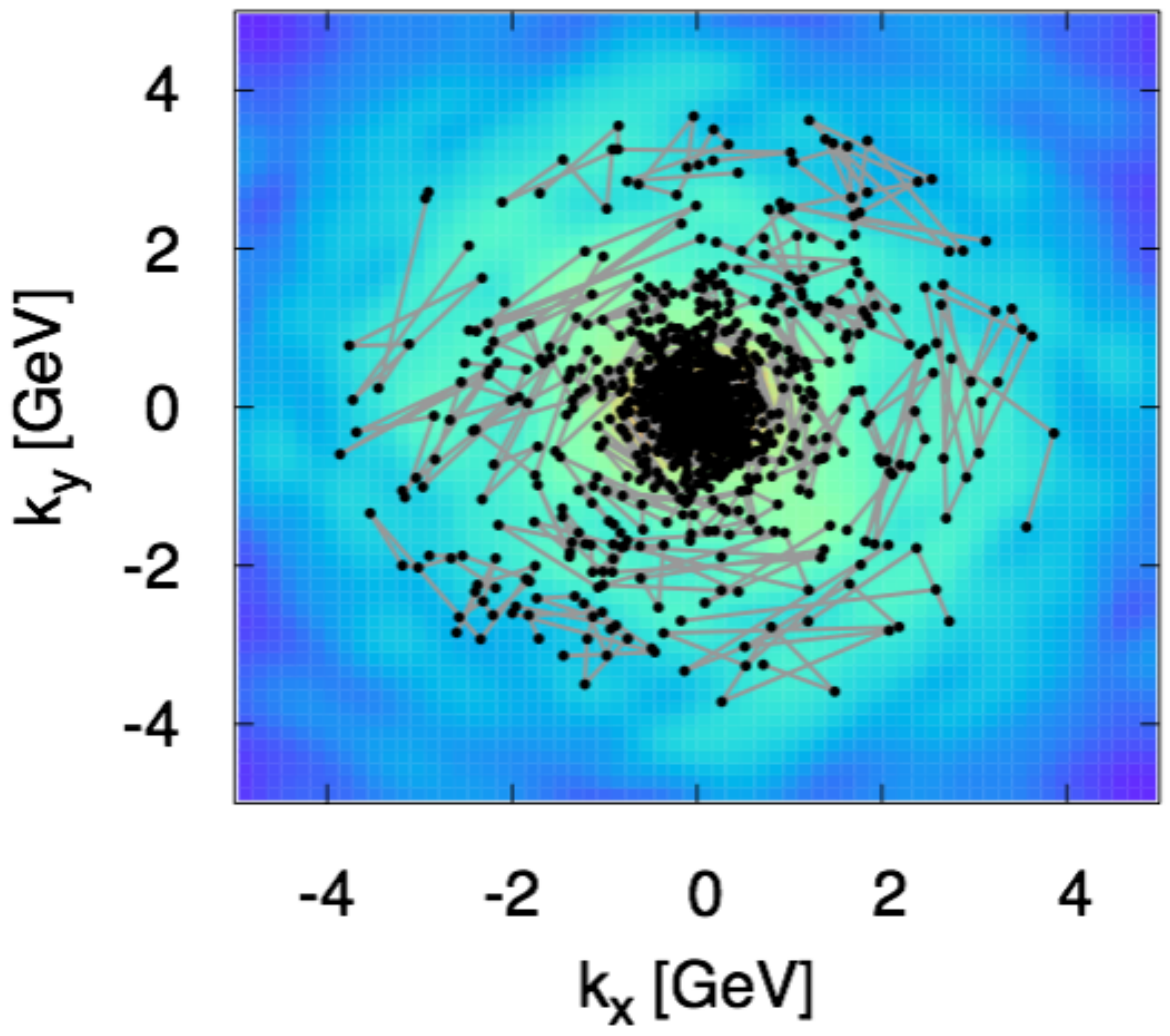
$$\frac{dN}{d\mathbf{k}_T dy}$$

$$N_g = \int_{-Y_{\text{beam}}}^{Y_{\text{beam}}} dy \int d\mathbf{k}_T \frac{dN_g}{d\mathbf{k}_T dy}$$

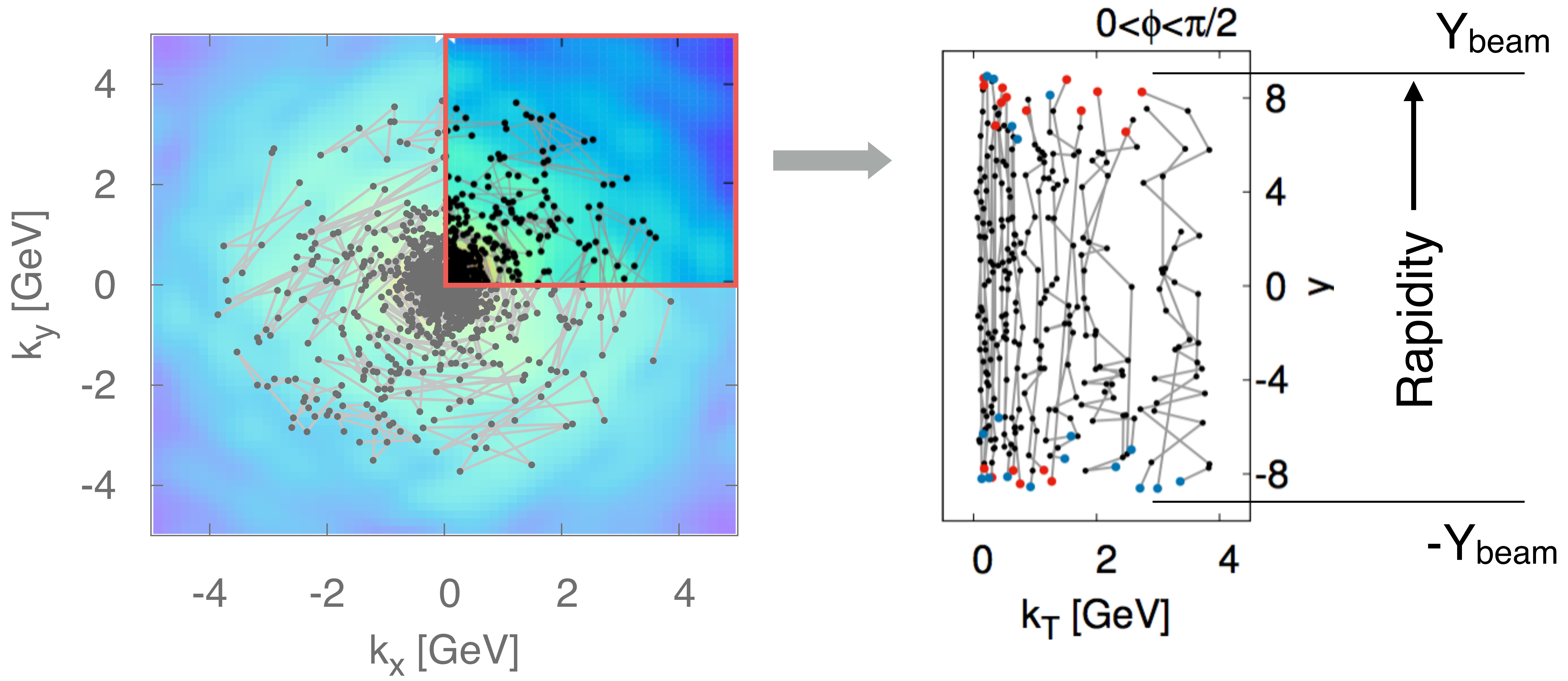
$$N_{gs} = \frac{N_g}{\langle Q_S^2 S_\perp \rangle}$$







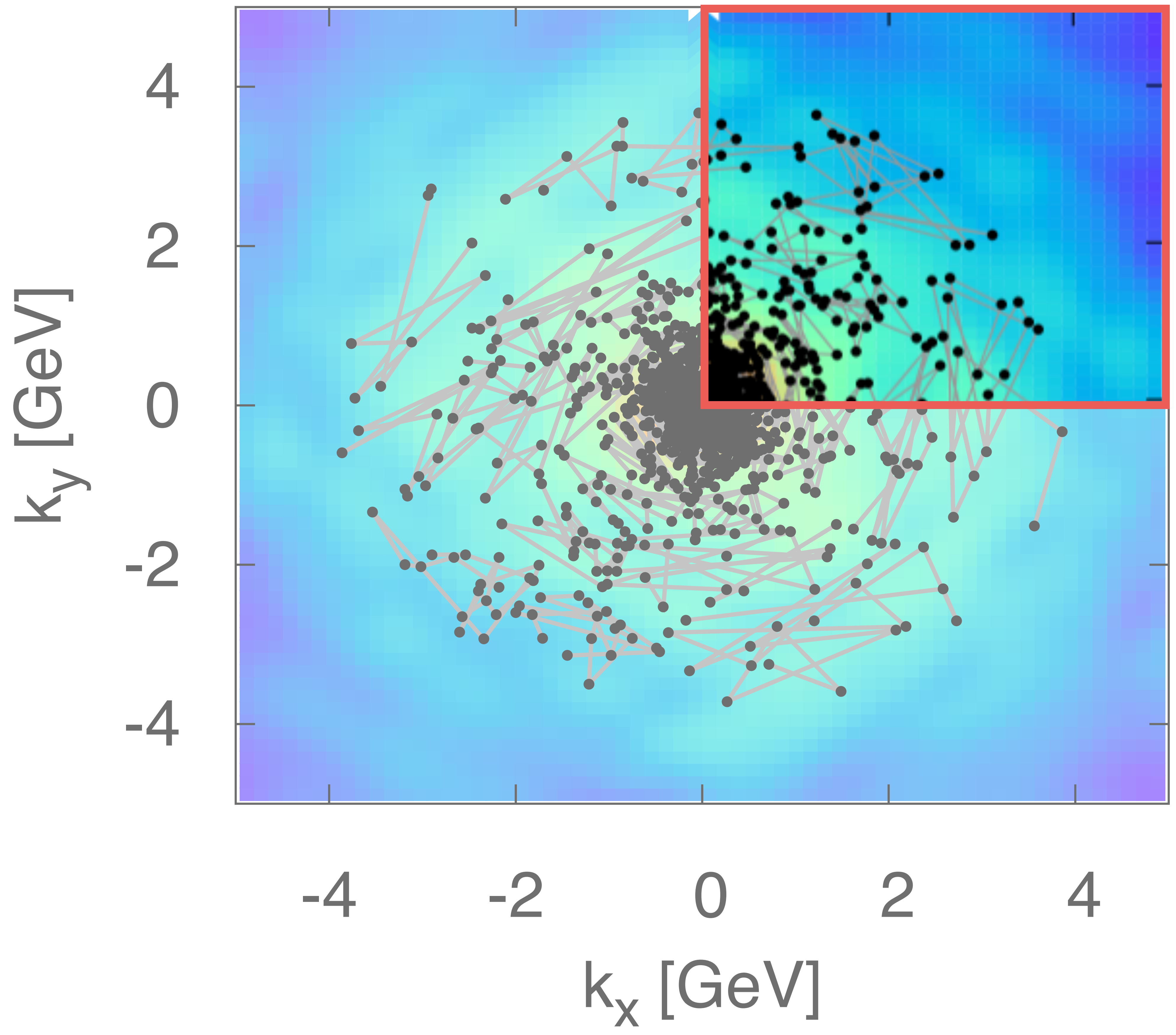
PYTHIA strings stretch in the rapidity direction



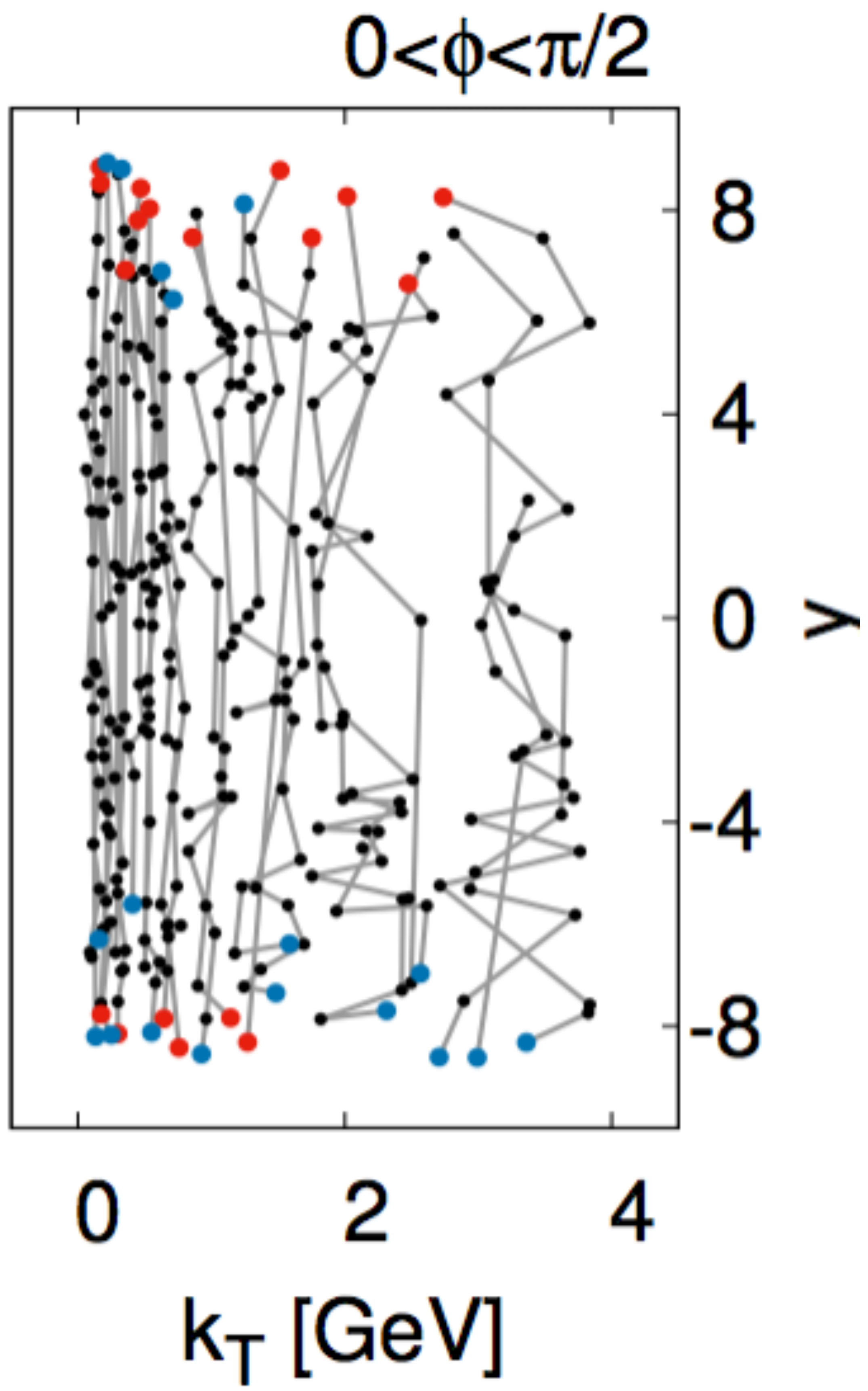
Group gluons close in (k_x-k_y) into strings stretching mainly in the rapidity direction

Need to add a quark and an anti-quark at string ends for color neutrality

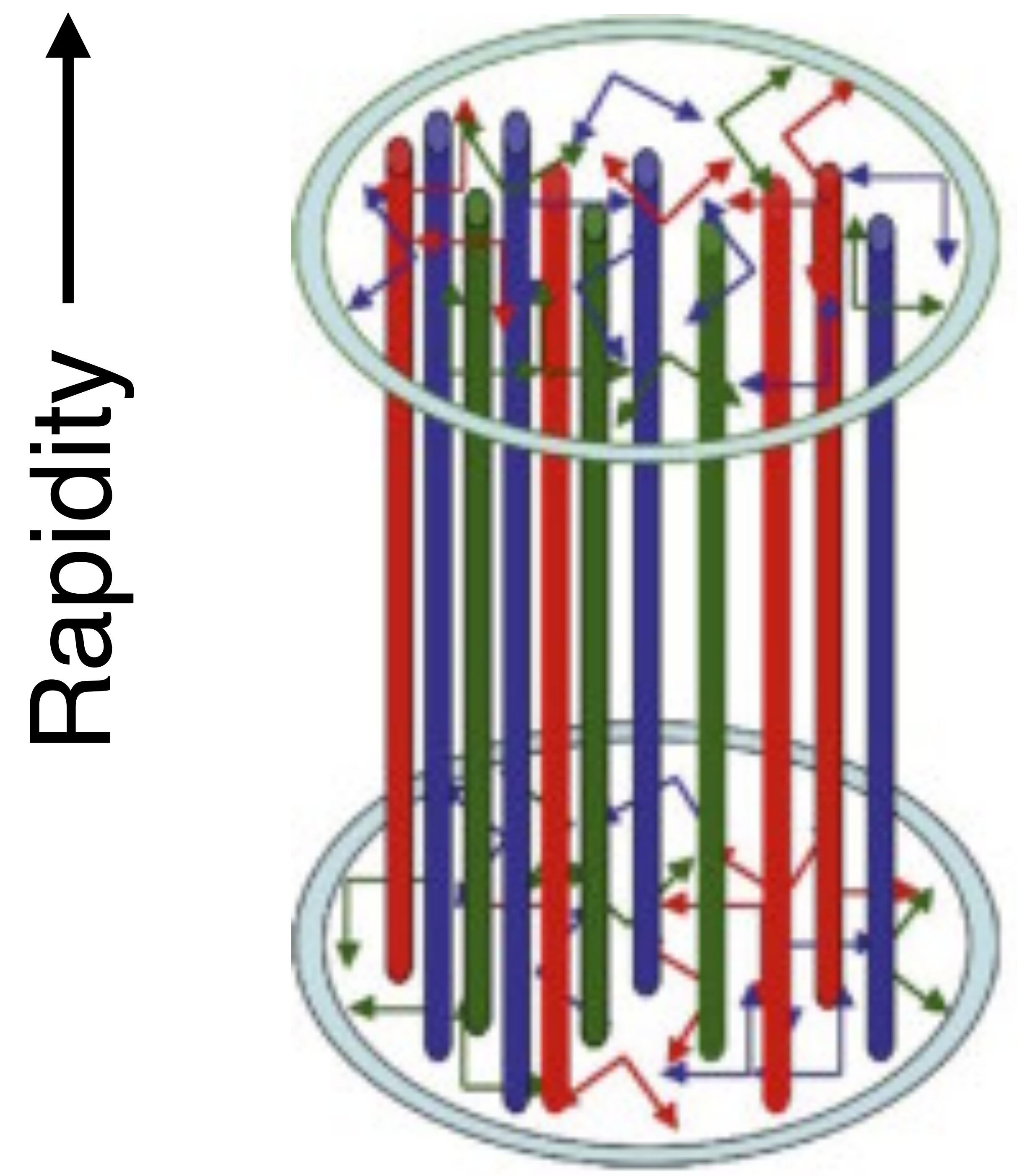
Pythia strings stretch in the rapidity direction



Pythia strings



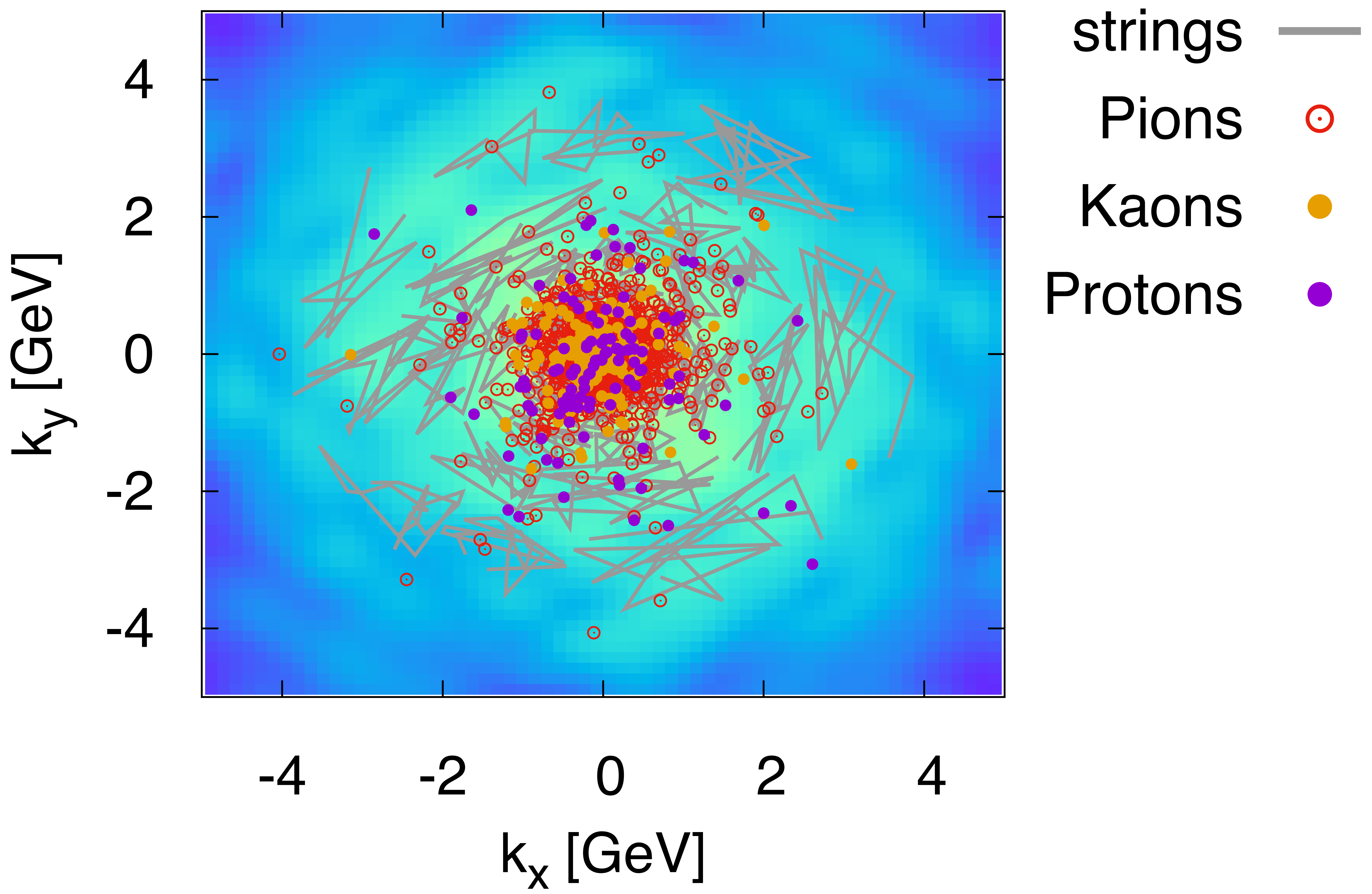
Glasma fluxtubes

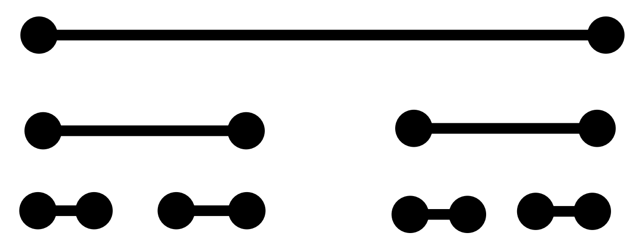


Inspired by Glasma fluxtubes picture we approximate the number of gluons/string = $N_g/\langle Q_S^2 S_\perp \rangle$

Step-III: fragment the PYTHIA strings

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





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

Lund String Fragmentation

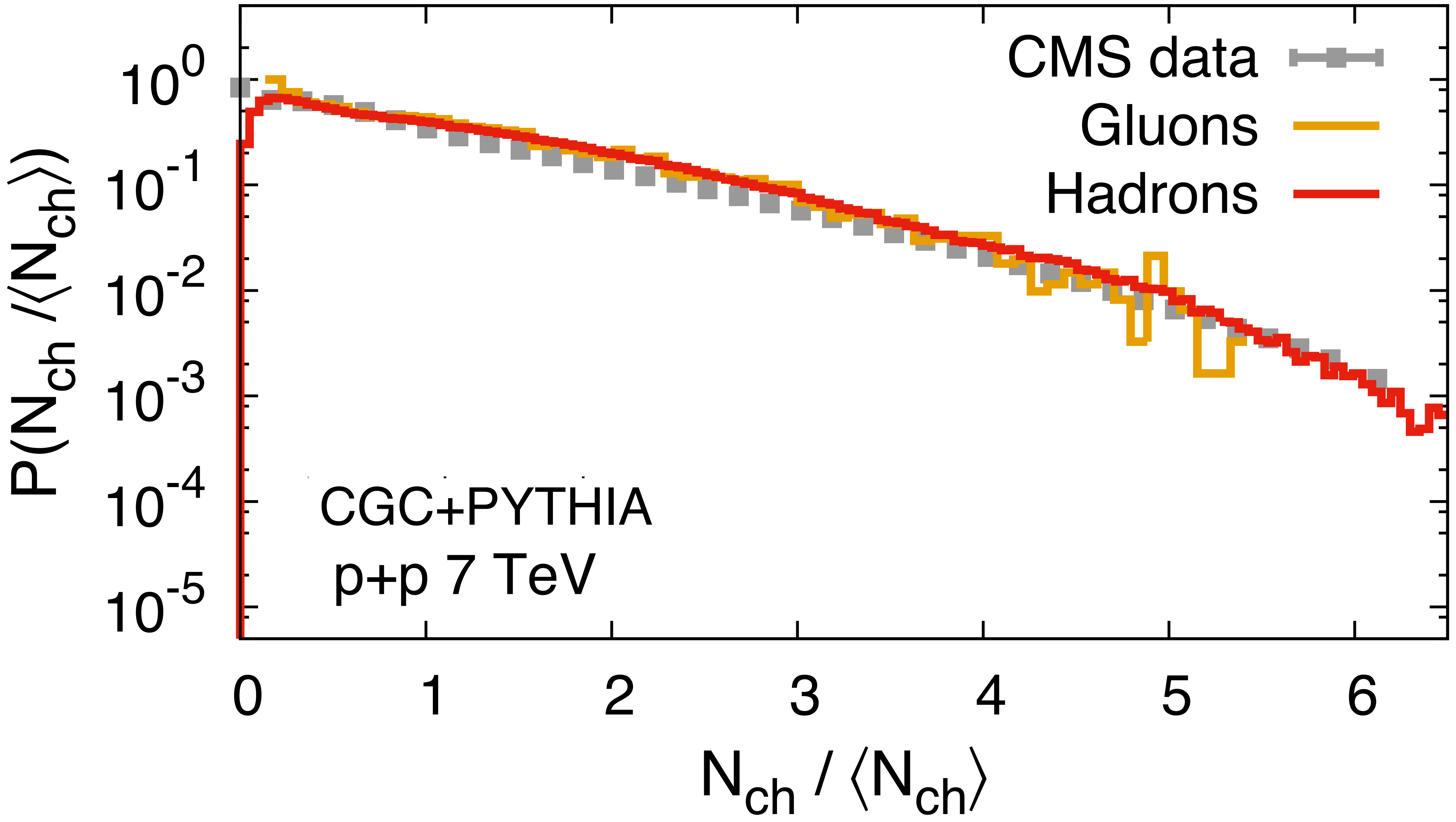
PYTHIA fragments strings to produce hadrons which carry the anisotropy

Phenomenology of high multiplicity events

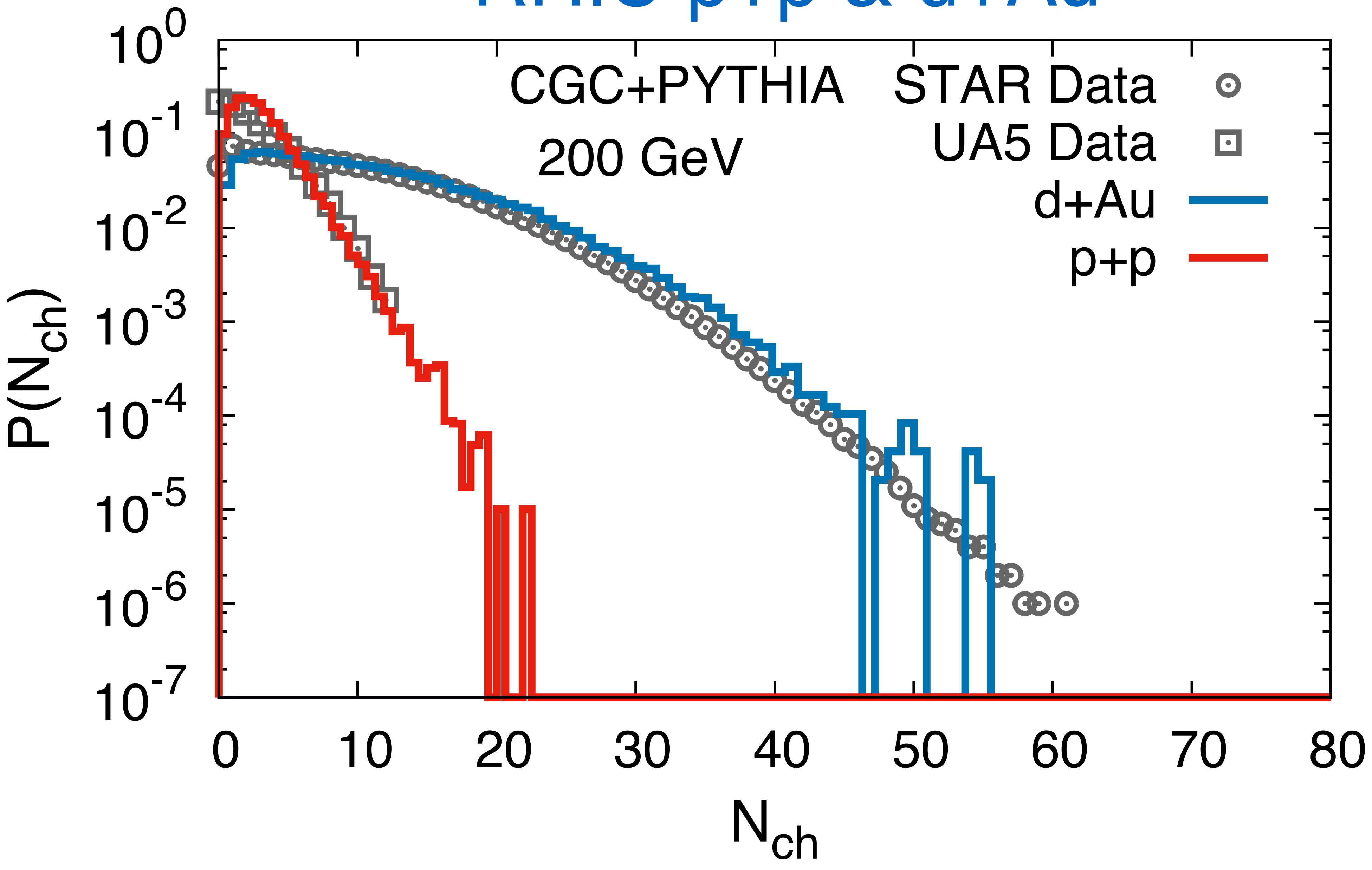
n-particle correlations & origin of high multiplicity events

Schenke, Schlichting, PT, Venugopalan
Phys. Rev. Lett. 117 (16) 162301

LHC p+p



RHIC p+p & d+Au



One of the most successful phenomenological results from the CGC approach

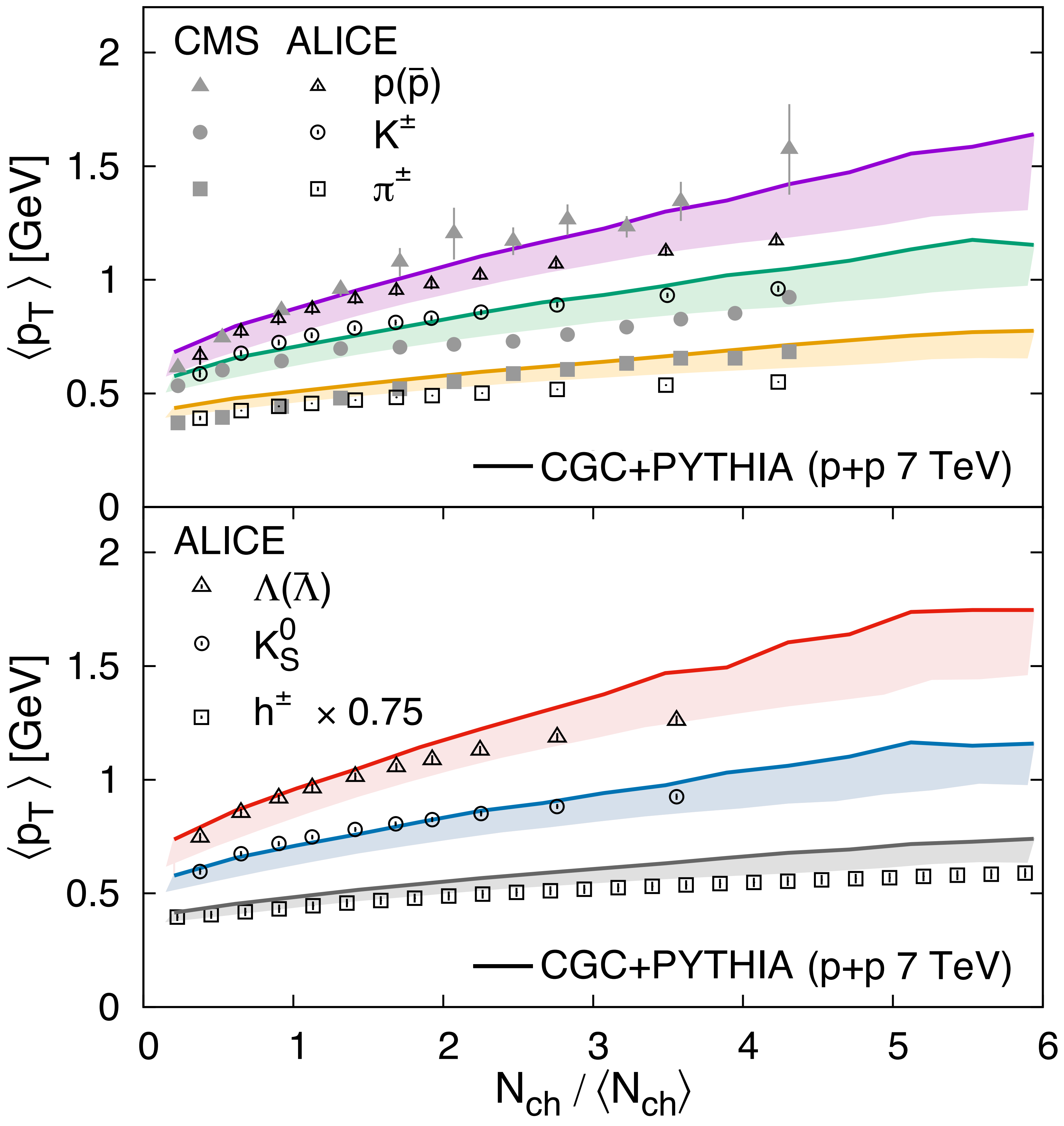
Negative binomial distribution is an input (by hand) in most phenomenological models, CGC naturally generates it, fragmentation does not modify the shape of it

Bulk observables in p+p@LHC from CGC+PYTHIA

Mass ordering of mean p_T

Schenke, Schlichting, PT, Venugopalan
Phys. Rev. Lett. 117 (16) 162301

$$\langle p_T \rangle_p > \langle p_T \rangle_K > \langle p_T \rangle_\pi \quad \& \quad \langle p_T \rangle_\Lambda > \langle p_T \rangle_{K^0_S} > \langle p_T \rangle_h$$

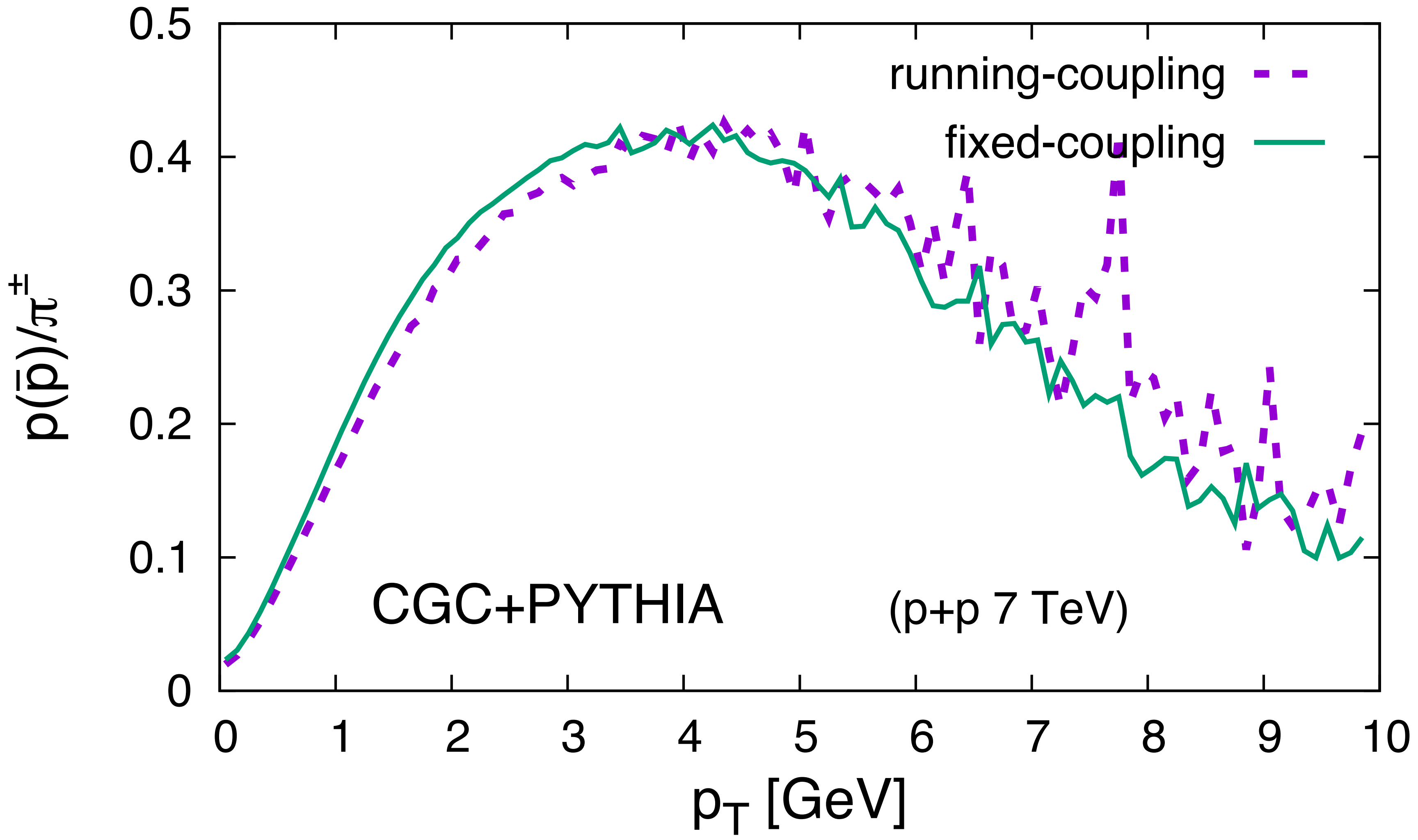


$$N_g \propto Q_S^2 S_\perp$$

$$\langle p_T \rangle_g \propto \langle Q_S \rangle$$

$$\langle p_T \rangle_g \propto \sqrt{N_g / S_\perp}$$

Proton to pion ratio



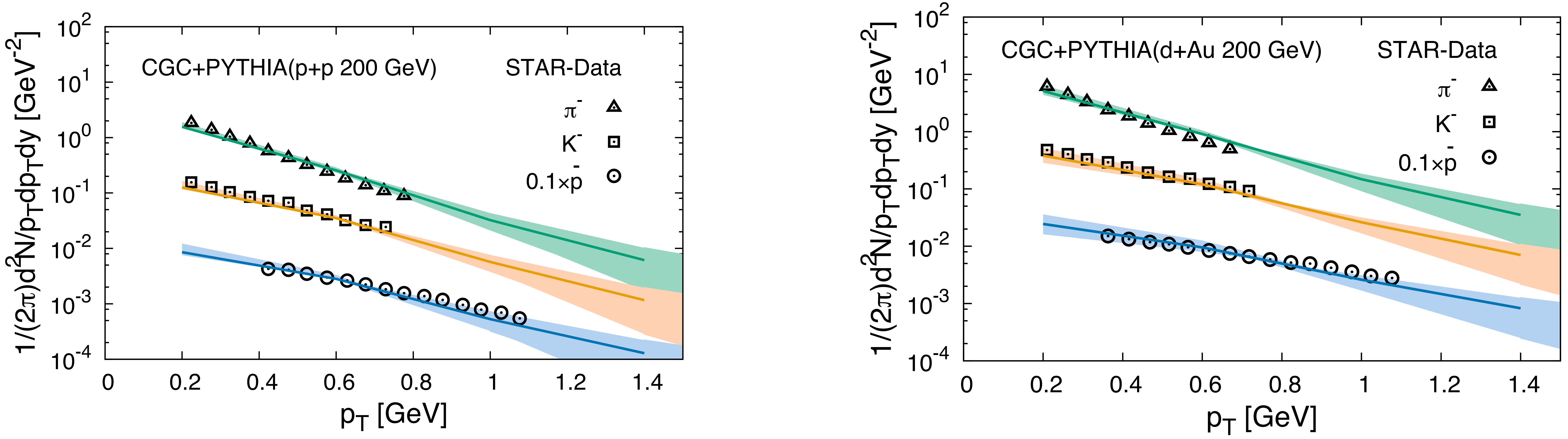
The growth of $\langle p_T \rangle$ with N_{ch} is a consequence of saturation scale driving multi particle production

Mass ordering, p/π ratio → feature of the fragmentation functions

A closer look at the RHIC data

Identified particle spectra from CGC+PYTHIA at RHIC

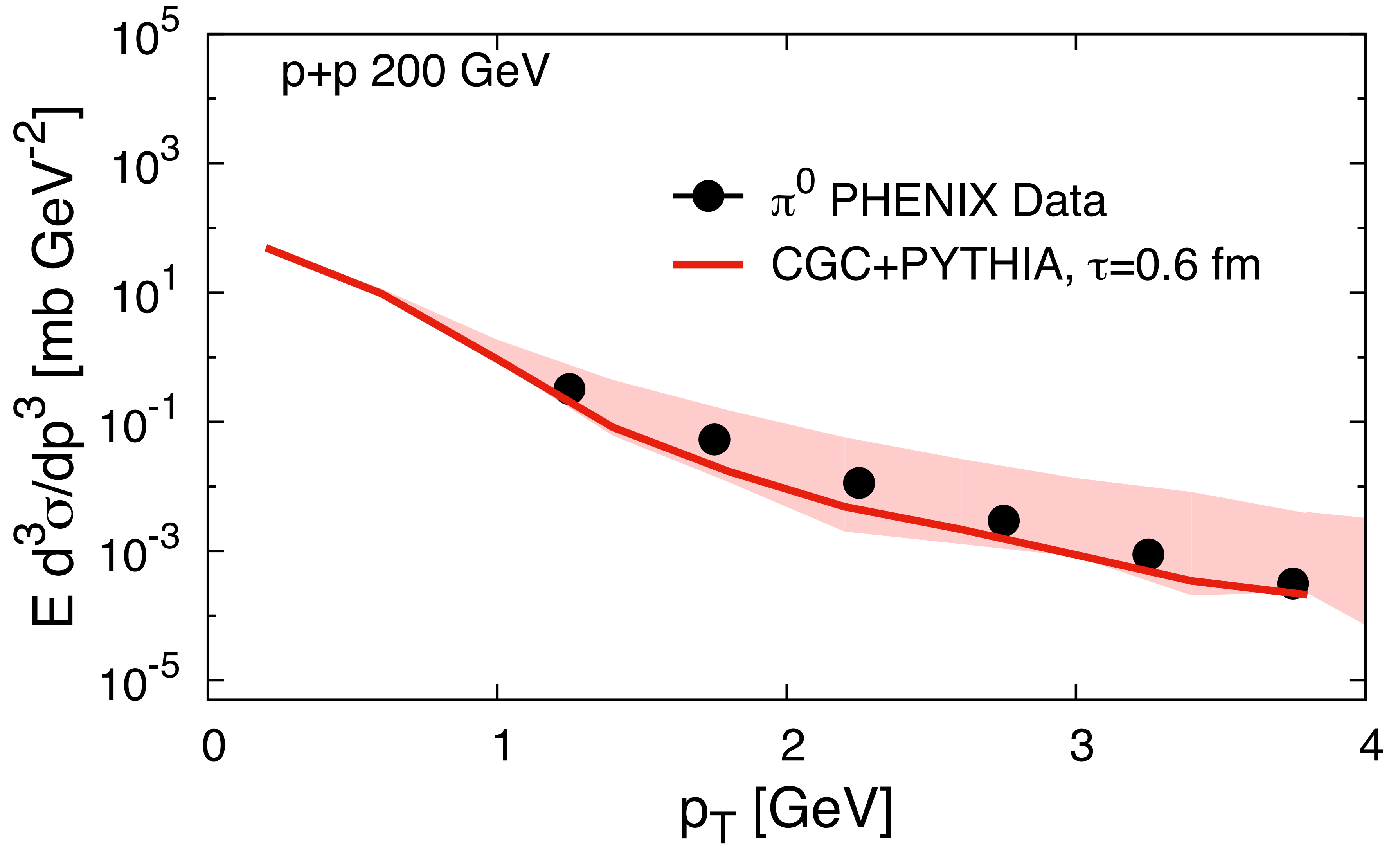
Schenke, PT work in progress

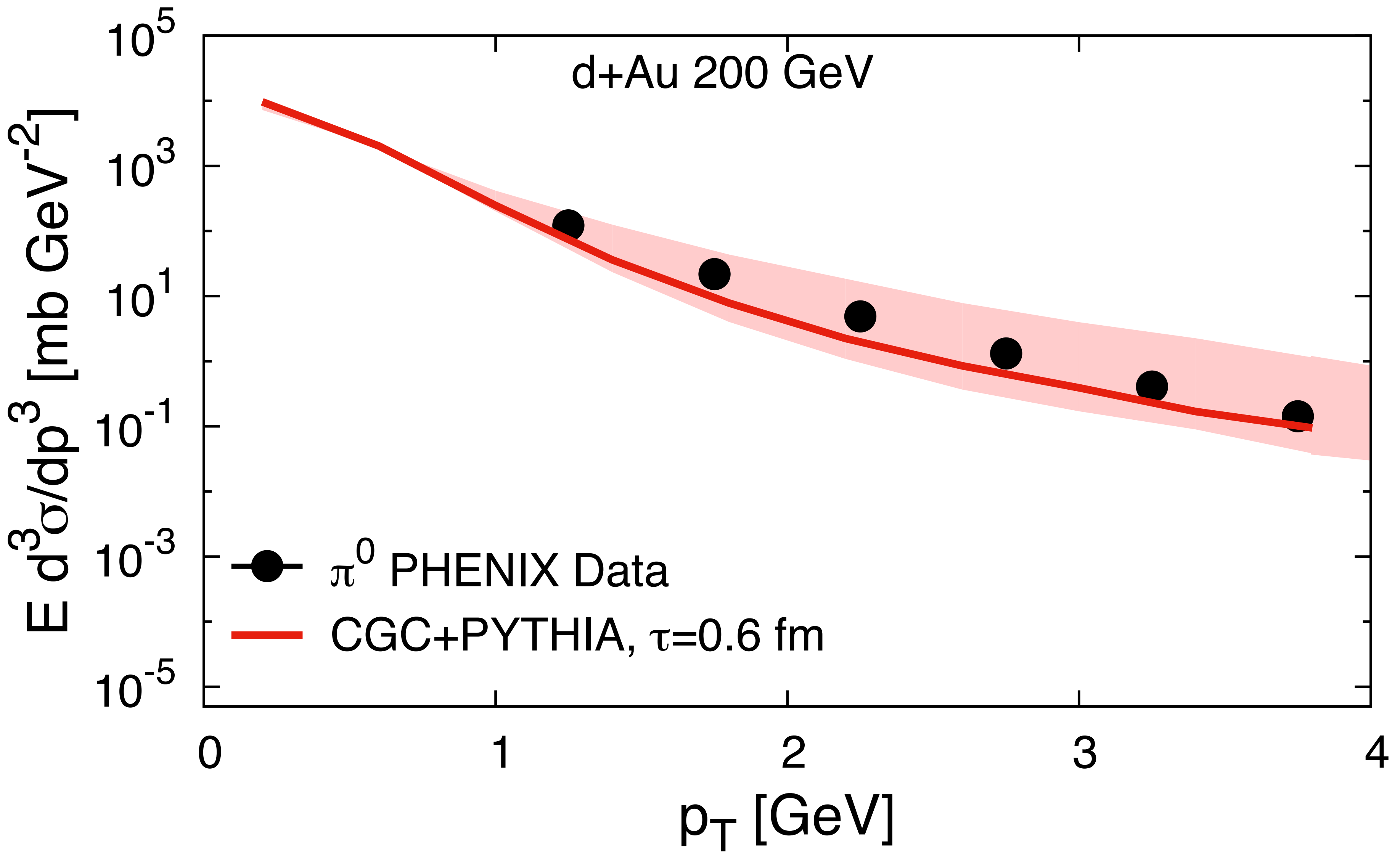


A good description of p+p & d+Au transverse momentum distributions, systematics due to lattice artifacts, fragmentation parameters → work in progress

Neutral pion spectra and nuclear suppression

Schenke, PT work in progress





A promising description of p+p & d+Au transverse momentum distributions, systematics due to lattice artifacts, fragmentation parameters → work in progress

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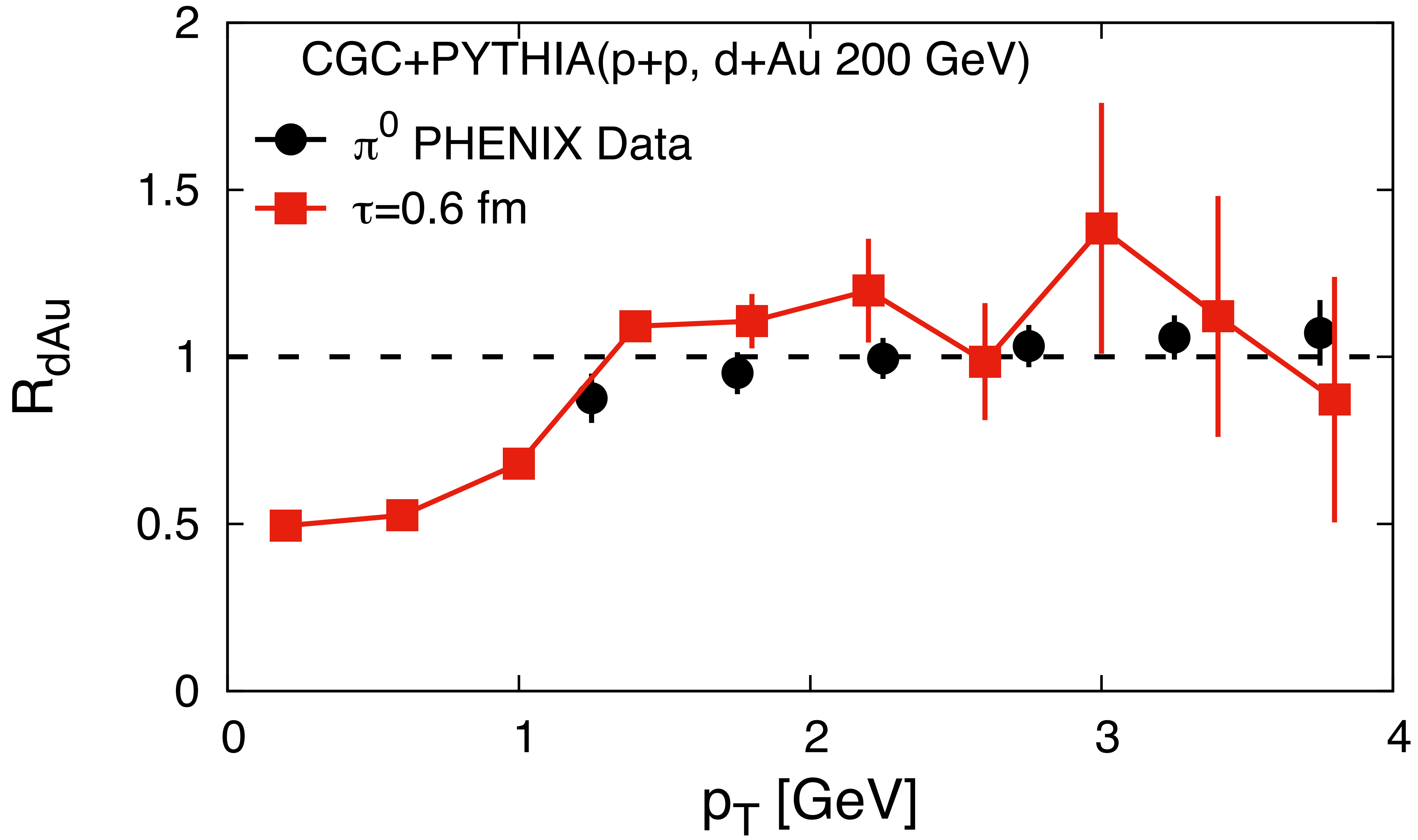
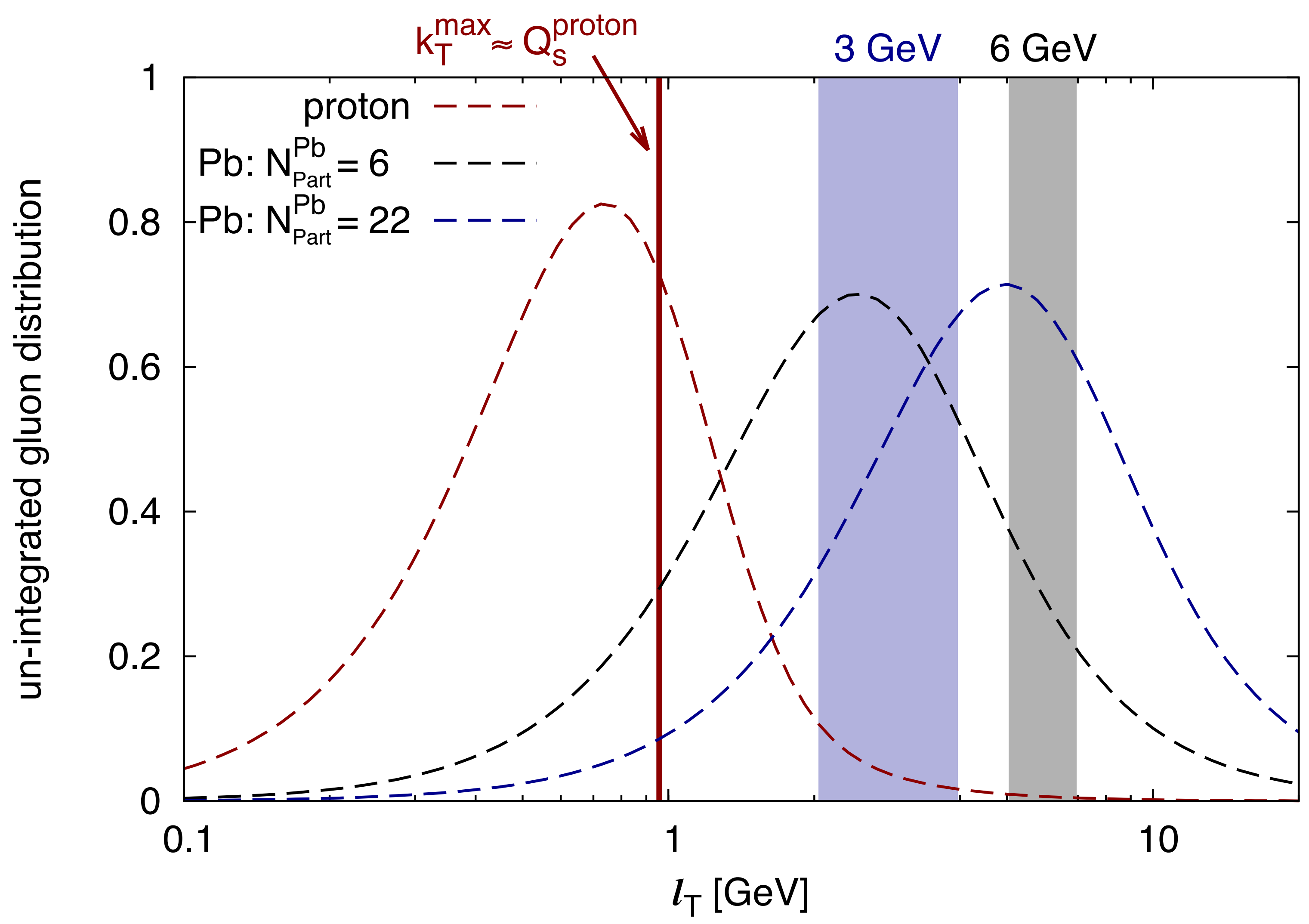


fig : Dusling, Venugopalan 1211.3701

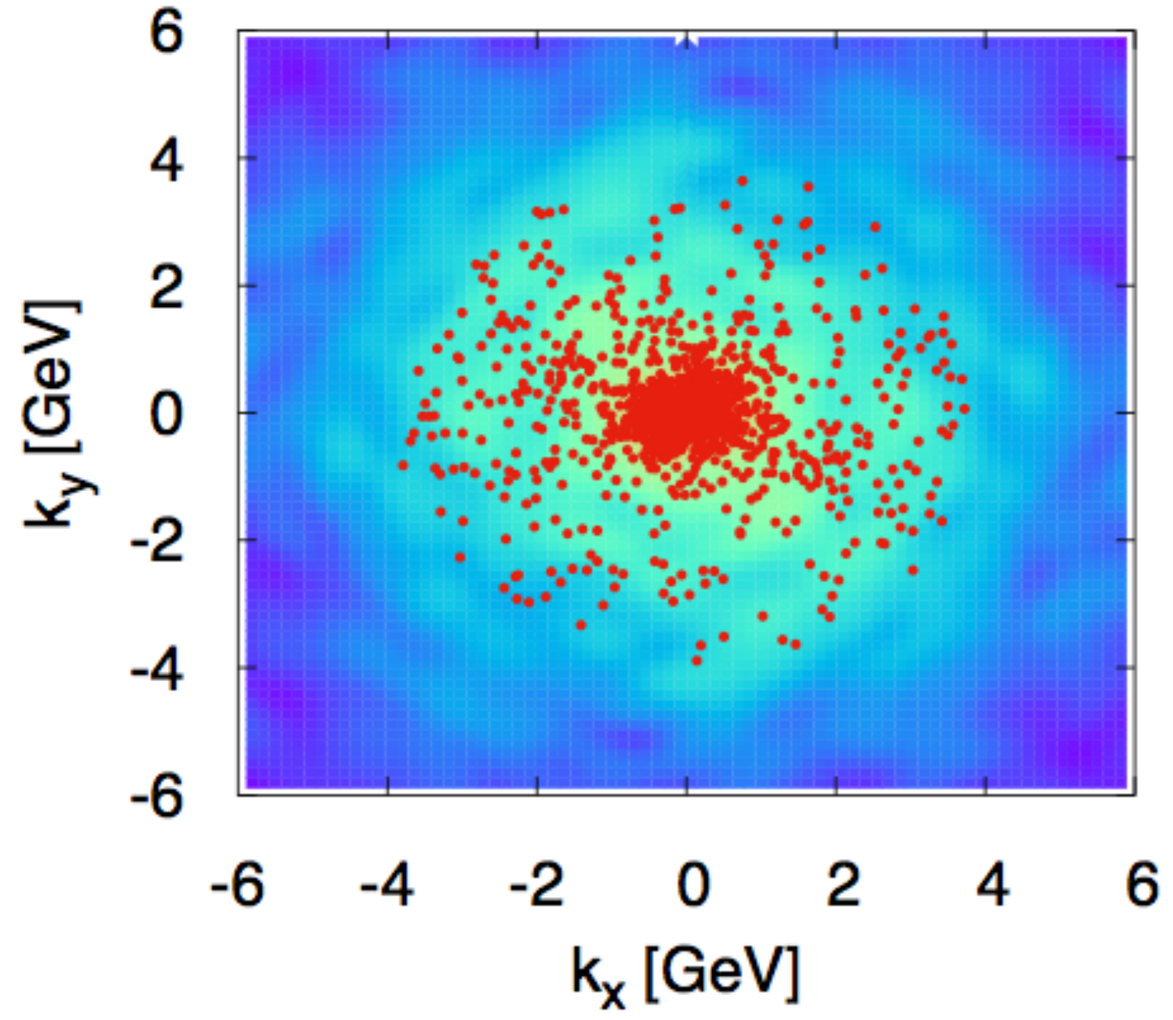


At a fixed p_T, gluon distribution inside projectile & target wave functions control the shape of R_{d+A}

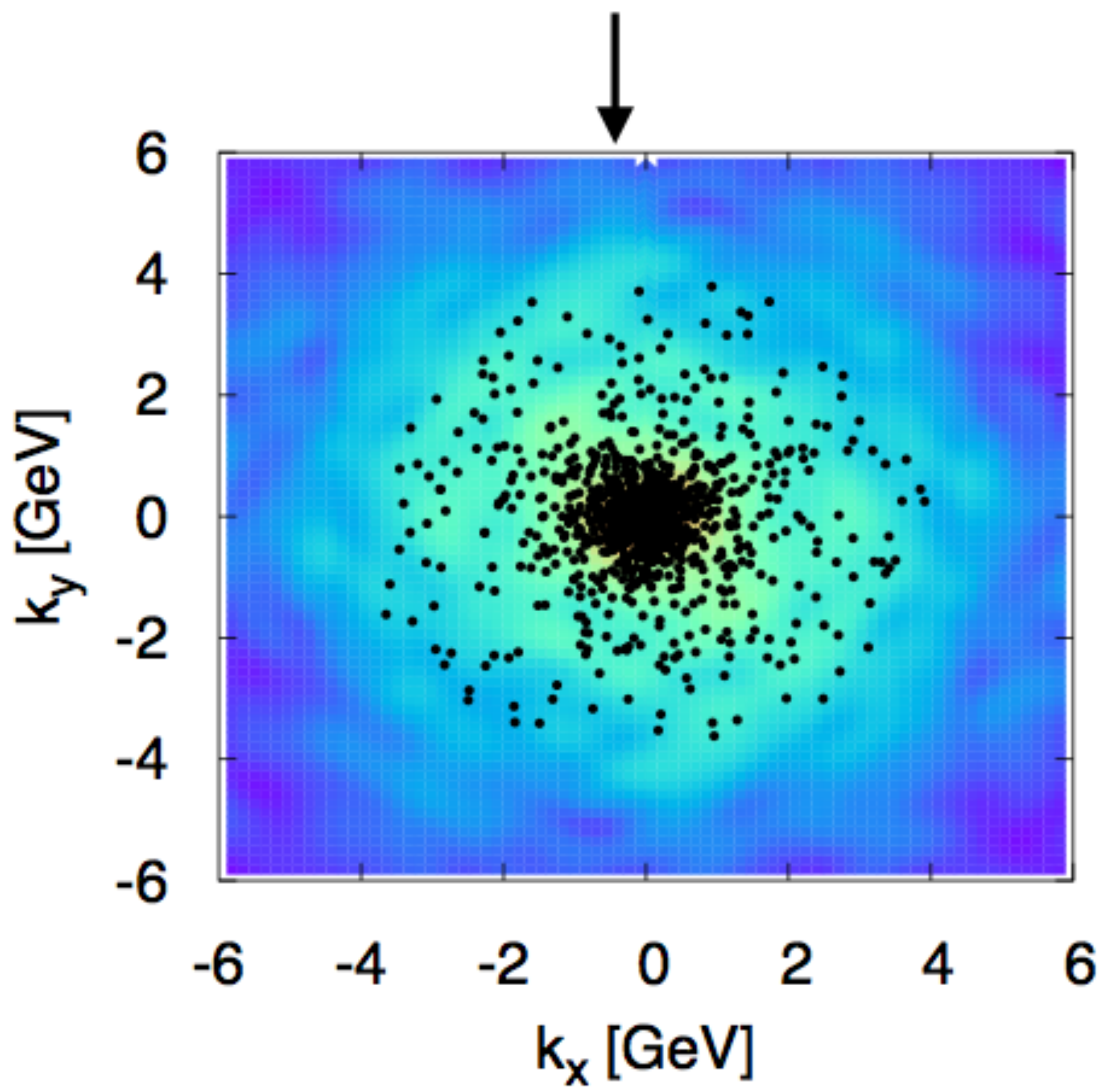
CGC+PYTHIA → ideal framework, captures e-by-e fluctuations of the target/projectile wave functions

Results on azimuthal correlations

Long range di-hadron correlations form CGC+PYTHIA

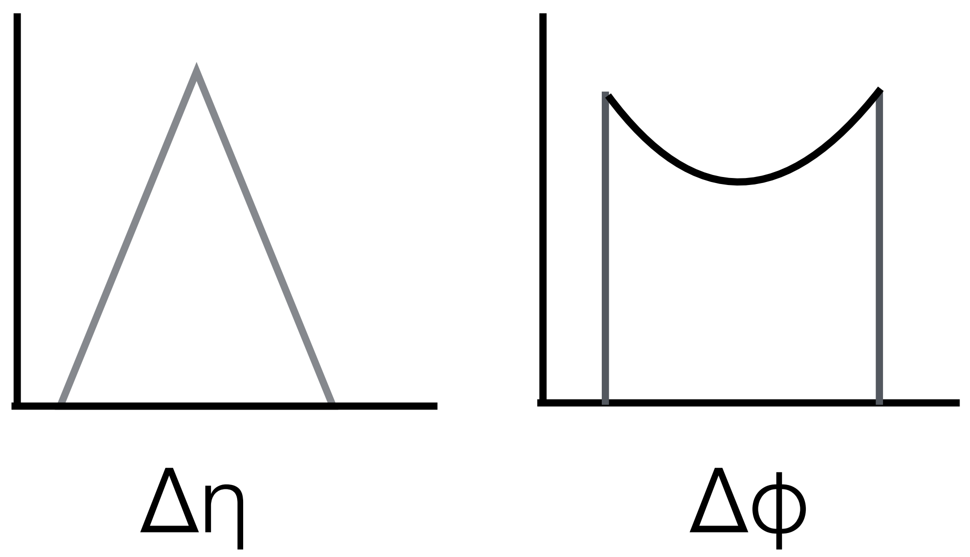


randomize φ [0-2π]



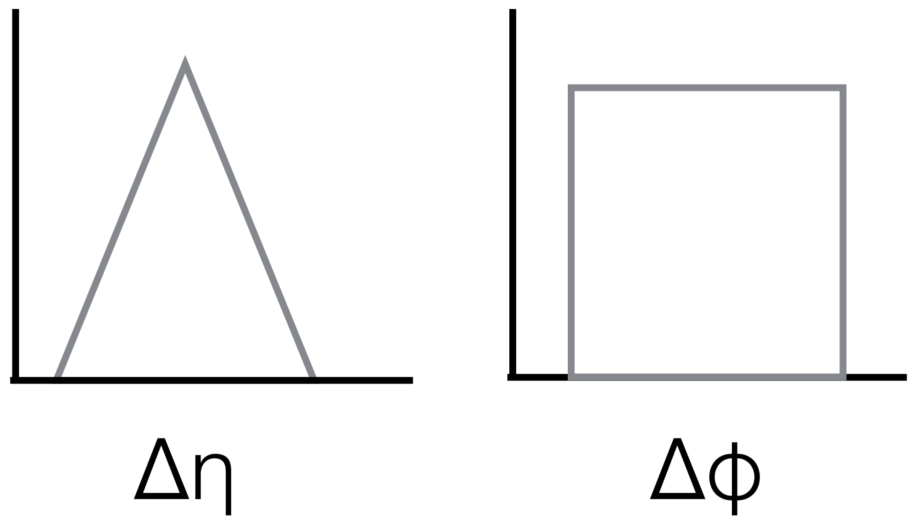
$S(\Delta\eta, \Delta\phi)$

Real events



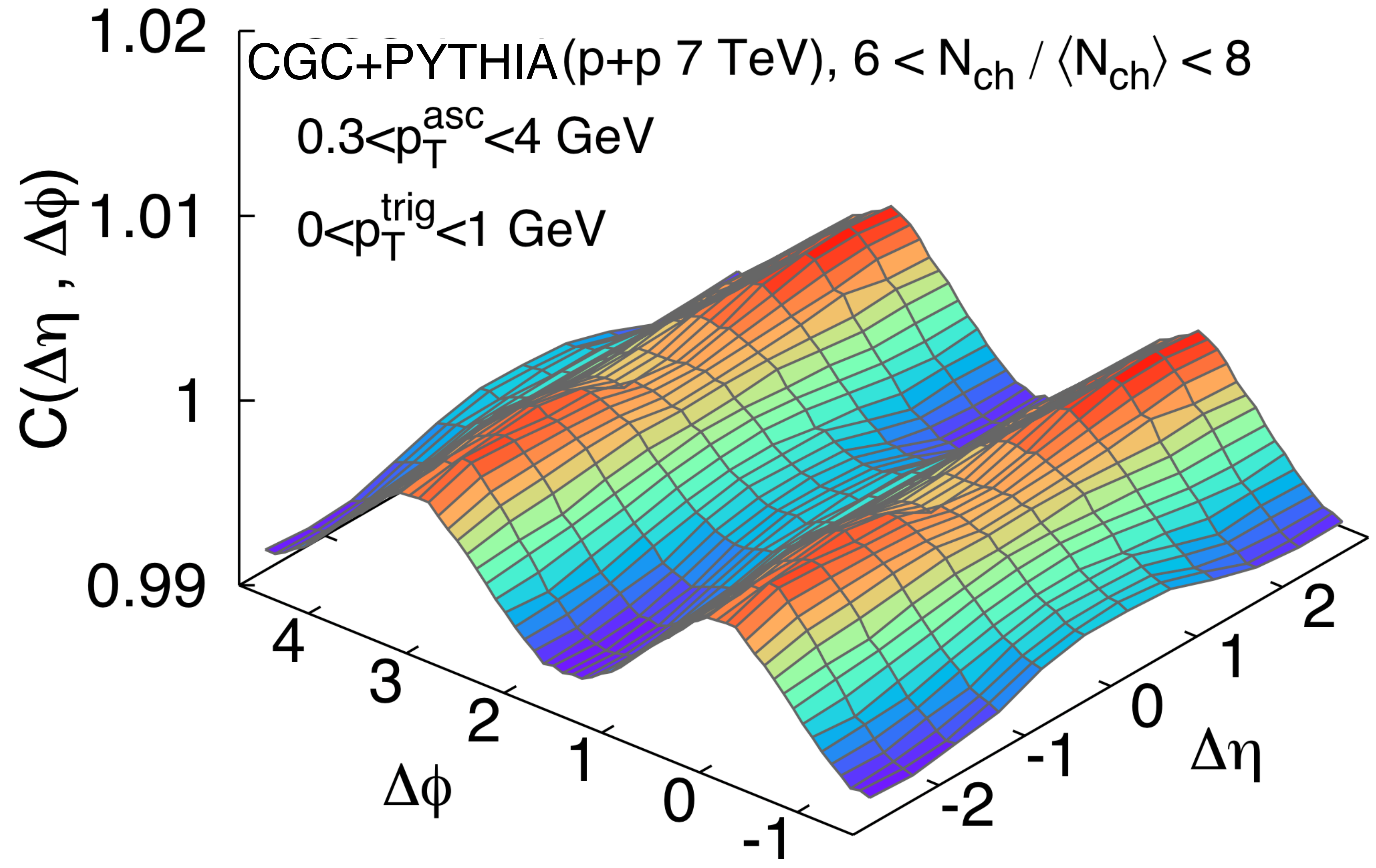
$B(\Delta\eta, \Delta\phi)$

Mixed events



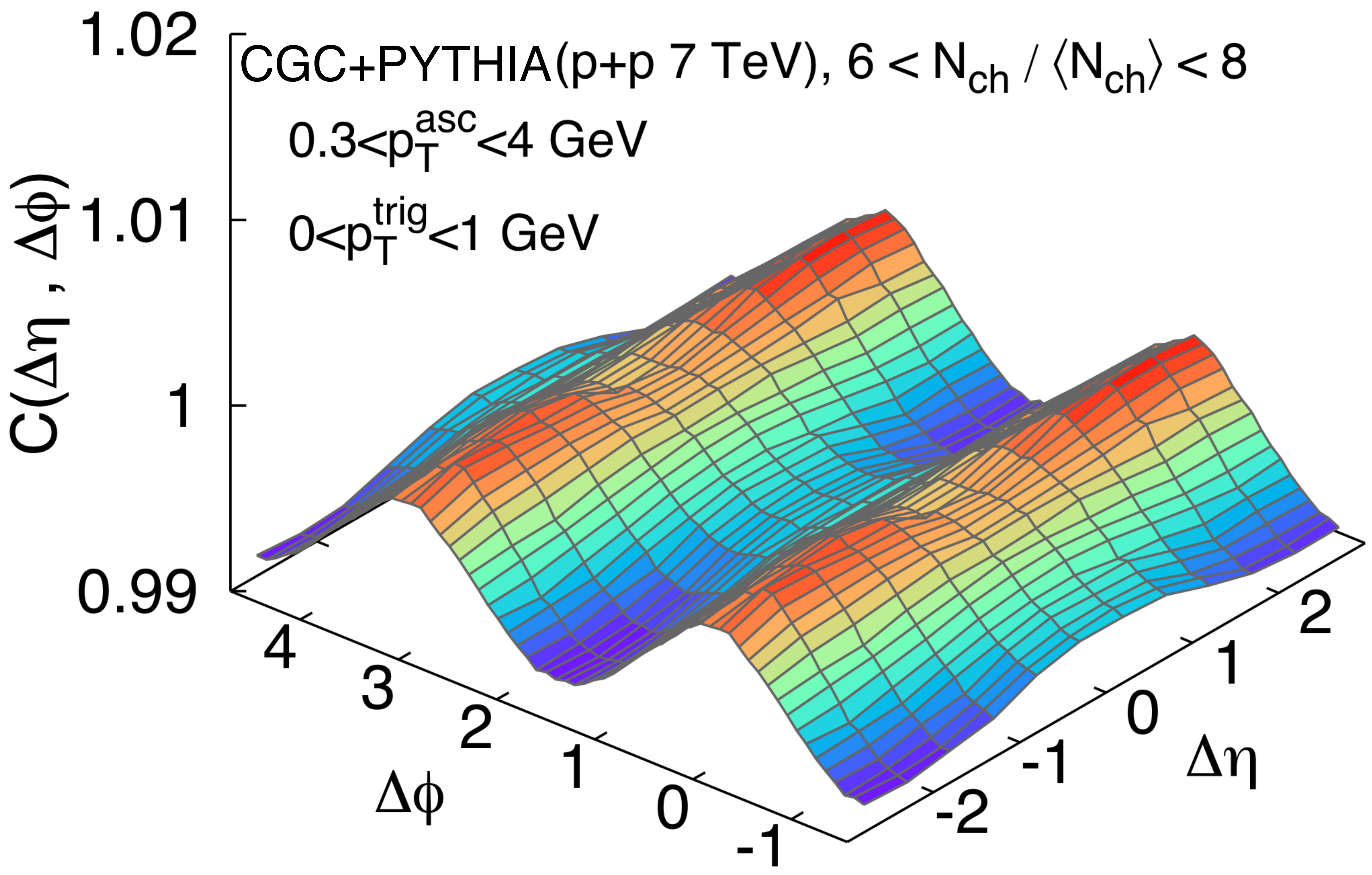
Schenke, Schlichting, PT, Venugopalan
Phys. Rev. Lett. 117 (16) 162301

Obtaining the normalized two dimensional correlation function

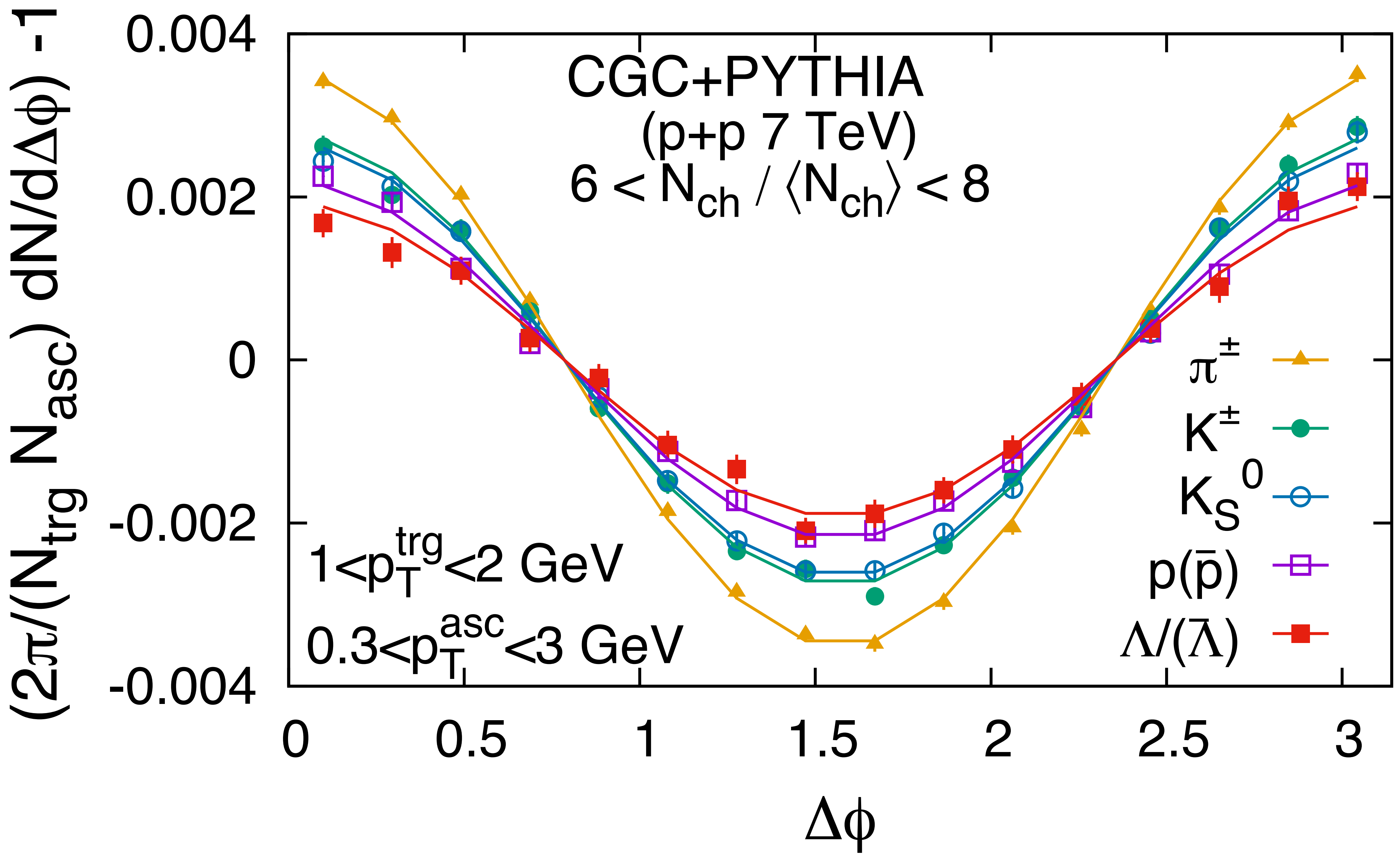


Mass ordering of ridge form CGC+PYTHIA

Schenke, Schlichting, PT, Venugopalan
Phys. Rev. Lett. 117 (16) 162301



Mass ordering of the correlations functions with identified particles as trigger

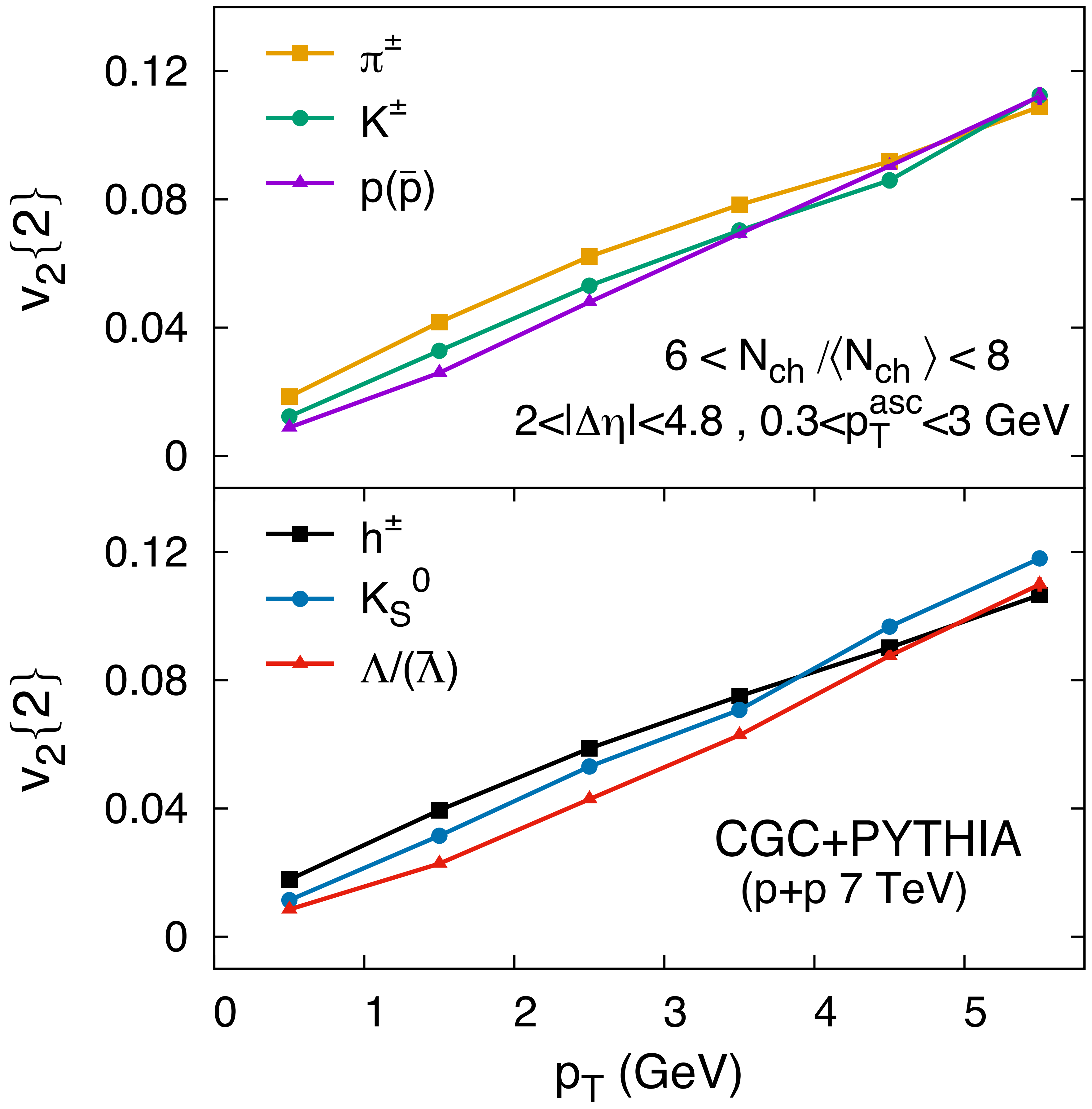


$$\frac{2\pi}{N_{\rm trig}^{\rm PID} N_{\rm assoc}^{h^\pm}} \frac{dN^{\rm pair}}{d\Delta\phi} = 1 + \sum_n 2V_{n\Delta} \cos(n\Delta\phi)$$

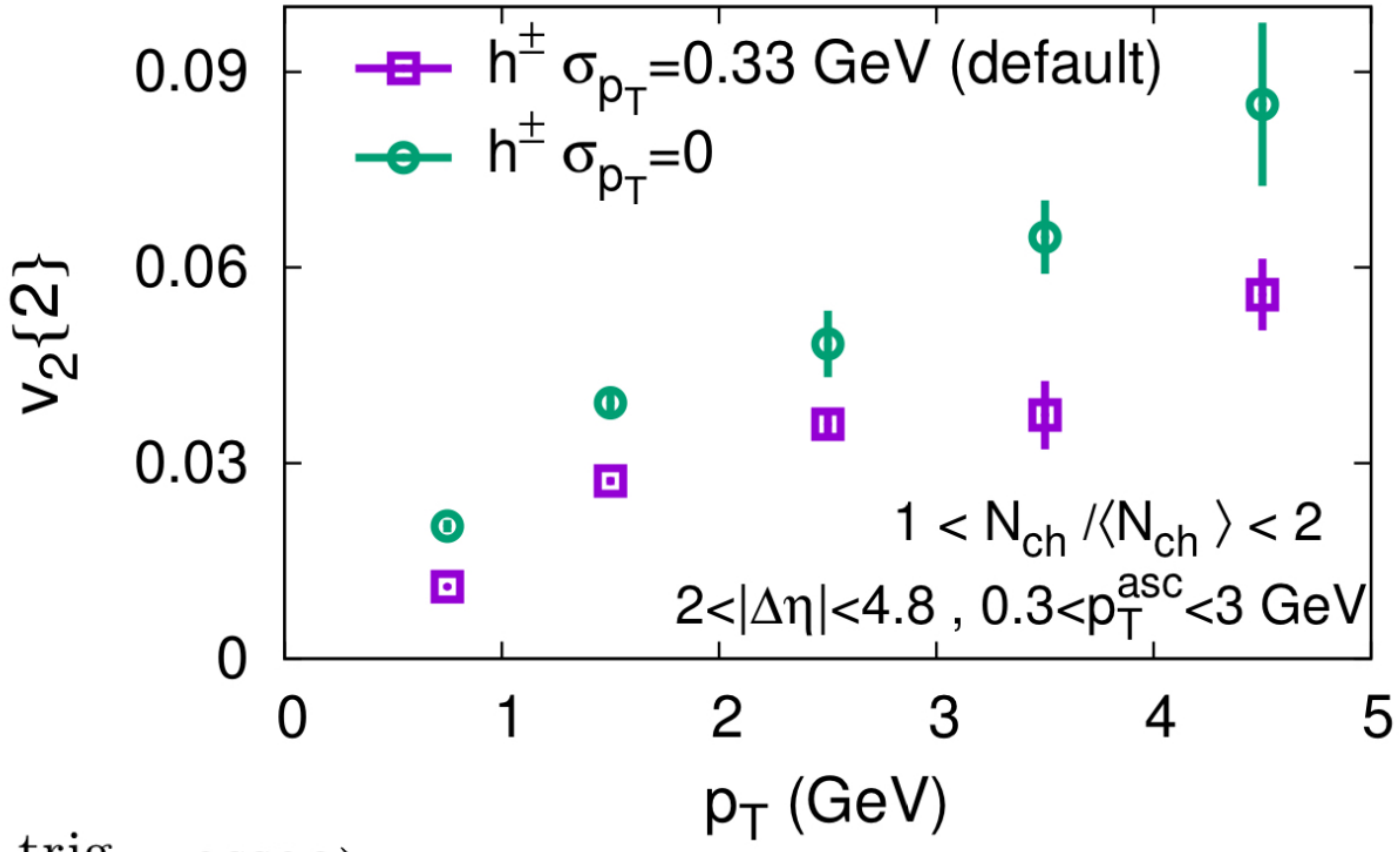
Mass ordering of v_2 form CGC+PYTHIA

Mass ordering of v_2, identified hadrons as trigger

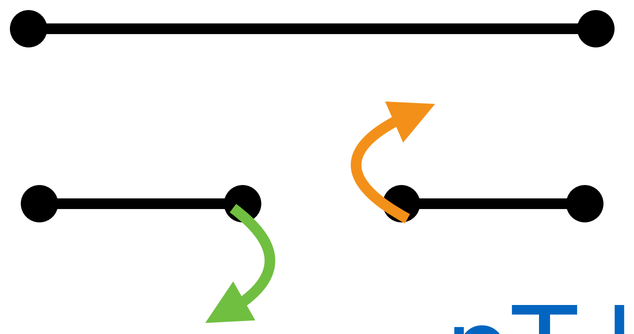
Schenke, Schlichting, PT, Venugopalan
Phys. Rev. Lett. 117 (16) 162301



Systematics from pT smearing during PYTHIA string fragmentation



$$v_n\{2\}(p_T^{\rm trig}) = \frac{V_{n\Delta}(p_T^{\rm trig}, p_T^{\rm assoc})}{\sqrt{V_{n\Delta}(p_T^{\rm assoc}, p_T^{\rm assoc})}}$$



pT kick

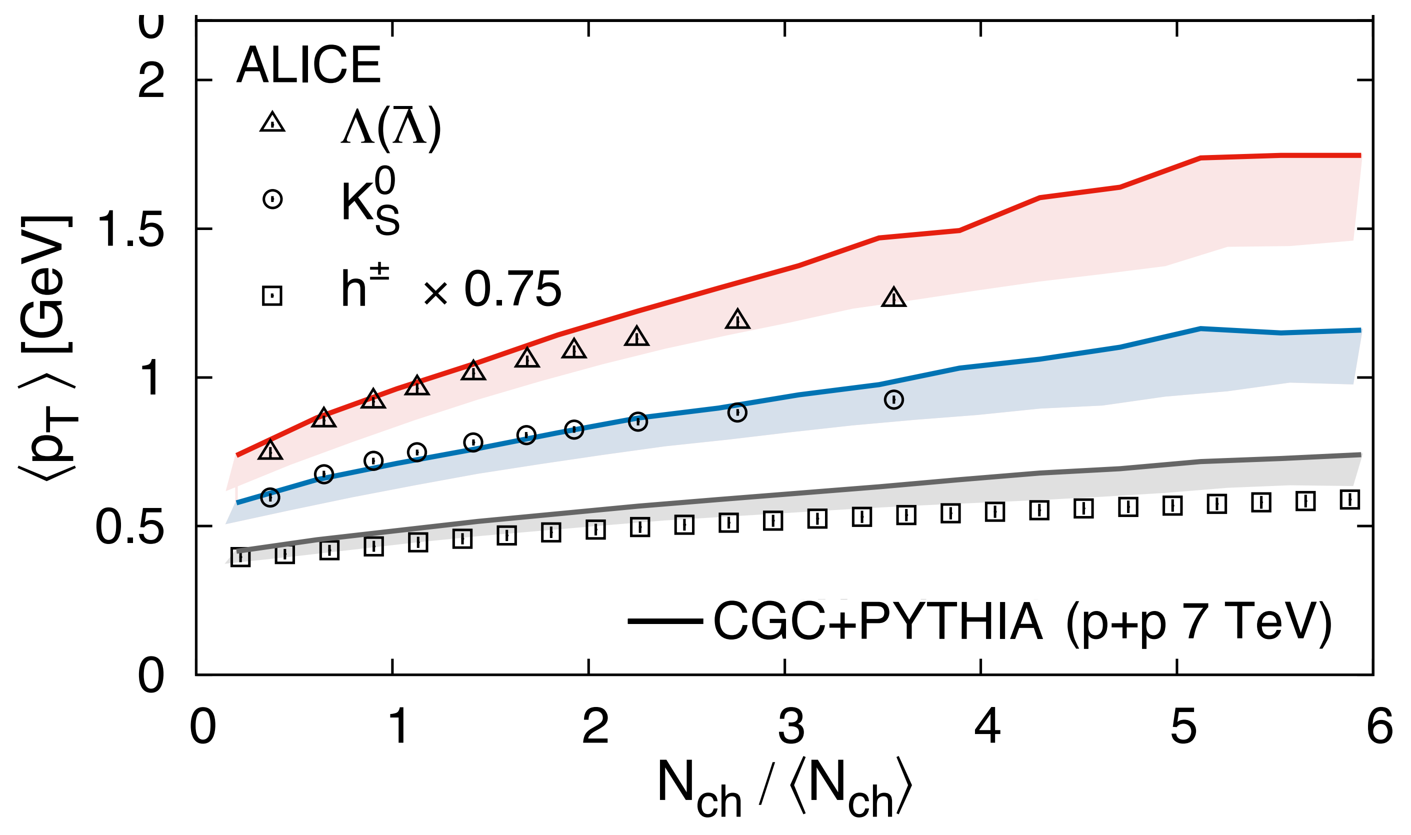
v_2 in p+Au, d+Au, He+Au : talk by Mark Mace (this afternoon)

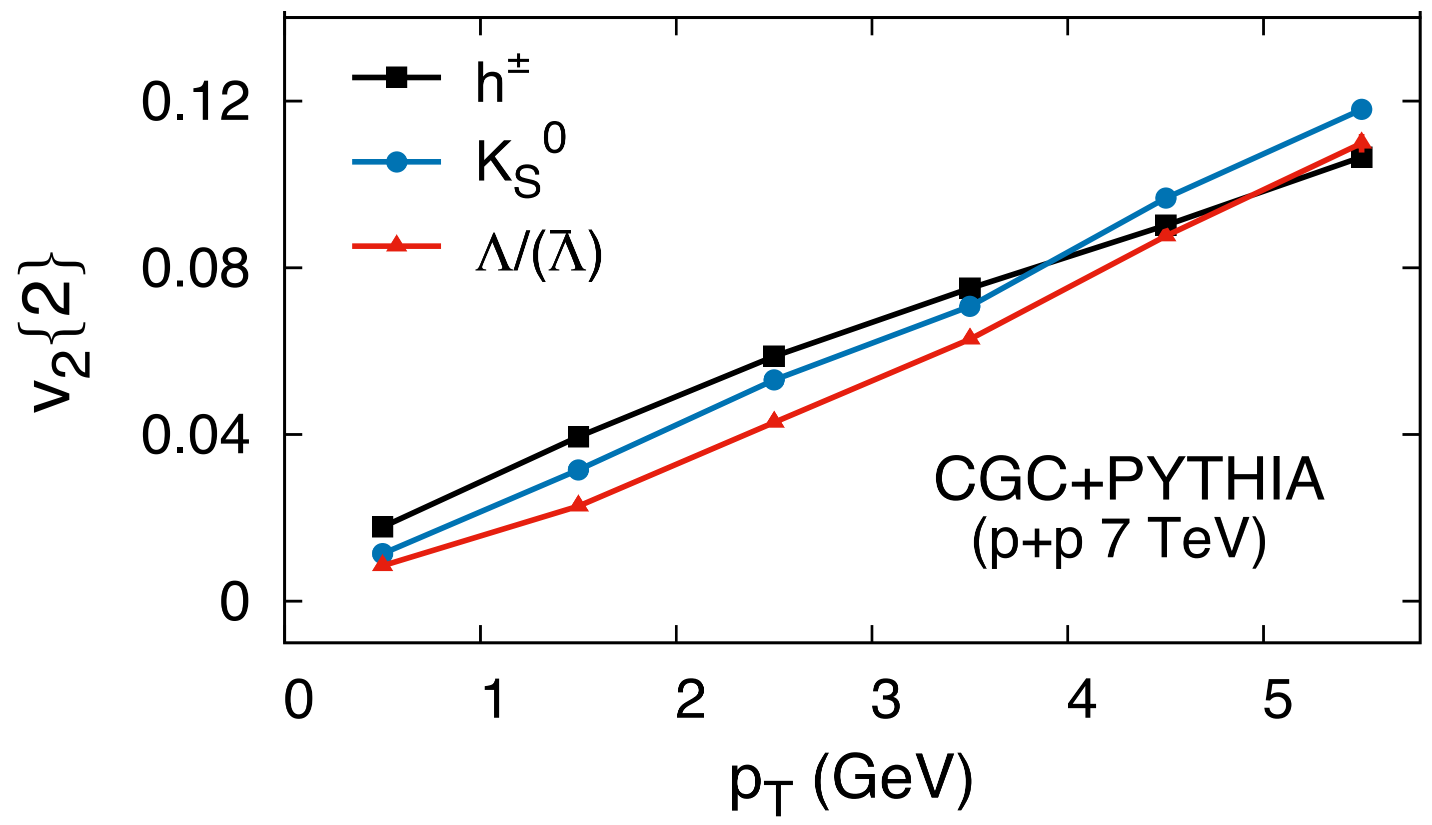
Summary

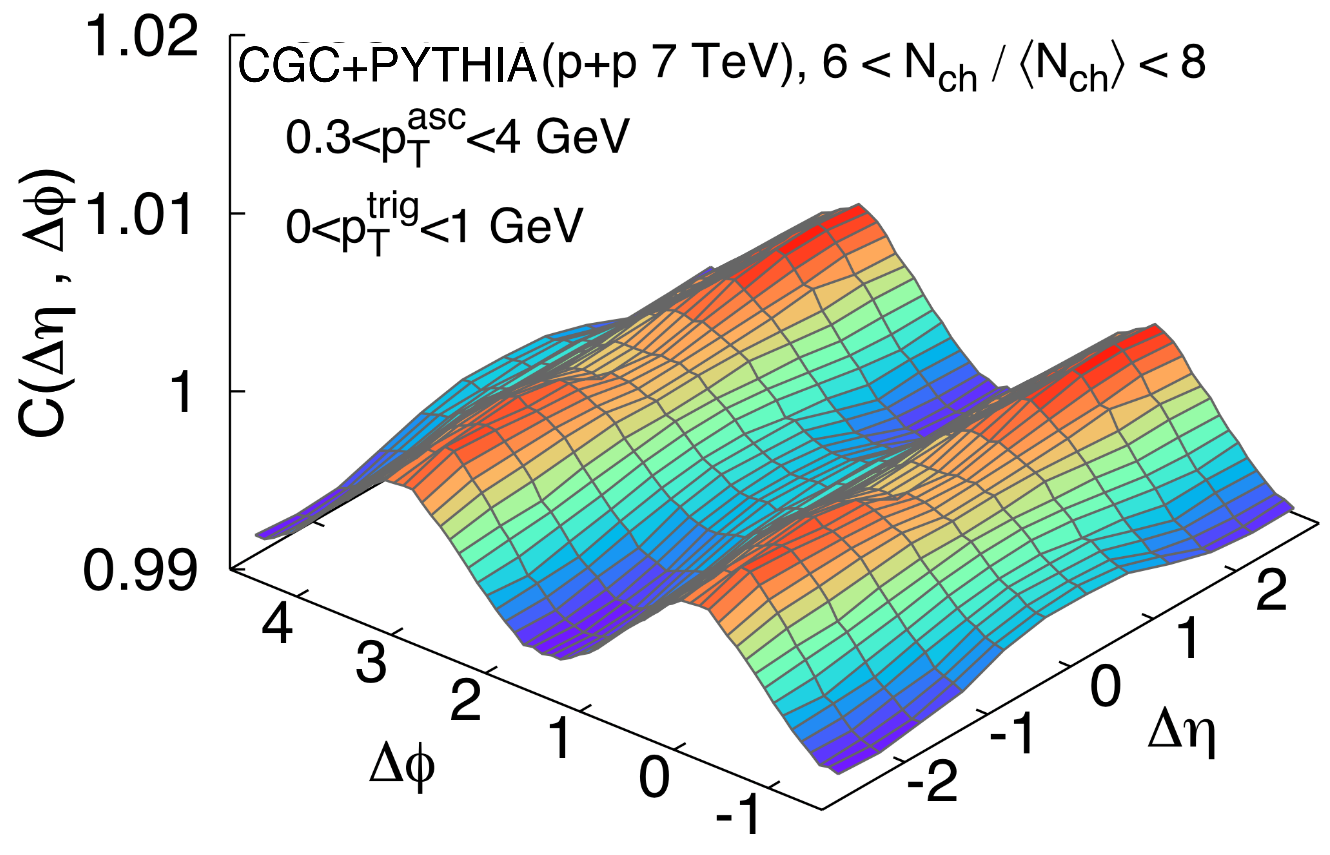
Very first attempt to combine CGC model with the fragmentation in PYTHIA

Description of many observable without invoking final state rescattering and collective expansion

The state of the art fragmentation will boost the phenomenology of CGC

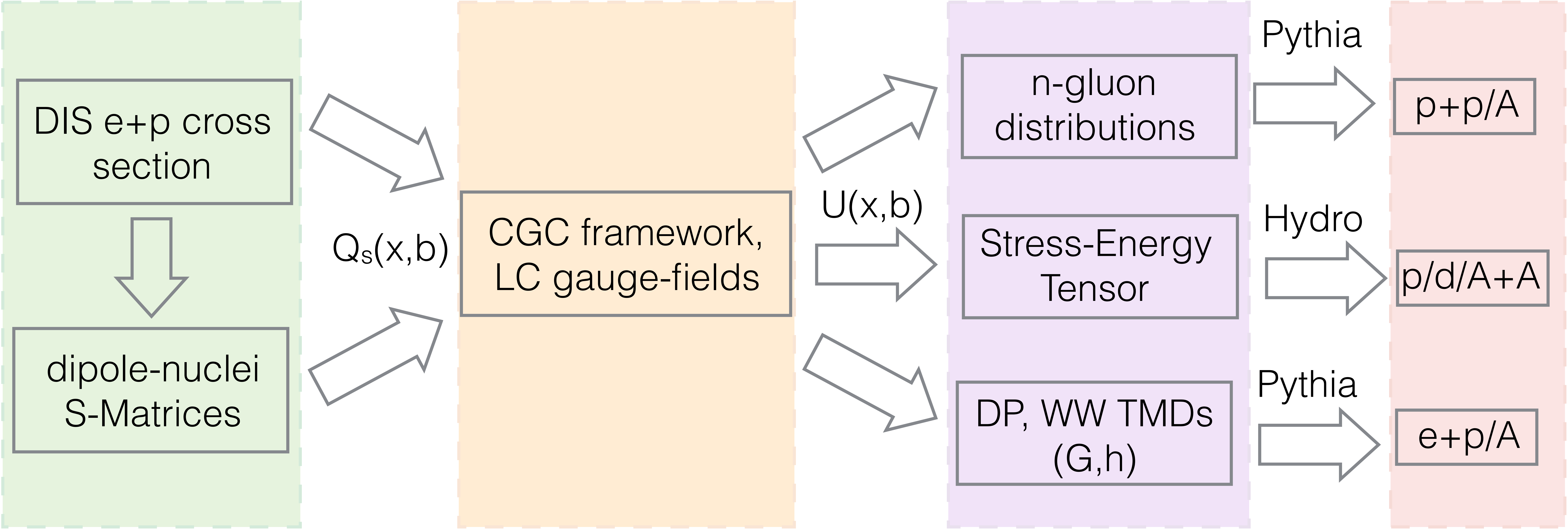






Thank You

Backup

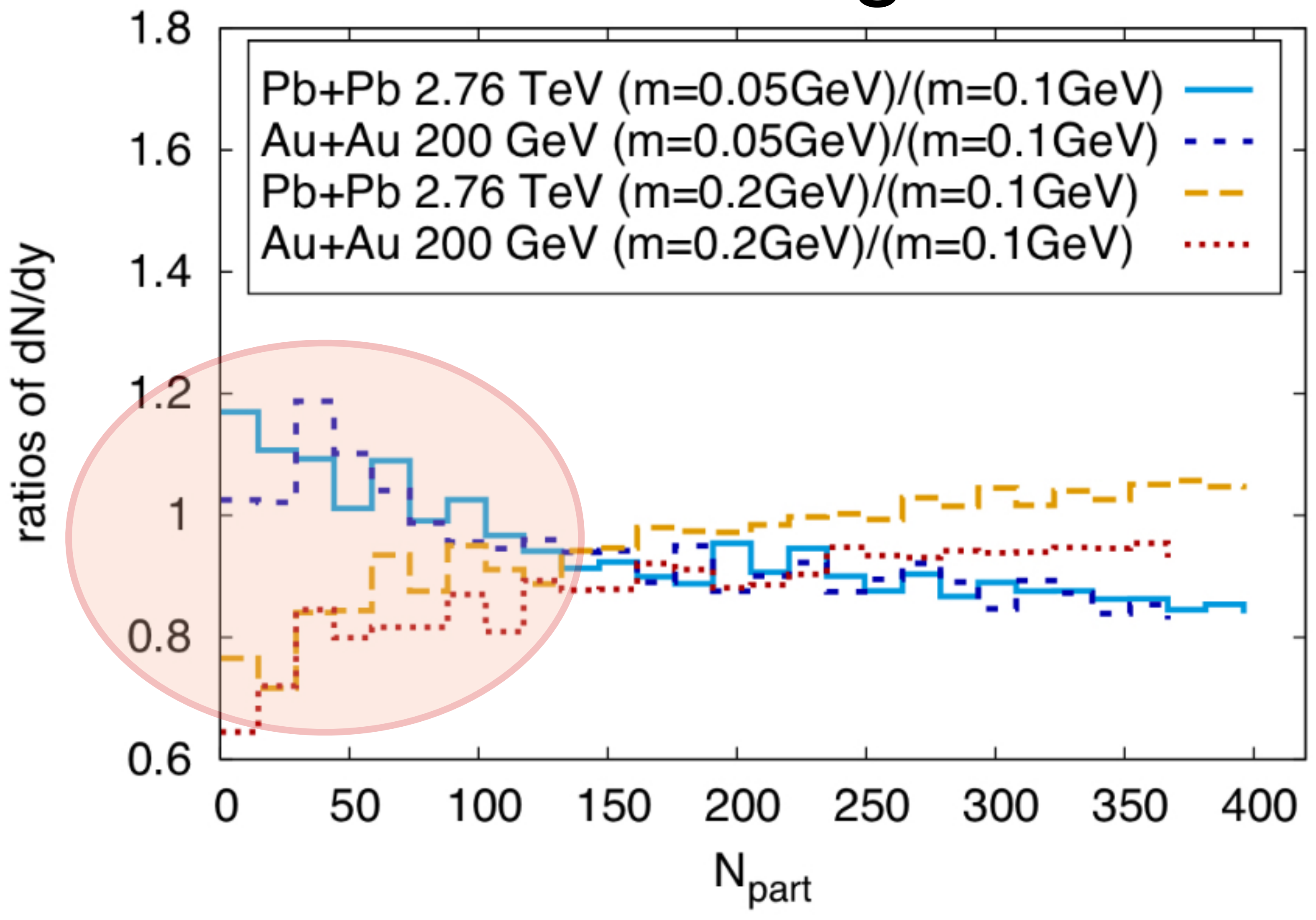


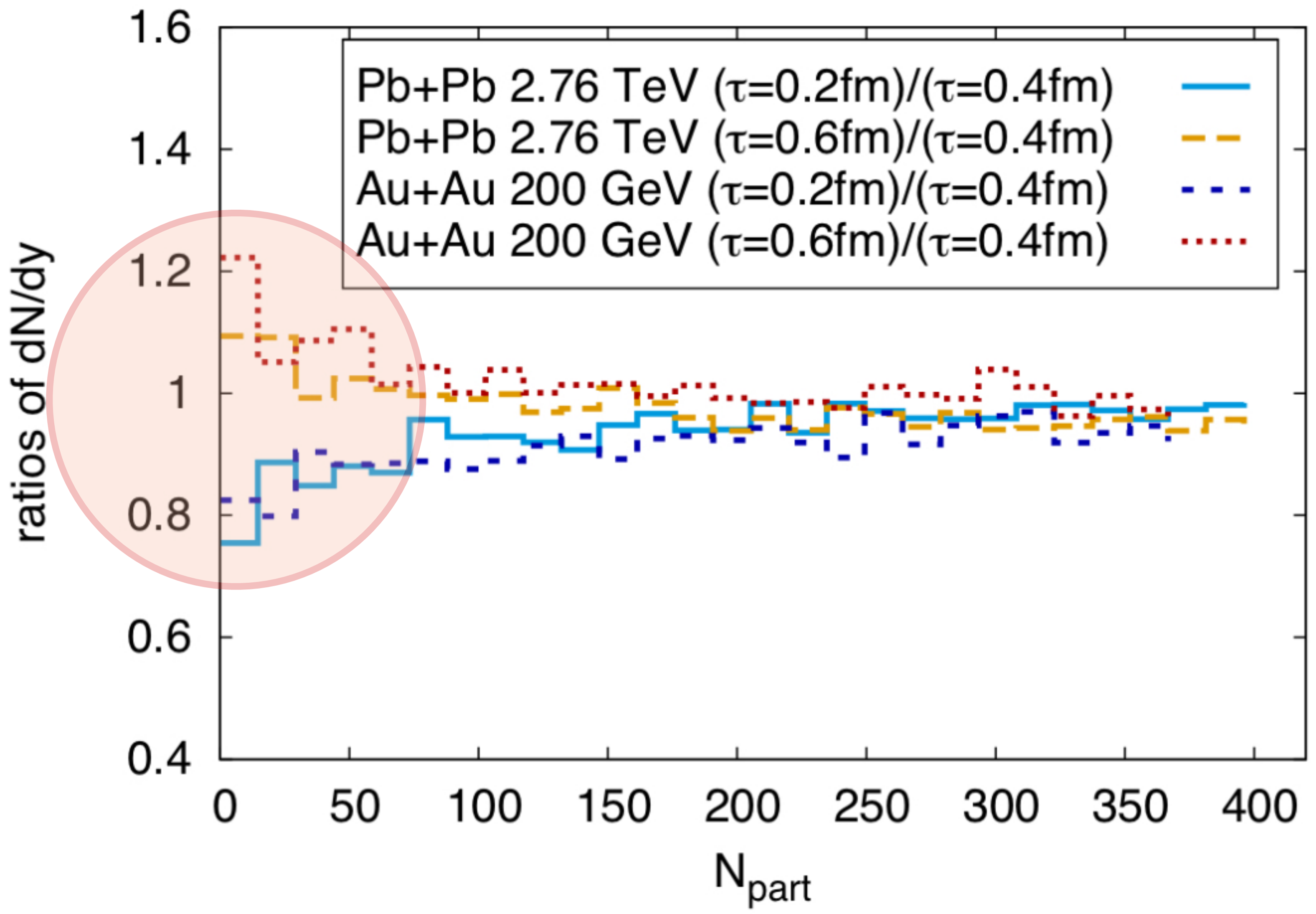
DIS e+p cross section
dipole-nuclei S-Matrices
$Q_s(x,b)$
CGC framework, LC gauge-fields
U(x,b)
n-gluon distributions
Stress-Energy Tensor
DP, WW TMDs (G,h)
Pythia
Hydro
Pythia
p+p/A
p/d/A+A
e+p/A

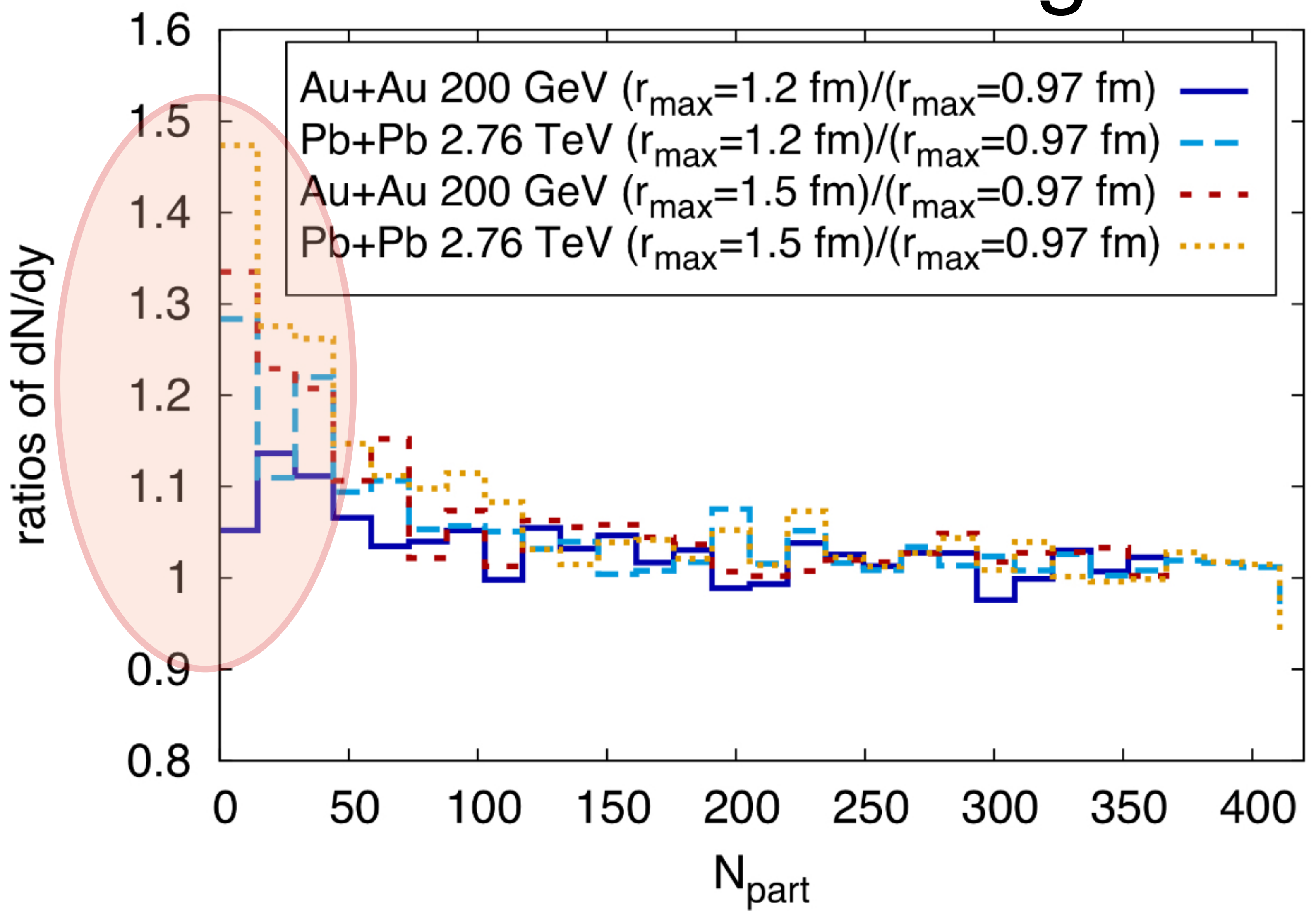
Systematics of CGC computations on Lattice

Schenke, PT, Venugopalan Phys. Rev. C 89 (2), 024901

Strong Lattice artifacts in the limit of small system size



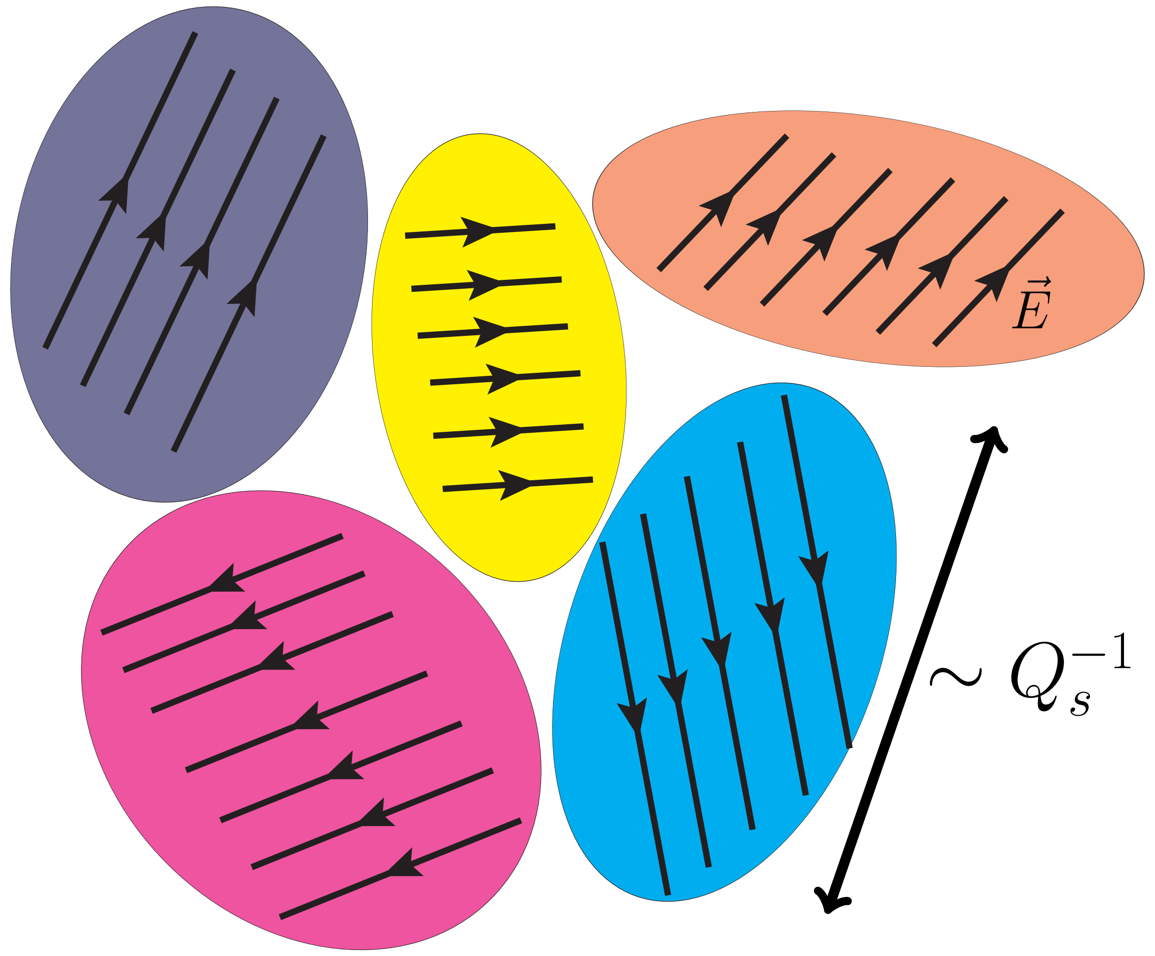




Azimuthal Correlations from CGC

$$\mathcal{D}(\mathbf{x},\mathbf{y}) \simeq 1 - \frac{(x-y)^i (x-y)^j}{4N_c} E_i^a\left(\frac{\mathbf{x}+\mathbf{y}}{2}\right) E_j^a\left(\frac{\mathbf{x}+\mathbf{y}}{2}\right),$$

- Intrinsic momentum space correlation from initial state
- Originate probe scattering off a color domain
- Suppressed by number of color sources/domains pT > Qs
- Multiple scattering dominate pT<Qs



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)