Initial state and pre-equilibrium effects in small systems

Soeren Schlichting

Based on work in collaboration with:
Dusling, Lappi, Schenke, Tribedy, Venugopalan

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BROOKHAVEN NATIONAL LABORATORY

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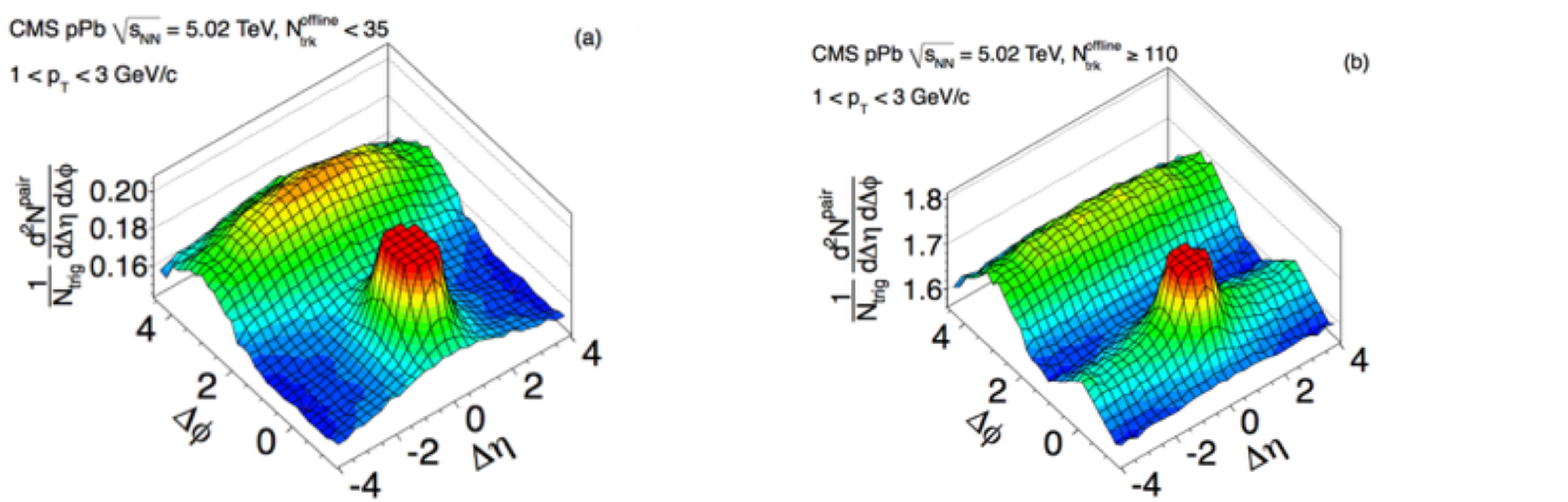
Long-range azimuthal correlations

Experimentally long-range azimuthal correlations have been observed in high multiplicity p+p,p+A and p/d/He3+A collisions

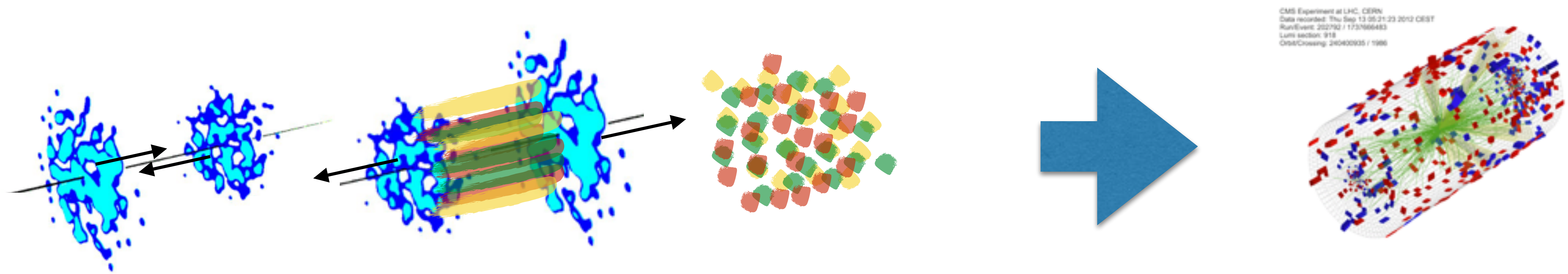
(c.f. overview talk by Wei Li)



low multiplicity → high multiplicity →

Even though several features of correlations observed in p+p/A reminiscent of A+A collisions, where this is attributed to hydrodynamics flow, there are also important differences, e.g. absence of jet-quenching

Initial state correlations



Initial state multi-particle production leads to momentum space correlations between the produced particles

While initial state effects are typically suppressed in A+A collisions (naively inversely proportional to system size) they can be sizable in small systems (p+p/A) in particular for larger p_T (~ a few GeV) which are less affected by final state effects

Outline

- Origin of initial state correlations
- Calculations in Color-Glass Condensate framework
- Initial state vs. final state effects
- Phenomenology
- Conclusions & Outlook

Back-to-back correlations between (mini-) jets

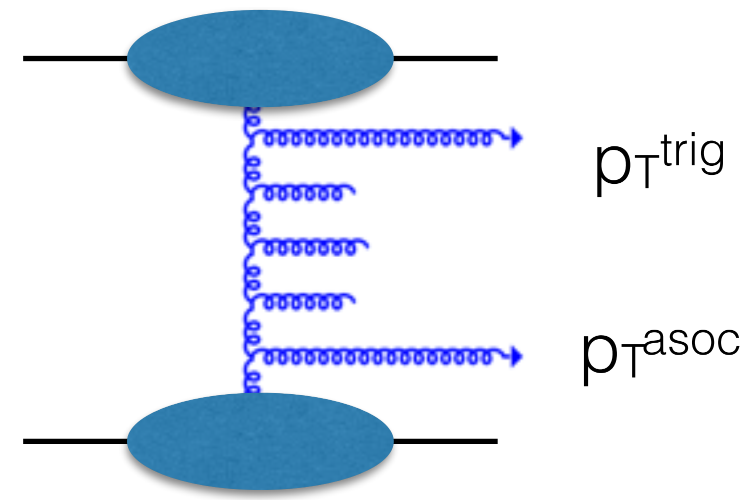
Multi-particle production from a single hard scattering

- Momentum conservation gives rise to long range ($\Delta\eta$) away side ($\Delta\phi \sim \pi$) correlation

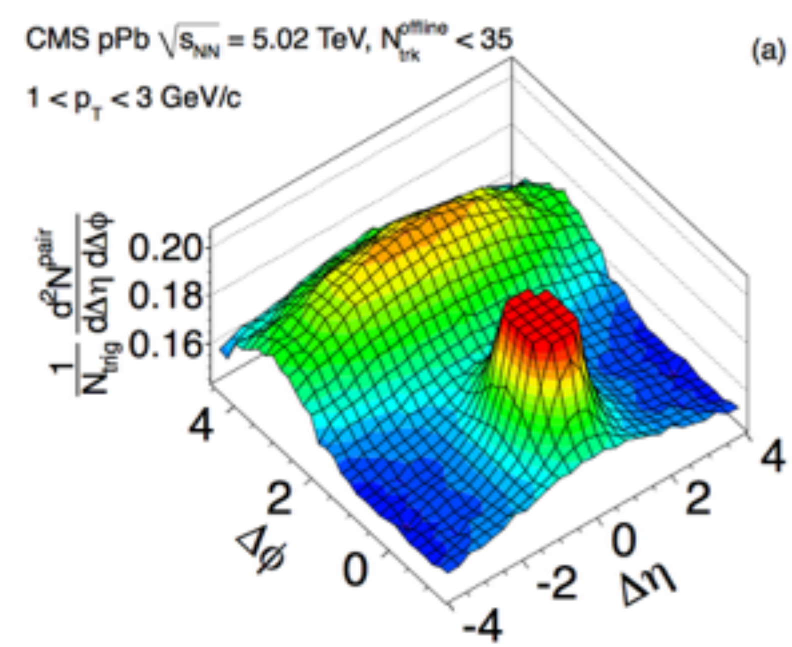
Dominant process for particle production in min. bias and low multiplicity p+p/A events

- Consistently observed in low-multiplicity events across all experiments

Included in standard multi-purpose event-generators (PYTHIA,…)



"jet graph"



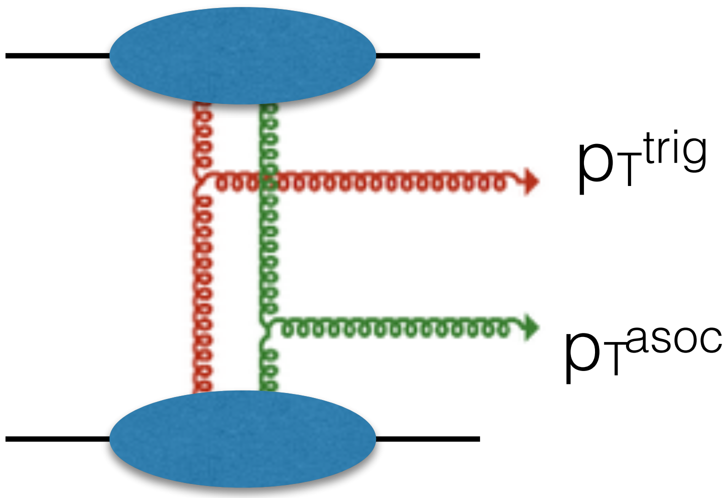
CMS PLB 718 (2013) 795

Correlated multi-particle production in high-multiplicity events

In high-multiplicity events one is probing rare configurations of the proton wave function with larger gluon densities

Multi-particle production from multiple gluon exchange becomes increasingly important

Correlation between produced particles are due to correlations of gluons inside the wave function of projectile and the target



"Glasma graph"

Dumitru, Dusling, Gelis, Jalilian-Marian,Lappi,Venugopalan PLB 697 (2011) 21-25

(Gelis,Lappi Venugopalan PRD 78 (2008) 054020, PRD 79 (2009) 094017; Dumitru, Gelis, McLerran,Venugopalan NPA8 10, 91 (2008); Dumitru, Jalilian-Marian PRD 81 (2010) 094015)

Correlated multi-particle production in high-multiplicity events

Intuitive picture at small x:

Bose enhancement of small x gluons in wave function allows treatment as a classical color-electric field

Color electric fields inside the projectile and target fluctuate from event-to-event and are locally organized in domains of size ~$1/Q_s$

Each parton scattering off the same domain receives a kick in the direction of the chromo-electric field which leads to a correlation in azimuthal angle

-> Near side long-range correlation ~$1/(N_c^2 Q_s^2 S_T)$

(Kovner,Lublinsky PRD 83 (2011) 034017; Dumitru, Giannini NPA 933 (2014) 212-228; Dumitru, Skokov PRD 91 (2015) 7, 074006; Lappi, Schenke, SS, Venugopalan 1509.03499)

Theoretical calculations

1 Initial state multi-particle production

perturbative calculation

Dumitru, Dusling, Gelis, Jalilian-Marian, Lappi, Venugopalan
PLB 697 (2011) 21-25

Dusling, Venugopalan
PRD 87 (2013) 5, 051502,
PRD 87 (2013) 5, 054014,
PRD 87 (2013) 9, 094034

Dusling,Tribedy, Vengopalan
PRD 93 (2016) 1 014034

hybrid formalism

Dumitru,Giannini
NPA933 (2015) 212-228

Dumitru,McLerran,Skokov
PLB 743 (2015) 134-137

Lappi
PLB 744 (2015) 315-319

Lappi,Schenke,SS,Venugopalan
JHEP 1601 (2016) 061

McLerran,Skokov
NPA 947 (2016) 142-154

Classical Yang-Mills simulations

Schenke, SS, Venugopalan
PLB 747 (2015) 76-82

Schenke,SS,Tribedy,Venugopalan
arXiv:1607.02496

2 Hadronization

Gluon level results

Fragmentation functions

Monte-Carlo fragmentation schemes (PYTHIA HSA)

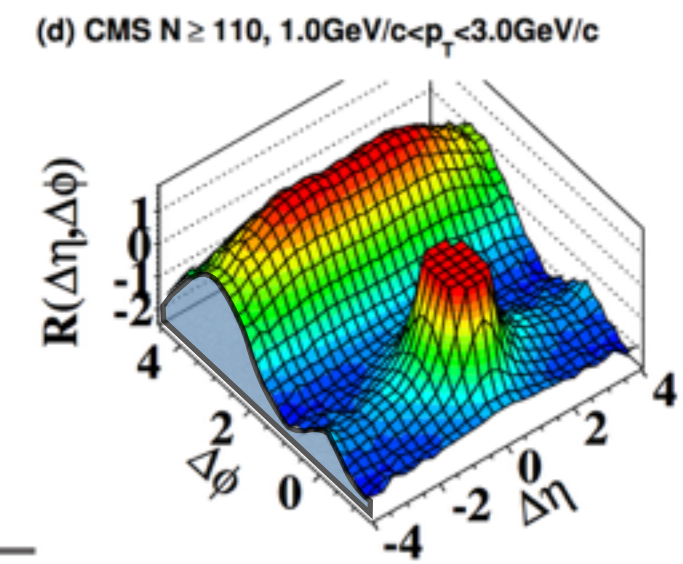
Theoretical calculations

Perturbative calculation in CGC framework

(Dusling, Venugopalan PRD 87 (2013) 5, 051502, PRD 87 (2013) 5, 054014, PRD 87 (2013) 9, 094034
Dusling,Tribedy, Vengopalan PRD 93 (2016) 1 014034)

Direct computation of “Jet graph” + “Glasma graph” in k_T factorized approximation (valid at $p_T > Q_s$)

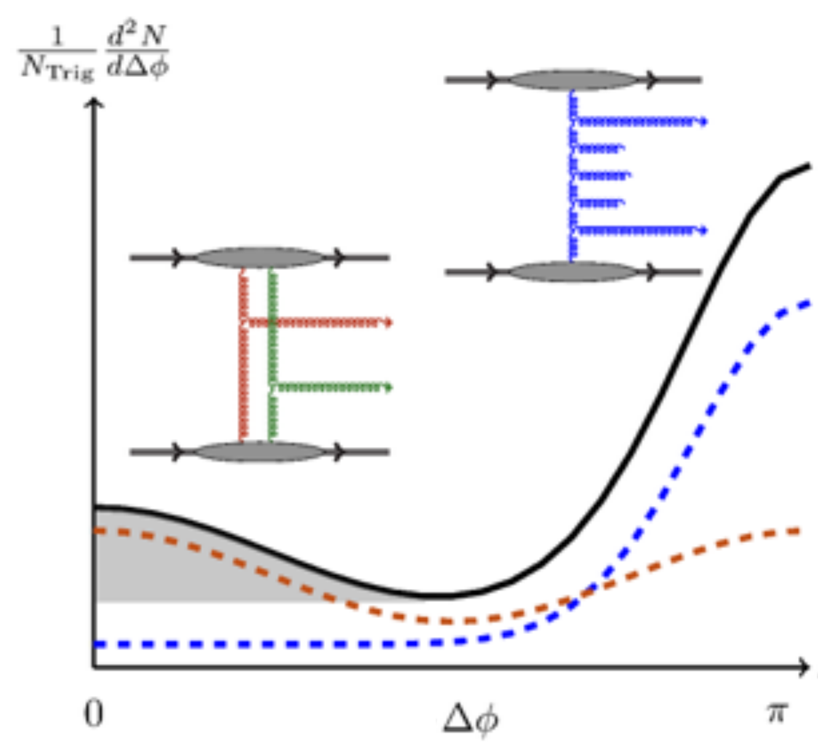
— unintegrated gluon densities constrained from DIS and evolved to small x using rcBK evolution



CMS JHEP 1009 (2010) 091

Glasma graphs produce long range azimuthal correlation symmetric around $\Delta\phi=\pi/2$ which gives rise to even harmonics $v_2, v_4, \ldots$

-> Enhancement of Glasma graph in high-multiplicity events, gives rise to emergence of near-side ridge



Dusling, Venugopalan PRD 87 (2013) 5, 051502

Theoretical calculations

Hybrid model CGC calculations

(Dumitru,Giannini NPA933 (2015) 212-228, Dumitru,McLerran,Skokov PLB 743 (2015) 134-137, Lappi PLB 744 (2015) 315-319, Lappi,Schenke,SS,Venugopalan JHEP 1601 (2016) 061, McLerran, Skokov NPA 947 (2016) 142-154)

Include multiple scattering effects
on one of the hadrons (e.g. forward p+Pb)

$$\left\langle \frac{dN_{q/g}}{d^2\mathbf{k}_1 d^2\mathbf{k}_2} \right\rangle = \int_{\mathbf{p}_1,\mathbf{b}_1,\mathbf{r}_1}^{\mathbf{p}_2,\mathbf{b}_2,\mathbf{r}_2} W_{q/g}(\mathbf{p}_1,\mathbf{b}_1)\, e^{-i(\mathbf{k}_1-\mathbf{p}_1)\mathbf{r}_1}\, W_{q/g}(\mathbf{p}_2,\mathbf{b}_2)\, e^{-i(\mathbf{k}_2-\mathbf{p}_2)\mathbf{r}_2}$$
$$\left\langle \mathrm{tr}_{f/a} V(\mathbf{b}_1+\mathbf{r}_1/2)V^\dagger(\mathbf{b}_1-\mathbf{r}_1/2)\mathrm{tr}_{f/a} V(\mathbf{b}_2+\mathbf{r}_2/2)V^\dagger(\mathbf{b}_2-\mathbf{r}_2/2)\right\rangle$$

color-electric field

$$E_i(\mathbf{x}_T) = \frac{i}{g} V(\mathbf{x}_T)\partial_i V^\dagger(\mathbf{x}_T)$$

So far projectile has been modeled
rather crudely (e.g. uncorrelated quarks)

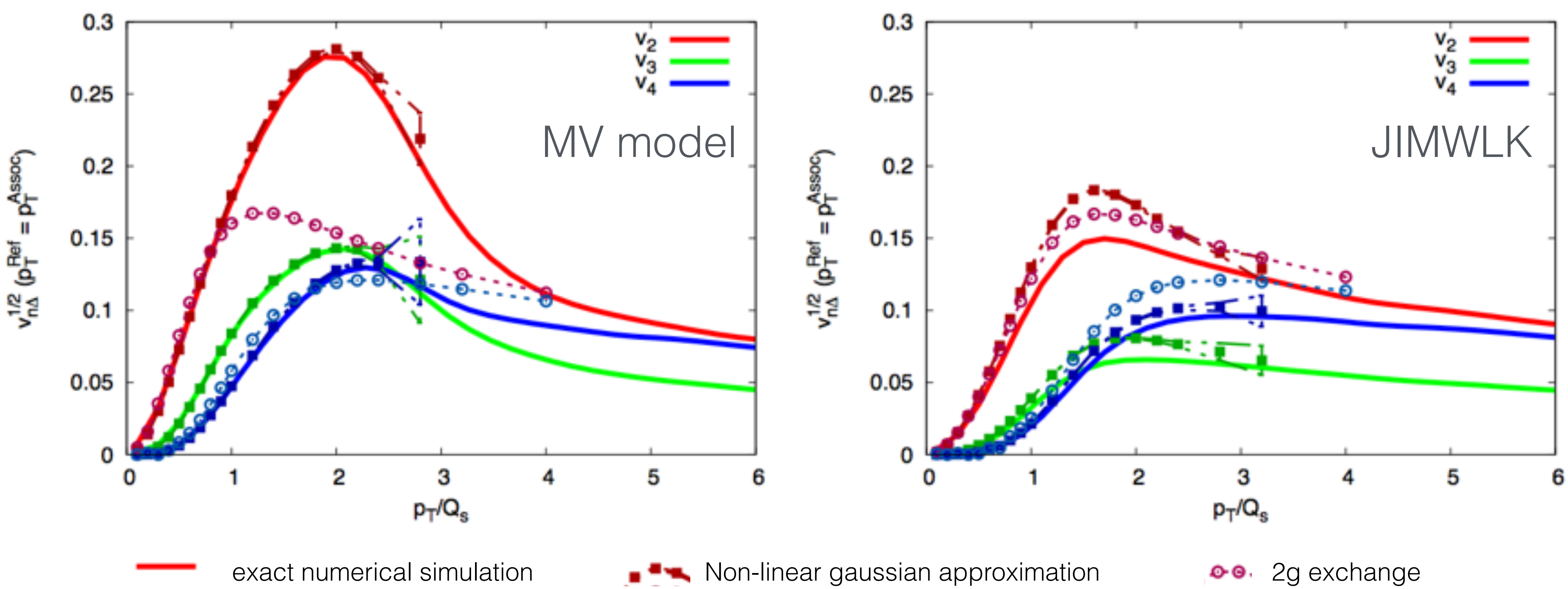
-> Qualitative insights into multi-particle correlations

Theoretical calculations

Hybrid model CGC calculations

(Lappi,Schenke,SS,Venugopalan JHEP 1601 (2016) 061)

azimuthal correlations in q+A scattering



-> Sizeable v_n's up to high p_T
Qualitative agreement between different models

Theoretical calculations

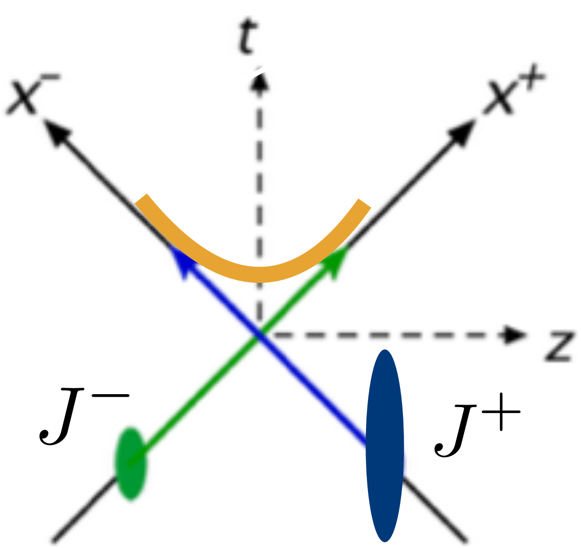
Event-by-event simulations in classical-Yang Mills theory

(Schenke, SS, Venugopalan PLB 747 (2015) 76-82, Schenke,SS,Tribedy, Venugopalan 1607.02496)

Based on IP-Glasma model one obtains numerical solution to Yang-Mills equations

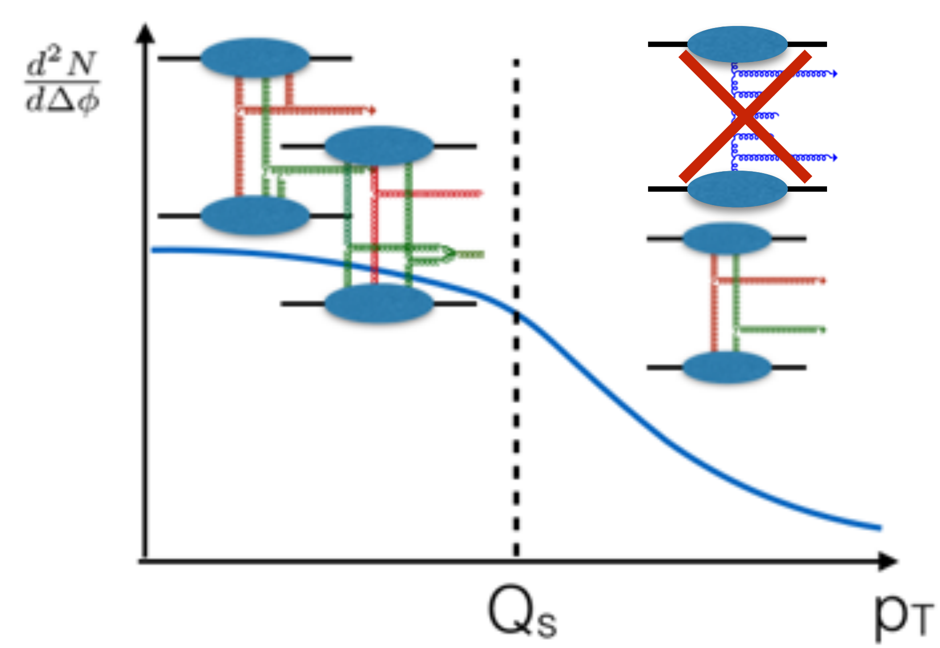
$$[D_\mu, F^{\mu\nu}] = J^\nu$$

to study particle production at mid-rapidity



-> Event-by-event simulations include multi-particle production via Glasma graphs

-> Extend range of validity of perturbative calculation by including multiple-scattering effects (important at $p_T<Q_s$)



So far simulations do no include Jet graphs
(work in progress Dusling,SS,Tribedy,Venugopalan)

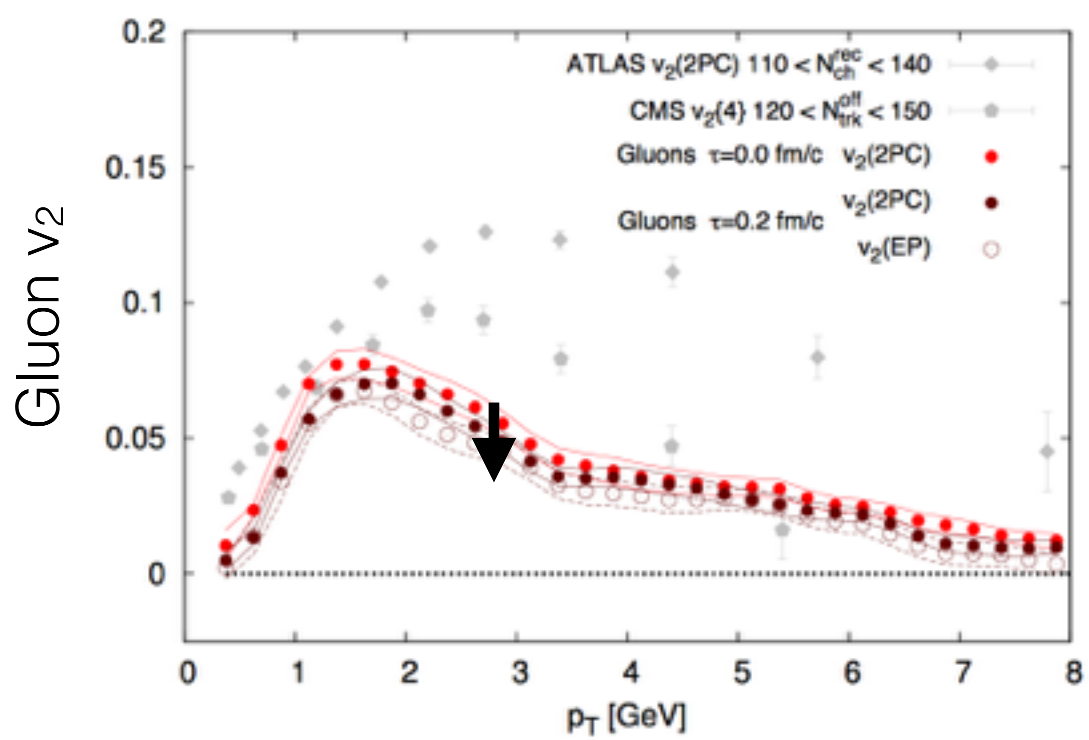
Theoretical calculations

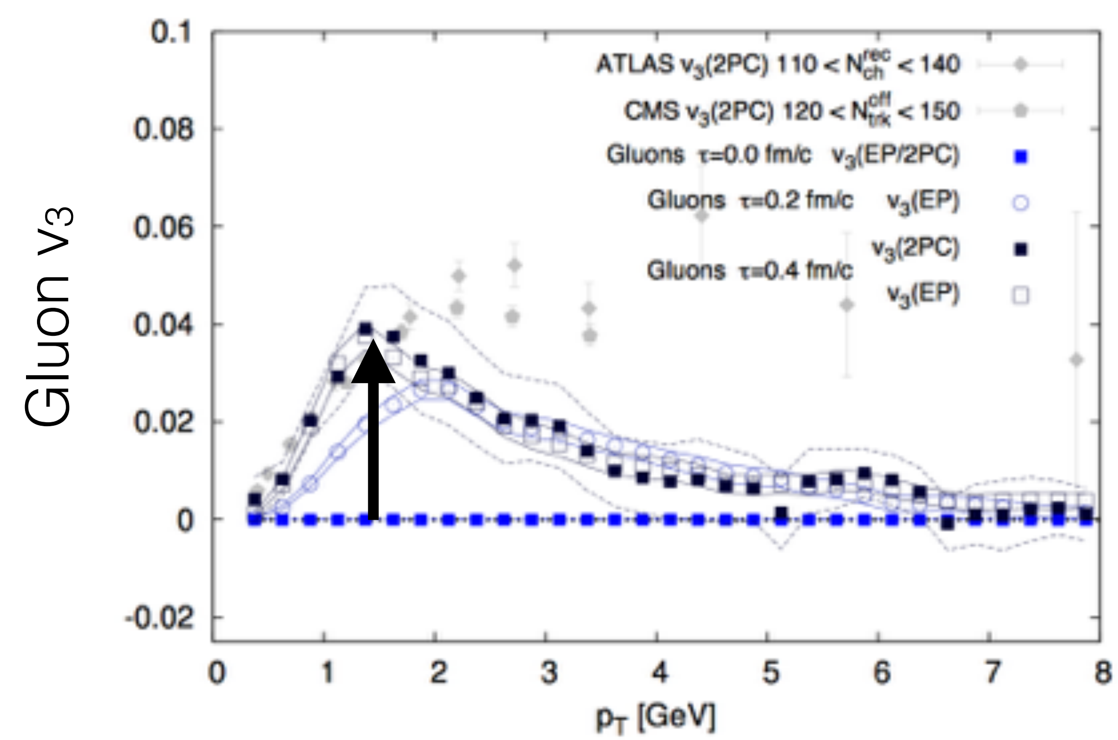
Event-by-event simulations in classical-Yang Mills theory

(Schenke, SS, Venugopalan PLB 747 (2015) 76-82, Schenke,SS,Tribedy, Venugopalan 1607.02496)

Gluons are produced with a momentum space correlation already at $\tau=0^+$

-> Initially correlation function only features even harmonics $v_2, v_4, \ldots$





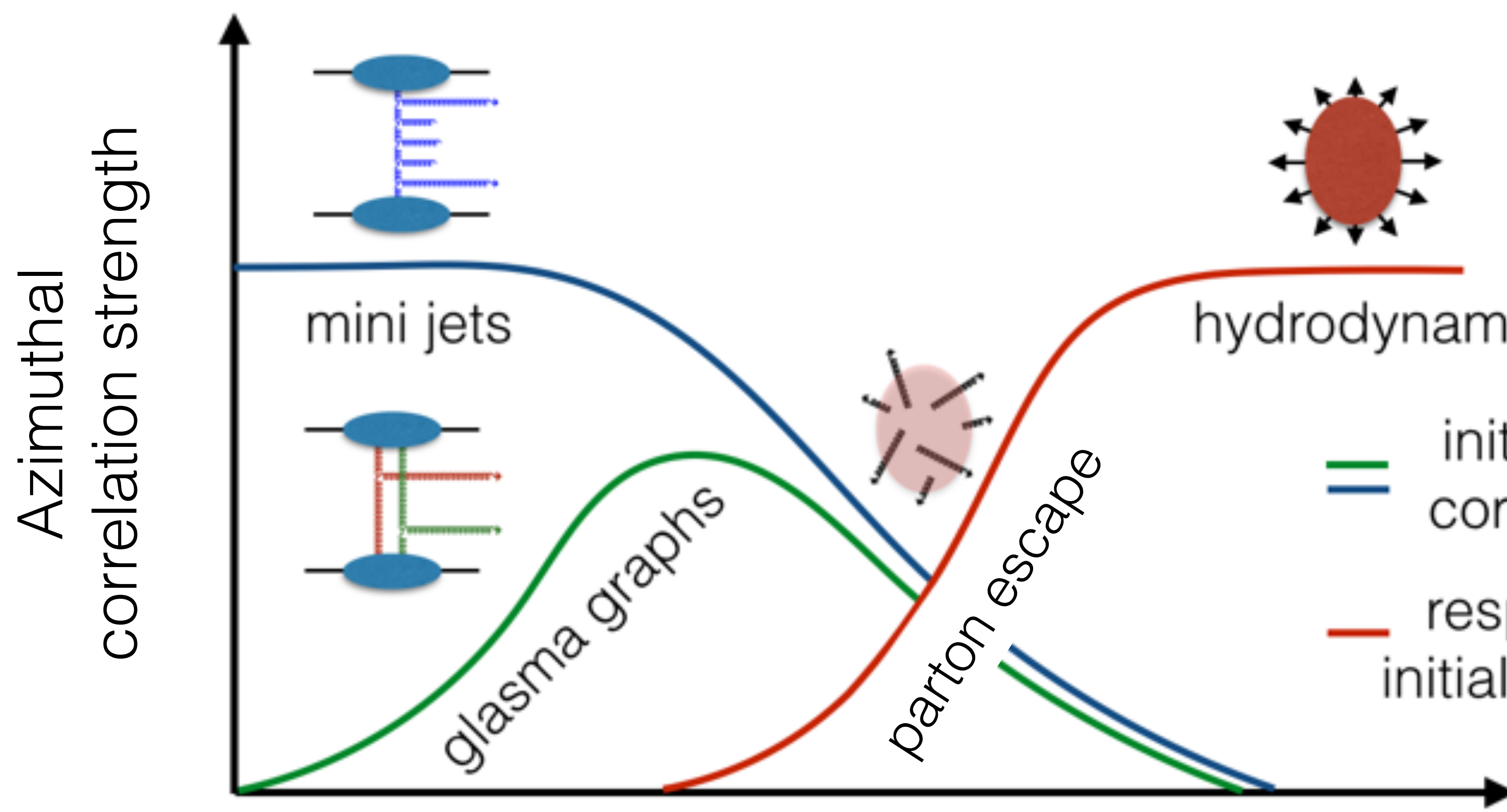
Including final state re-scattering via CYM evolution generates a positive v_3 on the time scale $\sim 1/Q_s$ of a single scattering

Initial state vs. final state effects

Sizable correlations exist between particles produced in the initial state of p+p/A collisions

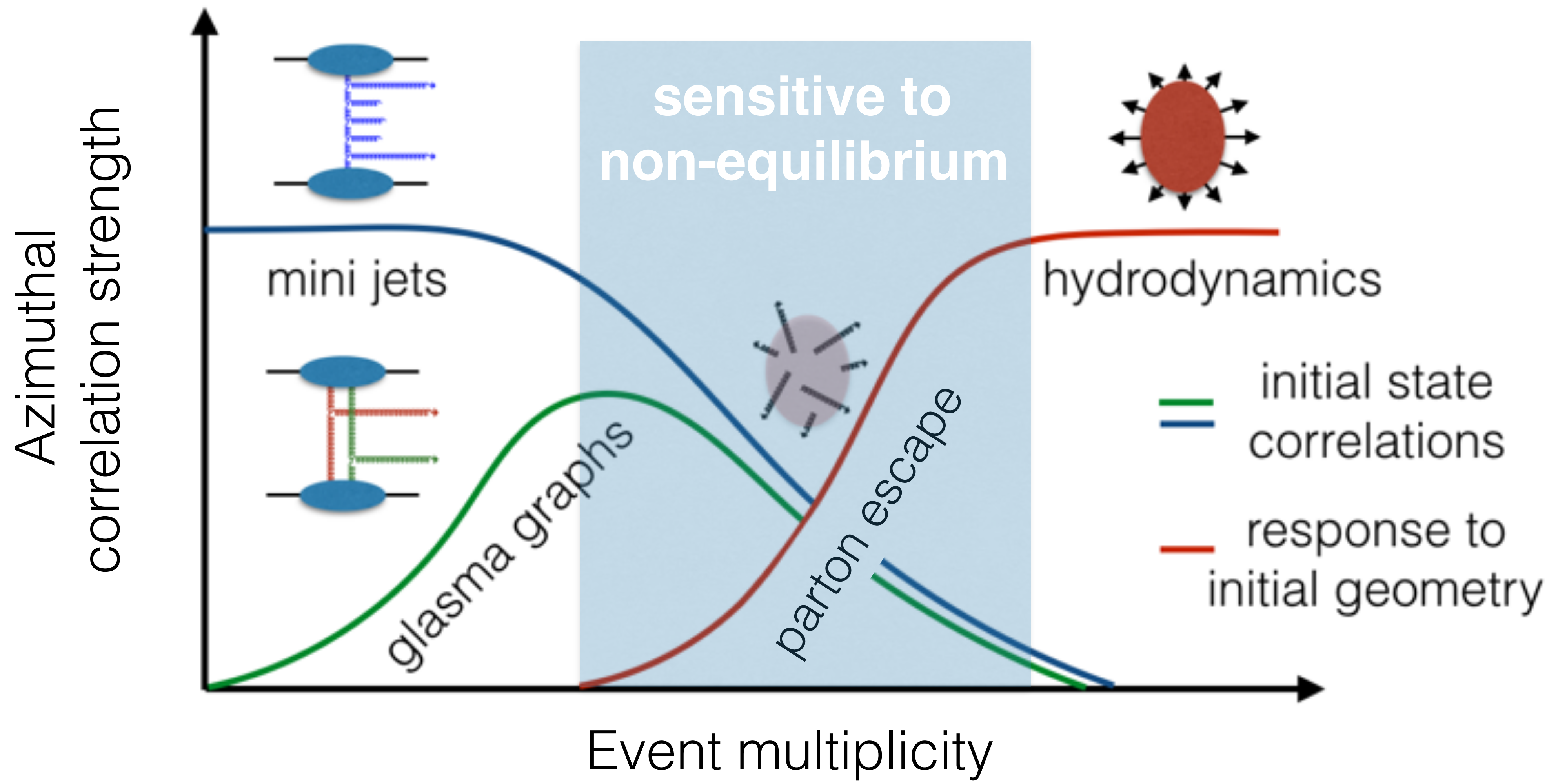
How they translate into final state observables depends to what extent they are modified by final state effects (N_{ch},p_T,…)

Qualitative picture:



Initial state vs. final state effects

Ultimately it would be desirable to develop a consistent theoretical treatment including initial state & final state effects



How to distinguish the different regimes experimentally?

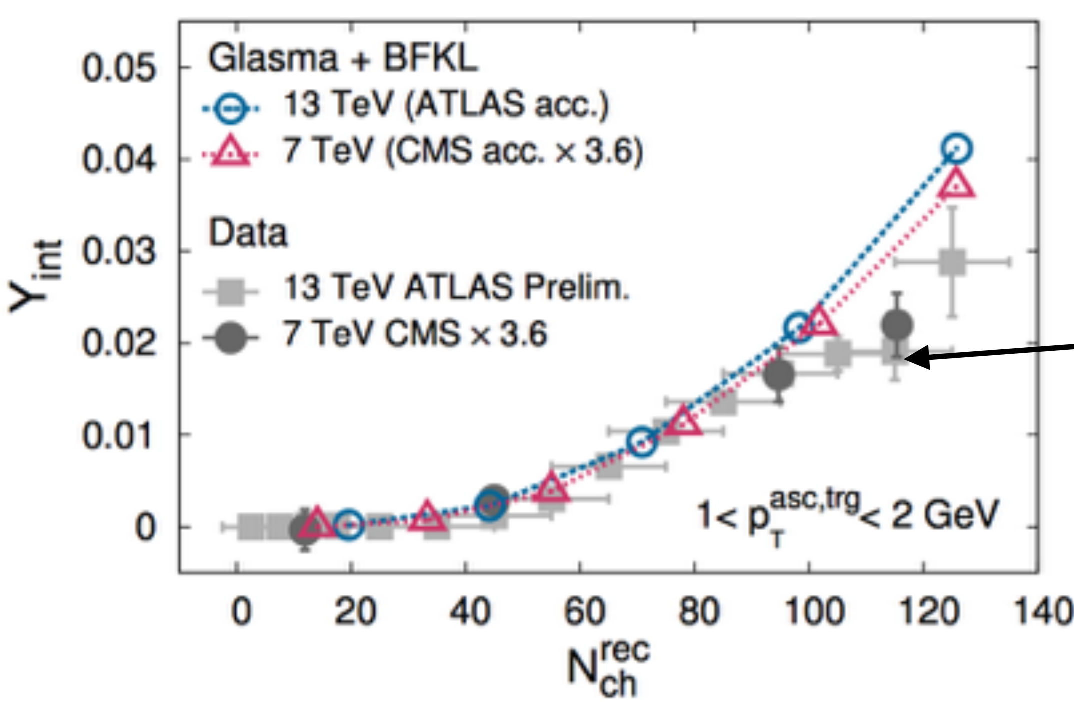
Will assume dominance initial state correlations in the following and compare to experimental data where calculations exist

p+p collisions

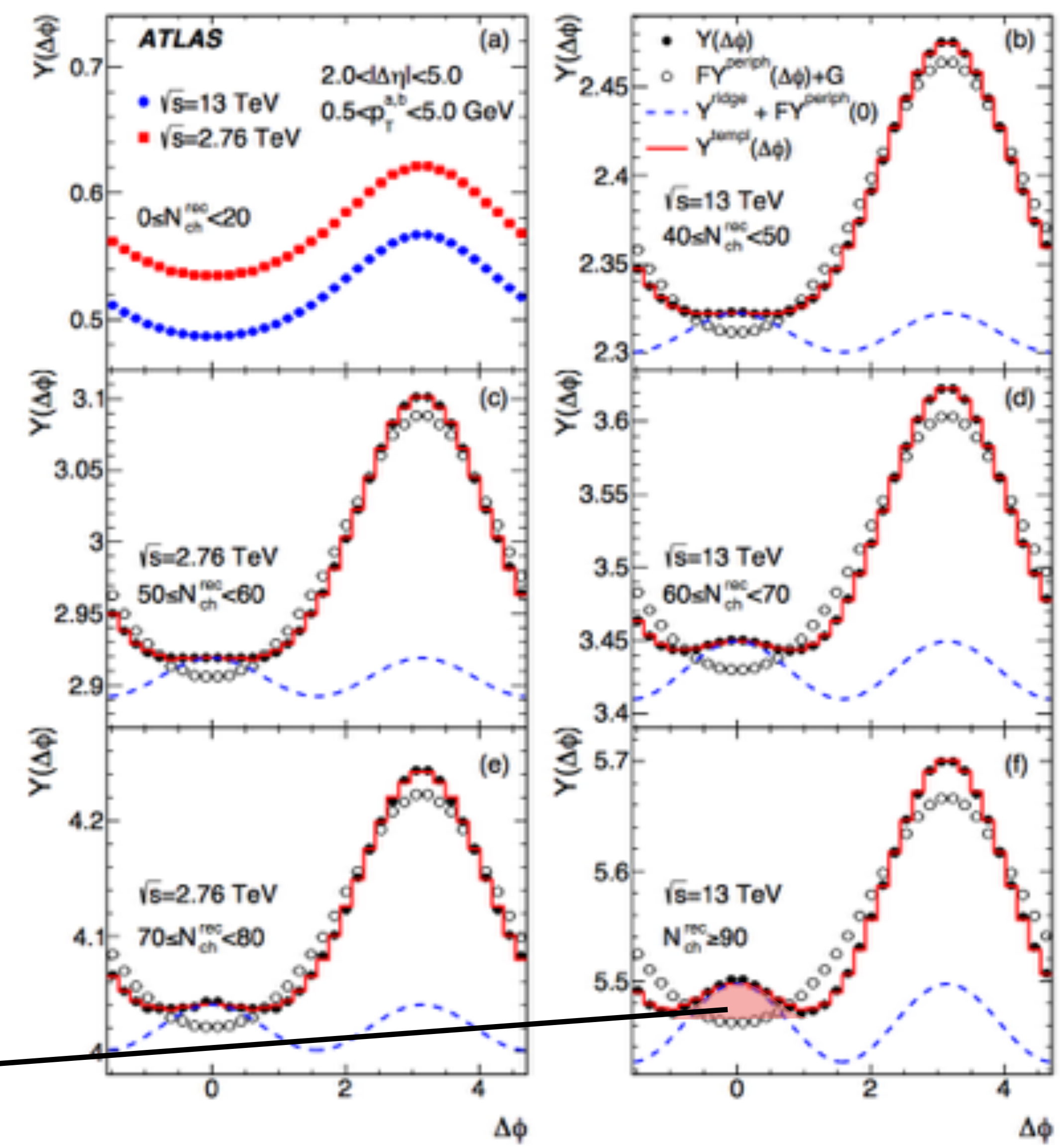
Correlation dominate by the away side “jet” contribution

-> strong indication that initial state correlations survive

Near-side contribution increases with multiplicity



Dusling, Tribedy, Venugopalan arXiv:1509.04410



ATLAS PRL 116, 172301 (2016)

Quantitative description of near-side yield from initial state correlations

Detailed comparison in p+p & p+Pb

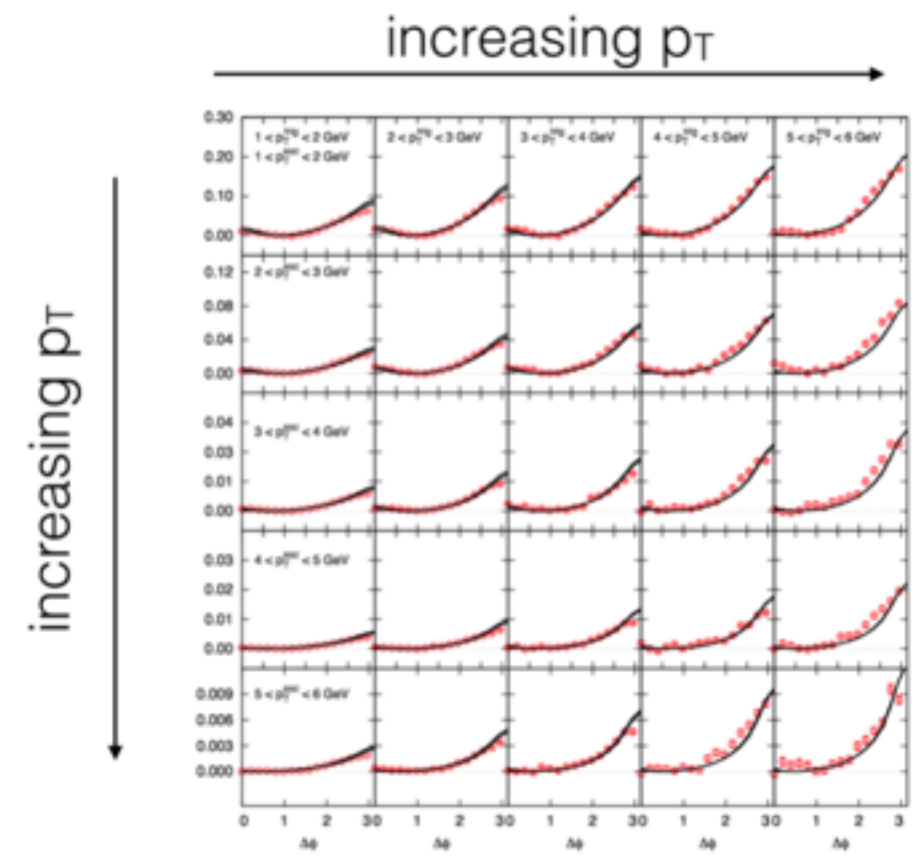
Differential comparison in p_T and N_{trk} yields good overall agreement for two-particle correlations in wide kinematic range (p_T>1 GeV)

Dusling, Venugopalan PRD 87 (2013) 9, 094034

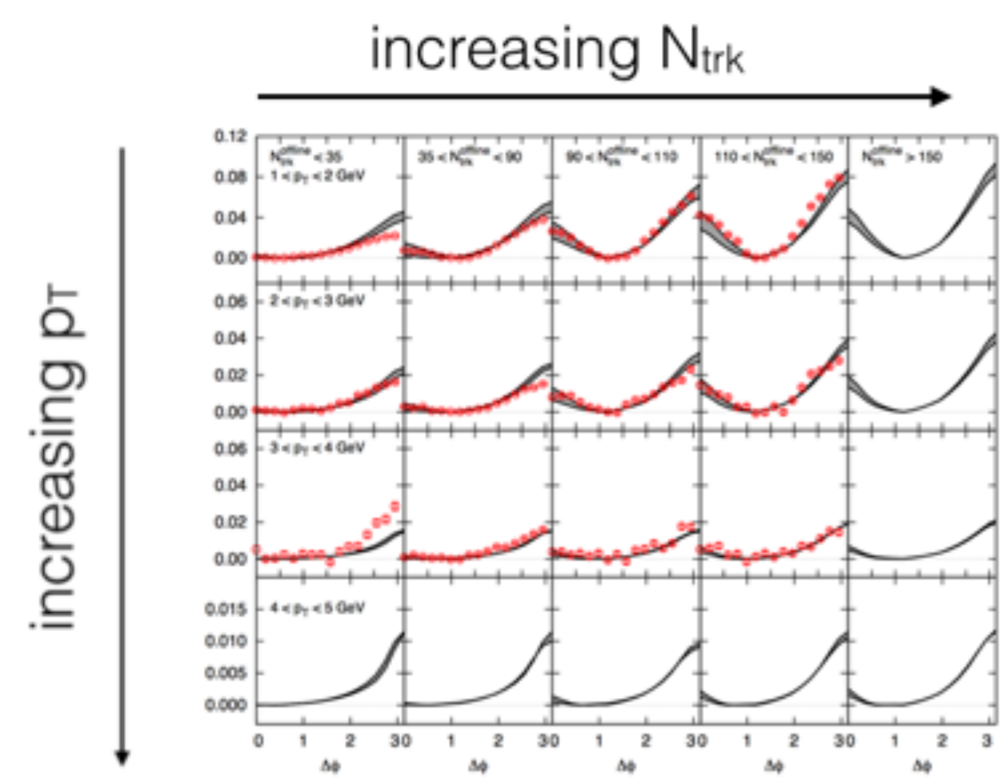
Enormous experimental progress since the first results:

Can other "collective phenomena" also be consistently reproduced within initial state framework?

-> Challenge to extend range of validity of initial state calculations to smaller momenta (p_T<Q_s)



p+p 7 TeV high mult. N_{trk}>110



p+Pb 5.02 TeV

New theoretical developments

Event-by-event simulations in classical-Yang Mills theory + MC Lund string fragmentation

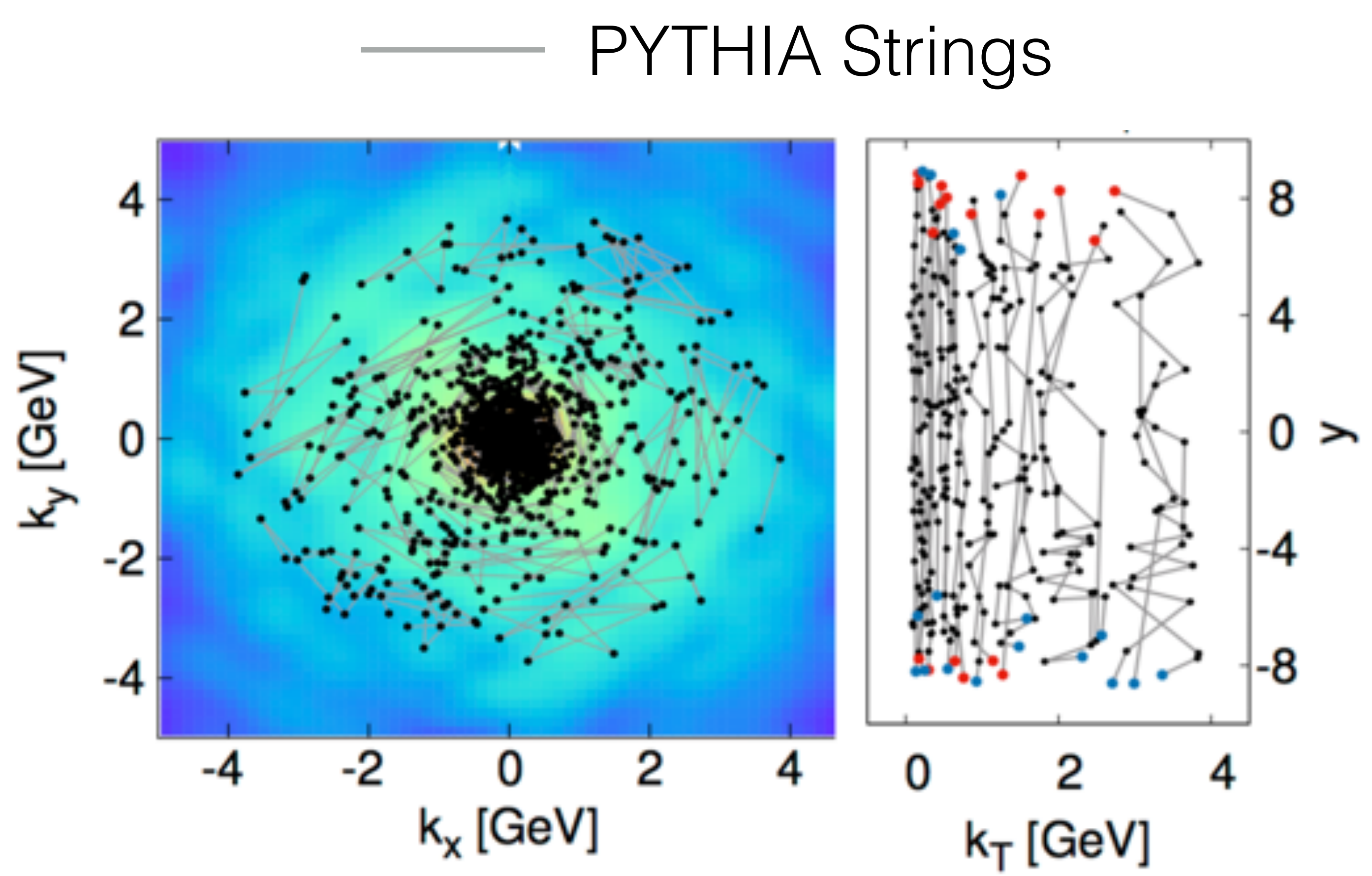
(Schenke,SS,Tribedy, Venugopalan 1607.02496)

Extract event-by-event gluon spectra from classical Yang-Mills simulation

-> includes initial state correlations

Sample individual gluons according to dN_g/d^2k, group into strings and perform Lund string fragmentation implemented in PYTHIA

-> "CGC+Lund event generator"

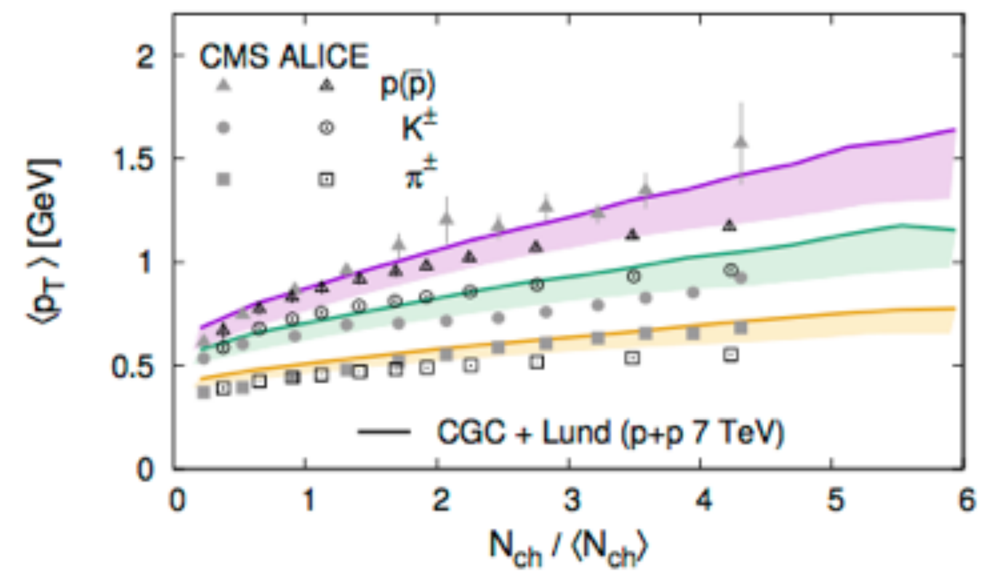


Can follow experimental analysis to compute hadronic observables

$\langle p_T \rangle$ & $\langle v_2 \rangle$ mass ordering

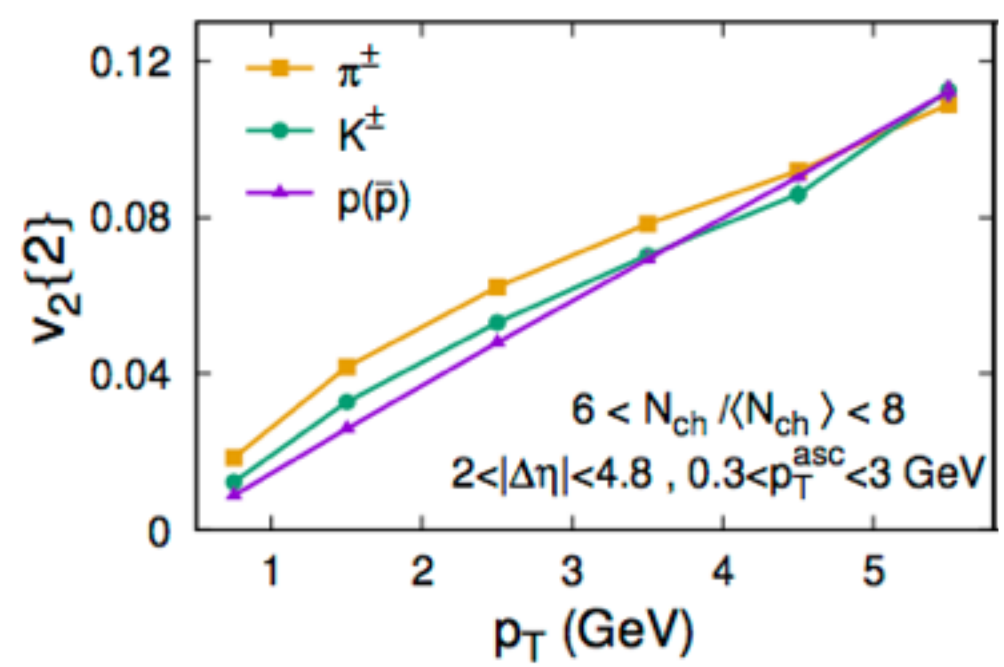
p+p 7 TeV

Increase of $\langle p_T \rangle$ with N_{ch} due to increase of Q_s already present at gluon level



String fragmentation naturally leads to observed “mass splitting”

Correlations at the gluon level due to initial state production (Glasma graphs)



String fragmentation naturally leads to “mass splitting”

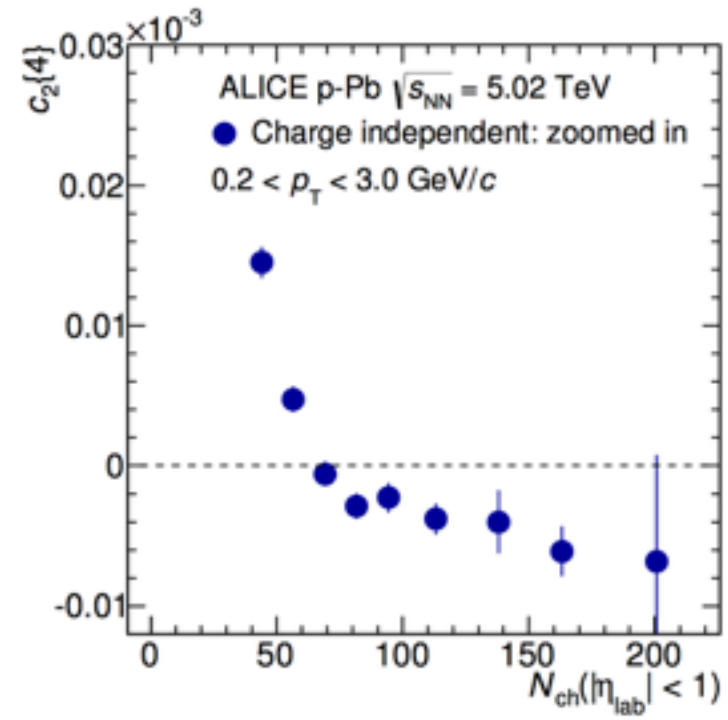
(Schenke,SS,Tribedy, Venugopalan 1607.02496)

-> Mass ordering property of identified particle correlations sensitive to hadronization mechanism rather than origin of correlation

Future directions

Collectivity from initial state?

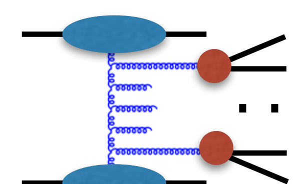
Experiments observe similar features in multi-particle correlations (n>2)



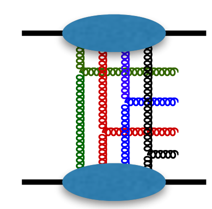
ALICE PRC 90, 054901 (2014)

Difficult to compute because no Δη gap and low p_T

-> many possible contributions



Initial state framework naturally extends to higher order correlations



Sensitive to higher order correlations of gluons inside the projectile and target wave-functions

Qualitative results:

(Dumitru,McLerran,Skokov B743 (2015) 134-137)

$$c_2\{4\} = -\frac{1}{N_D^3}\left(\mathcal{A}^4 - \frac{1}{4(N_c^2-1)^3}\right)$$

perturbative result

non-linear/non-Gaussian effects

Future directions

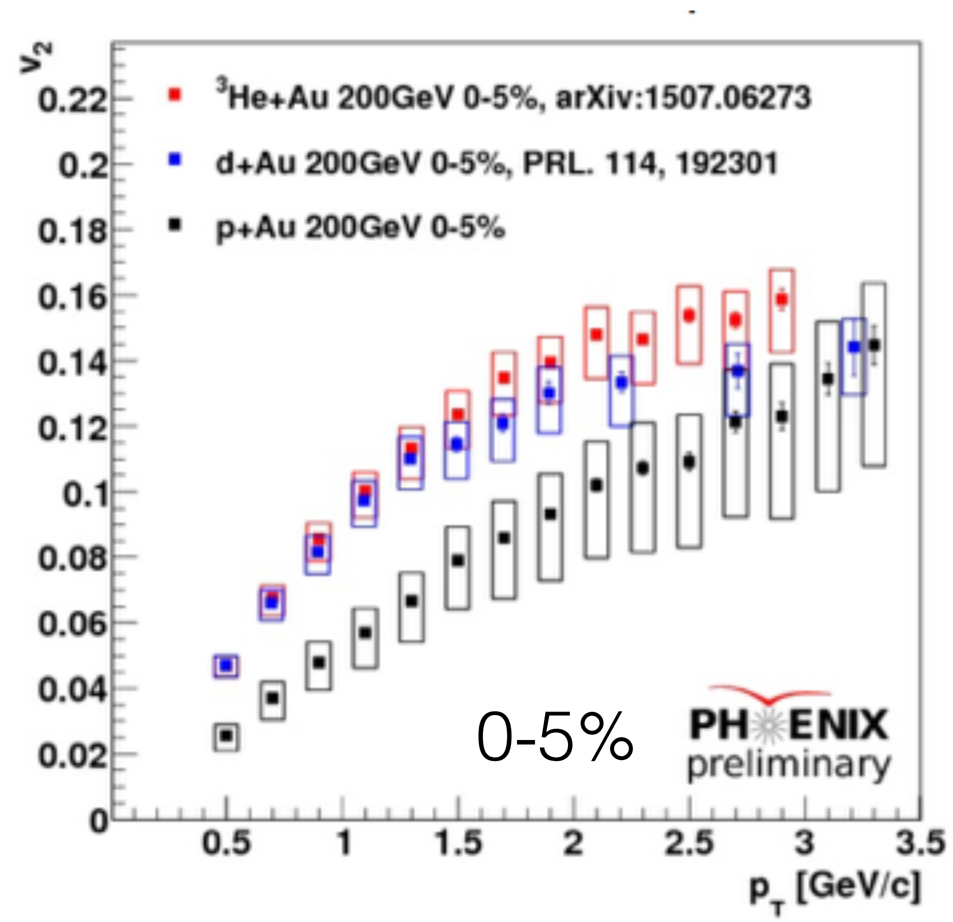
Systematic comparison in p/d/He3+A @ RHIC

Striking observation of hierarchy
in p/d/He3+A collisions observed

$v_2(p+Au) < v_2(d+Au) \leq v_2\,(He3+Au)$

Extracted from event-plane method

Back-to-back mini jets?



Theoretical description requires to properly
include impact parameter dependence

-> Event-by-event Yang-Mills simulations +Jets + Hadronization

(work in progress Dusling,SS,Tribedy,Venugopalan)

Summary & Conclusions

Multi-particle production in QCD leads to long range azimuthal correlations in momentum space

-> Effects are large in small systems and have to be taken into account in the theoretical description

Calculations based purely on initial state correlations can consistently describe high p_T data in p+p/Pb collisions

-> Non-modification of away side (mini-)jet puts strong constraints on the magnitude of final state effects

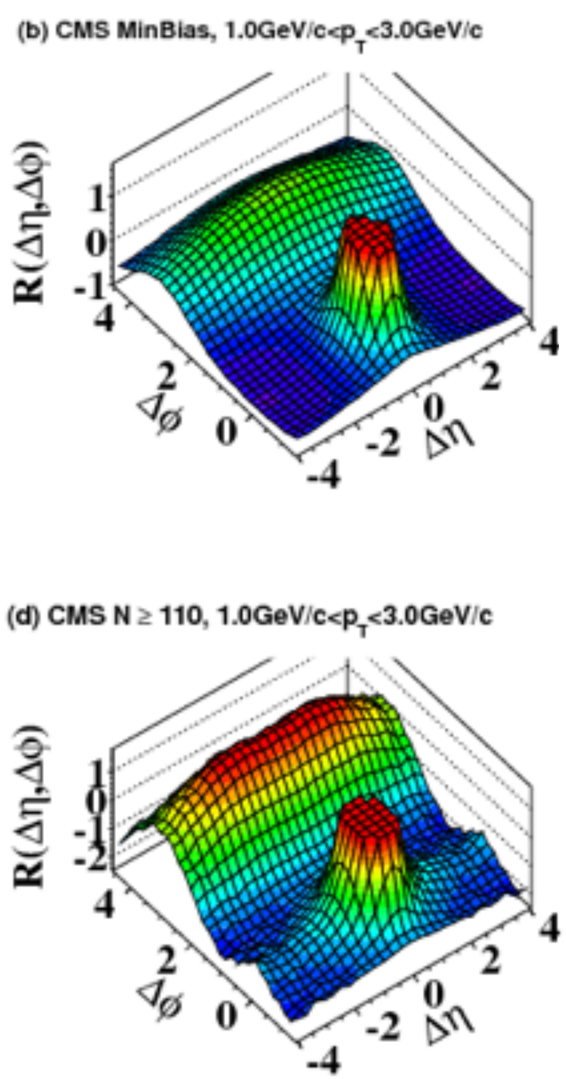
Simultaneous description of low p_T and high p_T data across a wide range of multiplicities remains a challenge within any theoretical framework

-> Need theoretical description including initial state and final state effects

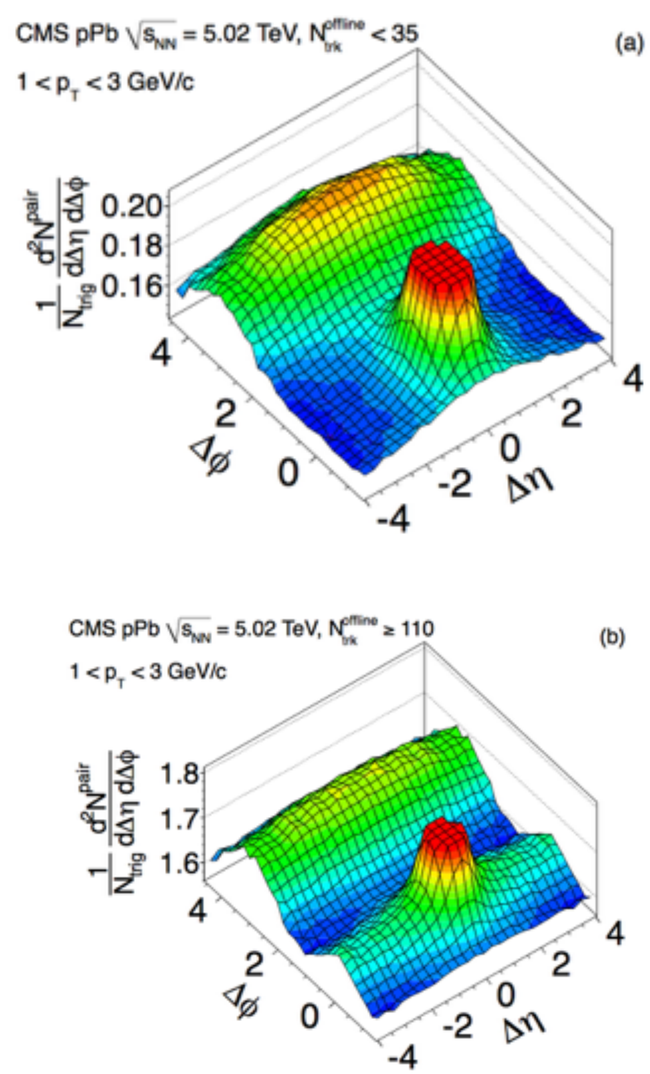
Backup

The ridge in p+p,p+Pb & Pb+Pb

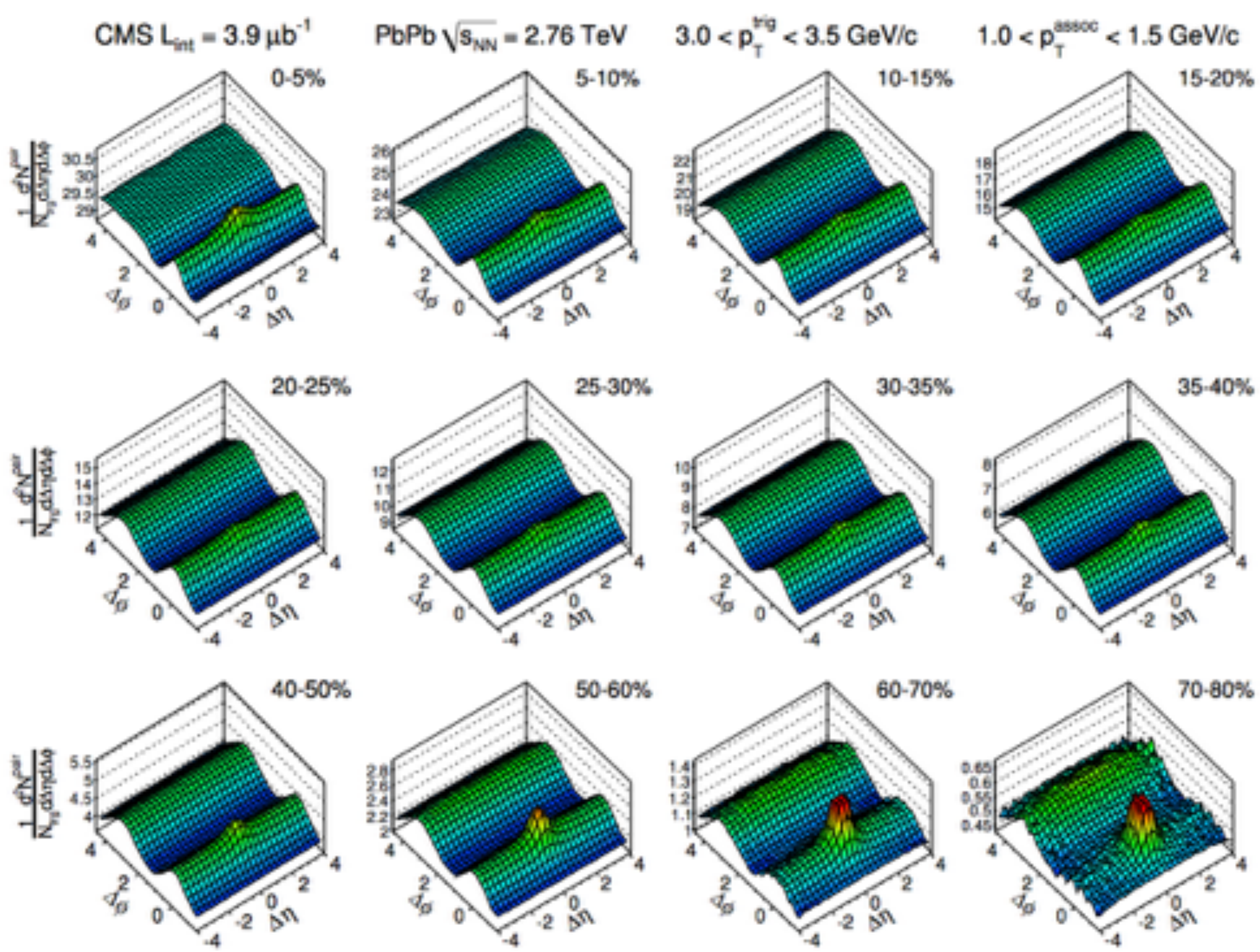
p+p @ 7 TeV



p+Pb @ 5.02 TeV

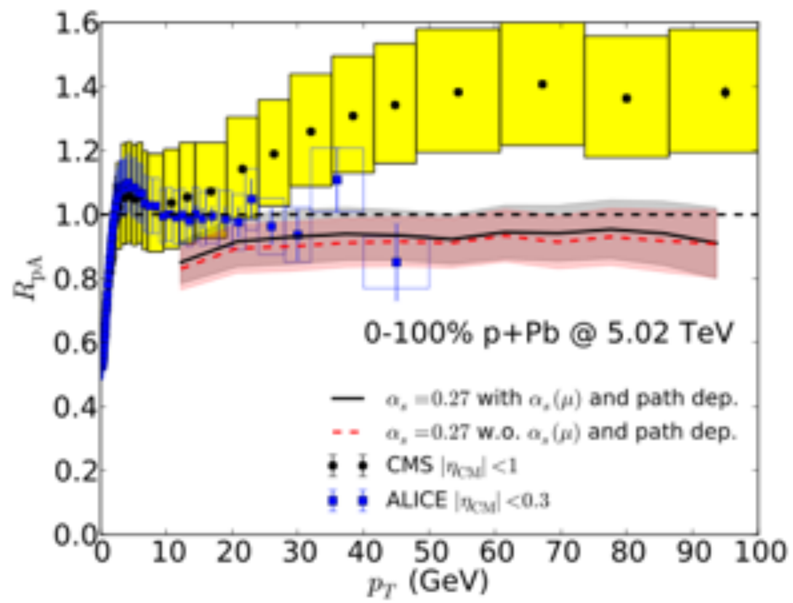


Pb+Pb @ 2.76 TeV

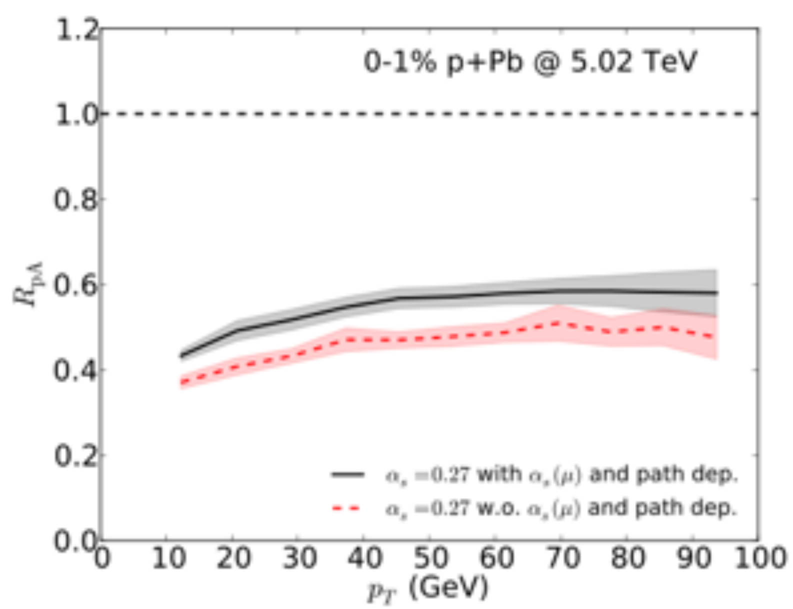


Jet-Quenching in p+A?

Jets in the pA medium?
Here, charged hadrons



- Situation in min. bias pA clearly sensitive to the value of α_s
- Some possibility of suppression @~10-20 GeV, but data mostly 1



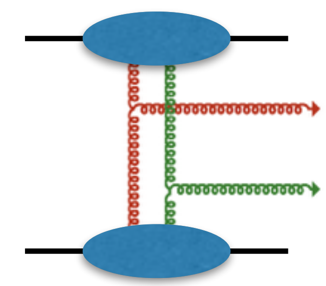
- A large(r) effect in central collisions
- Enhanced sensitivity to physical conditions and model characteristics (medium size and granularity)
- Much more to do: y, jet R_{pA}...
- A clear manifestation of the medium in pA collisions

(C.Gale — Quark Matter 2015)

Charles Gale
McGill

Glasma graph

Expression in k_T factorized approximation



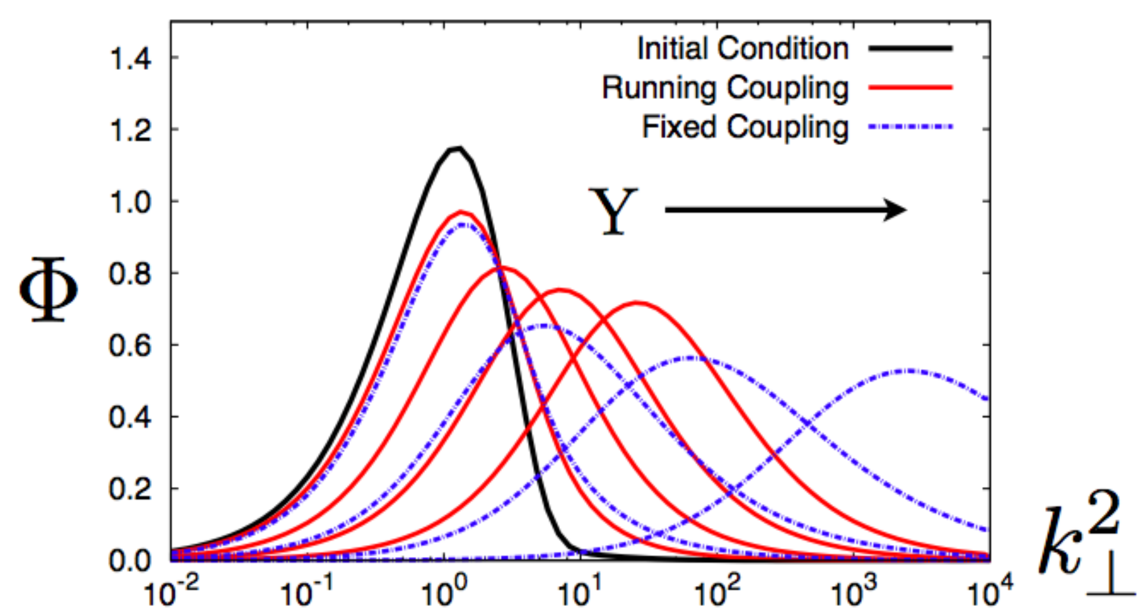
$$C(\mathbf{p},\mathbf{q}) = \left\langle \frac{dN_2}{dy_p d^2\mathbf{p}_\perp dy_q d^2\mathbf{q}_\perp} \right\rangle - \left\langle \frac{dN}{dy_p d^2\mathbf{p}_\perp} \right\rangle \left\langle \frac{dN}{dy_q d^2\mathbf{q}_\perp} \right\rangle$$

$$= \frac{\alpha_s^2}{16\pi^{10}} \frac{N_c^2 S_\perp}{(N_c^2-1)^3 \mathbf{p}_\perp^2 \mathbf{q}_\perp^2} \int d^2\mathbf{k}_\perp \times$$

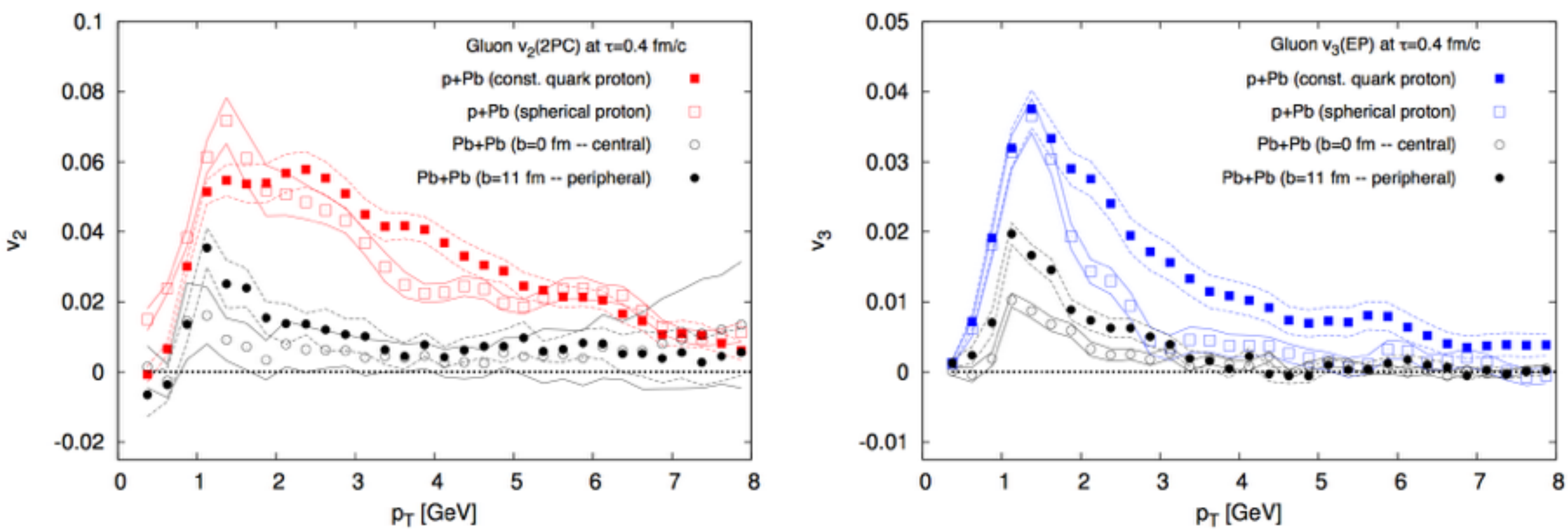
$$\Big\{ \phi_{A_1}^2(y_p,\mathbf{k}_\perp)\phi_{A_2}(y_p,\mathbf{p}_\perp-\mathbf{k}_\perp)[\phi_{A_2}(y_q,\mathbf{q}_\perp+\mathbf{k}_\perp)+\phi_{A_2}(y_q,\mathbf{q}_\perp-\mathbf{k}_\perp)]$$

$$\phi_{A_2}^2(y_q,\mathbf{k}_\perp)\phi_{A_1}(y_p,\mathbf{p}_\perp-\mathbf{k}_\perp)[\phi_{A_1}(y_q,\mathbf{q}_\perp+\mathbf{k}_\perp)+\phi_{A_1}(y_q,\mathbf{q}_\perp-\mathbf{k}_\perp)] \Big\}$$

Overlap of unintegrated gluons distributions determines the properties of correlation



Dependence on event geometry & system size



(Schenke, Schlichting, Venugopalan PLB 747 (2015) 76-82)

Event-geometry irrelevant for initial state correlation in p+A

Substantially smaller effect even in rather peripheral A+A