Monte-Carlo event generators for gluon saturation

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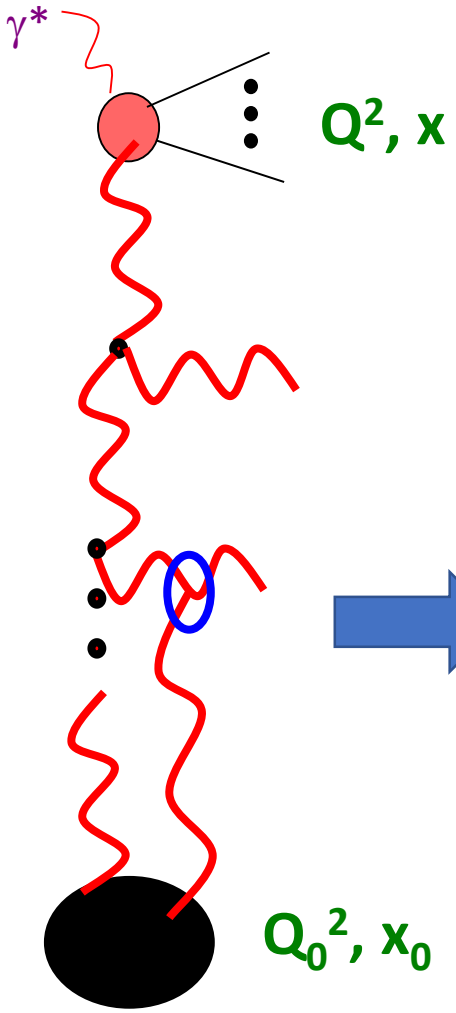
Monte-Carlo workshop, Vienna, November 21, 2019

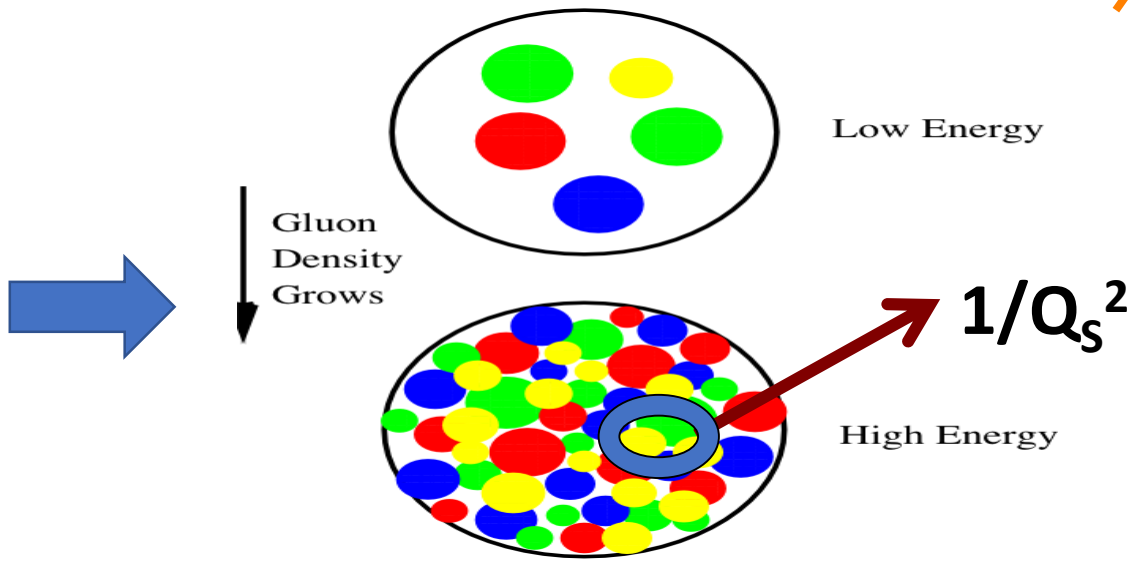
Talk outline

- The CGC EFT for gluon saturation: brief introduction
- Monte-Carlo event generators for p+p/p+A/A+A collisions:
  IP-Glasma+Classical Yang-Mills+Hydro/string fragmentation
- MCEG for small x in e+A: some ideas

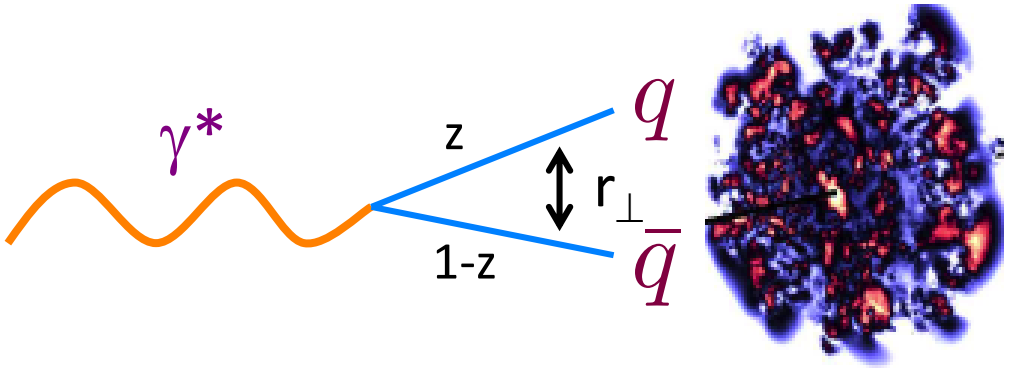
CGC EFT for gluon saturation: brief intro



Bremsstrahlung leads to recombination and screening – “higher twist” effects



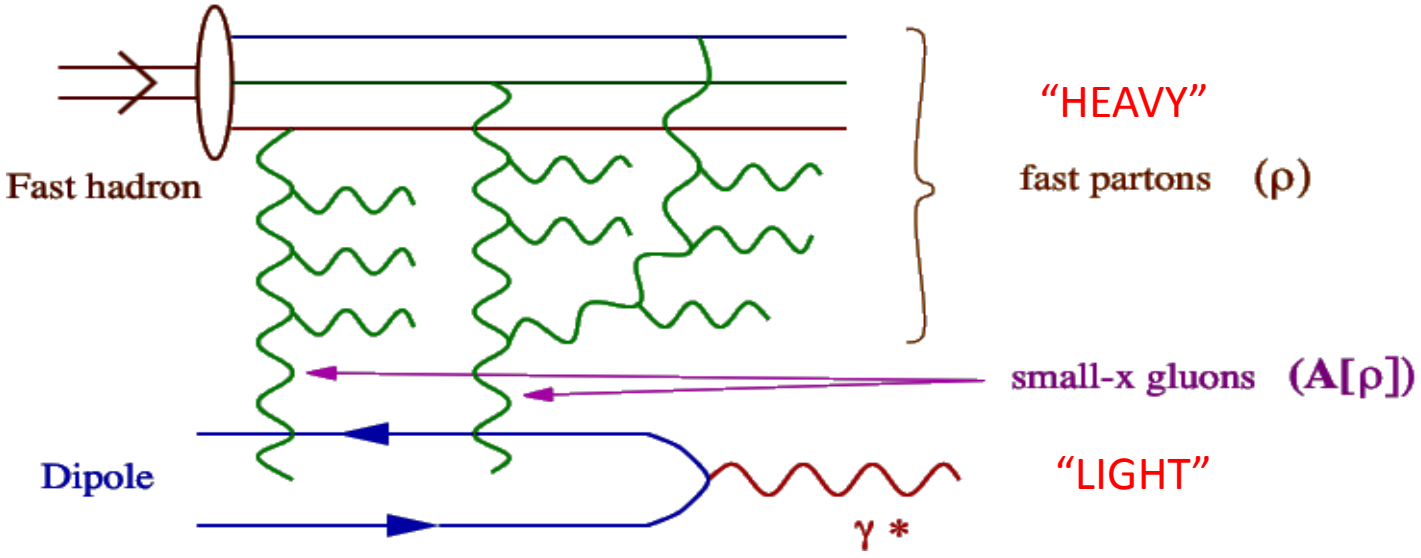
Head-on view:
Maximal phase-space density leads to gluon saturation
Emergent scale $Q_{S,A}(x)$



Perturbative unitarization of dipole cross-section

Classicalization in the Regge limit: the Color Glass Condensate EFT

Born-Oppenheimer separation between fast and slow modes

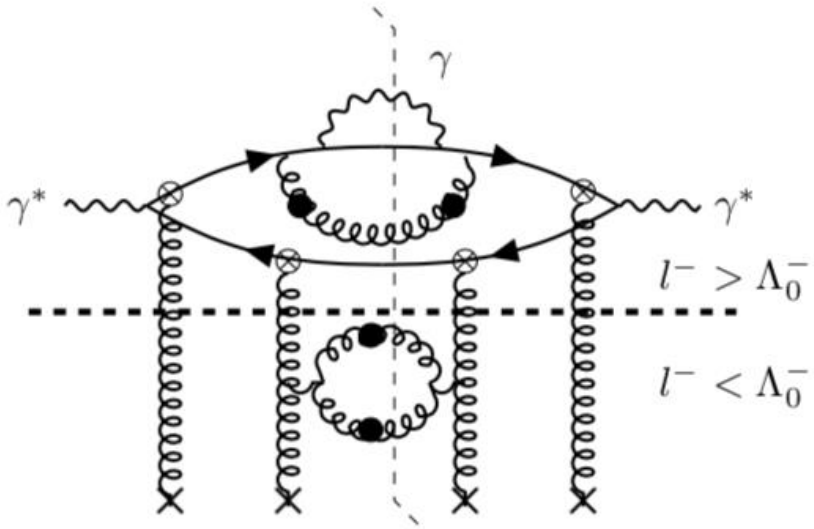


CGC: Effective Field Theory
of classical static quark/gluon sources
and dynamical gluon fields

Remarkably, physics of extreme quantum fluctuations
becomes classical because of high gluon occupancy…

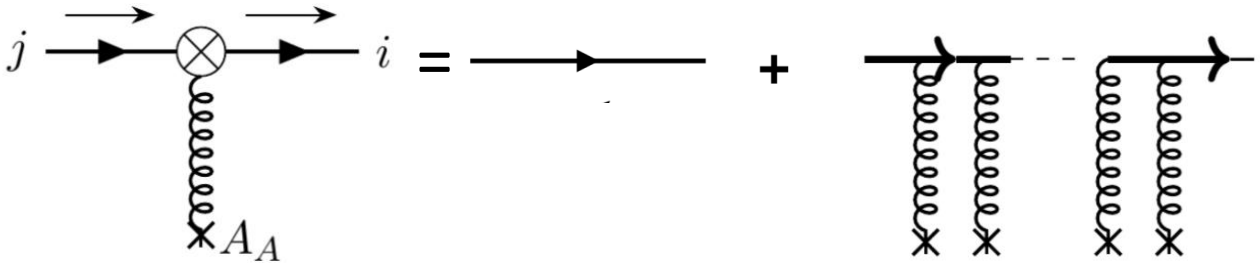
McLerran, RV (1994)

The power of Colored Glass: photons and di-jets to NLO+NLLx



Compton amplitude for $eA \to \gamma + dijets + X$

Roy, RV: arXiv: 1911.04519 and arXiv: 1911.04530



Mom. dependent effective quark (and gluon) vertices include "all-twist" corrections $(Q_S^2/Q^2)^n$

Differential DIS computations in the CGC EFT now available to $O(\alpha_S^3 \, \mathrm{Ln}(1/x))$ accuracy

Can be tested to $\sim 10\%$ $accuracy$ at an Electron-Ion Collider

Colored glass in p+p, p+A and A+A collisions: IP-Glasma framework

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

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

$$\langle \rho^a(\mathbf{x}_\perp)\rho^b(\mathbf{y}_\perp)\rangle \propto \delta^{ab}\delta^2(\mathbf{x}_\perp - \mathbf{y}_\perp)Q_s^2(\mathbf{x}_\perp)$$

- Color field before collisions : solving Yang Mills equations for each configuration of source $\rho(x_\perp)$ & current $J^\nu = \delta^\nu\, \rho(x_\perp)$

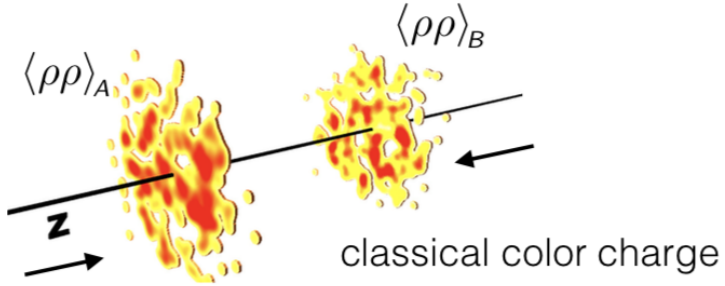
$$[D_\mu, F^{\mu\nu}] = J^\nu$$

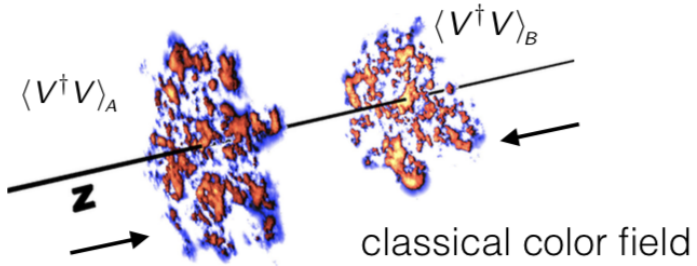
- Compute & evolve the color fields after collisions :

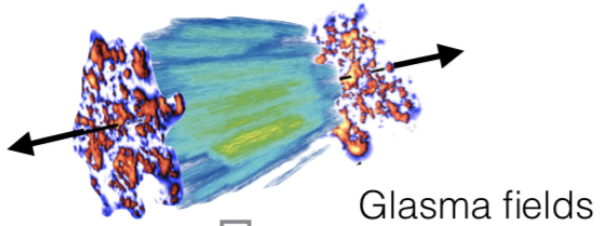
$$A^i = A^i_{(A)} + A^i_{(B)} \qquad A^\eta = \frac{ig}{2}\left[A^i_{(A)}, A^i_{(B)}\right]$$

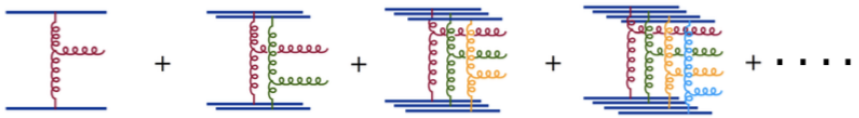
Light-cone gauge fields $A^i(x_\perp)$

→ Building blocks for any calculation





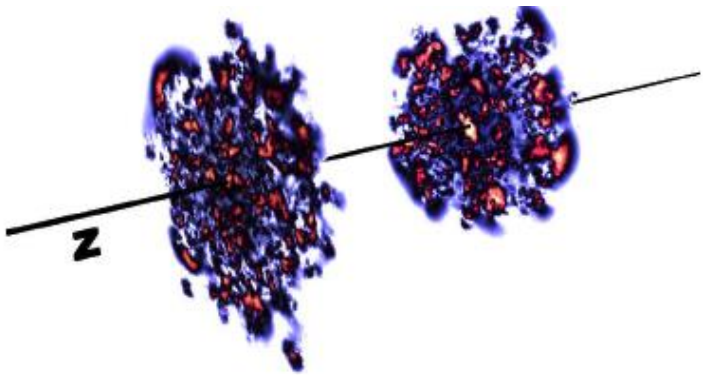


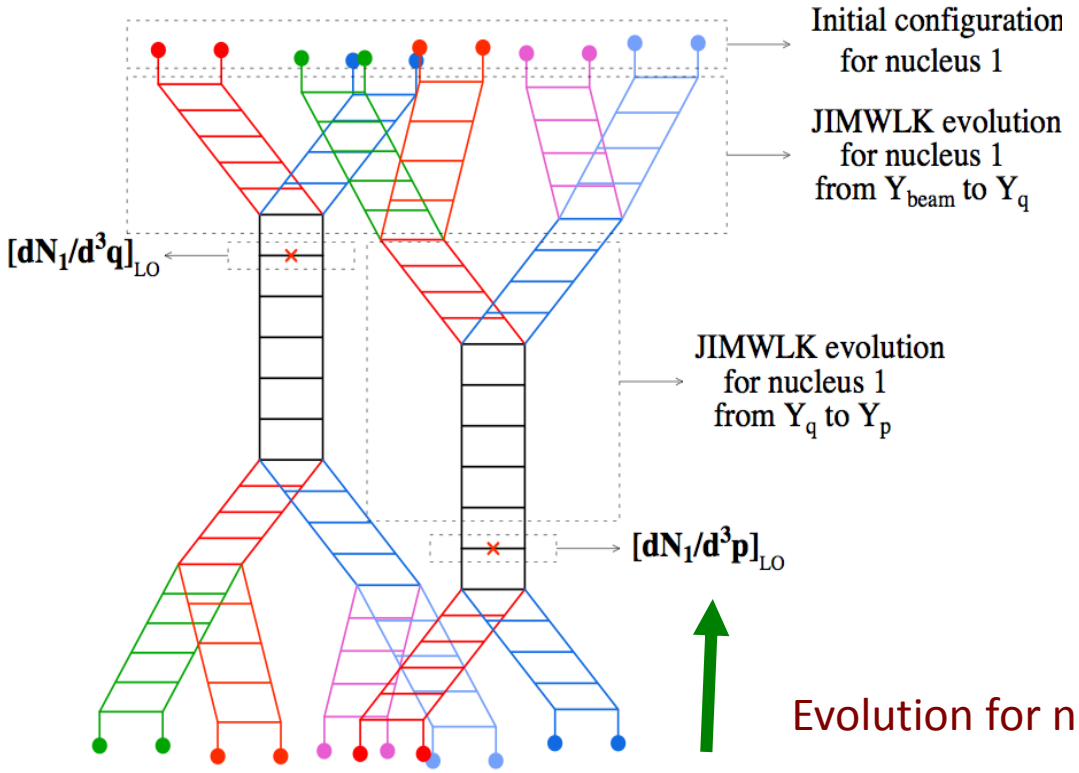


hep-ph/9809433, hep-ph/0303076, arXiv:1206.6805,arXiv: 1202.6646

Slide courtesy of Prithwish Tribedy

Example: two particle correlations





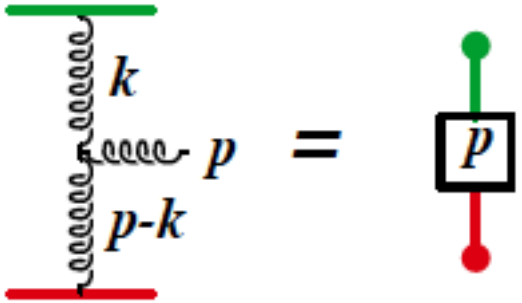
Evolution for nucleus 2

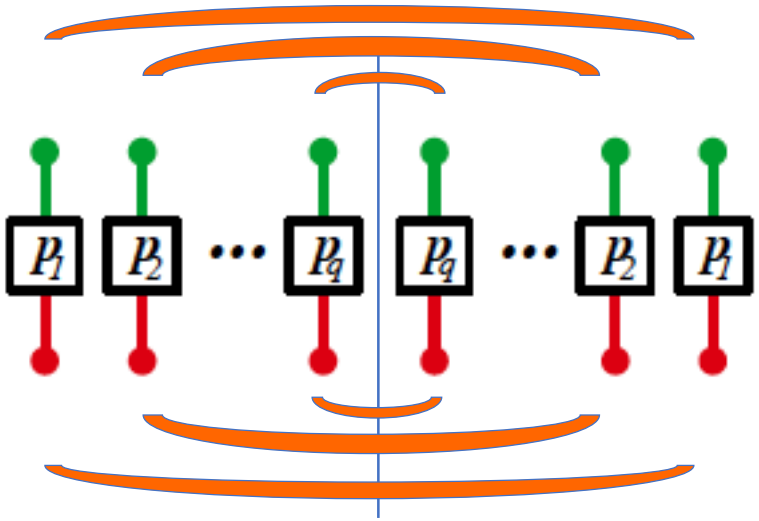
$$\langle \frac{dN_2}{d^3p\, d^3q} \rangle_{\mathrm{LLogs}} = \int [d\rho_1][d\rho_2] W_{Y_1}[\rho_1]\, W_{Y_2}[\rho_2]\, \frac{dN}{d^3p}|_{\mathrm{LO}}\, \frac{dN}{d^3q}|_{\mathrm{LO}}$$

JIMWLK evolution

From solution of Yang-Mills Eqns.

Lasing gluons: Stimulated emission from Glasma flux tubes





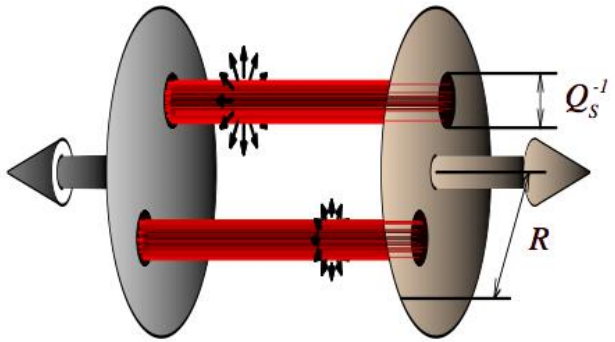
Dumitru,Gelis,McLerran,RV (2008)
Dusling,Fernandez-Fraile,RV (2009)
Gelis,Lappi,McLerran (2009)

Color combinatorics of cut graphs: a negative binomial distribution

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

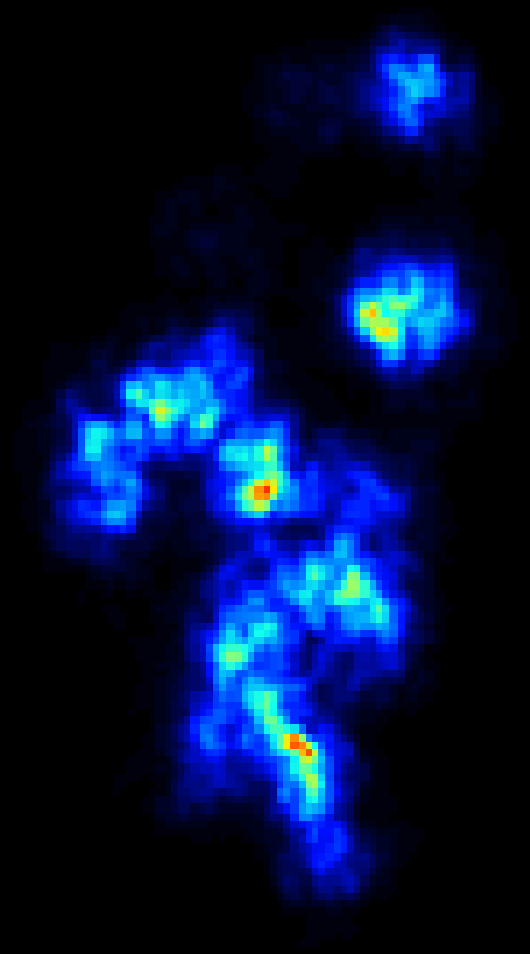
k=1: Bose-Einstein dist.
k=∞: Poisson distribution

$$k = \kappa \frac{(N_c{}^2 - 1) Q_s^2 S_\perp}{2\pi}$$

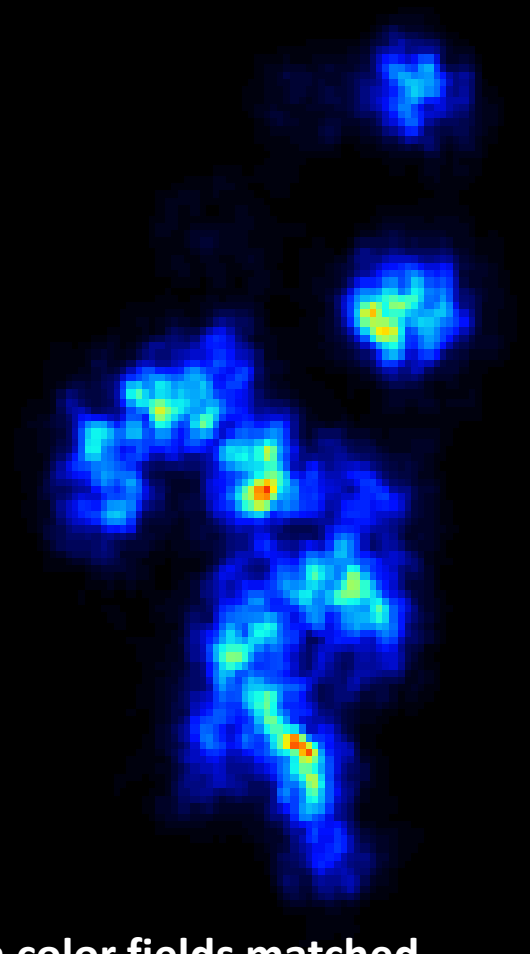


For $Q_S{}^2 \approx 1/S_T$
close to a Bose-dist!

The Glasma: colliding gluon shock waves



Glasma color fields



Glasma color fields matched to viscous hydrodynamics

Krasnitz,Venugopalan, Nucl.Phys.B557 (1999)
Lappi, Phys.Rev. C67 (2003)
Schenke,Tribedy,Venugopalan,PRL108 (2012)

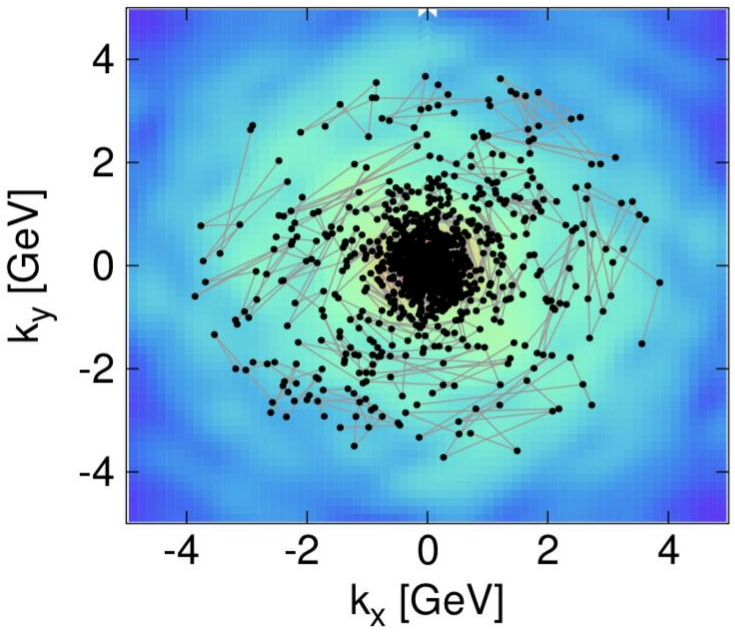
t = 0.0 fm/c

Note: 1 fm/c = $3*10^{-24}$ seconds!

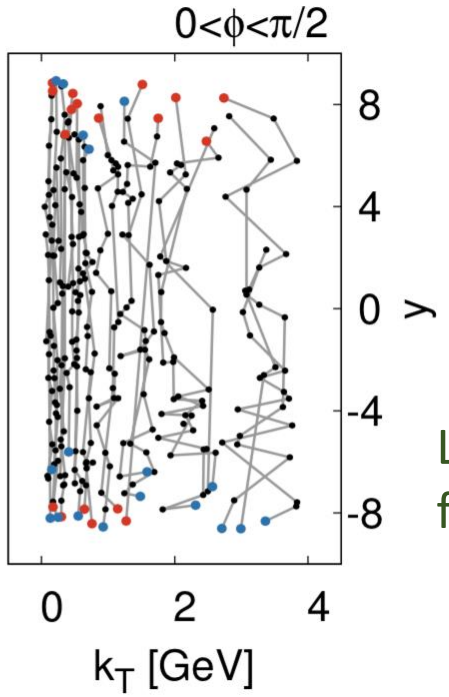
CGC+Lund fragmentation: Glasma flux tubes to strings

Schenke,Schlichting,Tribedy,RV, PRL 117 (2016) 162301

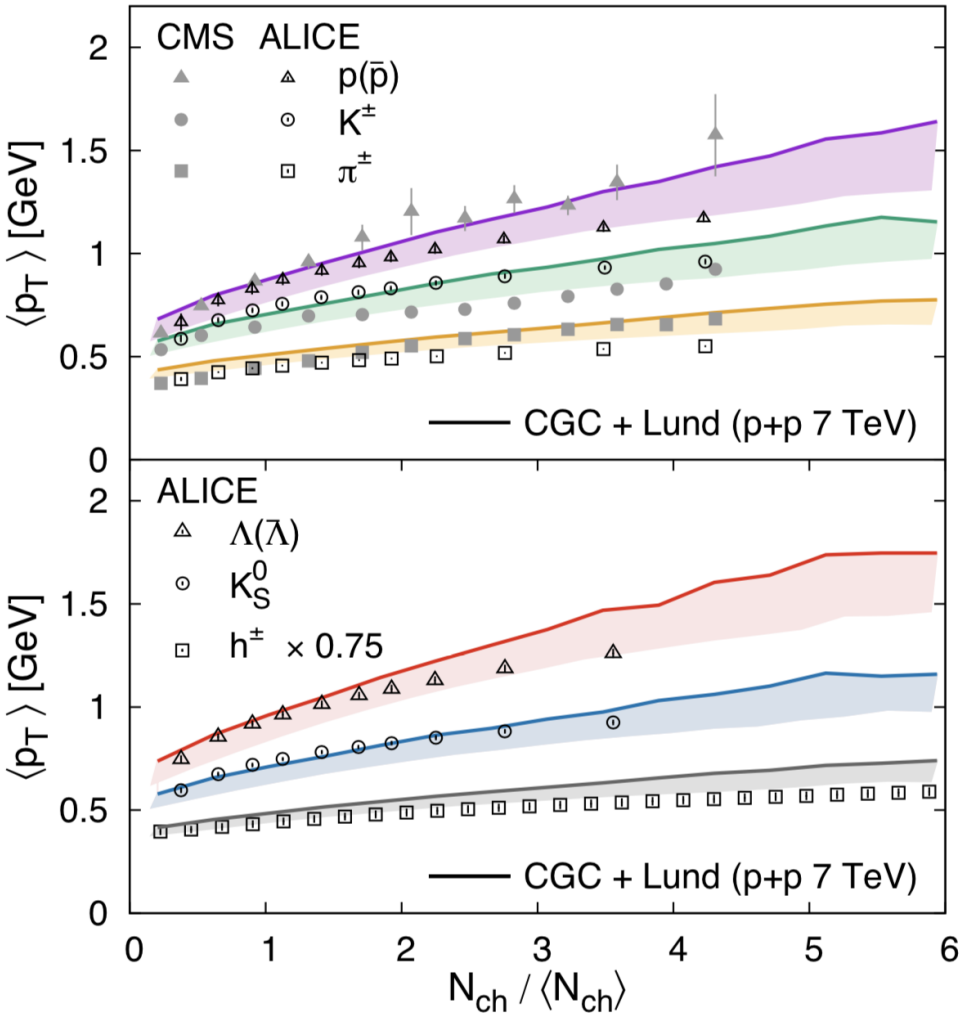
Gluon distribution in a single IP-Glasma event



Strings extended in y & clustered in k_T



Lund string fragmentation



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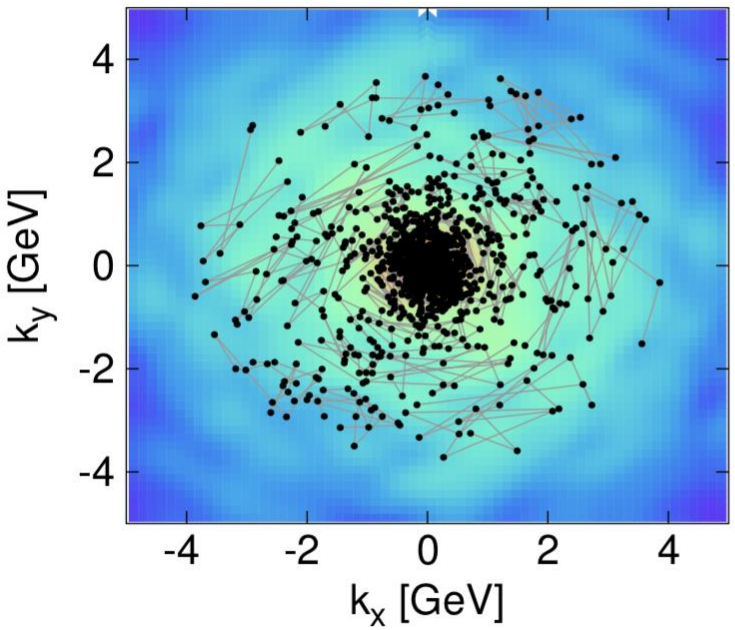

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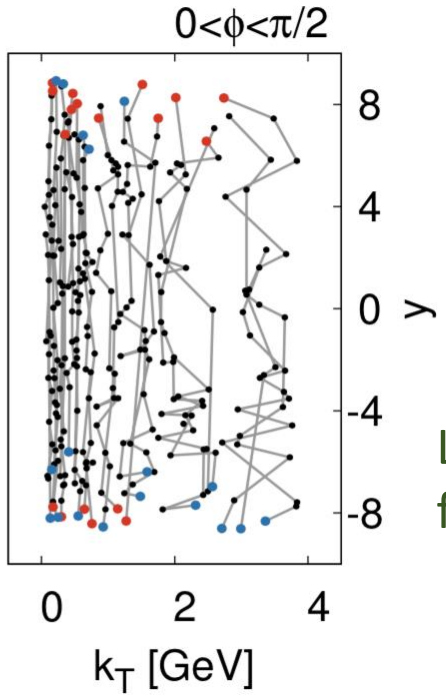

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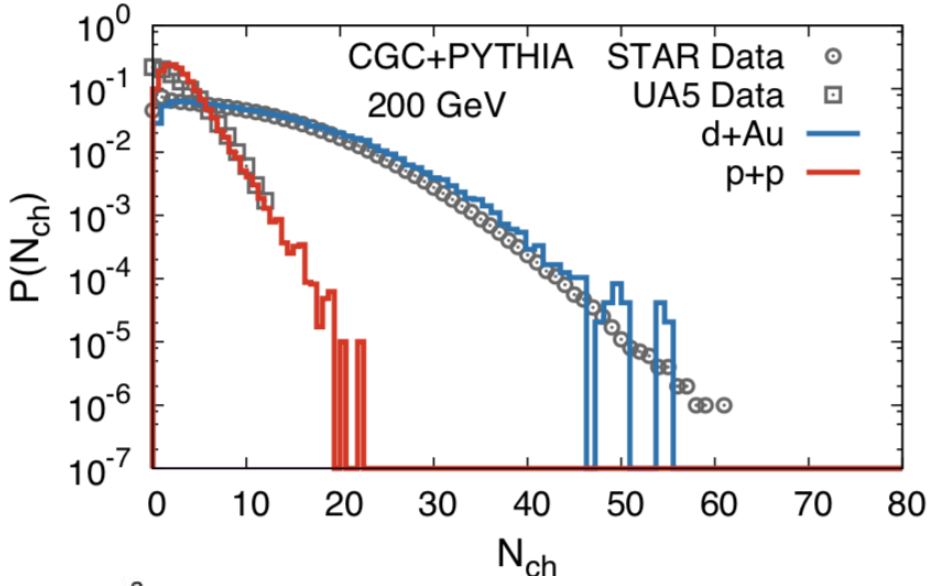
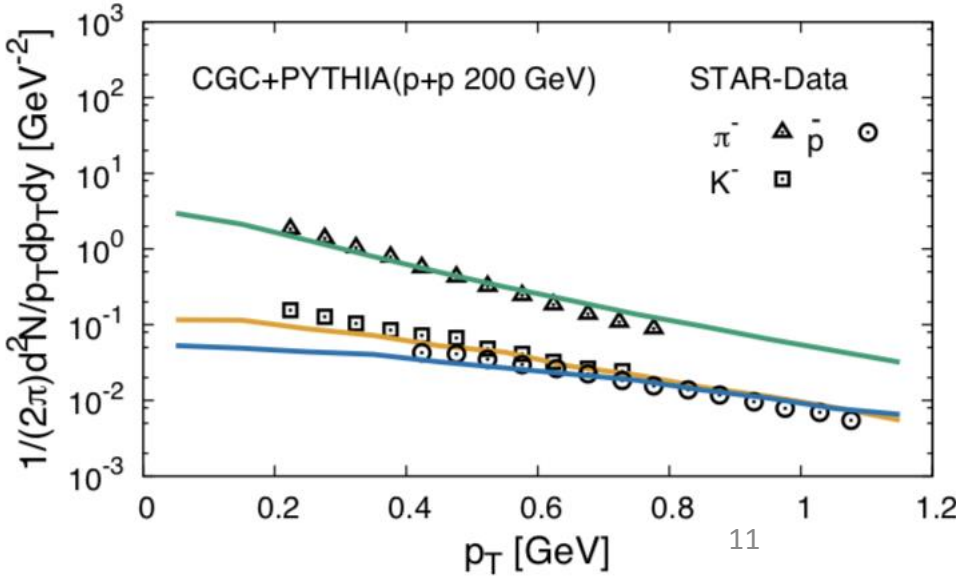




Also generates the "ridge" in p+p and *mass ordering* of "elliptic flow" v_2 coefficient of azimuthal anisotropy

What about e+A ?

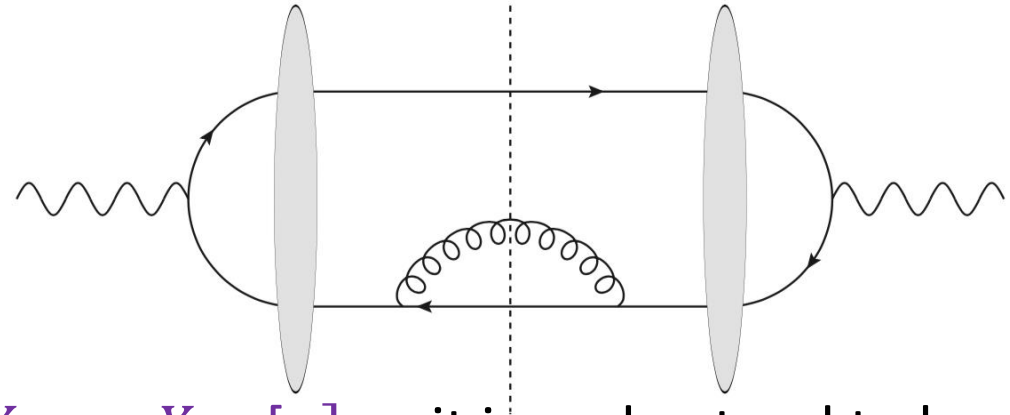
- First, the good news: a lot of nice work on small x evolution by the Lund Group (Leif,Christian,Christine,…)
- From the CGC/Saturation perspective: Not much beyond the work of Thomas & Tobias
- This needs to change – because understanding saturation effects is important for a number of final states.
- I don’t see any showstoppers. The IP-Glasma+PYTHIA is a good template.
- I will outline ideas on how to make progress.

Monte-Carlo for DIS final states at small x

$$d\sigma^{eA\to e+q\bar{q}+ng+X} \propto L^{\mu\nu} X_{\mu\nu}$$

where $L_{\mu\nu}$ is the lepton tensor (contains information on x_{Bj} and Q^2)

$X_{\mu\nu}$ is the hadron tensor to produce a dijet



$X_{\mu\nu} \equiv X_{\mu\nu}\,[\rho]$ so it is understood to be produced in some gluon background field with a color charge distribution ρ which has to be averaged over with a stochastic dist.

In our usual thinking, this ρ is produced by the nucleus – but we can turn this logic around.

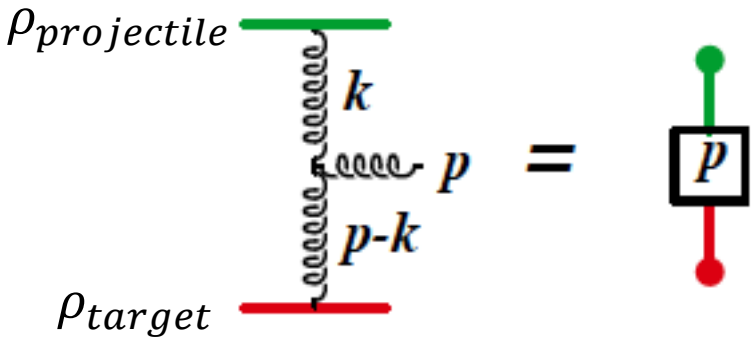
Given an arbitrary choice of ρ that generates a given $X_{\mu\nu}\,[\rho]$ one can treat that as $\rho_{\text{projectile}}$ that generates a gluon field $A^- = \int \frac{d^2 z_\perp}{4\pi} \ln \frac{1}{(x_\perp - z_\perp)^2 \Lambda^2} \rho_{\text{projectile}}(z_\perp, x^+)$

Monte-Carlo for DIS final states at small x

A technical detail is that this gauge field has to be rotated to light cone gauge:
it is the gauge field of the dipole projectile

This interacts with the gauge field of the target to produce n-gluons…
in analogy to the IP-Glasma – and the rest follows as previously

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



The physics of the target – saturation scale at a given impact parameter –
is encoded in ρ_{target} which has then to be averaged over with those scales

Monte-Carlo for DIS final states at small x

Caveats:

- This likely holds only for gluons and dijets/di-hadrons produced in a few units in rapidity
- For larger rapidities, there is a formalism by Iancu and Triantafyllopolous (also Lappi and Ramnath) that can be implemented in principle, but it is numerically challenging…
- Should compare to semi-analytical results in the literature (Kovchegov+Tuchin) to see if this approach is reasonable and reproduces known results.

Comments/questions/brickbats ?