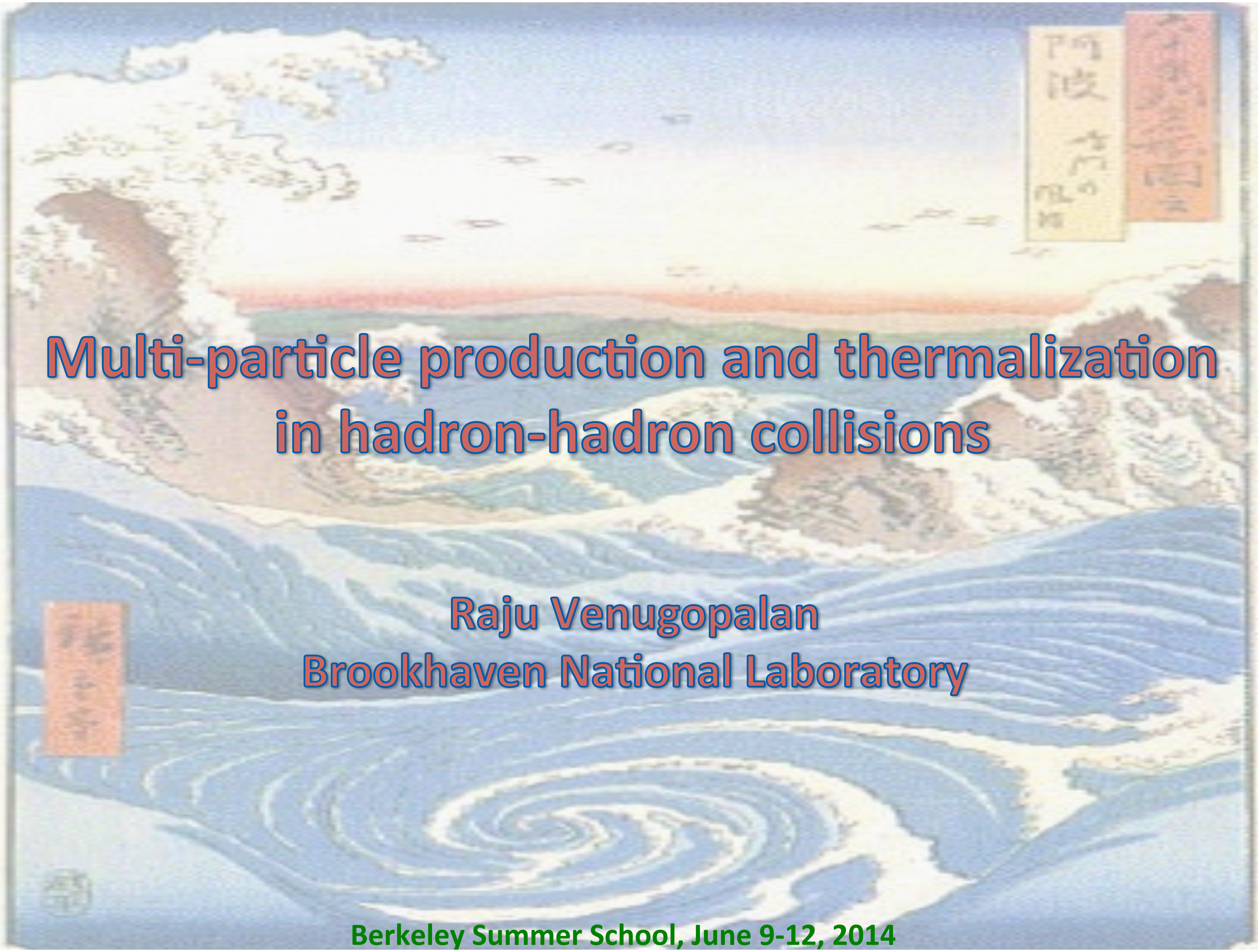
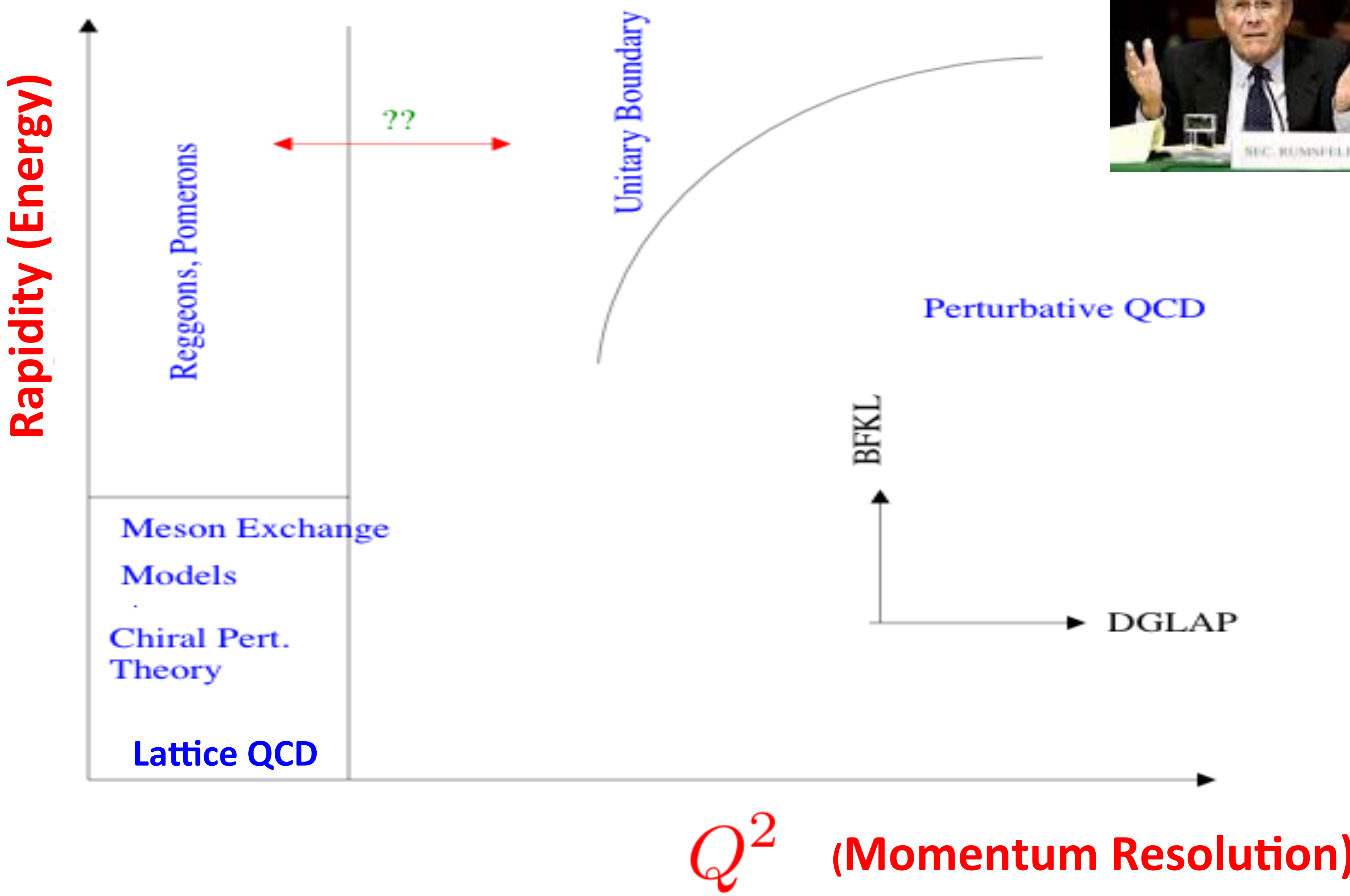


Multi-particle production and thermalization in hadron-hadron collisions

Raju Venugopalan
Brookhaven National Laboratory

Berkeley Summer School, June 9-12, 2014

QCD: Known Knowns and Known Unknowns



QCD: Known Knowns and Known Unknowns

Known knowns in QCD:

- **Perturbative QCD: precision physics for large Q^2 – rare processes (also weak coupling techniques in finite T and μ_B QFT)**

- **Lattice QCD: Quantitative description of (mostly) hadron ground state properties. (see Prof. Fodor's talk)**

- **Chiral perturbation theory: low energy meson and baryon interactions**

QCD: Known Knowns and Known Unknowns

Known unknowns in QCD:

◆ **The bulk of elastic, inelastic and diffractive cross-sections in QCD (sometimes called ``soft" physics – though includes scales of a few GeV).**

◆ **Fragmentation/hadronization is not understood— though useful and successful parametrizations exist.**

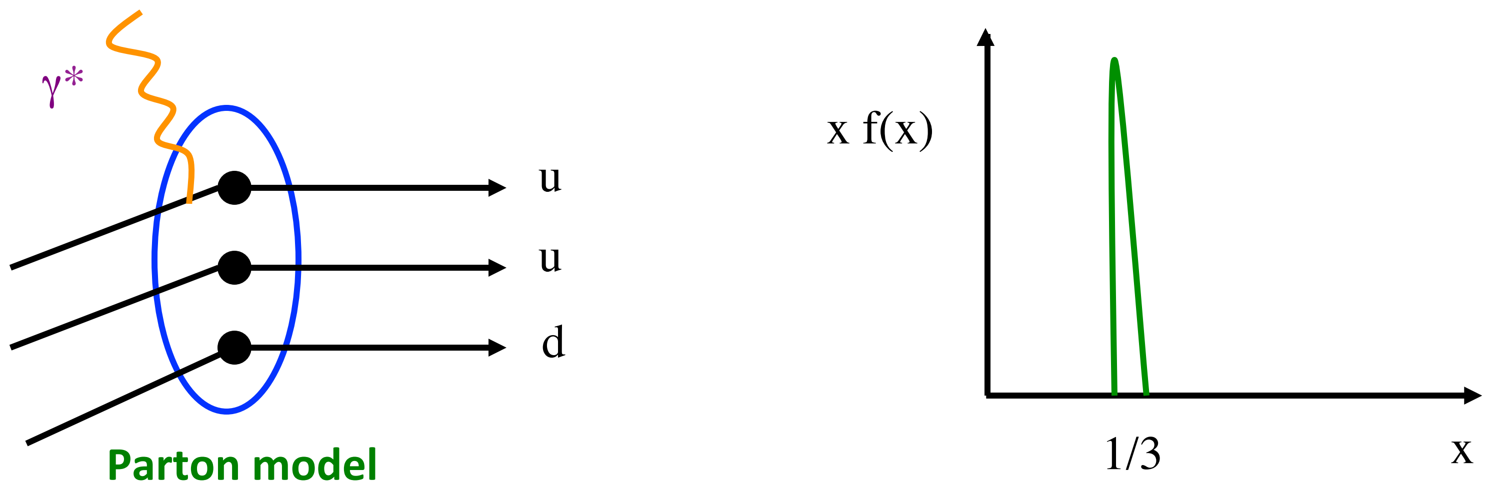
◆ **Stringy models (PYTHIA,DPM,AMPT,EPOS) successfully parametrize a lot of data and loosely capture features of the underlying theory.**

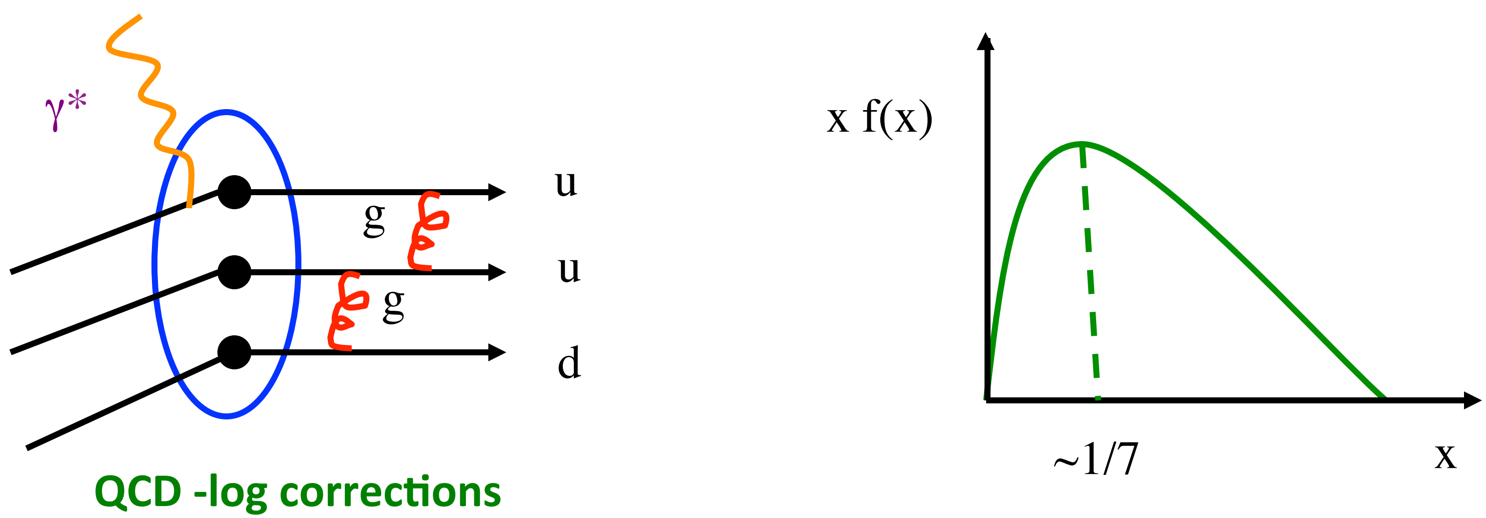
◆ **However, they *cannot be derived* in any limit from QCD, and require further ad hoc assumptions and parameters when applied In extreme environments**

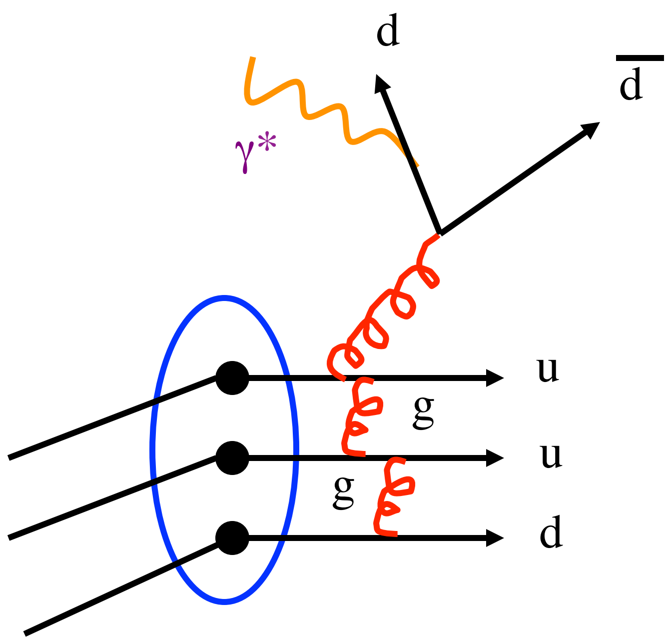
What we need

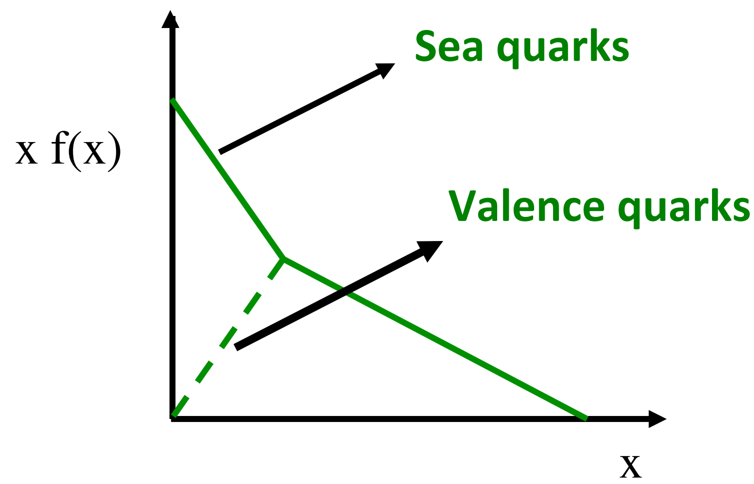
- An effective theory to describe the varied phenomena of multi-particle production in high energy collisions
- Smoothly matches to QCD in appropriate kinematic limits
- The rest of my talk will briefly outline the elements of such a theory.
- The theory has much predictive power—however, it is least effective when the physics is sensitive to the infrared scales that govern chiral symmetry breaking and confinement.

The proton at high energies







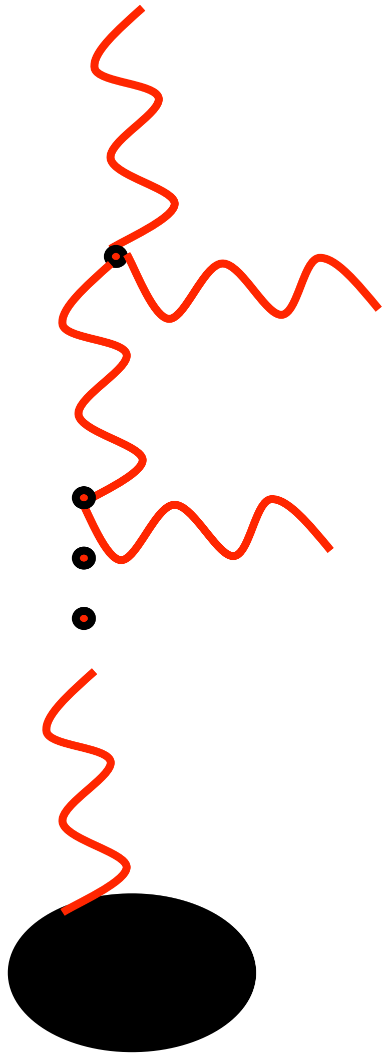


"x-QCD"- small x evolution

$$\int_0^1 \frac{dx}{x}\,(xq(x) - x\bar{q}(x)) = 3$$ ⟶ **# of valence quarks**

$$\int_0^1 \frac{dx}{x}\,(xq(x) + x\bar{q}(x)) \to \infty$$ ⟶ **# of quarks**

Bremsstrahlung
-linear QCD evolution



Each rung of the ladder gives

$$\alpha_S \int \frac{dk_t^2}{k_t^2} \int \frac{dx}{x} \equiv \alpha_S \ln\left(\frac{x_0}{x}\right) \ln\left(\frac{Q^2}{Q_0^2}\right)$$

If only transverse momenta are ordered from target to projectile:

$$k_{T1}^2 << k_{T2}^2 << \cdots Q^2$$

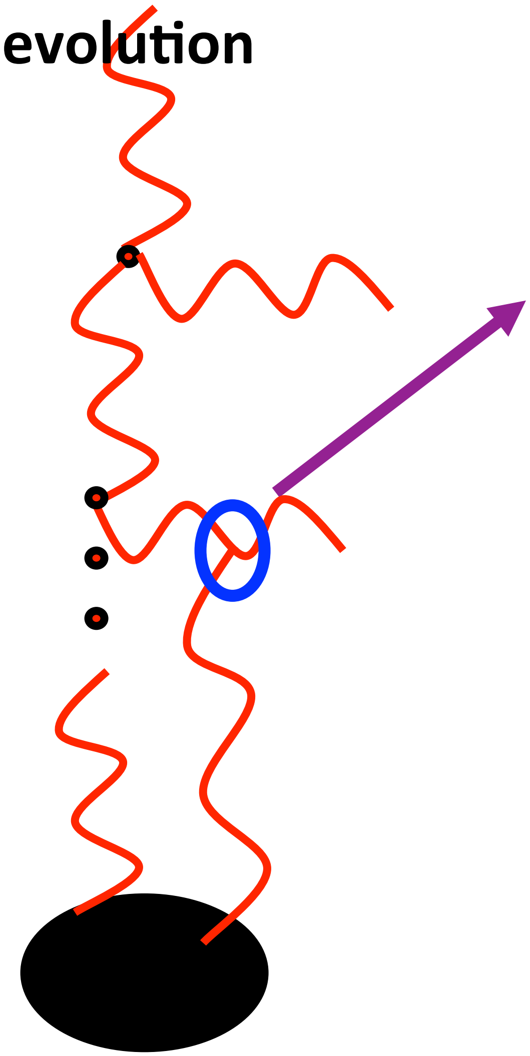
Sum leading logs in Q^2 (DGLAP evolution)

Conversely, $x_0 >> x_1 \cdots >> x$

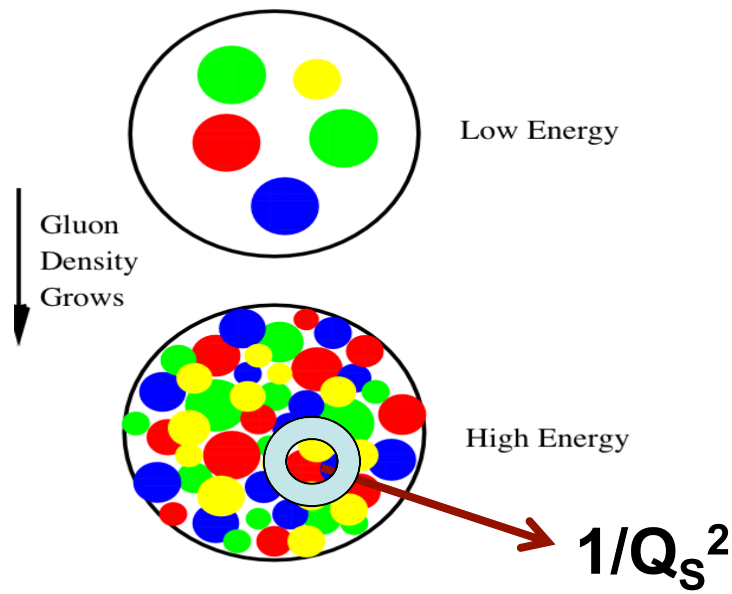
Sum leading logs in x (BFKL evolution)

Both DGLAP and BFKL give rapid growth of gluon density at small x

Bremsstrahlung
-linear QCD evolution



Gluon recombination
and screening
-non-linear QCD evolution



Proton becomes a dense many body system at high energies

Parton Saturation

Gribov,Levin,Ryskin (1983)
Mueller,Qiu (1986)

- **Competition between attractive bremsstrahlung and repulsive recombination and screening effects**

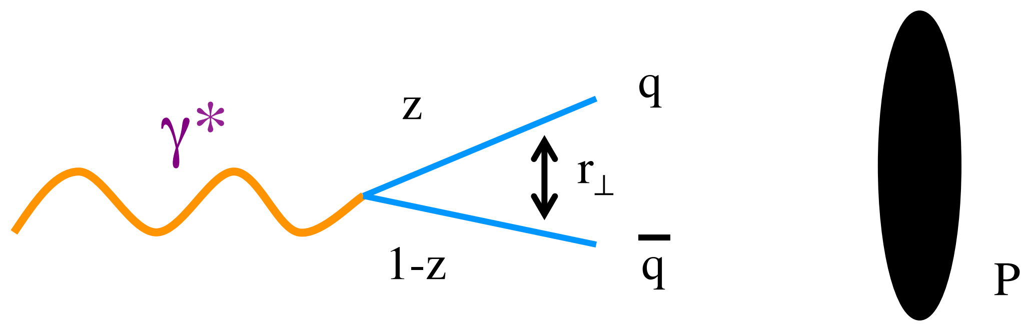
Maximum phase space density (f = $1/\alpha_s$) =>

$$\frac{1}{2(N_c^2-1)}\,\frac{x\,G(x,Q^2)}{\pi R^2\,Q^2} = \frac{1}{\alpha_S(Q^2)}$$

This relation is saturated for

$$Q = Q_s(x) >> \Lambda_{\rm QCD} \approx 0.2\ {\rm GeV}$$

Parton Saturation:Golec-Biernat --Wusthoff dipole model



$$\sigma^{\gamma^*,P}_{\mathrm{T,L}} = \int d^2 r_\perp \int dz\, |\psi_{\mathrm{T,L}}(r_\perp, z, Q^2)|^2\, \sigma_{q,\bar{q},P}(r_\perp, x)$$

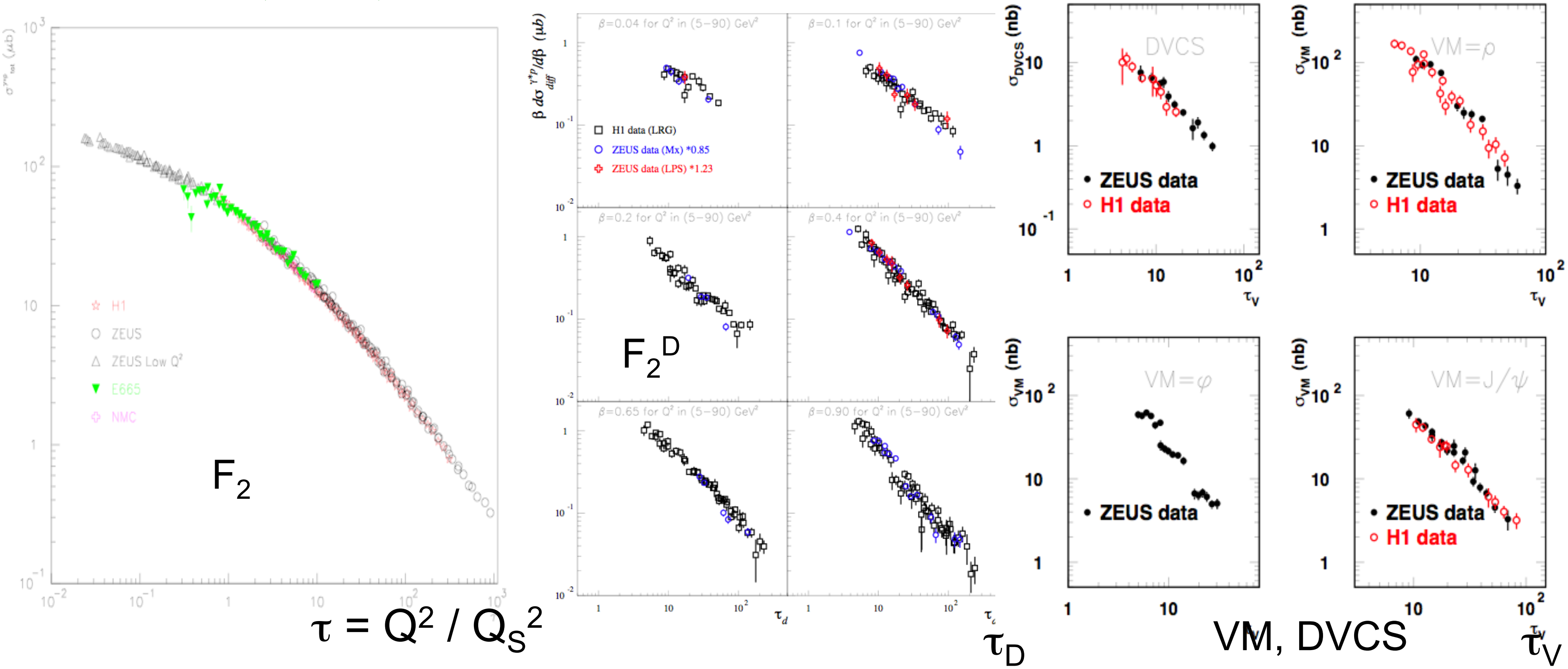
$$\sigma_{q\bar{q}P}(r_\perp, x) = \sigma_0\, \left[1 - \exp\left(-r_\perp^2\, Q_s^2(x)\right)\right]$$

$$Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^\lambda$$

Parameters: Q_0 = 1 GeV; λ = 0.3; $x_0 = 3 * 10^{-4}$; σ_0 = 23 mb

Evidence from HERA for geometrical scaling

Golec-Biernat, Stasto,Kwiecinski

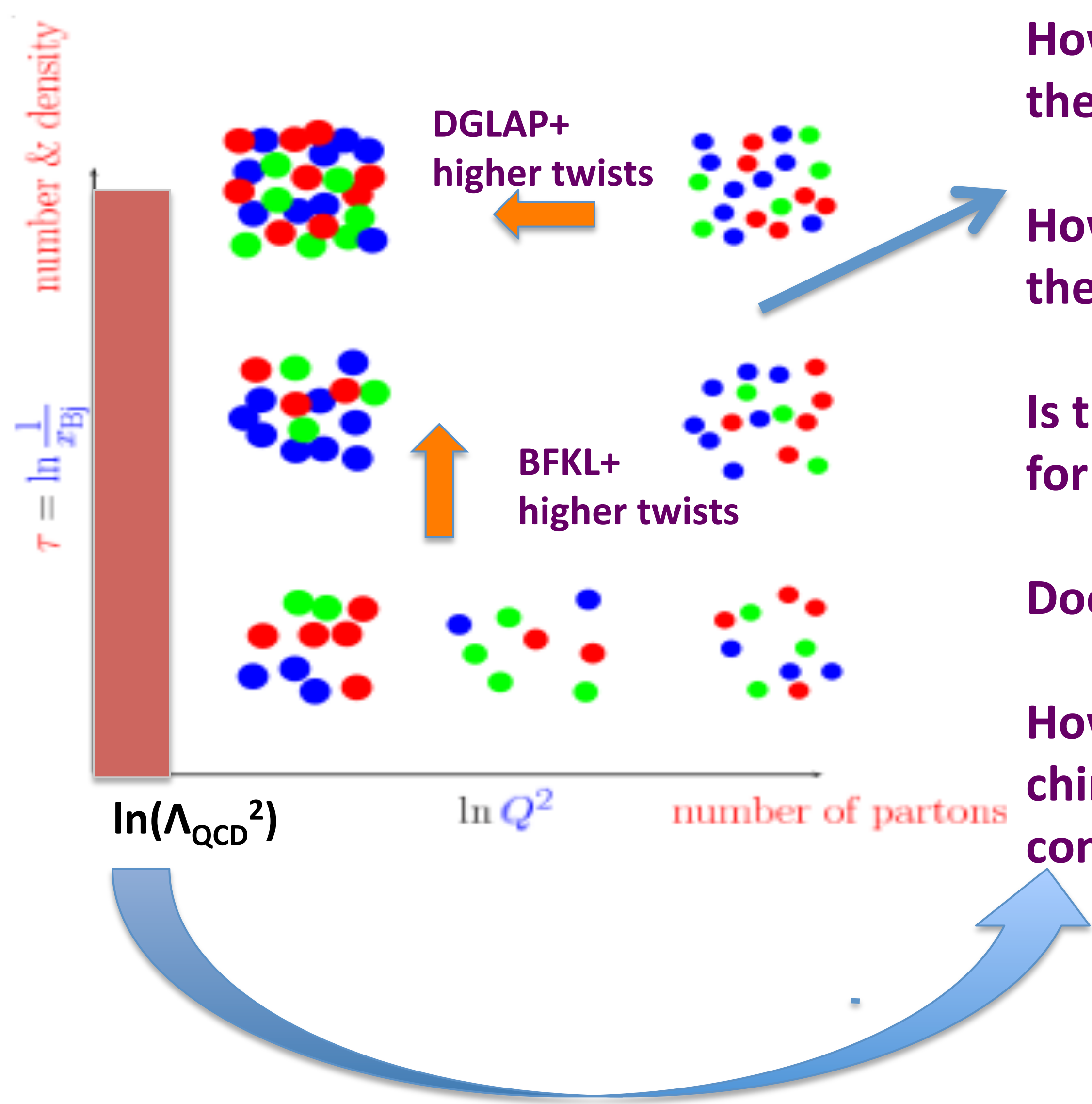


Marquet, Schoeffel hep-ph/0606079

- **Scaling seen for F_2^D and VM,DVCS for same Q_S as F_2**

Gelis et al., hep-ph/0610435

Many-body dynamics of universal gluonic matter



How does this happen ? What are the right degrees of freedom ?

How do correlation functions of these evolve ?

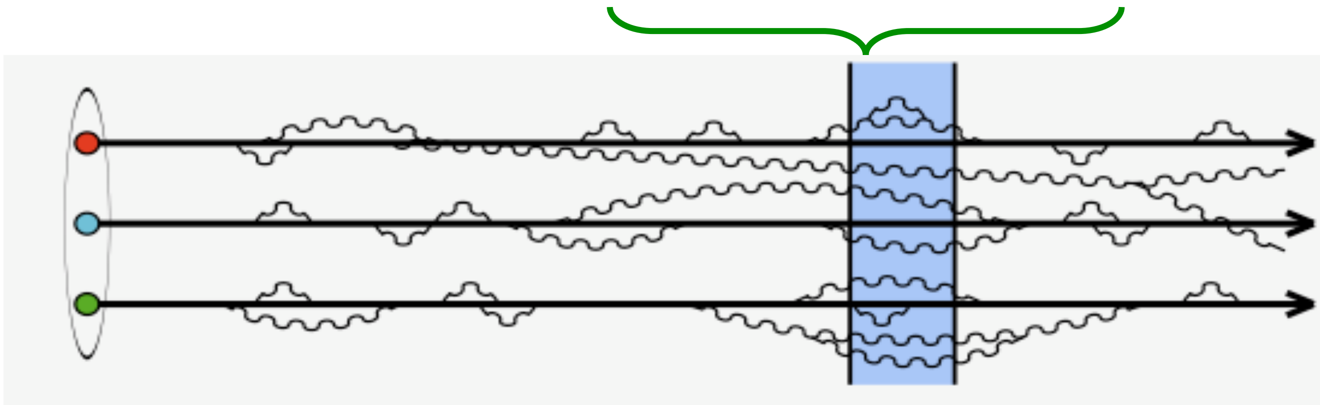
Is there a universal fixed point for the RG evolution of d.o.f

Does the coupling run with Q_s^2 ?

How does saturation transition to chiral symmetry breaking and confinement

The high energy nuclear wavefunction in QFT

|A> = |qqq…q> + … + |qqq…qgg…g>



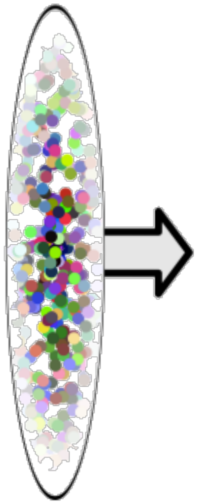
- At high energies, interaction time scales of fluctuations are dilated well beyond typical hadronic time scales

- Lots of short lived (gluon) fluctuations now seen by probe -- proton/nucleus -- dense many body system of (primarily) gluons

- Fluctuations with lifetimes much longer than interaction time for the probe function as static color sources for more short lived fluctuations

Nuclear wave function at high energies is a Color Glass Condensate

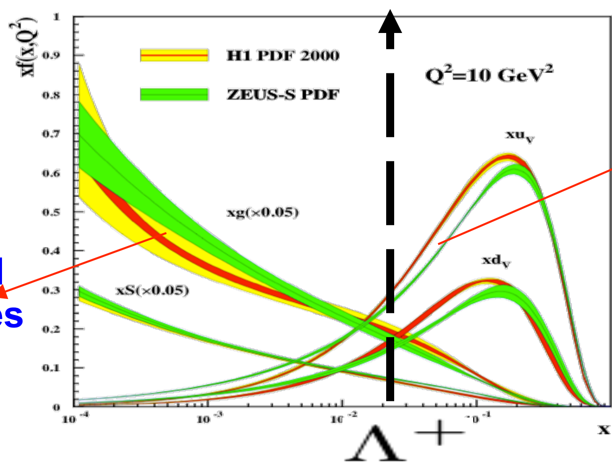
The nuclear wavefunction at high energies



$$|A\rangle = |qqq\ldots q\rangle + \ldots + |qqq\ldots q\,gg\ldots gg\rangle$$

Higher Fock components dominate multiparticle production- construct Effective Field Theory

Dynamical Wee modes

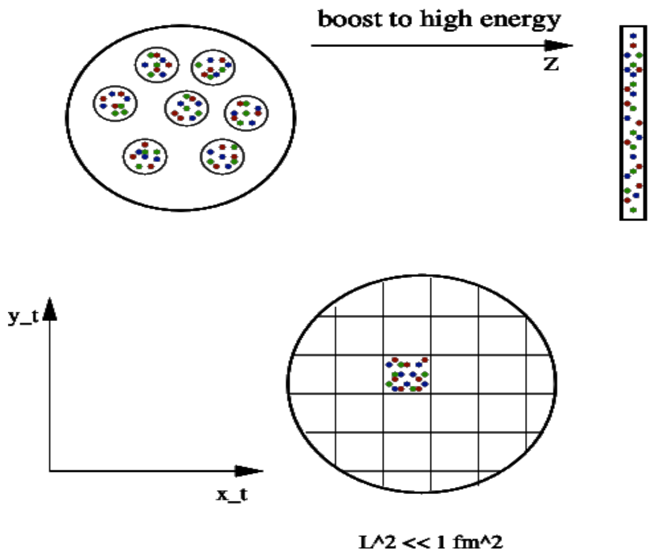


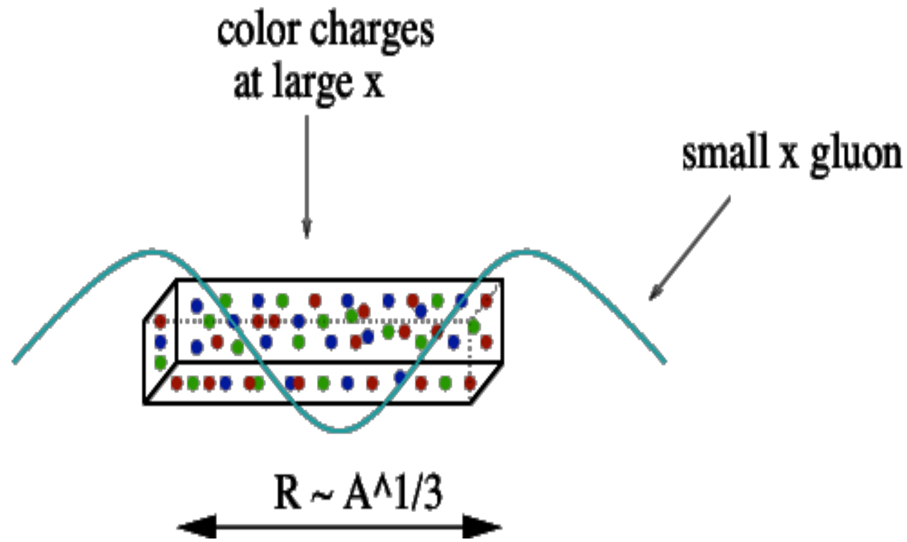
Valence modes- are static sources for wee modes

Born--Oppenheimer LC separation natural for EFT.

RG eqns describe evolution of wavefunction with energy

What do sources look like in the IMF ?





$$\lambda_{\rm wee} \approx \frac{1}{k^+} \equiv \frac{1}{xP^+} >> \lambda_{\rm val.} \equiv \frac{Rm_p}{P^+} => x << A^{-1/3}$$

Wee partons "see" a large density of color sources at small transverse resolutions

Effective Field Theory on Light Front

Susskind
Bardacki-Halpern

Poincare group on LF ⟷ Galilean sub-group of 2D Quantum Mechanics

isomorphism

Eg., LF dispersion relation $P^- = \frac{P_\perp^2}{2P^+}$

Energy (P^-), Momentum ($P_\perp^2$), Mass ($2P^+$)

Large x (P^+) modes: static LF (color) sources ρ^a

Small x ($k^+ \ll P^+$) modes: dynamical fields A_μ^a

McLerran, RV

CGC: Coarse grained many body EFT on LF

$$< P|\mathcal{O}|P > \longrightarrow \int [d\rho^a][dA^{\mu,a}]\, W_{\Lambda^+}[\rho]\, e^{iS_{\Lambda^+}[\rho,A]}\, \mathcal{O}[\rho, A]$$

$W_{\Lambda^+}[\rho]$ non-pert. gauge invariant "density matrix" defined at initial scale Λ_0^+

RG equations describe evolution of W with x

JIMWLK, BK

Classical field of a large nucleus

$$< AA >_\rho = \int [d\rho] A_{\rm cl.}(\rho) A_{\rm cl.}(\rho) W_{\Lambda^+}[\rho]$$

For a large nucleus, A >>1,

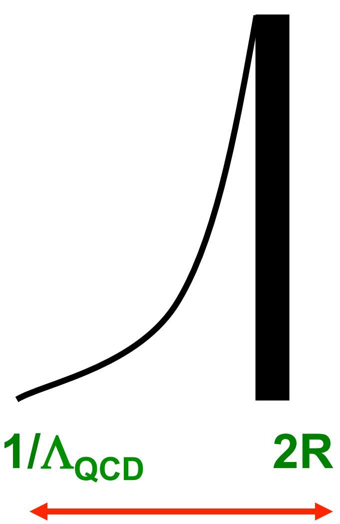
"Pomeron" excitations

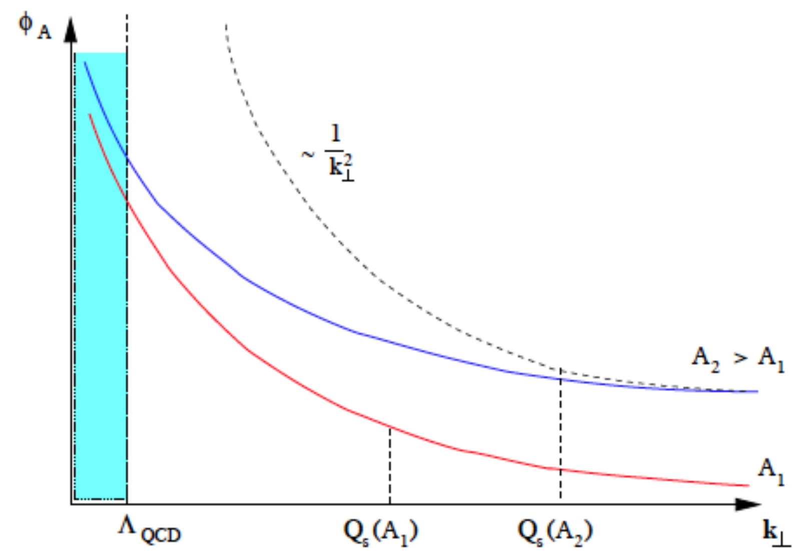
"Odderon" excitations

$$W_{\Lambda^+} = \exp\left(- \int d^2 x_\perp \left[\frac{\rho^a \rho^a}{2\,\mu_A^2} - \frac{d_{abc}\,\rho^a \rho^b \rho^c}{\kappa_A} \right] \right)$$

McLerran,RV
Kovchegov
Jeon, RV

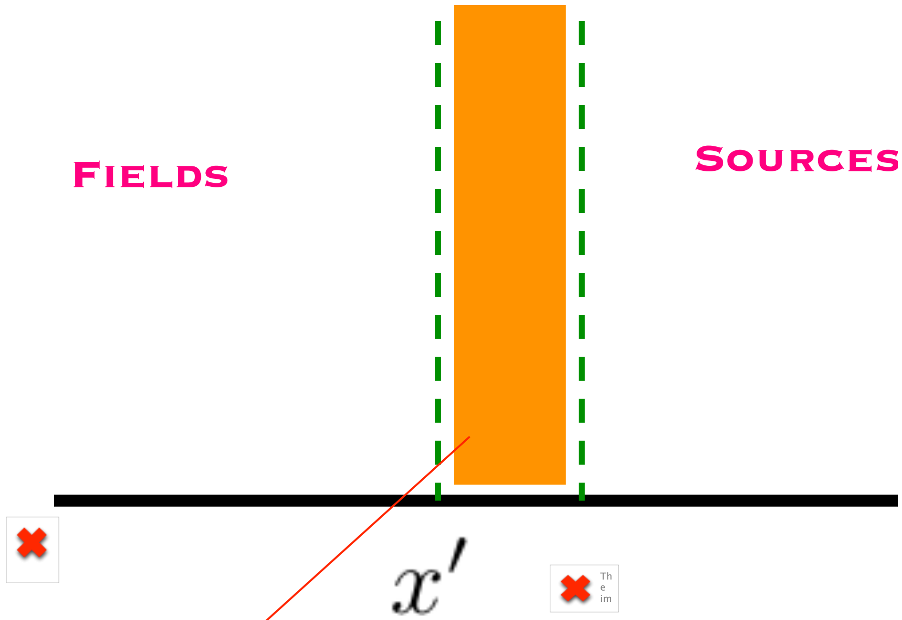
A_{cl} from $\longrightarrow$ $(D_\mu F^{\mu\nu})^a = J^{\nu,a} \equiv \delta^{\nu +}\,\delta(x^-)\,\rho^a(x_\perp)$

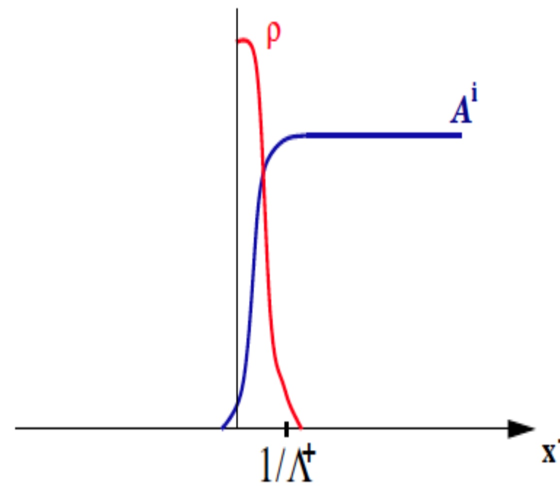




Wee parton dist. : $\frac{1}{\Lambda_{\rm QCD}} e^{-\lambda \Delta Y/2}$ → determined from RG

Quantum evolution of classical theory: Wilson RG



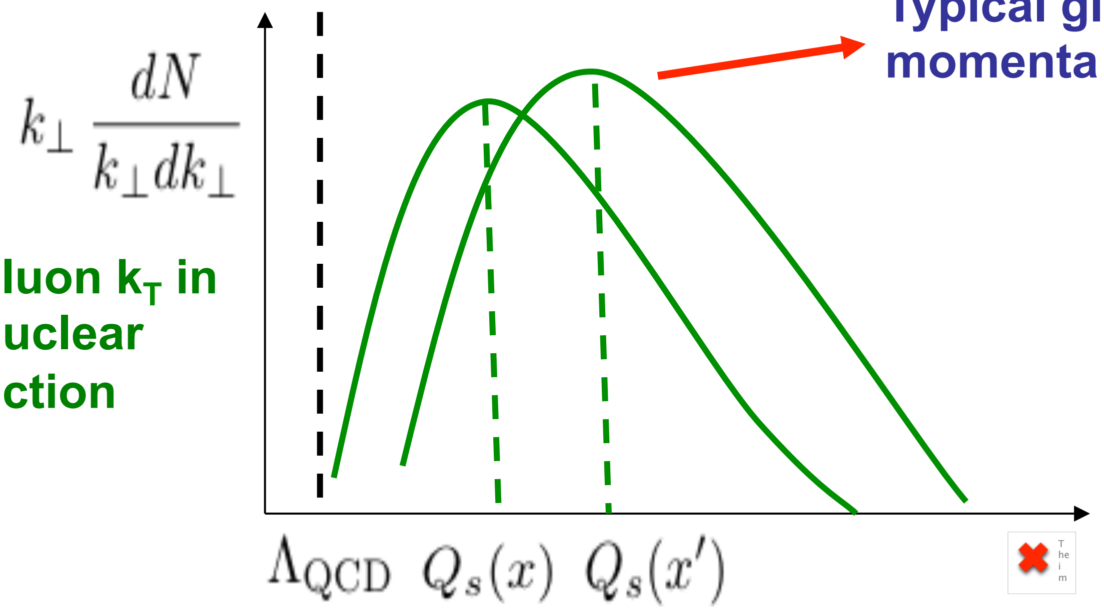


Integrate out
Small fluctuations => Increase color charge of sources

Wilsonian RG equations describe evolution of all N-point correlation functions with energy

JIMWLK Jalilian-marian, Iancu, McLerran,Weigert, Leonidov,Kovner

Saturation scale grows with energy



Typical gluon momenta are large

Typical gluon k_T in hadron/nuclear wave function

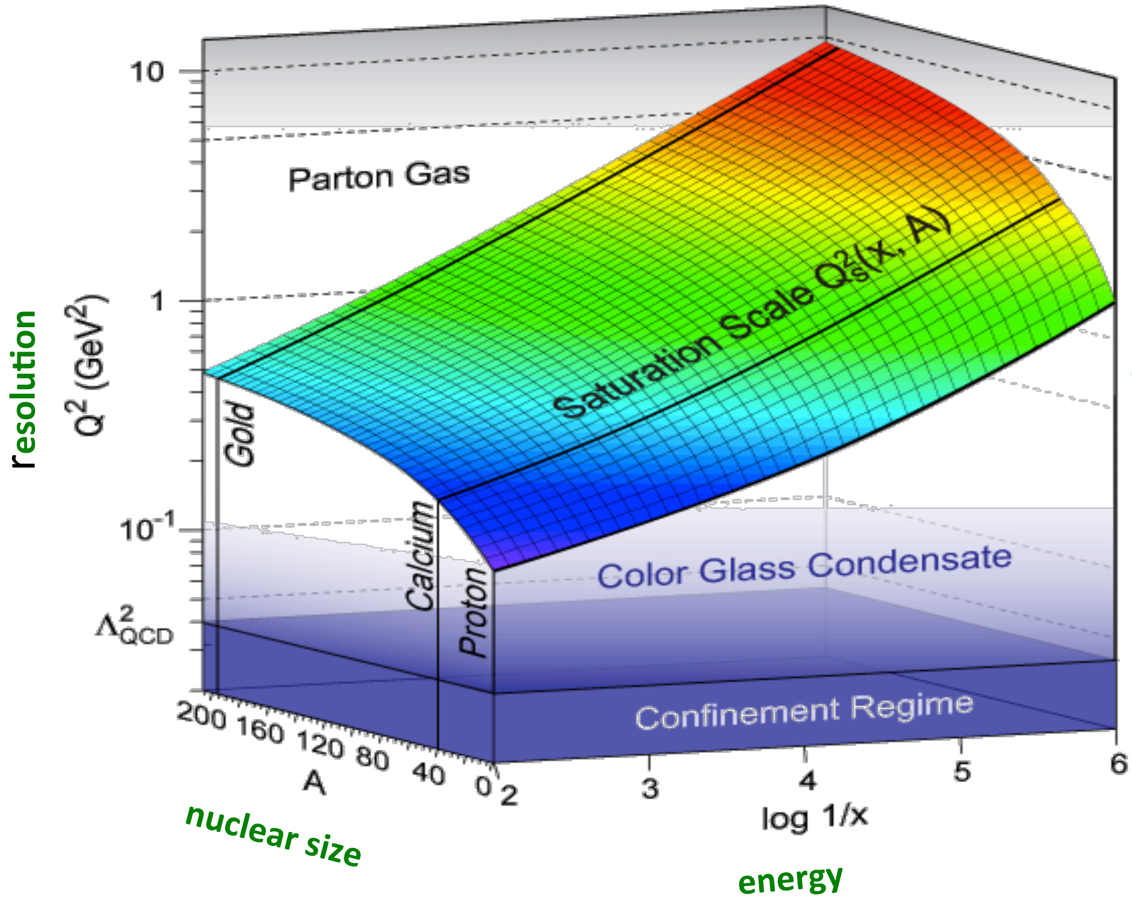
Bulk of high energy cross-sections:

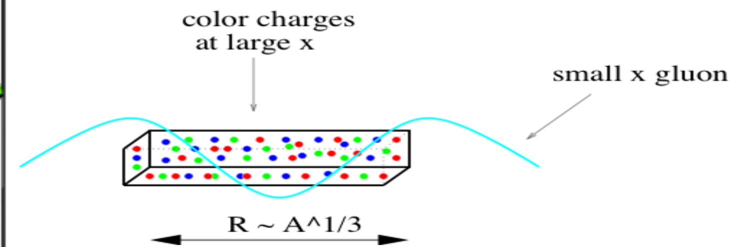
a) obey dynamics of novel non-linear QCD regime

b) Can be computed systematically in weak coupling

Many-body high energy QCD:
The Color Glass Condensate

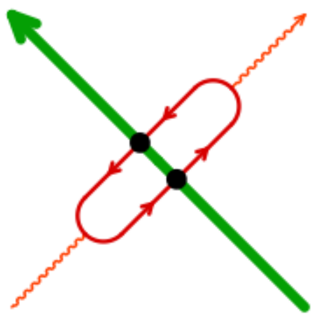
Gelis,Iancu,Jalilian-Marian,RV:
Ann. Rev. Nucl. Part. Sci. (2010), arXiv: 1002.0333





Dynamically generated semi-hard "saturation scale" opens window for systematic weak coupling study of non-perturbative dynamics

Inclusive DIS: dipole evolution

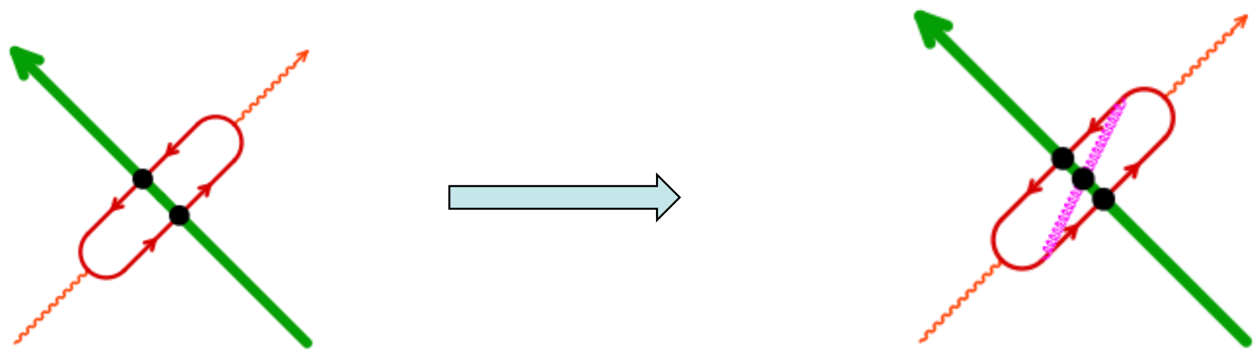


$$\sigma_{\gamma^* T} = \int_0^1 dz \int d^2 r_\perp \, |\psi(z, r_\perp)|^2 \sigma_{\text{dipole}}(x, r_\perp)$$

$$\sigma_{\text{dipole}}(x, r_\perp) = 2 \int d^2 b \int [D\rho] \, W_{\Lambda^+}[\rho] \, T(b + \frac{r_\perp}{2}, b - \frac{r_\perp}{2})$$

$$1 - \frac{1}{N_c} \text{Tr} \left(V \left(b + \frac{r_\perp}{2} \right) V^\dagger \left(b - \frac{r_\perp}{2} \right) \right)$$

Inclusive DIS: dipole evolution



B-JIMWLK eqn. for dipole correlator

$$\frac{\partial}{\partial Y}\langle \mathrm{Tr}(V_x V_y^\dagger)\rangle_Y = -\frac{\alpha_S N_c}{2\pi^2}\int_{z_\perp} \frac{(x_\perp - y_\perp)^2}{(x_\perp - z_\perp)^2 (z_\perp - y_\perp)^2}\,\langle \mathrm{Tr}(V_x V_y^\dagger) - \frac{1}{N_c}\mathrm{Tr}(V_x V_z^\dagger)\,\mathrm{Tr}(V_z V_y^\dagger)\rangle_Y$$

Dipole factorization:

$$\langle \mathrm{Tr}(V_x V_z^\dagger)\,\mathrm{Tr}(V_z V_y^\dagger)\rangle_Y \longrightarrow \langle \mathrm{Tr}(V_x V_z^\dagger)\rangle_Y \langle \mathrm{Tr}(V_z V_y^\dagger)\rangle_Y$$ **N_c ➔ ∞**

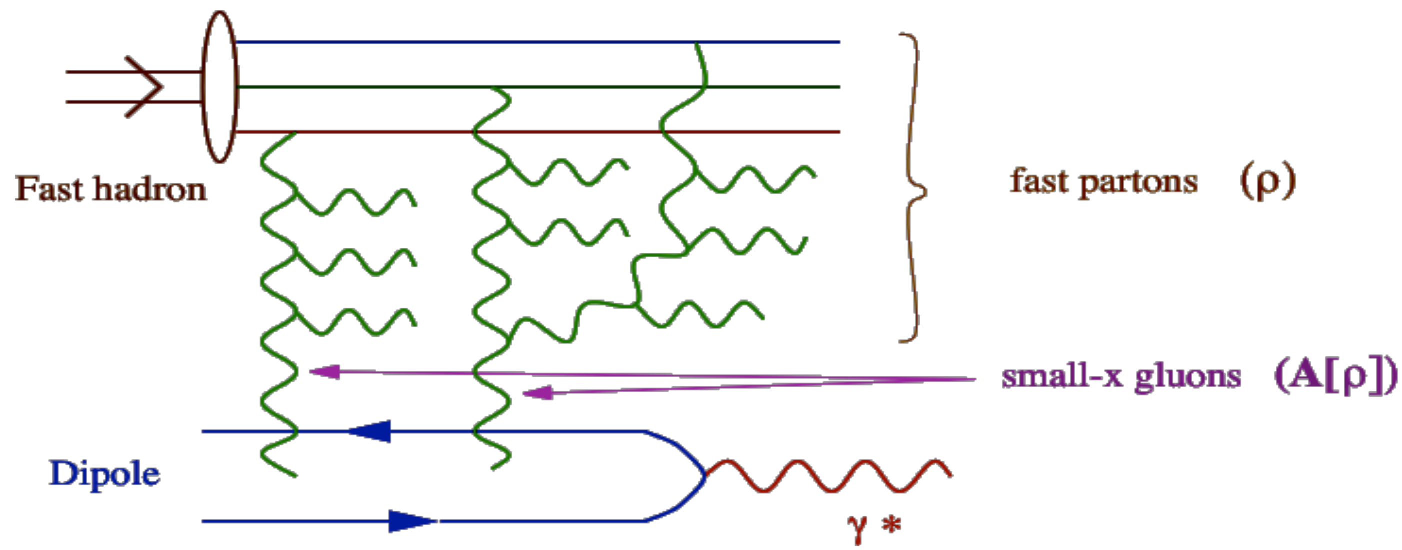
Resulting closed form eqn. is the Balitsky-Kovchegov eqn.
Widely used in phenomenological applications

CGC Effective Theory: B-JIMWLK hierarchy of correlators

$$\frac{\partial}{\partial Y} < O[\alpha] >_Y = < \frac{1}{2} \int_{x,y} \frac{\delta}{\delta \alpha_Y^a(x)} \chi_{x,y}^{ab} \frac{\delta}{\delta \alpha_Y^b(y)} O[\alpha] >_Y$$

"time"

"diffusion coefficient"



At high energies, the d.o.f that describe the frozen many-body gluon configurations are novel objects: dipoles, quadrupoles, …

Universal – appear in a number of processes in p+A and e+A; how do these evolve with energy ?

Solving the B-JIMWLK hierarchy

- JIMWLK includes multiple scatterings & leading log evolution in x

- Expectation values of Wilson line correlators at small x satisfy a Fokker-Planck eqn. in functional space

Weigert (2000)

- This translates into a hierarchy of equations for n-point Wilson line correlators

- As is generally the case, Fokker-Planck equations can be re-expressed as Langevin equations – in this case for Wilson lines

Blaizot,Iancu,Weigert
Rummukainen,Weigert

B-JIMWLK hierarchy: Langevin realization

Numerical evaluation of Wilson line correlators on 2+1-D lattices:

$$\left\langle \mathcal{O}[U] \right\rangle_Y = \int D[U]\, W_Y[U]\, \mathcal{O}[U] \longrightarrow \frac{1}{N} \sum_{U \epsilon W} \mathcal{O}[U]$$

Langevin eqn:

$$\partial_Y [V_x]_{ij} = [V_x i t^a]_{ij} \left[\int d^2y\, [\mathcal{E}^{ab}_{xy}]_k\, [\xi^b_y]_k + \sigma^a_x \right]$$

Gaussian random variable

$$\mathcal{E}^{ab}_{xy} = \left(\frac{\alpha_S}{\pi^2} \right)^{1/2} \frac{(x-y)_k}{(x-y)^2} \left[1 - U^\dagger_x U_y \right]^{ab}$$

"square root" of JIMWLK kernel

$$\sigma^a_x = -i \left(\frac{\alpha_S}{2\pi^2} \int d^2z \frac{1}{(x-z)^2} \mathrm{Tr}(T^a\, U^\dagger_x U_z) \right)$$

"drag"

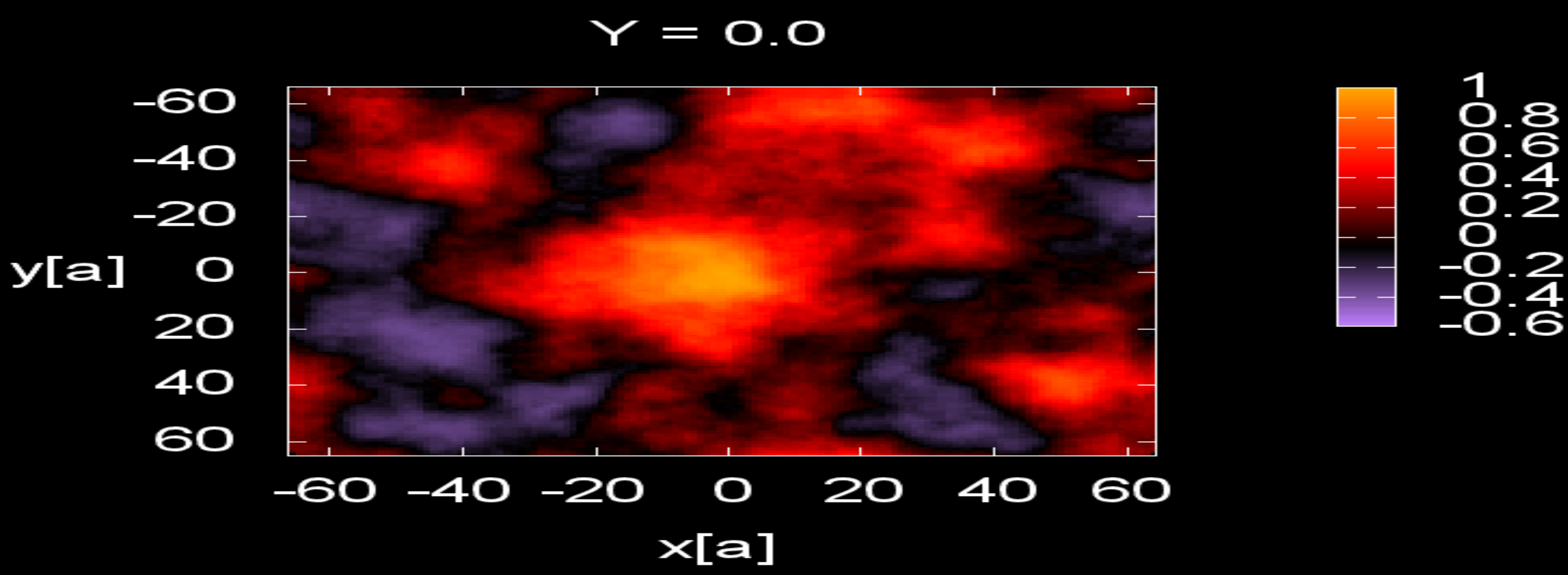
- Initial conditions for V's from the MV model
- Daughter dipole prescription for running coupling

Functional Langevin solutions of JIMWLK hierarchy

Rummukainen,Weigert (2003)

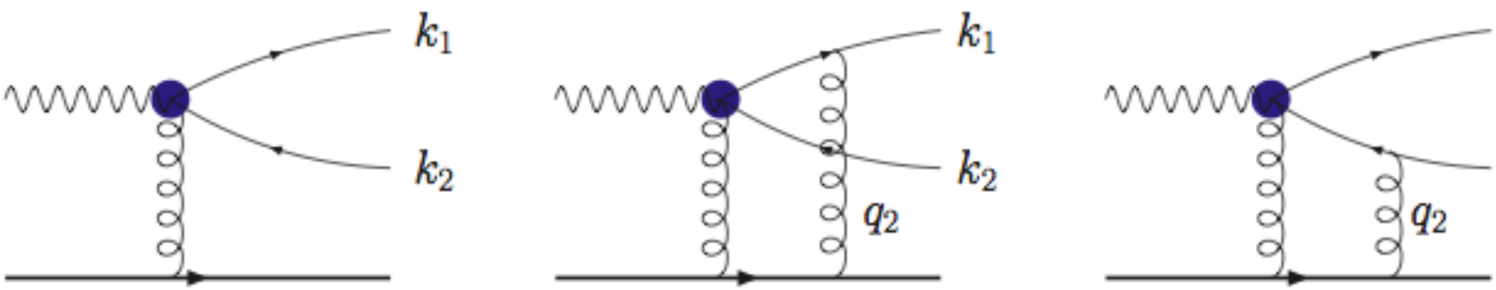
Dumitru,Jalilian-Marian,Lappi,Schenke,RV, PLB706 (2011)219

✓ ***We are now able to compute all n-point correlations of a theory of strongly correlated gluons and study their evolution with energy!***



Correlator of Light-like Wilson lines Tr(V(0,0)V^dagger (x,y))

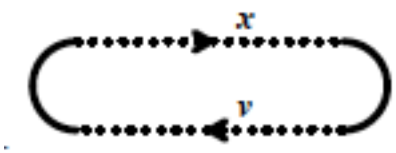
Semi-inclusive DIS: quadrupole evolution

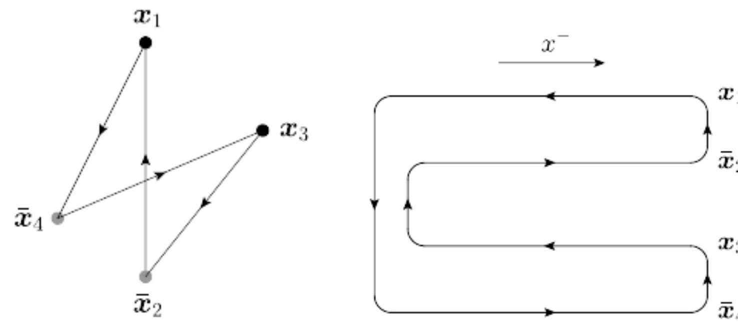


Dominguez,Marquet,Xiao,Yuan (2011)

$$\frac{d\sigma^{\gamma^*_{\mathrm{T,L}}A\to q\bar{q}X}}{d^3k_1d^3k_2} \propto \int_{x,y,\bar{x}\bar{y}} e^{ik_{1\perp}\cdot(x-\bar{x})}e^{ik_{2\perp}\cdot(y-\bar{y})}\ \left[1+Q(x,y;\bar{y},\bar{x})-D(x,y)-D(\bar{y},\bar{x})\right]$$

Semi-inclusive DIS: quadrupole evolution



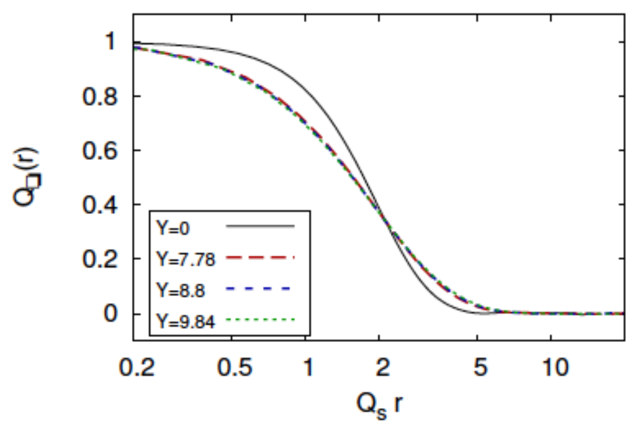


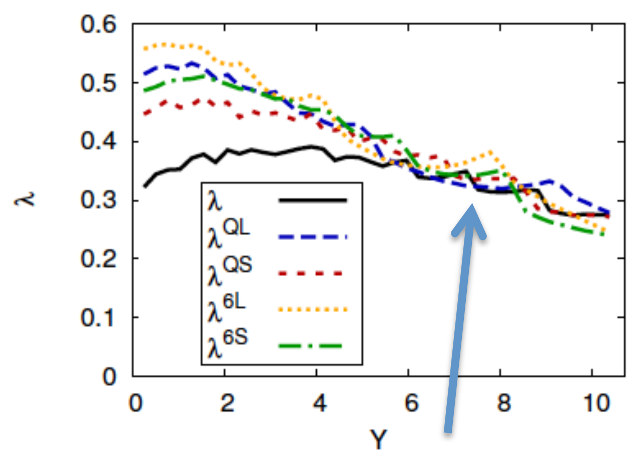
$$D(x,y) = \frac{1}{N_c}\langle \mathrm{Tr}(V_x V_y^\dagger)\rangle_Y \qquad Q(x,y;\bar{y},\bar{x}) = \frac{1}{N_c}\langle \mathrm{Tr}(V_x V_{\bar{x}}^\dagger V_{\bar{y}} V_y^\dagger)\rangle_Y$$

RG evolution provides fresh insight into multi-parton correlations

Dumitru,Jalilian-Marian,Lappi,Schenke,RV: arXiv:1108.1764

Quadrupoles, like Dipoles, exhibit Geometrical Scaling



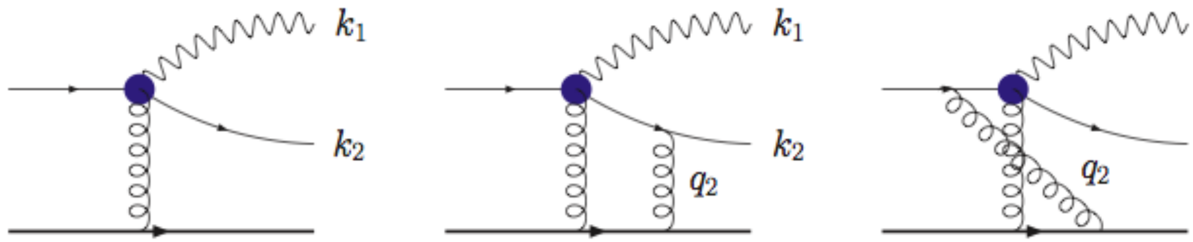


Iancu,Triantafyllopolous,arXiv:1112.1104

Rate of energy evolution of dipole and quadrupole saturation scales

Universality: Di-hadrons in p/d-A collisions

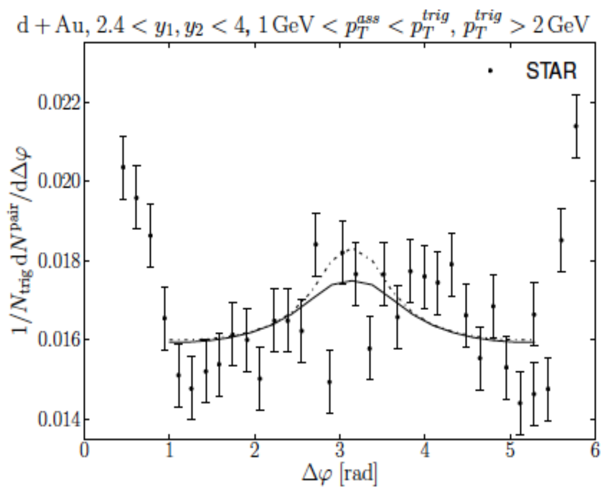
Jalilian-Marian, Kovchegov (2004)
Marquet (2007), Tuchin (2010)
Dominguez,Marquet,Xiao,Yuan (2011)
Strikman,Vogelsang (2010)

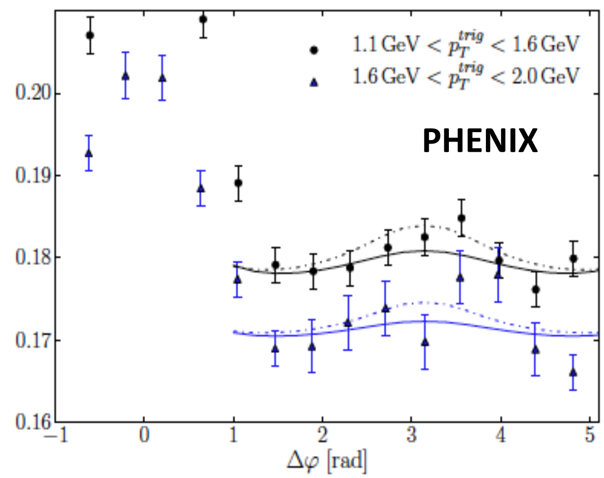


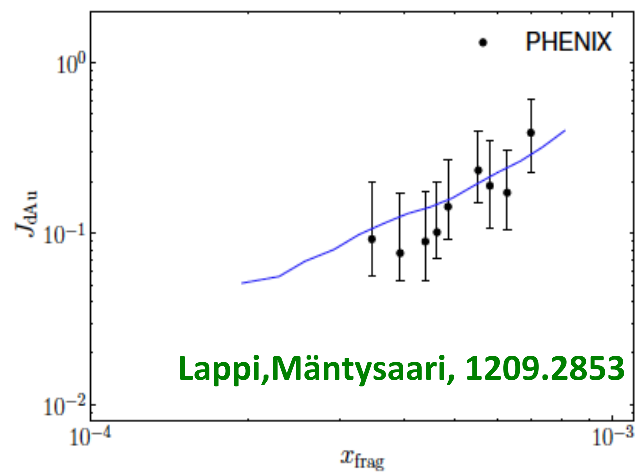
$$\frac{d\sigma^{qA\to qgX}}{d^3k_1 d^3k_2} \propto \int_{x,y,\bar{x},\bar{y}} e^{ik_{1\perp}\cdot(x-\bar{x})} e^{ik_{2\perp}\cdot(y-\bar{y})} \left[S_6(x,y,\bar{x},\bar{y}) - S_4(x,y,v) - ...\right]$$

$$\frac{N_c}{2\,C_F}\left\langle Q(x,y\,\bar{y},\bar{x})D(y,\bar{y}) - \frac{D(x,\bar{x})}{N_c}\right\rangle \quad \frac{N_c}{2\,C_F}\left\langle D(x,y)D(\bar{y},\bar{x}) - \frac{D(x,\bar{x})}{N_c}\right\rangle$$

Forward-forward di-hadrons sensitive to both dipole and quadrupole correlators





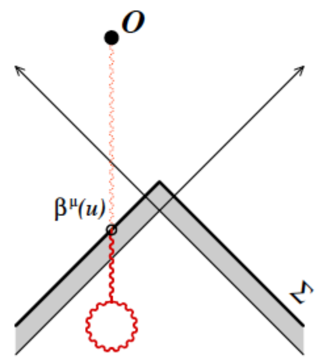


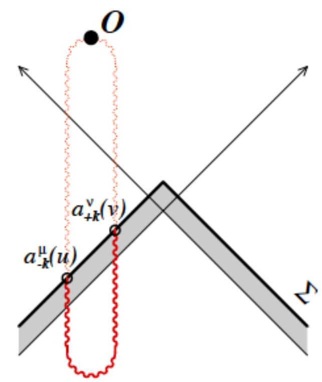
Recent computations (Stasto,Xiao,Yuan + Lappi,Mäntysaari) include Pedestal, Shadowing (color screening) and Broadening (multiple scattering) effects in CGC

RG evolution for 2 nuclei

Gelis,Lappi,RV (2008)

Log divergent contributions crossing nucleus 1 or 2:



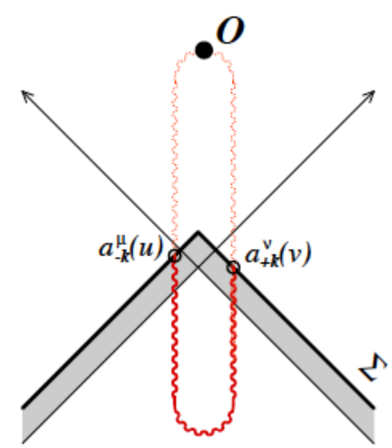


$$\mathcal{O}_{\rm NLO} = \left[\frac{1}{2}\int_{\vec{u},\vec{v}} \mathcal{G}(\vec{u},\vec{v})\;\mathcal{T}_u\mathcal{T}_v + \int_{\vec{u}} \beta(\vec{u})\;\mathcal{T}_u\right] \mathcal{O}_{\rm LO}$$

$\mathcal{G}(\vec{u},\vec{v})$ **and** $\beta(\vec{u})$ **can be computed on the initial Cauchy surface**

$\mathcal{T}_u = \dfrac{\delta}{\delta A(\vec{u})}$ **linear operator on initial surface**

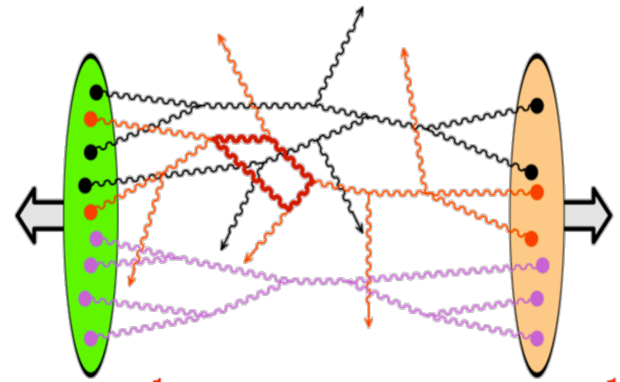
Contributions across both nuclei are finite-no log divergences => factorization



$$\mathcal{O}_{\rm NLO} = \left[\ln\left(\frac{\Lambda^+}{p^+}\right)\mathcal{H}_1 + \ln\left(\frac{\Lambda^-}{p^-}\right)\mathcal{H}_2\right]\mathcal{O}_{\rm LO}$$

Factorization + temporal evolution in the Glasma

$$T^{\mu\nu}_{\rm LO} = \frac{1}{4} g^{\mu\nu} F^{\lambda\delta} F_{\lambda\delta} - F^{\mu\lambda} F^{\nu}_{\lambda} \qquad O\left(\frac{Q_S^4}{g^2}\right)$$



ε=20-40 GeV/fm³ for τ=0.3 fm @ RHIC

NLO terms are as large as LO for α_S ln(1/x):
small x (leading logs) and strong field (gρ) resummation

Gelis,Lappi,RV (2008)

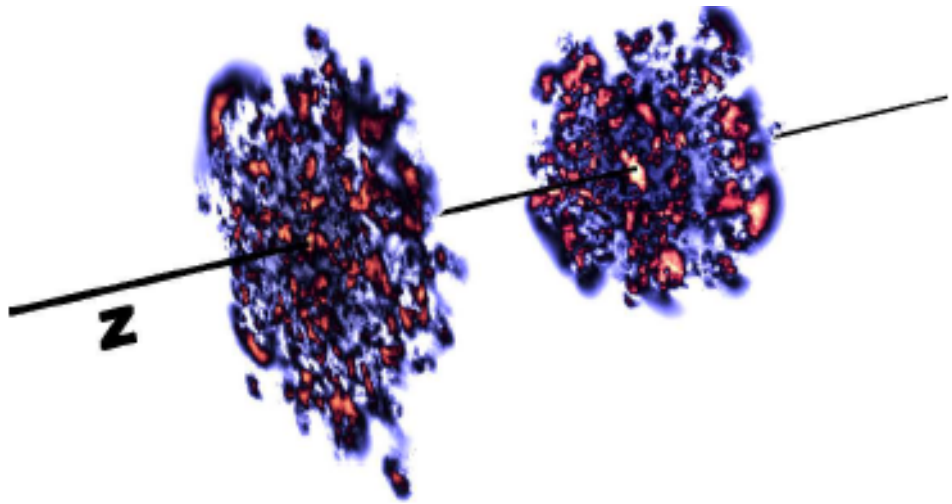
$$\langle T^{\mu\nu}(\tau, \underline{\eta}, x_\perp)\rangle_{\rm LLog} = \int [D\rho_1 d\rho_2]\, W_{Y_1}[\rho_1]\, W_{Y_2}[\rho_2]\, T^{\mu\nu}_{\rm LO}(\tau, x_\perp)$$

$$Y_1 = Y_{\rm beam} - \eta\,;\; Y_2 = Y_{\rm beam} + \eta$$

Glasma factorization => universal "density matrices W" ⊗ "matrix element"

Heavy ion phenomenology in weak coupling

Collisions of lumpy gluon ``shock" waves



Systematic framework: Quantum field theory in presence of strong time dependent color sources.

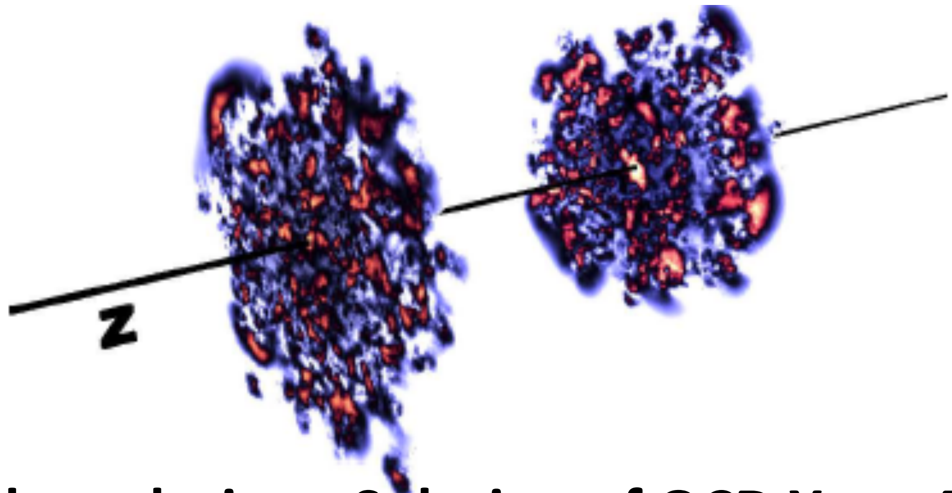
For inclusive quantities*, initial value problem in the Schwinger-Keldysh formalism.*

In QCD, important and subtle issues: factorization, renormalization, universality

Gelis, Venugopalan (2006)
Gelis, Lappi, Venugopalan (2008,2009)
Jeon (2014)

Heavy ion phenomenology in weak coupling

Collisions of lumpy gluon ``shock" waves



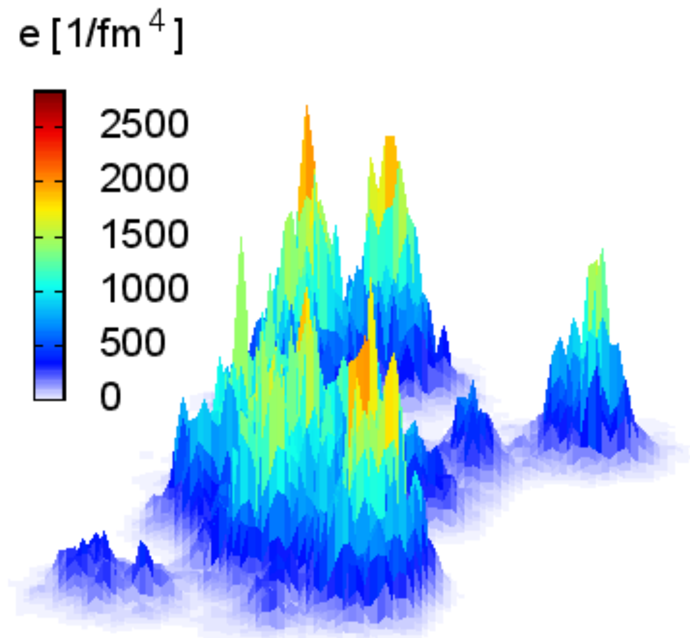
Leading order solution: Solution of QCD Yang-Mills eqns

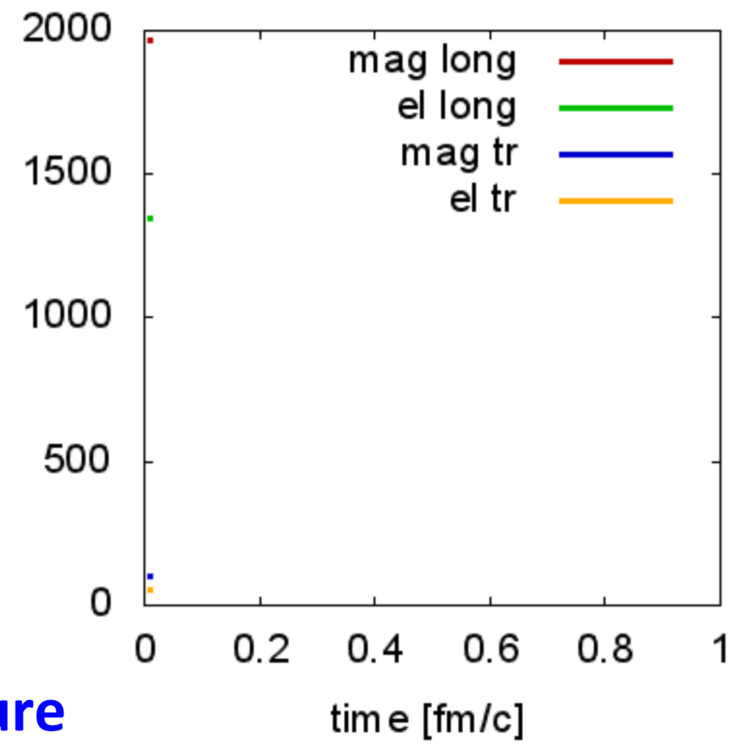
$$D_\mu F^{\mu\nu,a} = \delta^{\nu+}\rho_A^a(x_\perp)\delta(x^-) + \delta^{\nu-}\rho_B^a(x_\perp)\delta(x^+)$$

$$x^\pm = t \pm z$$

$$F^{\mu\nu,a} = \partial_\mu A^{\nu,a} - \partial_\nu A^{\nu,a} + g f^{abc} A^{\mu,b} A^{\nu,c}$$

$T^{\mu\nu}$ from Yang-Mills dynamics



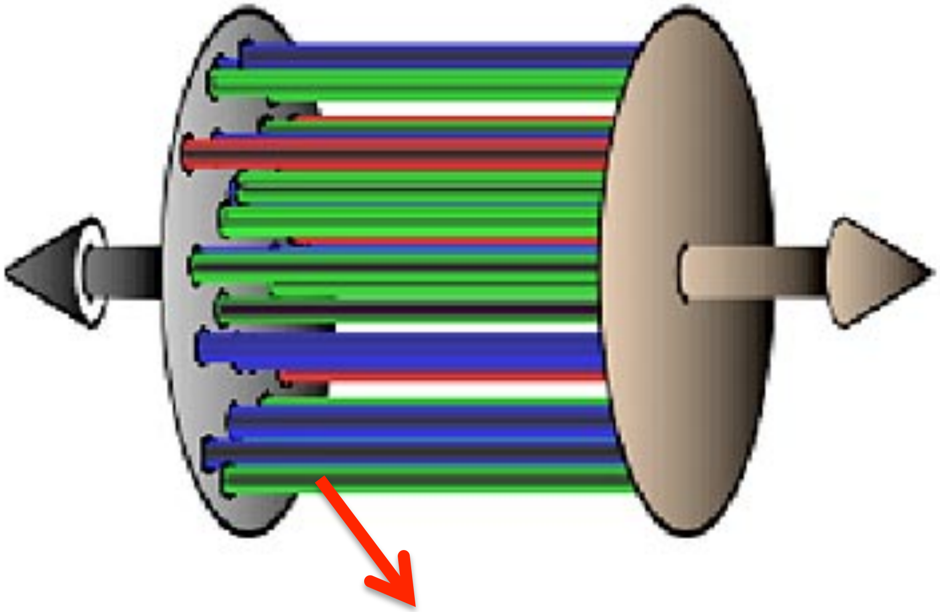


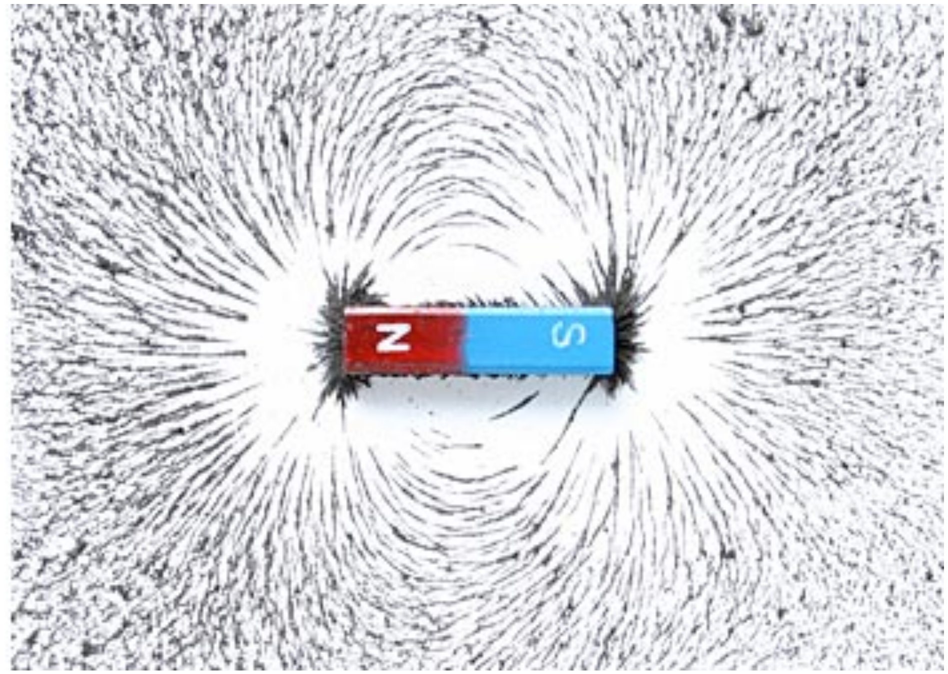
Glasma energy density and pressure

$$T_{\mu\nu}(\tau = 0) = \frac{1}{2}(B_z^2 + E_z^2) \times \mathrm{diag}(1, 1, 1, -1)$$

Initial longitudinal pressure is negative:
Goes to P_L =0 from below with time evolution

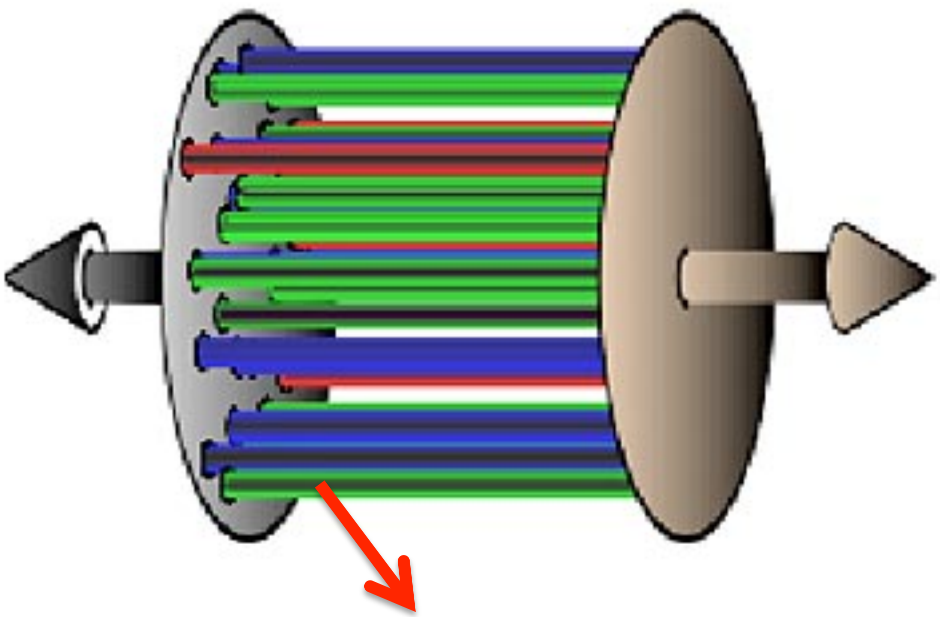
Imaging the force fields of QCD

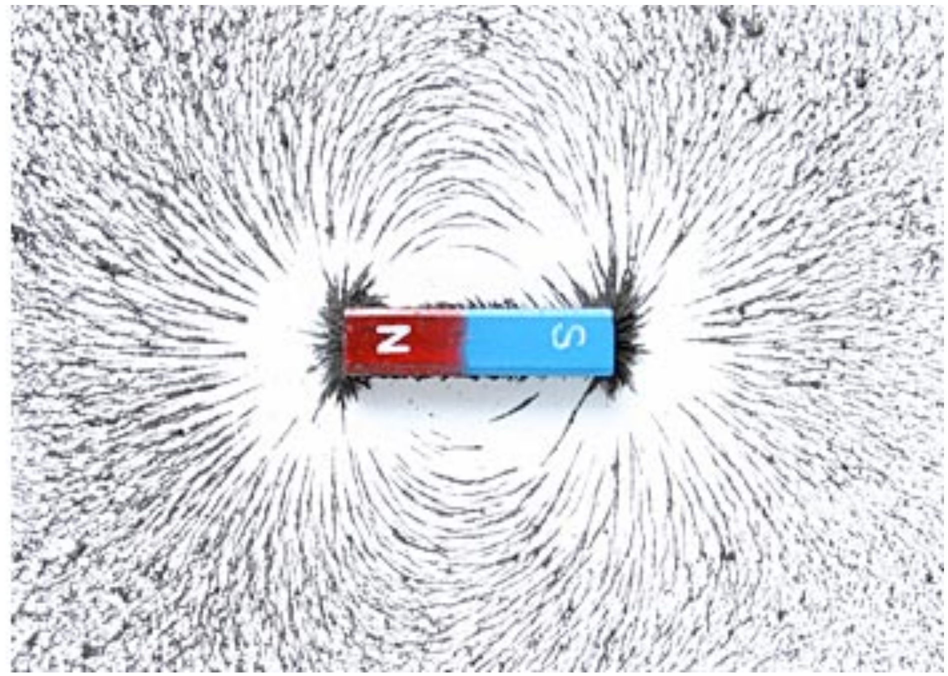




Solns. of QCD Yang-Mills eqns. demonstrate that each of these color "flux tubes" stretching out in rapidity is of transverse size $1/Q_S << 1$ fm

Imaging the force fields of QCD

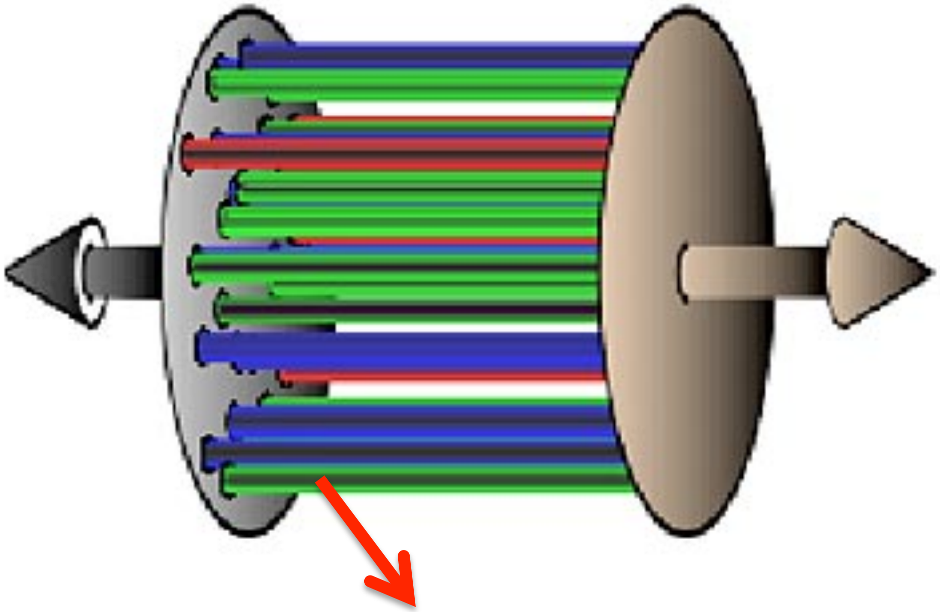


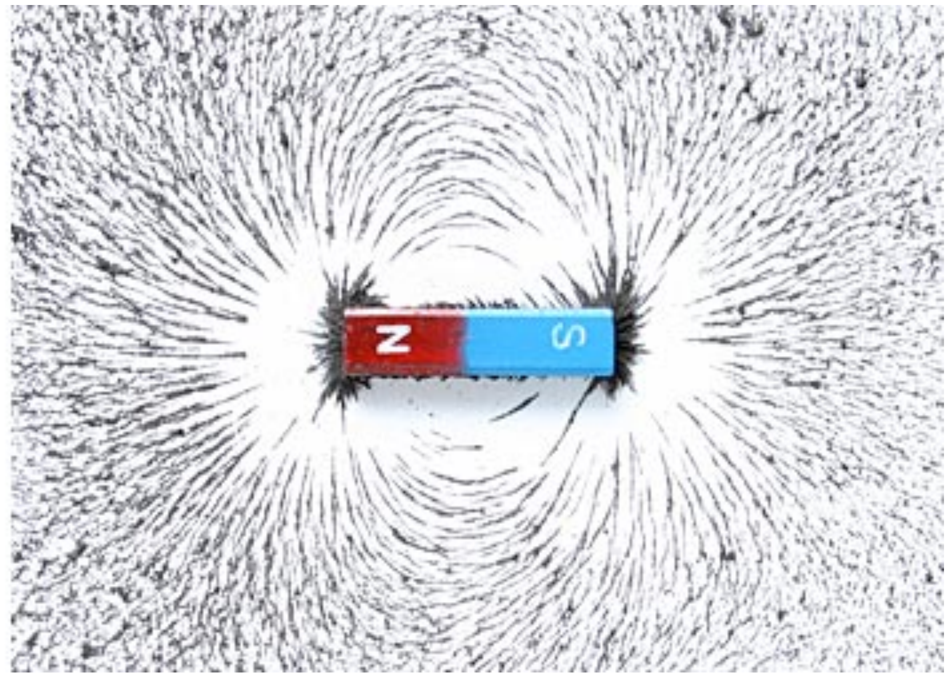


Solns. of QCD Yang-Mills eqns. demonstrate that each of these color "flux tubes" stretching out in rapidity is of transverse size $1/Q_S \ll 1$ fm

Multiparticle dynamics is controlled by sub-nucleon QCD scales

Imaging the force fields of QCD



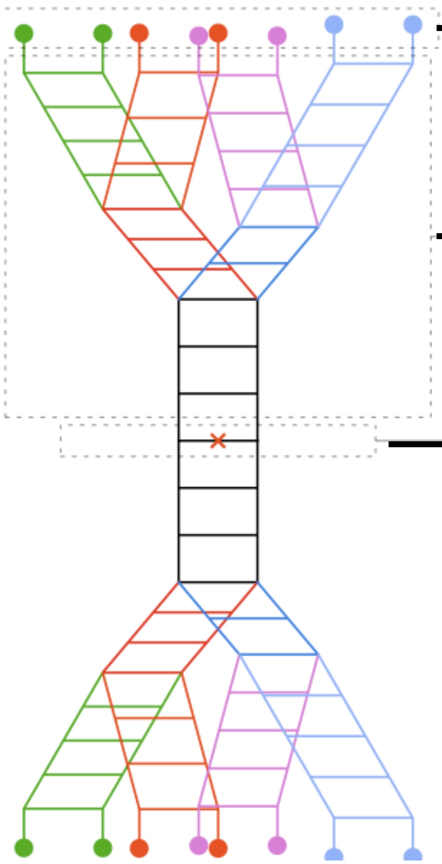


Solns. of QCD Yang-Mills eqns. demonstrate that each of these color "flux tubes" stretching out in rapidity is of transverse size $1/Q_S << 1$ fm

Multiparticle dynamics is controlled by sub-nucleon QCD scales

There are ~ $\pi R^2 Q_S^2$ flux tubes – multiplicity, $dn/d\eta \approx \pi R^2 Q_S^2/\alpha_S$

Single inclusive gluon production



Gelis,Lappi,RV
arXiv:0804.2630 [hep-ph];
arXiv:0807.1306 [hep-ph]
arXiv:0810.4829 [hep-ph]

Initial configuration of sources for nucleus 1

BK/JIMWLK evolution for nucleus 1

$\frac{dN_{\rm LO}}{d^3p}$ Computed from Yang-Mills Glasma gluon fields

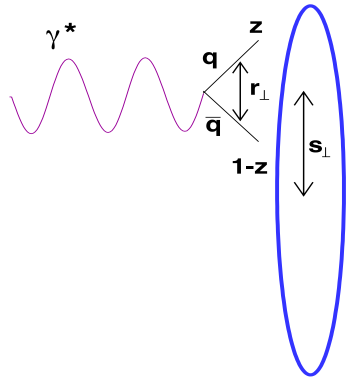
Krasnitz, Nara, RV; Lappi

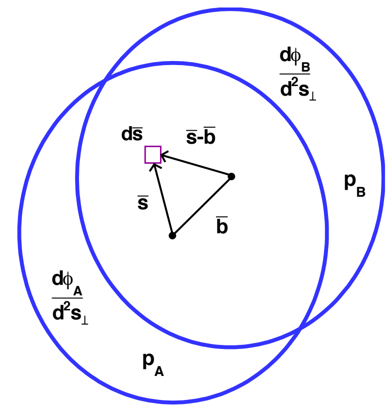
Identical evol. for nucleus 2

- Full JIMWLK+YM evolution feasible Lappi, PLB 703 (2011)209
- In practice: approximations of varying rigor

Extracting lumpy glue in the proton-IPSat model

Bartels,Golec-Biernat,Kowalski
Kowalski,Teaney
Kowalski,Motyka,Watt



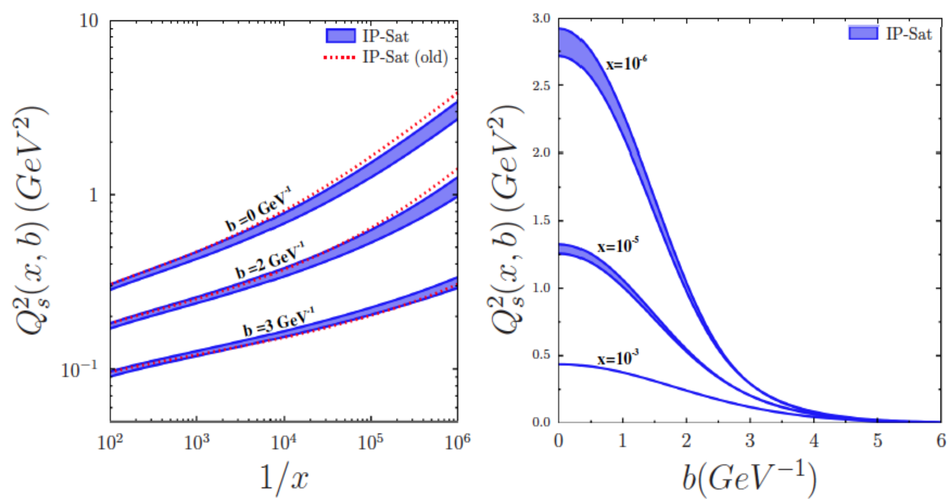


$$\frac{d\sigma^{p}_{dip}}{d^2 \mathbf{b}_\perp}(\mathbf{r}_\perp, x, \mathbf{b}_\perp) = 2\mathcal{N}(\mathbf{r}_\perp, x, \mathbf{b}_\perp) = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c}\mathbf{r}_\perp{}^2 \alpha_s(\tilde{\mu}^2) x g(x, \tilde{\mu}^2) T_p(\mathbf{b}_\perp)\right)\right]$$

$$T_p(b_\perp) = e^{-\frac{b_\perp^2}{2B_G}}$$

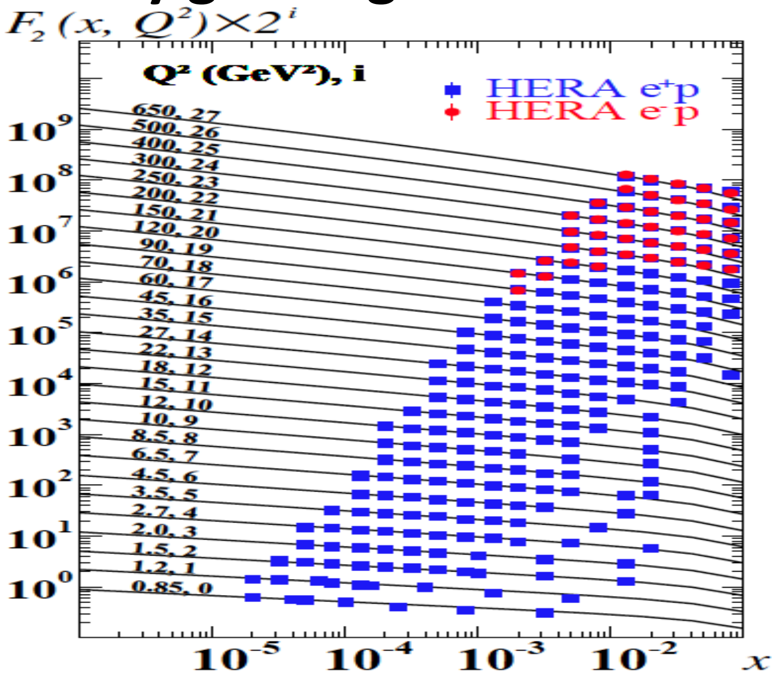
Average gluon radius of the proton extracted from HERA diffractive data

$$\tilde{\mu}^2 = \mu_0^2 + \frac{4}{r_\perp}^2$$

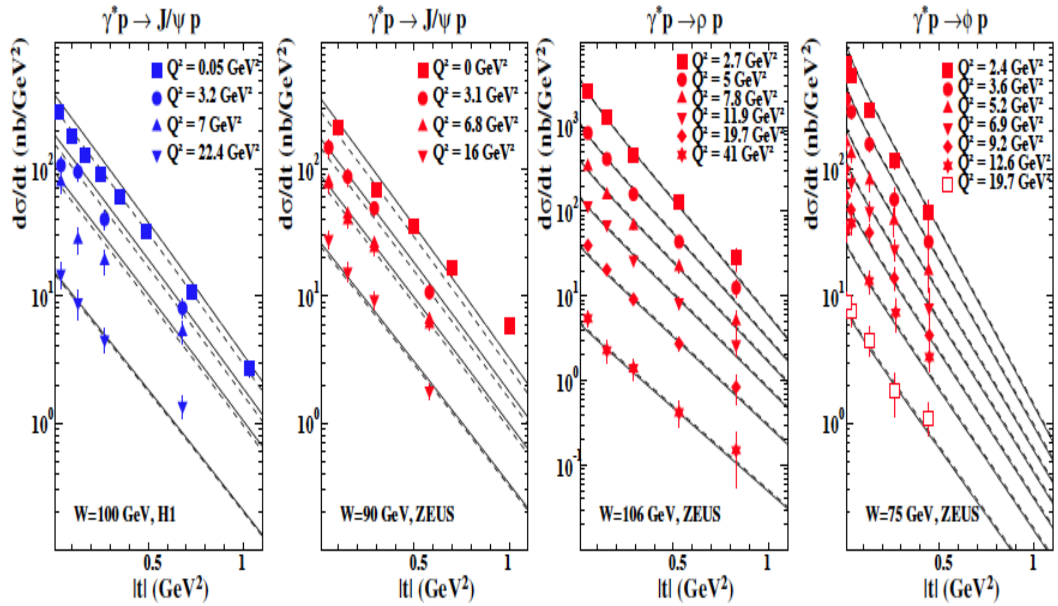


Extracting lumpy glue in the proton-IPSat model

Very good agreement of IPSat model with combined HERA data



Rezaiean,Siddikov,Van der Klundert,RV:1212.2974

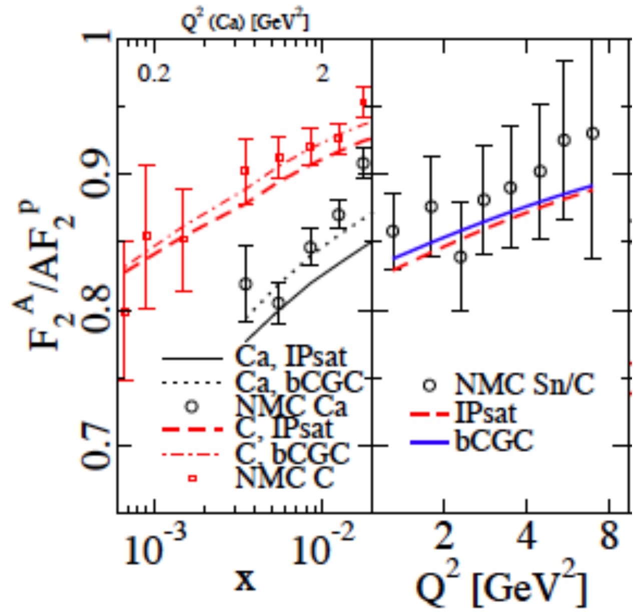


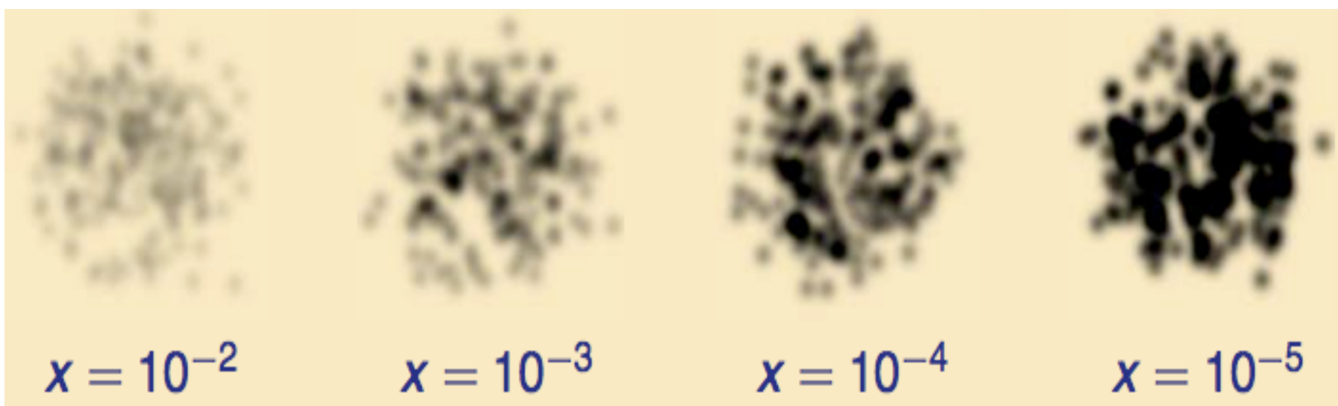
Inclusive DIS off proton

Exclusive DIS off proton

Lumpy nuclei: constrained by (limited) DIS data

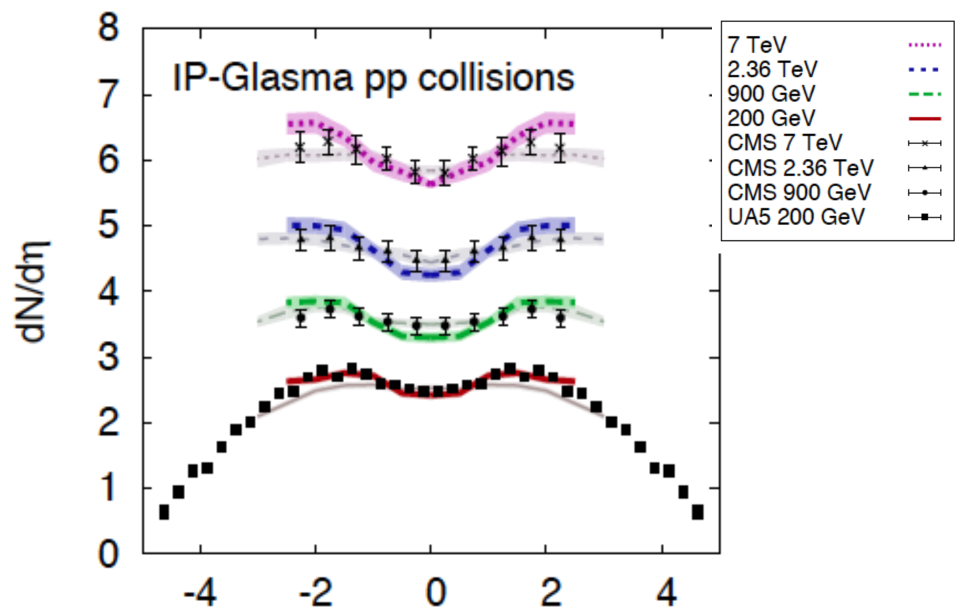
Kowalski, Lappi, RV, PRL (2008)

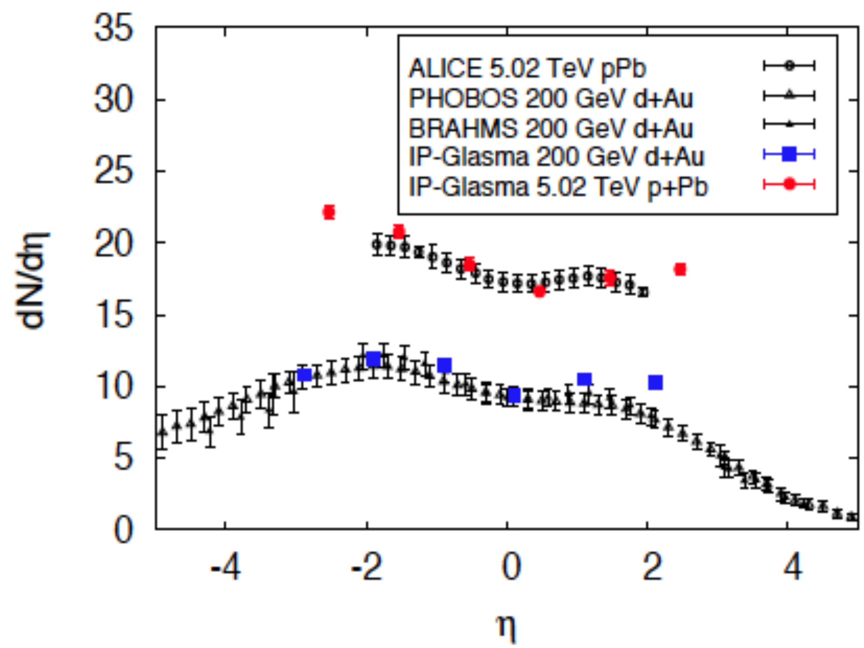


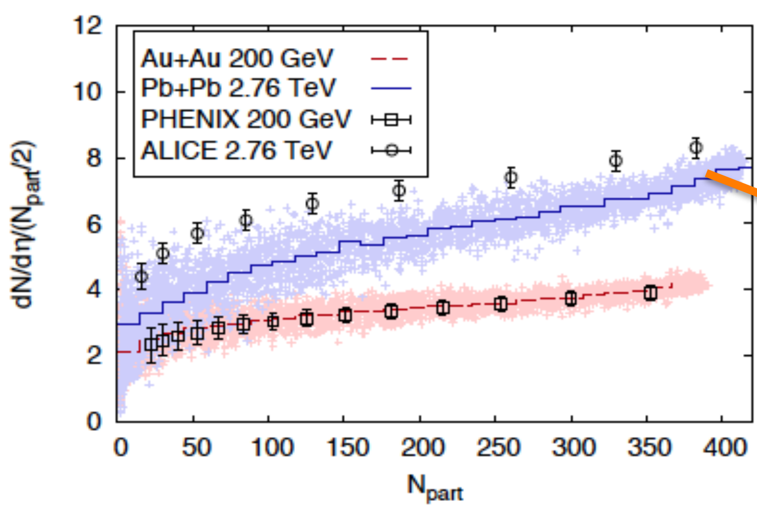


Multiplicities from Yang-Mills dynamics

Schenke,Tribedy,RV:1311.3636

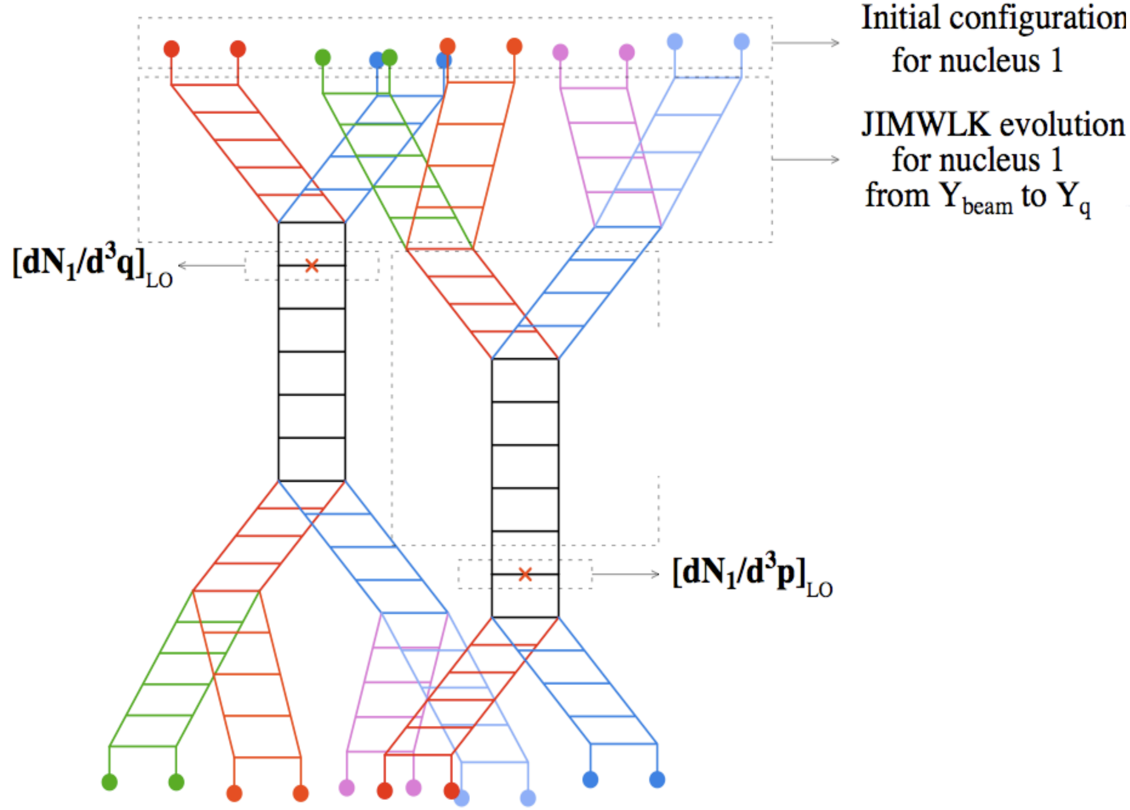




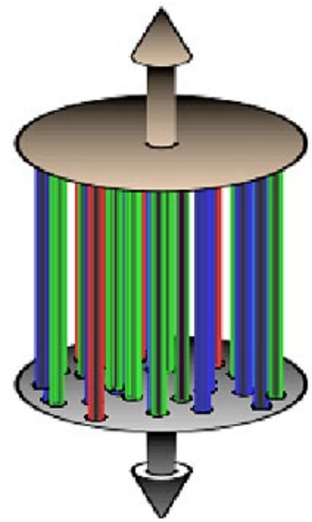


15% (30 %) shortfall for large N_{part} (low N_{part}) at LHC possibly due to the ~70% greater η/s

High multiplicity events: two particle correlations



Gelis,Lappi,RV
arXiv:0804.2630 [hep-ph];
arXiv:0807.1306 [hep-ph]



- Full YM+JIMWLK evolution – not available yet

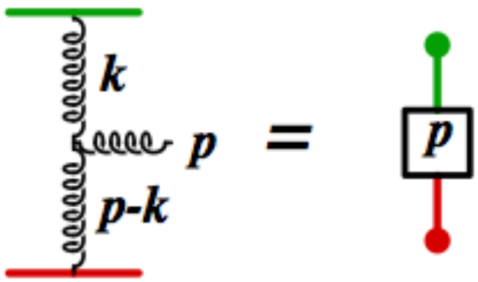
- Approximations:

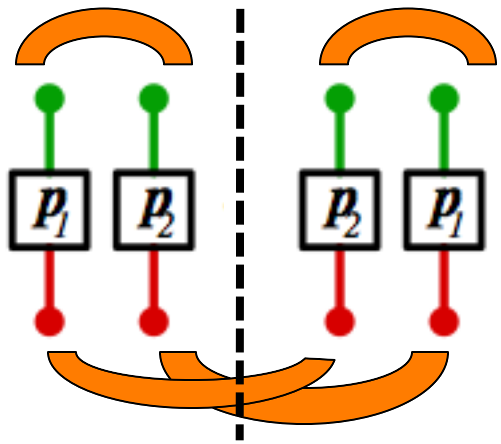
I) BK Gaussian truncation approximation -evolution but no rescattering

II) YM results for MV model: rescattering but no evolution

Dusling,Gelis,Lappi,RV:0911.2720; Lappi,Srednyak,RV:0911.2068;
Kovchegov,Wertepny: 1212.1195

2-particle correlations





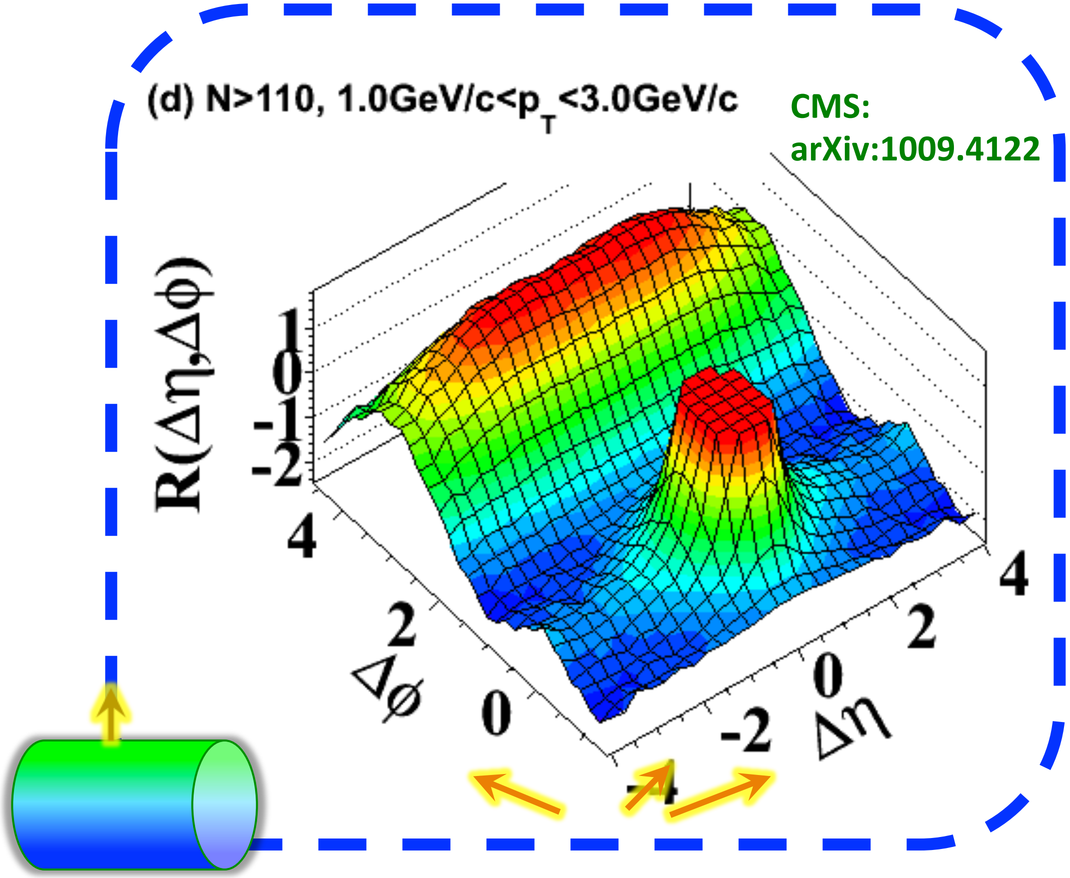
Dumitru,Gelis,McLerran,RV
Dusling,Fernandez-Fraile,RV

Glasma flux tube picture: two particle correlations proportional to ratio $1/Q_S^2$ / S_T

Only certain color combinations of "dimers" give leading contributions

Two particle correlations: the ridge

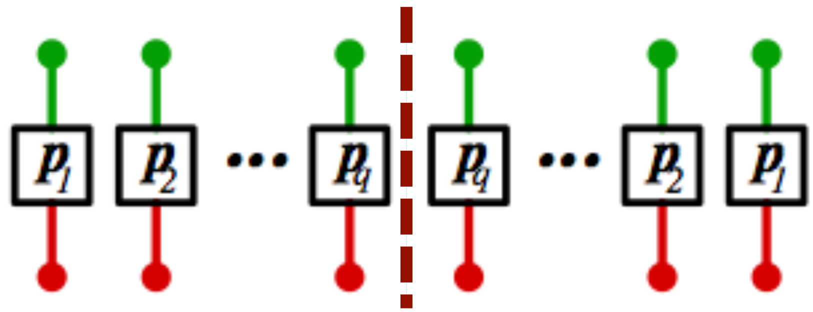
"Discovery"



- To be discussed in the next lecture…

2-particle ➡ n-particle correlations

Gelis, Lappi,McLerran



Multiplicity distribution: Leading combinatorics of dimers gives the negative binomial distribution

$$P_n^{\mathrm{N.B.}}(\bar{n},k) = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)} \frac{\bar{n}^n k^k}{(\bar{n}+k)^{n+k}}$$

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

k = 1 : Bose-Einstein

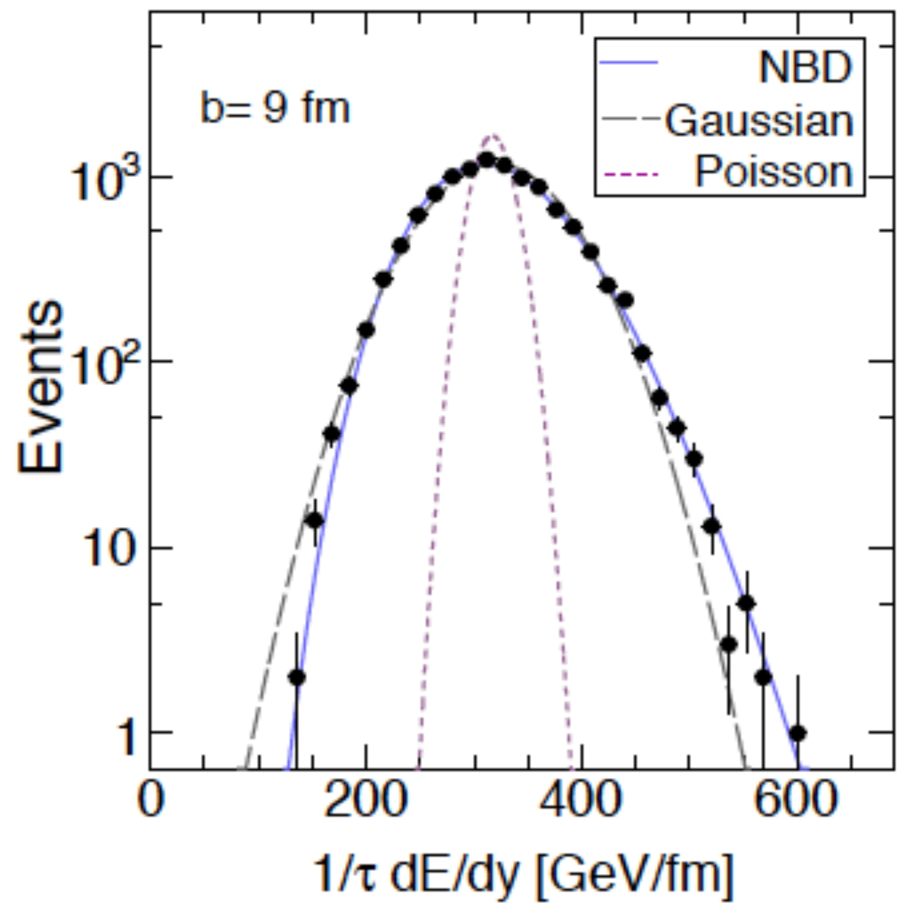
k = ∞ : Poisson

Non.pert.constant-can be computed in Yang-Mills simulations

Lappi, Srednyak, RV, 0911.2068
Schenke, Tribedy, RV, 1206.6805

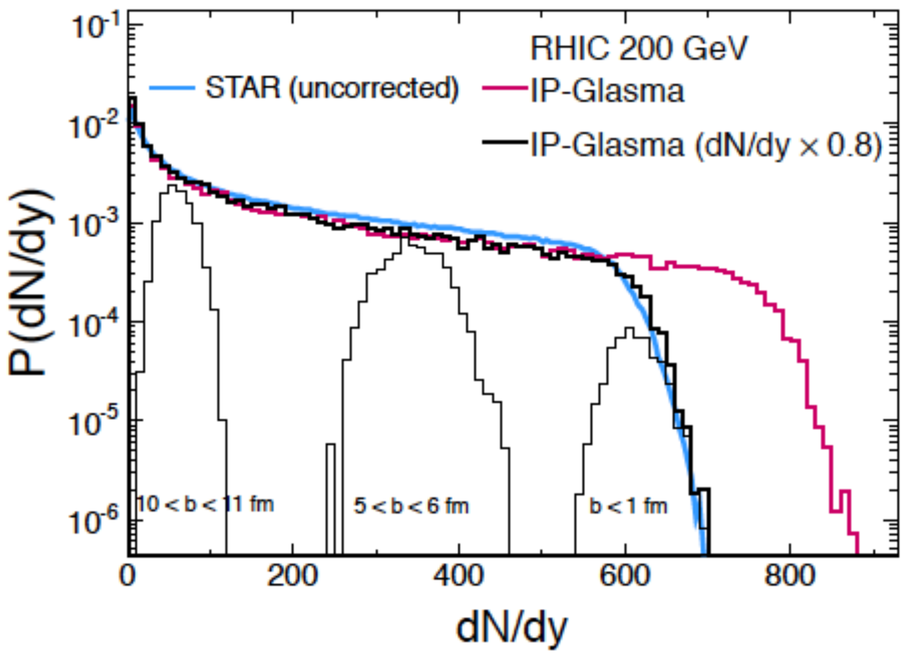
Negative Binomial Distributions from non-perturbative Yang-Mills dynamics

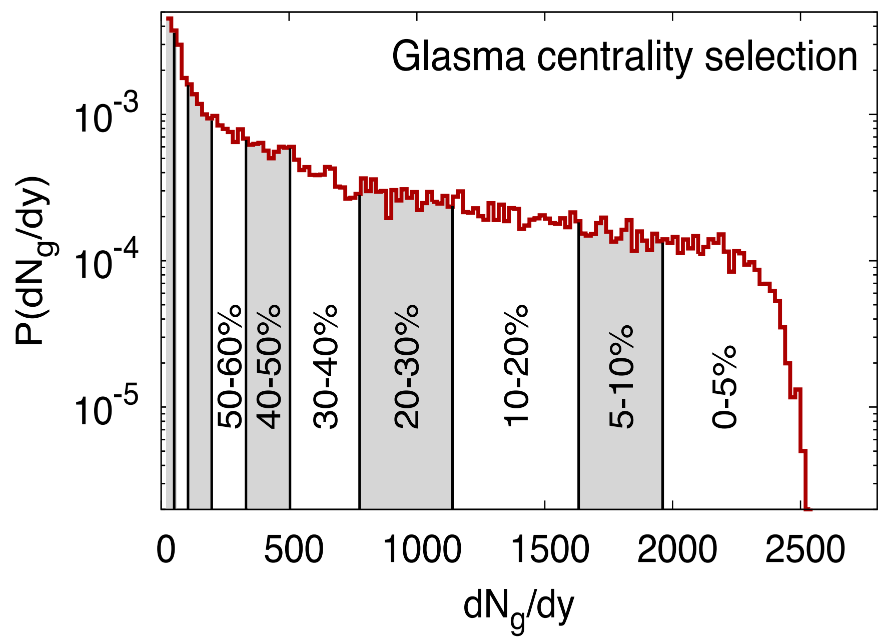
Schenke,Tribedy,RV:1202.6646



NBDs in heavy ion collisions

Schenke,Tribedy,RV: arXiv:1206.6805

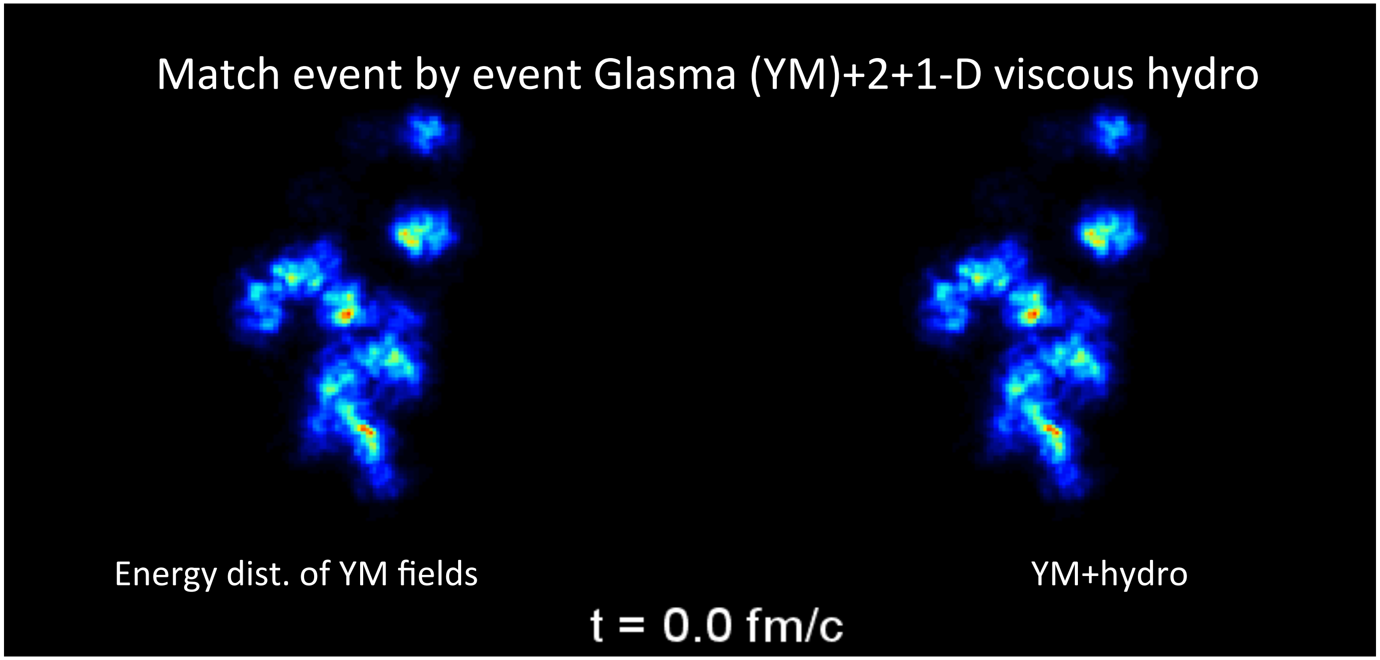




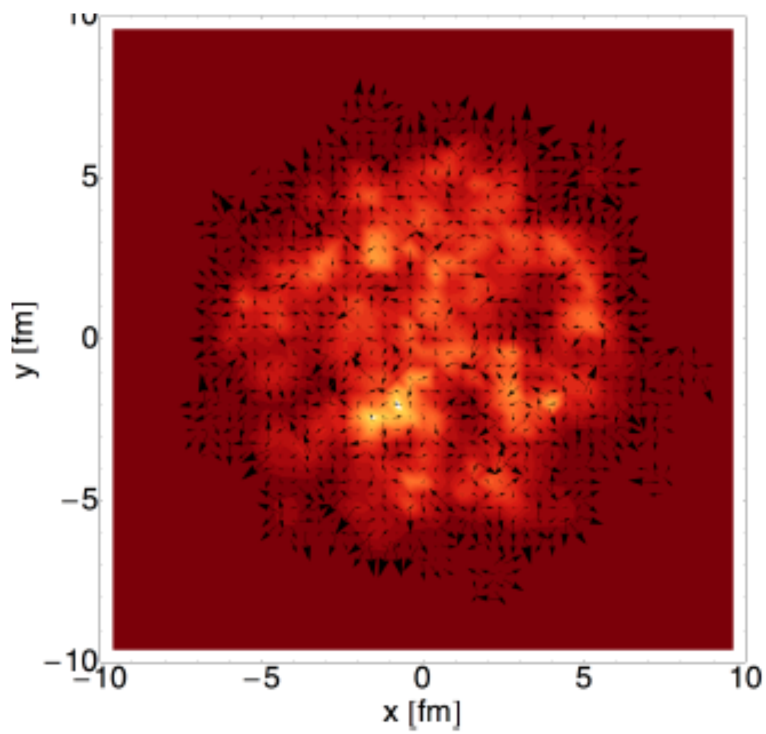
Only model of heavy ion collisions where multiplicity dist./centrality selection Is not an external input

Matching boost invariant Yang-Mills to hydrodynamics

State of the art phenomenology: Solve relativistic viscous hydrodynamic equations with Glasma (Yang-Mills) initial conditions



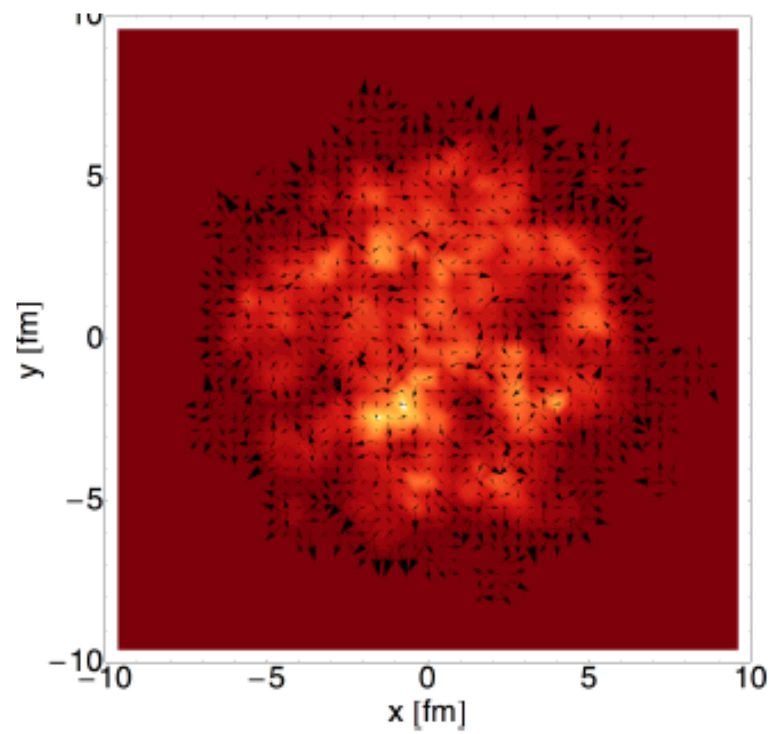
Matching boost invariant Yang-Mills to hydrodynamics



Energy density and (u_x, u_y) at $\tau = 0.4\,\mathrm{fm}/c$

Energy density and (u_x,u_y) from $u_\mu T^{\mu\nu} = \varepsilon u^\nu$

Matching boost invariant Yang-Mills to hydrodynamics



Energy density and (u_x, u_y) at $\tau = 0.4\,\mathrm{fm}/c$

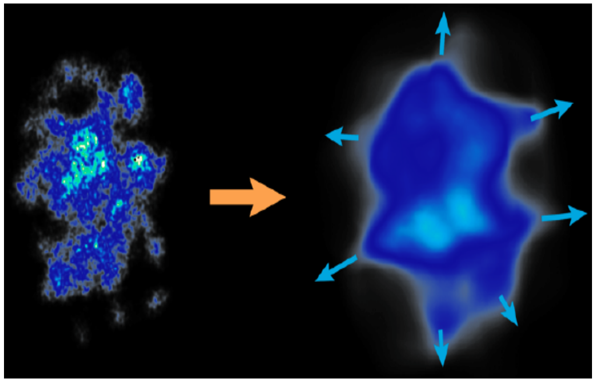
Matching to viscous hydro is "brutal" :
assume very rapid isotropization at initial hydro time

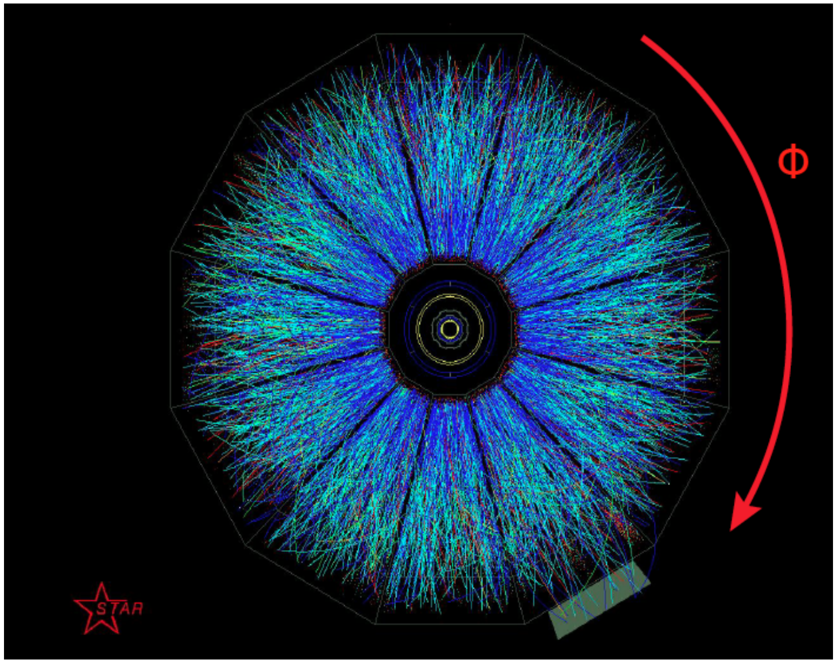
Large systematic uncertainty: how does isotropization/ thermalization occur on times < 1 fm/c ?

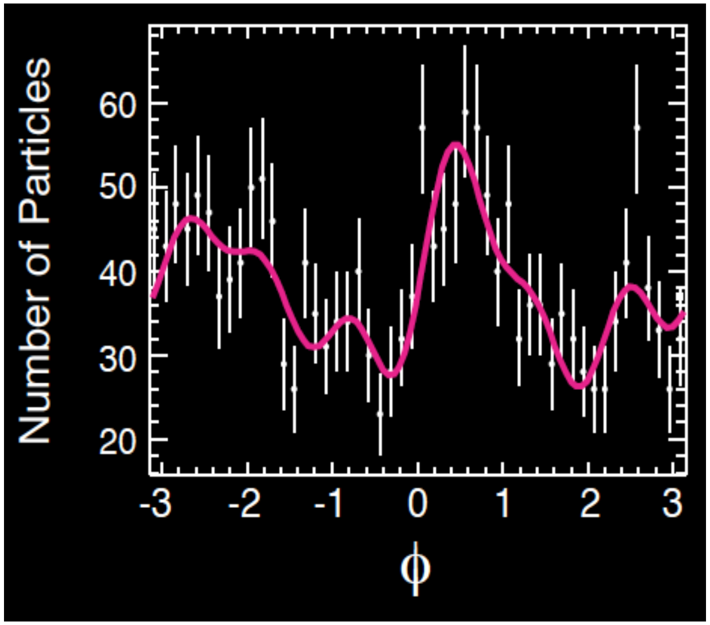
Heavy ion phenomenology in weak coupling

Hydrodynamics: efficient translation of spatial anisotropy into momentum anisotropy

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + 2v_3\cos(3\phi) + 2v_4\cos(4\phi) + \cdots\right)$$







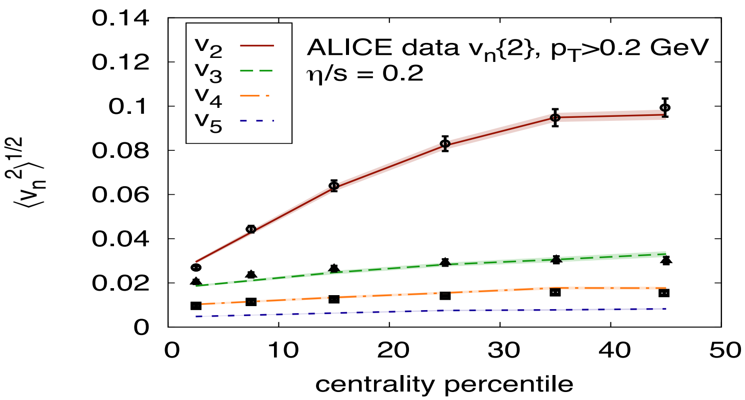
MUSIC: 3+1-D event-by-event viscous relativistic hydro model

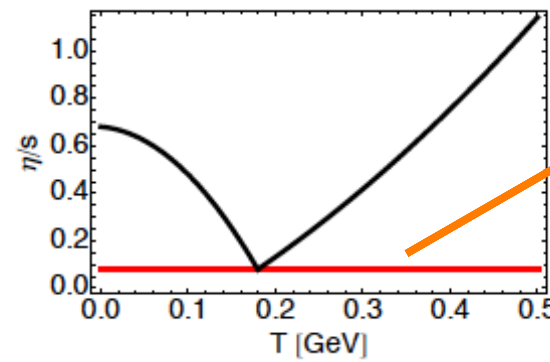
Schenke,Jeon, Gale

Heavy ion phenomenology in weak coupling

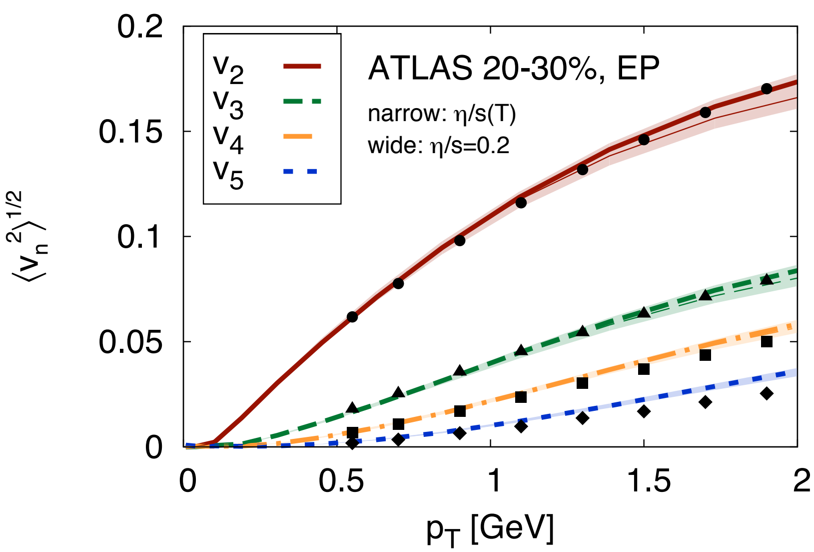
Gale,Jeon,Schenke,Tribedy,Venugopalan, PRL (2013) 012302

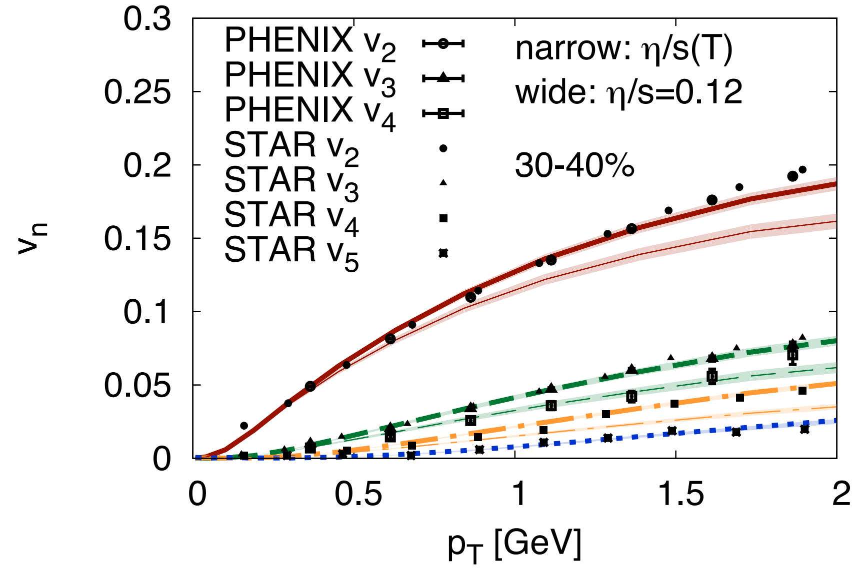
Results from the IP-Glasma +MUSIC model:





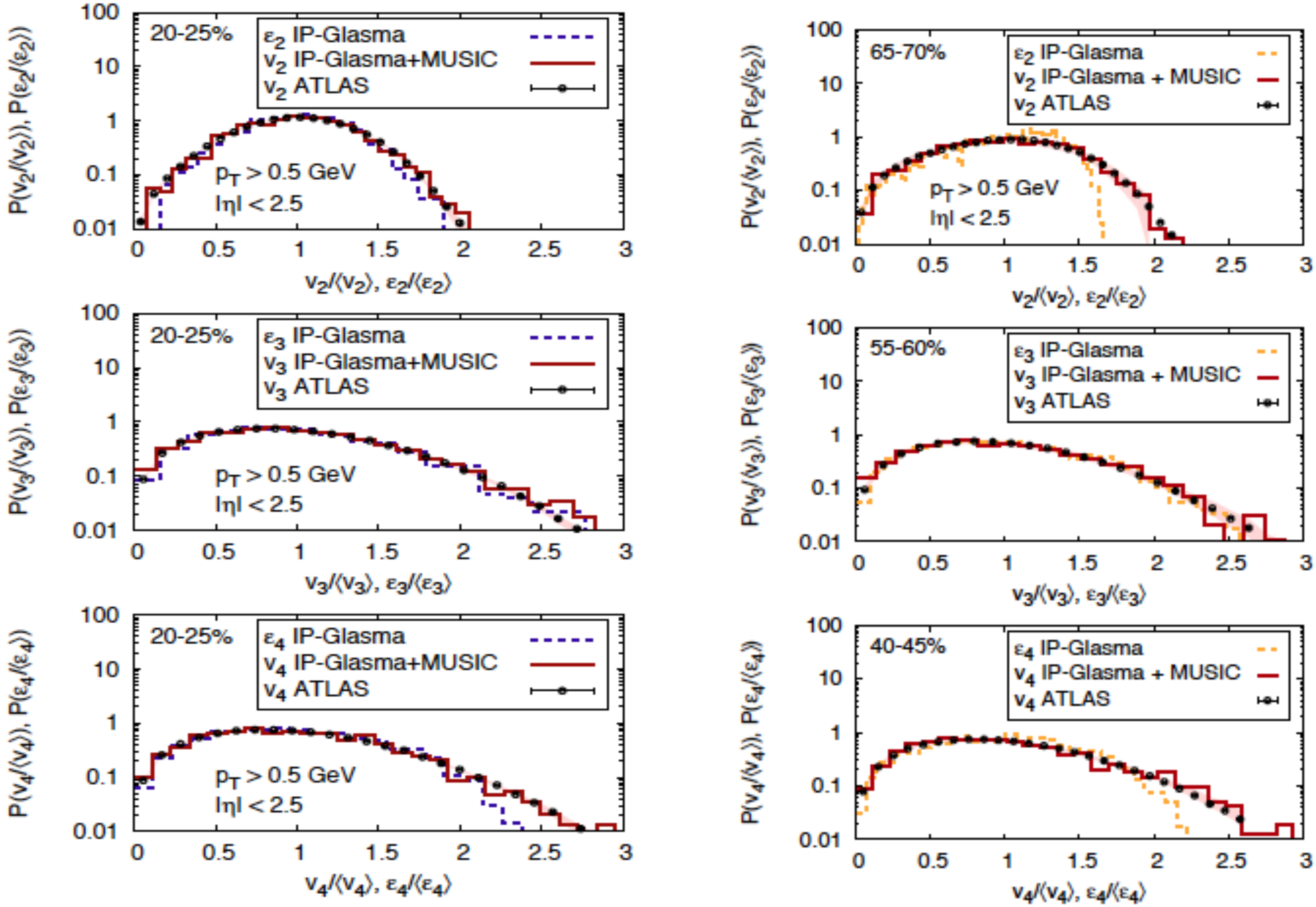
AdS/CFT bound = 0.08





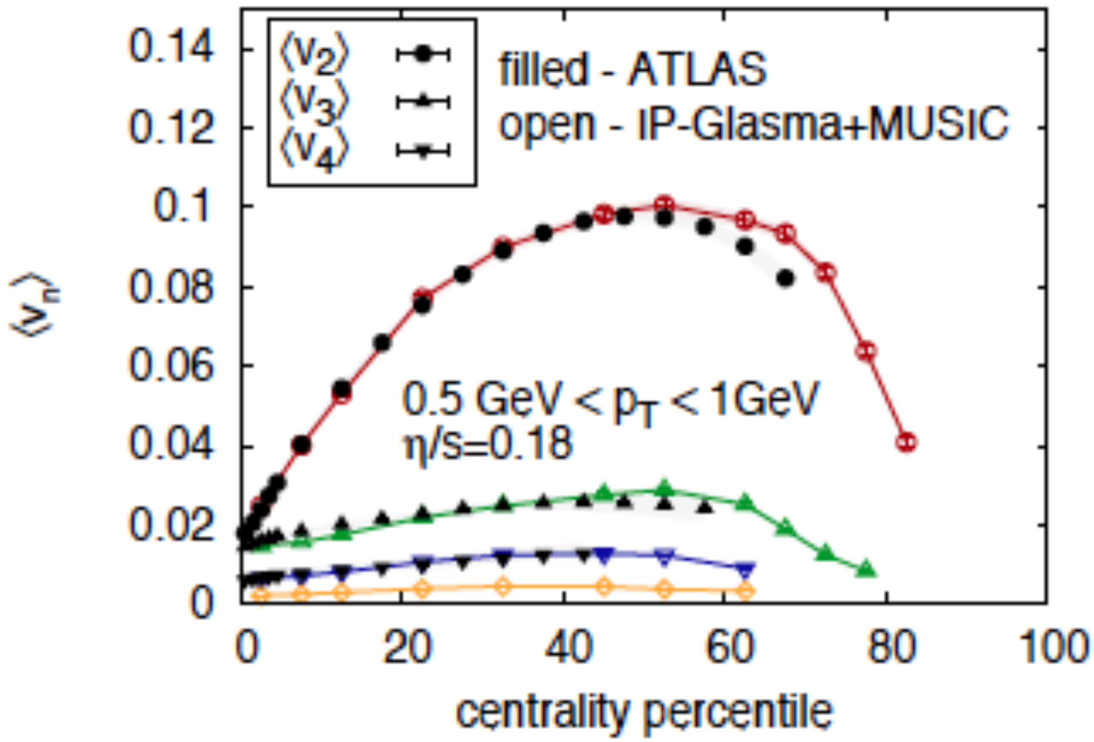
RHIC data require lower average value of η/s relative to LHC

Heavy ion phenomenology in weak coupling



Heavy ion phenomenology in weak coupling

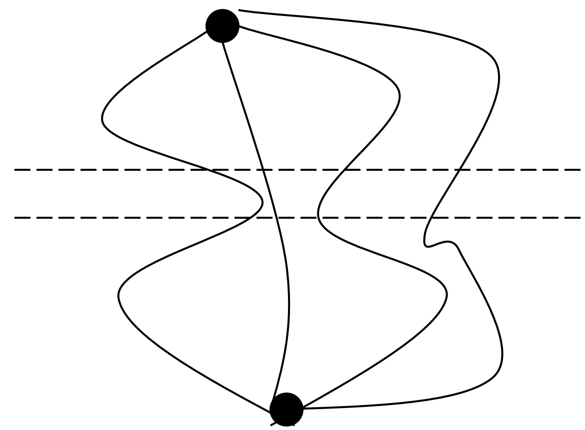
Schenke,Venugopalan, arXiv:1405.3605



Remarkable agreement of IP-Glasma+MUSIC with data out to fairly peripheral overlap geometries…

BACKUP SLIDES

PATH INTEGRAL:



Coarse graining -> Box of size 1/p_t in transverse plane

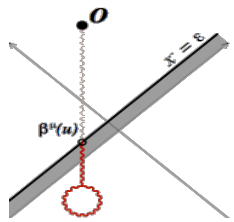
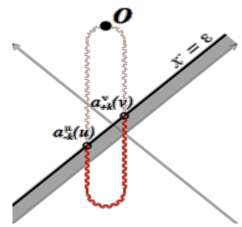
Sum over spins in box:

$$\sum_l v_l^{(k)} \sum_{m=-l}^{l} |l,m><l,m| \rightarrow \int d^3l\, e^{-2\,l^2/k}$$

Classical color/spin density:

$$l^a = (\Delta x_\perp)^2 \frac{1}{g} \rho^a(x_\perp) \quad \Rightarrow \quad 2\,\frac{l^2}{k} = \frac{\pi R^2}{g^2 A} (\Delta x_\perp)^2 \rho^a \rho^a$$

JIMWLK RG evolution for a single nucleus:

$$\mathcal{O}_{\rm NLO} = \Bigg($$

+


$$\chi(x_\perp, y_\perp)$$
$$\Bigg)\, \mathcal{O}_{\rm LO}$$

$$= \ln\left(\frac{\Lambda^+}{p^+}\right) \mathcal{H}\, \mathcal{O}_{\rm LO}$$

(keeping leading log divergences)

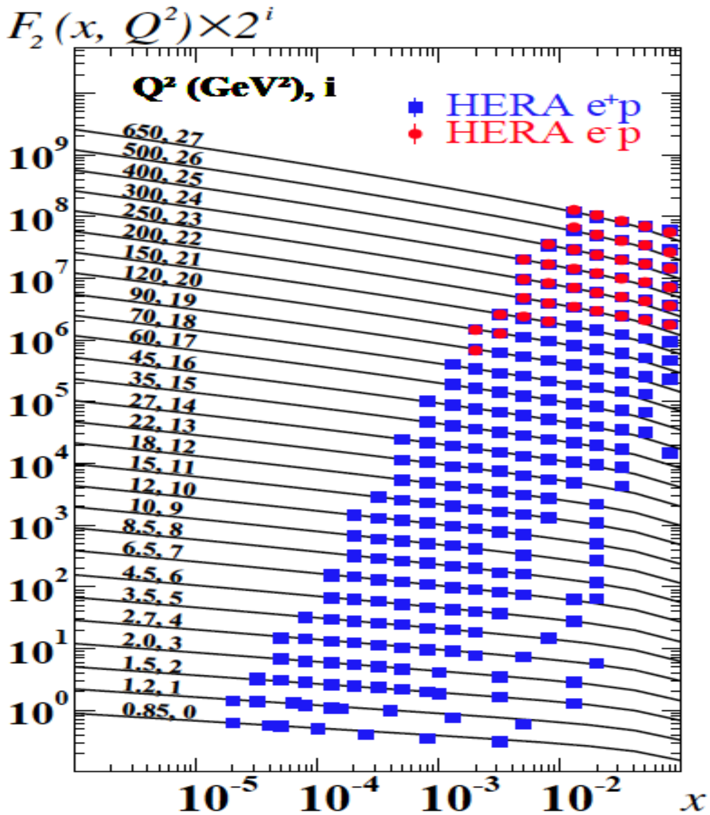
$$\langle \mathcal{O}_{\rm LO} + \mathcal{O}_{\rm NLO} \rangle = \int [d\tilde{\rho}] W[\tilde{\rho}] \left[\mathcal{O}_{\rm LO} + \mathcal{O}_{\rm NLO}\right]$$
$$= \int [d\tilde{\rho}] \left\{ \left[1 + \ln\left(\frac{\Lambda^+}{p^+}\right) \mathcal{H} \right] W_{\Lambda^+} \right\} \mathcal{O}_{\rm LO}$$

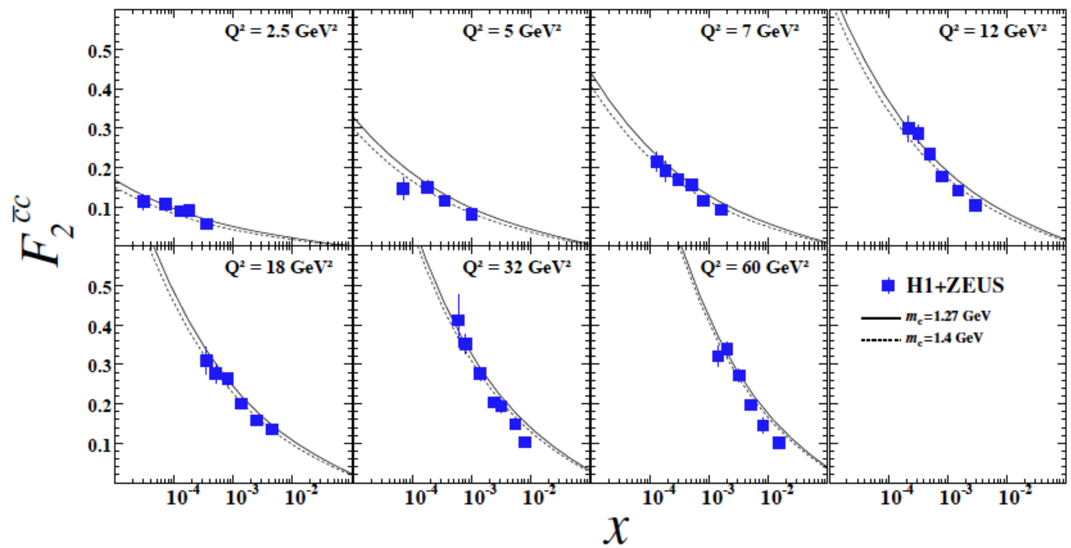
LHS independent of Λ^+ **=>** $$\frac{\partial W[\tilde{\rho}]}{\partial Y} = \mathcal{H}\, W[\tilde{\rho}]$$

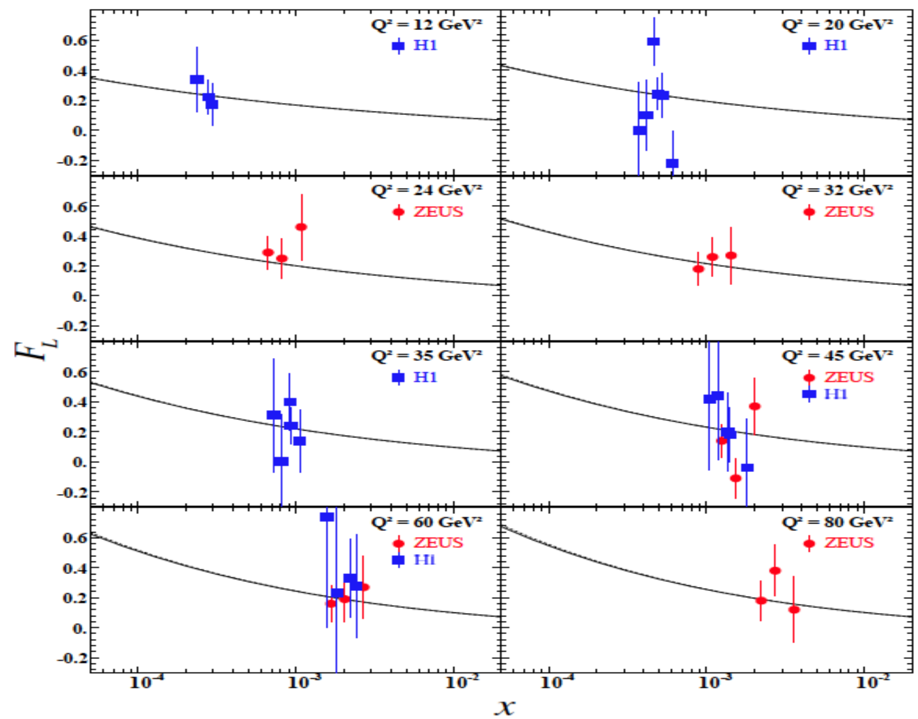
JIMWLK eqn.

Jalilian-Marian,Iancu,McLerran,Weigert,Leonidov,Kovner

Inclusive DIS: dipole evolution a la IP-Sat





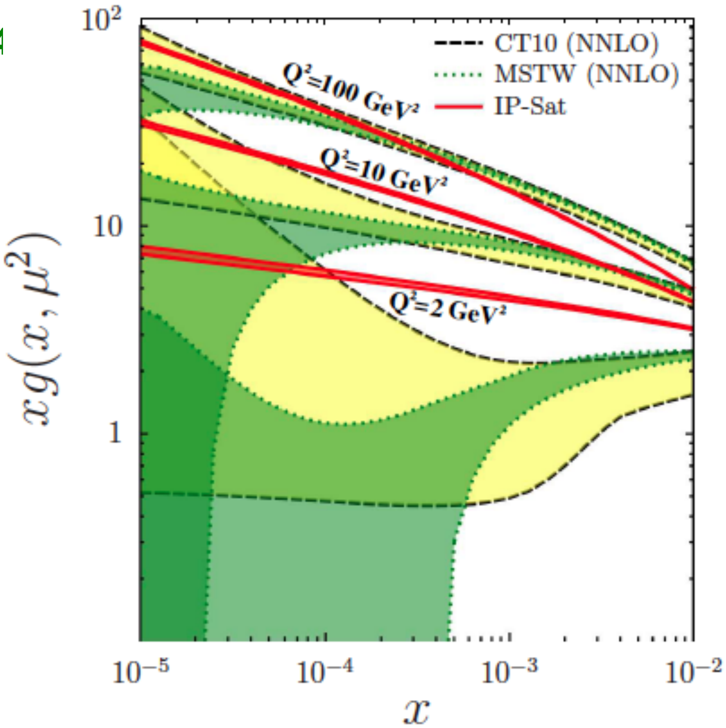


(Few) parameters fixed by
χ2 ~ 1 fit to combined
(H1+ZEUS) red. cross-section

Rezaiean,Siddikov,Van de Klundert,RV: 1212.2974

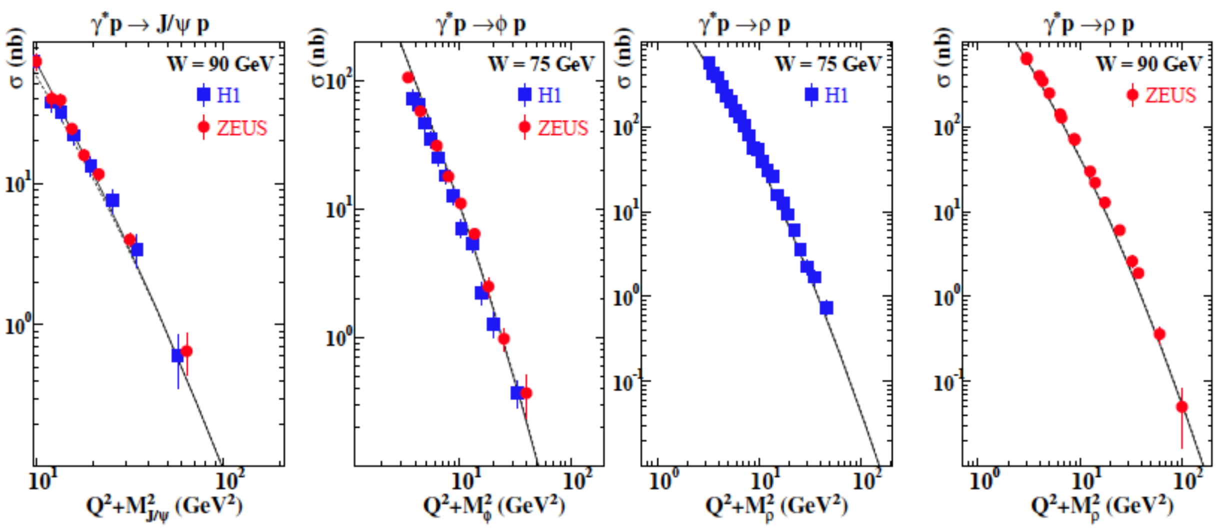
Inclusive DIS: dipole evolution a la IP-Sat

Rezaiean,Siddikov,Van de Klundert,RV: 1212.2974



More stable gluon dist. at small x relative to NNLO pdf fits

Exclusive Vector meson production:



Comparable quality fits for energy (W) and t-distributions