High Energy QCD:
The Color Glass Condensate, the Glasma & the Quark-Gluon Plasma

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Outline of lectures

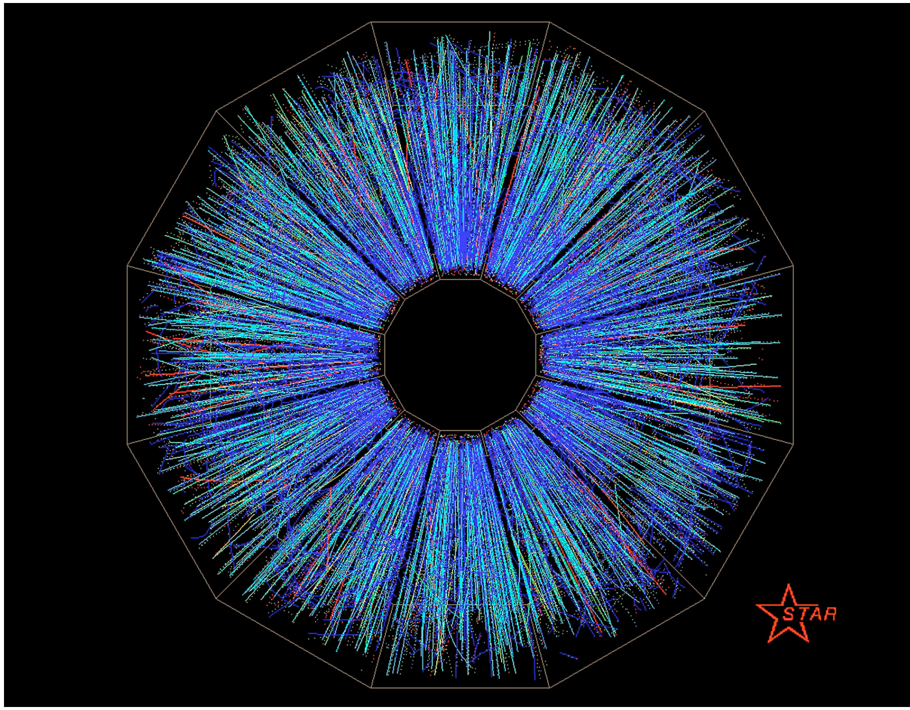
- **Lecture I: The parton model, pQCD, the Color Glass Condensate, QCD Factorization in strong fields**

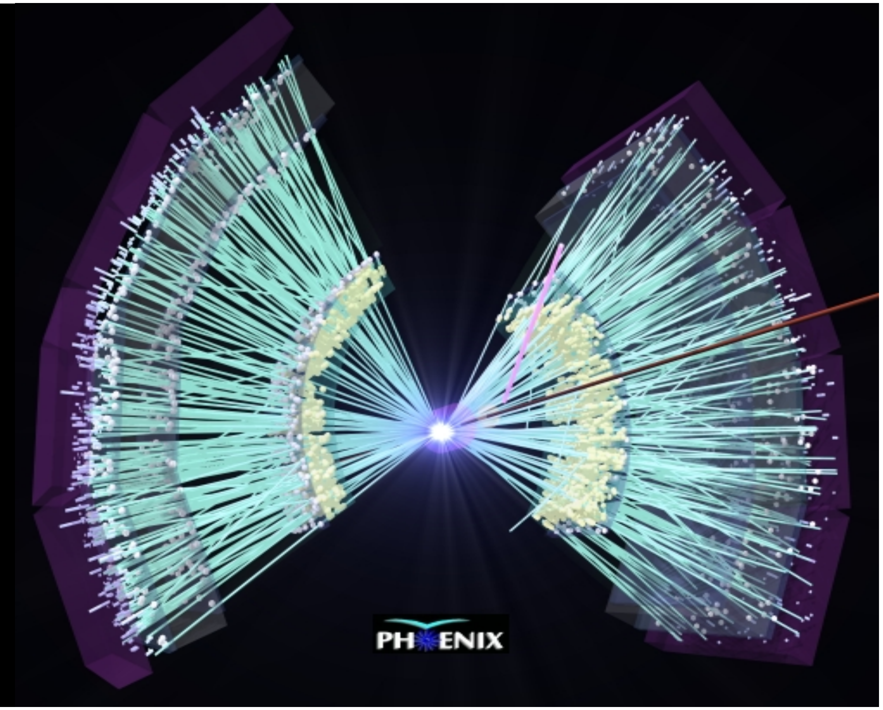
- **Lecture II: The Glasma: instabilities, turbulence, thermalization, hydodynamics**

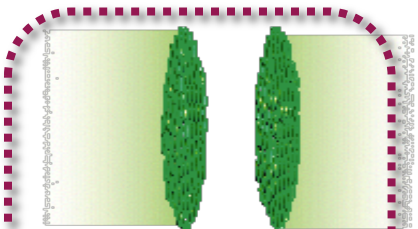
- **Lecture III: The Ridge puzzle: Long range gluon entanglement or collectivity in the world's smalles fluids**

A standard model of heavy ion collisons

RV, ICHEP talk, arXiv:1012.4699

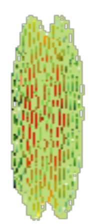






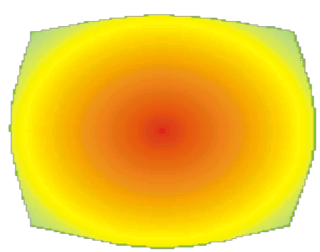
Color Glass

Condensates

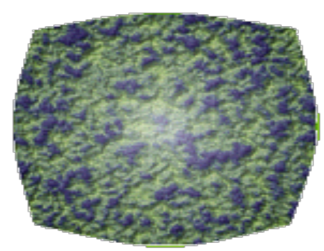


Initial

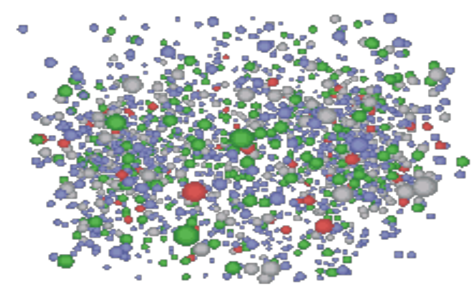
Singularity



Glasma

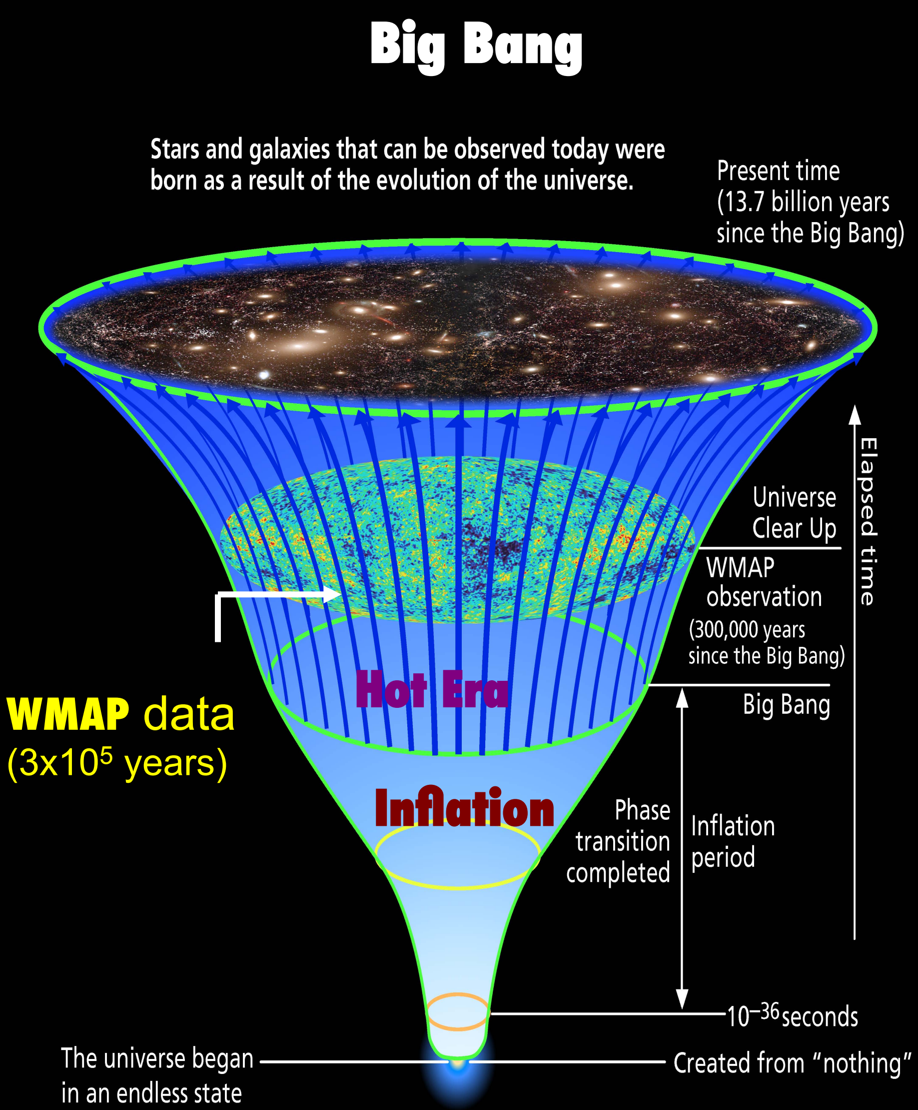


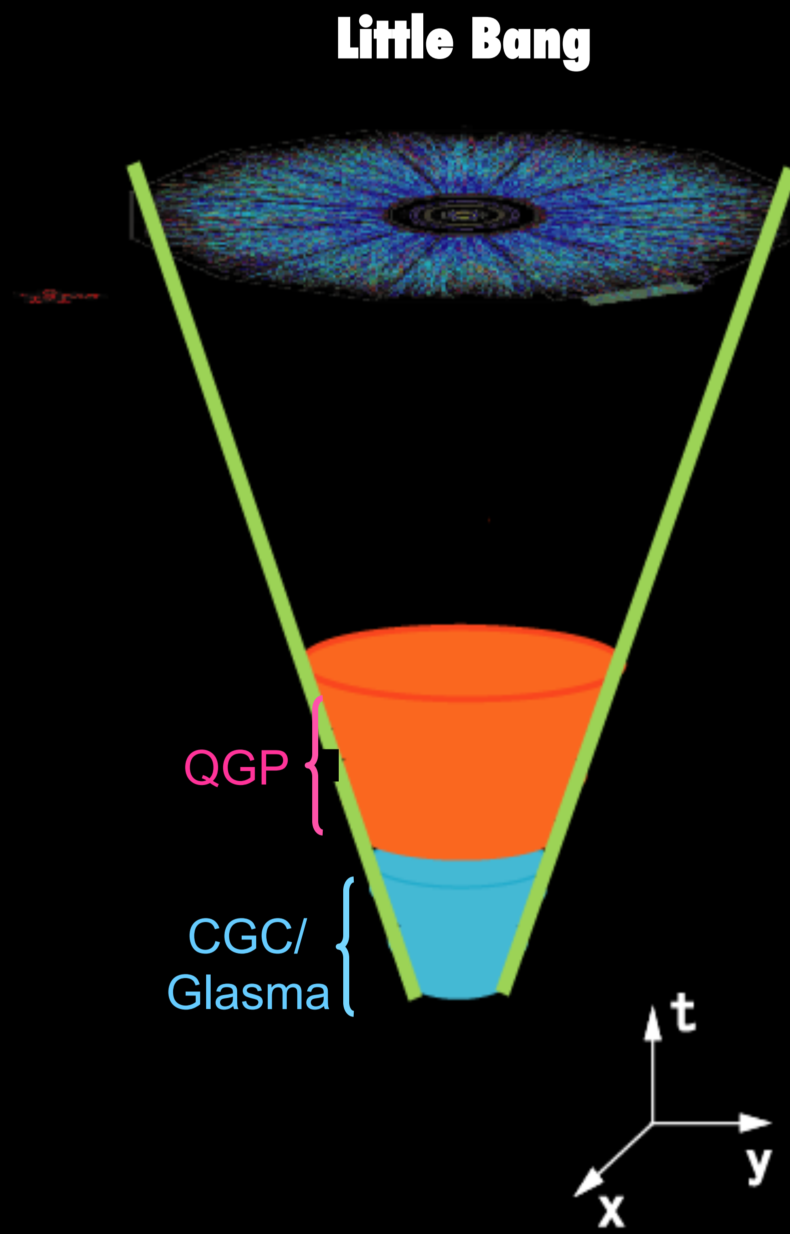
sQGP -
perfect fluid



Hadron
Gas

t

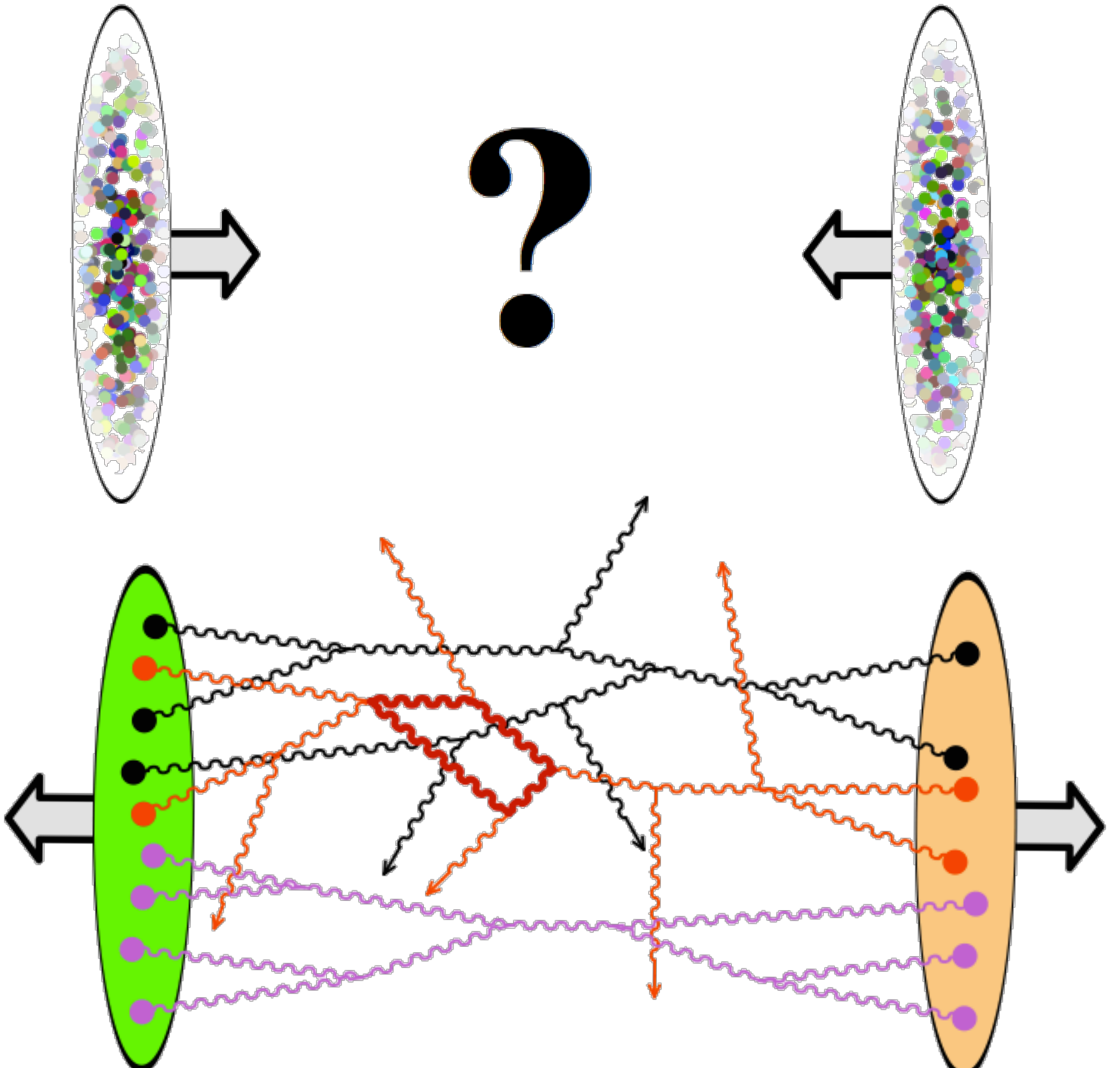




Plot by T. Hatsuda

The Color Glass Condensate

The big role of wee gluons



The big role of wee glue

(Nucleus-Nucleus Collisions at Fantastic Energies)

D. Nucleus-Nucleus Collisions at Fantastic Energies

Before leaving this subject it is fun to consider the collision of two nuclei at energies sufficiently high so that in addition to the fragmentation regions, a central plateau region can develop. Let us consider a central collision of a relatively small nucleus, say carbon, with a big one, say lead. Let us look at this collision in a center-of-mass frame for which the rapidities of both of the nucleus projectiles exceeds the critical rapidity. In such a frame they both possess the fur coat of wee-parton vacuum fluctuations. In such a central collision we see that the collision initially occurs between the fur of wee partons in each of the projectiles. Therefore the number of independent collisions will be of order of the area of overlap of the two projectiles; namely the cross-sectional area of the smaller nucleus.

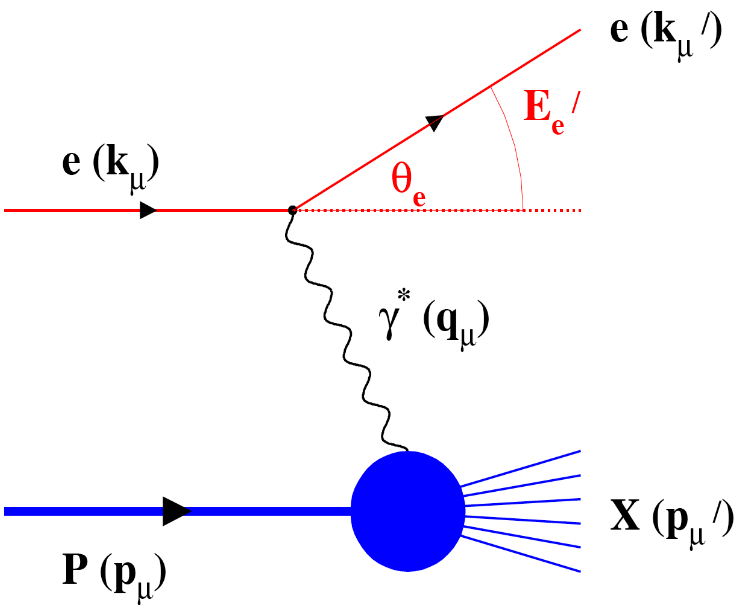
At LHC, ~14 units in rapidity!

Bj, DESY lectures (1975)

The big role of wee glue

- What is the role of wee partons ? ✔
- How do the wee partons interact and produce glue ? ✔
- Can it be understood *ab initio* in QCD ? ✔

The DIS Paradigm



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 4E_e E'_e \sin^2\left(\frac{\theta'_e}{2}\right)$$

Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

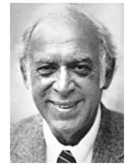
Measure of momentum fraction of struck quark

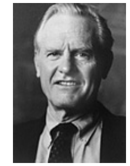
$$\frac{d^2\sigma^{eh\to eX}}{dx dQ^2} = \frac{4\pi\alpha_{em}^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

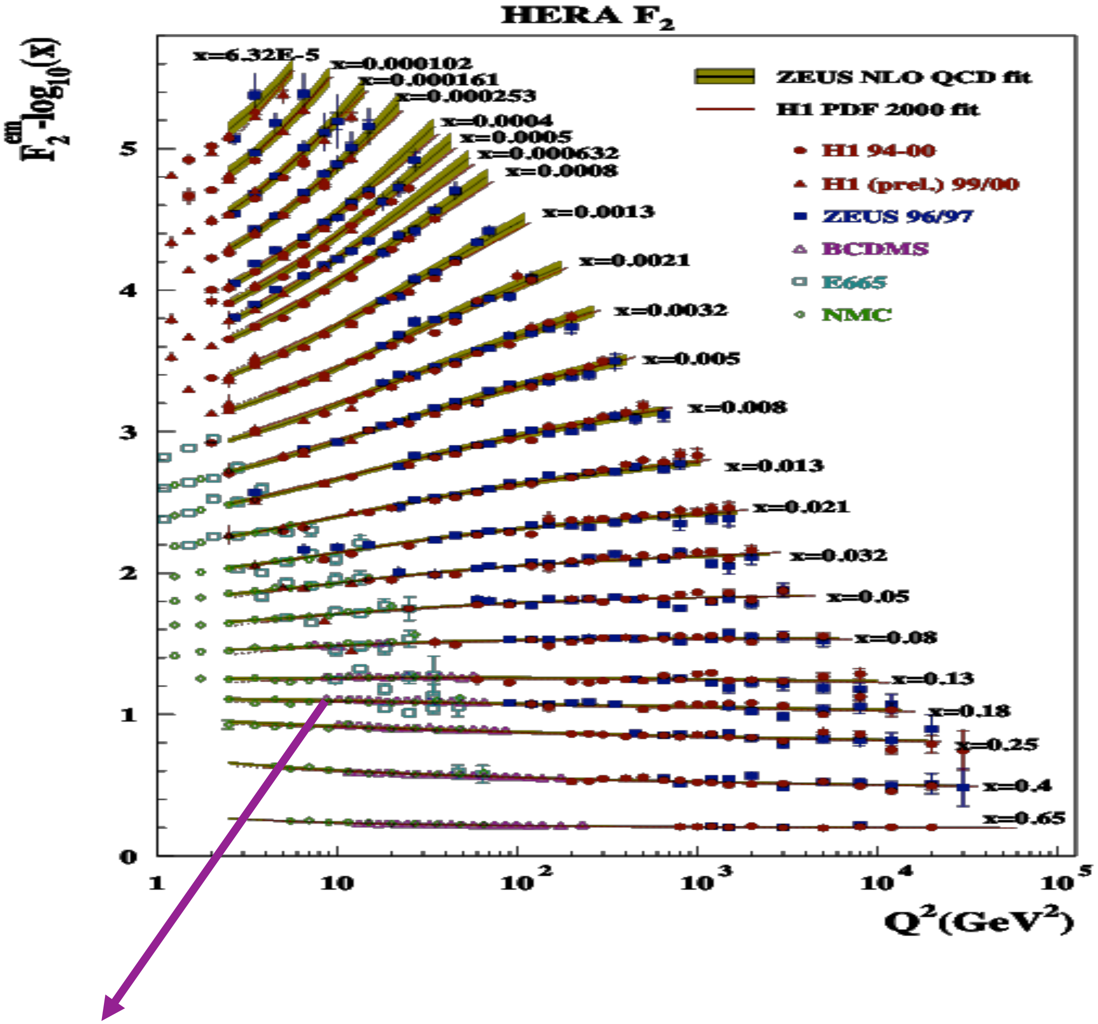
quark+anti-quark mom. dists.

gluon mom. dists

Nobel to Friedman, Kendall, Taylor

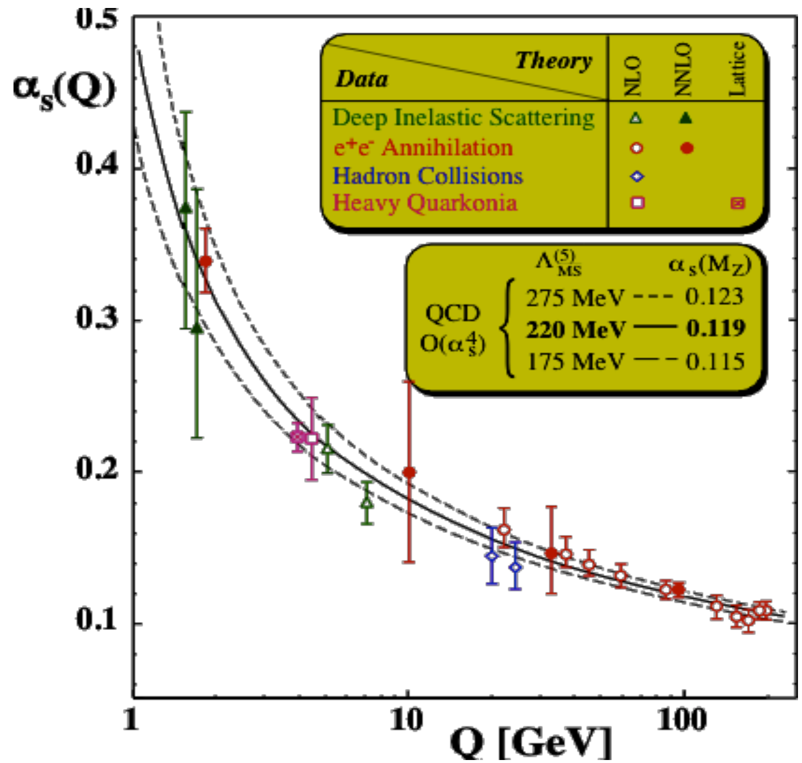






Bj-scaling: apparent scale invariance of structure functions

Puzzle resolved in QCD…



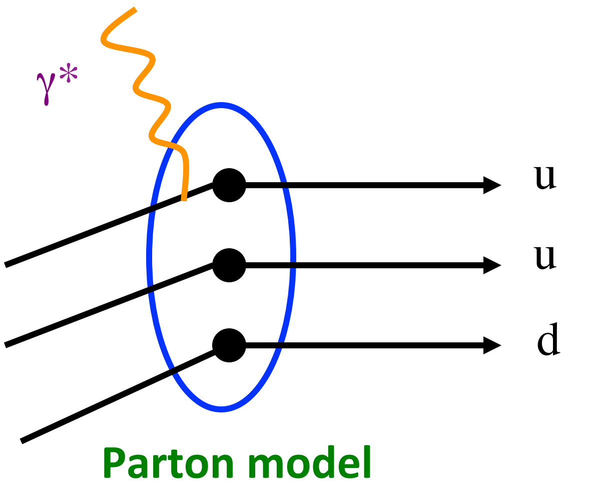
Gross, Wilczek, Politzer

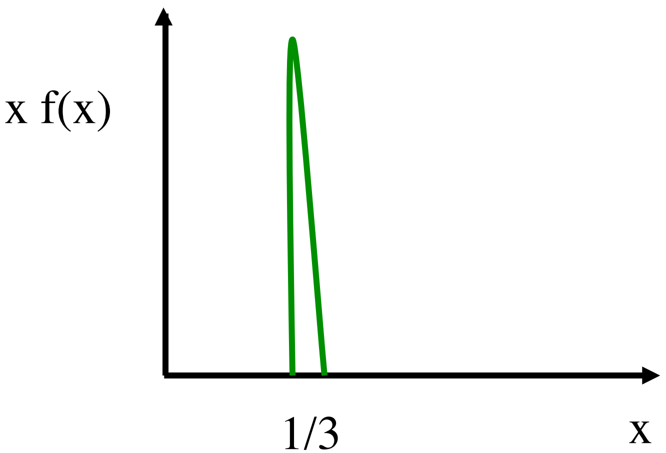
 

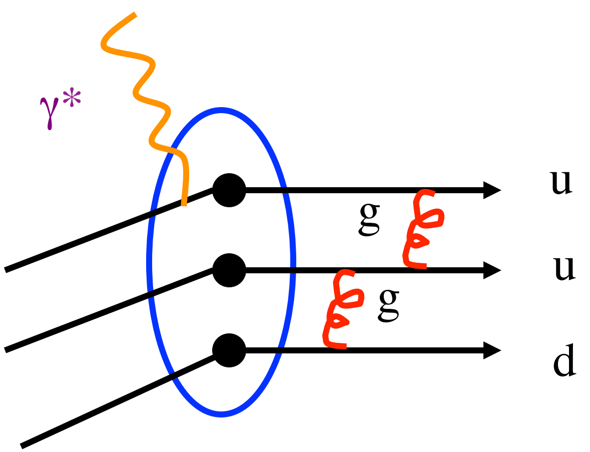
QCD ≠ Parton Model
Logarithmic scaling violations

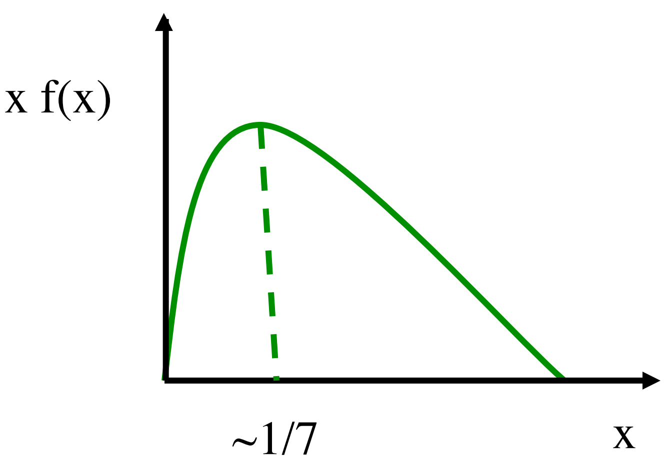
$$F_2(x,Q^2) = \sum_{\substack{q=u,c,t \\ d,s,b}} e_q^2 \left(x\, q(x,Q^2) + x\, \bar{q}(x,Q^2)\right)$$

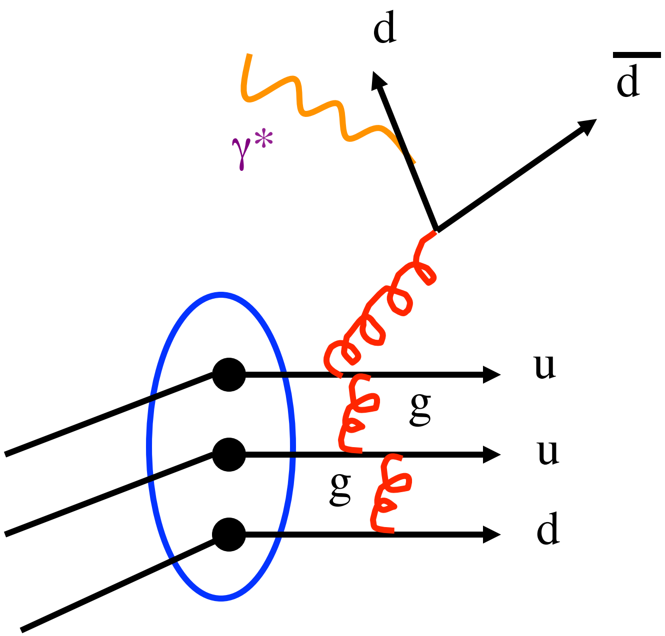
The proton at high energies

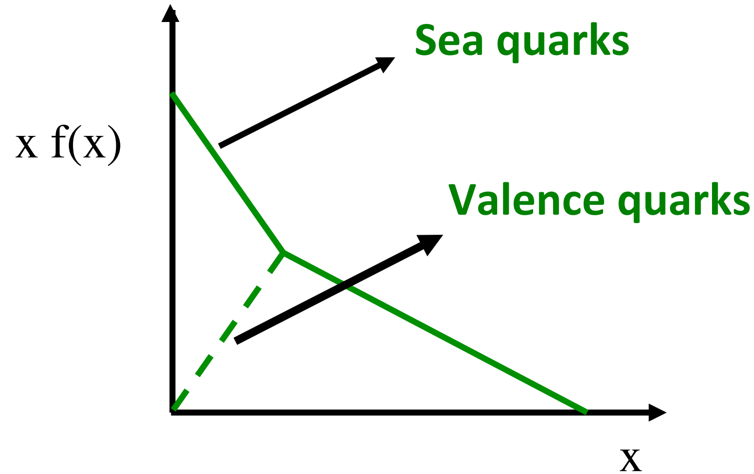








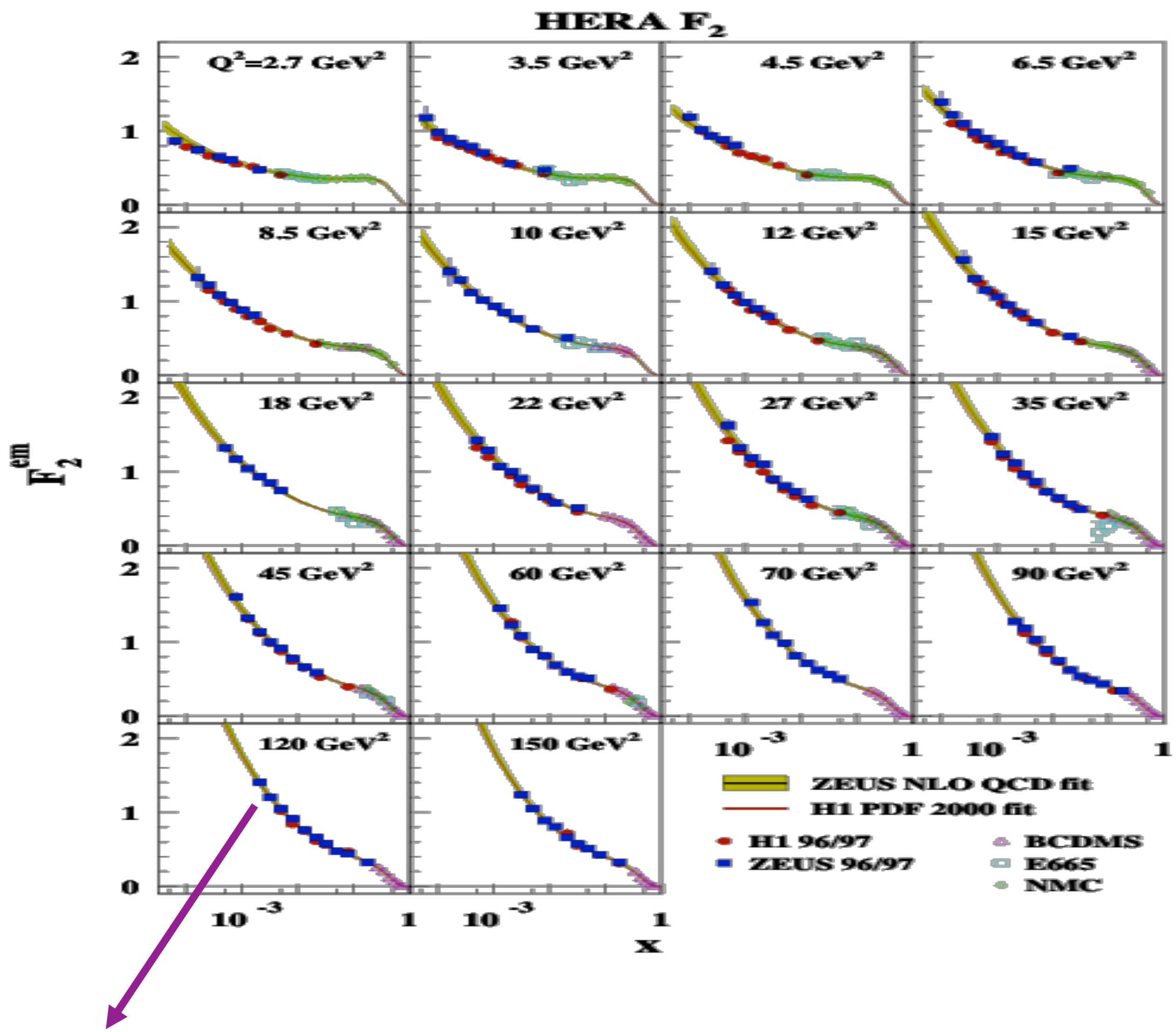




"x-QCD"- small x evolution

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

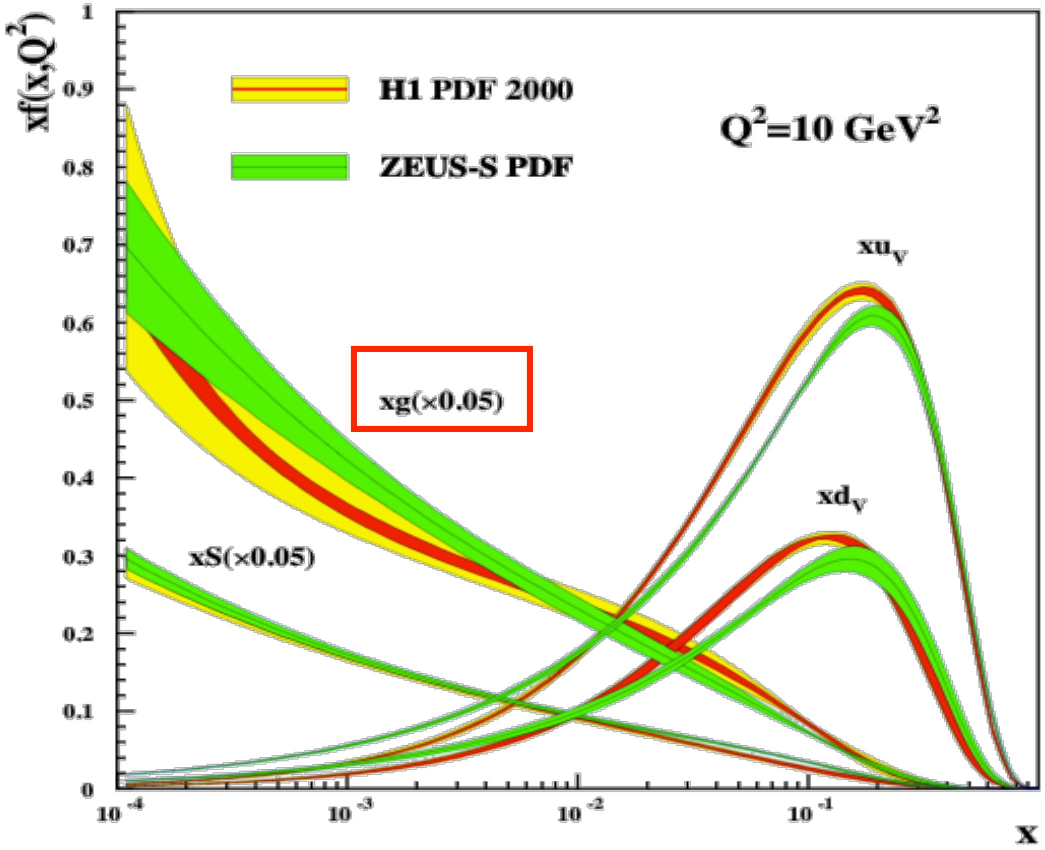
$$\int_0^1 \frac{dx}{x} \left(xq(x) + x\bar{q}(x)\right) \to \infty$$ → **# of quarks**



Structure functions grow rapidly at small x

Where is the glue ?

partons / unit rapidity



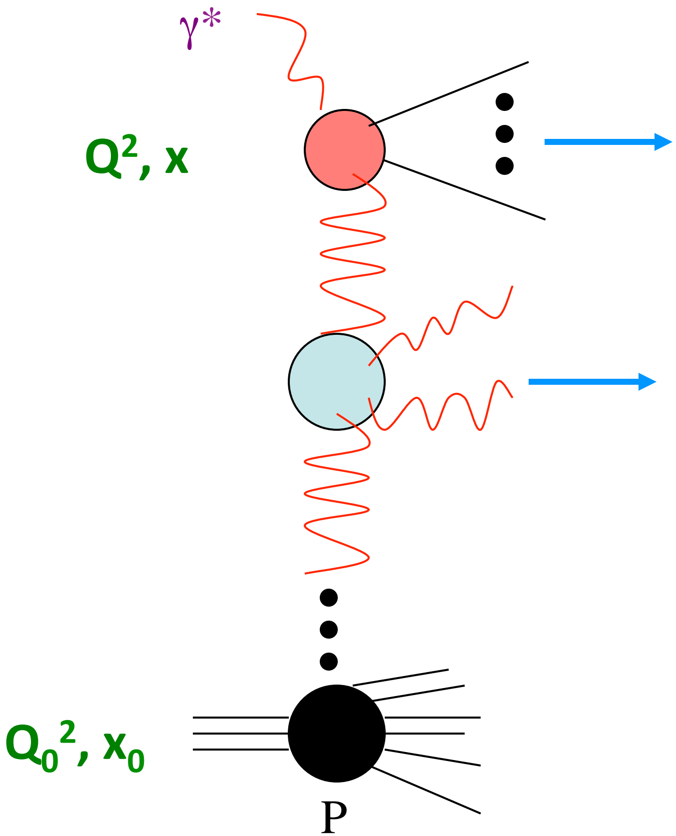
For x < 0.01, proton dominated by glue-grows rapidly
What happens when glue density is large ?

The Bjorken Limit

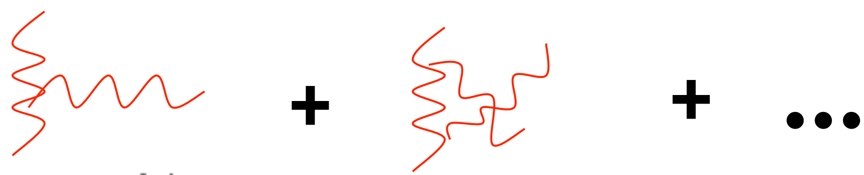
$$Q^2 \to \infty\,;\; s \to \infty\,;\; x_{\mathrm{Bj}} \approx \frac{Q^2}{s} = \mathrm{fixed}$$

- Operator product expansion (OPE), factorization theorems, machinery of precision physics in QCD

Structure of higher order perturbative contributions in QCD



$$C_2(x, \alpha_S) = \delta(1-x) + \alpha_S C_2^{(1)}(x) + \alpha_S^2 C_2^{(2)} + \cdots$$



$\alpha_S P^{(1)}$ + $\alpha_S^2 P^{(2)}$ + ...

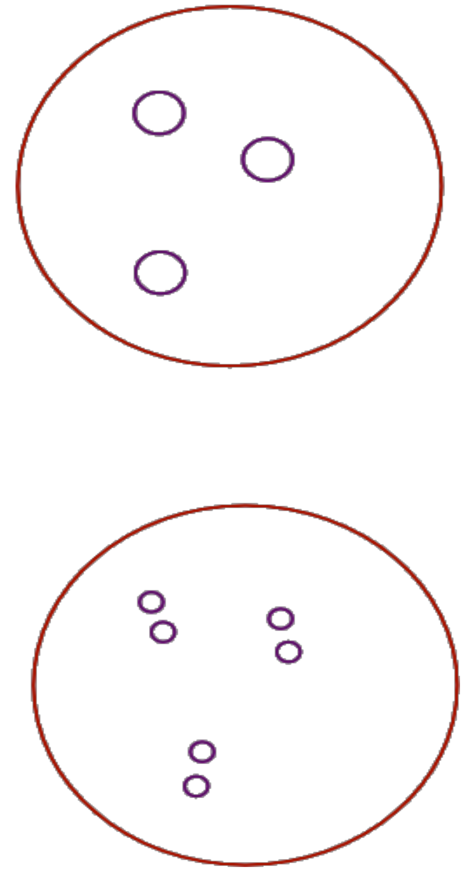
+ higher twist (power suppressed) contributions...

- Coefficient functions C - computed to NNLO for many processes
- Splitting functions P - computed to 3-loops

Resolving the hadron…

Ren.Group-DGLAP evolution
(sums large logs in Q^2)

Increasing Q^2



Phase space density (# partons / area / Q^2) decreases
- the proton becomes more dilute…

BEYOND pQCD IN THE Bj LIMIT

- **Works great for inclusive, high Q^2 processes**
- **Higher twists important when $Q^2 \approx Q_S^2(x)$**
- **Problematic for diffractive/exclusive processes**
- **Formalism not convenient to treat shadowing, multiple scattering, diffraction, energy loss, impact parameter dependence, thermalization…**

The Regge-Gribov Limit in QCD

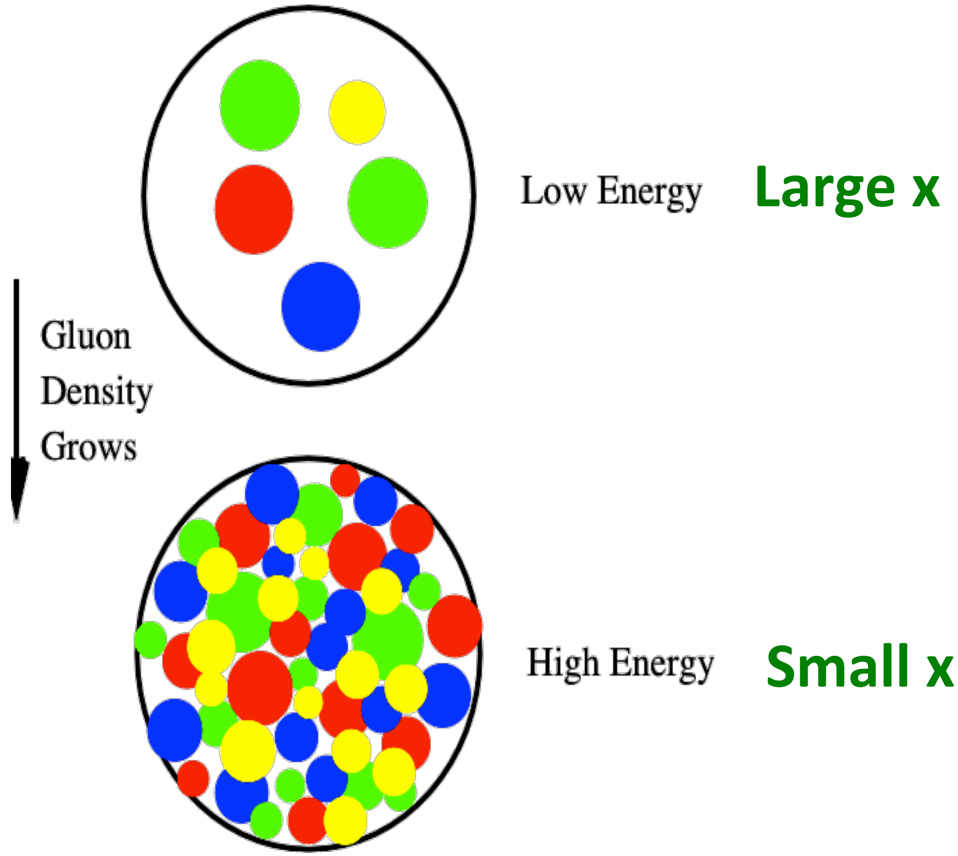
 

$$x_{\mathrm{Bj}} \to 0\,;\ s \to \infty\,;\ Q^2 (>> \Lambda^2_{\mathrm{QCD}}) = \mathrm{fixed}$$

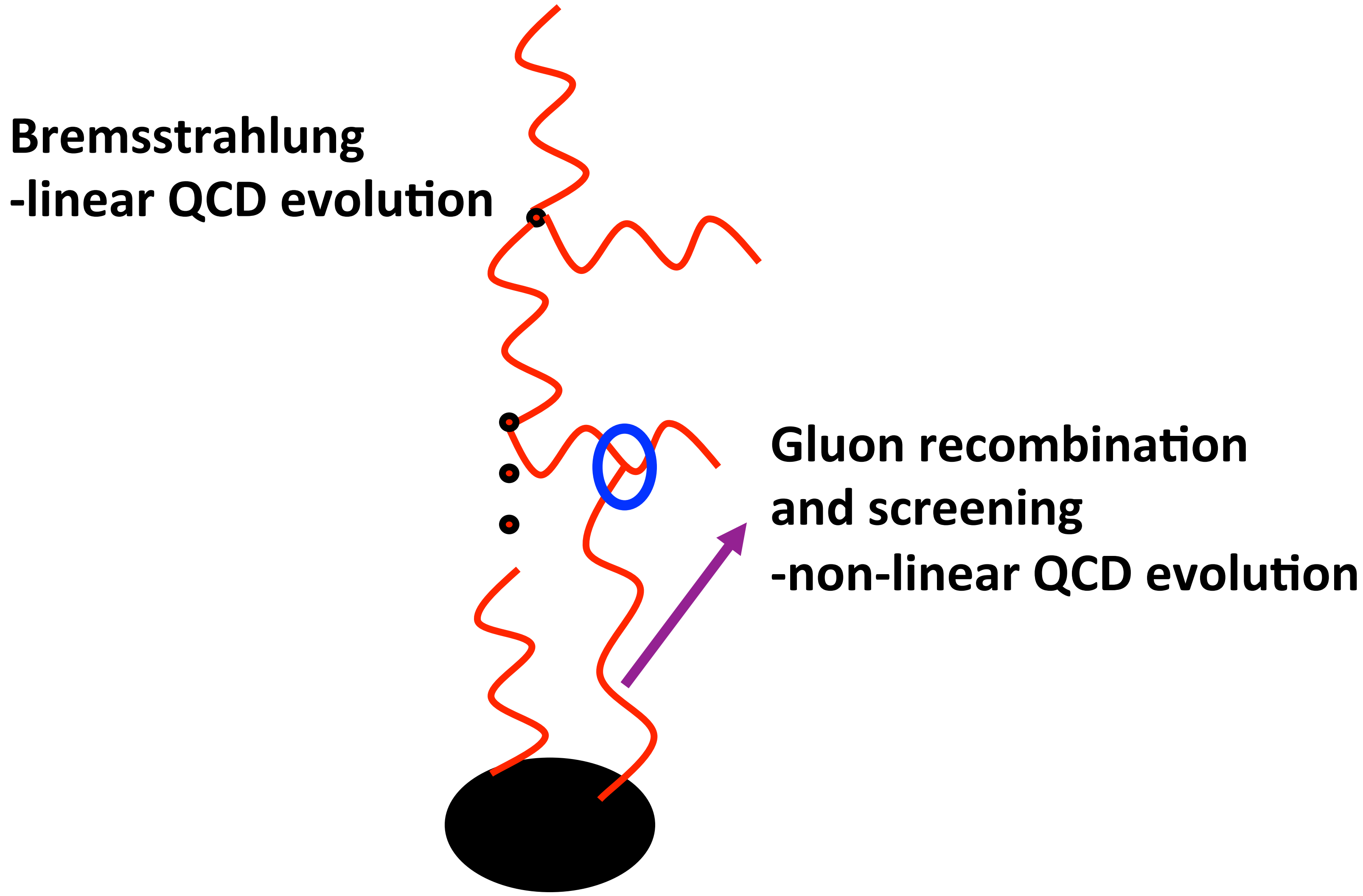
- **Physics of strong fields in QCD, multi-particle production, Novel universal properties of QCD ?**

Resolving the hadron…

Ren.group-BFKL evolution in QCD (sums large logs in x)



Gluon density saturates at phase space density f = 1 /α_s
- strongest (chromo-) E&M fields in nature…



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**

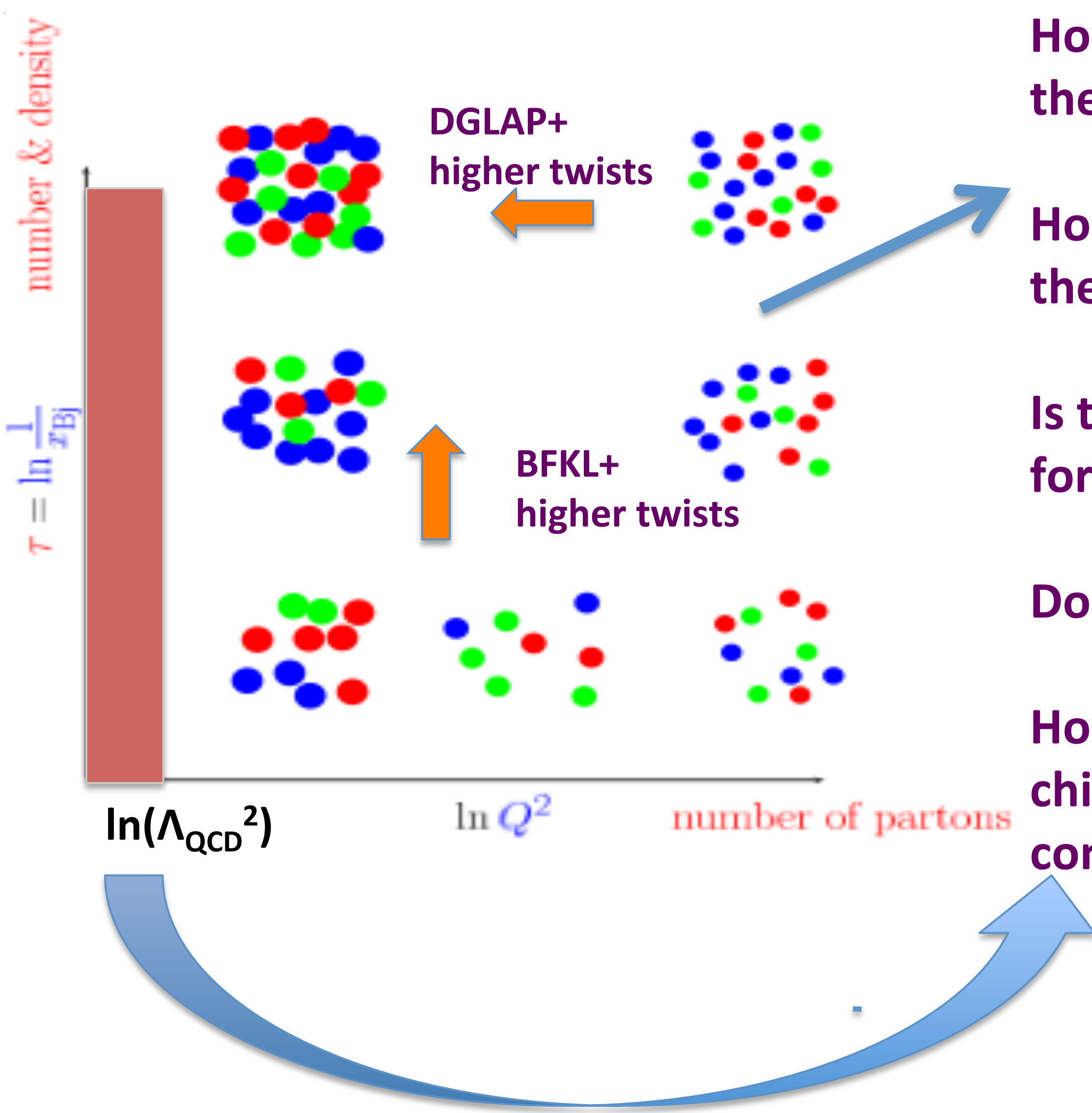
Maximum phase space density (f = 1/α_S) =>

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

This relation is saturated for

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

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

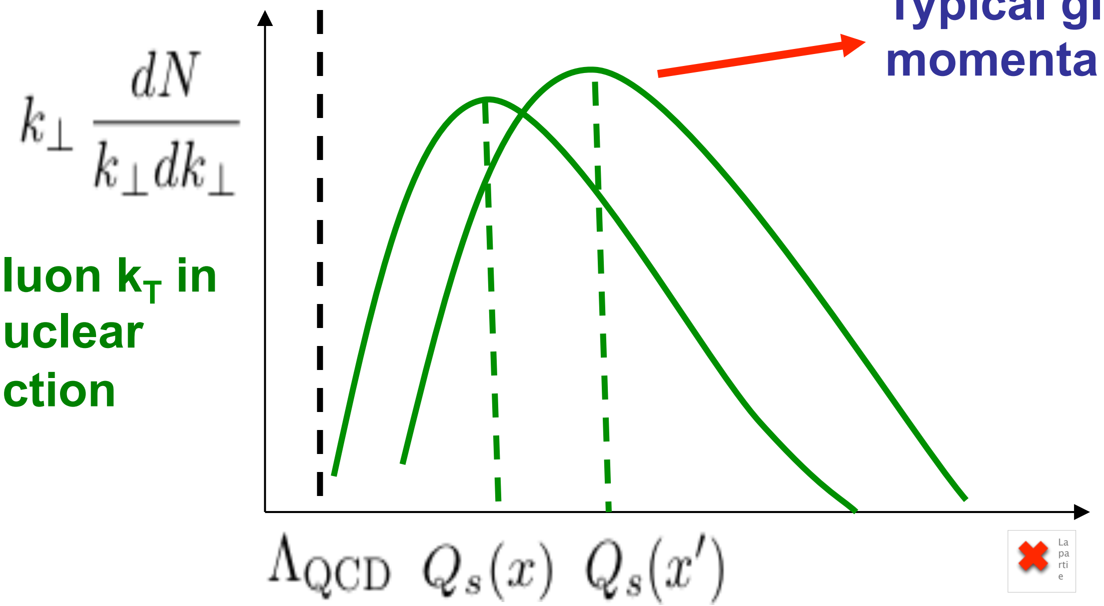
Does the coupling run with Q_s^2 ?

How does saturation transition to chiral symmetry breaking and confinement

Saturation scale grows with energy

Typical gluon momenta are large

Typical gluon k_T in hadron/nuclear wave function



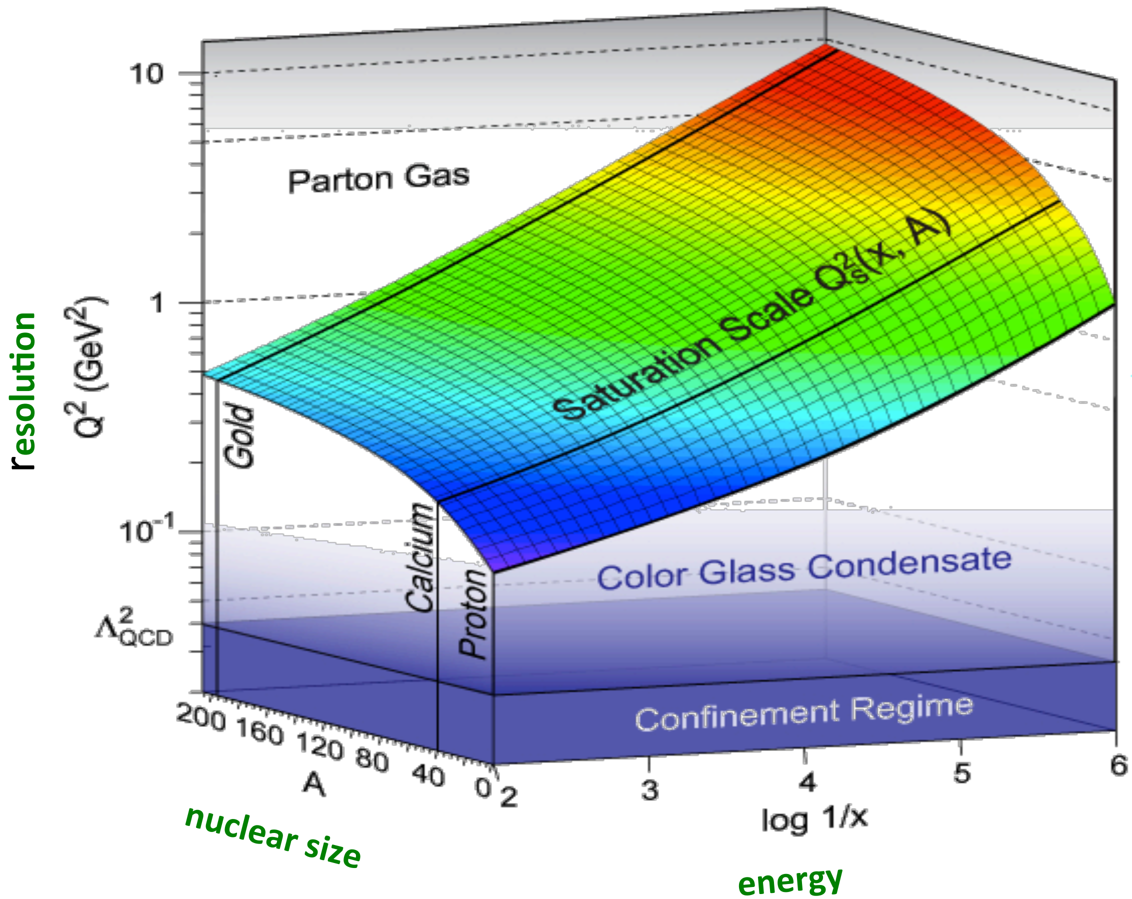
Bulk of high energy cross-sections:

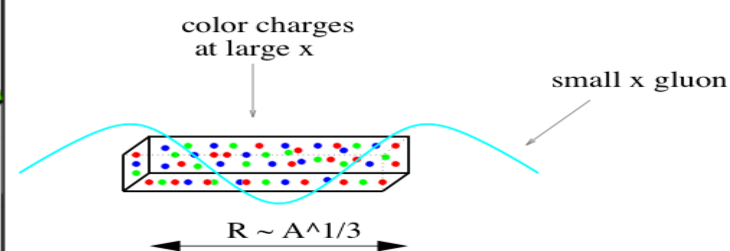
a) obey dynamics of novel non-linear QCD regime

b) Can be computed systematically in weak coupling

Many-body high energy QCD:
The Color Glass Condensate

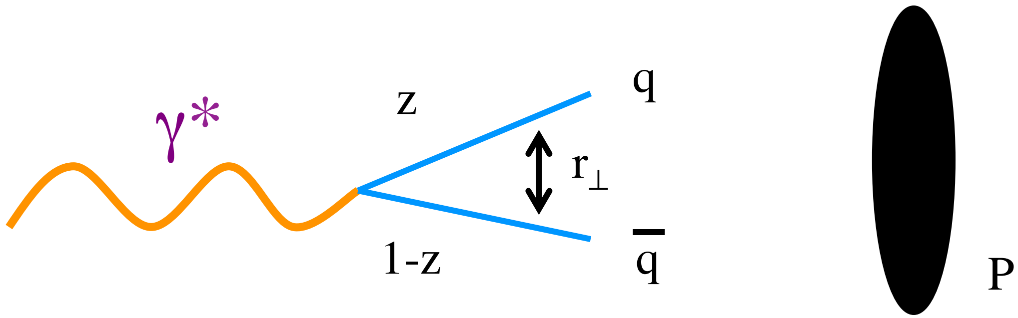
Gelis,Iancu,Jalilian-Marian,RV:
Ann. Rev. Nucl. Part. Sci. (2010), arXiv: 1002.0333





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

Parton Saturation:Golec-Biernat --Wusthoff dipole model



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

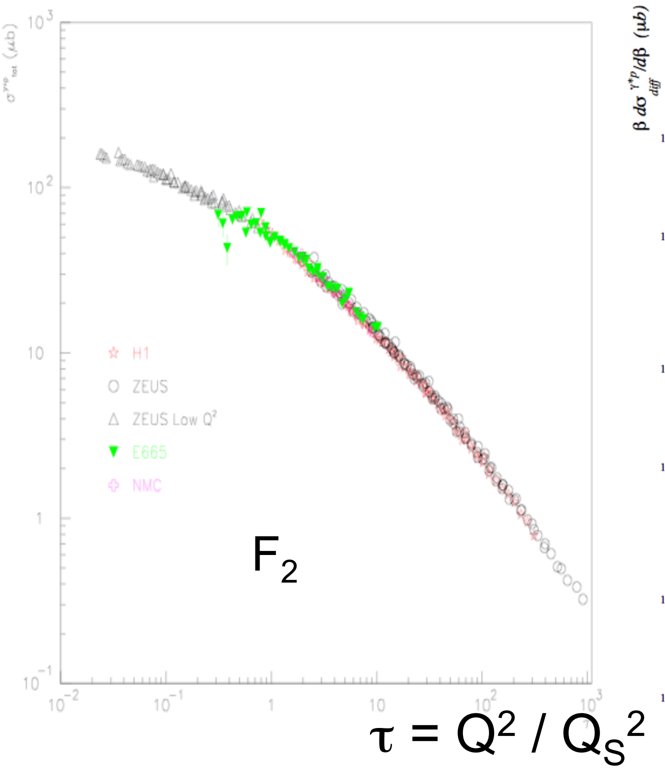
$$\sigma_{q\bar{q}P}(r_\perp, x) = \sigma_0 \left[1 - \exp\left(-r_\perp^2 \, Q_s^2(x)\right)\right]$$

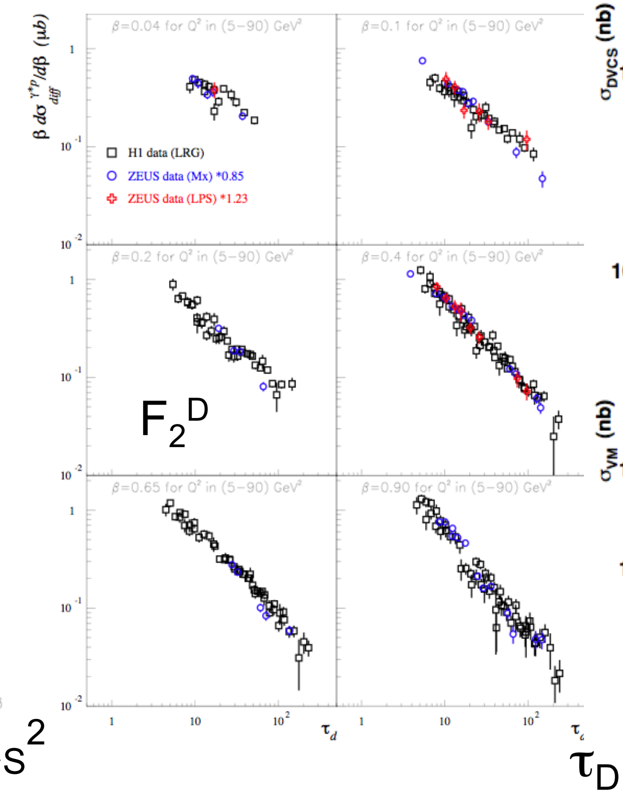
$$Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^\lambda$$

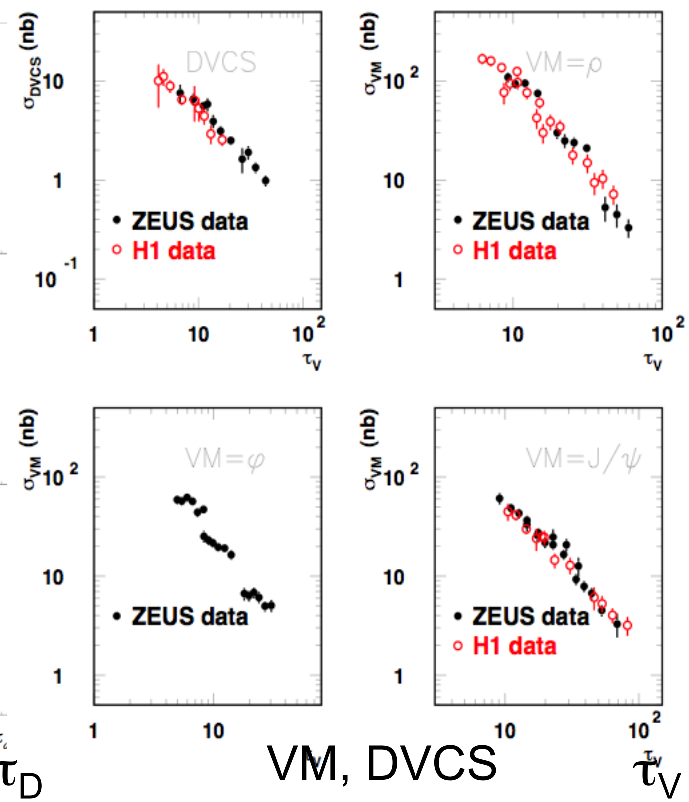
Parameters: Q_0 = 1 GeV; λ = 0.3; x_0 = 3* 10^{-4} ; σ_0 = 23 mb

Evidence from HERA for geometrical scaling

Golec-Biernat, Stasto,Kwiecinski





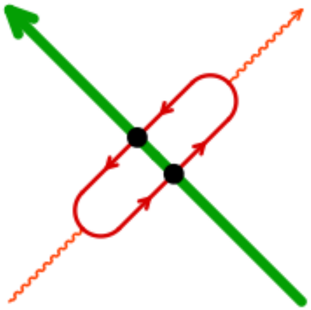


Marquet, Schoeffel hep-ph/0606079

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

Gelis et al., hep-ph/0610435

Inclusive DIS: dipole evolution



Photon wave function

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

State of the art dipole saturation models:

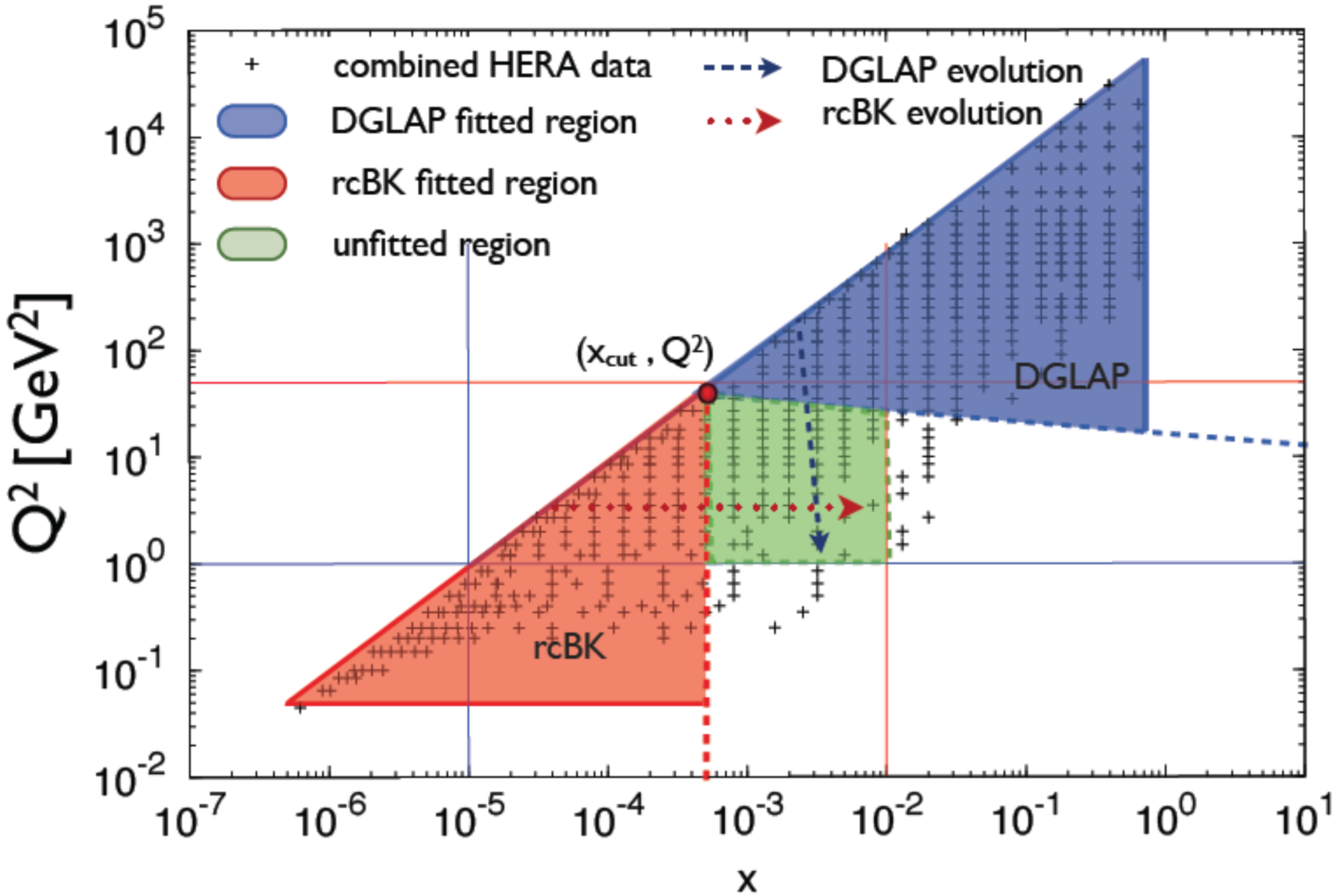
i) rcBK –higher twist corrections to pQCD BFKL small x evolution Albacete,Kovchegov

ii) IP-Sat based on eikonalized treatment of DGLAP higher twists – form same as MV model

$$\frac{d\sigma_{\text{dipole}}}{d^2 b_\perp} = 2\left(1 - \exp\left(-\frac{\pi^2 r_\perp^2}{2N_c}\,\alpha_S(\mu^2)\, xg(x,\mu^2)\, T_G(b_\perp)\right)\right)$$

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

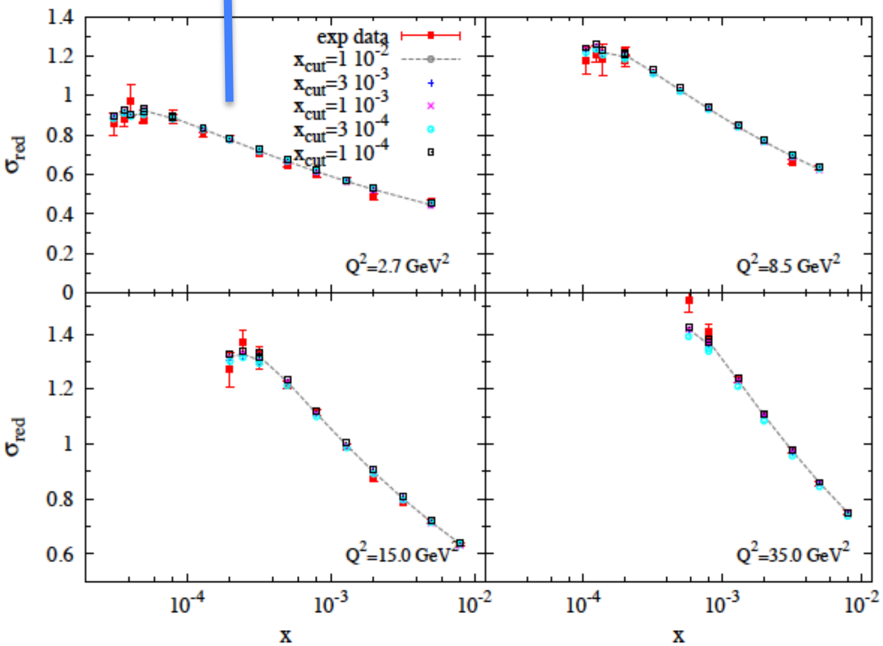
Inclusive DIS: dipole evolution a la BK



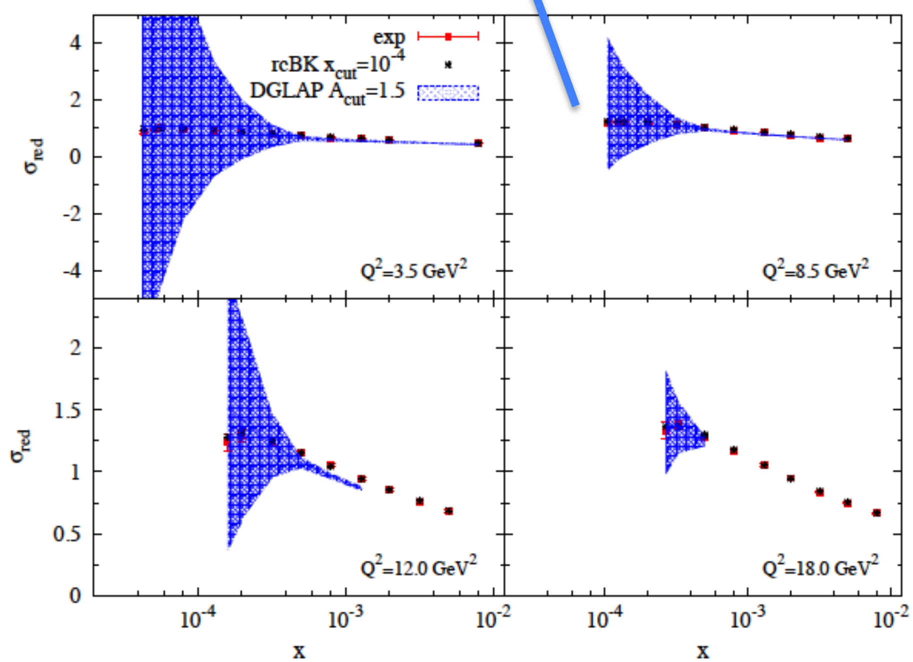
Albacete,Milhano,Quiroga-Arias,Rojo, arXiv:1203.1043

Inclusive DIS: dipole evolution a la BK

Comparison of running coupling rcBK eqn. with precision small x combined HERA data

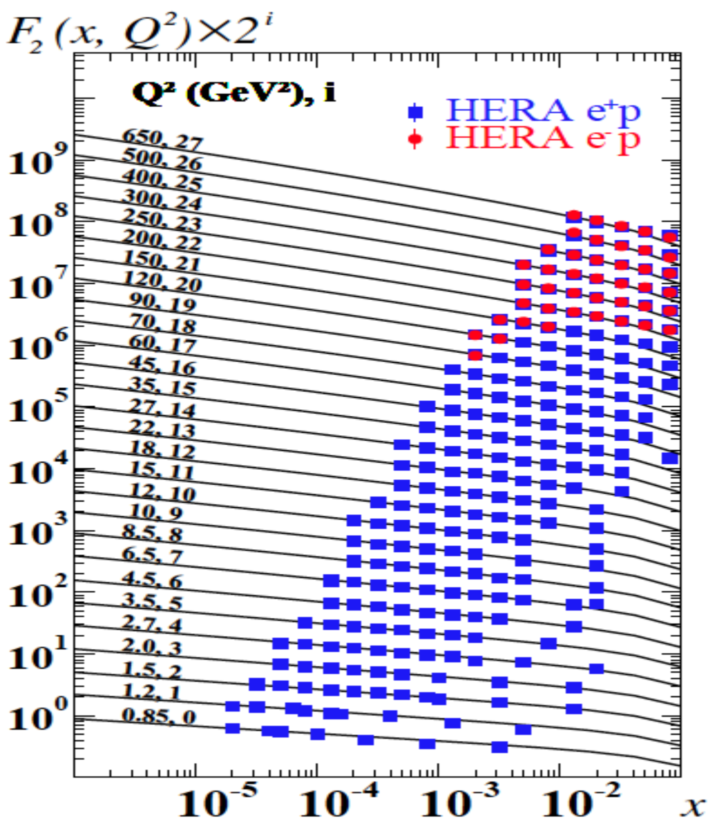


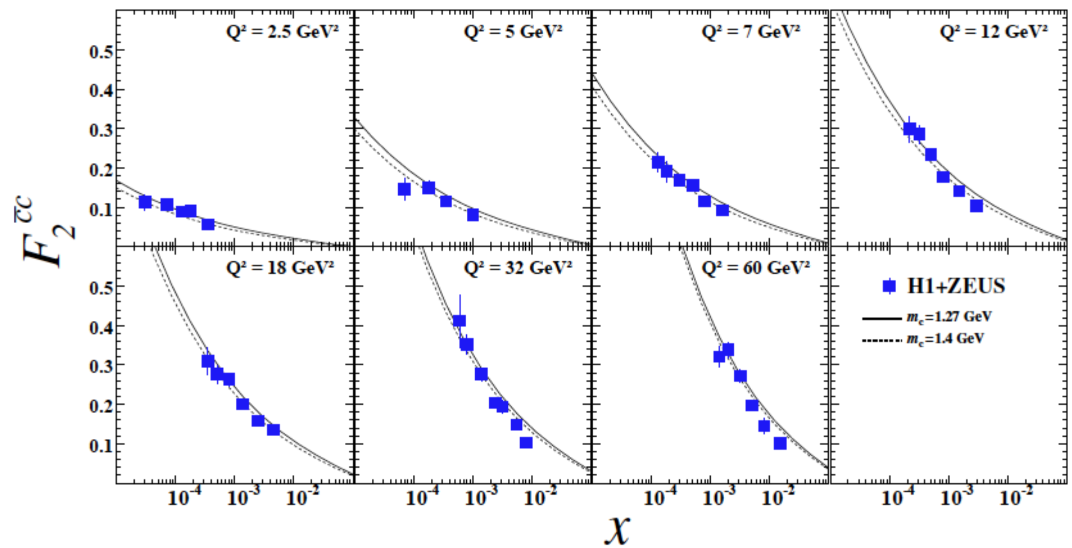
Comparison of rc BK to DGLAP fits-bands denote pdf uncertainties

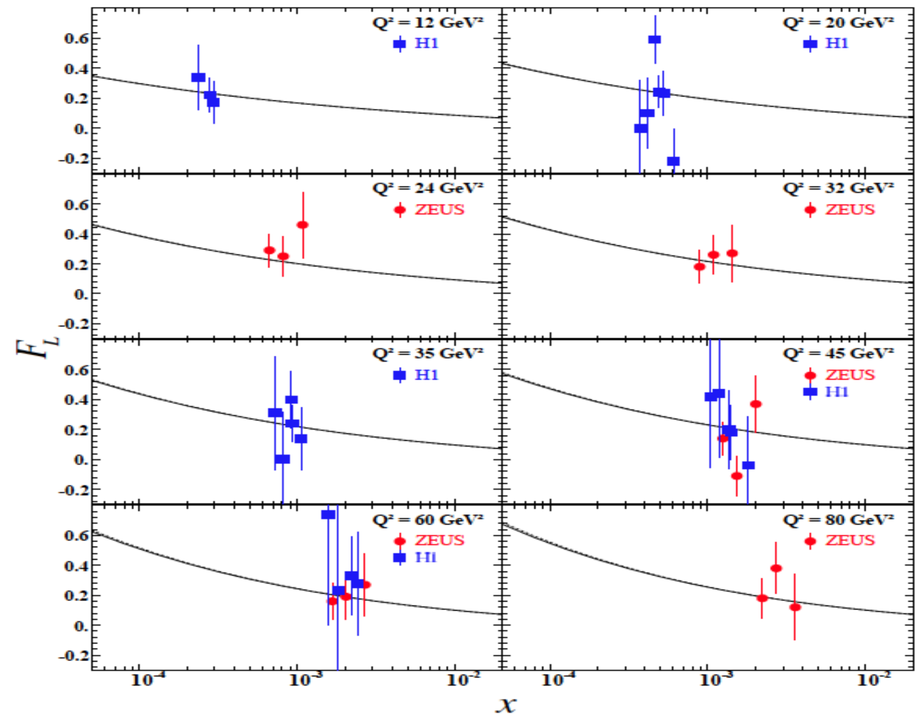


Albacete,Milhano,Quiroga-Arias,Rojo, arXiv:1203.1043

Inclusive DIS: dipole evolution a la IP-Sat





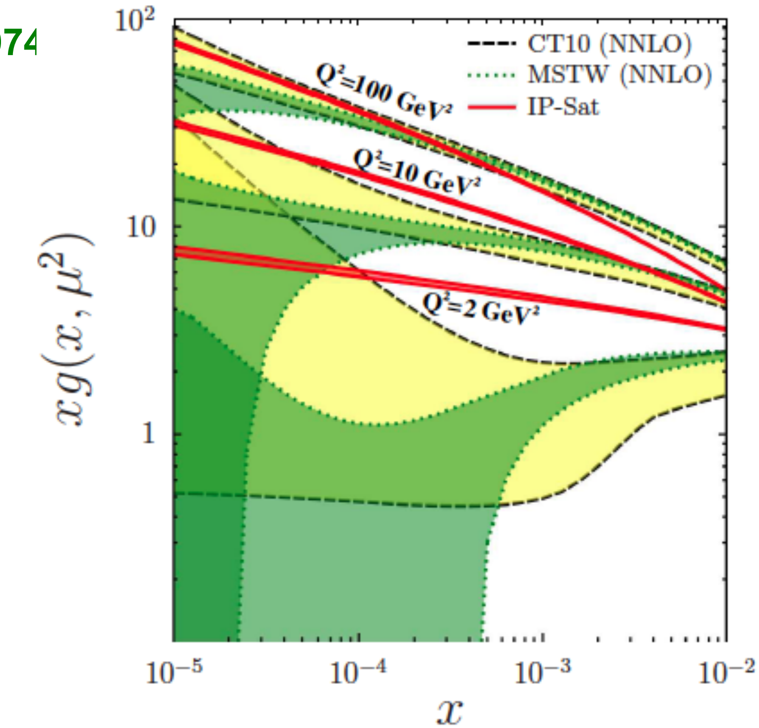


(Few) parameters fixed by $\chi 2 \sim 1$ fit to combined (H1+ZEUS) red. cross-section

Rezaiean,Siddikov,Van de Klundert,RV: 1212.2974

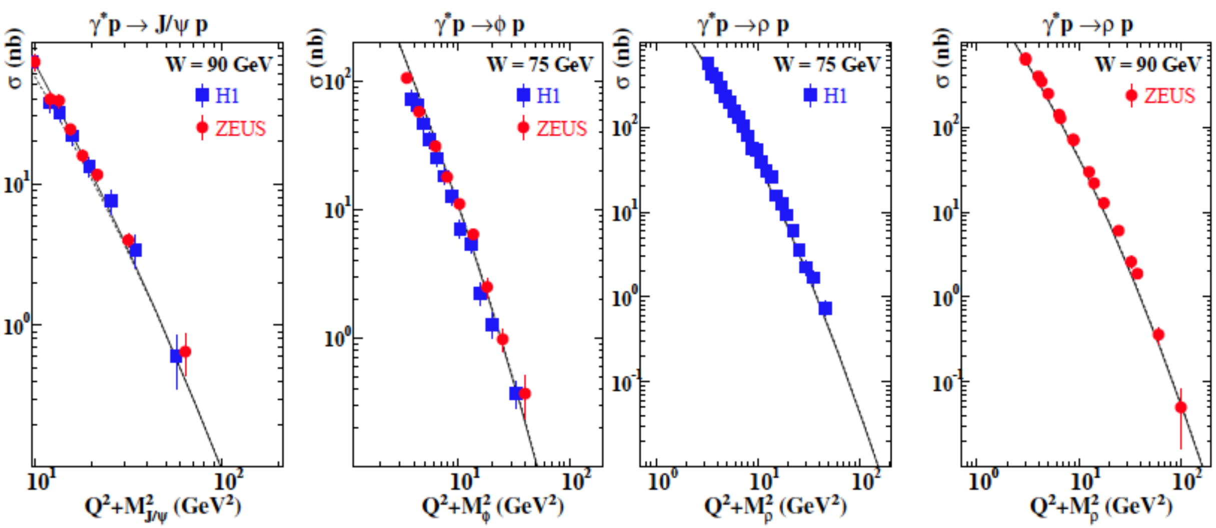
Inclusive DIS: dipole evolution a la IP-Sat

Rezaiean,Siddikov,Van de Klundert,RV: 1212.2974



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

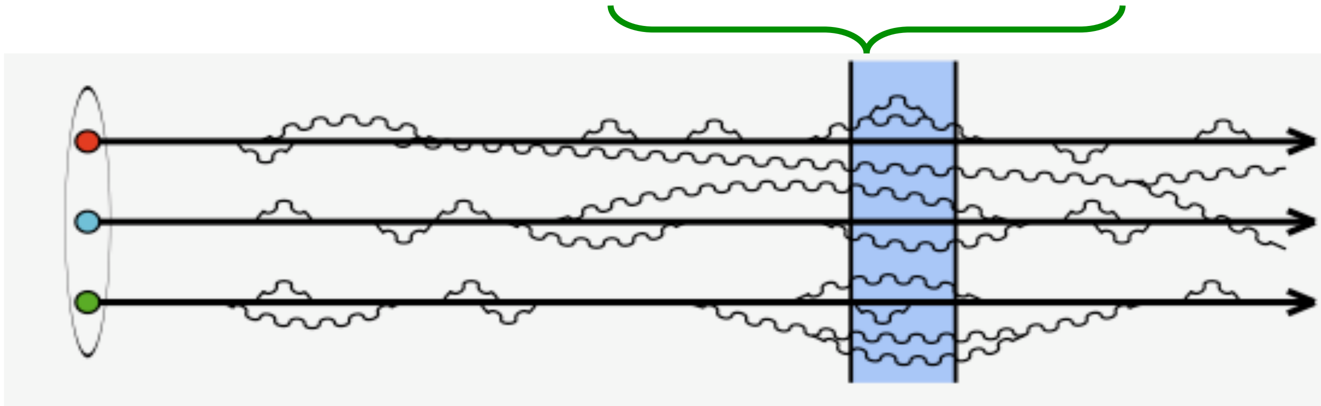
Exclusive Vector meson production:



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

The nuclear wavefunction at high energies

$$|A\rangle = |qqq...q\rangle + ... + |qqq...q\mathbf{gg...g}\rangle$$



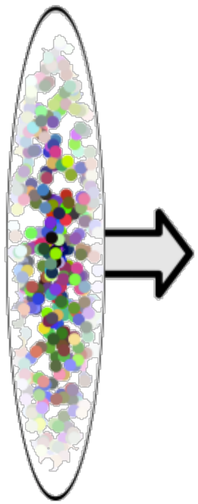
- At high energies, interaction time scales of fluctuations are dilated well beyond typical hadronic time scales

- 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

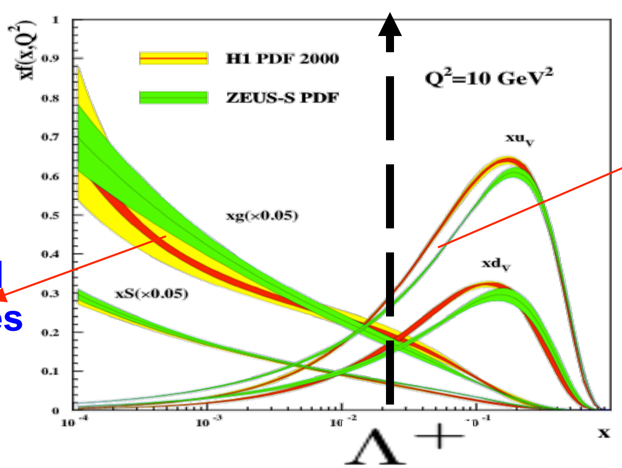
The nuclear wavefunction at high energies



|A> = |qqq…q> + … + |qqq…q**gg…gg**>

Higher Fock components dominate multiparticle production- construct Effective Field Theory

Dynamical Wee modes

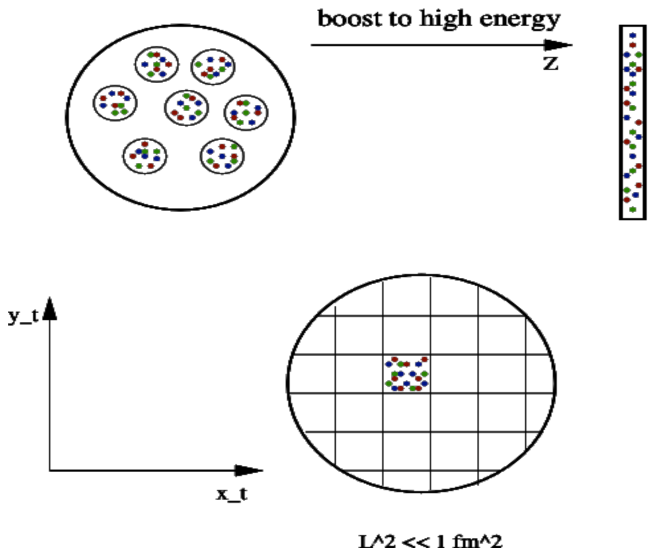


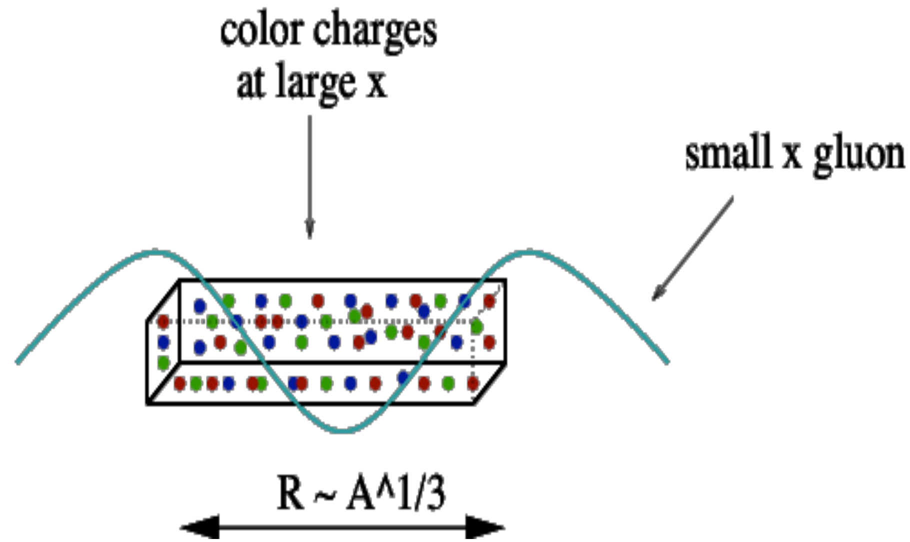
Valence modes- are static sources for wee modes

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,

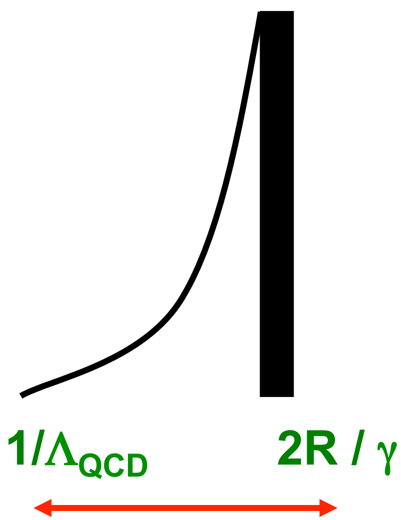
"Pomeron" excitations

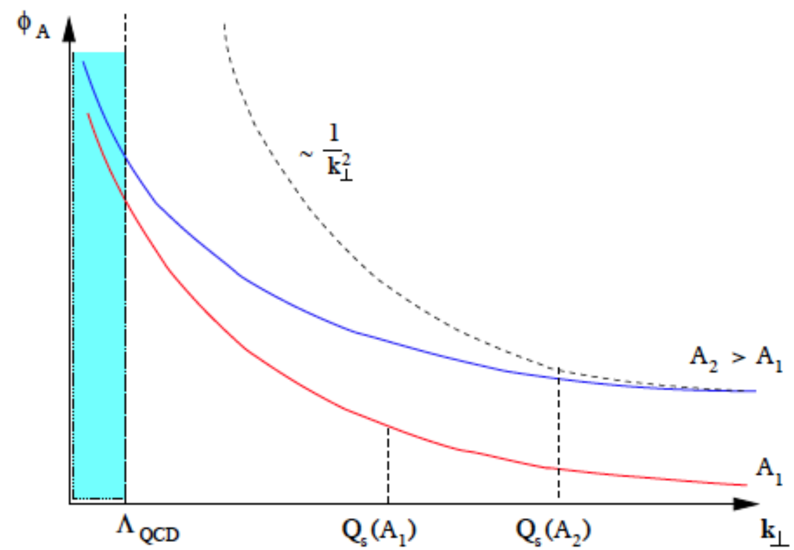
"Odderon" excitations

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

McLerran,RV
Kovchegov
Jeon, RV

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

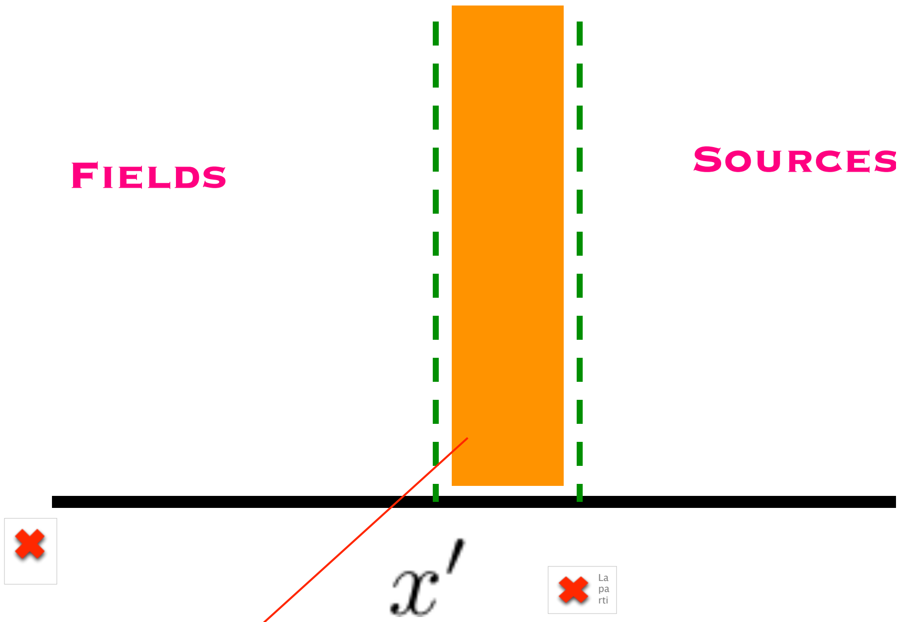


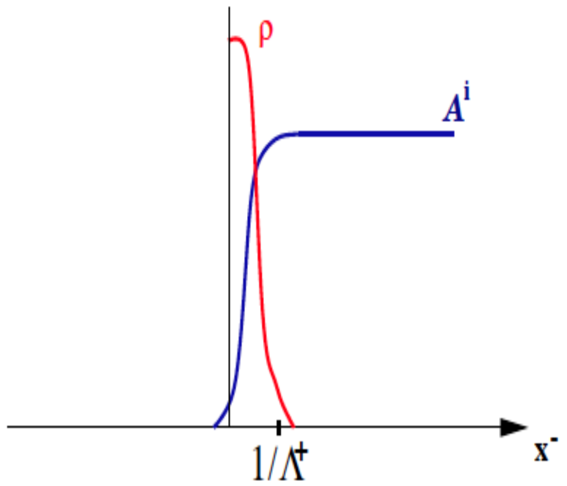


Wee parton dist. : $$\frac{1}{\Lambda_{\rm QCD}} e^{-\lambda\Delta Y/2}$$

determined from RG

Quantum evolution of classical theory: Wilson RG



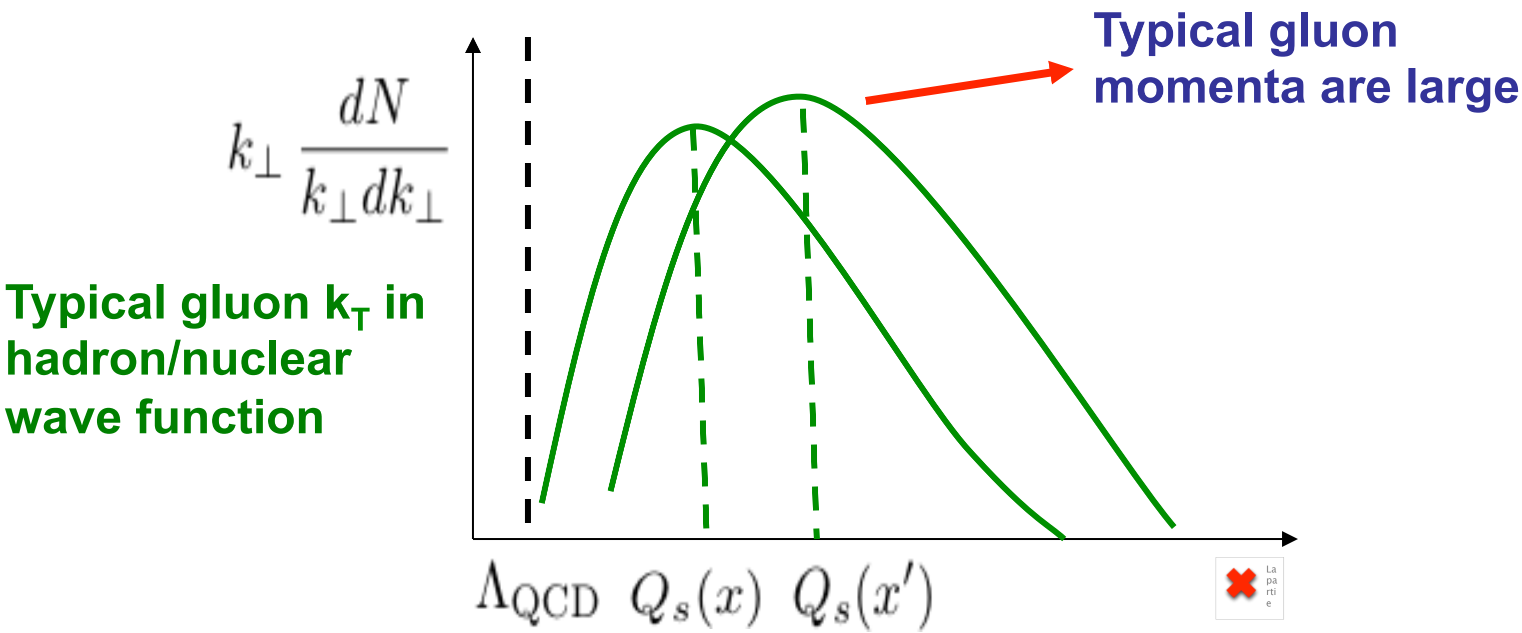


Integrate out
Small fluctuations => Increase color charge of sources

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



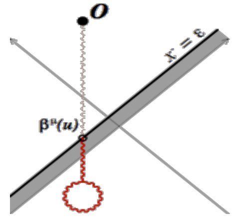
Bulk of high energy cross-sections:

a) **obey dynamics of novel non-linear QCD regime**

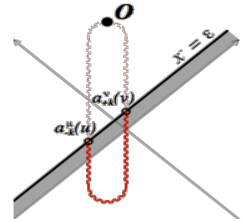
b) **Can be computed systematically in weak coupling**

JIMWLK RG evolution for a single nucleus:

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



$+$



$\chi(x_\perp, y_\perp)$

$\Big)\, \mathcal{O}_{\rm LO}$

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

(keeping leading log divergences)

$$\langle \mathcal{O}_{\rm LO} + \mathcal{O}_{\rm NLO} \rangle = \int [d\tilde{\rho}] W[\tilde{\rho}]\, [\mathcal{O}_{\rm LO} + \mathcal{O}_{\rm NLO}]$$

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

LHS independent of Λ^+ **=>**

$$\frac{\partial W[\tilde{\rho}]}{\partial Y} = \mathcal{H}\, W[\tilde{\rho}]$$

JIMWLK eqn.

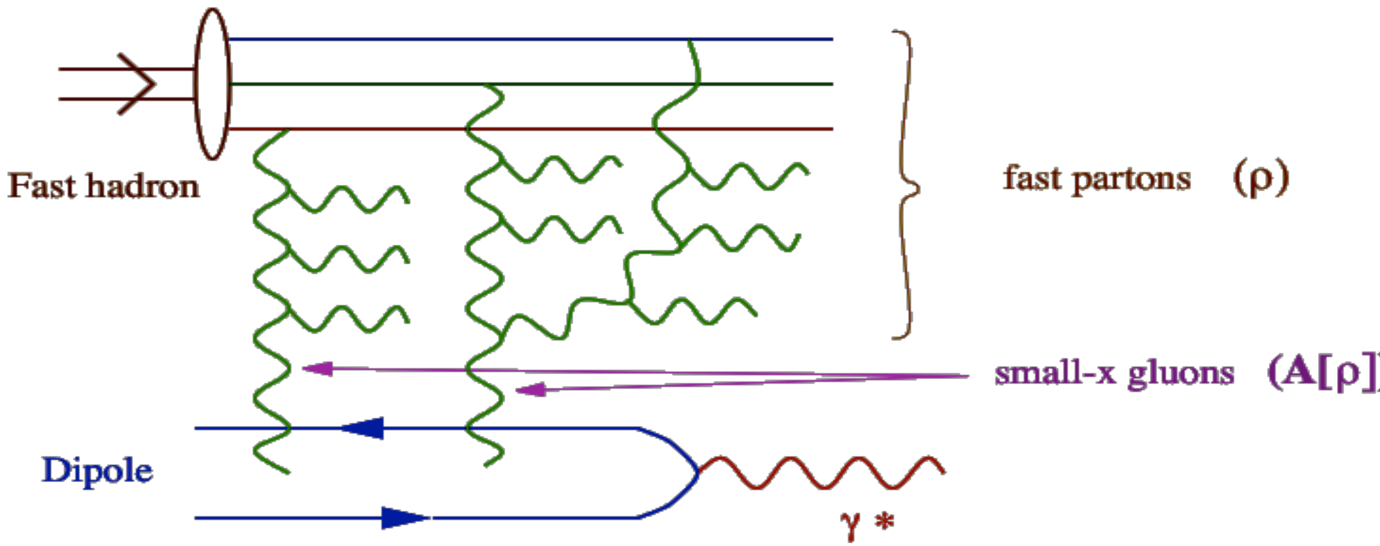
Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner

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:

Gaussian random variable

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

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

"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**

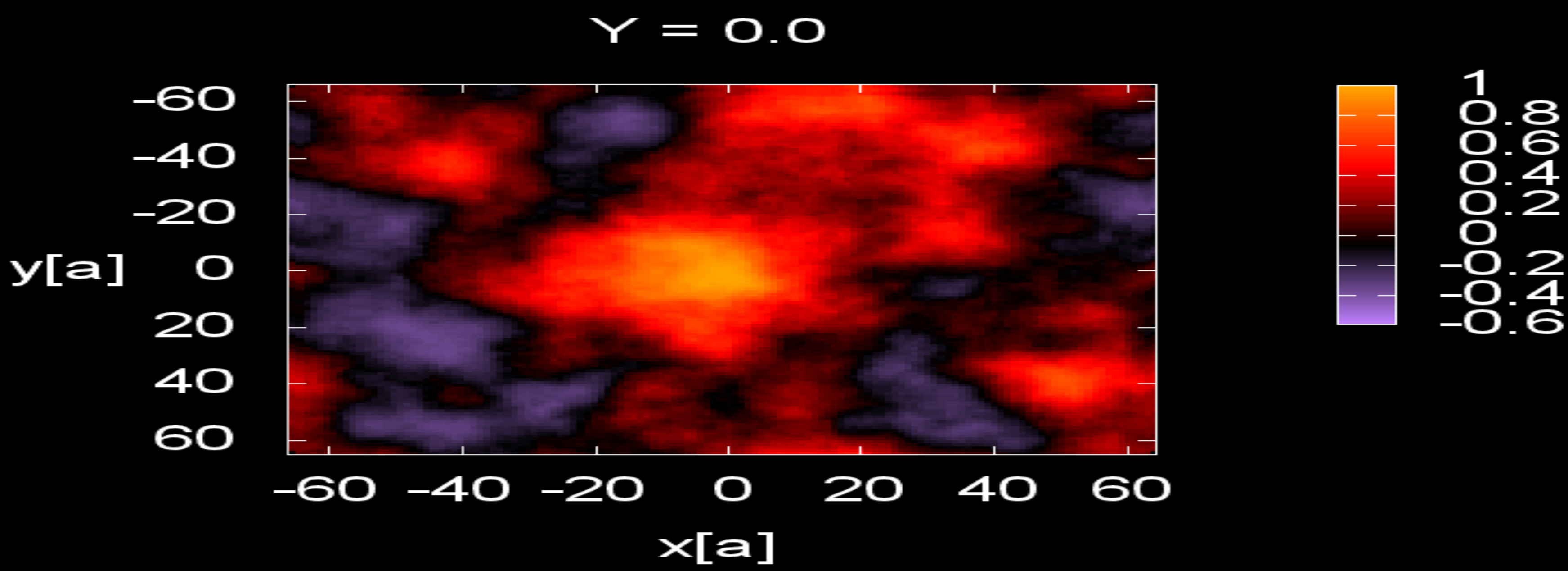
(more sophisticated treatment recently by Lappi & Mantysaari)

Functional Langevin solutions of JIMWLK hierarchy

Rummukainen,Weigert (2003)

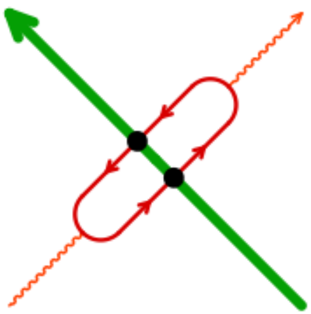
Dumitru,Jalilian-Marian,Lappi,Schenke,RV, PLB706 (2011)219

✓ *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))

Inclusive DIS: dipole evolution

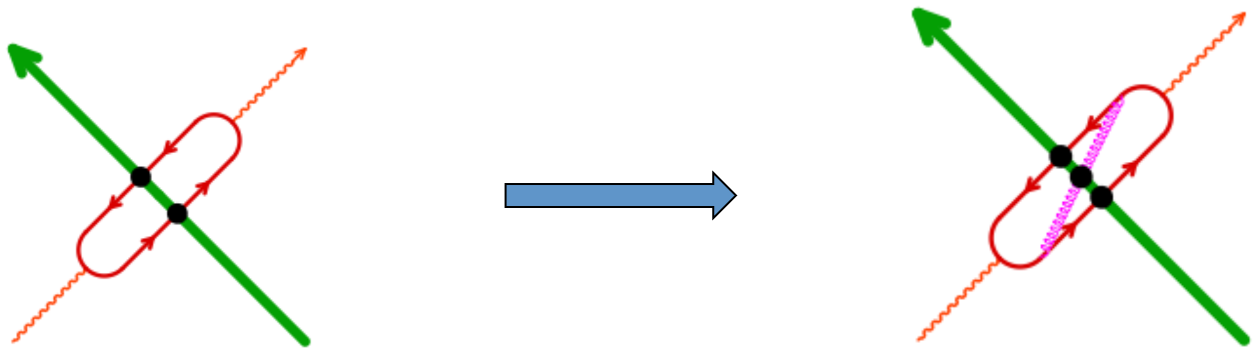


$$\sigma_{\gamma^* T} = \int_0^1 dz \int d^2 r_\perp \, |\psi(z, r_\perp)|^2 \sigma_{\rm dipole}(x, r_\perp)$$

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

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

Inclusive DIS: dipole evolution



B-JIMWLK eqn. for dipole correlator

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

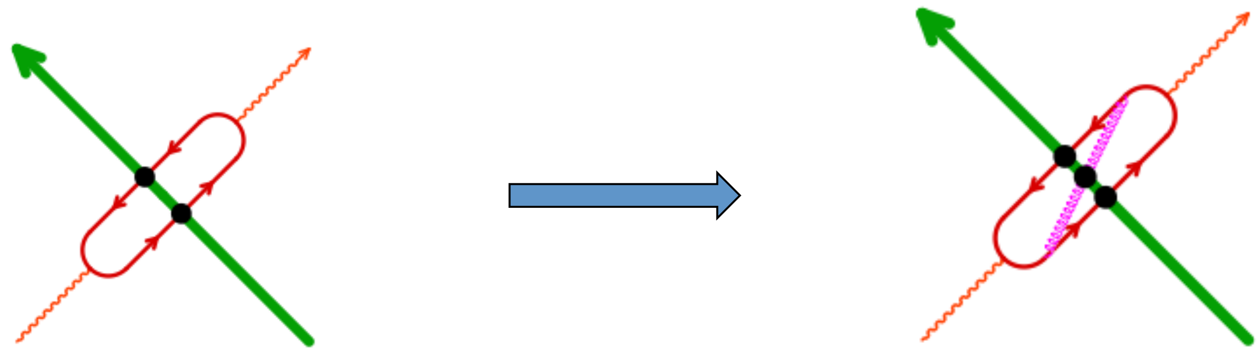
Dipole factorization:

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

$N_c \rightarrow \infty$

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

Inclusive DIS: dipole evolution



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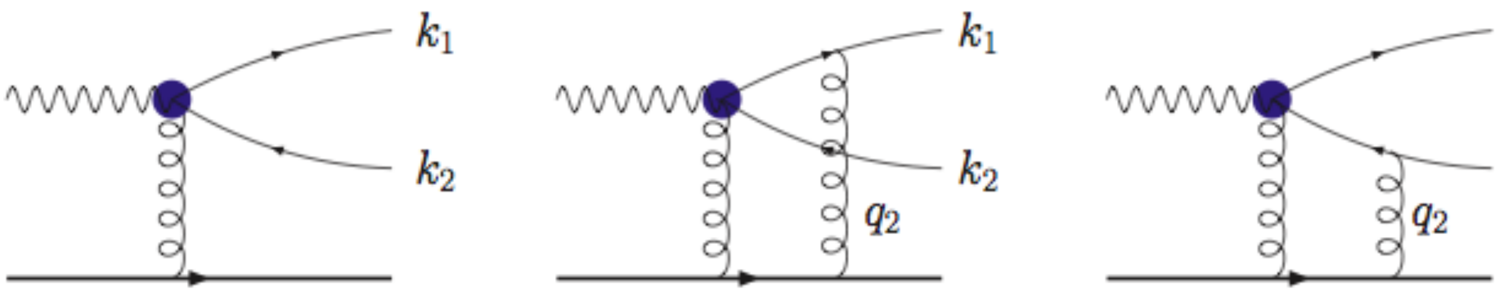
State-of-the art is now increasingly NLL
-significant theory advances

Balitsky,Chirilli,Kovchegov,Weigert,
Kovner,Lublinsky, Mulian,Caron-Huot,
Triantafyllopolous,Grabovsy,Stasto,Xiao,…

Semi-inclusive DIS: quadrupole evolution



Dominguez,Marquet,Xiao,Yuan (2011)

$$\frac{d\sigma^{\gamma^*_{\rm T,L} A\to q\bar{q}X}}{d^3k_1 d^3k_2} \propto \int_{x,y,\bar{x}\bar{y}} e^{ik_{1\perp}\cdot(x-\bar{x})} e^{ik_{2\perp}\cdot(y-\bar{y})} \left[1 + Q(x,y;\bar{y},\bar{x}) - D(x,y) - D(\bar{y},\bar{x})\right]$$

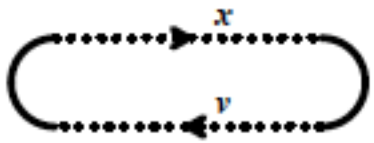
$$D(x,y) = \frac{1}{N_c}\langle \mathrm{Tr}(V_x V_y^\dagger)\rangle_Y$$

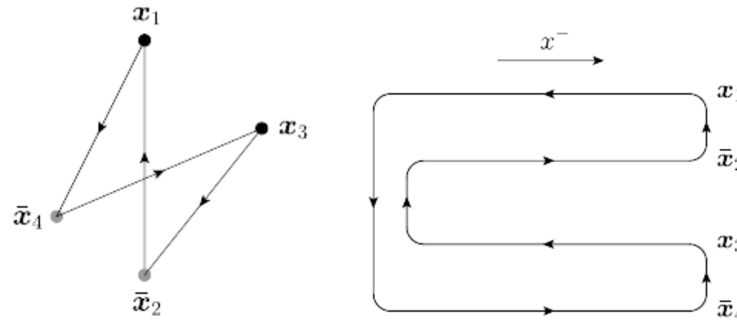
Dipoles: Fundamental in high energy QCD, ubiquitous in DIS and hadronic collisions

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

Quadrupoles: also fundamental, appear in less inclusive processes

Semi-inclusive DIS: quadrupole evolution



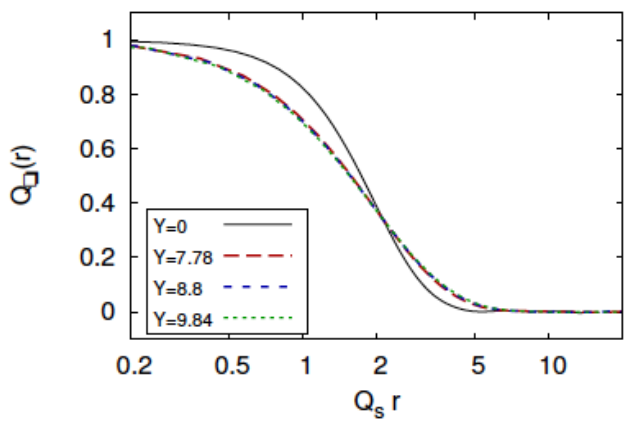


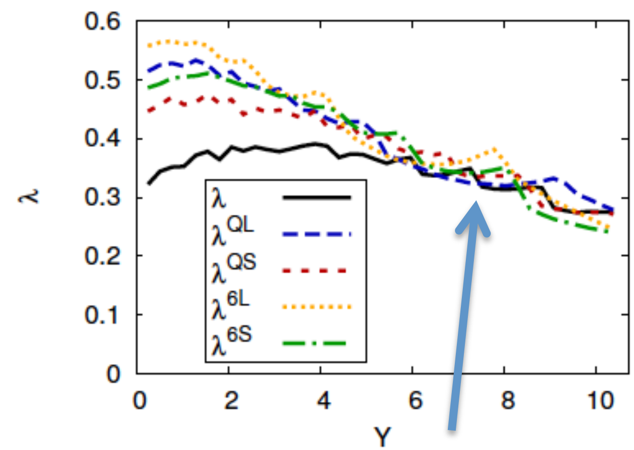
$$D(x,y) = \frac{1}{N_c}\langle \mathrm{Tr}(V_x V_y^\dagger)\rangle_Y \qquad Q(x,y;\bar{y},\bar{x}) = \frac{1}{N_c}\langle \mathrm{Tr}(V_x V_{\bar{x}}^\dagger V_{\bar{y}} V_y^\dagger)\rangle_Y$$

RG evolution provides fresh insight into multi-parton correlations

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

Quadrupoles, like Dipoles, exhibit Geometrical Scaling

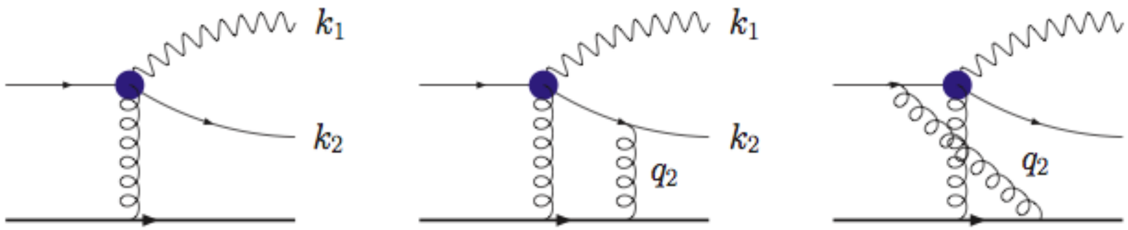




Rate of energy evolution of dipole and quadrupole saturation scales

Iancu,Triantafyllopolous,arXiv:1112.1104

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



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

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

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

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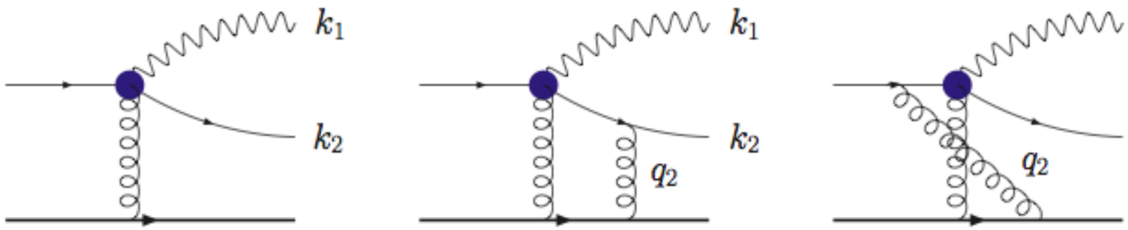

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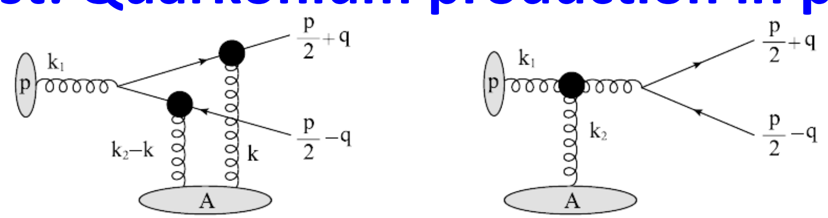
- **Another test: Quarkonium production in p+A**

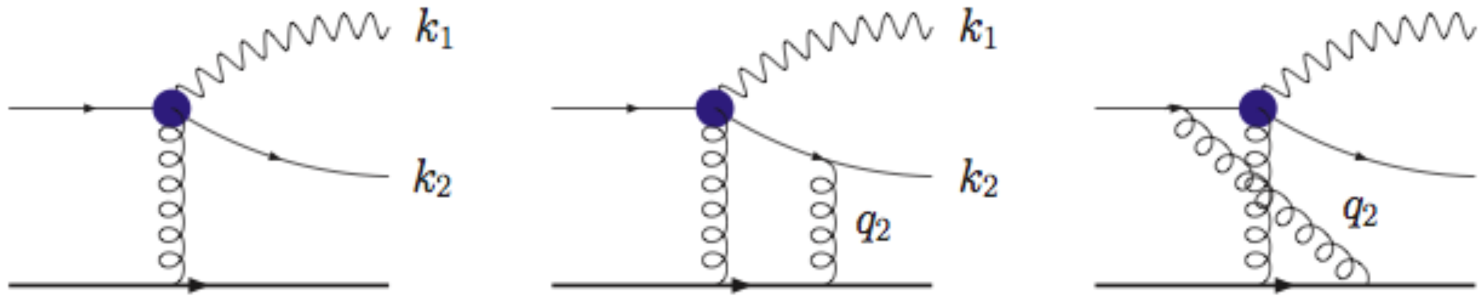


Color singlet channel is sensitive to dipoles & quadrupoles

Color octet to dipole correlators alone

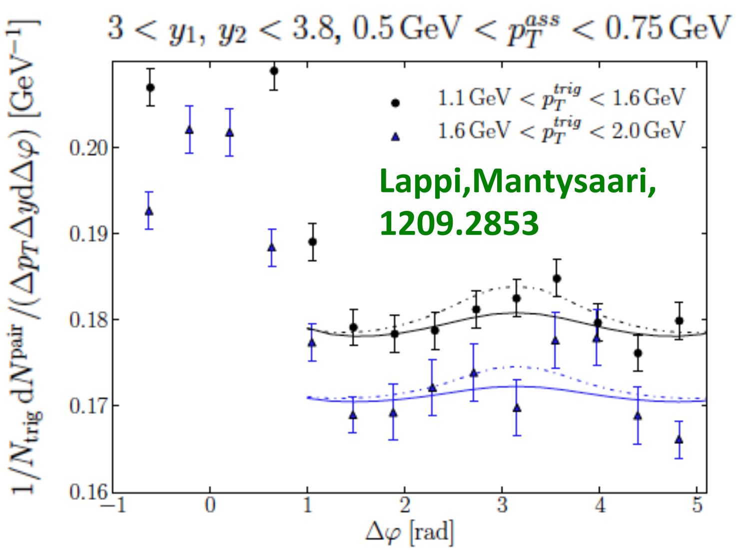
Kang,Ma,RV: 1309.7337
Ma, RV: in preparation
Qiu,Sun,Xiao,Yuan: 1310.2230

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

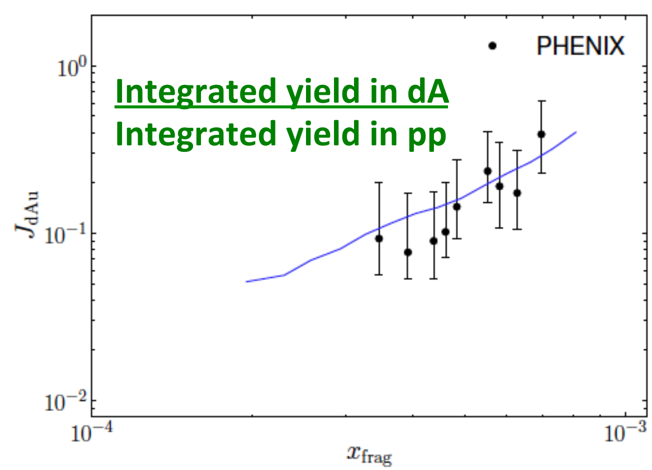


Away-side (ΔΦ ~ π) forward-forward di-hadron correlations: very sensitive to strong color fields

PHENIX, PRL107, 172301 (2011)



Lappi,Mantysaari, 1209.2853



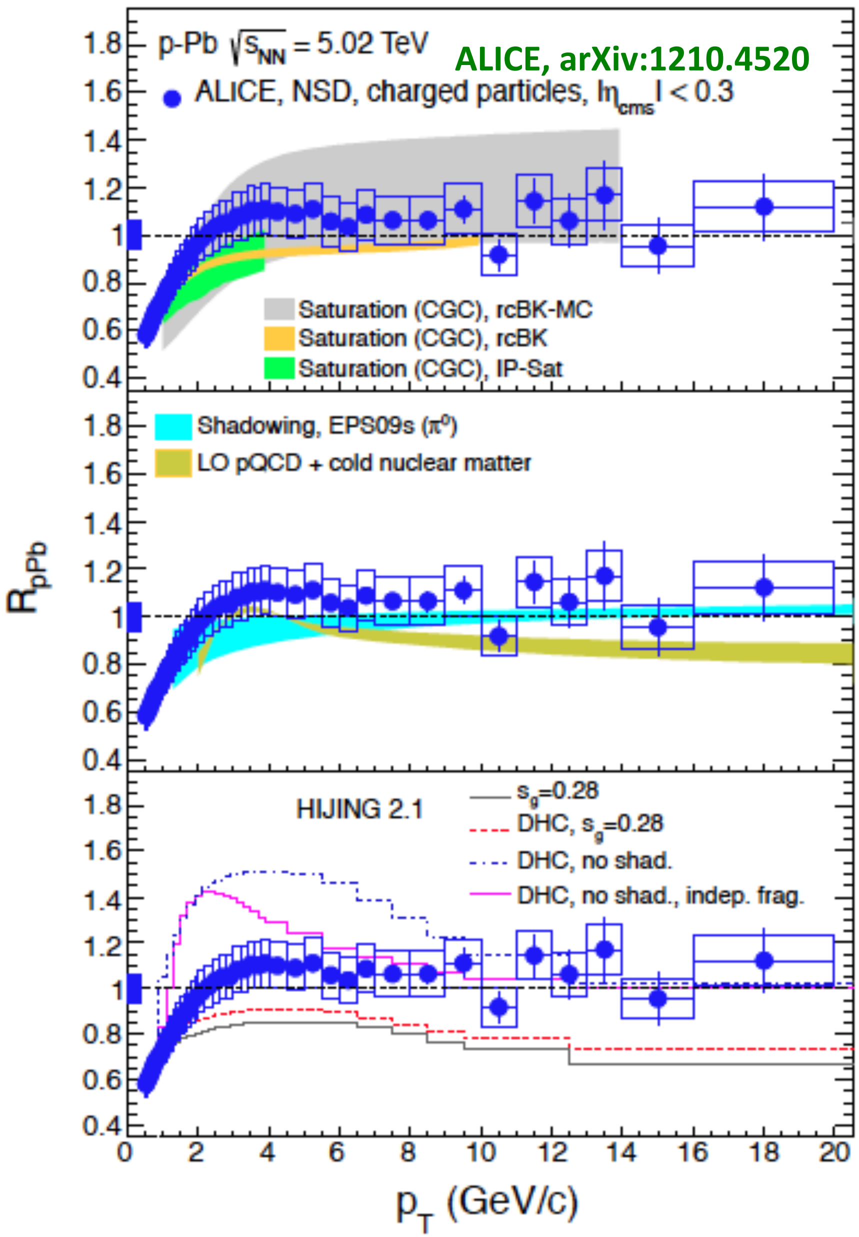
Integrated yield in dA / Integrated yield in pp

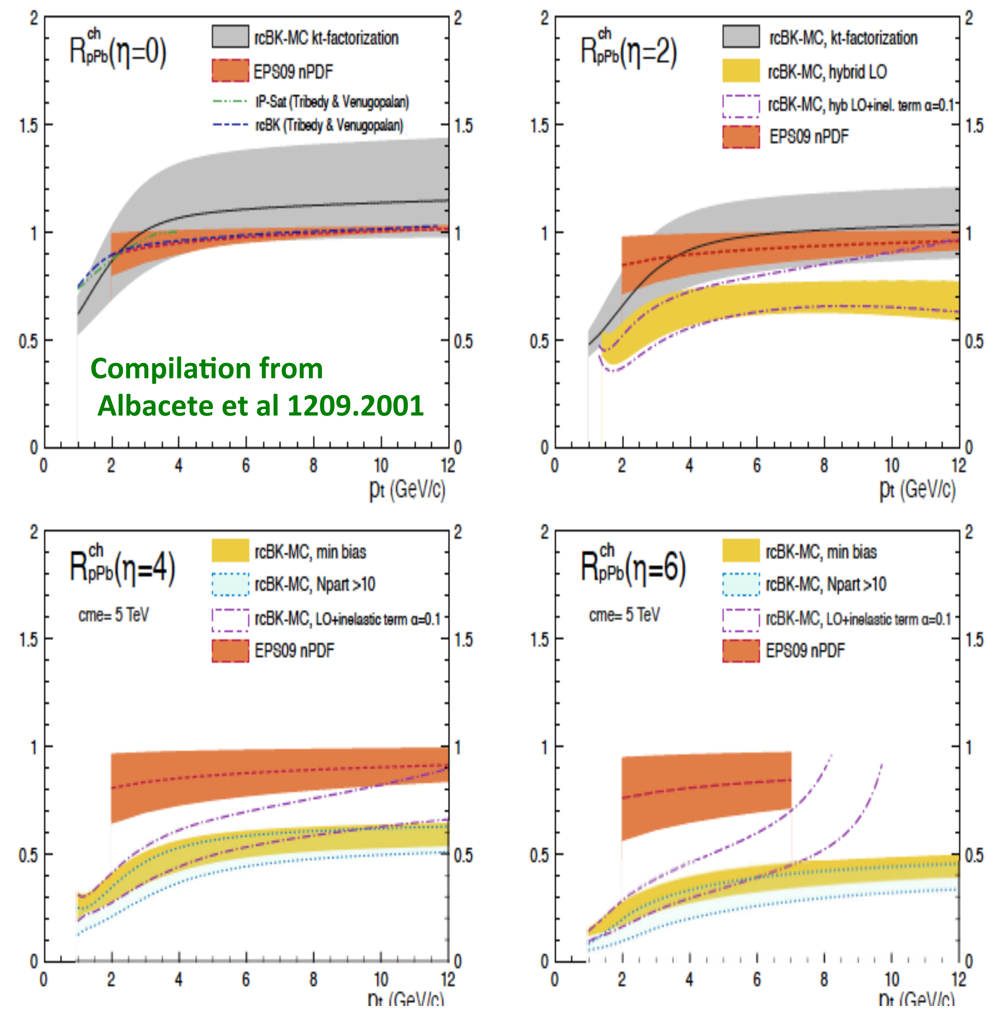
See also Stasto,Xiao,Yuan, 1109.1817

Related approach, Kang,Vitev,Xing, 1112.6021

Recent computations includes pedestal, shadowing (color screening) and broadening (multiple scattering) effects in CGC framework

Going forward with p+A at the LHC ?

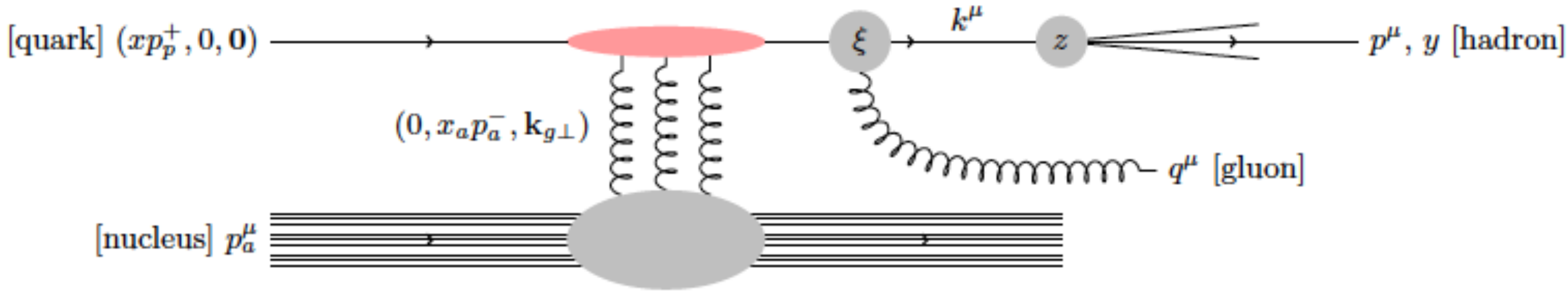


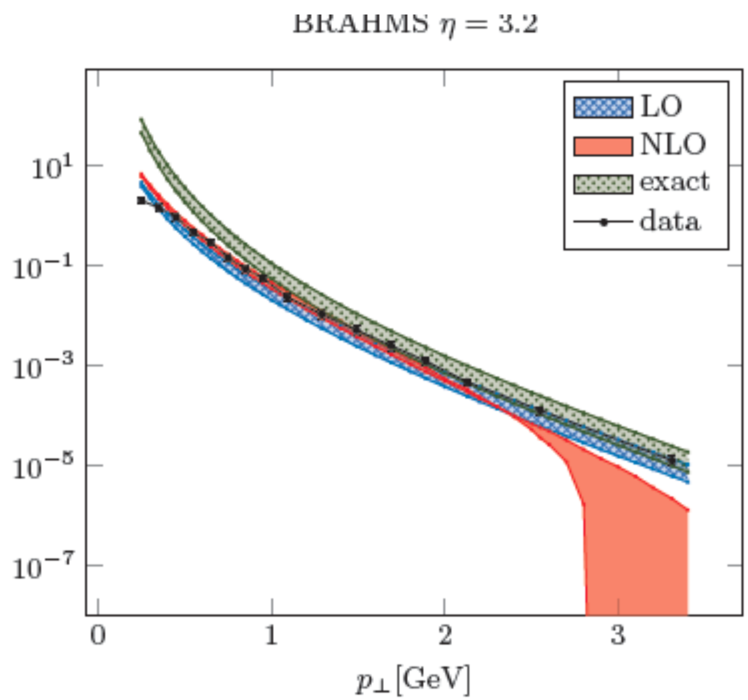


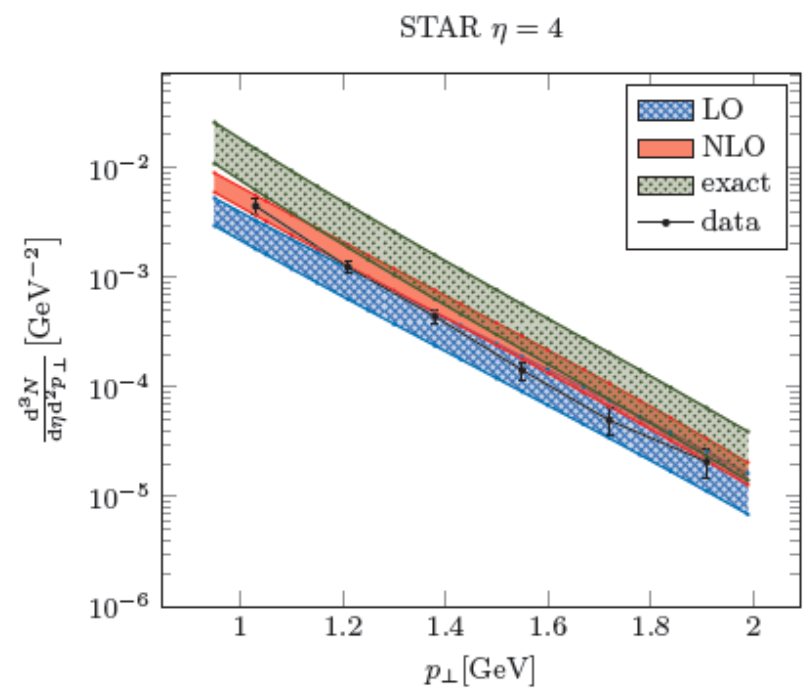
Hybrid formulation –matching collinear and small x factorization in forward physics

Matching collinear and small x formalisms

Stasto,Xiao,Yuan,Zaslavsky,1405.6311







CGC: the state of the art

- **Numerical solutions of Leading Log JIMWLK hierarchy – and good analytical approximations** Rummukainen, Weigert, Dumitru,Jalilian-Marian,Lappi,Schenke,RV, Mantysaari,Iancu,Triantafyllopolous

- **Influence of non-Gaussian initial conditions on evolution**

  Dumitru,Jalilian-Marian,Petreska,RV,Schenke,Jeon

- **Factorization of leading logs in A+A; first discussions of NLLx**

  Braun,Kovner,Lublinsky,Dusling,Gelis,Lappi,RV; Gelis,Jeon,RV

- **Increasing number of NLO+ computations: Structure functions, single inclusive hadron production in p+A**

  Balitsky,Chirilli,Kovchegov,Weigert, Gardi, Rummukainen,Kuokkonen,Albacete,Horowitz, Xiao, Yuan, Mueller, Munier, Stasto, Motyka, Triantafyllopolous, Tuchin; Gelis, Laudet

- **NLO corrections to the BK/JIMWLK kernel beyond running coupling corrections ?** Salam,Ciafaloni,Colferai,Stasto,Triantafyllopolous, Sabio-Vera, Kovner,Lublinsky,Mulian,Grabovsjy,Balitsky,Chirilli,Kovchegov, Caron-Huot

- **Beginnings of global analysis** AAMQS collaboration,Rezaiean,Levin,Tribedy,RV,Siddikov