Introduction to the Color Glass Condensate

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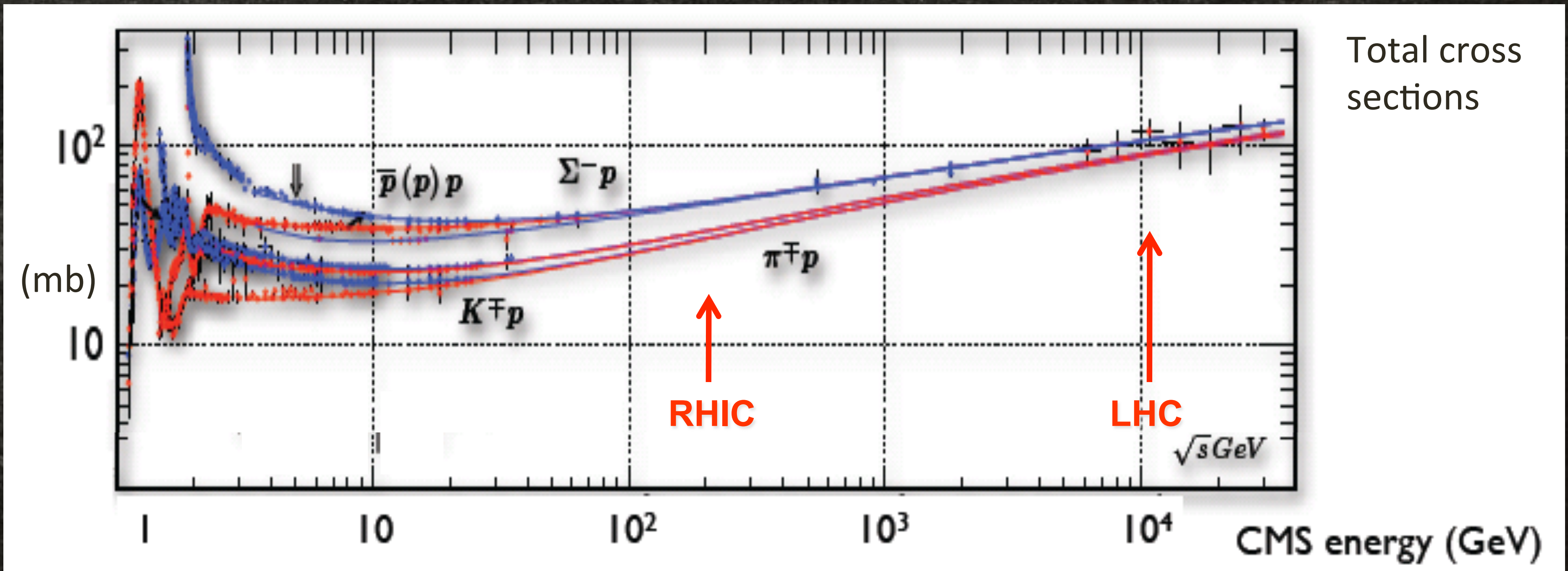
Aim

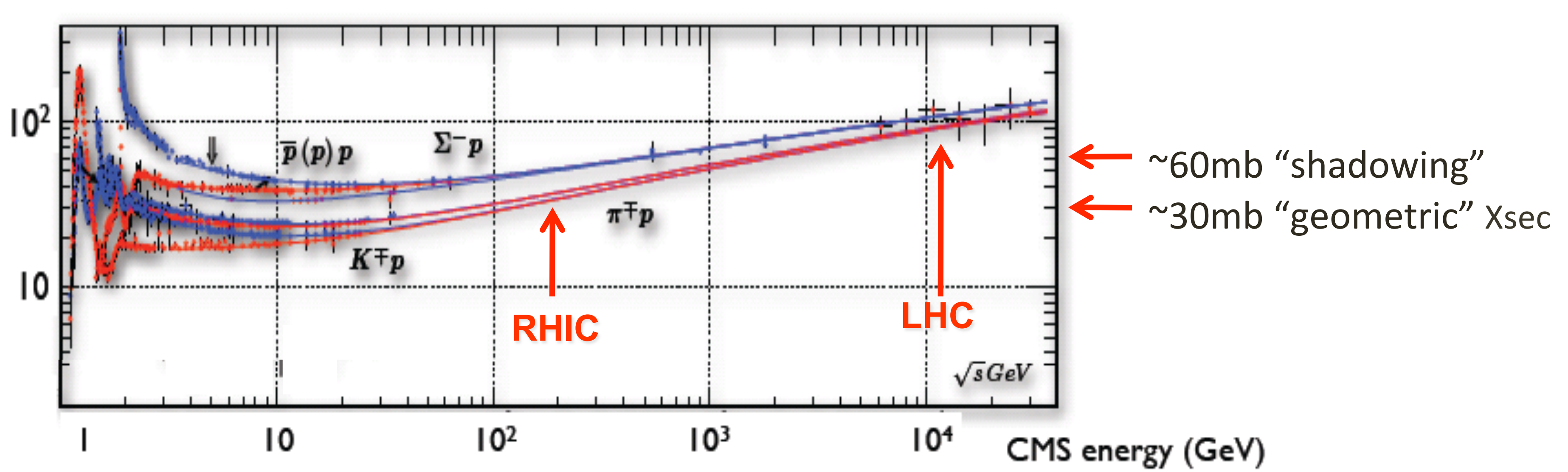
- Understand, at the conceptual level, the importance of Color Glass Condensate (CGC) in the high-energy hadron scattering
- Learn how to apply it to heavy-ion collisions: "Glasma"
- Know how it works in comparison with the most recent experimental data from RHIC and LHC

Hadron cross sections



Cross sections **GROW** with increasing energies and amount to **> 100 mb** at cosmic ray or LHC energies

How to “read” these data?



- Proton’s “geometric” cross section πr_c^2 ~ 30 mb (charge radius r_c~1 fm)
  maximum absorption “shadowing” ~ $2\pi r_c^2$ ~ 60 mb < 100 mb

  → Proton is “expanding” !?

- Particle Data Group (COMPETE Collab. Phys. Rev.D65 (2002))

$$\sigma_{total}^{ab}(s) = Z^{ab} + B \ln^2 s + \ldots$$

Z^{ab} : constant
B : independent of hadron species a, b
$\ln^2 s$: consistent with the Froissart bound (unitarity bound)

This example implies …

- **At high energies, *something "unusual and interesting"* must be happening in hadrons.**
  - "expansion" of a target
  - unitarity
  - universal picture!

→ consistent with the Color Glass Condensate.

(but only qualitatively at present for the total cross section)

We want to understand …

- universal picture of hadrons/nuclei in the high-energy limit (if any)
- if we can describe it in QCD, in particular, in weak-coupling technique
- at which energy scale it starts to appear
- to what extent we can understand the experimental results at current energies with this picture

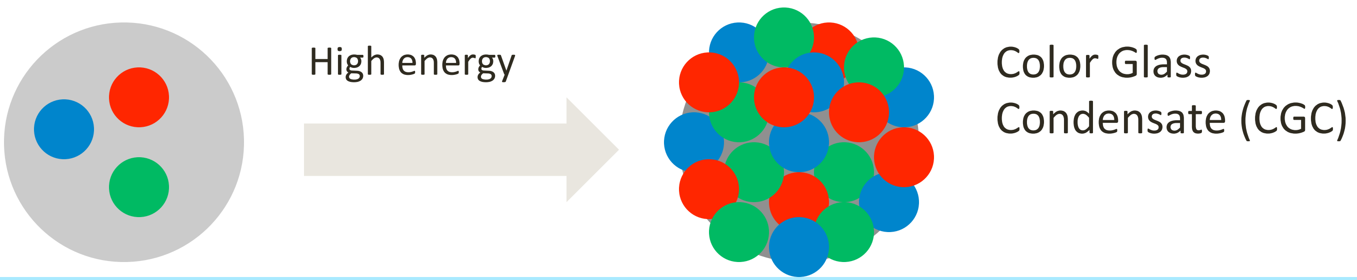
What is the CGC?

- ***Dense gluonic states* in hadrons which *universally* appear in the *high-energy limit* of scattering**

Color … gluons have "colors"

Glass … gluons with small longitudinal mom. fractions (x <<1) are created by long-lived partons that are distributed randomly on the transverse disk

Condensate … gluon density is very high, and saturated



- **Most advanced (and still developing) theoretical picture of high energy scattering in QCD**

Based on QCD (weak coupling due to Qs >> Λ_{QCD} , but non-perturbative)

Unitarity effects (multiple scattering, nonlinear effects)

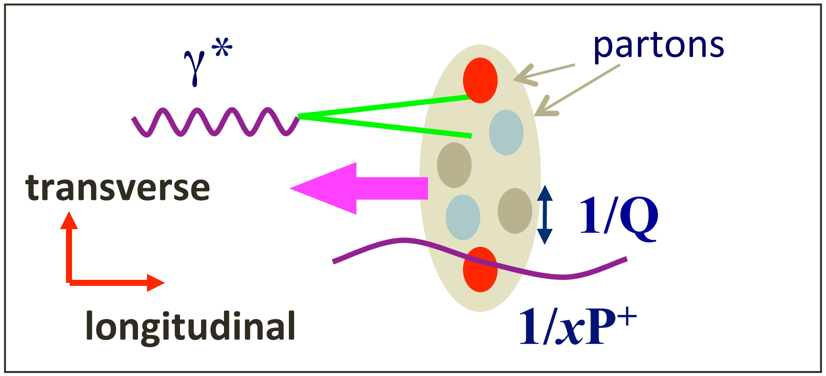
LO description completed around 2000

Proton composition changes with energy

Deep inelastic scattering (DIS: ep → eX)

can probe quarks and gluons in a proton

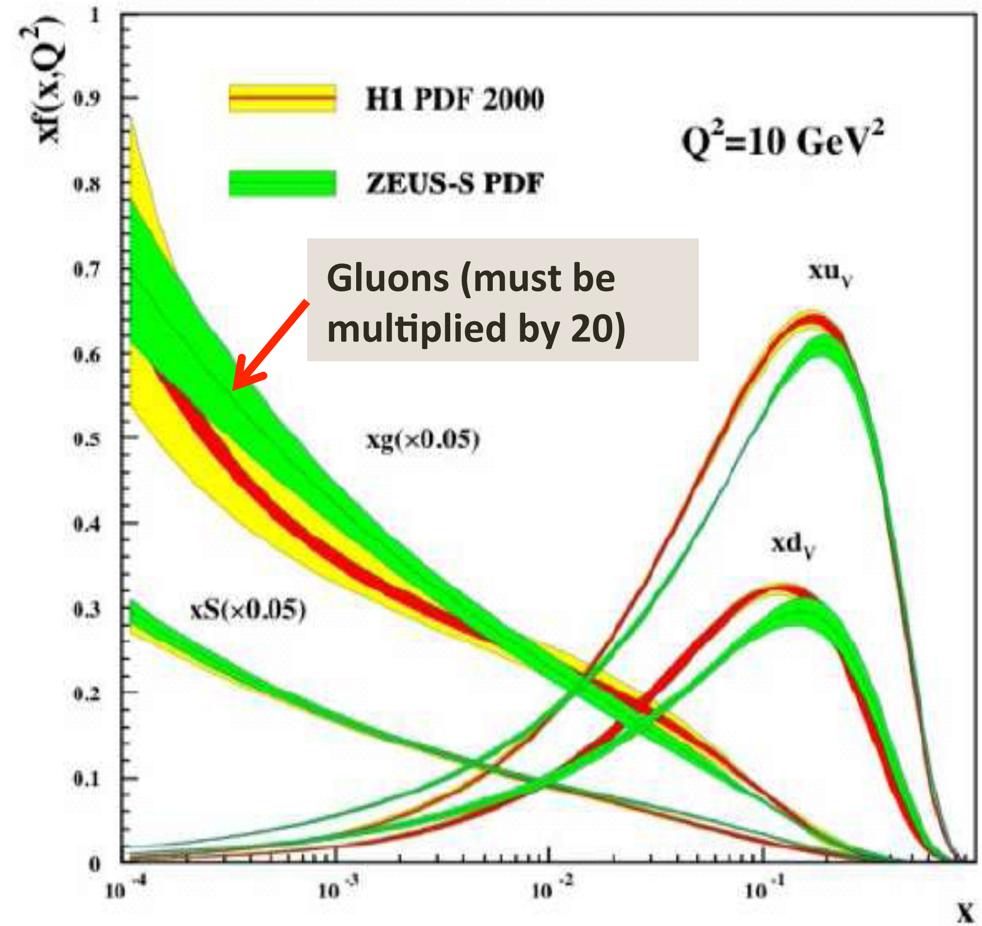
HERA @ DESY



Two kinematical variables

- Q^2 : transverse resolution
- x : longitudinal mom. fraction of partons

Gluons are the dominant component at high energy (small x)

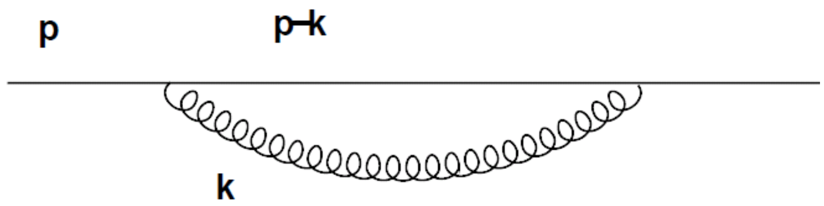


longitudinal fraction x

← higher energies

Life and death of fluctuation

fluctuation of a fast moving parton



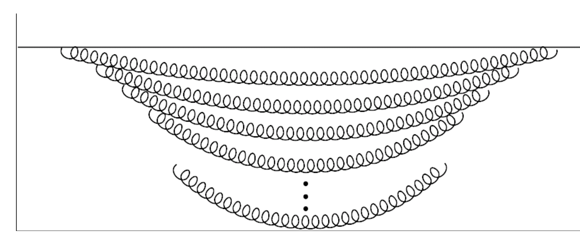
$$p^\mu = (p,\ 0_\perp, p)$$

$$k^\mu = (E_k, k_\perp^i, k^z = xp)$$

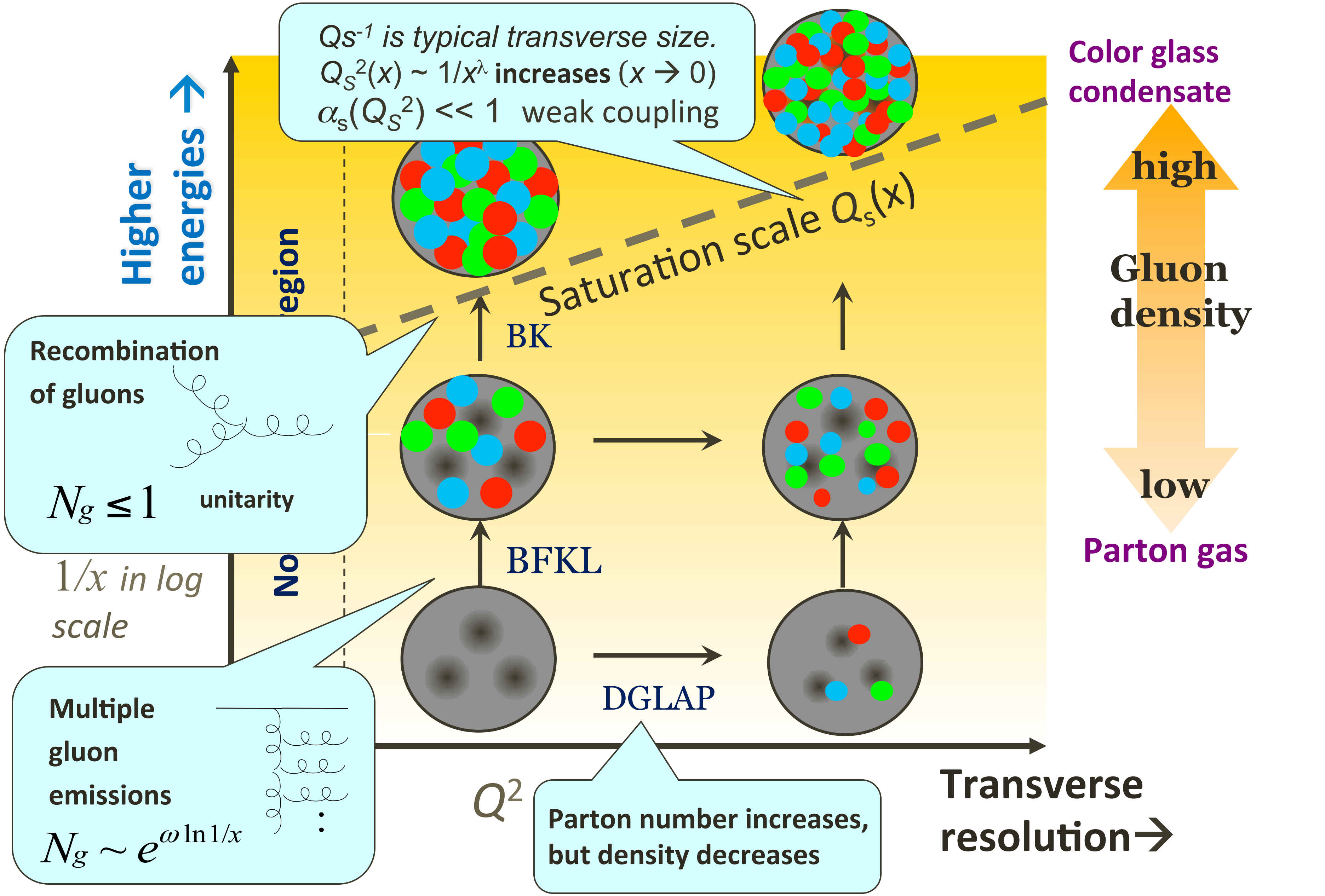
Lifetime of fluctuation
($xp >> k_t$)

$$\Delta t \sim \frac{1}{\Delta E} = \frac{1}{E_k + E_{p-k} - p} \sim \frac{2x(1-x)p}{k_\perp^2}$$

- If parent parton has large energy $xp >> k_t$,
  → fluctuation becomes **long lived**
- With increasing *p*, long-lived fluct. w/ smaller *x* becomes possible
- If daughter parton is long-lived, it can further fluctuate:
  → multiple parton (gluon) production
- One gluon emission is enhanced: **$\alpha_s \ln 1/x >> 1$ at small $x <<1$**
  Need to sum up many-gluon emissions $(\alpha_s \ln 1/x)^n$
- When the density of gluons becomes high, they start to interact with each other **→ CGC**
- Fluctuations become real particles in reactions



Phase diagram of a proton as seen in DIS



Saturation scale : $Q_s(x)$

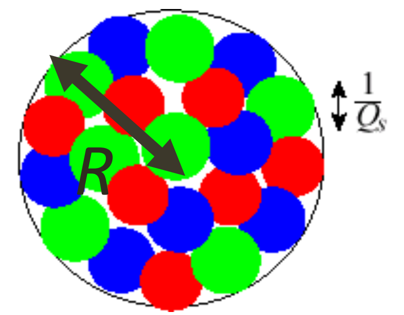
- Gluon distribution function: $xG(x, Q^2)$

  number of gluons having longitudinal fraction in the interval "$x - x+dx$" looked at transverse resolution scale $1/Q$.

- Typical pQCD cross section : $\sigma \sim \alpha_s / Q^2$

Gluons fill the transverse area of hadron (πR^2) when

$$\frac{\alpha_s}{Q^2} \cdot xG(x, Q^2) = \pi R^2$$



Q satisfying this is called "saturation momentum" Q_s

Intuitive picture :

$1/Q_s$ is the "**transverse size**" of gluons when they fill the transverse area of a hadron.

Typical transverse momentum carried by gluons in a hadron

Saturation scale : $Q_s(x)$

$$\frac{\alpha_s}{Q_s^2} \cdot xG(x, Q_s^2) = \pi R^2$$

- **Small-x limit of DGLAP equation** (Double Log App.)

$$xG(x, Q^2) \sim e^{\sqrt{4\bar{\alpha}_s y \rho}} \qquad y = \ln\frac{1}{x}, \ \rho = \ln\frac{Q^2}{Q_0^2}, \ \bar{\alpha}_s = \frac{N_c \alpha_s}{\pi}$$

$$Q_s^2 \propto e^{4\bar{\alpha}_s y} = (1/x)^{4\bar{\alpha}_s}$$

- **BFKL equation** (resummation : LO $(\alpha_s \ln 1/x)^n$, NLO: $\alpha_s (\alpha_s \ln 1/x)^n$)

gluon number (LO) ~ $e^{\omega y}$ $\qquad \omega = \bar{\alpha}_s 4 \ln 2 = 2.77\bar{\alpha}_s$

$$Q_s^2 \propto (1/x)^\lambda$$

LO $\lambda = 4.88\,\bar{\alpha}_s$ [Iancu,Itakura,McLerran'02]

NLO $\lambda \sim 0.3 \quad x = 10^{-2} - 10^{-4}$

[Triantafyllopoulos, '03]

Q_s grows with increasing energy (decreasing x)

→ weak-coupling at high energies

Going up higher energies: evolution eqs.

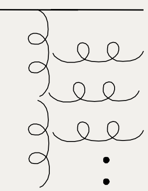
Evolution wrt x (or rapidity $y = \ln 1/x$)

- **BFKL** (LO : $(\alpha_s \ln 1/x)^n$, NLO: $\alpha_s (\alpha_s \ln 1/x)^n$)

$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t})$$

Multiple gluon emissions

$N_g \sim e^{\omega \ln 1/x}$



K : gluon splitting g→ gg

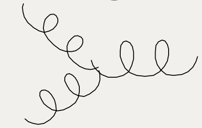
ϕ : unintegrated gluon distr.

- **BK** (includes the nonlinear effects)

Recombination of gluons

$N_g \leq 1$

Unitarity



$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t}) - \phi(\mathbf{x}, \mathbf{k_t})^2$$

Known up to full NLO accuracy. [Balitsky, Chirilli 2008]

But for practical purposes, we use **BK with running coupling** → "rcBK" [Balitsky, Gardi et al. , Kovchegov-Weigert]

$$K^{\mathrm{run}}(\mathbf{r}, \mathbf{r_1}, \mathbf{r_2}) = \underbrace{\frac{N_c\, \alpha_s(r^2)}{2\pi^2} \left[\frac{r^2}{r_1^2\, r_2^2}\right.}_{\mathrm{LO}} \left. + \frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1\right) + \frac{1}{r_2^2}\left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1\right)\right]$$

Evidence : Geometric Scaling

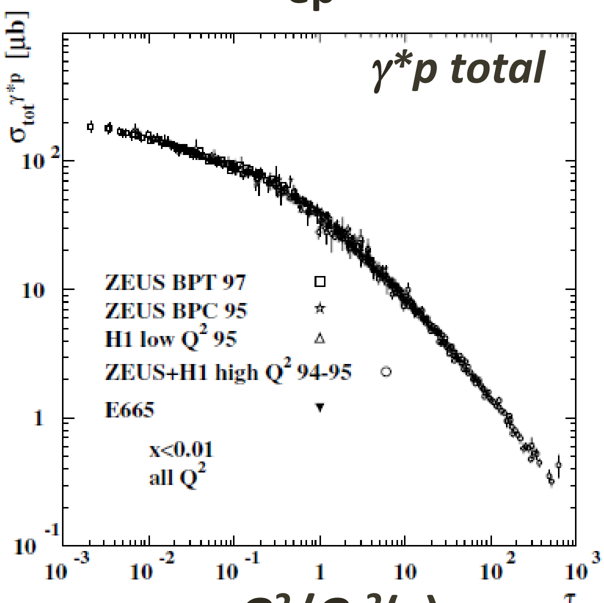
DIS (ep, eA) cross sections scale with Q^2/Qs^2

Stasto, Golec-Biernat, Kwiecinski PRL 86 (2001) 596

Freund, Rummukainen, Weigert, Schafer PRL 90 (2003) 222002

Marquet, Schoeffel Phys. Lett. B639 (2006) 471

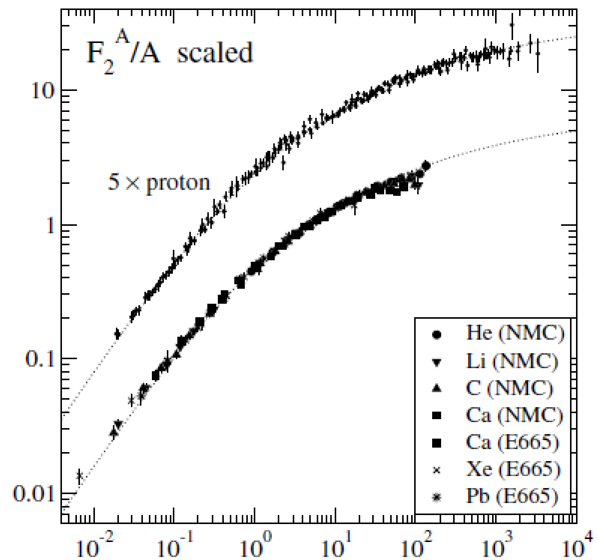
ep



$Q^2/Q_s^2(x)$

FIG. 1. Experimental data on $\sigma_{\gamma^* p}$ from the region $x < 0.01$ plotted versus the scaling variable $\tau = Q^2 R_0^2(x)$.

eA



$Q^2/Q_s^2(x,A)$

FIG. 3. Scaling behavior of NMC and E665 F_2^A data vs $\tau = (\frac{x_N}{x_0})^{2\lambda} \frac{Q^2}{A^{1/3}}$. The vertical axis corresponds to the left-hand side of Eq. (5). The dashed line corresponds to the geometric scaling curve obtained from HERA data. These are shown offset by a factor of 5.

Diffractive ep

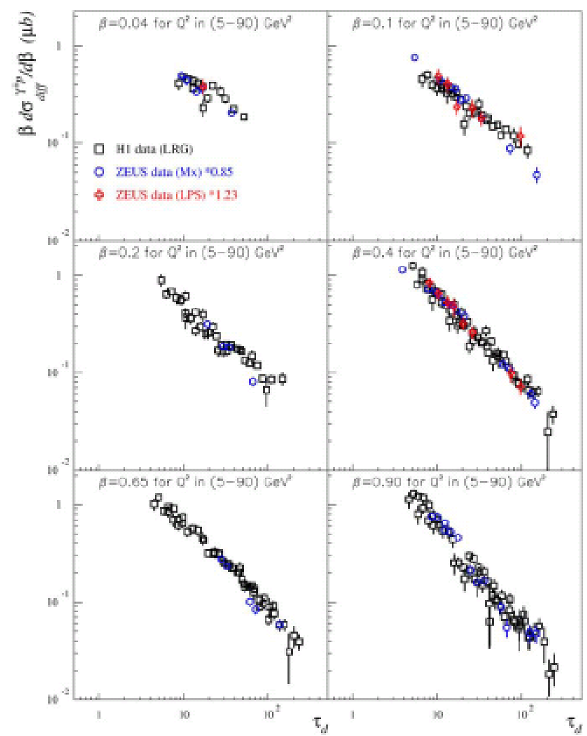


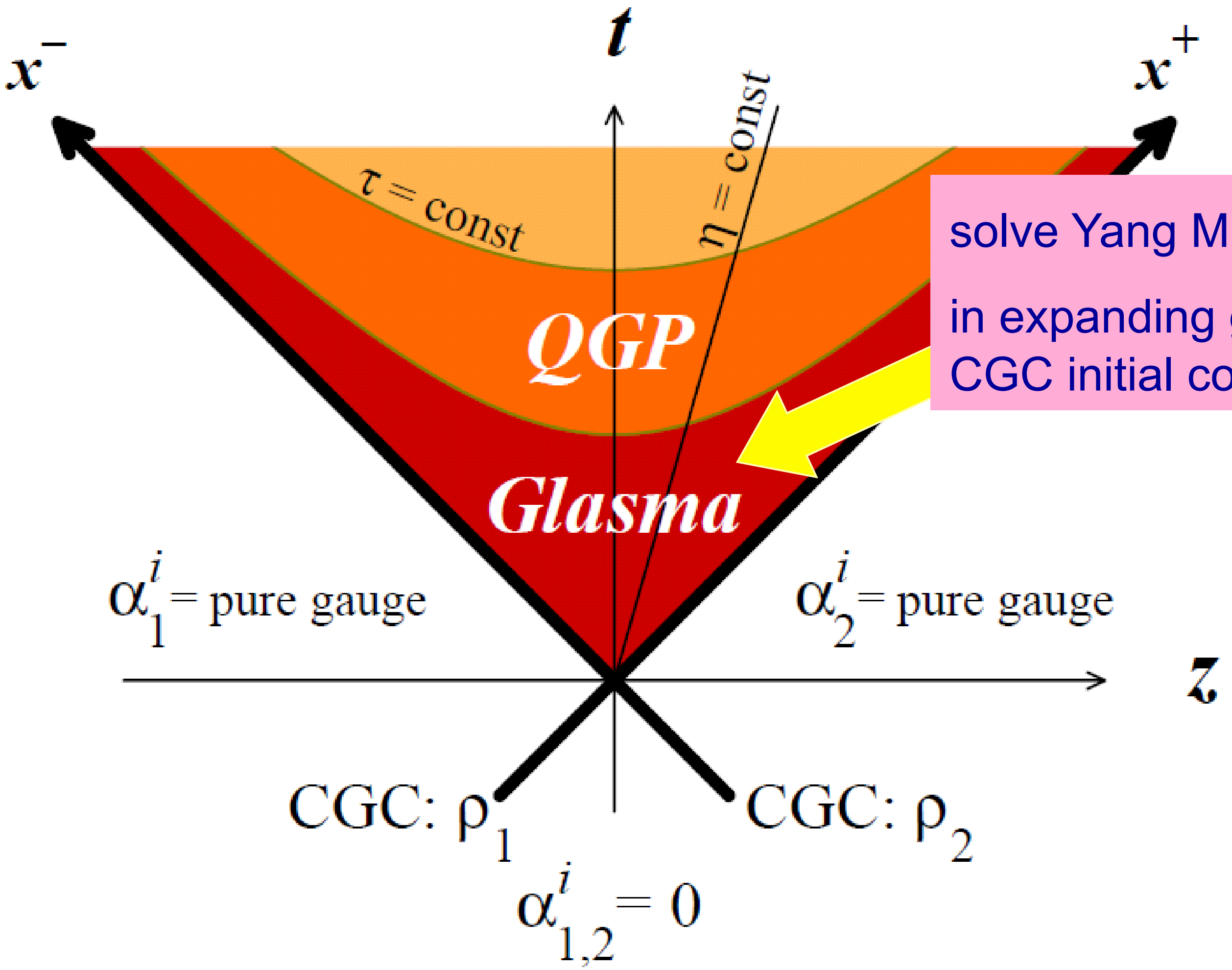
Fig. 2. The diffractive cross-section $\beta d\sigma_{diff}^{\gamma^* p \to X p}/d\beta$ from H1 and ZEUS measurements, as a function of τ_d in bins of β for Q^2 values in the range [5; 90] GeV^2 and for $x_{\mathbb{P}} < 0.01$. Only statistical uncertainties are shown.

$Q^2/Q_s^2(x_P)$

- Existence of saturation scale Qs
- Can determine x and A dependences of Qs
- Extends outside of the saturation regime $k_t < Q_s^2/\Lambda_{QCD}$ (Iancu,Itakura,McLerran)

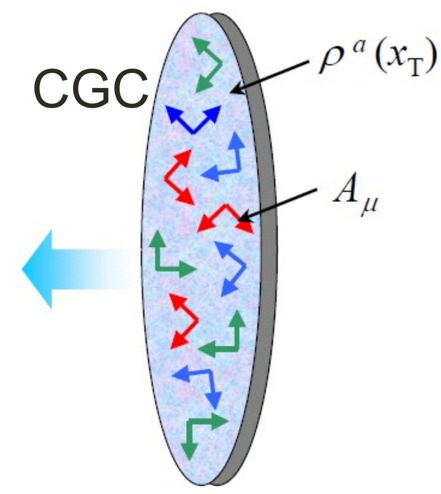
CGC turns into Glasma after heavy-ion collision

Glasma : non-equilibrium matter between Color Glass Condensate (CGC) and Quark Gluon Plasma (QGP). Created in heavy-ion collisions.



solve Yang Mills eq. $[D_\mu , F^{\mu\nu}]=0$

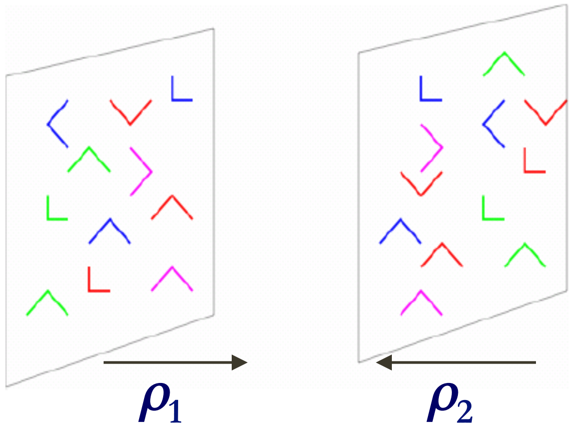
in expanding geometry with the CGC initial condition



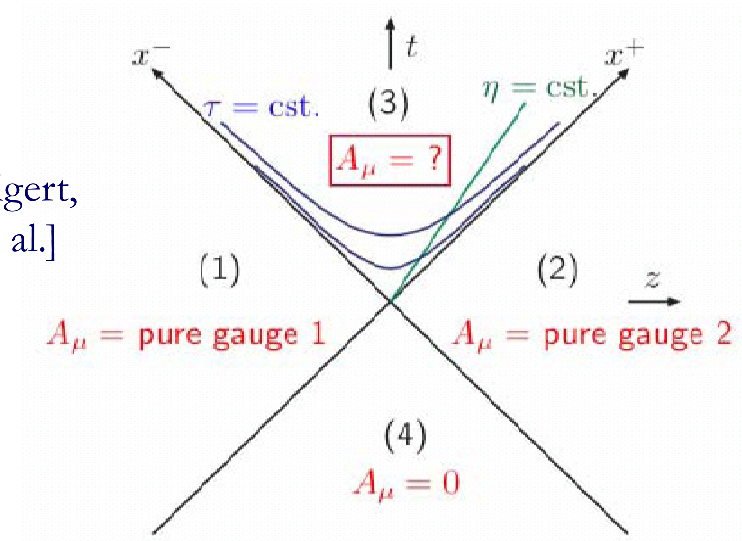
Randomly distributed

CGC as the initial condition for H.I.C.

HIC = Collision of two sheets of CGCs



[Kovner, Weigert, McLerran, et al.]



Each source creates the gluon field for each nucleus.← Initial condition

$$J^\mu = \delta^{\mu+}\delta(x^-)\rho_1(\mathbf{x}_T) + \delta^{\mu-}\delta(x^+)\rho_2(\mathbf{x}_T)$$

$$-D_i\alpha^i_{(m)} = \rho_{(m)}(\mathbf{x}_\perp).$$

α_1 , α_2 : gluon fields of nuclei

In Region (3), and at $\tau = 0+$, the gauge field is determined by α_1 and α_2

$$A^\pm = \pm x^\pm \alpha(\tau, x_T)$$

$$A^i = \alpha_3^i(\tau, x_T).$$

$$\alpha_3^i \,|_{\tau=0} = \alpha_1^i + \alpha_2^i$$

$$\alpha \,|_{\tau=0} = \frac{ig}{2}\left[\alpha_1^i, \alpha_2^i\right]$$

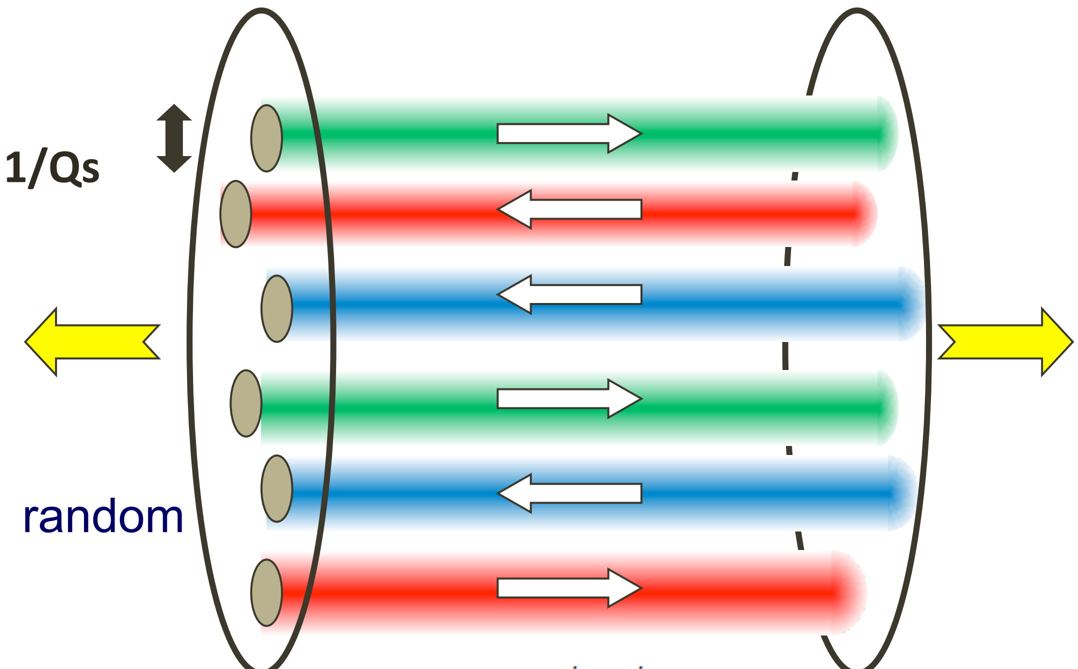
$$\partial_\tau \alpha \,|_{\tau=0} = \partial_\tau \alpha_3^i \,|_{\tau=0} = 0.$$

Glasma flux tube structure

Just after the collision: only E^z and B^z are nonzero

(Initial CGC is transversely random)

→ Glasma = **electric and magnetic flux tubes** extending in the longitudinal direction



$$E^z = ig[\alpha_1^i, \alpha_2^i]$$

$$B^z = ig\epsilon^{ij}[\alpha_1^i, \alpha_2^j].$$

Typical configuration of a single event just after the collision

Unstable dynamics

Color-electric flux tube

→gluon pair, qqbar pair production via **Schwinger mechanism**

Color-magnetic flux tube

→Unstable against rapidity dependent fluctuation via **Nielsen-Olesen instability**

[Fujii,Itakura 2008]

When both are present

→ **Schwinger production of gluons enhanced by the N-O instability** [Tanji,Itakura 2012]

Unsolved issues on glasma

- How does the glasma thermalize into QGP?

  unstable dynamics? → turbulent distribution leading to isotropization
  Bose-Einstein Condensation? → see talks by J.P.Blaizot and F.Gelis
  Other mechanisms, such as induced cascade by high pt partons?

- What is the observable consequence?

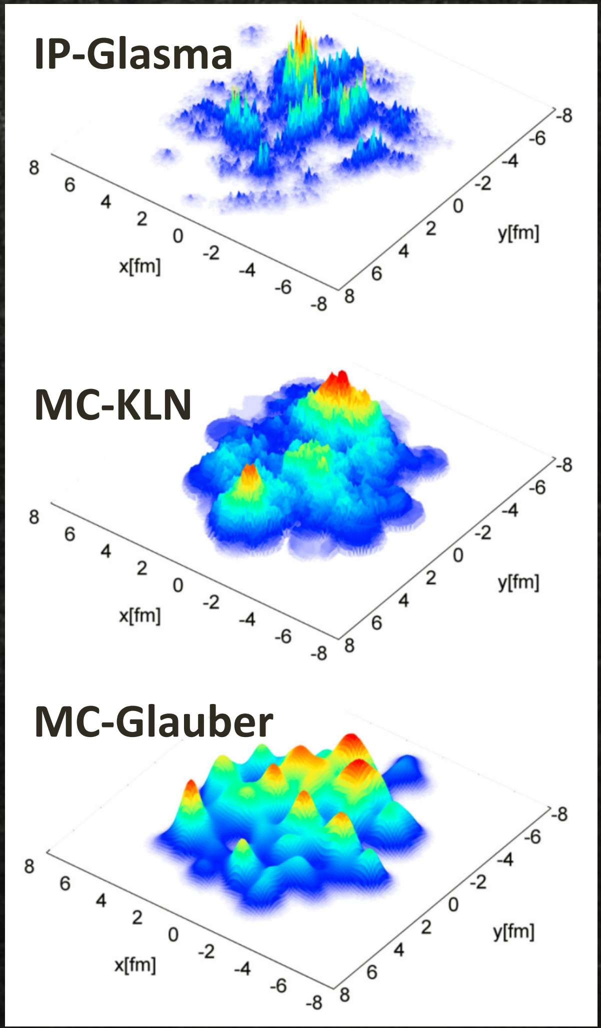
  Ridge as remnants of longitudinal flux tube structure?

- What kind of fluctuations are there?

  Color fluctuation inherent to CGC generates higher harmonics of flow?

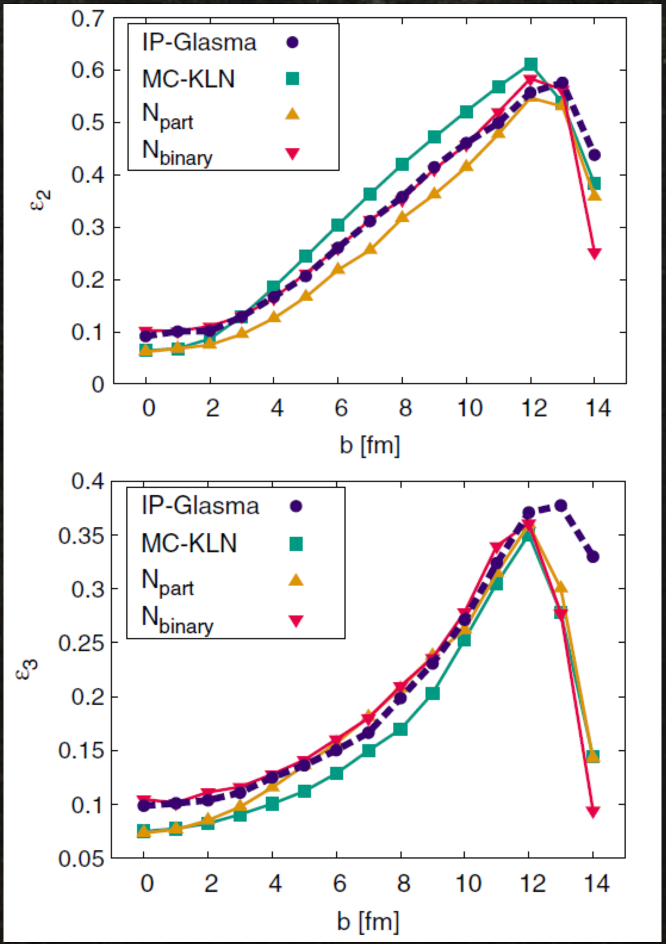
Examples of new progress (1)

- Schenke, Tribedy and Venugopalan, 2012 computed eccentricity and triangularity with IP-Glasma model



Fluctuations from nucleon position and color dynamics

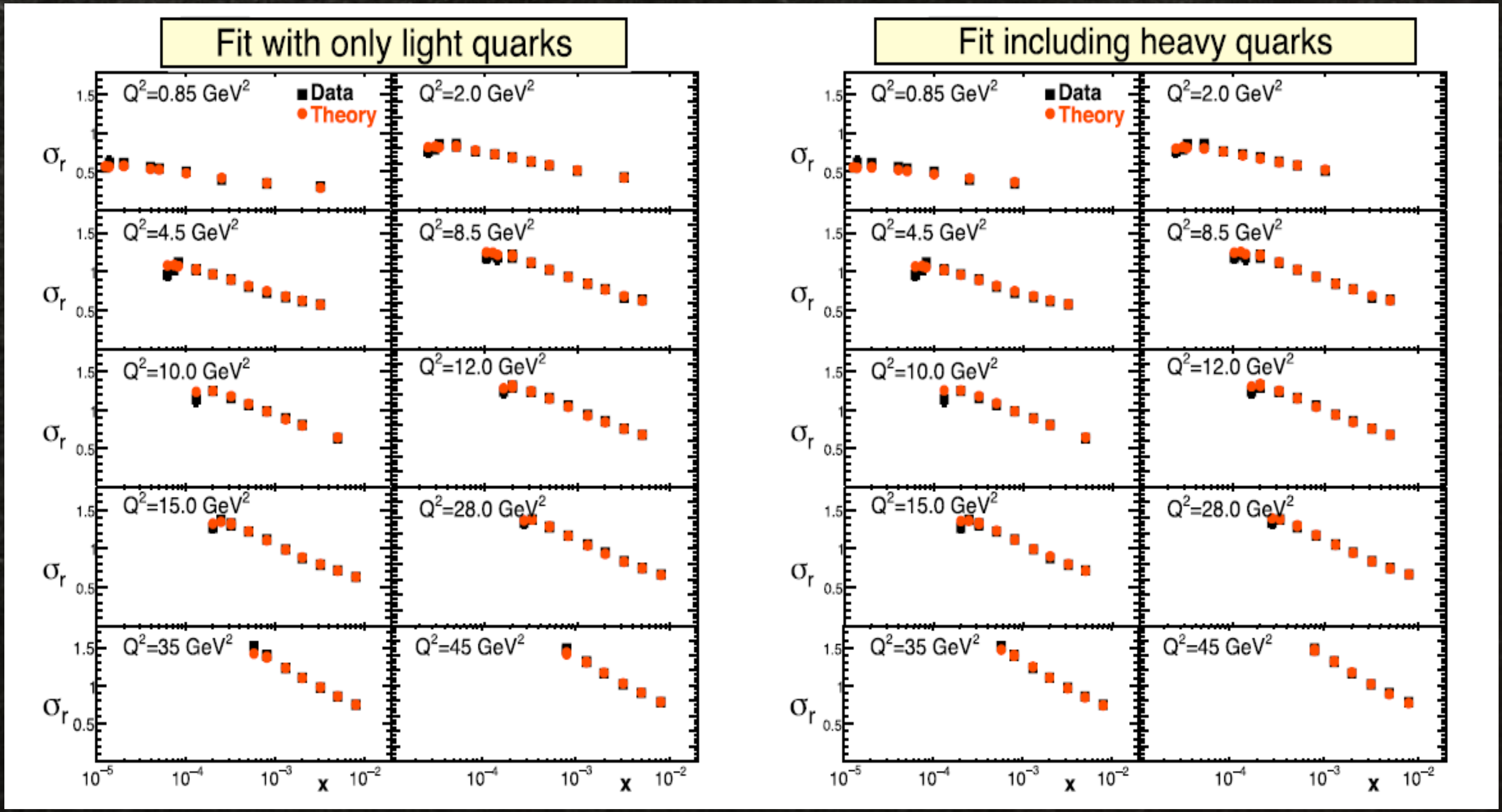
Only fluctuations from nucleon positions included



Also computed many other observables

Examples of new progress (2)

- Global analysis of DIS data with rcBK solution (AAMQS) and its application to forward particle production in dAu at RHIC



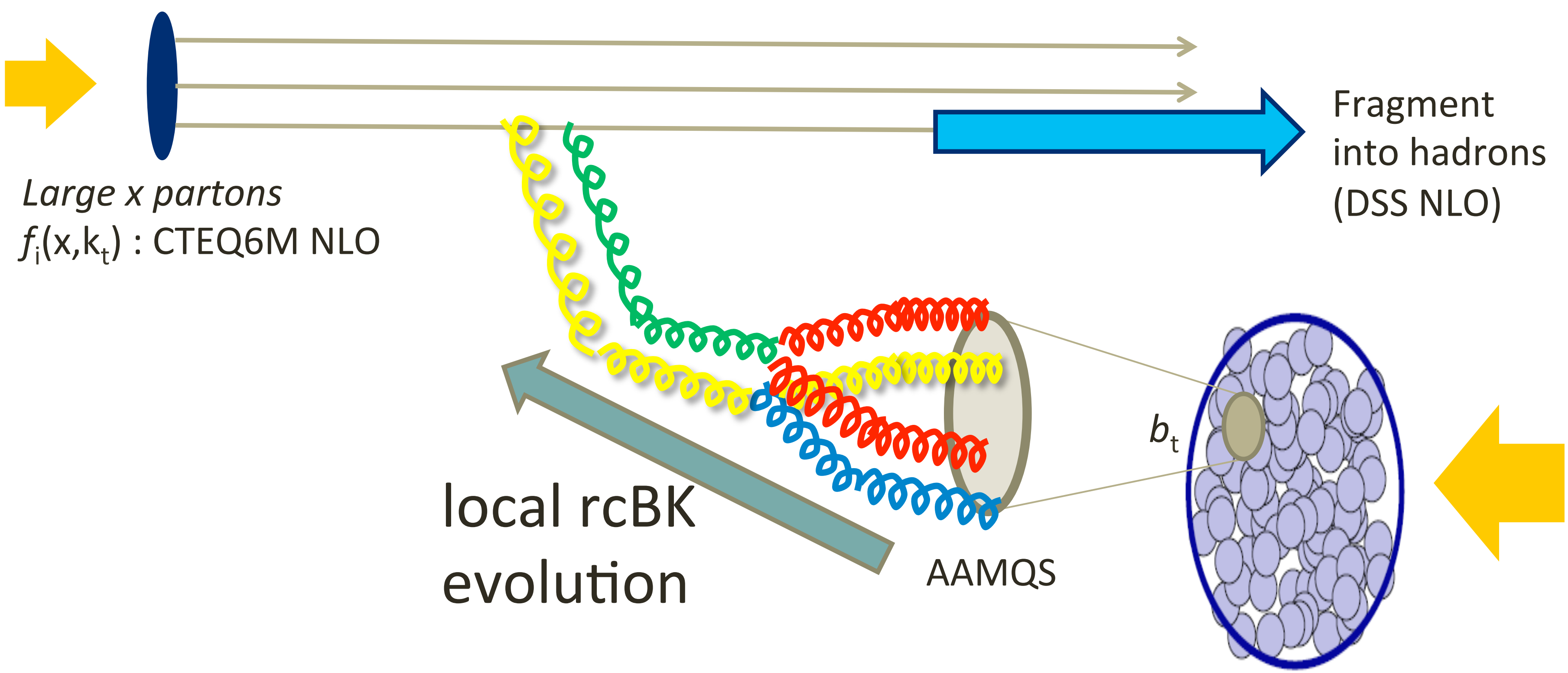
MC-DHJ/rcBK

[Fujii,Itakura,Nara, 2011,2012]

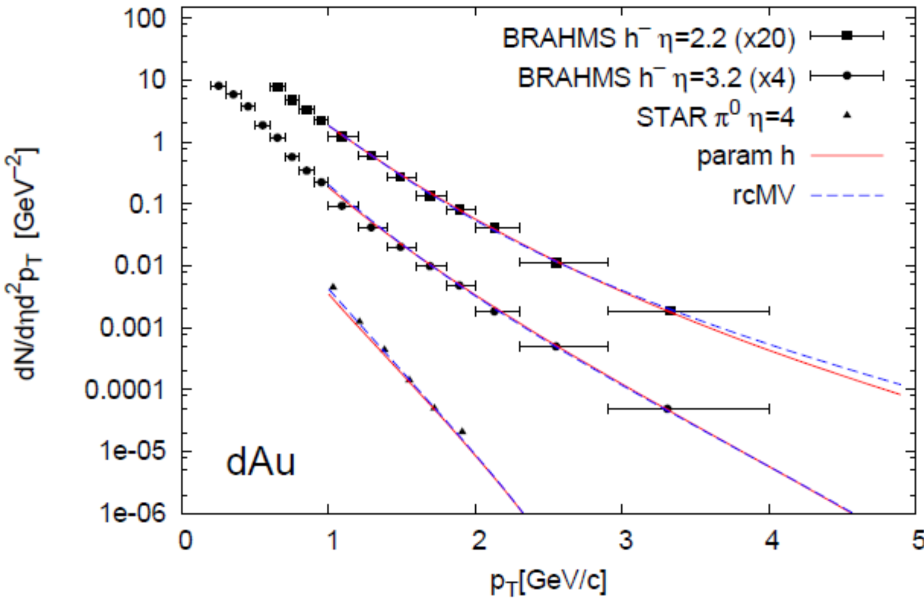
To reduce ambiguity

- construct a nucleus by randomly placing nucleons
- use AAMQS parameters for proton IC optimized for DIS at small-x
- quantum evolution is performed "locally" in b space

(to avoid IR div. in b-dep BK)



MC-DHJ/rcBK : results



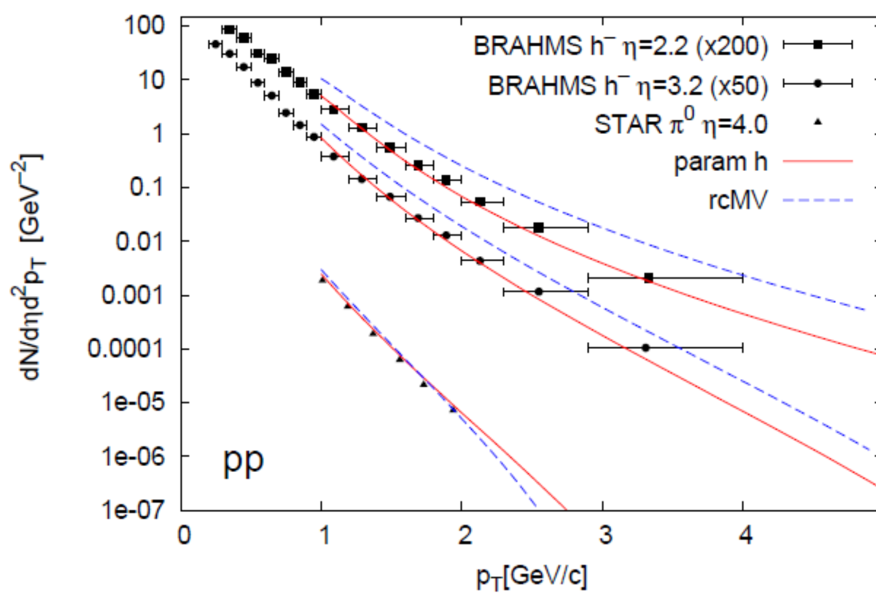
modified MV model ($\gamma = 1.118$)

"running coupling" version of MV model [Iancu-Itakura-Triantafylopoulos] : to be consistent with rcBK evolution

- reproduce the data nicely
- AAMQS set h and rcMV for $\mathcal{N}(r,y)$
- Q^2_{s0A} fixed by MC; no additional parameter

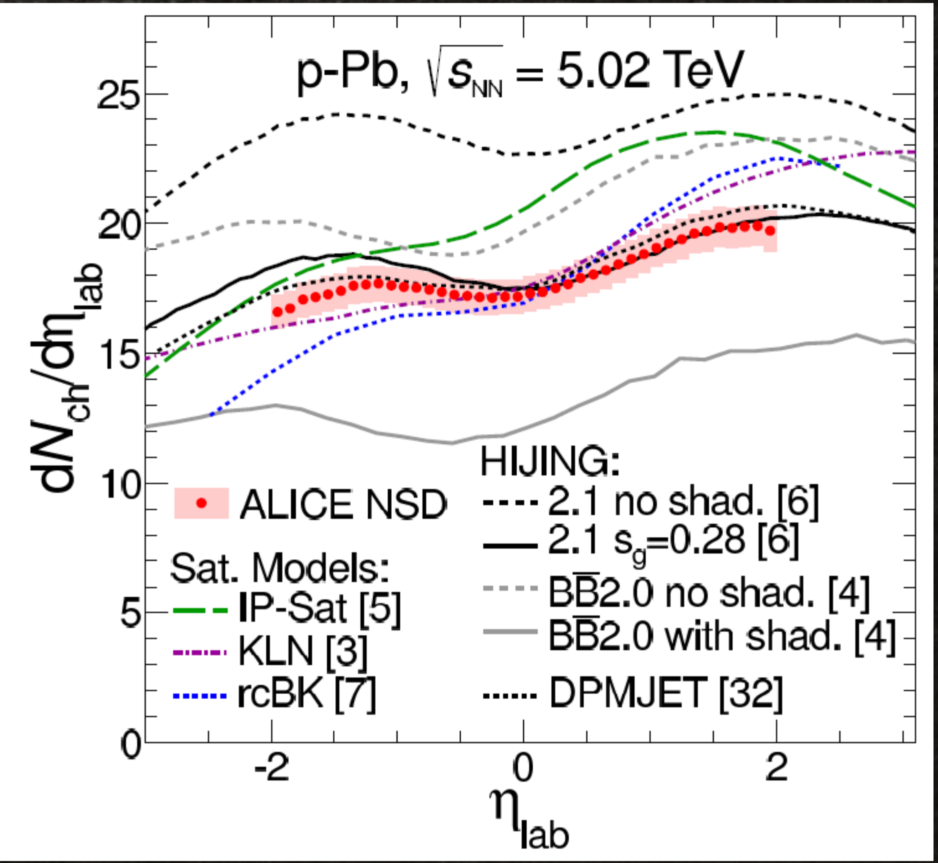
Best results from theoretical point of view, but still needs better (global) description including pp data (tuning of rcMV is necessary)

- Set *h* works well even in *pp*, but not as good as Albacete-Marquet
- rcMV is not "tuned" (similar param as MV)
- However, both work quite well in dAu (IC dependence reduces at high rapidity)

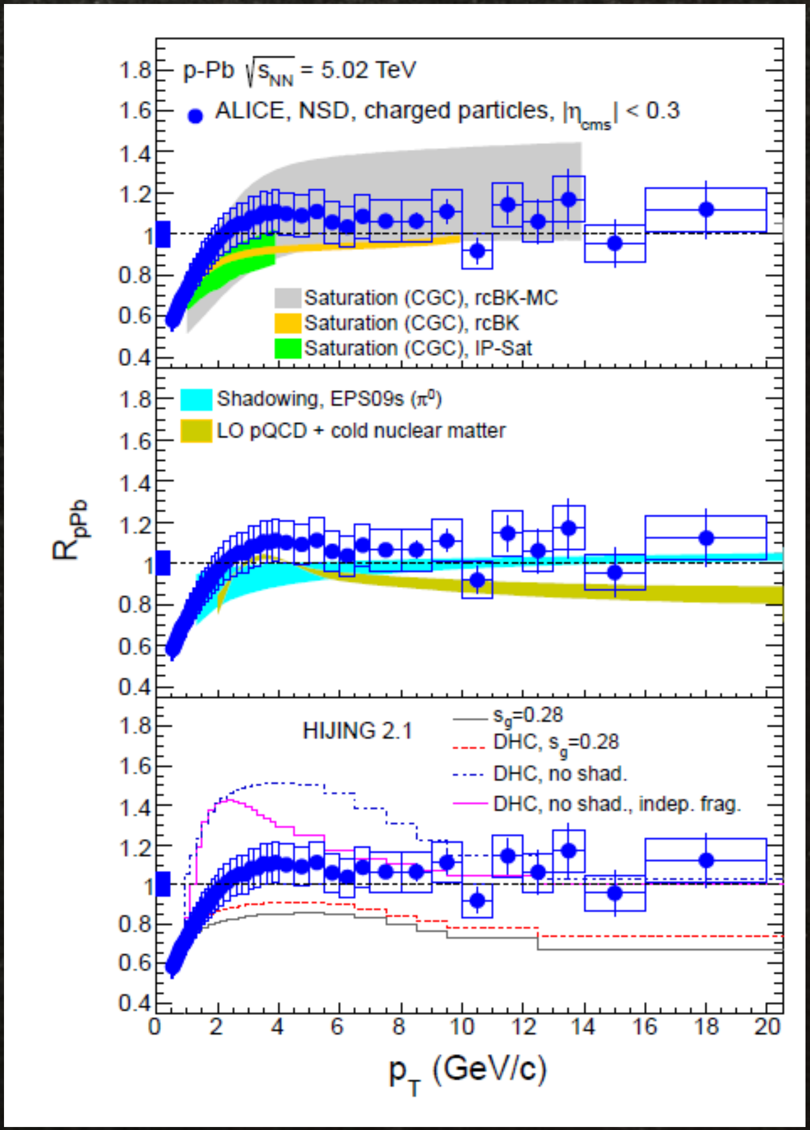


New ALICE data on pPb @ 5.02TeV

arXiv:1210.3615



arXiv: 1210.4520



Summary

- CGC is the universal picture of hadrons at high energies, which appears as a result of gluon 3-point vertex. Its theoretical framework is established at the LO level, but is developing beyond the LO.

- CGC provides the initial conditions for the heavy ion collisions, and turns into Glasma. The Glasma is responsible for thermalization, but is not solved yet.

- CGC picture is getting precise and is now seriously compared with experimental data at RHIC (forward rapidity) and LHC. MC-DHJ/rcBK model works well in describing the forward dAu data.

backup

High-energy scattering

High-energy limit = "Regge limit"

total scatt. energy >> typical energy/momentum scale in reaction

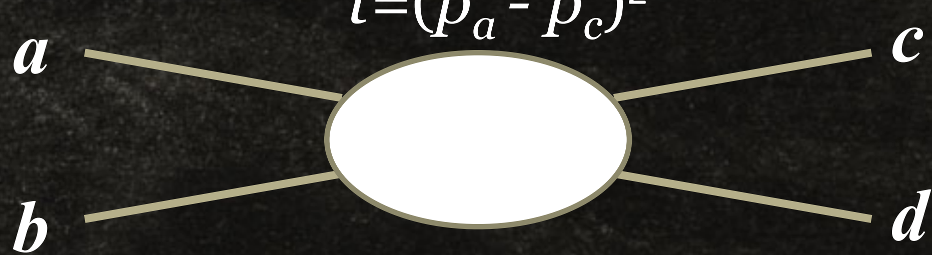
Hadron-hadron scattering

Momentum transfer squared

$t=(p_a - p_c)^2$

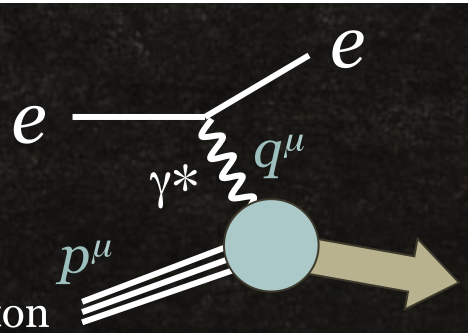
Total scattering energy squared

$s=(p_a+p_b)^2$



$s >> |\, t \,|$

Deep inelastic ep scattering



$W^2 = (p+q)^2$ *Total γ*p scattering energy squared*

$Q^2 = -q^2$ *Virtuality of photon*

$W^2 >> Q^2$

$x \sim Q^2/(W^2+Q^2) \rightarrow 0$