Colored Glass Condensate

and

proton-nucleus collisions

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OUTLINE

- What is a C G C ?
- Applications:
  - DIS: ep (HERA), eA (EIC)
  - AA (RHIC, LHC)
  - pA (RHIC, LHC)
  - pp (very forward RHIC ? and LHC)
- Applications to pA
  - Pion (jet) production
  - Photon and dilepton production
  - ......

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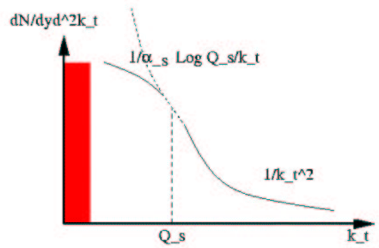
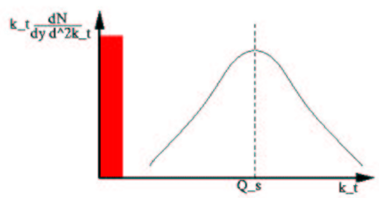
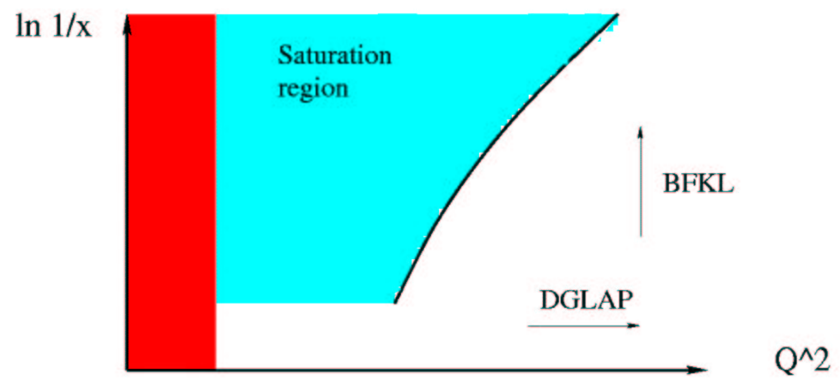
What is a C G C ?





- Complications:
  - pQCD fails (DGLAP, Colinear factoriz.)
  - Higher twist operators are important
- "Simplifications":
  - Weak coupling methods $\alpha_s(Q_s^2) \ll 1$

High energy QCD "phase diagram"



The tools of saturation region

- Classical fields
- Effective action, renormalization group

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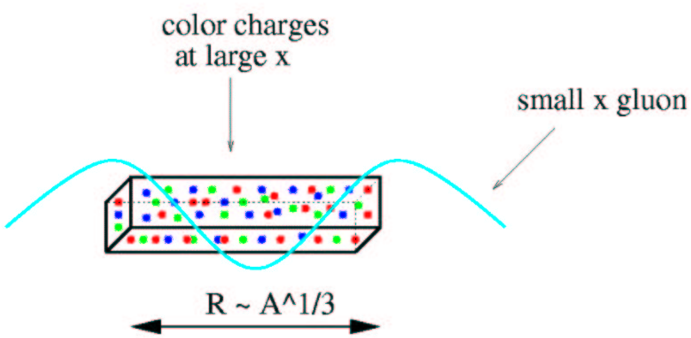
Enhancement of C G C : Nuclei

- $Q_s^2(x)$ is enhanced by $\sim A^{1/3}$



- Reaching equal Q_s in a proton would require orders of magnitude larger energies

- Nuclei are the ideal environment for C G C

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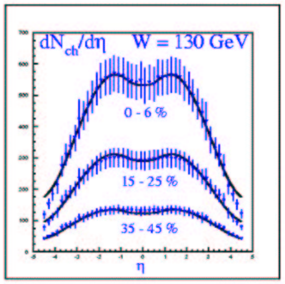
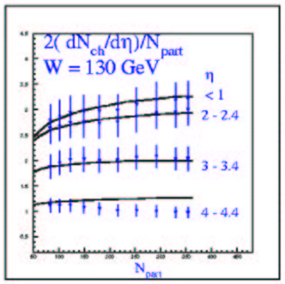
Applications of C G C : AA at RHIC

- Multiplicities (from D. Kharzeev, et al.)





- QGP, thermalization, hadronization, etc.

- AA is complicated!

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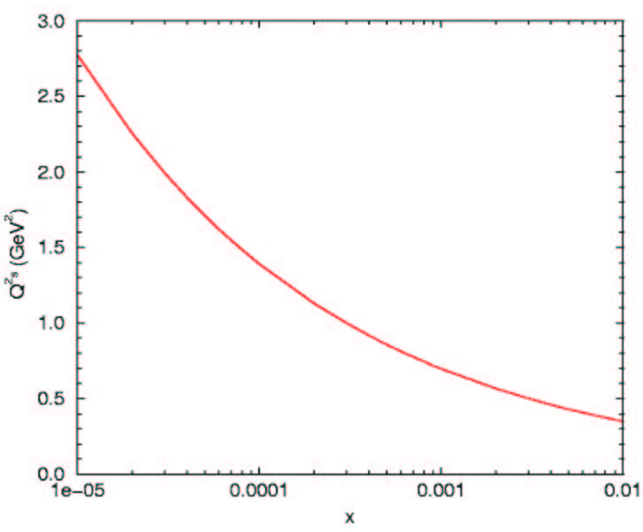
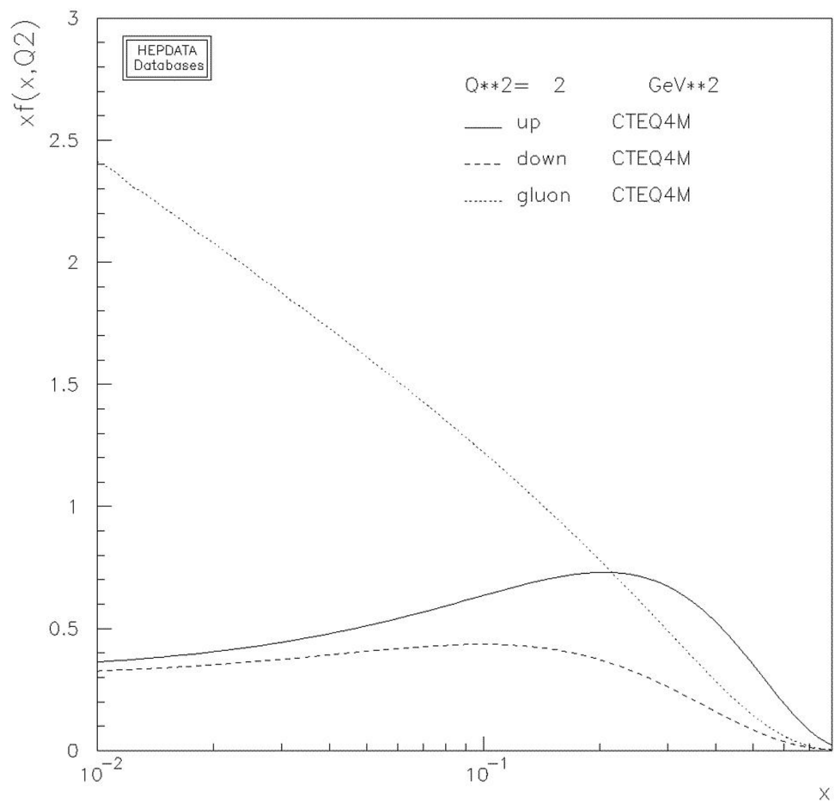
- Nuclei are described by C G C
- How about protons ?
- GB-W parameterization of $Q_s(x)$

$$Q_s^2(x) = Q_0^2\,(x_0/x)^\lambda$$

$$Q_0 = 1GeV, x_0 = 3 \times 10^{-4}, \lambda = 0.3$$





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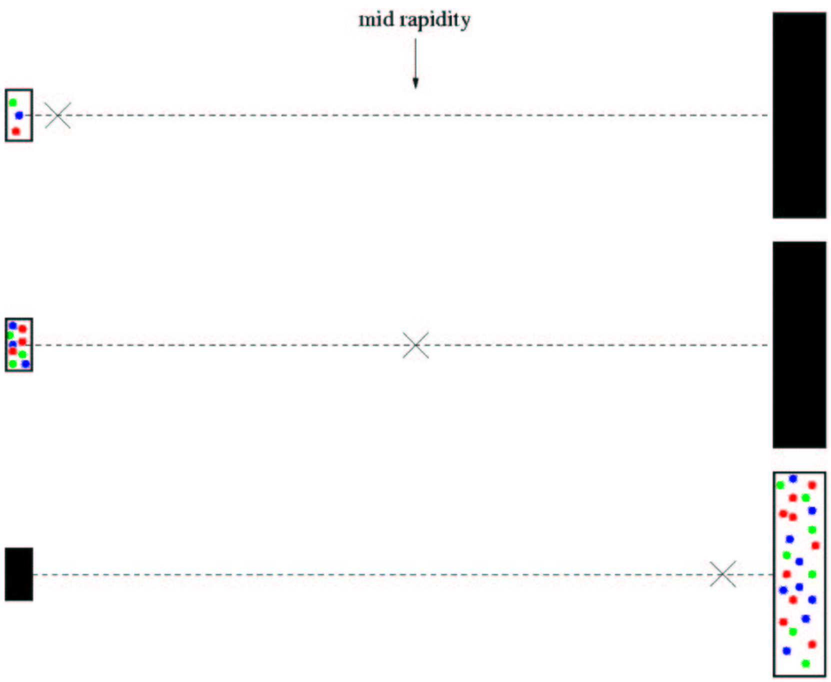
pA at RHIC and LHC



pA at RHIC and LHC

- Scattering amplitude $q\,A \to q\,X$ (with A. Dumitru)

$$\langle\, q\,(p)_{out}\,|\,q\,(q)_{in}\,\rangle_\rho = \langle out|b_{out}(q)b^\dagger_{in}(p)|in\rangle$$

and

$$\begin{aligned}\langle out|b_{out}(q)b^\dagger_{in}(p)|in\rangle &= -\int d^4x d^4y e^{-i(px-qy)}\bar{u}(q)[i\,\overrightarrow{\not\partial}_y - m] \\ &\quad \langle out|T\psi(y)\bar{\psi}(x)|in\rangle[-i\,\overleftarrow{\not\partial}_x - m]u(p) \\ &= i\int d^4x d^4y e^{-i(px-qy)}\bar{u}(q)[i\,\overrightarrow{\not\partial}_y - m] \\ &\quad G_F(y,x)[-i\,\overleftarrow{\not\partial}_x - m]u(p)\end{aligned}$$

where $G_F(y,x)$ is the Feynman propagator in the background field.

$$\begin{aligned}G_F(q,p) &= (2\pi)^4\delta^4(q-p)G_F^0(p) - igG_F^0(q)\int\frac{d^4k}{(2\pi)^4}\not A(k)G_F(q+k,p) \\ &= (2\pi)^4\delta^4(q-p)G_F^0(p) + G_F^0(q)\tau(q,p)G_F^0(p)\end{aligned}$$

$$\langle q(q)_{out}|q(p)_{in}\rangle = \bar{u}(q)\tau(q,p)u(p)$$

pA at RHIC and LHC

- Scattering amplitude

$$\langle q(q)_{out}|q(p)_{in}\rangle = \bar{u}(q)\tau(q,p)u(p)$$

$\tau(q,p)$ is the interaction part of the quark propagator

$$\tau(q,p) = (2\pi)\delta(p^- - q^-)\gamma^- \int d^2z_t [V(z_t) - 1] e^{i(q_t - p_t)z_t}$$

where

$$V(z_t) \equiv \hat{P}\exp\Big[-ig^2\int_{-\infty}^{+\infty} dz^- \frac{1}{\partial_t^2}\rho_a(z^-, z_t)t_a\Big]$$

- $V(z_t)$ includes multiple scattering of the quark on the nucleus

- $\delta(p^- - q^-)$ is due to (light cone) time independence of the target

$$\langle q(q)_{out}|q(p)_{in}\rangle = (2\pi)\delta(p^- - q^-)M(p,q)$$

pA at RHIC and LHC

- Color averaging with a Gaussian

$$\langle V(z_t)\rangle_\rho = \exp\Big[-\frac{g^4(N_c^2-1)}{4N_c}\chi\int d^2y_t\, G_0^2(z_t - y_t)\Big]$$

and

$$\langle V^\dagger(z_t)V(\bar{z}_t)\rangle_\rho = \exp\Big[-\frac{g^4(N_c^2-1)}{4N_c}\chi\int d^2y_t \, [G_0(z_t - y_t) - G_0(\bar{z}_t - y_t)]^2\Big]$$

where

$$G_0(z_t - y_t) = -\int \frac{d^2k_t}{(2\pi)^2}\frac{e^{ik_t(z_t - y_t)}}{k_t^2}$$

and $\chi(x^-) \equiv \int_{x^-}^{x_A^-} dz^- \mu^2(z^-)$

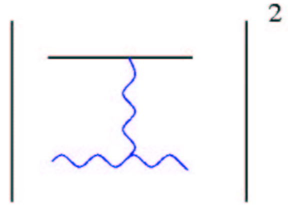
- Scattering cross section

$$d\sigma = \int \frac{d^4q}{(2\pi)^4}(2\pi)\delta(q^2)\frac{\theta(q^+)}{2p^-}(2\pi)\delta(p^- - q^-)|M(p,q)|^2$$

pA at RHIC and LHC

- Differential cross section
  - Perturbative limit ($q_t^2 \gg Q_s^2$)

$$\frac{d\sigma^{qA\to qX}}{d^2q_t\,d^2b} \sim \frac{Q_s^2}{q_t^4}$$



  - When $q_t^2 \sim Q_s^2$

$$\frac{d\sigma^{qA\to qX}}{d^2q_t\,d^2b} \sim \frac{1}{q_t^2}$$

  - When $q_t^2 \ll Q_s^2$

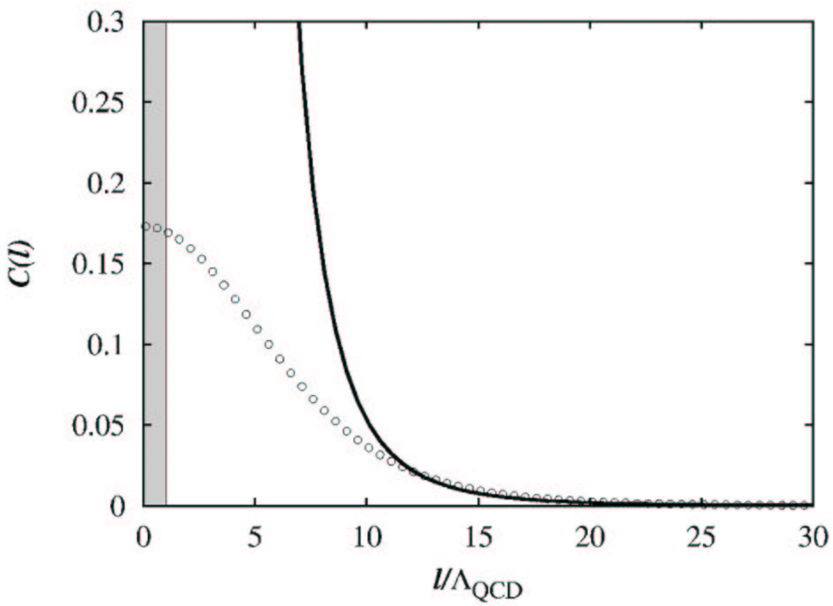
$$\frac{d\sigma^{qA\to qX}}{d^2q_t\,d^2b} \sim \frac{1}{Q_s^2}$$

pA at RHIC and LHC

- Differential cross section

$$\frac{d\sigma^{qA\to qX}}{d^3l\,d^2b} = \delta(p^- - l^-)C(l_t)$$

where $C(l_t)$ is the F.T. of $\langle V^\dagger(z_t)V(\bar{z}_t)\rangle_\rho$

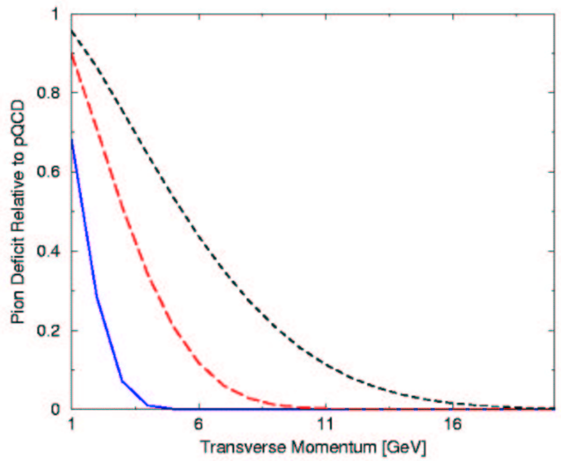


pA at RHIC and LHC

- Pion production
- Quark/gluon scattering on nucleus

$$\frac{d\sigma^{pA\to\pi X}}{d^2p_t\,dy} \sim F_{i/p}(x,Q^2) \otimes \frac{d\sigma^{i\,A\to i\,X}}{d^2p_t\,dy} \otimes D_{i/\pi}(z,Q^2)$$

- Gluon contribution (figure from J. Lenaghan and K. Tuominen)



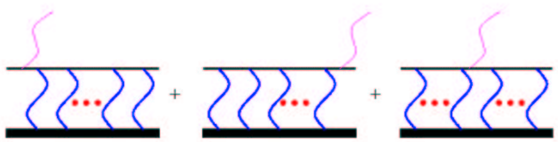
pA at RHIC and LHC

- Look for pions in the forward (proton fragmentation) region
- $Q_s^2 \sim 2GeV^2$ in mid rapidity and $\sim 10GeV^2$ in the forward region
- Soft physics will be much less important
- What to look for?
  - P_t distribution at fixed (forward) rapidity as a sign of C G C
  - Rapidity dependence of p_t distribution
  - A dependence

pA at RHIC and LHC

- Photon Bremsstrahlung in C G C (with F. Gelis)

$$q\ A \to q\ \gamma\ X$$



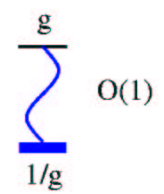
- Scattering amplitude

$$\langle q(q)\gamma(k)_{\rm out}|q(p)_{\rm in}\rangle = -e\,\overline{u}(q)\Big[(2\pi)^4\delta^4(k+q-p)\not\epsilon + \mathcal{T}_F(q,p-k)\,G^0_F(p-k)\not\epsilon + \not\epsilon\, G^0_F(q+k)\,\mathcal{T}_F(q+k,p) + \int\frac{d^4l}{(2\pi)^4}\mathcal{T}_F(q,l)\,G^0_F(l)\not\epsilon\, G^0_F(k+l)\,\mathcal{T}_F(k+l,p)\Big]\,u(p)$$

- First and last term vanish

pA at RHIC and LHC

- Photon bremsstrahlung in C G C is $O(\alpha_{em})$
- Bremsstrahlung photons are more leading than direct photons!



$$\frac{d\sigma^{q\,A\to q\,\gamma\,X}}{d^2k_t\,d^2b} = \frac{e^2}{(2\pi)^5k_t^2}\int_0^1 dz\,\frac{1+(1-z)^2}{z}\int d^2l_t\,\frac{l_t^2\,C(l_t)}{[l_t-k_t/z]^2}$$

- $z \equiv k^-/p^-$ and $\frac{1+(1-z)^2}{z}$ is the standard photon splitting function
- $l_t \equiv q_t + k_t$ is the transverse momentum transfered from the C G C to the quark + photon system
- Photon emission decouples in the soft photon ($k_t \to 0$) limit
- Dilepton production (in progress, with F. Gelis)

Summary

- Hadron/nucleus is a C G C at high energy
- pA is an excellent environment in which to investigate C G C
- C G C is more pronounced in diffractive events
- C G C is magnified in the forward (proton fragmentation) region

LOOK FORWARD in pA