Probing gluon saturation in a DIS process via nonconformal soft-wall holography

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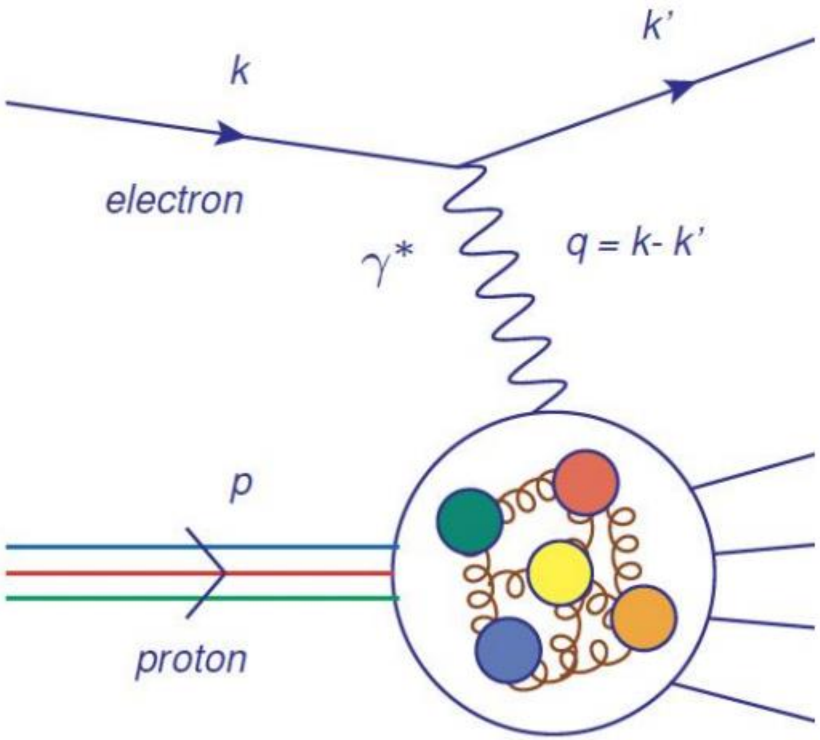
Deep Inelastic Scattering process and gluon saturation

Deep Inelastic Scattering process

Picture credit: Rojae Mighty's talk, CFNS 2025

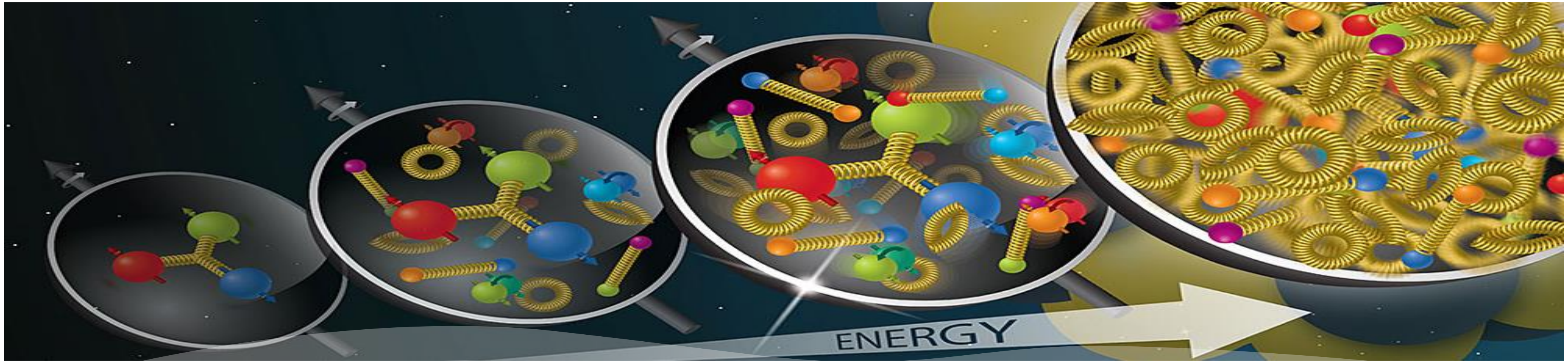


- A lens to observe the constituent of a hadron. (quarks and gluons)
- Scattered quarks radiate gluons and forms a cascade of quarks and gluons, known as parton shower..

<u>Some salient observables:</u>

- Momentum transfer Q^2 (Virtuality of photon)
- (high $Q^2 \Longrightarrow$ higher resolution of scattering or deep scattering)
- Bjorken-$x \equiv \frac{Q^2}{2\, p.q}$ (Fraction of proton momentum carried by the scattered quark)
- Final hadronic state captures the energy of the virtual photon, hence inelastic.

High energy gluon saturation in DIS



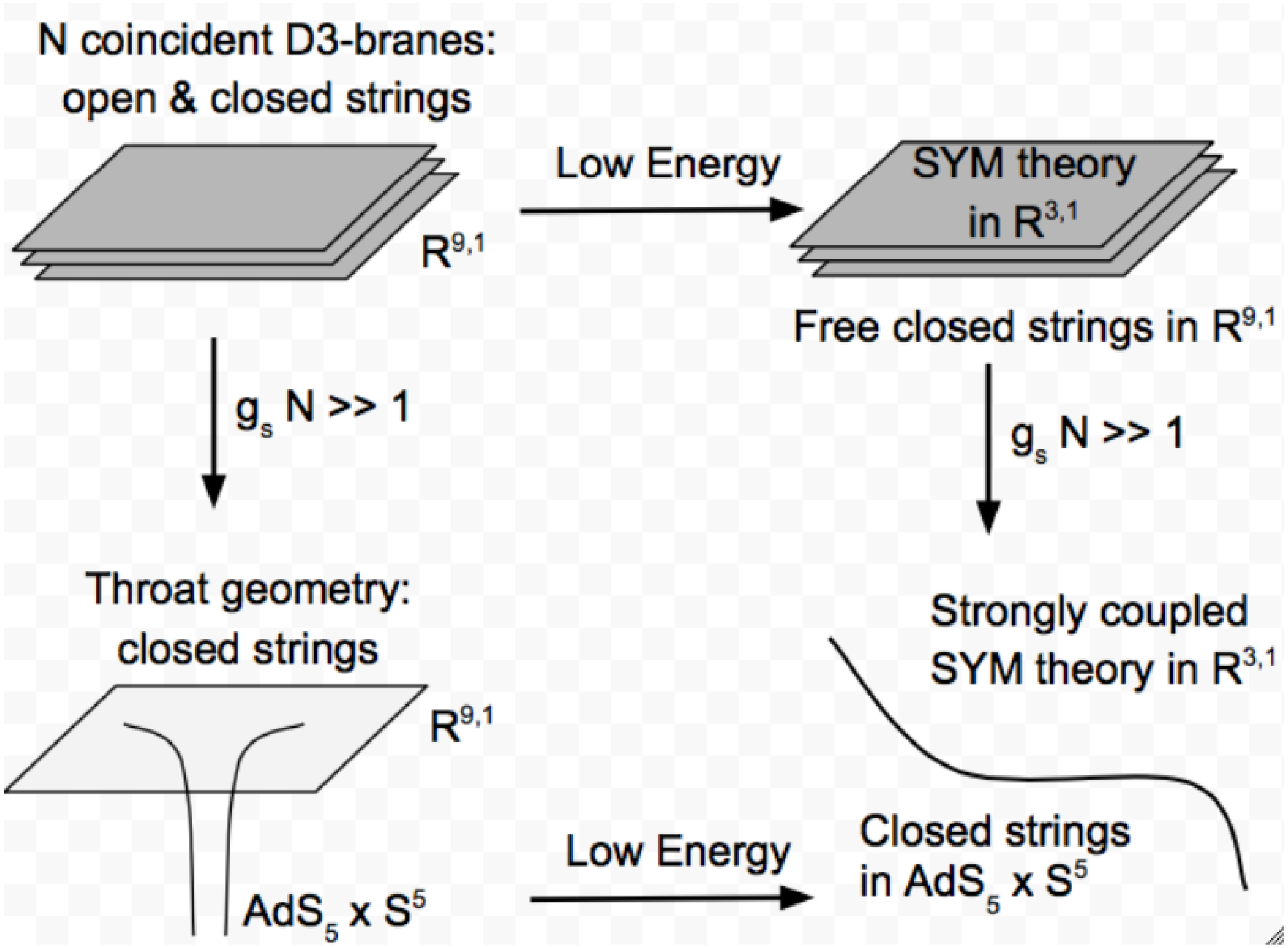
- Gluon density grows rapidly for higher energy and smaller Bjorken-x.
- For even higher energy, gluons start to interact and recombine, slowing down the growth.
- Eventually, gluon density reaches a saturation at sufficiently high energy of the projectile.
- Saturation is characterized by saturation scale $Q_s(x)$, in general, as a function of Bjorken-x.

<u>*We will extract a gluon saturation scale in a soft-wall holographic prescription of DIS</u>

<u>*For a sufficiently IR boundary theory, the saturation scale is expected to be a function of the soft-wall effect of the holographic bulk.</u>

Holographic understanding of DIS process and gluon saturation

Gauge/Gravity holographic correspondence
(AdS/CFT)



Maldacena, 1998

DIS and gluon saturation from AdS/CFT

- Target hadron or nucleus ⟹ Gravitational Shockwave in AdS (Highly boosted in one light-cone direction)

  (in the form of a slice of plasma)

  ⟹ Holographically dual to an excitation in boundary correlators

- **Associated current correlators in CFT** : $\Pi^{\mu\nu}(x,y) = i\theta(x^0 - y^0)\langle p|\,[J^\mu(x), J^\nu(y)]\,|p\rangle$

  In bulk: $$\Pi^{\mu\nu}(x,y) = \frac{\delta S^{\rm cl}_{\rm Maxwell}}{\delta A^a_\mu(x)|_{z=0}\delta A^a_\nu(y)|_{z=0}}.$$

- **Gluon structure function**: $F(x,Q^2) = \mathrm{Im}\,\Pi(x,Q^2) \quad Q^2 \equiv q^\mu q_\mu = -2q^+q^- > 0.$
- **Gluon saturation momentum scale** : $Q_s^2 \sim \frac{1}{x}$,
- **From AdS/CFT holography**, $Q_s^2 = \pi\Lambda^3 L/2x$, Λ is the IR cutoff defining the confinement scale.

Maldacena 2008; Kovchegov 2010; Avsar, Iancu, McLerran, Triantafyllopoulos, 2009

Nonconformal gauge/gravity holography

Gravity in deformed 5D AdS ⟷ dual ⟷ 4D Nonconformal pure Yang-Mills theory

1. Relaxation in conformal symmetry by introducing either running dilaton or modified vector field components.

2. Extra dimensionful parameter appears to deform the AdS metric with dominating effect in the IR regime.

3. Running effective coupling of the boundary QCD-like theory can capture the physics of confinement.

4. Deformed metric merges to conformal AdS when the extra parameter vanishes.

5. Mimics the effects of IR cutoff in hard-wall scenario and is known as soft-wall AdS/QCD model.

Witten, 1998; Maldacena, Aharony, Gubser, Oz, Ooguri, 1999

Probing gluon saturation using shockwave in nonconformal holography

Nonconformal warped bulk and shockwave

- Generic metric ansatz : $ds^2 = e^{-2A(z)}\left[dx^+dx^- - dx_1^2 - dx_2^2 - dz^2\right]$
- Ansatz for warp factor : $A(z) = \ln z + h(z)$
- Considering the vector fields to satisfy $F_{-1}F_{+1} + F_{-2}F_{+2} + F_{-z}F_{+z} = \text{Const.} = \mu, \quad A_1'^2 + A_2'^2 = 3A_+'A_-'$

  the Einstein's equations of motion approximately gives $A(z) = \ln z - \frac{\mu z^4}{54}$

- μ is the deformation parameter with length dimension -4, $\mu = 0$ retrieves the conformal AdS metric.
- The effect of the warp factor is dominant in sufficiently deep inside the bulk (z >> 0).

Shockwave in nonconformal bulk

- Metric with highly boosted shockwave: $ds^2 + \delta ds^2 = e^{-2A(z)}\left[dx^+dx^- - dx_1^2 - dx_2^2 - dz^2\right] + \epsilon e^{-2A(z)}\delta(x^-)f(x^\perp, z)dx^{-2}$
- For large z, IR Shockwave profile from gravity equations of motion: $f(x^\perp, z) = \frac{e^{-\frac{\mu z^4}{9}}}{\sqrt{2\pi}} \frac{\left(\frac{\mu z^3}{9}\right)^{\frac{3}{4}}}{\Gamma\left(\frac{1}{4}\right)} \frac{K_{\frac{3}{4}}\left(\frac{2\mu z^3}{9}r\right)}{r^{\frac{3}{4}}}$
- UV Shockwave profile near the boundary z ⟶ 0 : ~ z^4

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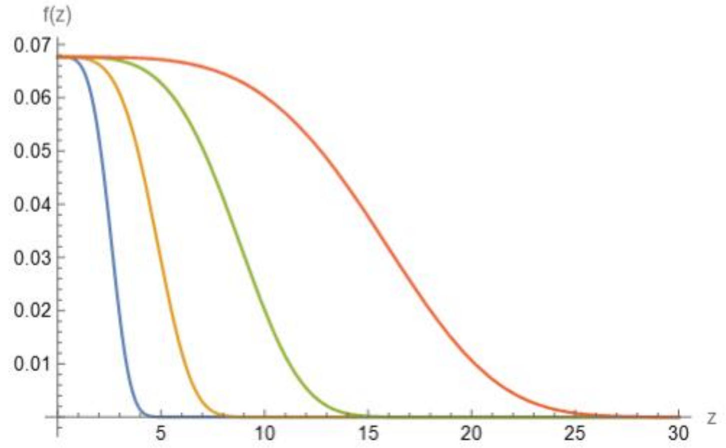
Confinement scale from the IR shockwave profile



Shockwave decays exponentially from a small finite value, decrease is sharper for higher μ $\Longrightarrow$ explains confinement in IR.

Confinement scale:

$$z_0 \approx \left(\frac{9}{\mu}\right)^{\frac{1}{4}} \left[\frac{1}{2} + \frac{1}{4}\ln\mu + \ln r\right]^{\frac{1}{4}} + \left(\frac{9}{\mu r}\right)^{\frac{1}{3}} \left[\frac{1}{2} + \frac{1}{4}\ln\mu + \ln r\right]^{\frac{1}{3}}$$

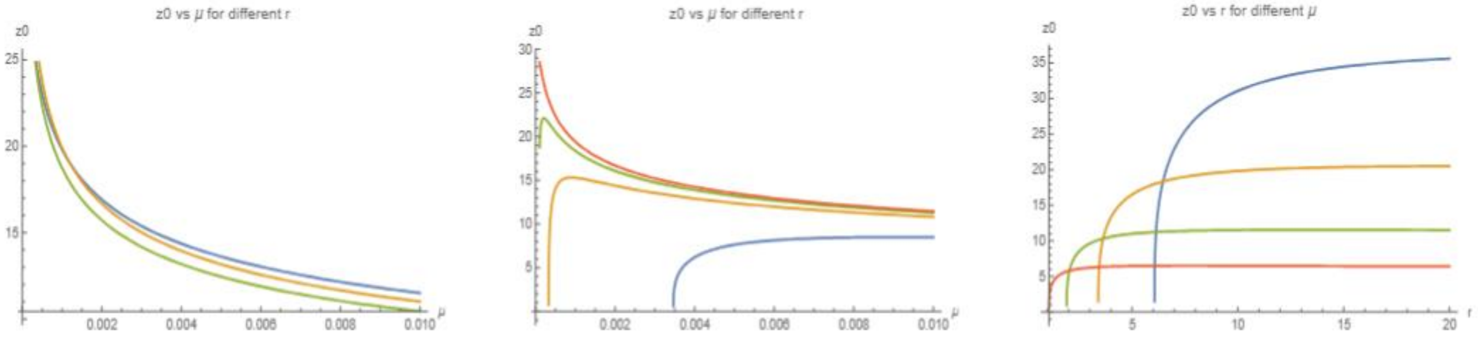


Figure 6. Variation of the IR scaling z_0 in (4.4) with μ is shown in the left pannel for $r = 10$(Blue), $r = 100$(Yellow) and $r = 100$(Green). Variation of z_0 with μ is shown in the middle pannel for smaller r such as $r = 2.5$(Blue), $r = 4.5$(Yellow), $r = 6.5$(Green) and $r = 8.5$(Red). Variation of z_0 with r is shown in the right pannel for smaller r such as $\mu = 0.1$(Blue), $\mu = 0.01$(Yellow), $\mu = 0.001$(Green) and $\mu = 0.0001$(Red).

Ranges of r and μ:

$$r \geq \frac{1}{\mu^{\frac{1}{4}}\sqrt{e}} \qquad \frac{1}{10r^4} \lesssim \mu \ll 1\,.$$

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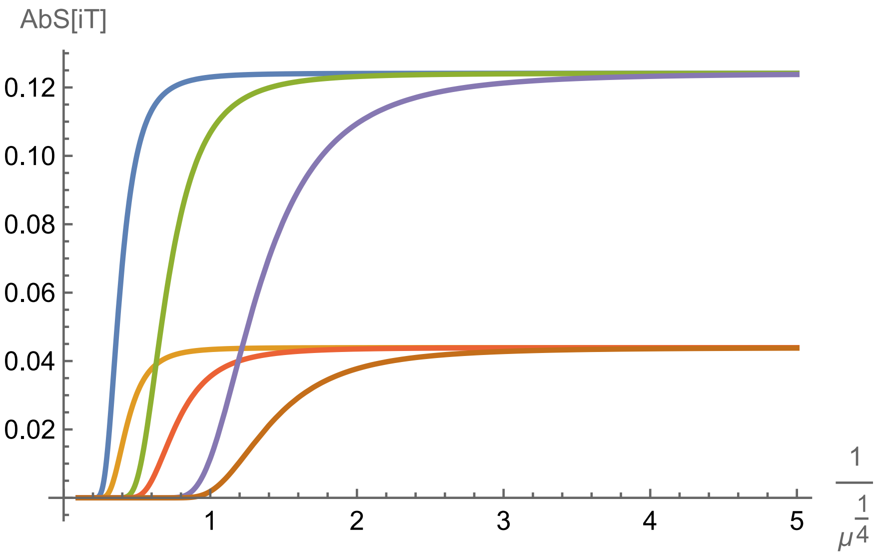
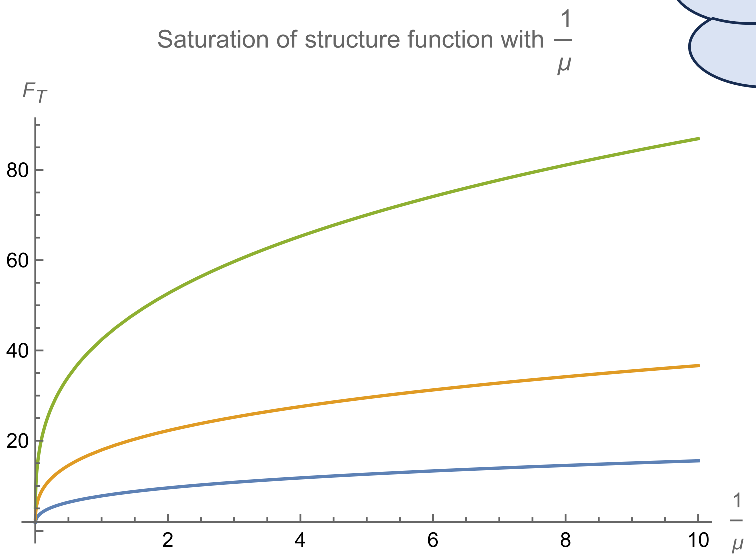
Current correlators and structure functions

- IR boundary theory at large z is nonconformal unlike AdS/CFT.
- As a gauge condition, we choose all Maxwell's field components to be finite except $A_z = 0$.
- Iterative solutions of Maxwell's equations gives eikonal scattering amplitude

$$i\mathcal{T}(z,r) = 1 - \exp\left[2iq^- f(z,r)\right] = 1 - \exp\left[iq^- \frac{\sqrt{2}(\mu z^3)^{\frac{3}{4}} e^{-\frac{\mu z^4}{9}}}{\pi \Gamma\left(\frac{1}{4}\right)} \frac{K_{\frac{3}{4}}\left(\frac{2\mu z^3}{9} r\right)}{9 r^{\frac{3}{4}}}\right]$$ in IR limit.

- Current correlator: $\Pi^{ii}(q) \propto \left(\frac{Q}{\mu^{\frac{1}{4}}}\right)^{\frac{5}{4}} \left[a_1 + a_2 \left(\frac{Q}{\mu^{\frac{1}{4}}}\right)^{-2} + \mathcal{O}\left(\frac{Q}{\mu^{\frac{1}{4}}}\right)^{-4}\right]$





Empirical gluon saturation scale ~ $f\left(\frac{1}{\mu^{1/4}}\right)$ for fixed z and r

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Summary

- Preparation of shockwave in soft-wall warped holographic set-up.
- Decaying shockwave profile suggests confinement in IR regime.
- Dimensionful deformation parameter causes a confinement scale.
- Eikonal scattering amplitude and gluon structure functions in IR boundary theory yield a saturation scale which is a nontrivial function of the deformation of the bulk geometry.
- Gluon saturation is observed in IR boundary theory of a nonconformal holographic framework without introducing IR cutoff.

However !

- **Saturation scale is still empirical, needs more study.**

For now, we just have $f\left(\frac{1}{\mu^{1/4}}\right) \propto \frac{1}{x}$. We are working on a more explicit expression of $f\left(\frac{1}{\mu^{1/4}}\right)$ and its relation with Bjorken $- x$.

- **Studying other existing current correlator**

will yield the whole information on the effect of μ on gluon saturation.

We will soon come back addressing these issues in our arXiv submission. Stay tuned!

Thanks all!
Questions and comments are welcome