Saturation framework results on multiplicity biased pA collisions

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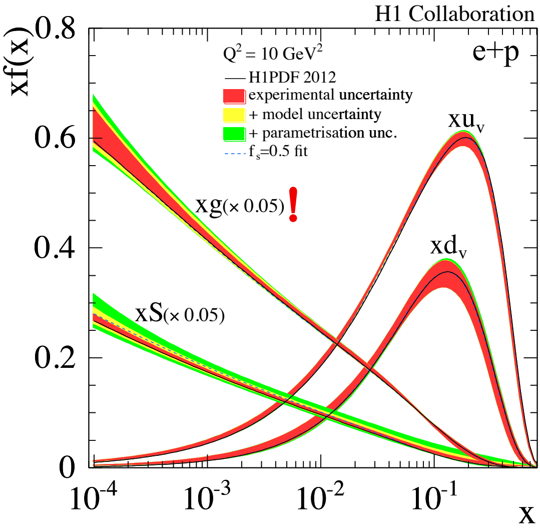
Outline

- Introduction: saturation framework/CGC and why theorists like it
- Phenomenological challenges or where CGC fails to describe data. Does it?!

  CGC inspired models $\neq$ CGC

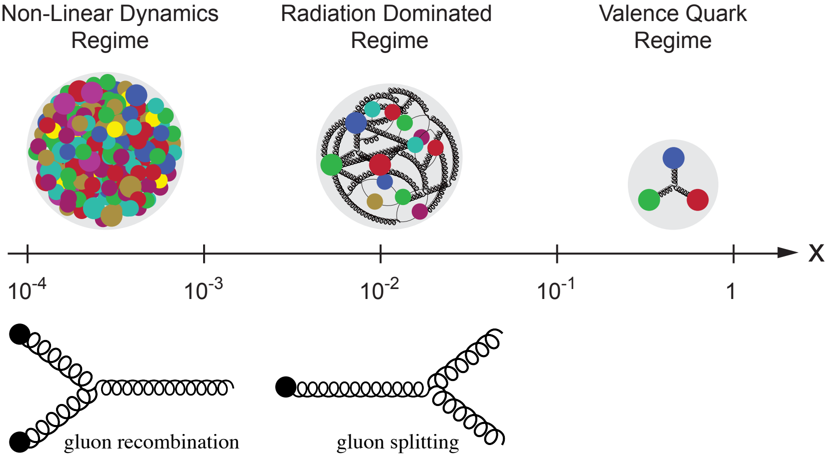
- What do we know from first principle QCD?
- Fluctuations in CGC
- Application: Q_{pA}
- Conclusion and Outlook

High energy limit of QCD



High energy limit (small $x \propto 1/\sqrt{s}$) $\equiv$ high gluon density

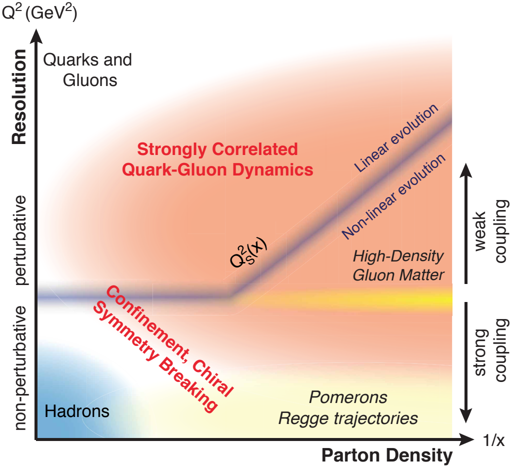
High energy limit of QCD



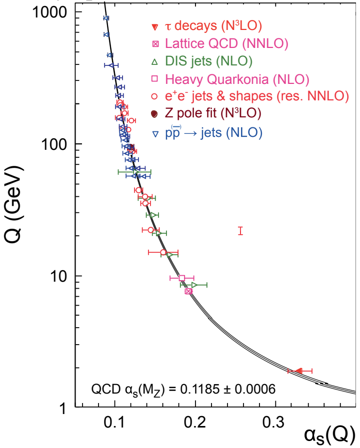
Emerging dynamical scale: saturation momentum, Q_s.

Classical Yang-Mills fields at scale λ: $R_{\text{proton}} > \lambda > 1/Q_s$.

High energy "phase diagram" of QCD

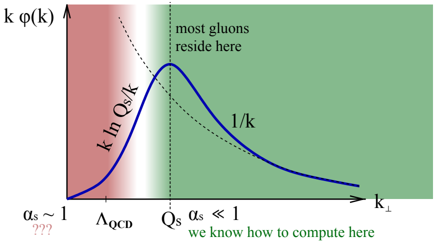


Asymptotic freedom: $\alpha_s(Q \to \infty) \to 0$.



Only left corners of the diagram are well studied.

Saturation regime



- Particle production is dominated by $k_\perp \sim Q_s$
- Weak coupling methods can be applied $\alpha_s(Q_s) \ll 1$
- Still non-perturbative, as fields are strong, $A \sim \frac{1}{g} \rightsquigarrow$ non-linearities are important

  Other examples of non-perturbative weak coupling regimes:

  - instantons, monopoles, ...
  - holonomy (Polyakov Loop) of Yang-Mills at finite T, $A_0 \propto T/g$
  - phase transitions, $\sigma^2 \propto |m^2|/\lambda$
  - resurgence program and plethora of QCD-like theories
  - gravitational (and other non-linear FT) memory effect

  Common futures:

  - calculable!
  - non-trivial as go beyond perturbative

Saturation framework/CGC provides an opportunity to study regions of

high parton density in the small coupling regime,

where calculations are still under control!

Challenges

There are a lot of successes. Nonetheless challenges remain.

- Thermalization?! Indications: requires non-perturbative physics…
- Rare high multiplicity events?! Indications: requires non-perturbative physics…
- Odd harmonics of two particle azimuthal correlations, $v_3\{2\}$ ✓
  - CGC inspired k_T factorization approach $v_3\{2\} = 0$
  - About 7 years of the community effort
  - Solution: original idea in L. McLerran & V.S., arXiv:1611.09870;
    cross-check and evaluation in Yu. Kovchegov & V.S., arXiv:1802.08166
- Higher order correlations, $v_2\{n > 2\}$
  - CGC inspired k_T factorization approach $v_2^4\{4\} < 0$

    V.S., arXiv:1412.5191
  - We know what has to be done but it requires analytical and numerical effort
- Centrality dependent nuclear modification factor R_{pA} (Q_{pA})

  this talk and A. Dumitru, G. Kapilevich & V.S., arXiv:1802.06111

What do we know analytically?

Asymmetric collisions, when Q_s of the projectile $\neq Q_s$ of the target, is the easiest case.

Single inclusive production

- In general

$$\frac{dN}{d^3k} = \frac{1}{\alpha_s} f\left(\frac{Q_{sp}}{k_\perp^2}, \frac{Q_{sA}}{k_\perp^2}\right)$$

  $f\left(\frac{Q_{sp}}{k_\perp^2}, \frac{Q_{sA}}{k_\perp^2}\right)$ is known only numerically

- If $k_\perp > Q_{sp}$,

$$\frac{dN}{d^3k} = \frac{1}{\alpha_s}\frac{Q_{sp}}{k_\perp^2} f^{(1)}\left(\frac{Q_{sA}}{k_\perp^2}\right) + \frac{1}{\alpha_s}\left(\frac{Q_{sp}}{k_\perp^2}\right)^2 f^{(2)}\left(\frac{Q_{sA}}{k_\perp^2}\right) + \cdots$$

  Functions $f^{(n)}$ are calculable!

Single inclusive production

Asymmetric collisions, when Q_s of the projectile $\neq$ Q_s of the target, is the easiest case.

$$\frac{dN}{d^3k} = \frac{1}{\alpha_s}\frac{Q_{sp}}{k_\perp^2} f^{(1)}\left(\frac{Q_{sA}}{k_\perp^2}\right) + \frac{1}{\alpha_s}\left(\frac{Q_{sp}}{k_\perp^2}\right)^2 f^{(2)}\left(\frac{Q_{sA}}{k_\perp^2}\right) + \cdots$$

- $f^{(1)}$ is known since ’98

Y. V. Kovchegov and A. H. Mueller, Nucl. Phys. B529, 451 (1998), hep-ph/9802440
A. Dumitru and L. D. McLerran, Nucl. Phys. A700, 492 (2002), hep-ph/0105268

- $f^{(2)}$: no complete result yet, attempted in ’15

G. A. Chirilli, Y. V. Kovchegov, and D. E. Wertepny, JHEP 03, 015 (2015), 1501.03106

Double inclusive production

Asymmetric collisions, when Q_s of the projectile $\neq Q_s$ of the target, is the easiest case.

$$\frac{d^2N}{d^3k d^3p} = \frac{1}{\alpha_s^2} Q_{sp}^2 h^{(1)}(Q_{sA}) + \frac{1}{\alpha_s^2} Q_{sp}^4 h^{(2)}(Q_{sA}) + \cdots$$

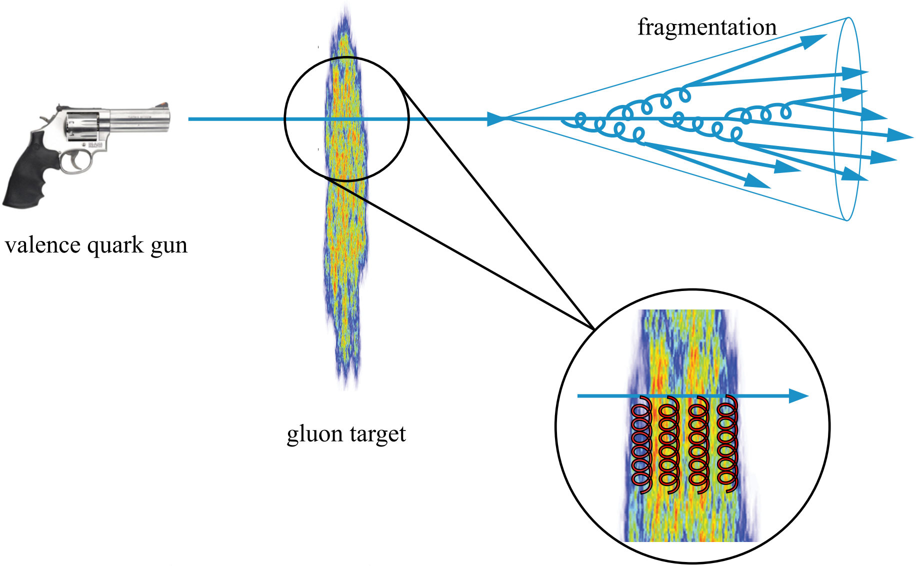
- $h^{(1)}$ is known since '12; invariant under $(k_\perp \to -k_\perp) \rightsquigarrow$ no odd harmonics

  A. Kovner and M. Lublinsky, Int. J. Mod. Phys. E22, 1330001 (2013), 1211.1928
  Y. V. Kovchegov and D. E. Wertepny, Nucl. Phys. A906, 50 (2013), 1212.1195

- $h^{(2)}$: no complete result yet, but odd part under $(k_\perp \to -k_\perp)$ was found

  L. McLerran and V. S., Nucl. Phys. A959, 83 (2017), 1611.09870;
  Yu. Kovchegov and V. S., arXiv:1802.08166

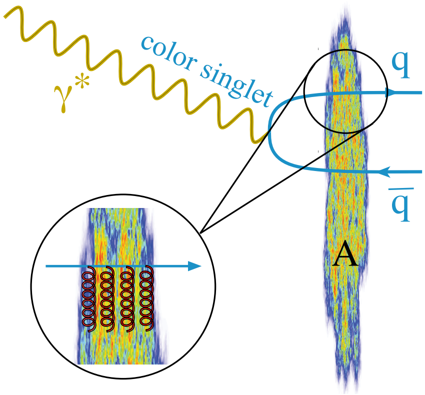
"…we conclude that the odd azimuthal harmonics are
an inherent property of particle production in the saturation framework…"



$U(\mathbf{x}_\perp) = \mathcal{P} \exp\left(ig \int dx^+ A^-(x^+, \mathbf{x}_\perp)\right)$ $\Leftarrow$ multiple rescattering

Color Memory

• Gravitational wave memory: permanent shift of two inertial observers after the passage of gravitational memory



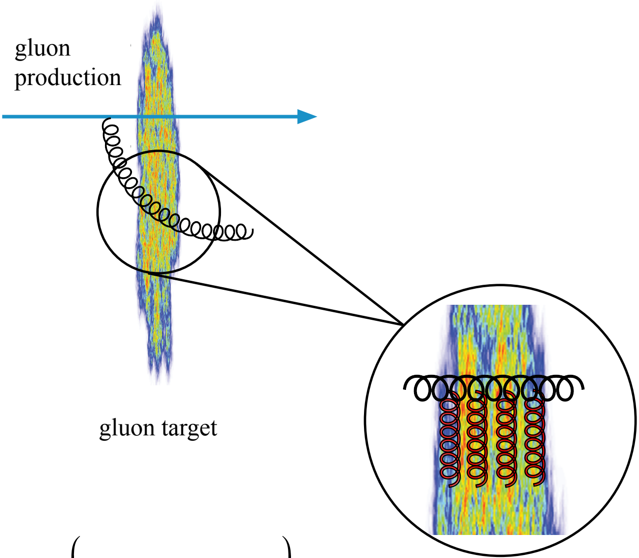
• Analogous effect in YM: two color charges in color singlet state will not be in color singlet state after the passage of color "wave"

• A. Strominger and coathours:
"Color Memory: a Yang Mills analog of gravitational wave memory";

M. Pate, A. Raclariu & A. Strominger, PRL **119***, 261602 (2017)*

• Most of observables in saturation framework are related to "color memory".

Gluon production



$$W(\mathbf{x}_\perp) = \mathcal{P} \exp\left(ig \int dx^+ \underbrace{A^-}_{\text{adj.}}(x^+, \mathbf{x}_\perp) \right) \quad \Leftarrow \quad \text{multiple rescattering}$$

Gluon production

- Computing analytically

$$E_k \frac{dN}{d^3k}\left\{\rho_p, \rho_T\right\} = \frac{1}{2(2\pi)^3 k_\perp^2} (\delta_{ij}\delta_{lm} + \epsilon_{ij}\epsilon_{lm})\, \Omega^b_{ij}(\mathbf{k}_\perp)\ \left[\Omega^b_{lm}(\mathbf{k}_\perp)\right]^*$$

Here $\delta_{ij}\Omega_{ij} = \Omega_{xx} + \Omega_{yy}$ and $\epsilon_{ij}\Omega_{ij} = \Omega_{xy} - \Omega_{yx}$ and

$$\underbrace{\Omega^a_{ij}(\mathbf{x}_\perp) = g \left[\frac{\partial_i}{\partial^2} \overbrace{\rho^b(\mathbf{x}_\perp)}^{\text{val. sour.}}\right] \partial_j\ \overbrace{W^{ab}(\mathbf{x}_\perp)}^{\text{target W line}}}_{\text{valence sources rotated by the target}}$$

- Note that $W(\mathbf{x}_\perp)$ depends on positions of color charges in the target.

Glauber N_{part} fluctuations are also in $W(\mathbf{x}_\perp)$.

- Min. bias:

$$E_k \frac{dN}{d^3k} = \left\langle E_k \frac{dN}{d^3k}\left\{\rho_p, \rho_T\right\}\right\rangle_{\rho_p, \rho_T}$$

A. Dumitru and L. D. McLerran, Nucl. Phys. A700, 492 (2002), hep-ph/0105268
L. McLerran and V. S., Nucl. Phys. A959, 83 (2017), 1611.09870
Yu. Kovchegov and V. S., arXiv:1802.08166

"GLITTERING GLASMAS"

- For fixed N_{part}, $E_k \frac{dN}{d^3k}\left\{\rho_p, \rho_T\right\}$ fluctuates on $\underbrace{\text{configuration-by-configuration}}_{\text{event-by-event}}$ basis

$\rightsquigarrow$ Larry's "Glittering glasma"; in plain words: color density fluctuations

- These fluctuations are negative binomial:

  the fact derived from first principles at momentum $\gg Q_{sT}$!

F. Gelis, T. Lappi and L. McLerran, Nucl. Phys. A **828***, 149 (2009), arXiv:0905.3234*

- Numerical calculations in whole range of $k_\perp$ in satur. framework support the above

M. Mace & V.S., work in progress

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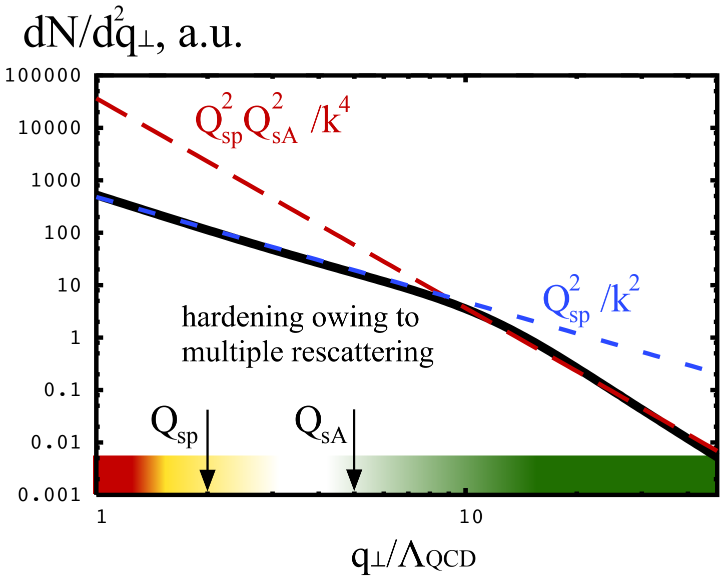
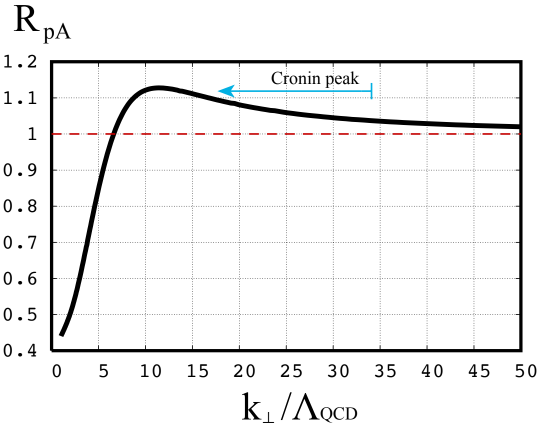
Numerical result for single inclusive production in pA



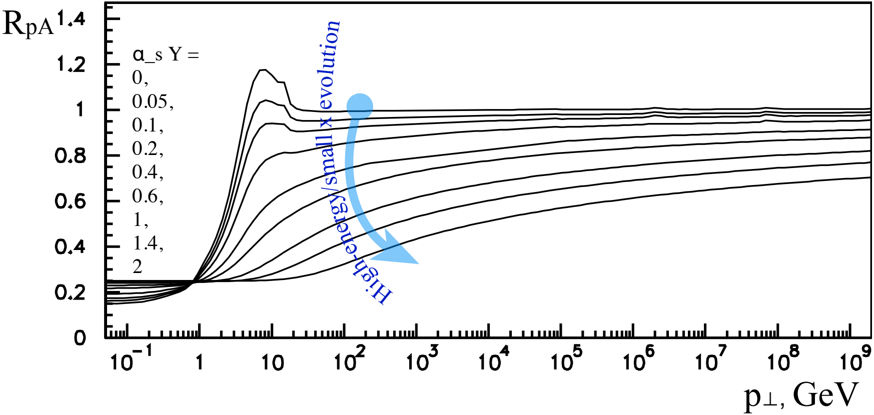
Min. bias R_{pA}: schematically

- Nuclear modification factor $R_{pA} = \frac{\frac{dN_{pA}}{d^3k}}{N_{\text{part}}^{\text{min.bias}} \frac{dN_{pp}}{d^3k}}$
- Minimum bias corresponds to an average over color fluctuations, N_{part} etc.



Min. bias R_{pA}: numerical results

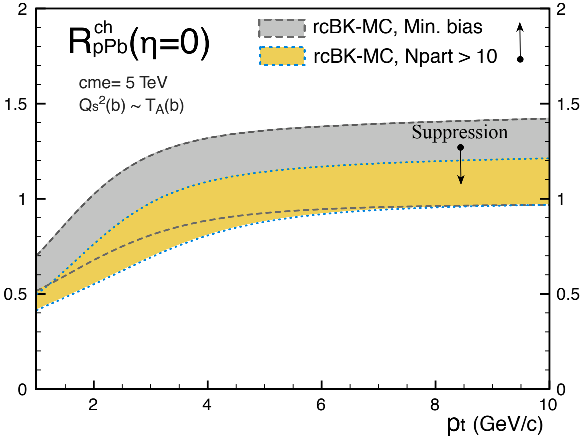
- High energy evolution



J. L. Albacete, N. Armesto, A. Kovner, C. A. Salgado and U. A. Wiedemann, "Energy dependence of the Cronin effect from nonlinear QCD evolution," Phys. Rev. Lett. **92***, 082001 (2004)*

N_{part}-BIAS R_{pA}

- R_{pA} goes down with N_{part}-bias towards larger values



J. L. Albacete, A. Dumitru, H. Fujii and Y. Nara, Nucl. Phys. A 897, 1 (2013)

Central pA collisions

• Naively, central collisions correspond to those where the projectile proton suffers an inelastic collision with a greater than average number of target nucleons.

• This is analogous to minimum bias pA collisions with a target nucleus with many more than ~ 200 nucleons.

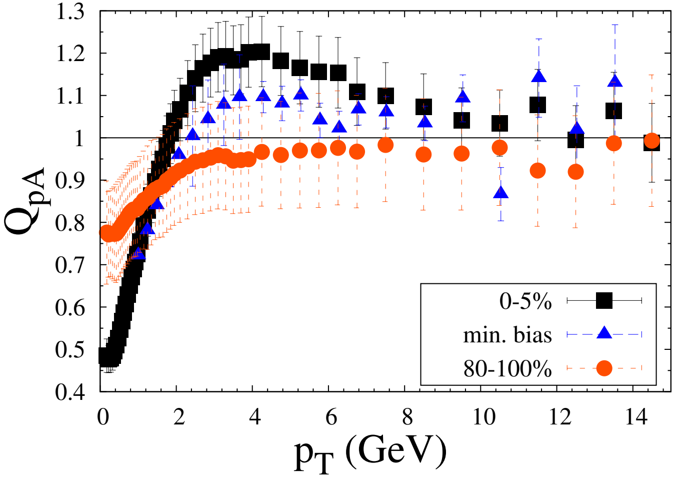
$\rightsquigarrow$ a stronger suppression of $R_{pA}(k)$ for central versus minimum bias events.

• N_{part} or N_{coll} can not be measured directly.
Experimentally, one therefore employs a variety of different centrality measures

ALICE Q_{pA}

- Loosely speaking Q_{pA} is R_{pA} in collisions of different centrality

(details: How to define “centrality”?! See thorough investigation by ALICE)



J. Adam et al. [ALICE Collaboration], Phys. Rev. C **91**, *no. 6, 064905 (2015)*

- Re-emerging Cronin peak ⇑ in central collisions

$\rightsquigarrow$ Something is missing and we know what it is:

color fluctuations!

Small x ensemble

- Distribution of classical field

$$\mathcal{W}[A^+] = \exp\left(-S[A^+]\right)$$

- Expectation values

$$\langle O[A^+]\rangle = \frac{1}{Z}\int \mathcal{D}A^+ \mathcal{W}[A^+] O[A^+]; \qquad Z = \int \mathcal{D}A^+ \mathcal{W}[A^+] \qquad k^2 A^+(k) = g\rho_T(k)$$

L. D. McLerran and R. Venugopalan, Phys. Rev. D **49***, 2233 (1994), hep-ph/9309289*
L. D. McLerran and R. Venugopalan, Phys. Rev. D **49***, 3352 (1994), hep-ph/9311205.*

- Example: McLerran and Venugopalan (MV) model

$$S_{\mathrm{MV}} = \int dx^- \int \frac{d^2 k_\perp}{(2\pi)^2} \frac{\mathrm{tr}\left[\, k^2 A^+(x^-, \mathbf{k}_\perp)\, k^2 A^+(x^-, -\mathbf{k}_\perp)\right]}{g^2 \mu^2 (x^-)}$$

Keep the relevant: constraint effective action

- $S[A^+]$ contains a pleathora of possible excitations/fluctuations

- Integrate out fluctuations which do not change the observable of interest $O[A^+]$
$\rightsquigarrow$ effective action/potential for $X(q) = O[A^+(q)]$.

$$e^{-V_{\text{eff}}[X(q)]} = \frac{1}{Z} \underbrace{\int \mathcal{D}A^+}_{\text{integrate the rest}} \; \mathcal{W}[A^+] \; \underbrace{\delta(X(q) - O[A^+(q)])}_{\text{keep interesting}}$$

- The normalization

$$\int \mathcal{D}X e^{-V_{\text{eff}}[X(q)]} = 1$$

- Consider $O[A^+] = g^2 \text{tr}|A^+(q)|^2$ – simplest but still non-trivial

L. O'Raifeartaigh, A. Wipf and H. Yoneyama, Nucl. Phys. B 271, 653 (1986);
YM with non-trivial holonomy: C. P. Korthals Altes, Nucl. Phys. B 420, 637 (1994)

$O[A^+] = g^2 \mathrm{tr}|A^+(q)|^2$

- The effective action

$$V_{\text{eff}} = \int \frac{d^2q}{(2\pi)^2} \left[\frac{q^4}{g^4\mu^2} X(q) - \frac{1}{2} A_\perp N_c^2 \log X(q) \right]$$

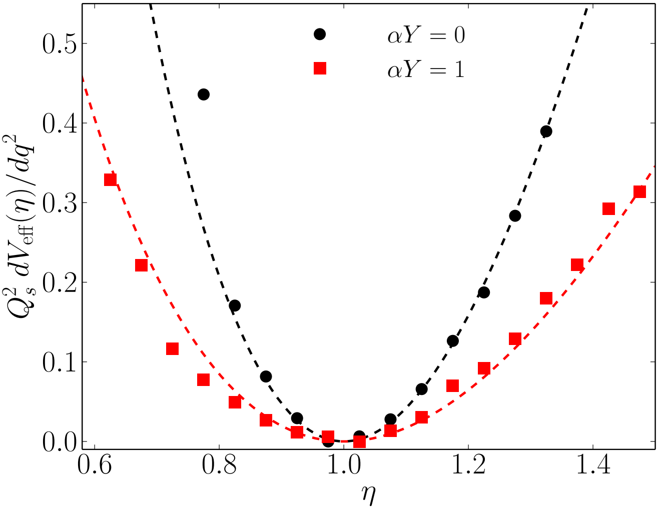
with redefinition $\exp[\Phi(q)] = X(q)/X_{\text{saddle}}(q)$
$\rightsquigarrow$ Liouville action/potential
$\rightsquigarrow$ 2-d gravity results can be used for V_{eff}

$$V_{\text{eff}} = A_\perp N_c^2 \int \frac{d^2q}{(2\pi)^2} \left[e^{\Phi(q)} - \Phi(q) - 1 \right]$$

Negative Ricci scalar ⇑

✗Kinetic term: work in progress

$O[A^+] = g^2 \mathrm{tr}|A^+(q)|^2$: NUMERICAL RESULT

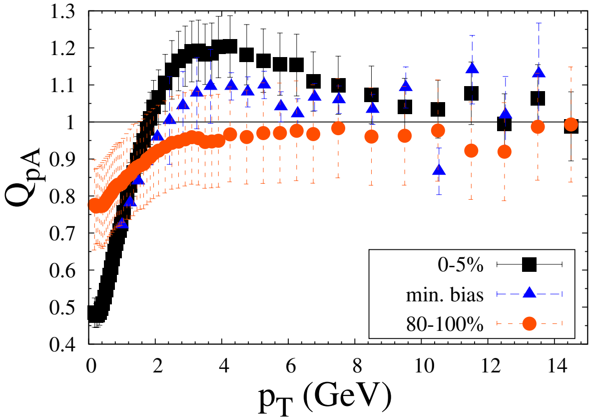


$\eta = X/X_{\mathrm{saddle}}$

A. Dumitru & V. S., Phys. Rev. D ***96****, no. 5, 056029 (2017)*

ALICE Q_{pA}

- Centrality classes based on signal in zero degree calorimeter in nucleus hemisphere
- N_{coll} for each centrality class is defined through N_{ch} at mid-rapidity



J. Adam et al. [ALICE Collaboration], Phys. Rev. C **91***, no. 6, 064905 (2015)*

Application

- We cannot replicate ALICE centrality selection
(a theorist's question: what is the zero degree calorimeter?)

- We can reweight towards configuration with more gluons at

$$p_\perp > Q_{\text{geom. scal.}} \sim Q_{sT}^2(Y)/\Lambda$$

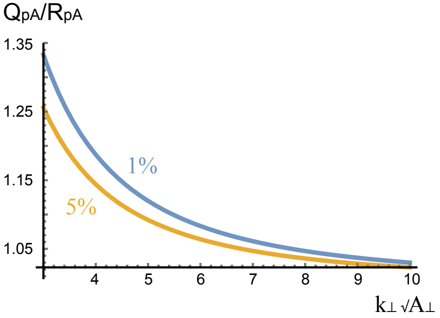
(where the anomalous dimensions ~ 1, close to DGLAP limit)

Schematically ⇓

- Take $N_{\text{coll}} = \dfrac{\int_{Q_{\text{geom. scal.}}} \left\langle \dfrac{d^2 N_{pA}}{d^2 p dy} \right\rangle_{\text{rw}}}{\int_{Q_{\text{geom. scal.}}} \left\langle \dfrac{d^2 N_{pp}}{d^2 p dy} \right\rangle}$

- Using formalism of constraint action

$$Q_{pA}(k_\perp) \approx \left(1 + \frac{8\pi \log p_r^{-1}}{N_c^2 A_\perp k_\perp^2 \log \frac{Q_{\text{UV}}^2}{Q_{sT}^2}} \right) R_{pA}(k_\perp)$$



- JIMWLK – functional renormalization group equation describing evolution of ensemble of Wilson lines at small x ($Y = \ln x_0/x$).

$$\frac{\partial}{\partial Y}\mathcal{W}[U(\mathbf{x}_\perp)] = -H\left[U, \frac{\partial}{\partial U}\right]\mathcal{W}[U]$$

- Analogous to Fokker-Plank equation.

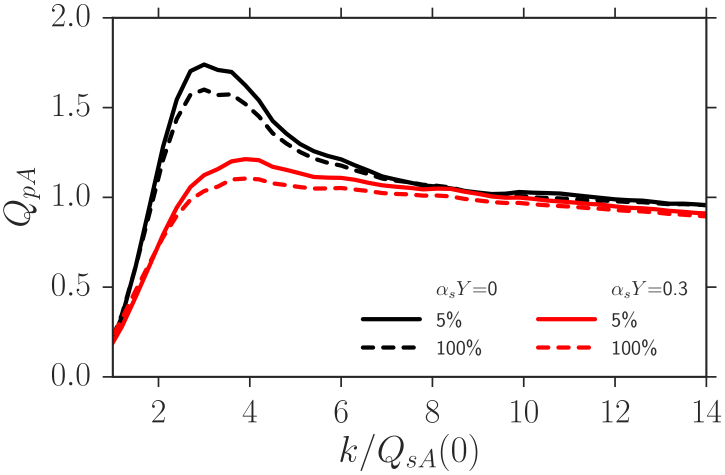
$\rightsquigarrow$ Langevin form: stochastic evolution of $U(\mathbf{x}_\perp)$ in Y.
"Random walk" in space of Wilson lines

$$\partial_Y U(\mathbf{x}) = U(\mathbf{x})\frac{i}{\pi}\int \mathbf{d}^2\mathbf{u}\frac{(\mathbf{x}-\mathbf{u})^i\eta^i(\mathbf{u})}{(\mathbf{x}-\mathbf{u})^2} - \frac{i}{\pi}\int \mathbf{d}^2\mathbf{v}U(\mathbf{v})\frac{(\mathbf{x}-\mathbf{v})^i\eta^i(\mathbf{v})}{(\mathbf{x}-\mathbf{v})^2}U^\dagger(\mathbf{v})U(\mathbf{x})$$

Gaussian white noise $\eta^i = \eta^i_a t^a$: $\langle\eta^a_i(\mathbf{x})\,\eta^b_j(\mathbf{y})\rangle = \alpha_s\,\delta^{ab}\delta_{ij}\delta^{(2)}(\mathbf{x}-\mathbf{y})$.
Noise describes gluon emission/absorption.

In mean-field approximation JIMWLK reproduces BK (Balitsky-Kovchegov) equation.

NUMERICS: RESULTS



MV initial condition with $\left(Q_{sT}(0)/Q_{sp}(0)\right)^2 \approx 6$

Numerics: Q_{pA} and $A_\perp$ dependence

$$Q_{pA}(k) \approx \left(1 + \frac{8\pi \log p_r^{-1}}{N_c^2 \, A_\perp \, k^2 \log \frac{Q_{\rm UV}^2}{Q_{sT}^2}} \right) R_{pA}(k)$$

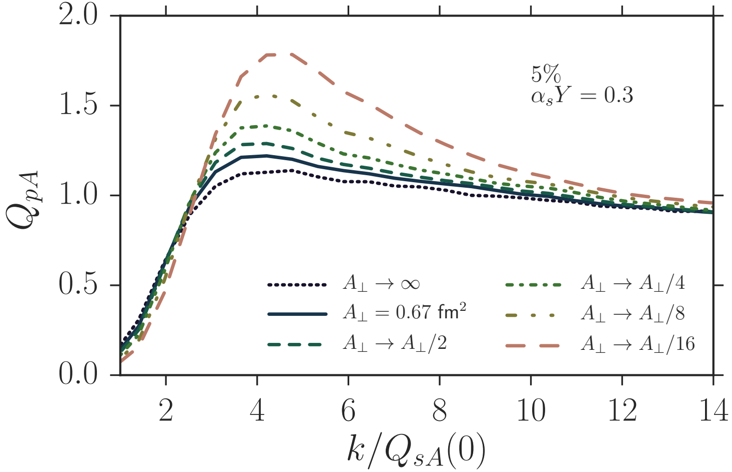
Area of projectile ⇑

Smaller projectile

$\leadsto$ larger fluctuations

$\leadsto$ larger deviation from R_{pA}

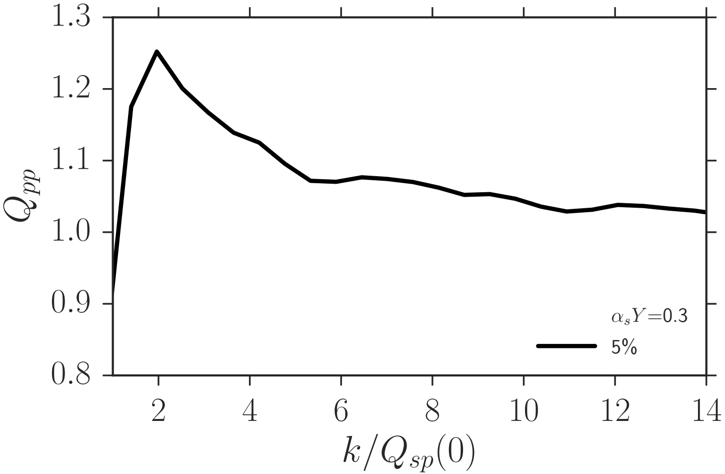
Numerics: Q_{pA} and $A_\perp$ dependence



MV initial condition with $\left(Q_{sT}(0)/Q_{sp}(0)\right)^2 \approx 6$

Varying $A_\perp$ through dijet/Z-boson trigger?!

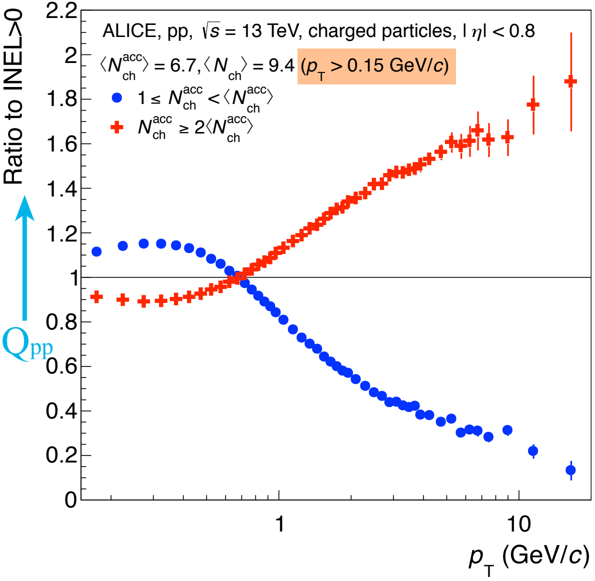
NUMERICS: Q_{pp}



MV initial condition with $\left(Q_{sT}(0)/Q_{sp}(0)\right)^2 \approx 1$

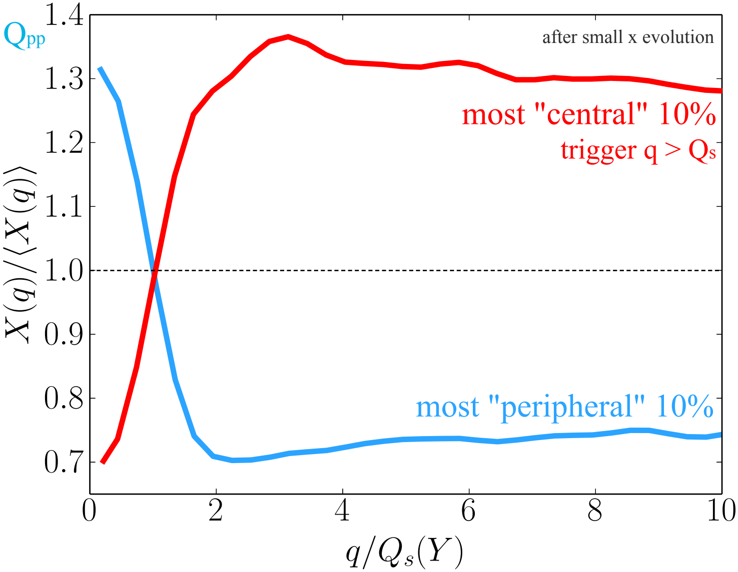
- Naive implementation: tiny number of particles with $q > Q_{gs}$

Different "centrality" definition, Q_{pp}



J. Adam et al. [ALICE Collaboration], Phys. Lett. B **753**, *319 (2016), arXiv:1509.08734*

Different "centrality" definition, Q_{pp}



A. Dumitru & V. S., Phys. Rev. D **96***, no. 5, 056029 (2017), arXiv:1704.05917*

Conclusions

- Saturation framework/CGC provides an opportunity
  to study regions of high parton density from first principles.

- CGC inspired models ≠ CGC

- Naive handwaving arguments ≠ CGC

- “Shut up and compute!”

- Nuclear modification factor: promising if color fluctuations are accountred for.
  In this talk: proof of the concept. Resolves the conundrum $Q_{pA} > R_{pA}$;
  $\rightsquigarrow$ re-apperence of Cronin peak

- Quantitatve comparison: in progress