Correlations of Quark-antiquarks in pA collisions

Mauricio Martinez Guerrero

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Collaborators: M. Sievert, D. Werteptny, J. Noronha-Hostler

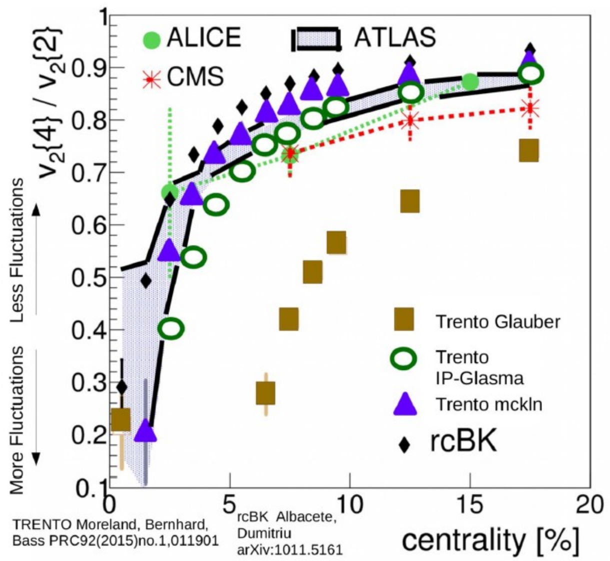
JHEP 1807 (2018) 03, JHEP 1902 (2018) 024, Forthcoming

BEST COLLABORATION

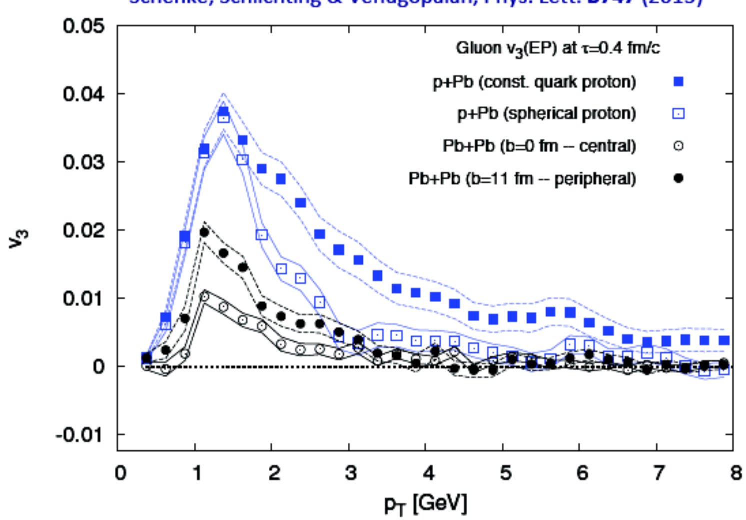
NC STATE UNIVERSITY

Role of sub-nucleonic fluctuations

G. Giacalone et al., Phys. Rev. **C95** (2017)



Schenke, Schlichting & Venugopalan, Phys. Lett. **B747** (2015)

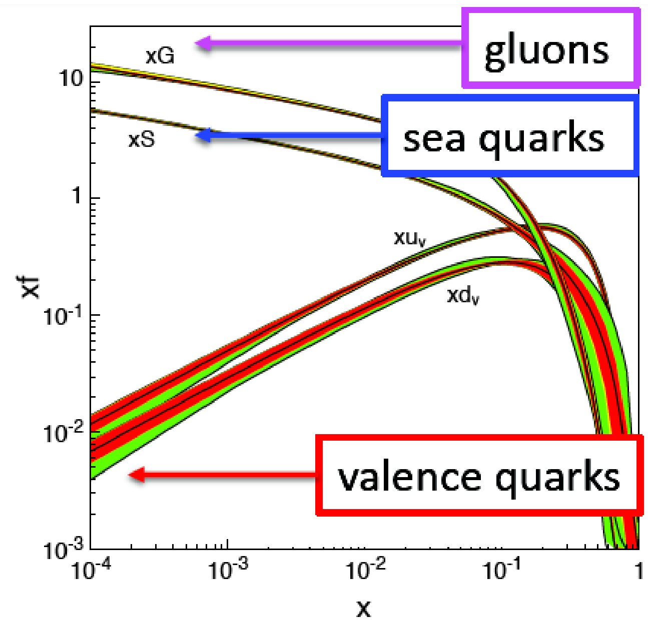


- Fluctuations in the initial state of heavy ion collisions contribute to measured anisotropic flow

- For especially sensitive observables, **sub-nucleonic fluctuations** significantly enhance the total flow and are necessary to describe heavy ion collisions.

Including quarks in the initial state

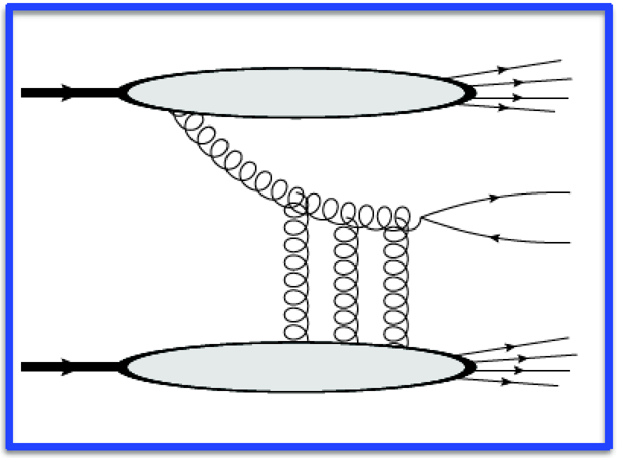
- In high-energy collisions, the nuclei are dominated by **soft gluon radiation**
  - ➢ Contribute to sub-nucleonic fluctuations of the **energy density**



- **Other quantum numbers** like flavor and baryon number are carried only by **quarks**

➢ The **net** production of these conserved charges is **nearly zero**

➢ But there is a characteristic pattern of **fluctuations** due to **pair production**



Observable

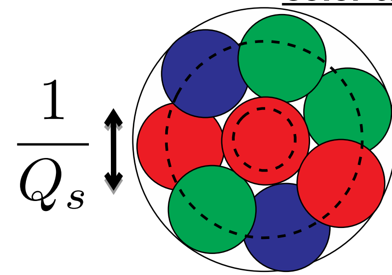
- **Goal**: Calculate (anti)quark correlations in heavy-light ion collisions
  - ➢ Coordinate space profile for hydro
  - ➢ What is the typical size of a baryon number domain?

$$\mathcal{C}^{q\bar{q}}(B_{1\perp}, Y_1; B_{2\perp}, Y_2) = \left\langle \frac{dn^q}{d^2B_1\, dY_1} \frac{dn^{\bar{q}}}{d^2B_2\, dY_2} \right\rangle - \left\langle \frac{dn^q}{d^2B_1\, dY_1} \right\rangle \left\langle \frac{dn^{\bar{q}}}{d^2B_2\, dY_2} \right\rangle$$

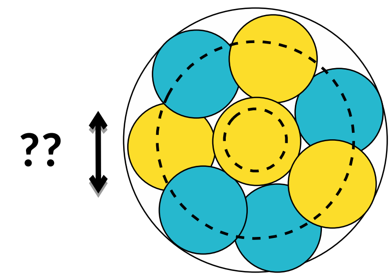
$$\left\langle \frac{dn^q}{d^2B_1\, dY_1} \frac{dn^{\bar{q}}}{d^2B_2\, dY_2} \right\rangle = \frac{1}{\sigma_{inel}} \frac{d\sigma^{q\bar{q}}}{d^2B_1\, dY_1\, d^2B_2\, dY_2}$$

$$\left\langle \frac{dn^q}{d^2B_1\, dY_1} \right\rangle = 0$$

Color charge



Baryon Number

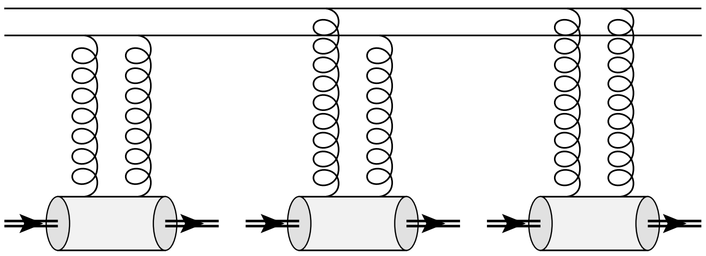


- Various mechanisms dominate at various length scales
  - ➢ Work to LO in each regime
  - ➢ Avoid complicated rescattering corrections

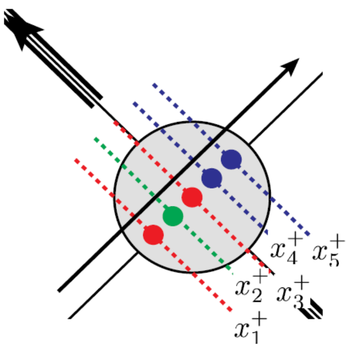
Theoretical setup

- Dilute-Dense (pA) resummation of QCD
  - Dense target: classical gluon fields
  - High density sets hard momentum scale

$$\alpha_s^2 A^{1/3} \sim 1 \qquad Q_s^2 \sim \alpha_s \rho$$



- Light-cone "time"-ordered dynamics
  - Wave functions in light-front perturbation theory ($A^+=0$ gauge)
  - Eikonal scattering via Wilson lines



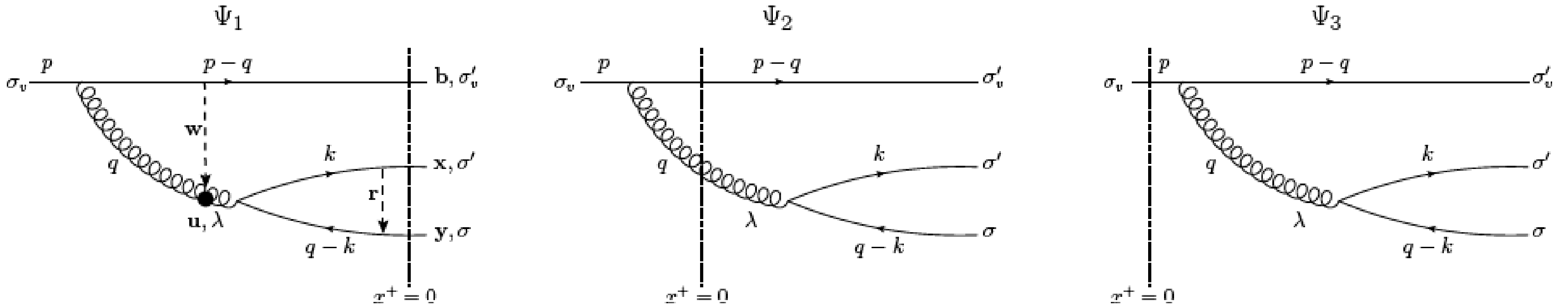
D. Wertepny, Ph. D. Thesis (2016) arXiv: 1608.08618

- "Heavy-light" (aA) paradigm incorporates projectile density order by order in perturbation theory
  - E.g.) [3]He+Au or Cu+Au
  - Moves toward the dense-dense limit

$$\alpha_s^2 A^{1/3} \sim 1$$

$$\alpha_s \ll \alpha_s^2 a^{1/3} \ll 1$$

Ingredients I: wave functions



$$\Psi_1 + \Psi_2 + \Psi_3 = 0$$

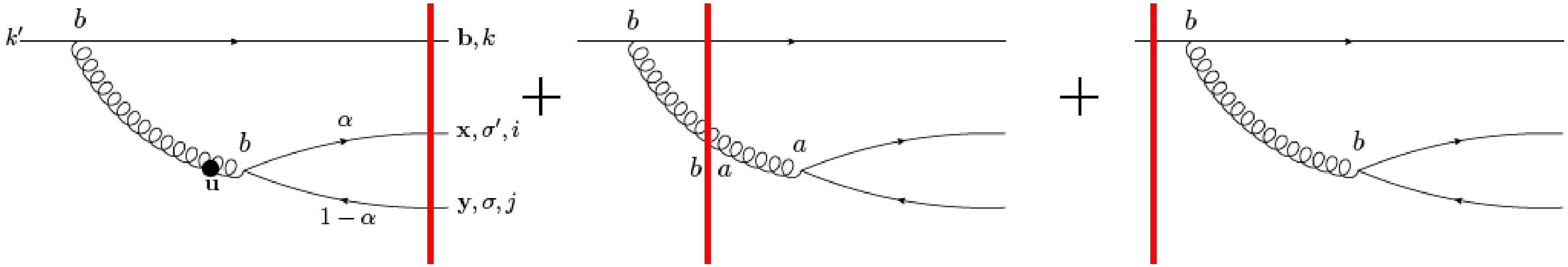
Blaizot, Gelis, & Venugopalan, Nucl. Phys. **A743** (2004)

Kovchegov & Tuchin, Phys. Rev. **D74** (2006)

- **"Time"-ordered wave functions** in coordinate space:

E.g.) $$\Psi_2(w_\perp, r_\perp, \alpha) = -\frac{2\alpha_s}{\pi}\sqrt{\alpha(1-\alpha)}\left\{\delta_{\sigma,-\sigma'}\frac{m}{w_T}K_1(mr_T)\left[(1-2\alpha)\frac{\vec{w}_\perp\cdot\vec{r}_\perp}{w_T r_T} - i\sigma'\frac{\vec{w}_\perp\times\vec{r}_\perp}{w_T r_T}\right]\right.$$
$$\left. + i\sigma'\delta_{\sigma\sigma'}\frac{m}{w_T}K_0(mr_T)\left[\frac{w_\perp^1}{w_T} - i\sigma'\frac{w_\perp^2}{w_T}\right]\right\}$$

Ingredients II: amplitude



- The high-energy scattering **dresses the WFs** with **Wilson lines**:

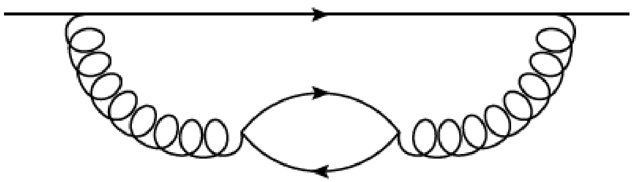
$$V_{\boldsymbol{x}} \equiv \mathcal{P} \exp\left[ig \int dx^+ A^-(x^+, 0^-, \boldsymbol{x}) \right]$$

- **Building block:** color and spin matrix at the amplitude level

$$(\tilde{\mathcal{A}}_{NA})_{(ij)\,(kk')\,(\sigma\sigma')}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{b}, \boldsymbol{u}, \alpha) \equiv (V_{\boldsymbol{b}} t^b)_{kk'} \left[\left[W_1^b(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{b})\right]_{ij} \left[\tilde{\Psi}_1(\boldsymbol{u}-\boldsymbol{b}, \boldsymbol{x}-\boldsymbol{y}, \alpha)\right]_{\sigma', -\sigma} + \left[W_2^b(\boldsymbol{u}, \boldsymbol{b})\right]_{ij} \left[\tilde{\Psi}_2(\boldsymbol{u}-\boldsymbol{b}, \boldsymbol{x}-\boldsymbol{y}, \alpha)\right]_{\sigma', -\sigma} \right],$$

$$W_1^b(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{b}) \equiv V_{\boldsymbol{x}} t^b V_{\boldsymbol{y}}^\dagger - V_{\boldsymbol{b}} t^b V_{\boldsymbol{b}}^\dagger \qquad W_2^b(\boldsymbol{u}, \boldsymbol{b}) \equiv V_{\boldsymbol{u}} t^b V_{\boldsymbol{u}}^\dagger - V_{\boldsymbol{b}} t^b V_{\boldsymbol{b}}^\dagger$$

Single pair quark correlations



$$\left\langle |\tilde{A}_{NA}|^2 \right\rangle = \frac{1}{2N_c} \sum_{i,j=1}^{2} \left(\mathcal{U}_i \mathcal{U}_j - \mathcal{L}_i \mathcal{L}_j + \boldsymbol{\mathcal{T}}_i \cdot \boldsymbol{\mathcal{T}}_j \right) \underbrace{\left\langle \mathrm{tr}_C [W_i^b W_j^{b\,\dagger}] \right\rangle}_{\Omega_{ij}}$$

- The **single-pair result** is simple and familiar:

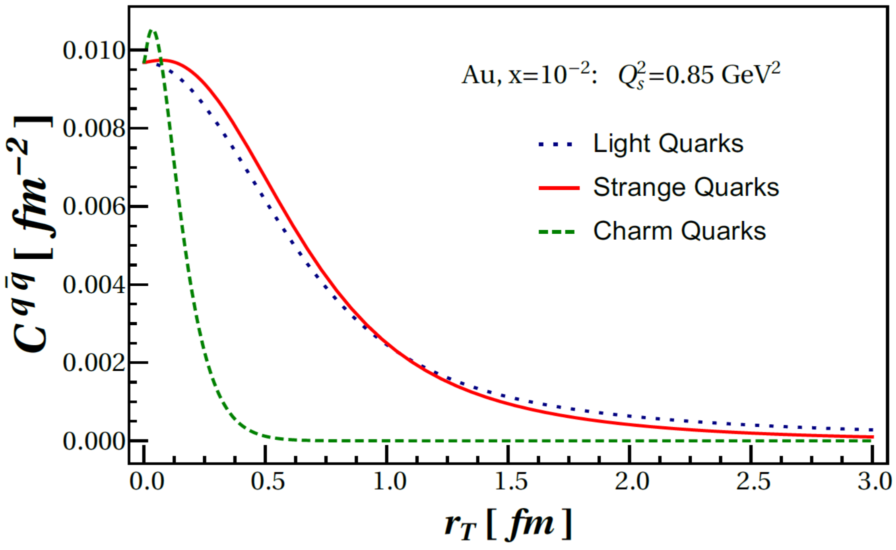
E.g.) $$\Omega_{11} = 2N_c C_F - \frac{1}{2} N_c^2 \left\langle \hat{D}_2(\boldsymbol{B}_1, \boldsymbol{b}_1) \hat{D}_2(\boldsymbol{b}_1, \boldsymbol{B}_2) \right\rangle - \frac{1}{2} N_c^2 \left\langle \hat{D}_2(\boldsymbol{B}_2, \boldsymbol{b}_1) \hat{D}_2(\boldsymbol{b}_1, \boldsymbol{B}_1) \right\rangle + \frac{1}{2} \left\langle \hat{D}_2(\boldsymbol{B}_1, \boldsymbol{B}_2) \right\rangle + \frac{1}{2} \left\langle \hat{D}_2(\boldsymbol{B}_2, \boldsymbol{B}_1) \right\rangle$$

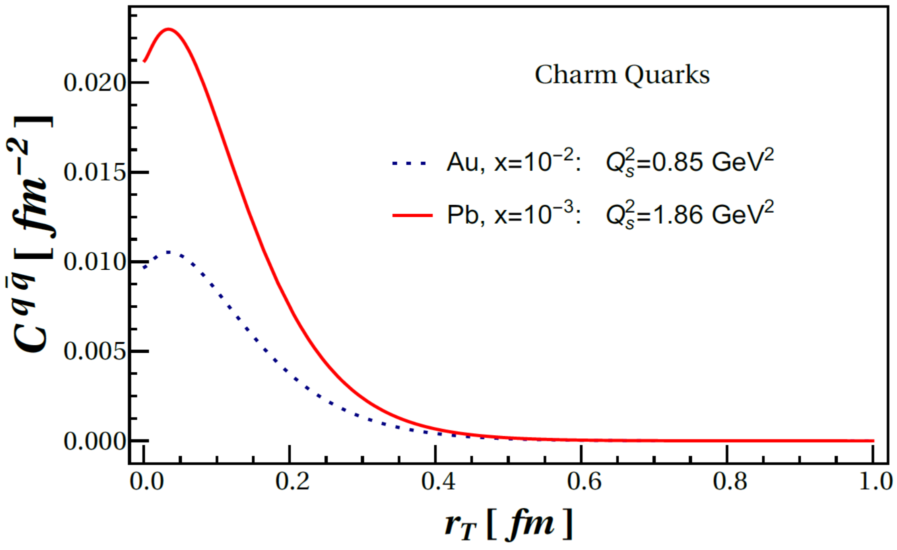
- **Dipole** degrees of freedom: $\hat{D}_2(\boldsymbol{x}, \boldsymbol{y}) \equiv \frac{1}{N_c} \mathrm{tr}_C \left[V_{\boldsymbol{x}} V_{\boldsymbol{y}}^\dagger \right]$

- Normalize by the inelastic cross-section (**1-gluon production**)

$$\sigma_{inel} = \frac{\alpha_s N_c}{\pi^2} (a\, \Delta Y) \int \frac{d^2 x_1\, d^2 x_2}{(x_{21})_T^2} \left\langle 1 - \left| \hat{D}_2(\boldsymbol{x}_1, \boldsymbol{x}_2) \right|^2 \right\rangle$$

Correlation function

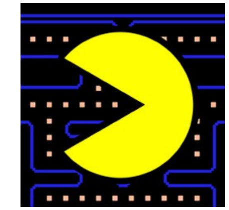


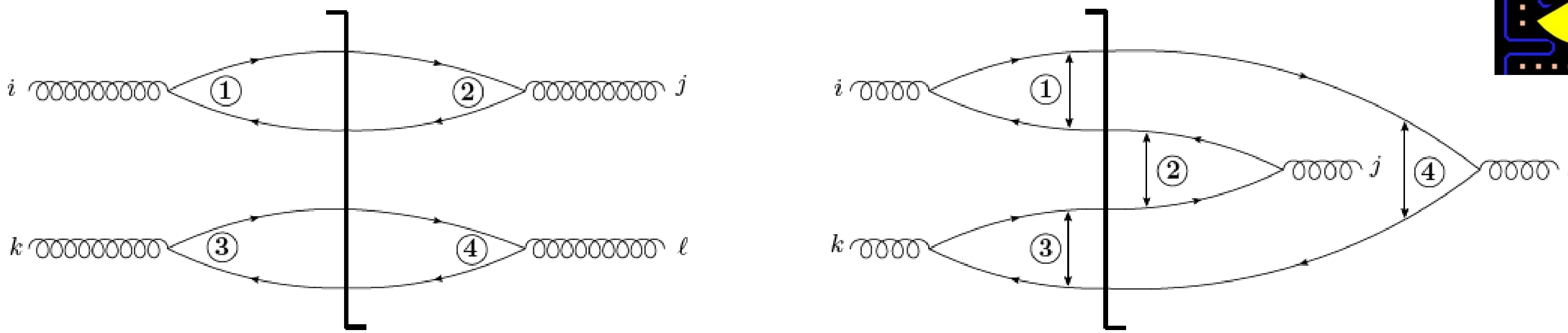


- The **range of the correlation** is controlled by the **quark mass**, not the saturation scale

- But the **strength of the correlation** is controlled by **Qs**
  - Interaction mediated correlations: a **genuine pA / aA effect**
  - Arises from the **interference of gluon / pair scattering**

Double pair production: Direct emissions vs. pacman diagrams





$$K_1^+ K_2^+ \frac{d\sigma_{double}}{d^2B_1 dK_1^+ \, d^2B_2 dK_2^+} = \int d^2B \, d^2b_1 \, d^2b_2 \, T_a(\boldsymbol{b}_1 - \boldsymbol{B}) \, T_a(\boldsymbol{b}_2 - \boldsymbol{B}) \int \left(\prod_{i=1}^{4} d^2x_i \frac{dk_i^+}{4\pi k_i^+} \right)$$

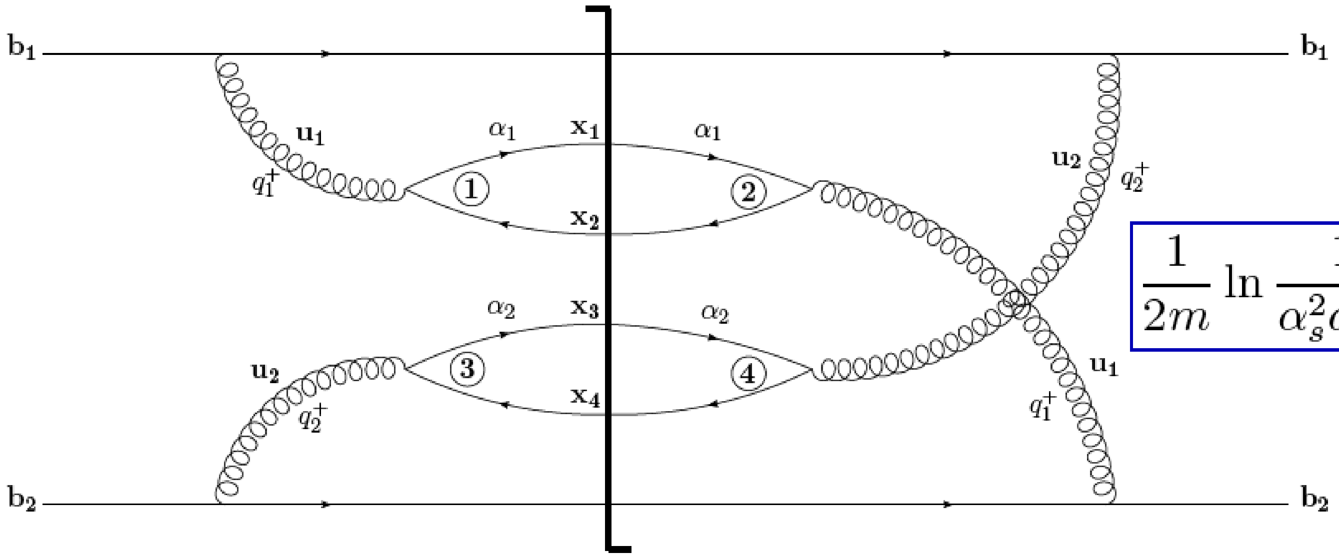
$$\times \, |\tilde{A}_{NNA}(\boldsymbol{b}_1, \boldsymbol{b}_2; \{\boldsymbol{x}_i, k_i^+\}_{i=1}^4)|^2 \, Z(\boldsymbol{B}_1, K_1^+, \boldsymbol{B}_2, K_2^+, \{\boldsymbol{x}_i, k_i^+\}_{i=1}^4).$$

Tagging delta functions

Altinoluk et. al., (2017)
MSW (2018)

- In heavy-light power counting, **double-pair production is suppressed vs single-pair**, but it becomes important for **quark/quark correlations** and at **distances larger than 1/m**
  - Opens up several **new channels** for correlations

Double pair production: intermediate regime

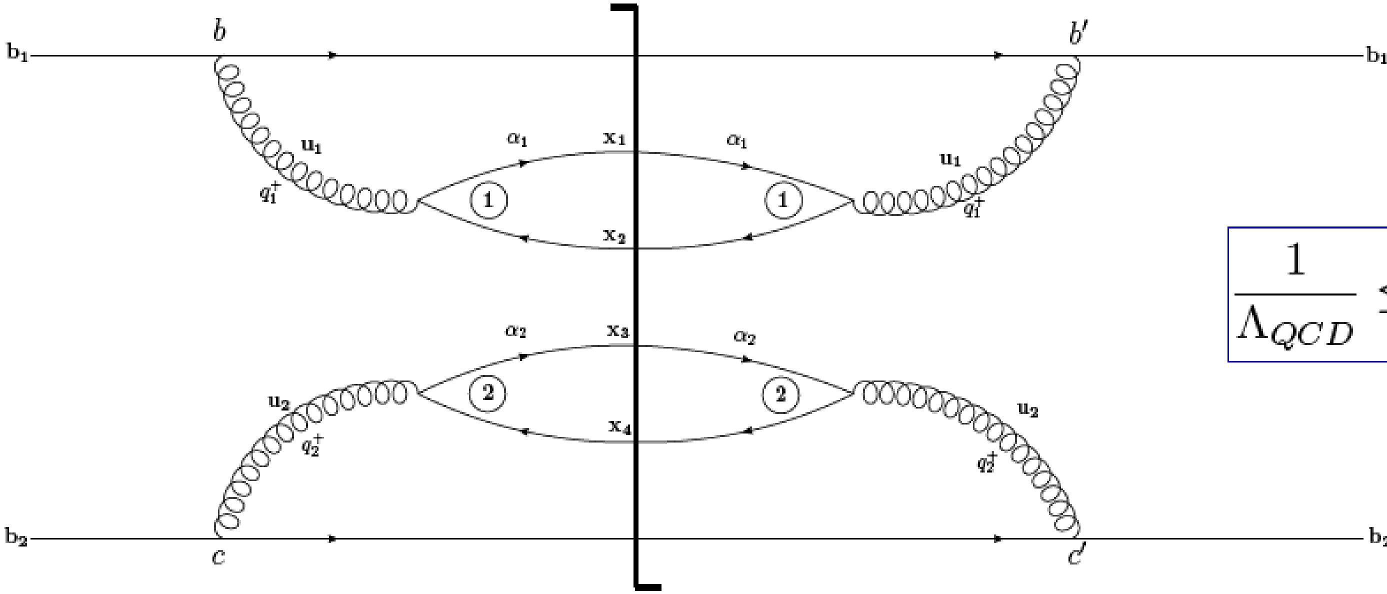


$$\frac{1}{2m}\ln\frac{1}{\alpha_s^2 a^{1/3}} \ll |\boldsymbol{B}_1 - \boldsymbol{B}_2|_T \ll \frac{1}{\Lambda_{QCD}}$$

- For **heavy quarks**, there is an intermediate region which is dominated by **separated double-pair production**, but is still **perturbative**.

- Correlations arise from **perturbative mechanisms**:
  - Gluon entanglement
  - Scattering in correlated color fields

Double pair production: geometrical



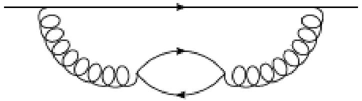
$$\frac{1}{\Lambda_{QCD}} \leq |\boldsymbol{B_1} - \boldsymbol{B_2}|_T \leq R_a$$

- Over **nonperturbative distances**, the two pairs are not connected by any perturbative degrees of freedom
  - Scatter in **uncorrelated color fields** from disjoint nucleons
  - Cross-section **factorizes**, but **geometrical correlations** remain

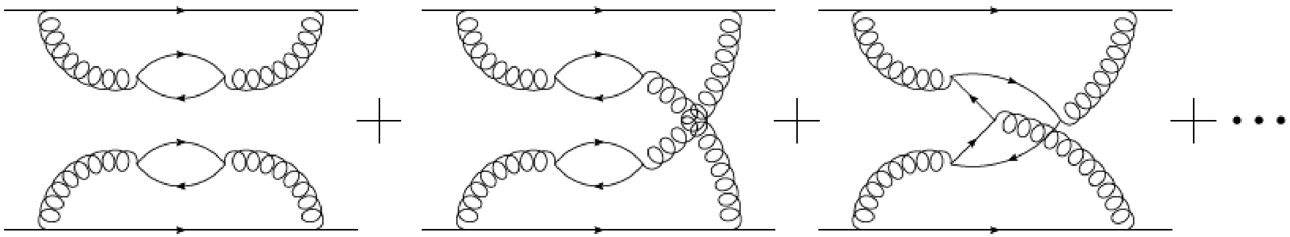
Summary I

$$|\boldsymbol{B_1} - \boldsymbol{B_2}|_T \le \min\left[\frac{1}{2m}\ln\frac{1}{\alpha_s^2 a^{1/3}}\,,\ \frac{1}{\Lambda_{QCD}}\right]$$

$\mathcal{C}_{q\bar{q}} \sim$

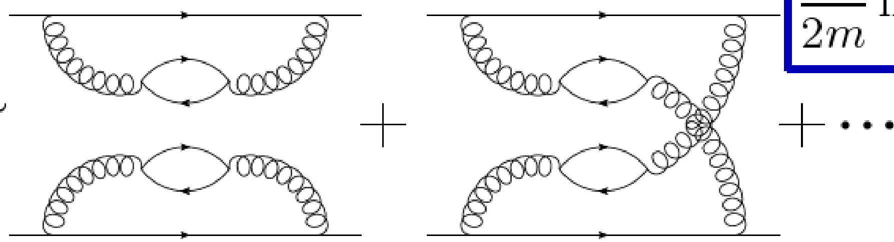


$\mathcal{C}_{qq} \sim \mathcal{C}_{\bar{q}\bar{q}} \sim$



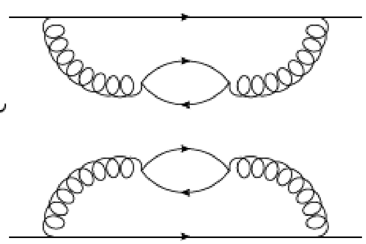
$$\frac{1}{2m}\ln\frac{1}{\alpha_s^2 a^{1/3}} \ll |\boldsymbol{B_1} - \boldsymbol{B_2}|_T \ll \frac{1}{\Lambda_{QCD}}$$

$\mathcal{C}_{q\bar{q}} \sim \mathcal{C}_{qq} \sim \mathcal{C}_{\bar{q}\bar{q}} \sim$

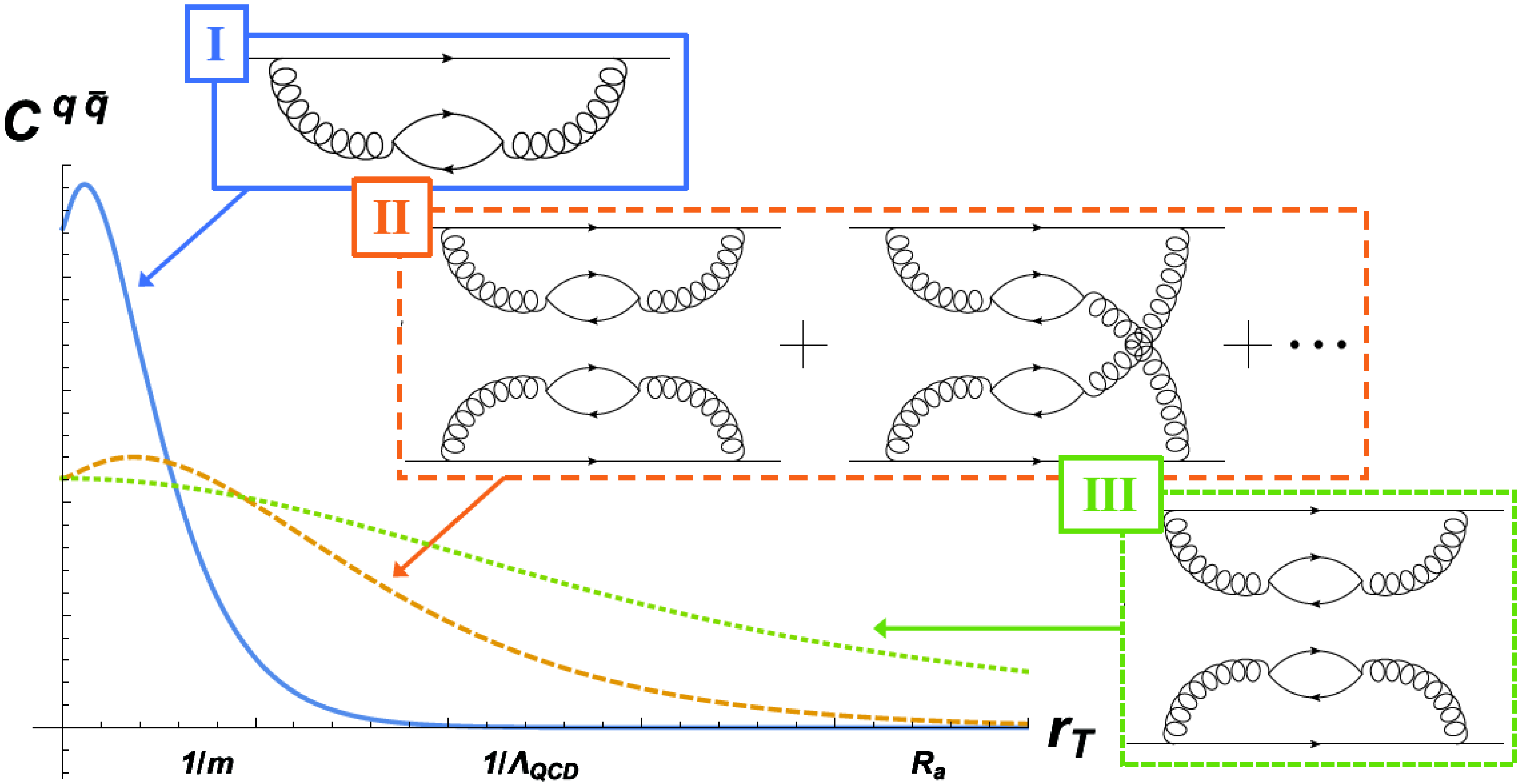


$$\frac{1}{\Lambda_{QCD}} \le |\boldsymbol{B_1} - \boldsymbol{B_2}|_T \le R_a$$

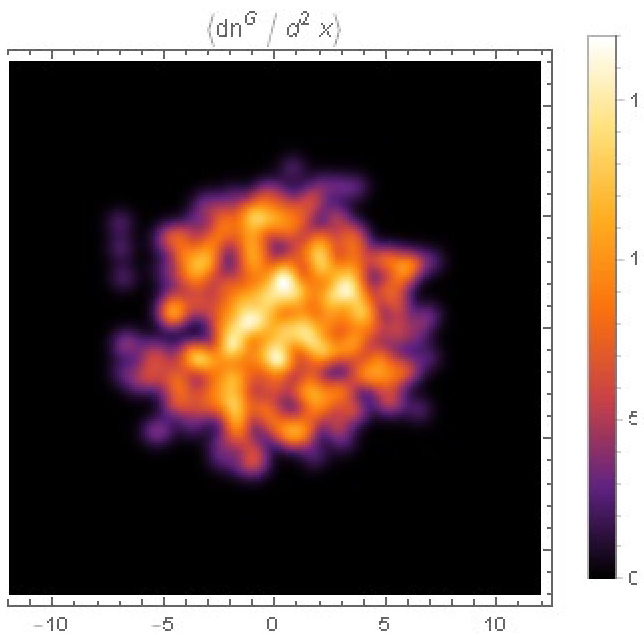
$\mathcal{C}_{q\bar{q}} \sim \mathcal{C}_{qq} \sim \mathcal{C}_{\bar{q}\bar{q}} \sim$

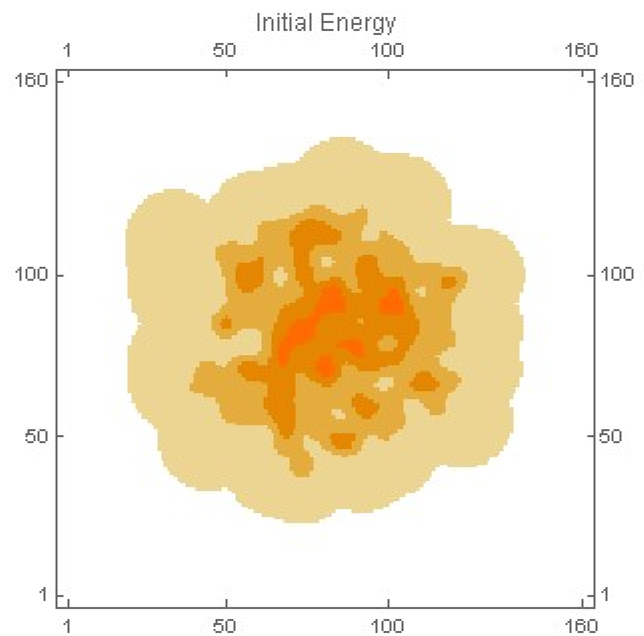


Summary II



Towards initial conditions for conserved charges



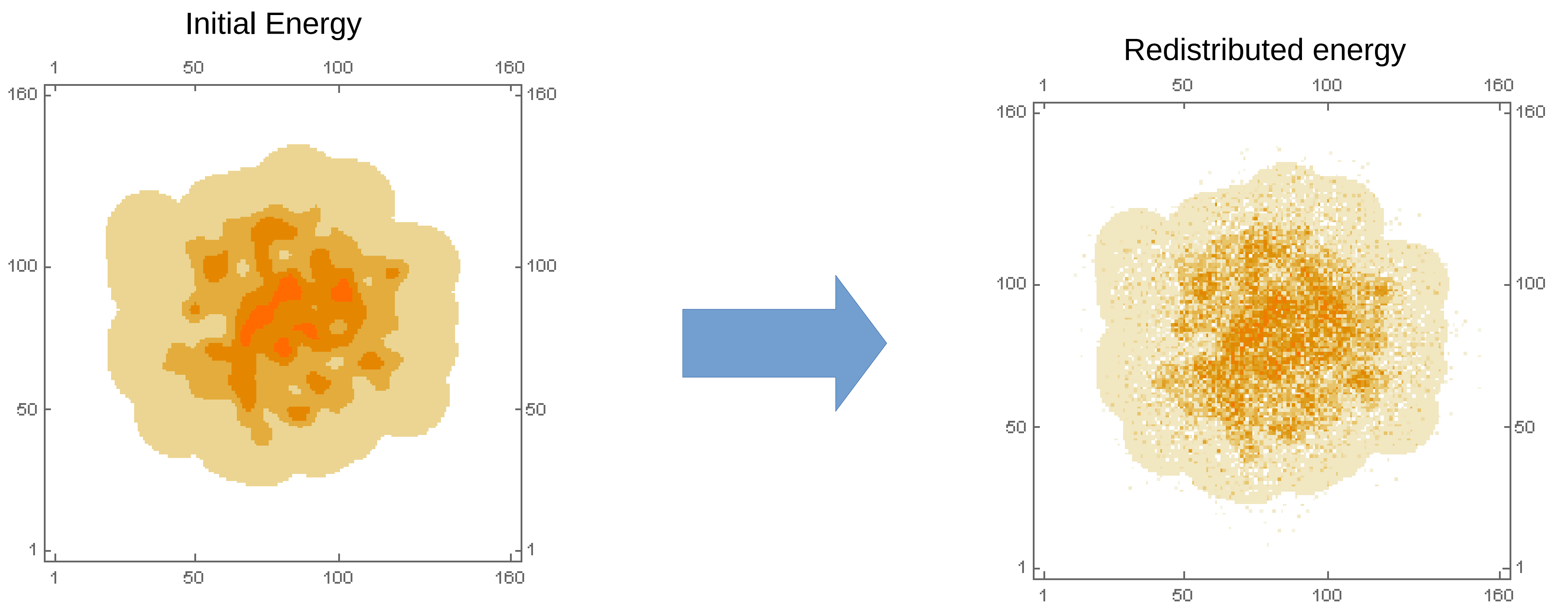


Step 1

- MC Glauber is used to generate the initial energy distribution of the collision.
- Since this is dominated by gluons we can use this to find the gluon density at a given point.

Forthcoming: Carzon, Martinez, Noronha-Hostler, Sievert, Werteptny

Redistributing energy $g \rightarrow q\bar{q}$

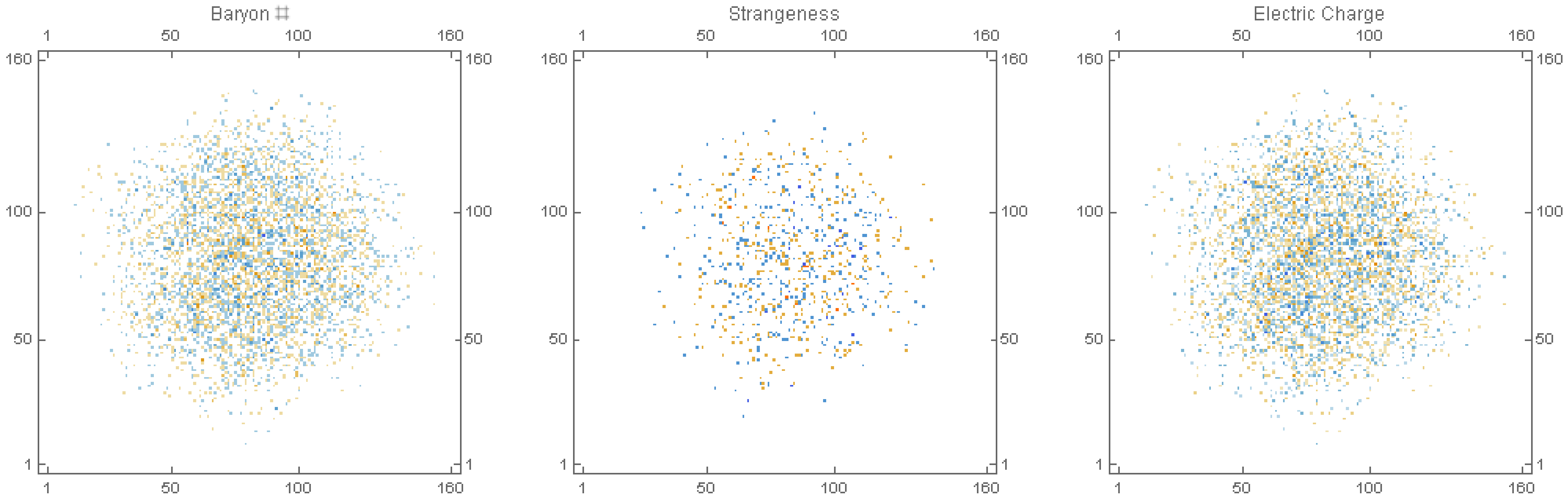


Step 2

- Once we know the number of gluons produced we can find the number of quark – antiquark pairs produced at a given point in the transverse plane

Forthcoming: Carzon, Martinez, Noronha-Hostler, Sievert, Werteptny

Conserved charge distributions



- We can also take a look to fluctuations of baryon number distributions, strangeness and electric charge in a given event in pA collisions

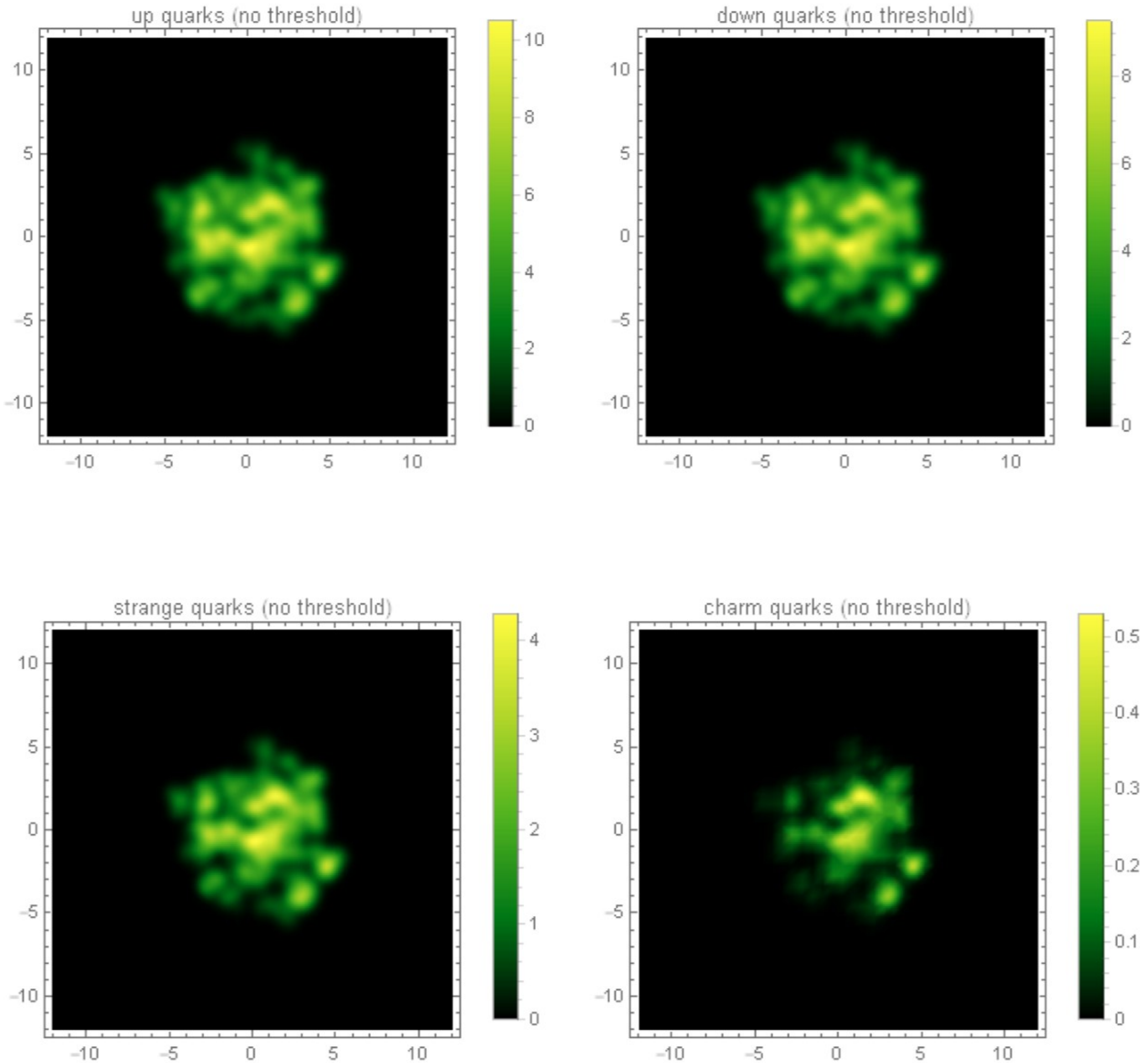
Forthcoming: Carzon, Martinez, Noronha-Hostler, Sievert, Werteptny

Quark pair density distribution in pA collisions: preliminary results

Mean $q\bar{q}$ density distribution for different flavors.

- Shape of the distribution changes depending on the mass of the pair.
- Different eccentricities

  which are flavor-dependent



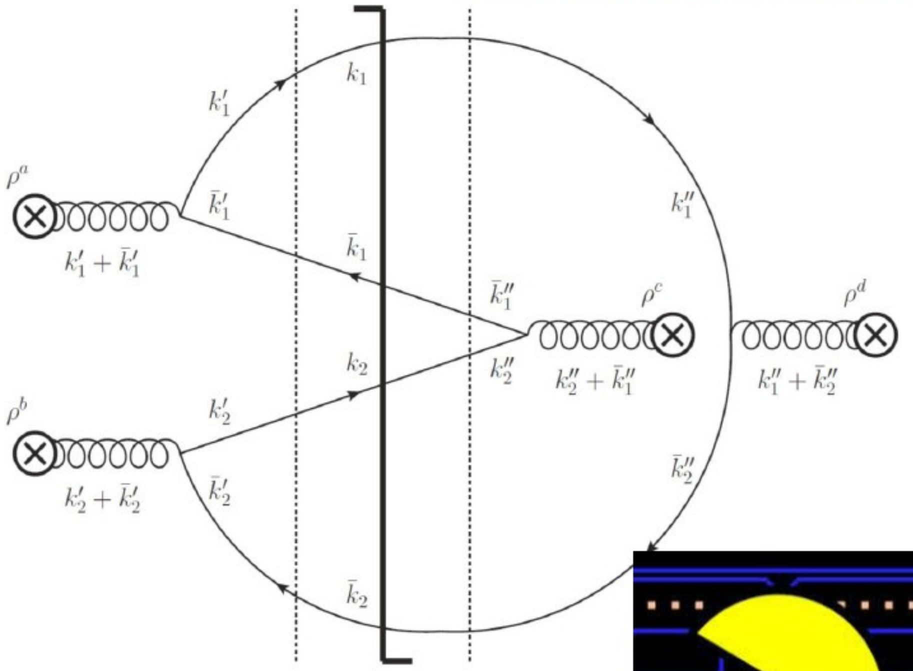
Forthcoming: Carzon, Martinez, Noronha-Hostler, Sievert, Werteptny

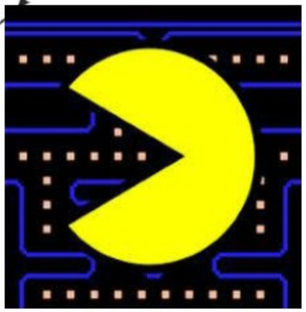
More about double pair correlations

- **Double $c\bar{c}$ production** introduces a first sensitivity to **quark Fermi statistics**
  - Antisymmetric wave functions
  - Reduces correlations among quarks
  - Not a **"ridge,"** but a **"trough"**

- New classes of "non-flow" quantum correlations are possible
  - Cleanest identification of quark channels in the **heavy sector**

"Pac Man Correlations"





T. Altinoluk et al., Phys. Rev. **D95** (2017)

M. Martinez, **MS**, D. Wertepny, JHEP **19 02** (2019)

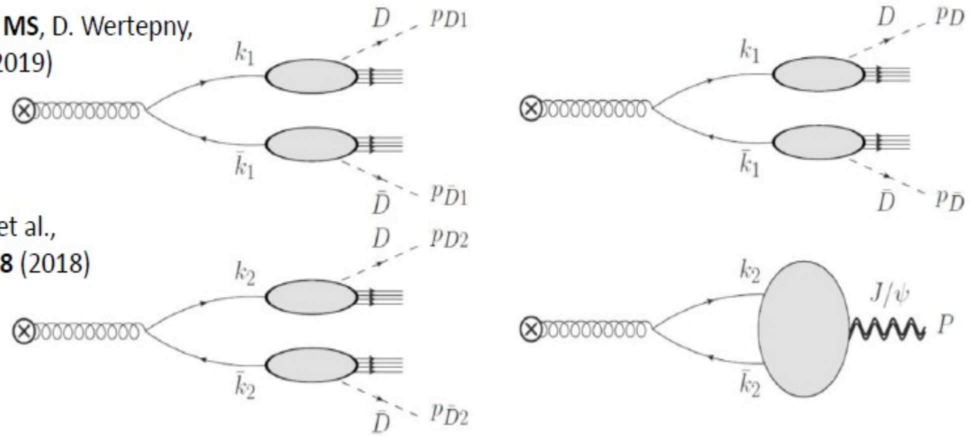
One calculation to rule them all

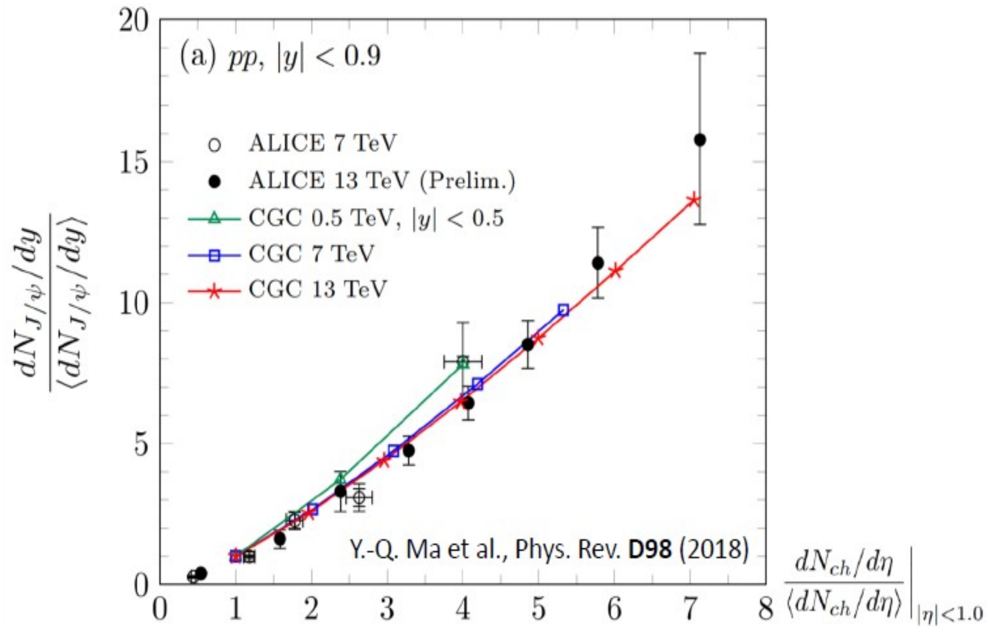
- One $(c\bar{c})(c\bar{c})$ calculation can be **simultaneously constrained** in both the D and J/ψ sectors
  - ➢ $c\bar{c} \rightarrow D\bar{D}$ by fragmentation
  - ➢ $c\bar{c} \rightarrow J/\psi$ by NRQCD / ICEM

- Like in **pQCD for pp**, we can honestly **test the partonic** mechanisms
  - ➢ $(D\bar{D})\,(D\bar{D})$
  - ➢ $(D\bar{D})\,(J/\psi)$
  - ➢ $(J/\psi)\,(J/\psi)$
  - ➢ $(D\bar{D})\,h$
  - ➢ $(J/\psi)\,h$
  - ➢ Bottom sector?

M. Martinez, **MS**, D. Wertepny, JHEP **19 02** (2019)

R. Boussarie et al., Phys. Rev. **D98** (2018)





Conclusions

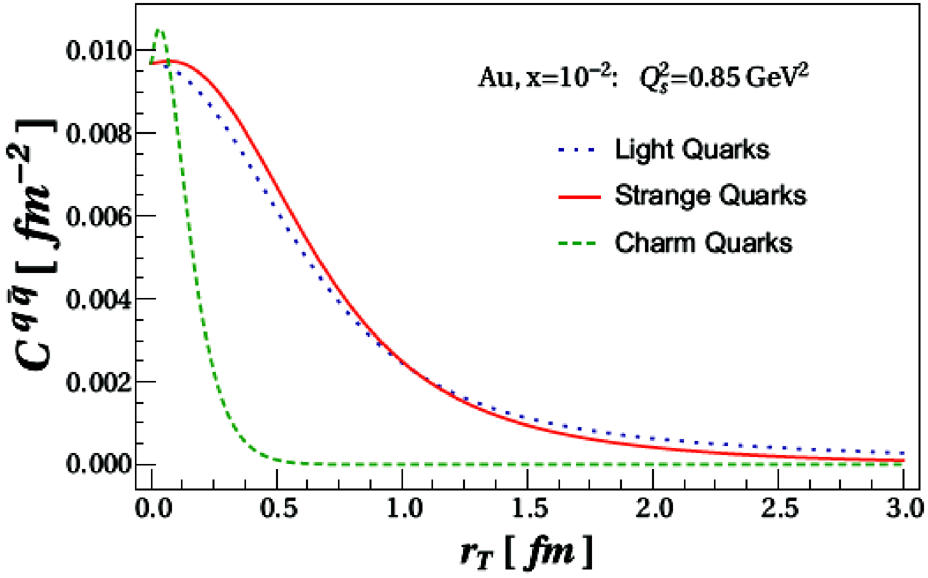
- We have computed in detail the **spatial correlations among quarks and antiquarks** in the initial stages of heavy-ion collisions
  - **Explicit results** for single-pair production
  - **Operator-level results** for double-pair production
- **Ultimate goal:** perform event-by-event sampling of all 3 regions to initialize various conserved charges.

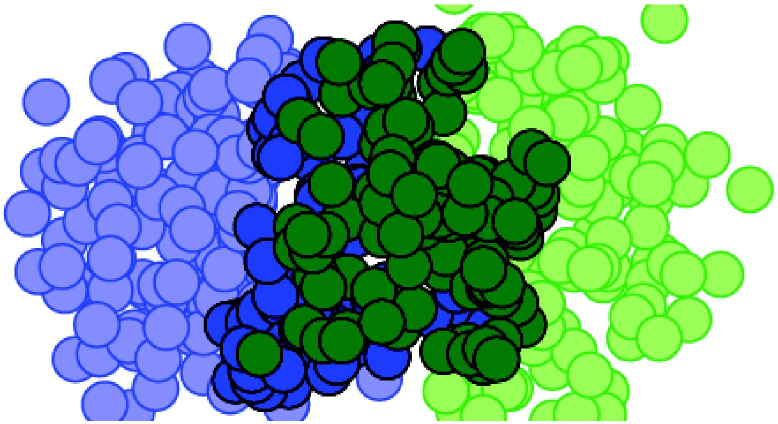
Outlook

- There are many places we can **improve on the approximations** for the single-pair result

➢ In addition to the correlations, we can also calculate the **local fluctuations**

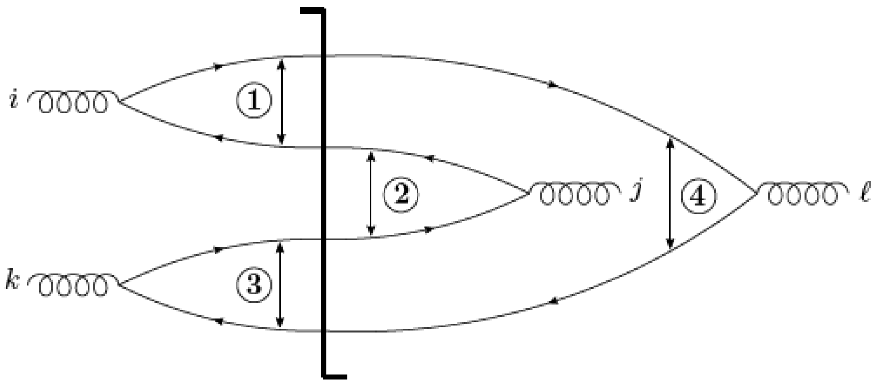
- This is an ideal **testbed for the Monte Carlo sampling** and proof of principle.





Outlook II

- We have the **formal results** for the double-pair calculation, but they're **long and unwieldy**



  - Analytic tools are likely to be of limited value; need **numerics**

- ...But directly applicable to **many measured correlations**
  - **Double-quarkonia** correlations
  - **4-particle open heavy / light flavor** correlations
  - Same sign / opposite sign **charge correlations**, etc.

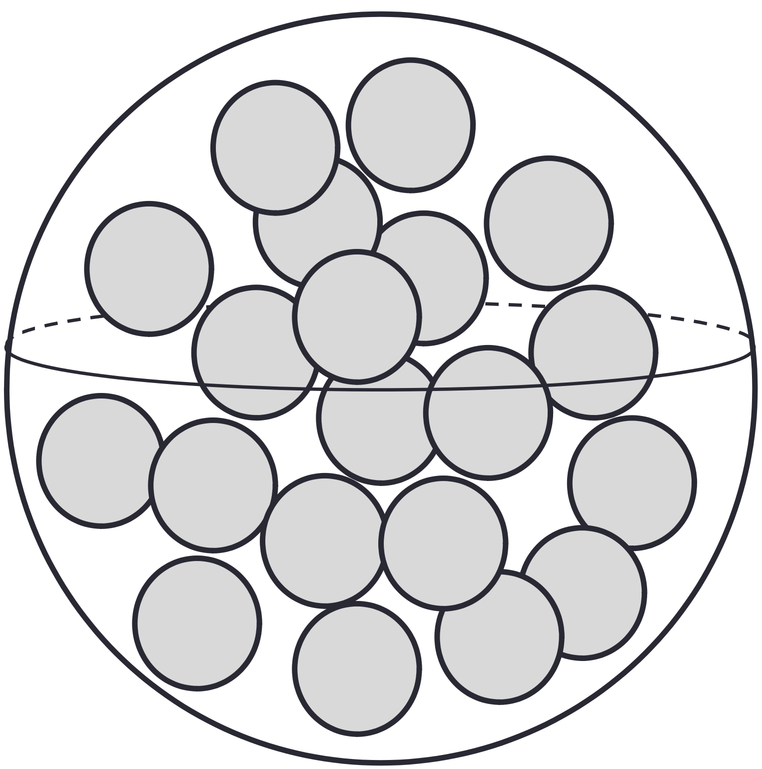
Backup slides

Model for the nucleus at high energies

- Heavy Ions can be thought of as a bag of nucleons.
- Volume scales with the number of nucleons: $r \sim A_T^{\frac{1}{3}}$

$$\int d^3r\, \rho(\vec{r}) = A_T$$

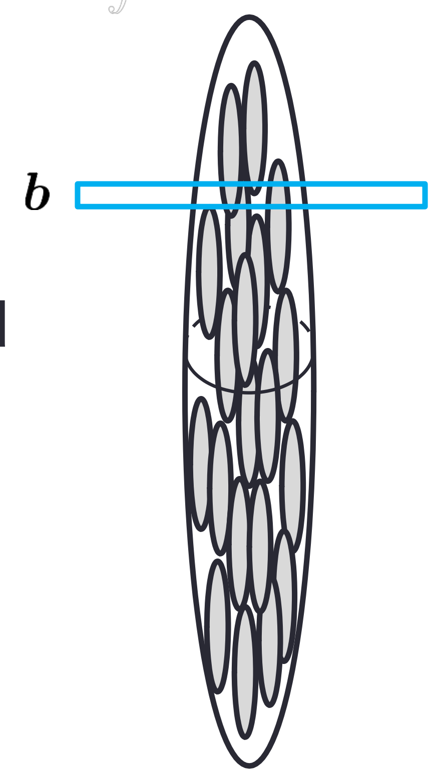
$$T(b) = \int dz\, \rho(\vec{r}) \sim A_T^{\frac{1}{3}}$$



Lorentz Contracted (per nucleon):

RHIC: $\gamma \sim 200$

LHC: $\gamma \sim 5000$



Interacting with a single nucleon

- Quark/gluon interacts with a nucleon
- Exchanges 2 gluons
- Introduces the saturation scale (classical)

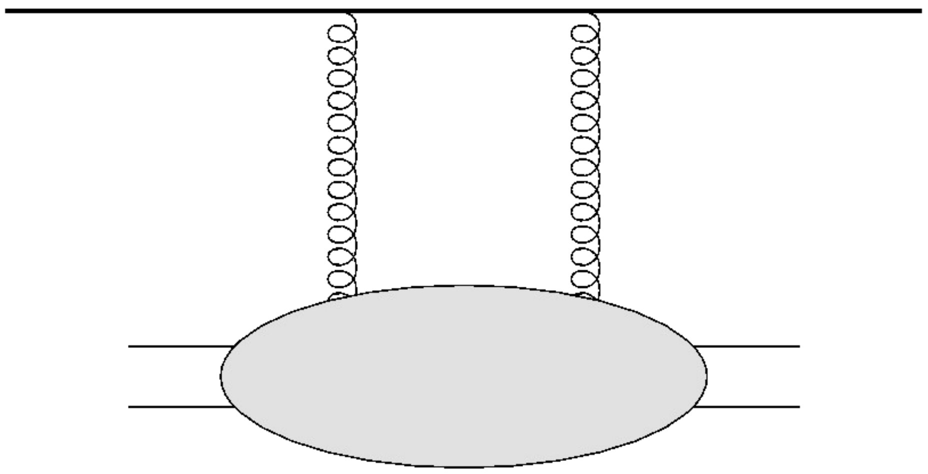
$$Q_{s0}^2 = 4\pi\alpha_s^2 T(\boldsymbol{b})$$

- On the order of

$$Q_{s\,T}^2 \sim \alpha_s^2 A_T^{\frac{1}{3}}$$

- In heavy ions

$$\alpha_s^2 A_T^{\frac{1}{3}} \sim 1$$



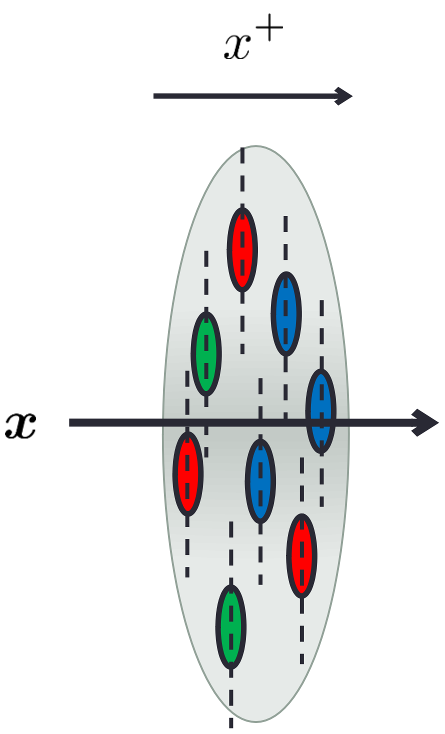
Interacting with many nucleons

- Quarks and gluons pass through the shock wave
- Interaction is nearly instantaneous
- Doesn't change transverse position
- Interacts with fields from many nucleons
- Gains a factor per nucleon

$$Q_{sT}^2 \sim \alpha_s^2 \, A_T^{\frac{1}{3}}$$

- For a heavy ion we can consider all the scatterings if

$$\alpha_s^2 \, A_T^{\frac{1}{3}} \sim 1$$



$$Q_{sT}^2 \sim \alpha_s^2 \, A_T^{\frac{1}{3}}$$

The interaction is a Wilson line

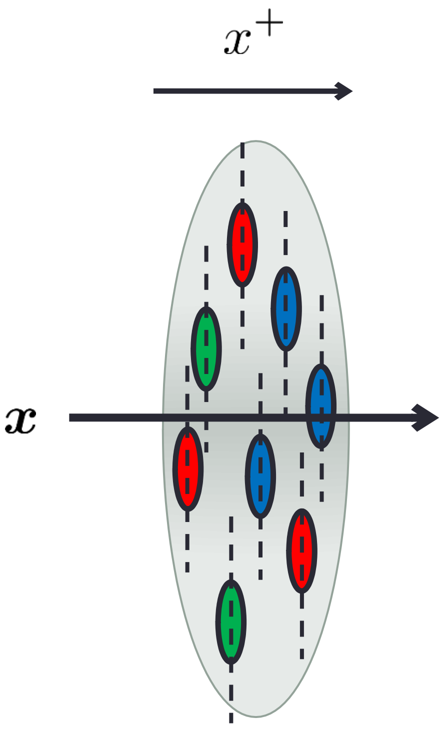
- These can be represented as Wilson lines in the light-cone gauge, $A^+ = 0$.
- Path ordered exponentials

- Quarks:

$$V_{\boldsymbol{x}} = \mathrm{P}\exp\left\{i\,g\int dx^+\, t^a A_a^-(x^+, x^- = 0, \boldsymbol{x})\right\}$$

- Gluons:

$$U_{\boldsymbol{x}} = \mathrm{P}\exp\left\{i\,g\int dx^+\, T^a A_a^-(x^+, x^- = 0, \boldsymbol{x})\right\}$$



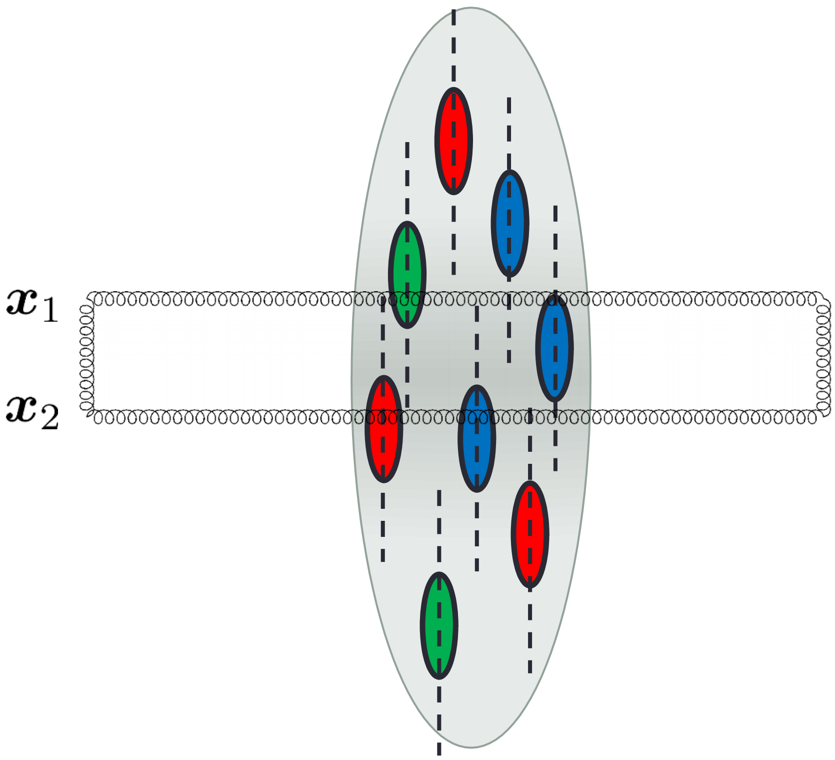
$$Q_{sT}^2 \sim \alpha_s^2\, A_T^{\frac{1}{3}}$$

Gluon dipole

- Lets look at the simple case of a gluon dipole
- Gluon dipole passing through the target can be represented with Wilson lines.
- The survival probability for the gluon dipole is:

$$S_G(\boldsymbol{x}_1, \boldsymbol{x}_2) \equiv \frac{1}{N_c^2 - 1} \left\langle Tr[U_{\boldsymbol{x}_1} U^{\dagger}_{\boldsymbol{x}_2}] \right\rangle$$

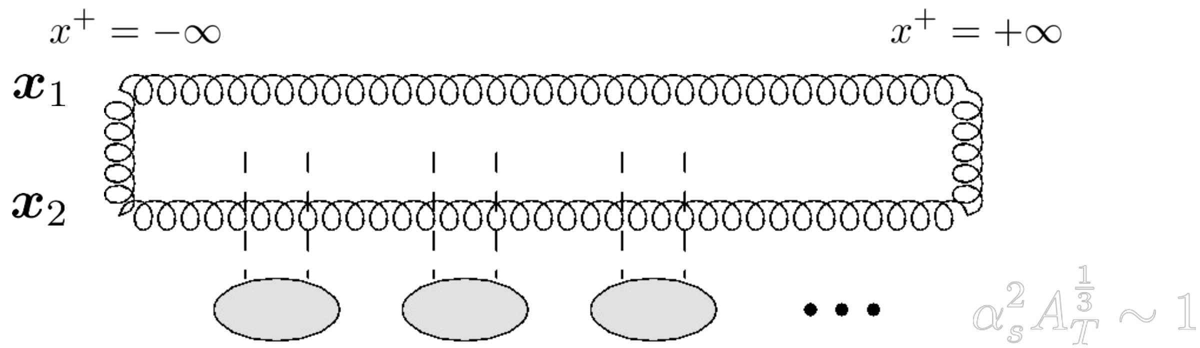
- Angle brackets represent averaging over all possible charge configurations.



Gluon dipole – survival probability

- The gluon dipole interacts with many nucleons in the target, exchanging two gluons each time (McLerran Venugopalan (MV) model).

$$S_G(\boldsymbol{x}_1, \boldsymbol{x}_2) \equiv \frac{1}{N_c^2 - 1} \langle Tr[U_{\boldsymbol{x}_1} U^\dagger_{\boldsymbol{x}_2}] \rangle$$



$$S_G(\boldsymbol{x}_1, \boldsymbol{x}_2) = \exp\left[-\frac{1}{4} |\boldsymbol{x}_1 - \boldsymbol{x}_2|^2 Q_{s\,T}^2 \left(\frac{\boldsymbol{x}_1 + \boldsymbol{x}_2}{2}\right) \ln\left(\frac{1}{|\boldsymbol{x}_1 - \boldsymbol{x}_2|\,\Lambda}\right)\right]$$

- Λ is an IR cutoff:

$$\Lambda \sim \Lambda_{QCD} \approx 250\text{MeV}$$

Heavy-light ion paradigm

- Take into account all nucleons in one of the ions (heavy) and only a few in the other (light).

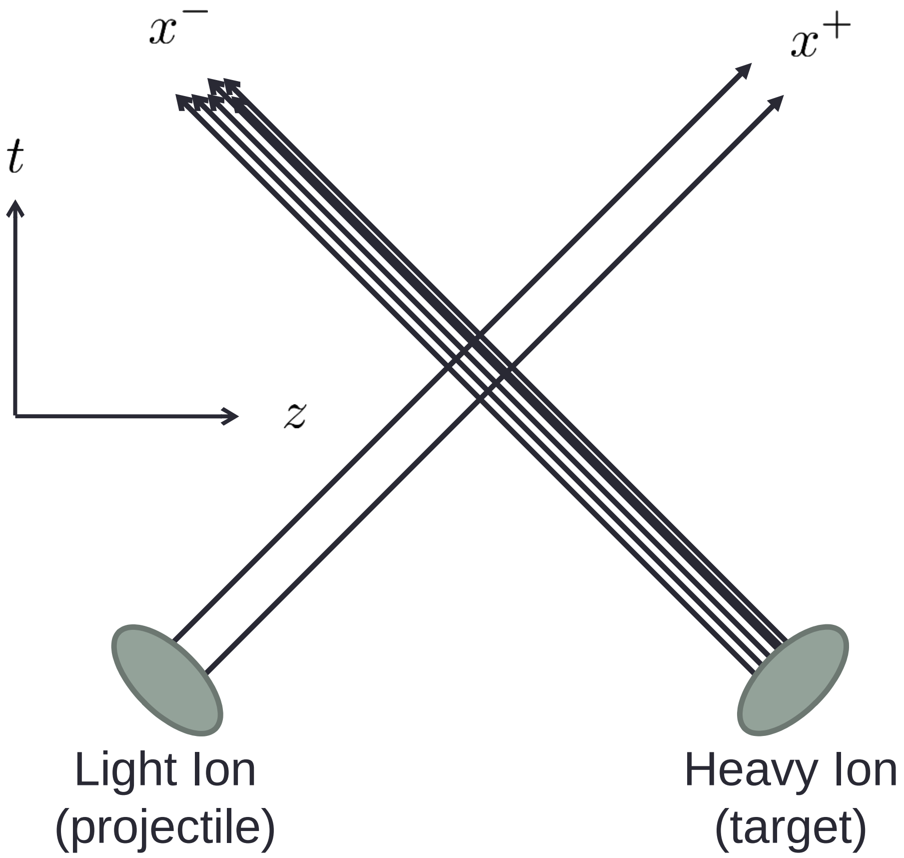
$$1 \ll A_P^{\frac{1}{3}} \ll A_T^{\frac{1}{3}}$$

- Target power counting:

$$\alpha_s^2 A_T^{\frac{1}{3}} \sim 1$$

- Projectile power counting:

$$\alpha_s \ll \alpha_s^2 A_P^{\frac{1}{3}} \lesssim 1$$



Definitions

- **Multiplicities**: inclusive probability densities

$$\left\langle \frac{dn^i}{d\omega_1} \right\rangle = \frac{1}{\sigma_{inel}} \frac{d\sigma^i}{d\omega_1} \qquad \left\langle \frac{dn^i}{d\omega_1} \frac{dn^j}{d\omega_2} \right\rangle = \frac{1}{\sigma_{inel}} \frac{d\sigma^{ij}}{d\omega_1 d\omega_2} + \delta^{ij} \delta(\omega_1 - \omega_2) \frac{1}{\sigma_{inel}} \frac{d\sigma^i}{d\omega_1}$$

- Quarks and antiquarks:

$$\left\langle k_1^+ \frac{dn^q}{d^2B_1\, dk_1^+}\, k_2^+ \frac{dn^q}{d^2B_2\, dk_2^+} \right\rangle_{ev} = \frac{1}{\sigma_{inel}} \left[k_1^+ k_2^+ \frac{d\sigma^{qq}}{d^2B_1\, dk_1^+\, d^2B_2\, dk_2^+} + \delta^{(2)}(\boldsymbol{B}_1 - \boldsymbol{B}_2)\, k_2^+ \delta(k_1^+ - k_2^+)\ k_1^+ \frac{d\sigma^q}{d^2B_1\, dk_1^+} \right]$$

$$\left\langle k_1^+ \frac{dn^q}{d^2B_1\, dk_1^+}\, k_2^+ \frac{dn^{\bar{q}}}{d^2B_2\, dk_2^+} \right\rangle_{ev} = \frac{1}{\sigma_{inel}} \left[k_1^+ k_2^+ \frac{d\sigma^{q\bar{q}}}{d^2B_1\, dk_1^+\, d^2B_2\, dk_2^+} \right]$$

- **Correlation function** (various definitions!):

$$\mathcal{C}_{ij}(\boldsymbol{B}_1, k_1^+;\, \boldsymbol{B}_2, k_2^+) \equiv \left\langle k_1^+ \frac{dn^i}{d^2B_1 dk_1^+}\, k_2^+ \frac{dn^j}{d^2B_2 dk_2^+} \right\rangle_{ev} - \left\langle k_1^+ \frac{dn^i}{d^2B_1 dk_1^+} \right\rangle_{ev} \left\langle k_2^+ \frac{dn^j}{d^2B_2 dk_2^+} \right\rangle_{ev}$$

- "Parton-level" **baryon number**: $\mathcal{B} \equiv \frac{1}{3} \sum_f (n^{q_f} - n^{\bar{q}_f})$

MV model quick review

- Target averages in classical random color fields (MV model)

$$\langle \mathcal{A}_a^-(x^+, x^-, \boldsymbol{x}) \mathcal{A}_b^-(y^+, x^-, \boldsymbol{y}) \rangle = \delta_{ab} \delta(x^+ - y^+) \gamma(\boldsymbol{x} - \boldsymbol{y})$$

- Take the large-Nc limit to simplify the color algebra

$$\left\langle \hat{D}_2(\boldsymbol{x}, \boldsymbol{y}) \hat{D}_2(\boldsymbol{u}, \boldsymbol{v}) \right\rangle \approx \left\langle \hat{D}_2(\boldsymbol{x}, \boldsymbol{y}) \right\rangle \left\langle \hat{D}_2(\boldsymbol{u}, \boldsymbol{v}) \right\rangle$$

$$\left\langle \hat{D}_2(\boldsymbol{B}_1, \boldsymbol{B}_2) \right\rangle = \left\langle \hat{D}_2(\boldsymbol{B}_2, \boldsymbol{B}_1) \right\rangle = e^{-\frac{1}{4} |\boldsymbol{B}_1 - \boldsymbol{B}_2|_T^2 Q_s^2}$$

- Neglect the weak spatial dependence of the saturation scale

$$\langle k_T^2 \rangle \sim Q_s^2(b_T) \propto \rho_{2D}(b_T)$$

- Work in the quasi-classical approximation (no small-x evolution)