Introduction to Heavy-Ion Physics
Part III

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Recap Lecture II

- Energy loss in the medium by elastic and inelastic processes
- Quark-mass dependence expected
  - Fragmentation needs to be considered
  - Harder fragmentation of quark over gluon

- $R_{AA}$ of D and B mesons
  - Analysis complex due to small S/B ratio
  - Mass dependence of energy loss

\[ R^{\pi}_{AA} \approx R^{D}_{AA} < R^{B}_{AA} \]
Quarkonia (c-cbar, b-bar) “melt” due to color screening in the QGP

- $J/\psi$ suppression
- Abundance of c at LHC so large that $J/\psi$ regenerate statistically
- States with lower binding energy are more suppressed

Hadron yields described by statistical models for $\sqrt{s_{NN}} = 2\text{–}2760$ GeV

- Matter created in HI collisions is in local thermal equilibrium

Expansion of QGP changes momenta of particles

- Radial flow (dependent on particle mass)
Overlap of colliding nuclei not isotropic in non-central collisions

Defines reaction plane $\Psi_{RP}$ (spanned by beam axis and impact parameter vector)

Pressure gradients dependent on direction

here: $\frac{dp_x}{dL} > \frac{dp_y}{dL}$
Elliptic Flow (2)

- Spatial anisotropy (almond shape)
  - Quantified by eccentricity $\varepsilon$
    $$\varepsilon = \frac{y^2 - x^2}{y^2 + x^2}$$

- Pressure gradient larger in-plane
- Pressure pushes partons
  - More in in-plane than out-of-plane

- Spatial anisotropy converts into momentum-space anisotropy
  - “Faster” particles in-plane
  - Measurable in the final state!
Elliptic Flow (3)

- Particles as a function of $\varphi - \Psi_{RP}$

$$\frac{dN}{d\varphi} = A(1 + 2v_2 \cos 2(\varphi - \Psi_{RP}))$$

- Define $v_2 = < \cos 2 (\varphi - \Psi_{RP}) >$
  - Second coefficient of Fourier expansion

- $\Psi_{RP}$ common symmetry plane (for all particles)

- What if there were no correlations with $\Psi_{RP}$?
Measuring Elliptic Flow

\[ v_2 = \langle \cos 2(\varphi - \Psi_{RP}) \rangle \]

- **Reaction plane angle**
  - From the particles themselves
    \[ Q_x = \sum_i w_i \cos 2\varphi_i \quad Q_y = \sum_i w_i \sin 2\varphi_i \quad \Psi_{RP} = \tan^{-1}(Q_x, Q_y) / 2 \]
  - \( \Psi_{RP} \) approximates true reaction-plane angle (called *event plane*)
- **Calculation of integrated** \( v_2 = \langle \cos 2(\varphi - \Psi_{RP}) \rangle \)
- \( v_2(p_T) \) by considering only particles at given \( p_T \)
- Called *event plane method*, denoted \( v_2\{EP\} \)
$\sqrt{s_{NN}}$ Dependence

- Increases with $\sqrt{s_{NN}}$
- At LHC $v_2 \sim 0.06$
  - What does that mean?
  $$dN \over d\phi = A(1 + 2v_2 \cos 2(\phi - \Psi_{RP}))$$
  - $2v_2 = 12\%$ of particles “move” from out-of-plane to in-plane

$\sqrt{s_{NN}}$ (GeV)

CMS, PRC 87(2013) 014902
Centrality Dependence

- Strong centrality dependence
- $v_2$ largest for 40-50%
- Spatial anisotropy very small in central collisions
- Largest anisotropy in mid-central collisions
- Small overlap region in peripheral collisions
Centrality dependence independent of $p_T$

Largest $v_2$ for $p_T \sim 3$ GeV/c

Low and intermediate $p_T$, $v_2$ caused by collective expansion

Large $p_T$, $v_2$ caused by \textit{length-dependent jet quenching}

- Longer path length out of plane than in plane

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Recap

- Pressure in dense medium affects momenta
- Isotropic expansion effect called *radial flow*

- Overlap of colliding nuclei causes spatial anisotropy
- Converted into momentum-space anisotropy in medium evolution
- Modulation of observed particles
- Quantified by $v_2 = \langle \cos 2(\varphi - \Psi_{RP}) \rangle$

**What other methods exist to measure $v_2$?**

**What effect do jet-related particles have on $v_2$?**
Two-Particle Correlations

- Reaction-plane estimation can be experimentally tricky
- Rewrite $v_2 = \langle \cos 2(\varphi - \Psi_{RP}) \rangle$ as $v_2 = \langle e^{i2(\varphi - \Psi_{RP})} \rangle$
- $v_2$ can also be measured from 2-particle correlations

\[
\frac{e^{i2(\varphi_1 - \varphi_2)}}{e^{i2(\varphi_1 - \Psi_{RP} - (\varphi_2 - \Psi_{RP}))}} = \frac{e^{i2(\varphi_1 - \Psi_{RP})}e^{i2(\varphi_2 - \Psi_{RP})}}{e^{i2(\varphi_1 - \Psi_{RP})}e^{i2(\varphi_2 - \Psi_{RP})}} = v_2^2
\]

Modulation smaller due to $v_2 \rightarrow (v_2)^2$ but statistical power similar
Higher-Order Correlations

- Trivial extension to 4-particles (and higher-orders)

\[ v_2^4 = \langle e^{i2(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)} \rangle \]

\[ v_2^6 = \langle e^{i2(\varphi_1 + \varphi_2 + \varphi_3 - \varphi_4 - \varphi_5 - \varphi_6)} \rangle \]

- NB. sign is arbitrary as long as same amount of positive and negative angles
  \[ \rightarrow \text{rotational symmetry} \]
Cumulants

• Cumulants extract genuine n-particle correlations
• For 2-particle correlations

$$\langle x_1 x_2 \rangle = \langle x_1 \rangle \langle x_2 \rangle + \langle x_1 x_2 \rangle_c$$

measured correlation  lower order “correlations”  genuine 2-particle correlations  $\phi$ dependence only from detector acceptance

• Rewrite (trivially) $\langle x_1 x_2 \rangle_c = \langle x_1 x_2 \rangle - \langle x_1 \rangle \langle x_2 \rangle$

• For 3-particle correlations

$$\langle x_1 x_2 x_3 \rangle = \langle x_1 \rangle \langle x_2 \rangle \langle x_3 \rangle + \langle x_1 x_2 \rangle_c \langle x_3 \rangle + \langle x_1 x_3 \rangle_c \langle x_2 \rangle + \langle x_2 x_3 \rangle_c \langle x_1 \rangle + \langle x_1 x_2 x_3 \rangle_c$$

Higher-order cumulants zero $\rightarrow$ no genuine multi-particle correlation! No matter what multi particles correlations (i.e. not cumulants) show
Cumulants for Elliptic Flow

- For uniform detector acceptance, cumulants of 2\textsuperscript{nd} and 4\textsuperscript{th} order:

\[ c_2\{2\} = \left\langle e^{i2(\varphi_1 - \varphi_2)} \right\rangle = v_2^2 \]

identical to two-particle correlation

\[ c_2\{4\} = \left\langle e^{i2(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)} \right\rangle - 2\left\langle e^{i2(\varphi_1 - \varphi_2)} \right\rangle^2 = -v_2^4 \]

lower orders are removed

- \( c_2\{4\} \) is genuine 4-particle correlations
  - I.e. if only pairs of particles are correlated \( \rightarrow c_2\{4\} = 0 \)
Flow Methods

• Now we have tons of methods to measure flow
  – Event plane
  – 2-particle and 4-particle correlations, …
  – 2-particle and 4-particle cumulants, …

They all estimate $v_2$, so what?

Let’s have a look, what spoils the flow measurement…
Non-Flow

- Particles are correlated through reaction plane $\Psi_{RP}$
- Additional isotropically distributed particles
  - Add to baseline, reduce $\cos 2\Delta\phi$ magnitude, but don’t distort shape
- Jets
  - Particles which exhibit correlations close in angle (within the same jet) and at $\Delta\phi = \pi$ (back-to-back jet)
  - Distort $\Psi_{RP}$ estimate
  - Distorts shape in 2 particle correlations
- A pure jet-signal results in $v_2 > 0$ (e.g. Pythia)
Non-Flow (2)

- Different effect on different flow methods
- 2-particle correlations / cumulants
  \[ c_2 \{2\} = \langle e^{i2(\varphi_1 - \varphi_2)} \rangle = v_2^2 + \delta_2 \]
- 4-particle correlations
  \[ \langle e^{i2(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)} \rangle = v_2^4 + 4v_2^2\delta_2 + 2\delta_2^2 + \delta_4 \]
- 4-particle cumulants
  \[ c_2 \{4\} = \langle e^{i2(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)} \rangle - 2\langle e^{i2(\varphi_1 - \varphi_2)} \rangle = \]
  \[ = v_2^4 + 4v_2^2\delta_2 + 2\delta_2^2 + \delta_4 - 2(v_2^2 + \delta_2) = -v_2^4 + \delta_4 \]

Second order non-flow dropped out!
**Experiment**

**v₂ vs. Centrality**

CMS PbPb \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

\[ 0.3 < p_T < 3.0 \text{ GeV/c, } |\eta| < 0.8 \]

\[ v_2\{2\} = \sqrt{v_2^2 + \delta_2} \]

\[ v_2\{EP\} \]

\[ v_2\{4\} = 4\sqrt{v_2^4 - \delta_4} \]

Larger non-flow influence* for \( v_2\{2\} \) than \( v_2\{4\} \)

* neglects fluctuations, see [backup](#)

PRC 87(2013) 014902

[Backup link](#)
Up to 8 Particles…

\[ v_2 \text{ vs. } N_{\text{part}} \]

\[ v_2\{4\} \sim v_2\{6\} \sim v_2\{8\} \]

→ influence of non-flow (and fluctuations) small for \( \geq 4 \) particles

ATLAS

Pb+Pb \( \sqrt{s_{NN}} = 2.76 \) TeV

\( \text{L}_{\text{int}} = 7 \mu b^{-1} \)  \( |\eta| < 2.5 \)

\( 0.5 < p_t < 20 \) GeV

EPJC (2014) 74: 3157
Recap

• Elliptic flow can be measured with different methods
• Cumulants of $n^{th}$ order measure genuine $n$-particle correlations – not reducible to lower orders
• Mini(jets) and resonances distort the $v_2$ measurement
• Non-flow influence is different for different methods
  – The higher the order of the cumulant, the smaller the influence

For now we have discussed elliptic flow $v_2$ – is that all?
Higher-Order Flow

• Geometrical picture
  → $2^{\text{nd}}$ order modulation ($v_2$)

• In practice interacting nucleons need to be considered
  – E.g. estimated with Glauber MC
  – Initial state density fluctuations

• These produce all kinds of shapes
  – Elliptic, triangular, quadruple, …
  – And mixtures of those
Higher-Order Flow (2)

- Reaction plane $\Psi_{RP} \rightarrow n^{th}$ order participant plane $\Psi_n$

$$\frac{dN}{d\phi} = A(1 + 2v_2 \cos 2(\phi - \Psi_{RP})) \quad \rightarrow \quad \frac{dN}{d\phi} = A(1 + 2\sum_n v_n \cos n(\phi - \Psi_n))$$

- Formalism can be trivially extended from $v_2$ to $v_n$
- E.g. $v_2^2 = \langle e^{i2(\phi_1 - \phi_2)} \rangle \quad \rightarrow \quad v_n^2 = \langle e^{in(\phi_1 - \phi_2)} \rangle$

PRC81 (2010) 054905
Experiment

$v_n$ vs. Centrality

$v_2\{2\}$

$v_3\{2\}$

$C(\Delta \phi)$ vs. $\Delta \phi$

Centrality 0-1%, $|\eta| < 0.8$

$|\Delta \eta| > 1$

$v_{2,3,4,5}\{2, |\Delta \eta| > 1\}$

$2.0 < p_{t,\text{trig}} < 3.0$

$1.0 < p_{t,\text{assoc}} < 2.0$

Two-particle correlations can be fully described by $v_2 \ldots v_5$

$PRL107, 032301 (2011)$

$v_3$ sizable

$v_3 \sim \frac{1}{2} v_2$

Weaker centrality dependence
And even higher orders…

\[ V_{n\Delta} = (v_n)^2 \text{ vs. } n \]

Centrality

- 0-2%

\[ 2 < p_T^i < 2.5 \text{ GeV/c} \]
\[ 1.5 < p_T^a < 2 \text{ GeV/c} \]

\[ v_n \text{ vs. } p_T \]

Significant up to 6 orders

ATLAS-CONF-2011-074
PLB708 (2012) 249
Recap

- Geometry of overlapping nuclei $\rightarrow$ elliptic flow
- Initial-state density fluctuations lead to different ‘shapes’ of overlap region $\rightarrow$ flow at higher orders
- Flow measured up to $6^{th}$ order

What does a medium need for collective effects?

What can we learn from these results?
Hydrodynamics

- Calculating space-time evolution of QGP from first principles (QCD Lagrangian) is too complex (non-abelian, strong coupling, many-body system, …)

- Expanding medium can be described macroscopically with hydrodynamical models
  - Conservation of energy-momentum
  - Conservation of charges, mainly baryon number
  - Local thermodynamical equilibrium

- Needed input
  - Initial conditions
  - Equation of State (EoS), from lattice QCD
  - Relativistic fluid dynamics
    - Perfect or dissipative (→ transport coefficients)

\[
\partial_\mu T^{\mu\nu} = 0 \\
\partial_\mu N_i^\mu = 0 \\
N_i^\mu = n u^\mu \\
T^{\mu\nu} = (\varepsilon + P) u^\mu u^\nu - P g^{\mu\nu}
\]
Once dynamics well described, hydrodynamic “output” can be used in other calculations: jet quenching, J/ψ melting, etc.

Flow observables:
Initial-state anisotropies $\rightarrow$ final-state anisotropies
  – Translate from initial-state eccentricity $\varepsilon_n$ to final-state flow $v_n$

Deduce conclusions on initial conditions, EoS and transport coefficients by data comparison
Shear Viscosity

- Shear viscosity washes out initial-state anisotropies
  - Expressed as $\eta/s$ (shear viscosity over entropy)
  - Ideal hydrodynamics: $\eta/s = 0$
  - Viscous hydrodynamics: $\eta/s > 0$
  - Large influence on higher-order flow

**Density in collision region (x vs. y)**

**Initial conditions**

- $\eta/s = 0$
- $\tau \eta/s = 0.16$

**Water:** $\eta/s \sim 30$ | **Olive oil** $\eta/s \sim 240$
Example: Shear Viscosity

Shear viscosity hampers the build-up of flow!

\[ \eta/s = 0.08 \]

Larger \( \eta/s \) reduces flow

\[ \eta/s = 0.16 \]

\( v_3 \) vs. \( p_T \)

PRC 82, 034913 (2010)
Hydro vs. Data

MC-KLN with $\eta/s = 0.16$ or MC-Glauber with $\eta/s = 0.08$

Water: $\eta/s \sim 30$ | Olive oil $\eta/s \sim 240$

• $v_2$ measured for 7 different species
  
  \[ v_2 \text{ vs. } p_T \]

  \[ 30-40\% \]

  \[ \pi, p, \Lambda, K, \phi, \Omega \]

• Strong species dependence
  – Different masses and quark content

• Stringent test for hydro
  – Very good agreement with VISHNU
    (hydro + hadronic cascade model (UrQMD), initial conditions MC-KLN, $\eta/s \sim 0.16$)
Summary
Collective Flow & Hydrodynamics

- Quark-gluon plasma expands rapidly (up to ~0.65c)
- Spatial anisotropy of collision region causes anisotropic flow quantified as Fourier coefficients $v_n$
  - Measured up to 6th order
  - Initial-state fluctuations influence $v_n$
- Well described by viscous hydrodynamics with a very low shear viscosity ($\eta/s \sim 0.08 – 0.16$) “perfect liquid”
Collectivity in Small Systems

Some surprises…
Recap Two-Particle Correlations

- For $v_n$ measurement, we discussed contribution from flow and non-flow ((mini)jets)
- This can also be looked at in two dimensions
  - Azimuth $\Delta \phi$ and pseudorapidity $\Delta \eta$

![Graph showing flow modulation with (mini)jet](image1)

![Graph showing yield vs. $\Delta \phi$ vs. $\Delta \eta$](image2)

(a) CMS PbPb | $s_{\text{NN}} = 2.7$  
1 < $p_T^{\text{trig}}$ < 3 GeV/c  
1 < $p_T^{\text{assoc}}$ < 3 GeV/c
Typical Two-Particle Correlation

Away-side jet + flow
($\Delta \phi \sim \pi$, elongated in $\Delta \eta$)

Near-side jet + resonances, ...
($\Delta \phi \sim 0$, $\Delta \eta \sim 0$)

Near-side flow ridge
($\Delta \phi \sim 0$, elongated in $\Delta \eta$)
Near-side ridge 
(flow) only in Pb-Pb

at least everyone thought so for a long time…
Near-Side Ridge

- ...observed in very high-multiplicity pp collisions
  - 0.005% events with highest multiplicity

- ...observed in high multiplicity p-Pb collisions
  - ~40% events with highest multiplicity
  - Surprisingly large magnitude

here: $\eta = \eta_{\text{lab}}$

(d) CMS $N \geq 110$, 1.0GeV/c < $p_T$ < 3.0GeV/c

3.1% of MB

CMS, JHEP09(2010)091

CMS, PLB718 (2013) 795

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The Double Ridge

- Subtraction procedure to “isolate” ridge contribution from jet correlations
  - No ridge seen in 60-100% and similar to pp

Two ridges!
Today’s Understanding

- Various “HI observables” in p-Pb and high-multiplicity pp
  - $v_2$, $v_3$, ...
  - Multi-particle correlation $v_2\{4\} = v_2\{6\} = v_2\{8\}$
  - Mass ordering of particle species E.g. $v_2\{p\} < v_2\{\pi\}$ for $p_T < 2$ GeV/c

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**v$_2$ vs. Multiplicity**

- **pp**
  - CMS $\sqrt{s} = 13$ TeV
  - $v_2^{\text{subj}}\{2, |\Delta\eta|>2\}$

- **p-Pb**
  - $p_{\text{Pb}} \sqrt{s_{\text{NN}}} = 5$ TeV
  - $v_2\{4\}$
  - $v_2\{6\}$
  - $v_2\{8\}$
  - $v_2\{\text{LYZ}\}$

- **Pb-Pb**
  - $\text{PbPb} \sqrt{s_{\text{NN}}} = 2.76$ TeV
  - $0.3 < p_T < 3.0$ GeV/c
  - $|\eta| < 2.4$
Today’s Understanding (2)

• Particle ratios and strangeness
  – Smooth increase of strange baryon production
  – From pp, over p-Pb to Pb-Pb
  – Multiplicity dependence not reproduced by MC generators

• But: No sign of parton energy loss
Summary Collectivity in Small Systems

- Typical Pb-Pb collision effects observed in pp and p-Pb
- Paradigm shift in interpretation of small systems
- Many hints that (mini) QGP is created in high-multiplicity p-Pb collisions (and pp collisions?)

<table>
<thead>
<tr>
<th>For LHC</th>
<th>pp</th>
<th>p-Pb</th>
<th>Pb-Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size collision region (fm$^2$)</td>
<td>2</td>
<td>12</td>
<td>150</td>
</tr>
<tr>
<td>Volume at freeze-out (fm$^3$)</td>
<td>25</td>
<td>160</td>
<td>5000</td>
</tr>
<tr>
<td>Energy density (GeV/fm$^3$)</td>
<td>?</td>
<td>3 (?)</td>
<td>10</td>
</tr>
</tbody>
</table>

- Debate on influence of the initial state effect as opposed to a collective approach (rescattering)

Topic of ongoing exciting research – Stay tuned… or even better: join in!
What Next?

• Observations challenge two paradigms at once
  – For how small systems does the HI “standard model” remain valid?
  – Can the standard tools for pp physics remain standard?

Run 1 + 2 (2009-2018)
• Discovery of heavy-ion like phenomena in small systems
• Characterization of multi-particle correlations and strangeness enhancement

Non-flow-free correlation measurements → nature of higher-order correlations

Energy-loss signals → role of final-state interactions

Run 3 + 4

Thermal radiation → isotropization / equilibration

Strangeness enhancement → insight into baryon production

Chance to find unified description of underlying dynamics across system size
Summary
Medium Evolution

\[ \frac{dN_{\text{ch}}}{d\eta} \sim 1600 \text{ particles} \]

**Large pressure** ↓
**collective flow**

**Density fluctuations** ↓
**spatial anisotropies**

**Dense medium** ↓
**Energy loss, Quarkonia melting**

**Kinetical freeze-out**
\~ 90 MeV

**Chemical freeze-out**
\~ 155 MeV

**Viscous hydrodynamics**
\[ \eta/s \sim 0.08 \text{ – } 0.16 \]

**Initial temperature***
\~ 300 MeV

Values for central \[ \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \] collisions (LHC)
* from direct photons (not discussed)
Take-Home Messages

• Dense colored strongly coupling medium is produced in heavy-ion collisions (the Quark-Gluon Plasma)
  – Particle production is strongly suppressed

• Created matter is in local thermal equilibrium
  – Particle production described by statistical models
  – Expansion described by viscous hydrodynamics “perfect liquid”

• Recent discoveries and observations in p-Pb collisions hint at collective “QGP-like” effects in small systems
  – Universal description across system size?

Thank you for your attention

Many thanks for useful discussions and inspiring previous lectures to Federico Antinori, Davide Caffarri, Leticia Cunqueiro, Andrea Dainese, Michele Floris, Alexander Kalweit, Andreas Morsch, Raimond Snellings, Alberica Toia
Fluctuations

• Initial-state density fluctuations cause higher-order flow

• For a given order
  – Value is not the same event by event
  – Usually we look at averages

\[ \left\langle e^{in(\phi_1 - \phi_2)} \right\rangle = v_n^2 \text{ means actually } \left\langle \left\langle e^{in(\phi_1 - \phi_2)} \right\rangle \right\rangle_{\text{tracks}} = \left\langle \left\langle 2 \right\rangle \right\rangle = \left\langle v_n^2 \right\rangle \]

\[ \left\langle \left\langle 4 \right\rangle \right\rangle = -\left\langle v_n^4 \right\rangle \text{ etc.} \]

  – However we look for \( \left\langle v_n \right\rangle \)

• \( \left\langle v_n \right\rangle^k = \left\langle v_n^k \right\rangle \) without fluctuations

  Deviates with fluctuations

\( v_n \{2\} = \left\langle v_n^2 \right\rangle^{1/2} \approx \left\langle v_n \right\rangle + \frac{1}{2} \frac{\sigma_{v_n}^2}{\left\langle v_n \right\rangle} \)

\( v_n \{4\} = \left\langle v_n^4 \right\rangle^{1/4} \approx \left\langle v_n \right\rangle - \frac{1}{2} \frac{\sigma_{v_n}^2}{\left\langle v_n \right\rangle} \)

non-flow not shown for simplicity

for \( \sigma_{v_n} \ll \left\langle v_n \right\rangle \)
**Fluctuations (2)**

- $v_2$ distribution is broad
- Influence of fluctuations significant
- Estimate of fluctuations

$$v_n\{2\} \approx \langle v_n \rangle + \frac{1}{2} \frac{\sigma_{v_n}^2}{\langle v_n \rangle}$$

$$v_n\{4\} \approx \langle v_n \rangle - \frac{1}{2} \frac{\sigma_{v_n}^2}{\langle v_n \rangle}$$

$$\frac{\sigma_{v_n}}{\langle v_n \rangle} \approx \sqrt{\frac{v_n^2\{2\} - v_n^2\{4\}}{v_n^2\{2\} + v_n^2\{4\}}}$$

For $\sigma_{v_n} \ll \langle v_n \rangle$
• Observed effects associated to hydrodynamical evolution in Pb-Pb collisions

• Hydrodynamics in p-Pb collisions?
  – Number of interactions?
  – Sufficient time for constituents to see each other?

• Hydrodynamics in p-Pb collisions reproduces measurements
  – Assuming 0.2-0.6 fm/c for beginning of hydro evolution
At low $x$, gluon density rises

In nucleus density increases by $A^{1/3} \sim 6$ → saturation

Model of *Color Glass Condensate*

Color: gluon color charge

Glass: solid on short time scale, liquid on large time scales

Condensate: high density
Interpretation (2)
Initial-state effect?

- Saturation enhances certain graphs by orders of $\alpha_S$
  - Glasma graph enhanced by twice the order of magnitudes than jet graph

Within these models, ridge can be calculated quantitatively

Then there are lots of other qualitative ideas…

PRD 87, 094034 (2013)