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
  \[
  R_{AA}^\pi \approx R_{AA}^D < R_{AA}^B
  \]
Recap Lecture II

- 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 $\sqrt{s_{NN}} = 2-2760$ 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)

$\rightarrow$ 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 $v_2 = \langle \cos 2 (\varphi - \Psi_{RP}) \rangle$
  - 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
    \[ Q_x = \sum w_i \cos 2\varphi_i \quad Q_y = \sum w_i \sin 2\varphi_i \quad \Psi_{RP} = \tan^{-1}(Q_x, Q_y) / 2 \]
  - \( \Psi_{RP} \) 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?
    \[
    \frac{dN}{d\phi} = A(1 + 2v_2 \cos 2(\phi - \Psi_{RP}))
    \]
  - $2v_2 = 12\%$ of particles “move” from out-of-plane to in-plane

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
p_T Dependence

- 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 length-dependent jet quenching
  - Longer path length out of plane than in plane

$\textit{out of plane}$

$\textit{in plane}$

$\textbf{v}_2$ vs. $p_T$

CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV

$|\eta| < 0.8$

CMS, PRC 87(2013) 014902
Recap

- Pressure in dense medium affects momenta
- Isotropic expansion effect called \textit{radial flow}

- Overlap of colliding nuclei causes spatial anisotropy
- Converted into momentum-space anisotropy in medium evolution
- Modulation of observed particles
- Quantified by \( \nu_2 = \langle \cos 2 (\phi - \Psi_{RP}) \rangle \)

What other methods exist to measure \( \nu_2 \)?

What effect do jet-related particles have on \( \nu_2 \)?
Two-Particle Correlations

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

$$\langle e^{i2(\varphi_1 - \varphi_2)} \rangle = \langle e^{i2(\varphi_1 - \Psi_{RP} - (\varphi_2 - \Psi_{RP}))} \rangle = \langle e^{i2(\varphi_1 - \Psi_{RP})} \rangle \langle e^{i2(\varphi_2 - \Psi_{RP})} \rangle = v_2^2$$

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)

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

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

- NB. sign is arbitrary as long as same amount of positive and negative angles
  \( \rightarrow \) 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
- 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:

\[
c_2\{2\} = \left\langle e^{i2(\varphi_1 - \varphi_2)} \right\rangle = v_2^2 \quad \text{identical to two-particle correlation}
\]

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

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 $\cos 2\Delta\varphi$ magnitude, but don’t distort shape
• Jets
  – Particles which exhibit correlations close in angle (within the same jet) and at $\Delta\varphi = \pi$ (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

\[ c_2 \{2\} = \left< e^{i2(\varphi_1 - \varphi_2)} \right> = v_2^2 + \delta_2 \]

• 4-particle correlations

\[ \left< e^{i2(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)} \right> = v_2^4 + 4v_2^2\delta_2 + 2\delta_2^2 + \delta_4 \]

• 4-particle cumulants

\[ c_2 \{4\} = \left< e^{i2(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)} \right> - 2\left< e^{i2(\varphi_1 - \varphi_2)} \right> = v_2^4 + 4v_2^2\delta_2 + 2\delta_2^2 + \delta_4 - 2(v_2^2 + \delta_2) = -v_2^4 + \delta_4 \]

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

**v$_2$ vs. Centrality**

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

\( 0.3 < p_T < 3.0 \) GeV/c, \( |\eta| < 0.8 \)

\[
\begin{align*}
v_2\{2\} &= \sqrt{v_2^2 + \delta_2} \\
v_2\{EP\} \\
v_2\{4\} &= 4\sqrt{v_2^4 - \delta_4}
\end{align*}
\]

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

* neglects fluctuations, see [backup](#)
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**

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

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

\( 0.5 < p_T < 20 \text{ GeV} \)
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
  $\rightarrow$ 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 $\Psi_n$

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

- 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 \longleftrightarrow \quad v_n^2 = \langle e^{in(\phi_1 - \phi_2)} \rangle$

PRC81 (2010) 054905
Weaker centrality dependence

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

PRL107, 032301 (2011)
And even higher orders...

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

Centrality
- 0-2%

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

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

Significant up to 6 orders
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\textsuperscript{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)

\[ \partial_{\mu} T^{\mu\nu} = 0 \]
\[ \partial_{\mu} N_{i}^{\mu} = 0 \]
\[ N_{i}^{\mu} = nu^{\mu} \]
\[ T^{\mu\nu} = (\varepsilon + P) u^{\mu} u^{\nu} - Pg^{\mu\nu} \]
Hydrodynamics (2)

- 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

**Initial conditions**

$\eta/s = 0$

$\tau \eta/s = 0.16$

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

---

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

MUSIC, Sangyong Jeon
Example: Shear Viscosity

Shear viscosity hampers the build-up of flow!

Larger $\eta/s$ reduces flow.

$\eta/s = 0.08$

$\eta/s = 0.16$

$\nu_3$ vs. $p_T$

PRC 82, 034913 (2010)
Hydro vs. Data

MC-KLN ← Initial conditions → MC-Glauber

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

Hydro vs. Data (2)

- $v_2$ measured for 7 different species

- 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”

Hydrodynamical models describe collective flow
Matter created in HI collisions is in local thermal equilibrium
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 $\Delta \varphi$ and pseudorapidity $\Delta \eta$

Counts

flow modulation
+ (mini)jet

$\Delta \varphi = \varphi_1 - \varphi_2$

Yield vs. $\Delta \varphi$ vs. $\Delta \eta$

(a) CMS PbPb $|s_{NN}| = 2.7$

$1 < p_T^{\text{trig}} < 3$ GeV/c

$1 < p_T^{\text{assoc}} < 3$ GeV/c

Introduction to Heavy-Ion Physics – Jan Fiete Grosse-Oetringhaus
Typical Two-Particle Correlation

(a) CMS PbPb $|s_{NN}| = 2.76$ TeV, $220 \leq N_{\text{trk}}^{\text{offline}} < 260$

$1 < p_T^{\text{trig}} < 3$ GeV/c

$1 < p_T^{\text{assoc}} < 3$ GeV/c

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

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

Near-side flow ridge
$(\Delta \phi \sim 0, \text{elongated in } \Delta \eta)$
Near-side ridge (flow) only in Pb-Pb at least everyone thought so for a long time...

(a) CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $220 \leq N_{\text{trk}}^{\text{coll}} < 260$

$1 < p_T^{\text{trig}} < 3$ GeV/c
$1 < p_T^{\text{assoc}} < 3$ GeV/c

CMS 2010, $\sqrt{s}=7$ TeV
MinBias, $1.0\text{GeV/c} < p_T < 3.0\text{GeV/c}$

$R(\Delta \eta, \Delta \phi)$
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
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 “heavy-ion observables” found in p-Pb and high-multiplicity pp collisions
  – $v_2$, $v_3$, …
  – Multi-particle correlation $v_2\{4\} = v_2\{6\} = v_2\{8\}$
  – Mass ordering of different particle species
    • E.g. $v_2\{p\} < v_2\{\pi\}$ for $p_T < 2$ GeV/c
  – Particle ratios and strangeness enhancement

• Paradigm shift in the field
  – Challenges two paradigms
  – How far down in system size HI modelling is valid?
  – Can standard tools for pp remain standard?

Chance to find unified description of underlying dynamics across system size
Summary Collectivity in Small Systems

- Typical Pb-Pb collision effects observed in pp and p-Pb collisions
- 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 (fm²)</td>
<td>2</td>
<td>12</td>
<td>150</td>
</tr>
<tr>
<td>Volume at freeze-out (fm³)</td>
<td>25</td>
<td>160</td>
<td>5000</td>
</tr>
<tr>
<td>Energy density (GeV/fm³)</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!
Values for central $\sqrt{s_{NN}} = 2.76$ TeV collisions (LHC) * from direct photons (not discussed)
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

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Backup
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
    \( \langle e^{in(\phi_1-\phi_2)} \rangle = v_n^2 \) means actually \( \langle \langle e^{in(\phi_1-\phi_2)} \rangle \rangle_{\text{tracks}} \) \( = \langle \langle 2 \rangle \rangle = \langle v_n^2 \rangle \)
    \( \langle \langle 4 \rangle \rangle = -\langle v_n^4 \rangle \) etc.
  – However we look for \( \langle v_n \rangle \)
• \( \langle v_n \rangle^k = \langle v_n^k \rangle \) without fluctuations
  Deviates with fluctuations
  \[ v_n \{2\} = \langle v_n^2 \rangle^{1/2} \approx \langle v_n \rangle + \frac{1}{2} \frac{\sigma_{v_n}^2}{\langle v_n \rangle} \]
  \[ v_n \{4\} = \langle v_n^4 \rangle^{1/4} \approx \langle v_n \rangle - \frac{1}{2} \frac{\sigma_{v_n}^2}{\langle v_n \rangle} \]
• $v_2$ distribution is broad
• Influence of fluctuations significant
• Estimate of fluctuations

\[
v_n\{2\} \approx \langle v_n \rangle \pm \frac{1}{2} \frac{\sigma_{v_n}^2}{\langle v_n \rangle}
\]

\[
v_n\{4\} \approx \langle v_n \rangle \mp \frac{1}{2} \frac{\sigma_{v_n}^2}{\langle v_n \rangle}
\]

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

for $\sigma_{v_n} \ll \langle v_n \rangle$
Experiment

**v\textsubscript{2} vs. Centrality**

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

0.3 < \(p_{\text{T}}\) < 3.0 GeV/c, |\(\eta\)| < 0.8

\[v_2\{2\} = \sqrt{v_2^2 + \delta_2} + \frac{1}{2} \frac{\sigma_{v_n}^2}{\langle v_n \rangle}\]

\[v_2\{4\} = 4 \sqrt{v_2^4 - \delta_4} - \frac{1}{2} \frac{\sigma_{v_n}^2}{\langle v_n \rangle}\]

Opposite influence of fluctuations for \(v_2\{2\}\) than \(v_2\{4\}\) (in addition to non-flow)

PRC 87(2013) 014902
Hydro vs. Data (3)

- Fluctuations sensitive to initial conditions ($\varepsilon_n$) and hydro ($v_n$)
- Check approximation used in fluctuation measurement

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

→ Not valid for central events

Neither MC-KLN nor MC-Glauber initial conditions describe fluctuations completely

$$\frac{\sigma_{\varepsilon_n}}{\langle \varepsilon_n \rangle} \approx \sqrt{\frac{\varepsilon_n^2 \{2\} - \varepsilon_n^2 \{4\}}{\varepsilon_n^2 \{2\} + \varepsilon_n^2 \{4\}}}$$
Event-by-event $v_n$ reproduced very well
- Initial conditions correctly modeled
- IP-GLASMA initial conditions, hydro evolution by “MUSIC”, $\eta/s = 0.2$

PRL 110 (2013) 1, 012302
Constituent Quark Scaling

- Split between mesons and baryons?
- Quarks degrees of freedom?
  - Each quark flows in common velocity field
  - Baryons (qqq) pick up more flow than mesons (q-qbar)

- How can we test this idea?
  → Rescale $v_2$ and $p_T$ with number of quarks

\[ v_2 \text{ vs. } p_T \]

Baryons ($p$, $\Lambda$, $\Xi$, $\Omega$)

Mesons ($\pi$, $K$, $\phi$)

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

arXiv:1405.4632
Constituent Quark Scaling (2)

\( v_2 \rightarrow v_2 / n_q \)  
Mesons: \( n_q = 2 \)

\( p_T \rightarrow p_T / n_q \)  
Baryons: \( n_q = 3 \)

Number of constituent quark scaling within ~20% above 1 GeV/c

arXiv:1405.4632
Constituent Quark Scaling (3)

Phenomenological observation:
Low $p_T$ scales better as fct of
*transverse kinetic energy* “$K_E T$”

\[ v_2 \rightarrow v_2/n_q \]
\[ p_T \rightarrow (m_T - m_0)/n_q \]

**KE$_T$ scaling within ~20% above ~0.5 GeV/c**

arXiv:1405.4632
Coalescence

- \( v_n \) approximately scale with number of constituent quarks
- Interpreted as hadronization by quark coalescence
  - Strength of \( v_n \) depends on number of quarks

Quarks within phase space cell (spatially and \( p_T \) in vicinity)

- However, the \( \phi \) meson makes trouble
  - \( m_\phi \approx m_p \) but 2 vs. 3 quarks
  - Behaves like \( p \) in central collisions even at high \( p_T \)
  - Is the mass deciding on the flow?

Open question – actively debated

\[ v_2 \text{ vs. } p_T \]

arXiv:1405.4632
Quantification of Ridges

- $v_n$ coefficients
  - Significant $v_2$ and $v_3$
- Multi-particle correlation
  - $v_2\{4\} = v_2\{6\} = v_2\{8\}$
  - At least 8 particles correlated
- Particle species dependence
  - $v_2\{p\} < v_2\{\pi\}$ for $p_T < 2$ GeV/c
  - $v_2\{p\} > v_2\{\pi\}$ for $p_T > 2$ GeV/c
  - Similar for K and $\Lambda$

Features reminiscent of Pb-Pb collisions
\[\rightarrow\] strong hints that same effects at play in p-Pb and Pb-Pb collisions

PRL110, 182302 (2013)
PLB 726 (2013) 164

PRL115,012301(2015)
PLB 742 (2015) 200
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 $A^{1/3} \sim 6 \rightarrow$ 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**

**Initial-state effect?**

$q/g$ densities vs. $x$
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)