Initial state, an experimental perspective

Gunther Roland
Using pp and pA to cleanse AA from initial state physics (early 2000’s)

Local structure of QCD vacuum

Local QCD + initial state/cold nuclear matter

Local QCD + initial state/cold nuclear matter + Quark-Gluon Plasma
Using pp and pA to cleanse AA from initial state physics (early 2000’s)

Local structure of QCD vacuum

2003 dAu run shows that jet quenching is a final state effect

Local QCD + initial state/cold nuclear matter + Quark-Gluon Plasma

Physical Review Letters
Articles published week ending 15 August 2003
Volume 91, Number 7

0.0 0.5 1.0
Density Measure $\mu_B$ (GeV)

0.0 100 200
Temperature T (MeV)

Quark-Gluon Plasma

Hadron Gas

Phase Boundary

Atomic Nuclei

Neutron Stars
Using $pp$ and $pA$ to cleanse $AA$ from initial state physics
Initial state, an experimental perspective

Using pp and pA to cleanse AA from initial state physics
**iconoclast** *(i-kōnˈo-klast′)*

*n.*

1. One who attacks and seeks to overthrow traditional or popular ideas or institutions.
2. One who destroys sacred religious images.

**iconoclastic** *(i-kōnˈo-klas′tĭ-kal′)*

*adv.*

**Word History:** An iconoclast can be unpleasant company, but at least the modern iconoclast only attacks such things as ideas and institutions. The original iconoclasts destroyed countless works of art.

*Warning:*
Geometry

this is what nuclei looked like in early 2000's
Hydro-dynamics with fluctuating initial conditions

In summary, experimental measurements of elliptic flow ($v_2$) might be affected by fluctuations.

But: Geometry fluctuations still treated as a perturbation of reaction plane eccentricity.
QM’05: First results on $v_2$ in CuCu from PHENIX, PHOBOS, STAR

In the pre-2005 view, density-scaling of $v_2/\epsilon$ broken in Cu+Cu vs Au+Au
Geometry Fluctuations and Participant Eccentricity

Participant Eccentricity

\[ \epsilon_{\text{part}} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2} \]

PHOBOS
QM2005
PRL 98, 242302 (2007)

PHOBOS
PRL 104, 142301 (2010)
PRC81, 034915 (2010)

Relative Fluctuations

PHOBOS Glauber MC
Au+Au 200GeV

PHOBOS
PRL 104, 142301 (2010)

PHOBOS
PRC81, 034915 (2010)

\[ \sigma_{\text{flow} \langle v_2 \rangle / \langle v_2 \rangle_{\text{flow}}} \]

for the assumptions:

- \( \delta_{\text{app}2} = 0 \)
- \( \delta_{\text{app}2} = 1 \times \text{Hijing} \)
- \( \delta_{\text{app}2} = 3 \times \text{Hijing} \)

\[ \frac{\sigma_{\epsilon_{\text{part}}}}{\langle \epsilon_{\text{part}} \rangle} \]

- Glauber MC
- CGC MC

\[ \frac{\sigma_{\epsilon_{\text{part}}}}{\langle \epsilon_{\text{part}} \rangle} \]

\[ \frac{\epsilon_{\text{part}}}{\langle \epsilon_{\text{part}} \rangle} \]
Ridge


Mach cones
Ridge


Mach cones

Geometry fluctuations and final state correlations:
Mishra et al arXiv:0711.1323
Takahashi et al, arXiv:0902.4870
Sorensen, arXiv:1002.4878
Demise of Ridge and Mach Cones

“Triangular flow” and “Participant triangularity”
No ridge, no mach cone, just flow
Burak Alver
Mithig meeting
10/13/2009

Geometry fluctuations and final state correlations:
Mishra et al arXiv:0711.1323
Takahashi et al, arXiv:0902.4870
Sorensen, arXiv:1002.4878
Just like elliptic flow reflects event-by-event eccentricity, “triangular flow” ($v_3$) reflects event-by-event “triangularity” ($\varepsilon_3$)
Geometry Fluctuations and Higher Order Harmonics

Participant Triangularity (2010)

$$\psi_3 = \sqrt{\frac{\langle r^2 \cos(3\phi) \rangle^- + \langle r^2 \sin(3\phi) \rangle^-}{\langle r^2 \rangle}}$$

Alver, Roland

Just like elliptic flow reflects event-by-event eccentricity, “triangular flow” ($v_3$) reflects event-by-event “triangularity” ($\varepsilon_3$)

Single calculation describes Fourier coefficients at RHIC and LHC (2012) (small change in $\eta/s$ from RHIC to LHC)

Bjoern Schenke et al

Gunther Roland
International Conference on the Initial Stages of High-Energy Nuclear Collisions
Illa da Toxa September 2013
September 2010

Return of the Ridge
Pronounced structure at large $\delta \eta$ around $\delta \phi \sim 0$!

Intermediate $p_T$: 1-3 GeV/c

MinBias

MinBias, 1.0GeV/c<$p_T<$3.0GeV/c

N>110, 1.0GeV/c<$p_T<$3.0GeV/c

Results based on 1fb$^{-1}$, i.e. sampling 50billion pp events with high multiplicity trigger

Two-Particle Correlations in pp (Sep 2010)

CMS

JHEP 1009 (2010) 091
High multiplicity (N>110)

Interpretation:

- Multi-jet correlations
- Jet-Jet color connections
- Jet-proton remnant color connections
- Jet-remnant connections + medium
- Glasma correlations
- Quantum entanglement
- Angular momentum conservation
- Angular momentum conservation + medium
- Hydrodynamic flow

Multiplicity in these events is dominated by jet contribution.

~100 citations within a year
Similar correlations as in high-multiplicity pp, but larger strength (associated yield)

Opinion:
Phenomenology very similar in pp and pPb - same underlying physics
Most models of pp-ridge immediately ruled out
Peripheral subtraction in ALICE and ATLAS

Away side yield in pp and peripheral pPb is very similar (away-side jet)

Subtraction of peripheral pPb correlations reveals nearly symmetric “double-ridge” structure
PHENIX dAu correlations

“Quadrupole correlations” seen in dAu as well

PHENIX
arXiv:1303.1794
Direct comparison of $v_2$ in pPb and PbPb

$v_2$ shows similar shape in pPb and PbPb, but is smaller in pPb

$v_2\{4\}$ is only 20% smaller than $v_2\{2\}$ below 2 GeV/c

“Peripheral subtraction” has small effect at high multiplicity
Direct comparison of $v_3$ in pPb and PbPb

Triangular flow vs multiplicity rather similar in pPb vs PbPb
Mass-ordering of $v_2$ vs $p_T$ seen in pPb, similar to PbPb
$p_T$ Spectra in pp, pPb and PbPb

CMS arXiv:1307.3442

McLerran, Praszalowicz, Schenke
arXiv:1306.2350

ALICE arXiv:1307.6796

Radial flow, mini-jets, Cronin effect, Geometric Scaling, Recombination,....
Azimuthal Correlations in pp, pA and AA

- “Glauber+Hydro” dominant source of AA azimuthal correlations

- Important questions not settled:
  - Glasma/KLN/Glauber
  - Existence of other non-trivial azimuthal correlations

- Striking similarity of p(d)A and AA azimuthal correlations
  - $v_2$, $v_2\{4\}$, $v_3$ vs $p_T$, multiplicity, PID $v_2$
  - Relative magnitude understood in “Glauber+Hydro” picture
  - if pp fits in there as well: sub-nucleonic geometry fluctuations

- But, is this picture physical? Thermalization

Spectra: pp vs p(d)A vs AA - a mess or interesting physics in search of a big idea?
Momentum space
Dijet $dN/d\eta$ in pPb and nuclear PDFs

CMS PAS HIN-13-001

see talks by Yaxian Mao (plenary) and Doga Gulhan (parallel)
Dijet $dN/d\eta$ in pPb and nuclear PDFs

Modification vs Pythia of pPb dijet $dN/d\eta$ matches nuclear PDF

see talks by Yaxian Mao (plenary) and Doga Gulhan (parallel)
Charmonium $R_{p(d)A}$ and nuclear PDFs

Much of the rapidity dependence can be understood in terms of nPDFs.
“Centrality” (not really) dependence of dijet $\eta$

Correlation between dijet system and underlying event introduces “rapidity shift” that is much larger than nPDF effects

CMS Preliminary

CMS PAS HIN-13-001

see talks by Yaxian Mao (plenary) and Doga Gulhan (parallel)
Quarkonia yield and event activity

ALICE

Similar to dijets, strong correlation of hard probe and event activity

see talk by Camelia Mironov (Tuesday)
Recall: Factorization of centrality vs $\sqrt{s}$

Centrality dependence from mid-peripheral to central collisions similar from 0.02 to 2.76 TeV

$N_{\text{coll}}/N_{\text{part}}$ for central events changes by more than 2 over this energy range

This cannot be understood in incoherent superposition of hard/soft processes

$$dN/d\eta = x*N_{\text{coll}} + (x-1)*N_{\text{part}}$$  \textbf{NO!}
Summary

• Last decade has seen a dramatic evolution of our understanding of the initial state in nuclear collisions

• Unified picture of the bulk of correlations in pp, pPb and PbPb in terms of hydrodynamics
  • Is this picture \textit{physical}?

• Hard probes in pA show significant nuclear effects
  • nPDFs, saturation, cold (hot?) matter e-loss?

• Strong correlations between hard scattering system and underlying event cannot be ignored
Dijet $\eta$ and nuclear PDFs

Leading jet $p_{T,1} > 120$ GeV/c
subleading jet $p_{T,2} > 30$ GeV/c  "$x_1$"
$|\Delta\phi_{12}| > 2\pi/3$

Boosted PYTHIA6 Z2
@ 5.02 TeV

Translation from $n_{dijet}$ to $x_1$

$p$

"$x_1$"

$\eta_{dijet} = \frac{\eta_1 + \eta_2}{2}$

$\eta_{dijet}$

$p_T,1 > 120$ GeV/c
$p_T,2 > 30$ GeV/c
$|\Delta\phi_{12}| > 2\pi/3$

$Q^2 = 10000$ GeV$^2$

$R = \frac{nPDF}{PDF}$

$10^{-3}$ $10^{-2}$ $10^{-1}$ $x$

$10^{-3}$ $10^{-2}$ $10^{-1}$ $x_1$

Gunther Roland
Subtract $N_{\text{trk}}^{\text{offline}}<20$ (70-100%) to avoid removing signal

- ATLAS subtract 50-100%; forward-calorimeter centrality

Some difference vs ATLAS in $v_2\{4\}$: multiplicity fluctuations?
$v_3$ in pPb compared to hydro

Schenke et al

Perfect liquid ($\eta/s = 1/4\pi$) in pPb collisions?
“Centrality” (multiplicity density) binning

n.b., particles are counted for $p_T > 0.4 \text{GeV/c}$, $|\eta| < 2.4$

<table>
<thead>
<tr>
<th>$N_{\text{trk}}$ binned</th>
<th>Fraction</th>
<th>$\langle N_{\text{trk}} \rangle$</th>
<th>$\langle N_{\text{trk}} \rangle$</th>
<th>$&lt;\text{Centrality}&gt;$</th>
<th>$\langle N_{\text{trk}} \rangle$</th>
<th>$\langle N_{\text{trk}} \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[0, \infty)$</td>
<td>1.00</td>
<td>40</td>
<td>50±2</td>
<td>92±4</td>
<td>10</td>
<td>13±1</td>
</tr>
<tr>
<td>$[0, 20)$</td>
<td>0.31</td>
<td>10</td>
<td>12±1</td>
<td>86±4</td>
<td>24</td>
<td>30±1</td>
</tr>
<tr>
<td>$[20, 30)$</td>
<td>0.14</td>
<td>25</td>
<td>30±1</td>
<td>83±4</td>
<td>34</td>
<td>43±2</td>
</tr>
<tr>
<td>$[30, 40)$</td>
<td>0.12</td>
<td>35</td>
<td>42±2</td>
<td>80±4</td>
<td>44</td>
<td>55±2</td>
</tr>
<tr>
<td>$[40, 50)$</td>
<td>0.10</td>
<td>45</td>
<td>54±2</td>
<td>78±3</td>
<td>54</td>
<td>68±3</td>
</tr>
<tr>
<td>$[50, 60)$</td>
<td>0.09</td>
<td>54</td>
<td>66±3</td>
<td>75±3</td>
<td>69</td>
<td>87±4</td>
</tr>
<tr>
<td>$[60, 80)$</td>
<td>0.12</td>
<td>69</td>
<td>84±4</td>
<td>72±3</td>
<td>89</td>
<td>112±5</td>
</tr>
<tr>
<td>$[80, 100)$</td>
<td>0.07</td>
<td>89</td>
<td>108±5</td>
<td>70±3</td>
<td>109</td>
<td>137±6</td>
</tr>
<tr>
<td>$[100, 120)$</td>
<td>0.03</td>
<td>109</td>
<td>132±6</td>
<td>73±3</td>
<td>134</td>
<td>168±7</td>
</tr>
<tr>
<td>$[120, 150)$</td>
<td>0.02</td>
<td>132</td>
<td>159±7</td>
<td>64±3</td>
<td>167</td>
<td>210±9</td>
</tr>
<tr>
<td>$[150, 185)$</td>
<td>$4 \times 10^{-3}$</td>
<td>162</td>
<td>195±9</td>
<td>67±3</td>
<td>202</td>
<td>253±11</td>
</tr>
<tr>
<td>$[185, 220)$</td>
<td>$5 \times 10^{-4}$</td>
<td>196</td>
<td>236±10</td>
<td>62±2</td>
<td>202</td>
<td>253±11</td>
</tr>
<tr>
<td>$[220, 260)$</td>
<td>$6 \times 10^{-5}$</td>
<td>232</td>
<td>280±12</td>
<td>59±2</td>
<td>239</td>
<td>299±13</td>
</tr>
<tr>
<td>$[260, 300)$</td>
<td>$3 \times 10^{-6}$</td>
<td>271</td>
<td>328±14</td>
<td>57±2</td>
<td>279</td>
<td>350±15</td>
</tr>
<tr>
<td>$[300, 350)$</td>
<td>$1 \times 10^{-7}$</td>
<td>311</td>
<td>374±16</td>
<td>55±2</td>
<td>324</td>
<td>405±18</td>
</tr>
</tbody>
</table>
4\textsuperscript{th} order cumulants in multiplicity bins

Cumulant analysis in bins of multiplicity
Need to consider bin widths carefully
CMS analysis: (narrow bins + averaging)