Ultra-Relativistic Heavy Ion Collision Results

John Harris (Yale), September 17, 2016

Nuclear Matter under Extreme Conditions, Erice-Sicily, Italy
I. Overview of Effects Observed in Large Nucleus-Nucleus Collision Systems (Au+Au, Pb+Pb)
High $p_T$ Hadrons Are Suppressed at LHC & RHIC

Central Pb-Pb and Au-Au Collisions

Suppression $\rightarrow$ parton energy loss in hot QCD medium

Also enhancement at lower energies $\rightarrow$ initial state effects (Cronin enhancement)

\[ R_{AA} = \frac{N_{AA}^{\text{particle}}}{N_{\text{coll}} N_{PP}^{\text{particle}}} \]

\[ R_{CP} = \frac{N_{\text{central}}}{N_{\text{peripheral}}} \sim R_{AA} \]

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Jets Are Quenched at RHIC & LHC

**RHIC**

Charge jets

- AuAu/Pythia
- tracking eff. uncertainty
- unfolding uncertainty
- $T_{AA}$ uncertainty
- Uncertainties added linearly

$R_{AA}^{(Au+Au/Pythia)}$

- Run 11 $Au+Au \sqrt{s_{NN}}=200$ GeV, 60 $\mu$b$^{-1}$
- 0-10% Central Collisions
- $\Delta k_T$, $R = 0.2$
- $p_T^{\text{leading}} > 0.2$ GeV/c
- $p_T^{\text{const}} > 5.0$ GeV/c
- $A_{\text{reco, jet }}> 0.09$ sr

**LHC**

$R_{AA}^{(LHC)}$

ALICE Preliminary, Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
- $\Delta k_T$, $R = 0.2$
- ALICE 0-10%
- ALICE 10-30%
- CMS 0-5%
- CMS 10-30%

CMS: Read from HIN-12-004-PAS
CMS: Syst. Unc. $R = 0.3$

**RHIC Jets less suppressed than LHC Jets at low jet momentum**

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**Suppression of Quarkonium States expected in a hot QCD Medium!**

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Elliptic Flow Saturates Hydrodynamic Limit

- Azimuthal asymmetry of charged particles:
  \[ \frac{dn}{d\phi} \sim 1 + 2 v_2(p_T) \cos(2\phi) + \ldots \]
Elliptic Flow Saturates Hydrodynamic Limit

Azimuthal asymmetry of charged particles:
\[ \frac{d\eta}{d\phi} \sim 1 + 2 v_2(p_T) \cos(2\phi) + \ldots \]

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Elliptic Flow Saturates Hydrodynamic Limit

Azimuthal asymmetry of charged particles:
\[ \frac{dN}{d\phi} \sim 1 + 2v_2(p_T) \cos(2 \phi) + \ldots \]

Curves = hydrodynamic flow
zero viscosity, \( T_c = 165 \text{ MeV} \)

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**Elliptic Flow Saturates Hydrodynamic Limit**

Azimuthal asymmetry of charged particles:

\[ \frac{dn}{d\phi} \sim 1 + 2 \, v_2(p_T) \cos(2\phi) + \ldots \]

- Mass dependence of \( v_2 \)
- Requires:
  - Early thermalization (0.6 fm/c)
  - Near-ideal hydrodynamics (near-zero viscosity) → “nearly perfect liquid”
  - \( \varepsilon \sim 25 \text{ GeV/fm}^3 \) (\( \gg \varepsilon_{\text{critical}} \))
  - Quark-Gluon Equ. of State
Flow Consequences → a Strongly-Coupled Medium with Ultra-low $\eta/s$ (shear viscosity / entropy)

The strong-coupling limit of non-Abelian gauge theories with a gravity dual (ref: Kovtun, Son, Starinets, PRL 94, 111601 (2005))

Universal lower bound on shear viscosity / entropy ratio ($\eta/s$)

$\eta/s = 1 / 4\pi$ for a “perfect liquid”

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II. Effects in $p(d) + A$ compared to $A + A$
High $p_T$ Particles & Jets
**High $p_T$ Hadrons $R_{p(d)A}$ & $R_{AA}$ at LHC and RHIC**

- **LHC p-Pb & RHIC d-Au ($p_T > 2$ GeV/c)**
  - Binary scaling ($R_{dAu} \sim R_{pPb} \sim 1$), except “bump” at $\sim 4$ GeV/c
  - Absence of Nuclear Modification $\rightarrow$ Initial state effects small

- **RHIC Au-Au and LHC Pb-Pb**
  - Suppression ($R_{pPb} \ll 1$, $R_{AuAu} \ll 1$) $\rightarrow$ Final state effects (hot QCD matter)

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Jets in p-Pb & Pb-Pb at LHC

Binary scaling, no initial state effects!

ALICE ≈ ATLAS ≈ CMS: $R_{p-Pb}$ (jet) ≈ 1

Jets quenched in Pb-Pb collisions

ALICE ≈ ATLAS ≈ CMS: $R_{Pb-Pb}$ (jet)<<1

ALICE Preliminary

Pb-Pb $s_{NN} = 2.76$ TeV

anti-$k_T$ $R = 0.2$

ALICE 0-10%

ALICE 10-30%

CMS 0-5%

CMS 10-30%

CMS: Read from HIN-12-004-PAS

CMS: Syst. Unc. $R = 0.3$
Jets in d-Au at RHIC

PHENIX arXiv:1509.04657v2

Jets reconstructed in p+p and d+Au
$12 < p_T < 50$ GeV/c

$R_{dAu} \approx 1$ for min.bias d+Au

$R_{dAu}$ exhibits strong centrality dependence
Peripheral collisions: jets enhanced
Central collisions: jets suppressed
**Centrality Dependence of Jets in p (d) + A**

ATLAS, PLB 748 (2015) 392

**R_{pPb} jets → strong centrality dependence**

Peripheral collisions: jets enhanced
Central collisions: jets suppressed

**R_{dAu} jets → strong centrality dependence**

Peripheral collisions: jets enhanced
Central collisions: jets suppressed

Challenge to factorization in hard-scattering?

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Identified Particles
Hardening with multiplicity and particle mass indicative of collective effects in A-A-A!

Similar to effects observed in A-A → has been attributed to radial flow.
$R_{pPb}$ for Identified Hadrons

$R_{pPb}$ mass dependence
→ Protons peak at intermediate $p_T$
→ $\pi$ and $K$ flat over measured $p_T$ range

Suppression in Pb-Pb

pp reference interpolated from 2.76 and 7.0 TeV

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Similar Effects at RHIC in d+Au

PHENIX

arXiv: 1304.3410
Indications of Collective Flow of Identified Particles in p-Pb

Strong mass ordering in pPb

Identified π, K, p
\[ \pi, K, p - \text{Blast Wave} \quad pPb \ & \ PbPb \]

**Blast wave model**
(Schnedermann, PRC 48 (1993) 2462)

Hydro-inspired
- Particle source at \( T \)
- Radial flow \( \beta \)
  \[ \beta (r) = \beta_s (r/R)^n \]
- Fit particle spectra simultaneously
  \( \langle \beta_T \rangle \) from \( 2\beta_s / (2+n) \)
- \( T_{\text{kin}} \)
- \( n \)

**Similar trends \( \rightarrow \) indicative of radial flow in p-Pb and Pb-Pb**
- \( T_{\text{kin}} \) similar in Pb-Pb and p-Pb for same multiplicities
- \( \langle \beta_T \rangle \) larger in p-Pb for similar multiplicities
  \( \rightarrow \) stronger collective flow for smaller system size…?


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Heavy Flavor – D-Mesons: $R_{pPb}$ & $R_{PbPb}$

**D-meson NOT suppressed in p-Pb**

$R_{pPb}$ consistent with $\approx 1$

Initial state effects small!

**D-meson central $R_{PbPb}$ suppressed!**

Centrality dependence

Not initial state effect!

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Particle Correlations:
Flow Harmonics of Lighter Systems
Initial (Historical) STAR Discovery of the AA Ridge


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Long-range Di-hadron Correlations in pp, p-A

CMS, JHEP 09 (2010) 091

LHC near-side ridge for $\sqrt{s_{NN}} = 7$ TeV pp
5.02 TeV p-Pb

CMS, PLB 718 (2013) 795

ALICE, PLB 719 (2013) 29


Potential interpretations include CGC, long-range color correlations……., hydro??

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Observation of p-Pb Double Ridge

After subtraction (central – peripheral):
- Fourier decomposition
- Components shown as dotted/dashed curves

After subtraction of low multiplicity from high multiplicity events:
- Fourier decomposition seen as curves


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Comparing $v_2$ and $v_3$ from Long-range Correlations


Symbols are (back-to-back jet) subtracted data. Curves are before subtraction. Notice $v_2$ trends and $v_3$ almost identical (p-Pb and Pb-Pb)
Collective Flow $v_2(n)$ in Pb-Pb & p-Pb


For PbPb and pPb – Collective effects!

$v_2$ (n) remains large when using more (n) particles

$v_2 (4) = v_2 (6) = v_2 (8) = v_2 (LYZ)$ within 10%
Fourier Decomposition of p-Pb Double Ridge

After subtraction Fourier coefficient $v_2$ (2PC, sub)

Observe ordering in mass!

p-Pb ordering similar to Pb-Pb

$v_2$ (2PC, sub) mass hierarchy
~ described by
Hydro with Glauber initial conditions
ref: Bozek, Broniowski, Torrieri, arXiv:1307.5060

ALICE, arXiv:1307.3237

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Collective Flow of Identified Particles in p-Pb!

CMS, arxiv:1409.3392

Identified $K_S$, $\Lambda$ & charged hadrons

$v_2$ from 2-particle correlations

Exhibit mass ordering in pPb and PbPb

NCQ scaling better in pPb
Particle Correlations:
System Size from Freeze-out Radii
System Size in pp, p-Pb and Pb-Pb

Invariant radii vs $<N_{ch}>$
- pp similar to pPb
- pPb smaller than PbPb

Invariant Source Radii from HBT fits of 2 & 3 Pion Correlation Measurements:

$R_{inv}^{E_w}(p-Pb) \sim 1.05-1.15 R_{inv}^{E_w}(pp)$

$R_{inv}^{E_w}(Pb-Pb) \sim 1.35-1.55 R_{inv}^{E_w}(p-Pb)$

Perhaps only small hydrodynamic expansion in pPb beyond that in pp at same Nch
Evolution of p-Pb System

3d radii ($R_{\text{out}}$, $R_{\text{side}}$, $R_{\text{long}}$) in LCMS from two-pion correlations

Radii decrease with increasing $k_T$ as in AA (and in hydro)

Similarity between pPb and high multiplicity pp

ALICE, PLB 739 (2014) 139

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What are the Freezeout Radii Telling Us?

ALICE, Physics Letters B739 (2014) 139–151:

Invariant Source Radii from HBT 2 & 3 Pion Correlation Measurements

\[ R_{\text{inv}}(p-Pb) \approx 1.05-1.15 \ R_{\text{inv}}(pp) \]

\[ R_{\text{inv}}(Pb-Pb) \approx 1.35-1.55 \ R_{\text{inv}}(p-Pb) \]

- This disfavors models incorporating significantly larger flow in p-Pb than in pp at same multiplicity!
- Consistent with CGC initial conditions without a hydro-dynamical phase!
- See also (Shuryak interpretation)
  
  arxiv:1404.1888 – “collective implosion”

Demonstrates importance of initial conditions on the final-state – and/or – indicates significant collective expansion in peripheral Pb–Pb collisions.
What Have We Learned from p(d)A + A?

- p(d)+A studies confirm quenching/suppression in A+A is final state effect

- p(d)+A hard probes described by pQCD-inspired models
  Exceptions – High $p_T$ hadrons (enhancement?)
  High $p_T$ jets (peripheral enhanced? Central suppressed?)

- Many aspects of p(d)+A (at lower $p_T$) exhibit effects attributed to collective behavior – e.g. strong mass ordering, radial flow, $v_2(4) = v_2(6) = v_2(8)$

- Size of system much smaller in p(d)+A than in A+A
  p+A close to p+p at similar multiplicity – important to understand theoretically

- Need more theoretical guidance, direct model comparisons, more precise data!
A Final Comment

- We seek to investigate high density QCD phenomena in collisions of various (large and small) systems!
- Can we separate the initial state from the final state (even in theory) to compare p+p, p+A, A+A results and extract vital answers on:
  - The initial state: CGC, Glauber, pdf’s, etc?
  - The effect of cold nuclear matter on final state observables?
  - The basic parton energy loss mechanisms?
  - The dependence on multiplicity and energy in p+p, p+A & A+A?
  - The basic mechanisms of equilibration, transport and production?
- What are the key measurements to discriminate models or better yet theories?

We are investigating collective phenomena in a variety of nuclear systems to learn how the many-body system emerges from the fundamental interactions!
Thanks for your attention!