p(d)+A collisions at LHC and RHIC

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Relativistic Heavy Ion Collisions Goals

Study the phases of QCD
- the structure
- thermodynamics properties
- Emergent behaviors
- Search for critical point

pA or dA collisions
- No QGP?
- Cold vs hot QCD matter
- Initial vs final state effects
Key Discoveries in AA collisions at RHIC

Physics Today, May 2005

$\eta \lessgtr \frac{\hbar}{4\pi k_B}$

$\text{Au+Au } \sqrt{s_{\text{NN}}} = 200 \text{GeV, 0-10\%}$

PHENIX preliminary

$R_A$

$V_2/n$

$K^+ + K^-$ (PHENIX) $\Lambda + \bar{\Lambda}$ (STAR)

$\pi^0$ (PHENIX) $\phi$ (STAR)

$d$ (PHENIX)

$\pi^+ + \pi^-$ (PHENIX) $p + \bar{p}$ (PHENIX)

$\pi^0$ (PHENIX) $\Lambda + \bar{\Lambda}$ (STAR)

$K^+ + K^-$ (PHENIX) $\Xi^- + \Xi^+$ (STAR)

$K_S^0$ (STAR) $\phi$ (STAR)

$K_S^0$ (STAR) $\phi$ (STAR)
d+Au in 2003: No jet quenching in d+Au hints of saturation at forward $\eta$ (small $x$)

**PHENIX**

- $R_A$ vs. $p_T$ (GeV/c)
  - Charged hadrons
  - Neutral pions

**PHOBOS**

- $R_{dAu}$ vs. $p_T$ (GeV/c)
  - 70-100%
  - 40-70%
  - 20-40%
  - 0-20%

**BRAHMS**

- Nuclear Modification Factor
- $d+Au$ (MB)
- $Au+Au$ (0-10%)

**STAR**

- $(1/N_{\text{trigger}}) dN/d\phi$ vs. $\Delta\phi$ (degrees)
  - $Au+Au$ Central
  - $d+Au$ Central
  - $p+p$ Minimum Bias
d+Au in 2003

- Paradigm confirmed!
- Jet quenching is caused by the hot medium (final state effect)
- d+Au is a “control” system
A new look 10 years later

• $p+Pb$ at the LHC and higher statistics $d+Au$ in 2008
  – Look closer at the soft sector
  – Further reach with hard probes
    • EWK bosons
    • Jets and high-pt hadrons
    • Heavy flavor
    • Quarkonia
pPb collisions could be violent!

- 418 charged particles detected!

Are there correlations between the particles?
Given enough particles (about 50), we find ridges everywhere ...

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $N_{\text{offline}}^{\text{trk}} \geq 110$

$1 < p_T < 3$ GeV/c

PLB 718 (2013) 795
Azimuthal anisotropies in AA collisions

Flow harmonics probe the system at different length scales
Taken together: constrain fluctuations and viscosity of QGP
Even-by-event hydro: The effect of viscosity

average, then evolve  

initial energy density  

initial energy density  

evolve, then average  

initial  

ideal  

viscous  

energy density in the transverse plane  

Even-by-event hydro: The effect of viscosity

- Presently:
  - large uncertainty in the initial conditions
  - Limiting factor for precise determination of $\eta/s$
  - EIC will help establish the initial state

Questions to address from pA and dA

• What is the origin of the ridge in small systems?
  – Collective flow?
  – Quantum interference of gluons (CGC)?
  – … or something else?

• What are the initial state fluctuations?

• Methods:
  – Compare 2- and multi-particle correlations in different collision systems
  – multiplicity dependence
  – Particle species dependence
  – Study high-order harmonics
Multiparticle correlations

• $v_2$ stays large when calculated with multi-particles
  - $v_2(4) \neq v_2(2)$ (non-flow, fluctuations…)

![Graph showing $v_2$ vs. $N_{\text{trk}}$ for PbPb and pPb collisions with event multiplicity criteria.](image)
Multiparticle correlations

- $v_2$ stays large when calculated with multi-particles
  - $v_2(4) = v_2(6) = v_2(8) = v_2(LYZ)$ within 10%
  - True collectivity in pPb collisions!
p(d)A: Particle species dependence of $v_2$

Clear mass ordering
Similar to AA
Compatible with expectation from hydro
Higher harmonics: pPb vs PbPb

ATLAS Preliminary

$V_2$ vs $p_T$ [GeV]

$V_3$ vs $p_T$ [GeV]

$V_4$ vs $p_T$ [GeV]

Julia Velkovska (Vanderbilt)  
EIC user meeting, June 24-26, 2014
Hard probes

In AA: large dijet and $\gamma$-jet momentum imbalance
The $R_{AA}$ collection

$$R_{AA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{d^2N_{AA}}{dp_T d\eta} / \frac{d^2N_{pp}}{dp_T d\eta} \sim \frac{\text{“QCD medium”}}{\text{“QCD vacuum”}}$$

Colorless probes unsuppressed; hadrons and jets - modified
Less b-hadron suppression at low $p_T$; b-jets - similar to q/g jets
• Excess at backward rapidity in the Pb-going beam direction
• Consistent with nPDF predictions
• EIC will provide information about the sea quark distributions
W$^+$ and W$^-$ in pPb

Showing small deviations from unmodified PDFs
– A hint of a different u/d modification? (not in EPS09)
Unmodified jet energy in pPb

- Jet energy is essentially unmodified in pPb
  - As seen for instance in gamma-jet correlations
  - \( R_{J\gamma} \) = fraction of photons with a jet of \( p_{T\text{jet}} > 30 \) GeV

\[
R_{J\gamma} = \frac{\text{fraction of photons with a jet of } p_{T\text{jet}} > 30 \text{ GeV}}{\text{total number of photons}}
\]
Jets and dijets in pPb

ATLAS preliminary

CMS preliminary

minimum-bias p-Pb $\sqrt{s_{NN}} = 5.02$ TeV
charged jets ALICE Preliminary
anti-$k_T$ $R=0.4$, $|\eta_{\text{lab}}|<0.5$
charged hadrons, NSD, $|\eta_{\text{cms}}|<0.3$

normalization uncertainty reference + Glauber (charged jets)

anti-$k_T$(PFlow) $R=0.3$
$\Delta\phi_{1,2} > 2\pi/3$, $|\eta|<3$

$E_{T}[E_{T}^{\text{HF}}[n]>4]$ (GeV)
Jets and dijets in pPb

No significant modifications of jets are seen

Can we access the initial state?
How to get to different x values?

- Dijet $\eta$ distribution correlated with parton x from Pb

**Graphs and Diagrams:**
- CMS Preliminary pPb 31 nb$^{-1}$
- Min. bias
- Large x from nucleus
- Small x
- EMC
- Anti-shadowing
- Shadowing
How to get to different x values?

The shape of the distribution evolves with event activity.
What can we learn about nPDF?

- pp PDF ruled out by shape of dijet $\eta$ distribution
- Good agreement with EPS09 nPDF predictions

CMS pPb 35 nb$^{-1}$

$\sqrt{s_{NN}} = 5.02$ TeV

- $p_{T,1} > 120$ GeV/c
- $p_{T,2} > 30$ GeV/c
- $\Delta\phi_{1,2} > 2\pi/3$
- All $E_T^{4<|\eta|<5.2}$

arXiv: 1401.4433
What to expect for hadron $R_{pPb}$?

$pPb \sqrt{s_{NN}} = 5.02$ TeV

Helenius et al., JHEP 1207 (2012) 073

Smaller $Q^2$ and $x$  
Large $Q^2$ and $x$
The $R_{pPb}$ data!

The $R_{pPb}$ data is shown in the graph. The pp reference is interpolated from lower and higher energy data.

CMS-PAS-HIN-12-017

Anti-shadowing: larger than predicted although, with large systematic uncertainty.

- $N_{coll}$
- Correlated
- Partially correlated 10% from pp reference

The graph shows:
- $p_{T}$ [GeV/c] on the x-axis
- $R_{pPb}$ ($|\eta_{CM}| < 1$) on the y-axis

Key points:
- Smaller $Q^2$ and $x$
- Large $Q^2$ and $x$

CMS Preliminary

$N_{coll}=6.9$
• Same conclusion from CMS and ATLAS; tension with ALICE (mainly) in pp reference. **We need pp data at 5 TeV !**
Look for asymmetry in hadron yield vs $\eta_{cm}$

$$Y_{\text{asym}} = \frac{\text{Yield Pb-going}}{\text{Yield p-going}}$$

Small $x$ from Pb in denominator
Large $Q^2$ and $x$
Increase in shadowing region
Small change in antishadowing

CMS-PAS-HIN-12-017
At lower $p_T$: baryon enhancement

Significant baryon enhancement in $\text{dAu}$ and $\text{pPb}$

and

Universal behavior in peripheral $\text{AuAu}$ and central $\text{dAu}$
Enhancement at RHIC (looks like flow)
Smaller or no effect at LHC

EIC can help elucidate heavy quark propagation through cold nuclear matter
Quarkonia: PbPb, pPb and event activity

The suppression of 5 quarkonia observed in PbPb
Well-ordered with binding energy
Inclusive bottomonia
Charmonia $p_T > 6.5$ GeV
+ $p_T$-inclusive J/$\psi$ from ALICE
less suppressed than at RHIC, calling for recombination

Interesting behavior vs event activity in all collision systems
What is the correct reference for PbPb collisions?
EIC - will help?
Conclusions

- dA and pA collisions have proven to be:
  - interesting in their own right
  - Not quite “control experiment”
- Many indications from soft physics for similar behavior in AA and p(d)A

EIC will provide information for the initial state of the fluid evolution and thus - better define the QGP properties

- Some nuclear modifications are present in the hard sector

EIC will provide information on:
  - Sea quark and gluon distributions
  - Heavy quark propagation through nuclear matter
Implications for E loss in PbPb?

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EIC user meeting, June 24-26, 2014
Other hints of collective effects?

Inverse slope of $m_T$ distributions, $T_{\text{slope}}$:

$$\frac{1}{m_T} \frac{dN}{dm_T} \sim \exp\left( -\frac{m_T}{T_{\text{slope}}} \right)$$

Inverse slope increases with particle mass and with multiplicity. Reminiscent of radial flow.