Hot and Cold Nuclear Matter Effects in p-Pb Collisions at the LHC

1 August 2014
Why Run pA Collisions?

Traditional Heavy-Ion Playbook:
- AA – Create a Quark Gluon Plasma (QGP)
- pp – Establish baseline for observables
- pA – Control environment to isolate initial state effects
  - Energy density not high enough to create thermalized medium
  - Additional nuclear matter can alter incoming wavefunction
  - Referred to as “cold nuclear matter” effects

ALICE p-Pb Collision 5.02 TeV
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the best laid plans…

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However, pA collisions themselves presented interesting phenomena!
• Collective effects:
  Is there a thermalized medium created in pA?
• High $p_T$ enhancement:
  vs suppression seen in AA
• Understanding heavy flavor
  test of pQCD, shadowing/antishadowing
• Electroweak bosons
  pQCD candlestick, initial state nuclear modification

ALICE p-Pb Collision 5.02 TeV
September 2012 pilot run
• 4h data taking, 1 μb⁻¹ per experiment

January 2013 production run
• 3 weeks data taking
• 35 nb⁻¹ to ATLAS, CMS, ALICE
• Reversed beam (2/3 p-Pb, 1/3 Pb-p)

\( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
• Asymmetric center-of-mass
  • 4 TeV proton beam
  • 1.57 TeV/nucleon Pb beam
• \( \Delta y = 0.465 \) in direction of proton beam
Collective Flow
Important Distinction:
- a system of individual particles and
- a medium in which individual degrees of freedom do not matter anymore – thermodynamic regime

- Thermodynamic concepts are used for systems with large numbers of particles (>10^4) in local thermal equilibrium
  - Central Pb-Pb (0-5%) collisions (LHC): \( \frac{dN_{\text{ch}}}{d\eta} \approx 1600 \)
  - High mult p-Pb (0-5%) collisions (LHC): \( \frac{dN_{\text{ch}}}{d\eta} \approx 45 \)
  - pp collisions (LHC): \( \frac{dN_{\text{ch}}}{d\eta} \approx 6 \)

- Lifetime of system must be long enough to establish equilibrium between constituents
  - Simulations show typically 3-6 interactions sufficient
Collectivity and Equilibrium

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\rightarrow Equilibrium in smaller systems such as p-Pb??
Radial and Elliptic Flow from expanding medium

Isotropic Radial Flow:
- Medium expansion driving $p_T$ distributions
- lower $p_T$ particles $\rightarrow$ higher $p_T$ (mass hierarchy)

Anisotropic Elliptic Flow:
- Geometrically asymmetric pressure gradient
- Momentum anisotropy $\rightarrow$ spatial anisotropy
- Long-range azimuthal correlations
- Quantified by Fourier decomposition of the azimuthal angle wrt reaction plane ($x$-$z$)

$$\frac{d^3N}{dp_T d\eta d\phi} = \frac{d^2N}{dp_T d\eta} \frac{1}{2\pi} \left[ 1 + 2v_1 \cos(\phi - \Psi_1) + 2v_2 \cos 2(\phi - \Psi_2) + \ldots \right]$$

$\nabla p_x > \nabla p_y$
• Hydrodynamic models (EPOS, Krakow) agree better than QCD based DPMJET.

• Blast-wave fit (simplified hydro model) to combined data also reasonable.
  - 2 essential parameters: $T_{\text{kin}}$, $\beta$
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- p-Pb (and Pb-Pb) consistent with collective expansion!

- PYTHIA8 with color reconnection shows similar trend (w/o hydrodynamic flow)
  - Mimicking flow-like patterns (even in pp!)
Two Particle Correlations

- Two particle correlations contain:
  - "jet like" correlations (all systems)
  - collective flow (only expected in AA)
    - hydrodynamic expansion
    - result of initial collision geometry
- Double ridge understood in AA
- Near-side ($\Delta\phi \sim 0$), long-range (large $\Delta\eta$) shoulders in high multiplicity pp and pA
  - indicates medium-like expansion?

\[ \text{pp} \quad [1009.4122] \quad \text{p-Pb} \quad [1210.5482] \quad \text{Pb-Pb} \]
Double Ridge in p-Pb

- Long range, non jet-like correlations in p-Pb
- Fourier decomposition dominated by $v_2$, $v_3$
  - looks like medium-induced flow!

$$v_n = \langle \cos n(\phi - \Psi_n) \rangle$$

Angular Correlations

**Elliptic Flow:**
- Mass ordering observed by CMS, ALICE
  - also seen at RHIC
- Similar behavior in Pb-Pb
- Hydrodynamic signature?
  - $p = \beta \gamma m$

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mass ordering

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Intermediate/High $p_T$ and Jets
Nuclear Modification Factor
Nuclear Modification Factor

AA example

\[ R_{AA} = \frac{dN_{AA} / dp_T}{\langle N_{coll} \rangle dN_{pp} / dp_T} \]

- Quantifies spectral modification due to nuclear effects
  - How different are AA collisions compared to a superposition of \( N_{coll} \) pp collisions?
- \( R_{AA} \approx 1 \rightarrow \) no modification from \( N_{coll} \) independent pp hard scatterings – no medium effects!

Characteristic Heavy Ion \( R_{AA} \):
- Energy dependent suppression
- Centrality dependent suppression
Nuclear Modification Factor

$pA$ analog

$R_{pA} = \frac{dN_{pA}}{dN_{pp}} / \frac{p_{T}}{p_{T}}$

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Characteristic Heavy Ion $R_{AA}$:
- Energy dependent suppression
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$pA$ reveals “Cronin Effect”:
- Hardening of $pT$ spectrum
- Typically attributed to multiple scattering of $p$ in nucleus
- Glauber model – number of binary collisions:
  $p$-$Pb < N_{coll} > = 6.9 \pm 0.6$
Mass Dependent Cronin Effect:

- Strong particle species dependence
- No Cronin peak for $\pi$, $K$
  - evolves with increasing mass
- Radial flow picture predicts mass dependent hardening of $p_T$ spectrum
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- Radial flow picture predicts mass dependent hardening of $p_T$ spectrum
- Qualitatively consistent picture at RHIC
- Another hydrodynamic thumbprint in pA?
Surprise at high $p_T$:

- CMS observes charged particle enhancement
- ATLAS confirms observation!
- ALICE sees different trend…
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- All experiments agree on jet $R_{pA}$ nearly consistent with unity  
  - could it be jet fragmentation?
Charged Hadron $R_{p\text{Pb}}$ explanations?

- PDFs modification expected in nucleus
- However, anti-shadowing cannot explain rise
Moreover, “disagreement” is possibly overstated:

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Heavy Flavor
Precise measurements of quarkonia are crucial to understand hot and cold nuclear matter and to probe de-confinement in QGP matter.

Two major effects in AA collisions:
- Thermal dissociation (breakup)
- Statistical regeneration (recombination)

However, must disentangle pA effects:
- PDF modifications in nuclei (shadowing)
- Gluon saturation
- Energy loss
- Nuclear absorption

In addition, HF can help constrain nuclear PDFs
Rapidity dependence of $R_{pPb}$:
- Suppression in positive-$y$ (low-$x$ in Pb nucleus)
- Little modification at negative-$y$

Described reasonably well by models:
- NLO with ESP09 shadowing
- Coherent energy loss (w/wo ESP09)
- CGC models, less well
Quarkonia

\( J/\psi - p_T \)

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- LHCb recently joined p-Pb activities
Rapidity dependence of $R_{pPb}$:
- $\psi'$ is more suppressed than J/$\psi$
- Models predict similar behavior for J/$\psi$ and $\psi'$
- Ratio of $R_{pA}$ for $\psi'$ to J/$\psi$ similar at RHIC
  - RHIC: 200 GeV, d+Au
- Hints at final state effect?
- Unexpected since charmonia formation time larger than $c\bar{c}$ crossing time in nucleus
Quarkonia

$J/\psi$ vs $\psi'$

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$p_T$ dependence of relative $R_{pPb}$:
- Constant, within uncertainties
Y(1S) agrees with NLO (+ nuclear modification)

- Similar to J/ψ though different PDF scale
• Y(1S) agrees with NLO (+ nuclear modification)
  • Similar to J/ψ though different PDF scale

• Y(2S) less suppressed with respect to Y(1S) in p-Pb than PbPb
• Varies with event multiplicity
• Do excited states add multiplicity (event selection bias)?
• Or does activity suppress excited states (à la Pb-Pb)?
Electroweak Bosons
**Z\(^0\) Production**

Z → μμ candidate in p-Pb

Why measure Z bosons in p-Pb?

- Sensitive to nuclear PDF modifications
  - but not final state effects
- Clean probe to understand p-Pb scaling properties
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- ATLAS sees ~3500 $Z^{0}$
- Seem to observe modification to simple pp,pn scaling
Z$^0$ Production

**CMS, ATLAS**

- Sensitive to nuclear PDF modifications but not final state effects
- Clean probe to understand p-Pb scaling properties
- CMS sees $\sim$1600 Z$^0$
- Better agreement with modified nucleus predictions

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- Seem to observe modification to simple pp,pn scaling
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• Forward/backward asymmetry to constrain nuclear PDFs
**Z^0 Production**

*LHCb*

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- Clean probe to understand p-Pb scaling properties
- LHCb sees \(~15\) Z^0

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Z⁰ Production

centrality calibrator

- Production is expected to not be modified by any medium effects
- Scales with number of binary collisions
- Can be used to constrain centrality approaches
Z\(^0\) Production

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"Yesterday's sensation is today's calibration"

– M Tannenbaum
Cross section of muons from W decays
Electroweak medium-blind probes
Consistent with binary scaling expectation
W Production
$W \rightarrow \mu \nu$

Charge Asymmetry

- Showing some deviations from *unmodified* PDFs
- Modified PDFs do a better job
- Some hint of different u,d modification (not in EPS09)?
• **p-Pb** contains lots of interesting physics
  • not simply a sidecar for AA!

• Thermalized medium-like features observed for most particles at low $p_T$
  • Elliptic flow, radial flow, thermal fits…

• No indication of *quenching* at high $p_T$
  • Hadrons, jets, heavy flavor
  • However, *enhancement* at high $p_T$ still unexplained

• Quarkonia measurements provide essential control baseline for Pb-Pb

• Electroweak bosons constrain nPDFs and centrality estimators
Coordinate System

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

\[ |\Delta y_{\text{c.m.}}| = 0.465 \]

**p-Pb**
- \( p \) 4 TeV
- \( \eta_{\text{lab}} < 0 \)
- \( y > 0 \)
- \( \eta_{\text{cms}} > 0 \)

**Pb-p**
- \( \text{Pb} \) 1.58 ATeV
- \( \eta_{\text{lab}} > 0 \)
- \( y < 0 \)
- \( \eta_{\text{cms}} < 0 \)

**The direction of the proton is always at positive \( y \equiv y_{\text{c.m.}} \) and positive \( \eta_{\text{c.m.}} \)**
Color Reconnection