Collective behavior of high-$p_T$ particles in 8.16 TeV $p+Pb$ collisions with ATLAS

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$v_n$ in Pb+Pb

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    title={ATLAS
    $|n| < 2.5$
    20-30 %
    Pb+Pb, 22 \mu b^{-1}
    $\sqrt{s_{NN}} = 5.02$ TeV
    \}
    xlabel={$p_T$ [GeV]},
    ylabel={$v_n$ [SP]},
    legend style={at={(0.5,0.5)}, anchor=north},
    legend cell align=left
    ]
    \addplot[black,mark=*,line width=1.0pt] coordinates {
        (0.5,0.3)
        (1,0.25)
        (2,0.2)
        (3,0.15)
        (4,0.1)
        (5,0.05)
        (6,0.0)
    };
    \addlegendentry{$n=2$}
    \addplot[red,mark=square*,line width=1.0pt] coordinates {
        (0.5,0.25)
        (1,0.2)
        (2,0.15)
        (3,0.1)
        (4,0.05)
        (5,0.0)
    };
    \addlegendentry{$n=3$}
    \addplot[green,mark=diamond*,line width=1.0pt] coordinates {
        (0.5,0.2)
        (1,0.15)
        (2,0.1)
        (3,0.05)
        (4,0.0)
    };
    \addlegendentry{$n=4$}
    \addplot[blue,mark=square*,line width=1.0pt] coordinates {
        (0.5,0.15)
        (1,0.1)
        (2,0.05)
        (3,0.0)
    };
    \addlegendentry{$n=5$}
    \addplot[green,mark=diamond*,line width=1.0pt] coordinates {
        (0.5,0.1)
        (1,0.05)
        (2,0.0)
    };
    \addlegendentry{$n=6$}
    \addplot[blue,mark=square*,line width=1.0pt] coordinates {
        (0.5,0.05)
        (1,0.0)
    };
    \addlegendentry{$n=7$}
\end{axis}
\end{tikzpicture}
\end{center}
$v_n$ in Pb+Pb

ATLAS
$|n| < 2.5$
20-30%

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

Hydrodynamics

$v_n$ in Pb+Pb

Hydrodynamics

Differential energy loss
$v_n$ in Pb+Pb

Hydrodynamics

Differential energy loss

Transition region

ATLAS $|n| < 2.5$

20-30 %

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

$v_n$ in $p+Pb$

Hydrodynamics

Transition region
Event selection

• 165 nb\(^{-1}\) of 8.16 TeV \(p+Pb\) data taken in 2016

• Select events with three different triggers
  • Minbias
  • Jet \(p_T > 75\) GeV
  • Jet \(p_T > 100\) GeV
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- Charged particles in tracker $|\eta| < 2.5$
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- Jets in calorimeter: $|\eta| < 4.9$
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• Charged particles in tracker $|\eta| < 2.5$
• Jets in calorimeter: $|\eta| < 4.9$
• Centrality measured via $\Sigma E_T$ in Pb-going FCal: $3.1 < \eta < 4.9$
• Make standard 2-particle $\Delta\phi$ correlations
2-particle correlations

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- Require $|\Delta \eta| > 2$
2-particle correlations

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$$Y(\Delta \phi) = G \left\{ 1 + 2 \sum_{n=1}^{\infty} v_{n,n} \cos(n\Delta \phi) \right\}$$
2-particle correlations

- Make standard 2-particle $\Delta \phi$ correlations
- Require $|\Delta \eta| > 2$

\[
Y(\Delta \phi) = G \left\{ 1 + 2 \sum_{n=1}^{\infty} v_{n,n} \cos(n \Delta \phi) \right\}
\]

Assume factorization to extract $v_2$ from $v_{2,2}$
Template fit non-flow subtraction

Minimum bias (0-5% central)

\( \Delta \phi \)

\[ Y(\Delta \phi) \]

\[ \Delta \phi \]

\[ Y(\Delta \phi) \cdot G - F Y^{pol}(\Delta \phi) \]

\[ 0-5\% \text{ central} \]

\[ \chi^2/NDF = 1.03 \]

\[ \nu_{2,2} \times 10^3 = 10.58 \pm 0.08 \]

\[ \nu_{3,3} \times 10^3 = 1.91 \pm 0.08 \]

\( \rho + Pb \) \( \sqrt{s}_{NN} = 8.16 \text{ TeV} \), 165 nb\(^{-1}\) \( 3.5 < p_t < 4.0 \text{ GeV} \)

"ATLAS"
Template fit non-flow subtraction

\[ Y_{\text{Central}}(\Delta \phi) = F_{\text{temp}} \cdot Y_{\text{Peripheral}}(\Delta \phi) + Y_{\text{Flow}}(\Delta \phi) \]

Peripheral data used to form template
Template fit non-flow subtraction

\[ Y_{\text{Central}}(\Delta \phi) = F_{\text{temp}} \cdot Y_{\text{Peripheral}}(\Delta \phi) + Y_{\text{Flow}}(\Delta \phi) \]
Template fit non-flow subtraction

\[ \Delta T \]

\[ Y(\Delta \phi) \]

\[ \text{ATLAS} \quad p+\text{Pb} \quad \sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}, \quad 165 \text{ nb}^{-1} \]

\[ 3.5 < p_T < 4.0 \text{ GeV} \]

\[ \chi^2/\text{NDF} = 1.03 \]

\[ \nu_{2,2} \times 10^3 = 10.58 \pm 0.08 \]

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\[ 0-5\% \text{ central} \]
Template fit non-flow subtraction

**Minimum bias**

Jet $p_T > 100$ GeV

**ATLAS**

$p+Pb \sqrt{s_{NN}} = 8.16$ TeV, 165 nb$^{-1}$

$\chi^2$/NDF = 1.03

$\phi = 2.5$

$\phi = 2.6$

$\phi = 2.7$

$\phi = 2.8$

$\phi = 2.9$

$\Delta \phi$

$Y_{\text{cent}}$

$Y_{\text{Fit}}$

Peri

$Y_{\text{F}} + G$

$Y_{\text{peri}}$

$Y_{\text{peri}}(0)$

$G + F Y_{\text{peri}}$

$G + F Y_{\text{peri}}(0)$

$\chi^2$/NDF = 3.36

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$0.13 \pm 2.43 \times 10^3$

$0.13 \pm 5.01 \times 10^3$

$0.13 \pm 10.58 \times 10^3$

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Jet events have significantly stronger away-side peak from non-flow
Restricting associated particles in jet events

Associated particles are required to have $|\Delta \eta| > 1$ w.r.t. jets in event with $p_T^{\text{Jet}} > 15$ GeV

\[ p_T^{\text{Jet}} > 15 \text{ GeV} \]
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Restricting associated particles in jet events

Associated particles are required to have $|\Delta \eta| > 1$ w.r.t. jets in event with $p_T > 15$ GeV

$p_T^{Jet} > 15$ GeV
Restricting associated particles in jet events

Associated particles are required to have $|\Delta \eta| > 1$ w.r.t. jets in event with $p_T^{\text{Jet}} > 15$ GeV

Not done in Minbias events
Restricting associated particles in 100 GeV jet events

Jet rejection drastically improves ‘signal-to-noise’
- Reduces sensitivity to template method assumptions

Before jet restriction

After jet restriction

Jet rejection drastically improves ‘signal-to-noise’
- Reduces sensitivity to template method assumptions
$p_T$ dependent $v_2$ results

- MB $p_T$ reach extended to ~20 GeV
• MB $p_T$ reach extended to $\sim 20$ GeV
• Clear non-zero $v_2$ out to $\sim 50$ GeV in jet events
**$p_T$ dependent $v_2$ results**

- MB $p_T$ reach extended to ~20 GeV
- Clear non-zero $v_2$ out to ~50 GeV in jet events
- Consistency at low $p_T$

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ATLAS

$p+$Pb $\sqrt{s_{NN}} = 8.16$ TeV, 165 nb$^{-1}$

- 0-5% central

- MB $p_T$ reach extended to ~20 GeV
- Clear non-zero $v_2$ out to ~50 GeV in jet events
- Consistency at low $p_T$
$p_T$ dependent $v_2$ results

- MB $p_T$ reach extended to $\sim 20$ GeV
- Clear non-zero $v_2$ out to $\sim 50$ GeV in jet events
- Consistency at low and high $p_T$
$$p_T$$ dependent $$v_2$$ results

- MB $$p_T$$ reach extended to $$\sim 20$$ GeV
- Clear non-zero $$v_2$$ out to $$\sim 50$$ GeV in jet events
- Consistency at low and high $$p_T$$
- Transition to high $$p_T$$ behavior happens at lower $$p_T$$ for jet events
Very similar behavior when $p+Pb$ scaled up, though high-$p_T$ seems to have less $p_T$ dependence for $p+Pb$
Comparison to jet quenching calculation

\[ V_2 \]

**ATLAS**

\[ p+Pb \quad \sqrt{s_{NN}} = 8.16 \text{ TeV}, \quad 165 \text{ nb}^{-1} \]

0-5\% central

Zhang, Liao

- \( v_2 \) size a
- \( v_2 \) size b

arXiv: 1311.5463
Jet quenching calculation cannot simultaneously describe flow and spectra modification
What about the transition region?

Transition behavior could be driven by admixture of particles from hard scattering (jet) and from the underlying event (bulk)
Transition behavior could be driven by admixture of particles from hard scattering (jet) and from the underlying event (bulk)

- Measure the relative contribution of each type
Jet and bulk particle yield

**Toward**

**Transverse**

**Leading Jet**

(particle if no jet present)
Assume:
1. **Transverse** has only **bulk** particles
2. **Toward** has both **bulk** and **jet** particles

Solve for yield of **bulk** and **jet**
Particle pair composition

ATLAS
$p+\text{Pb}$ $\sqrt{s_{NN}} = 8.16$ TeV

Pair fraction

$0-5\%$ central

$\frac{p^{\text{int}} > 100 \text{ GeV}}{p^{\text{int}}}$

$L^{\text{int}} = 165$ nb$^{-1}$

$V_2$
Particle pair composition

- Associated particles highly likely to be from bulk
Particle pair composition

- Associated particles highly likely to be from bulk
- Low and high \( p_T \) dominated by bulk and jet particles respectively
Particle pair composition

- Associated particles highly likely to be from **bulk**
- **Low** and **high** $p_T$ dominated by **bulk** and **jet** particles respectively
- **Transition** region sensitive to relative mixture of **bulk** and **jet**
  - e.g. ~4 GeV particle more likely to be from a jet if it’s in a jet triggered event
Conclusions

ATLAS

$p+\text{Pb} \sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}, 165 \text{ nb}^{-1}$

0-5% central

$V_2$

$p_T^A [\text{GeV}]$

$\rho_T^\text{jet} > 100 \text{ GeV}$

MBT
Hydrodynamics

Conclusions

ATLAS

\[ p+\text{Pb} \sqrt{s_{NN}} = 8.16 \text{ TeV}, 165 \text{ nb}^{-1} \]

0-5% central

\[ p_T^{\text{jet}} > 100 \text{ GeV} \]
Conclusions

Hydrodynamics

Particle mixing transition

$\mathcal{A}$
Conclusions

Hydrodynamics

Particle mixing transition

$\frac{dN}{d\phi} = \int \frac{d^2p_T}{2\pi} \frac{1}{\sqrt{s}} f(p_T) \frac{1}{\sqrt{z}} f(z)$

$\frac{dN}{d\phi} \propto \frac{1}{\sqrt{z}} f(z)$

$\frac{dN}{d\phi} \propto \frac{1}{\sqrt{z}} f(z) \propto \frac{1}{\sqrt{z}} \frac{1}{\sqrt{s}} f(p_T)$

$\frac{dN}{d\phi} \propto \frac{1}{\sqrt{s}} f(p_T)$
These results and more are detailed in new paper 

arXiv:1910.13978
Backup
Both $v_2$ and $v_3$ show similar behavior between MB and jet events

- Consistency at low and high $p_T$
- Transition to high $p_T$ behavior happens at lower $p_T$ for jet events
Factorization test

Minbias

Jet $p_T > 75$ GeV

Jet $p_T > 100$ GeV
Centrality dependent $v_2$ results

**Low $p_T$**

- At low and high $p_T$, $v_2$ roughly independent of centrality and event type

**Mid $p_T$**

- At mid $p_T$, $v_2$ decreases with centrality and is lower for high $p_T$ jet events
Particle pair yields

Total pairs

\[ P_{\text{total}} = N^A \cdot N^B \]
\[ = (N_{\text{HS}}^A + N_{\text{UE}}^A) \cdot (N_{\text{HS}}^B + N_{\text{UE}}^B) \]
\[ = N_{\text{HS}}^A \cdot N_{\text{HS}}^B + N_{\text{HS}}^A \cdot N_{\text{UE}}^B + N_{\text{UE}}^A \cdot N_{\text{HS}}^B + N_{\text{UE}}^A \cdot N_{\text{UE}}^B \]

HS correlations  Cross correlations  UE correlations

Associated particles are required to be separated by 2 units in \( \Delta \eta \), so these are not simple products

\[ N_X^A \cdot N_Y^B = \int_{-2.5}^{2.5} \frac{dN_X^A(\eta^A)}{d\eta^A} \left[ \int_2^5 \frac{d^2N_Y^B(\eta^A, |\Delta \eta|)}{d\eta^A d|\Delta \eta|} d|\Delta \eta| \right] d\eta^A \]
Centrality dependent pair fractions

Low $p_T$

Mid $p_T$

High $p_T$

- Again, *low* and *high* $p_T$ roughly independent of centrality and event type
- Centrality changes pair fractions most in *mid* $p_T$ region
Eremite calculation comparison

- Ideal hydro limit at low $p_T$ (short mean free path) and eremitic limit at high $p_T$ (large mean free path)
Run Pythia8 with HardQCD:all=on and PartonLevel:MPI=off
  - Select events with truth jet \( p_T > 100 \) GeV
  - Embed Pythia jet events into MB \( p+p \) using Angantyr model

Pythia jet events have long range nearside ridge from implementation of ISR
  - Correlation washed out by UE and thus gets smaller in more central events
  - Opposite behavior as what is seen in data

Pythia8 \( \sqrt{s_{NN}} = 8.16 \) TeV
  - For \( p+p \) and \( p+Pb \) Angantyr UE
  - For \( pp \) hard \( p_T \) jet > 100 GeV

\[ \chi^2/NDF = 1.04 \]
\[ \chi^2/NDF = 1.20 \]