Measurements of electroweak boson tagged jet energy loss and modification by ATLAS

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6 November 2019, Wuhan, China
Run: 286834  
Event: 124877733  
2015-11-28 01:15:42 CEST

Pb+Pb $\sqrt{s_{\text{NN}}} = 5.02$ TeV
photon + multijet event
$\Sigma E_T^{\text{HCal}} = 4.06$ TeV

$\gamma$+jet event
Photon-tagged jet quenching

ATLAS

$pp$ 5.02 TeV, 25 pb$^{-1}$
Pb+Pb, 0.49 nb$^{-1}$

$p_T^\gamma$ = 79.6-100 GeV

$\gamma$-tag ($p_T^\gamma = 80-126$ GeV, $p_T^{\text{jet}} = 63-144$ GeV)

Data, 5.02 TeV, 0-30% Pb+Pb / $pp$

SCET$_{G}$

Inclusive jets ($p_T^{\text{jet}} = 80-110$ GeV)

Data, 2.76 TeV, 0-10% Pb+Pb / $pp$

Photon+jet $p_T$ balance, $x_{J\gamma} = p_T^{\text{jet}} / p_T^\gamma$

$\Rightarrow$ unfolded distributions give information
event-by-event (absolute) energy loss

$\Rightarrow$ stronger modification than for inclusive jets (lack of surface bias)


Run: 287038
Event: 237848612
2015-12-01 02:47:45 CEST

Pb+Pb, $\sqrt{s_{NN}} = 5.02$ TeV
Z+jet candidate
FCal $\Sigma E_T = 2.40$ TeV

$Z(\rightarrow \ell\ell)+$jet event

muon

muon
\( p_T^Z > 30 \text{ GeV} \)  

\( p_T^h > 1 \text{ GeV} \)  
\( \Delta \phi^{hZ} > 3\pi/4 \)

- Lower \( p_T^{\text{boson}} \) selection than \( \gamma \) measurements, no explicit jet requirement
  -> in MC, these select mostly hadrons in the leading jet (like a frag. func.)
- Z-tagged charged particle yields vs. \( p_T^h \) and \( x_{hZ} = p_T^h / p_T^Z \)
  -> \( I_{AA} = \text{Pb+Pb} / \text{pp} \) ratio of per-Z yields, vs. centrality & \( p_T^Z \)
Z boson reconstruction

Similar to previous Z measurements in Pb+Pb

\[ p_T^{e,\mu} > 20 \text{ GeV} \]
\[ p_T^Z > 30 \text{ GeV} \]

\[ 76 < m_{\ell\ell} < 106 \text{ GeV} \]
(non-Z backgrounds ~1% or smaller)

1300 Z→ee events (1.7/nb 2018 data)

1500 Z→μμ events (1.4/nb 2018 data)

Plots above from 2015 Z yield measurement:
nucl-ex/1910.13396, see poster by A. Sickles
- Large integration window ($\Delta \eta \times \Delta \phi = 5 \times \pi/2$), low-$p_T^{\text{parton}}$ (down to $p_T^Z = 30$ GeV)
  - significant UE contribution, $S/B \sim 0.01$ in 0-10% Pb+Pb, $p_T^{\text{ch}} = 1-2$ GeV
- Estimated in data using minimum bias Pb+Pb events with closely matching centrality
  - $Z$ bosons produced with $\sim$flat $\phi^Z - \Psi_2$, but dominant uncertainty is from residual sensitivity to this & other background modeling effects
$p_T^Z = 30-60 \text{ GeV}$

$\frac{d^2N_{ch}}{dp_T^Z dx_h^Z}$

$30 < p_T^Z < 60 \text{ GeV}$

$\frac{d^2N_{ch}}{dp_T^Z dx_h^Z}$

$60 < p_T^Z \text{ GeV}$

Visible centrality-dependent suppression of Pb+Pb yields @ high $p_T^{ch} / x_h^Z$

Moderest enhancement at low-$p_T^{ch} / x_h^Z$ (?)

...quantify with $I_{AA}$ ratio, cancelling common systematics
$l_{AA}$ for $p_{T}^{Z} = 30$-$60$ GeV

Centrality-dependent suppression / enhancement pattern

$\Rightarrow$ large modifications, $l_{AA} \sim 0.3$-$0.4 / l_{AA} \sim 2$ in 0-10% Pb+Pb events!
$I_{AA}$ for $p_T^Z > 60$ GeV

\[ I_{AA} \text{ vs. } p_T^{ch} \]

\[ \text{vs. } x_{hZ} = \frac{p_T^{ch}}{p_T^Z} \]

At large $p_T^Z$, somewhat smaller modification, weaker centrality dependence.
Comparison to other data I

**ATLAS** Preliminary

$pp$, $\sqrt{s} = 5.02 \text{ TeV}$, 260 pb$^{-1}$

$Pb+Pb$, $\sqrt{s_{NN}} = 5.02$, 1.4-1.7 nb$^{-1}$


- **Inclusive jet FF ratio**
- **Photon-tagged FF ratio**

- similar overall pattern of modifications
- but smaller magnitude due to: $z$ is defined in ratio to jet $p_T$, larger parton $p_T$
Comparison to other data II

- 0-10% Pb+Pb, $p_{T}^{\text{boson}} > 60$ GeV
- **ATLAS** Z-tagged hadron yield vs. $p_{T}^{\text{ch}} / p_{T}^{Z}$
- **CMS** $\gamma$-tagged hadron yield vs. $p_{T}^{\text{ch}} / p_{T}^{\gamma}$

➤ significantly smaller suppression in $x > 0.05$ region

➤ bias from jet requirement, $R=0.3$ $p_{T}^{\text{jet}} > 30$ GeV, which selects less-quenched configurations

➤ uncorrected Pb+Pb jets / smeared $pp$ jets — impact?
Comparison to other data III

- Compare **ATLAS** data to $\gamma+h$ correlations from **PHENIX** and **STAR** at RHIC
  
  ➔ note: different centrality selections, $\Delta\phi$ integration windows, kinematics

- Qualitatively similar suppression in $x > 0.1$ region, but extended kinematics at the LHC allow measurements to $x < 0.1$
  
  ➔ interesting future comparisons of Run-3 LHC to high-lumi RHIC (sPHENIX)

**PHENIX**: PRL 111 (2013) 032301
**STAR**: PLB 760 (2016) 689
Theory comparison: $I_{AA}(p_T^{ch})$

ATLAS Data compared to Hybrid Strong/Weak Coupling model for $p_T^Z = 30-60$ GeV and $p_T^Z > 60$ GeV selections

- calculation captures overall $p_T^{ch}$-dependence, and the difference between $p_T^Z$ selections
- calculation includes back reaction effects, responsible for rise at low-$p_T^{ch}$

ATLAS Preliminary

$pp$, $\sqrt{s} = 5.02$ TeV, 260 pb$^{-1}$

$Pb+Pb$, $\sqrt{s_{NN}} = 5.02$ TeV, 1.4-1.7 nb$^{-1}$

Hybrid Model:

JHEP 03 (2016) 053
Theory comparison: \( I_{AA}(x_{hZ}) \)

\[ p_T^Z = 30-60 \text{ GeV} \]

\[ p_T^Z > 60 \text{ GeV} \]

ATLAS Data compared to SCET\(_G\) calculation by Li & Vitev with \( g = 1.8-2.2 \)

\( \Rightarrow \) calculation well-reproduces large suppression at high-\( x_{hZ} \), and \( p_T^Z \)-dependence

ATLAS Preliminary
\( p\bar{p}, \sqrt{s} = 5.02 \text{ TeV}, 260 \text{ pb}^{-1} \)
\( \text{Pb}+\text{Pb}, \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}, 1.4-1.7 \text{ nb}^{-1} \)

Hybrid Model: JHEP 03 (2016) 053
SCET\(_G\) / Li & Vitev: PRD 93 (2016) 074030 hep-ex/1908.06979
**Z-tagged probes of how jet structure is modified now possible!**

- access to energy loss for low parton-$p_T$ in a calibrated way
- unbiased measurement from lack of jet requirement
**ATLAS Preliminary**

$pp$, $\sqrt{s} = 5.02$ TeV, 260 pb$^{-1}$

$Pb+Pb$, $\sqrt{s_{NN}} = 5.02$ TeV, 1.4-1.7 nb$^{-1}$

$30-60$  $60+$  $p_T^c$ [GeV]

- Red: ATLAS 0-10% Pb+Pb
- Blue: Hybrid Model

$I_{AA}$ = 0.3  $R_{AA}$ = 0.3