Photon and jet probes of small systems in ATLAS

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Hard processes in $p$+Pb collisions

- Modification of PDFs in nuclei, initial state energy loss, etc.
- Non-linear QCD effects: angular broadening, monojet production, etc.
- In this talk: recent photon/jet measurements in **2016 p+Pb** data

⇒ All results at: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults
$$R = 0.4$$ jets in calorimeter system ($$|\eta| < 4.9$$)

Photons in EM Barrel ($$|\eta| < 1.37$$) and EM Endcap ($$1.56 < |\eta| < 2.37$$)

+ High-level trigger system sampling 162/nb of 8.16 TeV and 0.36/nb of 5.02 TeV $$p+Pb$$ data
Prompt photons in $p+$Pb collisions (nucl-ex/1903.02209)

- Results on Z/W in Pb+Pb shown by M. Dumancic (ATLAS) + others
  - Z’s, W’s only probe $Q^2 > m_{W/Z}^2$, and probe primarily quark nPDFs
  - Photons probe lower-$Q^2$, give access to nuclear gluons
- Full statistics, 8.16 TeV $p+$Pb data
- Measurement presented here is centrality-integrated (0-100%)
Photon+multijet event
\( p+Pb \sqrt{s_{\text{NN}}} = 8.16 \text{ TeV} \), \( \sum E_T^{\text{Pb}} = 33.1 \text{ GeV} \)
photon: \( \rho_T = 154 \text{ GeV}, \eta = -2.07, \phi = 2.96 \)
jet 1: \( \rho_T = 214 \text{ GeV}, \eta = 0.63, \phi = 0.58 \)
jet 2: \( \rho_T = 110 \text{ GeV}, \eta = -0.54, \phi = -2.05 \)
jet 3: \( \rho_T = 48 \text{ GeV}, \eta = -0.72, \phi = -1.58 \)

**high-\( \rho_T \) photon \( p+Pb \) event**
Prompt photon cross-section in $p+$Pb

- Full cross-section vs. \( \eta \) (\( \Delta \eta \sim 4.5 \)) and \( E_T = 20-500 \text{ GeV} \)

- total uncertainties reach 2% in certain regions!

- under-prediction of \( d\sigma/dE_T \) by JETPHOX NLO pQCD, as in \( pp \) collisions —> need \( pp \) data reference!
Prompt photon $R_{pPb}$

Multiplicative correction for larger $\sqrt{s}$ and center-of-mass shift of $p+Pb$
- construct with LO generator or NLO calculation (w/ varied PDFs)
- resulting uncertainties are sub-dominant to those on $\sigma^{p+Pb}$ or $\sigma^{pp}$

Use 8 TeV $pp$ data as the reference in the photon $R_{pPb}$

$$R_{pPb} = \frac{\sigma^{p+Pb}}{A \sigma^{pp}}$$

nucl-ex/1903.02209
In shadowing region, data compatible with free nucleon PDFs but favors anti-shadowing in line with global nPDF fits.

Note: $R_{pPb} < 1$ just from isospin effects.

**free nucleon PDFs**

**global nPDF fits**

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ATLAS

$p + \text{Pb}$, 165 nb$^{-1}$

\( \sqrt{s} = 8.16 \text{ TeV} \)

$\eta^* < 1.90$

$\eta^* < 0.91$

$\eta^* < -2.02$

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nucl-ex/1903.02209
• In shadowing region, data compatible with free nucleon PDFs
  ➞ but favors anti-shadowing in line with global nPDF fits

\textbf{note: }\textit{R}_{pPb} < 1\textit{ just from isospin effects}
In **shadowing** region, data compatible with **free nucleon PDFs**

but favors **anti-shadowing** in line with **global nPDF fits**

- Disfavors large initial state E-loss

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**Note:** $R_{pPb} < 1$ just from isospin effects
Forward / backward $R_{pPb}$ ratio vs. $p_T$

- $R_{pPb}^{\text{Forward}}/R_{pPb}^{\text{Backward}}$ — cancel many systematic uncertainties

- At low-$E_T$, ratio sensitive to *gluon* shadowing / *quark* anti-shadowing
  - data almost compatible with **free nucleon PDFs**
  - modifications more in line with **EPPS16** than **nCTEQ15**

- New information for global nPDF fits!

nucl-ex/1903.02209
Forward dijets in $p+$Pb collisions
(nucl-ex/1901.10440)

- Measure forward ($2.7 < y^* < 4.0$, i.e. proton-going), low-$p_T$ ($\sim 20-40$ GeV) di-jets
  - 5.02 TeV $p+$Pb data 2016, paired with 5.02 TeV $pp$ data 2015
- Measurement presented here is centrality-integrated (0-90%)

PHENIX suppression of central-forward per-trigger hadron yields

STAR broadening of di-hadron away-side $\Delta \phi$ correlation
Conditional (i.e. per-trigger jet normalized) yield

\[
I_{12}(p_{T,1}, p_{T,2}, y^*_1, y^*_2) = \frac{1}{N_1 \int dy^*_1 \int dy^*_2 \int dp_{T,1} \int dp_{T,2}} d^4N_{12}
\]

explored as a function of leading & subleading jet kinematics

Fix leading jet rapidity \( y = 2.7-4.0 \) (far proton-going), scan in subleading jet rapidity

\[ I_{12}(p+Pb) < I_{12}(pp) \text{ for forward-forward pairs?} \]
Quantify $p+\text{Pb}$ modifications via: $\rho_I = I_{12}(p\text{Pb}) / I_{12}(pp)$
(cancelling common systematic uncertainties)

- No suppression for central+forward pairs
- ~20% suppression for forward-forward pairs (no significant dependence on $p_{T,1}$, $p_{T,2}$)

$\Rightarrow$ these dijets probe $x_A \sim 10^{-4}$ to $10^{-3}$

$\Rightarrow$ does the suppression change the $\Delta \phi$?
Per-trigger normalized $\Delta\phi$ of jet pair

$$C_{12}(p_{T,1}, p_{T,2}, y_1^*, y_2^*) = \frac{1}{N_1} \frac{dN_{12}}{d\Delta\phi},$$

in $pp$ and $p+Pb$

Systematic study of $W_{12}$ (characteristic width of the distribution) for kinematics

scan in sub-leading jet rapidity
Quantify $p+$Pb modifications via: $\rho_W = W_{12}(pPb)/W_{12}(pp)$

- No significant angular broadening within uncertainties, for any set of kinematics

Figure 6: Ratios (top) $\rho_{pPb}$ of $W_{12}$ and (bottom) $\rho_{pPb}$ of $I_{12}$ values between $p+$Pb collisions and pp collisions for different selections of $p_T$,1 and $p_T$,2 as a function of $y$ $\ast$. The data points are shifted horizontally for visibility, and do not reflect an actual shift in rapidity. The vertical size of the open boxes represents systematic uncertainties and the error bars indicate statistical uncertainties. The horizontal size of the open boxes does not represent the width of the bins. Some points are not presented due to large statistical uncertainties. Results are shown with no $p_T$ requirement, where $p_T = p_T$,1 $p_T$,2.

ATLAS
2015 pp data, 25 pb$^{-1}$
2016 $p+$Pb data, 360 µb$^{-1}$
$\sqrt{s_{NN}} = 5.02$ TeV
anti-$k_t$ $R = 0.4$ jets
$2.7 < y_1^* < 4$
Quantify $p+$Pb modifications via: $\rho_W = W_{12}(p$Pb$)/W_{12}(pp)$

No significant angular broadening within uncertainties, for any set of kinematics

Theory calculations: interplay of saturation and proper treatment of Sudakov effects

→ interesting to explore centrality dependence!
Photon and jet probes of $p+$Pb collisions

New information to constrain nPDFs & $E$-loss with low-$Q^2$ probes sensitive to gluons, nucl-ex/1903.02209

Evidence of non-linear QCD effects in suppression of forward-forward dijets, nucl-ex/1901.10440
Prompt photon selection

Photons required to pass shower-shape based ID cuts, and be experimentally isolated

~90% efficiency at moderate-$E_T$

Remaining background (predominantly $\pi^0$'s in jets) removed via a double sideband procedure
**ATLAS**

25 < $E_T^{\gamma}$ < 35 GeV

1.09 < $\eta^*$ < 1.90

-1.84 < $\eta^*$ < 0.91

-2.83 < $\eta^*$ < -2.02

Efficiency

1.09 < $\eta^*$ < 1.90

-1.84 < $\eta^*$ < 0.91

-2.83 < $\eta^*$ < -2.02
**ATLAS**

Relative uncertainty in $d\sigma/dE_T^\gamma$

$1.09 < \eta^* < 1.90$

$-1.84 < \eta^* < 0.91$

$-2.83 < \eta^* < -2.02$

**ATLAS**

Relative Uncertainty in $R_{\text{pPb}}$

$1.09 < \eta^* < 1.90$

$-1.84 < \eta^* < 0.91$

$-2.83 < \eta^* < -2.02$
$\sqrt{s} = 8.16\text{ TeV } p + \text{Pb}, \ 165\text{ nb}^{-1}$

**Data**

ATLAS

$R_{pPb}$

$1.09 < \eta^* < 1.90$

-1.84 < $\eta^*$ < 0.91

-2.83 < $\eta^*$ < -2.02

**JETPHOX** + CT14

**JETPHOX** + CT14 + EPPS16

**JETPHOX** + nCTEQ15
Relative uncertainty in $R^{\text{Forward}}_{p\text{Pb}} / R^{\text{Backward}}_{p\text{Pb}}$

**ATLAS**

- Relative uncertainty
- Combined
- Purity
- Detector performance
- Reference extrapolation
- Other

$E_T$ [GeV]
**ATLAS Simulation**

\(\sqrt{s} = 5.02\) TeV

*pp anti-\(k_t\) R = 0.4 jets*

\(p_T^{\text{truth}}\) distribution for different \(\eta\) ranges:
- \(-4.5 < \eta_{\text{truth}} < -2.7\)
- \(-2.7 < \eta_{\text{truth}} < -1.8\)
- \(-1.8 < \eta_{\text{truth}} < 0.0\)
- \(0.0 < \eta_{\text{truth}} < 1.8\)
- \(1.8 < \eta_{\text{truth}} < 4.0\)

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**Simulation ATLAS**

\(\sqrt{s} = 5.02\) TeV

*\(p+Pb\) anti-\(k_t\) R = 0.4 jets*

\(p_T^{\text{truth}}\) distribution for different \(\eta\) ranges:
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- \(0.0 < \eta_{\text{truth}} < 1.8\)
- \(1.8 < \eta_{\text{truth}} < 4.0\)

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**ATLAS Simulation**

\(\sqrt{s_{\text{NN}}} = 5.02\) TeV

*p+Pb data overlay*

\(p_T^{\text{truth}}\) distribution for different \(\eta\) ranges:
- \(-4.5 < \eta_{\text{truth}} < -2.7\)
- \(-2.7 < \eta_{\text{truth}} < -1.8\)
- \(-1.8 < \eta_{\text{truth}} < 0.0\)
- \(0.0 < \eta_{\text{truth}} < 1.8\)
- \(1.8 < \eta_{\text{truth}} < 4.0\)
$\Delta \rho_{\text{pPb}}^{\text{pPb}} / \rho_{\text{pPb}}^{\text{pPb}}$ [%]

- $28 < p_{T,1} < 35$ GeV
- $28 < p_{T,2} < 35$ GeV
- $2.7 < y_1^* < 4$
- anti-$k_t$ $R = 0.4$ jets

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

2016 $p$+Pb data, 360 $\mu$b$^{-1}$

2015 $pp$ data, 25 $\mu$b$^{-1}$
**ATLAS**

anti-$k_t$ $R = 0.4$ jets

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

$2.7 < y^* < 4$

$28 < p_{T,1} < 35$ GeV

$28 < p_{T,2} < 35$ GeV

$2.7 < y^* < 4$

$C_{12}$ [rad$^{-1}$]

$2.5 < \Delta \phi < 3$

2015 $pp$ data, 25 pb$^{-1}$

2016 $p$+Pb data, 360 \mu$b^{-1}$
\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

2015 \( pp \) data, 25 \( \text{pb}^{-1} \)
2016 \( p+\text{Pb} \) data, 360 \( \mu\text{b}^{-1} \)
\( \Delta p_T > 3 \text{ GeV} \)

\( y_1^* < 4 \)

\[ \rho_p^{\text{Pb}} \]

\[ \rho_W^{\text{Pb}} \]

\( \rho_p^{\text{Pb}} \)

\( \rho_W^{\text{Pb}} \)

\( \Delta \rho_p^{\text{Pb}} \)

\( \Delta \rho_W^{\text{Pb}} \)