Hard processes in small systems

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2 October 2017
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inclusive rates (nPDF’s, initial state $E$-loss)

(di-)jet, $\gamma/Z/W$, $b/c/t$, etc.
jets & $h^\pm$ in 5.02 TeV $p+$Pb

**ATLAS** jet

$-0.3 < y^* < +0.3$

**ATLAS** fragmentation

⇒ hep-ex/1706.02859

**final since QM**
Impact of LHC Run I data on the nPDFs of EPS09 (left) and DSSZ (right) before (black/grey) and after reweighting (red/light red), for valence (upper panels), sea (middle panels) and gluon (lower panels) distributions at $Q^2 = 1.69$ GeV$^2$, except the DSSZ gluon that are plotted at $Q^2 = 2$ GeV$^2$.

Replicas fall far from the central prediction. Thus, $N_{\text{eff}}$ alone should not be blindly used to judge whether a reanalysis is required. Given the tiny improvements in reweighted $\chi^2$ values one expects no strong modifications to be induced in the nPDFs either. Indeed, the only noticeable effect, as can be seen in Fig. 10, is in the EPS09 gluon for which the CMS dijet data place new constraints [45].

It should be recalled that, for technical reasons, in the EPS09 analysis the RHIC pion replicas fall far from the central prediction. Thus, $N_{\text{eff}}$ alone should not be blindly used to judge whether a reanalysis is required. Given the tiny improvements in reweighted $\chi^2$ values one expects no strong modifications to be induced in the nPDFs either. Indeed, the only noticeable effect, as can be seen in Fig. 10, is in the EPS09 gluon for which the CMS dijet data place new constraints [45].

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Photon+multi-jet event

8.16 TeV p+Pb

ATLAS data
photons in $p+\text{Pb}$

25-500 GeV, $|\eta^{\text{lab}}| < 2.37$

Comparison spectra:
8 TeV pp Standard Model measurements
The plots show the ratio of rapidity distributions, $R_{pPb}$, for different rapidity ranges: $1.10 < \eta^* < 1.91$, $-1.83 < \eta^* < 0.91$, and $-2.83 < \eta^* < -2.02$. The data is compared to theoretical predictions from JETPHOX and ATLAS-CONF-2017-072.

**Favorable comparison to pQCD & nPDF**

The data is compared to predictions from JETPHOX, CT14, and CT14 + EPPS16, showing a favorable comparison to pQCD and nPDF models.

**Disfavors large initial state E-loss**

The plots also show a comparison to the model of T. Vitev et al., which disfavors large initial state energy loss ($E$-loss).

The plots are labeled with ATLAS Preliminary and note the cms energy $\sqrt{s} = 8.16$ TeV and the integrated luminosity of 162 nb$^{-1}$. The data is shown as yellow bars, while the theoretical predictions are shown as lines or shaded regions.
$tt$ candidate event

8.16 TeV $p+\text{Pb}$

CMS data
$\bar{t}t$ in $p+\text{Pb}$

new since QM

**Data scaled by $A = \frac{\sigma_{\text{NNLO+NNLL}}(8.16 \text{ TeV})}{\sigma_{\text{NNLO+NNLL}}(8 \text{ TeV})}$**

- **CMS**
  - pp, 19.6 fb$^{-1}$, ($\sqrt{s}=8$ TeV)
  - l+jets EPJC 77 (2017) 15
  - @ JHEP 1608 (2016) 029

- **pPb, 174 nb$^{-1}$, ($\sqrt{s_{NN}}=8.16$ TeV)**
  - l+jets
  - e+jets
  - $\mu$+jets

**Th. unc.**: pdf, pdf@scales
**Exp. unc.**: stat, stat+syst

**JHEP 1608 (2016) 029**

**EPJC 77 (2017) 15**

**PLB 746 (2015) 64**

d’Enterria, Krajczar, Paukkonen

new particle observed (for HI collisions)

... modest impact for large-x gluon PDFs
Figure 13: Display of an event with large rapidity gap taken with the ZDC XOR trigger, firing on more than one spectator neutrons on one side and no neutrons on the other side. Rapidity gap is on the side with no neutrons in the ZDC.

Single sided ZDC triggers select photonuclear events: unwanted background to “normal” HI events…

Photo-nuclear ($\gamma$+Pb) event 5.02 TeV Pb+Pb, ATLAS data
dijets in $\gamma$+Pb

ATLAS Preliminary
2015 Pb+Pb data, 0.38 nb$^{-1}$
$\gamma$$_{NN}$ = 5.02 TeV

anti-$k_T$, $R$=0.4 jets
$p_{\text{lead}}^{\text{jet}} > 20$ GeV
$m_{\text{jets}} > 35$ GeV

Data
Pythia+STARlight scaled to data

Not unfolded for detector response

QM result

cleanly access nPDF effects in entirely new ($x_A$, $Q^2$) range

Photo-nuclear dijets
Nuclear breakup

Figure adapted from EPPS16
1612.05741 [hep-ph]
interesting kinematic regions:

small-$X_A$

large-$X_A$

large-$X_p$
Low-$x_A$ : di-jets and di-photons

Low-$p_T$ central + forward dijet correlations

Di-photon production

Kutak, Sapeta, hep-ph/1205.5035 (& other papers)
Low-$x_A$: heavy flavor mesons

ATLAS Preliminary

$p+$Pb $\sqrt{s_{NN}} = 8.16$ TeV, $76.3 \mu b^{-1}$

Prompt $D^0$ Production

Data / Theory

ATLAS-CONF-2017-073
(Very) large-$x_A$: "superfast" quarks

short-range $p$-$n$ correlation

quark with $x_A = A p_q / \rho_A > 1$

• Possibility to observe $x_A > 1$ configurations!

• Rates are sensitive to details of 2-$N$ and 3-$N$ Short-Range Correlations (SRCs)
(Very) Large-\(x_p\), >0.1: centrality distorted by “shrinking” of the proton

typical proton

small proton

DVP, Cole, Strikman, PRC 93 (2016) 011902
Global analysis of large-$x_p$ color fluctuation ("shrinking proton") effects

Systematic extraction of
\[ \lambda(x_p) = \frac{\langle \sigma_{NN}(x_p) \rangle}{\sigma_{NN}} \]
vs. $x_p$ and energy

\( R_{CP} \)

Alvioli, Frankfurt, DVP, Strikman

hep-ph/1709.04993
double parton scattering in $p+A$ ("MPI" but at very large $p_T$)

In $pp$ collisions, production of certain final states receives contribution from both:
- Involves normal PDFs
- Involves parton-parton correlations in each proton: GPD

In $pA$ collisions, dominant contribution is from mixed parton parton scattering $\mathcal{GPD}_{ab}|_f^\text{projectile} \cap f^\text{target}$

Can "cleanly" measure $2\mathcal{GPD}$, also this contribution dominates: 60-70% of total

Select $\text{large-}x_p$ configuration

Look for independent parton scattering

Image the structure of the beam remnant ($2\mathcal{GPD}$’s)

4-jets: Blok, Strikman, Wiedemann EPJC 73 (2013) 2433

credit to A. Angerami
jet quenching in small systems?
Energy loss in small systems?

\( R_{AA} < 1 \) even in very peripheral collisions…

Systematic extractions: \( E_{\text{loss}} \) in \( p+Pb \) sized systems?

27.4 \( \text{pb}^{-1} \) (5.02 TeV pp) + 404 \( \mu\text{b}^{-1} \) (5.02 TeV PbPb)

CMS

\[ R_{AA} < 1 \text{ even in very peripheral collisions…} \]

(P. Christiansen, this conf.)
Bias in peripheral A+A events?

both new since QM

Suppression from “centrality bias” (e.g. low-mult. jet veto?)

Check this with high-statistics $W^\pm$ yields… … similarly with $Z$'s

ATLAS-CONF-2017-067

Preliminary

\begin{align*}
\frac{N_{W\to \mu\nu}}{\langle T_{AA} \rangle / N_{\text{evt}}} \quad \text{[nb]}
\end{align*}

\begin{align*}
\langle N_{\text{part}} \rangle
\end{align*}

\begin{align*}
\text{ATLAS} \quad \text{Preliminary}
\end{align*}

Pb+Pb, $\sqrt{s_{NN}}$=5.02 TeV, 0.49 nb$^{-1}$

$W\to \mu\nu$

\begin{align*}
W^+: \quad \text{Data} & \quad \text{POWHEG (CT10 NLO) } \times k_{\text{NNLO}} \\
W^-: \quad \text{Data} & \quad \text{POWHEG (CT10 NLO) } \times k_{\text{NNLO}}
\end{align*}

Morsch, Loizides

nucl-ex/1705.08856

\begin{align*}
70-90\% \text{ PbPb, 5.02 TeV}
\end{align*}

\begin{align*}
0.02 \pm 0.02
\end{align*}

\begin{align*}
0.74 \pm 0.02
\end{align*}

\begin{align*}
0.02
\end{align*}

\begin{align*}
50-80\%
\end{align*}

\begin{align*}
0.5
\end{align*}
Ratios of event activity biased recoil distributions

\[ c^{\text{GeV/\text{ch}}} \]

\( 9 < p_T^a < 12 \text{ GeV} \)

\textbf{ALICE Preliminary} $= 5.02 \text{ TeV} \text{NN}s \text{ Pb at } -p\)

\text{charged jets, } t_k - \text{Anti} \text{TT}\{6,7\} - \text{TT}\{12,50\} < 0.6 \pi - \Delta \varphi < 0.6$

\textbf{QM result}

\[ R = 0.2 \]

\text{p–Pb at } \sqrt{s_{_{\text{NN}}}} = 5.02 \text{ TeV}

\text{unmodified recoil jet distributions in 0-20% events}

\textbf{ATLAS}


\textbf{high-$p_T$ near-side ridge in <1%}

... search for onset of jet quenching?
High-$p_T$ $D$ meson & $J/\Psi$ flow in $p+A$ (?!)

ATLAS long-range, near-side $D^{*+}h$ correlation, $p_T > 3$ GeV

ALICE $J/\Psi$ $v_2$ (from + hadron correlation), $p_T = 4$-6 GeV

ATLAS-CONF-2017-073

nucl-ex/1709.06807
Jet shapes in $p+\text{Pb}$

**QM result**

Z+jet effects in high-mult. $pp$

hep-ph/1708.08369

γ+jet $p_T$ balance vs. $p+\text{Pb}$ event multiplicity…

→ … excellent control demonstrated in $pp$

**new since QM**

Observables for possible QGP signatures in central $pp$ collisions

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ALICE hep-ex/1702.00804

80 < $p_T, \text{ch jet}$ < 100 GeV/c

Charged jets, anti-$k_T$

$R = 0.4$, $|y_{\text{jet}}| < 0.5$

100 < $p_T, \text{ch jet}$ < 120 GeV/c

$\text{p-Pb } \sqrt{s_{NN}} = 5.02 \text{ TeV}$

$\text{PYTHIA Perugia 2011}$

$\text{HERWIG EE5C}$

$\text{ALICE hep-ex/1702.00804}$

$\text{pp}$, 5.02 TeV

$\text{ATLAS}$ Preliminary

$\text{pp, 5.02 TeV}$

60 < $p_T^\gamma$ < 80 GeV

80 < $p_T^\gamma$ < 100 GeV

$(1/N_{\gamma})(dN/dx_{\gamma})$

$(1/N_{\gamma})(dN/dx_{\gamma})$

$0 < x_{\gamma} < 1$

$0 < x_{\gamma} < 2$
Detour: $\gamma + \text{jet in Pb+Pb}$
Run: 286834
Event: 124877733
2015-11-28 01:15:42 CEST
Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV
photon + multijet event
$\sum E_T^{FCal} = 4.06$ TeV

Pb+Pb 5.02 TeV
LHC Run 2

balancing jet?
1. What is the (absolute) amount of energy lost in cone? ➡ \( \text{photon} + \text{jet} \) \( p_T \)-balance

2. How is the parton shower in cone modified by medium? ➡ \( \text{photon} \)-tagged frag. function (w.r.t. jet)

3. Where does the lost energy end up? ➡ \( \text{photon-hadron} \) corr. broadly in angle / momentum
1. What is the (absolute) amount of energy lost in cone?
   \[ \Rightarrow \text{photon} + \text{jet} \ p_T\text{-balance} \]

2. How is the parton shower in cone modified by medium?
   \[ \Rightarrow \text{photon-tagged } \text{frag. function (w.r.t. jet)} \]

3. Where does the lost energy end up?
   \[ \Rightarrow \text{photon-hadron corr. broadly in angle / momentum} \]
\[ x_{J\gamma} = \frac{p_T^{\text{jet}}}{p_T^{\gamma}} \]

**vary system size**
Photon-tagged jet fragmentation functions: $pp$

**Photon-tagged jet**
(quark jet-dominant)

**Inclusive jet**
(gluon jet-dominant)

Gluons fragment softer!

*ATLAS Preliminary
$pp$, 26 pb$^{-1}$, 5.02 TeV

Data, $\gamma$-tagged jets
PYTHIA 8 A14 NNPDF23LO
Data, inclusive jet ($p_T^{\text{jet}} = 80-110$ GeV)

Talks: C. Nattrass, A. Milov

ATLAS-CONF-2017-074
**γ-tagged jet FF: Pb+Pb / pp**

**30-80% Pb+Pb:**
*Photon-tagged jets* modified similar to *inclusive jets*

**0-30% Pb+Pb:** *Photon-tagged jets* are more strongly modified (ask me about this...)

*Preliminary ATLAS* 0-30% Pb+Pb / *pp* 5.02 TeV

*Preliminary ATLAS* 30-80% Pb+Pb / *pp* 5.02 TeV

*Preliminary ATLAS* inclusive jets 2.76 TeV (30-40%)

*Preliminary ATLAS* inclusive jets 2.76 TeV (0-10%)

*ATLAS-CONF-2017-074*
small systems at sPHENIX

large statistics for precision probes of small systems
Figure 13: Display of an event with large rapidity gap taken with the ZDC

XOR trigger, firing on more than one spectator neutrons on one side and no neutrons on the other side. Rapidity gap is on the side with no neutrons in the ZDC.

Single sided ZDC triggers select photonuclear events:
unwanted background to "normal" HI events…

Photon+multijet event:
\( p + Pb = 8.16 \text{ TeV}, \)
\( P_E \text{Pb} = 33.1 \text{ GeV} \)
\( \gamma \) photon:
\( p_T = 154 \text{ GeV}, \)
\( \beta = -2.07, \gamma = 2.96 \)

jet 1:
\( p_T = 214 \text{ GeV}, \)
\( \beta = 0.63, \gamma = 0.58 \)

dijets in UPC:
\( \gamma + A\) event candidate
\( p + Pb = 8.16 \text{ TeV}, \)
\( P_E \text{Pb} = 33 \text{ GeV} \)
electron:
\( p_T = 125 \text{ GeV} \)
\( \beta = 0.23, \gamma = 1.41 \) charge +1

muon:
\( p_T = 37.6 \text{ GeV} \)
\( \beta = -1.71, \gamma = 1.29 \) charge -1

b-jet 1:
\( p_T = 99.4 \text{ GeV} \)
\( \beta = -1.65, \gamma = -0.51 \)
b-jet 2:
\( p_T = 66.8 \text{ GeV} \)
\( \beta = 0.18, \gamma = 0.33 \)
jet 1:
\( p_T = 98.6 \text{ GeV} \)
\( \beta = -0.60, \gamma = -2.80 \)
jet 2:
\( p_T = 61.3 \text{ GeV} \)
\( \beta = -2.91, \gamma = -2.52 \)

Thank you!
Inclusive jet FF

\[ D(z; p_T^{\text{jet}}) \text{ in } A+A \]

\[ \frac{D(z; p_T^{\text{jet}}) \text{ in } p+p}{\text{after quenching}} \]

**ATLAS**

- 100 < \( p_T^{\text{jet}} < 398 \text{ GeV}, |\eta| < 2.1 \)
- 1 < \( p_T^{\text{ch}} < 4 \text{ GeV} \)

Pb+Pb data / pp data

- 2011 Pb+Pb data, 0.14 nb\(^{-1}\)
- 2013 pp data, 4.0 pb\(^{-1}\)
- \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \)

\( \frac{1}{N_{\text{jet}}} \frac{1}{N_{\text{evt}}} \frac{d^2 N_{\text{jet}}}{d y \, dp_T} \)

\[ \langle T_{\text{AA}} \rangle \]

2015 Pb+Pb data, 0.49 nb\(^{-1}\)
2015 pp data, 25 pb\(^{-1}\)

\( |\eta| < 2.8 \)

- 0-10% (x10^2)
- 20-30% (x10^4)
- 30-40% (x10^6)
- 60-70% (x10^6)

\( \text{pp data} \)
γ-tagged jet FF

Different "unquenched" jet-$p_T$ distribution

0-30%/30-80% ratio: γ-tagged jets more strongly modified than inclusive jets