LHC forward physics from hard probes
Martin Rybar
Forward Hard Probes of Initial Stages

- Do we have reliable theoretical description of this kinematic regions?
- How far do our approximations in QCD stay valid?
- Can we see onset of gluon saturation or non-linear QCD effects?
- What is the size of modification of the quark and gluon structure functions for nucleons inside nuclei?
- How cold nuclear matter (CNM) influence the production of hard processes?

arXiv:1212.3482
Instrumentation in forward region

Challenges of measurements in forward regions:
- Limited coverage.
- Detector granularity.
- Triggering on forward signatures.
- Uncertainty in modeling.
- Knowledge of performance.
Instrumentation in forward region

Challenges of measurements in forward regions:

- Limited coverage.
- Detector granularity.
- Knowledge of performance.
- Uncertainty in modeling.

arXiv: 0808.1847
Forward jet production

- Collinear factorization and DGLAP successful in describing large-$Q^2$ processes and moderate $x$.
- Expected to fail at low-$x$.
- Do we need BFKL describe forward jet production?
- What is role of MPI?
- Steep rise of gluon PDFs at low-$x$ versus unitary.
- Saturation can bring expected change of trend at low $x$.
- Measurement to be performed with as low $p_T$ and as forward direction as possible.
Forward jet production

- Collinear factorization and DGLAP successful in describing large-$Q^2$ processes and moderate $x$.
- Expected to fail at low-$x$.
- Can BFKL describe forward jet production?
- What is role of MPI?
- Steep rise of gluon PDFs at low-$x$ versus unitary.
- Saturation can bring expected change of trend at low $x$.
- Measurement to be performed with as low $p_T$ and as forward direction as possible.
- Gluon density increased in nuclear collisions → increased sensitivity.
- Sensitive also to the onset of non-linear QCD.
Forward jets@CMS

- Measured in CASTOR detector at $-6.6 < \eta < -5.2$
  - Longitudinal and $\phi$ segmentation; no $\eta$ segmentation.
- Resolution 25% (10%) at 550 GeV (2500 GeV)

$$x \approx \frac{p_T}{\sqrt{s}} e^{\pm \eta} \approx 10^{-6} \quad [p_T=10 \text{ GeV}; \eta=-6; \sqrt{s}=13 \text{ TeV}]$$

Large bin migration due to the energy resolution → requires ~80 iteration in the unfolding!

Also significant uncertainty in modeling.

→ Large systematic uncertainties.

More details in talk by A. Bylinkin

FSQ-16-003-PAS
All models consistent with the data due to the large systematic uncertainties.
All models consistent with the data due to the large systematic uncertainties. 
But sensitivity to MPI.

More details in talk by Alexander Bylinkin
Jet cross-section in proton going side in 5.02 \( p+Pb \) collisions.

Despite the large uncertainties data prefers HIJING MC with saturation effects through shadowing.

arXiv:1812.01691
Jet cross-section in lead going side in 5.02 Pb+p collisions.

→ Ratios should be directly sensitive to saturation effects + significant cancellation of systematic uncertainties.

However the interpretation difficult due to different center-of-mass rapidity selection.
Forward dijet@ATLAS in $p+Pb$

- Measurement of forward-forward and forward-central dijet correlations.
- The forward-forward configuration at lowest $p_T$ (28 GeV) probes $x$ down to $1.5 \times 10^{-4}$.

More details in talk by D. Perepelitsa

\[
\begin{align*}
C_{12} &= \frac{1}{N_1} \frac{dN_{1,2}}{d\Delta \phi} \\
W_{12} &= \text{RMS}(C_{12}) \\
\rho^{pPb}_W &= \frac{W^{p+Pb}_{12}}{W^{pp}_{12}} \\
\rho^{pPb}_I &= \frac{I^{p+Pb}_{12}}{I^{pp}_{12}}
\end{align*}
\]
Angular correlations

No significant changes in shapes but visible changes in integrals, i.e. conditional yields

arXiv:1812.01691
Angular correlations

The forward-forward configuration at lowest $p_T$ probes $x$ down to $1.5 \times 10^{-4}$.

Theoretical calculations

Effects due to gluon saturation and the resummation of large logarithms of the hard scale included.

arXiv:1903.01361
Di-jets in $p+Pb$ and $pp$

- Widths of azimuthal correlations increase with increasing rapidity separation and $p_T$ imbalance between jets.
- Dependence of yield given by faster decrease of the di-jet cross-section at large rapidity compared to inclusive jet cross-section.
No significant broadening of azimuthal correlations in \( p+Pb \) compared to \( pp \).
$p+Pb$ vs $pp$: yields

- Up to 20% suppression of conditional yields for forward-forward configuration in $p+Pb$ compared to $pp$.
- Together with CMS dijet measurement (arXiv:1812.01691) will improve nPDFs.
Measurement of longitudinal fragmentation functions and transverse momentum of charged hadrons in Z-tagged forward.

\[ z \equiv \frac{p_{\text{jet}} \cdot p_{\text{hadron}}}{|p_{\text{jet}}|^2} \quad j_T \equiv \frac{|p_{\text{jet}} \times p_{\text{hadron}}|}{|p_{\text{jet}}|} \]

- Dominated by light-quark jets → information about non-perturbative harmonization important also for HI physics.
Measurement of longitudinal fragmentation functions and transverse momentum of charged hadrons in Z-tagged forward.

\[ z = \frac{p_{\text{jet}} \cdot p_{\text{hadron}}}{|p_{\text{jet}}|^2} \]

\[ j_T = \frac{|p_{\text{jet}} \times p_{\text{hadron}}|}{|p_{\text{jet}}|} \]

- Significant discrepancy when compared to PYTHIA8.
- Jet cross-section (arXiv1605.00951; not shown) described better.
Electroweak bosons@ALICE

- Measurement of Z and W in -4<\eta<-2.5 in 5.02 TeV Pb+Pb and 8.16 TeV p+Pb.
  - “p-going”: 2.03 < y_{cms} < 3.53
  - “Pb-going”: -4.46 < y_{cms} < -2.96
  - Pb-Pb: 2.5 < y_{cms} < 4

From slides by Nicolo Valle

- Accessing nPDFs in regions of large Q^2.
- Complementary to midrapidity measurements by ATLAS and CMS.
Z bosons@ALICE

Z in 5.02 TeV Pb+Pb collisions

- Yields and $R_{AA}$ (not shown) consistent with nPDF, 2.3σ from free PDF.

More details in talk by Nicole Valle
Current precision of the p+Pb measurement not sufficient for firm conclusions.

More details in talk by Nicole Valle
Photon measurements limited to mid-rapidity and semi-forward regions. ATLAS measures of $R_{pPb}$ in center-of-mass rapidity from -2.83 up to 1.90.

**Forward/backward $R_{pPb}$ ratio**

- Sensitive to gluon shadowing/quark anti-shadowing at low $E_T$.
- Data seems to be more compatible with free PDFs.

More details in talk by D. Perepelitsa.
Test pQCD calculations, MPIs and CNM in $p+Pb$ collisions.
Access to different $x$ and $Q^2$ region compared to EW bosons.
  - Low-$x$ down to $\sim 10^{-6}$ at forward rapidity & high-$x$ $\sim 10^{-2}$ in backward rapidity
Forward Heavy-flavours @LHCb

- Test pQCD calculations, MPIs and CNM in $p+$Pb collisions.
- Access to different $x$ and $Q^2$ region compared to EW bosons.
  - Low-$x$ down to $\sim 10^{-6}$ @ forward rapidity & high-$x$ $\sim 10^{-2}$ in backward rapidity

Fully reconstructed prompt $D^0$ by LHCb

- Can provide constrain on gluons nPDFs.
- Similar measurement of forward $B^+, B^0, \Lambda_b^0$ production in 8.02 TeV $p+$Pb.

arXiv:1707.02750
Forward Heavy-flavours @LHCb

- Test pQCD calculations, MPIs and CNM in $p + Pb$ collisions.
- Access to different $x$ and $Q^2$ region compared to EW bosons.
- Low-$x$ down to $\sim 10^{-6}$ at forward rapidity & high-$x$ $\sim 10^{-2}$ in backward rapidity.
- Fully reconstructed prompt $D^0$ by LHCb.
- Can provide constrain on gluons in (anti)shadowing regions.

Can be accommodated and improve EPPS16 and nCTEQ15
(Eskola, Helenius, Pakkinen, Paukkunen arXiv:1906.02512)

Can provide constrain on gluons in (anti)shadowing regions.
Sensitive to gluon PDFs.
Production mechanism not fully understood.
  - In HI collisions affected also by MPIs, breakup with co-moving particles, energy loss.

**J/Ψ measurements:**

\[
R_{pPb} = \frac{dN_{pPb}}{d\eta} / \frac{dN_{pp}}{d\eta} = 8.16 \text{ TeV}
\]

- Suppression in forward rapidity well described by various models.
- LHCb (prompt) and ALICE (inclusive) results in good agreement.
Quarkonia@ALICE&LHCb

- Sensitive to gluon PDFs.
- Production mechanism not fully understood.
- In HI collisions affected also by MPIs, breakup with co-moving particles, energy loss.
- J/Ψ measurements:
  - Centrality dependence
  - More details in talk by S. Hayashi

Centrality dependence

- Small centrality dependence in forward region qualitatively described by models.
- Discrepancy between data and model in Pb-going side.

LHCb (prompt) and ALICE (inclusive) results in good agreement.

ArXiv:1805.04381v2
- Sensitive to gluon PDFs.
- Production mechanism not fully understood.
  - In HI collisions affected also by MPIs, breakup with co-moving particles, energy loss.

**Y measurements in 8.16 TeV p+Pb (LHCb):**

- Suppression in forward regions both for 1S and 2S.
- $R_{p\text{Pb}} (1S) > R_{p\text{Pb}} (2S)$ and well modeled with comovers models.
Sensitive to gluon PDFs.
Production mechanism not fully understood.
- In HI collisions affected also by MPIs, breakup with co-moving particles, energy loss.

**Y(1s) measurements in 8.16 TeV p+Pb (ALICE):**

More details in talk by Shinichi Hayashi

- Models describes forward region but overestimate backward.
- No significant centrality dependence.
Summary

- Every LHC experiment has unique capabilities for various forward hard probes measurements.
- We are gaining understanding of the structure of the nuclei by exploiting asymmetric $p+$Pb collisions.

**Forward jet measurements:**
- Very important benchmarks for the understanding and improvement of the soft/small-x modeling of the hadron collision interaction.
- Further improvement in precision and kinematic reach will put stronger constrain on models.
- New information about hadronization & fragmentation.

**Heavy flavours, EW bosons, and quarkonia measurements:**
- Test different suppression mechanisms.
- Provide significant improvement on nPDFs.

- Lack of calorimetric forward measurements in large systems.
Forward Heavy-flavours @ALICE

- Test pQCD calculations, MPIs and CNM in p+Pb collisions.
- Access to different $x$ and $Q^2$ region compared to EW bosons.
  - Low-$x$ down to $\sim 10^{-6}$ @ forward rapidity & high-$x$ $\sim 10^{-2}$ in backward rapidity

Muons from HF decays@ALICE

- Compatible with unity in forward region; deviation from binary scaling at low-$p_T$ in backward.

arXiv:1702.01479
Muons from HF decays @ALICE

- Test pQCD calculations, MPIs and CNM in $p+\text{Pb}$ collisions.
- Access to different $x$ and $Q^2$ region compared to EW bosons.
- Low-$x$ down to $\sim 10^{-6}$ @ forward rapidity & high-$x$ $\sim 10^{-2}$ in backward rapidity.

Forward-backward ratio

Forward-backward ratio

$R_{FB}$ vs. $p_T$ ($\text{GeV}/c$)

- $p+\text{Pb}$ $\sqrt{s_{NN}} = 5.02 \text{ TeV}$
- $\mu^\pm \leftrightarrow \text{HF}$, $2.96 < |y_{\text{cms}}| < 3.53$

- NLO (MNR) with EPS09 shadowing
- Systematic uncertainty on normalization
Measurement of forward-forward and forward-central dijet correlations.

The forward-forward configuration at lowest $p_T (28 \text{ GeV})$ probes $x$ down to $1.5 \times 10^{-4}$.

Effect from energy resolution (and scale) not so dramatic as in the very forward region.

→ able to use simply bin-by-bin unfolding.

\[
\rho^W_{W} = \frac{W_{PP}}{I_{12}}, \quad \rho^I_{I} = \frac{I_{PP}}{I_{12}}
\]

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

\[
\text{ATLAS Simulation} \quad \text{arXiv:1812.01691}
\]