Physics of ridge and hard processes in proton-lead and lead-lead collisions with ATLAS

Martin Spousta
for the ATLAS Collaboration

Charles University
Prague

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Hot and dense **deconfined matter** is created in heavy ion collisions, called quark-gluon plasma (QGP). This matter allows to:

- Study **non-perturbative** aspects of QCD and **collective phenomena** connected with the strong interaction.
- Study the **phase transition** between quarks and gluons and hadrons.
- Study matter which is similar to the matter present in the **early stages of the universe**.

How to access the information? Measure different processes:

- **hard processes** (e.g. jets and quarkonia)
- **soft processes** (e.g. flow harmonics and the ridge)
Centrality

- Centrality quantifies the **degree of overlap** of two colliding nuclei.
- More central collisions – higher deposited energy.
- Centrality quantified by the energy measured in Forward Calorimeters.
Hard processes
(jets & quarkonia)
Inputs: objects well understood in $p+p$ collisions

- high-$p_T$ partons / jets
- charmonia, heavy flavor mesons
- photon, $W$, $Z$

Outputs: modified yields and properties

- jet quenching = medium-induced gluon radiation, elastic scatterings
- dissociation, regeneration, energy loss
- unmodified, reference

QGP
Inclusive jet suppression in Pb+Pb collisions

\[ R_{AA} = \frac{1}{N_{\text{evnt}}} \frac{d^2 N_{\text{jet}}^{PbPb}}{dp_T dy} \bigg|_{\text{cent}} \times \langle T_{AA} \rangle_{\text{cent}} \times \frac{d^2 \sigma_{\text{jet}}^{PP}}{dp_T dy} \]

The **nuclear modification factor**, \( R_{AA} \), quantifies the magnitude of jet suppression, which arise mainly from final-state interactions with constituents of the medium.
Jet $R_{AA}$: $p_T$-dependence, $\sqrt{s_{NN}} = 5.02$ TeV

- Central collisions (0-10%): $R_{AA} \sim 0.6$ up to TeV scale.
- Peripheral collisions (60-70%): still significant suppression.
- Measured also differentially in rapidity (more suppression in the forward region).
Jet $R_{AA}$: $p_T$-dependence, 2.76 TeV versus 5.02 TeV

- Same magnitude of $R_{AA}$ within systematic uncertainties observed at the two different center-of-mass energies.
Internal structure of jets in Pb+Pb at 5.02 and 2.76 TeV

\[ R_D(z) = \frac{D(z)|_{\text{cent}}}{D(z)|_{pp}} \]
\[ D(z) = \frac{1}{N_{\text{jet}}} \frac{dN}{dz} \]
\[ z = \frac{p_T^{\text{jet}}}{p_T} \cos \Delta R \]

\[ \text{Pb+Pb, } \sqrt{s_{NN}} = 5.02 \text{ TeV, 0.49 nb}^{-1}, 0-10\% \]
\[ pp, \sqrt{s} = 5.02 \text{ TeV, 25 pb}^{-1} \]
Internal structure of jets in Pb+Pb at 5.02 and 2.76 TeV

Fragmentation (at 2.76 TeV) measured for:
- $p_{T,jet} > 100$ GeV,
- $p_{T,trk} > 1$ GeV,
- $|y_{jet}| < 2.1$

- **Enhancement** at low $z$ and at high $z$, **suppression** at intermediate $z$
- Result **fully corrected** to particle level
- **No $\sqrt{s}$** dependence
- **No $p_{T,jet}$** dependence observed
Photon-tagged jet fragmentation in Pb+Pb at 5.02 TeV

- γ-tagged jet fragmentation: q/g dependence. Unquenched γ kinematics!
  
  - More peripheral bin: ratios similar between photon-tagged and inclusive.
  - Central bin: ratios different between photon-tagged and inclusive.
  - Result fully corrected to particle level.

\[ p_{T,\gamma} = 80-126 \text{ GeV}, \]
\[ p_{T,\text{jet}} = 63-144 \text{ GeV}, \]
\[ |\Delta\phi(\text{jet,}\gamma)| > 7\pi/8, \]
\[ p_{T,\text{trk}} > 1 \text{ GeV}, \]
Jet fragmentation in p+Pb at 5.02 TeV

**No modifications** of jet internal structure seen in the p+Pb environment.

Measured for:
- $p_{T,\text{jet}} = 45$-260 GeV,
- $p_{T,\text{trk}} > 1$ GeV,
- $|y_{\text{jet}}^*| < 1.6$
Dijet production in Pb+Pb at 2.76 TeV

\[ x_J = \frac{p_{T,1}}{p_{T,2}} \]

**Measured for:**
- \( p_{T,subleadning} > 25 \text{ GeV}, \)
- \( p_{T,leadning} > 100 \text{ GeV} \)
  (various bins),
- \( |\Delta\phi(\text{jet,}\gamma)| > 7\pi/8 \)
- \( |\eta| < 2.1 \)
- \( R=0.4, R=0.3 \) jets

- First **fully corrected** dijet measurement in heavy ions (using 2D bayesian unfolding).

- Energy **loss very different** for the second jet.

- Similar difference between \( pp \) and Pb+Pb measured also in gamma-jet system.

**ATLAS**

\[ N \frac{dN}{dx_J} \]

\( 100 < p_{T,1} < 126 \text{ GeV} \)

\( 0 - 10 \% \)
Clear centrality dependence.

- **0-10%**: most probable value ~0.5.
- **60-80%**: consistent with pp.

*Pronounced jet p_T dependence,*

**Pb+Pb**

high-p_T jets almost unmodified

**Pb+Pb**

- 100 < p_T < 126 GeV
- 126 < p_T < 158 GeV
- p_T > 200 GeV

Clear centrality dependence.

- **0-10%**: most probable value ~0.5.
- **60-80%**: consistent with pp.
Strong suppression of quarkonia in Pb+Pb.

Similar suppression of prompt and non-prompt J/ψ, but different for prompt and non-prompt ψ(2S) (not shown).

Non-prompt fraction in Pb+Pb consistent with pp (not shown).
• J/$\psi$ $R_{pPb}$ consistent with unity, $\psi(2S)$ suppressed wrt J/$\psi$ (1σ).

• Prompt and non-prompt J/$\psi$, $\psi(2S)$, cross-sections consistent with NRQCD and FONLL predictions, respectively (not shown).

• Significant modifications seen also for $Y(1S,2S,3S)$ in p+Pb collisions.
Ultra-peripheral collisions

- Qualitatively different collisions compared to ordinary Pb+Pb collisions.
- EM interactions dominate at large impact parameters ($b$), photons of small virtuality ($Q^2 < 1/R^2 = 10^{-3}\text{GeV}^2$).
- Photon density $45 \cdot 10^6$ larger in Pb+Pb compared to p+p.
- May allow to access beyond-SM physics.
- Allows to restrict nuclear parton distribution functions at low $x$. 
Photo-nuclear dijet production

- Motivation: restrict nuclear parton distribution functions (nPDF) at low $x$

- **nPDF exhibit non-trivial behavior:**
  - suppression at low $x$ called “shadowing“
  - enhancement at larger $x$ called “anti-shadowing“
  - suppression at the largest $x$ called “EMC effect“

\[
\frac{f_i^p/A}{f_i^p}(x, Q^2) = R_i^A(x, Q^2) f_i^p(x, Q^2)
\]

Eskola et al. EPJC 77 (2017) n3, 163 (one of nPDFs groups)
Photo-nuclear dijet production

- Not the same as $F_2(x,Q^2)$, e.g. still contains $1/Q^4$ dependence.
- MC close to data but matching is not expected.
- Measurement not-yet unfolded.
- Also measured other slices of cross-section.

$H_T \equiv \sum_i p_T^i \sim Q$

$x_A \equiv \frac{m_{\text{jets}}}{\sqrt{s}} e^{-y_{\text{jets}}} \sim x$ of struck parton in nucleus
Photo-nuclear dijet production:
new inputs for nPDF

\[ \frac{d^2 \tilde{\sigma}}{dH_T \, dx_A} \text{ [} \mu \text{b GeV}^{-1}] \]

\begin{itemize}
  \item ATLAS Preliminary
  \item 2015 Pb+Pb data, 0.38 nb
  \item \( \sqrt{s_{NN}} = 5.02 \text{ TeV}, 0\text{XnX} \)
  \item anti-\( k_t \), \( R = 0.4 \text{ jets} \)
  \item \( p_T^{\text{lead}} > 20 \text{ GeV}, m_{\text{jets}} > 35 \text{ GeV} \)
  \item 0.0001 < \( z_f < 0.05 \)
\end{itemize}

Not unfolded for detector response

\[ H_T \text{ [GeV]} \]
\[ x_A \]

\[ Q^2 \text{ [GeV}^2] \]

\begin{itemize}
  \item fixed target DIS and DY
  \item LHC dijets
  \item LHC W & Z
  \item CHORUS neutrino data
  \item PHENIX \( \pi^0 \)
\end{itemize}

\textbf{UPC jets}

... allows to restrict nPDFs in the not-yet-explored subspace of \( x, Q^2 \) space
Soft processes
(physics of ridge and azimuthal anisotropies)
Soft processes – azimuthal anisotropies

- Initial shape and its fluctuations lead to pressure gradients giving rise to azimuthal anisotropies in particle production.
- Quantified by Fourier decomposition:

\[
\frac{dN}{d\phi} = N_0 \left( 1 + 2 \sum_{i=1} v_n \cos n(\phi - \Phi_n) \right)
\]

\[
v_n = \langle e^{in(\phi - \Phi_n)} \rangle = \langle \cos n(\phi - \Phi_n) \rangle
\]

- **Initial shape** of the interaction region drives elliptic flow, \( v_2 \).
- **Initial spatial fluctuations** of interacting nucleons dictate higher order flow, \( v_n \).
- Expected in Pb+Pb. Non-zero \( v_n \) seen in \( pp, p+Pb \) !? ... How about non-flow contributions (di-jets, resonances,...)?
Cumulants for flow

- Cumulant method: Fourier harmonics are obtained from 2k-particle azimuthal correlations. Example:

\[ \langle corr_n \{2k\} \rangle = \left\langle e^{in(\phi_1 + \ldots + \phi_k - \phi_{k+1} - \ldots - \phi_{2k})} \right\rangle \]

- 2 particle cumulant

\[ c_n\{2\} = \langle corr_n \{2\} \rangle \]

\[ v_n \{2\} = \sqrt{c_n \{2\}} \]

- Cumulants remove lower order correlations from non-flow effects.
- But still sensitive to fluctuations of the non-flow component.
Cumulants for flow

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\[
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\]

\[
c_n \{2\} = \langle \text{corr}_n \{2\} \rangle
\]

\[
v_n \{2\} = \sqrt{c_n \{2\}}
\]

- Cumulants remove lower order correlations from non-flow effects.
- \(v_2\) harmonics from cumulants larger for Pb+Pb then for \(p+Pb\).
- \(v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}\.\)
Cumulants and sub-event cumulants – small systems

- Strong dependence on the definition of the event class.
- Still sensitive to fluctuations of non-flow component. Can we do better?
- Is there a collectivity in small systems or not?
Cumulants and sub-event cumulants – small systems

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- Still sensitive to fluctuations of non-flow component. Can we do better?
- Is there a collectivity in small systems or not?

Sub-event cumulants – correlator calculated using particles from 2 or 3 subevents => removing non-flow contribution

\[ v_n \{4\} = \sqrt[4]{-c_n \{4\}} \]

... direct evidence for **collectivity in small systems**
Ridge in small systems

- Two particle correlations in $\Delta \eta \times \Delta \phi$ – long range, **near side** and away side correlations = the ridge.
- Seen in Pb+Pb, but also in $p+Pb$, **pp collisions**.
- Template fitting method to suppress non-flow contribution.
Ridge in small systems

- Two particle correlations in $\Delta \eta \times \Delta \phi$ – long range, near side and away side correlations = the ridge.
- Seen in Pb+Pb, but also in $p+Pb$, $pp$ collisions.
- Template fitting method to suppress non-flow contribution.

$$Y_{\text{template}}(\Delta \phi) = Y_{\text{ridge}}(\Delta \phi) + F Y_{\text{periph}}(\Delta \phi)$$
Ridge in small systems

$0.5 < p_T^{a,b} < 5$ GeV
$2 < |\Delta \eta| < 5$

**ATLAS** Preliminary Template Fits

- no $\sqrt{s_{NN}}$ dependence
- no $\sqrt{s}$ or $N_{ch}$ dependence in $pp$ collisions

- $p+Pb$ $\sqrt{s_{NN}}=8.16$ TeV, 171 nb$^{-1}$ (ATLAS-CONF-2017-006)
- $p+Pb$ $\sqrt{s_{NN}}=5.02$ TeV, 28 nb$^{-1}$ (arXiv:1609.06213)
- $pp$ $\sqrt{s}=13$ TeV, 64 nb$^{-1}$ (arXiv:1609.06213)
- $pp$ $\sqrt{s}=5.02$ TeV, 170 nb$^{-1}$ (arXiv:1609.06213)
Ridge in small systems: heavy flavor

- Ridge also present for heavy flavor:
  - muon-hadron correlations
  - D*-hadron correlations
Ridge in small systems: impact parameter dependence

- Selecting on high-$Q^2$ processes: **Z-tagged ridge.** May primarily select smaller impact parameter $pp$ collisions.
- New method to measure the ridge in events with large pile-up.
- $v_2$ 8% ± 6% larger in Z-tagged events compared to inclusive.
• **Jets** remain *quenched up to a TeV* scale.

• Jet **fragmentation** is modestly but significantly *modified*. Modifications are different for inclusive jets and gamma-tagged jets.

• **Quarkonia** production is modestly modified in $p$+Pb and **strongly modified in Pb+Pb** wrt pp production. The modification in Pb+Pb is similar for prompt and non-prompt charmonia.

• **Ultra-peripheral collisions** allows e.g. for studying nuclear modifications to parton distribution functions.

• Strong evidence is seen for **flow in small systems** by sub-event cumulants, ridge also present for heavy flavor.

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults
Backup slides
Quarkonia in \textbf{Pb+Pb, 5.02 TeV}

- \textbf{Prompt }\psi(2S)\textbf{ suppressed by a factor of }\sim 2\textbf{ more than prompt J}/\psi.  
- \textbf{Non-prompt }\psi(2S)\textbf{ exhibits }\textbf{similar suppression} as non-prompt J}/\psi.
Gamma-jet production in Pb+Pb at 5.02 TeV

- Clear modification (downward shift) due to the parton energy loss of the balancing jet.
- Not yet unfolded for the detector response.
- Smaller suppression in peripheral collisions (not shown).

\[ x_{J\gamma} = \frac{p_{T,\text{jet}}}{p_{T,\gamma}} \]
Gamma-jet production

- Good agreement between PYTHIA8 and $pp$ data
- Not unfolded for the detector response

$ATLAS$ Preliminary

$5.02$ TeV

$60 < p_T^\gamma < 80$ GeV

$80 < p_T^\gamma < 100$ GeV

$100 < p_T^\gamma < 150$ GeV

$x_{J\gamma} = \frac{p_{T,jet}}{p_\gamma}$
Quarkonia in $p+Pb$, 5.02 TeV

$$R_{pPb} = \frac{d\sigma_{pPb}}{dp_T} \frac{A}{A} \times \frac{d\sigma_{pp}}{dp_T}$$

\sim \text{ratio of } R_{pPb}

• $Y(1S)$ suppressed \textbf{at low-$p_T$}.

• $Y(2S), Y(3S)$ suppressed wrt $Y(1S)$.

\textbf{Allice} $p+Pb, \sqrt{s_{NN}} = 5.02 \text{ TeV}$

$L = 51 \mu b^{-1}, -1.37 < y^* < 0.43$

\textbf{ATLAS} $p+Pb, \sqrt{s_{NN}} = 5.02 \text{ TeV}$

$L = 28 \text{ nb}^{-1}, -2.0 < y^* < 1.5$

\textbf{ARXIV:1709.03089}
D meson in $p+Pb$, 8.16 TeV

$D^0 + \overline{D^0}$

$D^{(\pm)}_*$

**ATLAS Preliminary**

- $p+Pb \sqrt{s_{NN}} = 8.16$ TeV
- $-0.5 < y^* < 0.5$
- $5.0 < p_T < 6.0$ GeV
- $\chi^2/ndof = 0.9$

**Weighted Events / 5 MeV**

$m(K\pi)$ [GeV]

**Weighted Events / 0.5 MeV**

$m(K\pi\pi) - m(K\pi)$ [MeV]
D meson in $p+Pb$, 8.16 TeV

- Forward-backward ratio, $R_{FB}$ consistent with unity for both $D^0$ and $D^*$. 
- Cross-sections consistent with FONLL predictions (not shown).
Cumulants in Pb+Pb

- Measured $c_n\{4\}$ (n=1-4) allows to understand the nature of flow fluctuations.
- $c_1\{4\}$: negative, constraints on dipolar eccentricity fluctuations.
- $c_2\{4\}$: non-gaussian fluctuations of $v_2$ in ultra-central collisions.
Cumulants in Pb+Pb

- Measured $c_n\{4\}$ ($n=1-4$) allows to understand the nature of flow fluctuations.
- $c_1\{4\}$: negative, constraints on dipolar eccentricity fluctuations.
- $c_2\{4\}$: non-gaussian fluctuations of $v_2$ in ultra-central collisions.
- $c_4\{4\}$: non-linear contribution of $v_2^2$ to $v_4$. 

[Graph showing $c_4\{4, \Sigma E_T\}$ vs. Centrality [%]]

**ATLAS-CONF-2017-066**
Electroweak bosons
• Studying rapidity and centrality dependence.
• Data consistent with POWHEG scaled to NNLO accuracy.
• No modifications seen in $T_{AA}$-scaled yields – good understanding of geometry.
• No precision to distinguish nPDF effects yet.
W in Pb+Pb, 5.02 TeV

• Studying rapidity and centrality dependence: **same conclusions** as for Z. Data consistent with POWHEG scaled to NNLO accuracy.

• **Isospin effect**: d-quark excess => ~10% larger $W^+$ yield.

• Lepton charge asymmetry consistent with theory prediction (not shown).
Prompt photons in p+Pb, 8.16 TeV

- Measured up to $E_T = 500$ GeV.
- JETPHOX with CT14+EPPS16 underpredict data by ~ 20% (similar disagreement seen in pp, JHEP 08 (2016) 005).
- Evaluating ratios wrt to $pp$ collisions:

$$R_{pPb} = \frac{d\sigma^{pPb}}{dE_T^\gamma} \frac{A \times d\sigma^{pp}}{dE_T^\gamma}$$

... next slide
Prompt photons in p+Pb, 8.16 TeV

- Consistent with unity except in backward rapidity (isospin effects)
- Data compared to two nPDF sets: CT14+EPPS16, nCTEQ15 and initial state energy loss model (multiple scatterings in nuclear matter before hard process):
  - no ability to distinguish nPDF effects
  - no signs of initial state energy loss
Landscape of the suppression measurements

**ATLAS** Preliminary

- □ $Z$, 0-10% (ATLAS-CONF-2017-010)
- + *prompt $J/\psi$*, 0-80% (ATLAS-CONF-2016-109)
- ● $jet$, 0-10% (ATLAS-CONF-2017-009)
- ● $h^\pm$, 0-5% (ATLAS-CONF-2017-012)

$R_{AA}$ vs $p_T$ or $m_Z$ [GeV]

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

10th Excited QCD Conference
Boosted protons/nuclei are source of photons of small virtuality ($Q^2 < 1/R^2 = 10^{-3}\text{GeV}^2$) described using equivalent photon approximation (EPA)

$$n(k, b) = \frac{Z^2 \alpha}{\pi^2 (\hbar c)^2} \frac{k}{\gamma^2} K_1^2(x)$$

where

$$x = \frac{kb}{\gamma \hbar c}$$

45·10^6 larger photon density compared to pp

... EM interactions dominate at large $b$, qualitatively different collisions compared to ordinary Pb+Pb
Three UPC measurements ... 

Measurement of high mass dimuons (ATLAS-CONF-2016-025)

Photo-nuclear dijet production (ATLAS-CONF-2017-011)

Three UPC measurements ...

Measurement of high mass dimuons (ATLAS-CONF-2016-025)

Photo-nuclear dijet production (ATLAS-CONF-2017-011)


... all exclusive final states (i.e. nothing else is expected to get produced)
Measurement of high-mass dimuons

- Good agreement with Starlight MC – but the higher order QED corrections needs to be implemented into the MC
- Verifies the $Z^4$ scaling of cross-section and photon flux
- Significant kinematic extension over previous measurement by ALICE (EPJC 73 (2013) 2617)
Evidence for light-by-light scattering

- Event selection: 2 photons: $E_T > 6$ GeV, $|\eta| < 2.37$, $m_{\gamma\gamma} > 6$ GeV,
  $p_{T\gamma\gamma} < 2$ GeV, $Aco = (1-\Delta\phi/\pi)<0.01$; no tracks
- **13 events** seen in the data, expects: 7.3 signal, 2.6 background
- $p$-value for the background-only hypothesis: $5 \times 10^{-6} \Rightarrow 4.4$ sigma significance (3.8 sigma expected)
Search for light-by-light scattering

- Event selection: 2 photons: $E_T > 6$ GeV, $|\eta| < 2.37$, $m_{\gamma\gamma} > 6$ GeV, $p_T^{\gamma\gamma} < 2$ GeV, $Aco = (1 - \Delta\phi/\pi) < 0.01$; no tracks

- 13 events seen in the data, expects: 7.3 signal, 2.6 background

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Search for light-by-light scattering

• Measured cross-section: $70 \pm 20$ (stat.) $\pm 17$ (syst.) nb
• SM predictions:
  - $45 \pm 9$ nb (PRL 111 (2013) 080405),
  - $49 \pm 10$ nb (PRC 93 (2016) no.4, 044907)

\[
\sigma_{\text{fid}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{C \times \int L dt}
\]

C=0.31 ± 0.07, corrects for: trigger, diphoton, PID efficiencies and photon energy and angular resolutions
• Motivation: restrict nuclear parton distribution functions (nPDF) at low $x$
• nPDF exhibit **non-trivial behavior:**
  – suppression at low $x$ called “shadowing”
  – enhancement at larger $x$ called “anti-shadowing”
  – suppression at the largest $x$ called “EMC effect“

\[
\frac{f_i^{p/A}(x, Q^2)}{f_i^p(x, Q^2)} = R_i^A(x, Q^2) \]

Eskola et al. EPJC 77 (2017) n3, 163
(one of nPDFs groups)
Photo-nuclear dijet production: observables

$H_T \equiv \sum_i p_{T_i}$

$2 \rightarrow 2$ scattering limit:

$x_A \equiv \frac{m_{jets}}{\sqrt{s}} e^{-y_{jets}}$

$x$ of struck parton in nucleus

$z_{\gamma} \equiv \frac{m_{jets}}{\sqrt{s}} e^{+y_{jets}}$

$x_{\gamma} y_{\gamma}$

(y_{\gamma} ... E fraction of $\gamma$, $x_{\gamma}$ ... fraction of $\gamma$'s E carried by parton in $\gamma$)

... where

$y_{jets} \equiv \frac{1}{2} \ln \left( \frac{\sum_i E_i + \sum_i p_{z_i}}{\sum_i E_i - \sum_i p_{z_i}} \right)$

$m_{jets} \equiv \left[ \left( \sum_i E_i \right)^2 - \left| \sum_i \vec{p}_i \right|^2 \right]^{1/2}$

... $i$ goes through all the jets
Photo-nuclear dijet production: new inputs for nPDF

\[
\frac{d^3 \tilde{\sigma}}{dH_T x_A dz_\gamma} = \frac{1}{L \Delta H_T \Delta x_A \Delta z_\gamma} \frac{\Delta N}{\varepsilon_{\text{trig}} \varepsilon_{\text{sel}}}
\]

... measuring triple differential cross-section not unfolded for the response \(\rightarrow\) projections.
Photo-nuclear dijet production: slices of $x_A$

- Not the same as $F_2(x, Q^2)$
  - still contains $1/Q^4$ and $z_\gamma$ dependence
- MC close to data but matching is not expected
- Also measured slices of $H_T$ and $z_g$
... more results

**Femtoscopy with identified charged pions in p+Pb**


**Longitudinal flow decorrelations in Pb+Pb**

(arXiv:1709.02301)
Internal structure of jets in Pb+Pb at 2.76 TeV

\[ R_D(z) = \frac{D(z)\big|_{\text{cent}}}{D(z)\big|_{pp}} \]

\[ D(z) = \frac{1}{N_{jet}} \frac{dN}{dz} \]

\[ z = \frac{p_T}{p_{jet}} \cos \Delta R \]
Internal structure of jets at 5.02 TeV

\[ R_D(z) \]

\[ 1.0 \leq R_D(z) \leq 1.4 \]

- \( 126 < p_T^{\text{jet}} < 158 \text{ GeV} \)
- \( 200 < p_T^{\text{jet}} < 251 \text{ GeV} \)
- \( 316 < p_T^{\text{jet}} < 398 \text{ GeV} \)

\[ |y_{\text{jet}}| < 2.1 \]

\( \text{Pb+Pb, } \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV, } 0.49 \text{ nb}^{-1}, 0-10\% \)

\( pp, \sqrt{s} = 5.02 \text{ TeV, } 25 \text{ pb}^{-1} \)

\[ \text{no jet } p_T \text{ dependence observed} \]
Internal structure of jets at 5.02 TeV

... 5.02 TeV measurement agrees with 2.76 TeV measurement at the comparable $z$ domain.
Jet reconstruction performance in run 2

- Realistic jet simulations: NLO POWHEG+PYTHIA8 MC + minimum bias Pb+Pb data overlay.
- Good understanding of jet energy scale.
- Expected behavior of jet energy resolution.

Jet energy scale

Jet energy resolution
Jet reconstruction performance in run 2

... Example of the improvement in the jet energy scale: implementing the higher order flow corrections.

=> Jet energy scale does not depend on the orientation with respect to the reaction plane.

See also poster by Akshat Puri
Jet cross-section in pp collisions

2.76 TeV

5.02 TeV

ATLAS Experiment

ATLAS Preliminary

anti-$k_t$, $R=0.4$ jets, $\sqrt{s}=5.02$ TeV

2015 pp data, 25 pb$^{-1}$
Jet yields in Pb+Pb collisions

2.76 TeV

5.02 TeV

ATLAS Preliminary
anti-$k_t$, $R=0.4$ jets, $\sqrt{s_{NN}}=5.02$ TeV
2015 Pb+Pb data, 0.49 nb$^{-1}$
2015 pp data, 25 pb$^{-1}$

$\frac{1}{N_{\text{ext}}} \frac{1}{N_{\text{jet}}} \frac{d^2 N_{\text{jet}}}{dp_T dy}$ [nb/GeV]

$\frac{1}{\langle T_{AA} \rangle} \frac{1}{N_{\text{ext}}} \frac{d^2 N_{\text{jet}}}{dp_T dy}$ [nb/GeV]

$|y| < 2.8$

0-10% (x10^6)
20-30% (x10^5)
30-40% (x10^4)
60-70% (x10^3)

$|y| < 2.1$

0-10% (x10^6)
20-30% (x10^5)
30-40% (x10^4)
60-80% (x10^3)

$|y| < 0.3$ (x10^6)
0.3 $\leq |y| < 0.8$ (x10^5)
0.8 $\leq |y| < 1.2$ (x10^5)
1.2 $\leq |y| < 2.1$ (x10^5)
Jet $R_{AA}$: $y$-dependence, $\sqrt{s_{NN}} = 5.02$ TeV

- Vertical-axis: ratio of $R_{AA}$ in a given rapidity to the $R_{AA}$ for jets with $|y|<0.3$.
- With increasing jet $p_T$, $R_{AA}$ getting smaller in the forward region as compared to the mid-rapidity region (predicted in arXiv:1504.05169).

ATLAS Preliminary

anti-$k_t$, $R = 0.4$ jets, $\sqrt{s_{NN}} = 5.02$ TeV