Z and γ (+jet) measurements in lead-lead collisions with ATLAS

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Photon-jet and Z-jet production

unlike for dijet events, where both objects are potentially modified by the hot, dense medium...

electroweak bosons are unaffected by the medium, allow us to calibrate scale of hard process and directly probe jet energy loss
Photons and Z’s in nuclear collisions

- Photons & Z are penetrating probes of the hot, dense medium
  - Boson-jet correlations will be an important contribution to understanding of jet quenching!
- Important to check rates of production, calculable in pQCD @ NLO (γ) & NNLO (Z)
  - e.g. photon diagrams include direct photons & photons from jet fragmentation
- Fragmentation contributions for photons reduced using “isolation” condition
  - Require a maximum energy in a cone $R < R_{iso}$ around photon
- Both probes are sensitive to nPDF effects (e.g. shadowing, antishadowing)
The ATLAS Detector

- Muon Detectors: $|\eta|<2.7$
- Tile Calorimeter: $|\eta|<4.9$
- Liquid Argon Calorimeter: $|\eta|<2.5$

- Components:
  - Toroid Magnets
  - Solenoid Magnet
  - SCT Tracker
  - Pixel Detector
  - TRT Tracker
Integrated luminosity for 2011 Pb+Pb run

166 µb$^{-1}$ delivered, 158 µb$^{-1}$ recorded by ATLAS
Centrality selection

Centrality defined by $\Sigma E_T$ in ATLAS forward calorimeter (FCal) $3.2<|\eta|<4.9$

FCal $\Sigma E_T$ shape established to be identical to 2010 (after known 4.1% rescaling), where efficiency relative to total cross section known to be $98\pm2\%$

Uncertainties on geometric parameters include cross section & Glauber uncertainties
Data sample (photons)

- Using 0.13 nb\(^{-1}\) of 2011 lead-lead LHC run
  - Detailed calibration of luminosity scale to accepted minimum bias events (in a special data stream) gives a total of 755M events with <1\% precision for 0-80\% centrality

- Special selection of events triggered on 16 GeV EM cluster, with a photon or electron reconstructed offline with \(E_T\) > 40 GeV
  - From PYTHIA+HIJING simulations, 100\% efficient for photon \(p_T\) > 45 GeV

- Underlying event (UE) is removed from every calorimeter cell
  - Identical algorithm to that used for ATLAS jet analysis
  - Iterative elliptic-flow-sensitive subtraction performed in slices of \(\Delta\eta=0.1\), after excluding regions around \(R=0.2\) jets > 25 GeV and \(R=0.4\) track jets > 10 GeV

- Standard ATLAS photon & electron (“eGamma”) reconstruction then applied to full set of UE-subtracted calorimeter cells
Data sample (Z)

**Z to electrons**
- Triggered using similar EM trigger as for photons with 14 GeV threshold
- No use of ATLAS high level trigger
- Electron energy corrected for underlying event

**Z to muons**
- Full use of ATLAS trigger system
  - 4 GeV required at level 1
  - *If accepted, track properties required using precision MDT and CSC information, as well as inner detector information*
  - *Also performed “full scan” reconstruction in the trigger system, for muons above 10 GeV, initiated with ZDC coincidence or a total ET > 10 GeV deposited in the ATLAS calorimeters*

**Used full 2011 sample** $L_{\text{int}} = 0.15 \text{ nb}^{-1}$
- Sampled over 1 billion events
Z and photon yields
FIG. 12: ATLAS event display showing $Z \rightarrow e^+ e^-$ candidate.

FCal $P_T = 1.58$ TeV (10-20% Centrality), $m_{ee} = 92.2$ GeV, $p_Z T = 4.8$ GeV, $\gamma_Z = -0.2$. 

Run Number: 193546, 
Event Number: 27903149 
Date: 2011-11-20, 05:01:50 CET 

Electron: Red 
Cells: Tile, EMC
FIG. 13: ATLAS event display showing $Z \rightarrow \mu^+\mu^-$ candidate.

$P_T = 2.16$ TeV (10-20% Centrality), $m_{\mu\mu} = 102$ GeV, $p_T^Z = 5.0$ GeV, $y^Z = -0.1$.
Z reconstruction in 2011 data

Objects:
- Electrons: require match of track with EM cluster, along with shower shape cuts.
- Muons: reconstructed using combination of MS and/or ID, optimized for Z efficiency, high quality muons $p_T > 10$ GeV, lower quality $p_T > 20$ GeV.

Data:
- ATLAS Preliminary
- Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV
- Data 2011 $L_{int} = 0.15$ nb$^{-1}$

Graph:
- $dN/ dm$ [GeV$^{-1}$]
- $m_{ee}$ [GeV]
- $m_{\mu\mu}$ [GeV]
- $Z^{ee}$: Opposite sign: 772, Same sign: 42
- $Z^{\mu\mu}$: 1223, 14
- Simulation

Numbers:
- Opposite sign: 772
- Same sign: 42
- 1223
- 14
- 0.15 nb$^{-1}$
Z rapidity distribution

Z yield shown for minimum bias events, normalized to the number of events and compared to the PYTHIA rapidity shape normalized to NNLO cross section $x <T_{AA}>$. 

ATLAS Preliminary

Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV

Data 2011 $L_{int} = 0.15$ nb$^{-1}$

Centrality 0-80%

$\bullet$ $Z \rightarrow l\bar{l}$

Model
Z momentum distribution

Transverse momentum distribution averaged over $|y|<2.5$

Spectral shape is centrality independent

Good agreement with PYTHIA shape, normalized to $\sigma_{\text{NNLO}}$ & scaled by $<T_{\text{AA}}>$
Scaling of $Z$ with collision centrality

Integrated yields show a clear scaling with number of binary collisions

Same dependence observed for three momentum ranges (<10, 10-30, >30 GeV)
Elliptic flow (or lack thereof) of Z

Z elliptic flow checked, to test influence of nuclear geometry (not expected).

Main uncertainty stems from influence of jet on reaction plane calculation, addressed by comparing random choice of EP side (+ or - \(\eta\)) with choice correlated with Z direction.
Photon reconstruction in the 2011 data

- **Photon reconstruction is seeded by calorimeter clusters of at least 2.5 GeV**
  - Sliding window algorithm applied in 2nd sampling layer, which gets >50% of photon energy.

- **No conversion recovery is applied: all photons treated as unconverted.**
  - High energy converted photons deposit most energy in only a slightly wider $\phi$ region than photons.

- **Energy measurement is made using all three layers**
  - Area is 3x5 layer-2 cells (each cell is $\Delta\eta\times\Delta\phi \sim 0.025 \times 0.025$)
  - Background subtraction gives corrections of $O(1 \text{ GeV})$ even in central events.
Photon performance: shower shapes

Comparison of tight photons with fully simulated photon+jet events, total MC (yellow), unconverted (blue), and converted (red) photons. Small $p_T$ and $\eta$ dependent shifts (from pp) applied to MC.
Photon purity & efficiency


Efficiency controlled mainly by shower shape cuts & isolation selection: reconstruction & ID quite efficient in central HI, isolation leads to ~15-20% reduction.
ATLAS photon yields for 45<\textit{p}_T<200 \text{ GeV}

For \textit{R}=0.3, \textit{E}_T<6 \text{ GeV}

\[
\frac{1}{N_{\text{evt}}} \frac{dN_\gamma}{dp_T}(p_T, c) = \frac{N_\text{sig}}{\epsilon_{\text{tot}} N_{\text{evt}} \Delta p_T}
\]

For each centrality and \textit{p}_T bin, extracted signal counts scaled by
- total efficiency
- number of events
- width of \textit{p}_T bin
then scaled by \langle T_{AA} \rangle

CMS \textit{pp} & PbPb @ 2.76 \text{ TeV}
JETPHOX 1.3 E_T(\textit{R}=0.3)<6 \text{ GeV}
& PYTHIA MC11 tune shown for comparisons
Ratios relative to JETPHOX

- Comparisons of lead-lead data with \( pp \) cross sections from JETPHOX 1.3.0
  - CTEQ 6.6 PDFs
  - BFG fragmentation functions
  - No isospin or nPDFs included
  - Scale uncertainties (factor of 2 coherent variation of \( \mu_{I,F,R} \)): ±13%
  - PDF uncertainties at 7 TeV: ±5%
- Equivalent to \( R_{AA} \), but with MC reference
- Within stated statistical and systematic uncertainties, good agreement of data and JETPHOX, for all centrality bins over wide range in \( p_T \)

\( \text{Preliminary ATLAS} \)
\( b_\mu = 133 \) int
\( \text{Pb+Pb } L_{NN} \leq 1.3 \eta \)
Z and photon correlations with jets
Probing jet energy loss with Z-jet and γ-jet

- We test transverse momentum balance with “momentum fraction” (same notation as with first CMS results, arXiv:1205.0206)

\[ x_{JG} = \frac{p_T J}{p_T G} \]
\[ x_{JZ} = \frac{p_T J}{p_T Z} \]

- We test angular broadening of the correlation with \( \Delta \phi \)

\[ \Delta \phi_{JG} = |\phi_J - \phi_G| \]
\[ \Delta \phi_{JZ} = |\phi_J - \phi_Z| \]
Z-jet correlations

Jets reconstructed using standard iterative background subtraction

Above 50-60 GeV jet and Z are emitted back to back

Fake rejection (based on track jet or EM cluster within jet), removes uncorrelated jets (esp. in R=0.3)
Z jet correlations

Bin-by-bin unfolding in p\(_T\) performed to correct for finite jet resolution

Clear modification of x\(_{JZ}\) distribution seen even in minimum-bias selected events (over half being in 0-10%)

0-20% central

20-80% central

ATLAS Preliminary
Pb+Pb \( \sqrt{s}_{NN}=2.76\) TeV, \( L=0.15 \text{ nb}^{-1} \)
Anti-k, Jet R=0.3, p\(_{T}\)\(_{jet}\)>25, p\(_{T}\)\(_{Z}\)>60 GeV, p\(_{T}\)\(_{jet}\)/p\(_{T}\)\(_{Z}\)>25/60

PYTHIA: Mean=0.82±0.01

Pb+Pb: Mean=0.62±0.04±0.04

0-20% Centrality

ATLAS Preliminary
Pb+Pb \( \sqrt{s}_{NN}=2.76\) TeV, \( L=0.15 \text{ nb}^{-1} \)
Anti-k, Jet R=0.3, p\(_{T}\)\(_{jet}\)>25, p\(_{T}\)\(_{Z}\)>60 GeV, p\(_{T}\)\(_{jet}\)/p\(_{T}\)\(_{Z}\)>25/60

PYTHIA: Mean=0.72±0.04±0.04

Pb+Pb: Mean=0.76±0.06±0.06

20-80% Centrality
Shift of transverse momentum ratios

Centrality dependence: 0-20% vs. 20-80%
Peripheral bins consistent with PYTHIA predictions.
0-20% events show a clear downward shift of energy fraction
Reduction of Z+jet fraction

Centrality dependence: 0-20% vs. 20-80%
Peripheral bins consistent with PYTHIA predictions.
0-20% events show a clear downward shift of energy fraction
**γ-jet correlations**

- **Uses photon performance from PYTHIA+Data simulations**
  - Efficiencies, purities consistent with PYTHIA+HIJING

- **Jet performance determined from photon-jet “overlay”**
  - Fluctuations of data built-in by construction
  - Efficiencies determined for lower jet $p_T$ cut of 25 GeV

- **Jet response unfolded for jet energy resolution from PYTHIA+Data**
  - Uses SVD method to unfold inclusive jet distributions
  - Unfolding matrix then applied to single jet $p_T$ and mapped into $x_{J\gamma}$
60 < p_T^γ < 90 GeV, |η_γ| < 1.3, p_T^{jet} > 25 GeV, |η^{jet}| < 2.1 and |Δϕ_{jγ}| > 7π/8.

Fully unfolded result, normalized per photon. Uncertainties include both jet & photon.

Compared to PYTHIA true photon/truth jet quantities in events selected with same isolation and selection criteria as reconstructed events.
Centrality evolution of $\langle x_{J\gamma} \rangle$

In narrow photon $p_T$ bin (60-90 GeV), systematic but slow evolution of mean of $x_{J\gamma}$: clear degradation of average energy fraction of jet vs. photon
Suppression of overall photon-jet yield

Most peripheral events consistent with PYTHIA truth, and strong centrality dependence: nearly half of the photons in central events do not have a matching jet.
$\Delta \phi$ distributions

60 < $p_T^\gamma$ < 90 GeV, $|\eta_\gamma|$ < 1.3, $p_T^{\text{jet}}$ > 25 GeV, $|\eta^{\text{jet}}|$ < 2.1 and $|\Delta \phi_{\gamma \text{jet}}|$ > $7\pi/8$.

No unfolding performed: comparing background-subtracted data with fully-reconstructed simulated events
Exponential slope

Exponential fit performed over range $\Delta\phi > 2\pi/3$ (floating normalization)
Slope parameter shows no dependence over full centrality range: back-to-back emission persists
Conclusions

• **New results on Z and photon production, both yields and in correlation with jets**

• **Z**
  - Rapidity and momentum distribution agree well PYTHIA scaled by NNLO cross section
  - Scaling with binary collisions observed
  - No elliptic flow of Z observed
  - Correlation with jet shows clear attenuation of jet energy

• **Photons**
  - Yields measured out to 200 GeV, after background subtraction for dijets
  - Good agreement with JETPHOX 1.3.0, binary scaling observed
  - Correlation with jets shows clear back-to-back correlation but strong centrality-dependent attenuation of jet energy & reduction of fraction of photons with associated jet
Z. Citron, 1B, Study of correlations between neutral bosons and jets in lead-lead collisions at 2.76 TeV with the ATLAS detector

I. Grabowska-Bold, 4C, Measurement of isolated direct photons in lead-lead collisions at 2.76 TeV with the ATLAS detector

J. Dolejsi, 4C, Measurements of W and Z boson production in Pb+Pb collisions at 2.76 TeV with the ATLAS detector.

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavylonsPublicResults
Extra slides
Centrality dependence of yields

- Even without a reference distribution, can look at centrality dependence in bins of photon $p_T$
- Centrality represented here as mean number of participants in each bin
- No dependence on $N_{\text{part}}$ within statistical (error bars) and systematic uncertainties

\[ \frac{1}{(N_{\text{evt}}) dN_{\gamma} / dp_T / \langle T_{AA} \rangle [\text{pb/GeV}]} \]

$\langle N_{\text{part}} \rangle$
Unfolding photon-jet correlations

Unfolding performed on inclusive jet sample using SVD method, with response matrices determined from simulated gamma-jet events.

Unfolding matrix then applied to individual jets, and unfolded event filled into $x_{J\gamma}$ distribution

Clear narrowing of unfolded MC, mild effect on data
Use ATLAS electromagnetic object trigger, based on combinations of 0.1x0.1 “towers” and threshold of 16 GeV: 0.2x0.2 sliding window but trigger is only on 0.2x0.1 regions