

Fakultät Mathematik und Naturwissenschaften Institut für Kern- und Teilchenphysik

Measurements of underlying event properties and pQCD with **Photons, jets and vector boson + jets with ATLAS**

Frank Siegert (TU Dresden) on behalf of the ATLAS Collaboration

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Emmy Noether-Programm Deutsche Forschungsgemeinschaft DFG





spoilt for choice

Adjective

spoilt for choice (comparative more spoilt for choice, superlative most spoilt for choice)

1. Having such a selection of good choices, that deciding which one to pick is difficult.

- 2. Selecting ATLAS measurements for a conference talk.
- Short appetizer slides for
 Taxe 7 lists
 - 13 TeV Z+jets
 - 8 TeV W+jets angular dists
 - **13 TeV** Inclusive γ

13 TeV Inclusive jets

More details on new analyses



13 TeV Underlying event



Probing QCD purely or in clean testbed with $\gamma/W/Z$ as trigger.



Measurements of the production cross section of a Z boson in association with jets in *pp* collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

[arXiv:1702.05725]



- 3.16 fb⁻¹ of 2015 data at **13 TeV**
- $Z \rightarrow ee and Z \rightarrow \mu\mu$ selection, combined results
- Up to 7 anti- k_{t} jets with *R*=0.4, p_{τ} >30 GeV, |y|<2.5



Comparisons to

- Fixed NLO predictions
- NLO multi-jet merging
- LO multi-jet merging
- Even NLO multi-jet not perfect
 Sherpa (Z+0,1,2j@NLO+3,4j@LO)
 ≥ 5 jets (from shower) too hard
 MG5_aMC+Py8 (Z+0,1,2j@NLO)
 ≥ 4 jets (beyond NLO) too soft





Measurement of W boson angular distributions in events with high transverse momentum jets at $\sqrt{s} = 8$ TeV using the ATLAS detector

[arXiv:1609.07045]

[Phys.Lett. B765 (2017) 132-153]







Measurement of the cross section for inclusive isolated-photon production in *pp* collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector

[arXiv:1701.06882]

Presented by Ana in Tuesday's Young Scientists Forum!





3.2 fb⁻¹ of 2015 data at 13 TeV

- Photon p_T measured from 125 GeV to 1.5 TeV already! (~ reach of full 8 TeV dataset)
- Challenge: background from jets misidentified as photons
 - data-driven subtraction similar to previous analyses
- Good agreement with NLO (JetPhox) and Monte-Carlo predictions (Pythia & Sherpa)





Measurement of inclusive-jet cross-sections in proton–proton collisions at $\sqrt{s} = 13$ TeV centre-of-mass energy with the ATLAS detector

[ATLAS-CONF-2016-092]



3.2 fb⁻¹ of 2015 data at 13 TeV

- Anti- k_t jets with *R*=0.4 up to p_T =3.2 TeV and |y|=3
- MC- and data-based jet energy scale (JES) calibration
- Iterative dynamically stabilized unfolding
- PDFs and NLO pQCD calculations (NLOJET++) consistent with data
- Multiplicative EW corrections included in comparison (up to 8% at highest p_T)





High- $E_{\rm T}$ isolated-photon plus jets production in *pp* collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

[arXiv:1611.06586]



20.2 fb⁻¹ of 2012 data at 8 TeV

- γ + 1, 2, 3 jets studies
 - in 6(!) phase space regions
 - for 35(!) observables
- Generally good agreement with
 - NLO QCD (JetPhox, BlackHat)
 - Monte Carlo (Pythia, Sherpa)

in classical photon/jet observables

 Some deviations at high photon p_T and for Pythia8 in multi-jet regions









Measurement of charged-particle distributions sensitive to the underlying event in $\sqrt{s} = 13$ TeV proton–proton collisions with the ATLAS detector at the LHC

[arXiv:1701.05390]



1.6 nb⁻¹ of low-luminosity 2015 data at 13 TeV

- Measurement of energy and particle flow with respect to leading particle
- Charged particles with *p₁*>500 MeV and *|n|*<2.5













Measurement of the k_t splitting scales in $Z \rightarrow \ell \ell$ events in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector





SM measurement of jet evolution in Z+jets events

- Differential cross sections of splitting scales in k_T-clustering of hadronic activity
- 20.2 fb⁻¹ of 2012 data at 8 TeV
- Particularly interesting in transition region between jets and soft hadronic activity
 - sensitive to parton shower and its matching and merging
 - not probed directly by measurements based on jet observables



- Charged particle momenta $i, j \rightarrow$ input to cluster algorithm
- k_{τ} algorithm = sequential recombination algorithm, matches singularity structure of QCD:

$$d_{ij} = \min\left(p_{\mathrm{T},i}^2, p_{\mathrm{T},j}^2\right) \times \frac{\Delta R_{ij}^2}{R^2}$$
$$d_{ib} = p_{\mathrm{T},i}^2$$

• Recursively cluster *k*+1 to *k* momenta with smallest distance:

$$d_k = \min_{i,j}(d_{ij}, d_{ib})$$

- Zeroth order splitting scale d_o is leading jet p_T
- Higher orders probe further QCD evolution



• Z boson just used as a trigger \rightarrow clean testbed with high purity:

	$Z \rightarrow e^+ e^-$		$Z \rightarrow \mu^+ \mu^-$	
Process	Expected events	Contribution (%)	Expected events	Contribution (%)
QCD Z + jets	5 090 000	98.93 %	7 220 000	99.40 %
Multijet	42 000	0.81 %	25 000	0.34 %
Electroweak $Z + jets$	5 3 5 0	0.10%	7 3 4 0	0.10 %
Top quarks	6 1 9 0	0.12 %	8440	0.12 %
W(W)	1 100	0.02 %	1460	0.02 %
$Z \rightarrow \tau^+ \tau^-$	1 100	0.02 %	1 700	0.02 %
Total	5 150 000	100.00 %	7 260 000	100.00 %
Observed events	5 196 858		7 349 195	

- Particle level selection mimicks reconstructed detector level
 - Z candidate 71 GeV < m_{\parallel} < 111 GeV with dressed leptons
 - » $p_T^{lepton} > 25 \text{ GeV}$
 - » $|\eta_e| < 2.47$ excluding $1.37 < |\eta_e| < 1.52$ and $|\eta_u| < 2.4$
 - Charged particles with $p_T > 400$ MeV and $|\eta| < 2.5$, excluding Z candidate



- Similar backgrounds for $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$: mainly tops and multijets
 - Multijets estimated with data-driven approach
 - All other backgrounds from Monte Carlo simulation





Results

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- Iterative Bayesian unfolding of background-subtracted data
- Comparison to state-of-the-art Monte Carlo predictions
 - Z + 0,1,2jets@NLO + 3,4jets@LO (Sherpa 2.2 MEPS@NLO)
 - Z + 0j@NNLO (Powheg NNLOPS)







- Wealth of results with W, Z, photons and jets
 - → Allow for testing of pure QCD processes or QCD corrections in clean $\gamma/W/Z$ testbed
 - \rightarrow Generally good agreement with theoretical predictions
 - → Some regions of disagreement: calculations insufficient and opportunities for tuning of MC generators
- ATLAS provides Rivet analyses for all published measurements
 - \rightarrow Make use of them for your pheno studies!
- Still interesting measurements from 8 TeV data coming out, but also look forward to 13 TeV measurements with larger 13 TeV dataset

Thank you for your attention!



Backup material



- Experimental uncertainties:
 - Track reconstruction efficiency [~5%]
 - \rightarrow estimated with distorted geometry
 - Lepton efficiencies/momentum [~1%]
 - (Luminosity [1.9%])
- Unfolding
 - Generator model (prior) [dominant]
 - Number of iterations [negligible]
 - Closure differences [negligible]
- Statistical uncertainties
 - Not limited by data statistics anywhere





- Distributions also available for k_T clustering with *R=1.0*
- Different sensitivity to hadronisation and UE



- + analytical comparisons
- larger unfolding uncertainties

