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Soft and hard QCD processes in ATLAS

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Emmy Noether-Programm Deutsche Forschungsgemeinschaft DFG One QCD to rule them all...

- hard jet production and evolution
- hadronisation and soft processes

... measured in many different final states by the ATLAS detector!











Standard Model Production Cross Section Measurements

Status: July 2017



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~ all ATLAS measurements are corrected to particle level



m_{ii} [GeV]



Measurements related to non-perturbative QCD

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poster by Rafal

 \rightarrow talk by Oleg

- many aspects of non-perturbative QCD studied in ATLAS
- often important input for our simulation of hard processes
 - multiple parton interactions in MC generators
 - minimum-bias simulation in pile-up
- often very specialised measurements, e.g.
 - diffractive production, ---- poster by Sabina
 - elastic/inelastic proton-proton cross section,
 - Bose-Einstein correlations,
 - central exclusive production,
 - double parton scattering, ...
- here one recent example: Underlying Event





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 $p_{\gamma} > 500 \text{ MeV}$ and $|\eta| < 2.5$













Measurements in pure jet production

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Probing QCD properties in jet processes:

- jet production rates as function of p_T, rapidity, masses, ...
- event shapes in pure QCD events
- substructure of jets



Jet production in ATLAS





• reconstructed jets \neq jets built from true particles





Inclusive and dijet production







- jet energy uncertainties dominant:
 - scale (= shift)
 - resolution (= width)
- 5% accuracy over large range!

non-perturbative corrections for
 comparison with fixed-order theory
 significant differences between MC's
 → limited accuracy for exp vs. theory





- event shapes were measured extensively in e+e- collisions for QCD studies
- **Transverse Energy-Energy Correlations** measured now with 8 TeV ATLAS data
- different phase space regions in $H_{T2} = p_T(jet1) + p_T(jet2)$
- discriminating power between different parton showers
 → generally doing quite well





• extract α_s from fit to TEEC at different H_{T2} scales:

$$\chi^{2}(\alpha_{\rm s},\vec{\lambda}) = \sum_{\rm bins} \frac{(x_{i} - F_{i}(\alpha_{\rm s},\vec{\lambda}))^{2}}{\Delta x_{i}^{2} + \Delta \xi_{i}^{2}} + \sum_{k} \lambda_{k}^{2}$$

theory input including $\alpha_{s}(m_{z})$ and evolved with NLO RGE



• result:

 $\alpha_{\rm s}(m_Z) = 0.1162 \pm 0.0011 \text{ (exp.)} ^{+0.0076}_{-0.0061} \text{ (scale)} \pm 0.0018 \text{ (PDF)} \pm 0.0003 \text{ (NP)}$



- measuring jets beyond just momenta: shape & substructure
- tricky with large pile-up contaminations \rightarrow "old" 7 TeV data



Energy fraction of charged particles in jets





ATLAS

 $vs = 8 \text{ TeV}, L_{int} = 20.3 \text{ fb}^{-1}$

• 2012 Data

— Pythia 8.175 CT10 AU2 - - Herwig++ 2.63 CTEQ6L1 EE3

▼ 50 GeV < p_ < 100 GeV

20

23

100 GeV < p_T < 200 GeV
 1 TeV < p_T < 1.2 TeV

 $\frac{1}{N} \frac{dN}{dn_{track}}$

0.1

- most simple jet substructure: number of particles in jet
- here: tracks as proxy for (charged) particles
- recently used to build a "quark/gluon jet tagger":





Probing QCD in processes with colourless particles

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- 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, $p_T > 30$ 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





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_0 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

- 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)



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 isolation requirements: suppress non-prompt background, limit sensitivity to uncertain fragmentation component





- ("naive" cone isolation → not IR safe)
 experimental cone isolation
 - **limit** additional energy in **fixed** ΔR cone
 - main isolation requirement used in our measurements
- smooth cone isolation [Frixione, 1998]
 - **veto** additional energy in **dynamical** cone
 - completely discards fragmentation component in predictions
 - \rightarrow **convenient for fixed-order** calculations
 - not feasible in experiment
 - \rightarrow "incomplete" comparison ...



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







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ratio to best theory

Bonus: Monte-Carlo tuning in ATLAS

Tuning aspects of event generators

- Pile-up simulation
 - multiple simultaneous proton-proton collisions modelled with event generators for very inclusive inelastic collisions
 - tuning to data obtained with very inclusive triggers (minimum bias)
- Calibration
 - e.g. jet/tau identification and reconstruction (substructure)
- Unfolding
 - correction for detector effects using generator truth vs. full detector simulation
 - **dependence on truth model** typically small, but still adds to systematic uncertainties → need reliable tunes
- Background estimates in analyses
 - analyses use **background subtraction from MC generators** directly or via extrapolation from control regions
 - reliable tuning of non-perturbative aspects necessary for precision measurements and discoveries!

- even more so for Pythia 8 with interleaved shower+MPI
- **simultaneous** tuning necessary
- Tuning with comprehensive ATLAS dataset:
 - UE with jets and track-jets
 - jet structure (track jet properties; jet shapes, masses, substructure)
 - jet production (jet multiplicities, $\Delta \Phi$, Z pT, gap fractions in ttbar)
 - \rightarrow Sensitivity to MPI, final and initial state radiation

- Significant improvement over AU2 & Monash in ttbar and Z
- Damped shower reduces tension between ttbar and Z

ATL-PHYS-PUB-2014-021

 Restricted to p_T(Z)<50 GeV in tuning

ATL-PHYS-PUB-2014-021

- Systematic variation tunes for A14-NNPDF done using Professor eigentunes approach
 - normally: 2 variations for each parameter (up/down), with fixed $\Delta \chi^2$
- 20 variations too unwieldy → reduced to variation sets for UE activity, jet structure, jet production (3 options)

Param	+ variation	- variation		
VAR1: MPI+CR (UE activity and incl jet shapes)				
BeamRemnants:reconnectRange	1.73	1.69		
MultipartonInteractions:alphaSvalue	0.131	0.121		
VAR2: ISR/FSR (jet shapes and substructur	e)			
SpaceShower:pT0Ref	1.60	1.50		
SpaceShower:pTdampFudge	1.04	1.08		
TimeShower:alphaSvalue	0.139	0.111		
VAR3a: ISR/FSR (tt gap)				
MultipartonInteractions:alphaSvalue	0.125	0.127		
SpaceShower:pT0Ref	1.67	1.51		
SpaceShower:pTdampFudge	1.36	0.93		
SpaceShower:pTmaxFudge	0.98	0.88		
TimeShower:alphaSvalue	0.136	0.124		
VAR3b: ISR/FSR (jet 3/2 ratio)				
SpaceShower:alphaSvalue	0.129	0.126		
SpaceShower:pTdampFudge	1.04	1.07		
SpaceShower:pTmaxFudge	1.00	0.83		
TimeShower:alphaSvalue	0.114	0.138		
VAR3c: ISR ($t\bar{t}$ gap, dijet decorrelation and	Z-boson p _T)			
SpaceShower:alphaSvalue	0.140	0.115		

Conclusions

Take-home messages:

- ~ all measurements in ATLAS are sensitive to QCD
- important: clean definition of observables at the particle level, without introducing model dependence
- experimental uncertainties often rival or beat theoretical precision ↔ lots of interplay
- QCD measurements are no discovery channels, but probably no future discovery will come without understanding of QCD basics
 - Go and have fun measuring + calculating QCD effects!