# Probing PDFs and soft QCD at the LHC 

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## Introduction

## QCD is complex:

Fixed order perturbative calculations:

- Hard scattering

Perturbative series resummation
(DGLAP, BFKL):

- Parton shower
- Parton density function (PDF) evolution

Non-perturbative:

- PDF values
- Underlying event
- Hadronisation
- Multi-parton interactions

LHC gives access to new regimes of all QCD processes

This talk is dedicated to measurements sensitive
to non-perturbative QCD domain

## ATLAS and CMS detectors



## Soft QCD

## Soft QCD: introduction I

Study of QCD processes in the region where calculations from first principles are not developed

- Input for tuning of phenomenological MC models to better describe data

Good quantitative description of soft QCD processes is very important for pileup modelling

- Good understanding of detectors in high-pileup environment
- Understanding of QCD backgrounds

Impossible to perform soft-QCD studies with high pileup

- Primary tracks are contaminated with tracks from pileup
- Special low-pileup runs are needed

Low-pileup LHC data taken in Runll:

- "LHCf run" (June 9-13, O(10nb-1))
- VdM scans (Aug 24-25, O(10nb-1))
- Some dedicated runs with separated beams


## Soft QCD: introduction II

LHC provides data for cosmic ray MC tuning

## Wide variety of observables:

Cross-section, soft particle production, diffraction

LHC energy overcomes "knee" at cosmic ray spectrum



Total inelastic cross-section is of particular importance for correct atmospheric shower development description

Preliminary 13 TeV cross-section measurement from ATLAS

## On the next few slides:

- Soft particle production
- Underlying event
[Soft particle production in the presence of the hard probe]
- 2-particle correlations
- Bose-Einstein correlations


## CMS 13 TeV dN/dq measurement



Measured with 0 B-field
Two complimentary methods Tracks (counting straight tracks) Tracklets (counting pairs of hits)

First LHC publication at 13 TeV
Special run taken june 7th, $<$ PU>~0.05

ZeroBias trigger


Data is very well described by EPOS LHC (cosmic ray MC)

## ATLAS soft particle production

Preliminary results for wide variety of observables were obtained by ATLAS with first 13 TeV data
$170 \mu b^{-1},<$ PUU $>\sim 0.005$,
MinimumBias trigger, offline track pT $>500 \mathrm{MeV}$


None of MC describes multiplicity well
EPOS shows best agreement for $\mathrm{dN} / \mathrm{dn}$ and $\mathrm{pT}_{T}$

## Underlying event

## Preliminary uncorrected results at 13 TeV from ATLAS Same dataset as on the previous slide Leading track рт > 1 GeV

EPOS fails as the hardness of the probe increases
PYTHIA and HERWIG++ show better agreement


None of MC show drastic disagreement with data

## 2-particle correlations (ridge)

## CMS 7 TeV



First observation of ridge in pp


Preliminary ATLAS result at 13 TeV

$$
\begin{gathered}
14 \mathrm{nb}^{-1}, 0.002<\mathrm{PU}<0.04 \\
\text { MinBias trigger, } \\
\text { High-multiplicity trigger } \\
(>60 \text { tracks, } \mathrm{PT}>0.4 \mathrm{GeV})
\end{gathered}
$$

First probe of the ridge at 13 TeV


## Bose-Einstein correlations




Studies of correlations of identical boson can give information about the size of production region (R)

Size R increases with increase of multiplicity
CMS: similar size in pp, pPb and PbPb reactions at low multiplicity

ATLAS observed saturation of $R$ for $n_{\text {ch }}>55$


## Soft QCD summary

First 13 TeV measurements start to appear MC generators tuned using Run I data
show reasonable agreement with13 TeV results

Find more details in SM-QCD 3 parallel talks:
ATLAS: Stewart Martin-Haugh
CMS: Ekaterina Kuznetsova

PDF probes

## PDF probes: introduction I

Knowledge of PDF is necessary for calculation of any process at hadron collider

PDFs are determined from fits to various observables using LO, NLO or NNLO calculations

LHC provides an access to previously unexplored parton kinematics region

## PDF probes: introduction II

A number of PDF sets is available
Different in fitting method and data used

Large PDF uncertainty in high-x region: Limitation for BSM
heavy mass searches
PDF uncertainty in medium mass region is a limiting factor for precise SM parameter studies

Good knowledge of PDFs in low-x region is important for pQCD resummation tests


S. Dulat et. al. (CIFQ), arKiv:1506.0'7443

# PDF probes: introduction III <br> Large number of ATLAS and CMS Run I measurements can be used to constrain PDF's <br> <br> CMS 

 <br> <br> CMS}

## ATLAS

| Measurement | $\sqrt{s}$, year of data, $\mathcal{L}_{\text {int }}$ |
| :---: | :---: |
| $W, Z$ rapidity | 7 TeV , 2010, $36 \mathrm{pb}^{-1}$ |
| High mass Drell-Yan | 7 TeV , 2011, $4.9 \mathrm{fb}^{-1}$ |
| Low mass Drell-Yan | $7 \mathrm{TeV}, 2011+2010,1.6 \mathrm{fb}^{-1}+35 \mathrm{pb}^{-1}$ |
| $Z A_{F B}$ | 7 TeV , 2011, $4.8 \mathrm{fb}^{-1}$ |
| $W$ +charm production | 7 TeV , 2011, $4.6 \mathrm{fb}^{-1}$ |
| $W$ +beauty production | 7 TeV , 2010, $35 \mathrm{pb}^{-1}$ |
| $W$ +beauty production | 7 TeV , 2011, $4.6 \mathrm{fb}^{-1}$ |
| $Z+$ beauty production | 7 TeV , 2010, $36 \mathrm{pb}^{-1}$ |
| $Z+$ beauty production | 7 TeV , 2011, $4.6 \mathrm{fb}^{-1}$ |
| $Z \mathrm{p}_{T}$ | 7 TeV , 2010, $40 \mathrm{pb}^{-1}$ |
| $Z \mathrm{p}_{T}$ | 7 TeV , 2011, $4.7 \mathrm{fb}^{-1}$ |
| $W \mathrm{p}_{T}$ | $7 \mathrm{TeV}, 2010,31 \mathrm{pb}^{-1}$ |
| $Z+$ jets | 7 TeV , 2010, $36 \mathrm{pb}^{-1}$ |
| $Z+$ jets | 7 TeV , 2011, $4.6 \mathrm{fb}^{-1}$ |
| $W+$ jets | 7 TeV , 2010, $36 \mathrm{pb}^{-1}$ |
| $W+$ jets | 7 TeV , 2011, $4.6 \mathrm{fb}^{-1}$ |
| $R_{\text {jets }}(W+$ jets $/ Z+$ jets $)$ | 7 TeV , 2011, $4.6 \mathrm{fb}^{-1}$ |
| Inclusive jets | 7 TeV , 2010, $37 \mathrm{pb}^{-1}$ |
| Inclusive jets | 7 TeV , 2011, $4.5 \mathrm{fb}^{-1}$ |
| Inclusive jets (+7 TeV ratio) | 2.76 TeV , 2010, $0.2 \mathrm{pb}^{-1}$ |
| Dijets | 7 TeV , 2010, $37 \mathrm{pb}^{-1}$ |
| Dijets | 7 TeV , 2011, $4.6 \mathrm{fb}^{-1}$ |
| Trijets | 7 TeV , 2011, $4.5 \mathrm{fb}^{-1}$ |
| $\gamma$ inclusive production | 7 TeV , 2010, $35 \mathrm{pb}^{-1}$ |
| $\gamma$ inclusive production | 7 TeV , 2011, $4.6 \mathrm{fb}^{-1}$ |
| $\gamma+$ jets | $7 \mathrm{TeV}, 2010,37 \mathrm{pb}^{-1}$ |
| $t \bar{t}$ incl (single lepton, dilepton) | $7 \mathrm{TeV}, 2010,2.9 \mathrm{pb}^{-1}$ |
| $t \bar{t}$ incl (dilepton) | 7 TeV , 2010, $35 \mathrm{pb}^{-1}$ |
| $t \bar{t}$ incl (single lepton) | $7 \mathrm{TeV}, 2010,35 \mathrm{pb}^{-1}$ |
| $t \bar{t}$ incl (dilepton) | 7 TeV , 2011, $0.70 \mathrm{fb}^{-1}$ |
| $t \bar{t} \mathrm{incl}(\mathrm{e} / \mu+\tau)$ | 7 TeV , 2011, $2.05 \mathrm{fb}^{-1}$ |
| $t \bar{t}$ incl (tau+jets) | $7 \mathrm{TeV}, 2011,1.67 \mathrm{fb}^{-1}$ |
| $t \bar{t}$ incl (e $\mu$ b-tag jets) | $7+8 \mathrm{TeV}, 2012,24.9 \mathrm{fb}^{-1}$ |
| $t \bar{t}$ differential | 7 TeV , 2011, $2.05 \mathrm{fb}^{-1}$ |
| $t \bar{t}$ differential | 7 TeV , 2011, $4.6 \mathrm{fb}^{-1}$ |
| $W W, Z \rightarrow \tau \tau, t \bar{t} \mathrm{xsec}$ | 7 TeV , 2011, $4.6 \mathrm{fb}^{-1}$ |


| Measurement | $\sqrt{s}, \mathcal{L}_{\mathrm{int}}$ |
| :--- | :--- |
|  |  |
| High and low mass Drell-Yan | $7 \mathrm{TeV}, 5 \mathrm{fb}^{-1}$ |
| High and low mass Drell-Yan | $8 \mathrm{TeV}, 20 \mathrm{fb}^{-1}$ |
| Drell-Yan AFB | $7 \mathrm{TeV}, 5 \mathrm{fb}^{-1}$ |
| $W$ asymmetry | $7 \mathrm{TeV}, 36 \mathrm{pb}^{-1}$ |
| $W$ e asymmetry | $7 \mathrm{TeV}, 880 \mathrm{pb}^{-1}$ |
| $W \mu$ asymmetry | $7 \mathrm{TeV}, 4.7 \mathrm{fb}^{-1}$ |
| $W, Z$ production and rapidity | $7 \mathrm{TeV}, 3 \mathrm{pb}^{-1}$ |
| $W, Z$ inclusive production | $7 \mathrm{TeV}, 36 \mathrm{pb}^{-1}$ |
| $W, Z$ inclusive production | $8 \mathrm{TeV}, 19 \mathrm{pb}^{-1}$ |
| $Z p_{T}$ and rapidity | $7 \mathrm{TeV}, 36 \mathrm{pb}^{-1}$ |
| $Z p_{T}$ and rapidity | $8 \mathrm{TeV}, 19.7 \mathrm{fb}^{-1}$ |
| Inclusive jets | $7 \mathrm{TeV}, 5 \mathrm{fb}^{-1}$ |
| Dijets | $7 \mathrm{TeV}, 5 \mathrm{fb}^{-1}$ |
| Three-jets | $7 \mathrm{TeV}, 5 \mathrm{fb}^{-1}$ |
| Three-jets/Di-jets ratio | $7 \mathrm{TeV}, 5 \mathrm{fb}^{-1}$ |
| $W+$ charm | $7 \mathrm{TeV}, 5 \mathrm{fb}^{-1}$ |
| $Z+$ beauty | $7 \mathrm{TeV}, 5 \mathrm{fb}^{-1}$ |
| $\gamma$ inclusive production | $7 \mathrm{TeV}, 36 \mathrm{pb}^{-1}$ |
| $\gamma+$ jets | $7 \mathrm{TeV}, 2.1 \mathrm{fb}^{-1}$ |
| $t \bar{t}$ inclusive | $7 \mathrm{TeV}, 2.3 \mathrm{fb}^{-1}$ |
| $t \bar{t}$ differential | $7 \mathrm{TeV}, 5.0 \mathrm{fb}^{-1}$ |
| $t \bar{t}$ inclusive | $8 \mathrm{TeV}, 1.14 \mathrm{fb}^{-1}$ |
| $t \bar{t}$ inclusive | $8 \mathrm{TeV}, 2.8 \mathrm{fb}^{-1}$ |
| $t \bar{t}$ inclusive | $t \bar{t}$ differential |

Selected measurement are presented in this talk

More details in SM-QCD 2 parallel talks:

ATLAS: Mark Stockton
CMS: Matthias Arthur Weber

Comprehensive review of LHC data impact on PDF fits:

## Selected measurements are presented in this talk:

Inclusive jet cross-section and cross-section ratios Inclusive vector boson production W+charm production
Drell-Yan production
Top pair production cross-section

## Inclusive jet production I

Inclusive jet production cross-section - an important class of observables used for PDF fits

- Constraint on quark and gluon PDFs in wide range of $x$ and $Q^{2}$

High statistics ATLAS and CMS measurements of inclusive jet cross-section on the full 7 TeV datasets are available $\rightarrow$ up to 2 TeV reach in $\mathrm{p}_{\mathbf{T}}$
[ATLAS: doi:10.1007/JHEPO2(2015)153]
[CIMS: doi:10.1103.PhysRevD.87.112002]
Preliminary CMS measurement at 8 TeV [CIVS-PAS-FSQ-12-031, CIVS-PAS-SIMP-12-012]

Preliminary ATLAS measurement at 13 TeV [ATLAS-CONF-2015-034]

Dijet/Trijet measuments:
ATLAS: doi:10.1140/epjc/s10052-015-3363-3
doi:10.1007/JHEP05 (2014)059
CIVS 2015, doi:10.1140/epjc/s10052-015-3576-y

[ATLAS-CONF-2015-034]
CMIS-PAS-FSQ-12-031


## Inclusive jet production II



CMS, 7 TeV, $5 \mathrm{fb}^{-1}$ inclusive jets

## NLO PDF fit

- Combined with HERA I inclusive DIS cross-sections
- HERAfitter framework

Significant constraint on gluon PDF in large-x region



## Jet production ratios I

Ratios of inclusive jet cross-section at different energies First performed by ATLAS with 20117 TeV and 2.76 TeV data (0.2 pb-1)



ATLAS
$\int L \mathrm{dt}=0.20 \mathrm{pb}^{-1}$
$\rho=\sigma_{\text {jet }}^{2.76 \mathrm{TeV}} / \sigma_{\text {jet }}^{7 \mathrm{TeV}}$
anti- $k_{t} \mathrm{R}=0.6$
Data with
$\rightarrow$ statistical uncertainty
Systematic uncertainties
NLO pQCD $\otimes$
non-pert. corrections

CT10
......" HERA+ATLAS
-=- HERAI
Correlated systematics is reduced (JES)
NLO PDF fit is performed to test constraint potential wrt. HERA data

## Jet production ratios II

Preliminary CMS ratio measurement with 8 TeV and 2013 2.76 TeV pp run ( $5.43 \mathrm{pb}^{-1}$ )

Compared to NLO $\otimes N P$ predictions with different PDF sets

Best agreement is demonstrated by CT10 set





## Inclusive W, Z production

## Cross section is used in PDF fits since Tevatron <br> Constraint on quark content

## Preliminary result for inclusive W,Z production at 13 TeV is available from ATLAS

Ratio of $\mathrm{W}+/ \mathrm{W}$ - sensitive to difference of u and d quarks, $W \pm / Z$ to strange quark contribution

| $\quad$ W: | Z: |
| :--- | :--- |
| - $p_{\mathrm{T}}^{\ell}>25 \mathrm{GeV}$ | - $p_{\mathrm{T}}^{\ell}>25 \mathrm{GeV}$ |
| - $p_{\mathrm{T}}^{v}>25 \mathrm{GeV}$ | - $\left\|\eta_{\ell}\right\|<2.5$ |
| - $\left\|\eta_{\ell}\right\|<2.5$ | - $66<m_{\ell \ell}<116 \mathrm{GeV}$ |
| - $m_{\mathrm{T}}>50 \mathrm{GeV}$ |  |



## W + charm production I



Cross-section charge asymmetry is sensitive to difference between s and sbar content


## W + charm production II



Strange quark PDF enhancement consistent with result from W, Z x-sec fit (ATLAS-epWZ12):

ATLAS, full 7 TeV dataset
Fit of differential $x$-sec with HERAPDF1.5 set with free $f_{s}$ parameter

$$
r_{s} \equiv 0.5(s+\bar{s}) / \bar{d}=f_{s} /\left(1-f_{s}\right)
$$



Discrepancy with CMS fit results doi:10.1103/PhysRevD.90.032004

## Drell-Yan production



CMS measurement: full 2012 data sample, $19.7 \mathrm{fb}^{-1}$

Differential and double-differential cross-sections and
cross-section ratios
doi: 10.1007/JHEP06(2014)112


ATLAS Iow-mass DY

Double ratio -
cancelation of uncertainties (based on doi:10.100\%/JHEP12(2013)030)

$$
R\left(\mathrm{pp} \rightarrow \gamma^{*} / \mathrm{Z} \rightarrow \ell^{+} \ell^{-}\right)=\frac{\left(\frac{1}{\sigma_{\sigma}} \frac{\mathrm{d} \sigma}{\mathrm{~d} m}\right)(8 \mathrm{TeV})}{\left(\frac{1}{\sigma_{\mathrm{Z}}} \mathrm{~d} \sigma \tilde{d}\right)(7 \mathrm{TeV})}
$$

Good constraining power for quark PDF for $0.001<x<0.1$

## Top pair production cross-section

Constraint for gluon PDF with large x complimentary to inclusive jets

Many measurements from
Runl at ATLAS and CMS


Recent Run II results:

ATLAS-CONF-2015-033 ATL-PHYS-PUB-R015-017

CIVS-PAS-TOP-15-005 CIMS-PAS-TOP-15-010

## Conclusions

## CMS and ATLAS collaborations deliver first soft QCD results from 13 TeV collisions

A wide variety of measurements probing PDFs were performed in Runl; Many of them were used in global PDF fits

PDF-sensitive measurements at 13 TeV from Run II start to appear

## BACKUP

## Diffractive processes



