# Probing PDFs and soft QCD at the LHC

Grigory Safronov (ITEP NRC KI, Moscow)

on behalf of the ATLAS and CMS collaborations

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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 RunII:

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



#### CMS Integrated Luminosity, pp, 2015, $\sqrt{s}=$ 13 TeV

### 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

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### 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/dŋ measurement



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

Submitted

IXIV:1507.05915

# **ATLAS soft particle production**

Preliminary results for wide variety of observables were obtained by ATLAS with first 13 TeV data

170  $\mu$ b<sup>-1</sup>, <PU>~0.005, MinimumBias trigger, offline track p<sub>T</sub> > 500MeV



EPOS shows best agreement for dN/dŋ and  $p_T$ 

TLAS-CONF-2015-02

# **Underlying event**

Preliminary uncorrected results at 13 TeV from ATLAS Same dataset as on the previous slide Leading track previous 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

ash

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### 2-particle correlations (ridge)



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ATL/

ATLAS-COI





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







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### Soft QCD summary

First 13 TeV measurements start to appear

MC generators tuned using Run I data show reasonable agreement with 13 TeV results

Find more details in SM-QCD 3 parallel talks:

ATLAS: Stewart Martin-Haugh CMS: Ekaterina Kuznetsova

### **PDF probes**

### PDF probes: introduction I

### NNPDF 3.0 set:

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



### **PDF probes: introduction III**

### Large number of ATLAS and CMS Run I measurements can be used to constrain PDF's

### **ATLAS**

### CMS

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

Measurement	$\sqrt{s}, \mathcal{L}_{ ext{int}}$
High and low mass Drell-Yan	7 TeV, 5 fb $^{-1}$
High and low mass Drell-Yan	8 TeV, 20 fb $^{-1}$
Drell-Yan AFB	7 TeV, 5 fb $^{-1}$
W asymmetry	7 TeV, 36 $pb^{-1}$
W e asymmetry	7 TeV, 880 $pb^{-1}$
$W \mu$ asymmetry	7 TeV, $4.7 \text{ fb}^{-1}$
W, Z production and rapidity	7 TeV, 3 $pb^{-1}$
W, Z inclusive production	7 TeV, 36 $pb^{-1}$
W, Z inclusive production	8 TeV, 19 $pb^{-1}$
$Z p_T$ and rapidity	7 TeV, 36 $pb^{-1}$
$Z p_T$ and rapidity	8 TeV, 19.7 $fb^{-1}$
Inclusive jets	7 TeV, 5 $fb^{-1}$
Dijets	7 TeV, 5 fb $^{-1}$
Three-jets	7 TeV, 5 fb $^{-1}$
Three-jets/Di-jets ratio	7 TeV, 5 fb $^{-1}$
W+charm	7 TeV, 5 $fb^{-1}$
Z+beauty	7 TeV, 5 fb $^{-1}$
$\gamma$ inclusive production	7 TeV, 36 $pb^{-1}$
$\gamma$ +jets	7 TeV, 2.1 $fb^{-1}$
$t\bar{t}$ inclusive	7 TeV, $2.3 \text{ fb}^{-1}$
$t\bar{t}$ differential	7 TeV, $5.0 \text{ fb}^{-1}$
$t\bar{t}$ inclusive	8 TeV, 1.14 fb $^{-1}$
$t\bar{t}$ inclusive	8 TeV, $2.8 \text{ fb}^{-1}$
$t\bar{t}$ inclusive	8 TeV, 2.4 $fb^{-1}$
$t\bar{t}$ differential	8 TeV, 19.7 fb $^{-1}$

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:

J. Rojo et. al. (PDF4LHC workgroup), arXiv:1507.00556

### 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<sup>2</sup>

High statistics ATLAS and CMS measurements of inclusive jet cross-section on the full 7 TeV datasets are available → up to 2 TeV reach in p<sub>T</sub> [ATLAS: doi:10.1007/JHEP02(2015)153] [CMS: doi:10.1103.PhysRevD.87.112002]

> Preliminary CMS measurement at 8 TeV [CMS-PAS-FSQ-12-031, CMS-PAS-SMP-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 CMS 2015, doi:10.1140/epjc/s10052-015-3376-y

#### CMS-PAS-FSQ-12-031



#### [ATLAS-CONF-2015-034]



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# Inclusive jet production II



CMS, 7 TeV, 5fb<sup>-1</sup> inclusive jets

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

### Significant constraint on gluon PDF in large-x region



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#### <sup>30 40</sup> 10<sup>2</sup> 2×10<sup>2</sup> p<sub>τ</sub> [GeV] Jet production ratios I

Ratios of inclusive jet cross-section at different energies First performed by ATLAS with 2011 7 TeV and 2.76 TeV data (0.2 pb<sup>-1</sup>)



### Jet production ratios II

Preliminary CMS ratio measurement with 8 TeV and 2013 2.76 TeV pp run (5.43 pb<sup>-1</sup>)

Compared to NLO⊗NP predictions with different PDF sets

Best agreement is demonstrated by CT10 set



Exp. Uncertainty

# Inclusive W, Z production

Cross section is used in PDF fits since Tevatron Constraint on quark content

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

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Ratio of W+/W- sensitive to difference of u and d quarks, W±/Z to strange quark contribution

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- $p_{\rm T}^{\ell} > 25 \, {\rm GeV}$
- $p_{\rm T}^{\nu} > 25 \text{ GeV}$
- $|\eta_\ell| < 2.5$
- $m_{\rm T} > 50 {\rm ~GeV}$

- **Z:** •  $p_{\rm T}^{\ell} > 25 \, {\rm GeV}$
- $|\eta_\ell| < 2.5$
- $66 < m_{\ell\ell} < 116 \, \text{GeV}$





ATLAS-CONF-2015-03

### W + charm production I





### **Drell-Yan production**



# **Top pair production cross-section**

### Constraint for gluon PDF with large x complimentary to inclusive jets



### Many measurements from RunI at ATLAS and CMS



### **Recent Run II results:**

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

#### CMS-PAS-TOP-15-005 CMS-PAS-TOP-15-010

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### 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**



Diffractive processes constitute ~20% of inelastic cross-section

Many measurements by CMS and ATLAS

ATLAS 2012, <u>doi: 10.1140/epjc/s10052-012-1926-0</u> CMS 2015, <u>doi: 10.1103/PhysRevD.92.012003</u> CMS 2013, doi: <u>10.1103/PhysRevD.87.012006</u>

# **Exclusive yy interactions**

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Lepton production: **ATLAS 2015**, <u>doi:10.1016/j.physletb.2015.07.069</u> **CMS 2012**, <u>doi:10.1007/JHEP01(2012)052</u>

Exclusive WW pair production: **CMS 2013**, <u>doi:10.1007/JHEP07(2013)116</u> **CMS 2015 (preliminary)**, <u>CMS-PAS-FSQ-13-008</u>

