

# **QCD@LHC 2015, London**

Tuesday 01 September 2015 - Saturday 05 September 2015

Queen Mary University of London

## **Book of Abstracts**



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## **Welcome**

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## **Introduction**

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## **LHC Experimental Overview and Prospects (50+10)**

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## **Theoretical Developments in Hard QCD Predictions (50+10)**

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## **Recent QCD results from the LHC**

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## **Soft QCD and multi-parton interactions**

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## **Soft QCD measurements from the LHC**

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**Heavy Quarks / 60****Heavy flavour production with the ATLAS experiment****Author:** Arnaud Ferrari<sup>1</sup>**Co-author:** Cristobal Padilla Aranda<sup>2</sup><sup>1</sup> *Uppsala University (SE)*<sup>2</sup> *IFAE-Barcelona (ES)***Corresponding Author:** david.b@cern.ch

ATLAS has a wide programme to study the production cross section and decay properties of particles with beauty, as well as charmonium and bottomonium states. This presentation will cover ATLAS results in the domain of charmonium production, including J/psi, psi(2s), chi\_c and chi\_b states as well as the X(3872) resonance, using full Run-1 ATLAS dataset and extending upon previous measurements in precision and kinematic reach, but we also present the first quarkonia production results at 13 TeV collisions. In addition we report an updated measurement of the inclusive D(\*) meson cross-section. Results of the measurements are compared with the latest theoretical predictions from a variety of theoretical approaches.

**PDFs / 14****MMHT14 PDFs: updates and outlook (20+10min)****Authors:** Alan Martin<sup>None</sup>; Lucian Harland-Lang<sup>1</sup>; Patrick Motylinski<sup>1</sup>; Robert Samuel Thorne<sup>2</sup><sup>1</sup> *University College London*<sup>2</sup> *University College London (UK)***Corresponding Author:** l.harland-lang@ucl.ac.uk

We present the MMHT14 PDFs, an update of the previous major release in the same framework, i.e. MSTW08. We discuss the changes in both the central values and uncertainties in the PDFs due to changes in theoretical procedures and the impact of new, largely LHC data-sets. We note, however, that changes in predictions are rather small. We discuss the correlation between the PDFs and the strong coupling constant and the constraint on the latter. We also highlight plans for the future.

**Hard QCD / 54****Measurements of jet and photon production in pp collisions with the ATLAS detector (20+10min)****Author:** Arnaud Ferrari<sup>1</sup>**Co-author:** Cristobal Padilla Aranda<sup>2</sup><sup>1</sup> *Uppsala University (SE)*<sup>2</sup> *IFAE-Barcelona (ES)*

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Cross sections for jet and isolated photon production in pp collisions have been measured by the ATLAS collaboration at 7 and 8 TeV. Double-differential cross sections for inclusive, di, and tri-jet final states are measured and compared to expectations based on next-to-leading order QCD calculations as well as to next-to-leading order Monte Carlo simulations. First LHC Run2 results will be included if available. Cross-sections for four-jet production in 8 TeV pp collisions are measured differentially in a variety of kinematic variables, and are compared to a range of leading order Monte Carlo calculations as well as to state-of-the-art next-to-leading order fixed-order calculations. The observables studied include the momenta, masses, minimum and maximum angles between two or three jets, amongst others. Inclusive prompt photon cross sections have been measured precisely over a wide range of transverse momenta at different centre of mass energies. These experimental results are compared to next-to-leading order QCD calculations with different models of the parton content of the proton.

**Multi-parton dynamics / 12**

## Hard Diffraction at HERA

**Authors:** Matthew Wing<sup>1</sup>; Stefan Schmitt<sup>2</sup>

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Diffraction parton densities are derived from inclusive measurements of diffraction at HERA. Their application, interfaced to next-to-leading-order QCD predictions, to other final states and processes allows the factorisation theorem to be tested in diffractive scattering. The H1 and ZEUS collaborations have made many measurements of different final states, with the most recent H1 results on dijet production presented. Results are presented for different methods of reconstructing a diffractive event and for deep inelastic scattering and photoproduction. The H1 data indicate that factorisation is not held in photoproduction processes. ZEUS has recently measured prompt photon production in diffractive photoproduction for the first time. These data should provide another handle on understanding whether factorisation is held in diffraction.

**Heavy Quarks / 76**

## Quarkonia results in heavy ions from CMS

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Quarkonia are important probes of the quark-gluon plasma since they are produced at early times and propagate through the medium, mapping its evolution. In this talk we present the latest results on quarkonium production in pPb and PbPb collisions from CMS. Selected results from measurements of nuclear modification factors, excited-to-ground state ratios, elliptic flow and forward-backward asymmetries will be shown for the J/psi, Psi(2S) and/or the Upsilon 1S, 2S and 3S.

**Hard QCD / 111**

## Measurement of the Inclusive Isolated Prompt Photon production cross section in ppbar collisions at $\sqrt{s}=1.96\text{TeV}$ using the full CDF dataset (20+10min)

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The production of photons with large transverse energy in hadronic collisions is an important testing ground for perturbative Quantum Chromodynamics (pQCD), enabling to probe parton distribution functions (PDFs) and the parton-to-photon fragmentation functions (FFs). In addition, high-ET photons can also constitute an irreducible background for important searches such as  $H \rightarrow \gamma\gamma$ , or SUSY and extra-dimensions with energetic photons in the final state.

We present the measurement of the cross section for the inclusive production of isolated prompt photons in ppbar collisions at the Tevatron, using the full dataset collected with the upgraded Collider Detector at Fermilab (CDF). Measurements are performed as a function of the photon transverse energy in the range  $30 \text{ GeV} < ET < 500 \text{ GeV}$  and pseudorapidity region  $|\eta| < 1.0$ . The results are compared to the state-of-art calculations.

Multi-parton dynamics / 53

## Results on total pp cross sections, diffractive and exclusive final states from ATLAS

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The ATLAS Collaboration has measured the t-differential elastic pp cross section in a dedicated run at 7 TeV centre-of-mass energy with the ALFA Roman Pot detector. From the extrapolation to  $t=0$  the total cross section as well as the inelastic cross section are extracted. First LHC Run2 results will be presented for the measurement of the inelastic pp cross-section using minimum bias scintillators, if available. The ATLAS collaboration has carried out a study diffractive dijet production, i.e. events with a hadronic system containing at least two jets in addition to a large region of pseudorapidity devoid of hadronic activity. The data distributions are compared with Monte Carlo models and are found to be better described by diffractive dijet production. The rapidity gap survival probability has also been estimated. The exclusive  $\gamma+\gamma > ll$  production cross-section in proton-proton collisions at a centre-of-mass energy of 7 TeV has been carried out in the electron and muon channels. Results are found to be consistent with theory calculations taking into account proton absorptive effects due to finite proton size.

PDFs / 92

## The CT14 Global Analysis of QCD (20+10min)

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The CTEQ-TEA collaboration has published their next generation global analysis of QCD, with PDFs named CT14 PDFs.

The purpose of the talk is to summarize this work, and describe some methods that we use.

The talk will include these topics:

an overview of the CT14 PDFs; the LHC data, and other new data, that has been used in the CT14 analysis; the impact of CT14 PDFs on predictions for the LHC; parametrizations; some preliminary comments on the implications of the HERA1+2 combined data.

**Heavy Quarks / 2**

## Heavy quark spectroscopy

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The latest results on heavy quark spectroscopy from LHCb experiment will be reported, including the studies on excited bottom and charm mesons and charmonium-like exotic states such as X(3872).

**Multi-parton dynamics / 52**

## Results on minimum bias interactions, underlying event and particle production from ATLAS

**Author:** Arnaud Ferrari<sup>1</sup>

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Measurements of the properties of charged particle production are presented from proton-proton collisions at different centre-of-mass energies in the range of 0.9 to 13 TeV and compared to various Monte Carlo event generator models. Furthermore particle distributions sensitive to the underlying event in proton-proton collisions have been measured and are compared to theoretical models. The production properties of mesons and baryons are presented and compared to predictions. The effects of space-time geometry in the hadronization phase has been studied in the context of Bose-Einstein correlations between charged particles, for determining the size and shape of the source from which particles are emitted and for interpreting of quark confinement effects. Bose-Einstein correlation parameters are investigated in pp collisions at 900 GeV and 7 TeV, up to very high charged-particle multiplicities.

**PDFs / 84**

## On the impact of lepton PDFs (20+10min)

**Author:** Stefano Carrazza<sup>1</sup>

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We discuss the effect of the complete leading-order QED corrections to the DGLAP equations in the perturbative evolution of parton distribution functions (PDFs). This requires the extension of the purely QCD DGLAP evolution, including a PDF for the photon and, consistently, also for the charged leptons  $e^\pm$ ,  $\mu^\pm$  and  $\tau^\pm$ . We present the implementation of the QED-corrected DGLAP evolution in the presence of photon and lepton PDFs in the APFEL program and, by means of different assumptions for the initial scale PDFs, we produce for the first time PDF sets containing charged lepton distributions. We also present phenomenological studies that aim to assess the impact of the presence of lepton PDFs in the proton for some relevant processes at the LHC 13 TeV and the FCC-hh at 100 TeV.

**Hard QCD / 96**

## Numerical multi-loop calculations based on the program SecDec (15+5min)

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New features of the program SecDec will be presented, which allow the numerical calculation of multi-scale loop integrals in a highly efficient way. Results for two-loop integrals with several mass scales will be shown to illustrate some applications of the program.

**Heavy Quarks / 61**

## Spectroscopy and decay properties with b-hadrons at the ATLAS experiment

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We present the latest results from the ATLAS experiment on hadron decays and spectroscopy, including observation of the  $B_c(2S)$  state, production of the  $B_c$  meson, branching ratio measurements of  $B_c \rightarrow J/\psi D$ , extraction of fragmentation fractions  $f_s/f_d$  via reconstructed  $B_s \rightarrow J/\psi \Phi$  and  $B_d \rightarrow J/\psi K$  decays, and studies of the decay properties of the  $\Lambda_b$ . We also present the results of searches for the  $X_b$ , the bottomonium counterpart to the  $X(3872)$  exotic charmonium state.

**Hard QCD / 46****Five-point two-loop master integrals in QCD (15+5min)****Authors:** Johannes Henn<sup>1</sup>; Nicola Adriano Lo Presti<sup>2</sup>; Thomas Gehrmann<sup>None</sup><sup>1</sup> IAS<sup>2</sup> University of Zurich**Corresponding Author:** nicolaadriano.lopresti@uzh.ch

I present recent progress in the calculation of the master integrals for the five-point amplitude at two loops in QCD, which is a crucial contribution to computation of the the next-to-next-to-leading order cross section for three-jet production at the LHC.

After a brief review of the differential-equation method for evaluating Feynman integrals, I will discuss its application to compute the two-loop planar five point Feynman integrals in QCD, the determination of the boundary values and first physical applications.

**PDFs / 120****Self Organizing Maps Parameterization of Parton Distribution Functions****Author:** Simonetta Liuti<sup>1</sup><sup>1</sup> University of Virginia**Corresponding Author:** sl4y@virginia.edu

I will discuss the application of an alternative type of neural network, the Self-Organizing Maps (SOMs), to extract parton distribution functions from various hard scattering processes. SOMs provide a complementary algorithm to NNPDFs yielding a parametrization that is free from the bias implicit in choosing specific analytic forms. At the same time it enables us to extrapolate to kinematical regions where data are not available. I will show in particular the extraction using SOMs of the ratio  $d/u$  in the  $x=1$  limit, including the treatment of nuclear effects.

**Multi-parton dynamics / 51****Associated quarkonium production at ATLAS as a new probe of QCD****Author:** Arnaud Ferrari<sup>1</sup>**Co-author:** Cristobal Padilla Aranda<sup>2</sup><sup>1</sup> Uppsala University (SE)<sup>2</sup> IFAE-Barcelona (ES)**Corresponding Author:** david.bertsche@cern.ch

We present new measurements of the associated production of quarkonium with a vector boson or an additional quarkonium state using the ATLAS Run-1 dataset. These rare processes provide new insight into QCD models of quarkonium production, but also provide new opportunities to study double parton scattering, including cross-section measurements in single and double parton

scattering dominated regimes and a precise assessment of the  $\sigma_{\text{eff}}$  parameter governing the effective spatial area of parton-parton interactions at a variety of energy scales.

**Heavy Quarks / 114**

## **LHCb early measurements focusing on B and Charm production**

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**Hard QCD / 89**

## **Color and Kinematic Decomposition for QCD Amplitudes (15+5min)**

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We work out a new color decomposition for tree amplitudes in quantum chromodynamics with flavored quarks in a reduced basis of primitive amplitudes. These primitives, with  $k$  quark-antiquark pairs and  $(n-2k)$  gluons, are taken in the  $(n-2)!/k!$  Melia basis, and are independent under the color-algebra Kleiss-Kuijf relations. This generalizes the color decomposition of Del Duca, Dixon, and Maltoni to an arbitrary number of quarks. Since the latter decomposition can be used to compute loop amplitudes, such as the two-loop amplitude with five plus-helicity gluons, the new one should also have loop-level applications. Considering the kinematic structure, we show that color-kinematics duality holds for tree amplitudes with general configurations of gluons and massive quarks. The new (massive) amplitude relations that follow from the duality can be mapped to a well-defined subset of the familiar BCJ relations for gluons. They restrict the amplitude basis further down to  $(n-3)!(2k-2)/k!$  primitives, for two or more quark lines. We give a decomposition of the full amplitude in that basis. The presented results provide strong evidence that QCD obeys the color-kinematics duality, at least at tree level.

**Plenary / 26**

## **EW corrections at high energy**

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**Plenary / 27**

## **Developments in QCD analytic resummation**

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## QCD in Higgs and BSM

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## Status of PDFs

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## Proton structure and hard QCD at HERA

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## QCD at the LHeC

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The LHeC is a proposed upgrade of the LHC to study ep/eA collisions in the TeV regime, by adding a 60 GeV electron beam through an Energy Recovery Linac. In this talk the project will be briefly reviewed and its current status presented. Then the possibilities for QCD studies: precision proton and nucleus PDFs with complete flavour decomposition for use in hadron colliders, per mille accuracy determination of the strong coupling constant, and determination of the existence of a novel non-linear regime of QCD at small x through both inclusive and diffractive observables in ep and eA, will be addressed.

HardQCD+PDFs: Joint session / 93

## Studies of PDF sensitivity relevant for ATLAS measurements (20+10min)

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Several measurements performed by the ATLAS collaboration are either useful to constrain the proton structure or are affected by its

associated uncertainties.

The strange-quark density is rather poorly known at low  $x$ . Measurements of the  $W+c$  production and the inclusive  $W$  and  $Z$  differential cross sections are found to constrain the strange-quark density. Drell-Yan cross section measurements performed above and below the  $Z$  peak region have a different sensitivity to parton flavour, parton momentum fraction  $x$  and scale  $Q$  compared to measurements on the  $Z$  peak and can also be used to constrain the photon content of the proton.

Measurements of the inclusive jet and photon cross sections are standard candles and can be useful to constrain the medium and high  $x$  gluon densities.

Precision electroweak studies performed by ATLAS can be limited by the current knowledge on the proton structure. Among those are the measurement of the effective weak mixing angle and the mass of the  $W$  boson. Dedicated PDF studies were performed by ATLAS to evaluate the impact of PDF uncertainties in these measurements.

## Heavy Quarks / 10

### **t tbar + isolated photon production at NLO accuracy matched with parton shower**

**Author:** Zoltan Laszlo Trocsanyi<sup>1</sup>

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**Corresponding Author:** zoltan.trocsanyi@cern.ch

We simulate the hadroproduction of a  $t$   $t$ bar pair in association with one or two isolated photons at the LHC using the PowHel program. The generated events are stored according to the Les-Houches event format and constitute an almost inclusive event sample (regarding the photons), so that usual experimental photon isolation can be employed. We interface those events to the PYTHIA shower Monte Carlo program, allowing for decays of massive particles, showering and hadronization, and present predictions for differential distributions at the hadron level.

## Multi-parton dynamics / 13

### **Exclusive processes at HERA**

**Authors:** Matthew Wing<sup>1</sup>; Stefan Schmitt<sup>2</sup>

<sup>1</sup> *UCL*

<sup>2</sup> *Deutsches Elektronen-Synchrotron (DE)*

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The ratio of the exclusive electroproduction of  $\psi(2S)$  and  $J/\psi$  mesons has been measured at HERA. The results are sensitive to the wave functions of the vector mesons and are compared to predictions of QCD-inspired models of vector-meson production. Exclusive dijet production in diffractive deep inelastic scattering has been measured at HERA. Cross sections are presented as a function of  $\beta$ , the Bjorken variable defined with respect to the diffractive exchange and, in bins of  $\beta$ , as a function of  $\phi$ , the angle between the  $\gamma$ -dijet plane and the  $\gamma$ -e plane in the rest frame of the dijet final state. The results are compared to predictions from models which are based on different assumptions about the nature of the diffractive exchange.

The first measurement of exclusive photoproduction of rho mesons associated with leading neutrons with the H1 detector at HERA is also presented. The data are interpreted in terms of two dominant contributions: diffractive proton dissociation channel and elastic production via virtual pion exchange.

Measurements of normalised cross sections for the production of photons and neutrons at very small angles with respect to the proton beam direction in deep inelastic scattering are presented as a function of the Feynman variable  $x_F$  and of the centre-of-mass energy of the virtual photon-proton system,  $W$ . Predictions of deep inelastic scattering models and of models for hadronic interactions of high energy cosmic rays are compared to the measured cross sections.

**Heavy Quarks / 115**

## **On NLL soft gluon corrections to the t-tbar-Higgs boson production at the LHC**

**Corresponding Author:** leszek.motyka@uj.edu.pl

**HardQCD+PDFs: Joint session / 16**

## **Jet measurements, $\alpha_s$ and PDF results from CMS (20+10min)**

**Author:** Klaus Rabbertz<sup>1</sup>

<sup>1</sup> *KIT - Karlsruhe Institute of Technology (DE)*

**Corresponding Author:** klaus.rabbertz@cern.ch

Recent results from CMS on jet measurements as well as jet properties and jet variables are presented together with results on  $\alpha_s$  extraction and PDF constraints.

**Multi-parton dynamics / 66**

## **Small-x Physics at the LHeC**

**Author:** Nestor Armesto Perez<sup>1</sup>

<sup>1</sup> *Universidade de Santiago de Compostela (ES)*

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The Large Hadron-Electron Collider LHeC is a proposed upgrade of the LHC to study ep/eA collisions in the TeV regime, by adding a 60 GeV electron beam through an Energy Recovery Linac. In this talk we will review the possibilities for studying the small-x region in this machine, with emphasis in the potential for unravelling the existence of a novel, non-linear saturation regime of QCD through inclusive and exclusive observables in ep and eA collisions.

**Heavy Quarks / 62**

## Top quark pair production measurements using the ATLAS detector at the LHC

**Author:** Arnaud Ferrari<sup>1</sup>

**Co-author:** Cristobal Padilla Aranda<sup>2</sup>

<sup>1</sup> *Uppsala University (SE)*

<sup>2</sup> *IFAE-Barcelona (ES)*

**Corresponding Author:** katsuya.yamauchi@cern.ch

Measurements of the inclusive top quark pair production cross sections in proton-proton collisions with the ATLAS detector at the Large Hadron Collider are presented. The most precise result requires opposite sign electrons and muons and uses the full data-set at a centre-of-mass energy of 7 and 8 TeV. In addition, differential measurements of the top transverse momentum and kinematic properties of the top-anti-top pair are discussed. These measurements, including results using boosted tops, probe our understanding of top pair production in the TeV regime. The results, unfolded to particle and parton level, are compared to recent Monte Carlo generators implementing LO and NLO matrix elements matched with parton showers and NLO QCD calculations. In addition, measurements of the production of top quark pairs in association with gauge bosons or jets are presented.

**HardQCD+PDFs: Joint session / 126**

## Subleading Logarithms in High Energy Jets (15+5min)

**Author:** Jeppe Rosenkrantz Andersen<sup>1</sup>

**Co-author:** Helen Brooks<sup>2</sup>

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**Multi-parton dynamics / 95**

## Di-photon and photon-hadron correlations at the LHC

**Author:** Amir Rezaeian<sup>1</sup>

<sup>1</sup> *Universidad Tecnica Federico Santa Maria*

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I will discuss recent developments in calculation of prompt di-photon and photon-hadron production in proton-nucleus collisions within the Color-Glass-Condensate approach. I will discuss in details whether there is a ridge like structure in di-photon and photon-hadron correlations in high-multiplicity events in proton-proton and proton-nucleus collisions at the LHC. Such measurements at the LHC and future colliders provides useful complementary information about the underlying dynamics of particle production in high-multiplicity events, and help to understand the true nature of the observed ridge phenomenon in di-hadron production at the LHC.

**Heavy Quarks / 63**

## Top quark pair properties using the ATLAS detector at the LHC

**Author:** Arnaud Ferrari<sup>1</sup>

**Co-author:** Cristobal Padilla Aranda<sup>2</sup>

<sup>1</sup> *Uppsala University (SE)*

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The latest measurements of the properties of the top quark using the ATLAS experiment are presented. The top quark mass is one of the fundamental parameters of the Standard Model. A measurement based on a multi-dimensional template fit that can constrain the uncertainties on the energy measurements of jets is presented and combined with a measurement using dilepton events. In addition, novel measurements aiming to measure the mass in a well-defined scheme are presented. The top quark pair charge asymmetry is an asymmetry predicted to occur beyond leading-order QCD in the Standard Model, and may be significantly enhanced by the presence of new physics. The  $t\bar{t}$  production charge asymmetry is measured inclusively and differentially using the 7 and 8 TeV ATLAS datasets. Making use of the large number of top quark pairs collected, we also present measurements of the spin correlation between top and anti-top quarks and discuss their sensitivities to new physics. The large number of top quark pair events is also used to measure the jet pull between the jets from the hadronic decay of the W boson, which is an observable that is sensitive to the QCD colour flow between the jets. A search for flavour changing neutral current processes in top quark decays is also presented.

**HardQCD+PDFs: Joint session / 107**

## Recent developments in the fast reproduction of QCD calculations with the APPLgrid project (15+5min)

**Authors:** Mark Sutton<sup>1</sup>; Mark Sutton<sup>None</sup>

<sup>1</sup> *University of Sussex (GB)*

**Corresponding Author:** sudd@cern.ch

Recent developments in the fast reproduction of the results of QCD calculations using the APPLgrid project are presented. The calculation of cross-sections at Next-to-Leading order in QCD involves the integration over the final state phase space in order to cancel the infra-red divergences. For the calculation of cross sections for observables at hadron-hadron colliders this integration requires the Monte Carlo generation of a large number of event weights. These calculations typically need to be repeated if a different choice of parton densities within the proton are required or a different choice of factorisation or renormalisation scales. This makes the full calculation with many of the available parton density function error sets, and indeed the inclusion of these calculations in iterative fits to the proton parton densities, computationally prohibitive. The APPLgrid project allows the *a posteriori* inclusion of the parton densities in the calculation of the cross section by storing the weights from the Monte Carlo integration over the hard-subprocess phase space from the underlying QCD Calculation code in a look-up table so that the full calculation need be performed only once, after which the cross section can be recreated with any parton density set using a fast convolution over the stored weights. This reduces the time required to obtain the cross section from many days, down to a few milliseconds. Detailed examples from the increasingly large portfolio

of QCD calculations of physics processes interfaced to APPLgrid will be presented.

**Multi-parton dynamics / 98**

## Data-driven approaches to pile-up treatment at the LHC

**Author:** Hans Van Haevermaet<sup>1</sup>

**Co-authors:** Francesco Hautmann<sup>2</sup>; Hannes Jung<sup>3</sup>

<sup>1</sup> *University of Antwerp (BE)*

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Experiments in the upcoming high-luminosity runs at the LHC face the challenges of very large pile-up. Primary techniques to deal with this are based on vertexing by trackers. Outside the detector tracking acceptances, however, lie regions of much interest for a great many aspects of the LHC physics program. Treatments of pile-up in these regions rely more strongly on Monte Carlo simulations. Here, on the other hand, one is also approaching parts of the phase space in which the tuning of the Monte Carlo event generators becomes subject to increasingly large uncertainties. In this work we explore complementary approaches to pile-up corrections, with a view to developing data-driven techniques which treat pile-up and do not spoil the physics of the signal process. We present numerical illustrations of these approaches in Drell-Yan + jets processes.

**HardQCD+PDFs: Joint session / 9**

## fastNLO v2 Developments (15+5min)

**Author:** Klaus Rabbertz<sup>1</sup>

**Co-authors:** Daniel Britzger<sup>2</sup>; Fred Stober<sup>1</sup>; Georg Sieber<sup>1</sup>; Markus Wobisch<sup>3</sup>

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The precise calculation of hadron-hadron collisions at higher orders of perturbative QCD requires a large amount of processing power. In addition, thorough analyses require that these calculations are repeated many times for different parameters. The fastNLO toolkit can be interfaced with next-to-leading order (NLO) and next-to-next-to-leading order (NNLO) Monte-Carlo programs to make these computations more efficient. Using multi-dimensional interpolation techniques, coefficient tables are produced that allow to quickly evaluate the cross section for different PDFs, values of  $\alpha_s$ , and scale choices.

This talk focuses on recent developments of the fastNLO framework, in particular on the increased flexibility with respect to scale variations and the new generators that are already interfaced.

**Heavy Quarks / 88****Measurement of t-channel single top quark production in pp collisions****Author:** Ulrich Goerlach<sup>1</sup><sup>1</sup> *Institut Pluridisciplinaire Hubert Curien (FR)***Corresponding Author:** steffen.roecker@cern.ch

Measurements are presented of t-channel single top quark production in proton-proton collisions at the LHC at centre-of-mass energies of 7 and 8 TeV, using data collected with the CMS experiment during the years 2011 and 2012. The analyses consider decay channels where the W from the top decays into electron-neutrino or muon-neutrino, and makes use of kinematic characteristics of electroweak single top production for the separation of signal from backgrounds using multivariate methods. The results are compared with the most precise standard model theory predictions. Measurements of top/antitop cross section ratio and of various differential single top quark production cross sections are also presented.

**Hard QCD / 104****Higgs measurements from CMS (20+10min)****Corresponding Authors:** amina.zghiche@cern.ch, zghiche@lapp.in2p3.fr**Multi-parton dynamics / 74****Searches for resonant and non-resonant new phenomena in CMS****Author:** Ulrich Goerlach<sup>1</sup><sup>1</sup> *Institut Pluridisciplinaire Hubert Curien (FR)***Corresponding Author:** hwi.dong.yoo@cern.ch

Many new physics scenarios beyond the Standard Model predict the presence of narrow or broad resonances decaying to a pair of quarks/gluons, charged/neutral leptons, photons and their combinations, or a multi-jet final state. Non-resonant excess in tails of mass and transverse momentum distributions is another strong indication of new physics. This talk highlights recent CMS searches on new phenomena in di-jet, multi-jet, di-lepton, photon+jet, diphoton and multi-jet final states using LHC Run 1 data. First LHC Run-2 results and/or prospects will be privileged, if available.

**PDFs / 108****Measurements of  $W$  charge asymmetry (20+10min)****Author:** Bjoern Penning<sup>1</sup><sup>1</sup> *Imperial College Sci., Tech. & Med. (GB)*

**Corresponding Author:** bjoern.penning@cern.ch

We present  $W$  boson and lepton charge asymmetry measurements from  $W$  decays in the electron channel, with  $9.7 \text{ fb}^{-1}$  of RunII data collected by the D0 detector at the Fermilab Tevatron Collider. The electron charge asymmetry is presented as a function of the electron transverse momentum and pseudo-rapidity out to  $|\eta| \leq 3.2$ ; we also give the  $W$  charge asymmetry as a function of  $W$  boson rapidity. The asymmetries are compared with next-to-leading order perturbative quantum chromodynamics calculations. These charge asymmetry measurements will allow more accurate determinations of the proton parton distribution functions.

**Heavy Quarks / 125**

## 3-loop heavy flavor non-singlet contributions to different observables

**Corresponding Author:** johannes.bluemlein@desy.de

We present the 3-loop heavy flavor non-singlet contributions to different polarized and unpolarized structure functions and associated sum-rules.

**Heavy Quarks / 71**

## Decay rate of the SM Higgs boson to bottom quarks at $\mathcal{O}(\alpha^2)$

**Author:** Luminita Mihaila<sup>None</sup>

**Co-author:** Matthias Steinhauser<sup>1</sup>

<sup>1</sup> *KIT*

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In this talk, we are going to report on the recent calculation of the decay rate of the SM Higgs boson to bottom quarks at  $\mathcal{O}(\alpha^2)$  and discuss its phenomenological implications. In the second part of the talk, we would like to point out the significance of these results in constraining the possible SM extensions.

**Hard QCD / 105**

## Higgs measurements from ATLAS (20+10min)

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**PDFs / 8**

## HERAFitter project and its related studies (20+10min)

**Authors:** Ringaile Placakyte<sup>1</sup>; Voica Ana Maria Radescu<sup>2</sup>



<sup>1</sup> *Deutsches Elektronen-Synchrotron (DE)*

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The uncertainties of protons parton distribution functions (PDFs) play a dominant role for the precision tests of the Standard Model (SM) and they also impact substantially the theory predictions of Beyond SM high mass production. We present the HERAFitter project which provides a unique open-source software framework for the determination of the proton's PDFs and for the interpretation of the physics analyses in the context of Quantum Chromodynamics (QCD).

We report here the highlighted results based on the HERAFitter functionalities, as well as novel studies performed by HERAFitter. The latter includes the impact of correlations between uncertainties for PDFs extracted at different perturbative QCD orders as well as the QCD analysis of the recent Drell-Yan production measurements at Tevatron.

Reference of studies that the abstract covers are:

1. "HERAFitter Open Source QCD Fit Project", arXiv:1410.4412 [accepted by EPJC]
2. "Parton distribution functions at LO, NLO and NNLO with correlated uncertainties between orders", EPJC (2014) 74:3039, arXiv:1404.4234
3. "QCD analysis of W- and Z-boson production at Tevatron", arXiv:1503.05221 [submitted to EPJC]

**Multi-parton dynamics / 124**

## Searches for resonant and non-resonant new phenomena from ATLAS

**Author:** Arnaud Ferrari<sup>1</sup>

<sup>1</sup> *Uppsala University (SE)*

**Corresponding Author:** alison.elliott@cern.ch

**Heavy Quarks / 83**

## Heavy quark production asymmetries at LHCb

**Author:** Rhorry Graham Gauld<sup>None</sup>

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Last year, LHCb performed the first measurement of the angular asymmetry present in bottom-quark pair production at a hadron collider. I will compare the available data to SM predictions, and comment on the potential sensitivity of similar measurements in Run-II. In addition, I will also discuss the feasibility of charm- and top-quark pair asymmetry measurements with Run-II data.

**Multi-parton dynamics / 50**

## Precision calculations for squark and gluino production at threshold

**Authors:** Anna Kulesza<sup>1</sup>; Christoph Borschensky<sup>1</sup>; Eric Laenen<sup>2</sup>; Michael Krämer<sup>3</sup>; Vincent Theeuwes<sup>1</sup>; Wim Beenakker<sup>4</sup>

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In light of the recent upgrade of the Large Hadron Collider (LHC), precise calculations for the production of supersymmetric particles are required to test new physics models. The all-order resummation of soft and Coulomb gluons deals with potentially large terms endangering the perturbative series and can enhance the production cross sections in certain kinematical regions.

In this talk, state-of-the-art results on squark and gluino production will be presented, including the resummation of soft gluons in Mellin-moment space up to next-to-next-to-leading logarithmic accuracy and Coulomb corrections using a next-to-leading order Coulomb potential. Furthermore, the contributions from higher-order hard interactions will be considered, as well as boundstate corrections, arising from the behaviour of the Coulomb corrections below the production threshold. A particular emphasis will be placed on the production of stops, the superpartners of the heavy top quarks.

## Hard QCD / 22

### NNLO cross sections using the jettiness method (15+5min)

**Author:** Walter Giele<sup>None</sup>

**Corresponding Author:** giele@fnal.gov

The calculation and phenomenology of  $PP \rightarrow H+1$  jet and  $PP \rightarrow V+1$  jet at NNLO will be presented. The calculations use the so-called jettiness subtraction which makes it easy to combine the 2-loop virtual corrections into MCFM by using the already build-in NLO  $PP \rightarrow H+2$  parton and  $PP \rightarrow V+2$  parton processes.

## PDFs / 65

### Nuclear PDFs in eA collisions at the LHeC (20+10min)

**Author:** Nestor Armesto Perez<sup>1</sup>

<sup>1</sup> *Universidade de Santiago de Compostela (ES)*

**Corresponding Author:** nestor.armesto@usc.es

The Large Hadron-Electron Collider LHeC is a proposed upgrade of the LHC to study ep/eA collisions in the TeV regime, by adding a 60 GeV electron beam through an Energy Recovery Linac. In this talk new results are presented on the physics prospects on energy frontier eA collisions with this machine, with emphasis new results on the precise determination of nuclear parton densities.

## Heavy Quarks / 73

## Searches for top/bottom partners and new phenomena in top/bottom quark pair signatures in CMS

**Author:** Ulrich Goerlach<sup>1</sup>

<sup>1</sup> *Institut Pluridisciplinaire Hubert Curien (FR)*

**Corresponding Author:** fabrizio.margaroli@cern.ch

This talk presents searches for new phenomena in signatures with a pair of top-quarks, a top and bottomquark, together with searches for fermionic top/bottom partners (VLQs). CMS results from Run-1 and Run-2 (if available) will be presented together with their interpretations, with a view to the reconstruction techniques used in the searches.

Hard QCD / 110

## Higgs + jet at NNLO QCD: Fiducial cross sections (15+5min)

**Corresponding Author:** markus.schulze@cern.ch

I will present new results for the fully differential Higgs plus jet cross section at NNLO in perturbative QCD which include decays of the Higgs boson to electroweak vector bosons. I will review some technical details of the computation, present kinematic distributions for a realistic final state, and compare our findings with the experimental measurements.

PDFs / 67

## Proton PDFs at the LHeC (20+10min)

**Author:** Nestor Armesto Perez<sup>1</sup>

<sup>1</sup> *Universidade de Santiago de Compostela (ES)*

**Corresponding Author:** c.gwenlan1@physics.ox.ac.uk

The LHeC is a proposed upgrade of the LHC to study ep/eA collisions in the TeV regime, by adding a 60 GeV electron beam through an Energy Recovery Linac. New evaluations are presented on the prospects for precisely determining the proton PDFs, with complete flavour unfolding in a single experiment, and the strong coupling constant with per mille accuracy.

Multi-parton dynamics / 69

## Hadronization processes in neutrino interactions for oscillation physics

**Author:** Teppei Katori<sup>1</sup>

**Co-author:** Shivesh Mandalia<sup>2</sup>

<sup>1</sup> *Queen Mary University of London*

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Next generation neutrino oscillation experiments utilize details of hadronic final states to improve the precision of neutrino interaction measurements. The hadronic system was often neglected or poorly modelled in the past, but they have significant effects on high precision neutrino oscillation and cross-section measurements.

Among the physics of hadronic systems in neutrino interactions, the hadronization model controls multiplicities and kinematics of final state hadrons from the primary interaction vertex.

For relatively high invariant mass events, many neutrino experiments rely on the PYTHIA program.

Here, we show a possible improvement of this process in neutrino event generators,

by utilizing expertise from the HERMES experiment.

Finally, we estimate the impact on the systematics of hadronization models for neutrino mass hierarchy analysis using atmospheric neutrinos such as the PINGU experiment.

**Heavy Quarks / 64**

## Single Top quark production cross section and properties using the ATLAS detector at the LHC

**Author:** Arnaud Ferrari<sup>1</sup>

**Co-author:** Cristobal Padilla Aranda<sup>2</sup>

<sup>1</sup> *Uppsala University (SE)*

<sup>2</sup> *IFAE-Barcelona (ES)*

**Corresponding Author:** sebastian.pedraza.lopez@cern.ch

Measurements of single top-quark production in proton proton collisions at 7 and 8 TeV are presented. In the leading order process, a W boson is exchanged in the t-channel. The single top-quark and anti-top total production cross sections, their ratio, as well as a measurement of the inclusive production cross section is presented. In addition, a measurement of the production cross section of a single top quark in association with a W boson is presented. All measurements are compared to state-of-the-art theoretical calculations and the CKM matrix element  $|V_{tb}|$  is determined. In addition, the s-channel production is explored and limits on exotic production in single top quark processes are discussed. This includes the search for flavor changing neutral currents and the search for additional  $W'$  bosons or a search for monotops.

**Hard QCD / 42**

## Approximate N3LO: Higgs and more (15+5min)

**Author:** Marco Bonvini<sup>1</sup>

<sup>1</sup> *University of Oxford*

**Corresponding Author:** marco.bonvini@cern.ch

I will describe how approximate higher order results can be obtained from known asymptotic regimes, in turn determined by all-order resummed expressions. Specifically, threshold (large-x) resummation combined with high-energy (small-x) resummation can lead to reliable determinations of inclusive N3LO cross sections such as those of Higgs,  $t\bar{t}$  or Drell-Yan productions. The method is validated

against known lower-order results, and includes an estimate of the uncertainty associated with the approximation itself.

**Hard QCD / 48**

## **Analytic NNNLO corrections to the total Higgs production cross section in the $qq'$ -Channel (15+5min)**

**Author:** Alexander Hasselhuhn<sup>1</sup>

<sup>1</sup> *Karlsruhe Institute of Technology*

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The total production cross section from gluon fusion is an important ingredient in further studies of the discovered Higgs boson. I will present the analytic computation of the NNNLO QCD corrections to its total production cross section in the  $qq'$ -channel. The computation is performed using differential equations for canonical bases of master integrals, and the results are exact in the Higgs mass and the total center of mass energy.

**Plenary / 31**

## **Heavy flavour theory developments**

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**Plenary / 32**

## **Heavy quark production results**

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**Plenary / 33**

## **Top quark production at the LHC**

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**Heavy Quarks / 116**

## **LHCb CP Violation in B decays**

**Corresponding Author:** lucia.grillo@cern.ch

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## Parton Distributions for the LHC Run II (20+10min)

**Author:** Juan Rojo Chacon<sup>1</sup>

<sup>1</sup> *University of Oxford (GB)*

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I will present NNPDF3.0, the first set of parton distribution functions (PDFs) determined with a methodology validated by a closure test. NNPDF3.0 uses a global dataset including HERA-II deep-inelastic inclusive cross-sections, the combined HERA charm data, jet production from ATLAS and CMS, vector boson rapidity and transverse momentum distributions from ATLAS, CMS and LHCb, W+c data from CMS and top quark pair production total cross sections from ATLAS and CMS. I will explore some of the phenomenological implications of our results for the upcoming 13 TeV Run of the LHC. Then I discuss some recent developments in the NNPDF framework, including fits with threshold resummation, fits with running masses, the addition of more recent LHC datasets, and the Hessian representation of MC sets.

Hard QCD / 11

## Fully differential decay rate of a standard model Higgs boson into a b-quark pair at NNLO accuracy (15+5min)

**Author:** Zoltan Laszlo Trocsanyi<sup>1</sup>

**Co-authors:** Claude Duhr<sup>2</sup>; Francesco Tramontano<sup>3</sup>; Gabor Somogyi<sup>1</sup>; Vittorio Del Duca<sup>4</sup>

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We compute the fully differential decay rate of the standard model Higgs boson to a b-quark pair at NNLO accuracy. We use a general subtraction scheme developed for computing QCD jet cross sections in perturbation theory. The double real and real-virtual contributions to the second order radiative corrections, regularized by subtractions, are finite in four space-time dimensions and their contribution to the decay rate can be computed with any jet function defined in four dimensions. We also demonstrate the finiteness of the regularized double virtual correction analytically. We present the differential decay rate into b-jets as a function of the jet resolution parameter for the JADE and Durham clustering algorithms.

Hard QCD / 49

## Fully differential VBF Higgs production at NNLO (15+5min)

**Author:** Frederic Alexandre Dreyer<sup>1</sup>

**Co-authors:** Alexander Karlberg<sup>2</sup>; Gavin Salam<sup>3</sup>; Giulia Zanderighi<sup>3</sup>; Matteo Cacciari<sup>4</sup>

<sup>1</sup> *LPTHE & CERN*

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<sup>3</sup> CERN<sup>4</sup> LPTHE Paris**Corresponding Author:** frederic.dreyer@cern.ch

In this talk, we will present the fully differential NNLO corrections to vector-boson fusion (VBF) Higgs production at hadron colliders, in the limit in which there is no cross-talk between the hadronic systems associated with the two protons. This result is achieved by combining an inclusive NNLO calculation in the structure-function approach and a suitably factorised NLO VBF Higgs plus 3-jet calculation, supplemented with appropriate Higgs plus 2-parton counterevents. An earlier calculation of the fully inclusive cross section had found small NNLO corrections, at the percent level. In contrast, we will show that the cross section after typical experimental VBF cuts and differential distributions receive large NNLO corrections.

**Heavy Quarks / 117**

## LHCb rare decays

**Corresponding Author:** harry.victor.cliff@cern.ch

PDFs / 7

## Reduction strategies for the combination of PDF sets (20+10min)

**Author:** Juan Rojo Chacon<sup>1</sup><sup>1</sup> University of Oxford (GB)**Corresponding Author:** juan.rojo@cern.ch

The current PDF4LHC recommendation to estimate uncertainties due to parton distribution functions (PDFs) in theoretical predictions for LHC processes involves the combination of separate predictions computed using PDF sets from different groups, each of which comprises a relatively large number of either Hessian eigenvectors or Monte Carlo (MC) replicas. While many fixed-order and parton shower programs allow the evaluation of PDF uncertainties for a single PDF set at no additional CPU cost, this feature is not universal, and moreover the a posteriori combination of the predictions using at least three different PDF sets is still required. In this work, we present a strategy for the statistical combination of individual PDF sets, based on the MC representation of Hessian sets, followed by a compression algorithm for the reduction of the number of MC replicas. We illustrate our strategy with the combination and compression of the recent NNPDF3.0, CT14 and MMHT14 NNLO PDF sets. The resulting Compressed Monte Carlo PDF (CMC-PDF) sets are validated at the level of parton luminosities and LHC inclusive cross-sections and differential distributions. We determine that 40 replicas provide an adequate representation of the probability distribution for the original combined PDF set, suitable for general applications to LHC phenomenology.

**Hard QCD / 43**

## Higgs production in gluon fusion in association with jets (15+5min)

**Author:** Nicolas Greiner<sup>1</sup>

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The largest contribution of the production of a Standard Model Higgs comes from the gluon fusion mechanism. The production of a Higgs in association with jets in this production mode is an important and dominant background to the VBF case. Its precise understanding is therefore mandatory for the reliable determination of the Higgs couplings and its properties. In this talk we present a detailed phenomenological analysis of this production mode, taking up to three jets at next-to-leading order QCD accuracy into account.

Heavy Quarks / 118

## LHCb exotics

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PDFs / 101

## New PDF4LHC recommendations for parton distribution uncertainties for the LHC run-II era (20+10min)

**Author:** Albert De Roeck<sup>1</sup><sup>1</sup> CERN**Corresponding Author:** deroeck@mail.cern.ch

In 2010 the PDF discussion forum PDF4LHC provided a recommendation for parton distributions and uncertainties based on existing PDF sets from different PDF fitting groups. These recommendations have been widely used, notably in the LHC Higgs study groups, and for experimental result systematics by the experiments. PDF4LHC has worked over the past few years to re-evaluate the procedures and recommendation. A new recommendation will be released which will take advantage of META-PDF and CMC-PDF techniques. This contribution will detail the new recommendation.

Hard QCD / 44

## Electroweak and QCD corrections with MadGraph5\_aMC@NLO: top quark pair production in association with heavy bosons (15+5min)

**Author:** Huasheng Shao<sup>1</sup><sup>1</sup> CERN**Corresponding Author:** huasheng.shao@cern.ch

I will first review the status of the perturbative computations with QCD and electroweak corrections in the MadGraph5\_aMC@NLO framework. Then, I will focus on its first phenomenological application to top quark pair associated production with a Higgs/Z/W boson at next-to-leading order QCD and electroweak accuracy. As a by product, I also present some preliminary results for the top quark pair production at the complete one-loop level, i.e. including  $\alpha_s^n \alpha^m (n+m=3)$  corrections.



Plenary / 34

## Frontiers of QCD: new insights from SCET

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Plenary / 35

## Multiboson production at the LHC (theory)

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Plenary / 36

## Multiboson production at the LHC

Corresponding Author: chiara.rovelli@cern.ch

Hard QCD / 56

## Vector boson plus jets measurements with the ATLAS detector (20+10min)

Author: Arnaud Ferrari<sup>1</sup>

Co-author: Cristobal Padilla Aranda<sup>2</sup>

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The inclusive production of W and Z bosons as well the off-shell Z/gamma\* production are standard candles at hadron colliders. The measurement of their production cross-sections can be compared to theory calculations at NNLO QCD and have an impact on our knowledge of the parton densities of the proton. Run1 studies carried out by the ATLAS Collaboration are reviewed and first LHC Run2 results will be included if available. Productions of jets in association with a W or a Z boson in proton-proton collisions are important processes to study QCD in multi-scale environments. The cross section, differential in several kinematics variables, have been measured with the ATLAS detector in 7 TeV proton-proton collisions and compared to high-order QCD calculations and Monte Carlo simulations. The ratio of (Z+jets)/(W+jets) provides a precise test of QCD due to the large cancellations of theoretical and experimental uncertainties. In addition the cross section of single W and Z boson production is measured in the boson hadronic decay channels, in the high pT region. In this measurement substructure techniques have been employed to enhance the signal sensitivity.

Heavy Quarks / 109

## Measurements of heavy-flavour production in pp and p-Pb collisions with ALICE at the LHC

**Author:** Minjung Kim<sup>1</sup>

<sup>1</sup> *Inha University (KR)*

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Heavy quarks (charm and beauty) are essential probes of the evolution of the medium created in heavy-ion collisions, because heavy-quark production in high-energy collisions occurs early compared to the formation time of the strongly-interacting partonic matter. To quantify medium effects in AA collisions, one needs to study pp collisions and p-A collisions as references. The measurements of heavy-flavour production in pp collisions can be also used to test perturbative QCD calculations of the production of heavy quarks with well controlled accuracy. Measurements in p-A collisions can be used to study cold nuclear matter effects, such as modifications to the parton densities in nuclei, kT broadening and energy loss in cold nuclear matter. In addition, heavy-flavour correlations in p-Pb collisions can be used to investigate a potential collective phenomena in such collisions. The ALICE detector is dedicated to the study of the strongly-interacting partonic medium, produced in heavy-ion collisions. Thanks to excellent tracking, vertexing and particle-identification capabilities provided by ALICE, we have been able to perform full reconstruction of hadronic D-meson decays at mid rapidity and measure electrons (muons) from semi-leptonic heavy-flavour hadron decays at mid (forward/backward) rapidity. In this talk, we present the results of heavy-flavour production in pp and p-Pb collisions, and the azimuthal correlation between heavy-flavour decay electrons and hadrons in p-Pb collisions.

PDFs / 21

## New CTEQ-Jefferson Lab (CJ15) analysis of parton distributions (20+10min)

**Authors:** Alberto Accardi<sup>1</sup>; Cynthia Keppel<sup>2</sup>; Eric Christy<sup>1</sup>; Joseph F. Owens<sup>3</sup>; Lucas Brady<sup>4</sup>; Nobuo Sato<sup>2</sup>; Peter Ehlers<sup>5</sup>; Peter Monaghan<sup>6</sup>; Wally Melnitchouk<sup>2</sup>

<sup>1</sup> *Hampton University*

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We present the results of a new global QCD analysis of PDFs from the CTEQ-Jefferson Lab collaboration (dubbed “CJ15”), which includes several new data sets and recent theoretical developments. In particular, we study the constraints from new D0 data on  $W$  boson asymmetries on the  $d/u$  PDF ratio at large  $x$ , and, indirectly, on the models of nuclear corrections in the deuteron. The analysis also considers for the first time the impact of Jefferson Lab data on the free neutron/deuteron structure function ratio at large  $x$ , and reanalyzes the light antiquark asymmetry in the proton from Drell-Yan data using more flexible parametrizations and nuclear corrections to deuterium cross sections. The results provide a new set of baseline PDFs which can be used to more reliably calibrate the effects of future data from the LHC.

Heavy Quarks / 87

## Higgs production in association with top quarks in CMS

**Author:** Ulrich Goerlach<sup>1</sup>

<sup>1</sup> *Institut Pluridisciplinaire Hubert Curien (FR)*

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In this talk searches for Higgs bosons produced in association with top quarks are presented. The searches are performed using the data collected during the first LHC run at a center-of-mass energy of 7 and 8 TeV and results are presented for different Higgs decay final states, including  $b\bar{b}$ ,  $\tau\tau$ ,  $WW/ZZ$  and  $gg$ , as well as their combination. The talk highlights experimental and theoretical challenges, in particular in view of the upcoming, higher energy LHC run.

PDFs / 90

## Impact of heavy-flavour production cross sections measured by the LHCb experiment on parton distribution functions at low $x$ (20+10min)

**Author:** Katerina Lipka<sup>1</sup>

**Co-authors:** Achim Geiser<sup>2</sup>; Ringaile Placakyte<sup>1</sup>

<sup>1</sup> *Deutsches Elektronen-Synchrotron Hamburg and Zeuthen (DE)*

<sup>2</sup> *DESY*

**Corresponding Authors:** amanda.cooper-sarkar@physics.ox.ac.uk, a.cooper-sarkar1@physics.ox.ac.uk

The impact of recent measurements of heavy-flavour production in deep inelastic  $ep$  scattering and in  $pp$  collisions on parton distribution functions is studied in a QCD analysis in the fixed-flavour number scheme at next-to-leading order. Differential cross sections of charm- and beauty-hadron production measured by LHCb are used together with inclusive and heavy-flavour production cross sections in deep inelastic scattering at HERA. The heavy-flavour data of the LHCb experiment impose additional constraints on the gluon and the sea-quark distributions at low partonic fractions  $x$  of the proton momentum, down to  $x \approx 5 \times 10^{-6}$ . This kinematic range is currently not covered by other experimental data in perturbative QCD fits.

Hard QCD / 41

## Automated NLO QCD+EW corrections for V+multijet production (15+5min)

**Author:** Jonas Lindert<sup>None</sup>

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Run-II of the LHC is probing the Standard Model of particle physics at unprecedented energies and precision. At such large energy scales higher-order electroweak (EW) corrections are strongly enhanced due to the presence of large Sudakov logarithms. Their inclusion in the experimental analyses will significantly enhance the sensitivity for new phenomena. In my talk I will present a fully automated implementation of next-to-leading order (NLO) EW corrections in the OpenLoops matrix-element generator combined with the Sherpa and Munich Monte Carlo frameworks. The process-independent character of the implemented algorithms opens the door to NLO QCD+EW simulations for a vast range of Standard Model processes, up to high particle multiplicity. As a first application, I will present NLO QCD+EW predictions for vector boson production in association with up to three jets.

**Hard QCD / 119****Z boson production in association with a jet at NNLO QCD (15+5min)**

**Author:** Thomas Morgan<sup>1</sup>

<sup>1</sup> *IPPP Durham University*

**Corresponding Author:** t.a.morgan@durham.ac.uk

We will review our recent calculation of Z boson production in association with a jet up to Next-to-Next-to Leading Order (NNLO) precision in QCD, as shown in arXiv:1507.02850. This is a key process at the LHC, given its large event rate and clean signature with the Z boson decaying leptonically. We will discuss our approach using the antenna subtraction scheme and present new results of the fully inclusive Z pT distribution.

**Heavy Quarks / 102****Recent V+charm/beauty jets measurements from DZero**

**Author:** Darren Price<sup>1</sup>

<sup>1</sup> *University of Manchester (GB)*

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The production of heavy flavour jets in association with a vector boson is a process of some importance for searches for new phenomena and precision studies of QCD, which has nonetheless proven difficult to extract and measure in detail. A large and precisely-understood dataset from  $p\bar{p}$  collisions at the Tevatron, and the development of techniques at the DZero experiment to isolate the heavy flavour jets from light jets, allow for unique insight into the production of  $V + b/c$ -jets relevant to future studies at the LHC. We present an overview of the latest results from DZero and a summary of the key findings.

**PDFs / 82****Forward charm production and the small-x gluon PDF (20+10min)**

**Author:** Rhorry Gauld<sup>1</sup>

<sup>1</sup> *IPPP Durham University*

**Corresponding Author:** rggauld@gmail.com

Measurements of forward heavy quark production simultaneously provides sensitivity to relatively large- and small- $x$  PDFs. I will discuss how measurements of prompt charm production (with carefully selected observables) can be used to constrain the gluon PDF for values of  $x < 10^{-5}$  – a kinematic region which is not well constrained by pre-LHC data.

**Hard QCD / 112**

## Loop-tree duality and its application to NLO computations (15+5min)

**Authors:** German Rodrigo<sup>1</sup>; German Sborlini<sup>2</sup>; Roger Hernandez Pinto<sup>2</sup>

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Higher-order computations require to combine real and virtual contributions in order to cancel infrared (IR) singularities. Loop-tree duality (LTD) allows to express virtual contributions in terms of phase-space integrals, which enables to add them directly to the real radiation terms. Thus, we obtain expressions that can be integrated in four dimensions and we avoid the introduction of IR counterterms, as done in usual subtraction methods. In this talk, we describe some technical details of this novel implementation and we explain how to carry out the computation of physical observables.

**HardQCD+PDFs: Joint session / 57**

## Measurements of Drell-Yan transverse momentum, lepton azimuthal decorrelation and angular distributions with the ATLAS detector (20+10min)

**Author:** Arnaud Ferrari<sup>1</sup>

**Co-author:** Cristobal Padilla Aranda<sup>2</sup>

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The ATLAS Collaboration has performed precision measurements of the transverse momentum of  $Z/\text{gammabosons}$  and their decay lepton angular decorrelation with the  $\phi$  observable. Measurements have been performed at 7 and 8 TeV in different dilepton invariant mass and rapidity regions. These measurements are sensitive to soft resummation effects and hard jet emissions for small and large momentum transfers, respectively, probing QCD in a unique way. The ATLAS Collaboration is engaged in precision measurement of fundamental Standard Model parameters, e.g. the weak mixing angle and the complete set of coefficients that describe the angular distributions of Drell-Yan production. A measurement of the forward-backward asymmetry for the neutral current Drell-Yan process is presented and the results are then used to extract a measurement of the effective weak mixing angle. This measurement shows significant sensitivity to the uncertainties of the parton density functions of the proton. The angular distributions of the Drell-Yan lepton pairs around the Z-boson mass peak probe the underlying QCD dynamic of the Z-boson production mechanisms. We present a measurement of the complete set of angular coefficients describing these distributions and compare to theoretical predictions highlighting different approaches of the QCD and EWK modeling.

**HardQCD+PDFs: Joint session / 72**

## W/Z results from CMS (20+10min)

**Author:** Ulrich Goerlach<sup>1</sup>

<sup>1</sup> Institut Pluridisciplinaire Hubert Curien (FR)

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The production of W and Z bosons is studied in pp collisions at a center-of-mass energy of 8 TeV using data collected in the CMS experiment. W events are selected containing an isolated, energetic electron or muon. Z events are selected containing a pair of isolated, energetic electrons or muons. Data-driven methods are used to estimate reconstruction and triggering efficiencies, and well as the main backgrounds. We present recent results on W/Z production cross sections, discuss the measurements of the lepton charge asymmetry in W events, forward-backward asymmetry in the Drell-Yan process.

**HeavyQuarks+PDFs: Joint session / 45**

## **A Variable Flavour Number Scheme with Intrinsic Charm (20+10min)**

**Author:** Marco Bonvini<sup>1</sup>

<sup>1</sup> *University of Oxford*

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I will discuss the inclusion of an intrinsic component of the Charm PDF to the FONLL variable flavour number scheme, and the implications for a PDF fit.

**Hard QCD / 91**

## **NNLOPS Simulations of Higgs and Vector Boson Production (20+10min)**

**Author:** Keith Hamilton<sup>1</sup>

<sup>1</sup> *UCL*

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I will discuss the matching of next-to-next-to-leading order QCD corrections with parton shower simulations for simple processes, via extension of the multi-scale improved NLO (MiNLO) framework.

**HeavyQuarks+PDFs: Joint session / 3**

## **EW and quarkonia production studies in the forward acceptance (20+10min)**

**Author:** Stefania Vecchi<sup>1</sup>

<sup>1</sup> *INFN Ferrara*

**Corresponding Author:** ronan.wallace@cern.ch

LHCb's unique forward acceptance allow for complementary measurements of production processes of electroweak bosons and quarkonia at large

rapidities and low transverse momenta. A review of the latest results based on run 1 data will be presented.

**Hard QCD / 70**

## **Combining parton showers with NNLO matrix elements (20+10min)**

**Author:** Ye Li<sup>1</sup>

**Co-authors:** Stefan Hoeche<sup>1</sup>; Stefan Prestel

<sup>1</sup> SLAC

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We discuss recent developments in combining parton showers and fixed-order calculations. We focus on the UNNLOPS method for matching next-to-next-to-leading order computations to the parton shower, and we present results from Sherpa for Drell-Yan lepton-pair and Higgs-boson production at the LHC.

**Hard QCD / 58**

## **Recent electroweak results from ATLAS (20+10min)**

**Author:** Arnaud Ferrari<sup>1</sup>

**Co-author:** Cristobal Padilla Aranda<sup>2</sup>

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ATLAS measurements of multi-boson production processes involving combinations of W, Z and isolated photons are summarized. In processes like WW, ZZ, Zgamma or Wgamma large next-to-next-to-leading order QCD corrections were recently calculated and are confronted with integrated and differential data measurements. Furthermore a measurement of the differential cross section for the inclusive four-lepton production as a function of the mass ranging from 80 to 1000 GeV is presented. Several distinct physics processes give rise to the production of 4-lepton final state: the single Z resonant processes, the Higgs production at 125 GeV, as well as continuum

ZZ production processes with qq and gg initial states. Production processes sensitive to vector boson fusion and vector boson scattering such as electroweak production of single and double vector boson associated with two forward jets at 8 TeV pp collisions are also presented and compared to Standard Model expectations.

**HeavyQuarks+PDFs: Joint session / 59**

## **Measurements of heavy flavour production in association with W and Z bosons with the ATLAS detector (20+10min)**

**Author:** Arnaud Ferrari<sup>1</sup>

**Co-author:** Cristobal Padilla Aranda<sup>2</sup>

<sup>1</sup> *Uppsala University (SE)*

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The production of heavy flavour in association with a W or Z boson represent important backgrounds to Higgs and BSM studies and are challenging to calculate in QCD. Several precision measurements were performed using pp data at 7 TeV of integrated as well as differential cross sections. Comparisons are made to a diverse set of state-of-the-art NLO QCD calculations, some of which are interfaced to MC generators for parton showering and hadronization. Z+b, Z+bb and W+b production probe the b-quark production by high-order QCD processes. Cross sections are measured differentially as a function of a diverse set of kinematic variables like the jet multiplicity, transverse momentum or rapidity of the leading bjet or variables describing the kinematics of the di-bjet system. Measurement of W+c production cross section has a unique sensitivity to the strange-quark density, which is poorly known at low x.

**Hard QCD / 94**

## **Diboson production at NNLO (20+10min)**

**Author:** Massimiliano Grazzini<sup>1</sup>

<sup>1</sup> *Universitaet Zuerich (CH)*

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We consider QCD radiative corrections to vector boson pair production in hadron collisions. We report on the computation of radiative corrections to NNLO in QCD perturbation theory. We present results for Zgamma, Wgamma and ZZ production at the LHC by using the selection cuts typically applied by the LHC experiments. Our calculation consistently includes the leptonic decay of the vector-bosons with the corresponding spin-correlations, off-shell effects and singly resonant diagrams. We also present a comparison of our results to the ATLAS and CMS data.

**HeavyQuarks+PDFs: Joint session / 15**

## **Vector boson production in association with jets and heavy flavor quarks from CMS (20+10min)**

**Author:** Jelena Luetic<sup>1</sup>

<sup>1</sup> *Institute Rudjer Boskovic (HR)*

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Accurate modeling of V+jets is important for many measurements at the LHC. W/Z+jets is for example a dominant background for precision top quark measurements. After the discovery of the Higgs boson and the beginning of the Higgs precision measurement era, accurate modeling of the background processes is essential. Many searches for physics beyond standard model also rely on precise SM measurements. Another important role of V+jets measurements is probing different aspects of QCD calculations by testing perturbative QCD in a new energy regime. In this talk recent results on vector bosons, produced with light and heavy jets at CMS, are presented.



**HeavyQuarks+PDFs: Joint session / 4**

## **Jets in the forward acceptance (20+10min)**

**Author:** Stefania Vecchi<sup>1</sup>

<sup>1</sup> *INFN Ferrara*

**Corresponding Author:** philten@cern.ch

LHCb has a unique capability to separate beauty and charm jets. We present recent results on jet tagging performance, W+b,c jets and the observation of the top quark in the forward acceptance at the LHC.

**Hard QCD / 47**

## **Automated NNLL+NLO Resummation for Jet-Veto Cross Sections (20+10min)**

**Authors:** Lorena Rothen<sup>1</sup>; Matthias Neubert<sup>2</sup>; Rikkert Frederix<sup>3</sup>; Thomas Becher<sup>1</sup>

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<sup>3</sup> *CERN*

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In electroweak-boson production processes with a jet veto, higher-order corrections are enhanced by logarithms of the veto scale over the invariant mass of the boson system. We resum these Sudakov logarithms at next-to-next-to-leading logarithmic (NNLL) accuracy and match our predictions to next-to-leading order (NLO) fixed-order results. The calculation is performed in an automated way, for arbitrary electroweak final states and in the presence of kinematic cuts on the leptons produced in the decays of the electroweak bosons. The resummation is based on a factorization theorem for the cross sections into hard functions, which encode the virtual corrections to the boson production process, and beam functions, which describe the low- $p_T$  emissions collinear to the beams. The one-loop hard functions for arbitrary processes are calculated using the MadGraph5\_aMC@NLO framework, while the beam functions are process independent. We perform the resummation for a variety of processes, in particular for  $W+W^-$  pair production followed by leptonic decays of the W bosons.

**Plenary / 37**

## **Recent developments in QCD MCs**

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**Plenary / 38**

## **Overview of MC tuning to LHC data**

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Plenary / 121

## **QCD in Heavy Ion Collisions**

**Corresponding Author:** andreas.morsch@cern.ch

Plenary / 39

## **Theory summary and outlook**

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## **Experimental summary and outlook**

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## **Close-out**

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## **Vector boson plus jets measurements from CMS**

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## **CMS or CDF talk (to be finalised)**

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## **Studies of jet production properties and the strong coupling constant with the ATLAS detector**

**Author:** Arnaud Ferrari<sup>1</sup>

**Co-author:** Cristobal Padilla Aranda<sup>2</sup>

<sup>1</sup> *Uppsala University (SE)*

<sup>2</sup> *IFAE-Barcelona (ES)*

Several aspects of jet production in pp collisions have been measured by the ATLAS collaboration. The momentum-weighted sum of the charges of tracks associated to a jet is sensitive to the electrical charge of the parton initiating the jet. The distribution of the so-called jet charge has been measured in dijet events using pp collision data at 8 TeV with the ATLAS detector. The measurement of the dijet azimuthal decorrelations, as well as the jet-jet energy correlations are sensitive to the strong coupling constant. Measurements of multi-jet systems with or without a veto on additional jets, probe QCD radiation effects. Jet shapes have been measured in ttbar events for light flavour as well as heavy flavour jets. These measurements constitute precision tests of QCD in a new energy regime.

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## Testing QCD with CMS using jets down to very low-pt and into the forward phase space

**Author:** Ulrich Goerlach<sup>1</sup>

<sup>1</sup> *Institut Pluridisciplinaire Hubert Curien (FR)*

Several measurements of jet final states are presented performed at different center-of-mass energies and down to very low pt. The simultaneous observation of several jets in the same event is exploited to study for example the angular correlations of Mueller Navelet jet topologies in order to search for the signature of BFKL parton dynamics. But multi-jet measurements are also used to test higher-order QCD effects, and by lowering the jet pt to the smallest possible values the minijet production close to the factorization limit is studied.

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## Higgs differential cross sections at CMS Higgs fiducial and differential cross sections

**Author:** Ulrich Goerlach<sup>1</sup>

<sup>1</sup> *Institut Pluridisciplinaire Hubert Curien (FR)*

This talk will present in detail the analysis by CMS on the Higgs fiducial and differential cross sections

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## Resummation of Multi-Differential Cross Sections (15+5min)

**Author:** Wouter Waalewijn<sup>1</sup>

**Co-authors:** Lisa Zeune ; Massimiliano Procura

<sup>1</sup> *Nikhef / UvA*

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Many LHC analyses involve cuts on several observables, but resummed predictions are mostly restricted to single variables. We show how the simultaneous resummation of multiple observables can be achieved through the construction of novel effective field theories, increasing the precision of theoretical predictions. I will discuss two different prototypical examples:

(1) Jet substructure: the measurement of two angularities on one jet.

(2) Higgs cross sections: the measurement of the transverse momentum of a Higgs boson in the presence of a jet veto.

Numerical results will be presented. [This talk is based on JHEP 1502 (2015) 117 and a forthcoming publication.]

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## Higgs boson properties and tests of the Standard Model at CMS

**Author:** Ulrich Goerlach<sup>1</sup>

<sup>1</sup> *Institut Pluridisciplinaire Hubert Curien (FR)*

The measurements of the Higgs boson properties, mass, spin/CP, couplings, off-shell cross sections and constraints on invisible width, as well as other Standard model measurements at CMS will be presented. The analysis is based on pp collision data collected at centre-of-mass energies of 7 and 8 TeV by the CMS experiment at the LHC, corresponding to integrated luminosities of 5/fb and 20/fb, respectively.

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## Unordered Emissions in High Energy Jets (15+5min)

**Authors:** Helen Brooks<sup>1</sup>; Jeppe Rosenkrantz Andersen<sup>2</sup>

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High Energy Jets calculates the leading corrections to partonic processes with at least two jets and in the Multi-Regge-Kinematic limit of large invariant masses between all partons compared to the individual transverse momenta. An all-order calculation is constructed by explicitly combining the leading virtual and real corrections. This leads to a superior description in the relevant region of phase space. In this talk I will demonstrate how to improve the description away from the strict limit by including sub-leading processes in the all-order treatment.

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## Small-x QCD and forward physics results from CMS

**Author:** Ulrich Goerlach<sup>1</sup>

<sup>1</sup> *Institut Pluridisciplinaire Hubert Curien (FR)*

The CMS Collaboration has a comprehensive program of small- $x$  QCD and forward physics measurements, which is supported by an excellent experimental coverage into the very forward phase space. Some of the highlights in terms of testing QCD at low- $p_T$  and at high pseudorapidities with jets and charged particles are summarized. Also extremely rare processes, as the measurement of exclusive  $W$ -pair production in photon-photon collisions in  $pp$  data are discussed. The range of physics results is complemented with studies of diffractive collisions, as well as of multi-parton interaction and soft-QCD phenomena. The measurement of the underlying event at different center-of-mass energies is another core result that will be presented. An outlook to the prospects at 13 TeV is given.

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## Measurement of the underlying event using track-jets with the CMS Experiment

**Author:** Ulrich Goerlach<sup>1</sup>

<sup>1</sup> *Institut Pluridisciplinaire Hubert Curien (FR)*

A measurement of the underlying event activity in  $pp$  collisions is performed using events with a leading charged particle jet produced at central pseudorapidities and of transverse momentum in the range of 1 to 100 GeV. The underlying event activity is measured independently in the two halves of the transverse region with the maximum as well as minimum activities. The results obtained from  $pp$  collisions at center-of-mass energies of 0.9, 2.76 and 7 TeV are presented and compared to model prediction.

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## Diffractive processes in $pp$ collisions measured with the CMS experiment

**Author:** Ulrich Goerlach<sup>1</sup>

<sup>1</sup> *Institut Pluridisciplinaire Hubert Curien (FR)*

The differential diffractive cross section is measured as a function of  $x_i = M_X^2/s$  in the region dominated by single dissociation (SD) and double dissociation (DD), where  $M_X$  is the mass of one of the two final-state hadronic systems separated by the largest rapidity gap in the event. The cross section is also measured as a function of the width of the central rapidity gap in the region dominated by DD, as well as for events with a forward gap over 8.4 units of pseudorapidity. The total SD and DD cross sections are extracted. Single diffraction is one of the main uncertainties both, experimentally and in theoretical calculations, of the particle-production cross section in proton-lead collisions as measured at the centre-of-mass energy per nucleon pair of 5.02 TeV. Furthermore, the observation of a hard color-singlet exchange process in events with a large rapidity gap between two leading jets (jet-gap-jet) is reported. The fraction of jet-gap-jet to all dijet events is measured as a function of the second leading jet transverse momentum and the size of the pseudorapidity gap.

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## On NLL soft gluon corrections to the $t$ - $\bar{t}$ -Higgs boson production at the LHC

**Authors:** Anna Kulesza<sup>1</sup>; Leszek Motyka<sup>None</sup>; Tomasz Stebel<sup>2</sup>; Vincent Michel Theeuwes<sup>3</sup>

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A report will be given on work in progress on the calculation of the soft gluon corrections to the Higgs boson production at the LHC in association with  $t$ - $\bar{t}$  pair. Preliminary results will be presented for the inclusive cross-section including the resummed soft gluon corrections at the NLL accuracy matched to the known NLO QCD results. The estimates of theoretical uncertainty of the NLL+NLO cross-section will be given.

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## Loop-tree duality and its application to NLO computations

**Authors:** German Rodrigo<sup>1</sup>; German Sborlini<sup>2</sup>; Roger Hernandez Pinto<sup>2</sup>

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Higher-order computations require to combine real and virtual contributions in order to cancel infrared (IR) singularities. Loop-tree duality (LTD) allows to express virtual contributions in terms of phase-space integrals, which enables to add them directly to the real radiation terms. Thus, we obtain expressions that can be integrated in four dimensions and we avoid the introduction of IR counterterms, as done in usual subtraction methods. In this talk, we describe some technical details of this novel implementation and we explain how to carry out the computation of physical observables.

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## Unordered Emissions in High Energy Jets

**Author:** Helen Brooks<sup>1</sup>

**Co-author:** Jeppe Rosenkrantz Andersen <sup>2</sup>

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High Energy Jets calculates the leading corrections to partonic processes with at least two jets and in the Multi-Regge-Kinematic limit of large invariant masses between all partons compared to the individual transverse momenta. An all-order calculation is constructed by explicitly combining the leading virtual and real corrections. This leads to a superior description in the relevant region of phase space. In this talk I will demonstrate how to improve the description away from the strict limit by including sub-leading processes in the all-order treatment.

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### **3-loop heavy flavor non-singlet contributions to different observables (20+10min)**

**Author:** Johannes Bluemlein<sup>1</sup>

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We present the 3-loop heavy flavor non-singlet contributions to different polarized and unpolarized structure functions and associated sum-rules.

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### **Exclusive $W^+W^-$ production measured with the CMS experiment and constraints on Anomalous Quartic Gauge Couplings (20+10min)**

**Author:** Ulrich Goerlach<sup>1</sup>

<sup>1</sup> *Institut Pluridisciplinaire Hubert Curien (FR)*

A search for exclusive or quasi-exclusive  $W^+W^-$  production induced by photon-photon exchange in pp collisions at  $\sqrt{s}=8$  TeV is reported using data corresponding to an integrated luminosity of 19.7/fb. Events are selected by requiring the presence of an electron-muon pair with large transverse momentum  $p_T > 30$  GeV and no associated charged particles detected from the same vertex. The observed yields and kinematic distributions are compatible with the Standard Model prediction for exclusive and quasi-exclusive  $W^+W^-$  production. The di-lepton transverse momentum spectrum is studied for deviations from the Standard Model, and the resulting upper limits are compared to predictions assuming anomalous quartic gauge couplings.