QCD Physics with ATLAS and CMS detectors

Olga Kodolova, SINP MSU
(on behalf of the ATLAS and CMS collaborations)
Outline

- Motivation
- Soft physics
- Hard physics
- Summary

QCD is the theory that explains strong interactions as part of the Standard Model
Soft underlying event

\[ h_1 \quad \text{i} \quad \text{j} \quad h_2 \]

Soft interaction: production of the low-\( p_T \) hadrons

\[ \mu_F \] – factorization scale separates long and short distance physics

\[ \alpha_S (\mu_R) \] – running coupling constant

\[ \mu_R \] – renormalization scale

\[ Q^2 = -q^2 \] – transferred momentum

\[ p_1 = x_1 P_1 \]
\[ p_2 = x_2 P_2 \]

Factorization theorem

\[ \sigma (P_{h_1}, P_{h_2}) = \sum_{i,j} \int dx_1 dx_2 f_{i/h_1} (x_1, \mu_F^2) f_{j/h_2} (x_2, \mu_F^2) \hat{\sigma}_{ij} (p_1, p_2, \alpha_S (\mu_R), Q^2; \mu_F^2, \mu_R^2) \]

Parton distribution function (PDF)

Hard interaction: production of the high-\( p_T \) objects

\[ F(Q) \]

Partonic cross-section computed in pQCD

\[ \hat{\sigma}_{ij} = \alpha_S^k \sum_n \left( \frac{\alpha_S}{\pi} \right)^n \sigma_{ij}^n \]

Fixed order pQCD

QCD at hadron colliders
Posted questions

Why:
Important background for new territory in physics searches
enormous cross section: QCD can hide many possible signals of new physics

QCD defines the hadronization process of partons whatever interaction mediator is in the hard production vertex

What:
we need to estimate all parts of equation
Study the parton structure, constrain the strong coupling, …
all other pQCD theory components
Study non-perturbative effects and
Tune Monte-Carlo generators

Where:
Probing the new territory \((x,Q^2)\) range
How do we proceed

Theory approximations:
- Perturbative QCD (pQCD): LO, NLO, NNLO calculations: ME + parton showering (PS), threshold resummation
- non-pQCD: (Multi-parton interactions (MPI), String/Cluster fragmentation models)

Estimate:
- Hard interaction cross-section
- Parton Distribution Functions
- Parton showering details

2 step unfolding meet at particles level

Reconstructed particles, reconstructed jets

Differential Cross-sections
Multiplicity
Rapidity
Momentum of Particles and Jets, missing E_{T}
Soft particle production

Charged particle multiplicity
Scaling, correlations
Underlying event
Charged particles density

new input to the dynamics of soft hadronic interactions: interplay between soft and hard processes

No-one MC can describe all data in all configurations

CMS: $p_T>500$ MeV, $|\eta|<2.4$

ATLAS: $p_T>500$ MeV, $|\eta|<2.4$

CMS: $\tau>300$ ps

Data are unfolded and corrected for Reconstruction Inefficiency and background contribution

No-one MC can describe all data in all configurations

CMS: $p_T>500$ MeV, $|\eta|<2.4$

ATLAS: $p_T>500$ MeV, $|\eta|<2.4$

CMS: $\tau>300$ ps

CMS-PAS-FSQ-15-008
Charged particle multiplicity

Evidence of the multi-component structure (change of the slope at n~20)

KNO (Koba-Nielsen-Olesen) scaling assumes the independence of $C_q$ on the collision energy: violation in the range $|\eta|<2.4$

normalized moments of the multiplicity distribution of the order-$q$

- CMS
- UA5
- NA22
- CMS
- UA5

Figure 4: Primary charged-particle multiplicities as a function of (a) pseudorapidity $\eta$ and (b) transverse momentum $p_T$, (c) the primary charged-particle multiplicity $n_{ch}$ and (d) the mean transverse momentum $h_{p_T}$ versus $n_{ch}$ for events with at least two primary charged particles with $p_T>100$ MeV and $|\eta|<2.5$, each with a lifetime $\tau>300$ ps. The black dots represent the data and the coloured curves the different MC model predictions. The vertical bars represent the statistical uncertainties, while the shaded areas show statistical and systematic uncertainties added in quadrature. The lower panel in each figure shows the ratio of the MC simulation to data. As the bin centroid is different for data and simulation, the values of the ratio correspond to the averages of the bin content.

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JHEP01(2011)079
\( p_T \) & \( x_T \) & limiting fragmentation

The CMS results are consistent with the hypothesis of limiting fragmentation: production of forward particles is independent on collision energy. Consistent with the energy independence of the rise of the \( \langle p_T \rangle \) with multiplicity, the interplay between soft, semi-hard, and hard particles production is sensitive to the interplay between soft, semi-hard, and hard particles production.

\[ x_T = 2p_T / \sqrt{s} \] scaling (pQCD prediction with exponent \( N = 4.9 \pm 0.1 \))
Long-range correlations

Ridge at $\Delta \phi \sim 0$ and large $\Delta \eta$ at high multiplicity in pp events at intermediate $p_T$

Can be described by superposition of the low multiplicity yield and modulation as $\cos(2\Delta \phi)$.

Extracted $V_{2,2}$ exhibit factorization, i.e.

is defined by modulation of single particle distribution
Hard interactions

PDFs and $\alpha_s$ measurement
DPS
DGLAP vs BFKL
Multijet correlations
Jet clustering technique

Fixed cone algorithms:
- Iterative Cone (CMS) / JetClu (ATLAS)
- Midpoint algorithm (CDF/D0)
- Seedless Infrared Safe Cone (SISCone)

Successive recombination algorithms:

\[ d_{ij} = \min \left( k_{ti}^{2p}, k_{ij}^{2p} \right) \frac{\delta_{ij}^2}{R^2} \]

\[ d_{iB} = k_{ti}^{2p} \]

if \( d_{ij} < d_{iB} \) add i to j and recalculate \( p_j \)

- \( p=1 \rightarrow k_T \) jet algorithm
- \( p=0 \rightarrow \text{CA jet algorithm} \)
- \( p=-1 \rightarrow \text{“Anti-}k_T\text{” jet algorithm} \)

CMS uses \( R=0.5,0.7 \) in Run1
- \( R=0.4,0.6 \) in Run2
ATLAS uses \( R=0.4,0.6 \) in Run1,2

JHEP 1009 (2010) 091
Underlying events

Everything in event that is not “triggered” interaction

Soft & semi-hard & hard
Beam remnants (BR): what remains after the interacting partons left the hadron

Initial (ISR) and final (FSR) state radiation

Multiple Parton Interactions (MPI). If higher pt interactions → Double Parton Scattering

UE activity is typically studied in the transverse region in pp collisions as a function of the hard scale of the event, and at different centre-of-mass energies (√s):
Particle production in MinBias events or events with high energy track or jet (hadronic events)
Drell-Yan events
Underlying events

None of models describe initial rise well

UE in hadronic events with leading track or track jet reflecting the direction of the parton. Sensitive to ISR, FSR, MPI.

JHEP07(2018)032
JHEP03(2017)157
Double Parton scattering (DPS)

Two and more hard interactions within the same production vertex can happen.

DPS is characterized by

\[
\sigma_{DPS}^{AB} = \frac{m}{2} \frac{\sigma_{SPS}^A \sigma_{SPS}^B}{\sigma_{eff}}
\]

\[
\sigma_{eff} = \left[ \int d^2b \left( T(b) \right)^2 \right]^{-1}
\]

\(\sigma_{eff}\) differs from 10 to 20 mb

T(b) is the overlap function of two interacting hadrons

Why it is important: increase of SM background for the searches.

Question: is \(\sigma_{eff}\) independent on the process and interaction energy?

**Experiment (energy, final state, year)**

- ATLAS \((\sqrt{s} = 7\,\text{TeV}, 4\,\text{jets}, 2016)\)
- CDF \((\sqrt{s} = 1.8\,\text{TeV}, 4\,\text{jets}, 1993)\)
- UA2 \((\sqrt{s} = 630\,\text{GeV}, 4\,\text{jets}, 1991)\)
- AFS \((\sqrt{s} = 63\,\text{GeV}, 4\,\text{jets}, 1986)\)
- DØ \((\sqrt{s} = 1.96\,\text{TeV}, 2\gamma + 2\,\text{jets}, 2016)\)
- DØ \((\sqrt{s} = 1.96\,\text{TeV}, \gamma + 3\,\text{jets}, 2014)\)
- DØ \((\sqrt{s} = 1.96\,\text{TeV}, \gamma + b/c + 2\,\text{jets}, 2014)\)
- DØ \((\sqrt{s} = 1.96\,\text{TeV}, \gamma + 3\,\text{jets}, 2010)\)
- CDF \((\sqrt{s} = 1.8\,\text{TeV}, \gamma + 3\,\text{jets}, 1997)\)
- ATLAS \((\sqrt{s} = 8\,\text{TeV}, Z + J/\psi, 2015)\)
- CMS \((\sqrt{s} = 7\,\text{TeV}, W + 2\,\text{jets}, 2014)\)
- ATLAS \((\sqrt{s} = 7\,\text{TeV}, W + 2\,\text{jets}, 2013)\)
- DØ \((\sqrt{s} = 1.96\,\text{TeV}, J/\psi + \Upsilon, 2016)\)
- LHCb \((\sqrt{s} = 7\,\text{TeV}, \Upsilon(1S)D^0, 2015)\)
- DØ \((\sqrt{s} = 1.96\,\text{TeV}, J/\psi + J/\psi, 2014)\)
- LHCb \((\sqrt{s} = 7\,\text{TeV}, J/\psi D^+, 2012)\)
- LHCb \((\sqrt{s} = 7\,\text{TeV}, J/\psi D^{*+}, 2012)\)
- LHCb \((\sqrt{s} = 7\,\text{TeV}, J/\psi D^0, 2012)\)

WW at 13 TeV: \(\sigma_{DPS}=1.09\pm0.5-0.49\,\text{pb}\)

Significance = 2.29

UL in the absence of signal \(\sigma_{DPSobs}<1.94\,\text{pb}\)

\(\sigma_{DPSexp}<0.97\,\text{pb}\)

**References**

JHEP02 (2018)032

CMS-PAS-FSQ-16-009

JHEP11(2016)110
PDFs and $\alpha_S$

For the fixed pQCD order and definite PDF evolution (DGLAP, BFKL, CCFM,..):

A) Define PDFs at fixed $\alpha_S$

A) Define $\alpha_S$ for the particular PDF set which gives the best approximation of the Data by Theory

C) Combined PDFs and $\alpha_S$ fit

Using available sensitive processes:

W,Z: light quarks at low and high x, s,c,b-quarks PDFs

Top: gluon at high x; u,d,b quarks

Jets: gluons at medium x

Transverse energy-energy correlation and assymetry
Of transverse energy-energy correlation
Inclusive jets: PDF, $\alpha_S$
Double differential cross-section: $p_T$, $y<2.5$

Dominated by $gg\rightarrow gg$ at low $p_T$
$qg\rightarrow qg$ at medium $p_T$
$qq\rightarrow qq$ at high $p_T$

$$\frac{d\sigma}{dp_T} = \alpha_S^2(\mu_R)\bar{X}^{(0)}(\mu_F, p_T) [1 + \alpha_S(\mu_R)K_1(\mu_R, \mu_F, p_T)],$$

Uses CT10 NLO PDF

\[ a_S(M_Z) \text{ NLO}=0.1164+0.006-0.0043 \]

For NNPDF3.0 NLO PDF

\[ a_S(M_Z) = 0.1172+0.0083-0.0075 \]

NLOJet++ + EWK + PS; $N_f=5$

JHEP03(2017)156
Multijets: dijet events
triple differential cross-section

NLO with 3-4 partons (NLOJets++) sensitive to different PDFs (depending on the $p_{Tave}$, $y^*$ interval) and $\alpha_s$

$$m_3^2 = (p_1+p_2+p_3)^2, \quad y_b = 0.5(|y_1+y_2|), \quad y^* = 0.5|y_1-y_2|, \quad p_{Tave} = 0.5(p_{T1}+p_{T2})$$

Small $y_b$, large $p_{Tave}$: $qq$
Large $y_b$: $qg, gg$

Agreement with pQCD(NLOJet++) @ NLO x NP x EWK PDF
Most PDF sets compatible with data: CT14, MMHT2014, NNPDF3.0

Deviations observed with NLO + ABM11 PDF

$\alpha_s = 0.1199 + 0.0015 - 0.0016$ (exp)
$\quad + 0.0031 - 0.002$ (theory)

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Multijets: dijet events
Dijet azimuthal decorrelation

$\alpha_s$ extracted from measurement of $R(\Delta \phi)$ with max = $7\pi/8$, $0 < y^* < 0.5$ and $0.5 < y^* < 1.0$.

$R_{\Delta \phi}(H_T, y^*, \Delta \phi_{\text{max}}) = \frac{d^2\sigma_{\text{dijet}}(\Delta \phi_{\text{dijet}} < \Delta \phi_{\text{max}})}{dH_T dy^*}$

HT-transverse momentum sum

$y^* = (y_1 - y_2)/2$

Jets, akT=0.6

2 highest jets

PDF: CT14, MMHT2014, NNPDF2.3
Additional: ABM16(NNLO), HERAPDF2.0(NLO)
Summary of $\alpha_s$ extraction

LHC at 7 TeV and 8 TeV enables measurements up to 2 TeV

Theory at NLO and NNLO (tt cross-sections) plus the additional electroweak corrections

Typical uncertainty:
- Experimental 1-2%
- PDF 1-2%
- Scale 4-5%
- Non-perturbative effects <1%
- Other theory uncertainties ?

EPJC 75 (2015) 288
JHEP 03 (2017) 156
EPJC 77 (2017) 872
ttbar (sensitive to g-PDF): final state $e\mu$

Refered to Hera+CMS $W^+$

Simultaneous fit of HERA data and $tt/W$ distributions

8 TeV data

$$A(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \rightarrow \mu^+\nu) - \frac{d\sigma}{d\eta}(W^- \rightarrow \mu^-\bar{\nu})}{\frac{d\sigma}{d\eta}(W^+ \rightarrow \mu^+\nu) + \frac{d\sigma}{d\eta}(W^- \rightarrow \mu^-\bar{\nu})}$$

SIG:POWHEG+PY6+CT10 NLO
BG:PY6+CTEQ6L
Template fit for signal extraction
Reach from $x=10^{-3}$ to $10^{-1}$

Compared with FEWZ simulation+CT10,
NNPDF3.0,HERAPDF1.5,MMHT2014,ABM12

**EPJC 76(2016)469**
ATL-PHYS-PUB-2018-017
**EPJC 77(2017)459**
W+c: strange quark PDF

13 TeV:

\[ \sigma (W + c) = 1026 \pm 31 \text{ (stat)} \pm 72 \text{ (syst)} \text{ pb} \]

PDFs are probed at \(< x > \approx 0.007\) at the scale of W mass

EPJC 77 (2017) 367
CMS-PAS-SMP-17-004
PRD 90 (2014) 032004
Z+c/Z+b: towards c- and b-quarks PDFs

4-flavour vs 5 flavour?

For Z+\geq 1b 4F schema fails to describe bjet vs p_T

extraction of Z+c and Z+b yields from template fits to
• corrected secondary vertex mass (semileptonic mode)
• probability that tracks come from primary vertex (D_± D^* modes)

EPJC 77 (2017) 751
EPJC 78 (2018) 287
QCD Evolution equation

Connection between various scales in QCD (for instance, between PDF and the high-momentum scattering) is performed via evolution differential equations.

In small-\(x\) region standard approach to NLO QCD perturbative calculations. DGLAP (expansion in terms of power of \(a_s \ln(Q^2)\)) is predicted to be not sufficient.

Need to develop alternative approaches: BFKL (expansion in terms of \(\ln(1/x)\)). CCFM angular and energy ordering LDC (Linked dipole chain) …

Non perturbative effects, Multi Parton Interaction (MPI) etc. models have to be tuned to data.
Angular correlations of jets

- Events with at least two jets passing cuts: $p_T > 35$ GeV in $|\eta| < 4.7$
- For a pair of jets with the largest $\Delta \eta$ (CMS) the angular distance is calculated: $\Delta \phi = \phi_1 - \phi_2$

$$C_n(\Delta y, p_{T\text{min}}) = \langle \cos(n(\pi-\Delta \phi)) \rangle$$

DGLAP generators start to be worse in high $\Delta y$ description

Analytical BFKL calculations at NLL accuracy with an optimized renormalization schema provide reasonable description of data for the measured jet variables at $\Delta y > 4$
Multi-jet correlations

Theoretical predictions are based on

• Matrix element expansion and parton shower
• Multi-parton interactions and hadronization
Azimuthal decorrelations

$\Delta \phi_{jj}$ in bins of $p_T$ for $p_T > 100$ GeV, $p_T > 200$ GeV, $|y_1| < 2.5$, $|y_2| < 2.5$

Comparison is done with fixed-order pQCD (NLO) and with LO ME+PS

Back-to-back region of dijet correlations-sensitive probe of soft gluon radiation

Deviations (~10%) are observed for all tested generators

EPJC 76 (2016) 536
CMS-PAS-SMP-17-009
Summary

- ATLAS and CMS measure both hard and soft QCD processes in various phase space regions and compare them with a wide range of LO and NLO calculations.
- ATLAS and CMS measurements are used for the combinations with other experiments in global fits and in Monte-Carlo Models tuning. Validation of the QCD predictions (scaling properties, particles spectra, strong coupling behaviour, PDFs, evolution, etc) allows to further constrain and tune existing models.

More results can be found in CMS public web page:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

More details about ATLAS QCD studies in the talk of James Robinson
Back-up
W/Z+jets

\[ \sigma(pp \rightarrow Z+c+X) = 8.6 \pm 0.5 \text{(stat)} \pm 0.7 \text{(syst)} \text{pb} \]

Test predictions of pQCD – give better understanding of strong interactions
And proton structure (intrinsic charm in proton)
Major background for the major of searches

CMS-PAS-SMP-15-009
CMS-PAS-SMP-16-005
ATLAS-CONF-2016-046
Perturbative QCD (pQCD)

pQCD prediction at fixed order calculation

Singularity (soft and collinear) are:

- partially cancelled between real and virtual contributions,
- partially absorbed in PDFs and coupling renormalizations

Finally, fixed order QCD calculations are matched with parton showers (PYTHIA or HERWIG) Monte-Carlo models which represent soft and collinear radiation patterns

OR in alternative approach non-perturbative and Electroweak corrections are applied as weights

Jet reconstruction in detector

**Calorimeter jets (CaloJets):**
Jet clustered from Calorimeter Towers (CMS, ATLAS) or TopoClusters (ATLAS)
CaloMET

Anti-Kt clustering algorithm is applied to the different objects

**Tracker jets (TrackJets):**
Jet clustered from Tracks
Subdetectors: Tracker
(ATLAS, CMS)

**ParticleFlow jets (PFJets):**
Jet clustered from Particle Flow objects (a la generator level particles) which are reconstructed based on cluster separation.
Subdetectors: ECAL, HCAL, Tracker, Muon
PFMET CMS

All subdetectors participate in reconstruction

**JetPlusTrack jets (JPTJets):**
Starting from calorimeter jets tracking information is added via subtracting average response and replacing with tracker measurements.
Subdetectors: ECAL, HCAL, Tracker, Muon
TcMET CMS

The residual jet energy corrections is applied on top of all algorithms