QCD Physics with the CMS Experiment

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Outline

- Introduction
  - QCD at LHC
- CMS Detector
- QCD measurements on the LHC data *(Run I and Run 2)*
  - **Soft QCD**
    - Underlying event (UE) activity
    - Multiple Partonic Interaction (MPI)
    - Cross sections
    - Diffraction
  - **Hard QCD**
    - Jets
    - The strong coupling constant from jets
    - PDFs
- Summary
QCD @ LHC

The main goal of QCD studies is to improve our detailed description of the SM physics.

QCD is the theory of strong interaction describing the interactions between quarks & gluons.

- Perturbation theory pQCD
- PDFs
- Initial & final state radiation (ISR, FSR)
- Parton shower & hadronization

QCD events are immensely complicated
  - theoretical predictions very hard
  - Experimental challenges

Studies of QCD are key to understand production of all (B)SM signals & backgrounds at the LHC.
Why care about the QCD measurements?

- Very rich and interesting theory:
  - needs to be better understood
  - deserves exploration

- QCD measurements are important for
  - data interpretation
  - precise studies
  - sizable background for new physics searches

- LHC provides
  - Unexplored & accessible large phase space
  - Many various final states to study with high accuracy
  - tests pQCD in a new energy regime (totally unexplored kinematic region).
  - Provide constraints on PDFs,
  - measure strong coupling constant,
  - study initial and final state radiation
  - fragmentation and parton showering effects.
  - Tune MC generators to better describe the data

Experimental access to large phase space
CMS Detector

- **Pixels Tracker**
- **ECAL**
- **HCAL**
- **Solenoid**
- **Steel Yoke**
- **Muons**

**STEEL RETURN YOKE**
- ~13,000 tonnes

**ZERO-DEGREE CALORIMETER**

**SUPERCONDUCTING SOLENOID**
- Niobium-titanium coil carrying ~18,000 A

**HADRON CALORIMETER (HCAL)**
- Brass + plastic scintillator

**CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)**
- 76k scintillating PbWO4 crystals

**PRESHOWER**
- Silicon strips
- ~16 m², 137k channels

**CASTOR CALORIMETER**
- Tungsten + quartz plates

**FORWARD CALORIMETER**
- Steel + quartz fibres

- **Total weight**: 14,000 tonnes
- **Overall diameter**: 15.0 m
- **Overall length**: 28.7 m
- **Magnetic field**: 3.8 T

**MUON CHAMBERS**
- Barrel: 250 Drift Tube & 500 Resistive Plate Chambers
- Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers
What are jets?

- Jets
  - Collimated spray of particles
  - The experimental signatures of quarks and gluons.
  - Invaluable objects to probe QCD
  - Abundantly produced at hadron colliders ("jet laboratories")
  - Important signature for many physics processes (Higgs, top, SUSY, ...)
  - Important for almost all LHC physics analyses!
Jet reconstruction and jet calibration @ CMS

- Jet reconstruction procedure:
  input objects (e.g. particles) → apply jet finding algorithm → jet reconstruction

- Anti-\(k_T\) jet clustering algorithm is used by CMS measurements

- Particle Flow (PF) is an event reconstruction technique which attempts to reconstruct and identify all stable particles in the event, through the optimal combination of all CMS sub-detectors.

- PF Jets are the output of the jet algorithm on the reconstructed particles (e, \(\mu\), \(\gamma\), charged and neutral hadrons)

- Factorized Jet Energy Correction approach in CMS:

  ![Diagram showing the Factorized Jet Energy Correction approach]

  - Calibrated Jet
  - Raw Jet
  - Offset Correction (pile-up)
  - Relative Correction (vs \(\eta\))
  - Absolute Correction (vs \(p_T\))

CMS DP-2015/044
Improve the differential power in the quantification of the activity coming from MPI which allows for the better tuning of the model parameters describing the MPI.

Transverse region divided:

• **TransMIN** – lower activity, sensitive to MPI + BBR

• **TransMAX** – higher activity, sensitive to MPI + BBR

  + initial and final radiation

• **TransDIF** = TransMAX – TransMIN, sensitive to initial and final radiation

• **TransAVE** = (TransMIN+TransMAX) / 2

**Leading jet**: $p_T > 1$ GeV, $|\eta|< 2$

**Leading track**: $p_T > 0.5$ GeV, $|\eta|< 2$

**Observables**:

- The charge density: $N_{ch}$
- The transverse momentum density: $\sum p_T$
Average charged particle multiplicity density – energy dependence

Strong rise in the UE activity as a function of the centre-of-mass energy as predicted by the MC tunes.

The level of agreement between simulations and the measurements fall within 10–20% in the plateau region but differ in the low $p_T$ region.

The sharp rise with $p_T$ is interpreted in the MC models as due to an increase in the MPI contribution which reaches a plateau at high $p_T$.

- transMIN rise faster than transDIF;
  - MPI activity rises faster than ISR/FSR activity
UE activity @ 13 TeV

- Average transverse momentum density – energy dependence

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Sensitivity seen for data to momentum scale at which parton densities saturate, MPI, soft-hard QCD transition

Fixed order partonic cross section diverges at low $p_T$.

EPOS LHC gives the best description at low $p_T$.

PYTHIA the rise of $\sigma_{\text{int}}$ is
tamed by:

$$\sigma \rightarrow \sigma \times \frac{\alpha_s^2(p_T^2 + p_T^2)}{\alpha_s^2(p_T^2)} \frac{p_T^4}{(p_T^2 + p_T^2)^2}$$

- Normalized integrated charged-particle or charged particle jet event cross-section as a function of $p_T^{\text{min}}$ for events with a leading charged particle (jet) with $p_T > p_T^{\text{min}}$
  - No sensitivity to particle multiplicities in events.
  - Distribution converges to one by construction
  - Predictions scaled to data @ $p_T^{\text{min}} = 9$ and 14 GeV
  - EPOS provides the best description of data

$$r(p_T^{\text{min}}) = \frac{1}{N_{\text{evi}}} \sum_{p_T^{\text{lead}} > p_T^{\text{min}}} \frac{\Delta p_T^{\text{lead}}}{\Delta p_T^{\text{lead}}}$$
Mueller-Navelet dijet azimuthal decorrelations

- Mueller-Navelet dijets: pair of jets with the largest rapidity interval
- Decorrelation of $\Delta \phi$ MN pair: sensitive to QCD dynamics
- Cross section vs. $\Delta \phi$ expanded in terms of $\cos[n(\pi - \Delta \phi)]$
  - expansion coefficients and their ratio depend on $\Delta y$
  - region of large $\Delta y$ probes the BFKL evolution

Good data-theory agreement: NLL BFKL analytical calculations at large $\Delta y$
BFKL NLL calculations, parton level (small effects from hadronization) (JHEP 1305(2013) 096) sensitivity to MPI and angular ordering

\[
\frac{1}{\sigma} \frac{d\sigma}{d(\Delta \phi)}(\Delta y, p_{T\text{min}}) = \frac{1}{2\pi} \left[ 1 + 2 \sum_{n=1}^{\infty} C_n(\Delta y, p_{T\text{min}}) \cdot \cos(n(\pi - \Delta \phi)) \right]
\]

arXiv:1601.06713
Inclusive jets

- Parton density functions (PDFs)
  - evolution with DGLAP equations ($Q^2$ ordered)

- Hard scattering cross section
  - depend on process
  - valid in short distance
  - small coupling constant
  - calculable with pQCD

\[
\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu^2) f_j(x_2, \mu^2) \hat{\sigma}_{ij}(p_1, p_2, \alpha_s(\mu^2), Q^2/\mu^2)
\]

\[
\frac{d^2\sigma}{dp_T dy} = \frac{1}{\epsilon \cdot L_{\text{eff}}} \frac{N_{\text{jets}}}{\Delta p_T(2 \cdot \Delta |y|)} \propto \alpha_s^2
\]

- Inclusive jet production probes the dynamics of QCD
  - counting the number of jets as a function of rapidity and $p_T$
  - stringent test of QCD
  - PDFs, strong coupling constant, perturbative calculations
Inclusive Jet Cross Sections @ 7 TeV

- Run I (2011 data) – 5 fb⁻¹
- Kinematic range: |y| < 2.5, 100 GeV < p_T < 2 TeV
- Exp. and Theo. uncertainties have roughly same size
  - exp. unc. dominated by jet energy scale (JES)
  - theo. unc. dominated by scale choice and PDFs
- NLO pQCD predictions compatible with data
  - ABKM09 and HERA 1.5 (for central jets) do show deviations
Inclusive Forward Jet Cross Sections @ 7 TeV

Exp. Unc.: dominant source JES ~6%
→ scales to 20-30%
Fixed order QCD, NLO+PS and DGLAP MC describe data
BFKL-type HEJ describes Data
CCFM CASCADE seems to be below
NLO is 20% above the central value

Forward jets in LHC
• access to x~10^{-6} appear
• usually in asymmetric collisions x_1 << x_2
Forward jet in HF with p_T > 35 GeV:
x~10^{-4}
• Access to gluon densities @ small x
• BFKL vs DGLAP-correlation between jets
PDF Constraints from Inclusive Jet x-section @ 7 TeV

- Inclusive jet production at CMS: sensitivity to PDFs
- **DATA**: combined HERA I DIS + CMS inclusive jet production [Phys. Rev. D 87 (2012) 12002]
- **THEORY**: NLOJET++ version 4.1.3
  - QCD scales $\mu_r = \mu_f = p_{T,\text{jet}}$, strong coupling $\alpha_s(M_Z) = 0.1176$;

- PDFs with and without CMS jets are consistent within uncertainties
- CMS jet data prefer harder gluon
- Big improvement: reduced uncertainty on the gluon PDF

- Running of the strong coupling $\alpha_s(Q)$ and its total uncertainty also determined
- Agreement on $\alpha_s(M_Z)$ determination with the CMS measurements

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S. Cerci
Inclusive Jet Cross Sections @ 8 TeV

- First preliminary measurements @ 8 TeV
- Dedicated measurement with low PU data
  - full coverage of CMS: $|y| < 4.7$
  - $p_T > 21$ GeV (for fwd. Jets $p_T < 80$ GeV)
- Experimental unc. comparable to theoretical ones
- NLO pQCD predictions compatible with data

QCD Physics with the CMS Experiment, ICNFP 2016
No deviation from the QCD predictions is observed.

- **Data:** HERA I+II DIS [EPJ C 75 (2015) 2604]
  + CMS inc.jet at 8 TeV, 19.7 fb⁻¹

- **Theory for jet production in pp:** NLOJET++ version 4.1.3, interfaced via fastNLO
  
  QCD scales: \( \mu_r = \mu_f = p_{T,jet}, \alpha_s(M_Z) = 0.1180 \)
Inclusive Jet Cross Sections @ 13 TeV

- Full coverage of CMS: $|y| < 4.7$
- Experimental uncertainties comparable to theoretical ones
- NLO pQCD predictions compatible with data
- Predicted cross sections follow the data quite well in each rapidity bin
Significant ongoing effort to improve our understanding of QCD
- both experimental and theoretical
- rich QCD programs pursued LHC

CMS results
- provide new constraints for non-perturbative and semi-hard QCD dynamics on MC
- wide range at various collision energies

Many jet measurements provided
- test of new physics models,
- constrain and tune PDFs,
- extract the strong coupling constant and its running
- provide useful information for various aspects of the theoretical modeling
- considerable impact on gluon and u/d quark PDFs

Measurements of $\alpha_s$ at the TeV scale for the first time, with no deviation from the QCD predictions.
Run II era started and many more new measurements will come in the near future.
THANKS FOR YOUR ATTENTION!
The dependence on $\alpha_s$ of the differential inclusive jet production cross section at NLO is given by

$$\frac{d\sigma}{dp_T} = \alpha_s^2(\mu_R) \hat{X}^{(0)}(\mu_F, p_T) [1 + \alpha_s(\mu_R) \hat{K}(\mu_R, \mu_F, p_T)]$$

$$\chi^2(\alpha_s(M_Z)) = \sum_{i,j} (D_i - T_i(\alpha_s(M_Z)))^T C_{ij}^{-1} (D_j - T_j(\alpha_s(M_Z)))$$

The value of $\alpha_s(M_Z)$ is determined by minimising the $\chi^2$ between the N measurements $D_i$ and the theoretical predictions $T_i$. 

Figure 9: The $\chi^2$ minimisation with respect to $\alpha_s(M_Z)$ using the CT10-NLO PDF set and data from all rapidity bins. The experimental uncertainty is obtained from the $\alpha_s(M_Z)$ values for which $\chi^2$ is increased by one with respect to the minimum value, indicated by the dashed line. The curve corresponds to a second-degree polynomial fit through the available $\chi^2$ points.
Ratio $R_{32}$: probability to find a third jet in an inclusive dijet event
- Sensitive to high order radiation and $\alpha_s(Q)$
- $Q$ is the average transverse momentum of the two jets leading in $p_T$ ($Q = \frac{p_{T1} + p_{T2}}{2}$)
- Measurements of the running of $\alpha_s(Q)$ provide a stringent test of QCD.
- Almost independent of PDFs
- Many experimental uncertainties (eg. JES) cancel out in the ratio
- One of the first and very precise measurement at the TeV scale.
- The extracted constant is compatible with the world average and the running of $\alpha_s$ is also predicted accurately

$\alpha_s(M_Z) = 0.1148 \pm 0.0014_{\text{exp.}} \pm 0.0018_{\text{PDF}} \pm 0.0050_{\text{theo.}}$

$$R_{32}(< p_{T1,2} >) = \frac{\sigma_3}{\sigma_2} = \frac{\sigma(pp \rightarrow \text{njets} + X; n \geq 3)}{\sigma(pp \rightarrow \text{njets} + X; n \geq 2)}$$

$\bar{s} = 7 \text{ TeV}$

$\alpha_s(M_Z) = 0.1148 \pm 0.0055$
The different kinematical configuration can be exploited to discriminate the two processes using the observables:

\[
\Delta \phi(j_i^j, j_k^j) = |\phi_i - \phi_k|
\]

\[
\Delta S = \arccos \left( \frac{\bar{p}_T^b \cdot \bar{p}_T^b}{|p_T^b| \cdot |p_T^b|} \right)
\]

\[
\Delta_{\text{pair}}^\text{rel} p_T = \frac{|p_T(j_i^j, j_k^j)|}{|p_T(j_i^j)| + |p_T(j_k^j)|}
\]

Comparison with different MC models and test of their performance

Study and separate the different topologies for events coming from single chain and double chain processes

Correlation observables depend on the DPS:
- HERWIG++ tends to underestimate data at low \( p_T \) region

Study of QCD evolution in a heavy flavour scenario
- One of the two jet pairs is emitted by the hard scattering
- Hard radiation can produce softer jets

Distributions of correlation observables not fully described by any of the theoretical models (simulation of UE tuned to soft MPI).
3 Jet Mass Cross Section and $\alpha_s @ 7$ TeV

- Double-diff. 3-jet mass cross section: invariant mass $m_3$ and $y_{\max}$ of the three jets with the highest $p_T$ in the event.

$$m_3^2 = (p_1 + p_2 + p_3)^2$$

$$y_{\max} = \text{sign}(|\max(y_1, y_2, y_3)| - |\min(y_1, y_2, y_3)|) \cdot \max(|y_1|, |y_2|, |y_3|)$$

- Sensitive to PDFs and $\alpha_s$

- Agreement between data and the predictions of pQCD @ NLO
  - except for ABM11 PDF set, significant deviations observed

- Measurements compatible with the world average

**CMS-PAS-SMP-12-027**