QCD probes at LHC

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CMS Collaboration
(on behalf of the ATLAS, CMS, and LHCb Collaborations)
The CERN—LHC complex

- LHC (2008, 27 km)
- ATLAS
- CMS
- ALICE (2008, 27 km)
- ELENA (2016, 31 m), AD (1999, 182 m)
- Booster (1972, 157 m)
- SPS (1976, 7 km)
- LHCb
- HiRadMat (2011)
- n-ToF (2001)
- LEIR (2005, 78 m)
- PS (1959, 628 m)
- ISOLDE (1989)
- CTE3

East Area

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XIV Hadrons Physics 2018, Florianópolis, Brazil
The LHC experiments

- LHC has **4 main caverns** where the experiments are placed.

- These caverns are placed where the particle beams **cross** each other.
Data recorded by the experiments: $p$

**ATLAS Online Luminosity**

- 2011 pp $\sqrt{s} = 7$ TeV
- 2012 pp $\sqrt{s} = 8$ TeV
- 2015 pp $\sqrt{s} = 13$ TeV
- 2016 pp $\sqrt{s} = 8$ TeV
- 2017 pp $\sqrt{s} = 13$ TeV

**Total Delivered Luminosity (fb$^{-1}$):**

- 112.8 fb$^{-1}$
- 125.4 fb$^{-1}$
- 6.8 fb$^{-1}$
Data recorded by the experiments: Pb

By the end of 2018, we expect to collect around $150 \text{ fb}^{-1}$ of data!
Results from proton-proton collisions

Measurements performed by the ATLAS and CMS detectors
Usual particle production corresponds to **high** transferred momentum (hard scatter)

Single Parton Scattering

\[
f_i(x_1) \rightarrow f_i(x_2)
\]

\[
p_i^\mu = x_1 P_1^\mu
\]

\[
p_j^\mu = x_2 P_2^\mu
\]

by Bora Isildak
Underlying events (UE)

- Usual particle production corresponds to **high** transferred momentum (hard scatter).

- We also see other interactions like:
  - Initial- and final-state radiation;
  - Interactions with beam remnants.

by Stefan Höche
Underlying events (UE)

- Usual particle production corresponds to high transferred momentum (hard scatter).

- We also see other interactions like:
  - Initial- and final-state radiation;
  - Interactions with beam remnants.

- Secondary events can occur producing low-\(p_T\) particles, the so-called Underlying Events.

- These type of interactions are known as Multiple Parton Interaction (MPI).

**Diagram:**

- Hard scatter
- Leading charged particle
- Transverse (min) \(60^\circ < |\Delta \phi| < 120^\circ\)
- Transverse (max) \(60^\circ < |\Delta \phi| < 120^\circ\)
- Towards \(|\Delta \phi| < 60^\circ\)
- Away \(|\Delta \phi| > 120^\circ\)

**Figure 1:** Definition of regions in the azimuthal angle with respect to the leading (highest-\(p_T\)) charged particle, with arrows representing particles associated with the hard scattering process and the leading charged particle highlighted in red. Conceptually, the presence of a hard-scatter particle on the right-hand side of the transverse region, increasing its \(p_T\), typically leads to that side being identified as the “trans-max” and hence the left-hand side as the “trans-min”, with maximum sensitivity to the UE.

As the scale of the hard scattering increases, the leading charged particle acts as a convenient indicator of the main flow of hard-process energy. The towards and away regions are dominated by particle production from the hard process and are hence relatively insensitive to the softer UE. In contrast, the transverse region is more sensitive to the UE, and observables defined inside it are the primary focus of UE measurements.

A further refinement is to distinguish on a per-event basis between the more and the less active sides of the transverse region \([15, 16]\), defined in terms of their relative scalar sums of primary charged-particle \(p_T\) and termed “trans-max” and “trans-min” respectively. The trans-min region is relatively insensitive to wide-angle emissions from the hard process, and the difference between trans-max and trans-min observables (termed the “trans-di\(\phi\)”) hence represents the effects of hard-process contamination. In this analysis, an event must have a non-zero primary charged-particle multiplicity in the trans-min region in order to be included in either the trans-min, -max, or -di\(\phi\) observables.
Observables of UE in ATLAS & CMS

Mean particle multiplicity vs. $p_T^{\text{lead}}$

- Charged particles
- Transverse

$pp( p^-) \rightarrow Z + X \rightarrow \mu^+\mu^- + X$

CMS

1/[Δ(ΔΦ)] (N_{ch}) [rad⁻¹]

- CMS, pp, $\sqrt{s} = 13$ TeV
- CMS, pp, $\sqrt{s} = 7$ TeV
- CDF, pp, $\sqrt{s} = 1.96$ TeV
- POWHEG + PYTHIA8, pp, $\sqrt{s} = 13$ TeV
- POWHEG + PYTHIA8, pp, $\sqrt{s} = 7$ TeV
- POWHEG + PYTHIA8, pp, $\sqrt{s} = 1.96$ TeV
- POWHEG + HERWIG++, pp, $\sqrt{s} = 13$ TeV
- POWHEG + HERWIG++, pp, $\sqrt{s} = 7$ TeV
- POWHEG + HERWIG++, pp, $\sqrt{s} = 1.96$ TeV

MC / Data

Model / Data

Total uncertainty

Leading particle: $Z^0 \rightarrow \mu^+\mu^-$

Results of ATLAS|CMS show a 5% accuracy of UE modelling in MC event generators

Needed for high precision physics measurements

CMS, Submitted to JHEP, arXiv:1711.04299 [hep-ex]
Double Parton Scattering (DPS)

- **Two** hard scatterings may occur to produce high-$p_T$ particles, known as **Double Parton Scattering (DPS)**.

- A (simple) model that **ignores** correlation between partons offers a production cross section for DPS like:

$$\sigma_{\text{DPS}}^{AB} = \frac{m \sigma_A \sigma_B}{2 \sigma_{\text{eff}}}$$

- **Goal**: extract $\sigma_{\text{eff}}$ to have an idea about the **transverse profile** of partons inside the hadrons (typically 10–25 mb).

$m = 1$: different pairs

$m = 2$: identical pairs

$\sigma_i$: 2 $\rightarrow$ 2 cross section
CMS employs a multivariate model to measure DPS in same-sign WW events:

- No excess observed in data
- Upper limit of $\sigma_{WW} = 0.32 \text{ pb}$ with 95% CL
- Lower limit of $\sigma_{eff} = 12.2 \text{ mb}$ with 95% CL

ATLAS uses Artificial Neural Network to determine the fraction of DPS events and $\sigma_{eff}$ for 4-jet events:

\[ f_{DPS} = 0.092^{+0.005}_{-0.011} \text{(stat.)}^{+0.033}_{-0.037} \text{(syst.)} \]

\[ \sigma_{eff} = 14.9^{+1.2}_{-1.0} \text{(stat.)}^{+5.1}_{-3.8} \text{(syst.) mb} \]
Results from proton-Lead and Lead-Lead collisions

Measurements performed by the ATLAS, CMS, and LHCb detectors
Jet quenching in Pb-Pb collisions

- The Pb-Pb collisions produces a **hot medium** of the deconfined colour charges known as Quark Gluon Plasma (QGP).

- Jet produced in the initial stage loose energy while crossing the hot medium, originating the jet quenching effect.

- An asymmetry in dijet distributions would indicate an **energy loss** by the jets while crossing the QGP.
Asymmetry effect

- ATLAS observed such **asymmetry** in Pb-Pb collisions in comparison to the \( p-p \) data.

- The distributions show a **high unbalance** in the dijet \( p_T \), which does not happen in \( p-p \) collisions.

- These results are **consistent** with **medium-induced energy loss** expected in Pb-Pb collisions.

ATLAS, *PLB 774* (2017) 379
Azimuthal correlations

- The azimuthal distribution is a key observable to study medium effects in heavy-ion collisions.
- The hot medium may produce an azimuthal anisotropy as a spatial asymmetry in off-centre collisions.
- By using the cumulant method, ATLAS has obtained results showing multi-particle correlations in Pb-Pb collisions, in agreement with CMS|ALICE.

ATLAS, EPJC 77 (2017) 428
The two-particle angular correlations gives rise to the ridge effect: collimated emission of pairs with small $\Delta \phi$ and large $\Delta \eta$

Origin of this effect is still under investigations by many groups

It is studied by a Fourier decomposition of the correlation function:

$$\frac{dN_{\text{pair}}}{d\Delta \phi} \propto 1 + \sum_n 2v_n^2 \cos(n\Delta \phi)$$

$\mathbf{v}_2$: elliptical flow
$\mathbf{v}_3$: triangular flow
$\mathbf{v}_4$: anisotropy coefficients

Information about collective behaviour
ATLAS and CMS results

- Both Collaborations employ the **cumulant method** to extract $v_n$ from data.
- CMS obtains **consistent** results from the p-Pb data in comparison to the expectations from Pb-Pb collisions;
- The CMS results suggest a **similar origin** of collective behaviour for small ($p$-$p$ and $p$-$A$) and large (A-A) systems.

**Figure 1**: The $v_2$ coefficient for different systems as a function of multiplicity in 13 TeV pp, 5.02 TeV PbPb, and 8.16 TeV pPb collisions. The results corrected by low-multiplicity subtraction are denoted as CMS, *PRL* **120** (2018) 092301.
Both Collaborations employ the **cumulant method** to extract $v_n$ from data.

ATLAS has analysed the **four-particle correlation** in a more broad rapidity interval in order to extract the values of $v_2$ and $v_3$ coefficients from data;

These results provide direct evidence that the ridge effect is a **long-range collective phenomenon**.

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ATLAS, *PRC* 97 (2018) 024904
LHCb is reporting very interesting measurements in the forward region;

- Measurements of $J/\psi$ and $D_0$ mesons provides **constraints** on low-$x$ gluons in nuclei;
- It also improves the description of the nuclear modification factor $R_{pPb}$;
- Exploring $pAr$ in **fixed-target mode** provides more hints on $R_{pPb}$ using the SMOG system;

**Important to constrain the **intrinsic** charm contributions**

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Other targets: $p\text{He}$

- LHCb explores $p\text{He}$ collisions as fixed-target experiment for antiproton production;

- This is relevant given its relation with $\bar{p}$ from **Cosmic Rays** (CR);

- Measurement of the production cross section at 100 GeV found as:

$$\sigma_{\text{inel}}^{\text{LHCb}}(p\text{He}) = (140 \pm 10) \text{ mb}$$

- Important to **constrain** the $\bar{p}$ flux from CR interstellar medium interaction for the AMS experiment.
Summary

- The LHC experiments have reported a variety of data analyses from proton-proton, proton-Lead, and Lead-Lead collisions at various energies;

- These reports cover important physics aspects like:
  - Detailed study of underlying events at 7 and 13 TeV;
  - Investigations of the ridge effect in large systems;
  - Azimuthal correlations to study collective behaviour; and
  - Constraints by measurements in different colliding systems.

- More interesting reports to come in 2018 with additional data from RunII.