Precision QCD Measurements

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Introduction

• The LHC is a QCD factory.
  • QCD is at the centre of the Standard Model, and by studying it we understand nature better.
  • And it’s crucial to understand QCD if we are going to understand the rest of what we see at the LHC.

• We can probe QCD at many different scales:
  • High energy jets, Drell-Yan, V+jets, Fragmentation and Hadronisation, Hadronic production cross-sections, Spectroscopy, Low Energy Event Level observables...
Drell-Yan and V+jet Physics
CMS: $\alpha_s$ from W and Z cross-sections

- Analysis compares measurements at $\sqrt{s} = 7, 8$ TeV to predictions at NNLO.

![Graph showing CMS measurements of $\alpha_s$ from W and Z cross-sections.](image-url)
CMS: $\alpha_s$ from W and Z cross-sections

- Analysis compares measurements at $\sqrt{s} = 7$, 8 TeV to predictions at NNLO.

$$\alpha_s(m_Z) = 0.1175^{+0.0025}_{-0.0028} \text{ (considering PDFs from NNPDF and MMHT)}$$
CMS: Differential $Z$ cross-sections

- CMS analyses the $\sqrt{s} = 13$ TeV dataset.

- Consider rapidity, $p_T$ distributions (and more) – compare to wide variety of theoretical predictions.

- Modelling of low $p_T$ regime remains a challenge.
ATLAS: Differential Z cross-sections

• ATLAS analyses the $\sqrt{s} = 13$ TeV dataset – achieves very high precision.

• Considers $p_T$ distributions (and more) – compare to wide variety of theoretical predictions.

• Pythia8 describes data at low $p_T$, Sherpa describes data at high $p_T$, RadISH NNLO + $N^3LL$ describes entire spectrum well.

Accepted in EPJC (arXiv:1912.02844)
CMS: Differential W boson cross-sections

- Analysis of $\sqrt{s} = 13$ TeV dataset to determine double differential cross-section in rapidity and $p_T$.
- High precision study of QCD – and crucial step towards $m_W$ measurement.
- Key sensitivity to and ability to constrain Parton Distribution Functions.
- Reasonable consistency between data and NLO QCD predictions (accounting for correlations in data).
CMS: $Z + \text{Jet}$, $\gamma + \text{Jet}$

- New measurement of differential cross-sections, their ratio, and boosted topologies.

- Extends measurements of SM processes to extreme regions of phase space.

- Good agreement with theoretical predictions.
CMS: Photon + Jet

- Triple differential cross-section for isolated $\gamma + \text{jet}$ (as a function of $y_\gamma, p_{T,\gamma}, \eta_j$).
- Analysis of $\sqrt{s} = 8$ TeV dataset.
- Measurement sensitive to gluon PDF; good agreement with NLO predictions.
ATLAS: Photon + 2 Jet

• Measurement spans phase space sensitive to direct and fragmentation processes.
• Many differential distributions considered: reasonable agreement with theory predictions except at high dijet mass or separation.
CMS: Z + HF jets

- First measurements of associated V+HF production at $\sqrt{s} = 13$ TeV.

- Reasonable agreement with NLO predictions (b-jet case shown here).

- Also see good agreement in c-jet case.
ATLAS: Z + b jets

- ATLAS measure fiducial cross-section of Z+ >= 1 b and Z+ >= 2 b jets
- Compare with a large number of predictions (including Sherpa fusing scheme that combines 4FNS and 5FNS).
- NLO Predictions using 5FNS describe data well; 4FNS predictions agree with data in the two-b-jets case
Physics with jets
(including jet substructure and fragmentation and hadronisation in jets)
ATLAS: Event Shapes

• New measurement of event shape observables in bins of $H_{T2}$ and jet multiplicity – probes multijet energy flow at TeV scales.

• $\tau_\perp = 1 - T_\perp$; $T_\perp = \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_T|}{\sum_i |\vec{p}_{T,i}|}$

• Discrepancies between measurements and predictions at low jet multiplicities.

• Shapes are better described at high jet multiplicities, but discrepancies in the normalisation are observed.
ALICE: Inclusive jet production

- Study dependence of inclusive jet production on the distance parameter $R$ in the anti-$k_T$ algorithm ($\sim$ extent of phase space clustered into jets) [and much more in paper...].

- Measurement made using $pp$ data for $\sqrt{s} = 5.02$ TeV and in Pb-Pb collisions.

- Ratio of inclusive cross-sections measured for values of $0.1 < R < 0.6$.

- Very good agreement with NLO predictions.
CMS: Inclusive jet production

• Similar study made by the CMS collaboration.

• Analyse $pp$ dataset collected at $\sqrt{s} = 13$ TeV.

• Ratio of inclusive cross-sections measured for values of $0.1 < R < 1.2$.

• Much better agreement with NLO predictions than LO predictions.

• Non-perturbative effects also critical.
CMS, Totem: Hard Colour Singlet Exchange

- Study fraction of dijet events with a rapidity gap between two leading jets.
- Sensitive to hard colour singlet exchange.

\[
\frac{N_{\text{F}} - N_{\text{non-CSE}}}{N} \times 100\% = f_{\text{CSE}}
\]

- CMS Preliminary
- 0.66 pb\(^{-1}\) (13 TeV)

- CMS Preliminary
- Central gap in \(\eta<1\)
- \(\eta_{\text{jet-1}} \times \eta_{\text{jet-2}} < 0\)

- CMS-TOTEM Preliminary
- 0.40 pb\(^{-1}\) (jet-gap-jet)
- 0.66 pb\(^{-1}\) (p-gap-jet-gap-jet)
- 40 < \(p_{T,\text{jet-2}}\) < 100 GeV
ATLAS: Jet substructure with soft-drop

- Soft-drop algorithm: reclustering technique removes soft and wide angle radiation in the jet.

- ATLAS study jet mass, momentum carried by subjets (and more!) – see good agreement between predictions and unfolded measurements.

\[ \rho = \log\left( \frac{m^2}{p_T^2} \right) \]
ATLAS: Measurement of the Lund Jet Plane

• Evolution of jets characterised by Lund plane.
• Use similar reclustering technique to determine protojets and emissions and to populate the plane.

\[
\Delta R^2 = (y_{\text{emission}} - y_{\text{core}})^2 + (\phi_{\text{emission}} - \phi_{\text{core}})^2
\]

\[
z = \frac{p_T^{\text{emission}}}{p_T^{\text{emission}} + p_T^{\text{core}}}
\]
ATLAS: Measurement of the Lund Jet Plane

- Comparison to many different predictions.
- Herwig 7.1.3 Angular Ordering gives the best descriptions across the plane.
ALICE: First Observation of Dead Cone Effect

- Emissions suppressed within angle $\sim m_q/E_q$ – significant for charm and beauty jets.
- Consider $D^0$ tagged jets, and inclusive jets (as similarly as possible).
- Suppression of low angle radiation seen in $D^0$ tagged jets – observe the dead cone effect.
- Effect more pronounced with harder $k_T$ cuts that reduce impact of non-perturbative physics (e.g. hadronisation effects).
LHCb: Jet Fragmentation and Hadronisation

- Measure production of charged hadrons within jets recoiling against a $Z$ boson.
- LHCb sample dominated by light-quark jets.
ATLAS: Jet Fragmentation and Hadronisation

- Similar measurement at ATLAS considering dijet events.

- Data / theory agreement in jet multiplicity and energy composition reasonable - Pythia8, Herwig++ and Sherpa accurate to about 20%.
Hadronic Production Measurements
ALICE: D meson production cross-section

- Measurement made using $pp$ data for $\sqrt{s} = 5.02$ TeV
- Sensitive to low-$x$ gluon content of proton.
- Data compared to a range of theoretical predictions, with reasonable agreement, and compared to measurement in different rapidity interval by LHCb.
ATLAS: High \( p_T \) \( J/\psi \) and \( \psi(2S) \) production

- Measure prompt and non-prompt contributions.
- Non-prompt contribution compared to FONLL model – agreement seen at low \( p_T \), but exceed data at higher \( p_T \).
Hadron Spectroscopy
LHCb: new $\Xi_c^0$ resonances

- Measure the $\Lambda_c^+ K^-$ mass spectrum in Run II data.

- New states reported: precise mass and width measurements made.

- Two lowest mass states are observed for the first time; the highest mass state requires further study to confirm it is a separate state to the $\Xi_c^0(2970)$ baryon.
LHCb: new $\Omega_b^-$ resonances

- Measure the $\Xi_b K^-$ mass spectrum using entire LHCb dataset.

- Four peaking structures reported - with local significances between 3.6σ and 7.2σ.

- Accounting for the look-elsewhere effect, the two lowest mass states have < 3σ significance, but the two higher mass states have significances above 5σ.
LHCb and CMS: new $\Lambda_b$ resonances

• Measure the $\Lambda_b \pi^+ \pi^-$ mass spectrum; three new states observed in the last year.

• Separate analyses at CMS and LHCb; different decay modes studied. The excesses are seen at both experiments.

• Suggested interpretation: doublet of $\Lambda_b (1D)^0$ states and the $\Lambda_b (2S)^0$ resonance.
LHCb: $B_c^+$ mass measurement

- Multiple decay modes studied.
- Improvement on current world average by a factor 2.
- Best prediction from Unquenched Lattice QCD is $6278 \pm 6 \pm 4$ MeV.
LHCb: $\chi_{c1}(3872)$ mass and width

- First measurement to determine $\chi_{c1}(3872)$ has non-zero width; most precise determination of mass and binding energy ($70 \pm 120$ keV).

- Independent analyses consider $J/\psi \pi^+\pi^-$ using an inclusive selection and an exclusive selection.

- Extensive study of branching fractions and lineshape (modeled using Flatté and Breit-Wigner distributions).

- First pole of complex amplitudes implies results consistent with bound state.
Conclusions

• Studies of QCD at the LHC cover a range of scales – from high momentum, to low momentum – and allow us to probe a range of phenomena.

• Stunning levels of precision reached by ALICE, ATLAS, CMS and LHCb, with new and exciting measurements in the last year.

• Do connect to the parallel sessions to learn more!

• Zoom chat:
  https://cern.zoom.us/j/96669257413?pwd=SGhYUUkwSVg1L3BYTjFhOWw0QzZ0QT09
Backup Slides
CMS: $\alpha_s$ from W and Z cross-sections

$$\exp \left\{ -\frac{1}{2} \left[ \left( \frac{\sigma - \sigma_{\text{exp}}}{\delta_{\text{exp}}} \right)^2 + \left( \frac{\sigma - \sigma_{\text{exp}} - k(\alpha_s - \alpha_s(m_Z))}{\delta_{+-}} \right)^2 \right] \right\}$$
CMS: Z + Jet, γ + Jet

- New measurement of differential cross-sections, their ratio, and boosted topologies.
- Extends measurements of SM processes to extreme regions of phase space.
- Good agreement with theoretical predictions.
ATLAS: Photon + 2 Jet

- Measurement spans phase space sensitive to (a) direct and (b) fragmentation processes.

![Diagram](image)
CMS, Totem: Hard Colour Singlet Exchange

- Study events with a rapidity gap between two leading jets, and events where at least one of the protons does not dissociate.
ATLAS: Jet substructure with soft-drop

- **Soft-drop algorithm:** [JHEP 1405 (2014) 146]
  - Jet constituents re-clustered using Cambridge-Aachen algorithm - cluster ordering sensitive to parton shower evolution.
  - Final clustering step undone – so jet $j_0$ has sub-jets $j_1$ and $j_2$.
  - Test if $j_1$ and $j_2$ pass the soft-drop condition.
  - If no: relabel $j_1$ as $j_0$, removing soft and wide-angle radiation, and repeat procedure.
  - If yes: $j_0$ is the soft-dropped jet.
  - Soft-drop gives access to the hardest $1 \rightarrow 2$ splitting in the jet.

- ATLAS study jet mass, momentum carried by subjets (and more!)...
ATLAS: Jet substructure with soft-drop

- Good agreement between analytical predictions and unfolded measurements
- First comparison of this kind for $r_g$

$$\rho = \log \left( \frac{m^2}{p_T^2} \right)$$

$$r_g = \Delta R_{12}$$
LHCb: Jet Fragmentation and Hadronisation

• LHCb sample more collimated than ATLAS sample; ATLAS γ + jet data looks more similar to LHCb sample.
ALICE: D meson production cross-section

- Measurement made using $pp$ data for $\sqrt{s} = 5.02$ TeV
- Sensitive to low-$x$ gluon content of proton.
- Data compared to a range of theoretical predictions, with reasonable agreement, and compared to measurement in different rapidity interval by LHCb.
LHCb: $\eta_c$ production and mass

- Measure production rate relative to $J/\psi$, with both processes measured using decays to $p\bar{p}$. Two analysis techniques used.
- Also determine mass difference of the two states – in good agreement with PDG, and most precise measurement from a single experiment to date.