High $p_T$ QCD at the LHC

Vieri Candelise
on behalf of the ATLAS and CMS collaboration

30th International Symposium on Lepton-Photon Interactions
Manchester, UK 10/01/2022
Outline

- QCD at high $p_T$: phenomenology at the LHC
- Recent results on high $p_T$ QCD physics from ATLAS and CMS
  - Perturbative tests: Inclusive jet production
  - Event Topology: shape & correlations with $Z+\text{jets}$
  - Flavour: pQCD with heavy quarks: $Z+\text{bb}$
- Summary, conclusions and perspectives
High $p_T$ QCD @ LHC

QCD @ LHC is everywhere

- test the perturbative regime ($pQCD$) requires high momentum (low-$x$) quarks and gluons $\rightarrow$ jets
- associated production of bosons ($W, Z, H$) can be a powerful experimental handle
- $pQCD$ is critical to understand the Standard Model and go beyond it

vast phenomenology of high $p_T$ QCD
High $p_T$ QCD @ LHC: jets production

LHC is the most efficient Jet Factory of the world!

Jets are the experimental signatures of quarks and gluons

what can we do with jets at high $p_T$?

**pure-QCD**
- Explore the pQCD at high $p_T$
- Constrain the PDFs
- Probe and measure $\alpha_S$
- Access the QCD dynamics of heavy quarks
- Compare up to NNLO calculations
- Tune Monte Carlo Generators
- ... much more!

**not-purely-QCD**
- Extensive test of the Standard Model: V+Jets, H+Jets, V+heavy flavors...
- Test the SM at NNLO precision
- QCD to Beyond the Standard Model:
  - dijet resonances
  - monojet & dark matter
  - new strongly produced states
  - hadronic resonances
- ... much more!
High $p_T$ QCD @ LHC: jets plus vector bosons

An experimental laboratory to test QCD

- Data-driven way to “tune” our simulation and improve perturbative calculations
- QCD modeling plays a prime role: impact of the initial state (PDF, resummation, $\alpha_S$, scales)
- Wide phenomenology: V+jets/HF, multiboson interactions, EW production (VBF/VBS)…
- Precision tests of the SM with W/Z: quark sea, hadronization effects, constrain PDFs

LHC is also the most efficient V+jet Factory of the world!

It’s the perfect experimental ground field to test the SM!
High $p_T$ QCD @ LHC: the role of heavy flavours

**perturbative QCD**

- $Wc$: access the strange quark content of the proton
- $Zb$: understand the production mechanism
  - tree level vs NLO
  - 4FS ($m_b \neq 0$) vs 5FS ($m_b = 0$)
- PDF studies, NLO effects
  - intrinsic beauty/charm

Different interpretations for the b/c treatment in the perturbative expansion of QCD

How *flavoured* are we all?
Disclaimer!

High $p_T$ QCD at the LHC means a huge collection of extraordinary experimental results… a lot of amazing publications are available!

what comes next is my personal overview of the most recent results at 13 TeV from ATLAS and CMS

[enjoy!]

you can have a look at the full gallery of results from the two experiments here:


https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome#Recent_Results
Inclusive jet differential cross section at 13 TeV

- inclusive jet and dijet cross sections in six $|y| < 3$ bins
- theoretical comparison: NLOJet++ using CT14, MMHT, NNPDF3.0
- dijet tested up to 300 GeV $< m_{jj} < 9$ TeV

overall good agreement with NLO predictions!
Inclusive jet differential cross section at 13 TeV

ATLAS

$\mathcal{L} = 81 \text{ nb}^{-1} - 3.2 \text{ fb}^{-1}$

$s = 13 \text{ TeV}$

anti-$k_t$ $R=0.4$

data/theory tension seen over all-jet and rapidity

several PDF sets tested

NLO and NNLO QCD x EW x NP

Theory/Data

$|y| < 0.5$

$0.5 \leq |y| < 1.0$

$1.0 \leq |y| < 1.5$

$1.5 \leq |y| < 2.0$

$2.0 \leq |y| < 2.5$

$2.5 \leq |y| < 3.0$

$p_T$ [GeV]
Inclusive jets measurements at 13 TeV

- Inclusive jets cross section in seven $y$ bins
- Comparison pQCD at NLO, NNLO, and NLO + NLL, using various PDFs
- Standard jet and pile-up corrections are refined in order to reach percent-level precision
- 2D unfolded cross sections in $y$ ranges up to 2.5 TeV

Accepted in JHEP

Overall good agreement with NLO predictions!
Inclusive jets measurements at 13 TeV

All predictions include NP X EW corrections.

strong impact of the measurement on different PDF sets

QCD analysis on this data to determine $\alpha_S$:

$$\alpha_S(M_Z) = 0.1170 \pm 0.0014 \ (\text{fit}) \pm 0.0007 \ (\text{model}) \pm 0.0008 \ (\text{scale}) \pm 0.0001$$
Event shape using multi-jet events with ATLAS

- dynamics of energy flow in multijet final states @ hight $p_T$
- very sensitive to QCD @ hight $p_T$!
- 6 observables able to discriminate $n \rightarrow n$ processes
- unfolded differential xsec VS multiplicity and scale

**transverse thrust**

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

$$\tau_\perp = 1 - T_\perp$$

**NLO prediction**

**different showers**

**disagreement at hight $p_T$**
Event shape using multi-jet events with ATLAS

sphericity

discrepancies at high PT

all MC need further refinement

high multiplicity most affected

normalised to the inclusive two-jet cross section to reduce exp. uncertainty
Azimuthal correlations in Z+jets with CMS

unfolded differential cross sections

Crucial for deep understanding and modeling of QCD interactions.
• Sensitive to higher-order corrections and soft gluon resummation.

low $Z p_T$, the jet production is the dominant process, and the $Z$ boson appears as a higher order EW correction.

low $Z p_T$, the jet production is the dominant process, and the $Z$ boson appears as a higher order EW correction.

high $Z p_T$, $Z$+jet production is dominant with significant corrections coming from QCD.

$p_T(Z) \geq 100$ GeV

$Z$ boson is highly correlated with the leading jet, and peaks in the back-to-back region.
Azimuthal correlations in Z+jets with CMS

**unfolded differential cross sections**

**MADGRAPH5 aMC@NLO + pythia8**
- NLO matrix element up to 2 partons
- FxFx jet merging
- NNPDF3.0 NLO PDF, CUETP8M1 Pythia8 tune

**MCatNLO-CA3 (Z+1) NLO**
- Fixed-order perturbative QCD calculation at NLO (2→Z+1)
- PB-NLO-set2 NLO PDF.

**MCatNLO-CA3 (Z+2) NLO**
- Fixed-order perturbative QCD calculation at NLO (2→Z+2)
- PB-NLO-set2 NLO PDF

**GENEVA NNLO**
- Resummed NNLO+NNLL' calculations for inclusive Z production at NNLO
- NNPDF 3.1, CUETP8M1 Pythia8 tune
High $p_T$ QCD in Z+jets with ATLAS

Probing for real Z emission

Cross sections in different phase spaces:
- Inclusive High $p_T$ : lead jet $p_T > 500$ GeV
- High $H_T$ : $ST > 600$ GeV
- Collinear and back-to-back Z emission

Z($\to e^+e^-,\mu^+\mu^-$) + ≥1 jet
71 ≤ $m_{ll}$ ≤ 111 GeV
jet $p_T > 100$ GeV, |$y$| < 2.5
High $p_T$ QCD in $Z$+jets with ATLAS

ATLAS Preliminary • Data, stat. unc.

**Collinear**

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

$Z + \geq 1$ jet

**back-to-back**

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

$Z + \geq 1$ jet

$\rho_{T/Z} \geq 500$ GeV, $\Delta R_{Z,j}^{\text{min}} \leq 1.4$

ATLAS-CONF-2021-033
High $p_T$ QCD in $Z$+jets with ATLAS

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

$Z + \geq 1$ jet

**ATLAS** Preliminary

- Data $\oplus$ Total Unc.
- SHERPA 2.2.1
- SHERPA 2.2.11
- MG5_aMC+PY8 FxFx

**ATLAS-CONF-2021-033**

Large QCD scale uncertainties

EW corrections applied in Sherpa

| Relative uncertainty for $\sigma(Z(\rightarrow \ell^+\ell^-) +$ jets) [%] |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Uncertainty source | Inclusive | High-$p_T$ | Collinear | Back-to-back | High-$S_T$ |
| Jet JER/JES       | 4.4        | 3.4        | 3.3        | 3.8        | 3.7        |
| Muon              | 0.5        | 1.1        | 0.7        | 1.4        | 0.8        |
| Electron          | 0.7        | 1.1        | 0.9        | 1.3        | 0.8        |
| Luminosity        | 1.7        | 1.7        | 1.7        | 1.7        | 1.7        |
| Pile-up           | 0.2        | 0.4        | 0.4        | 0.3        | 0.4        |
| Unfolding         | 0.9        | 3.2        | 4.0        | 3.8        | 1.7        |
| Background modelling | 0.3      | 1.7        | 1.8        | 1.5        | 1.5        |
| Signal modelling  | 0.5        | 0.6        | 0.6        | 0.6        | 0.6        |
| Total syst. uncertainty | 4.9      | 5.6        | 5.9        | 6.2        | 5.0        |
| Stat. uncertainty  | 0.1        | 2.2        | 2.9        | 2.9        | 1.2        |
| Total uncertainty  | 4.9        | 6.0        | 6.6        | 7.0        | 5.1        |
Associated production of Z and beauty with CMS

Deep neural network-based b-tagging reaching 70% efficiency mistag rate c-quark and light ~10% and ~1%

strategy
Unfolded differential spectra for Z (ll) + (>0), (>1) b-jets and ratios
usual Z(ll)+jets kinematic cuts + b-tagging
Exploring the Zbb phenomenology over a vast set of observables
Predictions at LO and NLO, 4F and 5F by MadGraph5_aMC@NLO and Sherpa
Associated production of Z and beauty with CMS

leading b-jet and Z boson \( p_T \) for Z+->1b, test pQCD @ NLO with different PDF, PS tunes and generators
Associated production of Z and beauty with CMS

\[ A_{ZBB} = \frac{\max \Delta R_{ZB} - \min \Delta R_{ZB}}{\max \Delta R_{ZB} + \min \Delta R_{ZB}} \]

A(Zbb) → 0
2 b-jets emitted symmetrically with respect to the Z direction

very good agreement over the full \( \Delta R \) range within the uncertainties

\[ A(Zbb) \rightarrow 0 \]

Emission of additional gluon radiation

A is not described by any prediction

A(Zbb) → 1
Emission of additional gluon radiation

test gluon density and gluon radiation effects in pQCD
Associated production of Z and beauty with ATLAS

discriminate the effect of the b quark PDF of the proton (5/4-FS)

important test of pQCD: gluon splitting, HF mass, NLO effects

crucial background for VH->bbll, V’

combined MVA-based b-tagging reaching 70% efficiency for high pt jets

mistag rate c-quarks and light 8% and 0.26%

new Sherpa 4F+5F @ NLO prediction tested for the first time!

all 4F prediction underestimate the Z+1b xsec

fuse approach fails to describe the high pT tail
Associated production of Z and beauty with ATLAS

sensitive to additional QCD radiation

sensitive to resummation and b PDF

“fusing” is not improving
Associated production of Z and beauty with ATLAS

5FS with either MG or Sherpa gives the best prediction
4FS with either MG or Sherpa generally underestimates the xsec
Present and future of high $p_T$ QCD @ LHC

high $p_T$ QCD physics is a super-rich and growing field in HEP experiments

- New ideas on topologies, variables, final states and reaching historical open questions with unprecedented precision

- Impressive set of results from ATLAS and CMS on large variety of physics channels including jets, V+jets and heavy flavours

- Ongoing efforts: 13 TeV photon-QCD is a huge missing in this picture, and we can do a lot of QCD with it… new results coming up soon! new ideas, new approaches…lots of space for creativity!

- New era of theory predictions and high precision (NNLO, TMDs, PB, mergedFS) will expand our knowledge of QCD at high energy more than ever…
backup
Associated production of $W$ and charm with CMS

Associated production of W and charm with CMS

Associated production of W and charm with CMS

Azimuthal correlations in Z+jets with CMS

**unfolded differential cross sections**

MADGRAPH5 aMC@NLO + pythia8
- NLO matrix element up to 2 partons
- FxFx jet merging
- NNPDF3.0 NLO PDF, CUETP8M1 Pythia8 tune

MCatNLO-CA3 (Z+1) NLO
- Fixed-order perturbative QCD calculation at NLO (2->Z+1)
- PB-NLO-set2 NLO PDF.

MCatNLO-CA3 (Z+2) NLO
- Fixed-order perturbative QCD calculation at NLO (2->Z+2)
- PB-NLO-set2 NLO PDF

GENEVA NNLO
- Resummed NNLO+NNLL' calculations for inclusive Z production at NNLO
- NNPDF 3.1, CUETP8M1 Pythia8 tune

higher order matrix elements become important
Collinear Z emission

First study of collinear emission of Z at the LHC

Dominated by back-to-back production of Z and jet.

At NLO, contribution from events where Z is emitted collinear with jet.

lead jet $p_T > 300$ GeV

Data

Stat + syst unc

Sherpa + OpenLoops ($\leq 4j$@NLO QCD+EW)

MG5_aMC + PY8 ($\leq 2j$@NLO+PS)

MG5_aMC + PY8 ($\leq 4j$@LO+PS) NNLO

CMS 35.9 fb$^{-1}$ (13 TeV)
Collinear Z emission

First study of collinear emission of Z at the LHC
Collinear Z emission

First study of collinear emission of Z at the LHC

NLO MADGRAPH shows general agreement

mismodelling at $\Delta R(Z,J)$ below 0.8, dominated by events with the mission of a Z boson in close proximity to a jet
Z+b/Z+c, Z+b/Z+j and Z+c/Z+j

- pp collisions @13 TeV, 35.9 fb⁻¹ data (2016) reduce impact of several systematic uncertainties
- Important test of pQCD, background to ZH production
- Measured inclusive and differential cross-section as function of $p_T$ jet and $p_T(Z)$ compared to LO and NLO QCD predictions

- Secondary vertex mass template from MC (c-jet) or data (b-jet) fitted to observation → Z + c and Z + b event yield

- $\sigma(Z+b/c) / \sigma(Z+jets)$ and $\sigma(Z+c) / \sigma(Z+b)$

[Graph showing CMS data and models for $M_{SV}$]
NLO MG5_aMC (NNPDF) and LO MG5_aMC (NNPDF) predictions higher but compatible with data in most bins. For R(c/j) deviations more pronounced, data better described at LO.

LO MCFM, NLO MCFM (NNPDF), NLO MCFM (MMHT): prediction for R(c/j) and R(b/j) disagree with data at high $p_T(Z)$.
NLO MG5_aMC (NNPDF) and LO MG5_aMC (NNPDF) predictions higher but compatible with data in most bins. For R(c/j) deviations more pronounced, data better described at LO.

LO MCFM, NLO MCFM (NNPDF), NLO MCFM (MMHT): prediction for R(c/j) and R(b/j) disagree with data at high $p_T(Z)$. 

NLO MG5_aMC (NNPDF) and LO MG5_aMC (NNPDF) predictions higher but compatible with data in most bins. For R(c/j) deviations more pronounced, data better described at LO.

LO MCFM, NLO MCFM (NNPDF), NLO MCFM (MMHT): prediction for R(c/j) and R(b/j) disagree with data at high $p_T(Z)$. 

NLO MG5_aMC (NNPDF) and LO MG5_aMC (NNPDF) predictions higher but compatible with data in most bins. For R(c/j) deviations more pronounced, data better described at LO.
Associated production of Z and beauty with CMS

Submitted to PRD

bb and Zbb invariant masses important for searches/resonant structures

no deviations w.r.t. the SM
Standard Model measurements in 2020

Experimental test of the SM over 15 orders of magnitude!

All results at: http://cern.ch/go/pNj7
Status of theoretical calculations

- **MadGraph5_aMC@NLO** (ME) + **PYTHIA8 / HERWIG** (PS)
  - **LO**: up to 4 partons, kT-MLM matching
  - **NLO**: up to 2 partons, FxFx merging
- **Powheg** (ME) + **PYTHIA8** (PS) up to NLO
- **Sherpa** (ME + PS) up to NLO
- **Geneva 1.0-RC2** (ME) + **PYTHIA8** (PS):
  - **NNLO** DY production + NNLL higher order resummation
  - Only for Z+jets processes
- **MCFM (ME)**
  - Z/W+1 jet NNLO calculations

**Samples**

<table>
<thead>
<tr>
<th>Samples</th>
<th>0 j</th>
<th>1 j</th>
<th>2 j</th>
<th>3 j</th>
<th>4 j</th>
<th>&gt; 4 j</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO MG5_aMC</td>
<td>LO</td>
<td>LO</td>
<td>LO</td>
<td>LO</td>
<td>LO</td>
<td>PS</td>
</tr>
<tr>
<td>NLO MG5_aMC/Powheg</td>
<td>NLO</td>
<td>NLO</td>
<td>NLO</td>
<td>LO</td>
<td>PS</td>
<td>PS</td>
</tr>
<tr>
<td>Geneva</td>
<td>NLO</td>
<td>NLO</td>
<td>LO</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
</tr>
<tr>
<td>Z/W+1 jet @ NNLO</td>
<td>-</td>
<td>NNLO</td>
<td>NLO</td>
<td>LO</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- **HF treatment**
  - 4FS, b mass and 4 PDFs
  - 5FS b mass=0 and 5 PDFs

**NNPDF PDFs** available at LO and NLO
**MMTH PDF set at NLO**
several (CP5) PYTHIA8 tunes
How all of this is possible

precision SM tests, differential spectra and sensitivity to very rare processes are possible exploiting the ATLAS and CMS excellent detector performances

Electrons identification with $Z \rightarrow e^+e^-$ and $J/\psi \rightarrow e^+e^-$

both ATLAS and CMS achieve sub-% precision
How all of this is possible

Muons identification with $Z \rightarrow e^+e^-$ up to 1 TeV

Outstanding precision
How all of this is possible

ATLAS ↔ both deliver jet energy corrections ↔ CMS

Less than 2% in the region $p_T > 100$ GeV!

LHCb: ~10-15% for $p_T$ of 10–100 GeV

Correct for

- Pile-Up
- Jet Flavor Composition
- Absolute/Relative Scale

thanks to several in-situ methods
Jet Reconstruction: Strategy

**ATLAS**
- topological calorimeter-cell clusters
- anti-$k_T$ clustering algorithm (infrared and collinear safe)

\[ d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}, \]
\[ d_{iB} = k_{ti}^{2p}, \]

**CMS**
- particle-flow

**ATLAS/CMS: R=0.4 (Run II)**

LHCb: R=0.5

- uses all the sub-detectors information to reconstruct objects

**LHCb**
- Particle Flow
- calo cell $E_T \sim 10$ GeV saturation
- forward direction
- $(2 < \eta < 5)$

- use the precise tracking information
- use particles! ($\Lambda, K_s, \pi,$..)
Heavy flavor tagging at collider

**recipe**

- reconstruct jets with the anti-kT05 algorithm
- tagging using b- and c- inclusive tagger
- reconstruct the two-body vertices in the event
- merge SV n-body by linking tracks and vertices associated
- associate vertices/jets requiring $\Delta R(SV, jet) < 0.5$

BDT trained on SV/j properties to separate heavy/light

**light-jet mistag rate < 1% for b-tag efficiency of 65% and c-tag efficiency of 25%**
Heavy flavor tagging at collider

- several taggers:
  - track based (impact parameter tag)
  - soft muon (discriminate μ from b decays)
  - vertex based

- high-level taggers: MVA using all the information available to maximize the b-tag performance

Combine inputs from track, particle and vertex-based physics taggers using multivariate classifier

**b-tag efficiency of 77% and c-tag efficiency of 25%**

Mistag rate of light flavored jets using dijet events with negative tag < 2% under $p_T = 1$ TeV
Heavy flavor tagging at collider

- several taggers:
  - Jet Probability: likelihood that jets is coming from primary vertex using tracks
  - Combined (CSV): combination of displaced tracks with SV info associated to the jet using an MVA
  - CSVv2: evolution of CSV using neural networks
    - cMVAv2 combines all the taggers

<table>
<thead>
<tr>
<th>Tagger</th>
<th>operating point</th>
<th>discriminator value</th>
<th>$\epsilon_b$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JetProbability (JP)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JPL</td>
<td>0.245</td>
<td>≈ 82</td>
<td></td>
</tr>
<tr>
<td>JPM</td>
<td>0.515</td>
<td>≈ 62</td>
<td></td>
</tr>
<tr>
<td>JPT</td>
<td>0.760</td>
<td>≈ 42</td>
<td></td>
</tr>
<tr>
<td>Combined Secondary Vertex (CSVv2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSVv2L</td>
<td>0.460</td>
<td>≈ 83</td>
<td></td>
</tr>
<tr>
<td>CSVv2M</td>
<td>0.800</td>
<td>≈ 69</td>
<td></td>
</tr>
<tr>
<td>CSVv2T</td>
<td>0.935</td>
<td>≈ 49</td>
<td></td>
</tr>
<tr>
<td>Combined MVA (cMVAv2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cMVAv2L</td>
<td>-0.715</td>
<td>≈ 88</td>
<td></td>
</tr>
<tr>
<td>cMVAv2M</td>
<td>0.185</td>
<td>≈ 72</td>
<td></td>
</tr>
<tr>
<td>cMVAv2T</td>
<td>0.875</td>
<td>≈ 53</td>
<td></td>
</tr>
</tbody>
</table>

- deepCSV: based on CSVv2 + more charged particles, based on deep NN

CERN-CMS-DP-2017-005
CMS-PAS-BTV-15-001

Improves ~4% the b-tag efficiency with a mistag rate of 0.1%
Azimuthal correlations in Z+jets with CMS

unfolded differential cross sections

MADGRAPH5 aMC@NLO + pythia8
• NLO matrix element up to 2 partons
• FxFx jet merging
• NNPDF3.0 NLO PDF, CUETP8M1 Pythia8 tune

MCatNLO-CA3 (Z+1) NLO
• Fixed-order perturbative QCD calculation at NLO (2->Z+1)
• PB-NLO-set2 NLO PDF.

MCatNLO-CA3 (Z+2) NLO
• Fixed-order perturbative QCD calculation at NLO (2->Z+2)
• PB-NLO-set2 NLO PDF

GENEVA NNLO
• Resummed NNLO+NNLL’ calculations for inclusive Z production at NNLO
• NNPDF 3.1, CUETP8M1 Pythia8 tune

Z boson is only weakly correlated with the leading jet

CMS-PAS-SMP-21-003
Associated production of Z and beauty with CMS

very good agreement over the full ΔR range within the uncertainties

overall good agreement
Azimuthal correlations in Z+jets with CMS

**unfolded differential cross sections**

MADGRAPH5 aMC@NLO + pythia8
- NLO matrix element up to 2 partons
- FxFx jet merging
- NNPDF3.0 NLO PDF, CUETP8M1 Pythia8 tune

MCatNLO-CA3 (Z+1) NLO
- Fixed-order perturbative QCD calculation at NLO (2->Z+1)
- PB-NLO-set2 NLO PDF.

MCatNLO-CA3 (Z+2) NLO
- Fixed-order perturbative QCD calculation at NLO (2->Z+2)
- PB-NLO-set2 NLO PDF

GENEVA NNLO
- Resummed NNLO+NNLL' calculations for inclusive Z production at NNLO
- NNPDF 3.1, CUETP8M1 Pythia8 tune

**CMS-PAS-SMP-21-003**

Multi-parton interaction contribution is about 40%