NNLO QCD corrections to W+2 b-jet production

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in collaboration with Bayu Hartanto, Andrei Popescu, Simone Zoia
based on: [2102.02516], [2205.01687] and [2209.03280]
**W + b - jets**

**Motivation:**
- testing perturbative QCD: large NLO QCD corrections, 4FS vs. 5 FS
- modelling of flavoured jets

![Diagram of W + 1b-jet](image1)

- probe b quark PDFs

![Diagram of W + 2b-jet](image2)

- background for:
  - WH(H→ bb)
  - single top

**Experiment:**
- [D0,1210.0627,0410062] [ATLAS,1109.1470,1302.2929][CMS,1312.6608,1608.07561]

**Theory W+1 b-jet:**
- [Campbell et al,0611348,0809.3003][Caola et al.,1107.3714]

**Theory W+2 b-jet:**
- mb=0 [Ellis et al,9810489] onshell W: [Cordero et al,0606102 ]W(lv)bb: [Campbell et al,1011.6647]
- W(lv)bb+≤3j: [Anger et al, 1712.05721]
NLO QCD corrections for W+2b-jet

[Anger et al, 1712.05721]

- Large NLO QCD corrections + scale dependence
- Opening of qg-channel
- NNLO QCD corrections required!

Main challenges:
- Twoloop amplitudes [Bager'21, Hartanto'22]
- Subtraction for high-multiplicity processes → Stripper [Czakon'10'14'19]
Twoloop amplitudes

Generate diagrams (contributing to leading-colour) with QGRAF

Factorizing decay:
\[ A_6^{(L)} = A_5^{(L)\mu} D_\mu P \]
\[ M_6^{2(L)} = \sum_{\text{spin}} A_6^{(0)*} A_6^{(L)} = M^{(L)\mu\nu} D_{\mu\nu} |P|^2 \]

Projection on scalar functions (FORM+Mathematica):
\[ \rightarrow \text{anti-commuting } \gamma_5 + \text{Larin prescription} \]

\[ a_i^{(L)} = a_i^{(L),\text{even}} + \text{tr}_5 a_i^{(L),\text{odd}} \]
\[ a_i^{(L),p} = \sum_i c_{j,i}(\{p\}, \epsilon) I(\{p\}, \epsilon) \]
Amplitude reduction

Automated framework using finite fields to reconstruct the rational coefficients of Pentagon functions based on FiniteFlow [Peraro'19]

Independent method w.r.t. [Abreu et. al.'21] → cross check (projection and $\gamma_5$)

Projection
Integration-by-parts
LiteRed $^\text{[Lee]}$
Differential equations
$\text{d} \tilde{M} = \epsilon \text{d} \tilde{A}\{p\} \tilde{M}$

Feynman diagrams
Scalar integrals
Master integrals
Pentagon functions

[Chicherin, Sotnikov, 20]
[Chicherin, Sotnikov, Zoia, 21]

[Remiddi, 97]
[Gehrmann, Remiddi, 99]
[Henn, 13]
NNLO QCD subtraction scheme

Cross section requires combination with real-radiation contributions

Sector-improved residue subtraction scheme → C++ implementation STRIPPER
[Czakon’10][Czakon,Heymes’14][Czakon,Hameren,Mitov,Poncelet’19]

(established framework: top-quark pairs, 2- & 3-jet, VV, V+jet, H, 3-photon)

Oneloop-amps from OpenLoops2 [Bucionni,Lang,Lindert,Maierhoefer,Pozzorini,Zhang,Zoller(2018,2019)]
Born-amps from AvH lib [Bury,van Hameren(2015)]

Credit: Bayu Hartanto
Phenomenology

- LHC @ 8 TeV in 5 FS, NNPDF31, scale: $H_T = E_T(lv) + p_T(b1) + p_T(b2)$
- Phasespace definition to model [CMS, 1608.07561]:
  \[ p_T(l) \geq 30 \text{ GeV} \quad |y(l)| < 2.1 \quad p_T(j) \geq 25 \text{ GeV}, \quad |y(j)| < 2.4 \]
- Inclusive (at least 2 b-jets) and exclusive (exactly 2 b-jets, no other jets) jet phase spaces (defined by the flavour-kT jet algorithm [Banfi’06])

- Inclusive:
  ~ +20% corrections
  ~ 7% scale dependence
- Exclusive:
  ~ + 6% corrections
  ~ 2.5% scale dependence (7-pt)

Compare decorrelated model: [Steward’12]
~ 11% scale dependence

\[
\sigma_{Wb\bar{b},\text{excl.}} = \sigma_{Wb\bar{b},\text{incl.}} - \sigma_{Wb\bar{b}j,\text{incl.}}
\]

\[
\Delta \sigma_{Wb\bar{b},\text{excl.}} = \sqrt{\left(\Delta \sigma_{Wb\bar{b},\text{incl.}}\right)^2 + \left(\Delta \sigma_{Wb\bar{b}j,\text{incl.}}\right)^2}
\]
Differential cross sections

Transverse momentum of lepton

Invariant mass b-jet pair

28.11.22 QCD@LHC 22

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Fixed order flavoured jets beyond NLO

What is the problem with FO flavoured jets?

Example NNLO: double real radiation and subtraction

\[ d\sigma \supset d\Phi_{n+2} \left( F_{n+2} + \cdots + d\tilde{\Phi}_{n+2} S_2 \right) \]

Double real matrix element

Flavour structure depends on the angular configuration

- If \( F(n+2) \) does not treat the flavour pair appropriately:
  - double soft singularity not subtracted
  - Implies correlated treatment of kinematics and flavour information

Double soft subtraction term: Double soft function * tree ME

Fixed flavour structure

IR safety: Have to match in double soft limit
Solution: Modified jet algorithms

Flavour kT algorithm:
Pair distance:
\[ d_{ij} = R_{ij}^2 \left\{ \begin{array}{ll}
\max(k_{T,i}, k_{T,j})^\alpha \min(k_{T,i}, k_{T,j})^{2-\alpha} & \text{softer of } i,j \text{ is flavoured} \\
\min(k_{T,i}, k_{T,j})^{\alpha} & \text{else}
\end{array} \right. \]

Beam distance:
\[ d_{i,B} = \left\{ \begin{array}{ll}
\max(k_{T,i}, k_{T,B}(y_i))^{\alpha} \min(k_{T,i}, k_{T,B}(y_i))^{2-\alpha} & i \text{ is flavoured} \\
\min(k_{T,i}, k_{T,B}(y_i))^{\alpha} & \text{else}
\end{array} \right. \]
\[ d_B(\eta) = \sum_i k_{T,i}(\theta(\eta_i - \eta) + \theta(\eta - \eta_i)e^{\eta_i - \eta}) \]
\[ d_{\bar{B}}(\eta) = \sum_i k_{T,i}(\theta(\eta - \eta_i) + \theta(\eta_i - \eta)e^{\eta - \eta_i}) \]

Problem: Measurements are done with anti-kT
A proper comparison would require to unfold experimental data
→ (flavour-) kT and anti-kT cluster partonic jets differently
→ Non-trivial procedure.
Renewed interest:

- Anti-kT + flv.-kT flavour matching:
  - QCD-aware partonic jet clustering for truth-jet flavour labelling, Buckley, Pollard 1507.00508
  - Practical Jet Flavour Through NNLO, Caletti, Larkoski, Marzani, Reichelt 2205.01109
  - A dress of flavour to suit any jet, Gauld, Huss, Stagnitto 2208.11138

- Fixed-order fragmentation:
  - B-hadron production in NNLO QCD: application to LHC ttbar events with leptonic decays, Czakon, Generet, Mitov and Poncelet, 2102.08267
  - A Fragmentation Approach to Jet Flavor, Caletti, Larkoski, Marzani, Reichelt 2205.01117

- Modified anti-kT algorithm:
  - Infrared-safe flavoured anti-kT jets, Czakon, Mitov, Poncelet 2205.11879

Proposed modification:
A soft term designed to modify the distance of flavoured pairs.

\[
d_{ij}^{(F)} = \begin{cases} 
S_{ij} & \text{i,j is flavoured pair} \\
1 & \text{else} 
\end{cases}
\]

\[
S_{ij} = 1 - \theta(1 - x) \cos\left(\frac{\pi}{2}x\right) \quad \text{with} \quad x = \frac{k_{T,i}^2 + k_{T,j}^2}{2ak_{T,\text{max}}^2}
\]
W+2 bjets: flavour anti-kT

Flavour anti-kT algorithm applied to Wbb production at the LHC
Hartanto, Poncelet, Popescu, Zoia 2209.03280

Comparison to data
Measurement of the production cross section of a W boson in association with two b jets in pp collisions at $\sqrt{s} = 8$ TeV, CMS 1608.07561
(assumes small unfolding corrections → wip)

Significant differences between kT and anti-kT
In small DeltaR(bb) region. → Beam-function?!
Summary & Outlook

Summary

• Independent computation of two-loop five-point amplitudes with external mass
• NNLO QCD corrections to W+2b-jet production at the LHC
• Comparison of flavour sensitive jet-algorithms

Outlook

• Application of Stripper to further 5-point signatures
• Working towards non-planar contributions (also for 1 ext. mass)
  → See Abreu’s summary at (HP)^2
• Flavour-tagging
  → more studies and comparisons between different algorithms needed
• Comparison with 4FS computation