# NNLO QCD corrections to W+2 b-jet production

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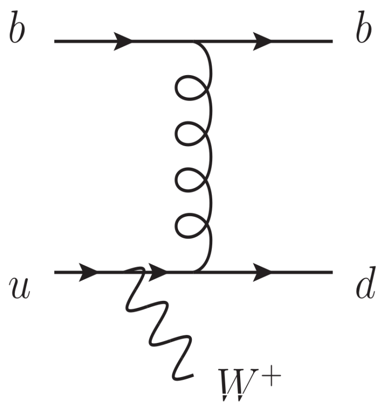
based on: [2102.02516], [2205.01687] and [2209.03280]

# W + b - jets

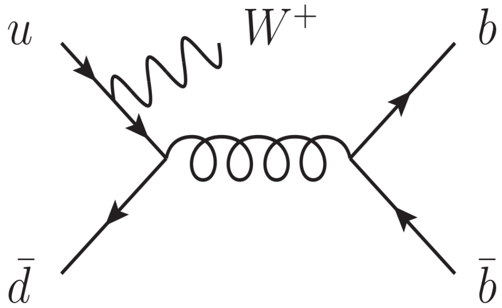
Motivation: → testing perturbative QCD: large NLO QCD corrections, 4FS vs. 5 FS
→ modelling of flavoured jets

W + 1b-jet




→ probe b quark PDFs

W + 2b-jet

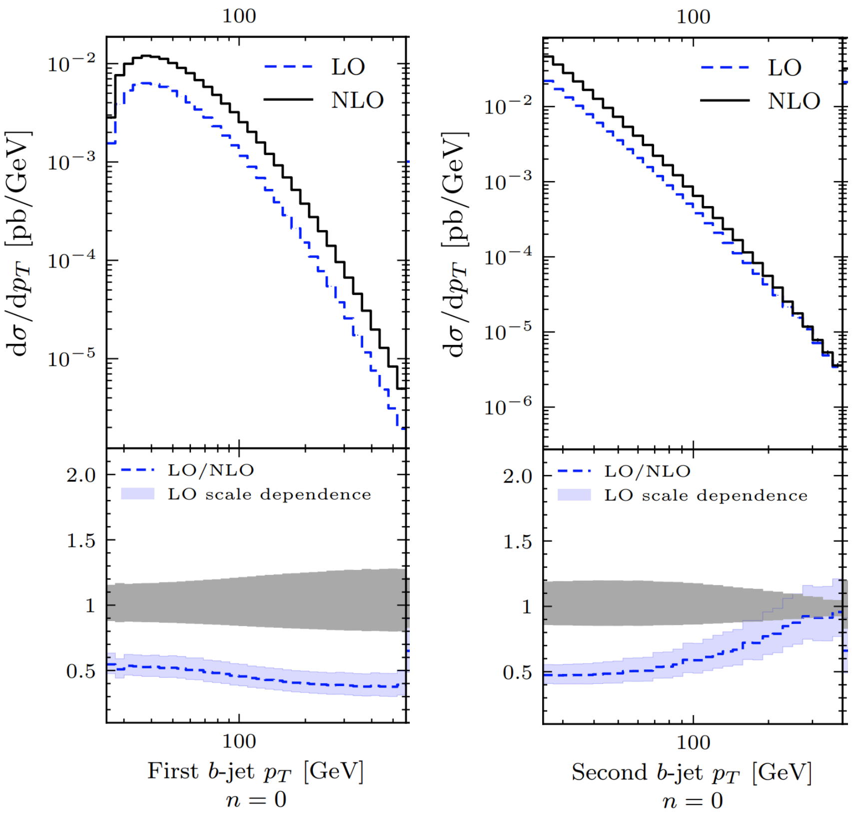



background for:
→ WH(H→ bb)
→ single top

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]
NLO+PS: [Oleari et al,1105.4488][Frederix et al,1110.5502] W(lv)bb: [Luisoni et al,1502.01213 ]
W(lv)bb+≤3j: [Anger et al, 1712.05721]

# NLO QCD corrections for W+2b-jet

**[Anger et al, 1712.05721]**

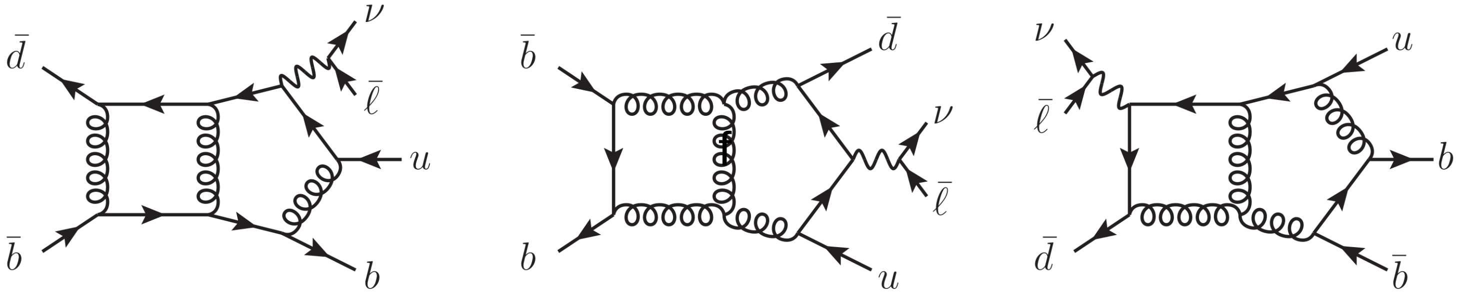



- Large NLO QCD corrections + scale dependence
- Opening of qg-channel

- 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: $A_6^{(L)} = A_5^{(L)\mu} D_\mu P$ $\quad$ $M_6^{2(L)} = \sum_{\text{spin}} A_6^{(0)^*} A_6^{(L)} = M^{(L)\mu\nu} D_{\mu\nu} |P|^2$

Projection on scalar functions (FORM+Mathematica):
→ anti-commuting $\gamma_5$ + Larin prescription

$$M_5^{(L)} = \sum_{i=1}^{16} a_i^{(L)} v_i^{\mu\nu}$$

$$a_i^{(L)} = a_i^{(L),\text{even}} + \text{tr}_5 a_i^{(L),\text{odd}} \qquad a_i^{(L),p} = \sum_i c_{j,i}(\{p\},\epsilon) \mathcal{I}(\{p\},\epsilon)$$

# Amplitude reduction

Projection

Integration-by-parts
LiteRed [Lee]

Differential equations

$$\mathrm{d}\vec{\mathrm{MI}} = \epsilon\,\mathrm{d}\tilde{A}(\{p\})\vec{\mathrm{MI}}$$

[Remiddi, 97]
[Gehrmann, Remiddi, 99]
[Henn, 13]

Feynman diagrams

Scalar integrals

Master integrals

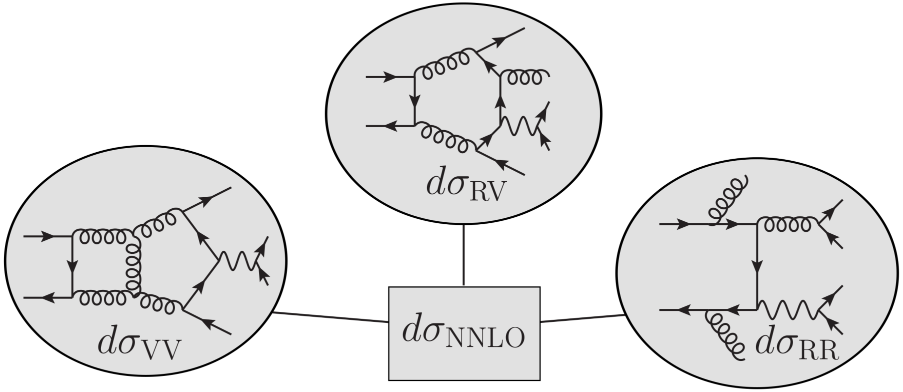
Pentagon functions
[Chicherin, Sotnikov, 20]
[Chicherin, Sotnikov, Zoia, 21]

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 γ5)

# NNLO QCD subtraction scheme

Cross section requires combination with real-radiation contributions




Credit: Bayu Hartanto

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)]

# Phenomenology

**NNLO QCD corrections to Wbb production at the LHC**
Hartanto, **Poncelet**, Popescu, Zoia 2205.01687

- LHC @ 8 TeV in 5 FS, NNPDF31, scale: $H_T = E_T(l\nu) + pT(b1) + pT(b2)$
- Phasespace definition to model **[CMS, 1608.07561]:**
  $pT(l) \geq 30$ GeV $|y(l)| < 2.1$ $pT(j) \geq 25$ GeV, $|y(j)| < 2.4$
- 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

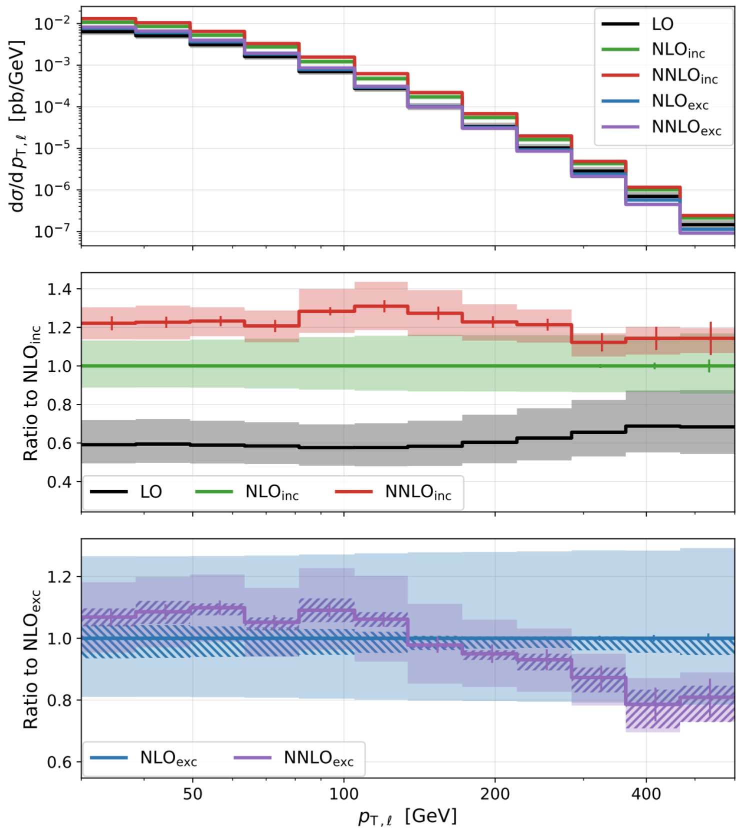
| | inclusive [fb] | $\mathcal{K}_{\rm inc}$ | exclusive [fb] | $\mathcal{K}_{\rm exc}$ |
|---|---|---|---|---|
| $\sigma_{\rm LO}$ | $213.2(1)^{+21.4\%}_{-16.1\%}$ | - | $213.2(1)^{+21.4\%}_{-16.1\%}$ | - |
| $\sigma_{\rm NLO}$ | $362.0(6)^{+13.7\%}_{-11.4\%}$ | 1.7 | $249.8(4)^{+3.9(+27)\%}_{-6.0(-19)\%}$ | 1.17 |
| $\sigma_{\rm NNLO}$ | $445(5)^{+6.7\%}_{-7.0\%}$ | 1.23 | $267(3)^{+1.8(+11)\%}_{-2.5(-11)\%}$ | 1.067 |

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

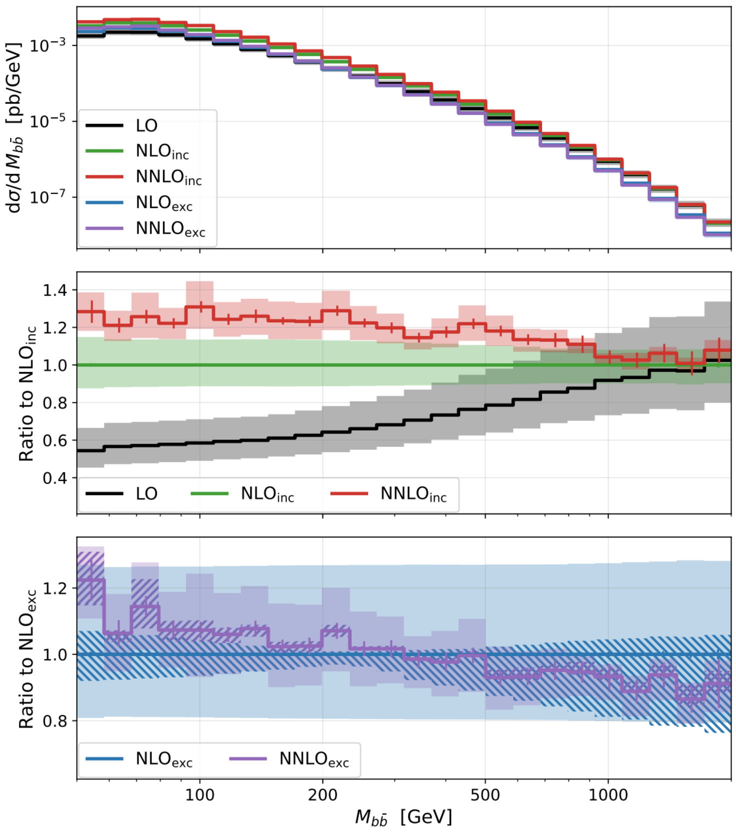
$$\Delta\sigma_{Wb\bar{b},excl.} = \sqrt{(\Delta\sigma_{Wb\bar{b},incl.})^2 + (\Delta\sigma_{Wb\bar{b}j,incl.})^2}$$

# Differential cross sections

## Transverse momentum of lepton




## Invariant mass b-jet pair



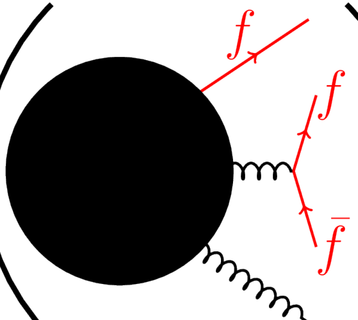
# Fixed order flavoured jets beyond NLO

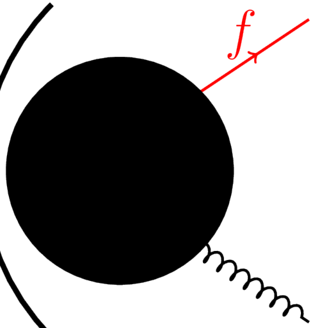
## What is the problem with FO flavoured jets?

Example NNLO: double real radiation and subtraction

Double soft subtraction term:
Double soft function * tree ME

Double real matrix element

$d\sigma \ni d\Phi_{n+2} \Bigg($ 

$\Bigg) F_{n+2} + \cdots + d\tilde{\Phi}_{n+2}\mathcal{S}_2 \Bigg($ 

$\Bigg) F_n$

Flavour structure depends on the angular configuration

IR safety:
Have to match in double soft limit

Fixed flavour structure

- If F(n+2) does not treat the flavour pair appropriately:
  → double soft singularity not subtracted

➔ Implies correlated treatment of kinematics and flavour information

# Solution: Modified jet algorithms

Flavour kT algorithm:

**Infrared safe definition of jet flavor,**
Banfi, Salam, Zanderighi hep-ph/0601139

Pair distance:

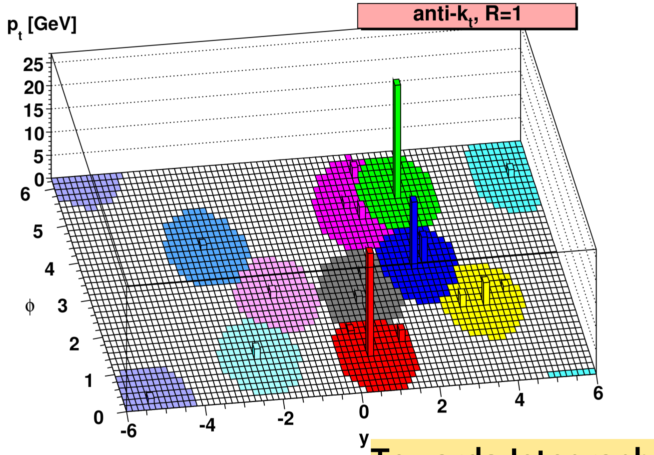
$$d_{ij} = R_{ij}^2 \begin{cases} \max(k_{T,i}, k_{T,j})^\alpha \min(k_{T,i}, k_{T,j})^{2-\alpha} & \text{softer of i,j is flavoured} \\ \min(k_{T,i}, k_{T,j})^\alpha & \text{else} \end{cases}$$

Beam distance:

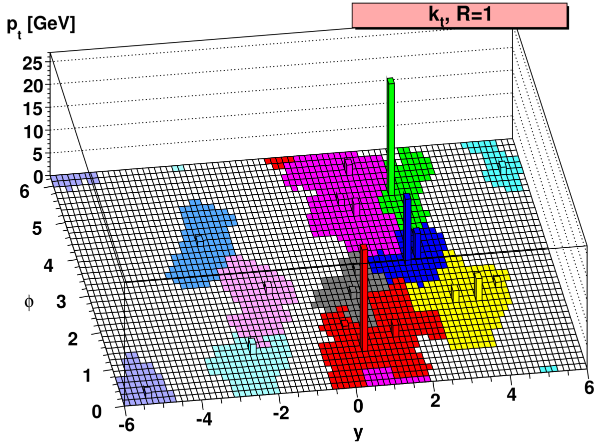
$$d_{i,B} = \begin{cases} \max(k_{T,i}, k_{T,B}(y_i))^\alpha \min(k_{T,i}, k_{T,B}(y_i))^{2-\alpha} & \text{i is flavoured} \\ \min(k_{T,i}, k_{T,B}(y_i))^\alpha & \text{else} \end{cases}$$

$$d_B(\eta) = \sum_i k_{T,i}(\theta(\eta_i - \eta) + \theta(\eta - \eta_i)e^{\eta_i - \eta}$$

$$d_{\bar{B}}(\eta) = \sum_i k_{T,i}(\theta(\eta - \eta_i) + \theta(\eta_i - \eta)e^{\eta - \eta_i}$$




**Towards Jetograph**
Salam 0906.1833




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.

# Old problem, new approaches

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

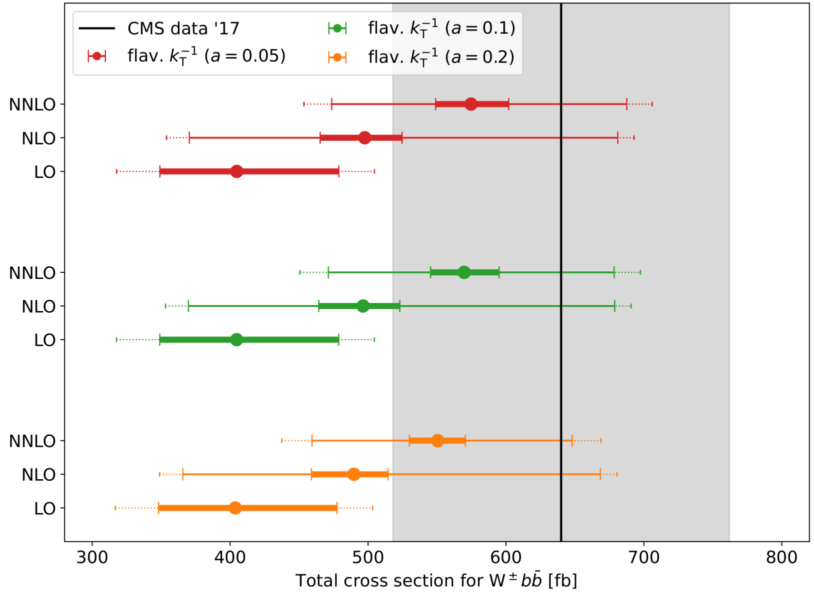
Proposed modification:
A soft term designed to modify the distance of flavoured pairs.

$$d_{ij}^{(F)} = d_{ij} \begin{cases} \mathcal{S}_{ij} & \text{i,j is flavoured pair} \\ 1 & \text{else} \end{cases}$$

$$\mathcal{S}_{ij} = 1 - \theta(1-x)\cos\left(\frac{\pi}{2}x\right) \quad \text{with} \quad x = \frac{k_{T,i}^2 + k_{T,j}^2}{2ak_{T,\max}^2}$$

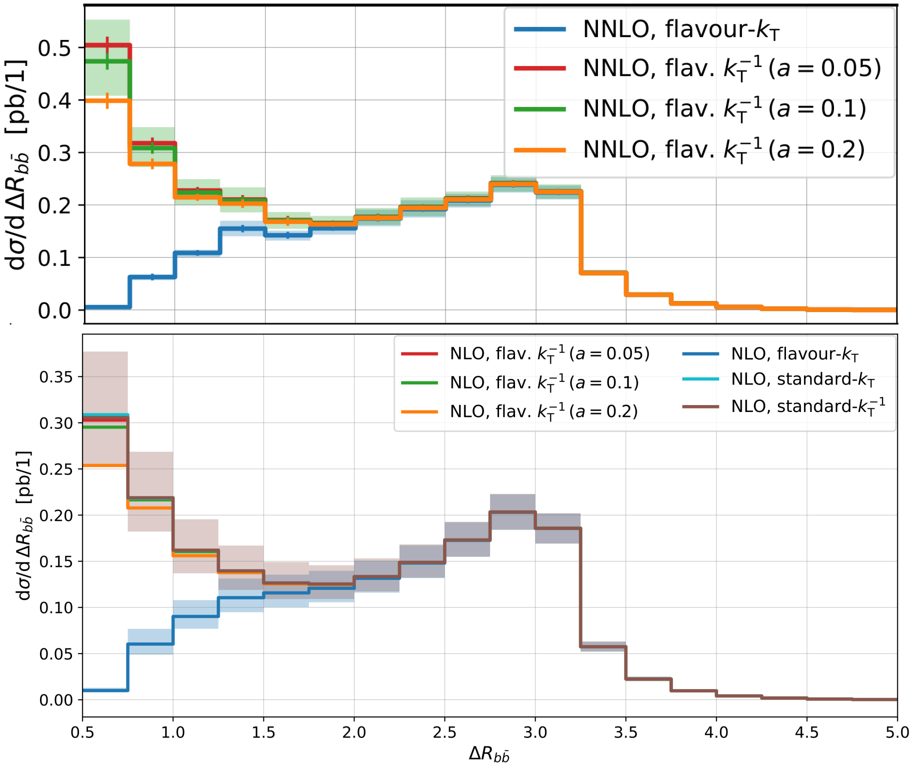
# W+2 bjets: flavour anti-kT

**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