$Wb\bar{b}$ production at NNLO QCD

Heribertus Bayu Hartanto

based on work with: Simon Badger, Rene Poncelet,
Andrei Popescu and Simone Zoia

arXiv:2102.02516, arXiv:2205.01687, arXiv:2209.03280

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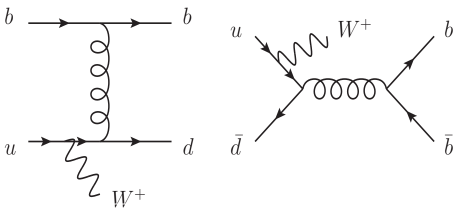
$W + b$ jets



⇒ test perturbative QCD

⇒ modelling of flavoured jets

⇒ theoretical approach: 4FS vs 5FS

$W + 1b$ jet: probe b quark PDFs

$W + 2b$ jets: backgrounds for

- Higgs-strahlung $pp \to WH(H \to b\bar{b})$
- single top $pp \to bt(t \to bW)$

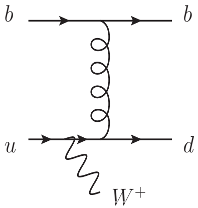
Measured at Tevatron[hep-ex/0410062][arXiv:1210.0627] and LHC[arXiv:1109.1470][arXiv:1302.2929][arXiv:1312.6608][arXiv:1608.07561]
talk by Vieri Candelise on Friday

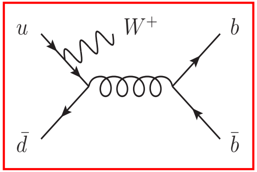
Theoretical predictions available at NLO:

$W + 1b$: [Campbell,Ellis,Maltoni,Willenbrock(2006)][Campbell,Ellis,Febres Cordero,Maltoni,Reina,Wackeroth,Willenbrock(2008)]
[Caola,Campbell,Febres Cordero,Reina,Wackeroth(2011)]

$W + 2b$: $m_b = 0$[Ellis,Veseli(1999)], onshell W[Febres Cordero,Reina,Wackeroth(2006,2009)], $W(\ell\nu)b\bar{b}$[Badger,Campbell,Ellis(2010)]
NLO+PS[Oleari,Reina(2011)][Frederix etal(2011)], $W(\ell\nu)b\bar{b}j$ [Luisoni,Oleari,Tramontano(2015)]
$W(\ell\nu)b\bar{b}+ \leq 3$j[Anger,Febres Corder,Ita,Sotnikov(2018)]

$W + b$ jets





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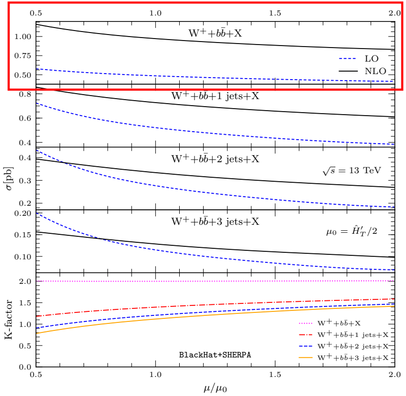
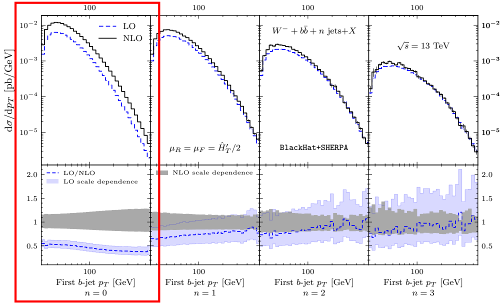
$Wb\bar{b}$+jets production at NLO QCD

[Anger,Febres Cordero,Ita,Sotnikov(2017)]





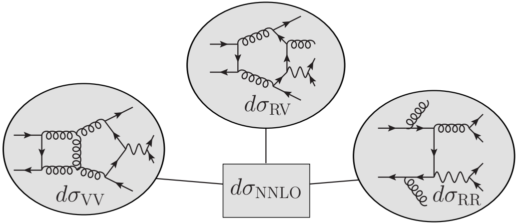
⇒ $Wb\bar{b} + X$ (inclusive, $n = 0$): large NLO corrections, large NLO scale dependence

⇒ due opening of qg channel at NLO

NNLO QCD corrections to $Wb\bar{b}$ production is required!

NNLO QCD corrections to $W(\to \ell\nu)b\bar{b}$ production

NNLO QCD calculation for $W + 2b$-jets: massless b (5FS)[**HBH**,Poncelet,Popescu,Zoia(2022)]
massive b (4FS)[Buonocore,Devoto,Kallweit,Mazzitelli,Rottoli,Savoini(2022)]



- Amplitudes:
  - Tree-level $pp \to W(\to \ell\nu)b\bar{b}jj$: AvH[Bury,van Hameren(2015)]
  - 1-loop $pp \to W(\to \ell\nu)b\bar{b}j$: OpenLoops[Bucionni,Lang,Lindert,Maierhoefer,Pozzorini,Zhang,Zoller(2018,2019)]
  - 2-loop $u\bar{d} \to W(\to \ell\nu)b\bar{b}$: [Abreu,Febres Cordero,Ita,Klinkert,Page(2021)][**HBH**,Poncelet,Popescu,Zoia(2022)]
- NNLO subtraction scheme: Sector Improved Residue Subtraction Scheme (Stripper) [Czakon(2010)][Czakon,Heymes(2014)]

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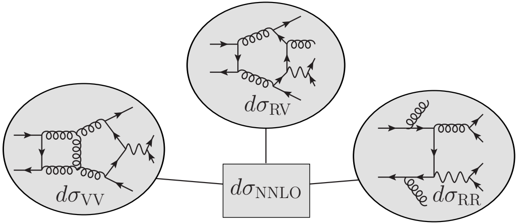

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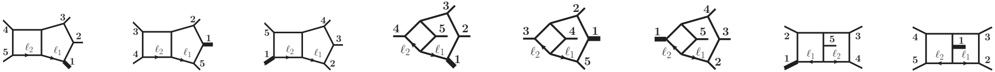
Two-Loop Scattering Amplitude

$2 \to 3$ scattering with an off-shell leg at two loops

talk by Federica Devoto on Monday on massless 2-loop 5-point amplitudes

- Multi-loop scattering amplitude: $A^{(2)} = c(\epsilon, \{p\})\ \mathrm{MI}(\epsilon, \{p\})$
- All two-loop master integrals are known!!!

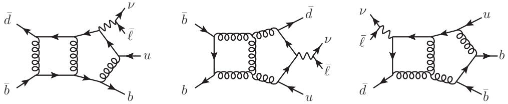


[Papadopoulos,Tommasini,Wever(2015)] [Papadopoulos,Wever(2019)] [Abreu,Ita,Moriello,Page,Tschernow,Zeng(2020)]
[Canko,Papadopoulos,Syrrakos(2020)] [Syrrakos(2020)][Abreu,Ita,Page,Tschernow(2021)] [Kardos,Papadopoulos,Smirnov,Syrrakos,Wever(2022)]
[Abreu,Chicherin,Ita,Page,Sotnikov,Tschernow,Zoia(2023)]

$\Rightarrow$ Pentagon function basis $\Rightarrow$ fast numerical evaluation available
[Chicherin,Sotnikov,Zoia(2021)][Abreu,Chicherin,Ita,Page,Sotnikov,Tschernow,Zoia(2023)]

- Several two-loop QCD amplitudes known analytically at leading colour
  - $pp \to Wb\bar{b}$, $pp \to W^+(\to \bar{\ell}\nu)b\bar{b}$, $pp \to Hb\bar{b}$ (massless b)
    [Badger,**HBH**,Zoia(2021)][Badger,**HBH**,Krys,Zoia(2021)][**HBH**,Poncelet,Popescu,Zoia(2022)]
  - $pp \to W/Z + jj$ [Abreu,Febres Cordero,Ita,Klinkert,Page(2021)] $pp \to W^+(\to \bar{\ell}\nu)\gamma j$ [Badger,**HBH**,Krys,Zoia(2022)]
- Towards full colour amplitudes: determination of coefficients extremely complicated
  $\Rightarrow$ extremely large algebraic expressions and huge integral reduction tables!!!

$u\bar{d} \to W^+(\to \bar{\ell}\nu)b\bar{b}$ at two loops [Badger,**HBH**,Zoia(2021)][**HBH**,Poncelet,Popescu,Zoia(2022)]



⇒ leading colour approximation and massless b quark

⇒ compute squared matrix element

$$\sum \mathcal{M}^{(0)*}\mathcal{M}^{(2)} = M^{(2)}_{\text{even}} + \text{tr}_5\, M^{(2)}_{\text{odd}}$$

$$\text{tr}_5 = 4\text{i}\varepsilon_{\mu\nu\rho\sigma} p_1^\mu p_2^\nu p_3^\rho p_4^\sigma$$

employ CDR+Larin scheme to treat γ_5.

⇒ Incorporating $W \to \ell\nu$ decay

$$M_6^{(L)} = \sum_{\text{spin}} A_6^{(0)\dagger} A_6^{(L)} = M_5^{(L)\mu\nu}\, \mathcal{D}_{\mu\nu}\, |P(s_{56})|^2$$

$$M_5^{(L)\mu\nu} = \sum_{i=1}^{16} a_i^{(L)} v_i^{\mu\nu} \qquad v_i^{\mu\nu} \in \{p_1^\mu, p_2^\mu, p_3^\mu, p_W^\mu\}$$

Derive analytic expressions of the finite remainders using finite-field reconstruction method

talk by Xiao Liu on Tuesday on analytic reconstruction method

QGRAF[Nogueira], FORM[Vermaseren], LiteRed[Lee], FiniteFlow[Peraro], Mathematica

$$M_k^{(2)}(\{p\},\epsilon) = \sum_i c_{k,i}(\{p\},\epsilon)\, \mathcal{I}_{k,i}(\{p\},\epsilon)$$

$\downarrow$ IBP reduction

$$M_k^{(2)}(\{p\},\epsilon) = \sum_i d_{k,i}(\{p\},\epsilon)\, \text{MI}_{k,i}(\{p\},\epsilon)$$

$\downarrow$ map to pentagon function basis

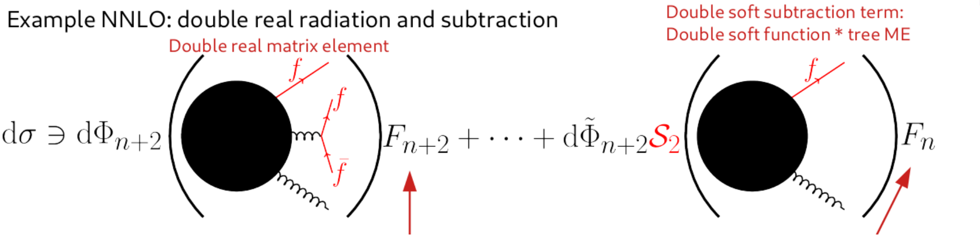
$\downarrow$ subtract UV/IR poles

$\downarrow$ ϵ expansion

$$F_k^{(2)}(\{p\}) = \sum_i e_{k,i}(\{p\})\, m_{k,i}(f) + \mathcal{O}(\epsilon)$$

Numerical Results

Fixed-order flavoured jets beyond NLO



Mistreatment of flavour pair in F_{n+2} $\Rightarrow$ mismatch w.r.t F_n $\Rightarrow$ double soft singularity not subtracted

Solutions:

- Flavour-k_T jet algorithm [Banfi,Salam,Zanderighi(2006)] $\rightarrow$ data/theory comparison requires unfolding
- Practical jet flavour through NNLO [Caletti,Larkoski,Marzani,Reichelt(2022)]
- Infrared-safe flavoured anti-k_T jets [Czakon,Mitov,Poncelet(2022)]
- A dress of flavour to suit any jet [Gauld,Huss,Stagnitto(2022)]
- Flavoured jets with exact anti-k_T kinematics [Caola,Grabarczyk,Hutt,Salam,Scyboz,Thaler(2023)]

talks by Mathieu Pellen this morning (W+c) and Ludovic Scyboz on Thursday

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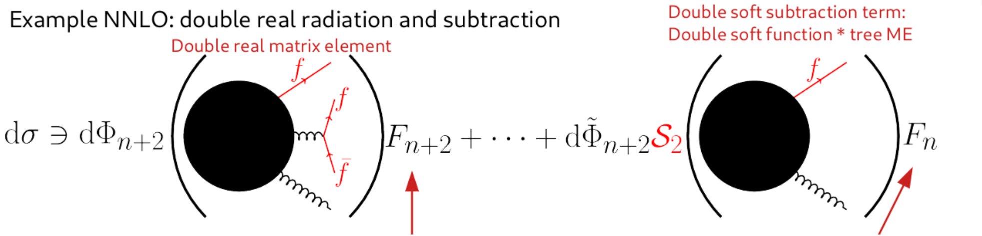

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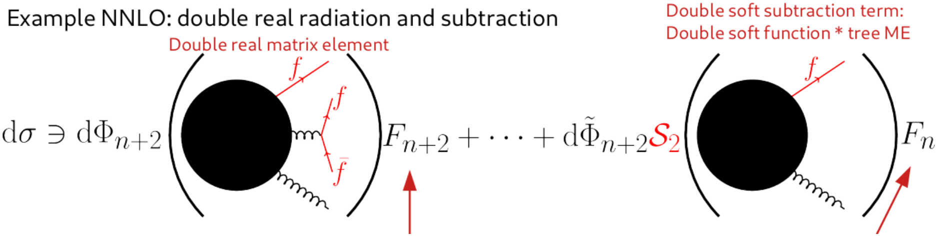

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Infrared-safe flavoured anti-k_T jet algorithm [Czakon,Mitov,Poncelet(2022)]
$\Rightarrow$ introduce damping function to the standard anti-k_T

$$\mathcal{S}_{ij} = 1 - \Theta(1-x)\cdot\cos\left(\frac{\pi}{2}x\right) \leq 1 \qquad x \equiv \frac{1}{a}\frac{k_{T,i}^2 + k_{T,j}^2}{2k_{T,\max}^2}$$

if i, j have the same non-zero flavour of opposite sign, a: tunable *softness* parameter

$\Rightarrow$ minimize the effect of unfolding

Setup (follows CMS measurement[arXiv:1608.07561])

⇒ **5FS**, LHC 8 TeV, PDFs: NNPDF31, cuts: $p_{T,\ell} > 30$ GeV, $|\eta_\ell| < 2.1$, $p_{T,j} > 25$ GeV, $|\eta_j| < 2.4$

⇒ jet algorithm: flavour-k_T[Banfi,Salam,Zanderighi(2006)] and flavour anti-k_T[Czakon,Mitov,Poncelet(2022)] with $R = 0.5$

⇒ central scale: $\mu_R = \mu_F = \mu_0$, where $H_T = E_T(\ell\nu) + p_T(b_1) + p_T(b_2)$.

⇒ final states: **inclusive** (at least 2 b jets) and **exclusive** (exactly two b jets and no other jets).

⇒ scale uncertainties: inclusive → 7-pt variation $1/2 \le \mu_R/\mu_F \le 2$

exclusive → 7-pt variation and uncorrelated prescription[Stewart,Tackmann(2012)]

Uncorrelated scale variation $\sigma_{Wb\bar{b},\mathrm{exc}} = \sigma_{Wb\bar{b},\mathrm{inc}} - \sigma_{Wbbj,inc}$ $\Delta\sigma_{Wb\bar{b},\mathrm{exc}} = \sqrt{\left(\Delta\sigma_{Wb\bar{b},\mathrm{inc}}\right)^2 + \left(\Delta\sigma_{Wbbj,inc}\right)^2}$

Leading colour approximation is only applied to *scale independent* double virtual finite remainder

$$\mathcal{V}^{(2)}(\mu_R^2) = \mathcal{V}^{(2)}_{\mathrm{LC}}(s_{12}) + \sum_{i=1}^{4} c_i \ln^i\left(\frac{\mu_R^2}{s_{12}}\right)$$

Double virtual contributions to σ: 5% (inc) and 10% (exc), expected SLC: 0.5% (inc) and 1% (exc)

Numerical results: cross sections

$$K_{\text{NLO}} = \frac{\sigma_{\text{NLO}}}{\sigma_{\text{LO}}} \qquad K_{\text{NNLO}} = \frac{\sigma_{\text{NNLO}}}{\sigma_{\text{NLO}}}$$

Inclusive $W^+(\to \ell^+\nu)b\bar{b}$ cross sections

Jet algorithm	σ_{LO} [fb]	σ_{NLO} [fb]	K_{NLO}	σ_{NNLO} [fb]	K_{NNLO}
flavour-k_T	$213.24(8)^{+21.4\%}_{-16.1\%}$	$362.0(6)^{+13.7\%}_{-11.4\%}$	1.70	$445(5)^{+6.7\%}_{-7.0\%}$	1.23
flavour anti-k_T ($a = 0.05$)	$262.52(10)^{+21.4\%}_{-16.1\%}$	$500.9(8)^{+16.1\%}_{-12.8\%}$	1.91	$690(7)^{+10.9\%}_{-9.7\%}$	1.38
flavour anti-k_T ($a = 0.1$)	$262.47(10)^{+21.4\%}_{-16.1\%}$	$497.8(8)^{+16.0\%}_{-12.7\%}$	1.90	$677(7)^{+10.4\%}_{-9.4\%}$	1.36
flavour anti-k_T ($a = 0.2$)	$261.71(10)^{+21.4\%}_{-16.1\%}$	$486.3(8)^{+15.5\%}_{-12.5\%}$	1.86	$647(7)^{+9.5\%}_{-8.9\%}$	1.33

Exclusive $W^\pm(\to \ell^\pm\nu)b\bar{b}$ cross sections

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flavour-k_T	$345.97(9)^{+21.4\%}_{-16.2\%}$	$408.4(5)^{+4.2\%\ (41\%)}_{-6.2\%\ (28\%)}$	1.18	$434(8)^{+1.7\%\ (16\%)}_{-2.5\%\ (16\%)}$	1.06
flavour anti-k_T ($a = 0.05$)	$425.71(12)^{+21.5\%}_{-16.2\%}$	$540.3(7)^{+6.2\%\ (42\%)}_{-7.4\%\ (29\%)}$	1.27	$636(11)^{+5.4\%\ (23\%)}_{-5.0\%\ (20\%)}$	1.18
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flavour anti-k_T ($a = 0.05$)	$262.52(10)^{+21.4\%}_{-16.1\%}$	$500.9(8)^{+16.1\%}_{-12.8\%}$	1.91	$690(7)^{+10.9\%}_{-9.7\%}$	1.38
flavour anti-k_T ($a = 0.1$)	$262.47(10)^{+21.4\%}_{-16.1\%}$	$497.8(8)^{+16.0\%}_{-12.7\%}$	1.90	$677(7)^{+10.4\%}_{-9.4\%}$	1.36
flavour anti-k_T ($a = 0.2$)	$261.71(10)^{+21.4\%}_{-16.1\%}$	$486.3(8)^{+15.5\%}_{-12.5\%}$	1.86	$647(7)^{+9.5\%}_{-8.9\%}$	1.33

Exclusive $W^\pm(\to \ell^\pm\nu)b\bar{b}$ cross sections

Jet algorithm	σ_{LO} [fb]	σ_{NLO} [fb]	K_{NLO}	σ_{NNLO} [fb]	K_{NNLO}
flavour-k_T	$345.97(9)^{+21.4\%}_{-16.2\%}$	$408.4(5)^{+4.2\%\ (41\%)}_{-6.2\%\ (28\%)}$	1.18	$434(8)^{+1.7\%\ (16\%)}_{-2.5\%\ (16\%)}$	1.06
flavour anti-k_T ($a = 0.05$)	$425.71(12)^{+21.5\%}_{-16.2\%}$	$540.3(7)^{+6.2\%\ (42\%)}_{-7.4\%\ (29\%)}$	1.27	$636(11)^{+5.4\%\ (23\%)}_{-5.0\%\ (20\%)}$	1.18
flavour anti-k_T ($a = 0.1$)	$425.63(12)^{+21.5\%}_{-16.2\%}$	$538.7(7)^{+6.1\%\ (42\%)}_{-7.4\%\ (29\%)}$	1.27	$630(10)^{+5.0\%\ (22\%)}_{-4.8\%\ (20\%)}$	1.17
flavour anti-k_T ($a = 0.2$)	$424.37(12)^{+21.5\%}_{-16.2\%}$	$530.6(7)^{+5.8\%\ (42\%)}_{-7.2\%\ (29\%)}$	1.25	$606(10)^{+4.2\%\ (21\%)}_{-4.2\%\ (19\%)}$	1.14

Numerical results: cross sections

$$K_{\mathrm{NLO}} = \frac{\sigma_{\mathrm{NLO}}}{\sigma_{\mathrm{LO}}} \qquad K_{\mathrm{NNLO}} = \frac{\sigma_{\mathrm{NNLO}}}{\sigma_{\mathrm{NLO}}}$$

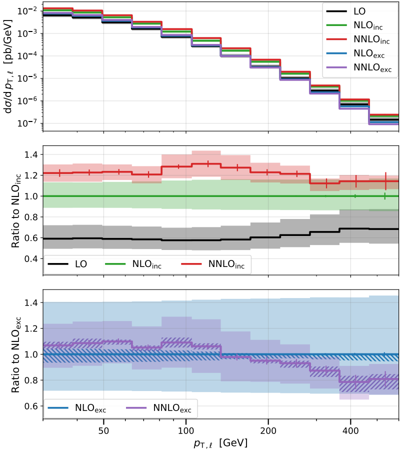
Inclusive $W^+(\to \ell^+\nu)b\bar{b}$ cross sections

Jet algorithm	σ_{LO} [fb]	σ_{NLO} [fb]	K_{NLO}	σ_{NNLO} [fb]	K_{NNLO}
flavour-k_T	$213.24(8)^{+21.4\%}_{-16.1\%}$	$362.0(6)^{+13.7\%}_{-11.4\%}$	1.70	$445(5)^{+6.7\%}_{-7.0\%}$	1.23
flavour anti-k_T ($a = 0.05$)	$262.52(10)^{+21.4\%}_{-16.1\%}$	$500.9(8)^{+16.1\%}_{-12.8\%}$	1.91	$690(7)^{+10.9\%}_{-9.7\%}$	1.38
flavour anti-k_T ($a = 0.1$)	$262.47(10)^{+21.4\%}_{-16.1\%}$	$497.8(8)^{+16.0\%}_{-12.7\%}$	1.90	$677(7)^{+10.4\%}_{-9.4\%}$	1.36
flavour anti-k_T ($a = 0.2$)	$261.71(10)^{+21.4\%}_{-16.1\%}$	$486.3(8)^{+15.5\%}_{-12.5\%}$	1.86	$647(7)^{+9.5\%}_{-8.9\%}$	1.33

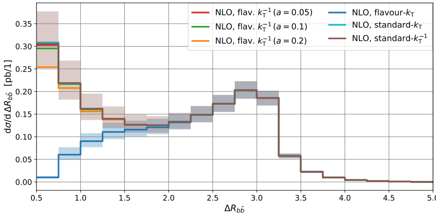
Exclusive $W^\pm(\to \ell^\pm\nu)b\bar{b}$ cross sections

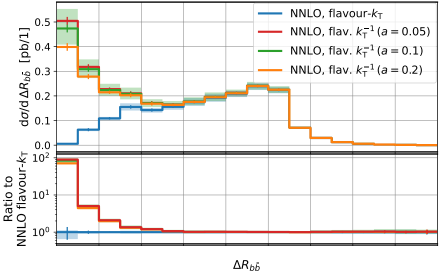
Jet algorithm	σ_{LO} [fb]	σ_{NLO} [fb]	K_{NLO}	σ_{NNLO} [fb]	K_{NNLO}
flavour-k_T	$345.97(9)^{+21.4\%}_{-16.2\%}$	$408.4(5)^{+4.2\%\,(41\%)}_{-6.2\%\,(28\%)}$	1.18	$434(8)^{+1.7\%\,(16\%)}_{-2.5\%\,(16\%)}$	1.06
flavour anti-k_T ($a = 0.05$)	$425.71(12)^{+21.5\%}_{-16.2\%}$	$540.3(7)^{+6.2\%\,(42\%)}_{-7.4\%\,(29\%)}$	1.27	$636(11)^{+5.4\%\,(23\%)}_{-5.0\%\,(20\%)}$	1.18
flavour anti-k_T ($a = 0.1$)	$425.63(12)^{+21.5\%}_{-16.2\%}$	$538.7(7)^{+6.1\%\,(42\%)}_{-7.4\%\,(29\%)}$	1.27	$630(10)^{+5.0\%\,(22\%)}_{-4.8\%\,(20\%)}$	1.17
flavour anti-k_T ($a = 0.2$)	$424.37(12)^{+21.5\%}_{-16.2\%}$	$530.6(7)^{+5.8\%\,(42\%)}_{-7.2\%\,(29\%)}$	1.25	$606(10)^{+4.2\%\,(21\%)}_{-4.2\%\,(19\%)}$	1.14

Numerical results: differential distributions



$W^+(\to \ell^+\nu)b\bar{b}$ with flavour-k_T

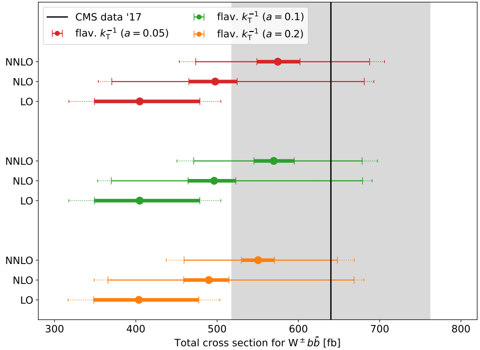




inclusive $W^+(\to \ell^+\nu)b\bar{b}$

Comparison to CMS data [arXiv:1608.07561]

- CMS measurement is done for exclusive final state configuration
- The use of flavour anti-k_T algorithm in theoretical calculation allows for close comparison with CMS data (standard anti-k_T)
  $\Rightarrow$ unfolding corrections expected to be small
- Correction factors included:
  hadronisation (multiplicative) $= 0.81 \pm 0.07$
  DPI (additive) $= 0.06 \pm 0.06$ pb



[**HBH**,Poncelet,Popescu,Zoia;arXiv:2209.03280]

- **Thick** bands: 7-pt scale variation (without DPI error)
  thin bands: uncorrelated prescription (without DPI error),
  dotted bands: uncorrelated prescription (with DPI error)

$Wb\bar{b}$: 4FS vs 5FS comparison

NNLO QCD calculation for $Wb\bar{b}$ with massive b quark (4FS) [Buonocore,Devoto,Kallweit,Mazzitelli,Rottoli,Savoini(2022)]

- main bottleneck: two-loop matrix element is still out of reach $\Rightarrow$ use massification procedure [Mitov,Moch(2007)]

$$\mathcal{M}^{Wb\bar{b},(m)} = \prod_{i\in b,\bar{b}} \left(Z_{[i]}^{(m|0)} \right)^{\frac{1}{2}} \mathcal{M}^{Wb\bar{b},(m=0)} + \mathcal{O}(m^k)$$

  predicts poles, $\log(m)$ and mass independent terms but not m^k and heavy quark loops
  talk by Simone Devoto on Friday

- b-quark mass regulates IR divergencies in the double soft limit
  $\Rightarrow$ can use standard anti-k_T jet algorithm

- massless (5FS) vs massive (4FS) comparison

order	σ^{4FS} [fb]	$\sigma^{5FS}_{a=0.05}$ [fb]	$\sigma^{5FS}_{a=0.1}$ [fb]	$\sigma^{5FS}_{a=0.2}$ [fb]
LO	$210.42(2)^{+21.4\%}_{-16.2\%}$	$262.52(10)^{+21.4\%}_{-16.1\%}$	$262.47(10)^{+21.4\%}_{-16.1\%}$	$261.71(10)^{+21.4\%}_{-16.1\%}$
NLO	$468.01(5)^{+17.8\%}_{-13.8\%}$	$500.9(8)^{+16.1\%}_{-12.8\%}$	$497.8(8)^{+16.0\%}_{-12.7\%}$	$486.3(8)^{+15.5\%}_{-12.5\%}$
NNLO	$636.4(1.6)^{+11.9\%}_{-10.5\%}$	$690(7)^{+10.9\%}_{-9.7\%}$	$677(7)^{+10.4\%}_{-9.4\%}$	$647(7)^{+9.5\%}_{-9.4\%}$

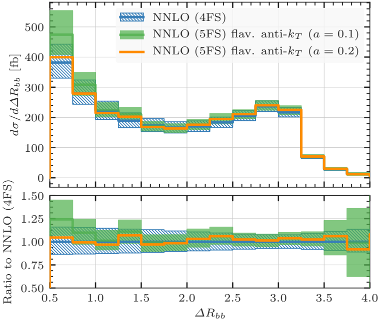


Table and Figure from [Buonocore,Devoto,Kallweit,Mazzitelli,Rottoli,Savoini(2022)]

Summary

Summary & Outlooks

Summary:

✓ NNLO QCD predictions for $W(\to \ell\nu)b\bar{b}$ production at the LHC
$\Rightarrow$ improved perturbative convergence
$\Rightarrow$ better agreement with CMS measurements

✓ Comparison between 4FS and 5FS calculations

✓ Two-loop amplitude for 5-point process with one external mass (at leading colour)

Outlooks:

- Full colour two-loop amplitude
- $W + 1b$ jet at NNLO QCD $\Rightarrow$ comparison with data, 4FS vs 5FS
- NNLO+PS matching for the massive $Wb\bar{b}$ calculation talk by Emanuele Re on Monday

Back-up Slides

NNLO vs NLO-merged calculation

$$K_{\mathrm{NNLO}} = \frac{\sigma_{\mathrm{NNLO}}}{\sigma_{\mathrm{NLO}}} \qquad K_{\mathrm{NLO+}} = \frac{\sigma_{\mathrm{NLO+}}}{\sigma_{\mathrm{NLO}}}$$

Inclusive $W^+(\to \ell^+\nu)b\bar{b}$ cross sections

Jet algorithm	σ_{NLO} [fb]	σ_{NNLO} [fb]	K_{NNLO}	$\sigma_{\mathrm{NLO+}}$ [fb]	$K_{\mathrm{NLO+}}$
flavour-k_T	$362.0(6)^{+13.7\%}_{-11.4\%}$	$445(5)^{+6.7\%}_{-7.0\%}$	1.23	$426(5)^{+7.6\%}_{-8.9\%}$	1.18
flavour anti-k_T ($a = 0.05$)	$500.9(8)^{+16.1\%}_{-12.8\%}$	$690(7)^{+10.9\%}_{-9.7\%}$	1.38	$635(6)^{+11.2\%}_{-11.1\%}$	1.27
flavour anti-k_T ($a = 0.1$)	$497.8(8)^{+16.0\%}_{-12.7\%}$	$677(7)^{+10.4\%}_{-9.4\%}$	1.36	$626(6)^{+10.8\%}_{-10.9\%}$	1.26
flavour anti-k_T ($a = 0.2$)	$486.3(8)^{+15.5\%}_{-12.5\%}$	$647(7)^{+9.5\%}_{-8.9\%}$	1.33	$602(6)^{+10.2\%}_{-10.5\%}$	1.24

Large corrections and scale dep at NLO

$\Rightarrow$ $qg(\bar{q}g) \to Wb\bar{b}q(\bar{q})$ subprocess

$\Rightarrow$ upgrade $pp \to Wb\bar{b}j$ to NLO

[Luisoni,Oleari,Tramontano(2015)]

Combine $Wb\bar{b}$ and $Wb\bar{b}j$ NLO cross sections using *exclusive sums* method

[The SM and NLO Multileg and SM MC Working Groups: Summary Report(2012)]

[Anger,Febres Cordero,Ita,Sotnikov(2017)]

$$\sigma_{\mathrm{NLO+},Wb\bar{b},\mathrm{inc}} = \sigma_{\mathrm{NLO},Wb\bar{b},\mathrm{exc}} + \sigma_{\mathrm{NLO},Wb\bar{b}j,\mathrm{inc}}$$