QCD corrections to $Wb\bar{b}$ production at the LHC

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based on **arXiv:2205.01687[hep-ph]**

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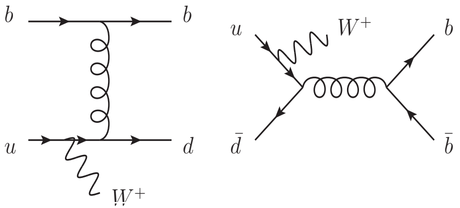
$W + b$ jets



⇒ testing 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]

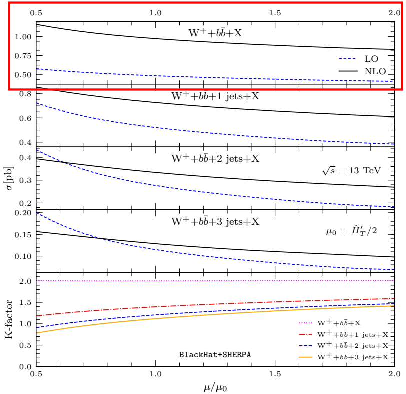
Theoretical predictions available at NLO:

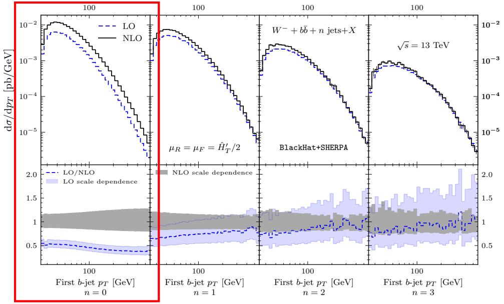
$W + 1b$: [Campbell,Ellis,Maltoni,Willenbrock(2006)][Campbell,Ellis,Febres Cordero,Maltoni,Reina,Wackeroth,Willenbrock(2008)]
[Caola,Campbell,Febres Cordero,Reina,Wackeroth(2011)]

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

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

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



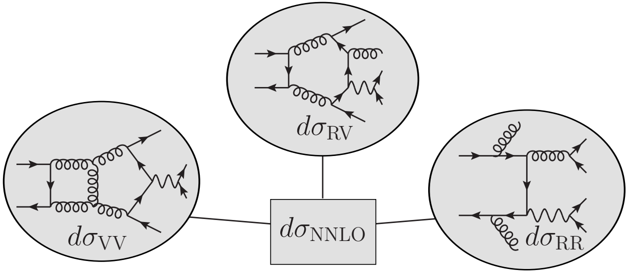


⇒ $n = 0$: large NLO corrections, large NLO scale dependence

⇒ opening of qg channel at NLO

Our work: compute NNLO QCD corrections to $Wb\bar{b}$ production

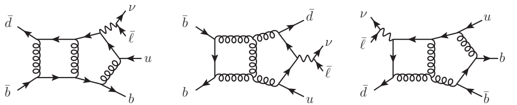
NNLO QCD corrections to $W(\to \ell\nu)b\bar{b}$ production



- 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 $u\bar{d} \to W(\to \ell\nu)b\bar{b}$: this work
- NNLO subtraction scheme: Sector Improved Residue Subtraction Scheme (Stripper) [Czakon(2010)][Czakon,Heymes(2014)]
- First NNLO QCD calculation for 2 → 3 process involving external mass

Two-loop amplitude

$$u\bar{d} \to W(\to \nu\bar{\ell})b\bar{b}$$



⇒ leading colour approximation and massless b quark

2-loop amplitude for on-shell W has been computed in [Badger,Hartanto,Zoia(2021)]

Incorporate $W \to \ell\nu$ decay:

$$A_6^{(L)} = A_5^{(L)\mu}\, D_\mu\, P(s_{56}), \qquad M_6^{(L)} = \sum_{\text{spin}} A_6^{(0)\dagger} A_6^{(L)} = M_5^{(L)\mu\nu}\, \mathcal{D}_{\mu\nu}\, |P(s_{56})|^2$$

$$M_5^{(L)\mu\nu} = \sum_{i=1}^{16} a_i^{(L)} v_i^{\mu\nu}, \qquad a_i^{(L)} = \sum_j \Delta_{ij}^{-1}\, \tilde{M}_{5,j}^{(L)}, \qquad \Delta_{ij} = v_{i\mu\nu} v_j^{\mu\nu}, \qquad v_i^{\mu\nu} \in \{p_1^\mu, p_2^\mu, p_3^\mu, p_W^\mu\}$$

⇒ Derive analytic expressions using finite-field reconstruction methods (within FiniteFlow[Peraro(2019)])

⇒ Evaluate master integrals (function basis) using PentagonFunctions++[Chicherin,Sotnikov,Zoia(2021)]

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

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

Numerical results: cross section

Setup follows CMS measurement[arXiv:1608.07561]:

$\Rightarrow$ LHC $\sqrt{s} = 8$ TeV, cuts: $p_{T,\ell} > 30$ GeV, $|\eta_\ell| < 2.1$, $p_{T,j} > 25$ GeV, $|\eta_j| < 2.4$

$\Rightarrow$ PDFs: NNPDF31, jet algorithm: flavour-k_T[Banfi,Salam,Zanderighi(2006)] $R = 0.5$.

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

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

$\Rightarrow$ scale uncertainties: inclusive $\rightarrow$ 7-pt variation $1/2 \leq \mu_R/\mu_F \leq 2$

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

Uncorrelated scale variation

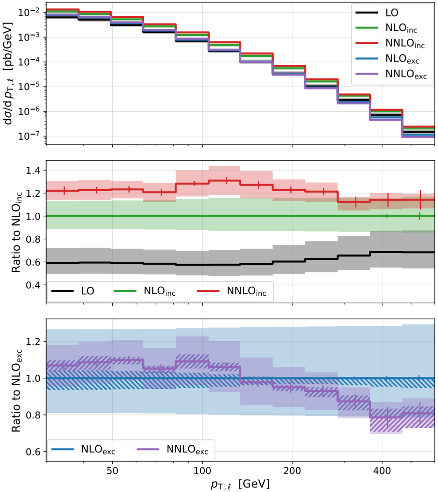
$$\sigma_{\mathrm{exc}} = \sigma_{\mathrm{inc}} - \sigma_{Wbbj,inc}$$

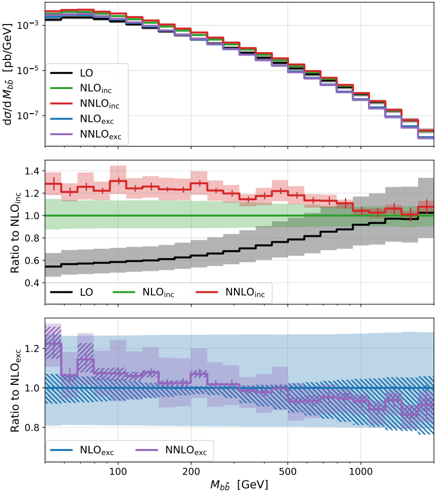
$$\Delta\sigma_{\mathrm{exc}} = \sqrt{(\Delta\sigma_{\mathrm{inc}})^2 + (\Delta\sigma_{Wbbj,inc})^2}$$

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

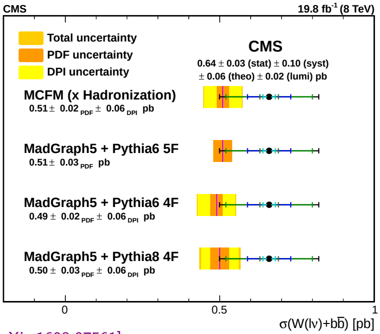
Double virtual contributions: 5% (inc) and 10% (exc), expected SLC: 0.5% (inc) and 1% (exc)

Numerical results: differential distributions

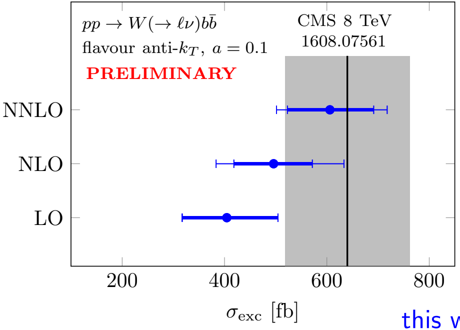




Comparison to data



CMS[arXiv:1608.07561]



this work

- Experimental measurements use anti-k_T jet algorithm:
  $\Rightarrow$ need to unfold data to match jet definition in theoretical calculation (flavour k_T)
- Use newly proposed flavour anti-k_T jet algorithm[Czakon,Mitov,Poncelet(2022)].
- hadronisation (0.81 ± 0.07) and DPI correction (0.06 ± 0.06 pb) factors included
- thick error bar → 7-pt scale variation, thin error bar → uncorrelated prescription

Conclusions

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

✓ Analytic form of the two-loop amplitude

✓ Comparison with CMS measurement using newly proposed flavour anti-k_T jet algorithm

✗ Better uncertainty prescription for exclusive cross section?

✗ PDF uncertainties

✗ Non-planar contributions to the two-loop amplitude

✗ $W + 1b$ jet at NNLO QCD

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- ✗ Better uncertainty prescription for exclusive cross section?
- ✗ PDF uncertainties
- ✗ Non-planar contributions to the two-loop amplitude
- ✗ $W + 1b$ jet at NNLO QCD

THANK YOU!!!

Back-up Slides

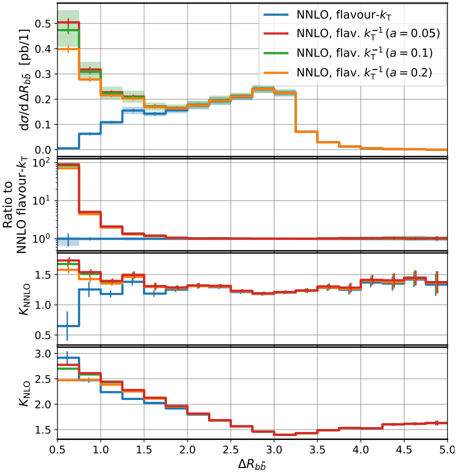
Flavoured jet algorithm study

Massless b beyond NLO: IR unsafe with standard jet algorithm due to soft wide angle $q\bar{q}$ pair

Flavour k_T [Banfi,Salam,Zanderighi(2006)] jet algorithm widely used in theoretical calculations

Experimental measurements use anti-k_T jet algorithm
⇒ unfold data to match theory definition by comparing NLO+PS employing both jet definitions
[Gauld,Gehrmann-De Ridder,Glover,Huss,Majer(2020)]

Flavour anti-k_T [Czakon,Mitov,Poncelet(2022)]
⇒ minimize the effect of unfolding
⇒ introduce damping function to the standard anti-k_T



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

if i, j have the same non-zero flavour of opposite sign

a: tunable *softness* parameter