Precise predictions for vector boson + heavy flavour production at the LHC

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State-of-the art theoretical predictions for V+heavy flavour production

NNLO NLO+PS NNLO+PS

W+c

"W+c-jet production at the LHC with NNLO QCD accuracy" [Czakon,Mitov,Pellen,Poncelet (arXiv:2110.05104)]
"A detailed investigation of W+c-jet at the LHC" [Czakon,Mitov,Pellen,Poncelet (arXiv:2212.00467)]
"Precise QCD predictions for W-boson production in association with a charm jet" [Gehrmann-De Ridder,Gehrmann,Glover,Huss, Rodriguez Garcia,Stagnitto (arXiv:2311.14991)]
"W+charm production with massive c quarks in PowHel" [Bevilacqua,Garzelli,Kardos,Toth (arXiv:2106.11261)]
"NLO + parton-shower generator for Wc production in the POWHEG BOX RES" [Ferrario Ravasio,Oleari (arXiv:2304.13791)]

Z+b

"Predictions for Z-Boson Production in Association with a b-Jet at $O(\alpha_s^3)$" [Gauld,Gehrmann-De Ridder,Glover,Huss,Majer (arXiv:2005.03016)]

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"NNLO QCD predictions for Z-boson production in association with a charm jet within the LHCb fiducial region" [Gauld,Gehrmann-De Ridder,Glover,Huss,Rodriguez Garcia,Stagnitto (arXiv:2302.12844)]

W+bb

"Next-to-next-to-leading order QCD corrections to Wbb production at the LHC" [HBH,Poncelet,Popescu,Zoia (arXiv:2205.01687)]
"Flavoured anti-kT algorithm applied to Wbb production at the LHC" [HBH,Poncelet,Popescu,Zoia (arXiv:2209.03280)]
"Associated production of a W boson and massive bottom quarks at next-to-next-to-leading order in QCD" [Buonocore,Devoto,Kallweit,Mazzitelli,Rottoli,Savoini (arXiv:2212.04954)]

Z+bb

"Next-to-next-to-leading order event generation for Z-boson production in association with a bottom-quark pair" [Mazzitelli,Sotnikov,Wiesemann (arXiv:2404.08598)]

State-of-the art theoretical predictions for V+heavy flavour production

talk by M. Grazzini on fixed order calculations ← NNLO

NLO+PS

NNLO+PS

talk by Ulla Blumenschein on recent V+HF measurements

W+c

"W+c-jet production at the LHC with NNLO QCD accuracy" [Czakon,Mitov,Pellen,Poncelet (arXiv:2110.05104)]
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Z+bb

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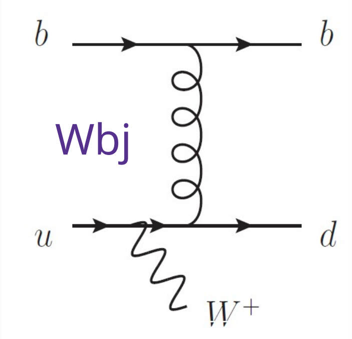
W/Z+b-jets production at the LHC

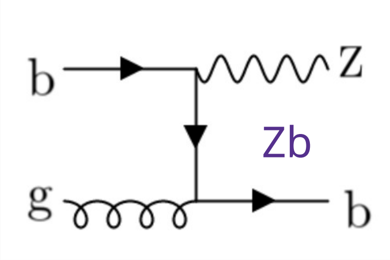
- Test perturbative QCD
- Modelling of flavoured jets (theory and experiment)
- Sensitivity to heavy flavour schemes: 4-flavour scheme (4FS) vs 5-flavour scheme (5FS)

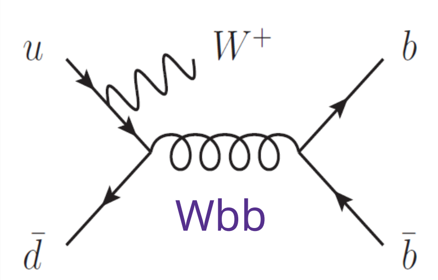
massive b — massless b



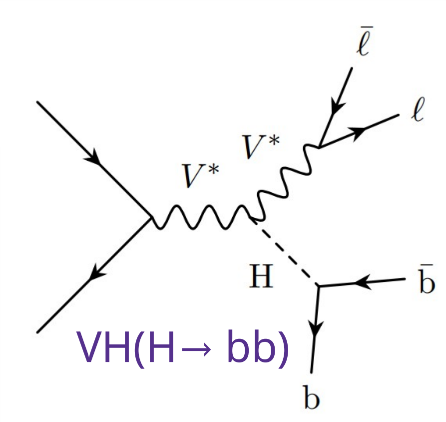
W/Z+1b jet: probe *b*-quark PDF

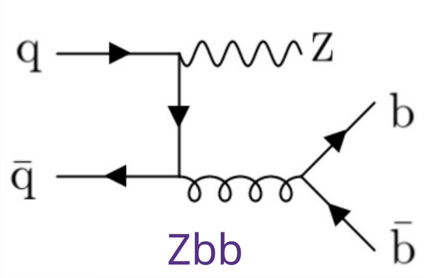
W+2b jets: background to single top production pp→bt(→bW)





W/Z+2b jets: background to VH(H→bb)



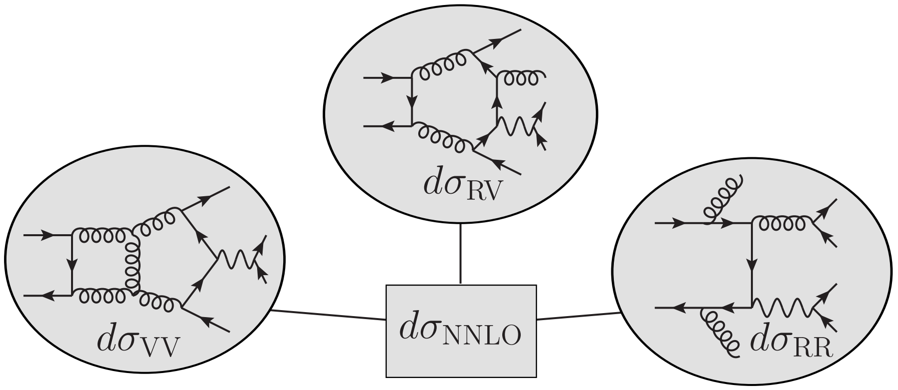


Feynman diagrams taken from arXiv:1907.05836, arXiv:2112.09659.

W+2*b* production at NNLO QCD accuracy

Massless *b* (5FS): HBH,Poncelet,Popescu,Zoia (arXiv:2205.01687,arXiv:2209.03280)

Massive *b* (4FS): Buonocore,Devoto,Kallweit,Mazzitelli,Rottoli,Savoini (arXiv:2212.04954)



W+b jets production

Searches/Measurements:

- Tevatron: W+2b [D0;hep-ex/0410062], W+1b [D0;arXiv:1210.0627]
- LHC: W+1b/2b at 7 TeV [ATLAS; arXiv:1109.1470] W+1b/2b at 7 TeV [ATLAS; arXiv:1302.2929]

  W+2b at 7 TeV [CMS; arXiv:1312.6608] W+2b at 8 TeV [CMS; arXiv:1608.07561]

Theory predictions at NLO QCD:

- 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)], on-shell *W* [Febres Cordero,Reina,Wackeroth(2006,2009)],

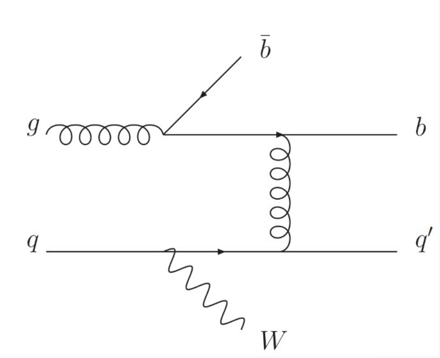
  $W(\to l\nu)bb$ [Badger,Campbell,Ellis(2010)], NLO+PS [Oleari,Reina(2011)][Frederix etal(2011)],

  $W(\to l\nu)bbj$ [Luisoni,Oleari,Tramontano(2015)]

  $W(\to l\nu)bb+\leq 3j$ [Anger,Febres Corder,Ita,Sotnikov(2018)]

$W+2b+\leq 3j$ at NLO QCD

[Anger,Febres Cordero,Ita,Sotnikov;arXiv:1712.05721]

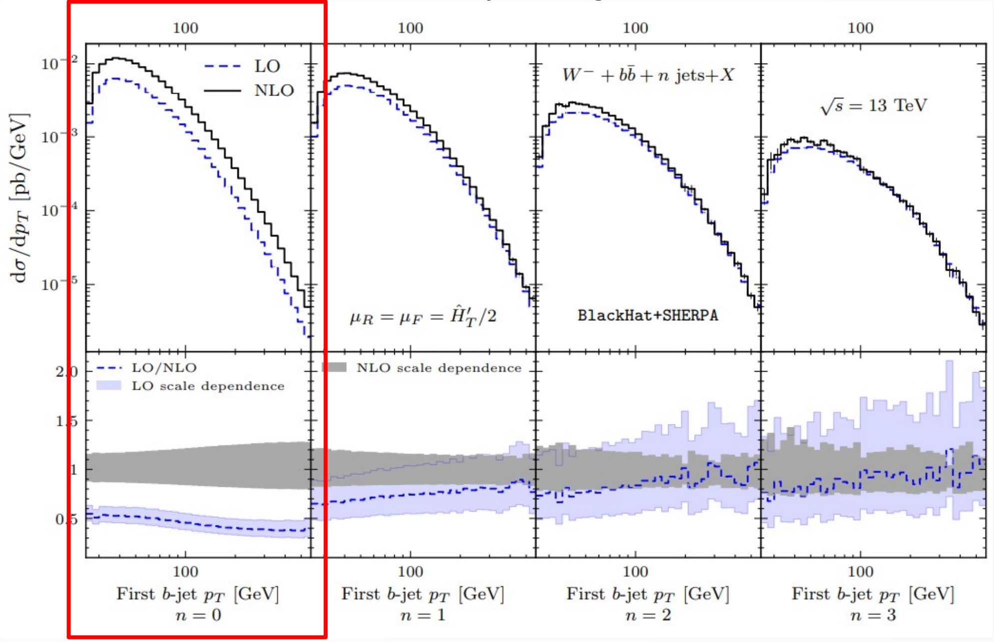


Feynman diagram from arXiv:1107.3714

Inclusive Wbb production ($pp \to Wbb+X$)

- large NLO corrections as well as large NLO scale dependence
- due to opening of qg channel ($qg \to Wbb+q$)

jets	$W^-b\bar{b}$ LO	$W^-b\bar{b}$ NLO	K-factor
0	$0.33278(12)^{+0.0619}_{-0.0490}$	$0.67719(60)^{+0.1288}_{-0.1000}$	2.03
1	$0.36153(13)^{+0.1408}_{-0.0945}$	$0.50484(63)^{+0.0851}_{-0.0800}$	1.40
2	$0.18501(44)^{+0.1053}_{-0.0626}$	$0.22604(87)^{+0.0407}_{-0.0400}$	1.22
3	$0.07204(25)^{+0.0540}_{-0.0289}$	$0.08288(89)^{+0.0189}_{-0.0200}$	1.15



~100% NLO QCD corrections

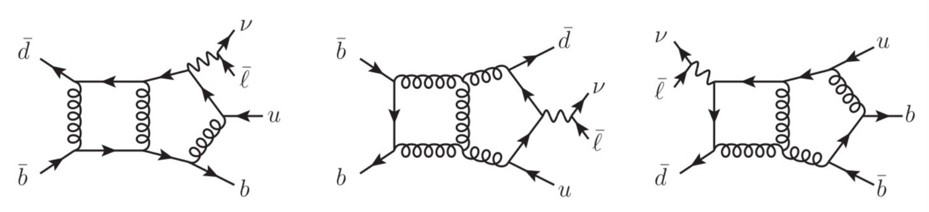
scale dependence: 19% at LO, 20% at NLO

Calls for a NNLO QCD calculation!!

W+2b at NNLO QCD: massless b (5FS)

[HBH,Poncelet,Popescu,Zoia (arXiv:2205.01687,arXiv:2209.03280)]

- Two-loop amplitudes ud→W(lν)bb: massless b, leading colour approximation: $1/N_c^2$ terms discarded



Extension of the 2L amplitude with onshell W [Badger,HBH,Zoia(2011)]

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

LC approximation only applied in the scale independent part of double virtual contribution

- Subtraction scheme: Sector Improved Residue Subtraction Scheme (STRIPPER)

[Czakon(2010)][Czakon,Heymes(2014)]

- Massless b quark: IRC safety problem starting at NNLO when using standard anti-k_T jet algorithm
  a number of solutions are available [Caola,Grabarczyk,Hutt, Salam,Scyboz,Thaler(2023)] [Gauld,Huss,Stagnitto(2022)][Caletti,Larkoski,Marzani,Reichelt(2022)] see Alex Mitov's talk
  → Flavour-kT jet algorithm [Banfi,Salam,Zanderighi(2006)]: data/theory comparison requires unfolding
  → Infrared-safe flavoured anti-kT jets [Czakon,Mitov,Poncelet(2022)]: unfolding effects minimized
- Numerical setup follows 8 TeV CMS measurement (arXiv:1608.07561)
- Final state considered: inclusive (at least 2 b jets)
  exclusive (exactly 2 b jets and no other jets)

$W+2b$ at NNLO QCD: massless b (5FS)

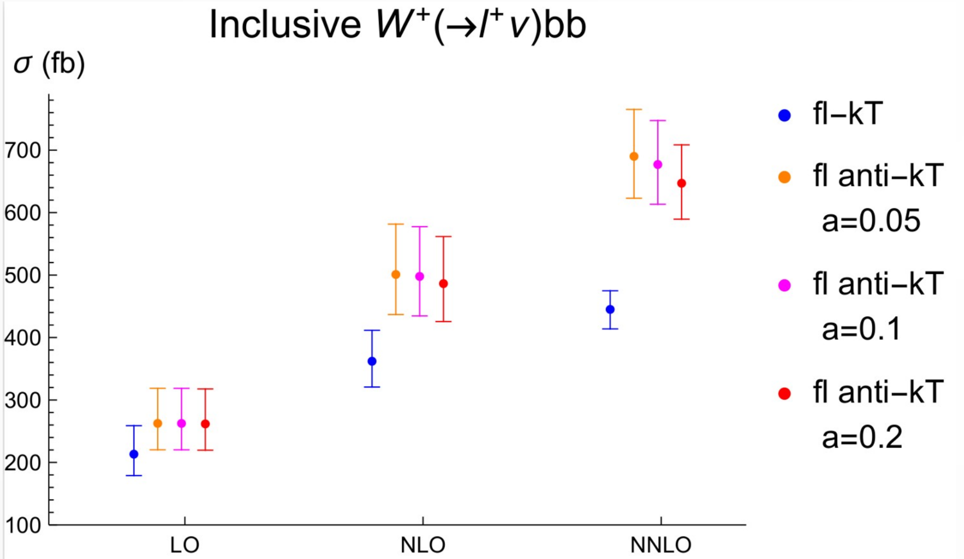
[HBH,Poncelet,Popescu,Zoia (arXiv:2205.01687,arXiv:2209.03280)]

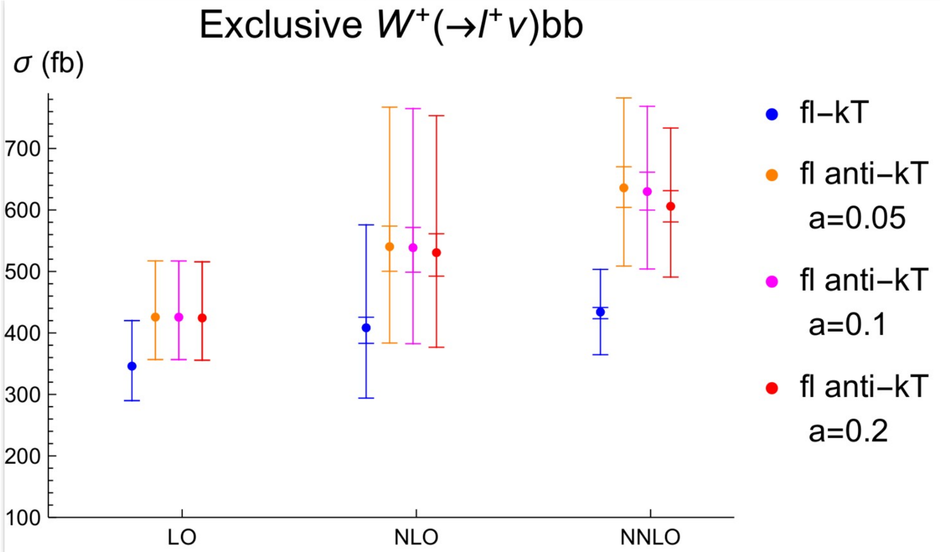
scale: $H_T = E_T(l\nu) + p_T(b_1) + p_T(b_2)$

a: tunable softness parameter in the fl anti-k_T jet algorithm

$a \to 0$: standard anti-kT

$p_T(l) > 30$ GeV, $|\eta(l)| < 2.1$, $p_T(j) > 25$ GeV, $|\eta(j)| < 2.4$, jet alg: flavour-kT and flavour anti-kT with R=0.5





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

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

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

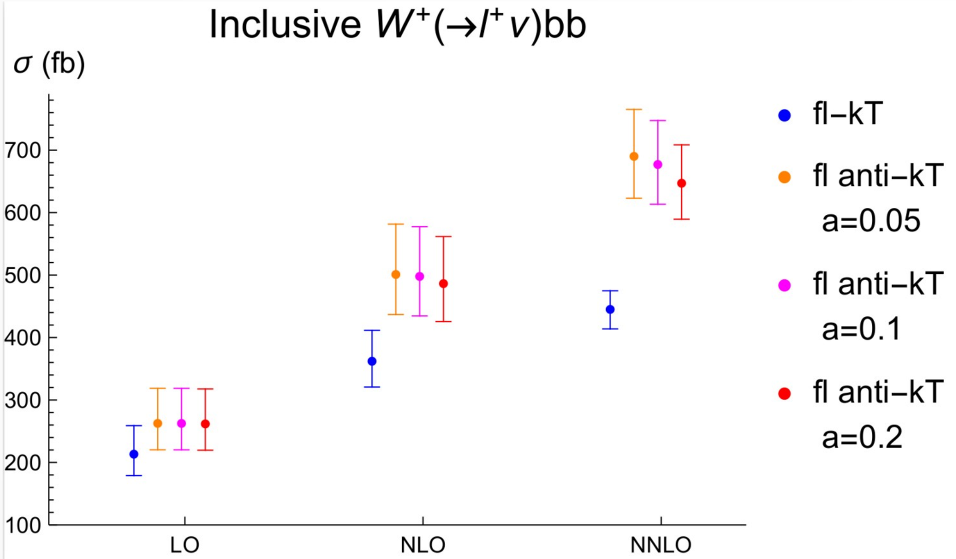
W+2b at NNLO QCD: massless b (5FS)

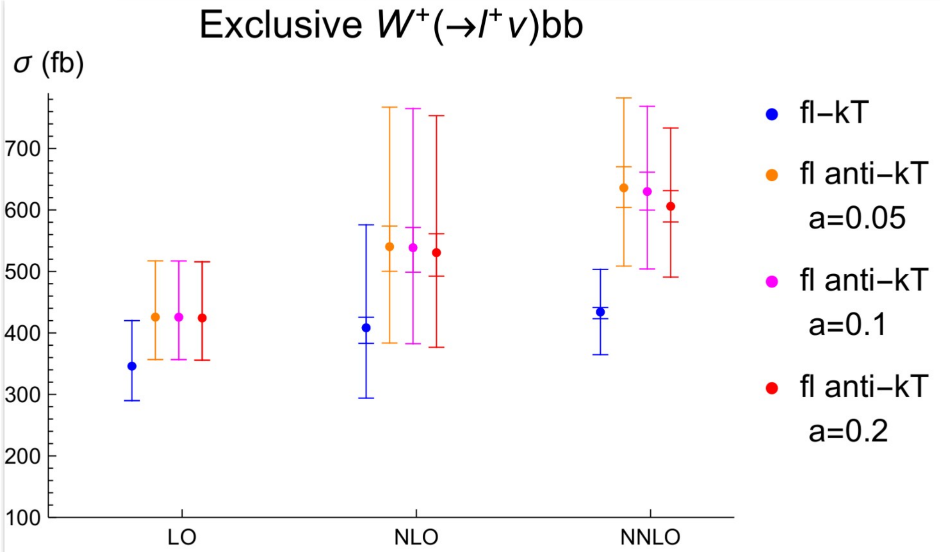
[HBH,Poncelet,Popescu,Zoia (arXiv:2205.01687,arXiv:2209.03280)]

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

double virtual: 5% (inc), 10% (exc)

expected subleading colour contribution: 0.5% (inc), 1% (exc)





$$K^{\text{fl}-k_T}_{\text{NLO}} \sim 1.7, \quad K^{\text{fl}-k_T^{-1}}_{\text{NLO}} \sim 1.9$$

$$K^{\text{fl}-k_T}_{\text{NNLO}} \sim 1.2, \quad K^{\text{fl}-k_T^{-1}}_{\text{NNLO}} \sim 1.3-1.4$$

$$K^{\text{fl}-k_T}_{\text{NLO}} \sim 1.2, \quad K^{\text{fl}-k_T^{-1}}_{\text{NLO}} \sim 1.3$$

$$K^{\text{fl}-k_T}_{\text{NNLO}} \sim 1.1, \quad K^{\text{fl}-k_T^{-1}}_{\text{NNLO}} \sim 1.2$$

W+2b at NNLO QCD: massless b (5FS)

[HBH,Poncelet,Popescu,Zoia (arXiv:2205.01687,arXiv:2209.03280)]

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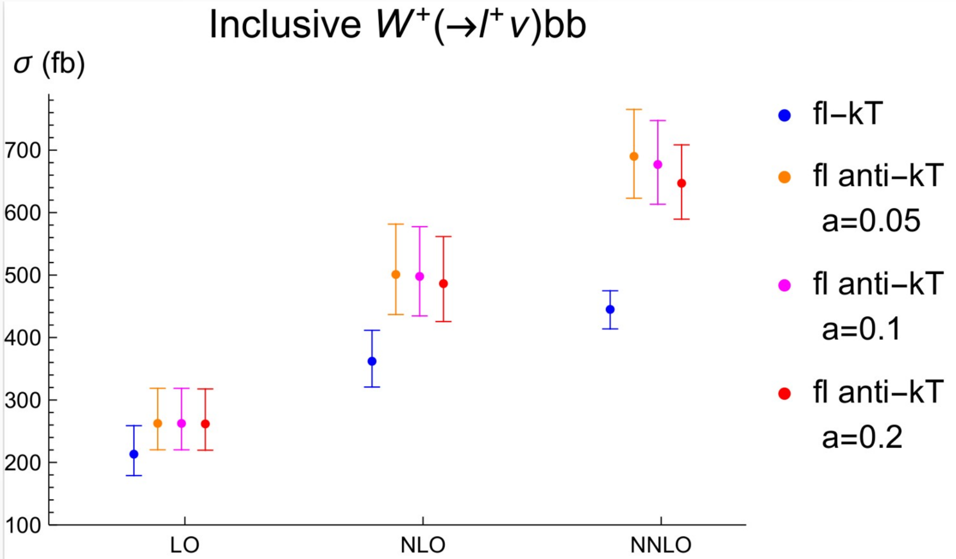
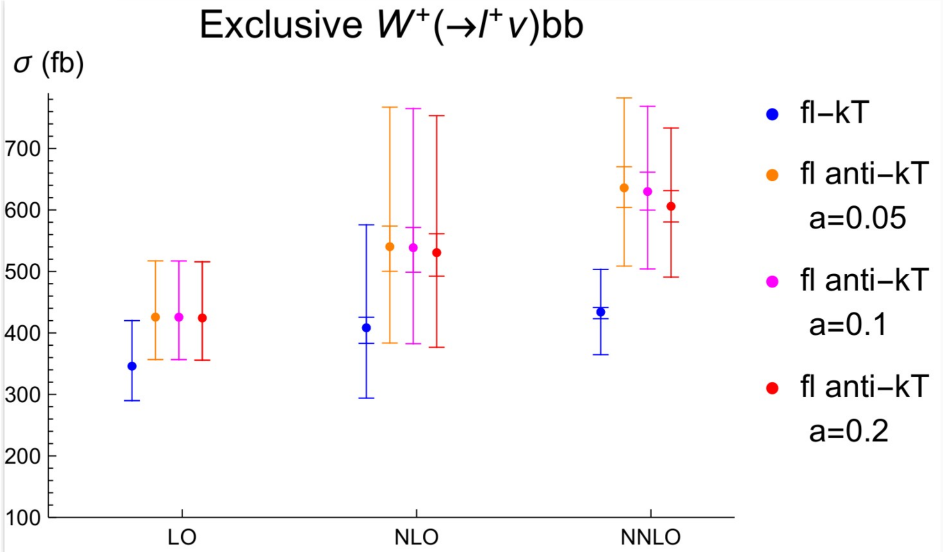




$\delta^{\text{fl}-k_T}_{\text{scale}}$: 20%(LO), 13%(NLO), 7%(NNLO)

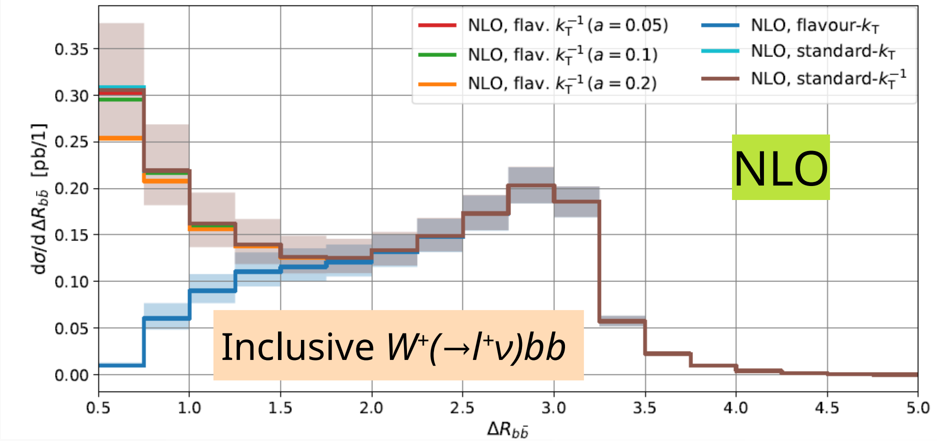
$\delta^{\text{fl}-k_T^{-1}}_{\text{scale}}$: 20%(LO), 15%(NLO), 10%(NNLO)

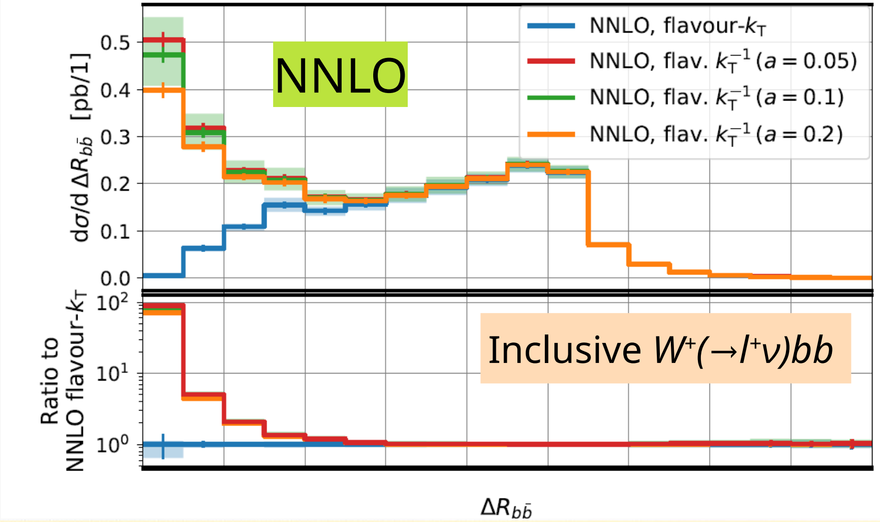
$\delta^{\text{fl}-k_T}_{\text{scale}}$: 20%(LO), 6%(NLO), 3%(NNLO) → 7-pt
30%(NLO), 16%(NNLO) → uncorrelated

$\delta^{\text{fl}-k_T^{-1}}_{\text{scale}}$: 20%(LO), 7%(NLO), 5%(NNLO) → 7-pt
35%(NLO), 22%(NNLO) → uncorrelated

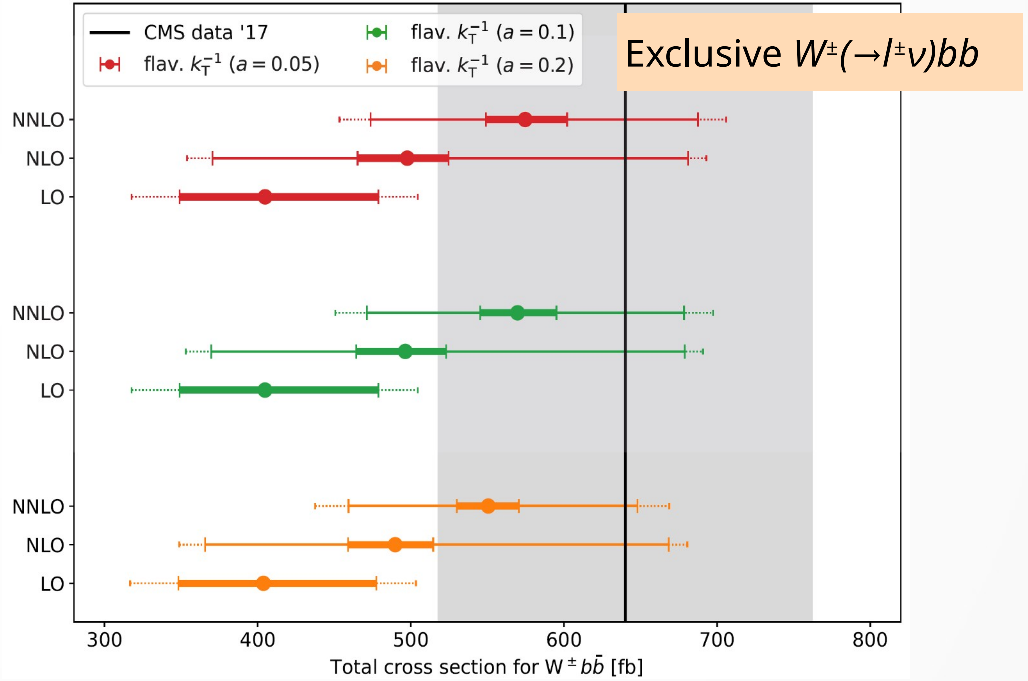
W+2b at NNLO QCD: massless b (5FS)

[HBH,Poncelet,Popescu,Zoia (arXiv:2205.01687,arXiv:2209.03280)]





- NLO: comparison to standard k_T/anti-k_T algorithm
- Supression at small ΔR_{bb} for flavour-kT algorithm



7-pt scale variation, uncorrelated presciption,
+ Hadronisation and MPI uncertainties

W+2*b* at NNLO QCD: massive *b* (4FS)

[Buonocore,Devoto,Kallweit,Mazzitelli,Rottoli,Savoini (arXiv:2212.04954)]

also applied to ttW
see talk by A. Kulesza yesterday

- Two-loop amplitude with massive *b* is still out of reach
  → capture leading contributions in m_b/Q using "massification" procedure [Mitov,Moch(2007)]

$$\mathcal{M}_2^m = \mathcal{M}_2^{m=0} + Z^1_{[q]}\mathcal{M}_1^{m=0} + Z^2_{[q]}\mathcal{M}_0^{m=0}$$

Massless two-loop *ud→lνbb* amplitude from [Abreu,Febres Cordero,Ita,Klinkert,Page,Sotnikov(2021)]

$Z_{[q]}$: universal, perturbative factor, obtained from the ratio of massive to massless *γ*qq* form factors

$$Z^l_{[q]} = f\left(\epsilon, \log m_b^2/Q^2\right)$$

power corrections in m_b and heavy loops contributions are not included

- Subtraction scheme: q_T slicing [Catani,Grazzini(2007)]

$$d\sigma_{\rm NNLO} = \mathcal{H}\otimes d\sigma_{\rm LO} + \lim_{r_{\rm cut}\to 0}\left[d\sigma_{\rm R} - d\sigma_{\rm CT}\right]_{r>r_{\rm cut}}$$

- *b*-quark mass: regulates IR divergencies in the double soft limit
  → standard anti-k_T jet algorithm can be used at NNLO

- Fiducial setup follows ATLAS *VH(→bb)* boosted analysis (arXiv:2007.02873)

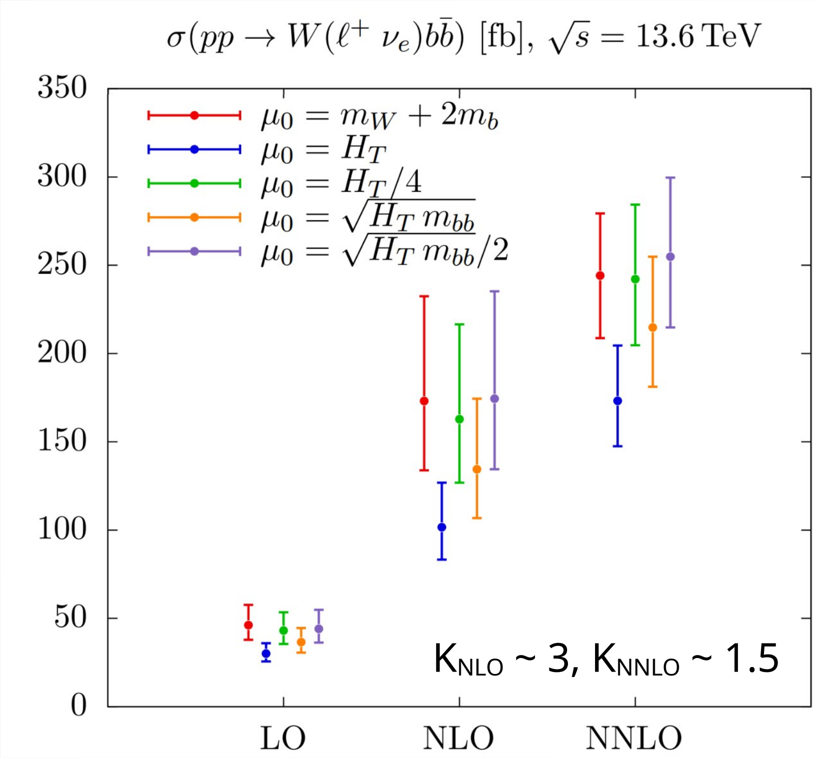
W+2*b*+*X* at 13.6 TeV, mb = 4.92 GeV, anti-k_T (and k_T) with R=0.4

$n_b = 2$, $p_T(b_1) > 45$ GeV, $0.5 < \Delta R_{bb} < 2$

$p_T(l) > 25$ GeV, $|\eta(l)| > 2.5$, $p_T(W) > 150$ GeV, $p_T(j) > 20$ GeV if $|\eta(j)| < 2.5$ or $p_T(j) > 30$ GeV if $2.5 < |\eta(j)| < 4.5$

W+2b at NNLO QCD: massive b (4FS)

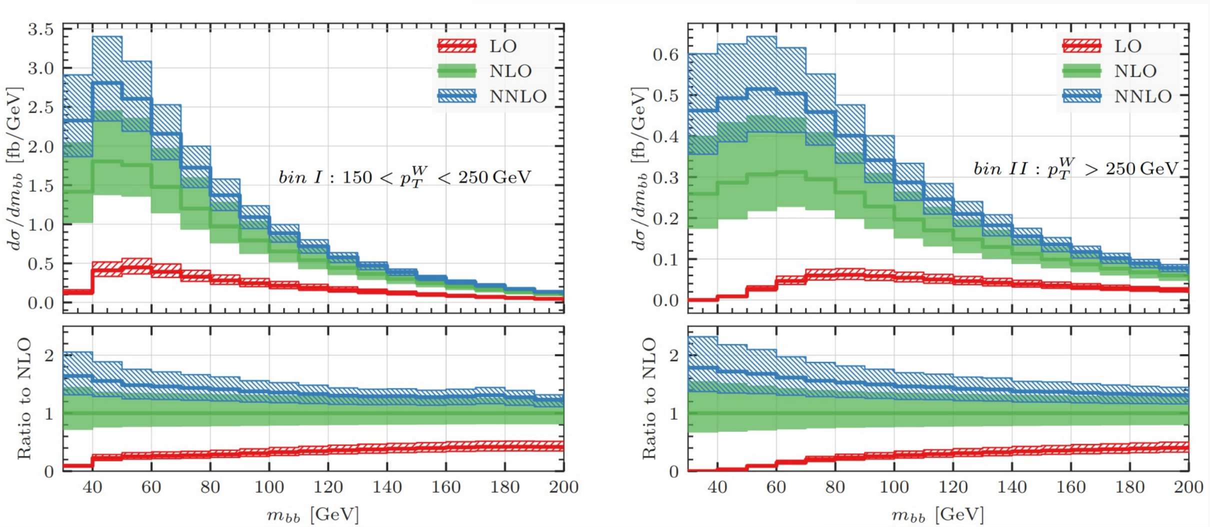
[Buonocore,Devoto,Kallweit,Mazzitelli,Rottoli,Savoini (arXiv:2212.04954)]



Plots from L. Buonocore's talk at Radcor2023

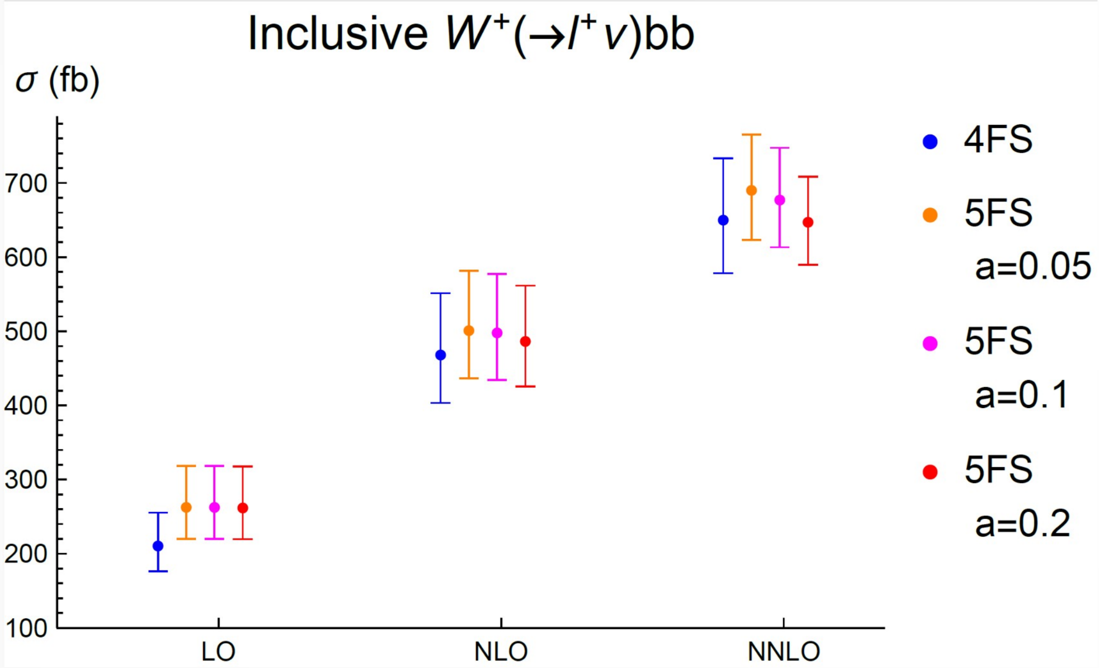
Theoretical uncertainties:

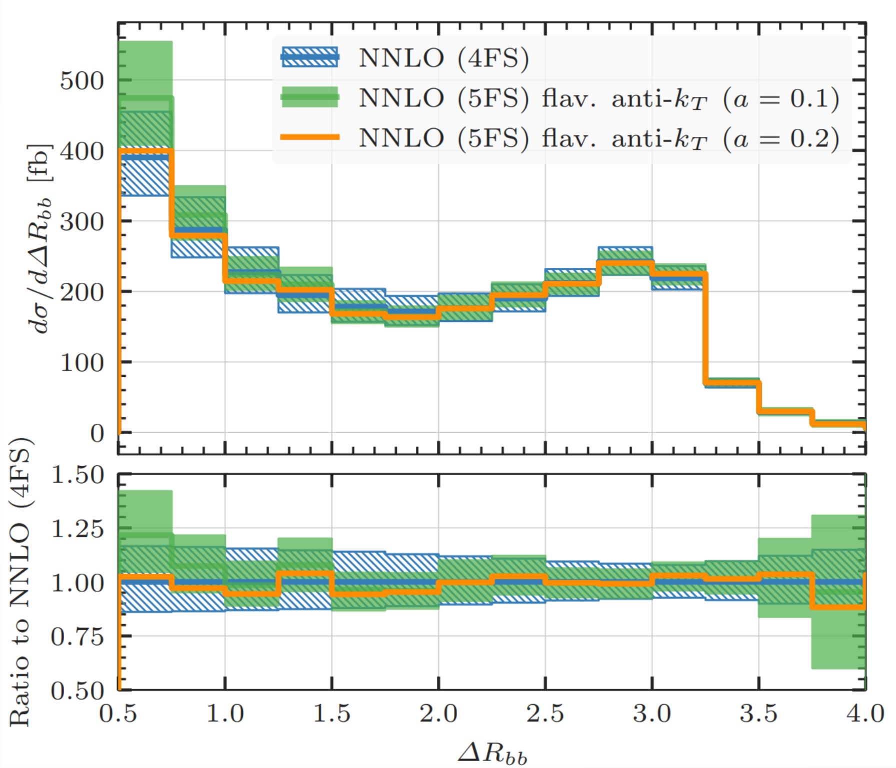
- Scale variation: ~30% at NLO, ~20% at NNLO
- m_b variation → 2% (at NNLO)
- Massification → 3% (estimated at NLO)
- Two-loop amplitude (LC) → 2% of NNLO cross section



W+2b at NNLO QCD: 4FS vs 5FS comparison

[Buonocore,Devoto,Kallweit,Mazzitelli,Rottoli,Savoini (arXiv:2212.04954)]

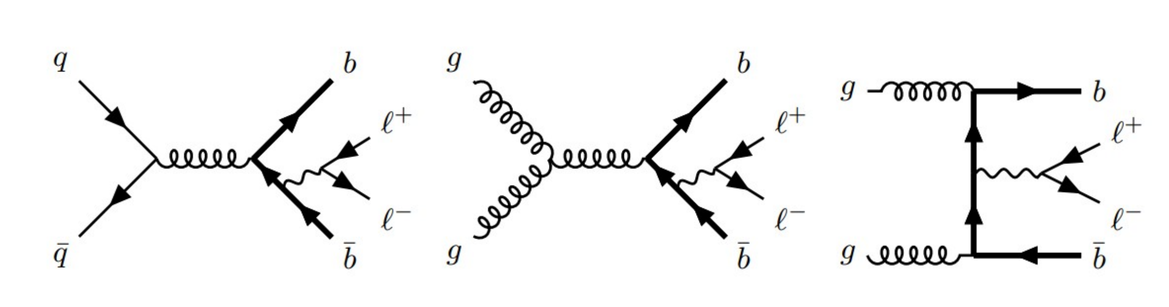




→ good agreement within scale variations

NNLO+PS prediction for *Zbb* production

Mazzitelli, Sotnikov, Wiesemann (arXiv:2404.08598)



Z+b jets

Measurements:

Tevatron: CDF [arXiv:0812.4458], D0 [arXiv:1010.6203]
D0 [arXiv:1301.2233]

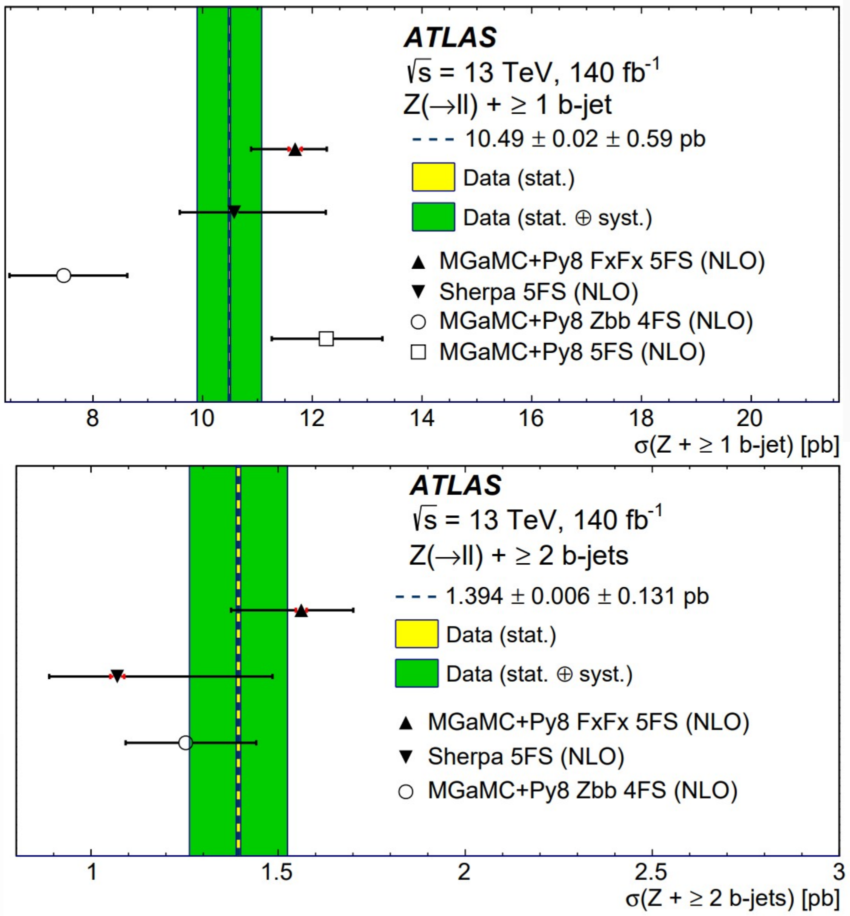
LHC 7 TeV: CMS [arXiv:1402.1521] ATLAS [arXiv:1407.3643]
LHCb [1411.1264]

LHC 8 TeV: CMS [arXiv:1611.06507]

LHC 13 TeV: ATLAS [arXiv:2003.11960] CMS [arXiv: 2112.09659]
ATLAS [arXiv:2204.12355] ATLAS [arXiv:2403.15093]

Theory predictions:

- NLO 5FS [Campbell,Ellis,Maltoni,Willenbrock(2003)]
- NLO 4FS [Febres Cordero,Reina,Wackeroth(2008,2009)]
- NLO+PS (+merging in 5FS) in MadGraph5_aMC@NLO [Frederix,Frixione,Hirschi,Maltoni,Pittau,Torielli(2011)]
- NLO+PS (+merging in 5FS) in Sherpa [Krauss,Napoletano,Schumann(2016)]
- NLO+PS (4FS and 5FS combination) [Hoche,Krause,Siegert(2019)]
- NNLO in 5FS (Z+b) [Gauld,Gehrmann-De Ridder,Glover,Huss,Majer(2020)]



arXiv:2403.15093

NNLO+PS predictions for *Zbb* production

[Mazitelli,Sotnikov,Wiesemann (arXiv:2404.08598)]

- Small mass expansion done directly for the two-loop finite remainders $|\mathcal{R}\rangle = \mathbf{Z}^{-1}|\mathcal{M}\rangle$

$$\mathcal{F}_{q\bar{q}} = \mathcal{Z}_{[Q]}\mathcal{Z}_{[q]}, \qquad \mathcal{F}_{gg} = \mathcal{Z}_{[g]}\mathcal{Z}_{[q]}$$

$$|\mathcal{R}_{m_b \ll \mu_h}\rangle = \mathbf{Z}^{-1}_{m_b \ll \mu_h}\,\mathcal{F}\,\mathbf{S}\;\mathbf{Z}_0\,|\mathcal{R}_0\rangle\Big|_{n_f = n_l + n_h}$$

S: soft function for heavy quark loops
[Wang,Xia,Yang,Ye (arXiv:2312.12242)]

$$2\,\mathrm{Re}\left\langle \mathcal{R}_0^{(0)} \middle| \mathcal{R}^{(2)}_{m_b \ll \mu_h} \right\rangle = 2\bar{\mathcal{F}}^{(2)}\left|\mathcal{R}_0^{(0)}\right|^2 + \bar{\mathcal{F}}^{(1)} 2\,\mathrm{Re}\left\langle \mathcal{R}_0^{(0)} \middle| \mathcal{R}_0^{(1)} \right\rangle + \mathcal{S}^{(2)} 2\,\mathrm{Re}\left\langle \mathcal{R}_0^{(0)} \middle| \mathbf{C}_d \middle| \mathcal{R}_0^{(0)} \right\rangle + 2\,\mathrm{Re}\left\langle \mathcal{R}_0^{(0)} \middle| \mathcal{R}_0^{(2)} \right\rangle$$

Massless W+4 parton two-loop amplitude in the leading colour approximation
no diagrams with Z coupled to closed quark loop
[Abreu,Febres Cordero,Ita,Klinkert,Page,Sotnikov (arXiv:2110.07541)]
!!!cutting edge two-loop amplitude calculation!!!

- MiNNLO$_{\text{PS}}$ method for parton shower matching

[Monni,Nason,Re,Wiesemann,Zanderighi (arXiv:1908.06987)]
[Monni,Re,Wiesemann (arXiv:2006.04133)]
[Mazzitelli,Monni,Re,Wiesemann,Zanderighi (arXiv:2012.14267,arXiv:2112.12135)]

NNLO+PS predictions for *Zbb* production

[Mazitelli,Sotnikov,Wiesemann (arXiv:2404.08598)]

Total *Zbb* cross section

66 GeV < m_{ll} < 116 GeV

No hadronization, MPI, QED shower

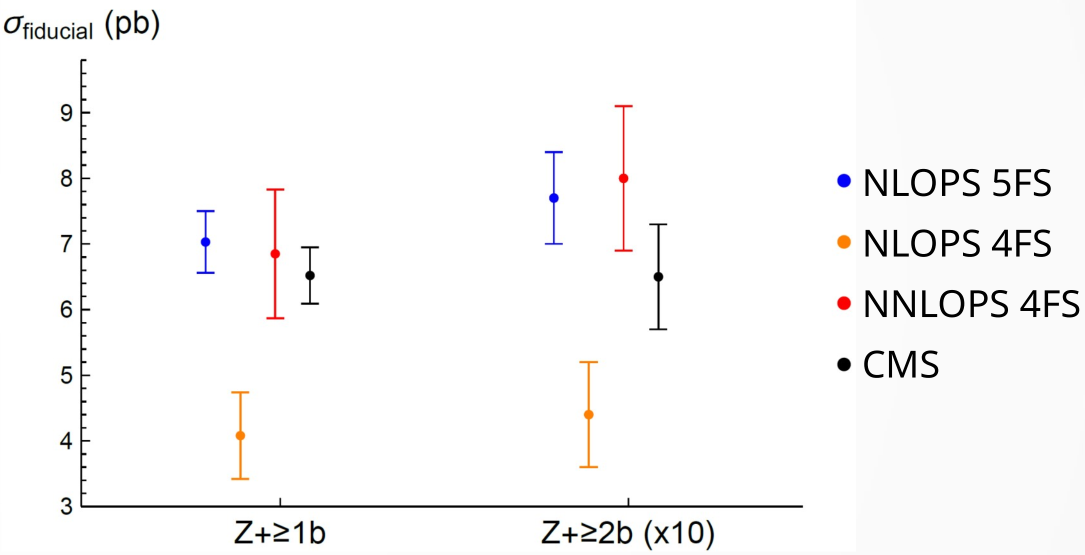
	σ_{total} [pb]	ratio to NLO
NLO+PS ($m_{b\bar{b}\ell\ell}$)	$32.21(0)^{+16.4\%}_{-13.4\%}$	1.000
MiNLO′ ($m_{b\bar{b}\ell\ell}$)	$22.33(1)^{+28.2\%}_{-17.9\%}$	0.693
MiNNLO$_{\text{PS}}$ ($m_{b\bar{b}\ell\ell}$)	$51.23(4)^{+17.3\%}_{-12.4\%}$	1.591
NLO+PS ($H_T/2$)	$40.14(1)^{+18.9\%}_{-15.0\%}$	1.000
MiNNLO$_{\text{PS}}$ ($H_T/2$)	$58.70(4)^{+19.0\%}_{-13.1\%}$	1.462

- Large NNLO corrections ~40-60%
- NNLO+PS more stable w.r.t scale choice
- Massless finite remainder: 5% of the total XS
- log(m_b) from closed *b*-quark loops: less than 1%

Fiducial cross section

Cuts from CMS 13 TeV analysis

arXiv:2112.09659 [hep-ex]

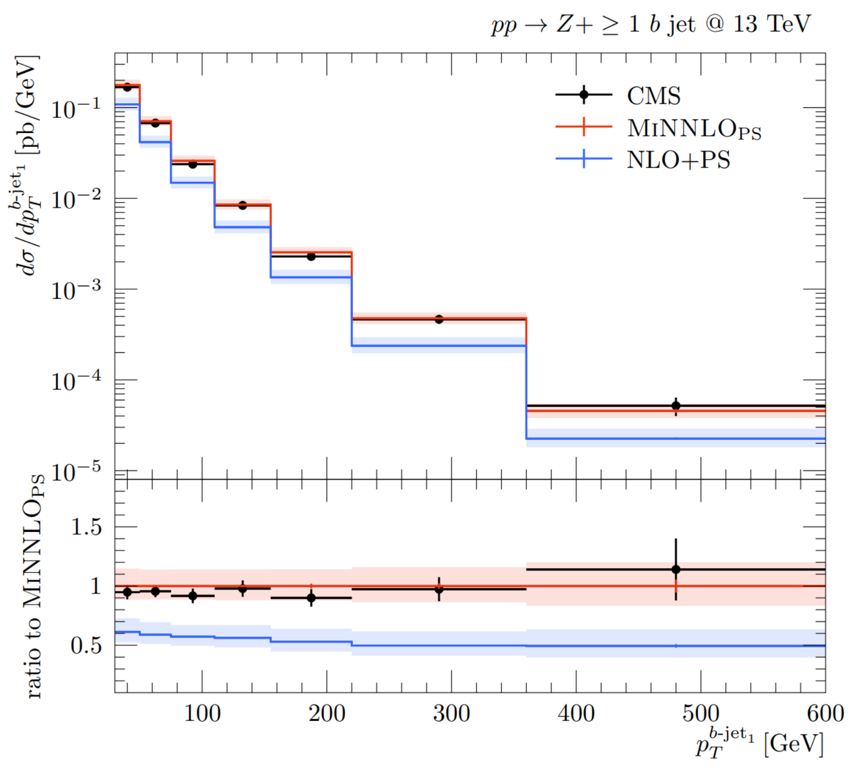


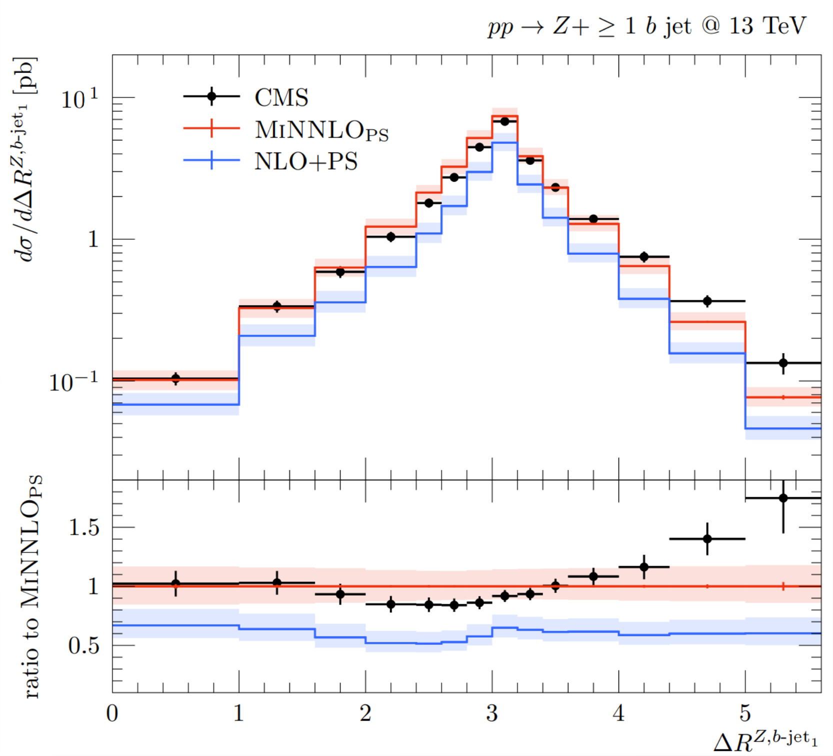
- Hadronization, MPI, QED shower included
- NLO+PS 4FS and 5FS are not compatible
- 4FS: full agreement with the data upon inclusion of NNLO QCD corrections

NNLO+PS predictions for *Zbb* production

[Mazitelli,Sotnikov,Wiesemann (arXiv:2404.08598)]

$pp \to Z + \geq 1b$ jet



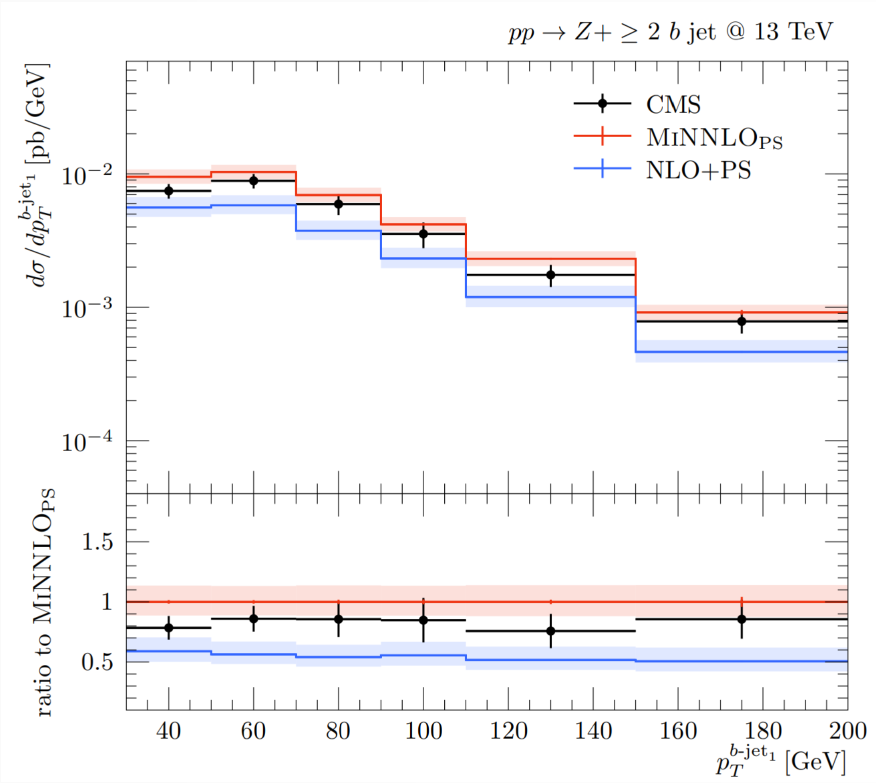


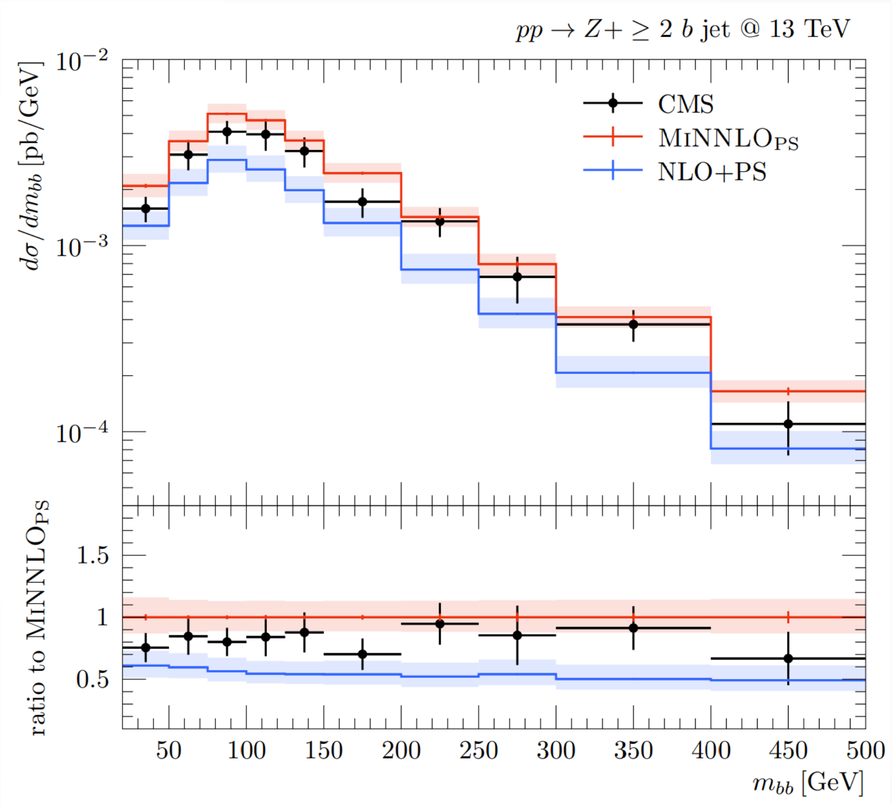
- Excellent agreement between $\text{MiNNLO}_{\text{PS}}$ prediction and data
- Deviation at high $\Delta R(Z,b_1)$: resummation of $\log(m_b)$?

NNLO+PS predictions for *Zbb* production

[Mazitelli,Sotnikov,Wiesemann (arXiv:2404.08598)]

$pp \to Z + \geq 2b$ jet





- Larger experimental error
- Good agreement between MiNNLO$_{PS}$ predictions and data (although MINNLO$_{PS}$ normalisation is slightly higher)

Summary

- NNLO QCD predictions for Wbb production: 4FS and 5FS
- NNLO+PS prediction for Zbb production in 4FS

✔ pQCD milestones!!!

2→3 NNLO calculation with external (+internal) mass

NNLO+PS for 2→3 process

✔ Higher order corrections are important, better agreement with data

✔ Technological developments: scattering amplitudes (differential equations for master integrals, finite-field reconstruction method), subtraction scheme, NNLO+PS matching.

Outlook

- ➢ NNLO+PS for Wbb in 4FS
- ➢ NNLO QCD for W+1b in 5FS (pp→Wbj) comparison with 4FS calculation
- ➢ Zbb: dedicated comparison with NNLO 4FS and 5FS fixed order calculations
- ➢ Subleading colour two-loop amplitude?