Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

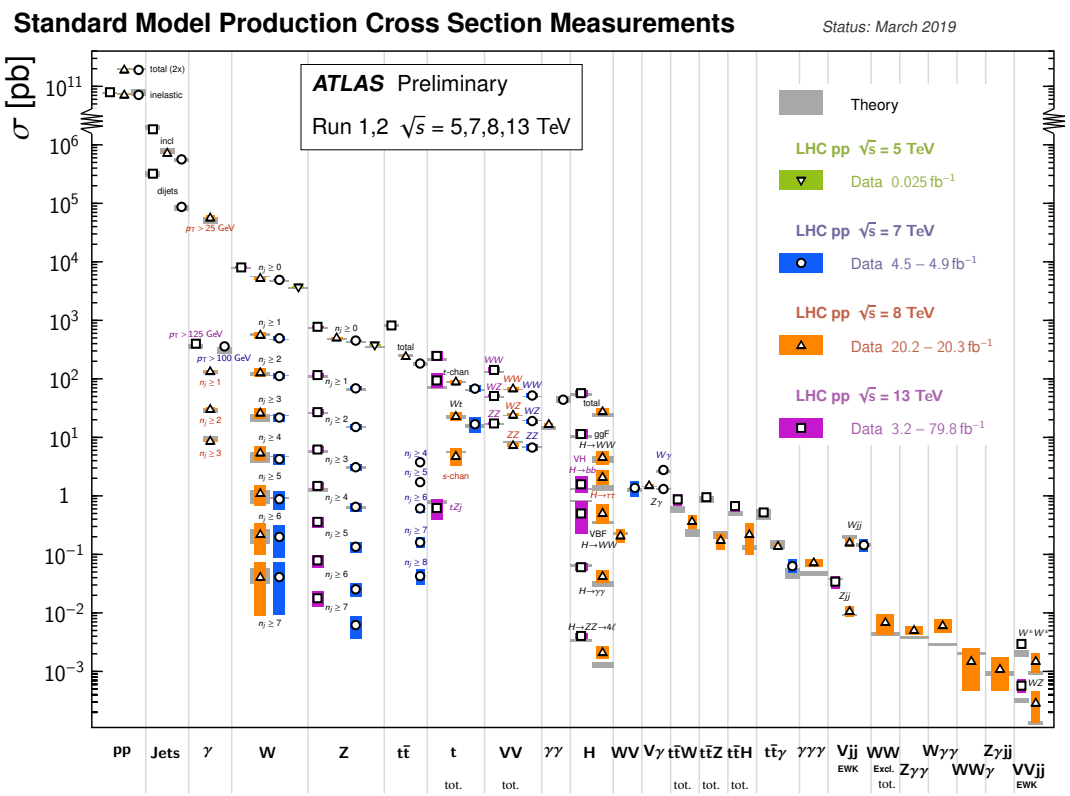
LHC observables with NNLOJET

Aude Gehrmann-De Ridder

RADCOR 2019, Avignon, 09.09.2019

Benchmark processes at LHC

- Low multiplicity processes with large production rates and small experimental uncertainties
- Allow precise determinations of:
  - Masses, couplings
  - Parton distributions
- Enable indirect new physics searches
- Require precise theory
  - Higher orders (with full event properties)



NNLOJET framework

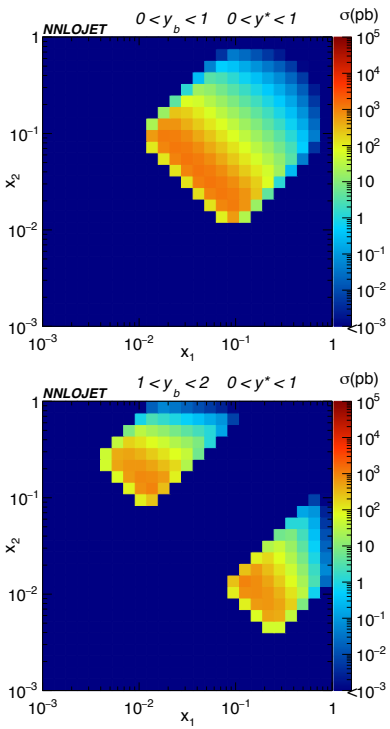
- Common infrastructure for computing NNLO observables for $2 \longrightarrow 1$ and $2 \longrightarrow 2$ hadron collider processes
  - $pp \longrightarrow$ di-jets
  - $pp \longrightarrow H+(0,1)$jets
  - $pp \longrightarrow H+2$ jets (VBF)
  - $pp \longrightarrow V/\gamma+(0,1)$jets
  - $ep \longrightarrow e+(1,2)$jets

NNLOJET project:
X. Chen, J. Cruz-Martinez, J. Currie, R. Gauld, T. Gehrmann, N. Glover, M. Höfer, A. Huss, I. Majer, J. Mo, T. Morgan, J. Niehues, J. Pires, D. Walker, J. Whitehead, AG

- New: N^3LO differential observables for $2 \longrightarrow 1$ processes
  - $ep \longrightarrow e+1$ jet
  - $pp \longrightarrow H$ (See talk by Xuan Chen)
- New: flavour-sensitive observables (this talk)
  - $pp \longrightarrow H+V$ with $(H \longrightarrow bb)$ and $(V \longrightarrow$ leptons$)$
  - $pp \longrightarrow Z+b$-jet with $(Z \longrightarrow$ leptons$)$

Triple differential di-jet cross section

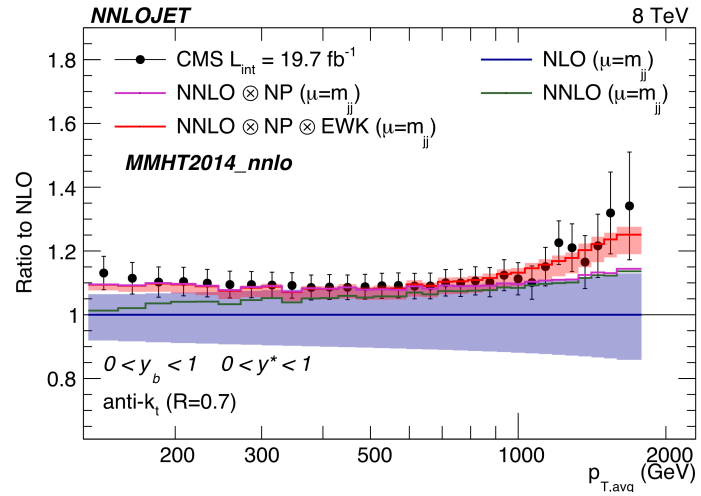
- Di-jet cross section: pp → 2 jets +X
  - Measured triple differentially by CMS 8 TeV [arXiv:1705.02628] as function of
    - Average p_T $p_{T,\mathrm{avg}} = (p_{T,1} + p_{T,2})/2$
    - Rapidity separation $y^* = |y_1 - y_2|/2$
    - Boost of the di-jet system $y_b = |y_1 + y_2|/2$
  - Probe of parton distributions: vary y_b at fixed y^*
    - Small y_b [0;1]: cross section largest for $x_1 \sim x_2$ (PDFs well-known)
    - Large y_b [1;2]: probe asymmetric x_1, x_2 values (PDFs have large uncertainties)

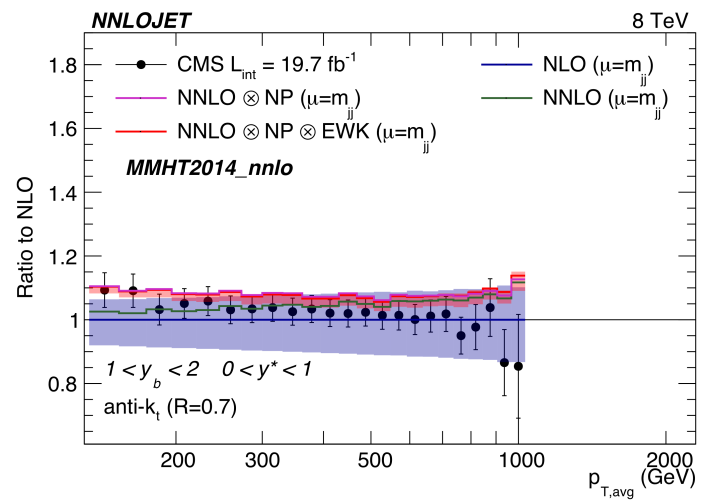


Rapidity slice: 0<y*<1
CMS set-up

Triple differential di-jet cross section

- NNLOJET: hadron collider jet production at NNLO
  - Single jet inclusive and di-jet observables
  - Recently: independent validation
    [M. Czakon, A. van Haemeren, A. Mitov, R. Poncelet, arXiv:1907.12911]
- Compare to triple differential CMS results [arXiv:1705.02628]
  - NNLO + electroweak + hadronization
    [T. Gehrmann, N.Glover, A.Huss, J.Pires, AG, arXiv:1905.09047 (PRL)]
  - Small y_b ($0<y_b<1$): Improved description at NNLO for entire range in $p_{T,avg}$
  - Large y_b ($1<y_b<2$): Data below NNLO predictions (PDF effect)





$W^{\pm}$ + jet at forward rapidity

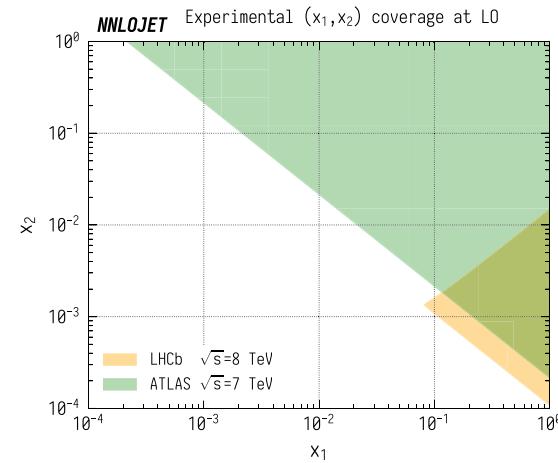
- Production of a vector boson with a forward jet

  $p + p \to W^{\pm}(\to l^{\pm} + \nu_{\ell}) + \text{jet} + \text{X}$ with : ($2 < \eta^{j} < 4.5$)

  – Measured by ATLAS @ 7TeV [arXiv:1408.6510] and LHCb @ 8TeV [arXiv: 1605:00951]

  Regions probed at LO by LHCb and ATLAS differ:

  - LHCb coverage assymmetric : large x_1, small x_2



- $W^{\pm}J$ fiducial cross sections @NNLO

  [T. Gehrmann, N.Glover, A.Huss, D.Walker, AG, arXiv:1901.11041]

  – Substantial reduction of scale uncertainty using central scale $\mu_0 = \sqrt{M_V^2 + \sum_i (p_{T,j_i})^2}$

  – agreement with LHCb result within errors

Process		Fiducial σ [pb]
W^+J	LO	$46.9^{+5.6}_{-2.2}$
	NLO	$62.8^{+3.6}_{-3.5}$
	NNLO	$63.1^{+0.4}_{-0.5}$
	LHCb	$56.9 \pm 0.2 \pm 5.1 \pm 0.7$
W^-J	LO	$27.2^{+3.2}_{-2.6}$
	NLO	$36.7^{+2.2}_{-2.1}$
	NNLO	$36.8^{+0.3}_{-0.2}$
	LHCb	$33.1 \pm 0.2 \pm 3.5 \pm 0.4$

$W^{\pm}$ + jet at forward rapidity

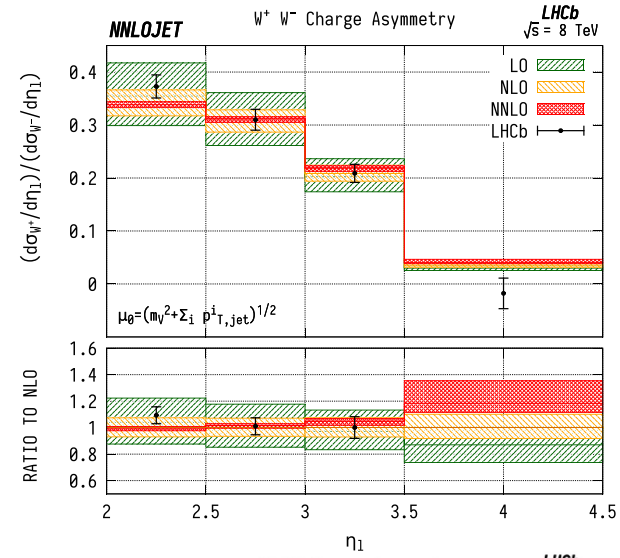
- Charged lepton asymmetry in $W^{\pm}$+jet

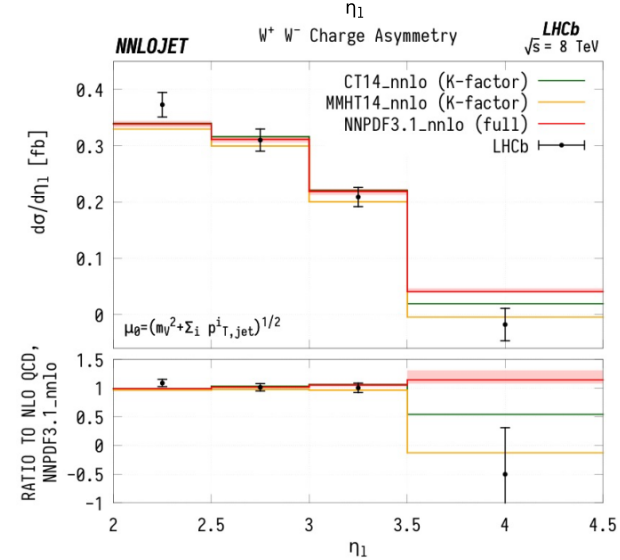
$$A^{\pm}(\eta_l) = \frac{d\sigma^{W^{+j}}/d\eta_l - d\sigma^{W^{-j}}/d\eta_l}{d\sigma^{W^{+j}}/d\eta_l + d\sigma^{W^{-j}}/d\eta_l}$$

  - Sensitive to (u/d) PDF ratio at large x
  - Similarities in $W^{\pm}$ process: Apply correlations
    - Scale uncertainty quantified by independent variation of numerator and denominator taken as the physical quantities

      Observe: theory above data in last η_l bin

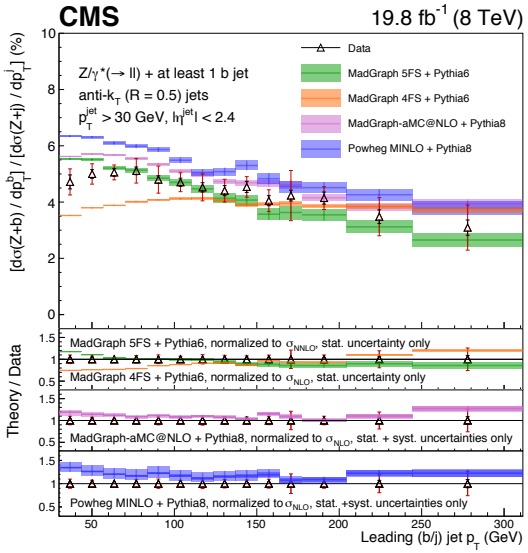
  - Study of PDF parametrisation sensitivity:
    - Observe: Spread of predictions (most pronounced in last η_l bin) reflecting the discriminative power of $A^{\pm}$





Flavour-sensitive jet observables

- Knowledge of V + HQ-jet(s) processes essential for phenomenology
  - Testing ground for probing the heavy quark content of the proton (4FNS vs. 5FNS)
  - Background to VH with H →bb and V→leptons
    - Most promising channel for precise determination of H→bb Yukawa coupling (y_b)



Leading p_T in (Z+b)/(Z+jet)

[CMS: arXiv 1611.06507v2]

- Data available and compared with NLO (+PS)
- Computations at NLO level not sufficient
  - Needed: NNLO massless computations (5FNS)

- HQ-jet identification: Essential in theory and experiment
  - For comparisons: similar prescription required

Selection of flavoured jets: Experiment

- Experimentally: flavoured jets constructed from flavour-less jets
  - Step 1: Jets defined by a flavour-blind jet clustering algorithm

    distance measure for final state pseudo-jets (i,j) k_t: p=1 , anti-k_t: p=-1

    $$d_{ij} = \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2} min\left(k_{ti}, k_{tj}\right)^{2p}$$

    anti-k_t: [M.Cacciari ,G. Salam: arXiv: 0802.1189]
  - Step 2: Partonic flavour assignment of the identified jet

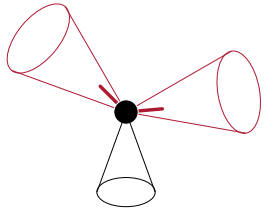
    using vertex + track reconstruction tools

- Flavour of jet: counting the number of flavoured partons in the jet
  - Jet viewed as flavoured if $|Nb(q_f) - Nb(\bar{q}_f)| \neq 0$
    and jets with no net flavour are identified as gluon jets

Selection of flavoured jets @ NNLO

- Flavour jet definition: problematic at parton level
  - When used with anti-k_T : not infrared safe from NNLO onwards

    Large-angle gluon-to-soft-bb splitting can alter the flavour of hard jet



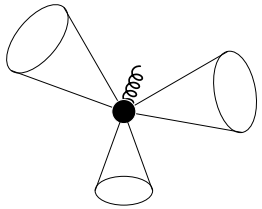
Anti-k_t:
bb clustering
in hard jet

- Need a flavour-sensitive jet algorithm
  - IR-safe flavour-k_t: A. Banfi, G. Salam, G. Zanderighi,
    [arXiv: 0601139, 0704.2999] (pre-dates anti-k_t)

    Treating flavoured and unflavoured partons differently:

    Use a flavour-dependent distance measure for final state pseudo-jets (i,j)

$$d_{ij} = \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2} \begin{cases} \max(k_{ti}^2, k_{tj}^2) & \text{softer of } i,j \text{ is flavoured.} \\ \min(k_{ti}^2, k_{tj}^2) & \text{softer of } i,j \text{ is unflavoured} \end{cases}$$



Flavour-k_t:
bb clustering
in soft gluon jet

  - Not used (so far) on the experimental side

Selection of flavoured jets @ NNLO

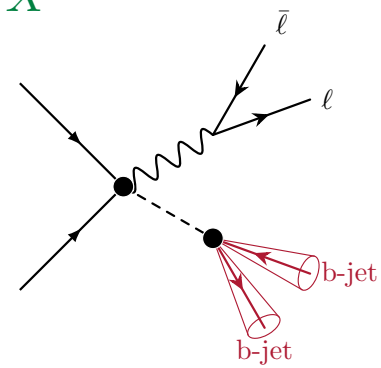
- Flavour information of individual partons is required before application of the flavour-sensitive jet algorithm
  - Step 1: Flavour assignment using a flavour dressing procedure
  - Step 2: Flavour-aware jet reconstruction with flavour-k_T using the identified partonic momenta and flavours

  Note: Steps 1 and 2 inverted compared to the experimental procedure

- Flavour dressing: Applied on top of existing flavour-blind computations in NNLOJET
  - Example: Z+b-jet using the existing Z+jet calculation (not a new process)
  - Requires tracking and storing of the flavour information for each parton present in all squared amplitudes of parton-level sub-processes
  - Applied so far to: VH (with H→bb) and Z+b-jet observables

Associated Higgs production at LHC

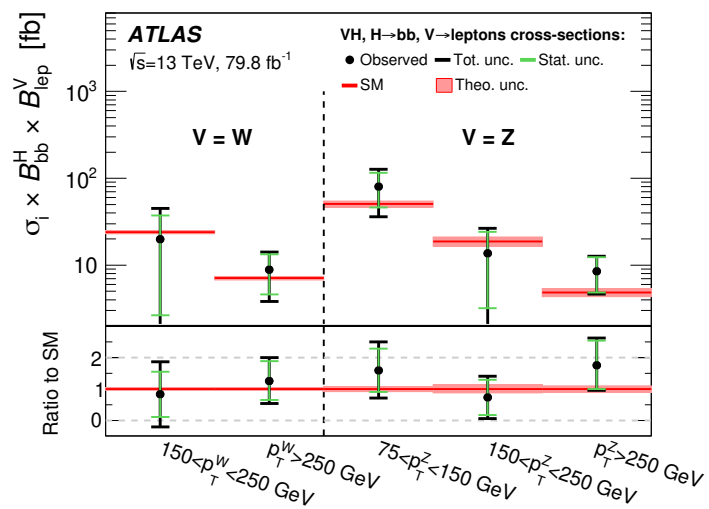
- Associated Higgs production: $pp \to VH + X \to l\,\bar{l}\,b\,\bar{b} + X$
  - Experimental status
    - Clear leptonic signature
    - First evidence for H -> bb decay through VH channel [ATLAS: arXiv:1808.08238, CMS: arXiv:1808:08242]



  - Towards differential distributions: Measurement as function of p_T^V
    - Using a simplified cross section (NRWA)

$$\sigma = \sigma_{VH} \times Br^H_{bb} \times Br^V_{ll}$$

    - Factorization of Higgs boson production and decay
    - In agreement with SM within uncertainties

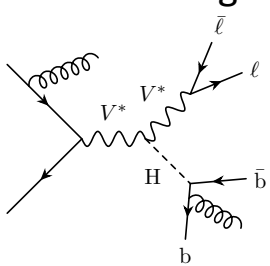


[arXiv: 1903.04618]

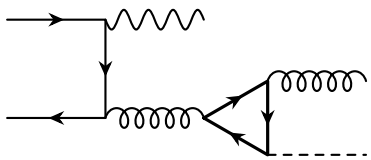
VH observables : Theory status

- Most accurate predictions: NNLO_Production ⊗ NNLO_Decay
  - (V=Z,W^+) [G. Ferrera, G Somogyi, F. Tramontano, arXiv:1705.10304]
  - (V=W^+,W^-) [F. Caola, G. Luisoni, K. Melnikov, R. Röntsch, arXiv:1712.06954]
  - (V=Z,W^+,W^-) [R. Gauld, N. Glover, A. Huss, I. Majer, AG, arXiv:1907.05836,(JHEP)]
    - Total cross section validated against [arXiv:1712. 06954]

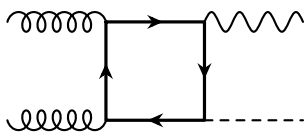
  - Common features:
    - Selection of b-jets with flavour–k_T clustering algorithm
    - Common ingredients in production process at O(α_s^2):



Drell-Yan like: Higgs couples to off-shell V



O(y_t) qq-induced: present for ZH and WH



O(y_t) gluon-gluon induced ZH: sizeable effects on observables

VH: comparison of predictions

- Treatment of Higgs decay part: Noticeable differences
  - Previously: cross section scaled to a fixed branching ratio $Br(H \to b\bar{b})$

$$\begin{aligned} \mathrm{d}\sigma^{\mathrm{scaled}}_{\mathrm{NNLO}} = {} & \mathrm{d}\sigma^{(0)}_{VH} \times \left(\mathrm{d}\sigma^{(0)}_{\mathrm{H}\to\mathrm{b}\bar{\mathrm{b}}} + \mathrm{d}\sigma^{(1)}_{\mathrm{H}\to\mathrm{b}\bar{\mathrm{b}}} + \mathrm{d}\sigma^{(2)}_{\mathrm{H}\to\mathrm{b}\bar{\mathrm{b}}}\right) \times K^{(2)} \\ & + \mathrm{d}\sigma^{(1)}_{VH} \times \left(\mathrm{d}\sigma^{(0)}_{\mathrm{H}\to\mathrm{b}\bar{\mathrm{b}}} + \mathrm{d}\sigma^{(1)}_{\mathrm{H}\to\mathrm{b}\bar{\mathrm{b}}}\right) \times K^{(1)} \\ & + \mathrm{d}\sigma^{(2)}_{VH} \times \left(\mathrm{d}\sigma^{(0)}_{\mathrm{H}\to\mathrm{b}\bar{\mathrm{b}}}\right) \times K^{(0)}. \end{aligned}$$

$$K^{(i)} = \frac{\mathrm{Br}(\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}})\,\Gamma_{\mathrm{H}}}{\sum_{j=0}^{i} \Gamma^{(j)}_{\mathrm{H}\to\mathrm{b}\bar{\mathrm{b}}}}$$

  - Unscaled cross section used in NNLOJET
    - Independent variation of QCD scales in production and decay using the central values:

$$\mu^{\mathrm{prod.}} = m_{VH}\,;\, \mu^{\mathrm{dec.}} = m_H$$

  - Compare fiducial results for W^+H up to $O(\alpha_s^2)$:
    - Essentially no difference on central value at NNLO
    - Theory uncertainty reduction

HXSWG set up @13TeV
[arXiv: 1610.07922]

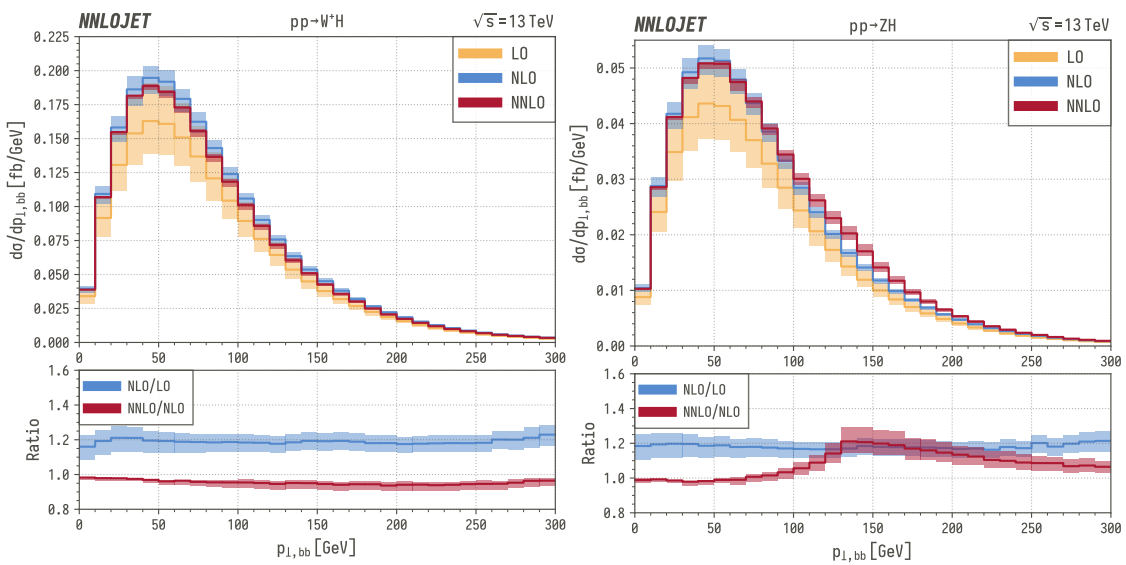
	unscaled $\mathrm{W^+H}$	scaled $\mathrm{W^+H}$
σ_{LO} [fb]	$18.06^{+2.87}_{-2.41}$	$22.52^{+0.63}_{-0.80}$
σ_{NLO} [fb]	$21.52^{+0.88}_{-1.08}$	$22.87^{+0.76}_{-0.87}$
σ_{NNLO} [fb]	$20.68^{+0.16}_{-0.46}$	$20.93^{+0.61}_{-0.73}$

Spoiled in scaled case: Different factors accompanying different production parts

Achieved in unscaled case: (<2% at NNLO), use for computing distributions

Flavour-sensitive VH observables @13 TeV

- Kinematical set-up for 13 TeV from LHC HXSWG [arXiv: 1610.07922]
  - at least two b-jets ($p_{T,b}$ >25 GeV, $|y_b|$< 2.5) selected according to the new flavour tagging procedure
    - Parton-level flavour dressing + flavour-k_T jet algorithm
- b-jet pair p_T spectrum for W^+H and ZH: sizeable differences



W^+H:

- stabilisation at NNLO
- clear reduction of scale uncertainty over the whole range in $p_{t,bb}$

ZH:

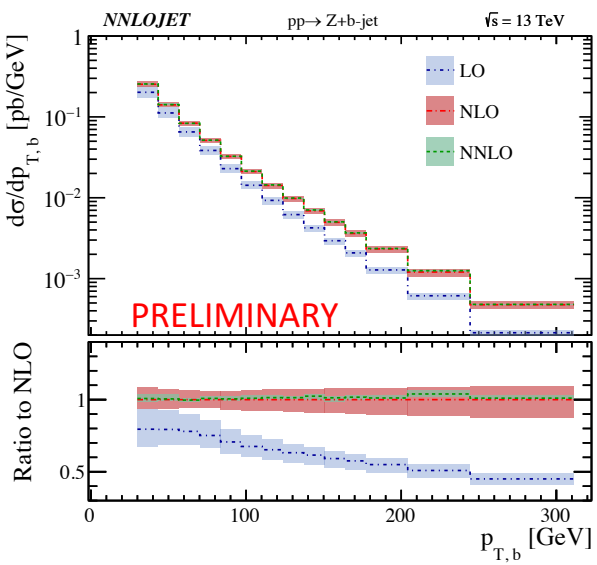
- Sizeable impact of gg-loop induced contributions at NNLO
- distortion of shape in central region (top quark threshold effects)
- Large remaining uncertainty band

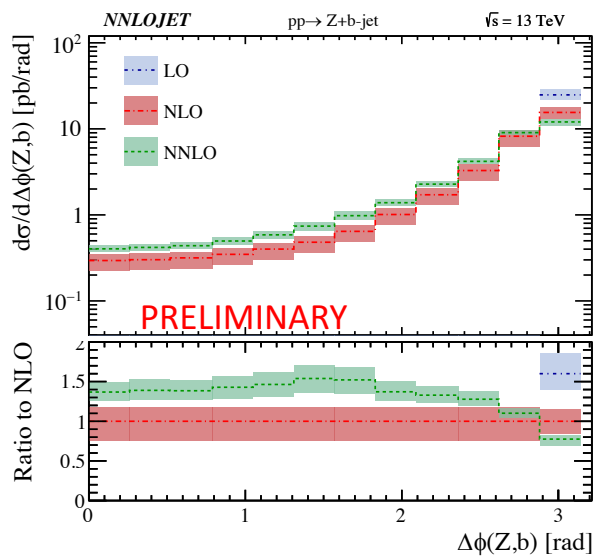
Z+b-jet observables @ NNLO

- Z+b-jet production with Z⟶leptons:

$$pp \to Z + b + X \to l^+l^- + b - \text{jet} + X$$

  - Computed with flavour tagging procedure to select b-jets
    - Use flavour dressing procedure applied to Z+jet@NNLO and flavour-k_t jet algorithm
  - Determine NNLO effects on distributions (central scale: $\mu_0 = \sqrt{m_Z^2 + p_{T,Z}^2}$)





$p_{T,b}$

- small NNLO corrections
- sizeable reduction of scale uncertainty (per-cent level)

$\Delta\phi(Z,b)$

- NNLO is NLO-like, since at LO $\Delta\phi=\pi$ (only in last bin)
- New phase space regions open @NLO
- Sizeable change in shape and normalisation at NNLO

Conclusions

- NNLO predictions are required for precision phenomenology of LHC benchmark processes

1) PDF-sensitive jet observables
   - Triple differential di-jet cross section
   - Charged lepton asymmetry in $W^{\pm}$+jet
   - Observe: Understanding of parton content of the proton (at large x) can be improved by inclusion of corresponding data in global PDF fits

2) Flavour-sensitive observables: New feature in NNLOJET
   - Presented: Procedure for selecting b-jets in theory and experiment
     - Experiment: use flavour-blind anti-k_t, safe only up to NLO
     - Theory @NNLO: use flavour-k_t, IR-safe and flavour-dependent
   - Study: Impact of NNLO corrections in b-jet dependent distributions for VH (with $H \rightarrow bb$) and Z+b-jet production