Precision studies of vector boson plus heavy quarks at the LHC

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Loops and Legs in Quantum Field Theory

St. Goar - May 4, 2018

Thanks to:

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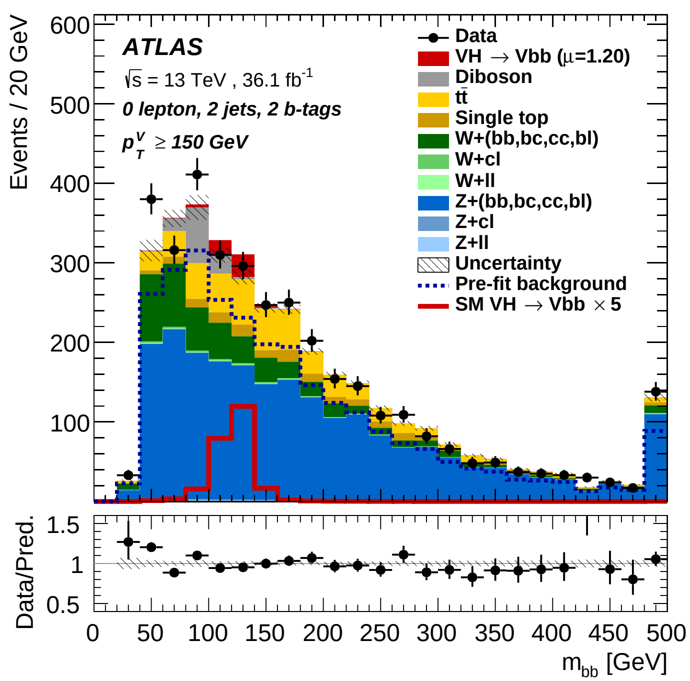
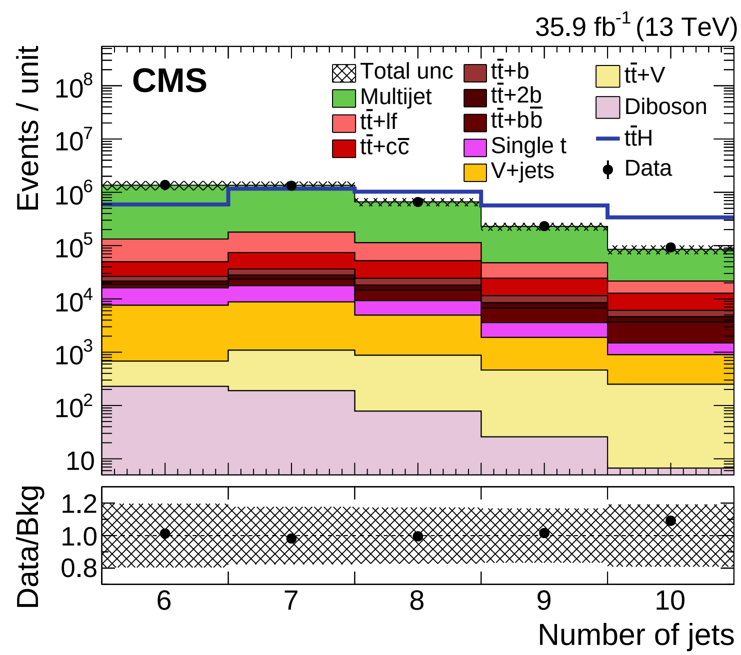
Outline

- V+HQ ($V = W/Z$, HQ$= b, t$): physics motivation
- Theoretical characterization of V+HQ production
- In a nutshell: status of $V + t$ quarks associated production
- Main focus: $V + b$ jets
  - $V + 1b$ jet vs $V + 2b$ jets vs LHC data
  - QCD+EW corrections
  - m_b effects
- Outlook

Motivations

- ▷ V+HQ (b,t) main **background** to several important SM and BSM signatures:
  - ▷ WH/ZH associated production, $H \to b\bar{b}$
  - ▷ $t\bar{t}H$ associated production
  - ▷ single-top production
  - ▷ several BSM signatures (with $l^{\pm}$, $\not{E}_T$, b jets, light jets)





Motivations (cont.)

- $V + t$ quarks: access to EW **top anomalous couplings**
- $V + b$ jets: **intriguing theoretical structure**
  - $W/Z + b$ jets are **multi-scale processes** ($m_b \gg \Lambda_{QCD}$, $m_b \ll M_{W/Z}$)
  - Need to control **sensitivity to $\mathbf{m_b}$ in theoretical predictions**
    - $\hookrightarrow$ hard matrix element
    - $\hookrightarrow$ parton shower
    - $\hookrightarrow$ PDF ...
  - direct access to b **parton density** (e.g. $bg \to Zb$)
  - **testing ground** for complex processes involving b jets (ex.: $t\bar{t} + b$ jets)

Theoretical synopsis: W vs. Z, and t vs. b–jets

$V+t\bar{t}$, $V+2b$ jets:

via the tree-level processes ($n_f=4\rightarrow$, $m_{t,b}\neq 0$)

- $\rightarrow$ $q\bar{q}'\rightarrow Wb\bar{b}$, $Wt\bar{t}$
- $\rightarrow$ $q\bar{q}, gg\rightarrow Zb\bar{b}$, $Zt\bar{t}$

and corresponding higher-order corrections.

$V+t$, $V+1b$ jet:

still via the tree-level processes ($n_f=4$, $m_b\neq 0$)

- $\rightarrow$ $q\bar{q}'\rightarrow Wb\bar{b}$
- $\rightarrow$ $q\bar{q}, gg\rightarrow Zb\bar{b}$

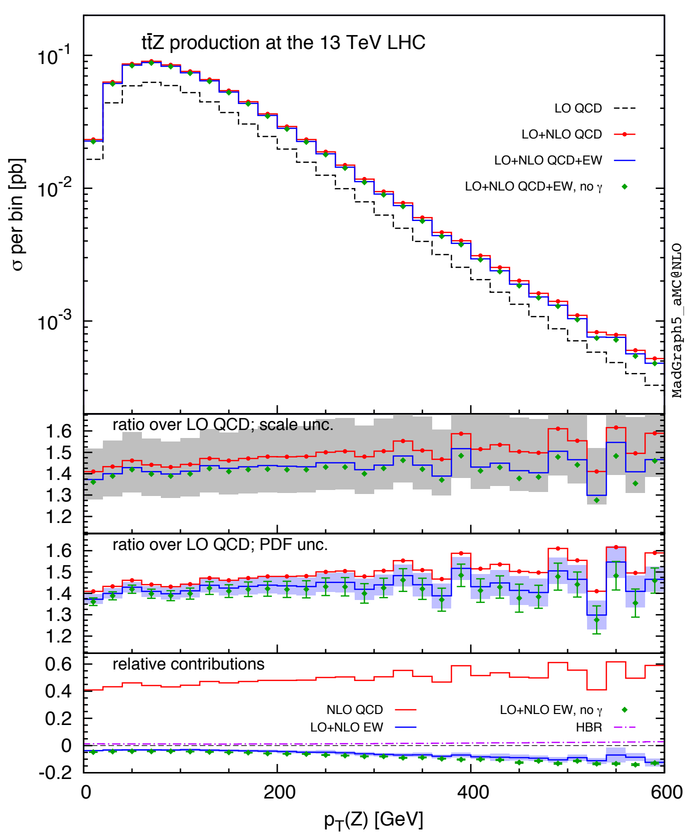
but also ($n_f=5\rightarrow$, $m_b=0$, only kept as IR regulator $\rightarrow$ 5FS),

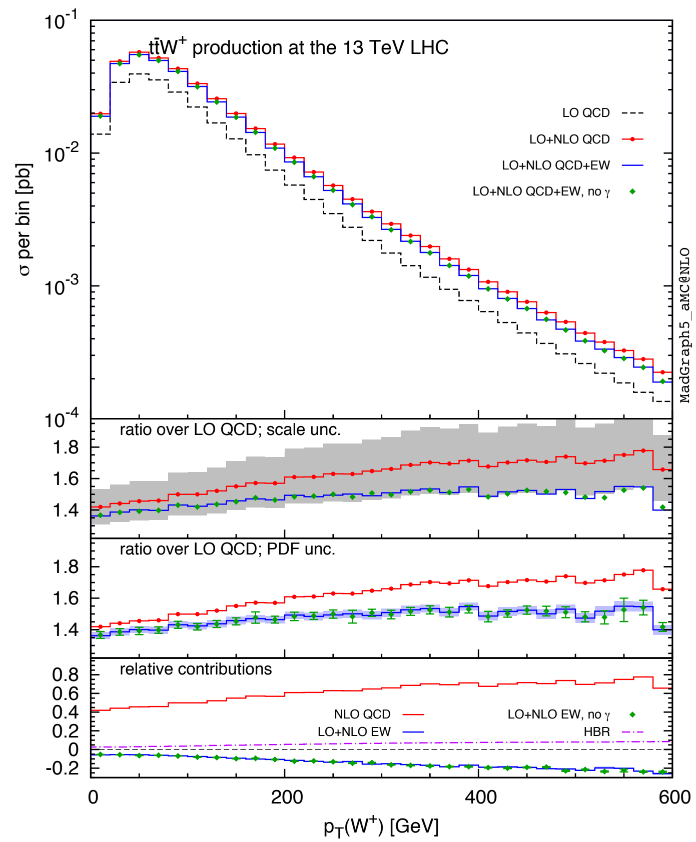
- $\rightarrow$ $bg\rightarrow Wt$
- $\rightarrow$ $b\bar{q}\rightarrow Wb+q'$
- $\rightarrow$ $bg\rightarrow Zb$

and corresponding higher-order corrections.

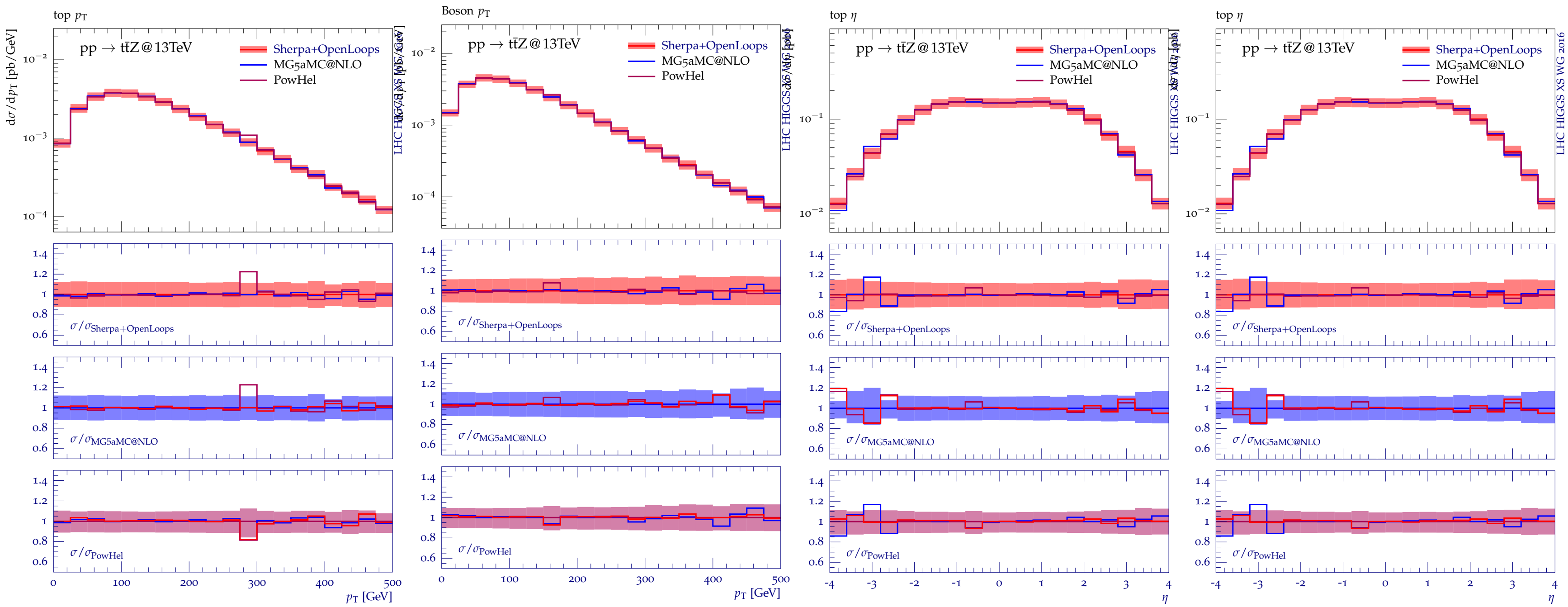
$W/Z + t\bar{t}$: theoretical developments

- ▷ **NLO QCD**: Lazopoulos, McElmurry, Melnikov, Petriello, arXiv:0804.2220; Kardos, Papadopoulos, Trócsányi, arXiv:1111.0610; Campbell, Ellis, arXiv:1204.5678
- ▷ **NLOQCD+PS**: Garzelli, Kardos, Papadopoulos, Trócsányi, arXiv:1111.1444, arXiv:1208.2665
- ▷ **NLO QCD+EW**: Frixione, Hirschi, Pagani, Shao, Zaro, arXiv:1504.03446





Comparison between different NLO+PS tools

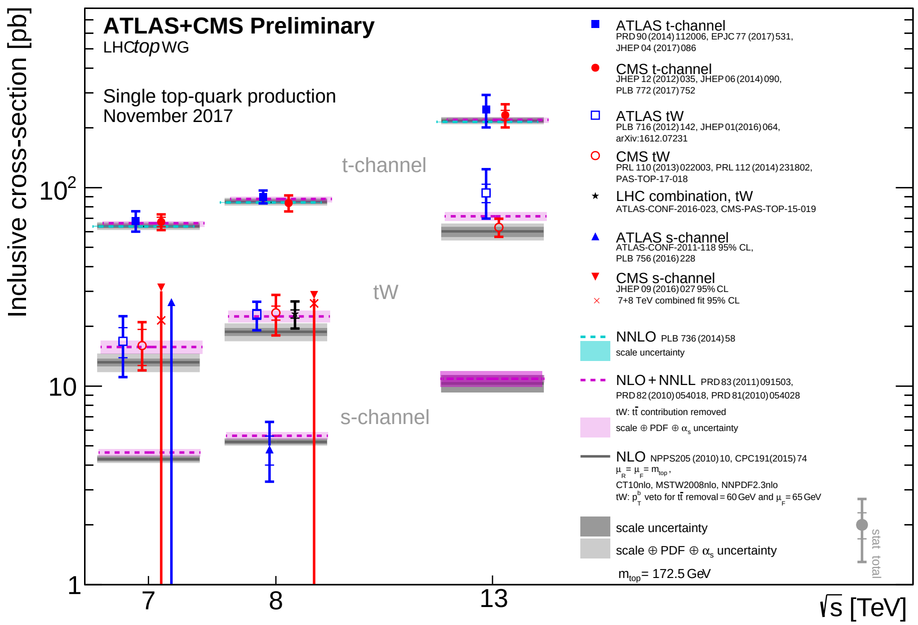


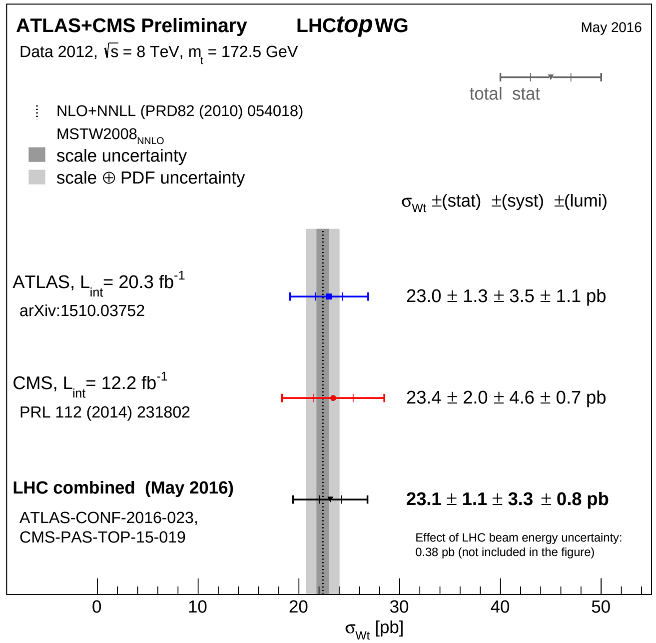
4^{th} CERN Yellow Report of the Higgs XS WG, $t\bar{t}H/tH$ WG, arXiv:1610.07922

$\hookrightarrow$ Consistency within still substantial theoretical uncertainty.

$W + t$: a component of single-top production

- ▷ **NLO QCD**: Zhu, hep-ph/0109269.
- ▷ **NLO+NNLL QCD**: Kidonakis, arXiv:1005.4451





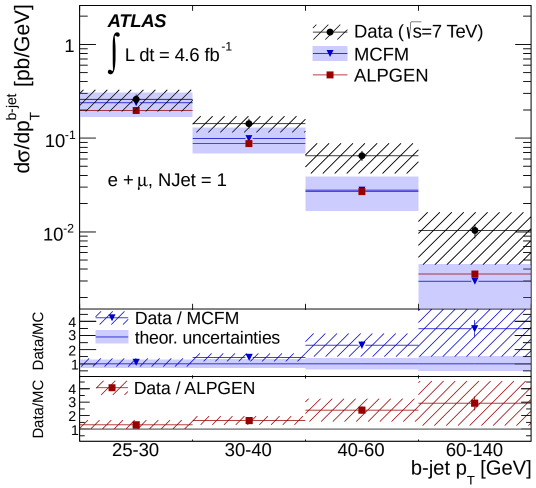
↪ NLO corrections ($gg \to Wt + b$) interfere with $t\bar{t}$ background.

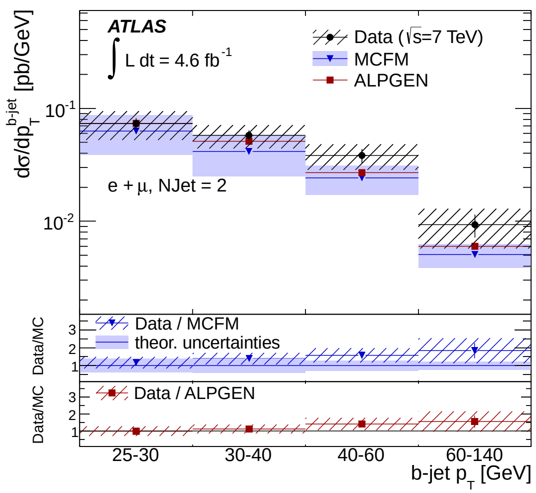
↪ Not an ideal candidate to study b-initiate processes, nor to measure b PDF.

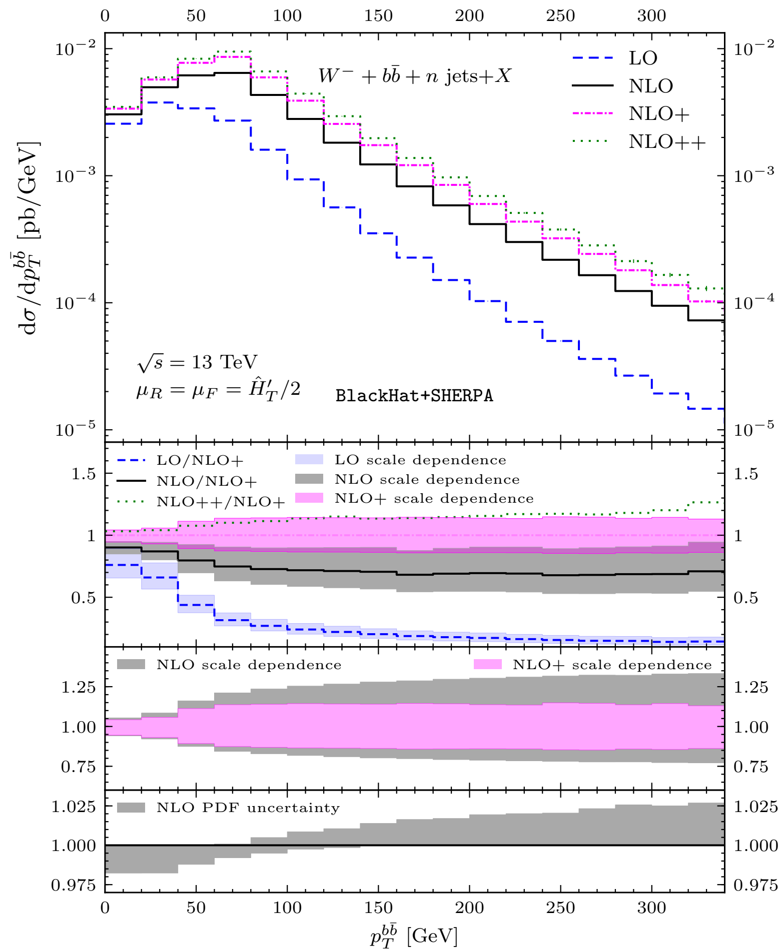
$V + b$ jets: NLO QCD and QCD+PS studies

- $W + 2b$ jets
  - Febres Cordero, L.R., Wackeroth, hep-ph/0606102, arXiv:0906.1923 (4FS)
  - Badger, Campbell, Ellis, arXiv:1011.6647 (4FS, $W \to l\nu$) $\to$ MCFM
  - Oleari, L.R., arXiv.1105.4488 (4FS) $\to$ POWHEG-BOX
  - Frederix, et al., arXiv:1106.6019 (4FS) $\to$ MG5aMC@NLO
- $W + 2b+$ jet
  - L.R., Schutzmeier, arXiv:1110.4438 (4FS, one-loop only)
  - Luisoni, Oleari, Tramontano, arXiv:1502.01213 (4FS) $\to$ POWHEG-BOX
- $W + 2b + n$ jets ($n = 0, 1, 2, 3$)
  - Anger, Febres Cordero, Ita, Sotnikov, arXiv:1712.05721
- $W + 2$ jets with at least one b jet
  - Campbell, et al., arXiv:0809.3003, arXiv:1107.3714 (5FS) $\to$ MCFM
- $Z + 2b$ jets
  - Febres Cordero, L.R., Wackeroth, arXiv:0806.0808, arXiv:0906.1923 (4FS)
  - Frederix, et al., arXiv:1106.6019 (4FS) $\to$ MG5aMC@NLO
  - Krauss, Napoletano, Schumann arXiv:1612.04640 (4FS) $\to$ OL+SHERPA
- $Z + 1b$ jet, $Z + 2$ jets with at least one b jet
  - Campbell, Ellis, Maltoni, Willenbrock, hep-ph/0312024 (5FS) $\to$ MCFM
  - Campbell, Ellis, Maltoni, Willenbrock, hep-ph/0510362 (5FS) $\to$ MCFM
  - Frederix, et al., arXiv:1106.6019 (5FS) $\to$ MG5aMC@NLO
  - Krauss, Napoletano, Schumann arXiv:1612.04640 (5FS) $\to$ OL+SHERPA

$W + b$ jets: theory vs experiments







[Anger, et al., arXiv:1712.05721]

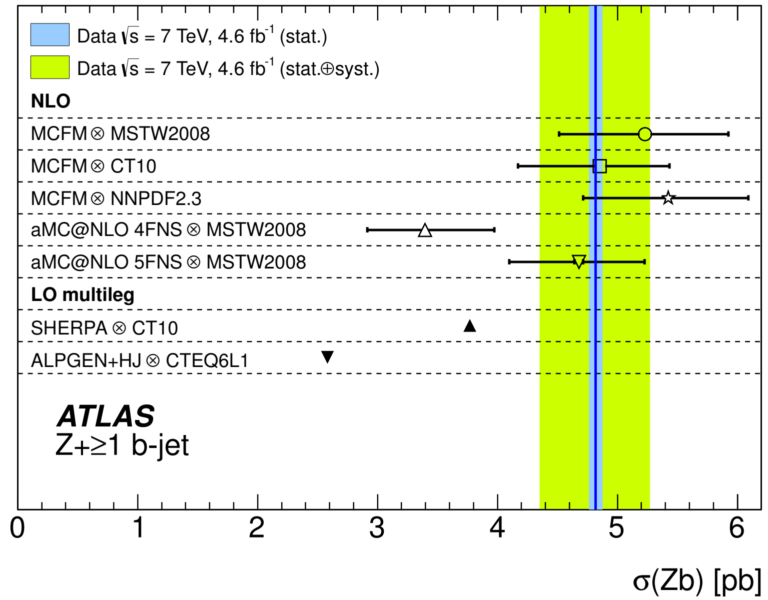
(↪ see Febres-Cordero's talk)

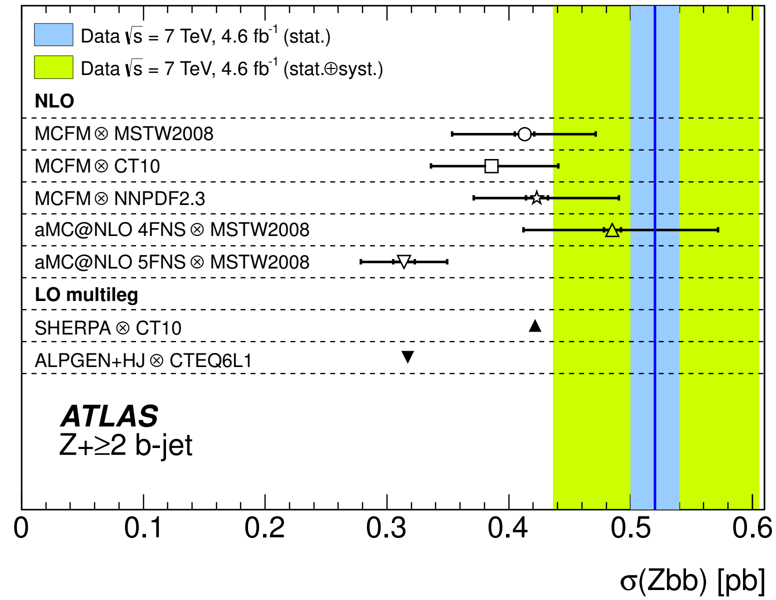
↪ well known **large NLO QCD** corrections

↪ **exclusive sums** of NLO QCD corrections to $Wb\bar{b} + \{j, 2j, 3j\}$ **add stability**

↪ **QCD NNLO** will certainly bring the **theory accuracy within percent level**.

$Z + b$ jets: theory vs experiments





↪ **Interesting comparison** 4FS ($gg, q\bar{q} \to Zb\bar{b}$+h.o.) vs. 5FS ($bg \to Zb$+h.o.)

↪ If QCD uncertainty is reduced, **need to investigate**:

- **QCD+EW corrections**
- $\mathbf{m_b}$ **effects** at all levels, from PDF to NLO PS interface

↪ $\mathbf{Z + 1b}$ **jet**: good candidate to study these effects:

- important for LHC phenomenology, and QCD of HQ
- 5FS: simple $2 \to 2$ process (nice if you want to add NNLO)
- clean w.r.t. (e.g.) 5FS $W + t$ ($bg \to Wt$)

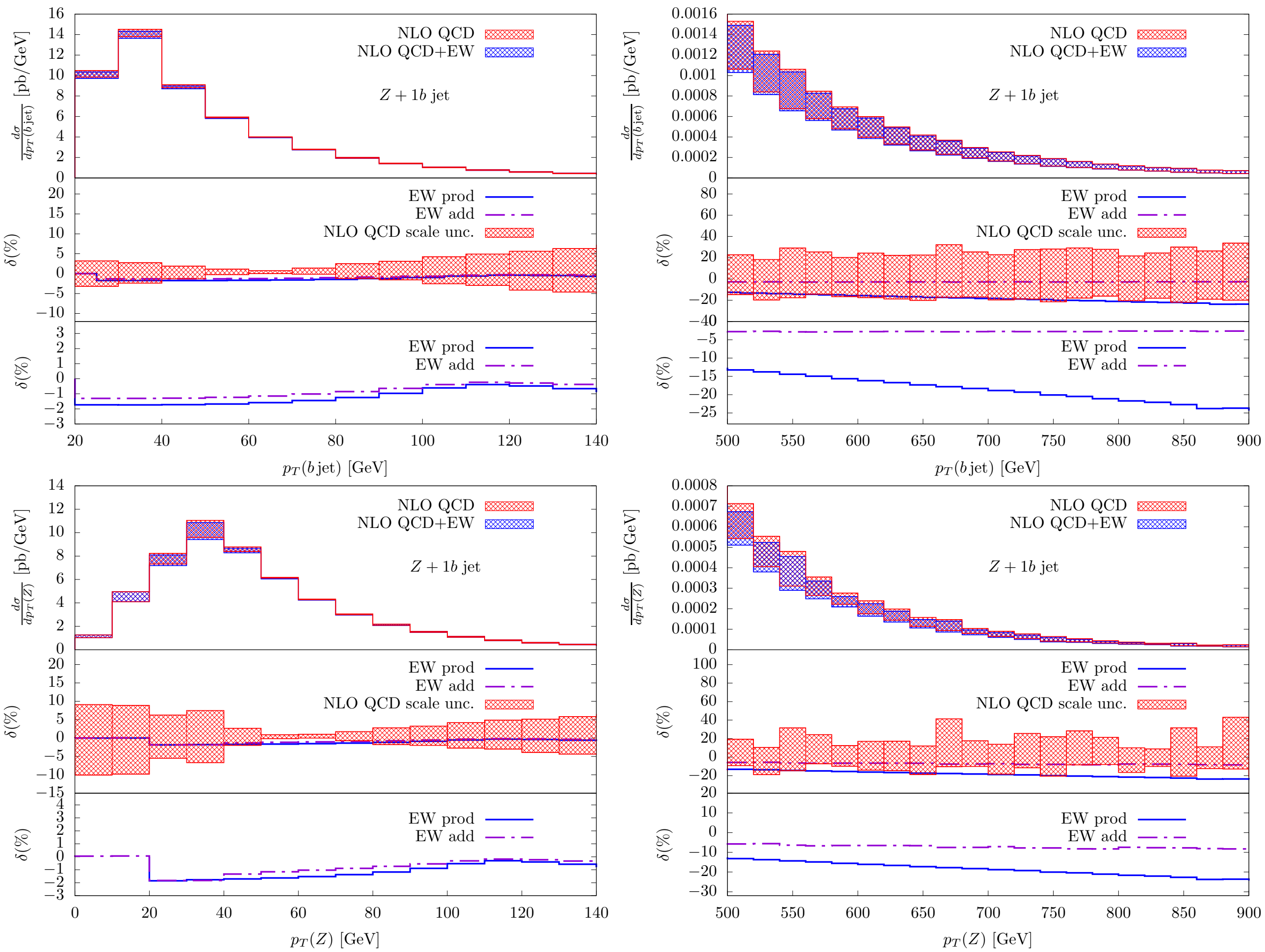
Aiming at a precision program for $Z + b$ jets

[Figueroa, Honeywell, Quackenbush, L.R., Reuschle, Wackeroth, arXiv:1805.01353]

- Focus on $\mathbf{Z + 1b}$ **jet** as best candidate process
  - $bg \to Zb + O(\alpha_s) + O(\alpha)$
  - $b\gamma \to bg$ very small (neglected)
- Added **NLO QCD and EW corrections**
  - one-loop corrections via `NLOX` (full fledged QCD+EW one-loop provider)
  - real correction (QED only) via PSS (δ_s, δ_c) and dipole subtraction
  - $N_f = 5$ active flavors, G_μ EW input scheme, CTEQ14qed PDFs.
- Included m_b **effects** at all different levels: *massive* 5FS
  - b quark massive in both initial and final state
  - dipole subtraction extended to include massive i.s. dipoles
    ($\hookrightarrow$ see Dittmaier, hep-ph/9904440)
  - m_b regulates collinear singularities from $b \to bg/\gamma$ and $g \to b\bar{b}$: i.s. collinear logs subtracted in b quark PDF $\to$ **caveat:**

    $\hookrightarrow$ proper matching with PDF (e.g. $b \to bg$ collinear logs) still incomplete
    $\hookrightarrow$ full m_b effects in PDF still incomplete

Adding NLO QCD+EW corrections



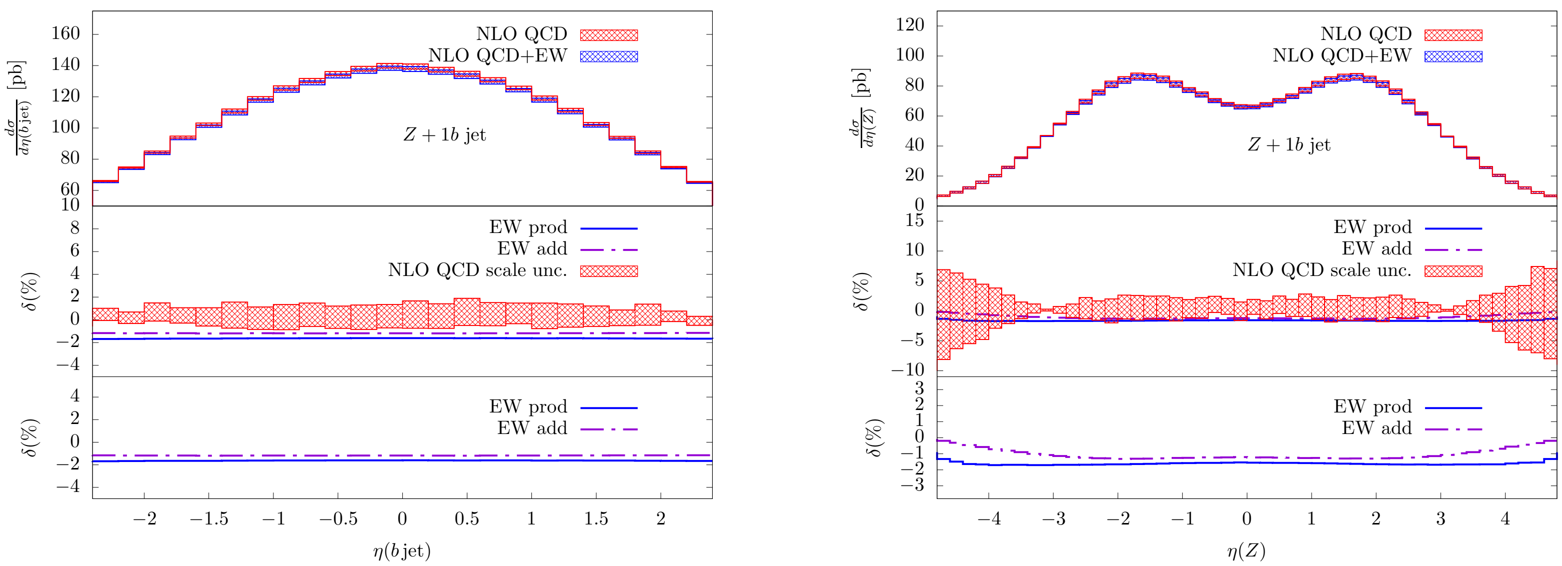
$$\sigma_{\rm NLO}^{\rm QCD+EW} = \sigma_{\rm LO} + \delta\sigma_{\rm NLO}^{\rm QCD} + \delta\sigma_{\rm NLO}^{\rm EW}$$

$$\delta_{\rm EW}^{\rm add} = \frac{\sigma_{\rm NLO}^{\rm QCD+EW} - \sigma_{\rm NLO}^{\rm QCD}}{\sigma_{\rm NLO}^{\rm QCD}}$$

$$\sigma_{\rm NLO}^{\rm QCD\times EW} = \sigma_{\rm NLO}^{\rm QCD} \times \frac{\sigma_{\rm NLO}^{\rm EW}}{\sigma_{\rm LO}}$$

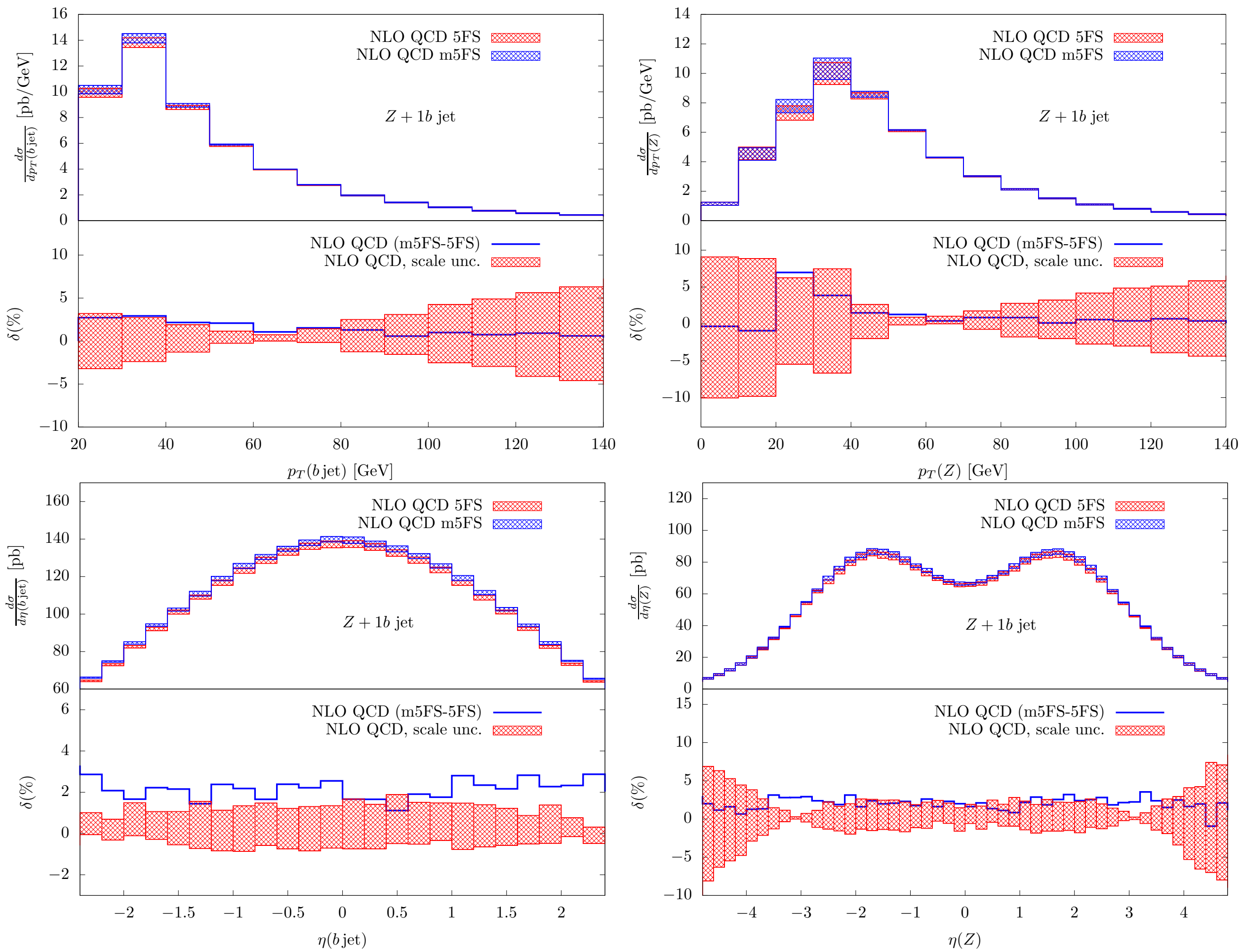
$$\delta_{\rm EW}^{\rm prod} = \frac{\sigma_{\rm NLO}^{\rm QCD\times EW} - \sigma_{\rm NLO}^{\rm QCD}}{\sigma_{\rm NLO}^{\rm QCD}} = \frac{\sigma_{\rm NLO}^{\rm EW}}{\sigma_{\rm LO}} - 1$$

Adding NLO QCD+EW corrections (cont.)



- ▷ EW effects mostly within current NLO QCD uncertainty
- ▷ still, clearly visible at high p_T and very visible using a multiplicative approach

Adding m_b effects in NLO QCD+EW corrections



$$\delta_{m_b} = \frac{\sigma_{\rm NLO}^{\rm QCD,m5FS} - \sigma_{\rm NLO}^{\rm QCD,5FS}}{\sigma_{\rm NLO}^{\rm QCD,5FS}} = \frac{\sigma_{\rm NLO}^{\rm QCD,m5FS}}{\sigma_{\rm NLO}^{\rm QCD,5FS}} - 1$$

- ▷ m_b effects mainly at low p_T and mostly within current NLO QCD uncertainty
- ▷ still clearly visible in angular distributions (e.g. pseudorapidity)

Outlook

- The **study of V+HQ** (t, b) production has very clear **phenomenological motivations** and has a very **clear impact on LHC physics**:
  - ↪ precision physics (Higgs couplings)
  - ↪ searches for new physics beyond the SM
- Theoretical prediction including NLO QCD are available, often interfaced with PS event generators. NLO EW have been calculated in several cases ($V + t\bar{t}$ and $Z + 1b$ jet).
- $\mathbf{V + b}$ **jets** has the largest NLO QCD uncertainty, and recent progress has shown that a **precision program** is **possible** if
  - ↪ NNLO as well as NLO EW corrections are included
  - ↪ a consistent massive b quark framework is used, at all stages of the calculation.