Higher-order corrections to processes with massive particles at hadron colliders

Bottom quark mass effects in $pp \to WH(b\bar{b})$ at NNLO

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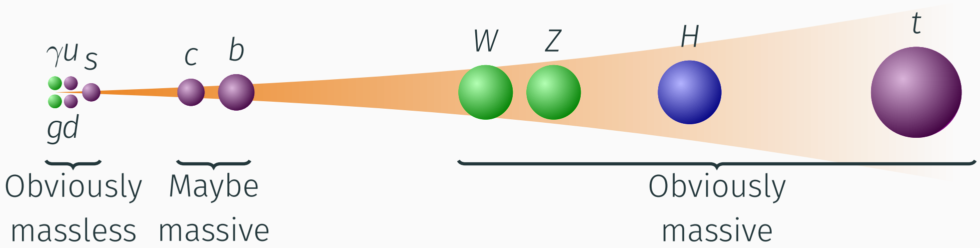
Massive particles at the LHC

What should be treated as massive depends on the context. For the LHC:



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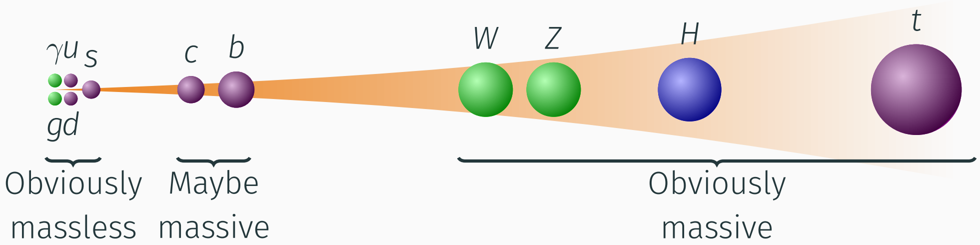
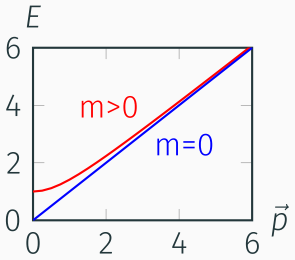
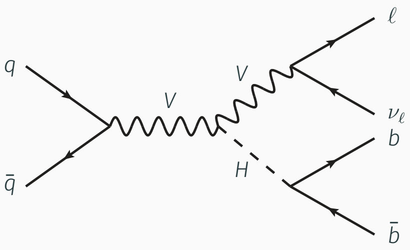
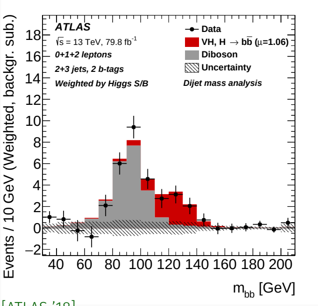




- Treating particles as massive comes at a cost
- Makes many calculations much more involved
- Gives rise to interesting mathematics
- Can make calculations more realistic

Associated Higgs boson production





[ATLAS '18]

- *VH* production is third largest production channel for the Higgs boson
  $\rightarrow$ gives access to *HVV* coupling
- $H \rightarrow b\bar{b}$ accessible in *VH* production via substructure techniques
  $\rightarrow$ observation by ATLAS and CMS relied heavily on VH production

Status of theory predictions

- Higher-order corrections to VH have a long history
  - NLO QCD
    [Han, Willenbrock '90] [Baer, Bailey, Owens '93] [Ohnemus, Stirling '93] [Mrenna, Yuan '97] [Spira '98] [Djouadi, Spira '99]
  - NLO EW
    [Ciccolini, Dittmaier, Krämer '03] [Denner, Dittmaier, Kallweit, Mück '11]
  - NLO matched to PS
    [Frixione, Webber '05] [Hamilton, Richardson, Tully '09] [Luisoni, Nason, Oleari, Tramontano '13] [Granata, Lindert, Oleari, Pozzorini '17]
  - Inclusive NNLO QCD
    [Brein, Djouadi, Harlander '03] [Brein, Harlander, Wiesemann, Zirke '12] [Brein, Harlander, Zirke '13]
  - Differential NNLO QCD
    [Ferrera, Grazzini, Tramontano '11] [Ferrera, Grazzini, Tramontano '13] [Campbell, Ellis, Williams '16] [Astill, Bizoń, Re, Zanderighi '16] [Ferrera, Somogyi, Tramontano '17] [Caola, Luisoni, Melnikov, Röntsch '17] [Gauld, Gehrmann-de Ridder, Glover, Huss, Majer '19] [Alioli, Broggio, Kallweit, Lim, Rottoli '19]
- Differential NNLO QCD calculation so far used massless b quarks

$\Rightarrow$ Investigate mass effects and compare massless and massive cases

Why use massive b quarks?

1. Kinematic distributions may have regions that are sensitive to b mass

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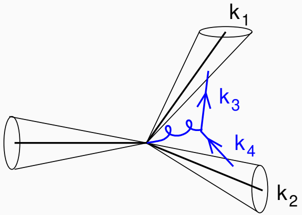
2. Ability to use conventional jet algorithms

   Massless b quarks:

   - Soft gluons can split into wide-angle $b\bar{b}$ pair
   - End up in different jets

   $\rightarrow$ need flavour-k_t algorithm to define b jets

$$d_{ij} = \frac{\Delta R_{ij}^2}{R^2} \times \begin{cases} \min(k_{t,i}^2, k_{t,j}^2), & \text{softer of } i,j \text{ is flavourless} \\ \max(k_{t,i}^2, k_{t,j}^2), & \text{softer of } i,j \text{ is flavoured} \end{cases}$$

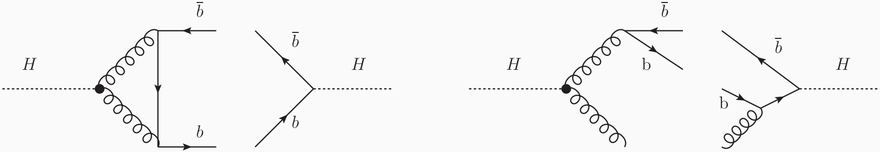


[Banfi, Salam, Zanderighi '06]

Or use **massive** b quarks and anti-k_t algorithm
$\rightarrow$ closer to current experimental analyses

Why use massive b quarks?

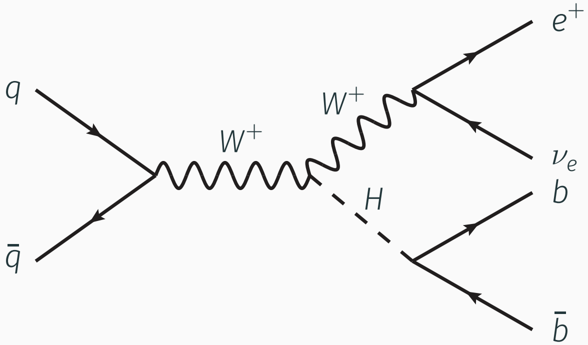
1. Kinematic distributions may have regions that are sensitive to b mass
2. Ability to use conventional jet algorithms
3. Top-loop contribution ($\sim y_b y_t$) to $H \to b\bar{b}$



[Caola, Luisoni, Melnikov, Röntsch '17]

- Only possible with chirality flip of b quark
- Consistent treatment requires massive b quarks

Our setup



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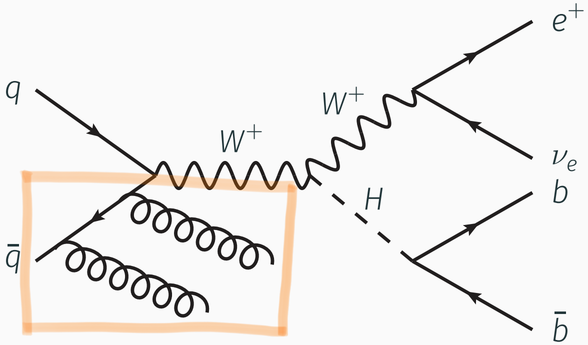
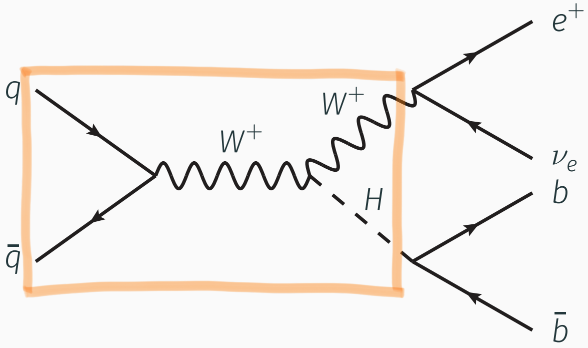
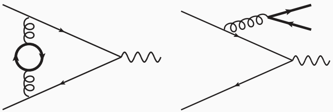


- Radiative corrections to production and decay cause IR singularities
- Work in nested soft-collinear subtraction scheme
  [Caola, Melnikov, Röntsch '17] [Caola, Melnikov, Röntsch '19]
- Extract poles of soft and collinear singularities from real radiation and cancel them against IR poles from virtual corrections

Our setup



- Production at NNLO QCD based on [Caola, Luisoni, Melnikov, Röntsch '17]
  - + New analytic results for integrated subtraction terms
    [Caola, Delto, Frellesvig, Melnikov '18] [Delto, Melnikov '19]
  - + Modifications from massive b quarks



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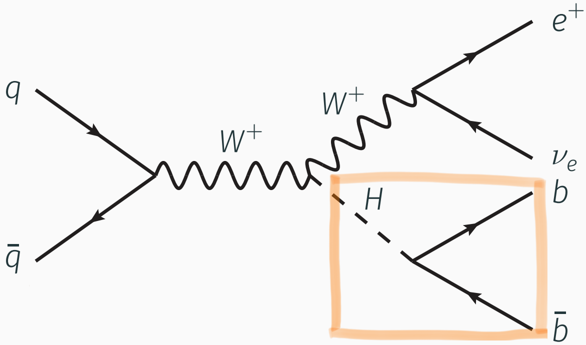
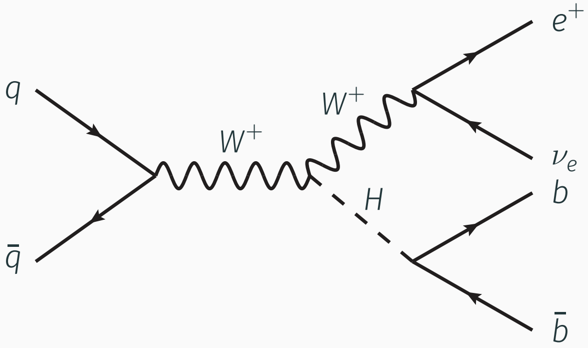


- Decay $H \to b\bar{b}$ at NNLO QCD
  - with massless b quarks based on [Caola, Luisoni, Melnikov, Röntsch '17] and updates from [Caola, Melnikov, Röntsch '19]
  - with massive b quarks based on [AB, Bizoń '19]

Our setup



- Combine production and decay processes using narrow-width approximation

$$\mathrm{d}\sigma_{WH(b\bar{b})} = \mathrm{Br}(H \to b\bar{b}) \times \mathrm{d}\sigma_{WH} \times \frac{\mathrm{d}\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}}$$

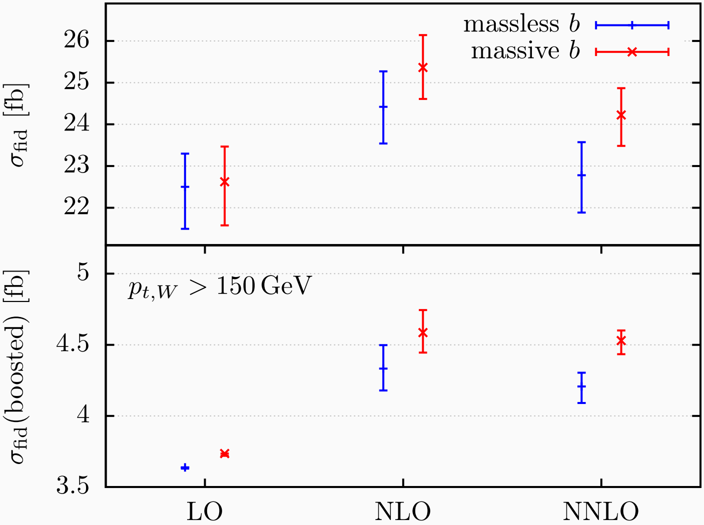
Our setup – fiducial cuts

- Use jet algorithm to cluster QCD partons;
  require at least two b jets ($R = 0.4$):
  - Massless case: flavour-k_t algorithm [Banfi, Salam, Zanderighi '06]
  - Massive case: anti-k_t algorithm [Cacciari, Salam '08]
- Impose cuts on final-state leptons and b jets

$$|\eta_l| < 2.5, \qquad |\eta_{j,b}| < 2.5,$$
$$p_{t,l} > 15\,\text{GeV}, \qquad p_{t,jb} > 25\,\text{GeV}$$

- Boosted setup: additional $p_{t,W} > 150\,\text{GeV}$ cut
  (interesting region to identify $H \to b\bar{b}$ decay)

Fiducial cross-sections



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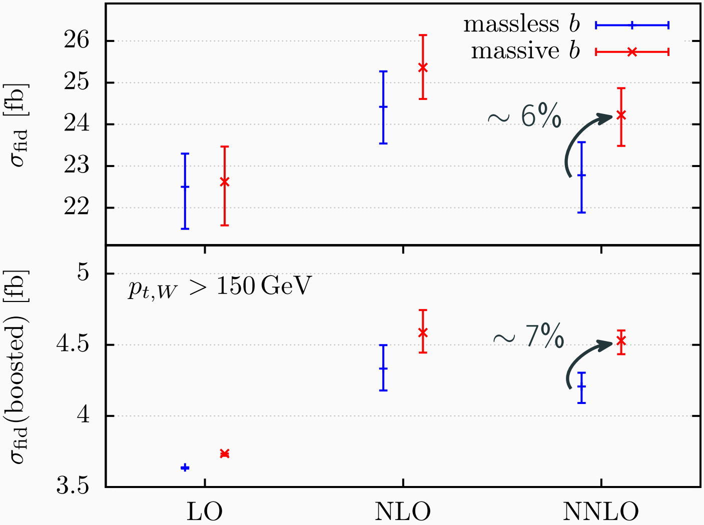
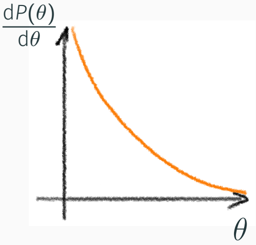


Fiducial cross-sections: Reasons for differences

- Main reason: Differences in gluon radiation for $H \to b\bar{b}$
- Collinear gluon emission probability differs:

Massless b quarks

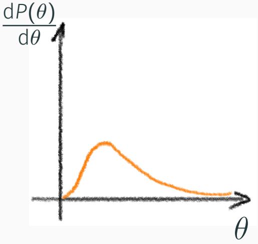
$$\mathrm{d}P(\theta) \sim \frac{\mathrm{d}\theta^2}{\theta^2}$$



$\to$ logarithmic enhancement

Massive b quarks

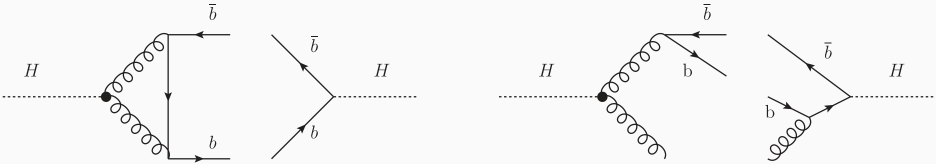
$$\mathrm{d}P(\theta) \sim \frac{\mathrm{d}\theta^2}{\theta^2 + m_b^2/E_b^2}$$



$\to$ mass screens singularity

- Fiducial cuts are harder to pass for $H \to b\bar{b}g$ with massless b quarks

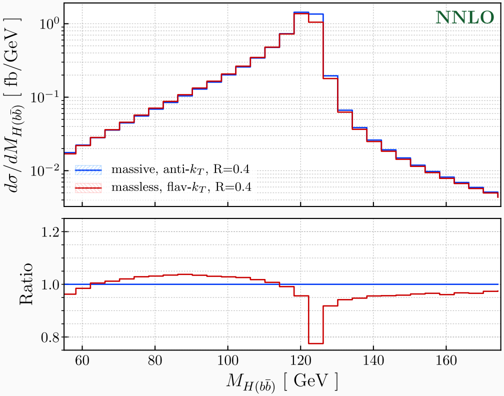
Top-loop contribution ($\sim y_b y_t$) to $H \to b\bar{b}$

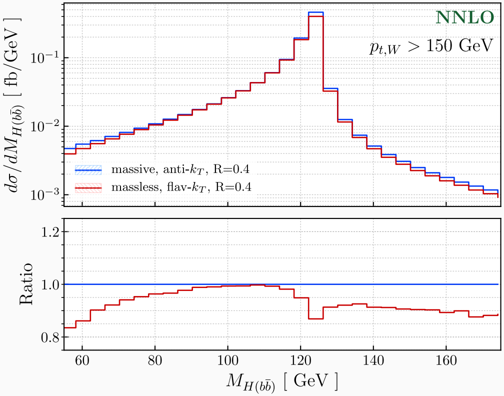


[Caola, Luisoni, Melnikov, Röntsch ’17]

- Calculated exactly in [Primo, Sasso, Somogyi, Tramontano ’18]
- Turns out to be only a minor effect
- Contribute to fiducial cross sections only at sub-percent level
- Included in all results with massive b quarks presented here anyway

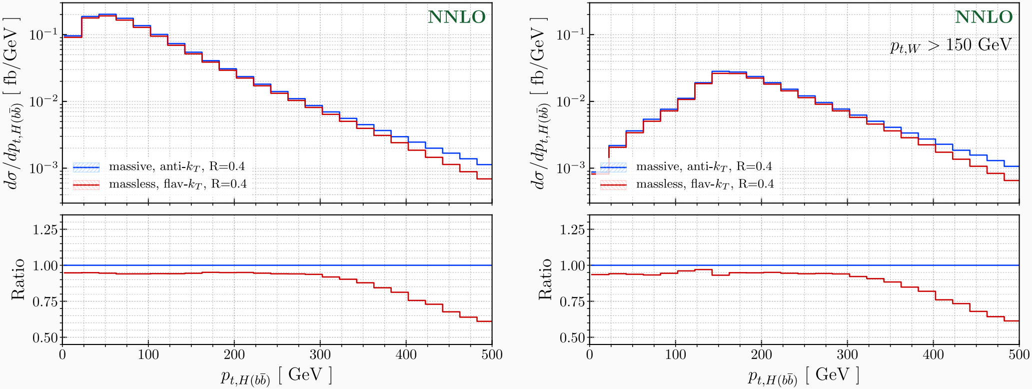
Invariant mass distribution





- Only delta peak at LO $\rightarrow$ shape is determined by radiative corrections
- Differences in gluon radiation between massless and massive case affect shape of the distribution

Transverse momentum of $b\bar{b}$ pairs



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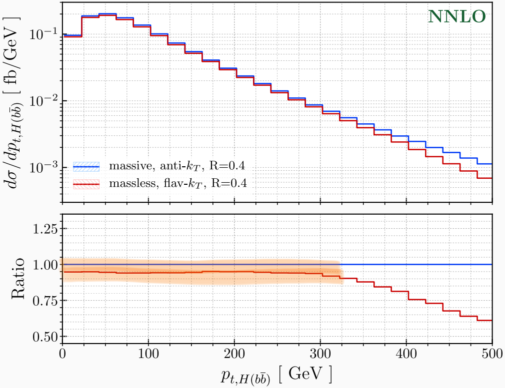
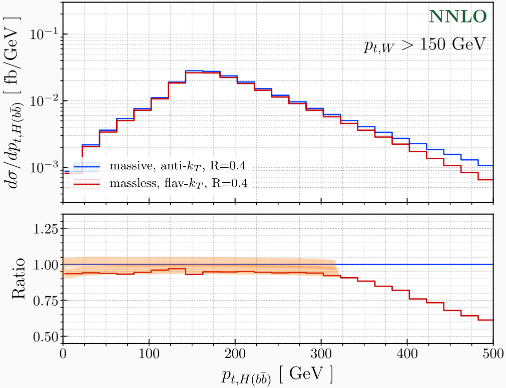
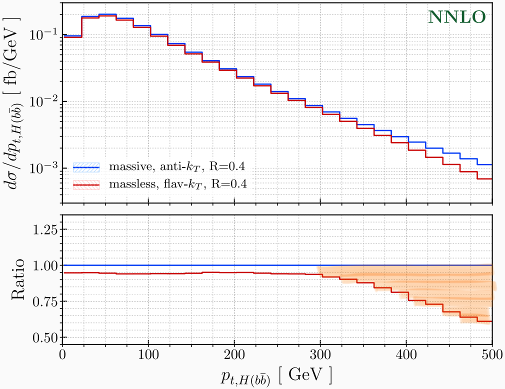
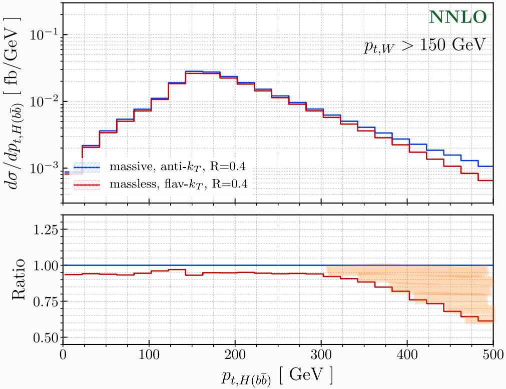




- Bulk shows flat, $\mathcal{O}(5\%)$, differences between massless and massive cases

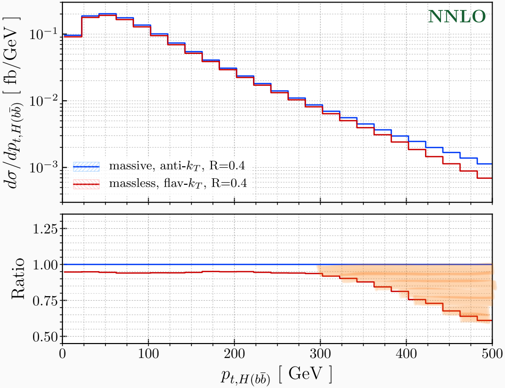
Transverse momentum of $b\bar{b}$ pairs

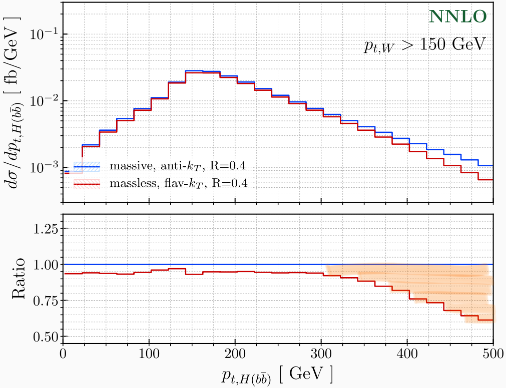




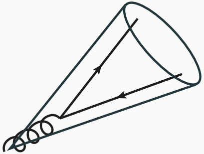
- Tails differ more substantially, up to $\mathcal{O}(35\%)$

Transverse momentum of $b\bar{b}$ pairs

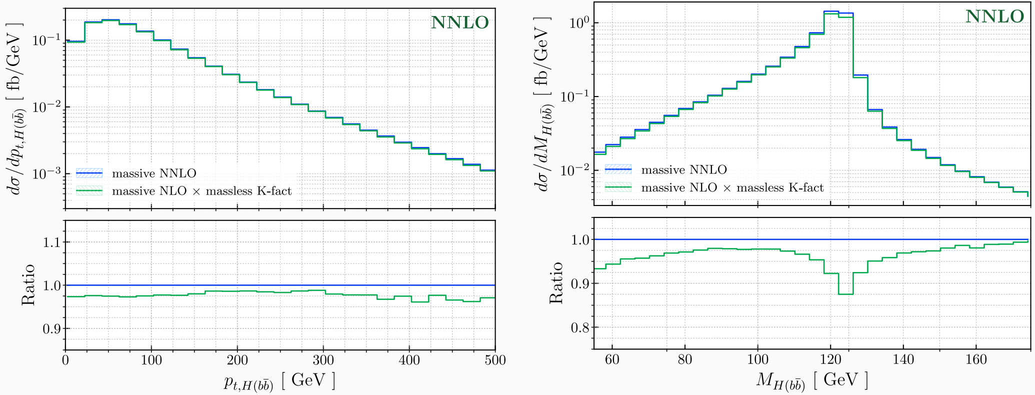




- Tails differ more substantially, up to $\mathcal{O}(35\%)$
- Flavour-k_t algorithm starts clustering high-p_t $b\bar{b}$ pairs as single jet earlier than anti-k_t
- Difference already present at LO

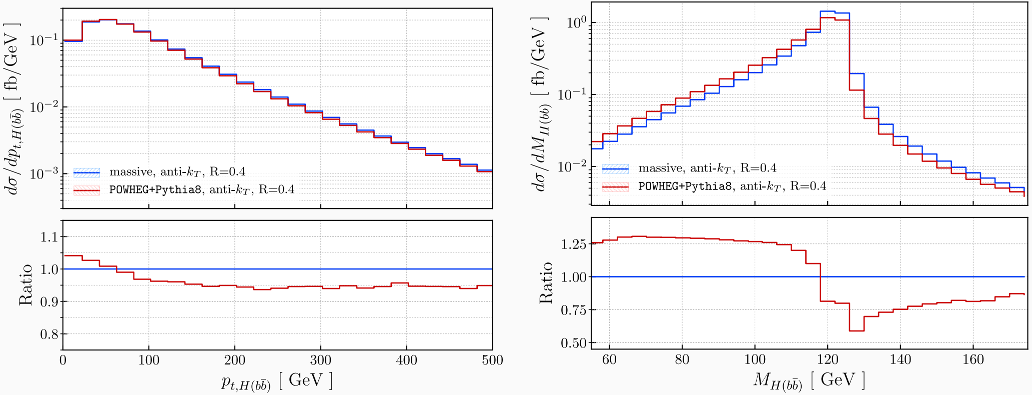


Approximate NNLO results



- Question: Can we avoid a massive NNLO calculation via K-factors?
- Answer: Depends (on the observable)
  - $p_{t,H(b\bar{b})}$: Works decently well
  - $M_{H(b\bar{b})}$: Does not capture all details, $\mathcal{O}(10\%)$ differences

Comparison to parton showers

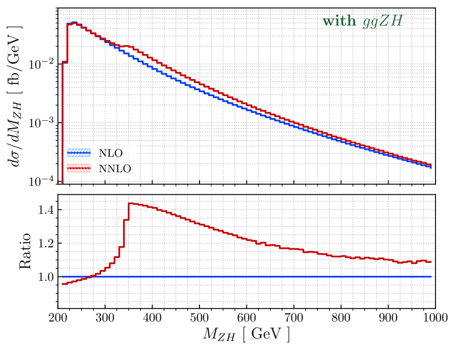


- Parton-level parton shower calculation with `POWHEG` and `Pythia8`
- $p_{t,H(b\bar{b})}$: $\mathcal{O}(5\%)$ differences
- $M_{H(b\bar{b})}$: Larger, up to $\mathcal{O}(25\%)$ differences
  $\rightarrow$ shift by $\delta M_{H(b\bar{b})} \sim -4$ GeV improves agreement

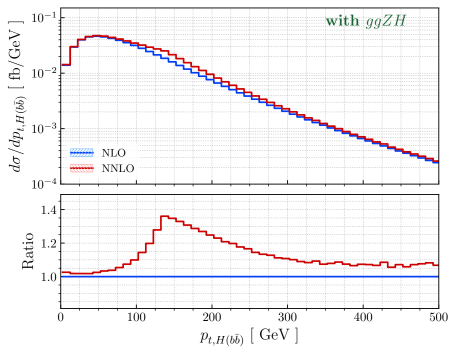
A glimpse on follow-up work: $pp \to ZH(b\bar{b})$

Follow-up work in [Bizon, Caola, Melnikov, Röntsch '21]:

- Implementation of ZH production with $H \to b\bar{b}$ decay
  - Similar to WH, but involves $gg \to ZH$ channel (starts at $\mathcal{O}(\alpha_s^2)$)
  - Noticable impact on fiducial cross-sections and distributions



[Bizon, Caola, Melnikov, Röntsch '21]

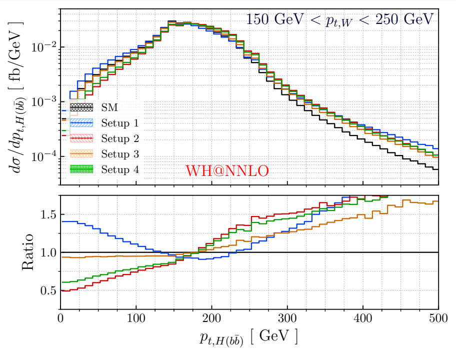


[Bizon, Caola, Melnikov, Röntsch '21]

A glimpse on follow-up work: $pp \to ZH(b\bar{b})$

Follow-up work in [Bizon, Caola, Melnikov, Röntsch '21]:

- Implementation of ZH production with $H \to b\bar{b}$ decay
- Investigation of impact of anomalous HVV couplings
  - Parametrise deviation from SM using SMEFT operators (only HVV sector)
  - Different scenarios become distinguishable away from peak



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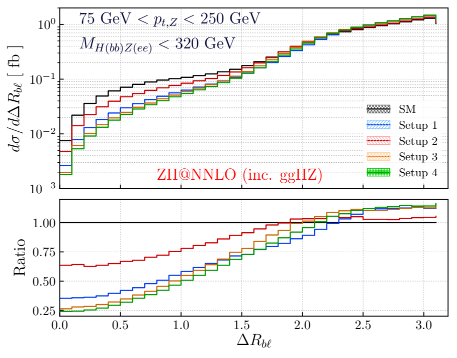

[Bizon, Caola, Melnikov, Röntsch '21]

Conclusions

- We calculated $pp \to W^+H \to e^+\nu_e b\bar{b}$ at NNLO QCD with massive b quarks
- Allows to use conventional jet algorithms
  $\to$ makes calculation more aligned with current experimental analyses
- Found $\mathcal{O}(5\%)$ differences between massive and massless fiducial cross sections
- Differences are more pronounced for certain distributions (e.g. $p_{t,H(b\bar{b})}$)
- Approximate NNLO via differential K-factors sometimes possible (depends on observable)
- Comparison between fixed-order and parton shower calculations allows to judge agreement between those descriptions