VH production with $H \to bb$ decay at NNLO matched to parton showers

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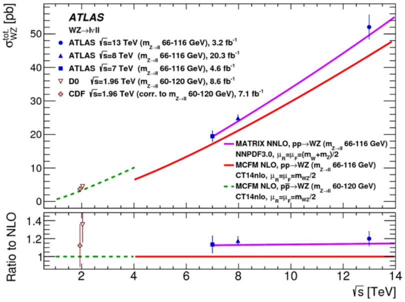
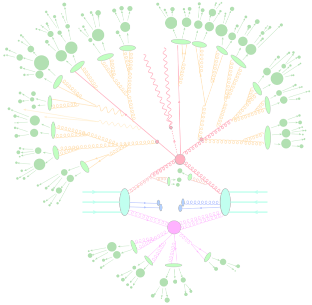
Precision Physics





- Current experimental precision demands at least NNLO accuracy
- Parton shower (PS) is needed for realistic phenomenology
- Combination of hard scattering and PS is crucial

Precision Physics

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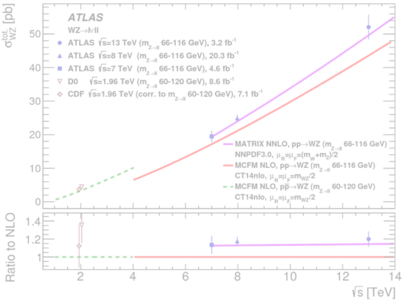
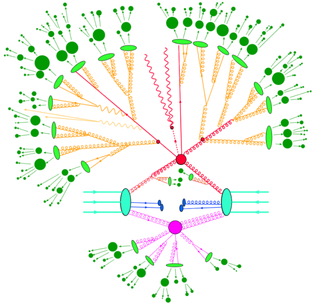




- Current experimental precision demands at least NNLO accuracy
- Parton shower (PS) is needed for realistic phenomenology
- Combination of hard scattering and PS is crucial

MiNNLO$_{PS}$ reaches NNLO+PS accuracy for the production of a colour singlet F.
Starting point → **MiNLO'** framework implemented within the **POWHEG** method. [Nason 2004]

MiNLO' [Hamilton,Nason,Oleari,Zanderighi 2012]

$$\overline{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int d\Phi_r [R(\Phi_{n+1}) - C(\Phi_{n+1})]$$

$$\downarrow$$

$$\overline{B}(\Phi_n) = e^{-\tilde{S}(p_T)} \left(B(\Phi_n)\left(1 + \alpha_s(p_T)[\tilde{S}]^{(1)}\right) + V(\Phi_n) + \int d\Phi_r [R(\Phi_{n+1}) - C(\Phi_{n+1})] \right)$$

$$\tilde{S}(p_T) = \int_{p_T^2}^{Q^2} \frac{dq^2}{q^2} \left[A(\alpha_s(q^2)) log \frac{Q^2}{q^2} + B(\alpha_s(q^2)) \right]$$

- **Finite result** for F+J production when the **jet is unresolved**
- Prescription for choosing the scales μ_R and μ_F
- **NLO** accuracy in observables inclusive in F and F+J

MiNNLO

[Monni,Nason,Re,Wiesemann,Zanderighi 2019]

starting point → analytic resummation formula $$\frac{d\sigma}{d\Phi_F dp_T} = \frac{d}{dp_T}\left\{e^{-\tilde{S}(p_T)}\mathcal{L}(p_T)\right\} + R_f(p_T)$$

$$\bar{B}(\Phi_{FJ}) = \overbrace{e^{-\tilde{S}(p_T)}\left\{\frac{\alpha_s(p_T)}{2\pi}\left[\frac{d\sigma_{FJ}}{d\Phi_{FJ}}\right]^{(1)}\left(1+\frac{\alpha_s(p_T)}{2\pi}[\tilde{S}]^{(1)}\right)+\right.}^{\text{MiNLO}}$$

$$\left. + \overbrace{\left(\frac{\alpha_s(p_T)}{2\pi}\right)^2\left[\frac{d\sigma_{FJ}}{d\Phi_{FJ}}\right]^{(2)}}^{\text{MiNLO}} + \overbrace{\left(\frac{\alpha_s(p_T)}{2\pi}\right)^3[D(p_T)]^{(3)}}^{\text{MiNNLO}}\right\}$$

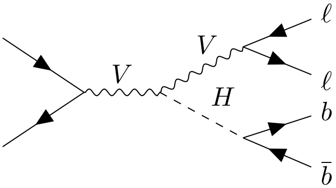
with

$$D(p_T) = -\frac{d\tilde{S}(p_T)}{dp_T}\mathcal{L}(p_T) + \frac{d\mathcal{L}(p_T)}{dp_T}$$

- NNLO accuracy reached for observables inclusive in F

pp $\rightarrow$ VH $\rightarrow$ ll$b\bar{b}$

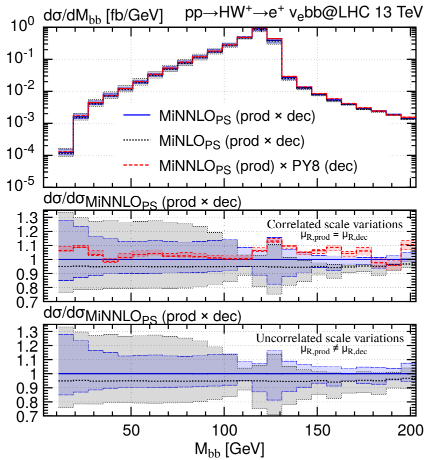
- One of the main production channels + largest branching fraction in the decay
- Needed for precision measurements in the Higgs sector
- Possible to study separately production and decay

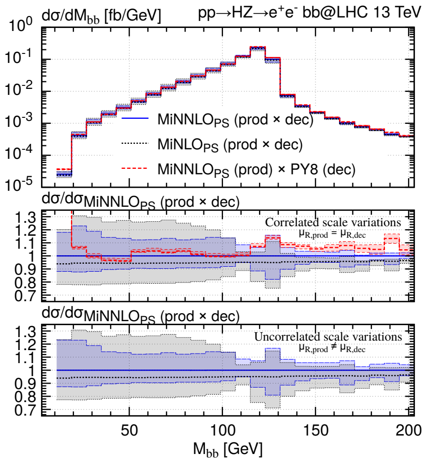


$$w_{full} = w_{prod} \cdot \mathrm{Br}(H \rightarrow b\bar{b}) \cdot \frac{w_{dec}}{\Gamma(H \rightarrow b\bar{b})}$$

- NNLO+PS accuracy in both production and decay
- MiNNLO$_{\mathrm{PS}}$ in prod + reweighting in decay
- Correlated vs uncorrelated scales variation
- Shower (PYTHIA8) consistently matched

Results





- Fully compatible regardless the scale variations
- PY8 error bands drastically underestimated

Results

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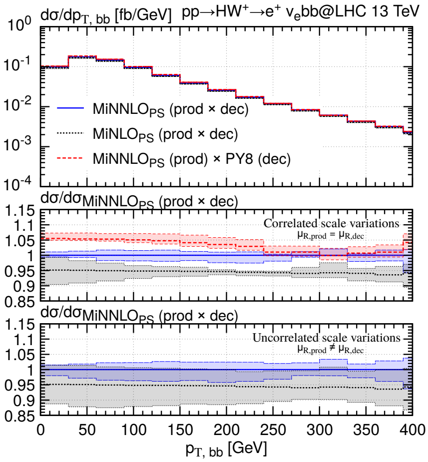

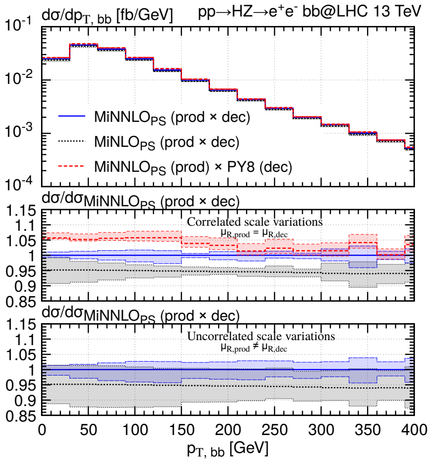

- $\mathrm{MiNNLO_{PS}}$ induces a mostly flat 5% correction on top of MiNLO'

Impact of jet-clustering algorithms

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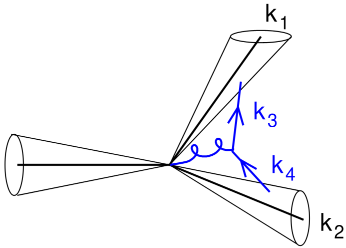
The definition of flavour in a clustering algorithm is not trivial → **IR-safe flavour**, insensitive to the addition of extra soft and collinear branchings.

Example: with a usual algorithm (kt, cone,..), sum of flavours of partons in a jet is IR unsafe



If a soft gluon emits a couple of quarks at wide angles, the flavours of jets can be contaminated.

Flavour-kt algorithm for hadron collisions

$$y_{ij}^{kt} = \frac{(\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2)}{R^2} \times min(k_{ti}^2, k_{tj}^2)$$
$$y_{iB}^{kt} = k_{ti}^2$$

[Banfi,Salam,Zanderighi 2006]

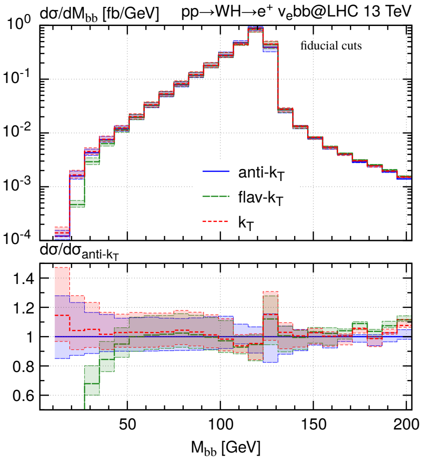
$$y_{ij}^{flav-kt} = \frac{(\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2)}{R^2} \times \begin{cases} max(k_{ti}^2, k_{tj}^2) & \text{softer (i,j) is flavoured} \\ min(k_{ti}^2, k_{tj}^2) & \text{softer (i,j) is flavourless} \end{cases}$$

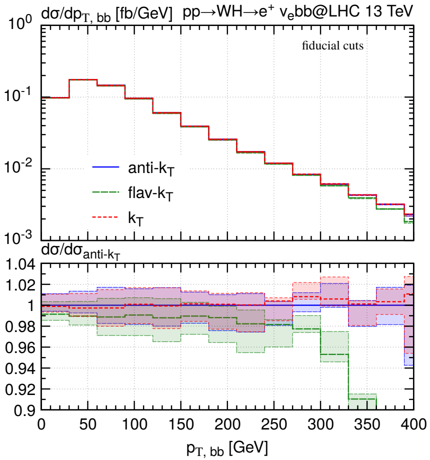
$$y_{iB}^{flav-kt} = \begin{cases} max(k_{ti}^2, k_{tB}^2) & \text{i flavoured} \\ min(k_{ti}^2, k_{tB}^2) & \text{i flavourless} \end{cases}$$

$$k_{tB}(\eta) = \sum_i k_{ti}\Big(\Theta(\eta_i - \eta) + \Theta(\eta - \eta_i)e^{\eta_i - \eta}\Big)$$

IDEA behind $\mathbf{k_{tB}}$: we have an emitting beam whose "transverse scale" depends on the emissions already occurred (higher rapidities) and on the light-cone momentum still left (lower rapidities). The same logic is applied to the beam moving in the opposite direction, defining $\mathbf{k_{t\overline{B}}}$

Results


dσ/dM_bb [fb/GeV]
pp→WH→e⁺ ν_e bb@LHC 13 TeV
fiducial cuts
anti-k_T
flav-k_T
k_T
dσ/dσ_anti-k_T
M_bb [GeV]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Conclusions

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- NNLO+PS accuracy is **strongly needed** for a realistic description of LHC events
- $\mathbf{MiNNLO_{PS}}$ is a **powerful tool** for reaching this accuracy
- In this context, I showed results for **VH production with H$\rightarrow$ bb decay**
- **Non trivial** impact of jet **clustering algorithms**

Thank you for your attention!

Back Up

MiNNLO$_{PS}$ reaches NNLO+PS accuracy for the production of a colour singlet F.
Starting point $\rightarrow$ **MiNLO'** framework implemented within the **POWHEG** method.

POWHEG

[Nason 2004]

$$d\sigma_{POW} = \bar{B}(\Phi_n) d\Phi_n \left\{ \Delta(\Phi_n, \lambda) + \Delta(\Phi_n, p_T) \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} d\Phi_r \right\}$$

with

$$\overline{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int d\Phi_r [R(\Phi_{n+1}) - C(\Phi_{n+1})]$$

$$\Delta(\Phi_n, p_T) = exp\left\{ - \int d\Phi'_r \frac{R(\Phi_n, \Phi_{r'})}{B(\Phi_n)} \theta(p'_T - p_T) \right\}$$

- **Hardest emission generated first** $\rightarrow$ subsequent emissions are p_T-vetoed
- Events generated with **positive weights**
- **NLO** accuracy in inclusive observables
- Almost **PS indipendent**

MiNLO'

[Hamilton,Nason,Oleari,Zanderighi 2012]

$$\overline{B}(\Phi_n)= e^{-\tilde{S}(p_T)}\left(B(\Phi_n)\left(1+\alpha_s(p_T)\tilde{S}^{-1}\right)+V(\Phi_n)+\int d\Phi_r[R(\Phi_{n+1})-C(\Phi_{n+1})]\right)$$

$$\tilde{S}(p_T)=\int_{p_T^2}^{Q^2}\frac{dq^2}{q^2}\left[A(\alpha_s(q^2))log\frac{Q^2}{q^2}+B(\alpha_s(q^2))\right]\}$$

- Finite result for F+J production when the jet is unresolved
- Prescription for choosing the scales μ_R and μ_F
- **NLO** accuracy in observables inclusive in F and F+J

Jet flavour

- Starting point: **kt algorithm**

$$y_{ij}^{kt} = 2 \cdot min(E_i^2, E_j^2)(1 - cos\theta_{ij}), \qquad E_j \ll E_i, \theta_{ij} \ll 1$$

- **Phyisical meaning**: QCD enhancement in soft/collinear regions for gluon emissions

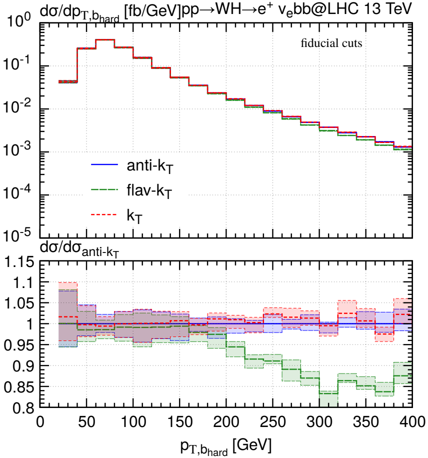
$$d\Phi |M_{g\to g_i g_j}|^2 \sim \frac{dE_j}{min(E_i, E_j)} \frac{d\theta_{ij}^2}{\theta_{ij}^2}$$

- Quark production has **no soft divergence**

$$d\Phi |M_{g\to q_i \bar{q}_j}|^2 \sim \frac{dE_j}{max(E_i, E_j)} \frac{d\theta_{ij}^2}{\theta_{ij}^2}$$

$\rightarrow$ **FATAL** for jet flavour studies

Results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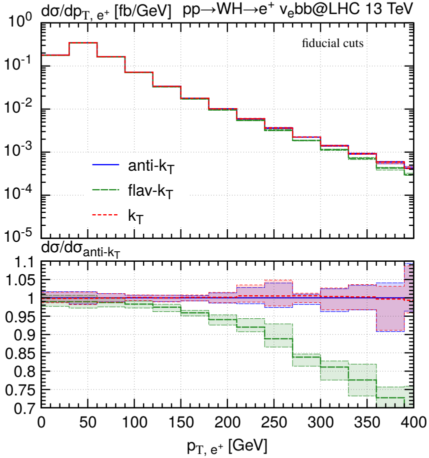
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