proVFBH: VBF production at NNLO

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CMS PH Generator Meeting

Based on PRL115(082002) and PRL117(072001) in collaboration with
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proVBFH

What it does:

- `Fortran90` code that computes VBF Higgs production inclusively in QCD radiation up to N^{3}LO-QCD in the VBF approximation
  - This calculation is fully differential in the Higgs boson kinematics
- Computes VBF Higgs production fully differentially at NNLO-QCD
- Fully flexible with respect to PDFs, analysis cuts, renormalization and factorisaztion scales, EW parameters etc.

What it lacks (at the moment):

- Higgs decays
- PDF and scale variations on the fly

proVBFH

Where to obtain it:

- https://github.com/fdreyer/proVBFH
  - proVBFH: Contains the full code
  - proVBFH-inclusive: Light-weight code dedicated to study of inclusive VBF cross section
  - proVBFHH: Same as proVBFH but for di-Higgs production

What it contains:

- analysis/user_analysis.f: Analysis code which can be modified by the user
- example/: Directory with example input files
- docs/provbfh-doc.pdf: Documentation on how to use the code
- aux/combine_runs.f: Script to combine independent runs
- src/: Source files which should not be touched by a typical user

proVBFH

Dependencies:

- HOPPET v1.3.0+ (https://github.com/hoppet-code/hoppet)
- FastJet
- LHAPDF
- gfortran > 4.4.7 or ifort

Based on:

- POWHEG-BOX-V2: Users familiar with POWHEG will find running the code straight-forward
- POWHEG VBF_H: Provides the VBF phase space
- POWHEG VBF_HJJJ: Provides the real, real-virtual and real-real corrections
- 2- and 3-loop DIS coefficient functions computed by S. Moch, A. Vogt, J. A. M. Vermaseren and M. Rogal

The input card

```
!!!!!!!!!!!!!!! USER PARAMETERS !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
qcd_order 3        ! 1: LO, 2: NLO, 3:NNLO, 4:N3LO (only for inclusive results)
inclusive_only 0   ! (default: 0) 1: computes only the inclsuive VBF cross section
                   ! differentially in the Higgs momentum. 0: Computes the cross
                   ! section fully differentially in the jets.

ebeam1 6500d0      ! energy of beam 1
ebeam2 6500d0      ! energy of beam 2

lhans1  261000         ! pdf set for hadron 1 (LHA numbering)
lhans2  261000         ! pdf set for hadron 2 (LHA numbering)

renscfact  1.0d0    ! (default 1d0) ren scale factor: muren  = muref * renscfact
facscfact  1.0d0    ! (default 1d0) fac scale factor: mufact = muref * facscfact

higgsbreitwigner 0 ! 0: Narrow width, 1: Breit Wigner for Higgs
higgsmasswindow  30 ! How many widths we integrate around the Breit Wigner peak.

runningscales 1     ! default 0 (no running scales); 0: MH, 1: scale of 1506.02660
                    ! if running the differential code. If running inclusive_only
                    ! then the scale choice will be Q1 on the upper line and Q2 on
                    ! the lower line.

ncall1  500000   ! number of calls for initializing the integration grid
ncall2  5000000   ! number of calls for computing the integral
itmx2    3      ! number of iterations for computing the integral

xgriditeration 1    ! identifier for grid generation
parallelstage 1     ! identifier for the stage. Stage 1 generates grids. Stage 2 is
                    ! the main stage which produces differential distributions.

fakevirt 0        ! Useful for generating stage 1 grids faster

phspcuts 1        ! (1:on ; 0: off (default)) Turns on/off analysis
                  ! cuts at the phasespace generation stage.
                  ! Significantly reduces run time.
```

The analysis

```
!!!!!!!!!!!!!!! CUTS USED FOR ANALYSIS and PHASE SPACE: !!!!!!!!!!!!!!!!!!!!!!!
ptalljetmin    25d0 ! Minimum pt for all jets
yjetmax        4.5d0 ! rapidity acceptance for jets
Rsep_jjmin     0.4d0 ! R to be used in jet algorithm
ptjetmin       25d0 ! Minimum pt for two tagging jets
mjjmin         600d0 ! Minimum invariant mass of dijet system
deltay_jjmin   4.5d0 ! rapidity separation between tagging jets
jet_opphem     1 ! 1: require the tagging jets in opposite detector hemispheres.
```

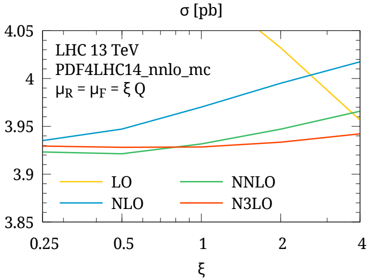
- The analysis cuts are used both for histograms and for constraining the phase space. As a result the code runs faster with tight cuts but can be run with loose or without cuts
- If multiple sets of cuts are needed one needs to make sure that the phase space cuts are inclusive enough to contain all the cuts

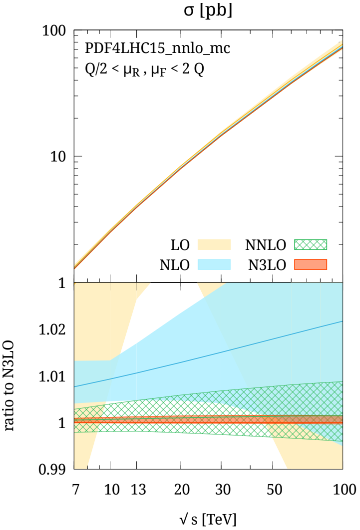
Parallel runs

Due to complexity of process one has to do several parallel runs

- Grid generation: 3 iterations of 200 runs with `ncall1 500000`
  - Each iteration takes a few hours on a modern machine
- Production run: 2500–10000 runs with `ncall2 5000000` and `itmx2 3`
  - Each run takes $\mathcal{O}(1\,\text{day})$ on a modern cluster
- Parallel runs have to be combined using the provided script `combine_runs` to remove statistical outliers
- Hence on `lxplus` differential distributions can be obtained in a few days
- Inclusive results can be obtained on a laptop in a few minutes

Inclusive N^{3}LO results

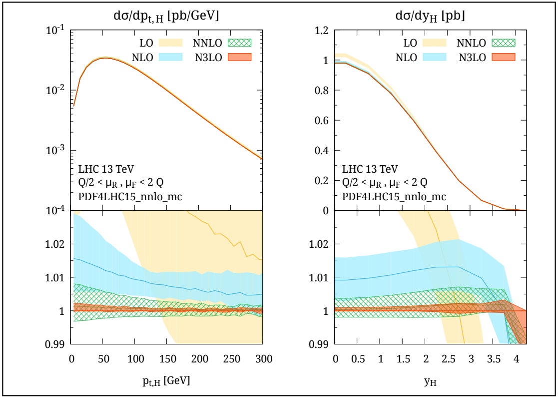




- the N^{3}LO corrections are tiny over a large range of energies and stay well within the scale uncertainty band of the NNLO prediction
- cross section becomes extremely stable under the variation of renormalisation and factorisation scales

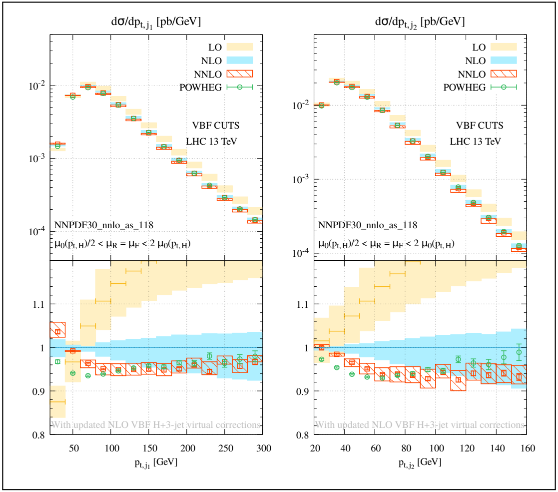
Inclusive N^{3}LO results

From the knowledge of Q_1 and Q_2 it is trivial to reconstruct the momentum of the Higgs. The calculation is therefore fully differential in the Higgs kinematics.



- the corrections are almost flat throughout the entire spectrum
- the N^{3}LO prediction completely contained within the scale uncertainty band of the NNLO prediction
- only differential in the momenta of the proton remnants, and hence no real information on the tagging jets

Differential NNLO results



- NNLO corrections can be large $\mathcal{O}(10\%)$ and are often outside the NLO band
- the NNLO corrections tend to be dominated by extra real radiation. These appear to make the jets softer
- NOTE: NNLO PDF used everywhere. Similar results hold when using LO/NLO PDFs
- expanding the scale variation from 3-point to 7-point doesn't change the size of the NLO bands noticeably

Conclusions

- Code availabe here:
  `https://github.com/fdreyer/proVBFH`
- The code can be run in a reasonable time, $\mathcal{O}(\text{days})$, on a big cluster
  - inclusive result up to N^{3}LO-QCD can be obtained on a laptop within a few minutes
- Many features could be implemented
  - Please get in touch if you want something implemented
- Code is fully flexible in terms of input parameters and analysis cuts
- User feedback greatly appreciated
- Code already used by LHCHWG for YR4 and STXS + plus updates in the pipeline