
DRAFT

# Higgs VBF Cross Section: Inclusive Results and Uncertainties

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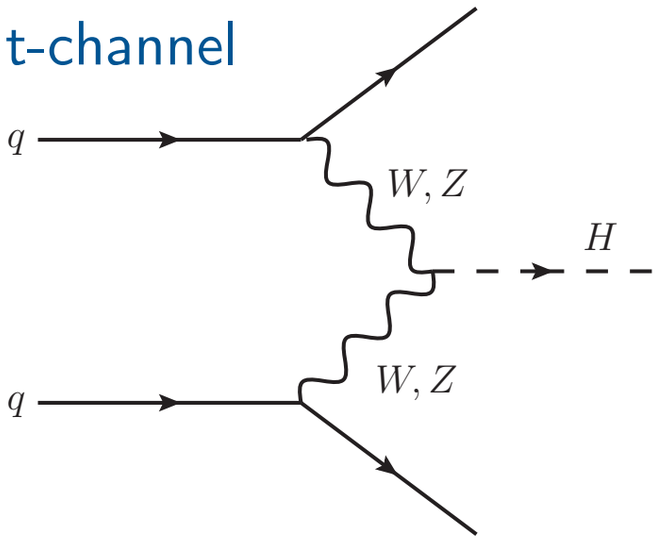
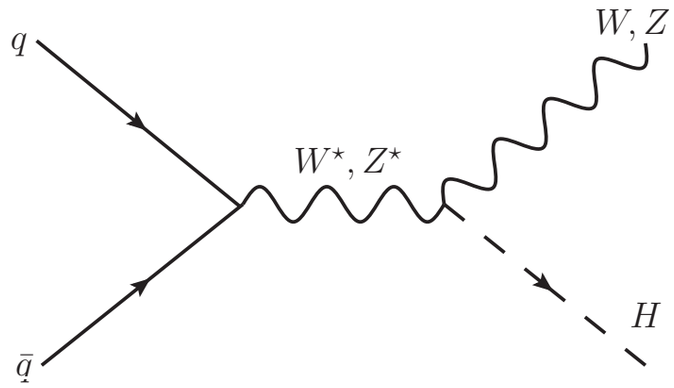
# VBF Process

t-channel




s-channel




**Vector Boson Fusion (VBF) process**

Second Higgs production channel in size, important discovery channel for SM Higgs with low mass, clean experimental signature

- it proceed through both t- and s-channel
- in general only t-channel considered as *true VBF* $\rightarrow$ s-channel is the so-called *Higgs-strahlung* or Higgs associate production
- but: s-channel shares same initial and final states $\rightarrow$ should in principle be generated as well, including interference
  - practically: s-channel contributions do not survive typical VBF analysis cuts

# VBF Calculations and Programs

- VBF is pure EW process at LO
- QCD NLO corrections account for 5-10%
- VBF process calculated at up NNLO QCD (very recent results) and NLO EW

**Available Programs:**

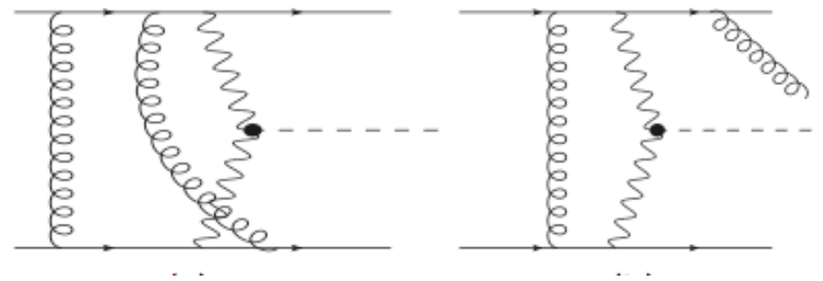
- VV2H [M. Spira]: only t-channel, NLO QCD
- VBF@NLO [D. Zeppenfeld et al]: NLO QCD
- HAWK [M. Ciccolini, A. Denner, A. Dittmaier]: NLO QCD and NLO EW, s- and t-channel included, but can also switch off s-channel
- NNLO QCD calculation [P. Bolzoni, F. Maltoni, S.-O. Moch, M. Zaro]

- Pythia/FHerwig: simulate only t-channel
- Sherpa: automatically has to include s-channel because of gauge invariance

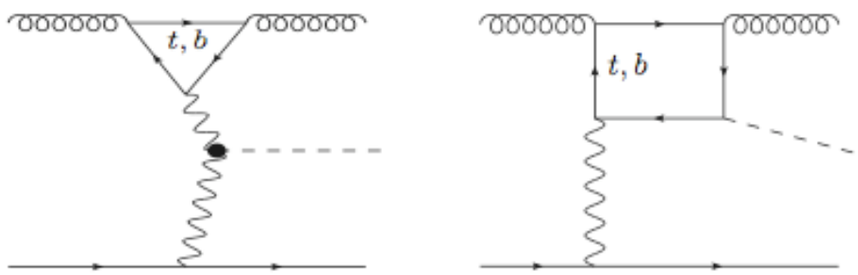
# VBF NNLO QCD: Calculations

[P. Bolzoni, F. Maltoni, S.-O. Moch, M. Zaro, arXiv:1003.4451v1]

- Calculations for t-channel (interference with s-channel at the order of per mil)
- Performed in *structure function approach* , i.e. VBF treated as a double DIS process where the two (virtual) vector bosons emitted by the hadronic initial states fuse into an Higgs boson
  - cross section computed as a product of the matrix element for VBF and the DIS hadronic tensor (expressed in terms of the standard DIS structure functions)
- This factorization is still valid at NLO (neglecting a small interference effects)
- At NNLO the factorization breaks down (possible links of the the two final quark lines) but most of the not included corrections are IR and UV finite, gauge invariant and suppressed

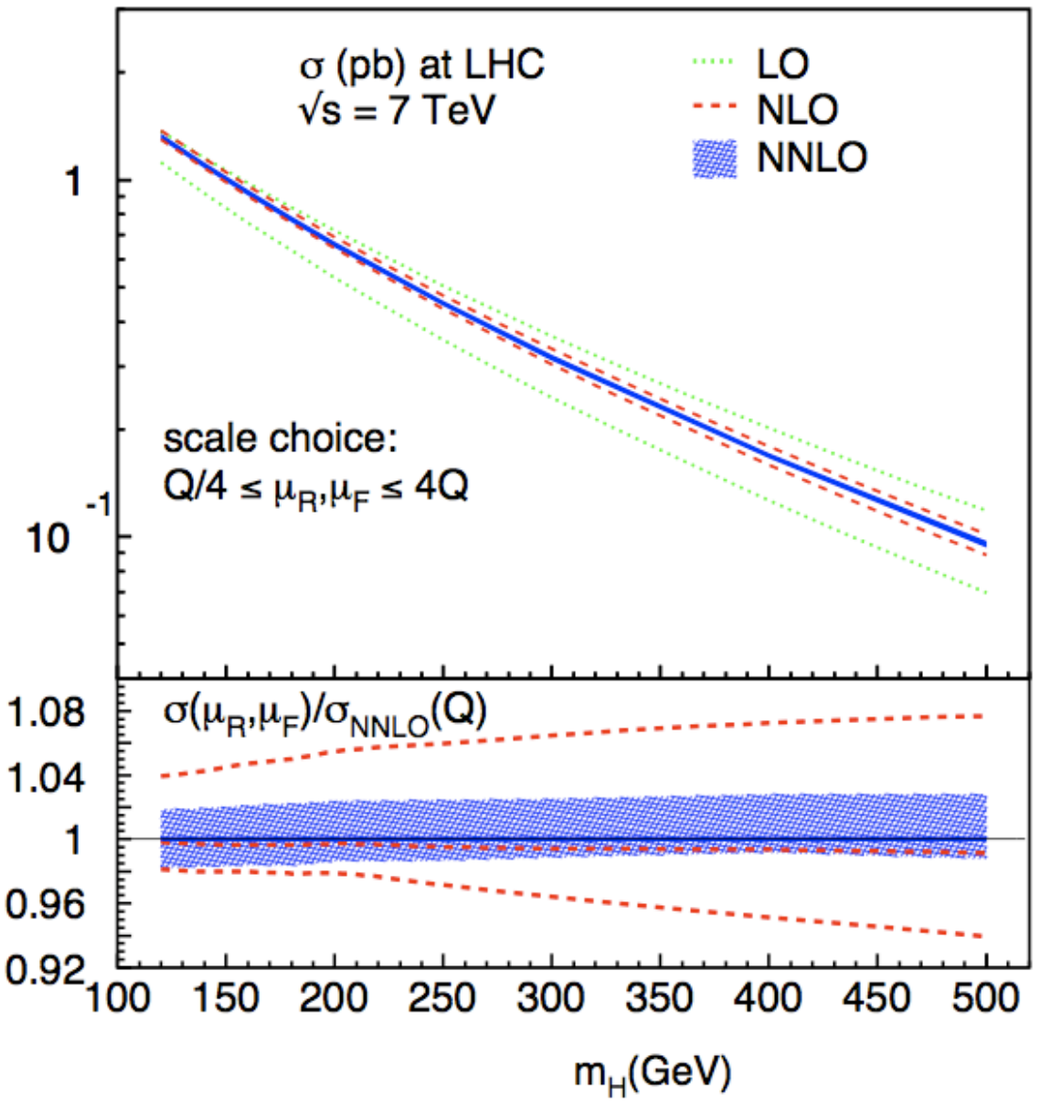


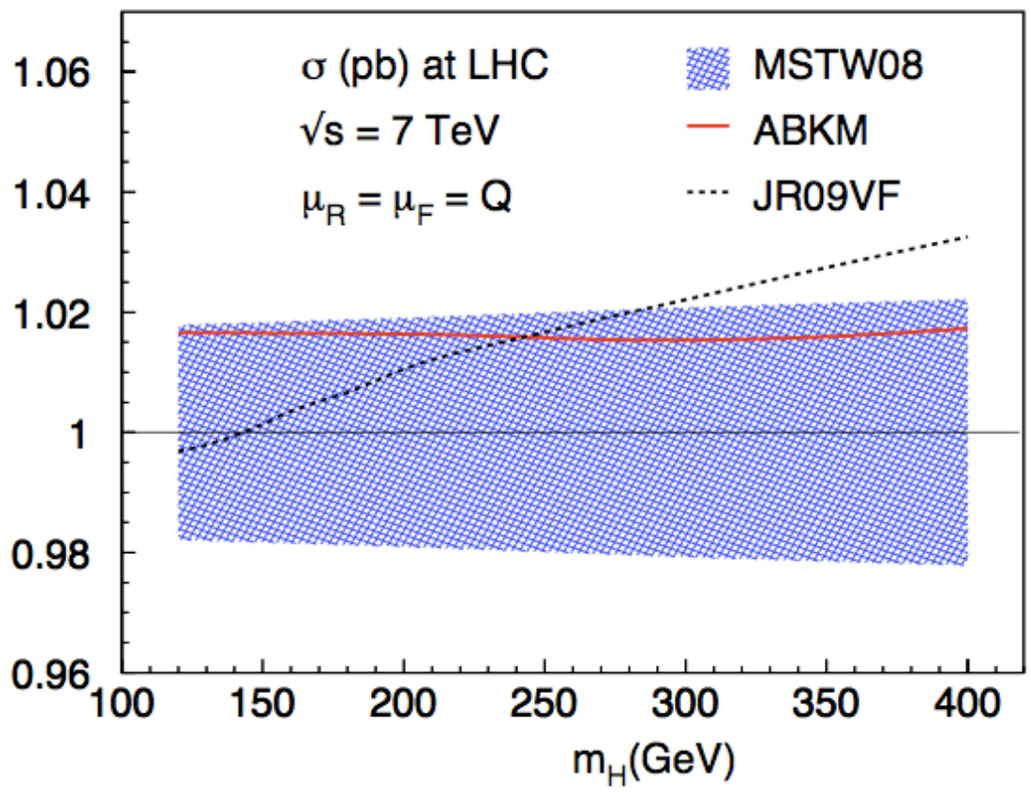
- Other corrections $O(\alpha^3_{EW}\,\alpha^2)$ are also included and computed in $m_b \to 0$, $m_t \to \infty$ limit and in this approximation they contribute below the percent level to the total cross section



# VBF NNLO QCD: Results

[P. Bolzoni, F. Maltoni, S.-O. Moch, M. Zaro, arXiv:1003.4451v1]




- Results stable at 2% against QCD scales variation and at 2% from PDF uncertainties, uniformly over the full mass range

→ *the highest precision in LHC cross section!*

| $\sqrt{S} = 7$ TeV | | | |
|---|---|---|---|
| Higgs mass | LO | NLO | NNLO |
| 120 | $1.235^{+0.131}_{-0.116}$ | $1.320^{+0.054}_{-0.022}$ | $1.324^{+0.025}_{-0.024}$ |
| 160 | $0.857^{+0.121}_{-0.099}$ | $0.915^{+0.046}_{-0.016}$ | $0.918^{+0.019}_{-0.015}$ |
| 200 | $0.614^{+0.106}_{-0.082}$ | $0.655^{+0.038}_{-0.012}$ | $0.658^{+0.015}_{-0.010}$ |
| 300 | $0.295^{+0.070}_{-0.049}$ | $0.314^{+0.022}_{-0.010}$ | $0.316^{+0.008}_{-0.004}$ |
| 400 | $0.156^{+0.045}_{-0.030}$ | $0.166^{+0.013}_{-0.007}$ | $0.167^{+0.005}_{-0.001}$ |

# HAWK Program

**HAWK** (Higgs bosons Attached to WeaK bosons) Monte Carlo integrator for pp $\to$ H + 2jets includes

- NLO QCD and electroweak corrections
- all weak-boson fusion and quark-antiquark annihilation diagrams
- all interferences at LO and NLO
- contributions from incoming photons
- leading heavy-Higgs-boson effects at two-loop order
- contributions of b-quark pdfs at LO
- an interface to LHApdf (default = standalone with MRST2004QED and CTEQ6 pdf tables)

# HAWK Results

**HAWK** version 1.0 (released on Jan 26, 2010, updated on Feb 24, 2010) results are presented in the following slides

- Job configuration
  - input parameters as in https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SMInputParameter
  - MSTW2008 and CTEQ6.6 PDF sets used
  - Central scale value $\mu = M_W$ (default)
  - renormalization and factorization scale varied (simultaneously) by factor $\xi = 2$, diagonally, i.e. with $\mu_R = \mu_F = \xi \cdot \mu$ (for results in the ATLAS Note $\xi = 4$)
  - Integration accuracy reached: 0.1%
- Some comments
  - main limitation: CPU time! NLO EW makes it rather slow
  - NWA for the Higgs boson $\rightarrow$ Ansgar is working on the implementation of the Breit-Wigner convolution - *status: ready but under test*
  - LHAPDF interface implemented $\rightarrow$ in principle MRST2004qed should be used, since it is the only $O(\alpha)$ PDF set available BUT no error sets

# Technical Issues

- HAWK CPU running time (EW + s-channel): 12-15 h for 2M events on a standard 2.2 GHz machine
- 16 (mass points, from 100 GeV to 400 GeV, 20 GeV step) x 44 (or 40, PDF eigenvectors) x 2 (PDF sets) ≈ 1400 jobs → *possibility to use the GRID exploited*
- A script to run HAWK (but in principle any static linked executable) is available on our TWiki https://twiki.cern.ch/twiki/bin/view/LHCPhysics/VBF
- Caveat: the pilot will kill job *not progressing*, where progress is defined as the output file being updated → options maxCpuCount should be properly set
- *Integration problem* found not observed before:

```
...
780000  :    109.99796 +-     1.07135  :    109.77335 +-     0.19175
800000  :          NaN +-         NaN  :          NaN +-         NaN
820000  :    112.41634 +-     1.98251  :          NaN +-         NaN
...
```

- Fix quickly provided by the authors
- The problem affected ~30% of the jobs, which had then to be rerun

# Cross Sections: Central Values

- only t-channel - s- and t- channels
- with and w/o EW corrections

# Scale Uncertainties

# PDF Uncertainties

- Cross sections evaluated on 44 PDF error sets for CTEQ6.6 or 40 for MSTW2008
- PDF uncertainties estimated as in [P. Nadolsky, et al. arXiv:0802.0007v2] (CTEQ prescription)

$$\Delta X = |\vec{\nabla} X| = \frac{1}{2}\sqrt{\Sigma_{i=1}^{N}(X_i^{(+)} - X_i^{(-)})^2}$$

  where $X_i^{(+)}$ and $X_i^{(-)}$ are the values of $X$ computed from the two sets of PDF along the ($\pm$) direction of the $i$-th eigenvector
- positive and negative PDF errors on X assumed to be the same
- No $\alpha_S$ uncertainty evaluated here - $\alpha_S$ value taken from the PDF set

# Uncertainty Combination

# VBF@NLO Results

# Plans

- Calculating uncertainties including $\alpha_S$, following the recipe from the PDF group (or the TEMPORARY one by S. Forte)
- Extent HAWK results to higher masses when the real Higgs mass will be implemented
- Additional improvement of HAWK: Higgs-boson decays, production of unweighted events, interface to parton showers, contributions from gg initial states with effective Hgg couplings, anomalous HWW and HZZ couplings
- VBF@NLO calculation ongoing, for comparison with HAWK results