

# NLO QCD+EW corrections in VBF and WH/ZH with HAWK

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# Outline

- 1 HAWK 2.0
- 2 Electroweak Corrections
- 3 Higgs production in VBF
- 4 Higgs production in WH/ZH
- 5 Anomalous couplings in HAWK 2.0
- 6 Conclusions

## HAWK 2.0

**HAWK: Higgs Attached to Weak bosons**

- version 2.0 released November 4th, 2013
  - ↳ manual published today, submitted to CPC  
[Denner, Dittmaier, SK, Mück [arXiv:1412.5390]]
- flexible **NLO parton-level Monte Carlo** program for
  - **VBF** [Ciccolini, Denner, Dittmaier [arXiv:0707.0381, arXiv:0710.4749]]
  - **WH/ZH** [Denner, Dittmaier, SK, Mück [arXiv:1112.5258]]
- complete **NLO QCD** and **electroweak** corrections
- **differential** predictions in form of **histograms**
- code **available** at  
<http://omnibus.uni-freiburg.de/~sd565/programs/hawk/hawk.html>
- used within the Handbooks of LHC Higgs Cross Sections 1-3  
[LHCHSWG [arXiv:1101.0593, arXiv:1201.3084, arXiv:1307.1347]]

# HAWK 2.0

## Features:

- any IR-safe parton-level cuts or histograms feasible
- off-shell Higgs-boson options
- anomalous Higgs couplings
- photon-induced processes ( $\mathcal{O}(1\%)$ )
- LHAPDF only external library needed (for up-to-date pdfs)

## Limitations:

- only distributions  $\Rightarrow$  no (weighted or unweighted) events
- no matching with parton showers
- no contributions from gg initial states
- no Higgs decays into specific final states
- no real weak-boson emission included

# Electroweak corrections

## Generic size of EW corrections

- percent level corrections expected
- can be of same size as QCD corrections
  - ↪ 5-10% in VBF Higgs production

## Enhanced electroweak corrections

- at high energies: Sudakov logarithms  $\propto \alpha \rightarrow \alpha \log^2(Q/M_V)$ 
  - ↪ boosted Higgs in WH/ZH
- (collinear) photon radiation from leptons (FSR)
- Relative EW corrections rather independent of
  - PDF choices
  - (QCD) scale choices
  - collider energy

# Combination of QCD and electroweak corrections

## How to **combine** QCD and EW corrections?

- start from best available QCD prediction  $d\sigma_{\text{best}}^{\text{QCD}}$
- assume approximate **factorization** of corrections:

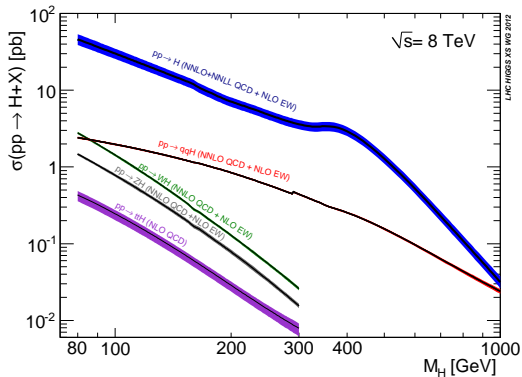
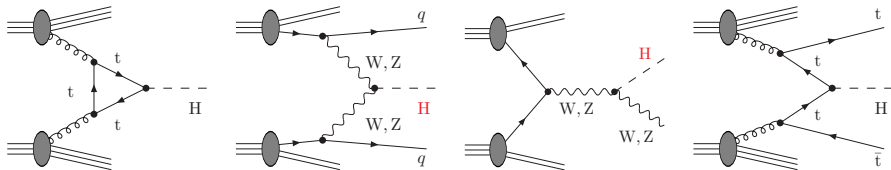
$$d\sigma = d\sigma_{\text{best}}^{\text{QCD}} (1 + \delta_{\text{EW}})$$

- difference to  $d\sigma = d\sigma_{\text{LO}}(1 + \delta_{\text{QCD}} + \delta_{\text{EW}})$  of higher order
- underlying assumptions:
  - QCD corrections dominated by soft-collinear physics
  - EW corrections in underlying hard process or FSR

## Recommended application of **HAWK**:

- use **differential reweighting** event by event  
 $\hookrightarrow \delta_{\text{EW}}$  from a **HAWK distribution** (e.g.  $p_{T,H}$ )

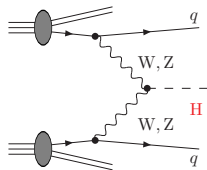
# Inclusive predictions for Higgs production channels



- Electroweak corrections included where available

# Higgs production in Vector-Boson Fusion (VBF)

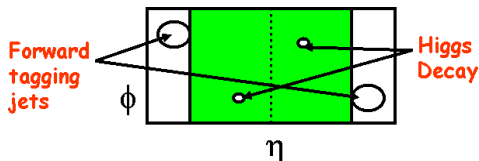
- sizeable fraction of inclusive Higgs production  
 $\hookrightarrow \sim 1.5 \text{ pb}$  at  $\sqrt{s} = 8 \text{ TeV}$  at the LHC



- special kinematics:**

forward and backward tagging jets ( $p_{T,j} > 20 \text{ GeV}$ ,  $|y_j| < 4.5$ )

$\Rightarrow$  **VBF signal**



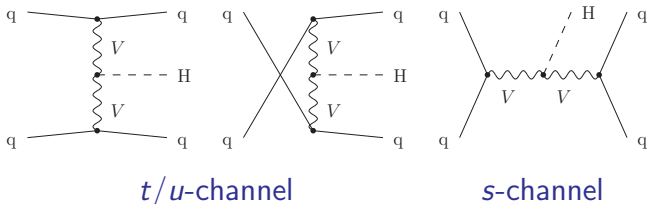
$\hookrightarrow$  powerful cuts for background suppression:

$$\Delta y_{jj} > 4, y_{j1} \cdot y_{j2} < 0, m_{jj} > 600 \text{ GeV}, \text{ etc.}$$



# Higgs production in Vector-Boson Fusion (VBF)

$pp \rightarrow Hjj$



**VBF cuts** on jets:

- background reduction
- separation from  $gg \rightarrow Hjj$  in gluon fusion (5% after cuts)
- $s$ -channel and interferences negligible ( $DIS^2$  like process)

**Higher-order** corrections:

- QCD corrections small ( $DIS^2$  like process)
- EW corrections of the same size as QCD corrections (5–10%)

# Higgs production Vector-Boson Fusion (VBF)

## Beyond NLO QCD

- NNLO QCD corrections

VBF@NNLO [Bolzoni, Maltoni, Moch, Zaro [arXiv:1003.4451, arXiv:1109.3717]]

- for total cross section in structure function approach
- inclusively QCD under excellent control at the 1% level

- NLO QCD matched to parton showers

- POWHEG [Nason, Oleari [arXiv:0911.5299]]
- aMC@NLO [Frixione, Torrielli, Zaro [arXiv:1304.7927]]

- Hjjj at NLO QCD via VBF

- VBF approximation [Figy, Hankele, Zeppenfeld [arXiv:0710.5621]]
- full calculation [Campanario, Figy, Plätzer, Sjödaahl [arXiv:1308.2932]]

# Higgs production Vector-Boson Fusion (VBF)

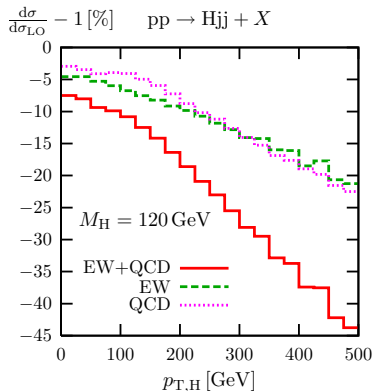
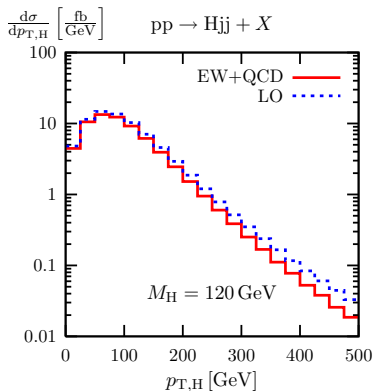
## EW corrections

([differential](#), NLO QCD corrections also included)

- **VBFNLO** [VBF collaboration [arXiv:1404.3940, arXiv:1107.4038, arXiv:0811.4559]]
  - s-channel and interferences neglected
  - EW corrections, also in the MSSM [Figy, Palmer, Weiglein [arXiv:1012.4789]]
  - many additional features  
(Higgs decays, different processes, etc.) ⇒ see Michael Rauch's talk
- **HAWK** [Ciccolini, Denner, Dittmaier [arXiv:0710.4749]]
  - no kinematic limitations  
(s-channel and interferences included)
  - cuts also on Higgs decay products supported  
(simple two-body decay)

# Higgs production Vector-Boson Fusion (VBF)

## EW effects on Higgs $p_T$ distribution (results for VBF cuts)

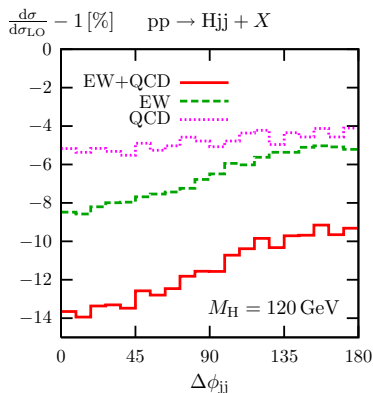
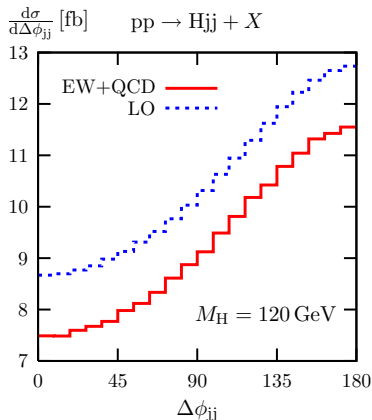


[Ciccolini, Denner, Dittmaier [arXiv:0710.4749]]

- QCD and EW corrections **distort shapes** of distributions
- Size of **EW corrections**  $\sim -20\%$  at  $p_{T,H} = 500 \text{ GeV}$
- ↪ electroweak Sudakov logarithms

# Higgs production Vector-Boson Fusion (VBF)

## EW effects on $\Delta\Phi_{jj}$ distribution (results for VBF cuts)



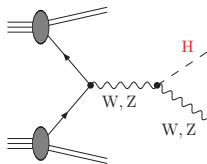
[Ciccolini, Denner, Dittmaier [arXiv:0710.4749]]

- QCD corrections relatively flat
- EW corrections distort shape of distribution by  $\sim 4\%$

# Higgs production via Higgs strahlung (WH/ZH)

$pp \rightarrow W/Z + H$  (associated production)

- cross section a bit smaller than in VBF
  - $\hookrightarrow \sim 1.1$  pb at  $\sqrt{s} = 8$  TeV at the LHC
    - main channel at the Tevatron
- leptonic  $W/Z$  decay allows for **additional tag**
  - $\hookrightarrow$  punished by **small leptonic  $W/Z$  branching ratios**
- for a 125 GeV Higgs  $H \rightarrow b\bar{b}$  accessible
  - $\hookrightarrow$  modern **jet-techniques**
- **boosted Higgs** analysis to improve S/B ratio
  - $\hookrightarrow$  restriction to high  $p_T$  Higgs bosons only,  $b$  jets resolved from the substructure of this “fat jet”



# Higgs production via Higgs strahlung (WH/ZH)

## QCD corrections

- similar to **Drell-Yan** ( $\rightarrow$  relatively simple)
- Drell-Yan-like **inclusive NNLO: VH@NNLO**  
[Brein, Djouadi, Harlander [hep-ph/0307206]]
- fully **differential** (Drell-Yan-like) **NNLO** for WH (ZH)  
[Ferrera, Grazzini, Tramontano [arXiv:1107.1164, arXiv:1312.1669, arXiv:1407.4747]]
- WH/ZH NNLO  **$q\bar{q}$  contribution beyond Drell-Yan: 1 – 2%**  
[Brein, Harlander, Wieseemann, Zirke [arXiv:1111.0761]]
- **MiNLO** merged WH/ZH + 0 and 1 jet at NLO QCD,  
via **POWHEG BOX** + **GoSam** [Luisoni, Nason, Oleari, Tramontano [arXiv:1306.2542]]  
 $\Rightarrow$  see Carlo Oleari's talk
- **$gg \rightarrow ZH$**  contribution at NLO ( $\sim 100\%$  correction):  $\lesssim 10\%$   
[Altenkamp, Dittmaier, Harlander, Rzehak, Zirke [arXiv:1211.5015]]
- **$N^3\text{LO}$  in threshold expansion** (Drell-Yan-like)  
[Kumar, Mandal, Ravindran [arXiv:1412.3357]]

# Higgs production via Higgs strahlung (WH/ZH)

- status before HAWK 2.0:  
only inclusive EW corrections [Ciccolini, Dittmaier, Krämer [hep-ph/0306234]]

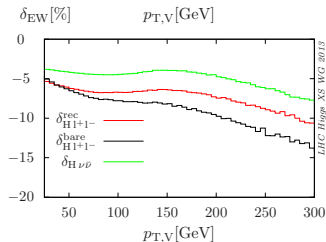
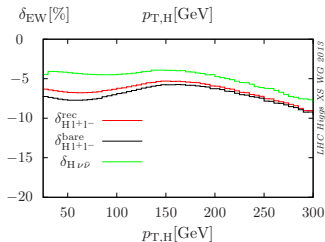
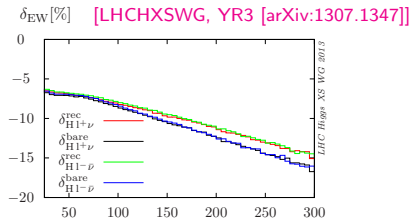
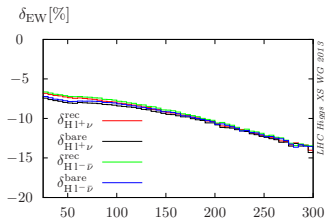
## WH/ZH implemented in HAWK 2.0 [Denner, Dittmaier, SK, Mück [1112.5142]]

- fully differential EW corrections for the processes  
 $pp \rightarrow Hl^+l^-$ ,  $pp \rightarrow Hl\nu_l$ ,  $pp \rightarrow H\bar{\nu}_l\nu_l$
- full access to leptons in final state
  - all results for specific leptonic channel
  - different lepton-photon recombination for  $\mu$  and  $e$
  - FSR included (beware of double counting)
- vector-boson resonance treated in complex-mass scheme
- analogous to VBF  $s$ -channel contribution
  - $\hookrightarrow$  replace hadronic by leptonic boson decay
  - $\hookrightarrow$  also hadronic final states available



## Higgs production via Higgs strahlung (WH/ZH)

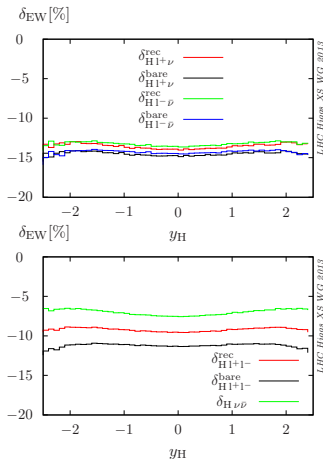
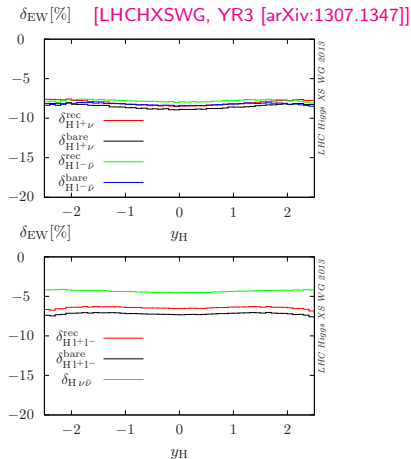
## differential EW corrections from HAWK 2.0



rec = photon-lepton recombination (electrons)

bare = no recombination → bare leptons (muons)

## Higgs production via Higgs strahlung (WH/ZH)

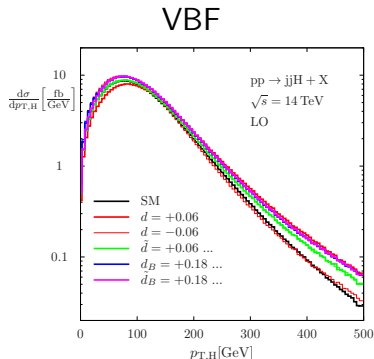
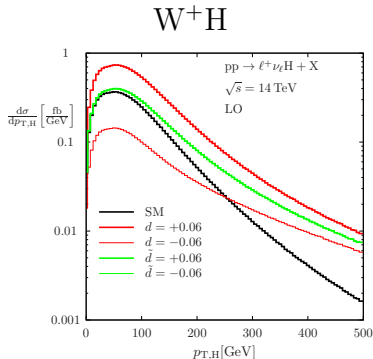
boosted ( $p_T > 200$  GeV)no  $p_{T,H/V}$  cuts

- larger EW corrections for boosted Higgs, up to  $-15\%$  for WH



# Anomalous HVV couplings

- AC's for VBF validated with VBFNLO
- AC's can be dressed with QCD corrections
- apply EW SM corrections (no interplay considered)



↪ impact of AC's larger for WH than for VBF

# Conclusions

- Status of higher-order QCD predictions
  - **VBF** – Higgs-production in **vector-boson fusion**
    - parton-shower matched NLO QCD
    - inclusive approximate NNLO QCD
  - **WH/ZH** – Higgs-production via **Higgs strahlung**)
    - parton-shower matched NLO QCD (and more)
    - fully differential (DY-like) NNLO QCD
    - effects beyond NNLO QCD
- **HAWK 2.0**
  - differential **NLO EW** corrections for VBF and WH/ZH
  - no events but histograms for **differential reweighting**
  - EW corrections **> 10%**
  - questions about HAWK: **just ask for support**