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NLO QCD & EW corrections to Higgs strahlung off W/Z bosons at Tevatron and the LHC with HAWK

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– in collaboration with A.Denner, S.Kallweit and A.Mück –

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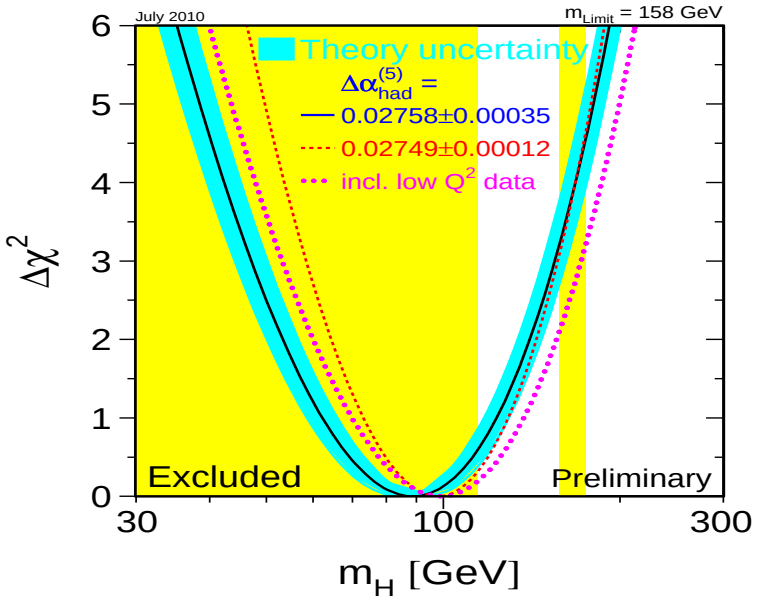
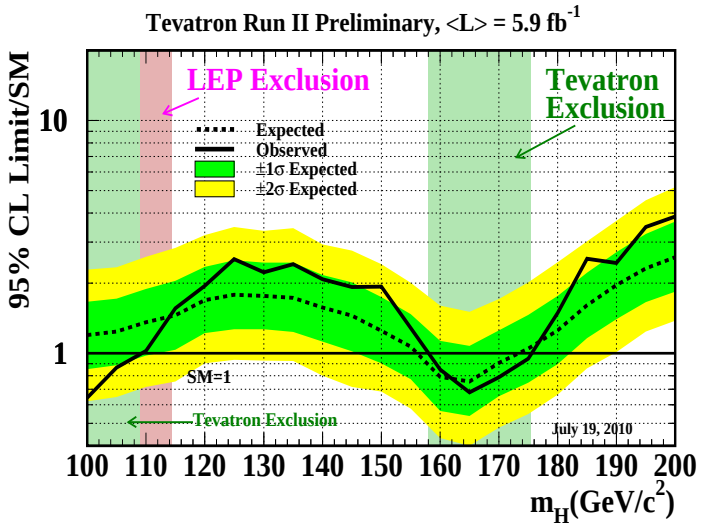
Introduction

SM Higgs boson of low mass

($M_{\mathrm{H}} \sim 120\,\mathrm{GeV}$)

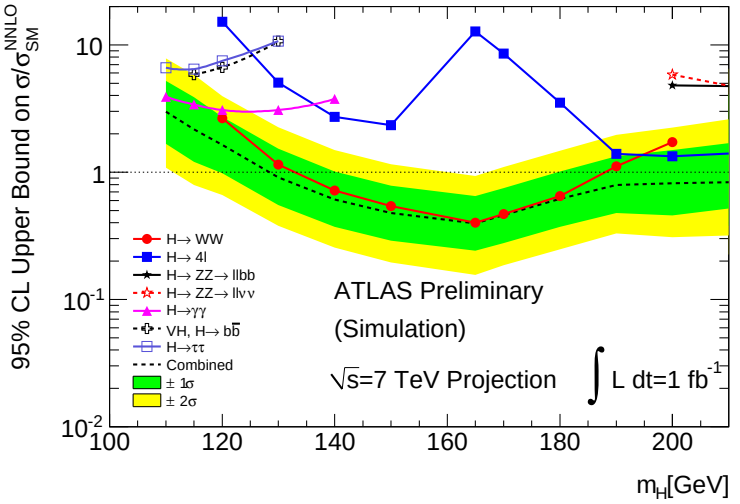
- . . . favoured by electroweak precision data





- . . . soon challenged by Tevatron via $\mathrm{p\bar{p}} \to \mathrm{WH/ZH} + X$

- . . . gets contribution from $\mathrm{pp} \to \mathrm{WH/ZH} + X$ at the LHC

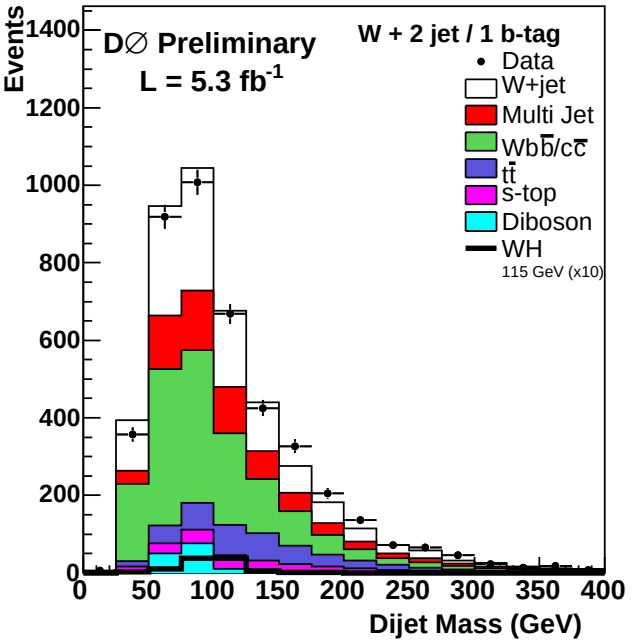


Experimental challenge

↪ background control

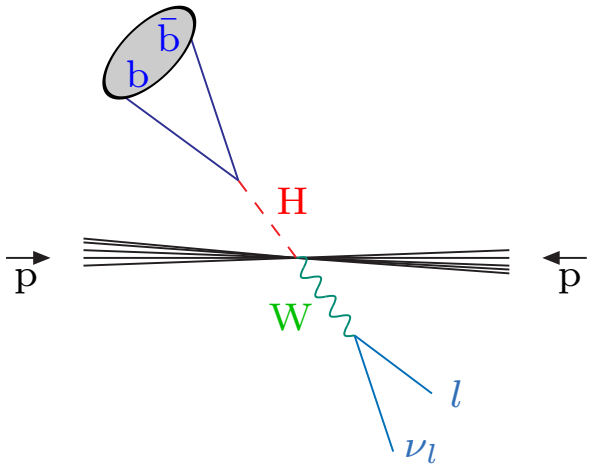
- at the Tevatron: analysis of

$$\mathrm{WH} \to \ell\nu\mathrm{b\bar{b}},\ jj\mathrm{b\bar{b}},\ jj\tau\tau,\ \ell^{\pm}\ell^{\pm}+X$$
$$\mathrm{ZH} \to \ell^{+}\ell^{-}\mathrm{b\bar{b}},\ \nu\bar{\nu}\mathrm{b\bar{b}},\ jj\mathrm{b\bar{b}},\tau\tau\mathrm{b\bar{b}},\ jj\tau\tau,\ \ell^{\pm}\ell^{\pm}+X$$



- at the LHC: analysis of jet substructure necessary for high-p_{T} Higgs

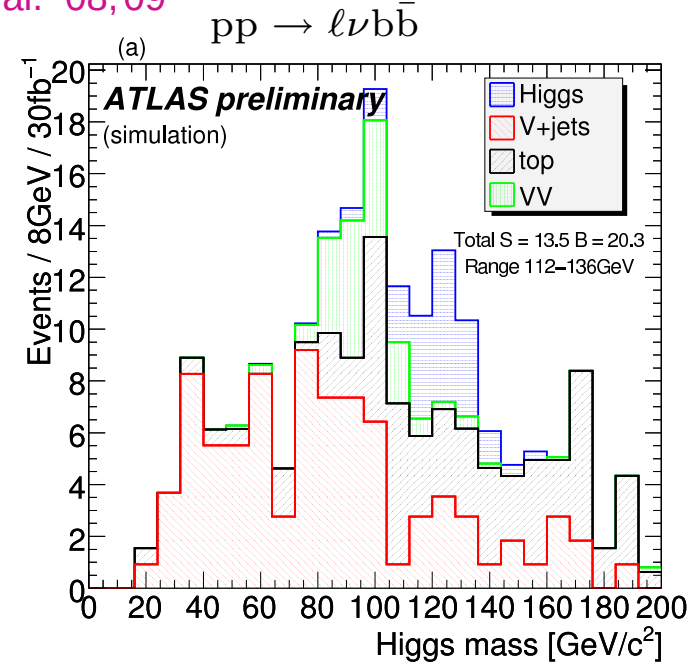
Butterworth et al. '08,'09



$p_{\mathrm{T,H}} > 200\,\mathrm{GeV}$
both sub-jets b-tagged

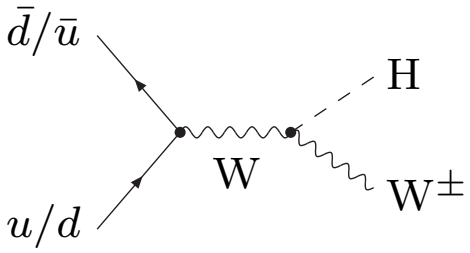
$p_{\mathrm{T,W}} > 200\,\mathrm{GeV}$
$\Delta\phi_{\mathrm{WH}} > 2\pi/3$

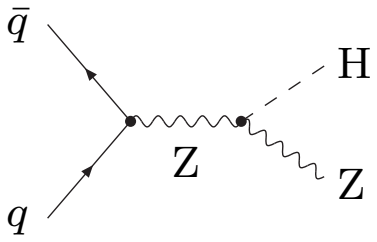
jet vetoes, etc.

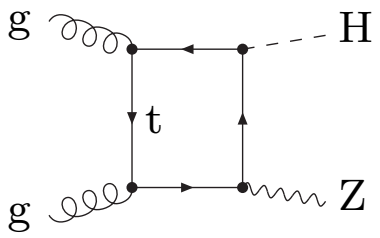


↪ significance $\sim 3\sigma$ for $30\,\mathrm{fb}^{-1}$ @ $\sqrt{s} = 14\,\mathrm{TeV}$

Theoretical predictions







- NLO QCD: corrections entirely Drell–Yan like
  Han, Willenbrock '91; Ohnemus, Stirling '93; Baer, Bailey, Owens '93
  VV2H (Spira); MCFM (Campbell, R.K.Ellis)
- NLO EW: stable W/Z bosons, total cross section
  Ciccolini, S.D., Krämer '03
- NNLO QCD: stable W/Z bosons, total cross section
  Drell–Yan-like part, $\mathrm{gg} \to \mathrm{ZH}$
  Brein, Djouadi, Harlander '03 (VH@NNLO)

New results / work in progress:

- NNLO QCD: WH with W decay, Drell–Yan-like part for differential XS
  Ferrera, Grazzini, Tramontano '11
- NLO EW: W/Z decays, differential cross sections via HAWK
  Denner, S.D., Kallweit, Mück '11 → subject of this talk
- NNLO QCD: non-Drell–Yan-like parts
  Brein, Harlander et al. (in progress)

Combination of NNLO QCD and NLO EW corrections for $\sigma_{\rm tot}$

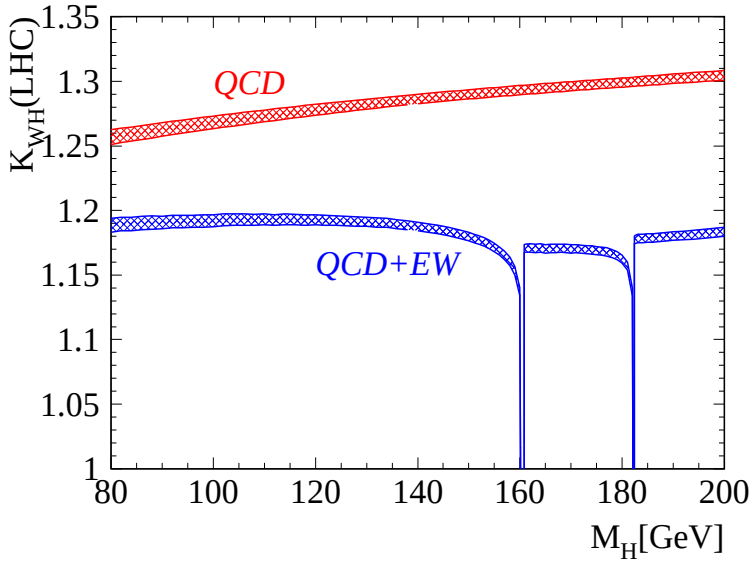
Brein et al. & Ciccolini et al. '04

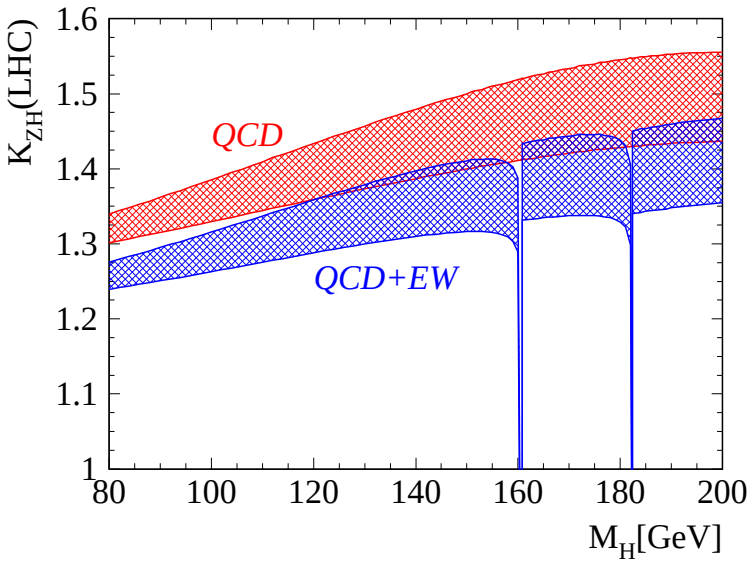
$$\sigma_{\rm WH} = \sigma_{\rm WH}^{\rm VH@NNLO} \times (1 + \delta_{\rm WH,EW})$$

$$\sigma_{\rm ZH} = \sigma_{\rm ZH}^{\rm VH@NNLO} \times (1 + \delta_{\rm ZH,EW}) + \sigma_{\rm gg\to ZH}$$

Note:
$\delta_{\rm VH,EW}$ insensitive to PDFs !

K factors for $\rm pp \to VH + X$ @ $\sqrt{s} = 14\,\rm TeV$:

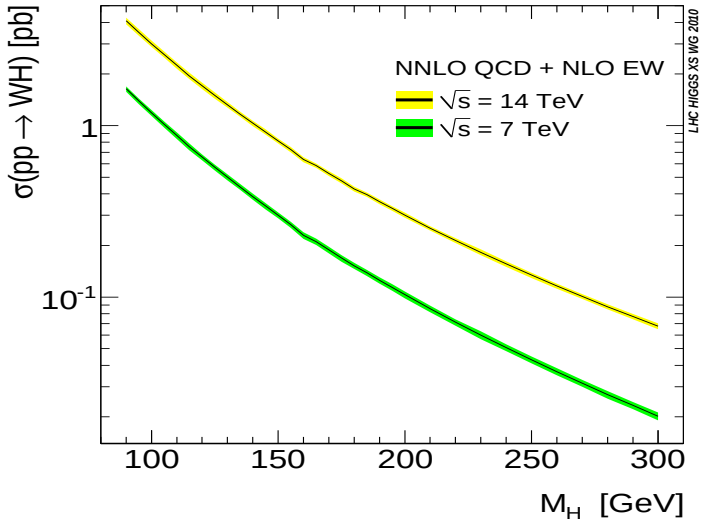


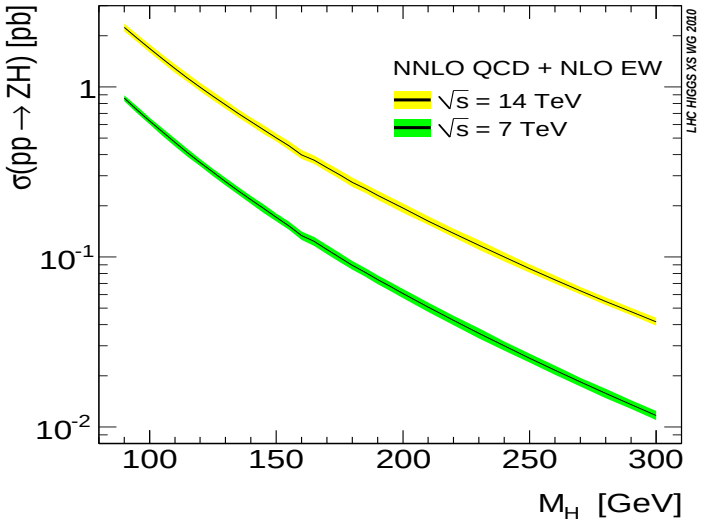


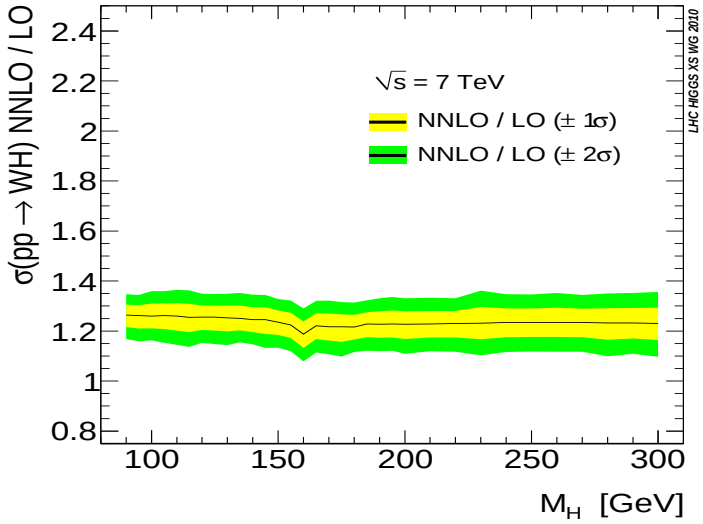
- typical size of corrections: $\mathcal{O}(\alpha_{\rm s}^2) \sim \mathcal{O}(\alpha) \sim 5{-}10\%$
- spikes at $M_{\rm H} = 2M_{\rm W}$ and $M_{\rm H} = 2M_{\rm Z}$
  = perturbative artifacts from WW/ZZ threshold
  $\hookrightarrow$ require inclusion of W/Z decays

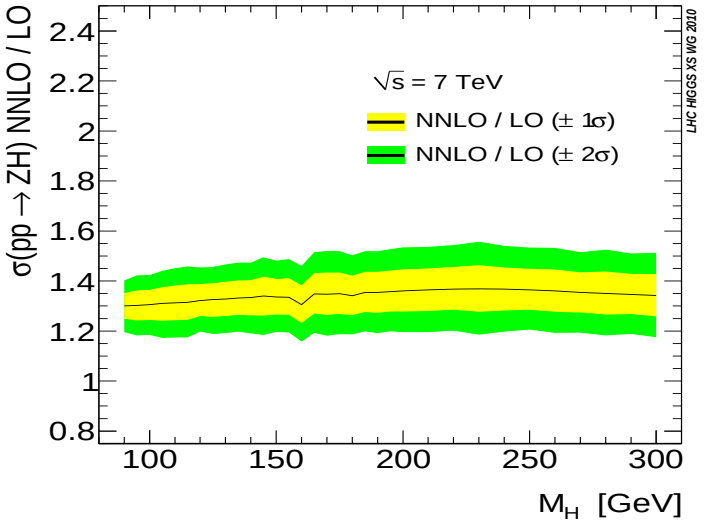
Recent update for $\sigma_{\rm tot}$ @ LHC (7 and $14\,\mathrm{TeV}$) in LHC Higgs XS report

CERN-2011-002
arXiv:1101.0593 [hep-ph







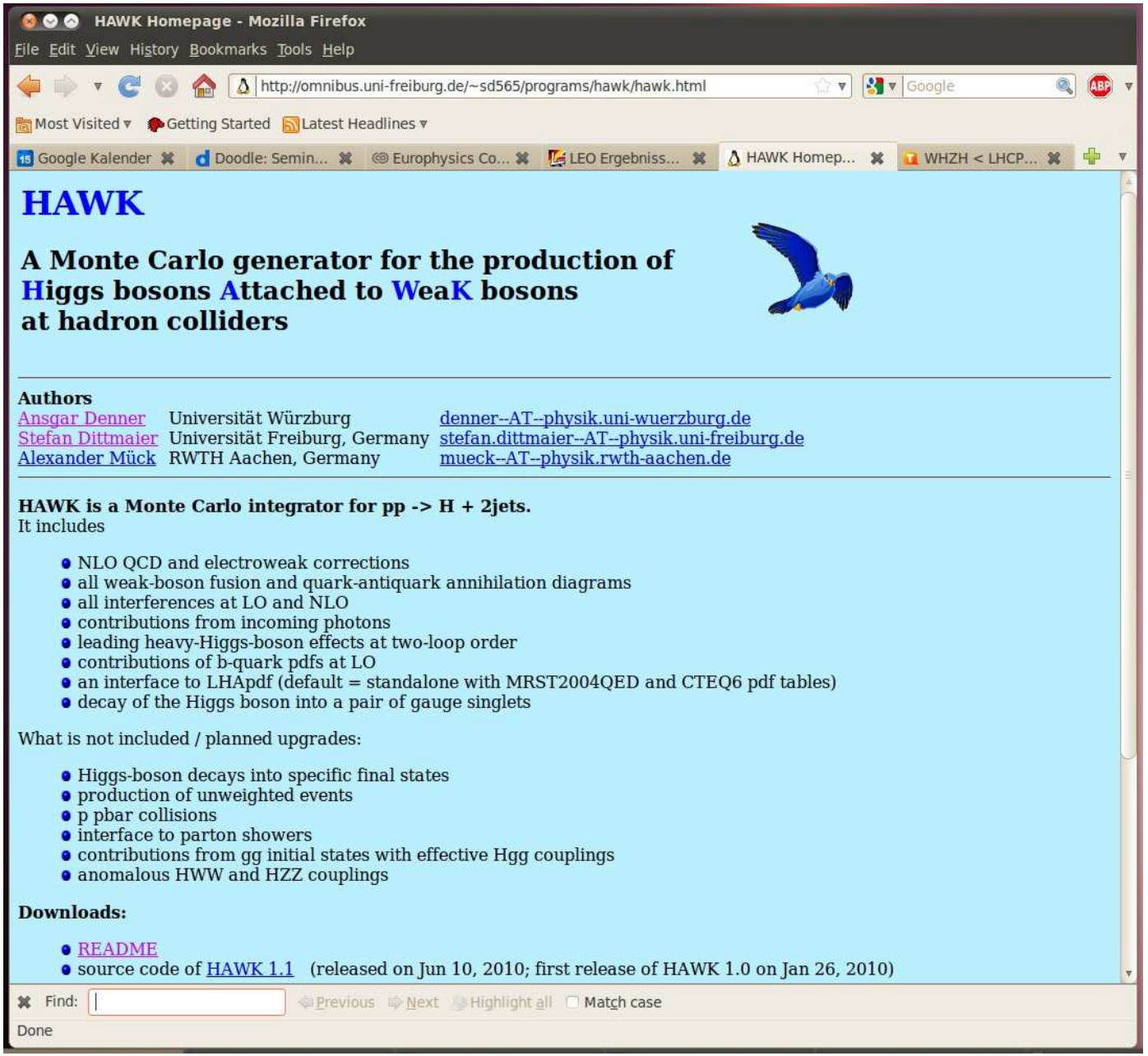


Uncertainties @ $7\,\mathrm{TeV}$: WH: PDF $\sim$ $3{-}4\%$, scale $\sim$ 1%
ZH: PDF $\sim$ $3{-}4\%$, scale $\sim$ $1{-}2\%$

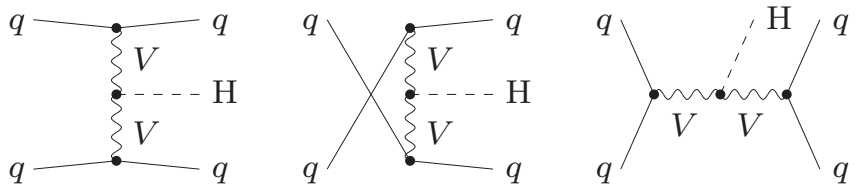
Predictions for WH/ZH @ NLO with HAWK

The program HAWK released Jan 2010

Denner, S.D., Mück



Current version HAWK 1.1



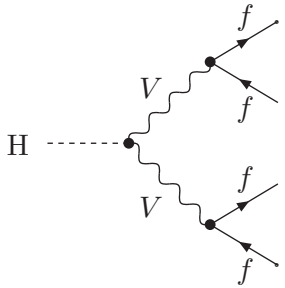
- $\mathrm{pp}/\mathrm{p\bar{p}} \to \mathrm{H}{+}2\mathrm{jets}$
  via VBF and WH/ZH channels
- all interferences included (in LO and NLO)
- multi-channel Monte Carlo program
  $\hookrightarrow$ all cuts & distributions possible
- NLO QCD + EW corrections (including photonic initial states)
- leading 2-loop heavy-Higgs effects $\propto G_\mu^2 M_\mathrm{H}^4$ Ghinculov '95
  Frink, Kniehl, Kreimer, Riesselmann '96
- optional: off-shell Higgs production and decay into a pair of singlets
- interface to LHApdf

New features of HAWK 2.0 (release in near future)

- $\mathrm{pp}/\mathrm{p\bar{p}} \to \mathrm{H}{+}\mathrm{W}/\mathrm{Z} \to \mathrm{H}{+}\ell\nu_\ell/\ell\ell/\nu_\ell\bar{\nu}_\ell$
  W/Z resonances described in NLO accuracy within "complex-mass scheme"
  $\hookrightarrow$ sound behaviour at WW/ZZ thresholds Denner, S.D., Roth, Wieders '05
- non-collinear-safe photon radiation off $\ell^\pm$ supported via dipole subtraction
  Catani, Seymour '96; S.D. '00; S.D., Kabelschacht, Kasprzik '08
- later: inclusion of anomalous $\mathrm{HWW}/\mathrm{HZZ}$ couplings

Survey of Feynman diagrams for NLO corrections

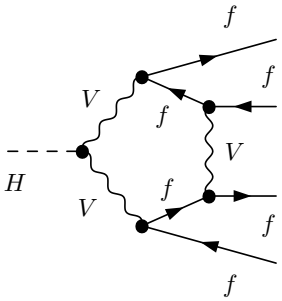
Lowest order:



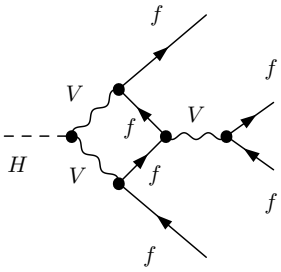
Typical one-loop diagrams:

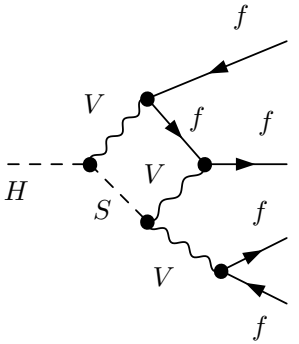
diagrams = $\mathcal{O}(200-400)$

pentagons

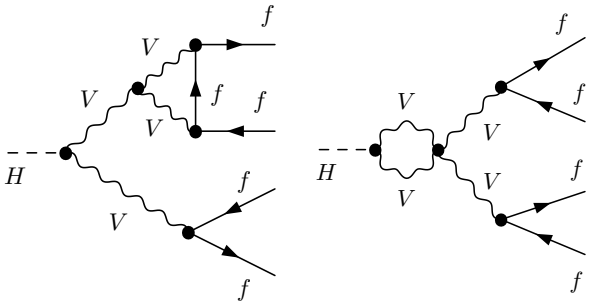


boxes

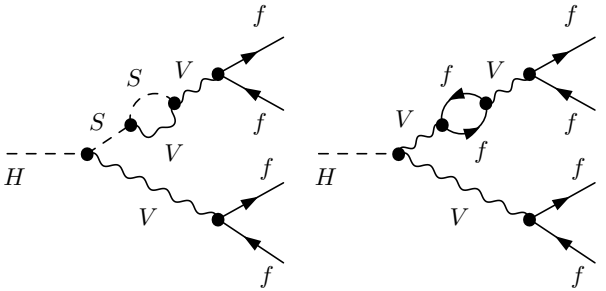




vertices



self-energies



$+$ tree graphs with real gluon or photons

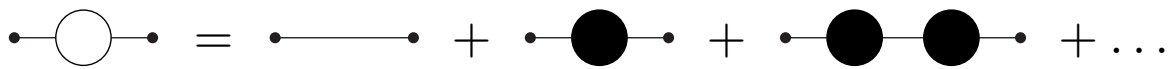
Note: amplitudes recycled from NLO corrections to $\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$ Bredenstein, Denner, S.D., Weber '06

Problem of unstable particles:

description of resonances requires resummation of propagator corrections

$\hookrightarrow$ mixing of perturbative orders potentially violates gauge invariance

Dyson series and propagator poles (scalar example)



$$G^{\phi\phi}(p) = \frac{\mathrm{i}}{p^2-m^2} + \frac{\mathrm{i}}{p^2-m^2}\,\mathrm{i}\Sigma(p^2)\,\frac{\mathrm{i}}{p^2-m^2} + \ldots = \frac{\mathrm{i}}{p^2-m^2+\Sigma(p^2)}$$

$\Sigma(p^2)$ = renormalized self-energy, m = ren. mass

stable particle: $\mathrm{Im}\{\Sigma(p^2)\} = 0$ at $p^2 \sim m^2$

$\hookrightarrow$ propagator pole for real value of p^2,
renormalization condition for physical mass m: $\Sigma(m^2) = 0$

unstable particle: $\mathrm{Im}\{\Sigma(p^2)\} \neq 0$ at $p^2 \sim m^2$

$\hookrightarrow$ location μ^2 of propagator pole is complex,
possible definition of mass M and width Γ: $\mu^2 = M^2 - \mathrm{i}M\Gamma$

The complex-mass scheme at NLO Denner, S.D., Roth, Wieders '05

Basic idea: mass^2 = location of propagator pole in complex p^2 plane

$\hookrightarrow$ consistent use of complex masses everywhere !

Application to gauge-boson resonances:

- replace $M_{\mathrm{W}}^2 \to \mu_{\mathrm{W}}^2 = M_{\mathrm{W}}^2 - \mathrm{i}M_{\mathrm{W}}\Gamma_{\mathrm{W}}, \qquad M_{\mathrm{Z}}^2 \to \mu_{\mathrm{Z}}^2 = M_{\mathrm{Z}}^2 - \mathrm{i}M_{\mathrm{Z}}\Gamma_{\mathrm{Z}}$

  and define (complex) weak mixing angle via $c_{\mathrm{W}}^2 = 1 - s_{\mathrm{W}}^2 = \frac{\mu_{\mathrm{W}}^2}{\mu_{\mathrm{Z}}^2}$

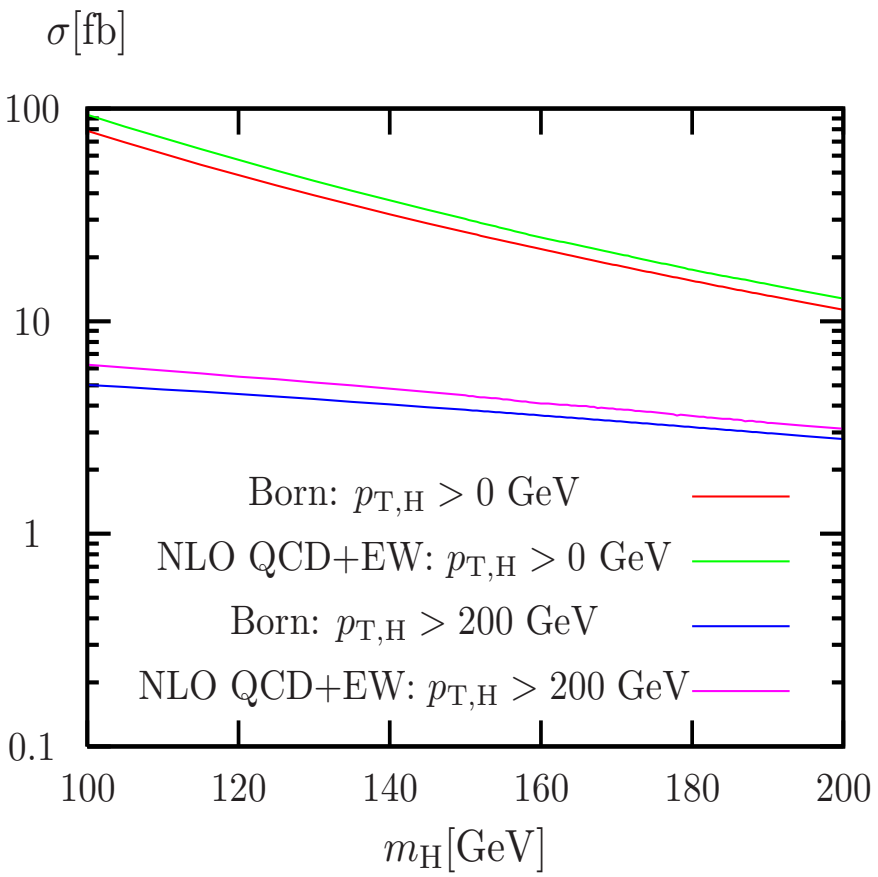
- features:
  - gauge-invariant result (Slavnov–Taylor identities, gauge-parameter independence)
    $\hookrightarrow$ unitarity cancellations respected !
  - perturbative calculations as usual (loops and counterterms)
  - no double counting of contributions (bare Lagrangian unchanged !)
  - complex gauge-boson masses in one-loop integrals needed,
    but results fully available Denner, S.D. '10

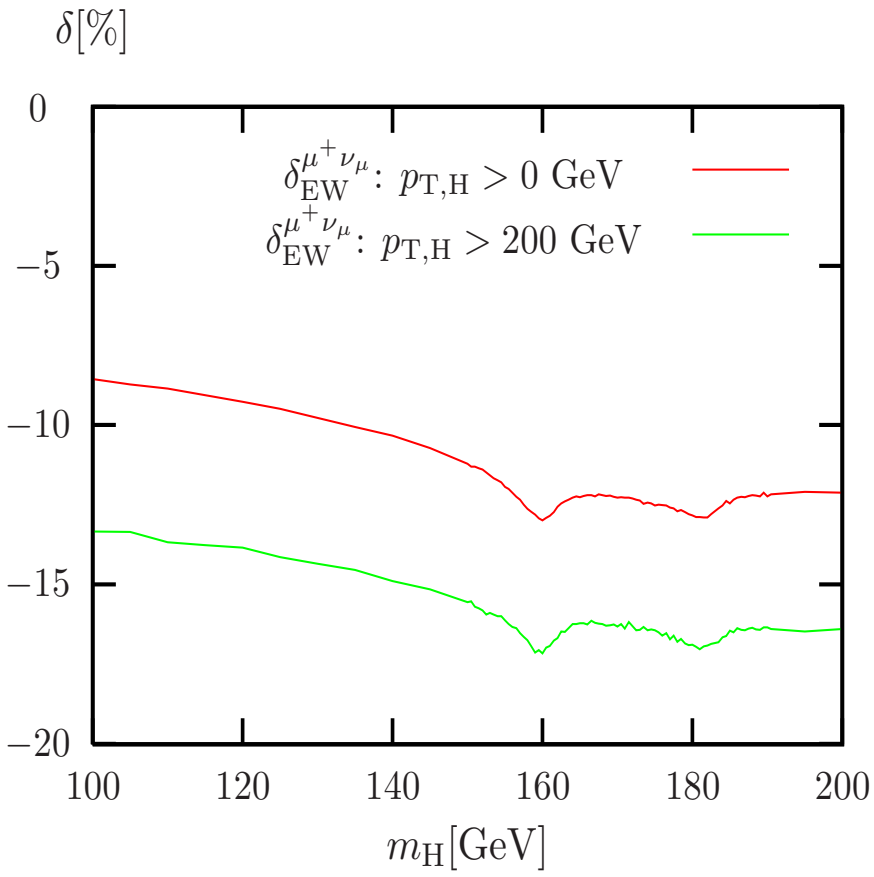
Numerical results on distributions

Setup of the evaluation

- LHC @ $\sqrt{s} = 14\,\mathrm{TeV}$
- $M_\mathrm{H} = 120\,\mathrm{GeV}$
- phase-space cuts: $p_{\mathrm{T},\ell} > 25\,\mathrm{GeV}, \quad \not{p}_\mathrm{T} > 25\,\mathrm{GeV}, \quad |\eta_\ell| < 2.5$
- jet algorithm irrelevant in fixed NLO for $\mathrm{pp} \to \mathrm{H}\ell\ell/\ell\nu/\nu\nu + X$
- optional: photon recombination with collinear leptons

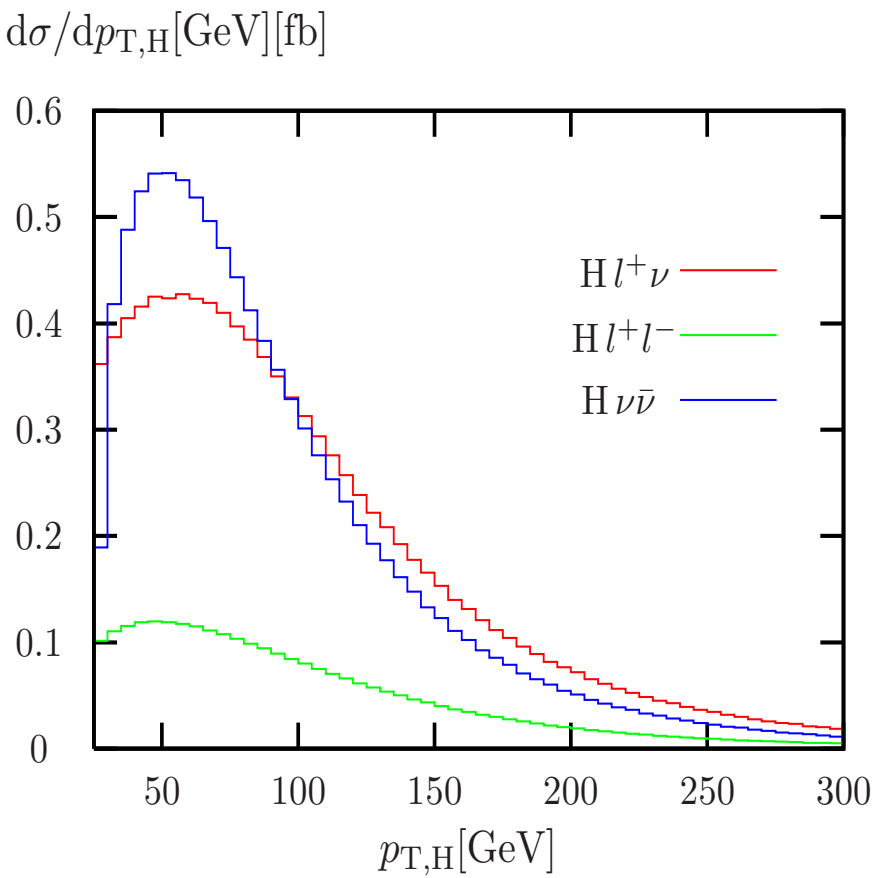
NLO EW corrections to the integrated cross section of $\mathrm{pp} \to \mathrm{H}\ell^+\nu_\ell + X$

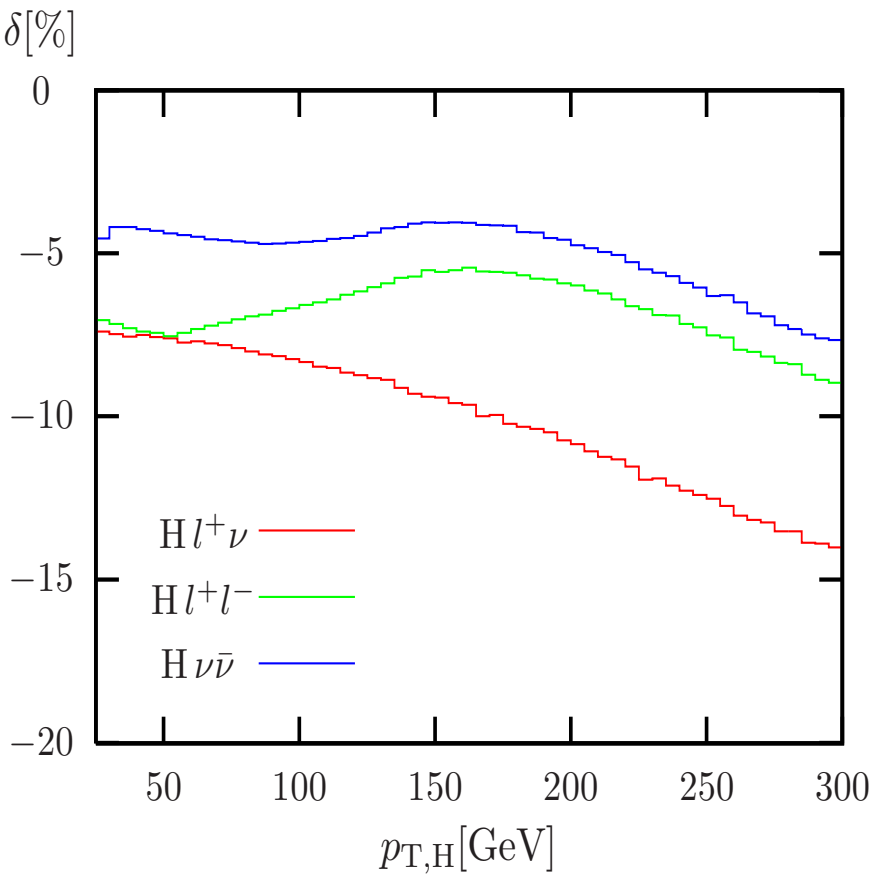




- sound behaviour of δ_{EW} near WW/ZZ thresholds
- size of EW corrections increases for boosted-Higgs scenario wrt σ_{tot} !

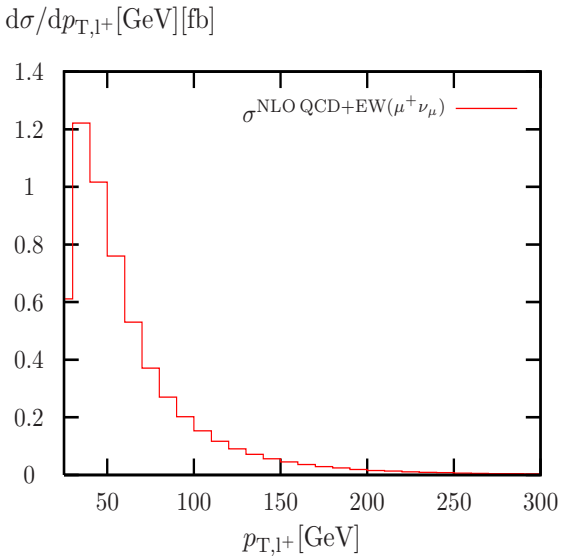
NLO EW corrections to the $p_{\mathrm{T,H}}$ distributions

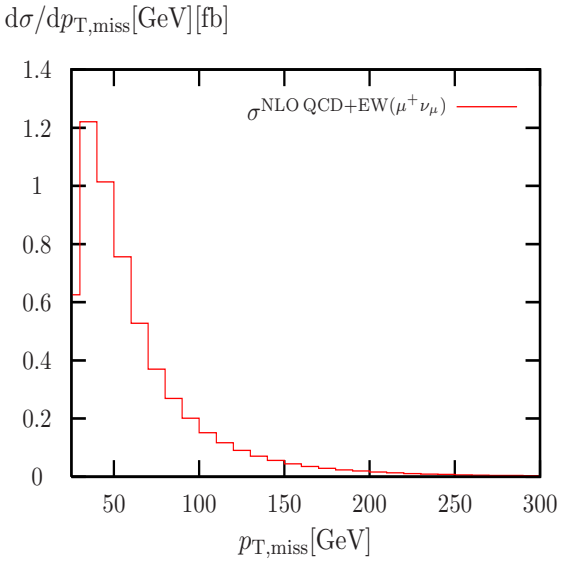


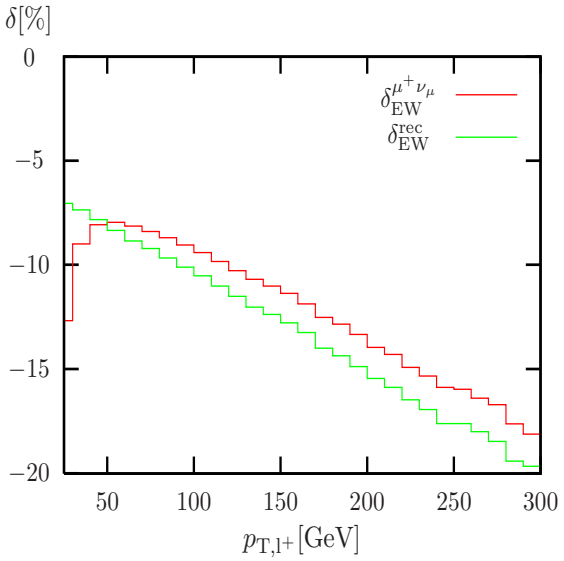


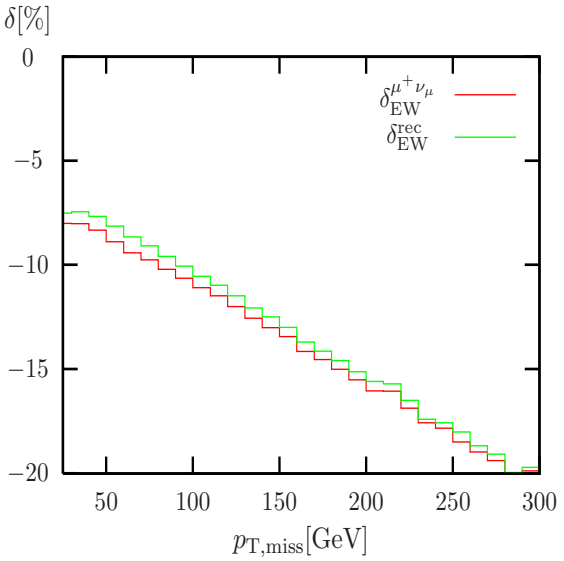
- δ_{EW} for $p_{\mathrm{T,H}} \lesssim 100\,\mathrm{GeV}$ roughly reflects corrections to total cross sections
- size of corrections increase with increasing $p_{\mathrm{T,H}}$,
  e.g. $\mathrm{H}\ell^+\nu$: $\delta_{\mathrm{EW}} < -11\%$ for $p_{\mathrm{T,H}} > 200\,\mathrm{GeV}$

NLO EW corrections to $p_{\mathrm{T},\ell}$ and $p_{\mathrm{T,miss}}$ distributions for $\mathrm{pp} \to \mathrm{H}\ell^+\nu_\ell + X$





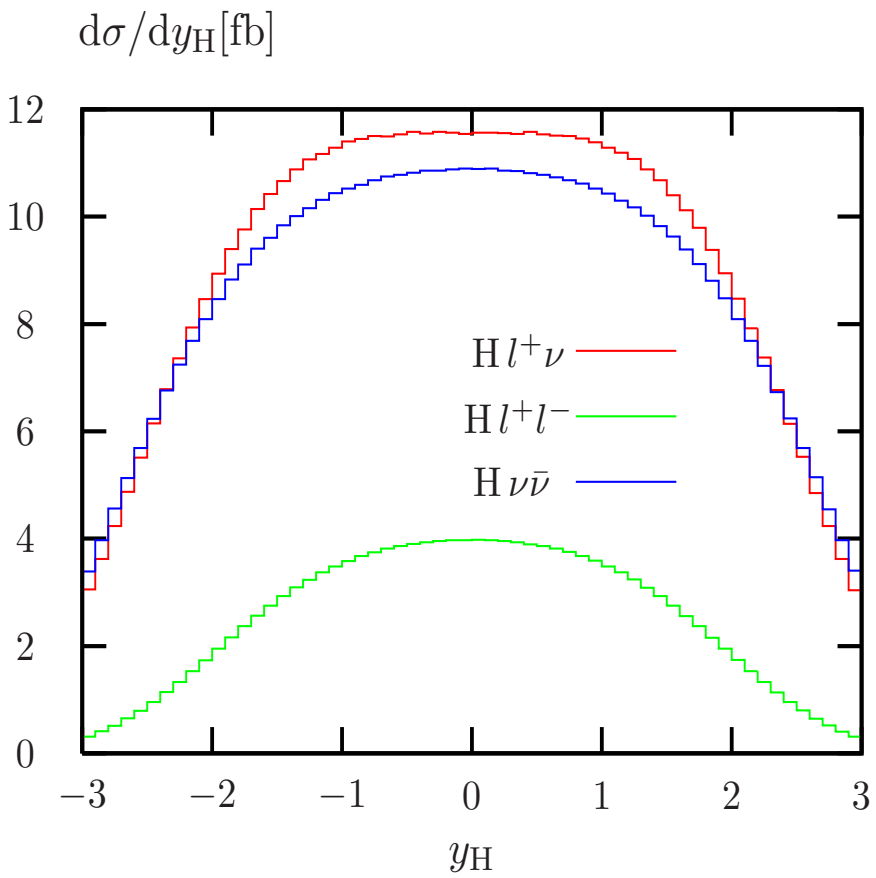


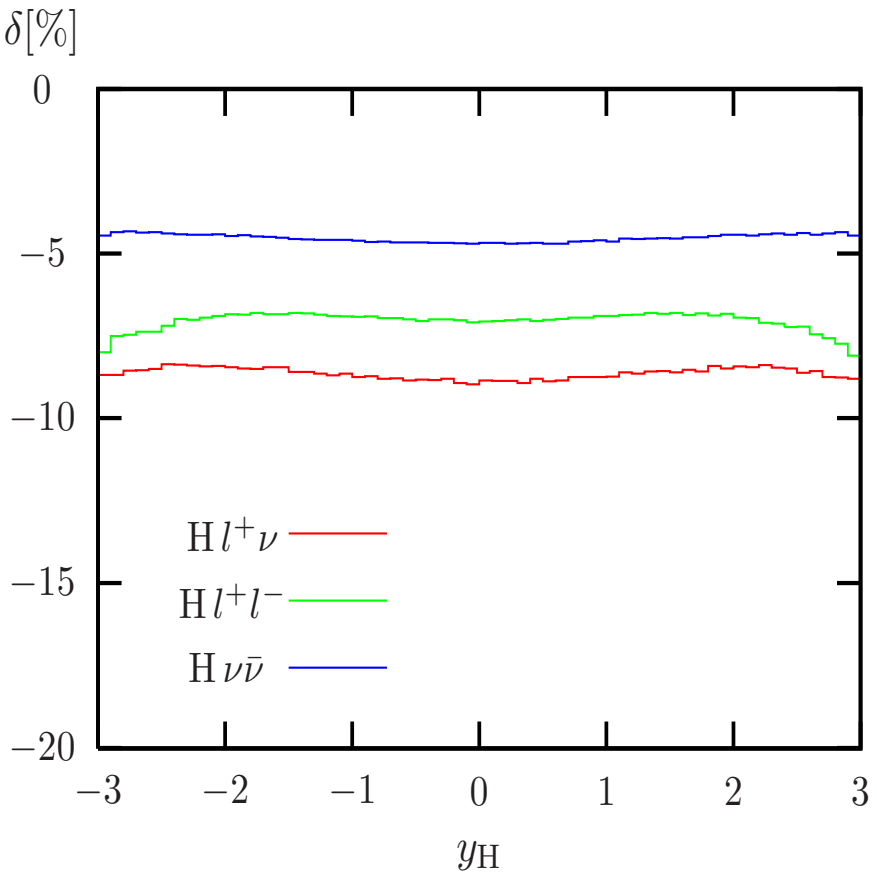


"bare muons": no γ recombination
$\hookrightarrow$ collinear μ and γ assumed separable
$\hookrightarrow$ mass-singular corrections $\propto \alpha \ln m_\mu$

"rec": recombination of collinear γ
$\hookrightarrow$ collinear $\mu\gamma = \widetilde{\mu\gamma}$ quasiparticle
$\hookrightarrow$ no mass-singular corrections

NLO EW corrections to the y_{H} distributions





EW corrections rather flat and similar to the ones to σ_{tot}.

Conclusions

WH/ZH production at hadron colliders

- basic Higgs search channels at the Tevatron for low M_{H} ($\sim 120\,\mathrm{GeV}$)
- accessible at the LHC for highly boosted $\mathrm{H} \to \mathrm{b\bar{b}}$ via $\mathrm{b\bar{b}}$ jet substructure

Experimental challenge: background suppression

$\hookrightarrow$ precise predictions for differential quantities required

Theoretical predictions

- total cross sections

  $\hookrightarrow$ recent update by LHC Higgs XS WG for LHC @ $7\,\mathrm{TeV}/14\,\mathrm{TeV}$ CERN-2011-002 arXiv:1101.0593 [hep-ph]
  based on older NNLO QCD + NLO EW calculations

- cross sections with cuts, differential cross sections

  new: NNLO QCD by Ferrera et al. & NLO EW within HAWK

  first differential result on EW corrections to $\mathrm{WH/ZH}$: ($M_{\mathrm{H}} = 120\,\mathrm{GeV}$)

$$\begin{aligned} \delta_{\mathrm{EW}}(\sigma_{\mathrm{tot}}) &\sim -7\,/-5\% \\ \delta_{\mathrm{EW}}(p_{\mathrm{T,H}}{>}200\,\mathrm{GeV}) &\lesssim -11/-7\% \end{aligned}$$

  $\hookrightarrow$ new predictions and error estimates planned for 2nd Yellow Report

  Release of HAWK 2.0 coming soon, see
  `http://omnibus.uni-freiburg.de/~sd565/programs/hawk/hawk.html`