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Electroweak corrections in Higgs-boson production & uncertainties in Higgs-boson decays

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Zurich phenomenology workshop: Higgs search confronts theory
Zurich, January 10, 2012

- Introduction
- Electroweak corrections to Higgs strahlung off W/Z bosons
- SM Higgs branching ratios with theoretical uncertainties
- Higgs production and decay in SM4

Electroweak (EW) corrections for Higgs production

Higgs production processes:

- gluon fusion: $\mathrm{gg} \to \mathrm{H}$
  NLO EW $\sim 5\%$ Aglietti, Bonciani, Degrassi, Vicini '04, '06
  Degrassi, Maltoni '04
  Actis, Passarino, Sturm, Uccirati '08
- vector-boson fusion: $\mathrm{qq} \to \mathrm{Hjj}$
  NLO EW $\sim 5\% \sim$ NLO QCD Ciccolini, Denner, Dittmaier '07
  Figy, Palmer, Weiglein '10
- associated Higgs production: $\mathrm{qq} \to \mathrm{HW/HZ}$
  NLO EW: $\mathcal{O}(5{-}10\%) \sim 1/3$ NLO QCD Ciccolini, Krämer, Dittmaier '03

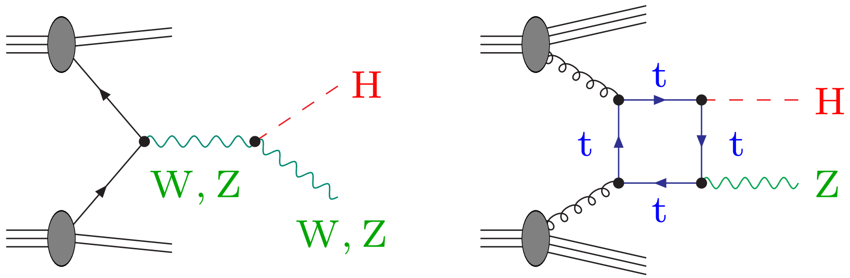
Higgs decays:

- $\mathrm{H} \to 4f$
  NLO EW: $\mathcal{O}(5{-}10\%)$ Bredenstein, Denner, Dittmaier, Weber '05
- $\mathrm{H} \to \gamma\gamma$
  NLO EW: few % Actis, Passarino, Sturm, Uccirati '07

larger corrections for distributions or SM4 (SM with 4th fermion generation)

Associated Higgs production

Relevance of associated Higgs production



- main search channel for low-mass Higgs at Tevatron ($\mathrm{H} \to \mathrm{b\bar{b}}$)
- at LHC: only small fraction of total Higgs cross section
  might contribute to discovery of low-mass Higgs and
  measurement of Hbb and HWW couplings
- small S/B ratio can be improved by selecting highly-boosted H and V
  back to back in transverse plane Butterworth et al. '08, '09
- control of background to 10% required in specific phase-space regions
  $\Rightarrow$ precise theoretical differential predictions needed

Theoretical predictions for WH/ZH production

Status January 2011 LHC Higgs Cross Section Working Group [arXiv:1101.0593]

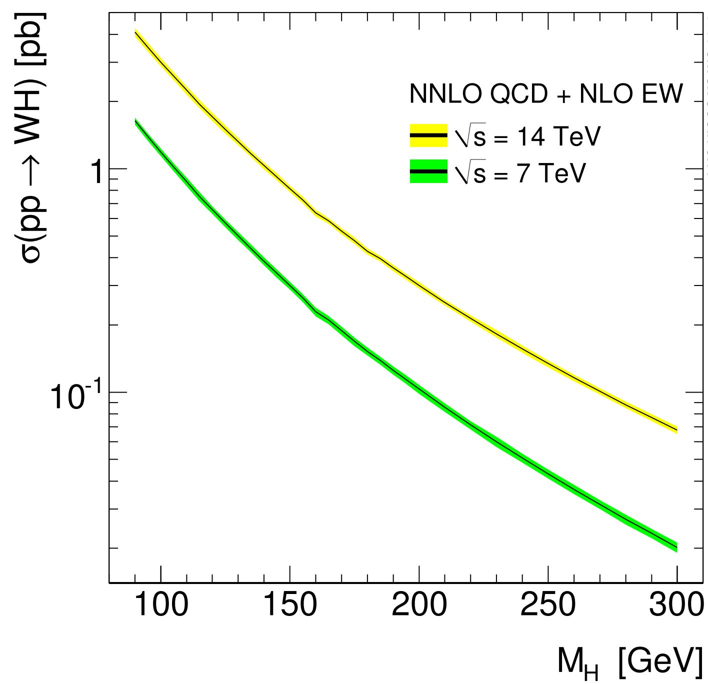
- NNLO QCD corrections for total cross section Brein, Djouadi, Harlander '04
  based on Drell-Yan results from Hamberg, van Neerven, Matsuura '91
  implemented in VH@NNLO
- NLO EW corrections for total cross section and stable gauge bosons
  Ciccolini, Dittmaier, Krämer '03
- combination of NNLO QCD and NLO EW
  assuming factorization Brein et al. '04

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

$\sigma_{\mathrm{gg}\to\mathrm{ZH}}$ contributes $2-6\%$ $(4-12\%)$
at $\sqrt{s} = 7\,\mathrm{TeV}$ $(14\,\mathrm{TeV})$

- scale uncertainty
  $\sim 1-2\%$ at NNLO
- PDF + α_s uncertainty (PDF4LHC)
  $\sim 3-5\%$

Higgs cross section WG '11



Theoretical predictions for WH/ZH production

New developments in 2011

- NNLO corrections beyond Drell–Yan with Higgs radiation from top loops
  for total cross section of WH and ZH production
  Brein, Harlander, Wiesemann, Zsirke [arXiv:1111.0761]
  $\Rightarrow$ talk of Robert Harlander

- fully differential NNLO QCD corrections to Drell-Yan-like contributions
  for WH production including Higgs and vector-boson decays
  Ferrara, Grazzini, Tramontano [arXiv:1107.1164]

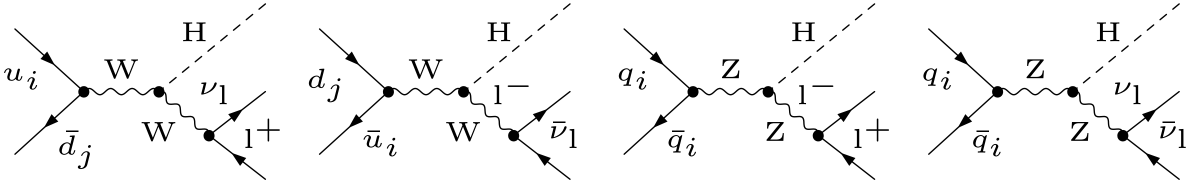
- fully differential NLO EW corrections to WH/ZH production
  including vector-boson decays
  Denner, Dittmaier, Kallweit, Mück [arXiv:1112.5142]
  implemented in Monte Carlo program HAWK (new release in preparation)
  $\hookrightarrow$ this talk

Electroweak corrections with W/Z decays

Denner, Dittmaier, Kallweit, Mück [arXiv:1111.6395]

- complete NLO electroweak corrections to
  $\mathrm{pp}/\mathrm{p\bar{p}} \to \mathrm{H} + \mathrm{W/Z} \to \mathrm{H} + l^+\nu_l/l^-\bar{\nu}_l/l^-l^+/\nu_l\bar{\nu}_l + X$
  including photon-induced processes (using MRST2004QED PDFs)
- recalculation of NLO QCD corrections

Feynman diagrams for LO processes



- leptons and quarks considered as massless
  - lepton masses appear as regulators of collinear divergences
  - quark-mixing matrix appears only as global factor
- $\mathrm{b\bar{b}}$ annihilation treated in LO only:
  contribution $\lesssim 1(3)\%$ for $\sqrt{s} = 7(14)\,\mathrm{TeV}$
- G_μ scheme for α_{em} (resums higher-order corrections: running α, ρ parameter)

Tools

- generation of Feynman diagrams with FeynArts version 1 and 3
  Küblbeck, Böhm, Denner, Eck '90,'92 Hahn '01
- algebraic simplifications using two independent in-house programs implemented in *Mathematica*, one building upon POLE Meier '05 and FORMCALC Hahn, Perez-Victoria '99, Hahn '00
- numerically stable reduction of tensor integrals according to
  Denner, Dittmaier, NPB658 (2003)175 [hep-ph/0212259], NPB734 (2006) 62 [hep-ph/0509141]
- gauge-invariant treatment of W and Z resonances with complex-mass scheme Denner, Dittmaier, Roth, Wieders '05
- scalar integrals for complex masses based on
  Denner, Dittmaier, NPB844 (2011) 199 [arXiv:1005.2076]
- soft and collinear singularities: dipole subtraction formalism
  Catani, Seymour '96, Dittmaier '99; Dittmaier, Kabelschacht, Kasprzik '08
- phase-space integration: multi-channel Monte Carlo integration with adaptive optimization Berends, Kleiss, Pittau '94; Kleiss, Pittau '94
- two independent calculations

Set-up for numerical calculation

- photon–lepton recombination
  - for electrons recombine if $R_{\gamma l} < 0.1$, $\quad R_{\gamma l} = \sqrt{(y_l - y_\gamma)^2 + \phi_{l\gamma}^2}$
  - no recombination for muons $\Rightarrow \log(m_\mu)$ terms
- charged leptons must obey
  $p_{\mathrm{T},l} > 20\,\mathrm{GeV}, \qquad |y_l| < 2.5$
- missing transverse momentum for channels with neutrino(s)
  $\not{p}_\mathrm{T} > 25\,\mathrm{GeV}$
- optional additional cuts (boosted Higgs setup)
  $p_{\mathrm{T,H}} > 200\,\mathrm{GeV}, \qquad p_{\mathrm{T,W/Z}} > 190\,\mathrm{GeV}$
  (symmetric cuts would cause large corrections near the cut in the $p_{\mathrm{T,H}}$ distribution)
- contribution of WH channel to $\mathrm{H}+\not{E}_{\mathrm{T,miss}}$ $(\mathrm{H}\nu_\mathrm{l}\bar{\nu}_\mathrm{l})$ production: $\mathrm{H}\nu_\mathrm{l}/\bar{\nu}_\mathrm{l}$
  $p_{\mathrm{T},l} < 20\,\mathrm{GeV}$ or $|y_l| > 2.5$

stable Higgs boson

renormalization and factorization scale: $\mu_\mathrm{F} = \mu_\mathrm{R} = M_V + M_\mathrm{H}$

Cross section for LHC7 with boosted Higgs

$M_{\mathrm{H}} = 120\,\mathrm{GeV}$

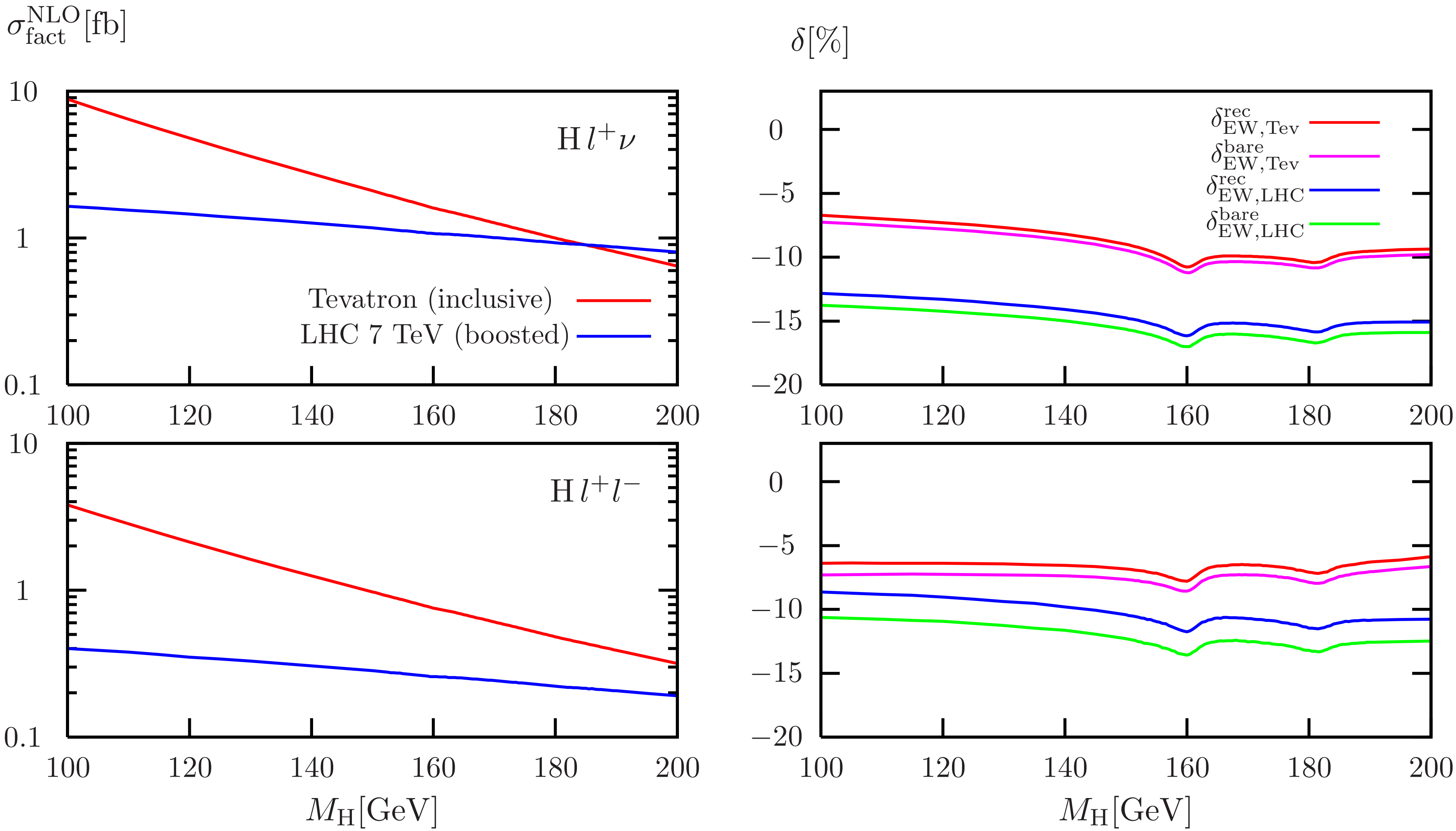
Denner, Dittmaier, Kallweit, Mück ’11

channel	$\mathrm{Hl}^{+}\nu_{\mathrm{l}} + X$	$\mathrm{Hl}^{-}\bar{\nu}_{\mathrm{l}} + X$	$\mathrm{Hl}^{+}\mathrm{l}^{-} + X$	$\mathrm{H}\nu_{\mathrm{l}}\bar{\nu}_{\mathrm{l}} + X$	$\mathrm{H}\nu_{\mathrm{l}}/\bar{\nu}_{\mathrm{l}} + X$
$\sigma_0/\,\mathrm{fb}$	1.50846(7)	0.66292(3)	0.35349(2)	0.74759(3)	0.058236(9)
$\sigma^{\mathrm{LO}}/\,\mathrm{fb}$	1.4183(2)	0.60926(9)	0.32845(5)	0.69519(9)	0.05417(3)
$\delta_{\mathrm{EW}}^{\mathrm{bare}}/\%$	−14.2	−14.0	−10.9	−6.9	−12.5
$\delta_{\mathrm{EW}}^{\mathrm{rec}}/\%$	−13.3	−13.0	−9.0	−6.9	−14.5
$\delta_{\mathrm{QCD}}/\%$	+9.5	+9.4	+9.8	+9.8	+6.8
$(K_{\mathrm{QCD}} - 1)/\%$	+16.5	+19.1	+18.1	+18.1	+14.9
$\delta_{\gamma}/\%$	+1.3	+1.5	+0.0	+0.0	+12.5
$\sigma_{\mathrm{fact}}^{\mathrm{NLO}}/\,\mathrm{fb}$	1.4522(4)	0.6406(2)	0.35329(7)	0.7646(2)	0.06043(6)
$\sigma_{\mathrm{HAWK}}^{\mathrm{NLO}}/\,\mathrm{fb}$	1.4713(4)	0.6488(2)	0.35639(7)	0.7697(2)	0.06100(6)

- LO predictions with LO PDFs: σ_0, with NLO PDFs: σ^{LO}
- NLO QCD prediction: $\sigma_{\mathrm{QCD}}^{\mathrm{NLO}} = \sigma_0\left(1 + \delta_{\mathrm{QCD}}\right) = K_{\mathrm{QCD}}\sigma^{\mathrm{LO}}$
- NLO prediction of HAWK: $\sigma_{\mathrm{HAWK}}^{\mathrm{NLO}} = \sigma_0 \times \left(1 + \delta_{\mathrm{QCD}} + \delta_{\gamma} + \delta_{\mathrm{EW}}\right)$
- improved NLO prediction based on factorization: $\sigma_{\mathrm{fact}}^{\mathrm{NLO}} = \sigma_{\mathrm{QCD}}^{\mathrm{NLO}} \times \left(1 + \delta_{\mathrm{EW}}\right) + \sigma_0\,\delta_{\gamma}$

NLO EW corrections for pp $\to$ H$l^+\nu/l^+l^-$

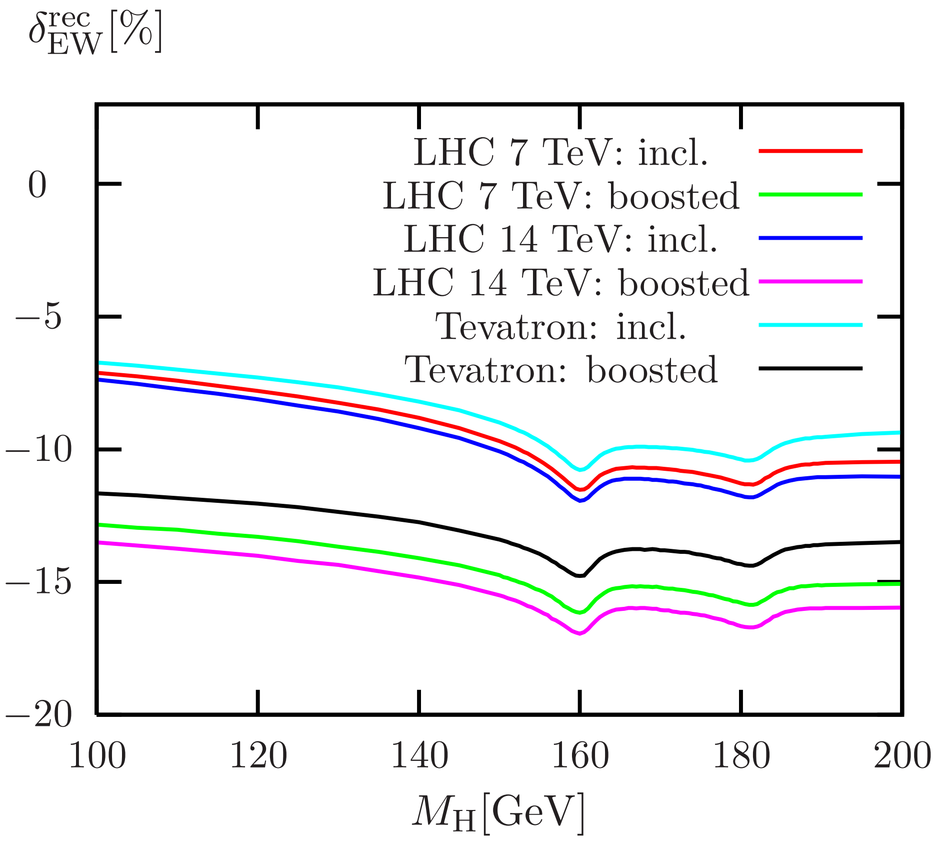
Denner, Dittmaier, Kallweit, Mück ’11



NLO EW corrections for $\mathrm{pp} \to \mathrm{H}l^+\nu$

Denner, Dittmaier, Kallweit, Mück ’11

Comparison of different colliders, inclusive and boosted setup



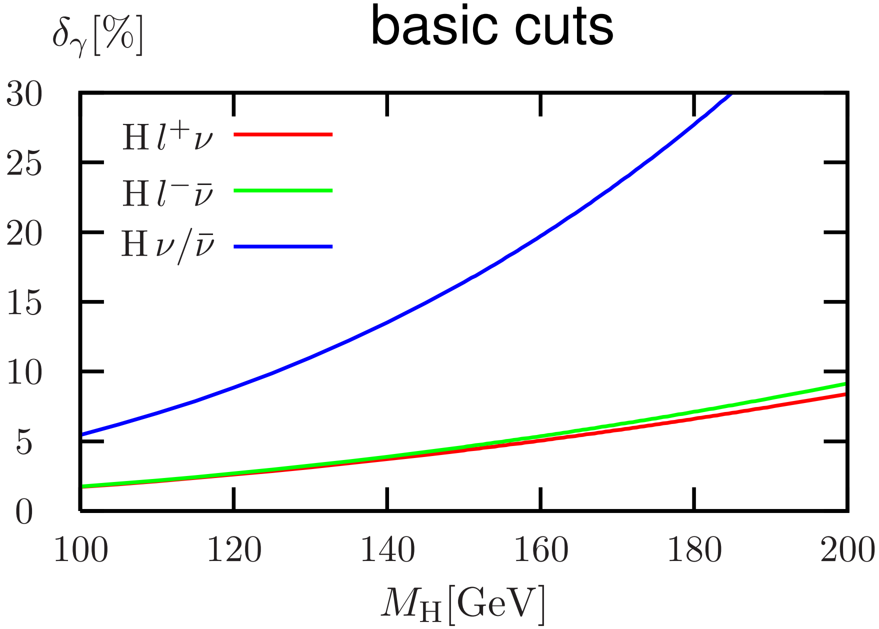
- corrections larger for boosted setup
- relative corrections depend only weakly on collider energy
- threshold singularities are regularized by complex-mass scheme

Contributions of photon-induced processes

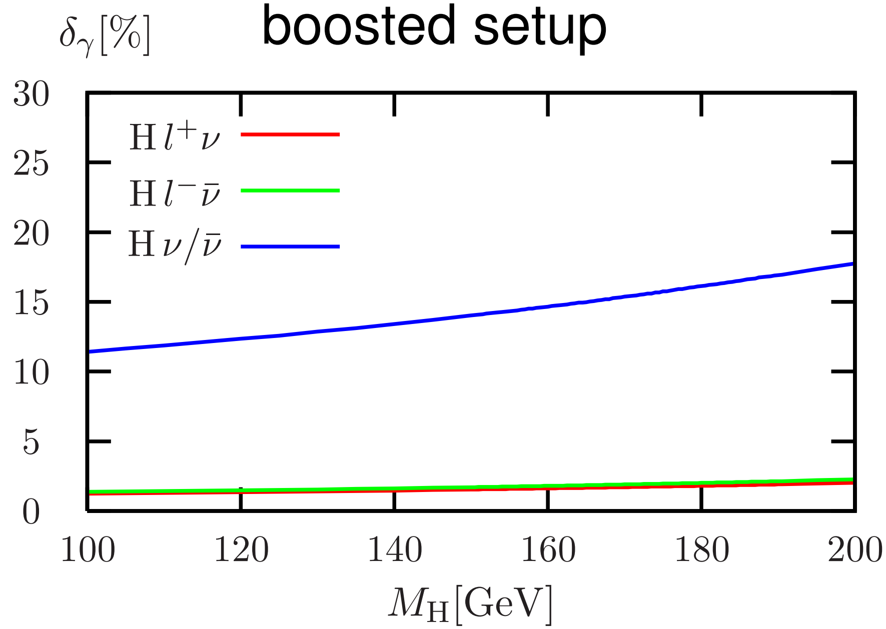
Denner, Dittmaier, Kallweit, Mück ’11

relative corrections from photon-induced processes for LHC7

basic cuts



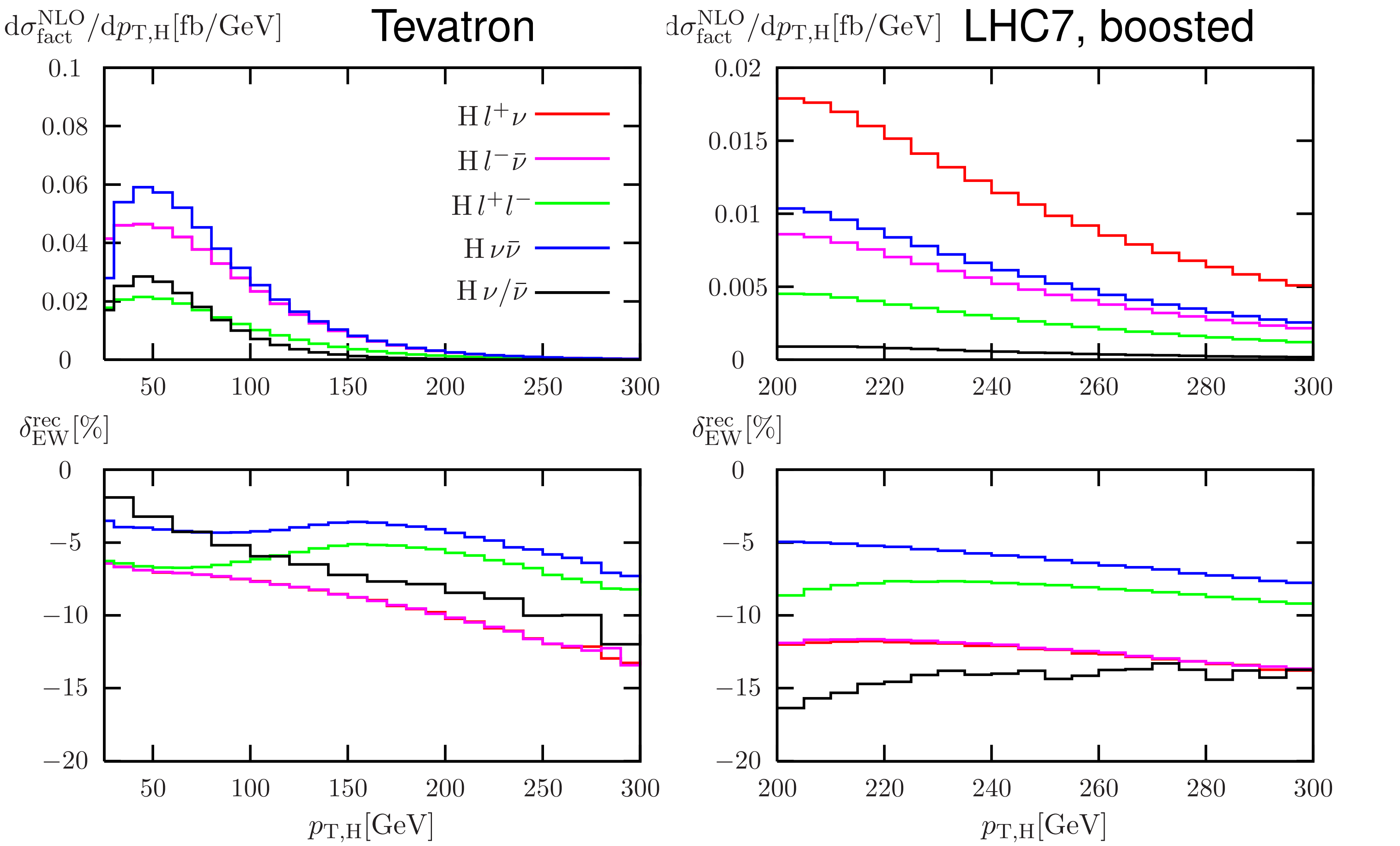
boosted setup



- photon-induced corrections for boosted setup and identified charged leptons below $1{-}2\%$ (contributions to HZ even smaller)
- corrections up to 10% for inclusive setup and identified charged leptons
- larger corrections for $\mathrm{H}\nu_\mathrm{l}/\bar{\nu}_\mathrm{l}$ channel owing to collinear logarithms phenomenologically relevant?

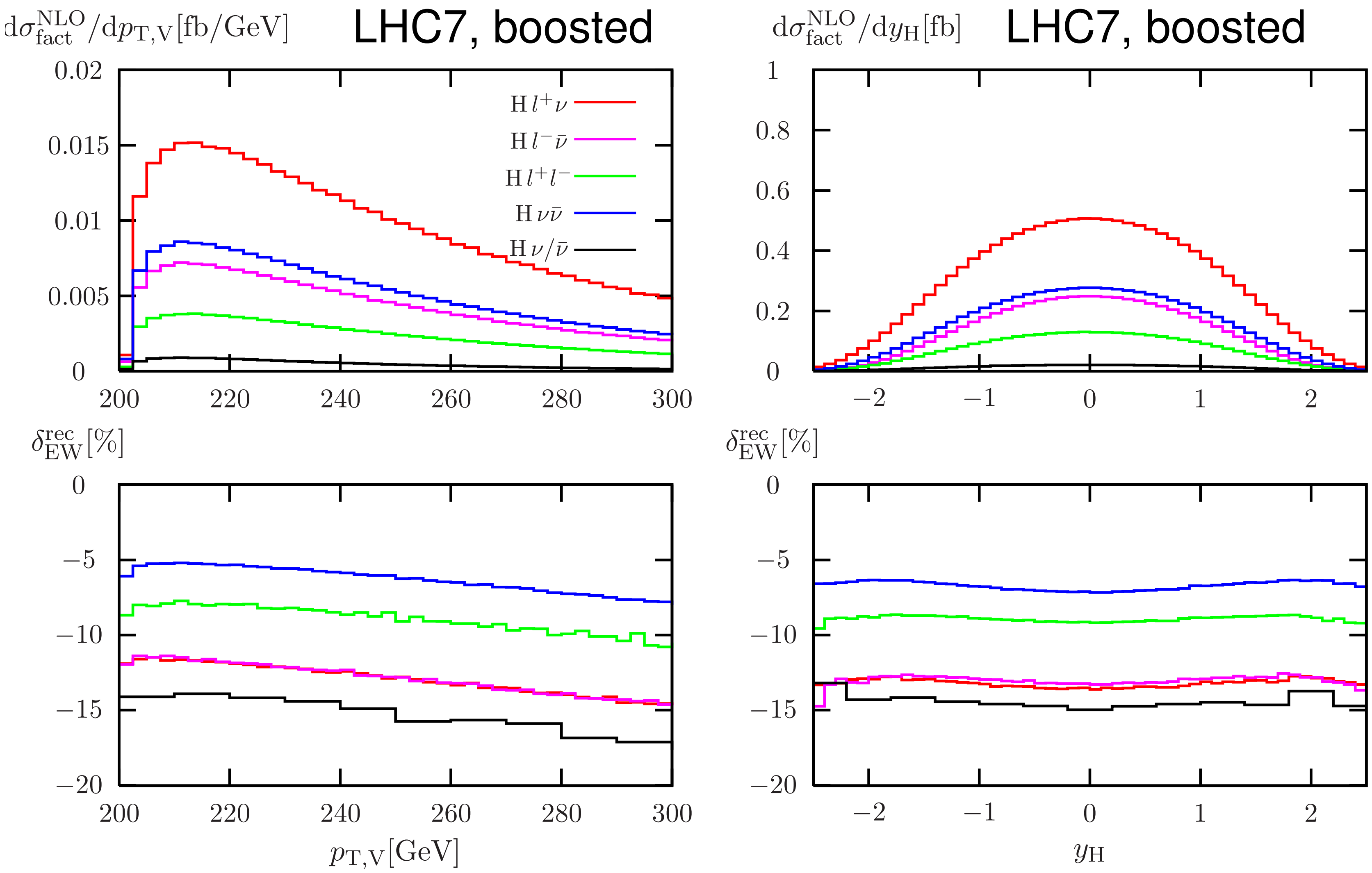
Distribution in transverse momentum of Higgs boson

Denner, Dittmaier, Kallweit, Mück ’11



Distributions for $pp \to Hl^{\pm}\nu / l^{+}l^{-} / \nu\bar{\nu}$

Denner, Dittmaier, Kallweit, Mück '11



SM Higgs branching ratios with uncertainties

Tools and Strategy for SM Higgs decays

Predictions for SM Higgs branching ratios with uncertainties

LHC HIGGS XS WG ’12, Denner et al. (BR subgroup) [arXiv:1107.5909]

Tools

- PROPHECY4F for $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ} \to 4f$ (complete QCD and EW NLO)
  Bredenstein, Denner, Dittmaier, Weber ’06
- HDECAY for other channels Djouadi, Kalinowski, Mühlleitner, Spira ’98, ’10
- EW NLO corrections to $\mathrm{H} \to \gamma\gamma$ and $\mathrm{H} \to \mathrm{gg}$ Actis, Passarino, Sturm, Uccirati ’08

Strategy

- calculate all partial decay widths as accurate as possible
- determine total width: $\Gamma_{\mathrm{H}} = \Gamma^{\mathrm{HD}} - \Gamma^{\mathrm{HD}}_{\mathrm{ZZ}} - \Gamma^{\mathrm{HD}}_{\mathrm{WW}} + \Gamma^{\mathrm{Proph.}}_{4f}$
- determine branching ratios $\mathrm{BR}_i = \Gamma_i/\Gamma_{\mathrm{H}}$
- PROPHECY4F includes all interferences :
  $\Gamma^{\mathrm{Proph.}}_{4f} = \Gamma_{\mathrm{H}\to\mathrm{W}^*\mathrm{W}^*\to 4f} + \Gamma_{\mathrm{H}\to\mathrm{Z}^*\mathrm{Z}^*\to 4f} + \Gamma_{\mathrm{WW/ZZ-int.}}$

Parametric uncertainties

earlier estimate Baglio, Djouadi '10

- uncertainties in input parameters:

Parameter	Central value	Uncertainty		$\overline{\mathrm{MS}}$ masses $m_\mathrm{q}(m_\mathrm{q})$
$\alpha_\mathrm{s}(M_\mathrm{Z})$	0.119	±0.002	$\pm1.7\%$	
m_c	$1.42\,\mathrm{GeV}$	$\pm0.03\,\mathrm{GeV}$	$\pm2.1\%$	$1.28\,\mathrm{GeV}$
m_b	$4.49\,\mathrm{GeV}$	$\pm0.06\,\mathrm{GeV}$	$\pm1.3\%$	$4.16\,\mathrm{GeV}$
m_t	$172.5\,\mathrm{GeV}$	$\pm2.5\,\mathrm{GeV}$	$\pm1.4\%$	$165.4\,\mathrm{GeV}$

one-loop pole masses show negligible dependence on α_s
$\Rightarrow$ use as independent parameters (HDECAY)

- uncertainties from G_μ, M_Z, M_W, m_l below one per mille $\Rightarrow$ neglected
- determine variation of Γ_i and BR_i for each input parameter separately
- combine uncertainties in quadrature $\Rightarrow$ total parametric uncertainty (PU)

Theoretical uncertainties

Estimate of missing higher-order corrections (THU) from

- variation of QCD scales by factor 2 up and down
- known omitted corrections or accuracy of approximations
- missing higher-order EW corrections

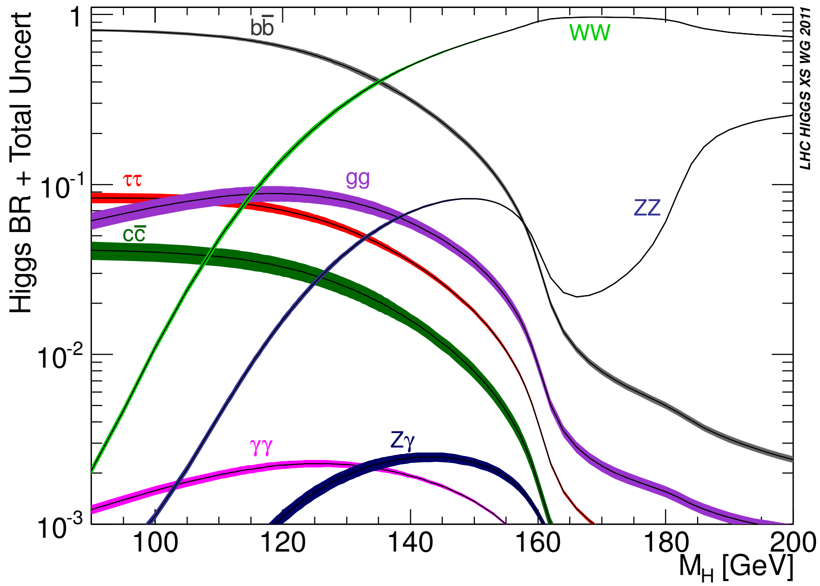
Partial Width	QCD	Electroweak	Total
$\mathrm{H} \to \mathrm{b\bar{b}/c\bar{c}}$	$\sim 0.1\%$	$\sim$ 1–2% for $M_\mathrm{H} \lesssim 135\,\mathrm{GeV}$	$\sim 2\%$
$\mathrm{H} \to \tau^+\tau^-/\mu^+\mu^-$		$\sim$ 1–2% for $M_\mathrm{H} \lesssim 135\,\mathrm{GeV}$	$\sim 2\%$
$\mathrm{H} \to \mathrm{t\bar{t}}$	$\lesssim 5\%$	$\lesssim$ 2–5% for $M_\mathrm{H} < 500\,\mathrm{GeV}$	$\sim 5\%$
		$\sim 0.1(\frac{M_\mathrm{H}}{1\,\mathrm{TeV}})^4$ for $M_\mathrm{H} > 500\,\mathrm{GeV}$	$\sim$ 5–10%
$\mathrm{H} \to \mathrm{gg}$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$
$\mathrm{H} \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$
$\mathrm{H} \to \mathrm{Z}\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$
$\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$	$< 0.5\%$	$\sim 0.5\%$ for $M_\mathrm{H} < 500\,\mathrm{GeV}$	$\sim 0.5\%$
		$\sim 0.17(\frac{M_\mathrm{H}}{1\,\mathrm{TeV}})^4$ for $M_\mathrm{H} > 500\,\mathrm{GeV}$	$\sim$ 0.5–15%

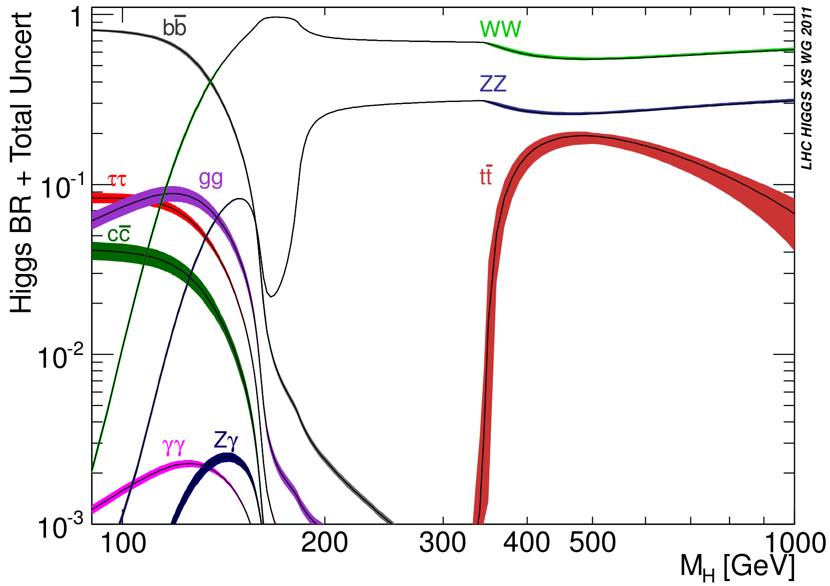
$M_\mathrm{H} > 500\,\mathrm{GeV}$: higher-order heavy-Higgs corrections dominate error

- THU on BRs calculated for each source (channel) separately
- individual THUs and PU are combined linearly

Results for SM branching ratios

LHC HIGGS XS WG ’12, Denner et al. ’11

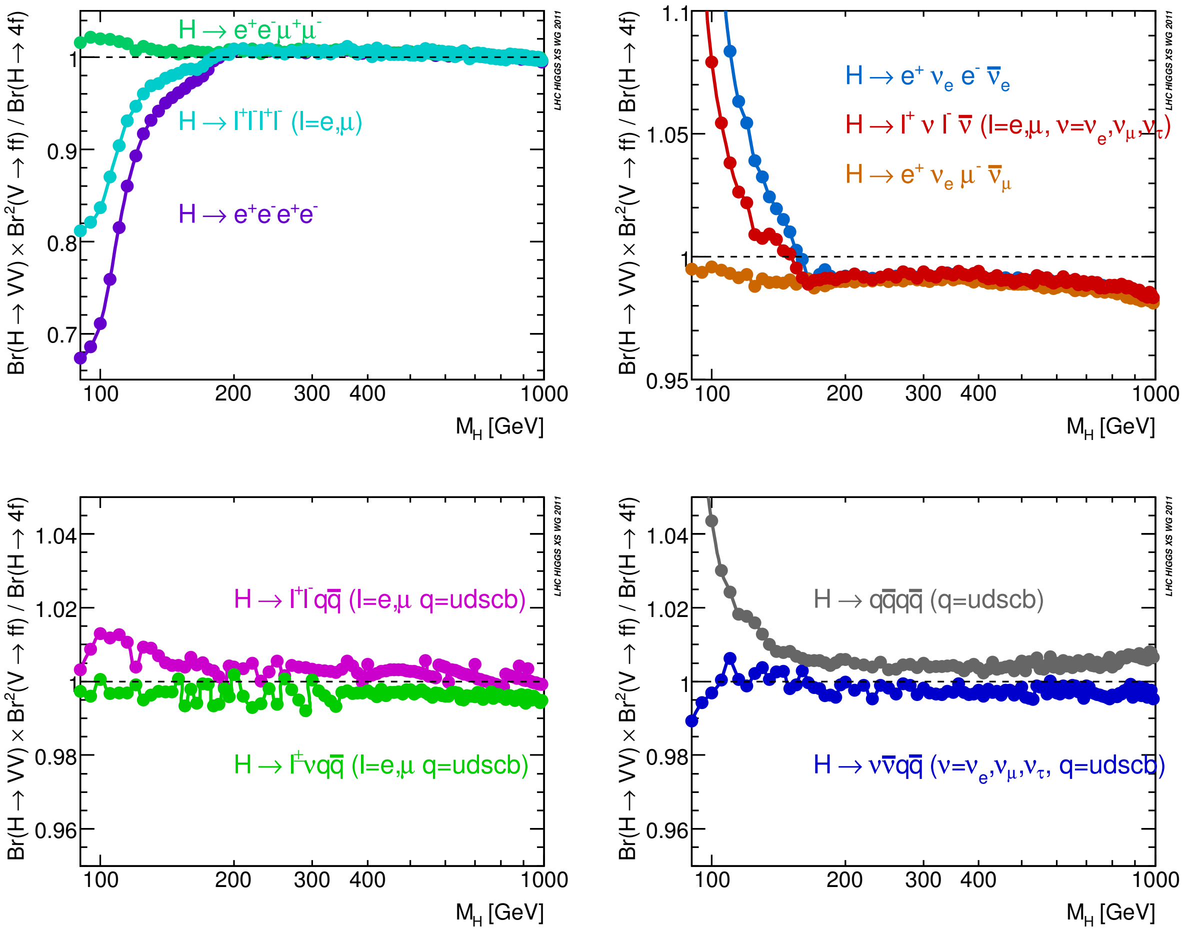




- THU $= \mathcal{O}(10\%)$ for $\mathrm{H} \to \mathrm{gg}$, $\mathrm{H} \to \mathrm{Z}\gamma$ and $\mathrm{H} \to \mathrm{t}\bar{\mathrm{t}}$
- THU < few % for $\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}$, $\mathrm{H} \to \mathrm{c}\bar{\mathrm{c}}$ and $\mathrm{H} \to \tau^+\tau^-$
- PU $= \mathcal{O}(10\%)$ for $\mathrm{H} \to \mathrm{c}\bar{\mathrm{c}}$ and $\mathcal{O}(5\%)$ for $\mathrm{H} \to \mathrm{gg}$ (mainly from α_s and m_c)
- PU $\sim 3\%$ for $\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}$ from m_b
- total uncertainty for $\mathrm{H} \to \gamma\gamma$ up to 5%
- THU and PU $\sim 1\%$ (2% for small M_H) for $\mathrm{H} \to \mathrm{ZZ}$ and $\mathrm{H} \to \mathrm{WW}$
  large uncertainties for partial width at large M_H cancel in BR

Interference effects in $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ} \to 4f$

Tanaka, LHC HIGGS XS WG '12



interference effects:

$$\frac{\mathrm{BR}(\mathrm{H} \to VV)\mathrm{BR}(V \to f\bar{f})^2}{\mathrm{BR}(\mathrm{H} \to 4f)}$$

$M_\mathrm{H} = 120\,\mathrm{GeV}$:

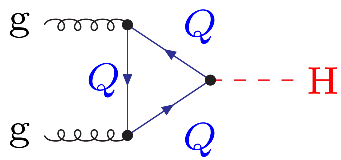
- 11% for $\mathrm{H} \to \mathrm{e}^+\mathrm{e}^-\mathrm{e}^+\mathrm{e}^-$
- -5.4% for $\mathrm{H} \to \mathrm{e}^+\nu_\mathrm{e}\mathrm{e}^-\bar{\nu}_\mathrm{e}$

$M_\mathrm{H} > 200\,\mathrm{GeV}$:

- $< 1\%$

Higgs production and decay in SM4

Higgs production in SM4

- gg → H: 

, $Q = \mathrm{t}, \mathrm{b}, \mathrm{t}', \mathrm{b}'$

  ⇒ factor $\lesssim 9$ enhancement in LO   Georgi, Glashow, Machacek, Nanopoulos ’78

- large NLO and NNLO QCD corrections
  Spira, Djouadi, Graudenz, Zerwas ’95, Anastasiou et al ’10, ’11
- screening: LO and NLO QCD corrections depend weakly on precise values of heavy fermion masses
- to escape EW precision constraints choose

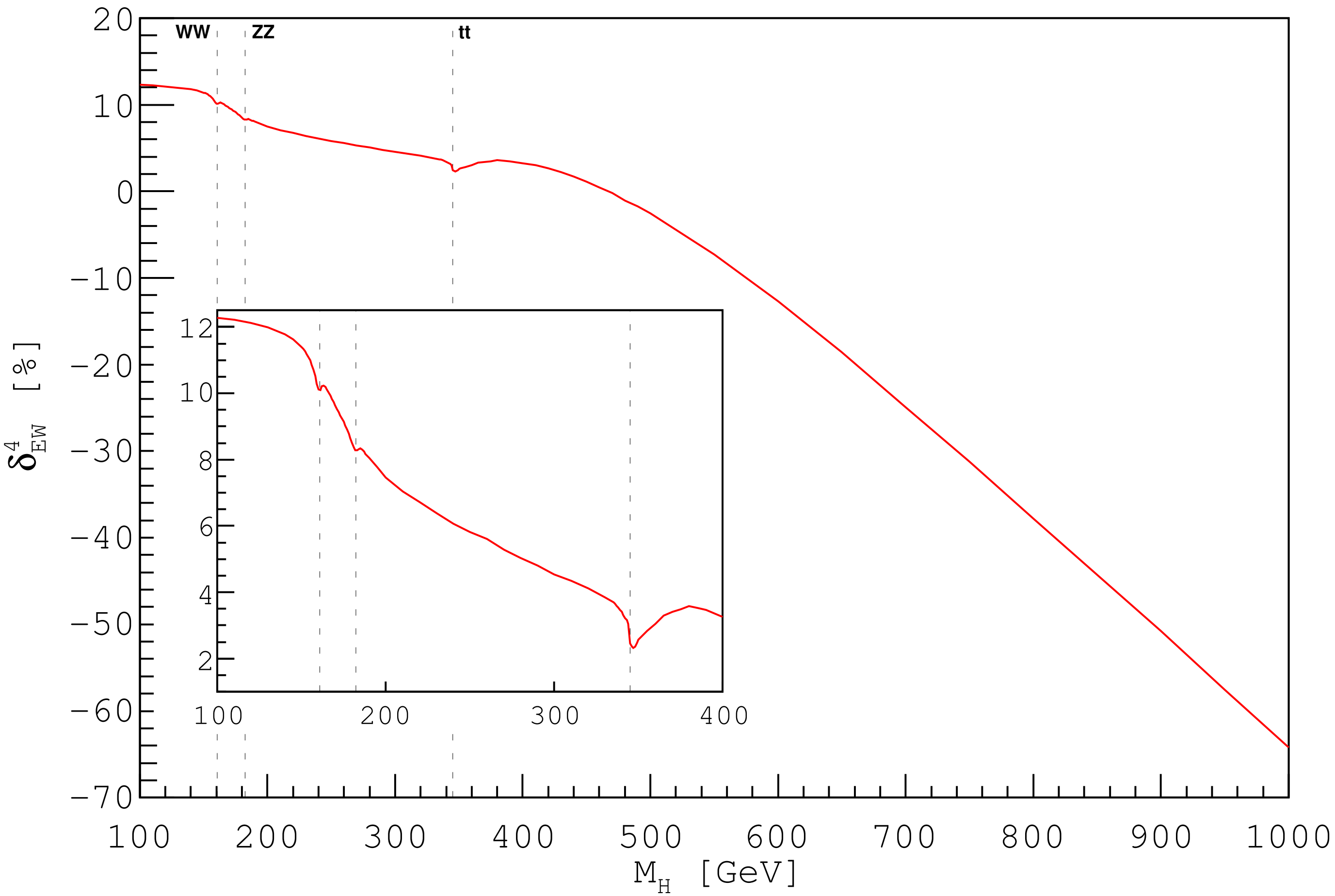
$$
\begin{aligned}
m_{\mathrm{b}'} &= m_{\mathrm{l}'} = m_{\nu'} = 600\,\mathrm{GeV}, \\
m_{\mathrm{t}'} &= m_{\mathrm{b}'} + \left[1 + \frac{1}{5}\ln\left(\frac{M_{\mathrm{H}}}{115\,\mathrm{GeV}}\right)\right] 50\,\mathrm{GeV},
\end{aligned}
$$

- large novel Yukawa couplings ⇒ sizeable EW corrections depending strongly on heavy fermion masses
- work by LHC HIGGS XS WG ’12, Denner et al. [arXiv:1111.6395]

EW corrections to Higgs production in SM4

Passarino, Sturm, Uccirati ’11, LHC HIGGS XS WG ’12

relative (2-loop) EW corrections to $gg \to H$ in SM4



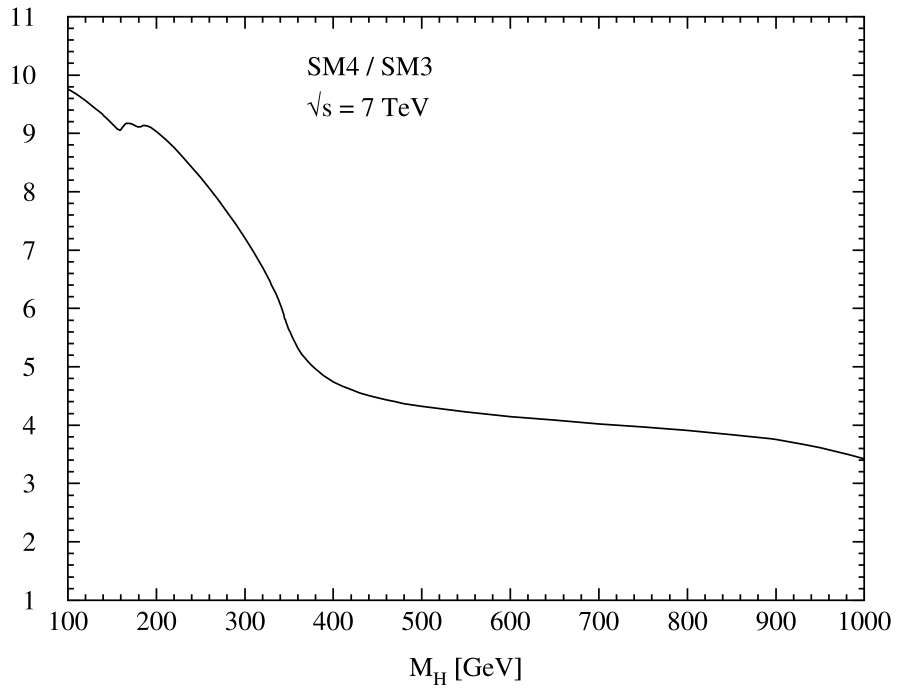
theoretical uncertainty $\sim 2\%$ for $M_{\rm H} < 600\,{\rm GeV}$

Higgs production cross section in SM4

assume factorization of EW and QCD corrections
(violation small Anastasiou, Boughezal, Petriello '08, non-factorizable EW effects $< 5\%$)

$$\sigma = \sigma^{\mathrm{LO}} \left(1 + \delta_{\mathrm{QCD}}\right) \left(1 + \delta_{\mathrm{EW}}\right)$$

ratio of Higgs production cross section via gluon fusion (SM4/SM3)
including NNLO QCD and NLO EW corrections



Denner et al. '11

LHC HIGGS XS WG '12

EW corrections to Higgs partial widths in SM4

enhanced Yukawa couplings ⇒ large EW corrections ⇒ large uncertainties

- $\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$: (PROPHECY4F) Denner, Dittmaier, Mück, Weber
  - NLO EW: -85%, $\delta_{\mathrm{EW}} \sim 2N_c X_A \left[-\frac{5}{6}(1+x) + \frac{x}{1-x}\ln x\right]$
    $x = m_B^2/m_A^2$, $X_A = G_\mu m_A^2/(8\sqrt{2}\pi^2)$ Chanowitz et al. '78
  - NNLO EW+QCD: $+15\%$ Kniehl '96; Djouadi, Gambino, Kniehl '97
  - uncertainty: $\sim 50\%$
- $\mathrm{H} \to f\bar{f}$:
  - NNNNLO QCD: $+20\%$
  - NLO EW: $+40\%$, $\delta_{\mathrm{EW}} \sim 2N_c X_A \left[\frac{7}{6}(1+x) + \frac{x}{1-x}\ln x\right]$
  - NNLO EW+QCD: $+20\%$ Kniehl '96; Djouadi, Gambino, Kniehl '97
    uncertainty: $\sim 10\%$
- $\mathrm{H} \to \mathrm{gg}$
  - NNNLO QCD: $+90\%$
  - NLO EW: as for $\mathrm{gg} \to \mathrm{H}$ Passarino, Sturm, Uccirati '11

EW corrections to Higgs decays in SM4

- $\mathrm{H} \to \gamma\gamma$ Passarino, Sturm, Uccirati '11
  - NLO EW: -320% for $M_{\mathrm{H}} = 100\,\mathrm{GeV}$
    large cancellations between W and f loops at LO $\Rightarrow$ square amplitude

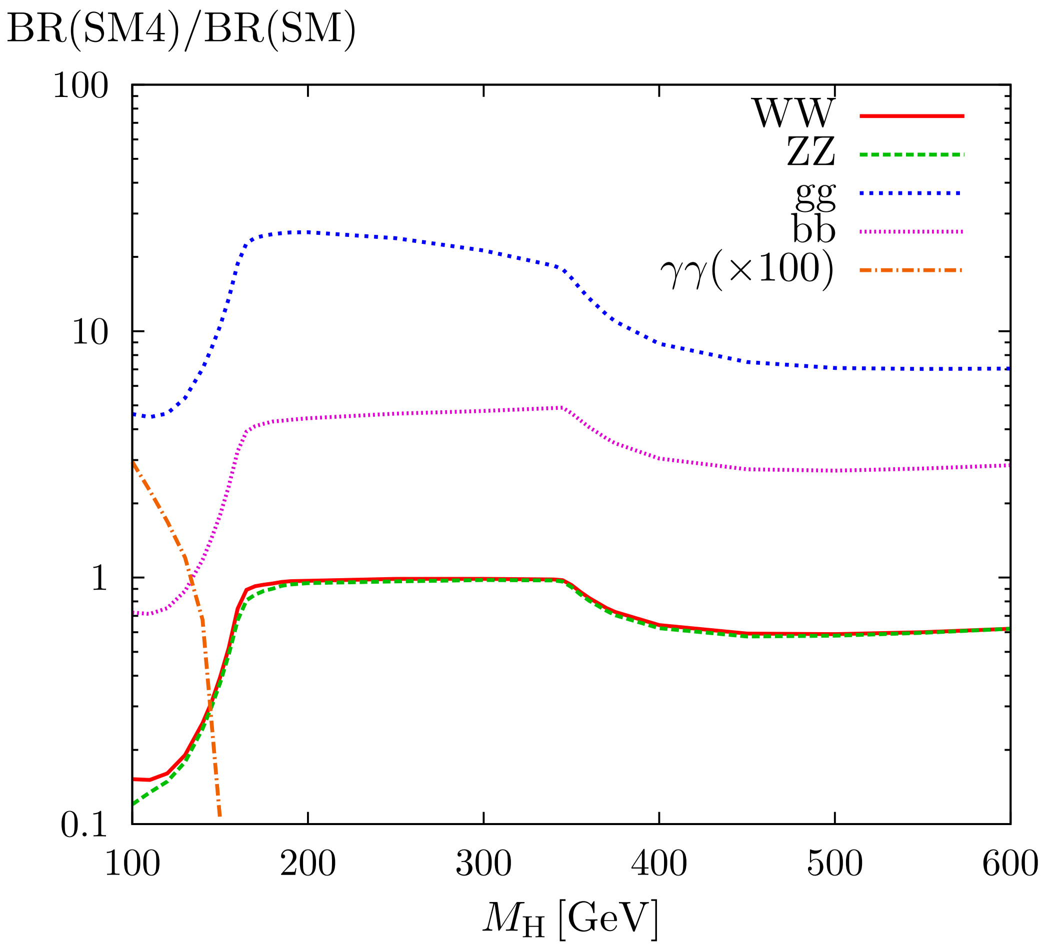
$$|A|^2 = |A_{\mathrm{LO}} + A_{\mathrm{NLO}}|^2 = |A_{\mathrm{LO}}|^2\,(1 + \delta_{\mathrm{EW}}^{(4)})$$

    $\Rightarrow$ NLO EW: -65% for $M_{\mathrm{H}} = 100\,\mathrm{GeV}$
  - uncertainty $\sim 14\%$

M_{H} [GeV]	$\delta_{\mathrm{EW}}^{(4)}$ $[\%]$	missing h.o. $[\%]$
100	-64.5	± 13.9
110	-74.4	± 13.9
120	-83.3	± 13.9
130	-90.8	$+13.9\,-9.2$
140	-96.6	$+13.9\,-3.4$
150	-99.7	$+13.9\,-0.3$

EW corrections to Higgs decays in SM4

Ratio of branching fractions SM4/SM3 for different channels



Conclusion

Conclusion

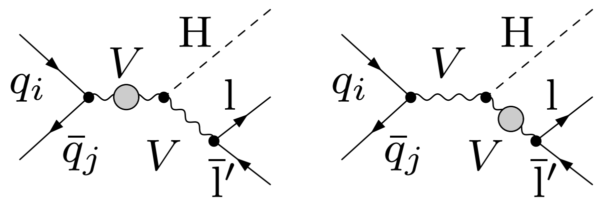
- Electroweak corrections to Higgs strahlung off W/Z bosons with decays
  - implemented in generator HAWK (new release in preparation)
    http://omnibus.uni-freiburg.de/sd565/programs/hawk/hawk.html
  - electroweak corrections of order 10%, larger for distributions
  - relative EW corrections (insensitive to PDFs)
    can be used to improve NNLO-QCD predictions assuming factorization
- SM Higgs branching ratios with theoretical uncertainties
  predictions for branching ratios including
  - parametric uncertainties from α_s, m_c, m_b, m_t
  - theoretical uncertainties from missing higher orders

  LHC Higgs Cross Section Working Group:
  https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections
- Higgs production and decay in SM4
  large masses of heavy fermions $\Rightarrow$ enhanced Yukawa couplings
  $\Rightarrow$ large EW corrections $\Rightarrow$ large uncertainties

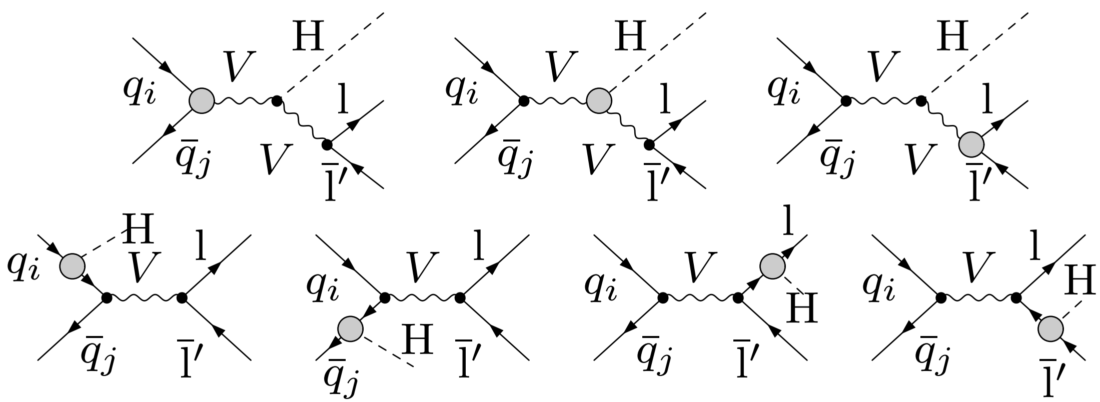
Backup

Classes of one-loop Feynman diagrams

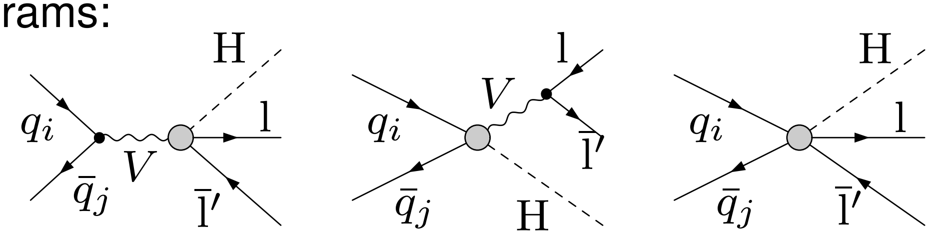
Self-energy diagrams:



Vertex diagrams:



Box and pentagon diagrams:



$\mathcal{O}(200)$ one-loop diagrams per tree diagram

Algebraic reduction of tensor integrals

For details see Denner, Dittmaier NPB734 (2006) 62 [hep-ph/0509141]

- 2-point integrals: numerically stable direct calculation
- 3-point and 4-point integrals: Passarino–Veltman reduction
  $\hookrightarrow$ inverse Gram determinants of up to three momenta
  $\hookrightarrow$ serious numerical instabilities where $\det G \to 0$
  (at phase-space boundary, but also within phase space !)

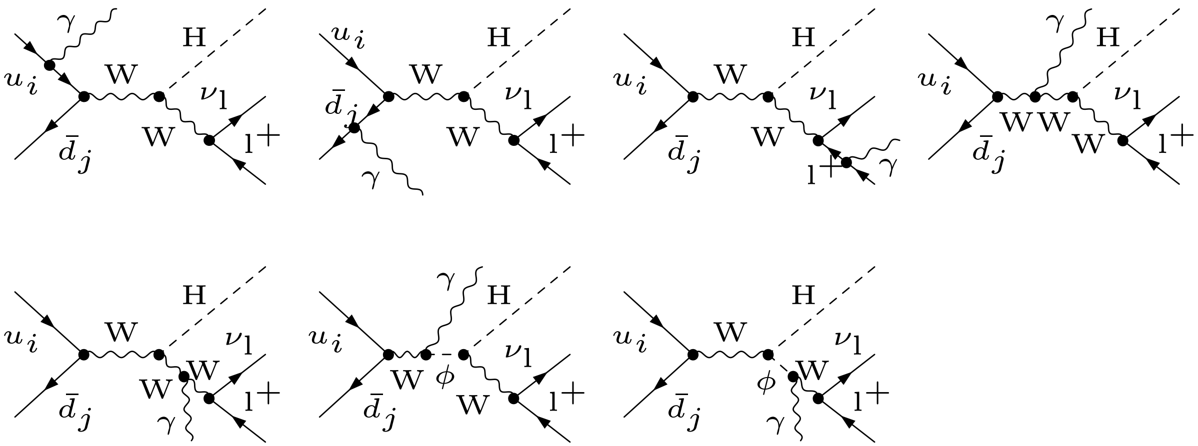
  two hybrid methods

  (i) Passarino–Veltman $\oplus$ expansions in small Gram and other kinematical determinants (see also Ellis et al. '05)

  (ii) Passarino–Veltman $\oplus$ analytical special cases
  $\oplus$ seminumerical method (in this calculation for checks only)
  (numerical calculation of logarithmic Feynman-parameter integral and algebraic reduction to this basis integral) (see also Binoth et al. '05, Ferroglia et al. '02)
- 5-point integrals $\to$ five 4-point integrals Melrose '65; Denner, Dittmaier '02, '05
  stable reduction without inverse Gram determinants

Real corrections

Feynman diagrams:



photon-induced processes:
diagrams obtained by crossing the photon into the initial state

matrix elements:
evaluated with Weyl-van der Waerden spinor technique Dittmaier ’99

Subtleties related to collinear singularities

- photonic initial-state radiation:
  coll. singularity absorbed by a redefinition of the PDFs in DIS scheme
  effect on PDFs at per-cent level at most Spiesberger '94
- collinear final-state radiation off leptons
  two different setups
  - inclusive: recombination with leptons $\Rightarrow$ IR-safe
  - exclusive: e.g. muons $\Rightarrow$ non-collinear safe $\Rightarrow$ logarithms of m_μ
    treated with appropriate subtraction formalism
    Dittmaier, Kabelschacht, Kasprzik '08
- photon-induced processes, $\gamma \to q\bar{q}^*/\bar{q}q^*$ splitting
  collinear singularities removed via redefinitions of quark PDFs
  evaluated with MRSTQED2004 PDF set Martin et al. '04
- photon-induced processes, $\gamma \to l\bar{l}^*/\bar{l}l^*$ splitting
  collinear singularity if charged leptons escape into the beam pipe
  collinear singularity cannot be absorbed in (lepton) pdf
  $\Rightarrow$ explict logarithm of lepton mass in corrections [$\log(m_\mathrm{e})$ for definiteness]

Cross section and corrections for Tevatron

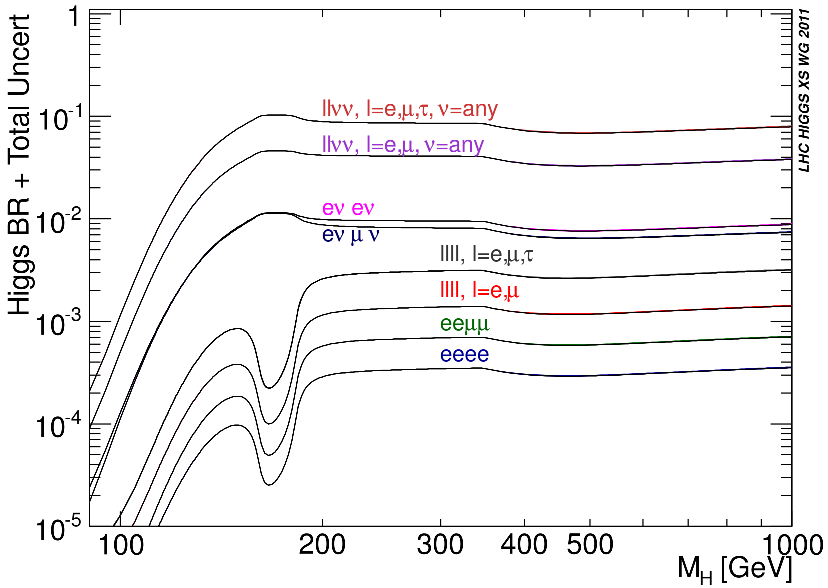
$M_{\mathrm{H}} = 120\,\mathrm{GeV}$

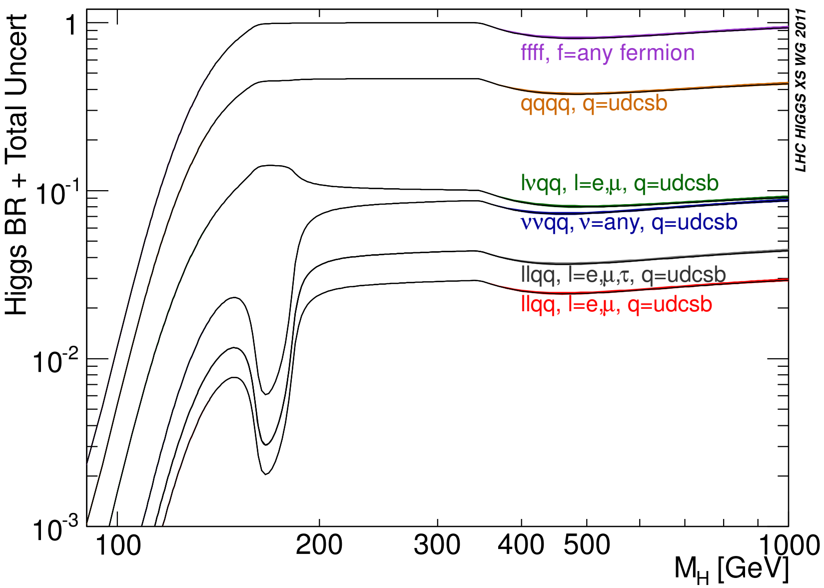
Denner, Dittmaier, Kallweit, Mück ’11

channel	$\mathrm{Hl}^+\nu_\mathrm{l} + X$	$\mathrm{Hl}^-\bar{\nu}_\mathrm{l} + X$	$\mathrm{Hl}^+\mathrm{l}^- + X$	$\mathrm{H}\nu_\mathrm{l}\bar{\nu}_\mathrm{l} + X$	$\mathrm{H}\nu_\mathrm{l}/\bar{\nu}_\mathrm{l} + X$
σ_0/ fb	4.1232(2)	4.1229(2)	1.82773(5)	4.1480(1)	1.6063(2)
σ^{LO}/ fb	3.6930(5)	3.6926(5)	1.6484(1)	3.7476(4)	1.4355(4)
$\delta_{\mathrm{EW}}^{\mathrm{bare}}$/%	−7.8	−7.8	−7.2	−4.1	−0.9
$\delta_{\mathrm{EW}}^{\mathrm{rec}}$/%	−7.3	−7.3	−6.3	−4.1	−3.5
δ_{QCD}/%	+24.9	+24.9	+24.6	+24.9	+25.1
$(K_{\mathrm{QCD}} - 1)$/%	+39.5	+39.5	+38.1	+38.2	+40.0
δ_γ/%	+0.3	+0.3	+0.0	−0.0	+1.0
$\sigma_{\mathrm{fact}}^{\mathrm{NLO}}$/ fb	4.7884(5)	4.7872(5)	2.1332(1)	4.9696(3)	1.9566(4)
$\sigma_{\mathrm{HAWK}}^{\mathrm{NLO}}$/ fb	4.8635(5)	4.8622(5)	2.1616(1)	5.0115(3)	1.9706(4)

Results for SM 4f branching ratios

LHC HIGGS XS WG '12, Denner et al. '11





SM Higgs branching ratios with uncertainties

Channel	M_H [GeV]	BR	Δm_c	Δm_b	Δm_t	$\Delta \alpha_s$	PU	THU	Total
$H \to b\bar{b}$	120	6.48E-01	−0.2% +0.2%	+1.1% −1.2%	+0.0% −0.0%	−1.0% +0.9%	+1.5% −1.5%	+1.3% −1.3%	+2.8% −2.8%
	150	1.57E-01	−0.1% +0.1%	+2.7% −2.7%	+0.1% −0.1%	−2.2% +2.1%	+3.4% −3.5%	+0.6% −0.6%	+4.0% −4.0%
	200	2.40E-03	−0.0% +0.0%	+3.2% −3.2%	+0.0% −0.1%	−2.5% +2.5%	+4.1% −4.1%	+0.5% −0.5%	+4.6% −4.6%
	500	1.09E-04	−0.0% +0.0%	+3.2% −3.2%	+0.1% −0.1%	−2.8% +2.8%	+4.3% −4.3%	+3.0% −1.1%	+7.2% −5.4%
$H \to \tau^+\tau^-$	120	7.04E-02	−0.2% +0.2%	−2.0% +2.1%	+0.1% −0.1%	+1.4% −1.3%	+2.5% −2.4%	+3.6% −3.6%	+6.1% −6.0%
	150	1.79E-02	−0.1% +0.1%	−0.5% +0.5%	+0.1% −0.1%	+0.3% −0.3%	+0.6% −0.6%	+2.5% −2.5%	+3.0% −3.1%
	200	2.87E-04	−0.0% +0.0%	−0.0% +0.0%	+0.0% −0.1%	+0.0% −0.0%	+0.0% −0.1%	+2.5% −2.5%	+2.5% −2.6%
	500	1.53E-05	−0.0% +0.0%	−0.0% +0.0%	+0.1% −0.1%	−0.1% +0.0%	+0.1% −0.1%	+5.0% −3.1%	+5.0% −3.2%
$H \to \mu^+\mu^-$	120	2.44E-04	−0.2% +0.2%	−2.0% +2.1%	+0.1% −0.1%	+1.4% −1.3%	+2.5% −2.5%	+3.9% −3.9%	+6.4% −6.3%
	150	6.19E-05	−0.0% +0.0%	−0.5% +0.5%	+0.1% −0.1%	+0.3% −0.3%	+0.6% −0.6%	+2.5% −2.5%	+3.1% −3.2%
	200	9.96E-07	−0.0% −0.0%	−0.0% +0.0%	+0.1% −0.1%	+0.0% −0.0%	+0.1% −0.1%	+2.5% −2.5%	+2.6% −2.6%
	500	5.31E-08	−0.0% +0.0%	−0.0% +0.0%	+0.1% −0.1%	−0.0% +0.0%	+0.1% −0.1%	+5.0% −3.1%	+5.1% −3.1%
$H \to c\bar{c}$	120	3.27E-02	+6.0% −5.8%	−2.1% +2.2%	+0.1% −0.1%	−5.8% +5.6%	+8.5% −8.5%	+3.8% −3.7%	+12.2% −12.2%
	150	7.93E-03	+6.2% −6.0%	−0.6% +0.6%	+0.1% −0.1%	−6.9% +6.8%	+9.2% −9.2%	+0.6% −0.6%	+9.7% −9.7%
	200	1.21E-04	+6.2% −6.1%	−0.2% +0.1%	+0.1% −0.2%	−7.2% +7.2%	+9.5% −9.5%	+0.5% −0.5%	+10.0% −10.0%
	500	5.47E-06	+6.2% −6.0%	−0.1% +0.1%	+0.1% −0.1%	−7.6% +7.6%	+9.8% −9.7%	+3.0% −1.1%	+12.8% −10.7%
$H \to t\bar{t}$	350	1.56E-02	+0.0% +0.0%	−0.0% +0.0%	−78.6% +120.9%	+0.9% −0.9%	+120.9% −78.6%	+6.9% −12.7%	+127.8% −91.3%
	360	5.14E-02	−0.0% −0.0%	−0.0% +0.0%	−36.2% +35.6%	+0.7% −0.7%	+35.6% −36.2%	+6.6% −12.2%	+42.2% −48.4%
	400	1.48E-01	+0.0% +0.0%	−0.0% +0.0%	−6.8% +6.2%	+0.4% −0.3%	+6.2% −6.8%	+5.9% −11.1%	+12.2% −17.8%
	500	1.92E-01	−0.0% +0.0%	−0.0% +0.0%	−0.3% +0.1%	+0.1% −0.2%	+0.1% −0.3%	+4.5% −9.5%	+4.6% −9.8%

SM Higgs branching ratios with uncertainties

Channel	M_H [GeV]	BR	Δm_c	Δm_b	Δm_t	$\Delta\alpha_s$	PU	THU	Total
$H \to gg$	120	8.82E-02	−0.2% +0.2%	−2.2% +2.2%	−0.2% +0.2%	+5.7% −5.4%	+6.1% −5.8%	+4.5% −4.5%	+10.6% −10.3%
	150	3.46E-02	−0.1% +0.1%	−0.7% +0.6%	−0.3% +0.3%	+4.4% −4.2%	+4.4% −4.3%	+3.5% −3.5%	+7.9% −7.8%
	200	9.26E-04	−0.0% −0.0%	−0.1% +0.1%	−0.6% +0.6%	+3.9% −3.8%	+3.9% −3.9%	+3.7% −3.7%	+7.6% −7.6%
	500	6.04E-04	−0.0% +0.0%	−0.0% +0.0%	+1.6% −1.6%	+3.4% −3.3%	+3.7% −3.7%	+6.2% −4.3%	+9.9% −7.9%
$H \to \gamma\gamma$	120	2.23E-03	−0.2% +0.2%	−2.0% +2.1%	+0.0% +0.0%	+1.4% −1.3%	+2.5% −2.4%	+2.9% −2.9%	+5.4% −5.3%
	150	1.37E-03	+0.0% +0.1%	−0.5% +0.5%	+0.1% −0.0%	+0.3% −0.3%	+0.6% −0.6%	+1.6% −1.5%	+2.1% −2.1%
	200	5.51E-05	−0.0% −0.0%	−0.0% +0.0%	+0.1% −0.1%	+0.0% −0.0%	+0.1% −0.1%	+1.5% −1.5%	+1.6% −1.6%
	500	3.12E-07	−0.0% +0.0%	−0.0% +0.0%	+8.0% −6.5%	−0.7% +0.7%	+8.0% −6.6%	+4.0% −2.1%	+11.9% −8.7%
$H \to Z\gamma$	120	1.11E-03	−0.3% +0.2%	−2.1% +2.1%	+0.0% −0.1%	+1.4% −1.4%	+2.5% −2.5%	+6.9% −6.8%	+9.4% −9.3%
	150	2.31E-03	−0.1% +0.0%	−0.6% +0.5%	+0.0% −0.1%	+0.2% −0.3%	+0.5% −0.6%	+5.5% −5.5%	+6.0% −6.2%
	200	1.75E-04	−0.0% −0.0%	−0.0% +0.0%	+0.0% −0.1%	+0.0% −0.0%	+0.0% −0.1%	+5.5% −5.5%	+5.5% −5.6%
	500	7.58E-06	−0.0% +0.0%	−0.0% +0.0%	+0.8% −0.6%	−0.0% +0.0%	+0.8% −0.6%	+8.0% −6.1%	+8.7% −6.7%
$H \to WW$	120	1.41E-01	−0.2% +0.2%	−2.0% +2.1%	−0.0% +0.0%	+1.4% −1.4%	+2.5% −2.5%	+2.2% −2.2%	+4.8% −4.7%
	150	6.96E-01	−0.1% +0.1%	−0.5% +0.5%	−0.0% +0.0%	+0.3% −0.3%	+0.6% −0.6%	+0.3% −0.3%	+0.9% −0.8%
	200	7.41E-01	−0.0% −0.0%	−0.0% +0.0%	−0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%
	500	5.46E-01	−0.0% +0.0%	−0.0% +0.0%	+0.1% −0.0%	−0.0% +0.0%	+0.1% −0.1%	+2.3% −1.1%	+2.4% −1.1%
$H \to ZZ$	120	1.59E-02	−0.2% +0.2%	−2.0% +2.1%	−0.0% +0.0%	+1.4% −1.4%	+2.5% −2.5%	+2.2% −2.2%	+4.8% −4.7%
	150	8.25E-02	−0.1% +0.1%	−0.5% +0.5%	+0.0% +0.0%	+0.3% −0.3%	+0.6% −0.6%	+0.3% −0.3%	+0.9% −0.8%
	200	2.55E-01	−0.0% +0.0%	−0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%
	500	2.61E-01	+0.0% −0.0%	−0.0% +0.0%	+0.0% +0.0%	−0.0% +0.0%	+0.1% −0.0%	+2.3% −1.1%	+2.3% −1.1%