Matrix element/NLO calculations

Ansgar Denner, Würzburg

Terascale Monte Carlo School 2014

DESY, Hamburg, March 10–14, 2014

- Lecture 1: Relevance and calculation of NLO QCD corrections
- Lecture 2: Relevance and calculation of NLO electroweak corrections
- Lecture 3: NLO Calculations for Higgs Physics

NLO calculations for Higgs Physics

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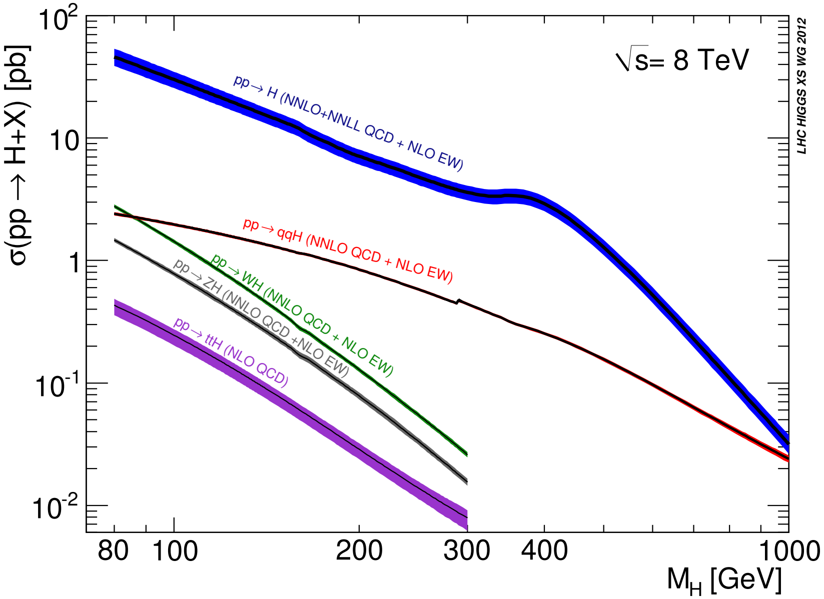
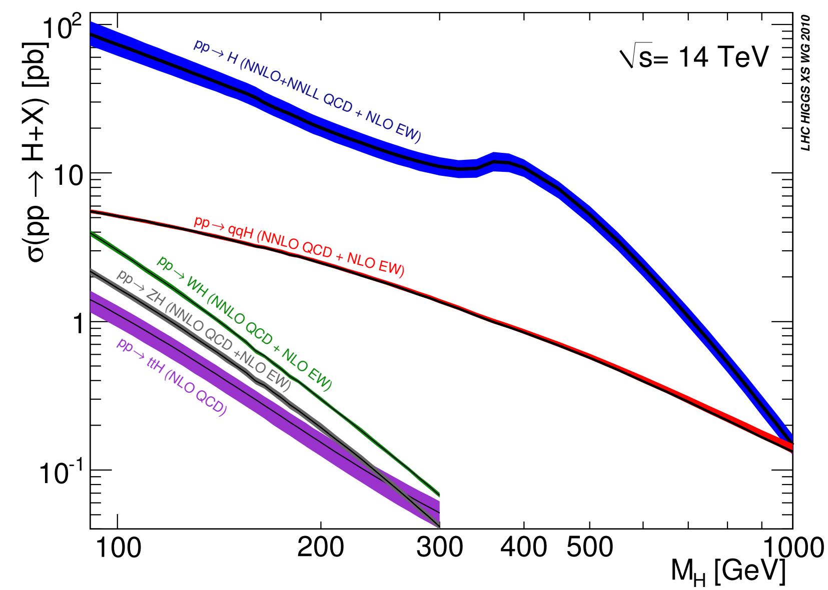
- Higgs-production processes
  - Higgs production via vector-boson fusion
  - Higgs production in association with vector bosons
  - Higgs production in gluon fusion
- Higgs-boson decays

Higgs-production processes

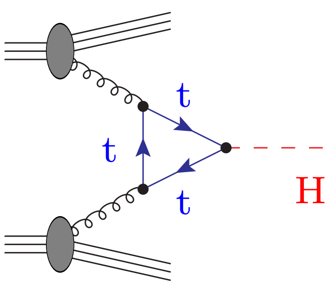
LHC HIGGS XS WG '10/12

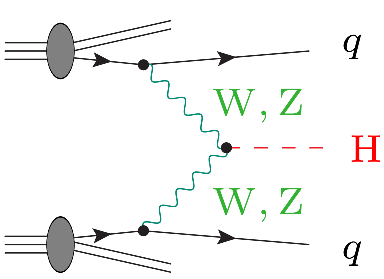


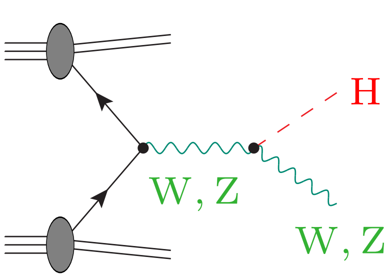


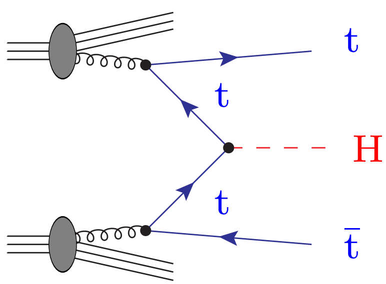
for $M_\mathrm{H} \sim 125\,\mathrm{GeV}$ cross sections relative to $8\,\mathrm{TeV}$ are enhanced by factor

2.6 2.6 2.1 4.7 for $14\,\mathrm{TeV}$



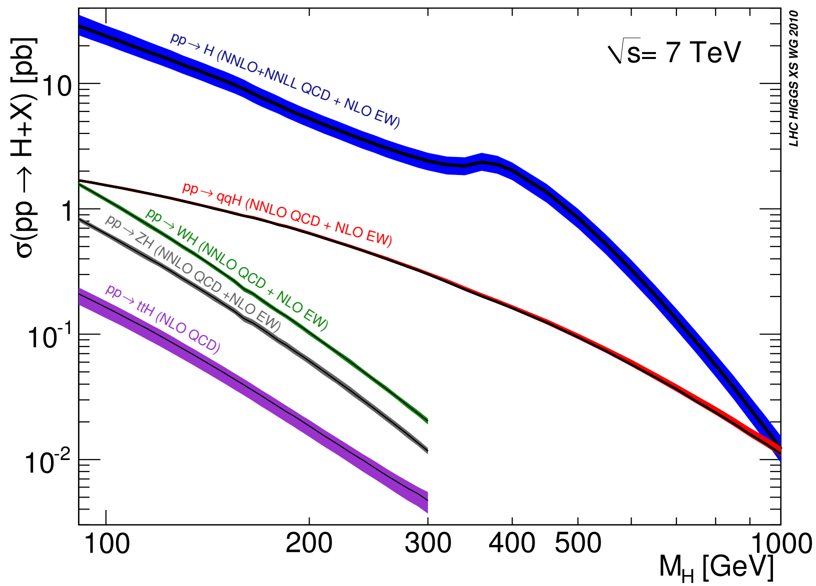


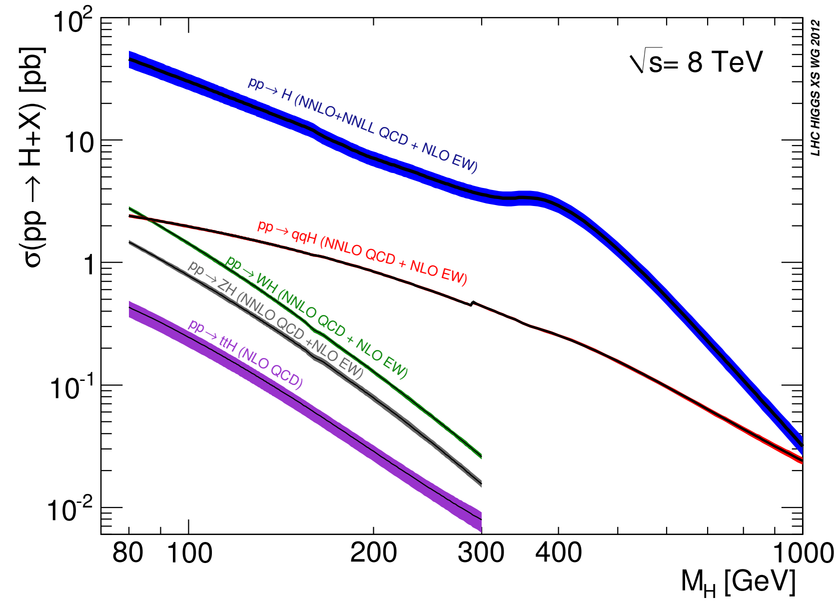




Higgs production cross sections at the LHC

LHC HIGGS XS WG '10/12

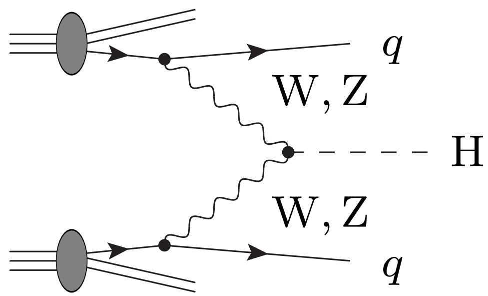




- Gluon fusion $\mathrm{pp} \to \mathrm{H}$
  dominant production mode
- Vector-boson fusion $\mathrm{pp} \to \mathrm{H}qq$
  characteristic signature, measurement of HWW and HZZ couplings
- Higgs-strahlung $\mathrm{pp} \to \mathrm{H}V$,
  measurement of HWW and HZZ couplings
- Associated production $\mathrm{pp} \to \mathrm{t\bar{t}H}$
  measurement of top-Yukawa coupling

Higgs production via vector-boson fusion

Process topology of Higgs production via VBF

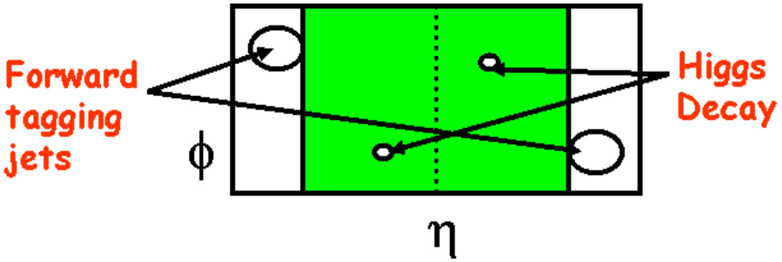


process dominated by t- and u-channel diagrams

$\Rightarrow$ t-channel approximation (DIS-like)

dominant contribution has two forward jets $\Rightarrow$ tags

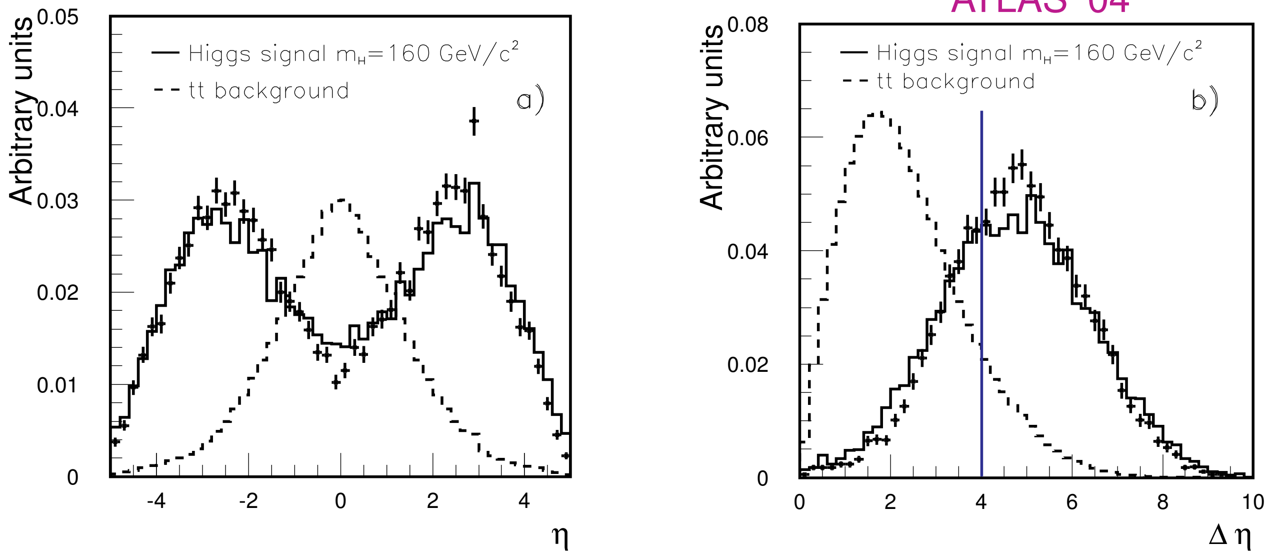
signature $=$ Higgs + 2 jets



VBF cuts and background suppression:

- 2 hard "tagging" jets demanded:
  $p_{\mathrm{Tj}} > 20\,\mathrm{GeV}, \quad |y_{\mathrm{j}}| < 4.5$
- tagging jets forward–backward directed:
  $\Delta y_{\mathrm{jj}} > 4, \quad y_{\mathrm{j}_1} \cdot y_{\mathrm{j}_2} < 0$

ATLAS '04

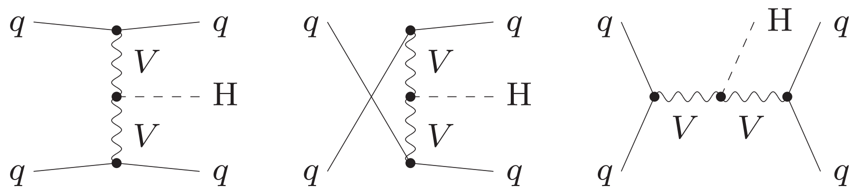


$$\eta = -\ln \tan\left(\frac{\theta}{2}\right) \sim y$$

Details of the NLO calculation for H + 2 jets

EW production of Higgs+2 jets in LO

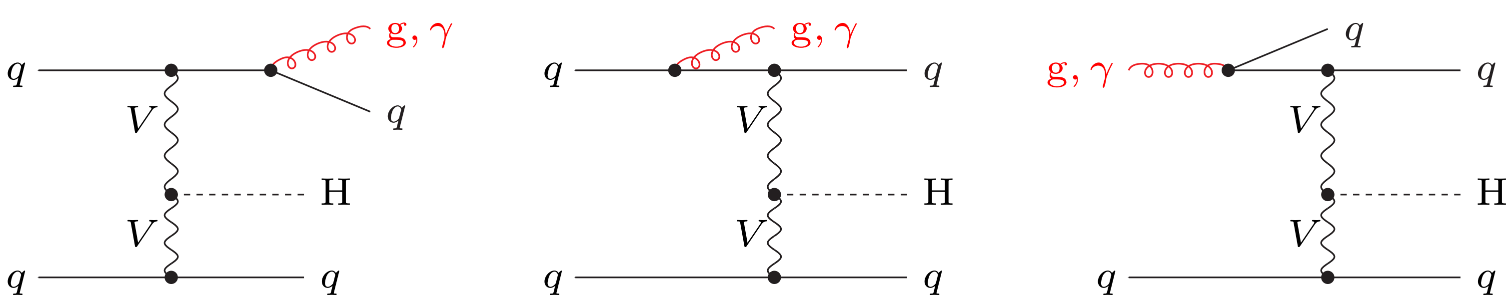
- many subcontributions from qq, $q\bar{q}$, and $\bar{q}\bar{q}$ channels ($q = \mathrm{u, d, c, s, b}$)
- each channel receives contributions from one or two topologies ("t, u, s"):



different channels related by crossing $\qquad V = \mathrm{W, Z}$

EW production of Higgs+2 jets in NLO

- partonic channels for
  - one-loop diagrams: qq, $q\bar{q}$, $\bar{q}\bar{q}$ $\qquad$ ($\mathcal{O}(200)$ diagrams per tree diagram)
  - real QCD corrections qq, $q\bar{q}$, $\bar{q}\bar{q}$ (gluon emission), $\quad qg$, $\bar{q}g$ (gluon induced)
  - real QED corrections qq, $q\bar{q}$, $\bar{q}\bar{q}$ (photon emission), $\quad q\gamma$, $\bar{q}\gamma$ (photon induced)



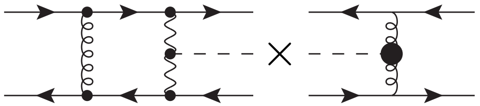
Status of predictions to Higgs+2 jets production

- NLO QCD corrections to VBF in "t-channel approximation" (DIS-like)
  - total cross section — Han, Valencia, Willenbrock '92; Spira '98; Djouadi, Spira '00
  - realistic cuts, distributions — Figy, Oleari, Zeppenfeld '03; Berger, Campbell '04
  - matching with parton shower (POWHEG, MC@NLO) — Nason, Oleari '09; Frixione, Torielli, Zaro, '13
- NLO QCD corrections to gluon-initiated channels — Campbell, R.K.Ellis, Zanderighi '06
  - contribution to VBF $\sim\ 5\%$ (NLO scale uncertainty $\sim 35\%$) — Nikitenko, Vázquez Acosta '07
  - matching with parton shower (POWHEG) — Ellis, Campbell, Frederix '12
- complete NLO QCD+EW corrections to VBF — Ciccolini, Denner, Dittmaier '07 (HAWK); Figy, Palmer, Weiglein '10 (VBF@NLO)

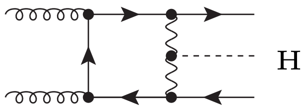
  $\hookrightarrow$ NLO QCD $\sim$ NLO EW $\sim\ 5{-}10\%$
- NNLO QCD corrections to VBF in DIS-like approximation (total cross section) — Bolzoni, Maltoni, Moch, Zaro '10,'11

  $\hookrightarrow$ NNLO QCD $\sim\ 1{-}2\%$ for scales $\mathcal{O}(M_\mathrm{W})$ (VBF@NNLO)
- QCD loop-induced interferences between VBF and gluon-fusion channels

  impact $\lesssim\ 10^{-3}\ \%$

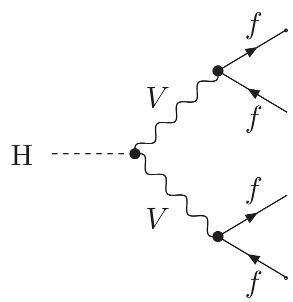
  Andersen, Binoth, Heinrich, Smillie '07; Bredenstein, Hagiwara, Jäger '08
- loop-induced VBF in gg scattering — Harlander, Vollinga, Weber '08

  $\hookrightarrow$ impact $\sim 0.1\%$

Survey of Feynman diagrams for H + 2 jets

Lowest order:

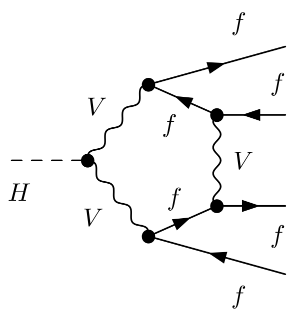


$V = W, Z$

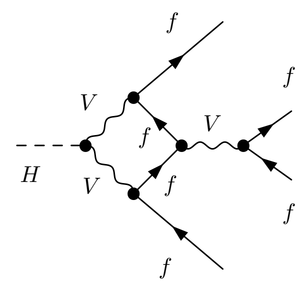
typical one-loop diagrams:

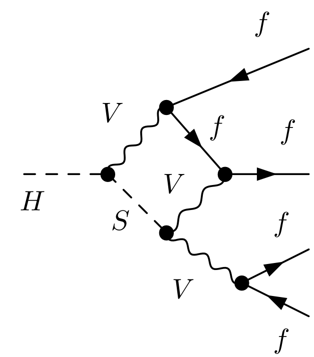
diagrams = $\mathcal{O}(200)$ per tree diagram

6/8 pentagons

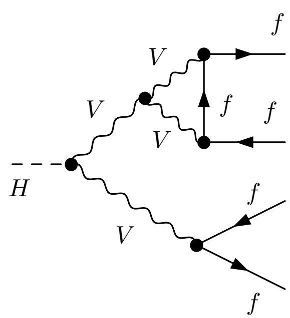


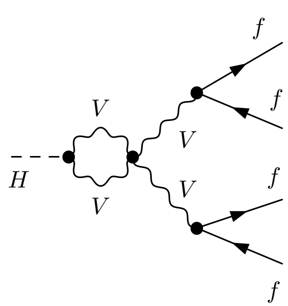
14/24 boxes



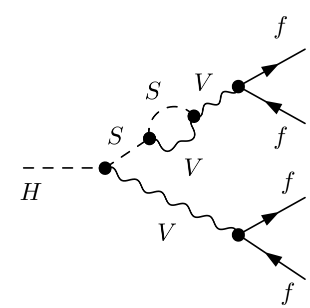


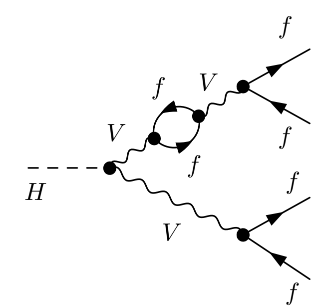
vertices





self-energies





$+$ tree graphs with real photons and gluons

Calculation of virtual corrections for H + 2 jets

Calculation based on Feynman diagrams   Ciccolini, Denner, Dittmaier '07

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 FormCalc
  Hahn, Perez-Victoria '99, Hahn '00
- automatic translation into *Fortran* code
- reduction of tensor integrals according to
  Denner, Dittmaier, NPB658 (2003)175 [hep-ph/0212259], NPB734 (2006) 62 [hep-ph/0509141]
  $\hookrightarrow$ numerically stable results
- scalar integrals with complex masses
  't Hooft, Veltman '79; Denner, Dittmaier '10

Input parameter scheme: G_μ scheme, α_{G_μ}
(process dominated by diagrams with internal W bosons)

Set-up for numerical calculation of H + 2 jets

Definition of observables

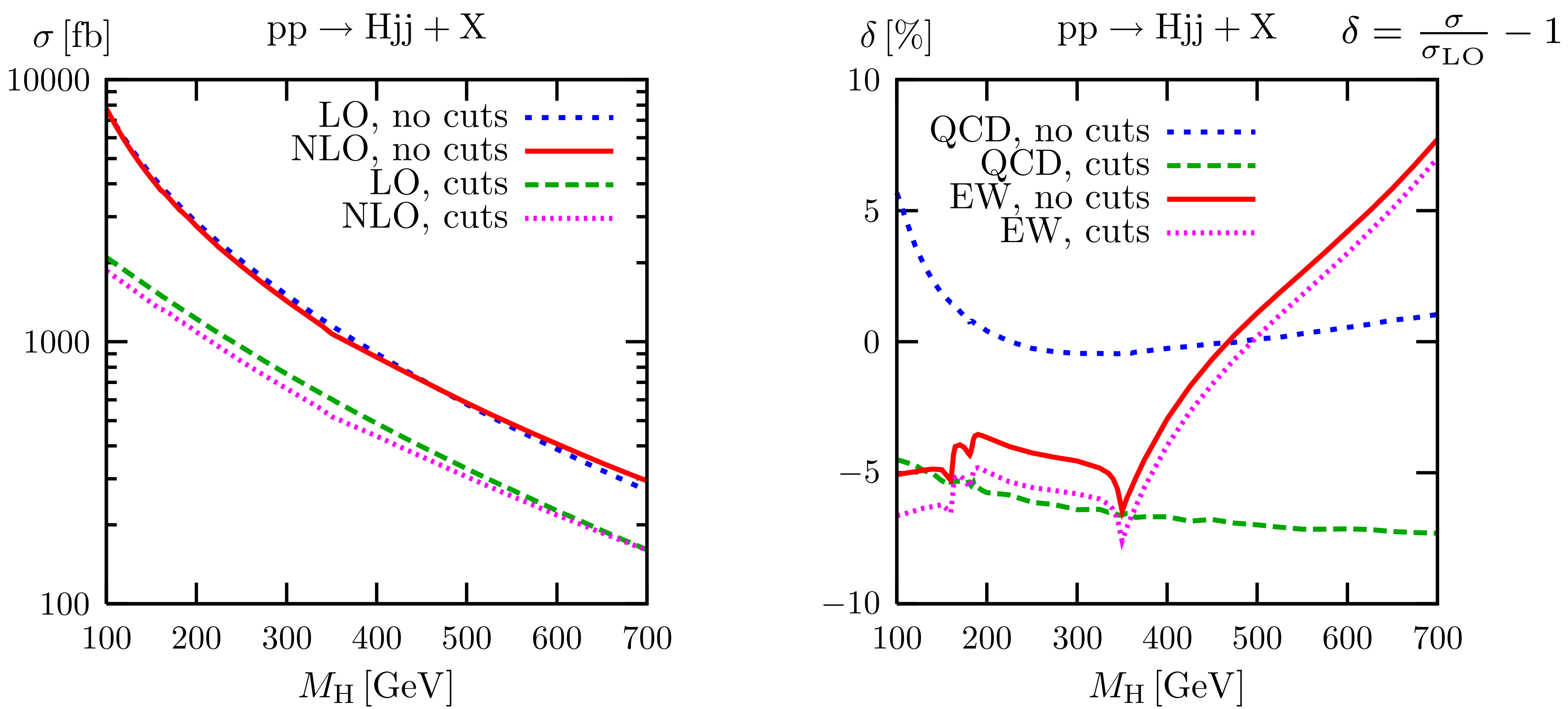
- jet definition: k_{T} algorithm as used at Tevatron run II Blazey et al. '00
  $\hookrightarrow$ clusters partons with $|\eta| < 5$ into jets with jet resolution $D = 0.8$
  photons included in clustering
- VBF cuts: following Figy, Zeppenfeld '04
  - 2 hard "tagging" jets demanded: $p_{\mathrm{Tj}_1} > p_{\mathrm{Tj}_2} > 20\,\mathrm{GeV}$, $|y_{\mathrm{j}1,2}| < 4.5$
  - tagging jets forward–backward directed: $|y_{\mathrm{j}_1} - y_{\mathrm{j}_2}| > 4$, $y_{\mathrm{j}_1} \cdot y_{\mathrm{j}_2} < 0$
  - no cuts on Higgs momentum (should be adjusted to specific decays)

NLO settings:

- central scales: $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = M_{\mathrm{W}}$
- PDFs: MRST2004QED which includes QED corrections and γ PDF
  with $\alpha_{\mathrm{S}}(M_{\mathrm{Z}}) = 0.1187$
- $\alpha_{\mathrm{s}}(\mu_{\mathrm{R}})$ with 5 active flavours (top-quark decoupled) and two-loop running
- α defined in G_μ scheme: $\alpha_{G_\mu} = \sqrt{2} G_\mu M_{\mathrm{W}}^2 (1 - M_{\mathrm{W}}^2/M_{\mathrm{Z}}^2)/\pi$
  $\hookrightarrow$ absorbs running of α from $Q = 0$ to EW scale and $\Delta\rho$ in $Wq\bar{q}'$ coupling

NLO QCD+EW corrections

Ciccolini, Denner, Dittmaier '07 (HAWK)

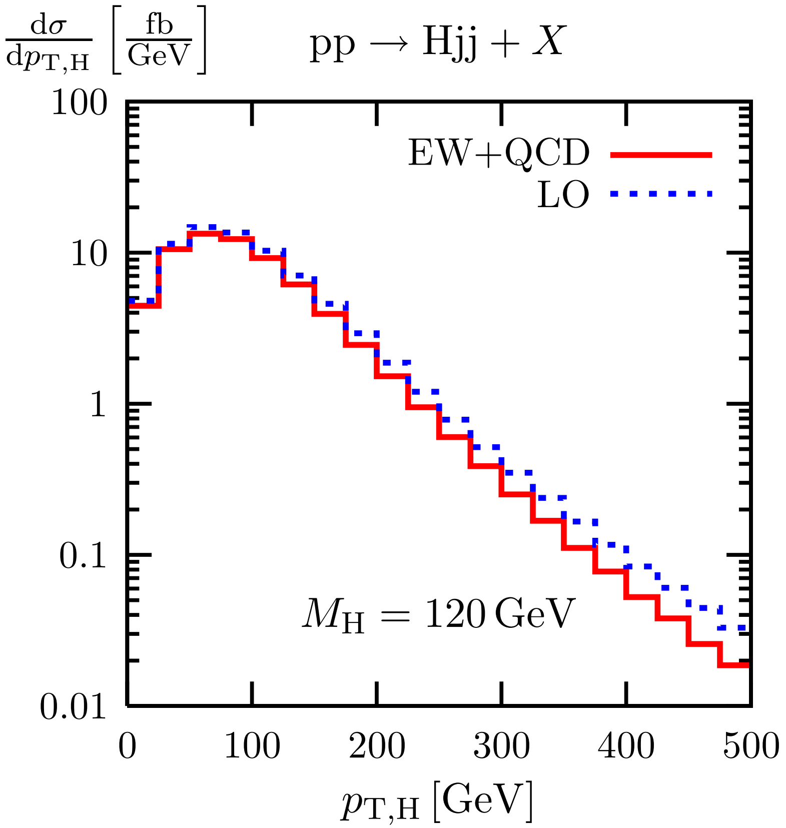


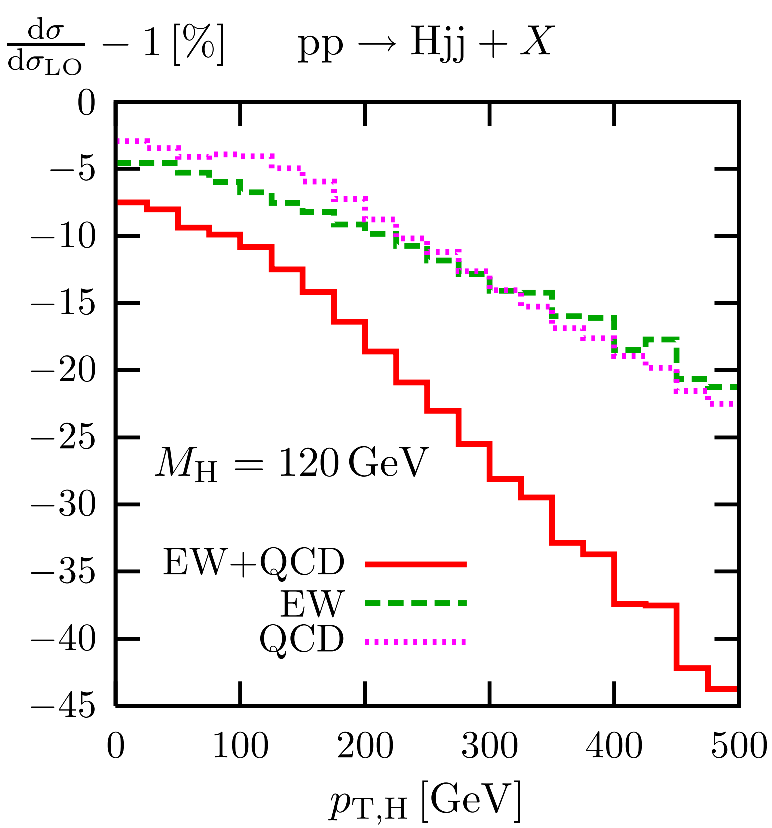
- QCD and EW corrections of same generic size ($\sim 5\%$)
  $M_{\rm H} = 126\,{\rm GeV}$: $\delta_{\rm EW} = -7\%/-5\%$ with/without cuts
  $\delta_{\rm QCD} = -5\%/+3\%$ with/without cuts (strongly depending on PDFs)
- scale uncertainty $\sim$ 2–3% within $M_{\rm W}/2 < \mu_{\rm R/F} < 2M_{\rm W}$ in NLO ($\sim 10\%$ in LO)
- corrections $\propto M_{\rm H}^2$: breakdown of perturbation theory for $M_{\rm H} \sim 700\,{\rm GeV}$

Transverse momentum of Higgs boson

VBF cuts

Ciccolini, Denner, Dittmaier '07 (HAWK)



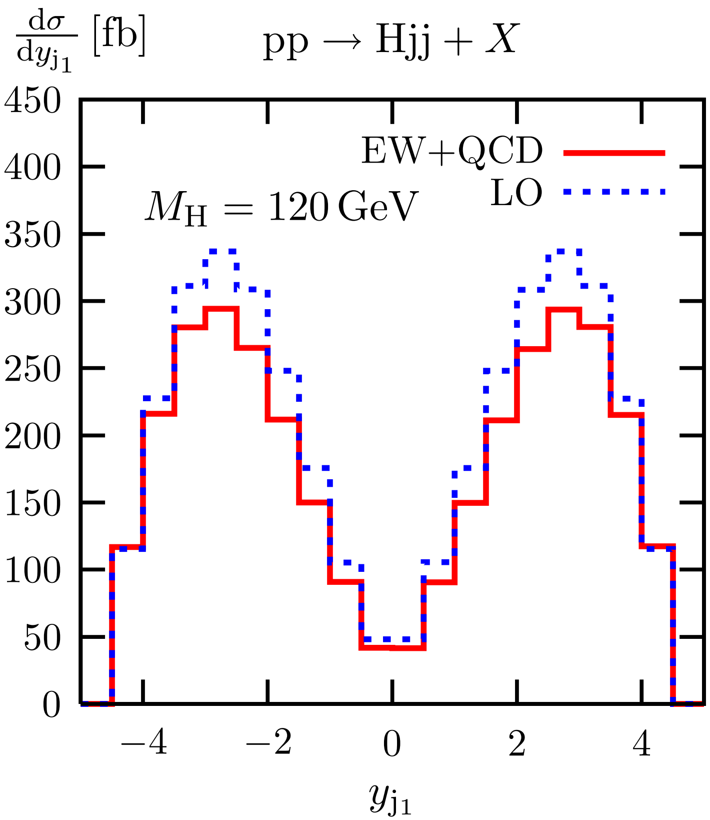


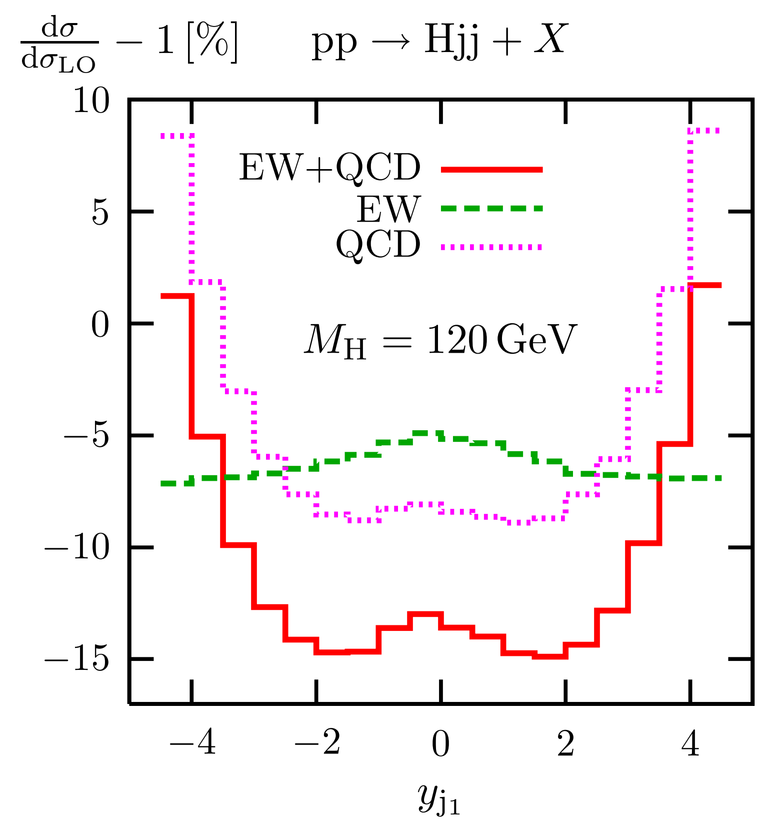
- EW and QCD corrections similar
- both distort shape of distribution
- EW corrections -20% at $p_{T,H} = 500\,\mathrm{GeV}$, from electroweak logarithms!

Rapidity of the harder tagging jet

VBF cuts

Ciccolini, Denner, Dittmaier ’07 (HAWK)



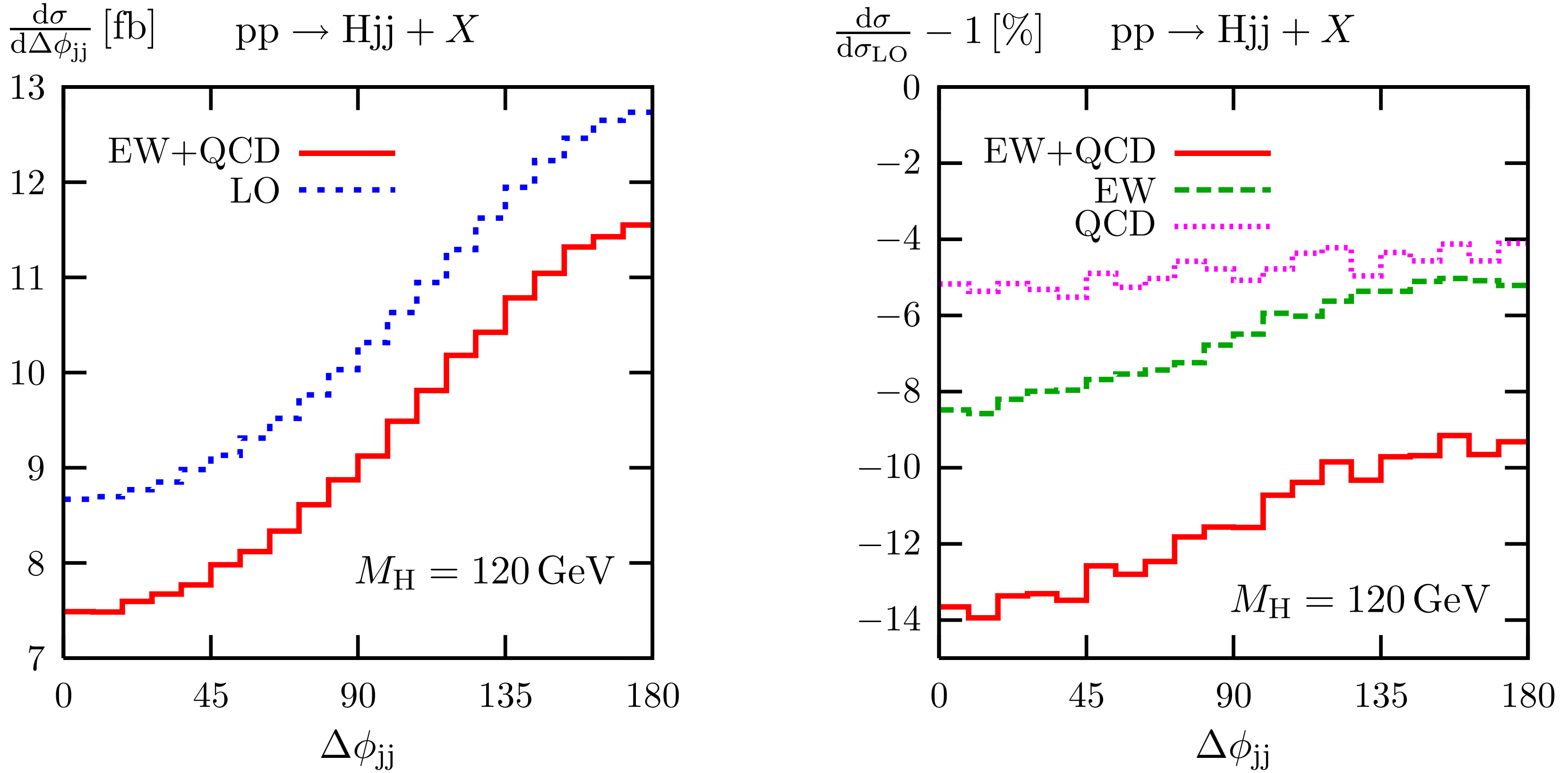


- tagging jets forward–backward
- QCD corrections distort shape significantly
- EW corrections depend only weakly on rapidity y_{j_1} $(-4\% - -7\%)$

Azimuthal angle separation of tagging jets

VBF cuts

Ciccolini, Denner, Dittmaier '07 (HAWK)



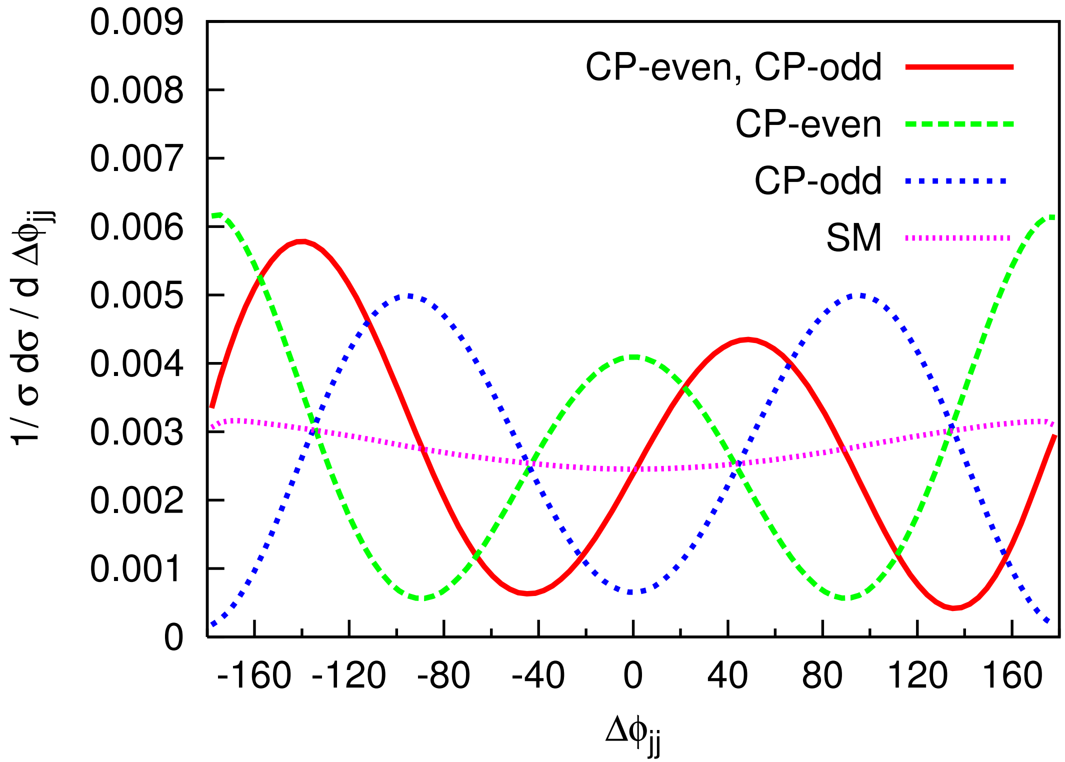
distribution in $\Delta\phi_{jj}$ sensitive to non-standard HVV couplings Figy, Zeppenfeld '04

EW corrections yield distortion of distribution by 4%

WWH and ZZH coupling analyses

azimuthal angle difference $\Delta\phi_{\mathrm{jj}}$ of the tagging jets is sensitive to BSM effects

Hankele, Klämke, Zeppenfeld, Figy '06
Ruwiedel, Schumacher, Wermes '07



Individual contributions without SM,
$M_{\mathrm{H}} = 120\,\mathrm{GeV}$
plot from Hankele et al.

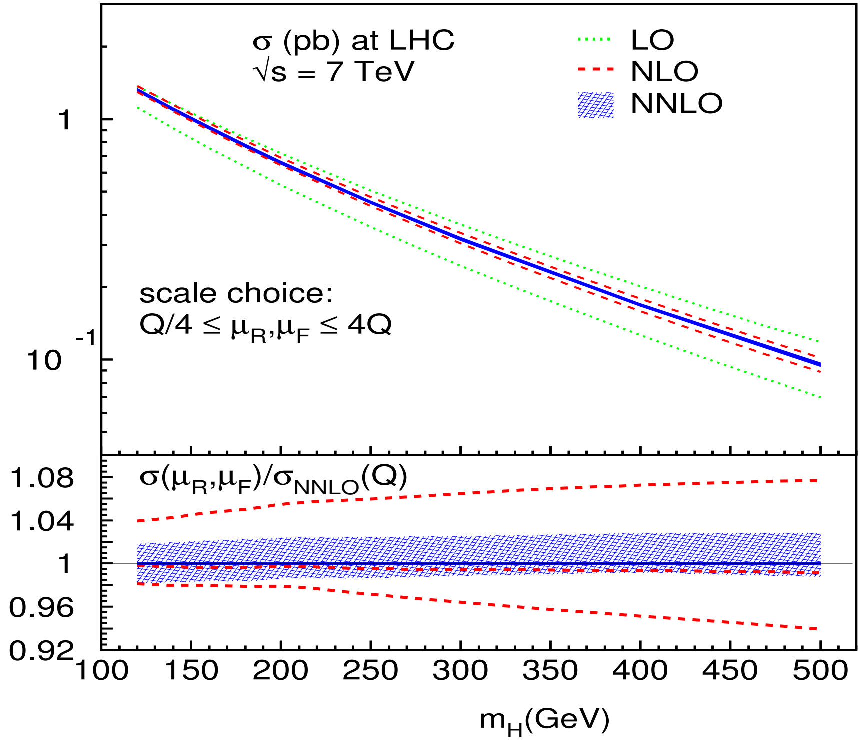
CP-even: $\mathcal{L} \propto HW^{+}_{\mu\nu}W^{-,\mu\nu}, \qquad \Gamma^{HW^+W^-}_{\mu\nu} \propto g_{\mu\nu}(k_+k_-) - k_{+,\nu}k_{-,\mu}$

CP-odd: $\mathcal{L} \propto H\tilde{W}^{+}_{\mu\nu}W^{-,\mu\nu}, \qquad \Gamma^{HW^+W^-}_{\mu\nu} \propto \epsilon_{\mu\nu\rho\sigma}k^{\rho}_{+}k^{\sigma}_{-}$

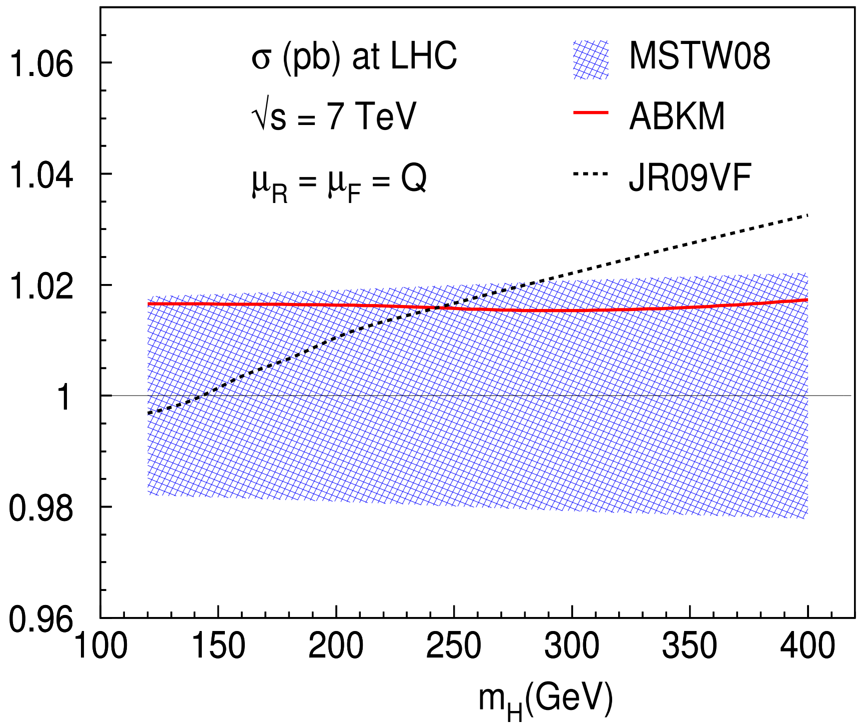
NNLO QCD corrections to total VBF cross section

Bolzoni, Maltoni, Moch, Zaro '10

Scale uncertainty



PDF uncertainty (68% C.L.)



Results for total cross section at LHC:

- NNLO QCD corrections $\sim 1\%$ with scale $Q =$ virtuality of W/Z $= \mathcal{O}(M_\mathrm{W})$
- scale uncertainty $\lesssim$ PDF uncertainty $\sim 2\%$ (MSTW2008NNLO)

Best prediction and theoretical uncertainties

Combination of NNLO QCD corrections with NLO EW corrections for total inclusive cross section based on assumption of complete factorization LHC HIGGS XS WG ’13

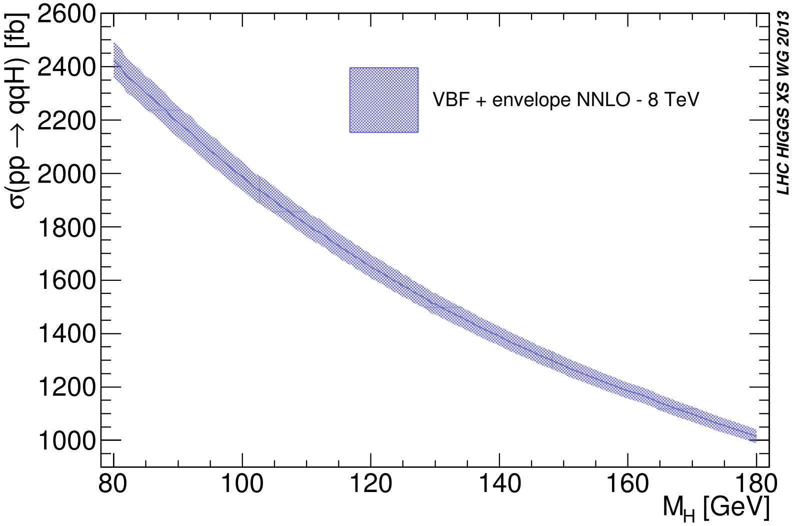
$$\sigma = \sigma_{\mathrm{NNLO}}(1+\delta_{\mathrm{EW}})$$

- NNLO QCD cross section σ_{NNLO} from VBF@NNLO Bolzoni et al.
- relative NLO EW corrections δ_{EW} from HAWK Ciccolini et al.

Theoretical uncertainties

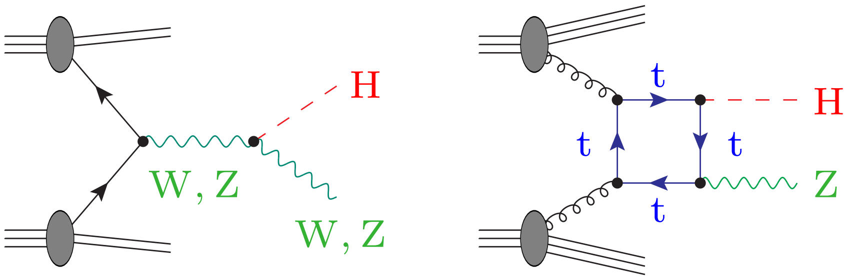
- PDF + α_{s} uncertainty (PDF4LHC)
  - $\pm 3\%$ for $M_{\mathrm{H}} = 125\,\mathrm{GeV}$
- scale uncertainty ($M_{\mathrm{W}}/2 < \mu_{\mathrm{R/F}} < 2M_{\mathrm{W}}$)
  - $\pm 0.5\%$ for $M_{\mathrm{H}} = 125\,\mathrm{GeV}$

LHC HIGGS XS WG ’13



Higgs production in association with vector bosons

WH/ZH production



- leptonic $\mathrm{W/Z}$ decay allows for additional tag
  but small leptonic $\mathrm{W/Z}$ branching ratios
- main channel for Higgs at Tevatron
- at LHC: $\mathrm{H} \to \mathrm{b\bar{b}}$ accessible with modern jet techniques
  $\Rightarrow$ measurement of Hbb coupling
- requires use of highly-boosted H and V back to back in transverse plane
  and $30\,\mathrm{fb}^{-1}$ at $14\,\mathrm{TeV}$ Butterworth et al. ’08, ’09
- control of background to 10% required in specific phase-space regions
  $\Rightarrow$ precise theoretical predictions needed

Status of predictions for WH/ZH production

- NLO QCD: corrections entirely Drell–Yan (DY) like
  Han, Willenbrock '91; Ohnemus, Stirling '93; Baer, Bailey, Owens '93
  VV2H (Spira); MCFM (Campbell, R.K.Ellis)

  matching with parton shower (POWHEG) for 0 and 1 additional jet
  Luisoni, Nason, Oleari, Tramontano '13

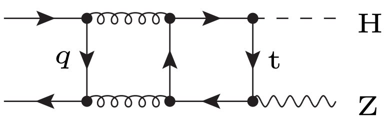
- NLO EW: stable W/Z bosons, total cross section (XS): $5{-}7\%$ for $M_{\mathrm{H}} = 126\,\mathrm{GeV}$
  Ciccolini, Dittmaier, Krämer '03

  differential cross section including W/Z decays, HAWK
  Denner, Dittmaier, Kallweit, Mück '11

- NNLO QCD: stable W/Z bosons, DY part for total XS, $\mathrm{gg} \to \mathrm{ZH}$
  Brein, Djouadi, Harlander '03 (VH@NNLO)

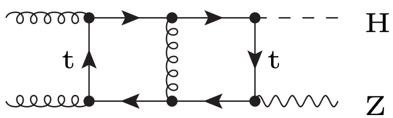
  DY part for differential XS including W/Z decays
  Ferrera, Grazzini, Tramontano '11, '13

  non-DY parts, total XS: $1{-}2\%$
  Brein, Harlander, Wiesemann, Zirke '11



gluon-induced contributions $\mathrm{gg} \to \mathrm{ZH}$: LO $\lesssim 10\%$

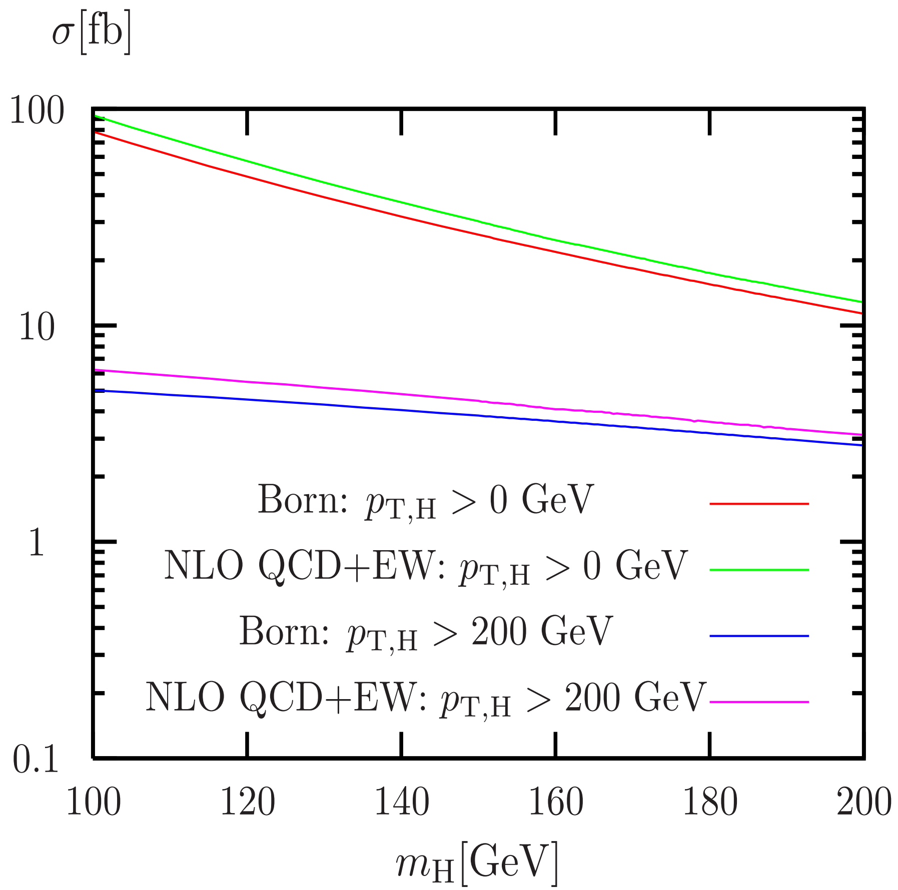
- NLO QCD: stable Z boson, total XS: $\lesssim 10\%$
  Altenkamp, Dittmaier, Harlander, Rzehak, Zirke '12

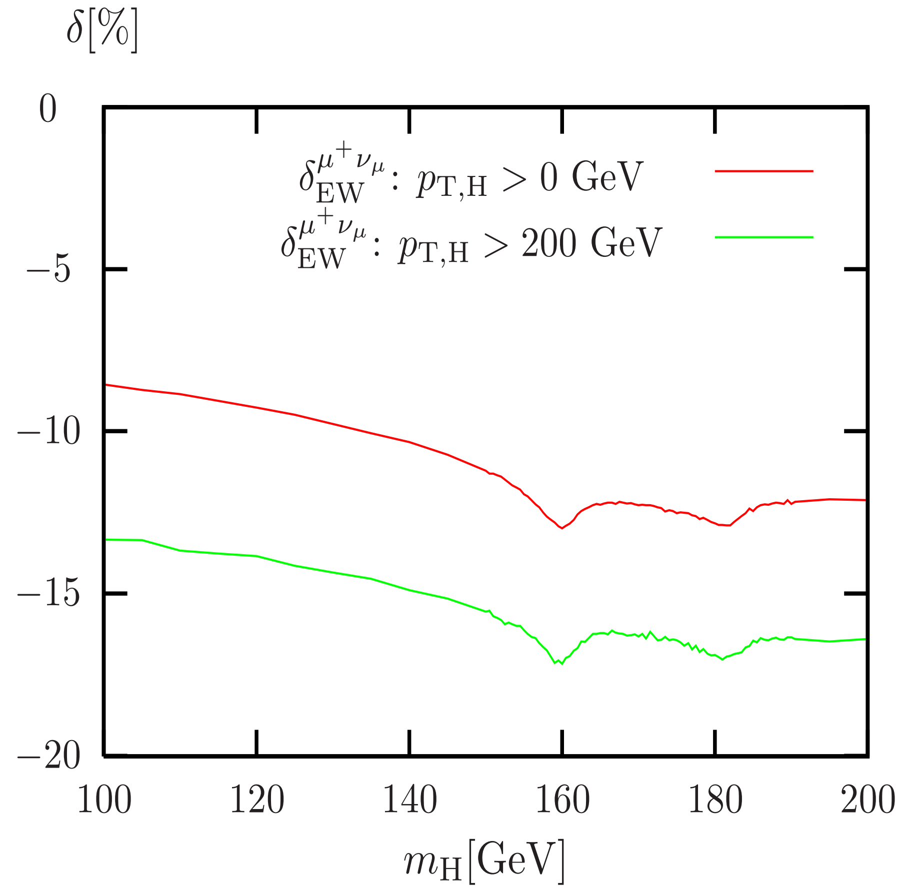


EW corrections to the integrated cross section

Process $\mathrm{pp} \to \mathrm{Hl}^+\nu_\mathrm{l} + X$

Denner, Dittmaier, Kallweit, Mück '11 (HAWK)



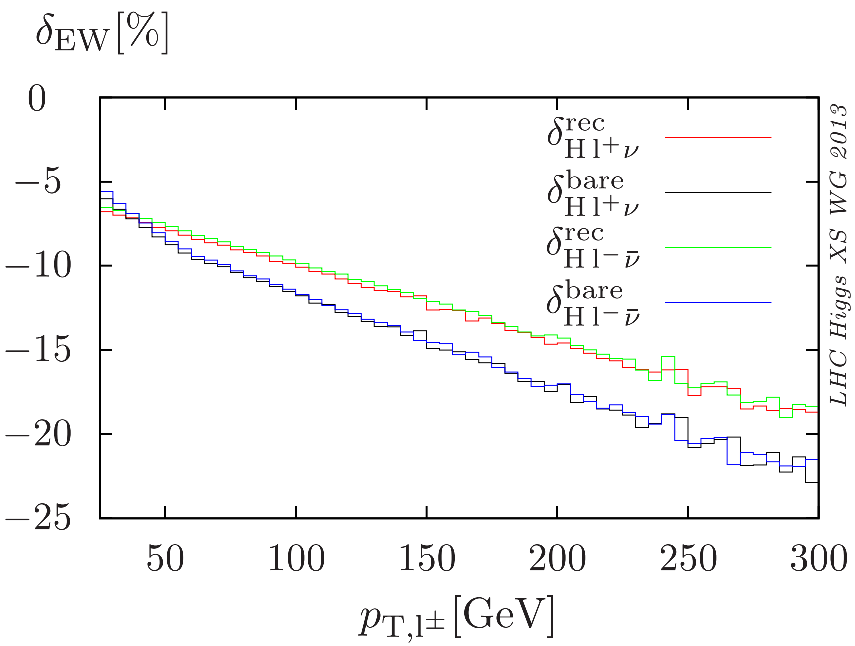


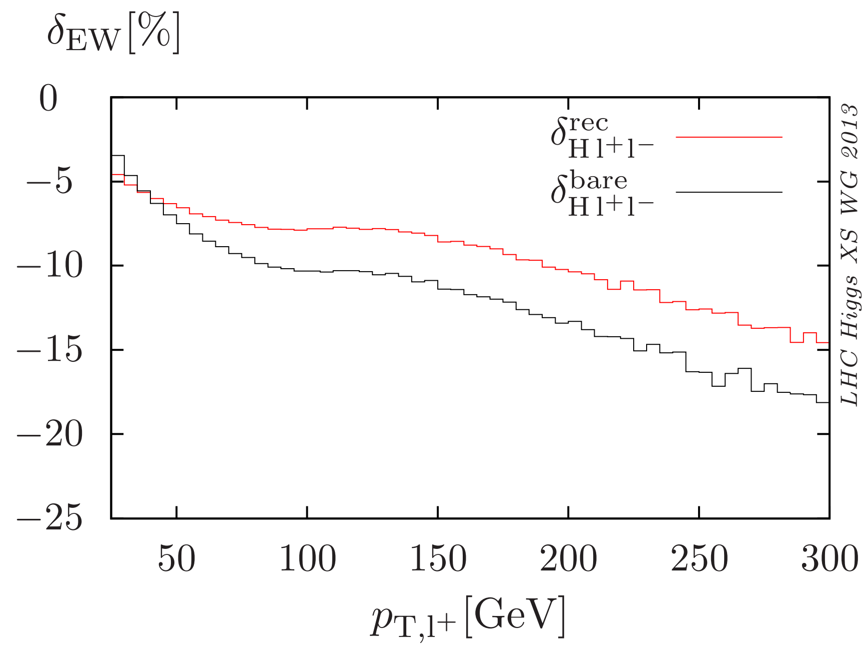
- sound behaviour of δ_EW near WW/ZZ thresholds (complex-mass scheme)
- size of EW corrections increases for boosted-Higgs scenario !

EW corrections to differential distributions

basic cuts

Denner, Dittmaier, Kallweit, Mück ’11 (HAWK)





- large EW corrections at high $p_{\mathrm{T},l}$ from electroweak logarithms!
- different lepton-photon recombination:
  - “rec”: leptons recombined with collinear photons
    $\hookrightarrow$ collinear quasi particle $(\mu\gamma)$ $\rightarrow$ no mass-singular corrections
  - “bare”: no photon recombination
    $\hookrightarrow$ collinear μ and γ asumed separable $\rightarrow$ mass-singular corrections $\propto \log(m_\mu/E)$
- final-state QED corrections not dominant

Best predictions and theoretical uncertainties

Combination of NNLO QCD corrections with NLO EW corrections

based on factorization LHC HIGGS XS WG '13

- total cross section

$$\sigma_{V\mathrm{H}} = \sigma_{V\mathrm{H}}^{\text{NNLO QCD(DY)}} \times (1 + \delta_{V\mathrm{H,EW}}) + \sigma_{V\mathrm{H}}^{\text{NNLO QCD(NON-DY)}}$$

  - NNLO QCD cross section σ_{NNLO} from VH@NNLO Brein, Harlander, Zirke '13
  - relative NLO EW corrections δ_{EW} from Ciccolini, Dittmaier, Krämer '03
- differential cross section

$$\mathrm{d}\sigma = \mathrm{d}\sigma^{\text{NNLO QCD(DY)}} \times (1 + \delta_{V\mathrm{H,EW}}) + \mathrm{d}\sigma_{V\mathrm{H},\gamma}$$

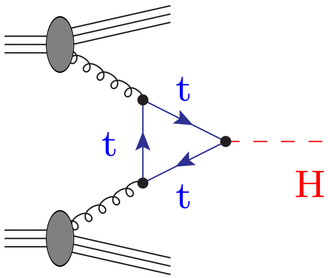
  - NNLO QCD cross section σ_{NNLO} from Ferrera Grazzini, Tramontano '11, 13'
  - relative NLO EW corrections δ_{EW} and $\mathrm{d}\sigma_{V\mathrm{H},\gamma}$ from HAWK Denner et al. '11

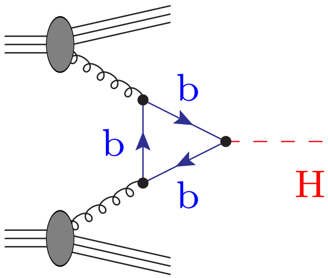
Size of EW corrections and theoretical uncertainties: Higgs cross section WG '12, '13

- EW corrections up to -15% (WH, $p_{\mathrm{T,H}} > 200\,\mathrm{GeV}$)
- scale uncertainty: $1–2\%$
- PDF + α_{s} uncertainty: $3–5\%$
- missing higher orders 1% (7%) for WH (ZH) (differential cross section)

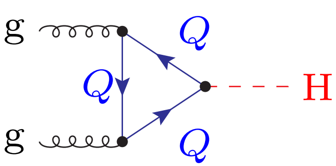
Higgs production in gluon fusion

Higgs production in gluon-gluon fusion





- dominant Higgs-production mode at LHC
- process is loop-induced



  - dominant contribution: $Q =$ top quark
  - subleading contribution: $Q =$ bottom quark ($< 10\%$)

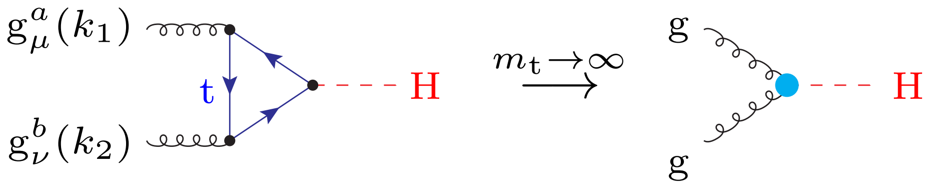
- strong dependence on factorization and renormalization scales (100%)
  $\Rightarrow$ higher-order corrections very important
- sensitive to new heavy particles in the loop (no decoupling)
  $\hookrightarrow$ exclusion of 4th generation

Effective theory for $m_{\rm t} \to \infty$

Effective theory for $m_{\rm t} \to \infty$, $m_{\rm b} \to 0$ simplifies loop calculations considerably

physical picture: long-range gluon interaction does not resolve Higgs production

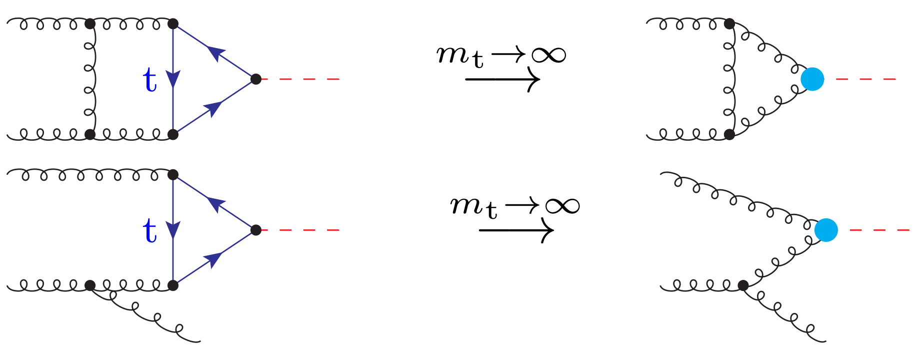
$\Rightarrow$ effective gluon-Higgs coupling



$$= \frac{{\rm i}\alpha_{\rm s}\delta_{ab}}{3\pi v}\left[-g_{\mu\nu}k_1k_2 + k_{1,\mu}k_{2,\nu}\right]$$

$\Rightarrow$ local effective interaction: $\mathcal{L}_{\rm Hgg} = \frac{\alpha_{\rm s}}{12\pi}F^a_{\mu\nu}F^{a,\mu\nu}\frac{H}{v}\left(1 + \frac{11\alpha_{\rm s}}{4\pi} + \ldots\right)$

NLO



quality of approximation for ${\rm pp} \to {\rm H}$ in NLO:

- NLO: $\lesssim 1\%$ for $M_{\rm H} \lesssim 2m_{\rm t} \approx 350\,{\rm GeV}$ Krämer, Laenen, Spira '96
- NNLO: $\lesssim 1\%$ for $M_{\rm H} < 300\,{\rm GeV}$ Marzani et al. '08; Pak, Rogal, Steinhauser '09; Harlander, Ozeren '09

Corrections to Higgs production via gluon fusion

- QCD corrections
  - complete NLO: $80-100\%$ — Graudenz, Spira, Zerwas '93; Djouadi, Graudenz, Spira, Zerwas '95
  - NNLO: 25% — Harlander, Kilgore '01,'02; Catani, de Florian, Grazzini '01; Anastasiou, Melnikov '02; Ravindran, Smith, van Neerven '03, '04; Anastasiou, Melnikov, Petriello '04; Catani, Grazzini '07; Marzani et al. '08; Harlander, Ozeren '09; Pak, Rogal, Steinhauser '09

    as expansion for $m_{\mathrm{t}} \to \infty$

    matched with $\hat{s} \to \infty$

$$K = \frac{\sigma_{\mathrm{NNLO}}}{\sigma_{\mathrm{LO}}} \sim 2.0$$

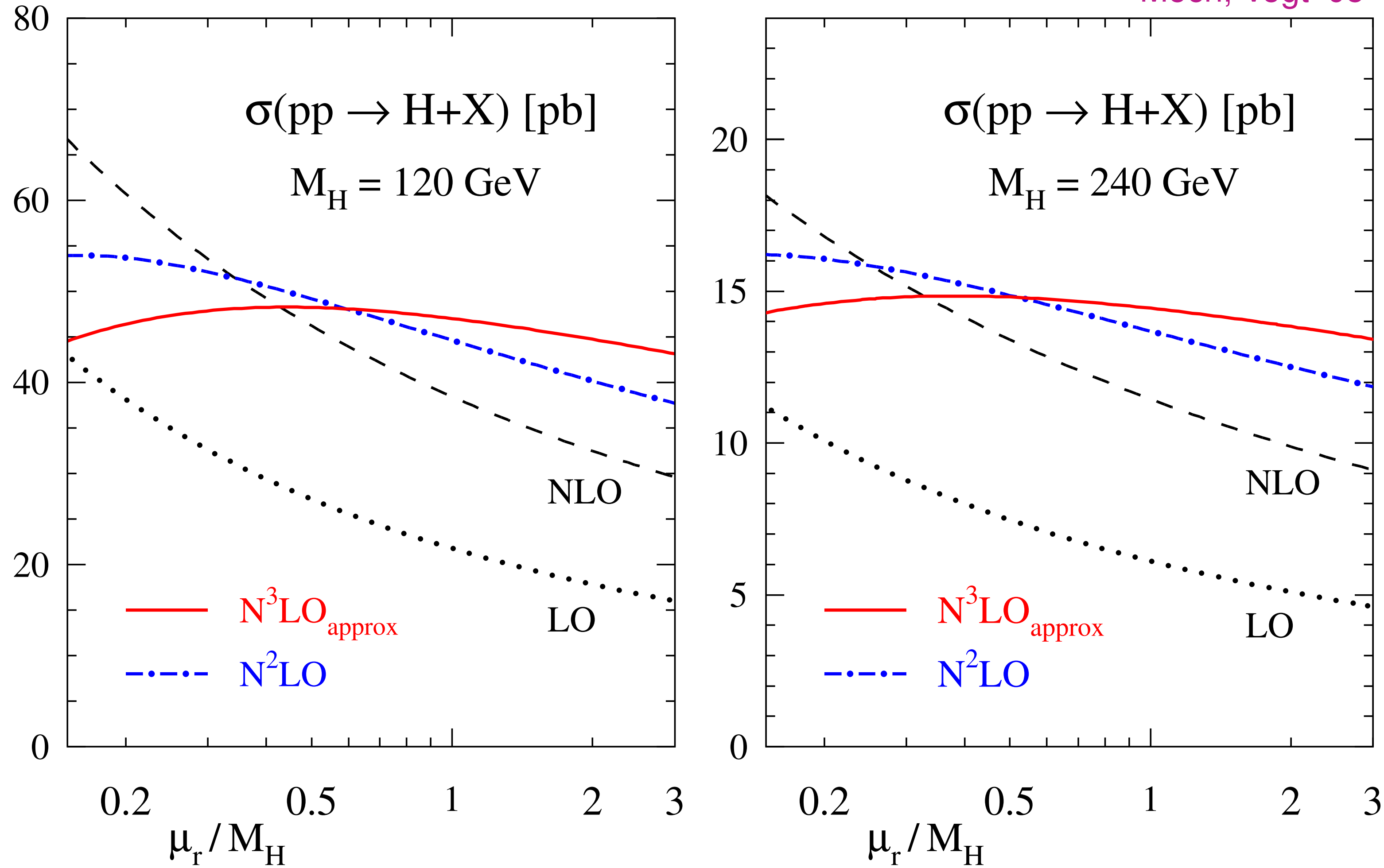
  - resummation of soft-gluon contribution to NNLL: $6-9\%$ — Catani et al. '03, Moch, Vogt '05; Laenen, Magnea '05; Idilbi et al. '05; Ravindran '05,'06;Ravindran, Smith, van Neerven '06; Ahrens, Becher, Neubert, Yang '08, '11; Berger et al. '10; Stewart, Tackmann '11; Banfi et al. '12; Becher, Neubert '12

    leading soft contribution to NNNLO in limit $m_{\mathrm{t}} \to \infty$

- EW corrections
  - complete NLO $\sim \mathcal{O}(5\%)$ — Aglietti, Bonciani, Degrassi, Vicini '04, '06; Degrassi, Maltoni '04; Actis, Passarino, Sturm, Uccirati '08
  - $\mathcal{O}(\alpha\alpha_{\mathrm{s}})$ corrections for $M_{\mathrm{H}} \ll M_{\mathrm{W}}$ — Anastasiou, Boughezal, Petriello '08
  - NLO for $\mathrm{H}+\mathrm{jet}$: $\lesssim 1\%$ — Keung, Petriello '09; Brein '10

QCD scale dependence for $gg \to H$

Moch, Vogt '05



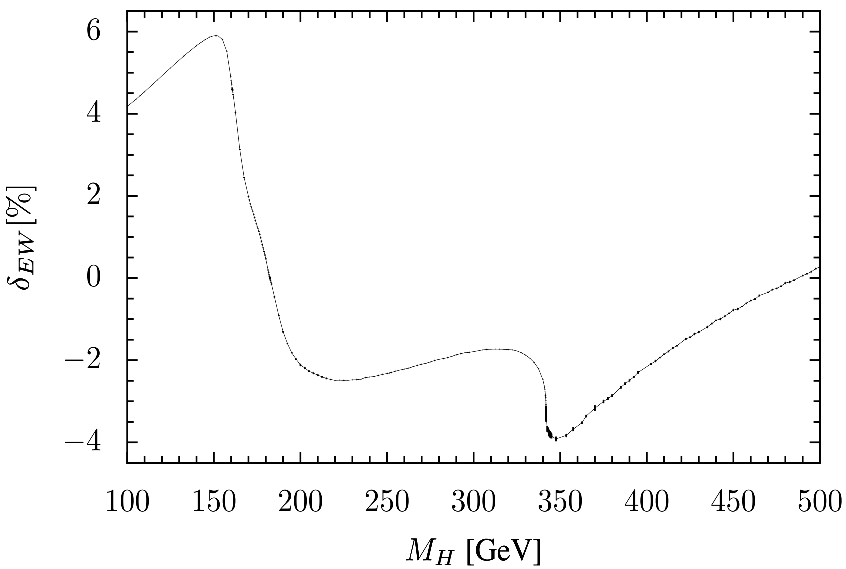
Reduction of renormalization scale dependence with increasing orders!

$\Rightarrow$ residual scale uncertainty $\lesssim 5$–10%

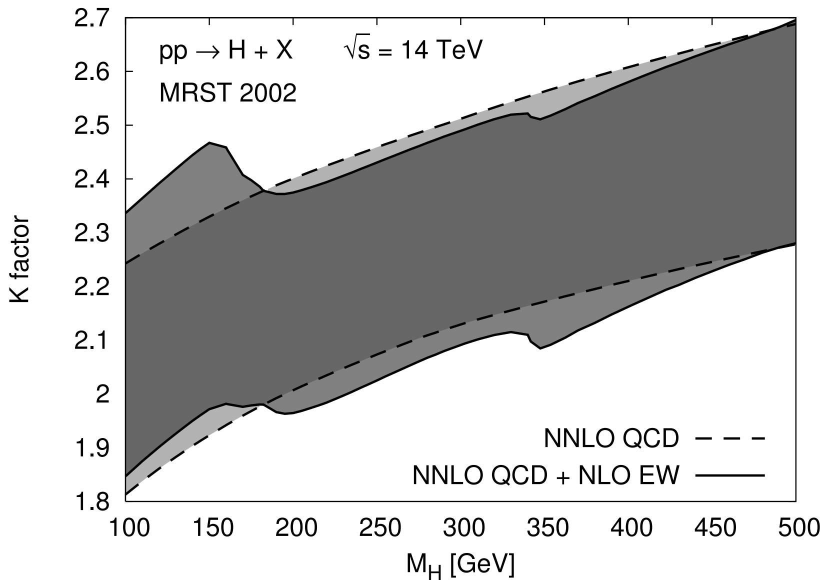
NLO EW corrections

Actis, Passarino, Sturm, Uccirati '08

Correction to partonic cross section:



K factors for pp cross section:
(band width: $M_\mathrm{H}/2 < \mu_\mathrm{R/F} < 2M_\mathrm{H}$, $\mu_\mathrm{R}/2 < \mu_\mathrm{F} < 2\mu_\mathrm{R}$)



- NLO EW: $\mathcal{O}(5\%)$ $(+5\%$ for $M_\mathrm{H} = 125\,\mathrm{GeV})$
- show non-trivial structures near WW, ZZ, tt thresholds
  $\Rightarrow$ require finite decay widths of particles in loops (complex-mass scheme)
- mixed $\mathcal{O}(\alpha\alpha_\mathrm{s})$ corrections for $M_\mathrm{H} \ll M_\mathrm{W}$ Anastasiou, Boughezal, Petriello '08
  suggest factorization of QCD and EW corrections within good accuracy

Theoretical uncertainties

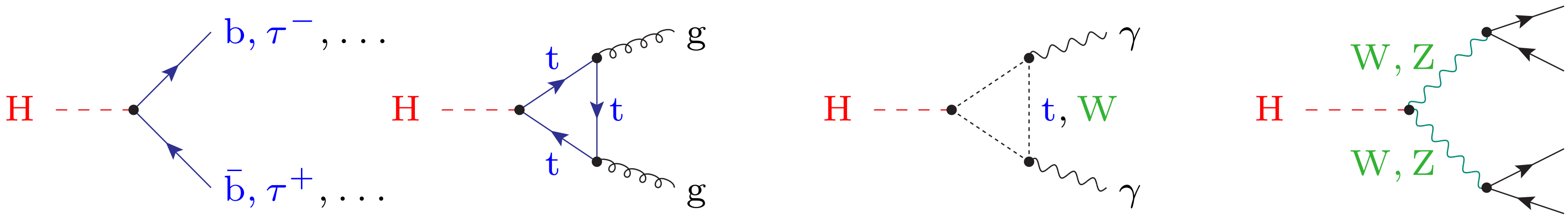
LHC HIGGS XS WG '11 (calc. by Anastasiou, Boughezal, Petriello, Stöckli; de Florian, Grazzini)

- unknown higher-order QCD corrections (scale uncertainty)
  TU $\sim 8{-}12\%$ for $M_{\mathrm{H}} \lesssim 300\,\mathrm{GeV}$
- PDF + α_{s} uncertainty (PDF4LHC recipe)
  TU $\sim 7\%$ for $M_{\mathrm{H}} \lesssim 300\,\mathrm{GeV}$
- large m_{t} approximation for NNLO corrections
  TU $\sim 1\%$ for $M_{\mathrm{H}} \lesssim 300\,\mathrm{GeV}$
- uncertainty from missing EW corrections
  TU $\sim 1\%$ for $M_{\mathrm{H}} \lesssim 300\,\mathrm{GeV}$
- input value for m_{b}: TU ~ 1–2%

Higgs-boson decays

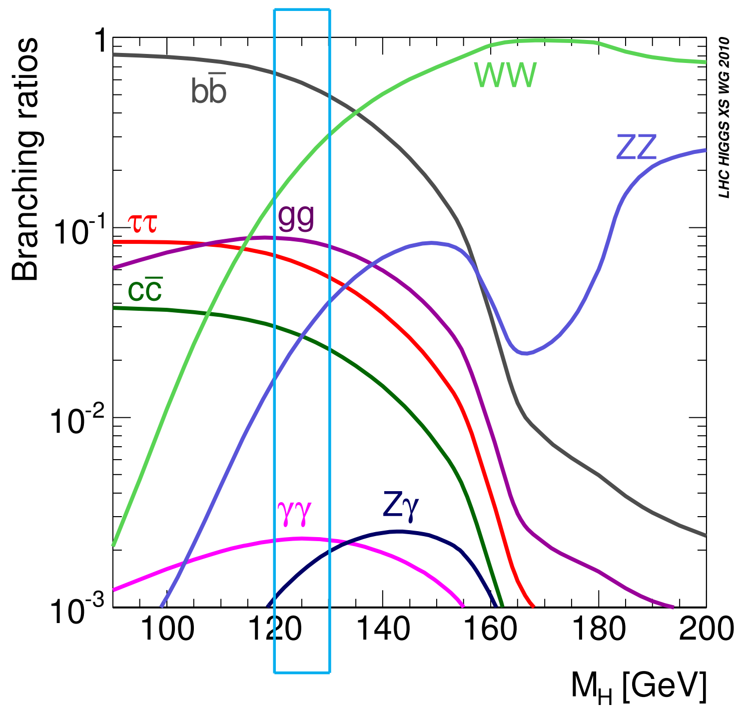
Higgs-boson branching ratios

Higgs-boson decay channels



Higgs-boson branching ratios

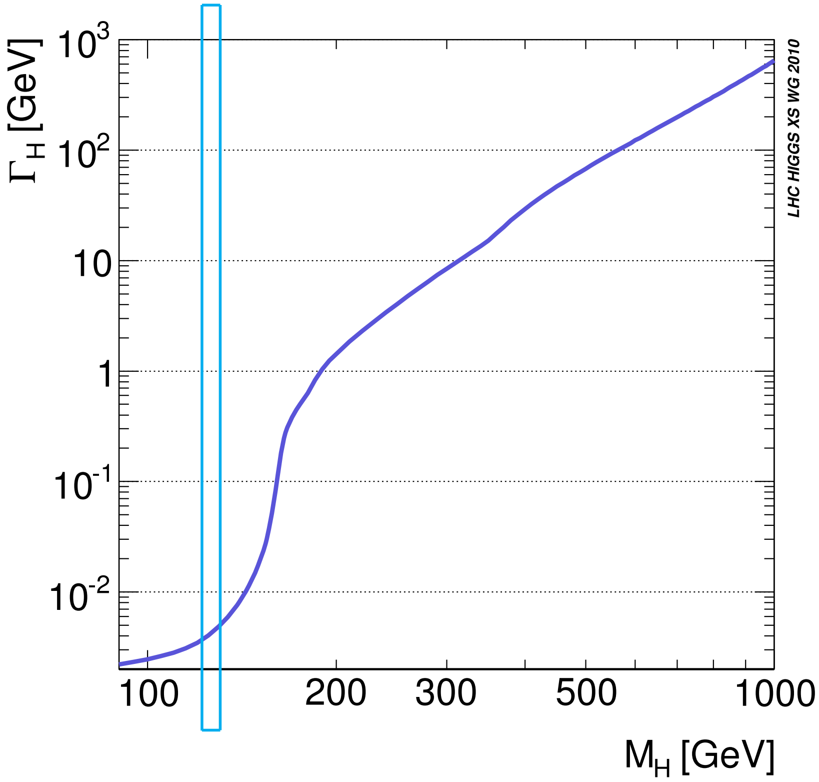
LHC HIGGS XS WG ’11



- branching ratio = fraction of decays to specific final state $\mathrm{BR}(\mathrm{H} \to i) = \frac{\Gamma(\mathrm{H}\to i)}{\Gamma^{\mathrm{H}}_{\mathrm{tot}}}$
- for $M_{\mathrm{H}} \sim 125\,\mathrm{GeV}$ many decay modes accessible

Higgs-boson decay width

LHC HIGGS XS WG '11



- light Higgs boson: $M_{\rm H} < 150\,{\rm GeV}$
  - very narrow $\Gamma_{\rm H}/M_{\rm H} < 0.001$
    $\Gamma_{\rm H} = 4\,{\rm MeV}$ for $M_{\rm H} = 125\,{\rm GeV}$
    below experimental resolution
  - narrow-width approximation applicable (up to small effects)
- steep increase for $M_{\rm H} \sim 160\,{\rm GeV}$
  WW and ZZ channels open
- $\Gamma_{\rm H} \propto M_{\rm H}^3$ for $M_{\rm H} \gtrsim 200\,{\rm GeV}$
  heavy Higgs is very broad

Calculation of branching ratios

- Calculate partial widths for each decay mode: $\Gamma_i^{\mathrm{H}} = \Gamma(\mathrm{H} \to i)$
- calculate total width: $\Gamma^{\mathrm{H}} = \sum_i \Gamma_i^{\mathrm{H}}$ $\Rightarrow$ need all (relevant) decay modes
- calculate branching ratio: $\mathrm{BR}(\mathrm{H} \to i) = \frac{\Gamma_i^{\mathrm{H}}}{\Gamma^{\mathrm{H}}}$

$\sum_i \mathrm{BR}(\mathrm{H} \to i) = 1 \Rightarrow$ correlations between BRs

- changes/uncertainties of Γ_i^{H} affect all BRs
- dominant BR has small uncertainties

W and Z bosons unstable:
$\Rightarrow$ calculate $\Gamma(\mathrm{H} \to 4f)$ instead of $\Gamma(\mathrm{H} \to \mathrm{WW})$ and $\Gamma(\mathrm{H} \to \mathrm{ZZ})$

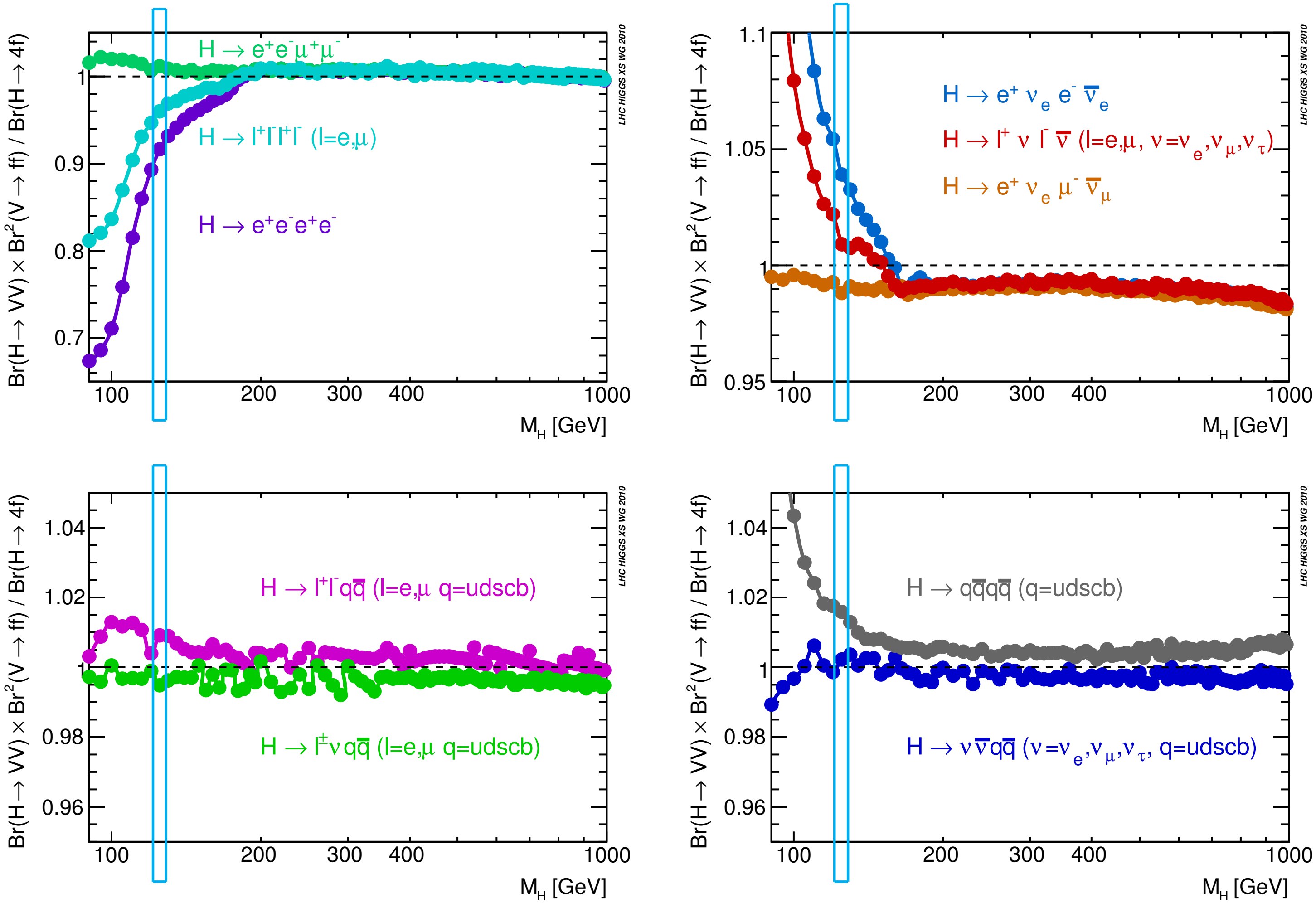
$$\Gamma_{4f} = \Gamma_{\mathrm{H}\to\mathrm{W}^*\mathrm{W}^*\to 4f} + \Gamma_{\mathrm{H}\to\mathrm{Z}^*\mathrm{Z}^*\to 4f} + \Gamma_{\mathrm{WW/ZZ-int.}}$$

approximation $\Gamma(\mathrm{H} \to \mathrm{WW/ZZ})$ neglects interferences

approximation $\Gamma(\mathrm{H} \to 4f) = \Gamma(\mathrm{H} \to \mathrm{WW/ZZ})[\mathrm{BR}(\mathrm{W/Z} \to 2f)]^2$
neglects in addition off-shell effects of $\mathrm{W/Z}$ bosons

Interference and off-shell effects in Γ_{4f}

$\mathrm{BR}(\mathrm{H} \to VV) \times \mathrm{BR}^2(V \to 2f)/\mathrm{BR}(\mathrm{H} \to 4f)$ LHC HIGGS XS WG ’12



$M_{\mathrm{H}} \sim 125\,\mathrm{GeV}$: interference effects of order 5%

Γ_{4f} in PROPHECY4F

PROPHECY4F calculates partial widths for specific $4f$ final states

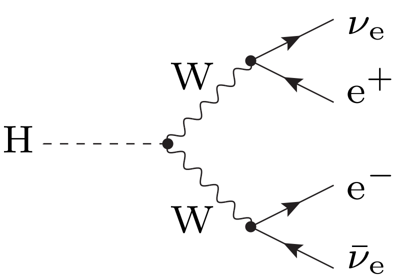
$$\Gamma_{4f}^{\mathrm{Proph.}} = \Gamma_{\mathrm{H}\to\mathrm{W}^*\mathrm{W}^*\to 4f} + \Gamma_{\mathrm{H}\to\mathrm{Z}^*\mathrm{Z}^*\to 4f} + \Gamma_{\mathrm{WW/ZZ-int.}}$$

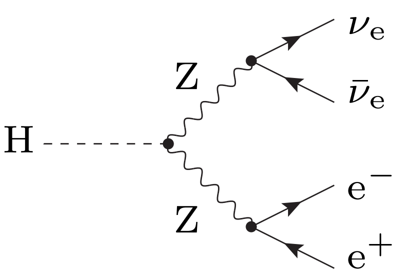
$$\Gamma_{\mathrm{H}\to\mathrm{W}^*\mathrm{W}^*\to 4f} = 9\cdot\Gamma_{\mathrm{H}\to\nu_\mathrm{e}\mathrm{e}^+\mu^-\bar{\nu}_\mu} + 12\cdot\Gamma_{\mathrm{H}\to\nu_\mathrm{e}\mathrm{e}^+\mathrm{d}\bar{\mathrm{u}}} + 4\cdot\Gamma_{\mathrm{H}\to\mathrm{u}\bar{\mathrm{d}}\mathrm{s}\bar{\mathrm{c}}}$$

$$\begin{aligned}\Gamma_{\mathrm{H}\to\mathrm{Z}^*\mathrm{Z}^*\to 4f} = {} & 3\cdot\Gamma_{\mathrm{H}\to\nu_\mathrm{e}\bar{\nu}_\mathrm{e}\nu_\mu\bar{\nu}_\mu} + 3\cdot\Gamma_{\mathrm{H}\to\mathrm{e}^-\mathrm{e}^+\mu^-\mu^+} + 9\cdot\Gamma_{\mathrm{H}\to\nu_\mathrm{e}\bar{\nu}_\mathrm{e}\mu^-\mu^+} \\ & + 3\cdot\Gamma_{\mathrm{H}\to\nu_\mathrm{e}\bar{\nu}_\mathrm{e}\nu_\mathrm{e}\bar{\nu}_\mathrm{e}} + 3\cdot\Gamma_{\mathrm{H}\to\mathrm{e}^-\mathrm{e}^+\mathrm{e}^-\mathrm{e}^+} \\ & + 6\cdot\Gamma_{\mathrm{H}\to\nu_\mathrm{e}\bar{\nu}_\mathrm{e}\mathrm{u}\bar{\mathrm{u}}} + 9\cdot\Gamma_{\mathrm{H}\to\nu_\mathrm{e}\bar{\nu}_\mathrm{e}\mathrm{d}\bar{\mathrm{d}}} + 6\cdot\Gamma_{\mathrm{H}\to\mathrm{u}\bar{\mathrm{u}}\mathrm{e}^-\mathrm{e}^+} + 9\cdot\Gamma_{\mathrm{H}\to\mathrm{d}\bar{\mathrm{d}}\mathrm{e}^-\mathrm{e}^+} \\ & + 1\cdot\Gamma_{\mathrm{H}\to\mathrm{u}\bar{\mathrm{u}}\mathrm{c}\bar{\mathrm{c}}} + 3\cdot\Gamma_{\mathrm{H}\to\mathrm{d}\bar{\mathrm{d}}\mathrm{s}\bar{\mathrm{s}}} + 6\cdot\Gamma_{\mathrm{H}\to\mathrm{u}\bar{\mathrm{u}}\mathrm{s}\bar{\mathrm{s}}} + 2\cdot\Gamma_{\mathrm{H}\to\mathrm{u}\bar{\mathrm{u}}\mathrm{u}\bar{\mathrm{u}}} \\ & + 3\cdot\Gamma_{\mathrm{H}\to\mathrm{d}\bar{\mathrm{d}}\mathrm{d}\bar{\mathrm{d}}}\end{aligned}$$

$$\begin{aligned}\Gamma_{\mathrm{WW/ZZ-int.}} = {} & 3\cdot\Gamma_{\mathrm{H}\to\nu_\mathrm{e}\mathrm{e}^+\mathrm{e}^-\bar{\nu}_\mathrm{e}} - 3\cdot\Gamma_{\mathrm{H}\to\nu_\mathrm{e}\bar{\nu}_\mathrm{e}\mu^-\mu^+} - 3\cdot\Gamma_{\mathrm{H}\to\nu_\mathrm{e}\mathrm{e}^+\mu^-\bar{\nu}_\mu} \\ & + 2\cdot\Gamma_{\mathrm{H}\to\mathrm{u}\bar{\mathrm{d}}\mathrm{d}\bar{\mathrm{u}}} - 2\cdot\Gamma_{\mathrm{H}\to\mathrm{u}\bar{\mathrm{u}}\mathrm{s}\bar{\mathrm{s}}} - 2\cdot\Gamma_{\mathrm{H}\to\mathrm{u}\bar{\mathrm{d}}\mathrm{s}\bar{\mathrm{c}}}\end{aligned}$$

$\Gamma_{\mathrm{H}\to\nu_\mathrm{e}\mathrm{e}^+\mathrm{e}^-\bar{\nu}_\mathrm{e}}$ and $\Gamma_{\mathrm{H}\to\mathrm{u}\bar{\mathrm{d}}\mathrm{d}\bar{\mathrm{u}}}$ contribute to $\Gamma_{\mathrm{H}\to\mathrm{W}^*\mathrm{W}^*\to 4f}$, $\Gamma_{\mathrm{H}\to\mathrm{Z}^*\mathrm{Z}^*\to 4f}$ and $\Gamma_{\mathrm{WW/ZZ-int.}}$





Estimate of theoretical uncertainties (TU)

LHC HIGGS XS WG '12, '13 predictions for partial widths obtained with

- PROPHECY4F for $\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$ (complete QCD and EW NLO)
  Bredenstein, Denner, Dittmaier, Mück, Weber
- HDECAY for Higgs-boson decays in other channels
  Djouadi, Kalinowski, Mühlleitner, Spira

Estimate of TU for partial decay widths from missing higher orders

partial width	QCD	electroweak (EW)	total
$\mathrm{H} \to \mathrm{bb/cc}$	~ 0.1–0.2%	~ 1–2% for $M_\mathrm{H} \lesssim 135\,\mathrm{GeV}$	$\sim 2\%$
$\mathrm{H} \to \tau\tau$		~ 1–2% for $M_\mathrm{H} \lesssim 135\,\mathrm{GeV}$	$\sim 2\%$
$\mathrm{H} \to \mathrm{tt}$	$\lesssim 5\%$	$\sim 2\%$ for $M_\mathrm{H} < 500\,\mathrm{GeV}$	$\sim 5\%$
$\mathrm{H} \to \mathrm{gg}$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$
$\mathrm{H} \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$
$\mathrm{H} \to \gamma\mathrm{Z}$	$< 1\%$	$\sim 5\%$	$\sim 5\%$
$\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$	$< 0.5\%$	$\sim 0.5\%$ for $M_\mathrm{H} < 500\,\mathrm{GeV}$	$\sim 0.5\%$

$M_\mathrm{H} = 125\,\mathrm{GeV}$: $\mathrm{TU} \leq 2\%$ for important channels

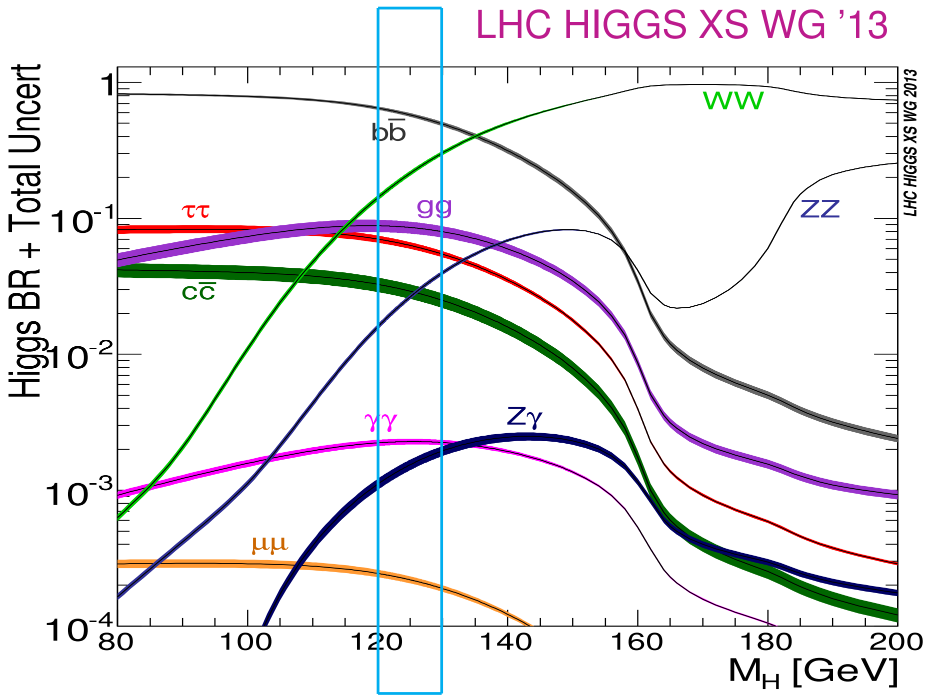
Parametric uncertainties in Higgs decays

Imperfect knowledge of input parameters $m_c = 1.42 \pm 0.03\,\mathrm{GeV}$,

$m_b = 4.49 \pm 0.06\,\mathrm{GeV}$, $\alpha_s(M_Z) = 0.119 \pm 0.002$ (per-cent level errors)

$\Rightarrow$ sizeable parametric uncertainties (PU) in partial widths $\mathrm{H} \to \mathrm{b\bar{b}}, \mathrm{c\bar{c}}, \mathrm{gg}$

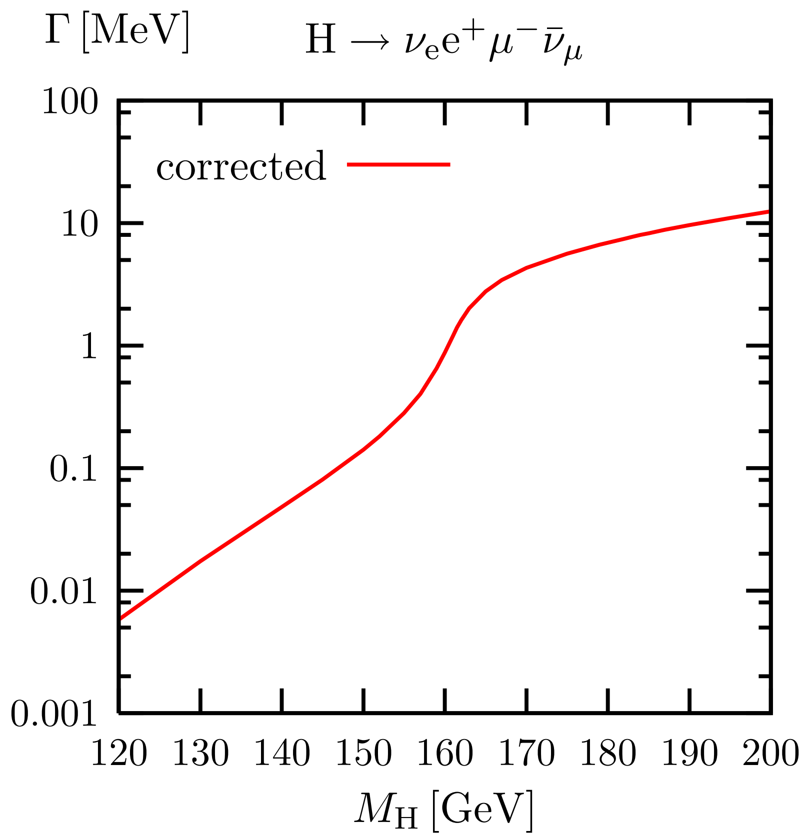
total theoretical uncertainties

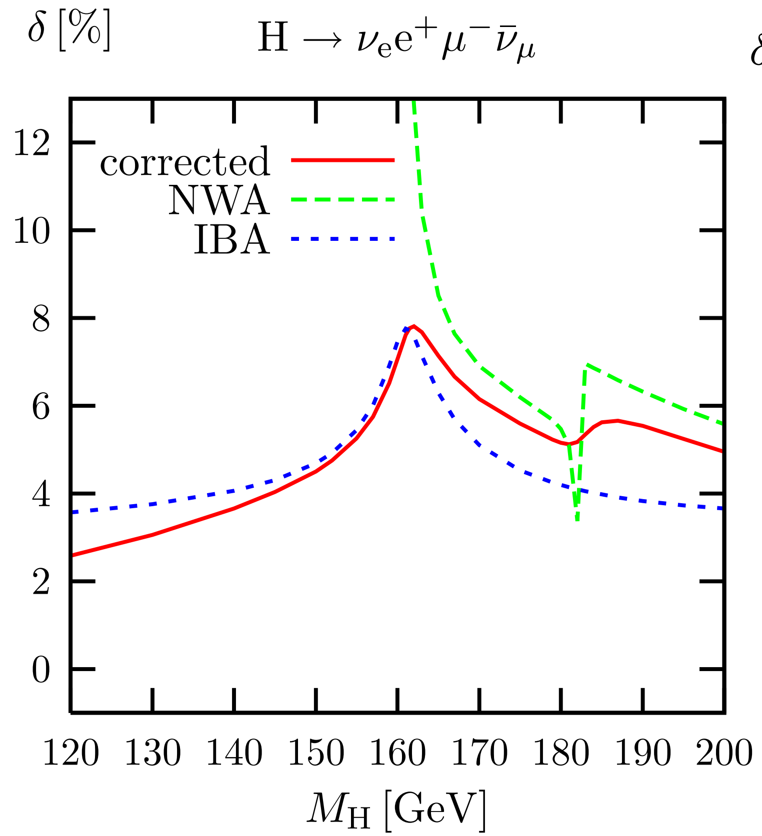


$M_\mathrm{H} \sim 125\,\mathrm{GeV}$

- $\mathrm{BR(H \to b\bar{b})}$
  PU from m_b, α_s: 1% each
  TU: 1%, total uncertainty 3%
- $\mathrm{BR(H \to c\bar{c})}$:
  PU from m_c, α_s: 6% each
  TU: 4%, total uncertainty 12%
- $\mathrm{BR(H \to WW, ZZ)}$, $\mathrm{BR(H \to \gamma\gamma)}$, $\mathrm{BR(H \to} \mathit{ll})$
  PU 2.5% indirectly via $\Gamma(\mathrm{H \to b\bar{b}})$
  TU: $2{-}4\%$, total uncertainty $5{-}6\%$

Partial width for $\mathrm{H} \to \mathrm{WW} \to \nu_e e^+ \mu^- \bar{\nu}_\mu$





$$\delta = \frac{\Gamma}{\Gamma_\mathrm{Born}} - 1$$

Bredenstein, Denner, Dittmaier, Weber '06

PROPHECY4F

↑ Coulomb singularity for $M_\mathrm{H} \sim 2M_\mathrm{W}$

↑ threshold effect in loops for $M_\mathrm{H} \sim 2M_\mathrm{Z}$

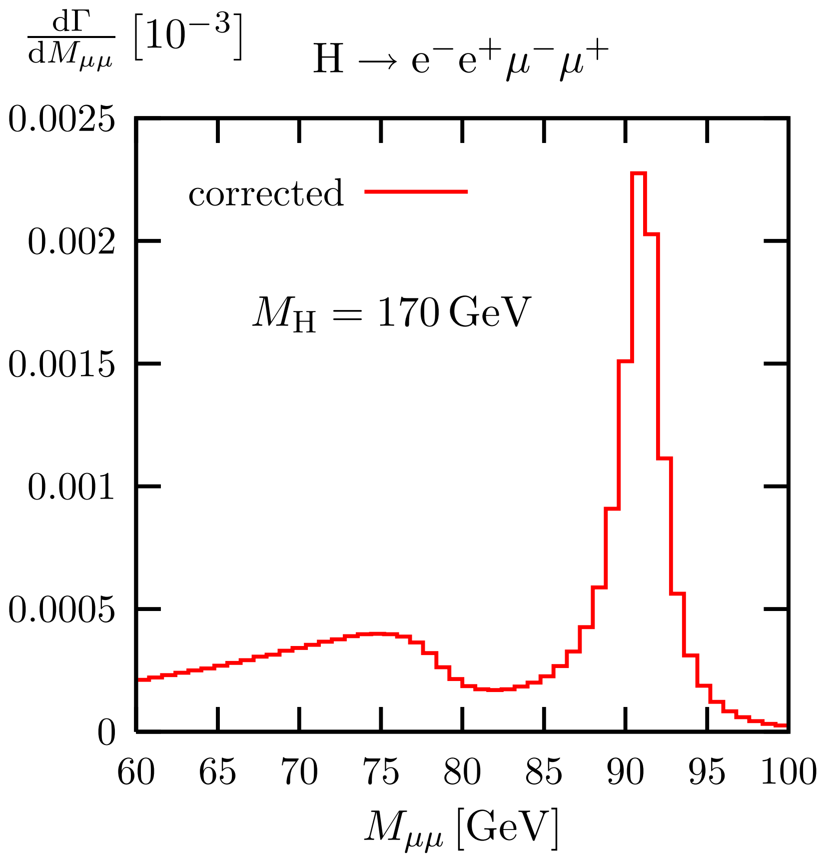
NWA = narrow-width approximation
(on-shell W bosons)

IBA = improved Born approximation
(universal corrections)

(Coulomb singularity, fitting constant, leading effects for $M_\mathrm{H}, m_\mathrm{t} \gg M_\mathrm{W}$)

Z-invariant mass for $H \to ZZ \to e^-e^+\mu^-\mu^+$

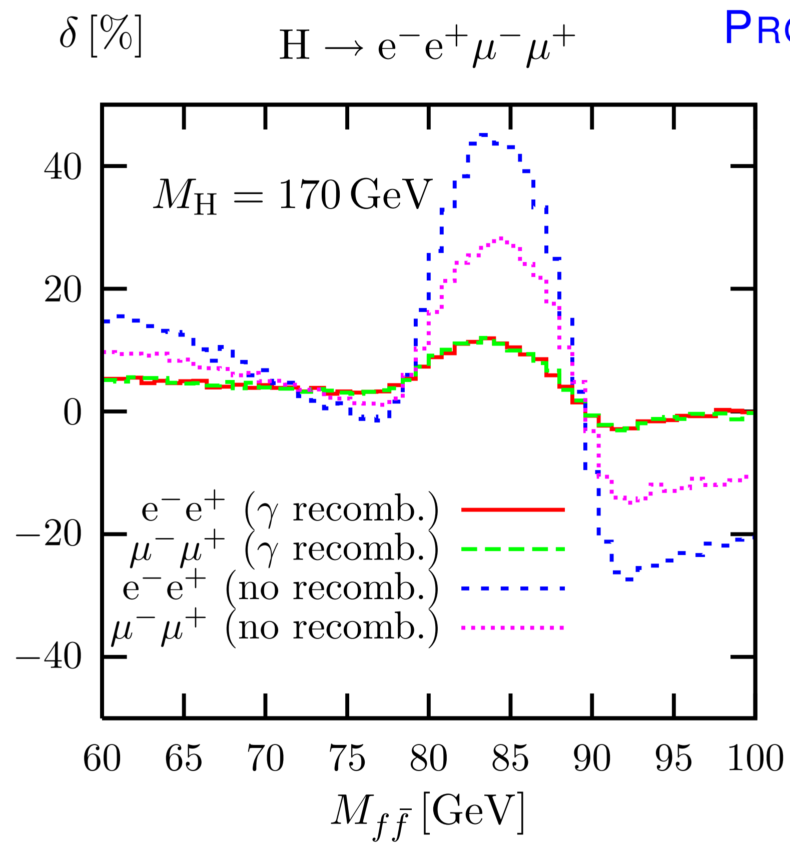
Partial width:



relative corrections:

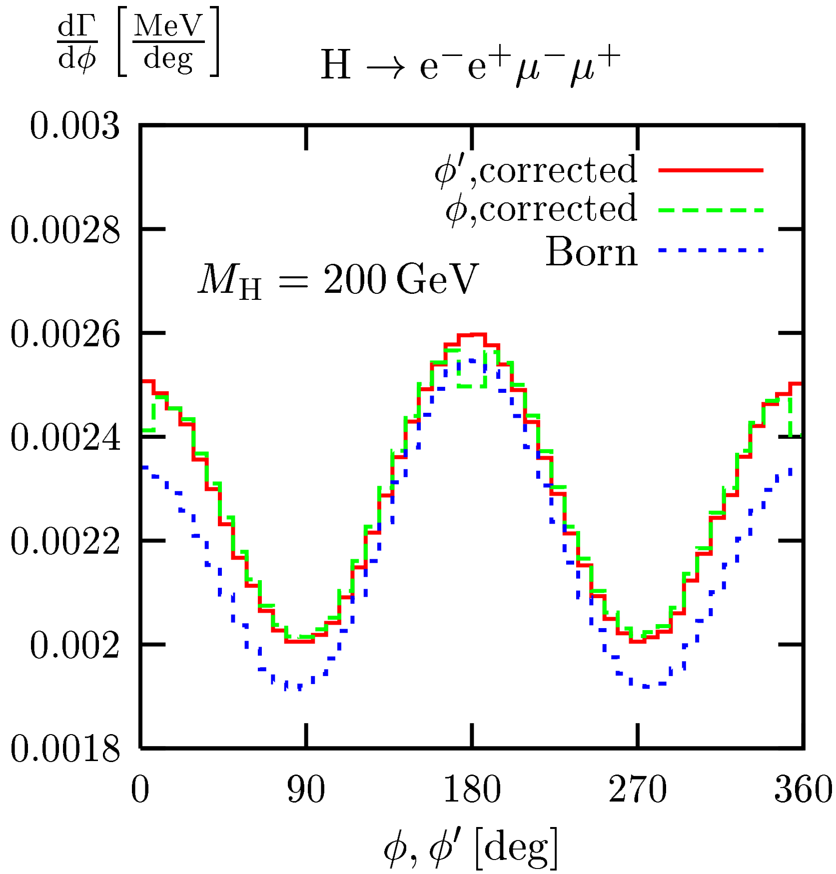
Bredenstein, Denner, Dittmaier, Weber '06

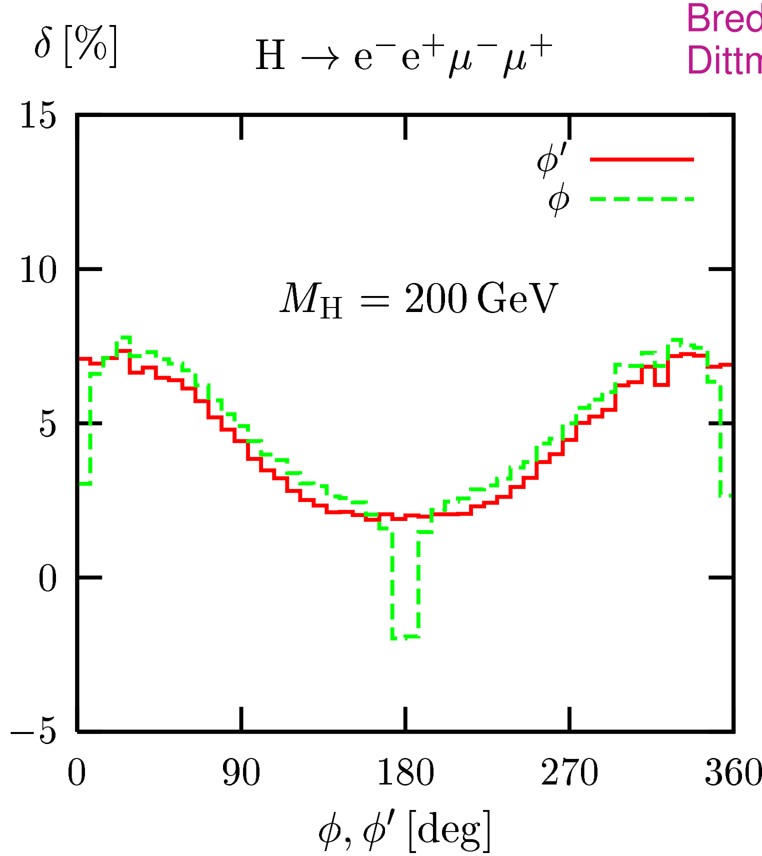
PROPHECY4F



- photon recombination for $M_{e\gamma/\mu\gamma} < 5$ GeV
- one resonant gauge boson for $M_{\mu\mu} \sim M_Z$ or $M_{\mu\mu} \lesssim M_H - M_Z$
- large corrections due to radiative tail of Z resonance

Angle of decay planes for $\mathrm{H} \to \mathrm{ZZ} \to \mathrm{e}^-\mathrm{e}^+\mu^-\mu^+$

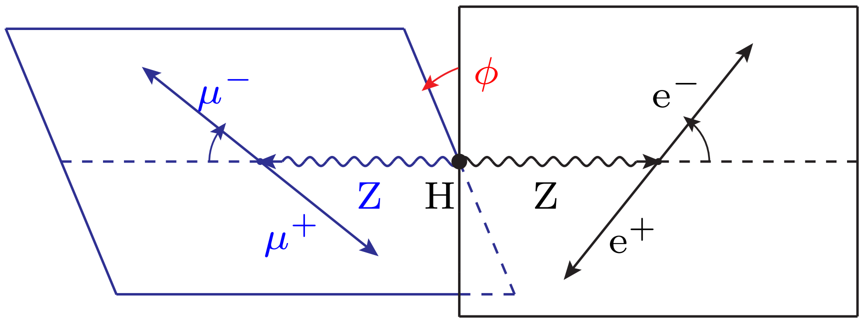




Bredenstein, Denner, Dittmaier, Weber '06

PROPHECY4F

shape distortion 5–10%



$$\cos\phi = \frac{\left((\mathbf{p}_{\mathrm{e}^-}+\mathbf{p}_{\mathrm{e}^+})\times\mathbf{p}_{\mathrm{e}^-}\right)\left(-(\mathbf{p}_{\mu^-}+\mathbf{p}_{\mu^+})\times\mathbf{p}_{\mu^-}\right)}{\left|(\mathbf{p}_{\mathrm{e}^-}+\mathbf{p}_{\mathrm{e}^+})\times\mathbf{p}_{\mathrm{e}^-}\right|\left|-(\mathbf{p}_{\mu^-}+\mathbf{p}_{\mu^+})\times\mathbf{p}_{\mu^-}\right|}$$

$$\cos\phi' = \frac{\left((\mathbf{p}_{\mathrm{e}^-}+\mathbf{p}_{\mathrm{e}^+})\times\mathbf{p}_{\mathrm{e}^-}\right)\left((\mathbf{p}_{\mathrm{e}^-}+\mathbf{p}_{\mathrm{e}^+})\times\mathbf{p}_{\mu^-}\right)}{\left|(\mathbf{p}_{\mathrm{e}^-}+\mathbf{p}_{\mathrm{e}^+})\times\mathbf{p}_{\mathrm{e}^-}\right|\left|(\mathbf{p}_{\mathrm{e}^+}+\mathbf{p}_{\mathrm{e}^-})\times\mathbf{p}_{\mu^-}\right|}$$

Conclusion Lecture 3

Conclusion for Lecture 3

LHC observed boson compatible with SM Higgs boson

next step: verification of its nature via measurement of its properties

precise theoretical predictions are vital including

- NLO and NNLO (and even NNNLO) QCD corrections
- NLO EW corrections

best predictions collected and provided by LHC Higgs cross section working group

- precise predictions with errors exist
  for Higgs production and decay
- production and decay need to be combined properly
- inclusion of background and signal–background interference needed
  - crucial for heavy Higgs bosons
  - relevance for light Higgs boson depends on analysis (cuts)
- strategies for precise measurement of couplings being developed

Prospects

- Continuous improvements of calculational techniques
- automation of NLO calculations
- NLO parton-shower matching will become standard
- full inclusion of EW corrections
  - in NLO corrections
  - in parton distribution functions (consistent photon distributions)
  - in parton showers (photons, electroweak bosons?)
  - in parton shower matching

NLO QCD becomes standard

NLO EW needed for large cross sections or at high energies

Theoretical interest shifts to NNLO QCD

Backup

Theoretical predictions for Higgs-boson decays

- $\mathrm{H} \to f\bar{f}$
  EW NLO for massive and massless fermions
  Fleischer, Jegerlehner '81; Bardin, Vilenskii, Khristova '91; Dabelstein, Hollik '92; Kniehl '92
- $\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}, \mathrm{c}\bar{\mathrm{c}}$
  QCD NLO: Braaten, Leveille '80, Sakai '80, Inami, Kubota '81; Gorishnii, Kataev, Larin '84; Drees, Hikasa '90, '91
  QCD NNLO: Gorishnii, Kataev, Larin, Surguladze '90, '91; Kataev, Kim '94, Larin, van Ritbergen, Vermaseren '95; Chetyrkin, Kwiatkowski '95, Chetyrkin '96
  QCD NNNLO: Chetyrkin '97, Chetyrkin, Steinhauser '97
- $\mathrm{H} \to \mathrm{t}\bar{\mathrm{t}}$
  QCD NLO: Braaten, Leveille '80, Sakai '80, Inami, Kubota '81; Gorishnii, Kataev, Larin '84; Drees, Hikasa '90, '91, Djouadi, Gambino '95
  QCD NNLO: Melnikov '96; Harlander, Steinhauser '97
  Mixed $\mathcal{O}(\alpha_{\mathrm{s}} G_\mu m_{\mathrm{t}}^2)$: Kniehl, Spira '94; Kwiatkowski, Steinhauser '94
  Mixed $\mathcal{O}(\alpha_{\mathrm{s}}^2 G_\mu m_{\mathrm{t}}^2)$: Chetyrkin, Kniehl, Steinhauser '97
  EW $\mathcal{O}(G_\mu^2 M_{\mathrm{H}}^4)$: Ghinculov '94, Durand, Riesselmann, Kniehl '94

Theoretical predictions for Higgs-boson decays

- $\mathrm{H} \to \gamma\gamma$
  QCD: NLO Spira et al. '95, Zheng, Wu '90; Djouadi et al '91, '93; Dawson, Kauffmann '93, Melnikov, Yakovlev '93; Inoue et al '94, Fleischer, Tarasov '95, '04
  EW: NLO Aglietti, Bonciani, Degrassi, Vicini '04, '06; (Actis), Passarino, Sturm, Uccirati '07, '08
- $\mathrm{H} \to \mathrm{gg}$
  QCD: NLO, NNLO and NNNLO for heavy top quarks Spira et al. '91,'95; Chetyrkin, Kniehl, Steinhauser '97; Baikov, Chetyrkin '06
  EW: NLO Aglietti et al. '04, '06; Actis, Passarino, Sturm, Uccirati '08
- $\mathrm{H} \to \mathrm{WW} \to 4f$
  - stable gauge bosons:
    EW: NLO Fleischer, Jegerlehner '81; Kniehl '91; Bardin, Vilenskii, Khristova '91
  - off-shell gauge bosons:
    EW and QCD NLO Bredenstein et al. '06

SM prediction for Higgs decays in good shape