Precision calculations for $\mathbf{H \to WW/ZZ \to 4}$ fermions with PROPHECY4F

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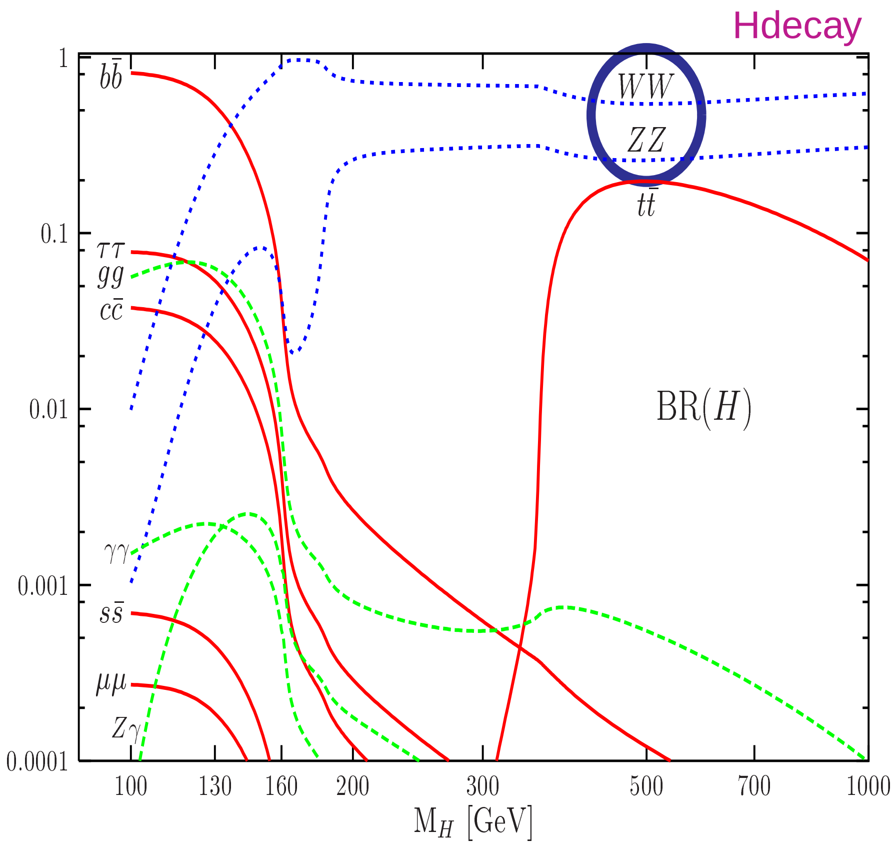
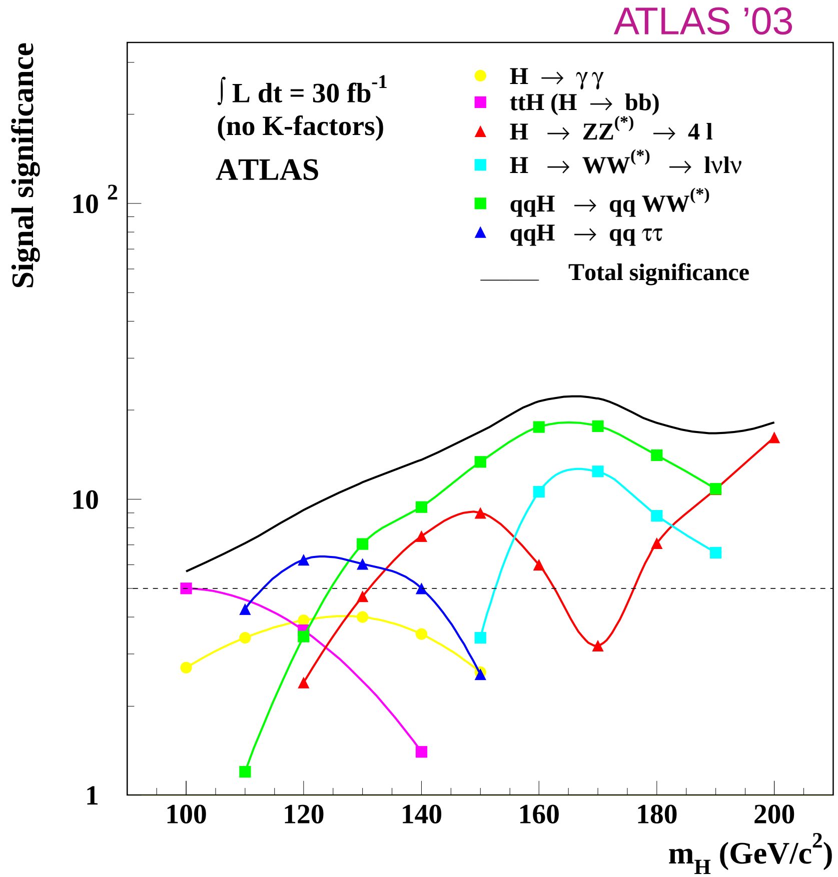
based on PRD74 (2006) 013004 [hep-ph/0604011] and MPP-2006-138 (in preparation)

Contents

1 Introduction — the decays H $\longrightarrow$ WW/ZZ $\longrightarrow$ 4 fermions





Importance of decays $\mathrm{H} \to \mathrm{WW}^{(*)}/\mathrm{ZZ}^{(*)}$ at the LHC:

LHC:
- most important Higgs decay channels for $M_\mathrm{H} \gtrsim 125\,\mathrm{GeV}$
- most precise determination of M_H via $\mathrm{H}{\to}\mathrm{ZZ}{\to}4l$ for $M_\mathrm{H} \gtrsim 130\,\mathrm{GeV}$

ILC:
- measurements of branching ratios at per-cent level
- full reconstruction of $\mathrm{H} \to \mathrm{WW}$ in semileptonic / hadronic final states

Theoretical description of $\mathrm{H} \to \mathrm{WW}^{(*)}/\mathrm{ZZ}^{(*)}$:

- previous work on partial decay widths:
  - $\mathcal{O}(\alpha)$ corrections to $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ}$ with stable W’s/Z’s
    Fleischer, Jegerlehner ’81; Kniehl ’91; Bardin, Vilenskii, Khristova ’91
  - lowest-order predictions for $\mathrm{H} \to \mathrm{WW}^{(*)}/\mathrm{ZZ}^{(*)}$
    e.g. by Hdecay (Djouadi, Kalinowski, Spira ’98)
- however: proper description of distributions required
  - for the kinematical reconstruction of Z’s, W’s, and H
    (including radiative corrections, in particular γ radiation)
    $\hookrightarrow$ invariant-mass distributions
  - for the verification of spin 0 and CP parity of the Higgs boson
    $\hookrightarrow$ angular and invariant-mass distributions
    Nelson ’88; Soni, Xu ’93; Chang et al.’93; Skjold, Osland ’93; Barger et al.’93; Arens, Sehgal ’94; Buszello et al.’02; Choi et al.’0

$\Rightarrow$ Monte Carlo generator for $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ} \to 4f$ with corrections needed

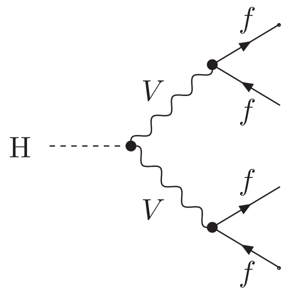
Recent work and work in progress:

- PROPHECY4F: generator for $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ} \to 4f$ with EW and QCD corrections
  Bredenstein, Denner, S.D., Weber ’06
- generator for $\mathrm{H} \to \mathrm{ZZ} \to 4l$ with QED corrections
  Carloni-Calame et al.

2 Calculation of EW and QCD corrections

Survey of Feynman diagrams

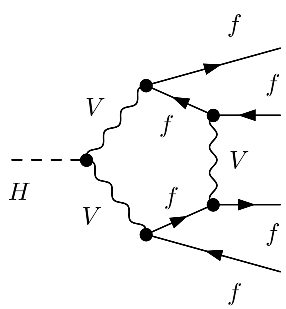
Lowest order:



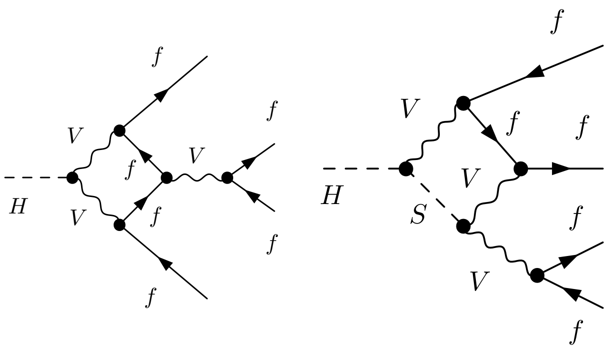
Electroweak $\mathcal{O}(\alpha)$ corrections:

typical one-loop diagrams: # diagrams = $\mathcal{O}(200\!-\!400)$

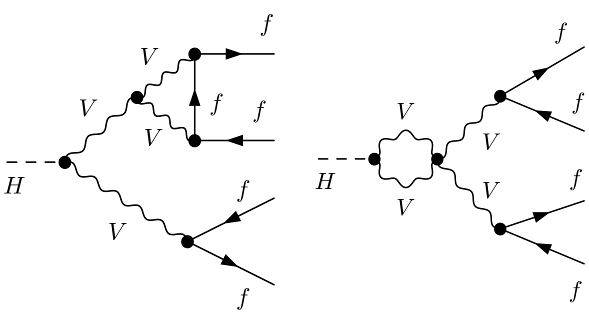
pentagons



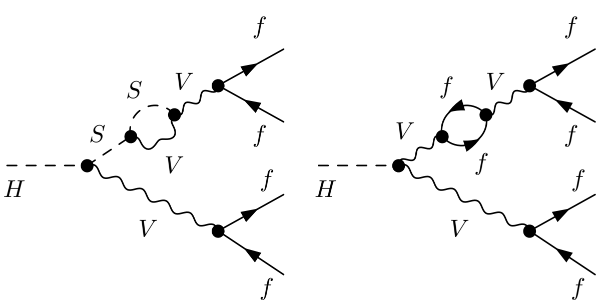
boxes



vertices



self-energies

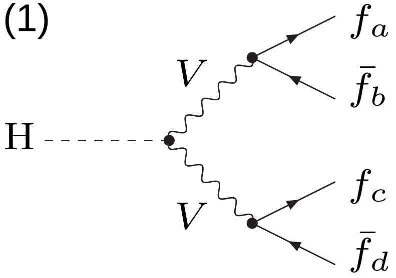


$+$ photon bremsstrahlung (final-state radiation only)

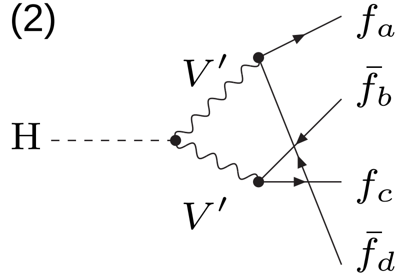
QCD corrections to semileptonic or hadronic final states:

Possible Born diagrams:

(1)



(2)

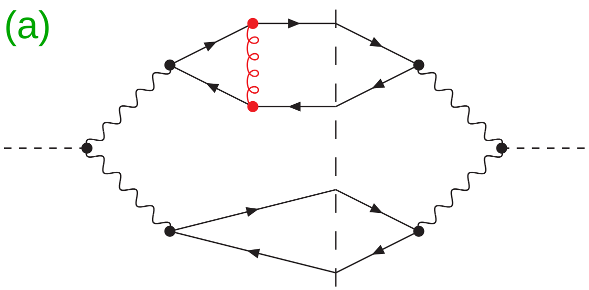


diagrams (2) only for $q\bar{q}q\bar{q}$ and $q\bar{q}q'\bar{q}'$ final states

(q' = weak-isospin partner of q)

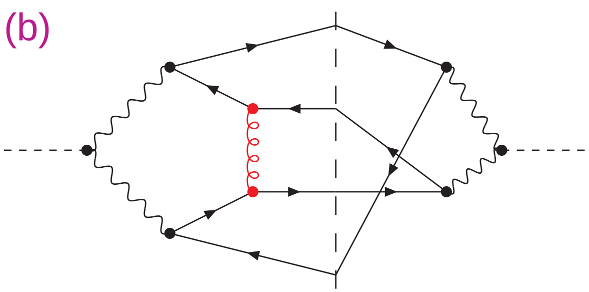
Classification of QCD corrections into four categories: (typical diagrams shown)

(a)

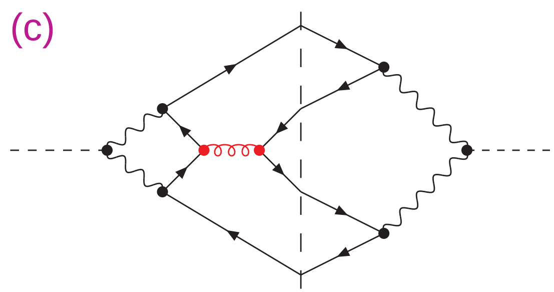


(a) = correction to W/Z decays

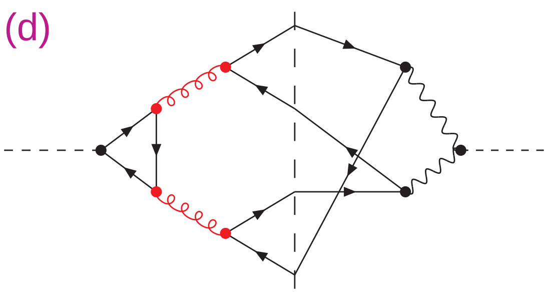
(b)



(c)



(d)



(b,c,d) = corrections to interferences (only for $q\bar{q}q\bar{q}$ and $q\bar{q}q'\bar{q}'$ final states)

Comments on the calculation of corrections

- Main complications in the loop calculation:
  - ◇ gauge-invariant treatment of W and Z resonances
    $\hookrightarrow$ "complex-mass scheme" Denner, S.D., Roth, Wieders '05
  - ◇ numerical instabilities in Passarino–Veltman reduction of tensor integrals
    $\hookrightarrow$ new reduction methods developed Denner, S.D. '05

  New concepts already used in $\mathcal{O}(\alpha)$ correction to $\mathrm{e}^+\mathrm{e}^- \to 4f$
  Denner, S.D., Roth, Wieders '05

- Features of PROPHECY4F:
  - ◇ $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha_\mathrm{s})$ calculation to all channels $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ} \to 4f$
  - ◇ improved Born approximation for simplified evaluation
  - ◇ final-state radiation beyond $\mathcal{O}(\alpha)$ via structure functions
  - ◇ multi-channel Monte Carlo integration (checked by VEGAS)
    Berends, Kleiss, Pittau '94; Kleiss, Pittau '94
  - ◇ still to be done: unweighted events, interface to parton showers

Numerical evaluation of one-loop integrals

Passarino–Veltman reduction of tensor to scalar integrals

$\hookrightarrow$ inverse Gram determinants of external momenta

$\hookrightarrow$ serious numerical instabilities where $\det(G) \to 0$
(at phase-space boundary but not only !)

Our solutions: Denner, S.D., NPB734 (2006) 62 [hep-ph/0509141]

- 1- and 2-point integrals $\longrightarrow$ stable direct calculation
- 3- and 4-point integrals $\longrightarrow$ two hybrid methods
  (i) Passarino–Veltman $\oplus$ seminumerical method $\oplus$ analytical special cases
  (ii) Passarino–Veltman $\oplus$ expansions in small Gram and other kin. determinants
- 5-(and 6-)point integrals
  $\hookrightarrow$ stable reduction to lower-point integrals without Gram determinants

$\Rightarrow$ Techniques ready for further applications
(dim. regularization for IR singularities possible; complex masses supported)

Practical experience

$\hookrightarrow$ Power + reliability of techniques can only be assessed via non-trivial applications !

Checks:

- UV structure of virtual corrections

  $\hookrightarrow$ independence of reference mass μ of dimensional regularization

- IR structure of virtual + soft-photonic corrections

  $\hookrightarrow$ independence of $\ln m_\gamma$ (m_γ = infinitesimal photon mass)

- mass singularities of virtual + related collinear photonic corrections

  $\hookrightarrow$ independence of $\ln m_{f_i}$ (m_{f_i} = small masses of external fermions)

- gauge invariance of amplitudes with $\Gamma_{\mathrm{W}}, \Gamma_{\mathrm{Z}} \neq 0$

  $\hookrightarrow$ identical results in 't Hooft–Feynman and background-field gauge

  Denner, S.D., Weiglein '94

- real corrections

  $\hookrightarrow$ squared amplitudes compared with MADGRAPH Stelzer, Long '94

- combination of virtual and real corrections

  $\hookrightarrow$ identical results with two-cutoff slicing and dipole subtraction

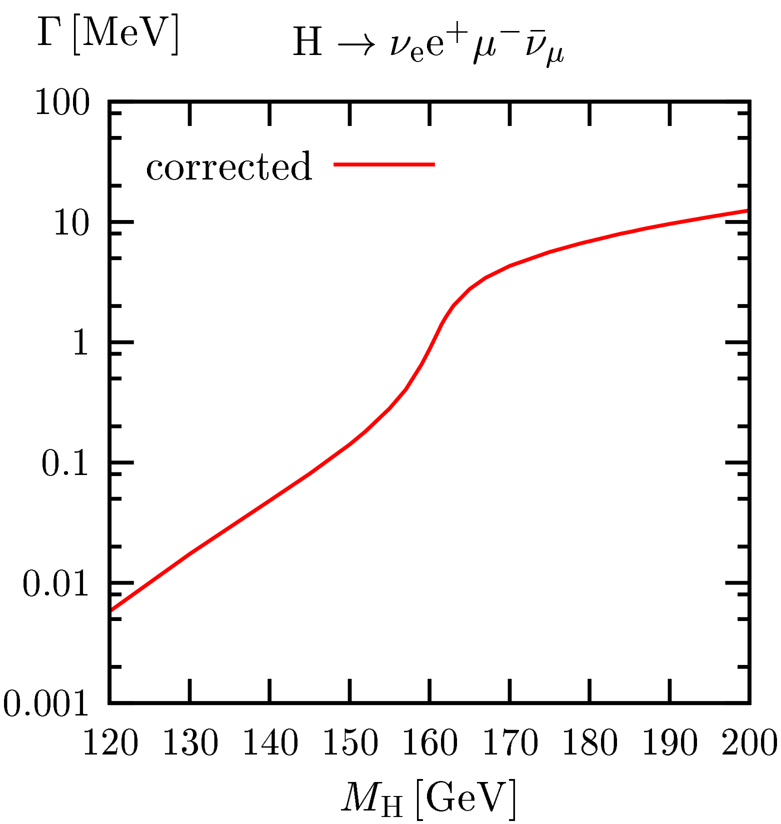
  Catani, Seymour '96; S.D. '00; Bredenstein, S.D., Roth '05

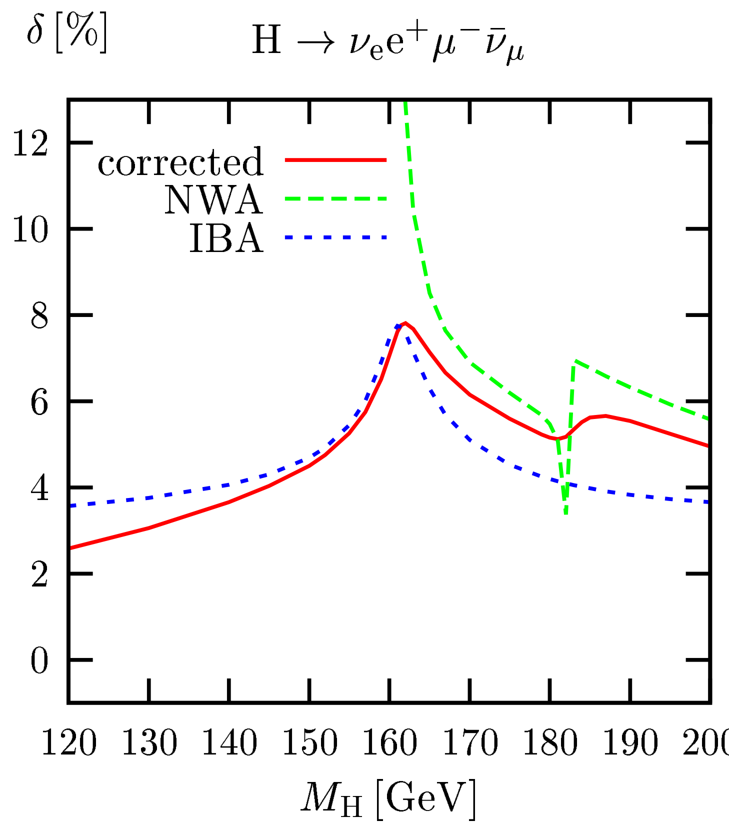
- two completely independent calculations of all ingredients !

3 Selection of numerical results

3.1 Leptonic final states

Partial decay width for $\mathrm{H} \to \mathrm{WW} \to \nu_\mathrm{e}\mathrm{e}^+\mu^-\bar{\nu}_\mu$ G_μ-scheme





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

Bredenstein, Denner, S.D., Weber '06

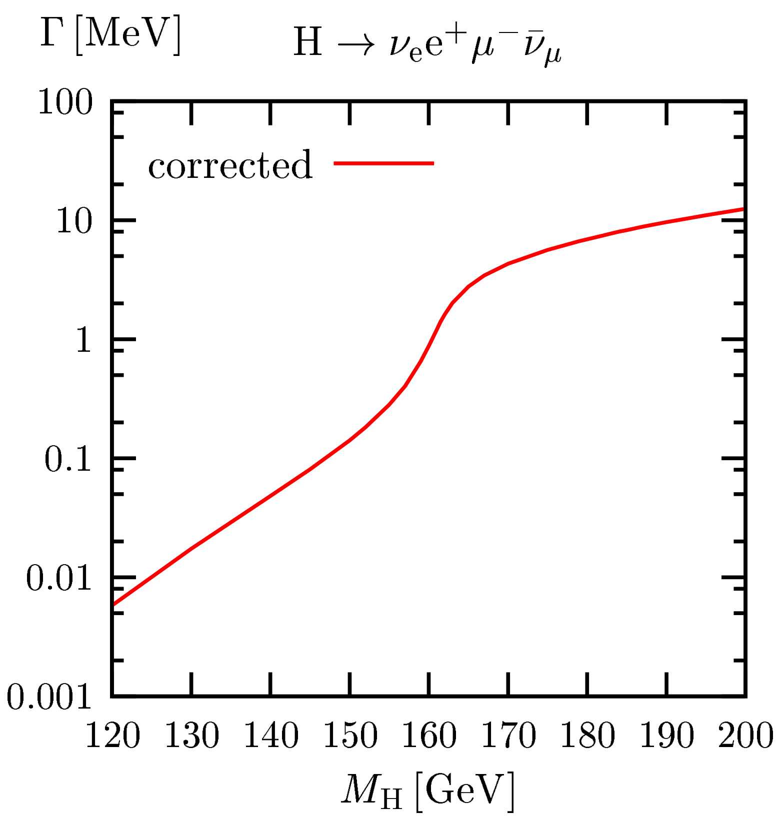
↑ Coulomb singularity for $M_\mathrm{H} \sim 2M_\mathrm{W}$

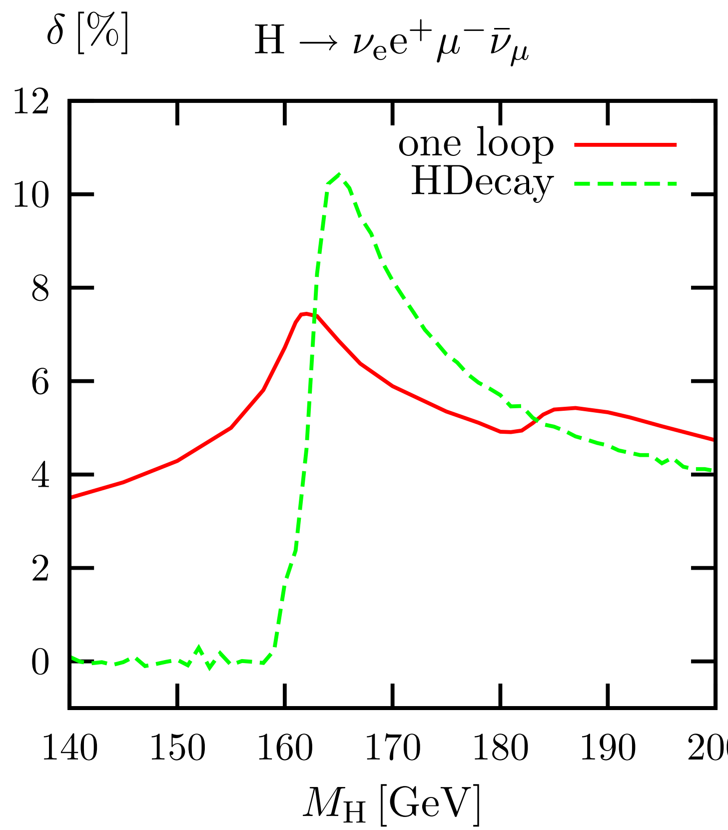
↑ threshold effect in loops for $M_\mathrm{H} \sim 2M_\mathrm{Z}$

NWA = narrow-width approximation

IBA = improved Born approximation
(Coulomb singularity, one fitting constant, leading effects for $M_\mathrm{H}, m_\mathrm{t} \gg M_\mathrm{W}$)

Comparison with HDECAY





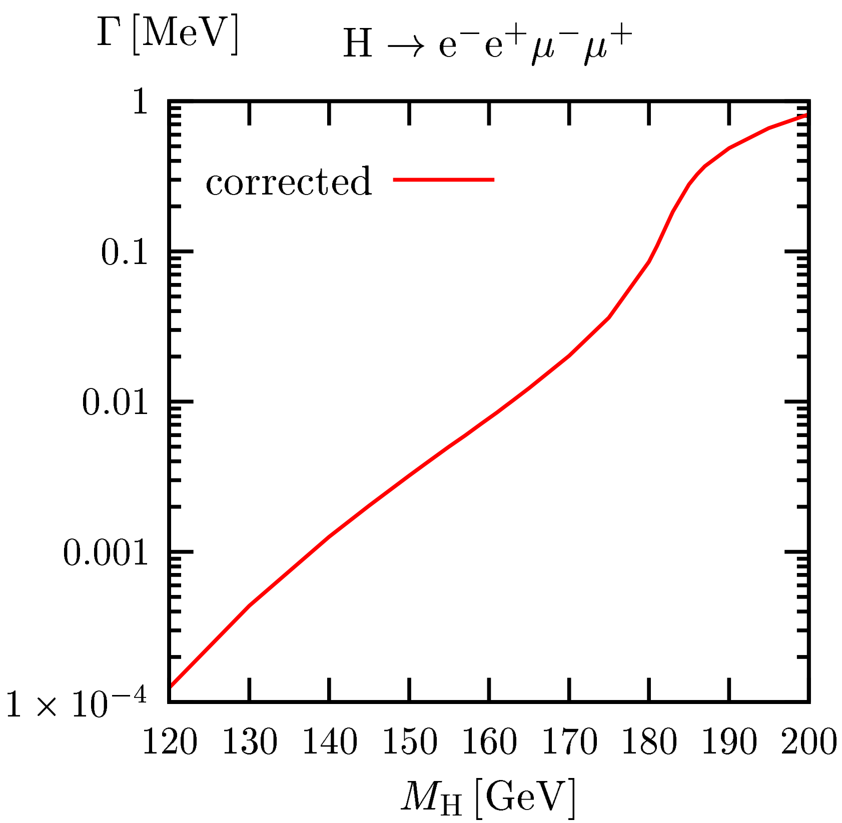
$$\delta = \frac{\Gamma}{\Gamma_{\text{Born}}} - 1$$

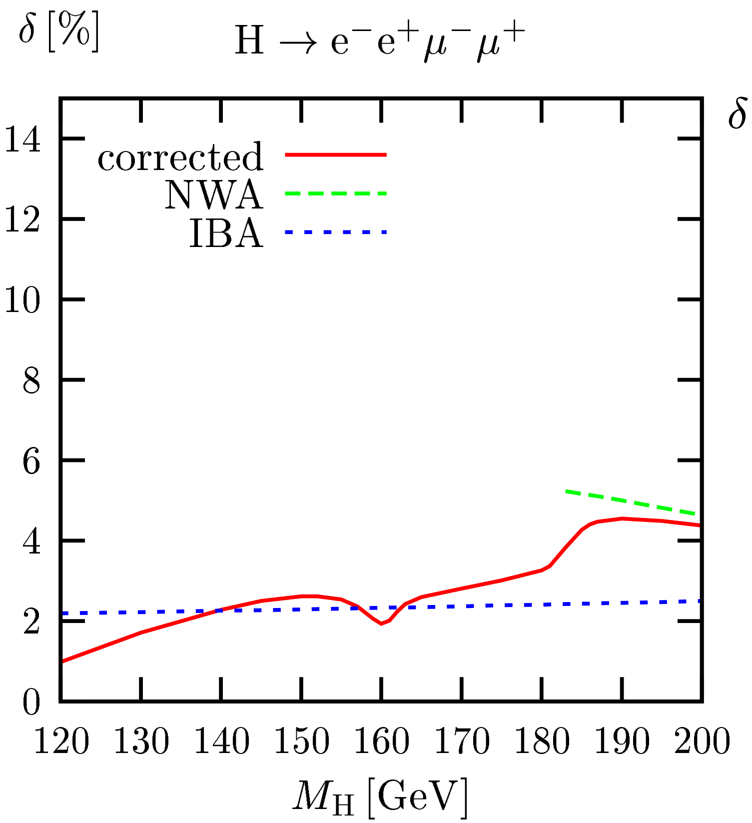
↑ Coulomb singularity for $M_\mathrm{H} \sim 2M_\mathrm{W}$

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

Note: peak structure in HDECAY is an artefact of the on-shell approximation above threshold.

Partial decay width for $\mathrm{H} \to \mathrm{ZZ} \to \mathrm{e}^-\mathrm{e}^+\mu^-\mu^+$ G_μ-scheme





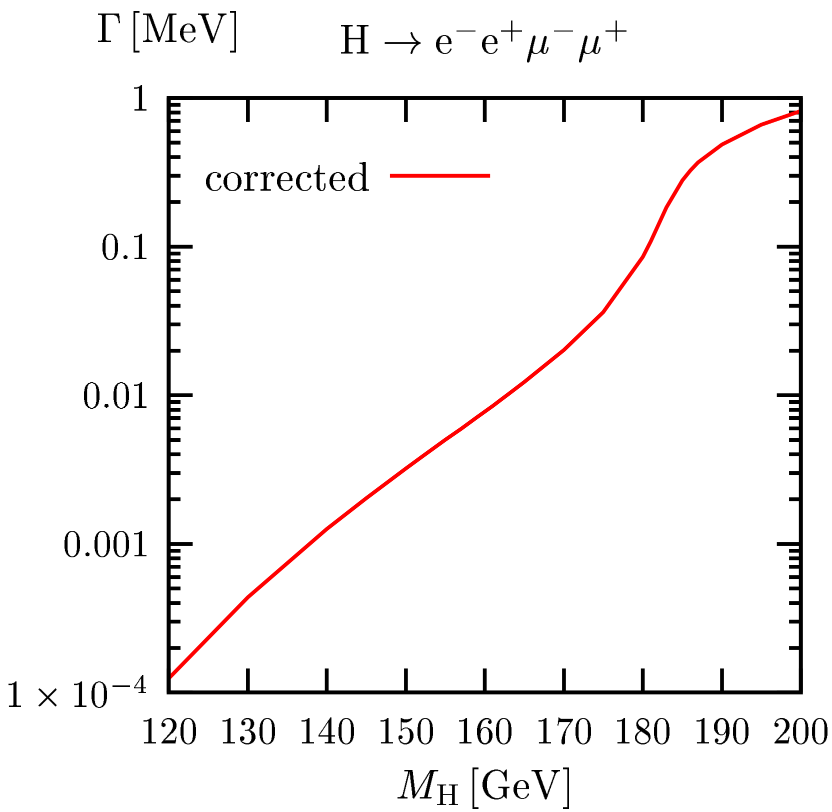
$$\delta = \frac{\Gamma}{\Gamma_{\mathrm{Born}}} - 1$$

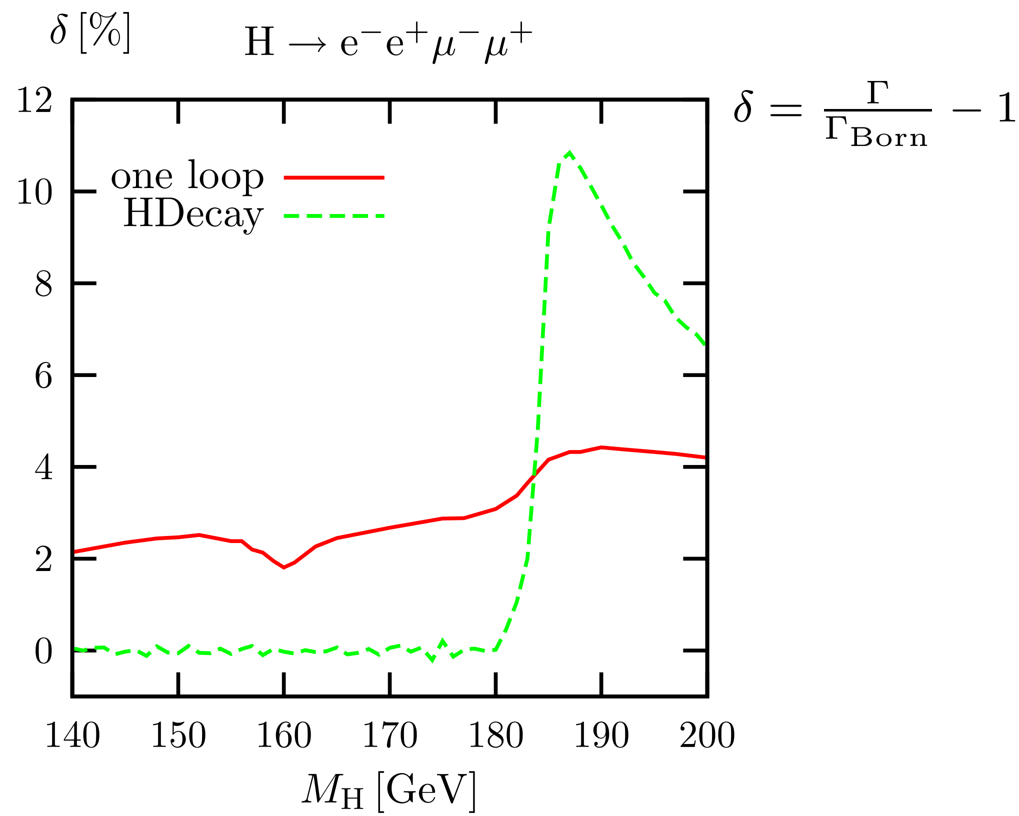
Bredenstein, Denner, S.D., Weber '06

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

↑ kinematic threshold at $M_\mathrm{H} \sim 2M_\mathrm{Z}$

Comparison with HDECAY





↑ threshold effect in loops for $M_H \sim 2M_W$

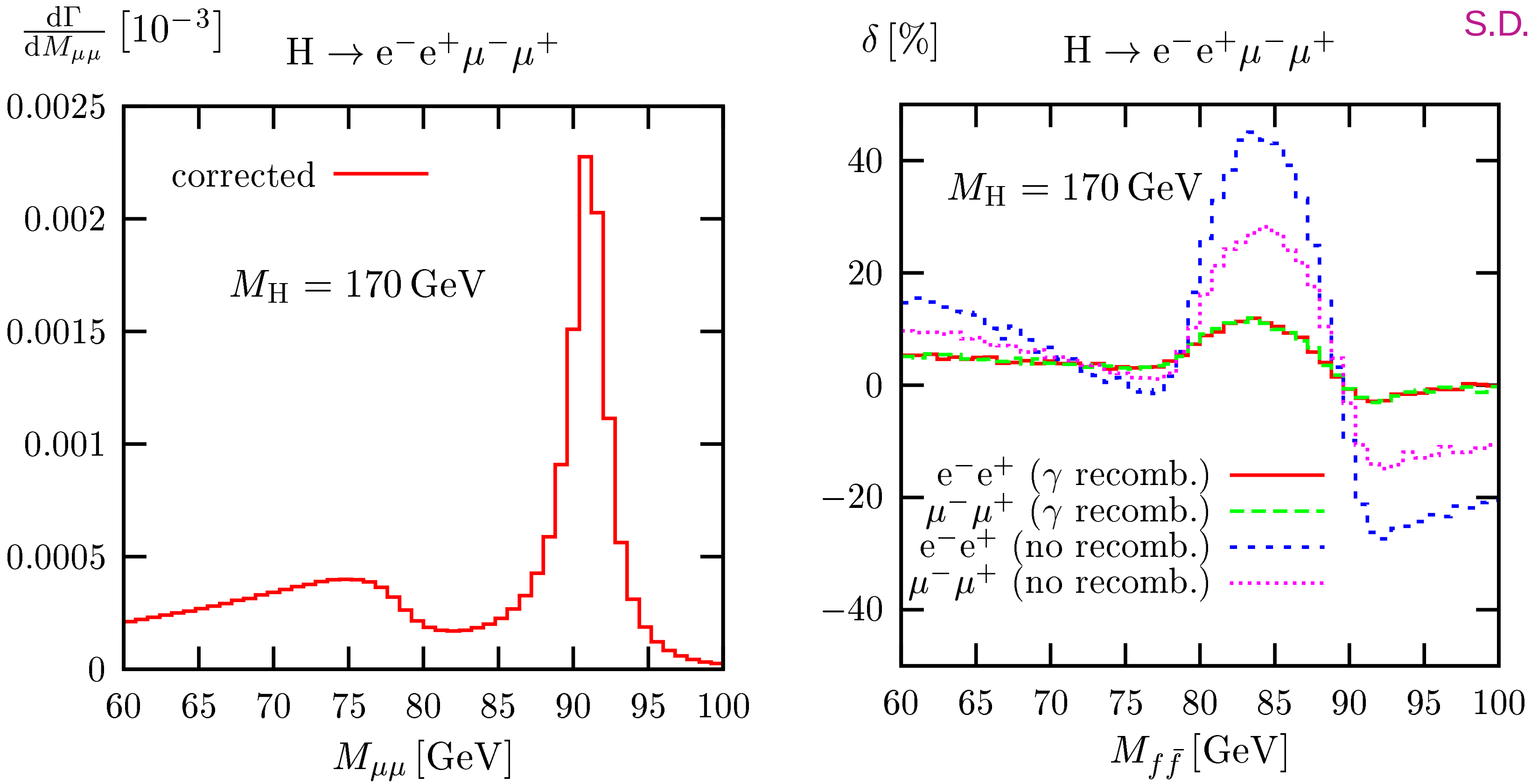
↑ kinematic threshold at $M_H \sim 2M_Z$

Note: peak structure in HDECAY is an artefact of the on-shell approximation above threshold.

Invariant-mass distribution for the Z boson in $\mathrm{H} \to \mathrm{ZZ} \to \mathrm{e}^-\mathrm{e}^+\mu^-\mu^+$

G_μ-scheme

Bredenstein, Denner, S.D., Weber '06

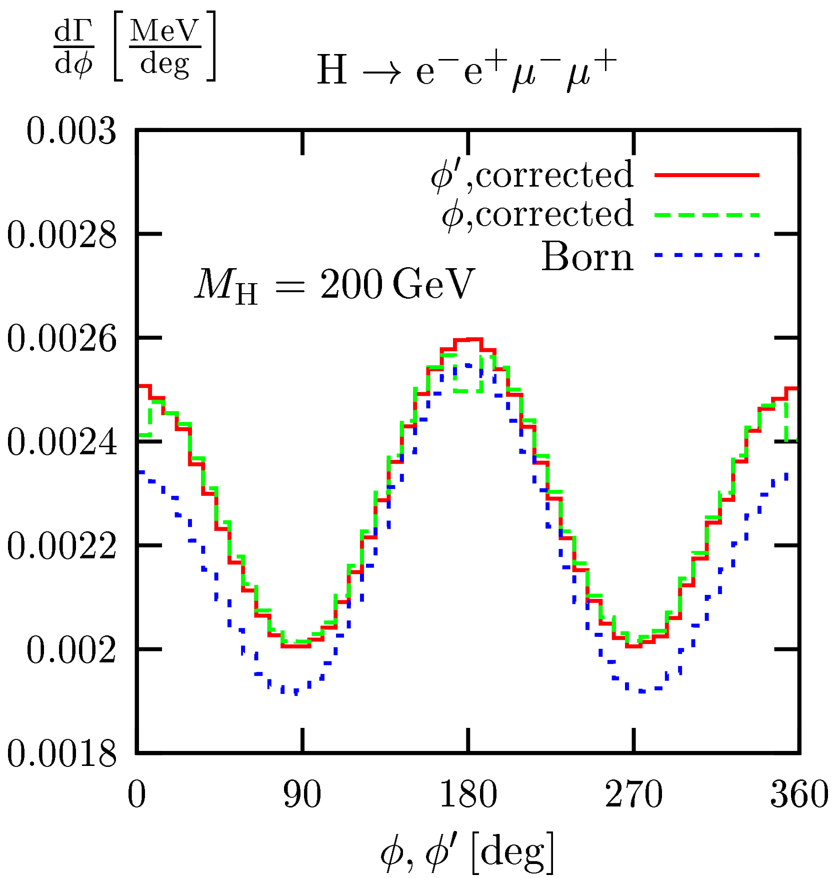


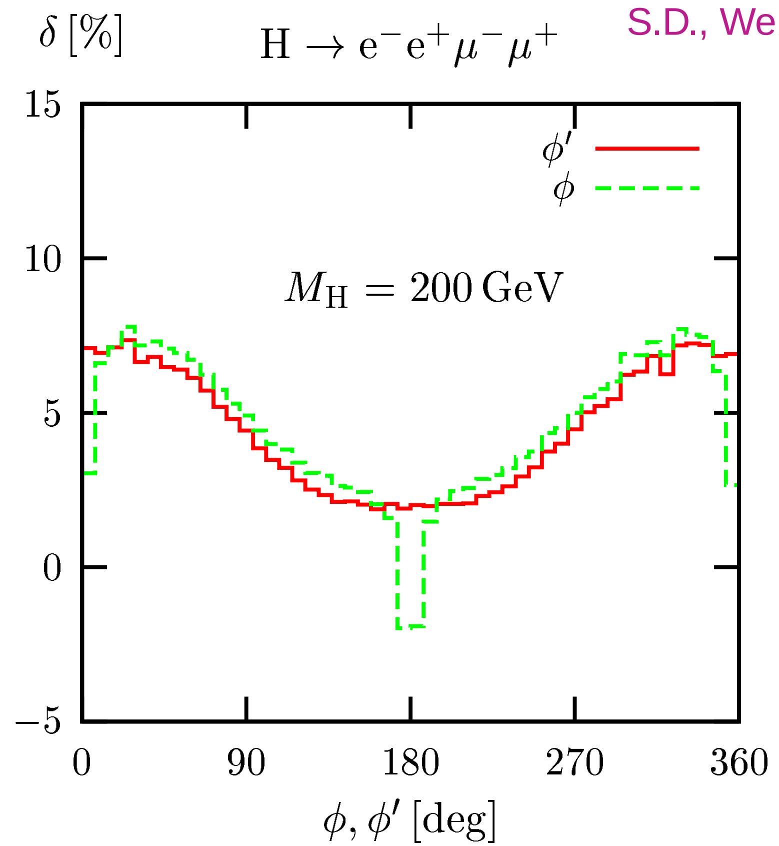
γ recombination if $M_{\mathrm{e}\gamma/\mu\gamma} < 5\,\mathrm{GeV}$

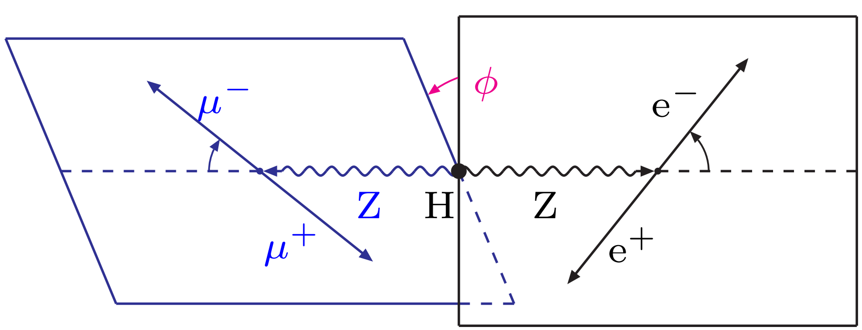
Large corrections from photon radiation in Z reconstruction

Angle between decay planes for $\mathrm{H} \to \mathrm{ZZ} \to \mathrm{e}^-\mathrm{e}^+\mu^-\mu^+$ $\qquad G_\mu$-scheme

Bredenstein, Denner, S.D., Weber '06







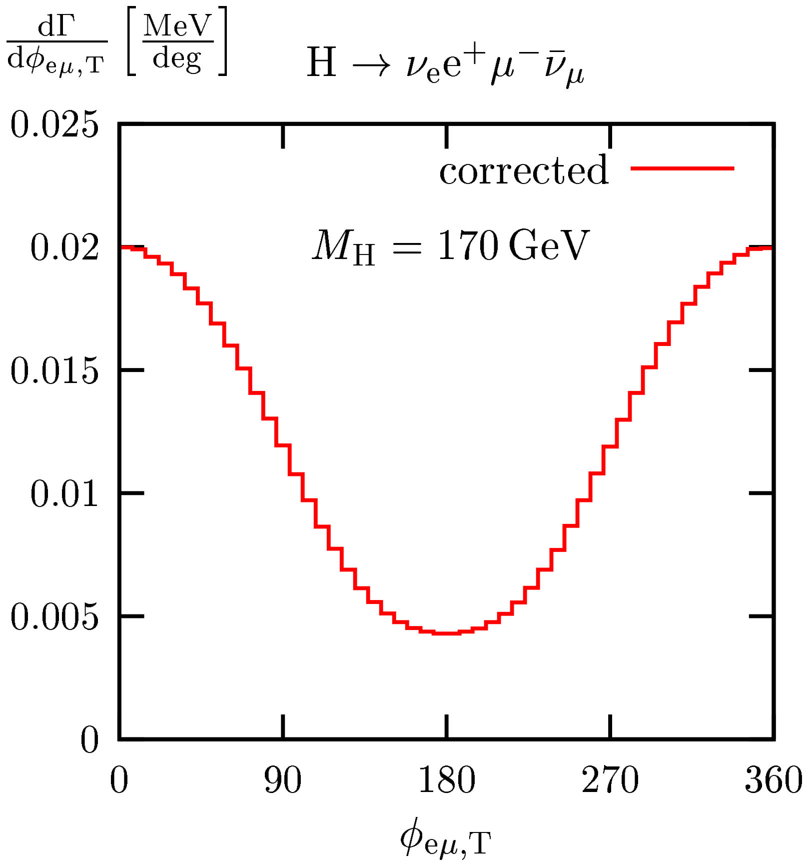
$$\cos\phi = \frac{\left(\mathbf{p}_{\mathrm{e}^-\mathrm{e}^+} \times \mathbf{p}_{\mathrm{e}^-}\right)\left(-\mathbf{p}_{\mu^-\mu^+} \times \mathbf{p}_{\mu^-}\right)}{\left|\mathbf{p}_{\mathrm{e}^-\mathrm{e}^+} \times \mathbf{p}_{\mathrm{e}^-}\right|\left|-\mathbf{p}_{\mu^-\mu^+} \times \mathbf{p}_{\mu^-}\right|}$$

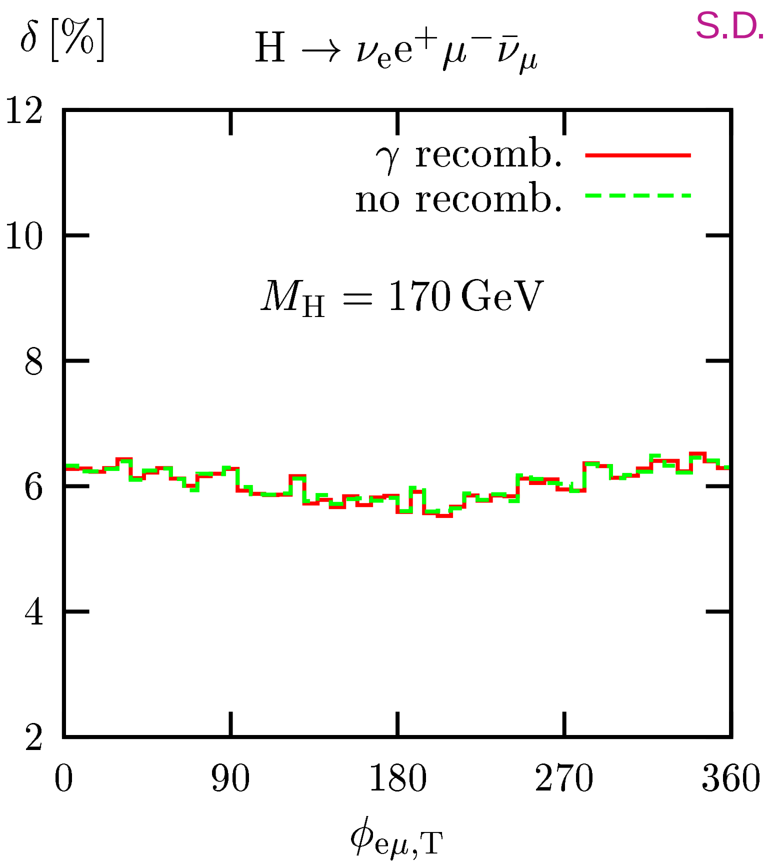
$$\cos\phi' = \frac{\left(\mathbf{p}_{\mathrm{e}^-\mathrm{e}^+} \times \mathbf{p}_{\mathrm{e}^-}\right)\left(\mathbf{p}_{\mathrm{e}^-\mathrm{e}^+} \times \mathbf{p}_{\mu^-}\right)}{\left|\mathbf{p}_{\mathrm{e}^-\mathrm{e}^+} \times \mathbf{p}_{\mathrm{e}^-}\right|\left|\mathbf{p}_{\mathrm{e}^-\mathrm{e}^+}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

Distribution in the transverse angle between e^+ and μ^- in $\mathrm{H} \to \mathrm{WW} \to \nu_\mathrm{e}\mathrm{e}^+\mu^-\bar{\nu}_\mu$

G_μ-scheme

Bredenstein, Denner, S.D., Weber '06





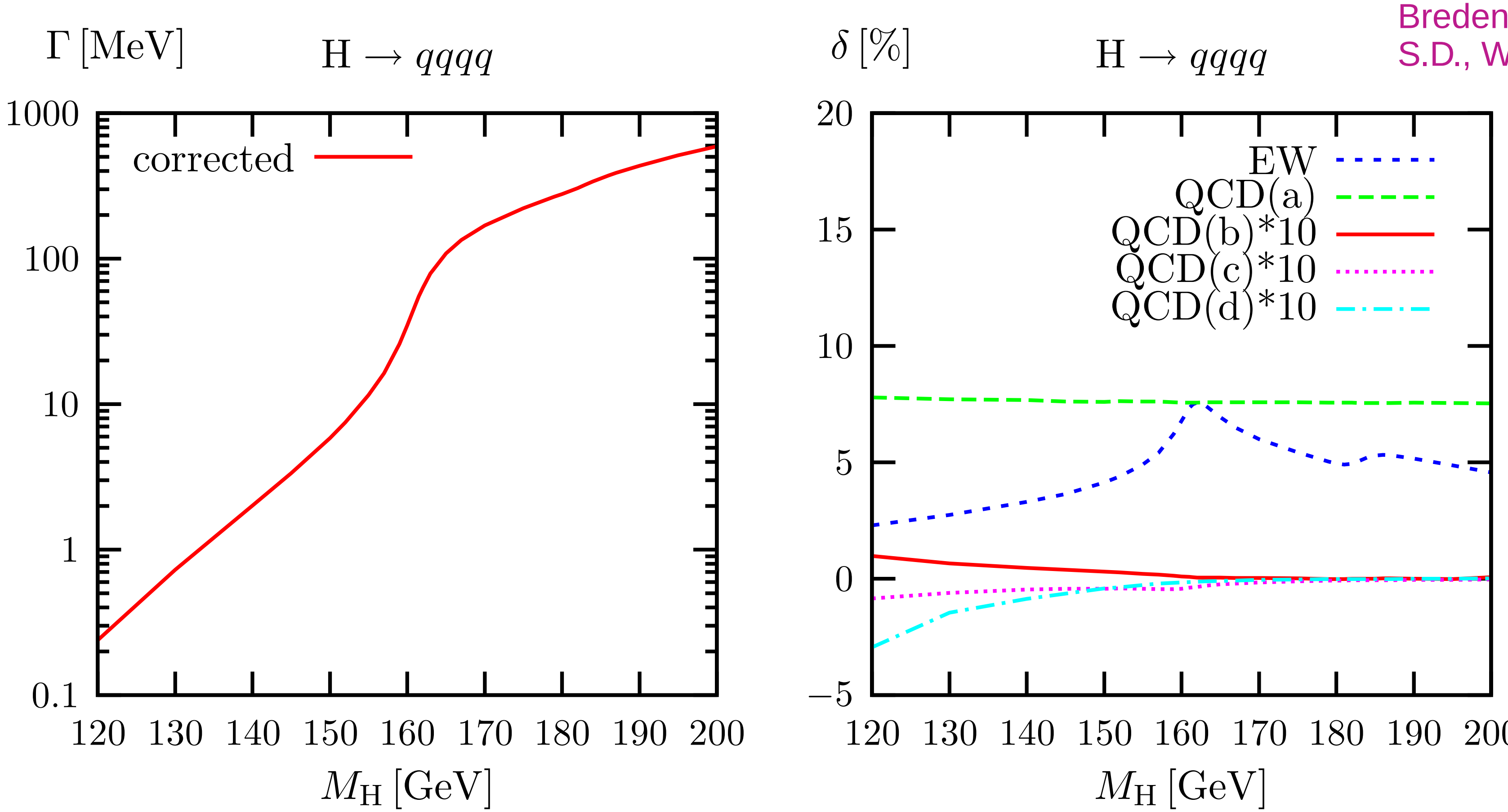
No significant distortion of shape by electroweak corrections

3.2 Semileptonic and hadronic final states

EW corrections: very similar for leptonic, semileptonic, and hadronic final states

QCD corrections: only type (a) significant (=corrections to W/Z decays)

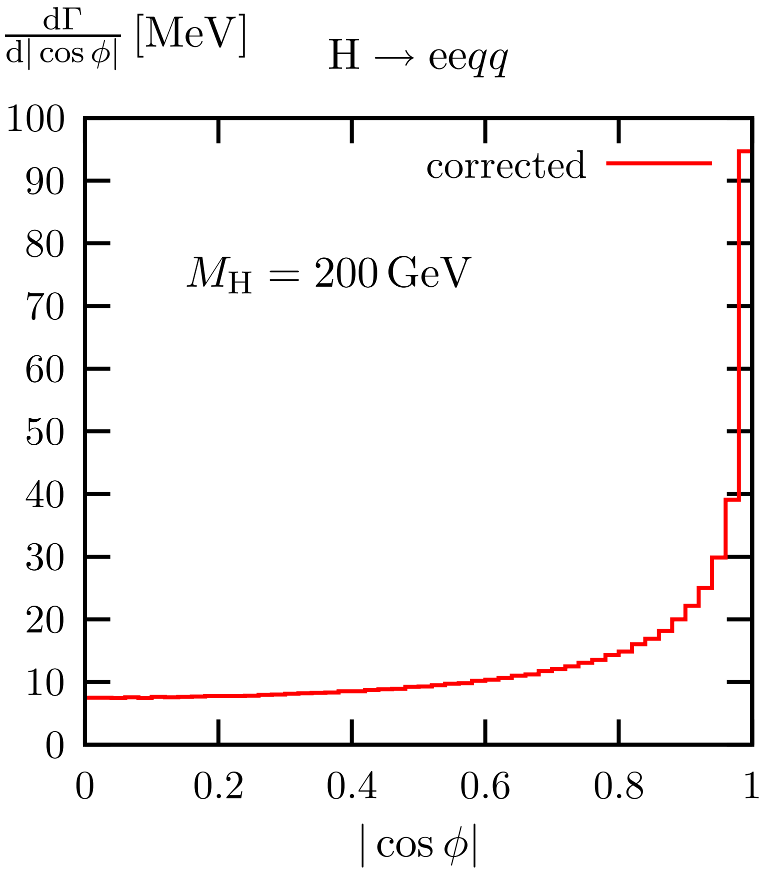
Bredenstein, Denner, S.D., Weber ’06

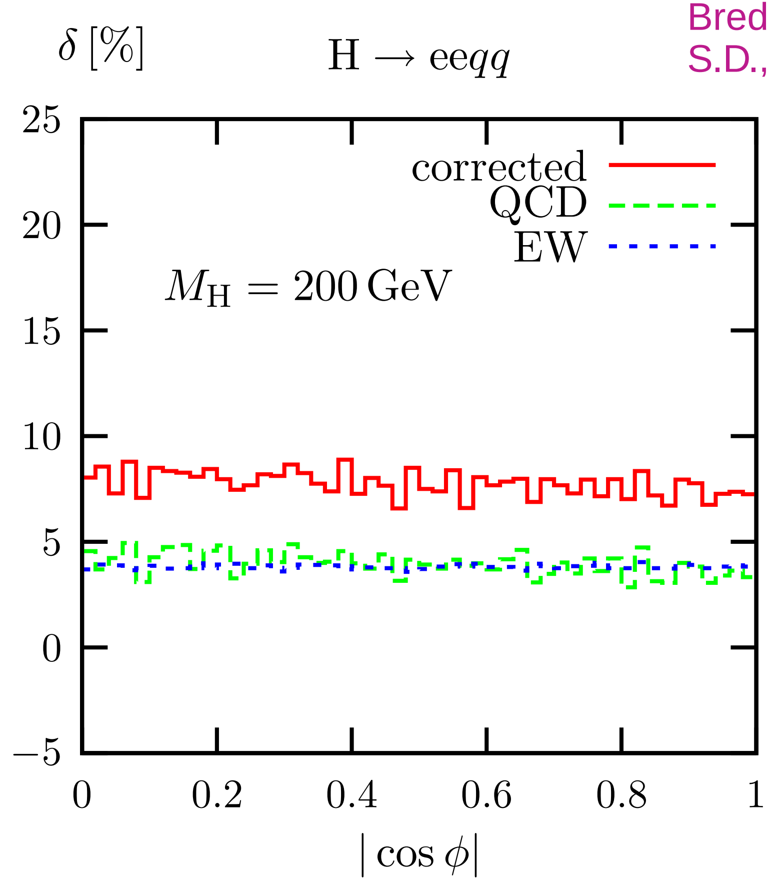


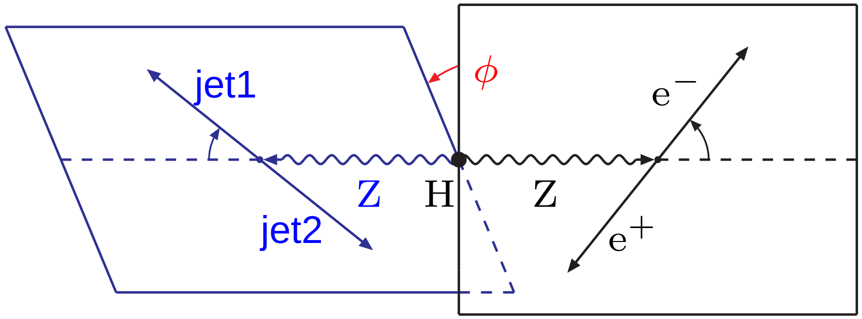
$$\delta_{\mathrm{QCD}}^{\mathrm{semileptonic}} \approx \frac{\alpha_s}{\pi} = 3.8\%, \qquad \delta_{\mathrm{QCD}}^{\mathrm{hadronic}} \approx \frac{2\alpha_s}{\pi} = 7.6\%,$$

Angle between decay planes for $\mathrm{H} \to \mathrm{ZZ} \to \mathrm{e^-e^+}qq$ G_μ-scheme

Bredenstein, Denner, S.D., Weber ’06







$$\cos\phi = \frac{(\mathbf{p}_{2\mathrm{jets}} \times \mathbf{p}_{\mathrm{e}^-})(\mathbf{p}_{\mathrm{jet1}} \times \mathbf{p}_{\mathrm{jet2}})}{|\mathbf{p}_{2\mathrm{jets}} \times \mathbf{p}_{\mathrm{e}^-}||\mathbf{p}_{\mathrm{jet1}} \times \mathbf{p}_{\mathrm{jet2}}|}$$

4 Conclusions

Higgs decays $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ} \to 4f$ are important for

- Higgs discovery at the LHC and precision Higgs studies at the ILC
- confirmation of Higgs quantum numbers (spin, CP) via differential distributions

NEW: PROPHECY4F – a generator for $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ} \to 4f$ including

- full $\mathcal{O}(\alpha)$ EW and $\mathcal{O}(\alpha_\mathrm{s})$ QCD corrections
  - W and Z resonances treated within the complex-mass scheme
  - tensor reduction numerically stabilized via seminumerical or expansion methods
- universal corrections beyond $\mathcal{O}(\alpha)$ (FSR via structure functions, large-M_H effects)

First results of PROPHECY4F on $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ} \to 4f$

- partial decay widths: EW corrections of $\mathcal{O}(8\%)$ for $M_\mathrm{H} \lesssim 500\,\mathrm{GeV}$
  (reproduced by a simple improved Born approximation within $\lesssim 2\%$ for $M_\mathrm{H} \lesssim 400\,\mathrm{GeV}$)
- angular distributions: EW corrections of $\mathcal{O}(5{-}10\%)$ distort shapes
- invariant-mass distributions of W's and Z's:
  EW corrections of some 10% distort shapes (depend on inclusiveness of γ radiation)
- QCD corrections can be associated with W/Z decay (interference effects negligible)