Electroweak corrections to $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ} \to 4$ leptons

Stefan Dittmaier

MPI Munich

in collaboration with A. Bredenstein, A. Denner and M.M. Weber

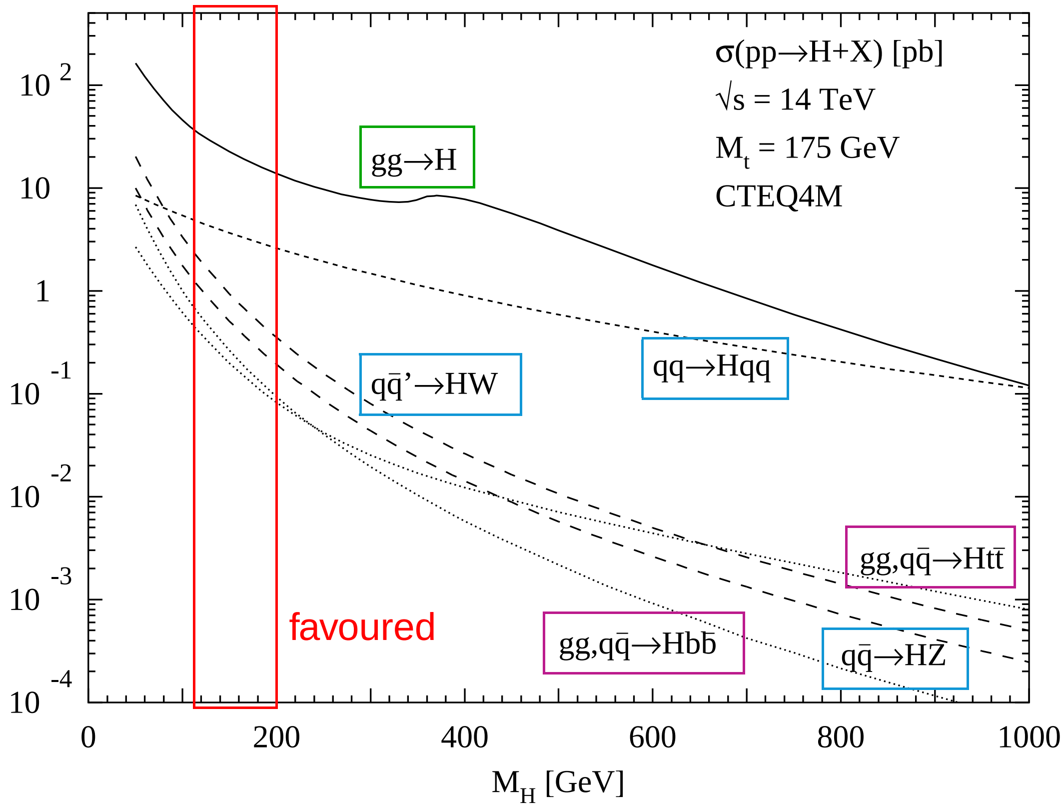
based on hep-ph/0604011

Contents

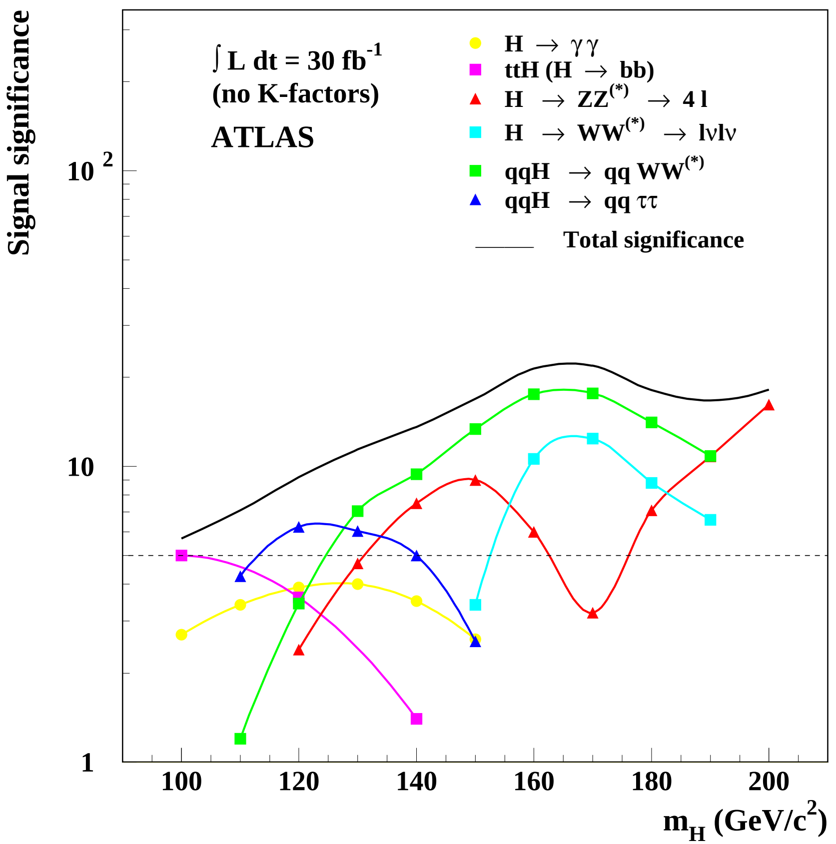
1 Introduction — the decays $H \to WW/ZZ \to 4$ fermions

Cross sections and significance of the Higgs signal at the LHC

Spira et al. '98



ATLAS '03



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

– most important Higgs decay channels for $M_\mathrm{H} \gtrsim 125\,\mathrm{GeV}$

– most precise determination of M_H via $\mathrm{H} \to \mathrm{ZZ} \to 4$ leptons for $M_\mathrm{H} \gtrsim 130\,\mathrm{GeV}$

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

- existing 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 for 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.'03

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

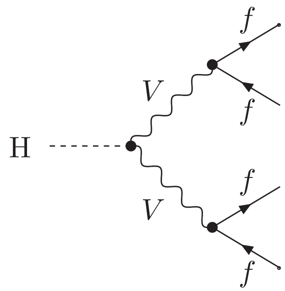
Recent work and work in progress:

- PROPHECY4F: generator for $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ} \to 4f$ with electroweak 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 electroweak corrections

Survey of Feynman diagrams

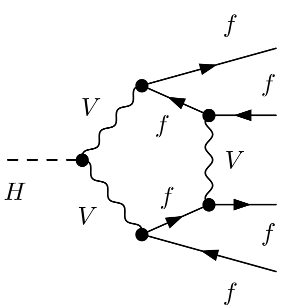
Lowest order:



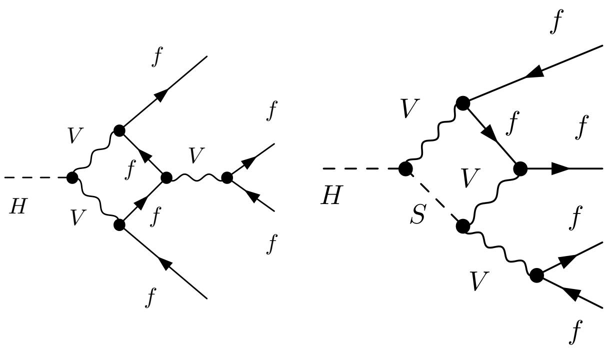
Electroweak $\mathcal{O}(\alpha)$ corrections:

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

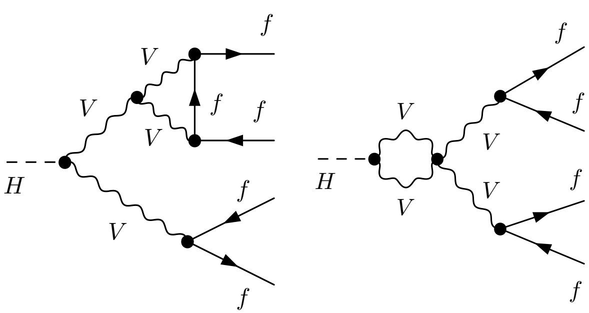
pentagons



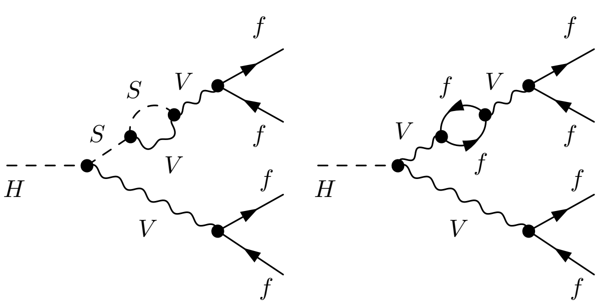
boxes



vertices



self-energies



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

Comments on the $\mathcal{O}(\alpha)$ calculation

- Main complications in the loop calculation:
  - ◇ gauge-invariant treatment of W and Z resonances
    $\hookrightarrow$ "complex-mass scheme" Denner, S.D., Roth, Wieders '05
    $\hookrightarrow$ talk of A. Denner
  - ◇ 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:
  - ◇ $\mathcal{O}(\alpha)$ 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
  - ◇ in progress: unweighted events and QCD corrections for final-state quarks

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 $\quad \to$ stable direct calculation
- 3- and 4-point integrals $\quad \to$ 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

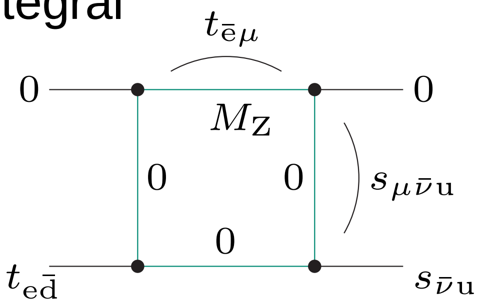
(dim. regularization for IR singularities possible; complex masses supported)

Practical experience

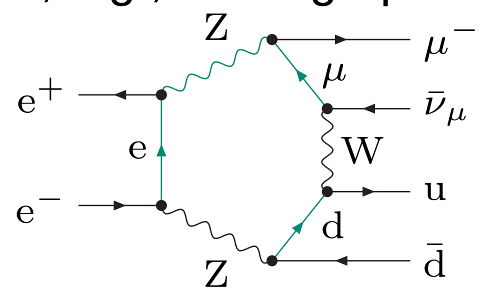
$\hookrightarrow$ Power + reliability of techniques can only be assessed via non-trivial applications !

A typical example with small Gram determinant:

Box integral

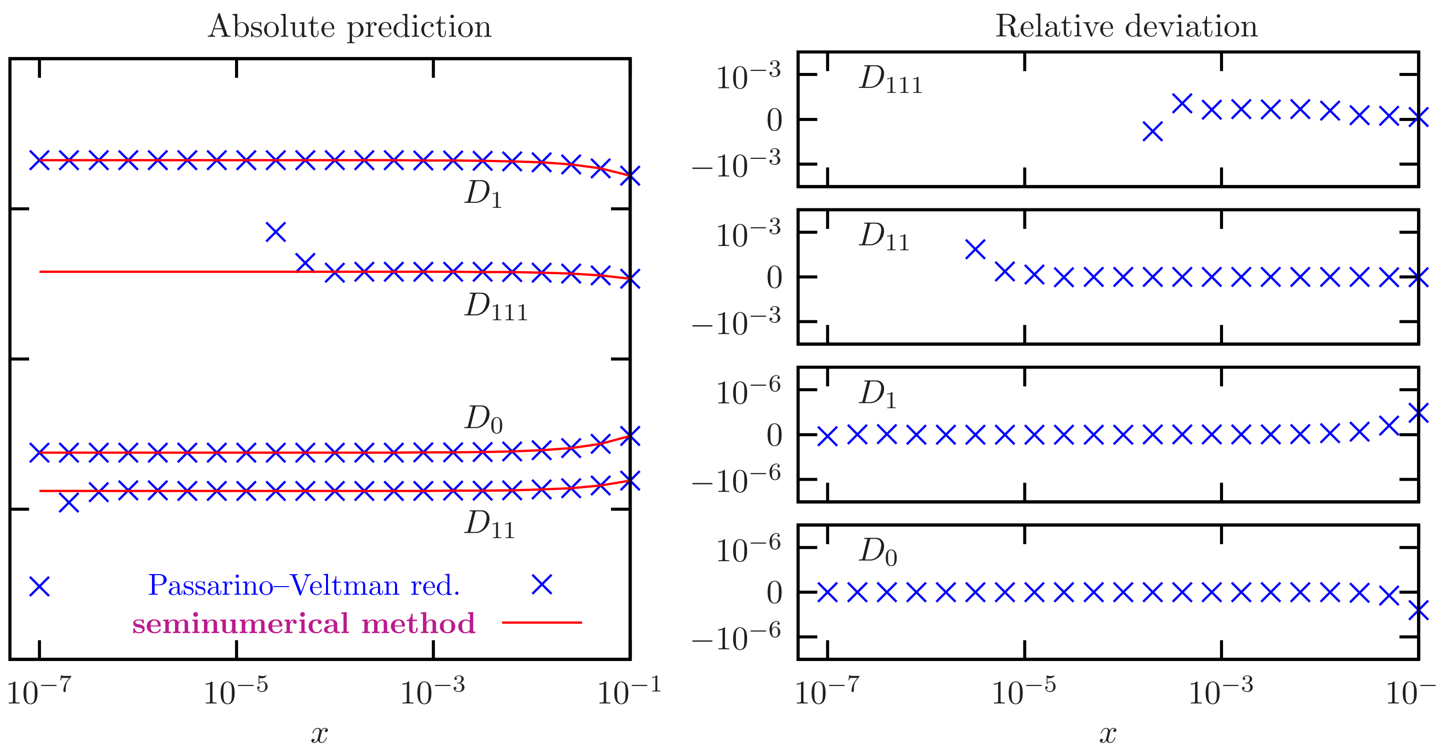


appears, e.g., in subgraph of diagram



Gram det.: $\det(G) \to 0$ if $t_{\mathrm{e}\bar{\mathrm{d}}} \to t_\mathrm{crit} \equiv \dfrac{s_{\mu\bar{\nu}\mathrm{u}}(s_{\mu\bar{\nu}\mathrm{u}} - s_{\bar{\nu}\mathrm{u}} + t_{\bar{\mathrm{e}}\mu})}{s_{\mu\bar{\nu}\mathrm{u}} - s_{\bar{\nu}\mathrm{u}}}$

Passarino–Veltman versus seminumerical method:



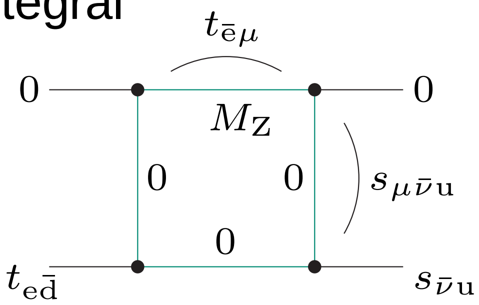
$$x \equiv \frac{t_{\mathrm{e}\bar{\mathrm{d}}}}{t_\mathrm{crit}} - 1$$

$$\begin{aligned} s_{\mu\bar{\nu}\mathrm{u}} &= +2\times10^4\,\mathrm{GeV}^2 \\ s_{\bar{\nu}\mathrm{u}} &= +1\times10^4\,\mathrm{GeV}^2 \\ t_{\bar{\mathrm{e}}\mu} &= -4\times10^4\,\mathrm{GeV}^2 \\ t_\mathrm{crit} &= -6\times10^4\,\mathrm{GeV}^2 \end{aligned}$$

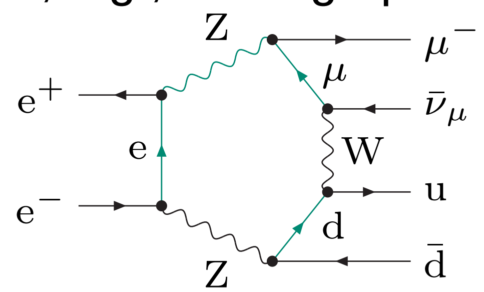
PV reduction breaks down,
but seminum. method stable
for $\det(G) \to 0$!

A typical example with small Gram determinant:

Box integral

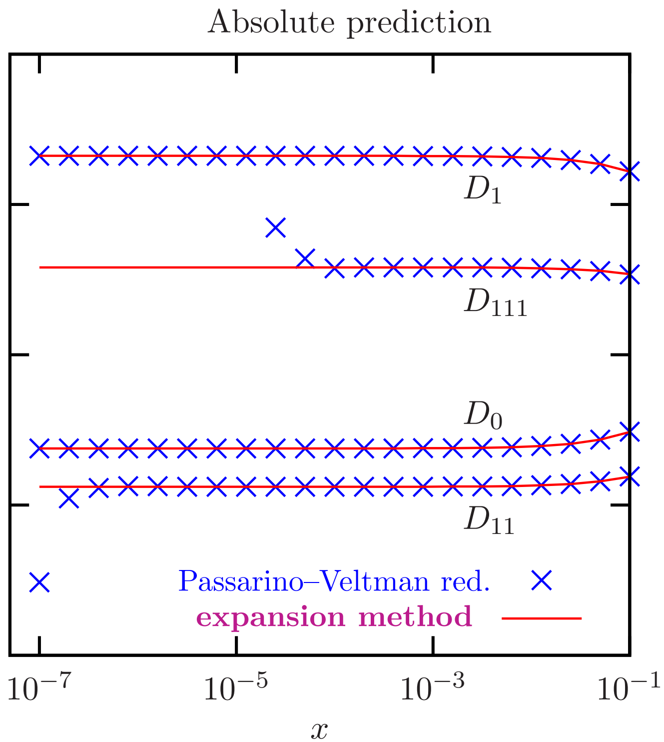


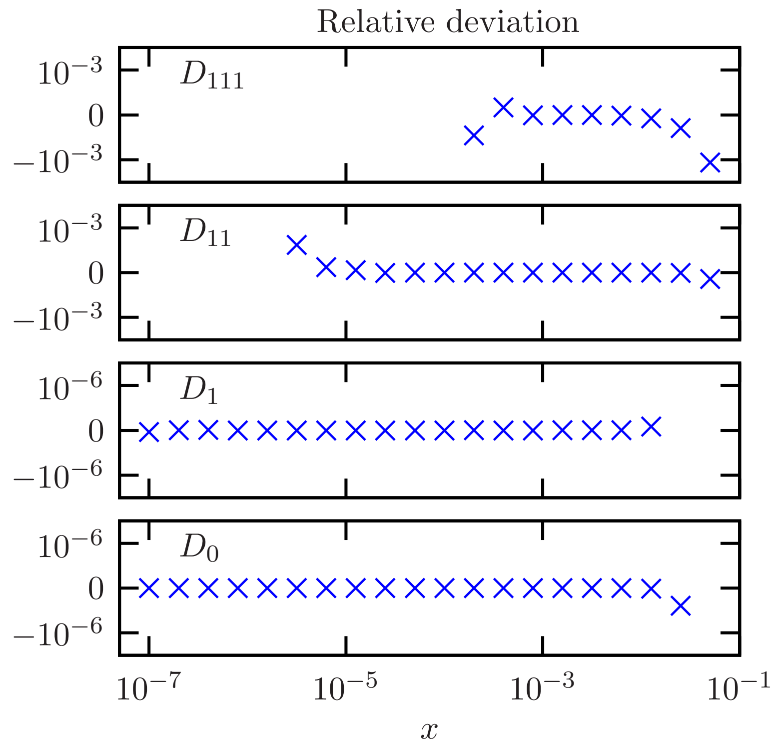
appears, e.g., in subgraph of diagram



Gram det.: $\det(G) \rightarrow 0$ if $t_{e\bar{d}} \rightarrow t_{crit} \equiv \dfrac{s_{\mu\bar{\nu}u}(s_{\mu\bar{\nu}u} - s_{\bar{\nu}u} + t_{\bar{e}\mu})}{s_{\mu\bar{\nu}u} - s_{\bar{\nu}u}}$

Passarino–Veltman versus expansion method:





$$x \equiv \frac{t_{e\bar{d}}}{t_{crit}} - 1$$

$$\begin{aligned} s_{\mu\bar{\nu}u} &= +2\times10^4 \text{ GeV}^2 \\ s_{\bar{\nu}u} &= +1\times10^4 \text{ GeV}^2 \\ t_{\bar{e}\mu} &= -4\times10^4 \text{ GeV}^2 \\ t_{crit} &= -6\times10^4 \text{ GeV}^2 \end{aligned}$$

PV reduction breaks down,

but expansion method stable

for $\det(G) \rightarrow 0$!

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

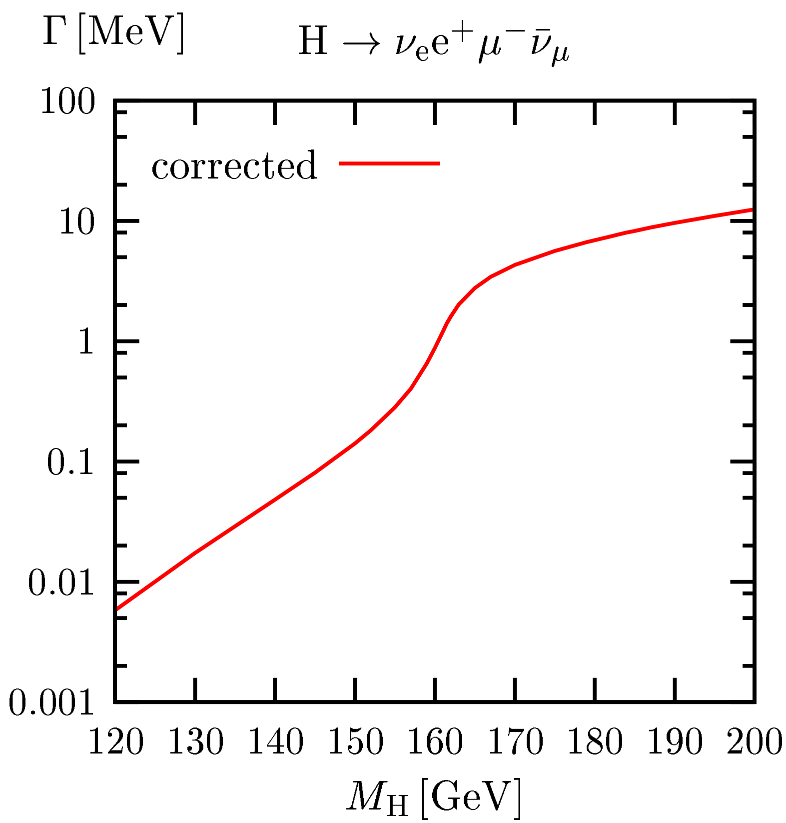
  $\hookrightarrow$ identical results with two-cutoff slicing and dipole subtraction

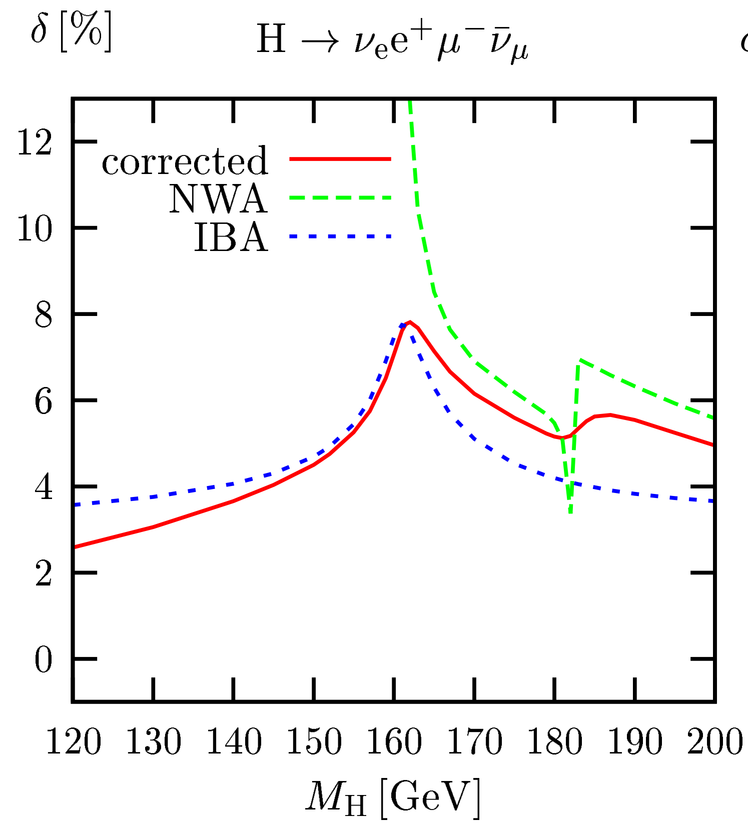
  Catani, Seymour '96; S.D. '00

- two completely independent calculations of all ingredients !

3 Numerical results

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





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

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

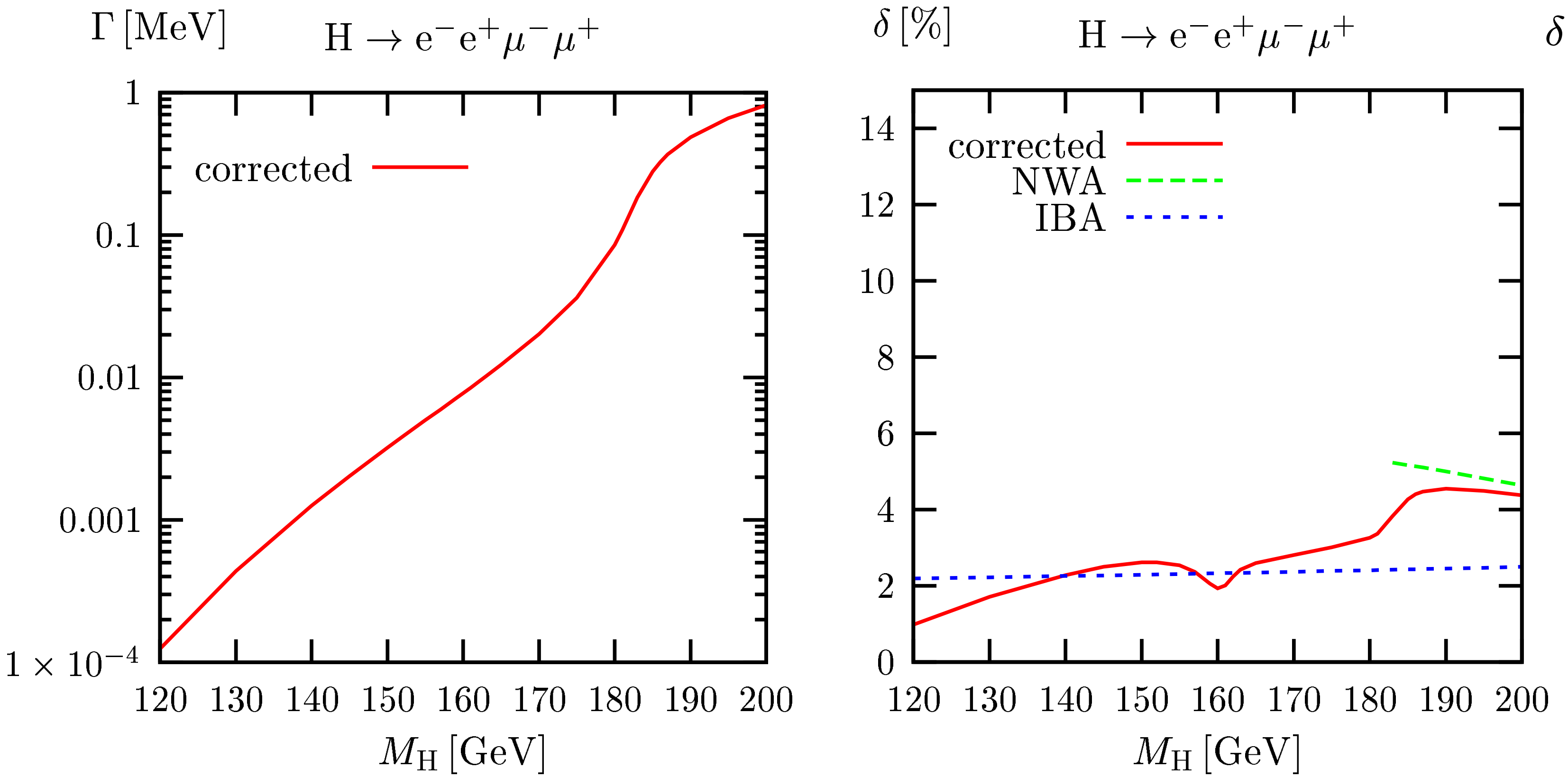
↑ Coulomb singularity for $M_{\mathrm{H}} \sim 2M_{\mathrm{W}}$

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

NWA = narrow-width approximation

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

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



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

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

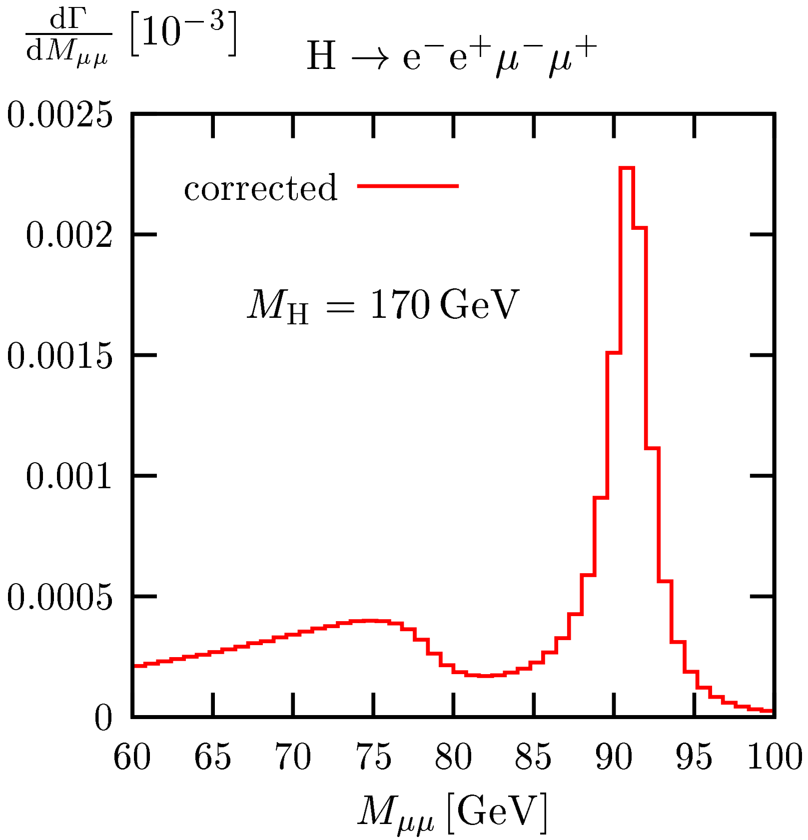
↑ threshold effect in loops for $M_\mathrm{H} \sim 2M_\mathrm{W}$

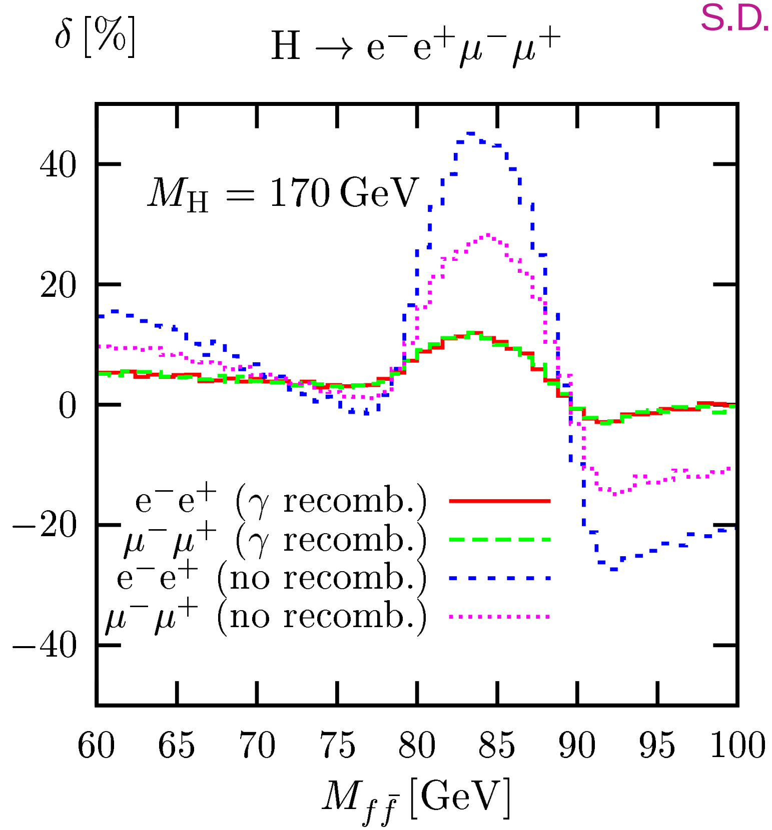
↑ kinematic threshold at $M_\mathrm{H} \sim 2M_\mathrm{Z}$

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



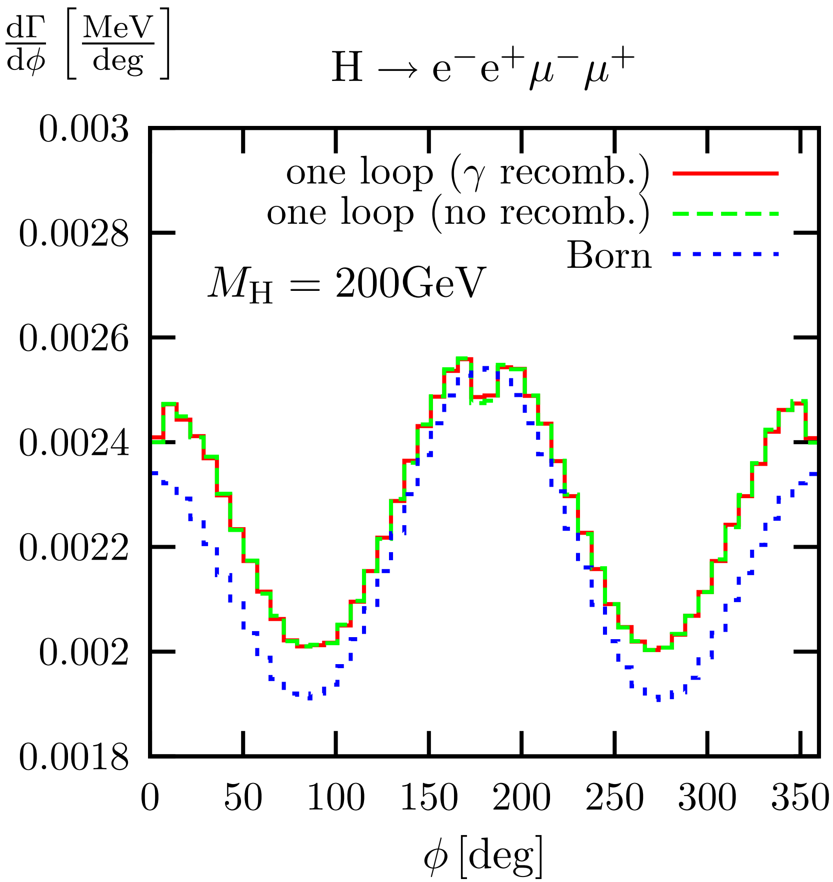


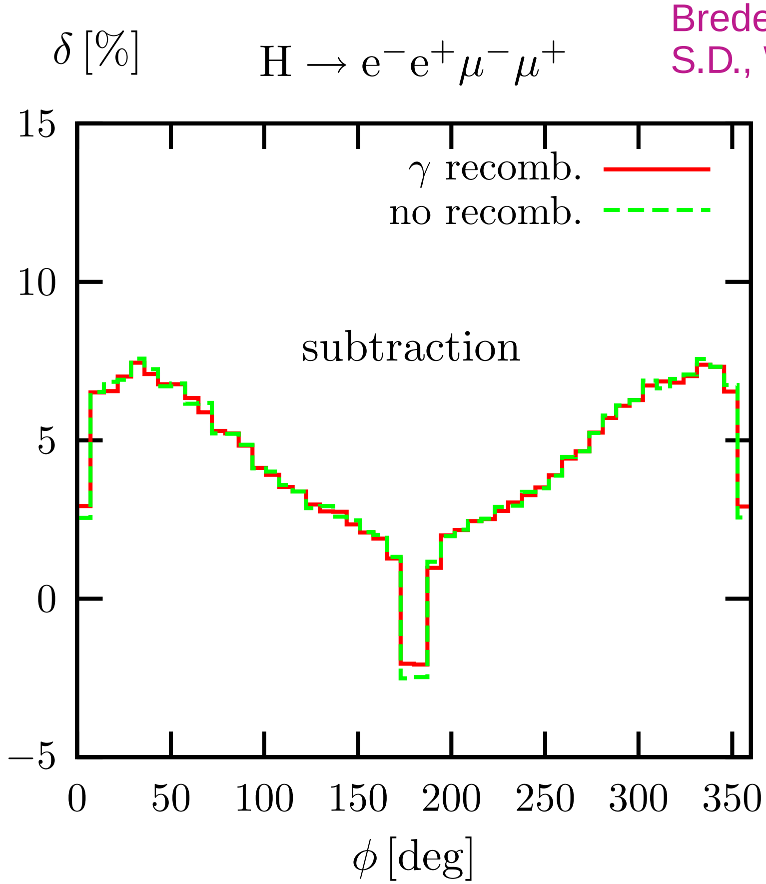
γ recombination if $M_{\mathrm{e}\gamma/\mu\gamma} < 5\,\mathrm{GeV}$

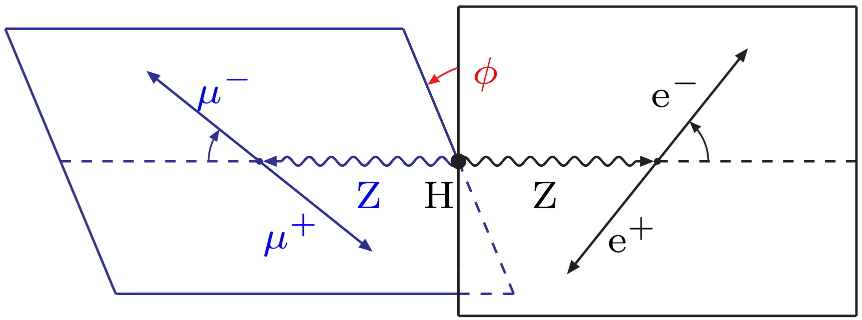
Large corrections from photon radiation in Z reconstruction

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

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



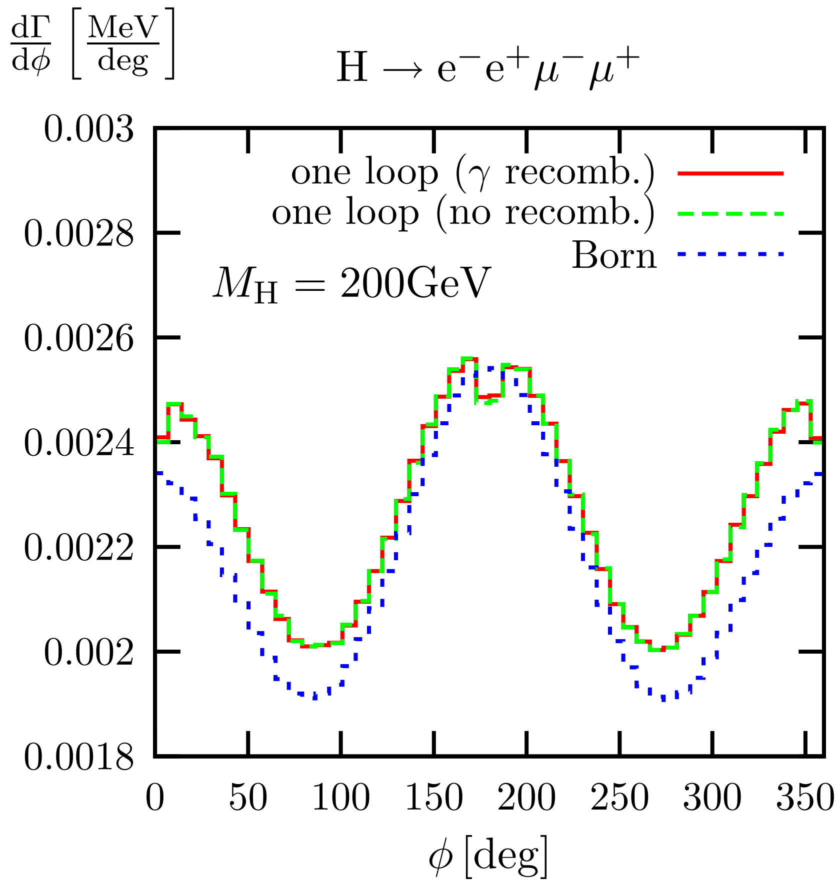


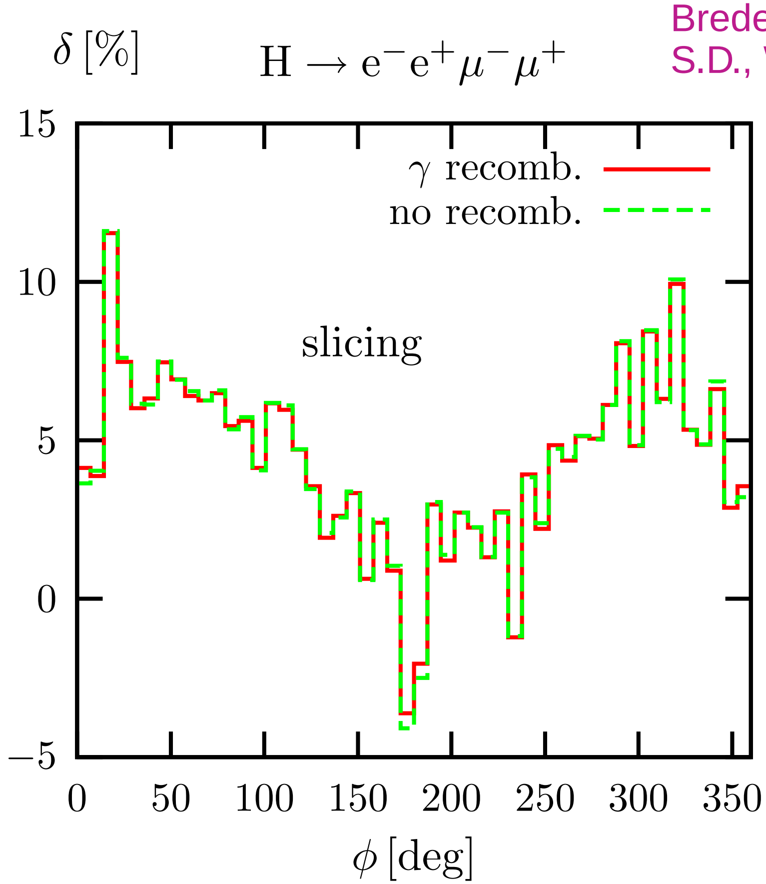


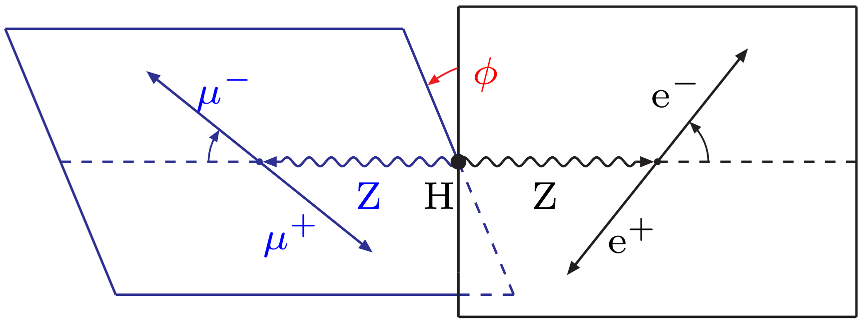
$$\cos\phi = \frac{\left((\mathbf{p}_{\mathrm{e}^-}+\mathbf{p}_{\mathrm{e}^+})\times\mathbf{p}_{\mathrm{e}^-}\right)\left(-(\mathbf{p}_{\mu^-}+\mathbf{p}_{\mu^+})\times\mathbf{p}_{\mu^-}\right)}{\left|(\mathbf{p}_{\mathrm{e}^-}+\mathbf{p}_{\mathrm{e}^+})\times\mathbf{p}_{\mathrm{e}^-}\right|\left|-(\mathbf{p}_{\mu^-}+\mathbf{p}_{\mu^+})\times\mathbf{p}_{\mu^-}\r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

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

Bredenstein, Denner, S.D., Weber ’06





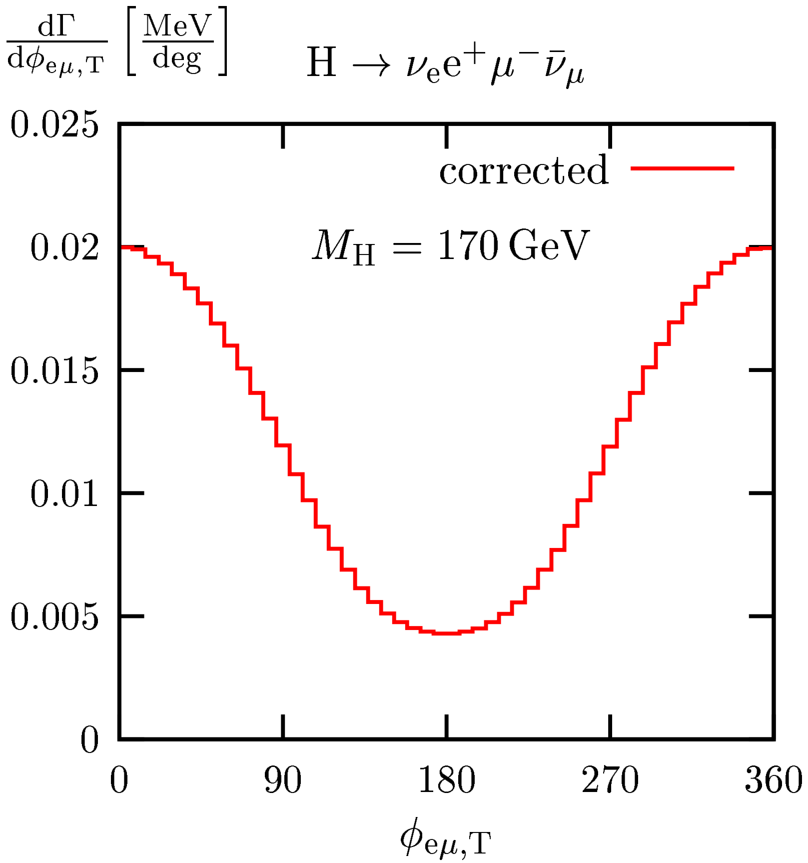


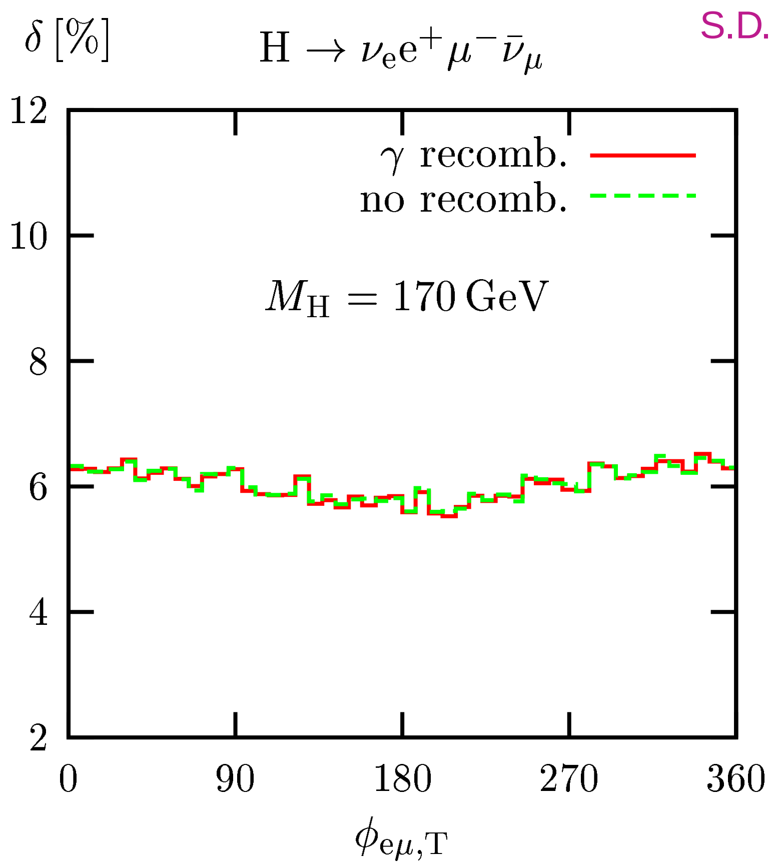
$$\cos\phi = \frac{\left((\mathbf{p}_{\mathrm{e}^-}+\mathbf{p}_{\mathrm{e}^+})\times\mathbf{p}_{\mathrm{e}^-}\right)\left(-(\mathbf{p}_{\mu^-}+\mathbf{p}_{\mu^+})\times\mathbf{p}_{\mu^-}\right)}{\left|(\mathbf{p}_{\mathrm{e}^-}+\mathbf{p}_{\mathrm{e}^+})\times\mathbf{p}_{\mathrm{e}^-}\right|\left|-(\mathbf{p}_{\mu^-}+\mathbf{p}_{\mu^+})\times\mathbf{p}_{\mu^-}\r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

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

4 Conclusions

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

- Higgs discovery at the LHC and Higgs mass measurement
- confirmation of Higgs quantum numbers (spin, CP) via differential distributions

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

- full $\mathcal{O}(\alpha)$ electroweak 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)
- QCD corrections to hadronic final states (in progress)

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

- partial decay widths: 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: corrections of $\mathcal{O}(5{-}10\%)$ distort shapes
- invariant-mass distributions of W's and Z's:
  corrections of several 10% distort shapes (depend on inclusiveness of γ radiation)