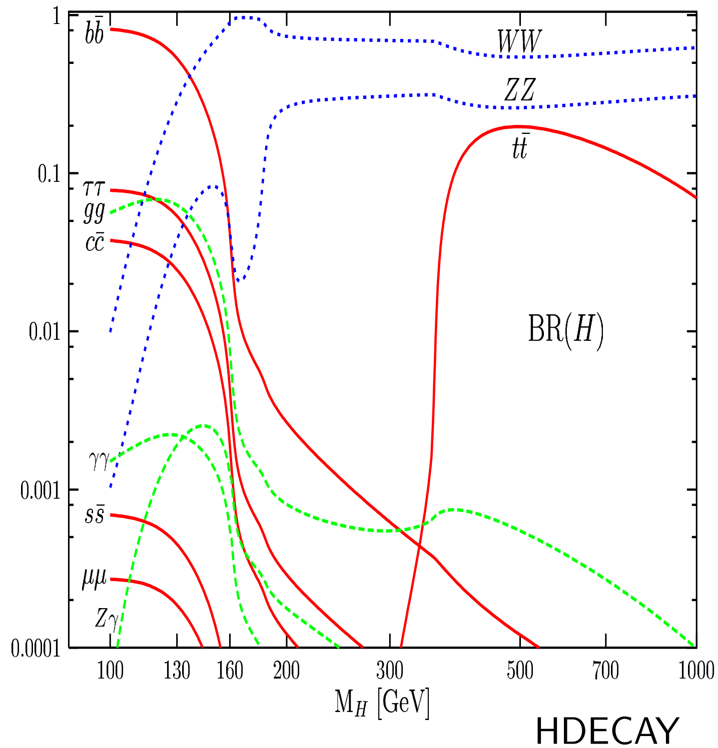
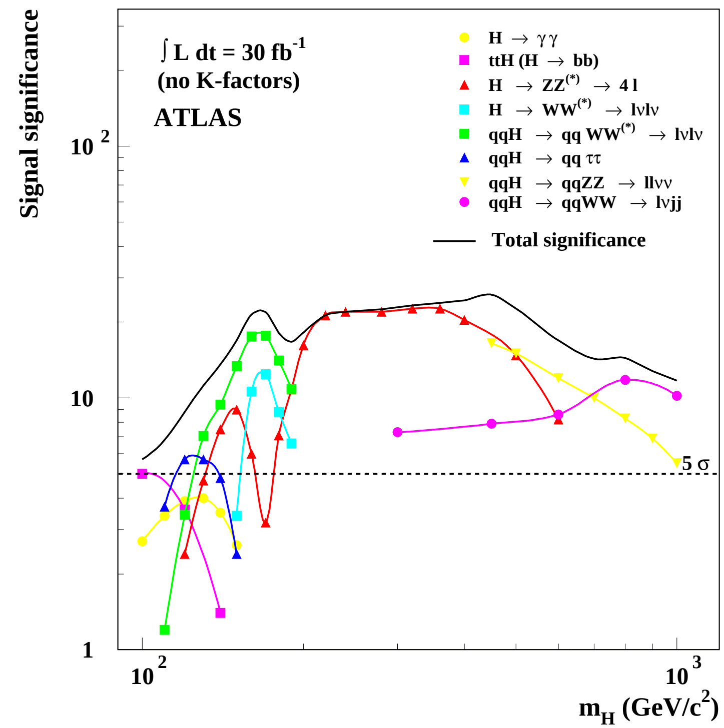
# Electroweak corrections to $H \to 4f$

Marcus Weber
University of Wuppertal

in collaboration with
Axel Bredenstein, Ansgar Denner, Stefan Dittmaier

# Introduction




- $H \to WW^{(*)}/ZZ^{(*)}$ most important decay channel for $m_{\text{H}} \gtrsim 140\,\text{GeV}$
- linear collider: measure $\text{BR}(H \to WW^{(*)})$ up to 3%
- Higgs discovery at LHC: $H \to WW^{(*)} \to l\nu l\nu$ and $H \to ZZ^{(*)} \to 4l$: most important channels for intermediate Higgs masses

$\to$ precise theoretical prediction for $H \to WW^{(*)}/ZZ^{(*)} \to 4f$ needed

# Theoretical status

radiative corrections for $H \to WW/ZZ$

| | |
|---|---|
| $\mathcal{O}(\alpha)$ | Kniehl '91, Bardin et al '91 |
| $\mathcal{O}(\alpha_s G_F m_{\mathrm{t}}^2)$ | Kniehl, Spira '95 |
| $\mathcal{O}(\alpha_s^2 G_F m_{\mathrm{t}}^2)$ | Kniehl, Steinhauser '95 |
| $\mathcal{O}(G_F^2 m_{\mathrm{t}}^4)$ | Djouadi, Gambino, Kniehl '98 |
| $\mathcal{O}(G_F^2 m_{\mathrm{H}}^4)$ | Ghinculov '95; Frick et al '96 |

pair production region: under theoretical control

$H \to WW^{(*)}/ZZ^{(*)}$
tree level only

$\longrightarrow$ threshold region?

$H \to WW^{(*)}/ZZ^{(*)} \to 4f$

- covers all Higgs masses (including threshold region)
- distributions $\longrightarrow$ verification of spin 0 [Choi et al '02]
- recently: QED corrections: Carloni-Calame et al
- full $\mathcal{O}(\alpha)$ electroweak corrections
  $\longrightarrow$ this talk

# Radiative corrections to $H \to 4f$: outline

- external fermions: massless where possible
  $\longrightarrow$ keep only $\log(m_f)$ terms
- about 400 Feynman diagrams (Feynman gauge)
- reduction of tensor loop integrals
  use techniques from $e^+e^- \to 4f$ [Denner, Dittmaier, Wieders '05]
  $\longrightarrow$ stable evaluation for exceptional kinematics
- renormalization: on-shell / $G_\mu$ scheme: $\alpha_{G_\mu} = \frac{\sqrt{2} G_\mu m_W^2 s_W^2}{\pi}$

  absorbs: – running from $Q^2 = 0$ to $Q^2 = m_Z^2$
  – universal $m_t^2 / m_W^2$ corrections related to CC
- phase space
  multi channel Monte Carlo integration [Berends,Kleiss,Pittau '94]
  adaptive weight optimization [Kleiss, Pittau '94]
- parton level Monte Carlo generator
  distributions available

# IR singularities: collinear safe observables

real and virtual corrections: soft and collinear singularities
$\longrightarrow$ cancel in inclusive quantities (KLN theorem)

inclusive quantities insensitve to emission of

- soft photons
- photons collinear to charged fermions
- energy fraction in collinear limit $z = \frac{p^0}{p^0+k^0}$
  $\longrightarrow$ independent of $z$

## soft and collinear singularities: collinear safe case

- phase space slicing

$$\int_5 \mathrm{d}\Gamma^R = \left(\int_{5,\mathrm{hard}} + \int_{5,\mathrm{soft}} + \int_{5,\mathrm{coll}}\right) \mathrm{d}\Gamma^R = \int_{5,\mathrm{hard}} \mathrm{d}\Gamma^R + \int_4 [\mathrm{d}\Gamma^{\mathrm{soft}} + \mathrm{d}\Gamma^{\mathrm{coll}}]$$

- dipole formalism [Catani,Seymour '96], [Dittmaier '98]

$$\Gamma^{\mathrm{NLO}} = \int_5 [\mathrm{d}\Gamma^R - \mathrm{d}\Gamma^{\mathrm{sub}}] + \int_4 [\mathrm{d}\Gamma^V + \int_1 \mathrm{d}\Gamma^{\mathrm{sub}}]$$

$\mathrm{d}\Gamma^{\mathrm{sub}}$: observable calculated from reduced 4-particle PS point

- $z$ integrated out

# IR singularities: non-collinear safe observables

## non-collinear safe observables

- need separate identification of collinear $f^{\pm}$ and $\gamma$
- depend on energy fraction $z = \frac{p^0}{p^0 + k^0}$
  $\longrightarrow$ no analytical integration over $z$ possible
- collinear singularities remain $\longrightarrow \log(m_f)$

$\longrightarrow$ modification of slicing and dipole methods needed

## soft and collinear singularities: non-collinear safe case

[Bredenstein et al '05]

- phase space slicing
  keep $z$ integration $\longrightarrow$ performed numerically

$$\int_{5,\text{coll}} \mathrm{d}\Gamma^R = \int_4 \int \mathrm{d}z \, \mathrm{d}\tilde{\Gamma}^{\text{coll}}$$

- dipole formalism
  - keep information on $z$ in subtraction function
  - additional term, $z$ integration numerically

$$\int_4 \int \mathrm{d}z \, \mathrm{d}\Gamma^{\text{sub,coll}}$$

- $z$ not integrated out

# Resonances

Resonances: finite width needed
$\longrightarrow$ Dyson resummation of self energies
$\longrightarrow$ gauge invariance problematic

tree level: several schemes
fixed-width scheme, complex-mass scheme, effective Lagrangians, fermion-loop scheme

1-loop: pole expansion

- gauge invariant
- not in threshold region

**complex mass scheme at 1-loop** [Denner et al '05]

- splitting of (real) bare mass: $m_{V,0}^2 = \mu_V^2 + \delta\mu_V^2$
- renormalization condition: $\hat{\Sigma}(\mu_V^2) = 0$
  $\longrightarrow$ $\mu_V^2 = m_V^2 - i m_V \Gamma_V$ complex mass, used everywhere
  $\longrightarrow$ derived quantities complex, e.g. $\cos\theta_W = \frac{\mu_W}{\mu_Z}$
  $\longrightarrow$ complex masses in loop integrals
- Ward identities valid

$\longrightarrow$ consistent scheme at 1-loop

# Checks

- virtual corrections:
  't Hooft-Feynman gauge and background field method
  $\longrightarrow$ gauge independence

- UV divergences: cancel after renormalization

- soft singularities: cancel after real–virtual combination

- collinear singularities ($\log m_f$): drop out in collinear safe observables (e.g. $\Gamma$)

- combination of real & virtual contributions
  phase space slicing and dipole formalism

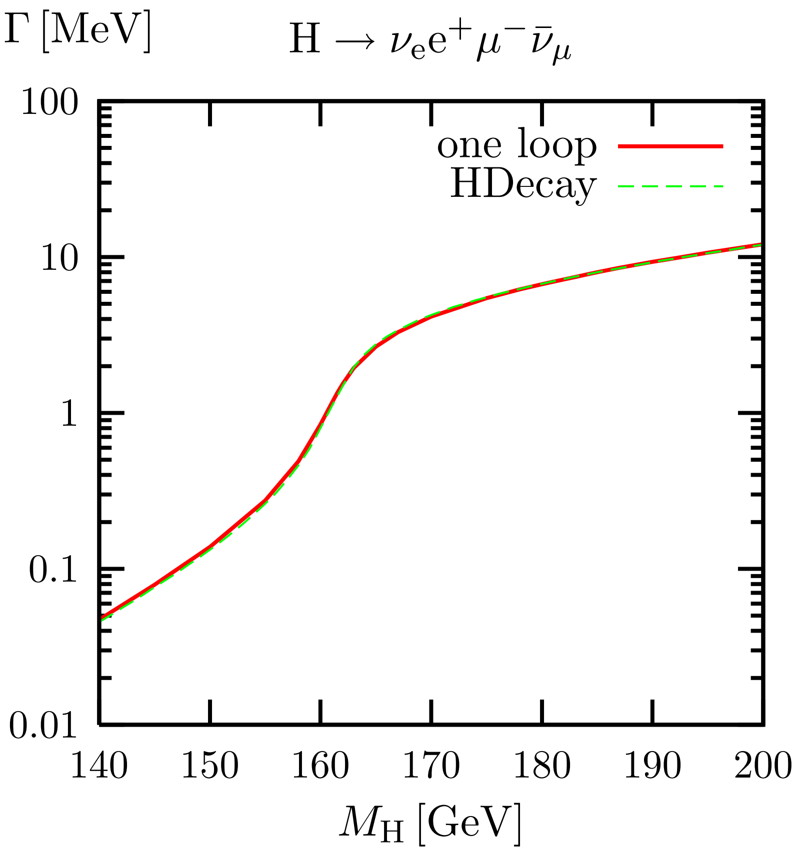
- 2 independent calculations
  $\longrightarrow$ 2 computer codes for numerical evaluation
  $\longrightarrow$ full numerical agreement (12 digits for $d\Gamma$)

# Partial widths

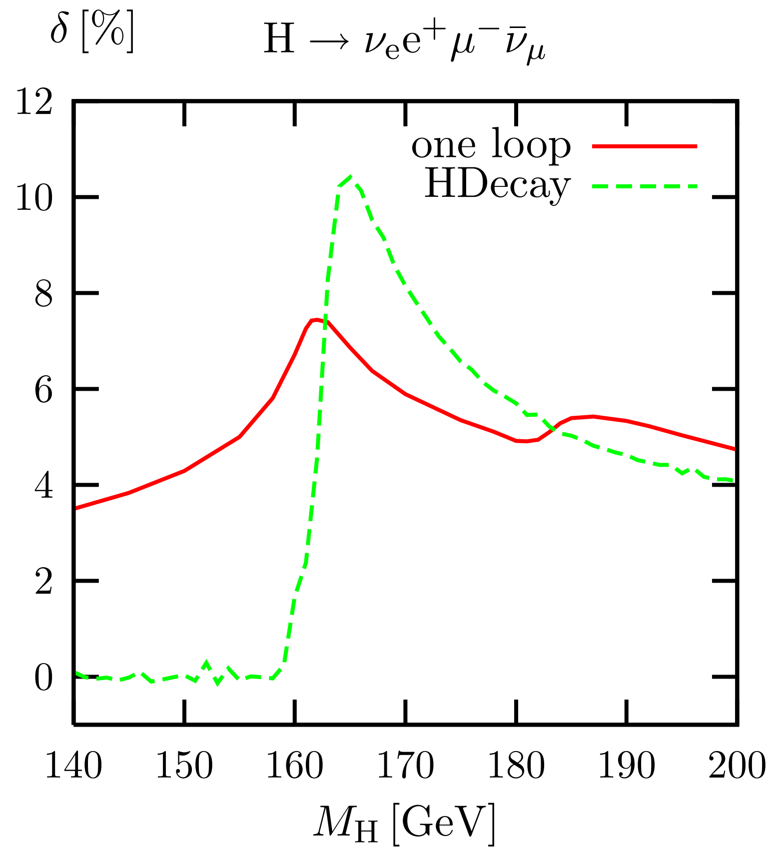
$$\mathbf{H} \rightarrow \nu_{\mathrm{e}}\mathbf{e}^{+}\mu^{-}\bar{\nu}_{\mu}$$

$G_{\mu}$-scheme

partial width




relative corrections



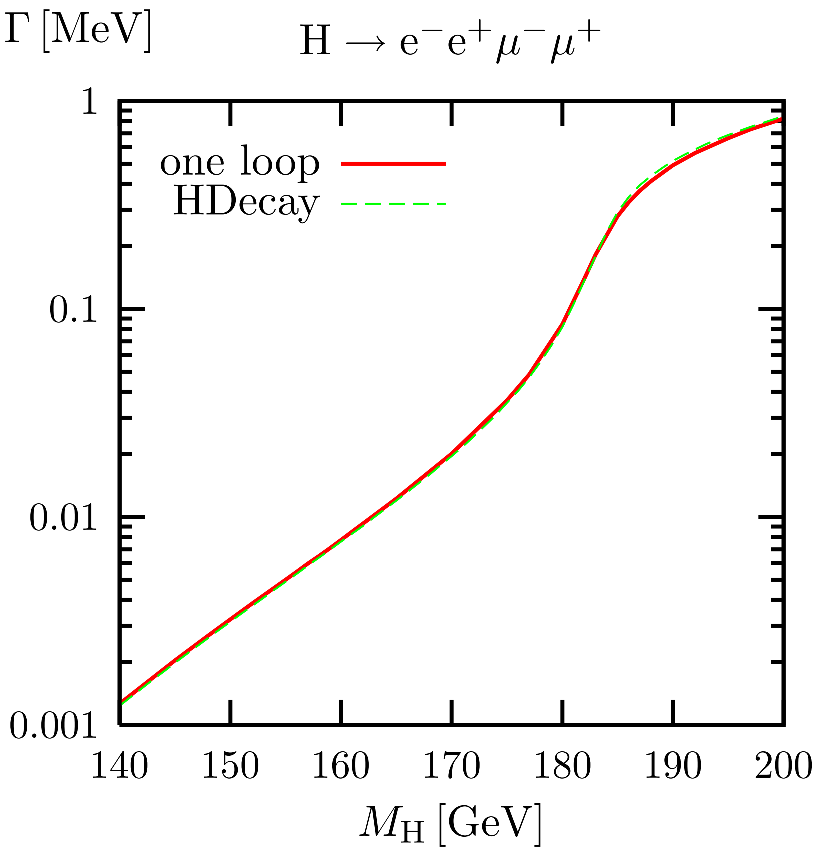

- $\mathcal{O}(\alpha)$ corrections: 3 - 8%

# Partial widths

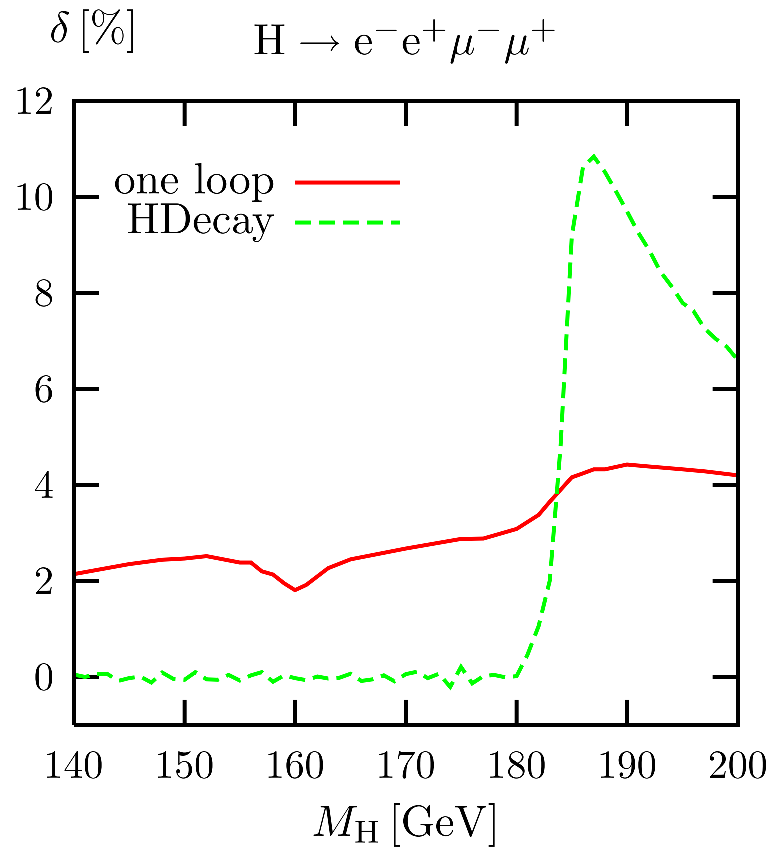
## $\mathbf{H \to e^-e^+\mu^-\mu^+}$

$G_\mu$-scheme

partial width




relative corrections



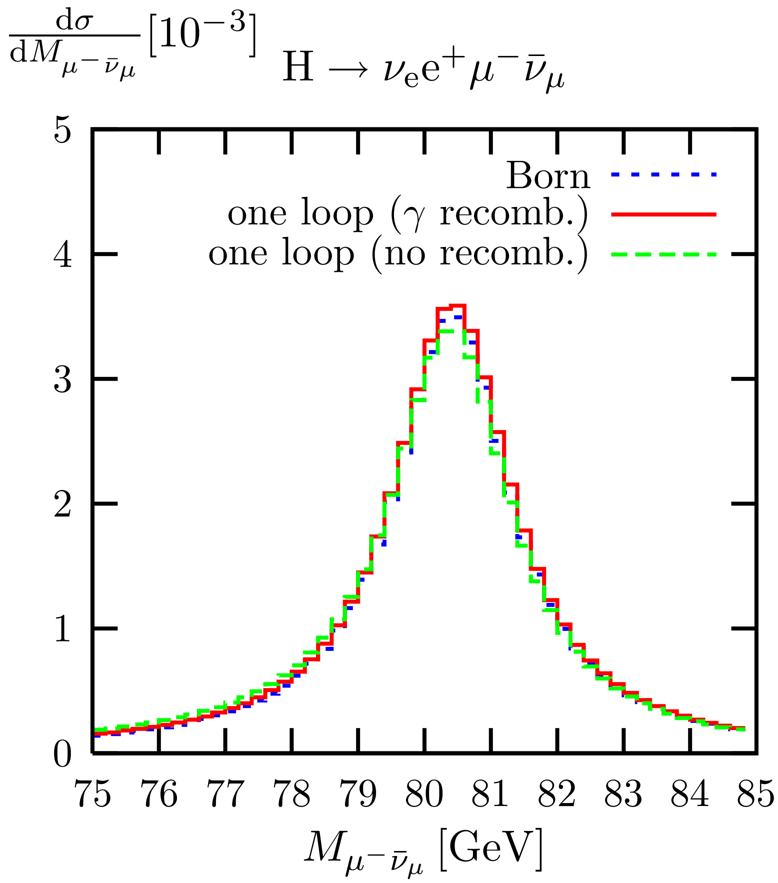

- $\mathcal{O}(\alpha)$ corrections: 2 - 4%

# Distributions: invariant mass

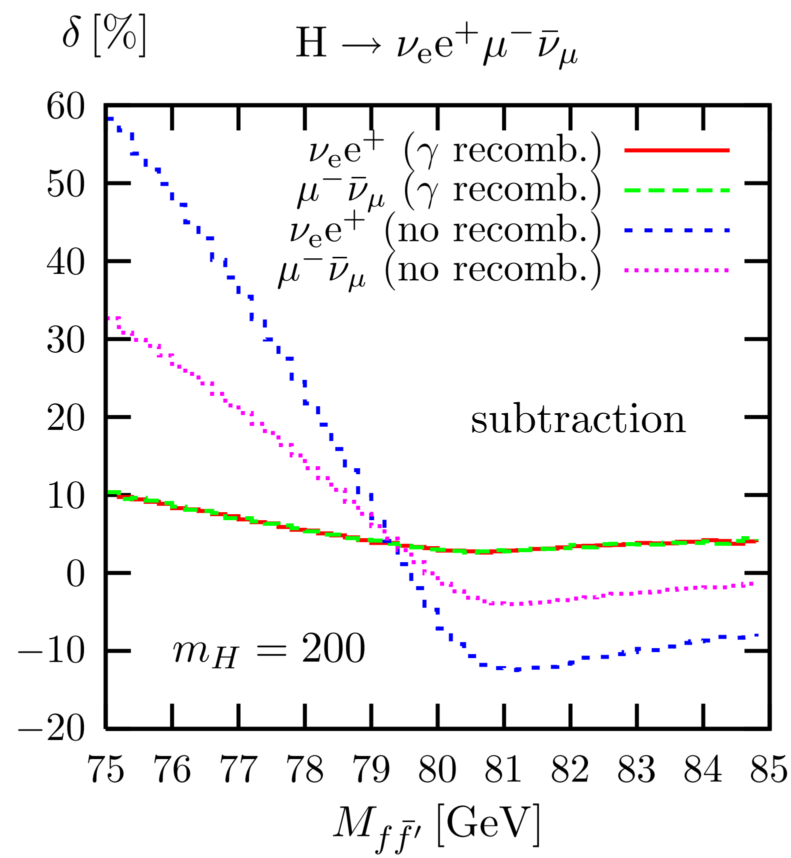
## $\mathbf{H} \to \nu_{\mathrm{e}}\mathbf{e}^{+}\mu^{-}\bar{\nu}_{\mu}$

$G_{\mu}$-scheme, $m_H = 200$ GeV

invariant mass distribution




relative corrections




photon recombination: if $m_{f\gamma} < 5$ GeV

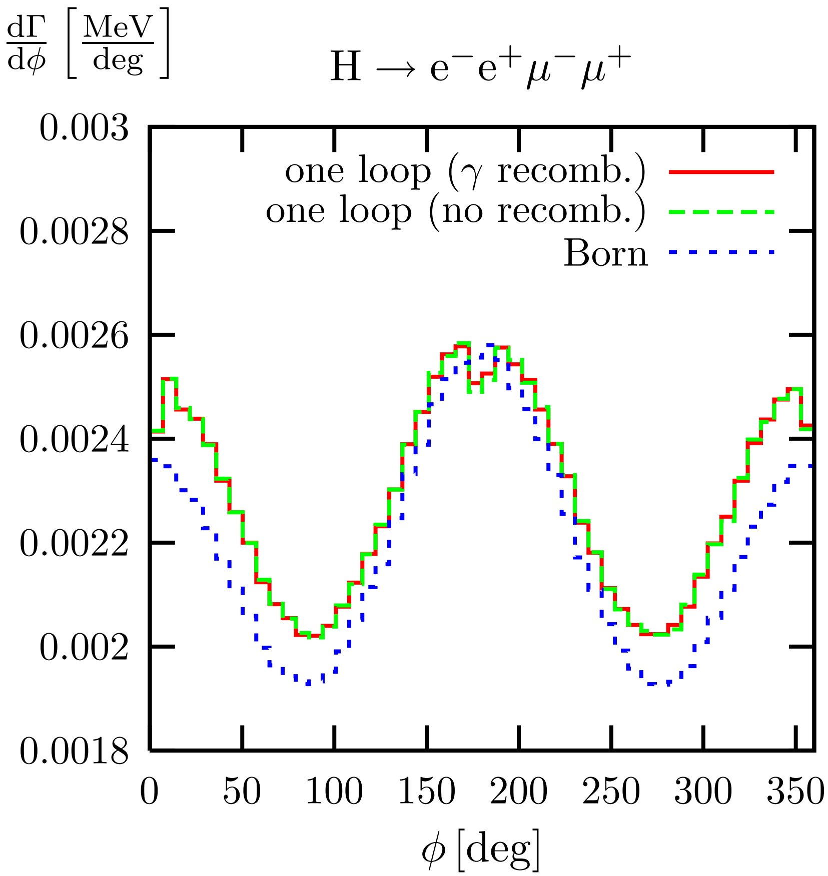
# Distributions: angular

$$\mathbf{H} \to \mathbf{e^-e^+\mu^-\mu^+}$$

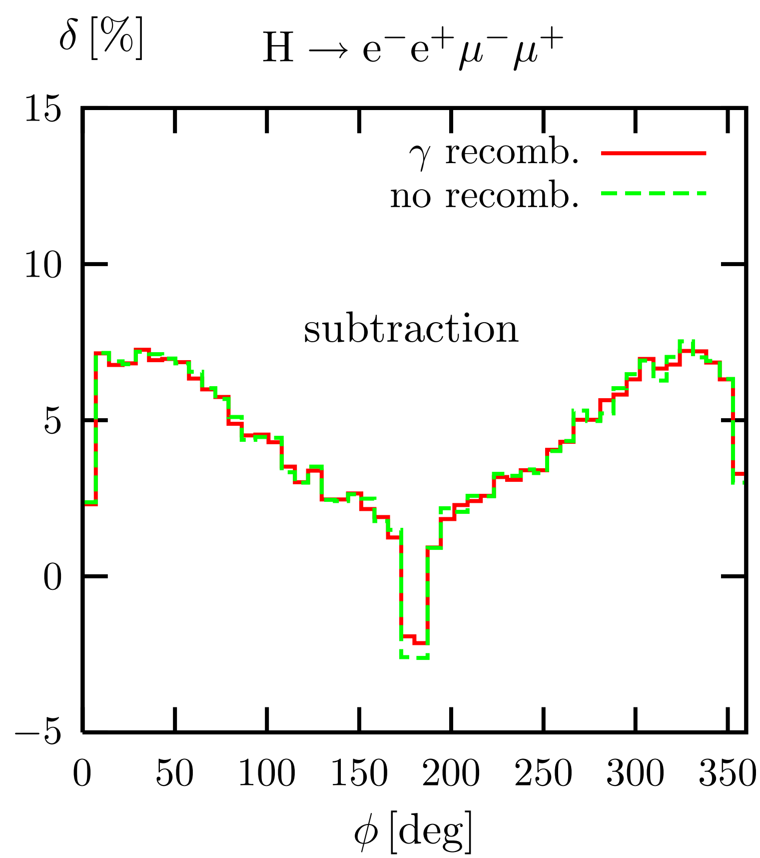
$G_\mu$-scheme, $m_H = 200$ GeV

$\phi$ angle between decay planes of $e^+e^-$ and $\mu^+\mu^-$

angular distribution




relative corrections




$$\cos\phi = \frac{((\mathbf{p}_1+\mathbf{p}_2)\times\mathbf{p}_1)(-(\mathbf{p}_3+\mathbf{p}_4)\times\mathbf{p}_3)}{|(\mathbf{p}_1+\mathbf{p}_2)\times\mathbf{p}_1||-(\mathbf{p}_3+\mathbf{p}_4)\times\mathbf{p}_3|}$$

# Conclusions

- $H \to WW^{(*)}/ZZ^{(*)} \to 4f$: important decay channel
  $\longrightarrow$ precise theoretical description needed
- complete $\mathcal{O}(\alpha)$ electroweak corrections available
- corrections for partial width: 2 - 8%
  larger for distributions
- Monte Carlo generator:
  $\longrightarrow$ partial widths and distributions
- non-collinear safe observables possible
- outlook
  - QCD corrections
  - higher order final state radiation
  - comparison with narrow width approximation