Radiative corrections to $H \longrightarrow 4f$ decays

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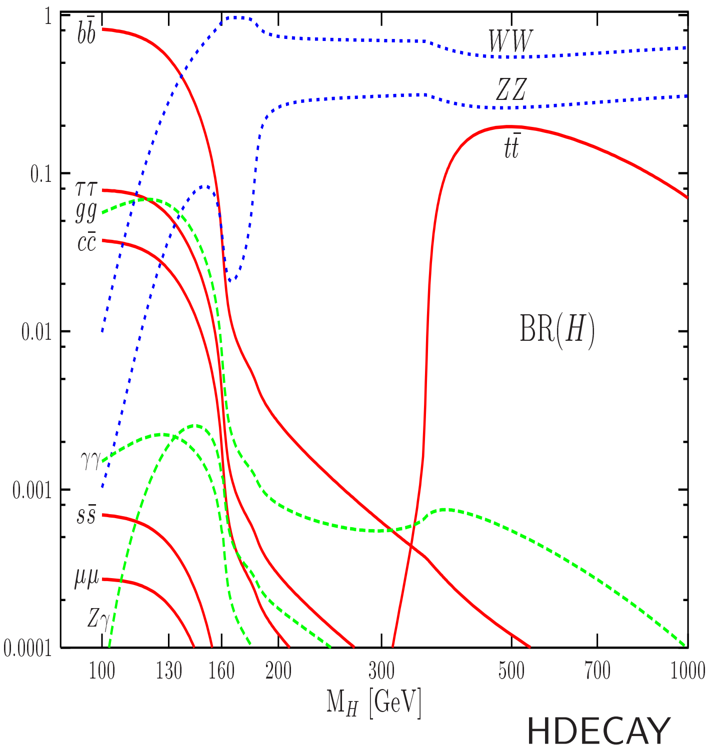
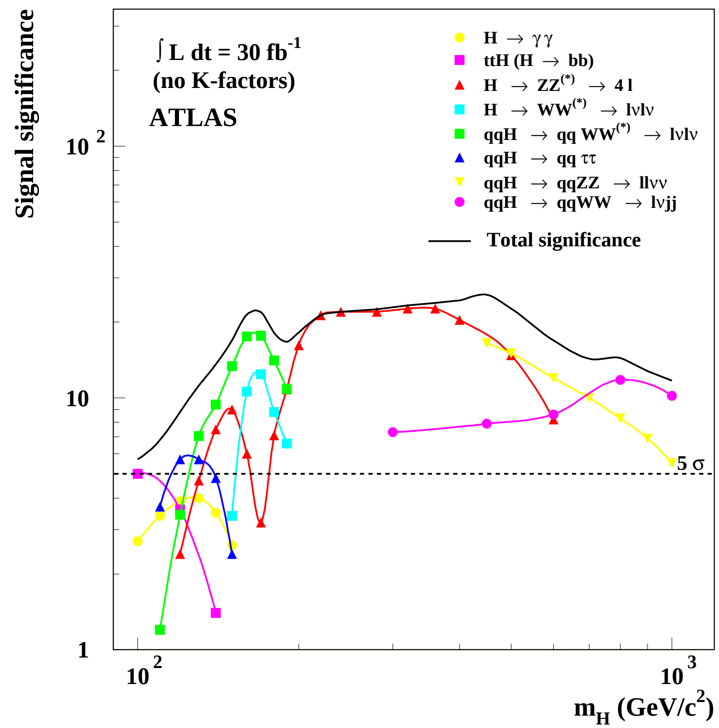
Introduction: $H \to WW^{(*)}/ZZ^{(*)}$ decays





most important decay channels for $m_{\mathrm{H}} \gtrsim 140$ GeV

LHC

- most important discovery channels for $m_{\mathrm{H}} \gtrsim 130$ GeV
- most accurate Higgs mass measurement for $m_{\mathrm{H}} \gtrsim 130$ GeV using $H \to ZZ \to 4l$

linear collider

- measurement of branching fractions to several percent level

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

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

theoretical status

- $m_\mathrm{H} > 2m_V$: $H \to WW/ZZ$ real pair production
  $\mathcal{O}(\alpha)$ corrections known [Kniehl '91, Bardin et al '91]
  some leading higher order [Kniehl, Spira '95; Kniehl, Steinhauser '95] [Ghinculov '95; Frink et al '96]
- $m_\mathrm{H} < 2m_V$: $H \to WW^{(*)}/ZZ^{(*)}$ three-body decay
  leading order only [e.g. HDECAY:Djouadi, Kalinowski, Spira '98]

distributions important

- kinematical reconstruction of Higgs and W/Z
  $\longrightarrow$ real photon radiation important
- verification of Higgs boson spin and CP:
  $\longrightarrow$ uses angular and invariant-mass distributions [Choi et al '02]

$\Rightarrow$ $H \to WW/ZZ \to 4f$ Monte Carlo generator with NLO corrections needed

recent work

this talk: full $\mathcal{O}(\alpha)$ electroweak corrections to $H \to WW/ZZ \to 4f$

related: QED corrections to $H \to WW/ZZ \to 4l$: [Carloni-Calame et al '06]

Radiative corrections to $H \longrightarrow 4f$

general

- external fermions massless
- virtual corrections:
  about 400 Feynman diagrams (Feynman gauge), up to pentagons
- mostly standard techniques

evaluation of 1-loop integrals

Passarino-Veltman reduction of tensor loop integrals

- introduces Gram determinants in denominator
- Gram determinants may vanish (at phase space boundary & inside)
  $\longrightarrow$ numerical instabilities

solution [Denner, Dittmaier '05]

- 5-point
  $\longrightarrow$ direct reduction without inverse Gram determinants
- 3- and 4-point: 2 methods
  - reduction to 1 tensor coefficient $\longrightarrow$ numerical integration
  - expansion in small Gram (and other) determinants
- works with complex masses

resonances: 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
- gauge invariant, no double counting
- straightforward implementation

real-virtual combination & higher order corrections

combination of real and virtual corrections

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

- combination method: dipole formalism and phase space slicing

- non-collinear safe observables:
  depend on energy fraction $z = \frac{p^0}{p^0+k^0}$ of fermion emitting a photon
  $\longrightarrow$ modified dipole formalism and slicing needed [Bredenstein, Dittmaier, Roth '05]
  collinear singularities remain $\longrightarrow \log m_f$

corrections beyond $\mathcal{O}(\alpha)$

- higher order final state radiation
  collinear photon emission $\longrightarrow \alpha \log(m_f^2/q^2)$
  included using structure function approach

- Higgs boson self interaction corrections: leading 2-loop [Ghinculov '95; Frink et al '96]

Checks

checks

- gauge independence: 't Hooft-Feynman gauge and background field method
- UV divergences: cancel after renormalization
  $\longrightarrow$ no dependence on mass scale μ of dimensional regularization
- soft singularities: cancel after real–virtual combination
  $\longrightarrow$ no dependence on $\log m_\gamma$
- collinear singularities: drop out in collinear safe observables (e.g. Γ)
  $\longrightarrow$ no dependence on $\log m_f$
- real corrections: checked against MADGRAPH
- 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 (10 digits for $d\Gamma$)

Monte Carlo program

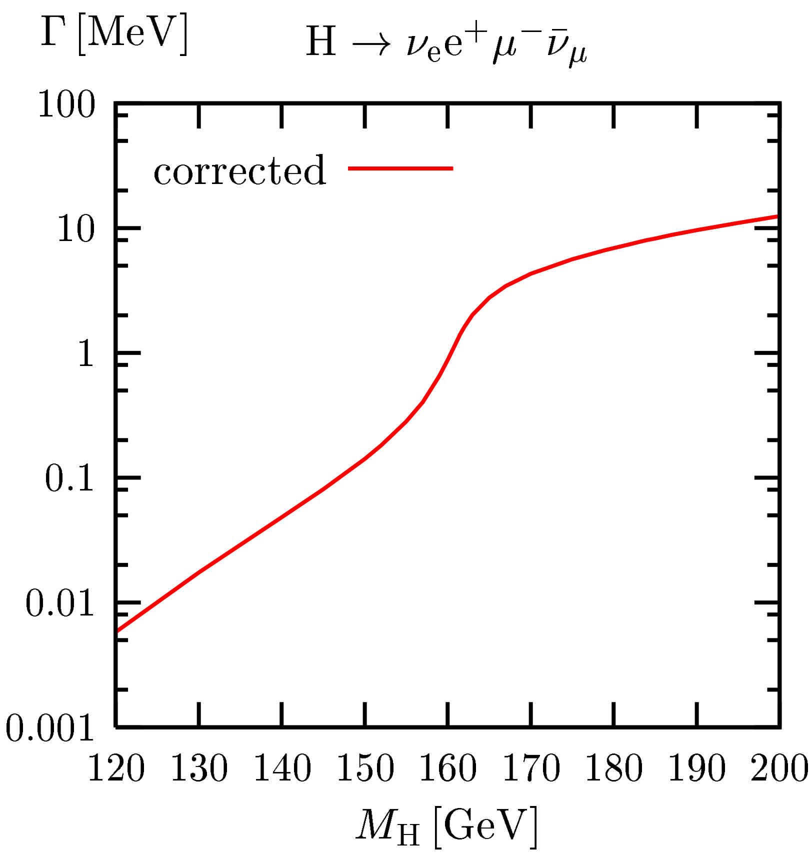
PROPHECY4F

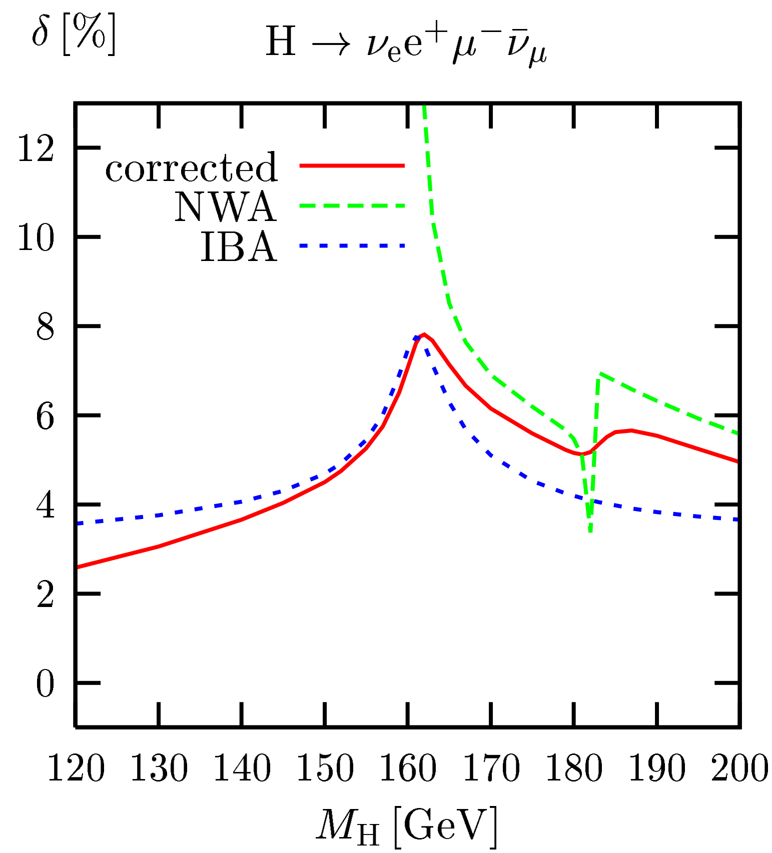
- Monte Carlo generator for $H \to WW/ZZ \to 4f$ including $\mathcal{O}(\alpha)$ corrections
- improved Born approximation
  includes: Coloumb singularity, leading effects for $m_\mathrm{H}, m_\mathrm{t} \gg m_\mathrm{W}$, fitting constant
- phase space integration
  multi channel Monte Carlo integration [Berends,Kleiss,Pittau '94]
  adaptive weight optimization [Kleiss, Pittau '94]
- partial widths
- histograms: arbitrary observables (also non-collinear safe)

Partial widths: leptonic

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

G_{μ}-scheme





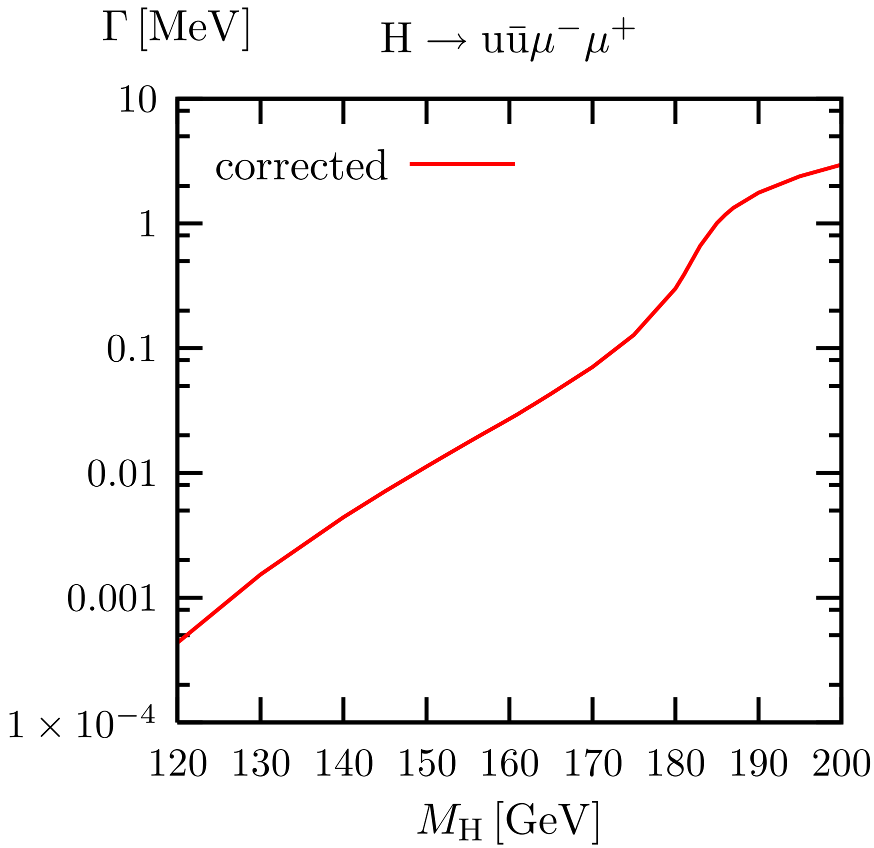
NWA: narrow width approximation

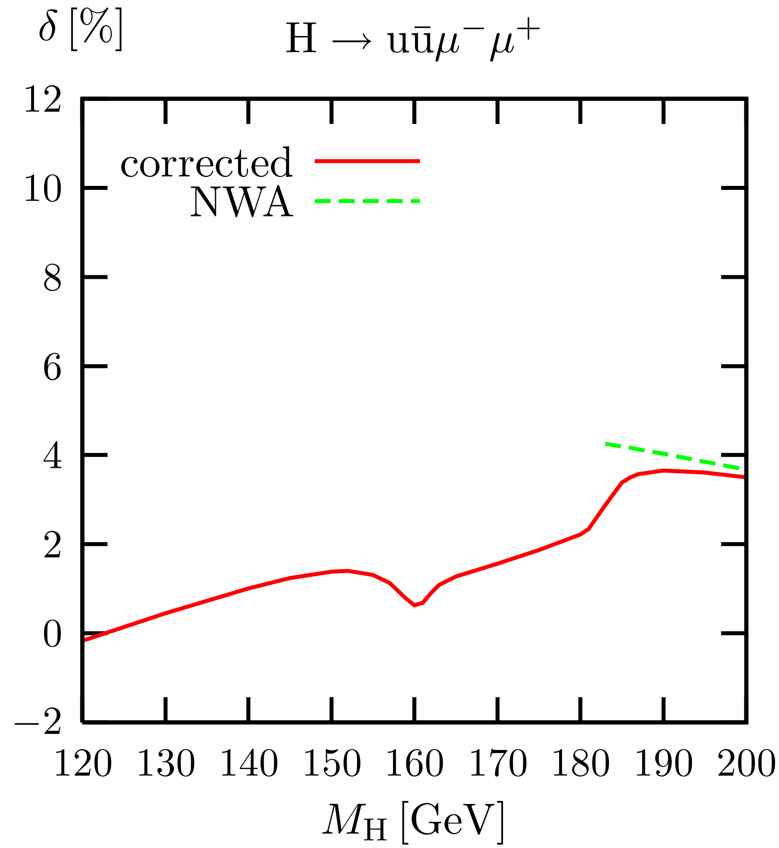
IBA: improved Born approximation

Partial widths: semileptonic

$\mathbf{H \to u\bar{u}\mu^-\mu^+}$

G_μ-scheme

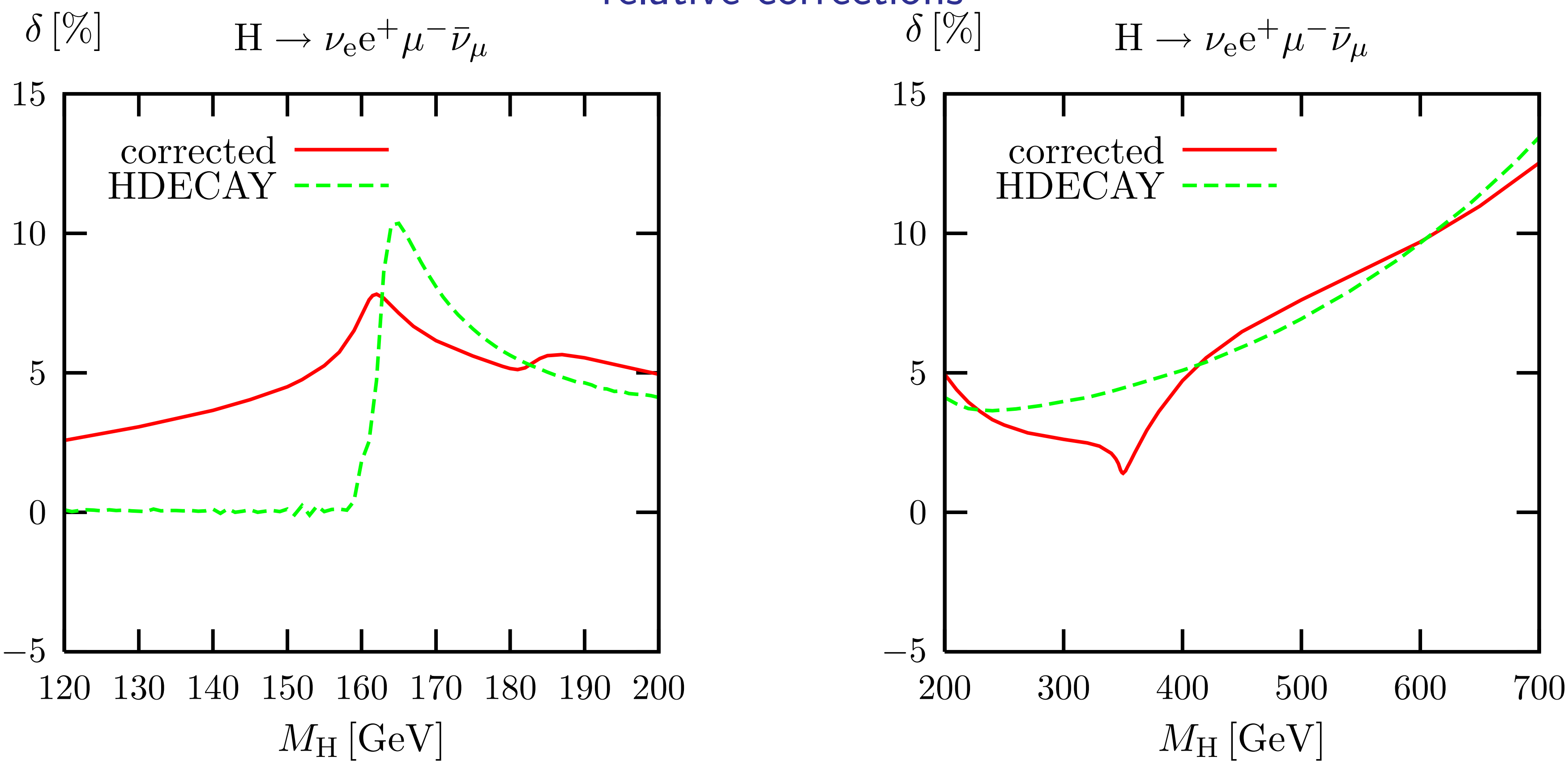




Comparison with HDECAY

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

relative corrections



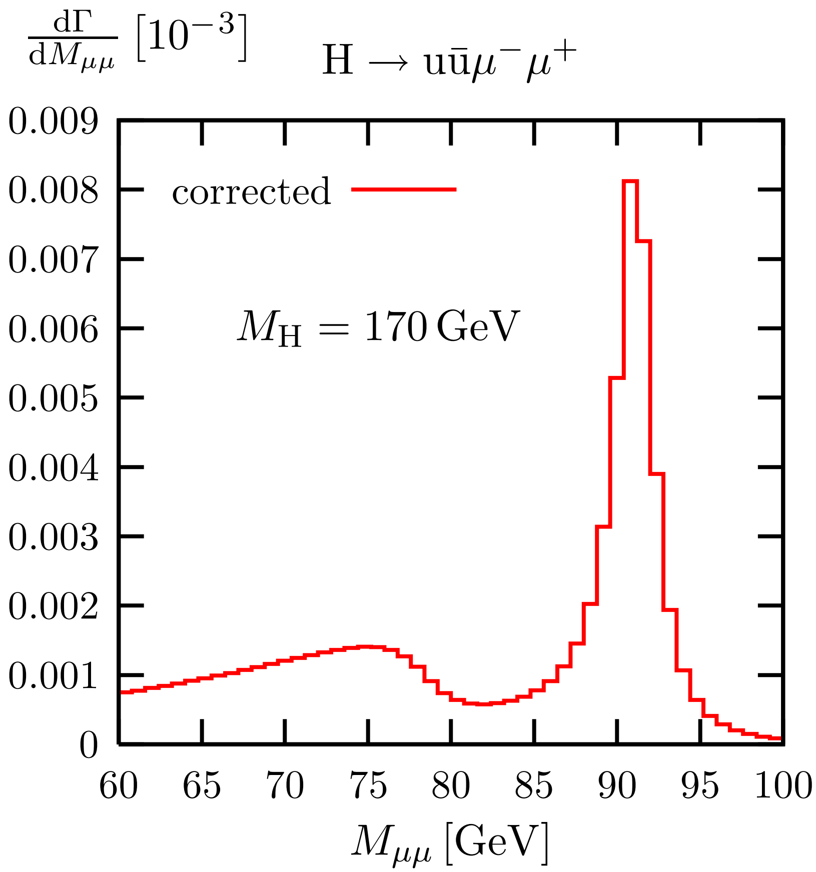
HDECAY

- includes leading 1 and 2-loop corrections for large m_{H}
- off-shell effects taken into account below threshold

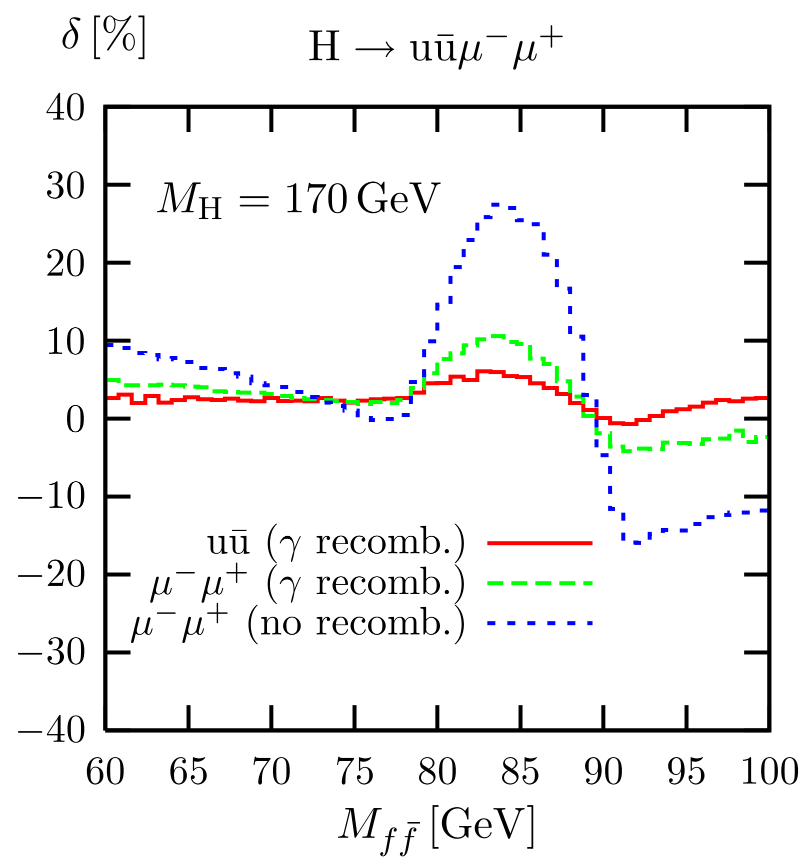
$\mathbf{H} \to \mathbf{u\bar{u}}\mu^-\mu^+$

G_μ-scheme, $m_H = 170$ GeV

invariant mass distribution



relative corrections



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

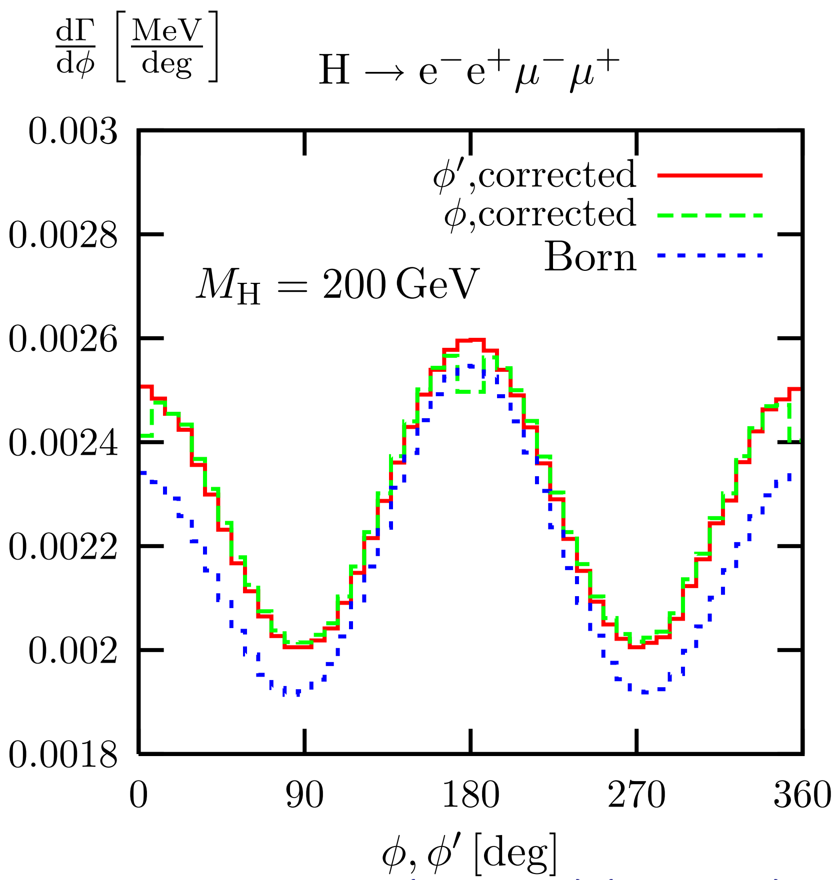
Distributions: angular

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

G_μ-scheme, $m_H = 200$ GeV

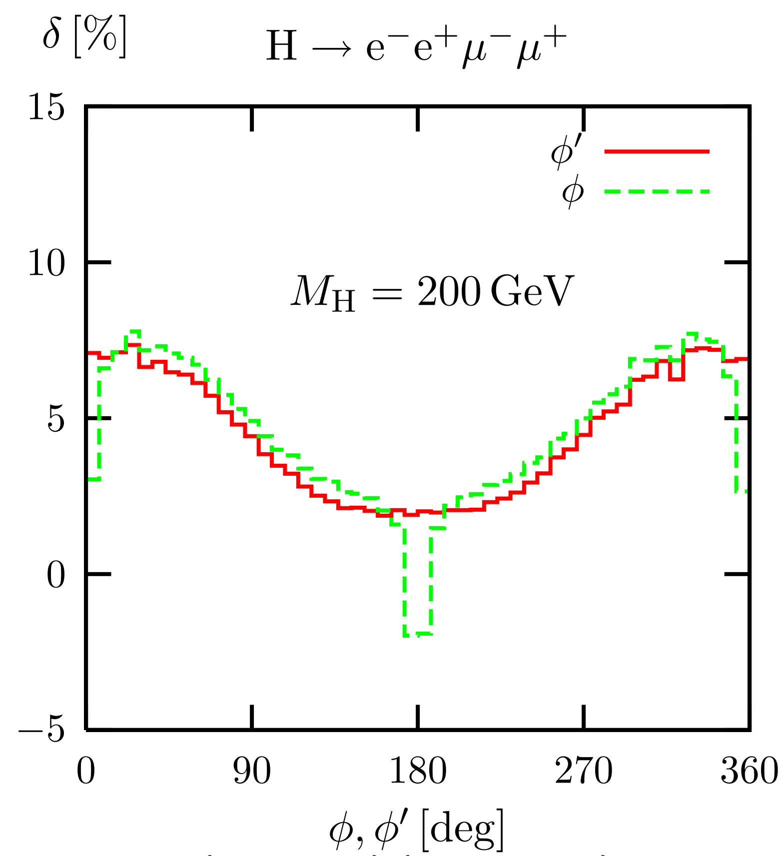
ϕ angle between decay planes of e^+e^- and $\mu^+\mu^-$

angular distribution



$$\cos\phi' = \frac{(\mathbf{p}_+ \times \mathbf{p}_1)(\mathbf{p}_+ \times \mathbf{p}_3)}{|\mathbf{p}_+ \times \mathbf{p}_1||\mathbf{p}_+ \times \mathbf{p}_3|}$$

relative corrections



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

Conclusions

$H \to WW/ZZ \to 4f$ important decay channel

- discovery and mass measurement at LHC
- distributions important for verification of Higgs properties (spin,CP)

available: complete $\mathcal{O}(\alpha)$ electroweak corrections to $H \to WW/ZZ \to 4f$

- resonances: complex mass scheme
- beyond $\mathcal{O}(\alpha)$: heavy-Higgs effects and final state radiation
- non-collinear safe observables possible

$\Rightarrow$ Monte Carlo generator: PROPHECY4F

results

- partial width up to $\simeq 8\%$ for $m_\mathrm{H} \lesssim 500\,\mathrm{GeV}$
  improved born approximation: accurate to within $\lesssim 2\%$ for $m_\mathrm{H} \lesssim 500\,\mathrm{GeV}$
- distributions
  $\mathcal{O}(10\%)$ with γ-recombination
  several 10% without γ-recombination for invariant mass distributions

outlook

- QCD corrections
- unweighted events