Precise Predictions for $H \longrightarrow WW/ZZ \longrightarrow 4$ Fermion Decays with PROPHECY4f

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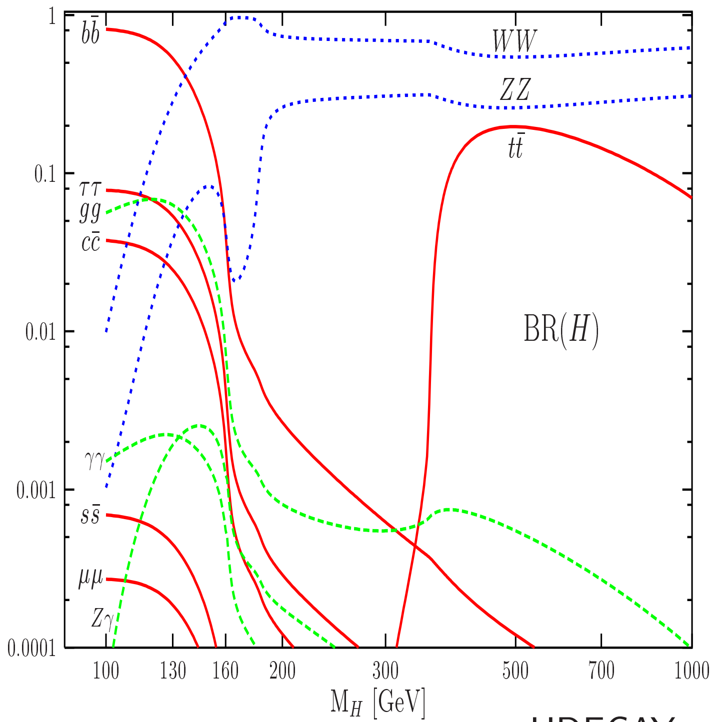
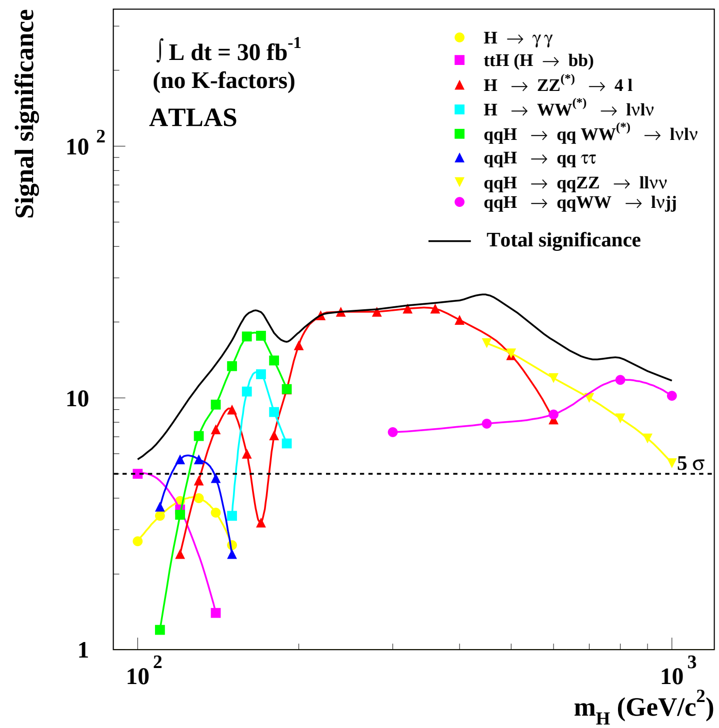
- Introduction to $H \to WW^{(*)}/ZZ^{(*)} \to 4f$
- Calculation of radiative corrections
- Numerical results
- Monte Carlo generator
- Conclusions

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



HDECAY



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

$\longrightarrow$ 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 [Fleischer, Jegerlehner '81, 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
  invariant mass distributions $\longrightarrow$ real photon radiation important
- verification of Higgs boson spin and CP:
  $\longrightarrow$ uses angular and invariant-mass distributions [Choi et al '02]

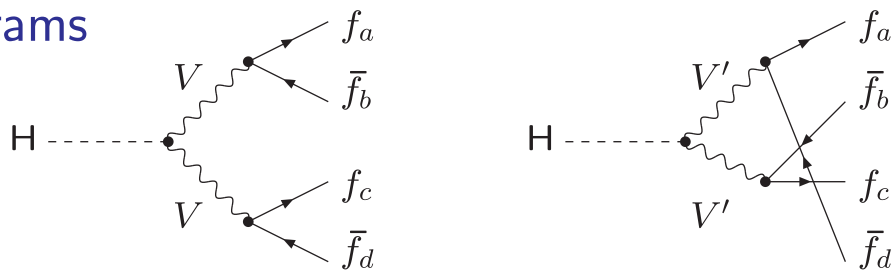
$\Rightarrow$ $H \to WW/ZZ \to 4f$ Monte Carlo generator with NLO corrections needed

recent work

PROPHECY4F: generator for $H \to WW/ZZ \to 4f$ with EW and QCD corrections
related: QED corrections to $H \to WW/ZZ \to 4l$: [Carloni-Calame et al '06]

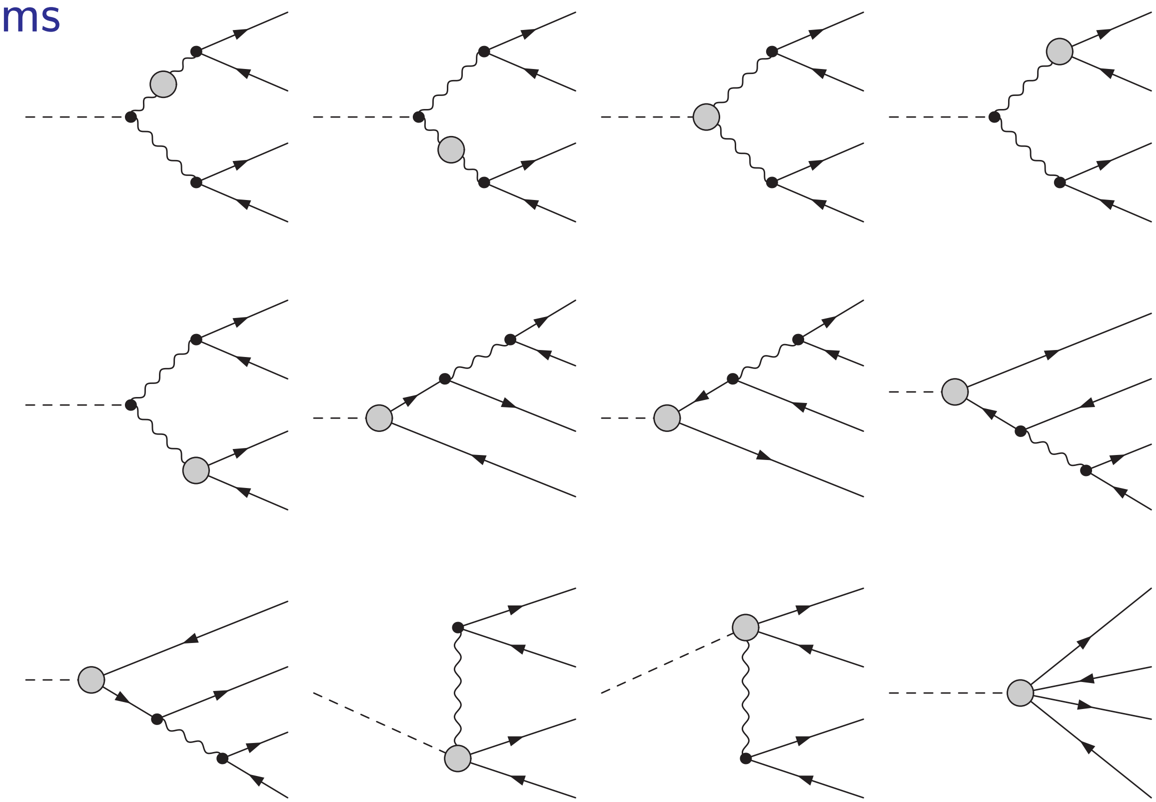
$H \to 4f$ Feynman diagrams

Born diagrams



crossed diagram only for $f\bar{f}f\bar{f}$ and $f\bar{f}f'\bar{f}'$ final states
(f, f' form isodoublet)

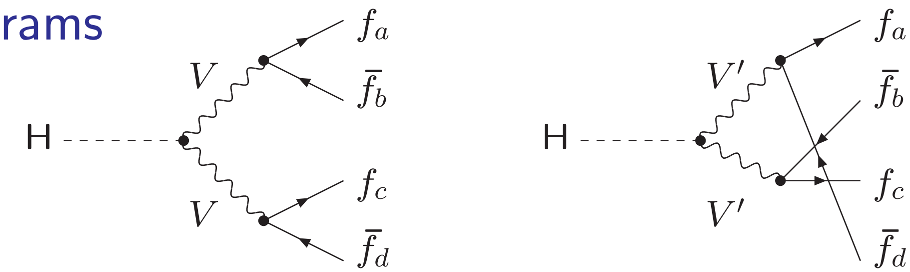
EW virtual diagrams



- about 400 Feynman diagrams (Feynman gauge), up to pentagons
- external fermions massless

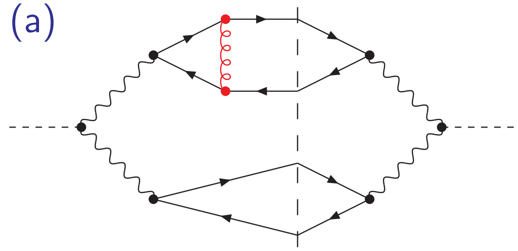
$H \to 4f$ Feynman diagrams

Born diagrams

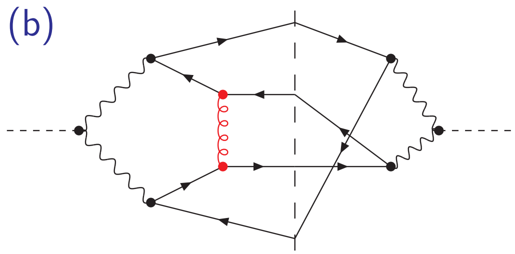


QCD virtual diagrams: categories

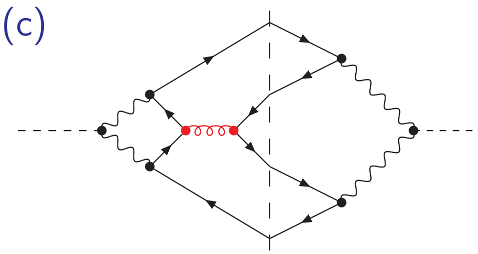
(a)



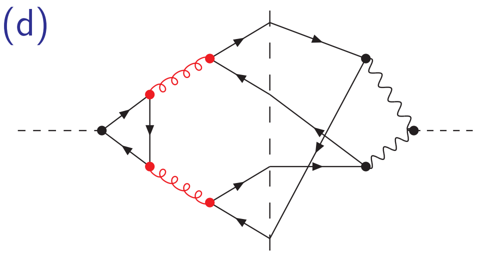
(b)



(c)



(d)



(a): corrections to W/Z decays

(b),(c),(d): interference corrections, only for $f\bar{f}f\bar{f}$ and $f\bar{f}f'\bar{f}'$ final states

NLO calculation: general remarks

- external fermions massless where possible
  $\longrightarrow$ keep fermion mass only in mass singular logarithms
- diagram generation: FeynArts
- algebraic evaluation: FormCalc / Mathematica
  $\longrightarrow$ decomposition into standard matrix elements and coefficients
- real amplitudes: evaluation with Weyl–van der Waerden spinor formalism
- renormalization scheme

  on-shell scheme generalized to complex masses

  derive α from Fermi constant (G_μ-scheme): $\alpha_{G_\mu} = \frac{\sqrt{2} G_\mu m_{\mathrm{W}}^2 s_{\mathrm{W}}^2}{\pi}$

  includes

  – running of α from $Q^2 = 0$ to EW scale

  – universal corrections related to ρ parameter

main technical complications in loop calculation:

- gauge invariant treatment of gauge boson resonances
- numerical instabilities in Passarino-Veltman tensor reduction

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)

  but: tensor integrals regular

  $\longrightarrow$ cancellations in numerator

  $\longrightarrow$ numerical instabilities

solution [Denner, Dittmaier '05]

- 5-point direct reduction without inverse Gram determinants
- 3- and 4-point: 2 methods
  - both: Passarino-Veltman reduction where possible
  - reduction to specific tensor coefficient

    $\longrightarrow$ Feynman parameter integral logarithmic

    $\longrightarrow$ numerical integration
  - expansion in small Gram (and other) determinants
- works with complex masses

Resonances

Resonances: finite width needed

→ Dyson resummation of self energies, mixes perturbative orders

→ potential gauge invariance violation

solutions at tree level

fixed-width scheme, complex-mass scheme, effective Lagrangians, fermion-loop scheme

solutions at 1-loop

- naive fixed-width scheme
  only weak breaking of gauge invarianve
  singularity structure changed
- pole expansion [Stuart '91; Aeppli et al '93]
  gauge invariant
  not in threshold region
- effective field theory approach [Beneke et al '04, Hoang, Reisser '04]
  gauge invariant, only in specific phase space regions
- complex mass scheme [Denner et al '05]
  gauge invariant, all phase space regions, simple
  → see below

Complex mass scheme at leading order

[Denner et al '05]

idea: mass^2 $=$ location of propagator pole in complex p^2 plane

- decomposition into real mass and width:
  $\mu_V^2 = m_V^2 - i m_V \Gamma_V$
- μ_V^2 is consistently used everywhere
  $\longrightarrow$ derived quantities complex, e.g. $\cos\theta_W = \frac{\mu_W}{\mu_Z}$

advantages:

- gauge invariant
  Ward identities valid, unitarity cancellations hold
- no double counting
- straightforward implementation

disadvantages:

- spurious terms of $\mathcal{O}(\Gamma/M) = \mathcal{O}(\alpha)$
  width in spacelike propagators, complex θ_W
- unitarity broken
  unitarity cancellations not spoiled since Ward identities remain valid

$\longrightarrow$ these are due to truncation of the perturbative series

Complex mass scheme at NLO

complex on-shell renormalization scheme: [Denner et al. '05]

- mass and field splitting:

  $$m_{W,0}^2 = \mu_W^2 + \delta\mu_W^2$$
  $$W_0^\pm = (1 + \tfrac{1}{2}\delta Z_W) W^\pm$$

  μ, δZ complex

  bare Lagrangian unchanged $\longrightarrow$ no double counting

- renormalized self energy:

  $$\Sigma_R^T(p^2) = \Sigma^T(p^2) - \delta\mu_W^2 + (p^2 - \mu_W^2)\delta Z_W$$

- renormalization conditions

  $$\Sigma_R^T(p^2 = \mu_W^2) = 0 \qquad \text{mass}^2 \text{ is complex propagator pole}$$
  $$\frac{\partial}{\partial p^2}\Sigma_R^{T'}(p^2 = \mu_W^2) = 0 \qquad \text{pole residue is } 1$$

  solutions:

  $$\delta\mu^2 = \Sigma^T(\mu_W^2) \qquad \delta Z_W = -\Sigma^{T'}(\mu_W^2)$$

Complex mass scheme at NLO

expansion around real masses

$$\Sigma^T(\mu_W^2) = \Sigma^T(m^2) + (\mu_W^2 - m_W^2)\Sigma^{T'}(m_W^2) + \mathcal{O}(\alpha^3)$$

$$\delta\mu_W^2 = \Sigma^T(m_W^2) + (\mu_W^2 - m_W^2)\Sigma^{T'}(m_W^2) \qquad \delta Z_W = -\Sigma_{T'}(m_W^2)$$

$\longrightarrow$ renormalized self energy

$$\Sigma_R^T(p^2) = \Sigma^T(p^2) - \delta m_W^2 + (p^2 - m_W^2)\delta Z_W$$

with

$$\delta m_W^2 = \Sigma^T(m_W^2) \qquad \delta Z_W = -\Sigma^{T'}(m_W^2)$$

$\longrightarrow$ same form as usual on-shell scheme, but without Re

width calculation

implicitly defined by $\quad m_{W,0}^2 = \mu_W^2 + \delta\mu_W^2$

$$\rightarrow m_W\Gamma_W = \mathrm{Im}(\Sigma^T(m_W^2)) - m_W\Gamma_W\,\mathrm{Re}(\Sigma^{T'}(m_W^2)) + \mathcal{O}(\alpha^3)$$

$\longrightarrow$ iterative solution

but: needs 2-loop self energies

equivalent: width from $W \rightarrow f\bar{f}'$ with real W mass

Complex mass scheme at NLO

charge renormalization

$$\frac{\delta e}{e} = \frac{1}{2}\Sigma'^{AA}(0) - \frac{\sin\theta_W}{\cos\theta_W}\frac{\Sigma_T^{AZ}(0)}{\mu_Z^2}$$

complex due to μ^2, θ_W $\rightarrow$ renormalized charge complex
but: $\mathrm{Im}(e)$ drops out at 1-loop, contributes starting at 2-loop

top quark
complex mass $\mu_t^2 = m_t^2 - i m_t \Gamma_t$
renormalization constants

$$\delta m_t = \tfrac{m_t}{2}\left[\Sigma^{t,R}(m_t^2) + \Sigma^{t,L}(m_t^2) + 2\Sigma^{t,S}(m_t^2)\right]$$
$$\delta Z_{t,\sigma} = -\Sigma^{t,\sigma}(m_t^2) - m_t^2\left[\Sigma'^{t,R}(m_t^2) + \Sigma'^{t,L}(m_t^2) + 2\Sigma'^{t,S}(m_t^2)\right]$$

$\rightarrow$ same form as usual on-shell scheme, but without Re

complex mass scheme at NLO

- needs 1-loop integrals with complex masses
- gauge invariant, no double counting, straighforward implementation
- spurious terms, unitarity violation
  effects of $\mathcal{O}(\alpha^2)$ in NLO calculation

combination of real and virtual corrections

real and virtual corrections: soft and collinear singularities

$\longrightarrow$ cancel in inclusive quantities (KLN theorem)

inclusive quantities:

- insensitve to emission of soft photons
- insensitve to emission of photons collinear to charged fermions
- energy fraction of fermion emitting photon in collinear limit $z = \frac{p^0}{p^0 + k^0}$

  $\longrightarrow$ independent of z

real/virtual combination: collinear safe case

- phase space slicing

  divide phase space using cuts on photon energy E_γ and photon polar angle $\theta_{\gamma f}$

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

  analytical integration over photon phase space (z integrated out)

  $\longrightarrow$ singular terms: $\log m_\gamma$, $\log m_f$

combination of real and virtual corrections

real/virtual combination: collinear safe case

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

- process independent approach

$$\sigma^{\text{NLO}} = \int_5 [d\sigma^R - d\sigma^{\text{sub}}] + \int_5 d\sigma^{\text{sub}} + \int_4 d\sigma^V$$

- subtraction function $d\sigma^{\text{sub}}$
  sum of dipole terms
  cancels singularities of $d\sigma^R$
  $\Rightarrow d\sigma^R - d\sigma^{\text{sub}}$ integrable without IR regularization
- phase space factorization

$$\int d\Phi_5 = \int d\tilde{\Phi}_4 \otimes \int d\Phi_\gamma$$

- analytical integration over singular phase space regions

$$\int_5 d\sigma^{\text{sub}} = \int_4 \int_1 d\sigma^{\text{sub}} = \int_4 G_{\text{sub}}\, d\sigma^0$$

- result for decay process

$$\Gamma^{\text{NLO}} = \int_5 [\mathrm{d}\Gamma^R - \mathrm{d}\Gamma^{\text{sub}}] + \int_4 [\mathrm{d}\Gamma^V + G_{\text{sub}}\, \mathrm{d}\Gamma^0]$$

non-collinear safe observables

- need separate identification of collinear $f^\pm$ and γ
- 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

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

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

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

- z not integrated out

higher order corrections

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

- higher order final state radiation

  collinear photon emission $\longrightarrow \alpha \log(m_f^2/q^2)$

  structure function approach $\longrightarrow$ resummation of leading-logs

  $\longrightarrow$ only relevant for non-collinear safe observables

- Higgs boson self interaction

  leading 2-loop corrections to HVV vertex [Ghinculov '95; Frink et al '96]

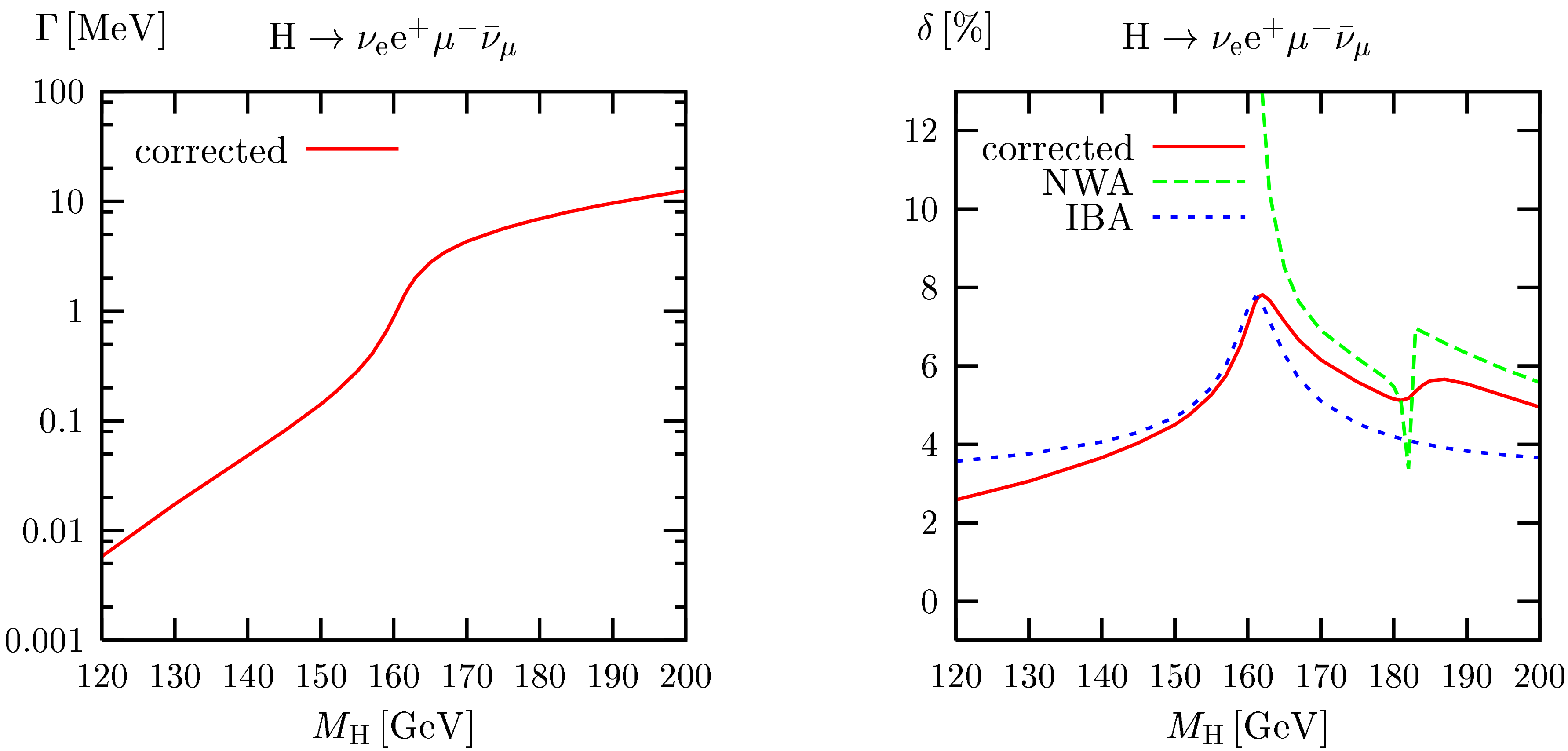
  $\longrightarrow$ relevant for $m_{\mathrm{H}} \gtrsim 400\,\mathrm{GeV}$

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 $d\Gamma$)

Partial widths: leptonic

$$\mathbf{H \to W^{(*)}W^{(*)} \to \nu_e e^+ \mu^- \bar{\nu}_\mu}$$



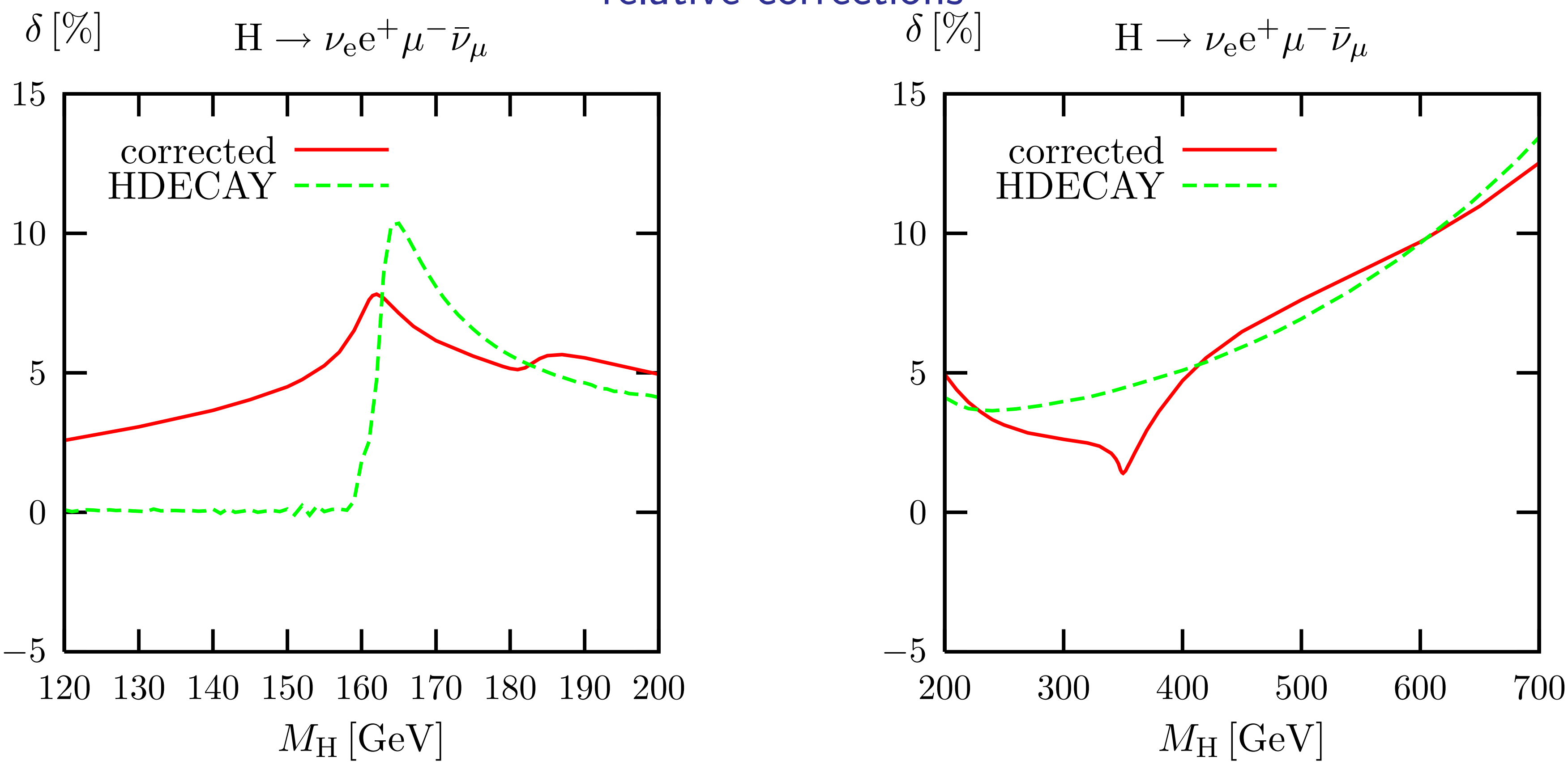
NWA: narrow width approximation = on-shell $H \to WW$ with $BR(W \to f\bar{f}')$

IBA: improved Born approximation

Comparison with HDECAY

$$\mathbf{H} \to \mathbf{W}^{(*)}\mathbf{W}^{(*)} \to \nu_{\mathbf{e}}\mathbf{e}^{+}\mu^{-}\bar{\nu}_{\mu}$$

relative corrections



HDECAY

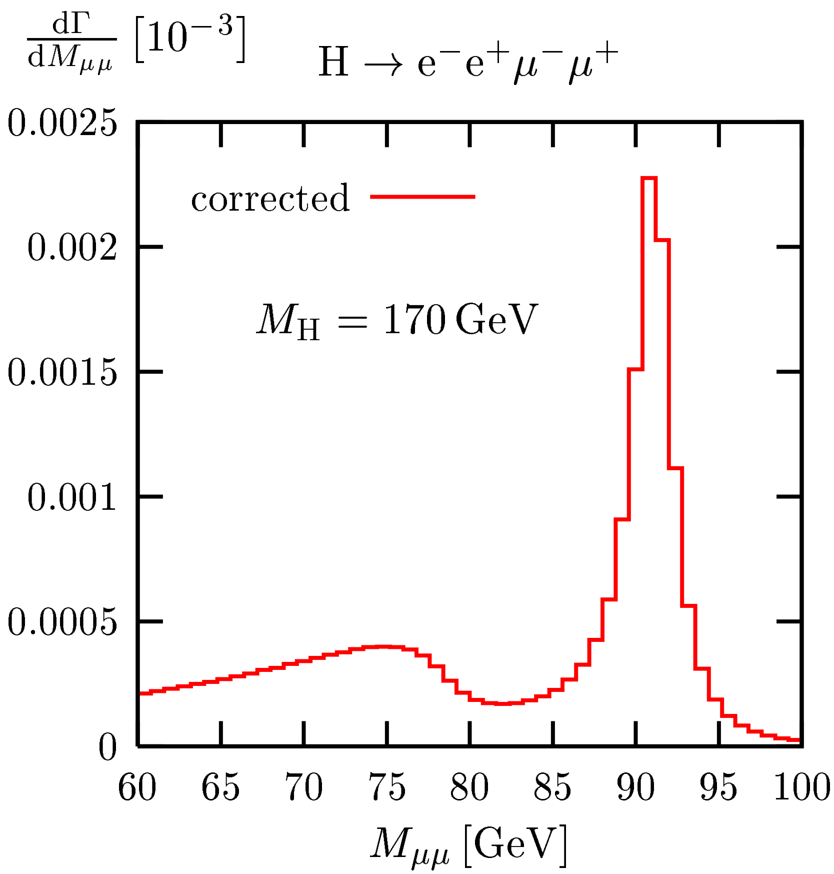
- includes leading 1 and 2-loop corrections for large m_{H}
- off-shell effects taken into account below threshold

Distributions: invariant mass

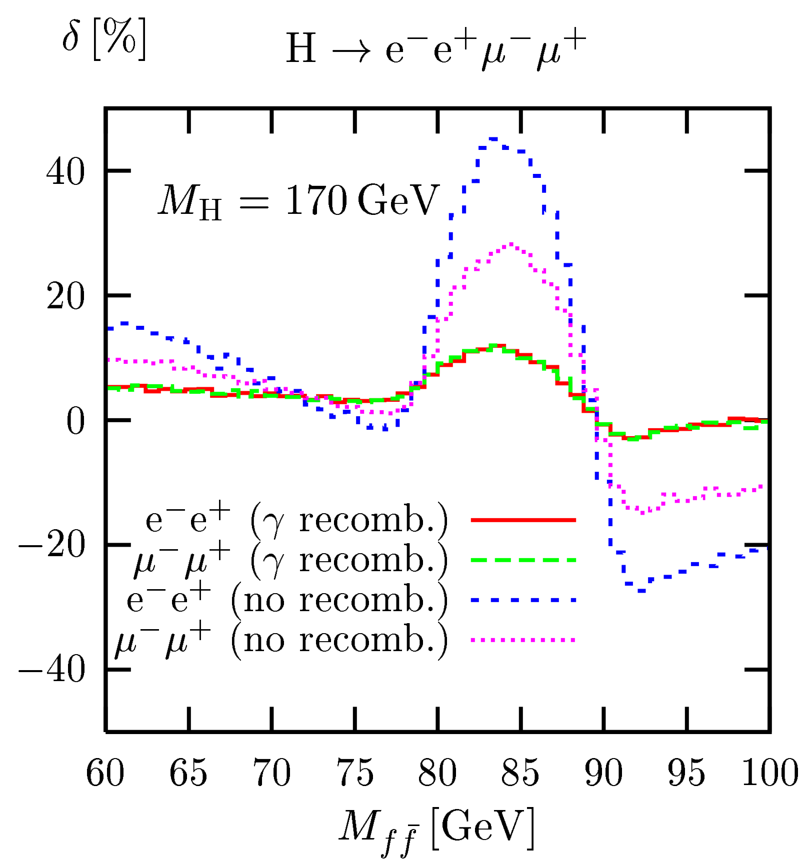
$$\mathbf{H} \rightarrow \mathbf{Z}^{(*)}\mathbf{Z}^{(*)} \rightarrow \mathbf{e}^-\mathbf{e}^+\mu^-\mu^+$$

$m_H = 170$ GeV

invariant mass distribution



relative corrections



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

→ large corrections from photon recombination in Z reconstruction

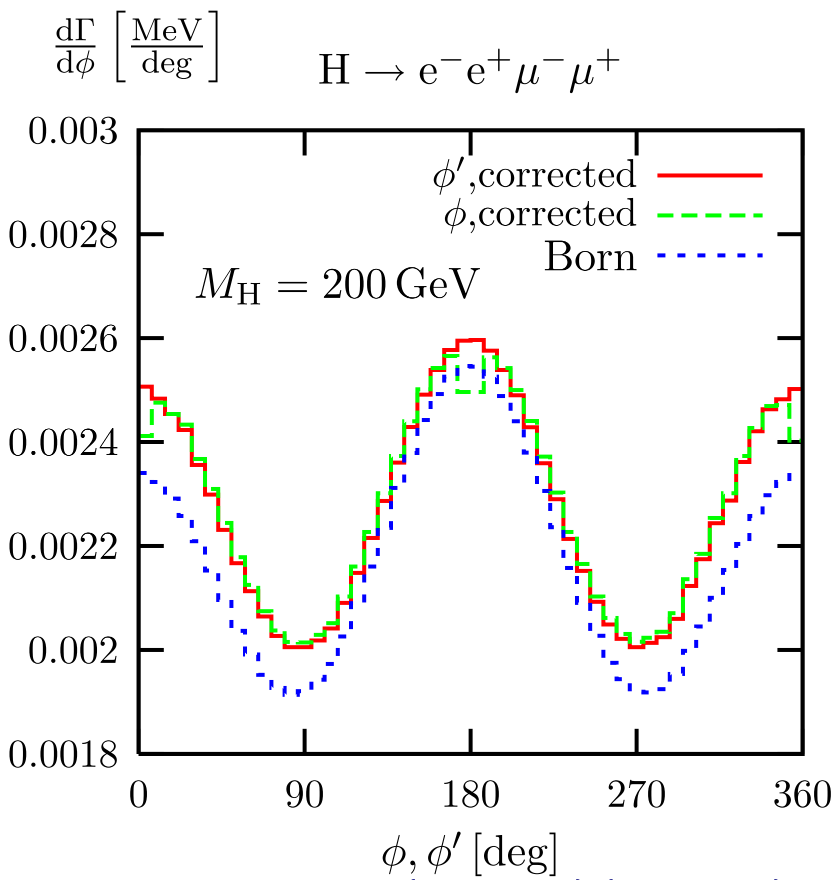
Distributions: angular

$$\mathbf{H} \to \mathbf{Z}^{(*)}\mathbf{Z}^{(*)} \to \mathbf{e}^-\mathbf{e}^+\mu^-\mu^+$$

$$m_H = 200\ \text{GeV}$$

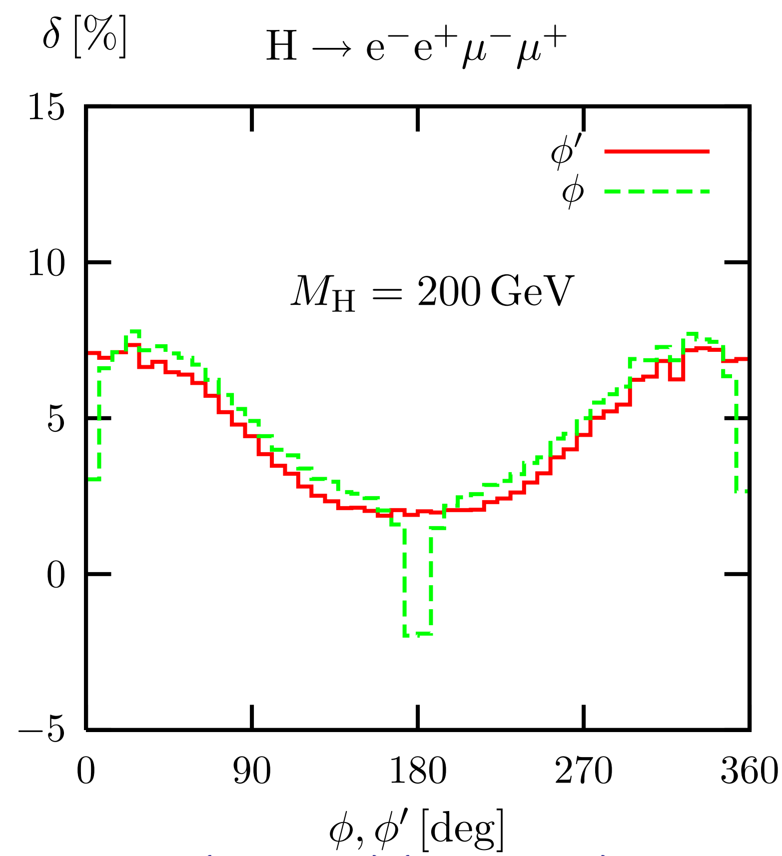
ϕ angle between decay planes of e^+e^- and $\mu^+\mu^-$

angular distribution



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

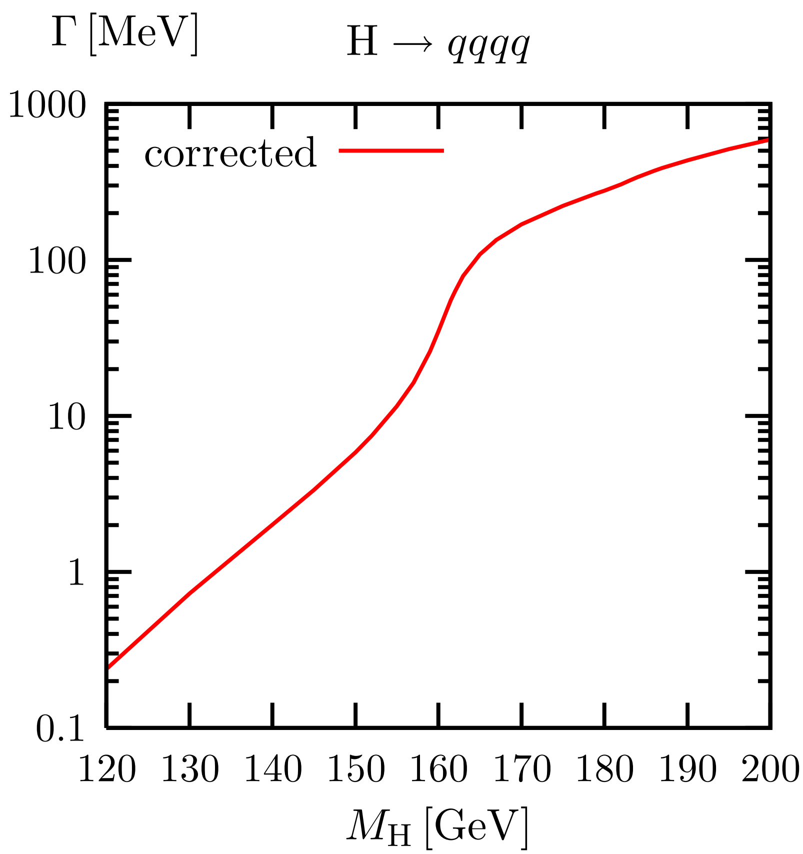
relative corrections

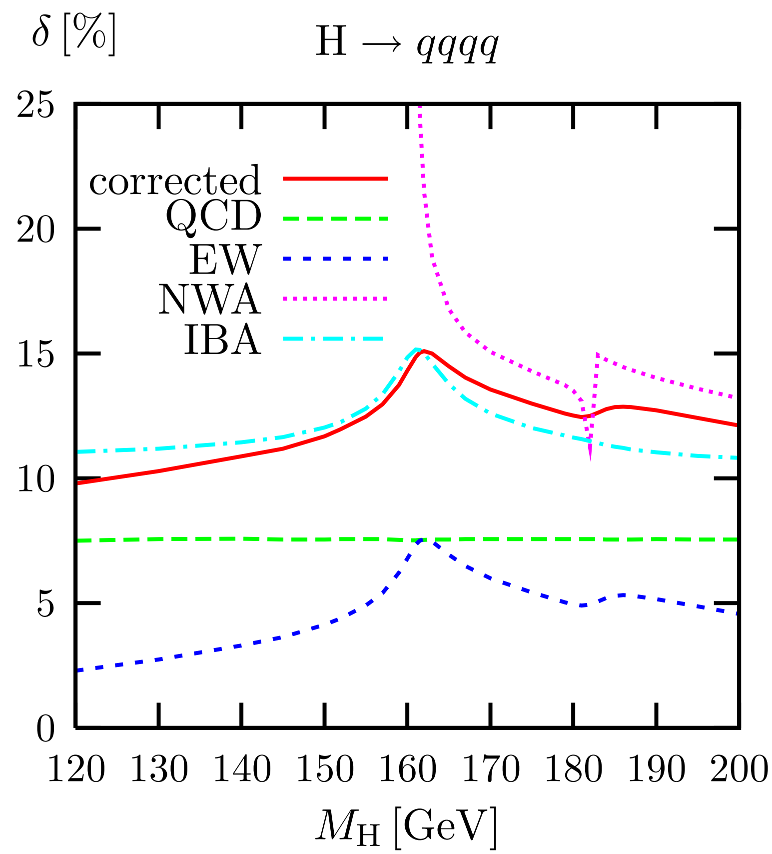


$$\cos\phi = \frac{(\mathbf{p}_+ \times \mathbf{p}_1)(-\mathbf{p}_- \times \mathbf{p}_3)}{|\mathbf{p}_+ \times \mathbf{p}_1||-\mathbf{p}_- \times \mathbf{p}_3|}$$

Partial widths: hadronic

$\mathbf{H} \to \mathbf{qqqq}$



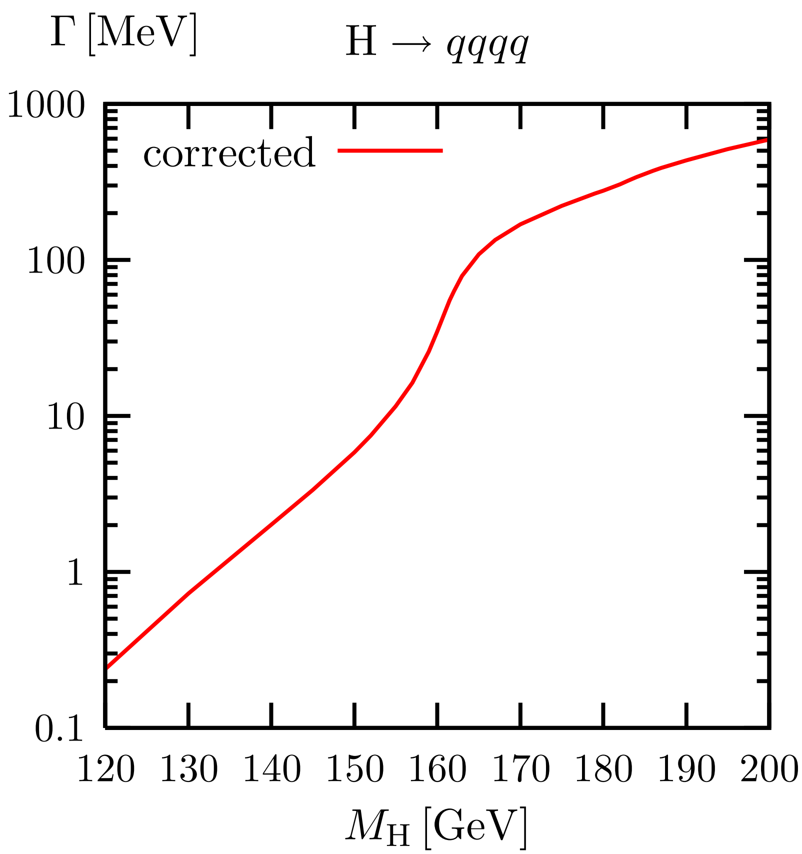


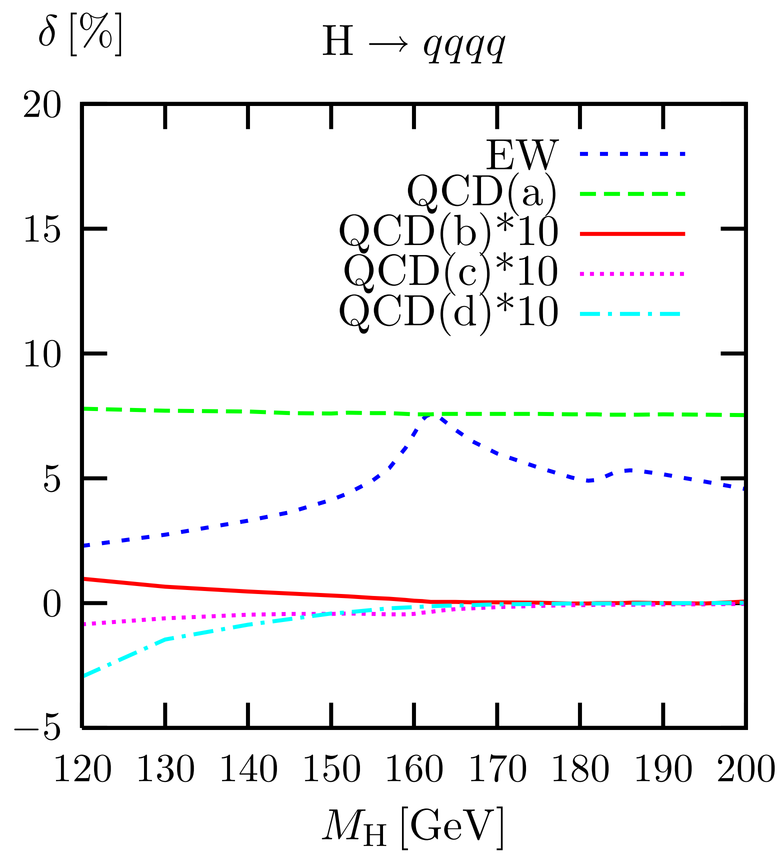
EW corrections: similar for leptonic, semileptonic and hadronic final states

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

Partial widths: hadronic

$H \to qqqq$





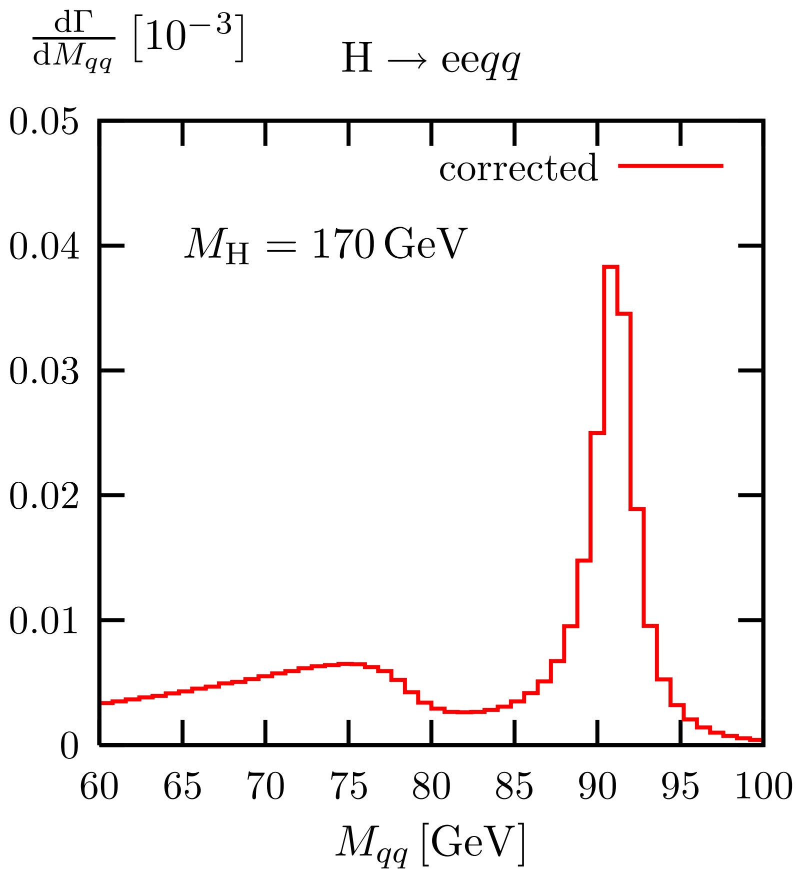
QCD corrections:

- only type (a) relevant = corrections to W/Z decays
- b),c),d): interference corrections $< 0.5\%$

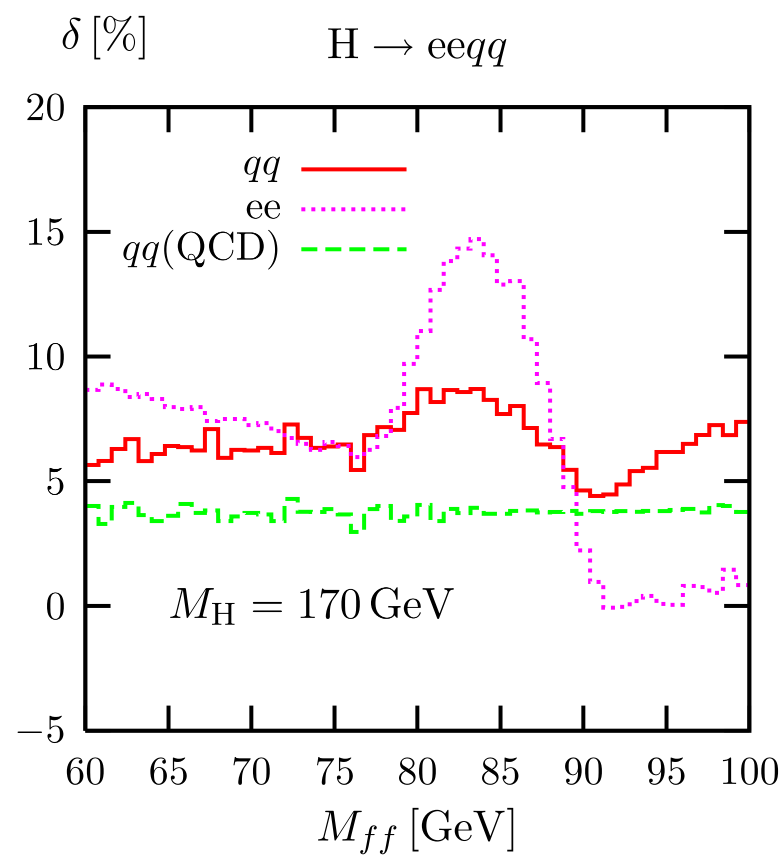
Distributions: invariant mass

$\mathbf{H} \to \mathbf{eeqq}$

invariant mass distribution



relative corrections



gluon recombination: force 2-jet event, recombine 2 partons with smallest m_{jj}^2

Monte Carlo generator: PROPHECY4F

PROPHECY4F = a PROPer description for the Higgs dECaYs into 4 Fermions

Features of Monte Carlo generator PROPHECY4F

- $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha_s)$ calculation of $H \to WW/ZZ \to 4f$
  all final states
  partial widths and distributions

- non-collinear-safe observables possible

- corrections beyond $\mathcal{O}(\alpha)$
  higher order final state radiation, large m_H effects

- improved Born approximation for partial widths
  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]
  $\longrightarrow$ up to 10 channels for real corrections
  adaptive weight optimization [Kleiss, Pittau '94]
  uses Cuba integration library [Hahn '05]

Unweighted event generation

generation of unweighted events

- using hit-and-miss algorithm
- only with phase space slicing
- currently only for leptonic final states
- no final state radiation
  higher order FSR: up to 4% (10%) for muons (electrons) in distributions
  but only where leading order is small
- fills Les Houches Accord COMMON block for each event
  $\longrightarrow$ user can read out events
- negative weight events: can not be completely avoided
  are unweighted too
  but: only few negative events: $0.1\% \ldots 1\%$

efficiency of unweighted event generation

- 1 unweighted event $= \mathcal{O}(100 - 1000)$ weighted events
- runtime: 5×10^5 unweighted events $=$ 1-2 days (single PC)

Example input file

```
outputfile=out.eemumu.300       ! name of outputfile
nevents=10000000                ! nevents: number of weighted events
nunwevents=50000                ! nunwevents: number of unweighted events

contrib=1                       ! contrib: 1=best 2=IBA 3=Born
qqcd=1                          ! qqcd: 0=EW 1=EW+QCD 2=QCD corrections incl.
qsoftcoll=2                     ! qsoftcoll: 1=subtraction 2=slicing

fname(1)=e                      ! fermion 1
fname(2)=anti-e                 ! (anti-)fermion 2
fname(3)=mu                     ! fermion 3
fname(4)=anti-mu                ! (anti-)fermion 4

qrecomb=0                       ! qrecomb: 0=no recomb., 1=photon recomb.
invrecomb=5d0                   ! recombination condition (for qrecomb=1)

mh        = 300d0               ! Higgs boson mass
1/alpha0 = 137.03599911d0       ! 1/alpha(0)
alphas    = 0.118d0             ! strong coupling constant
gf        = 1.16639d-5          ! Fermi constant
mz        = 91.187d0            ! Z boson mass
mw        = 80.41d0             ! W boson mass
me        = 0.51099892d-3       ! electron mass
mmu       = 105.658369d-3       ! muon mass
mtau      = 1.77699d0           ! tau mass
md        = 0.190d0             ! d-quark mass
mu        = 0.190d0             ! u-quark mass
ms        = 0.190d0             ! s-quark mass
mc        = 1.4d0               ! c-quark mass
mb        = 4.6d0               ! b-quark mass
mt        = 172d0               ! t-quark mass
```

Example output file

```
Input paramaters:
-----------------
  1/alpha(0) = 1/137.03599911           alphas =   0.1180
          GF = .1166390E-04 GeV^-2
          MW =  80.41000 GeV     MZ =  91.18700 GeV     MH = 300.00000 GeV
          me =   0.51100 MeV    mmu =   0.10566 GeV   mtau =   1.77699 GeV
          mu =   0.19000 GeV     mc =   1.40000 GeV     mt = 172.00000 GeV
          md =   0.19000 GeV     ms =   0.19000 GeV     mb =   4.60000 GeV

Derived paramaters:
-----------------
     1/alpha = 1/132.44307185
          GW =   2.09130 GeV     GZ =   2.49866 GeV     gt =   1.46541 GeV

Options:
--------
 Process:  H ->   e anti-e mu anti-mu (+Photon/Gluon)

 number of weighted events   =  10000000
 number of unweighted events =     50000

     contrib = 1 : Born cross section + radiative corrections
        qqcd = 1 : EW+QCD corrections
   qsoftcoll = 2 : slicing method

     qrecomb = 0 : no photon recombination applied

       qcuts = 0 : no separation cuts

      DeltaE =  0.4E-02 :  Slicing energy cut
     DeltaTh =  0.3E-01 :  Slicing angular cut
```

Example output file

```
Narrow width approximation (incl EW+QCD):
-----------------------------------------
Partial width:  5.97660     MeV
         Born:  5.82024     MeV (NLO gauge-boson width)
   Correction: 0.156355     MeV


Results:
-------

Average              =       5.8390875572 MeV
Standard deviation   =       0.0034318569 MeV

Subcontributions:
-----------------
Born cross section (NLO gauge-boson width):
 Average             =       5.6660697095 MeV
 Standard deviation =        0.0015014548 MeV
 largest event       =       0.0000048078 MeV
  event number       3054, channel  4

EW Virtual corrections:
 Average             =      -1.2061697571 MeV
 Standard deviation =        0.0018532689 MeV
 largest event       =       0.0000215364 MeV
  event number       3091, channel  4

Photon Bremsstrahlung:
 Average             =       1.3791876048 MeV
 Standard deviation =        0.0026299759 MeV
 largest event       =       0.0000864870 MeV
  event number       4455, channel  8
```

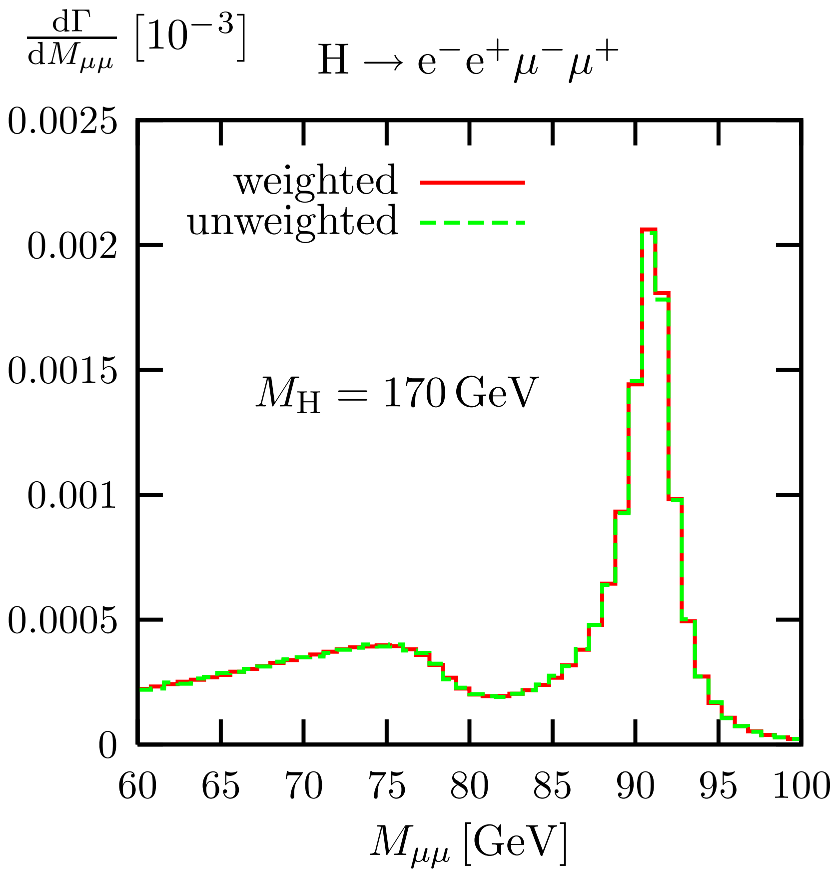
Example output file

```
 Unweighted events:
 ------------------
generated   50090 unweighted events (including negative events)
  by generating weighted events   11048670 times
number of weights larger than largest weight from 1st cycle:    0
number of negative unweighted events:    45
maximal weight used for generating unweighted events: 1297.3
```

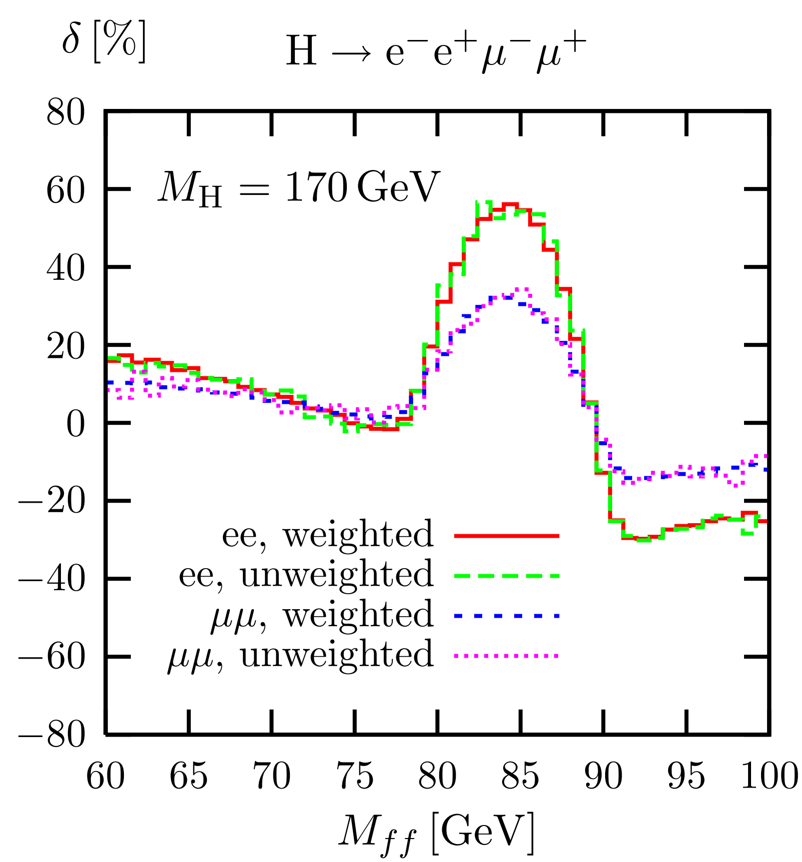
Unweighted events

$$\mathbf{H} \to \mathbf{Z}^{(*)}\mathbf{Z}^{(*)} \to \mathbf{e}^-\mathbf{e}^+\mu^-\mu^+$$

invariant mass distribution



relative corrections



no photon recombination

5×10^7 weighted events

5×10^5 unweighted events

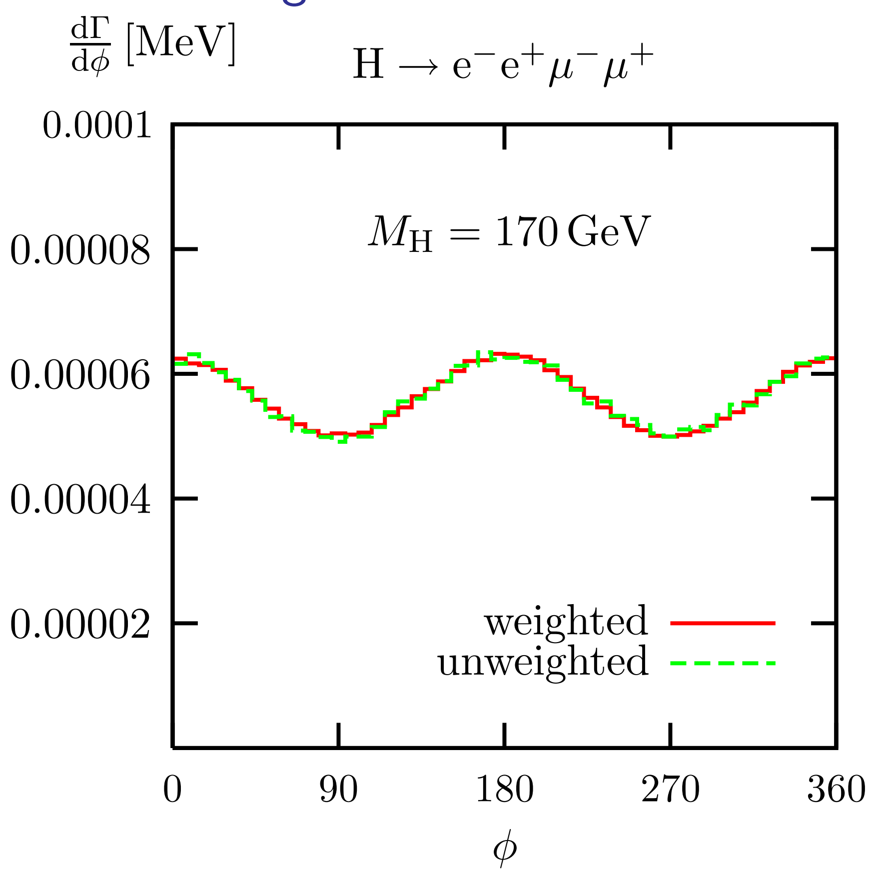
runtime: 1-2 days (single PC)

Unweighted events

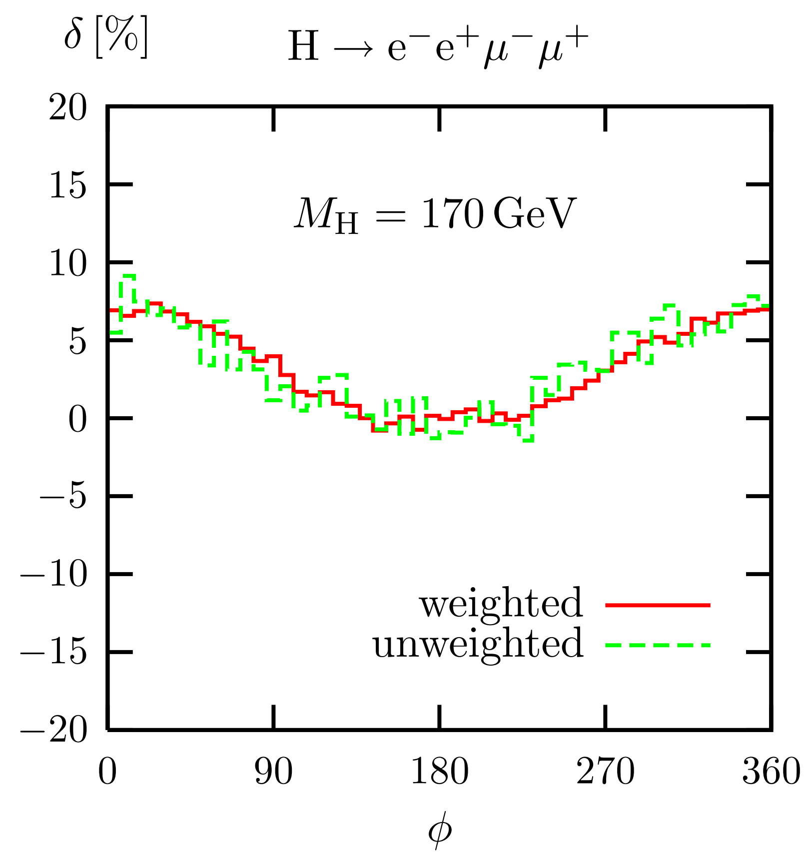
$$\mathbf{H} \to \mathbf{Z}^{(*)}\mathbf{Z}^{(*)} \to \mathbf{e}^-\mathbf{e}^+\mu^-\mu^+$$

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

angular distribution



relative corrections



5×10^7 weighted events

5×10^5 unweighted events

runtime: 1-2 days (single PC)

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

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)

PROPHECY4F: Monte Carlo generator for $H \to WW/ZZ \to 4f$

- complete $\mathcal{O}(\alpha)$ electroweak and $\mathcal{O}(\alpha_s)$ QCD corrections
  gauge boson resonances: complex mass scheme
- universal beyond $\mathcal{O}(\alpha)$ corrections:
  heavy-Higgs effects and final state radiation
- non-collinear safe observables possible
- weighted and unweighted event generation
- (almost) publically available

results

- partial width EW corrections 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
  EW corrections $\mathcal{O}(10\%)$ with γ-recombination (depending on γ recombination)
- QCD corrections
  associated with W/Z decay