Precision calculations for $H \to WW/ZZ \to$ 4 fermions with PROPHECY4f

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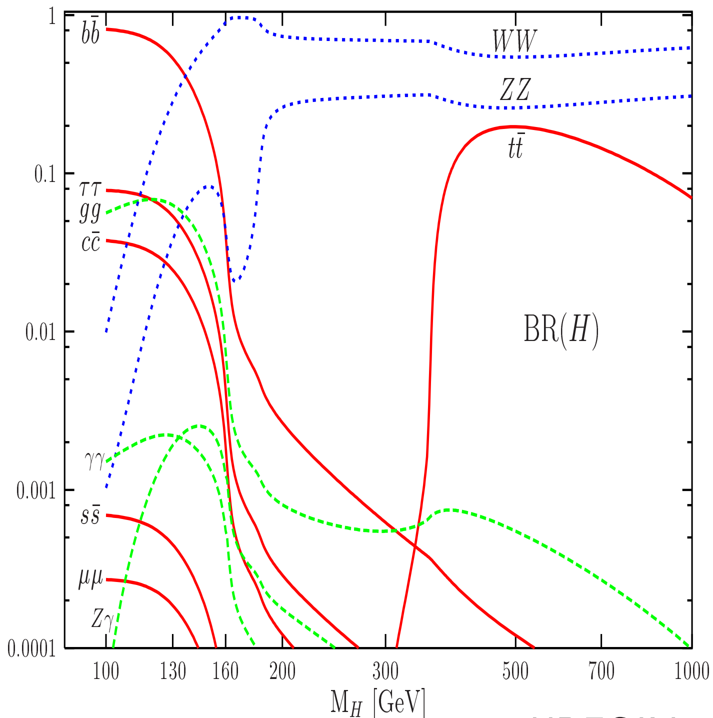
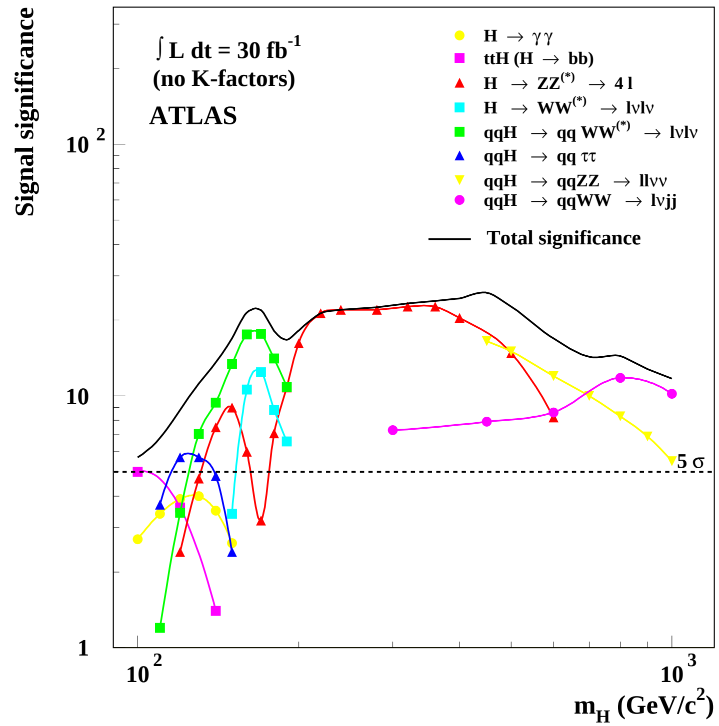
Introduction: $H \to WW^{(*)}/ZZ^{(*)}$decays



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

$\to$ 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 [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
  $\longrightarrow$ invariant mass distributions
- verification of Higgs boson spin and CP:
  $\longrightarrow$ uses 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 '02]

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

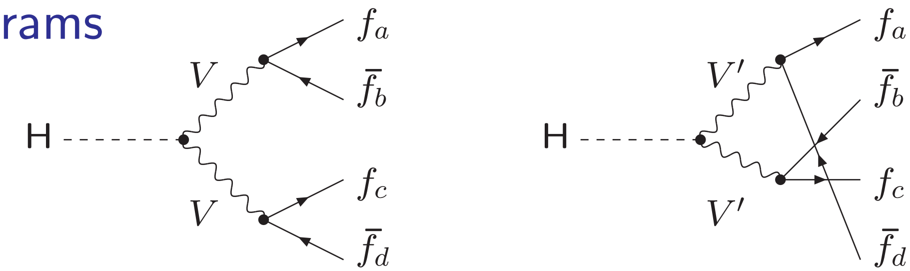
recent work

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]

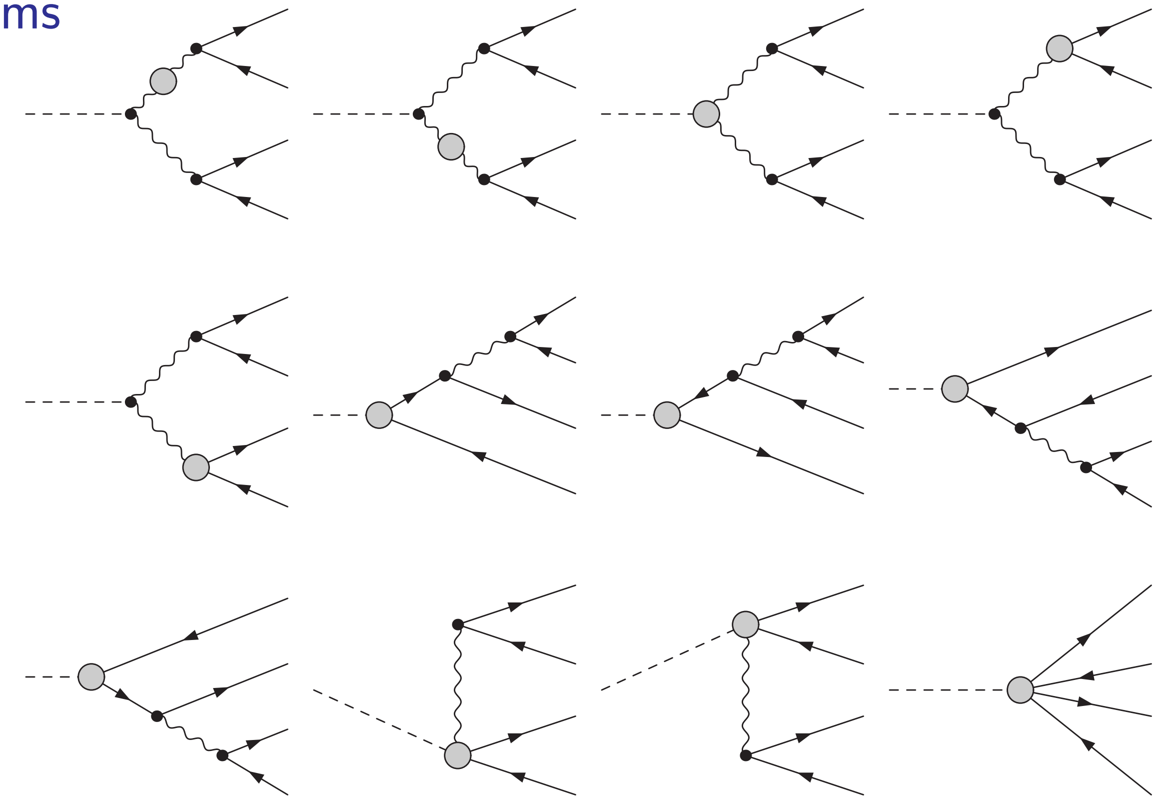
Radiative corrections to $H \to 4f$

Born diagrams



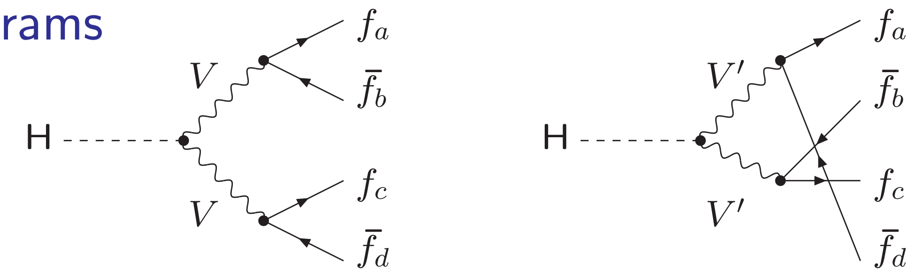
crossed diagram only for $q\bar{q}q\bar{q}$ and $q\bar{q}q'\bar{q}'$ final states

EW virtual diagrams

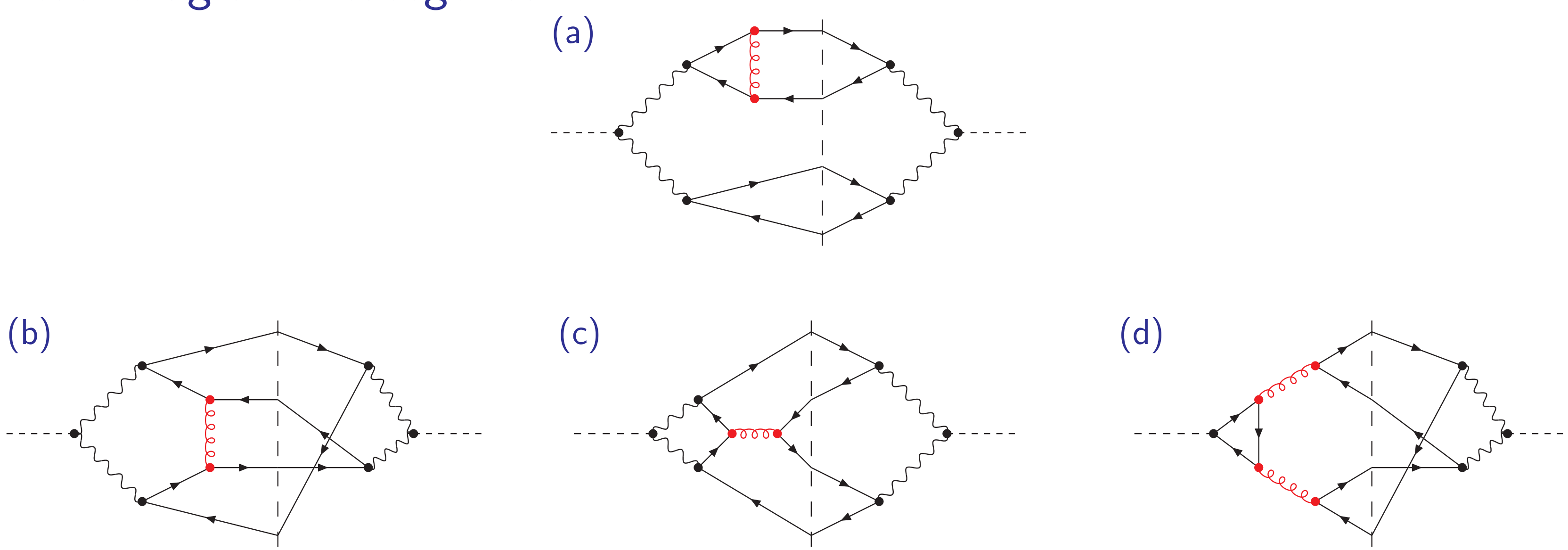


- about 400 Feynman diagrams (Feynman gauge), up to pentagons
- external fermions massless

Born diagrams



QCD virtual diagrams: categories



(a): corrections to W/Z decays

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

NLO Calculation: general remarks

numerical instabilities in Passarino-Veltman tensor integral reduction

$\longrightarrow$ alternative reduction using expansions/numerical integration if necessary

[Denner, Dittmaier '05]

gauge invariant treatment of resonances

$\longrightarrow$ complex mass scheme [Denner, Dittmaier, Roth, Wieders '05]

idea: mass^2 = complex pole of propagator

consistently use complex mass everywhere:

- in loop integrals
- in derived quantities: $\cos\theta_W = \frac{\mu_W}{\mu_Z}$

$\longrightarrow$ gauge invariant, no double counting

but:

- spurious $\mathcal{O}(\Gamma/M) = \mathcal{O}(\alpha)$ terms
- unitariy violated at $\mathcal{O}(\alpha^2)$

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 $d\Gamma$)

PROPHECY4F

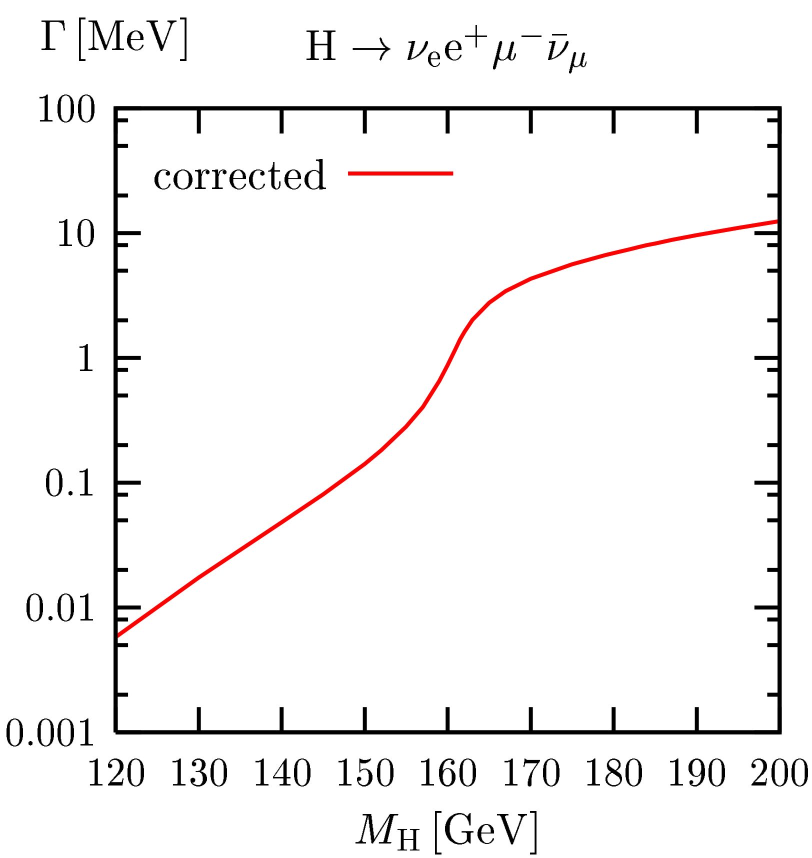
Features of Monte Carlo generator PROPHECY4F

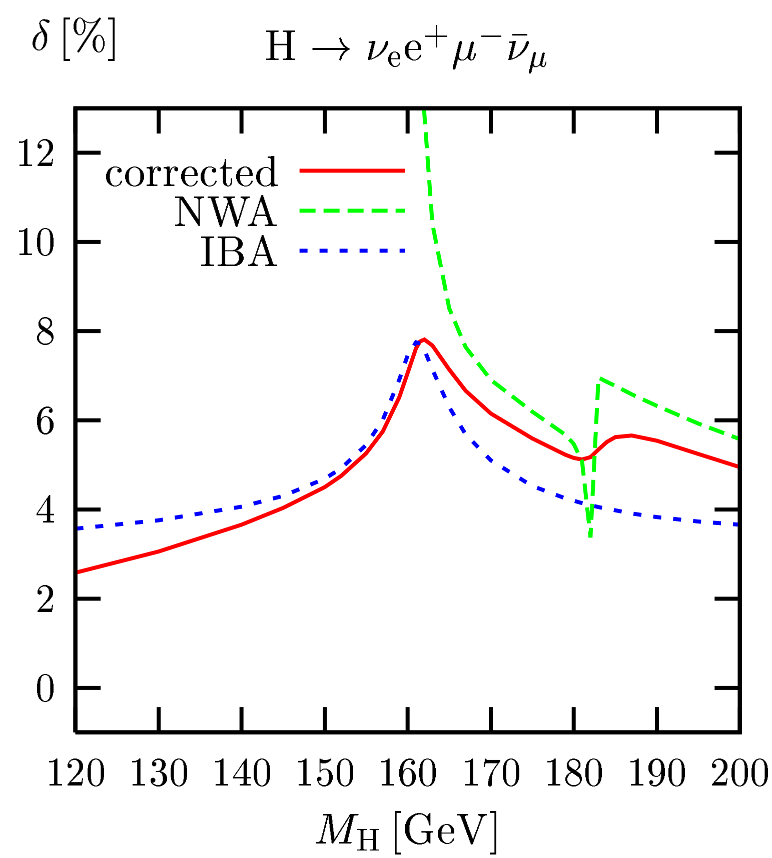
- $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha_s)$ calculation of $H \to WW/ZZ \to 4f$
  partial widths and distributions
- non-collinear-safe observables possible
- corrections beyond $\mathcal{O}(\alpha)$
  higher order final state radiation, large m_H effects
- improved Born approximation for partial 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]
  adaptive weight optimization [Kleiss, Pittau '94]

Partial widths: leptonic

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

G_μ-scheme





NWA: narrow width approximation

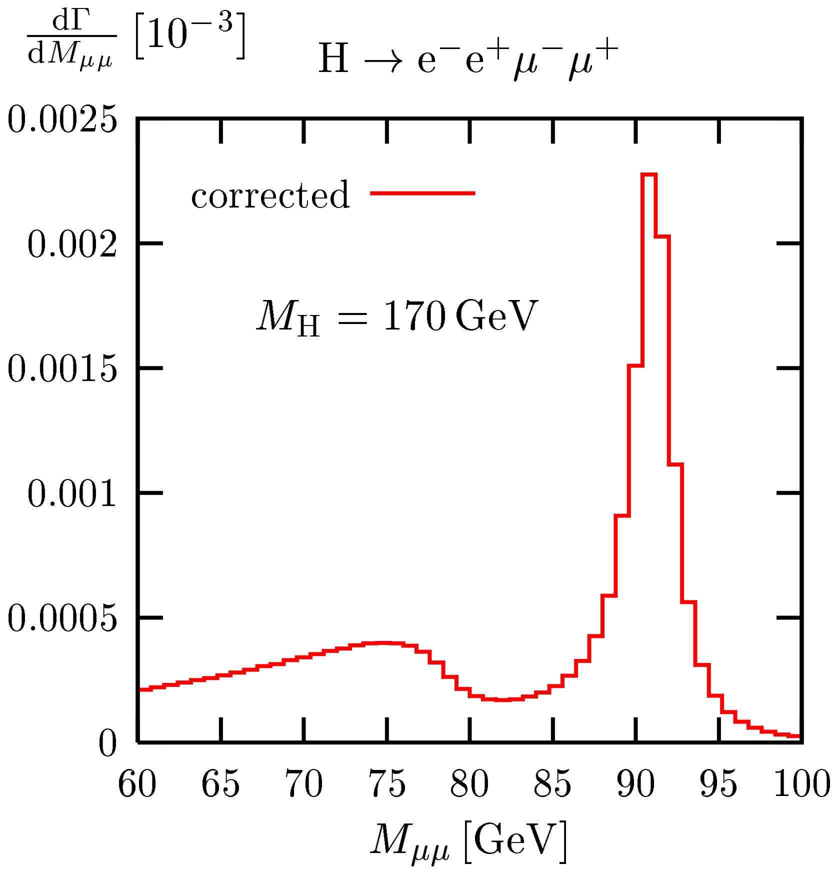
IBA: improved Born approximation

Distributions: invariant mass

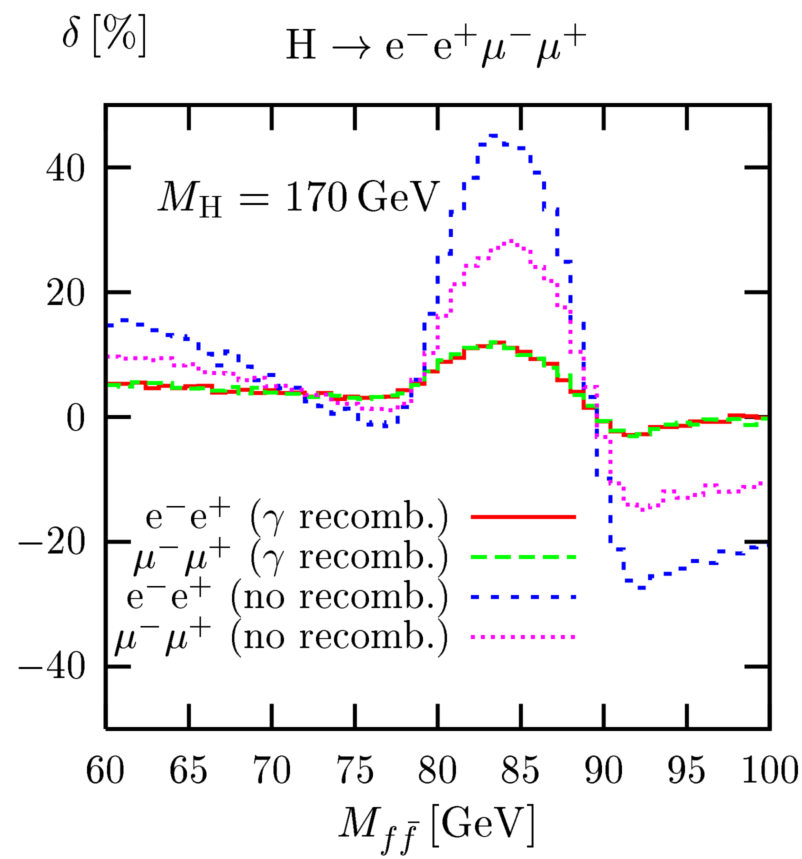
$\mathbf{H \to e^- e^+ \mu^- \mu^+}$

G_μ-scheme, $m_H = 170$ GeV

invariant mass distribution



relative corrections



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

→ large corrections from photon recombination in Z reconstruction

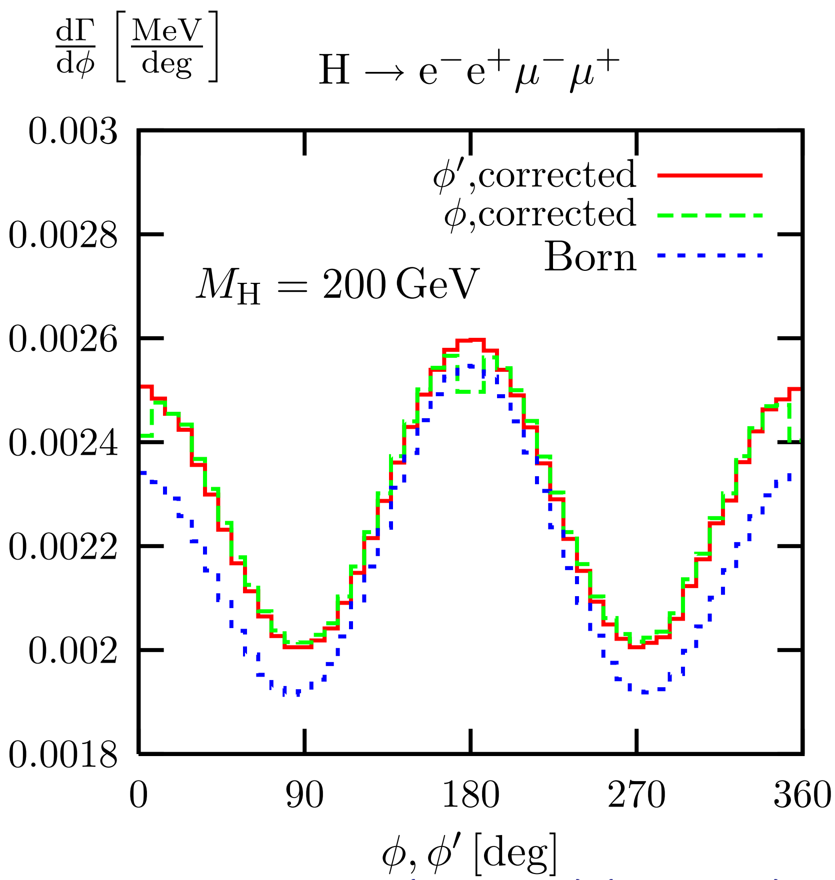
Distributions: angular

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

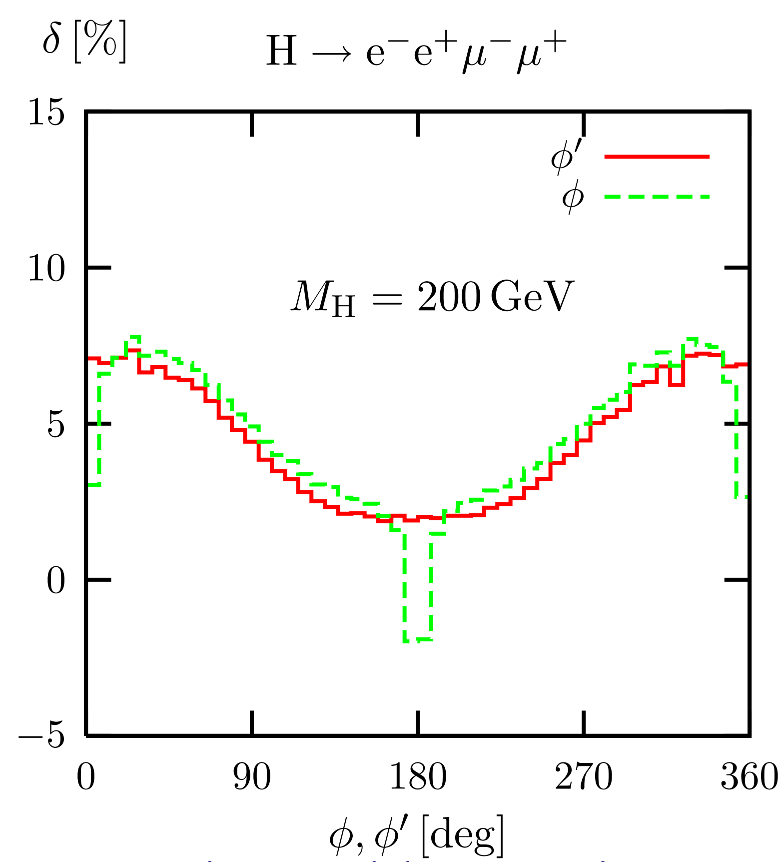
G_μ-scheme, $m_H = 200$ GeV

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

angular distribution

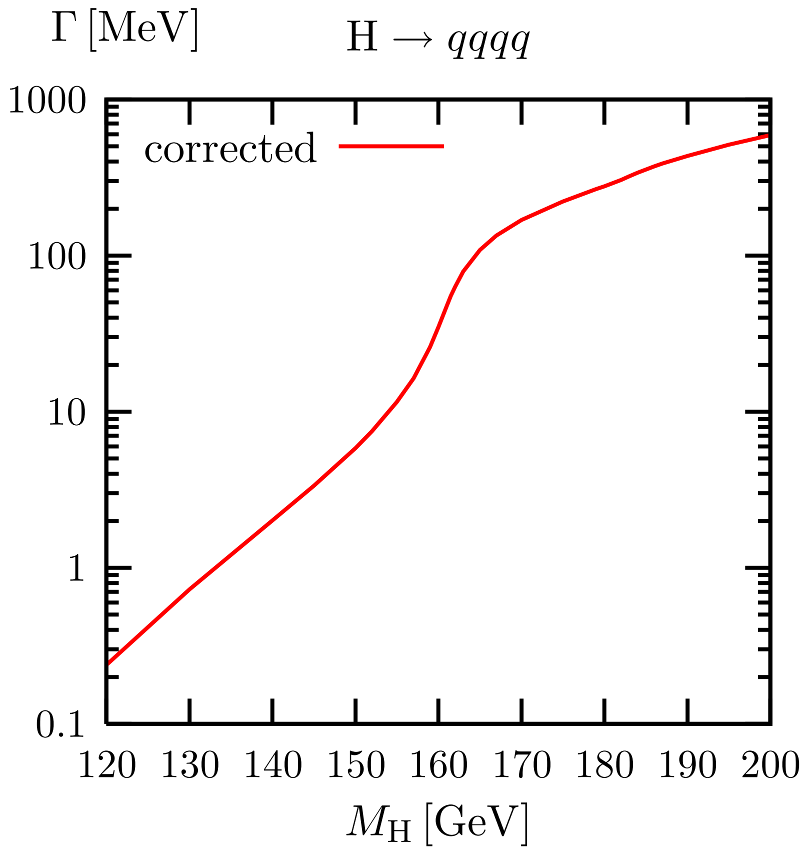


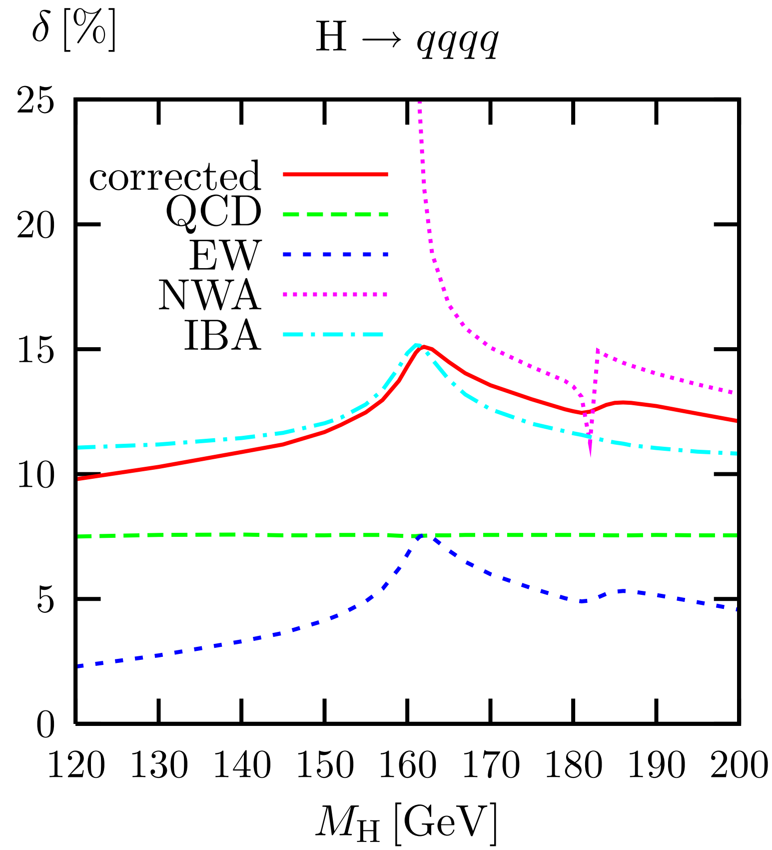
relative corrections



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

$\mathbf{H \to qqqq}$



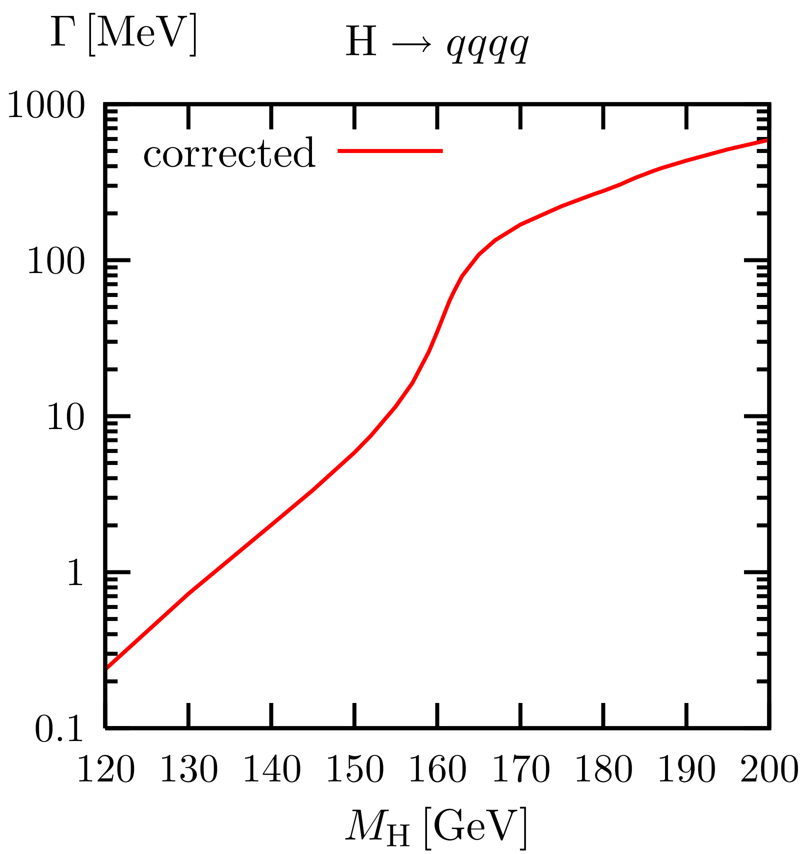


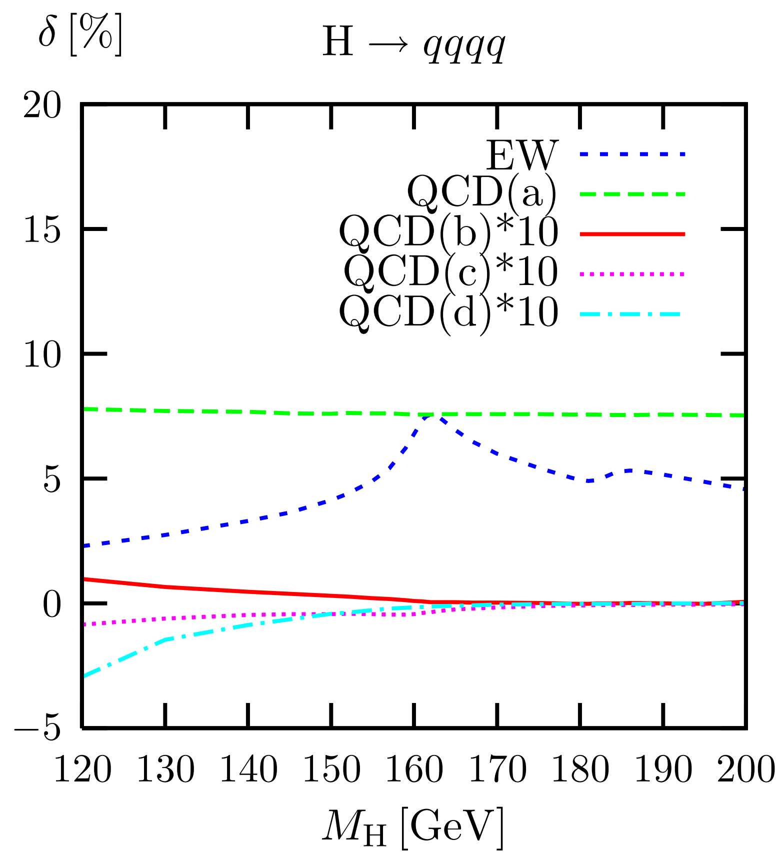
EW corrections: similar for leptonic, semileptonic and hadronic final states

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

Partial widths: hadronic

contributions to $\Gamma(\mathbf{H} \to \mathbf{qqqq})$



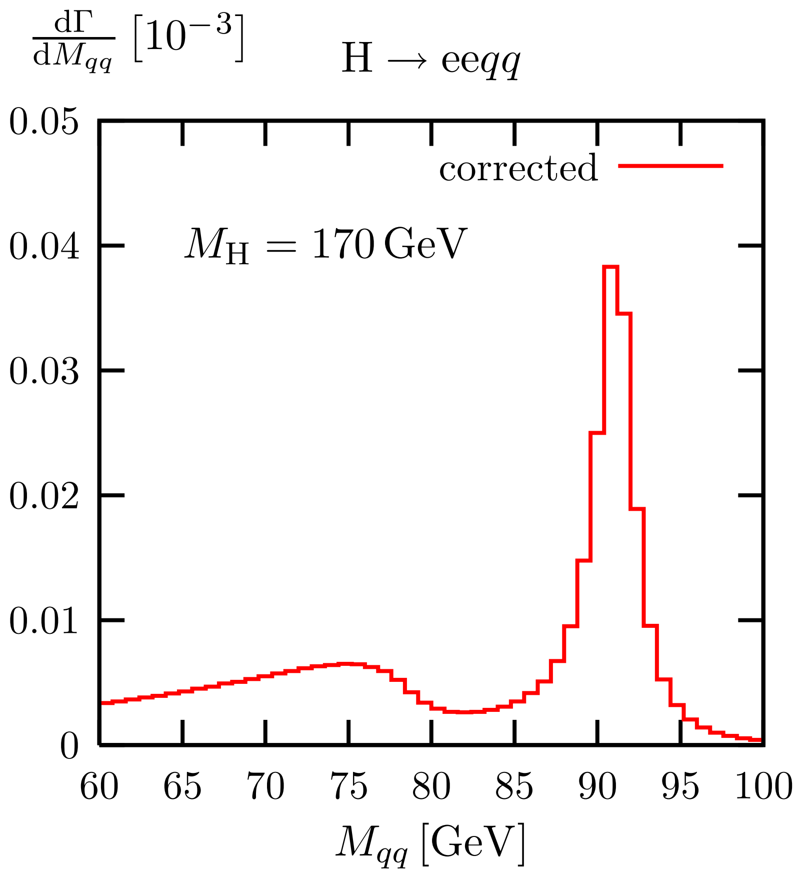


QCD corrections: only type (a) relevant = corrections to W/Z decays

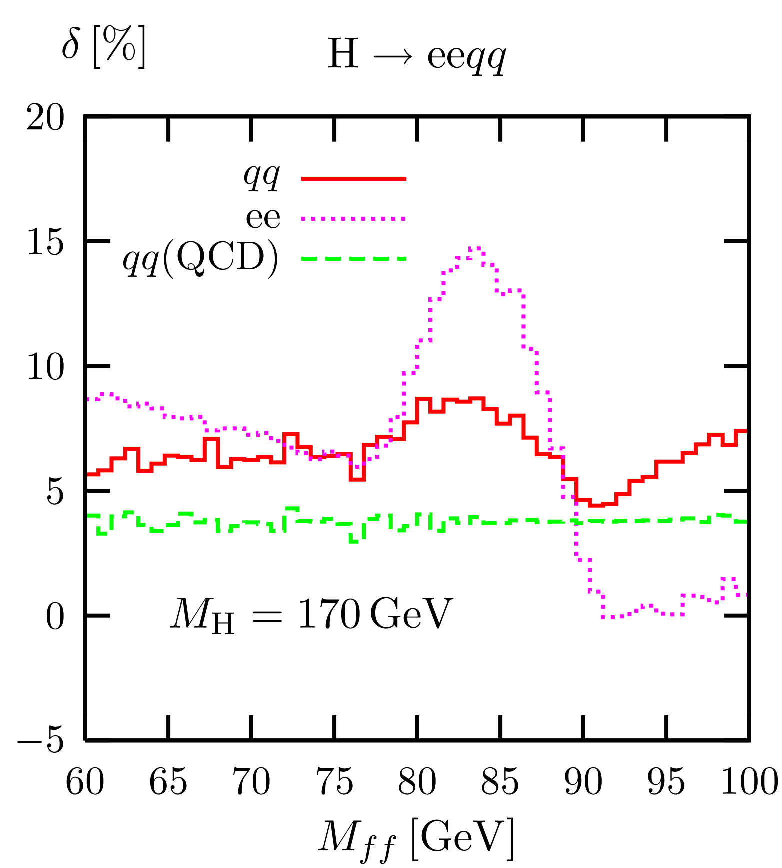
Distributions: invariant mass

$\mathbf{H \to eeqq}$

invariant mass distribution



relative corrections



gluon recombination: force 2-jet event

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
  tensor loop integrals: numerically stable methods
- universal beyond $\mathcal{O}(\alpha)$ corrections:
  heavy-Higgs effects and final state radiation
- non-collinear safe observables possible

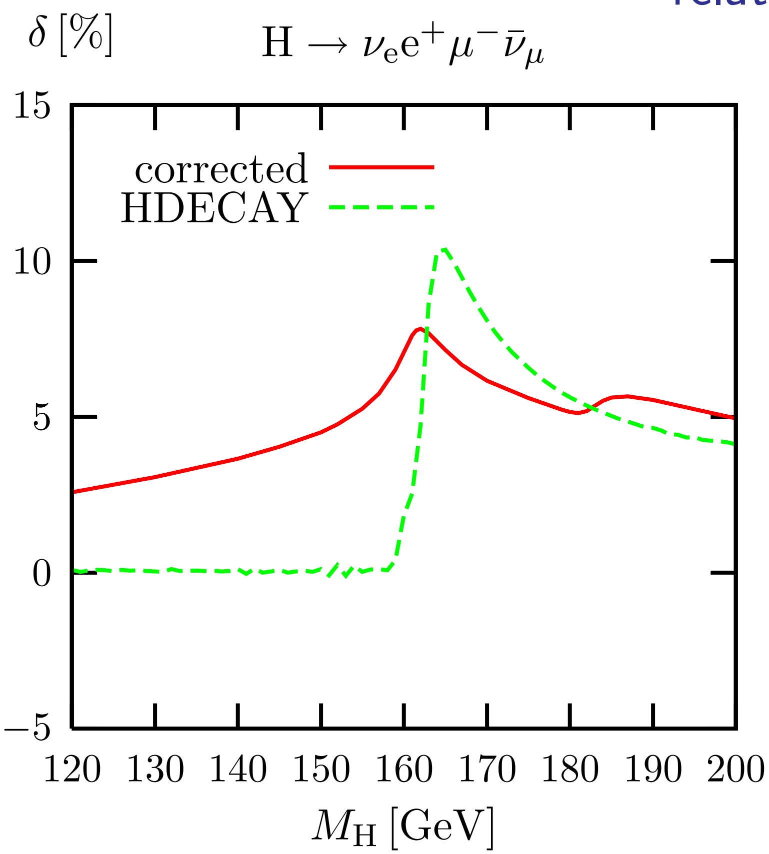
results

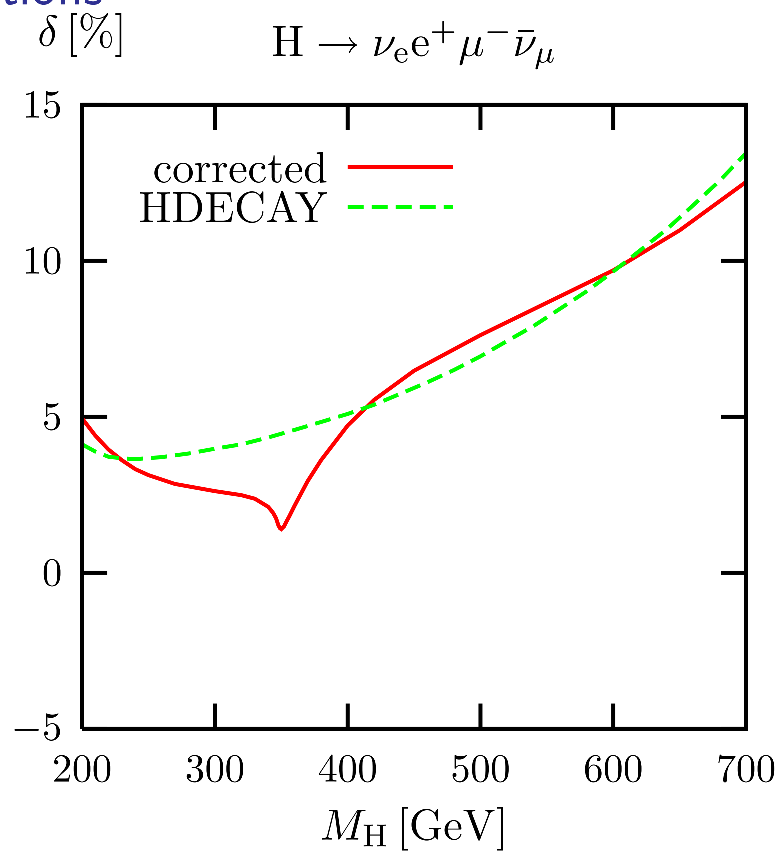
- partial width EW corrections up to $\simeq 8\%$ for $m_\mathrm{H} \lesssim 500\,\mathrm{GeV}$
  improved born approximation: accurate to within $\lesssim 2\%$ for $m_\mathrm{H} \lesssim 500\,\mathrm{GeV}$
- distributions
  EW corrections $\mathcal{O}(10\%)$ with γ-recombination (depending on γ recombination)
- QCD corrections
  associated with W/Z decay

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