Precision calculations for Higgs and gauge-boson production at the LHC and ILC

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Contents

1 Introduction

Electroweak issues for the future (LHC/ILC):

- search for the Higgs boson
- study mechanism of electroweak symmetry breaking
- search for SUSY and other new physics
- top-quark physics
- further studies of gauge-boson self-interactions
- electroweak high-precision physics

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Electroweak issues for the future (LHC/ILC):

- search for the Higgs boson
  e.g. $\mathrm{pp} \to q\bar{q}\mathrm{H}$, $\mathrm{pp} \to Q\bar{Q}\mathrm{H}$, background procs, $\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$
- study mechanism of electroweak symmetry breaking
  e.g. $\mathrm{e^+e^-/pp\,(WW{\to}WW)} \to 6f$
- search for SUSY and other new physics
  e.g. $\mathrm{pp} \to \tilde{q}\bar{\tilde{q}}$, $\mathrm{e^+e^-} \to \tilde{\chi}^+\tilde{\chi}^-/\tilde{\chi}^0\tilde{\chi}^0$ with cascade decays to LSPs
- top-quark physics
  e.g. $\mathrm{e^+e^-} \to \mathrm{t\bar{t}} \to \mathrm{WbW\bar{b}} \to 6f$
- further studies of gauge-boson self-interactions
  e.g. $\mathrm{e^+e^-} \to \mathrm{WW} \to 4f$, $\mathrm{e^+e^-/pp\,(WW{\to}WW)} \to 6f$
- electroweak high-precision physics
  e.g. m_t, M_W

Precise predictions for many-particle processes very important !

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Precise predictions for many-particle processes very important !

$\hookrightarrow$ addressed in this talk

Existing precision calculations for many-particle processes at the LHC/ILC:

- with up to 5-point loop diagrams:

  $e^+e^- \to$ 4jets (QCD), $\nu\bar{\nu}H$, $t\bar{t}H$, $e\bar{e}H$, $\nu\bar{\nu}\gamma$, ZHH, ZZH, $\quad \gamma\gamma \to t\bar{t}H$

  NLO EW/QCD: Glover/Miller, Campbell et al., Bern et al., Dixon/Signer, Nagy/Trocsanyi, Weinzierl/Kosower, GRACE-loop, Denner et al., You et al., Chen et al., Zhang et al., Zhou et al. '96–'06

  $pp \to$ 3jets, $\gamma\gamma$+jet, V+2jets, $t\bar{t}H$, $b\bar{b}H$, $t\bar{b}H^-$, $b\bar{b}V$, HHH

  NLO QCD: Bern et al., Kunszt et al., Kilgore/Giele, Campbell et al., Nagy, Del Duca et al., Campbell/Ellis, Beenakker et al., Dawson et al., S.D. et al., Peng et al., Plehn/Rauch, Febres Cordero et al. '96–'06

  $H \to 4$ fermions: NLO QCD + EW for $H \to WW/ZZ \to 4f$ Bredenstein et al. '06

  NLO QED for $H \to ZZ \to 4l$ Carloni-Calame et al. '06

- with up to 6-point loop diagrams (current technical frontier)

  $e^+e^- \to 4$ fermions (CC): NLO EW Denner, S.D. Roth, Wieders, '05

  $e^+e^- \to \nu\bar{\nu}HH$: NLO EW GRACE-loop '05

  $gg \to gggg$: NLO QCD amplitude "only" Bern et al., Bedford et al., Berger/Forde, Bidder et al., Britto et al., R.K.Ellis et al., Xiao et al., '93–'06

Complications in corrections to many-particle processes

- huge amount of algebra, long final expressions
  - ↪ computer algebra / automization
- multi-dimensional phase-space integration
  - ↪ Monte Carlo techniques
- complicated structure of singularities and matching of virtual and real corrections
  - ↪ subtraction and slicing techniques
- treatment of unstable particles, issue of complex masses
  - ↪ "complex-mass scheme" recently proposed for higher orders

    Denner, S.D., Roth, Wieders '05
- numerically stable evaluation of one-loop integrals with up to 5,6,. . . external legs
  - ↪ techniques that avoid inverse kinematical (e.g. Gram) determinants

    Stuart et al. '88/'90/'97; v.Oldenborgh/Vermaseren '90; Campbell et al. 96; Ferroglia et al. '02; del Aguila/Pittau '04; Binoth et al. '02/'05; Denner/S.D. '02/'05; v.Hameren et al. '05; R.K.Ellis et al. '05; Anastasiou/Daleo '05

    [But: most proposed methods not (yet?) used in complicated applications]

2 The processes $e^+e^- \to WW \to 4$ fermions

From LEP to the ILC

- cross-section measurement:

  LEP2: $\Delta\sigma_{WW}/\sigma_{WW} \sim 1\%$

  ILC: $\Delta\sigma_{WW}/\sigma_{WW} \lesssim 0.5\%$

- W-boson mass:

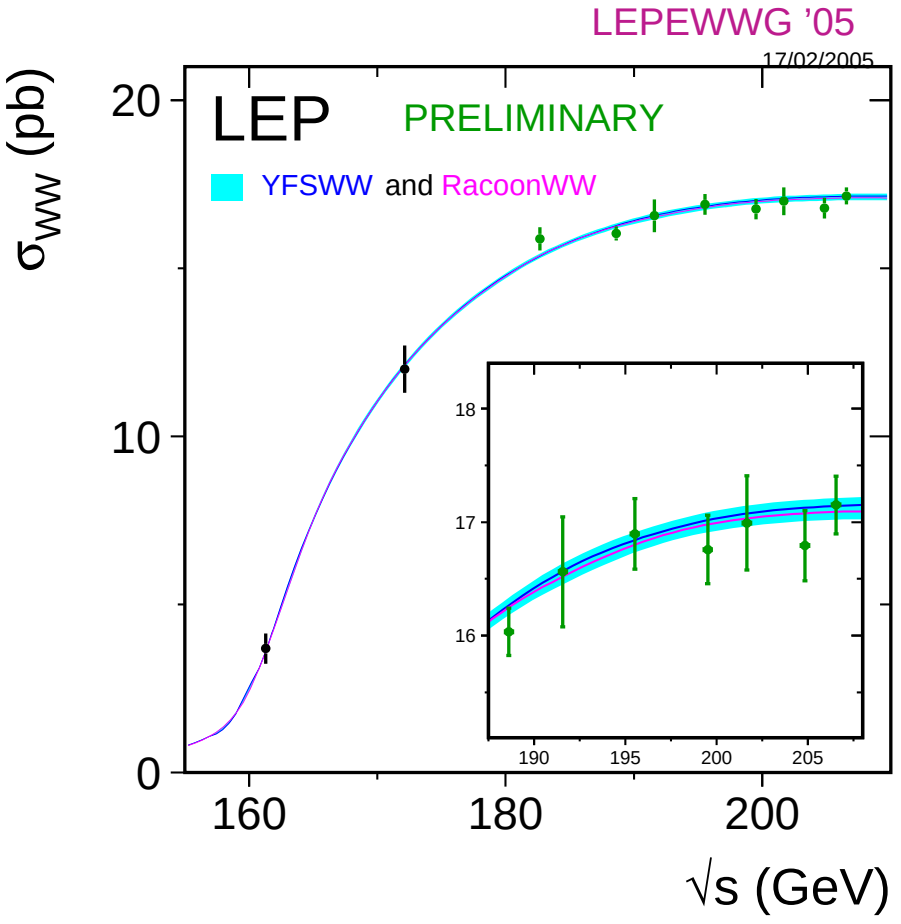
  LEP2: $\Delta M_W \sim 40\,\mathrm{MeV}$
  by reconstruction

  ILC: $\Delta M_W \sim 7\,\mathrm{MeV}$
  expected from threshold scan

- constraints on anomalous triple gauge-boson couplings:

  LEP2: level of a few $\%$

  ILC: level of 0.1%



$\Rightarrow$ full NLO calculation for $e^+e^- \to 4$ fermions needed at ILC

Recent theoretical progress:

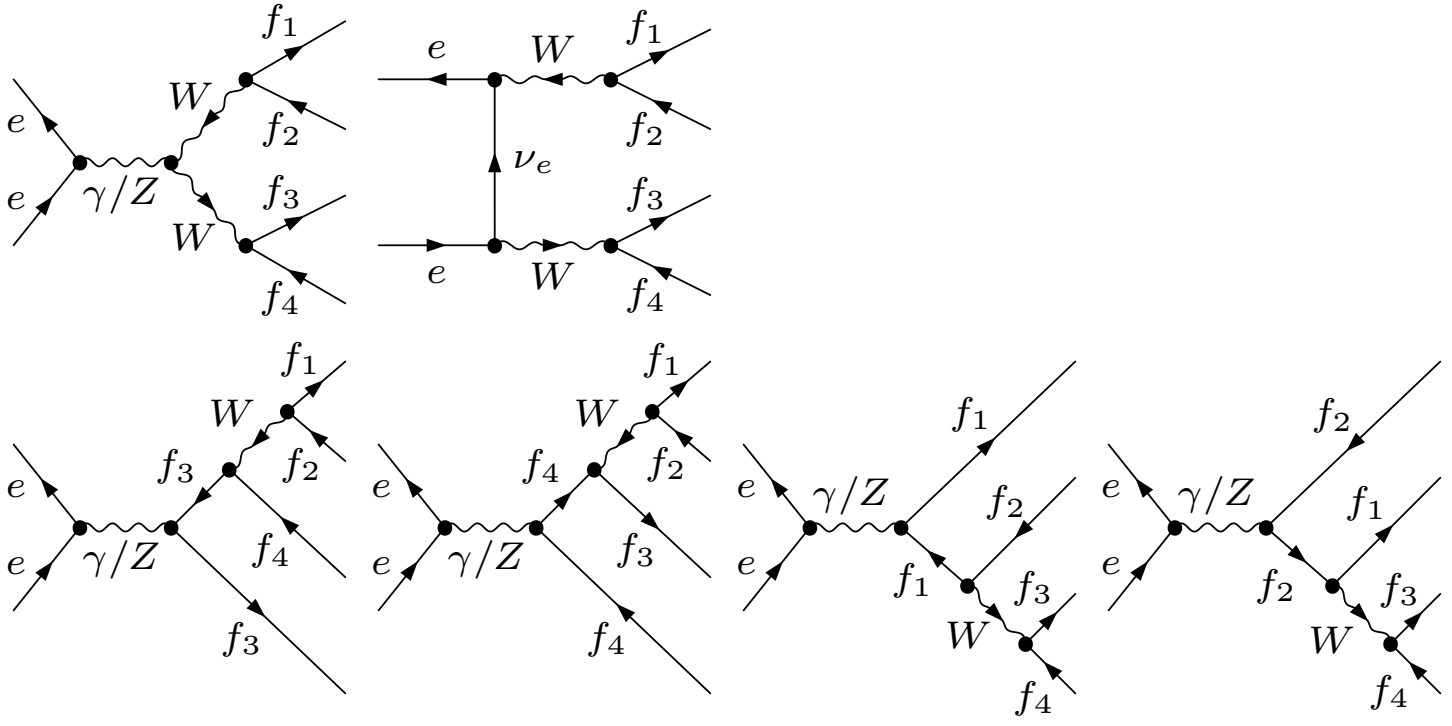
First complete $\mathcal{O}(\alpha)$ calculation for $e^+e^- \to \nu_\tau \tau^+ \mu^- \bar{\nu}_\mu$ leptonic

Denner, S.D., Roth, Wieders '05

$u\bar{d}\mu^-\bar{\nu}_\mu$ semileptonic

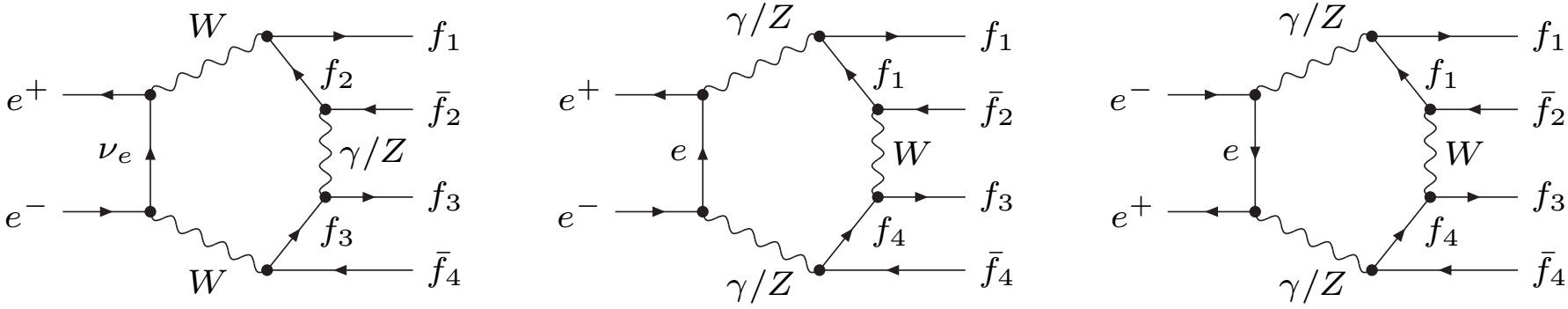
$u\bar{d}s\bar{c}$ hadronic final state

11 lowest-order diagrams: ("CC11 class")



$\mathcal{O}(10^3)$ one-loop diagrams per channel:

- 40 hexagons



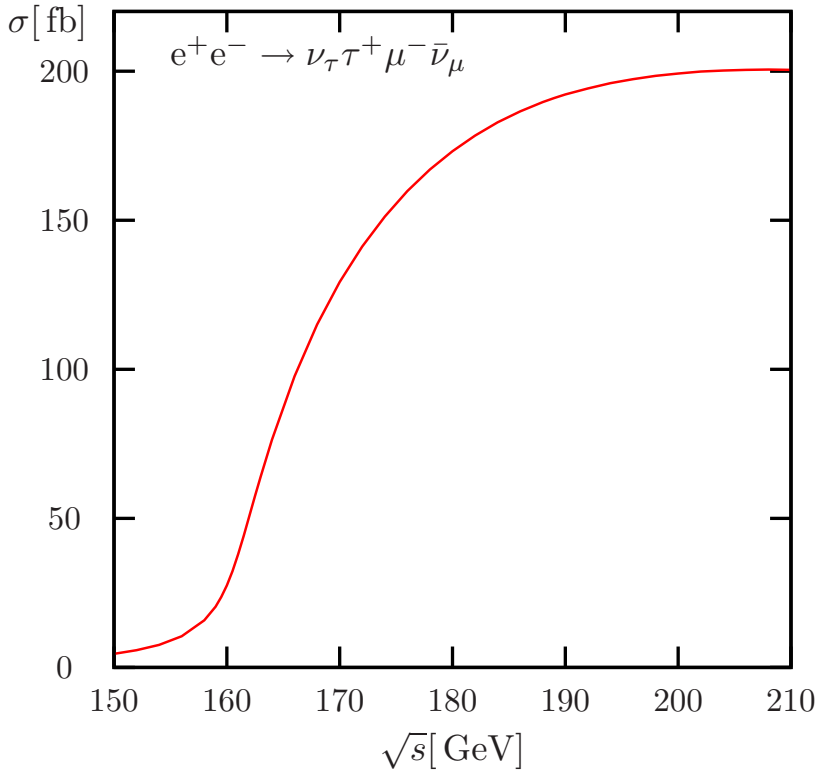
+ graphs with reversed fermion-number flow in final state

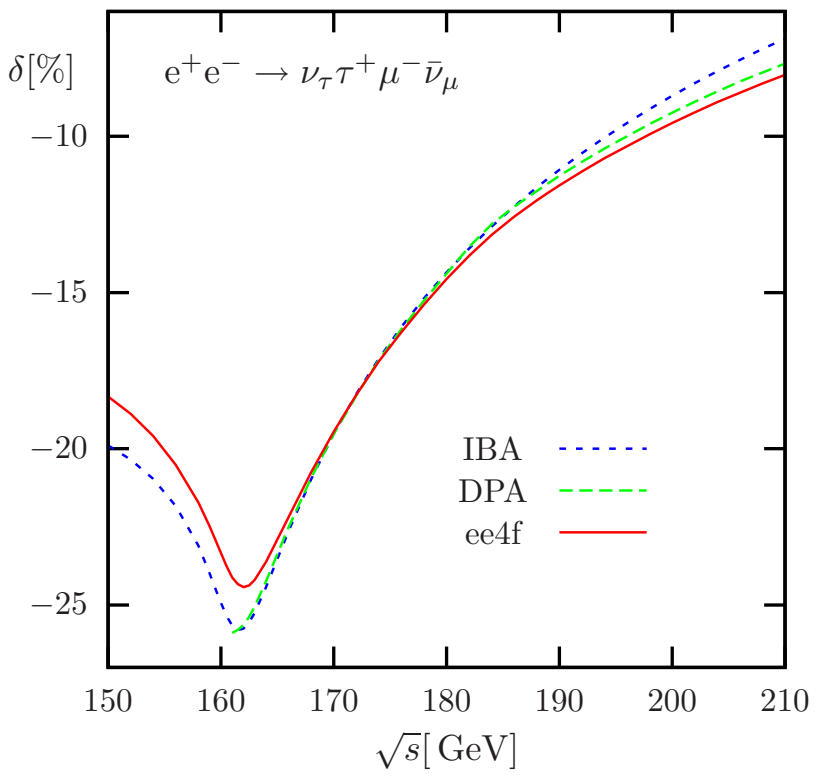
- 112 pentagons
- 227 boxes (’t Hooft–Feynman gauge)
- many vertex corrections and self-energy diagrams

Some numerical results:

Complete $\mathcal{O}(\alpha)$ corrections to the total cross section – LEP2 energies

Denner, S.D., Roth, Wieders '05

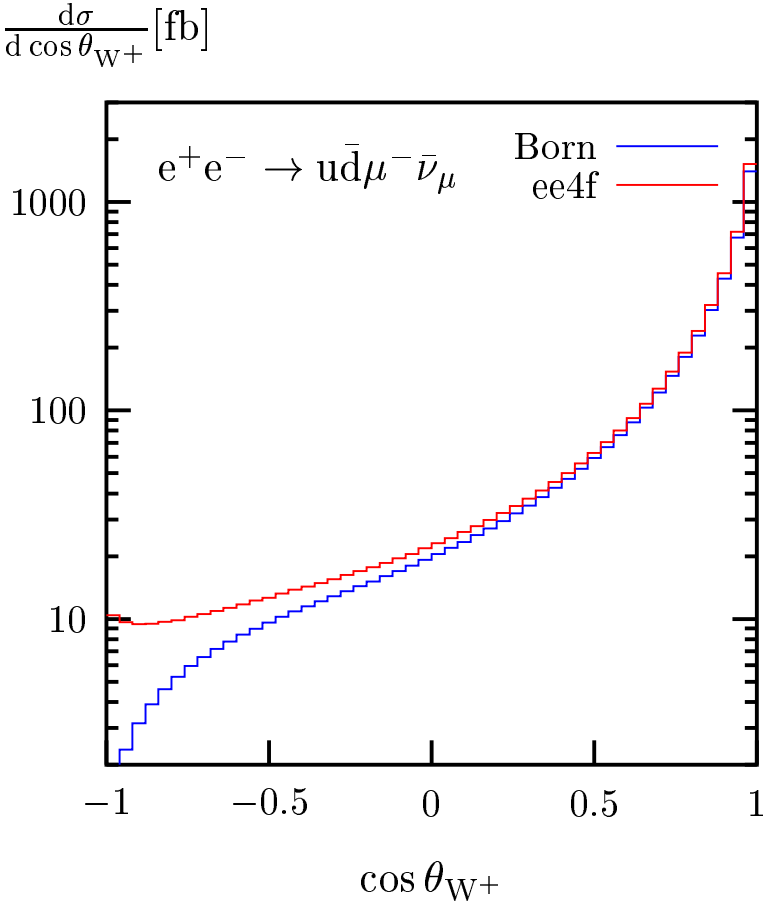


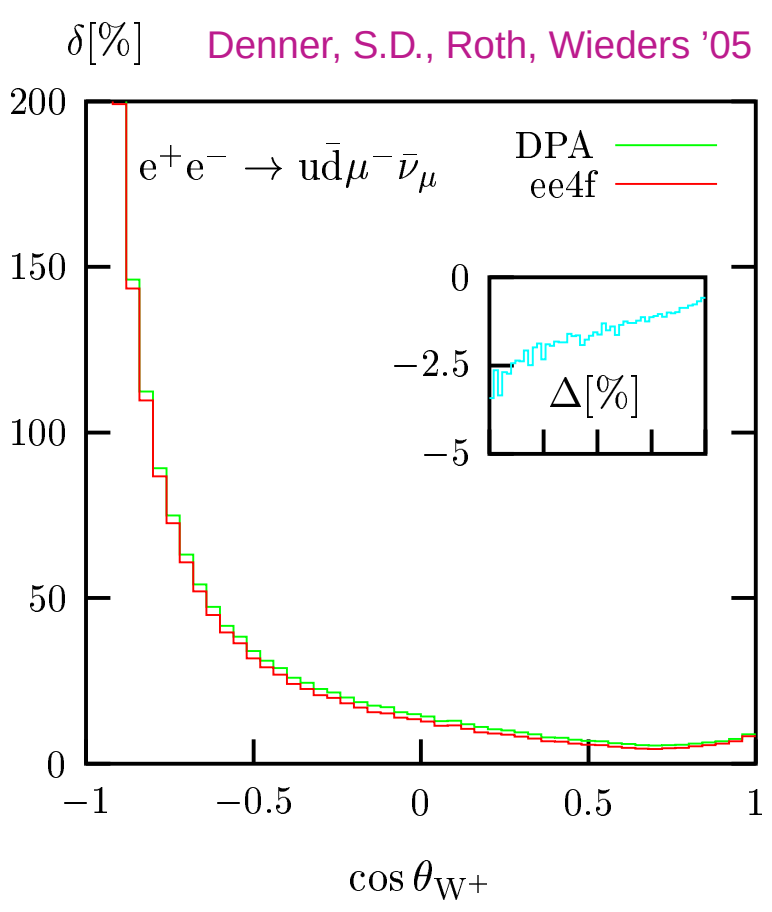


- $|\text{ee4f} - \text{DPA}| \sim 0.5\%$ for $170\,\text{GeV} \lesssim \sqrt{s} \lesssim 210\,\text{GeV}$
- $|\text{ee4f} - \text{IBA}| \sim 2\%$ for $\sqrt{s} \lesssim 170\,\text{GeV}$

↪ agreement with error estimates
of "double-pole approximation " (DPA) and "improved Born approximation" (IBA)

W-production angle distribution at $\sqrt{s} = 500\,\mathrm{GeV}$





Denner, S.D., Roth, Wieders '05

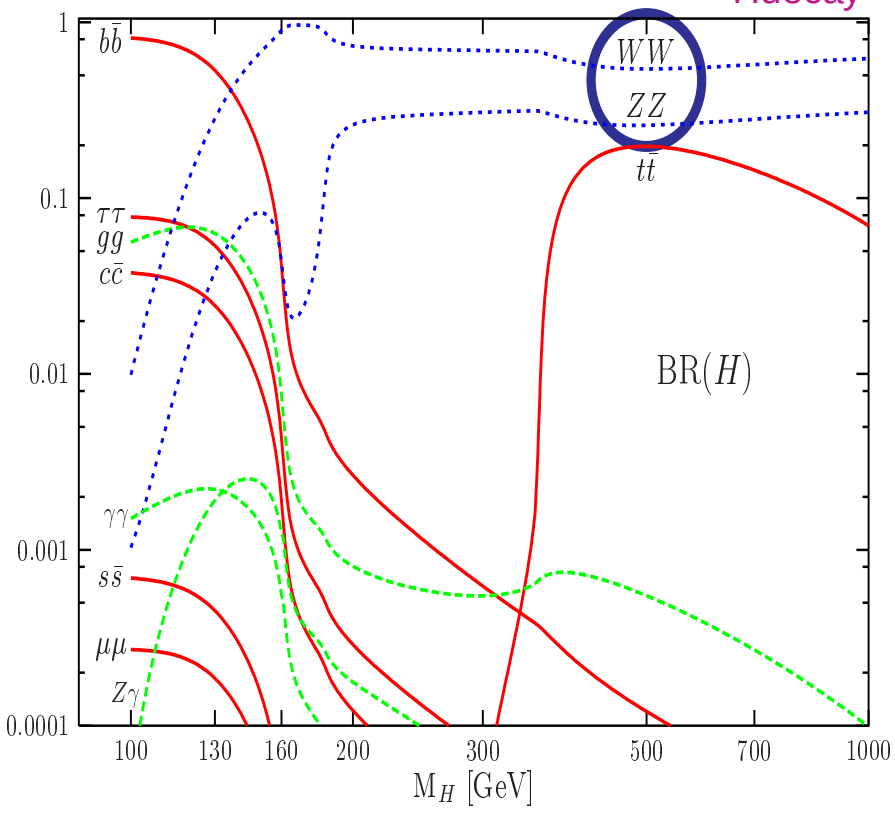
$\Delta = \mathrm{ee4f} - \mathrm{DPA}$

Significant distortion of shape w.r.t. DPA at ILC energies

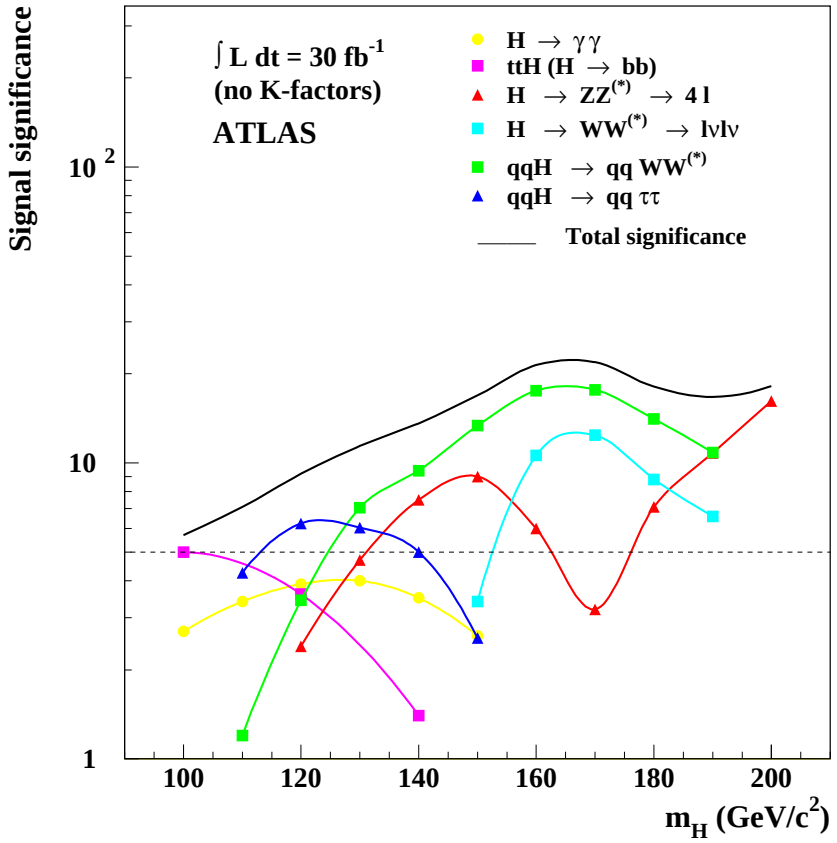
↪ Important for TGC studies at ILC

3 The decays H → WW/ZZ → 4 fermions

Hdecay



ATLAS '03



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

LHC:
- most important Higgs decay channels for $M_\mathrm{H} \gtrsim 125\,\mathrm{GeV}$
- most precise determination of M_H via $\mathrm{H}\to\mathrm{ZZ}\to 4l$ for $M_\mathrm{H} \gtrsim 130\,\mathrm{GeV}$

ILC:
- measurements of branching ratios at per-cent level
- full reconstruction of $\mathrm{H} \to \mathrm{WW}$ in semileptonic / hadronic final states

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

- limitations of previous work:
  - $\mathcal{O}(\alpha)$ corrections only for stable W's/Z's — Fleischer, Jegerlehner '81; Kniehl '91; Bardin, Vilenskii, Khristova '91
  - off-shell W's/Z's only in lowest order — e.g. Hdecay (Djouadi, Kalinowski, Spira '98)
- new: Monte Carlo generator PROPHECY4f — Bredenstein, Denner, S.D., Weber '06

  for $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ} \to 4f$ with EW+QCD corrections

Note: Monte Carlo generator with corrections needed

- for the kinematical reconstruction of Z's, W's, and H

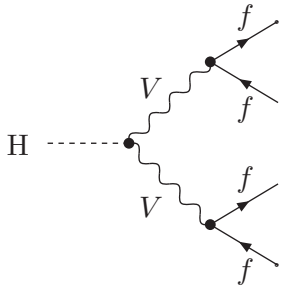
  (including radiative corrections, in particular γ radiation)

  $\hookrightarrow$ invariant-mass distributions
- for the verification of spin 0 and CP parity of 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.'0

Survey of Feynman diagrams for NLO EW and QCD corrections

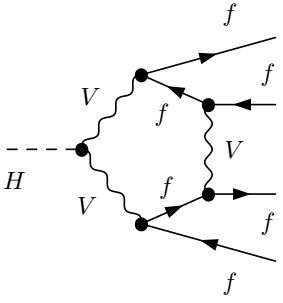
Lowest order:



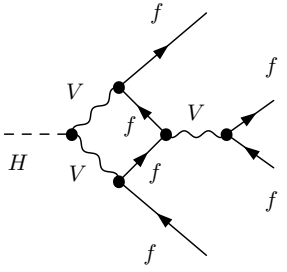
Electroweak $\mathcal{O}(\alpha)$ corrections:

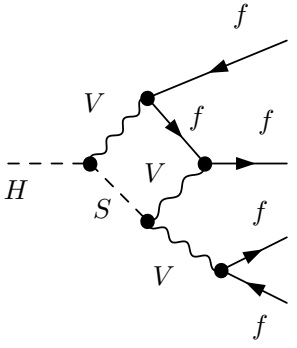
typical one-loop diagrams: # diagrams = $\mathcal{O}(200-400)$

pentagons

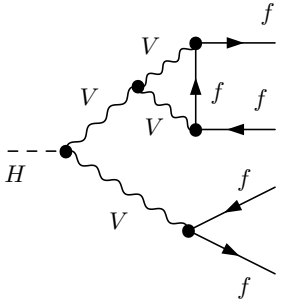


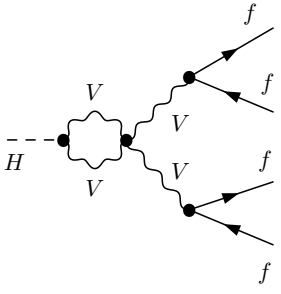
boxes



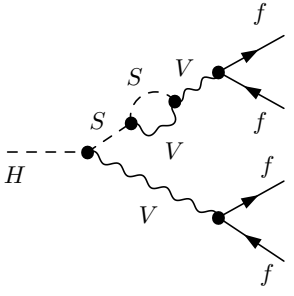


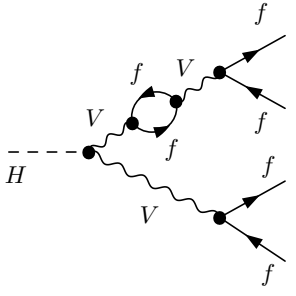
vertices





self-energies

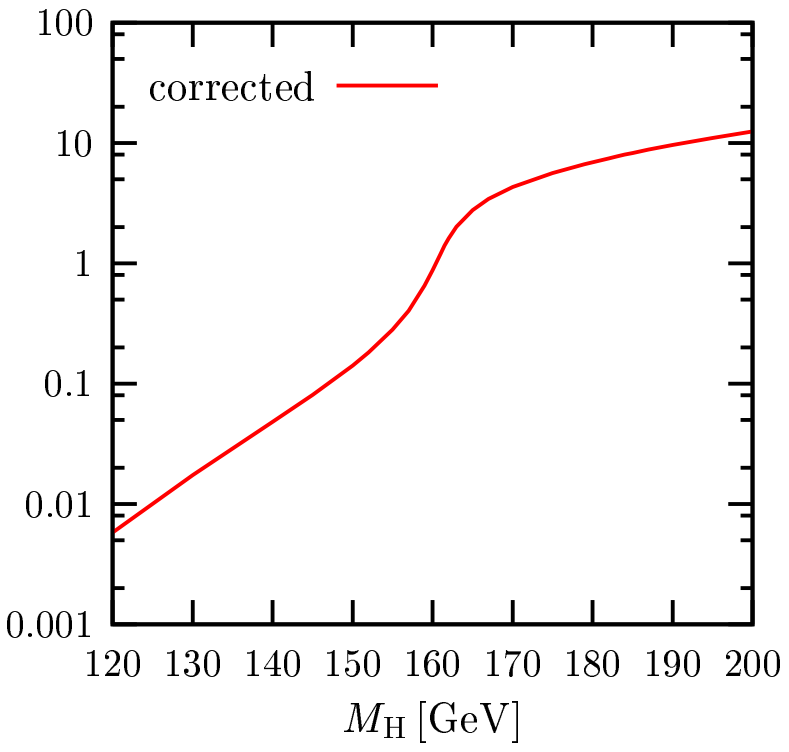


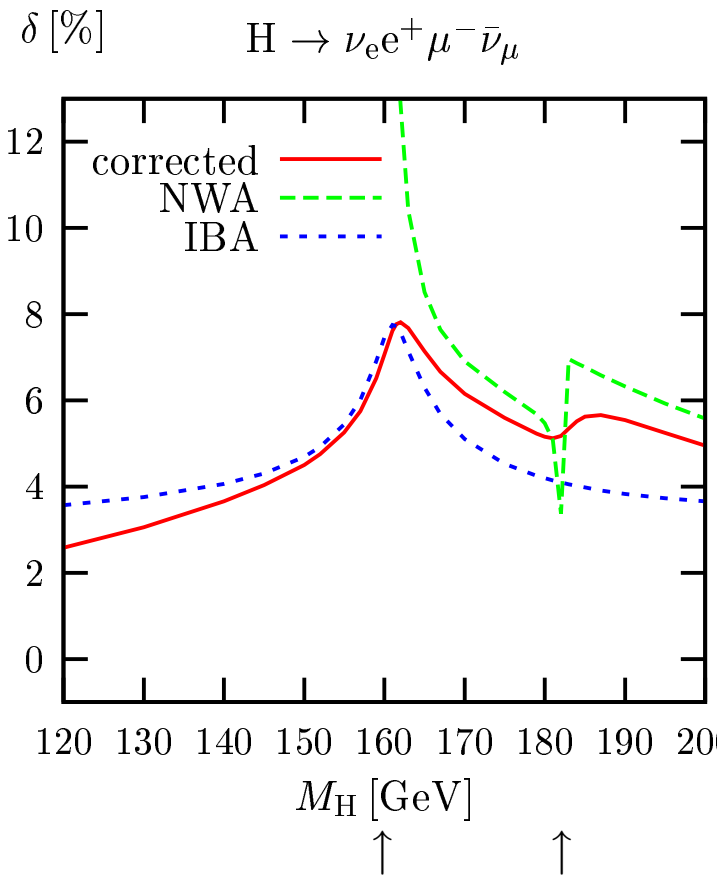


$+$ photon bremsstrahlung (final-state radiation only)

Results for leptonic final states

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





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

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

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

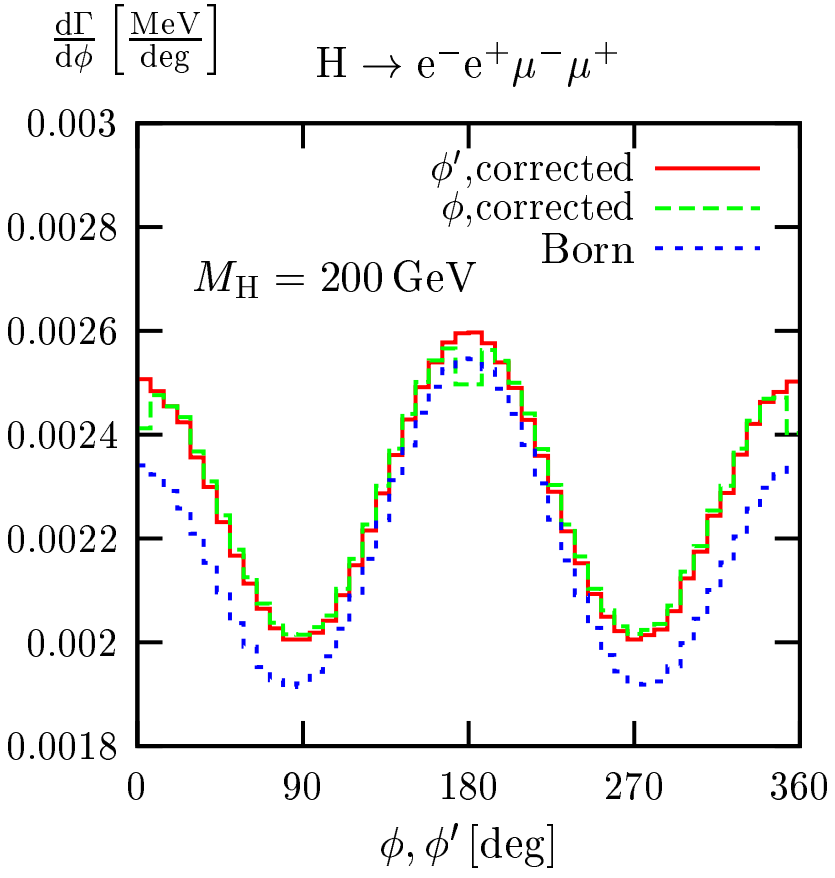
↑ threshold effect in loops for $M_\mathrm{H} \sim 2M_\mathrm{Z}$

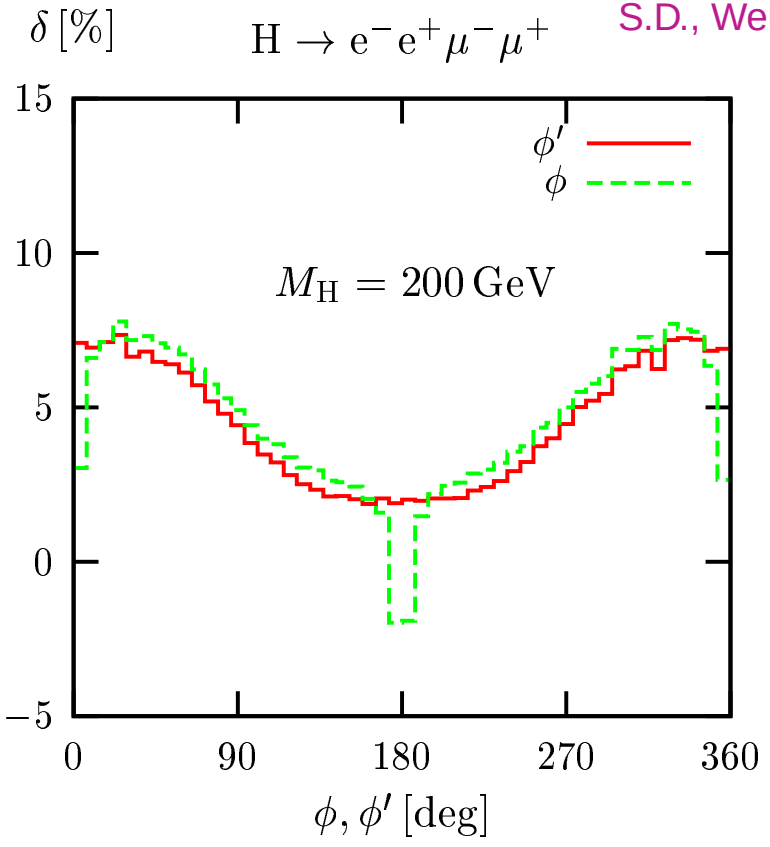
NWA = narrow-width approximation

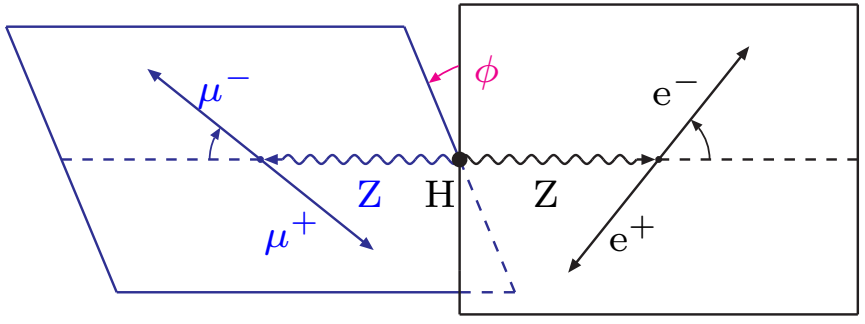
IBA = improved Born approximation
(Coulomb singularity, one fitting constant, leading effects for $M_\mathrm{H}, m_\mathrm{t} \gg M_\mathrm{W}$)

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

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







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

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

4 Conclusions

LHC and ILC physics requires precise description of multi-particle processes:

- final states from resonance processes (WW, $\mathrm{t\bar{t}}$, $\tilde{q}\bar{\tilde{q}}$, $\tilde{\chi}\tilde{\chi}$, etc.)
- irreducible background

Progress of recent years enables NLO corrections to $2 \to 4$ processes:

- complex-mass scheme for treatment of unstable particles at NLO
- numerically stable tensor reduction via seminumerical and expansion methods

Presented phenomenological results:

complete NLO corrections to

- $\mathrm{e^+e^-} \to \mathrm{WW} \to 4$ fermions
  $\hookrightarrow$ needed to exploit full ILC potential in M_W measurement and TGC constraints
- $\mathrm{H} \to \mathrm{WW/ZZ} \to 4$ fermions (new event generator PROPHECY4f)
  $\hookrightarrow$ necessary for Higgs reconstruction and verification of quantum numbers

Further phenomenologically interesting results expected in the future