(Recent) Higher-order corrections to Higgs Phenomenology at the ILC

Marcus Weber

MPI Munich

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Outline

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Why Higher Orders?

linear collider is precision machine

- Higgs mass
  $\Delta m_H = 50\,\text{MeV}$ (ILC), $\Delta m_H = 0.2\,\text{GeV}$ (LHC)
- cross sections
  $\sigma(HZ), \sigma(\nu\nu H)$: $\Delta\sigma = 2 - 10\%$ for $m_H = 120 - 160\,\text{GeV}$.
- branching fractions and couplings
  $\Delta\text{BR}(bb, cc, \tau\tau, gg, WW) = 2 - 6\%$ for $m_H = 120\,\text{GeV}$
  $\Delta g_{ttH} \approx 10\%$ for $m_H < 200\,\text{GeV}$

$\rightarrow$ need higher order corrections

Outline

Standard Model Higgs sector

1 Higgs doublet $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v+H+i\chi) \end{pmatrix}$

- Lagrangian

$$\mathcal{L}_{\text{higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$$
$$D_\mu \Phi = (\partial_\mu + igT^a G^a_\mu)\Phi$$
$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \frac{\lambda}{4}(\Phi^\dagger \Phi)^2$$
$$\mathcal{L}_{\text{Yuk}} = -\lambda_e \bar{L}\Phi e_R - \lambda_d \bar{Q}\Phi d_R - \lambda_u \bar{Q}\Phi^* u_R$$

- EW symmetry breaking: VEV $v \neq 0$
  Goldstone bosons ϕ^+, χ: give mass to W^+, Z
  1 physical Higgs state H, 1 parameter m_H
- Higgs couplings

$$g_{Hff} = m_f/v \qquad g_{HVV} = 2m_V^2/v \qquad g_{HHVV} = 2m_V^2/v^2$$
$$g_{3H} = 3m_H^2/v \qquad g_{4H} = 3m_H^2/v^2$$

SM Higgs production

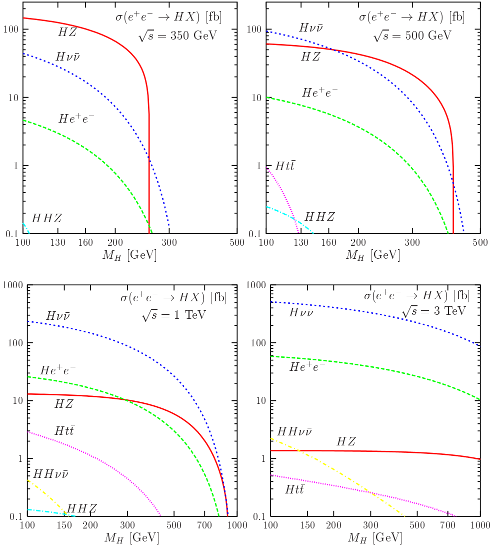
main production channels

- Higgsstrahlung
  low $\sqrt{s}$
  $e^+e^- \to HZ$
- Weak Boson Fusion
  high $\sqrt{s}$
  $e^+e^- \to \nu_e\bar{\nu}_e H$
  $e^+e^- \to e^+e^- H$

couplings

- top Yukawa
  $e^+e^- \to t\bar{t}H$
- Higgs self coupling
  $e^+e^- \to ZHH$
  $e^+e^- \to \nu_e\bar{\nu}_e HH$

Djouadi '05



SM Higgs production

status of higher order corrections

- ZH [Fleischer, Jegerlehner '83] [Kniehl '92] [Denner, Kublbeck, Mertig, Bohm '92]
- $\nu\nu H$ [Belanger et al. '03] [Denner, Dittmaier, Roth, M.W. '03] [Jegerlehner, Tarasov '03]
- e^+e^-H [Boudjema et al. '04]
- $t\bar{t}H$
  QCD [Dawson, Reina '99] [Dittmaier, Kraemer, Liao, Spira, Zerwas '98]
  EW [Denner, Dittmaier, Roth, M.W '03] [Belanger et al. '03]
  [You, Ma, Chen, Zhang, Sun, Hou '04]
- ZHH [Belanger et al. '03] [Chen, Hou, Ma, Sun, Zhang '04]
- $\nu\nu HH$ [Boudjema et al. '04]
- WWH [Song, Ma, Zhang, Guo, Wang '08]

typical size of EW corrections $= \mathcal{O}(5 - 10\%)$

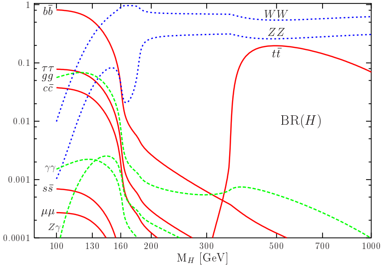
SM Higgs decays

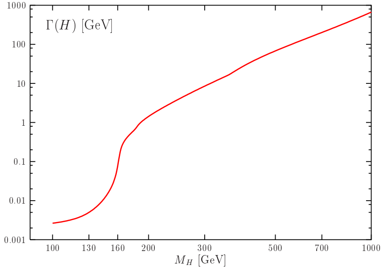
dominant decay channel

- $m_H < 140\,\text{GeV}$
  $H \to b\bar{b}$
- $m_H > 140\,\text{GeV}$
  $H \to WW/ZZ \to 4f$

$H \to \gamma\gamma$ channel
BR $= \mathcal{O}(10^{-3})$, but exp. clean

Djouadi ’05





SM $H \to b\bar{b}$

- 1-loop exact
  $\mathcal{O}(\alpha_s)$ [Braaten and Leveille, '80]
  $\mathcal{O}(G_F)$ [Kniehl, '92]
- higher orders in large m_t limit
  $\mathcal{O}(\alpha_s^2)$ [various '91-97]
  $\mathcal{O}(\alpha_s^3)$ [Chetyrkin and Steinhauser, '97]
  $\mathcal{O}(\alpha_s G_F m_t^2)$ [Kniehl and Spira, '94]
  $\mathcal{O}(\alpha_s^2 G_F m_t^2)$ [Chetyrkin, Kniehl and Steinhauser, '97]

calculation of $\mathcal{O}(G_F^2 m_t^4)$ 2-loop corrections in large m_t limit
[Butenschoen, Fugel, Kniehl '07]

- asymptotic expansion technique
- result $\frac{\Gamma(G_F^2 m_t^4)}{\Gamma_0} = +0.047\%$
  larger than known $\frac{\Gamma(\alpha_s G_F m_t^2)}{\Gamma_0} = -0.022\%$

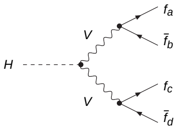
SM $H \to 4f$

PROPHECY4f MC generator
[Bredenstein, Denner, Dittmaier, M. W.]

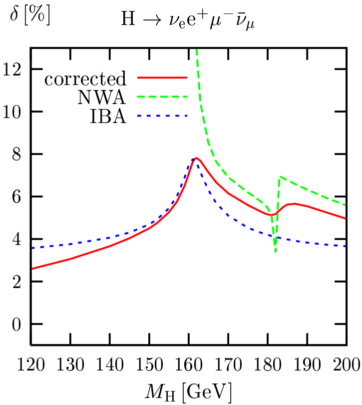
- $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha_s)$ to $H \to WW/ZZ \to 4f$
- complex mass scheme for W/Z
  all kinematic regions
- partial widths and distributions
- non-collinear-safe observables possible
- leading 2-loop from Higgs self interaction
- weighted events
- code now public here

HDECAY update [Spira]

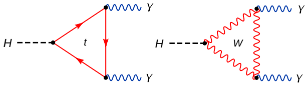
- IBA to $H \to 4f$ decays
  Γ accurate within 1%



Bredenstein, Denner, Dittmaier, Weber '06



SM $H \to \gamma\gamma/gg$



loop induced: W and top loops

- LO [Ellis, Galliard, Nanopoulos '76] [Vainshtain, Voloshin, Zakharov, Shifman '79]
- NLO QCD $m_H < 2m_t$
  [Zheng, Wu '90] [Djouadi, Spira, v.d.Bij, Zerwas '91] [Dawson,Kauffmann '93]
  including 3 loops [Steinhauser '96]
- NLO QCD all m_H
  [Melnikov,Yakovlev'93] [Djouadi,Spira,Zerwas'93] [Inoue,Najima,Oka,Saito'94]
  analytic form [Fleischer,Tarasov,Tarasov'04] [Harlander,Kant'05]
  [Aglietti,Bonciani,Degrassi,Vicini'06]

partial EW NLO (2-loop)

- $\mathcal{O}(G_F m_t^2)$ asymptotic expansion [Liao,Li'96] [Djouadi,Gambino, Kniehl'97]
  [Fugel,Kniehl,Steinhauser'04]
- light fermions analytically [Aglietti,Bonciani,Degrassi,Vicini'04]
- top/YM below WW with Taylor expansion [Degrassi,Maltoni'05]

similar size as QCD corrections

SM EW NLO $H \to \gamma\gamma/gg$

complete EW & QCD NLO (2-loop) corrections to $H \to \gamma\gamma/gg$
[Actis, Passarino, Sturm, Uccirati '07]
method

- numerical approach
  – Generation of Feynman diagrams
  – Algebraic manipulations
  – Map different topologies on form factors
  – Extract UV-pole part analytically
  – Check their cancellation with counter terms
  – Finite remainder evaluated numerically in parametric space
- treshold singularities
  regularized by complex W/Z masses
  covers all kinematic regions including thresholds
- complete mass dependence m_W, m_Z, m_t, m_H
  no expansions

SM EW NLO $H \to \gamma\gamma/gg$

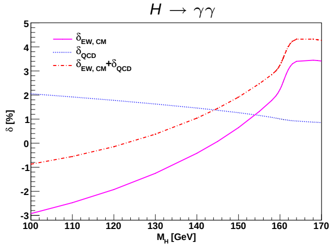
$H \to \gamma\gamma$

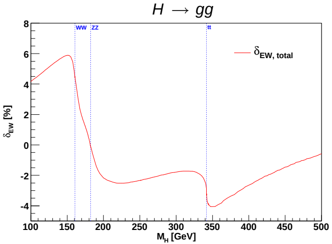
- QCD corrections
  $\delta = +1.8 \ldots + 0.9\%$
- EW effects
  $\delta = -1.9 \ldots + 3.5\%$
- Cancellation between δ_{QCD} and δ_{EW} below threshold -0.1%(120 GeV)
- dominant $\mathcal{O}(G_F m_t^2)$ corrections large but not dominant
- complete 2-loop:
  $\delta = -0.1 \ldots + 4\%$

$H \to gg$

- corrections $-4 \ldots + 6\%$

Actis, Passarino, Sturm, Uccirati '07





Outline

MSSM Higgs Sector

constrained 2 Higgs Doublet Model type II

$$H_1 = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 - \mathrm{i}\chi_1) \\ -\phi_1^- \end{pmatrix} \qquad H_2 = \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + \mathrm{i}\chi_2) \end{pmatrix}$$

$$V = m_1^2\, H_1 \bar{H}_1 + m_2^2\, H_2 \bar{H}_2 - (m_{12}^2\, \varepsilon_{\alpha\beta} H_1^\alpha H_2^\beta + \mathrm{h.c.}) \\ + \frac{g_1^2 + g_2^2}{8}\, (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g_2^2}{2}\, |H_1 \bar{H}_2|^2$$

- 5 physical Higgs states: h_0, H_0, A_0, $H^\pm$
- 2 parameters: $\tan\beta = \frac{v_2}{v_1}$ and m_{A_0}
- 5 Higgs masses
  calculate m_{h_0}, m_{H_0}, $m_{H^\pm}$ from $\tan\beta$ and m_{A_0}

complex MSSM (cMSSM)

MSSM with complex parameters

- additional CP violating phases from soft breaking terms
  $A_f = |A_f| e^{i\phi_f} \quad \mu = |\mu| e^{i\phi_\mu} \quad M_i = |M_i| e^{\phi_i}$
- Higgs sector
  no CP violation at leading order
  CP violation enters through loops at NLO
- h, H, A mix $\rightarrow$ mass eigenstates h_1, h_2, h_3
  $m_{h_1} < m_{h_2} < m_{h_3}$

MSSM Higgs masses

higher order corrections to mass matrix

$$\begin{pmatrix} q^2 - m_h^2 + \hat{\Sigma}_{hh}^{\bullet\bullet\bullet\circ} & \hat{\Sigma}_{hH}^{\bullet\bullet\bullet\circ} & \hat{\Sigma}_{hA}^{\bullet\circ} \\ \hat{\Sigma}_{Hh}^{\bullet\bullet\bullet\circ} & q^2 - m_H^2 + \hat{\Sigma}_{HH}^{\bullet\bullet\bullet\circ} & \hat{\Sigma}_{HA}^{\bullet\circ} \\ \hat{\Sigma}_{Ah}^{\bullet\circ} & \hat{\Sigma}_{AH}^{\bullet\circ} & q^2 - m_A^2 + \hat{\Sigma}_{AA}^{\bullet\circ} \end{pmatrix}, \quad \hat{\Sigma}_{H^+H^-}^{\bullet\circ}$$

- leading $\mathcal{O}(\alpha_t \alpha_s)$ complex MSSM 2-loop
  [Heinemeyer, Hollik, Rzehak, Weiglein '07]
- leading $\mathcal{O}(\alpha_t^2)$ + subleading $\mathcal{O}(\alpha_b \alpha_s,\, \alpha_t \alpha_b,\, \alpha_b^2)$ 2-loop real MSSM
  [Degrassi, Slavich, Zwirner '01] [Brignole, Degrassi, Slavich, Zwirner '01, '02] [Dedes, Degrassi, Slavich '03]
- ◦ full one-loop [Frank, Heinemeyer, Hollik, Weiglein '02]

3-loop LL and NLL $\mathcal{O}(\alpha_t \alpha_s^2, \alpha_t^2 \alpha_s, \alpha_t^3)$ [Martin '07]

MSSM Higgs masses

impact of radiative corrections on masses

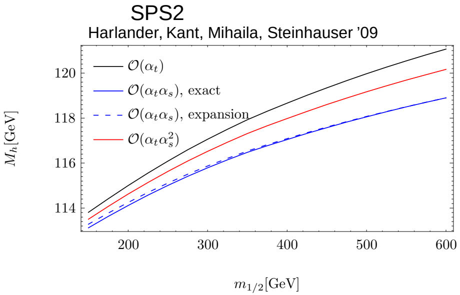
- LO: $m_{h_0} < m_Z$
- NLO: $+35\,\text{GeV}$ shift
- residual uncertainty $2 - 3\,\text{GeV}$ [Allanach et al '04]
  much larger than ILC error $\delta m_H \approx 50\,\text{MeV}$

$\Rightarrow$ need higher precision

MSSM m_{h_0} at 3-loop

3-loop SUSY QCD corrections $\mathcal{O}(\alpha_t\alpha_s^2)$ to m_{h_0}
[Harlander, Kant, Mihaila, Steinhauser '08]

- full calculation not feasible
  use expansions in mass ratios
  $\longrightarrow$ one-scale integrals
- all sps points covered
- automatic: QGRAF, Q2E, EXP, MINCER, MATAD, FORM
- check: expansion accurate within $\mathcal{O}(100\,\text{MeV})$ for known 2-loop results
- code public: H3m



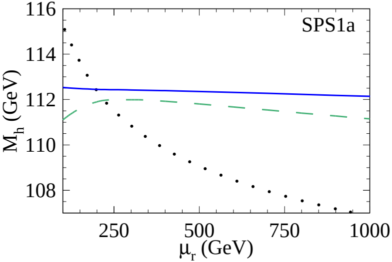
3-loop corrections about $0.5 - 2\,\text{GeV}$

MSSM m_{h_0} at 3-loop

remaining uncertainty

- scale uncertainty reduced to $\mathcal{O}(100\,\text{MeV})$
- theory uncertainty
  conservative estimate
  50% of Δm_{h_0}(3-loop)
  $\rightarrow \delta m_{h_0} = 0.1 - 1\,\text{GeV}$ for
  $m_{1/2} = 100\,\text{GeV} - 1\,\text{TeV}$
- parametric uncertainty α_s, m_t, ...
  about $\mathcal{O}(500\,\text{MeV})$

scale dependence
Harlander, Kant, Mihaila, Steinhauser '09



MSSM $A_0 \to \gamma\gamma$

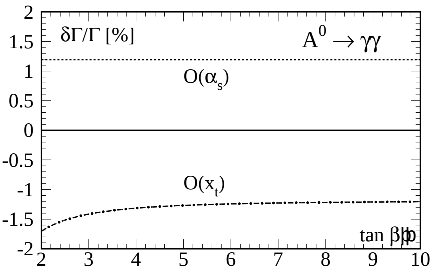
$\Gamma(A_0 \to \gamma\gamma)$

- LO loop induced: heavy quarks, light leptons, light charginos
- NLO QCD $\mathcal{O}(\alpha_s)$
  [Spira, Djouadi, Graudenz, Zerwas '93]
  [Harlander, Kant '05] [Aglietti, Bonciani, Degrassi, Vicini '07]
- NNLO QCD $\mathcal{O}(\alpha_s^2)$ for $m_t \to \infty$
  [Chetyrkin, Kniehl, Steinhauser, Bardeen '98]

dominant EW NLO (2-loop) $\mathcal{O}(G_f m_t^2)$
[Brod, Fugel, Kniehl '08]

- susy particles decoupled
- all Higgs particles light
- asymptotic expansions in mass ratios

Brod, Fugel, Kniehl '08



δ_{EW} similar size as δ_{QCD}
cancellations between EW and QCD

MSSM fermionic Higgs decays

[Mihaila, Reisser '10]

$\mathcal{O}(\alpha_s^2)$ corrections to fermionic Higgs decays

- 2-loop sqcd to $H \to b\bar{b}$ and $H \to \tau\tau$ in MSSM
- effective Lagrangian approach: assume $m_H \ll m_t, m_{\tilde{g}}, m_{\tilde{q}}$

result

- scale dependence reduced
- light m_h
  large NLO of about 50%
  NNLO about 8%

MSSM $H^+ \to W^+ h_0$

full NLO to $H^+ \to W^+ h_0$ [Bejar, Lopez-Val, Hollik '09]

H^+ decay channels

- dominant $H^+ \to \tau\nu_\tau$, $H^+ \to t\bar{b}$
- gauge boson channels $H^+ \to W^+ Z/\gamma$
- $H^+ \to W^+ h_0$
  can be dominant, test CP

study different scenarios

scenario	m_{h_0} max	no mixing	small α_{eff}	low M_{SUSY}	large $\tan\beta$
$\tan\beta$	3.5	3.5	3.5	3	55
$M_{H^\pm}(GeV)$	450	425	420	320	850
M_{SUSY}	2000	2000	800	300	970
μ	200	200	2000	300	1800
M_2	200	200	500	300	200
$A_t - \mu/\tan\beta$	2000	0	-1100	-300	1000

MSSM $H^+ \to W^+ h_0$

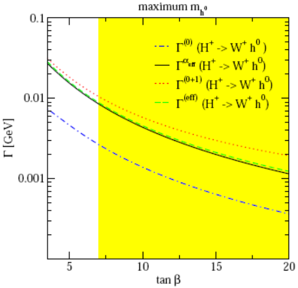
NLO main contributions

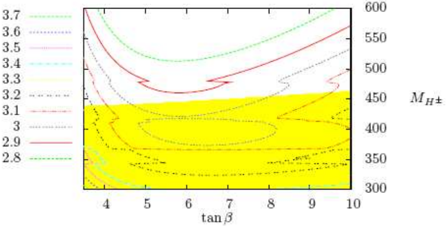
- top (stop) and bottom (sbottom) diagrams
  from the H^+tb and h_0tt (and bb) Yukawa couplings
- wave function $h_0 - H_0$ mixing terms

results

- corrections large $> 100\%$ in all scenarios

Bejar, Lopez-Val, Hollik '09





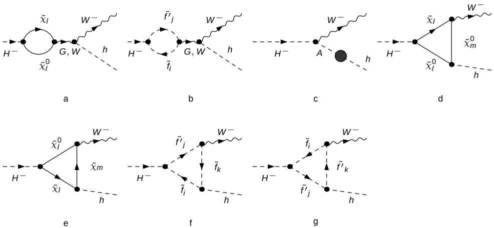
MSSM CP asymmetry for $H^+ \to W^+ h_1$

CP violating observable

$$\delta_{CP} = \frac{\Gamma(H^- \to W^- h_1) - \Gamma(H^+ \to W^+ h_1)}{\Gamma(H^- \to W^- h_1) + \Gamma(H^+ \to W^+ h_1)}$$

only at NLO, not present at LO

diagrams contributing to CP asymmetry



[Christova, Ginina, Stoilov '03] CP asymmetry from phases of A_τ and M_1
$\to$ least sensitive phases

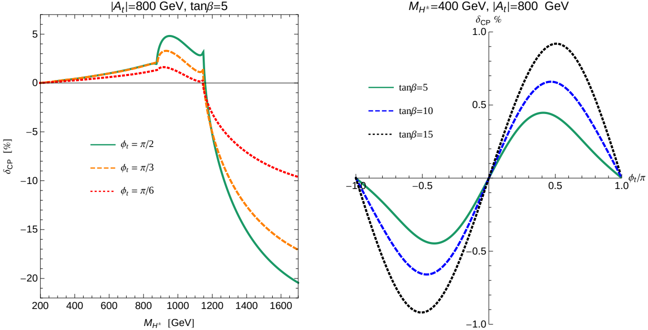
[Dao, Hollik '10] CP asymmetry from all cMSSM phases

- masses up to 2-loop using FeynHiggs
- threshold singularities regularized using complex masses in singular loop integrals
- study impact of phases separately

MSSM CP asymmetry for $H^+ \to W^+ h_1$

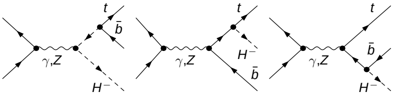
$$\mu = 200\,\text{GeV}, M_2 = 200\,\text{GeV}, M_3 = 0.8 M_{\text{SUSY}}\,\text{GeV}, |A_\tau| = |A_t| = |A_b|,$$
$$M_{\tilde{Q}} = M_{\tilde{D}} = M_{\tilde{U}} = M_{\text{SUSY}} = 500\,\text{GeV}, M_{\tilde{L}} = 200\,\text{GeV}, M_{\tilde{E}} = 150\,\text{GeV}$$

Dao, Hollik '10



- ϕ_τ, ϕ_1 impact small $\delta < 1\%$
- ϕ_b impact moderate $\delta < 8\%$ near $\tilde{t}\tilde{b}$ thresholds
- ϕ_t effect largest: up to $\delta = +10\ldots-50\%$ for large $\tan\beta$
- strong dependence on A_t, $m_{H^\pm}$ and $\tan\beta$

MSSM $H^{\pm}tb$ production



NLO SUSY-QCD corrections to $e^+e^- \to H^-t\bar{b}$ [Kniehl, Maniatis, M.W. '10]

- complements QCD (gluonic) corrections [Kniehl, Madricardo, Steinhauser '02]

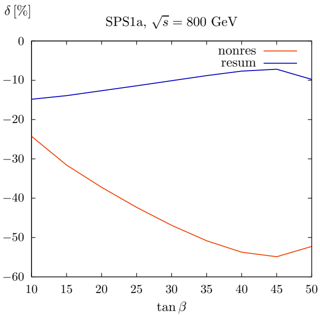
use numerical method [Ferroglia, Passera, Passarino, Uccirati '03]

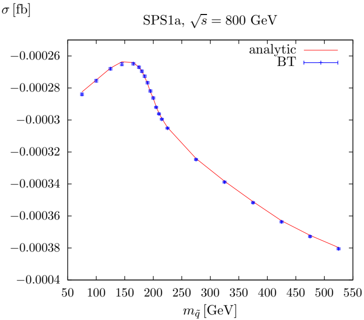
- start from Feynman parametrization
- transform integral to smoothe integrand
  use Bernstein-Tkachov theorem [Bernstein '72] [Tkachov '97]
- combined numerical integration of phase space variables + Feynman parameters
- no inverse Gram determinants, numerically stable

resummation of $\tan\beta$ enhanced contributions in $tbH^{\pm}$ Yukawa coupling
[Carena, Garcia, Nierste, Wagner '00]

MSSM $H^{\pm}t\bar{b}$ production

Kniehl, Maniatis, M.W. '10





- $\mathcal{O}(10 - 60\%)$ SUSY-QCD corrections
- bulk from $\tan\beta$ enhanced contributions, absorbed by resummation
- remaining corrections $\mathcal{O}(10\%)$
- numerical method works, agrees with analytical loop integrals errors numerical method

Outline

2 Higgs Doublet Model (2HDM)

2 Higgs doublets, both $Y = +1$

$$\Phi_1 = \begin{pmatrix} \Phi_1^+ \\ \Phi_1^0 \end{pmatrix} = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+\phi_1^0+i\chi_1^0}{\sqrt{2}} \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+\phi_2^0+i\chi_2^0}{\sqrt{2}} \end{pmatrix}$$

$$V = \lambda_1 \left(\Phi_1^\dagger\Phi_1 - \frac{v_1^2}{2}\right)^2 + \lambda_2 \left(\Phi_2^\dagger\Phi_2 - \frac{v_2^2}{2}\right)^2 + \lambda_3 \left[\left(\Phi_1^\dagger\Phi_1 - \frac{v_1^2}{2}\right) + \left(\Phi_2^\dagger\Phi_2 - \frac{v_2^2}{2}\right)\right]^2$$
$$+ \lambda_4 \left[(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) - (\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)\right] + \lambda_5 \left[\mathrm{Re}(\Phi_1^\dagger\Phi_2) - \frac{v_1 v_2}{2}\right]^2 + \lambda_6 \left[\mathrm{Im}(\Phi_1^\dagger\Phi_2)\right]^2$$

- 3H, 4H coupling unconstrained
- 7 parameters: $M_{h_0}, M_{H_0}, M_{A_0}, M_{H^\pm}, \alpha, \tan\beta, \lambda_5$
  λ_5 can be large

2HDM: Higgsstrahlung $e^+e^- \to Zh/H$

[Bernal, Lopez-Val, Sola '10]

full NLO calculation for Higgsstrahlung $e^+e^- \to Z^* \to Zh_0/ZH_0$

- LO coupling fixed by gauge structure

$$\mathcal{L}_{Z^0Z^0h_0} = \frac{e\sin(\beta-\alpha)M_Z}{s_W c_W} g^{\mu\nu} Z^0_\mu Z^0_\nu h_0$$
$$\mathcal{L}_{Z^0Z^0H_0} = \frac{e\cos(\beta-\alpha)M_Z}{s_W c_W} g^{\mu\nu} Z^0_\mu Z^0_\nu H_0$$

  same as in MSSM

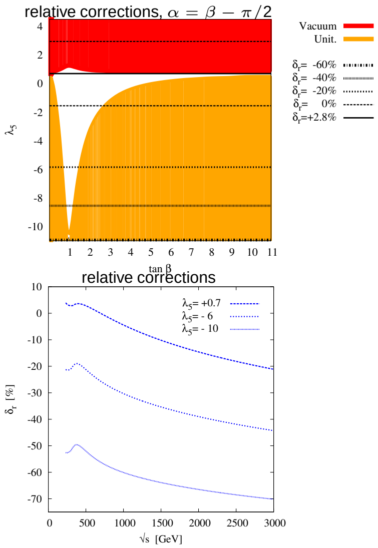
- NLO enhanced contributions
  – $h_0 Z\gamma$ loop induced vertex $\mathcal{O}(e\alpha_{ew}\lambda_{3H})$
  – $h_0 ZZ$ vertex corrections $\mathcal{O}(\alpha_{ew}^2, e\alpha_{ew}\lambda_{3H})$
  – h_0/H_0 wave function renormalization $\mathcal{O}(\lambda_{3H}^2)$

2HDM: Higgsstrahlung $e^+e^- \to Zh/H$

corrections

- large and negative up to -60%
- dominant contribution: h_0/H_0 wave function renormalization
- gauge boson and fermion (including Yukawa) loop subleading
- compare MSSM: dominant correction from Yukawa interaction

Bernal, Lopez-Val, Sola '10



2HDM: neutral Higgs pair production

[Lopez-Val, Sola '10]

full NLO for neutral Higgs pair production $e^+e^- \to A_0h_0/A_0H_0$

- LO coupling fixed by gauge structure

$$\mathcal{L}_{A_0Zh_0} = \frac{e\cos(\beta-\alpha)M_Z}{s_W c_W} Z_\mu A_0 \overleftrightarrow{\partial}^\mu h_0$$
$$\mathcal{L}_{A_0ZH_0} = \frac{e\sin(\beta-\alpha)M_Z}{s_W c_W} Z_\mu A_0 \overleftrightarrow{\partial}^\mu H_0$$

- NLO contributions
  $\mathcal{O}(\alpha_{ew}\lambda_{3H}^2)$: $A_0h_0H_0$, $WF\ h_0$, H_0h_0, A_0Z_0, A_0G_0

2HDM: neutral Higgs pair production

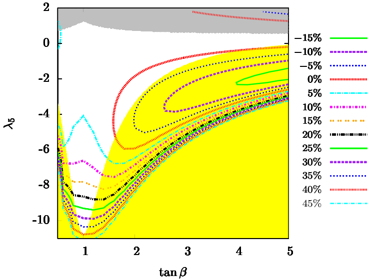
corrections

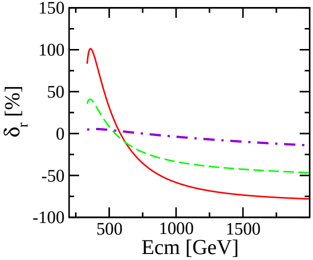
- large, positive for large λ_5, small $\tan\beta$
- dominant corrections from $A_0 h_0 Z$ vertex
- effects generic
  no strong dependence on
  – Higgs mass spectrum
  – pattern of Yukawa couplings
  – which channel $A_0 h_0$, $A_0 H_0$
- MSSM only 20% corrections from Yukawa-like couplings

large radiative corrections distinguish underlying model

Lopez-Val, Sola '09

$A_0 h_0$, $\sqrt{s} = 500$ GeV





Other Work

I did not talk about

- $\tan\beta$ resummation at 2-loop in MSSM
  see talk Michael Spira
- Higgs masses in complex MSSM
  see talk Sven Heinemeyer
- radiative corrections to NMSSM Higgs masses
  see talk Florian Staub
- $\gamma\gamma$ collider

Conclusions

- radiative corrections to Higgs physics needed for ILC precision
- SM predictions in good shape
- MSSM
  – push for higher orders
  – exploration of CP violation in cMSSM
- BSM (MSSM/2HDM): radiative corrections important for distinguishing underlying Higgs sector