PAUL SCHERRER INSTITUT PSI

EFFECTIVE LAGRANGIANS FOR (E)HDECAY

Michael Spira (PSI)

I Effective Lagrangians

II eHDECAY http://www.itp.kit.edu/∼maggie/eHDECAY/

III Conclusions

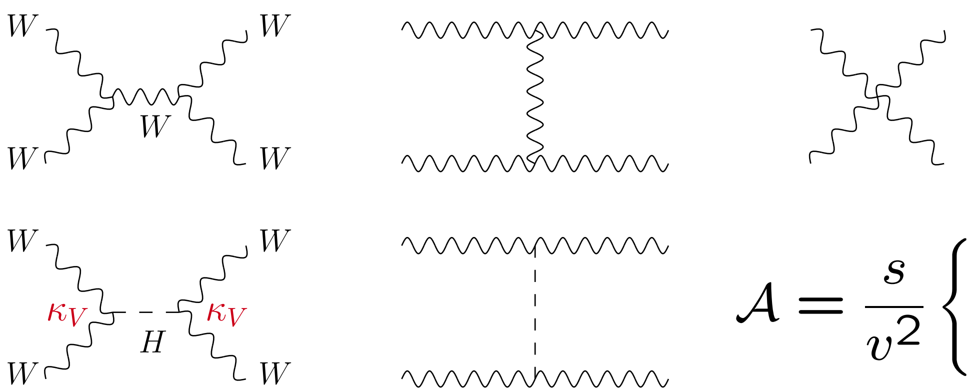
in collaboration with R. Contino, M. Ghezzi, C. Grojean and M. Mühlleitner

I *EFFECTIVE LAGRANGIANS*

- $WW \to WW$ @ high energies

(a)

(b)

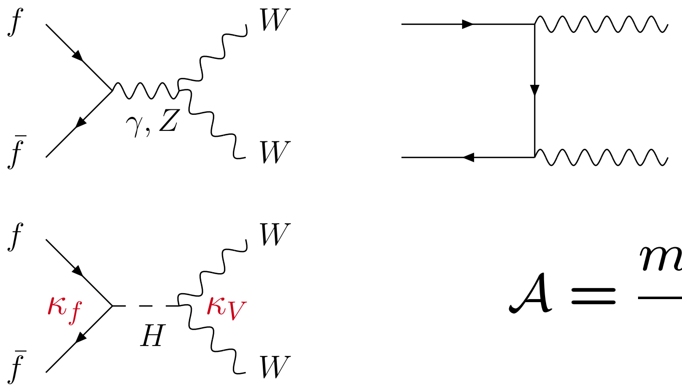


$$\mathcal{A} = \frac{s}{v^2}\left\{1 - \frac{\kappa_V^2 s}{s - M_H^2}\right\} \quad \Rightarrow \quad \kappa_V = 1$$

- $f\bar{f} \to WW$ @ high energies

(a)

(b)



$$\mathcal{A} = \frac{m_f\sqrt{s}}{v^2}\left\{1 - \frac{\kappa_f \kappa_V s}{s - M_H^2}\right\} \quad \Rightarrow \quad \kappa_f = \kappa_V = 1$$

- analogous for κ_H

(i) weakly interacting theories

- effective higher dimension operators up to dim 6

Buchmüller, Wyler
Grzadkowski, Iskrzynski, Misiak, Rosiek
Giudice, Grojean, Pomarol, Rattazzi

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i \alpha_i O_i \\
&\equiv \mathcal{L}_{SM} + \sum_i \bar{c}_i O_i \\
&\equiv \mathcal{L}_{SM} + \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{F_1} + \Delta\mathcal{L}_{F_2} + \Delta\mathcal{L}_{bos} + \Delta\mathcal{L}_{4f} + \Delta\mathcal{L}_{\mathcal{CP}}
\end{aligned}
$$

[assume Λ large]

- assume Higgs $SU(2)$-doublet

$$
H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}
$$

$$
\begin{aligned}
\Delta\mathcal{L}_{SILH} \;=\;& \frac{\bar{c}_H}{2v^2}\,\partial^\mu\Big(H^\dagger H\Big)\,\partial_\mu\Big(H^\dagger H\Big) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\Big(H^\dagger \overleftrightarrow{D}_\mu H\Big) - \frac{\bar{c}_6\,\lambda}{v^2}\Big(H^\dagger H\Big)^3 \\
&+ \left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R + h.c.\right) \\
&+ \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu}) \\
&+ \frac{i\bar{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu} \\
&+ \frac{\bar{c}_\gamma\,{g'}^2}{m_W^2}\,H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu}G^{a\mu\nu} \\
\Delta\mathcal{L}_{F_1} \;=\;& \frac{i\bar{c}_{Hq}}{v^2}\,(\bar{q}_L\gamma^\mu q_L)\Big(H^\dagger \overleftrightarrow{D}_\mu H\Big) + \frac{i\bar{c}'_{Hq}}{v^2}\Big(\bar{q}_L\gamma^\mu\sigma^i q_L\Big)\Big(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\Big) \\
&+ \frac{i\bar{c}_{Hu}}{v^2}\,(\bar{u}_R\gamma^\mu u_R)\Big(H^\dagger \overleftrightarrow{D}_\mu H\Big) + \frac{i\bar{c}_{Hd}}{v^2}\Big(\bar{d}_R\gamma^\mu d_R\Big)\Big(H^\dagger \overleftrightarrow{D}_\mu H\Big) \\
&+ \left(\frac{i\bar{c}_{Hud}}{v^2}\,(\bar{u}_R\gamma^\mu d_R)\Big(H^{c\,\dagger} \overleftrightarrow{D}_\mu H\Big) + h.c.\right) \\
&+ \frac{i\bar{c}_{HL}}{v^2}\Big(\bar{L}_L\gamma^\mu L_L\Big)\Big(H^\dagger \overleftrightarrow{D}_\mu H\Big) + \frac{i\bar{c}'_{HL}}{v^2}\Big(\bar{L}_L\gamma^\mu\sigma^i L_L\Big)\Big(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\Big) \\
&+ \frac{i\bar{c}_{Hl}}{v^2}\Big(\bar{l}_R\gamma^\mu l_R\Big)\Big(H^\dagger \overleftrightarrow{D}_\mu H\Big) \\
\Delta\mathcal{L}_{F_2} \;=\;& \frac{\bar{c}_{uB}\,g'}{m_W^2}\,y_u\,\bar{q}_L H^c\sigma^{\mu\nu}u_R\,B_{\mu\nu} + \frac{\bar{c}_{uW}\,g}{m_W^2}\,y_u\,\bar{q}_L\sigma^i H^c\sigma^{\mu\nu}u_R\,W^i_{\mu\nu} + \frac{\bar{c}_{uG}\,g_S}{m_W^2}\,y_u\,\bar{q}_L H^c\sigma^{\mu\nu}\lambda^a u_R\,G^a_{\mu\nu} \\
&+ \frac{\bar{c}_{dB}\,g'}{m_W^2}\,y_d\,\bar{q}_L H\sigma^{\mu\nu}d_R\,B_{\mu\nu} + \frac{\bar{c}_{dW}\,g}{m_W^2}\,y_d\,\bar{q}_L\sigma^i H\sigma^{\mu\nu}d_R\,W^i_{\mu\nu} + \frac{\bar{c}_{dG}\,g_S}{m_W^2}\,y_d\,\bar{q}_L H\sigma^{\mu\nu}\lambda^a d_R\,G^a_{\mu\nu} \\
&+ \frac{\bar{c}_{lB}\,g'}{m_W^2}\,y_l\,\bar{L}_L H\sigma^{\mu\nu}l_R\,B_{\mu\nu} + \frac{\bar{c}_{lW}\,g}{m_W^2}\,y_l\,\bar{L}_L\sigma^i H\sigma^{\mu\nu}l_R\,W^i_{\mu\nu} + h.c.
\end{aligned}
$$

$$
\begin{aligned}
\Delta\mathcal{L}_{bos} &= \frac{\bar{c}_{3W}\, g^3}{m_W^2}\,\epsilon^{ijk}W_\mu^{i\,\nu}W_\nu^{j\,\rho}W_\rho^{k\,\mu} + \frac{\bar{c}_{3G}\, g_S^3}{m_W^2}\,f^{abc}G_\mu^{a\,\nu}G_\nu^{b\,\rho}G_\rho^{c\,\mu} \\
&+ \frac{\bar{c}_{2W}}{m_W^2}\,(D^\mu W_{\mu\nu})^i\,(D_\rho W^{\rho\nu})^i + \frac{\bar{c}_{2B}}{m_W^2}\,(\partial^\mu B_{\mu\nu})\,(\partial_\rho B^{\rho\nu}) + \frac{\bar{c}_{2G}}{m_W^2}\,(D^\mu G_{\mu\nu})^a\,(D_\rho G^{\rho\nu})^a \\
\Delta\mathcal{L}_{4f} &= \sum_{\psi,L/R,T^a} \bar{\psi}_i\gamma^\mu T^a\psi_j\bar{\psi}_k\gamma_\mu T^a\psi_l + \bar{\psi}_i T^a\psi_j\bar{\psi}_k T^a\psi_l \\
\Delta\mathcal{L}_{\mathcal{CP}} &= \frac{i\tilde{c}_{HW}\, g}{m_W^2}\,(D^\mu H)^\dagger\sigma^i(D^\nu H)\tilde{W}_{\mu\nu}^i + \frac{i\tilde{c}_{HB}\, g'}{m_W^2}\,(D^\mu H)^\dagger(D^\nu H)\tilde{B}_{\mu\nu} \\
&+ \frac{\tilde{c}_\gamma\, g'^2}{m_W^2}\,H^\dagger H B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{\tilde{c}_g\, g_S^2}{m_W^2}\,H^\dagger H G_{\mu\nu}^a\tilde{G}^{a\mu\nu} \\
&+ \frac{\tilde{c}_{3W}\, g^3}{m_W^2}\,\epsilon^{ijk}W_\mu^{i\,\nu}W_\nu^{j\,\rho}\tilde{W}_\rho^{k\,\mu} + \frac{\tilde{c}_{3G}\, g_S^3}{m_W^2}\,f^{abc}G_\mu^{a\,\nu}G_\nu^{b\,\rho}\tilde{G}_\rho^{c\,\mu}
\end{aligned}
$$

$$
\tilde{V}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}V^{\alpha\beta}
$$

- after using EOM: 53 (59) independent dim6 operators

- power counting: $H \to \mathcal{O}(g_*/M = 1/f)$, $\partial_\mu \to \mathcal{O}(1/M)$

$\Rightarrow$ expansion in H/f and E/M

$$\bar{c}_H, \bar{c}_T, \bar{c}_6, \bar{c}_\psi \sim O\left(\frac{v^2}{f^2}\right), \quad \bar{c}_W, \bar{c}_B \sim O\left(\frac{m_W^2}{M^2}\right), \quad \bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_\gamma, \bar{c}_g \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

$$\bar{c}_{H\psi}, \bar{c}'_{H\psi} \sim O\left(\frac{\lambda_\psi^2}{g_*^2}\frac{v^2}{f^2}\right), \quad \bar{c}_{Hud} \sim O\left(\frac{\lambda_u \lambda_d}{g_*^2}\frac{v^2}{f^2}\right), \quad \bar{c}_{\psi W}, \bar{c}_{\psi B}, \bar{c}_{\psi G} \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

Giudice, Grojean, Pomarol, Rattazzi

- canonical normalization, unitary gauge:

$$\begin{aligned} v^2 &= v_{SM}^2 \left(1 + \frac{3}{4}\bar{c}_6\right) \\ h_{SM} &= h\left[1 - \frac{\bar{c}_H}{2} - \frac{\bar{c}_T}{8}\right] - \frac{3}{8}\bar{c}_6 v \\ m_h^2 &= m_{h_{SM}}^2 \left[1 - \bar{c}_H + \frac{3}{2}\bar{c}_6 - \frac{1}{2}\bar{c}_T\right] \end{aligned}$$

etc.

$$\mathcal{L} = \tfrac{1}{2}\partial_\mu h\, \partial^\mu h - \tfrac{1}{2}m_h^2 h^2 - c_3 \tfrac{1}{6}\left(\tfrac{3m_h^2}{v}\right) h^3 - \textstyle\sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar\psi^{(i)}\psi^{(i)}\left(1 + c_\psi \tfrac{h}{v} + \dots\right)$$
$$+ m_W^2\, W_\mu W^\mu \left(1 + 2c_W \tfrac{h}{v} + \dots\right) + \tfrac{1}{2}m_Z^2\, Z_\mu Z^\mu \left(1 + 2c_Z \tfrac{h}{v} + \dots\right) + \dots$$
$$+ \left(c_{WW}\, W^+_{\mu\nu}W^{-\mu\nu} + \tfrac{c_{ZZ}}{2}\, Z_{\mu\nu}Z^{\mu\nu} + c_{Z\gamma}\, Z_{\mu\nu}\gamma^{\mu\nu} + \tfrac{c_{\gamma\gamma}}{2}\,\gamma_{\mu\nu}\gamma^{\mu\nu} + \tfrac{c_{gg}}{2}\, G^a_{\mu\nu}G^{a\mu\nu}\right)\tfrac{h}{v}$$
$$+ \left(c_{W\partial W}\left(W^-_\nu D_\mu W^{+\mu\nu} + h.c.\right) + c_{Z\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + c_{Z\partial\gamma}\, Z_\nu\partial_\mu\gamma^{\mu\nu}\right)\tfrac{h}{v} + \dots$$

Higgs couplings	$\Delta\mathcal{L}_{SILH}$	MCHM4	MCHM5
c_W	$1 - \bar c_H/2$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
c_Z	$1 - \bar c_H/2 - 2\bar c_T$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
$c_\psi\ \ (\psi = u,d,l)$	$1 - (\bar c_H/2 + \bar c_\psi)$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
c_3	$1 + \bar c_6 - 3\bar c_H/2$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
c_{gg}	$8\,(\alpha_s/\alpha_2)\,\bar c_g$	0	0
$c_{\gamma\gamma}$	$8\sin^2\theta_W\,\bar c_\gamma$	0	0
$c_{Z\gamma}$	$\left(\bar c_{HB} - \bar c_{HW} - 8\,\bar c_\gamma \sin^2\theta_W\right)\tan\theta_W$	0	0
c_{WW}	$-2\,\bar c_{HW}$	0	0
c_{ZZ}	$-2\left(\bar c_{HW} + \bar c_{HB}\tan^2\theta_W - 4\bar c_\gamma \tan^2\theta_W \sin^2\theta_W\right)$	0	0
$c_{W\partial W}$	$-2(\bar c_W + \bar c_{HW})$	0	0
$c_{Z\partial Z}$	$-2(\bar c_W + \bar c_{HW}) - 2\,(\bar c_B + \bar c_{HB})\tan^2\theta_W$	0	0
$c_{Z\partial\gamma}$	$2\,(\bar c_B + \bar c_{HB} - \bar c_W - \bar c_{HW})\tan\theta_W$	0	0

small deviations from SM couplings

Contino, Ghezzi, Grojean, Mühlleitner, S.

$$
\begin{aligned}
\mathcal{L} = \quad & \tfrac{1}{2}\partial_\mu h\ \partial^\mu h - \tfrac{1}{2}m_h^2 h^2 - c_3\,\tfrac{1}{6}\left(\tfrac{3m_h^2}{v}\right) h^3 - \textstyle\sum_{\psi=u,d,l} m_{\psi^{(i)}}\,\bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi \tfrac{h}{v} + \dots\right) \\
& + m_W^2\, W_\mu W^\mu \left(1 + 2c_W\,\tfrac{h}{v} + \dots\right) + \tfrac{1}{2}m_Z^2\, Z_\mu Z^\mu \left(1 + 2c_Z\,\tfrac{h}{v} + \dots\right) + \dots \\
& + \left(c_{WW}\, W^+_{\mu\nu}W^{-\mu\nu} + \tfrac{c_{ZZ}}{2}\, Z_{\mu\nu}Z^{\mu\nu} + c_{Z\gamma}\, Z_{\mu\nu}\gamma^{\mu\nu} + \tfrac{c_{\gamma\gamma}}{2}\,\gamma_{\mu\nu}\gamma^{\mu\nu} + \tfrac{c_{gg}}{2}\, G^a_{\mu\nu}G^{a\mu\nu}\right)\tfrac{h}{v} \\
& + \left(c_{W\partial W}\left(W^-_\nu D_\mu W^{+\mu\nu} + h.c.\right) + c_{Z\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + c_{Z\partial\gamma}\, Z_\nu \partial_\mu \gamma^{\mu\nu}\right)\tfrac{h}{v} + \dots
\end{aligned}
$$

• also valid in case of a non-linear Lagrangian for a light Higgs-like scalar [h generic $\mathcal{CP}$-even scalar]

$\Rightarrow$ expansion in E/M (derivatives) only, large deviations from SM couplings

SILH: expansion in $v^2/f^2, E^2/M^2, \alpha_s/\pi, \alpha/\pi$

non-lin.: expansion in $E^2/M^2, \alpha_s/\pi$

II *eHDECAY* http://www.itp.kit.edu/~maggie/eHDECAY/

- $h \to f\bar{f}$:

$$\Gamma(\bar\psi\psi)\big|_{SILH} = \Gamma_0^{SM}(\bar\psi\psi)\left[1 - \bar c_H - 2\bar c_\psi + \frac{2}{|A_0^{SM}|^2}\mathrm{Re}\left(A_0^{*SM}A_{1,ew}^{SM}\right)\right]\left[1+\delta_\psi\,\kappa^{QCD}\right] + \mathcal{O}\left(\frac{v^4}{f^4}, \frac{v^2\alpha}{f^2\pi}, \frac{\alpha^2}{\pi^2}\right)$$

$$\Gamma(\bar\psi\psi)\big|_{NL} = c_\psi^2\,\Gamma_0^{SM}(\bar\psi\psi)\left[1+\delta_\psi\,\kappa^{QCD}\right] + \mathcal{O}\left(\frac{m_h^2}{M^2}, \frac{\alpha}{\pi}\right)$$

A_0^{SM}: SM tree-level amplitude
$A_{1,ew}^{SM}$: SM elw. amplitude [real corrections treated analogously]

- factorization of QCD $\leftrightarrow$ elw. [limit small m_h]

- NL: no elw. corrections!

- $h \to gg$:

$$
\begin{aligned}
\Gamma(gg)\big|_{SILH} &= \frac{G_F \alpha_s^2 m_h^3}{4\sqrt{2}\pi^3} \Bigg[\frac{1}{9} \sum_{q,q'=t,b,c} (1 - \bar{c}_H - \bar{c}_q - \bar{c}_{q'})\, A_{1/2}^*(\tau_{q'})\, A_{1/2}(\tau_q)\; c_{eff}^2\, \kappa_{soft} \\
&+ 2\,\mathrm{Re}\left(\sum_{q=t,b,c} \frac{1}{3} A_{1/2}^*(\tau_q)\, \frac{16\pi\, \bar{c}_g}{\alpha_2} \right) c_{eff}\, \kappa_{soft} \\
&+ \left| \sum_{q=t,b,c} \frac{1}{3} A_{1/2}(\tau_q) \right|^2 c_{eff}^2\, \kappa_{ew}\, \kappa_{soft} \\
&+ \frac{1}{9} \sum_{q,q'=t,b} (1 - \bar{c}_H - \bar{c}_q - \bar{c}_{q'}) A_{1/2}^*(\tau_q)\, A_{1/2}(\tau_{q'})\, \kappa^{NLO}(\tau_q, \tau_{q'}) \Bigg] \\
\Gamma(gg)\big|_{NL} &= \frac{G_F \alpha_s^2 m_h^3}{4\sqrt{2}\pi^3} \Bigg[\left| \sum_{q=t,b,c} \frac{c_q}{3} A_{1/2}(\tau_q) \right|^2 c_{eff}^2\, \kappa_{soft} \\
&+ 2\,\mathrm{Re}\left(\sum_{q=t,b,c} \frac{c_q}{3} A_{1/2}^*(\tau_q)\, \frac{2\pi c_{gg}}{\alpha_s} \right) c_{eff}\, \kappa_{soft} + \left| \frac{2\pi c_{gg}}{\alpha_s} \right|^2 \kappa_{soft} \\
&+ \frac{1}{9} \sum_{q,q'=t,b} c_q\, A_{1/2}^*(\tau_q)\, c_{q'}\, A_{1/2}(\tau_{q'})\, \kappa^{NLO}(\tau_q, \tau_{q'}) \Bigg]
\end{aligned}
$$

$$A_{1/2}(\tau) = \frac{3}{2}\tau\left[1+(1-\tau)f(\tau)\right]$$

$$f(\tau) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\frac{1}{4}\left[\ln\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \tau < 1\,. \end{cases}$$

$$\kappa_{soft}^{NLO} = 1 + \frac{\alpha_s^{NLO}}{\pi}\left(\frac{73}{4} - \frac{7}{6}N_F\right), \qquad c_{eff}^{NLO} = 1 + \frac{\alpha_s^{NLO}}{\pi}\frac{11}{4}$$

Inami, Kubota, Okada
Djouadi, S., Zerwas
Chetyrkin, Kniehl, Steinhauser
Krämer, Laenen, S.
Baikov, Chetyrkin

- $\kappa^{NLO}(\tau_q, \tau_{q'})$: NLO mass effects ($\lesssim$ 5% in SM)

- $h \to \gamma\gamma$:

$$\begin{aligned}
\Gamma(\gamma\gamma)\big|_{SILH} &= \frac{G_F \alpha_{em}^2 m_h^3}{128\sqrt{2}\pi^3}\Bigg\{ |A_{NLO}^{SM}(\gamma\gamma)|^2 + 2\,\mathrm{Re}\Big(A_{LO}^{SM*}(\gamma\gamma)\, A_{ew}^{SM}(\gamma\gamma)\Big) \\
&+2\,\mathrm{Re}\left[A_{NLO}^{SM*}(\gamma\gamma)\left(\Delta A(\gamma\gamma) + \frac{32\pi \sin^2\theta_W\, \bar{c}_\gamma}{\alpha_{em}}\right)\right]\Bigg\} \\
\Gamma(\gamma\gamma)\big|_{NL} &= \frac{G_F \alpha_{em}^2 m_h^3}{128\sqrt{2}\pi^3}\Bigg| \sum_{q=t,b,c} \frac{4}{3} c_q\, 3Q_q^2\, A_{1/2}^{NLO}(\tau_q) + \frac{4}{3} c_\tau Q_\tau^2 A_{1/2}(\tau_\tau) \\
&+ c_V A_1(\tau_W) + \frac{4\pi}{\alpha_{em}} c_{\gamma\gamma}\Bigg|^2 \\
\Delta A(\gamma\gamma) &= -\sum_{q=t,b,c} \frac{4}{3}\left(\frac{\bar{c}_H}{2} + \bar{c}_q\right) 3Q_q^2\, A_{1/2}^{NLO}(\tau_q) - \left(\frac{\bar{c}_H}{2} + \bar{c}_\tau\right)\frac{4}{3} Q_\tau^2\, A_{1/2}(\tau_\tau) \\
&- \left(\frac{\bar{c}_H}{2} - 2\bar{c}_W\right) A_1(\tau_W) \\
A_1(\tau) &= -\left[2 + 3\tau + 3\tau(2-\tau) f(\tau)\right] \\
A_{1/2}^{NLO}(\tau_q) &= A_{1/2}(\tau_q)(1 + \kappa_{QCD})
\end{aligned}$$

- κ_{QCD}: massive QCD corrections

Djouadi, S., Zerwas
Melnikov, Yakovlev
Inoue, Najima, Oka, Saito

- $h \to Z\gamma$:

$$\Gamma(Z\gamma)\Big|_{SILH} = \frac{G_F^2 \alpha_{em} m_W^2 m_h^3}{64\pi^4}\left(1-\frac{m_Z^2}{m_h^2}\right)^3$$
$$\times\Bigg\{ \left|A^{SM}(Z\gamma)\right|^2 + 2\,\mathrm{Re}\Big(A^{SM*}(Z\gamma)\,\Delta A(Z\gamma)\Big)$$
$$+2\,\mathrm{Re}\left[-\frac{4\pi\tan\theta_W}{\sqrt{\alpha_{em}\alpha_2}}(\bar{c}_{HB}-\bar{c}_{HW}-8\bar{c}_\gamma\sin^2\theta_W)\,A^{SM*}(Z\gamma)\right]\Bigg\}$$

$$\Gamma(Z\gamma)\Big|_{NL} = \frac{G_F^2 \alpha_{em} m_W^2 m_h^3}{64\pi^4}\left(1-\frac{m_Z^2}{m_h^2}\right)^3$$
$$\times\left|\sum_\psi \frac{c_\psi N_c Q_\psi \hat{v}_\psi}{\cos\theta_W} A_{1/2}^{Z\gamma}\left(\tau_\psi,\lambda_\psi\right) + c_V\, A_1^{Z\gamma}(\tau_W,\lambda_W) - \frac{4\pi}{\sqrt{\alpha_{em}\alpha_2}}\,c_{Z\gamma}\right|^2$$

$$A_{1/2}^{Z\gamma}(\tau,\lambda) = \left[I_1(\tau,\lambda) - I_2(\tau,\lambda)\right]$$

$$A_1^{Z\gamma}(\tau,\lambda) = \cos\theta_W\Bigg\{4\Big(3-\tan^2\theta_W\Big)I_2\Big(\tau,\lambda\Big)$$
$$+\left[\left(1+\frac{2}{\tau}\right)\tan^2\theta_W - \left(5+\frac{2}{\tau}\right)\right]I_1\Big(\tau,\lambda\Big)\Bigg\}$$

$$\Delta A(Z\gamma) = -\sum_\psi\left(\frac{\bar{c}_H}{2}+\bar{c}_\psi\right)\frac{N_c Q_\psi \hat{v}_\psi}{\cos\theta_W}A_{1/2}^{Z\gamma}\left(\tau_\psi,\lambda_\psi\right) - \left(\frac{\bar{c}_H}{2}-2\bar{c}_W\right)A_1^{Z\gamma}(\tau_W,\lambda_W)$$

$$A^{SM}(Z\gamma) = \sum_\psi \frac{N_c Q_\psi \hat{v}_\psi}{\cos\theta_W}A_{1/2}^{Z\gamma}\left(\tau_\psi,\lambda_\psi\right) + A_1^{Z\gamma}(\tau_W,\lambda_W)$$

$$
\begin{aligned}
I_1(\tau,\lambda) &= \frac{\tau\lambda}{2(\tau-\lambda)} + \frac{\tau^2\lambda^2}{2(\tau-\lambda)^2}\left[f(\tau)-f(\lambda)\right] + \frac{\tau^2\lambda}{(\tau-\lambda)^2}\left[g(\tau)-g(\lambda)\right] \\
I_2(\tau,\lambda) &= -\frac{\tau\lambda}{2(\tau-\lambda)}\left[f(\tau)-f(\lambda)\right] \\
g(\tau) &= \begin{cases} \sqrt{\tau-1}\,\arcsin\dfrac{1}{\sqrt{\tau}} & \tau \geq 1 \\ \dfrac{\sqrt{1-\tau}}{2}\left[\ln\dfrac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right] & \tau < 1\,. \end{cases}
\end{aligned}
$$

- $h \to Z^*Z^*, W^*W^*$:

$$\begin{aligned}
\Gamma(V^*V^*) &= \frac{1}{\pi^2}\int_0^{m_h^2}\frac{dQ_1^2\; m_V\Gamma_V}{\left(Q_1^2-m_V^2\right)^2+m_V^2\Gamma_V^2}\int_0^{(m_h-Q_1)^2}\frac{dQ_2^2\; m_V\Gamma_V}{\left(Q_2^2-m_V^2\right)^2+m_V^2\Gamma_V^2}\;\Gamma(VV)\\
\Gamma(VV)\Big|_{NL} &= \Gamma^{SM}(VV)\times\left\{c_V^2-2c_V\left[\frac{a_{VV}}{2}\left(1-\frac{Q_1^2+Q_2^2}{m_h^2}\right)+a_{V\partial V}\frac{Q_1^2+Q_2^2}{m_h^2}\right]\right.\\
&\left.+c_Va_{VV}\,\frac{\lambda\left(Q_1^2,Q_2^2,m_h^2\right)\ (1-(Q_1^2+Q_2^2)/m_h^2)}{\lambda\left(Q_1^2,Q_2^2,m_h^2\right)+12\,Q_1^2Q_2^2/m_h^4}\right\}\\
a_{VV} &= c_{VV}\,\frac{m_h^2}{m_V^2}\,,\qquad a_{V\partial V}=\frac{c_{V\partial V}}{2}\,\frac{m_h^2}{m_V^2}\\
\Gamma(VV)\Big|_{SILH} &= \Gamma^{SILH}(VV)+\Gamma^{SM}(VV)\frac{2}{|A_0^{SM}|^2}\,\mathrm{Re}\left(A_0^{*SM}A_{ew}^{SM}\right)\\
\Gamma^{SILH}(VV) &= \Gamma^{SM}(VV)\times\left\{1-\bar{c}_H-2\left[\frac{\bar{a}_{VV}}{2}\left(1-\frac{Q_1^2+Q_2^2}{m_h^2}\right)+\bar{a}_{V\partial V}\frac{Q_1^2+Q_2^2}{m_h^2}\right]\right.\\
&\left.+\bar{a}_{VV}\,\frac{\lambda\left(Q_1^2,Q_2^2,m_h^2\right)\ (1-(Q_1^2+Q_2^2)/m_h^2)}{\lambda\left(Q_1^2,Q_2^2,m_h^2\right)+12\,Q_1^2Q_2^2/m_h^4}\right\}\\
\Gamma^{SM}(VV) &= \frac{\delta_V G_F m_h^3}{16\sqrt{2}\pi}\sqrt{\lambda\left(Q_1^2,Q_2^2,m_h^2\right)}\left(\lambda\left(Q_1^2,Q_2^2,m_h^2\right)+\frac{12Q_1^2Q_2^2}{m_h^4}\right)\\
\bar{a}_{WW} &= -2\,\frac{m_h^2}{m_W^2}\,\bar{c}_{HW}\,,\qquad \bar{a}_{ZZ}=-2\,\frac{m_h^2}{m_Z^2}\left(\bar{c}_{HW}+\bar{c}_{HB}\tan^2\theta_W-4\bar{c}_\gamma\tan^2\theta_W\sin^2\theta_W\right)\\
\bar{a}_{W\partial W} &= -2\,\frac{m_h^2}{2m_W^2}\left(\bar{c}_W+\bar{c}_{HW}\right)\,,\quad \bar{a}_{Z\partial Z}=-2\,\frac{m_h^2}{2m_Z^2}\left(\bar{c}_W+\bar{c}_{HW}+(\bar{c}_B+\bar{c}_{HB})\tan^2\theta_W\right)
\end{aligned}$$

- approximate formulae [w/o elw. corrections]: $\alpha_2 = \sqrt{2} G_F m_W^2/\pi$

$$\frac{\Gamma(\bar\psi\psi)}{\Gamma(\bar\psi\psi)_{SM}} \simeq 1 - \bar c_H - 2\,\bar c_\psi$$

$$\frac{\Gamma(h\to W^{(*)}W^*)}{\Gamma(h\to W^{(*)}W^*)_{SM}} \simeq 1 - \bar c_H + 2.2\,\bar c_W + 3.7\,\bar c_{HW}$$

$$\frac{\Gamma(h\to Z^{(*)}Z^*)}{\Gamma(h\to Z^{(*)}Z^*)_{SM}} \simeq 1 - \bar c_H + 2.0\,\left(\bar c_W + \tan^2\theta_W\,\bar c_B\right) + 3.0\,\left(\bar c_{HW} + \tan^2\theta_W\,\bar c_{HB}\right) - 0.26\,\bar c_\gamma$$

$$\frac{\Gamma(h\to Z\gamma)}{\Gamma(h\to Z\gamma)_{SM}} \simeq 1 - \bar c_H + 0.12\,\bar c_t - 5\cdot 10^{-4}\,\bar c_c - 0.003\,\bar c_b - 9\cdot 10^{-5}\,\bar c_\tau + 4.2\,\bar c_W + 0.19\left(\bar c_{HW} - \bar c_{HB} + 8\,\bar c_\gamma \sin^2\theta_W\right)\frac{4\pi}{\sqrt{\alpha_2\alpha_{em}}}$$

$$\frac{\Gamma(h\to \gamma\gamma)}{\Gamma(h\to \gamma\gamma)_{SM}} \simeq 1 - \bar c_H + 0.54\,\bar c_t - 0.003\,\bar c_c - 0.007\,\bar c_b - 0.007\,\bar c_\tau + 5.04\,\bar c_W - 0.54\,\bar c_\gamma\,\frac{4\pi}{\alpha_{em}}$$

$$\frac{\Gamma(h\to gg)}{\Gamma(h\to gg)_{SM}} \simeq 1 - \bar c_H - 2.12\,\bar c_t + 0.024\,\bar c_c + 0.1\,\bar c_b + 22.2\,\bar c_g\,\frac{4\pi}{\alpha_2}$$

III *CONCLUSIONS*

- Higgs decays: eHDECAY

- inclusion of SILH (dim 6) and non-linear Lagrangians

- systematic extension of SM $\rightarrow$ well-defined expansions

- SILH: expansion in $v^2/f^2, E^2/M^2, \alpha_s/\pi, \alpha/\pi$

- non-lin.: expansion in $E^2/M^2, \alpha_s/\pi$

- eHDECAY provides consistent tool for BSM Higgs decays
  http://www.itp.kit.edu/~maggie/eHDECAY/

[• important impact on single and double Higgs production modes]

BACKUP SLIDES

- classification: $[\Phi = H,\ \tilde{\Phi} = i\sigma^2\Phi^*]$

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}_\Phi = (\Phi^\dagger\Phi)^3$	$\mathcal{O}_{e\Phi} = (\Phi^\dagger\Phi)(\bar{\ell}\,\Gamma_e e\Phi)$	$\mathcal{O}_G = f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{u\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_u u\widetilde{\Phi})$	$\mathcal{O}_{\widetilde{G}} = f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{d\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_d d\Phi)$	$\mathcal{O}_W = \varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
		$\mathcal{O}_{\widetilde{W}} = \varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$X^2\Phi^2$	$\psi^2 X\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}_{\Phi G} = (\Phi^\dagger\Phi) G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{uG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_u u\widetilde{\Phi}) G_{\mu\nu}^A$	$\mathcal{O}_{\Phi\ell}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{\ell}\gamma^\mu\ell)$
$\mathcal{O}_{\Phi\widetilde{G}} = (\Phi^\dagger\Phi)\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{dG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_d d\Phi) G_{\mu\nu}^A$	$\mathcal{O}_{\Phi\ell}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{\ell}\gamma^\mu\tau^I\ell)$
$\mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi) W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{eW} = (\bar{\ell}\sigma^{\mu\nu}\Gamma_e e\tau^I\Phi) W_{\mu\nu}^I$	$\mathcal{O}_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}\gamma^\mu e)$
$\mathcal{O}_{\Phi\widetilde{W}} = (\Phi^\dagger\Phi)\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uW} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\tau^I\widetilde{\Phi}) W_{\mu\nu}^I$	$\mathcal{O}_{\Phi q}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{q}\gamma^\mu q)$
$\mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi) B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dW} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\tau^I\Phi) W_{\mu\nu}^I$	$\mathcal{O}_{\Phi q}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{q}\gamma^\mu\tau^I q)$
$\mathcal{O}_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi)\widetilde{B}_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{eB} = (\bar{\ell}\sigma^{\mu\nu}\Gamma_e e\Phi) B_{\mu\nu}$	$\mathcal{O}_{\Phi u} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{\Phi WB} = (\Phi^\dagger\tau^I\Phi) W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{uB} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\widetilde{\Phi}) B_{\mu\nu}$	$\mathcal{O}_{\Phi d} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{d}\gamma^\mu d)$
$\mathcal{O}_{\Phi\widetilde{W}B} = (\Phi^\dagger\tau^I\Phi)\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dB} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\Phi) B_{\mu\nu}$	$\mathcal{O}_{\Phi ud} = i(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{u}\gamma^\mu\Gamma_{ud} d)$

- constraints from precision measurements:

$$\Delta\epsilon_1 \equiv \Delta\rho = \bar{c}_T(m_Z), \qquad -1.5\times 10^{-3} < \bar{c}_T(m_Z) < 2.2\times 10^{-3}$$

$$\Delta\epsilon_3 = \bar{c}_W(m_Z) + \bar{c}_B(m_Z)\,, \qquad -1.4\times 10^{-3} < \bar{c}_W(m_Z) + \bar{c}_B(m_Z) < 1.9\times 10^{-3}$$

- Z-pole measurements:

$$\frac{\delta g_{L\psi}}{g_{L\psi}} = \frac{1}{2}\,\frac{\bar{c}_{H\Psi} + 2\,T_{3L}\,\bar{c}'_{H\Psi}}{T_{3L} - Q\sin^2\theta_W}\,, \qquad \frac{\delta g_{R\psi}}{g_{R\psi}} = \frac{1}{2}\,\frac{\bar{c}_{H\psi}}{Q\sin^2\theta_W}$$

$$-0.03 < \bar{c}_{Hq1} < 0.02\,, \quad -0.002 < \bar{c}'_{Hq1} < 0.003\,,$$

$$-0.005 < \bar{c}_{Hq2} < 0.003\,, \quad -0.003 < \bar{c}'_{Hq2} < 0.005\,,$$

$$-0.008 < \bar{c}_{Hu} < 0.02\,, \quad -0.03 < \bar{c}_{Hd} < 0.02\,, \quad -0.03 < \bar{c}_{Hs} < 0.02$$

$$-0.004 < \bar{c}_{HL} + \bar{c}'_{HL} < 0.002\,, \quad -0.003 < \bar{c}_{HL} - \bar{c}'_{HL} < 0.0002\,, \quad -0.0007 < \bar{c}_{Hl} < 0.003\,,$$

$$-0.02 < \bar{c}_{Hq_2} + \bar{c}'_{Hq_2} < 0.005\,, \quad -0.02 < \bar{c}_{Hc} < 0.03\,,$$

$$-0.003 < \bar{c}_{Hq_3} - \bar{c}'_{Hq_3} < 0.009\,, \quad -0.07 < \bar{c}_{Hb} < -0.005$$

- EDMs: neutron & mercury:

$$-7.01\times10^{-6} < \mathrm{Im}(\bar{c}_{uB}+\bar{c}_{uW}) < 7.86\times10^{-6}\,,$$

$$-9.42\times10^{-7} < \mathrm{Im}(\bar{c}_{dB}-\bar{c}_{dW}) < 8.40\times10^{-7}\,,$$

$$-1.62\times10^{-6} < \mathrm{Im}(\bar{c}_{uG}) < 2.01\times10^{-6}\,,$$

$$-7.71\times10^{-7} < \mathrm{Im}(\bar{c}_{dG}) < 5.70\times10^{-7}\,,$$

- top quark: nEDM, $b\to s\gamma, s\ell^+\ell^-$:

$$-1.39\times10^{-4} < \mathrm{Im}(\bar{c}_{tG}) < 1.21\times10^{-4}$$

$$-0.057 < \mathrm{Re}(\bar{c}_{tW}+\bar{c}_{tB}) - 2.65\,\mathrm{Im}(\bar{c}_{tW}+\bar{c}_{tB}) < 0.20$$

$t\bar{t}$ cxns @ Tevatron & LHC:

$$-6.12\times10^{-3} < \mathrm{Re}(\bar{c}_{tG}) < 1.94\times10^{-3}$$

$$-1.2 < \mathrm{Re}(\bar{c}_{bW}) < 1.1\,, \qquad -0.01 < \mathrm{Re}(\bar{c}_{tW}) < 0.02$$

- leptons: EDMs & anomalous magnetic moments:

$$-1.64 \times 10^{-2} < \mathrm{Re}(\bar{c}_{eB} - \bar{c}_{eW}) < 3.37 \times 10^{-3}\,,$$

$$1.88 \times 10^{-4} < \mathrm{Re}(\bar{c}_{\mu B} - \bar{c}_{\mu W}) < 6.43 \times 10^{-4}\,,$$

$$-2.97 \times 10^{-7} < \mathrm{Im}(\bar{c}_{eB} - \bar{c}_{eW}) < 4.51 \times 10^{-7}\,,$$

$$-0.26 < \mathrm{Im}(\bar{c}_{\mu B} - \bar{c}_{\mu W}) < 0.29\,,$$