PAUL SCHERRER INSTITUT

EHDECAY

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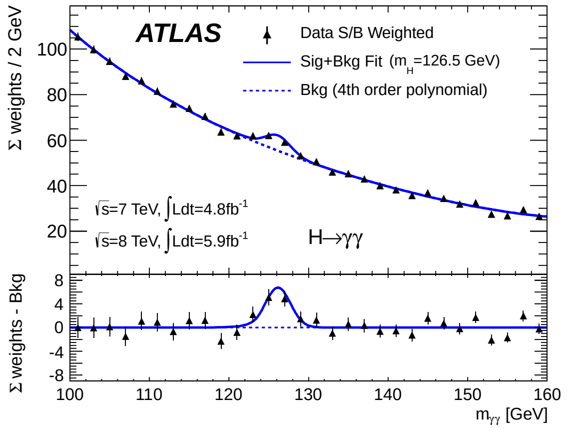
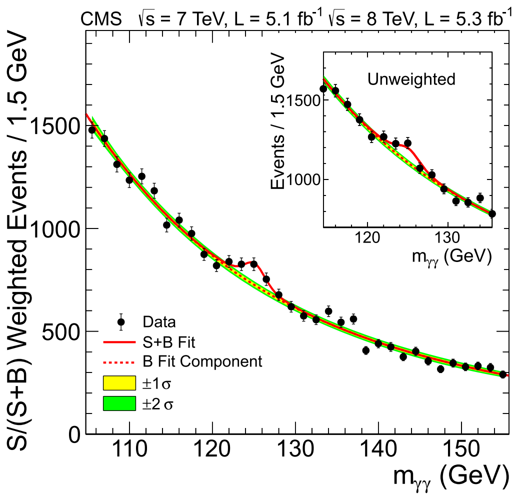
eHDECAY in collaboration with R. Contino, M. Ghezzi, C. Grojean and M. Mühlleitner

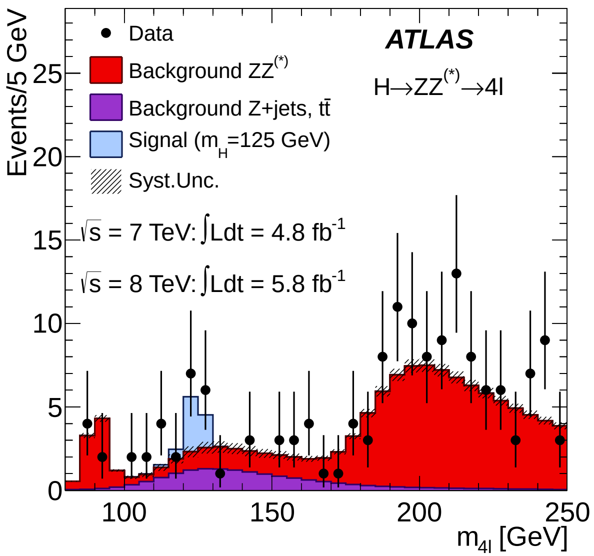
I INTRODUCTION

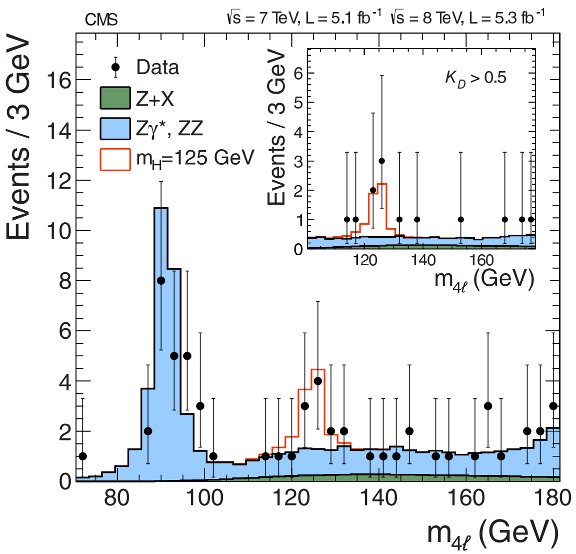
Standard Model

- we have found the Higgs: $M_H \sim 125$ GeV
- $gg \to H$ dominant

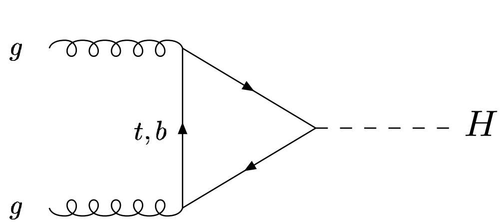


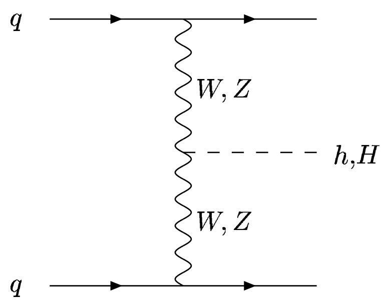


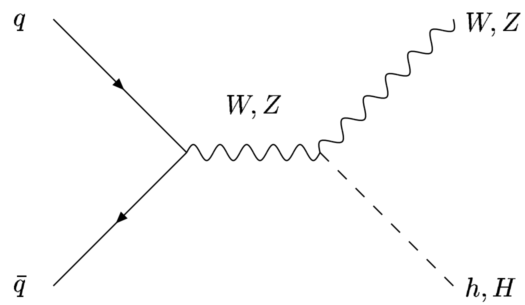


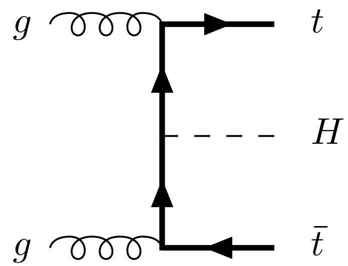


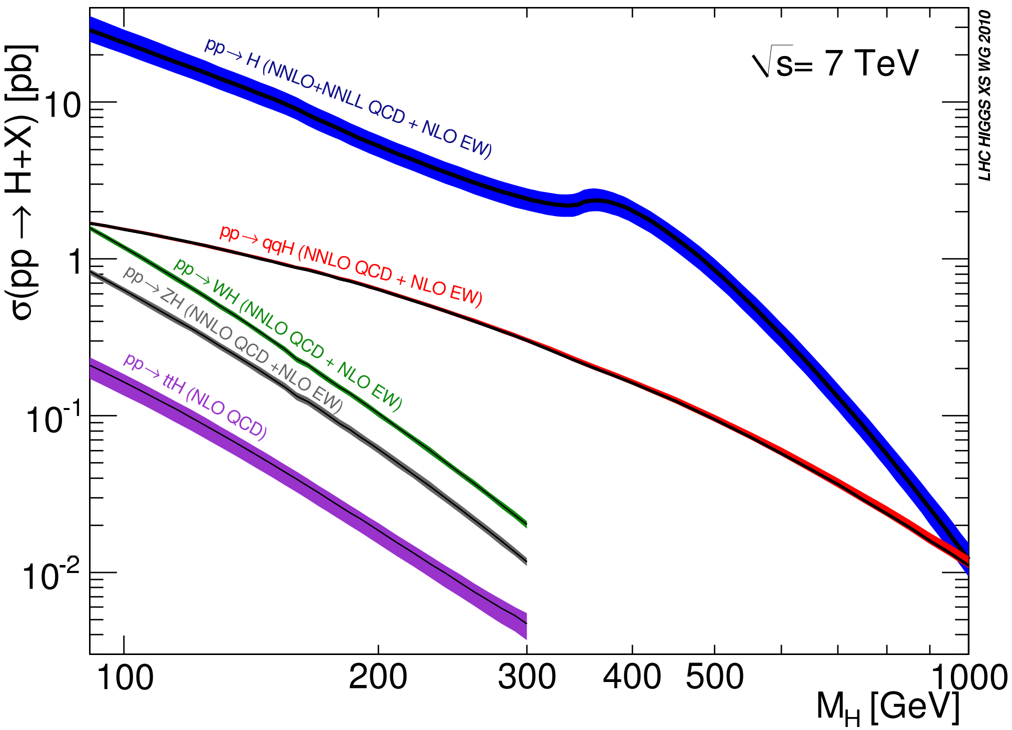
- Higgs Boson Production

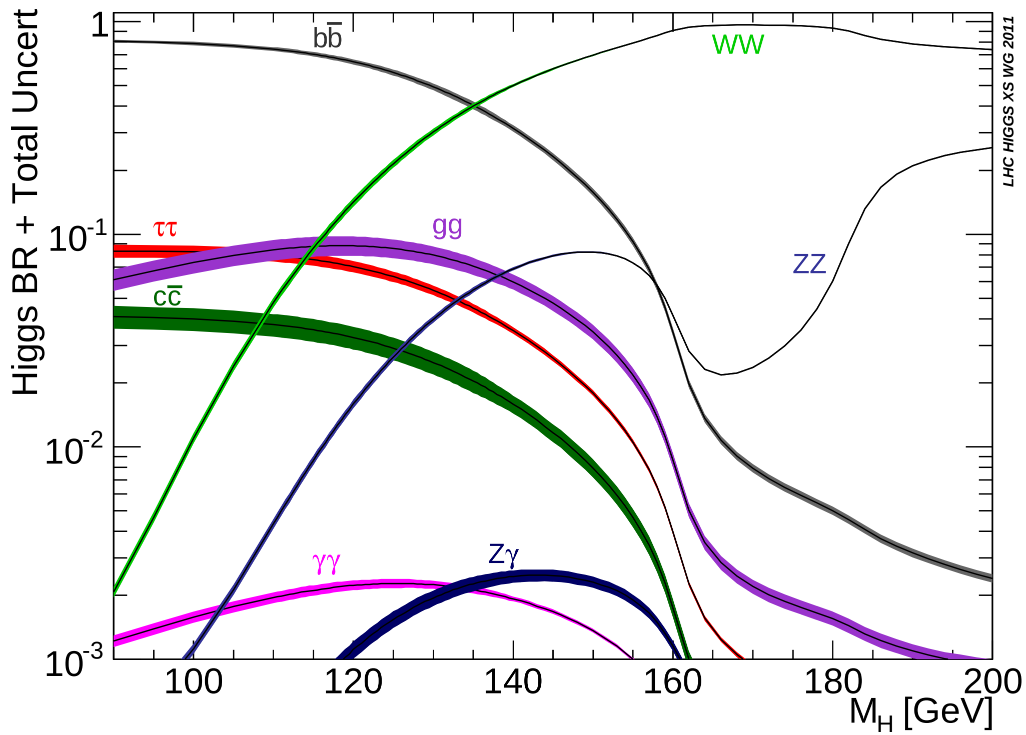












LHC Higgs XS WG

- Discovery: LHC [Tevatron]

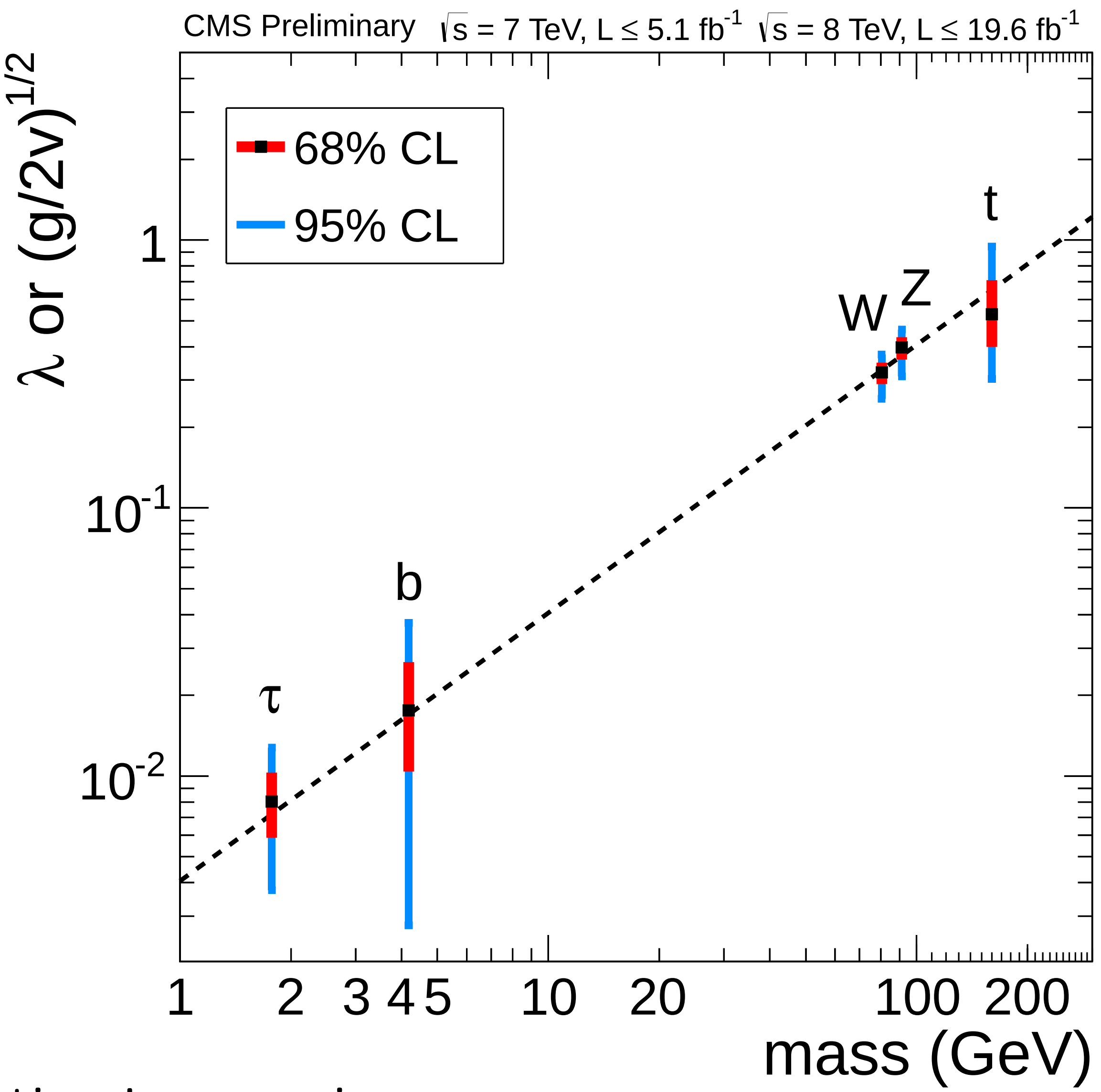
  → Higgs mass

  couplings

  spin

  $\mathcal{CP}$

  λ ?



CMS

- deviations → effective Lagrangians

II *EFFECTIVE LAGRANGIANS*

(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}
$$

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

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

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

- canonical normalization

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

Higgs couplings	$\Delta\mathcal{L}_{SILH}$	MCHM4	MCHM5
c_W	$1 - \bar{c}_H/2$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
c_Z	$1 - \bar{c}_H/2 - \bar{c}_T$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
$c_\psi \;\; (\psi = u, d, l)$	$1 - (\bar{c}_H/2 + \bar{c}_\psi)$	$\sqrt{1-\xi}$	$\dfrac{1-2\xi}{\sqrt{1-\xi}}$
c_3	$1 + \bar{c}_6 - 3\bar{c}_H/2$	$\sqrt{1-\xi}$	$\dfrac{1-2\xi}{\sqrt{1-\xi}}$
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.

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

- 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 allowed

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

Partial Width	QCD	Electroweak	Total	
$H \to b\bar{b}/c\bar{c}$	$\sim 0.1\%$	~ 1–2% for $M_H \lesssim 135$GeV	$\sim 2\%$	NNNNLO / NLO
$H \to \tau^+\tau^-/\mu^+\mu^-$		~ 1–2% for $M_H \lesssim 135$GeV	$\sim 2\%$	NLO
$H \to t\bar{t}$	$\lesssim 5\%$	$\lesssim 2$–5% for $M_H < 500$GeV	$\sim 5\%$	(NNN)NLO / LO
		$\sim 0.1(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500$GeV	~ 5–10%	
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$	NNNLO approx. / NLO
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$	NLO / NLO
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$	(N)LO / LO
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$ for $M_H < 500$GeV	$\sim 0.5\%$	(N)NLO
		$\sim 0.17(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500$GeV	~ 0.5–15%	

- QCD: variation of Higgs widths for scale by factor 2 and 1/2
  elw: missing HO estimated from known structure at NLO
  $M_H \gtrsim 500$ GeV: Higgs self-interactions dominate error
  different uncertainties added linearly for each channel

- parametric uncertainties:
  $m_t = 172.5 \pm 2.5$ GeV $\qquad \alpha_s(M_Z) = 0.119 \pm 0.002$
  $m_b(m_b) = 4.16 \pm 0.06$ GeV $\qquad m_c(m_c) = 1.28 \pm 0.03$ GeV
  different uncertainties added quadratically for each channel

- total uncertainties: parametric & theor. uncertainties added linearly

III $e\mathcal{HDECAY}$

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

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

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

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

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!

- other decay modes analogous

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

$$\frac{\Gamma(\bar{\psi}\psi)}{\Gamma(\bar{\psi}\psi)_{SM}} \simeq 1 - \bar{c}_H - 2\,\bar{c}_\psi \qquad \text{(small } \bar{c}_t \text{ contamination for } s\bar{s}, c\bar{c}, b\bar{b}\text{)}$$

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

$$\frac{\Gamma(h \to Z^{(*)}Z^*)}{\Gamma(h \to Z^{(*)}Z^*)_{SM}} \simeq 1 - \bar{c}_H - 2\bar{c}_T + 2.0\,\left(\bar{c}_W + \tan^2\theta_W\,\bar{c}_B\right) + 3.0\,\left(\bar{c}_{HW} + \tan^2\theta_W\,\bar{c}_{HB}\right) - 0.26\,\bar{c}_\gamma$$

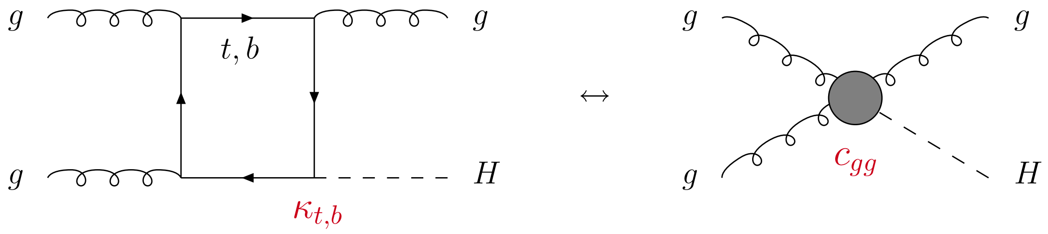
$$\frac{\Gamma(h \to Z\gamma)}{\Gamma(h \to Z\gamma)_{SM}} \simeq 1 - \bar{c}_H + 0.12\,\bar{c}_t - 5\cdot 10^{-4}\,\bar{c}_c - 0.003\,\bar{c}_b - 9\cdot 10^{-5}\,\bar{c}_\tau + 4.2\,\bar{c}_W + 0.19\,\left(\bar{c}_{HW} - \bar{c}_{HB} + 8\,\bar{c}_\gamma \sin^2\theta_W\right)\frac{4\pi}{\sqrt{\alpha_2\alpha_{em}}}$$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{SM}} \simeq 1 - \bar{c}_H + 0.54\,\bar{c}_t - 0.003\,\bar{c}_c - 0.007\,\bar{c}_b - 0.007\,\bar{c}_\tau + 5.04\,\bar{c}_W - 0.54\,\bar{c}_\gamma\,\frac{4\pi}{\alpha_{em}}$$

$$\frac{\Gamma(h \to gg)}{\Gamma(h \to gg)_{SM}} \simeq 1 - \bar{c}_H - 2.12\,\bar{c}_t + 0.024\,\bar{c}_c + 0.1\,\bar{c}_b + 22.2\,\bar{c}_g\,\frac{4\pi}{\alpha_2}$$

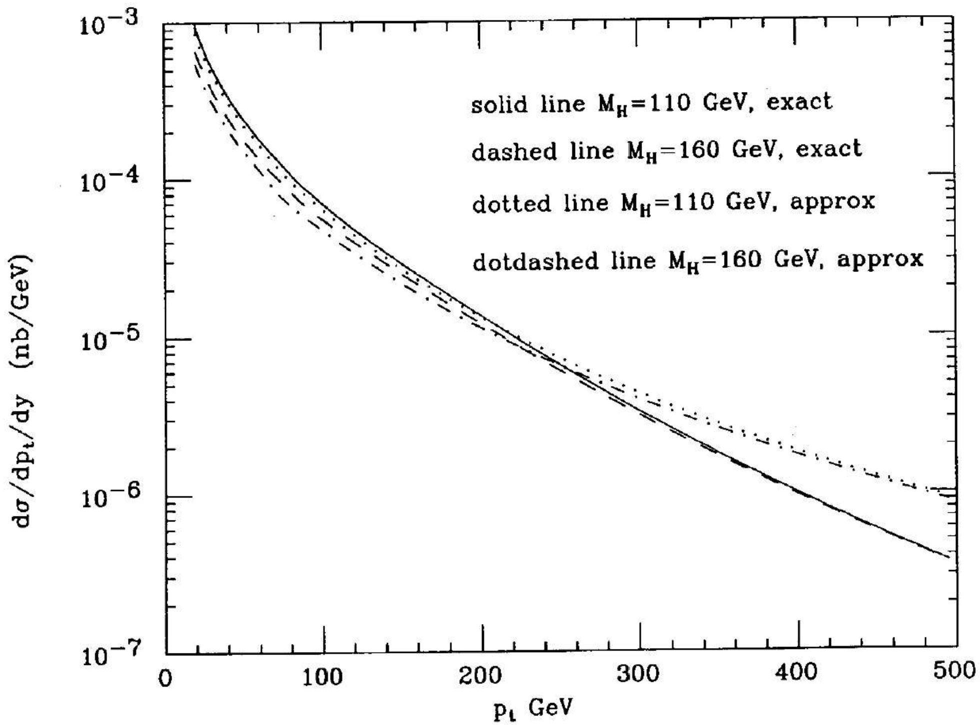
IV *OTHER APPLICATIONS*

Higgs p_T (or how to prove that ggF is loop-mediated)



- distinction dim4 $\leftrightarrow$ dim5

Harlander, Neumann



$m_t = 160$ GeV

Ellis, Hinchliffe, Soldate, van der Bij

- implementation of dim6 $G^{a\mu\nu}G^a_{\mu\nu}H$ in HIGLU (σ_{tot}, p_{TH}) planned

V *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/
  [extension to subleading operators planned]

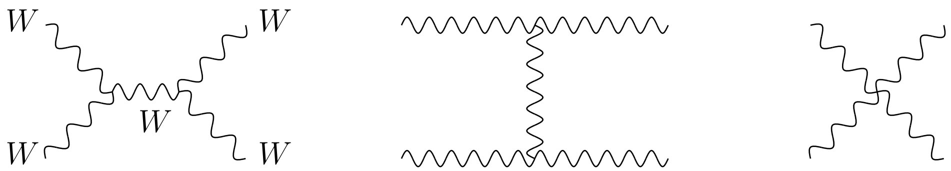
- important impact on Higgs production modes

BACKUP SLIDES

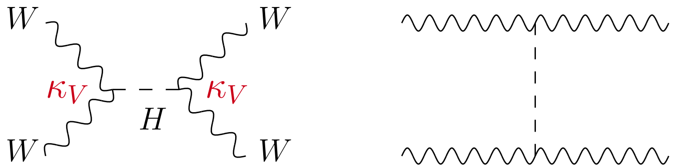
II *EFFECTIVE LAGRANGIANS*

- $WW \to WW$ @ high energies

(a)



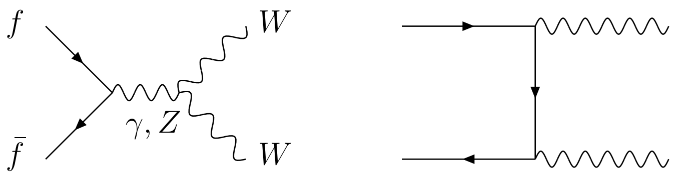
(b)



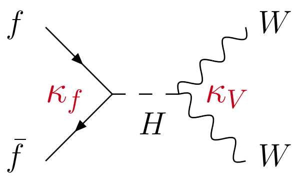
$$\mathcal{A} = \frac{s}{v^2}\left\{1 - \frac{\kappa_V^2 s}{s - M_H^2}\right\} \quad \Rightarrow \quad \kappa_V = 1$$

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

(a)



(b)



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

- analogously for κ_H

- 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:

$$-7.01 \times 10^{-6} < \mathrm{Im}(\bar{c}_{uB} + \bar{c}_{uW}) < 7.86 \times 10^{-6}\,,$$

$$-9.42 \times 10^{-7} < \mathrm{Im}(\bar{c}_{dB} - \bar{c}_{dW}) < 8.40 \times 10^{-7}\,,$$

$$-1.62 \times 10^{-6} < \mathrm{Im}(\bar{c}_{uG}) < 2.01 \times 10^{-6}\,,$$

$$-7.71 \times 10^{-7} < \mathrm{Im}(\bar{c}_{dG}) < 5.70 \times 10^{-7}\,,$$

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

$$-1.39 \times 10^{-4} < \mathrm{Im}(\bar{c}_{tG}) < 1.21 \times 10^{-4}$$

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

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

$$-6.12 \times 10^{-3} < \mathrm{Re}(\bar{c}_{tG}) < 1.94 \times 10^{-3}$$

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

- leptons: EDMs & anomalous magnetic moments:

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

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

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

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

- $h \to gg$:

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

$$
\begin{aligned}
A_{1/2}(\tau) &= \frac{3}{2}\tau\left[1+(1-\tau)f(\tau)\right] \\
f(\tau) &= \begin{cases} \arcsin^2 \dfrac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\dfrac{1}{4}\left[\ln \dfrac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \tau < 1 \,. \end{cases}
\end{aligned}
$$

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

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

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

- $h \to \gamma\gamma$:

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

- κ_{QCD}: massive QCD corrections

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

- $h \to Z\gamma$:

$$
\begin{aligned}
\Gamma(Z\gamma)\Big|_{SILH} &= \frac{G_F^2 \alpha_{em} m_W^2 m_h^3}{64\pi^4}\left(1-\frac{m_Z^2}{m_h^2}\right)^3 \\
&\times\left\{\left|A^{SM}(Z\gamma)\right|^2 + 2\,\mathrm{Re}\Big(A^{SM*}(Z\gamma)\,\Delta A(Z\gamma)\Big)\right. \\
&\qquad \left. +2\,\mathrm{Re}\left[-\frac{4\pi\tan\theta_W}{\sqrt{\alpha_{em}\alpha_2}}(\bar{c}_{HB}-\bar{c}_{HW}-8\bar{c}_\gamma\sin^2\theta_W)\,A^{SM*}(Z\gamma)\right]\right\} \\
\Gamma(Z\gamma)\Big|_{NL} &= \frac{G_F^2 \alpha_{em} m_W^2 m_h^3}{64\pi^4}\left(1-\frac{m_Z^2}{m_h^2}\right)^3 \\
&\times\left|\sum_\psi \frac{c_\psi N_c Q_\psi \widehat{v}_\psi}{\cos\theta_W}\,A_{1/2}^{Z\gamma}\left(\tau_\psi,\lambda_\psi\right) + c_V\,A_1^{Z\gamma}\left(\tau_W,\lambda_W\right) - \frac{4\pi}{\sqrt{\alpha_{em}\alpha_2}}\,c_{Z\gamma}\right|^2 \\
A_{1/2}^{Z\gamma}(\tau,\lambda) &= \left[I_1(\tau,\lambda) - I_2(\tau,\lambda)\right] \\
A_1^{Z\gamma}(\tau,\lambda) &= \cos\theta_W\left\{4\Big(3-\tan^2\theta_W\Big)I_2\Big(\tau,\lambda\Big)\right. \\
&\qquad \left. +\left[\left(1+\frac{2}{\tau}\right)\tan^2\theta_W - \left(5+\frac{2}{\tau}\right)\right]I_1\Big(\tau,\lambda\Big)\right\} \\
\Delta A(Z\gamma) &= -\sum_\psi\left(\frac{\bar{c}_H}{2}+\bar{c}_\psi\right)\frac{N_c Q_\psi \widehat{v}_\psi}{\cos\theta_W}\,A_{1/2}^{Z\gamma}\left(\tau_\psi,\lambda_\psi\right) - \left(\frac{\bar{c}_H}{2} - 2\bar{c}_W\right)\,A_1^{Z\gamma}\left(\tau_W,\lambda_W\right) \\
A^{SM}(Z\gamma) &= \sum_\psi \frac{N_c Q_\psi \widehat{v}_\psi}{\cos\theta_W}\,A_{1/2}^{Z\gamma}\left(\tau_\psi,\lambda_\psi\right) + A_1^{Z\gamma}\left(\tau_W,\lambda_W\right)
\end{aligned}
$$

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

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

$$\Gamma(V^*V^*) = \frac{1}{\pi^2}\int_0^{m_h^2} \frac{dQ_1^2\, m_V \Gamma_V}{\left(Q_1^2 - m_V^2\right)^2 + m_V^2\Gamma_V^2} \int_0^{(m_h - Q_1)^2} \frac{dQ_2^2\, m_V \Gamma_V}{\left(Q_2^2 - m_V^2\right)^2 + m_V^2\Gamma_V^2}\ \Gamma(VV)$$

$$\Gamma(VV)\Big|_{NL} = \Gamma^{SM}(VV) \times \Bigg\{ c_V^2 - 2c_V \left[\frac{a_{VV}}{2}\left(1 - \frac{Q_1^2 + Q_2^2}{m_h^2}\right) + a_{V\partial V}\frac{Q_1^2+Q_2^2}{m_h^2}\right] + c_V a_{VV}\, \frac{\lambda\left(Q_1^2, Q_2^2, m_h^2\right)\ (1 - (Q_1^2+Q_2^2)/m_h^2)}{\lambda\left(Q_1^2, Q_2^2, m_h^2\right) + 12\, Q_1^2 Q_2^2/m_h^4}\Bigg\}$$

$$a_{VV} = c_{VV}\,\frac{m_h^2}{m_V^2}\,, \qquad a_{V\partial V} = \frac{c_{V\partial V}}{2}\,\frac{m_h^2}{m_V^2}$$

$$\Gamma(VV)\Big|_{SILH} = \Gamma^{SILH}(VV) + \Gamma^{SM}(VV)\frac{2}{|A_0^{SM}|^2}\,\mathrm{Re}\left(A_0^{*SM} A_{ew}^{SM}\right)$$

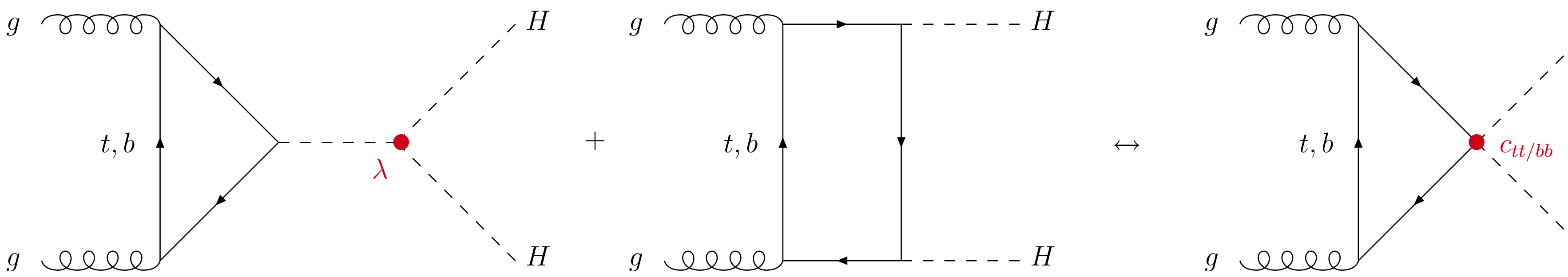
$$\Gamma^{SILH}(VV) = \Gamma^{SM}(VV) \times \Bigg\{1 - \bar{c}_H - 2\left[\frac{\bar{a}_{VV}}{2}\left(1 - \frac{Q_1^2+Q_2^2}{m_h^2}\right) + \bar{a}_{V\partial V}\frac{Q_1^2+Q_2^2}{m_h^2}\right] + \bar{a}_{VV}\, \frac{\lambda\left(Q_1^2, Q_2^2, m_h^2\right)\ (1 - (Q_1^2+Q_2^2)/m_h^2)}{\lambda\left(Q_1^2, Q_2^2, m_h^2\right) + 12\, Q_1^2 Q_2^2/m_h^4}\Bigg\}$$

$$\Gamma^{SM}(VV) = \frac{\delta_V G_F m_h^3}{16\sqrt{2}\pi}\sqrt{\lambda\left(Q_1^2, Q_2^2, m_h^2\right)}\left(\lambda\left(Q_1^2, Q_2^2, m_h^2\right) + \frac{12 Q_1^2 Q_2^2}{m_h^4}\right)$$

$$\bar{a}_{WW} = -2\,\frac{m_h^2}{m_W^2}\,\bar{c}_{HW}\,, \qquad \bar{a}_{ZZ} = -2\,\frac{m_h^2}{m_Z^2}\left(\bar{c}_{HW} + \bar{c}_{HB}\tan^2\theta_W - 4\bar{c}_\gamma \tan^2\theta_W \sin^2\theta_W\right)$$

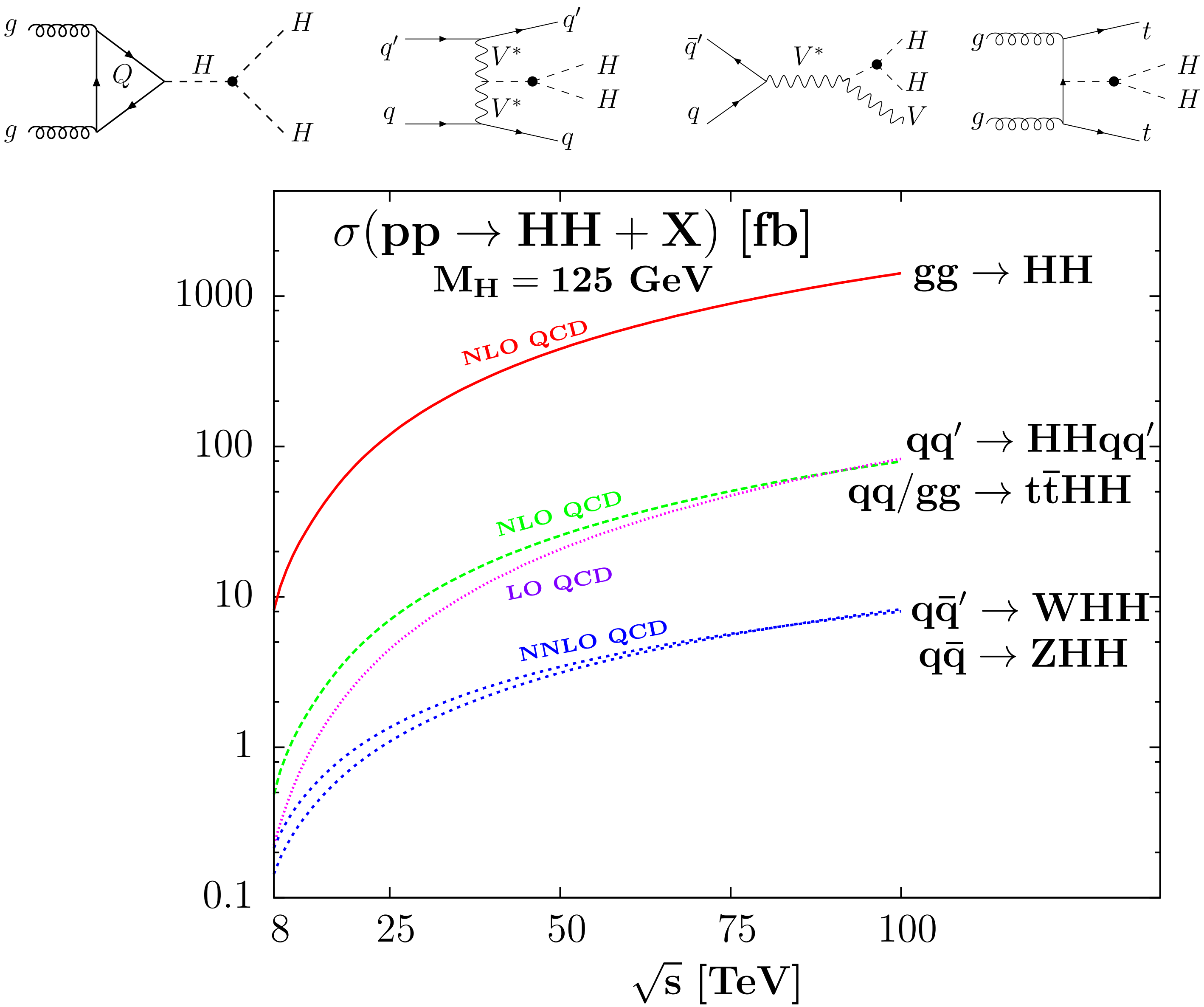
$$\bar{a}_{W\partial W} = -2\,\frac{m_h^2}{2m_W^2}\left(\bar{c}_W + \bar{c}_{HW}\right)\,, \quad \bar{a}_{Z\partial Z} = -2\,\frac{m_h^2}{2m_Z^2}\left(\bar{c}_W + \bar{c}_{HW} + (\bar{c}_B + \bar{c}_{HB})\tan^2\theta_W\right)$$

(ii) anomalous Higgs couplings [e.g. composite Higgs]



- threshold region: sensitive to λ
  large M_{HH}: sensitive to $c_{tt/bb}$ [e.g. boosted Higgs pairs]

- similar effects for other Higgs pair production modes



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