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I Introduction

II Effective Lagrangians

III Higgs Observables

IV Conclusions

I *INTRODUCTION*

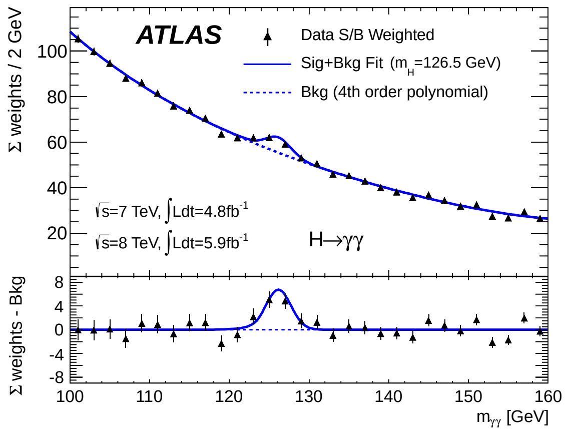
- SM very successful $\leftarrow$ precision data [LEP, Tevatron, LHC]

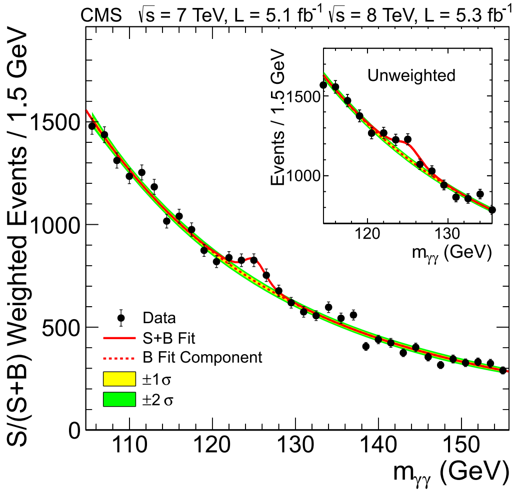
- open problems: – mechanism of electroweak symmetry breaking
  – unification of forces
  – space-time structure @ short distances

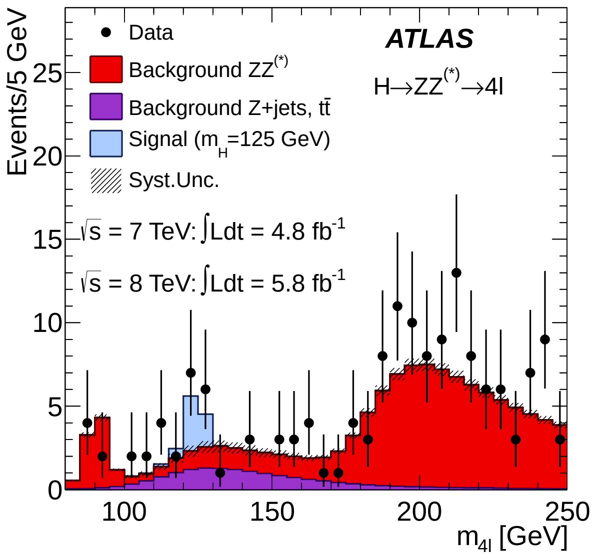
- LHC: fundamental discoveries: Higgs boson(s?)
  Supersymmetry ?
  Extra space dimensions ?

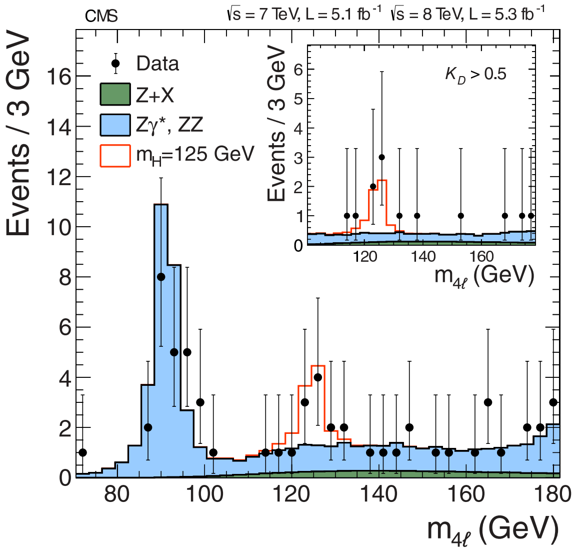
- electroweak symmetry breaking: two classes of realization:
  – standard Higgs mechanism [SM, SUSY,. . .]
  – strong elw. symmetry breaking [TC, LH, Higgsless, ED,. . .]

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

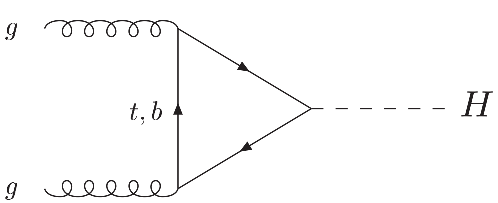


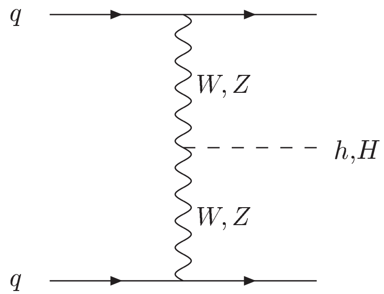


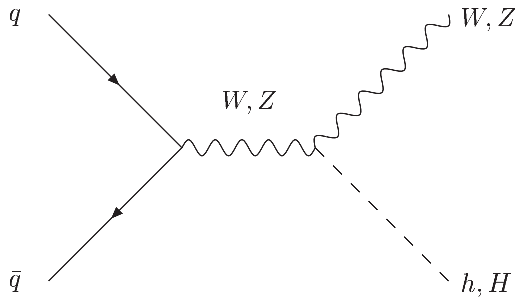


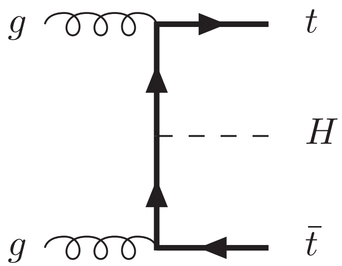


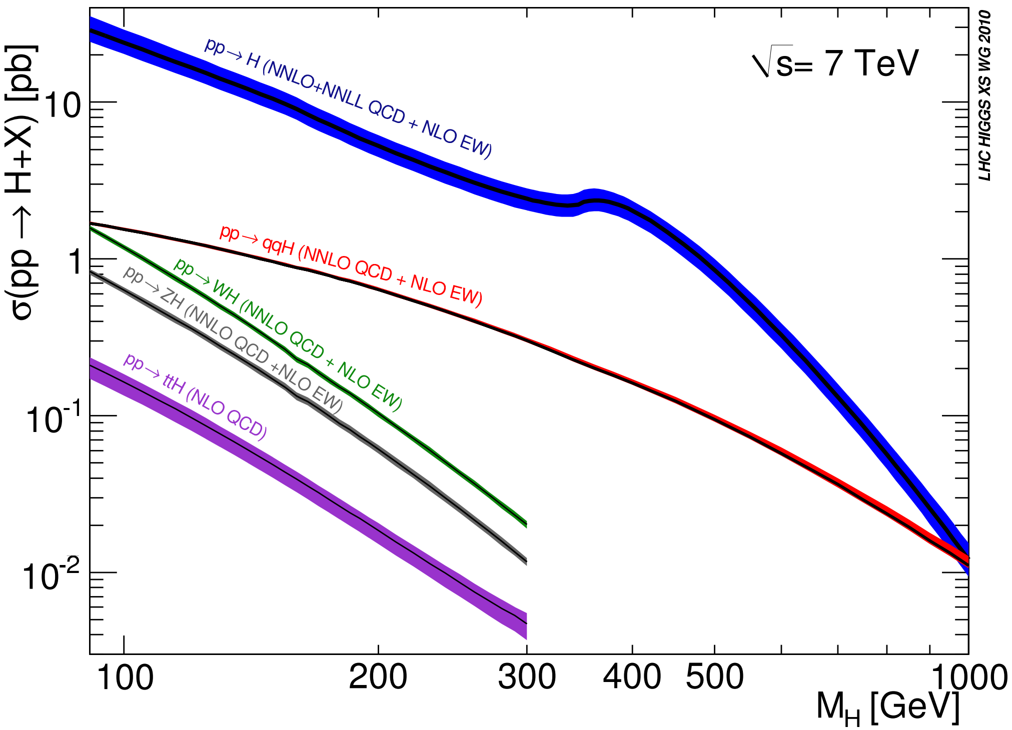
- Higgs Boson Production & Decay

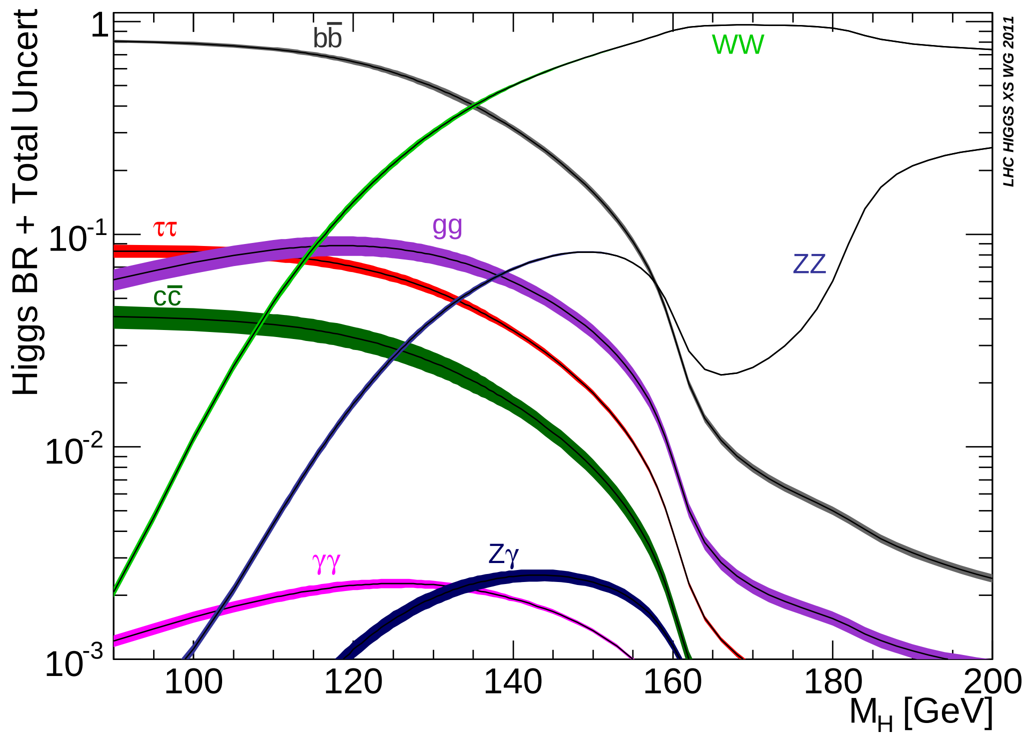






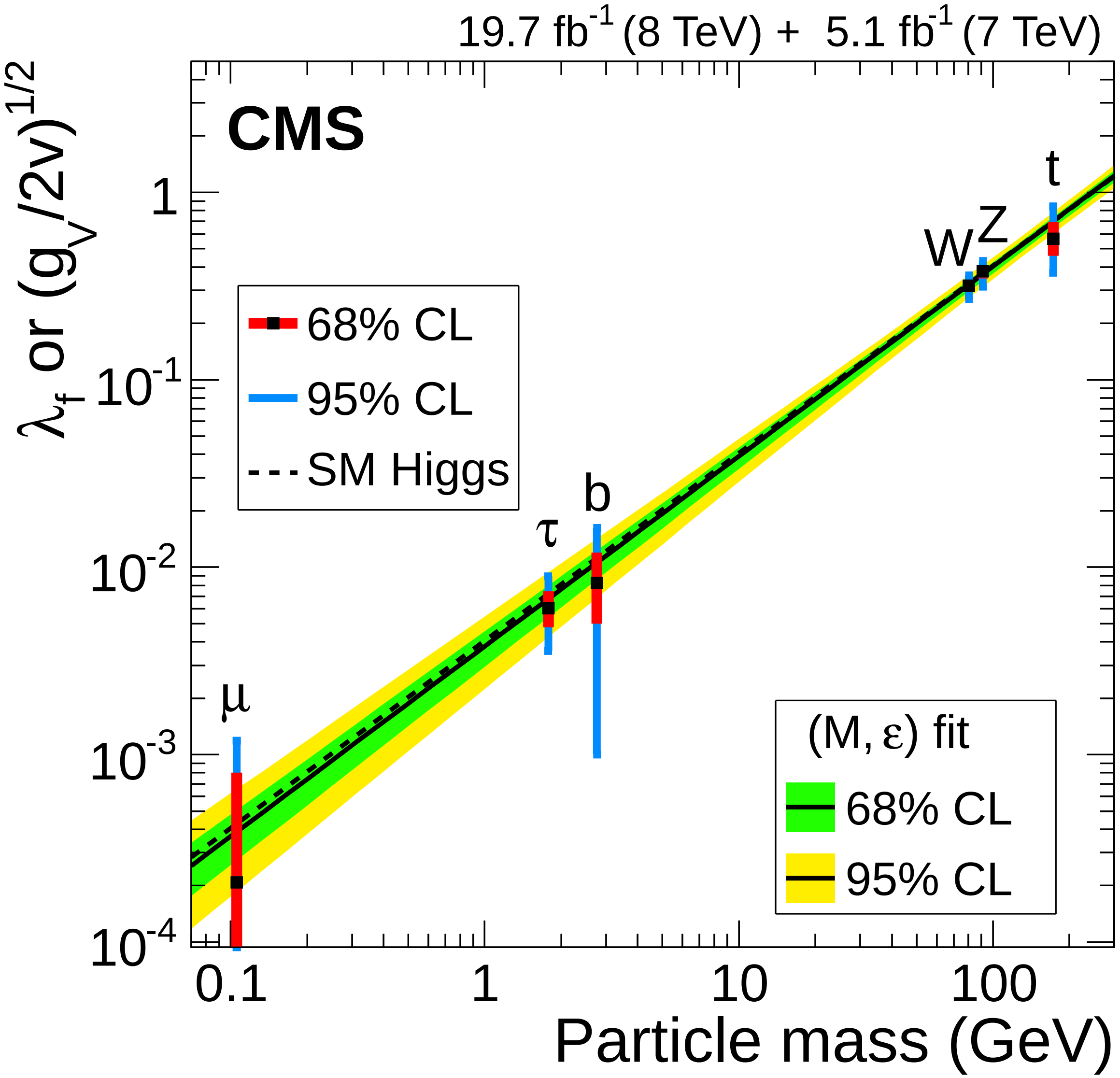






LHC Higgs XS WG

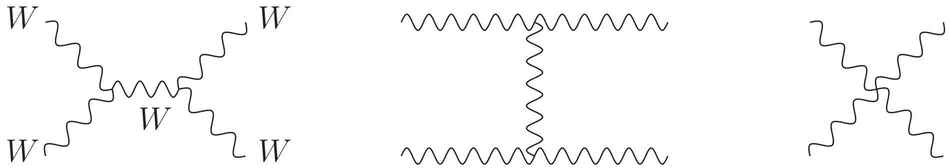
- Discovery: LHC [Tevatron]
  - → Higgs mass
  - couplings
  - spin
  - $\mathcal{CP}$
  - λ ?



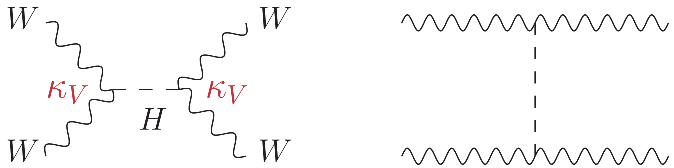
CMS

- $WW \to WW$ @ high energies

(a)



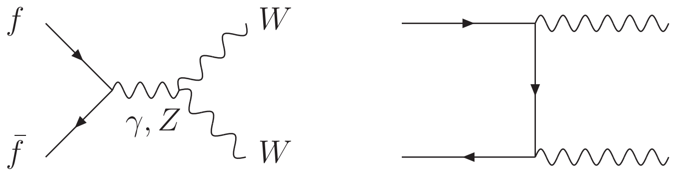
(b)



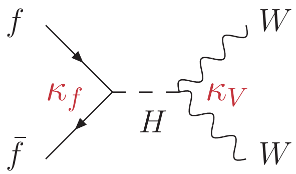
$$\mathcal{A} = \frac{s}{v^2}\left\{1 - \frac{\kappa_V^2 s}{s - M_H^2}\right\} \quad \Rightarrow \quad \kappa_V = 1$$

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

- modifications: (i) higher-dim. operators $\to$ eff. Lagrangians
  (ii) extended Higgs sectors (mixing, loop effects)

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

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\ \partial^\mu h - \frac{1}{2}m_h^2 h^2 - c_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 - \sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)}\psi^{(i)} \left(1 + c_\psi \frac{h}{v} + \dots\right)$$

$$+ m_W^2\, W_\mu W^\mu \left(1 + 2c_W \frac{h}{v} + \dots\right) + \frac{1}{2} m_Z^2\, Z_\mu Z^\mu \left(1 + 2c_Z \frac{h}{v} + \dots\right) + \dots$$

$$+ \left(c_{WW}\, W_{\mu\nu}^+ W^{-\mu\nu} + \frac{c_{ZZ}}{2}\, Z_{\mu\nu} Z^{\mu\nu} + c_{Z\gamma}\, Z_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{\gamma\gamma}}{2}\,\gamma_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{gg}}{2}\, G_{\mu\nu}^a G^{a\mu\nu}\right)\frac{h}{v}$$

$$+ \left(c_{W\partial W}\left(W_\nu^- D_\mu W^{+\mu\nu} + h.c.\right) + c_{Z\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + c_{Z\partial\gamma}\, Z_\nu \partial_\mu \gamma^{\mu\nu}\right)\frac{h}{v} + \dots$$

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

Contino, Ghezzi, Grojean, Mühlleitner, S.

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

- 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

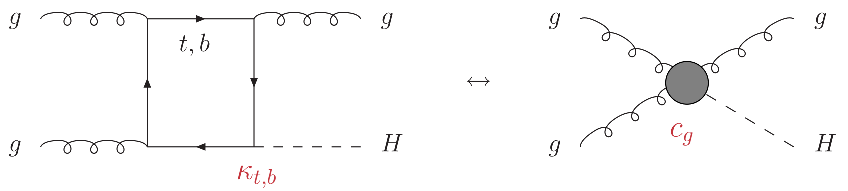
SILH: expansion in $v^2/f^2, E^2/M^2, \alpha_s/\pi, \alpha/\pi$

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

III *HIGGS OBSERVABLES*

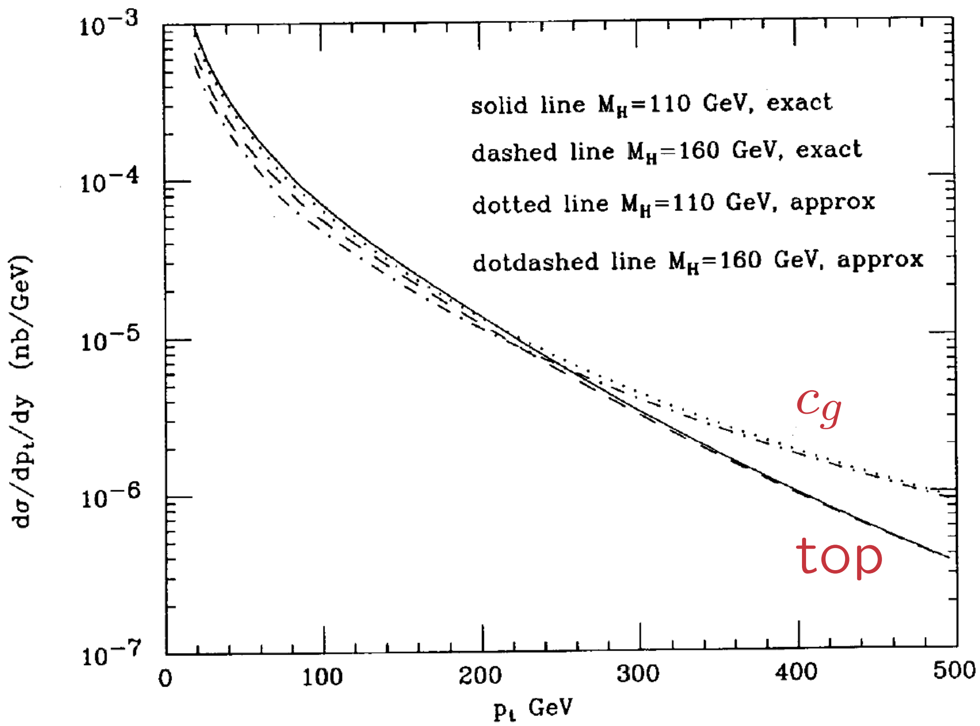
(i) Higgs p_T (or how to prove that ggF is loop-mediated)

$$\mathcal{L}_{eff} = \quad -\sum_{\psi=u,d,l} m_{\psi^{(i)}} \bar{\psi}^{(i)} \psi^{(i)} \left(1 + \kappa_\psi \frac{H}{v} + \dots\right) + \frac{\alpha_s}{\pi} c_g G^a_{\mu\nu} G^{a\mu\nu} \frac{H}{v} + \dots$$



- distinction dim4 $\leftrightarrow$ dim5: shape of p_T distribution (dim7 later)

Harlander, Neumann



$m_t = 160$ GeV

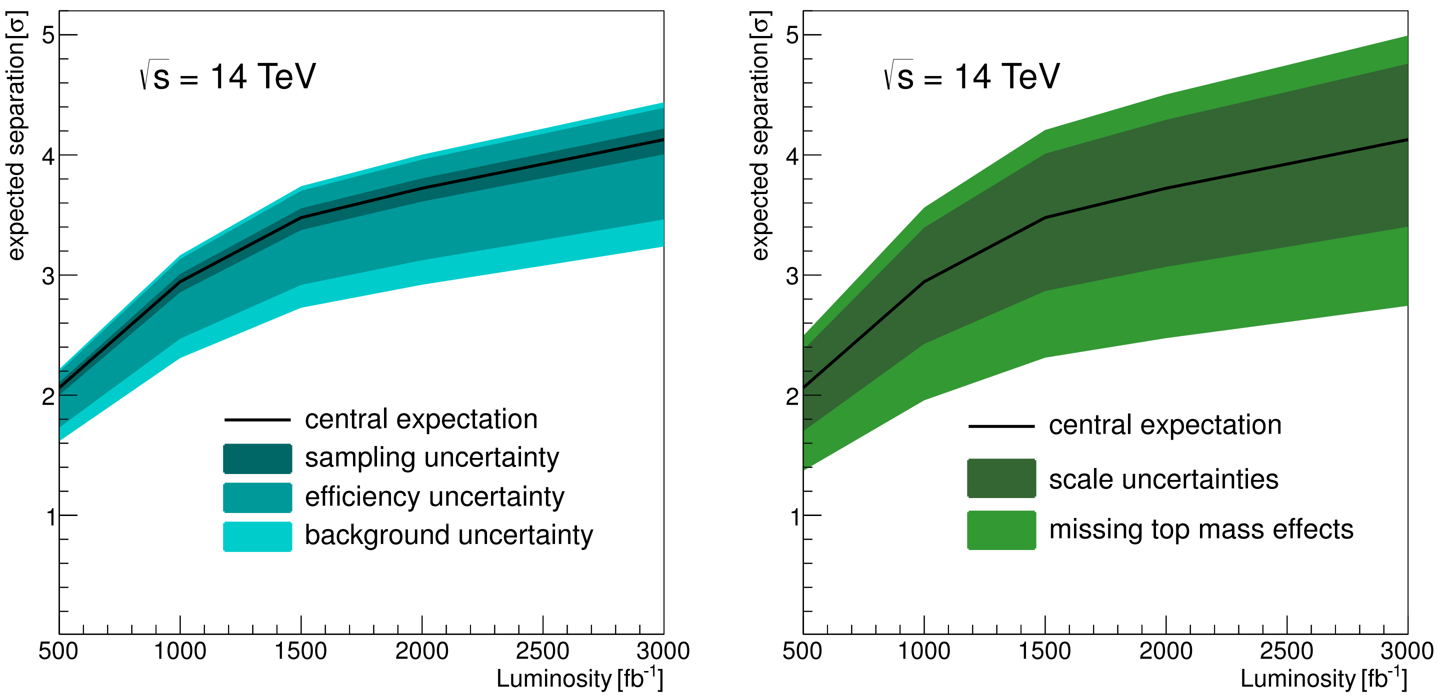
Ellis, Hinchliffe, Soldate, van der Bij (1987!)

- NLO, NNLO QCD corrections only known for $m_t \gg M_H, p_{TH}$

Glosser, Schmidt
de Florian, Grazzini, Kunszt
Anastasiou, Melnikov, Petriello
Boughezal, Caola, Melnikov, Petriello, Schulze
Chen, Gehrmann, Glover, Jaquier
Boughezal, Focke, Giele, Liu, Petriello

- heavy mass expansion known @ NLO Harlander, Neumann, Ozeren, Wiesemann

parametrization: $$\frac{\Delta x}{x} = \left(\frac{p_T - 40\text{GeV}}{100\text{GeV}}\right)^2 \times 1.5\% \qquad \left(x = \frac{d\sigma}{dp_T}\right)$$



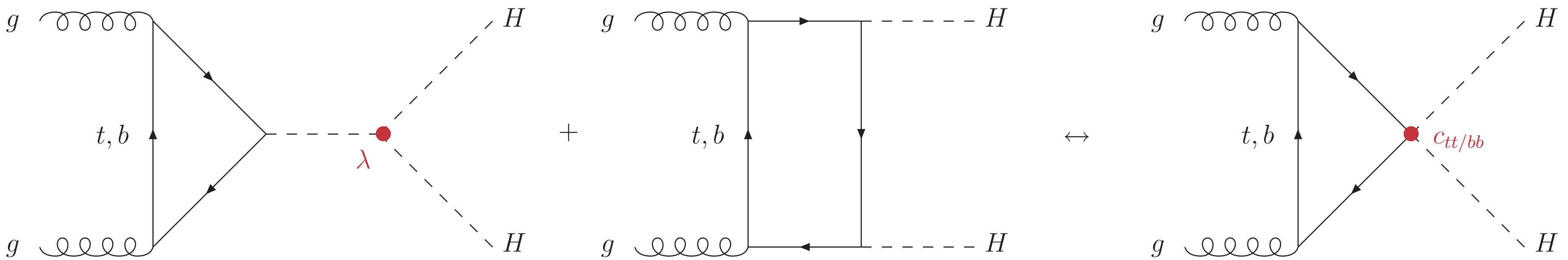
$pp \to H + j \to \gamma\gamma + j$

$\kappa_t \leftrightarrow c_g$

Langenegger, S., Strebel

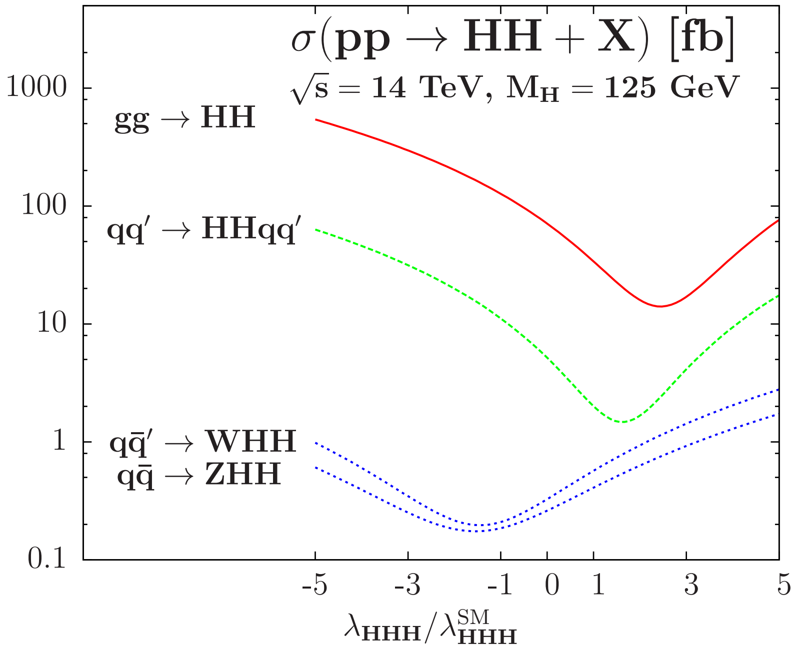
- large p_{TH}: elw. Sudakov logs $\sim \log^2 M_{W/Z}^2 / p_{TH}^2$

(ii) $gg \to HH$



- threshold region: sensitive to λ

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



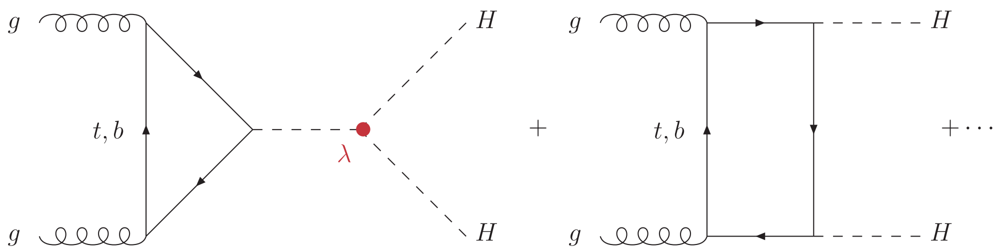
$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

[decreasing with M_{HH}^2]

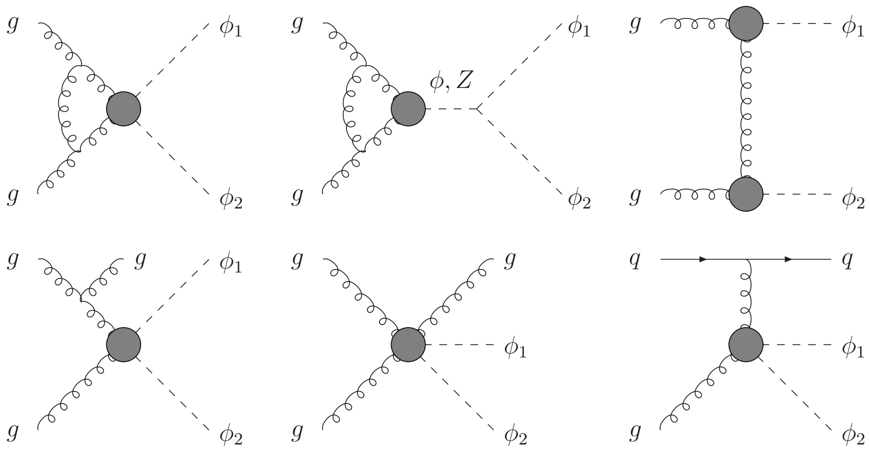
Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, S.

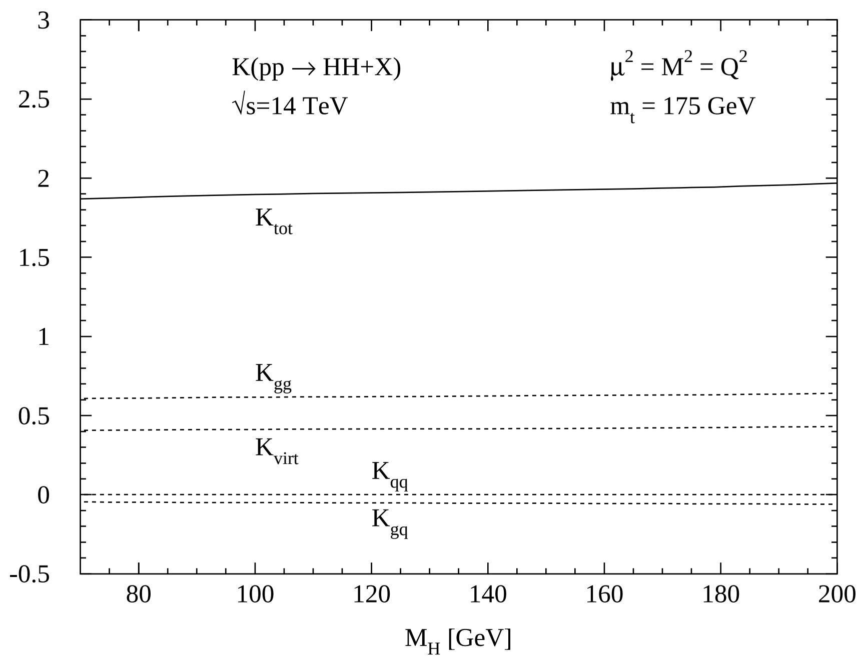
$gg \to HH$

SM



- third generation dominant $\to t, b$
- 2-loop QCD corrections: $\sim 90 - 100\%$
  $[M_H^2 \ll 4m_t^2, \qquad \mu = M_{HH}]$

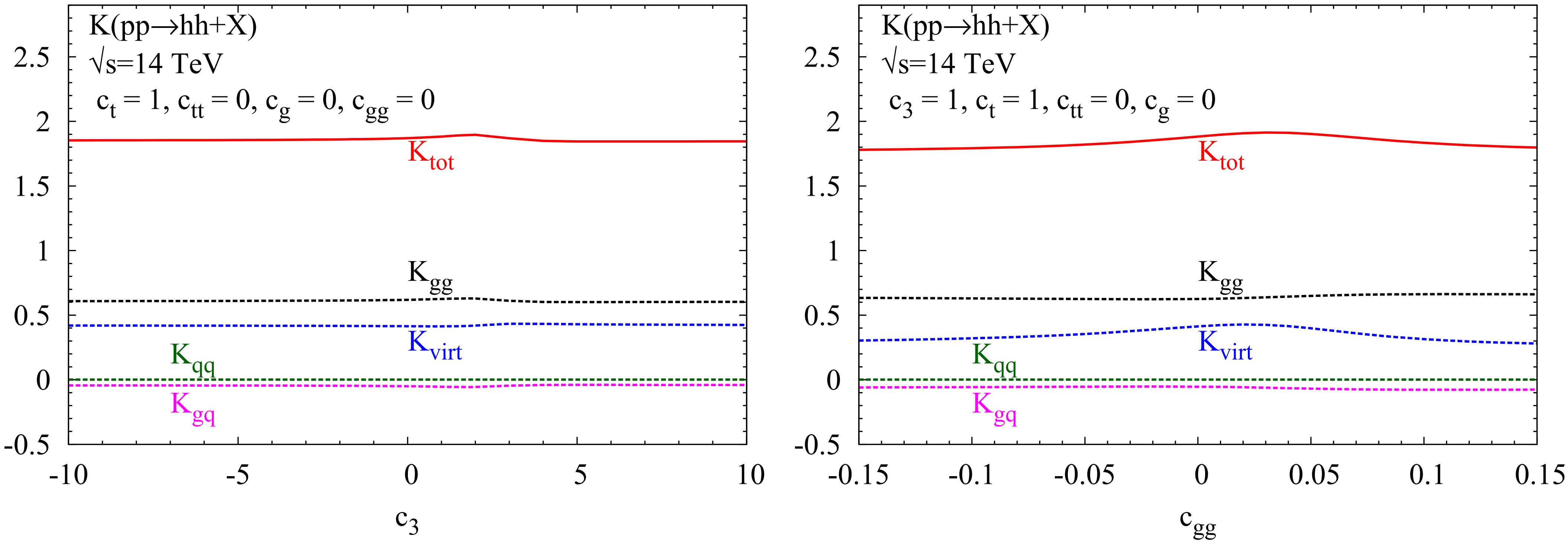




Dawson, Dittmaier, S.

- extended to dim6 → large impact on cxn
  small impact on K-factor

$$\mathcal{L}_{eff} = -m_t \bar{t}t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{2v^2} \right) - c_3 \frac{1}{6} \left(\frac{3M_h^2}{v} \right) h^3 + \frac{\alpha_s}{\pi} G^{a\,\mu\nu} G^a_{\mu\nu} \left(c_g \frac{h}{v} + c_{gg} \frac{h^2}{2v^2} \right)$$

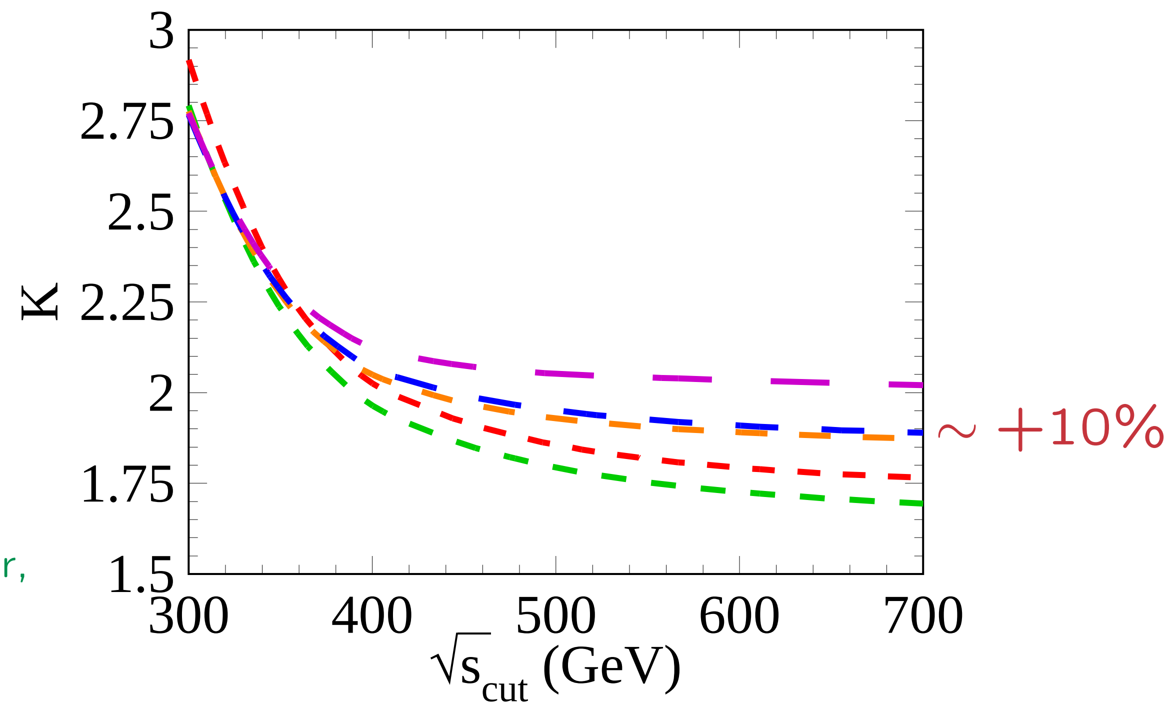


Gröber, Mühlleitner, S., Streicher

- 2-loop QCD corrections:

$$\sigma = \sigma_0 + \frac{\sigma_1}{m_t^2} + \cdots + \frac{\sigma_4}{m_t^8}$$

Grigo, Hoff, Melnikov, Steinhauser



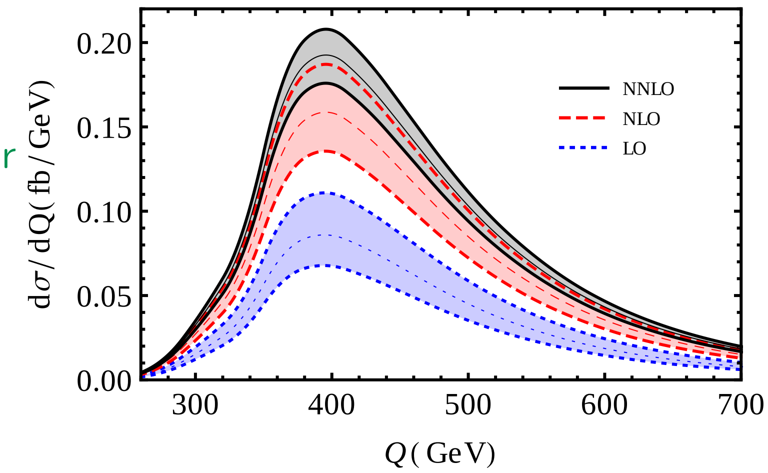
- NLO mass effects @ NLO in real corrections: $\sim -10\%$

  Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro

  → large virtual mass effects

- NNLO QCD corrections: $\sim 20\%$
  $[M_H^2 \ll 4m_t^2]$

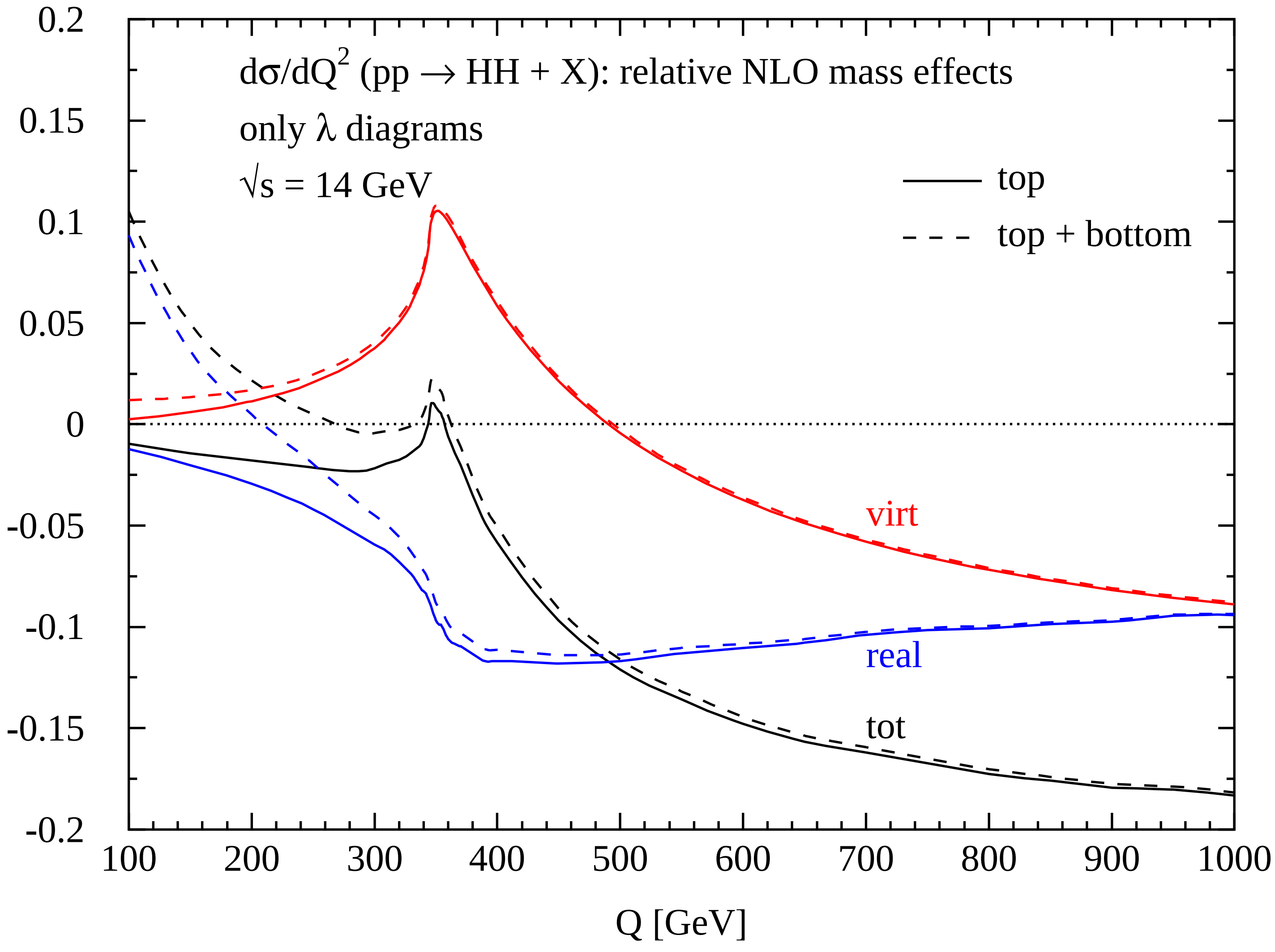
  de Florian, Mazzitelli
  Grigo, Melnikov, Steinhauser



- soft gluon resummation: $\sim 10\%$
  $[M_H^2 \ll 4m_t^2]$

Shao, Li, Li, Wang
de Florian, Mazzitelli

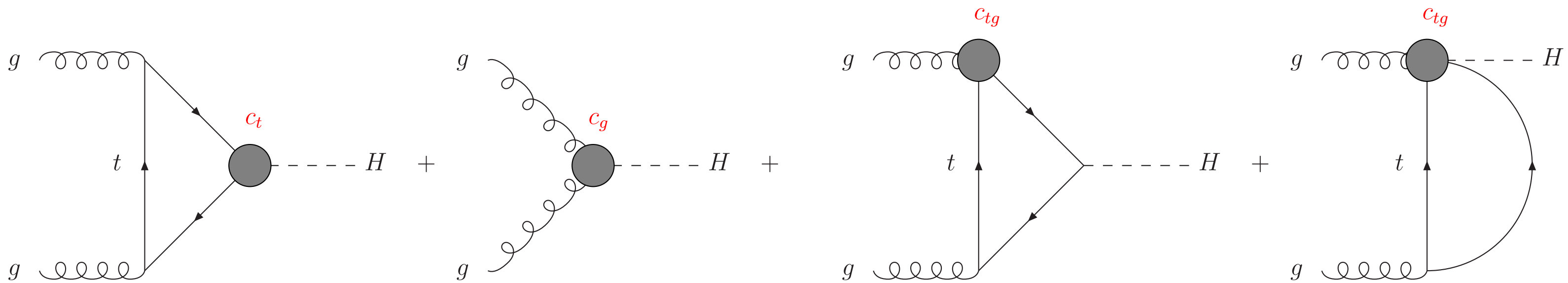
Diagrams with λ only:



- situation unclear $\leftarrow$ boxes different?

(iii) $gg \to H$

- chromomagnetic dipole operator



$$\mathcal{L}_{eff} = -c_t m_t \bar{t}t \frac{H}{v} + c_g \frac{g_s^2}{4\pi^2} G^{a\,\mu\nu} G^a_{\mu\nu} \frac{H}{v} + c_{tg} \frac{g_s m_t}{2v^3}(v+H) G^a_{\mu\nu} \left[\overline{t_L} \sigma^{\mu\nu} T^a t_R + h.c.\right]$$

$\to$ mixing of operators, renormalization @ 'LO':

$$\delta c_g = \frac{\alpha_t}{2\pi} \Re e(c_{tg}) \Gamma(1+\epsilon) \left(\frac{4\pi\mu^2}{\mu_R^2}\right)^{\epsilon} \frac{1}{\epsilon} \qquad \left(\alpha_t = \frac{y_t^2}{4\pi} = \frac{m_t^2}{2\pi v^2}\right)$$

Degrande, Gérard, Grojean, Maltoni, Servant

- c_g renormalized @ NNLO QCD ($\to$ HIGLU)

V *CONCLUSIONS*

• sensitivity of Higgs observables to dim 6 operators requires higher orders for SM and dim6 part

• several crucial higher orders are missing: e.g. top mass effects @ NLO in Higgs p_T, Higgs pair production

• large $M_{HH}, p_{TH}, \ldots$: elw. Sudakov logs [$\leftarrow$ Higgsstrahlung, VBF]

• important impact on single and double Higgs production modes

BACKUP SLIDES