

# *EFT@NLO (QCD)*

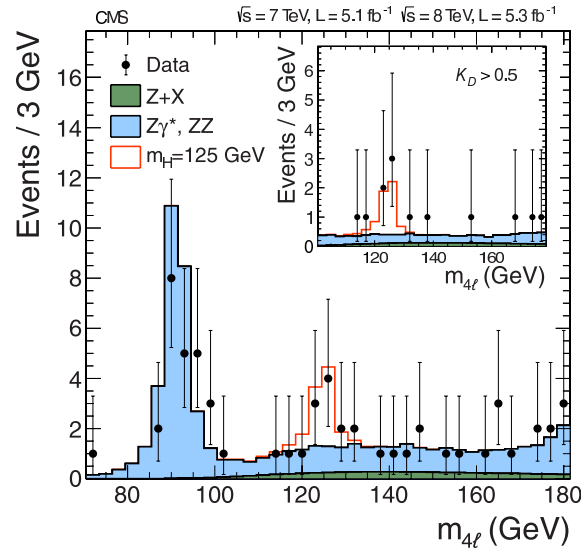
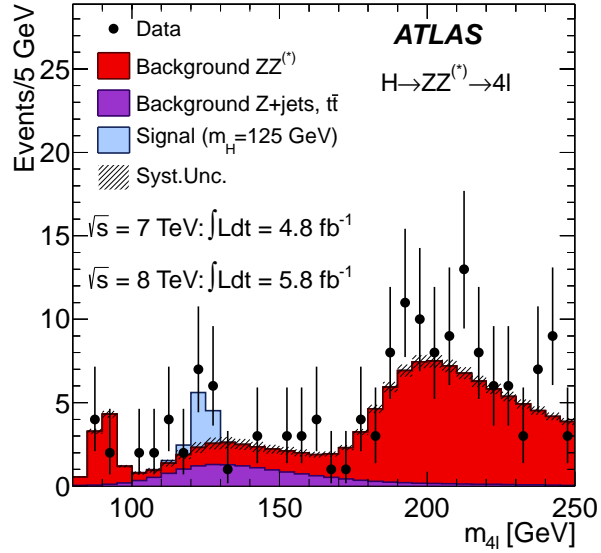
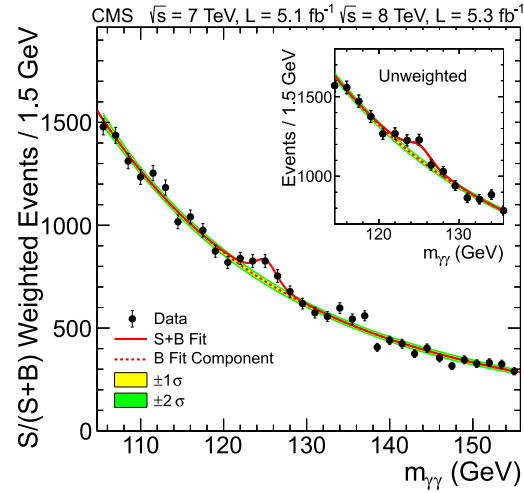
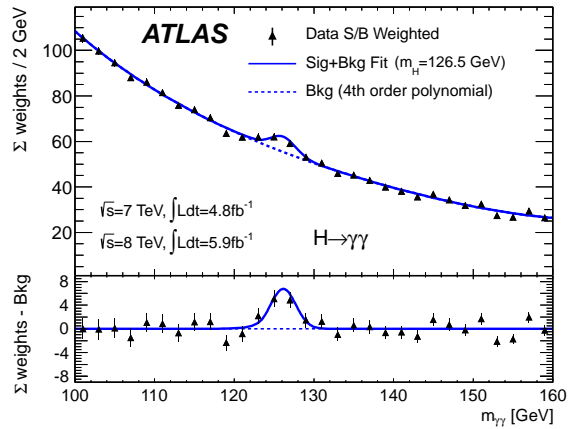
Michael Spira (PSI)

- I Introduction
- II Effective Lagrangians
- III Higgs Observables
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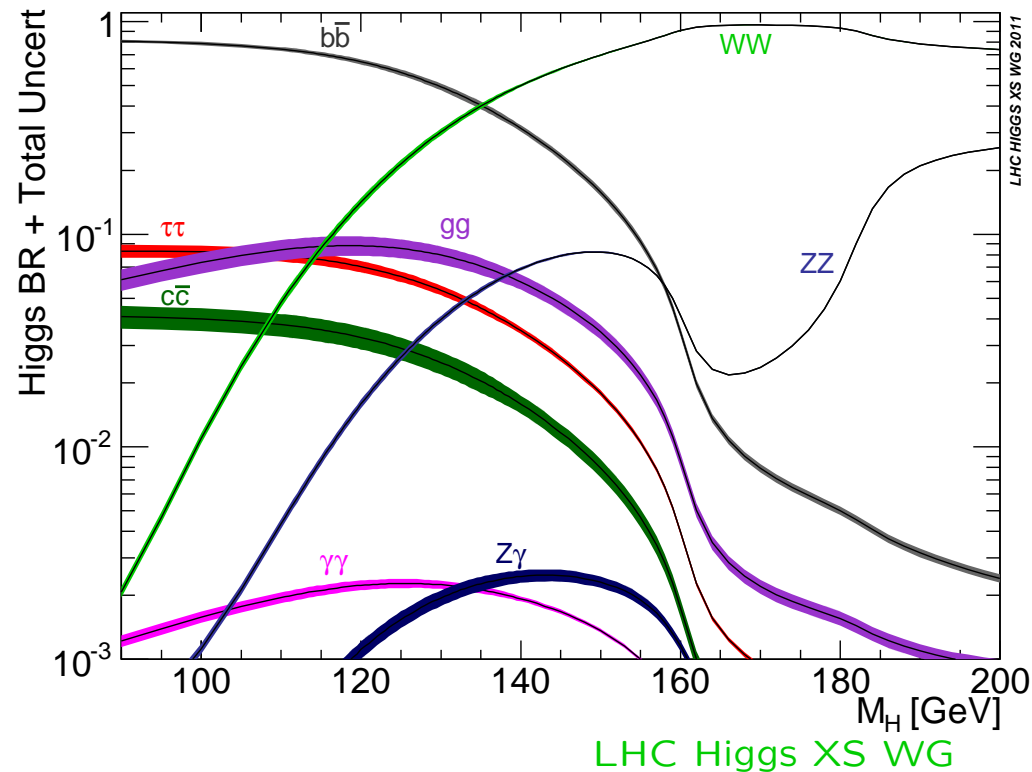
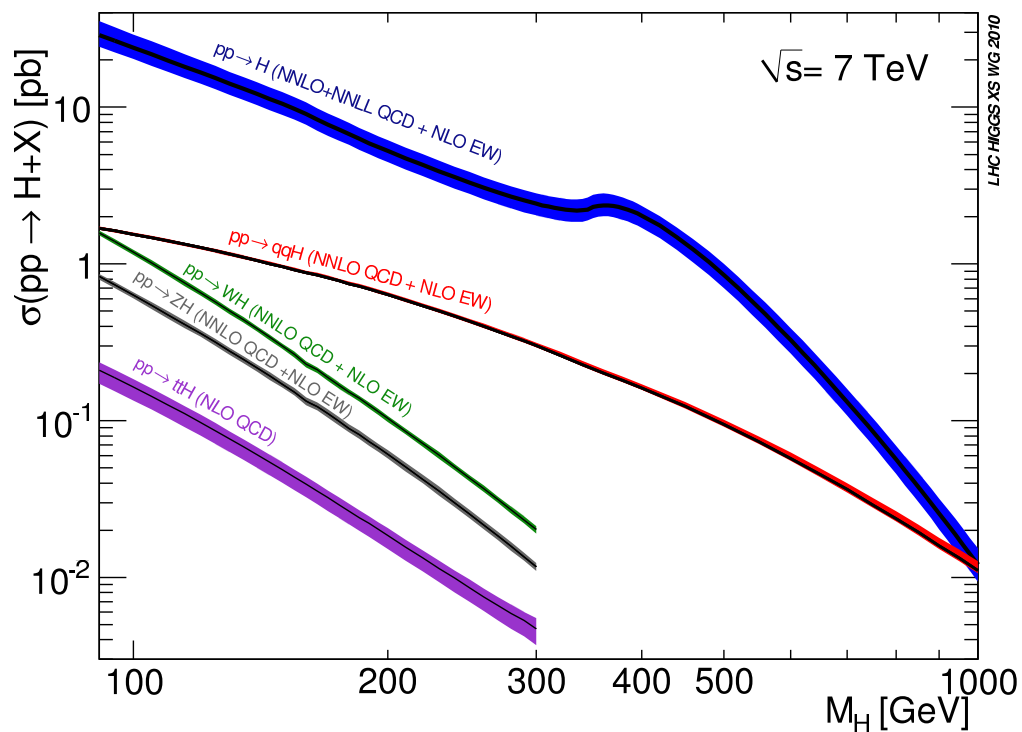
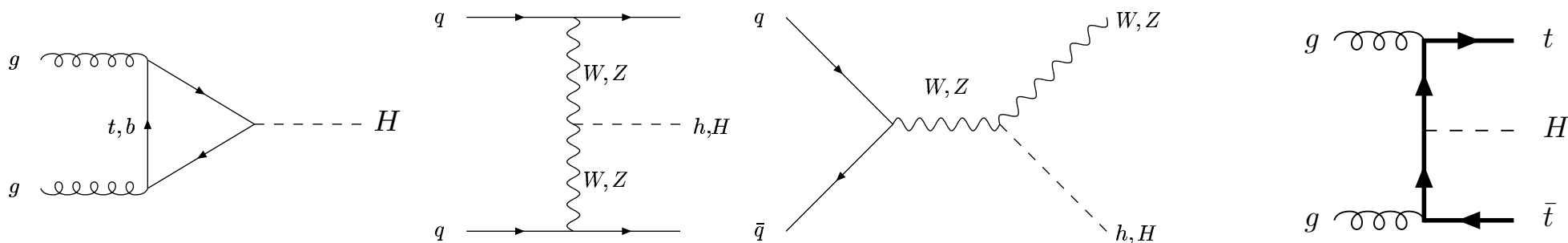
# I INTRODUCTION

- SM very successful ← 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
- $gg \rightarrow H$  dominant

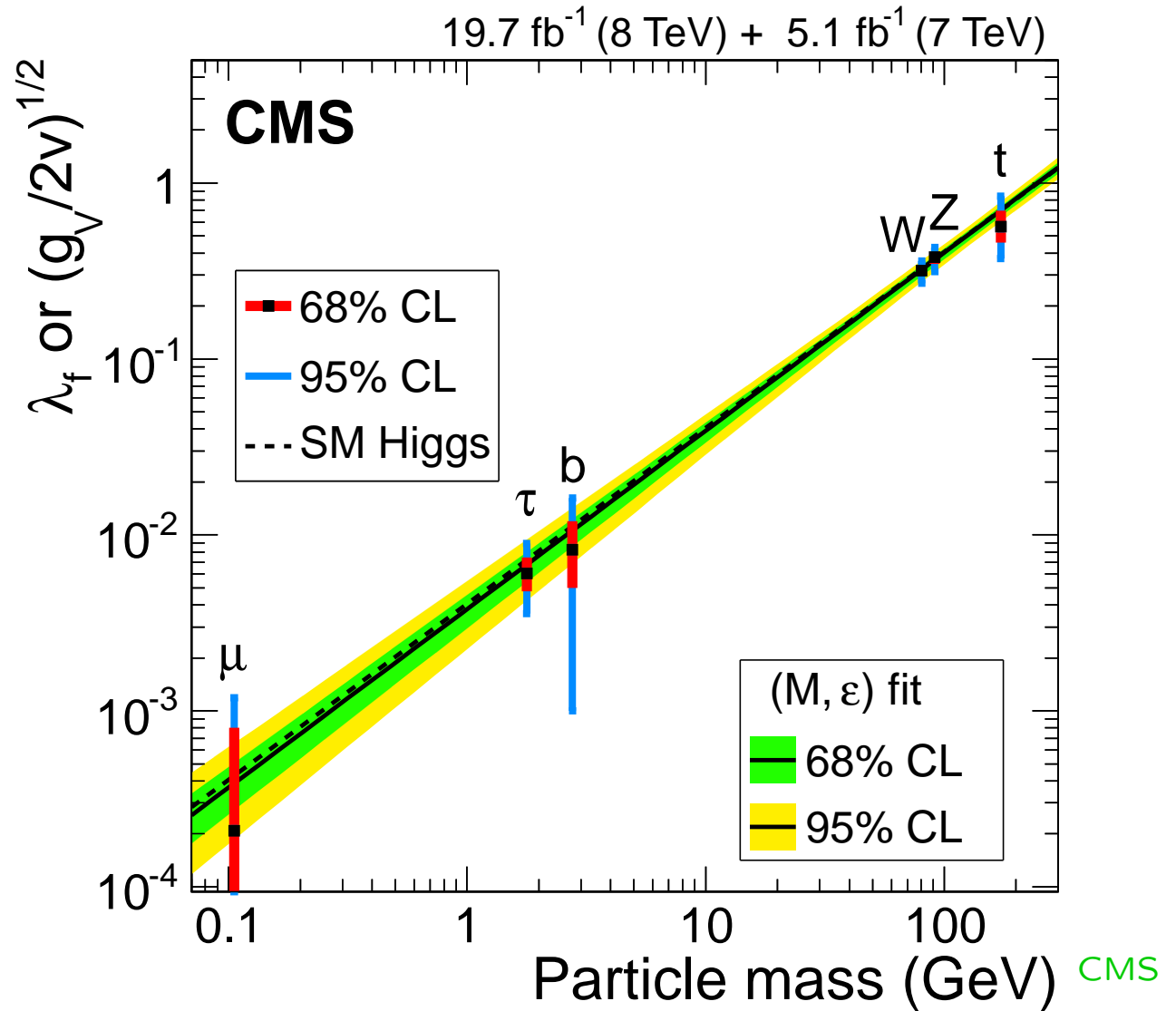


# ● Higgs Boson Production & Decay



- Discovery: LHC [Tevatron]

- Higgs mass
- couplings
- spin
- $CP$
- $\lambda ?$



- modifications: (i) higher-dim. operators → 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

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

[assume  $\Lambda$  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 (H^\dagger H) \partial_\mu (H^\dagger H) + \frac{\bar{c}_T}{2v^2} \left( H^\dagger \overleftrightarrow{D}^\mu H \right) \left( H^\dagger \overleftrightarrow{D}_\mu H \right) - \frac{\bar{c}_6 \lambda}{v^2} (H^\dagger H)^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_{\mu\nu}^i + \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_{\mu\nu}^a G^{a\mu\nu} \\
\Delta\mathcal{L}_{F_1} &= \frac{i\bar{c}_{Hq}}{v^2} (\bar{q}_L \gamma^\mu q_L) \left( H^\dagger \overleftrightarrow{D}_\mu H \right) + \frac{i\bar{c}'_{Hq}}{v^2} (\bar{q}_L \gamma^\mu \sigma^i q_L) \left( H^\dagger \sigma^i \overleftrightarrow{D}_\mu H \right) \\
&+ \frac{i\bar{c}_{Hu}}{v^2} (\bar{u}_R \gamma^\mu u_R) \left( H^\dagger \overleftrightarrow{D}_\mu H \right) + \frac{i\bar{c}_{Hd}}{v^2} (\bar{d}_R \gamma^\mu d_R) \left( H^\dagger \overleftrightarrow{D}_\mu H \right) \\
&+ \left( \frac{i\bar{c}_{Hud}}{v^2} (\bar{u}_R \gamma^\mu d_R) \left( H^{c\dagger} \overleftrightarrow{D}_\mu H \right) + h.c. \right) \\
&+ \frac{i\bar{c}_{HL}}{v^2} (\bar{L}_L \gamma^\mu L_L) \left( H^\dagger \overleftrightarrow{D}_\mu H \right) + \frac{i\bar{c}'_{HL}}{v^2} (\bar{L}_L \gamma^\mu \sigma^i L_L) \left( H^\dagger \sigma^i \overleftrightarrow{D}_\mu H \right) \\
&+ \frac{i\bar{c}_{Hl}}{v^2} (\bar{l}_R \gamma^\mu l_R) \left( H^\dagger \overleftrightarrow{D}_\mu H \right) \\
\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_{\mu\nu}^i + \frac{\bar{c}_{uG} g_S}{m_W^2} y_u \bar{q}_L H^c \sigma^{\mu\nu} \lambda^a u_R G_{\mu\nu}^a \\
&+ \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_{\mu\nu}^i + \frac{\bar{c}_{dG} g_S}{m_W^2} y_d \bar{q}_L H \sigma^{\mu\nu} \lambda^a d_R G_{\mu\nu}^a \\
&+ \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_{\mu\nu}^i + 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



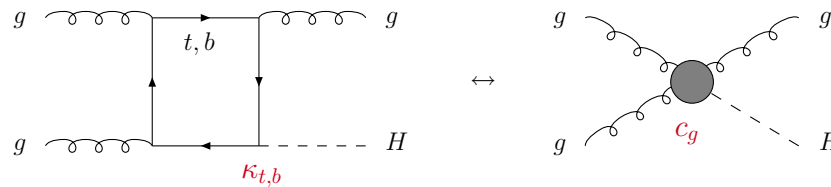
$$\begin{aligned}
\mathcal{L} = & \frac{1}{2} \partial_\mu h \partial^\mu h - \frac{1}{2} m_h^2 h^2 - c_3 \frac{1}{6} \left( \frac{3m_h^2}{v} \right) h^3 - \sum_{\psi=u,d,l} m_{\psi^{(i)}} \bar{\psi}^{(i)} \psi^{(i)} \left( 1 + c_\psi \frac{h}{v} + \dots \right) \\
& + m_W^2 W_\mu W^\mu \left( 1 + 2c_W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

| Higgs couplings               | $\Delta\mathcal{L}_{SILH}$   | MCHM4            | MCHM5                             |
|-------------------------------|--|------------------|-----------------------------------|
| $c_W$                         | $1 - \bar{c}_H/2$  | $\sqrt{1 - \xi}$ | $\sqrt{1 - \xi}$                  |
| $c_Z$                         | $1 - \bar{c}_H/2 - 2\bar{c}_T$   | $\sqrt{1 - \xi}$ | $\sqrt{1 - \xi}$                  |
| $c_\psi$ ( $\psi = u, d, l$ ) | $1 - (\bar{c}_H/2 + \bar{c}_\psi)$   | $\sqrt{1 - \xi}$ | $\frac{1 - 2\xi}{\sqrt{1 - \xi}}$ |
| $c_3$                         | $1 + \bar{c}_6 - 3\bar{c}_H/2$   | $\sqrt{1 - \xi}$ | $\frac{1 - 2\xi}{\sqrt{1 - \xi}}$ |
| $c_{gg}$                      | $8(\alpha_s/\alpha_2) \bar{c}_g$   | 0                | 0                                 |
| $c_{\gamma\gamma}$            | $8 \sin^2 \theta_W \bar{c}_\gamma$   | 0                | 0                                 |
| $c_{Z\gamma}$                 | $(\bar{c}_{HB} - \bar{c}_{HW} - 8 \bar{c}_\gamma \sin^2 \theta_W) \tan \theta_W$                     | 0                | 0                                 |
| $c_{WW}$                      | $-2 \bar{c}_{HW}$  | 0                | 0                                 |
| $c_{ZZ}$                      | $-2(\bar{c}_{HW} + \bar{c}_{HB} \tan^2 \theta_W - 4 \bar{c}_\gamma \tan^2 \theta_W \sin^2 \theta_W)$ | 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                                 |

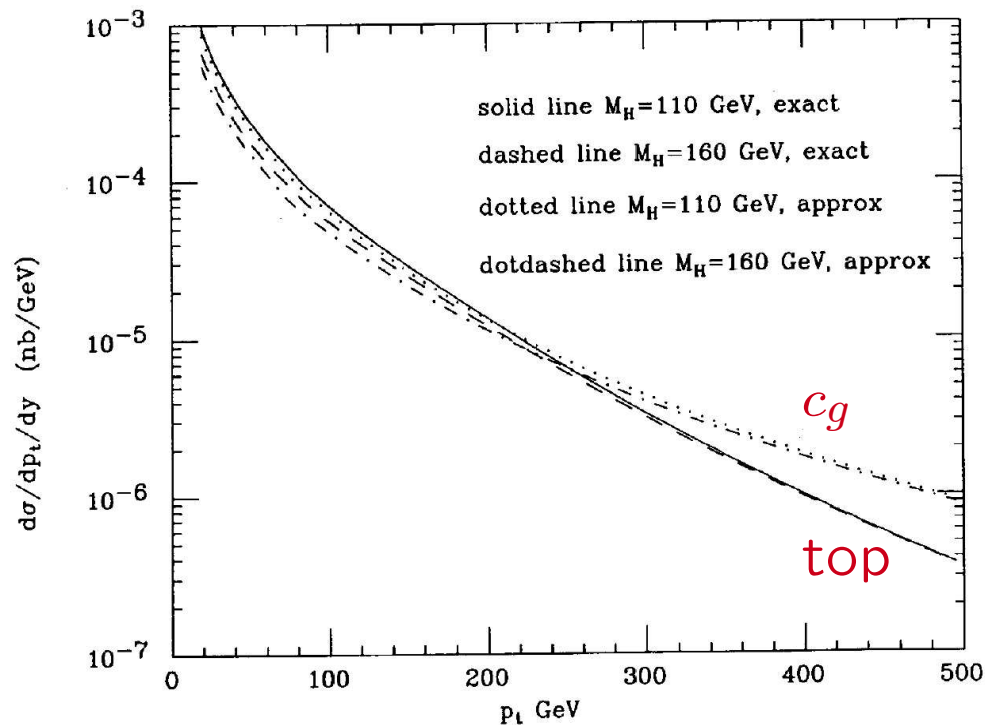
# III HIGGS OBSERVABLES

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

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



- distinction dim4  $\leftrightarrow$  dim5: shape of  $p_T$  distribution

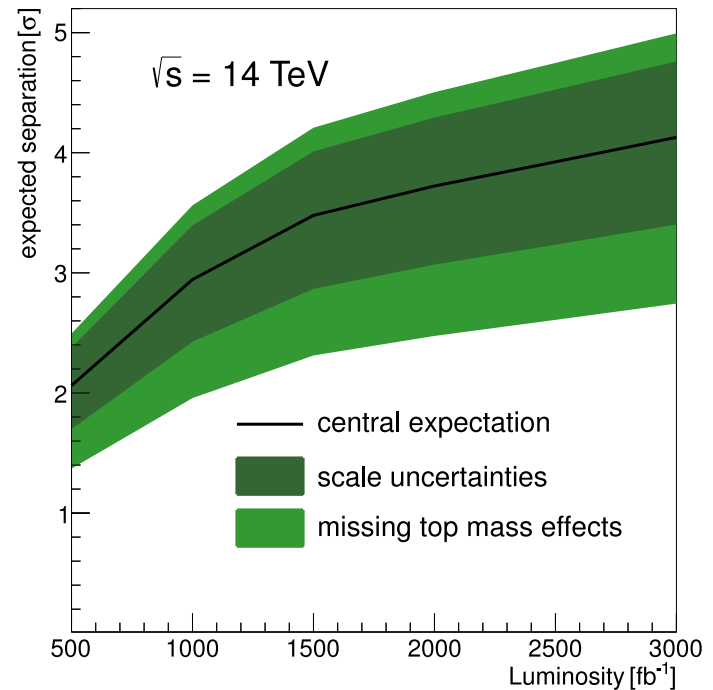
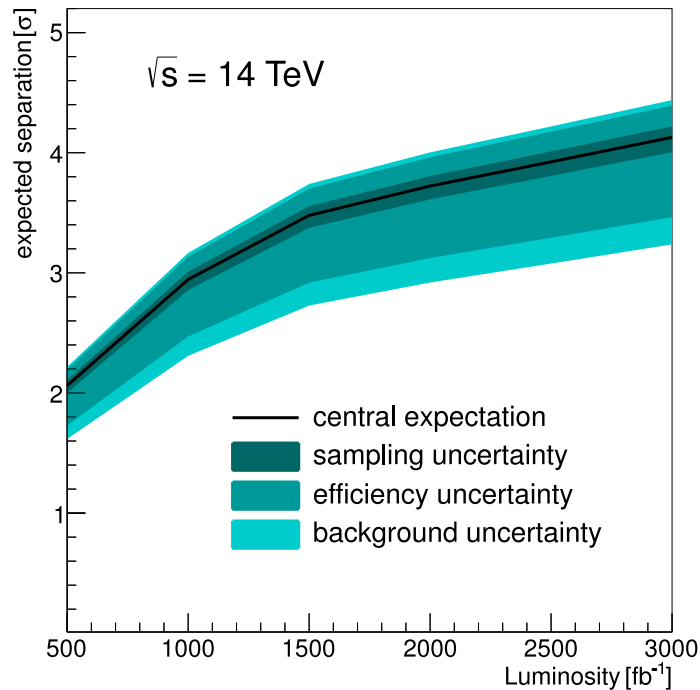


$$m_t = 160 \text{ GeV}$$

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

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

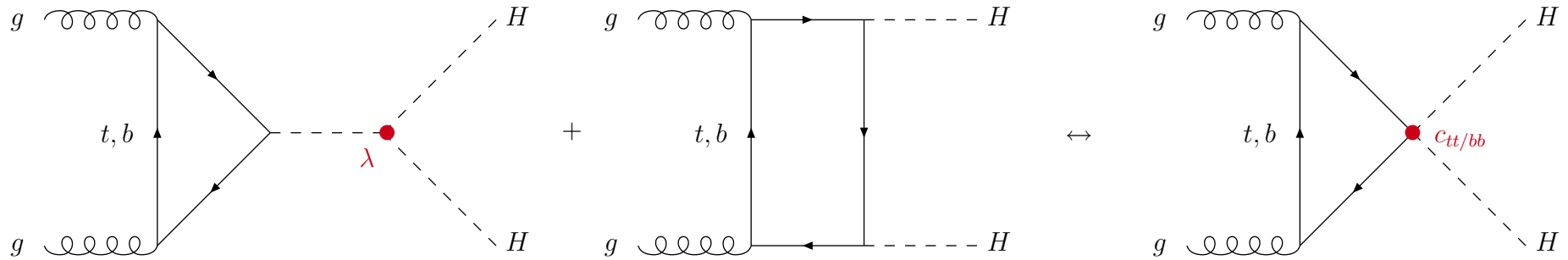
Glosser, Schmidt  
 de Florian, Grazzini, Kunszt  
 Anastasiou, Melnikov, Petriello  
 Boughezal, Caola, Melnikov, Petriello, Schulze  
 Chen, Gehrmann, Glover, Jaquier  
 Boughezal, Focke, Giele, Liu, Petriello  
 Harlander, Neumann, Ozeren, Wiesemann



Langenegger, S., Strebel

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

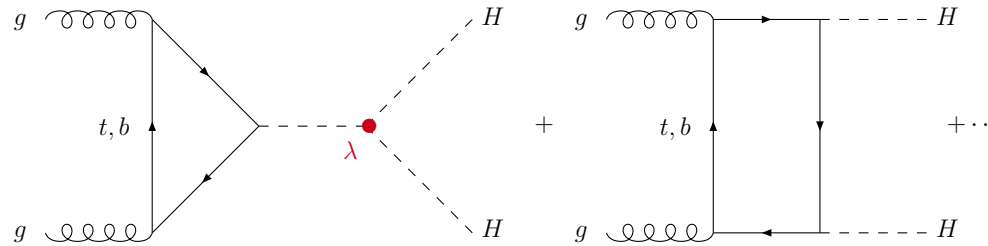
(ii) anomalous Higgs couplings [e.g. composite Higgs]



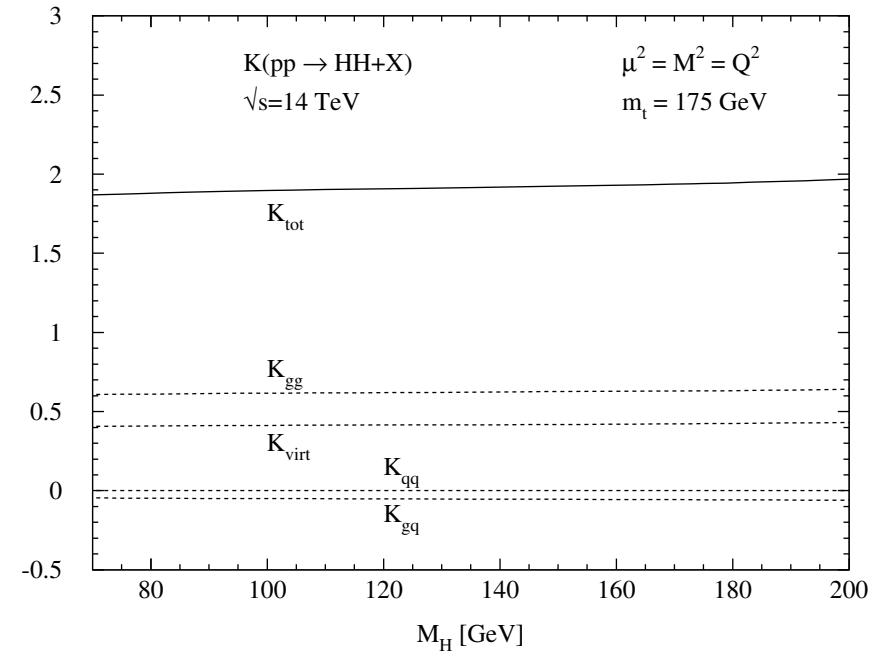
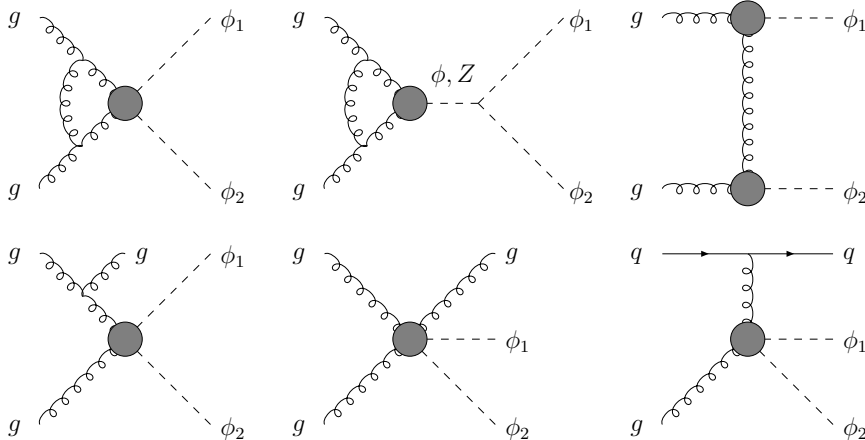
- threshold region: sensitive to  $\lambda$
- large  $M_{HH}$ : sensitive to  $c_{tt/bb}$  [e.g. boosted Higgs pairs]

$gg \rightarrow HH$

SM



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



Dawson, Dittmaier, S.

- extended to dim6  $\rightarrow$  small impact on K-factor

Gröber, Mühlleitner, S., Streicher

- 2-loop QCD corrections:

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

Grigo, Hoff, Melnikov, Steinhauser

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

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

→ clash of results

- NNLO QCD corrections:  $\sim 20\%$

$$[M_H^2 \ll 4m_t^2]$$

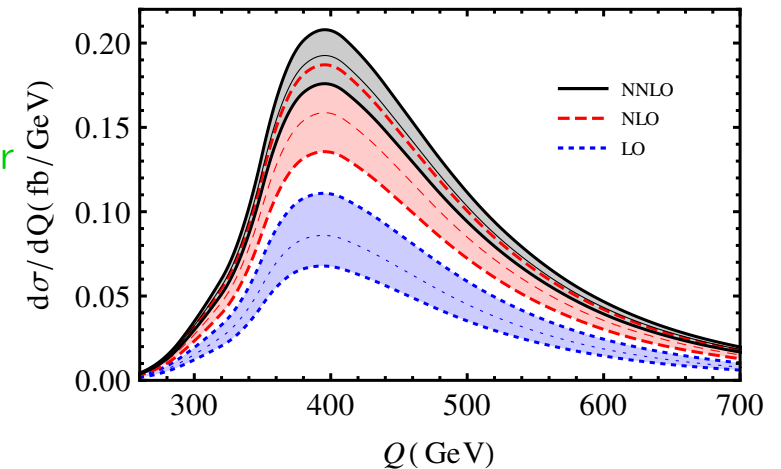
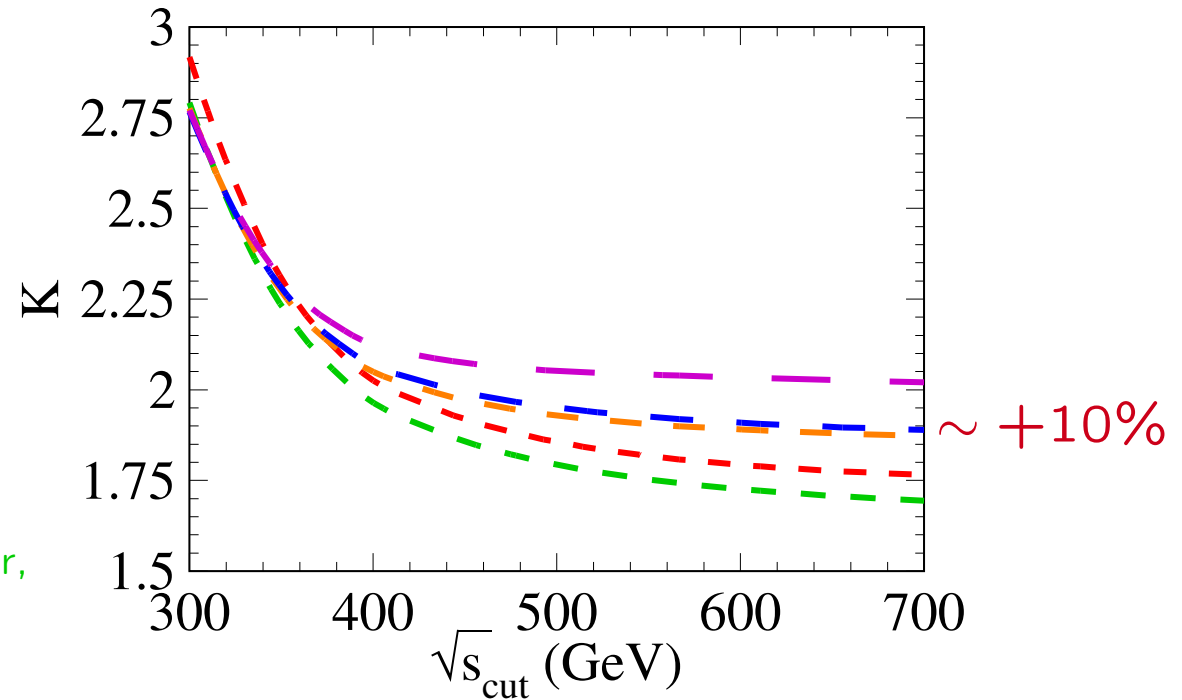
de Florian, Mazzitelli

Grigo, Melnikov, Steinhauser

- soft gluon resummation [SCET]:  $\sim 30\%$

$$[M_H^2 \ll 4m_t^2]$$

Shao, Li, Li, Wang



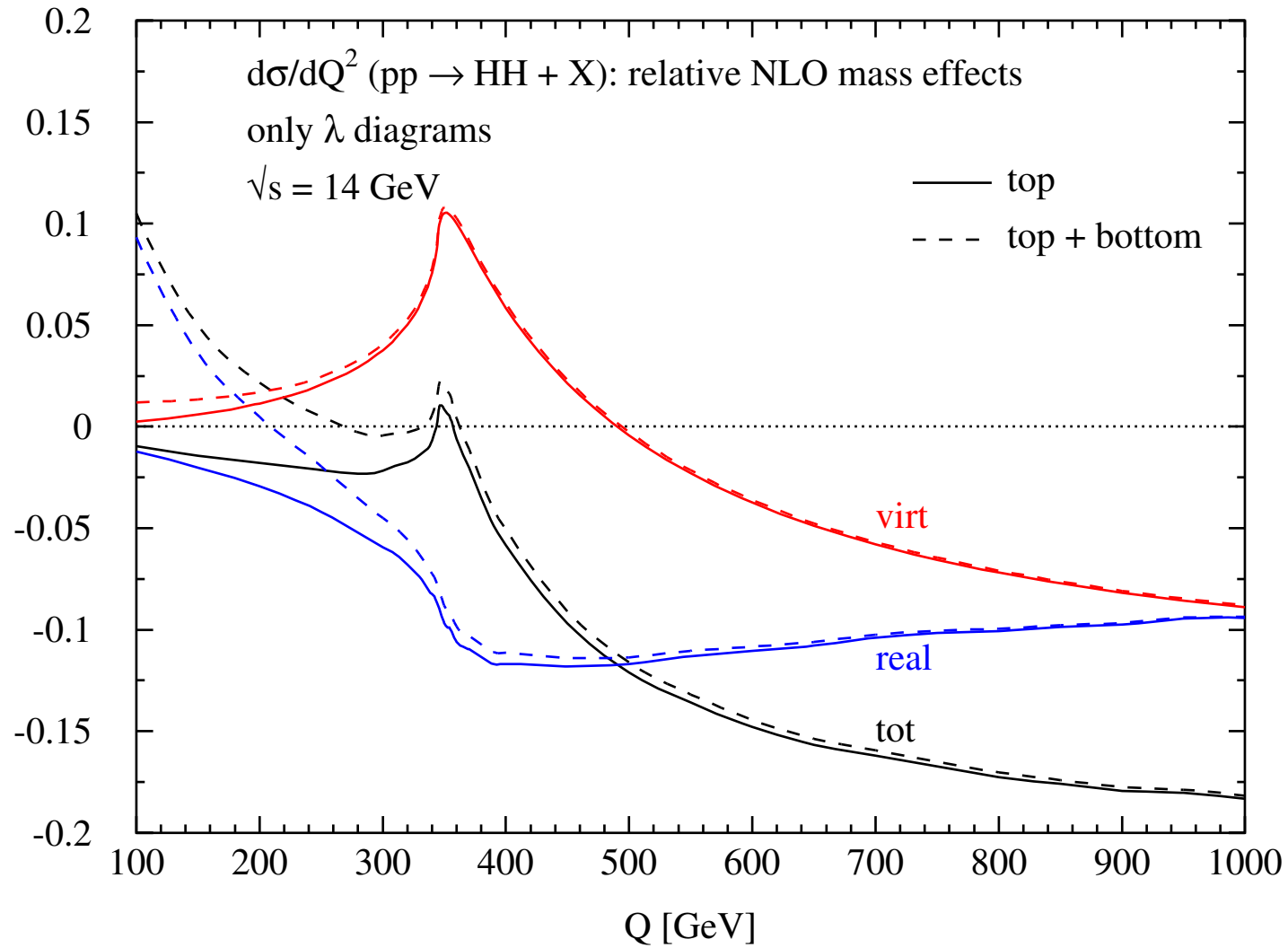
## V CONCLUSIONS

- 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  $M_{HH}, p_{TH}, \dots$ : elw. Sudakov logs [ $\leftarrow$  Higgsstrahlung, VBF]
- important impact on single and double Higgs production modes

*BACKUP SLIDES*



# Diagrams with $\lambda$ only:



- situation unclear ← boxes different?

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

- 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  $E^2/M^2, \alpha_s/\pi$