

SM HIGGS CROSS SECTIONS AND PRECISION MEASUREMENTS

Michael Spira (PSI)

- I Introduction
- II Higgs Boson Decays
- III Higgs Boson Production
- IV Conclusions

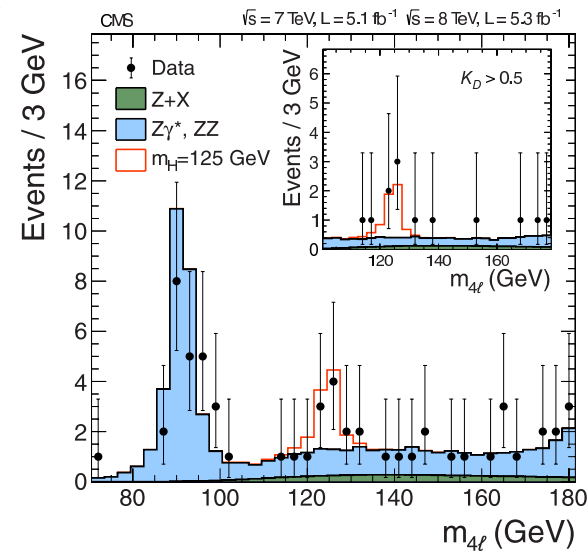
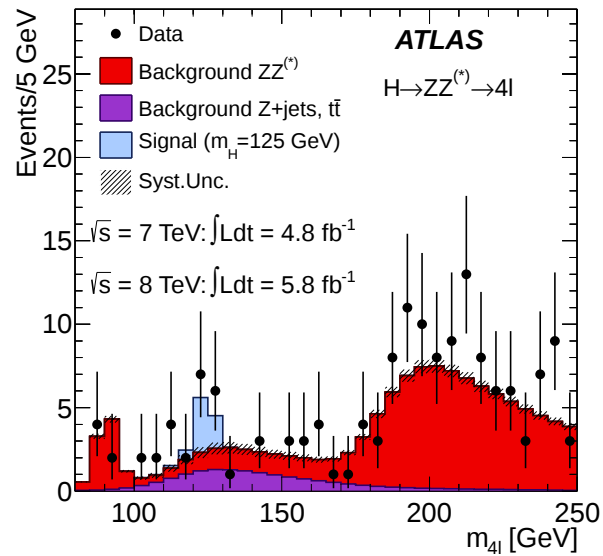
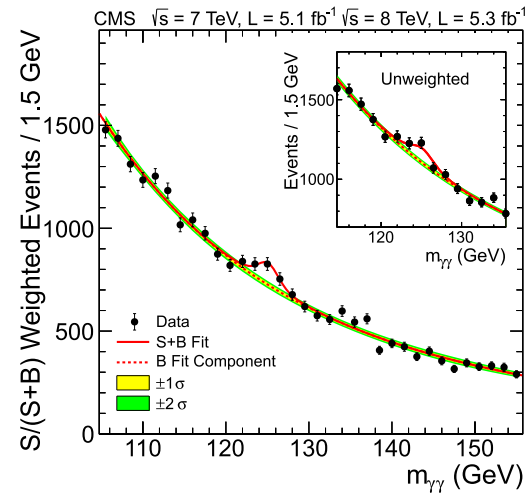
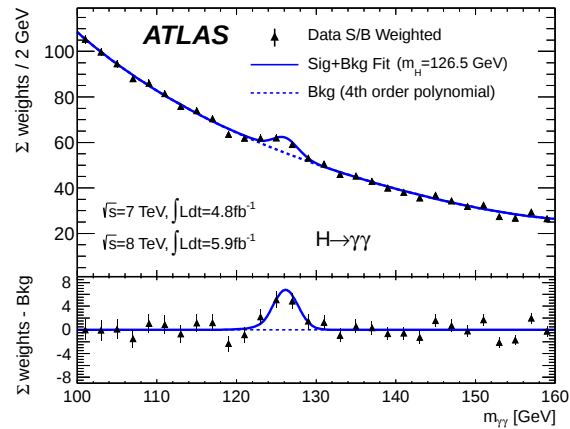
I INTRODUCTION

- 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, . . .]

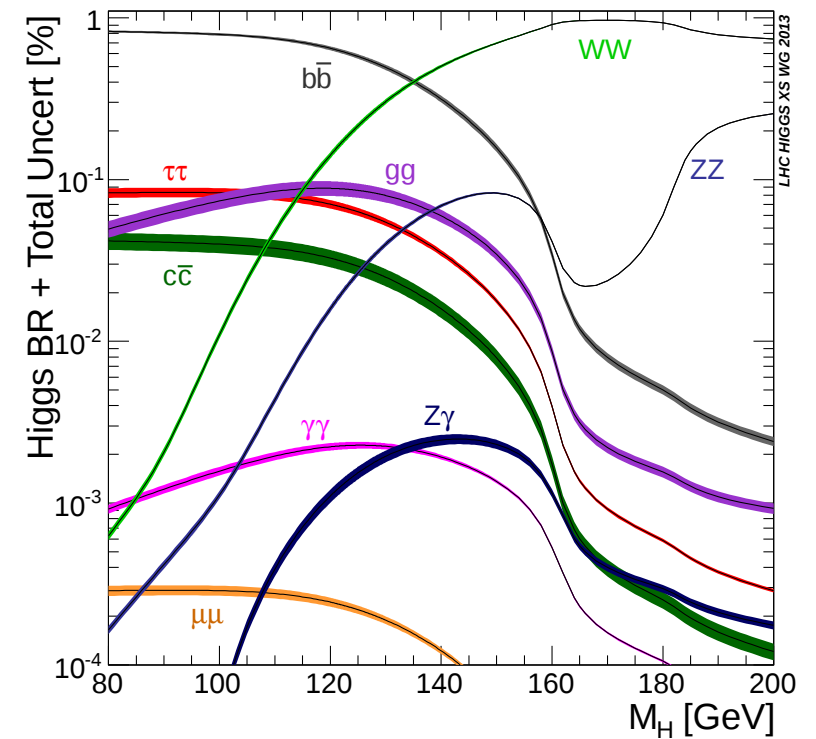
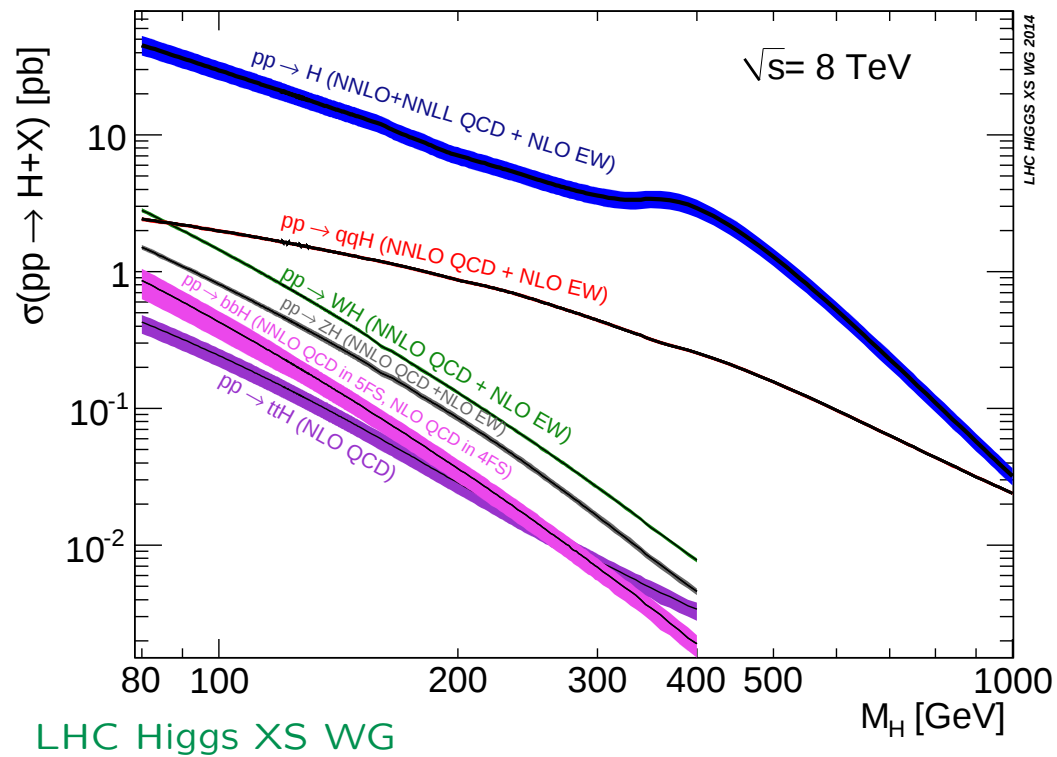
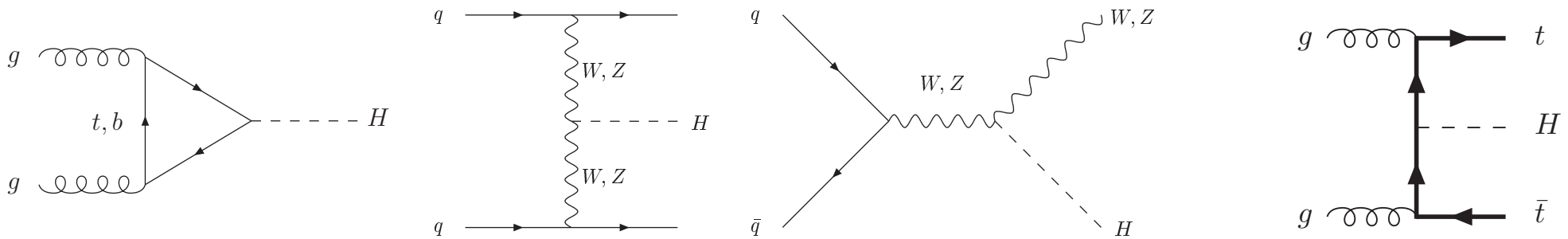
I INTRODUCTION

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Supersymmetry ?
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- electroweak symmetry breaking: two classes of realization:
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- we have found the Higgs: $M_H \sim 125$ GeV
- $gg \rightarrow H$ dominant



• Higgs Boson Production



- Discovery: LHC [Tevatron]

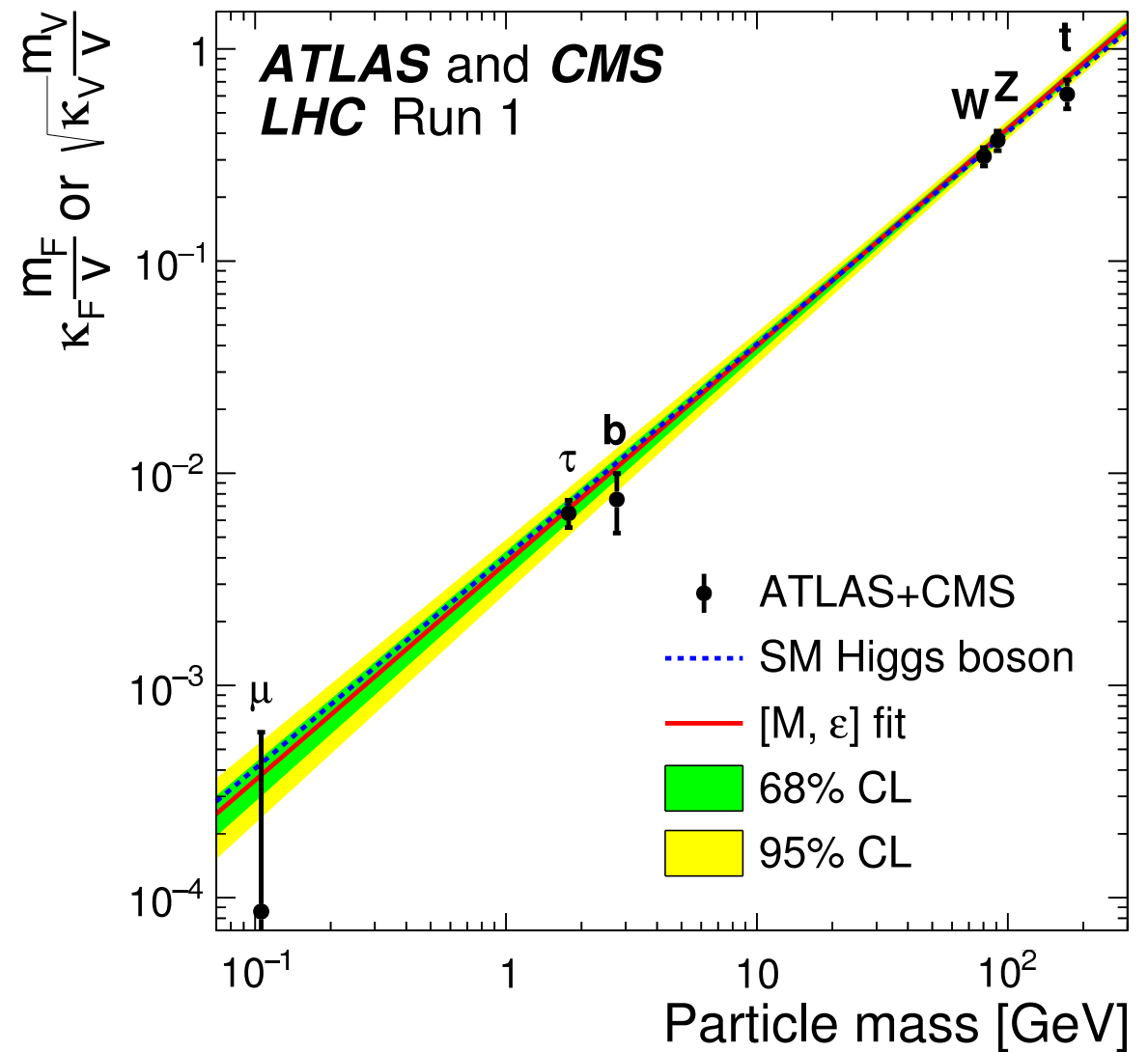
→ Higgs mass

couplings

spin

CP

λ ?



[simplified κ framework]

II HIGGS BOSON DECAYS

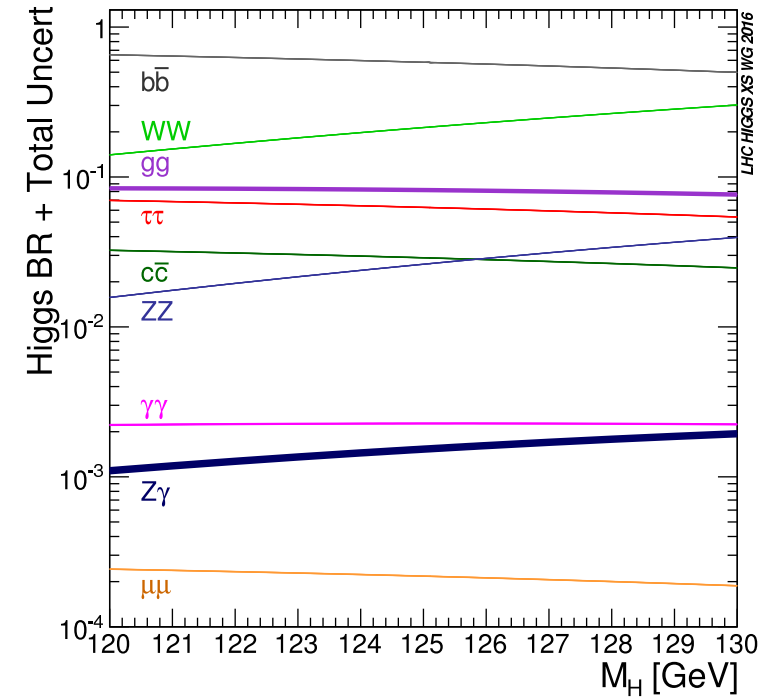
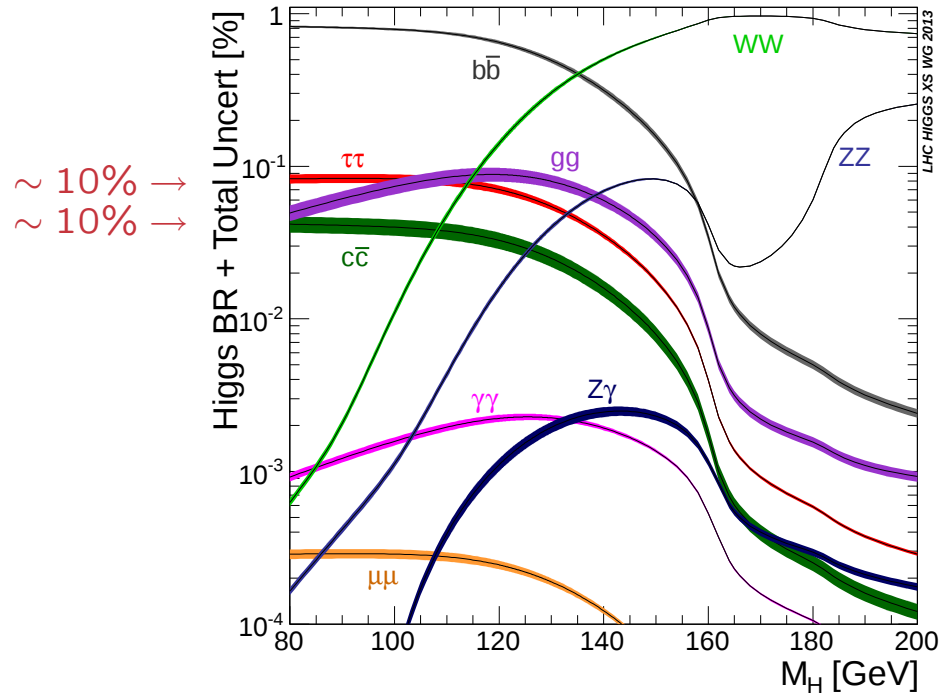
Partial Width	QCD	Electroweak	Total	on-shell Higgs
$H \rightarrow b\bar{b}/c\bar{c}$	$\sim 0.2\%$	$\sim 0.5\%$ for $M_H \lesssim 500\text{GeV}$ $\sim 0.1(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500\text{GeV}$	$\sim 0.5\%$ $\sim 0.5\text{--}10\%$	NNNNLO / NLO
$H \rightarrow \tau^+\tau^-/\mu^+\mu^-$		$\sim 0.5\%$ for $M_H \lesssim 500\text{GeV}$ $\sim 0.1(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500\text{GeV}$	$\sim 0.5\%$ $\sim 0.5\text{--}10\%$	NLO
$H \rightarrow t\bar{t}$	$\lesssim 5\%$	$\lesssim 0.5\%$ for $M_H < 500\text{GeV}$ $\sim 0.1(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500\text{GeV}$	$\sim 5\%$ $\sim 5\text{--}10\%$	(NNN)NLO / LO
$H \rightarrow gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$	NNNLO approx. / NLO
$H \rightarrow \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$	NLO / NLO
$H \rightarrow Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$	(N)LO / LO
$H \rightarrow WW/ZZ \rightarrow 4f$	$< 0.5\%$	$\sim 0.5\%$ for $M_H < 500\text{GeV}$ $\sim 0.17(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500\text{GeV}$	$\sim 0.5\%$ $\sim 0.5\text{--}15\%$	(N)NLO

- 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:
 $m_t = 172.5 \pm 1$ GeV $\alpha_s(M_Z) = 0.118 \pm 0.0015$
 $m_b(m_b) = 4.18 \pm 0.03$ GeV $m_c(3\text{GeV}) = 0.986 \pm 0.025$ GeV
different uncertainties added quadratically for each channel
- total uncertainties: parametric & theor. uncertainties added linearly

YR3

HDECAY & Prophecy4f

YR4

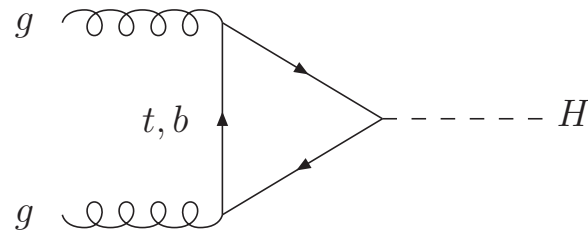


Denner, Heinemeyer, Puljak, Rebuszi, S.

- refinements input parameters
- full NLO elw. corrections to $H \rightarrow f\bar{f}$
- NLO quark-mass effects in $H \rightarrow gg$

III HIGGS BOSON PRODUCTION

(i) $gg \rightarrow H$



Georgi, Glashow, Machacek, Nanopoulos

S., Djouadi, Graudenz, Zerwas
Dawson, Kauffman

- NLO QCD corrections: $\sim 10 \dots 100\%$

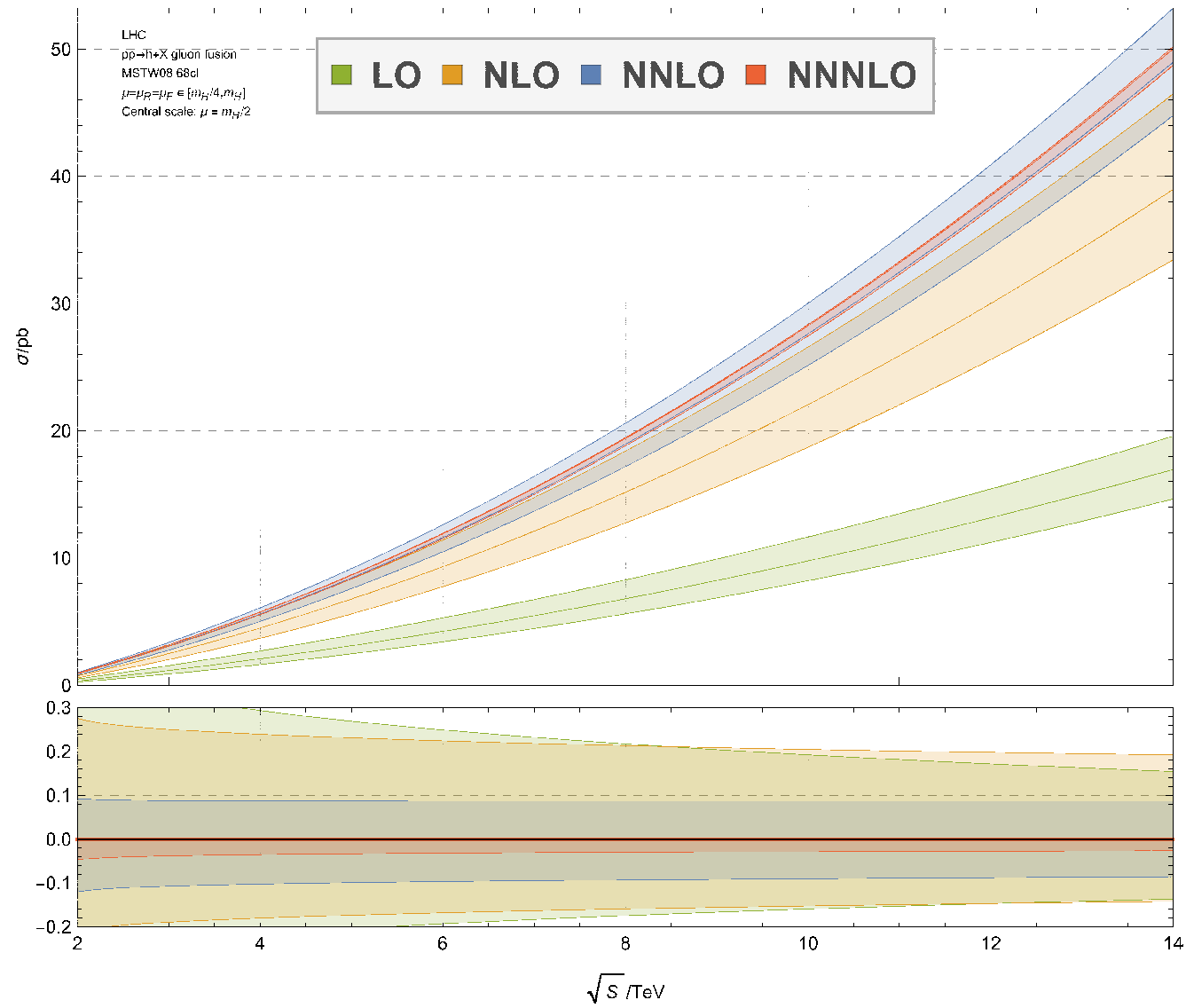
- NNLO calculated for $m_t \gg M_\phi \Rightarrow$ further increase by 20–30%
[mass effects small]

Harlander, Kilgore
Anastasiou, Melnikov
Ravindran, Smith, van Neerven

Marzani, Ball, Del Duca, Forte, Vicini
Harlander, Ozeren
Pak, Rogal, Steinhauser

- N³LO for $m_t \gg M_\phi \Rightarrow$ scale stabilization
scale dependence: $\Delta \lesssim 5\%$

Moch, Vogt
Ravindran
de Florian, Mazzitelli, Moch, Vogt
Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger
Ball, Bonvini, Forte, Marzani, Ridolfi



Anastasiou, Duhr, Dulat, Herzog, Mistlberger

- N³LL soft gluon resummation: $\lesssim 2\%$

Catani, de Florian, Grazzini, Nason
Ravindran
Ahrens, Becher, Neubert, Yang
Ball, Bonvini, Forte, Marzani, Ridolfi
Bonvini, Marzani
Schmidt, S.

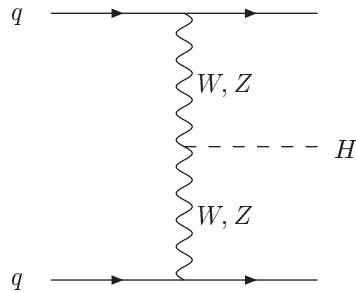
- elw. corrections: $\sim 5\%$

Aglietti, . . .
Degrassi, Maltoni
Actis, Passarino, Sturm, Uccirati

- impl. of $gg \rightarrow H$ in POWHEG including mass effects @ NLO

Bagnaschi, Degrassi, Slavich, Vicini

(ii) W/Z fusion: $pp \rightarrow W^*W^*/Z^*Z^* \rightarrow H$



Cahn, Dawson
Hikasa
Atarelli, Mele, Pitoli

- QCD corrections $\leftarrow$ DIS: $\sim 10\%$

[approx] 2-loop: $\lesssim 1\%$

[approx] 3-loop: $\lesssim 0.3\%$

Han, Valencia,
Willenbrock
Figy, Oleari, Zeppenfeld
Berger, Campbell

Bolzano, Maltoni, Moch, Zaro
Cacciari, Dreyer, Karlberg, Salam, Zanderighi

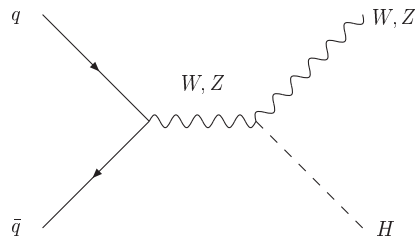
Dreyer, Karlberg

- elw. corrections: $\sim 10\%$

Ciccolini, Denner, Dittmaier

$\rightarrow$ HAWK, VBFNLO, VBF@NNLO, PROVBF
MG5_aMC@NLO, POWHEG

(iii) Higgs-strahlung: $pp \rightarrow W^*/Z^* \rightarrow W/Z + H$



Glashow, ...
Kunszt, ...

- QCD corrections $\leftarrow$ DY: $\sim 30\%$
2-loop: $\lesssim 5\%$

Han, Willenbrock

Brein, Djouadi, Harlander

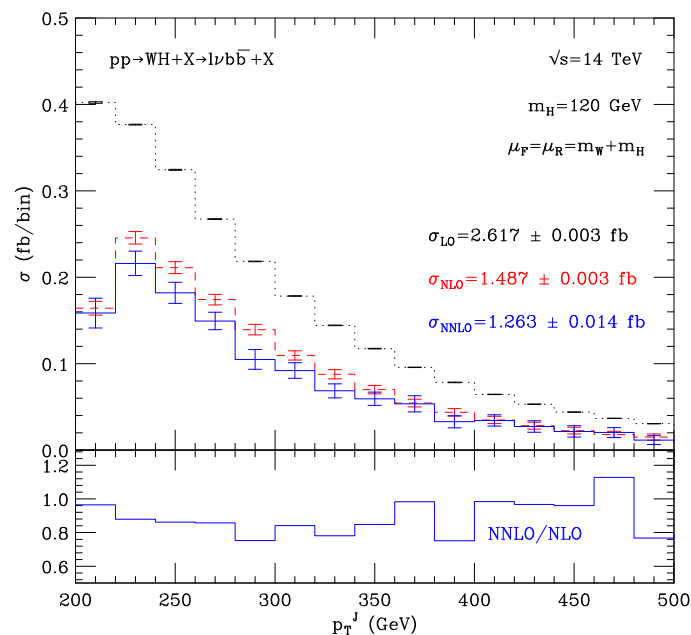
Ciccolini, Dittmaier, Krämer

- electroweak corrections: $\sim -10\%$

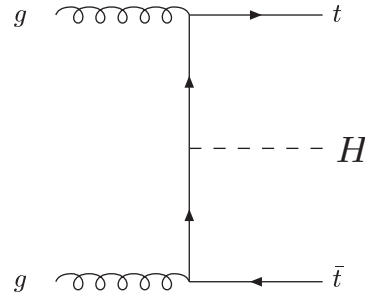
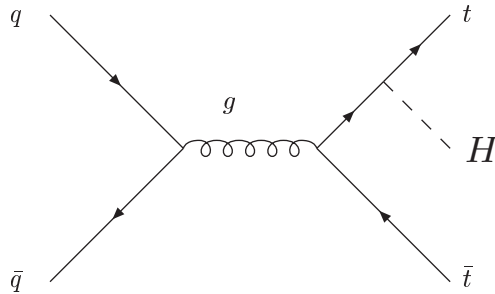
$\rightarrow$ HAWK, HVNNLO, MCFM, VHNNLO, NNLOPS, MG5_aMC@NLO, POWHEG

- $W/Z + H$: fully exclusive @ NNLO QCD

Ferrera, Grazzini, Tramantano



(iv) Bremsstrahlung: $pp \rightarrow t\bar{t} + H$



Kunszt
Gunion
Marciano, Paige

dominant

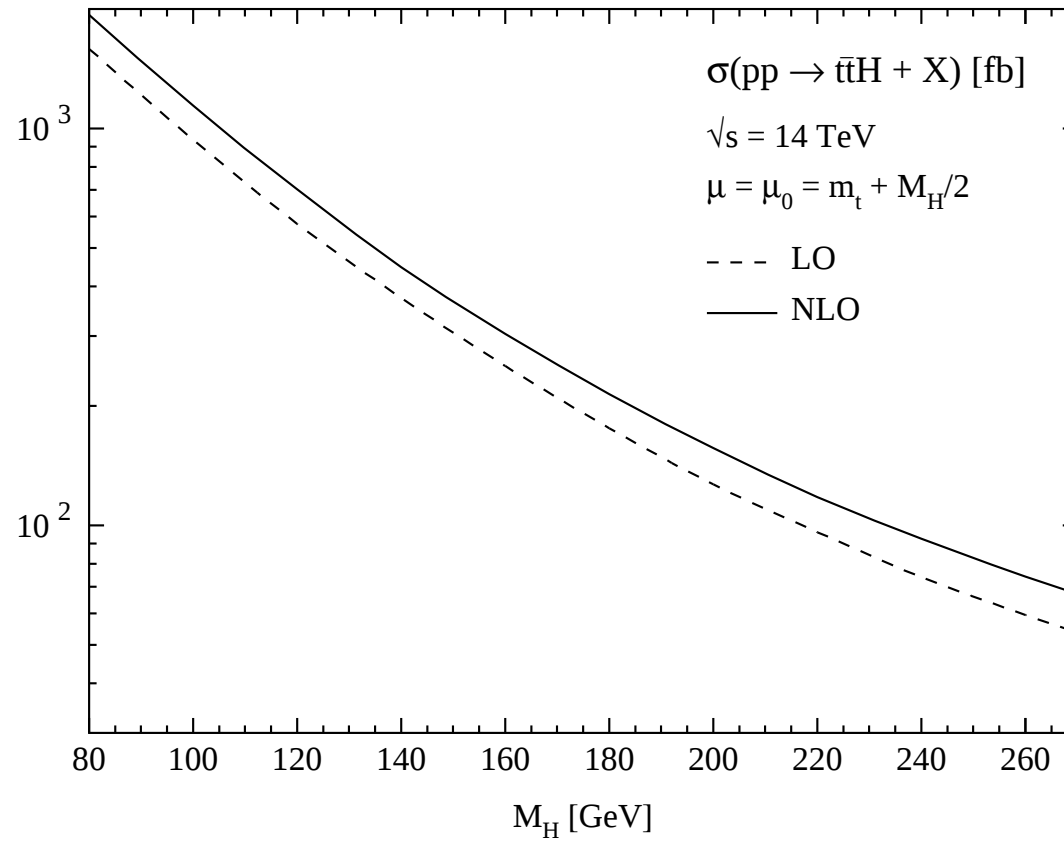
- $t\bar{t}h \rightarrow t\bar{t}b\bar{b}$ important @ LHC $\rightarrow$ top Yukawa cplg. [direct]
- QCD corrections [SM]: $\sim 20\%$ [threshold suppressed: $\sigma_{LO} \sim \beta^4$]

Beenakker, Dittmaier, Krämer, Plümper, S., Zerwas
Dawson, Orr, Reina, Wackerroth
Broggio, Ferroglia, Pecjak, Signer, Yang
Kulesza, Motyka, Stebel, Theeuwes
- link to parton showers: aMC@NLO, PowHel

Frederix et al.
Garzelli, Kardos, Papadopoulos, Trócsányi
- important work on backgrounds $t\bar{t}b\bar{b}, t\bar{t}jj$, etc.

Bredenstein, Denner, Dittmaier, Pozzorini
Bevilacqua, Czakon, Papadopoulos, Pittau, Worek
Cascioli, Maierhofer, Pozzorini

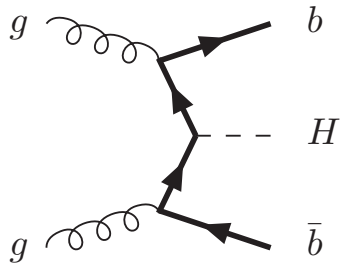
$\rightarrow$ Openloops + Sherpa



~ 1.2

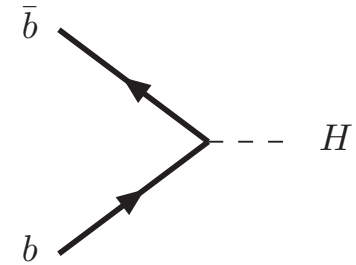
Beenakker, Dittmaier, Krämer, Plümper, S., Zerwas

(v) $b\bar{b}$ +Higgs production



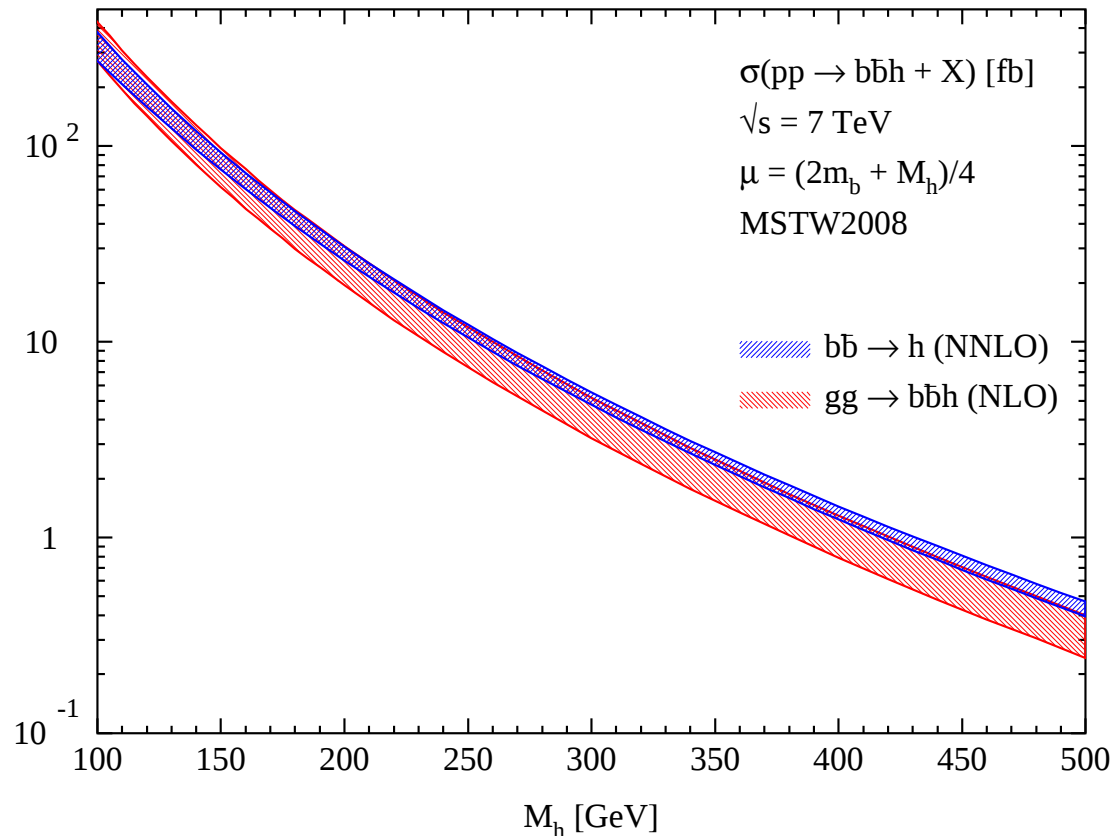
NLO

exact $g \rightarrow b\bar{b}$ splitting & mass/off-shell effects
no resummation of $\log M_H^2/m_b^2$ terms



NNLO

massless/on-shell b 's, no p_{Tb}
resummation of $\log M_H^2/m_b^2$ terms



Santander matching:

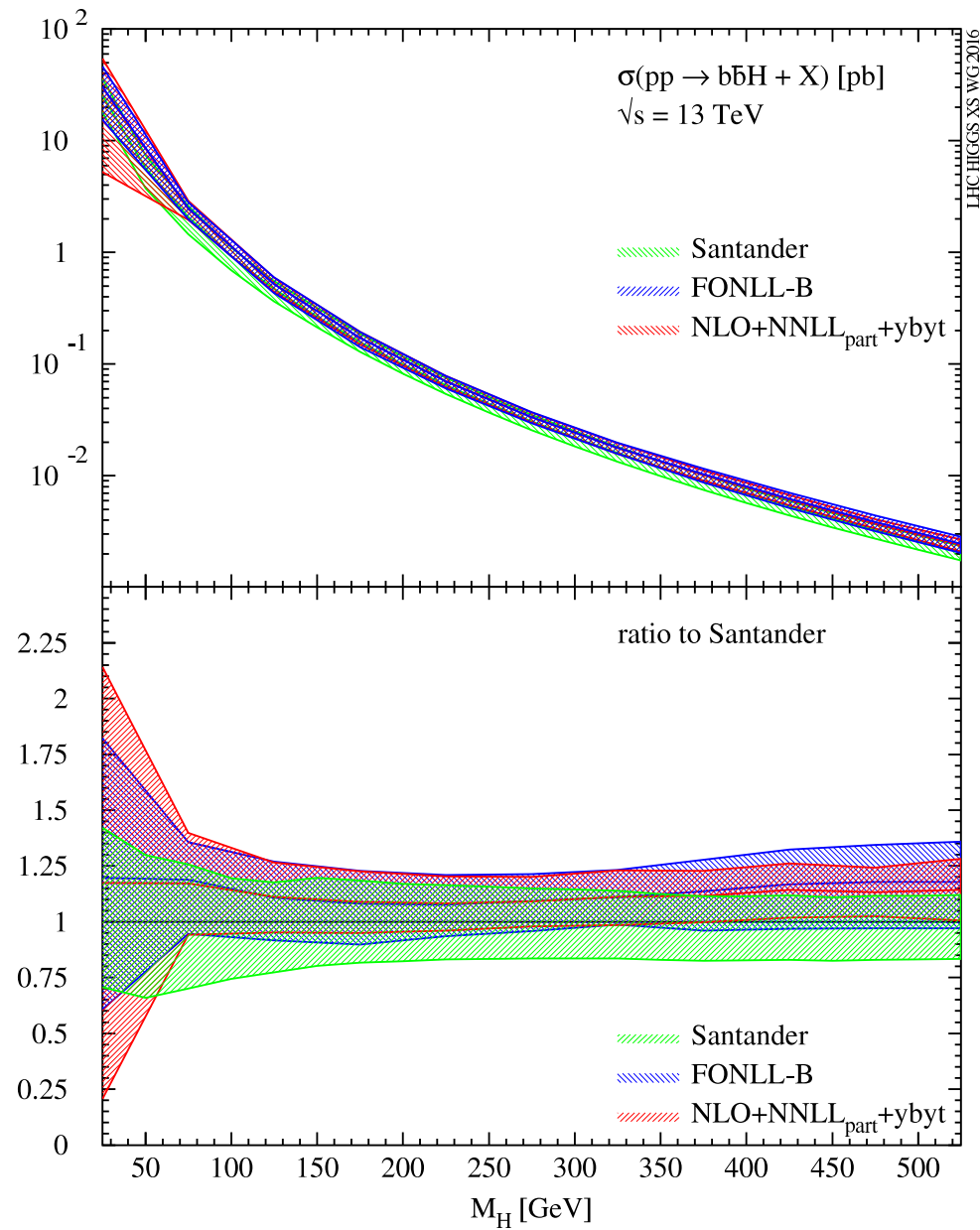
$$\sigma = \frac{\sigma^{4FS} + w\sigma^{5FS}}{1 + w}$$

$$w = \log \frac{M_H}{m_b} - 2$$

Harlander, Krämer, Schumacher

Dittmaier, Krämer, S.
Dawson, Jackson, Reina, Wackerroth
Harlander, Kilgore

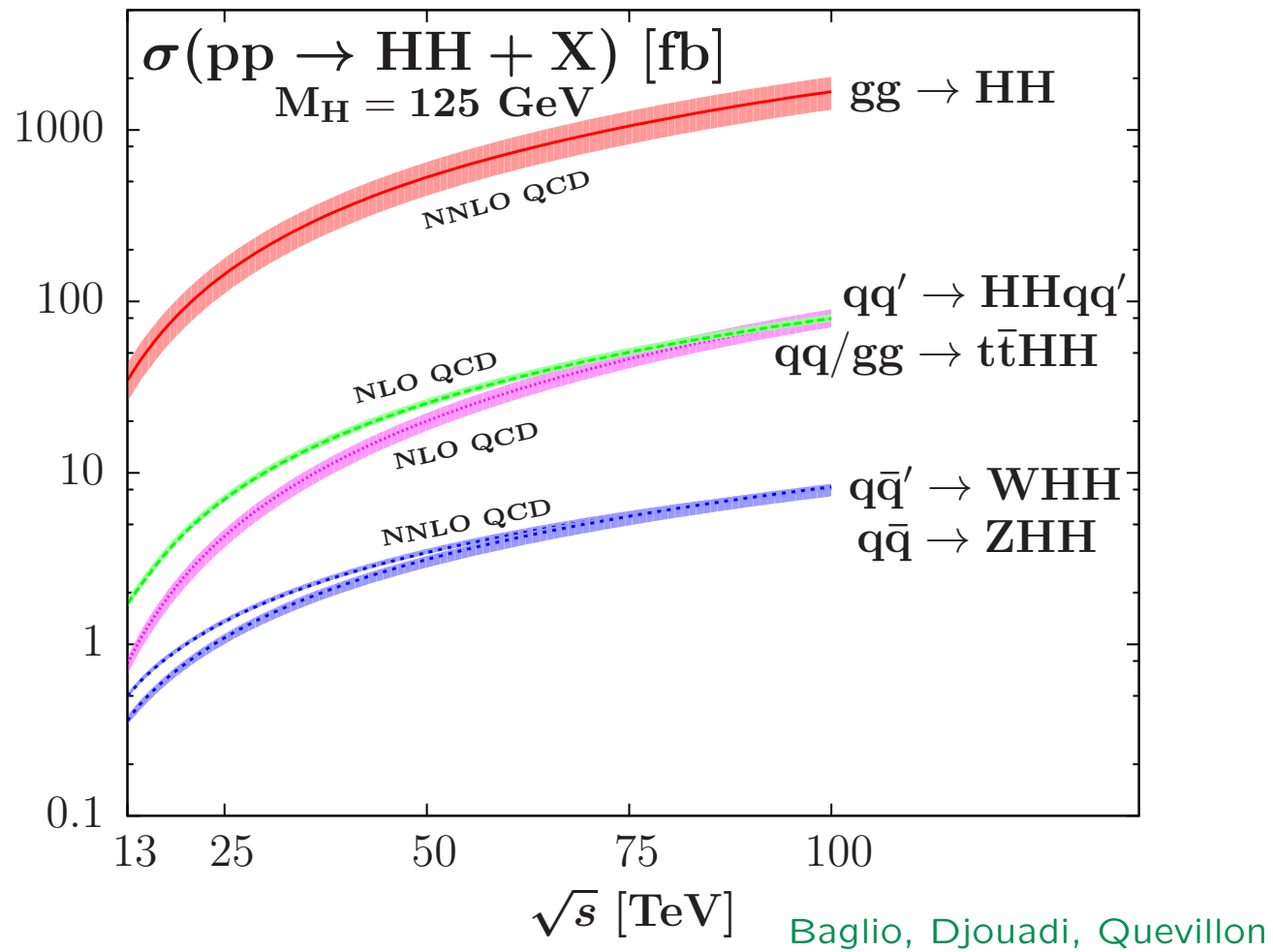
matching



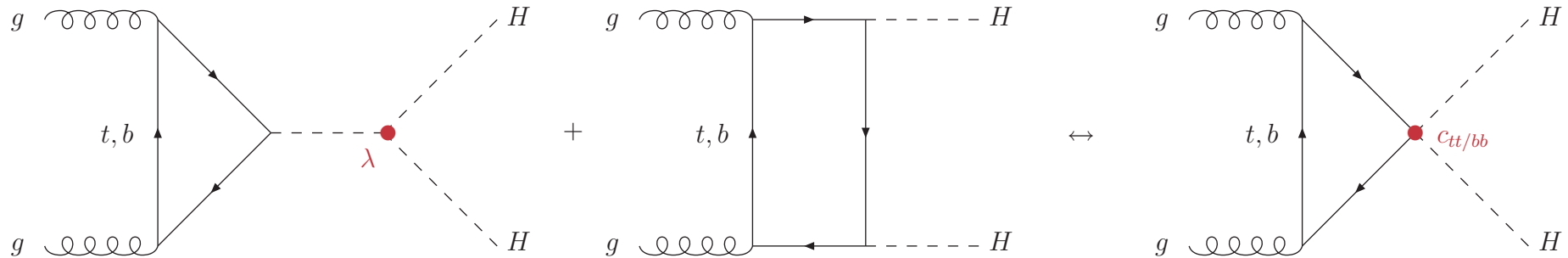
Bonvini, Papanastasiou, Tackmann

Forte, Napoletano, Ubiali

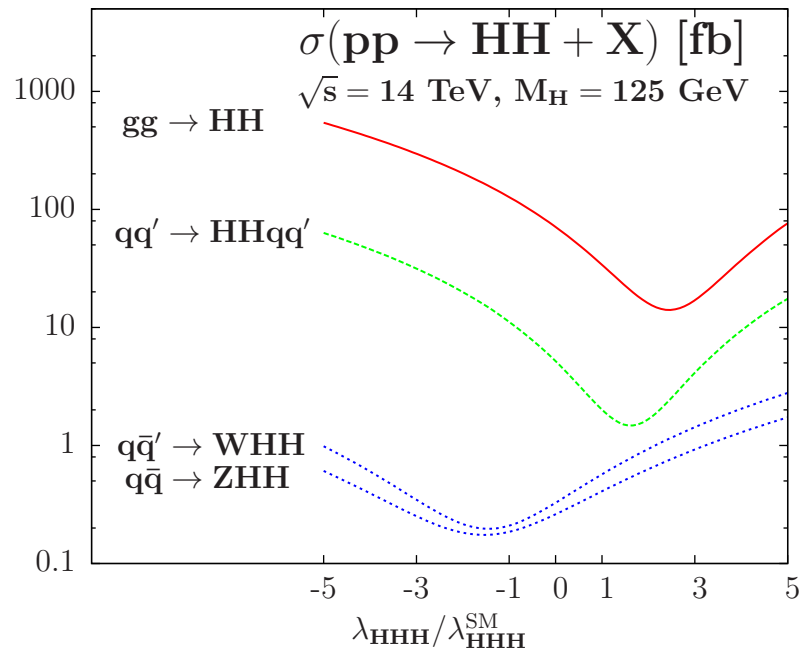
(vi) Higgs pair production



$gg \rightarrow HH$



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



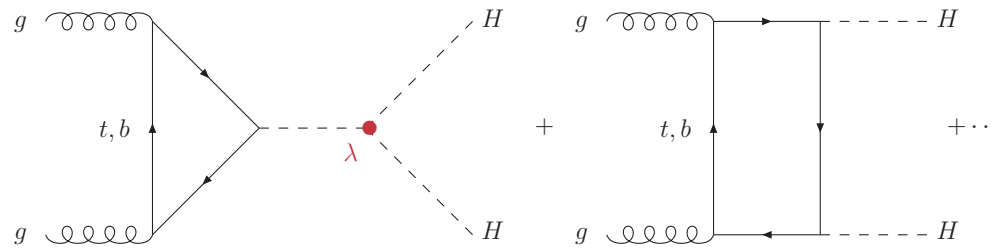
$$gg \rightarrow HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

[decreasing with M_{HH}^2]

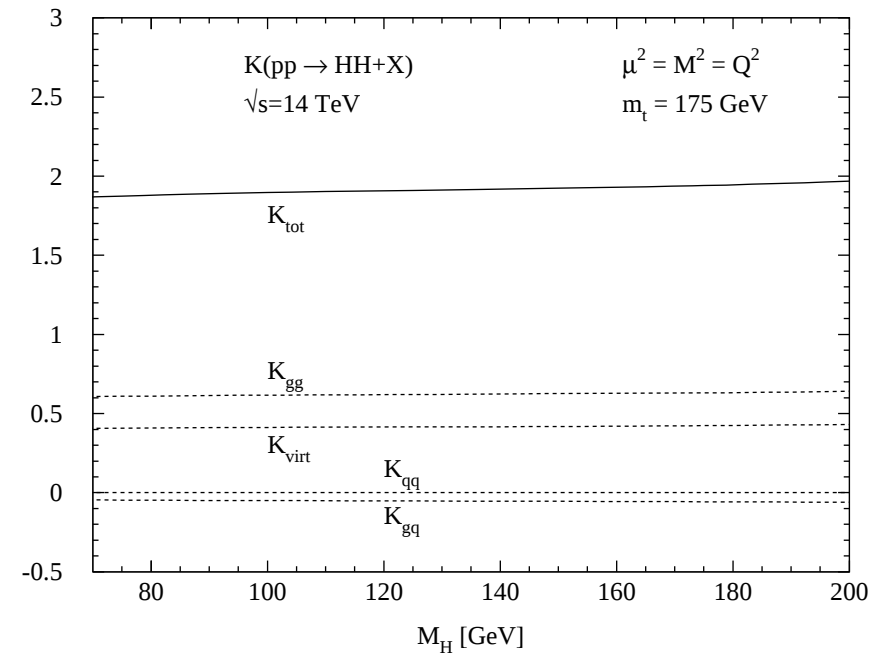
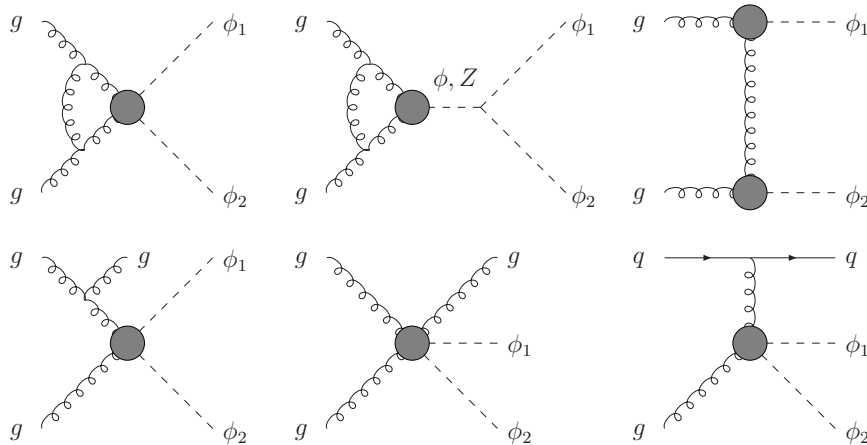
Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, S.

$gg \rightarrow HH$

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.

- 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

→ sizeable virtual mass effects

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

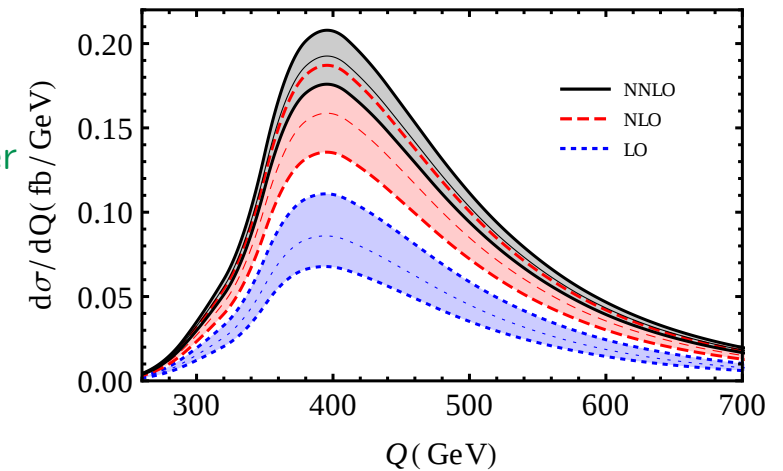
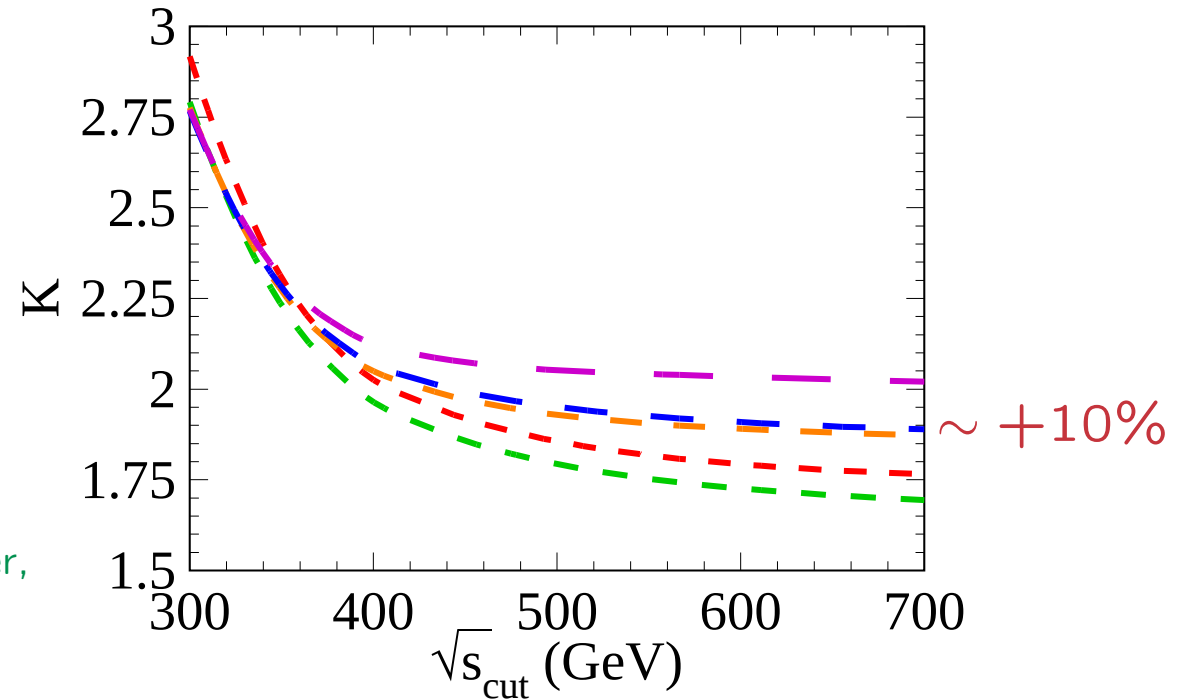
$$[M_H^2 \ll 4m_t^2]$$

de Florian, Mazzitelli

Grigo, Melnikov, Steinhauser

- soft gluon resummation: $\sim 10\%$

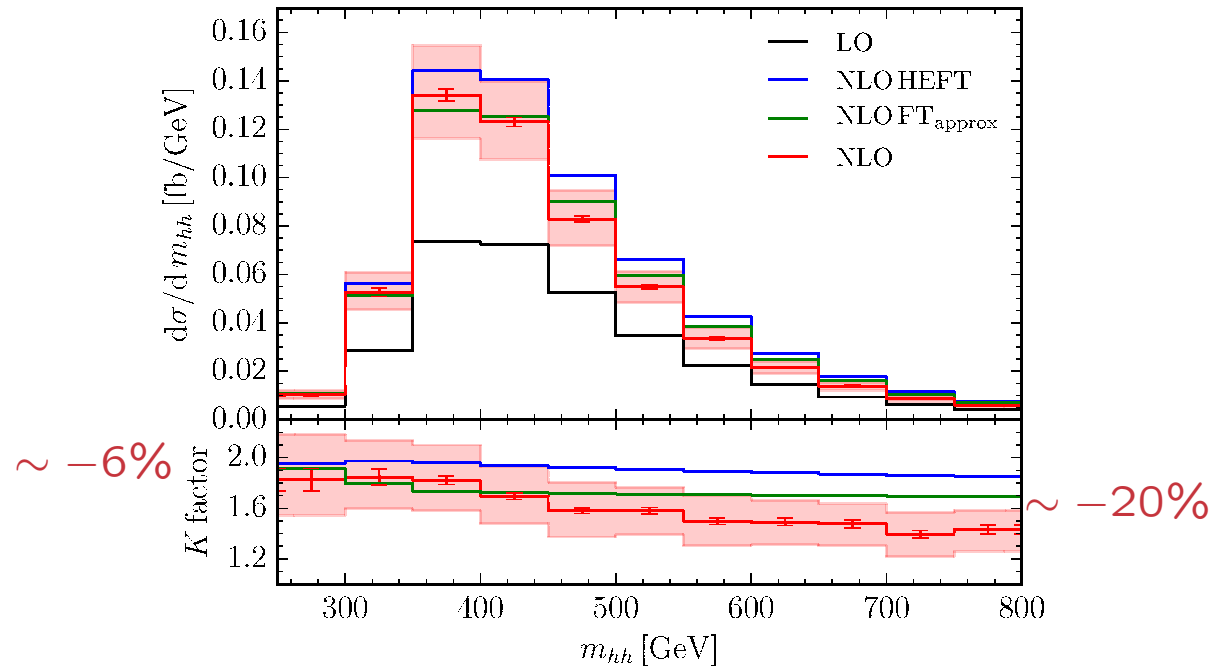
$$[M_H^2 \ll 4m_t^2]$$



Shao, Li, Li, Wang
de Florian, Mazzitelli

Full NLO calculation: top only

Numerical integration, sector decomposition, contour deformation



Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke
Baglio, Campanario, Glaus, Mühlleitner, S., Streicher (in preparation)

• 13 TeV:

$$\sigma_{NLO} = 27.80(8)^{+13.8\%}_{-12.8\%} \text{ fb}$$
$$\sigma_{NLO}^{HEFT} = 32.22^{+18\%}_{-15\%} \text{ fb}$$

$\Rightarrow -13.7\%$ mass effects

IV CONCLUSIONS

- Higgs boson searches/studies at LHC belong to major endeavours
- most QCD and -elw. corrections known $\rightarrow \Delta \lesssim 10 - 15\%$ @ LHC
- several dedicated HO-tools available for SM [MSSM, NMSSM, ...]
- important to develop NLO event generators [$\leftarrow$ backgrounds]

BACKUP SLIDES