PAUL SCHERRER INSTITUT

SM HIGGS PRODUCTION AND DECAY

Michael Spira (PSI)

I *INTRODUCTION*

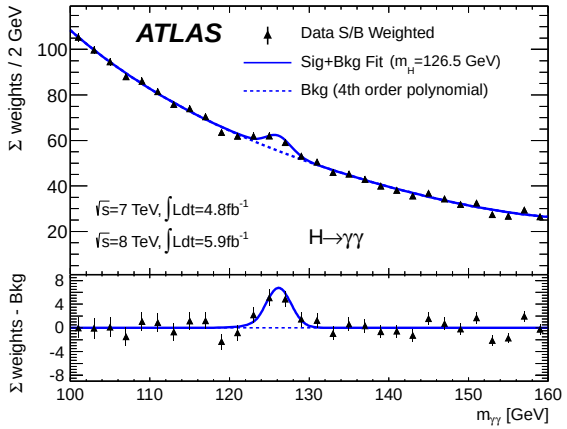
- SM very successful ← precision data [LEP, Tevatron, LHC]

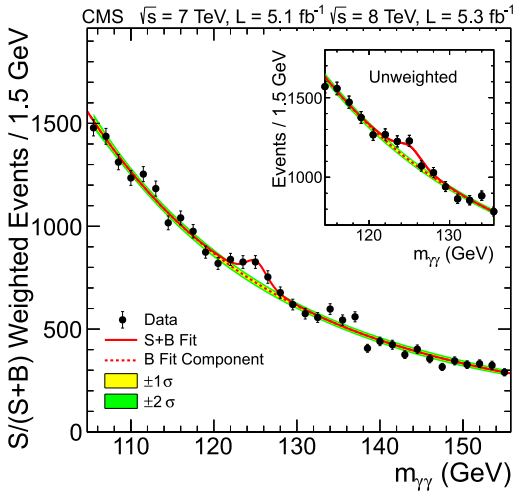
- open problems: – mechanism of electroweak symmetry breaking
  – unification of forces
  – space-time structure @ short distances

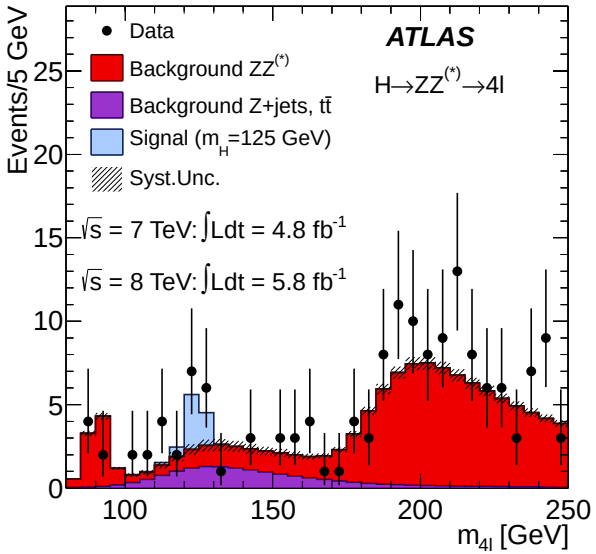
- LHC: fundamental discoveries: Higgs boson(s?)
  Supersymmetry ?
  Extra space dimensions ?

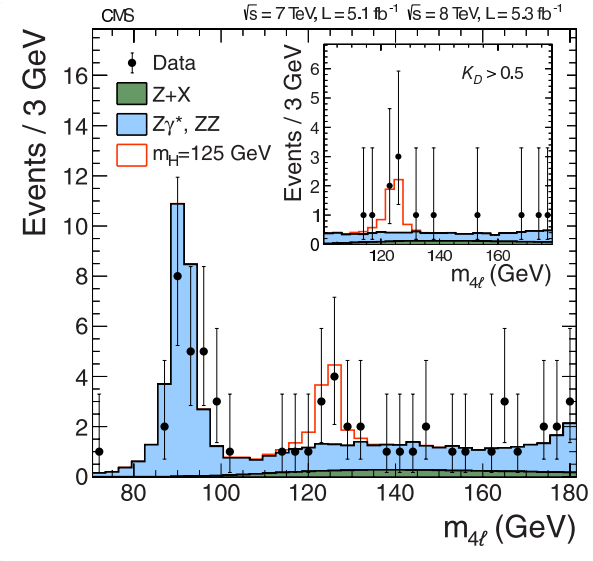
- electroweak symmetry breaking: two classes of realization:
  – standard Higgs mechanism [SM, SUSY,. . .]
  – strong elw. symmetry breaking [TC, LH, Higgsless, ED,. . .]

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

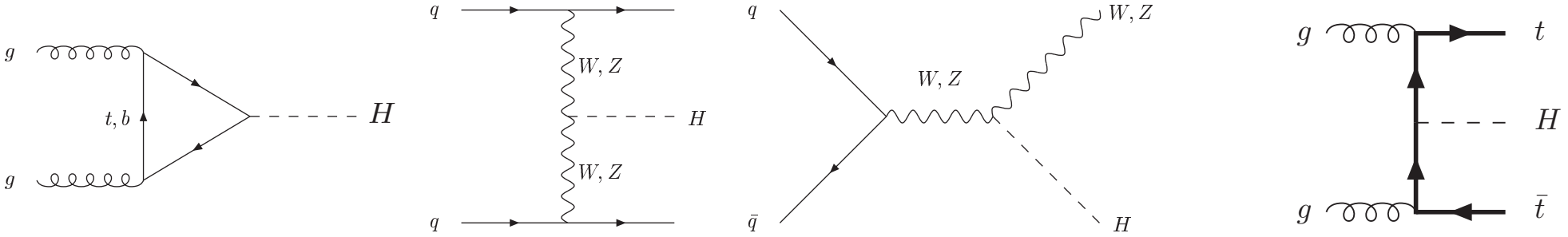


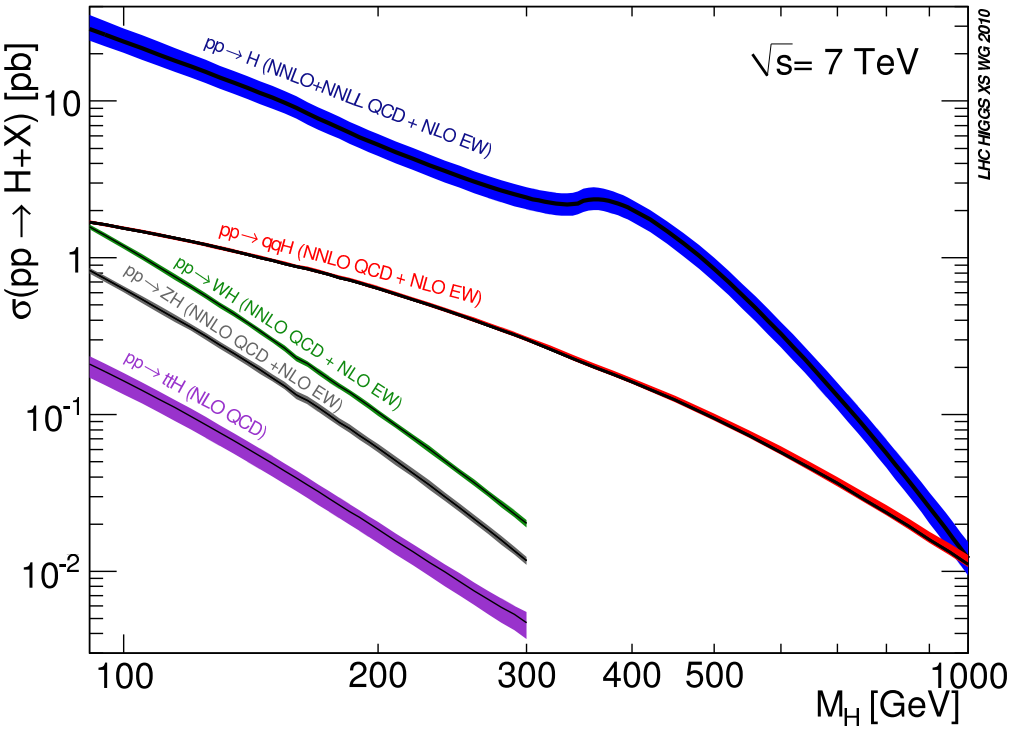


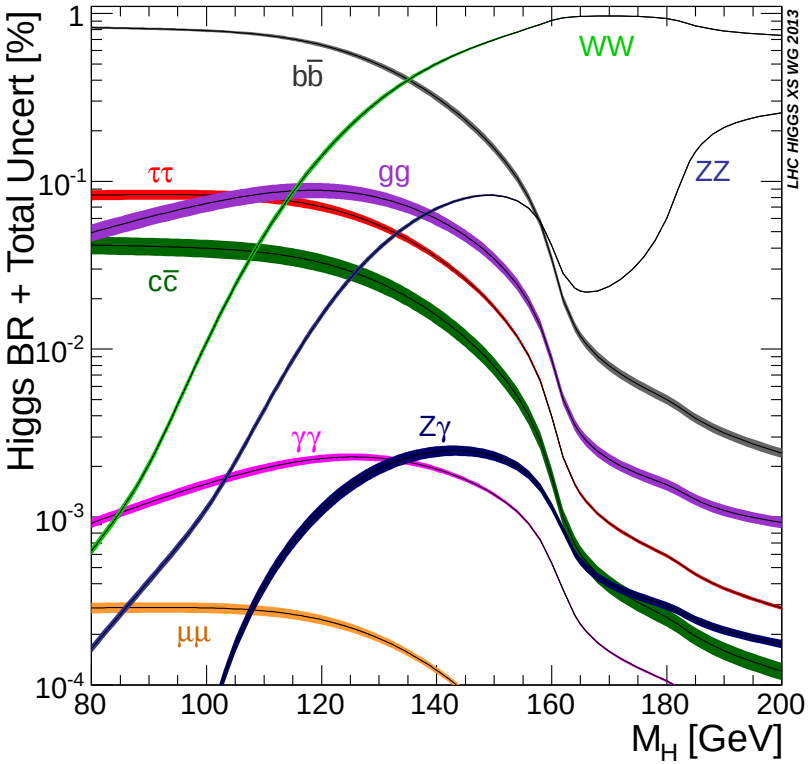




- Higgs Boson Production & Decay







LHC Higgs XS WG

ASYMPTOTIC FREEDOM IN PARTON LANGUAGE

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Institut des Hautes Etudes Scientifiques, Bures-sur-Yvette, France

Received 12 April 1977

A novel derivation of the Q^2 dependence of quark and gluon densities (of given helicity) as predicted by quantum chromodynamics is presented. The main body of predictions of the theory for deep-inleastic scattering on either unpolarized or polarized targets is re-obtained by a method which only makes use of the simplest tree diagrams and is entirely phrased in parton language with no reference to the conventional operator formalism.

LEPTONIC DECAY OF HEAVY FLAVORS: A theoretical update

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Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, Italy

Received 29 June 1982

OCTET ENHANCEMENT OF NON-LEPTONIC WEAK INTERACTIONS IN ASYMPTOTICALLY FREE GAUGE THEORIES

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L. MAIANI
Lab. di Fisica, Istituto Superiore di Sanità, Rome, Italy and Ist. Naz. di Fisica Nucleare, Sezione Sanità, Rome, Italy

Received 22 June 1974

LEPTOPRODUCTION AND DRELL-YAN PROCESSES BEYOND THE LEADING APPROXIMATION IN CHROMODYNAMICS *

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R.K. ELLIS
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

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Received 3 July 1978

* 12.07.1941 † 30.09.2015

LARGE PERTURBATIVE CORRECTIONS TO THE DRELL-YAN PROCESS IN QCD *

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Received 17 April 1979

Lower limit on the Higgs mass in the Standard Model: An update

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Received 15 July 1994
Editor: R. Gatto

Vacuum polarization effects of new physics on electroweak processes

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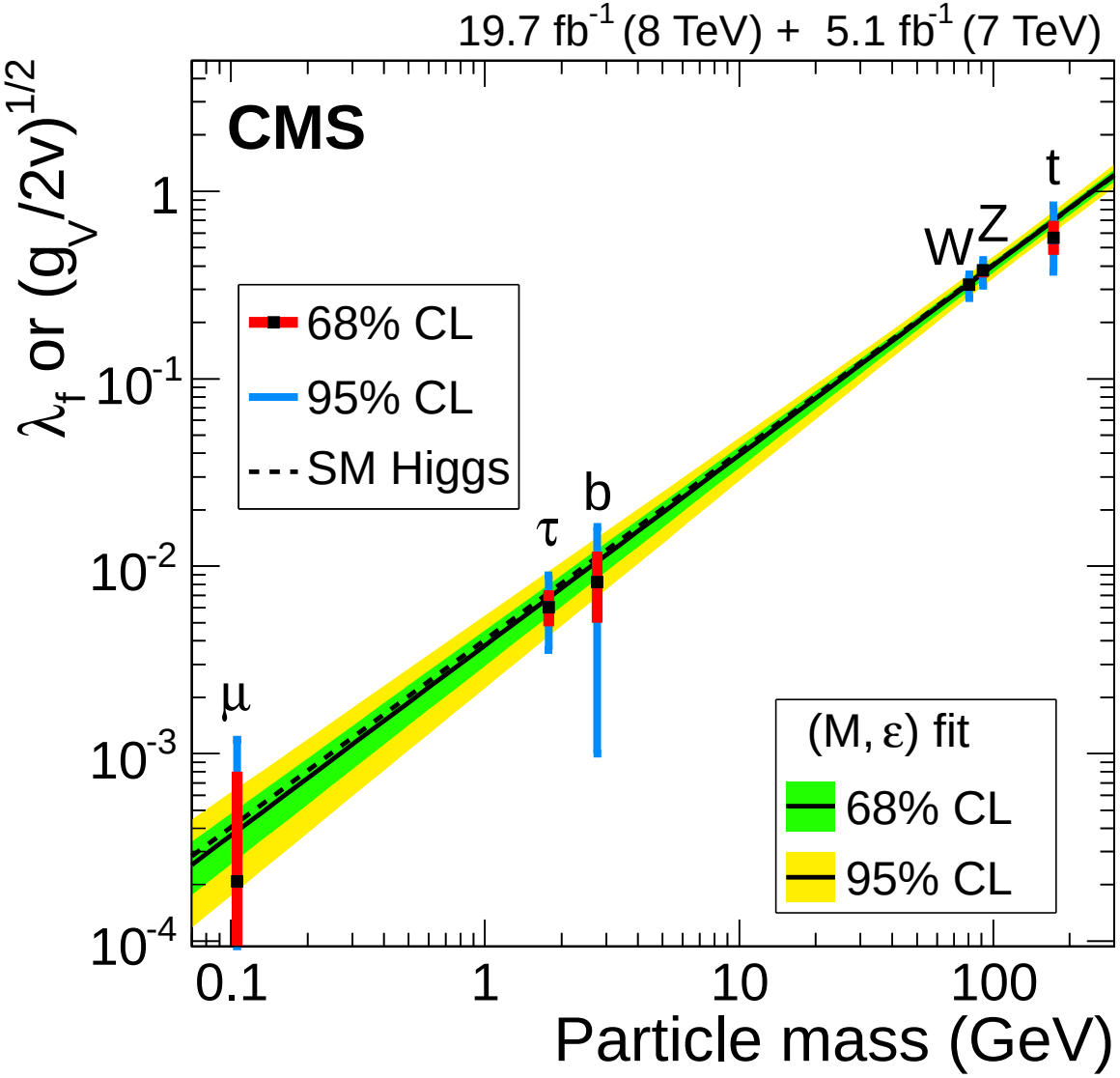
Received 28 September 1990

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



CMS

II HIGGS BOSON DECAYS

Partial Width	QCD	Electroweak	Total	on-shell Higgs
$H \to b\bar{b}/c\bar{c}$	$\sim 0.1\%$	~ 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

Partial Width	QCD	Electroweak	Total	on-shell Higgs
$H \to b\bar{b}/c\bar{c}$	$\sim 0.2\%$	$\sim 0.5\%$ for $M_H \lesssim 500$GeV	$\sim 0.5\%$	NNNNLO / NLO
		$\sim 0.1(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500$GeV	~ 0.5–10%	
$H \to \tau^+\tau^-/\mu^+\mu^-$		$\sim 0.5\%$ for $M_H \lesssim 500$GeV	$\sim 0.5\%$	NLO
		$\sim 0.1(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500$GeV	~ 0.5–10%	
$H \to t\bar{t}$	$\lesssim 5\%$	$\lesssim 0.5\%$ 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
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		$\sim 0.17(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500$GeV	~ 0.5–15%	

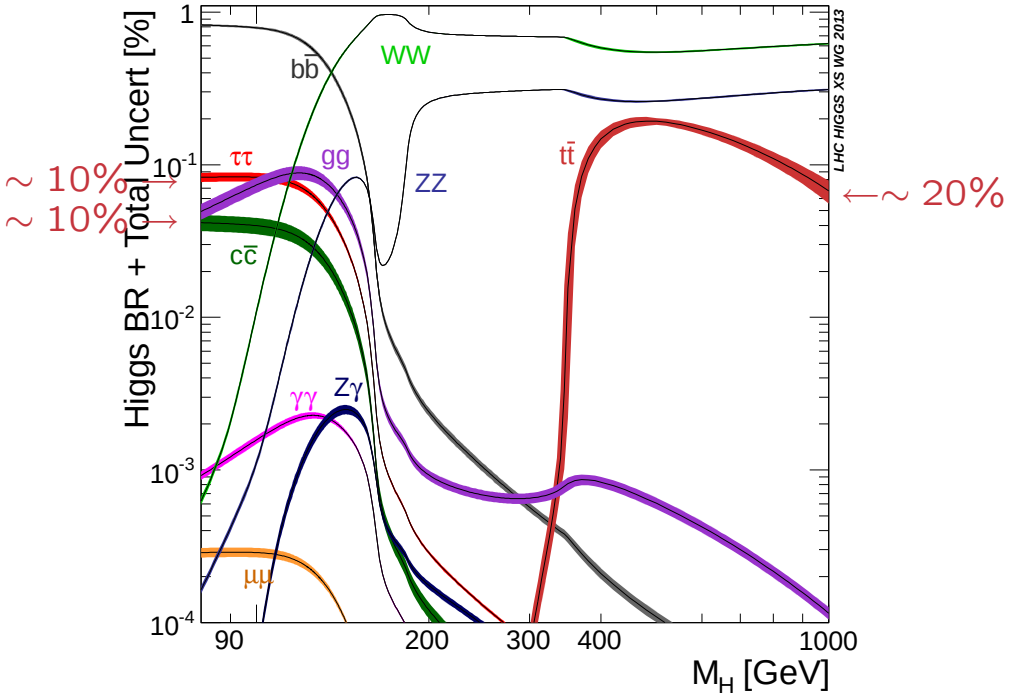
- QCD: variation of Higgs widths for scale by factor 2 and 1/2
  elw: missing HO estimated from known structure at NLO
  $M_H \gtrsim 500$ GeV: Higgs self-interactions dominate error
  different uncertainties added linearly for each channel

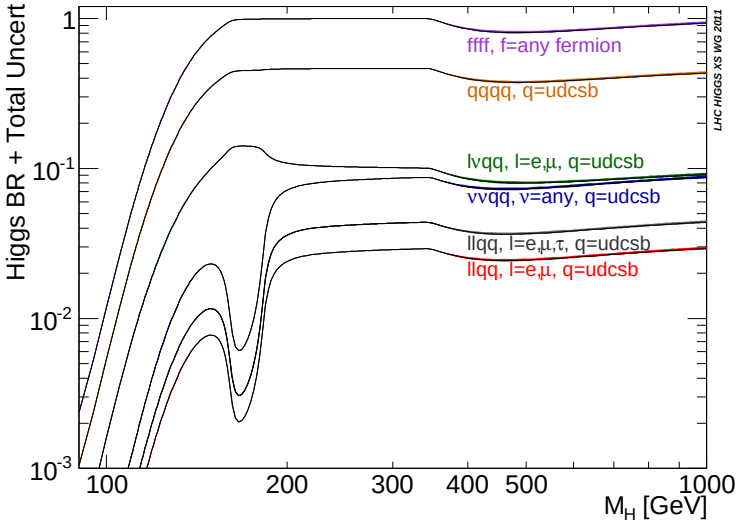
- parametric uncertainties: [→ discussions SM input parameters]
  $m_t = 173.2 \pm 0.9$ GeV $\alpha_s(M_Z) = 0.118 \pm 0.001$
  $m_b(m_b) = 4.18 \pm 0.03$ GeV $m_c(3\text{GeV}) = 0.986 \pm 0.025$ GeV
  different uncertainties added quadratically for each channel

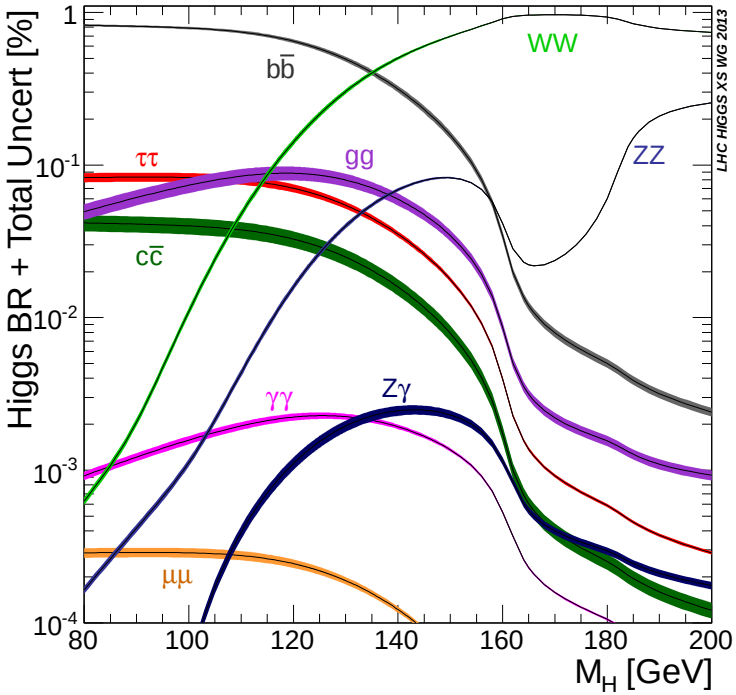
- total uncertainties: parametric & theor. uncertainties added linearly

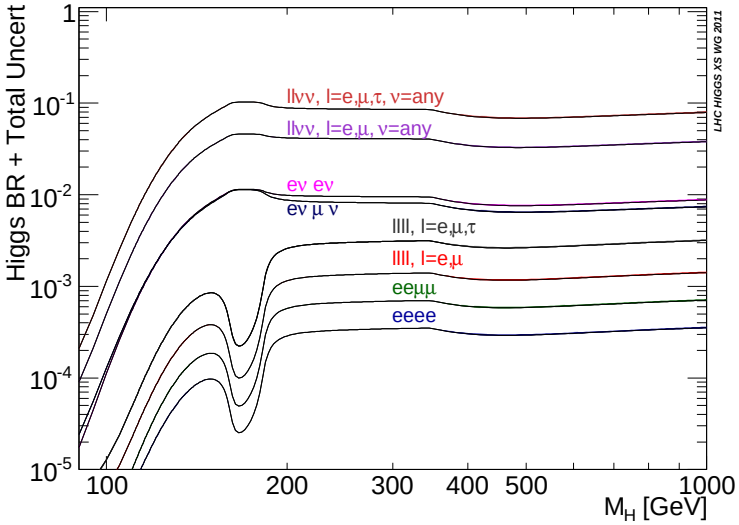
HDECAY & Prophecy4f Djouadi, Kalinowski, Mühlleitner, S.

Bredenstein, Denner, Dittmaier, Weber



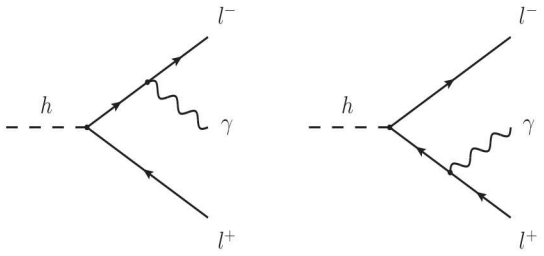




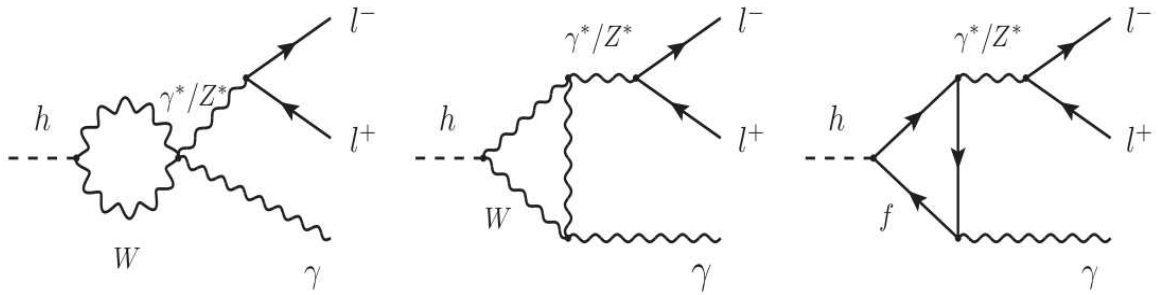


Denner, Heinemeyer, Puljak, Rebuzzi, S.

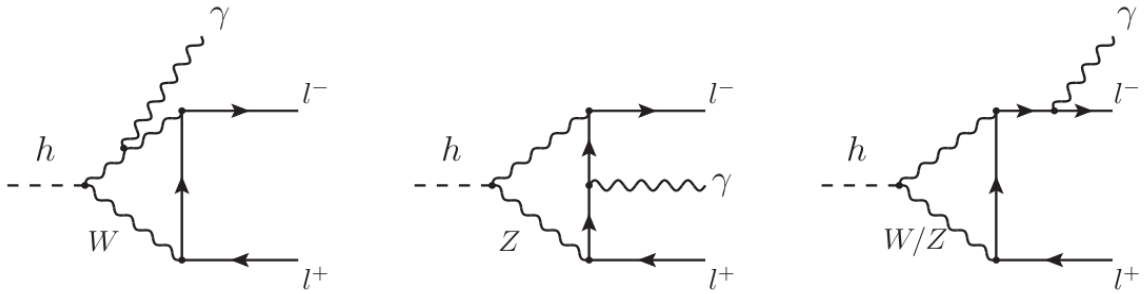
HIGGS DALITZ DECAYS



tree



off-shell



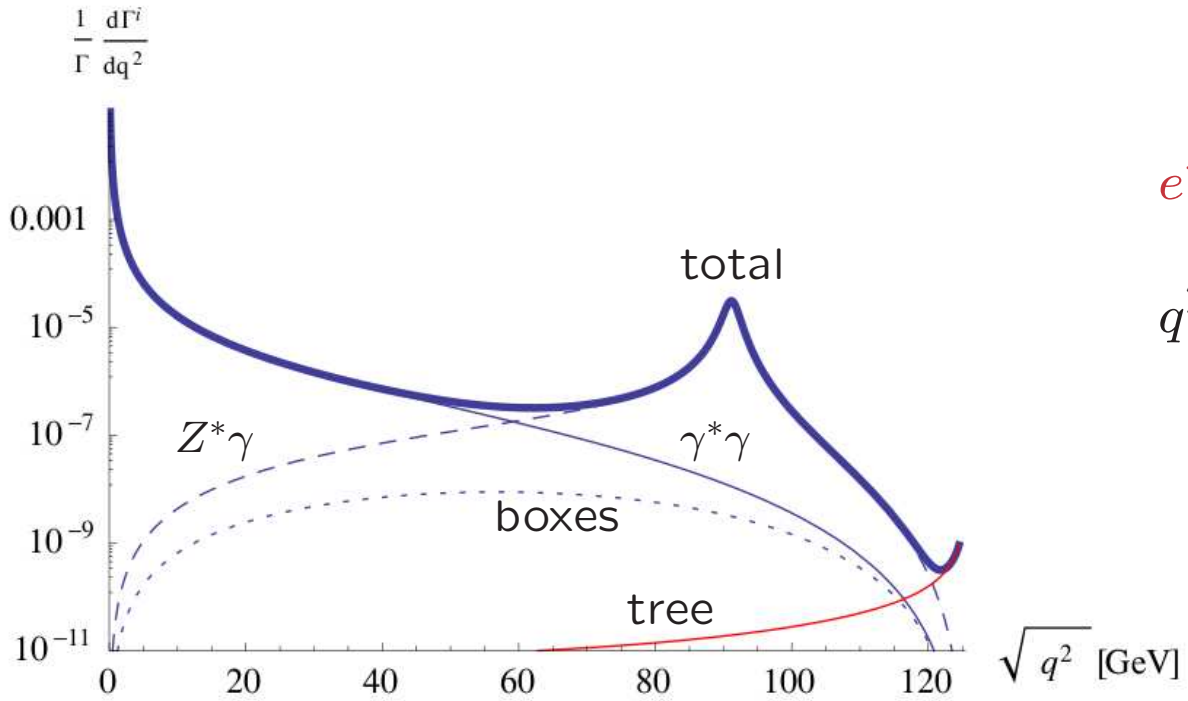
boxes

Abbasabadi, Bowser–Chao, Dicus, Repko
Sun, Chang, Gao
Passarino

$$\frac{\Gamma(h \to \gamma e^+ e^-)}{\Gamma(h \to \gamma\gamma)} = 5.7\%$$

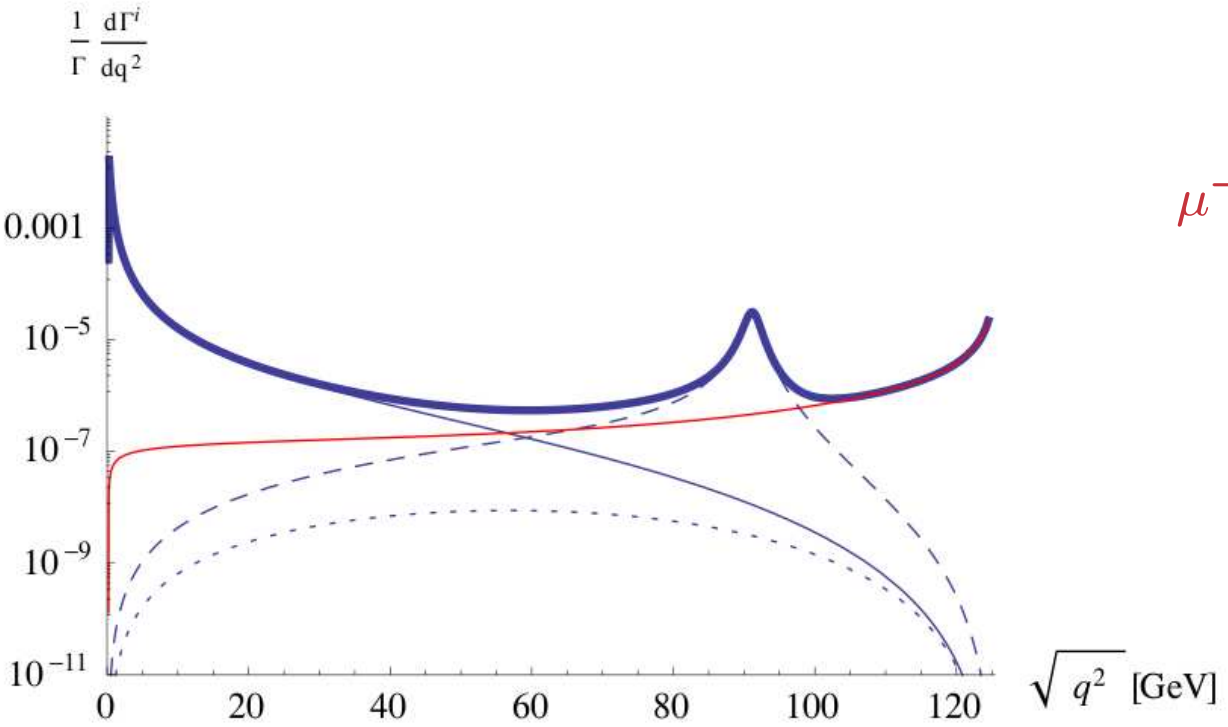
$$\frac{\Gamma(h \to \gamma \mu^+ \mu^-)}{\Gamma(h \to \gamma\gamma)} = 5.8\% \qquad (E_\gamma > 1 \text{ GeV})$$

$$\frac{\Gamma(h \to \gamma \tau^+ \tau^-)}{\Gamma(h \to \gamma\gamma)} = 3.04$$



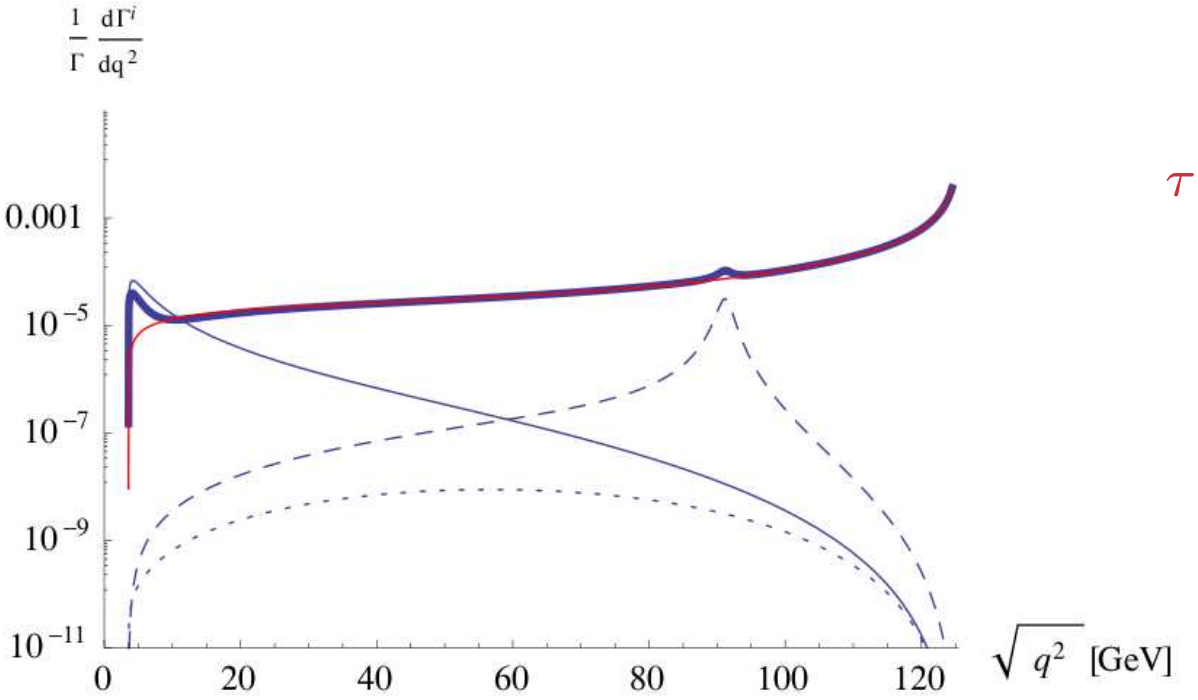
$e^+e^-\gamma$

$q^2 = M^2_{\ell^+\ell^-}$



Sun, Chang, Gao

$\mu^+\mu^-\gamma$



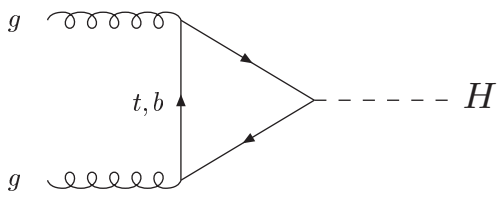
$\tau^+\tau^-\gamma$

Sun, Chang, Gao

- Dalitz decays ($H \to Z\gamma \Leftrightarrow H \to \ell^+\ell^-\gamma$)
  [waiting for agreement ATLAS/CMS]

II HIGGS BOSON PRODUCTION

(i) $gg \to H$



Georgi,. . .

S., Djouadi, Graudenz, Zerwas
Dawson, Kauffman

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

- NNLO calculated for $m_t \gg M_H \Rightarrow$ 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

- NNLL soft gluon resummation: $5 - 10\%$

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

- elw. corrections: -4% – 6%

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

- N^{3}LO estimated for $m_t \gg M_H$ $\Rightarrow$ scale stabilization
scale dependence: $\Delta \lesssim 10 - 15\%$

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

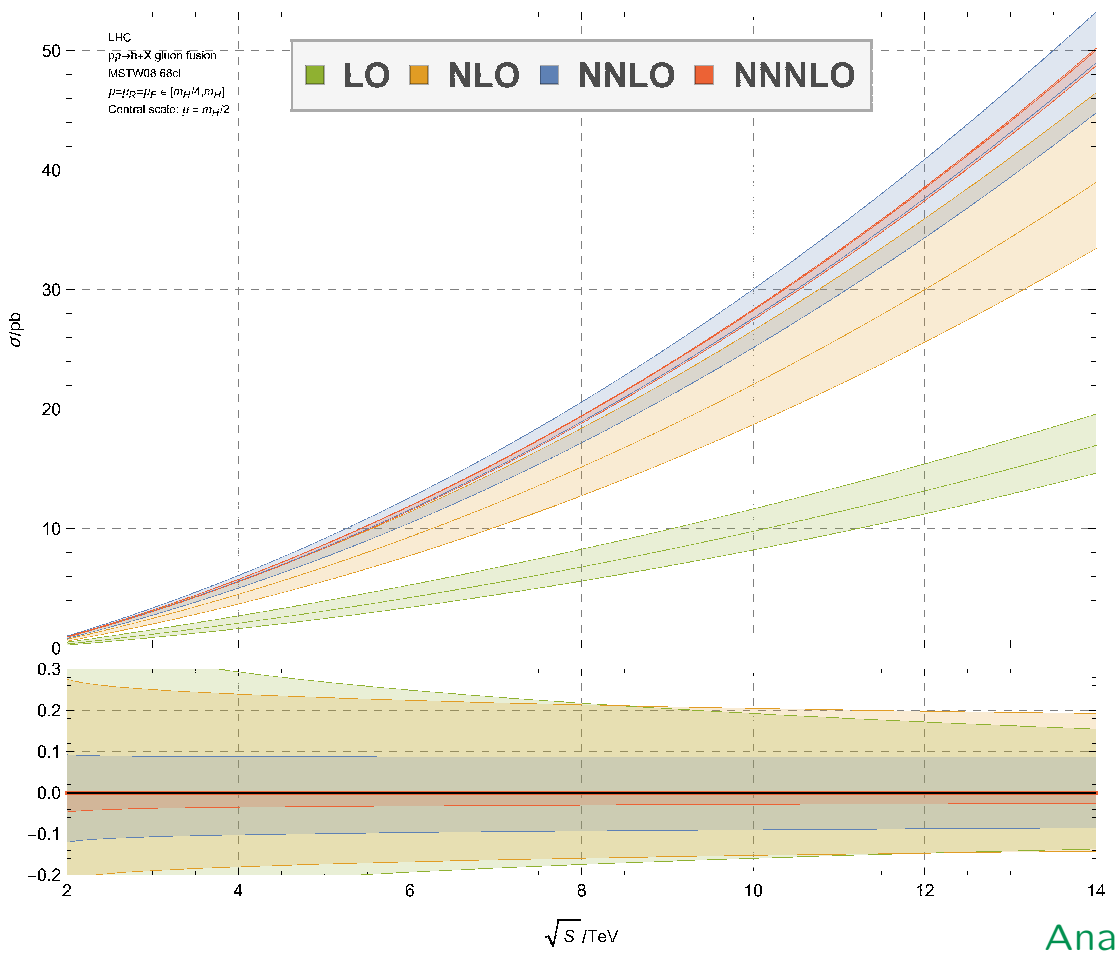
- N^{3}LO corrections for $m_t \gg M_H$: 2% Anastasiou, Duhr, Dulat, Herzog, Mistlberger

- N^{3}LL resummation for $m_t \gg M_H$: $\lesssim 5\%$ Schmidt, S.

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

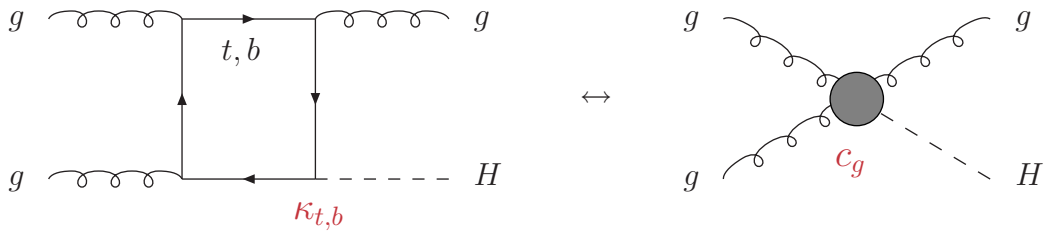
Bagnaschi, Degrassi, Slavich, Vicini

Jetzetle...

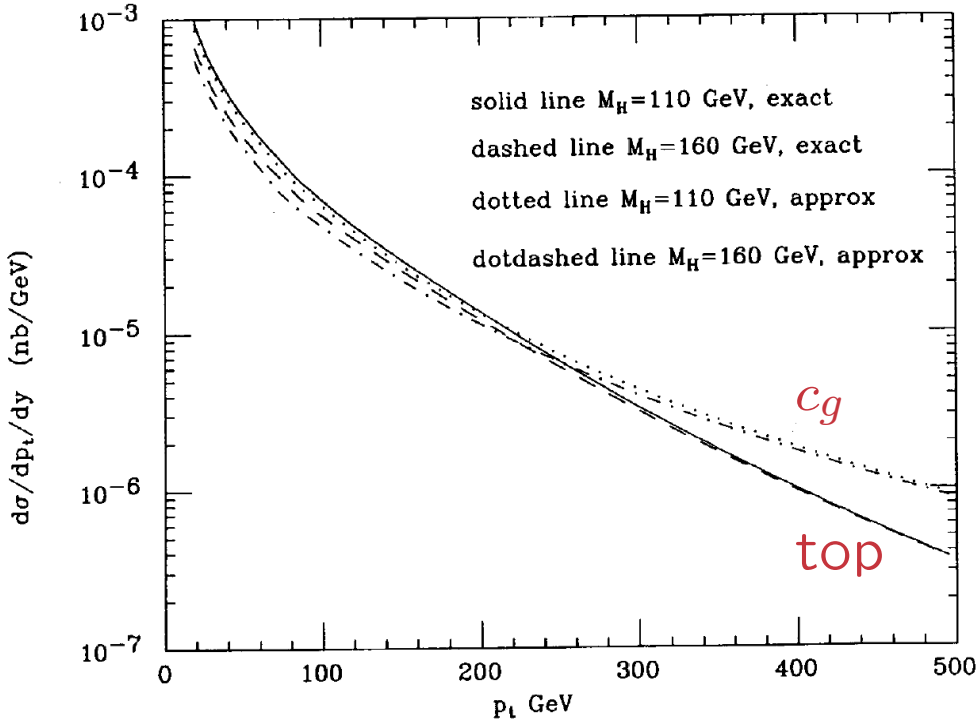


Anastasiou, Duhr, Dulat, Herzog, Mistlberger

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



- distinction dim4 $\leftrightarrow$ dim5



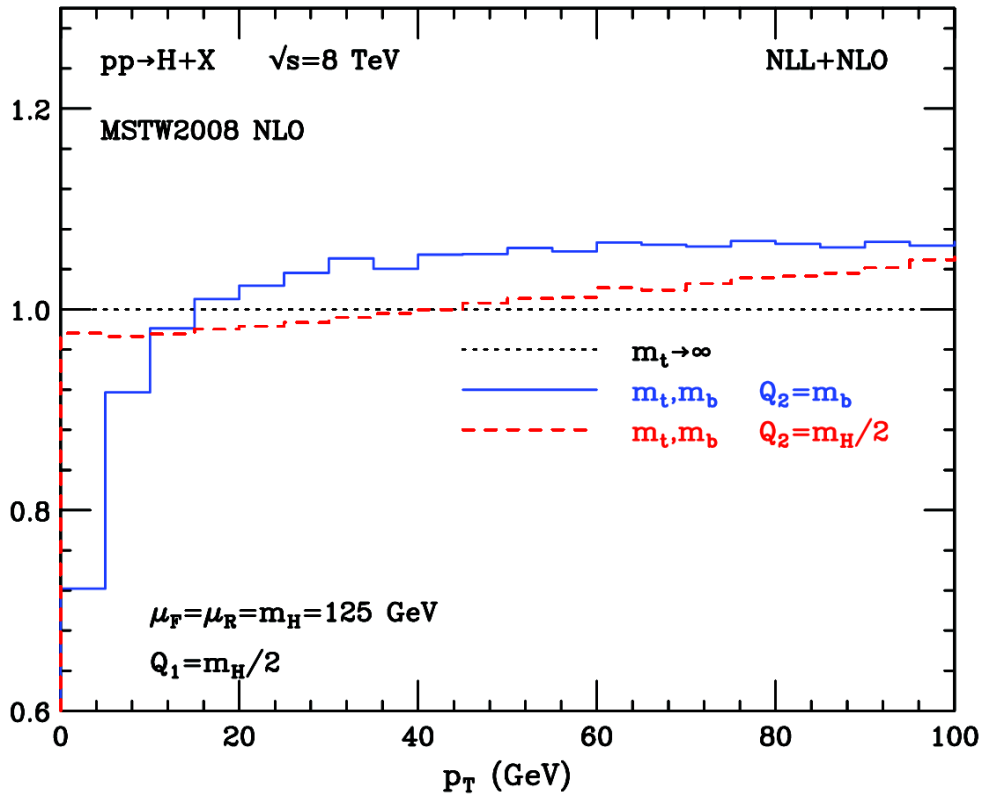
$m_t = 160$ GeV

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

- QCD corrections large $[m_t^2 \gg M_H^2, p_{TH}^2]$

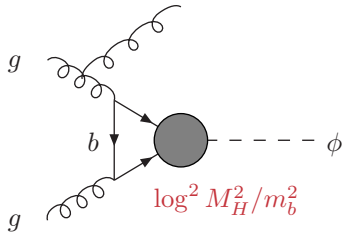
Glosser, Schmidt
de Florian, Grazzini, Kunszt
Bozzi, Catani, de Florian, Grazzini
Anastasiou, Melnikov, Petriello
Boughezal, Caola, Melnikov, Petriello, Schulze
Chen, Gehrmann, Glover, Jaquier
Boughezal, Focke, Giele, Liu, Petriello
Harlander, Neumann, Ozeren, Wiesemann

- factorization: $p_T \ll 2m_b \to Q \sim m_b$ [← POWHEG, MC@NLO]

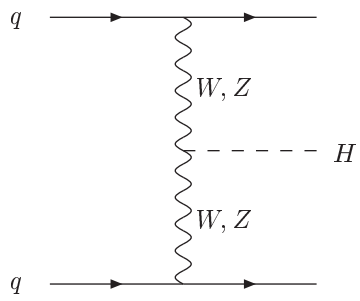


Grazzini, Sargsyan

- Sudakov form factor → unresummed logs



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



Cahn, Dawson
Hikasa
Atarelli, Mele, Pitolli

- QCD corrections ← DIS: $\sim 10\%$

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

2–loop: $\lesssim 1\%$ [approx]

Bolzano, Maltoni, Moch, Zaro

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

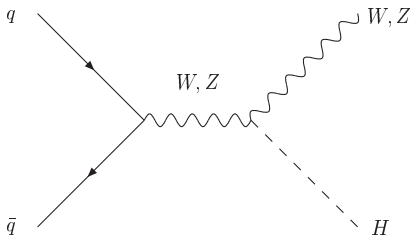
Ciccolini, Denner, Dittmaier

- implemented in VBFNLO

- fully differential @ NNLO

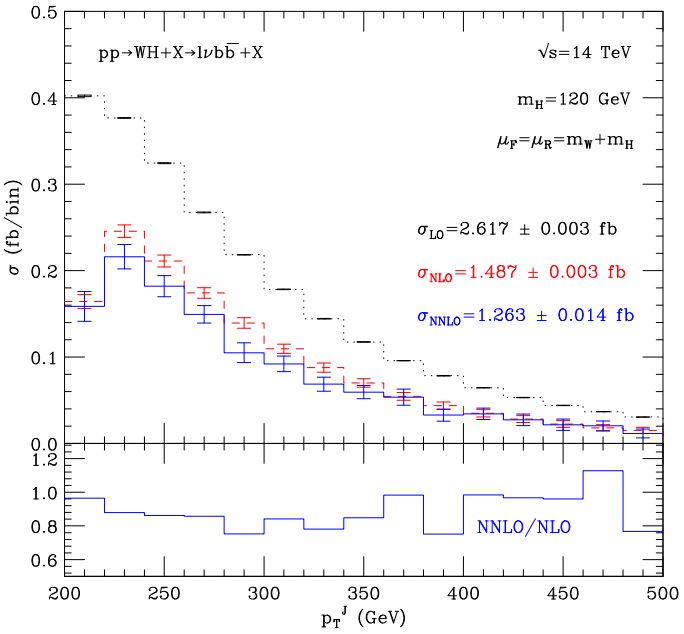
Cacciari, Dreyer, Karlberg, Salam, Zanderighi

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



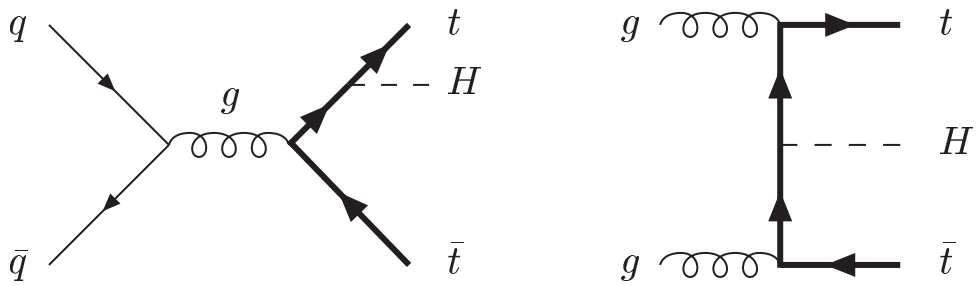
Glashow,. . .
Kunszt,. . .

- QCD corrections ← DY: $\sim 30\%$
  2–loop: $\lesssim 5\%$ — Han, Willenbrock
- electroweak corrections: $\sim -10\%$ — Brein, Djouadi, Harlander
- WH/ZH: fully exclusive @ NNLO QCD — Ciccolini, Dittmaier, Krämer; Ferrera, Grazzini, Tramantano



Sodele...

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



dominant

Kunszt
Gunion
Marciano, Paige

- $t\bar{t}H \to t\bar{t}b\bar{b}$ important @ LHC $\to$ top Yukawa cplg.

- QCD corrections [SM]: $\sim 20\%$

Beenakker,. . .
Dawson, . . .

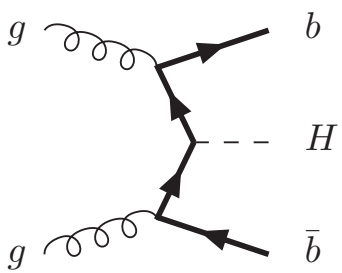
- link to parton showers: aMC@NLO, PowHel

Frederix et al.
Garzelli, Kardos, Papadopoulos, Trócsányi

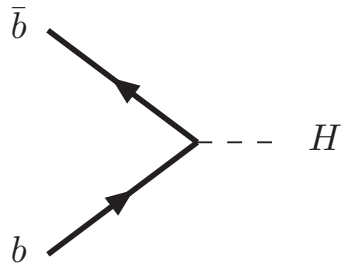
- important work on backgrounds $t\bar{t}b\bar{b}, t\bar{t}jj$, etc.

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

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



NLO



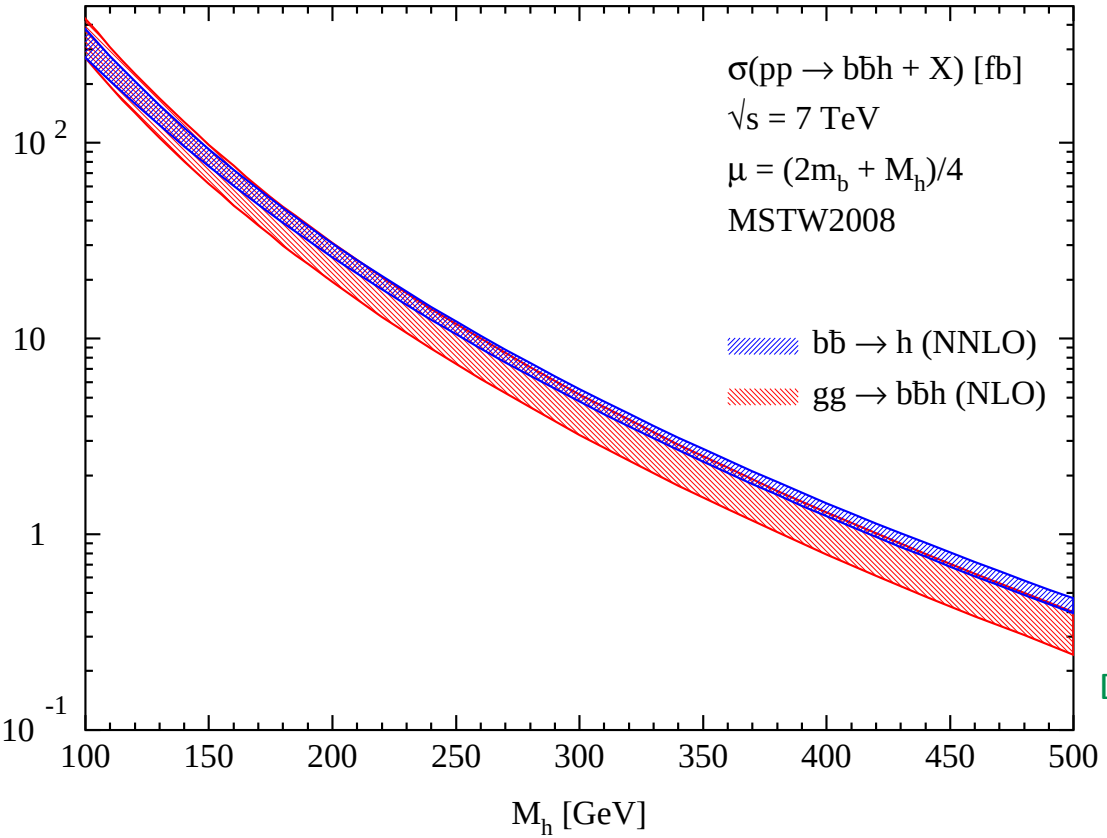
NNLO

exact $g \to b\bar{b}$ splitting & mass/off-shell effects

no resummation of $\log M_H^2/m_b^2$ terms

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

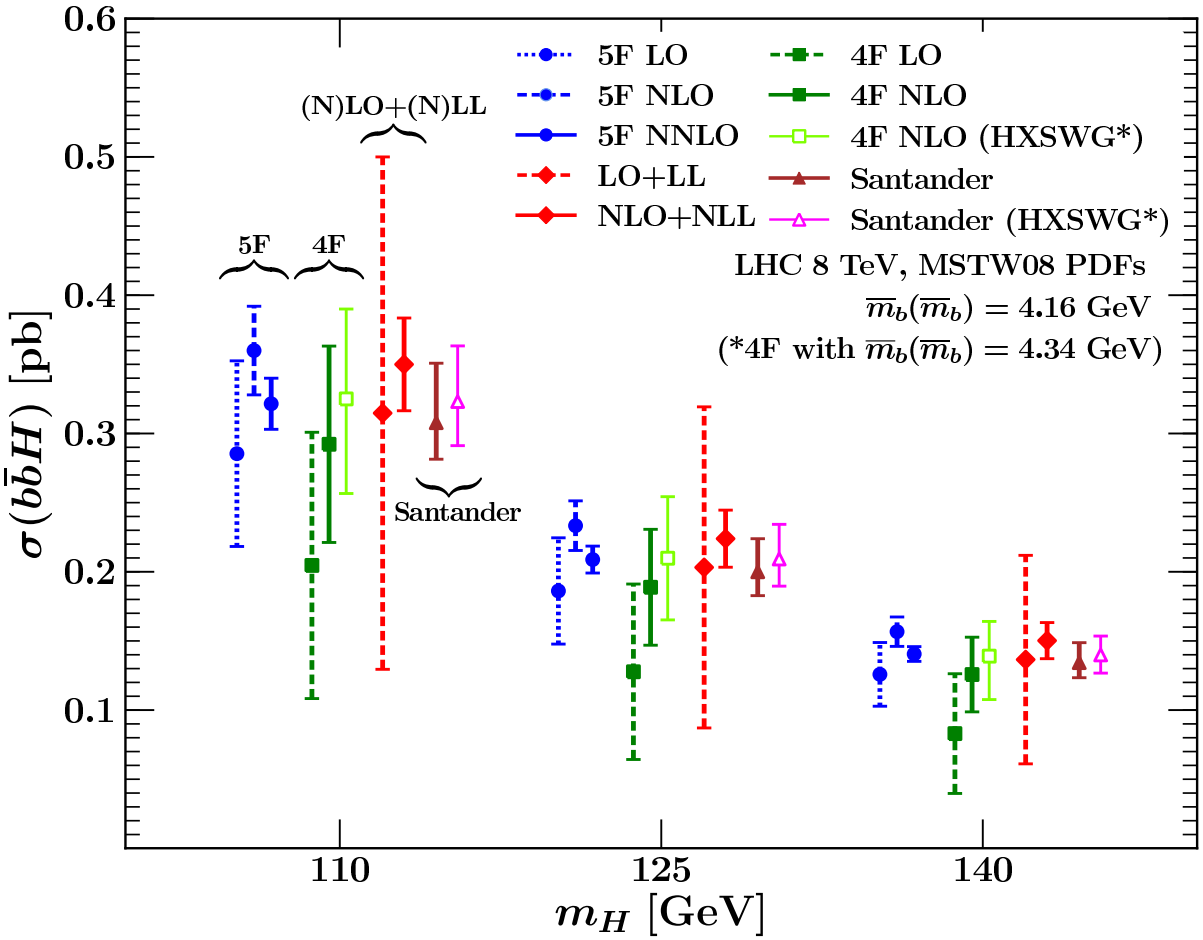
Dittmaier, Krämer, S. Dawson, Jackson, Reina, Wackeroth

Harlander, Kilgore

- two approaches for proper matching 4FS + 5FS

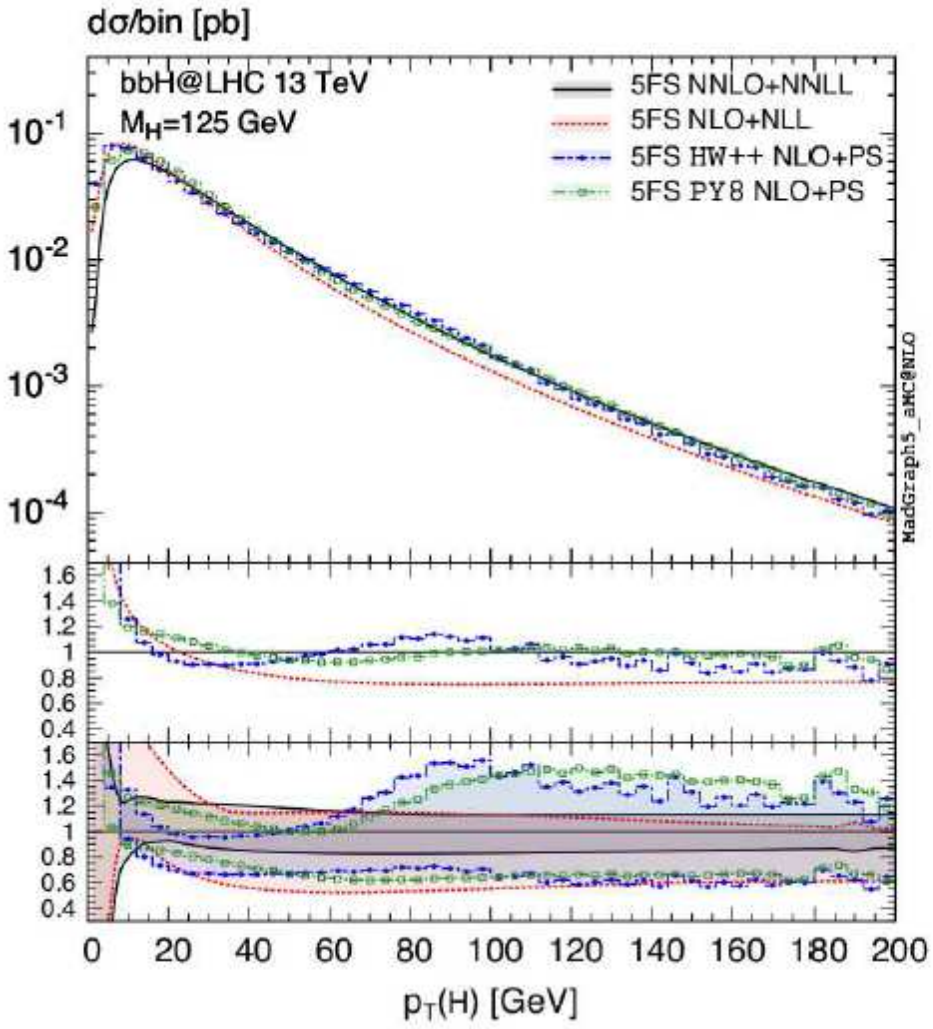
Bonvini, Papanastasiou, Tackmann

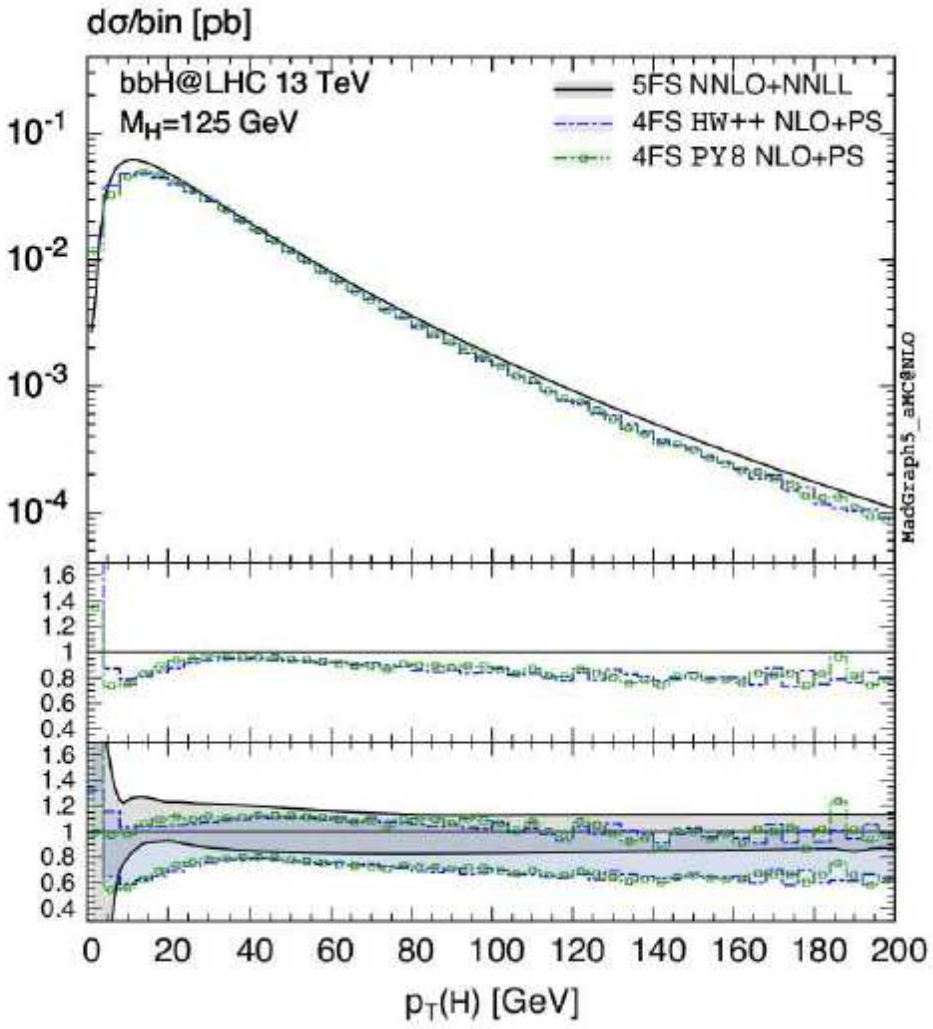
Forte, Napoletano, Ubiali



Bonvini, Papanastasiou, Tackmann

distributions





Wiesemann, Frederix, Frixione, Hirschi, Maltoni, Torrielli MG5_aMC@NLO

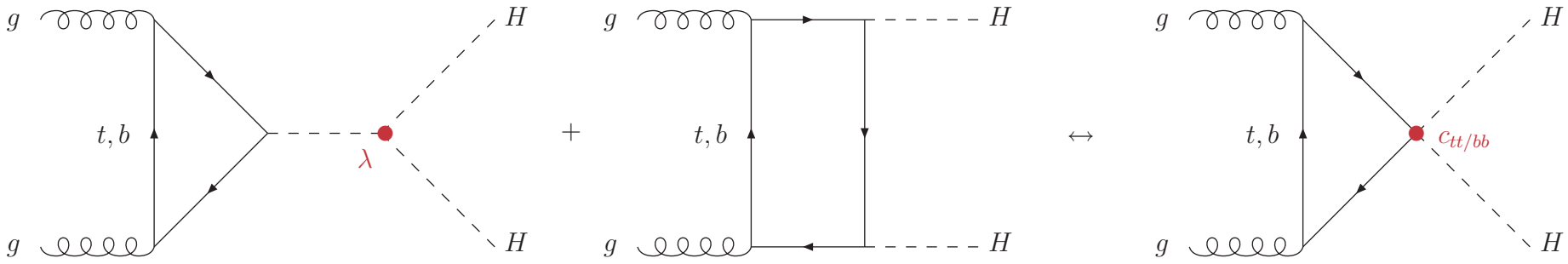
In Peter's group you have to talk, talk, talk... (think about Plehn, Spira, Zerwas. . .)

IV *CONCLUSIONS*

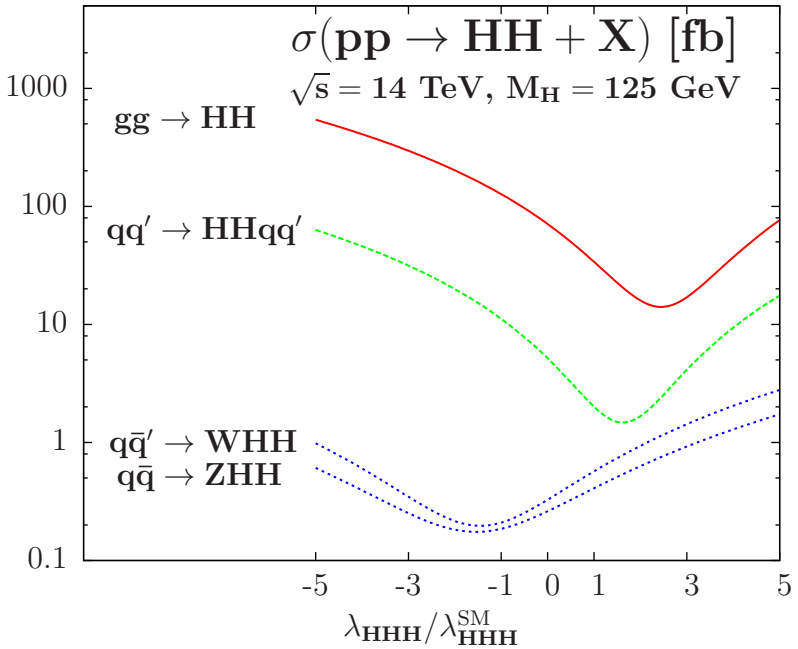
- Higgs boson searches/studies at LHC belong to major endeavours
- most QCD and elw. corrections known $\rightarrow \Delta \lesssim 10 - 15\%$ @ LHC
- several dedicated HO–tools available
- important to develop NLO event generators [$\leftarrow$ backgrounds]
- open problems: p_{TH} distribution for b-loops, quark mass effects in $gg \rightarrow H + X, \ldots$

BACKUP SLIDES

$gg \to HH$



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



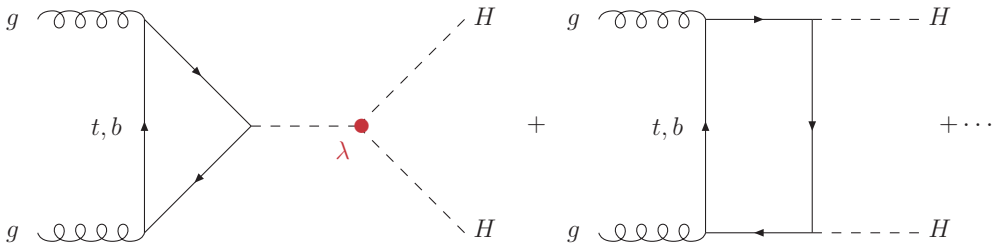
$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

[decreasing with M^2_{HH}]

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

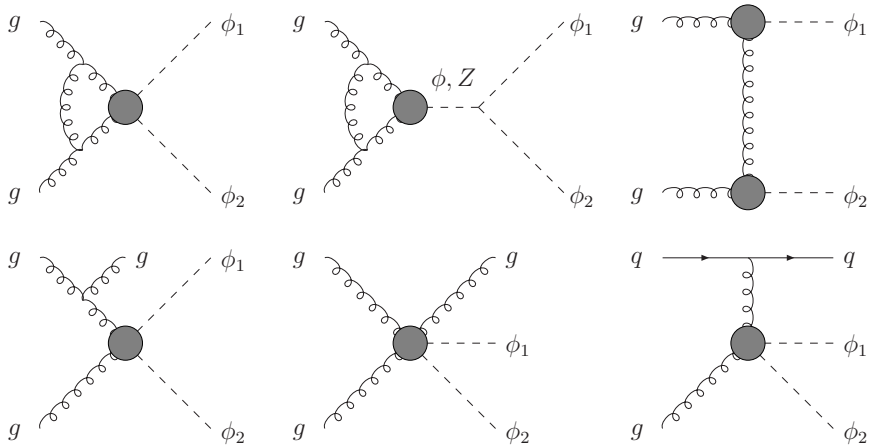
$gg \to HH$

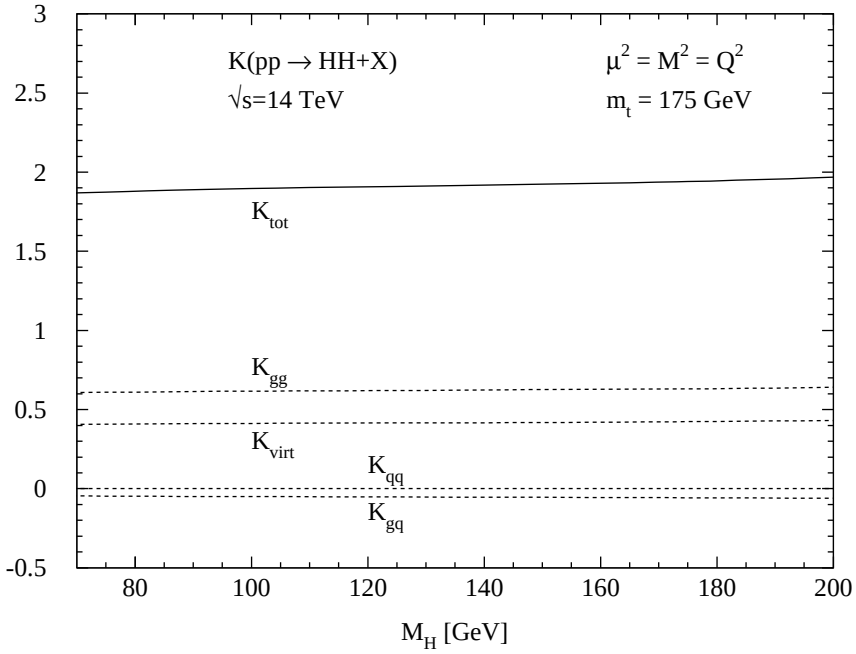
SM



- third generation dominant $\longrightarrow t, b$

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

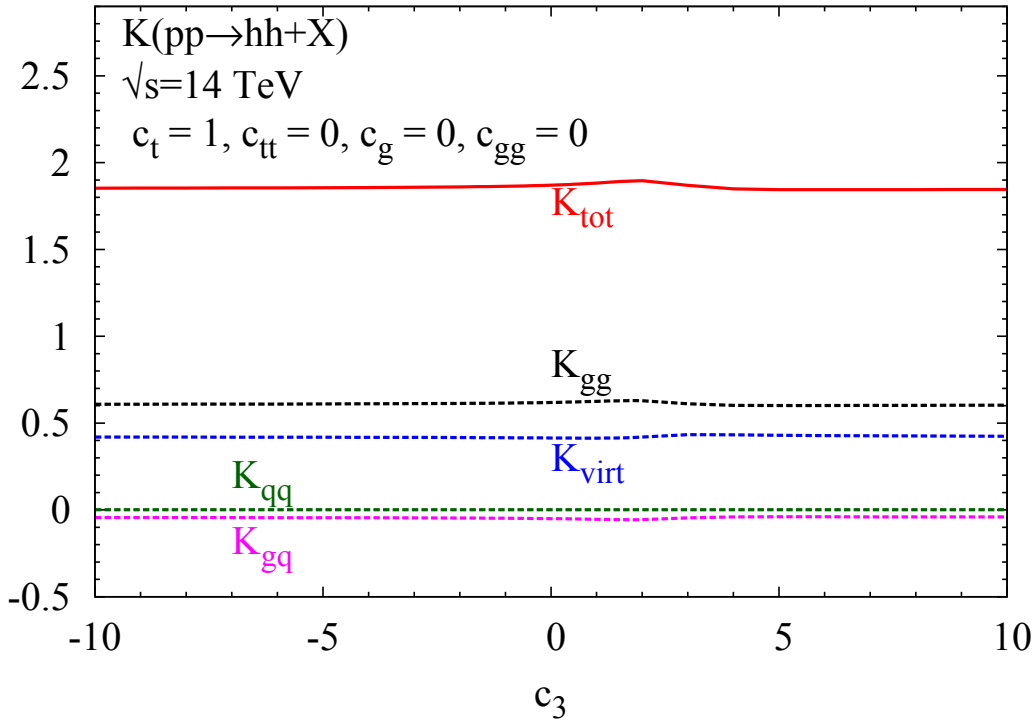


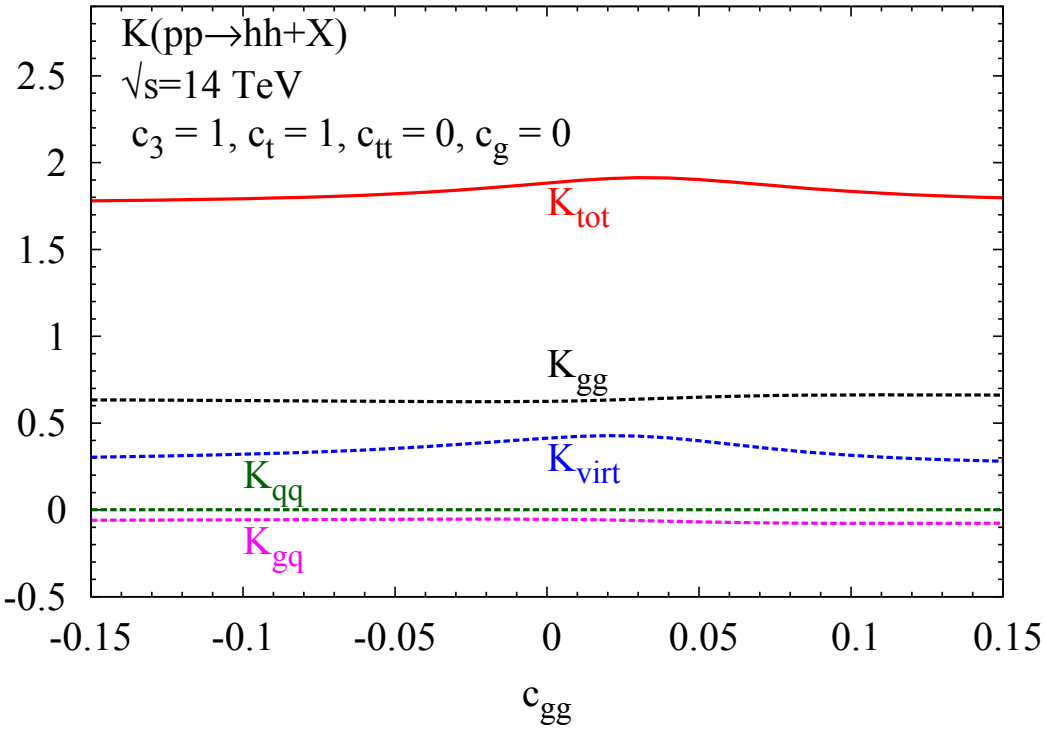


Dawson, Dittmaier, S.

- extended to dim6 $\rightarrow$ 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:

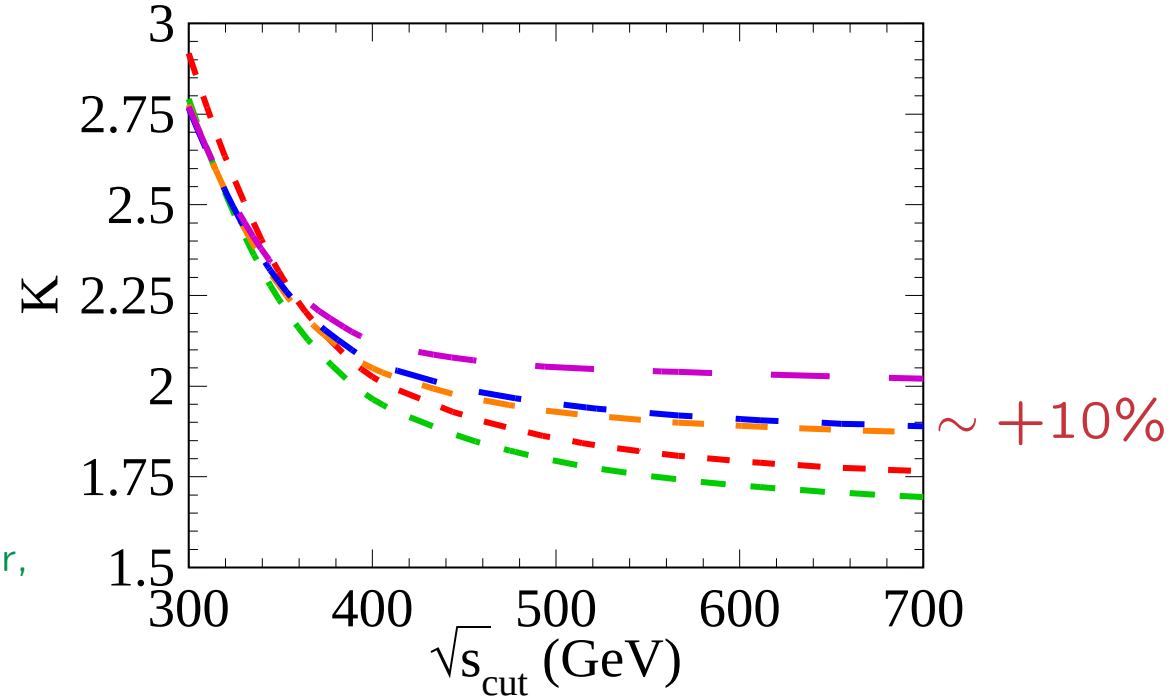
$$\sigma = \sigma_0 + \frac{\sigma_1}{m_t^2} + \cdots + \frac{\sigma_4}{m_t^8}$$

Grigo, Hoff, Melnikov, Steinhauser

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

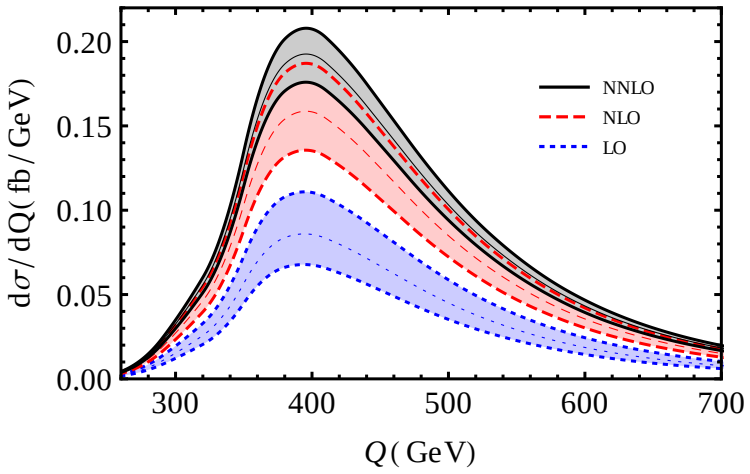
Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro

$\rightarrow$ large virtual mass effects



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

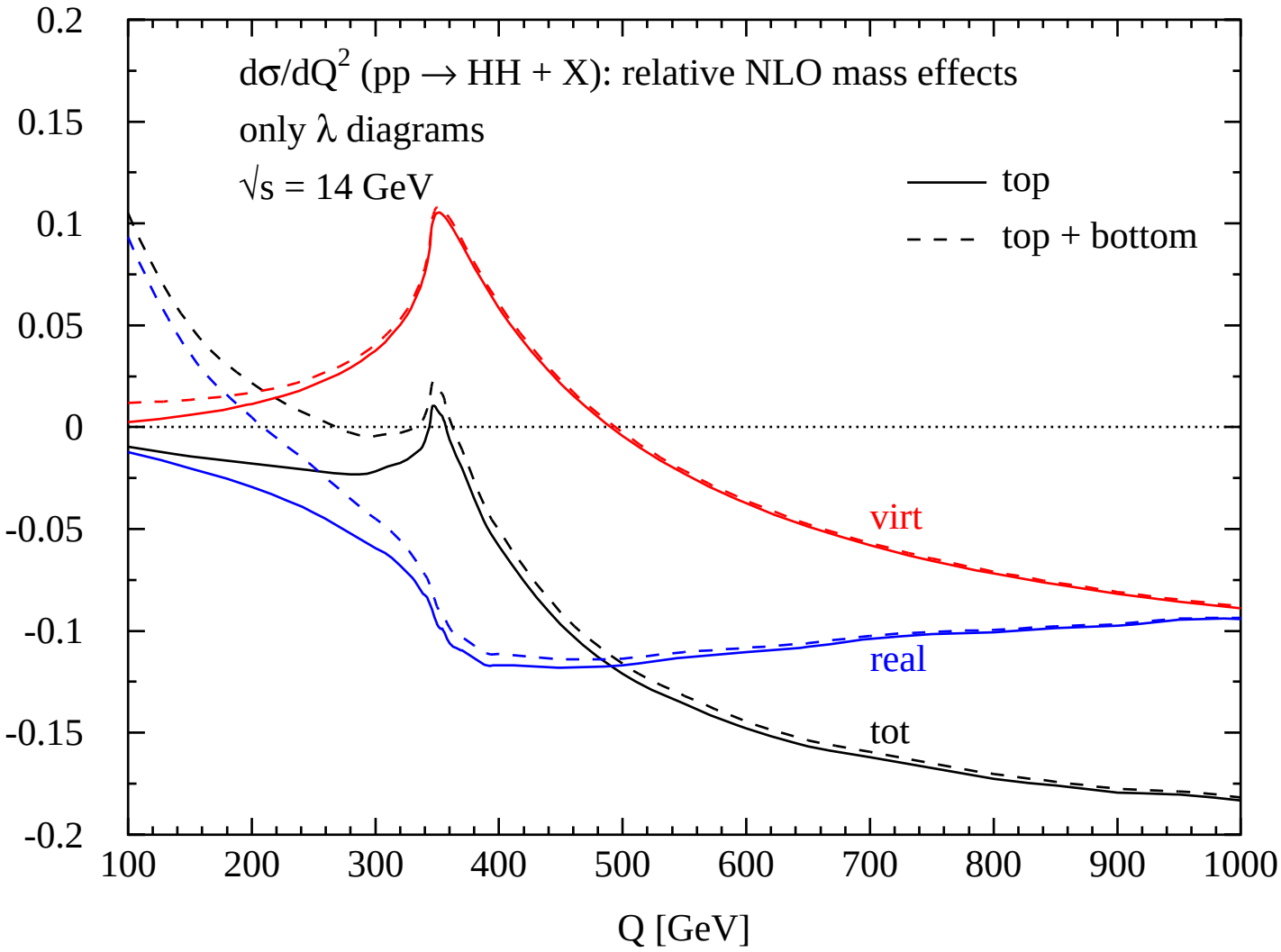
de Florian, Mazzitelli
Grigo, Melnikov, Steinhauser



- 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 ← boxes different?