Maria Laach
Herbstschule für Hochenergiephysik

# Electroweak Aspects of the Standard Model

—

# Lecture IV: Higgs Physics

Stefan Dittmaier
Albert-Ludwigs-Universität Freiburg

# Overview

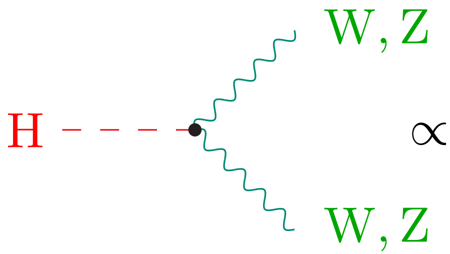
# Higgs search at the LHC

# –

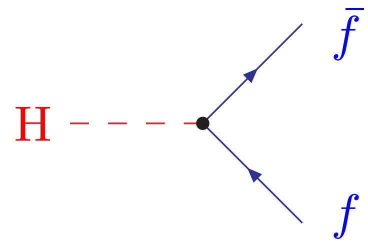
# generalities

# Higgs search at the LHC

Higgs bosons couple proportional to particle masses:




$\propto M_{\mathrm{W}}$

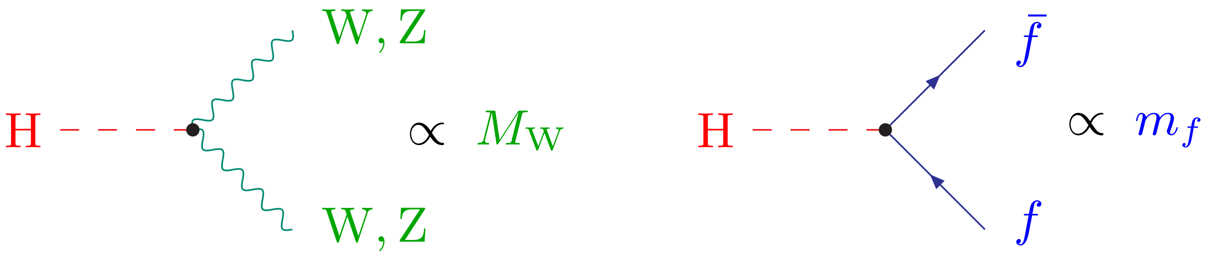



$\propto m_f$

$\Rightarrow$ Higgs production via couplings to W/Z bosons or top-quarks

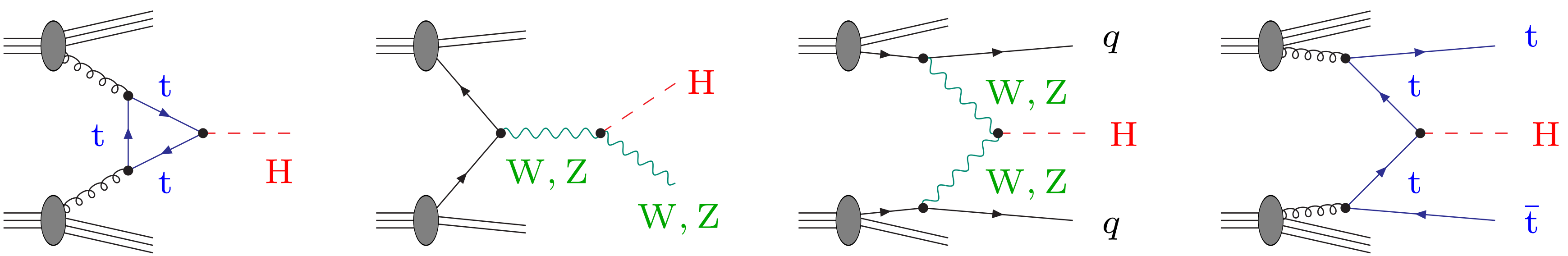
# Higgs search at the LHC

Higgs bosons couple proportional to particle masses:



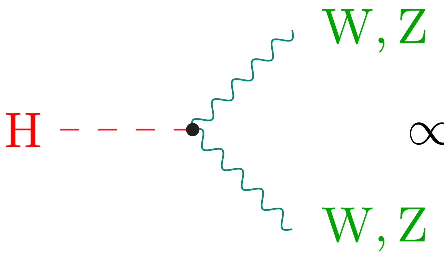

$\Rightarrow$ Higgs production via couplings to W/Z bosons or top-quarks

Processes at hadron colliders ($\mathrm{p\bar{p}/pp}$):

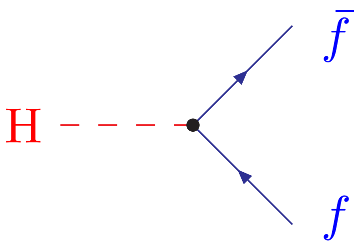


# Higgs search at the LHC

Higgs bosons couple proportional to particle masses:



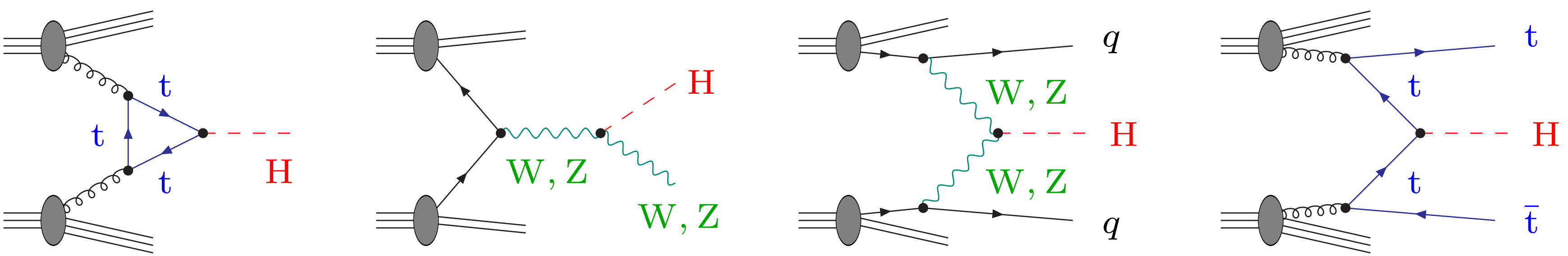

$\propto\ M_{\mathrm{W}}$



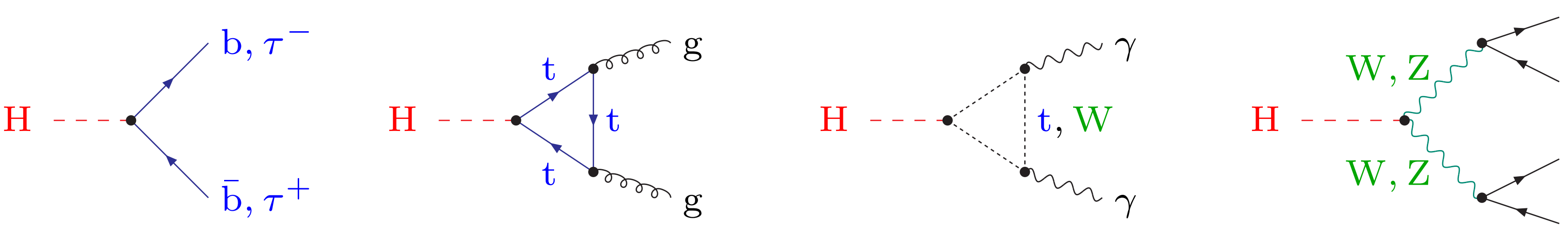

$\propto\ m_f$

⇒ Higgs production via couplings to W/Z bosons or top-quarks

Processes at hadron colliders ($\mathrm{p\bar{p}/pp}$):

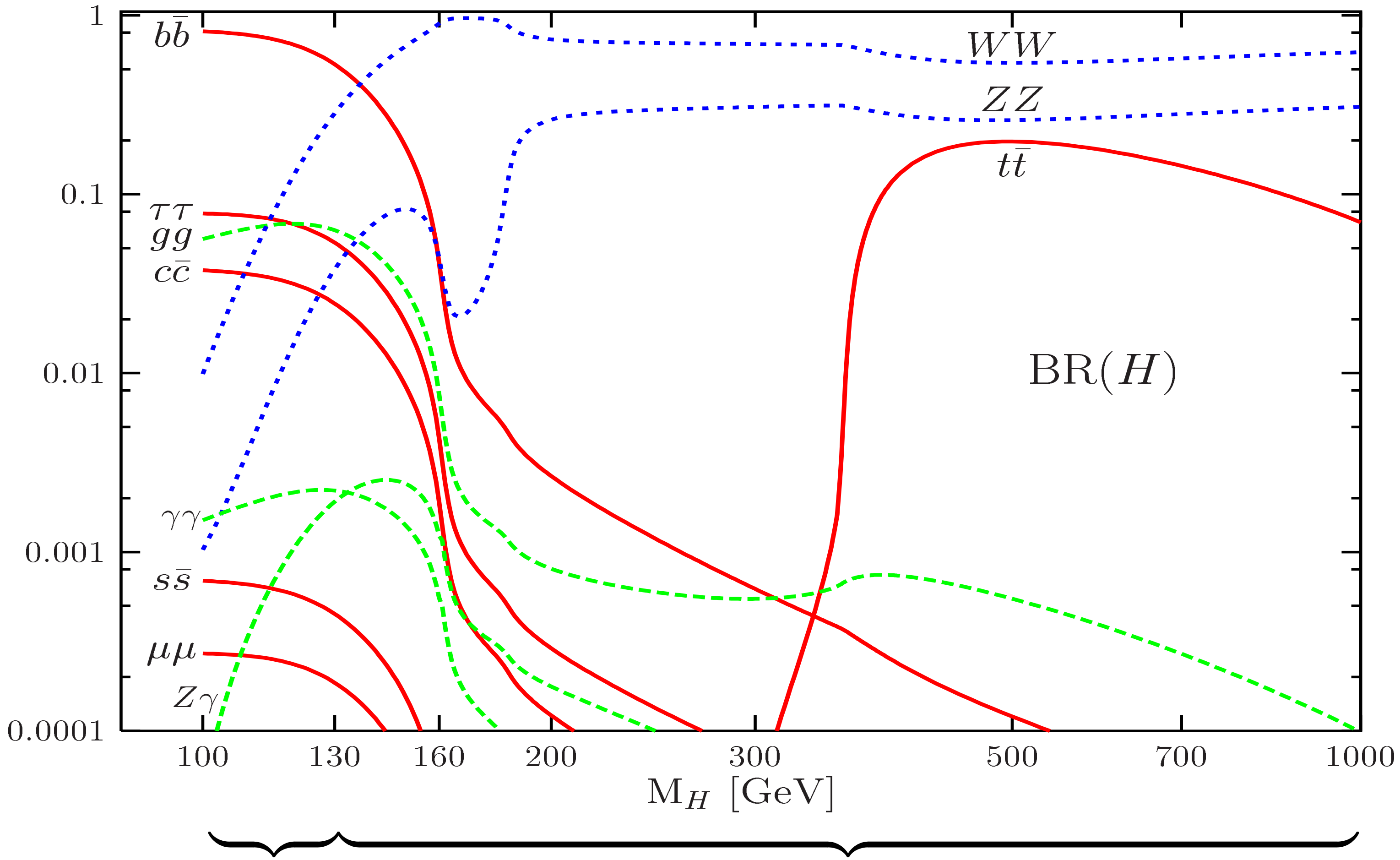



Decay channels for Higgs bosons of moderate mass ($M_{\mathrm{H}} \lesssim 300\,\mathrm{GeV}$):



# Branching ratios of the SM Higgs boson

HDECAY (Djouadi, Kalinoswki, Spira)

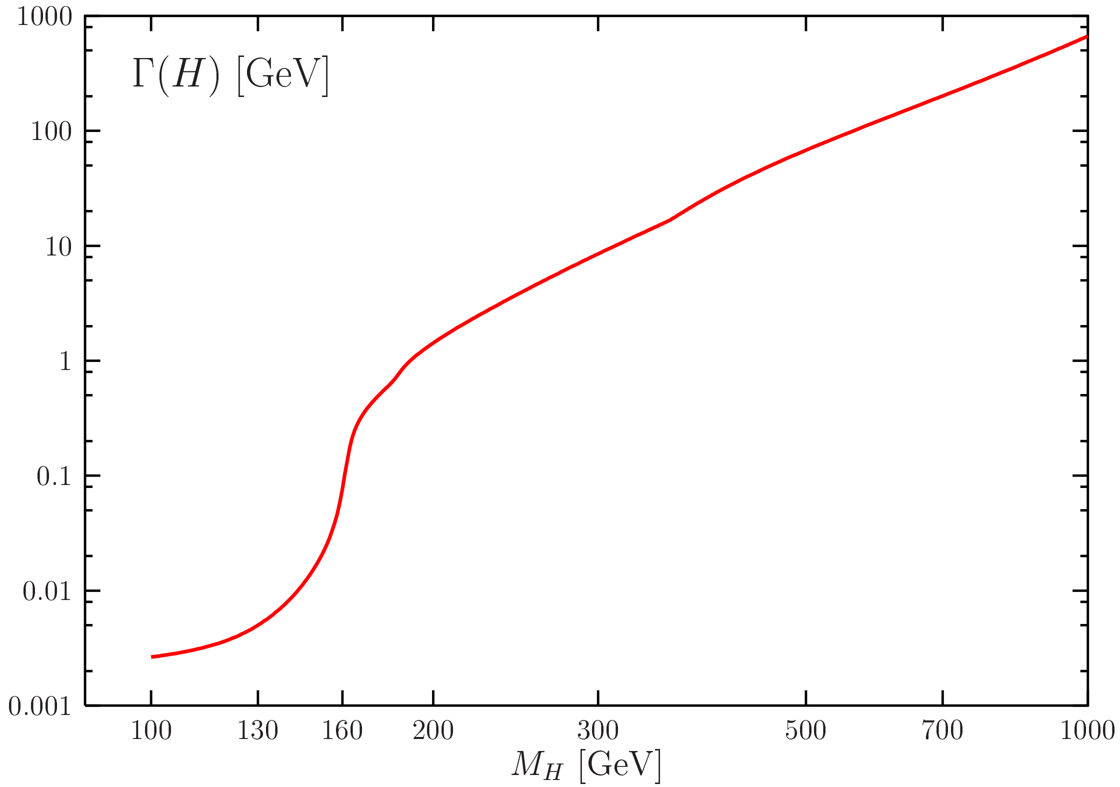



experimentally difficult:
$\mathrm{b\bar{b}}$ with large background,
decays into $\gamma\gamma$, $\tau\tau$ rare

experimentally clear signals by
$\mathrm{H} \to \mathrm{WW} \to 2$ leptons $+ 2$ neutrinos or
$\mathrm{H} \to \mathrm{ZZ} \to 4$ leptons

# Total Higgs decay width

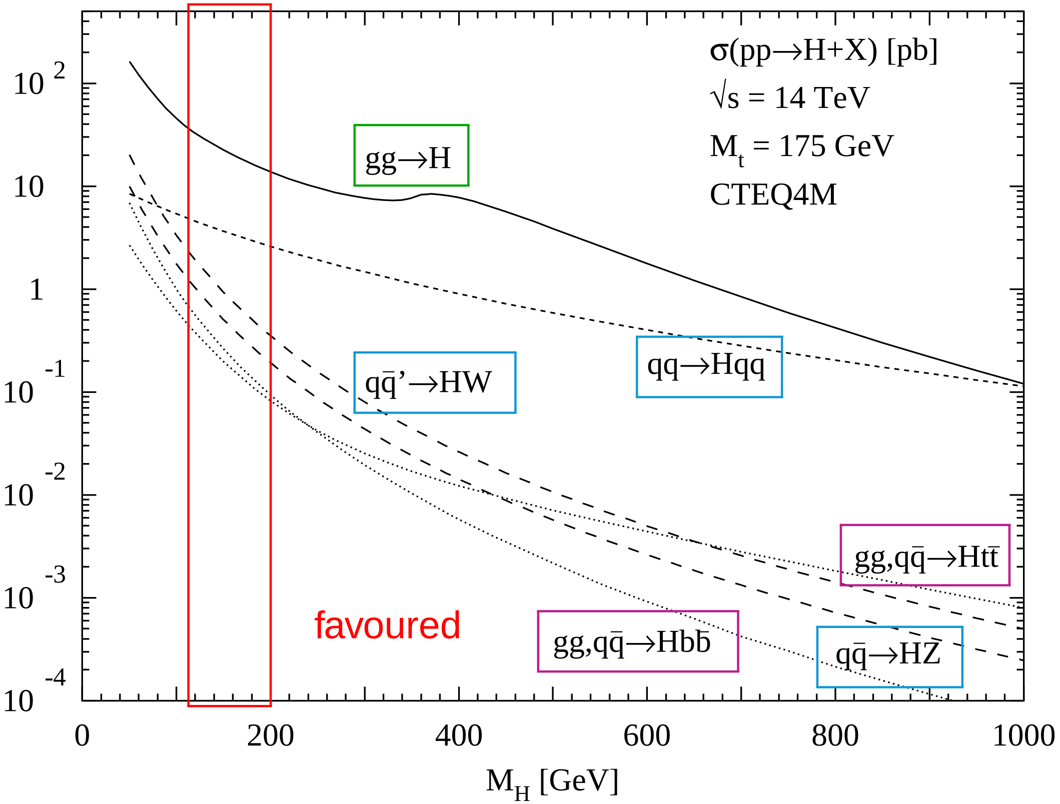
HDECAY (Djouadi, Kalinoswki, Spira)

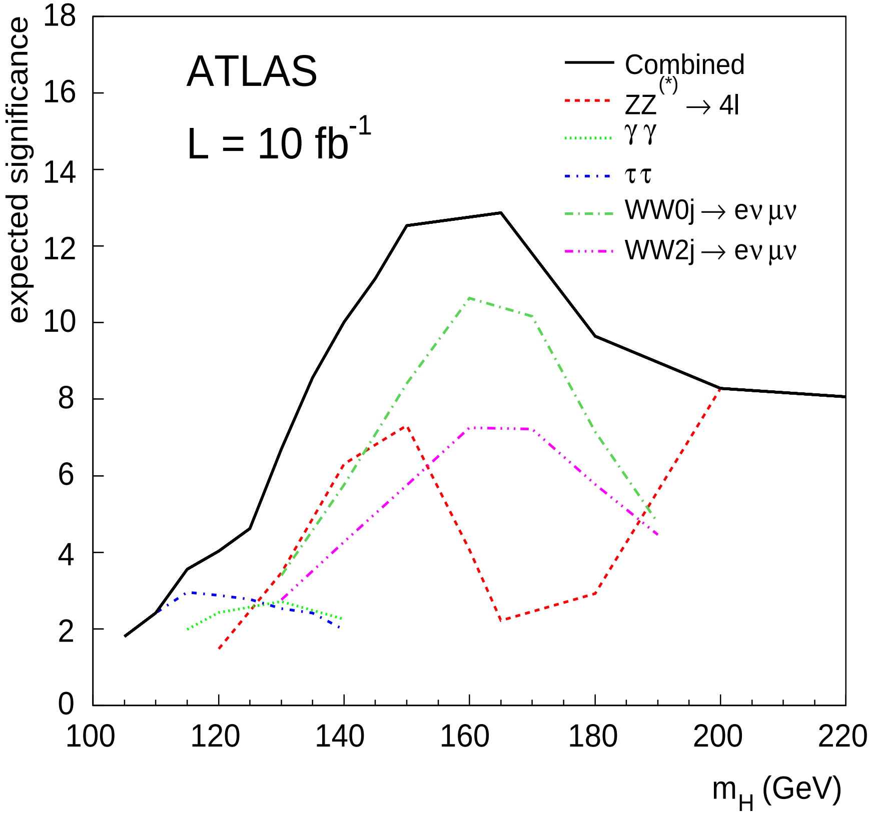



| $\Gamma_{\mathrm{H}}/M_{\mathrm{H}}$ | $\lesssim 0.001$ | $\sim 0.004 - 0.1$ | $\gtrsim 0.4 = \mathcal{O}(1)$ |
|---|---|---|---|
| | extremely narrow<br>$\downarrow$<br>$\Gamma_{\mathrm{H}}$ below exp. resolution | intermediate width | very broad<br>$\downarrow$<br>particle concept?<br>interference with background?! |

# Cross sections and significance of the Higgs signal at the LHC

(not only) Spira et al.



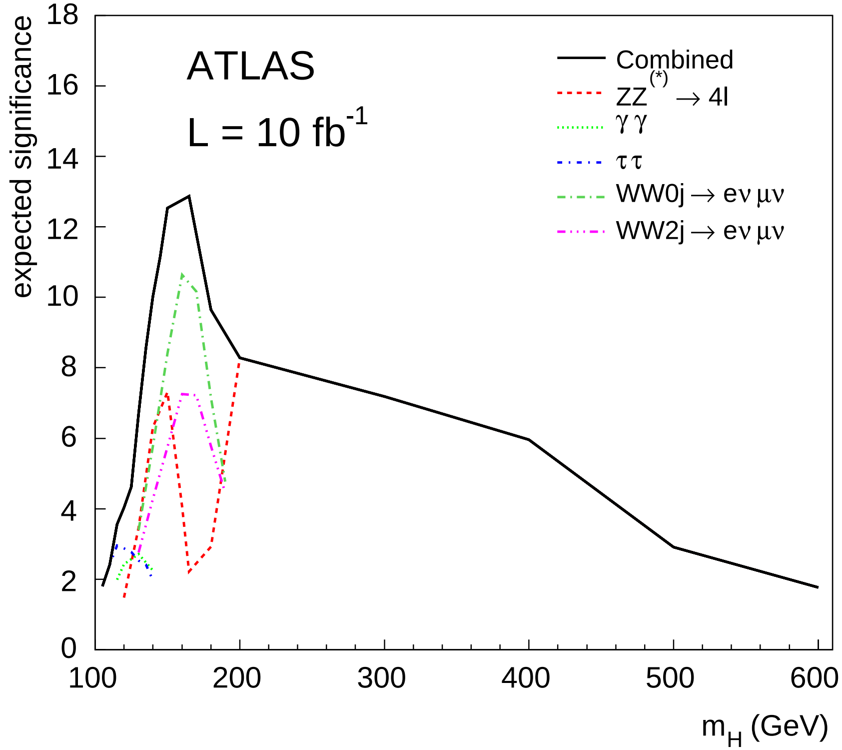

Typical size of perturbative corrections at next-to-leading order (NLO):

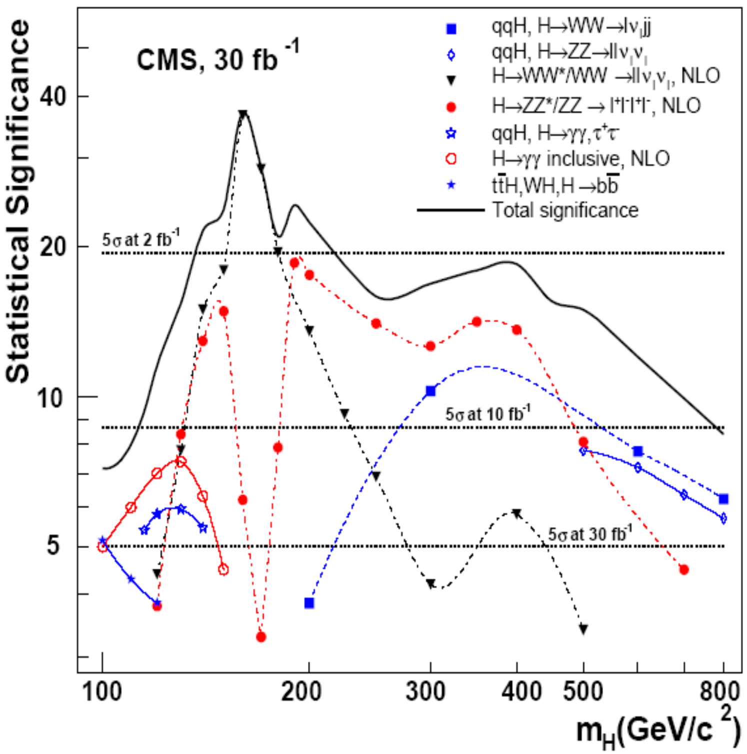
QCD: $\mathcal{O}(\alpha_s) \sim 10{-}100\%$ Electroweak: $\mathcal{O}(\alpha) \sim 10\%$

↪ calculate / control higher orders to reduce theoretical uncertainty down to the level of PDF ($q\bar{q} \sim 5\%$, $gg \sim 5{-}10\%$) and experimental uncertainties

Complication: task requires "multi-loop" or "multi-leg" computations

# Higgs signal significance at the LHC for higher Higgs masses



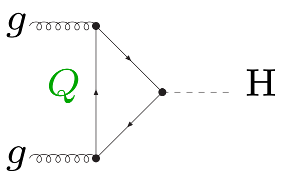

Significant signal in entire $M_{\mathrm{H}}$ range

But: perturbation theory runs out of control for $M_{\mathrm{H}} \gtrsim 700\,\mathrm{GeV}$

# Higgs-boson production
# –
# gluon fusion

# Higgs production via gluon fusion

LO:

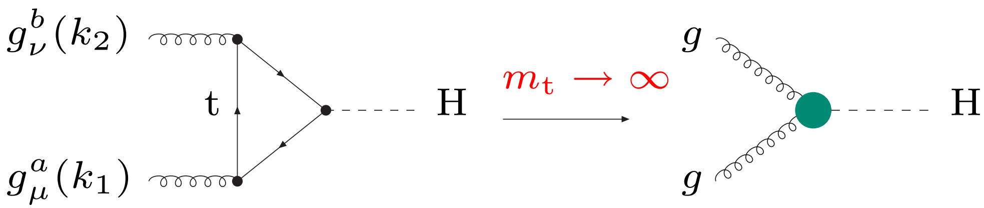



**Process is loop-induced**

- dominant contribution: $Q$ = top quark
- strong dependence on fact. & ren. scales ($\sim 100\%$ !)
  $\hookrightarrow$ hint to large corrections – higher orders important !

## Effective theory for $m_\mathrm{t} \to \infty, m_\mathrm{b} \to 0$ $\quad\to$ simplifies loop calculations considerably

LO:

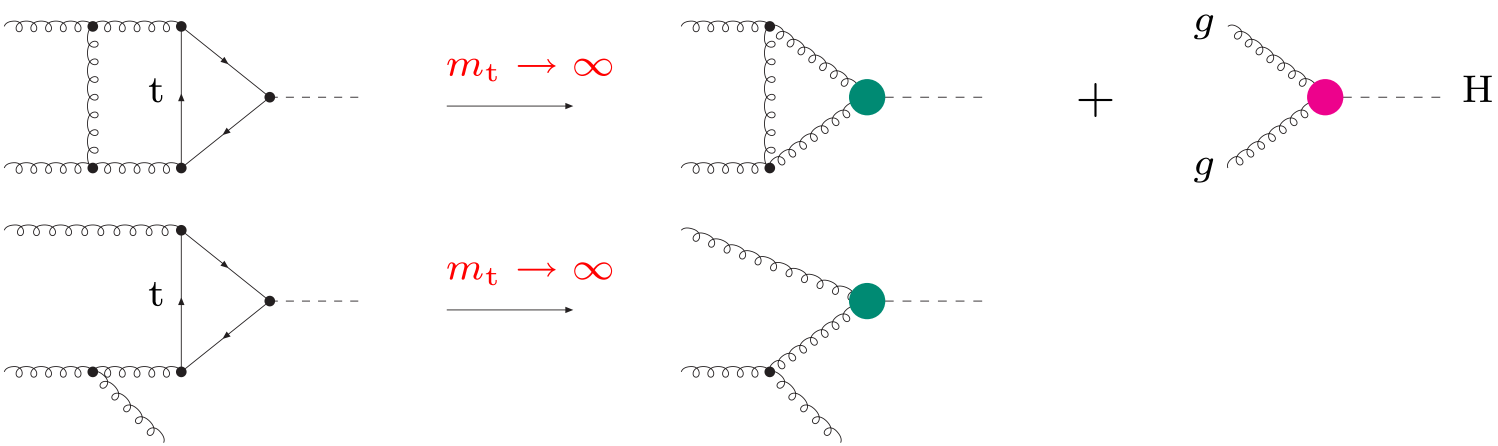



$$= \frac{\mathrm{i}\alpha_\mathrm{s}\delta_{ab}}{3\pi v}\Big[-g_{\mu\nu}(k_1 k_2) + k_{1,\nu}k_{2,\mu}\Big]$$

$\hookrightarrow$ local effective interaction: $\mathcal{L}_\mathrm{Hgg} = \frac{\alpha_\mathrm{s}}{12\pi} F^a_{\mu\nu} F^{a,\mu\nu} \frac{H}{v}$

$$\times \Big(1 + \underbrace{\frac{11\alpha_\mathrm{s}}{4\pi}}_{\text{from higher orders}} + \dots\Big)$$

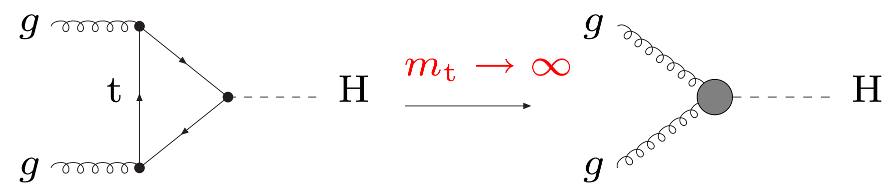
NLO:



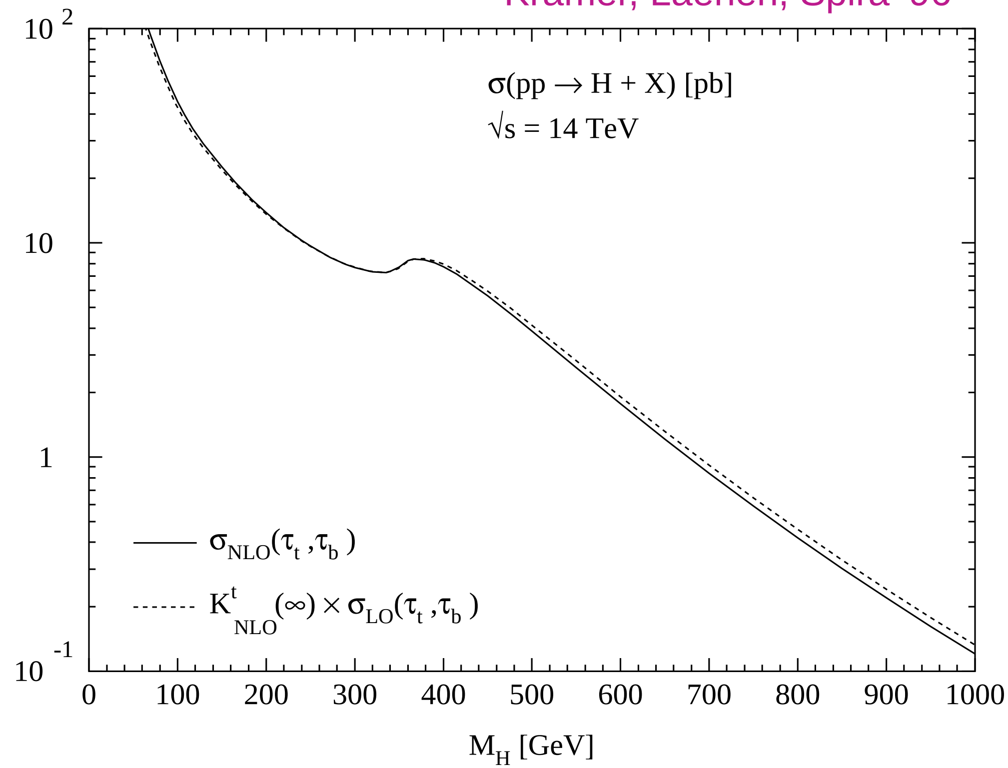
## Approximation of QCD corrections in limit $m_\mathrm{t} \to \infty, m_\mathrm{b} \to 0$:

physical picture: long-range gluon interaction does not resolve $\mathrm{H}$ production

$\hookrightarrow$ effective gluon–Higgs coupling:




Krämer, Laenen, Spira '96




Approximation for $\mathrm{pp} \to \mathrm{H}$ in NLO:

$\sim 5\%$ for $M_\mathrm{H} \lesssim 2m_\mathrm{t} \approx 350\,\mathrm{GeV}$

$\sim 10\%$ for $M_\mathrm{H} \lesssim 1\,\mathrm{TeV}$

# Corrections to Higgs-boson production via gluon fusion

- QCD corrections:
  - ◇ complete NLO correction known

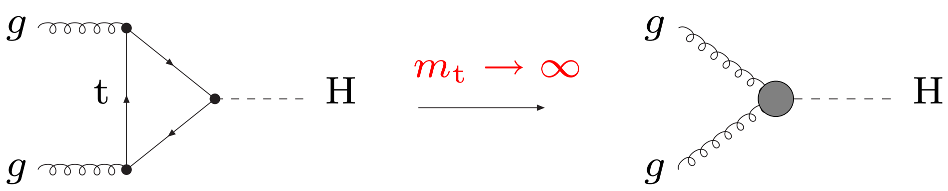
    Graudenz, Spira, Zerwas ’93
    Djouadi, Graudenz, Spira, Zerwas ’95

  - ◇ NNLO correction known as expansion for $m_t \to \infty$ matched with $\hat{s} \to \infty$

$$K = \frac{\sigma_{NNLO}}{\sigma_{LO}} \sim 2.0$$

    Harlander, Kilgore ’01,’02
    Catani, de Florian, Grazzini ’01
    Anastasiou, Melnikov ’02
    Ravindran, Smith, v.Neerven ’03,’04
    Anastasiou, Melnikov, Petriello ’04
    Marzani et al. ’08
    Pak, Rogal, Steinhauser ’09
    Harlander, Ozeren ’09

  - ◇ resummations / virtual / soft terms to NNNLO in limit $m_t \to \infty$




$m_t \to \infty$

    Catani et al. ’03; Moch, Vogt ’05
    Laenen, Magnea ’05; Idilbi, Ji, Ma, Yuan ’05
    Ravindran ’05,’06; Ravindran, Smith, v.Neerven ’06
    Ahrens, Becher, Neubert, Yang ’08

- EW corrections
  - ◇ complete NLO correction known $\sim \mathcal{O}(5\%)$

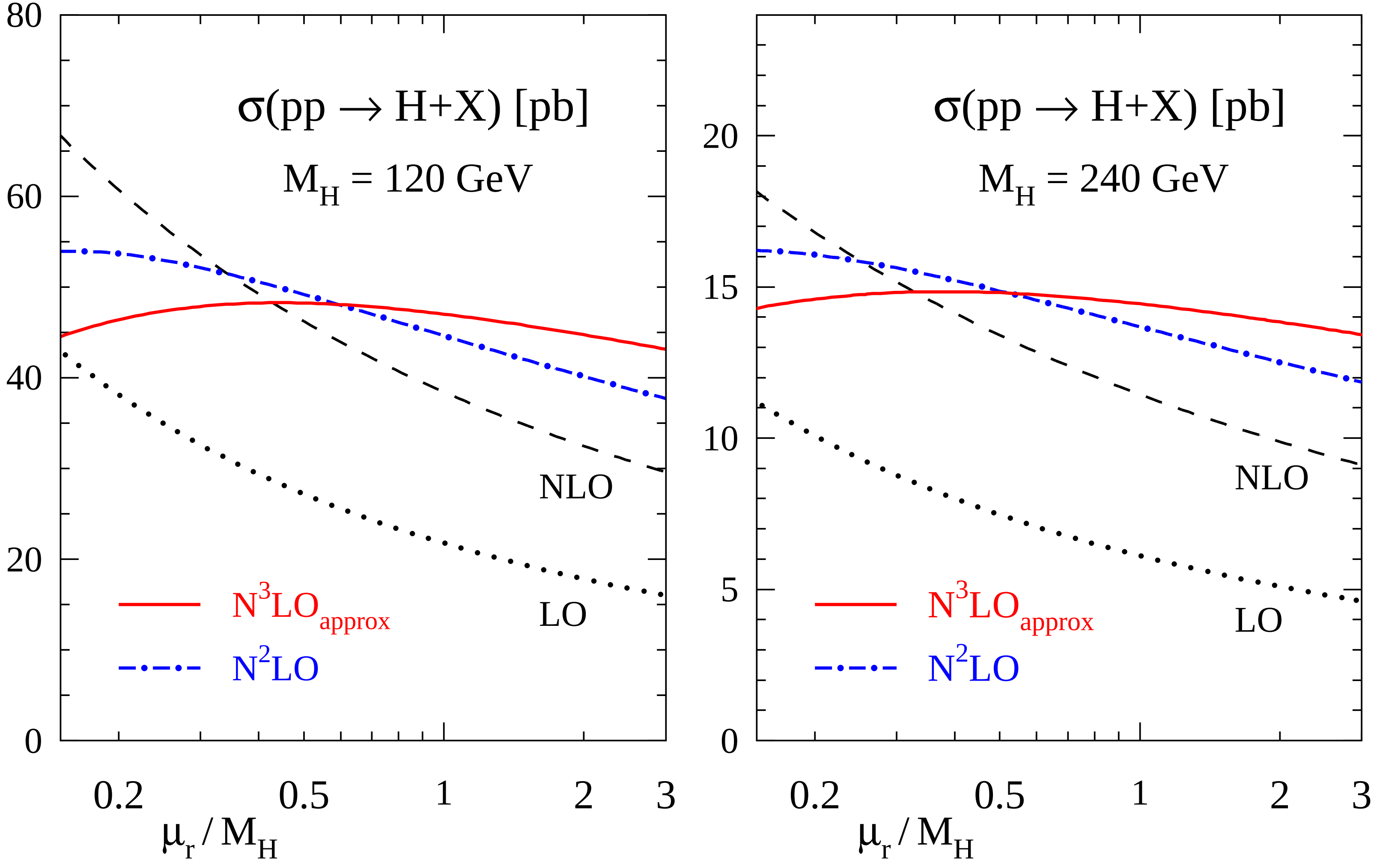
    Aglietti, Bonciani, Degrassi, Vicini ’04,’06
    Degrassi, Maltoni ’04
    Actis, Passarino, Sturm, Uccirati ’08

  - ◇ mixed $\mathcal{O}(\alpha\alpha_s)$ corrections for small $M_H$

    Anastasiou, Boughezal, Petriello ’08

## QCD scale dependence of predictions for inclusive $gg \to \mathrm{H}$

Moch, Vogt ’05



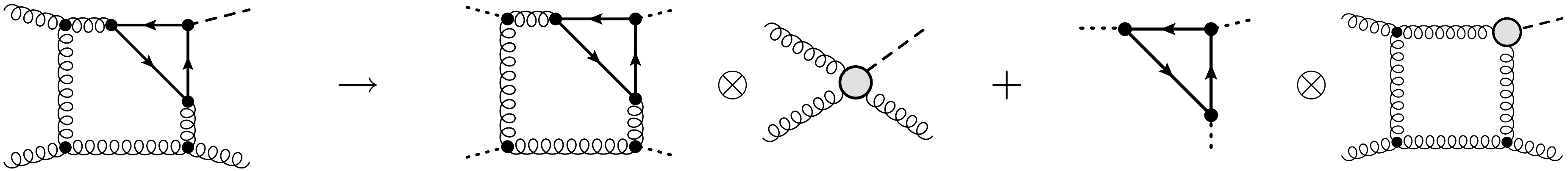

Reduction of renormalization-scale dependence with increasing orders !

$\hookrightarrow$ residual scale uncertainty $\lesssim 5{-}10\%$

Recent error estimate with MSTW2008 NNLO: $\delta_{\mathrm{PDF}} \lesssim 3\%$ de Florian, Grazzini ’09

# Improved $1/m_t$ expansion at NNLO QCD Harlander, Ozeren '09

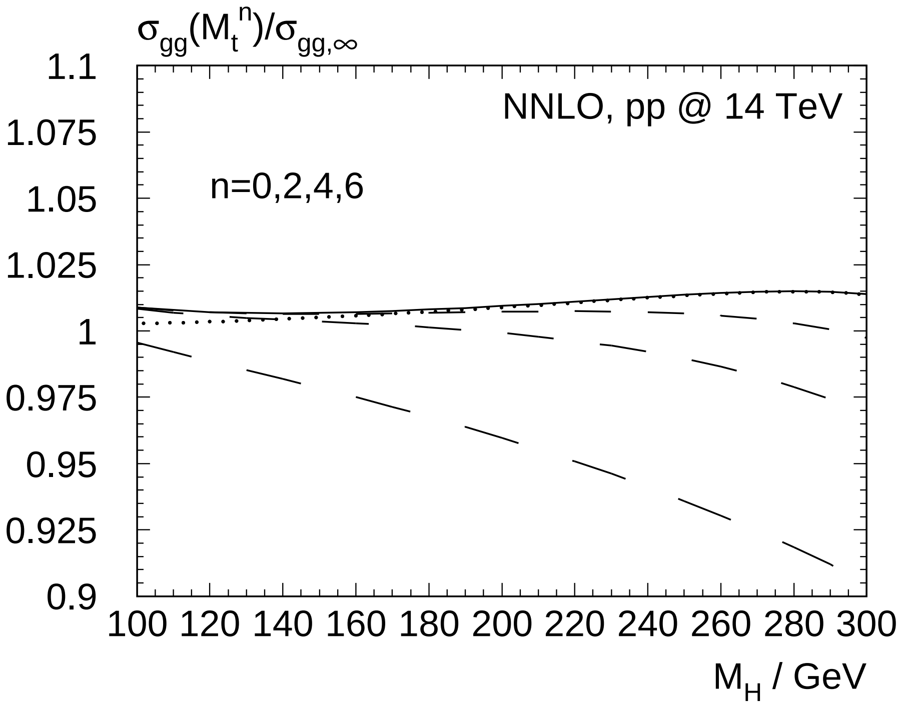
Heavy-top expansion (here illustrated for real–virtual part of NNLO)



with proper matching of the soft ($\hat{s} \to M_H^2$) and high-energy ($\hat{s} \to \infty$) limits

Marzani et al. '08

yields full $m_t$ dependence of cross section within $\mathcal{O}(0.5\%)$:




$\sigma_{gg,\infty}$ = pure $m_t \to \infty$ limit for NNLO part

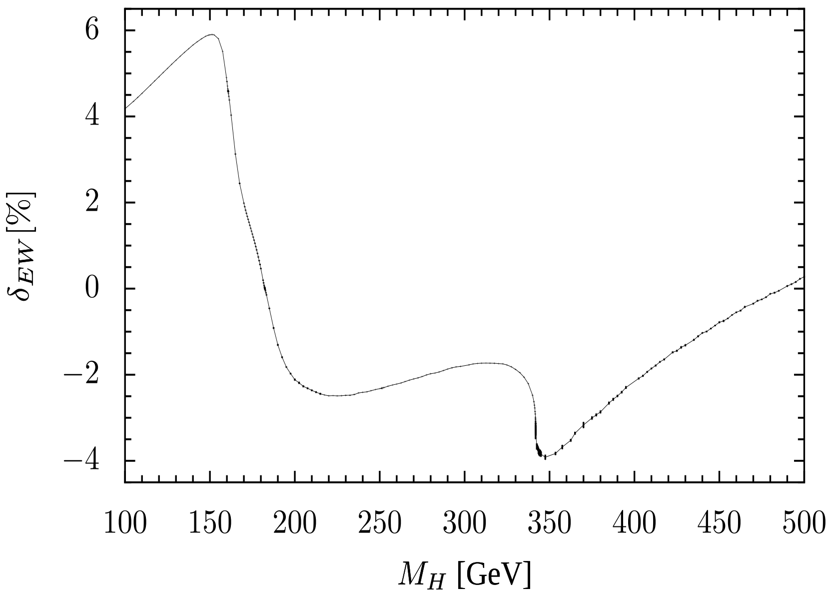
$\sigma_{gg}(M_t^n)$ includes NNLO terms of $\mathcal{O}(1/m_t^n)$

(dashes: $n = 0, 2, 4$; solid line: $n = 6$)

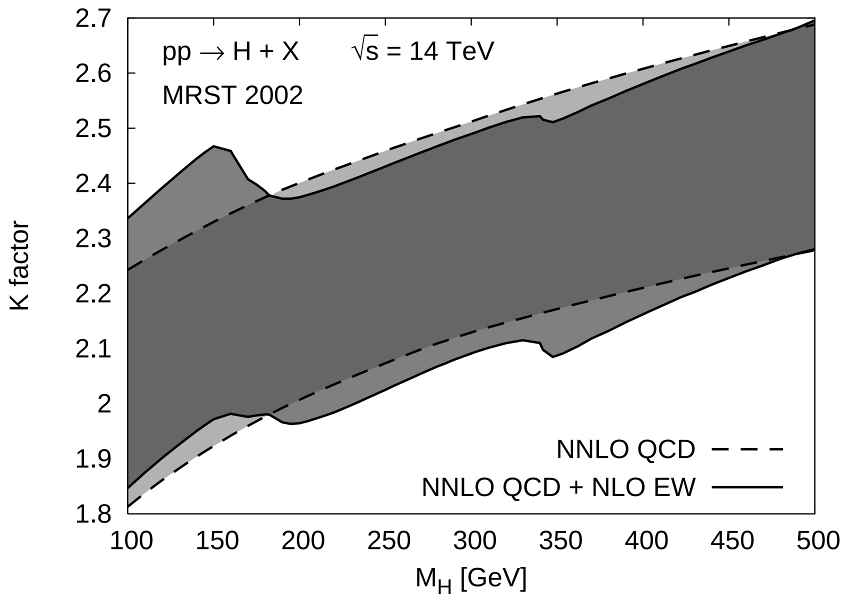
## NLO EW corrections

Actis, Passarino, Sturm, Uccirati '08

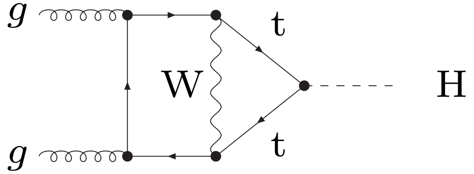
Correction to partonic cross section:




$K$ factors for $\mathrm{pp}$ cross section:
(band width: $M_\mathrm{H}/2 < \mu_{\mathrm{R/F}} < 2M_\mathrm{H}$, $\mu_\mathrm{R}/2 < \mu_\mathrm{F} < 2\mu_\mathrm{R}$)




EW corrections ...




etc.

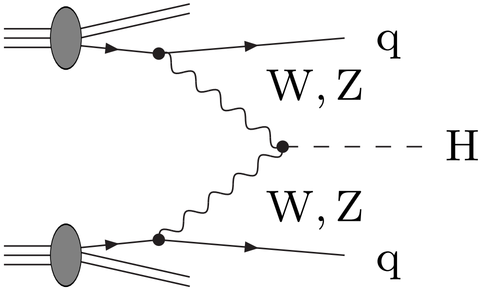
- matter at the $5\%$ accuracy level
- show non-trivial structures near $\mathrm{WW}$, $\mathrm{ZZ}$, $\mathrm{t\bar{t}}$ thresholds
  $\hookrightarrow$ finite widths of particles in loops required (otherwise unphysical peaks)
- mixed $\mathcal{O}(\alpha\alpha_\mathrm{s})$ corrections for small $M_\mathrm{H}$ Anastasiou, Boughezal, Petriello '08
  suggest factorization of QCD and EW corrections within good accuracy

# Higgs-boson production

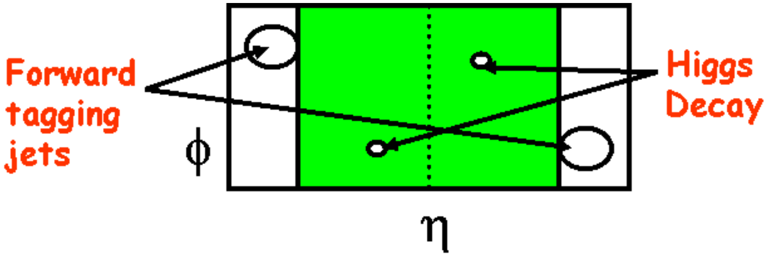
# –

# vector-boson fusion

## Higgs production via VBF
## and background suppression by cuts:

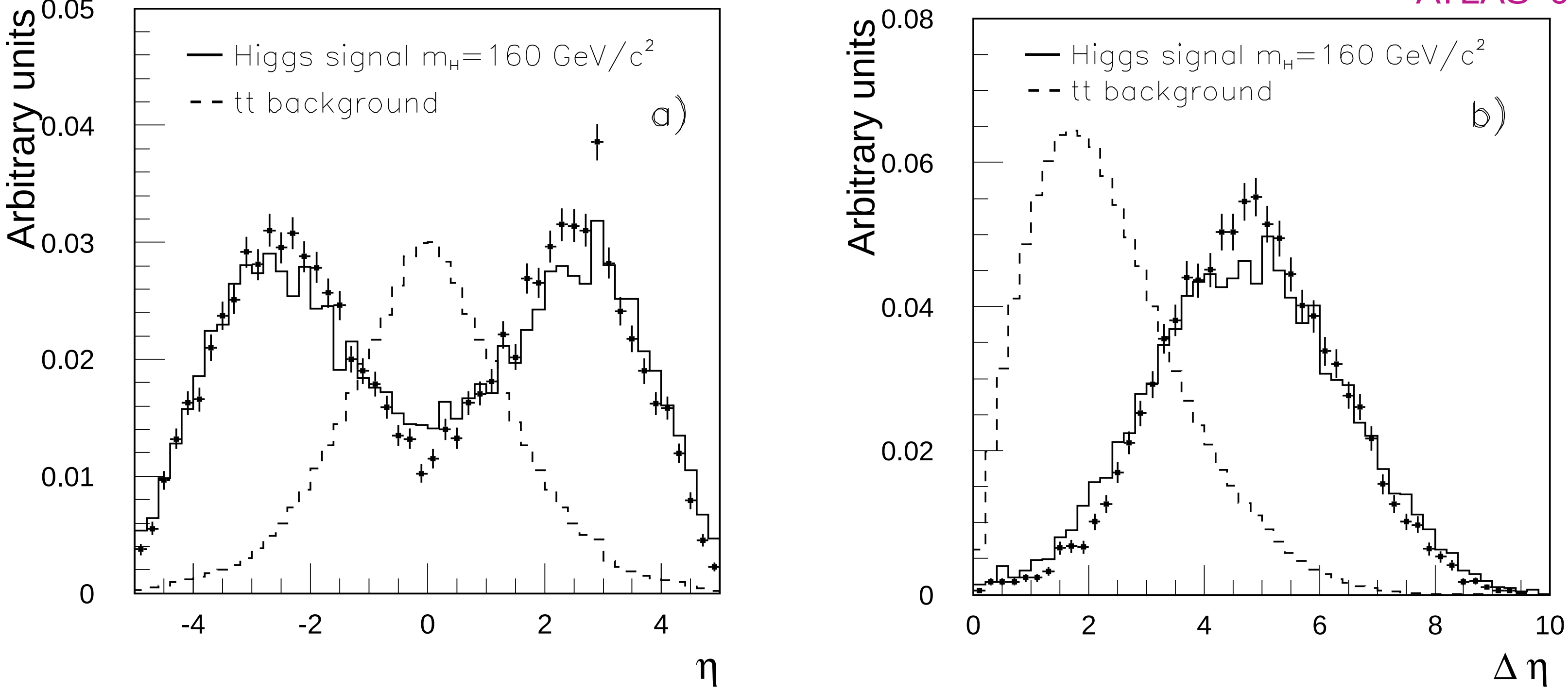



- 2 hard "tagging" jets demanded:
  $p_{\mathrm{Tj}} > 20\,\mathrm{GeV}, \quad |y_{\mathrm{j}}| < 4.5$
- tagging jets forward–backward directed:
  $\Delta y_{\mathrm{jj}} > 4, \quad y_{\mathrm{j1}} \cdot y_{\mathrm{j2}} < 0.$

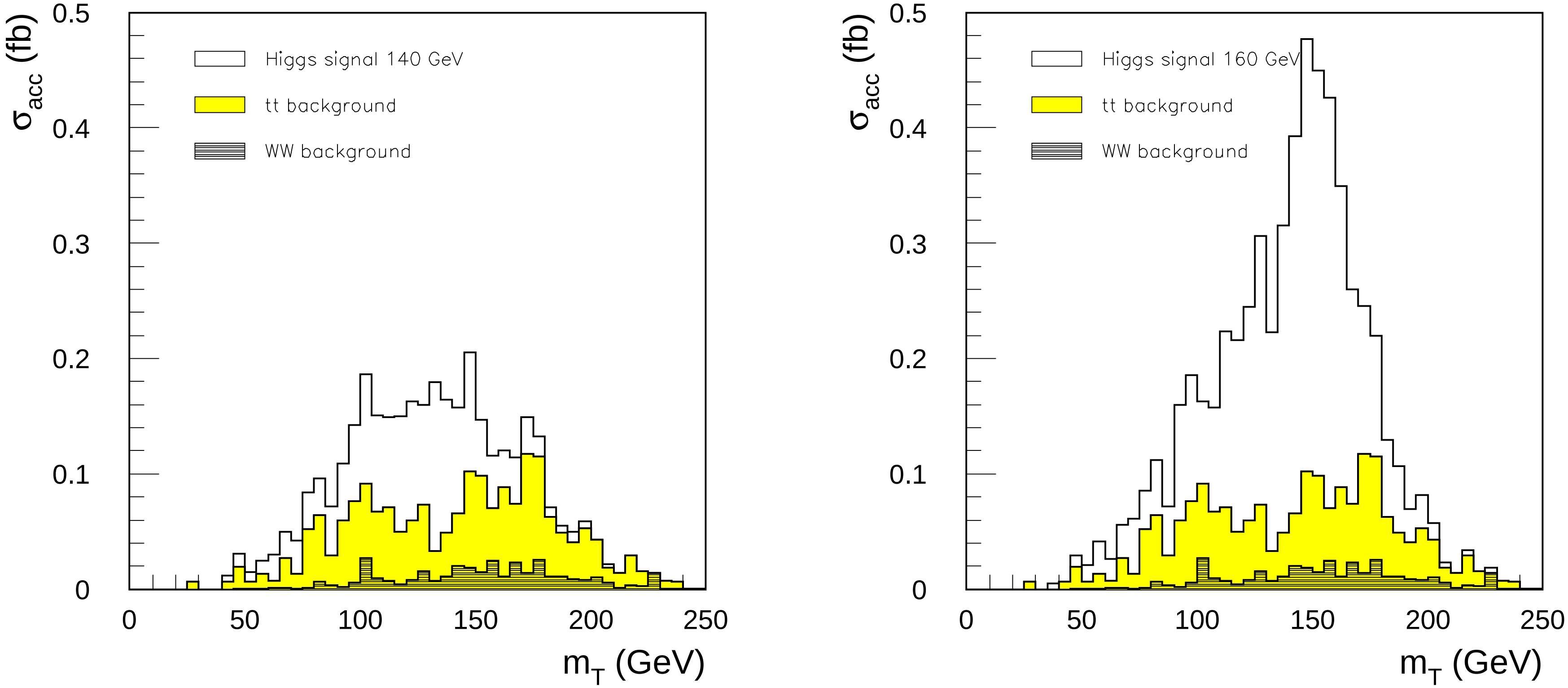



$\hookrightarrow$ Suppression of $\mathrm{t\bar{t}}$ background:

ATLAS '04



# Simulation of $\mathrm{H} \to \mathrm{WW}$ via VBF at ATLAS:



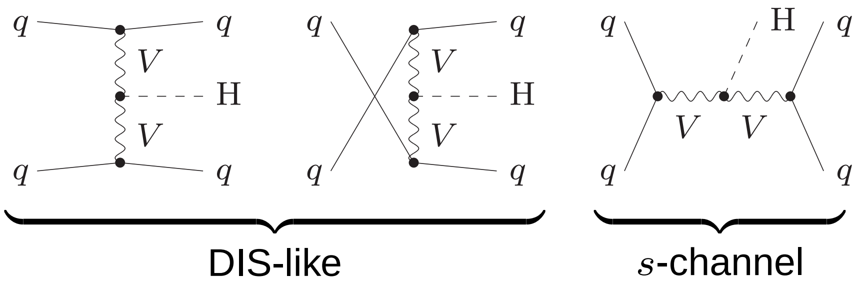

Higgs signal appears as "Jacobian peak" in transverse mass of charged leptons.

($\mathrm{t\bar{t}j}$ is major background component.)

$\hookrightarrow$ see also studies by Zeppenfeld et al. '94-'99

## LO predictions:

- $\sigma_{\mathrm{LO}} \propto \alpha^3$, no $\alpha_{\mathrm{s}}$ dependence
  $\hookrightarrow$ no $\mu_{\mathrm{ren}}$ dependence, scale dependence not a good measure of uncertainties
- many subcontributions from $qq$, $q\bar{q}$, and $\bar{q}\bar{q}$ channels
- each channel receives contributions from one or two topologies ("$t$, $u$, $s$"):




- $s$-channel involves $\mathrm{W/Z}$ resonances

## Size of specific contributions:

| | no cuts | | VBF cuts | | |
|---|---|---|---|---|---|
| $M_{\mathrm{H}}[\,\mathrm{GeV}]$ | $120-200$ | $700$ | $120-200$ | $700$ | |
| $\Delta_{s-\mathrm{channel}}[\%]$ | $30-10$ | $1$ | $< 0.6$ | $< 0.1$ | negligible with VBF cuts |
| $\Delta_{t/u-\mathrm{interference}}[\%]$ | $< 0.5$ | $< 0.1$ | $< 0.1$ | $< 0.1$ | negligible |
| $\Delta_{\mathrm{b-quarks}}[\%]$ | $\approx 4$ | $1$ | $\approx 2$ | $1$ | |

# Work on radiative corrections to the production of Higgs+2jets

- NLO QCD corrections to VBF in DIS-like approximation
  - ◇ total cross section Han, Valencia, Willenbrock '92; Spira '98; Djouadi, Spira '00
  - ◇ distributions Figy, Oleari, Zeppenfeld '03; Berger, Campbell '04
  - ◇ matching with parton shower (POWHEG) Nason, Oleari '09

- (full) NLO QCD+EW corrections to VBF Ciccolini, Denner, S.D. '07

  $\hookrightarrow$ NLO QCD $\sim$ NLO EW $\sim$ $5{-}10\%$

- NNLO QCD corrections to VBF in DIS-like approximation Bolzoni, Maltoni, Moch, Zaro '10

  $\hookrightarrow$ NNLO QCD $\sim$ $1{-}2\%$

- NLO QCD corrections to $gg \to Hgg$, etc. Campbell, R.K.Ellis, Zanderighi '06

  $\hookrightarrow$ contribution to VBF $\sim$ $5\%$ Nikitenko, Vazquez '07 (NLO scale uncertainty $\sim 35\%$)

- QCD loop-induced interferences between VBF and $Hgg$-initiated channels

  $\hookrightarrow$ impact $\lesssim 10^{-3}\,\%$ (negligible!) Andersen, Binoth, Heinrich, Smillie '07
  Bredenstein, Hagiwara, Jäger '08

- loop-induced VBF in $gg$ scattering Harlander, Vollinga, Weber '08

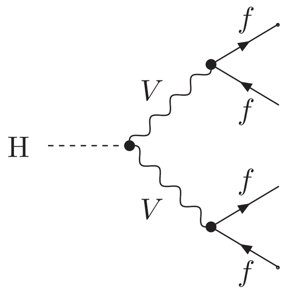
  $\hookrightarrow$ impact $\sim$ $0.1\%$

- SUSY QCD+EW corrections Hollik, Plehn, Rauch, Rzehak '08

  $\hookrightarrow$ $|\mathrm{MSSM} - \mathrm{SM}| \lesssim 1\%$ for SPS points ($2{-}4\%$ for low SUSY scales)

# Survey of Feynman diagrams for NLO corrections

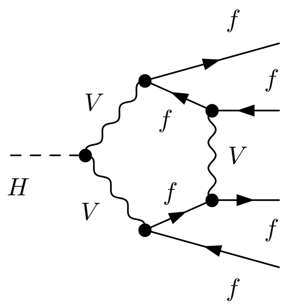
**Lowest order:**



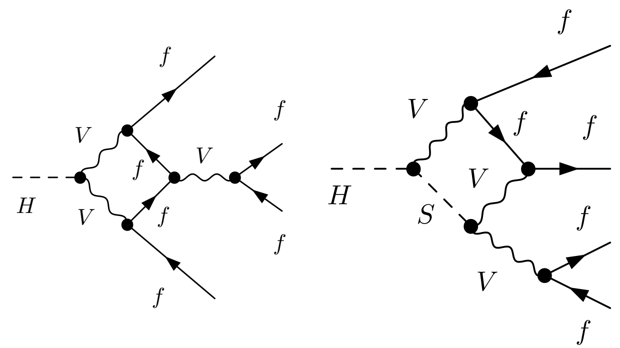

(one or two diagrams per flavour channel)

**Typical one-loop diagrams:** # diagrams = $\mathcal{O}(200-400)$

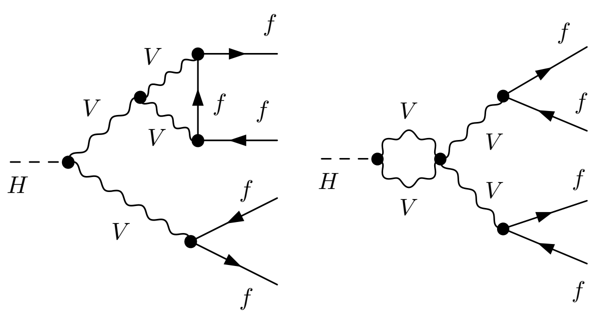
pentagons



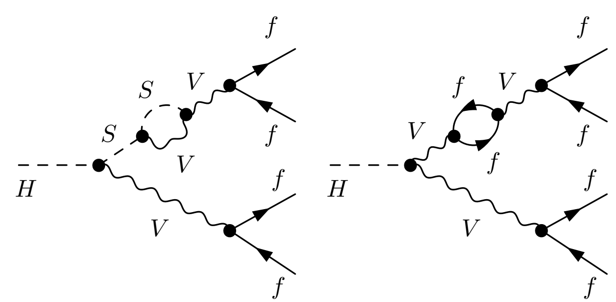

boxes




vertices




self-energies

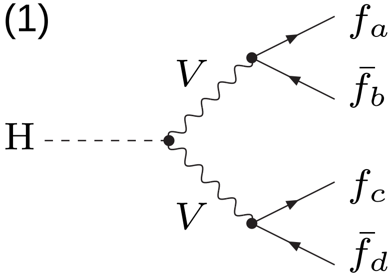



$+$ tree graphs with real gluon or photons

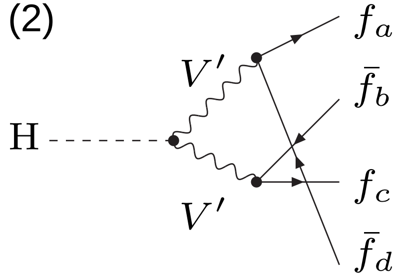
## Classification of NLO QCD corrections

Possible Born diagrams:

(1)




(2)



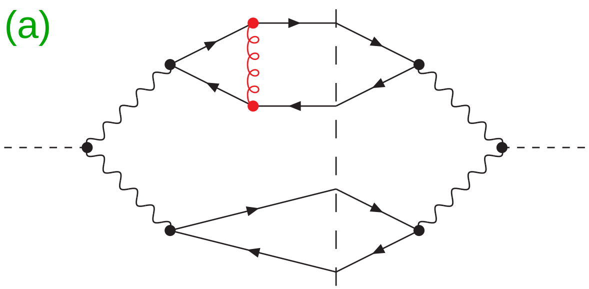

diagrams (2) only for

$q\bar{q}q\bar{q}$ and $q\bar{q}q'\bar{q}'$ channels

($q'$ = weak-isospin partner of $q$)

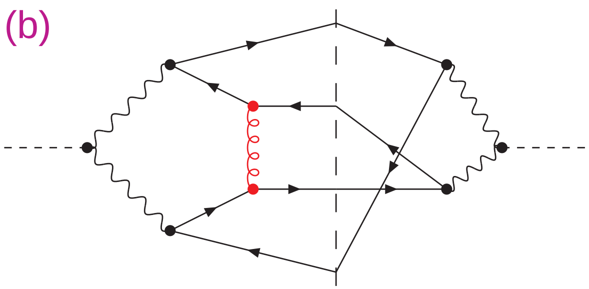
Classification of QCD corrections into four categories: (typical diagrams shown)

(a)

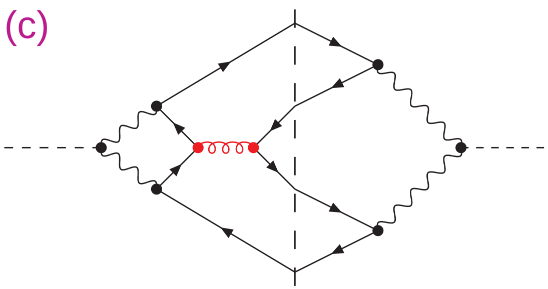


(a) defines DIS-like approximation

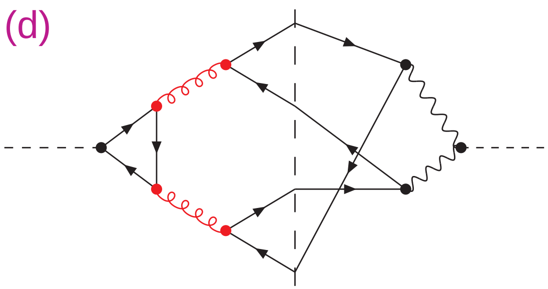
(b)



(c)

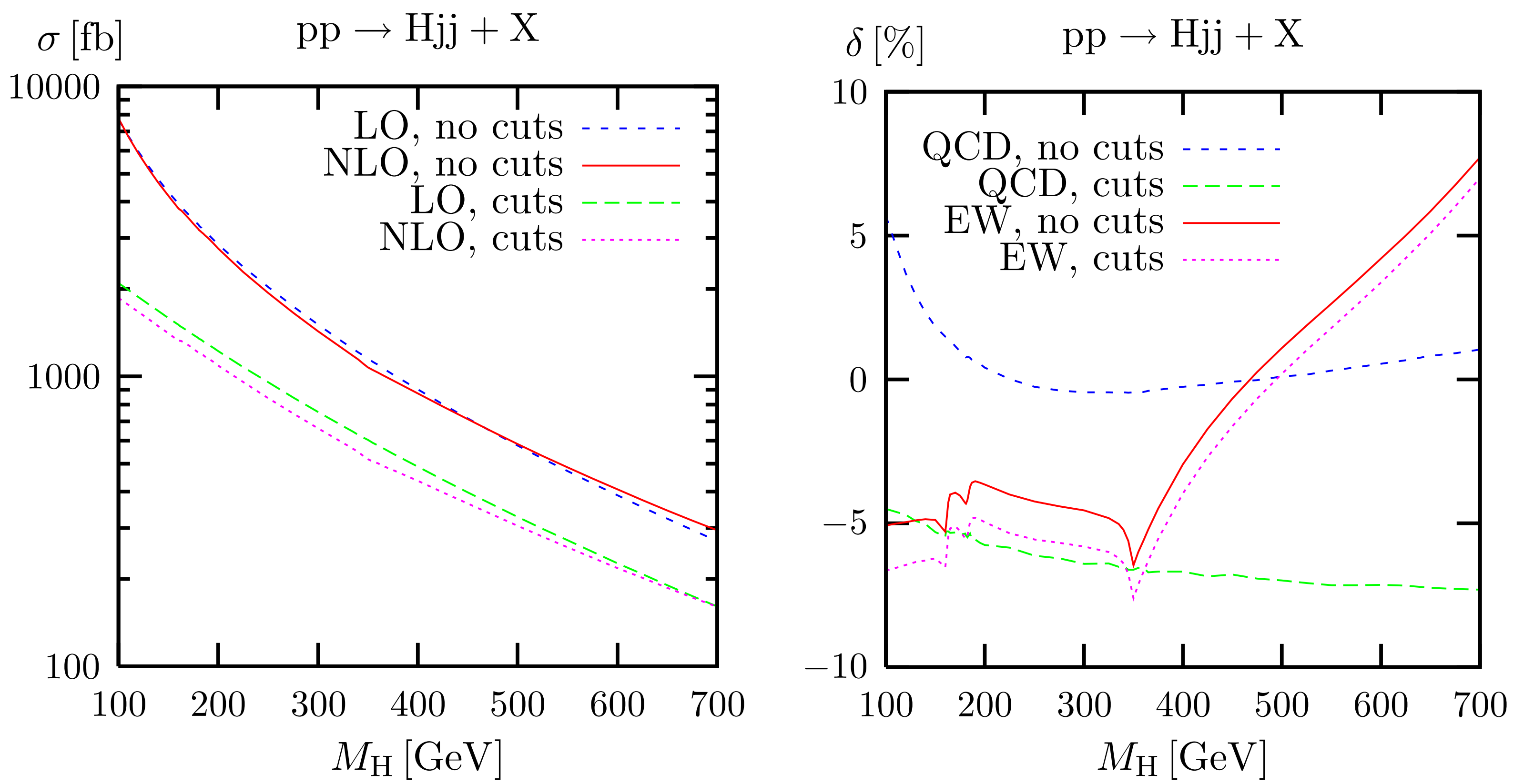


(d)



(b,c,d) = corrections to interferences (only for $q\bar{q}q\bar{q}$ and $q\bar{q}q'\bar{q}'$ channels)

# Results on integrated cross sections




Ciccolini, Denner, S.D. '07

*HAWK*

- QCD and EW corrections are of same generic size
- reasonable scale choice: $\mu_{\mathrm{ren/fact}} \sim M_\mathrm{W} \sim \mathrm{W/Z}$ virtuality (rather than $M_\mathrm{H}$)
- scale uncertainty $\sim 3\%$ within $M_\mathrm{W}/2 < \mu_{\mathrm{ren/fact}} < 2M_\mathrm{W}$ in NLO ($\sim 10\%$ in LO)
- sensitivity to cuts: large for QCD, small for EW corrections

## Size of specific corrections to cross sections:

| | no cuts | | VBF cuts | | |
|---|---|---|---|---|---|
| $M_{\rm H}\,[\,{\rm GeV}]$ | $120{-}200$ | $700$ | $120{-}200$ | $700$ | |
| $\delta_{\rm QCD(a)}\,[\%]$ | $4{-}0.5$ | $+1$ | $\approx -5$ | $-7$ | $\mathcal{O}(5{-}10\%)$ |
| $\delta_{\rm QCD(b+c+d)}\,[\%]$ | $\lesssim 0.2$ | $-0.1$ | $< 0.1$ | $< 0.1$ | negligible |
| $\delta_{{\rm EW},qq}\,[\%]$ | $\approx -6$ | $+6$ | $\approx -7$ | $+5$ | $\mathcal{O}(5{-}10\%)$ |
| $\delta_{{\rm EW},q\gamma}\,[\%]$ | $\approx +1$ | $+2$ | $\approx +1$ | $+2$ | |
| $\delta_{G_\mu^2 M_{\rm H}^4}\,[\%]$ | $< 0.1$ | $+4$ | $< 0.1$ | $+4$ | negligible for $M_{\rm H} < 400\,{\rm GeV}$ |

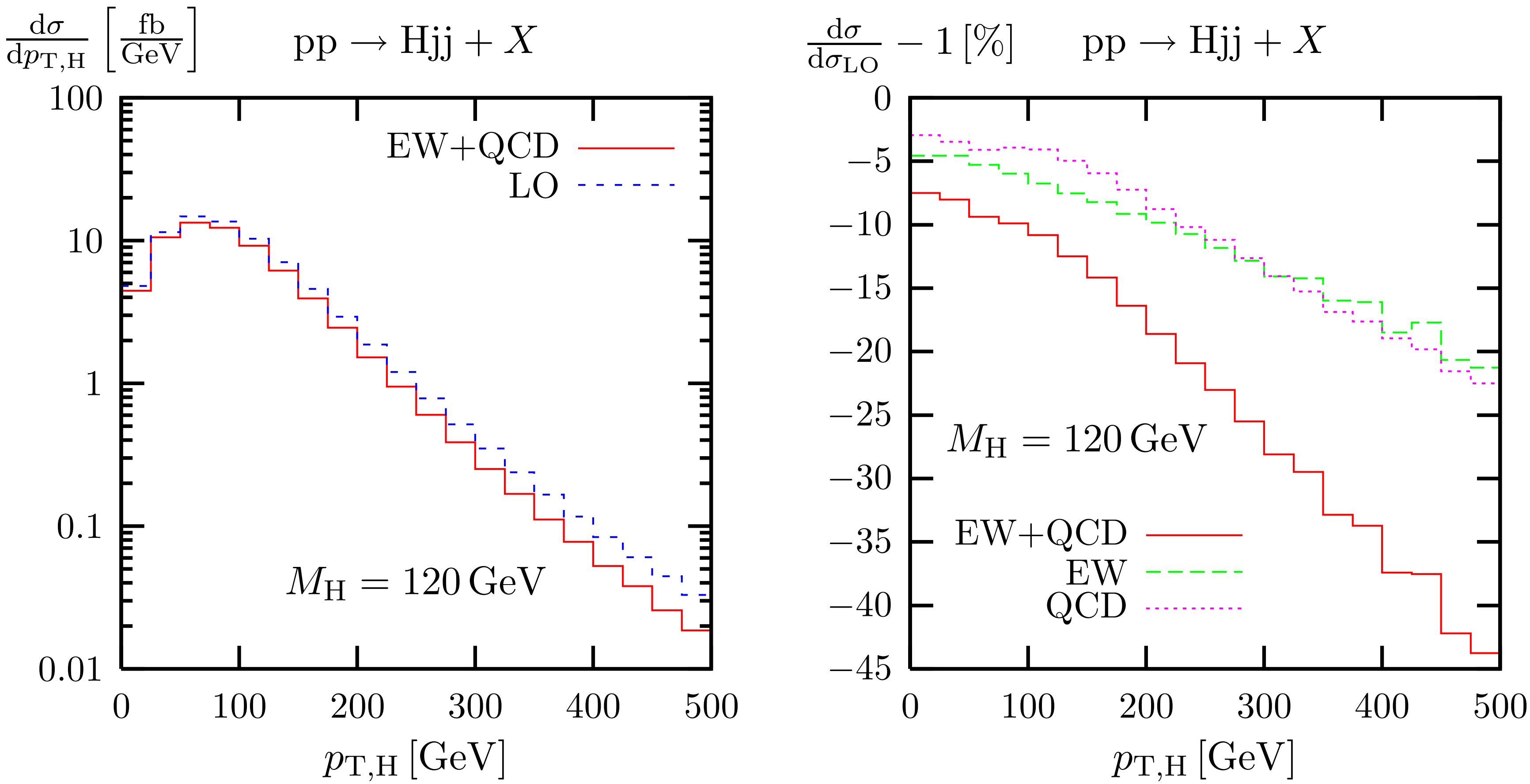
Heavy-Higgs corrections at $M_{\rm H} \sim 700\,{\rm GeV}$: $\underbrace{G_\mu M_{\rm H}^2}_{\text{1-loop}} \sim \underbrace{(G_\mu M_{\rm H}^2)^2}_{\text{2-loop}} \sim 4\%$

$\hookrightarrow$ breakdown of perturbation theory

$\uparrow$ taken from Ghinculov '95; Frink et al. '96

# Distribution in the Higgs transverse momentum $p_{\mathrm{T,H}}$

Ciccolini, Denner, S.D. '07



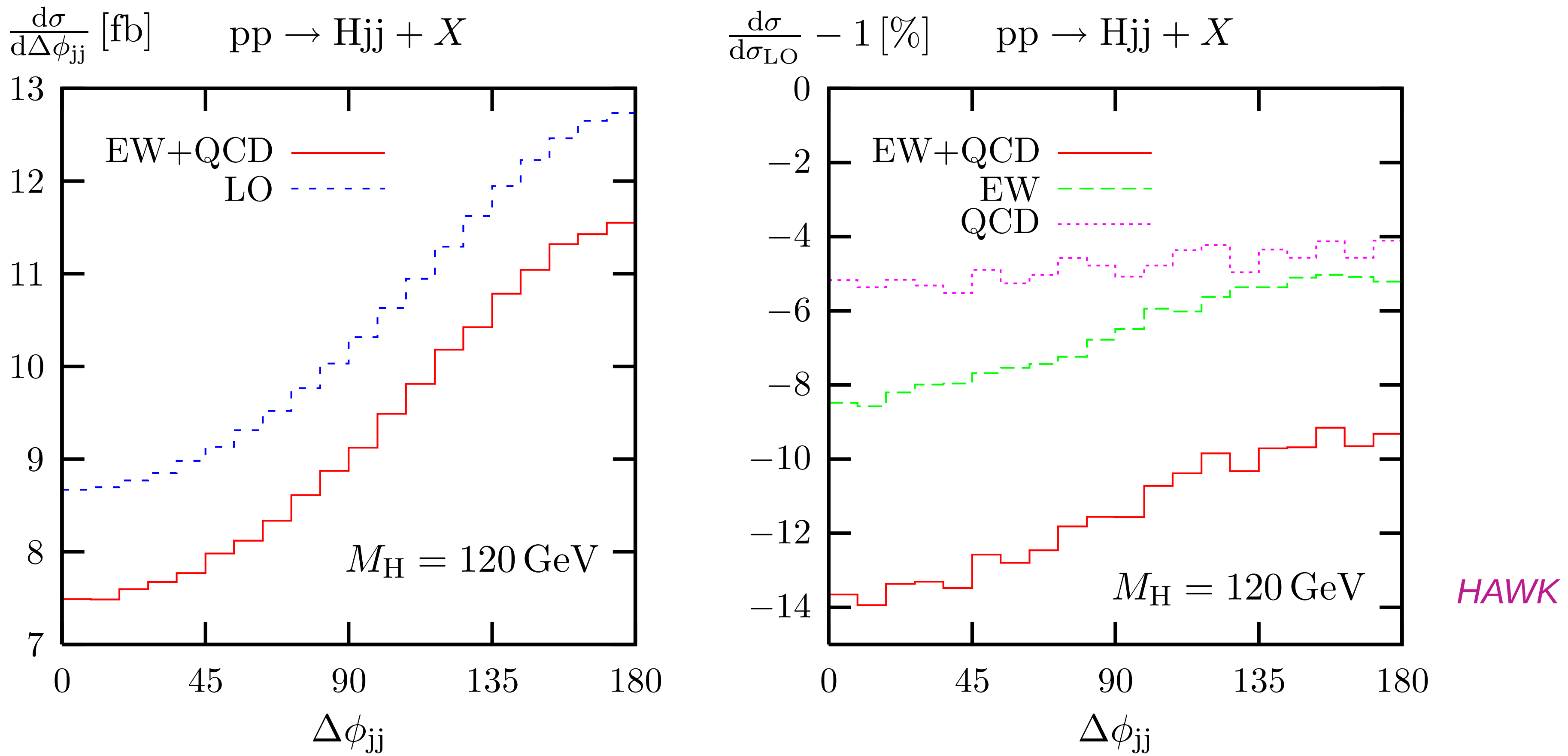

*HAWK*

$\hookrightarrow$ QCD and EW corrections distort shapes

QCD+EW $\sim$ $20\%(40\%)$ at $p_{\mathrm{T,H}} = 200\,\mathrm{GeV}(500\,\mathrm{GeV})$

# Distribution in the azimuthal angle difference $\Delta\phi_{jj}$ of the tagging jets

Ciccolini, Denner, S.D. '07




↪ QCD+EW corrections induce small distortions similar to BSM effects

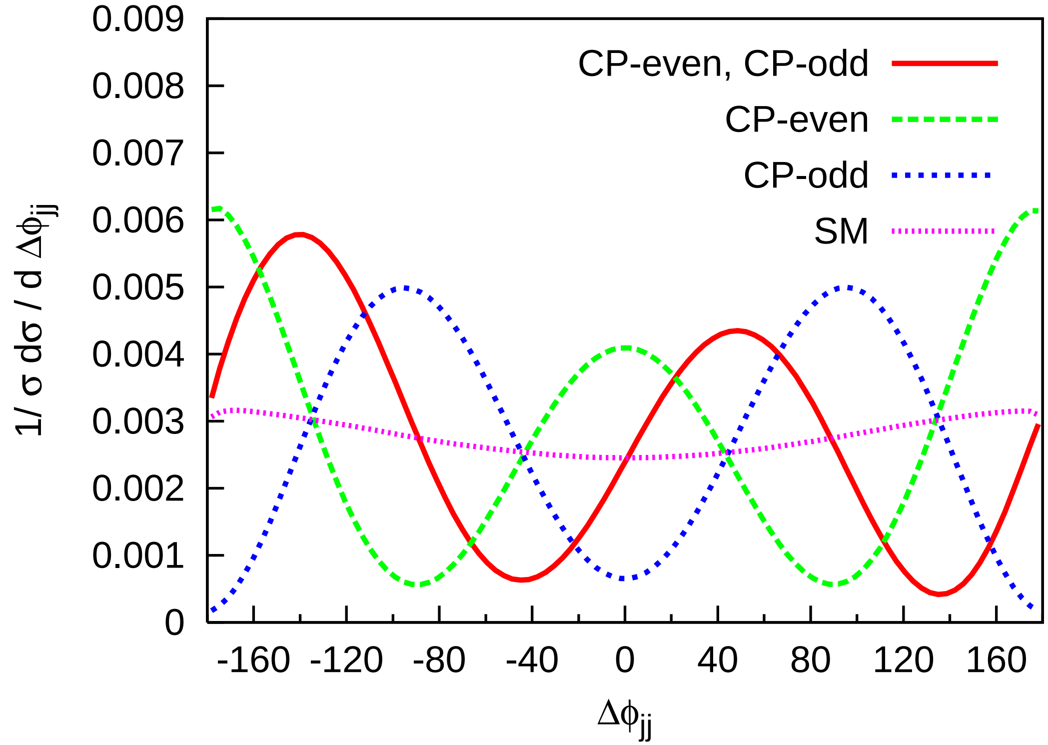
## WWH and ZZH coupling analyses

- Higgs via VBF plays important role in global Higgs couplings analysis

Dührssen et al. '04

- azimuthal angle difference $\Delta\phi_{\rm jj}$ of tagging jets is sensitive to BSM effects:

Hankele, Klämke, Zeppenfeld, Figy '06
Ruwiedel, Schumacher, Wermes '07




(Individual contributions without SM; plot from Hankele et al.)

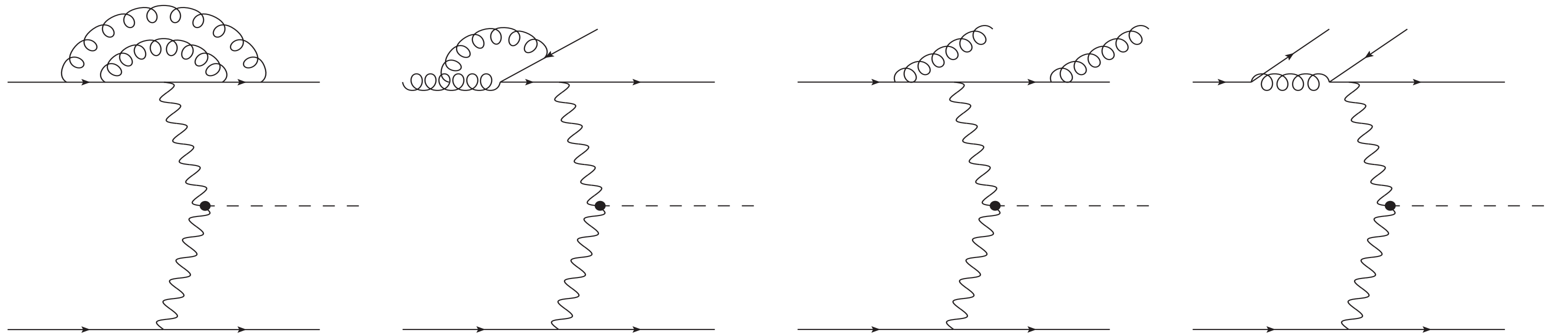
CP-even: $\mathcal{L} \propto HW^+_{\mu\nu}W^{-,\mu\nu}, \qquad \Gamma^{HW^+W^-}_{\mu\nu} \propto g_{\mu\nu}(k_+k_-) - k_{+,\nu}k_{-,\mu}$

CP-odd: $\mathcal{L} \propto H\tilde{W}^+_{\mu\nu}W^{-,\mu\nu}, \qquad \Gamma^{HW^+W^-}_{\mu\nu} \propto \epsilon_{\mu\nu\rho\sigma}k^\rho_+k^\sigma_-$

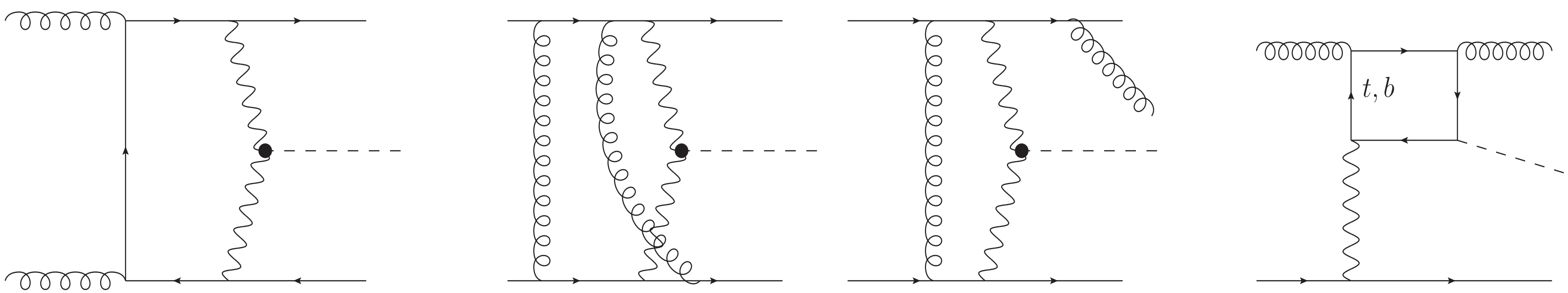
# NNLO QCD corrections

## DIS-like corrections $\longrightarrow$ structure-function approach

Bolzoni, Maltoni, Moch, Zaro '10



## Non-DIS-like corrections:



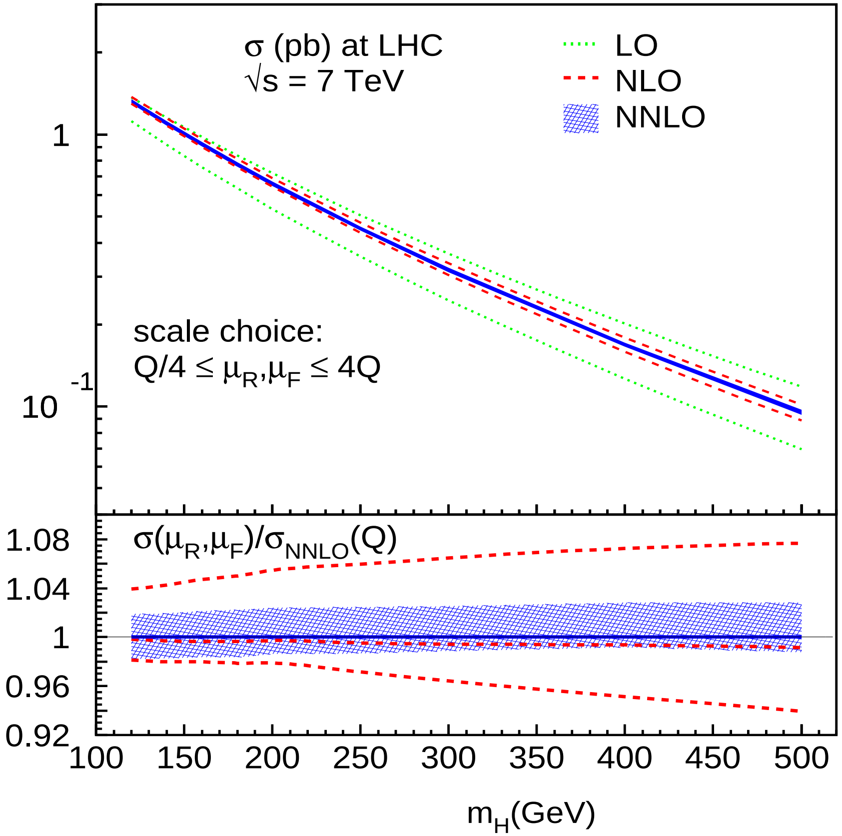

loop-induced contributions with
ext. gluons and $\mathrm{HVV}$ couplings
Harlander, Vollinga, Weber '08

colour-exchange diagrams and
Higgs radiation off quark loops
expected small $\longrightarrow$ neglected

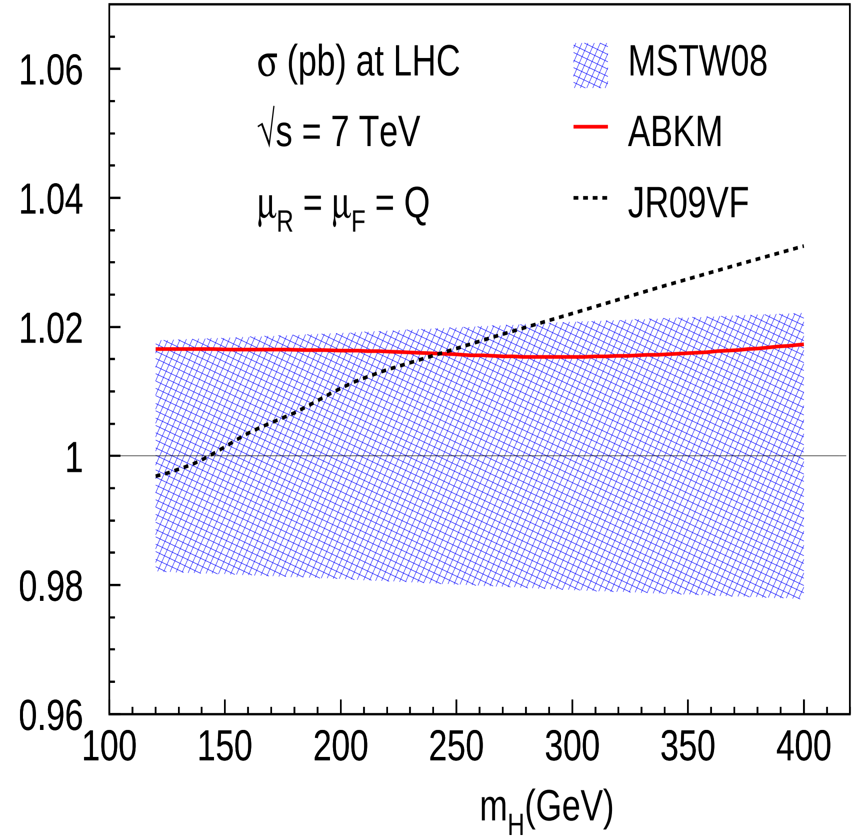
# DIS-like NNLO QCD corrections to the total VBF cross section

Bolzoni, Maltoni, Moch, Zaro '10

Scale uncertainty:




PDF uncertainty: (68% C.L.)




Results for $\sigma_{\mathrm{tot}}$ at the LHC:

- NNLO QCD corrections $\sim\ 1\%$ with scale $Q$ = $\mathrm{W/Z}$ virtuality = $\mathcal{O}(M_{\mathrm{W}})$
- scale uncertainty $\sim$ PDF uncertainty $\sim\ 2\%$

Implementation of VBF cuts $\rightarrow$ work in progress

# Higgs-boson decay

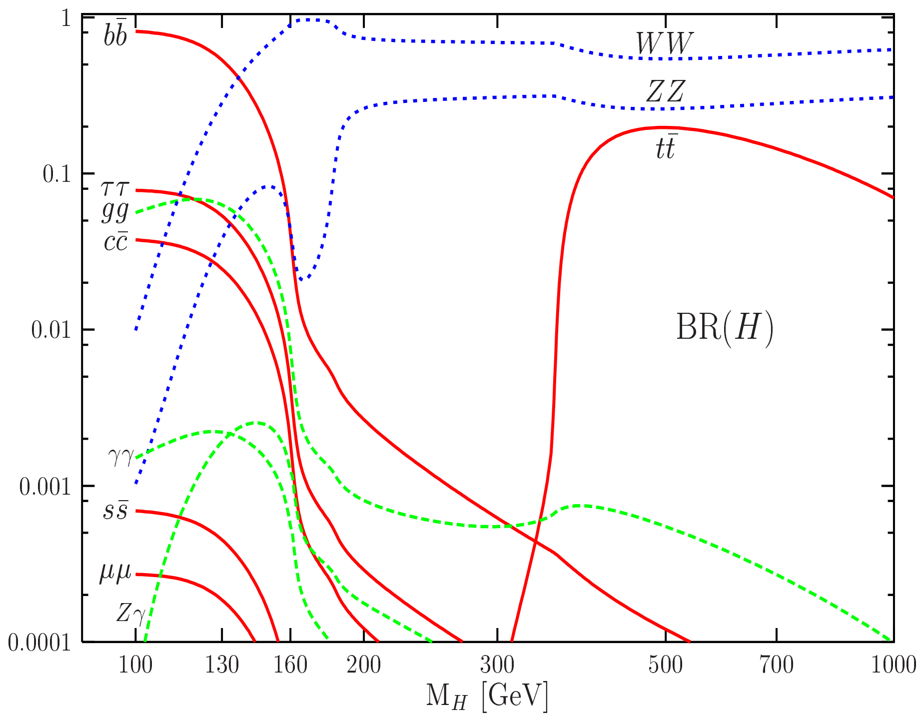
# Higgs-boson decays including NLO corrections

Hdecay

- $\mathrm{H} \to f\bar{f}$
  Bardin, Vilenskii, Khristova '91
  Dabelstein, Hollik '92; Kniehl '92

- $\mathrm{H} \to \gamma\gamma$
  full 2-loop result known
  (Actis,) Passarino, Sturm, Uccirati '07,'08

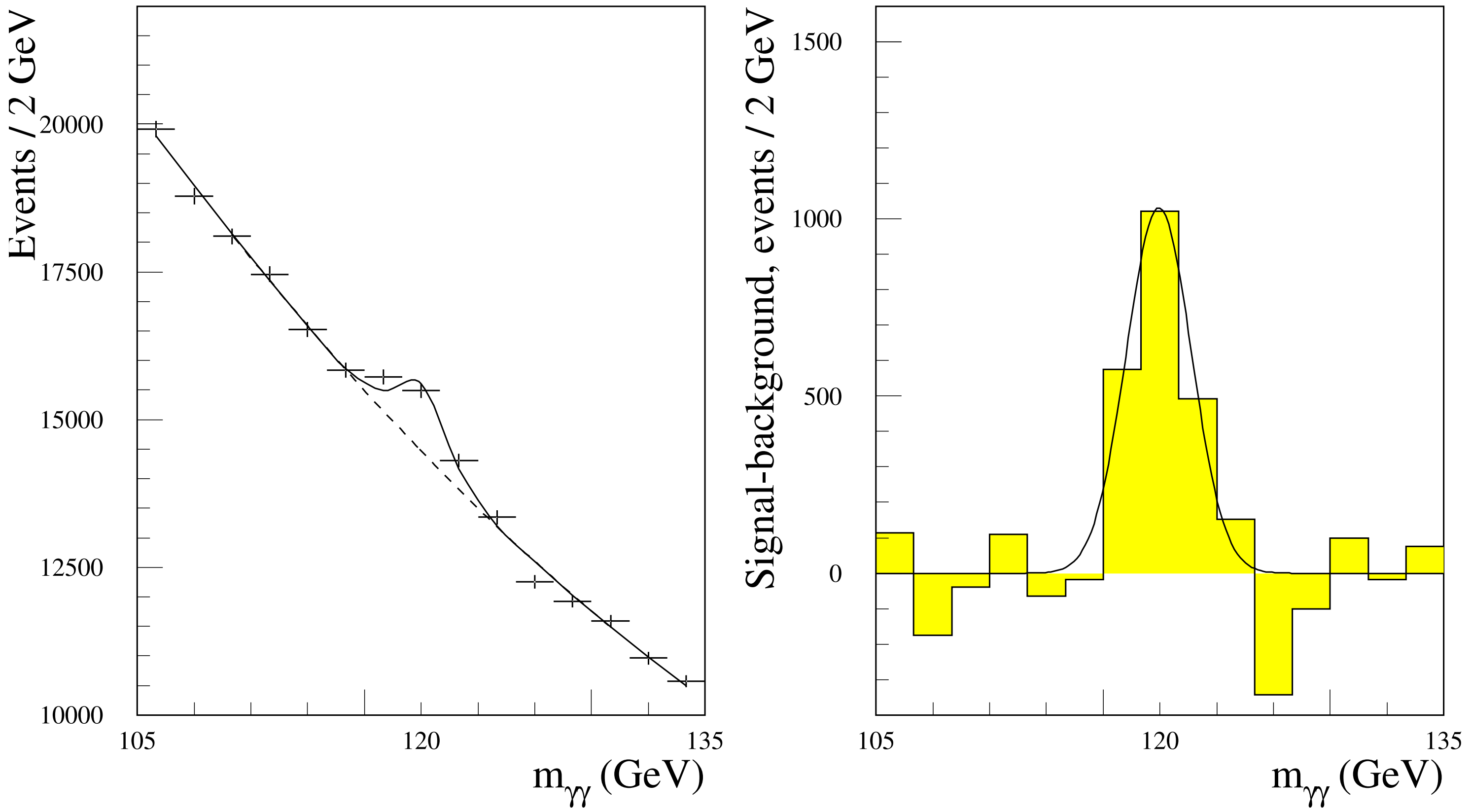
- $\mathrm{H} \to \mathrm{gg}$
  full 2-loop result known
  (same calculation as for $\mathrm{gg} \to \mathrm{H}$)
  Actis, Passarino, Sturm, Uccirati '08




- $\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$
  - for stable $\mathrm{W/Z}$ bosons Fleischer, Jegerlehner '81; Kniehl '91; Bardin, Vilenskii, Khristova '91
  - for off-shell/decaying $\mathrm{W/Z}$ bosons $\to$ *Prophecy4f* MC generator Bredenstein, Denner, S.D., Weber '06

$\hookrightarrow$ NLO EW corrections known for most important SM Higgs decays

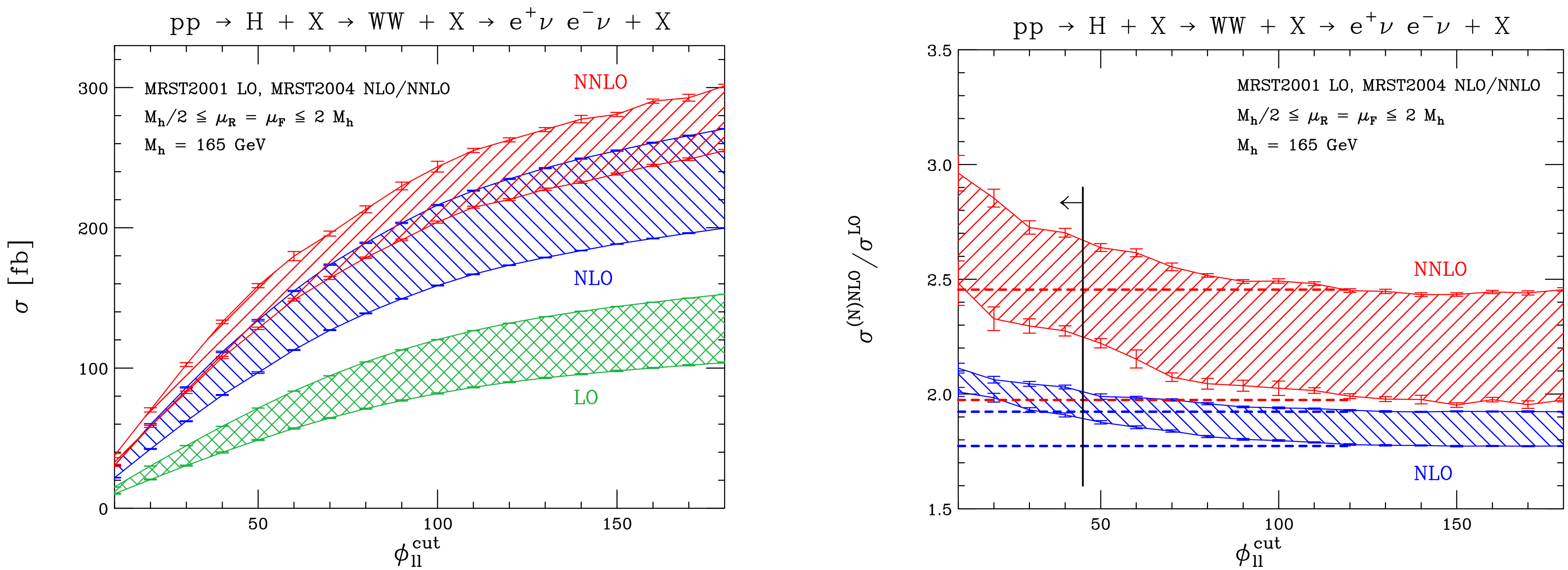
## Simulation of $gg \to H \to \gamma\gamma$ at ATLAS:




Huge QCD background can be subtracted via interpolation of sidebands.

# Combination of Higgs production and decay $\mathrm{H} \to \mathrm{WW} \to ll\nu\nu$

Anastasiou, Dissertori, Stöckli '07

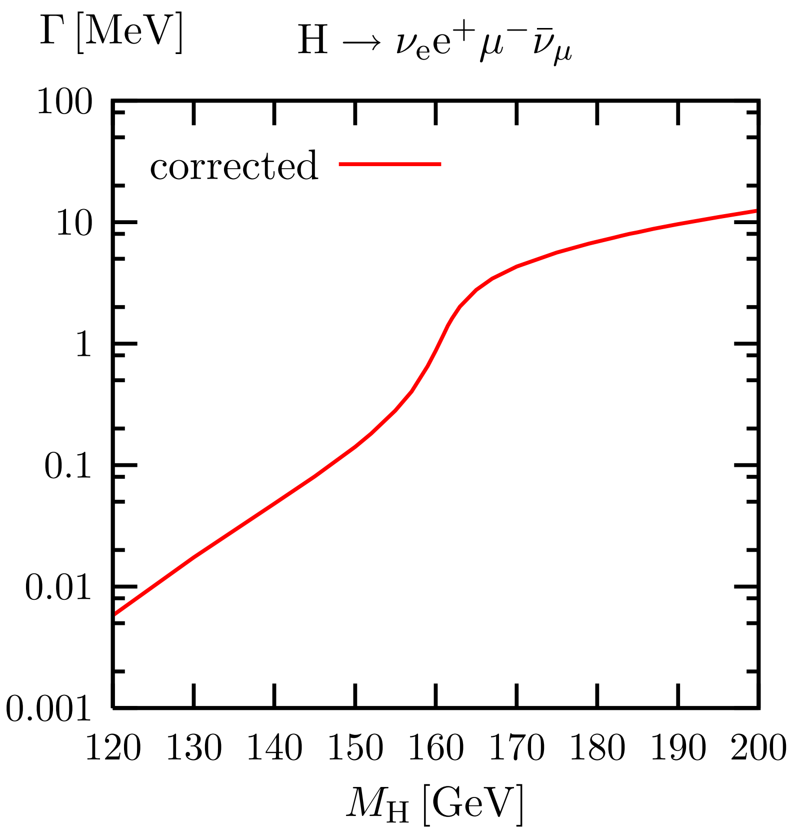


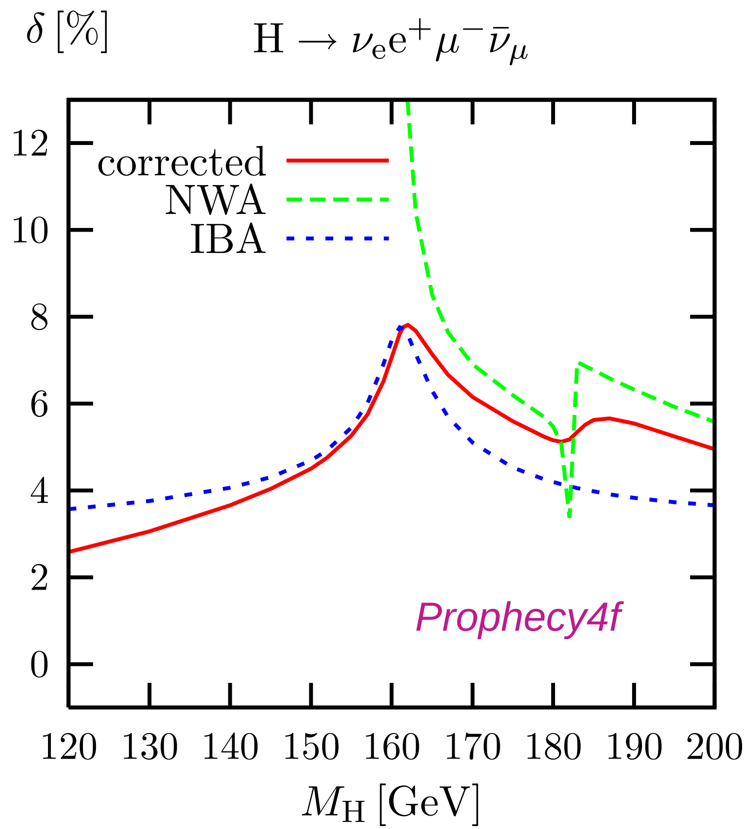

$\phi_{ll} =$ angle between charged decay leptons in the transverse plane

$K$ factors in general depend on decay phase space.

# Partial $\mathrm{H}$ width for $\mathrm{H} \to \mathrm{WW} \to \nu_{\mathrm{e}} \mathrm{e}^{+} \mu^{-} \bar{\nu}_{\mu}$

Bredenstein, Denner, S.D., Weber '06




$$\delta = \frac{\Gamma}{\Gamma_{\mathrm{Born}}} - 1$$

↑ Coulomb singularity at $M_{\mathrm{H}} \sim 2M_{\mathrm{W}}$

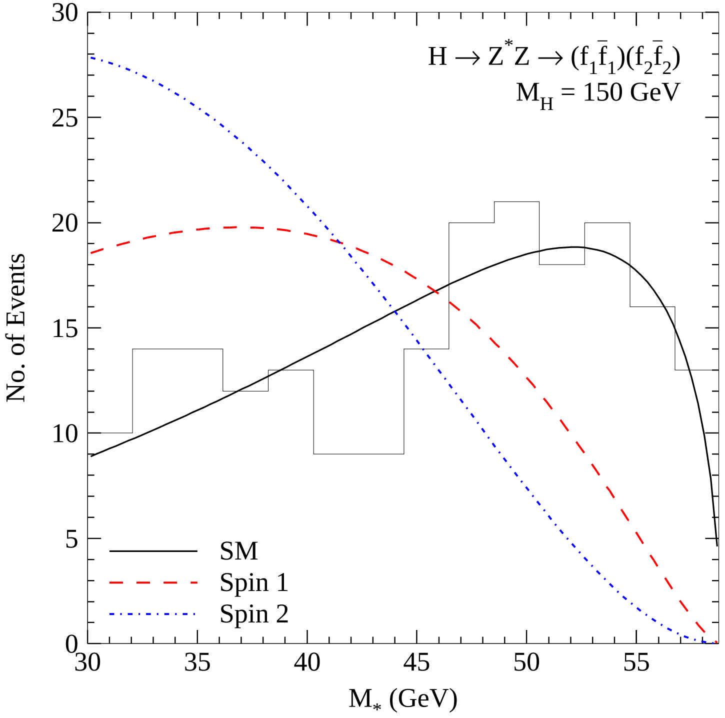
↑ threshold effect in loops at $M_{\mathrm{H}} \sim 2M_{\mathrm{Z}}$

NWA = "narrow-width approximation"

IBA = "improved Born approximation" (Coulomb singularity, fit constant, leading effects for $M_{\mathrm{H}}, m_{\mathrm{t}} \gg M_{\mathrm{W}}$)

# Important distributions in $\mathrm{H} \to \mathrm{ZZ} \to f_1 \bar{f}_1 f_2 \bar{f}_2$

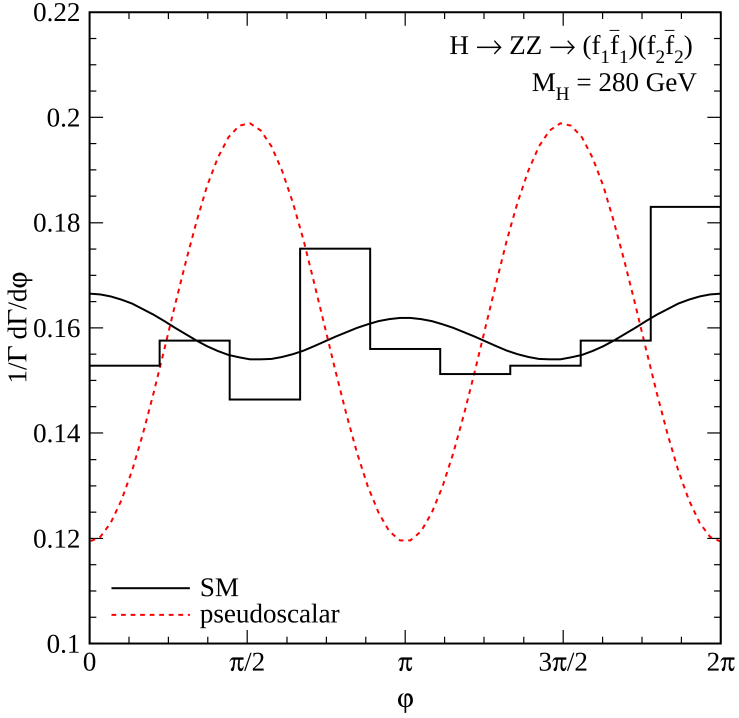
## Invariant $\mathrm{Z}$ mass:

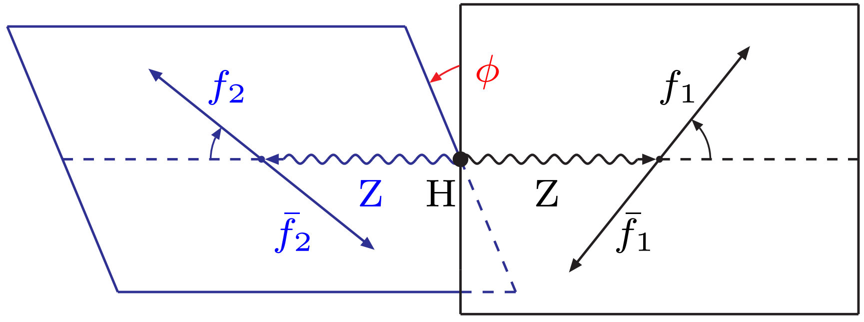



$$M_* = M_{f_1 \bar{f}_1}$$

## Angle between $\mathrm{Z}$ decay planes:

Choi, Miller, Mühlleitner, Zerwas '02



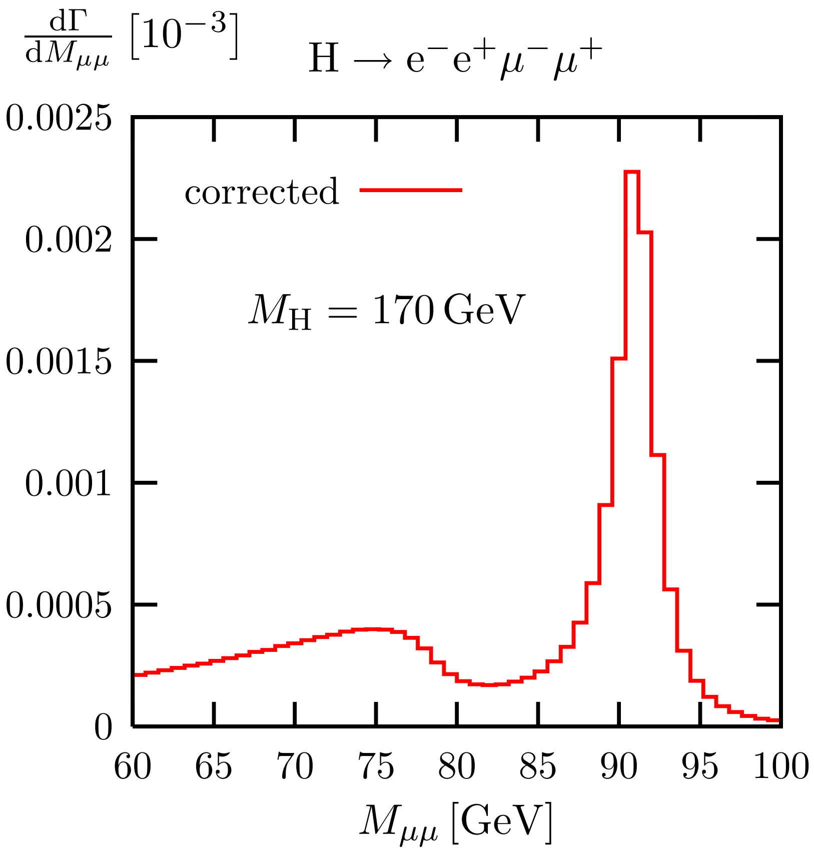



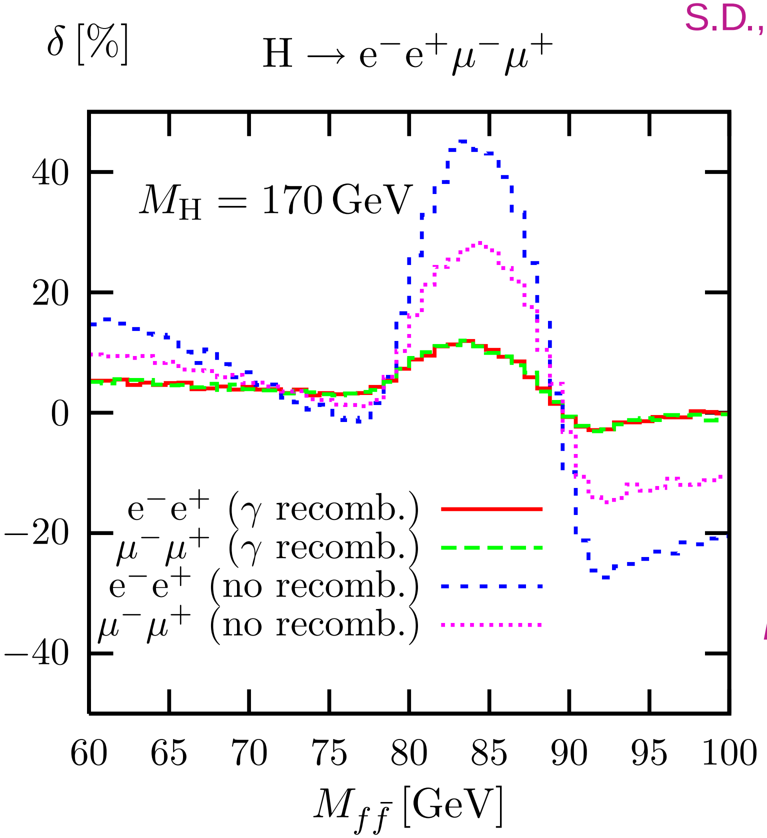

Histograms = SM simulation for $L = 300\,\mathrm{fb}^{-1}$

$\hookrightarrow$ distributions sensitive to spin and parity

# Distribution of invariant $\mathrm{Z}$ mass in $\mathrm{H} \to \mathrm{ZZ} \to \mathrm{e}^-\mathrm{e}^+\mu^-\mu^+$

Bredenstein, Denner, S.D., Weber '06




*Prophecy4f*

$\gamma$ recombination if $M_{\mathrm{e}\gamma/\mu\gamma} < 5\,\mathrm{GeV}$

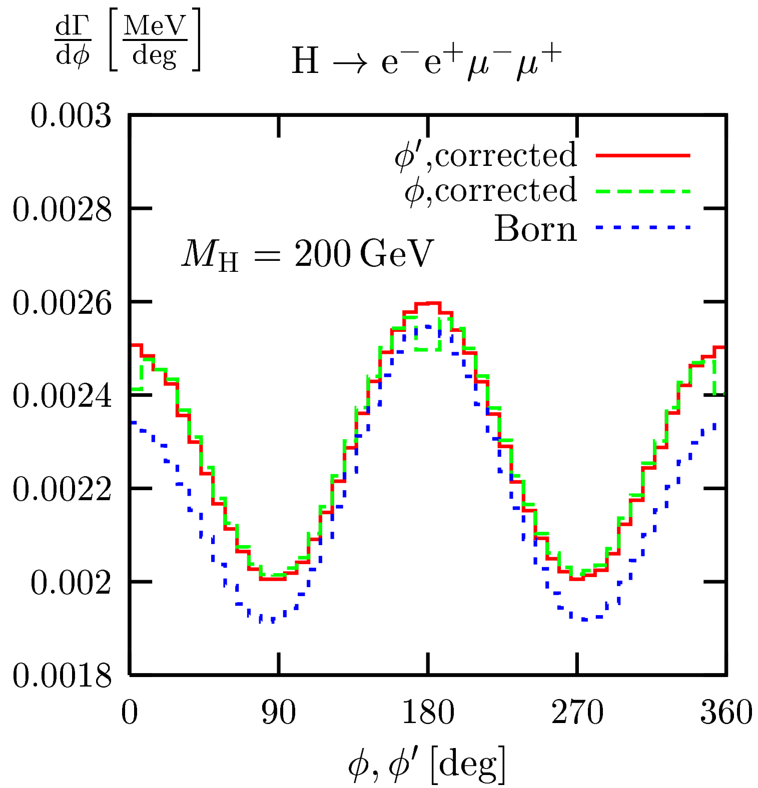
Large corrections due to photon emission in $\mathrm{Z}$ reconstruction

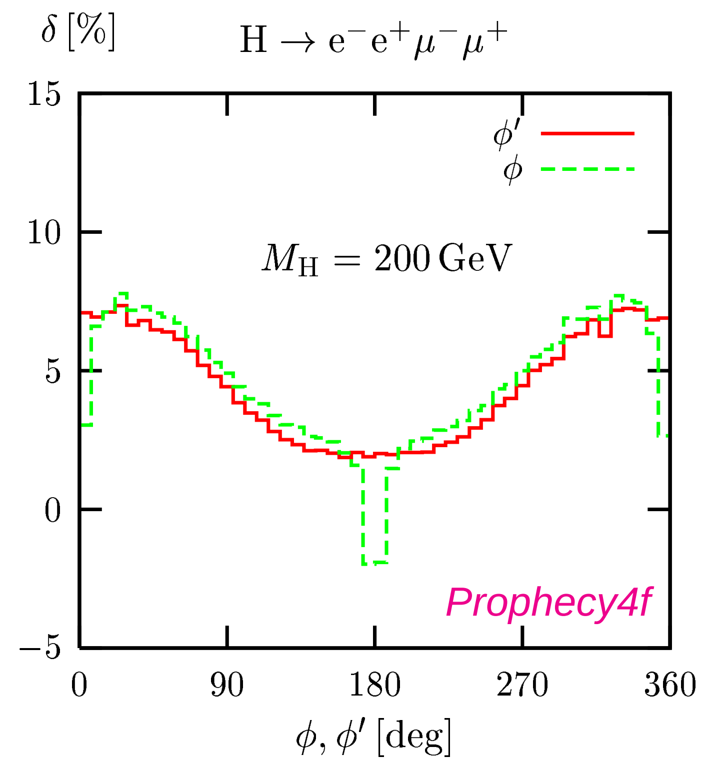
## Corrections to distribution in angle between $Z$ decay planes

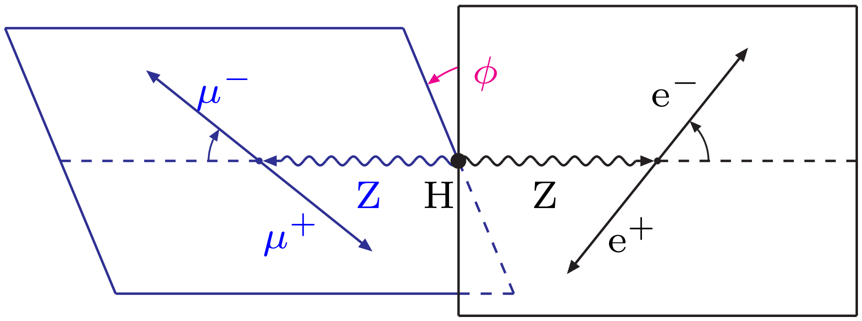
$\hookrightarrow$ $5-10\%$ **effects** that in general distort shapes of distributions

Bredenstein, Denner, S.D., Weber '06

An example:




$$\cos\phi = \frac{\left(\mathbf{p}_{e^-e^+} \times \mathbf{p}_{e^-}\right)\left(-\mathbf{p}_{\mu^-\mu^+} \times \mathbf{p}_{\mu^-}\right)}{\left|\mathbf{p}_{e^-e^+} \times \mathbf{p}_{e^-}\right|\left|-\mathbf{p}_{\mu^-\mu^+} \times \mathbf{p}_{\mu^-}\right|}$$

$$\cos\phi' = \frac{\left(\mathbf{p}_{e^-e^+} \times \mathbf{p}_{e^-}\right)\left(\mathbf{p}_{e^-e^+} \times \mathbf{p}_{\mu^-}\right)}{\left|\mathbf{p}_{e^-e^+} \times \mathbf{p}_{e^-}\right|\left|\mathbf{p}_{e^-e^+} \times \mathbf{p}_{\mu^-}\right|}$$

# Brief summary and outlook

## Higgs physics at the LHC

- LHC can detect / rule out SM-like Higgs bosons in entire mass range
- low-mass range $M_{\mathrm{H}} \sim 100{-}200\,\mathrm{GeV}$ favoured by EW precision data
- in high-mass range $M_{\mathrm{H}} \gtrsim 700\,\mathrm{GeV}$ perturbation theory runs out of control

## SM predictions for the LHC

- gluon fusion: multi-loop calculations (up to 3 loops), heavy-top expansions, QCD resummations
- VBF NLO QCD+EW corrections, NNLO QCD, impact of gg channel
- Higgs strahlung $(\mathrm{WH/ZH})$: NLO QCD+EW corrections, NNLO QCD
- $\mathrm{t\bar{t}H}$ production: NLO QCD known, also for main background $\mathrm{t\bar{t}b\bar{b}}$
- Higgs decays: NLO QCD+EW known, some improvements beyond, $\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$ fully differential

## Ongoing work on further refinements:

- particle decays in NLO simluations:
  Higgs, top, W/Z
- matching of parton showers with state-of-the-art NLO
- conservative reliable error assessments:
  theory, parametic, PDF errors
- high Higgs masses:
  proper $M_{\mathrm{H}}$ definition, interference with background, etc.
- predictions for BSM scenarios:
  Higgs radiation off b quarks, SUSY, invisible Higgs, smeared out Higgs, etc.

$\hookrightarrow$ see e.g. LHC-Higgs cross section group

# LHC-Higgs cross section group $\longrightarrow$ mandate for theory update

CrossSections < LHCPhysics < TWiki - Mozilla Firefox

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

## Organization

### Overall Contacts

| ATLAS | CMS | THEORY | |
|---|---|---|---|
| Reisaburo Tanaka (LAL) | Chiara Mariotti (Torino) | Stefan Dittmaier (Freiburg) | Giampiero Passarino (Torino) |

### Subgroup Contacts and Link for Subgroup Wiki

* We are organized in 10 subgroups, with 2 experimental contacts (one from ATLAS and one from CMS) and 2 theoretical contacts.

* LHCb collaboration participates in WH/ZH group.

| Group | ATLAS | CMS | LHCb | THEORY | |
|---|---|---|---|---|---|
| **1.** ***ggF*** | Jianming Qian (Michigan) | Fabian Stöckli (CERN) | | Massimiliano Grazzini (Firenze) | Frank Petriello (Wisconsin) |
| **2.** ***VBF*** | Daniela Rebuzzi (Pavia) Sinead Farrington (Oxford) | Christoph Hackstein (Karlsruhe) | | Ansgar Denner (PSI) | Carlo Oleari (Milano-Bicocca) |
| **3.** ***WH/ZH*** | Giacinto Piacquadio (CERN) | Jim Olsen (Princeton) | Clara Matteuzzi (Milano-Bicocca) | Stefan Dittmaier (Freiburg) | Robert Harlander (Wuppertal) |
| **4.** ***ttH*** | Simon Dean (UCL) | Chris Neu (Virginia) | | Laura Reina (Florida) | Michael Spira (PSI) |
| **5.** ***MSSM neutral*** | Markus Warsinsky (Freiburg) | Monica Vazquez Acosta (IC) | | Michael Spira (PSI) | Georg Weiglein (DESY) |
| **6.** ***MSSM charged*** | Martin Flechl (Freiburg) | Sami Lehti (Helsinki) | | Michael Krämer (Aachen) | Tilman Plehn (Heidelberg) |
| **7.** ***PDF*** | Joey Huston (Michigan State) | Kajari Mazumdar (TIFR) | | Stefano Forte (Milano) | Robert Thorne (UCL) |
| **8.** ***Branching ratios*** | Daniela Rebuzzi (Pavia) | Ivica Puljak (Split) | | Ansgar Denner (PSI) | Sven Heinemeyer (IFCA) |
| **9.** ***NLO MC*** | Jae Yu (Texas) | Marta Felcini (UCD) | | Fabio Maltoni (Louvain) | Paolo Nason (Milano-Bicocca) |
| **10.** ***Pseudo-observables*** | Michael Dührssen (CERN) | Martin Grünewald (Ghent) | | Sven Heinemeyer (IFCA) | Giampiero Passarino (Torino) |