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Electroweak Corrections to Higgs Production

Alexander Mück
RWTH Aachen University

Workshop on electroweak corrections for LHC physics
Durham, September 25, 2012

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Outline

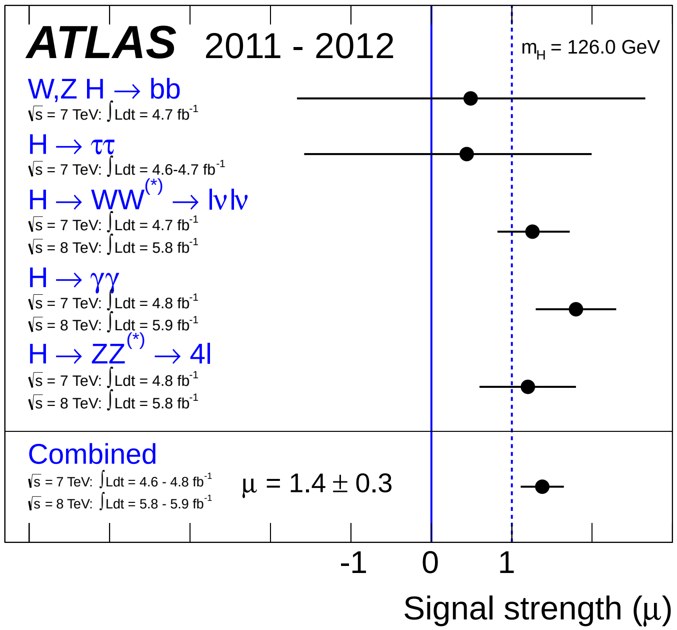
- Introduction (a few general remarks)
- Channels:

  Gluon fusion
  Vector-boson fusion (VBF)
  Higgsstrahlung (WH/ZH)
  (personal bias towards VBF and WH/ZH)
  Higgs decays
- Electroweak corrections:

  available calculations (tools)
  size ⇔ relevance ⇔ QCD uncertainties
  total cross sections ⇔ distributions
- Summary

The new boson

ATLAS-CONF-2012-127



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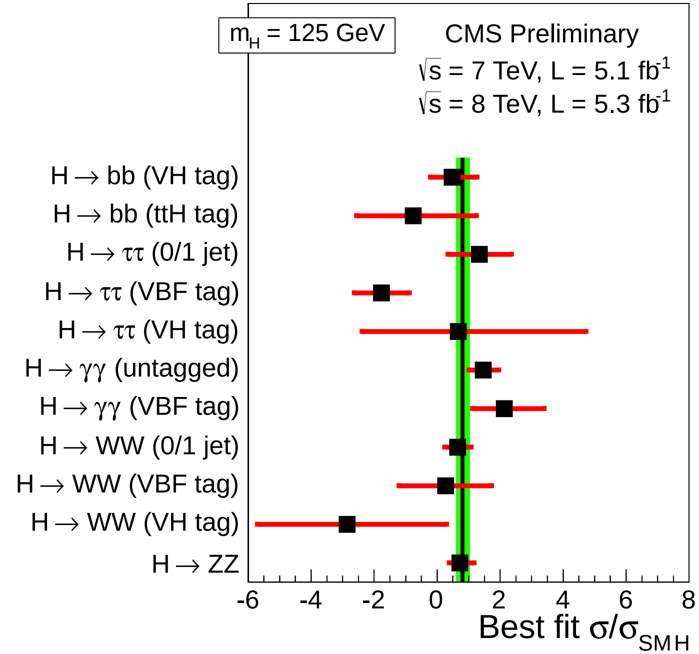

- Is it the SM Higgs boson?

  (spin, CP even/odd, anomalous couplings, etc.)

The new boson

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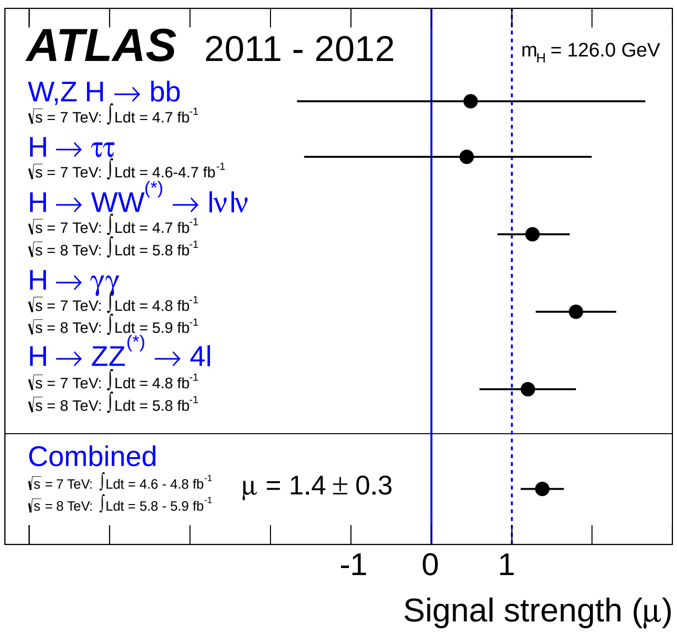

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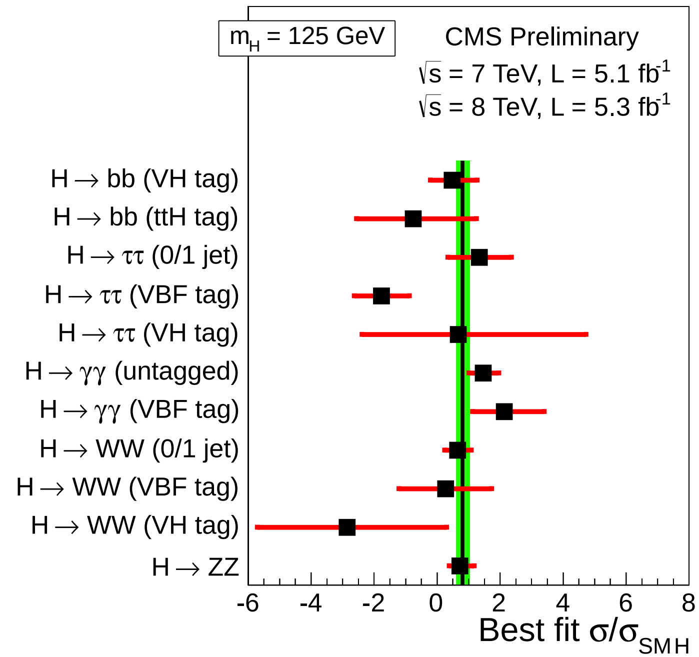

- Is it the SM Higgs boson?

  (spin, CP even/odd, anomalous couplings, etc.)

- EW corrections calculated in the (MS)SM

  (⇒ assume the new boson is the SM Higgs and search for deviations)

- QCD corrections might be more universal

EW corrections

generic size:

- expect percent level corrections

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EW corrections

generic size:

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- 5-10% in Higgs production

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EW corrections

generic size:

- expect percent level corrections
- 5-10% in Higgs production
- naive comparison with QCD: $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2)$
  $\Rightarrow$ needed for high precision observables
  (with small QCD uncertainties)
  $\Rightarrow$ vector-boson fusion

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(logarithmically) enhanced EW corrections:

- at high energies: Sudakov logs $\propto \alpha \to \alpha \log^2(Q/M_V)$
- in peaked distribution from photon radiation

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(logarithmically) enhanced EW corrections:

- at high energies: Sudakov logs $\propto \alpha \to \alpha \log^2(Q/M_V)$
- in peaked distribution from photon radiation
  $\Rightarrow$ boosted Higgs in WH/ZH

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EW corrections

Generic features:

- relative EW correction rather independent of:
  - collider energy
  - (QCD) scale choices
  - PDF choice
- EW effects neglected in PDFs
- $\mathcal{O}(1\%)$ contribution from photons in initial state
  (estimated from MRST2004 PDF)

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QCD and EW corrections

How to combine QCD and EW corrections?

- additive: $\sigma_{\rm best} = \sigma_{\rm LO}(1 + \delta_{\rm QCD} + \delta_{\rm EW})$?
- factorized: $\sigma_{\rm best} = \sigma_{\rm best}^{\rm QCD}(1 + \delta_{\rm EW})$?
- difference is of higher order

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- difference is of higher order

Factorized approximation is commonly used

- assumptions:

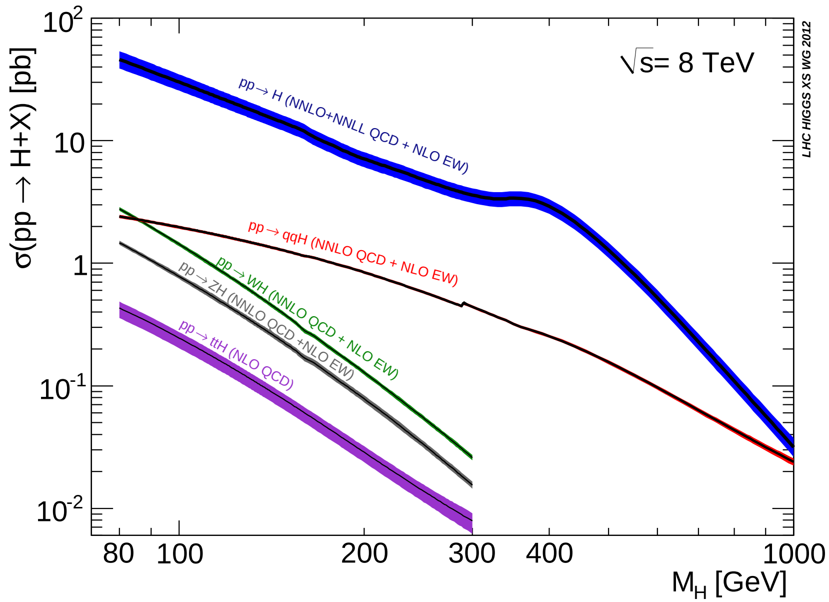
  QCD corrections dominated by soft-collinear physics

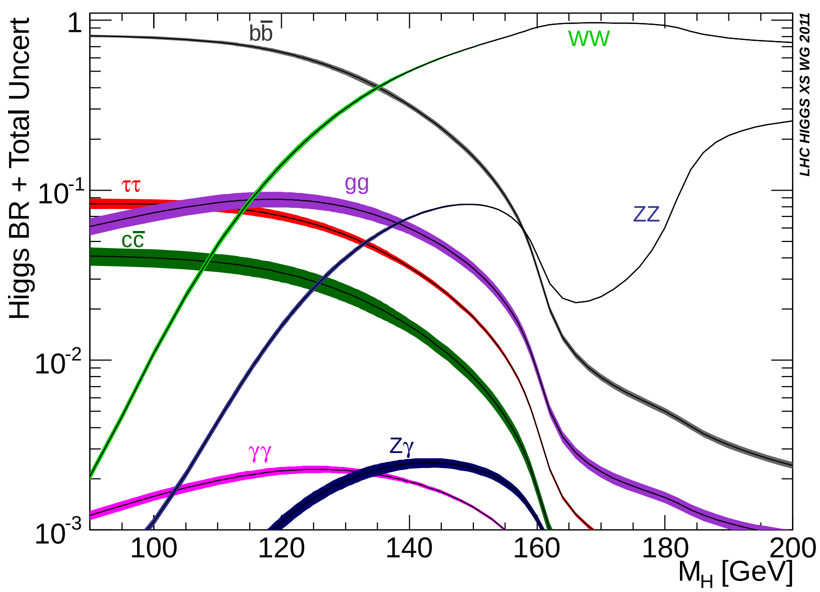
  EW corrections in underlying hard process or FSR

Higgs cross sections

LHC Higgs cross section working group:

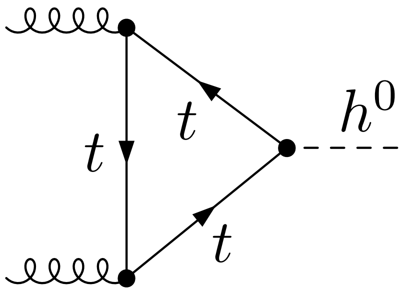
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections
Yellow reports: 1101.0593 and 1201.3084





- joint effort to provide best predictions for cross sections and distributions
- EW corrections included where available
- ongoing effort: EW corrections in differential analysis

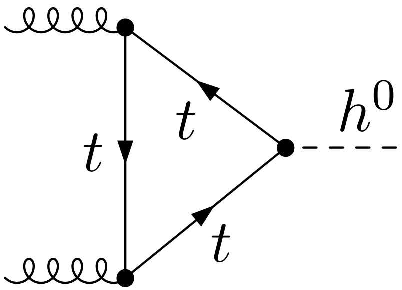
Gluon-Fusion

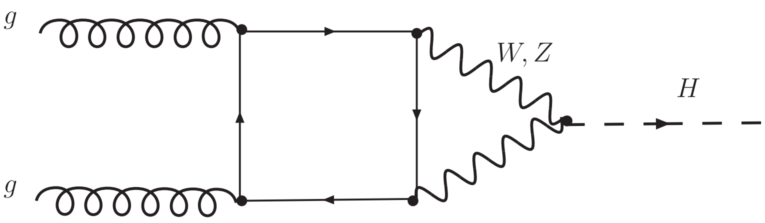


- dominant production process at LHC
- enormous efforts for the QCD prediction
  - NNLO, resummation ...
  - uncertainty $\mathcal{O}(20\%)$

Gluon-Fusion

- dominant production process at LHC
- enormous efforts for the QCD prediction
- full NLO (2-loop) EW corrections





Actis, Passarino, Sturm, Uccirati [arXiv:0809.1301]

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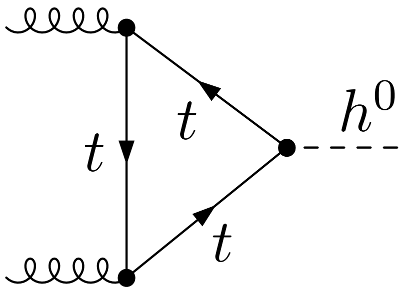

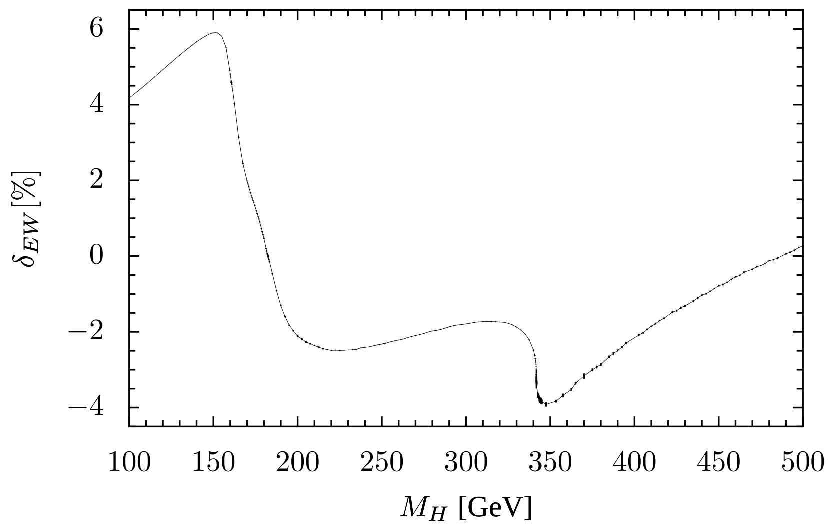

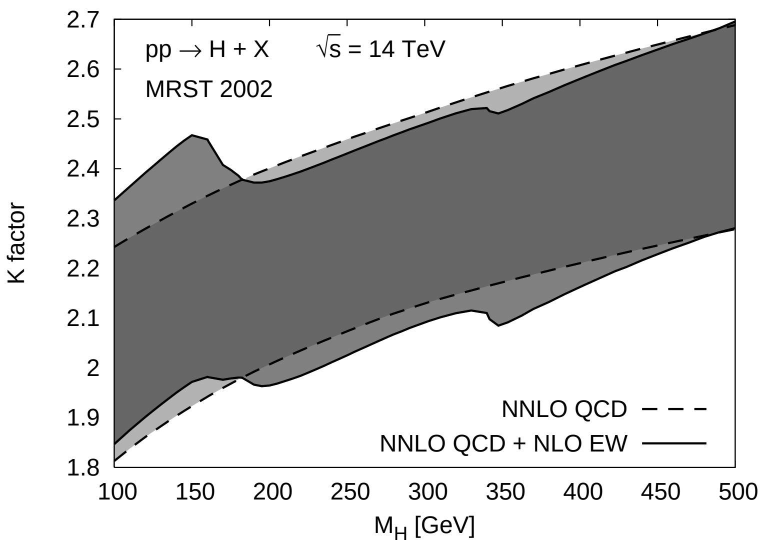

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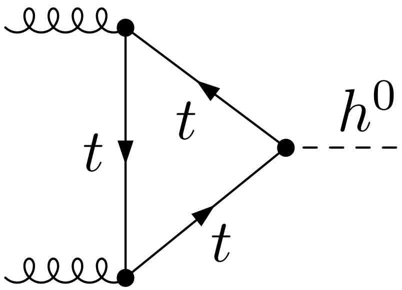
- non-trivial threshold behaviour inside loops (WW,ZZ,$t\bar{t}$)

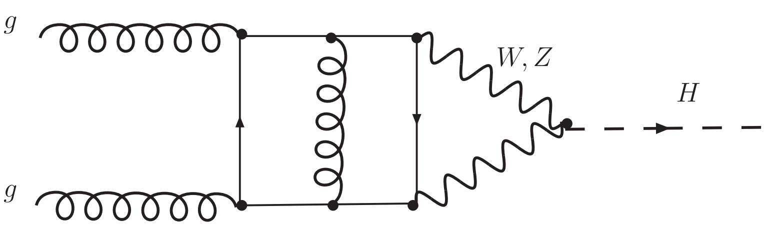
$\Rightarrow$ complex-mass scheme at two loops

Gluon-Fusion



- dominant production process at LHC
- enormous efforts for the QCD prediction
- full NLO (2-loop) EW corrections
- mixed $\mathcal{O}(\alpha\alpha_s)$ corrections (light fermion loops)

Anastasiou, Boughezal, Petriello [arXiv:0811.3458]



$\Rightarrow$ effective theory approach

(corrections to Wilson coefficient
in effective ggH coupling)

$\Rightarrow$ same philosophy like for QCD corrections

Gluon-Fusion

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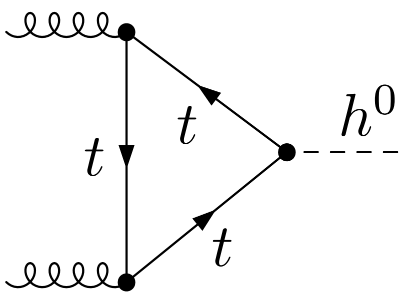

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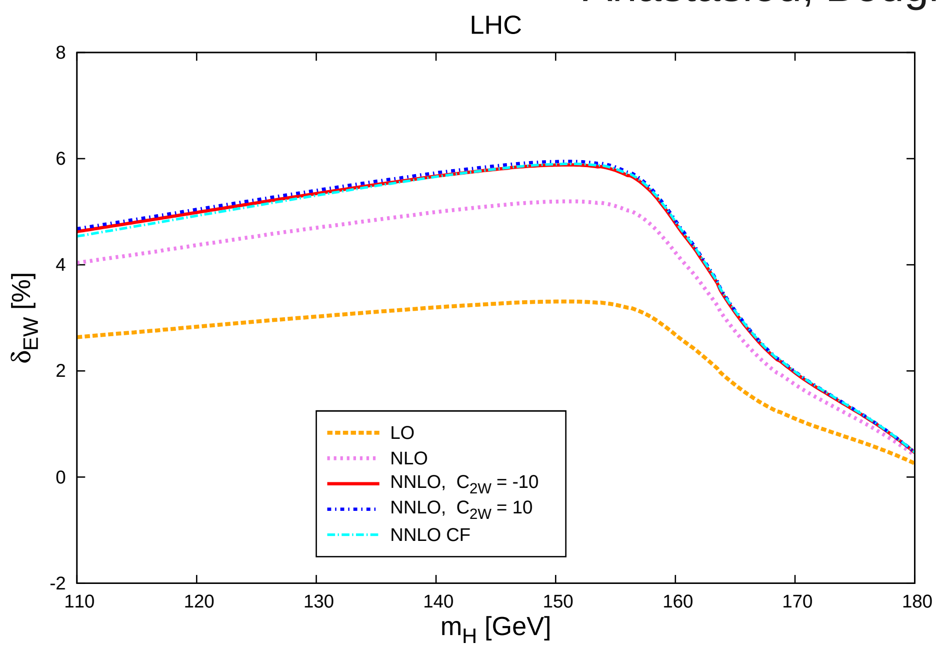
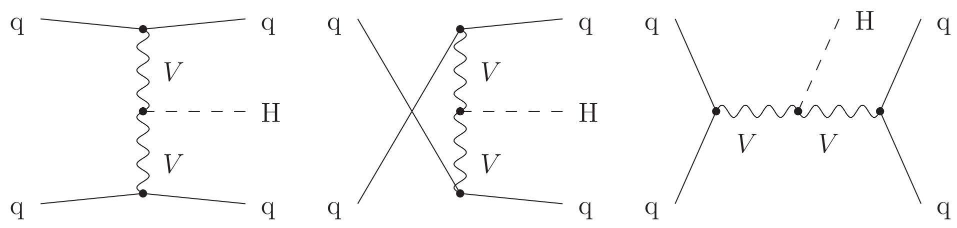


$\sim 5\%$ correction at $M_H = 125$ GeV

supports factorization of EW and QCD corrections

Vector-Boson Fusion

$$q\bar{q} \to \mathrm{H}jj$$



- sizeable fraction of inclusive Higgs production
- special kinematics: forward and backward jet $\Rightarrow$ VBF signal
- VBF cuts on jets (p_T, y, rapidity gap, central jet veto)
  - to reduce background
  - to separate from $gg \to \mathrm{H}jj$ in gluon fusion (5% after cuts)
  - s-channel and interferences negligible (DIS^2 like process)
- measure HWW and HZZ couplings
- investigate non-standard couplings

Vector-Boson Fusion

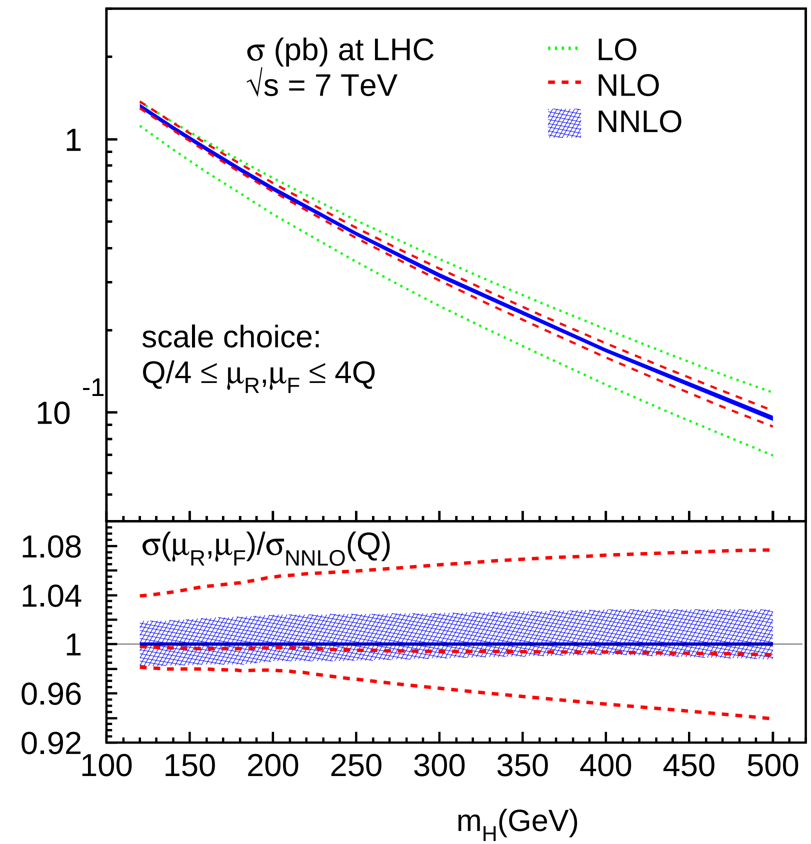
State of the art: Inclusive cross section

- NNLO QCD corrections: VBF@NNLO

Bolzoni,Maltoni,Moch,Zaro [arXiv:1003.4451]

structure function approach ($\rightarrow$ DIS^2)

QCD under excellent theoretical control at the 1% level



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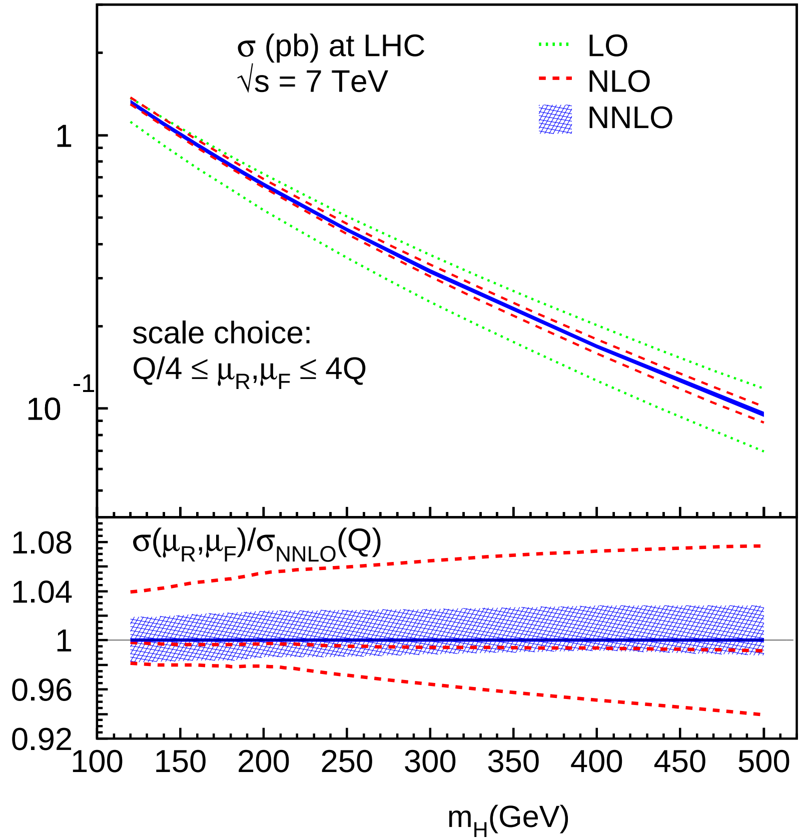
EW corrections relevant



Vector-Boson Fusion

State of the art: fully differential predictions

- NLO QCD+EW corrections available in public codes
  - VBFNLO (latest release: Arnold et al. [1207.4975])
    s-channel and interferences neglected
    EW corrections in the MSSM
    many additional features
  - HAWK (Denner, Dittmaier, Kallweit, AM)
    Ciccolini,Dittmaier, Krämer [hep-ph/0306234]
    no kinematic limitations (s-channel and interferences included)

http://omnibus.uni-freiburg.de/∼sd565/programs/hawk/hawk.html

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Vector-Boson Fusion

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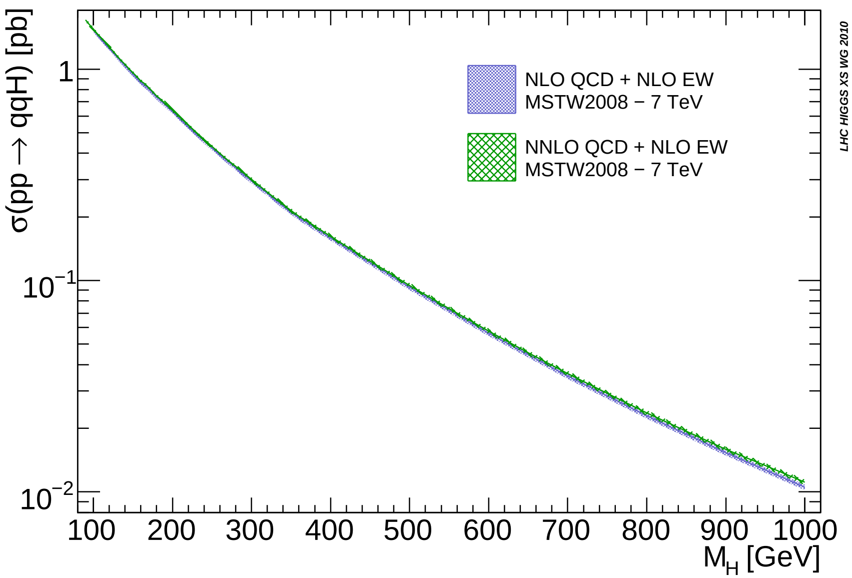
    Ciccolini,Dittmaier, Krämer [hep-ph/0306234]
    no kinematic limitations (s-channel and interferences included)
- Beyond fixed order
  - Powheg: merging NLO QCD with PS

Total cross section

- $\mathcal{O}$(5%) QCD corrections
- small uncertainties:
  scale: < 1% (for $M_{\rm H} < 250$ GeV)
  PDF+$\alpha_{\rm s}$: < 4% (for $M_{\rm H} < 300$ GeV)
- $\mathcal{O}$(-5%) EW corrections
- $\sigma = \sigma_{\rm NNLO}(1 + \delta_{\rm EW})$



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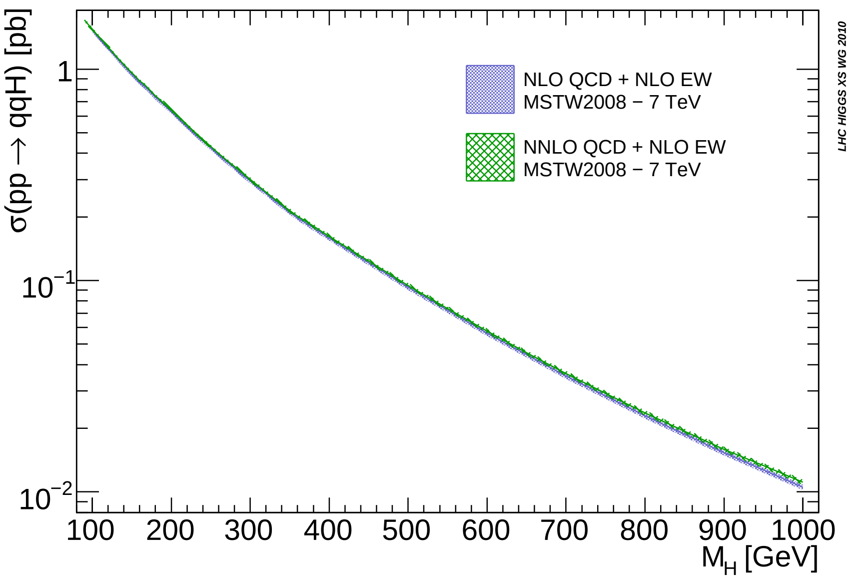

so far:

no VBF cuts, but no s-channel contribution

$\Rightarrow$ need for differential predictions (including cuts)

VBF cuts

Setup from second Yellow report (1201.3084):

Selection cuts:

$p_{\mathrm{T}j} > 20$ GeV

$|y_j| < 4.5$

VBF cuts:

$|y_{j1} - y_{j2}| > 4$

$M_{jj} > 600$ GeV

VBF cuts

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VBF cuts:

$|y_{j1} - y_{j2}| > 4$

$M_{jj} > 600$ GeV

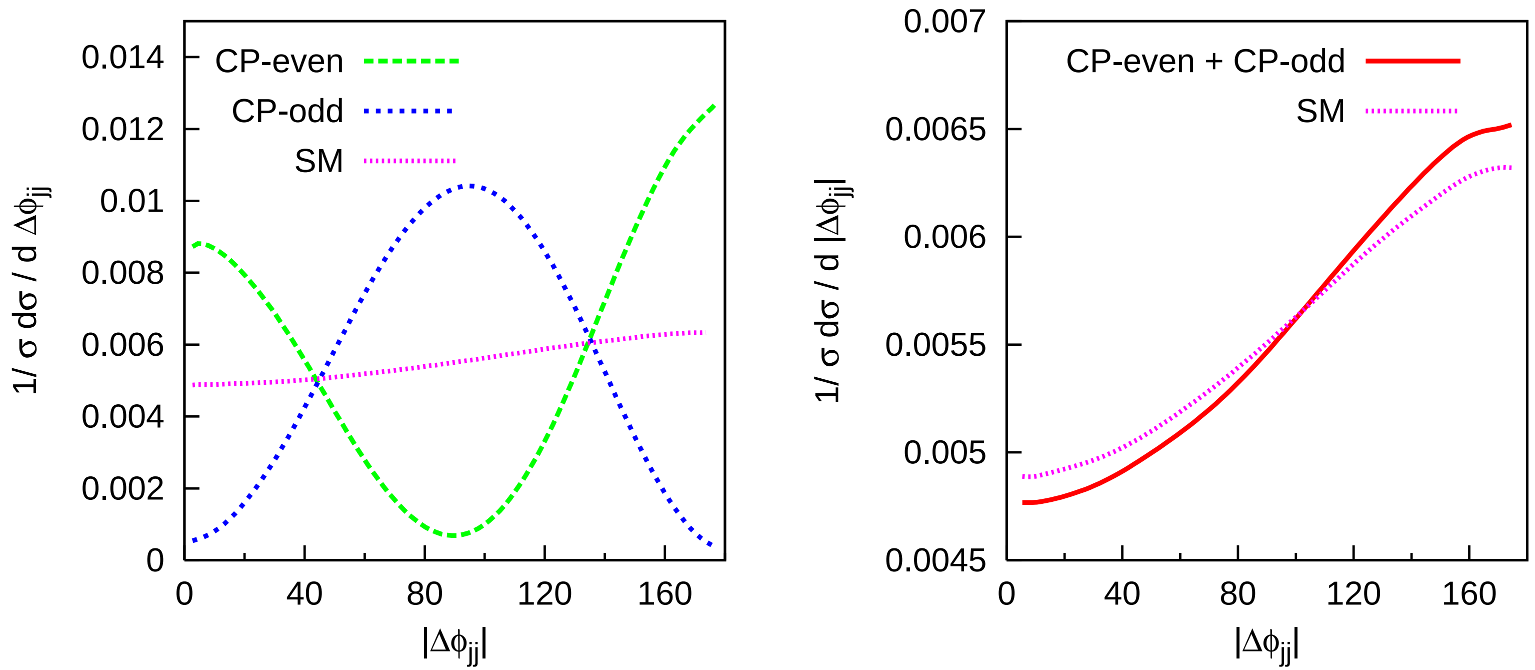
$\Rightarrow$ for $M_H = 125$ GeV:

- EW correction: $\delta_{\mathrm{EW}} = -8\%$
- scale uncertainty: $\sim 0.5\%$
- PDF uncertainty: $\sim 3.5\%$

Distributions

example: azimuthal angle between tagging jets

Hankele, Klämke, Zeppenfeld [hep-ph/0609075]



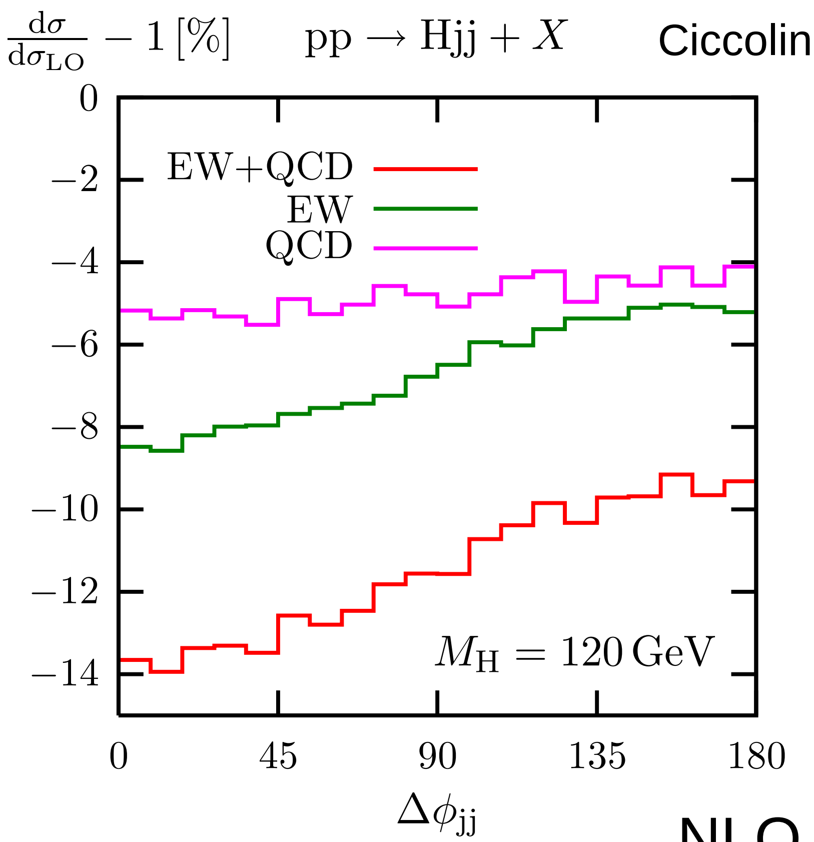
$\Rightarrow$ shape difference as signal for new physics

What about higher order corrections in distribution?

Distributions

example: azimuthal angle between tagging jets

Ciccolini,Dittmaier, Krämer [hep-ph/0306234]



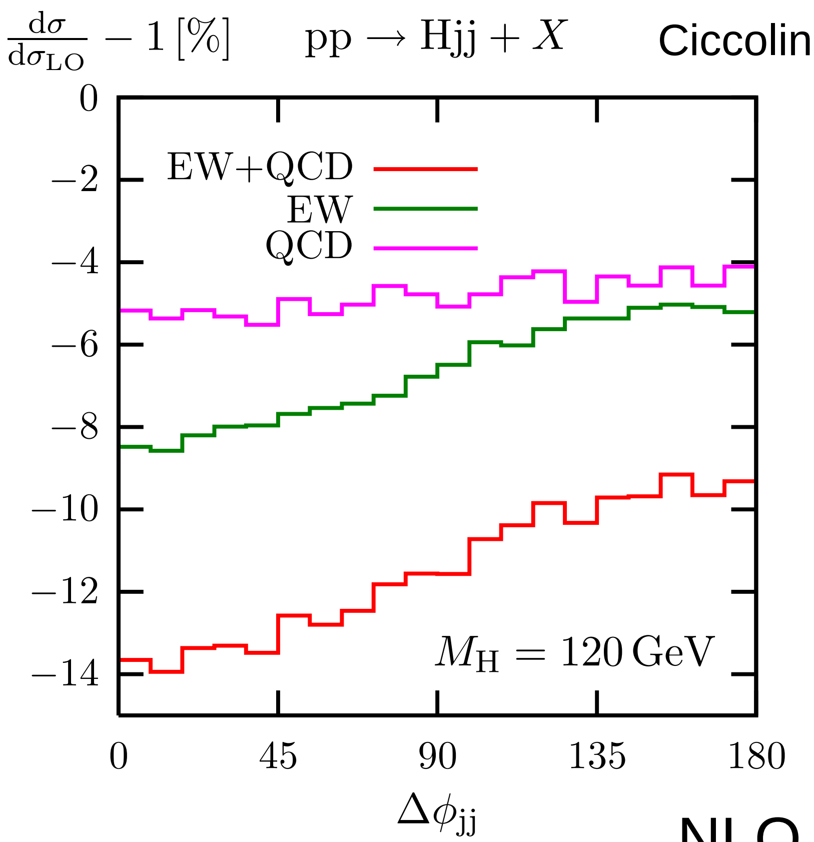
NLO QCD corrections rather flat

NLO EW corrections distort shape

Distributions

example: azimuthal angle between tagging jets

Ciccolini,Dittmaier, Krämer [hep-ph/0306234]



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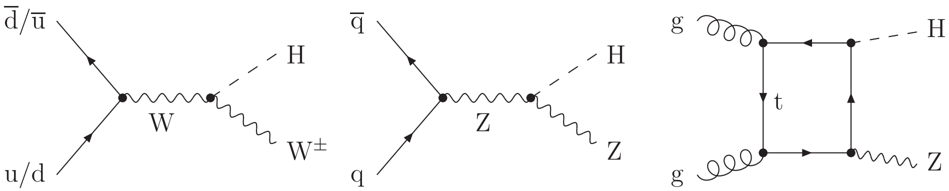
NLO EW corrections distort shape

$\Rightarrow$ differential reweighting to combine with best QCD prediction

Higgsstrahlung

$$pp \to W/Z + \mathrm{H}$$



- only small fraction of total Higgs cross section
- for a 125 GeV Higgs $H \to b\bar{b}$ should be accessible
- small signal to background ratio
  $\Rightarrow$ boosted Higgs: use high p_{T} Higgs bosons only
  b jets from "fat jet" substructure
- QCD corrections
  - similar to Drell-Yan ($\to$ relatively simple)
  - additional gluon-fusion contribution (5% level)
- EW corrections more involved

Higgsstrahlung

State of the art before 2011: Inclusive cross section

- NNLO QCD corrections: VH@NNLO

  Brein, Djouadi, Harlander [hep-ph/0307206]

  - only for total cross section

- NLO EW corrections   Ciccolini,Dittmaier, Krämer [hep-ph/0306234]

  - only for total cross section
  - stable W/Z bosons

Higgsstrahlung

State of the art before 2011: Inclusive cross section

- NNLO QCD corrections: VH@NNLO

  Brein, Djouadi, Harlander [hep-ph/0307206]
- NLO EW corrections   Ciccolini,Dittmaier, Krämer [hep-ph/0306234]
- scale uncertainty: 1-2 % @ NNLO
- PDF+α_s uncertainty: 3-5%
- EW correction: -5% for ZH and -7% for WH

  (at $M_H = 125$ GeV)

Higgsstrahlung

State of the art before 2011: Inclusive cross section

- NNLO QCD corrections: VH@NNLO

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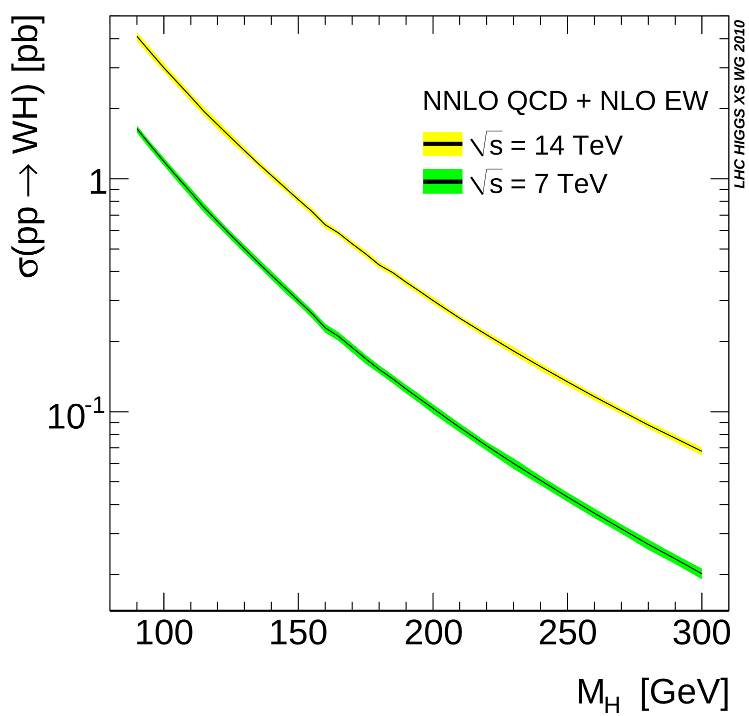
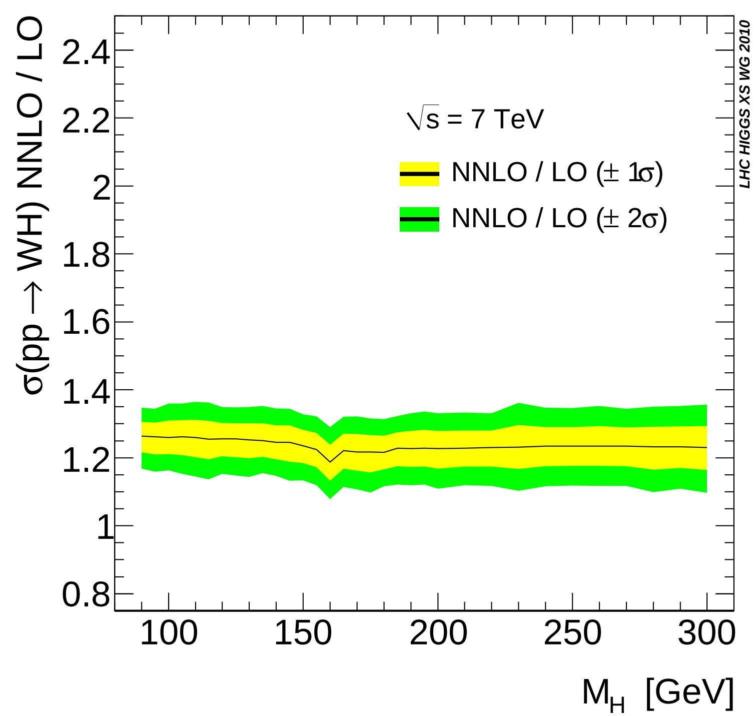
- NLO EW corrections Ciccolini,Dittmaier, Krämer [hep-ph/0306234]

$$\sigma_{\mathrm{WH}} = \sigma_{\mathrm{WH}}^{\mathrm{VH@NNLO}} \times (1+\delta_{\mathrm{WH,EW}}), \qquad \sigma_{\mathrm{ZH}} = \sigma_{\mathrm{ZH}}^{\mathrm{VH@NNLO}} \times (1+\delta_{\mathrm{ZH,EW}}) + \sigma_{\mathrm{gg}\to\mathrm{ZH}},$$





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- NLO EW corrections Ciccolini,Dittmaier, Krämer [hep-ph/0306234]

not applicable for boosted Higgs analysis

(very specific phase space region)

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Recent developments

- Differential NNLO QCD for WH

  Ferrera, Grazzini, Tramontano [arXiv:1107.1164]

  - fully differential Drell-Yan like NNLO QCD contributions
  - including Higgs and vector-boson decays
  - $\mathrm{H} \to b\bar{b}$ analysis possible (b-tagging, jet veto, etc...)

Recent developments

- Differential NNLO QCD for WH

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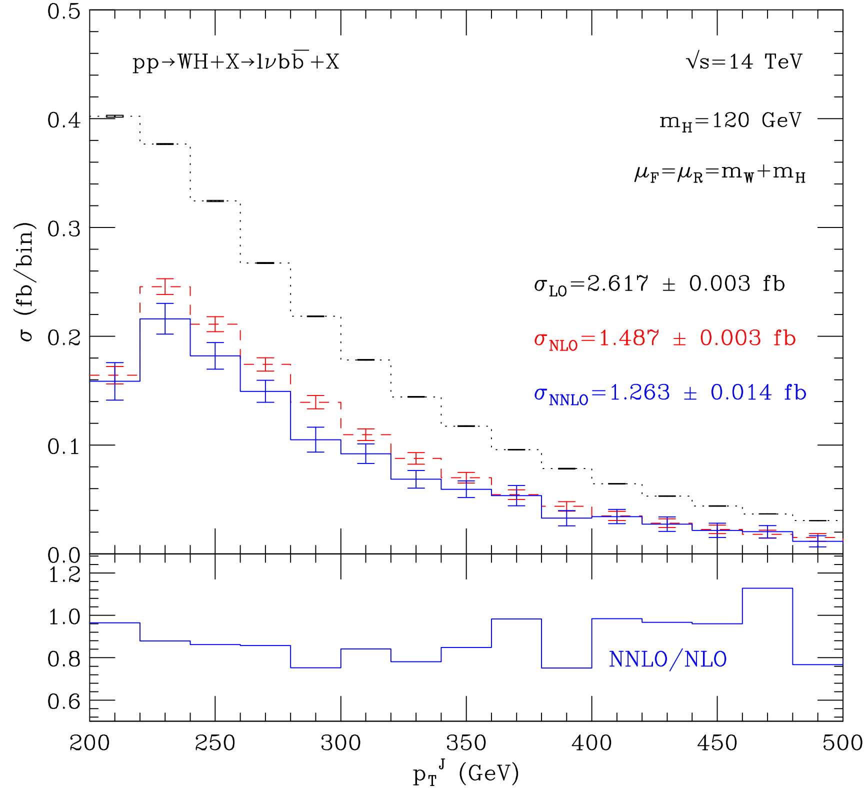


large negative correction due to strict jet veto

Recent developments

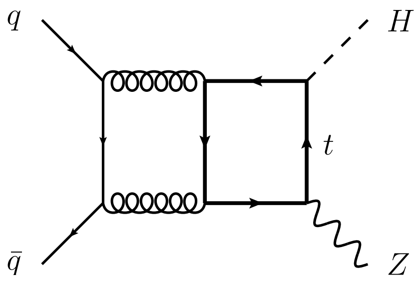
- Differential NNLO QCD for WH

  Ferrera, Grazzini, Tramontano [arXiv:1107.1164]

- NNLO beyond Drell-Yan

  Brein, Harlander, Wiesemann, Zirke [arXiv:1111.0761]

  - two-loop contribution in heavy-top limit
  - inclusive prediction only



Differential NLO EW

WH/ZH implemented in HAWK:

Denner, Dittmaier, Kallweit, Mück [1112.5142]

- fully differential EW corrections for the processes

$$pp \to Hl^+l^-, \quad pp \to Hl\nu_l, \quad pp \to H\bar{\nu}_l\nu_l$$

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- full access to leptons in final state

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- full access to leptons in final state
- vector-boson resonance

$\Rightarrow$ use the complex mass scheme

(will also regularize threshold spikes in EW corrections)

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- full access to leptons in final state
- vector-boson resonance

  $\Rightarrow$ use the complex mass scheme

  (will also regularize threshold spikes in EW corrections)

- HAWK for VBF includes s-channel contribution

  $\Rightarrow$ replace hadronic by leptonic boson decay

- independent second calculation
- HAWK for WH/ZH will also be public

Setup

- WH results: NNLO QCD from the authors of 1107.1164
  NLO EW from HAWK

  ZH results: NLO QCD and EW from HAWK

  QCD and EW corrections combined in factorized form:

$$\sigma = \sigma^{\mathrm{QCD}} \times (1 + \delta_{\mathrm{EW}}^{\mathrm{rec}}) + \delta_\gamma$$

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Setup

- WH results: NNLO QCD from the authors of 1107.1164
  NLO EW from HAWK

  ZH results: NLO QCD and EW from HAWK

- all results for 8 TeV LHC

- all results for $M_{\mathrm{H}} = 120$ GeV
  - on-shell Higgs without decay
  - for $M_{\mathrm{H}} = 125$ GeV results for EW corrections differ only by roughly 0.2%

Setup

- WH results: NNLO QCD from the authors of 1107.1164
  NLO EW from HAWK

  ZH results: NLO QCD and EW from HAWK

- all results for 8 TeV LHC
- all results for $M_{\mathrm{H}} = 120$ GeV
- off-shell vector bosons with leptonic decay
  - all results for specific leptonic channel
  - different lepton–photon recombination for μ and e

Setup

- WH results: NNLO QCD from the authors of 1107.1164
  NLO EW from HAWK

  ZH results: NLO QCD and EW from HAWK

- all results for 8 TeV LHC
- all results for $M_{\mathrm{H}} = 120$ GeV
- off-shell vector bosons with leptonic decay
- cuts for boosted Higgs bosons:

$$p_{\mathrm{T,l}} > 20\,\mathrm{GeV}, \quad |y_{\mathrm{l}}| < 2.5, \quad p_{\mathrm{T,miss}} > 25\,\mathrm{GeV}$$

$$p_{\mathrm{T,H}} > 200\,\mathrm{GeV}, \quad p_{\mathrm{T,W/Z}} > 190\,\mathrm{GeV}$$

(avoid symmetric cuts)

Setup

- WH results: NNLO QCD from the authors of 1107.1164
  NLO EW from HAWK

  ZH results: NLO QCD and EW from HAWK

- all results for 8 TeV LHC

- all results for $M_{\mathrm{H}} = 120$ GeV

- off-shell vector bosons with leptonic decay

- cuts for boosted Higgs bosons:

$$p_{\mathrm{T,l}} > 20\,\mathrm{GeV}, \quad |y_{\mathrm{l}}| < 2.5, \quad p_{\mathrm{T,miss}} > 25\,\mathrm{GeV}$$

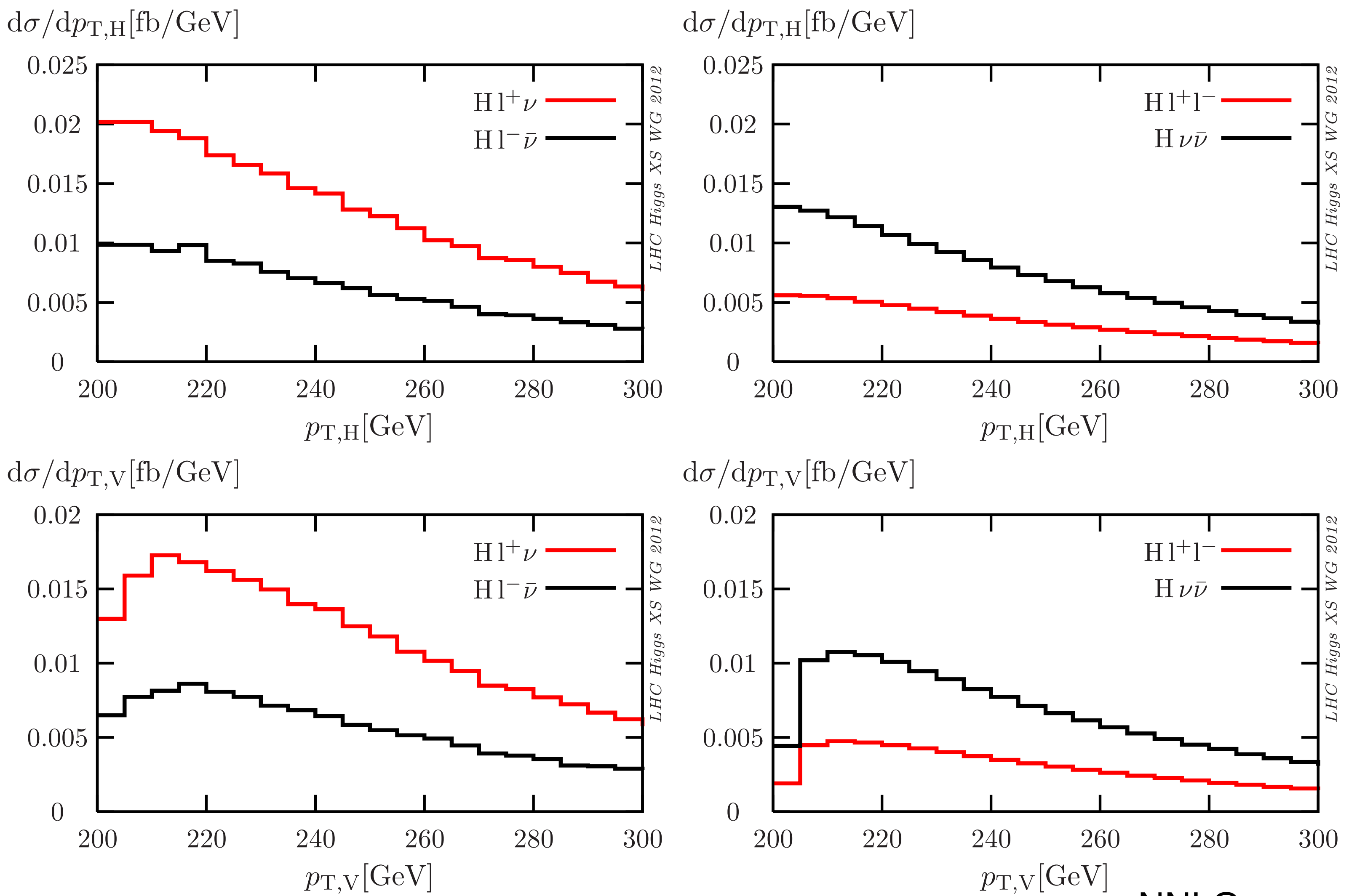
$$p_{\mathrm{T,H}} > 200\,\mathrm{GeV}, \quad p_{\mathrm{T,W/Z}} > 190\,\mathrm{GeV}$$

(avoid symmetric cuts)

- central scale choice: $\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = M_{\mathrm{H}} + M_V$

- default PDF set: MSTW2008

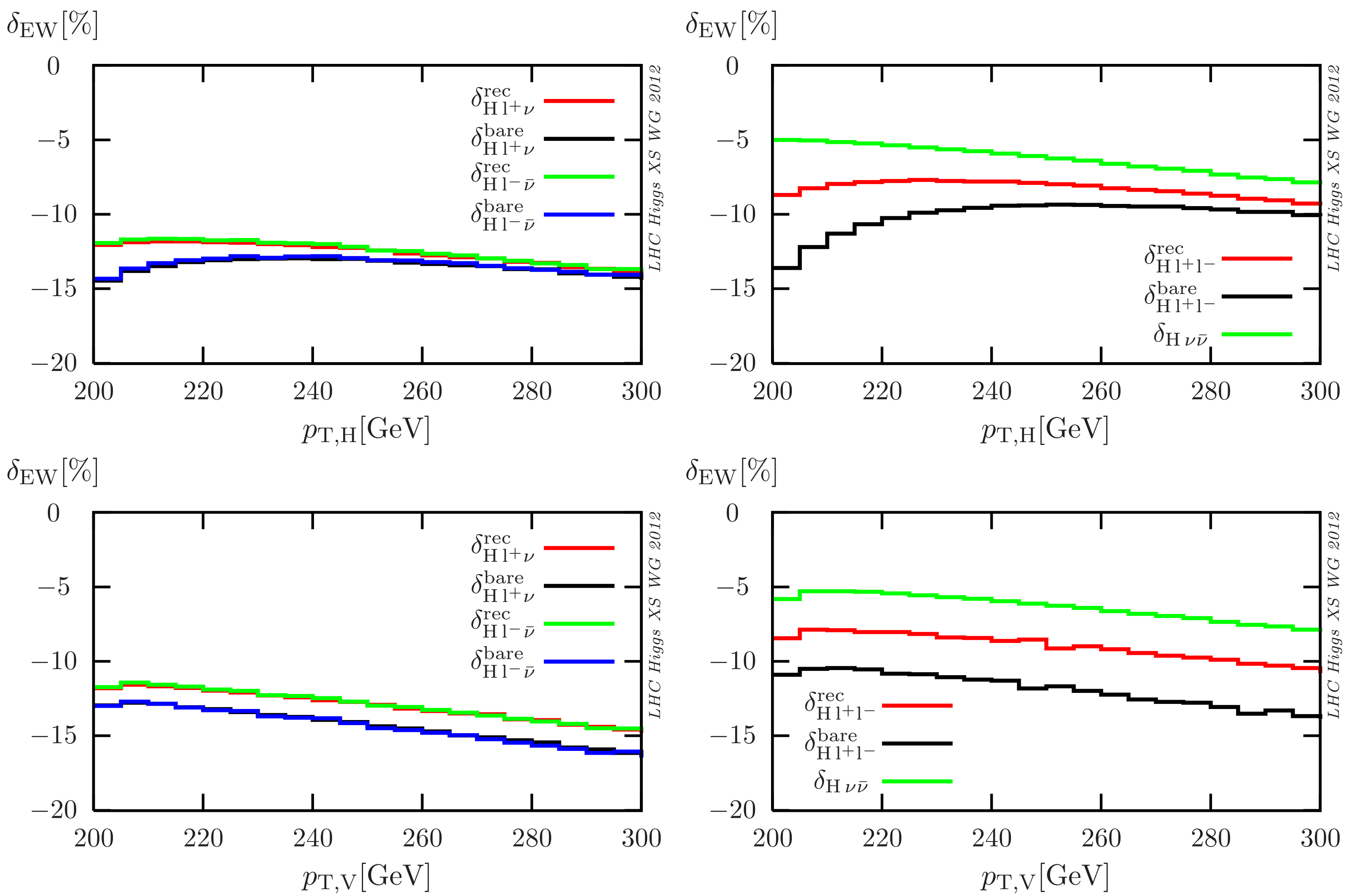
Results



$$\sigma = \sigma^{\mathrm{QCD}} \times (1 + \delta_{\mathrm{EW}}^{\mathrm{rec}}) + \delta_\gamma$$

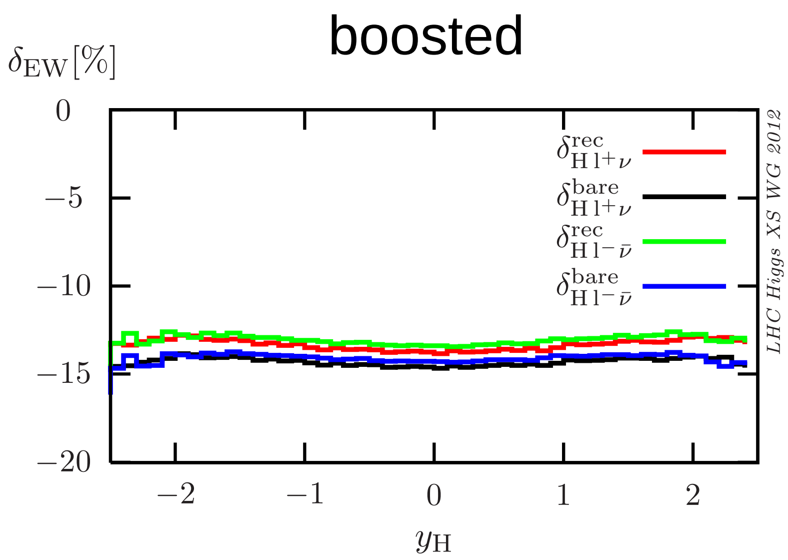
NNLO: green, blue
NLO: red, black

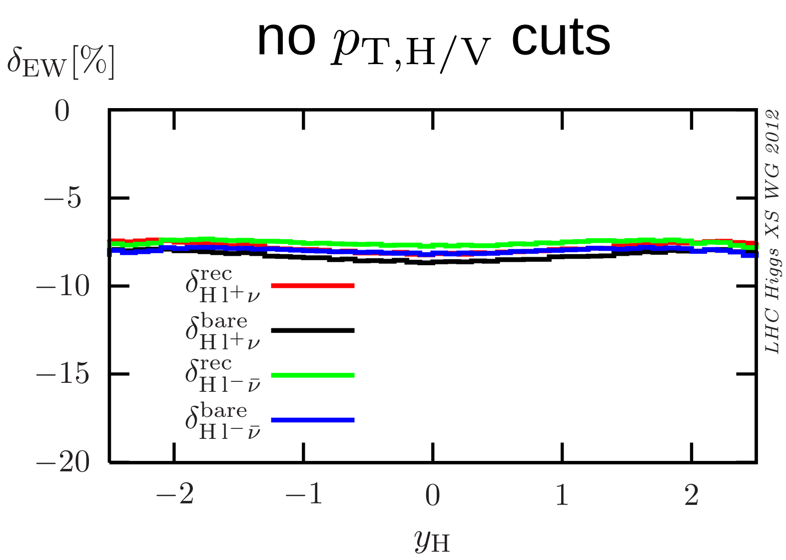
EW corrections



different lepton–photon recombination: rec for electrons
bare for muons

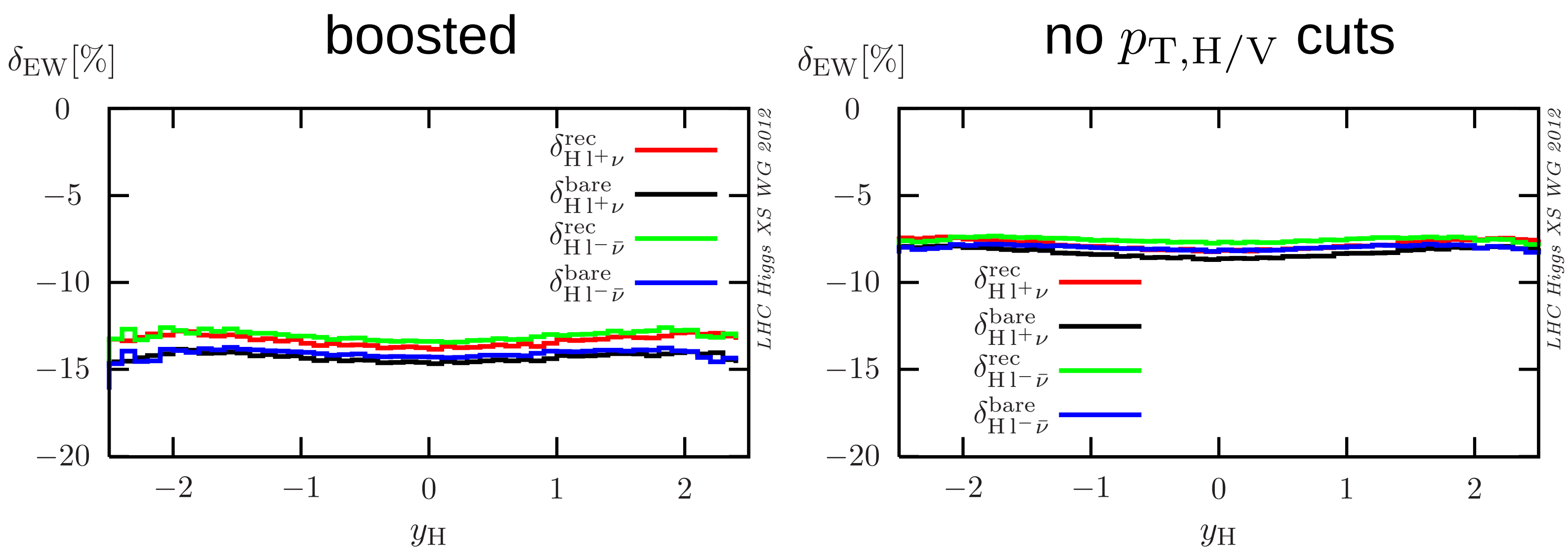
EW corrections





- larger EW corrections for boosted Higgs
- up to -15% for WH

EW corrections



- larger EW corrections for boosted Higgs
- up to -15% for WH
- uncertainties (for differential analysis):
  - scale: 2%
  - PDF: 5%
  - missing higher orders (e.g. $gg \to VH$): 1% (7%) for WH (ZH)

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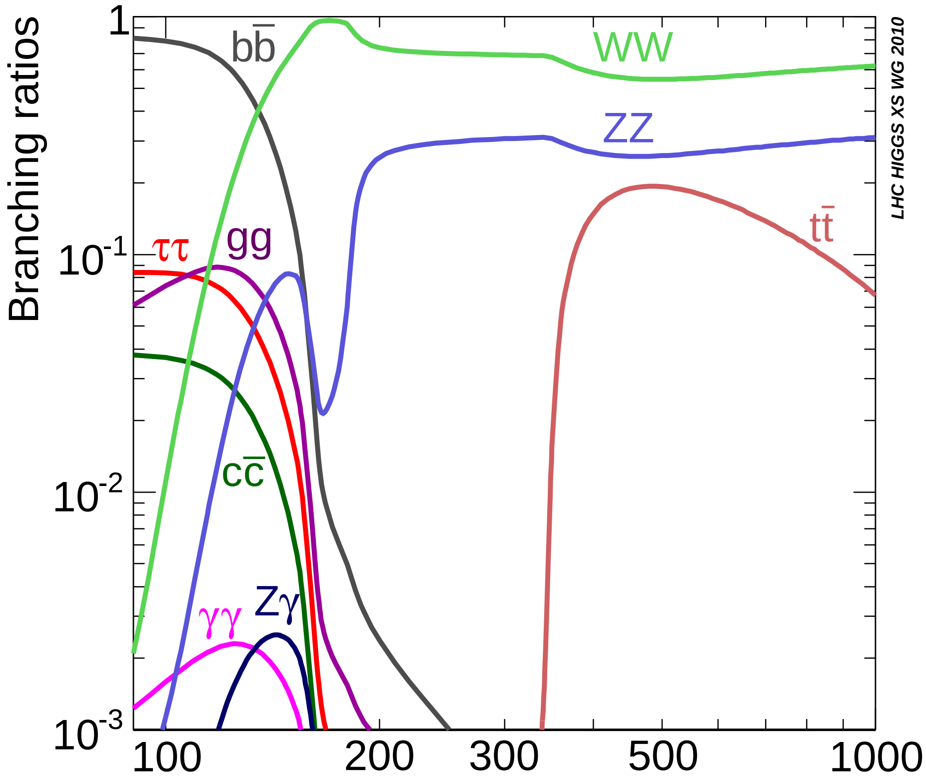
RWTH

Higgs Decays

NLO EW corrections to Higgs boson decays:

- $\mathrm{H} \to f\bar{f}$
  Bardin, Vilensky, Khristova
  [Sov.J.Nucl.Phys. 53 (1991) 152]
  Dabelstein, Hollik
  [Z.Phys. C53 (1992) 507]
  Kniehl
  [Nucl.Phys. B376 (1992) 3]
- $\mathrm{H} \to \gamma\gamma$
  Passarino, Sturm, Uccirati
  [arXiv:0707.1401]
- $\mathrm{H} \to gg$
  Actis, Passarino, Sturm, Uccirati
  [arXiv:0809.1301]



M_H [GeV]
LHC Higgs Cross Section Working Group
[arXiv:1101.0593]

all included in HDECAY
(together with QCD corrections)
Djouadi, Kalinowski, Spira [hep-ph/9704448]

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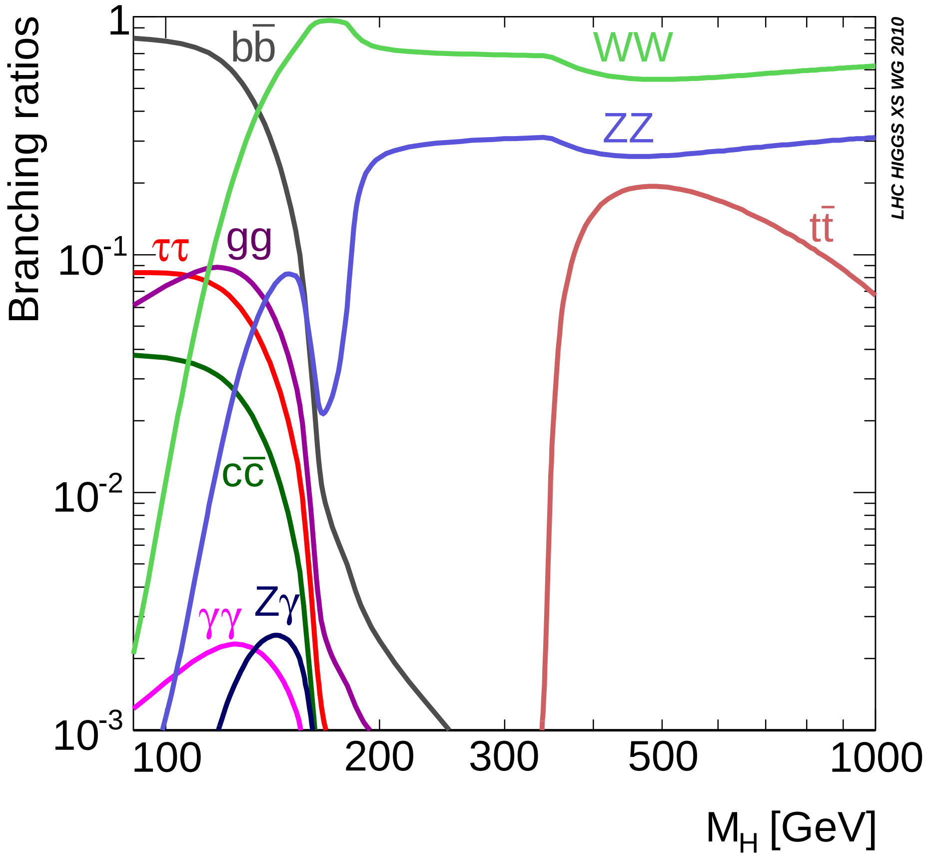

- $\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$

  for off-shell/decaying W/Z bosons

  Bredenstein, Denner, Dittmaier, Weber [hep-ph/0611234]

Higgs Decays

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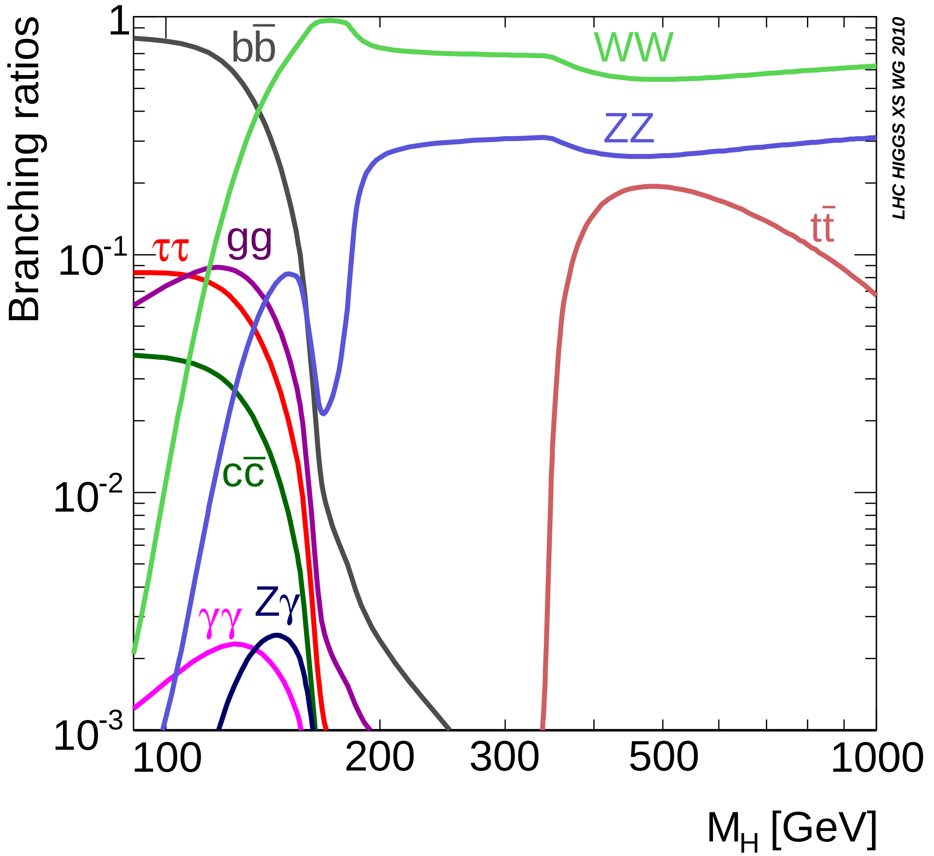

- $\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$
  $\Rightarrow$ Prophecy4f MC generator

Bredenstein, Denner, Dittmaier, AM, Weber
[http://omnibus.uni-freiburg.de/∼sd565/programs/prophecy4f/prophecy4f.html]

Summary

- Discovery of a 125 GeV boson
- Is it the SM Higgs?

$\Rightarrow$ search for deviations from the SM

$\Rightarrow$ precision predictions most important

(joint effort: Higgs cross section working group)

- EW corrections:
  - available for major channels
  - sizeable: 10% level
  - included at inclusive level
  - ongoing efforts for differential analysis

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HOCHSCHULE
AACHEN

Back-up slides

Resonances

problem: $\frac{1}{p^2-M^2} \overset{?}{\rightarrow} \frac{1}{p^2-M^2+iM\Gamma}$

solution: complex mass scheme

Denner, Dittmaier, Roth, Wieders [hep-ph/0505042]

- use complex W and Z masses everywhere by means of complex renormalization:

  $M^2_{\mathrm{V},0} = \mu^2_{\mathrm{V}} + \delta\mu^2_V$

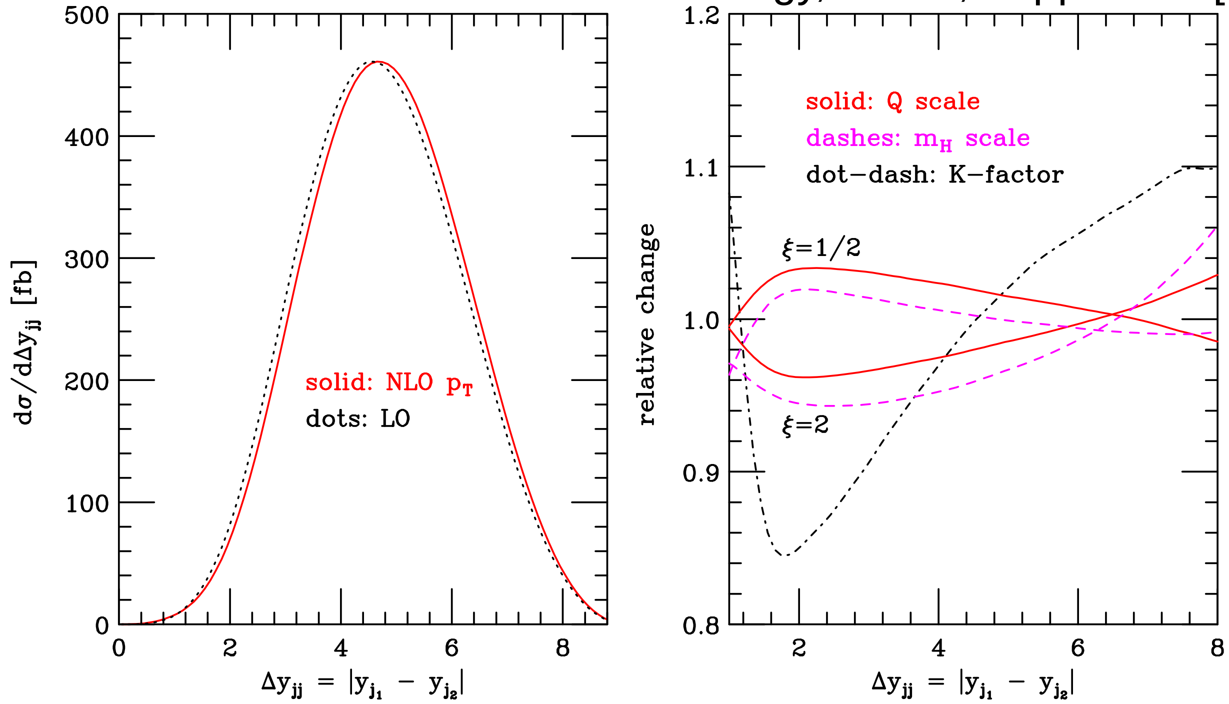
  with: $M^2_{\mathrm{V},0}$ = bare mass $(\mathrm{V} = \mathrm{W}, \mathrm{Z})$
  μ^2_{V} = ren. complex mass
  $\delta\mu^2_V$ = complex counterterm

- $\Rightarrow$ complex $s^2_{\mathrm{W}} = 1 - \mu^2_{\mathrm{W}}/\mu^2_{\mathrm{Z}}$
- loop-integrals for complex masses needed
- unitarity-violating beyond NLO accuracy
- gauge invariant
- valid everywhere in phase space

Distributions

example: rapidity separation (leading p_T jets)

Figy, Oleari, Zeppenfeld [hep-ph/0306109]

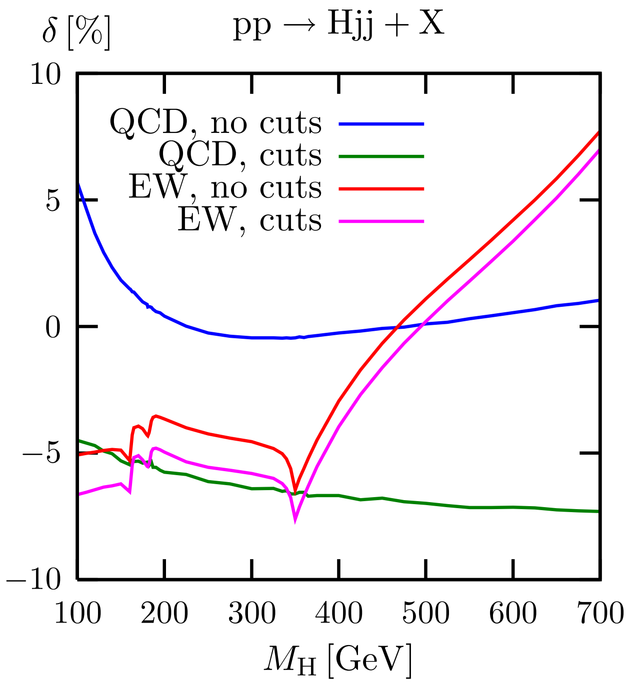


$\Rightarrow$ no uniform K-Factor

inclusive ⇔ VBF cuts

relative NLO corrections for VBF:

Ciccolini,Denner,Dittmaier [arXiv:0710.4749]



cuts ⇔ no cuts:
large difference for NLO QCD

however in this plot:

- s-channel included (large, positive correction)
- MRSTQED2004 PDF at LO/NLO

Tuned comparison in 2007:

LH Higgs working group [arXiv:0803.1154]

without cuts ($M_H = 120$ GeV)

$\sigma_{\rm LO}^{\rm VBFNLO} = 4227.1(1)$ fb

$\sigma_{\rm NLO}^{\rm VBFNLO} = 4414.8(2)$ fb

$\rightarrow$ NLO QCD corrections: 4.4%

with cuts ($M_H = 120$ GeV)

$\sigma_{\rm LO}^{\rm VBFNLO} = 1686.90(5)$ fb

$\sigma_{\rm NLO}^{\rm VBFNLO} = 1728.8(2)$ fb

$\rightarrow$ NLO QCD corrections: 2.5%