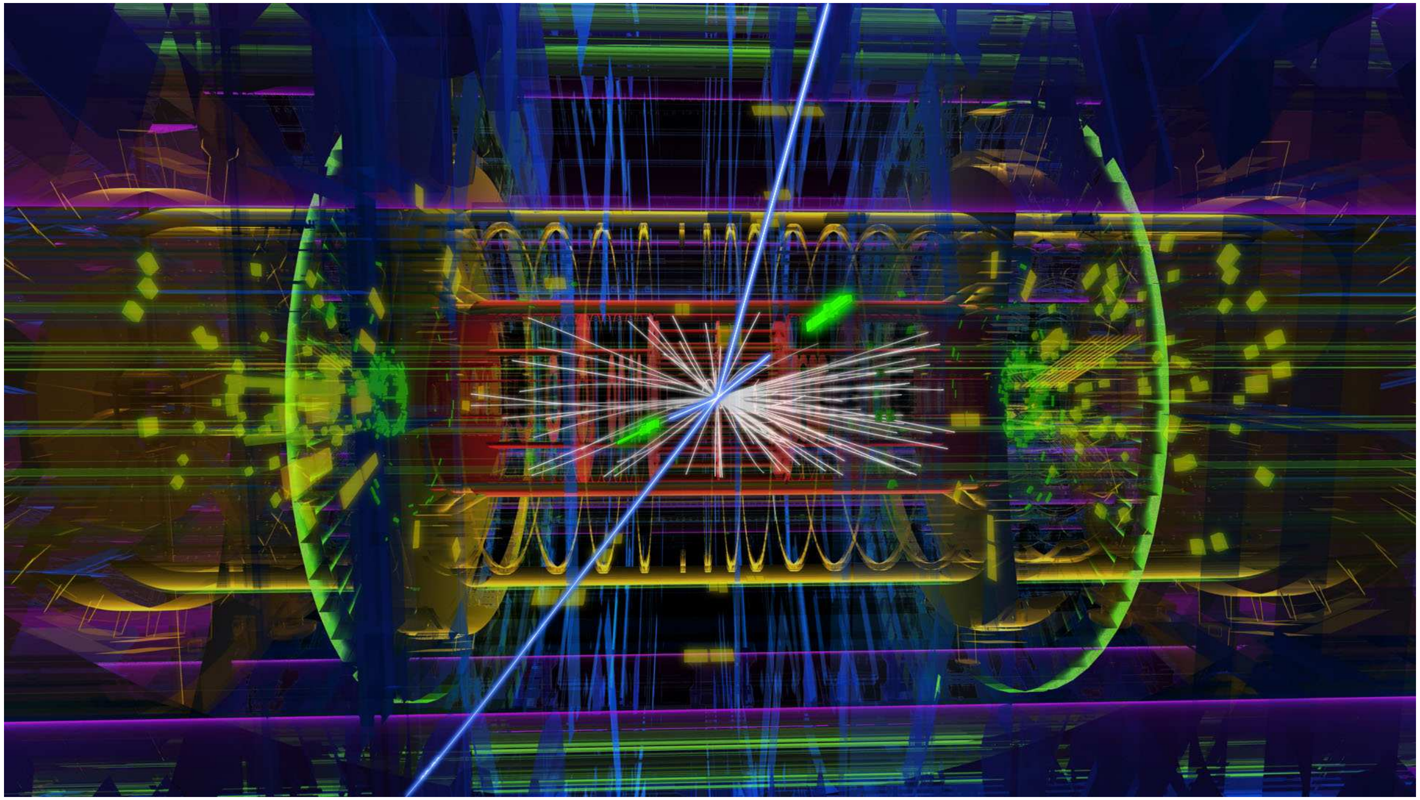


The Quest for the Higgs Boson

—

a Theory Perspective

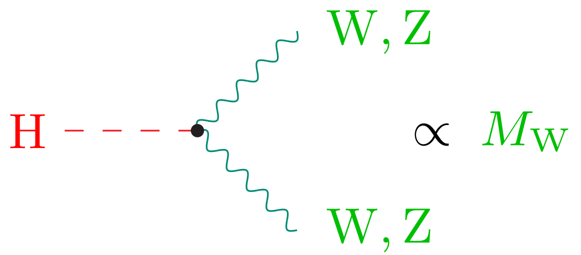
Stefan Dittmaier

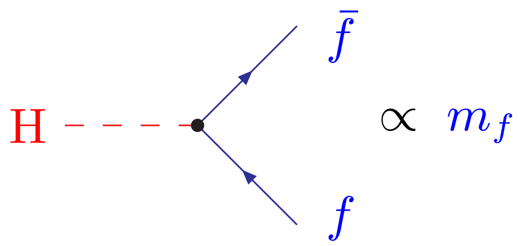
Albert-Ludwigs-Universität Freiburg

Introduction

Higgs search at present and future colliders

Higgs bosons couple proportional to particle masses:

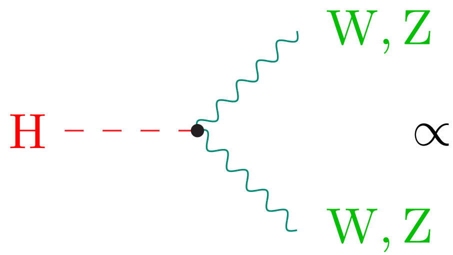




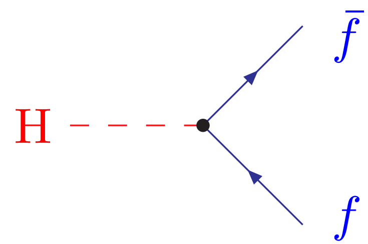
⇒ Higgs production/decay mainly via coupling to W/Z bosons or top quarks

Higgs search at present and future colliders

Higgs bosons couple proportional to particle masses:



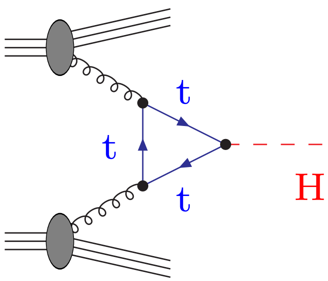
$\propto M_{\mathrm{W}}$

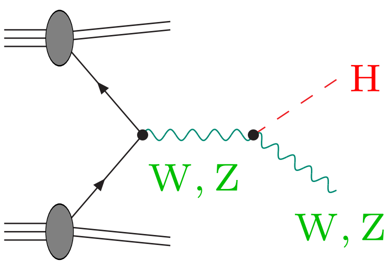


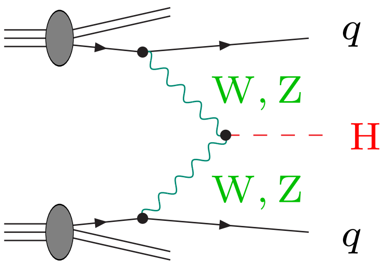
$\propto m_f$

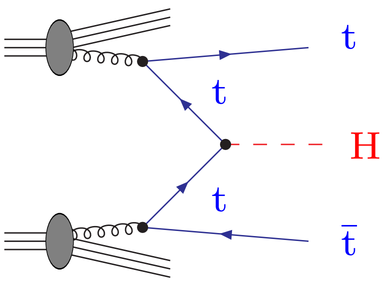
$\Rightarrow$ Higgs production/decay mainly via coupling to W/Z bosons or top quarks

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



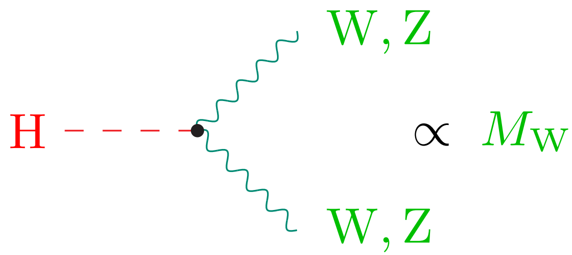


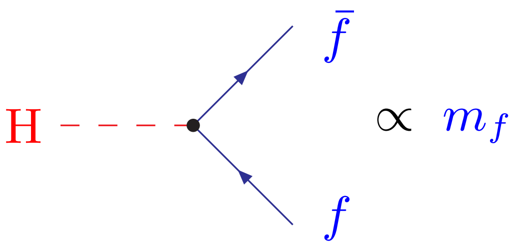




Higgs search at present and future colliders

Higgs bosons couple proportional to particle masses:





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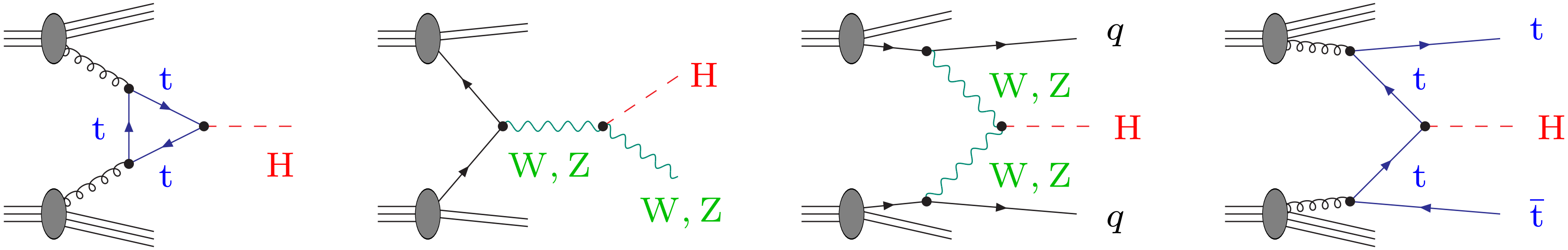
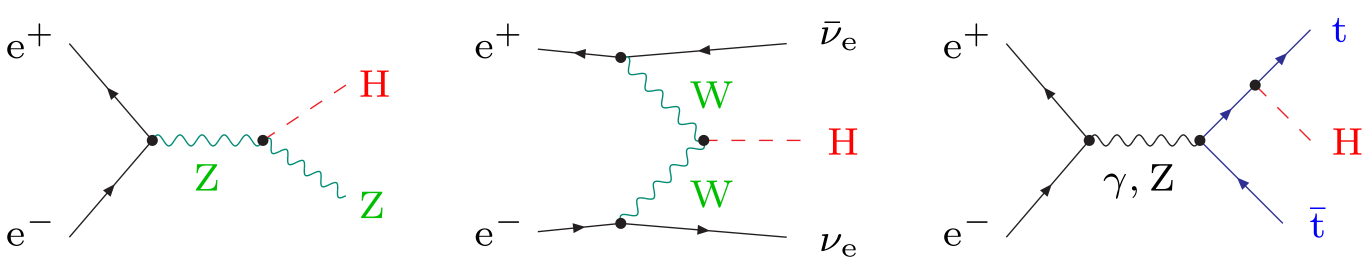
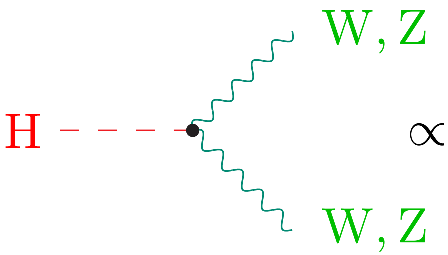


Processes at e^+e^- colliders:

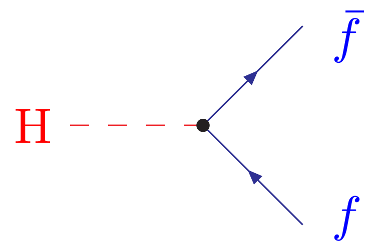


Higgs search at present and future colliders

Higgs bosons couple proportional to particle masses:



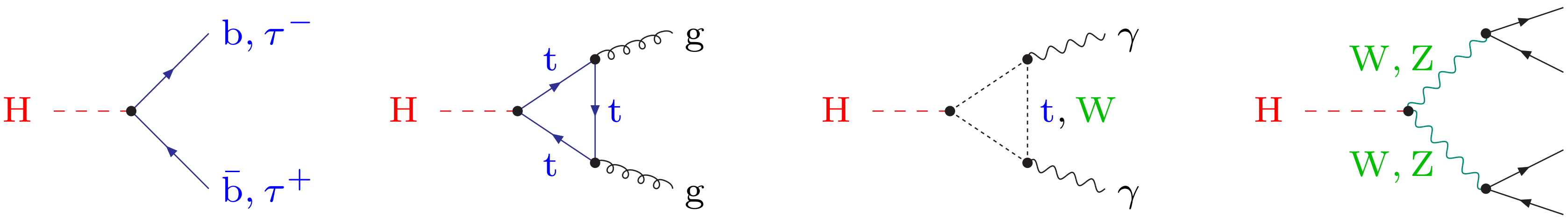
$\propto M_{\mathrm{W}}$



$\propto m_f$

$\Rightarrow$ Higgs production/decay mainly via coupling to W/Z bosons or top quarks

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



Higgs search at present and future colliders

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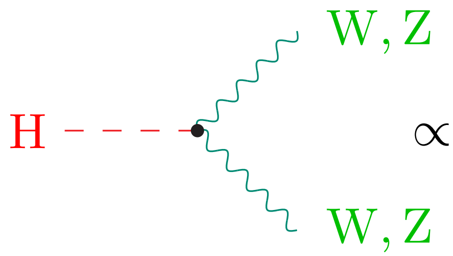

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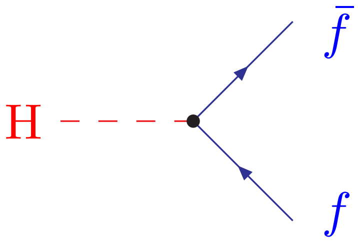

$\propto m_f$

$\Rightarrow$ Higgs production/decay mainly via coupling to W/Z bosons or top quarks

The role of Higgs physics in theoretical predictions

- Higgs mass enters EW precision calculations
  $\hookrightarrow$ M_H sensitivity of SM fit to precision data
- Preparation for Higgs-boson searches
  $\hookrightarrow$ particularly complicated at hadron colliders

$\Rightarrow$ Multi-loop and multi-leg higher-order calculations at the frontier !

Theory constraints on the Higgs-boson mass

- Upper limits from
  - unitarity of $\mathrm{W_L}$ scattering amplitudes ($\mathrm{W_L W_L} \to \mathrm{W_L W_L}$, etc.) for $s \gg M_\mathrm{W}^2$
    Lee, Quigg, Thacker '77, ...
  - triviality ($\lambda = 0$) of Higgs sector for too large M_H
    Hambye, Riesselmann '97, ...
- Lower limit from vacuum stability Coleman, Weinberg '73; Lindner, Sher, Zaglauer '89, ...

$\Rightarrow$ SM valid up to new-physics scale Λ requires $M_{\mathrm{H,vac.stab.}}(\Lambda) < M_\mathrm{H} < M_{\mathrm{H,triv.}}(\Lambda)$

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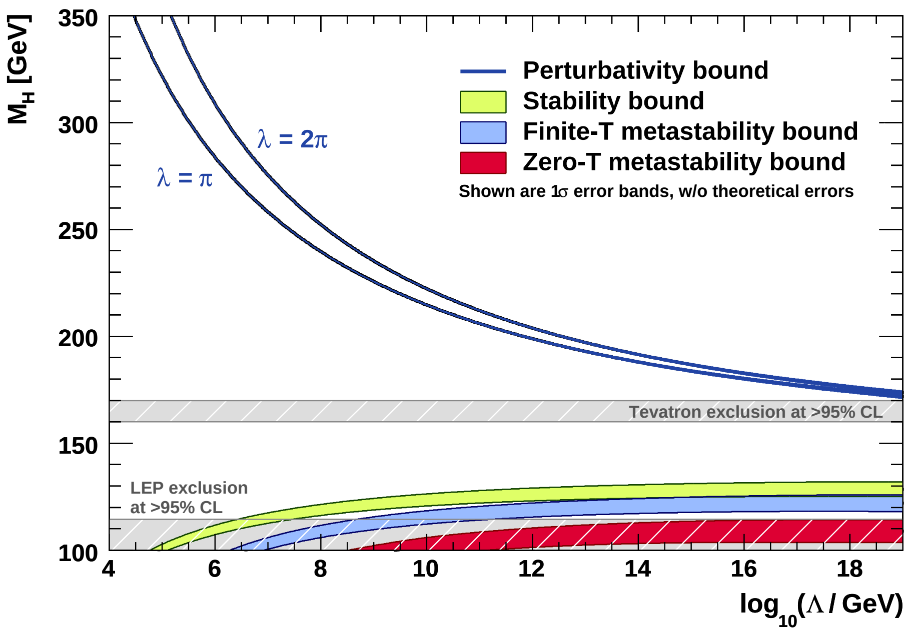
Ellis et al. '09



SM valid up to Planck scale
with Universe in metastable vacuum ?

$\leftarrow$ $M_H = 126$ GeV Higgs candidate

Intention of the talk – brief theorist's account ...

- on the history Higgs searches before LHC
  $\hookrightarrow$ EW precision physics, searches via e^+e^-
- on Higgs physics at hadron colliders
  $\hookrightarrow$ Where do we stand ?
- on future challenges for theory

... being more topical than comprehensive, restricted to the SM

Contents

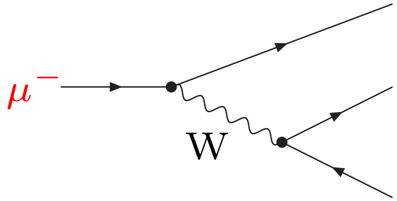
Electroweak precision observables

–

window to the Higgs sector

Important electroweak experiments

- Muon decay: Fermi constant G_μ delivers constraint on $\alpha, M_\mathrm{W}, M_\mathrm{Z}$

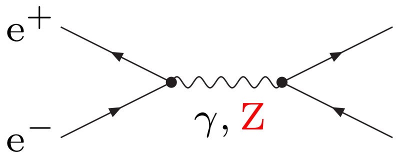


$$G_\mu = \frac{\pi\alpha M_\mathrm{Z}^2}{\sqrt{2}M_\mathrm{W}^2(M_\mathrm{Z}^2 - M_\mathrm{W}^2)} + \ldots$$

Important electroweak experiments

- Muon decay: Fermi constant G_μ delivers constraint on $\alpha, M_\mathrm{W}, M_\mathrm{Z}$

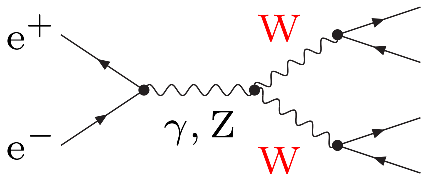
- Z production (LEP1/SLC): M_Z and precision observables at the Z pole

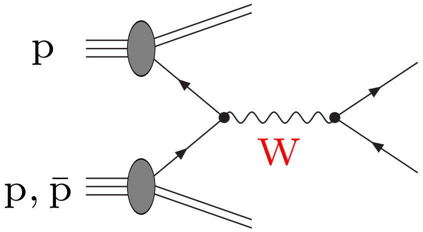


$\Gamma_\mathrm{Z}, \sigma_\mathrm{had}, A_\mathrm{FB}, A_\mathrm{LR}, \mathrm{etc.}$

Important electroweak experiments

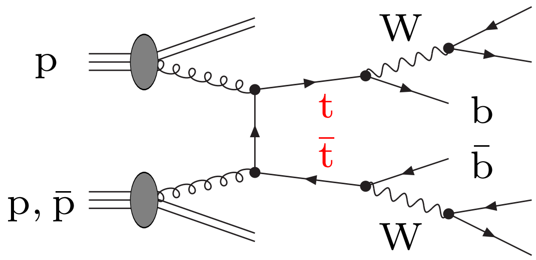
- Muon decay: Fermi constant G_μ delivers constraint on α, M_W, M_Z
- Z production (LEP1/SLC): M_Z and precision observables at the Z pole
- W production (LEP2/Tevatron/LHC): W-boson mass M_W





Important electroweak experiments

- Muon decay: Fermi constant G_μ delivers constraint on α, M_W, M_Z
- Z production (LEP1/SLC): M_Z and precision observables at the Z pole
- W production (LEP2/Tevatron/LHC): W-boson mass M_W
- top-quark production (Tevatron/LHC): top-quark mass m_t



Important electroweak experiments

- Muon decay: Fermi constant G_μ delivers constraint on $\alpha, M_\mathrm{W}, M_\mathrm{Z}$
- Z production (LEP1/SLC): M_Z and precision observables at the Z pole
- W production (LEP2/Tevatron/LHC): W-boson mass M_W
- top-quark production (Tevatron/LHC): top-quark mass m_t

Theoretical predictions

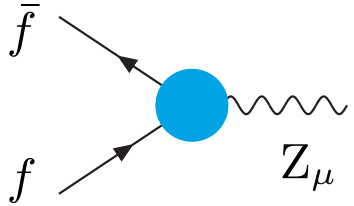
parametrized by $\alpha(M_\mathrm{Z})$, M_W, M_Z, m_t, m_f, $\alpha_\mathrm{s}(M_\mathrm{Z})$ and M_H

$\hookrightarrow$ global fit of SM to data yields bounds on M_H

But: high precision necessary,
since M_H sensitivity weak $\sim \frac{\alpha}{\pi}\log(M_\mathrm{H}/M_\mathrm{W})$
(in contrast to top-loops where sensitivity $\sim G_\mu m_\mathrm{t}^2$)

An example: the leptonic effective weak mixing angle $\sin^2\theta_{\rm eff}^{\rm lept}$

Effective Z-boson couplings measured from various asymmetries at LEP1/SLC



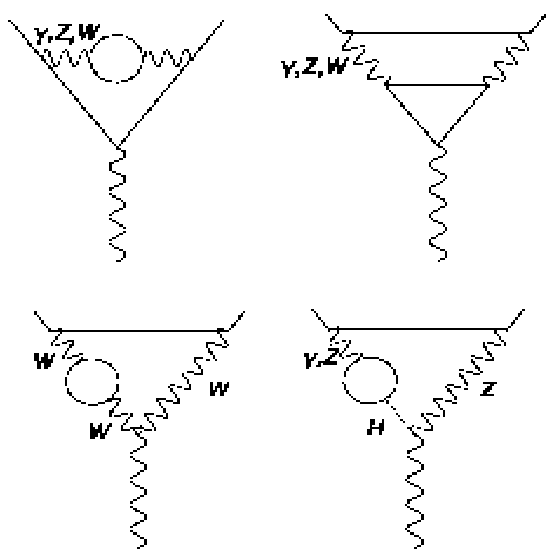
$$= ie\gamma_\mu(g_{Vf} - g_{Af}\gamma_5)$$

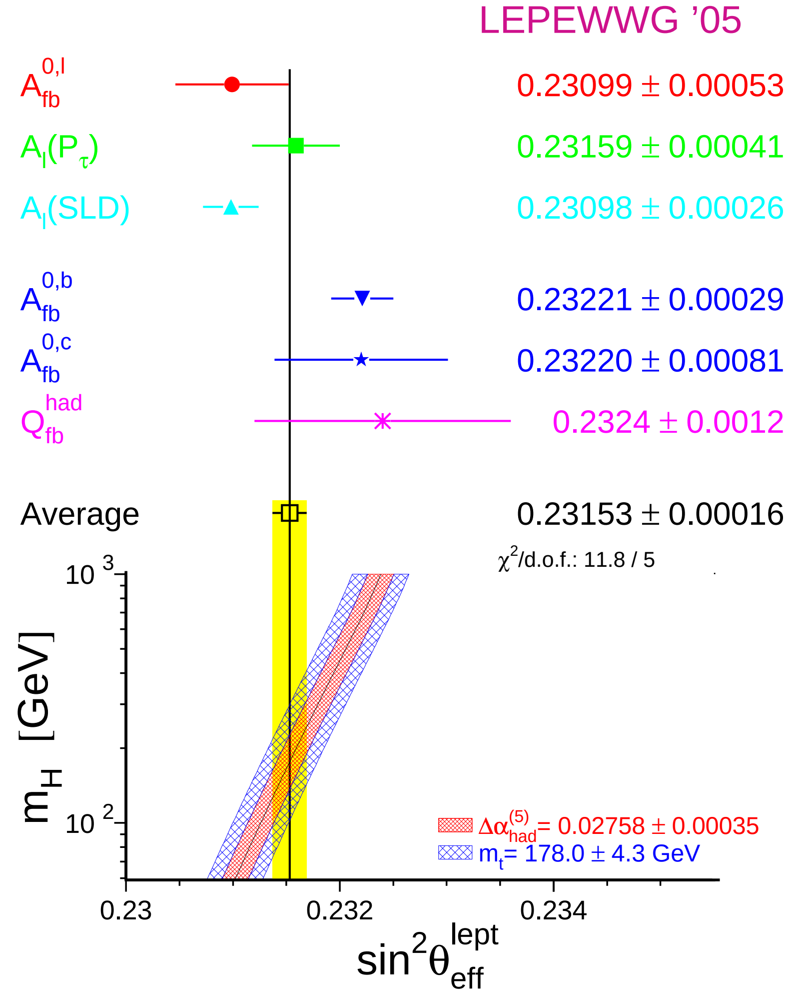
“Effective weak mixing angle”:

$$\sin^2\theta_{\rm eff}^{\rm lept} = \frac{1}{4}\left(1 - {\rm Re}\left\{\frac{g_{V{\rm lept}}}{g_{A{\rm lept}}}\right\}\right)$$

SM prediction known to two loops

Awramik, Czakon, Freitas ’06; Hollik, Meier, Uccirati ’06



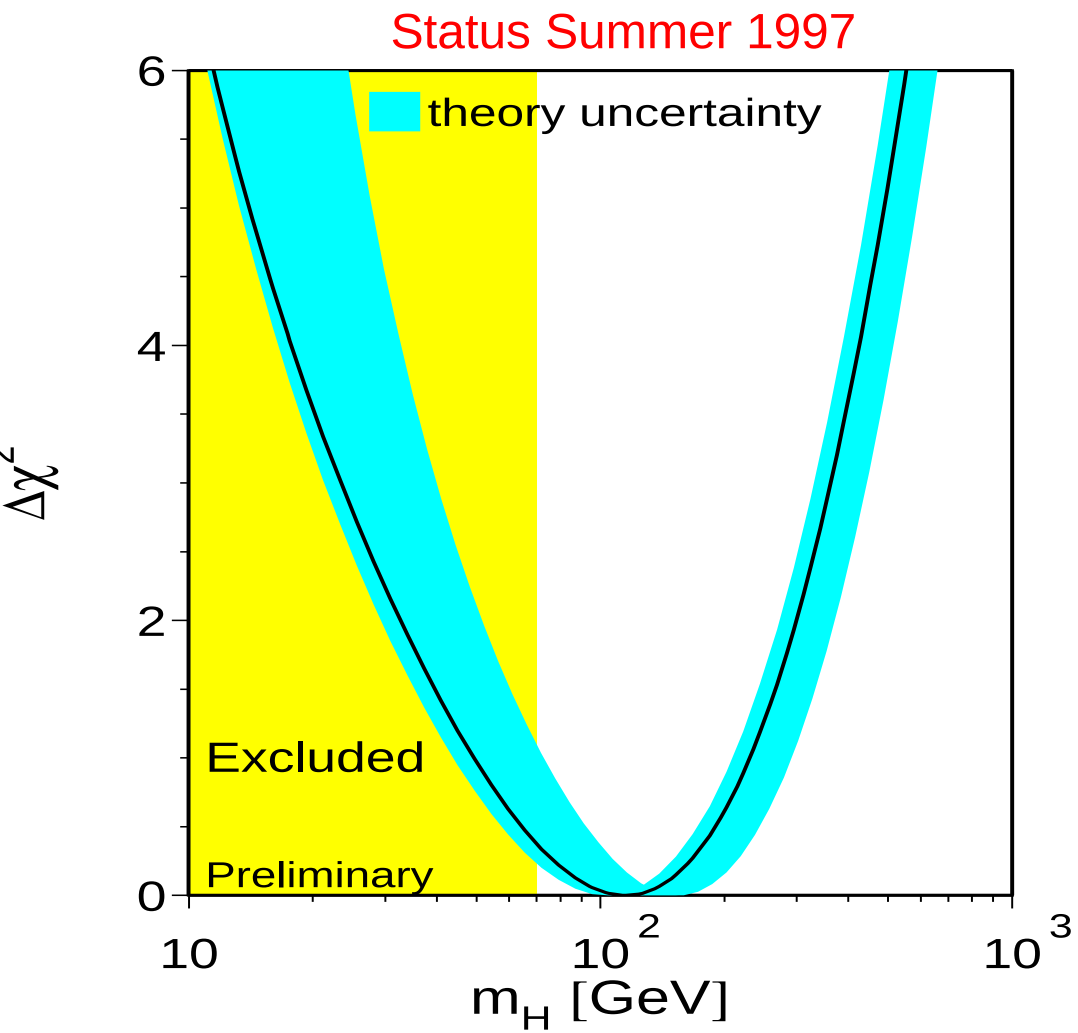


Expected ILC precision:

$$\Delta\sin^2\theta_{\rm eff}^{\rm lept} \sim 1.3\times10^{-5}$$

Bounds on $M_{\rm H}$ (95% C.L.) – a brief history

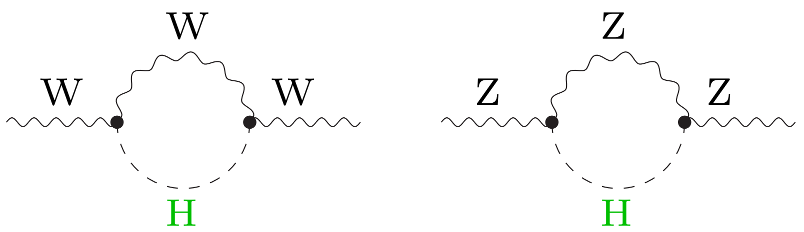
LEPEWWG '97–'12



$M_{\rm H} > 114.4\,{\rm GeV}$ (LEPHIGGS '02)

$e^+e^- \not\to$ ZH at LEP2

SM fit favours perturbative regime for $M_{\rm H}$

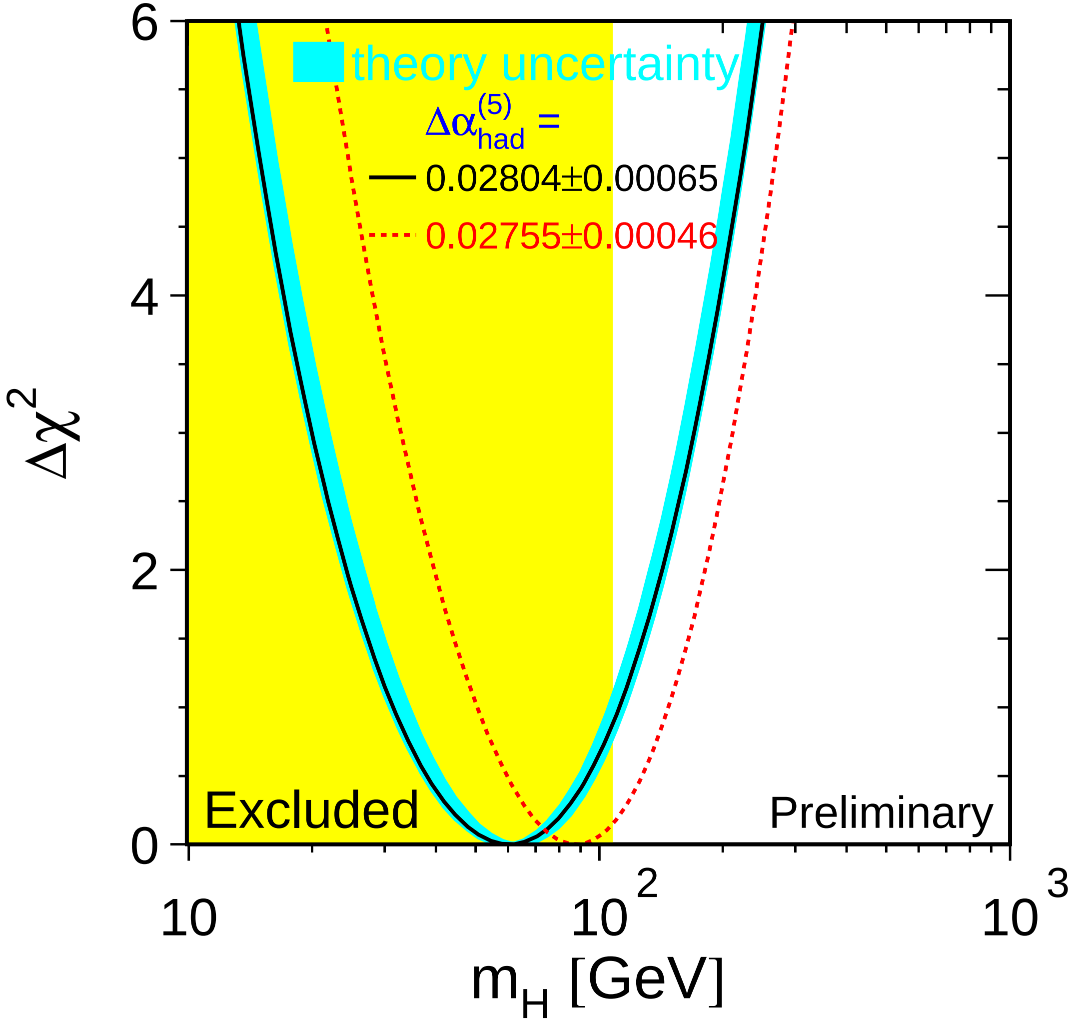


Highest sensitivity via "high-precision observables": $m_{\rm t}$, $M_{\rm W}$, $\sin^2\theta_{\rm eff}^{\rm lept}$, etc.

Bounds on M_H (95% C.L.) – a brief history

LEPEWWG '97–'12

Status Summer 2000

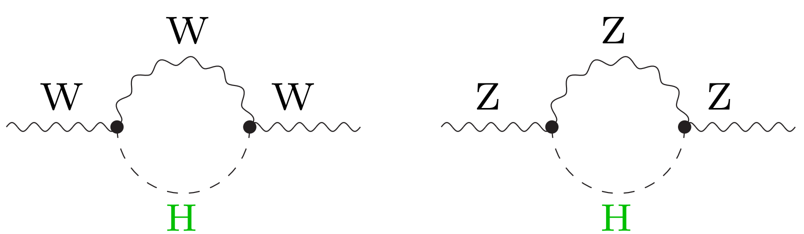


$M_\mathrm{H} > 114.4\,\mathrm{GeV}$ (LEPHIGGS '02)

$\mathrm{e^+e^-} \not\to \mathrm{ZH}$ at LEP2

SM fit favours

$M_\mathrm{H} \lesssim 200\,\mathrm{GeV}$



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Bounds on M_{H} (95% C.L.) – a brief history

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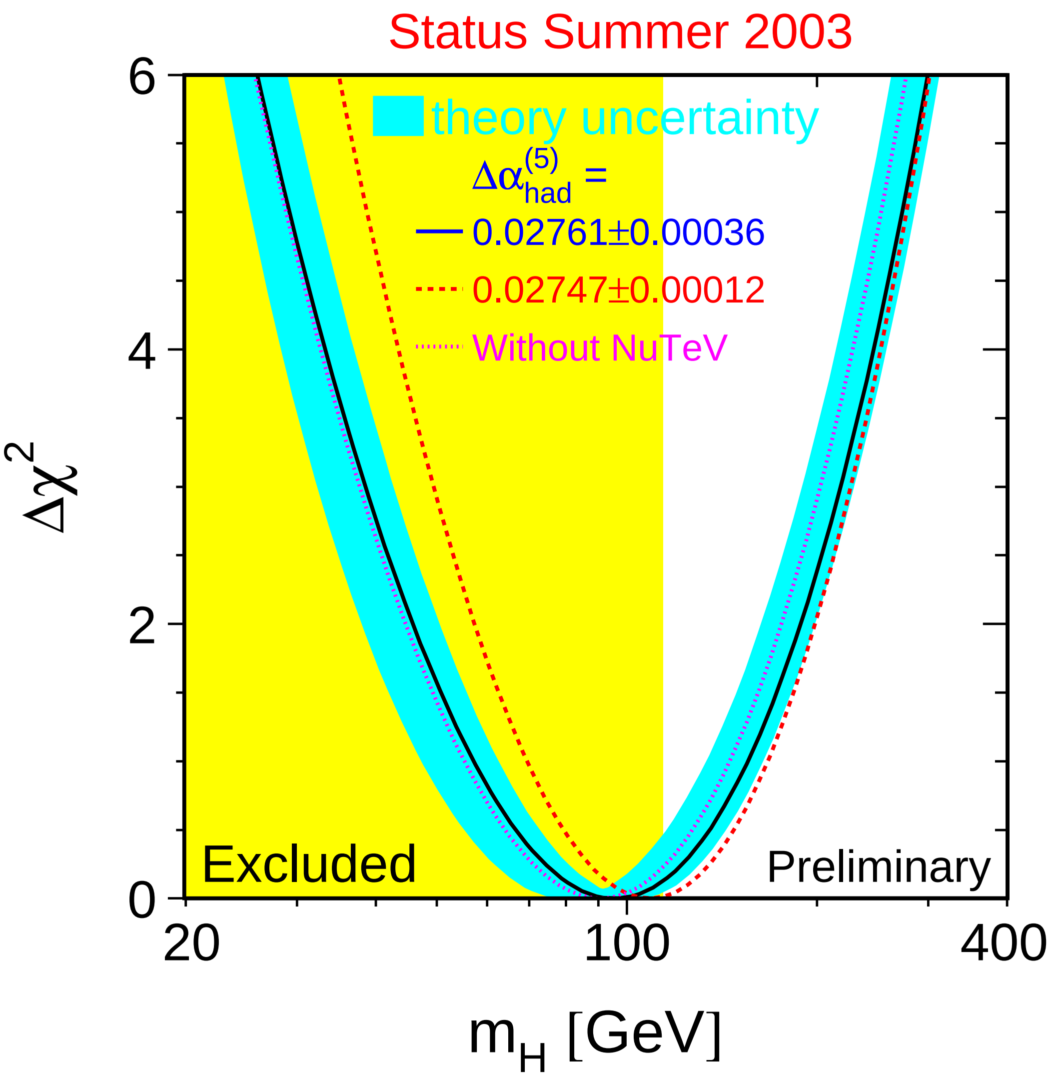

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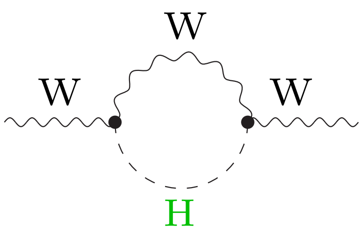

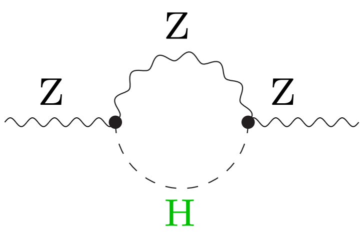

Highest sensitivity via
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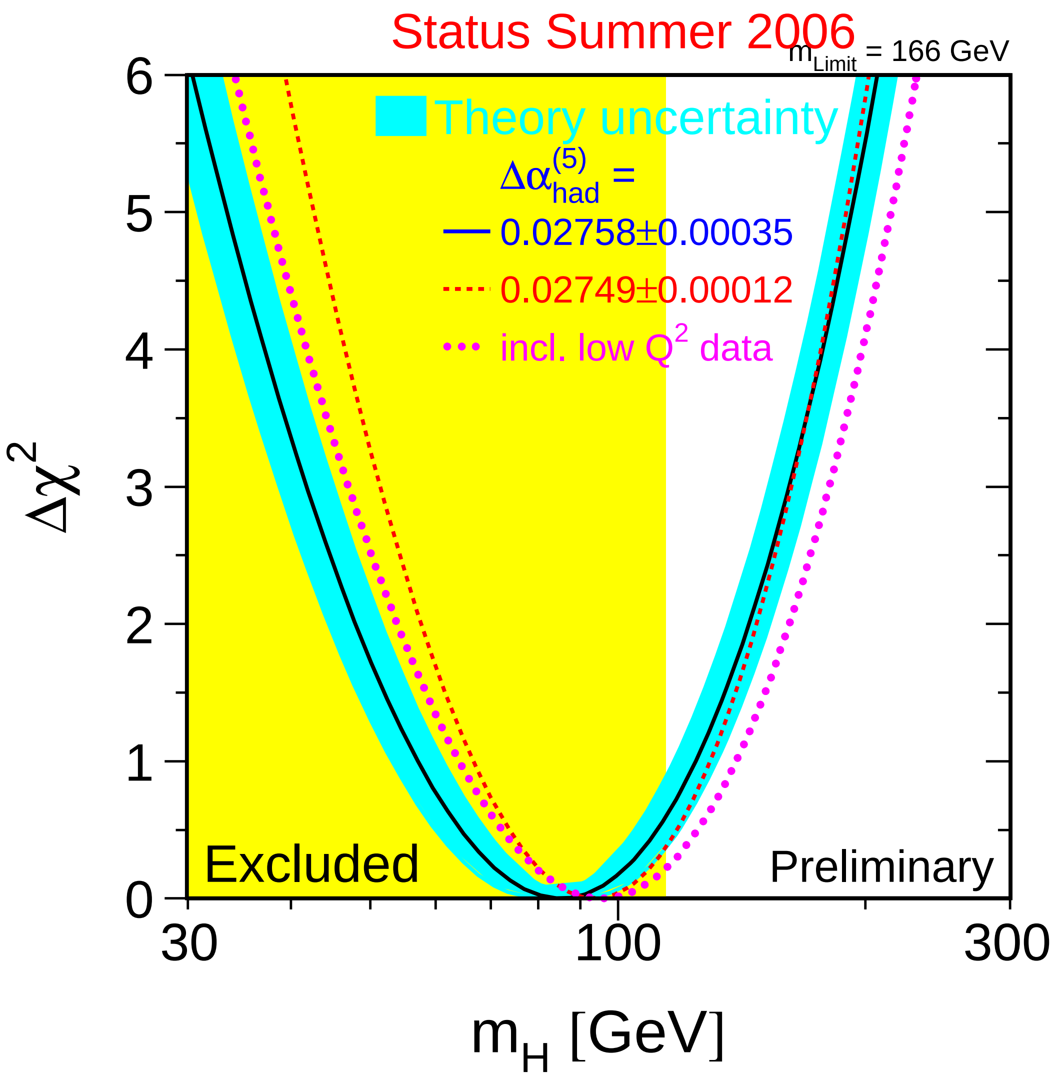
m_{t}, M_{W}, $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$, etc.

Bounds on $M_{\rm H}$ (95% C.L.) – a brief history

LEPEWWG '97–'12

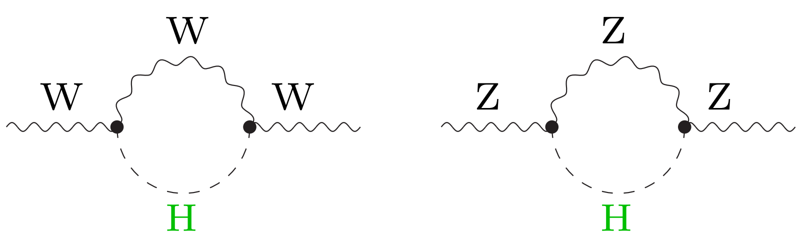


$M_{\rm H} > 114.4\,{\rm GeV}$ (LEPHIGGS '02)

$e^+e^- \not\to ZH$ at LEP2

SM fit favours

$M_{\rm H} < 166\,{\rm GeV}$



Highest sensitivity via
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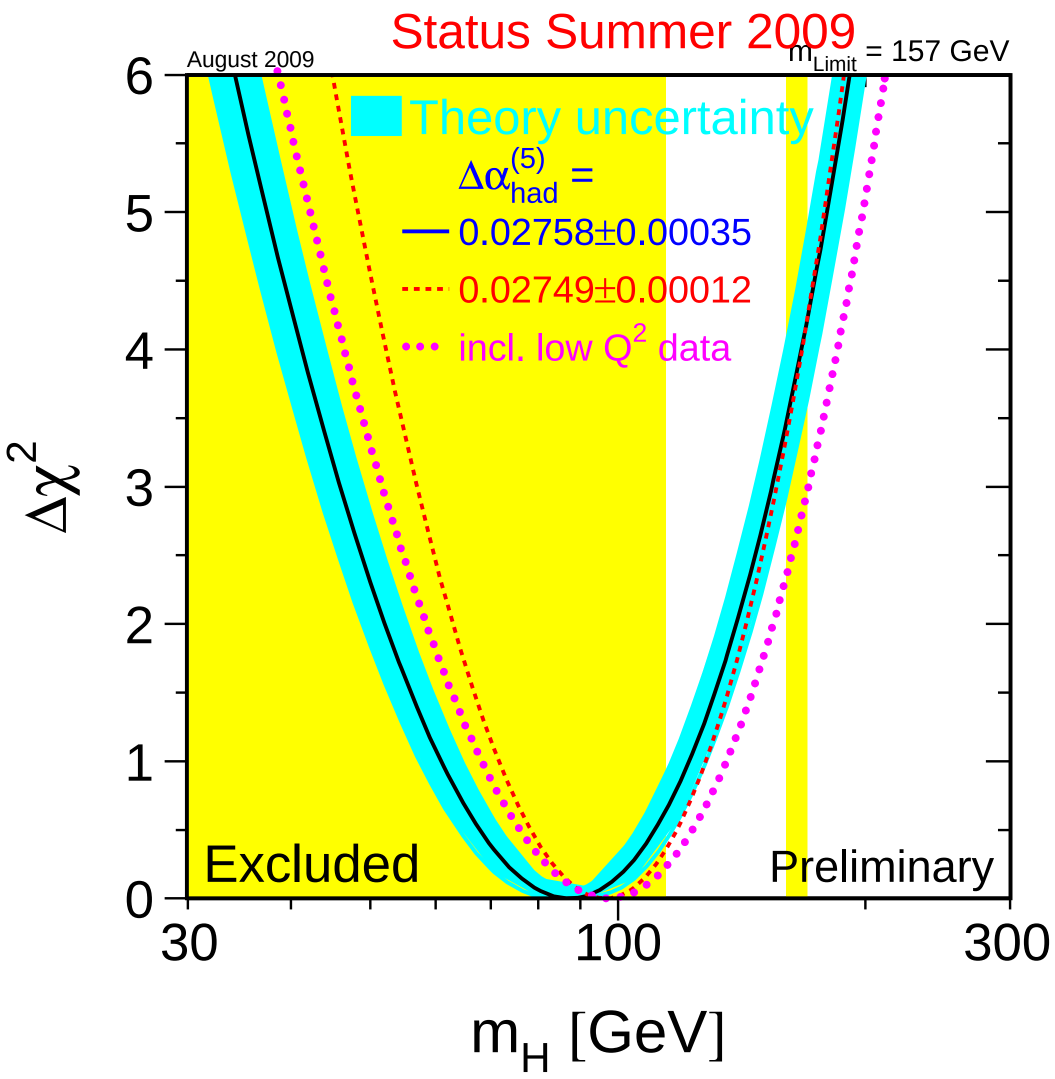
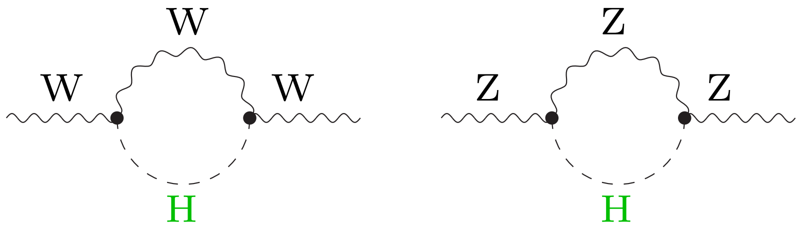


$M_{\mathrm{H}} > 114.4\,\mathrm{GeV}$ (LEPHIGGS '02)

$\mathrm{e^+e^-} \not\to \mathrm{ZH}$ at LEP2

SM fit favours

$M_{\mathrm{H}} < 157\,\mathrm{GeV}$



Highest sensitivity via "high-precision observables": m_{t}, M_{W}, $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$, etc.

Bounds on M_{H} (95% C.L.) – a brief history

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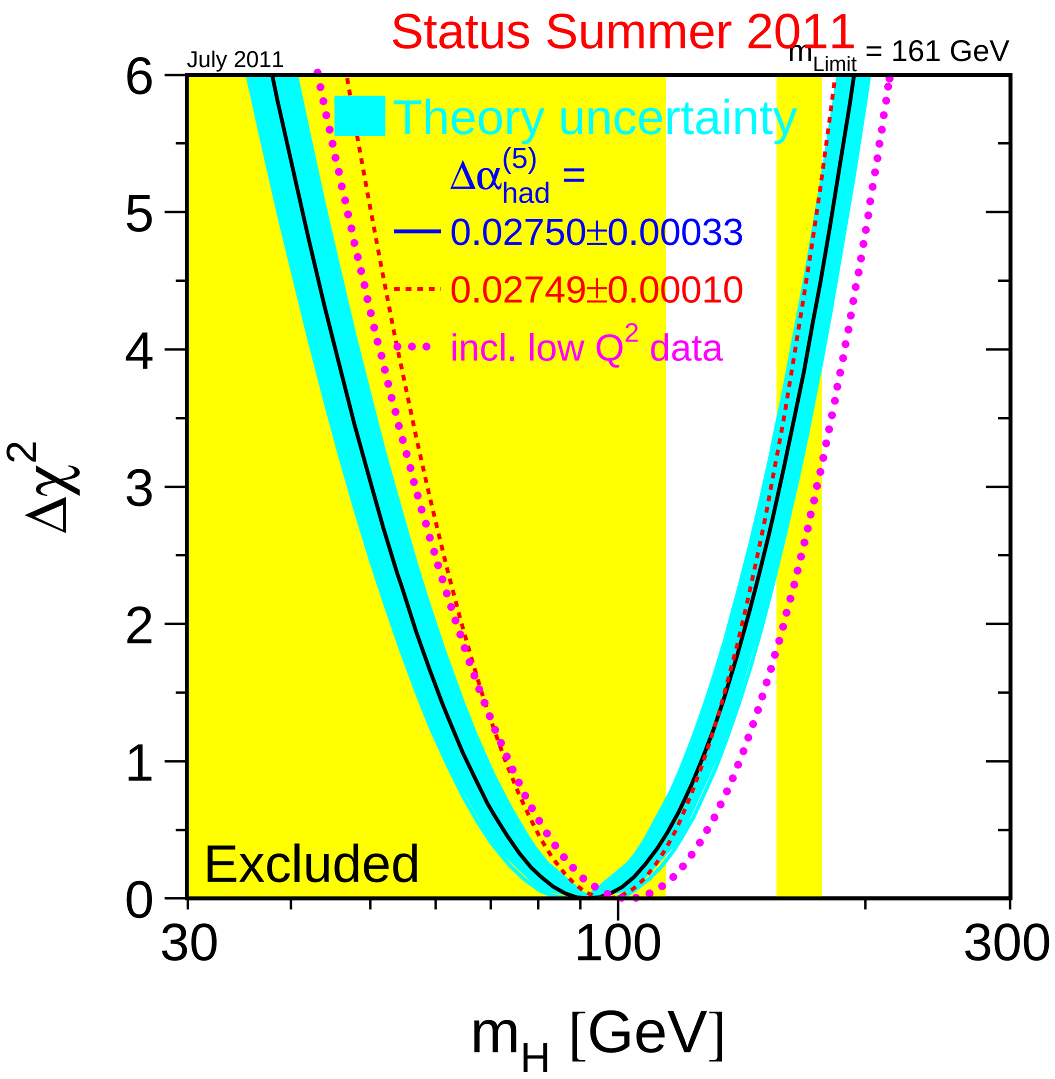
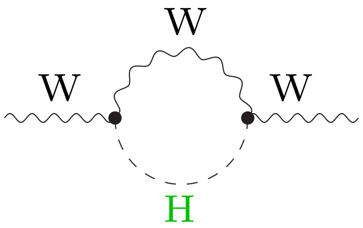


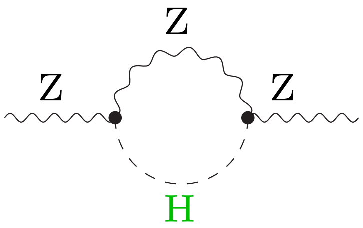
$M_{\mathrm{H}} > 114.4\,\mathrm{GeV}$ (LEPHIGGS '02)

$\mathrm{e}^+\mathrm{e}^- \not\to \mathrm{ZH}$ at LEP2

SM fit favours

$M_{\mathrm{H}} < 161\,\mathrm{GeV}$





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Bounds on M_{H} (95% C.L.) – a brief history

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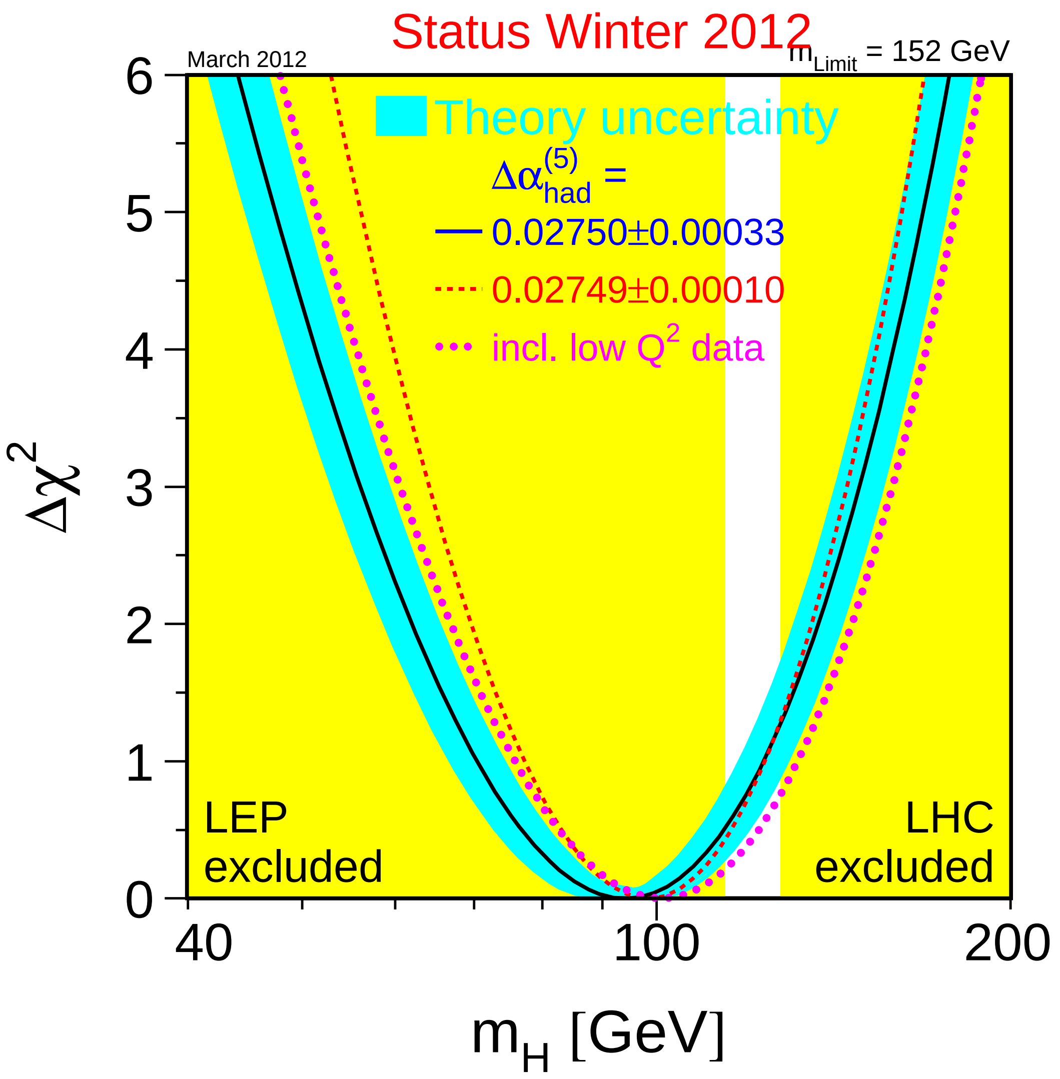
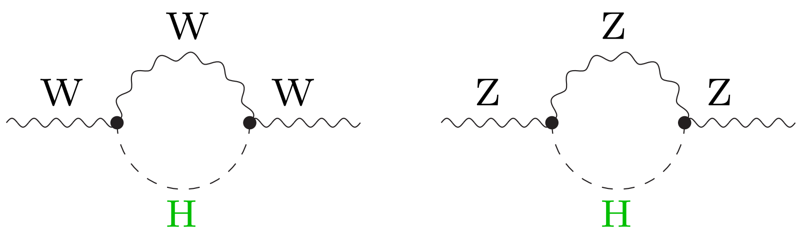


$M_{\mathrm{H}} > 114.4\,\mathrm{GeV}$ (LEPHIGGS '02)

$\mathrm{e}^+\mathrm{e}^- \not\to \mathrm{ZH}$ at LEP2

SM fit favours

$M_{\mathrm{H}} < 152\,\mathrm{GeV}$



Open window not excluded by the LHC:

$122\,\mathrm{GeV} < M_{\mathrm{H}} < 127\,\mathrm{GeV}$

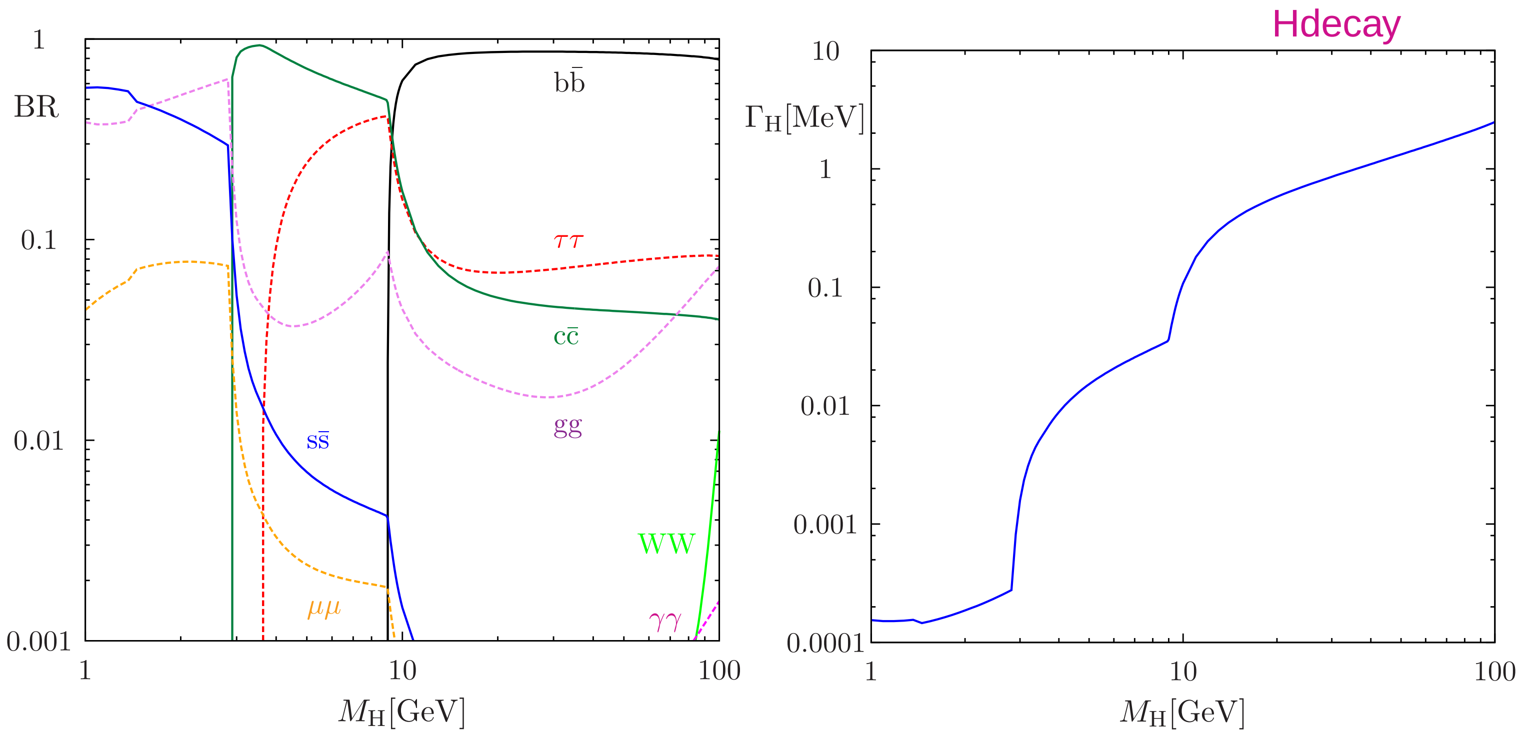
Highest sensitivity via "high-precision observables":

m_{t}, M_{W}, $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$, etc.

Higgs-boson decays

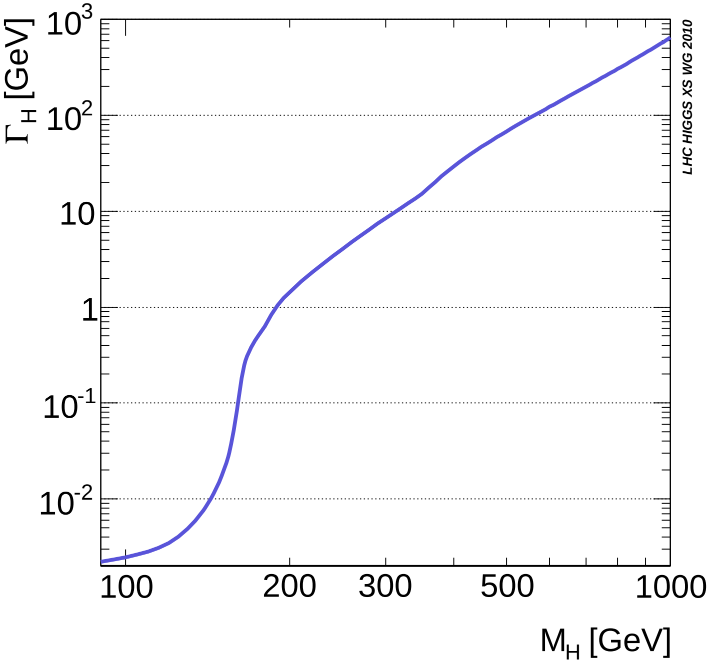
General considerations

- very light Higgs boson: $M_{\mathrm{H}} \lesssim 100\,\mathrm{GeV}$
  - ◇ large theoretical uncertainties for $M_{\mathrm{H}} \lesssim 20\,\mathrm{GeV}$
    (threshold effects, large α_{s}, hadronic effects)
    $\hookrightarrow$ LEP1 searches via $\mathrm{Z} \to \mathrm{Z}^*\mathrm{H}$ w/o assumptions on or modeled H decays
  - ◇ $\Gamma_{\mathrm{H}} \lesssim \mathrm{few\,MeV} \ll$ detector resolutions



General considerations

- very light Higgs boson: $M_{\mathrm{H}} \lesssim 100\,\mathrm{GeV}$



- heavy Higgs boson: $M_{\mathrm{H}} \gtrsim 600\,\mathrm{GeV}$
  - ◇ $\Gamma_{\mathrm{H}} \gtrsim 100\,\mathrm{GeV}$
    $\hookrightarrow$ broad resonance,
    large interference signal–background interference
    $\hookrightarrow$ Simultaneous treatment of signal + background required
  - ◇ perturbation theory runs out of control
    (often two-loop $\sim$ one-loop for $M_{\mathrm{H}} \sim 700\,\mathrm{GeV}$)

$\Rightarrow$ Precision of calculations seriously degrades,
but high-mass SM Higgs excluded
by candidate with $M_{\mathrm{H}} = 126\,\mathrm{GeV}$ and SM fit

General considerations

- very light Higgs boson: $M_{\rm H} \lesssim 100\,{\rm GeV}$

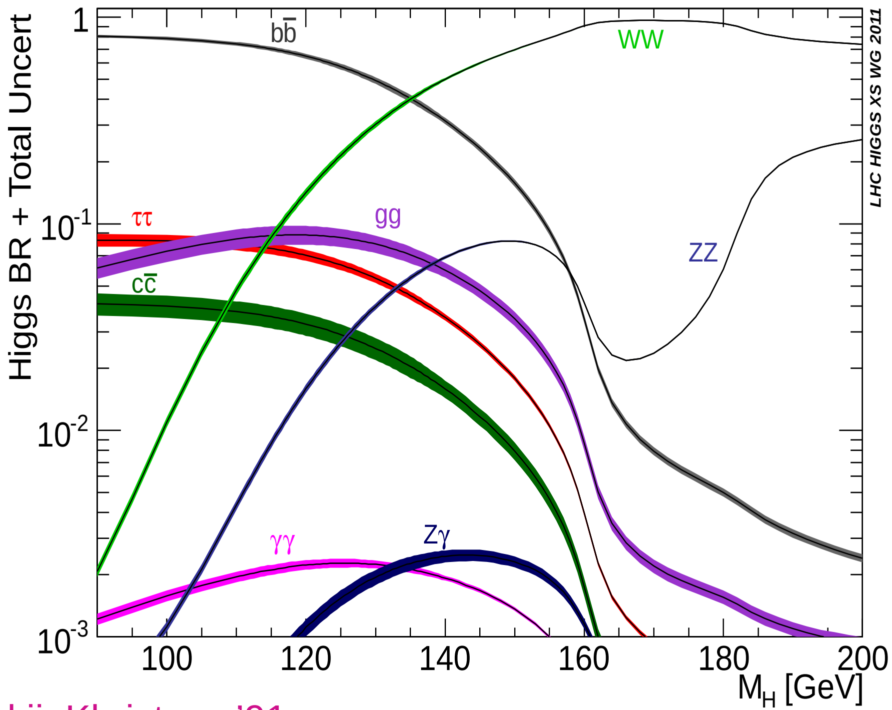
- heavy Higgs boson: $M_{\rm H} \gtrsim 600\,{\rm GeV}$

- $100\,{\rm GeV} \lesssim M_{\rm H} \lesssim 600\,{\rm GeV}$
  - ◇ $114\,{\rm GeV} < M_{\rm H} \lesssim 200\,{\rm GeV}$: favoured mass range after LEP
  - ◇ $M_{\rm H} \lesssim 135\,{\rm GeV}$: $\rm H \to b\bar{b}$ dominant, $\rm H \to \gamma\gamma$ well accessible
  - ◇ $M_{\rm H} \gtrsim 135\,{\rm GeV}$: $\rm H \to WW/ZZ \to 4\mathit{f}$ dominant and very well exp. accessible

  Note: $\rm H \to \mathit{VV} \to 4\mathit{f}$ for $M_{\rm H} < 2M_V$ to be treated as four-body decays

Precision calculations for SM Higgs-boson decays

Hdecay + Prophecy4f



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

  QCD up to NNNNLO QCD for $\mathrm{b\bar{b}}$

  ... Baikov, Chetyrkin, Kühn, Steinhauser ('97–'05)

- $\mathrm{H} \to \gamma\gamma/\mathrm{gg}$

  full 2-loop result + h.o. improvements

  Spira, Djouadi, Graudenz, Zerwas '95; ... (Actis,) Passarino, Sturm, Uccirati '07,'08

- $\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$
  - ◇ NLO for stable $\mathrm{W/Z}$ bosons

    Fleischer, Jegerlehner '81; Kniehl '91; Bardin, Vilenskii, Khristova '91
  - ◇ NLO for off-shell/decaying $\mathrm{W/Z}$ bosons Bredenstein, Denner, S.D., Weber '06

Tools

- HDECAY: all $1 \to 2$ decays (integrated) Djouadi, Kalinowski, Mühlleitner, Spira
- PROPHECY4F: $\mathrm{H} \to 4f$ decays (integrated & differential) Bredenstein, Denner, S.D., Mück, Weber

Precision calculations for SM Higgs-boson decays

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

  QCD up to NNNNLO QCD for $\mathrm{b\bar{b}}$

  ... Baikov, Chetyrkin, Kühn, Steinhauser ('97–'05)

- $\mathrm{H} \to \gamma\gamma/\mathrm{gg}$

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  Spira, Djouadi, Graudenz, Zerwas '95; ...
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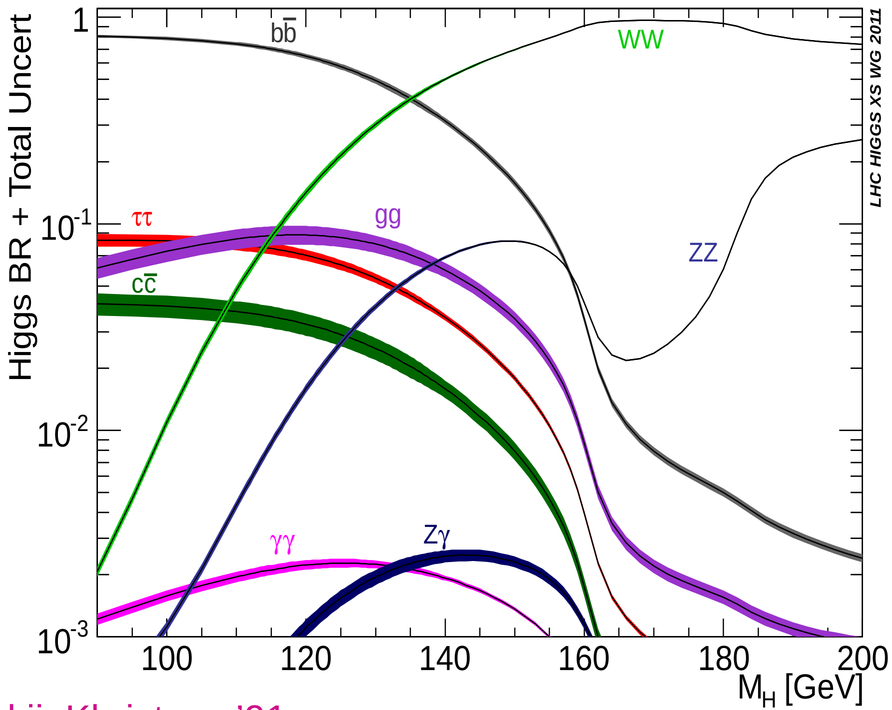
Hdecay + Prophecy4f



Parametric + theoretical uncertainty of BRs:

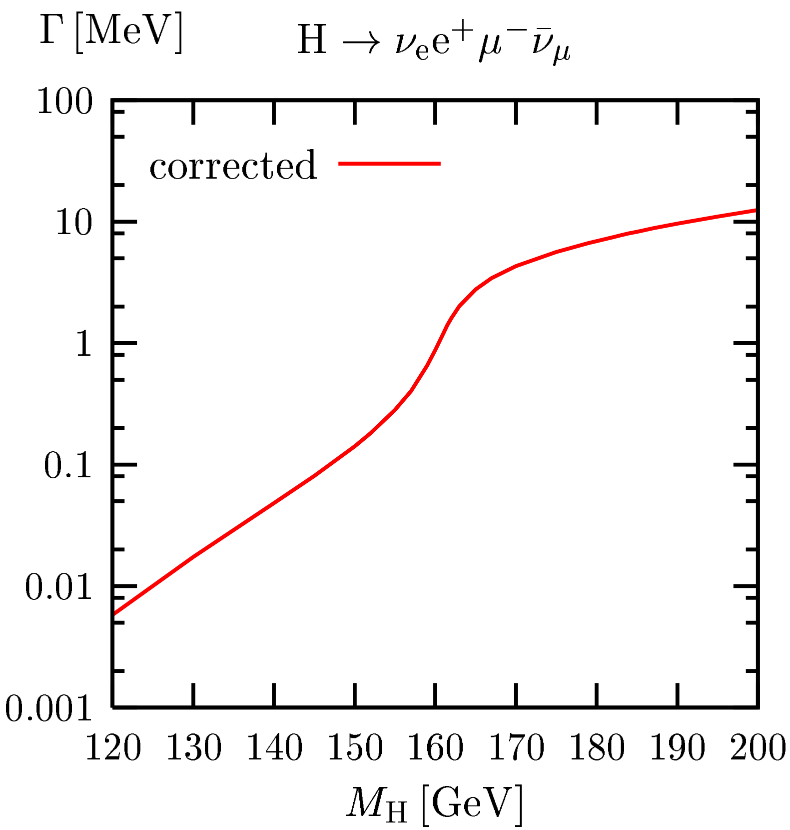
LHC Higgs XS WG 2011

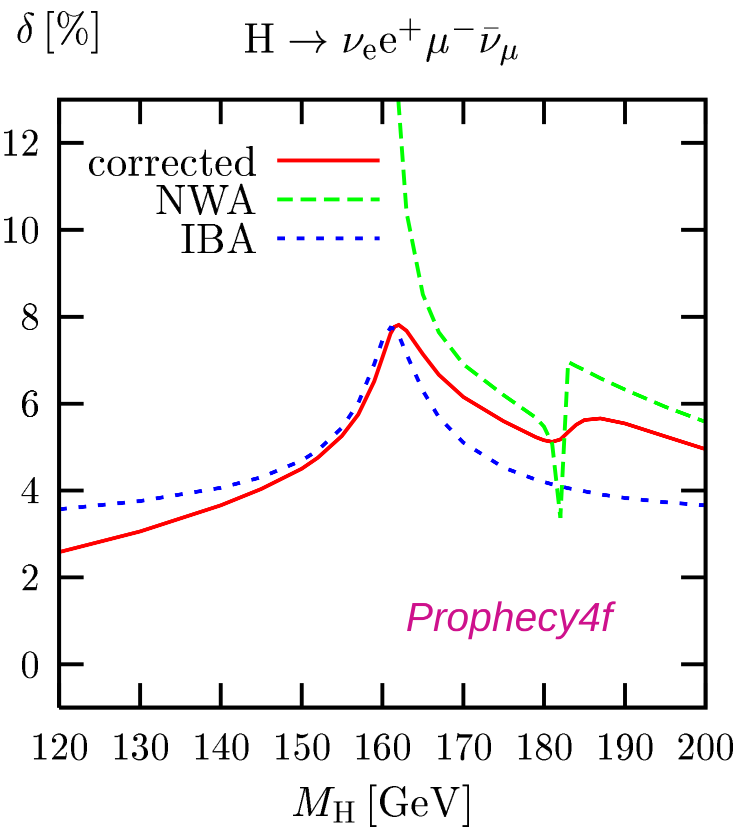
M_H[GeV] $\mathrm{H}\to$	$\mathrm{b\bar{b}}$	$\tau^+\tau^-$	$\mathrm{c\bar{c}}$	gg	$\gamma\gamma$	WW	ZZ
120	3%	6%	12%	10%	5%	5%	5%
150	4%	3%	10%	8%	2%	1%	1%
200	5%	3%	10%	8%	2%	$< 0.1\%$	$< 0.1\%$

← driven by $\delta\Gamma_{\mathrm{H}\to\mathrm{b\bar{b}}}$ (row 120)

Partial 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 $M_\mathrm{H} \sim 2M_\mathrm{Z}$

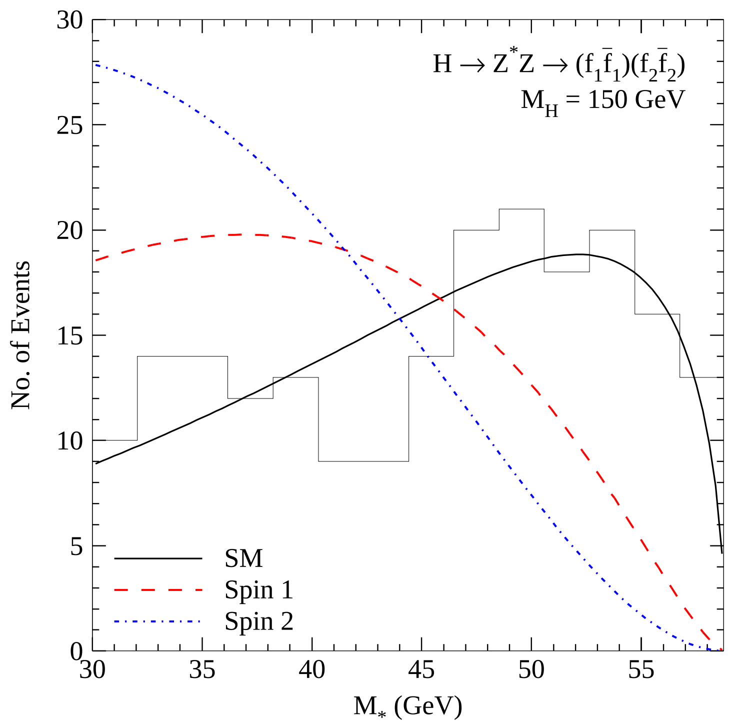
NWA = “narrow-width approximation” (on-shell W bosons)

IBA = “improved Born approximation” (universal corrections)

Corrections ~ 4–8%, NWA not useful for $M_\mathrm{H} \lesssim 165\,\mathrm{GeV}$

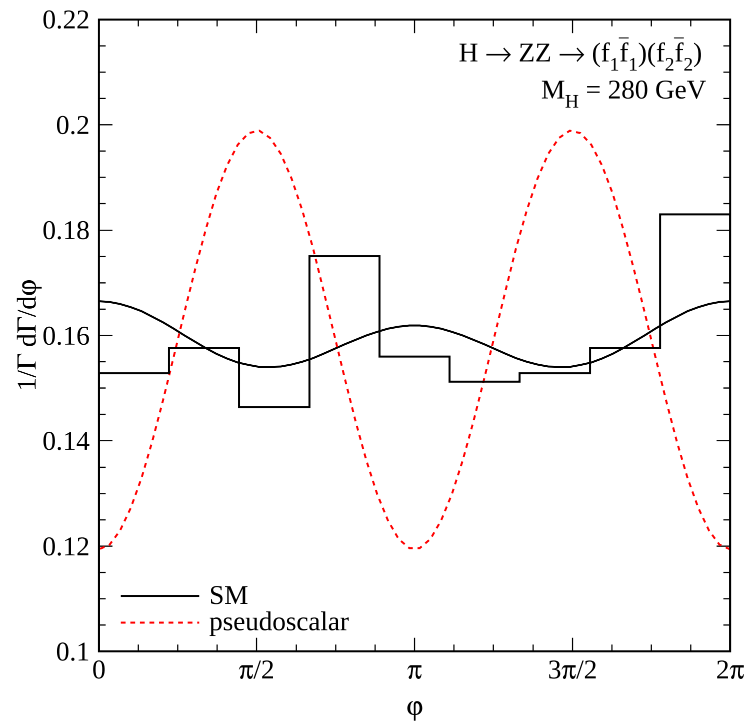
Kinematical studies of $\mathrm{H} \to \mathrm{ZZ} \to f_1 \bar{f}_1 f_2 \bar{f}_2$

Invariant Z mass:



Angle between Z decay planes:

Choi, Miller, Mühlleitner, Zerwas '02



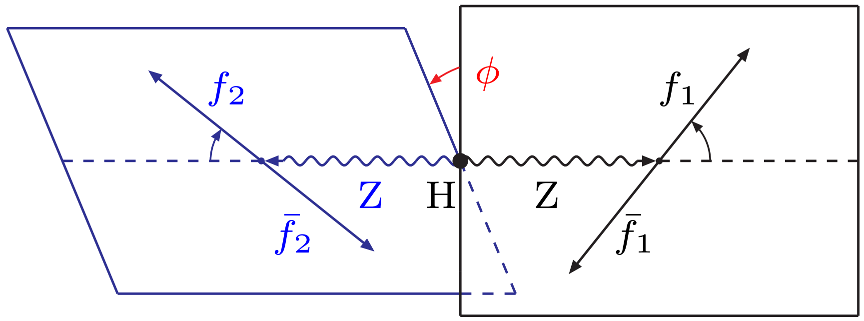
$$M_* = M_{f_1 \bar{f}_1}$$

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

$\hookrightarrow$ distributions sensitive to spin and parity

corrections available via PROPHECY4F

Bredenstein, Denner, S.D., Mück, Weber

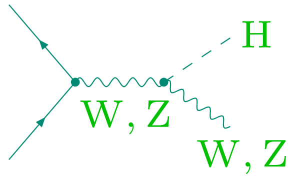


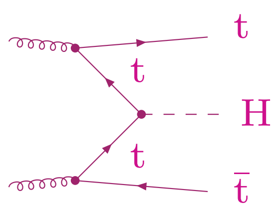
Higgs production

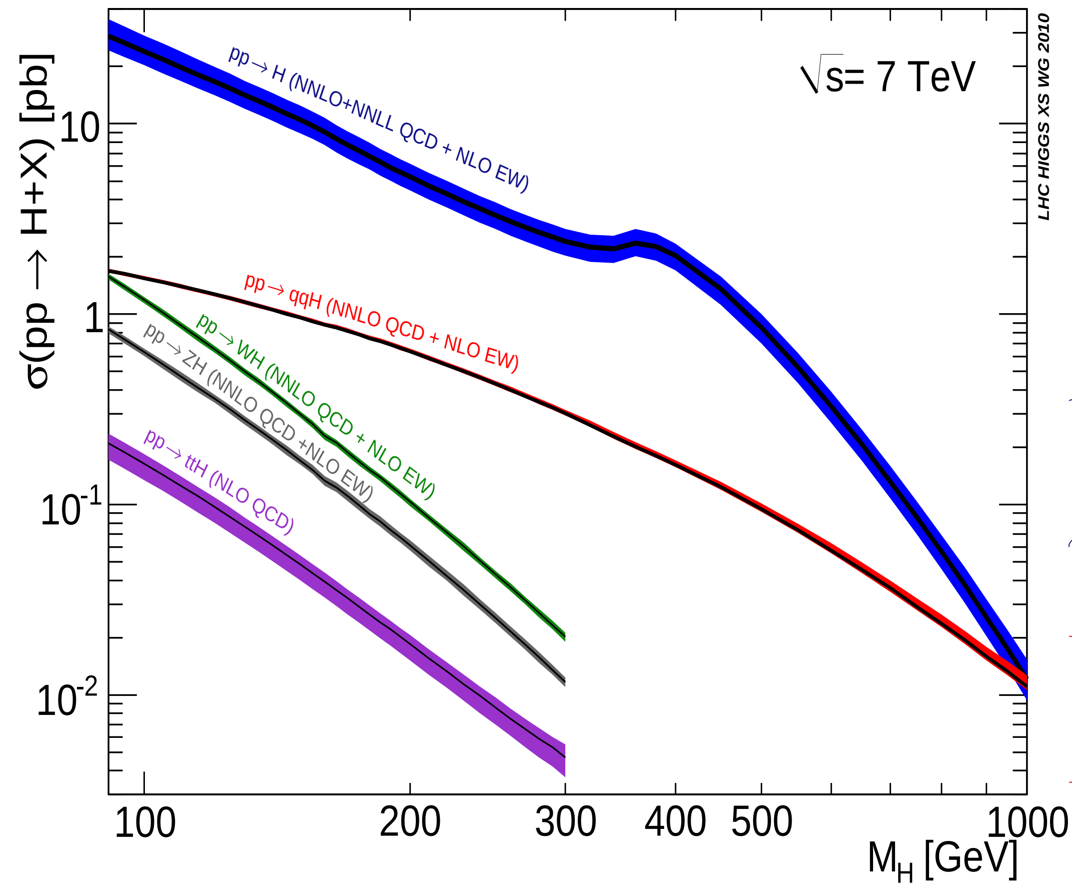
at hadron colliders

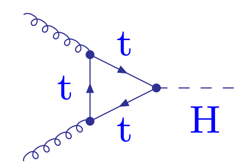
SM Higgs XS predictions for the LHC at $\sqrt{s} = 7\,\mathrm{TeV}$

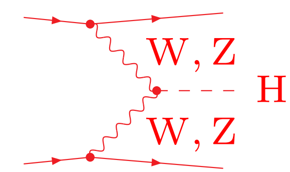
LHC Higgs XS WG 2010









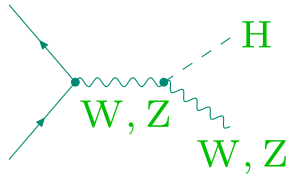


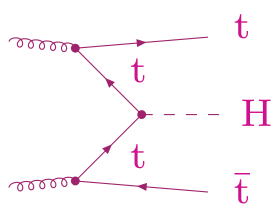
Rough numbers:

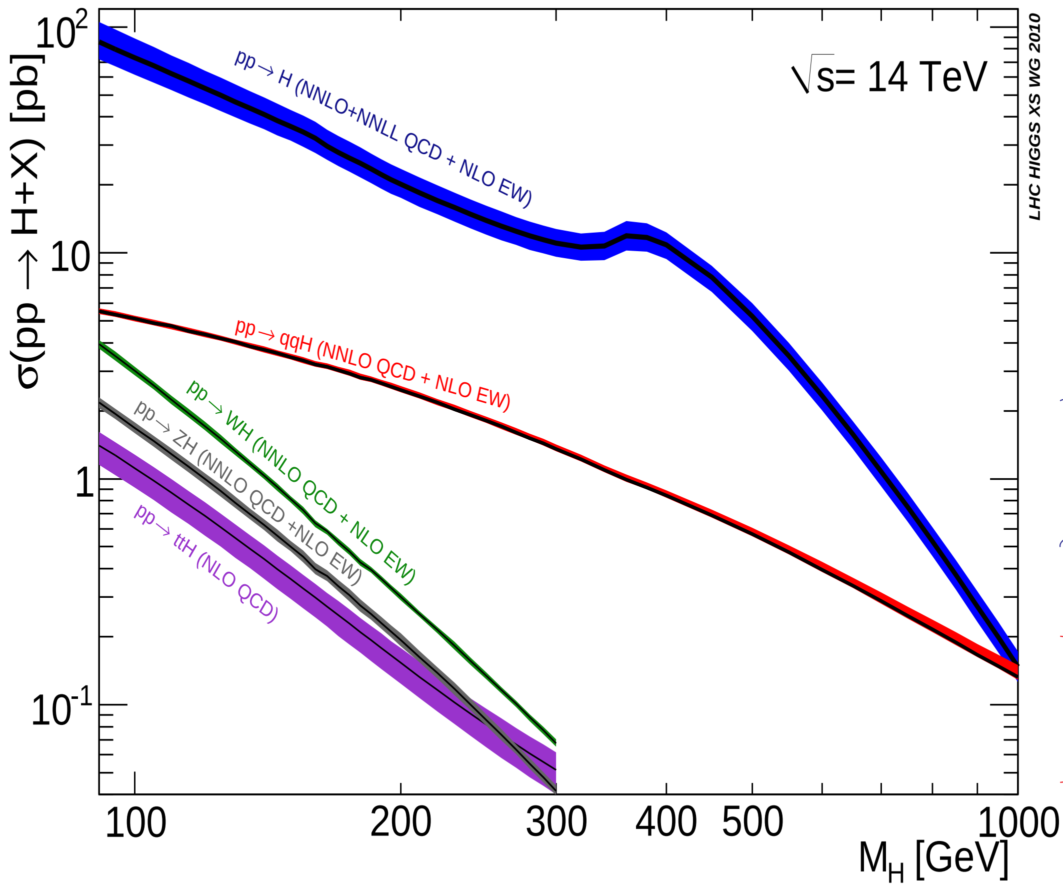
	M_H	Uncertainties scale	Uncertainties PDF4LHC	NLO/NNLO/NNLO+ QCD	NLO/NNLO/NNLO+ EW
ggF	$< 500\,\mathrm{GeV}$	$6{-}10\%$	$8{-}10\%$	$>100\%$	5%
VBF	$< 500\,\mathrm{GeV}$	1%	$2{-}7\%$	5%	5%
WH	$< 200\,\mathrm{GeV}$	1%	$3{-}4\%$	30%	$5{-}10\%$
ZH	$< 200\,\mathrm{GeV}$	$1{-}2\%$	$3{-}4\%$	40%	5%
ttH	$< 200\,\mathrm{GeV}$	10%	9%	5%	?

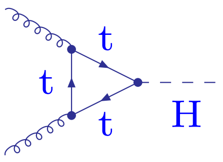
SM Higgs XS predictions
for the LHC at $\sqrt{s} = 14\,\mathrm{TeV}$

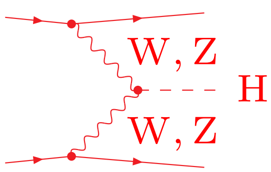
LHC Higgs XS WG 2010







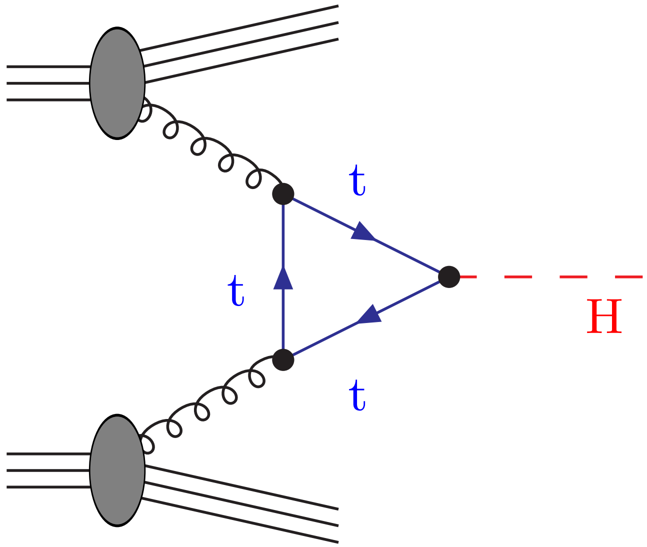




Rough numbers:

	M_{H}	Uncertainties: scale	Uncertainties: PDF4LHC	NLO/NNLO/NNLO+ QCD	NLO/NNLO/NNLO+ EW
ggF	$< 500\,\mathrm{GeV}$	$6{-}14\%$	7%	$>100\%$	5%
VBF	$< 500\,\mathrm{GeV}$	1%	$3{-}4\%$	5%	5%
WH	$< 200\,\mathrm{GeV}$	1%	$3{-}4\%$	30%	$5{-}10\%$
ZH	$< 200\,\mathrm{GeV}$	$2{-}4\%$	$3{-}4\%$	45%	5%
ttH	$< 200\,\mathrm{GeV}$	10%	9%	$15{-}20\%$	?

Higgs production via gluon fusion



Corrections to Higgs-boson production via gluon fusion

- QCD corrections:
  - complete NLO correction known

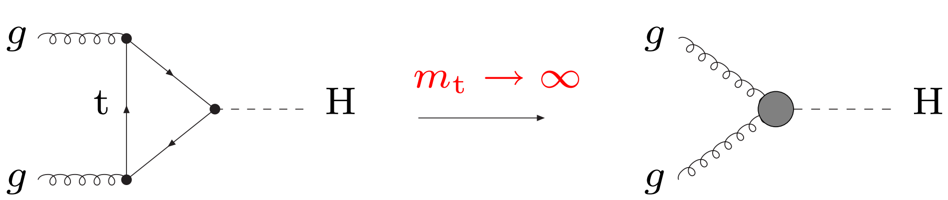
    Graudenz, Spira, Zerwas '93
    Djouadi, Graudenz, Spira, Zerwas '95

  - 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 $m_t \to \infty$



    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,'11
    Berger et al. '10; Stewart, Tackmann '11
    Banfi, (Monni,) Salam, Zanderighi '12
    Becher, Neubert '12

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

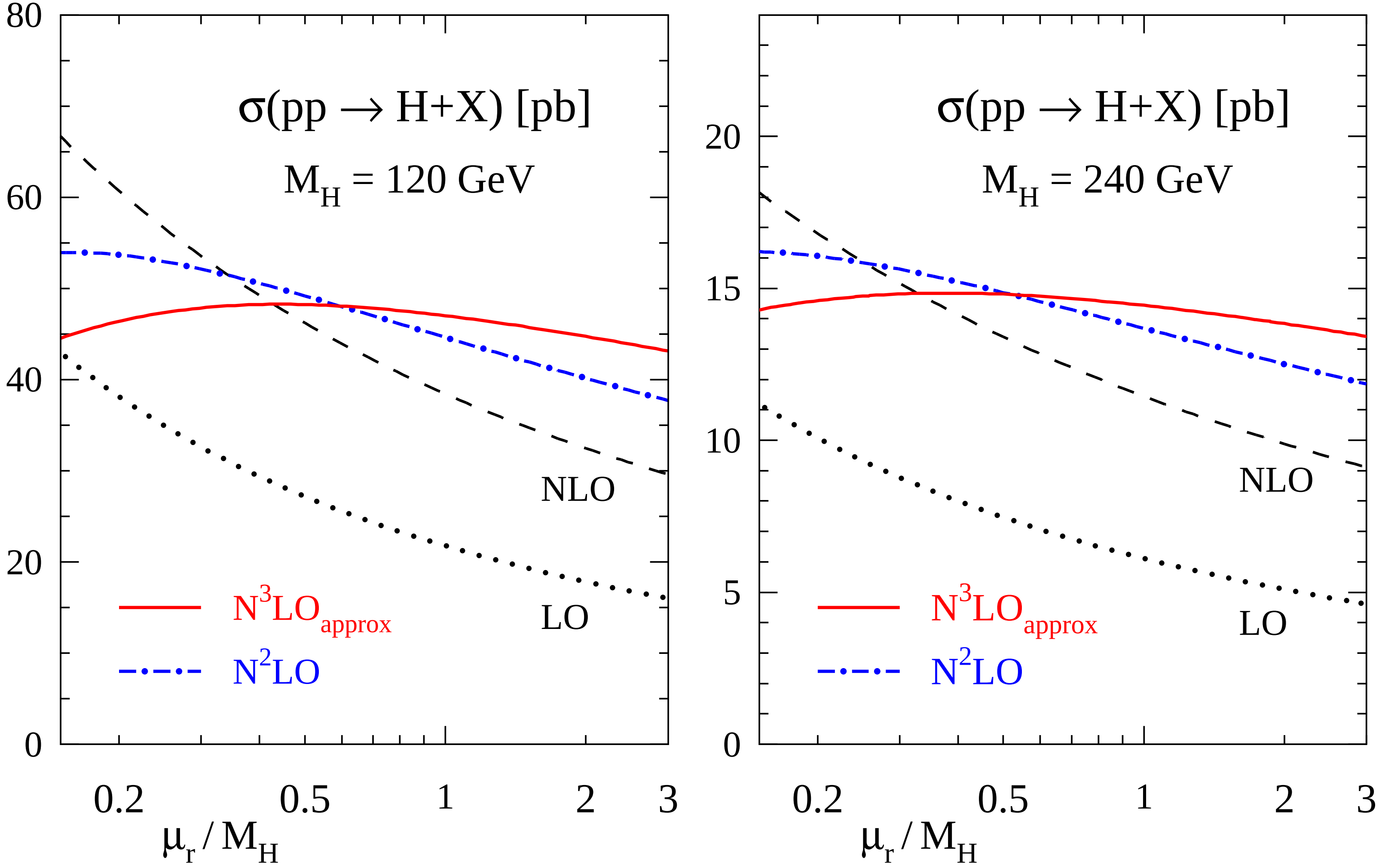
    Aglietti, Bonciani, Degrassi, Vicini '04,'06
    Degrassi, Maltoni '04
    Actis, Passarino, Sturm, Uccirati '08

  - 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



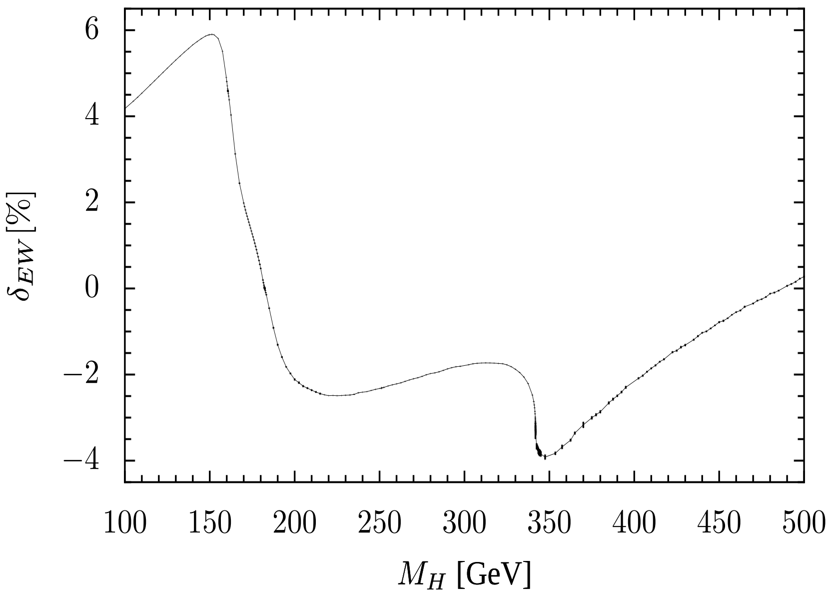
Reduction of renormalization-scale dependence with increasing orders !

$\hookrightarrow$ residual scale uncertainty $\lesssim$ 5–10%

NLO EW corrections

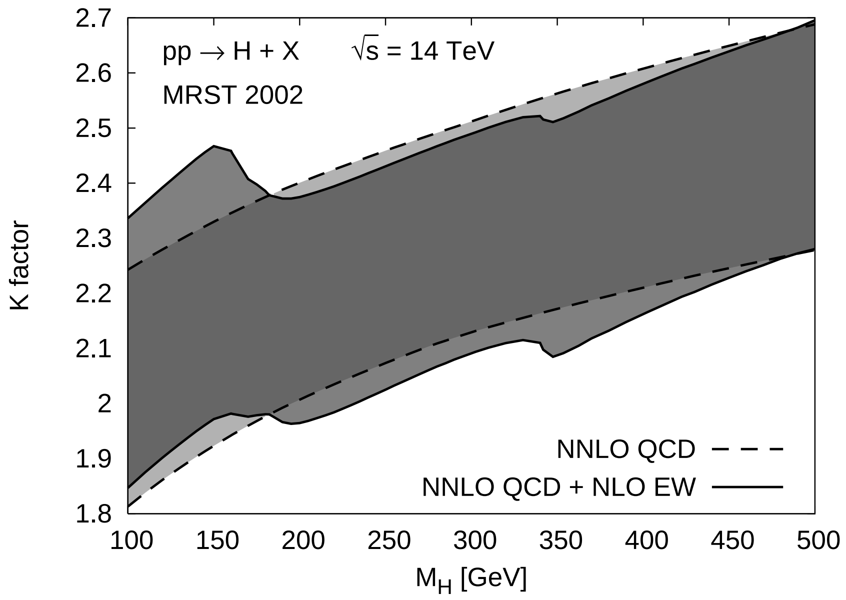
Actis, Passarino, Sturm, Uccirati '08

Correction to partonic cross section:

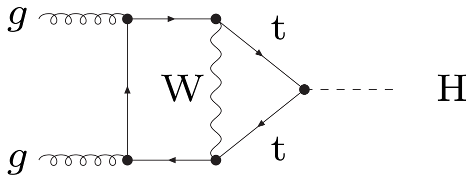


K factors for pp cross section:

(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 ...

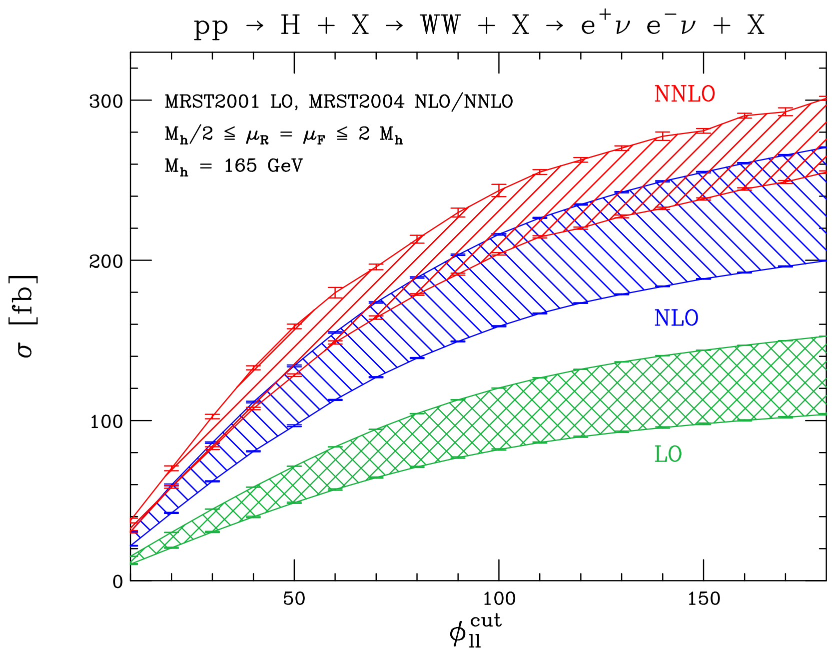


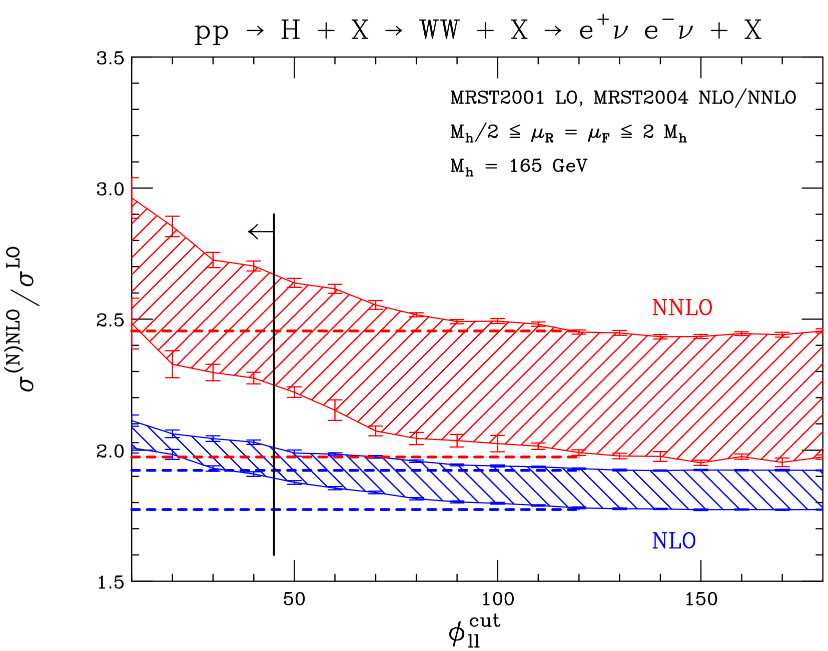
etc.

- matter at the 5% accuracy level
- show non-trivial structures near WW, 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_H Anastasiou, Boughezal, Petriello '08
  suggest factorization of QCD and EW corrections within good accuracy

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

Anastasiou, Dissertori, Stöckli '07

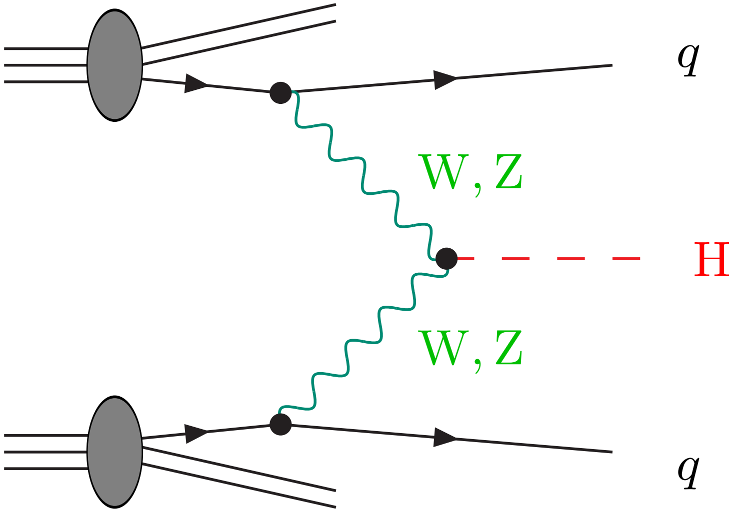




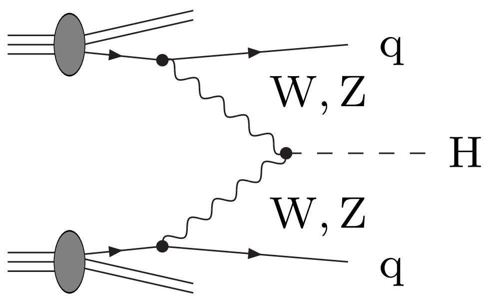
$\phi_{ll} =$ angle between charged decay leptons in the transverse plane

K factors in general depend on decay phase space.

Higgs production via vector-boson fusion



A multi-leg example: Higgs production via weak vector-boson fusion (VBF)



colour exchange between quark lines suppressed

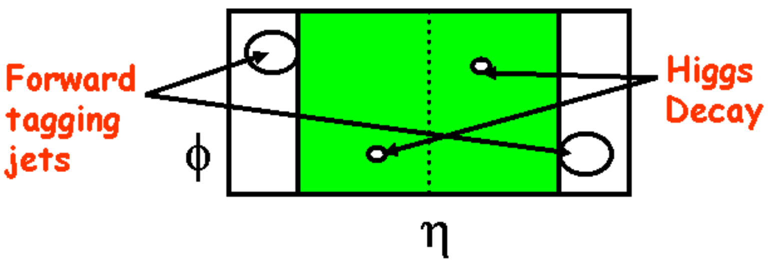
$\Rightarrow$ small QCD corrections

Han, Valencia, Willenbrock '92; Spira '98;
Djouadi, Spira '00; Figy, Oleari, Zeppenfeld '03

$\hookrightarrow$ t-channel approximation (vertex corrections)

VBF cuts and background suppression:

signature $=$ Higgs + 2jets



- 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 background

- from other (non-Higgs) processes,
  such as $\mathrm{t\bar{t}}$ or WW production Zeppenfeld et al. '94-'99
- induced by Higgs production via gluon fusion,
  such as $gg \to gg\mathrm{H}$ Del Duca et al. '06; Campbell et al. '06

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; Figy, Palmer, Weiglein '10 (DIS-like EW)

  $\hookrightarrow$ 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 $\mathrm{gg} \to \mathrm{Hgg}$, 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

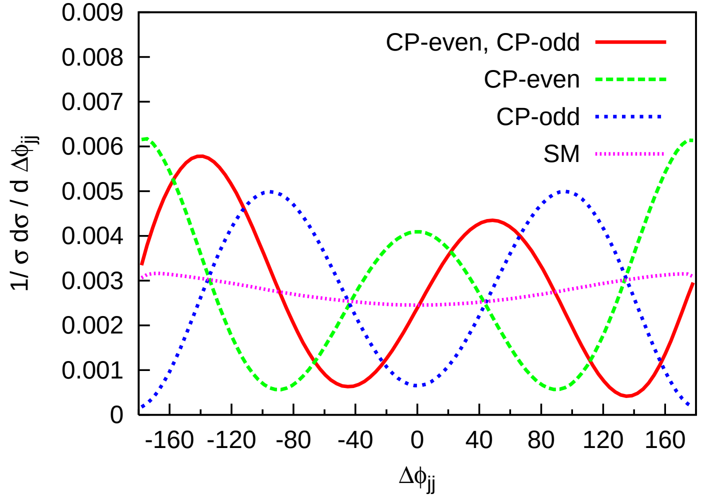
  $\hookrightarrow$ impact $\sim 0.1\%$
- SUSY QCD+EW corrections — Hollik, Plehn, Rauch, Rzehak '08

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

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

Sensitivity to non-standard effects:

Hankele, Klämke, Zeppenfeld, Figy '06



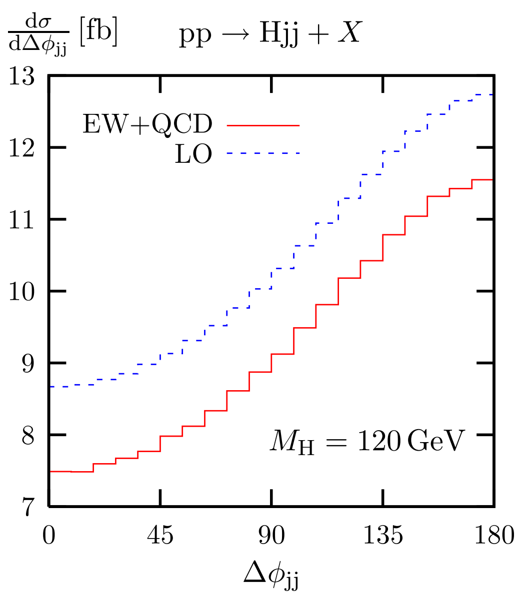
(Individual contributions without SM)

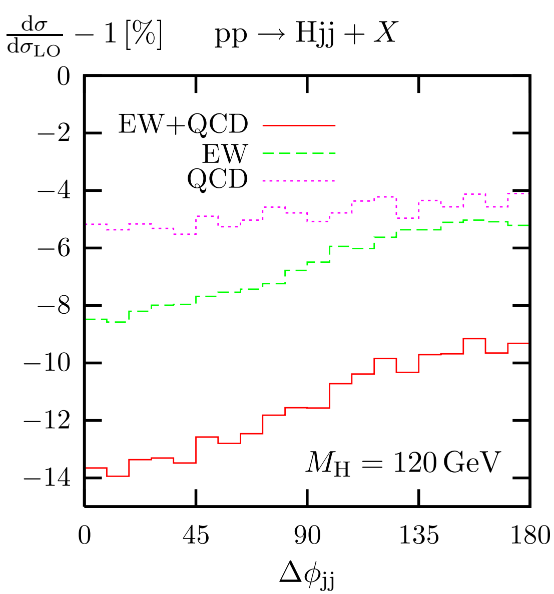
CP-even: $\mathcal{L} \propto HW^{+}_{\mu\nu}W^{-,\mu\nu}$

CP-odd: $\mathcal{L} \propto H\tilde{W}^{+}_{\mu\nu}W^{-,\mu\nu}$

Corrections to the $\Delta\phi_{\rm jj}$ distribution:

Ciccolini, Denner, S.D. '07

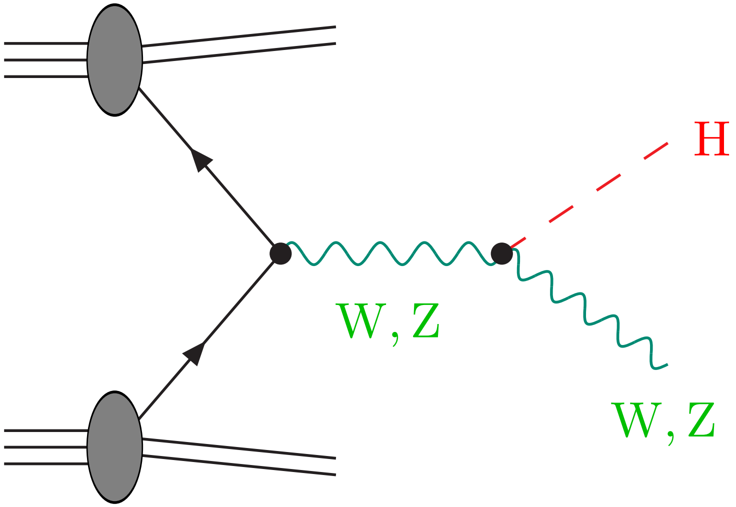




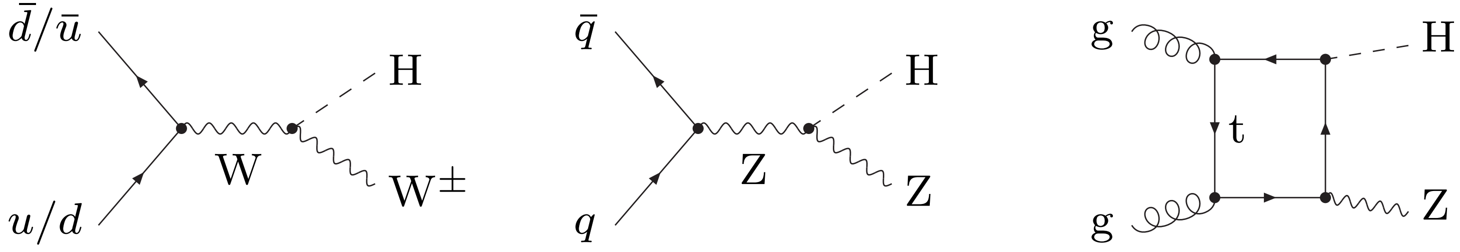
HAWK

Neglected corrections could be misinterpreted as non-standard couplings

Production via Higgs-strahlung



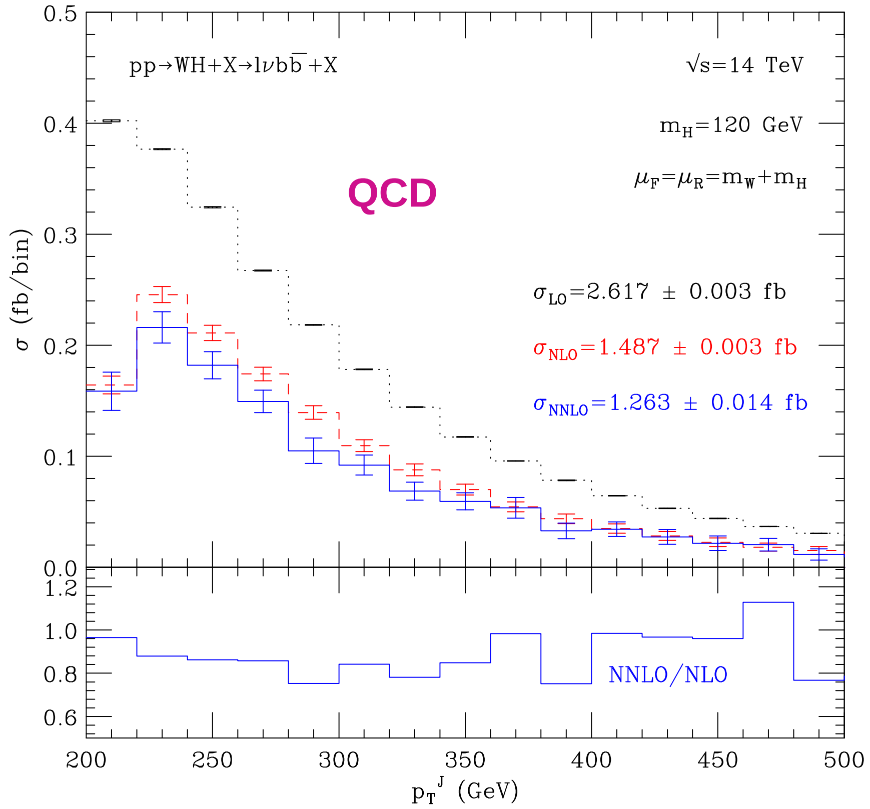
Current status of theoretical predictions



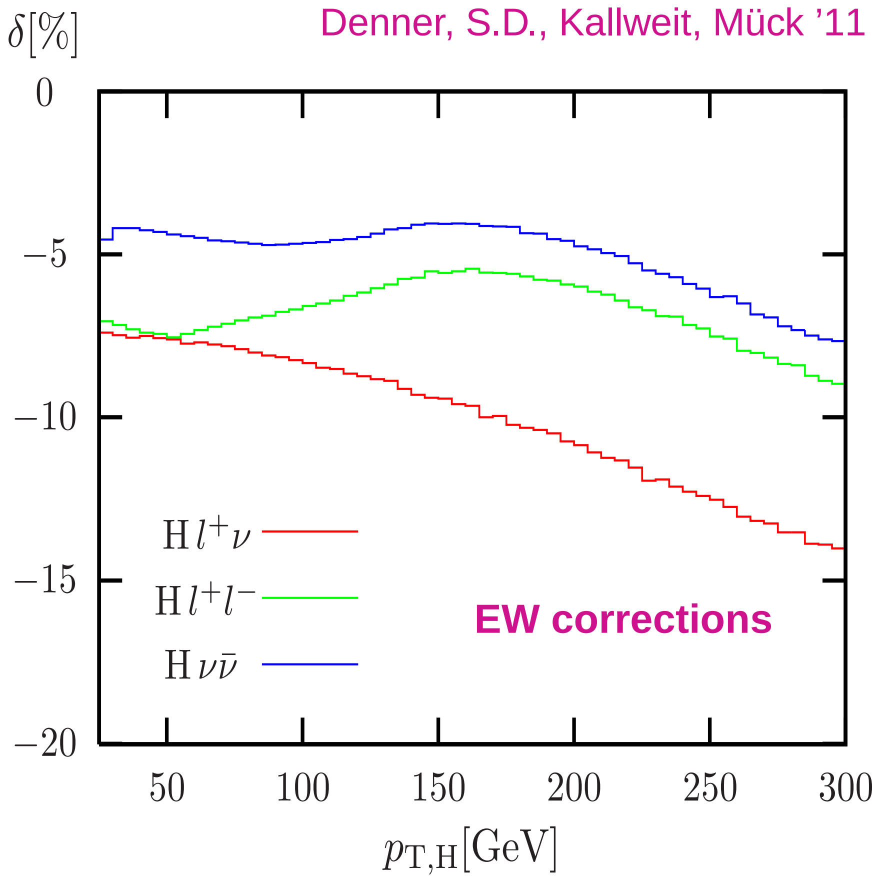
- NLO QCD: corrections entirely Drell–Yan like
  Han, Willenbrock '91; Ohnemus, Stirling '93; Baer, Bailey, Owens '93
  V2VH (Spira); MCFM (Campbell, R.K.Ellis)
- NLO EW: total cross section, stable W/Z bosons
  Ciccolini, S.D., Krämer '03
  differential cross sections, via HAWK with W/Z decays
  Denner, S.D., Kallweit, Mück '11
- NNLO QCD: total cross section, stable W/Z bosons
  Drell–Yan-like part, $gg \to ZH$
  Brein, Djouadi, Harlander '03 (VH@NNLO)
  differential WH XS, with W decay, Drell–Yan-like part
  Ferrera, Grazzini, Tramontano '11
  total cross section, non-Drell–Yan-like parts
  Brein, Harlander, Wiesemann, Zirke '11
- NNNLO QCD: total cross section, gg channel
  Altenkamp et al. '12

QCD and EW corrections to the $p_{\mathrm{T,H}}$ distributions

Ferrera, Grazzini, Tramontano '11



Denner, S.D., Kallweit, Mück '11



Boosted-Higgs $p_{\mathrm{T,H}} > 200\,\mathrm{GeV}$ ("fat jet" with $\mathrm{b\bar{b}}$ substructure) Butterworth et al. '08 ATL-PHYS-PUB-2009-088

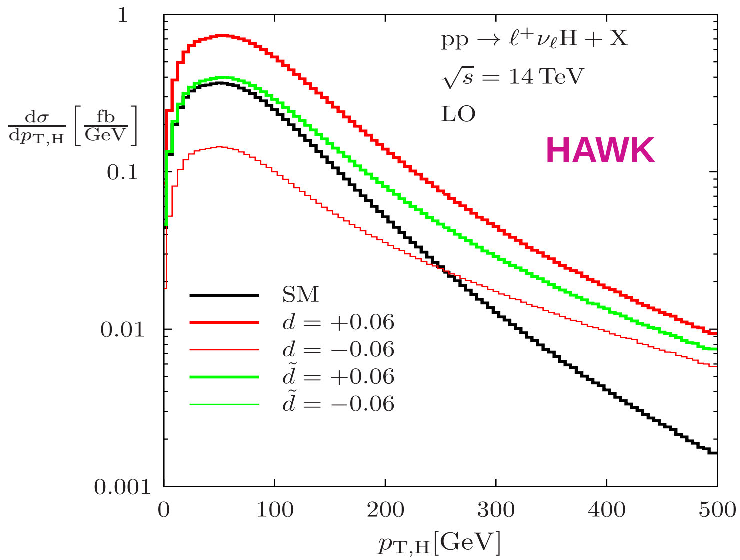
pronounces corrections to $\mathrm{HW} \to \mathrm{H}\ell^+\nu$ at $p_{\mathrm{T,H}} \sim 200{-}300\,\mathrm{GeV}$

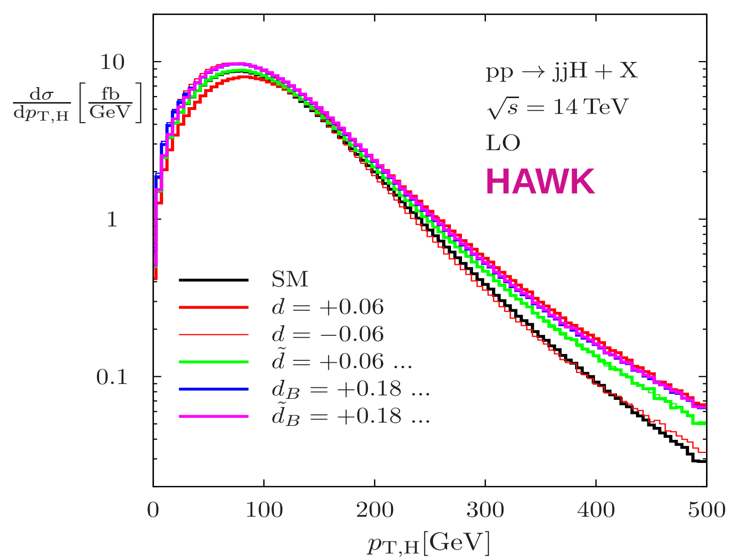
- $\delta_{\mathrm{QCD}} \sim -5{-}20\%$
- $\delta_{\mathrm{EW}} \sim -10{-}15\%$

Anomalous VHH couplings in $p_{\mathrm{T,H}}$ spectra

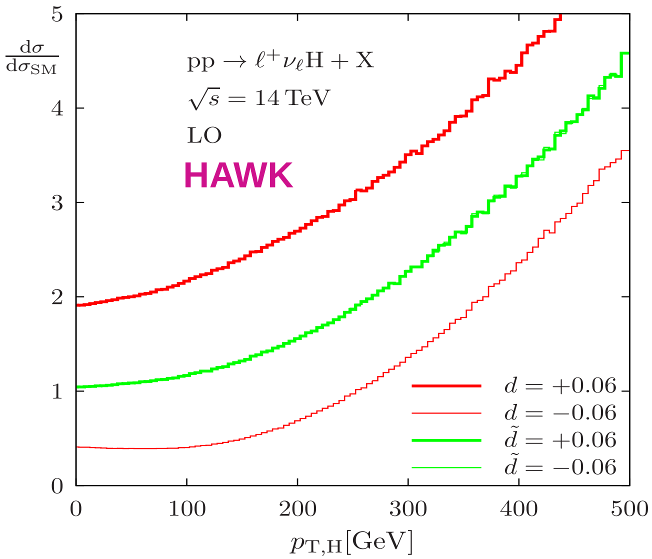
$\mathrm{W^+H}$ (acc. cuts)

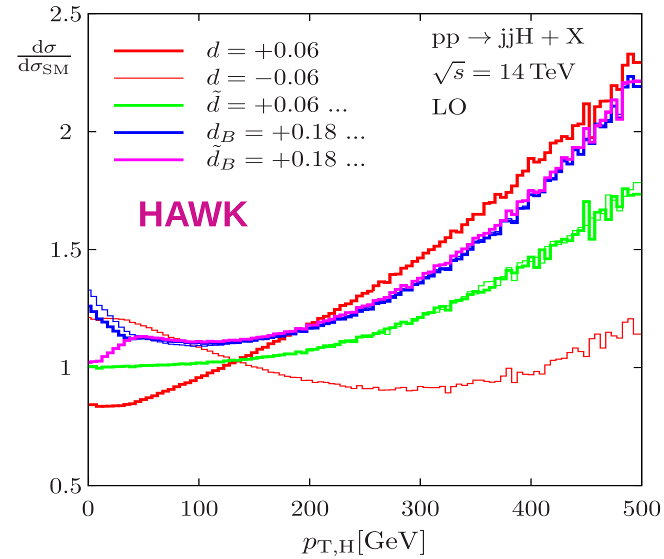
VBF (with VBF cuts)





similar VBF results by Hankele, Klämke, Zeppenfeld, Figy '06





$\mathcal{L} \propto H W_{\mu\nu} W^{\mu\nu}$

$\mathcal{L} \propto H \tilde{W}_{\mu\nu} W^{\mu\nu}$

$\mathcal{L} \propto H B_{\mu\nu} B^{\mu\nu}$

$\mathcal{L} \propto H \tilde{B}_{\mu\nu} B^{\mu\nu}$

Impact of ACs larger in WH production than in VBF !

A loop-theorist's summary of ...

Two decades of Higgs precision calculations

Successful predictions required + triggered great leaps forward

- at the multi-loop frontier
  $\hookrightarrow$ two loops with masses, massless multi-loop calculations
- at the LO multi-leg frontier
  $\hookrightarrow$ automatized MCs based on full MEs
- at the NLO multi-leg frontier
  $\hookrightarrow$ full $2 \to 4(5)$ calculations, automation
- for calculation beyond fixed orders
  $\hookrightarrow$ QCD resummations / parton showering / matching at NLO
- in many conceptual issues
  $\hookrightarrow$ unstable particles, etc.

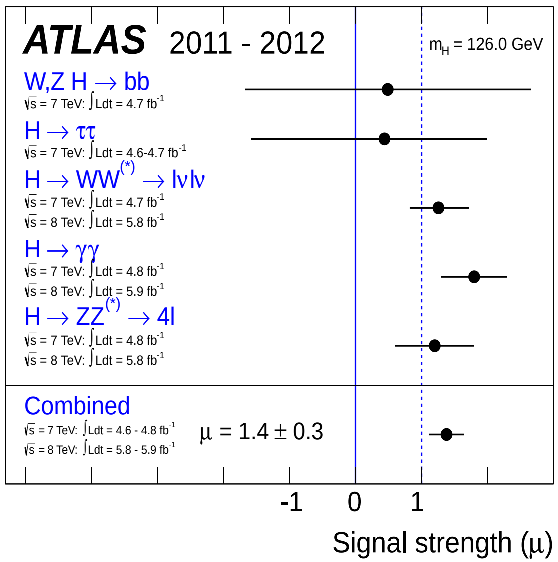
Outlook – next steps

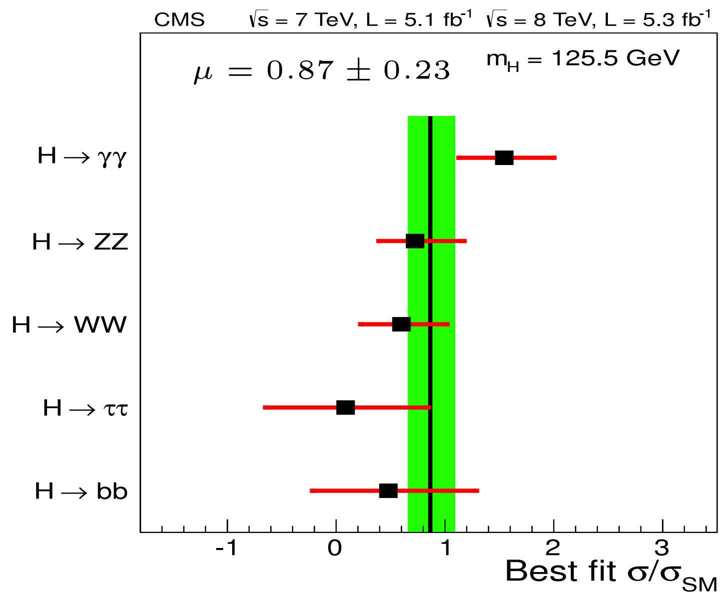
Higgs coupling analysis

- 1st step: global analysis of signal strengths μ

Signal strength μ: $\sigma_{\rm obs} = \mu \times \sigma_{\rm SM} \times {\rm BR}_{\rm SM}$

Status July 2012:





Higgs coupling analysis

- 1st step: global analysis of signal strengths μ
- 2nd step: rescaling of SM couplings

... different variant proposed by many authors

Zeppenfeld et al. '00; Dührssen et al. '04; Lafaye et al. '09; ...

Interim recommendation of the LHC HXS WG '12:

$\hookrightarrow$ rescale all SM Higgs couplings: $g_i = \kappa_i \times g_i^{\mathrm{SM}} \quad i = \mathrm{HWW}, \mathrm{HZZ}, \mathrm{Htt}, \dots$

with simplifying assumptions:

- ◇ no new tensor structures in couplings
  - $\hookrightarrow$ ignores shape distortions by BSM effects (e.g. CP-odd couplings)
- ◇ rescaling of SM corrections (to avoid artificial deviations in SM limit)
  - $\hookrightarrow$ QCD corrs: reasonable, since dominant correction factorize
  - EW corrs: failure for BSM $\rightarrow$ additional uncertainties of $\sim 5{-}10\%$
- ◇ narrow-width approximation for Higgs, no $\mathrm{gg} \rightarrow \mathrm{ZH}$, etc.

Recipe can give qualitative picture:

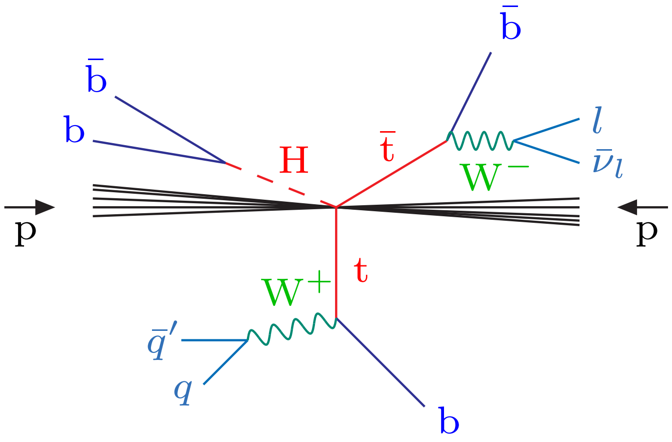
- ◇ deviations from SM rates significant ?
- ◇ pattern of deviations (W/Z sector? Custodial symmetry? fermion sector? ...)

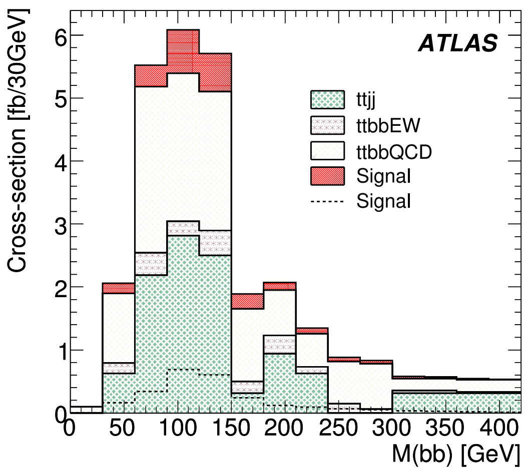
Higgs coupling analysis

- 1st step: global analysis of signal strengths μ
- 2nd step: rescaling of SM couplings
- 3rd+ steps: more sophisticated approaches
  - ◇ model-independent effective-field theory (EFT)
    - – SM with Higgs boson = low-energy theory
    - – inclusion of, e.g., all $d = 6$ operators for “Higgs” couplings
    - – consistent inclusion of higher-order corrections in EFT approach
    - $\hookrightarrow$ hints for BSM model building ?
  - ◇ precision analyses in specific BSM models
    - – THDM, triplet models
    - – with and w/o SUSY
    - $\hookrightarrow$ constraints on or hints for additional new Higgs-like states

Future challenges

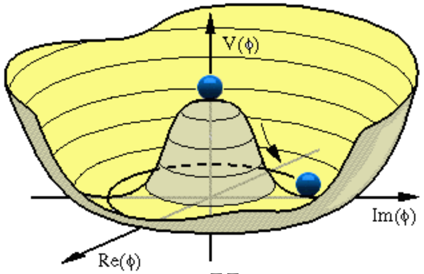
- Analyse $\mathrm{t\bar{t}H}$ production
  - Relevance: direct experimental access to $\mathrm{t\bar{t}H}$ Yukawa coupling
  - Problem: control background by $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}, \mathrm{t\bar{t}} + \mathrm{jets}$ $\quad (S/B \sim 1/10)$
    status 2008: signal not significant due to background contamination
    $\hookrightarrow$ activities: – more sophisticated tricks in analysis
    e.g. "fat jet" with $\mathrm{b\bar{b}}$ substructure Plehn, Salam, Spannowsky '09
    – NLO QCD prediction also for background
    $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$ Bredenstein, Denner, S.D., Pozzorini '09; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09
    $\mathrm{pp} \to \mathrm{t\bar{t}} + 2\mathrm{jets}$ Bevilacqua, Czakon, Papadopoulos, Worek '09





"CSC book"
CERN-OPEN-2008-020

Future challenges



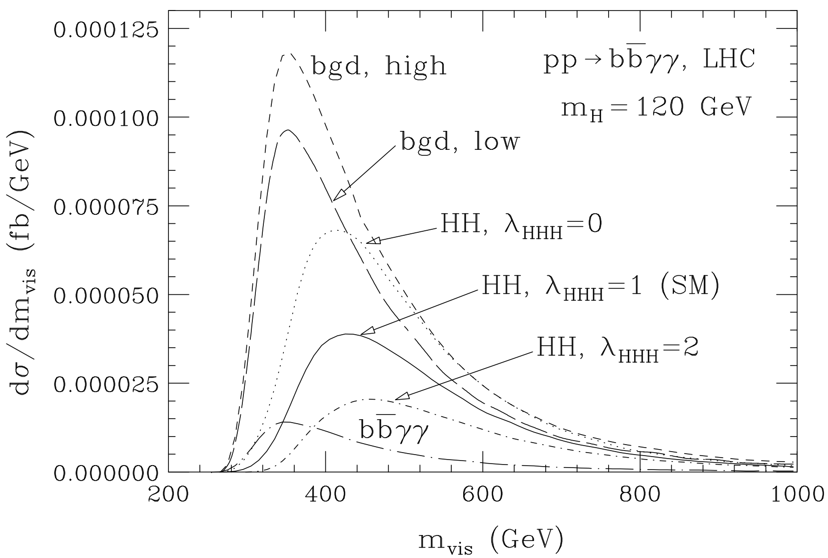
$=v+H$

- Analyse $\mathrm{t\bar{t}H}$ production
- Triple-Higgs coupling
  - ◇ Relevance: reconstruction of the Higgs potential
    (at least partially)

$$V(H)\Big|_{\mathrm{SM,U\;gauge}} = \mathrm{const} + \frac{1}{2}M_\mathrm{H}^2 H^2 + \frac{gM_\mathrm{H}^2}{4M_\mathrm{W}} H^3 + \frac{g^2 M_\mathrm{H}^2}{32 M_\mathrm{W}^2} H^4$$

  - ◇ Problem: – small Higgs pair production cross sections
    – $M_\mathrm{H} \sim 126\,\mathrm{GeV} \;\to\; \mathrm{b\bar{b}}\gamma\gamma$ final state with BR suppression

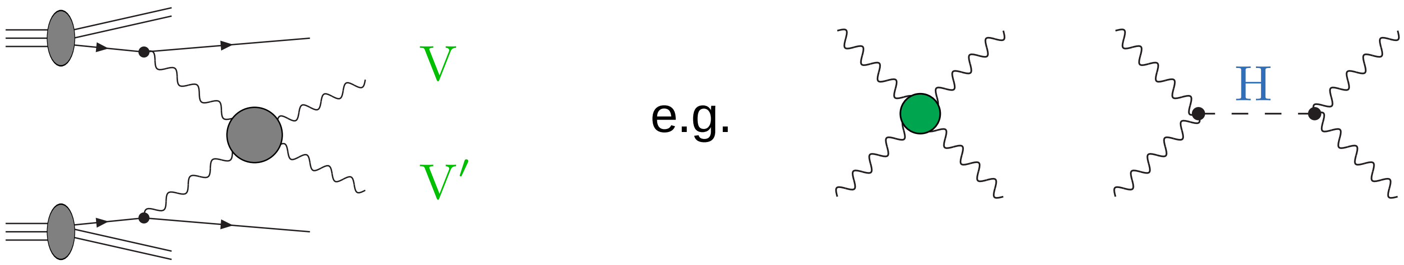
Baur, Plehn, Rainwater '03



  - ◇ H^3 coupling requires at least high-luminosity LHC
    $\hookrightarrow$ ILC highly desirable here
  - ◇ H^4 coupling out of reach
    (σ_{HHH} way too small)

Future challenges

- Analyse $\mathrm{t\bar{t}H}$ production
- Triple-Higgs coupling
- Vector-boson scattering
  - ◇ Relevance: – test of weak coupling of longitudinal vector bosons
    - – analysis of quartic gauge couplings
    - – high sensitivity to new physics related to EWSB
  - ◇ Problem: small cross sections, large background
  - ◇ Role of the Higgs boson:
    Off-shell Higgs exchange rescues unitarity in SM.
    $\hookrightarrow$ SM with low-mass Higgs boson = background in BSM searches !
  - ◇ Full potential of channels require high-luminosity LHC



Conclusions

Higgs physics – status 2012

- SM predictions in good shape for $\mathrm{gg} \to \mathrm{H}$, VBF, and $\mathrm{WH/ZH}$
  uncertainties $\sim 5{-}20\%$ depending on final state
- ATLAS/CMS find Higgs candidate at $M_\mathrm{H} = 126\,\mathrm{GeV}$ via $\mathrm{H} \to \gamma\gamma/\mathrm{ZZ}^*/\mathrm{WW}^*$
  compatible with Tevatron 3σ evidence for $\mathrm{H} \to \mathrm{b\bar{b}}$
  $\hookrightarrow$ spectacular agreement with SM fit to EW precision data
- BUT: scale of BSM physics might be very large
  $\hookrightarrow$ precision might be the way to new discoveries

The near future

- Establishment of $\mathrm{H} \to \mathrm{b\bar{b}}/\tau\tau$ and $\mathrm{t\bar{t}H}$ signals (hopefully)
- Higgs coupling analysis beyond simple rescalings of XS and BR
- Constraints on specific BSM models (MSSM, THDM, etc.)

The far future (including high-luminosity LHC)

Precision BSM physics, triple-Higgs coupling, $\mathrm{W_L}$ scattering, etc. (?)

$\Rightarrow$ Tremendous homework for theorists

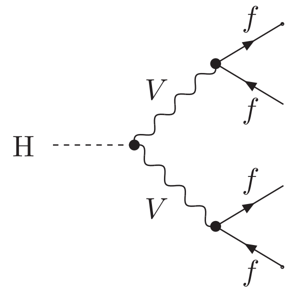
Higgs physics might guide the way to more comprehensive theories beyond SM !

Backup slides

An example: $\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$

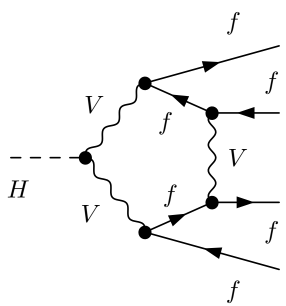
Survey of Feynman diagrams for NLO corrections

Lowest order:

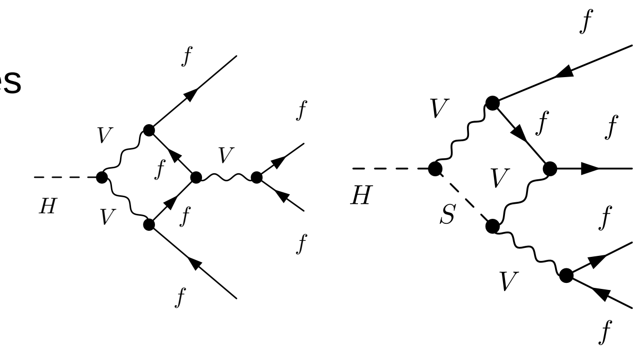


Typical one-loop diagrams: # diagrams = $\mathcal{O}(200\text{–}400)$

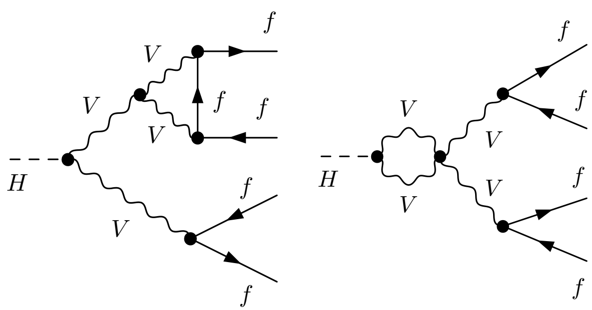
pentagons



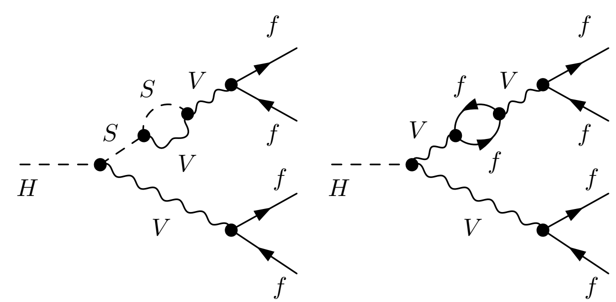
boxes



vertices



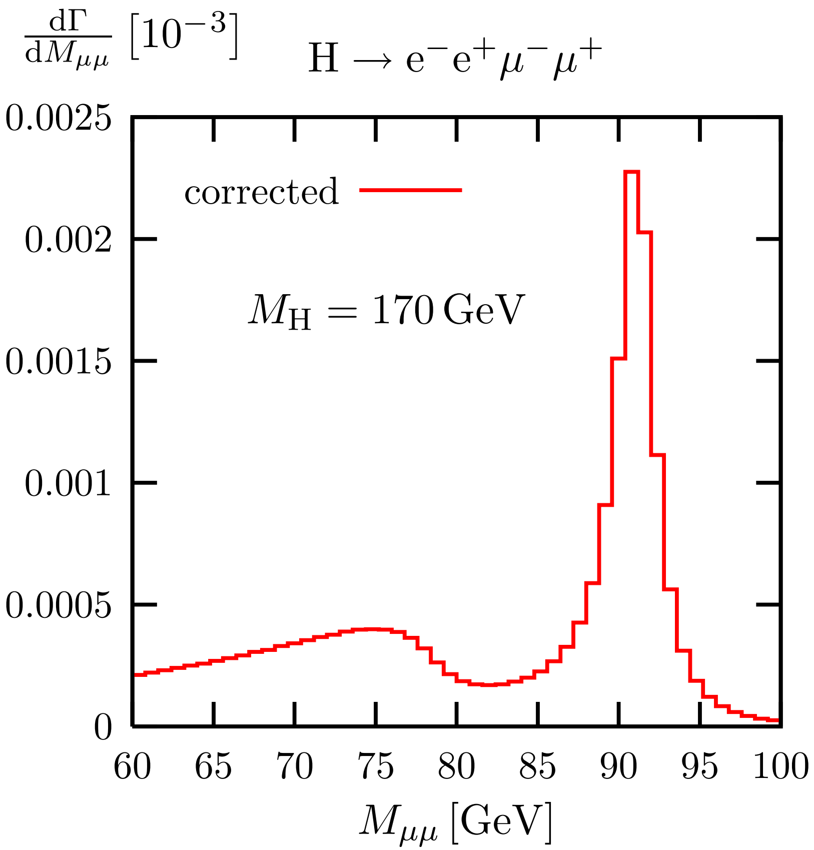
self-energies

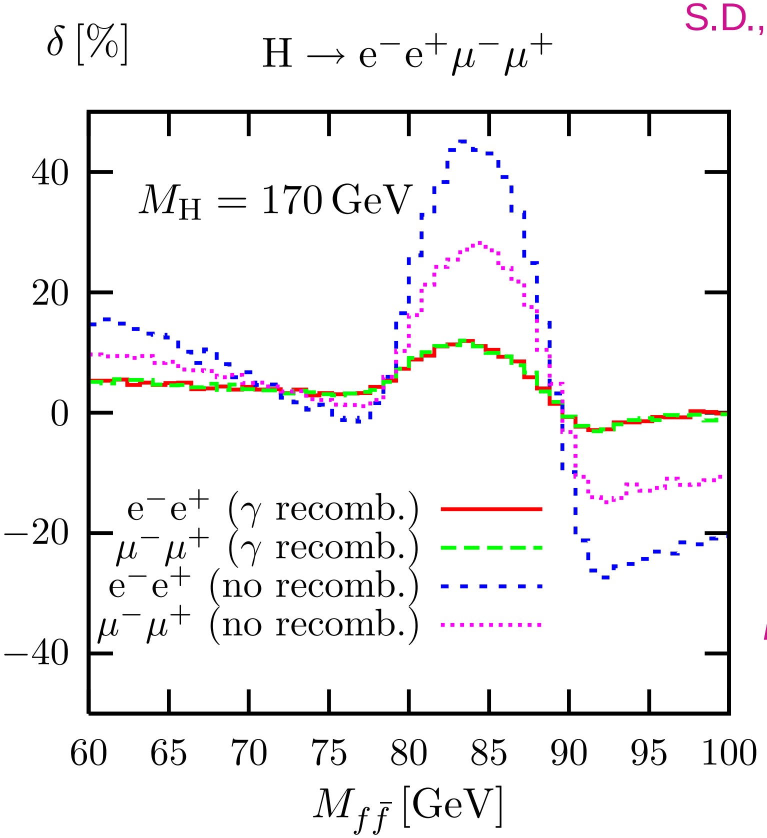


$+$ tree graphs with real gluon or photons

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

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





Prophecy4f

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

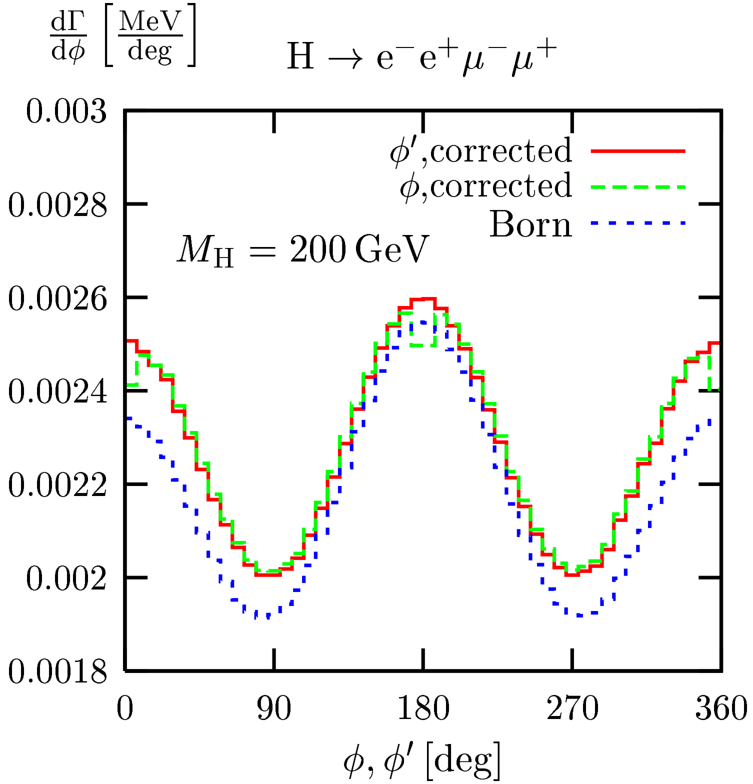
Large corrections due to photon emission in Z reconstruction

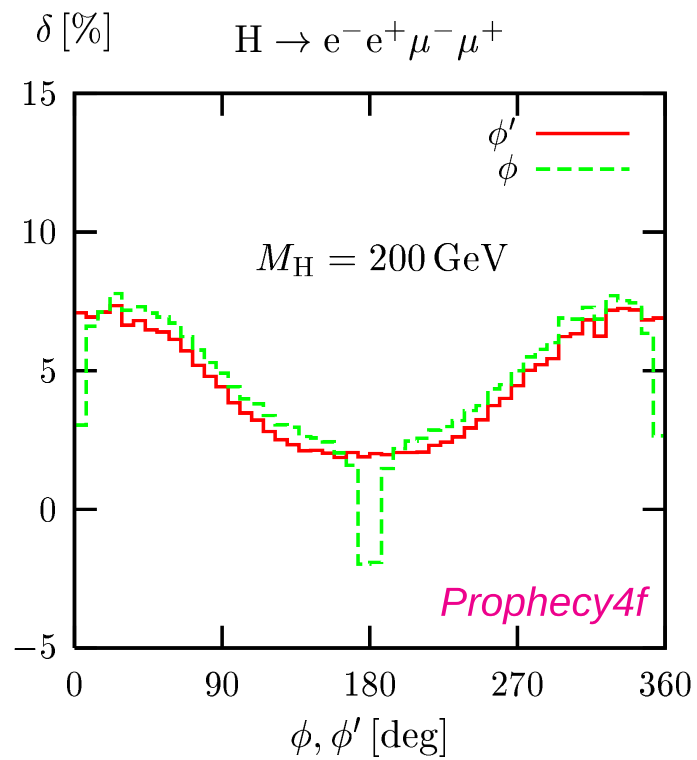
Corrections to distribution in angle between Z decay planes

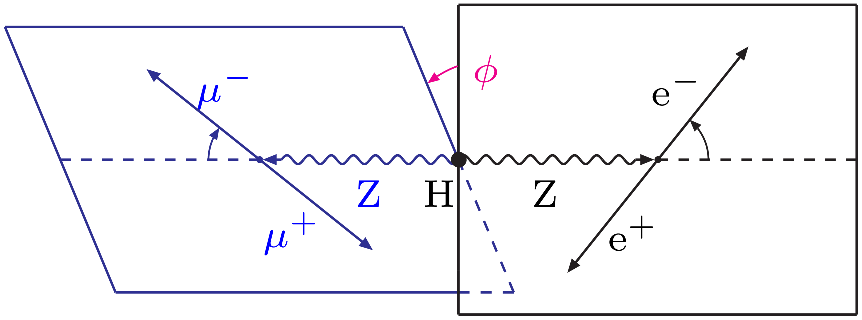
$\hookrightarrow$ $5-10\%$ effects that in general distort shapes of distributions

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

An example:



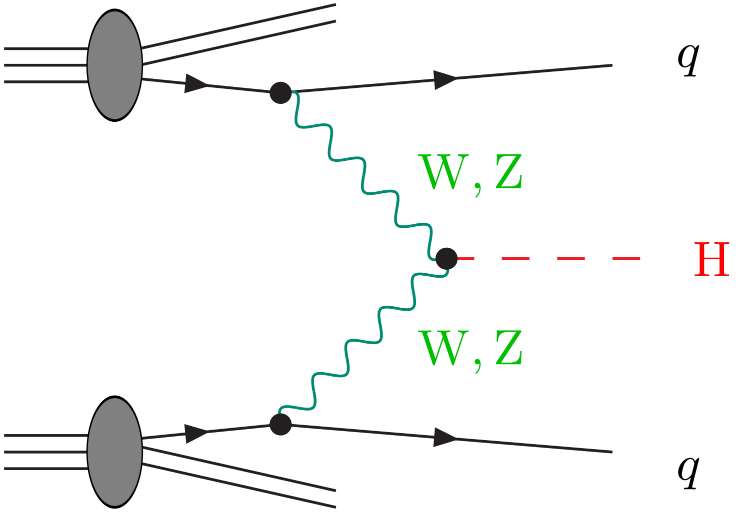




$$\cos\phi = \frac{(\mathbf{p}_{e^-e^+} \times \mathbf{p}_{e^-})(-\mathbf{p}_{\mu^-\mu^+} \times \mathbf{p}_{\mu^-})}{|\mathbf{p}_{e^-e^+} \times \mathbf{p}_{e^-}||-\mathbf{p}_{\mu^-\mu^+} \times \mathbf{p}_{\mu^-}|}$$

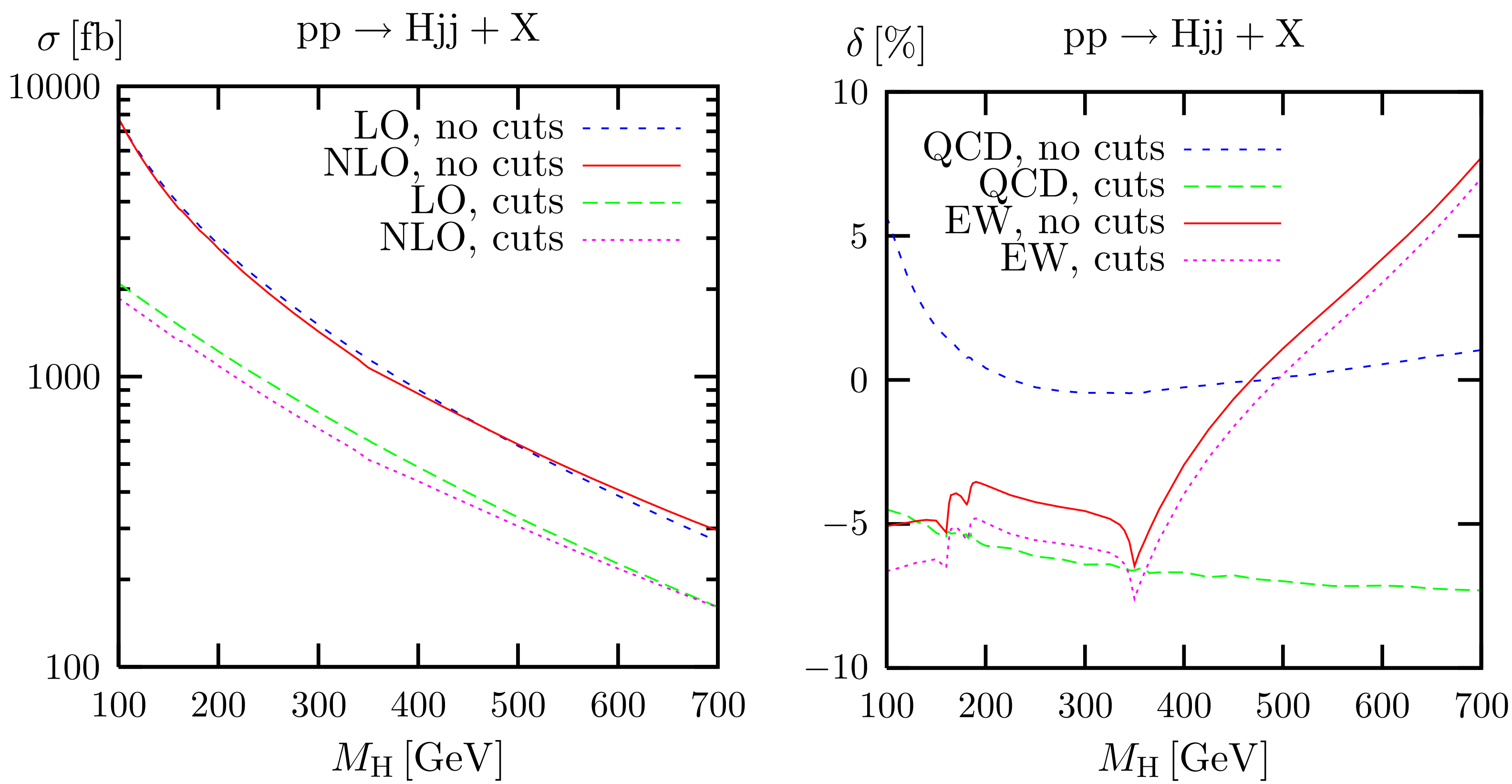
$$\cos\phi' = \frac{(\mathbf{p}_{e^-e^+} \times \mathbf{p}_{e^-})(\mathbf{p}_{e^-e^+} \times \mathbf{p}_{\mu^-})}{|\mathbf{p}_{e^-e^+} \times \mathbf{p}_{e^-}||\mathbf{p}_{e^-e^+} \times \mathbf{p}_{\mu^-}|}$$

Higgs production via vector-boson fusion



Integrated VBF cross section at NLO QCD $\oplus$ EW

Ciccolini, Denner, S.D. '07

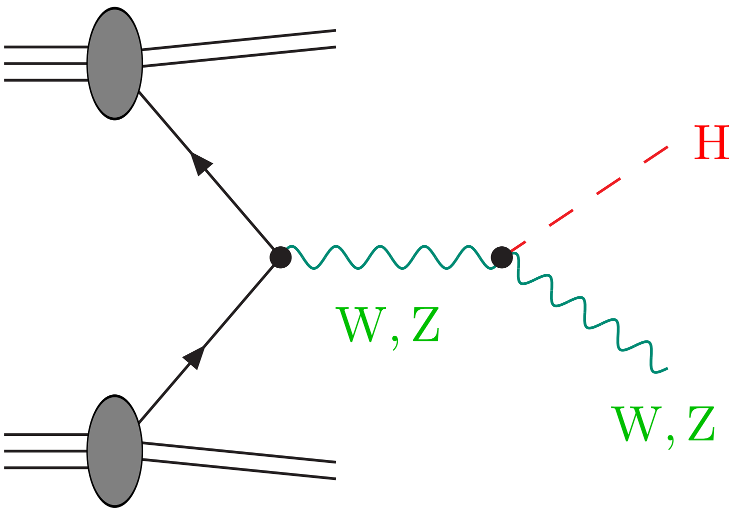


HAWK

- QCD and EW corrections are of same generic size
- $\mathrm{W/Z}$ resonances in s-channels described via complex-mass scheme
- sensitivity to cuts: large for QCD, small for EW corrections
- heavy-Higgs corrections at $M_\mathrm{H} \sim 700\,\mathrm{GeV}$: $\underbrace{G_\mu M_\mathrm{H}^2}_{\text{1-loop}} \sim \underbrace{(G_\mu M_\mathrm{H}^2)^2}_{\text{2-loop}} \sim 4\%$

  $\hookrightarrow$ breakdown of perturbation theory

Production via Higgs-strahlung



Total cross section: NNLO QCD and NLO EW corrections

LHC Higgs XS report
CERN-2011-002, arXiv:1101.0593 [hep-ph]

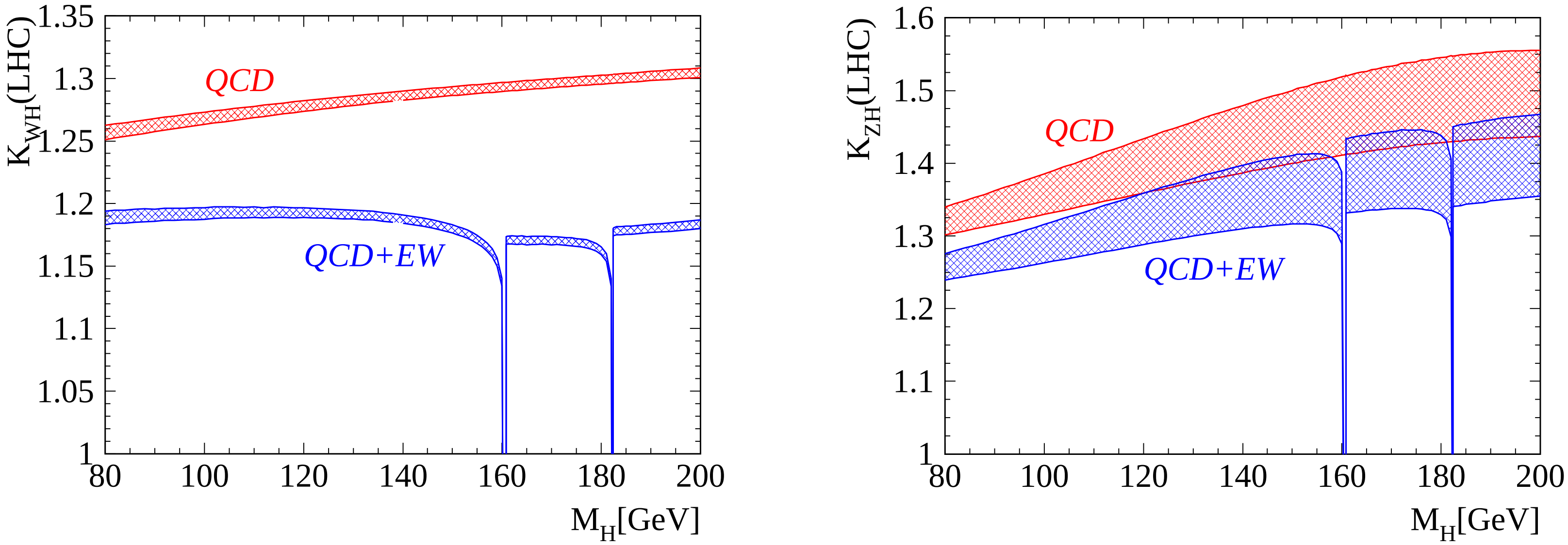
$$\sigma_{\mathrm{WH}} = \sigma_{\mathrm{WH}}^{\mathrm{VH@NNLO}} \times (1 + \delta_{\mathrm{WH,EW}})$$

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

Note:
$\delta_{\mathrm{VH,EW}}$ insensitive to PDFs !

K factors for $\mathrm{pp} \to \mathrm{VH} + X$ @ $\sqrt{s} = 14\,\mathrm{TeV}$:

Brein et al. & Ciccolini et al. '04



- typical size of corrections: $\mathcal{O}(\alpha_s^2) \sim \mathcal{O}(\alpha) \sim 5\text{–}10\%$
- spikes at $M_{\mathrm{H}} = 2M_{\mathrm{W}}$ and $M_{\mathrm{H}} = 2M_{\mathrm{Z}}$
  = perturbative artifacts from WW/ZZ threshold
  $\hookrightarrow$ require inclusion of W/Z decays (see below)

Differential cross section: (N)NLO QCD and NLO EW corrections

LHC Higgs XS report
CERN-2012-002, arXiv:1201.3084 [hep-ph]

$$\mathrm{d}\sigma_{\mathrm{WH}} = \mathrm{d}\sigma_{\mathrm{WH}}^{\text{VH@NNLO(DY)}} \times (1 + \delta_{\mathrm{WH,EW}})$$

$$\mathrm{d}\sigma_{\mathrm{ZH}} = \mathrm{d}\sigma_{\mathrm{ZH}}^{\text{VH@NLO}} \times (1 + \delta_{\mathrm{ZH,EW}})$$

Again:
$\delta_{\mathrm{VH,EW}}$ insensitive to PDFs !

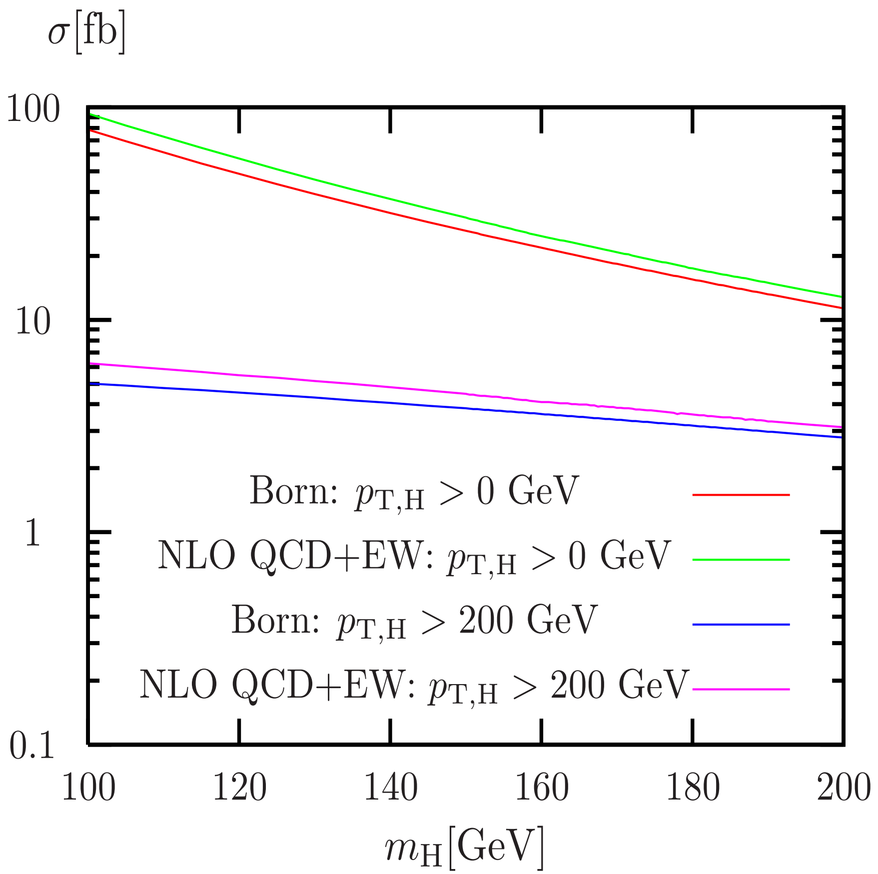
Features:

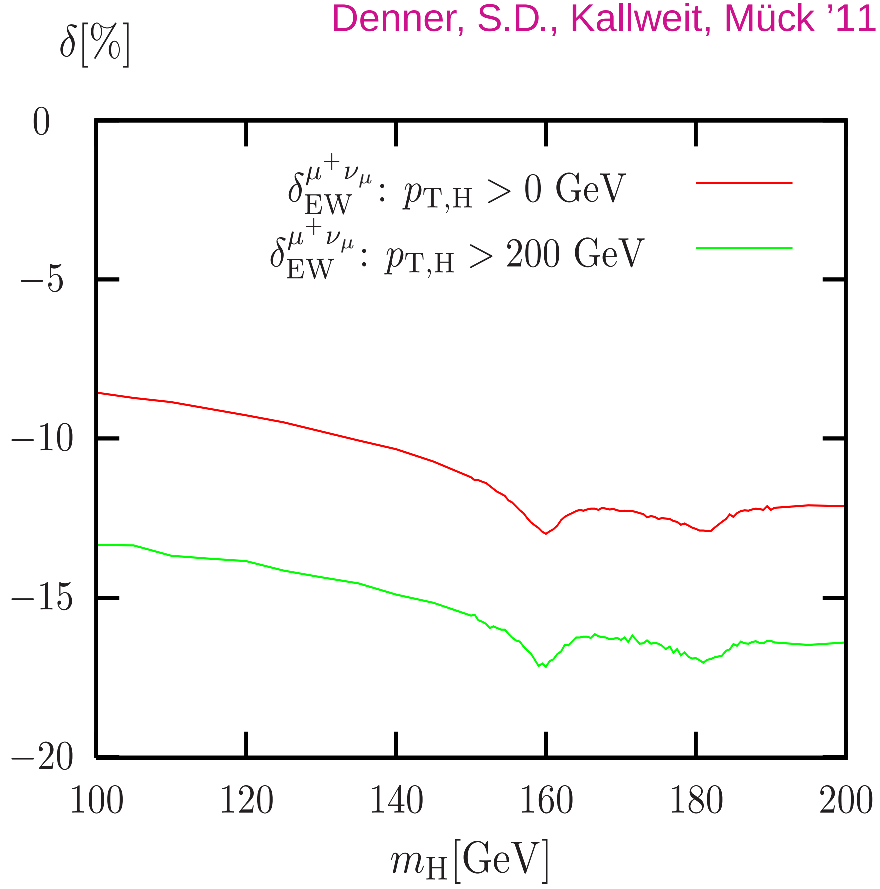
- NNLO QCD for WH in Drell–Yan-like approximation (ZH in progress)
  Ferrera, Grazzini, Tramontano ’11
- NLO EW (+QCD) calculated with HAWK
  Denner, S.D., Kallweit, Mück ’11
- size of corrections and TH uncertainties larger than for σ_{tot}

channel	$\mathrm{H}\mathrm{l}^+\nu_\mathrm{l}$	$\mathrm{H}\mathrm{l}^-\bar{\nu}_\mathrm{l}$	$\mathrm{H}\mathrm{l}^+\mathrm{l}^-$	$\mathrm{H}\nu_\mathrm{l}\bar{\nu}_\mathrm{l}$
$\delta_{\mathrm{EW}}^{\mathrm{bare}}/\%$	-14	-14	-11	-7
$\Delta_{\mathrm{PDF}}/\%$	±5	±5	±5	±5
$\Delta_{\mathrm{scale}}/\%$	±2	±2	±2	±2
$\Delta_{\mathrm{HO}}/\%$	±1	±1	±7	±7

NLO EW corrections to the integrated cross section of $\mathrm{pp} \to \mathrm{H}\ell^+\nu_\ell + X$

Denner, S.D., Kallweit, Mück '11

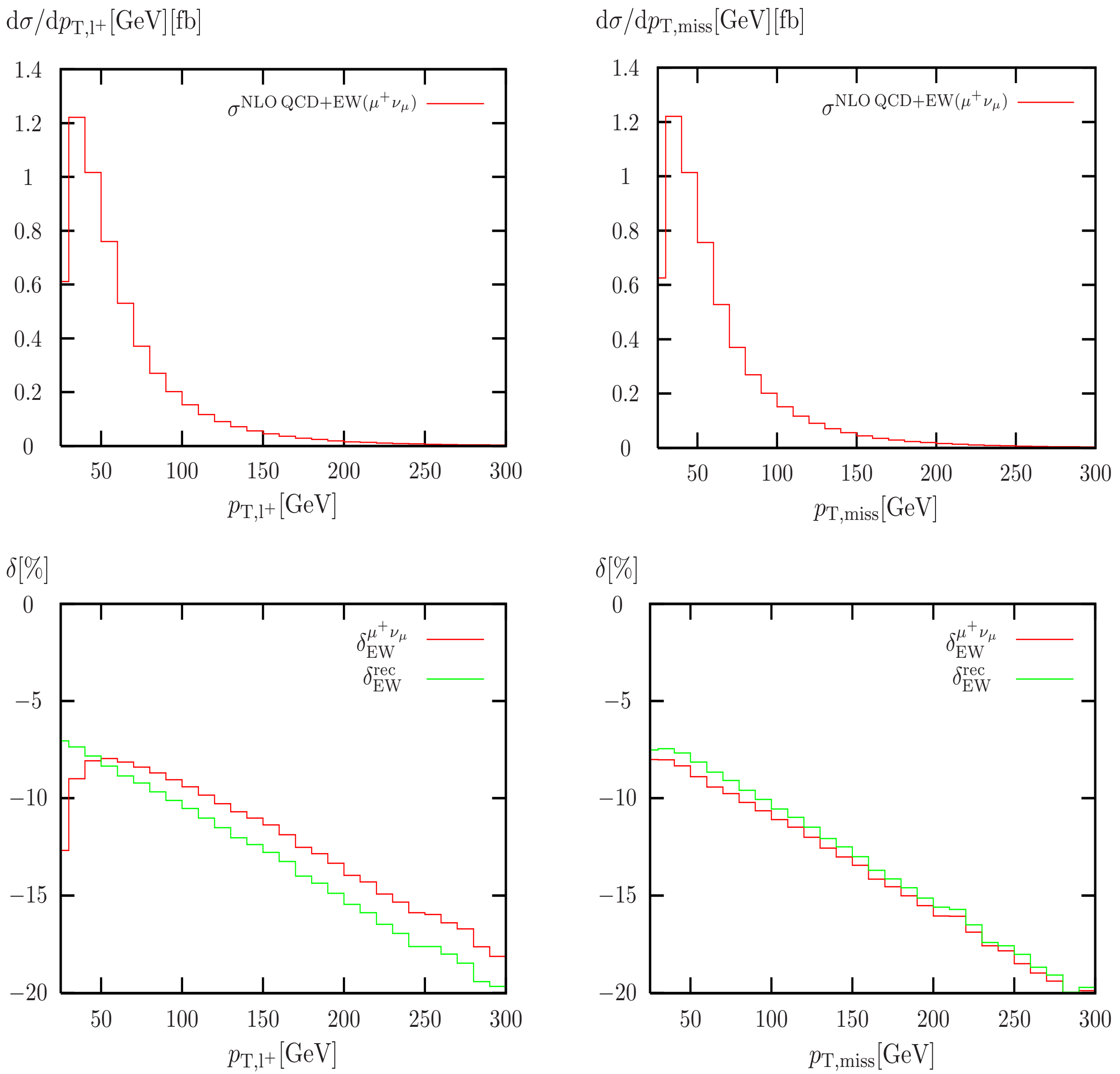




- sound behaviour of δ_{EW} near WW/ZZ thresholds
- size of EW corrections increases for boosted-Higgs scenario wrt σ_{tot} !

NLO EW corrections to $p_{\mathrm{T},\ell}$ and $p_{\mathrm{T,miss}}$ distributions for $\mathrm{pp} \to \mathrm{H}\ell^+\nu_\ell + X$

Denner, S.D., Kallweit, Mück '11



"bare muons": no γ recombination

$\hookrightarrow$ collinear μ and γ assumed separable

$\hookrightarrow$ mass-singular corrections $\propto \alpha \ln m_\mu$

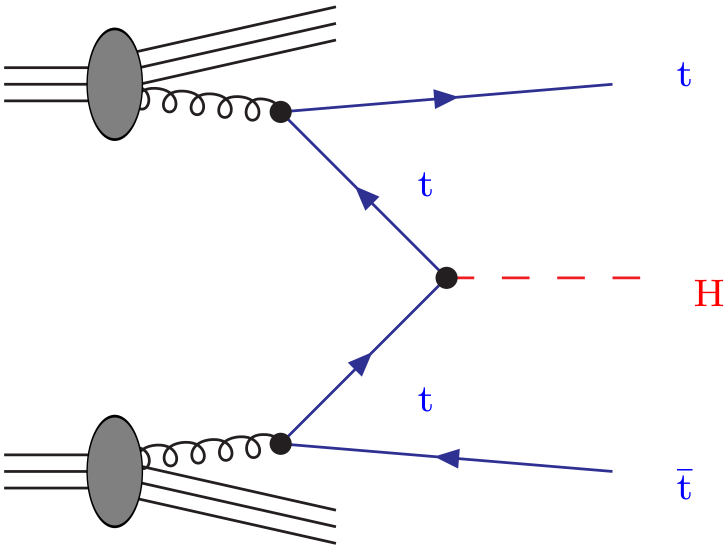
"rec": recombination of collinear γ

$\hookrightarrow$ collinear $\mu\gamma = \widetilde{\mu\gamma}$ quasiparticle

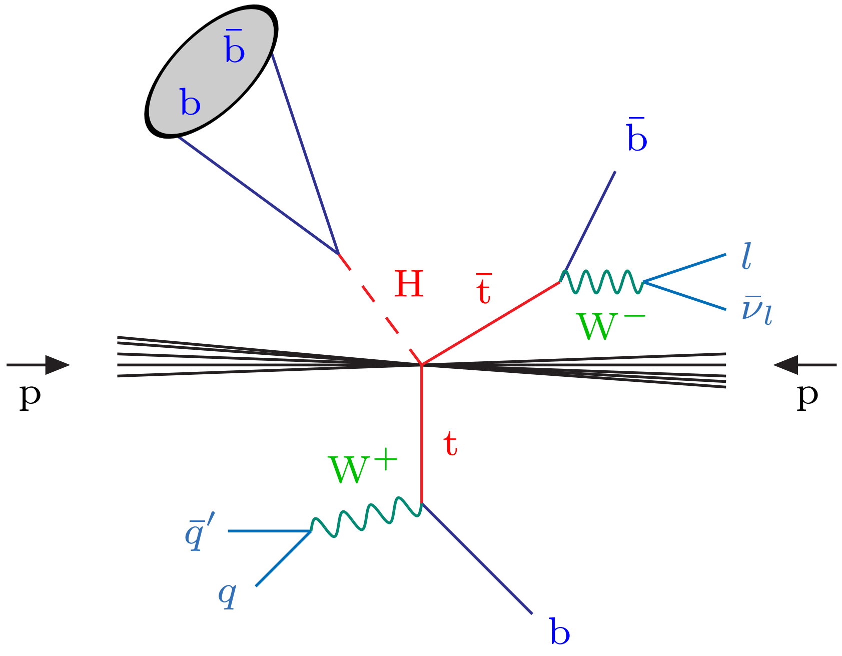
$\hookrightarrow$ no mass-singular corrections

$\hookrightarrow$ EW corrections mostly of non-universal origin (not simply FSR!)

Higgs production in association with $t\bar{t}$ pairs



Idea under discussion: highly boosted "fat jets"



Butterworth et al. '08; ATL-PHYS-PUB-2009-088

$\hookrightarrow$ fat jet containing $b\bar{b}$ pair from high-p_T Higgs (successful in WH/ZH revival!)

A theoretical study:

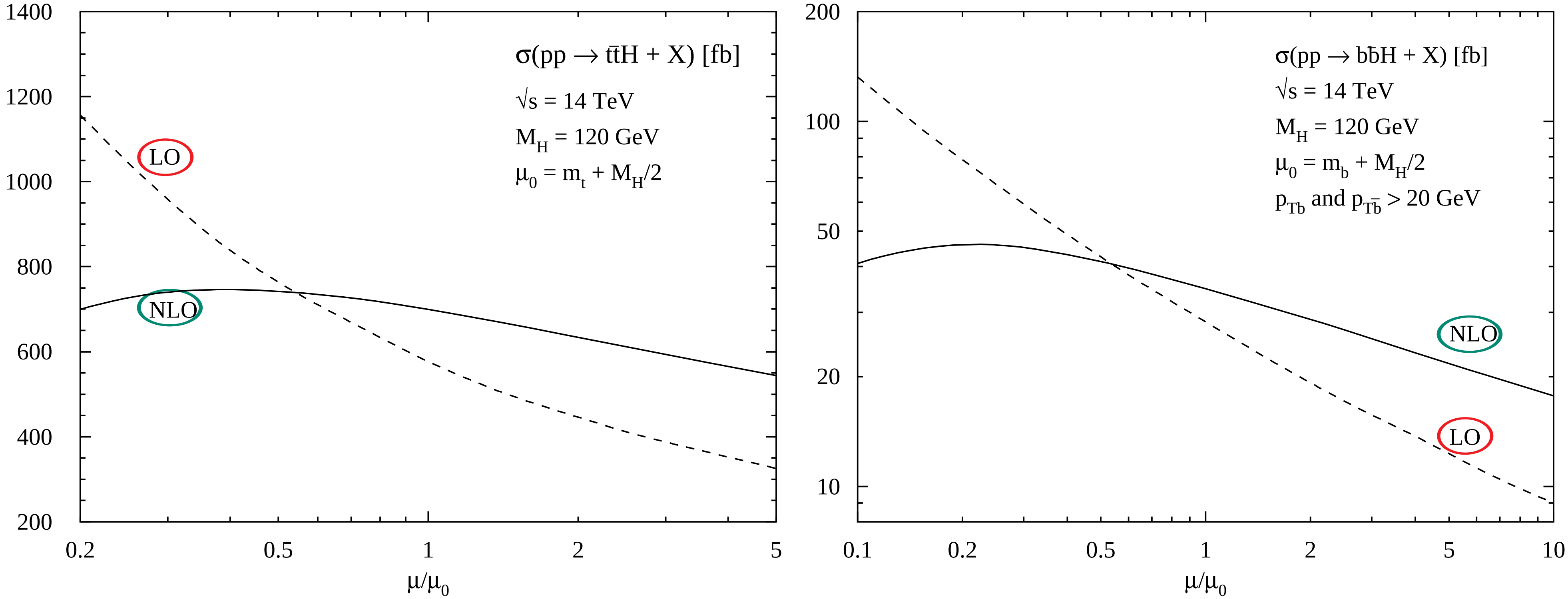
Plehn, Salam, Spannowsky '09

- fat jets: $p_T > 200\,\text{GeV}$ and $R = 1.5$
- substructures: $b\bar{b}$ pair with $|m_{b\bar{b}} - M_H| < 10\,\text{GeV}$, similar for $t \to 3j$, etc.
- $S/\sqrt{B}$ still ~ 2.2–2.6 for $\mathcal{L} = 30\,\text{fb}^{-1}$
- S/B raised from ~ 0.1 to 0.2–0.4
- background mainly due to $t\bar{t}b\bar{b}$ (suppression of $t\bar{t} + 2\text{jets}$)

Scale dependence of cross sections at the LHC

...for $\mathrm{t\bar{t}H}$ production: Beenakker et al. '03

...for $\mathrm{b\bar{b}H}$ production: S.D., Krämer, Spira '03



Drastic reduction of scale uncertainty in LO ($\sim 100\%$) $\rightarrow$ NLO (~ 10–20%)

Note: both both b's of $\mathrm{b\bar{b}H}$ tagged at $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, otherwise scale dependence larger!

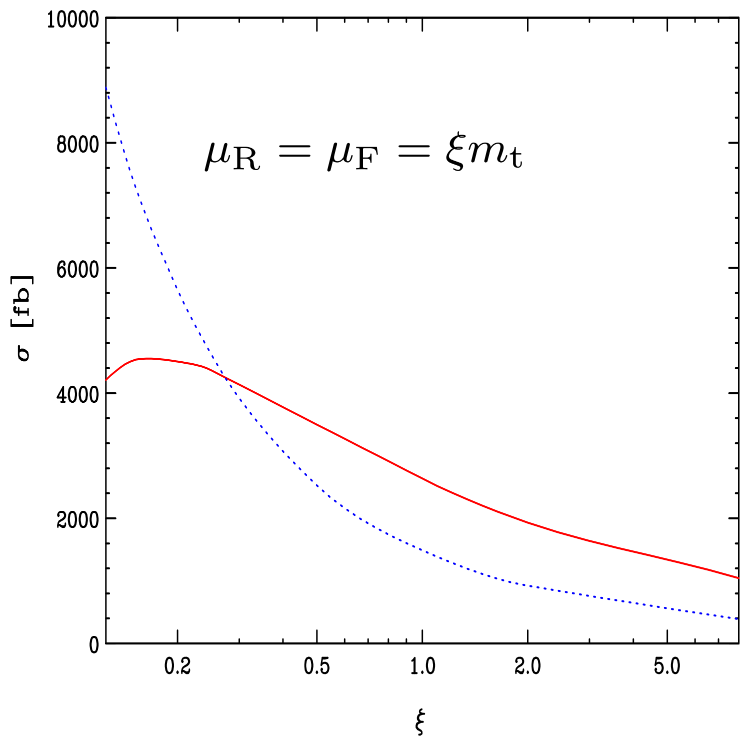
Similar results by

Dawson, Orr, Reina, Wackeroth '02; Wu et al. '05 (ttH) and

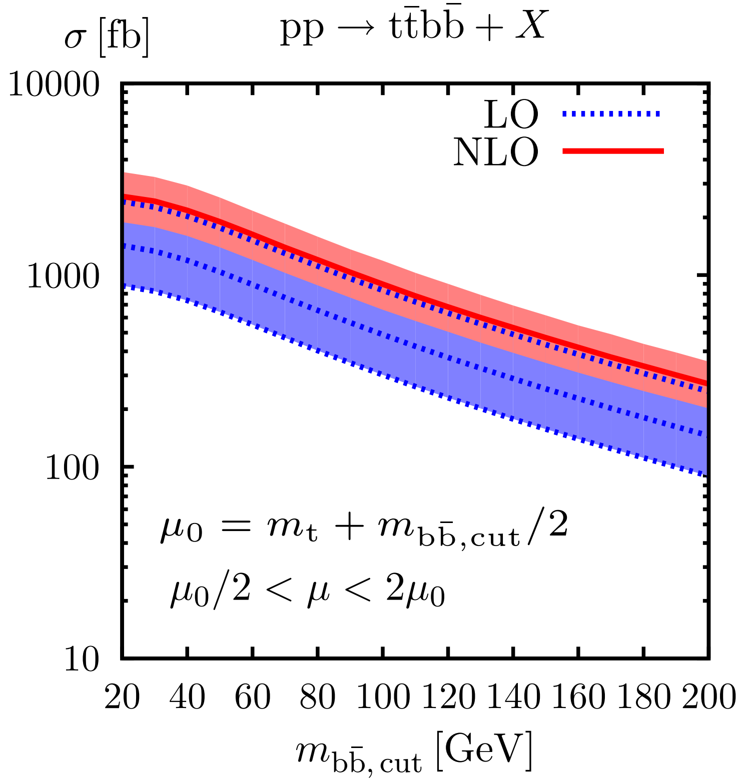
Dawson, Jackson, Reina, Wackeroth '05 (bbH)

Integrated cross section of $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}} + X$ in NLO QCD

Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09



Bredenstein, Denner, S.D., Pozzorini '09



Main results:

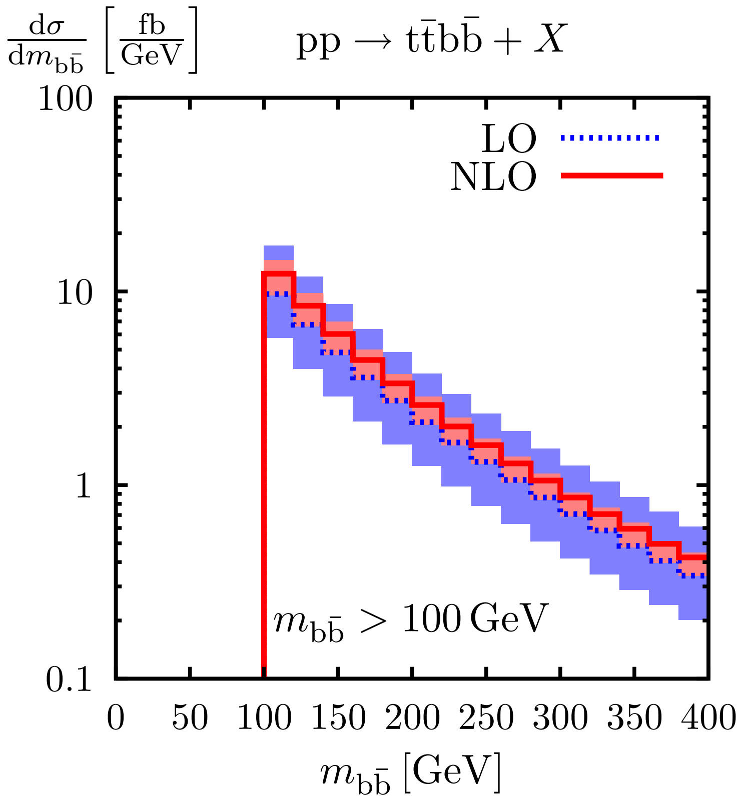
- results of the two groups agree
- correction very large at central scale $\mu_{R/F} = m_t$: $K = 1.77$
- NLO scale dependence still large: $\sim 33\%$ for $\mu_0/2 < \mu_{R/F} < 2\mu_0$ ($\sim 70\%$ at LO)

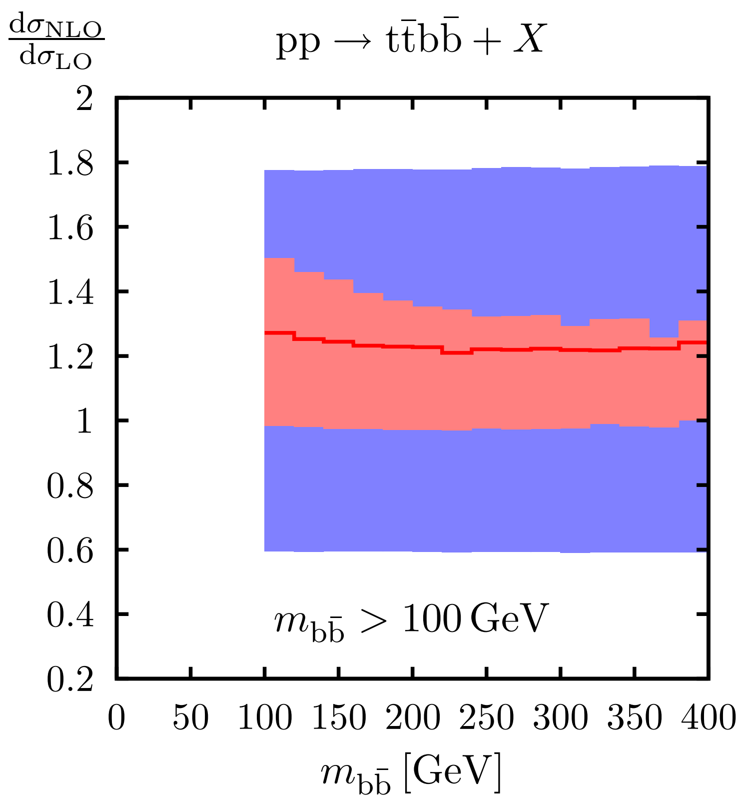
$\hookrightarrow$ further theoretical and/or phenomenological tricks necessary to stabilize analysis

More results on $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}} + X$

- Improvements on scale choice and selection cuts:

Bredenstein, Denner, S.D., Pozzorini '09





$\hookrightarrow$ reduced K factor ~ 1.2 and NLO scale dependence $\sim 21\%$ for new central scale $\mu_0^2 = m_\mathrm{t}\sqrt{p_{\mathrm{T,b}}\,p_{\mathrm{T,\bar{b}}}}$

- Another idea under discussion:

Butterworth et al. '08; ATL-PHYS-PUB-2009-088

fat jets containing $\mathrm{b\bar{b}}$ pairs from high-p_T Higgs (successful in WH/ZH revival!)

$\hookrightarrow$ better background suppression

Plehn, Salam, Spannowsky '09