

Status of MSSM & BSM Higgs cross section and branching ratio calculations

Heather Logan
Carleton University
Ottawa, Canada

SUSY 2015
Lake Tahoe, California, August 23-29, 2015

Motivation

Current situation:

$h(125)$ signal strength measurements

Bounds from additional Higgs searches



Constrain BSM model parameter space

Hoped-for future:

BSM Higgs signals are detected



Extract BSM parameters from signal strengths

We know from SM that QCD corrections are large and EW corrections can be several percent.

To make best use of data, need high-quality BSM σ /BR calcs

Outline

- BSM Higgs decays →
- Tools
 - Open issues
- BSM Higgs production →
- New developments
 - Works in progress

Summary

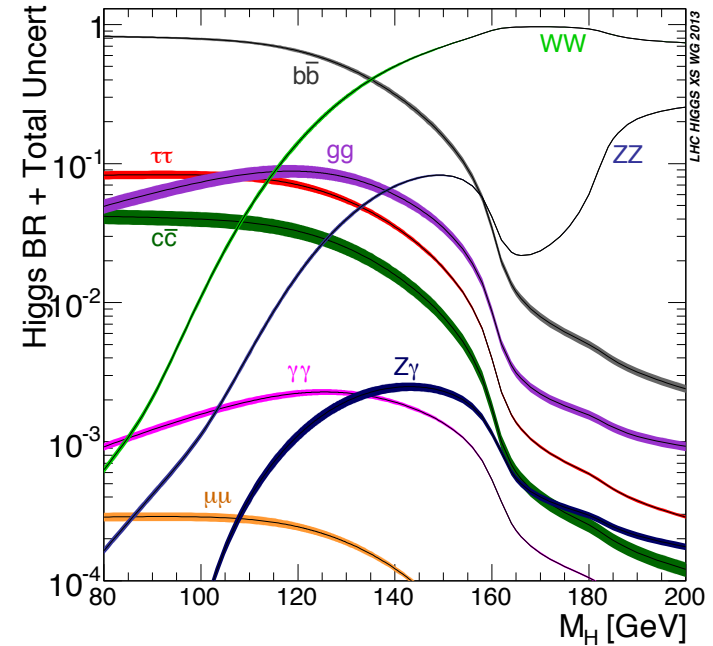
Related talks:

- State of art for SM Higgs → Radja Boughezal, tomorrow a.m.
Lineshape / interference issues → Sunghoon Jung, today
Status of FeynHiggs → Sven Heinemeyer, tomorrow p.m.
FlexibleSUSY spectrum gen. → Peter Athron, tomorrow p.m.
NLO EW corrs to Higgs-to-SUSY decays → Heinemeyer, Fri p.m.

Higgs decays: SM

Input the Higgs mass

→ all parameters known



New results from BR subgroup of LHC HXSWG:

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

M. Spira, 10th LHC HXSWG Workshop, July 2015

Higgs decays: BSM

First calculate spectrum in terms of underlying parameters.
Then compute decays & production xsecs.

★ SM QCD corrections apply if there are no new colored particles:
→ Extended Higgs sectors easy to handle
→ (N)MSSM: must include gluino/squark diagrams

★ SM EW corrections do NOT apply:
→ Must do full 1-loop EW renormalization of the model, or omit EW corrections entirely.

★ Novel decay processes → calculate from scratch:
→ Charged Higgs decays
→ $H_1 \rightarrow H_2 V$, $H_1 \rightarrow H_2 H_3$
→ Some loop-induced decays, e.g. $H_i^+ \rightarrow W^+ \gamma$

Higgs decays: BSM tools

MSSM: in very good shape – spectrum + decays

- FeynHiggs [Heinemeyer, Hahn, Rzehak, Weiglein & Hollik]
- HDECAY [Djouadi, Kalinowski, Mühlleitner & Spira]
- CPsuperH [Lee, Pilaftsis, Carena, Choi, Drees, Ellis & Wagner]
- + others [will focus here on HXSWG framework]

Current HXSWG benchmarks use FeynHiggs+HDECAY with Prophecy4F* to improve $H \rightarrow VV$
*[Bredenstein, Denner, Dittmaier, Mück & Weber] NLO QCD + NLO EW

Spectrum calculations:

- very sophisticated: leading/subleading 2-loop & beyond*
- real and complex MSSM *see Sven Heinemeyer's talk tomorrow

Decays:

- all known QCD corrections; EW corrections to fermionic decays
- Δ_b corrections (sbottom/gluino + stop/wino loops: $\tan\beta$ -enhanced)
- 3-body decays with off-shell t , W , Z , H_i
- decays into SUSY particles

Emphasis on highest precision possible; careful accounting of residual uncertainties → BSM gold standard

Higgs decays: BSM tools

NMSSM: also very well developed

- NMSSMCALC, NMSSMTools, SPheno (spectrum + decays)
- SoftSUSY → decays from NMHDECAY + NMSDECAY
- FlexibleSUSY → decays under construction

· Spectrum to 2-loop accuracy [with some approximations]

· Decays mostly at same level as MSSM

Spectrum comparisons: [Staub et al, 1507.05093](#)

NMSSMCALC: [Baglio, Gröber, Mühlleitner, Nhung, Rzehak, Spira, Streicher & Walz](#) [HDECAY]

NMSSMTools: [Ellwanger & Hugonie](#); incl. NMHDECAY [+ [Gunion](#)], NMSDECAY [+ [Das & Teixeira](#)]

SPheno: [Porod & Staub](#); uses SARAH [[Staub](#)]

SoftSUSY: [Allanach, Grellscheid, Slavich, Williams, et al.](#)

FlexibleSUSY: [Athron, Park, Stöckinger & Voigt](#) (uses SARAH + SoftSUSY components)

Higgs decays: BSM tools

Other models: tremendous progress in past few years

Higgs Effective Theory (SM + dim-6 operator basis): decays

- eHDECAY [Contino, Ghezzi, Grojean, Mühlleitner, & Spira]

All relevant QCD corrections from HDECAY; EW corrections in compatible EFT basis

2HDM: spectrum + decays

- HDECAY [Djouadi, Kalinowski, Mühlleitner & Spira]
- 2HDMC [Eriksson, Rathsman & Stål]

Full QCD corrections taken over from SM/MSSM calcs. No EW corrs yet.

Georgi-Machacek model: spectrum, some decays [under construction]

- GMCALC [Kunal, Hartling, HEL]

Decays under construction: some QCD corrs, mostly on-shell. No EW corrs yet.

Higgs decays: open issues I: NLO electroweak

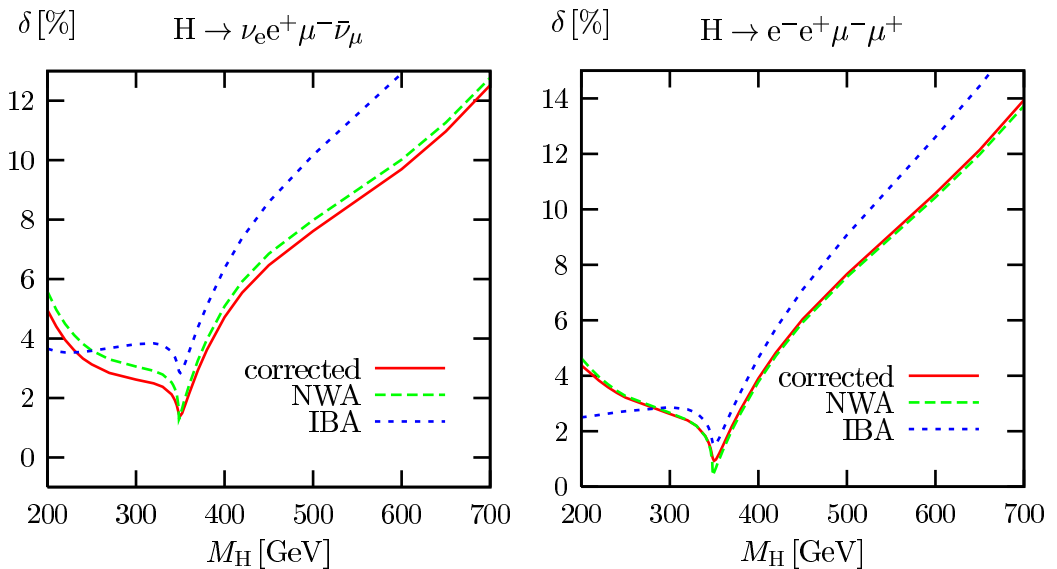
For *full* NLO EW, need full 1-loop EW renormalization of model.
MSSM+NMSSM include full 1-loop EW renorm for spectrum.

E.g., new NLO EW corrs to Higgs-to-SUSY decays in MSSM: 10–20%! [Heinemeyer, Fri]

For other models this is missing! → no NLO EW yet in codes

This is a big deal:
SM EW corrections to
 $H \rightarrow WW, ZZ$ up to 15%
for perturbative Higgs
quartic coupling.

Bredenstein, Denner, Dittmaier &
Weber, hep-ph/0604011



Progress in 2HDM: (4 Types, softly-broken Z_2)

On-shell renorm. scheme, complete set of $h(125)$ couplings

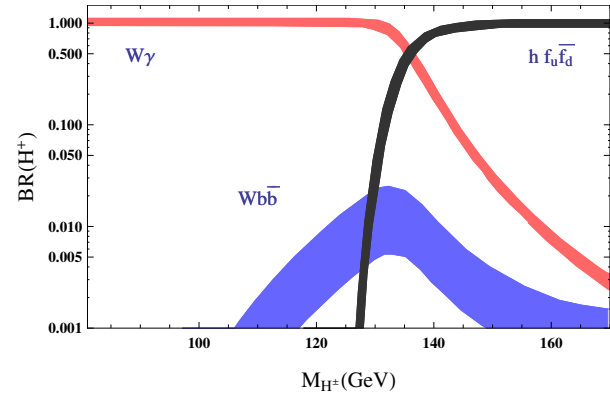
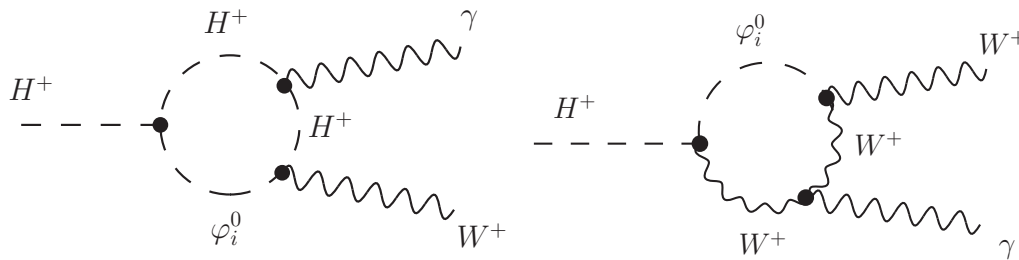
Kanemura, Kikuchi & Yagyu, 1502.07716

But no tools yet for full NLO EW in 2HDM production/decays

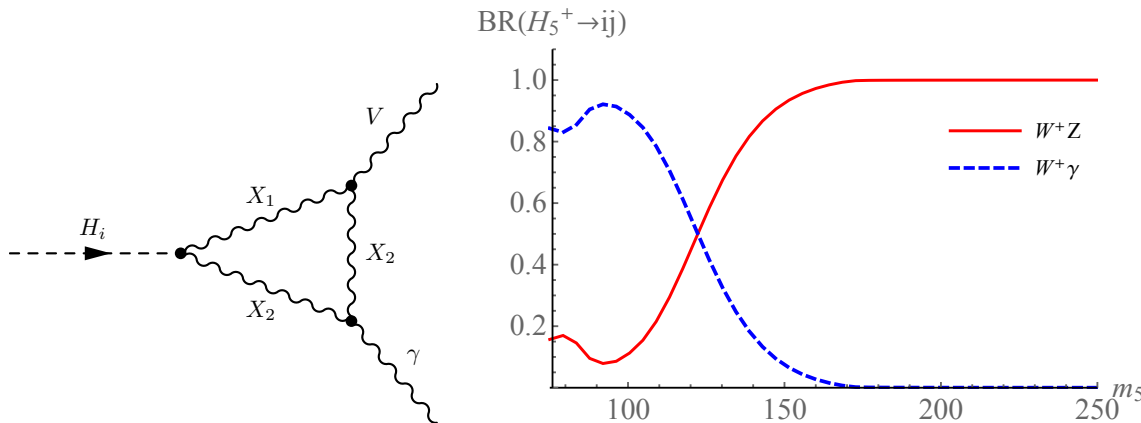
Higgs decays: open issues II: new loop decays

Loop-induced $H^+ \rightarrow W^+ \gamma$:

new loop structures not in Higgs Hunter's Guide!



Ilisie & Pich, 1405.6639 – fermiophobic H^+ in 2HDM

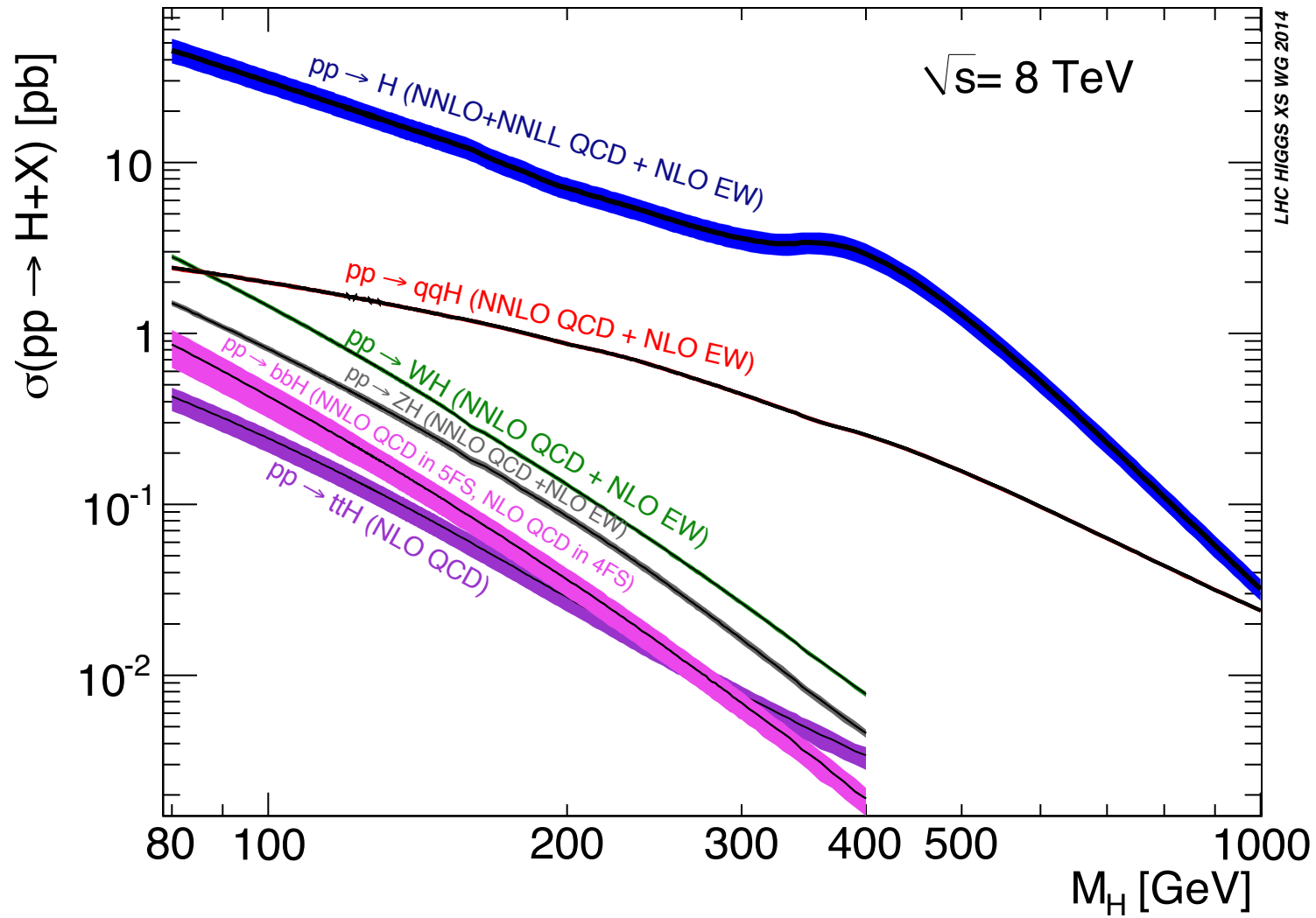


← VERY PRELIMINARY!

(no $H_5^+ \rightarrow W^+ h$ due to custodial symmetry)

Degrande, Hartling & H.E.L., in prep – custodial 5plet H_5^+ in Georgi-Machacek model

Higgs production: SM



Higgs production: BSM

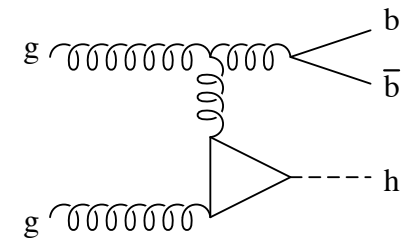
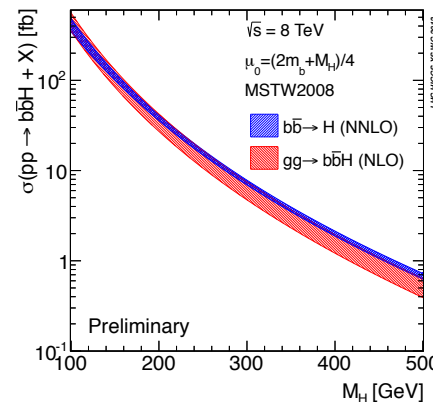
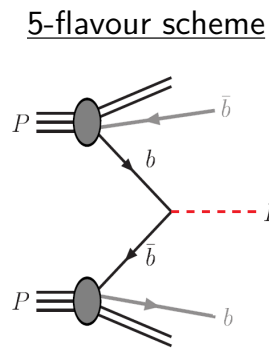
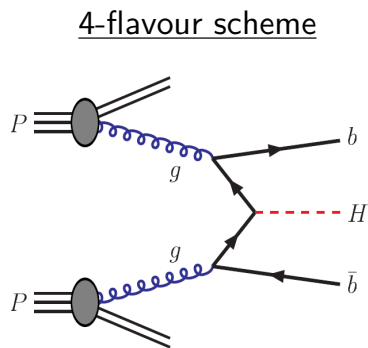
- ★ SM QCD corrections apply if there are no new colored particles:
 - (N)MSSM: must include gluino/squark diagrams
 - MSSM/2HDM large $\tan\beta$: $gg \rightarrow H^0$ b -loop NLO QCD only
- ★ SM EW corrections do NOT apply:
 - Must do full 1-loop EW renormalization of the model, or omit EW corrections entirely → theory uncertainty
 - Some subsets of EW corrections are safe to include by themselves:
 - e.g., light-quark contributions to $gg \rightarrow H_i$
- ★ Novel production processes → calculate from scratch:
 - Pseudoscalar production $gg \rightarrow A^0$ (done since long ago)
 - Charged Higgs production (via $\bar{t}bH^+$ vertex)
 - Custodial 5-plet production (VBF, VH_i) (triplet models)
 - Pair production (Drell-Yan) $q\bar{q} \rightarrow H_1H_2$

Higgs production: $pp \rightarrow H^0/A^0$

Gluon fusion:

- Dominates in SM, and whenever y_b is not significantly enhanced
- Main issue is at large $\tan\beta$ when b loop becomes sizable:
 - NNLO QCD corrections are known only in $m_t \rightarrow \infty$ limit
 - b -quark loop corrections only up to NLO QCD \rightarrow uncert

$b\bar{b}$ fusion:



Dawson, Jackson,
Reina & Wackerath,
hep-ph/0311067

M. Wiesemann, HXSWG mtg, July 2015

- Much recent effort for SM $h(125)$ production
- 4FS NLO: includes interference with $gg \rightarrow h + b\bar{b}$: terms $\propto y_t y_b$
- Santander matching procedure for unified prediction

Higgs production: $pp \rightarrow H^0/A^0$

Main codes in HXSWG framework:

- SusHi [Harlander, Liebler & Mantler, + Bagnaschi, Slavich, Vicini]
- HIGLU [Spira]
 - MSSM, NMSSM, 2HDM neutral Higgs production
 - Top loop to NNLO QCD, bottom loop to NLO QCD
 - Approx NNLO for top squarks; partial 2-loop involving $q/\tilde{q}/\tilde{g}$
 - Approx $\tan\beta$ -enhanced corrs (Δ_b , resummed)
 - partial NLO EW contrib'ns in (N)MSSM, 2HDM:
 - from light quarks (SusHi)
 - SM corrs rescaled by HWW/HZZ coups (HIGLU)
 - Spectrum calculations via interface to:
 - FeynHiggs and 2HDMC (SusHi)
 - FeynHiggs and HDECAY (HIGLU)

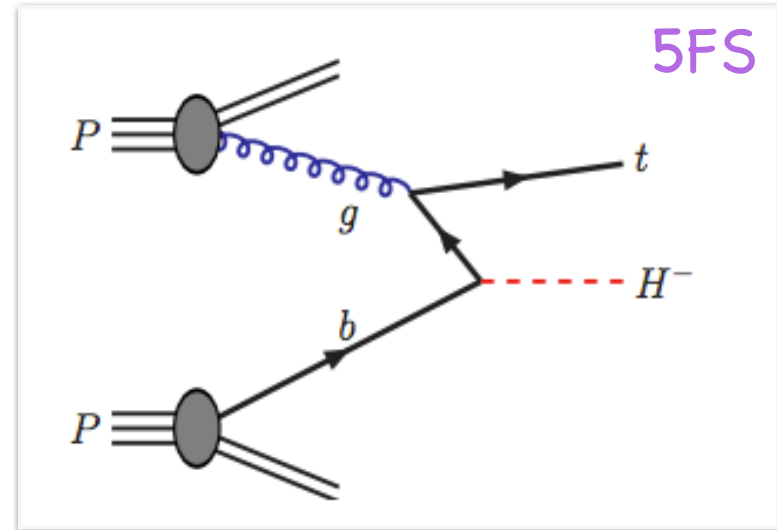
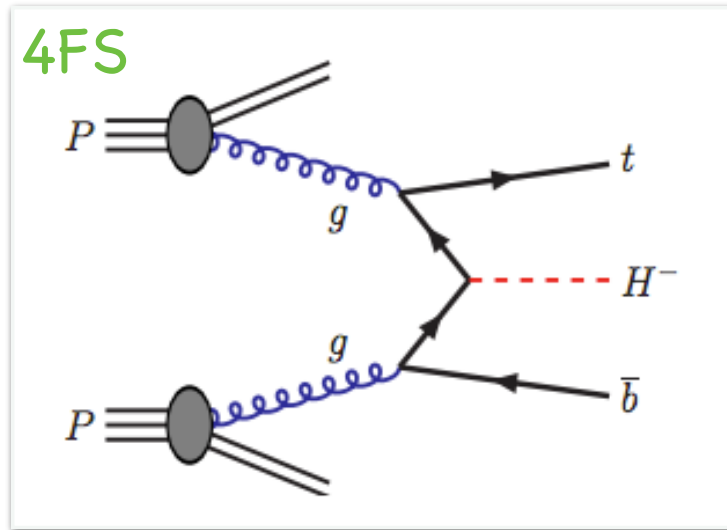
Comparison & recommendations for 2HDM:

Harlander, Mühlleitner, Rathsmann, Spira & Stål, 1312.5571

See also ggh@nnlo, bbh@nnlo, HNNLO, iHixs, POWHEG BOX

Higgs production: H^+ in MSSM

High mass range: very sophisticated treatment



- Fixed order NLO calculation (+ SUSY corrections)

Dittmaier et al., Phys. Rev. D83:055005 (2011)

- EW corrections

Nhung et al., Phys. Rev. D87:113006 (2013)

- Threshold resummation up to NNLL

- Fully differential NLO + PS computation

Degrande et al, arXiv:1507.02549 [MG5_aMCatNLO]

T. Plehn, Phys. Rev. D67:014018 (2003)

S. Zhu, Phys. Rev. D67:075006 (2003)

Berger et al, Phys. Rev. D71:115012 (2005)

Beccaria et al., Phys. Rev. D80:053011 (2009)

Kidonakis, Phys. Rev. D82:054018 (2010)

Weydert et al, Eur.Phys.J. C67 (2010) [MC@NLO]

Klasen et al, Eur.Phys.J. C72 (2012) [POWHEG]

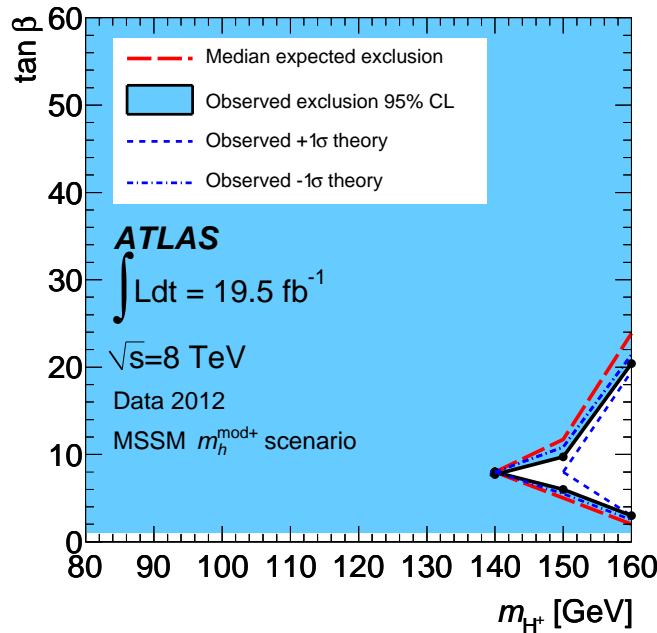
Degrande et al, arXiv:1507.02549 [MG5_aMCatNLO]

Unified prediction from Santander matching procedure

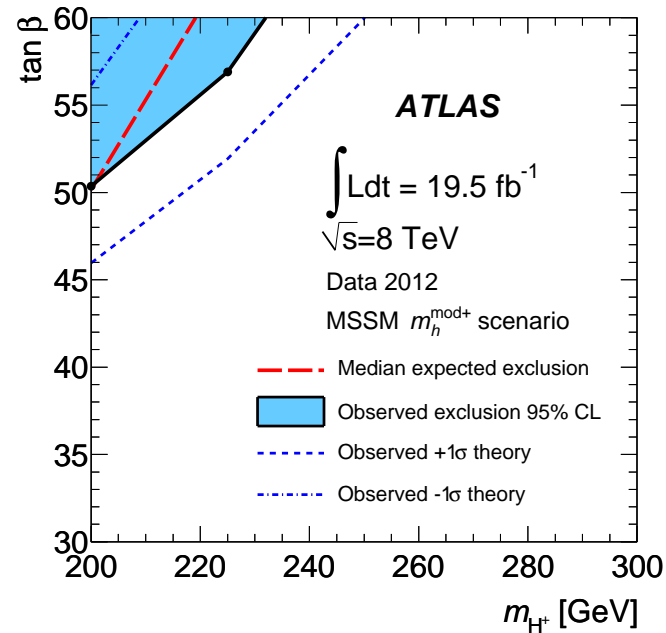
Slide from Maria Ubiali, 10th LHC HXSWG Workshop, July 2015

Higgs production: H^\pm in MSSM

Intermediate mass range: not studied in Run I!



\leftrightarrow



When $m_{H^\pm} \sim m_t$, width and interference effects are important: $t\bar{t}(\rightarrow H^- \bar{b})$ and direct $tH^-(\bar{b})$ diagrams contribute

Need Monte Carlo tool to simulate full $W^+ b H^-(b)$ signal process!

Work in progress by Degrande et al (MadGraph5_aMC@NLO group)

Higgs production: VBF

VBF@NNLO code

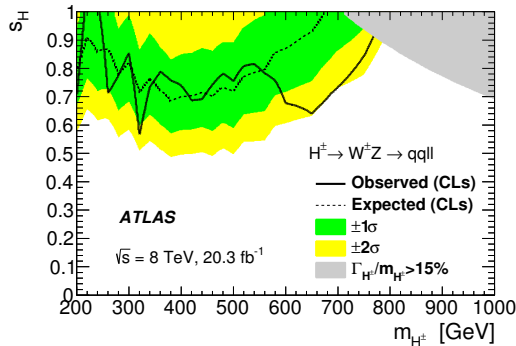
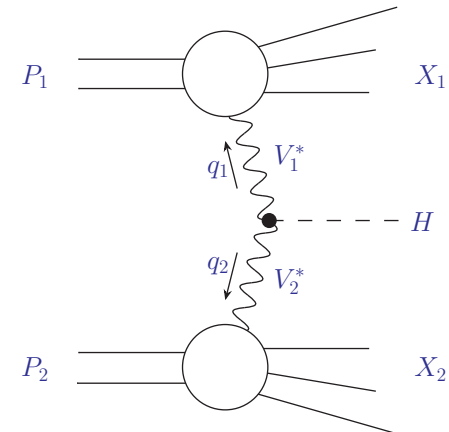
[Bolzoni, Maltoni, Moch & Zaro, 1003.4451, 1109.3717]

- Structure function approach: not full NNLO, but missing contributions $< 1\%$.

- Generic coupling structure:

$$\Gamma_{V_i V_j H}^{\mu\nu} = 2(\sqrt{2}G_F)^{1/2} M_i M_j F_{ij}(-ig^{\mu\nu}),$$

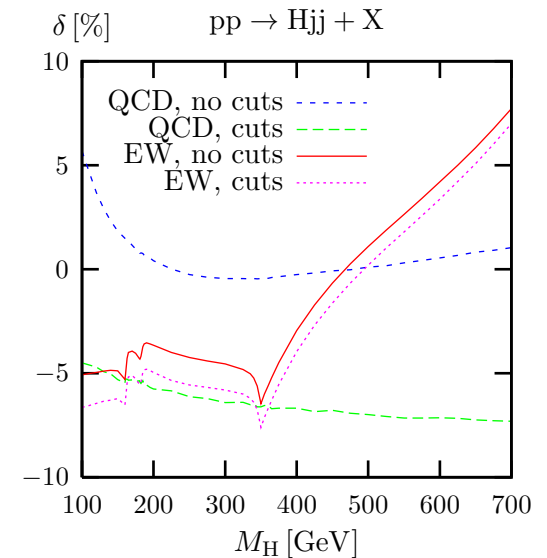
can also do $WZ \rightarrow H^+$, $WW \rightarrow H^{++}$:



relevant in Georgi-Machacek model

- Must exclude SM EW corrections: xsec uncertainty $\sim \mathcal{O}(7\%)$

SM: Ciccolini, Denner & Dittmaier, 0710.4749 (HAWK), 14 TeV LHC



Higgs production: VH

SM: WH/ZH known to NNLO QCD + NLO EW.

BSM: No dedicated tools that I know of.

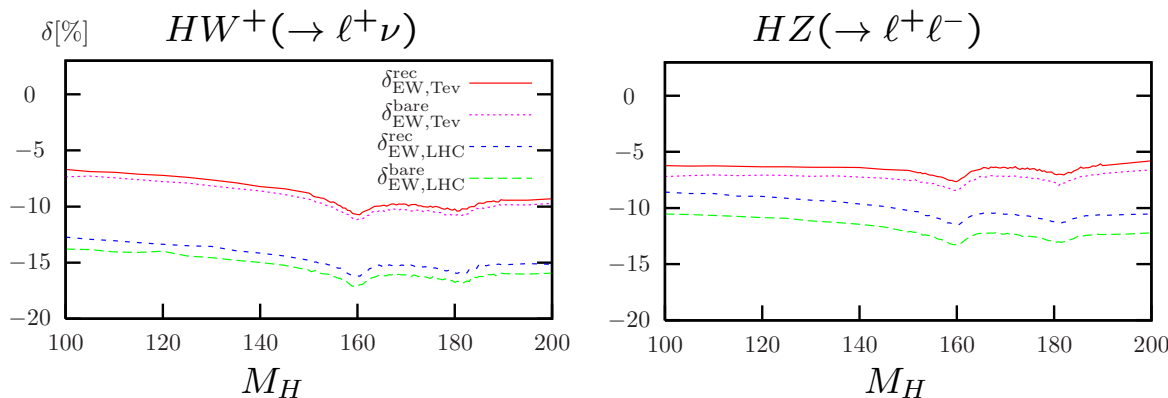
⇒ Automated NLO QCD via MadGraph5_aMC@NLO* Monte Carlo

*Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro, 1405.0301

Studies in progress, e.g., for $VH_5^{0,\pm,\pm\pm}$ in Georgi-Machacek model benchmark

EW corrections not included:

uncertainty $\sim \mathcal{O}(10 - 15\%)$ by comparison to SM



Sudakov logs
 $\ln(p^2/M_W^2)$
can give relatively
large EW
corrections

SM: Denner, Dittmaier, Kallweit, & Mück, 1112.5142 (HAWK), 7 TeV LHC

Higgs production: $H_1 H_2$ pairs

Drell-Yan style: e.g., $q\bar{q} \rightarrow Z^* \rightarrow H^+ H^-$, $q\bar{q}' \rightarrow W^* \rightarrow H^+ A^0$

Again no dedicated BSM tools that I know of.

Charged Higgs pair cross section at NLO QCD in private extension of Prospino2 [Plehn]

⇒ Automated NLO QCD via MadGraph5_aMC@NLO Monte Carlo

Studies in progress, e.g., for $H_5^{++} H_5^-$, etc. in Georgi-Machacek model benchmark

No EW corrections available:

expect uncertainties $\sim 10\text{--}15\%$ based on similar processes

Summary

Goals of LHC BSM Higgs program:

- Exclusion bounds \rightarrow constrain BSM model parameter space
- New Higgs discovery \rightarrow extract BSM model parameters

QCD *and* EW corr's to BSM Higgs prod'n/decay are **not small!**
Should be included to beat theory uncer'ts below the 10% level.

Model-specific **tools** are essential...

- spectrum calculation
- decay BRs
- [interface to] production xsec

... that can be used to specify **benchmarks**.

- benchmark planes currently best-loved by expts
- used to design searches to capture distinct model features

BACKUP SLIDES