EBERHARD KARLS UNIVERSITÄT TÜBINGEN

BSM Higgs pair production: charged Higgs pair and neutrino effects as case studies

CHARGED 2016, **Uppsala University, Uppsala, Sweden**

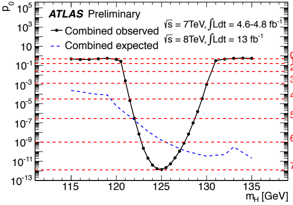
Julien Baglio | 06. 10. 2016

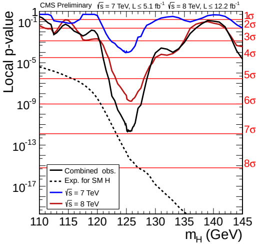
INSTITUT FÜR THEORETISCHE PHYSIK

Outline

Once upon a time...

4/7/2012: CERN presents the discovery of a bosonic particle
Its properties are compatible with those of the Higgs boson





$M_H \simeq 125$ GeV
[ATLAS, PLB 716 (2012) 1; CMS *ibid* 30]

2013 analyses have confirmed the discovery of a Higgs boson: spin 0, couplings to fermions and bosons as a function of their masses ⇒ 2013 Nobel Prize awarded to Englert and Higgs

Key question: what is the exact nature of the observed Higgs boson? Standard Model (SM)-like or more exotics?

Once upon a time...

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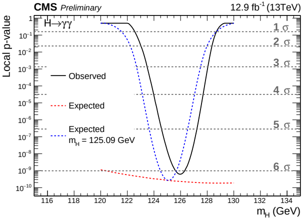
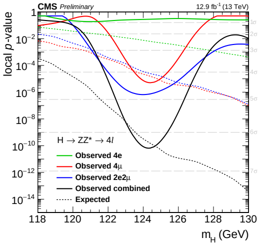
Observed again this year in 13 TeV data [CMS-PAS-HIG-16-020, CMS-PAS-HIG-16-033]





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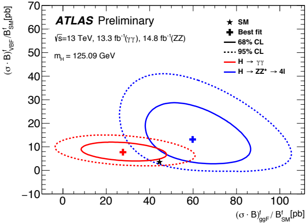
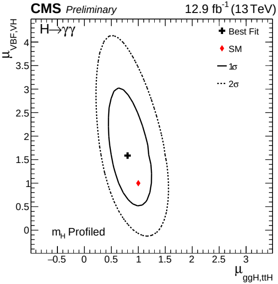
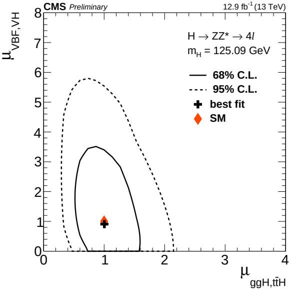
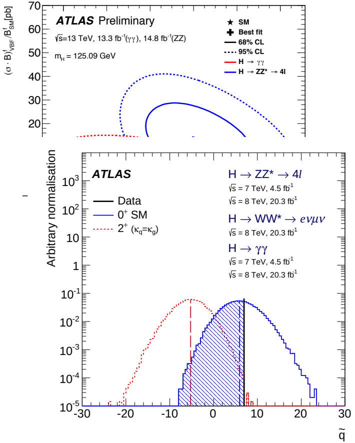
Coining the scalar boson

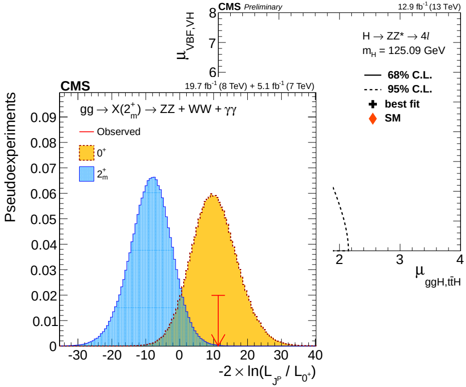




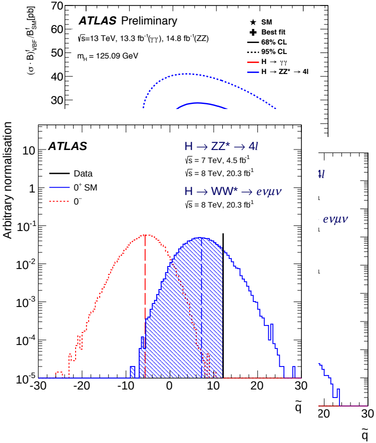


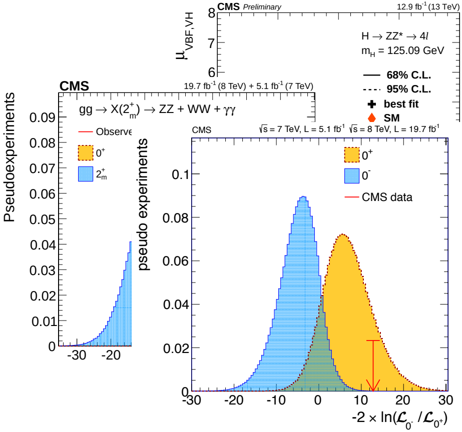
Coining the scalar boson





Coining the scalar boson





Coining the scalar boson

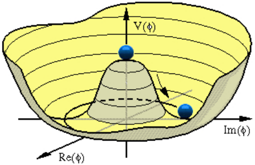
CP-even spin 0 hypothesis strongly preferred, no significant deviations from SM couplings: data up to now points toward an SM Higgs boson...

[ATLAS Collaboration, EPJC 75 (2015) 476, ATLAS-CONF-2016-081; CMS Collaboration, PRD 89 (2014) 092007, PRD 92 (2015) 012004, CMS-PAS-HIG-16-020, CMS-PAS-HIG-16-033]

The SM ultimate test: probing the scalar potential

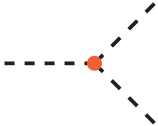
- **From the scalar potential before EWSB (ϕ as the Higgs field):**

$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$

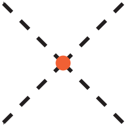


- **To $V(\phi)$ after EWSB, with $M_H^2 = 2m^2, v^2 = m^2/\lambda$:**

$$\phi = \begin{pmatrix} 0 \\ \frac{v + H(x)}{\sqrt{2}} \end{pmatrix} \Rightarrow V(H) = \frac{1}{2}M_H^2 H^2 + \mathbf{\frac{1}{2}\frac{M_H^2}{v}H^3} + \frac{1}{8}\frac{M_H^2}{v^2}H^4 + \text{constant}$$



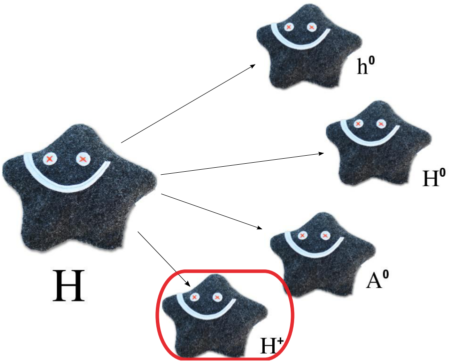
$$\frac{3M_H^2}{v} \times (-\imath)$$



$$\frac{3M_H^2}{v^2} \times (-\imath)$$

An extended Higgs sector?

Most models addressing beyond-the-SM (BSM) effects impact the Higgs sector



- **Two-Higgs-Doublet Models (2HDM)**: 2 CP-even Higgs bosons h^0, H^0, one CP-odd Higgs boson A^0, 2 charged Higgs bosons $H^\pm$
- **Popular example of 2HDM: minimal supersymmetric extension of the SM (MSSM)**, type II 2HDM where up-type (down-type) fermion couples to one doublet H_u (H_d)

Tree-level parameters for the charged Higgs bosons in the MSSM: M_A, $\tan\beta = \dfrac{v_u}{v_d}$

Charged Higgs pair production at the LHC

Disclaimer

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- **Focus in this section: theoretical predictions for charged Higgs pair production H^+H^-:** may help to measure the triple Higgs couplings hH^+H^- and HH^+H^-

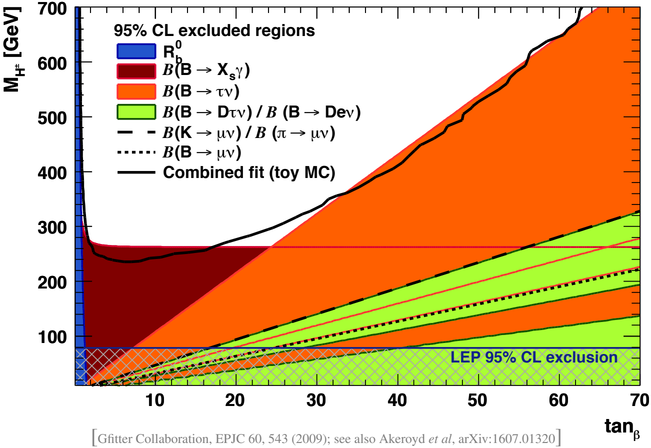
- **Framework of the presentation: 2HDM and in particular of type II (MSSM)** [Branco *et al*, Phys.Rept. 516 (2012) 1]

- **Only LHC discussed**; but many results exist for linear colliders in the literature [see for example in the last years Sonmez, arXiv:1601.01837; Ahmed, Hashemi, arXiv:1502.06445; Hashemi, Commun.Theor.Phys. 61 (2014) 69; see also the complete 1-loop calculation of $e^+e^- \to H^+H^-$ in Guasch, Hollik, Kraft, Nucl.Phys. B 596 (2001) 66]

- No experimental results will be shown (to the best of my knowledge, no results about H^+H^- production at the LHC yet)

Current limits on the charged Higgs bosons $H^{\pm}$

Constraints from precision physics in type II 2HDM:



[Gfitter Collaboration, EPJC 60, 543 (2009); see also Akeroyd *et al*, arXiv:1607.01320]

+ inclusion of higher-order corrections in $B \to X_s \gamma$ [Enomoto, Watanabe, JHEP 1605 (2016) 002]

$\Rightarrow$ more stringent limit $\Rightarrow M_{H^\pm} \geq 480$ GeV [Misiak *et al*, PRL 114 (2015) 221801]

Current limits on the charged Higgs bosons $H^{\pm}$

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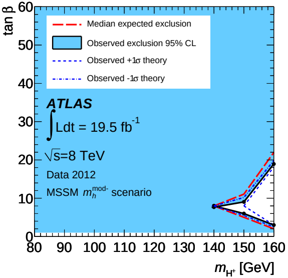
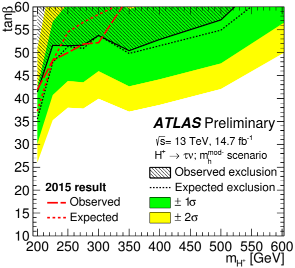
- **$H^{\pm}$ searches at LEP:** robust lower bound $M_{H^{\pm}} \gtrsim 80$ GeV in 2HDM of type II (MSSM-like) [LEP Higgs Working Group, EPJC 73 (2013) 2463]
- **Tevatron searches:** improved limits based on model assumptions, see [CDF & DO, PoS CHARGED2010 (2010) 004]
- **Limits from LHC searches:**

  → Run I data supersedes model-dependent limits from Tevatron, e.g. in an $m_h^{\text{mod}-}$-scenario, $M_{H^{\pm}} < 140$ GeV excluded [ATLAS, JHEP 03 (2015) 088]

  → Run II searches improve limits in the high-mass range, see [ATLAS-CONF-2016-088, ATLAS-CONF-2016-089, CMS-PAS-HIG-16-030]

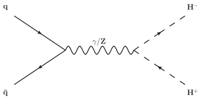




Limits weaker for type I 2HDM (only 1 doublet couples to all fermions), for example only $M_{H^{\pm}} \gtrsim 72.5$ GeV from LEP, $B \to X_s\gamma$ constraint does not apply

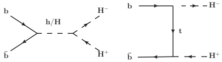
The main production channels

- Drell-Yan production



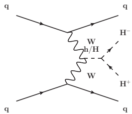
NLO in QCD

- Bottom quark fusion

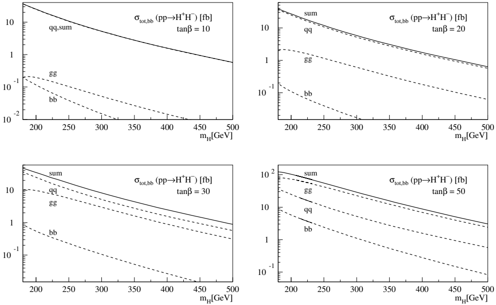


NLO in QCD

- Vector boson fusion

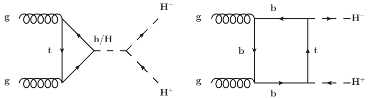


LO in QCD



2HDM of type II in [Alves, Plehn, PRD 71 (2005) 115014]

- Gluon fusion



LO in QCD

small cross sections ⇒ high $\mathcal{L}$ needed
(except when resonant production)

Drell-Yan production at NLO

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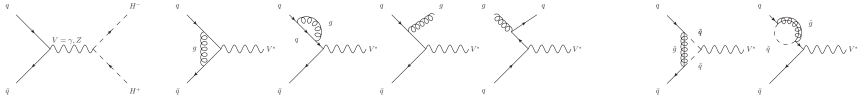
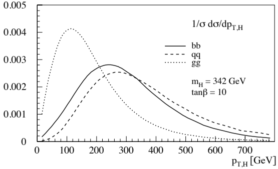
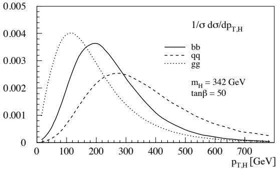
Drell-Yan (DY) production $pp \to q\bar{q} \to H^+H^-$: the largest cross section at low tan β



- **LO calculation:** first calculations in the 80's in the 2HDM/MSSM
  $\to$ From e^+e^- to $q\bar{q}$ [Lane, eConf C8206282 (1982) 222; Eichten *et al*, Rev.Mod.Phys. 56 (1984) 579]
  $\to$ Recalculated and corrected [Eichten *et al*, Rev.Mod.Phys. 58 (1986) 1065; Deshpande, Tata, Dicus, PRD 29 (1987) 1527]
  $\to$ Calculation reproduced later [Barrientos Bendezú, Kniehl, Nucl.Phys. B568 (2000) 305; Aoki *et al*, PR 84 (2011) 055028]
- **NLO QCD corrections:** usual DY corrections, $+27\,\%$ ($+17\,\%$) correction for $M_{H^\pm} = 160(500)$ GeV [Djouadi, Spira, PRD 62 (2000) 014004; Alves, Plehn, PRD 71 (2005) 115014] included in `Prospino2` (on request to the authors); SUSY-QCD corrections in the MSSM case negligible [Djouadi, Spira, PRD 62 (2000) 014004]





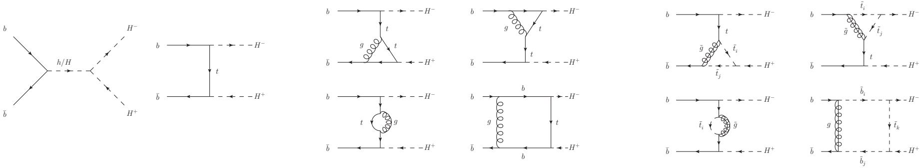
$\to$ Prediction independent on tan β
$\to$ Scale uncertainty $\sim \pm 25\,\%$
$\to$ dominant channel for tan $\beta \lesssim 30$

σ = 58 fb	for $M_{H^\pm}$ = 160 GeV
0.23	500

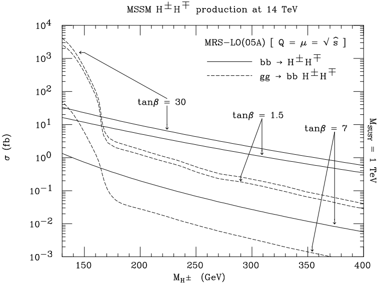
[Alves, Plehn, PRD 71 (2005) 115014]

Bottom quark fusion $b\bar{b} \to H^+H^-$ at NLO

Additional DY process, DY Feynman diagrams + new ones:



- **LO calculation, the b-parton problem:** b–quark in the proton from $g \to b\bar{b}$ splitting $\Rightarrow$ either direct $b\bar{b} \to H^+H^-$ production [Barrientos Bendezú, Kniehl, Nucl.Phys. B568 (2000) 305; Moretti, J.Phys.G 28 (2002) 2567] or twin process $gg \to H^+H^-b\bar{b}$ [Moretti, J.Phys.G 28 (2002) 2567; Moretti, Rathsman, EPJC 33 (2004) 41]

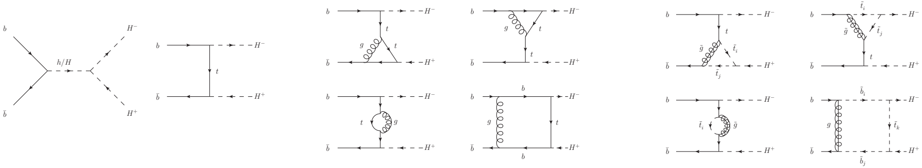


$\to$ Direct production one order of magnitude larger! [Moretti, J.Phys.G 28 (2002) 2567]

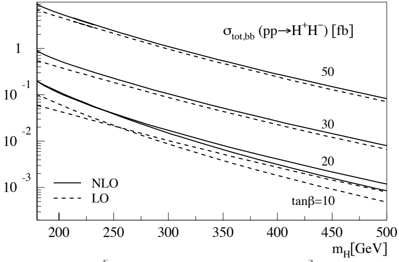
$\to$ Key issue: $\log(\mu_F/m_b)$–terms resummed in the b-parton picture could overestimate σ if μ_F big
$\Rightarrow$ what choice for μ_F?

Bottom quark fusion $b\bar{b} \to H^+H^-$ at NLO

Additional DY process, DY Feynman diagrams + new ones:



- **NLO (SUSY-)QCD correction solve the issue:**



[Alves, Plehn, PRD 71 (2005) 115014]

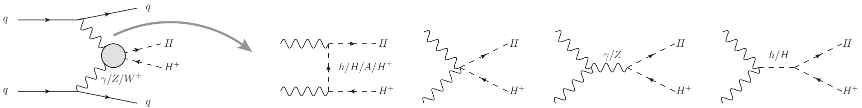
→ correct choice is $\mu_F = M_{H^\pm}/2$, stable and confirm the validity of the b–parton picture
[Hong-Sheng *et al*, PRD 71 (2005) 075014; Alves, Plehn, PRD 71 (2005) 115014]

→ $\sim +55\,\%$ correction (in 2HDM), scale uncertainty $\sim \pm 25\,\%$ [Alves, Plehn, PRD 71 (2005) 115014], tan β–dependent σ

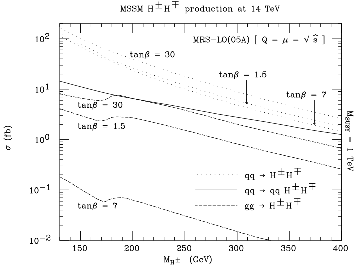
→ SUSY-QCD corrections dominated by negative resummed Δ_b–term, dependent of the MSSM spectrum
[Hong-Sheng *et al*, PRD 71 (2005) 075014; Alves, Plehn, PRD 71 (2005) 115014]

Vector boson fusion production at LO

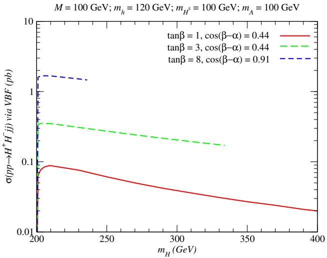
$pp \to qq' \to qq'H^+H^-$: usually the second production channel at the LHC



- First approximate calculation in the 80's for the 40 TeV Superconducting Super Collider [Éboli *et al*, PRD 37 (1987) 837]
- **LO calculation in the MSSM:** total cross section and distributions, $\sigma \sim 1 - 10$ fb with no visible $\tan\beta$ dependence [Moretti, J.Phys.G 28 (2002) 2567]
- **LO recalculated in the 2HDM:** resonant effects possible to obtain cross-sections at the pb level [Aoki *et al*, PRD 84 (2011) 055028], $\tan\beta$-dependent



[Moretti, J.Phys.G 28 (2002) 2567]



[Aoki *et al*, PRD 84 (2011) 055028]

Gluon fusion production $gg \to H^+H^-$ at LO

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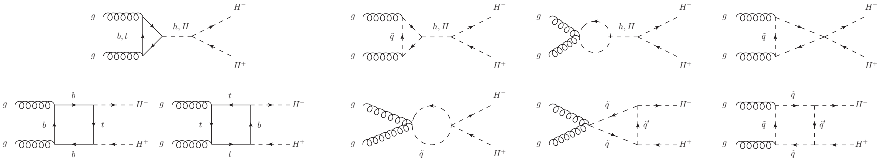

- **Earliest calculations in the 80's:**
  → 2HDM approximate, triangle quark loop [Eichten *et al*, FERMILAB-CONF-84-076-T (1984)]
  → Exact calculation of triangle quark loop + infinite quark/squark limit in the box loop (MSSM) [Willenbrock, PRD 35 (1987) 173] and in the 2HDM of type I/II [Foot, Lew, Joshi, PRD 37 (1988) 3161]

- **Path to the exact LO calculation:**
  → Exact quark loop in general 2HDM [Yi et al, J.Phys.G 23 (1997) 385, Erratum-*ibid* 23 (1997) 1151]
  → Exact quark loop in MSSM, squark loops neglected, correct errors in previous Ref. above [Krause, Plehn, Spira, Zerwas, Nucl.Phys.B 519 (1998) 85]

- **Exact LO calculation (MSSM/2HDM):** triangle+box loops with finite quark/squark masses [Yi et al, J.Phys.G 24 (1998) 83; Brein, Hollik, EPJC 13 (1999) 175; Barrientos Bendezú, Kniehl, Nucl.Phys. B568 (2000) 305]; see also [Hirschi, Mattelaer, JHEP 1015 (2015) 146] for 2HDM including parton-shower

Gluon fusion production $gg \to H^+H^-$ at LO

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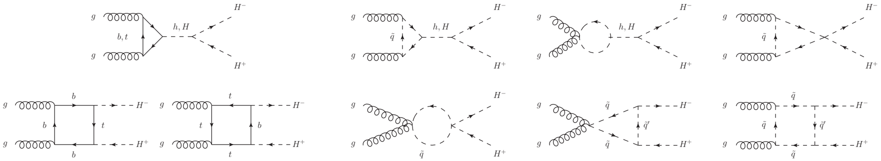
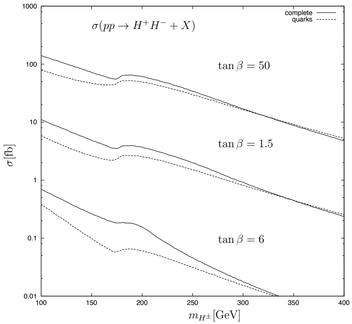




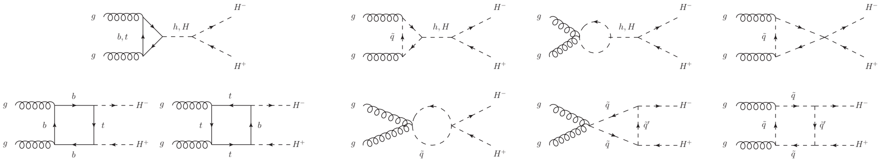
$M_{\tilde{q}} = 200$ GeV [Brein, Hollik, EPJC 13 (1999) 175]

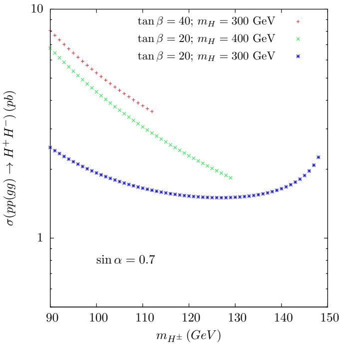
→ Large enhancement due to squark loops in the MSSM, dominant channel for $\tan\beta \gtrsim 50$

→ Scale uncertainty estimated to be $\sim \pm 50\,\%$
[Alves, Plehn, PRD 71 (2005) 115014]

→ Depending on MSSM parameters and $M_{H^\pm}$, can reach ~ 200 fb at high $\tan\beta$

Gluon fusion production $gg \to H^+H^-$ at LO





[Aoki *et al*, PRD 84 (2011) 055028]

→ Resonant enhancement possible in 2HDM (especially type I)

→ Cross section can reach ∼ 10 pb
[Aoki *et al*, PRD 84 (2011) 055028]

→ Very important to probe hH^+H^- and HH^+H^- couplings

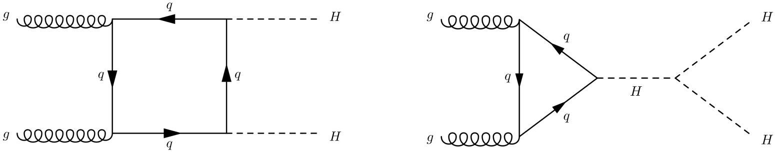
Neutrino effects on the triple Higgs coupling

[based on J.B., C. Weiland, PRD 94 013002 (2016)]

Neutrino impact on Higgs properties – motivation

- **Neutrino oscillations:** observed experimentally in 1998 [Super-Kamiokande, PRL 81 (1998) 1562]
  $\Rightarrow$ neutrinos are massive! $\Rightarrow$ new physics required to account for their mass
- ***HH* production:** one of the main motivation for high-luminosity LHC and future colliders
  $\Rightarrow$ need to study the impact of BSM on λ_{HHH} $\Rightarrow$ impact of heavy neutrino(s) on λ_{HHH}?

Experimental prospects for the sensitivity to λ_{HHH}



- HL-LHC: $\sim$ 50 % for ATLAS or CMS [CMS-PAS-FTR-15-002]
  $\sim$ 35 % combined
- ILC: 27 % at 500 GeV with 4 ab^{-1} [Fujii *et al*, arXiv:1506.05992]
  10 % at 1 TeV with 5 ab^{-1}
- FCC-hh: 8 % per experiment with 3 ab^{-1} using only $b\bar{b}\gamma\gamma$ [Je, Ren, Yao, PRD 93 (2016) 015003]
  $\sim$ 5 % combining all channels

SM 1-loop corrections

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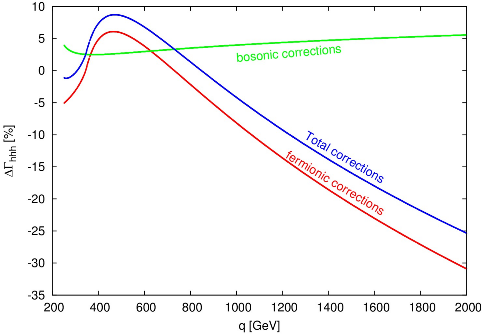

taken from [Arhrib *et al*, JHEP 12 (2015) 007]

- tree-level: $\lambda^0_{HHH} = -\frac{3M_H^2}{v}$
- Dominant contribution from top-quark loops [Kanemura *et al*, PRD 70 (2004) 115002]

$$\lambda_{HHH}(q^2, m_H^2, m_H^2) = -\frac{3m_H^2}{v}\left[1 - \frac{1}{16\pi^2}\frac{16m_t^4}{v^2 m_H^2}\times\left\{1 + \mathcal{O}\left(\frac{m_H^2}{m_t^2}, \frac{q^2}{m_t^2}\right)\right\}\right]$$

- Opposite sign for the threshold ($\sqrt{q^2} = 2m_t$) and m_t^4 contributions

Simplified 3+1 Dirac model

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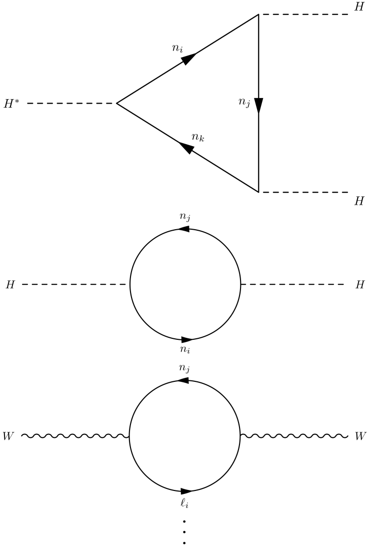
- A well-known class of renormalizable models for neutrino (ν) mass: seesaw models
  $\rightarrow$ To simplify the study of low-scale seesaw effects from a heavy ν: Simplified models

- Simplified model with 3 light ν ($m_n = 1\,\mathrm{eV}$) and 1 heavy sterile ν (m_4) parametrized by ν masses and mixing B_{ij}

$$\begin{aligned}
\mathcal{L} \ni & -\frac{g_2}{\sqrt{2}}\bar{\ell}_i \not{W}^- B_{ij} P_L n_j - \frac{g_2}{\sqrt{2}M_W}\bar{\ell}_i G^- B_{ij}(m_{\ell_i} P_L - m_{n_j} P_R) n_j + \text{h.c.} \\
& - \frac{g_2}{2M_W}\bar{n}_i C_{ij} H (m_{n_i} P_L + m_{n_j} P_R) n_j + \frac{\imath g_2}{2M_W}\bar{n}_i C_{ij} G^0 (-m_{n_i} P_L + m_{n_j} P_R) n_j \\
& - \frac{g_2}{2\cos\theta_W}\bar{n}_i \not{Z} C_{ij} P_L n_j
\end{aligned}$$

where $\quad B = R_{34} R_{24} R_{14} \tilde{U}_{PMNS}\,, \quad C_{ij} = \sum_{k=1}^{3} B^*_{ki} B_{kj}\,, \quad G^0/G^\pm$ Goldstone bosons,
$\tilde{U}_{PMNS}$ Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix extended to 4 neutrinos,
R_{ij} rotation matrices

New contributions and constraints



- Heavy ν generates new 1-loop diagrams and new counterterms
- Strongest experimental constraints on n_4: Electroweak precision observables

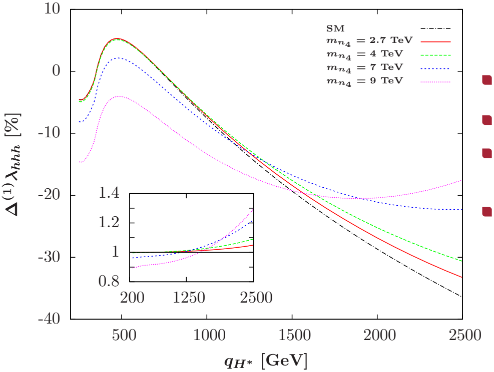
$$|B_{e4}| \leq 0.041$$
$$|B_{\mu 4}| \leq 0.030$$
$$|B_{\tau 4}| \leq 0.087$$

- Loose (tight) perturbativity bound:

$$\left(\frac{\max|C_{i4}|\, g_2\, m_{n_4}}{2M_W}\right)^3 < 16\pi\ (2\pi)$$

- Width limit: $\Gamma_{n_4} \leq 0.6\, m_{n_4}$

Numerical results I



- $\Delta^{(1)}\lambda_{HHH} = \frac{1}{\lambda^0}\left(\lambda^{1r}_{HHH} - \lambda^0\right)$
- $B_{\tau 4} = 0.087, B_{e4} = B_{\mu 4} = 0$
- Deviation of the BSM correction with respect to the SM correction in the insert
- $C_{44} m_{n_4} = m_t \Rightarrow m_{n_4} = 2.7\,\text{TeV}$
  tight perturbativity bound: $m_{n_4} = 7\,\text{TeV}$
  width bound: $m_{n_4} = 9\,\text{TeV}$

- Largest positive correction at $q_H^* \simeq 500\,\text{GeV}$, heavy ν decreases it
- Large negative correction at large q_H^*, heavy ν increases it

Numerical results II

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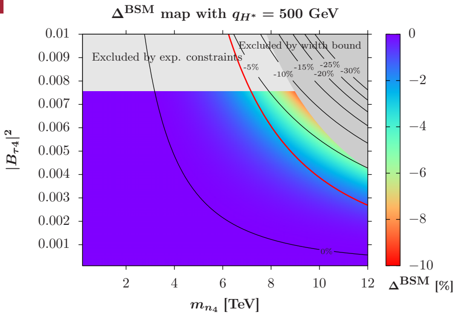

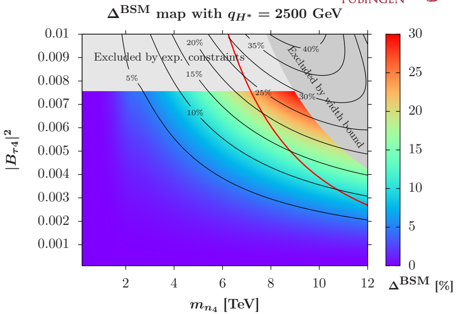

- $\Delta^{\mathrm{BSM}} = \frac{1}{\lambda_{HHH}^{1r,\mathrm{SM}}}\left(\lambda_{HHH}^{1r,\mathrm{full}} - \lambda_{HHH}^{1r,\mathrm{SM}}\right)$
- Red line: tight perturbativity bound
- Heavy ν effects at the limit of HL-LHC sensitivity (35 %)
- Heavy ν effects clearly visible at the ILC (10 %) and FCC-hh (5 %)
- Similar plots for B_{e4} and $B_{\mu 4}$

Conclusion and outlook

HH production at hadron colliders: One of the major goals for the LHC run II and the future colliders

- **Major news since 2012:** Higgs boson observed, now the next big questions:

  Is it standard or a first window on BSM physics?
  Is there an extended Higgs sector, with charged Higgs bosons?

- **The Higgs frontier at the high luminosity LHC:** the measure of the triple Higgs coupling(s) to probe directly the scalar potential

- **H^+H^- production status:** most recent overview study in 2HDM in [Aoki *et al*, PRD 84 (2011) 055028], prospects at 30 fb^{-1} given this year in [Akeroyd *et al*, arXiv:1607.01320]
  $\rightarrow$ Main production channel at low $\tan\beta$: Drell-Yan, known at NLO (SUSY-)QCD
  $\rightarrow$ Additional $b\bar{b}$ channel known at NLO QCD + dominant NLO SUSY-QCD corrections (MSSM)
  $\rightarrow$ VBF and gluon fusion known at LO (SUSY-)QCD $\Rightarrow$ precision may be improved

- **Neutrino effects on the triple Higgs coupling:**
  Corrections as large as 30 % $\Rightarrow$ measurable at future colliders
  $\rightarrow$ Probe neutrino mass regime hard to access otherwise
  $\rightarrow$ Larger effects expected with additional heavy neutrinos
  (work in progress in the inverse seesaw)

Thanks for your attention!