The Next-to-Minimal Supersymmetric Standard Model at the LHC

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Motivation for the NMSSM

The supersymmetric Higgs/higgsino mass term $\mu H_u H_d$ of the MSSM is replaced by a Yukawa coupling $\lambda S H_u H_d$ (+ a self interaction $\frac{\kappa}{3} S^3$) to a gauge singlet superfield S: $\mu H_u H_d \to \lambda S H_u H_d + \frac{\kappa}{3} S^3$

$\longrightarrow$ all supersymmetric interactions are scale invariant (see the talk by A. Linde), the Susy breaking scale is the only explicit mass scale which generates the electroweak symmetry breaking scale

S assumes a vev "s" of the order of the Susy breaking scale

$\longrightarrow$ an effective μ-term $\mu_{eff} = \lambda s$ is generated

$\longrightarrow$ the Grand Unification of the gauge couplings and the possibility to explain the dark matter by a LSP are preserved

The scalar and fermionic components of S mix with H_u and H_d and the neutralinos proportional to the Yukawa coupling λ

$\longrightarrow$ if λ (and κ) are small: "decoupling limit", one is left with an effective MSSM + decoupled singlets (possibly with a singlino LSP)

$\longrightarrow$ if λ is large: possible phenomenological consequences in the
— CP-even Higgs sector
— CP-odd Higgs sector
— neutralino sector
(depending on λ, κ, soft Susy breaking terms)

The cNMSSM

A simple scenario for Susy breaking is spontaneous Susy breaking in a hidden sector in supergravity, minimal Kähler potential and gauge kinetic terms: "mSUGRA"

$\longrightarrow$ universal scalar masses m_0, trilinear couplings A_0 and gaugino masses $M_{1/2}$ at the GUT/Planck scale

In the cNMSSM (A. Djouadi, U. E., A. M. Teixeira): m_0 must be small such that S can assume a vev, since m_S^2(weak scale) $\sim m_0^2$

$\longrightarrow$ in the cMSSM, small m_0 would generate an unacceptable stau LSP $\tilde{\tau}_1$

$\longrightarrow$ in the cNMSSM, the singlino-like neutralino must be the LSP with a mass just below ($\sim$ 5 GeV) the stau NLSP mass in order to give the correct dark matter relic density via coannihilation

Then: the complete sparticle spectrum is fixed by $M_{1/2}$

Impact on sparticle decay cascades

The singlino-like LSP χ_1^0 couples weakly to the MSSM-like sparticles
$\longrightarrow$ all sparticles decay first into the stau NLSP $\tilde{\tau}_1$, which decays subsequently into the singlino LSP χ_1^0 as

$$\begin{array}{ccccccc} \cdots & \longrightarrow \chi_2^0 & \longrightarrow & \tilde{\tau}_1 & \longrightarrow & \chi_1^0 \\ & & \searrow & & \searrow & \\ & & & \tau & & \tau \end{array}$$

$\longrightarrow$ $\gtrsim$ 4 τ-leptons in each Susy event!

Energy of the first τ: $M_{\chi_2^0} - M_{\tilde{\tau}_1} \gtrsim$ 60 GeV
Energy of the second τ: $M_{\tilde{\tau}_1} - M_{\chi_1^0} \lesssim$ 5 GeV, hardly visible

From LEP constraints on the Higgs and $\tilde{\tau}_1$ masses:
$M_{1/2} \gtrsim 500$ GeV $\rightarrow$ squark, gluino masses $\gtrsim$ 1 TeV

$\longrightarrow$ Squark and gluino production remains the dominant sparticle production process at the LHC (with $\lesssim$ 1 pb cross section, $M_{Squark} \lesssim M_{Gluino}$!)

Is the cNMSSM visible at the LHC?

Signal-, background- and detector simulations, dedicated cuts:

(With A. Florent, D. Zerwas, T. Plehn, results are preliminary)

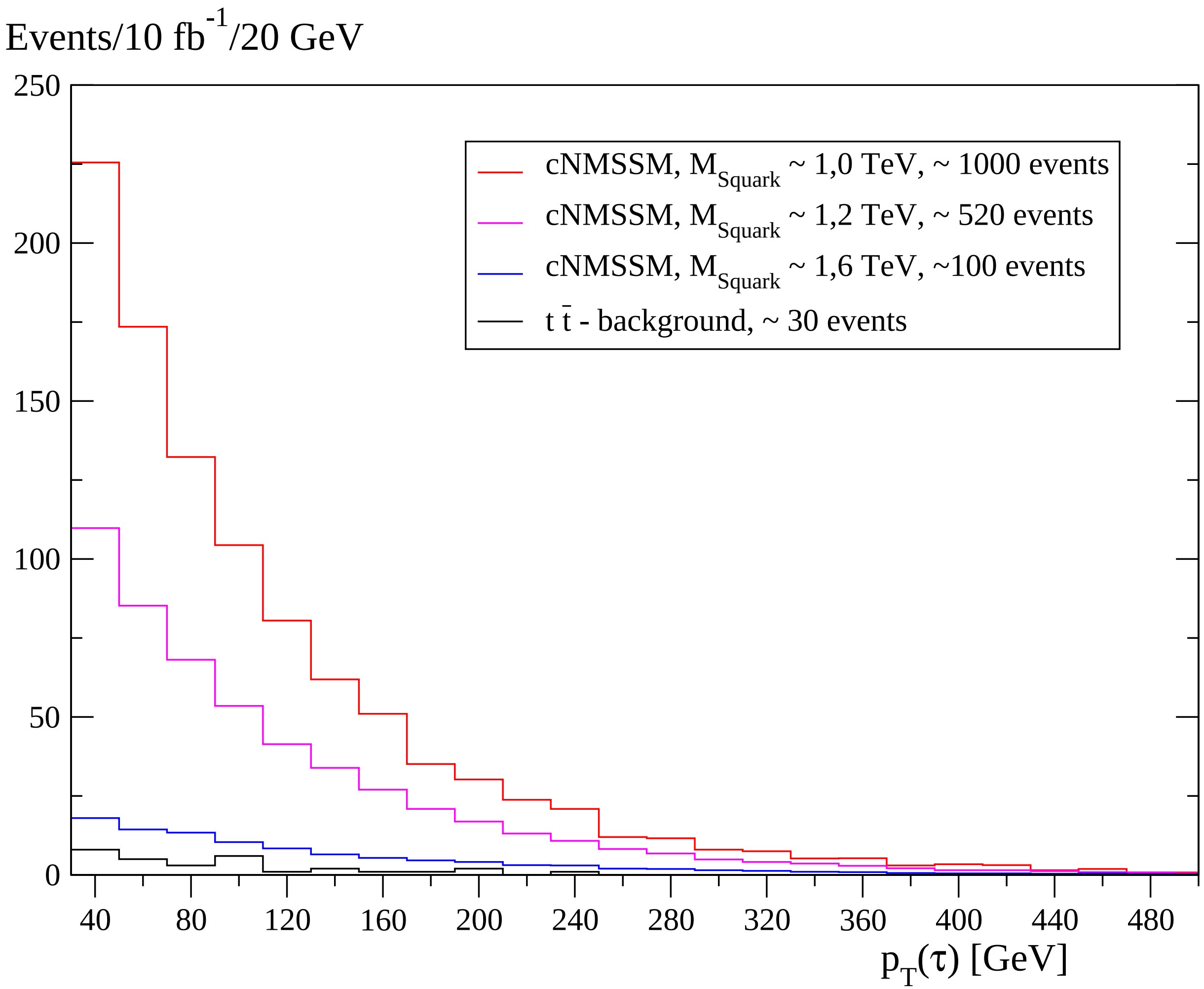
— Signal and $t\bar{t}$-background simulation: PYTHIA6.4 + TAUOLA
— W, Z, WW + jets backgrounds: ALPGEN + PYTHIA
— Detector: AcerDet
— Efficiencies for Susy searches in 4 jet/τ modes are reproduced

Cuts:

— $E_T(miss) > 300$ GeV
— $p_T(jet1, 2) > 300, 150$ GeV (hard!)
— $\phi(\vec{E}_T(miss),\ \vec{p}_T(jet)) > 0.2$ (reduces detector effects)
— 1 τ-lepton with $p_T > 30$ GeV $\rightarrow \sim 40\%$ efficiency on hadronic τ decays
— $M_{Trans}(\vec{p}_T(\tau),\ \vec{E}_T(miss)) > 100$ GeV reduces τ-leptons from W-decays (notably $t\bar{t}$-background)

$\longrightarrow$ $\sim 7-10\%$ efficiency on the signal (~ 1000 events/10 fb^{-1})
$\longrightarrow$ ~ 30 events/10 fb^{-1} from $t\bar{t}$-background, less from W+jets
$\longrightarrow$ practically no background from WW+(2-4) jets, Z+jets, QCD+τ-fakes

$p_T(\tau)$-spectrum for various cNMSSM-points:



→ Looks promising!

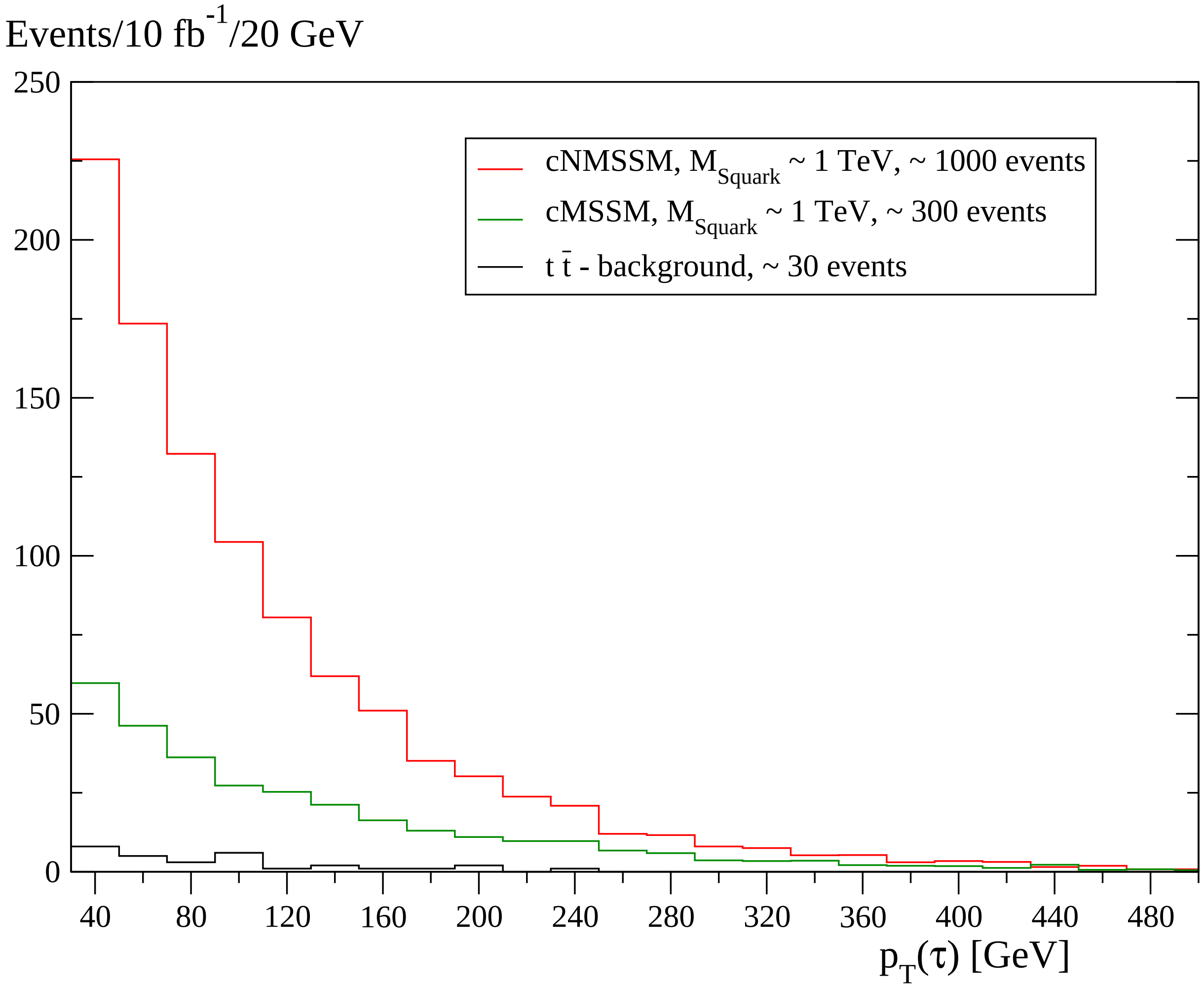
τ-rich Susy events exist also in the cMSSM coannihilation region (where the bino-like χ_1^0 relic density is reduced to an acceptable level via $\chi_1^0 - \tilde{\tau} -$ coannihilation)

Can this "cMSSM" be distinguished from the cNMSSM?

Note: less τ's per event in the cMSSM, since $\tilde{q} \to \chi_1^0 + q$ decays (without $\tilde{\tau}$) are possible

Study of a cMSSM with similar squark/gluino masses as the NMSSM, which gives similar distributions for p_T(jets), $E_T(miss)$ (not shown here):

$p_T(\tau)$-spectrum for the cNMSSM vs. the cMSSM:



$\rightarrow$ less events above $p_T(\tau) > 30$ GeV than in the cNMSSM!

Back to the cNMSSM with $M_{Squark} \sim 1$ TeV:

Present run at a c.m. energy of 7 TeV and an integrated luminosity of 1 fb^{-1}:

Require 2 jets with $p_T > 50,\ 20$ GeV, $E_T^{miss} > 200$ GeV, $p_T(\tau) > 10$ GeV

$\longrightarrow$ $\sim$ 5-6 signal events, ~ 2 from $t\bar{t}$ background

$\longrightarrow$ we could get a hint, if we are lucky...

The Higgs sector

Recall: MSSM: Two CP-even Higgs bosons h, H
One CP-odd Higgs boson A
One charged Higgs boson $H^{\pm}$

Typically:
h is SM-like $\leftrightarrow$ $\xi_h \equiv \frac{g_{hWW}}{g_{H(SM)WW}} \sim 1$, $M_h \lesssim 135$ GeV (max. for large $\tan\beta$)

NMSSM: Three CP-even Higgs bosons H_1, H_2, H_3
Two CP-odd Higgs bosons A_1, A_2
One charged Higgs boson $H^{\pm}$

For $\lambda \lesssim 0.7$: $M_{H_1} \lesssim$ 140 GeV, max. for $\tan\beta \sim 2$

But: More Higgs bosons in the NMSSM do not simplify the detection of (at least) one Higgs boson!

— Higgs-to-Higgs decays are possible;
the SM-like CP-even Higgs could decay, e.g., as $H_1 \to A_1 A_1$
— Singlet-doublet-mixing can reduce the couplings to gauge bosons of *all* Higgs bosons (respecting the sum rule $\sum_{i=1}^{3} \xi_i^2 = 1$)

Status of Higgs-to-Higgs decays as $H_1 \to A_1 A_1$:

Four possible scenarios: 1) $M_{H_1} \lesssim 110$ GeV or 2) $M_{H_1} \gtrsim 110$ GeV
a) $M_{A_1} \gtrsim 10.5$ GeV or b) $M_{A_1} \lesssim 10.5$ GeV

1) $M_{H_1} \lesssim 110$ GeV would alleviate the "little fine tuning problem" (Dermisek, Gunion), but: LEP constraints?

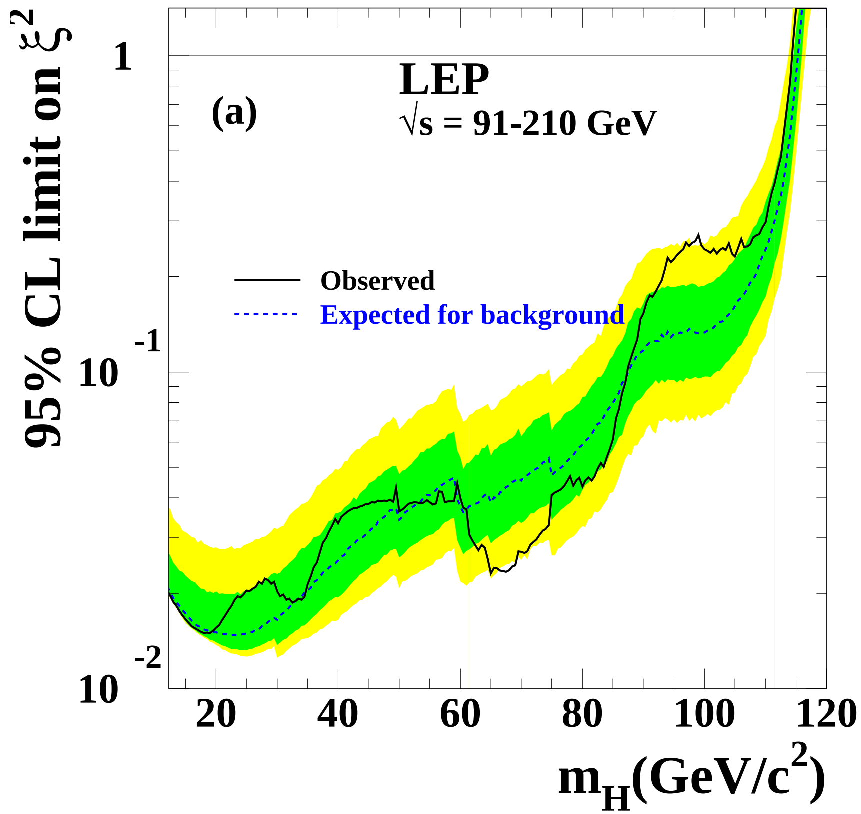
Search for $H \to b\bar{b}$, $\tau^+\tau^-$ (comb. 4 exp., LEP-Higgs Working Group):

Small excess of events for $m_H \sim 95 - 100$ GeV ($\sim 2.3\,\sigma$)

If such an H exists, it must possess:

$\longrightarrow$ Either a reduced coupling $g_{HZZ}/g_{HZZ\_SM} \equiv \xi \lesssim 0.4 - 0.5$

$\longrightarrow$ or a reduced BR to $b\bar{b}$: $BR(H \to b\bar{b})/BR_{SM} \lesssim 0.2$



$\longrightarrow$ $BR(H \to A_1 A_1) \sim 80-90\%$?

1a) If $M_{A_1} \gtrsim 10.5$ GeV: A_1 decays into $b\bar{b}$
$\longrightarrow$ ruled out by OPAL/DELPHI

1b) If $M_{A_1} \lesssim 10.5$ GeV: A_1 decays into $\tau\tau$
$\longrightarrow$ ruled out by ALEPH (2010),
except for a window around $M_{A_1} \sim 10$ GeV and/or $\tan\beta \lesssim 3$
where the $BR(A_1 \to c\bar{c}/gg)$ is enhanced (Dermisek, Gunion)
and constraints from CLEO/BaBar on $\Upsilon \to \gamma A_1$ are satisfied

2) $M_{H_1} \gtrsim 110$ GeV is allowed by LEP,
and $H_1 \to A_1 A_1$ would be challenging for the LHC!

2a) If $M_{A_1} \gtrsim 10.5$ GeV: A_1 decays into $b\bar{b}$ ($\sim 90\%$ BR) or $\tau\tau$ ($\sim 8\%$ BR)

$\longrightarrow$ Proposals to look for

— H_1 via VBF and $H_1 \to A_1 A_1 \to b\bar{b}\tau^+\tau^-$ (U.E. et al.)

— H_1 via ass. WH_1/ZH_1 production and $H_1 \to A_1 A_1 \to 4b$ or $H_1 \to A_1 A_1 \to b\bar{b}\tau^+\tau^-$, assuming 50% efficiency for b-tagging (Cheung et al., Carena et al.)

2b) If $M_{A_1} \lesssim 10.5$ GeV (but $\gtrsim 2m_\tau$):
A_1 decays into $\tau\tau$ ($\sim 98\%$ BR) or $\mu\mu$ ($\sim 0.4\%$ BR)

$\longrightarrow$ Proposals to look for

— $H_1 \to A_1 A_1 \to 2\tau + 2\mu$ (Lisanti, Wacker)

— $H_1 \to A_1 A_1 \to 4\tau$ with H_1 from VBF or ass. production (Belyaev et al.)

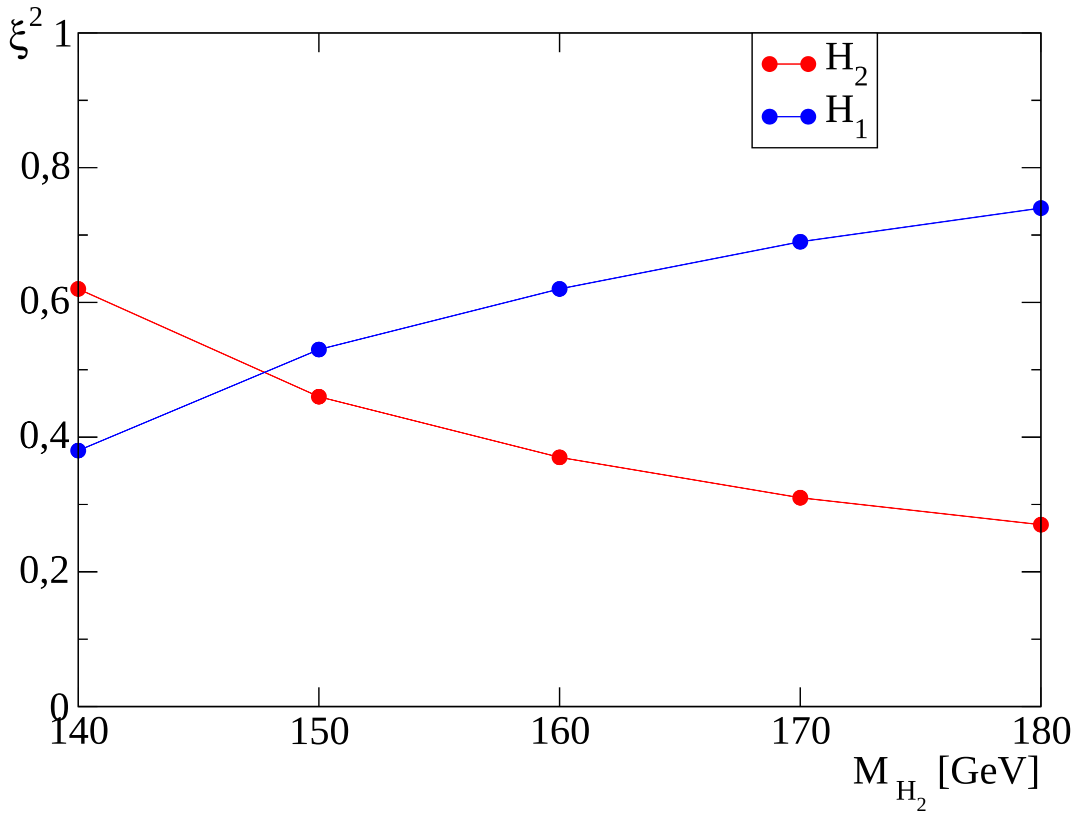
— $H_1 \to 4\mu$ if $M_{A_1} \lesssim 2m_\tau$ (Belyaev et al.)

BUT: no detector simulations, no guaranteed discovery

Singlet-doublet-mixing in the NMSSM:

Both H_1 *and* H_2 can have reduced couplings ξ^2 to gauge bosons, with $M_{H_1} \lesssim 115$ GeV $\longrightarrow$ hard to see at the LHC (reduced $BR(H_1 \to \gamma\gamma/\tau\tau)$)

$M_{H_2} \simeq 140 \ldots 180$ GeV $\longrightarrow$ visible at the LHC?



Properties of H_2

Can be produced in Gluon Fusion and Vector Boson Fusion

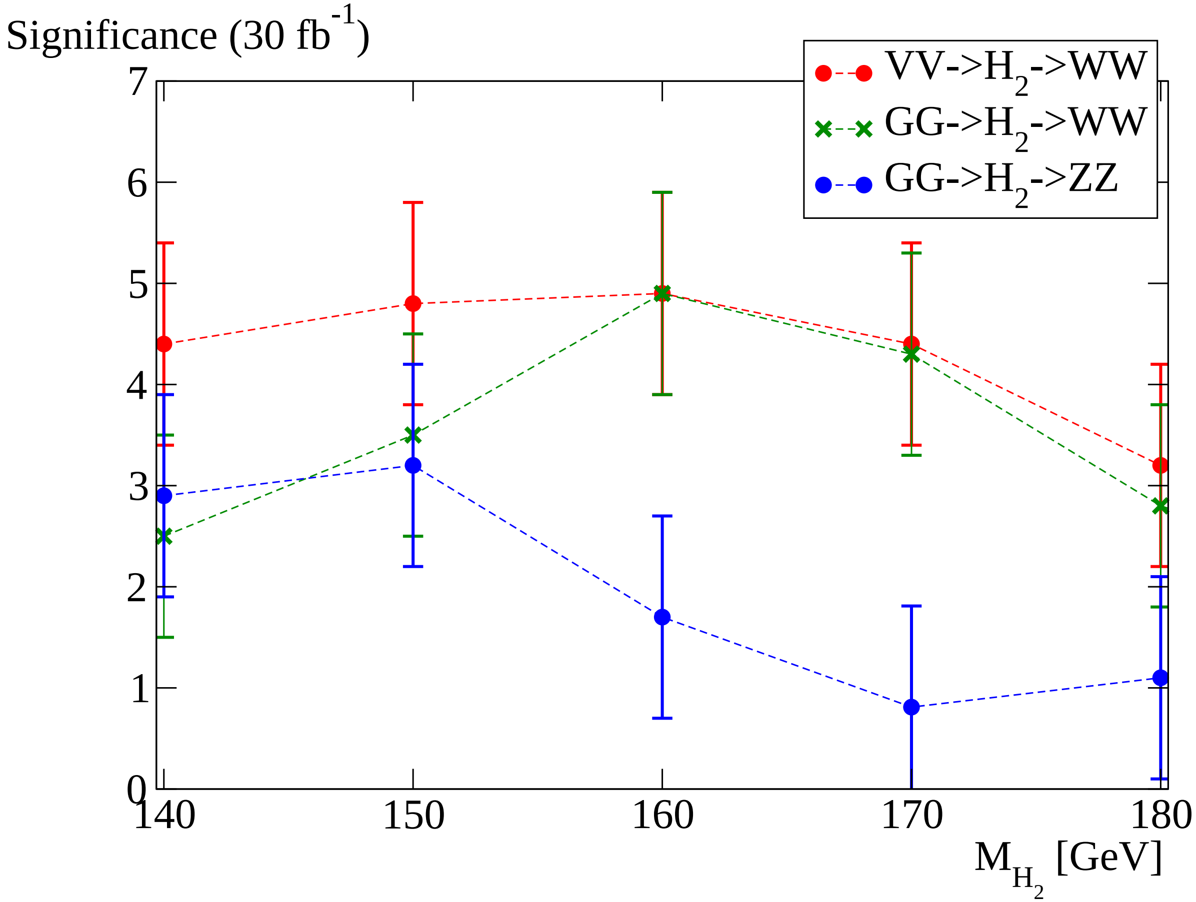
Large branching ratio into WW (40% – 90% for $M_{H_2} \simeq 140 - 180$ GeV), since $\tan\beta \sim$ 2–3 is small

The most interesting mass range at the Tevatron and the LHC in the near future!

Higgs bosons (H, A) with these properties do not exist in the MSSM!
(Larger $\tan\beta$ in the MSSM $\longrightarrow$ branching ratios into $b\bar{b}$ dominate)

Significances for H_2

(with D. Zerwas, using SFitter by R. Lafaye, T. Plehn, M. Rauch, D. Z.)



⟶ Discovery possible (once channels are combined, or for larger luminosity), but: tough for $M_{H_2} \gtrsim 180$ GeV

Conclusions and outlook

Assuming that a single SUSY breaking scale M_{SUSY} generates the weak scale $\sim M_Z$ (no explicit μ-term), the NMSSM is the most natural supersymmetric extension of the Standard Model

Sparticle and/or Higgs production processes can clarify whether the NMSSM is realised in nature:

$\longrightarrow$ τ-rich squark/gluino decay cascades would be a signal for the cNMSSM

$\longrightarrow$ a Higgs boson in the 140–180 mass range decaying into WW can be a signal for the NMSSM

But: Higgs-to-Higgs decays (as $H \to A_1 A_1$ with $A_1 \to b\bar{b}/\tau\tau$) remain a challenging scenario! No "no-lose-theorem" at present;

"No Higgs" at the LHC (but: sparticles) can be a signal for the NMSSM!