Exotic SUSY Higgs at the LHC

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based on

D. Eriksson, SH, J. Rathsman, EPJ C 53 (2008) 267 [hep-ph/0612198]

SH, S. Moretti, S. Munir, P. Poulose, accepted by EPJ C, arXiv:0706.4269

A. Belyaev, SH, S. Lehti, S. Moretti, A. Nikitenko, C. Shepherd-Themistocleous, in preparation

IPPP Seminar, Durham, 18 January 2008

Outline

- Introduction
- $H^{\pm}$ search at LHC with $H^{\pm}W^{\mp}$ production channel
  - CP-conserving MSSM: maximal mixing and resonant scenarios
  - CP-violating MSSM
- Impact of SUSY CP violation on $H \to \gamma\gamma$ channel at LHC
- Light pseudoscalars in NMSSM: $h_1 \to a_1 a_1 \to \tau^+\tau^-\tau^+\tau^-$
- Outlook: Beyond Higgs at LHC

Supersymmetry (SUSY)

- Symmetry fermions $\leftrightarrow$ bosons
- “Standard” particles get superpartners with spin $\pm\frac{1}{2}$
- Supersymmetry is broken $\Rightarrow$ soft SUSY parameters
- Motivation: unification of gauge couplings, hierarchy problem

Minimal Supersymmetric Standard Model (MSSM)

- Minimal extension of Standard Model (SM)
- SM gauge group
- Minimal Higgs sector: 2 doublets
- Many of MSSM parameters can be complex $\longrightarrow$ CP violation
- Higgs sector could be extended $\longrightarrow$ NMSSM

Introduction   CP-violating MSSM

- Complex parameters $\leftrightarrow$ new sources of CP violation
  - May help to explain baryon asymmetry of universe
  - Constraints from electric dipole moments (EDMs) of e, n, Hg, Tl

[Ibrahim, Nath, ’99; Barger, Falk, Han, Jiang, Li, Plehn, ’01; Abel, Khalil, Lebedev, ’01]
[Oshima, Nihei, Fujita, ’05; Pospelov, Ritz, ’05; Olive, Pospelov, Ritz, Santoso, ’05]
[Abel, Lebedev, ’05; Yaser Ayazi, Farzan, ’06, ’07]

- Global U(1) symmetries: some phases eliminated

  E.g. M_2 : real SU(2) gaugino mass parameter

- Physical phases remain for the parameters

  A_f : trilinear couplings of sfermions

  μ : Higgs-higgsino mass parameter

  M_1 : U(1) gaugino mass parameter

  M_3 : SU(3) gaugino mass parameter (gluino mass)

Introduction

MSSM Higgs sector

- MSSM: 2 Higgs doublets
  $\longrightarrow$ 5 physical Higgs particles at tree-level ($h, H, A, H^{\pm}$)
- $\tilde{t}$ and $\tilde{b}$ loops $\Rightarrow$ explicit CP violation in Higgs sector [Pilaftsis, '98]
  [Pilaftsis, Wagner, '99; Demir, '99, Carena, Ellis, Pilaftsis, Wagner, '00, '01; Choi, Drees, Lee, '00]
- CP-even (h, H) and CP-odd (A) neutral Higgs mix
  $\longrightarrow$ 3 neutral mass eigenstates (H_1, H_2, H_3), mixing matrix O
- Impact on Higgs search [LEP Higgs Working Group, hep-ex/0602042]
  $\longrightarrow$ MSSM Higgs search at LEP: no universal limit on m_{H_1}
- Spectrum calculation (masses m_{H_i} and mixing matrix O)
  - CPsuperH [Carena, Ellis, Pilaftsis, Wagner '00; Ellis, Lee, Pilaftsis, '06]
    [Lee, Pilaftsis, Carena, Choi, Drees, Ellis, Wagner '03; Lee, Carena, Ellis, Pilaftsis, Wagner, '07]
  - FeynHiggs [Heinemeyer '01; Frank, Heinemeyer, Hollik, Weiglein '02]
    [Frank, Hahn, Heinemeyer, Hollik, Rzehak, Weiglein, '06; Heinemeyer, Hollik, Rzehak, Weiglein, '07]

Introduction

Next-to-Minimal Supersymmetric Standard Model (NMSSM)

- “Simplest” extension of MSSM
- SM gauge group
- Additional singlet/singlino superfield $\hat{S}$
  $\longrightarrow$ extended Higgs sector: 2 doublets + 1 singlet
  and neutralino sector: 5 neutralinos
- Superpotential: μ term replaced by $W \supset \lambda \hat{H}_1 \hat{H}_2 \hat{S} + \frac{\kappa}{3} \hat{S}^3$
- Higgs potential: $V \supset \lambda A_\lambda \hat{H}_1 \hat{H}_2 \hat{S} + \frac{\kappa}{3} A_\kappa \hat{S}^3$
- Solution of μ problem: $\mu \to \mu_{\text{eff}} = \lambda \langle S \rangle$
- Larger mass of lightest scalar Higgs possible $\Rightarrow$ less fine-tuning

Introduction

Particle content

	"standard" particles	superpartners	
	e, μ, τ	$\tilde{e}_{L,R}, \tilde{\mu}_{L,R}, \tilde{\tau}_{1,2}$	sleptons
	ν_e, ν_μ, ν_τ	$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$	sneutrinos
	u, c, t d, s, b	$\tilde{u}_{L,R}, \tilde{c}_{L,R}, \tilde{t}_{1,2}$ $\tilde{d}_{L,R}, \tilde{s}_{L,R}, \tilde{b}_{1,2}$	squarks
	g	$\tilde{g}$	gluino
	$H^\pm, W^\pm$	$\tilde{H}^\pm, \tilde{W}^\pm$	charginos $\tilde{\chi}^\pm_{1,2}$
MSSM	γ, Z $h, H, A \xrightarrow{\text{CPV}} H_1, H_2, H_3$	$\tilde{\gamma}, \tilde{Z}$ $\tilde{H}_1, \tilde{H}_2$	neutralinos $\tilde{\chi}^0_{1,\dots,4}$
NMSSM	γ, Z h_1, h_2, h_3, a_1, a_2	$\tilde{\gamma}, \tilde{Z}$ $\tilde{H}_1, \tilde{H}_2, \tilde{S}$	neutralinos $\tilde{\chi}^0_{1,\dots,5}$

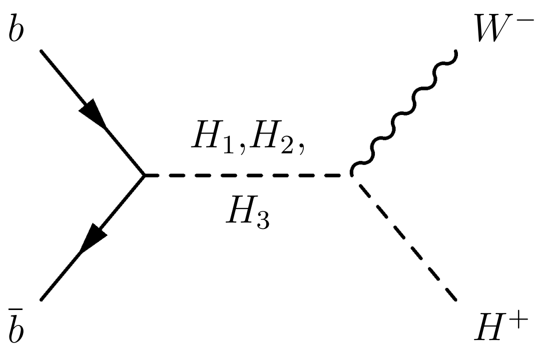
$H^{\pm}W^{\mp}$ at LHC — Introduction

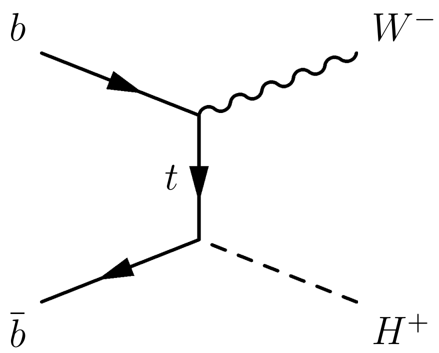
- Discovery of charged Higgs ($H^{\pm}$) $\Rightarrow$ new physics
- Main search channels at LHC: $gb \to H^- t$ and $gg \to H^- t\bar{b}$
- $H^{\pm}W^{\mp}$ production: large cross section
  [Barrientos Bendezú, Kniehl, '98; Brein, '02; Asakawa, Brein, Kanemura '05]
- $H^{\pm} \to tb$ decay: large irreducible background from $t\bar{t}$ production
  [Moretti, Odagiri, '98]
- Here: $H^{\pm}W^{\mp}$ production and $H^{\pm} \to \tau^{\pm}\nu$ decay
  [Eriksson, SH, Rathsman, EPJ C 53 (2008) 267, hep-ph/0612198]
  - Suppression of background by appropriate cuts
  - In MSSM with real and complex parameters
    $\longrightarrow$ Resonance enhancement possible
    [Akeroyd, Baek, '01; Mohn, Gollub, Assamagan, '05]
    $\longrightarrow$ Effects of CP violation, CP asymmetry [Akeroyd, Baek, '00]

$H^\pm W^\mp$ at LHC — Introduction

- At hadron colliders: $b\bar{b} \to H^\pm W^\mp$ and $gg \to H^\pm W^\mp$
- Here: focus on $m_{H^\pm} \sim m_t$ and large $\tan\beta$ with large $BR(H^\pm \to \tau\nu)$

  $\longrightarrow b\bar{b} \to H^\pm W^\mp$ dominates:





- Cross section calculation
  - Implemented as external process in PYTHIA [Sjöstrand et al.]
  - FEYNHIGGS: masses, mixing and BR of Higgs bosons

$H^\pm W^\mp$ at LHC Signature

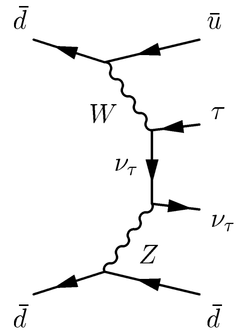
- Simulation of $pp \longrightarrow W^\pm + H^\mp \longrightarrow jj + \tau\nu$
- Decays $H^\pm \to \tau\nu$ and $W^\pm \to jj$ in PYTHIA
  with $BR(H^\pm \to \tau\nu)$ from FEYNHIGGS
- Tau decay with TAUOLA $\longrightarrow$ spin effects [Golonka et al.]
  Focus on hadronic τ decays
- Signature: $2j + \tau_{\text{jet}} + \not{p}_\perp$
- $\not{p}_\perp$ from 2ν: $H^\pm \to \tau\nu \to \tau_{\text{jet}} + 2\nu$
  $\longrightarrow$ reconstruction of $H^\pm$ invariant mass not possible
  $\longrightarrow$ analysis of transverse mass from $p_{\perp\tau_{\text{jet}}}$ and $\not{p}_\perp$:

$$m_\perp = \sqrt{2 p_{\perp\tau_{\text{jet}}} \not{p}_\perp [1 - \cos(\Delta\phi)]}$$

$\Delta\phi$: angle between $p_{\perp\tau_{\text{jet}}}$ and $\not{p}_\perp$

$H^{\pm}W^{\mp}$ at LHC   Background

- Dominant irreducible background: $pp \to W$ + 2 jets
- WZ + 2 jets and $Z \to \nu\nu$ ($\to$ potentially larger $\not{p}_\perp$):
  less than 3% contribution to background after cuts
- Simulation of background with ALPGEN
  [Mangano, Moretti, Piccinini, Pittau, Polosa, '02]
  - Exact tree-level matrix elements for $2j + \tau + \nu_\tau$ final state
  - Includes W + 2 jets, W pair production
    and contributions where τ and ν not from (virtual) W $\longrightarrow$ e.g.



  $\longrightarrow$ Important for tail of invariant mass $m_{\tau\nu} \gtrsim$ 100 GeV
- Background distributions cross checked with MADGRAPH
  [Murayama, Watanabe, Hagiwara, '91; Stelzer, Long, '94; Maltoni, Stelzer, '02]
  [Alwall, Demin, de Visscher, Frederix, Herquet, Maltoni, Plehn, Rainwater, Stelzer, '07]

$H^{\pm}W^{\mp}$ at LHC   Cuts

- Smearing of jet momenta $\longrightarrow$ first approximation of parton showering, hadronisation and detector effects

-

Basic cuts	Additional cuts
$\lvert\eta_{\tau_{\text{jet}}}\rvert < 2.5$	$p_{\perp\tau_{\text{jet}}} > 50$ GeV, $\not{p}_{\perp} > 50$ GeV
$\lvert\eta_j\rvert < 2.5$	70 GeV$< m_{jj} <$ 90 GeV
$\Delta R_{jj} > 0.4$	$m_{\perp} > 100$ GeV
$\Delta R_{\tau_{\text{jet}}j} > 0.5$	$p_{\perp hj} > 50$ GeV, $p_{\perp sj} > 25$ GeV
$p_{\perp jet} > 20$ GeV	

  - Basic cuts: define signal region $\leftrightarrow$ sensitive detector region
  - Additional cuts: suppress background, QCD background, detector miss-identifications

$H^\pm W^\mp$ at LHC   Cuts

Results for maximal mixing scenario with $m_{H^\pm}$ = 175 GeV, tan β = 50

μ = 200 GeV, M_{SUSY} = 1 TeV, X_t = X_b = 2 TeV, M_2 = 200 GeV, $m_{\tilde{g}}$ = 800 GeV

	Integrated cross-section (fb)		
Cut	Background	Signal	$S/\sqrt{B}$
Basic cuts	560000	63	0.8
$p_{\perp\tau_{\text{jet}}} > 50$ GeV, $\not{p}_\perp > 50$ GeV	22000	25	1.6
70 GeV$< m_{jj} < 90$ GeV	1700	21	5
$m_\perp > 100$ GeV	77	15	16
$p_{\perp hj} > 50$ GeV, $p_{\perp sj} > 25$ GeV	28	9.3	17

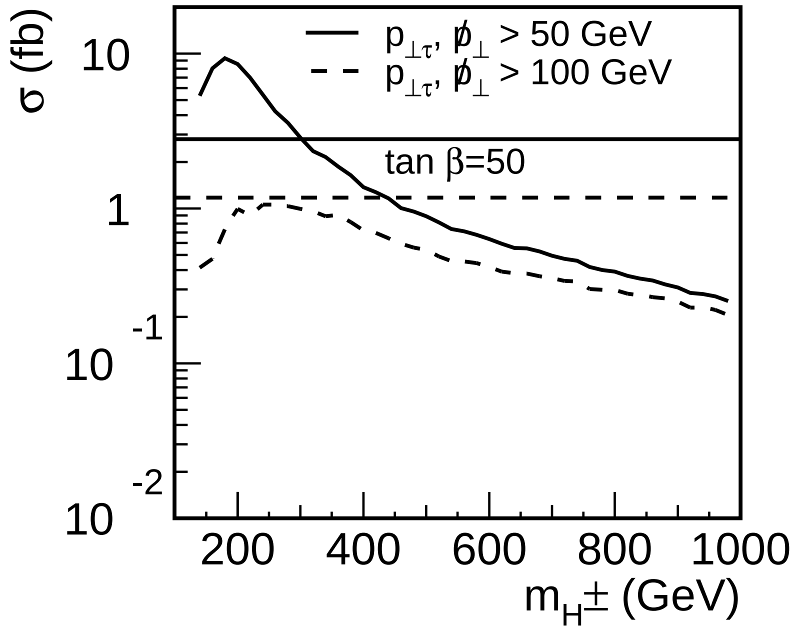
For calculation of $S/\sqrt{B}$: $\mathcal{L}_{\text{int}}$ = 300 fb^{-1}; 30% τ detection efficiency

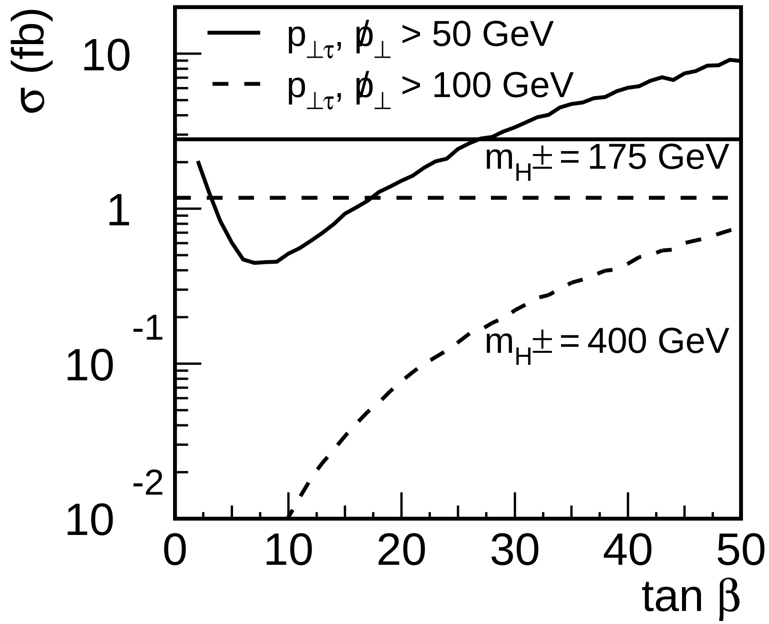
$H^{\pm}W^{\mp}$ at LHC

Results for real MSSM

Maximal mixing scenario

μ = 200 GeV, M_{SUSY} = 1 TeV, X_t = X_b = 2 TeV, M_2 = 200 GeV, $m_{\tilde{g}}$ = 800 GeV





Horizontal lines $\leftrightarrow$ $S/\sqrt{B}$ = 5

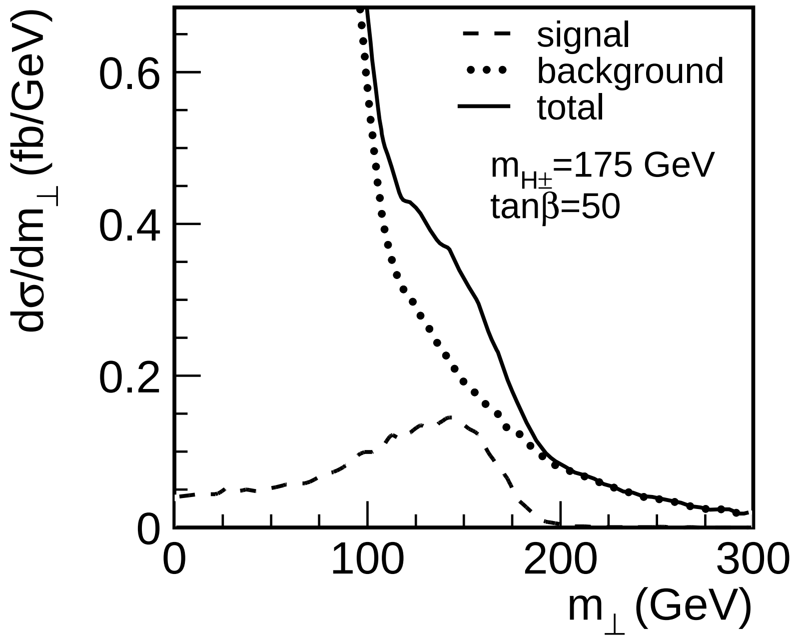
$\longrightarrow$ Detectable signal: 150 GeV $\lesssim m_{H^{\pm}} \lesssim$ 300 GeV if tan β = 50

tan $\beta \gtrsim$ 30 if $m_{H^{\pm}}$ = 175 GeV

$H^{\pm}W^{\mp}$ at LHC — Results for real MSSM

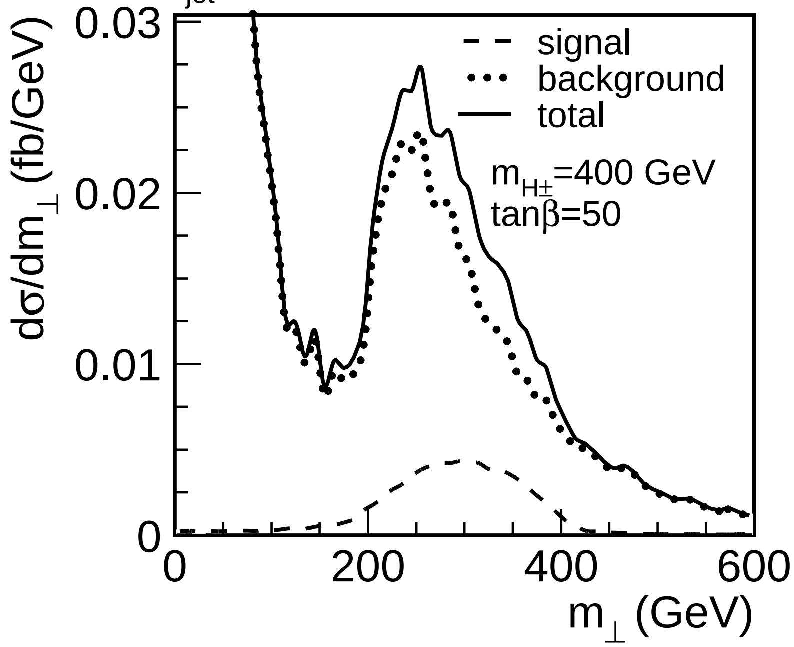
Maximal mixing scenario

μ = 200 GeV, M_{SUSY} = 1 TeV, $X_t = X_b$ = 2 TeV, M_2 = 200 GeV, $m_{\tilde{g}}$ = 800 GeV



$\rightarrow S/\sqrt{B}$ = 17

$p_{\perp\tau_{\text{jet}}} > 100$ GeV, $\not{p}_{\perp} > 100$ GeV



$\rightarrow S/\sqrt{B}$ = 3

$\rightarrow$ Fake peak in background!

$H^{\pm}W^{\mp}$ at LHC **Results for real MSSM**

Resonant scenario with $m_{H^\pm}$ = 175 GeV, $\tan\beta$ = 11

μ = 3.3 TeV, M_L = M_E = 500 GeV, M_Q = M_U = 250 GeV, M_D = 400 GeV,
A_t = A_b = 0, M_2 = 500 GeV, $m_{\tilde{g}}$ = 500 GeV

$\longrightarrow$ very large 1-loop corrections to CP-odd Higgs mass

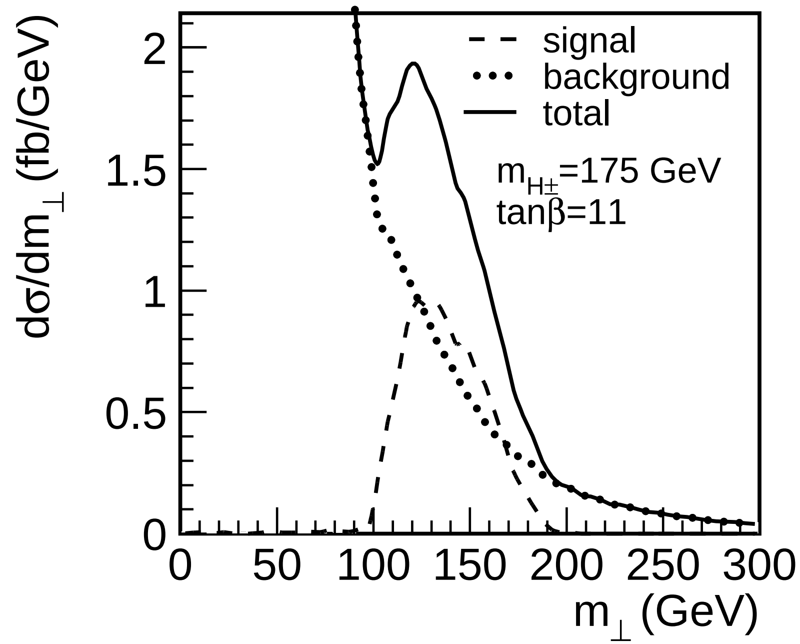
(2-loop effects much smaller $\longrightarrow$ perturbative expansion under control)

$\Rightarrow$ $m_A > m_{H^\pm}$ + m_W possible [Akeroyd, Baek, '02]

$\longrightarrow$ resonant s-channel production

$p_{\perp hj} >$ 20 GeV, $p_{\perp sj} >$ 20 GeV

$S/\sqrt{B}$ = 56 $\longrightarrow$



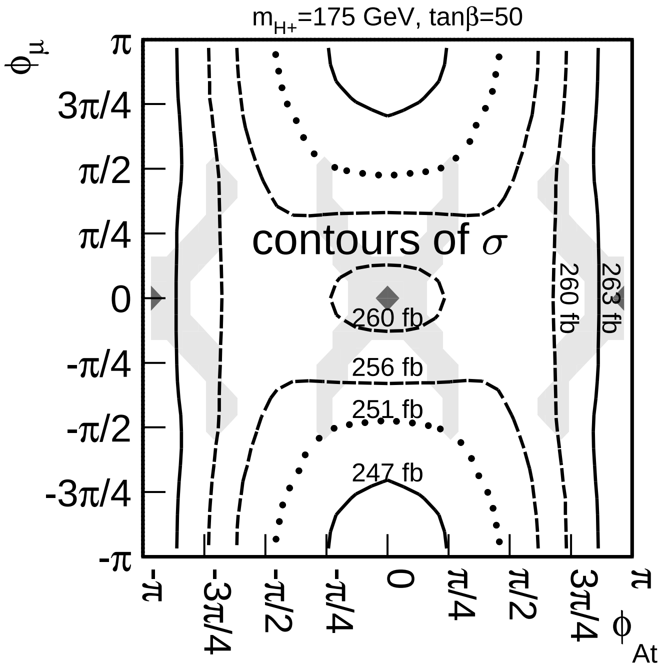
$H^\pm W^\mp$ at LHC

Results for CP-violating MSSM

- Higgs sector analysed with FeynHiggs
  Cross checks with CPsuperH

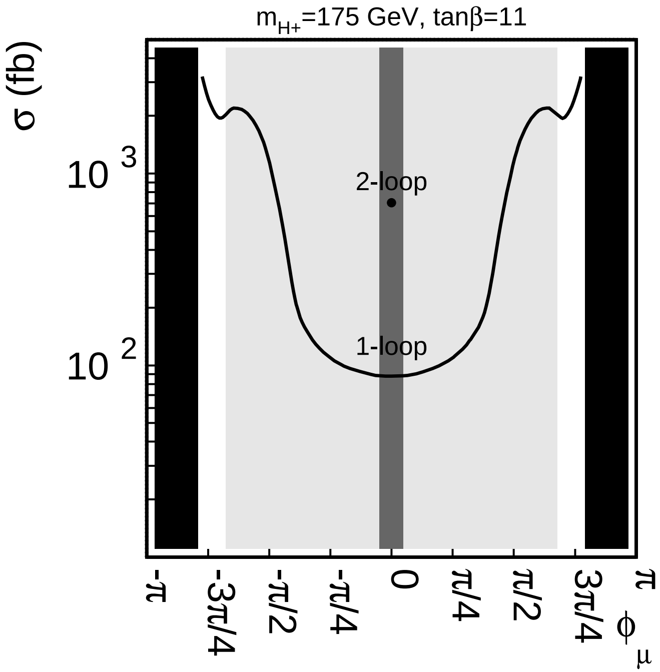
- Phases ϕ_μ and ϕ_{A_t}: largest effects on Higgs sector

- Maximal mixing scenario
  $(m_{H^\pm} \sim m_{H_2^0} \sim m_{H_3^0})$



$\Rightarrow$ small ($\sim$ 5%) phase effects on σ

Resonant scenario
$m_{H_3^0} > m_{H^\pm} + m_W$



$\Rightarrow$ large phase effects possible

$H^\pm W^\mp$ at LHC — Summary

- $pp \to W^\pm + H^\mp \to jj + \tau\nu$ at parton level with smearing of momenta
- Signature: $2j + \tau_{\text{jet}} + \not{p}_\perp$
- Dominant irreducible background: $pp \to W$ + 2 jets
- Appropriate cuts on $p_\perp$, m_{jj}, $m_\perp$
- Detectable signal at LHC in MSSM

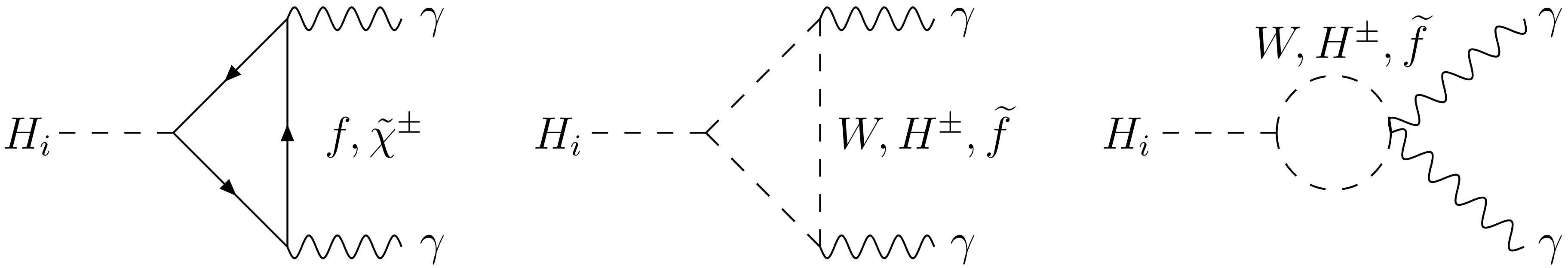
  $\rightarrow$ maximal mixing scenario: 150 GeV $\lesssim m_{H^\pm} \lesssim$ 300 GeV if $\tan\beta$ = 50

  $\tan\beta \gtrsim 30$ if $m_{H^\pm}$ = 175 GeV

  $\rightarrow$ resonant scenarios: also for smaller $\tan\beta$
- CP-violating MSSM
  - Large phase effects possible in resonant scenarios
  - CP-odd rate asymmetry $\lesssim$ 1%

$H_1 \to \gamma\gamma$ in CP-violating MSSM

- $pp \to H \to \gamma\gamma$: important search channel at LHC for $m_H \lesssim$ 150 GeV
- Decay at 1-loop via f, W, $H^\pm$, $\tilde{f}$, $\tilde{\chi}^\pm$ loops in MSSM



- CP violation enters via phase dependence of
  - Masses $m_{H_i} \longrightarrow$ small
  - Mixing matrix $O \leftrightarrow H_i$ couplings (also to SM particles)
  - $\tilde{f}$, $\tilde{\chi}^\pm$ sector (masses, couplings to H_i)

$H_1 \to \gamma\gamma$ Production and decay in CPV MSSM

- Production $gg \to H_i$ at LHC [Choi, Lee, '99; Dedes, Moretti, '99]

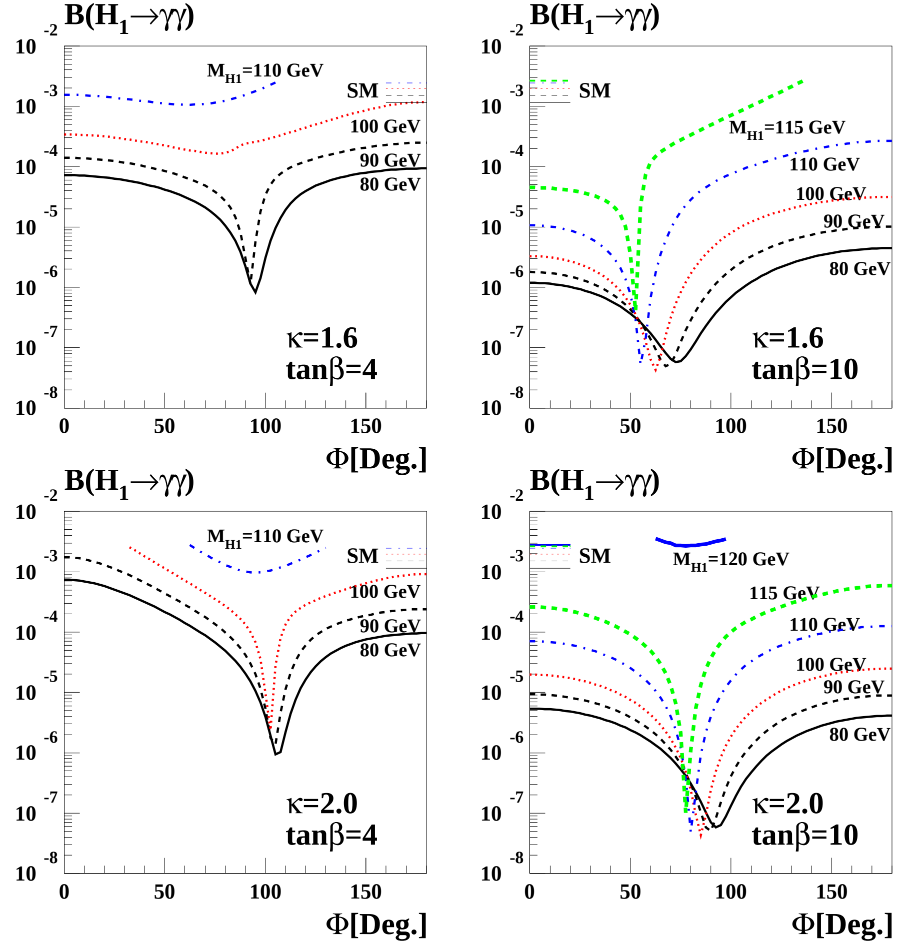
  $\longrightarrow$ factor 2–5 enhancement/reduction of σ with φ_μ and φ_{A_t}

- $gg \to H_i \to \gamma\gamma$ at LHC in CPV MSSM [Choi, Hagiwara, Lee, '01]
  - Heavy sparticles ($\tilde{f}$, $\tilde{\chi}^\pm$)

    $\leftrightarrow$ CPV in H_i couplings
  - $\mathcal{O}(10^2$–$10^3)$ suppression

    of BR($H_1 \to \gamma\gamma$) possible

    $\Rightarrow$ suppression of $\sigma \times$ BR



for

$M_{\tilde{Q},\tilde{U},\tilde{D}} = m_{\tilde{g}} = M_{\text{SUSY}} = 0.5$ TeV,

$|A_t| = |A_b| = \kappa M_{\text{SUSY}}$, $|\mu| = 2|A_t|$,

$\Phi = \text{Arg}(A_t\mu) = \text{Arg}(A_b\mu)$

$H_1 \to \gamma\gamma$ Analysis of Branching Ratio

- Here: [SH, S. Moretti, S. Munir, P. Poulose, accepted by EPJ C, arXiv:0706.4269]
  - Investigate possible effects of light sparticles
  - Calculation of m_{H_i}, O, $\Gamma(H_i)$, $\mathrm{BR}(H_i)$ with CPsuperH
  - Detailed discussion of A_f, μ, $\tan\beta$ dependence
  - Leading contributions to (h, H)-A mixing $\propto \mathrm{Im}(\mu A_f)$

    $\longrightarrow \varphi_{\text{eff}} = \varphi_\mu + \varphi_{A_f}$

    $\longrightarrow$ Choosing A_f real, analysing $\varphi_{\text{eff}} = \varphi_\mu$ effects in the following
  - First step: analysis of $\mathrm{BR}(H_1 \to \gamma\gamma)$

- Scan over MSSM parameters [Moretti, Munir, Poulose, '07]

  $\longrightarrow$ in average $\sim$ 50% deviation between CPV and CPC case possible

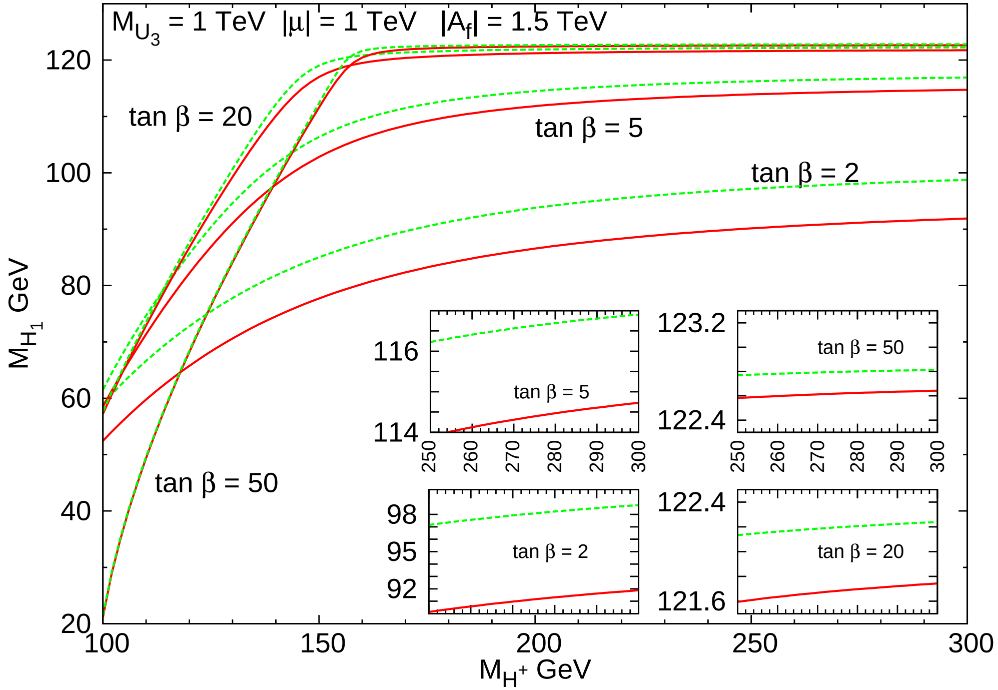
  for parameter points with m_{H_1} in bins of size 4 GeV

$H_1 \to \gamma\gamma$ Numerical results

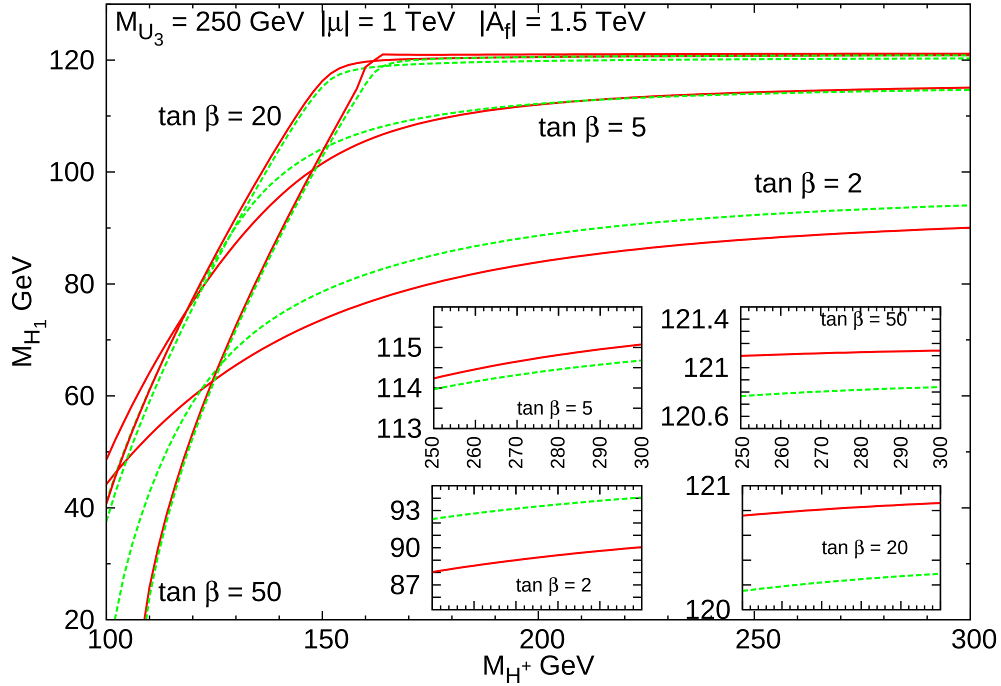
m_{H_1} as function of $m_{H^\pm}$

for $M_{(\tilde{Q}_3,\tilde{D}_3,\tilde{L}_3,\tilde{E}_3)}$ = 1 TeV, $|\mu|$ = 1 TeV, A_f = 1.5 TeV, φ_μ = 0, φ_μ = 90°

$M_{\tilde{U}_3}$ = 1 TeV



$M_{\tilde{U}_3}$ = 250 GeV ($m_{\tilde{t}_1} \sim$ 200 GeV)

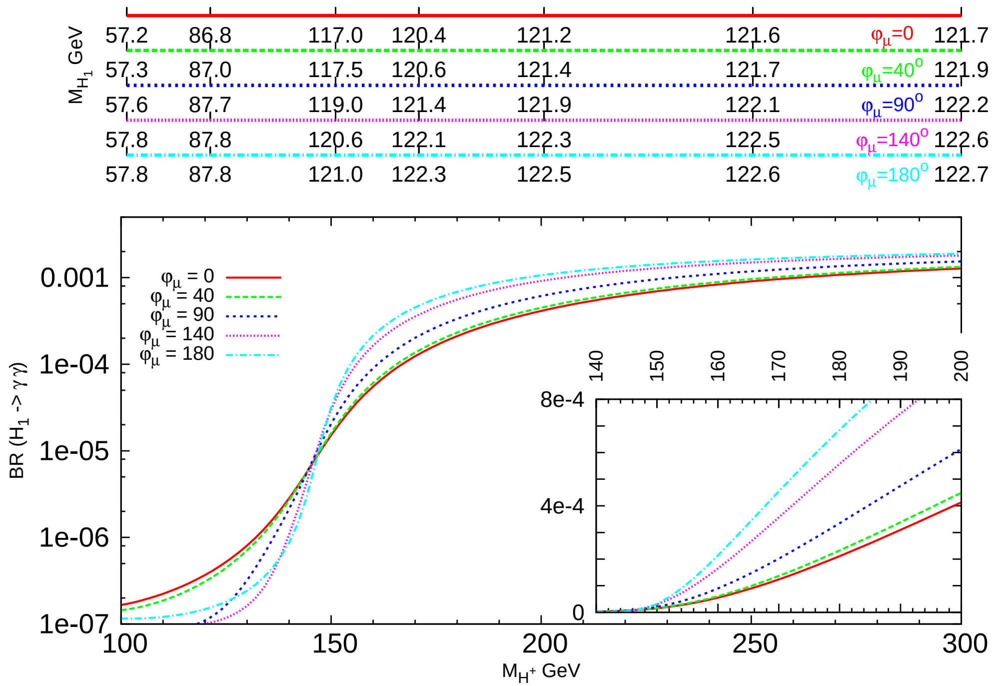


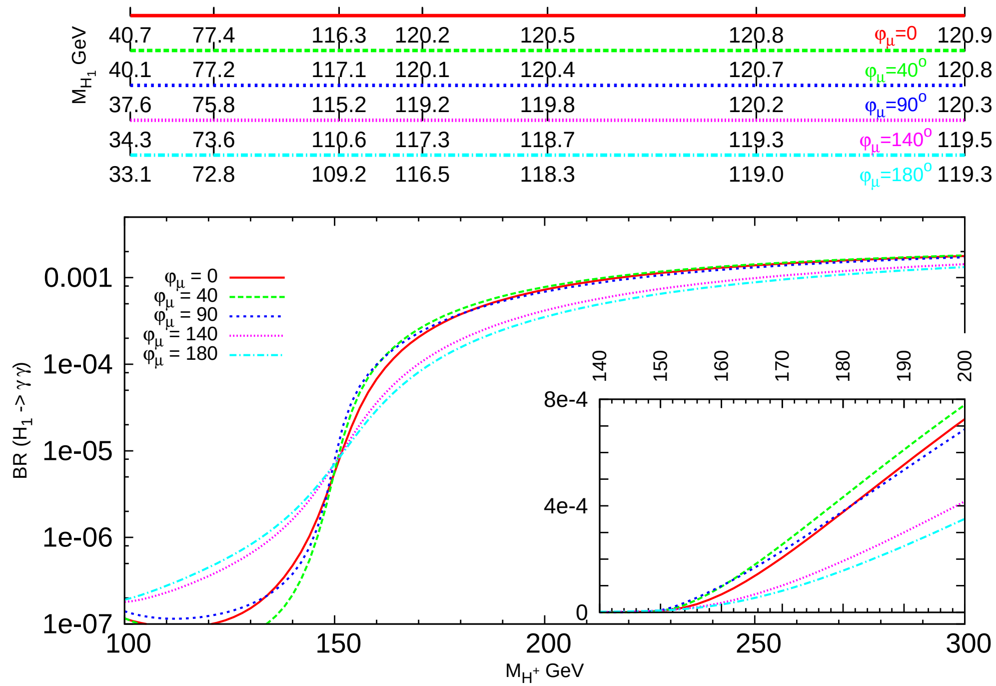
$\longrightarrow$ deviations $\Delta m_{H_1}(\varphi_\mu)$ within experimental uncertainty

$H_1 \to \gamma\gamma$ Numerical results

BR($H_1 \to \gamma\gamma$) as function of $m_{H^\pm}$

for $M_{(\tilde{Q}_3,\tilde{D}_3,\tilde{L}_3,\tilde{E}_3)}$ = 1 TeV, $|\mu|$ = 1 TeV, A_f = 1.5 TeV, tan β = 20





→ $M_{\tilde{U}_3}$ = 1 TeV (no light sparticles)

→ CP effects from H_1 couplings to W, t, b in loops

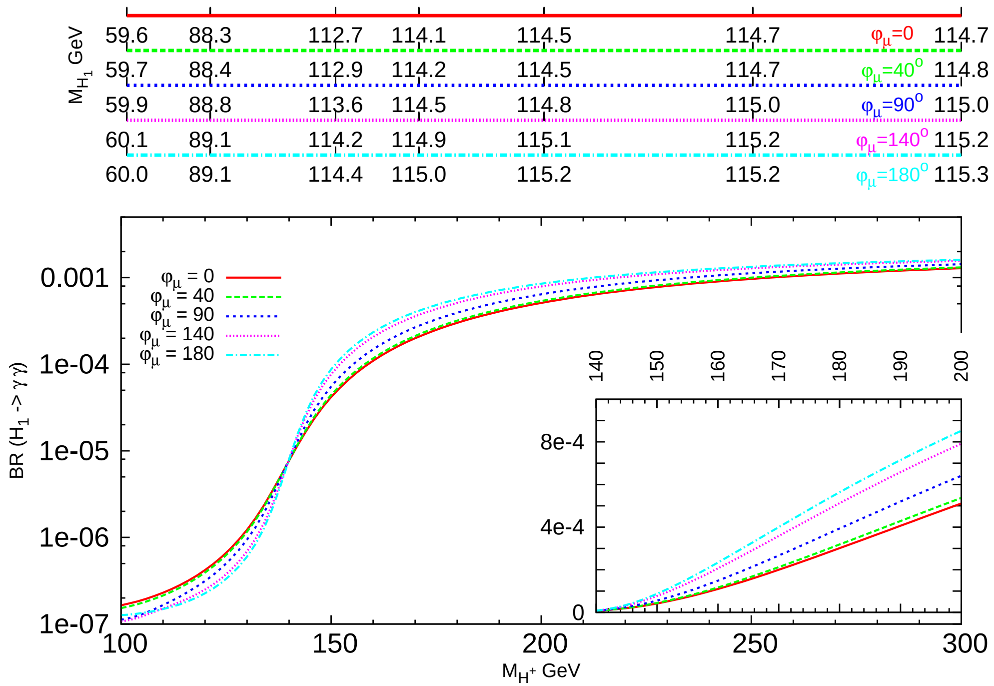
→ $M_{\tilde{U}_3}$ = 250 GeV ($m_{\tilde{t}_1} \sim$ 200 GeV)

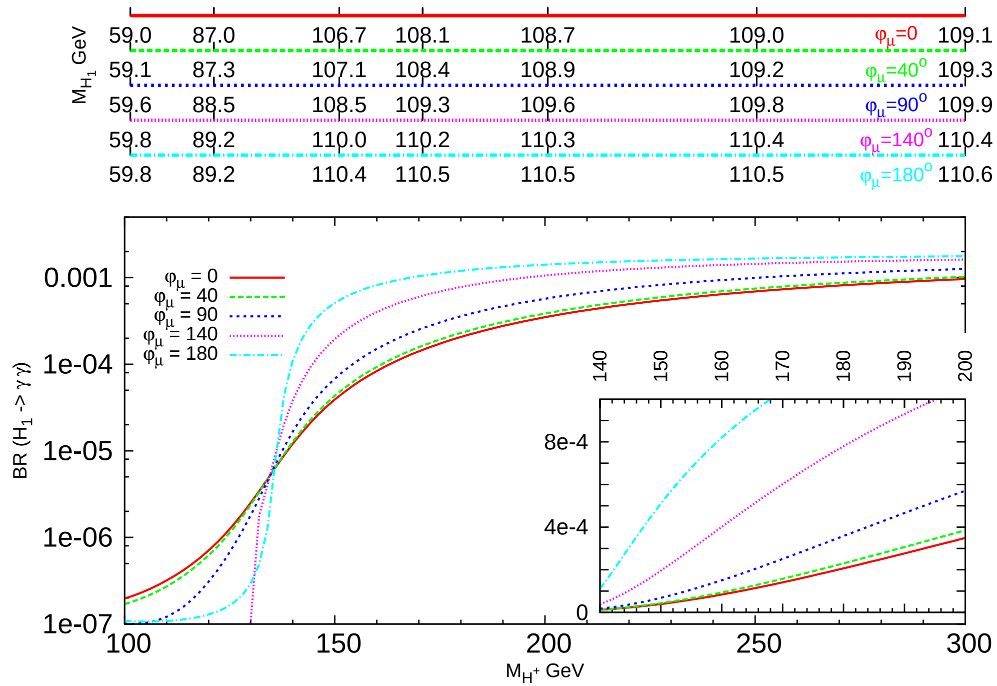
→ additional effects from light $\tilde{t}_1$

$H_1 \to \gamma\gamma$ Numerical results

BR($H_1 \to \gamma\gamma$) as function of $m_{H^\pm}$

for $M_{(\tilde{Q}_3,\tilde{D}_3,\tilde{L}_3,\tilde{E}_3)}$ = 1 TeV, $|\mu|$ = 1 TeV, A_f = 0.5 TeV, $\tan\beta$ = 20





$\to$ $M_{\tilde{U}_3}$ = 1 TeV (no light sparticles)

$\to$ $M_{\tilde{U}_3}$ = 250 GeV ($m_{\tilde{t}_1} \sim$ 200 GeV)

$\to$ strong A_f dependence

Summary: SUSY parameter dependence

BR($H_1 \to \gamma\gamma$) in CP-violating MSSM

- Impact of light sparticles
  $\longrightarrow$ light stops ($\tilde{t}_1$): possibly large effect
  $\longrightarrow$ other light sparticles ($\tilde{b}_1$, $\tilde{\tau}_1$, $\tilde{\chi}_1^\pm$): small effect
- Strong A_f dependence
- Smaller $|\mu|$ = 500 GeV $\longrightarrow$ φ_μ dependence decreases
- Smaller $\tan\beta$ = 5 $\longrightarrow$ sensitivity to φ_μ considerably reduced
- Conclusion: Strong phase dependence of BR($H_1 \to \gamma\gamma$)
  Increase or decrease depends on SUSY scenario
- Outlook: Analysis of full production and decay process at LHC
  Work in progress . . .

Light NMSSM pseudoscalars at LHC

NMSSM Higgs sector

[e.g. Elliott, King, White, ’93; Franke, Fraas, ’95]
[Ellwanger, Hugonie, ’99; Miller, Nevzorov, Zerwas, ’03; Barger, Langacker, Lee, Shaughnessy, ’06]

- 2 doublets + 1 singlet
  $\Rightarrow$ 3 scalars h_1, h_2, h_3, 2 pseudoscalars a_1, a_2 and 2 charged Higgs $H^\pm$
  $\longrightarrow$ (3×3), (2×2) mass matrices for neutral Higgs
- 6 parameters (tree-level): λ, κ, A_λ, A_κ, $\tan\beta$, $\mu_{\text{eff}} = \lambda\langle S\rangle$
  where $\tan\beta = \frac{v_2}{v_1}$, $v_{1,2} \equiv \langle H_{1,2}\rangle$
- h_1 mass bound
  - Tree-level: $m_{h_1}^2 < m_Z^2 \cos^2 2\beta + \lambda^2(v_1^2 + v_2^2)\sin^2 2\beta$
  - Including loop corrections: $m_{h_1} \lesssim$ 140 GeV
- Spectrum calculator: NMSSMTools: NMHDECAY, NMSPEC
  [Ellwanger, Gunion, Hugonie, ’04; Ellwanger, Hugonie, ’05, ’06; Domingo, Ellwanger, ’07]

Light NMSSM pseudoscalars at LHC

Difficult NMSSM scenario for LHC

[Ellwanger, Gunion, Hugonie, Moretti ’03, ’04; Miller, Moretti ’04; Gunion, Szleper, ’04]
[Ellwanger, Gunion, Hugonie, ’05; Moretti, Munir, ’06; Moretti, Munir, Poulose, ’06]
[Chang, Fox, Weiner, ’06; Arhrib, Cheung, Hou, Song, ’06; Cheung, Song, Yan, ’07]
[Carena, Han, Huang, Wagner, ’07; Forshaw, Gunion, Hodgkinson, Papaefstathiou, Pilkington, ’07]

- Singlet-like a_1 and/or h_1 can be light in large region of parameter space
- Large $BR(h_1 \to a_1 a_1)$ or $BR(h_2 \to h_1 h_1)$
- Very light a_1 ($m_{a_1} < 2m_b$) possible $\longrightarrow$ $a_1 \to \tau^+\tau^-$ [Dermisek, Gunion, ’06, ’07]
- Usual search channels for Higgs at LHC may fail

Light NMSSM pseudoscalars at LHC

Here [Belyaev, SH, Lehti, Moretti, Nikitenko, Shepherd-Themistocleous, in preparation]

- Scenarios with $m_{a_1} < 2m_b \quad \longrightarrow \quad BR(a_1 \to \tau^+\tau^-) \sim 1$
- $h_1 \to a_1 a_1 \to 4\tau$ mode at LHC for
  - Vector boson fusion: $pp \to h_1 jj$
  - Higgs-strahlung: $pp \to h_1 V$
- Analysis of signature $4\tau \to 2\mu + 2j$
- Work in progress . . .

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NMSSM parameter space with $m_{a_1} < 2m_b$ and large $BR(h_1 \to a_1 a_1)$

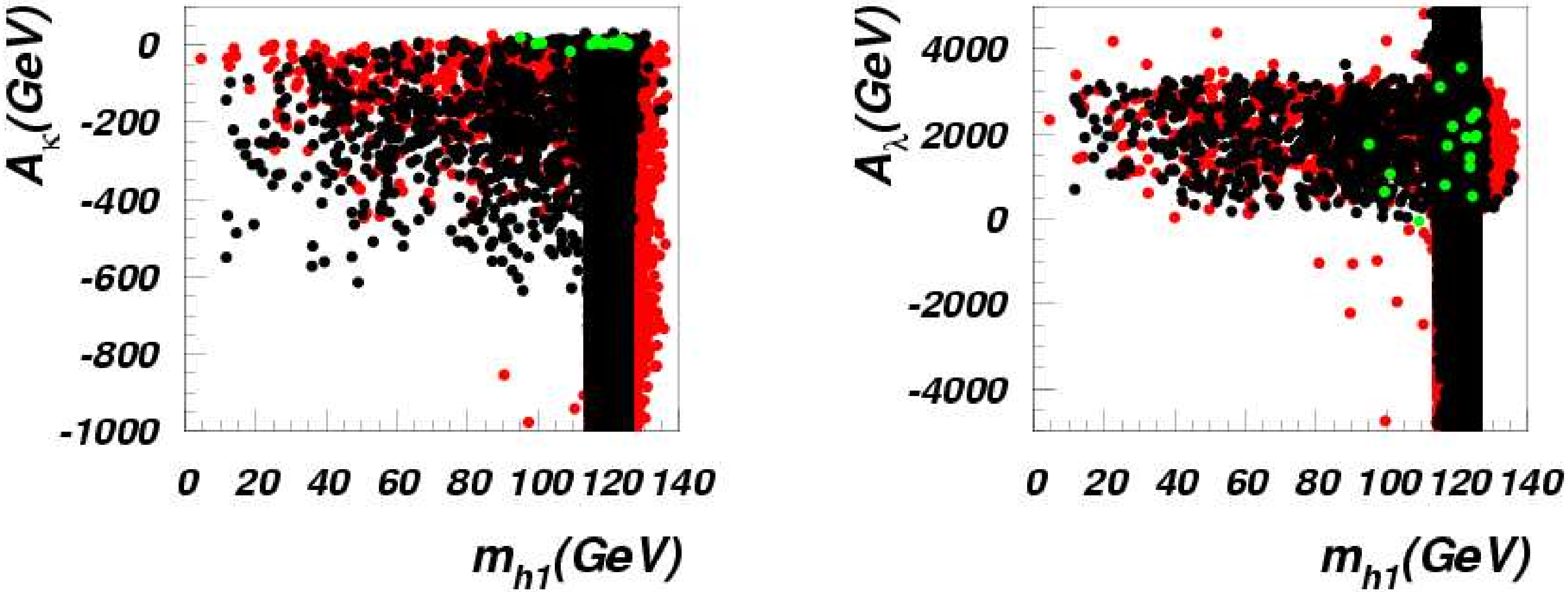
- Wide scan with NMHDECAY

  $M_1/M_2/M_3$ = 150/300/1000 GeV, A_t = A_b = A_τ = 2.5 TeV, M_{fL} = M_{fR} = 1 TeV

  $10^{-5} < \lambda, \kappa < 0.7$, $1.5 < \tan\beta < 50$

  -1000 GeV $< A_\kappa <$ 100 GeV, -5 TeV $< A_\lambda <$ 5 TeV, 100 GeV $< \mu_{\text{eff}} <$ 1000 GeV

  $\longrightarrow$ Points satisfying theoretical, LEP and B physics bounds:



red: $\Omega h^2 > 0.11$, black: $\Omega h^2 < 0.11$, $m_{a_1} > 10$ GeV, green: $\Omega h^2 < 0.11$, $m_{a_1} < 10$ GeV

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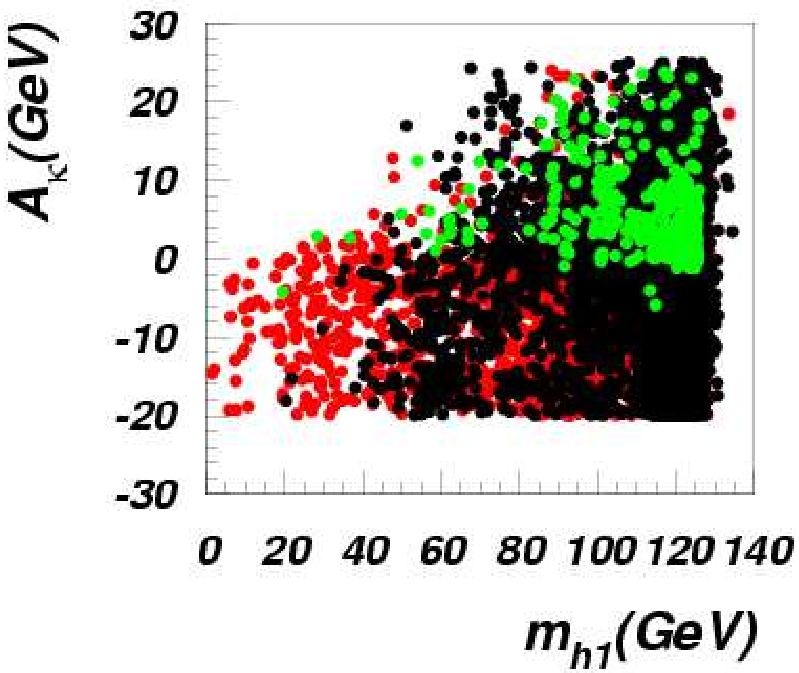
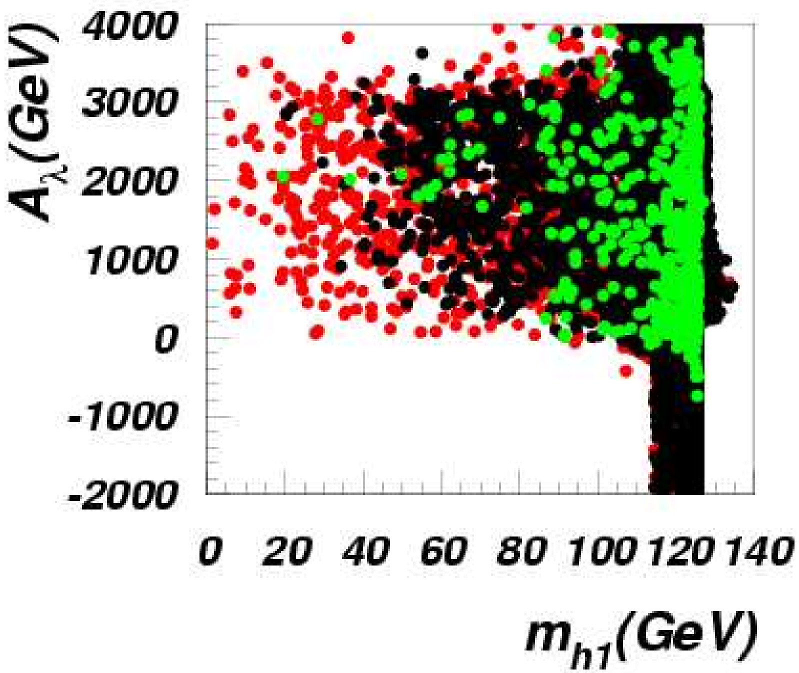
- Narrowed scan

  -20 GeV $< A_\kappa <$ 25 GeV, -2 TeV $< A_\lambda <$ 4 TeV, 100 GeV $< \mu_{\text{eff}} <$ 300 GeV





red: $\Omega h^2 > 0.11$, black: $\Omega h^2 < 0.11$, $m_{a_1} > 10$ GeV, green: $\Omega h^2 < 0.11$, $m_{a_1} < 10$ GeV

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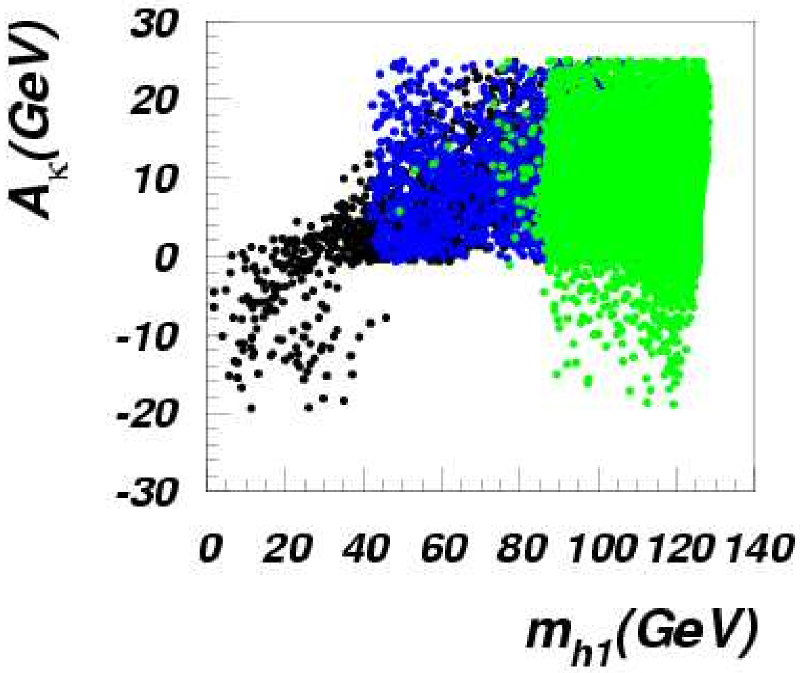
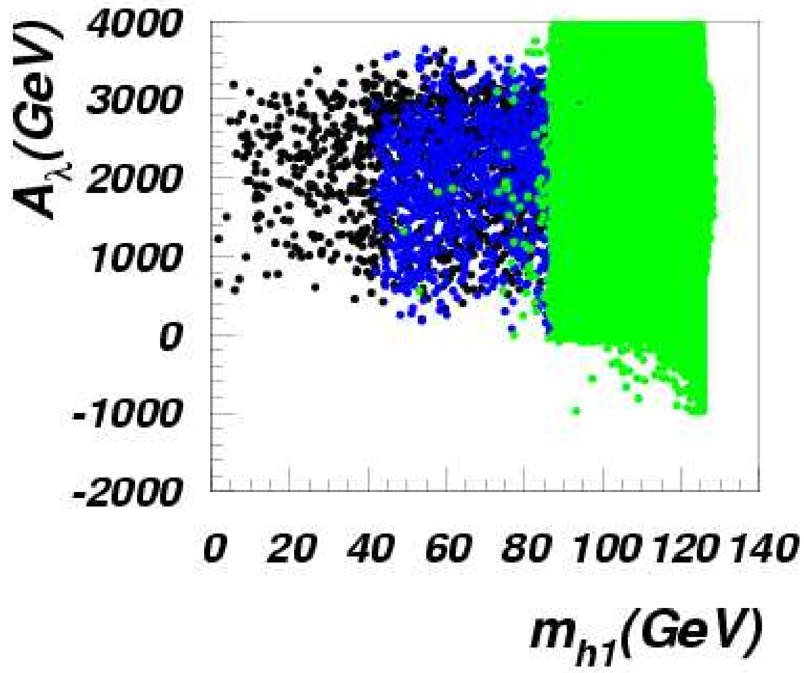
- Effective coupling $R_{ZZh} = \left(\frac{g^{NMSSM}_{ZZh_1}}{g^{SM}_{ZZH}}\right)^2$

$\longrightarrow$ Points with $m_{a_1} < 10$ GeV satisfying all contraints:





black: $R_{ZZh} < 0.1$, $0.1 < R_{ZZh} < 0.5$, $R_{ZZh} > 0.5$

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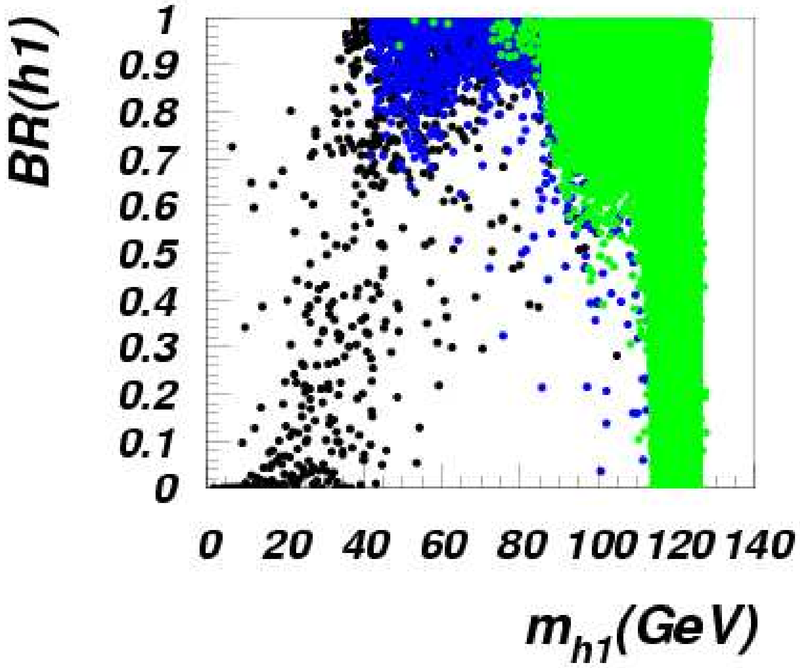
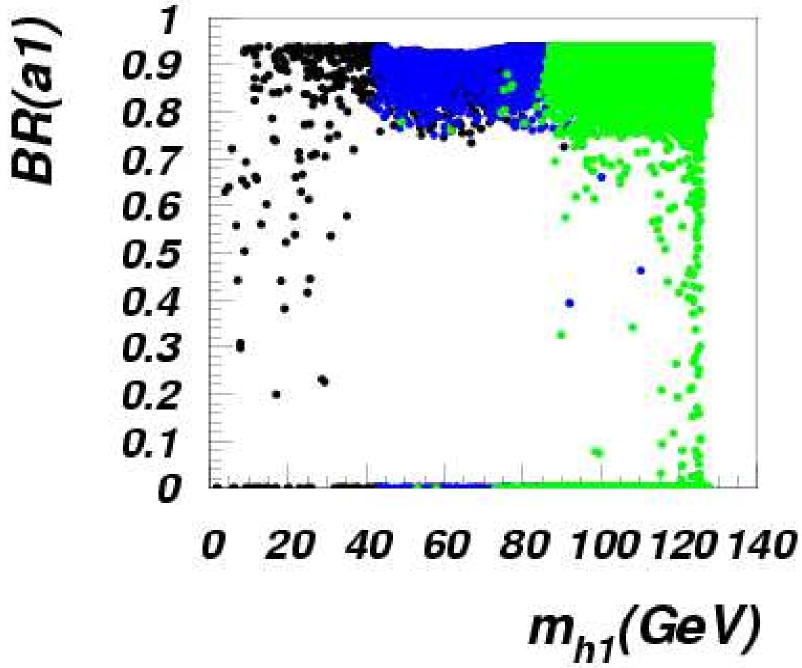
- Branching ratios of h_1 and a_1

$BR(h_1 \to a_1 a_1)$



$BR(a_1 \to \tau^+\tau^-)$

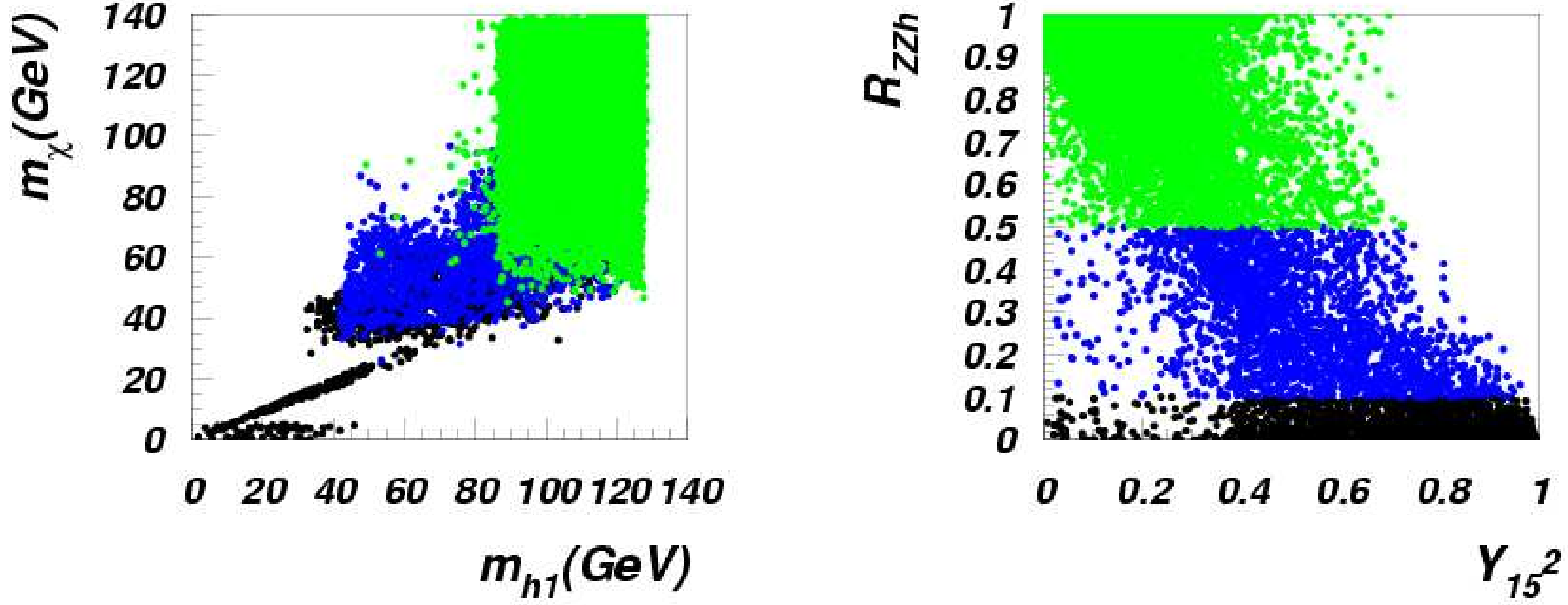


black: $R_{ZZh} < 0.1$, $0.1 < R_{ZZh} < 0.5$, $R_{ZZh} > 0.5$

Light NMSSM pseudoscalars at LHC

- Correlations with LSP character

y_{15}^2: singlino component of LSP



black: $R_{ZZh} < 0.1$, $0.1 < R_{ZZh} < 0.5$, $R_{ZZh} > 0.5$

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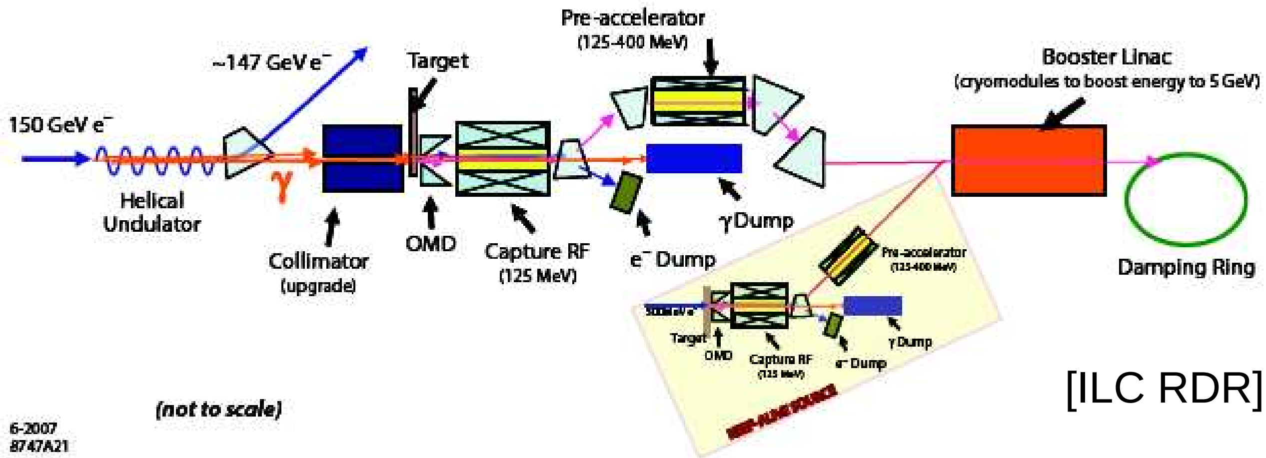
Outlook

- Work in progress . . .
- Combine with efficiencies from experimental collaborators
- Identify NMSSM parameter regions which can be covered
- Final aim: “no-lose” or even “more-to-gain” theorem for NMSSM

Accelerator Physics

- Collaboration with heLiCal group at Cockcroft Institute
- Positron source of e^+e^- linear collider



[ILC RDR]

$\longrightarrow$ Systematic study of multi-particle processes in target

$\longrightarrow$ Optimisation of yield

$\longrightarrow$ Optimisation of undulator parameters

$\longrightarrow$ Aspects of positron polarisation