Beyond SM Higgs

Shufang Su • U. of Arizona

SMU
Nov 4, 2013

Higgs is discovered

Now what?

Celebration !!!

Then What?

light, weakly coupled boson: m_h = 125-126 GeV, Γ < 1 GeV

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Then What? Still a lot of hard, but fun work to do!

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Then What? Theoretically ...

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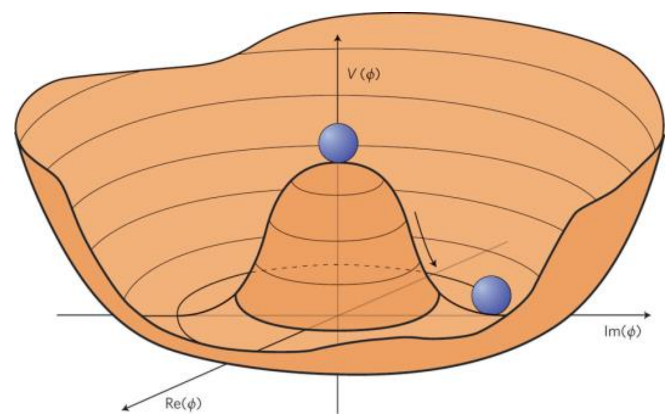
Then What? **Theoretically ...**



$$V(\phi) = \frac{1}{2}\mu_h^2\phi^2 + \frac{\lambda}{4}\phi^4$$

$$\langle\phi\rangle \equiv v \neq 0 \quad \rightarrow \quad m_W = g_W\frac{v}{2}$$

$$M_H^2 = -2\mu^2 = 2\lambda v^2$$

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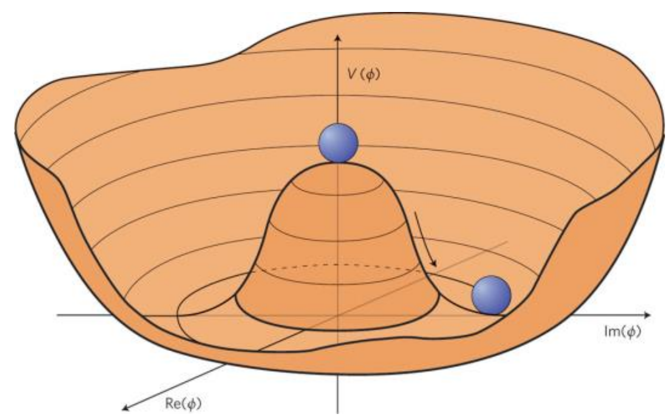
Then What? Theoretically ...

A new force of nature? $\lambda \sim 1/8$



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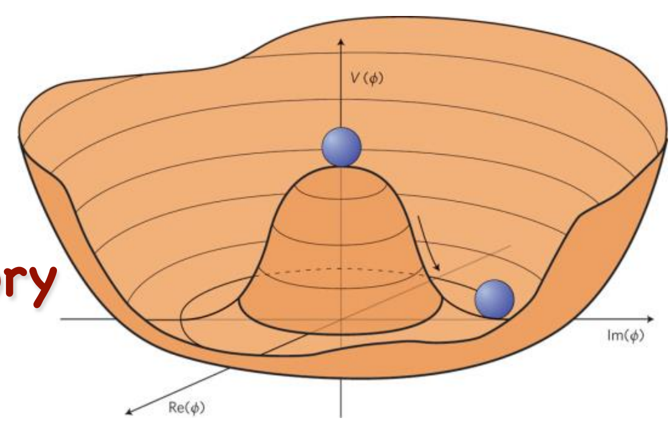
At the verge of uncovering a deep theory

- ◉ λ determined by guage couplings?

  e.g., SUSY, $\lambda = (g_1^2+g_2^2)/8$ ...

- ◉ or dynamically generated by a new strong force?

  e.g., technicolor, composite Higgs, Higgsless, extra dimensions,...



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Mass generation

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Higgs field → $4 = 3 + 1$

longitudinal modes of W^+, W^-, Z physical Higgs Boson

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$$\underset{\substack{\uparrow \\ \text{longitudinal modes of } W^+, W^-, Z}}{3} + \underset{\substack{\uparrow \\ \text{physical Higgs Boson}}}{1}$$

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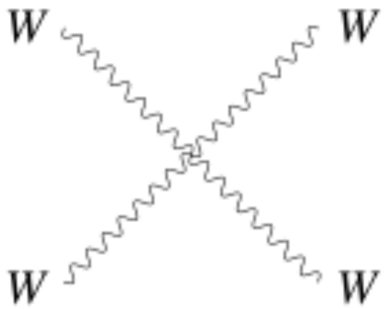
3

↑

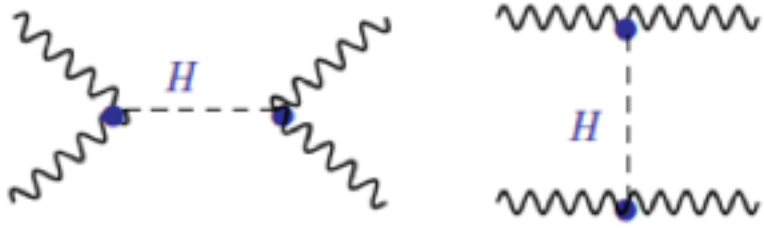
longitudinal modes of W^+,W^-,Z

Unitarity

But...



$E < m_h$



$E > m_h$

$$\mathcal{M}(W_L W_L \to W_L W_L) \sim \begin{cases} E_{cm}^2/v^2 & \text{no light Higgs,} \\ m_h^2/v^2 & \text{with a SM Higgs.} \end{cases}$$

Partial-wave unitarity demands

$$a_0 = \frac{1}{16\pi} \frac{m_h^2 \text{ or } E_{cm}^2}{v^2} \lesssim 1$$

$$\Rightarrow \quad m_h \text{ or } E_{cm} \lesssim \mathcal{O}(1 \text{ TeV}).$$

- **Picture is not valid at E ~ 4π m_W/g_W ~ 1 TeV**
- **Something new must happen before TeV scale.**

A Light Higgs is puzzling...

particle	spin
quark: u, d,...	1/2
lepton: e...	1/2
photon	1
W,Z	1
gluon	1
Higgs	0

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⇒ New Physics beyond the SM

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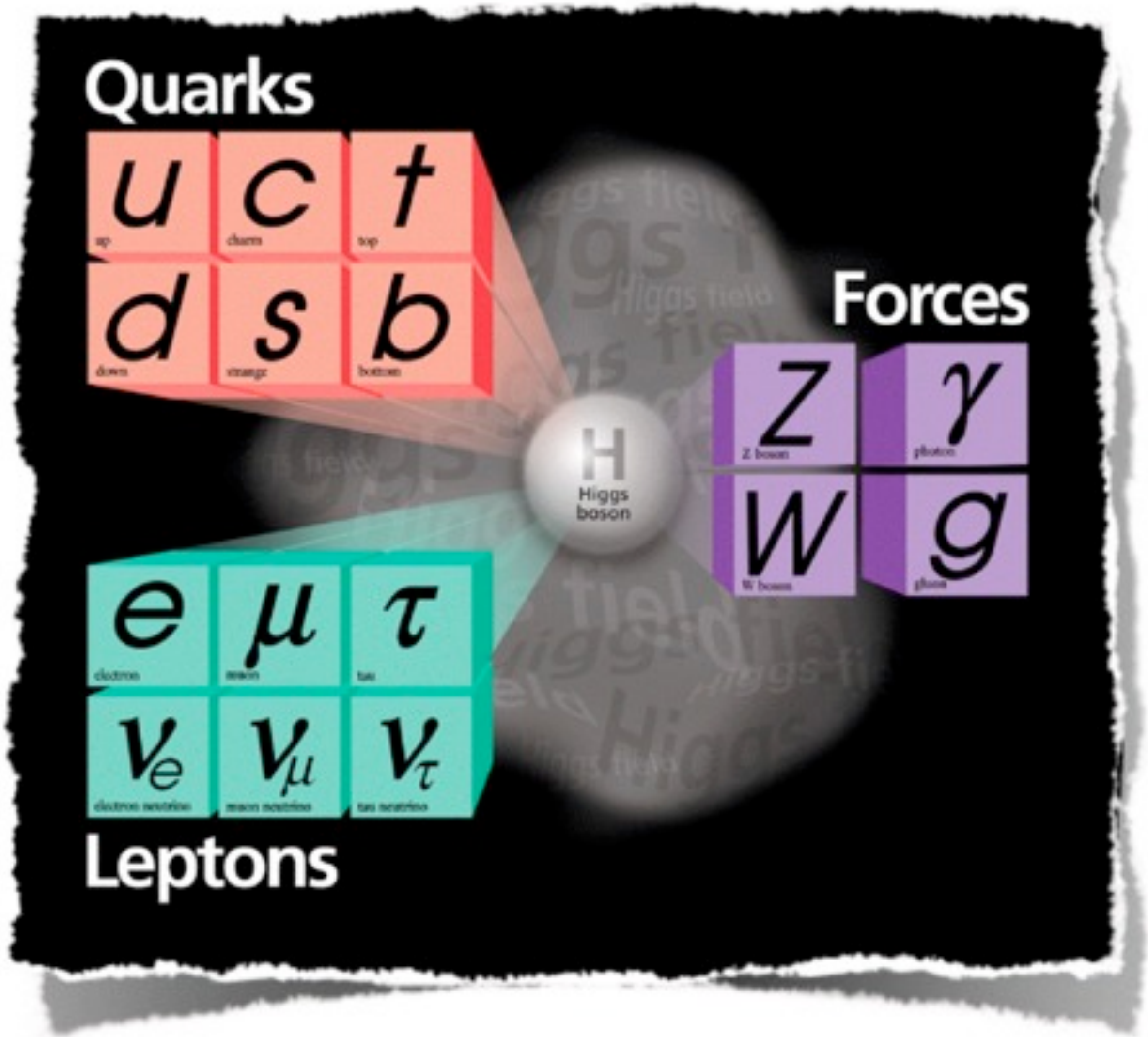
Quarks
u c t
d s b
Forces
Z γ
W g
H
Higgs boson
e μ τ
ν_e ν_μ ν_τ
Leptons


Quarks
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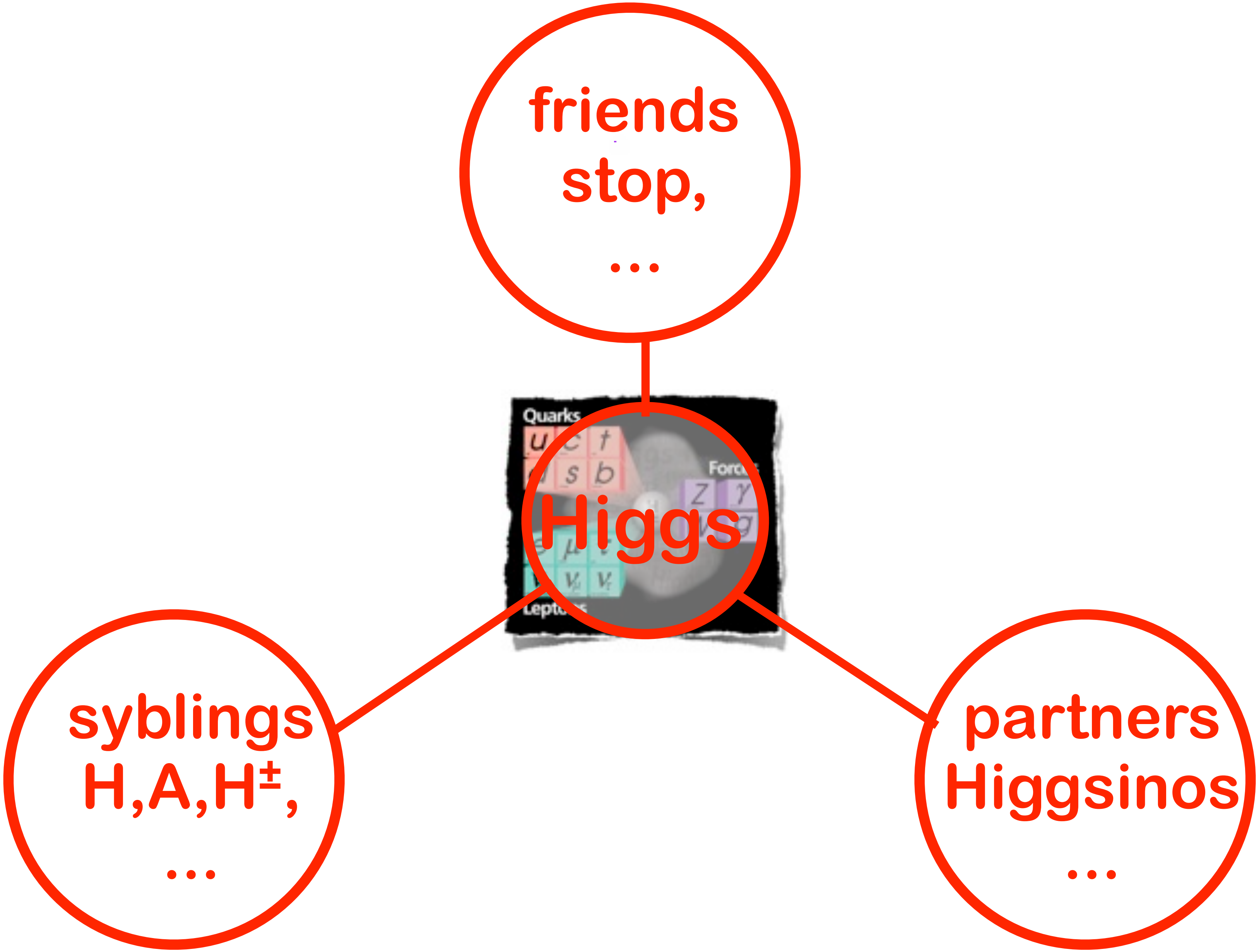
friends
stop,
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Outline

- Implication of SM Higgs search on BSM scenarios
  - MSSM, NMSSM, 2HDM
  - Dark matter connection
- Higgs-assisted BSM searches
  - SUSY electrowak-ino searches
- Searches for Higgs beyond the SM
  - exotic Higgs decays
- Conclusion

Review articles:
MSSM Higgs: xxx
NMSSM: 0304049
2HDM: 1106.0034

Talk based on work:
1203.3207, 1303.2113, 1305.0002,
1306.3229, 1308.6201, 1309.5966

I. Implication for BSM scenarios

Implication of 126 GeV Higgs

The current Higgs search results already impose non-trivial constraints on various new physics extensions.

Study the consequence of

(I) current Higgs search limit of 95% CL limit on $\sigma \times Br$

(II) H in the mass range of 124 - 128 GeV

(III) $\sigma \times Br$ ($gg \to H \to \gamma\gamma$, WW, ZZ) of SM strength

MSSM, NMSSM, 2HDM, ...

- Focus on the Higgs sector and stop sector
- Mostly only consider Higgs search results

MSSM Higgs Sector

- Type II Two Higgs Doublet Model

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \quad H_u^0 \to v_u/\sqrt{2} \qquad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \quad H_d^0 \to v_d/\sqrt{2}$$

$$v_u^2 + v_d^2 = v^2 = (246\mathrm{GeV})^2 \qquad \tan\beta = v_u/v_d$$

after EWSB
5 physical Higgses
CP-even Higgses: h^0, H^0
CP-odd Higgs: A^0
Charged Higgses: $H^\pm$

- tree level masses determined by mA, tanβ

$$m_{h^0,H^0}^2 = \frac{1}{2}\left((m_A^2 + m_Z^2) \mp \sqrt{(m_A^2 - m_Z^2)^2 + 4m_A^2 m_Z^2 \sin^2 2\beta}\right)$$

$$m_{H^\pm}^2 = m_A^2 + m_W^2, \quad \cos^2(\beta-\alpha) = \frac{m_{h^0}^2(m_Z^2 - m_{h^0}^2)}{m_A^2(m_{H^0}^2 - m_{h^0}^2)}.$$

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$\Rightarrow m_{h0} < m_Z$

Higgs Masses

- large radiative corrections from stop sector: large Yukawa coupling

$$\Delta m_{h^0}^2 \approx \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right)+\frac{\tilde{A}_t^2}{M_S^2}\left(1-\frac{\tilde{A}_t^2}{12M_S^2}\right)\right]+\ldots,$$

$$\tilde{A}_t = A_t - \mu\cot\beta.$$

- (m_h^{min}) scenario: $\tilde{A}_t = 0$

  m_{h0} < 117 GeV for Ms < 2 TeV

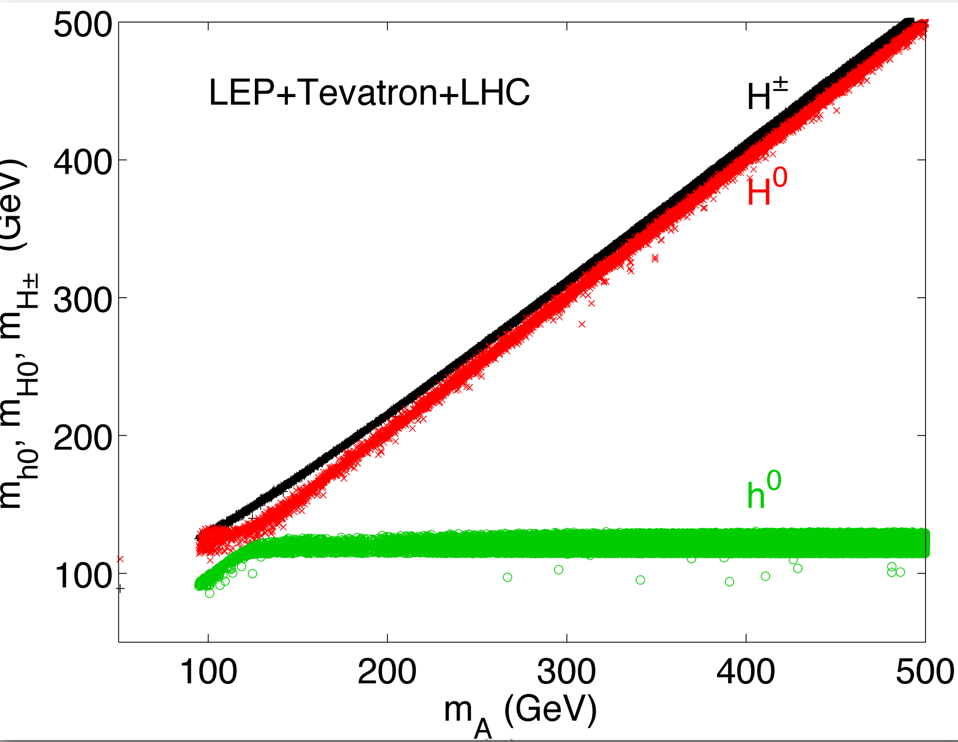
- (m_h^{max}) scenario: $\tilde{A}_t = \sqrt{6}\, M_s$

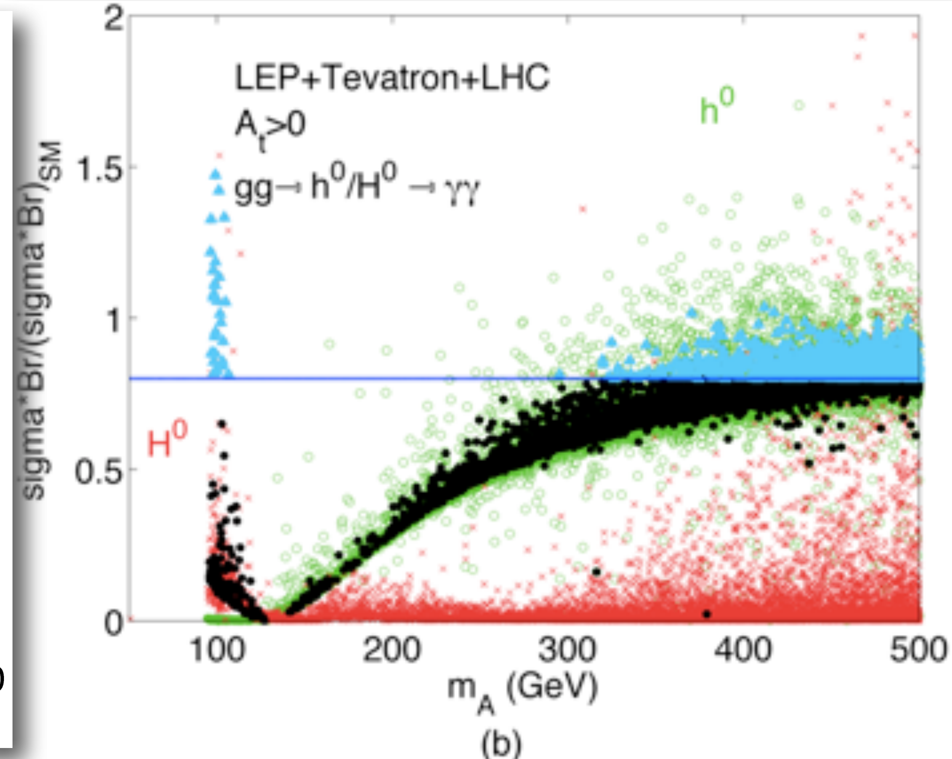
  m_{h0} < 127 GeV for M_s < 2 TeV

- To obtain relative large correction to m_{h0}
  - relatively large stop masses (at least one)
  - large stop LR mixing

non-decoupling vs. decoupling region

N. Christensen, T. Han, SS (2012)





black dots: $123 < m_{h0}$ or $m_{H0} < 127$ GeV

blue dots: $\sigma X Br\,(gg \to h^0, H^0 \to \gamma\gamma)_{MSSM} > 80\%\ (\sigma X Br)_{SM}$

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- **decoupling limit**

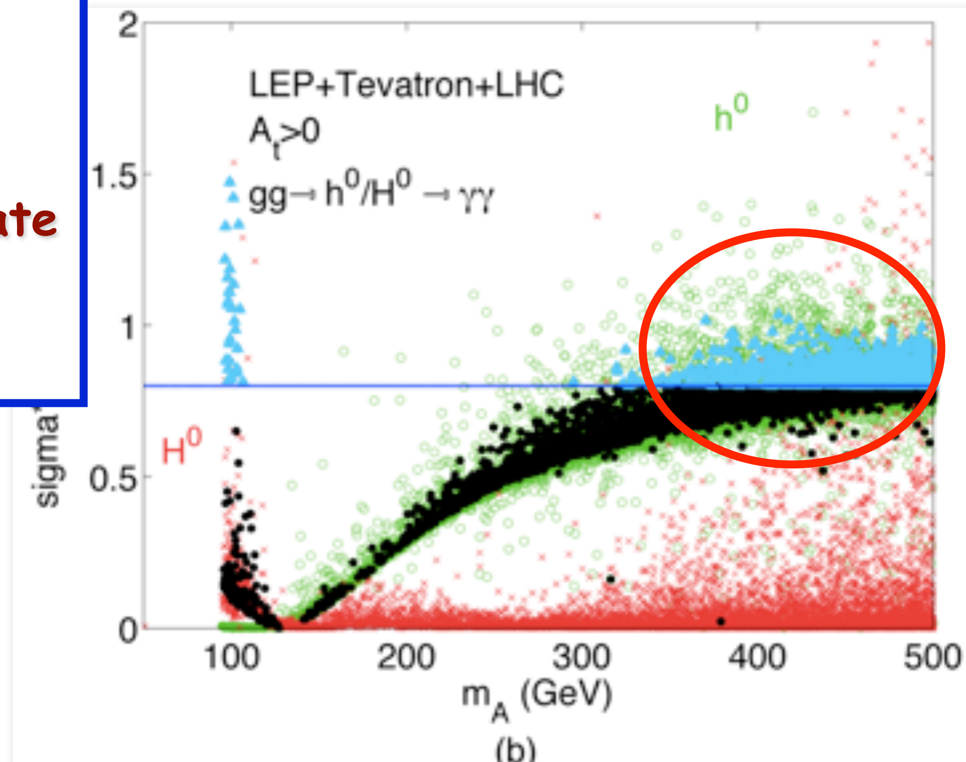
  $m_A \gg m_Z$

  $\sin(\beta-\alpha) \sim 1, \ \cos(\beta-\alpha) \sim 0$

  - h^0 light, SM like,
  - H^0, A^0, $H^\pm$ heavy, nearly degenerate
  - H^0WW, H^0ZZ coupling suppressed

    ~ $\cos(\beta-\alpha)$

decoupling region



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  $\sim \cos(\beta-\alpha)$

- **non-decoupling limit**

  $m_A \sim m_Z$

  $\sin(\beta - \alpha) \sim 0, \ \cos(\beta - \alpha) \sim 1$

  – all Higgses light

  – H^0 SM like

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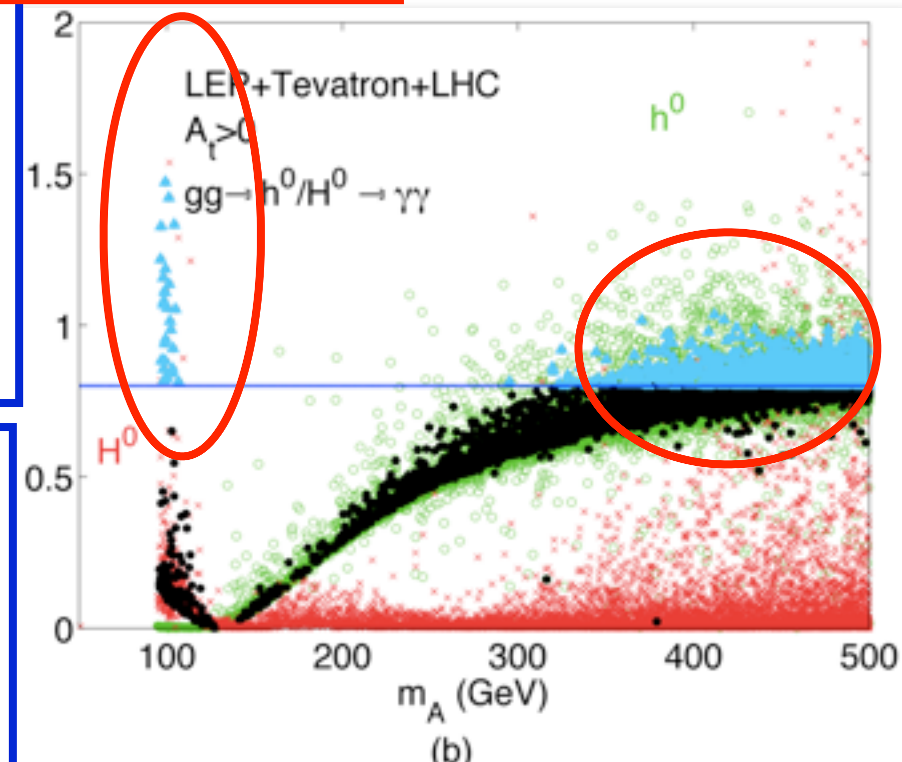
non-decoupling region

decoupling region



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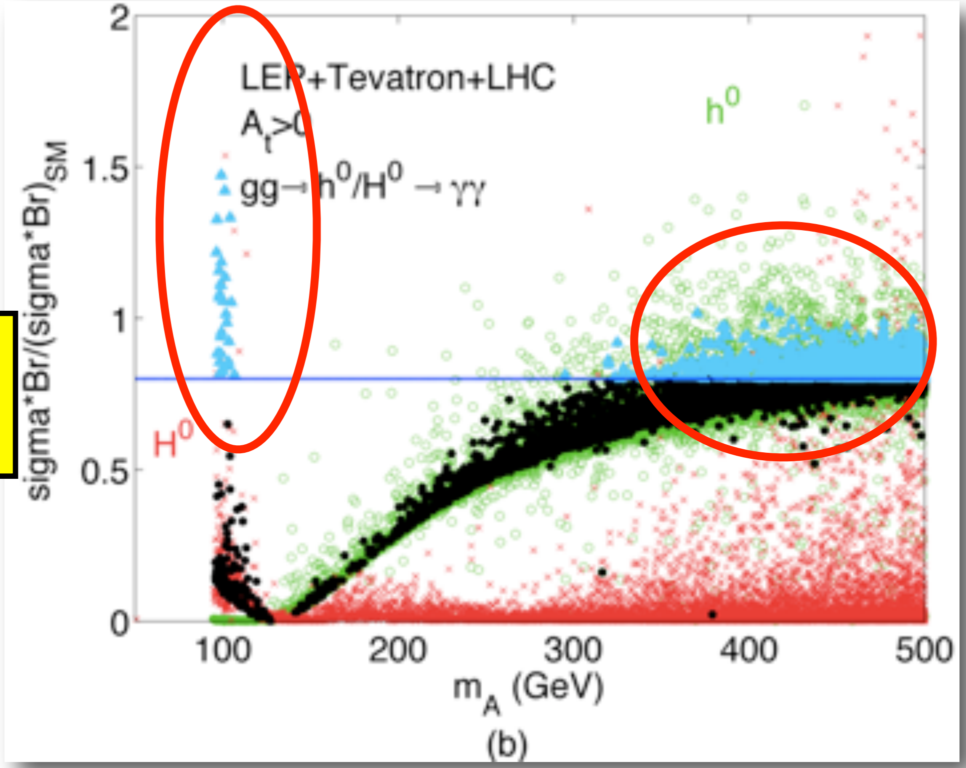

- h^0 SM-like: large $m_A \gtrsim 300$ GeV
- small $m_A \sim m_Z$: H^0 SM-like

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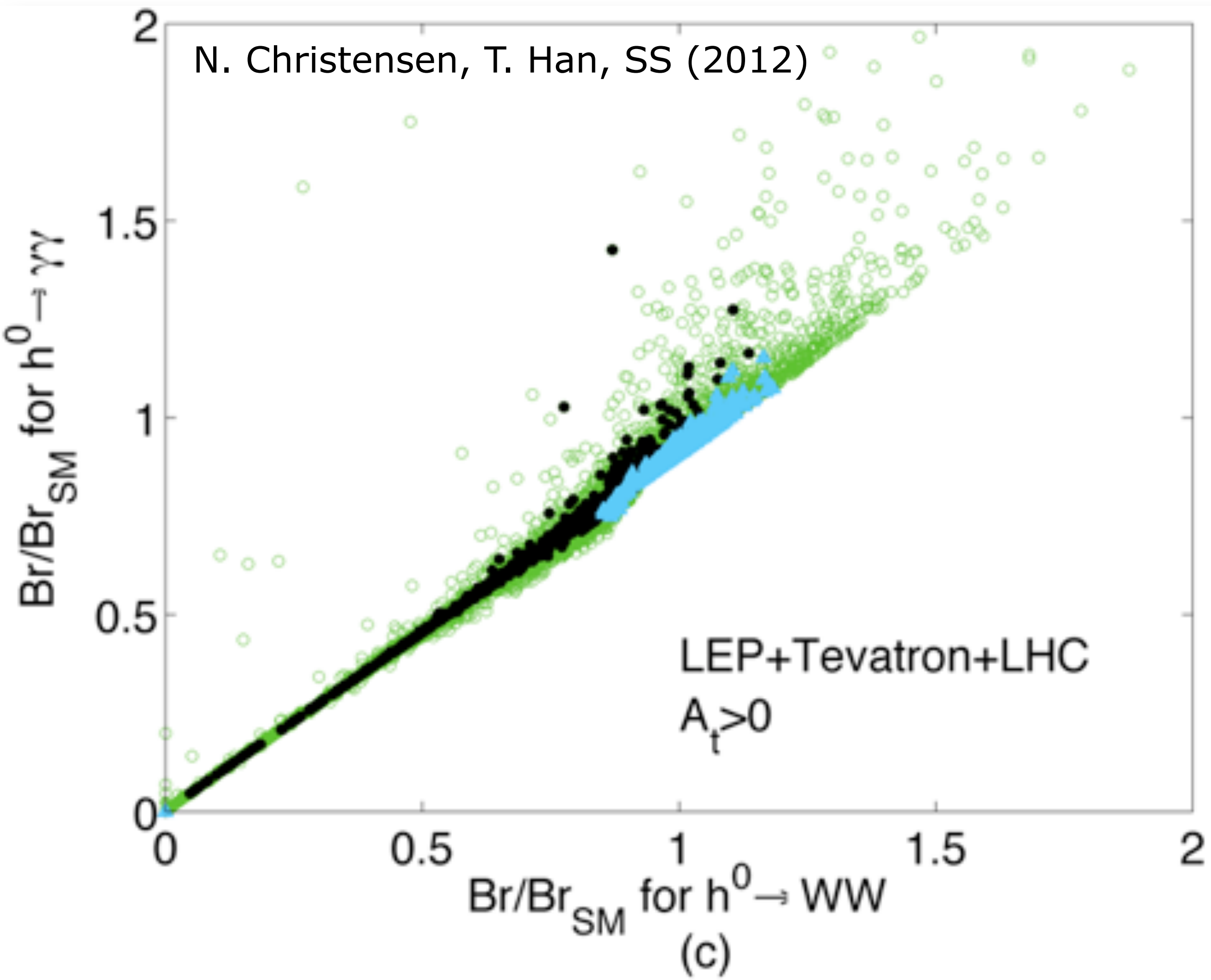
Allowed Region: gg→h^0,H^0→γγ, WW

- **correlation between γγ and WW**



h^0WW coupling: source for both h0 → γγ and WW

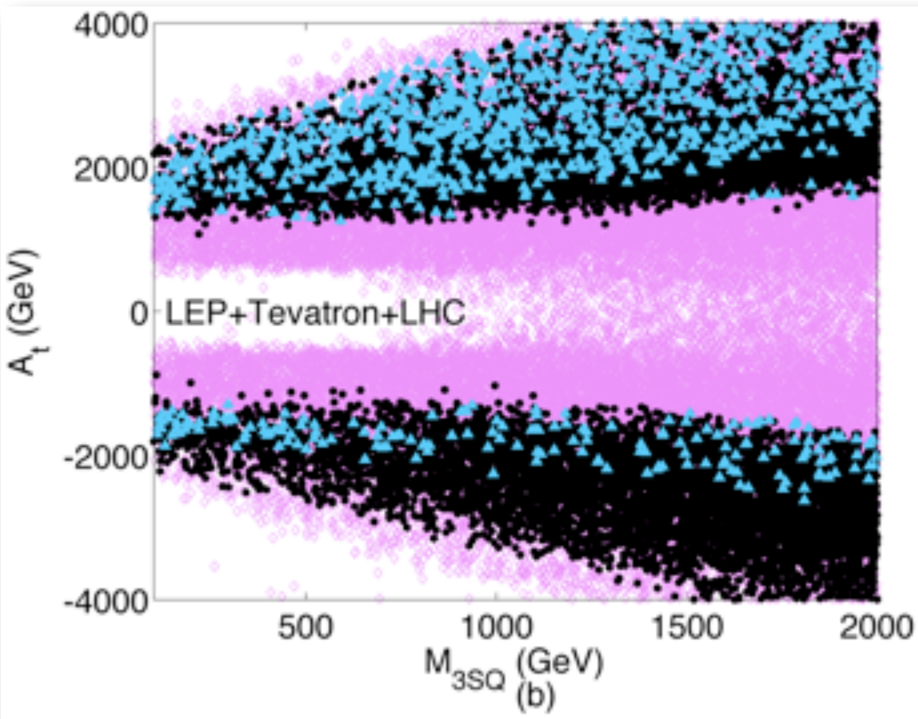
$$\frac{\mathrm{Br}(\gamma\gamma)}{\mathrm{Br}(\gamma\gamma)_{SM}} \approx 0.9\,\frac{\mathrm{Br}(W^+W^-)}{\mathrm{Br}(W^+W^-)_{SM}}.$$

Stop Masses

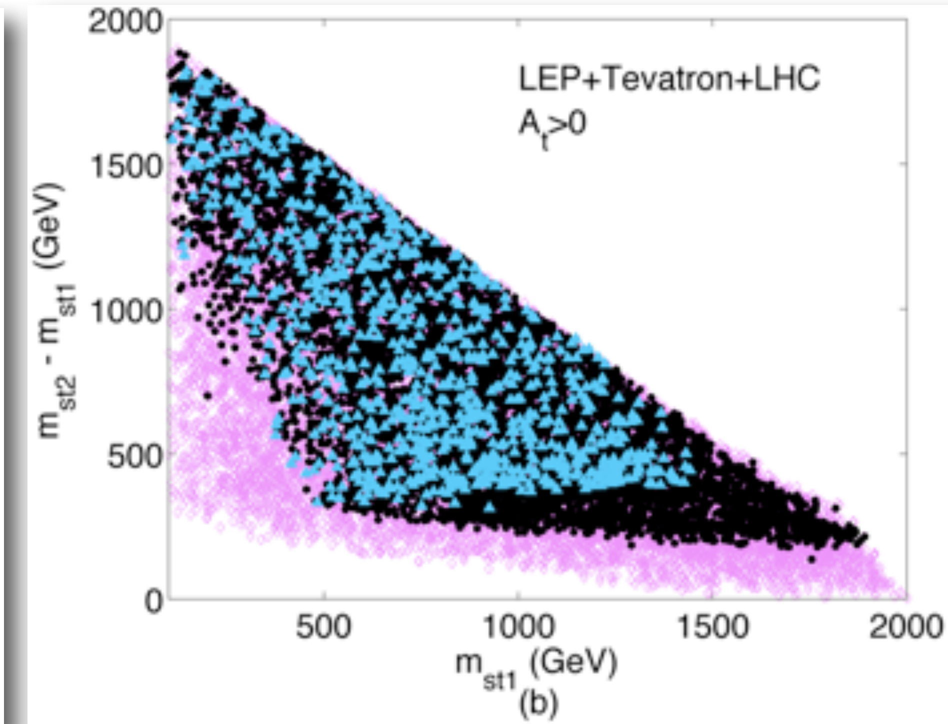
N. Christensen, T. Han, SS (2012)

Heavy stops and/or large LR mixing.

◉ M_{3SQ} vs A_t



◉ m_{st1} vs m_{st2}-m_{st1}



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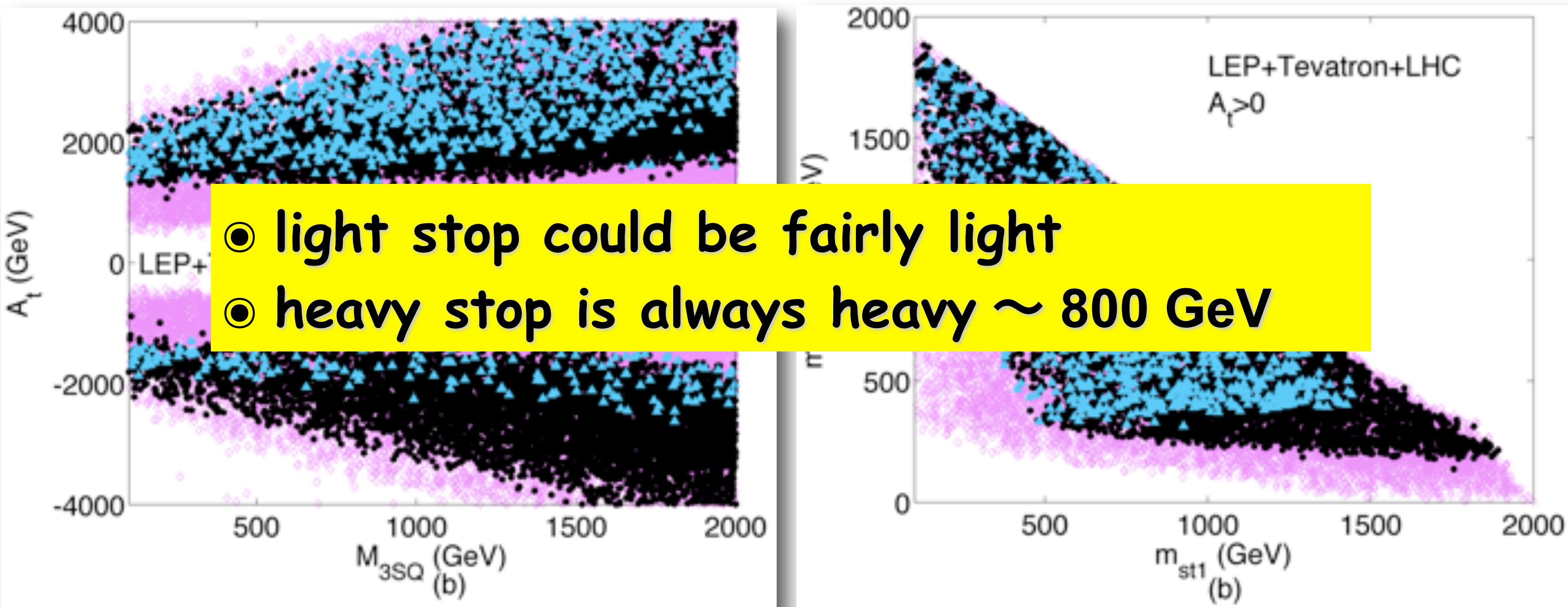

- ◉ light stop could be fairly light
- ◉ heavy stop is always heavy ~ 800 GeV

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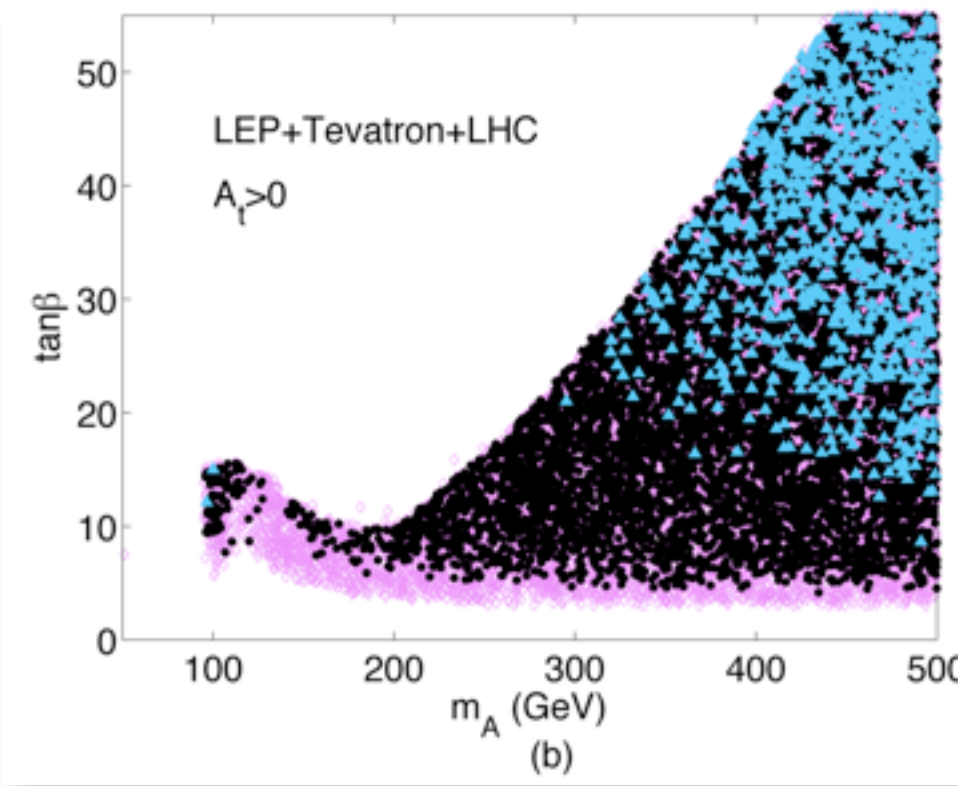
Allowed Parameter Region

N. Christensen, T. Han, SS (2012)

◉ **m_A vs tan β**



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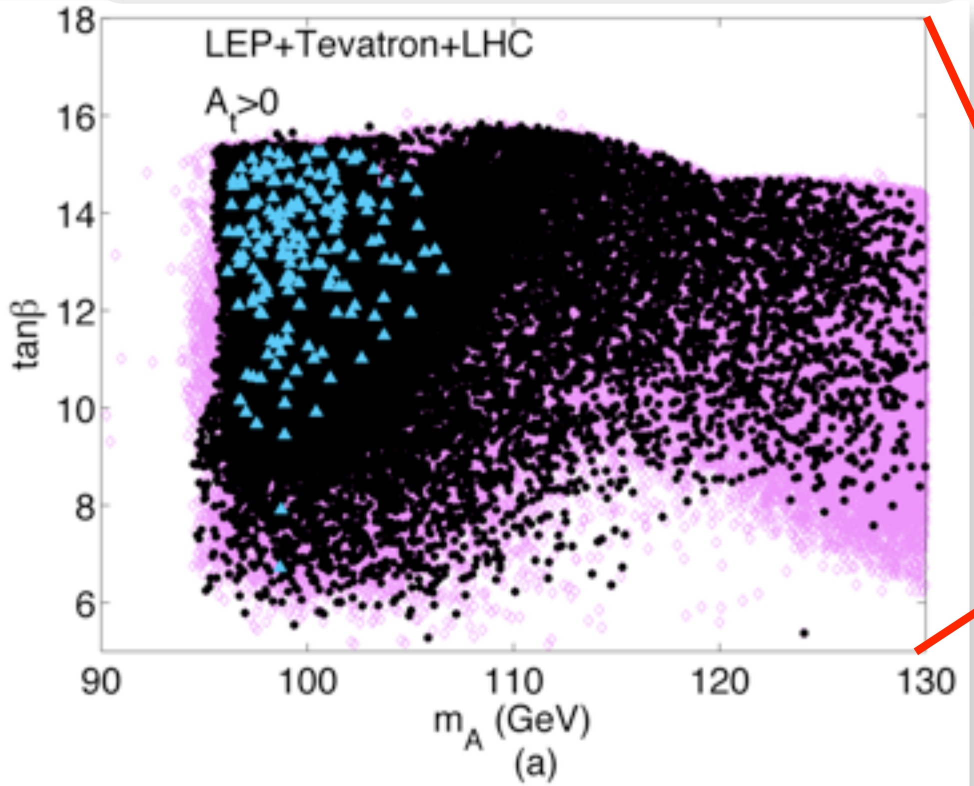
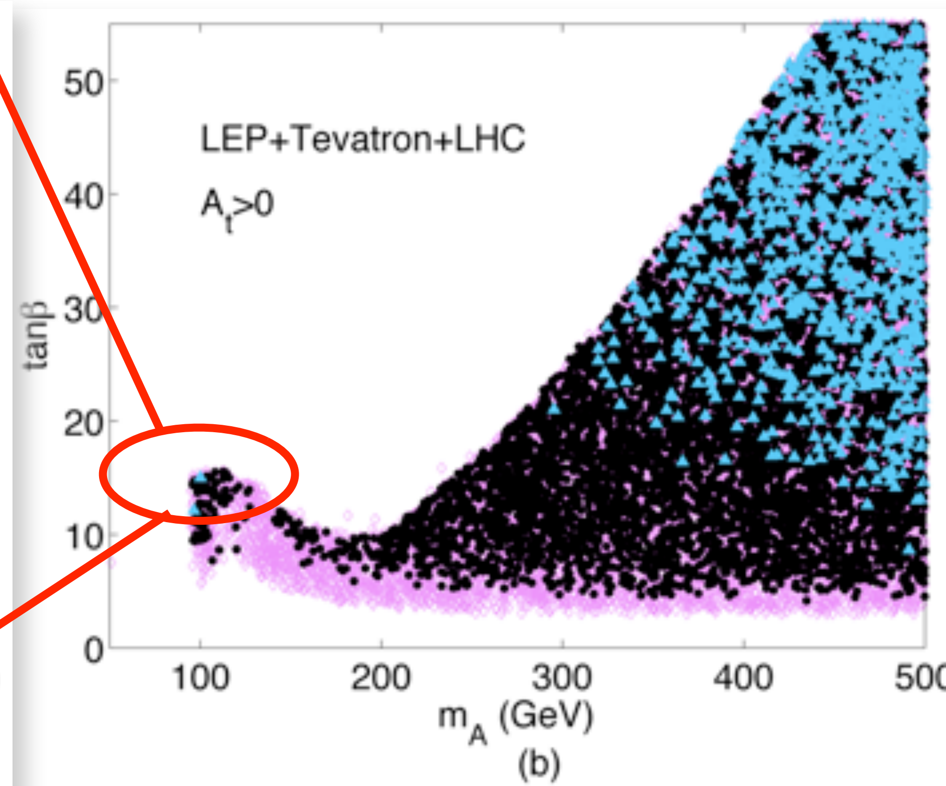
Non-decoupling region

$$95\ \mathrm{GeV} < m_A < 110\ \mathrm{GeV}, \quad 6 < \tan\beta < 16$$



- m_A vs $\tan\beta$



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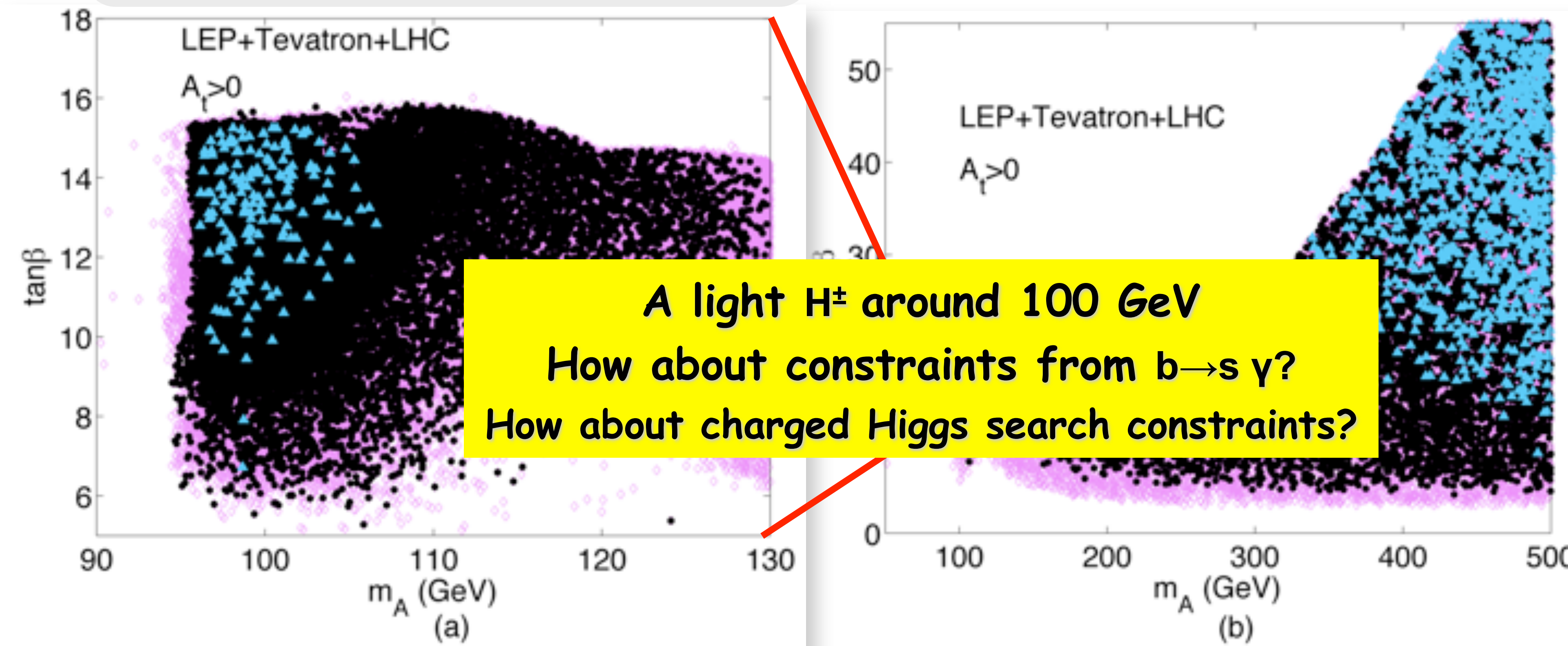

A light $H^{\pm}$ around 100 GeV

How about constraints from b→s γ?

How about charged Higgs search constraints?

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heavy stops (with large LR mixing): fine-tuning

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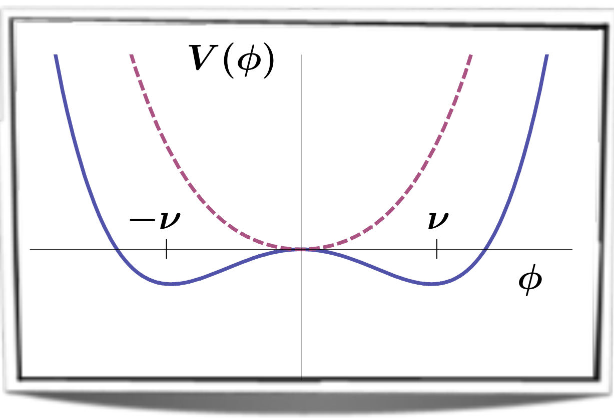

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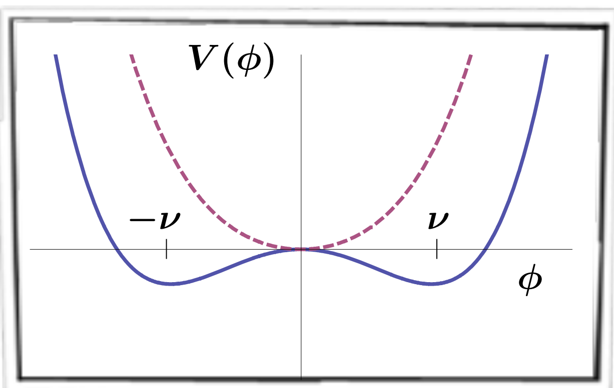

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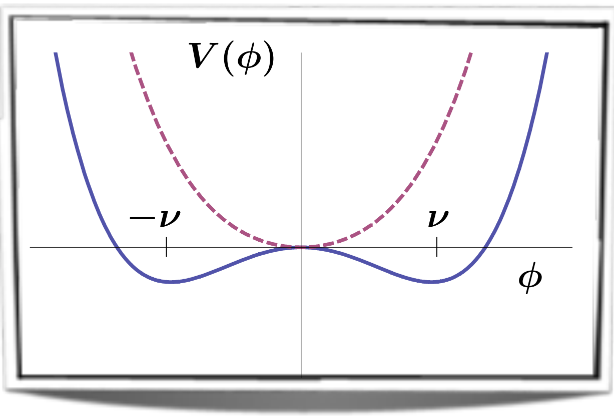

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$\lambda = (g_1^2+g_2^2)/8$

add another singlet S $\Rightarrow$ **NMSSM**

NMSSM Higgs Sector

- Type II Two Higgs Doublet Model plus singlet S

$$W_{\text{NMSSM}} = Y_u \hat{u}^c \hat{H}_u \hat{Q} + Y_d \hat{d}^c \hat{H}_d \hat{Q} + Y_e \hat{e}^c \hat{H}_d \hat{L} + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3}\kappa \hat{S}^3$$

$$V_{H,Soft} = m_{H_u}^2 H_u^\dagger H_u + m_{H_d}^2 H_d^\dagger H_d + M_S^2 |\mathcal{S}|^2 + \left(\lambda A_\lambda (H_t^T \epsilon H_d)\mathcal{S} + \frac{1}{3}\kappa A_\kappa \mathcal{S}^3 + c.c. \right)$$

- SSB

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \qquad H_u^0 \to v_u/\sqrt{2}$$

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \qquad H_d^0 \to v_d/\sqrt{2}$$

$$S \to v_s/\sqrt{2}$$
$$(\mu = \lambda v_s/\sqrt{2})$$

$$v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2$$
$$\tan\beta = v_u/v_d$$

after EWSB, 7 physical Higgses

CP-even Higgses: H_1, H_2, H_3

CP-odd Higgs: A_1, A_2

Charged Higgses: $H^\pm$

NMSSM: Masses for Higgs

- Effects of singlet
  - lift $(m_{hv})_{tree}$, small tanβ, large λ

$$(m^2_{h_v})_{\rm tree} = m_Z^2 \cos^2 2\beta + \frac{1}{2}(\lambda v)^2 \sin^2 2\beta$$

  - mixing with singlet: change H_iWW/ZZ, H_ibb, H_igg, $H_i\gamma\gamma$

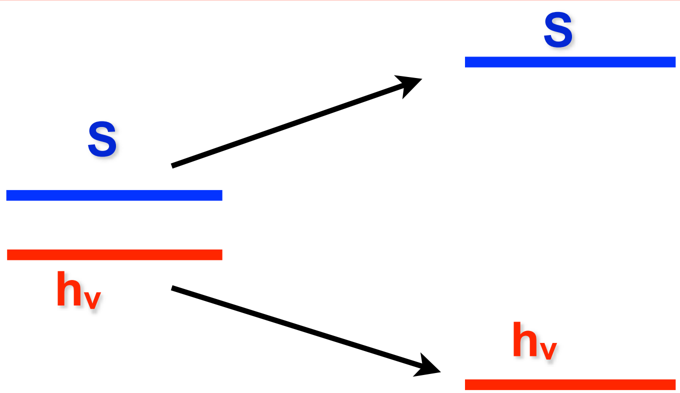
- Lots of work on (125 GeV) Higgs in NMSSM framework ...

Gunion et. al, 1201.0982
Ellwanger 1112.3548
King et. al., 1201.2671
Cao et. al., 1202.5821
EllWanger et. al., 1203.5048
Benbrik et. al., 1207.1096
Gunion et. al., 1207.1545
Gunion et. al., 1208.1817
Cheng et. al., 1207.6392
Belanger et. al., 1208.4952
Agashe et. al., 1209.2115
Belanger et. al., 1210.1976
Heng, 1210.3751
Choi et. al., 1211.0875
King et. al., 1211.5074
Dreiner et. al., 1211.6987
Das et. al., 1301.7548
... many other Jack's, Ellwanger's paper ...
(incomplete list)

- H3 heavy, m_A large
- H1 126 or H2 126
- h_v/S mixing

NMSSM: m_A decouple case

- push down: $m_{h_v} < m_S$

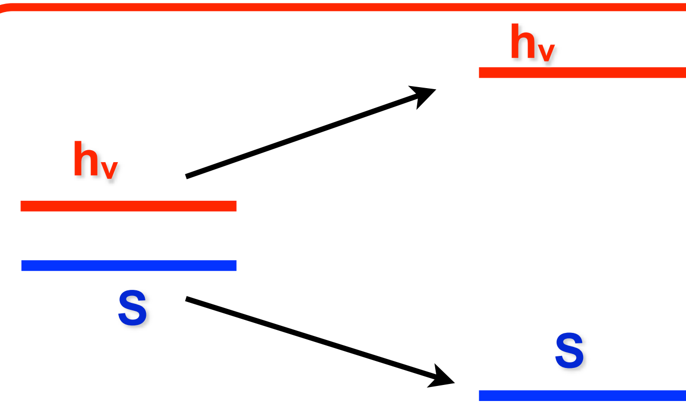


- H_1 (SM-like) still heavy enough $\geq$ 124 GeV

$\Rightarrow$ not too large mass mixing

(to push down m_{H1} too low)

- push up: $m_{h_v} > m_S$



- H_1 (singlet-like) not ruled out by LEP

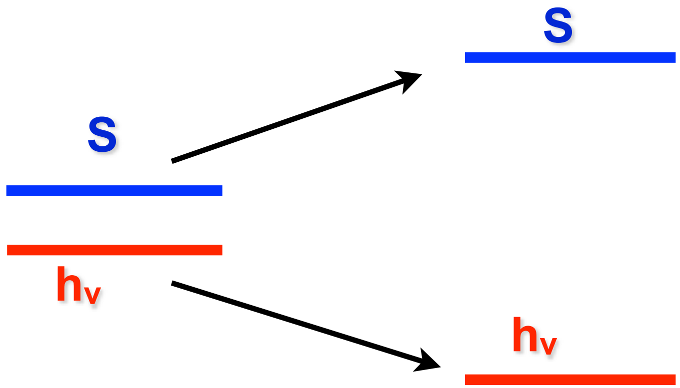
$\Rightarrow$ not too large state mixing

(to have too much H_1ZZ coupling)

Agashe et. al., 1209.2115

NMSSM: m_A decouple case

- push down: $m_{hv} < m_S$

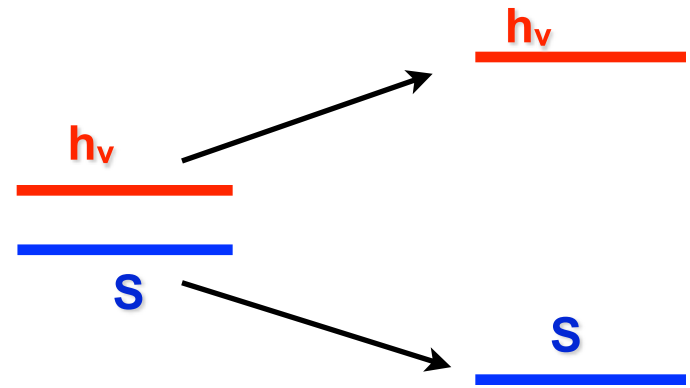


- H_1 (SM-like) still heavy enough ≥ 124 GeV

⇒ not too large mass mixing

(to push down m_{H1} too low)

- push up: $m_{hv} > m_S$



- H_1 (singlet-like) not ruled out by LEP

⇒ not too large state mixing

(to have too much H_1ZZ coupling)

Need some tuning to make it work (without too much help from stops)

Agashe et. al., 1209.2115

NMSSM: Masses for Higgses

Our work: Focus on the NMSSM low m_A region: $m_A \lesssim 2\, m_Z$

All Higgses light
- could have large mixing effects
- can be probed experimentally

NMSSM: Masses for Higgses

Our work: Focus on the NMSSM low m_A region: $m_A \lesssim 2\, m_Z$

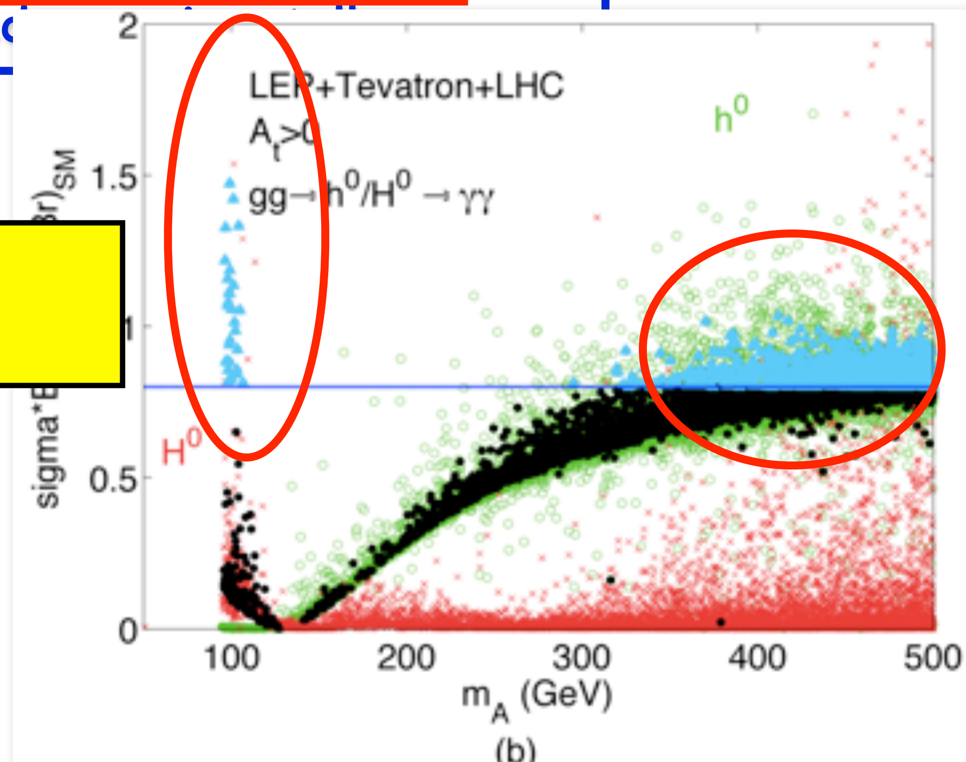
All Higgses light

– could have

– can be probed

non-decoupling region

decoupling region



- h^0 SM-like: large $mA \geq 300$ GeV
- small $m_A \sim m_Z$: H^0 SM-like

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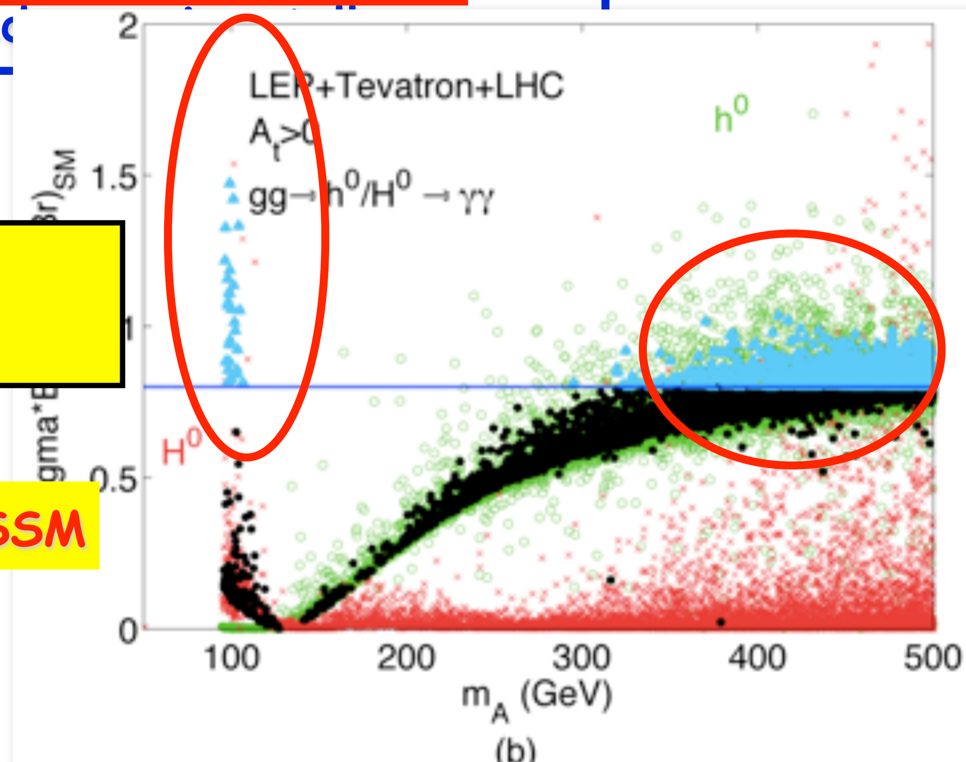
NMSSM: Masses for Higgses

Our work: Focus on the NMSSM low m_A region: $m_A \lesssim 2\, m_Z$

All Higgses light
– could hav
– can be probe

non-decoupling region

decoupling region



- h^0 SM-like: large mA $\geq$ 300 GeV
- small $m_A \sim m_Z$: H^0 SM-like

both are not necessary true in NMSSM

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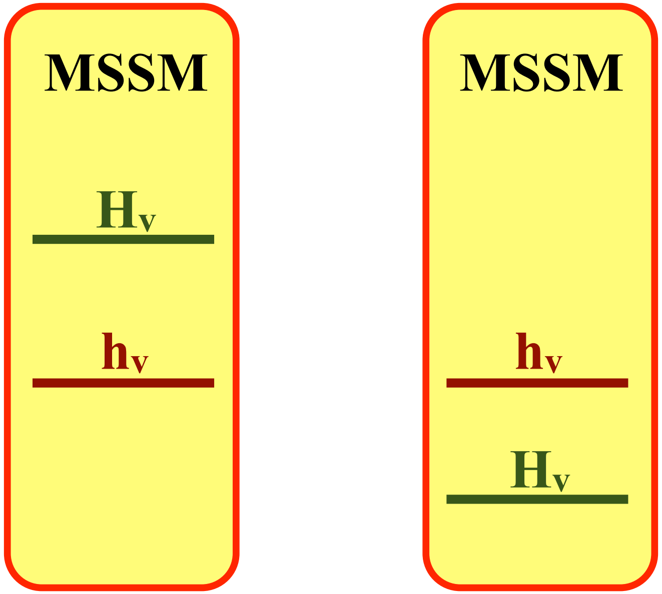
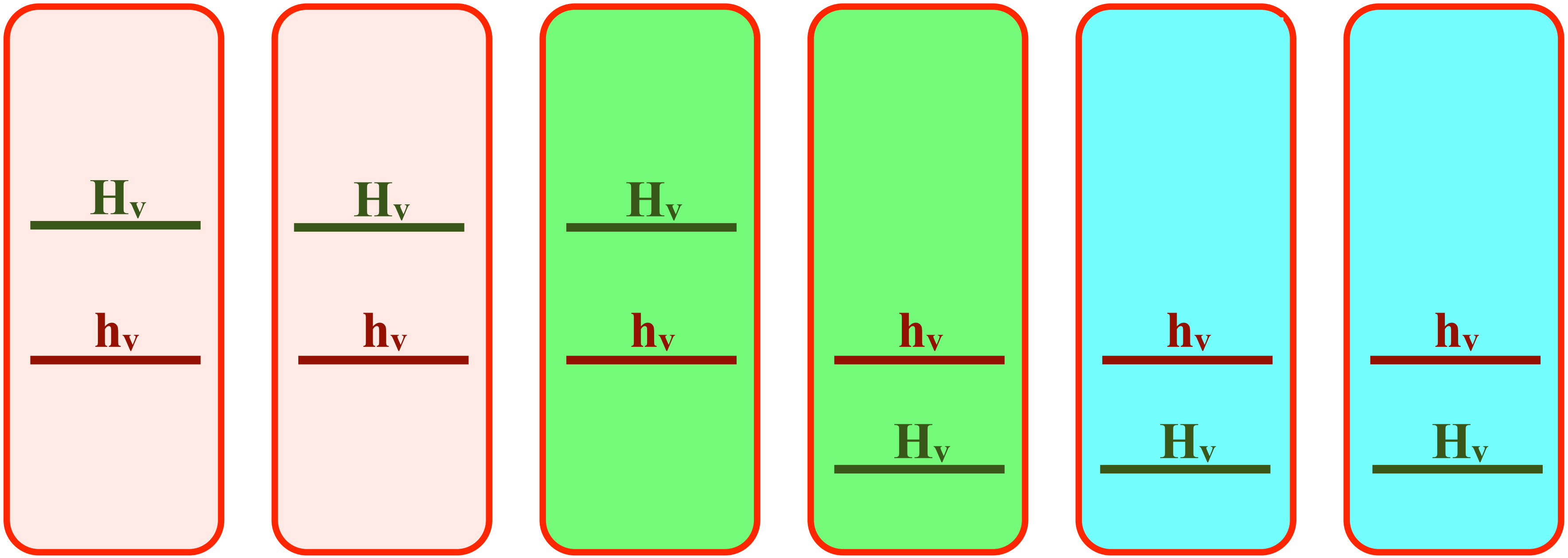
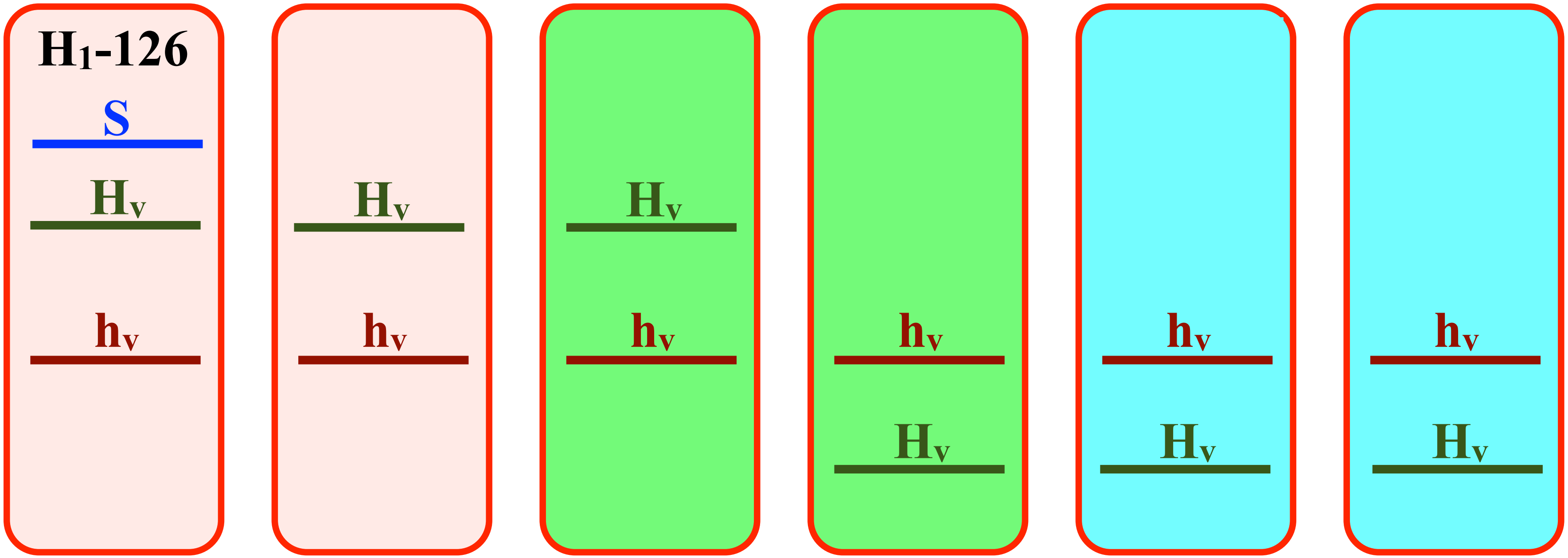
NMSSM non-decoupling cases



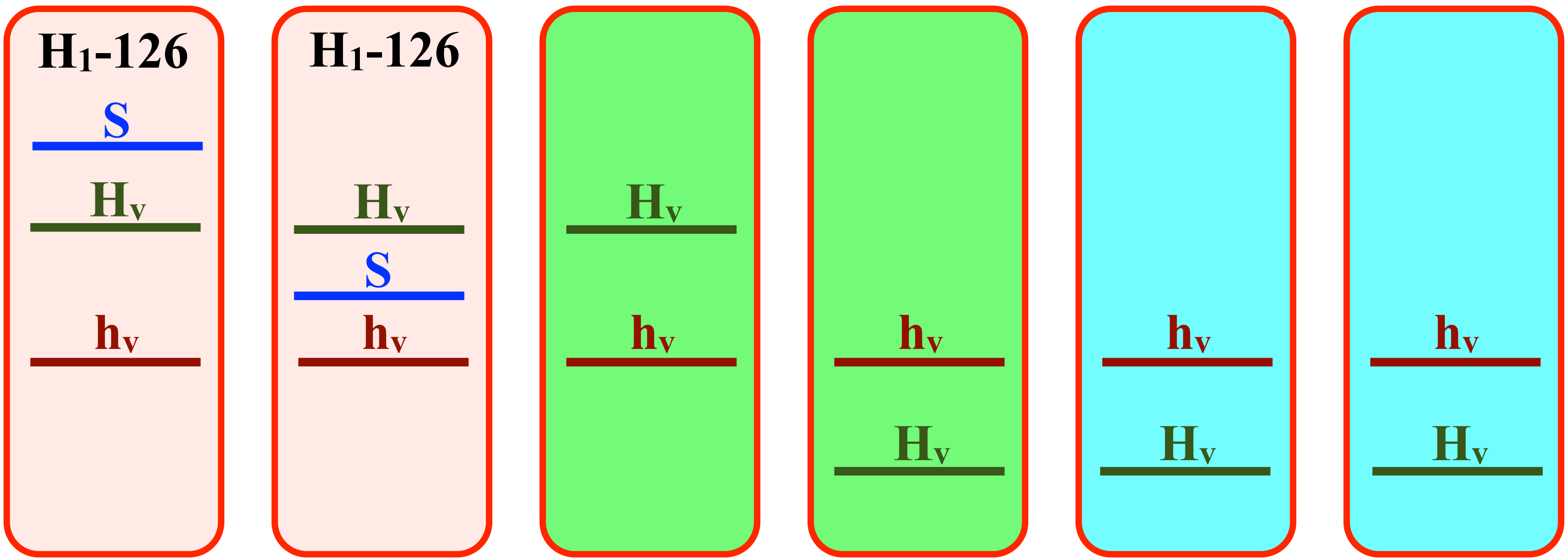
NMSSM non-decoupling cases



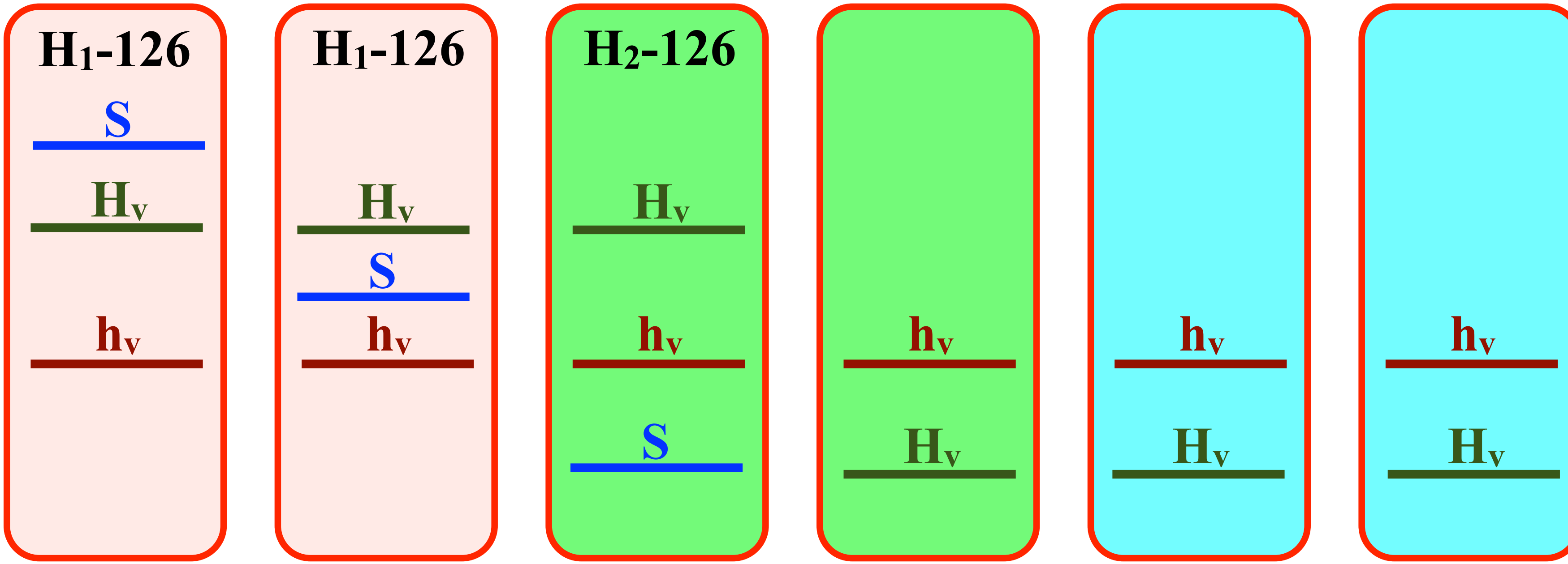
NMSSM non-decoupling cases



NMSSM non-decoupling cases



NMSSM non-decoupling cases



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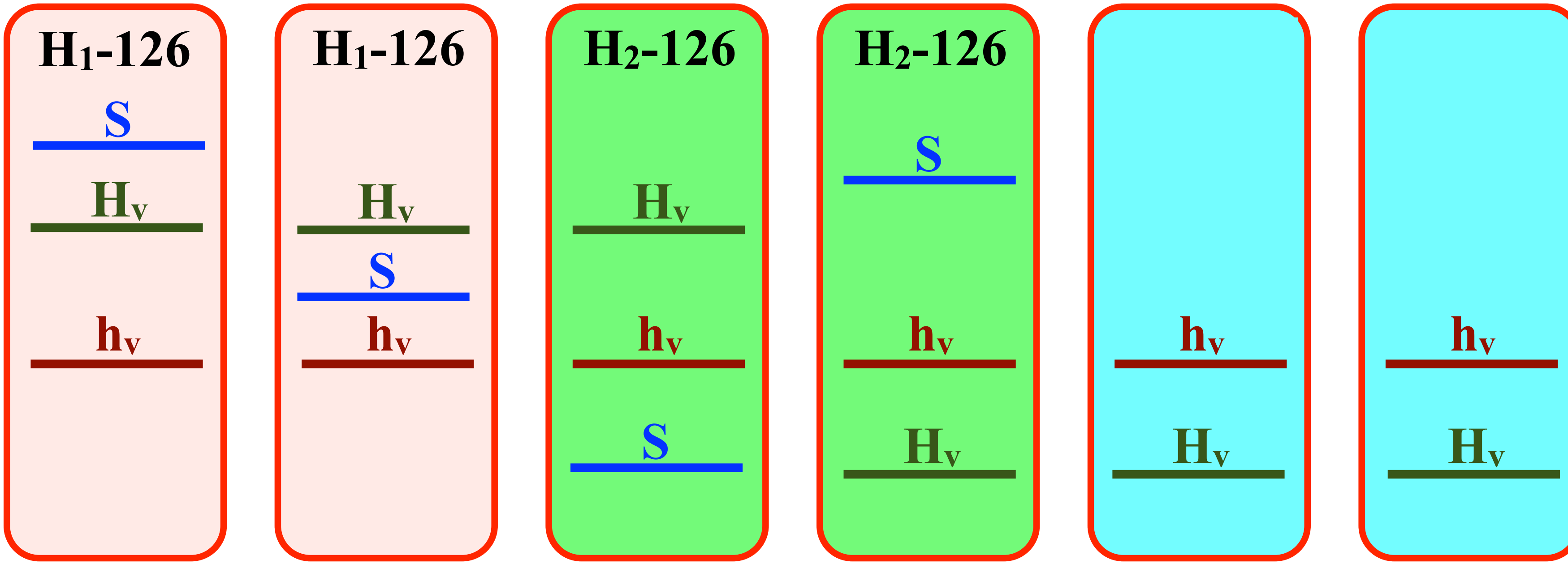
NMSSM non-decoupling cases



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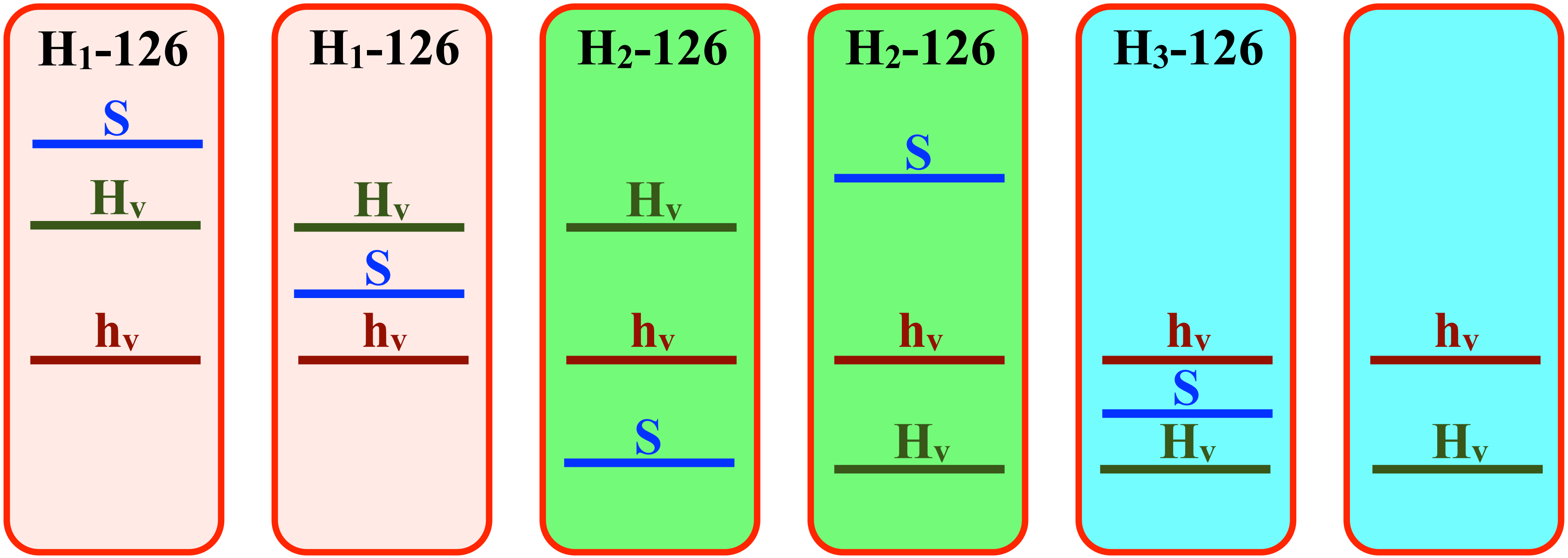
NMSSM non-decoupling cases



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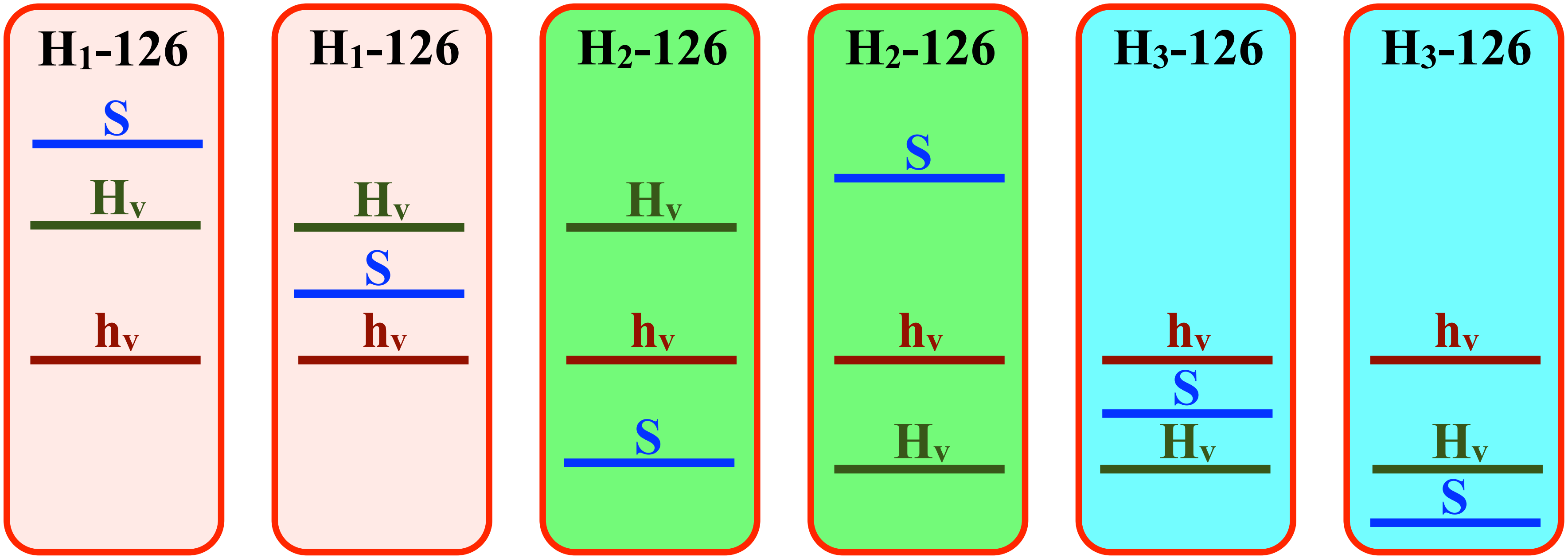
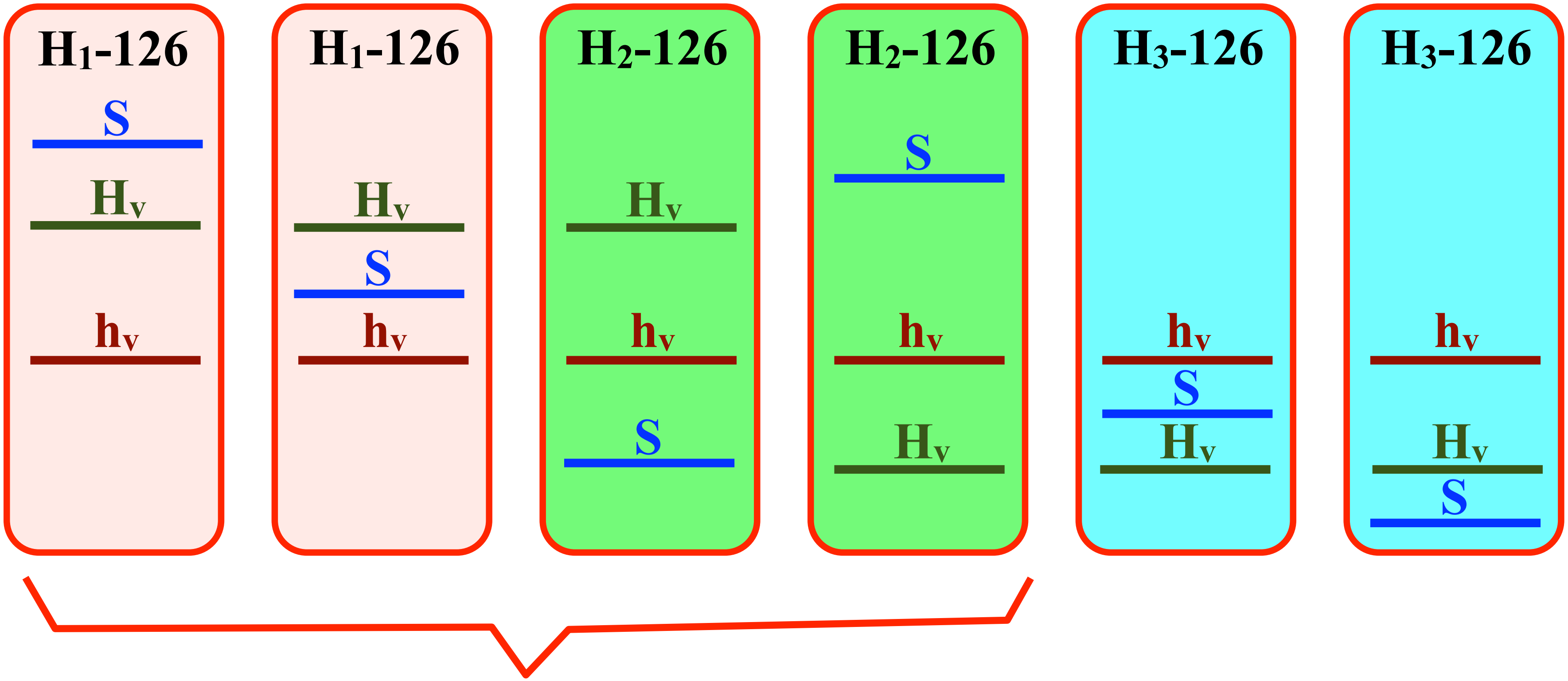
NMSSM non-decoupling cases



NMSSM non-decoupling cases



could be realized

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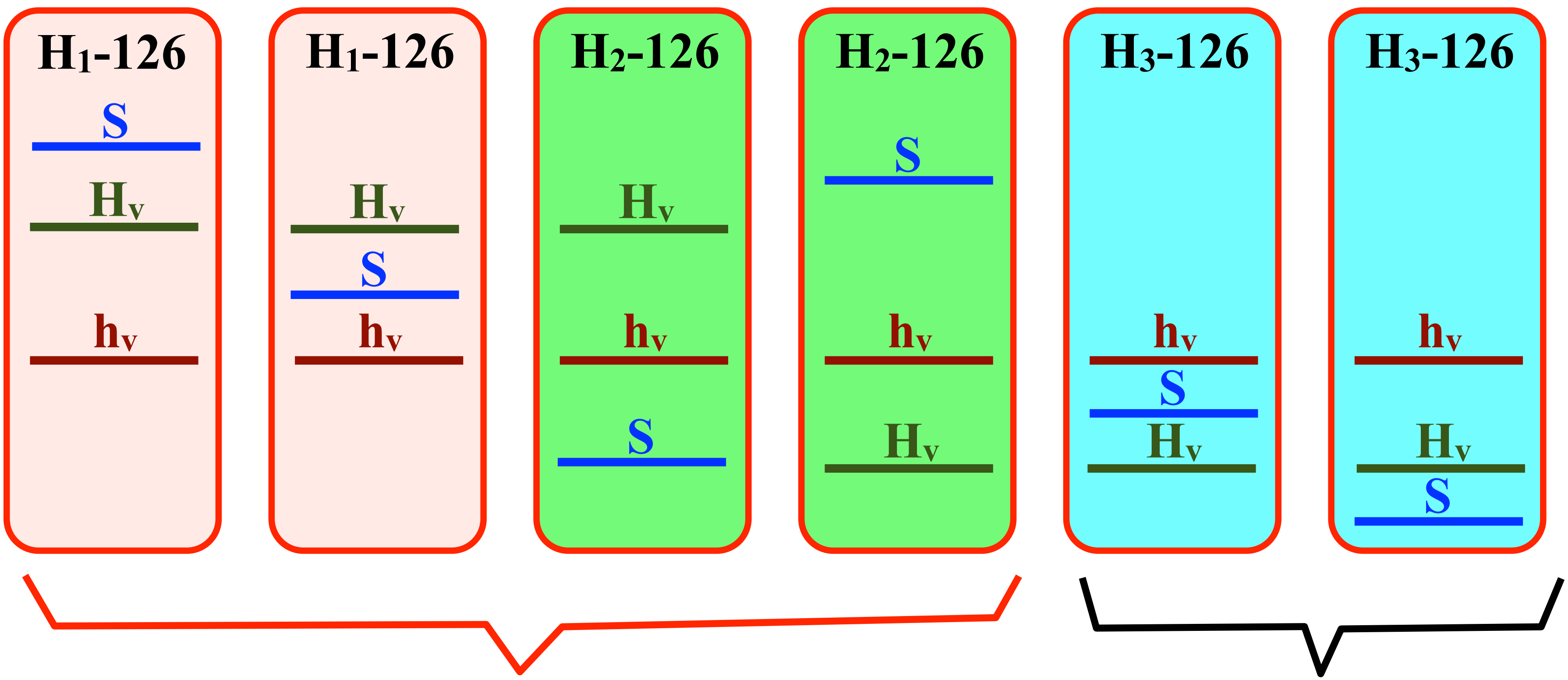
NMSSM non-decoupling cases



could be realized

hard to realized

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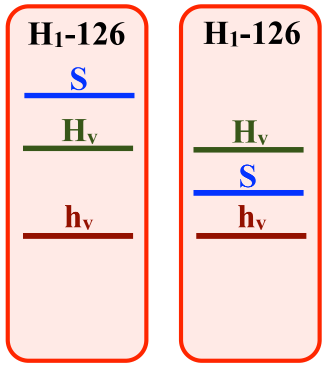
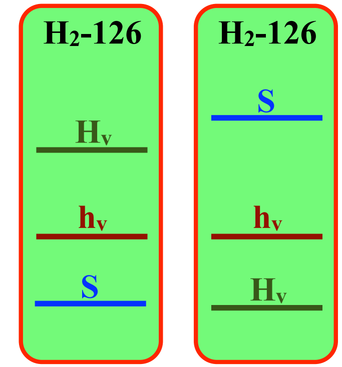
NMSSM Higgs

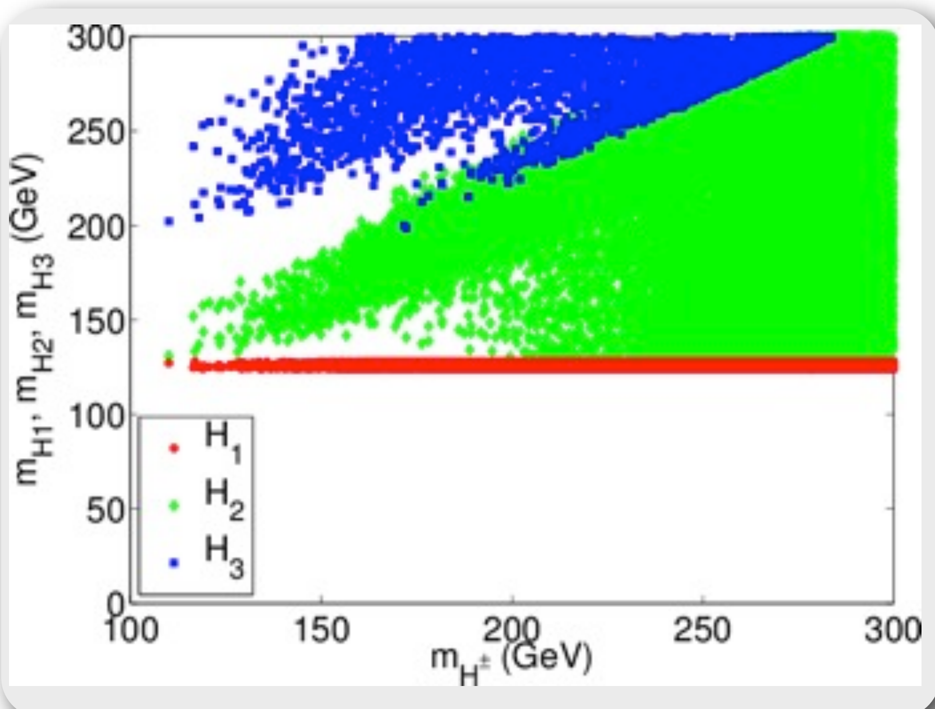
N. Christensen, T. Han, Z. Liu, SS (2013)

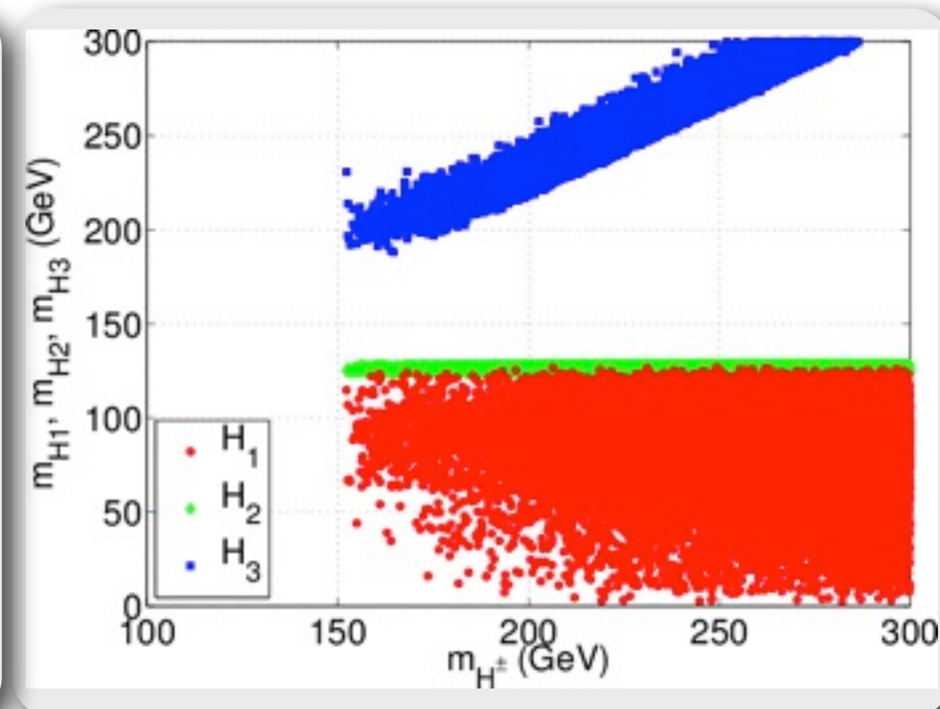
- H_1 126 GeV



- H_2 126 GeV



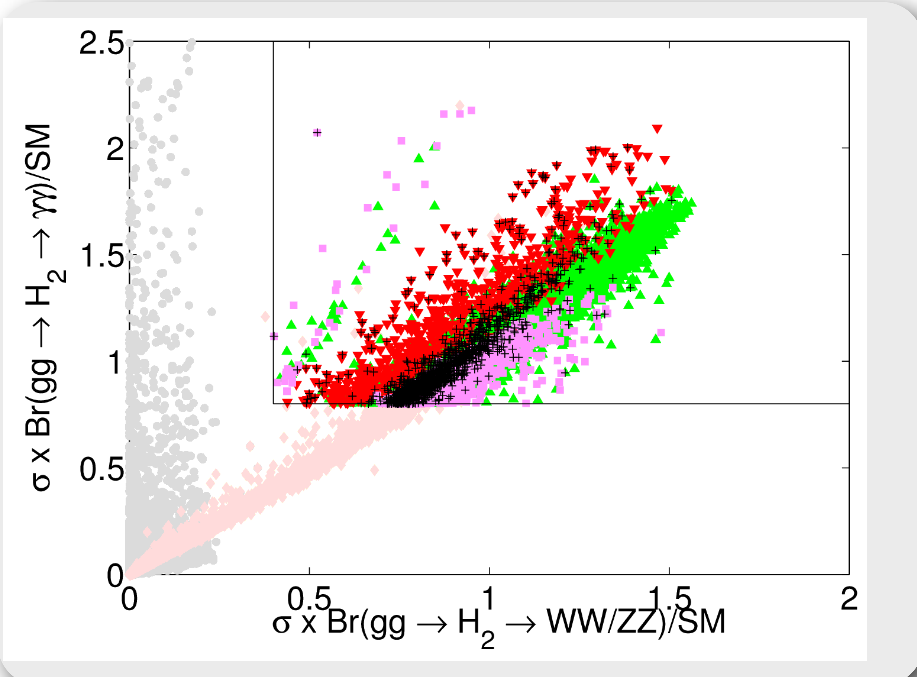




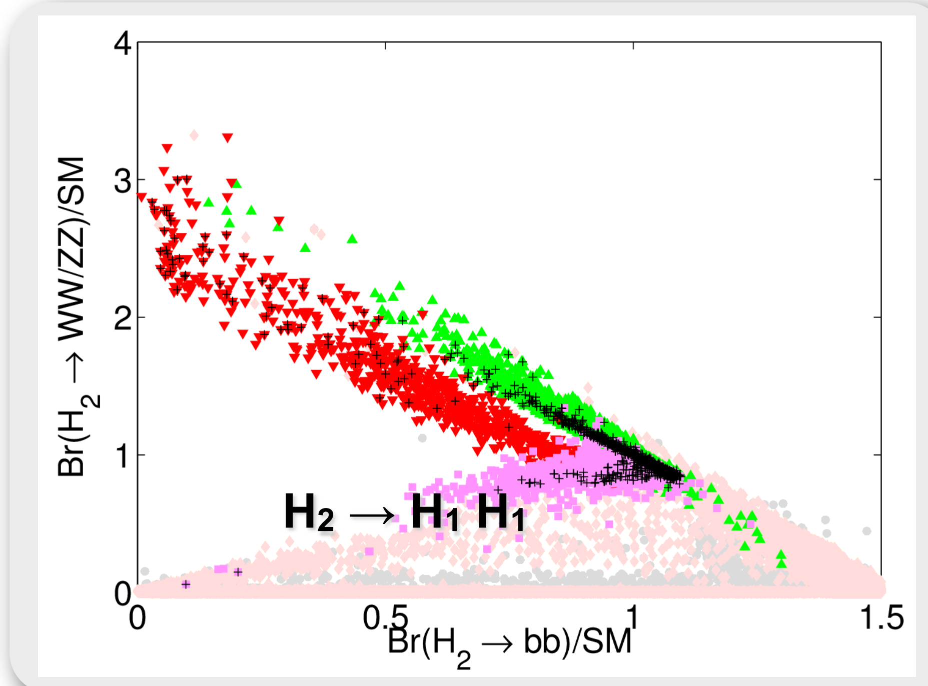
NMSSM Higgs

N. Christensen, T. Han, Z. Liu, SS (2013)

- $\sigma_{\gamma\gamma}$ vs σ_{WW}



- Br_{WW} vs Br_{bb}



- grey: pass exp
- pink: $124 < m_{H2} < 128$ GeV
- green, red, purple, black: satisfy $\sigma X Br(\gamma\gamma, WW)$
  - H_2 region IA, $m_{H1} > m_{H2}/2$, $|\xi_{H2}^{hv}|^2 > 0.5$
  - H_2 region IB, $m_{H1} > m_{H2}/2$, $|\xi_{H2}^{hv}|^2 < 0.5$
  - H_2 region II, $m_{H1} < m_{H2}/2$, $H_2 \rightarrow H_1 H_1$
- black: perturbativity till m_{GUT}

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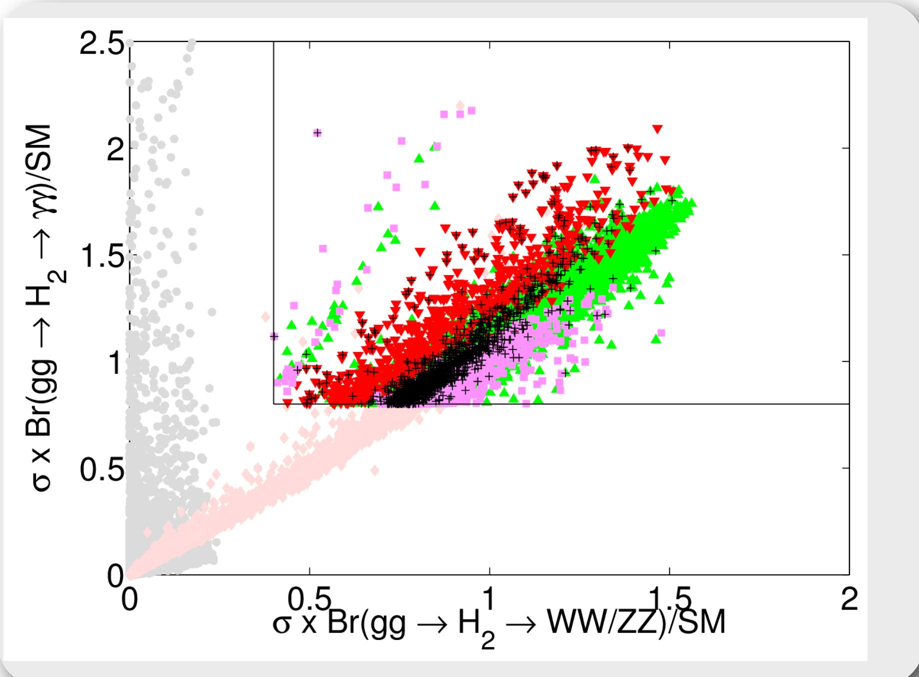
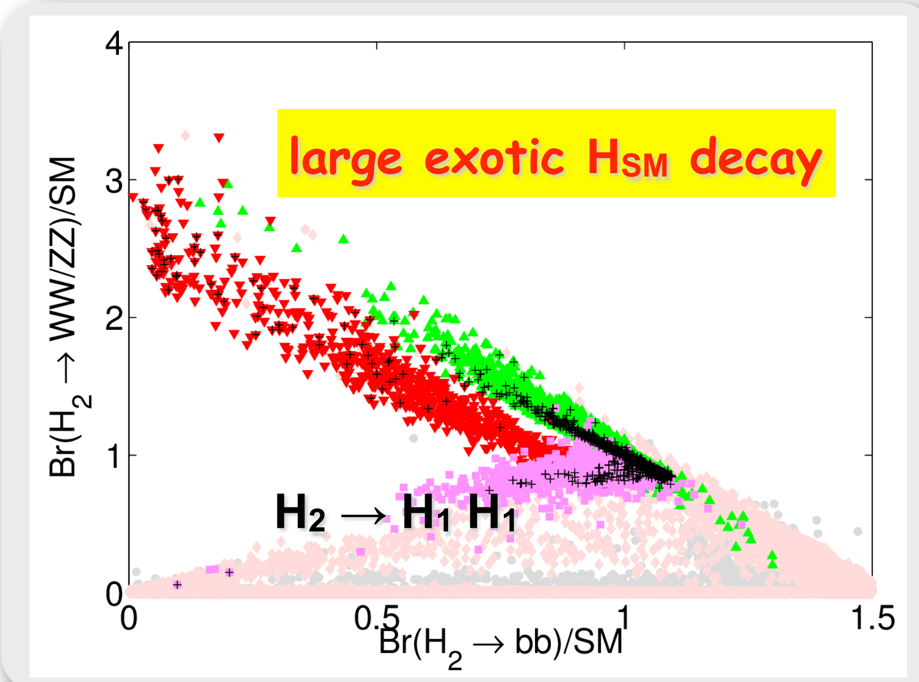
NMSSM Higgs

N. Christensen, T. Han, Z. Liu, SS (2013)

◉ $\sigma_{\gamma\gamma}$ vs σ_{WW}



◉ Br_{WW} vs Br_{bb}



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  - H_2 region II, $m_{H1} < m_{H2}/2$, $H_2 \to H_1 H_1$
- black: perturbativity till m_{GUT}

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Generic 2HDM

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$
$$+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}\right\} + \left\{\lambda_6\left[(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right](\Phi_1^\dagger\Phi_2) + \mathrm{h.c.}\right\}$$

after EWSB, 5 physical Higgses

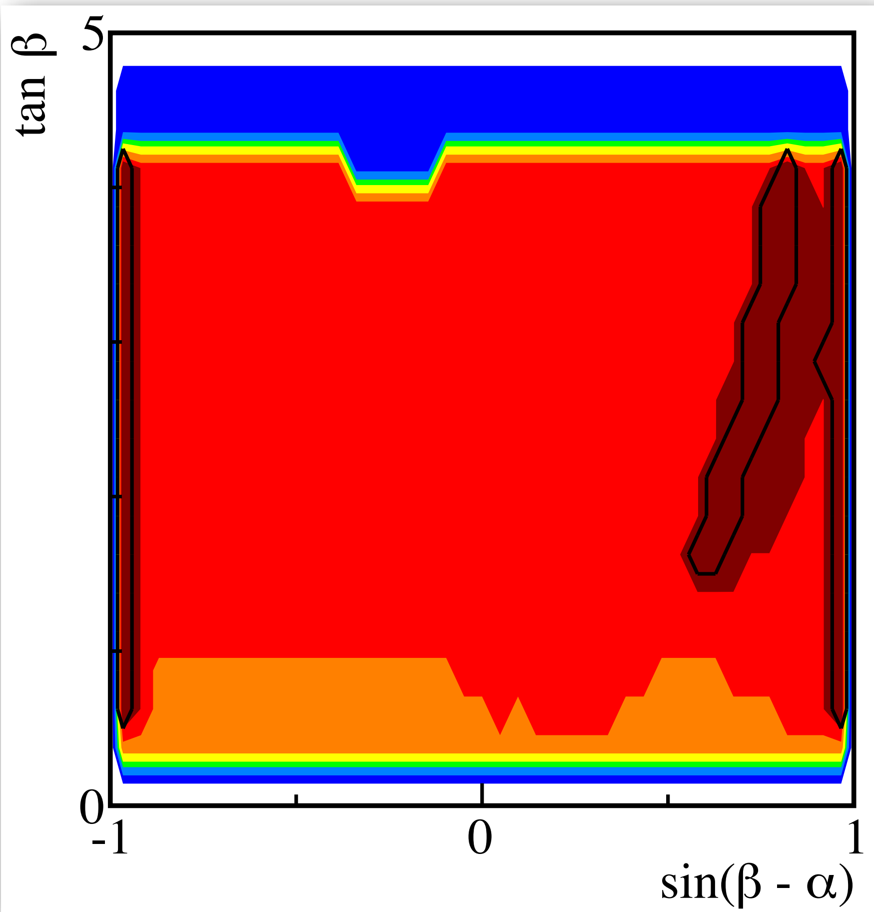
CP-even Higgses: h^0, H^0

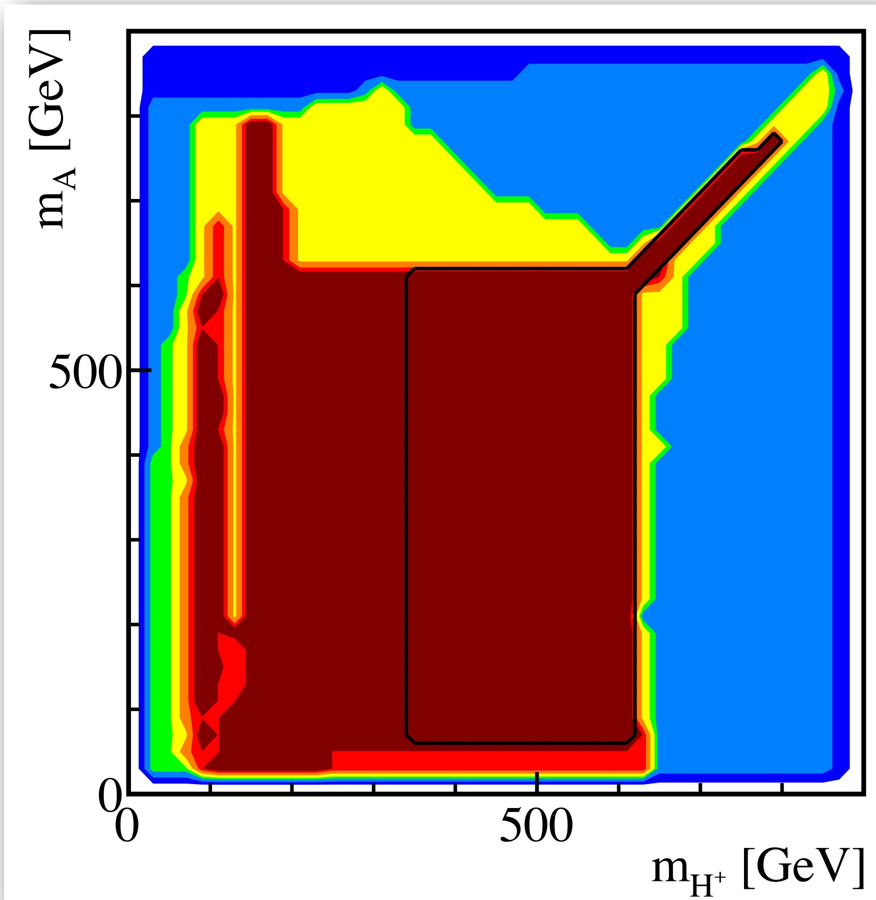
CP-odd Higgs: A^0

Charged Higgses: $H^\pm$

h^0 126 GeV

B. Coleppa, F. Kling and SS (2013)





h^0 126 GeV

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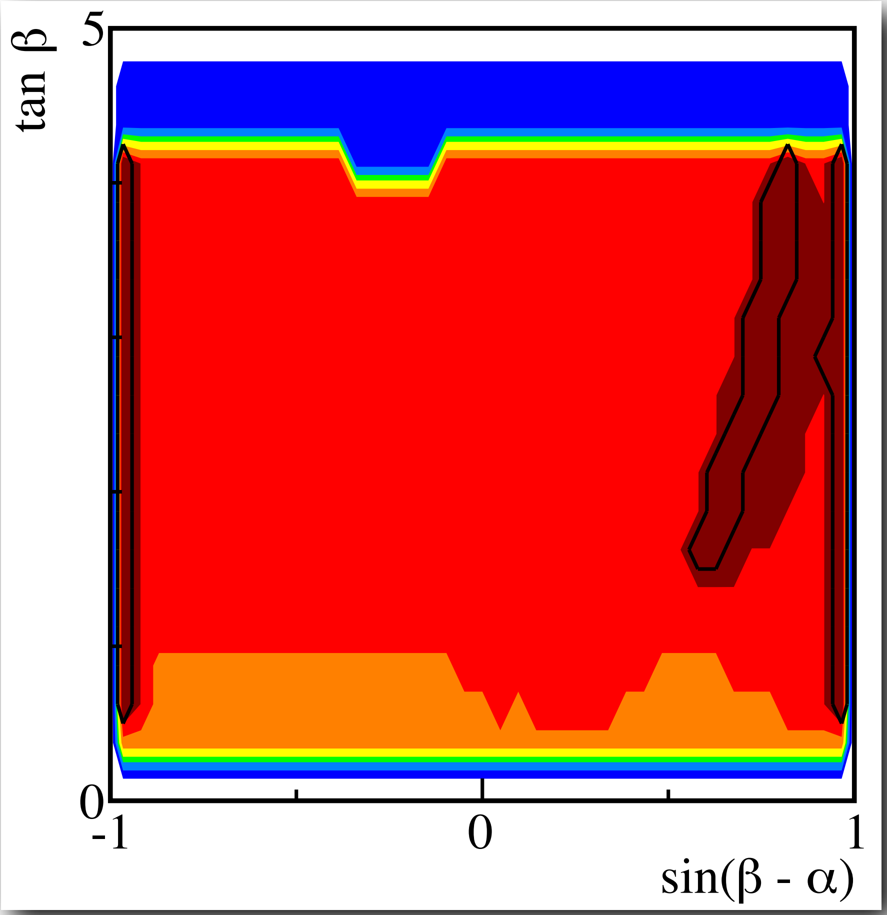

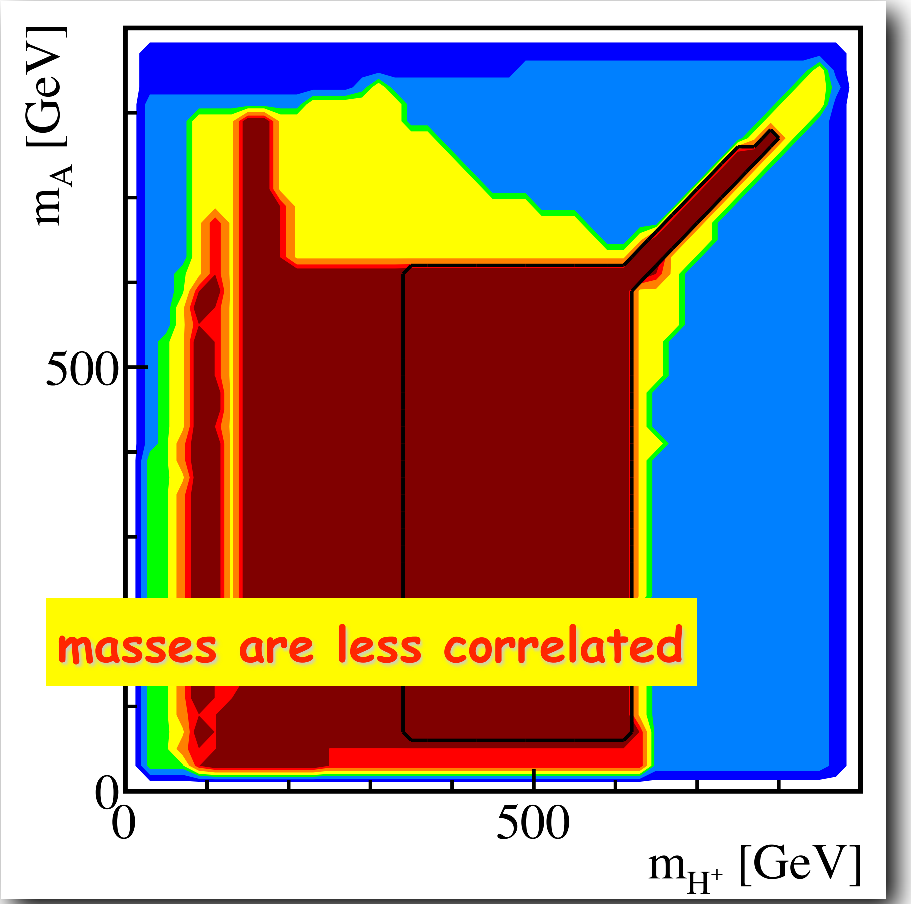

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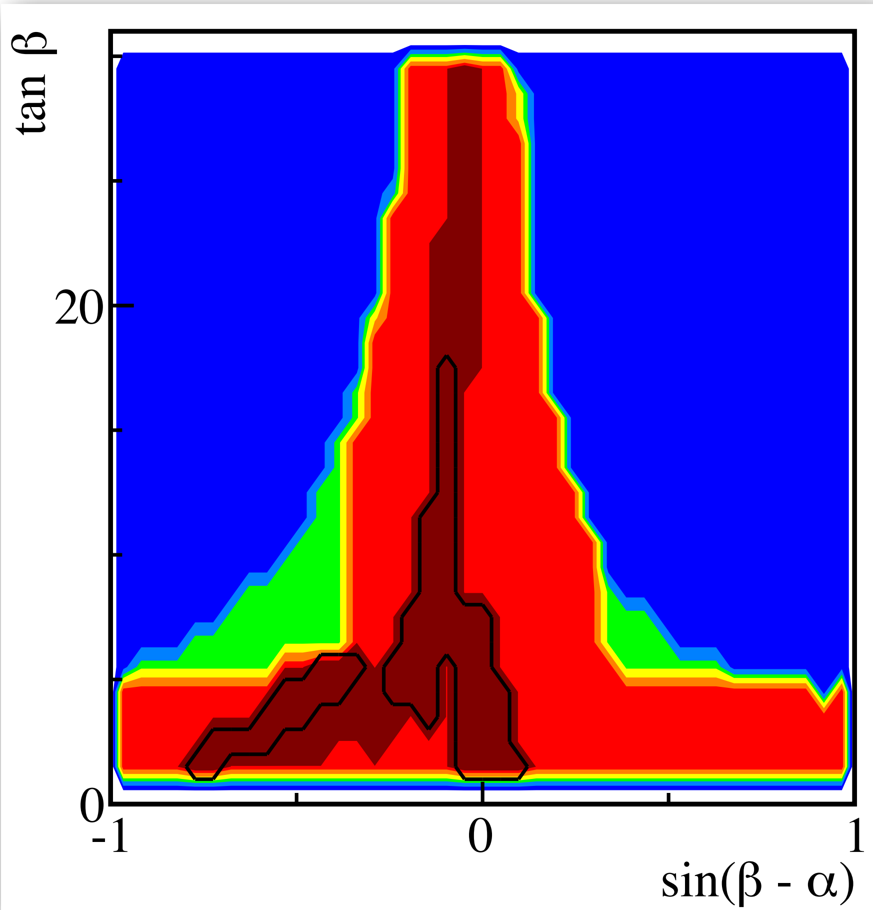

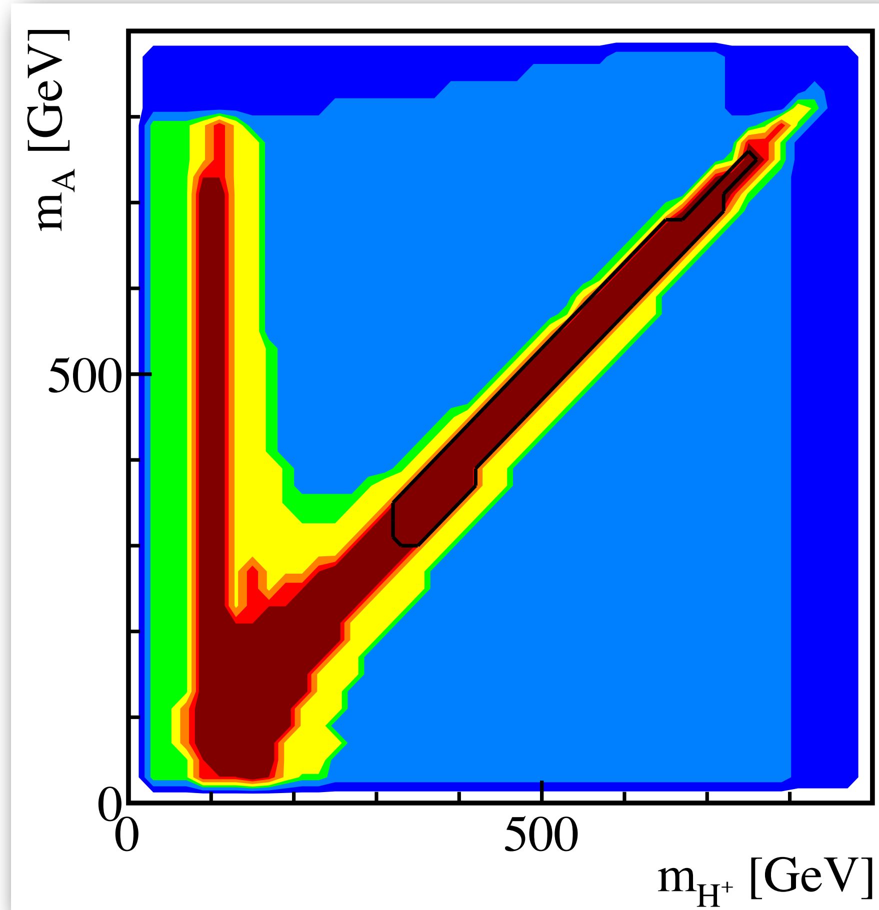

h^0 126 GeV

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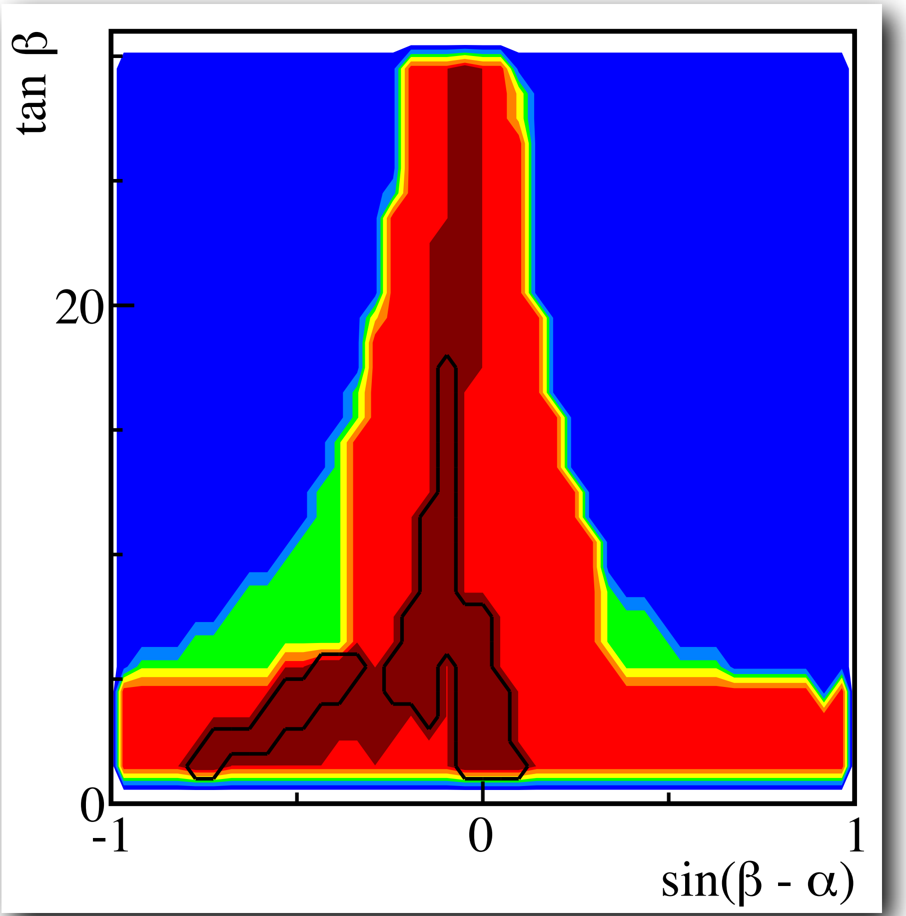
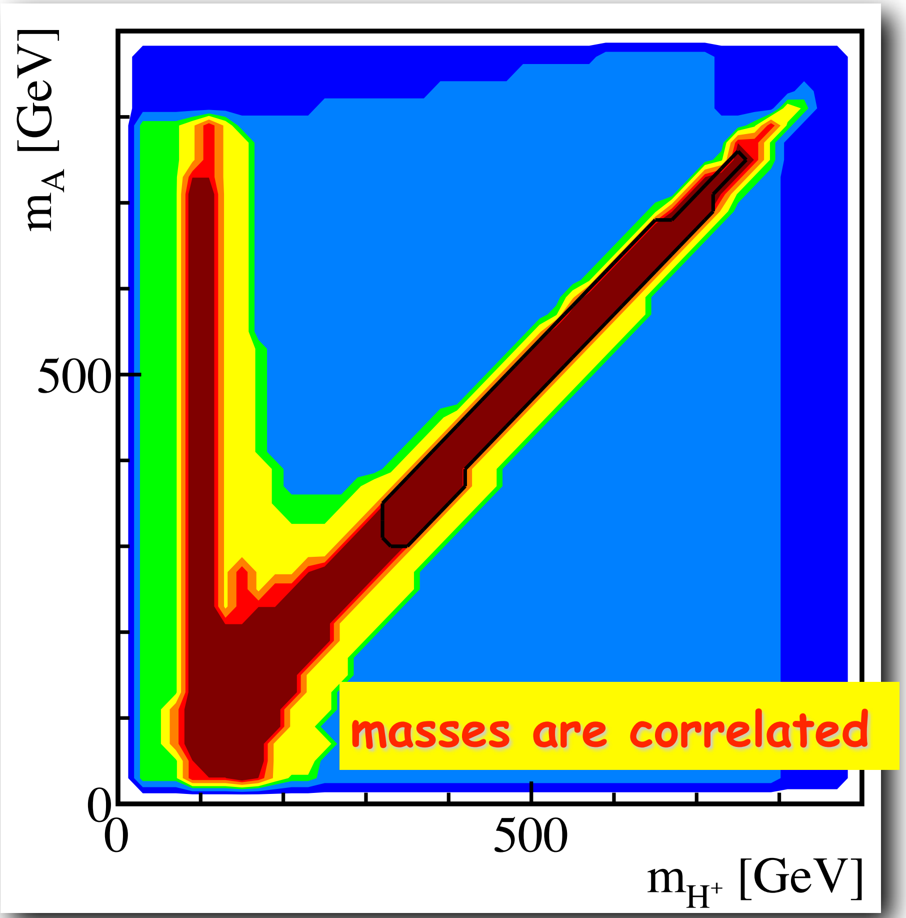
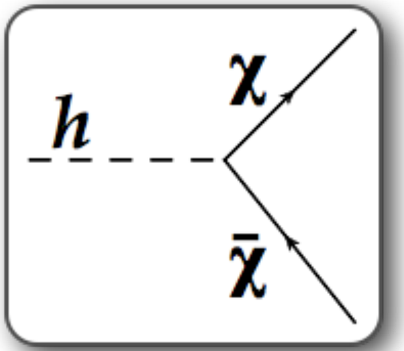


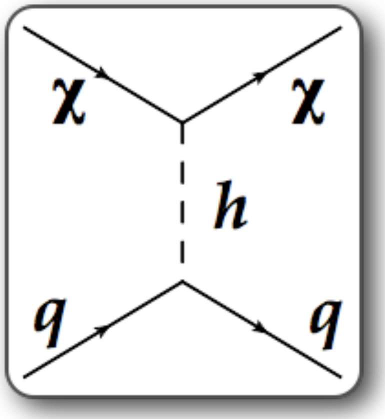


Connection to Cosmo

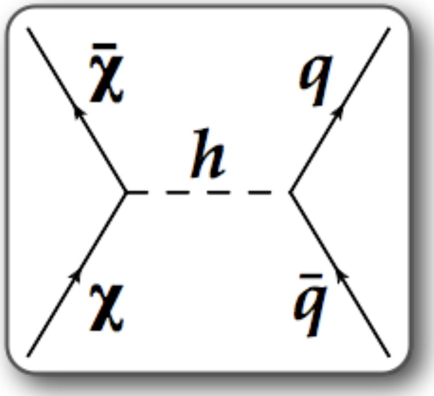
Higgs portal



invisible Higgs decay



direct detection



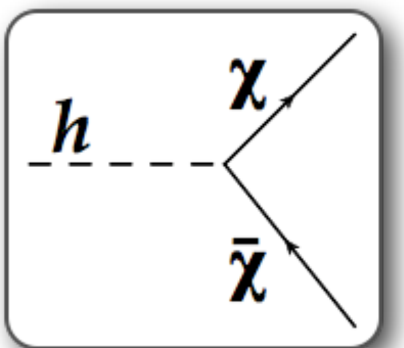
relic density

indirect detection

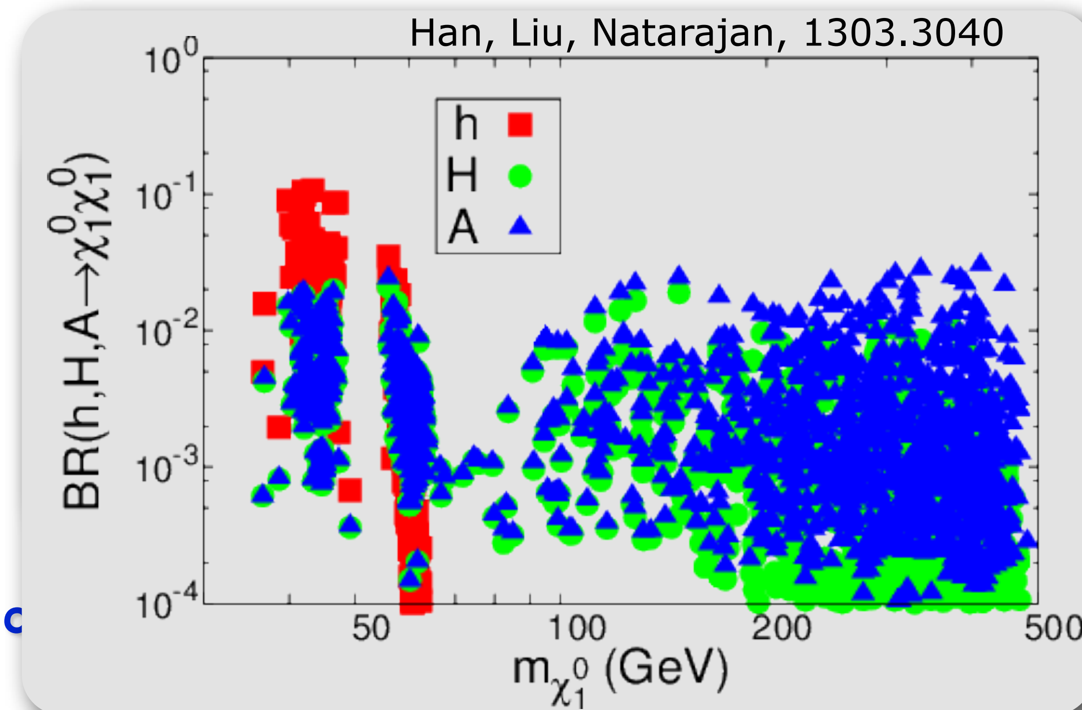
S. Su

Connection to Cosmo

Higgs portal



invisible Higgs decay



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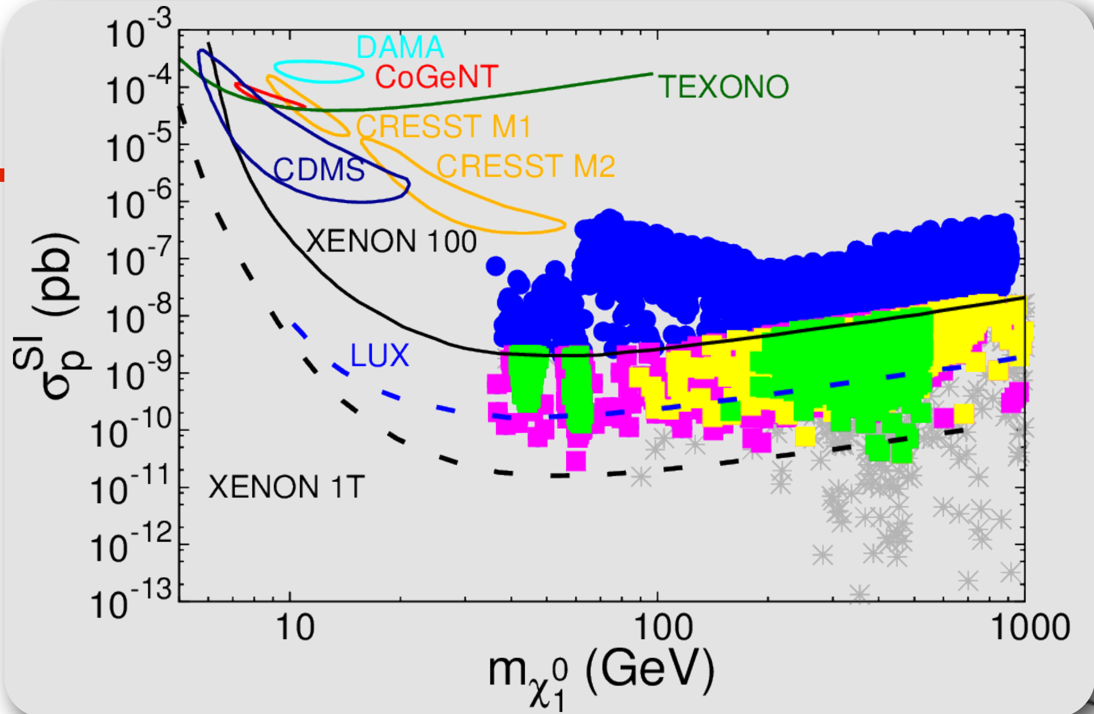
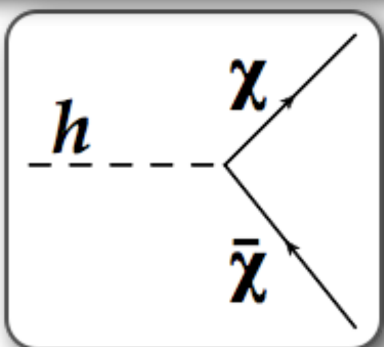
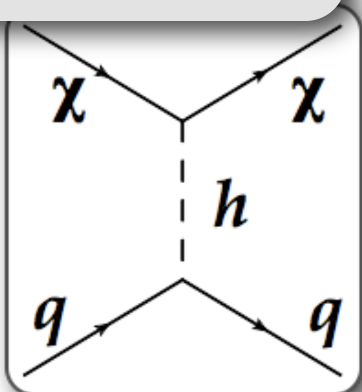
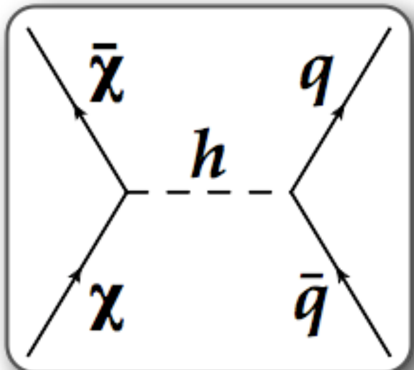
... Cosmo









invisible Higgs decay

direct detection

relic density

indirect detection

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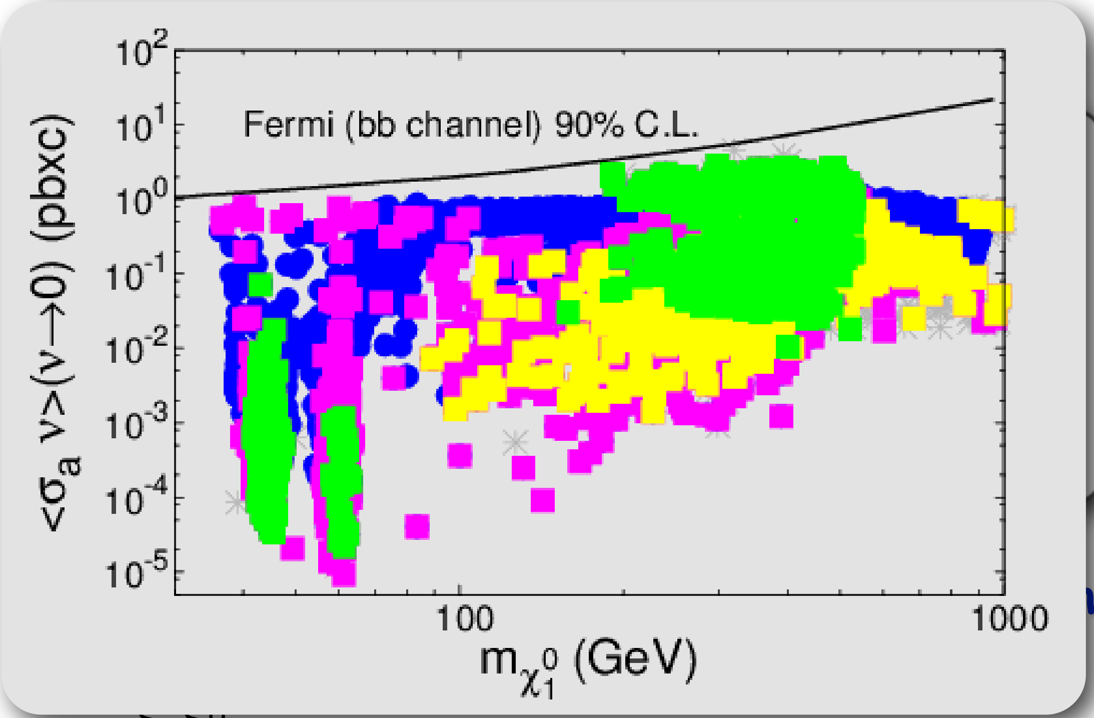
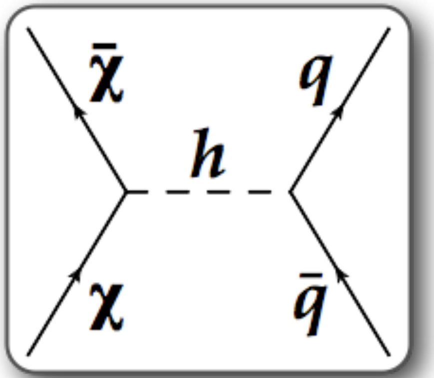
Connection to Cosmo

Higgs portal





relic density

indirect detection

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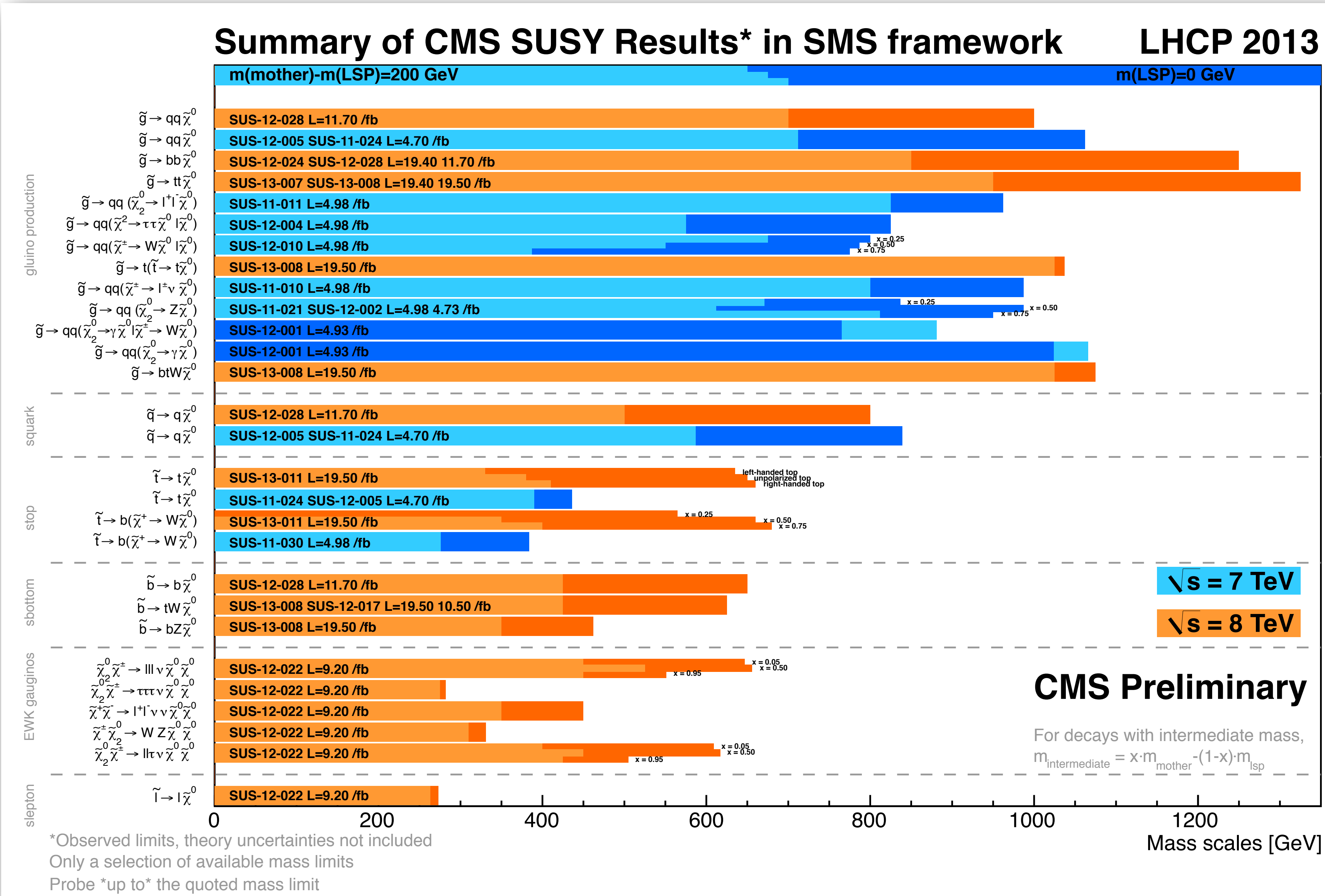
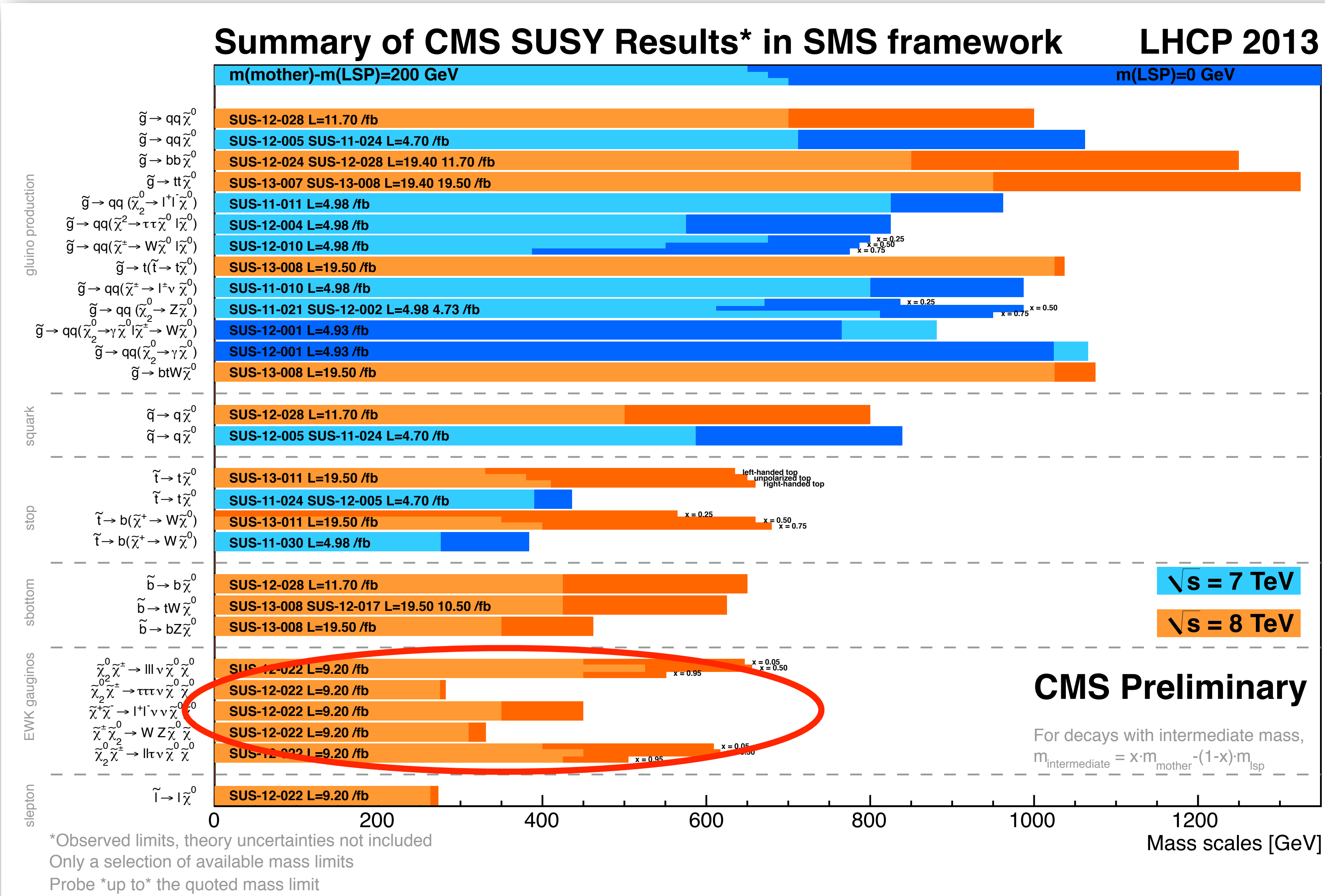
II. Higgs assisted new physics search

LHC SUSY Search limits (CMS)



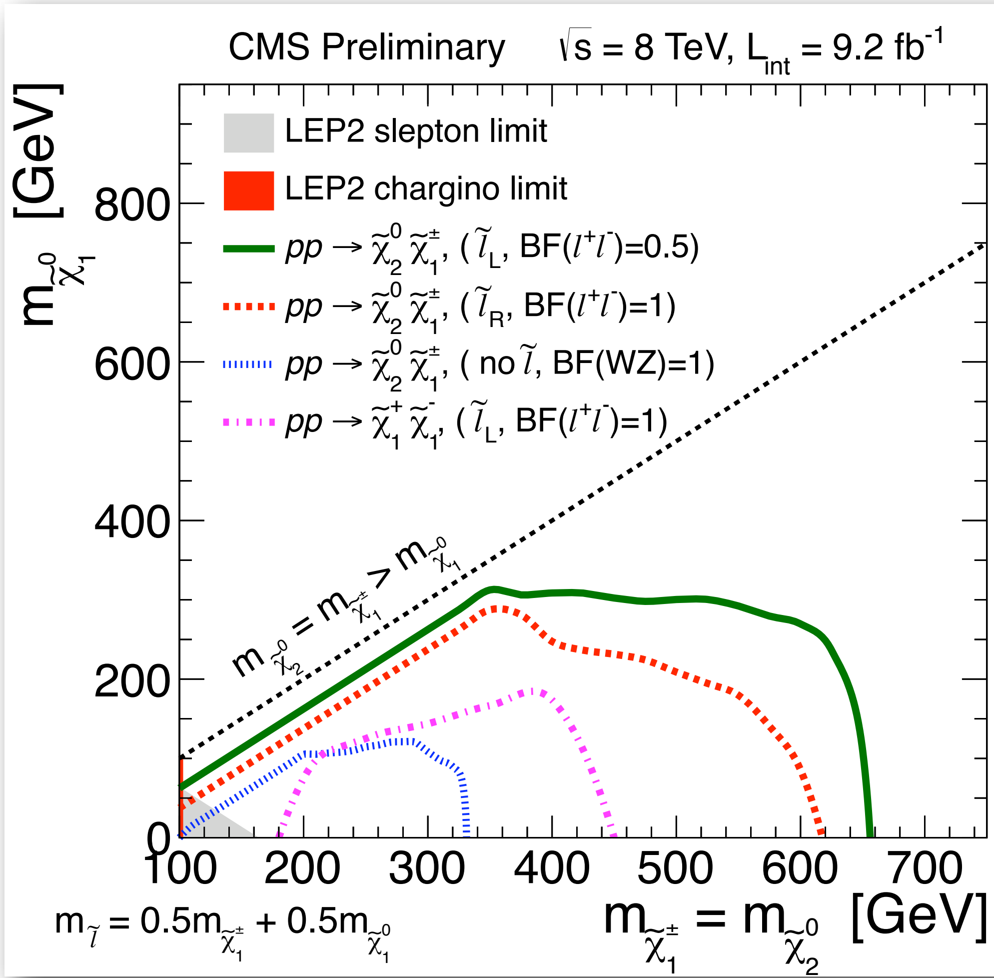
LHC SUSY Search limits (CMS)



CMS limits

dilepton/trilepton + MET

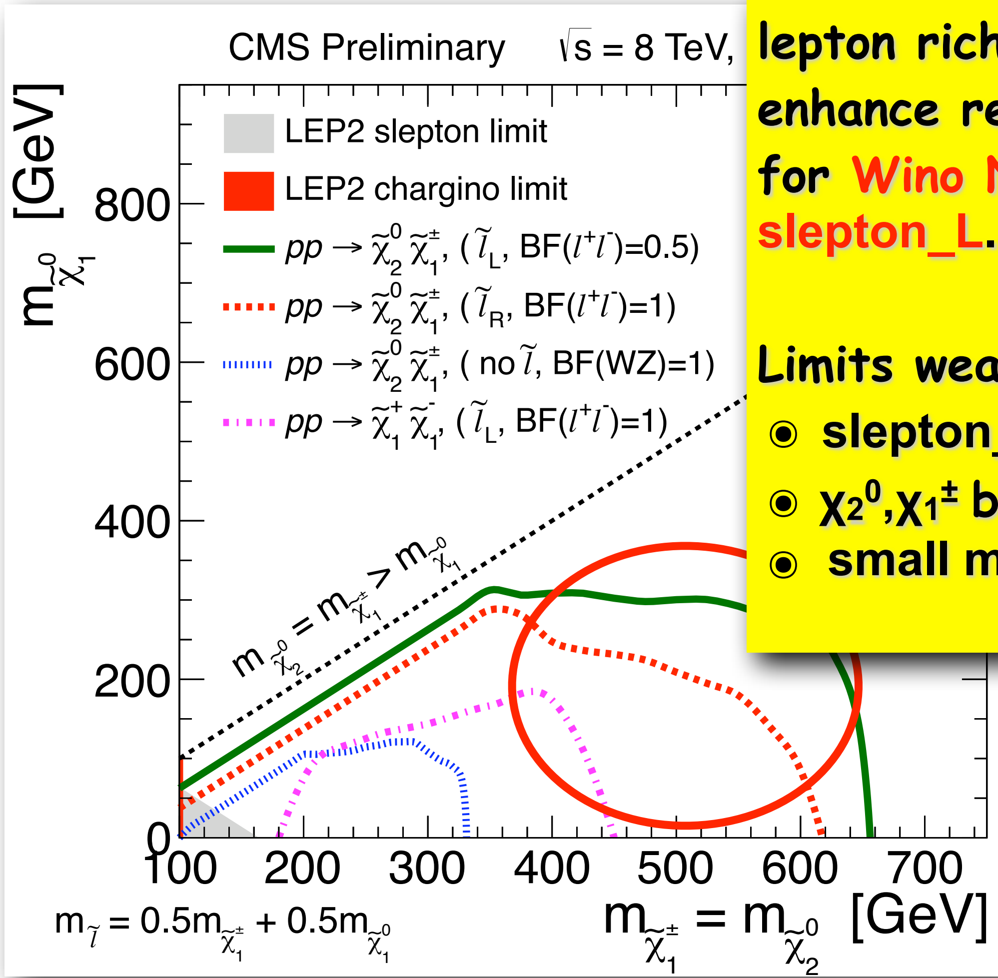
CMS PAS SUS-12-022



CMS limits

dilepton/trilepton + MET

CMS PAS SUS-12-022



lepton rich final states to enhance reach: only works for Wino NLSP with light slepton_L.

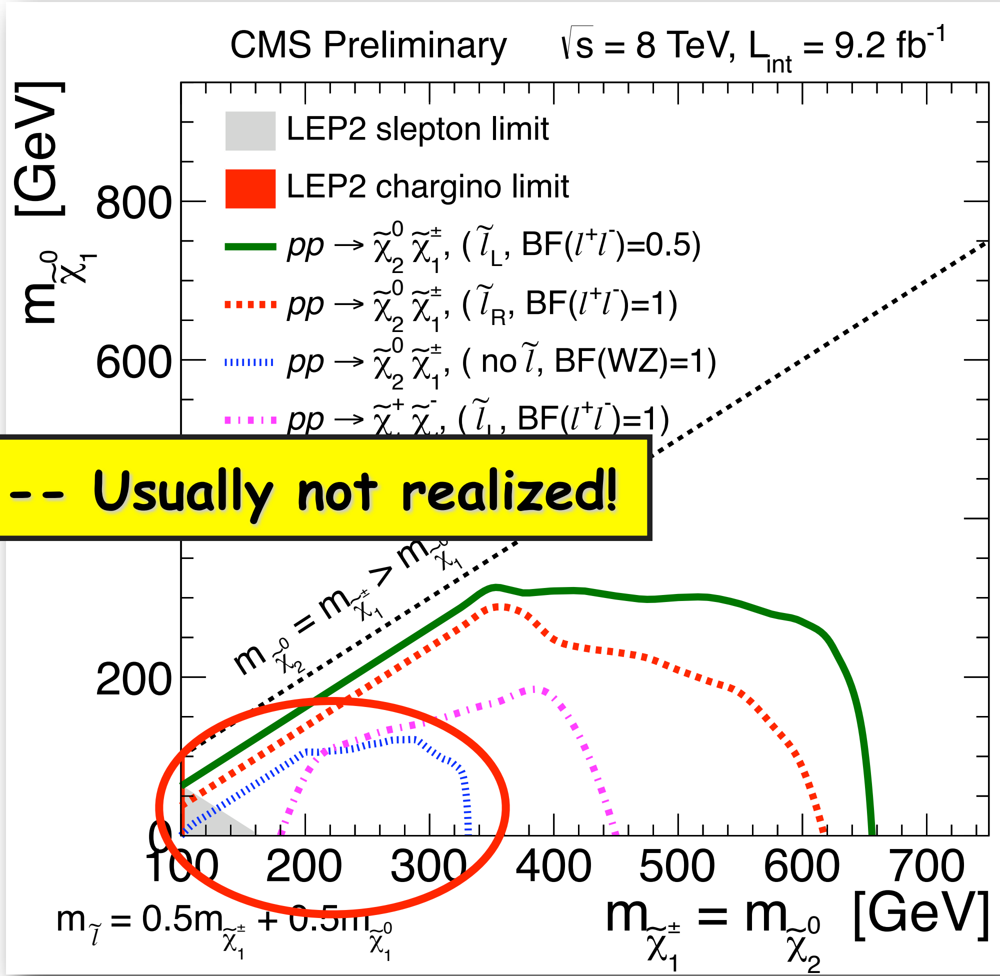
Limits weaker for

- **slepton_L heavy**
- **$\chi_2^0, \chi_1^\pm$ being Higgsinos**
- **small $m_{\chi_1^\pm} - m_{\chi_1^0}$**

CMS limits

dilepton/trilepton + MET

CMS PAS SUS-12-022



100% WZ Br -- Usually not realized!

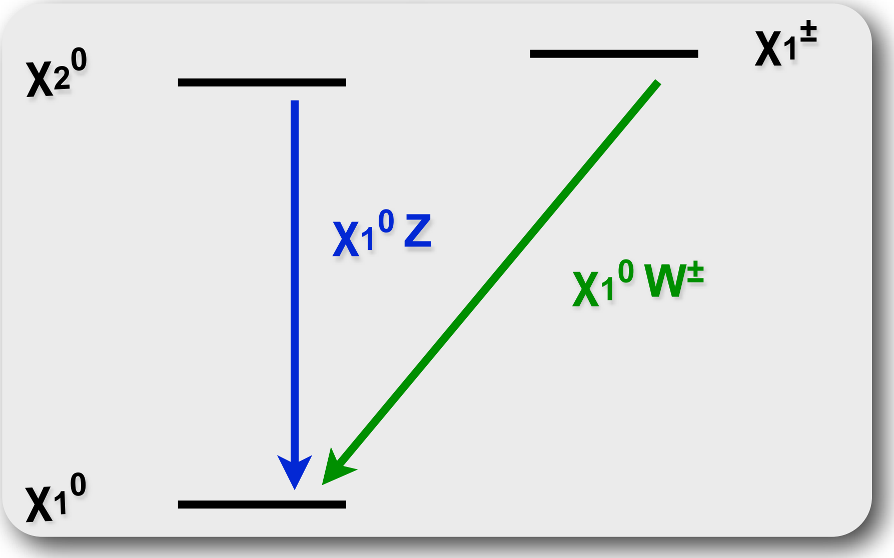
MSSM EW-ino sector 101

- Gauginos and Higgsinos
  - Neutral ones: Bino, Wino, $\tilde{H}_u^0$, $\tilde{H}_d^0$
  - charged ones: Winos, $\tilde{H}_u^+$, $\tilde{H}_d^-$
- Parameters: M_1, M_2, μ, $\tan\beta$

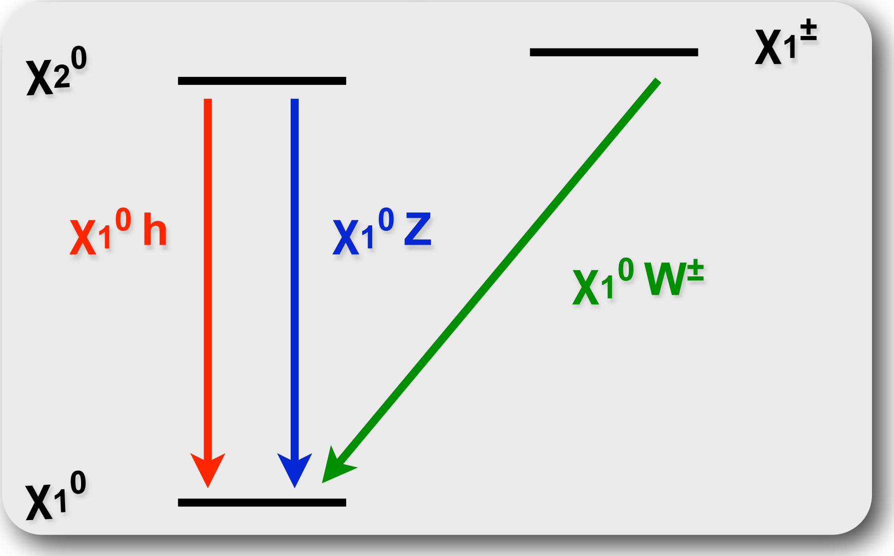
→

- Neutralinos and charginos

Decay of heavy neutralino and chargino



Decay of heavy neutralino and chargino



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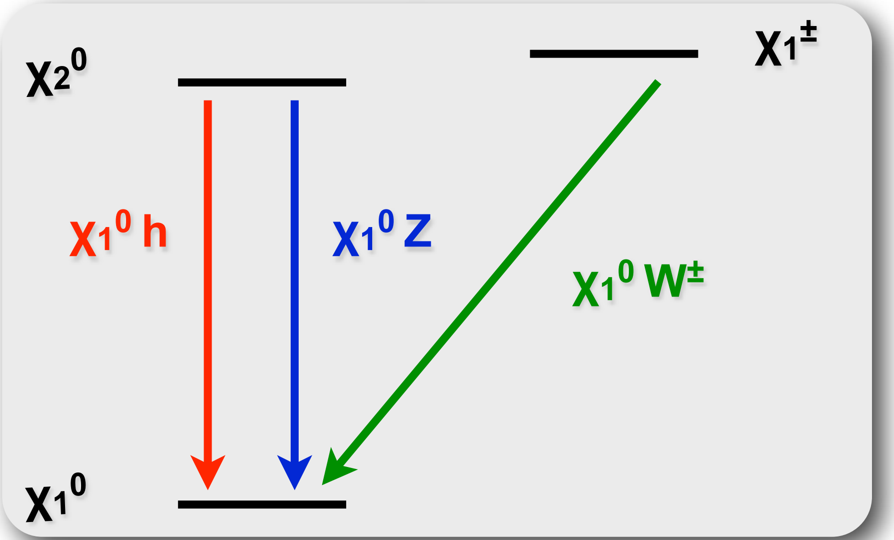

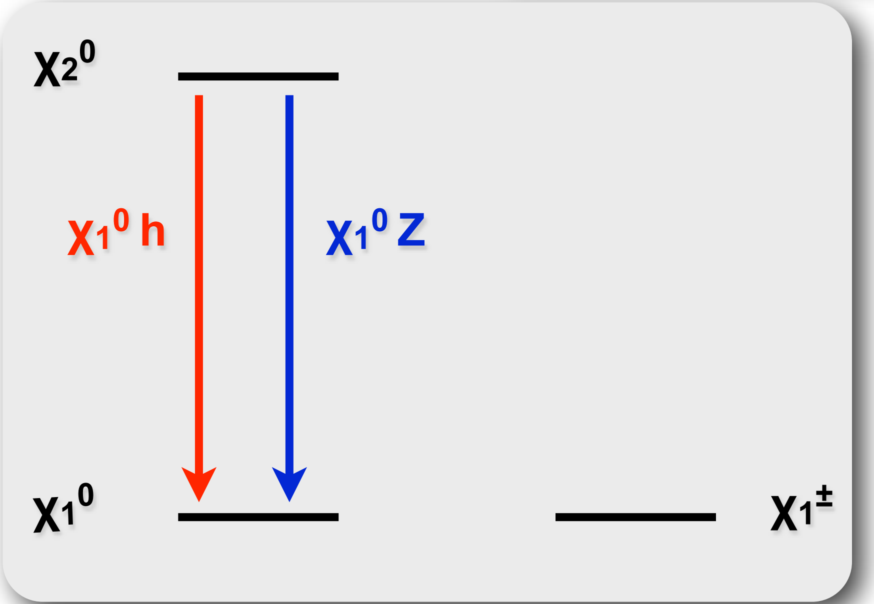

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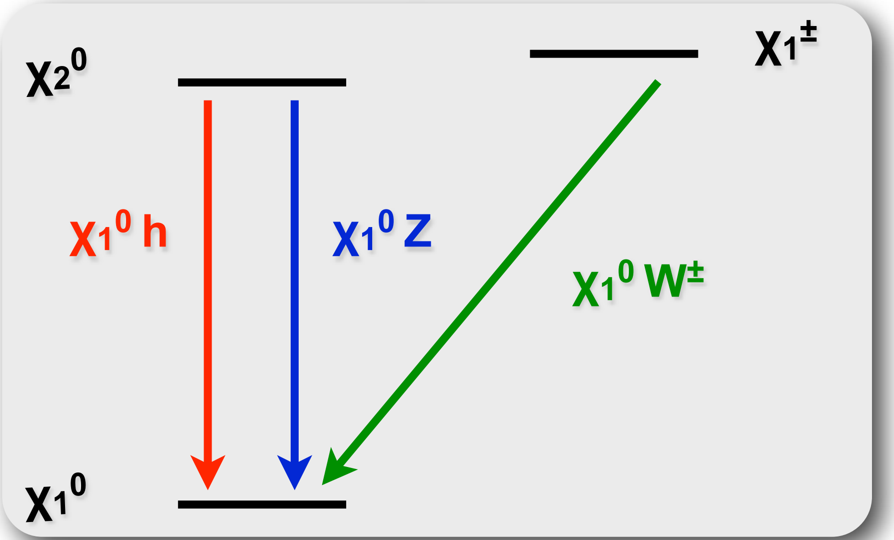

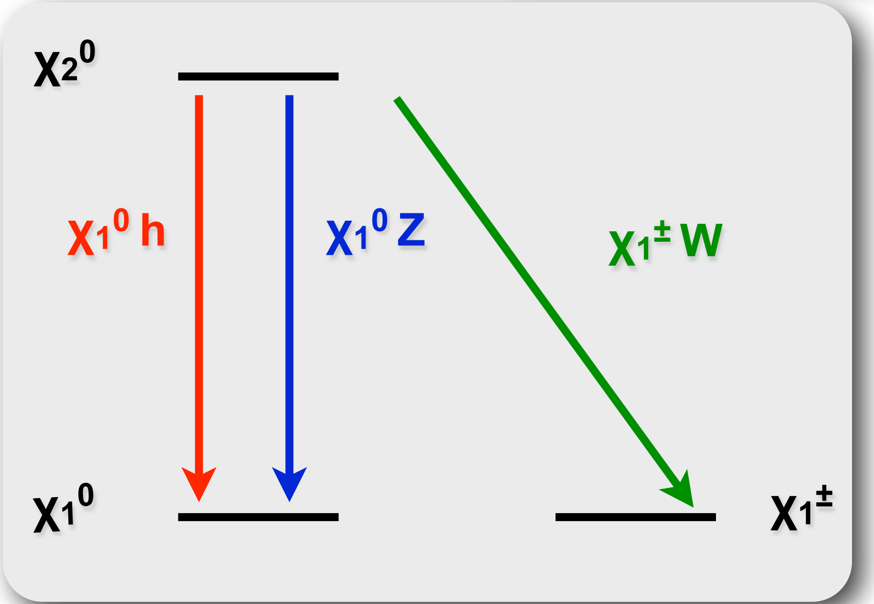

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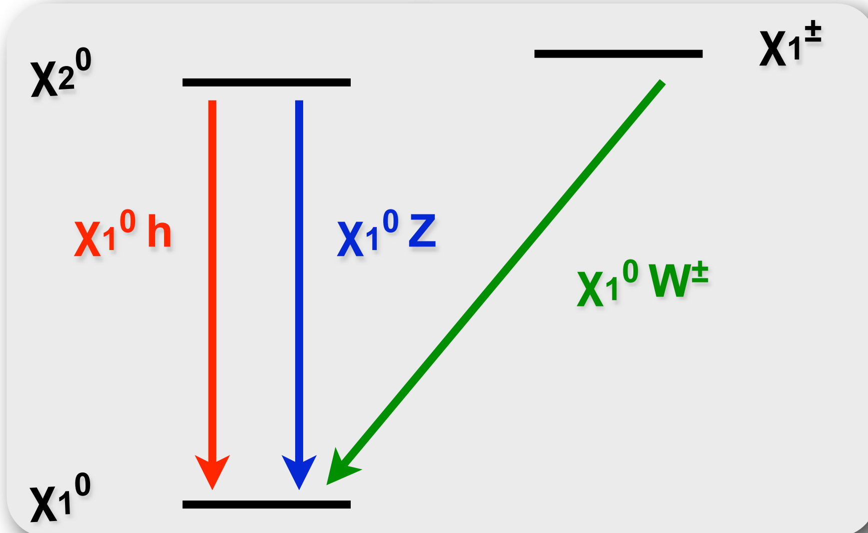
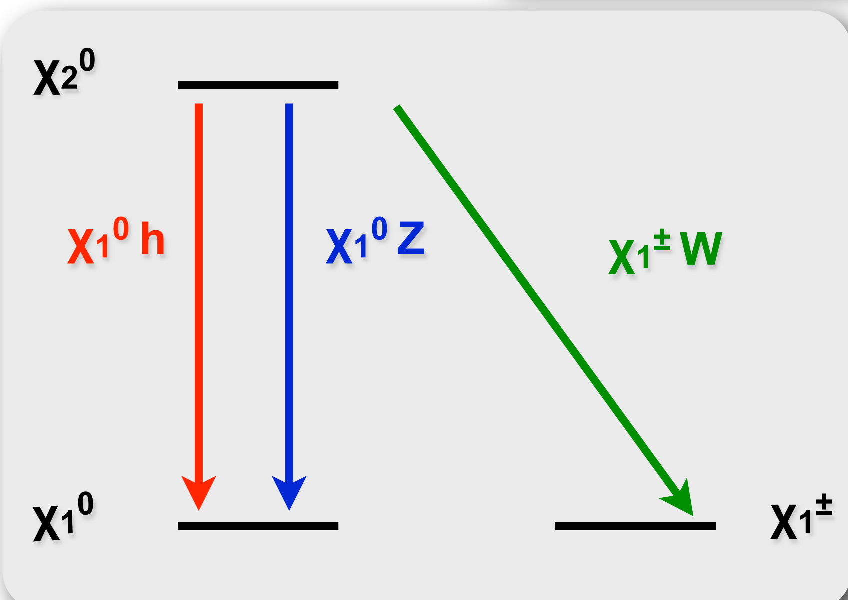
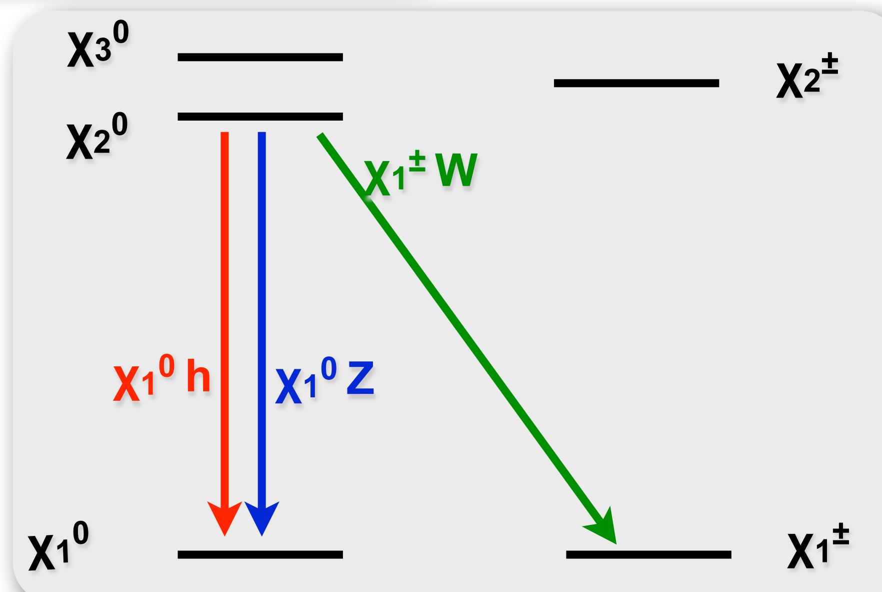
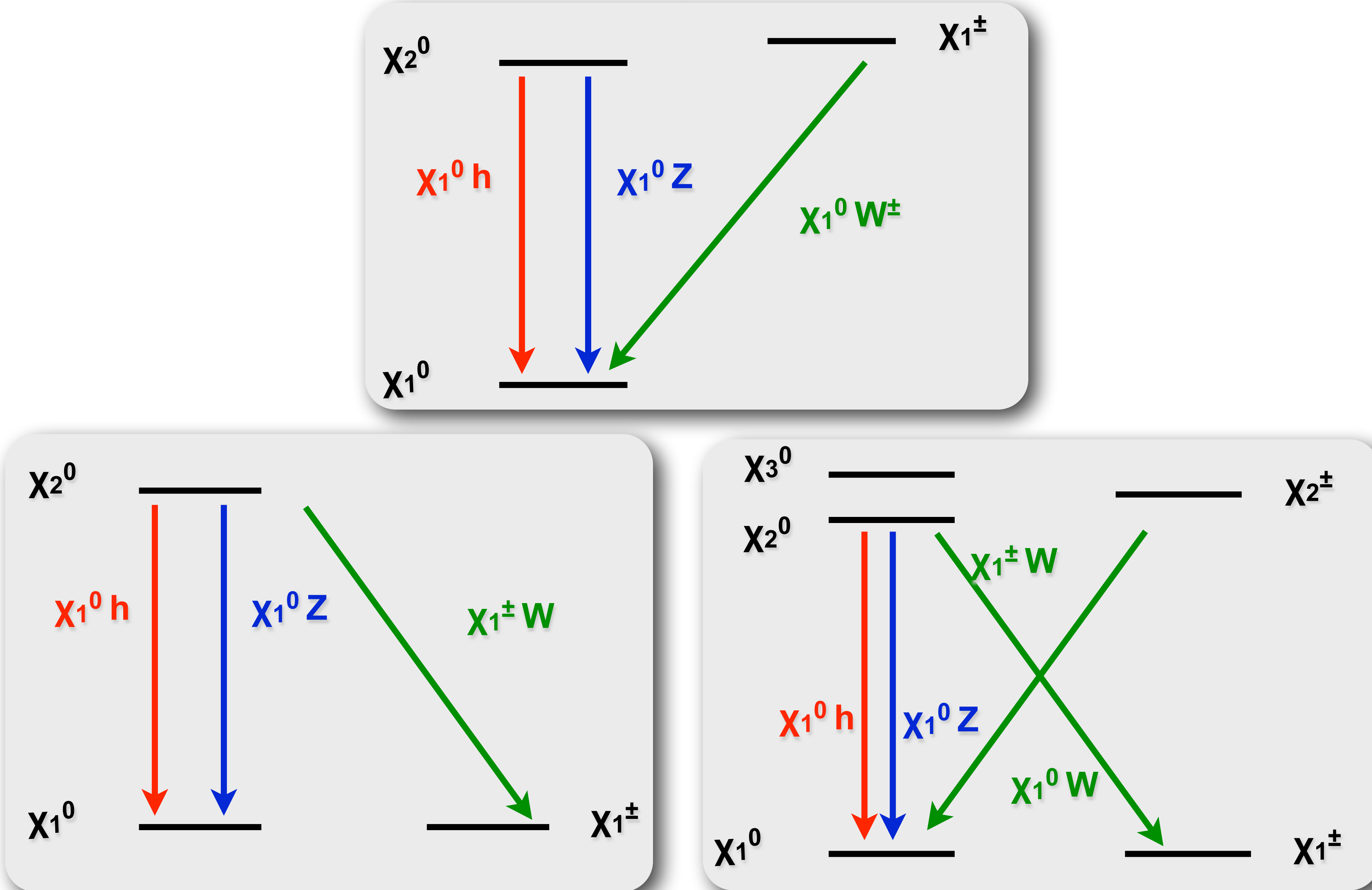


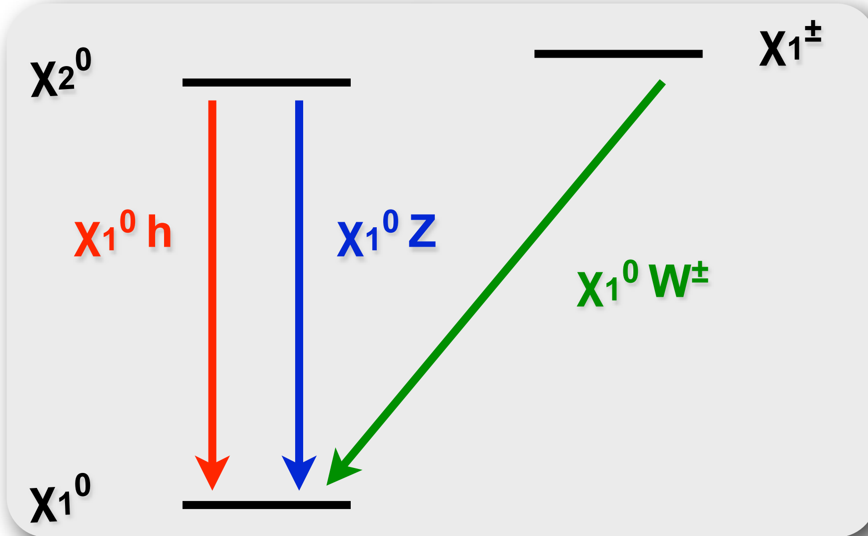


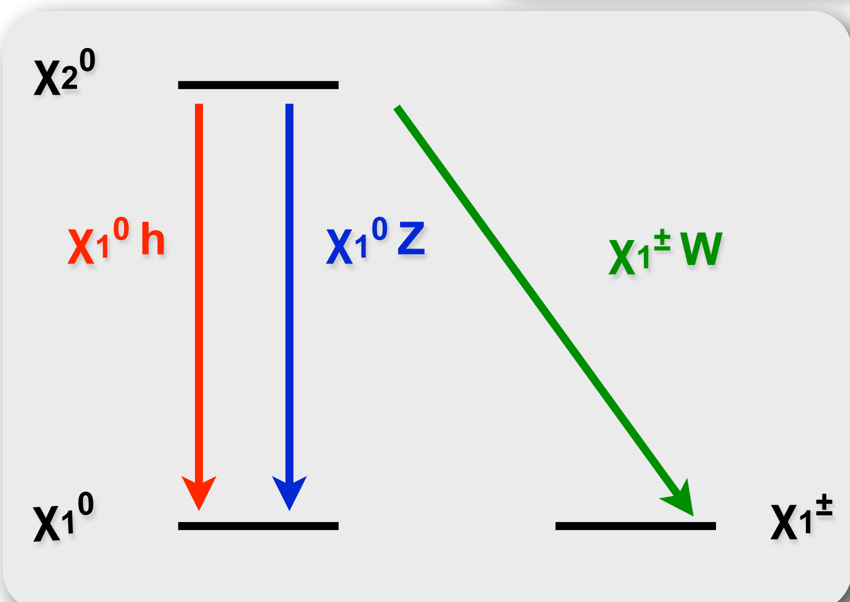


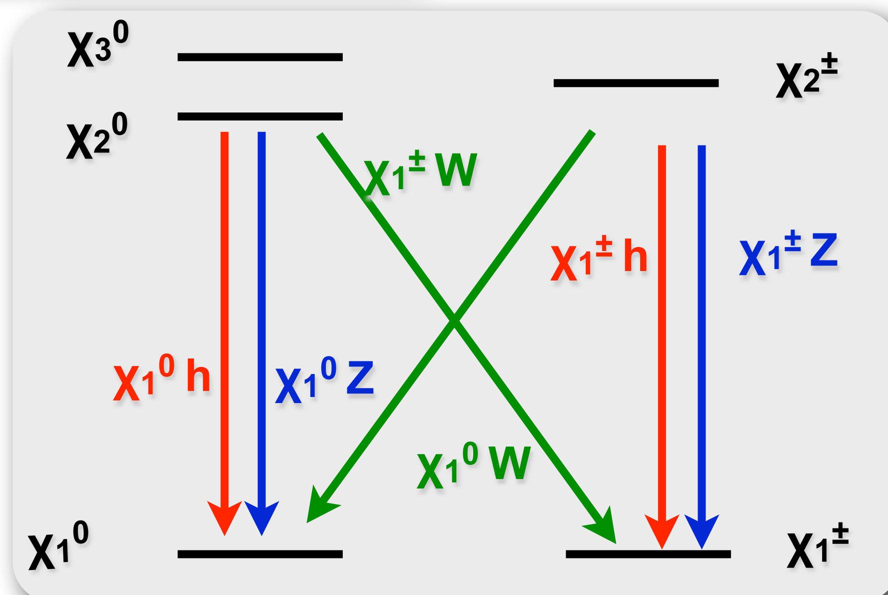
Decay of heavy neutralino and chargino



Decay of heavy neutralino and chargino

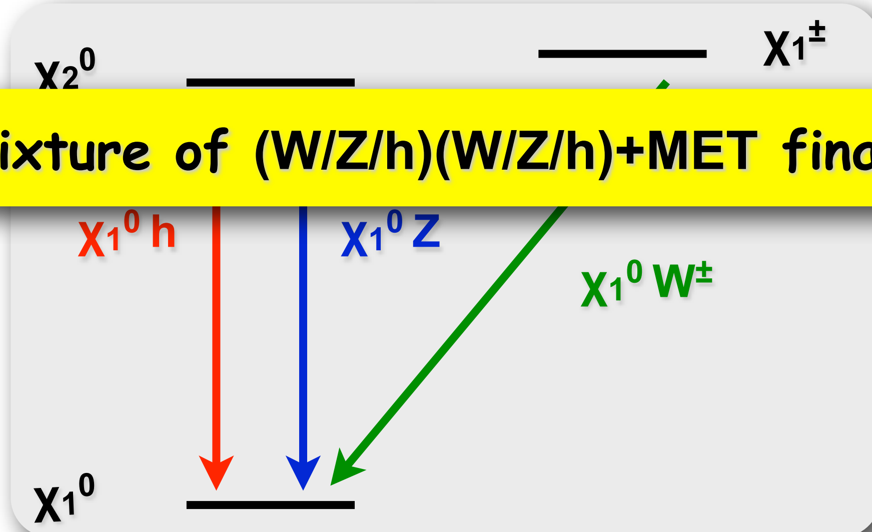


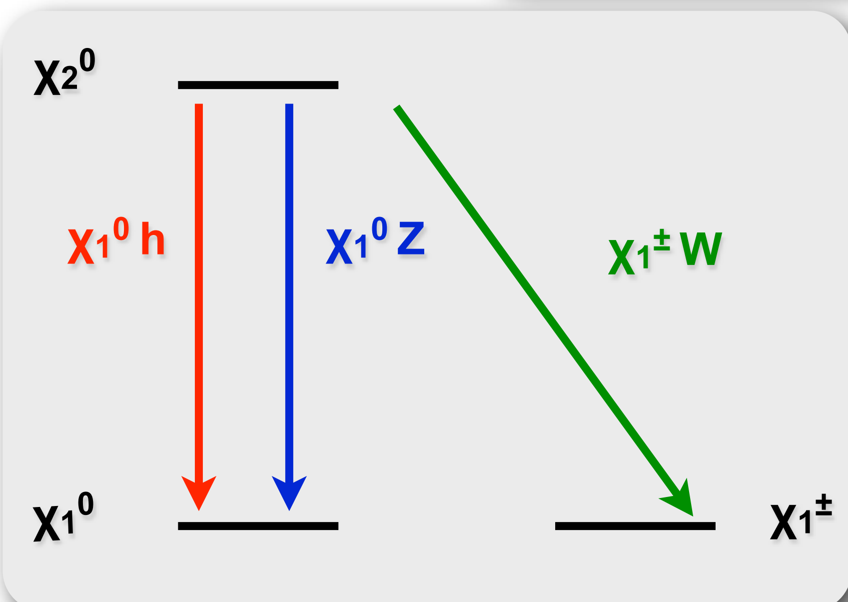


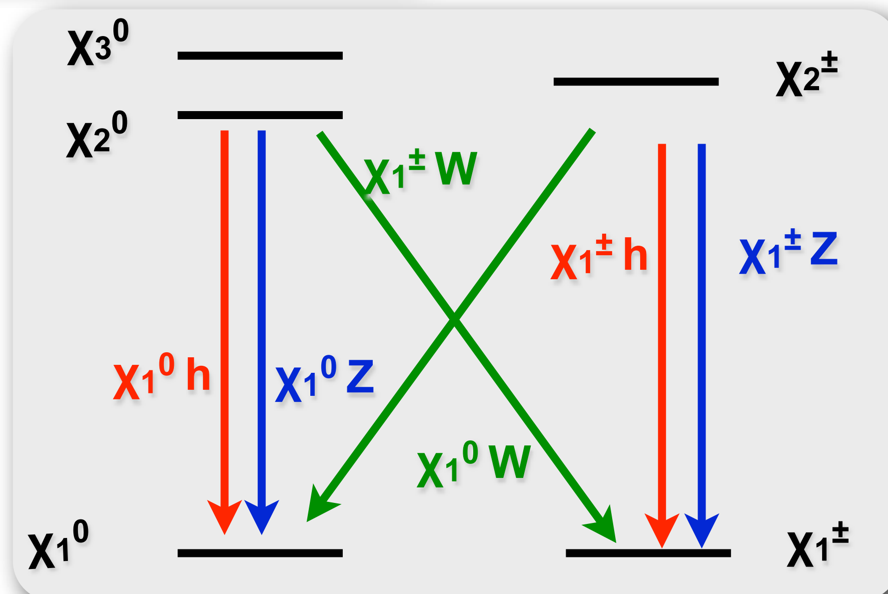


Decay of heavy neutralino and chargino

A rich mixture of (W/Z/h)(W/Z/h)+MET final states!







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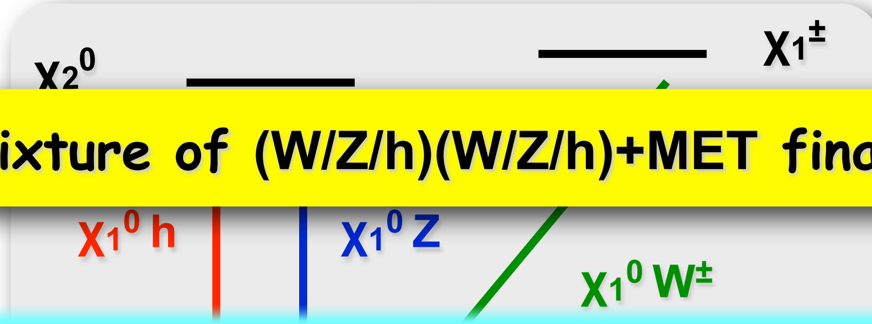

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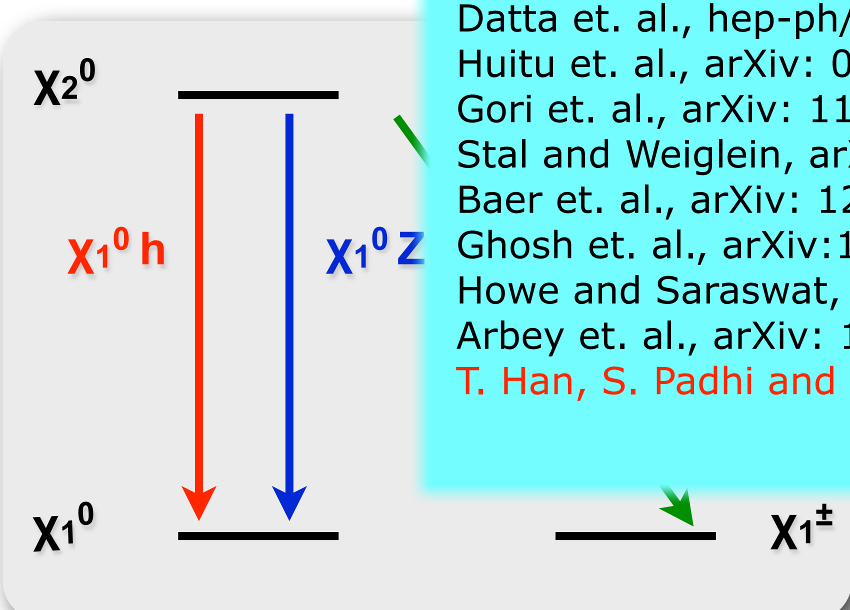
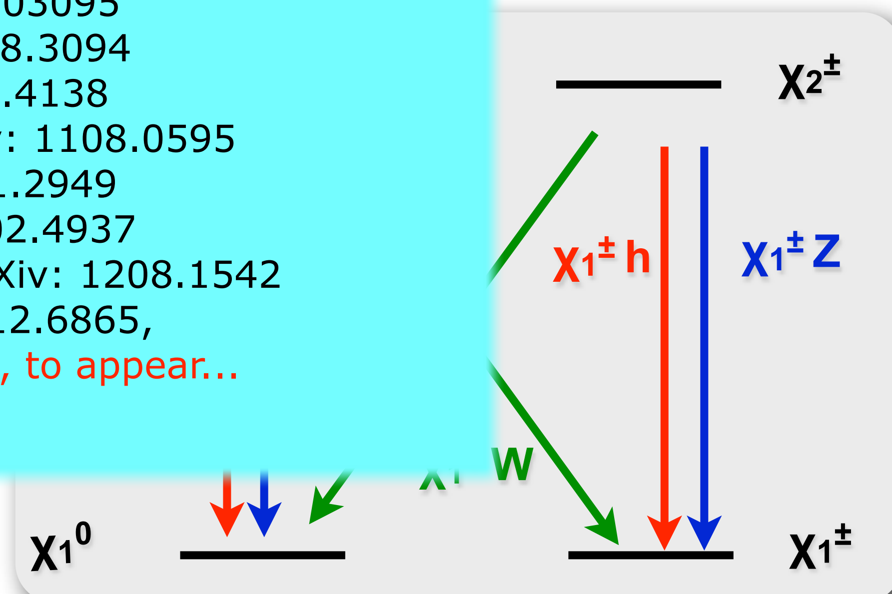
Gunion et. al., Int. J. Mod. Phys. A2 (1987) 1145
Gunion and Haber, PRD 37 (1988) 2515
Bartl et. al., PLB 216 (1989) 233
Djouadi et. al., hep-ph/0104115
Datta et. al., hep-ph/0303095
Huitu et. al., arXiv: 0808.3094
Gori et. al., arXiv: 1103.4138
Stal and Weiglein, arXiv: 1108.0595
Baer et. al., arXiv: 1201.2949
Ghosh et. al., arXiv:1202.4937
Howe and Saraswat, arXiv: 1208.1542
Arbey et. al., arXiv: 1212.6865,
T. Han, S. Padhi and SS, to appear...





Six cases

LSP(s): usual LSP+degenerate states

NLSP(s): 2nd set low-lying (degenerate) states

Case AI: Bino LSP-Wino NLSP $M_1 < M_2 < \mu$

Case AII: Bino LSP-Higgsino NLSP $M_1 < \mu < M_2$

Case BI: Wino LSP-Bino NLSP $M_2 < M_1 < \mu$

Case BII: Wino LSP-Higgsino NLSP $M_2 < \mu < M_1$

Case CI: Higgsino LSP-Bino NLSP $\mu < M_1 < M_2$

Case CII: Higgsino LSP-Wino NLSP $\mu < M_2 < M_1$

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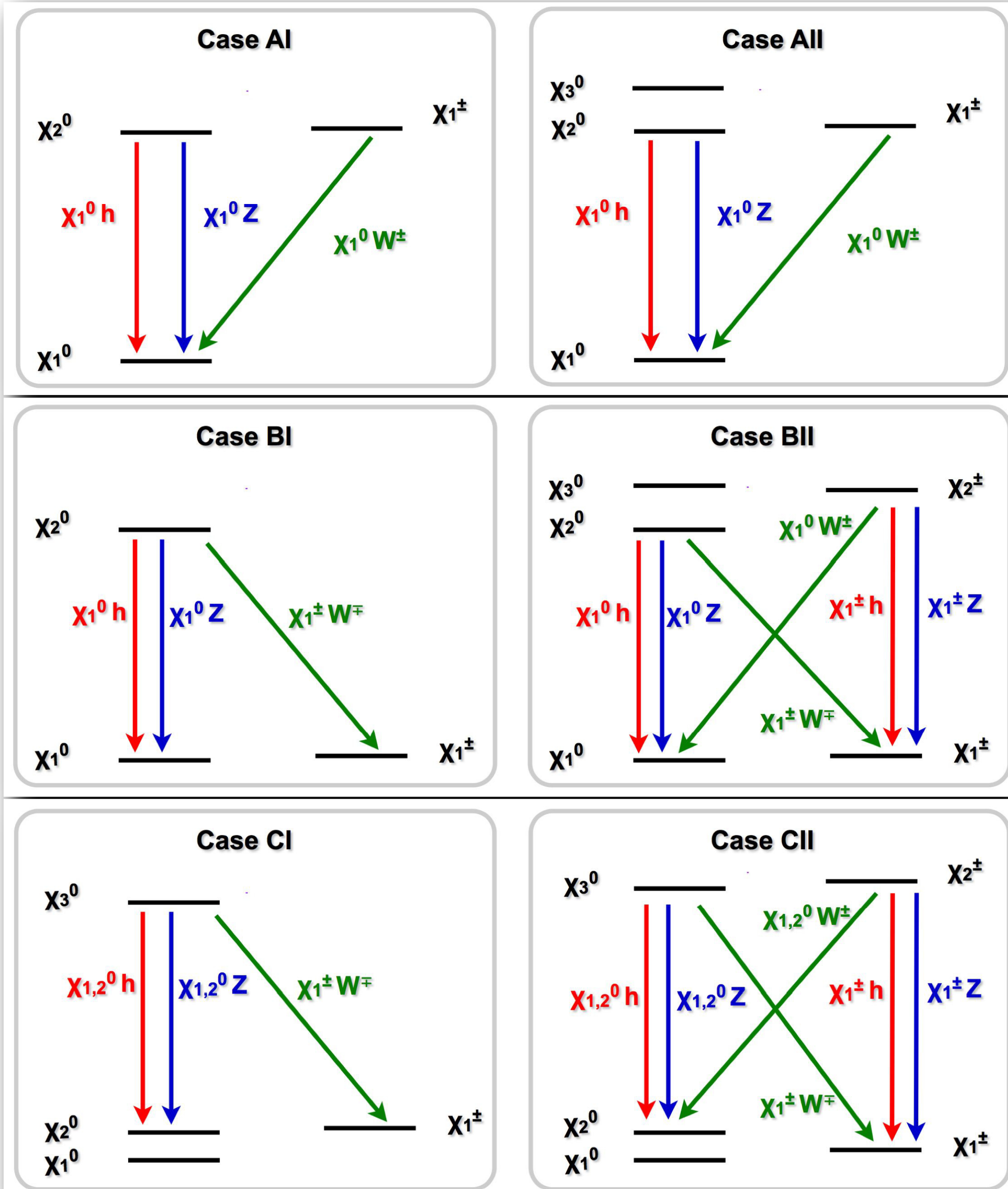
Small NLSP production at LHC: unobservable
nearly degenerate LSP pair productions at ILC: Unique opportunity!

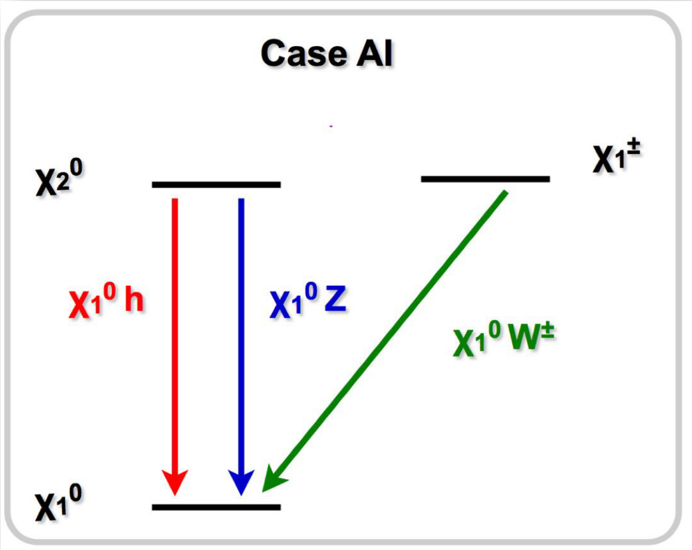


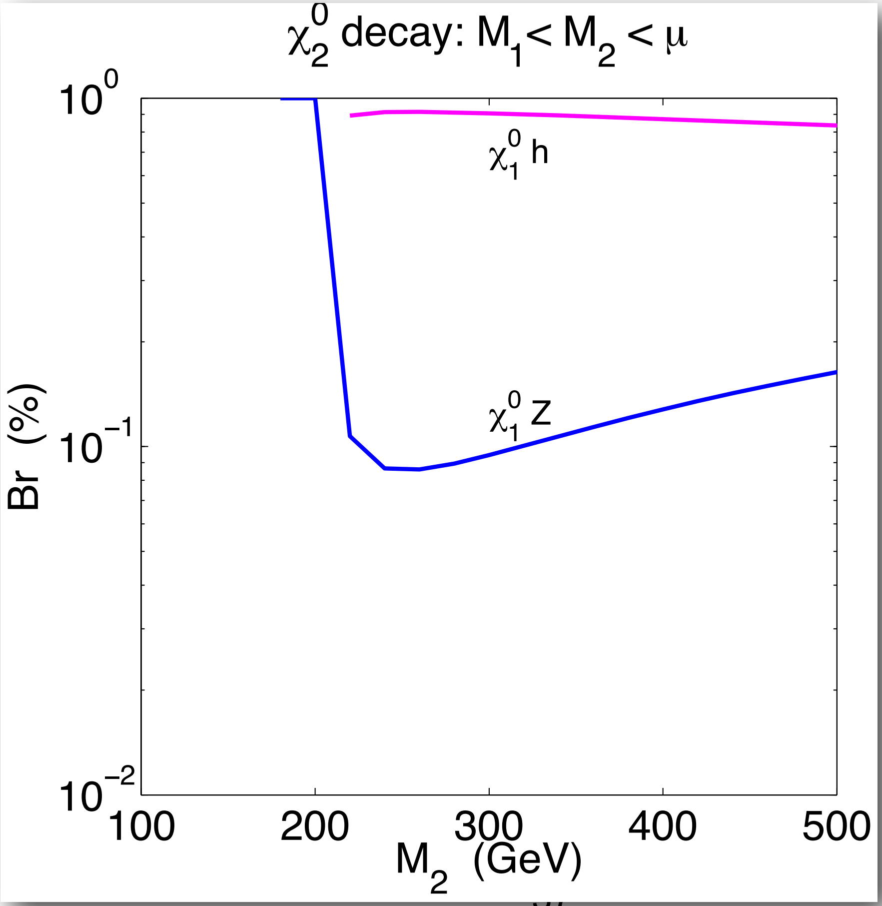
Case AI
χ_2^0
$\chi_1^\pm$
$\chi_1^0\, h$
$\chi_1^0\, Z$
$\chi_1^0\, W^\pm$
χ_1^0
Case AII
χ_3^0
χ_2^0
$\chi_1^\pm$
$\chi_1^0\, h$
$\chi_1^0\, Z$
$\chi_1^0\, W^\pm$
χ_1^0
Case BI
χ_2^0
$\chi_1^0\, h$
$\chi_1^0\, Z$
$\chi_1^\pm\, W^\mp$
χ_1^0
$\chi_1^\pm$
Case BII
χ_3^0
χ_2^0
$\chi_2^\pm$
$\chi_1^0\, W^\pm$
$\chi_1^0\, h$
$\chi_1^0\, Z$
$\chi_1^\pm\, h$
$\chi_1^\pm\, Z$
$\chi_1^\pm\, W^\mp$
χ_1^0
$\chi_1^\pm$
Case CI
χ_3^0
$\chi_{1,2}^0\, h$
$\chi_{1,2}^0\, Z$
$\chi_1^\pm\, W^\mp$
χ_2^0
χ_1^0
$\chi_1^\pm$
Case CII
χ_3^0
$\chi_2^\pm$
$\chi_{1,2}^0\, W^\pm$
$\chi_{1,2}^0\, h$
$\chi_{1,2}^0\, Z$
$\chi_1^\pm\, h$
$\chi_1^\pm\, Z$
$\chi_1^\pm\, W^\mp$
χ_2^0
χ_1^0
$\chi_1^\pm$

Case AI: Bino LSP - Wino NLSP

T. Han, S. Padhi, SS (2013)

$\chi_1^\pm$ decay 100% via on/off-shell W





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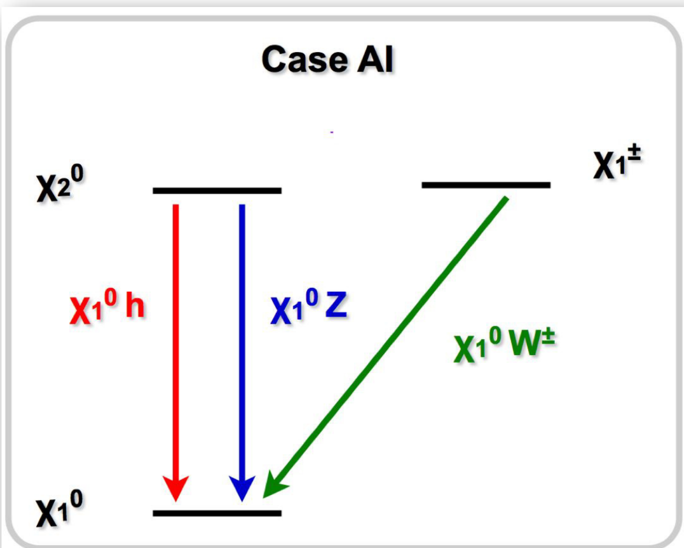
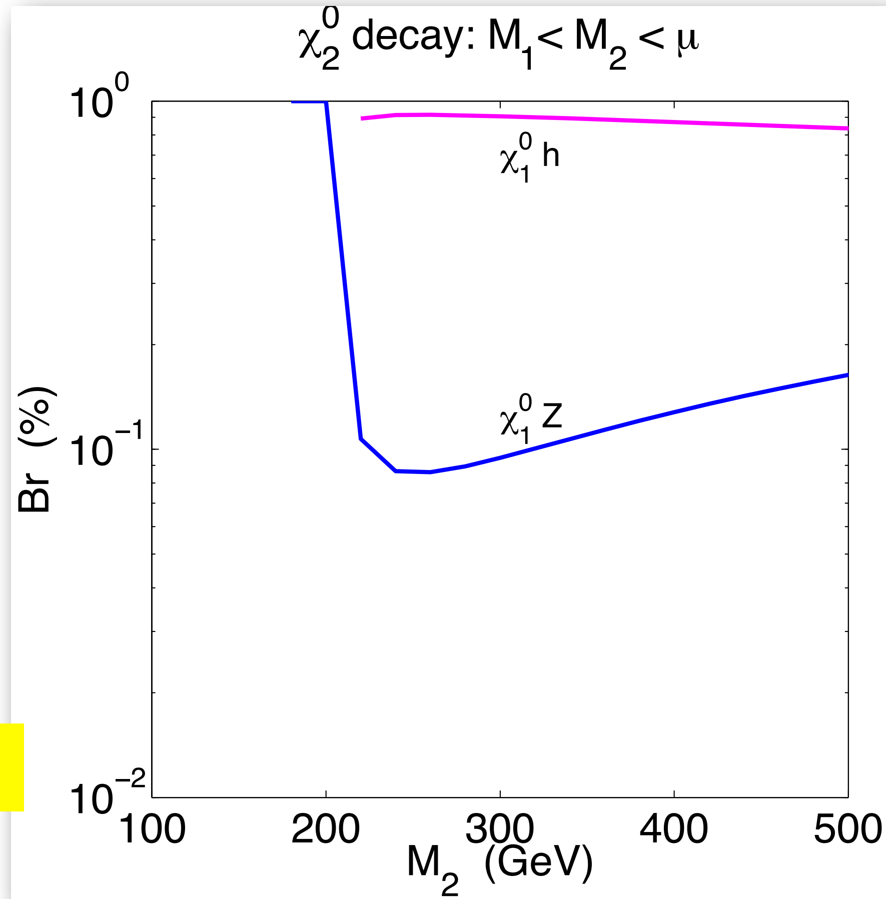
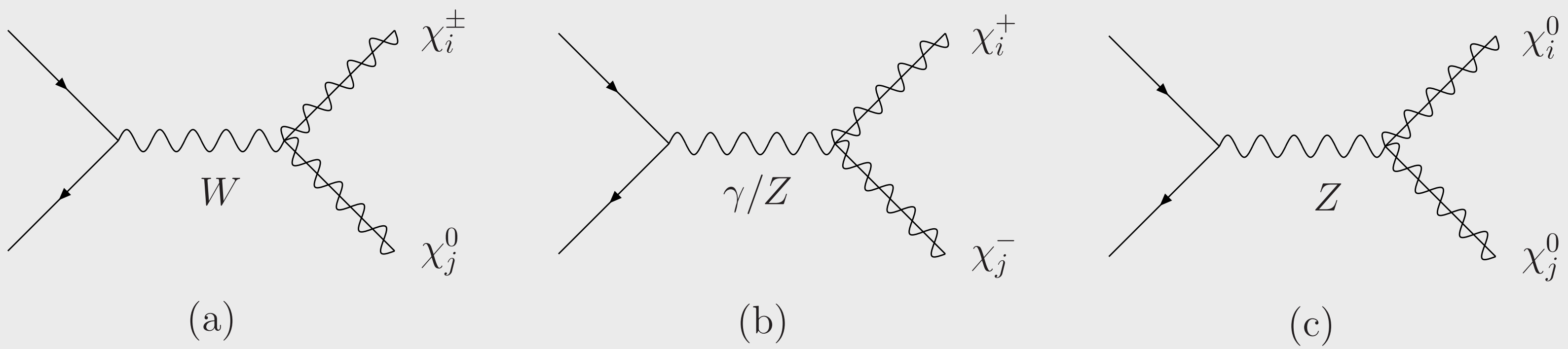




decay to h dominates over decay to Z !

Productions



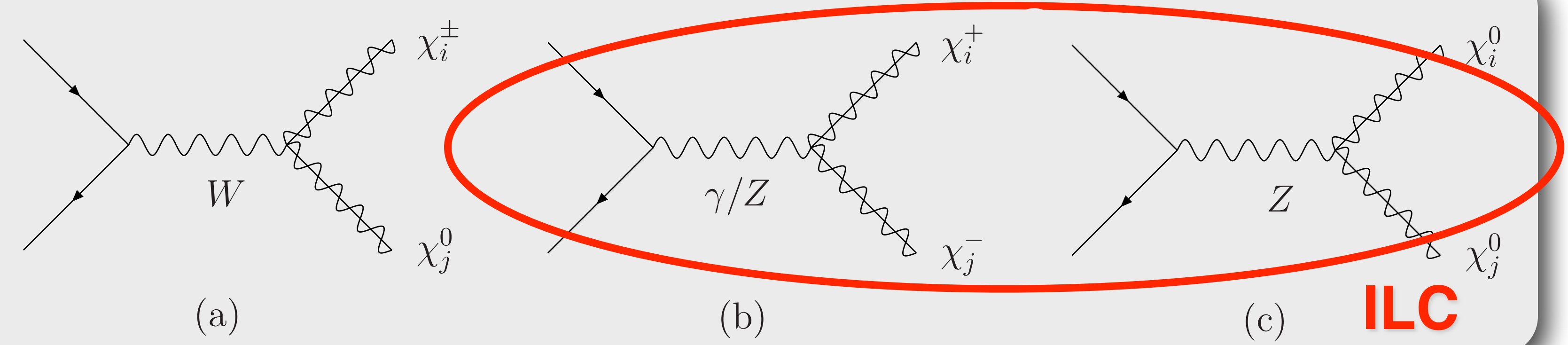
Dominant production:

- **Wino pair production: cha-cha, cha-neu**
- **Higgsino pair production: cha-cha, cha-neu, neu-neu**

$$\sigma_{XY}^{\rm tot} = \sum_{i,j} \sigma(\chi_i \chi_j) \times Br(\chi_i \chi_j \to XY),$$

$$XY = W^+W^-,\ W^\pm W^\pm,\ WZ,\ Wh,\ Zh,\ ZZ,\ \text{and } hh$$

Productions



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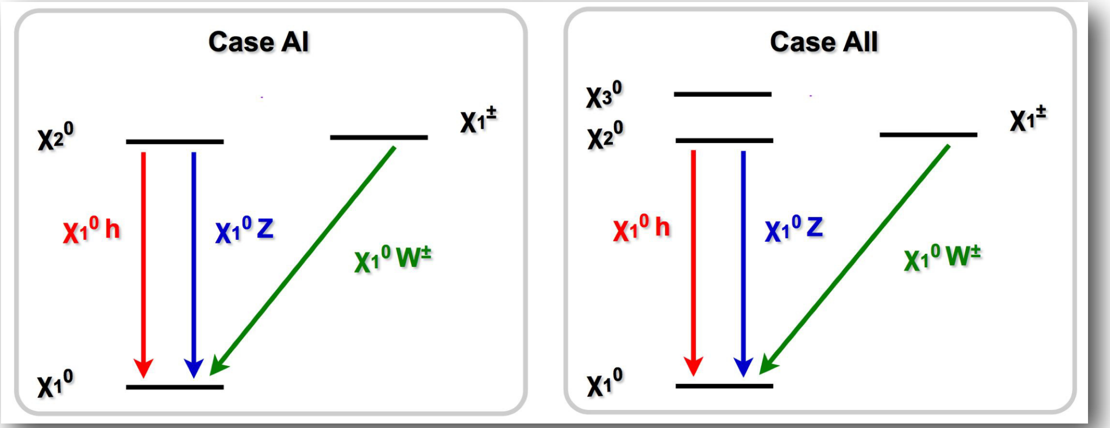
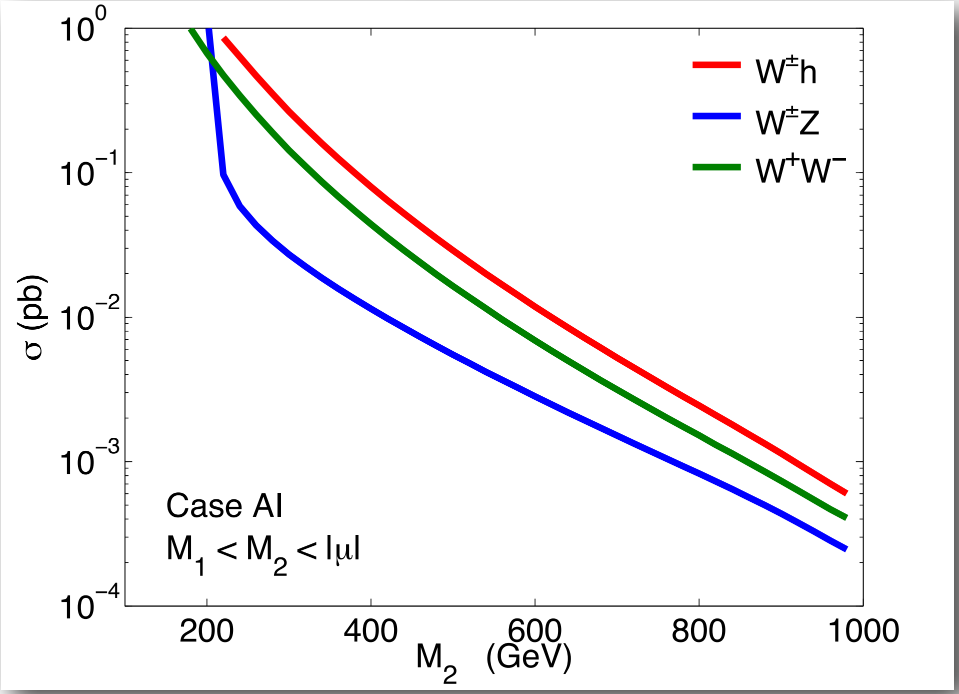
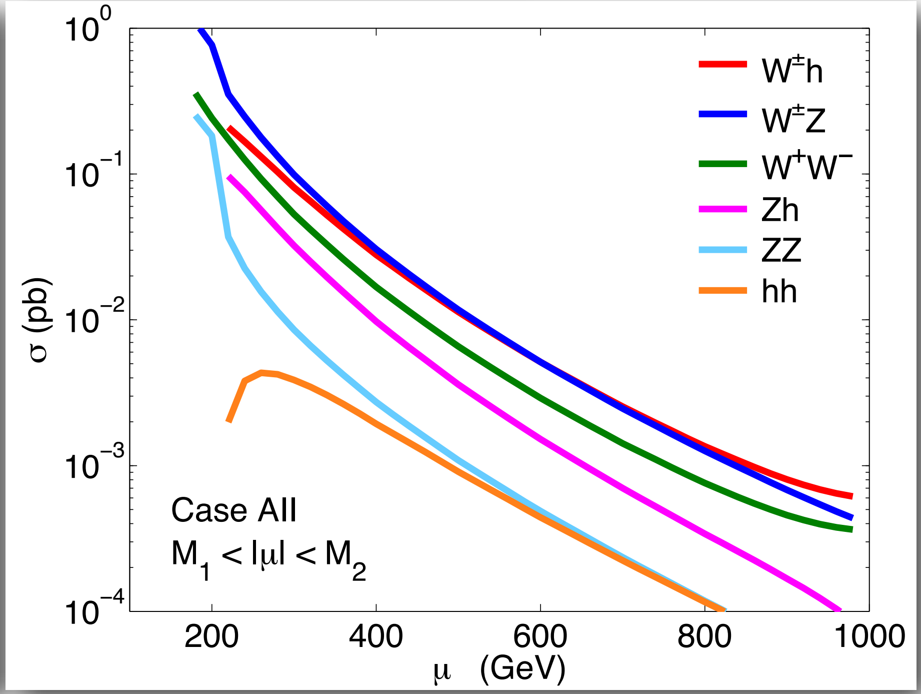
Productions: Bino LSP

T. Han, S. Padhi, SS (2013)







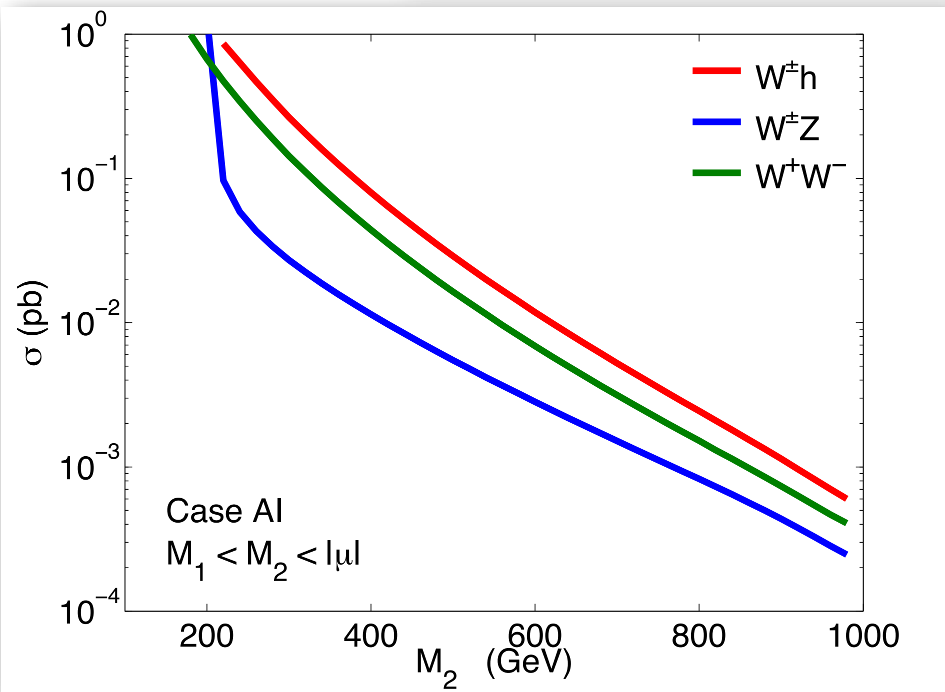
Productions: Bino LSP

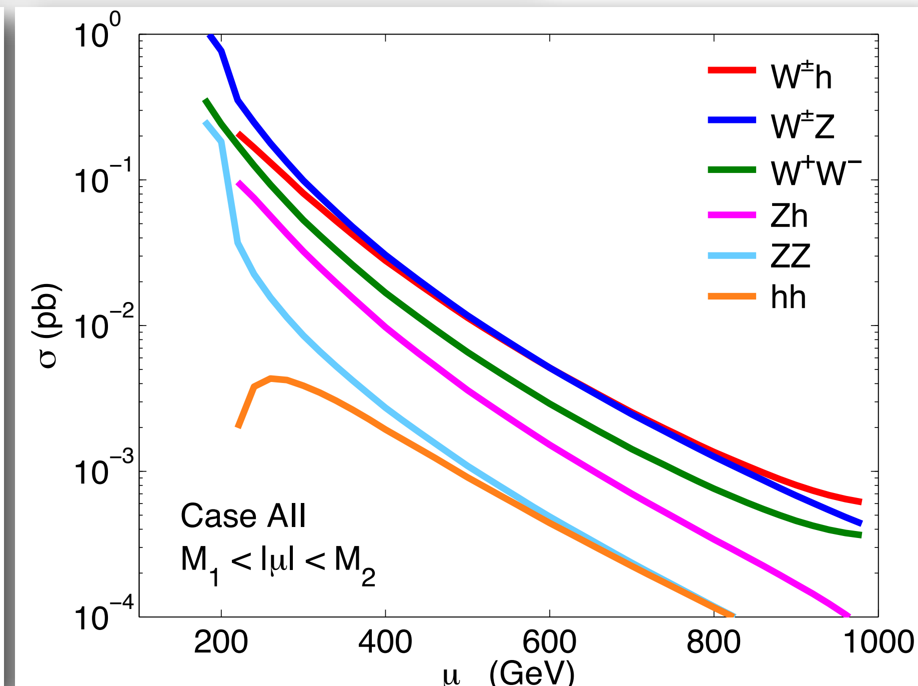
T. Han, S. Padhi, SS (2013)

Case AI

Case AII

- Br(WZ) < 100%, sometime highly suppressed
- Wh complementary to WZ channel: new discovery potential
- Zh could also be important
- hh usually is small





LHC/ILC searches

Channel	Signal (LHC)	Signal (ILC)
W^+W^-	OS2L + MET	hadronic (4j), semileptonic, leptonic final states +MT
$W^\pm W^\pm$	SS2L + MET	
WZ	3L + MET	
Wh	1L + bb + MET	
Zh	OS2l +bb + MET	
LSP pair		ISR photon + soft

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Wh and Zh channels comparable/complementary to WW, WZ channels!

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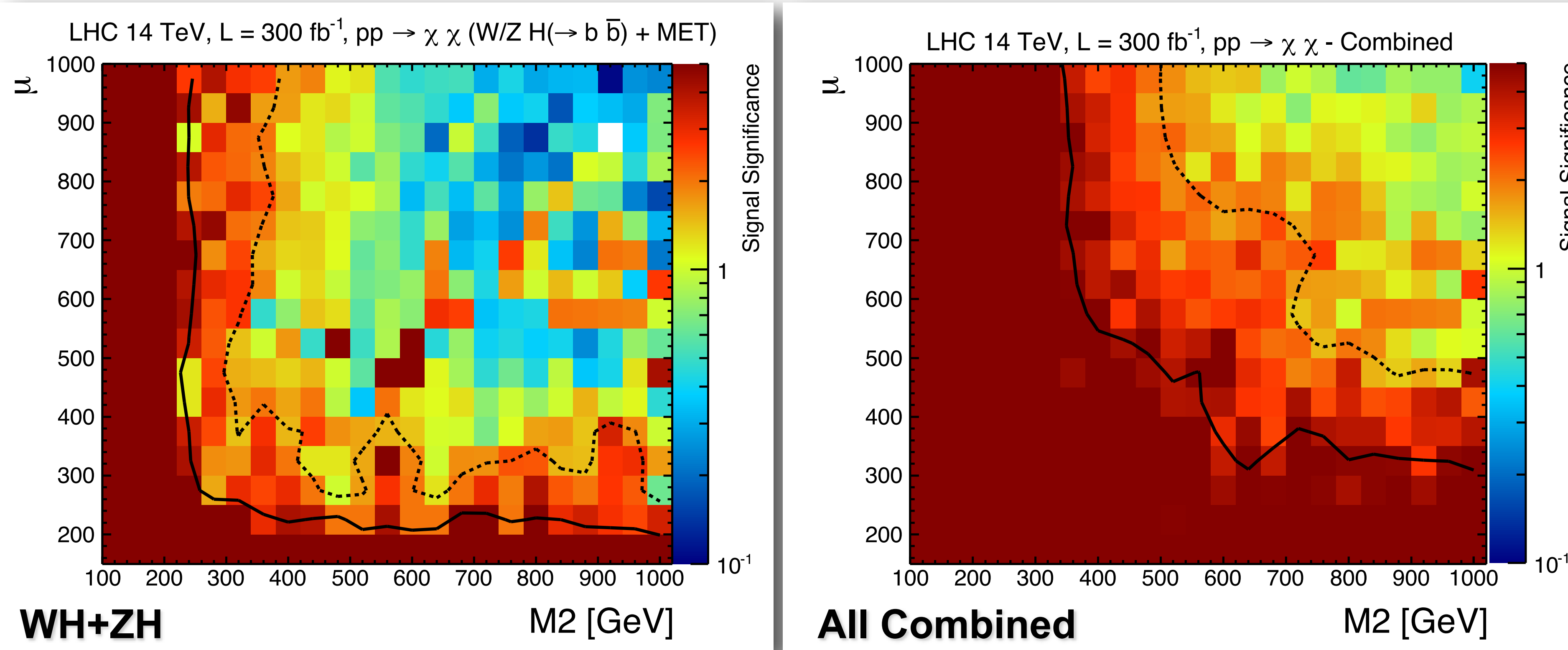
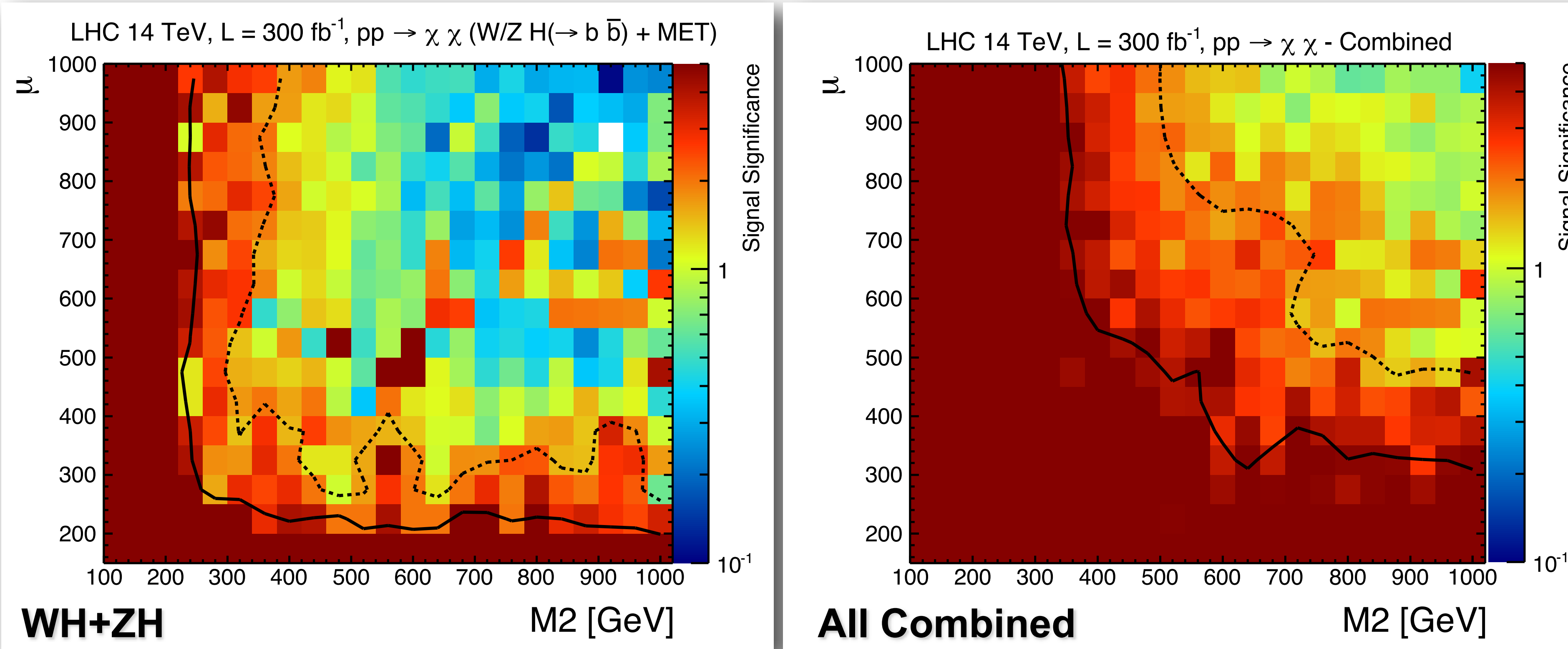
LHC-ILC complementarity

Neutralino/Chargino search



T. Han, S. Padhi, SS (2013)

Neutralino/Chargino search



T. Han, S. Padhi, SS (2013)

Unique signal !
Wh complementary to WZ channels !

III. Exotic decay of non-SM Higgs

- Conventional search channel (even for non-SM Higgs):

  $\gamma\gamma$, ZZ, WW, $\tau\tau$, bb

- New Higgs decay modes open for (non-)SM Higgs decay

Searching for Other Higgses

New channels open up for non-SM Higgs decay

HH type	$(bb/\tau\tau/WW/ZZ)(bb/\tau\tau/WW/ZZ)$	$h_{SM} \to AA$, $H \to h_{SM}\, h_{SM}$, $H \to AA$, $A_i \to H_j A_k$,...
H^+H^- type	$(\tau\nu/tb)(\tau\nu/tb)$	$H/A \to H^+H^-$
ZH type	$(ll/qq/\nu\nu)(bb/\tau\tau/WW/ZZ)$	$h_{SM} \to ZA$, $A \to Zh_{SM}$, ...
$WH^\pm$ type	$(l\nu/qq')\ (\tau\nu/tb)$	$H/A \to WH^\pm$
WH type	$(l\nu/qq')(bb/\tau\tau/WW/ZZ)$	$tH^\pm$ production, $H^\pm \to WH$ $H^\pm \to WA$

Searching for Other Higgses

New channels open up for non-SM Higgs decay

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H^+H^- type	$(\tau\nu/tb)(\tau\nu/tb)$	$H/A \to H^+H^-$
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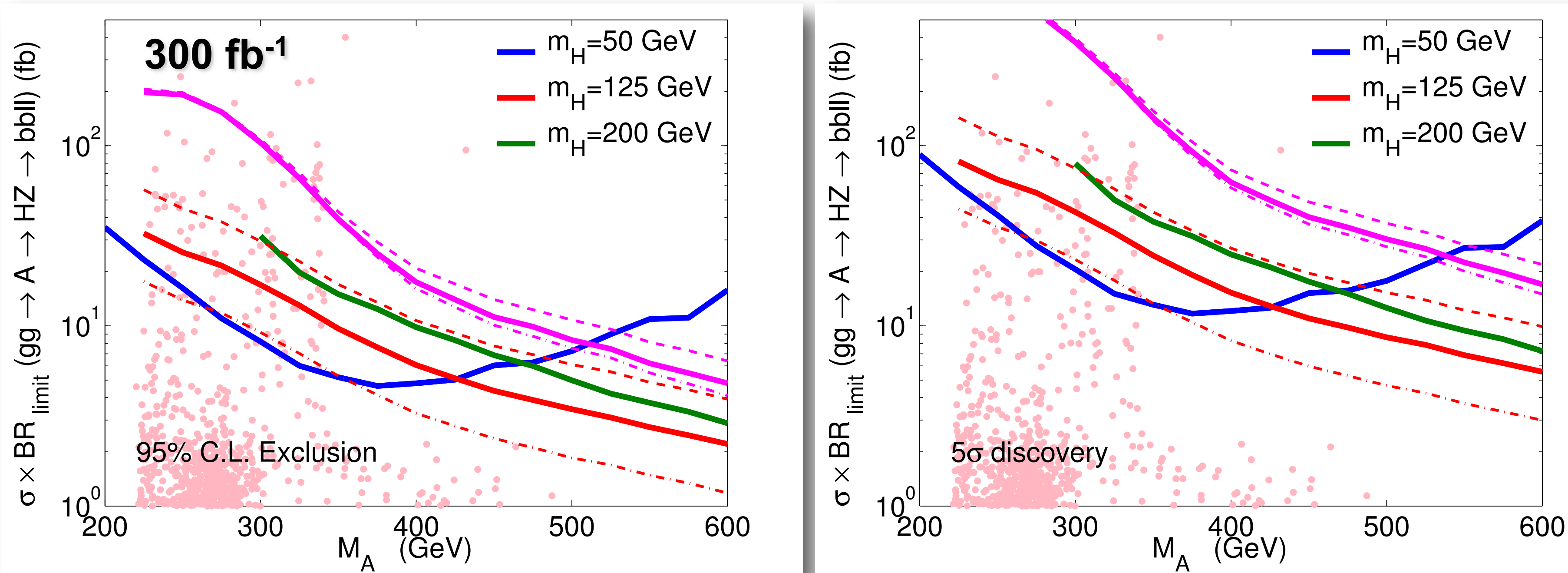
Searching for Other Higgses

B. Coleppa, F. Kling, SS (2013)



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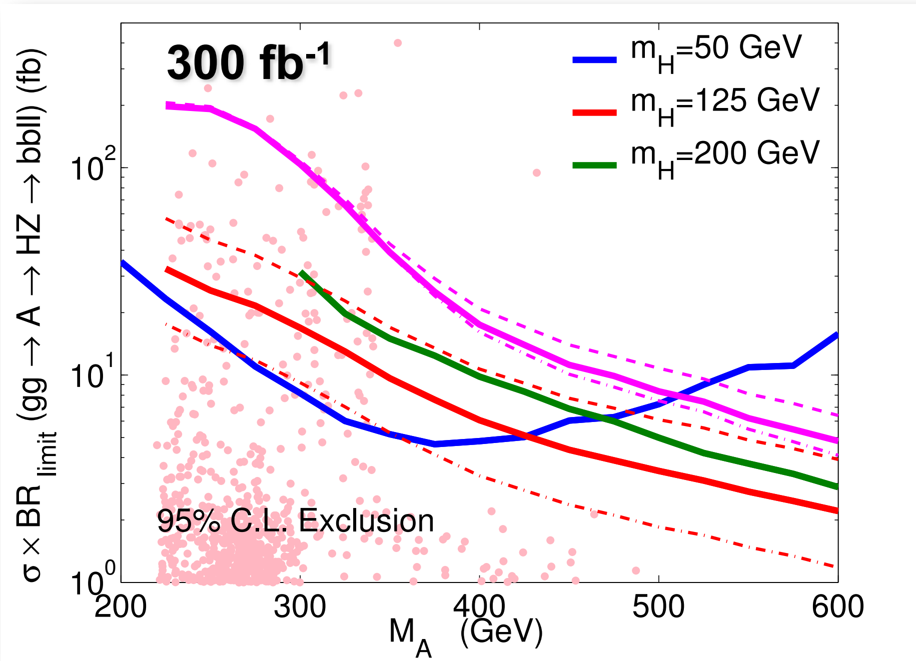

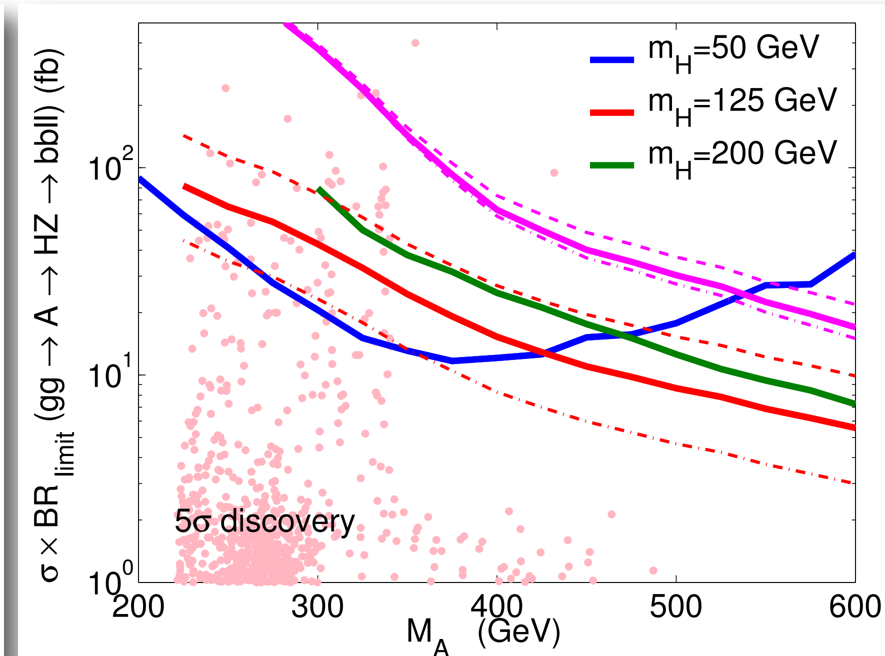

improved reach for m_A < 350 GeV

Conclusion

- the discovery of Higgs is a remarkable triumph in particle physics
- a light weakly coupled Higgs argues for new physics beyond SM
- current Higgs search results already impose strong constraints on new physics beyond the SM
- Higgs should not be a lonely particle: interactive friends and partners
- Higgs help with searches for other new physics
- search for Higgs in the unconventional channel
- LHC lights the way for the searches
- Higgs factory: precision measurements of Higgs properties

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An exciting journey ahead of us!

We found Higgs Great!

We found Higgs

Great!

We found Higgs   Great!

We found Higgs

Or

Great!

We found Higgs

Great!

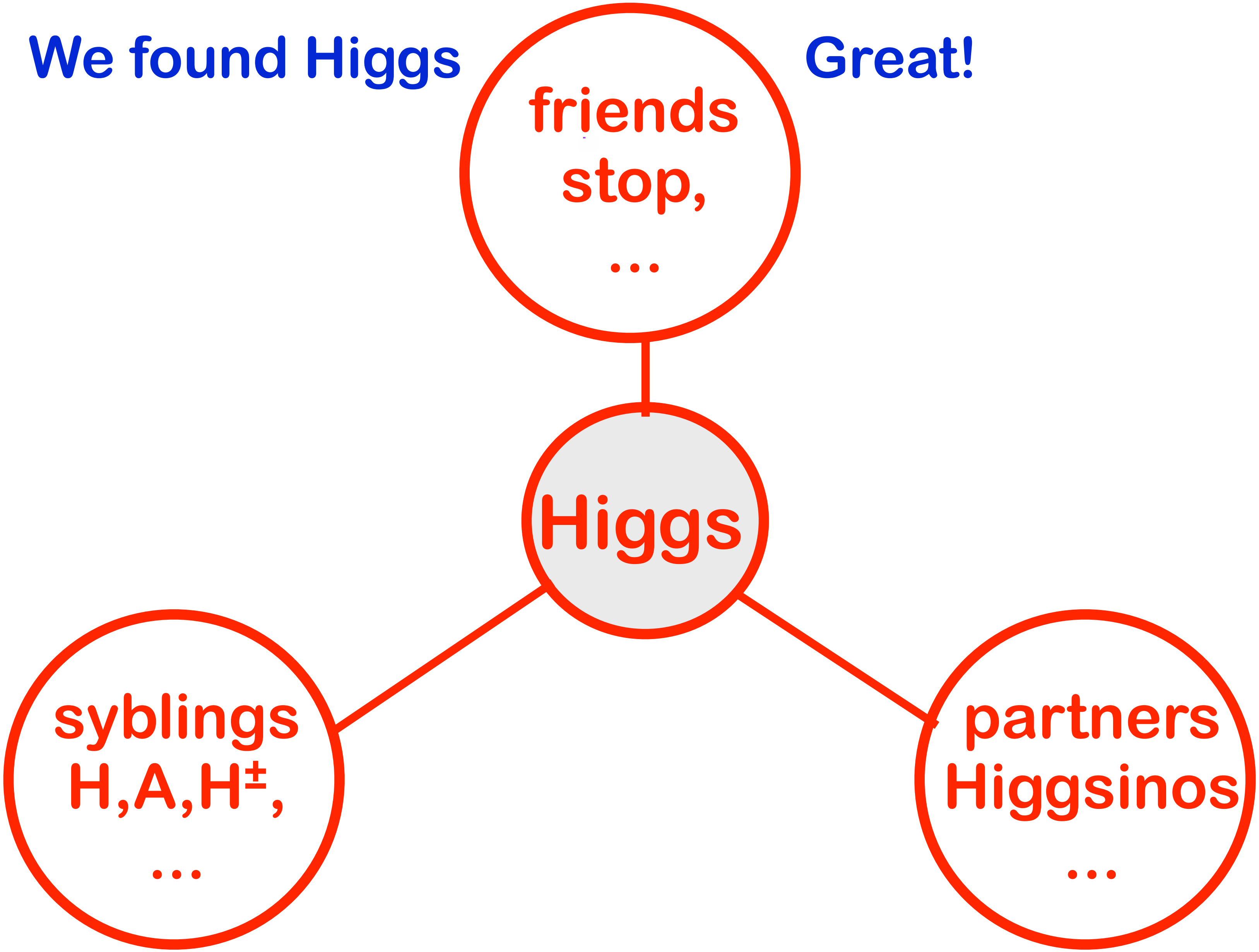
Or

We found Higgs

Or

Great!

We found Higgs Great!




We found Higgs
Great!
friends
stop,
...
Road ahead us
Brighter!!!
syblings
H,A,H±,
...
partners
Higgsinos
...