Probing signature of second Higgs peak

#### Ahmed Hammad

Signatures at Run-I

#### MSSM second CP-even Higgs

Decoupling region Coupling with SM particles

#### B-LSSM CP-even Higgs

Superpotential and gauge mixing CP-even Higgs mass matrix

Higgs coupling and unitarity test

#### Comparin

heoretical

at Run-I  $h' \rightarrow ZZ \rightarrow 4I$ 

 $\begin{array}{ccc} h' \rightarrow \gamma \gamma \\ h' \rightarrow Z \gamma \end{array}$ 

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# Probing signature of second Higgs peak Beyond MSSM

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Sildes based on the following papers:

- Can we have another light ( 145 GeV) Higgs boson? S. Khalil, S. Moretti
- Higgs boson decays into  $\gamma\gamma$  and  ${\rm Z}\gamma$  in the MSSM and BLSSM

A. Hammad, S. Khalil, S. Moretti

- Double Higgs peak in the minimal SUSY B-L model
   W. Abdallah, S. Khalil, S. Moretti
- Search of Heavy Higgs at LHC (Ingoing) A. Hammad, S. Khalil, S. Moretti

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neoretical expected with d

at Run-I  $h' \rightarrow 77 \rightarrow 41$ 

 $\begin{array}{ccc} h^{\prime} & \rightarrow & ZZ & \rightarrow & 4I \\ h^{\prime} & \rightarrow & \gamma \gamma \\ h^{\prime} & \rightarrow & Z\gamma \end{array}$ 

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• 
$$h' \rightarrow \gamma \gamma$$

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 $h' \rightarrow \gamma \gamma$  $h' \rightarrow Z \gamma$ 

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Both ATLAS and CMS have found a two sigma excess of the second Higgs signal over background around  $M_h = 140$  GeV in three channels:

$$\bullet h \to ZZ \to 4I$$

$$\bullet h \to \gamma \gamma$$

$$\bullet h \to Z\gamma$$

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 $h' \rightarrow 77 \rightarrow 41$  $\begin{array}{c} h' \to \gamma \gamma \\ h' \to Z \gamma \end{array}$ 

In MSSM we have two have two CP-even Higgs boson, one CP-odd and charged Higgs boson. The CP-even Higgs boson masses defined as:

$$M_{h,H}^2 = \frac{1}{2} \left[ M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2) - 4M_A^2 M_Z^2 \cos^2 2\beta} \right]$$

We adopt h to be SM-like Higgs and H the second heavy Higgs

The physical States obtained by ordinary rotation of the gauge eigenstates by an angle  $\alpha$ 

$$\left(\begin{array}{c}h\\H\end{array}\right) = \left(\begin{array}{cc}\cos\alpha & \sin\alpha\\-\sin\alpha & \cos\alpha\end{array}\right) \left(\begin{array}{c}h0\\H0\end{array}\right)$$

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expected with data at Run-1  $h' \rightarrow ZZ \rightarrow 4l$  $h' \rightarrow \gamma\gamma$  $h' \rightarrow Z\gamma$ 

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### Signatures at Run-l

# MSSM second CP-even Higgs Decoupling region Coupling with SM particles

### 3 B-LSSM CP-even Higgs

- Superpotential and gauge mixing
- CP-even Higgs mass matrix
- Higgs coupling and unitarity test

# Comparing theoretical expected with data at Run h' → ZZ → 4l

• 
$$h' \rightarrow \gamma \gamma$$

• 
$$h' \rightarrow Z\gamma$$

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# Decoupling region

### Conditions

- $M_A \gg M_Z$
- large  $\tan\beta$

### Adventages

- SM-Like Higgs reached its maximal masses.
- The coupling of SM-like Higgs *h* with SM particles approached the SM one.

# Veto against other regions!!!

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• 
$$h' \rightarrow \gamma \gamma$$

• 
$$h' \rightarrow Z\gamma$$

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# Coupling with SM particles

### For Large tan $\beta$ and $M_A$

Coupling with SM gauge bosons

$$egin{aligned} g_{hVV} &= 1 - rac{2M_Z^4}{M_A^4 an^2eta} \sim 1 \ g_{HVV} &= -rac{2M_Z^2}{M_A^2 an^2eta} \sim 0 \end{aligned}$$

### Coupling with SM fermions

$$egin{aligned} g_{h\!f\!f} &= 1 - rac{2M_Z^2}{M_A^2 an^2eta} \sim 1 \ g_{H\!f\!f} &= -rac{2M_Z^2}{M_A^2 an^2eta} \sim -\coteta \end{aligned}$$



# End of MSSM route!!!

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 $\begin{array}{l} h' \ \rightarrow \ ZZ \ \rightarrow \ 4l \\ h' \ \rightarrow \ \gamma\gamma \\ h' \ \rightarrow \ Z\gamma \end{array}$ 

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# Coupling with SM particles

The coupling of second CP-even MSSM Higgs boson with SM particles is highly supressed. Just look for another less constraint Higgs boson.



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 $\begin{array}{l} n & \rightarrow \ ZZ & \rightarrow \ 4I \\ h' & \rightarrow \ \gamma\gamma \\ h' & \rightarrow \ Z\gamma \end{array}$ 

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### $BLSSM \implies$ extending SM gauge groups by $U(1)_{B-L}$ $BLSSM \implies$ Three generations of superfields right handed neutrinos $\hat{\nu}$ . $BLSSM \implies$ Two bileptons $\chi_1 \chi_2$ , needed to break $U(1)_{B-L}$ . $BLSSM \implies$ One gauge boson Z'

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Signatures at Run-I

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Decoupling region Coupling with SM particles

#### B-LSSM CP-even Higgs

Superpotential and gauge mixing CP-even Higgs mass matrix

Higgs coupling and unitarity test

#### Comparin

theoretical expected with data at Run-I

```
 \begin{array}{l} h' \rightarrow ZZ \rightarrow 4I \\ h' \rightarrow \gamma \gamma \\ h' \rightarrow Z\gamma \end{array}
```

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$$h' \rightarrow \gamma \gamma$$

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```
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```

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# Superpotential and gauge mixing

$$W = Y_u \hat{U} \hat{Q} \hat{H}_u - Y_d \hat{D} \hat{Q} \hat{H}_d - Y_e \hat{E} \hat{L} \hat{H}_d + \mu \hat{H}_u \hat{H}_d + Y_\nu \hat{L} \hat{H}_u \hat{\nu} - \mu' \chi_1 \chi_2 + Y_\chi \hat{\nu} \chi_1 \hat{\nu}$$

 $\implies$ Yukawa term  $Y_{\chi}\hat{\nu}\chi_{1}\hat{\nu}$  generates right handed neutrinos masses

⇒at SUSY breaking scale additional soft breaking terms added

$$\begin{aligned} \mathcal{L}_{\mathcal{BLSSM}} &= \mathcal{L}_{\mathcal{MSSM}} - m_0^2 \left[ |\chi_1|^2 + |\chi_2|^2 + |\tilde{\nu}|^2 \right] + \\ T_{\nu} \tilde{L} H_u \tilde{\nu}^c + T_x \tilde{\nu}^c \chi_1 \tilde{\nu}^c + B_{\mu'} \chi_1 \chi_2 + h.c \\ \implies \text{The gauge coupling mixing arises due to} \\ U(1) \times U(1)_{B-L} \text{ expreseed as} \\ G &= \begin{pmatrix} g_1 & \tilde{g} \\ 0 & g_{B-L} \end{pmatrix} \\ \implies \text{for high scale } \tilde{g} = 0 \text{ " preserving gauge unification"} \end{aligned}$$

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- $h' \rightarrow \gamma \gamma$
- $h' \rightarrow Z\gamma$

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 $\begin{array}{ccc} h' \rightarrow \gamma \gamma \\ h' \rightarrow Z \gamma \end{array}$ 

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### CP-even Higgs mass matrix

After EWSB four Higgs bosons introduced  $H_{1,2} = \frac{1}{\sqrt{2}} (\upsilon_{1,2} + \eta_{1,2} + i\phi_{1,2}),$   $\chi_{1,2} = \frac{1}{\sqrt{2}} (\upsilon'_{1,2} + \eta'_{1,2} + i\phi'_{1,2}),$ 

If no gauge kinetic mixing exist e.g.  $\tilde{g} = 0$ , one end up with  $H_{1,2}$  are the MSSM ones

 $\begin{array}{l} \mbox{CP-even Higgs mass matrix can be digonalized by unitary} \\ 4\times 4 \mbox{ matrix} \\ \Gamma M^2 \Gamma = \left\{ m_h^2, m_{h'}^2, m_{H}^2, m_{H'}^2 \right\} \end{array}$ 

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 $h' \rightarrow \gamma \gamma$  $h' \rightarrow Z \gamma$ 

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### Higgs coupling and unitarity test



• Increasing of  $h^\prime$  coupling reduces the couplings of H and  $H^\prime$ 

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### BR MSSM Vs BLSSM





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Note: if  $\tilde{g} = 0$ , h' decoupled with SM particles and couple only with singlets.



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Higgs coupling and unitarity test

 $h' \rightarrow 77 \rightarrow 41$ 

 $h' \rightarrow \gamma \gamma$  $h' \rightarrow Z \gamma$ 

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4 A 1

# Signal strength for Second Higgs



### Dont worry about Unitarity condition



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# Comparing theoretical expected with data at Run-I

With out getting into deep boring long mathematical expressions

- The effective verices of  $h'\gamma\gamma$  and h'gg, calculated first by SPheno and added manually to MadGraph.
- The effective vertex of  $h'Z\gamma$ , we linked between CPsuper-H and SPheno and added the effective coupling manually to MadGraph.
- $h' \rightarrow \gamma \gamma$  and  $h' \rightarrow Z \gamma$  are calulated up to NLO level
- For NLO claculation we consider the QCD coreection from top and bottom SM quark only.

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# SUSY particles enhancing LO loop vertices

Light SUSY particles enhances loop amplitude.



photons coupled only with diagonal light SUSY coupling "vector coupling only"

Why light SUSY particles only???? why not the heavy ones????

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Z boson coupled with diagonal light SUSY coupling "vector coupling only" and off-diagonal light SUSY coupling "axial coupling"

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gauge mixing

 $h' \rightarrow 77 \rightarrow 41$ 

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- $h' \rightarrow Z\gamma$

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 $h' \rightarrow ZZ \rightarrow 4l$  $h' \rightarrow \gamma \gamma$ 

### $h' \rightarrow ZZ \rightarrow 4I$



### Real data extracted by g3data

Probing signature of second Higgs peak

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Higgs coupling and unitarity test

### $h' \rightarrow ZZ \rightarrow 4/$ at Run-II



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### 1 Signatures at Run-I

### 2 MSSM second CP-even Higgs

- Decoupling region
- Coupling with SM particles

### 3 B-LSSM CP-even Higgs

- Superpotential and gauge mixing
- CP-even Higgs mass matrix
- Higgs coupling and unitarity test

# Comparing theoretical expected with data at Run-I

- $h' \rightarrow ZZ \rightarrow 4I$
- $h' \rightarrow \gamma \gamma$
- $h' \rightarrow Z\gamma$

### Ingoing

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Signatures at Run-I

MSSM second CP-even Higgs

Decoupling region Coupling with SM particles

#### B-LSSM CP-even Higgs

Superpotential and gauge mixing CP-even Higgs mass matrix

Higgs coupling and unitarity test

### Comparin

theoretical

at Run-I  $h' \rightarrow ZZ \rightarrow 4I$   $h' \rightarrow \gamma \gamma$  $h' \rightarrow Z\gamma$ 

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 $h' \to \gamma \gamma$ 

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Signatures at



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### Oomparing theoretical expected with data at Run-I

- $h' \rightarrow ZZ \rightarrow 4I$
- $h' \rightarrow \gamma \gamma$
- $h' \rightarrow Z\gamma$

### 5 Ingoing

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Signatures at Run-I

MSSM second CP-even Higgs

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### Comparin

theoretical

expected with data at Run-I  $h' \rightarrow ZZ \rightarrow 4I$  $h' \rightarrow \gamma\gamma\gamma$ 

 $h' \rightarrow Z\gamma$ 

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 $h' \to Z\gamma$ 

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# $h' \rightarrow Z\gamma$ at Run-II



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#### Comparin

theoretical expected with data at Run-I

 $\begin{array}{l} h' \rightarrow ZZ \rightarrow 4I \\ h' \rightarrow \gamma\gamma \\ h' \rightarrow Z\gamma \end{array}$ 

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- Rescale real data collected at Run-I with the Lumi and total cross section at Run-II
- Caculate the exclusion limit and the two band confidence intervals

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Signatures at Run-I

MSSM second CP-even Higgs

Decoupling region Coupling with SM particles

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#### Comparin

theoretical expected with data

 $\begin{array}{l} h' \rightarrow ZZ \rightarrow 4I \\ h' \rightarrow \gamma\gamma \\ h' \rightarrow Z\gamma \end{array}$ 

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gauge mixing

 $h' \rightarrow 77 \rightarrow 41$ 

 $h' \rightarrow \gamma \gamma$ 

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Image: A = A

Thank you for

your patience