Di-Higgs and Missing Transverse Energy: A Signal of Supersymmetric Theory with Bilinear R-parity Violation at the LHC

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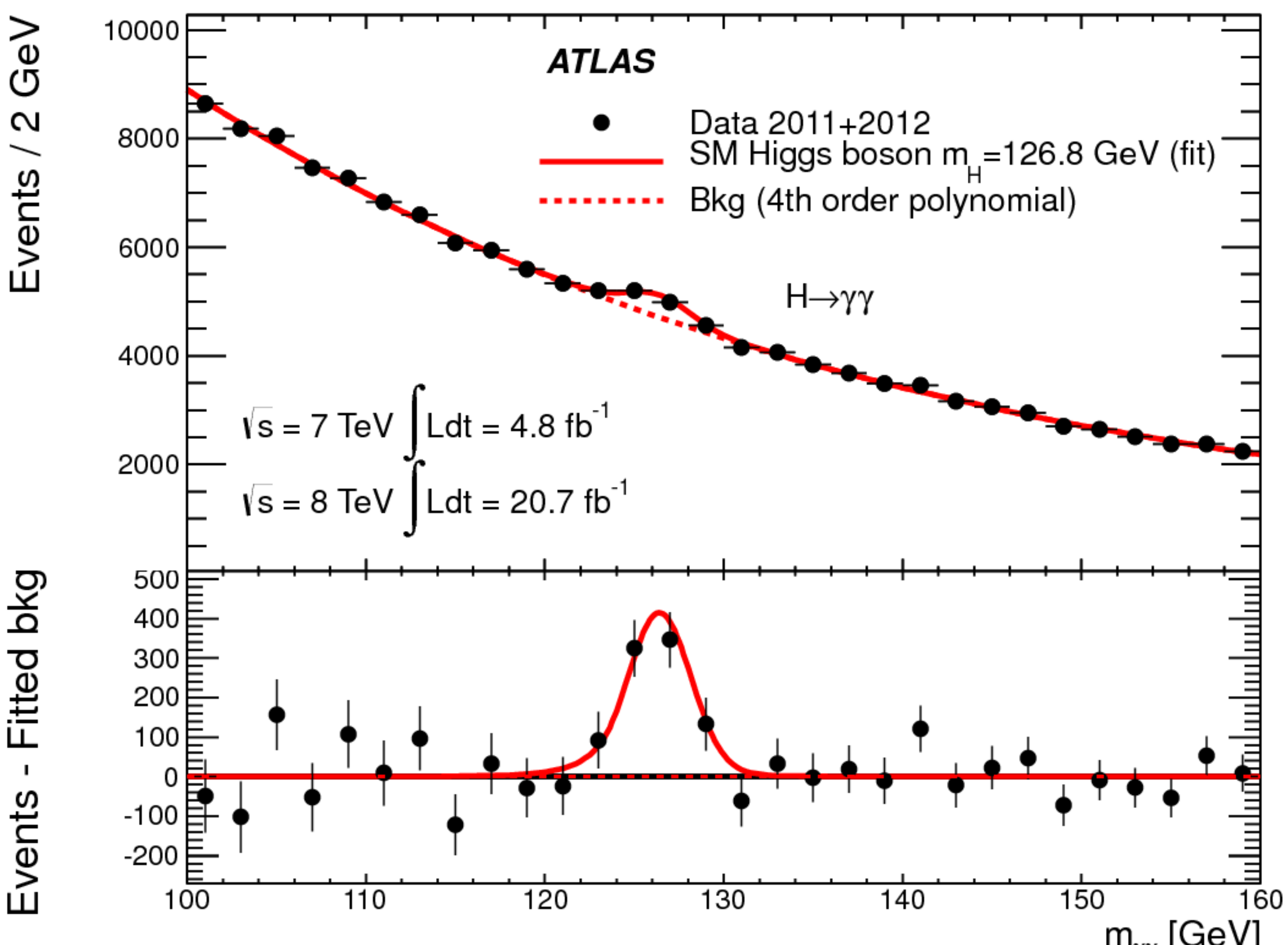
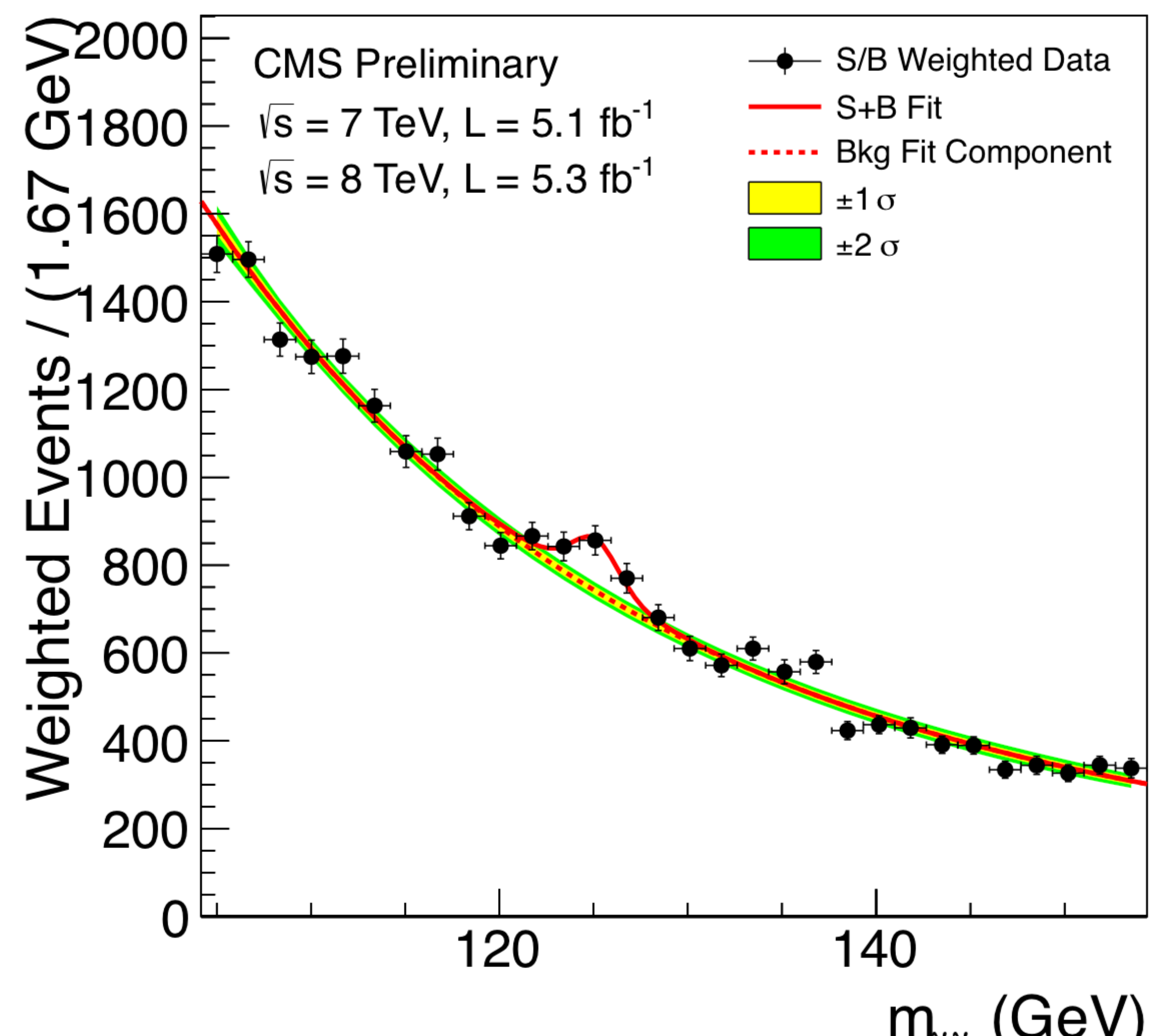
Introduction

- Our attention has changed by the **750 GeV** resonance

- History: 4th July, 2012 : LHC discovered a Higgs-like resonance

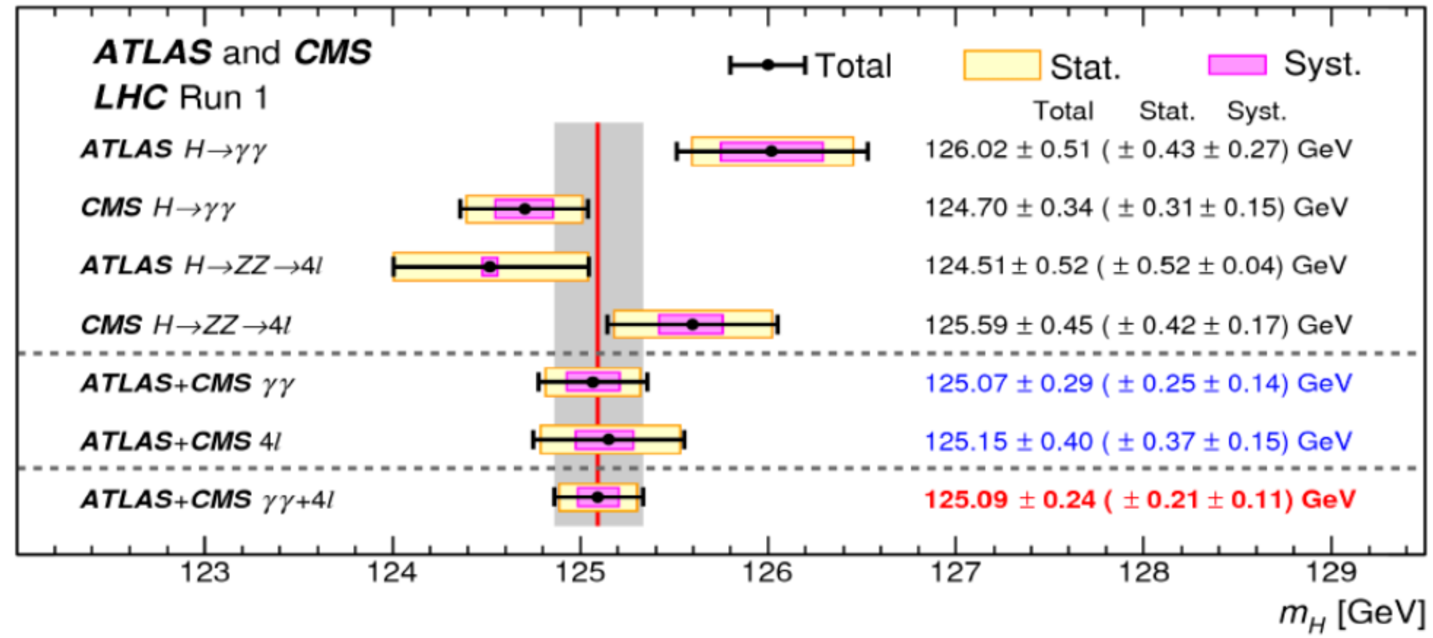
- For $H \to \gamma\gamma$: 4.5σ (ATLAS) and 4.1σ (CMS)



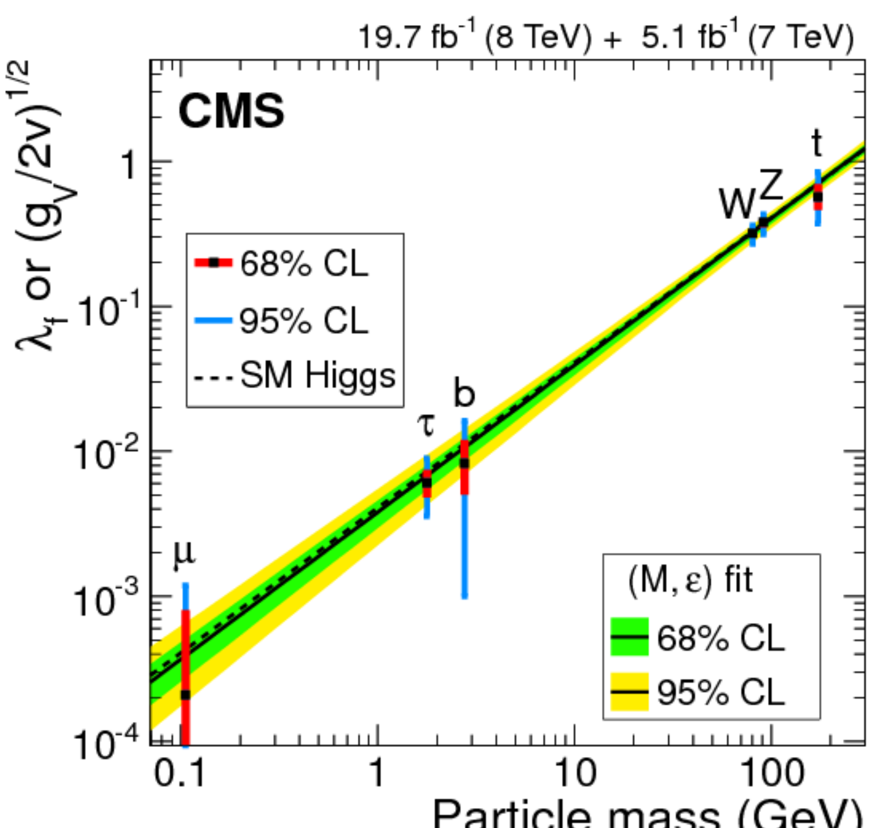


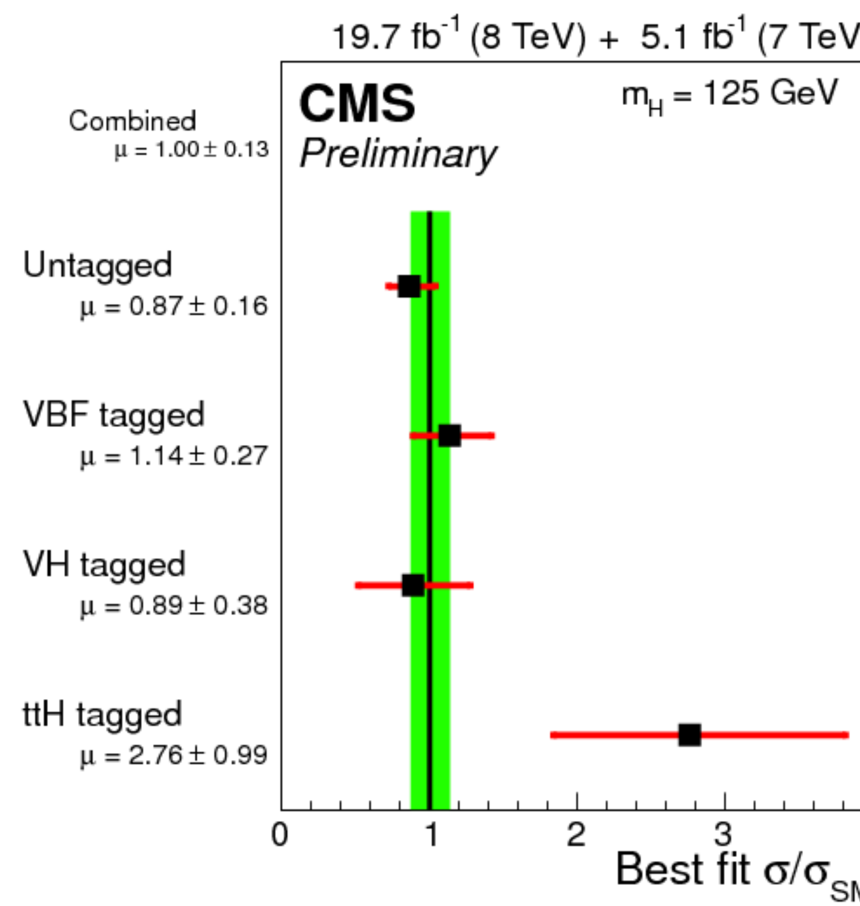
What we have found so far…

- We have measured many important properties of the **125 GeV** resonance: mass, spin and parity



- The signal strength in various channel is also measured



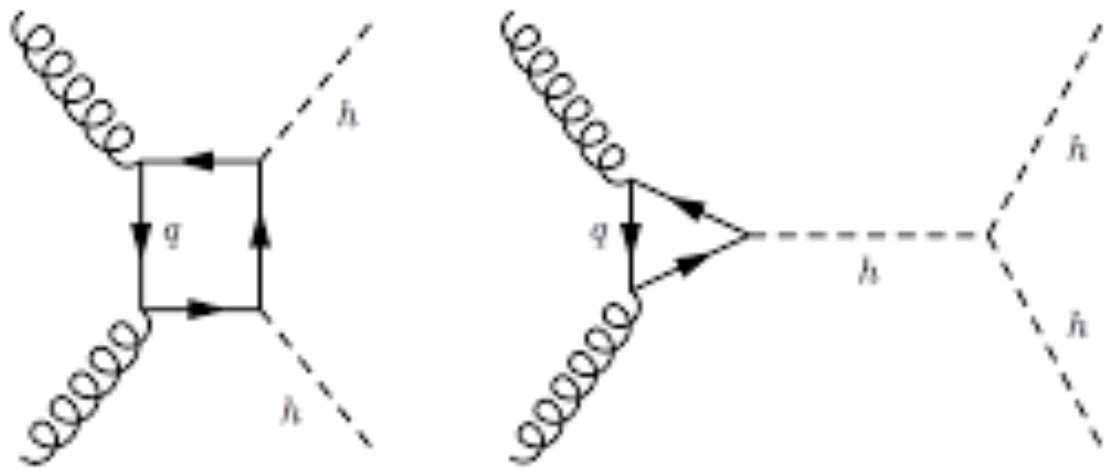


Self-Coupling

$$V = \frac{1}{2}m_h^2 h^2 + \lambda v h^3 + \frac{\tilde{\lambda}}{4}h^4$$

in the SM

$$\lambda = \tilde{\lambda}$$



$\sigma_{SM}(gg \to hh)$

$m_h = 125$ GeV

$\sqrt{s}$	σ (fb)
7 TeV	6.85
8 TeV	9.96
13 TeV	34.3
14 TeV	40.7

Preliminary recommendations from the hh group of LHXSWG

- Measurement of di-Higgs cross-section provides the information of the Higgs self coupling

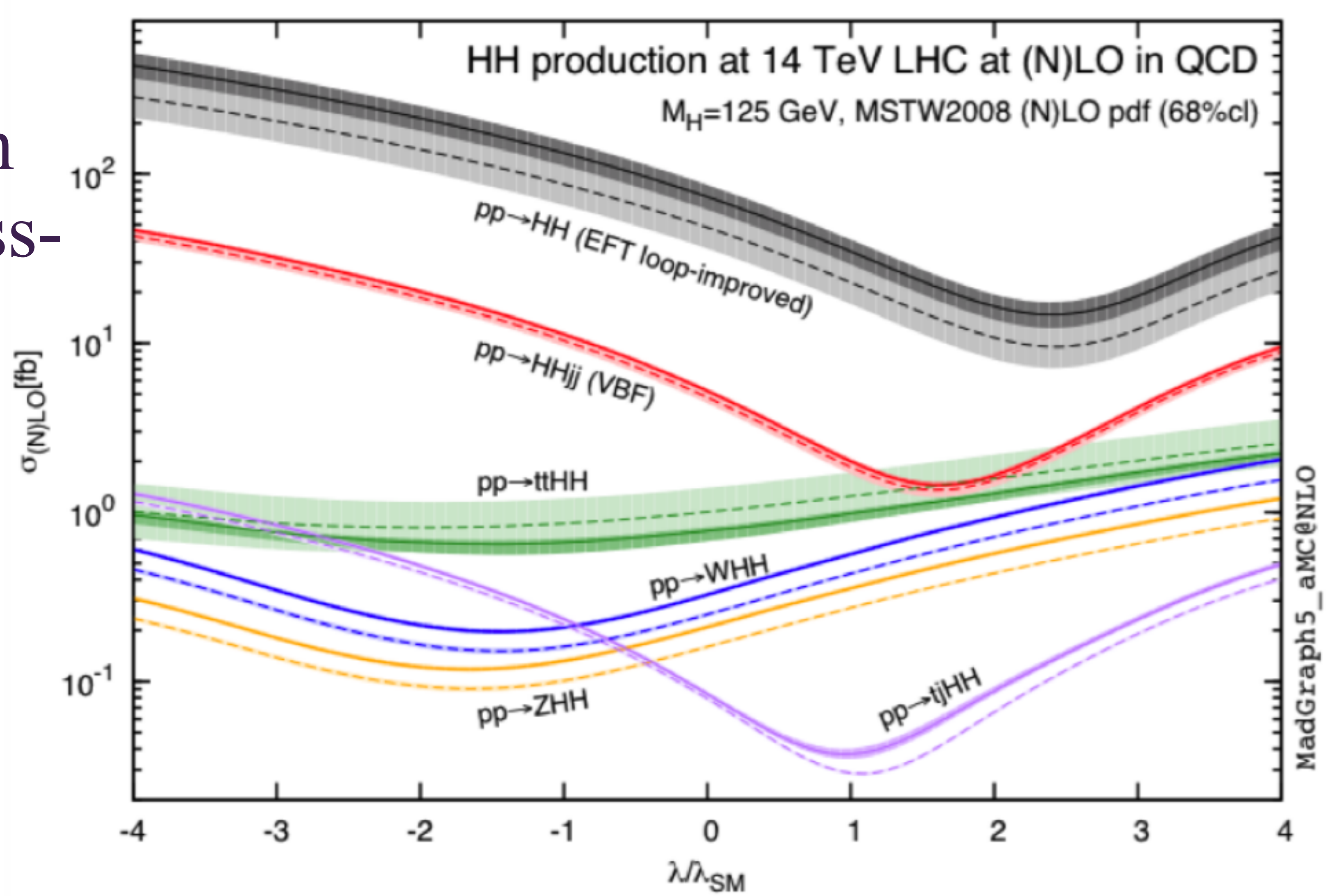
- This is also important to understand the structure of the electroweak symmetry breaking mechanism

di-Higgs as a window to New Physics

- Many physics scenario beyond the SM contribute to di-Higgs production

- The contributions come in the form of enhanced cross-sections (due to different coupling strength)

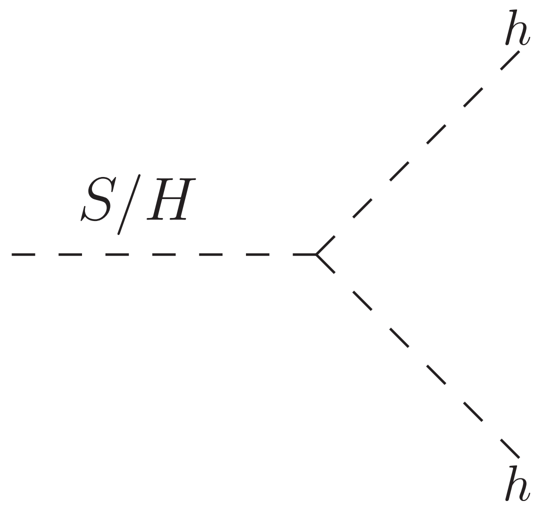
- and/or different event topology (e.g., resonant di-Higgs production)



[Ben Cooper & David Wardrope]

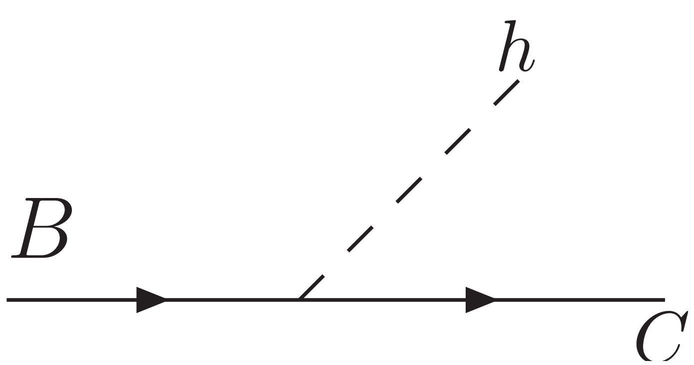
Resonant di-Higgs production

- Many extensions of the SM (singlet/doublet/.. scalar) model additional heavy scalar can decay to pair of SM Higgs



- The cross-section can be 10 times higher than the SM expectation at 14 TeV

di-Higgs production in Cascade



- One can have a pair of Higgs from two sides of the cascade

The Model

- We have considered supersymmetric extension of the SM with bilinear R-parity violation

- SUSY with bilinear R-parity violation can induces Majorana neutrino masses without the right-handed neutrino or exotic Higgs fields

- It also changes collider phenomenology through the decay of the LSP and helps to relax the LHC bounds

$$W_0 = \mu H_1 H_2 + h_i^e L_i H_2 E_i^c + h_i^d Q_i H_2 D_i^c + h_i^u Q_i H_1 U_i^c$$

$$W_1 = \epsilon_i \mu L_i H_1$$

$$V_{soft} = B\mu H_1 H_2 + B_i \epsilon_i \mu L_i H_1 + m^2_{L_i H_1} L_i H_2^\dagger + h.c. \,. \quad \text{(Bilinear)}$$

The Model

- Since the Lepton number is not a conserved quantum number anymore, L_i and H_2 loose their identity and can be rotated among themselves
- Due to the presence bilinear term in the superpotential one normally has mixing in the fermion sector, i.e., the neutralinos mix with the neutrino and charginos mix with the charged leptons

$$\begin{pmatrix} \nu_i \\ \chi_j^0 \end{pmatrix} \longrightarrow \begin{pmatrix} \nu_i - \theta_{ik}^N \chi_k^0 \\ \chi_j^0 + \theta_{lj}^N \nu_l \end{pmatrix}$$

$$\begin{pmatrix} e_i \\ \chi_j^- \end{pmatrix} \rightarrow \begin{pmatrix} e_i - \theta_{ik}^L \chi_k^- \\ \chi_j^- + \theta_{lj}^L e_l \end{pmatrix} \quad ; \quad \begin{pmatrix} e_i^c \\ \chi_j^+ \end{pmatrix} \rightarrow \begin{pmatrix} e_i^c - \theta_{ik}^R \chi_k^+ \\ \chi_j^+ + \theta_{lj}^R e_l^c \end{pmatrix}$$

- One can also have Higgs-slepton mixing through bilinear soft terms

LSP Decay

$\chi_1^0 \to \ell W$

$$\begin{aligned}
\mathcal{L}_{\chi^0 lW} &= \overline{\chi_i^0}\gamma^\mu \left[P_L L_{ij}^{\chi^0 lW} + P_R R_{ij}^{\chi^0 lW}\right] e_j W_\mu^+ + h.c. \\
\text{with} \quad L_{ij}^{\chi^0 lW} &= \frac{g}{\sqrt{2}}\left[c_1^N, c_2^N - \sqrt{2}c_1^L, c_3^N - c_2^L, c_4^N\right]\xi_j c_\beta \\
R_{ij}^{\chi^0 lW} &= \frac{g}{\sqrt{2}}\left[0, -\sqrt{2}c_1^R, 0, -c_2^R\right]\frac{m_j^e}{F_C}\xi_j c_\beta
\end{aligned}$$

$\chi_1^0 \to \nu Z$

$$\begin{aligned}
\mathcal{L}_{\chi^0 \nu Z} &= \overline{\chi_i^0}\gamma^\mu P_L L_{ij}^{\chi^0 \nu Z}\nu_j Z_\mu^0 + h.c. \\
\text{with} \quad L_{ij}^{\chi^0 \nu Z} &= \frac{g}{2c_W}\left[c_1^N, c_2^N, 0, 2c_4^N\right]\xi_j c_\beta\,.
\end{aligned}$$

$\chi_1^0 \to \nu h$

$$\begin{aligned}
\mathcal{L}_{\chi^0 \nu h} &= \overline{\chi_i^0} P_L L_{ij}^{\chi^0 \nu h}\nu_j\, h + h.c. \\
\text{with} \quad L_{ij}^{\chi^0 \nu h} &= \frac{g}{2c_W}\left[s_W(1 - c_3^N c_\beta + c_4^N s_\beta), -c_W(1 - c_3^N c_\beta + c_4^N s_\beta),\right. \\
&\qquad \left.(s_W c_1^N - c_W c_2^N)c_\beta, (s_W c_1^N - c_W c_2^N)s_\beta\right]\xi_j c_\beta
\end{aligned}$$

where,

$$(c_j^N) = \frac{M_Z}{F_N}\left(\frac{s_W M_2}{c_W^2 M_1 + s_W^2 M_2}, -\frac{c_W M_1}{c_W^2 M_1 + s_W^2 M_2}, -s_\beta\frac{M_Z}{\mu}, c_\beta\frac{M_Z}{\mu}\right)$$

$$(c_j^L) = -\frac{M_W}{F_C}\left(\sqrt{2}, 2s_\beta\frac{M_W}{\mu}\right) \quad \text{and} \quad (c_j^R) = -\frac{M_W}{F_C}\left(\sqrt{2}\left(1 - \frac{M_2}{\mu}t_\beta\right), \frac{M_2^2 c_\beta^{-1}}{\mu M_W} + 2\frac{M_W}{\mu}c_\beta\right)$$

with $F_C = M_2 + M_W^2 s_{2\beta}/\mu$ and $F_N = M_1 M_2/(c_W^2 M_1 + s_W^2 M_2) + M_Z^2 s_{2\beta}/\mu.$

Constraint from Neutrino Mass

- One neutrino get mass at tree level due to the presence of neutrino-neutralino mixing

$$\left(\begin{array}{c|c} \begin{array}{c}\text{MSSM}\\ \text{neutralino (chargino)}\\ \text{mass matrix}\end{array} & \not{R}_p \text{ terms} \\ \hline \not{R}_p \text{ terms} & \begin{array}{c}\text{neutrino}\\ \text{(charged lepton)}\\ \text{mass matrix}\end{array} \end{array}\right)$$

Constraint from Neutrino Mass

- One neutrino get mass at tree level due to the presence of neutrino-neutralino mixing $(-i\lambda_\gamma, -i\lambda_Z, \tilde{h}_u^0, \hat{\nu}_\alpha)_{\alpha=0\cdots 3}$

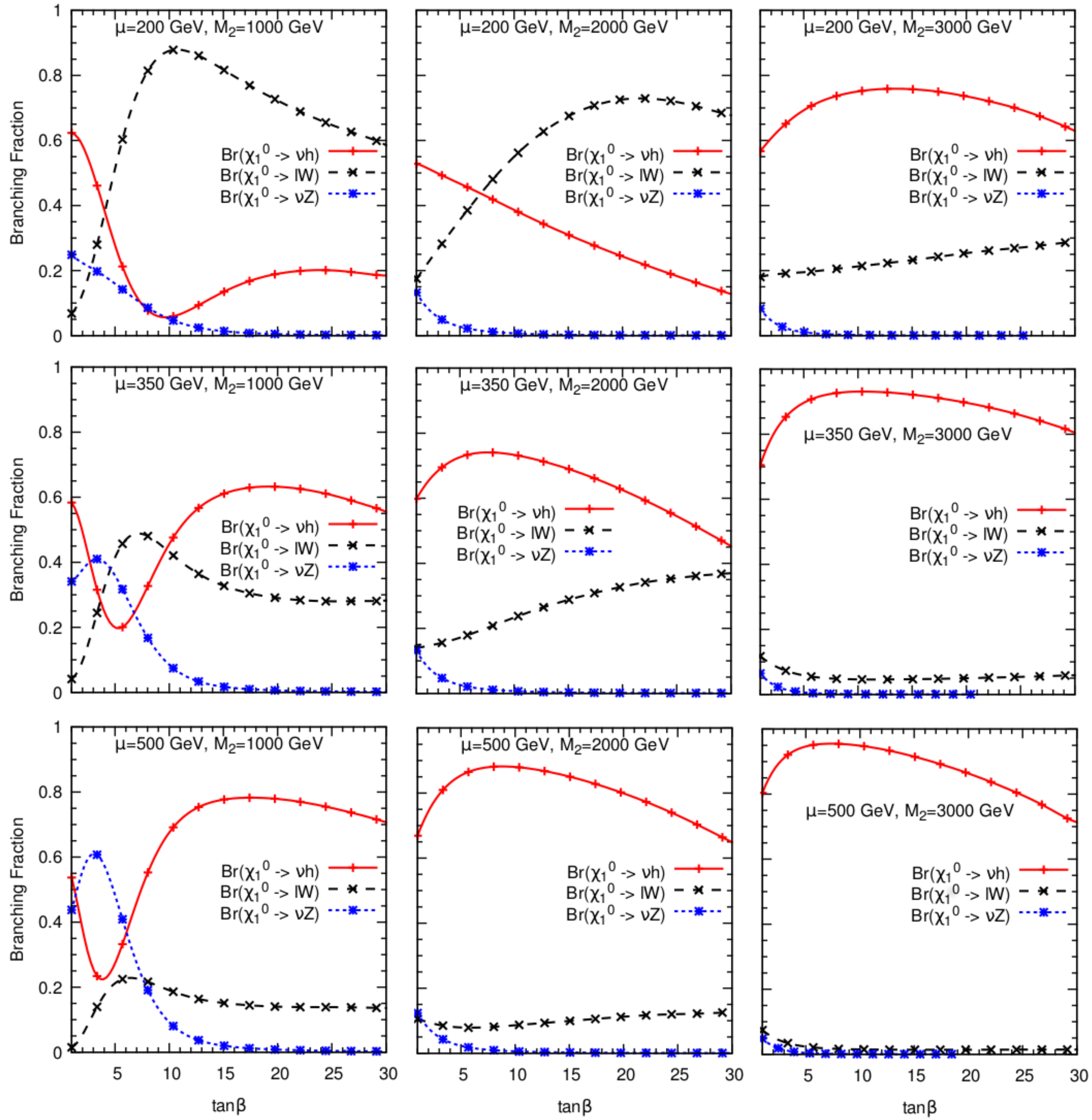
$$M_N = \begin{pmatrix} M_1 c_W^2 + M_2 s_W^2 & (M_2 - M_1) s_W c_W & 0 & 0_{1\times 4} \\ (M_2 - M_1) s_W c_W & M_1 s_W^2 + M_2 c_W^2 & \frac{g}{2c_W} v_u & -\frac{g}{2c_W} v_\alpha \\ 0 & \frac{g}{2c_W} v_u & 0 & -\mu_\alpha \\ 0_{4\times 1} & -\frac{g}{2c_W} v_\alpha & -\mu_\alpha & 0_{4\times 4} \end{pmatrix}$$

- The tree level neutrino mass matrix has the form

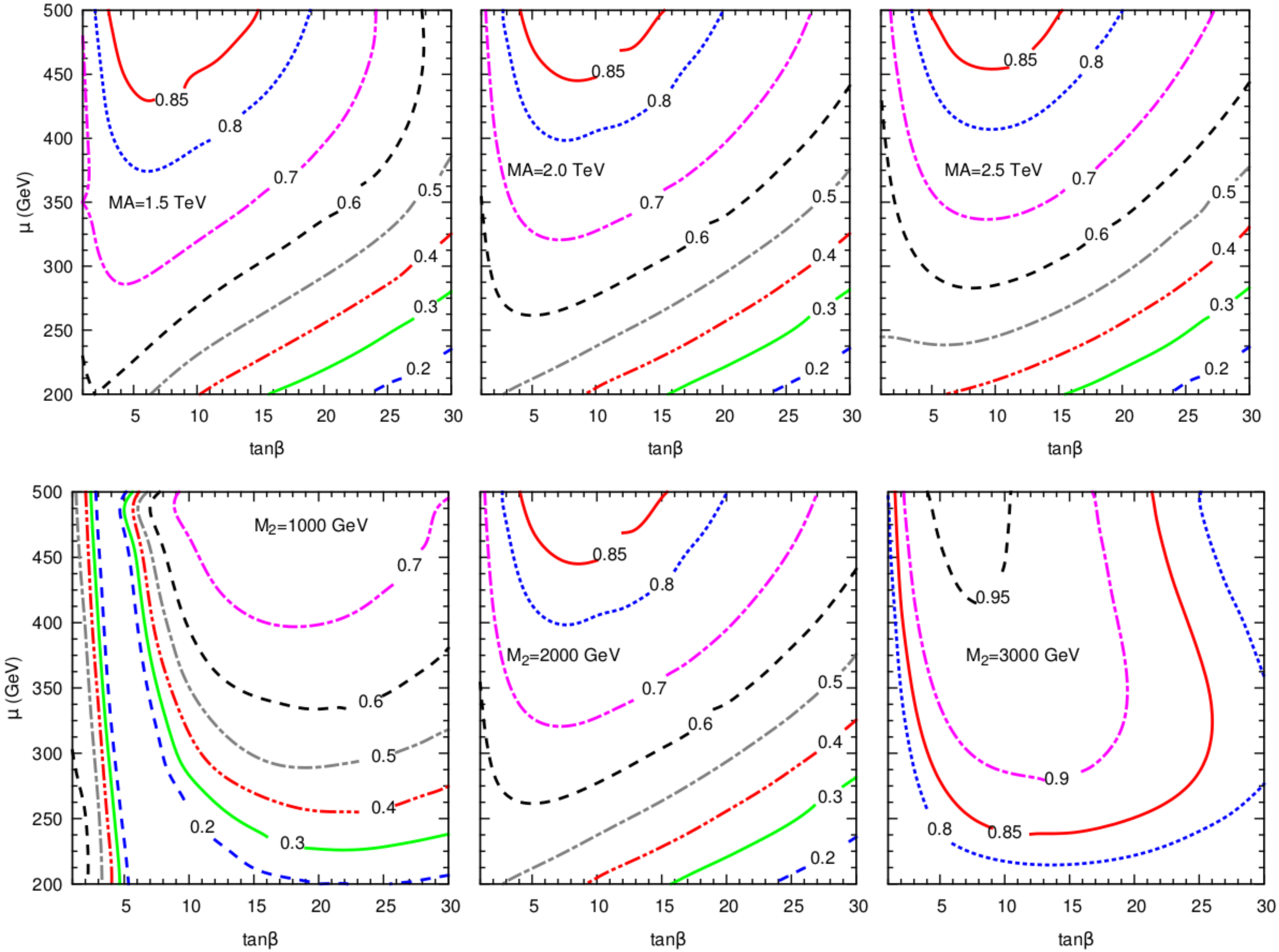
$$M_{ij}^{tree} = -\frac{M_Z^2}{F_N} \xi_i \xi_j c_\beta^2 \qquad \xi_i = \epsilon_i / \sqrt{\sum \epsilon_i^2}$$

$$\xi c_\beta = 0.74 \times 10^{-6} \left(\frac{F_N}{M_Z}\right)^{1/2} \left(\frac{m_{\nu_3}}{0.05\ \mathrm{eV}}\right)^{1/2}$$

Branching Ratio

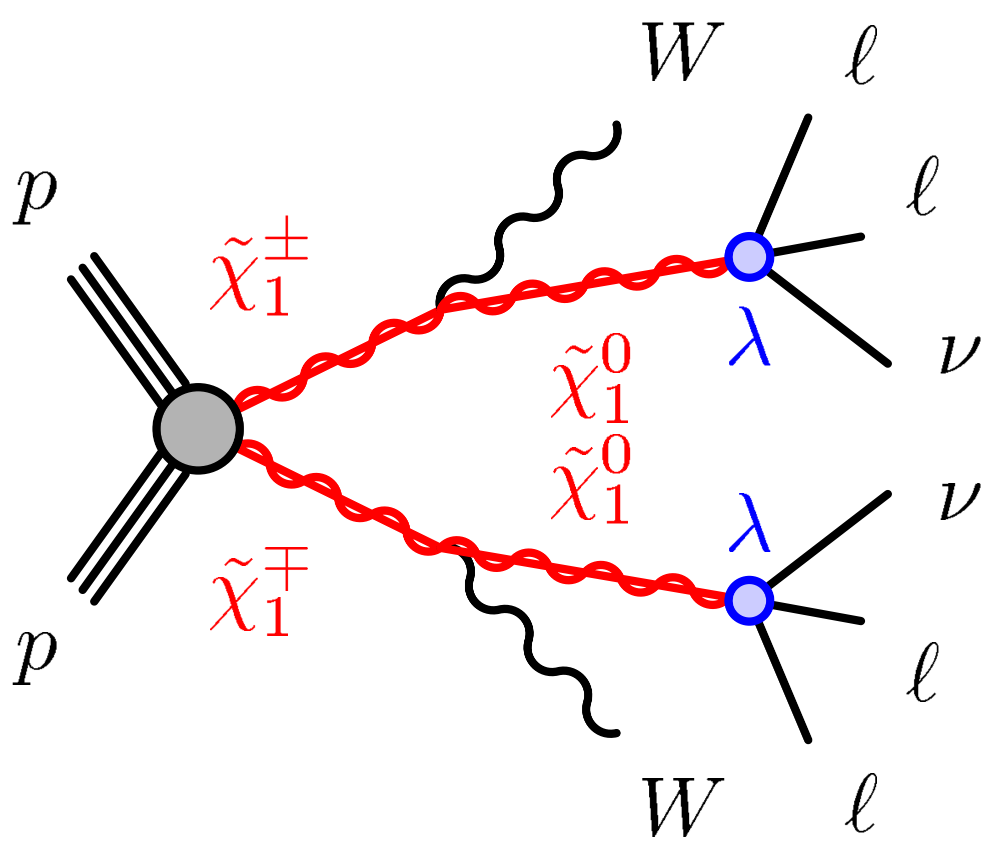


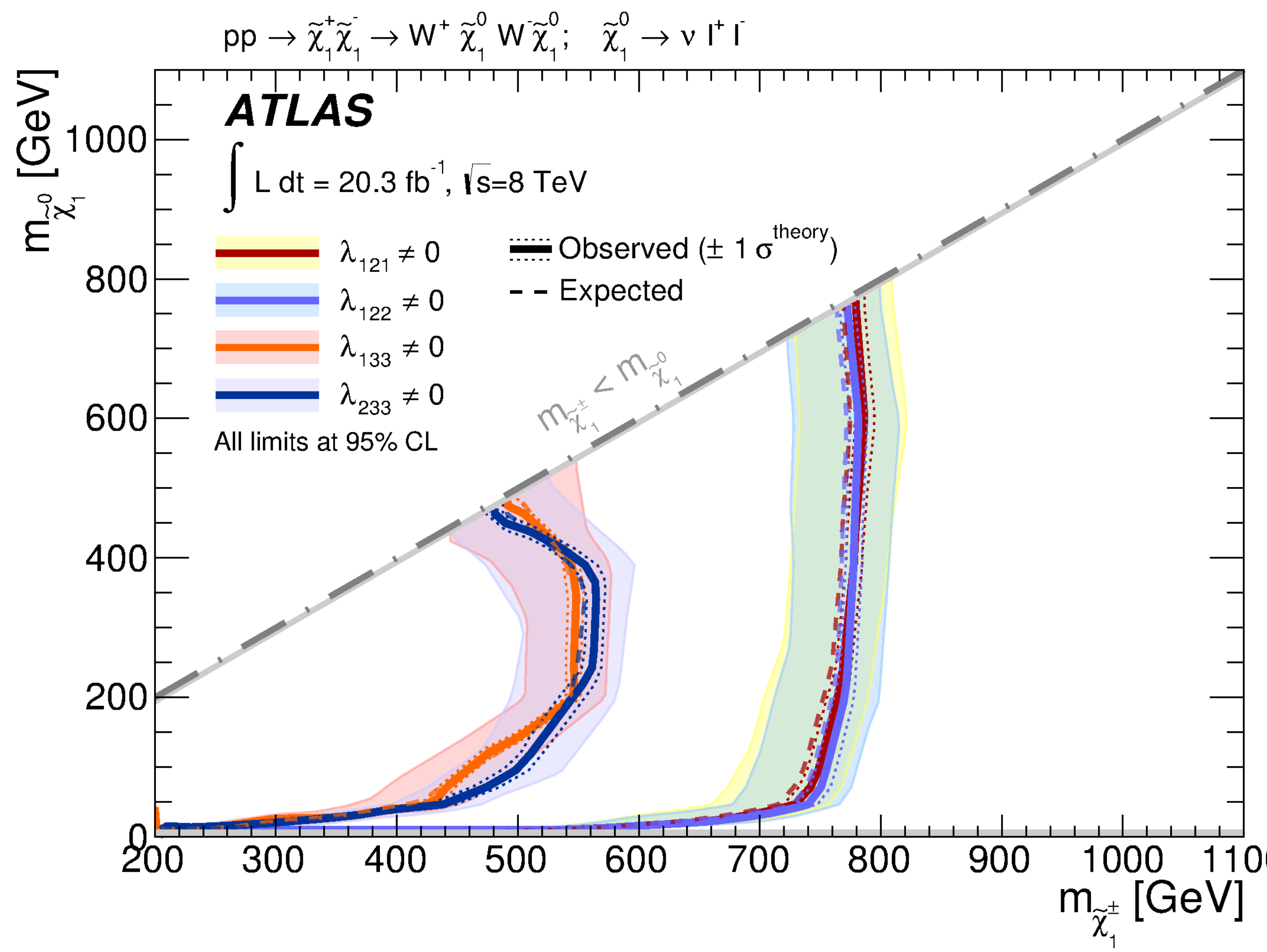
Branching Ratio



LHC Bounds

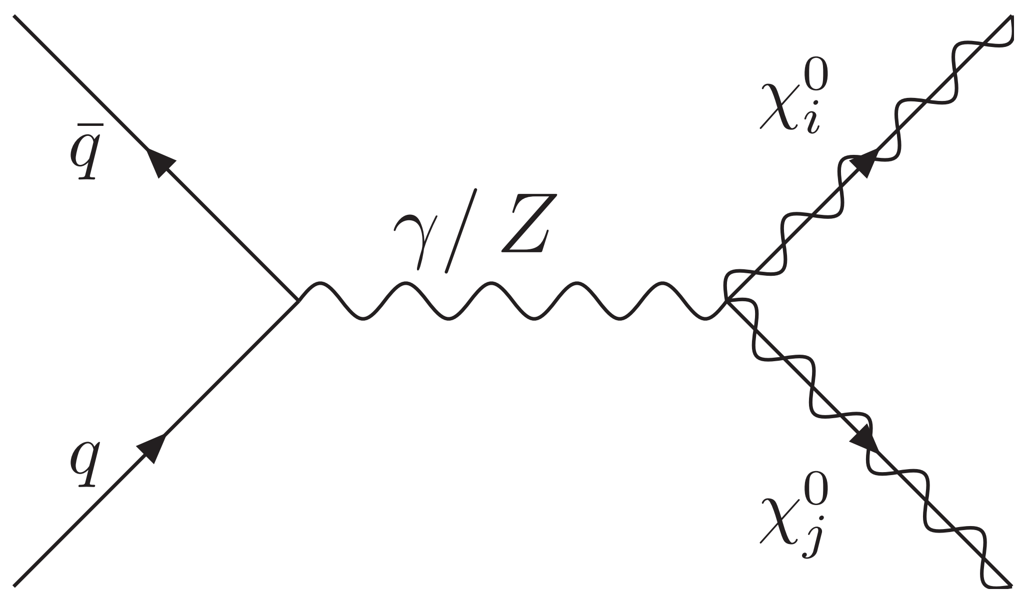
arxiv:1405.5086

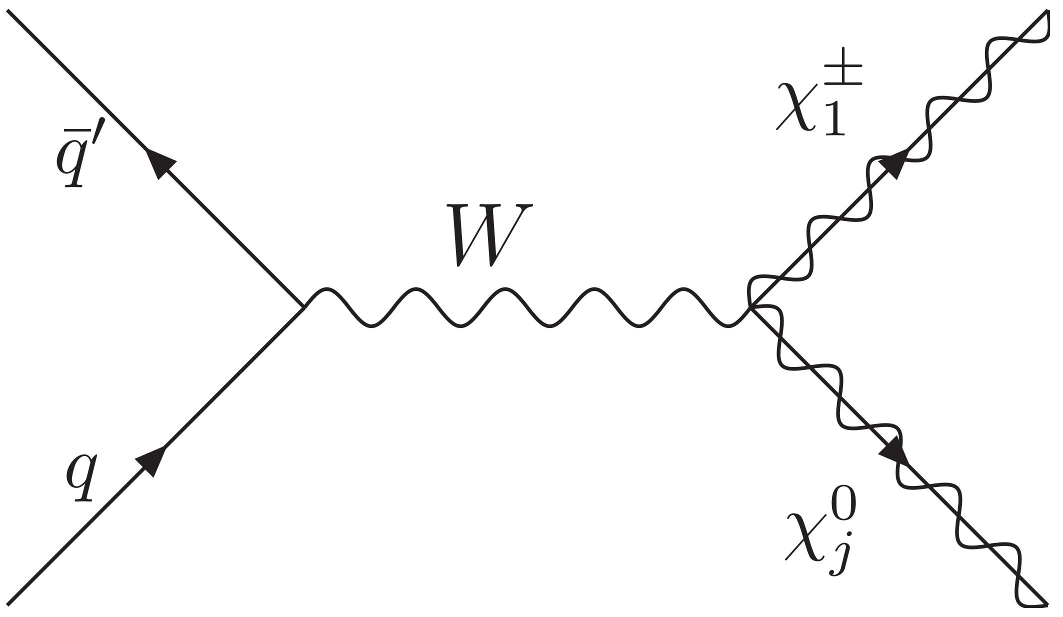




- The LHC bounds can be evaded due to the almost degenerate chargino and neutralino mass
- The bounds also get weaker due the suppression of the direct leptonic decay mode of the neutralino

Collider study





- We have considered pair production of electroweak gauginos

  $\chi_1^0\chi_1^\pm, \chi_2^0\chi_1^\pm, \chi_1^0\chi_2^0, \chi_1^\mp\chi_1^\pm$

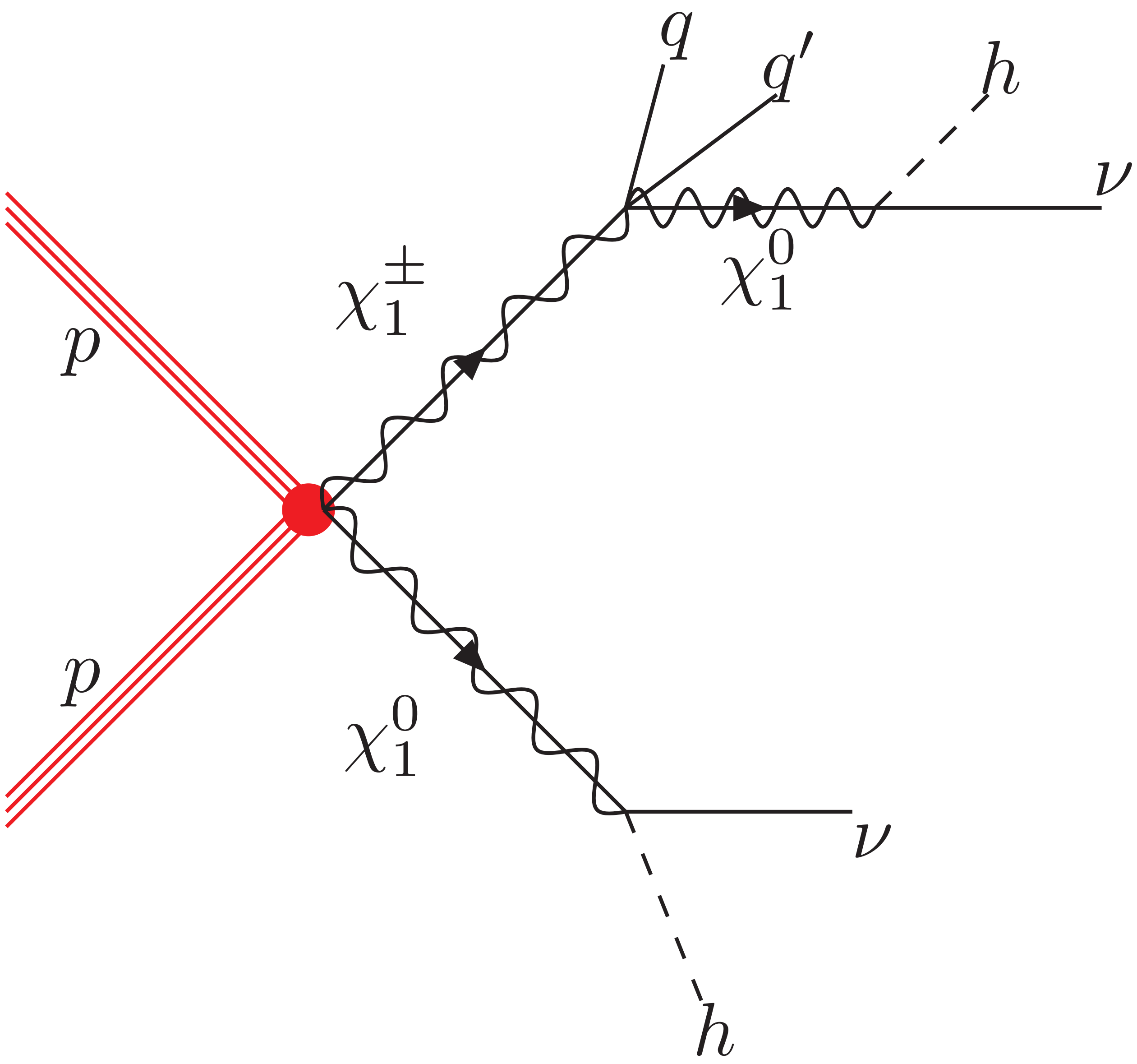
- The main contribution comes from the s-channel EW gauge boson exchange

- The t-channel contribution via squark exchange are suppressed due to large squark masses

Collider study

- Chargino almost 80% of time has 3-body decay via RPC coupling

- The decay products of chargino are soft due to almost degenerate mass



- The LSP decays to mostly a Higgs and a neutrino

- The final state contains a pair of Higgs and large MET

Possible decays of di-Higgs pair

Channel	BR(%)
bbWW	24.7
$bb\tau\tau$	7.3
$WWWW$	4.3
$bb\gamma\gamma$	0.27
$bbZZ(\to e^+e^-\mu^+\mu^-)$	0.015
$\gamma\gamma\gamma\gamma$	0.00052

Table 1: Branching ratios for different di-Higgs channels.

$b\bar{b}b\bar{b}$

- Large branching ratio
- Very challenging due to large QCD backgrounds
- Recently some boosted techniques have been propose

$b\bar{b}WW$

- single lepton+jets : can be promising
- reconstruction of the Higgs pair is possible
- ttbar, W+jets backgrounds plays a dominant role

$b\bar{b}\gamma\gamma$

- Clean channel, but suffers due to small BR
- At HL-LHC this can still be a important channel
- in presence of additional large MET can be more sensitive

Basic Cuts

- We have imposed following basic cuts on photons and b-jets

$$p_T^{\gamma_{1,2}} > (30, 20)\ \text{GeV} \qquad p_T^{b_{1,2}} > (20, 20)\ \text{GeV}$$

$$\eta^{b,\gamma} < 2.5 \qquad \Delta R(bb, \gamma\gamma, b\gamma)$$

- For jet faking as b-jet (or photons) same criteria applied

ϵ_γ	ϵ_b	$P_{c\to b}$	$P_{\tau\to b}$	$P_{j\to b}$	$P_{j\to\gamma}$
90%	70%	1/8	1/26	1/440	1/1000

- $b\bar{b}\gamma\gamma + \not{E}_{\mathrm{T}} > 100\ \text{GeV}$ (large MET required)

SM Backgrounds

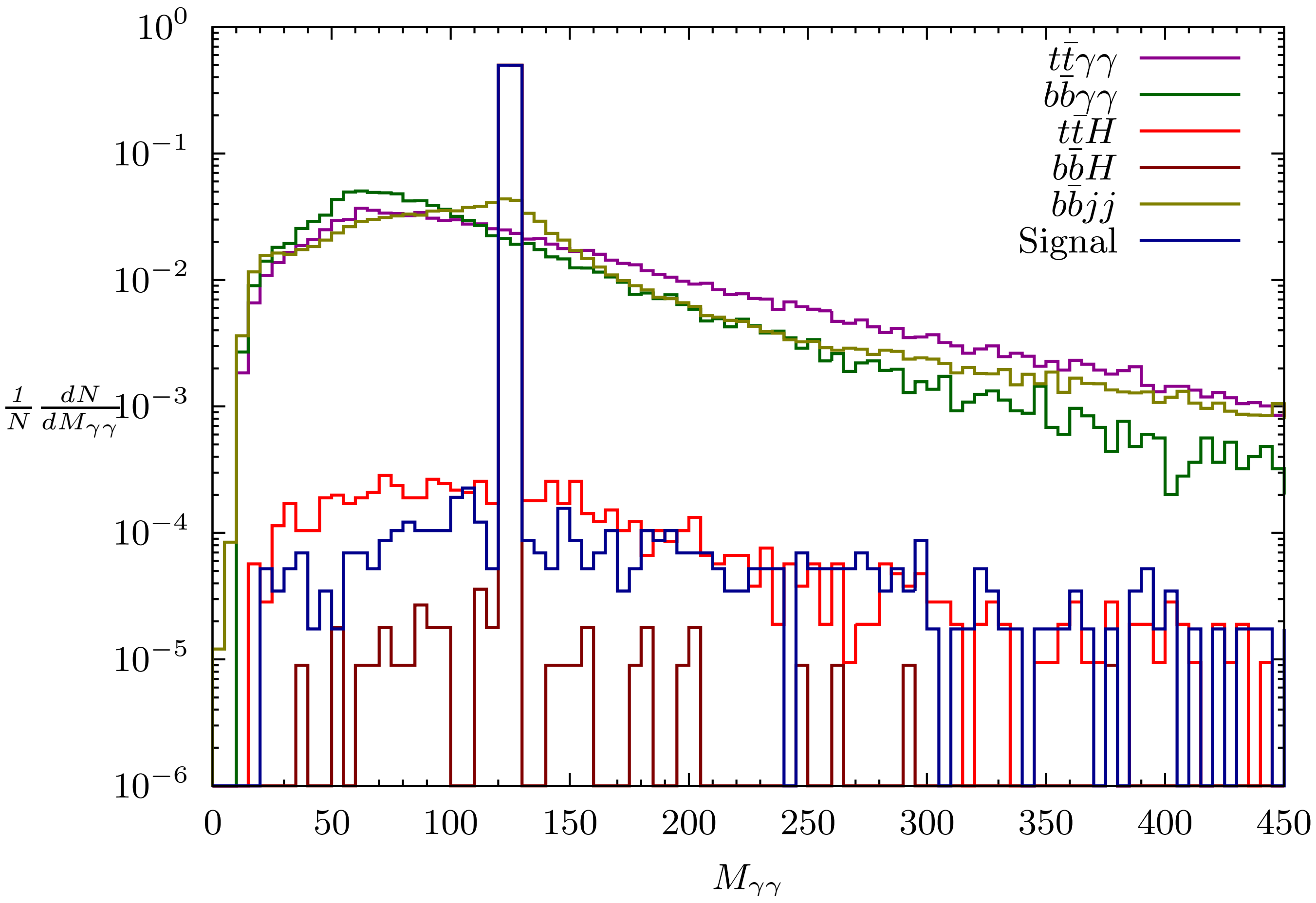
- $t\bar{t}h,\ b\bar{b}h,\ h + jets$ process with $h \to \gamma\gamma$ cam contribute to the final state.
- Though $t\bar{t}h$ has smaller cross-section due to the requirement of large MET, has dominant contribution
- $t\bar{t}\gamma\gamma, b\bar{b}\gamma\gamma$ - comparable contribution
- jet-faking backgrounds: $b\bar{b}jj, \gamma\gamma jj, jjjj$

  has large cross-section but are manageable

tth	bbh	h+jets	2phbtt	2phbb	bbjj	2phjj	multijets
430	35	1.5E+04	11.7	536	4E+08	1.2E+05	6E+09

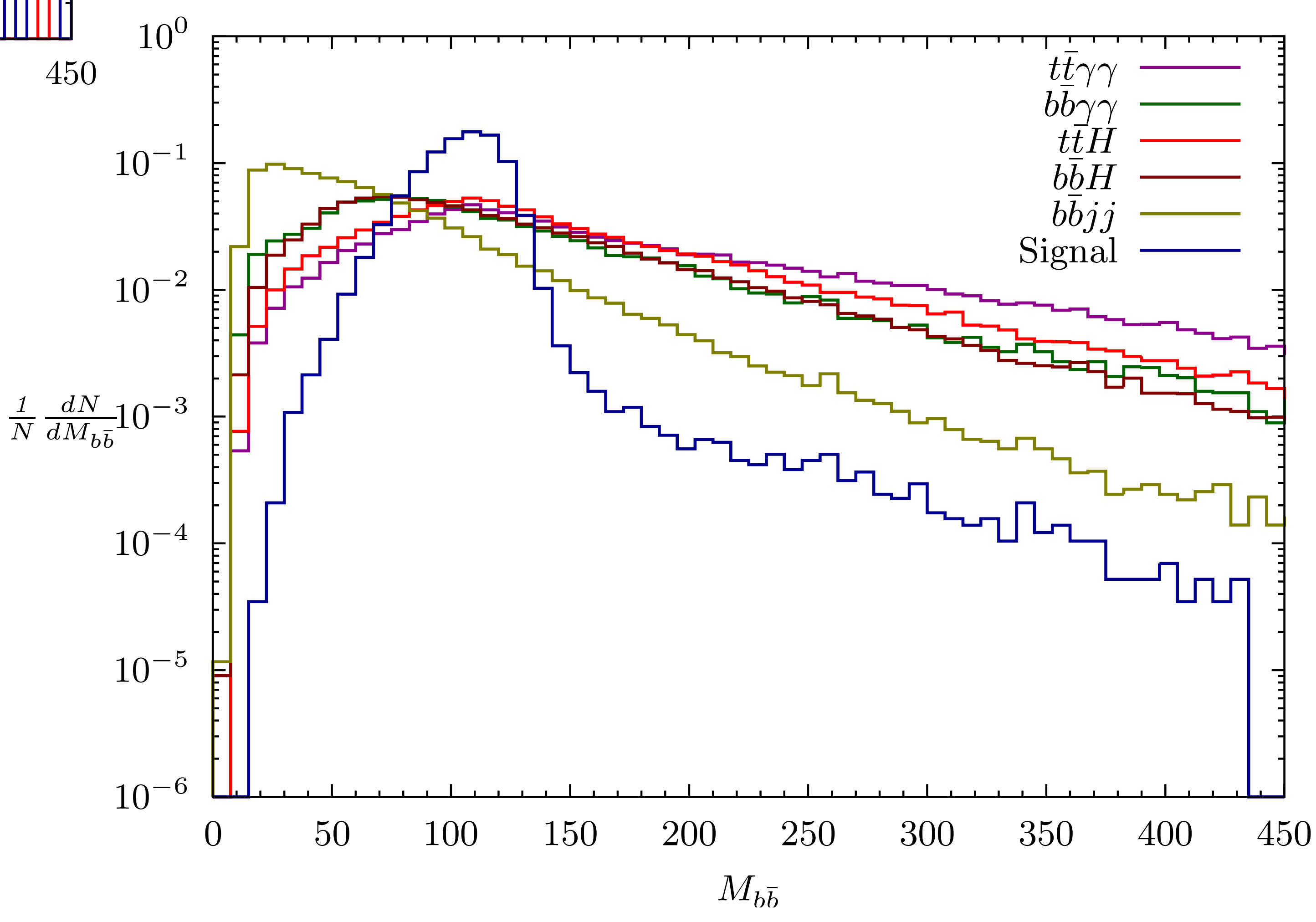
cross-sections in fb. MET cut not applied.

Reconstruction of the Higgs pair



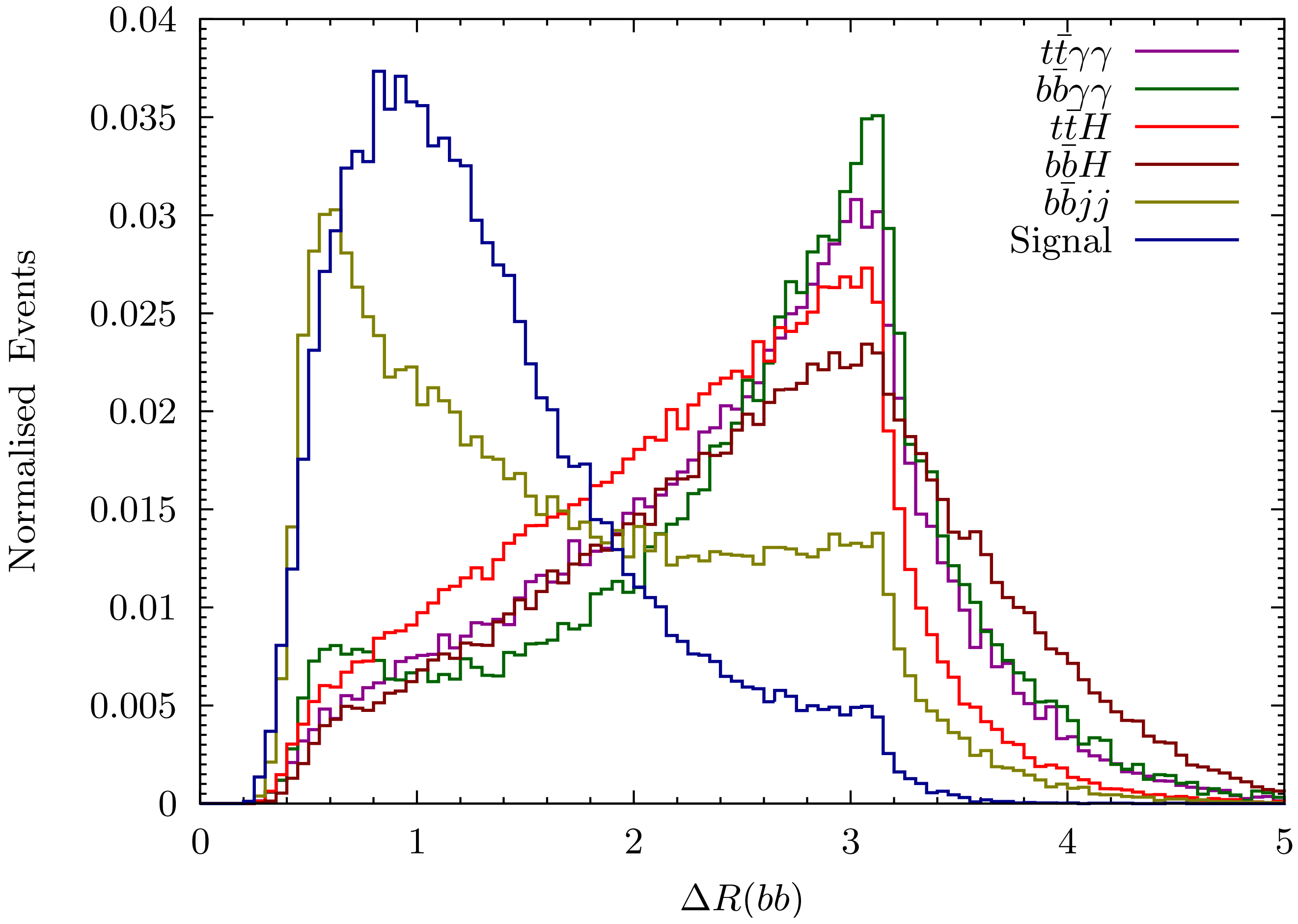
- Look for diphoton invariant mass distribution
- The mass resolution is very high in this mode
- The background containing Higgs also peaks at m_H

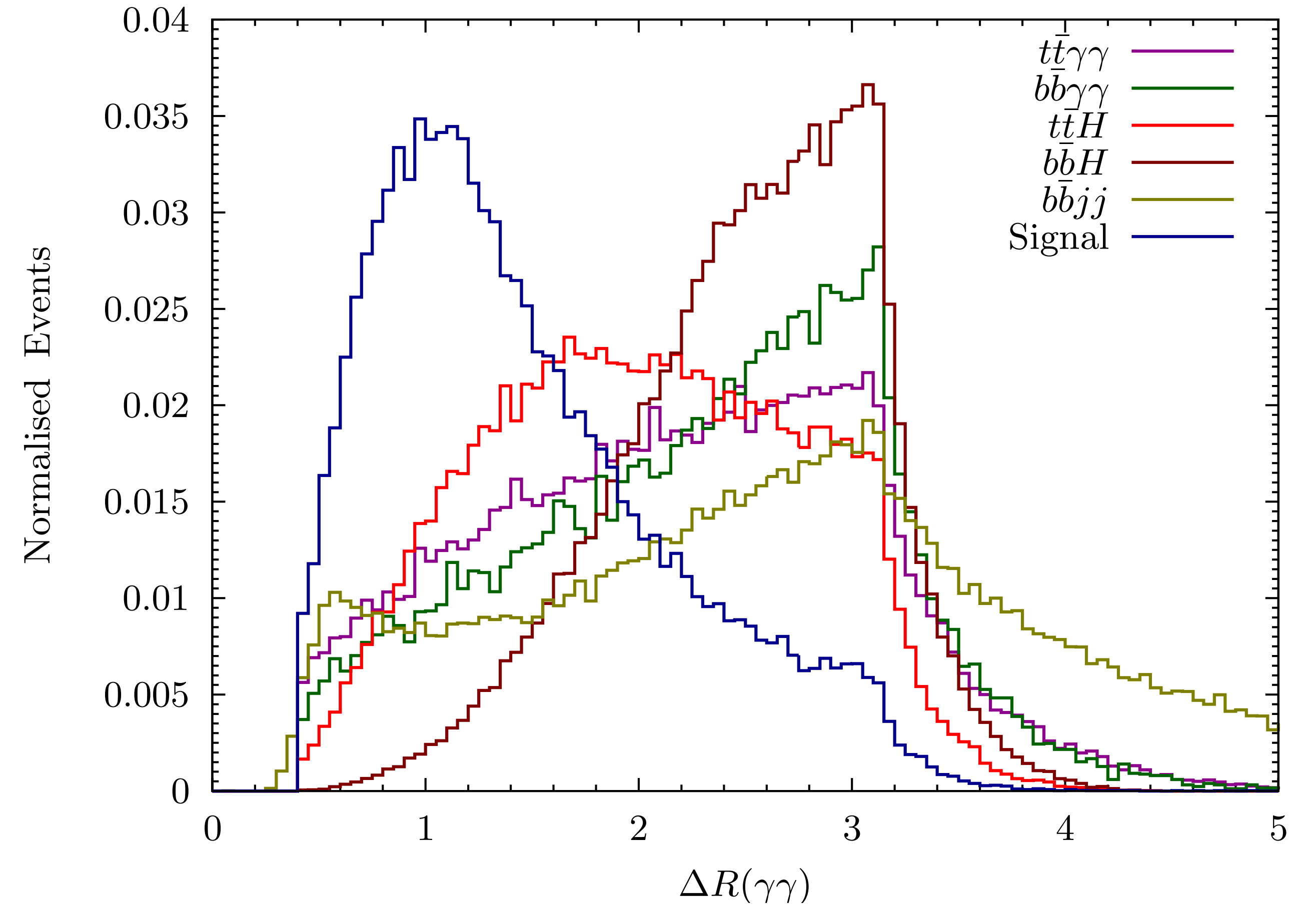
- The mass resolution is poor
- one needs a larger window
- Also it peaks at a lower value than m_H



$\Delta R(b\bar{b}), \Delta R(\gamma\gamma)$ Signal vs Background

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

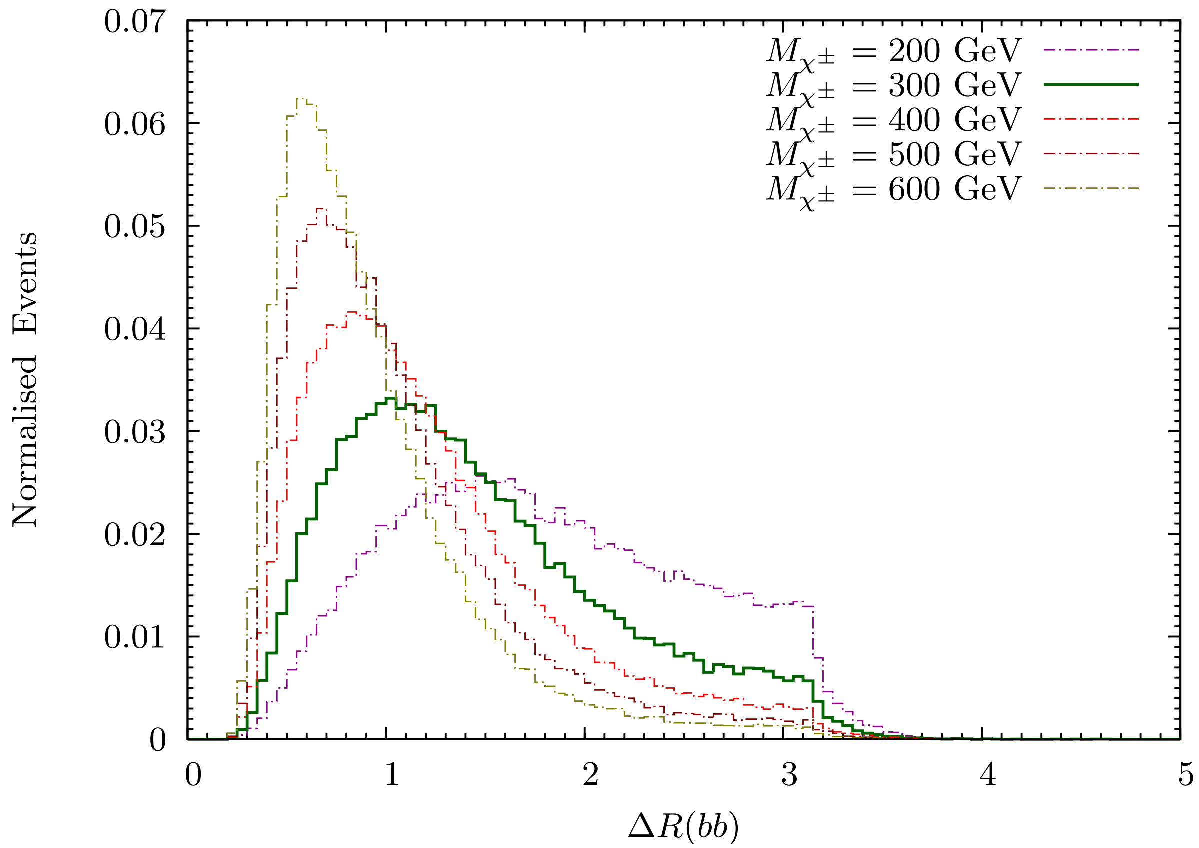


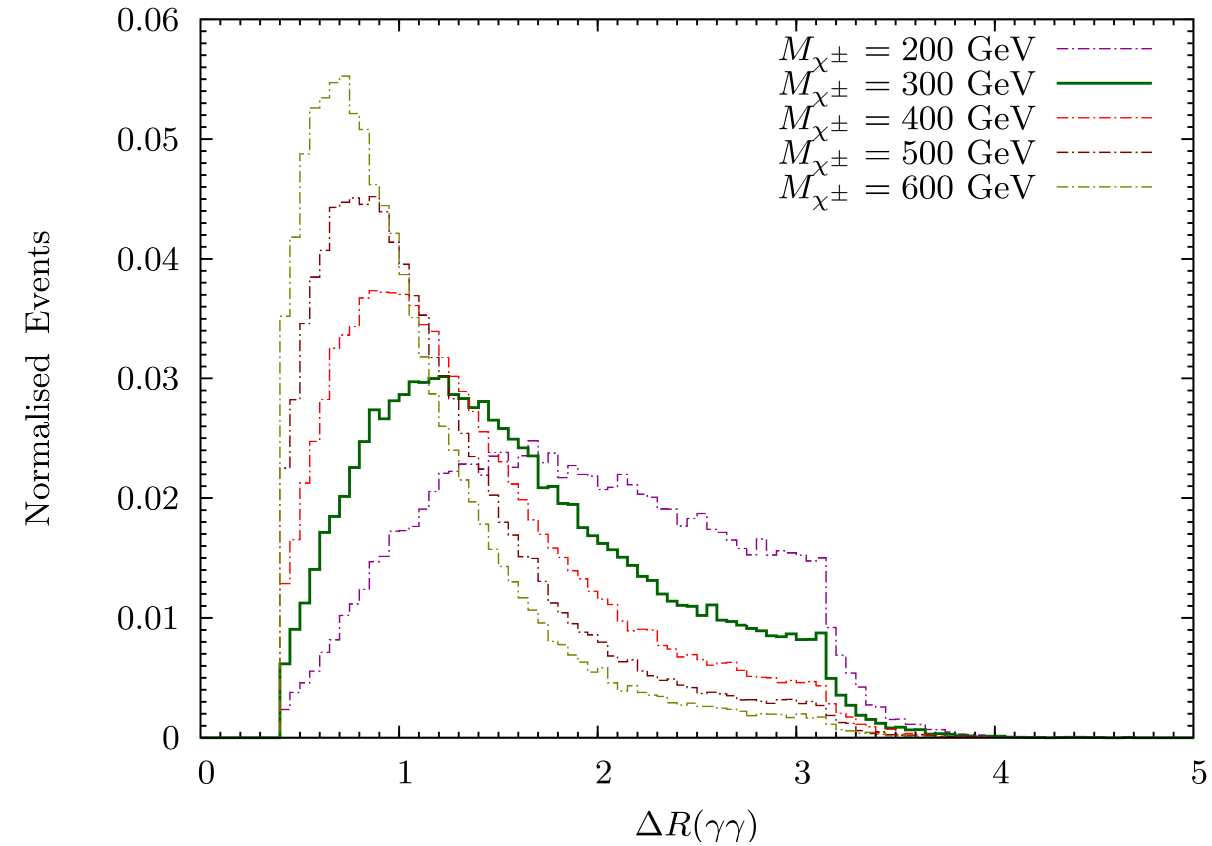


- The $b\bar{b}$ (and $\gamma\gamma$) pair are well isolated in the backgrounds

$\Delta R(b\bar{b}), \Delta R(\gamma\gamma)$

- As chargino/neutralino mass increases decay products of the Higgs become more colinear

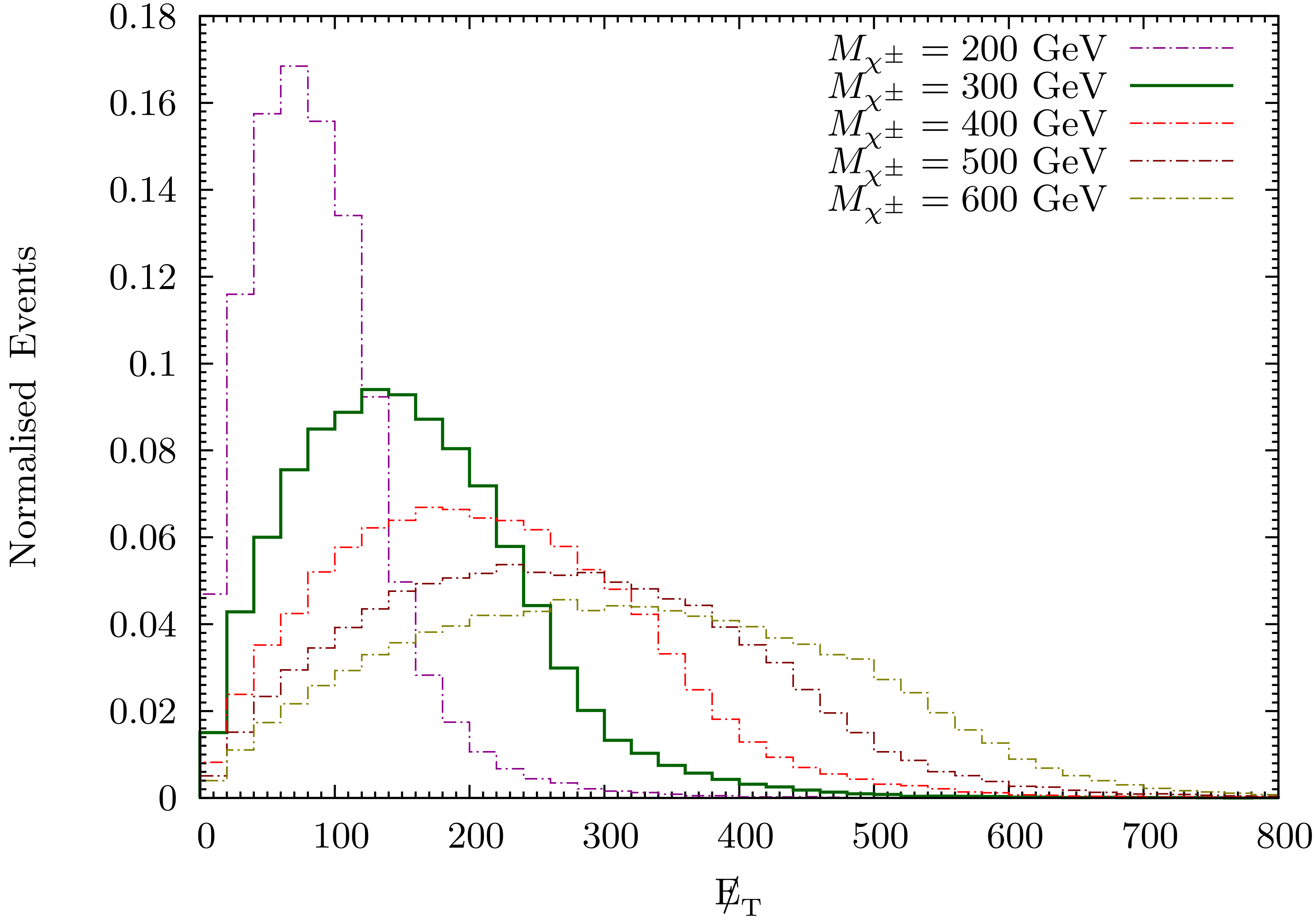




- The $b\bar{b}$ (and $\gamma\gamma$) pair separation for some of the benchmark points

$\Delta R(b\bar{b}) < 2$ $\Delta R(\gamma\gamma) < 2$

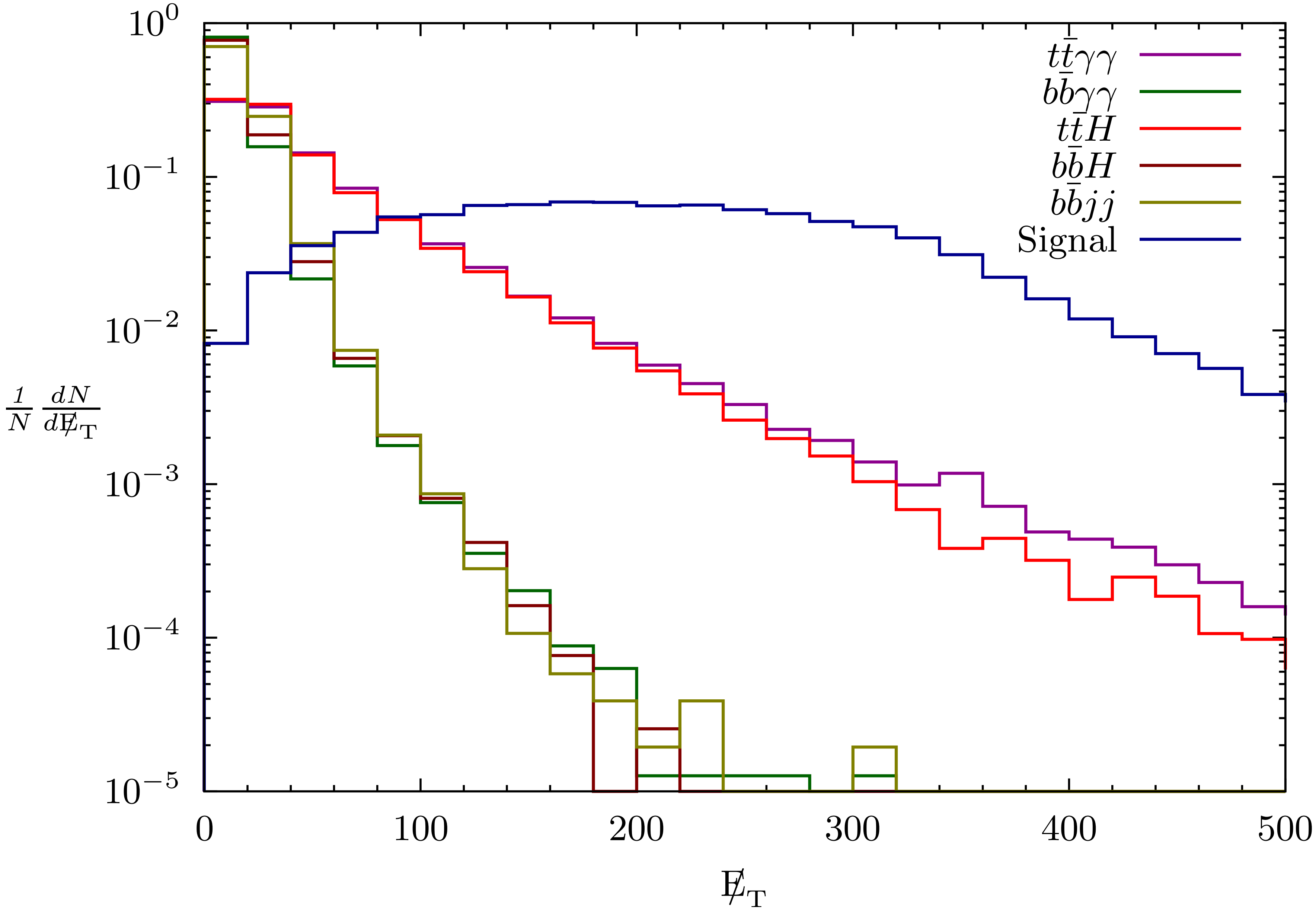
MET



- The missing transverse energy carried by the neutrino increases with increasing neutralino/chargino mass

- Cut efficiency also increases to compensate the XSEC

MET



- Taking into account detector resolution effects

- We have implemented basic cut on the photon and b-jet transverse momentum and rapidity

- In addition to MET > 100 GeV we have also used

$122\ \mathrm{GeV} < M_{\gamma\gamma} < 128\ \mathrm{GeV}$ and $110\ \mathrm{GeV} < M_{bb} < 140\ \mathrm{GeV}$

Signal significance

Signal	XSEC (fb)	XSEC*BR*A
300 GeV	232.1	2.8E-02
400 GeV	75.9	9.4E-03
500 GeV	30.3	6.9E-03

Signal cross-sections (fb) at 14 TeV

2phtt	ttH	2phbb	bbH	bbjj	2phjj	multijets
1.3E-04	9.9E-04	1.0E-04	4.8E-07	4.0E-04	—	—

Background cross-sections (fb) at 14 TeV (after cuts)

$$Sig = \sqrt{2((S+B)ln(1+\frac{S}{B})-S)}$$

The significance can be as large as 10σ (4.2σ) for a LSP ~ 300 (500) GeV at 1000 fbi integrated luminosity.

Conclusions…

- Measurement of the di-Higgs cross-section is important both in the context of the SM and NP searches
- We consider SUSY theory with bilinear R-parity violation
- Such a scenario can give rise to di-Higgs plus missing transverse energy signature
- $b\bar{b}\gamma\gamma$+met can be a clean signature and can be sensitive to HL-LHC Run to probe this scenario.