ATLAS & CMS SUSY studies with Higgs in the final state

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Outline

Introduction

Search for SUSY with Higgs in the final state

- SUSY Colored production with Higgs

- Electroweak production with Higgs

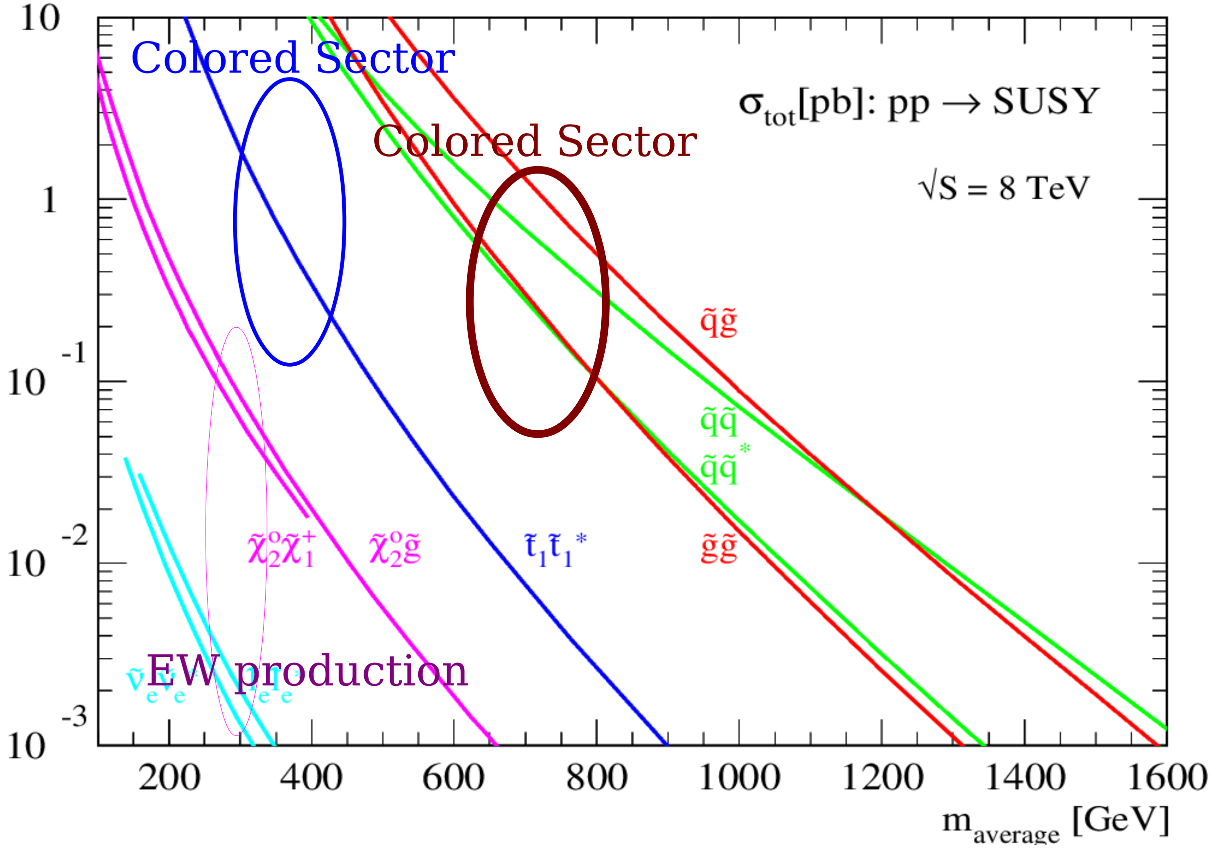
Direct Chargino & neutralino productions

Expectations for Run-II & HL-LHC

Generic topologies

Summary and Outlook

SUSY search strategy was driven by cross section and thus luminosity



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections (arXiv:1206.2892)

Early analyses were dominated by broad inclusive searches

- mainly gluino and squark production

Increase in luminosity gave access to rarer channels

- Also with added motivation from *Natural* SUSY paradigm

It was quickly realized to develop exclusive search modes to cover full spectrum

Search for SUSY with Higgs in the final state

Aided by the discovery of the Higgs boson, the focus of the experimental search strategy and corresponding interpretation moved towards *"Natural SUSY"* scenarios:

- Dedicated third generation searches
- Electroweak studies also with Higgs in the final state

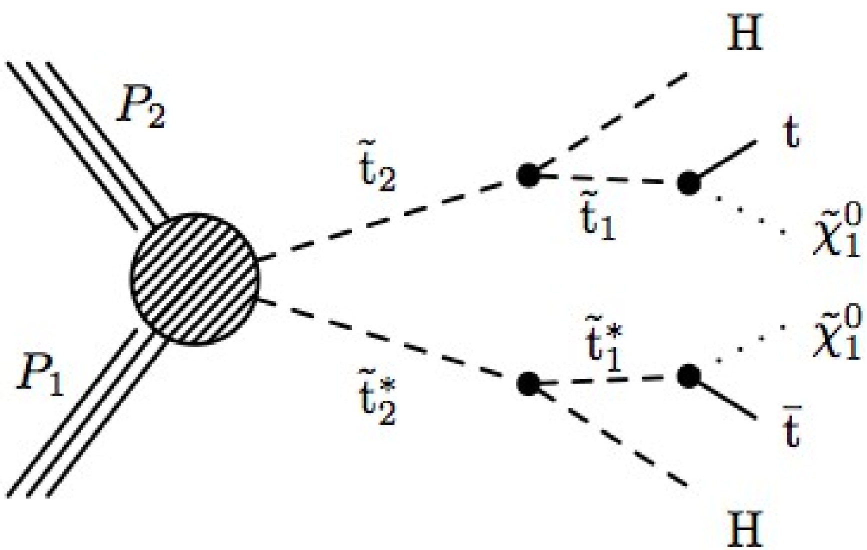
The goal from the experiments was to leave no stone unturned

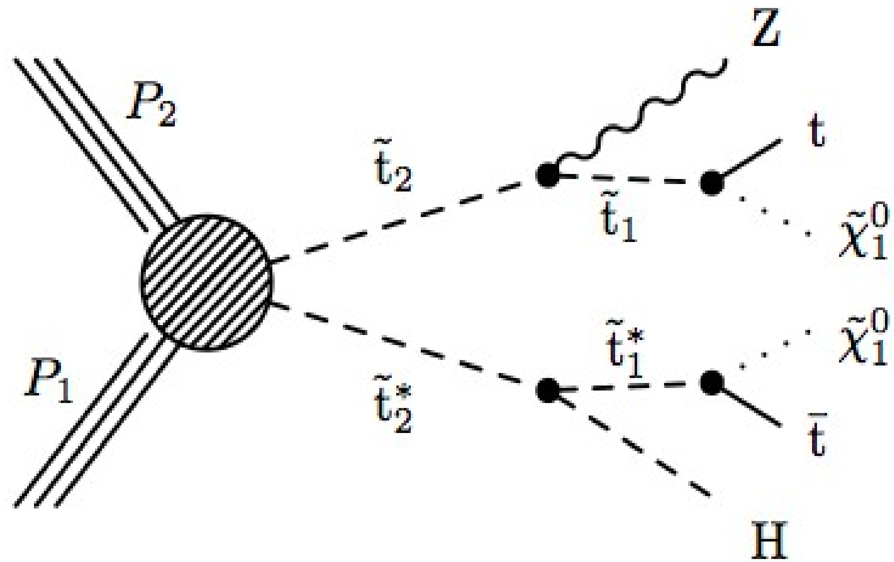
SUSY with "Higgs Tagging"

- Charginos and neutralinos decay to h+LSP or V+LSP with V = W, Z
- Direct observation of h in SUSY searches could provide SUSY solution for the hierarchy problem

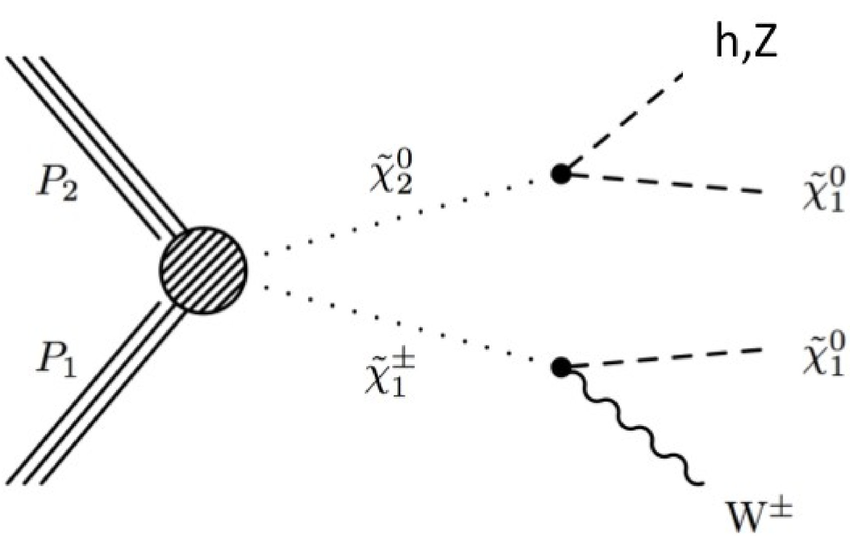
Search for SUSY with Higgs in the final state

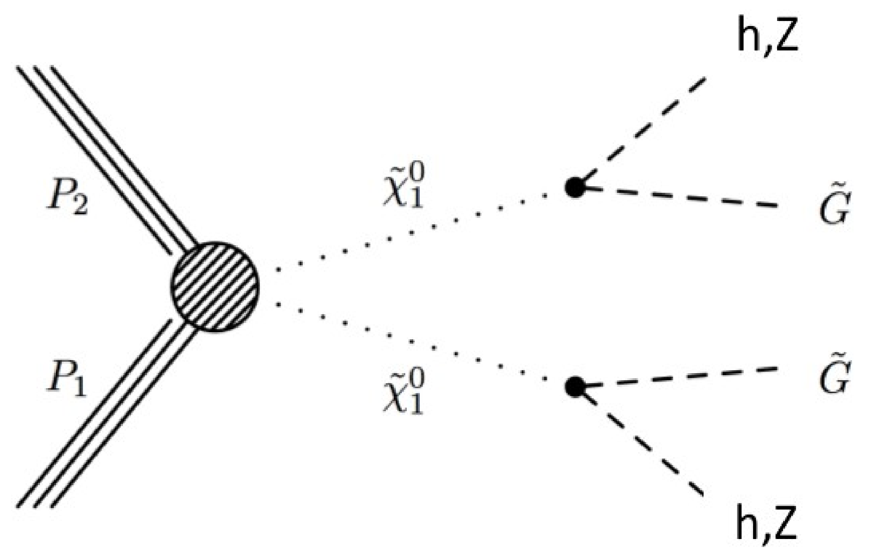
Colored production





Electroweak production





SUSY Colored Production with Higgs in the final state

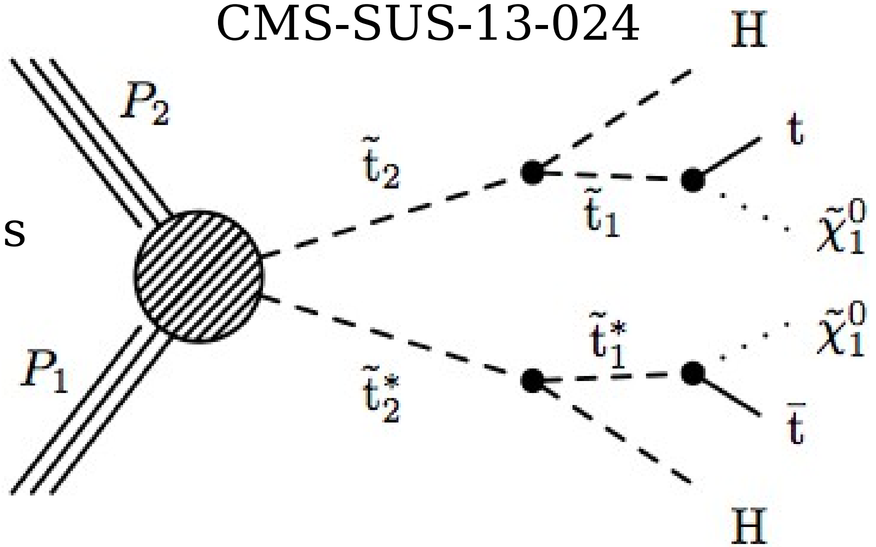
SUSY Cascade - Stop2 search with decay via Z or H

CMS-SUS-13-024

Search with 1l, 2l (OS + SS) and > 2l + btags

- Sensitive to $H \to bb$, $H \to ZZ$ & $H \to WW$ modes

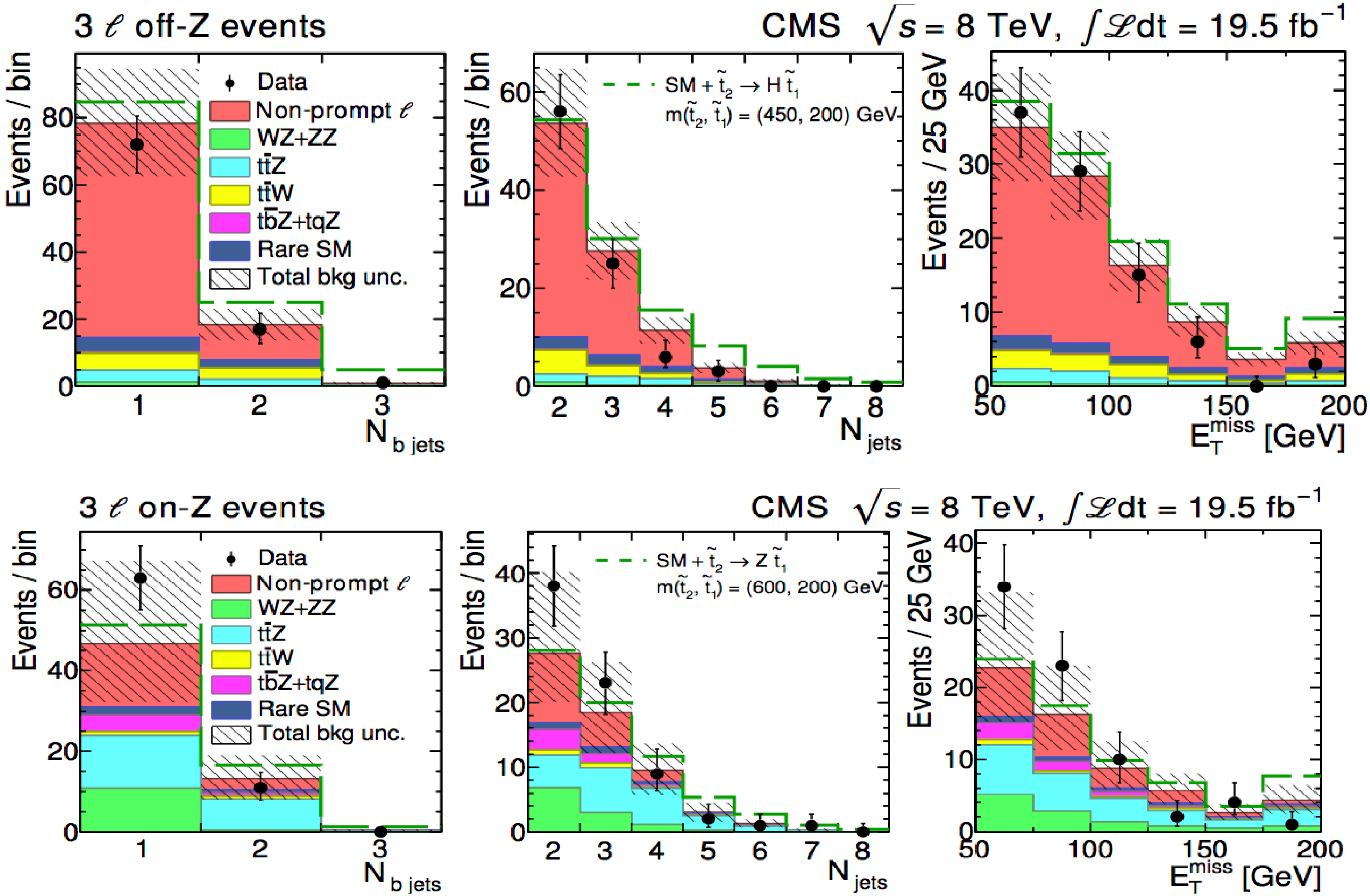
Analysis split by on-shell and off-shell Zs



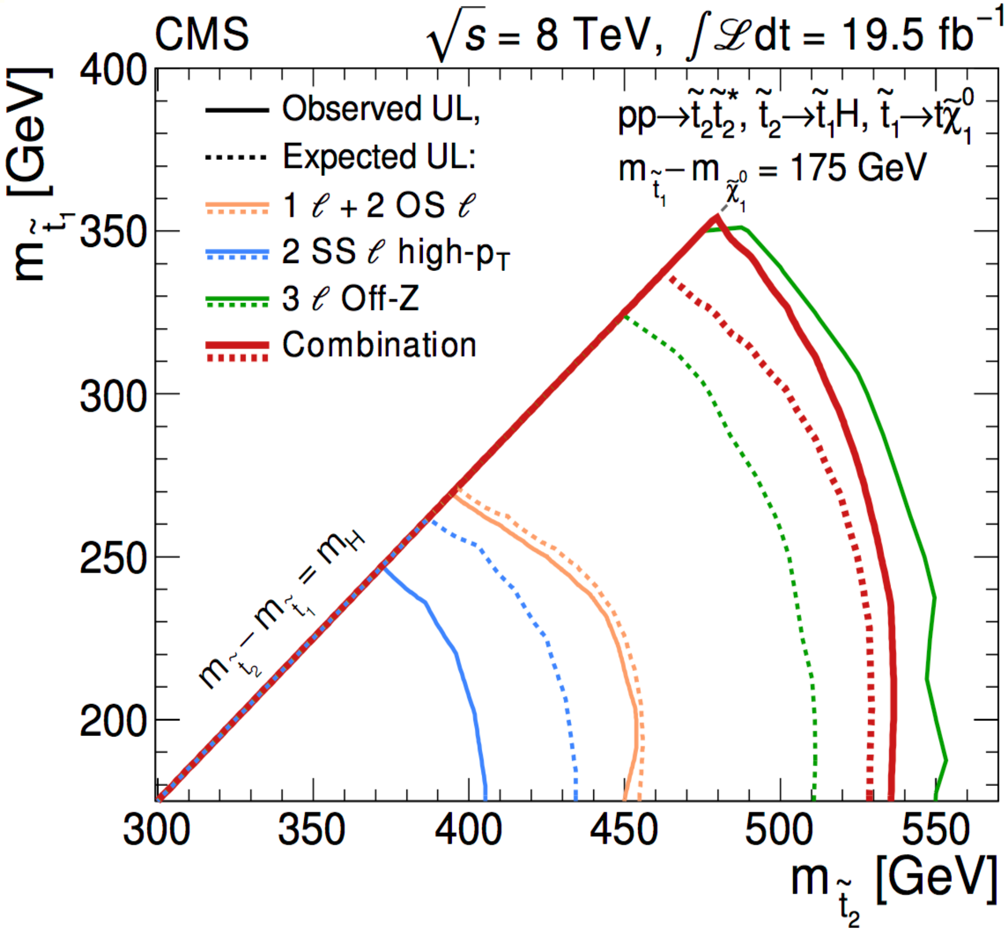
N_ℓ	Veto	$N_{\text{b jets}}$	N_{jets}	E_T^{miss} [GeV]	Additional requirements [GeV]
1	track or τ_h	$=3$ ≥ 4	≥ 5 ≥ 4	≥ 50	$m_T > 150$ $m_T > 120$
2 OS	extra e/μ	$= 3$ ≥ 4	≥ 5 ≥ 4	≥ 50	$N_{bb} = 1$ with $100 \leq m_{bb} \leq 150$, $N_{bb} \geq 2$
2 SS	extra e/μ	$=1$ ≥ 2	$[2,3], \geq 4$	$[50,120], \geq 120$	for low/high-p_T: $H_T \in [200,400], \geq 400$
≥ 3	—	$= 1$ $= 2$	$[2,3], \geq 4$	$[50,100], [100,200], \geq 200$	for on/off-Z: $H_T \in [60,200], \geq 200$
		≥ 3	≥ 3		

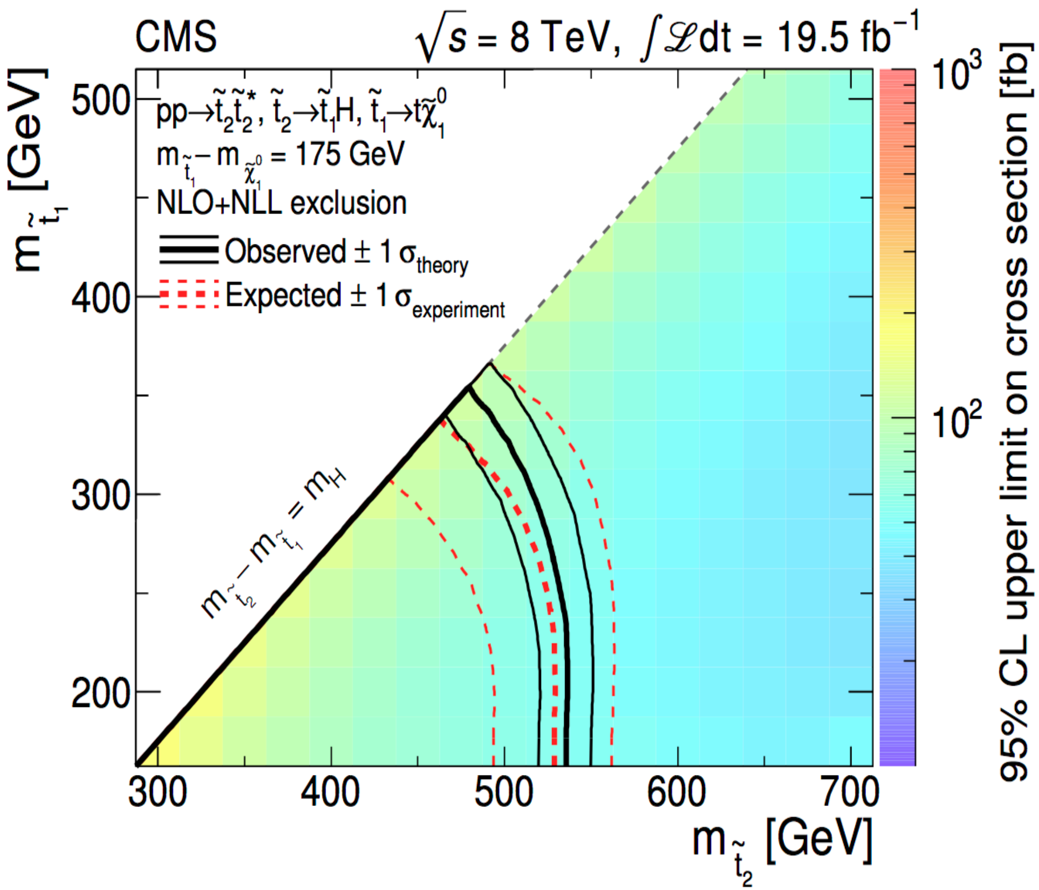
SUSY Cascade - Stop2 search with decay via Z or H

>= 3 l + btags mode is most sensitive in this search CMS-SUS-13-024



SUSY Cascade - Stop2 search with decay via Z or H





Search for t2 → t1 + H is interesting for light stops (t1)

100% branching ratio has been used

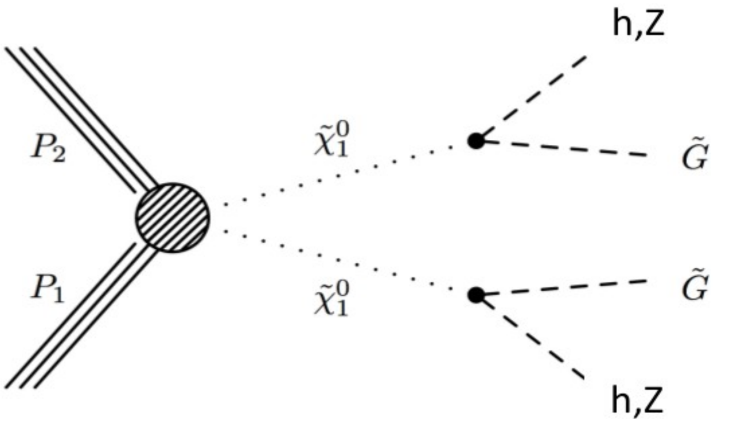
Mass range close to m(t2) < 575 GeV and m(t1) < 400 GeV are excluded

→ Light stops (t1) are already excluded in previous studies ~ 200-700 GeV

SUSY EWKino Production with Higgs in the final state

CMS-SUS-14-002

Higgs Tagging in EWK production



Various hh, hZ and hW modes are studied

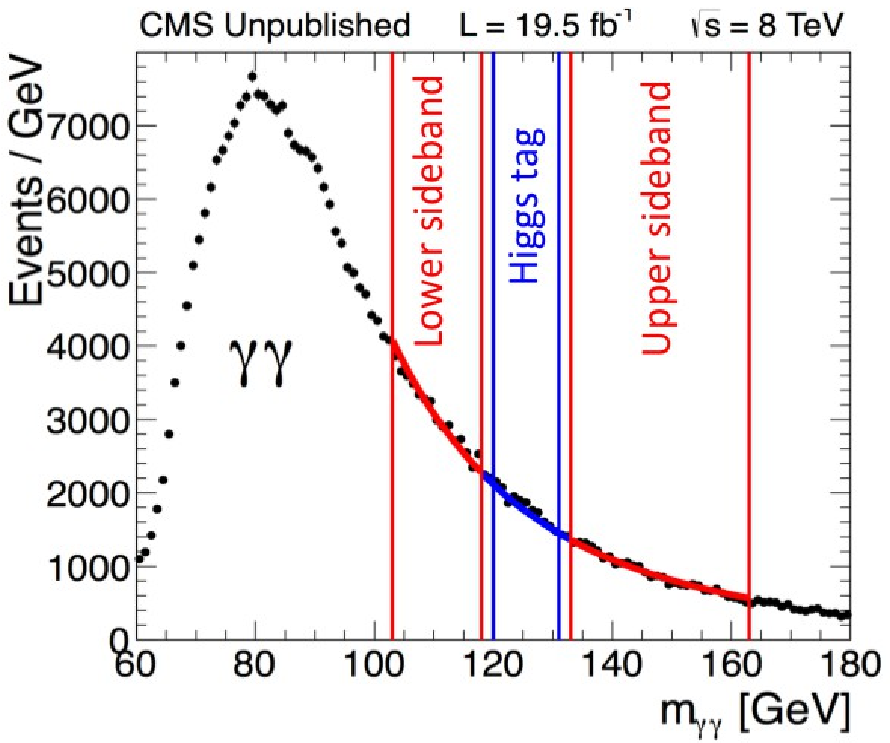
- Diphoton decays $h \rightarrow \gamma\gamma$
  - $(\gamma\gamma)$+(bb) : targets hh
  - $(\gamma\gamma)$ + (jj) : targets hZ and hW
  - $(\gamma\gamma)$ + (e or μ): targets hh, hZ, hW

Common diphoton selection

- 2 barrel photons with |eta| < 1.4
- E_T > 40 and 25 GeV

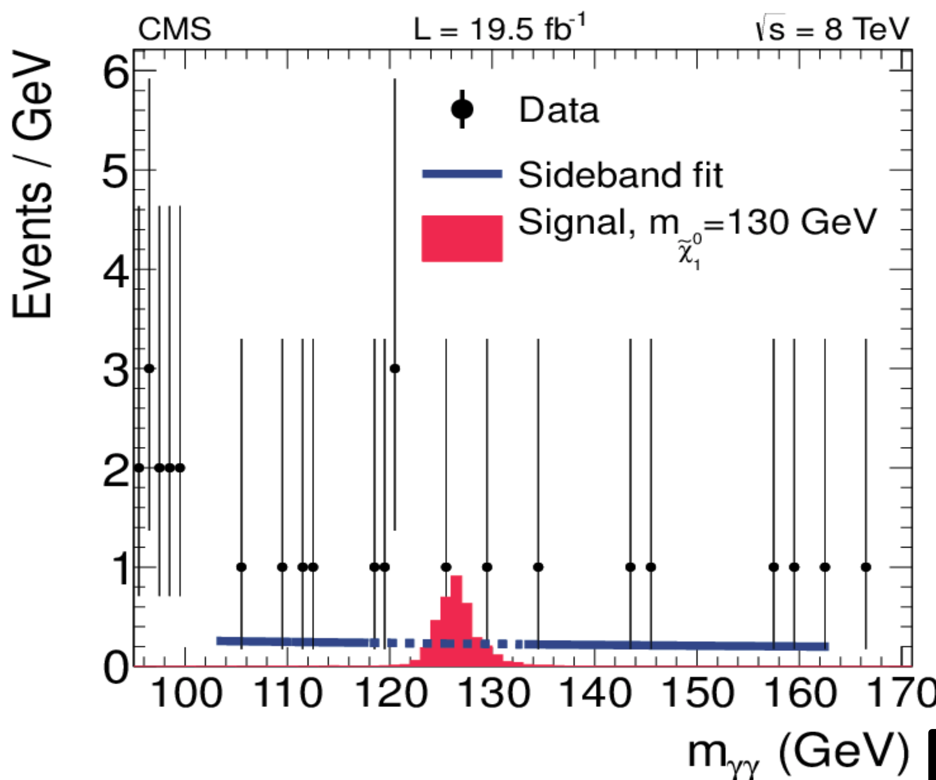
Common bkg estimation

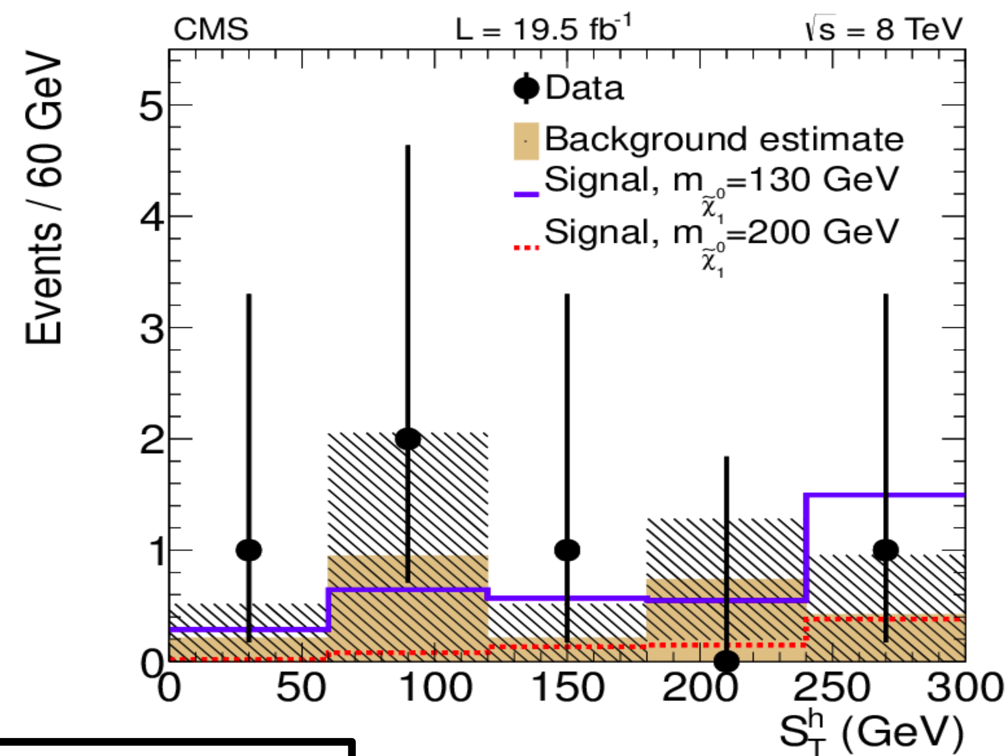
- Fit $m_{\gamma\gamma}$ in sidebands excluding tag regions
- Integrate power-law function in Higgs region
  normalize continuum (non-SM) bkg



- Bkg shape in discriminant (MET) taken from average of upper/lower bands

SUSY EWKino Production with Higgs (hh → γγ bb)





$$\boxed{hh \to \gamma\gamma b\bar{b}}$$

H → bb reconstruction

- 2 b-tagged jets (medium), p_T > 30 and jets are separated from photon (ΔR > 0.5)

M_{bb} window – [95, 155] GeV; Veto isolated leptons (e / μ)

Discriminating variable: Scalar sum pT of the two higgs candidates

SM Higgs background is negligible

Observation consistent with SM bkg predictions

$hh \rightarrow \gamma\gamma jj$

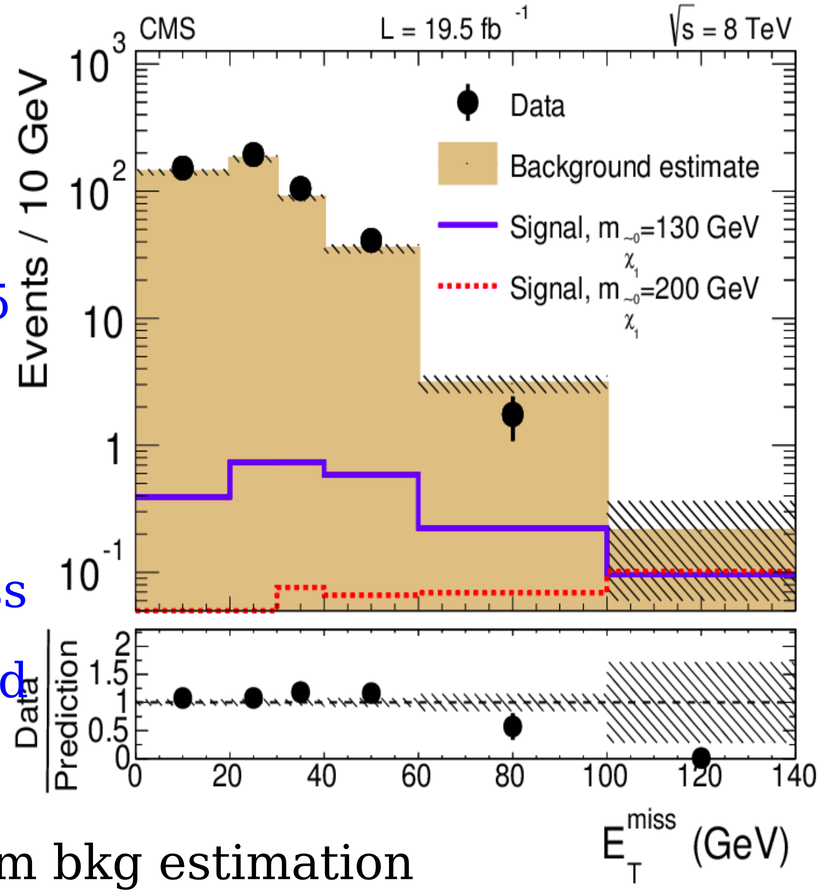
Veto isolated leptons, 2jets and m_{bb} [95, 155] GeV

Vector boson reconstruction

- jet p_T > 30 GeV, separated from photons dR > 0.5
- m_{jj} in [70, 110] GeV

Discriminating variable (MET)

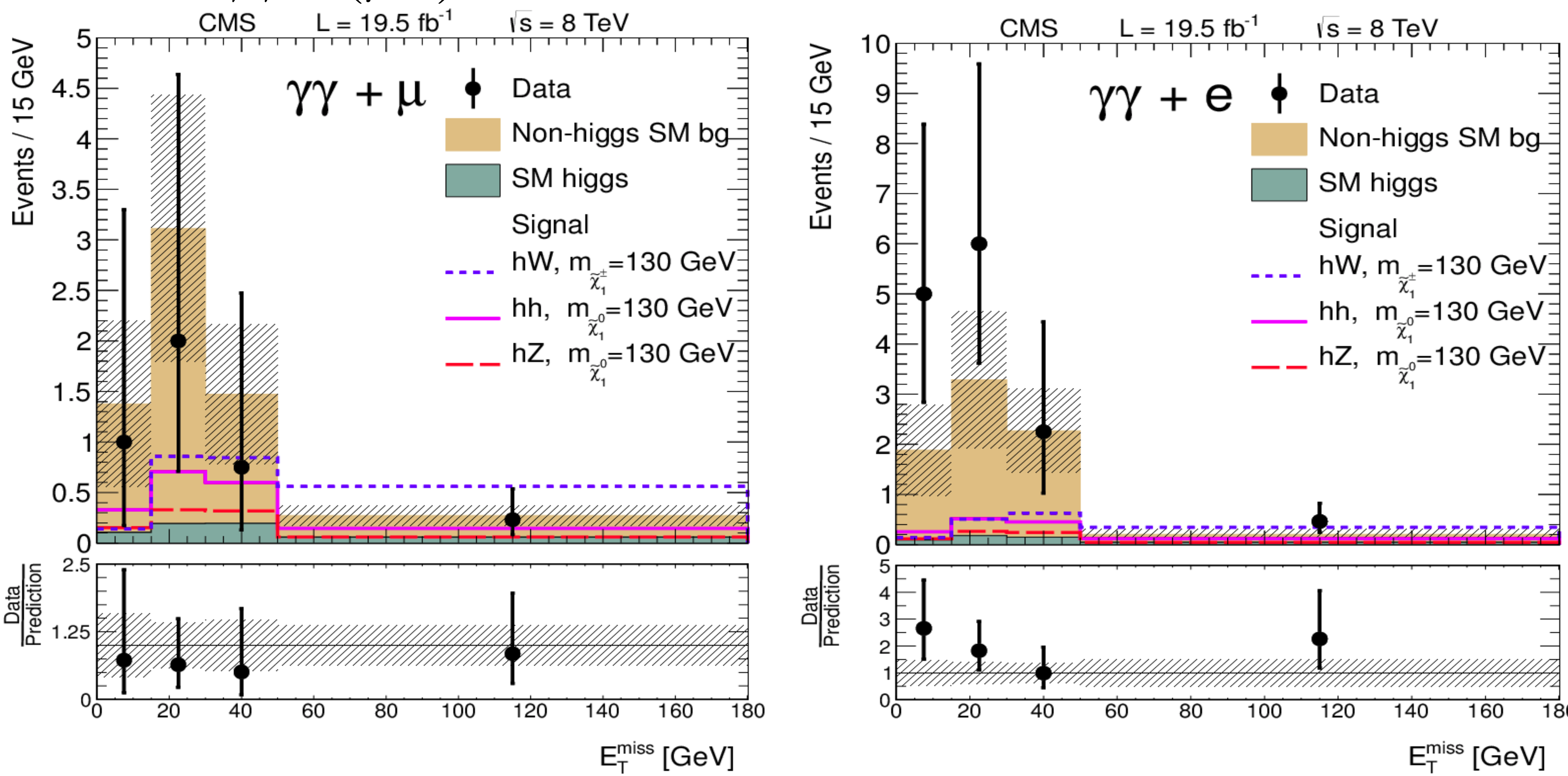
- Signal spectrum harder for larger NLSP-LSP mass
- Bkg from mγγ sidebands, averaged and normalized from mγγ SB fit



Small SM Higgs contribution added to the continuum bkg estimation

E_T^{miss} (GeV)	SM background	Data	hZ events, $m_{\tilde{\chi}_1^0} = 130$ GeV
0-20	282 ± 15	305	0.76 ± 0.03
20-30	180 ± 10	195	0.71 ± 0.03
30-40	89.0 ± 4.7	105	0.72 ± 0.03
40-60	70.8 ± 5.0	82	1.14 ± 0.04
60-100	12.2 ± 1.9	7	0.87 ± 0.03
>100	0.85 ± 0.61	0	0.37 ± 0.02

$hW^{\pm} \rightarrow \gamma\gamma e^{\pm}(\mu^{\pm})$



Less than 1b-tag jet to avoid overlap

Require >= 1 isolated lepton with p_T > 15 GeV and well separated from the photons

Discriminating variable MT (transverse mass)

Expectations agree with the observation

SUSY EWKino Production with Higgs hZ (→ bb ll)

Higgs reconstruction: two most b-like jets with m_{bb} in [100, 150] GeV

Z reconstruction: exactly two opposite sign same flavour leptons (ee or μμ) with m_{ll} [81, 101] GeV

- Veto 3rd lepton

Estimation of Z bkg:

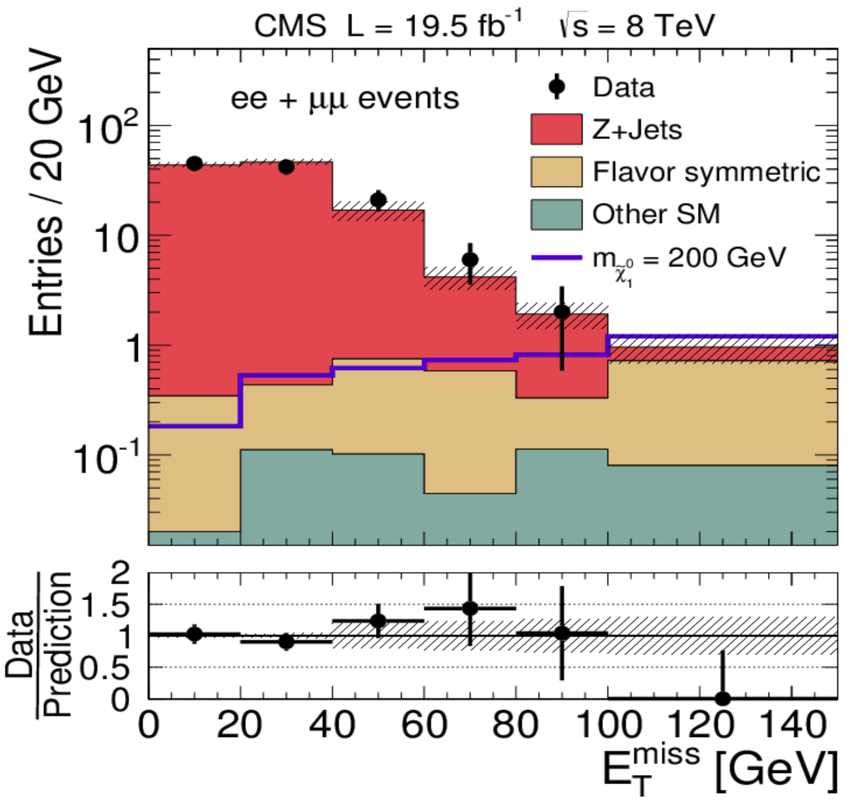
- MET template using photon + jets sample
- Normalize by data yields in MET < 50 GeV

Flavour symmetric bkg: tt, WW, tW, etc.

- MET templ. normalize using eμ samples

Other rare SM bkg from MC

Estimation agree with the observation



	$E_T^{miss} < 25$ GeV	$25 < E_T^{miss} < 50$ GeV	$50 < E_T^{miss} < 60$ GeV
Z+jets bkg	56.7 ± 1.9	43.3 ± 2.3	5.7 ± 1.2
Flavor symmetric	0.4 ± 0.3	0.4 ± 0.3	0.4 ± 0.3
Other SM bkg	< 0.1	0.1 ± 0.1	0.1 ± 0.1
Total SM bkg	57.2 ± 1.9	43.8 ± 2.3	6.2 ± 1.2
Data	54	47	7
	$E_T^{miss} > 60$ GeV	$E_T^{miss} > 80$ GeV	$E_T^{miss} > 100$ GeV
Z+jets bkg	5.7 ± 1.8	2.2 ± 0.9	0.6 ± 0.3
Flavor symmetric	2.4 ± 0.9	1.8 ± 0.7	1.6 ± 0.6
Other SM bkg	0.3 ± 0.2	0.3 ± 0.2	0.2 ± 0.1
Total SM bkg	8.5 ± 2.0	4.3 ± 1.2	2.4 ± 0.7
Data	8	2	0

SUSY EWKino Production with Higgs hh (→ bb bb)

At least 2 tight btag jets

Double Higgs reconstruction:

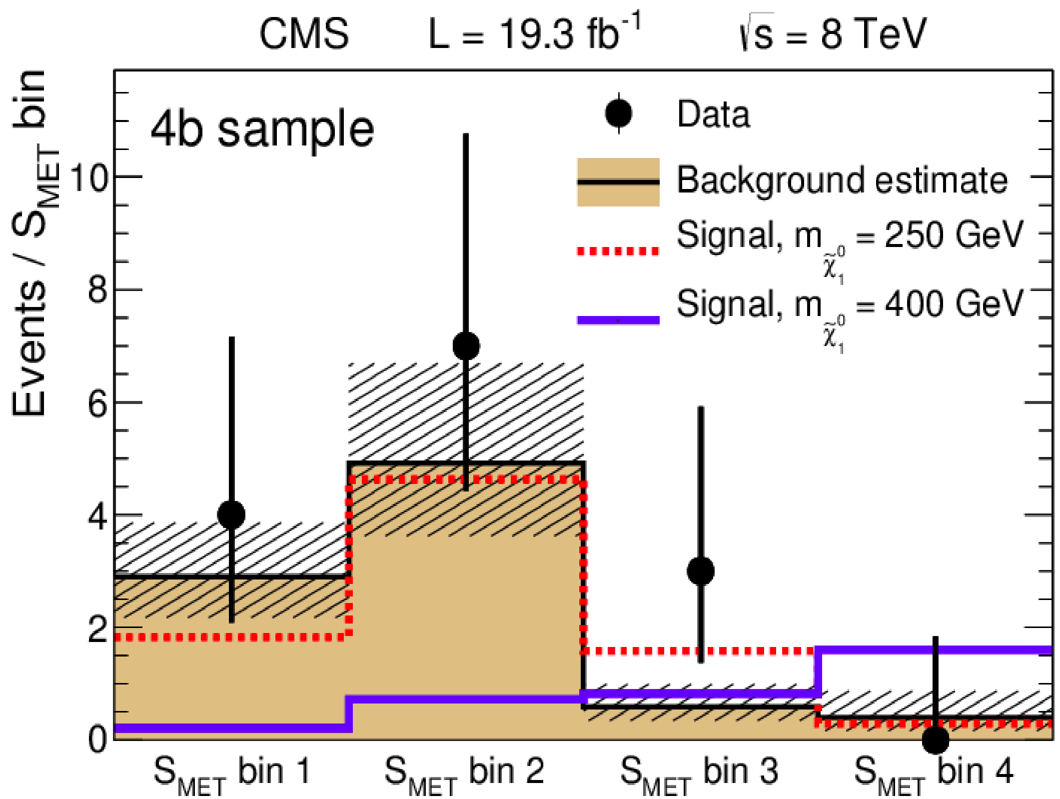
- comb. with smallest m_{bb} diff
- signal box $|dm_{bb}| < 20$ GeV
- $<m_{bb}>$ in [100, 140] GeV

Discriminant: MET significance S_{MET}

Background estimation:

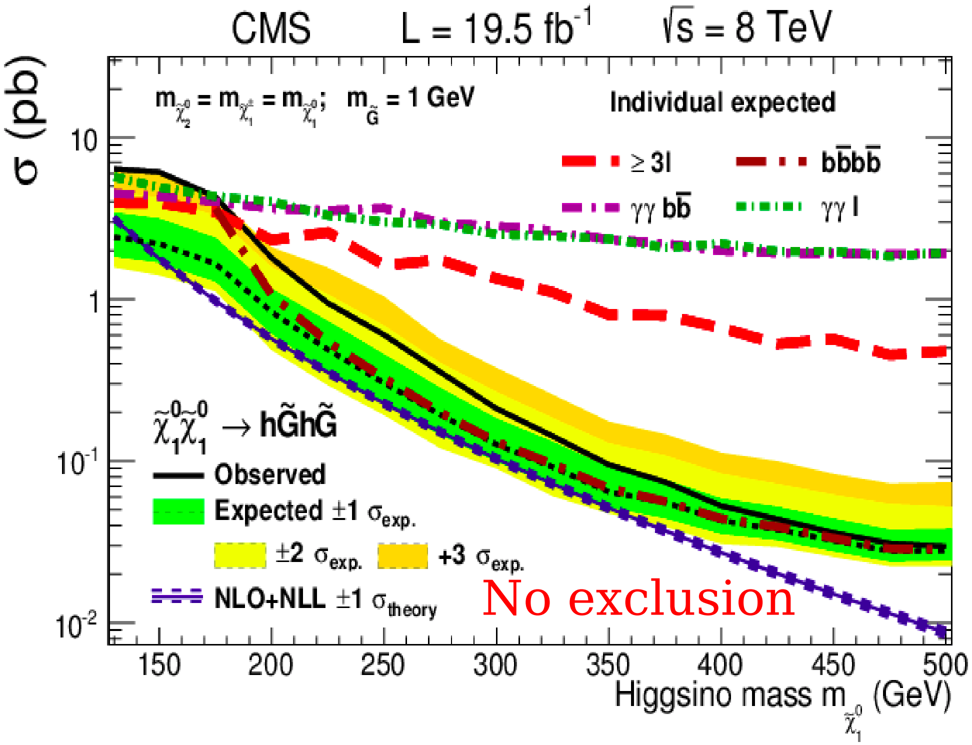
→ using ABCD method

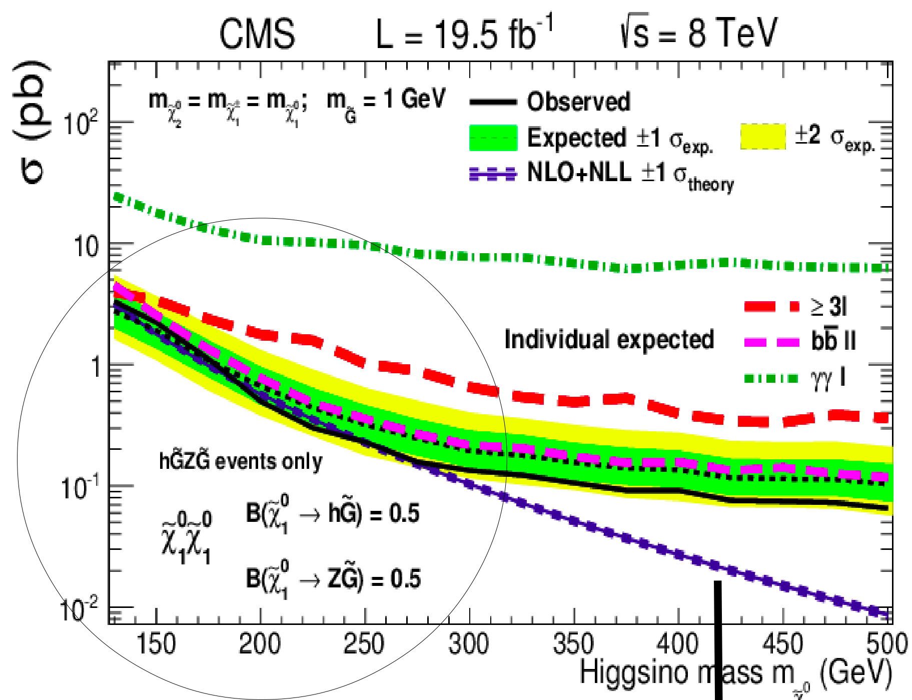
→ Sidebands higgs mass & nbtag



S_{MET} bin	S_{MET} range	SM background (3b-SIG)	Data (3b-SIG)	SM background (4b-SIG)	Data (4b-SIG)
1	30 – 50	$6.7^{+1.4+1.0}_{-1.1-0.7}$	4	$2.9^{+0.8+0.5}_{-0.6-0.4}$	4
2	50 – 100	$11.6^{+1.9+0.9}_{-1.6-0.7}$	15	$4.9^{+1.1+1.4}_{-0.9-0.9}$	7
3	100 – 150	$2.44^{+0.84+0.56}_{-0.64-0.35}$	1	$0.59^{+0.39+0.09}_{-0.26-0.09}$	3
4	> 150	$1.50^{+0.82+0.64}_{-0.54-0.32}$	0	$0.40^{+0.39+0.26}_{-0.22-0.10}$	0

Interpretation of the results





GMSB scenario where neutralinos and charginos are higgsinos

Nearly mass-degenerate gauginos $m_{\chi_1^0} \approx m_{\chi_2^0} \approx m_{\chi_1^\pm}$

NLSP is χ_1^0 , LSP is nearly massless gravitino

$Br(\chi_1^0 \to h\tilde{G}) = 100\%$ for hh decay modes (left)

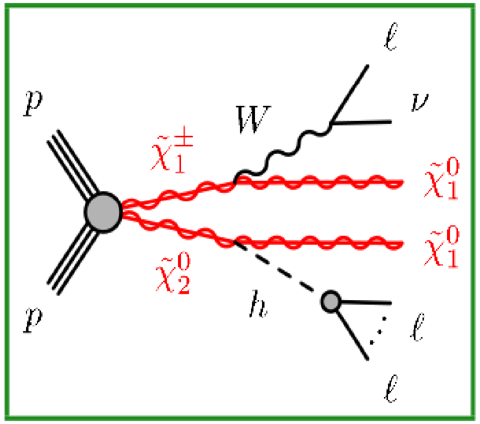
The hh → (bb) (bb) is most sensitive above 175 GeV

For low higgsino mass: multi-leptons and diphoton modes dominates

25% hh
50% hZ
25% ZZ

Charginos and Neutralino productions

- Cross sections are determined by the masses and composition of $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$, assumed to be wino-like and mass degenerate: $m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{\chi}_2^0}$

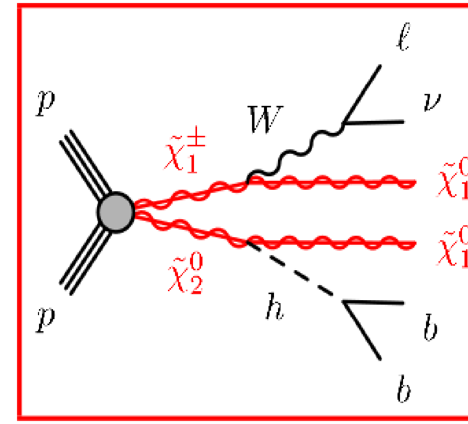


ArXiv:1402.7029

- Lightest Supersymmetric Particle (LSP) $\Rightarrow \tilde{\chi}_1^0$ (bino-like)
- Sleptons and sneutrinos assumed to be heavy
- $\mathrm{BR}(\tilde{\chi}_1^{\pm} \to W^{\pm}\, \tilde{\chi}_1^0) = 1$
- $\mathrm{BR}(\tilde{\chi}_2^0 \to h\, \tilde{\chi}_1^0) = 1$
- $\mathrm{BR}(h \to bb)$ = SM-like $\quad m_h = 125$ GeV

← 3 leptons (including **tau** new!)

1 lepton (e/μ) and 2 b-tagged jets from a Higgs boson →

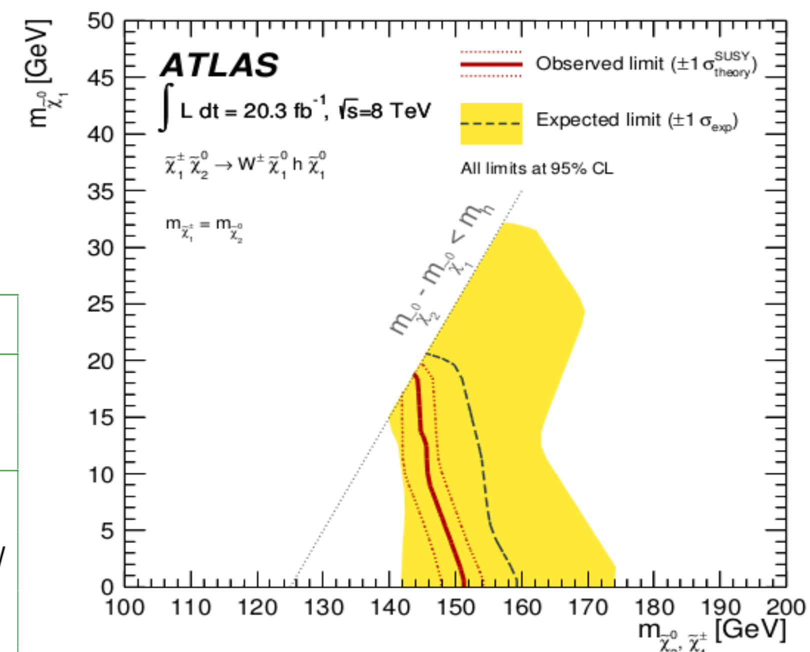


ATLAS-CONF-2013-093

$$\chi_1^{\pm}\chi_2^0 \to 3l + MET$$

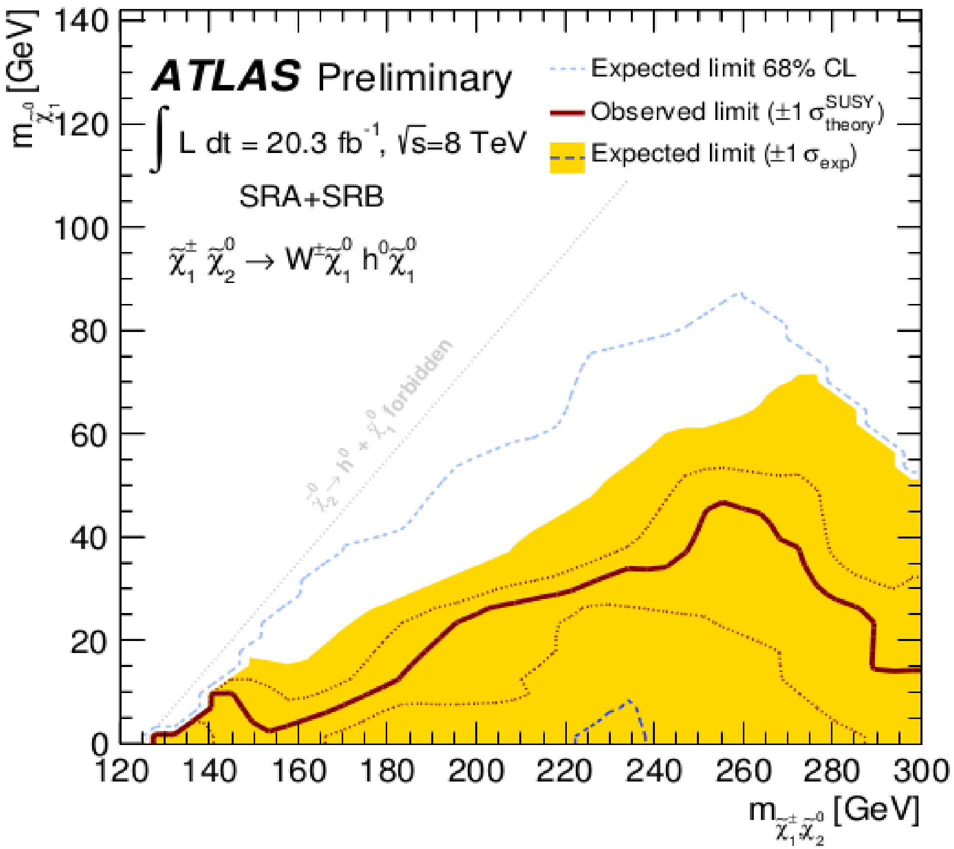
- Hadronically decaying τ identification using jet anti-k_t optimised with a boosted decision tree algorithm
- **exactly 3 tagged signal leptons** separated by $\Delta R > 0.3$ (with $\geq$ **1 electron or muon**, triggered)
- b-jets vetoed.

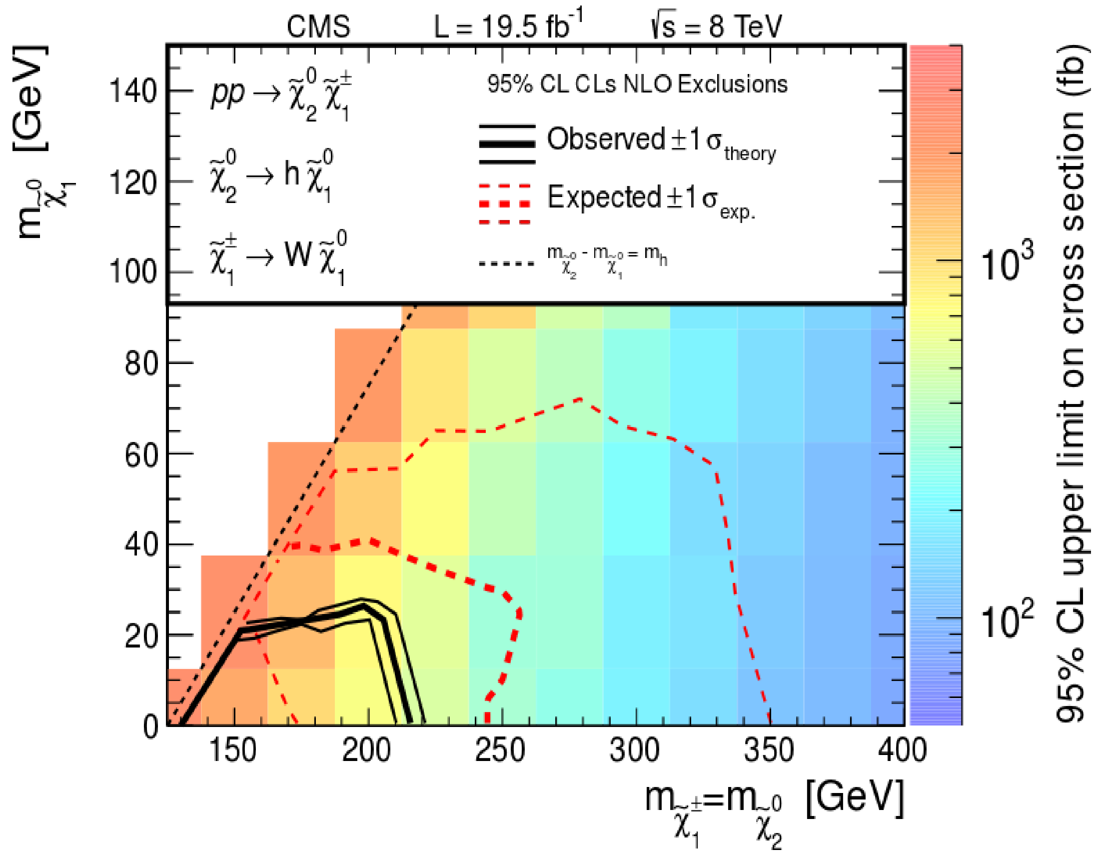
	SR0τa (20 bins)	SR0τb	SR1τ	SR2τb
Flavour/sign	$\ell^+\ell^-\ell$, $\ell^+\ell^-\ell'$	$\ell^{\pm}\ell^{\pm}\ell'^{\mp}$	$\tau^{\pm}\ell^{\mp}\ell^{\mp}$, $\tau^{\pm}\ell^{\mp}\ell'^{\mp}$	$\tau^+\tau^-\ell$
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 50 GeV	> 50 GeV	> 50 GeV	> 60 GeV
Kinematics	20 bins using $E_{\mathrm{T}}^{\mathrm{miss}}$, $m_{\ell^+\ell^-}$ and $m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\ell}E_{\mathrm{T}}^{\mathrm{miss}} - 2\mathbf{p}_{\mathrm{T}}^{\ell}\cdot\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}}$	$p_{\mathrm{T}}^{3^{\mathrm{rd}}\ell} > 20$ GeV $\Delta\phi_{\ell\ell'}^{\mathrm{min}} \leq 1.0$	$p_{\mathrm{T}}^{3^{\mathrm{rd}}\ell} > 30$ GeV $\Sigma p_{\mathrm{T}}^{\ell} > 70$ GeV $m_{\ell\tau} < 120$ GeV Z veto: $m_{ee} \notin [81.2, 101.2]$	$\Sigma p_{\mathrm{T}}^{\tau} > 110$ GeV $70 < m_{\tau\tau} < 120$ GeV



$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ excluded up to $m_{\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0} = 148$ GeV

Charginos and Neutralino productions





For massless LSP and with 100% BR

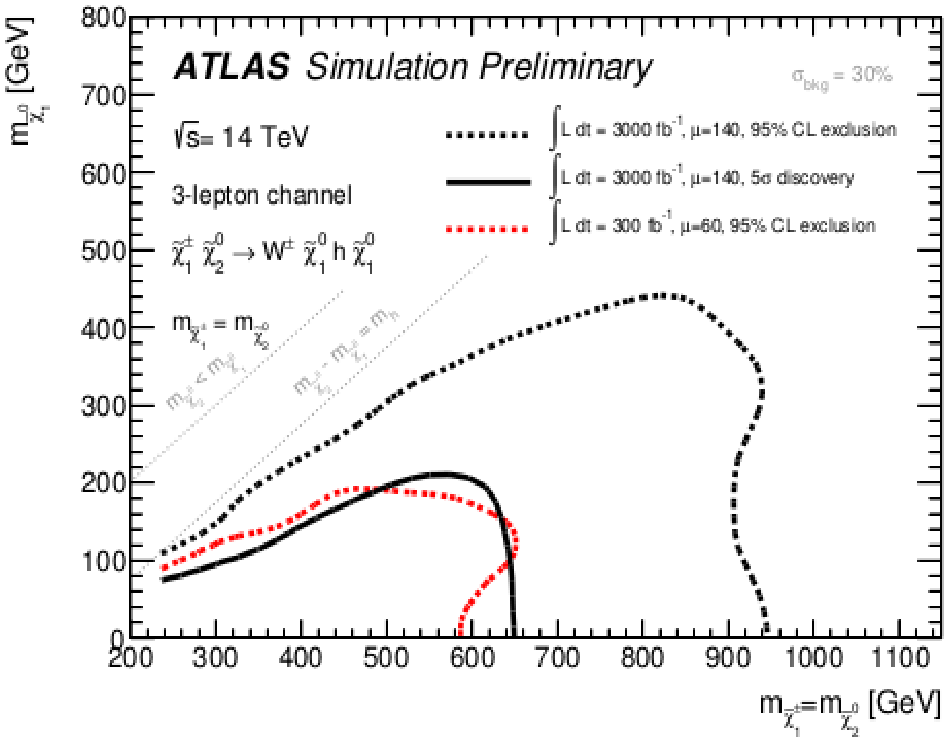
ATLAS: $125 < m_{\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0} < 141$ and $166 < m_{\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0} < 287$ GeV

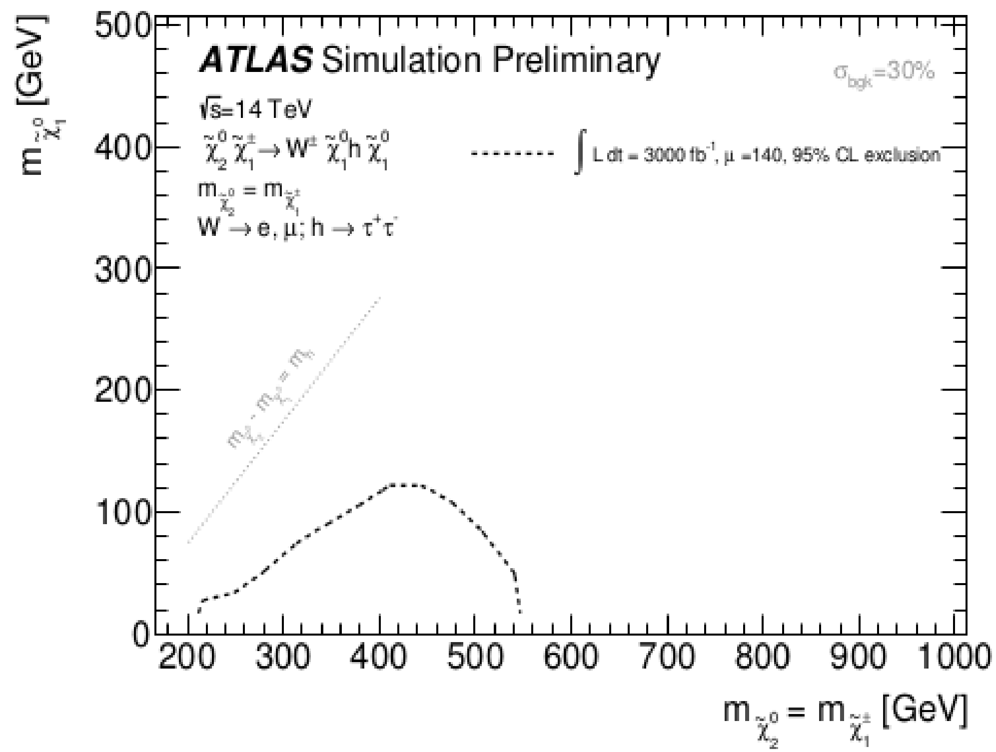
CMS: Values up to 210 GeV excluded using this mode

Charginos and Neutralino expectations from Run-II

Charginos and Neutralino expectations during Run-II

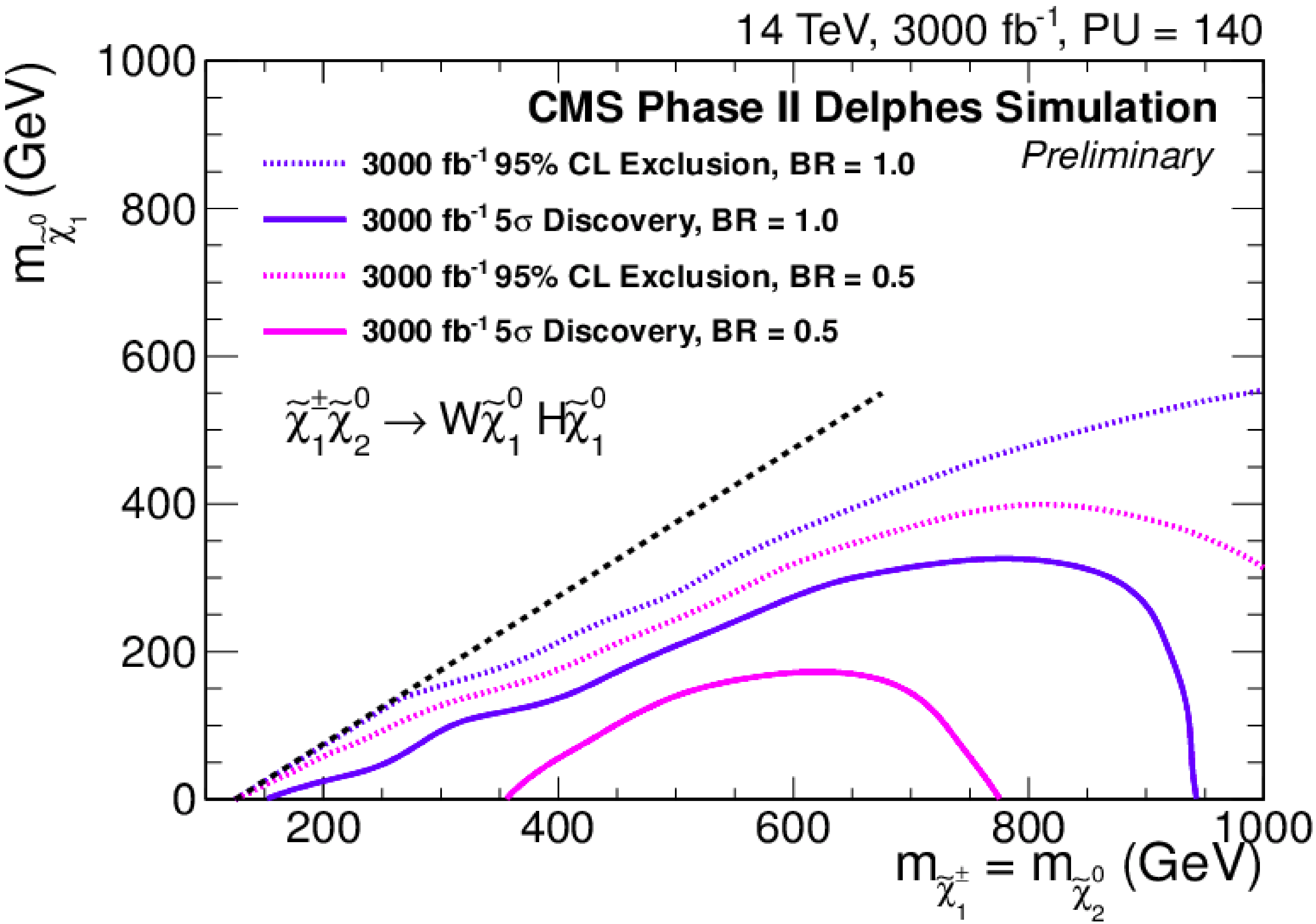
$pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0 \quad (L_{int} = 300/3000\ \mathrm{fb}^{-1})$ ATL-PHYS-PUB-2014-010





WZ and $Wh + E_t^{\text{miss}}$ searches complementary, ideally, realistic limits require a combination

Charginos and Neutralino expectations during Run-II



Similarly, large reach of phase space using HL-LHC

Generic topologies – SUSY EWKinos

Assume LSP based on SUSY breaking mass parameters M1, M2 and μ

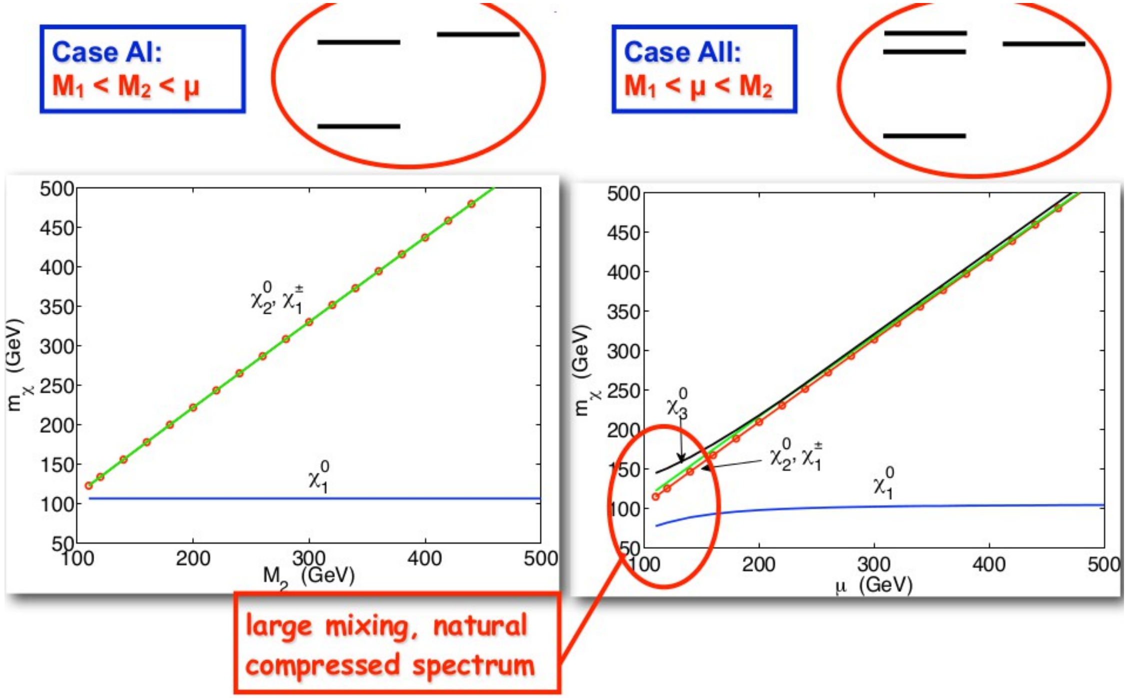
- Decouple the SUSY colored sector

<u>There can be three cases:</u>

A) Bino LSP (M1 < M2, μ)

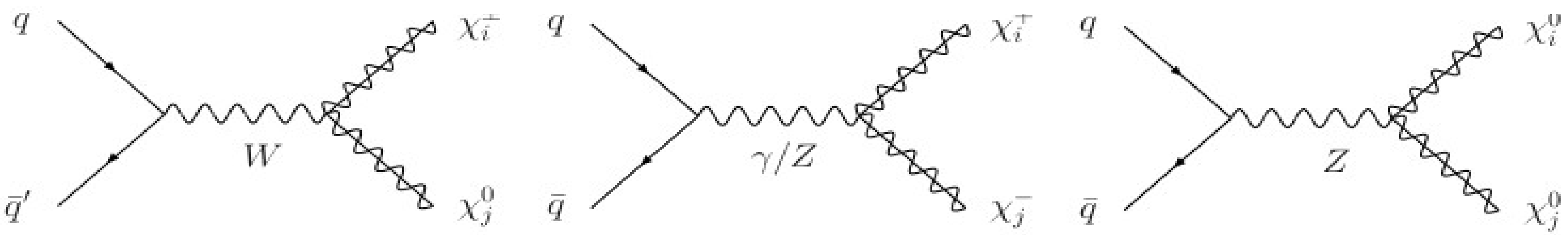
B) Wino LSP (M2 < M1, μ)

C) Higgsino LSP (μ < M1, M2)



$$\text{Case AI}: \quad M_2 < \mu, \quad \chi_1^\pm, \chi_2^0 \ \text{are Wino-like}; \ \chi_2^\pm, \chi_{3,4}^0 \ \text{are Higgino-like};$$

$$\text{Case AII}: \quad \mu < M_2, \quad \chi_1^\pm, \chi_{2,3}^0 \ \text{are Higgino-like}, \ \chi_2^\pm, \chi_4^0 \ \text{are Wino-like}.$$



(a) (b) (c)

Generic topologies and searches – SUSY EWKinos

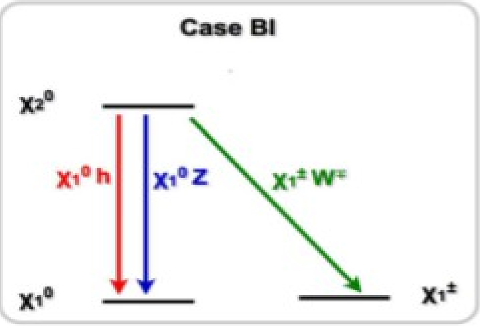
	NLSP decay Br's		Production	Total Branching Fractions (%)						
				W^+W^-	$W^\pm W^\pm$	WZ	Wh	Zh	ZZ	hh
Case AI	$\chi_1^\pm \to \chi_1^0 W^\pm$	100%	$\chi_1^\pm \chi_2^0$			18	82			
$M_1 < M_2 < \mu$	$\chi_2^0 \to \chi_1^0 h$	82%(96–70%)	$\chi_1^+ \chi_1^-$	100						
Case AII	$\chi_1^\pm \to \chi_1^0 W^\pm$	100%	$\chi_1^\pm \chi_2^0$			26	74			
$M_1 < \mu < M_2$	$\chi_2^0 \to \chi_1^0 h$	74%(90–70%)	$\chi_1^\pm \chi_3^0$			78	23			
	$\chi_3^0 \to \chi_1^0 Z$	78%(90–70%)	$\chi_1^+ \chi_1^-$	100						
			$\chi_2^0 \chi_3^0$					63	20	17
Case BI, $M_2 < M_1 < \mu$	$\chi_2^0 \to \chi_1^\pm W^\mp, \chi_1^0 h, \chi_1^0 Z$,	68%, 27%(31 − 24%), 5%(1 − 9%),	production suppressed.							
Case BII	$\chi_2^\pm \to \chi_1^0 W^\pm$	35%	$\chi_2^\pm \chi_2^0$	12	12	32	23	10	9	2
$M_2 < \mu < M_1$	$\chi_2^\pm \to \chi_1^\pm Z$	35%	$\chi_2^\pm \chi_3^0$	12	12	26	29	11	3	7
	$\chi_2^\pm \to \chi_1^\pm h$	30%	$\chi_2^+ \chi_2^-$	12		25	21	21	12	9
	$\chi_2^0 \to \chi_1^\pm W^\mp$	67%	$\chi_2^0 \chi_3^0$	23	23	23	21	7	2	2
	$\chi_2^0 \to \chi_1^0 Z$	26%(30–24%)								
	$\chi_3^0 \to \chi_1^\pm W^\mp$	68%								
	$\chi_3^0 \to \chi_1^0 h$	24%(30–23%)								
Case CI, $\mu < M_1 < M_2$	$\chi_3^0 \to \chi_1^\pm W^\mp, \chi_{1,2}^0 Z, \chi_{1,2}^0 h$,	52%, 26%, 22%,	production suppressed.							
Case CII	$\chi_2^\pm \to \chi_{1,2}^0 W^\pm$	51 %	$\chi_2^\pm \chi_3^0$	14	14	27	23	11	6	5
$\mu < M_2 < M_1$	$\chi_2^\pm \to \chi_1^\pm Z$	26 %	$\chi_2^+ \chi_2^-$	26		26	24	12	7	5
	$\chi_2^\pm \to \chi_1^\pm h$	23 %								
	$\chi_3^0 \to \chi_1^\pm W^\mp$	54 %								
	$\chi_3^0 \to \chi_{1,2}^0 Z$	24 %								
	$\chi_3^0 \to \chi_{1,2}^0 h$	22 %								

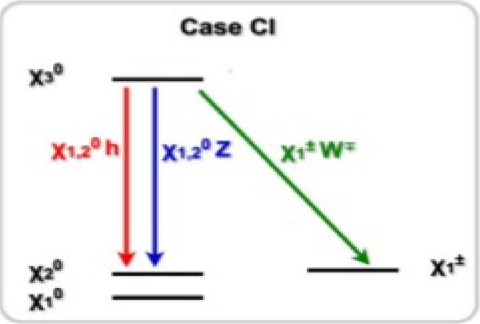
T. Han, SP, S. Su

PRD 88 (2013) 115010

4 out of 6 cases result in compressed spectra

Nearly degenerate LSP pair production





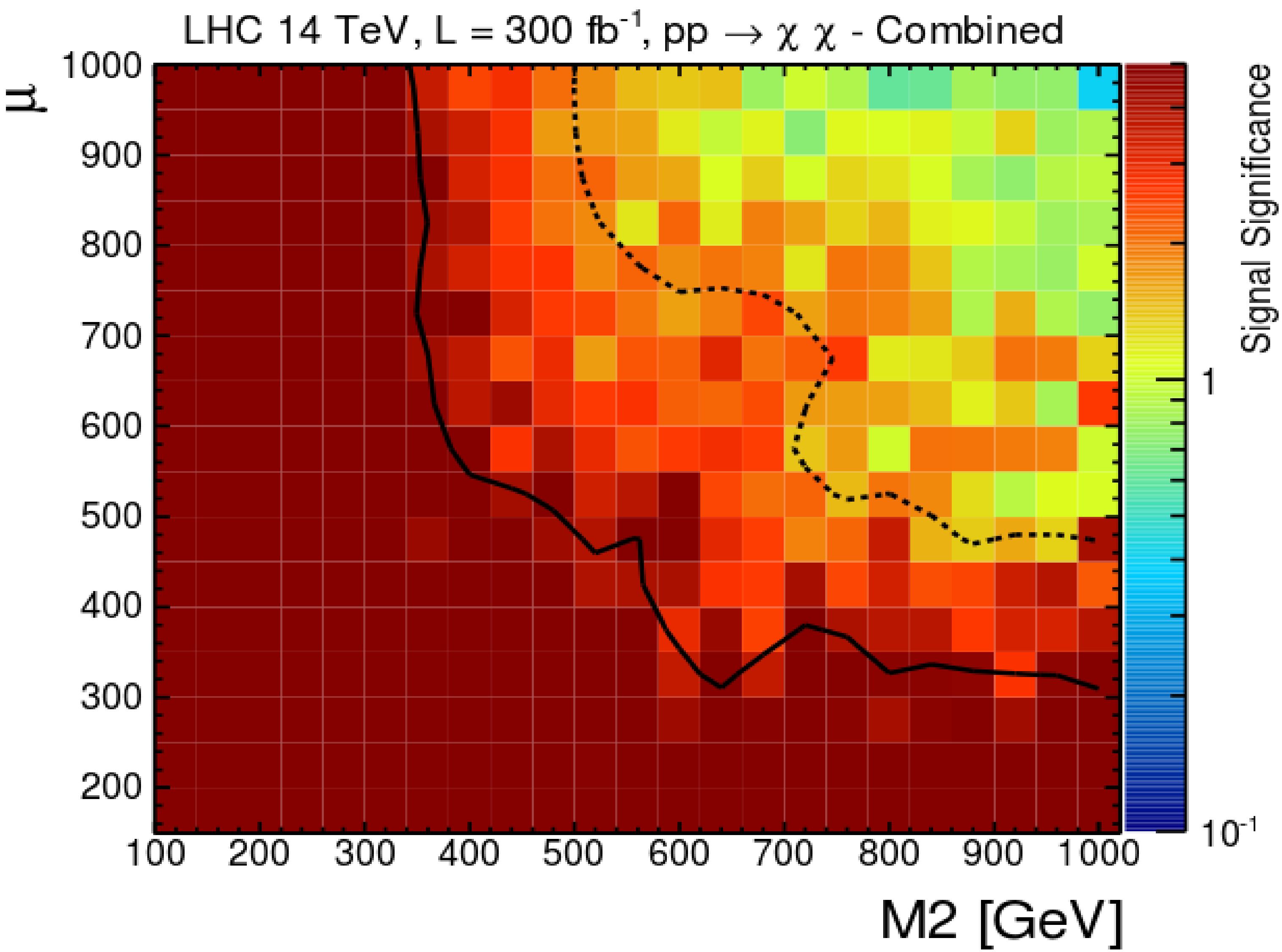
MET + ISR (Mono Jet studies)

Or VBF production

Generic topologies and searches – SUSY EWKinos

arXiv:1309.5966

T. Han, SP. S. Su, PRD 88 (2013) 115010



Large set of final states

Unique set of signals! **Opportunity to explore using HL-LHC**

Summary and Outlook

SUSY results from ATLAS and CMS studies provide breath of physics analysis

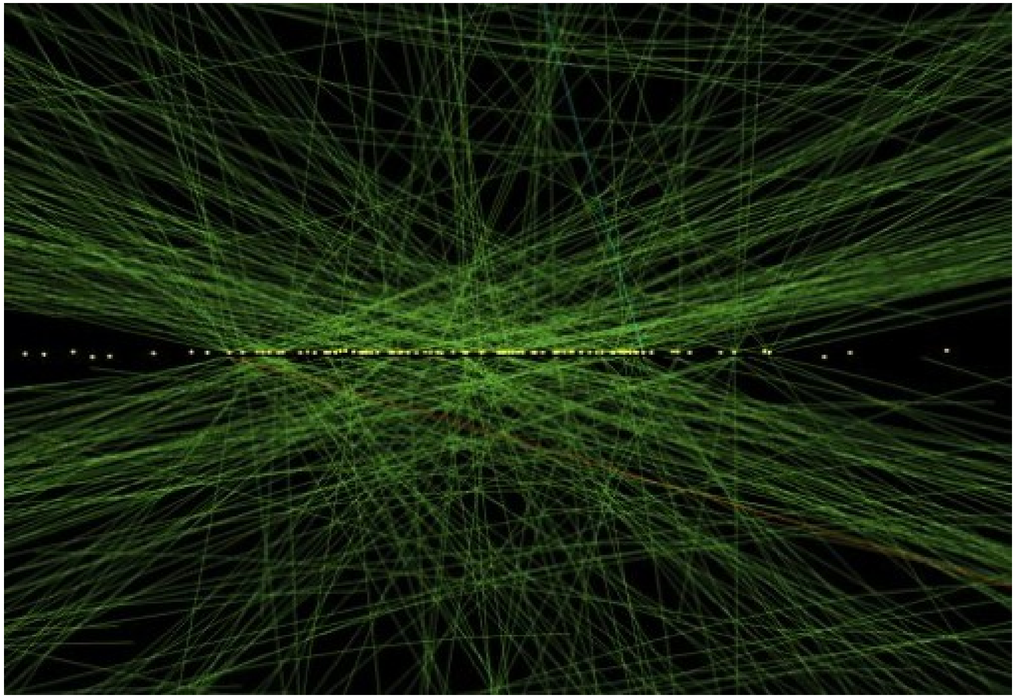
Several “new” EW production searches started using “Higgs tagging”

Although no evidence of new physics was found

→ the experiments will have the access to increase in cross section & lumi next year

There will be challenges as well

- Large increase in pileUp
- Effects on:
  - → trigger performance
  - → object reconstruction
  - → isolation variable



Real data event - 78 reconstructed vertices from high pile-up run

The results from ATLAS and CMS WILL set the agenda across the energy frontier for the foreseeable future!