Arnowitt Symposium and Mitchell Workshop on Collider and Dark Matter Physics

DM Searches at CMS Using LHC-data Collected at $\sqrt{s} = 8$ TeV

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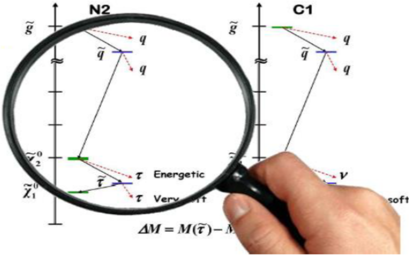
Outline

1. **Motivation**
2. **Latest Color Searches** (CMS-SUS-13019, CMS-SUS-14001)
3. **Electroweak SUSY Searches**
   - Searches with a $h \rightarrow \gamma\gamma$ Decay - (CMS-SUS-14002)
   - Probing SUSY with VBF (CMS-SUS-14005)
4. **DM Exotic Searches** (CMS-EXOT-14004)
5. **Summary**

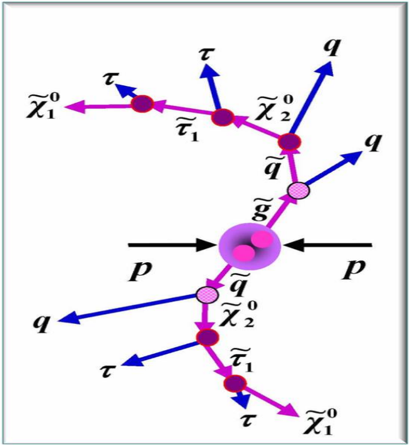
Motivation

- The aim of the talk is to show some of the **latest** results from CMS related to Dark Matter (DM) searches.
- A special focus in SUSY electroweak **higgs-tagging** searches and **VBF SUSY** searches is placed due their physics motivation and connection to DM:
  1. SM-Higgs boson discovery.
  2. Coannihilation and its relation with cosmology ($\tilde{\tau}$).
- For more information on SUSY-color searches please see (Oliver's talk)
- The latest results from searches in Exotic channels will also be presented.

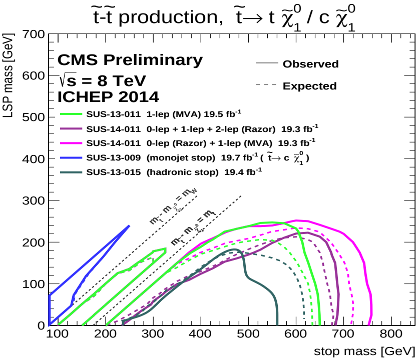
Classic SUSY Searches

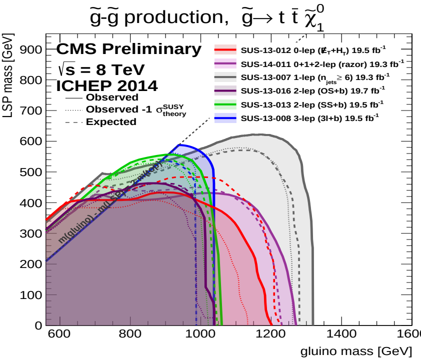


- Initial SUSY searches focused on the color sector.
- These type of signatures have final states with: $E_T^{miss} + jets + leptons(photons)$



CMS SUSY Color Searches

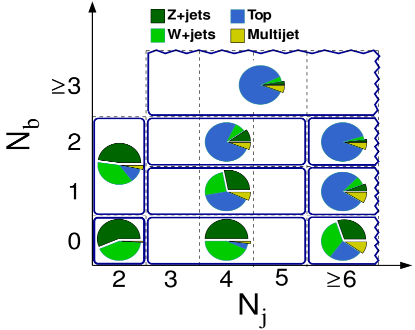


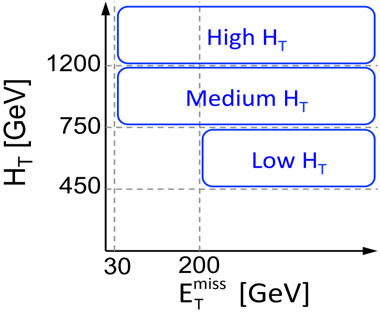


Recent Color SUSY Searches - M_T^2

(CMS-SUS-13019 - JHEP)

$$(M_T^{(i)})^2 = (m^{\text{vis}(i)})^2 + m_X^2 + 2\left(E_T^{\text{vis}(i)} E_T^{X(i)} - \vec{p}_T^{\text{miss vis}(i)} \cdot \vec{p}_T^{\text{miss } X(i)}\right)$$

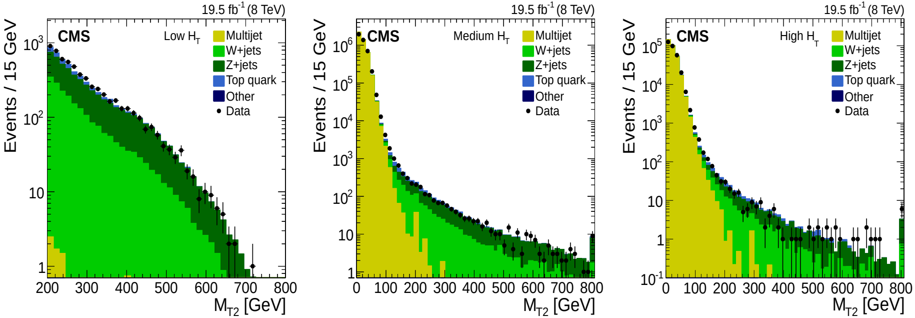




Recent Color SUSY Searches - M_T^2

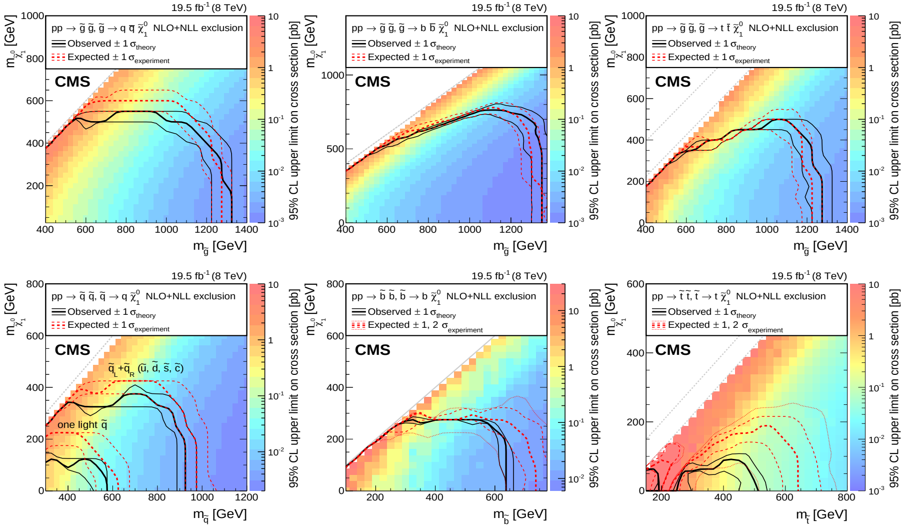
(CMS-SUS-13019 - JHEP)

- No excess above SM expectation.



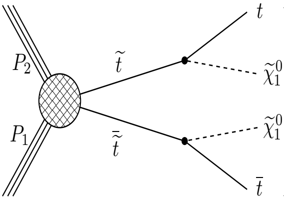
Recent Color SUSY Searches - M_T^2

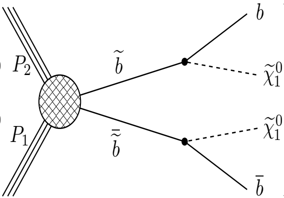
(CMS-SUS-13019 - JHEP)

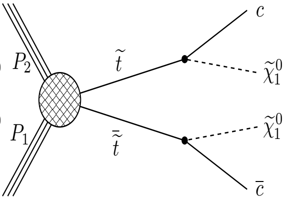


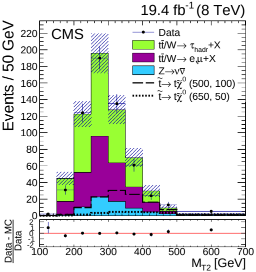
Recent Color SUSY Searches
3-rd Gen. $\bar{q}$ in Fully Hadronic Final States

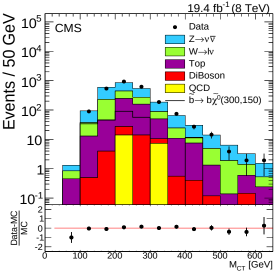
(CMS-SUS-14001 - JHEP, in press)

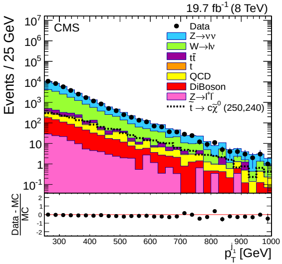












Recent Color SUSY Searches
3-rd Gen. $\bar{q}$ in Fully Hadronic Final States

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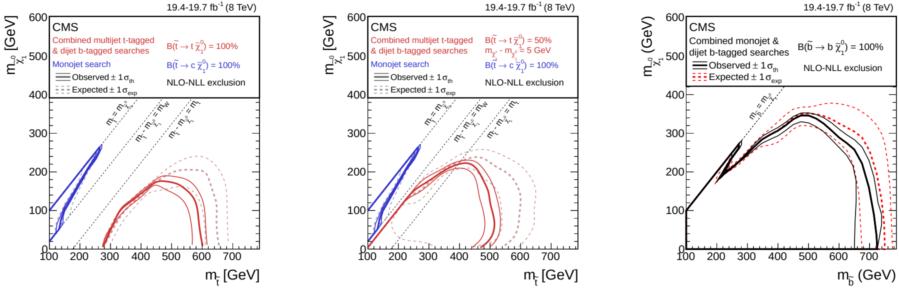
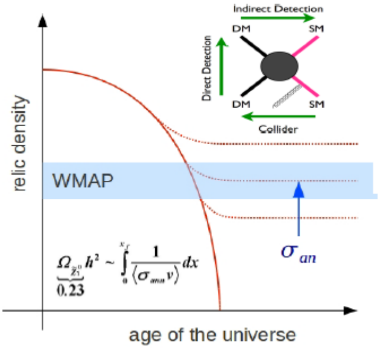


Dark Matter & Cosmology

It is important to directly probe the electroweak SUSY sector



℞ to Probe Ωh^2

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

$s_W = \sin(\theta_W) \quad c_W = \cos(\theta_W)$

$s_\beta = \sin(\beta) \quad c_\beta = \cos(\beta)$

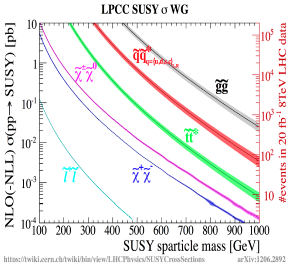
$M_1 << M_2,\ \mu \Rightarrow \tilde{\chi}_1^0 \approx \tilde{B}$ → *pure Bino*

$M_2 << M_1,\ \mu \Rightarrow \tilde{\chi}_1^0 \approx \tilde{W}$ → *pure Wino*

$\mu << M_1,\ M_2 \Rightarrow \tilde{\chi}_1^0 \approx \tilde{H}_u + \tilde{H}_d$ → *pure Higgsino*

Electroweak SUSY Searches

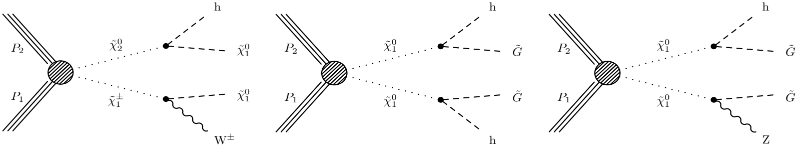
- Searches in the color sector have not yield positive signs of SUSY until now.
- SUSY searches in the electroweak (EWK) sector opens a different avenue to find new physics:
  - ✓ Smaller predicted cross sections but lower levels of hadronic activity
  - ✓ Complements the color searches



- **The discovery of the Higgs opens up new SUSY searches:**
  - ✓ Lightest neutral CP–even Higgs (h) expected to be SM–like, if others are heavy.
  - ✓ $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$ decay to h+LSP (RPC models) or $V_{(W/Z)} + \tilde{\chi}_1^0$ ($\tilde{\chi}_1^0$ LSP)
  - ✓ Would provide evidence for SUSY solution to hierarchy problem.

Electroweak SUSY Searches

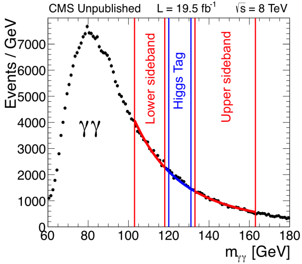
- Several new searches using Higgs Tagging (covered here)
  - ✓ $h \rightarrow \gamma\gamma \Rrightarrow$ several hh, hZ and hW channels covered!
  - ✓ $h \rightarrow b\bar{b} \Rrightarrow (h \rightarrow b\bar{b})(Z \rightarrow \ell_{e/\mu}\ell_{e/\mu})$, $hh \rightarrow b\bar{b}b\bar{b}$



- Previously released results (not covered here)
  - ✓ Final states with ≥ 3 leptons, LS (OS) dileptons
  - ✓ SUSY interpretations EWK $\tilde{\chi}_1^\pm$ & LSP $(\tilde{G}||\tilde{\chi}_1^0)$ production with decays through leptons and EWK slepton production.

Searches with a $h \to \gamma\gamma$ Decay

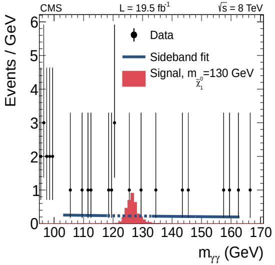
(CMS-SUS-14002 - PRD)



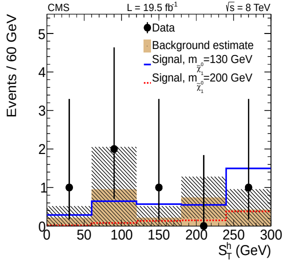
- Search channels:
  - ✓ $\gamma\gamma + b\bar{b}$: targets hh,
  - ✓ $\gamma\gamma + jj$: targets hZ & hW,
  - ✓ $\gamma\gamma + \ell_{e/\mu}\ell_{e/\mu}$:targets hh, hZ & hW
- Common $\gamma\gamma$ selection
  - ✓ 2 $\gamma's$ with $|\eta_\gamma| < 1.4$ (barrel)
  - ✓ $E_T^\gamma > 40$ GeV & 25 GeV
- Common background (BG) estimation:
  1. Fit $m_{\gamma\gamma}$ distribution in sidebands, excluding tag region, with power law.
  2. Integrate power-law function in Higgs tag region ($m_{\gamma\gamma}(120 \to 130\ GeV)$) to normalize continuum BG (SM-non h).
  3. BG shape in discriminating variable (e.g. E_T^{miss}) taken from average of upper and lower $m_{\gamma\gamma}$ sidebands.
  4. BG from SM-Higgs added to sideband-based continuum BG estimate.

$(h \to \gamma\gamma)(h \to b\bar{b})$

(CMS-SUS-14002 - PRD)



- Event selection criteria:
  1. Veto isolated e or μ
  2. $= 2$ b-tagged jets, $p_T^j > 30$ GeV
  3. $\Delta R(\gamma, j) > 0.5$
  4. $m_{b\bar{b}}(95 \to 155)$ GeV.
- Discriminating variable: $S_T^h = p_T^{h\to\gamma\gamma} + p_T^{h\to b\bar{b}}$
  1. S_T^h distribution for signal extends to high values
  2. BG S_T^h distribution obtained from $m_{\gamma\gamma}$ sidebands, averaged and normalized from $m_{\gamma\gamma}$ SF fit (SM-Higgs negligible).
  3. Observed events consistent with BG prediction

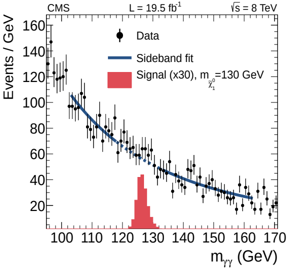


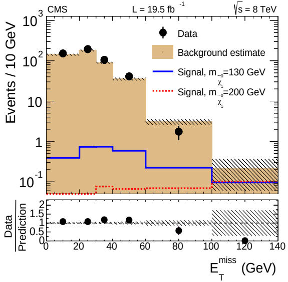
$(h \to \gamma\gamma)(W/Z \to jj)$

(CMS-SUS-14002 - PRD)

- Event selection criteria:
  1. Veto isolated e or μ
  2. Veto events w/ 2 b-tagged jets in $m_{b\bar{b}}(95 \to 155)$ GeV.
  3. $p_T^j > 30$ GeV, $\Delta R(\gamma, j) > 0.5$
  4. $m_{jj}(70 \to 110)$ GeV
- Discriminating variable: E_T^{miss}
  - ✓ Signal spectrum harder for larger NLSP -LSP mass difference.
  - ✓ BG E_T^{miss} distribution obtained from $m_{\gamma\gamma}$ (sidebands, averaged and normalized from $m_{\gamma\gamma}$ SB fit).
  - ✓ Small SM-Higgs BG contribution.
  - ✓ Observed events consistent with BG prediction

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

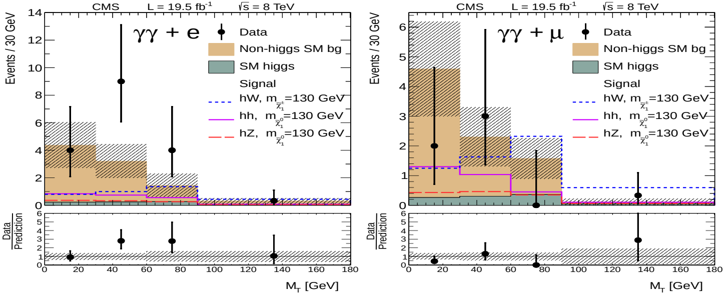




$hh, hZ, hW \rightarrow \gamma\gamma + \ell^{\pm}_{e\mu}$

(CMS-SUS-14002 - PRD)

- The hh search includes one h to WW, ZZ or $\tau\tau$
- Event selection criteria:
  1. ≤ 1 b-tagged jet to avoid overlap with $h \rightarrow b\bar{b}$.
  2. $\geq 1\mu || \geq 1e$
  3. $p_T(e||\mu) > 15$ GeV & $\Delta R(\ell_{e||\mu}, \gamma) > 0.3$
  4. Reject e miss ID's as γ by vetoing $m_{e\gamma}$ near $m_Z(86 \rightarrow 96)$ GeV.
- Discriminating variable: $M_T(\ell^{lead}, E_T^{miss}) = \sqrt{2E_T^{miss} \cdot p_T^{lead}(\ell)(1 - cos(\Delta\phi(\ell, E_T^{miss}))}$



$hh, hZ, hW \to \gamma\gamma + \ell^{\pm}_{e\mu}$

(CMS-SUS-14002 - PRD)

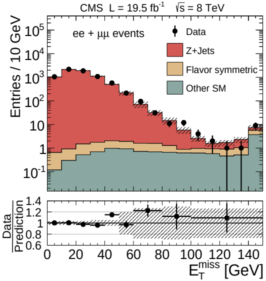
- Excess seen in $\gamma\gamma + e$ channel (2.1 σ), consistent with BG fluctuations:
  - ✓ E_T^{miss} shape for $\gamma\gamma + e$ consistent with BG.
  - ✓ Several checks of $m_{\gamma\gamma}$ show it is robust.

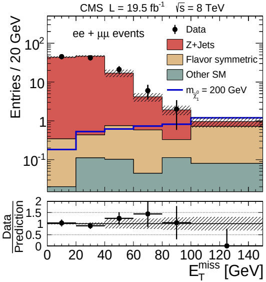
	Muon sample			Electron sample		
M_T (GeV)	SM background	Data	hW events	SM background	Data	hW events
0–30	4.6 ± 1.6	2	1.2 ± 0.1	4.4 ± 1.7	4	0.80 ± 0.06
30–60	2.31 ± 0.99	3	1.5 ± 0.1	3.2 ± 1.2	9	1.0 ± 0.1
60–90	1.59 ± 0.68	0	2.1 ± 0.1	1.44 ± 0.85	4	1.4 ± 0.1
>90	0.35 ± 0.30	1	1.6 ± 0.1	0.96 ± 0.58	1	1.3 ± 0.1

$(h \to b\bar{b})(Z \to \ell_{e/\mu}\ell_{e/\mu})$

(CMS-SUS-14002 - PRD)

- Event selection criteria:
  1. h : $=$ 2 b-tagged jets with $m_{b\bar{b}}(100 \to 150)$ GeV
  2. Z: $=$ 1 lepton pair ($e^{\pm}e^{\mp}$ || $\mu^{\pm}\mu^{\mp}$)
  3. Veto 3^{rd} lepton (e, μ or τ_h)
- Z+jets BG estimate:
  - ✓ E_T^{miss} template from $\gamma + jets$ control region.
  - ✓ Normalized by data yield in $E_T^{miss} < 50$ GeV.
- $t\bar{t}$, WW, $\tau\tau$ & tW BG's (flavor symmetric):
  - ✓ E_T^{miss} template normalized from $e\mu$ sample.
- Other SM BG's estimated from MC.

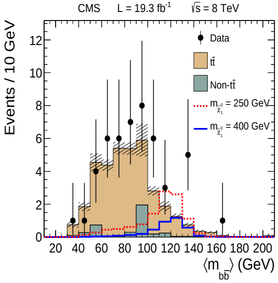


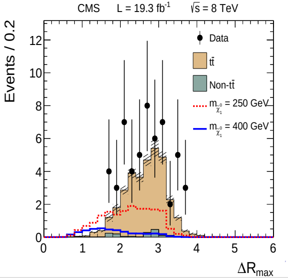


$(h \to b\bar{b})(h \to b\bar{b})$

(CMS-SUS-14002 - PRD)

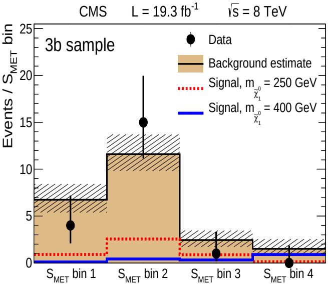
- Largest branching fraction ($h \to b\bar{b}$ is 56%)
- Event selection criteria:
  - ✓ Lepton veto, 4 or 5 jets ($\geq$ 2 b-tagged jets)
- hh reconstruction:
  - ✓ Combination with smallest $m_{b\bar{b}}$ difference
  - ✓ Signal box: $|\Delta m_{b\bar{b}}| < 20$ GeV, $< m_{b\bar{b}} >$ in [100, 140] GeV.
  - ✓ E_T^{miss} significance (S_{MET}): better fake E_T^{miss} rejection than plain E_T^{miss}.
- BG estimate (ABCD method):
  - ✓ Two sidebands: m_h & N_{b-tags}.
  - ✓ Measure mass SIG/BG in 2b, apply in 3b and 4b.

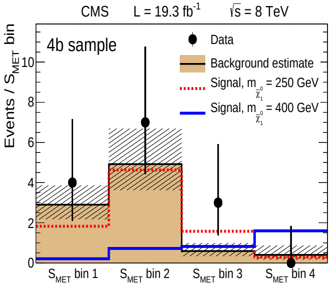




$(h \to b\bar{b})(h \to b\bar{b})$

(CMS-SUS-14002 - PRD)





Observed data consistent with BG prediction

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

Searches with ≥ 3 Leptons and $ZZ \to jj\ell\ell$

- New interpretation of previos results are presented.
- $ZZ \to jj\ell_{e/\mu}\ell_{e/\mu}$: requires two well reconstructed Z decays.
  - ✓ Discrimination variable: E_T^{miss}
  - ✓ $m_{jj}(70 \to 110)$ GeV $\Rrightarrow$ also used for WZ interpretation.
- Multi-lepton: ≥ 3 charged leptons including up to 1 τ_h
- Events categorized by N_{lep}, N_{OSSF}, N_{b-jet}, E_T^{miss}, and $H_T = \sum p_T(jets)$.
- Table shows the most sensitive channels for hh search with $m_{\tilde{h}} = 150 GeV$.
- Excess of 2.6 σ

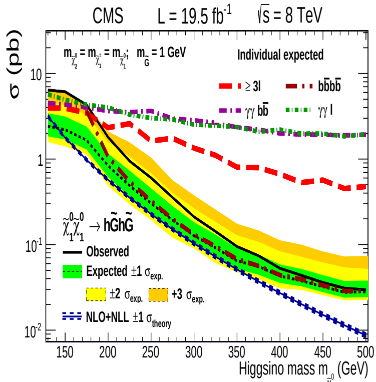
N_ℓ	Selection	$m_{\ell\ell}$	E_T^{miss} [GeV]	N_τ	data	background	signal
3	OSSF1 $H_T < 200$	Below-Z	(50,100)	0	142	130 ± 27	7.4 ± 1.6
3	OSSF0 $H_T < 200$	NA	(50,100)	0	35	38 ± 15	2.68 ± 0.60
3	OSSF0 $H_T < 200$	NA	(0,50)	0	53	51 ± 11	3.05 ± 0.64
4	OSSF1 $H_T < 200$	Off-Z	(50,100)	0	0	0.18 ± 0.06	0.45 ± 0.17
4	OSSF1 $H_T < 200$	Off-Z	(50,100)	1	4	2.1 ± 0.5	0.69 ± 0.19
3	OSSF0 $H_T < 200$	NA	(50,100)	1	406	402 ± 152	8.0 ± 1.4
4	OSSF1 $H_T < 200$	Off-Z	(0,50)	1	15	7.5 ± 2.0	0.85 ± 0.20
4	OSSF0 $H_T < 200$	NA	(0,50)	1	1	0.7 ± 0.3	0.30 ± 0.11
4	OSSF2 $H_T < 200$	Off-Z	(50,100)	0	2	0.18 ± 0.13	0.23 ± 0.12
3	OSSF1 $H_T < 200$	Above-Z	(50,100)	0	50	46.0 ± 9.7	1.10 ± 0.24

✓ Multi-lepton: PRD 90, 032006 (2014), arXiv:1409.3168

✓ $ZZ \to jjll$: EPJC 74 (2014) 3036, arXiv:1405.7570

hh: GMSB $\tilde{h}$ Interpretation

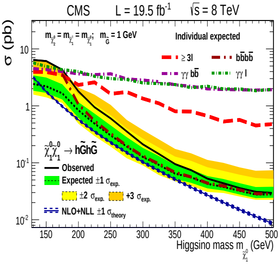
- GMSB scenario where $\tilde{\chi}_1^0$ & $\tilde{\chi}_1^{\pm}$ are Higgsinos and nearly mass degenerate ($m_{\tilde{\chi}_1^0} \approx m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^{\pm}}$).
- The $\tilde{\chi}_1^0$ is the NLSP and the $\tilde{G}$ is the LSP (nearly massless).
- This slide, $Br(\tilde{\chi}_1^0 \to h\tilde{G} = 1)$



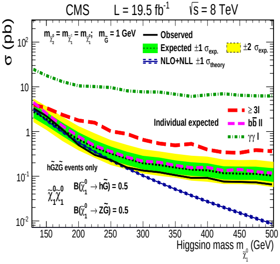
- ✓ $hh \to b\bar{b}b\bar{b}$ is the most sensitive channel above 175 GeV
- ✓ Multi-lepton and $\gamma\gamma$ channels most sensitive at low $\tilde{h}$ masses.
- ✓ Excess above 150 GeV (3 σ) consistent with statistical fluctuations $\Rightarrow$ mostly due to multi-lepton.

hh and hZ GMSB Higgsino Interpretation

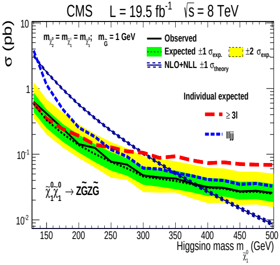
100% hh

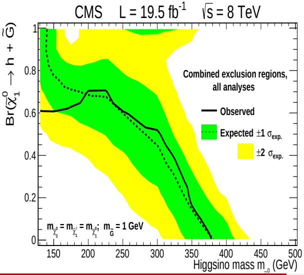


$25\%\ hh, 50\%\ hZ, 25\%\ ZZ$



100% ZZ

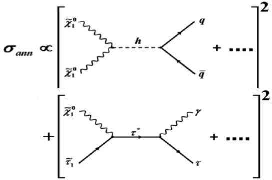




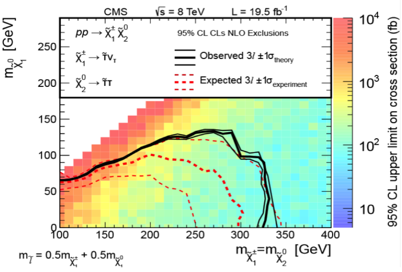
- ✓ 1D and 2D exclusion limits as a function of higgsino mass.
- ✓ The area under the solid black line in the 2D exclusion plot is excluded at 95% CL.

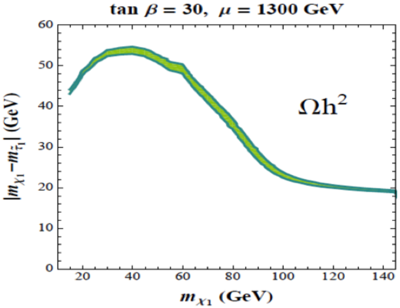
Third Generation EWK-SUSY Searches

- The experimental sensitivity in final states containing third generation particles is limited, especially in compressed spectra scenarios.



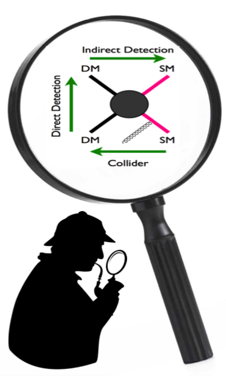
Lian Tao and Marcela Carena
http://arxiv.org/pdf/1205.5842v1.pdf

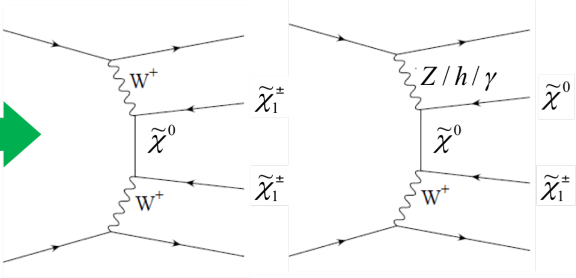


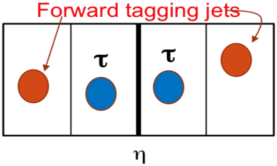


$$\Omega_{\tilde{\chi}_1^0} h^2 \sim \int_0^\infty \frac{1}{<\sigma_{an}\nu>} dx$$

Probing SUSY with VBF
(CMS-SUS-14005)







ϕ **MET + jj + leptons**

- Eight final states: $\mu\mu jj$, $e\mu jj$, $\mu\tau_h jj$, $\tau_h\tau_h jj$ (OS & LS).
- For the $\mu\mu jj$, $e\mu jj$, $\mu\tau_h jj$ channels we use an inclusive single muon trigger, while for the $\tau_h\tau_h jj$ channels we use a di-tau trigger.

Event Selection Criteria

(CMS-SUS-14005)

Summary of the event selection criteria for the different final states considered in the analysis. Note the selections for the $\mu\mu jj$ and $e\mu jj$ channels are presented in one column ($\ell_{(e/\mu)}\mu jj$) as they are very similar.

Cut	$\ell_{(e/\mu)}\mu jj$	$\mu\tau_h jj$	$\tau_h\tau_h jj$
Central Selections			
Trigger	HLT_IsoMu24_eta2p1	HLT_IsoMu24_eta2p1	HLT_DMIPFTau35_Pr1
$p_T(\mu)[GeV]$	≥ 30	≥ 30	
$p_T(e)[GeV]$	≥ 15 only $e\mu jj$		
$p_T(\tau_h)[GeV]$		≥ 20	≥ 45
$\lvert\eta(\ell_{\mu,e,\tau_h})\rvert$	< 2.1	< 2.1	< 2.1
N_{b-tag} jets (CSVL)	0	0	0
E_T^{miss} [GeV]	> 75	> 75	> 30
$p_T(jets)[GeV]$	$\geq 30/50$	≥ 50	≥ 30
$\lvert\eta(jets)\rvert$	≤ 5	≤ 5	≤ 5
$\Delta R(\ell^1_{e,\mu,\tau_h}, \ell^2_{e,\mu,\tau_h})$	≥ 0.3	≥ 0.3	≥ 0.3
$\Delta R(jet, \ell_{e,\mu,\tau_h})$	≥ 0.3	≥ 0.3	≥ 0.3
VBF Selections			
$\Delta\eta(jet_1, jet_2)$	> 4.2	> 4.2	> 4.2
$\eta^{jet1} \cdot \eta^{jet2}$	< 0	< 0	< 0
$mj, j[GeV]$	≥ 250	≥ 250	≥ 250

- We perform a shape-based analysis, using the m_{jj} distribution as a discrimination variable.

Background Estimation Strategy

(CMS-SUS-14005)

- We use a common BG estimation methodology across channels:
  1. We obtain SFs in high purity CRs to correct for any mismodeling in simulation, after applying central selections (No VBF selections).
  2. When possible, we measure the VBF efficiency from data.
  3. The contribution of a given BG in the SR, estimated with the method described above, is performed using the following formula:

$$N_{\mathrm{BG}}^{\mathrm{Data}} = N_{\mathrm{BG}}^{\mathrm{MC}}(\mathrm{central}) \cdot SF_{\mathrm{central}}^{\mathrm{CR1}} \cdot \epsilon_{\mathrm{VBF}}^{\mathrm{CR2}}(m_{jj})$$

  4. A closure test is performed in MC. The difference between the nominal and predicted yields in the closure test, is taken as a systematic error.
  5. When possible we also perform closure tests with data.
  6. We check that the signal contamination in the CRs is negligible.
- If the BGs are small, when possible we first show that the VBF shapes are well modelled in simulation and then simply correct the MC prediction with a SF:

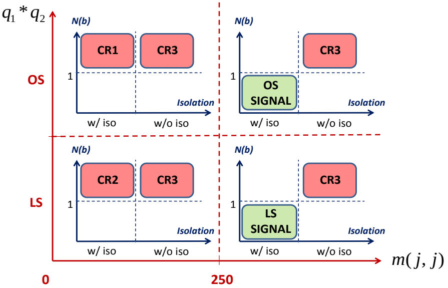
$$N_{\mathrm{BG}}^{\mathrm{Data}} = N_{\mathrm{BG}}^{\mathrm{MC}}(\mathrm{SR}) \cdot SF_{\mathrm{central}}^{\mathrm{CR1}}$$

$t\bar{t}$ Background Estimation For OS/LS $\mu\mu$

(CMS-SUS-14005)

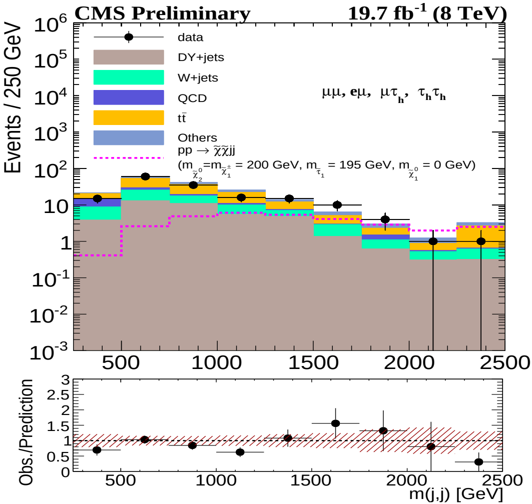
- $t\bar{t}$ is the largest BG source for both $\mu\mu$ channels (OS & LS)
- The estimation of this BG is done in a semi-data-driven way.
- Three CRs are used:
  1. CR1: $SF^{\rm CR1}_{\rm central}$ for central selections for OS events.
  2. CR2: $SF^{\rm CR2}_{\rm central}$ for central selections for LS events.
  3. CR3: measure VBF efficiency and dijet mass shape from data.

Top Pair Background Estimation & Validation/Closure Strategy



Combined m_{jj} Distribution

(CMS-SUS-14005)



Final yields: OS Channels
(CMS-SUS-14005)

Number of observed events in data and estimated background rates for the OS search channels. The uncertainties are based on the number of observed events in the CRs as well as the statistics in simulation.

Process	$\mu^{\pm}\mu^{\mp}jj$	$e^{\pm}\mu^{\mp}jj$	$\mu^{\pm}\tau_h^{\mp}jj$	$\tau_h^{\pm}\tau_h^{\mp}jj$
DY + jets	4.3 ± 1.7	$3.7\pm^{2.1}_{1.9}$	19.9 ± 2.9	12.3 ± 4.4
W + jets	< 0.01	$4.2\pm^{3.3}_{2.5}$	17.3 ± 3.0	2.0 ± 1.7
VV	2.8 ± 0.5	3.1 ± 0.7	2.9 ± 0.5	0.5 ± 0.2
$t\bar{t}$	24.0 ± 1.7	$19.0\pm^{2.3}_{2.4}$	11.7 ± 2.8	–
QCD	–	–	–	6.3 ± 1.8
Higgs	1.0 ± 0.1	1.1 ± 0.5	–	1.1 ± 0.1
VBF Z	–	–	–	0.7 ± 0.2
Total	32.2 ± 2.4	$31.1\pm^{4.6}_{4.1}$	51.8 ± 5.1	22.9 ± 5.1
Observed	31	22	41	31

Final yields: LS Channels

(CMS-SUS-14005)

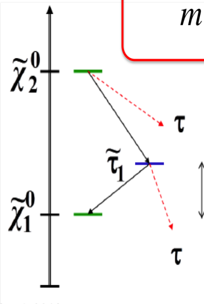
Number of observed events in data and estimated background rates for the LS channels. The uncertainties are based on the number of observed events in the CRs as well as the statistics in simulation.

Process	$\mu^{\pm}\mu^{\pm}jj$	$e^{\pm}\mu^{\pm}jj$	$\mu^{\pm}\tau_h^{\pm}jj$	$\tau_h^{\pm}\tau_h^{\pm}jj$
DY + jets	< 0.01	$0\pm^{1.7}_{0}$	0.5 ± 0.2	< 0.01
W + jets	$0.1 \pm 8.2 \times 10^{-4}$	$0\pm^{3.0}_{0}$	9.3 ± 2.3	0.5 ± 0.1
VV	2.1 ± 0.3	$1.9\pm^{0.4}_{0.2}$	1.1 ± 0.2	$0.1 \pm 6.5 \times 10^{-2}$
$t\bar{t}$	3.1 ± 0.1	$3.5\pm^{0.7}_{0.9}$	6.7 ± 2.8	$0.1 \pm 1.2 \times 10^{-2}$
Single top	–	–	–	< 0.1
QCD	–	–	–	7.6 ± 0.9
Higgs	–	–	–	< 0.01
Total	5.4 ± 0.3	$5.4\pm^{3.5}_{0.9}$	17.6 ± 3.8	8.4 ± 0.9
Observed	4	5	14	9

SUSY Scenario 1 – Compressed Mass Spectra & Large Mass Gaps

Slepton mass definition

$$m(\tilde{\chi}_1^{\pm}) - m(\tilde{l}) = 5GeV$$



Large mass gap

$$m(\tilde{\chi}_1^0) = 0$$

$$m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^0) = 50GeV$$

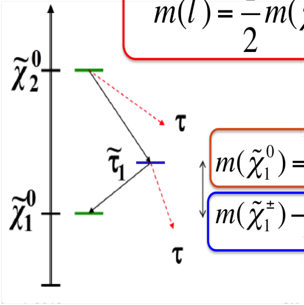
Compressed mass spectra

SUSY Scenario 2 – Compressed Mass Spectra & Large Mass Gaps

(CMS-SUS-14005)

Slepton mass definition

$$m(\tilde{l}) = \frac{1}{2} m(\tilde{\chi}_1^0) + \frac{1}{2} m(\tilde{\chi}_1^\pm)$$



Large mass gap

$$m(\tilde{\chi}_1^0) = 0$$

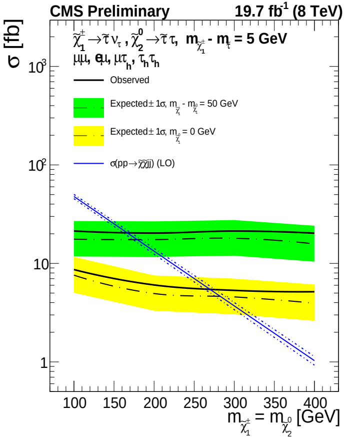
$$m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 50 GeV$$

Compressed mass spectra

Results - Combined Limits: Scenario 1

(CMS-SUS-14005)

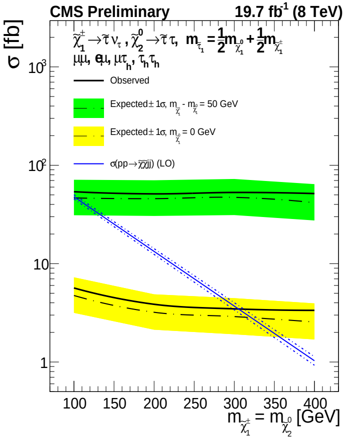
- No excess above the SM background is observed.
- A combined observed upper bound limit of 280 GeV and an expected limit on 295 GeV is set, for the large mass gap scenario where the mass difference between the chargino and the slepton is 5 GeV and the LSP mass is 0 GeV.
- For the compressed mass spectra scenario, where the mass difference between the chargino and the LSP is 50 GeV, we set a combined observed upper bound limit of 170 GeV and an expected limit of 180 GeV.



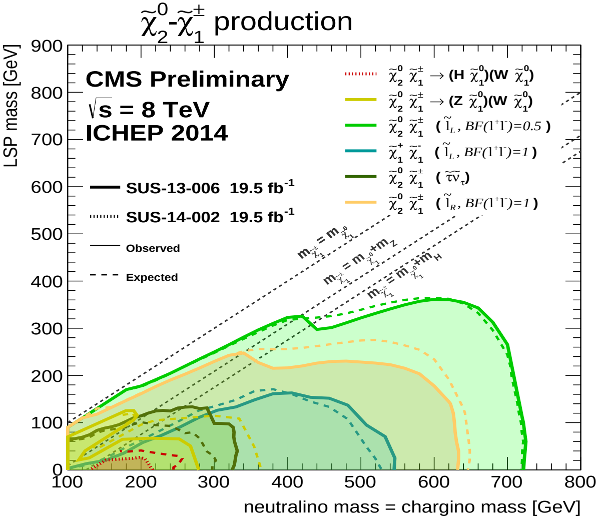
Results - Combined Limits: Scenario 2

(CMS-SUS-14005)

- No excess above the SM background is observed.
- A combined observed upper bound limit of ≈ 300 GeV and an expected limit on ≈ 310 GeV is set, for the compressed mass spectra scenario.
- We do not have sensitivity to exclude any masses in the large mass gap scenario, for this slepton mass definition.



Latest Limits in the Electroweak SUSY Sector



Exo DM Search: Razor Variabels

(CMS-EXO-14004)

- The analysis search for events with at least two jets and sizeable E_T^{miss}.
- The razor variables are defined as:

$$M_R = \sqrt{(|\vec{p}_{J1}| + |\vec{p}_{J1}|)^2 - (p_Z^{J_1} + p_Z^{J_2})^2}$$

$$R = \frac{M_T^R}{M^R} \text{ where } M_T^R \text{ is defined as:}$$

$$M_T^R = \sqrt{\frac{E_T^{miss}(p_T^{J_1} + p_T^{J_2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{J_1} + \vec{p}_T^{J_2})}{2}}$$

- Sensitivity comparable to monojet.

Exo DM Search: Razor Variabels

(CMS-EXO-14004)

- Study events with low values of M_R (unlike SUSY).
- Discrimination variables: R^2
- Dedicated trigger based in M_R & R^2.
- Event selection criteria:
  1. ≥ 1 high-quality vertex ($|z| < 24cm$).
  2. $p_T^{\mu} > 15$ GeV, $|\eta_\mu| < 2.4$
  3. $p_T^{e} > 15$ GeV, $|\eta_e| < 3.0$
  4. Leptons must be well isolated ($\Delta R < 0.3$)
  5. CVS b-jet algorithm (loose and tight).
  6. ≥ 2 jets with $p_T^j > 80$ GeV & $|\eta_j| < 2.4$
  7. Events forced into a dijet+E_T^{miss} topology, with 2 megajets (J).
  8. megajets are reco. with jets with $p_T^j > 40$ GeV & $|\eta_j| < 2.4$
  9. $|Df(J_1, J_2)| > 2.5$, $M_R > 200$ GeV & $R^2 > 0.5$

Event Categories
(CMS-EXO-14004)

- Events are classified in eight categories.

Sample	b-tagging selection	M_R selection
0μ, 1μ, and 2μ	no CSV loose jet	$200 < M_R \leq 300$ GeV (VL) $300 < M_R \leq 400$ GeV (L) $400 < M_R \leq 600$ GeV (H) $M_R > 600$ GeV (VH)
$0\mu bb$	≥ 2 CSV tight jets	$M_R > 200$ GeV
$0\mu b$	=1 CSV tight jets	
$1\mu b$	≥ 1 CSV tight jets	
$2\mu b$		
$Z(\mu\mu)b$	≥ 1 CSV loose jets	

- The 0μ, $0\mu b$ and $0\mu bb$ regions are searched for signal.
- The remaining regions are used as control samples.

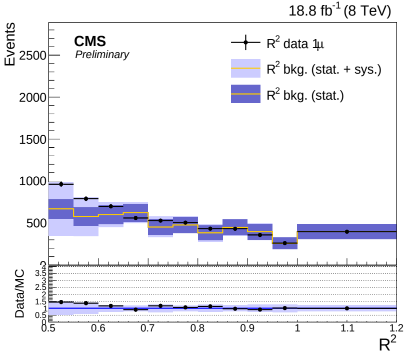
Background Prediction - 0μ

(CMS-EXO-14004)

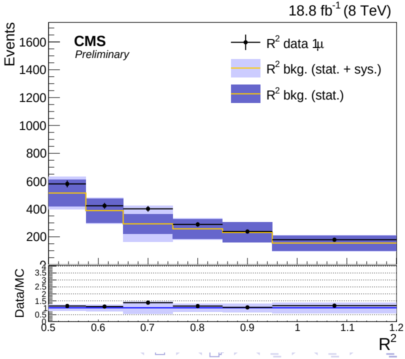
- 0μ samples: largest source of BGs result from $W + jets$ & $Z + jets$.
- 1μ samples are used to predict the $W + jets$ & $Z + jets$ contribution.

$$n_i^{0\mu} = (n_i^{1\mu} - N_i^{t\bar{t},1\mu} - N_i^{Z(\ell\ell)+jets,1\mu})\frac{N_i^{W+jets,0\mu} + N_i^{Z(\nu\bar{\nu})+jets,0\mu}}{N_i^{W+jets,1\mu}} + (n_i^{2\mu} - N_i^{t\bar{t},2\mu})\frac{N_i^{Z(\ell\ell)+jets,0\mu}}{N_i^{Z(\ell\ell)+jets,2\mu}}$$

Very Loose (VL) - M_R



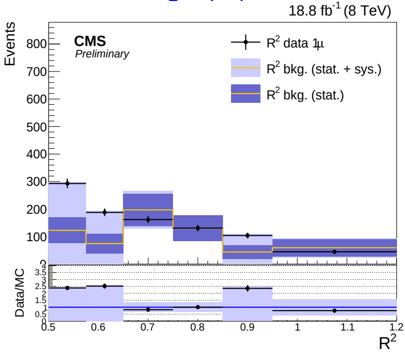
Loose (L) - M_R



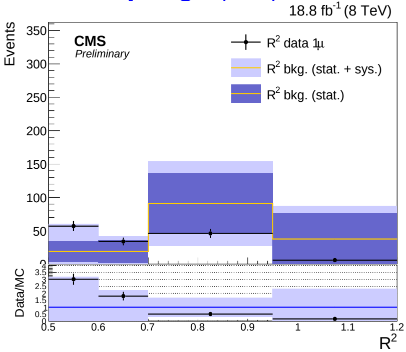
Background Prediction - 0μ

(CMS-EXO-14004)

High (H) - M_R



Very High (VH) - M_R



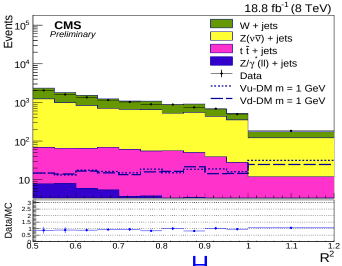
Observed & Predicted Yields

M_R category	$Z(\nu\bar{\nu})$+jets	$W(\ell\nu)$+jets	$Z(\ell\ell)$+jets	$t\bar{t}$	Predicted (simulation)	Predicted (data driven)	Observed
VL	6231 ± 37	4820 ± 33	49 ± 2	555 ± 7	11655 ± 50	12773 ± 899	11623
L	2416 ± 19	1513 ± 16	11 ± 1	104 ± 3	4044 ± 25	4165 ± 265	3785
H	1127 ± 7	625 ± 9	2.9 ± 0.3	24 ± 1	1778 ± 11	1654 ± 686	1559
VH	229 ± 2	103 ± 3	0.2 ± 0.1	3.1 ± 0.5	335 ± 4	243 ± 156	261

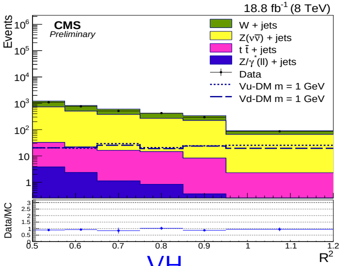
Signal Region - 0μ

(CMS-EXO-14004)

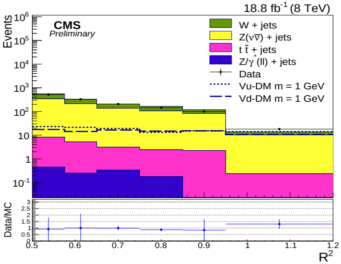
VL



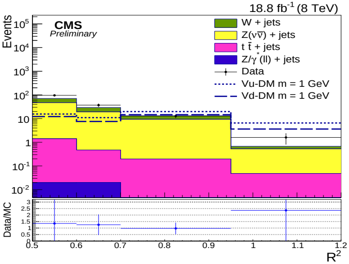
L



H



VH



Signal Region - $0\mu b$ & $0\mu bb$

(CMS-EXO-14004)

- Use similar data-driven technique to 0μ

$$n(t\bar{t})_i^{0\mu b} = \left(n(t\bar{t})_i^{2\mu b} - N_i^{Z(\ell\ell)+jets,2\mu b} - N_i^{W+jets,2\mu b}\right)\frac{N(t\bar{t})_i^{0\mu b}}{N(t\bar{t})_i^{2\mu b}}$$

- Background contribution from $W(\rightarrow \mu\nu)$+jets & $Z(\rightarrow \nu\bar{\nu})$+jets is predicted using the $Z(\rightarrow \mu\mu)b$ sample.
- Closure test: uses the $1\mu b$ sample.

Expected & Observed events in the 1μb sample

Sample category	$Z(\nu\bar{\nu})$+jets	$W(\ell\nu)$+jets	$Z(\ell\ell)$+jets	$t\bar{t}$	Predicted (simulation)	Predicted (data driven)	Observed
$Z(\mu\mu)$b	-	-	134 ± 3	17 ± 1	151 ± 3	-	175
1μb	0.2 ± 0.1	279 ± 7	11 ± 1	3038 ± 17	3328 ± 18	3405 ± 544	2920

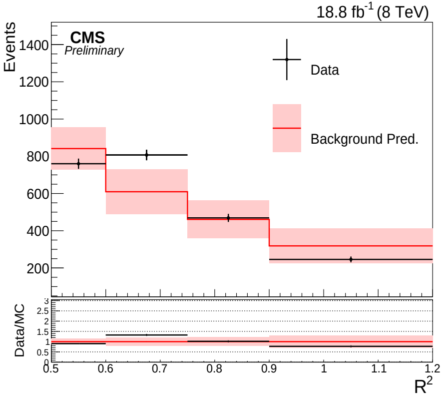
Expected & Observed events in the $0\mu b$ & $0\mu bb$ samples

Sample	$Z(\nu\bar{\nu})$+jets	$W(\ell\nu)$+jets	$Z(\ell\ell)$+jets	$t\bar{t}$	Predicted (simulation)	Predicted (data driven)	Observed
0μbb	44 ± 3	14 ± 2	0.2 ± 0.1	204 ± 4	262 ± 5	271 ± 37	247
0μb	417 ± 8	216 ± 7	2.4 ± 0.4	1480 ± 12	2116 ± 16	2231 ± 281	2282

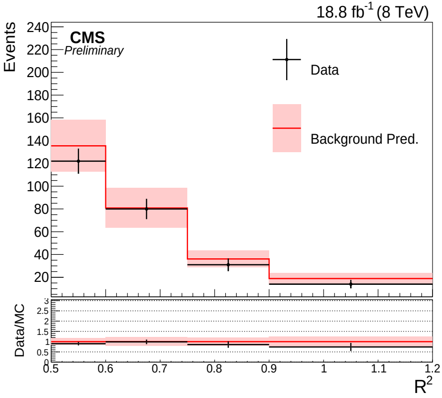
Signal Region - $0\mu b$ & $0\mu bb$

(CMS-EXO-14004)

0μ b



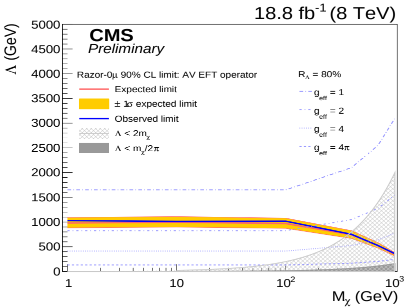
0μ bb

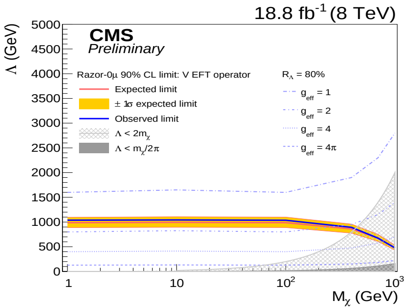


Results - 0μ
(CMS-EXO-14004)

- The result is interpreted in the context of a low-energy EFT: production of DM particles mediated by 6D and 7D operators.
- Operators generated assuming the existence of a heavy particle mediating the interaction between the DM and SM fields.
- Two benchmark scenarios considered:

$$\hat{\mathcal{O}}_V = \frac{1}{\Lambda^2}\left(\bar{\chi}\gamma_\mu\chi\right)\left(\bar{q}\gamma_\mu q\right) \; ; \quad \hat{\mathcal{O}}_A = \frac{1}{\Lambda^2}\left(\bar{\chi}\gamma_\mu\gamma_5\chi\right)\left(\bar{q}\gamma_\mu\gamma_5 q\right)$$



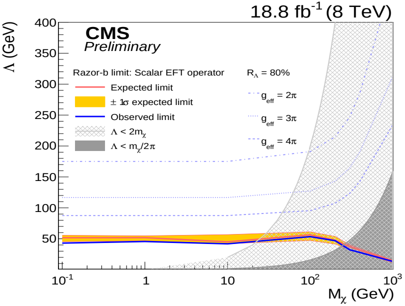


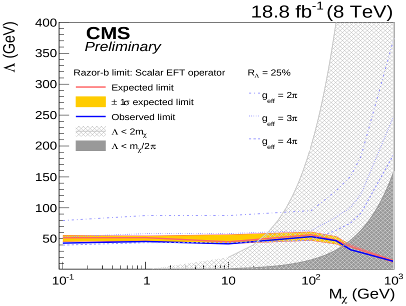
Results - $0\mu b$ & $0\mu bb$

(CMS-EXO-14004)

- Results are interpreted in a EFT scenario, considering a scalar operator:

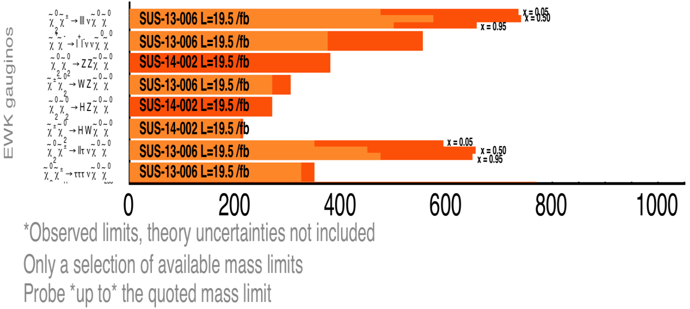
$$\hat{O}_S = \frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$$





Summary

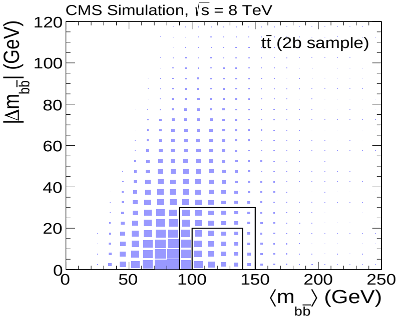
- Several new SUSY electroweak searches have been presented.
- There are some low-significance excesses in some channels, but no evidence of SUSY yet.
- Searches in Exo channels do not show evidence for DM yet.
- Stay tuned for the next run of the LHC!

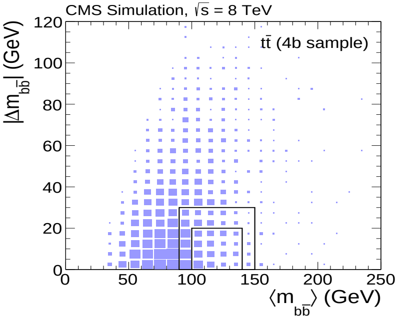


BACKUP

$(h \to b\bar{b})(h \to b\bar{b})$ BG Estimation

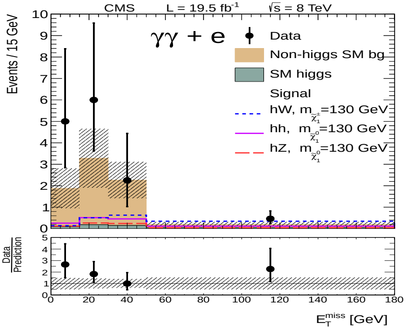
- ABDC method.

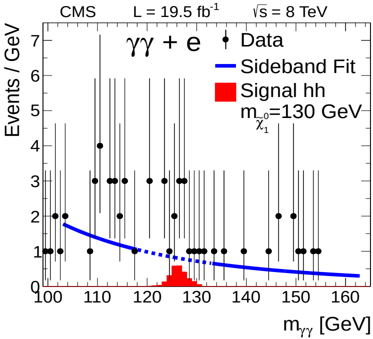




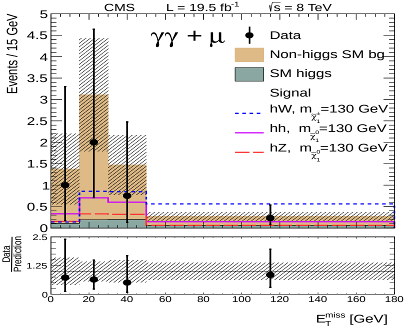
$(hh, hZ, hZ \to \gamma\gamma + \ell)$ Electron Channel

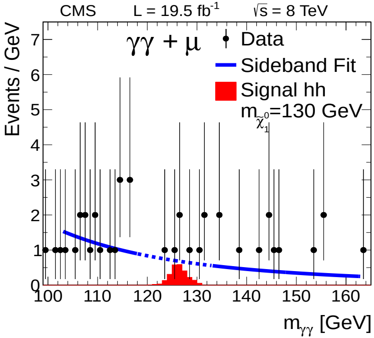
- 18 events in signal region vs 10.0 ± 2.3 from SM BG.
- Excess at low E_T^{miss}, therefore no signal-like.
- Toy MC studies of fit show that it's stable and unbiased with properly estimated errors.





$(hh, hZ, hZ \rightarrow \gamma\gamma + \ell) - \mu$ Channel



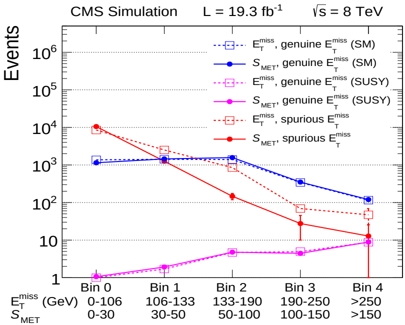


$(hh, hZ, hZ \to \gamma\gamma + \ell) - \mu$ Channel

- S_{MET}: χ^2 of the observed E_T^{miss} with the null (no true E_T^{miss}) hypothesis.
- Uses the covariant matrix for each reconstructed object in the E_T^{miss} sum:

$$U^i = \begin{pmatrix} \sigma^2_{E_{T_i}}, 0 \\ 0, E^2_{T_i}\sigma^2_{\phi_i} \end{pmatrix} \quad (1)$$

- For details on the E_T^{miss} significance: http://arxiv.org/pdf/1106.5048v1.pdf



- Distribution of simulated $t\bar{t}$ (genuine E_T^{miss} (SM)), signal (genuine E_T^{miss} (SUSY)), and QCD multijet (spurious E_T^{miss}) events using loosened selection criteria in bins of S_{MET} and E_T^{miss}.

Multilepton Excess

- Total of 64 channels, each with 3 E_T^{miss} bins, in ≥ 3 analysis (published in PRD [PRD 90, 032006 (2014)] - http://journals.aps.org/prd/abstract/10.1103/PhysRevD.90.032006).
- Excess seen in one channel, where:
  1. 4 leptons with one oposite sign electric charge, same flavor (OSSF) lepton pair and one hadronic tau decay candidate.
  2. $m_{\ell\ell}$ of the OSSF pair is not near the Z mass.
  3. No b-tagged jets.
  4. $H_T < 200$ GeV ($H_T = \sum p_T^{jets}$)
- Probability to observe 22 or more events with 10.1 ± 2.4 BG events expected is about 1%.
- Taking into account that there were 64 independent channels, the probability to observe one channel with such fluctuation is about 50 %.

$hZ \rightarrow b\bar{b}\ell_{e/\mu}\ell_{e/\mu}$

(CMS-SUS-14002 - PRD)

- Observed data consistent with BG prediction

	$E_T^{miss} < 25\,\text{GeV}$	$25 < E_T^{miss} < 50\,\text{GeV}$	$50 < E_T^{miss} < 60\,\text{GeV}$
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
	$E_T^{miss} > 60\,\text{GeV}$	$E_T^{miss} > 80\,\text{GeV}$	$E_T^{miss} > 100\,\text{GeV}$
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
hZ events			
$m_{\tilde{\chi}_1^0} = 130\,\text{GeV}$	5.4 ± 0.1	3.1 ± 0.1	1.7 ± 0.1
$m_{\tilde{\chi}_1^0} = 150\,\text{GeV}$	5.3 ± 0.1	3.3 ± 0.1	2.0 ± 0.1
$m_{\tilde{\chi}_1^0} = 200\,\text{GeV}$	4.7 ± 0.1	4.2 ± 0.1	3.3 ± 0.1
$m_{\tilde{\chi}_1^0} = 250\,\text{GeV}$	3.5 ± 0.1	3.2 ± 0.1	2.8 ± 0.1

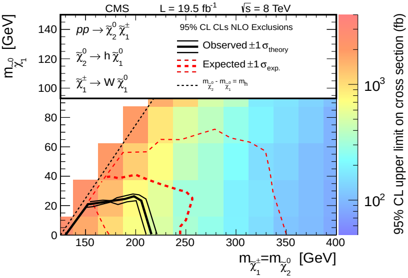
Multilepton Excess

≥4 leptons $H_T > 200$ GeV	$m_{\ell^+\ell^-}$	E_T^{miss} (GeV)	$N_{\tau_h}=0, N_b=0$ Obs.	Exp.	$N_{\tau_h}=1, N_b=0$ Obs.	Exp.	$N_{\tau_h}=0, N_b\geq 1$ Obs.	Exp.	$N_{\tau_h}=1, N_b\geq 1$ Obs.	Exp.
OSSF0	—	$(100,\infty)$	0	$0.01^{+0.03}_{-0.01}$	0	$0.01^{+0.06}_{-0.01}$	0	$0.02^{+0.04}_{-0.02}$	0	0.11 ± 0.08
OSSF0	—	$(50,100)$	0	$0.00^{+0.02}_{-0.00}$	0	$0.01^{+0.06}_{-0.01}$	0	$0.00^{+0.03}_{-0.00}$	0	0.12 ± 0.07
OSSF0	—	$(0,50)$	0	$0.00^{+0.02}_{-0.00}$	0	$0.07^{+0.10}_{-0.07}$	0	$0.00^{+0.02}_{-0.00}$	0	0.02 ± 0.02
OSSF1	Off-Z	$(100,\infty)$	0	$0.01^{+0.02}_{-0.01}$	1	0.25 ± 0.11	0	0.13 ± 0.08	0	0.12 ± 0.12
OSSF1	On-Z	$(100,\infty)$	1	0.10 ± 0.06	0	0.50 ± 0.27	0	0.42 ± 0.22	0	0.42 ± 0.19
OSSF1	Off-Z	$(50,100)$	0	0.07 ± 0.06	1	0.29 ± 0.13	0	0.04 ± 0.04	0	0.23 ± 0.13
OSSF1	On-Z	$(50,100)$	0	0.23 ± 0.11	1	0.70 ± 0.31	0	0.23 ± 0.13	1	0.34 ± 0.16
OSSF1	Off-Z	$(0,50)$	0	$0.02^{+0.03}_{-0.02}$	0	0.27 ± 0.12	0	$0.03^{+0.04}_{-0.03}$	0	0.31 ± 0.15
OSSF1	On-Z	$(0,50)$	0	0.20 ± 0.08	0	1.3 ± 0.5	0	0.06 ± 0.04	1	0.49 ± 0.19
OSSF2	Off-Z	$(100,\infty)$	0	$0.01^{+0.02}_{-0.01}$	—	—	0	$0.01^{+0.06}_{-0.01}$	—	—
OSSF2	On-Z	$(100,\infty)$	1	$0.15^{+0.16}_{-0.15}$	—	—	0	0.34 ± 0.18	—	—
OSSF2	Off-Z	$(50,100)$	0	0.03 ± 0.02	—	—	0	0.13 ± 0.09	—	—
OSSF2	On-Z	$(50,100)$	0	0.80 ± 0.40	—	—	0	0.36 ± 0.19	—	—
OSSF2	Off-Z	$(0,50)$	1	0.27 ± 0.13	—	—	0	0.08 ± 0.05	—	—
OSSF2	On-Z	$(0,50)$	5	7.4 ± 3.5	—	—	2	0.80 ± 0.40	—	—
≥4 leptons $H_T < 200$ GeV	$m_{\ell^+\ell^-}$	E_T^{miss} (GeV)	$N_{\tau_h}=0, N_b=0$ Obs.	Exp.	$N_{\tau_h}=1, N_b=0$ Obs.	Exp.	$N_{\tau_h}=0, N_b\geq 1$ Obs.	Exp.	$N_{\tau_h}=1, N_b\geq 1$ Obs.	Exp.
OSSF0	—	$(100,\infty)$	0	0.11 ± 0.08	0	0.17 ± 0.10	0	$0.03^{+0.04}_{-0.03}$	0	0.04 ± 0.04
OSSF0	—	$(50,100)$	0	$0.01^{+0.03}_{-0.01}$	2	0.70 ± 0.33	0	$0.00^{+0.02}_{-0.00}$	0	0.28 ± 0.16
OSSF0	—	$(0,50)$	0	$0.01^{+0.02}_{-0.01}$	1	0.7 ± 0.3	0	$0.00^{+0.02}_{-0.00}$	0	0.13 ± 0.08
OSSF1	Off-Z	$(100,\infty)$	0	0.06 ± 0.04	3	0.60 ± 0.24	0	$0.02^{+0.04}_{-0.02}$	0	0.32 ± 0.20
OSSF1	On-Z	$(100,\infty)$	1	0.50 ± 0.18	2	2.5 ± 0.5	1	0.38 ± 0.20	0	0.21 ± 0.10
OSSF1	Off-Z	$(50,100)$	0	0.18 ± 0.06	4	2.1 ± 0.5	0	0.16 ± 0.08	1	0.45 ± 0.24
OSSF1	On-Z	$(50,100)$	2	1.2 ± 0.3	9	9.6 ± 1.6	2	0.42 ± 0.23	0	0.50 ± 0.16
OSSF1	Off-Z	$(0,50)$	2	0.46 ± 0.18	15	7.5 ± 2.0	0	0.09 ± 0.06	0	0.70 ± 0.31
OSSF1	On-Z	$(0,50)$	4	3.0 ± 0.8	41	40 ± 10	1	0.31 ± 0.15	2	1.50 ± 0.47
OSSF2	Off-Z	$(100,\infty)$	0	0.04 ± 0.03	—	—	0	0.05 ± 0.04	—	—
OSSF2	On-Z	$(100,\infty)$	0	0.34 ± 0.15	—	—	0	0.46 ± 0.25	—	—
OSSF2	Off-Z	$(50,100)$	2	0.18 ± 0.13	—	—	0	$0.02^{+0.03}_{-0.02}$	—	—
OSSF2	On-Z	$(50,100)$	4	3.9 ± 2.5	—	—	0	0.50 ± 0.21	—	—
OSSF2	Off-Z	$(0,50)$	7	8.9 ± 2.4	—	—	1	0.23 ± 0.09	—	—
OSSF2	On-Z	$(0,50)$	*156	160 ± 34	—	—	4	2.9 ± 0.8	—	—

Electroweak

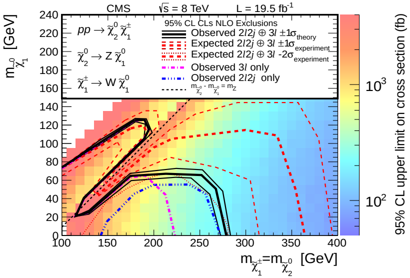
hW (CMS-SUS-14-002)

- $h \to \gamma\gamma$ channels added.
- Single lepton: $h \to b\bar{b}$, $W \to l\nu$
- Same-sign di-lepton: $h \to WW$ $W \to l\nu$
- Multilepton: $h \to WW/ZZ/\tau\tau$ $W \to l\nu$



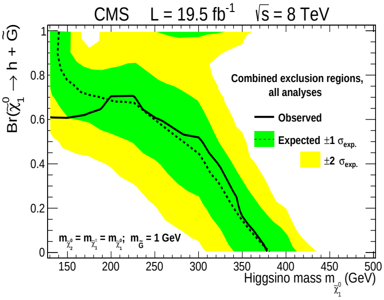
ZW (CMS-SUS-13-006)

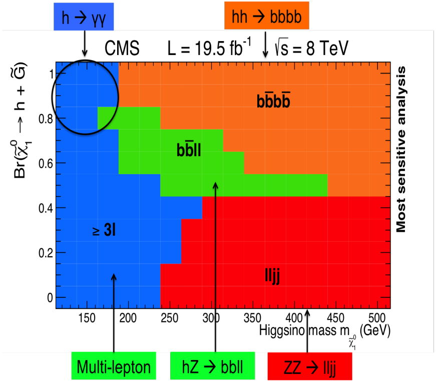
- $h \to \gamma\gamma$ channels added.
- $Z + jj$: $Z \to ll$ $W \to jj$
- Multilepton: $Z \to ll$ $W \to l\nu$
- Combination is also shown.



hh and hZ GMSB Higgsino Interpretation

2D Exclusion Region and Analysis Sensitivity





Multilepton Excess

- Signal MC generation: MadGraph 5.1.5.4
- Up to 2 ISR partons allowed.
- Detector response from fast simulation, excess $h \rightarrow b\bar{b}h \rightarrow b\bar{b}$ which uses Geant4.
- Cross sections NLO+NLL for GMSB hh, hZ, ZZ.
- For GMSB, the two lightest neutralinos and lightest chargino are pure higgsinos and mass degenerate.
  - ✓ Any SM particle from $\tilde{\chi}_0^2$ and $\tilde{\chi}_1^{\pm}$ are assumed too soft to be detected.
- Decays of GMSB NLSP use pure phase-space matrix elements.