Searches for electroweak SUSY in ATLAS and CMS

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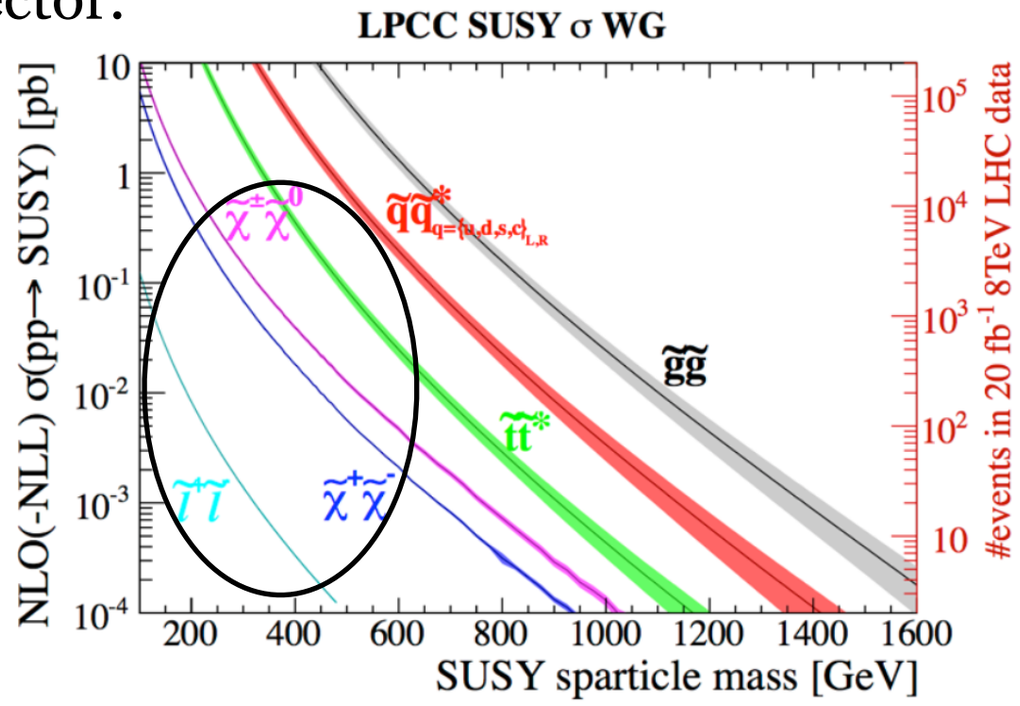
SUSY @ LHC

- Discovery of Higgs boson completes the Standard Model (SM).
- BUT still many open questions!!!

  Hierarchy problem , Dark Matter , Gravity, No gauge unification at higher scale.
- SuperSymmetry (SUSY) : very appealing extension of SM tries to answer these questions.
- Most of the SUSY searches focus on the colored sector.
- Limits of these models probe masses up to ~900 GeV (squarks) and ~1.4 TeV (gluinos).
- SUSY searches in the EWK sector provide a promising approach for new physics.

  low production cross-section but low hadronic activity.
- Experimental Parameters :

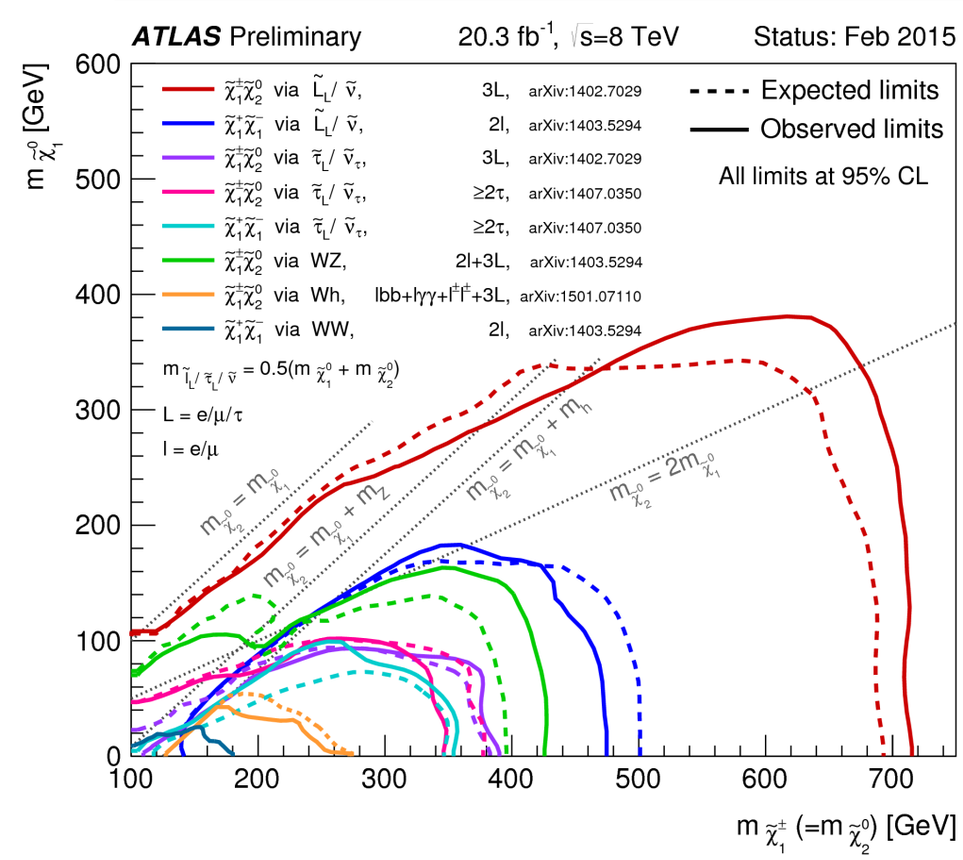
  1 -4 leptons , missing transverse energy (E_T^{miss}), 0-2 jets (or b-jets)



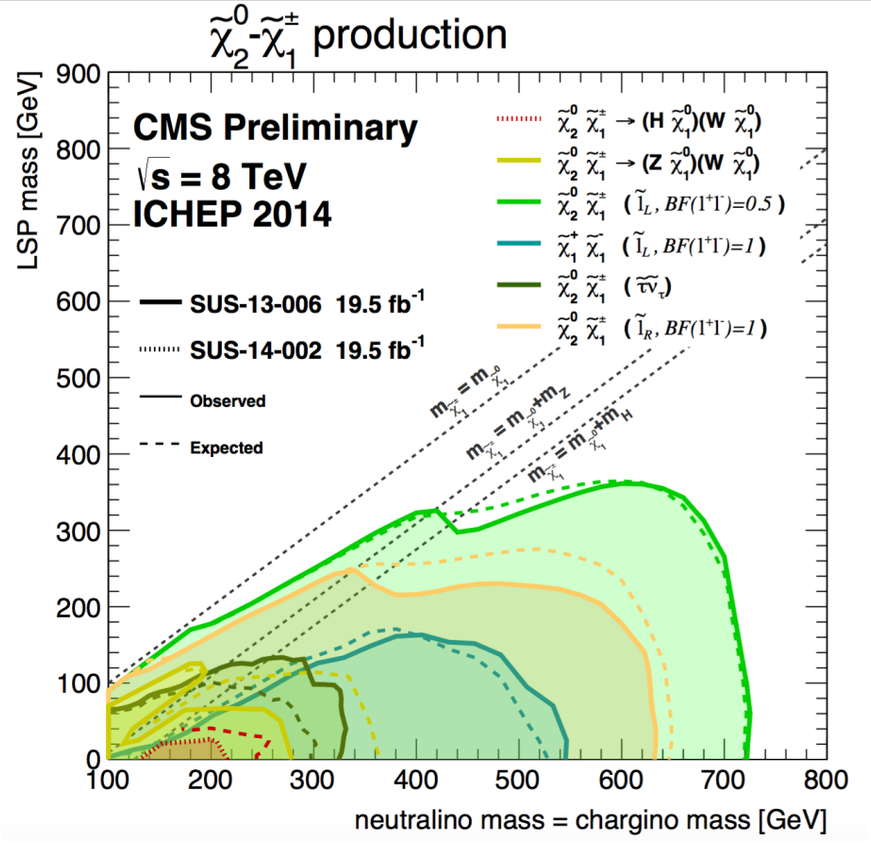
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections

arXiv:1206.2892

Electroweak SUSY Searches



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

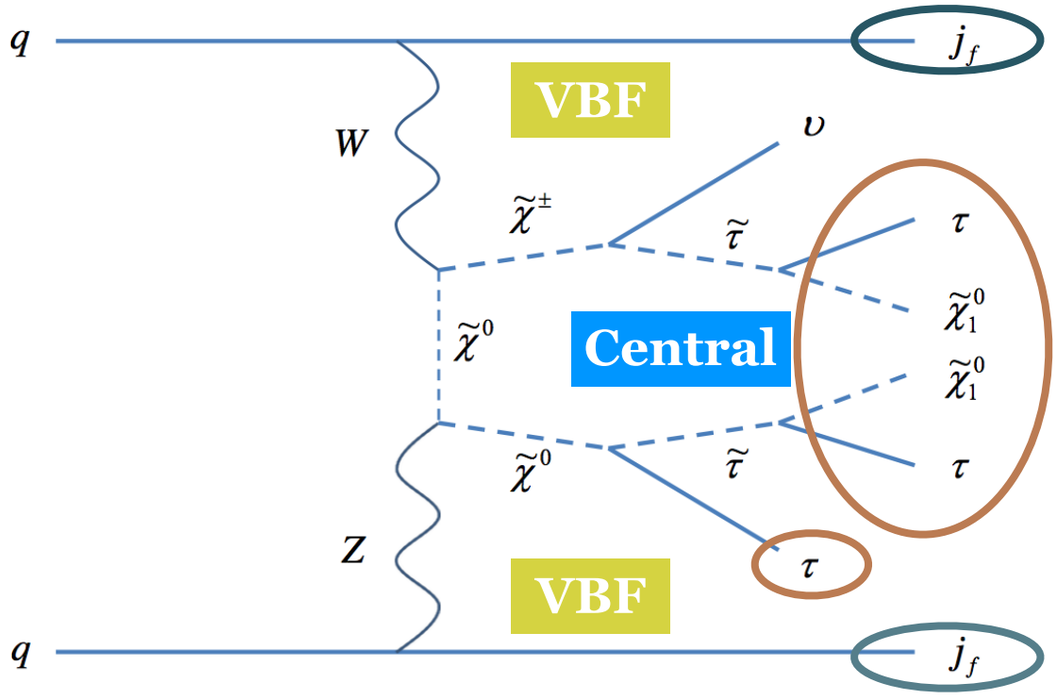
- Limits on chargino mass up to ~700 GeV.
- Lower Limits for higgsino and compressed mass spectra.

Selected Topics are:

- Searches via Vector Boson Fusion processes (CMS PAS SUS-14-005, ATLAS-CONF-2015-001)
- Searches through Higgs boson (CMS SUS-14-002 - PRD, ATLAS paper Eur. Phys. J. C (2015) 75:208)

Searches via VBF process with ≥ 2 leptons

CMS PAS SUS-14-005



- Experimental signature: forward jets, ≥ 2 leptons, E_T^{miss}.
- 8 channels are studied: eμjj, μμjj, μ$\tau_h$jj , $\tau_h\tau_h$jj (opposite sign and same sign leptons).
- Single muon triggers and di-τ_h triggers are used for this study.

- VBF topology provides a complementary probe to look for compressed spectra.
- 2 highly energetic jets with large dijet invariant mass and large pseudorapadity gap is powerful handle against SM backgrounds (reduction in rate by ~10^{-2} - 10^{-4}).
- tau-dominated region Br($\tilde{\chi}_1^{\pm} \rightarrow \tilde{\tau}$) ~ 1.

Analysis Strategy

Central Selections :
- 2 isolated leptons with |η| < 2.1, dR(l1,l2) > 0.3
- E_T^{miss} > 75 GeV (> 30 GeV for di - τ_h final state)
- no b-jets.

VBF Selections :
- ≥2 jets with p_T > 30 GeV "Loose" (or 50 GeV "Tight") with |η| < 5.0
- |Δη(j,j)| > 4.2 , η1*η2 < 0
- m_{jj} > 250 GeV (shape based analysis)

Background (BG) Estimation

- Main BG: ttbar, W/Z+jets, VV, QCD multijets
- BG in Signal Region are estimated from data using :

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

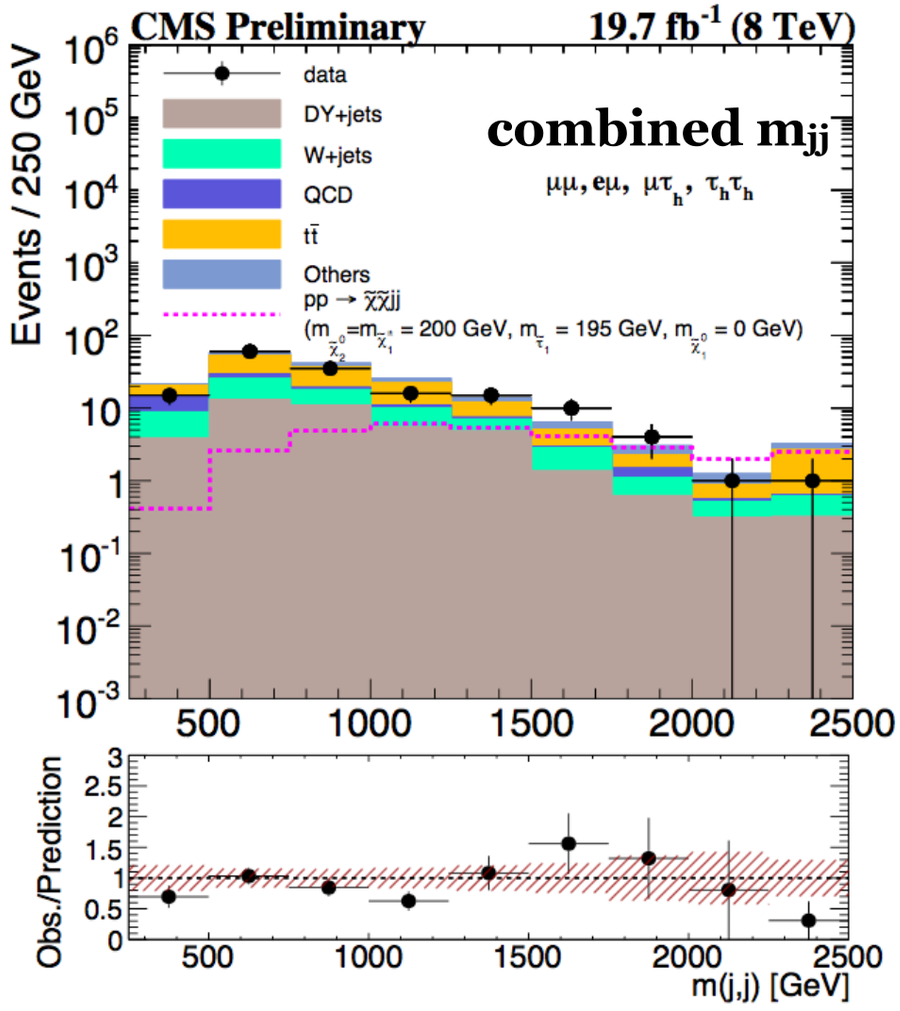
- Control region (CR) should not bias m_{jj} distributions.
- VBF efficiency is measured in CR after central selections.
- VBF efficiency is independent of E_T^{miss} cut within uncertainty.

Event rate in Signal region (for LS search channels)

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	$0^{+1.7}_{-0}$	0.5 ± 0.2	< 0.01
W + jets	$0.1 \pm 8.2 \times 10^{-4}$	$0^{+3.0}_{-0}$	9.3 ± 2.3	0.5 ± 0.1
VV	2.1 ± 0.3	$1.9^{+0.4}_{-0.2}$	1.1 ± 0.2	$0.1 \pm 6.5 \times 10^{-2}$
$t\bar{t}$	3.1 ± 0.1	$3.5^{+0.7}_{-0.9}$	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	$5.4^{+3.5}_{-0.9}$	17.6 ± 3.8	8.4 ± 0.9
Observed	4	5	14	9

for OS search channels

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	$3.7^{+2.1}_{-1.9}$	19.9 ± 2.9	12.3 ± 4.4
W + jets	< 0.01	$4.2^{+3.3}_{-2.5}$	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	$19.0^{+2.3}_{-2.4}$	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	$31.1^{+4.6}_{-4.1}$	51.8 ± 5.1	22.9 ± 5.1
Observed	31	22	41	31



no excess over SM prediction

Two scenarios for slepton mass

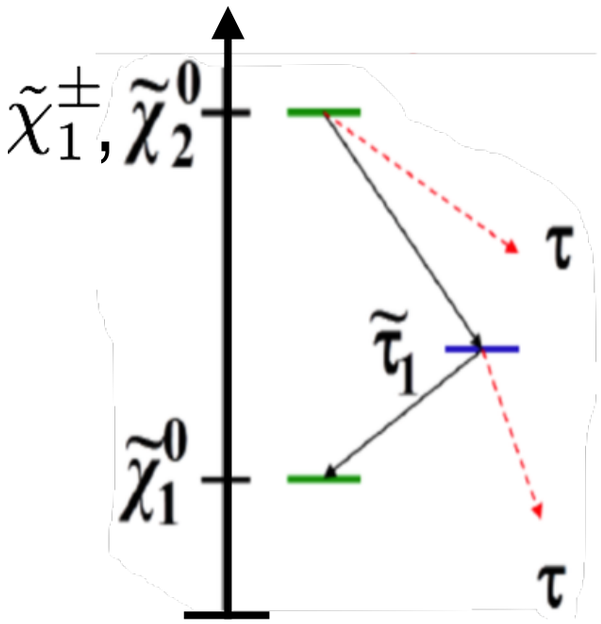
total 4 scenarios = 2 stau mass X 2 LSP mass scenarios

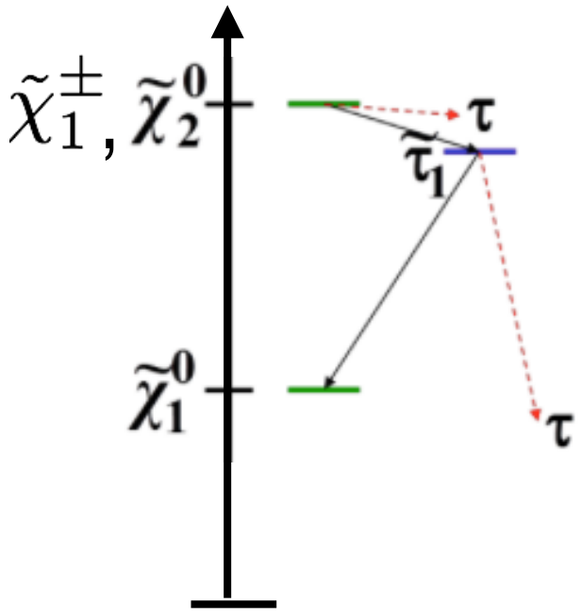
Scenario 1

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

Scenario 2

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

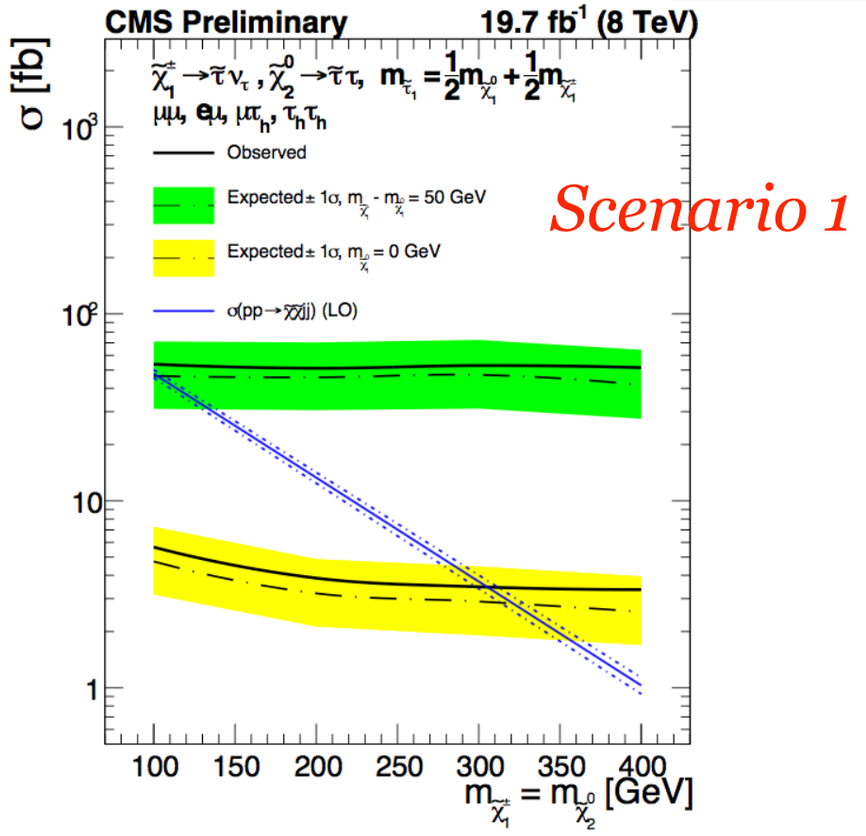




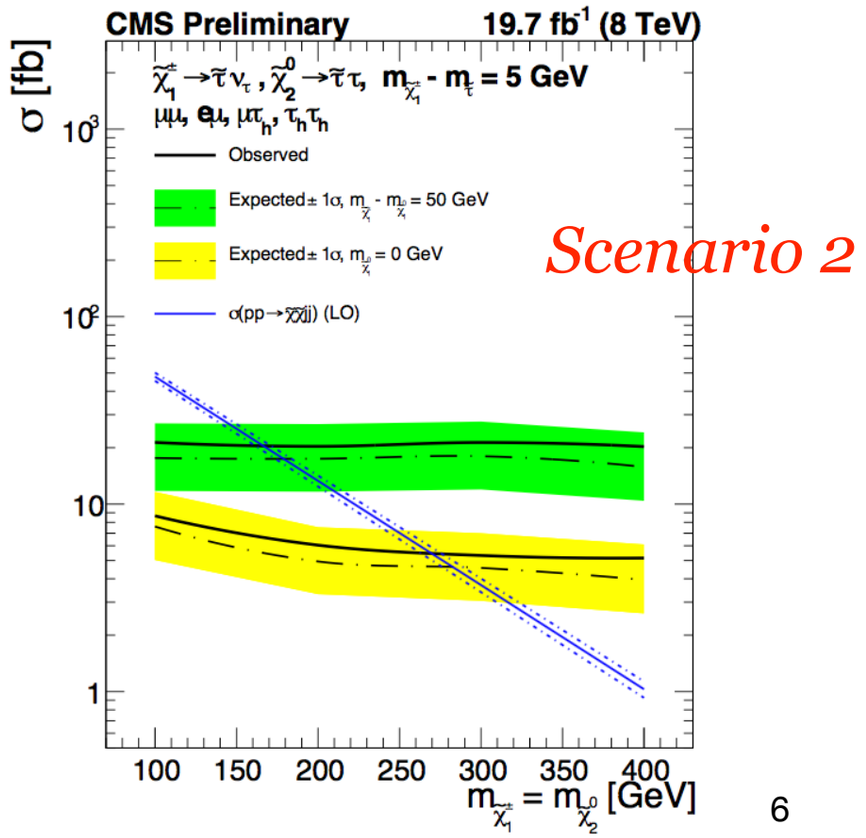
2 scenarios for each slepton mass

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

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



Scenario 1

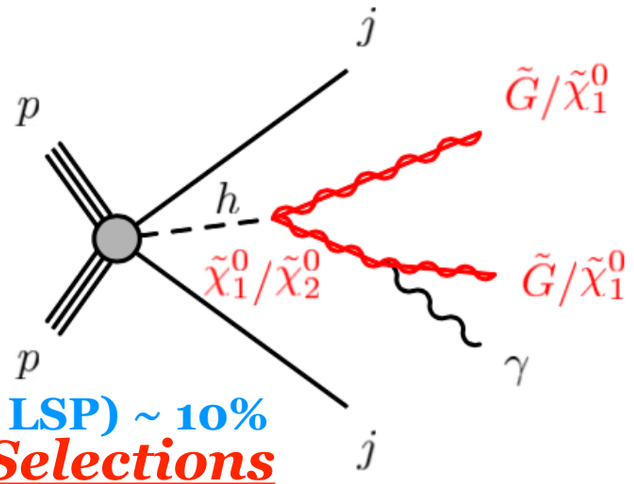


Scenario 2

- Scenario1 : combined observed limit of 300 GeV (expected at 310 GeV) for large mass gap scenarios.
- Scenario2 : combined observed limit of 280 GeV/170 GeV (expected at 285 GeV/180 GeV) for large gap/compressed mass scenarios.

Searches via exotic higgs decaying to γ(γγ)+ LSP

ATLAS-CONF-2015-001



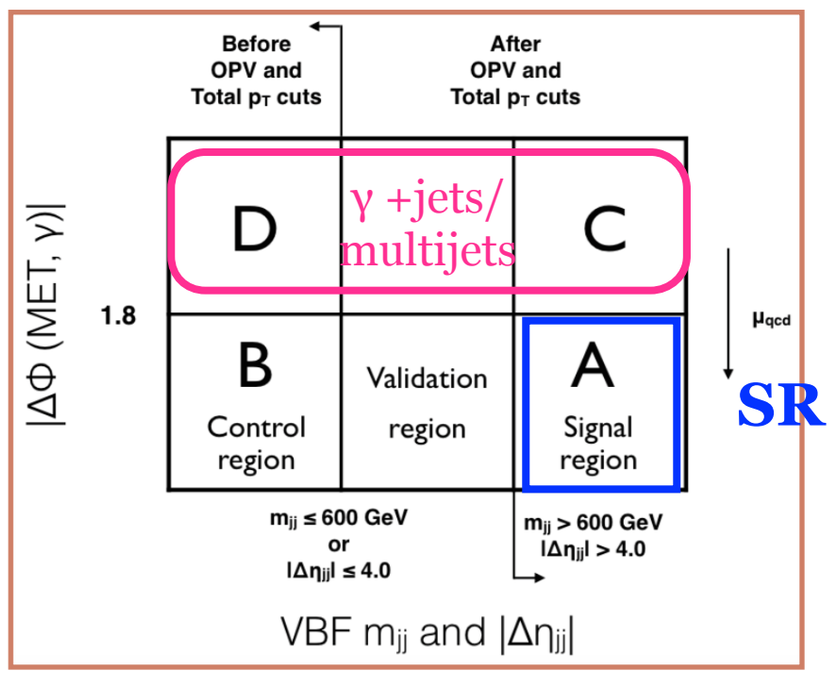
BF (h → NLSP + LSP) ~ 10%

- GMSB models predicts h decays to LSP($m_h/2 < m_{\tilde{\chi}_1^0} < m_h$)
- NMSSM models also predicts such decays.
- Higgs is more boosted in transverse plane so decay products are close to each other
- BG: γ+jets,multijets,W/Z+γ, W/Z+jets, W(→eν), Others(WW,WZ,ZZ, ttbar)
- Most selection requirements were optimized using the Validation Region.
- γ+jets/multijets BG is estimated from data, using an "ABCD" method.
- Other BG taken from simulation and normalized to data in dedicated CR.

Signal Selections

Requirement	Data	(m_{NLSP}, m_{LSP}) = (100, 0) GeV signal
Data quality and trigger	1.53×10^7	337±4
Good vertex	1.53×10^7	336±4
$E_T^{miss} > 50$ GeV	1.26×10^7	279±3
Selected photon $p_T > 40$ GeV	7.41×10^5	128±2
VBF m_{jj} >400 GeV and $\|\Delta\eta_{jj}\|$ >3.0	3.17×10^4	96.4±1.9
VBF jet $p_T \geq 40$ GeV	6870	58.0±1.5
Lepton veto	6040	57.2±1.5
≤ 1 non-VBF jet	4620	50.4±1.4
$\|\Delta\phi(E_T^{miss}, VBF\,jet)\|_{min} > 1.4$	600	30.1±1.1
$\|\Delta\phi(E_T^{miss}, non-VBF\,jet)\|_{min} < 2.0$	565	28.2±1.0
OPV	425	27.6±1.0
$\|\vec{p}_T^{\,TOT}\| \geq 50$ GeV	337	26.9±1.0
$\|\Delta\phi(E_T^{miss}, \gamma)\| \leq 1.8$	100	21.6±0.9
VBF m_{jj} >600 GeV and $\|\Delta\eta_{jj}\|$ >4.0	50	14.6±0.7

BG Estimation Strategy



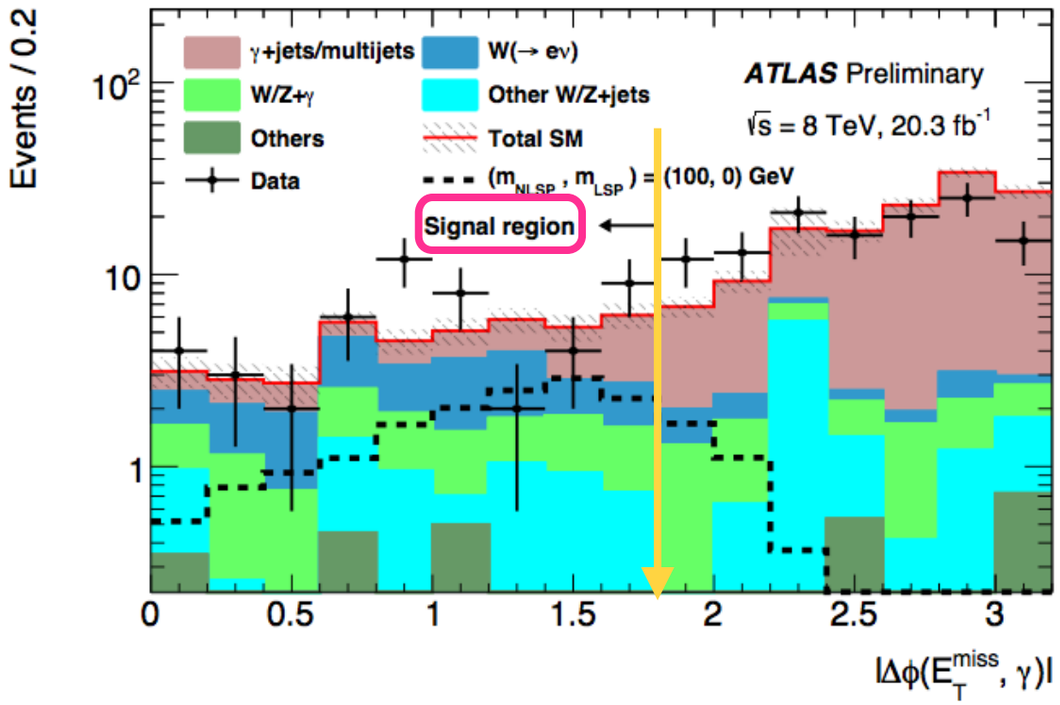
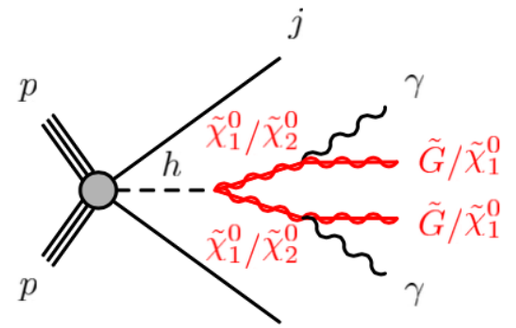


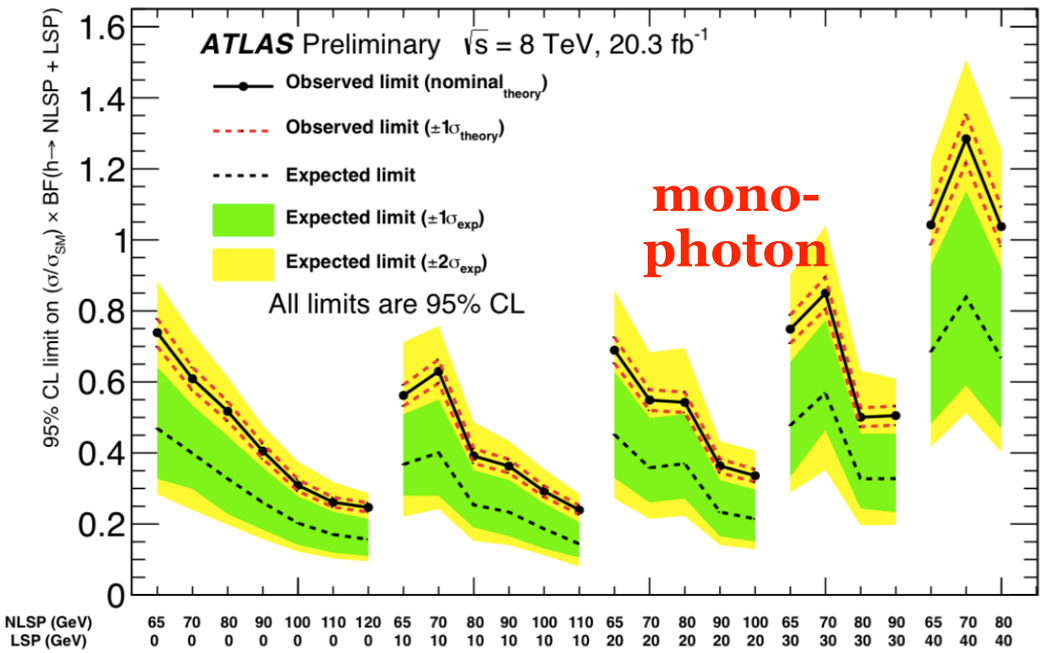
Table showing BG yield and Data in SR and BG control regions

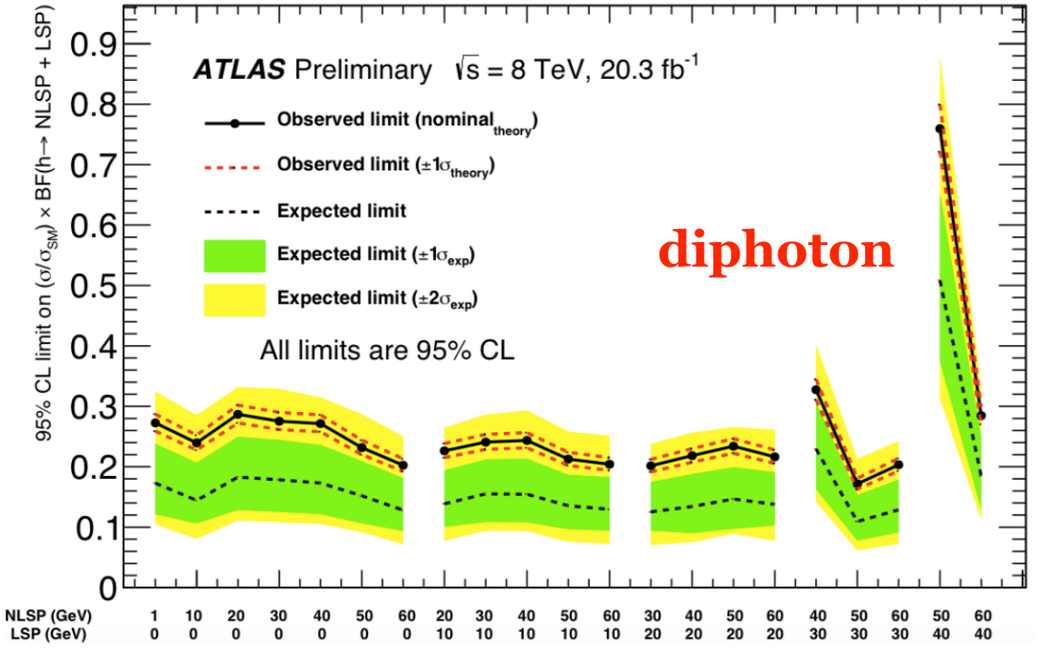
	SR	Region B	γ+jets A	e A	$l\nu\gamma$ A
$W(\rightarrow e\nu)$	10.7 ± 0.7 ± 1.5	24.5 ± 1.0 ± 3.3	5.2 ± 0.4 ± 0.6	956 ± 53 ± 133	0.02 ± 0.01 ± 0.00
$W(\rightarrow \mu\nu)$	0.21 ± 0.1 ± 0.24	1.4 ± 1.3 ± 0.3	0.1 ± 0.06 ± 0.06	0	0.66 ± 0.17 ± 0.09
$W(\rightarrow \tau\nu)$	4.2 ± 0.8 ± 0.6	4.7 ± 2.6 ± 2.4	1.7 ± 0.6 ± 0.8	62 ± 3.4 ± 37	0.9 ± 0.5 ± 0.33
$W(\rightarrow l\nu)\gamma$	7.2 ± 0.5 ± 2.3	11.9 ± 0.6 ± 4.1	3.6 ± 0.3 ± 1.2	4.0 ± 0.3 ± 0.2	6.0 ± 0.4 ± 0.4
Z+jets	0.52 ± 0.28 ± 0.54	3.7 ± 3.5 ± 3.5	0	12.3 ± 7.1 ± 2.9	0
$Z+\gamma$	0.61 ± 0.05 ± 0.2	2.6 ± 1.4 ± 1.4	1.1 ± 0.8 ± 0.8	0	0.37 ± 0.37 ± 0.09
Others	0.68 ± 0.4 ± 0.26	2.6 ± 0.8 ± 0.6	0.8 ± 0.4 ± 0.6	99.8 ± 5.1 ± 4.0	2.0 ± 0.7 ± 0.8
γ+jets and multijet	13.9 ± 1.7 ± 3.5	26.6 ± 2.2 ± 0.8	31.5 ± 6.7 ± 2.0	37 ± 11 ± 36	0
Total background	38.0 ± 2.2 ± 4.5	78 ± 5.4 ± 7	44 ± 6.8 ± 2.8	1170 ± 55 ± 143	10.0 ± 1 ± 0.9
Data	50	78	44	1079	12
(m_{NLSP}, m_{LSP}) (100, 0) GeV	14.6 ± 0.7 ± 1.2	8.5 ± 0.6 ± 0.6	3.0 ± 0.3 ± 0.5	0.3 ± 0.1 ± 0.1	0.11 ± 0.06 ± 0.07

1.1 σ excess is observed



- Due to excess in SR, observed limits are higher than expected ones.
- Strong upper limits are obtained in γγ+ E_T^{miss} final state also.





CMS ZH(→ γ(γγ) + MET) result shows no excess with BR (H → NLSP + LSP) = 100%

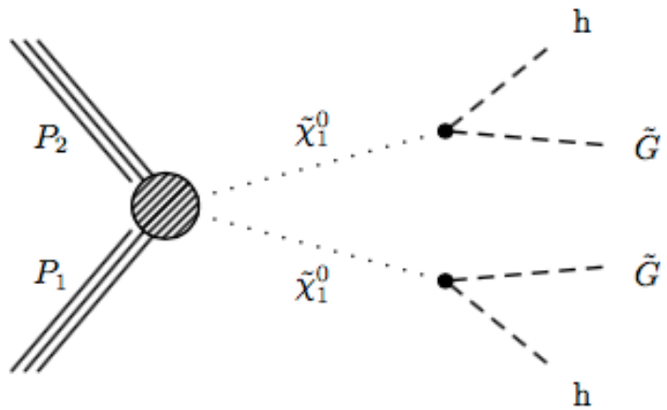
← **CMS PAS HIG-14-025**

Searches via Higgs tagging: hh,hZ,ZZ topologies

CMS SUS-14-002 - PRD

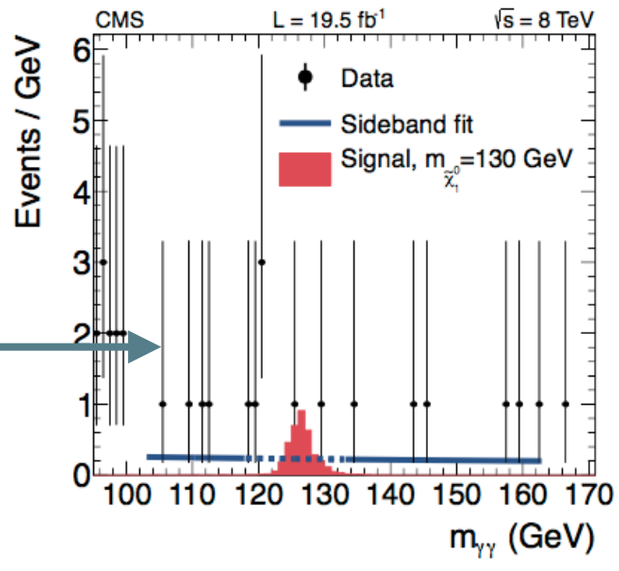
1. R-parity conserving gauge-mediated SUSY-breaking model (GMSB).
2. nearly mass degenerate $\tilde{\chi}_1^0, \tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ (higgsinos), Gravitino as LSP.
3. hh,hZ, ZZ searches with
   - h(→bb̄) h(→bb̄), h(→bb̄) h(→ γγ), h(→ γγ) h(→ ZZ/WW/$\tau\tau$) with atleast one e or μ.
   - h(→ γγ) Z(→2 jets), h(→ γγ) Z(→ee/$\mu\mu$/$\tau\tau$), h(→bb̄) Z(→ee/$\mu\mu$).
   - ZZ (to multileptons) , ZZ → l^+l^- + 2jets.

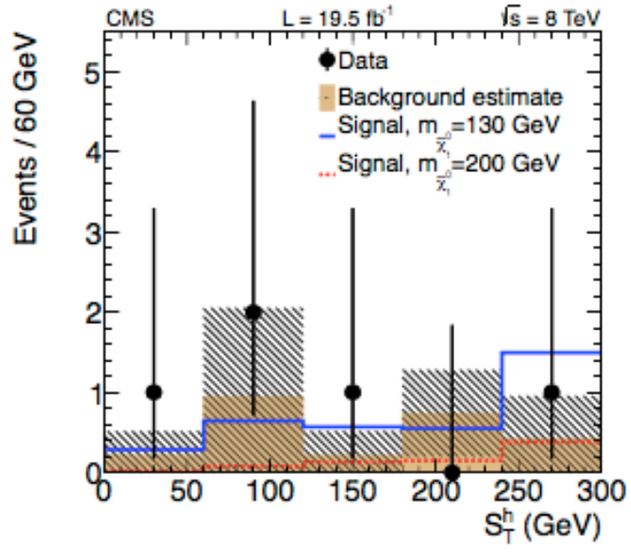
hh topology



h(→bb̄) h(→γγ)

- exactly 2 b-jets with 95< $m_{b\bar{b}}$ < 155 GeV.
- 2 γ's with 120 < $m_{\gamma\gamma}$ < 131 GeV
- no identified, isolated lepton.
- non-h BG estimated by fitting $m_{\gamma\gamma}$ distribution in SideBands (SB).





"Discriminating Variable"

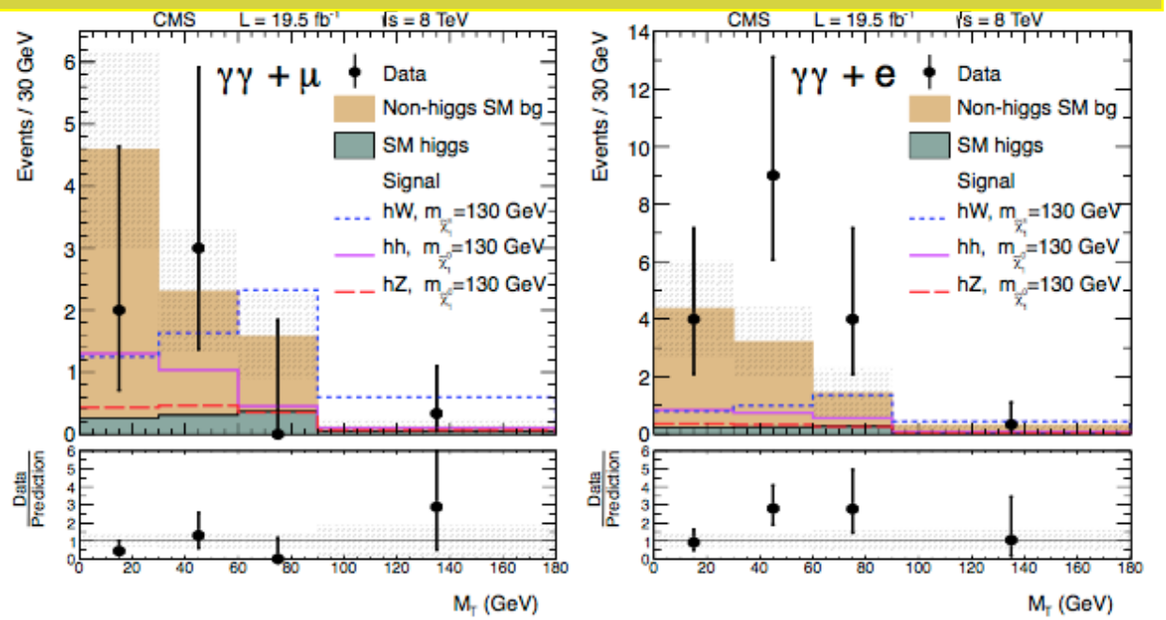
$$S_T^h = p_T^{h\to\gamma\gamma} + p_T^{h\to b\bar{b}}$$

no excess over SM prediction

hh (WW/ZZ/$\tau\tau$) , hZ , hW → γγ + l± (e,μ)

- ≥ 1μ or 1 e with p_T > 15 GeV.
- γ's with 120 < $m_{\gamma\gamma}$ < 131 GeV.
- rejects e faking γ by vetoing near m_Z (86-96) GeV.

excess in e+ γγ final state (~ 2.1 σ)
(events clustered at low E_T^{miss})
Combined excess (1.3σ) , considered consistent within statistical fluctuations.



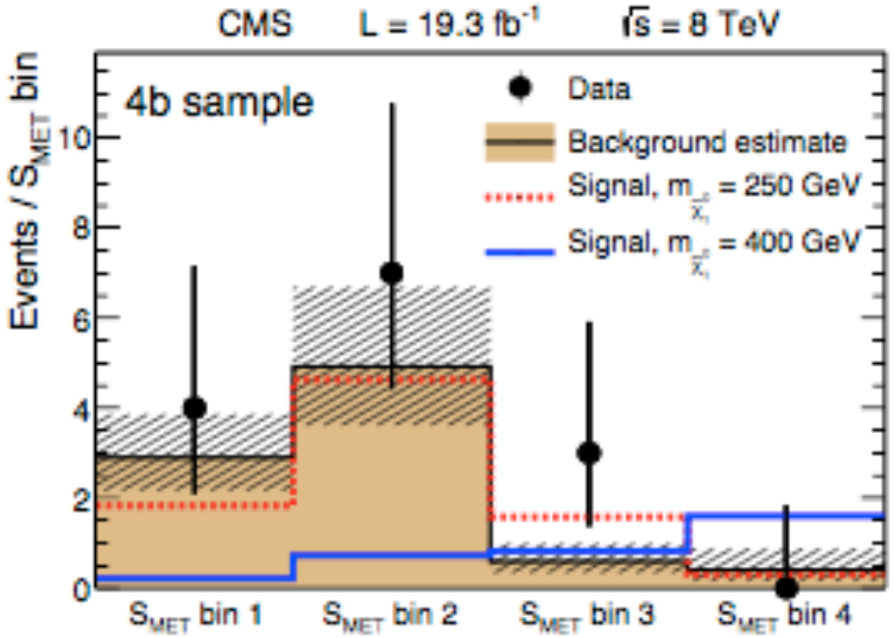
☑ Combined Observed Events : 24
☑ Combined SM prediction : 18.9± 3.1

h(→bb̄) h(→bb̄)

3 regions defined having exactly 2, 3 , and 4 b-jets.

Signal Region (SIG)
- 3 or 4 b-jets having $|\Delta m_{b\bar{b}}|$<20 GeV.
- max(ΔR(j,j)) < 2.2 and 100<⟨$m_{b\bar{b}}$⟩ < 140 GeV.
- E_T^{miss} significance S_{MET} > 30.

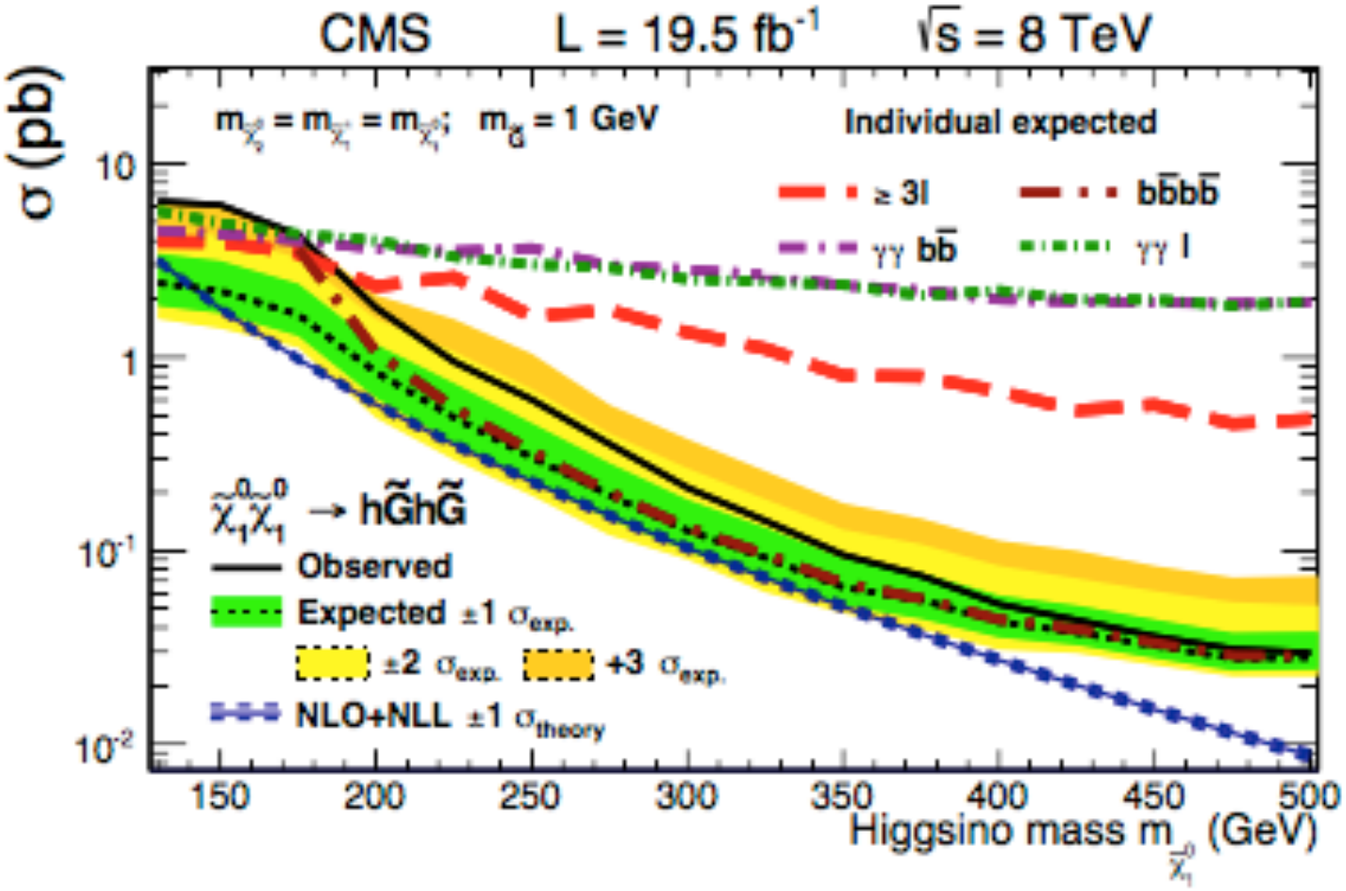
- SideBand (SB) : $|\Delta m_{b\bar{b}}|$<30 GeV , 90 <⟨$m_{b\bar{b}}$⟩ < 150 GeV.
- BG estimated from 2 b-jet region with ABCD/ matrix element method using fitted ratio of BG events in SIG and SB regions.



no significant excess observed over SM prediction

hh: GMSB interpretation

- Scenarios with Br($\tilde{\chi}_1^0 \rightarrow h\tilde{G}$) = 1.
- hh→bb̄bb̄ is more sensitive for masses above 200 GeV and loses sensitivity below 200 GeV (S_{MET} spectrum become SM-like) .
- Multi-leptons and γγ are more sensitive at low higgsino mass.



Searches via Higgs tagging: hW topologies

Eur. Phys. J. C (2015) 75:208

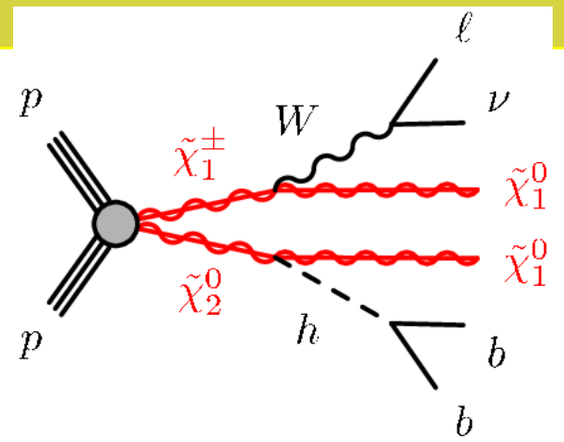
1. mass degenerate $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$ (pure wino) and $\tilde{\chi}_1^0$ LSP (bino).
2. prompt decays to W and h has ~100% branching ratios.
3. hW searches in h(→bb̄) W(→lν), h(→ γγ) W(→lν) , h(→ WW/ZZ,$\tau\tau$) W(→lν) final states.

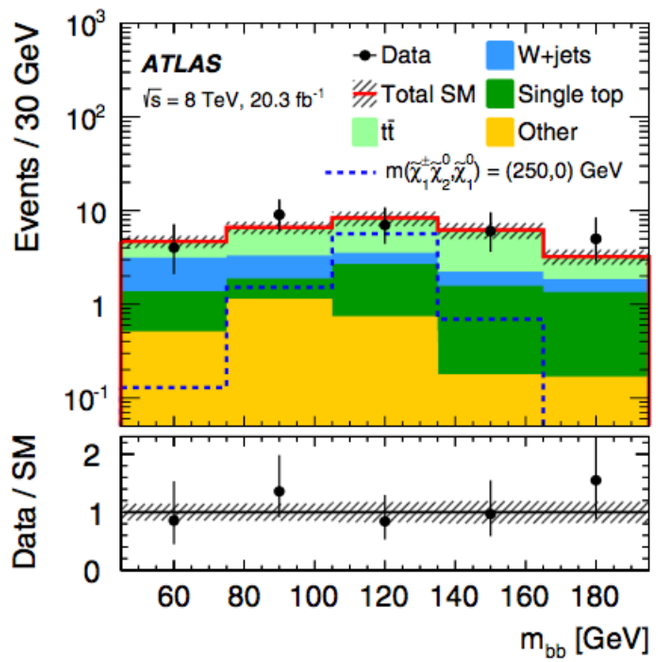
h(→bb̄) W(→lν)

- exactly 2 b-jets, 1 lepton.
- Discrimination variables : E_T^{miss} , m_{CT} , m_T^W.
- Signal is defined in 5 bins of $m_{bb̄}$ (47-75-**105-135**-165-185)
- ttbar and W+jets taken from simulation and normalized to data in dedicated CR .
- Multijet BG is estimated from data using Matrix Method **(arXiv:1403.5294)**.

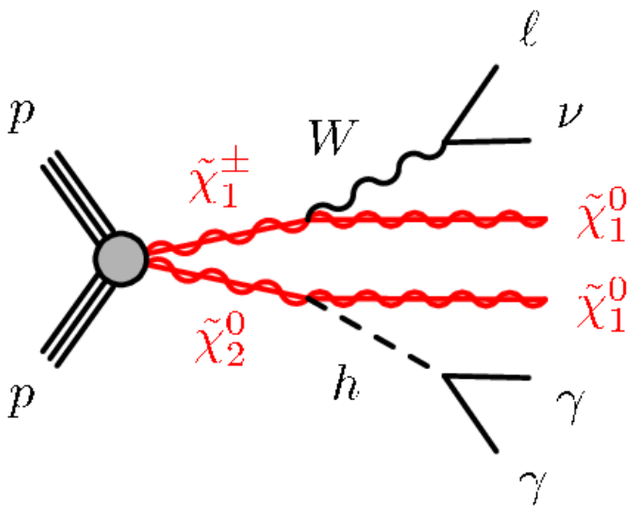
$$m_{CT} = \sqrt{(E_T^{b_1} + E_T^{b_2})^2 - |\mathbf{p}_T^{b_1} - \mathbf{p}_T^{b_2}|^2},$$

arXiv:0802.2879 [hep-ph]

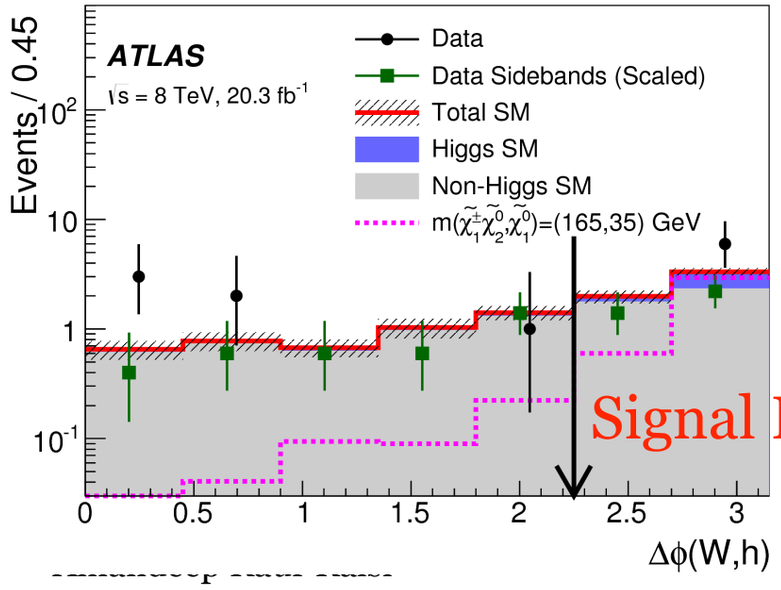




h(→ γγ) W(→lν)



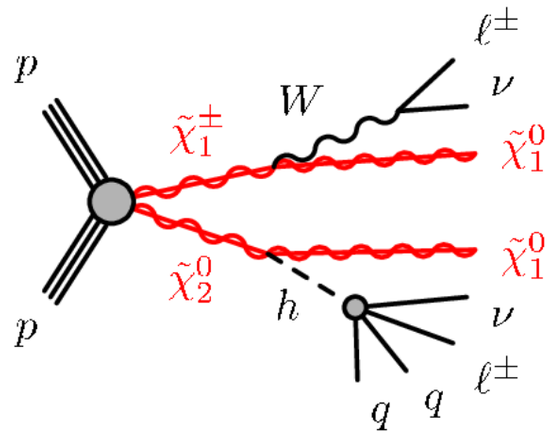
- Discriminating Variables: ΔΦ(W,h), $m_T^{W\gamma}$.
- contribution of non-h BG , modeled as exp(- α $m_{\gamma\gamma}$) ,is obtained from sidebands fitting $m_{\gamma\gamma}$ distribution (100-160) GeV excluding higgs window.
- SM processes with Higgs are estimated from simulation.



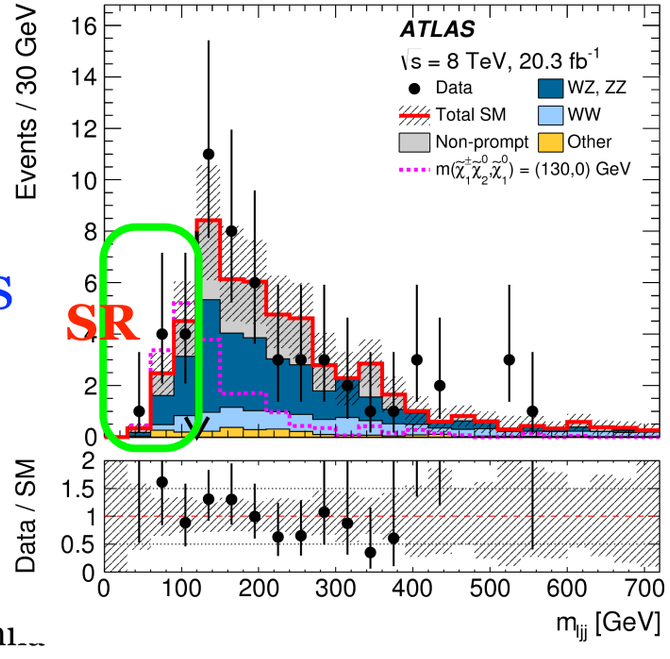
No significant excess over SM prediction

Signal Region

h(→ WW) W→ l±l±ν + jets



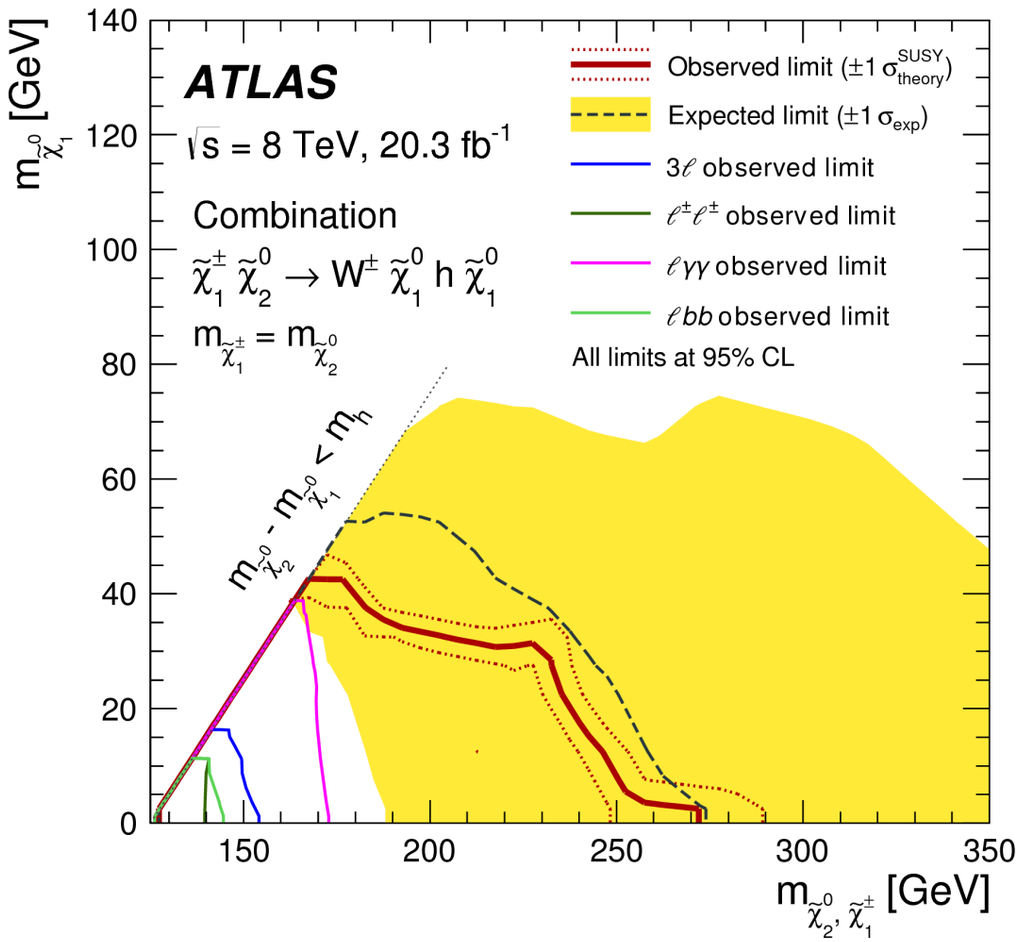
- 6 SR differing in lepton flavour(e/μ) and number of jets.
- Dominant background is from WZ and ZZ, which is estimated from MC simulation.
- Non-prompt leptons are estimated with the Matrix Method **(arXiv: 1403.5294)**.

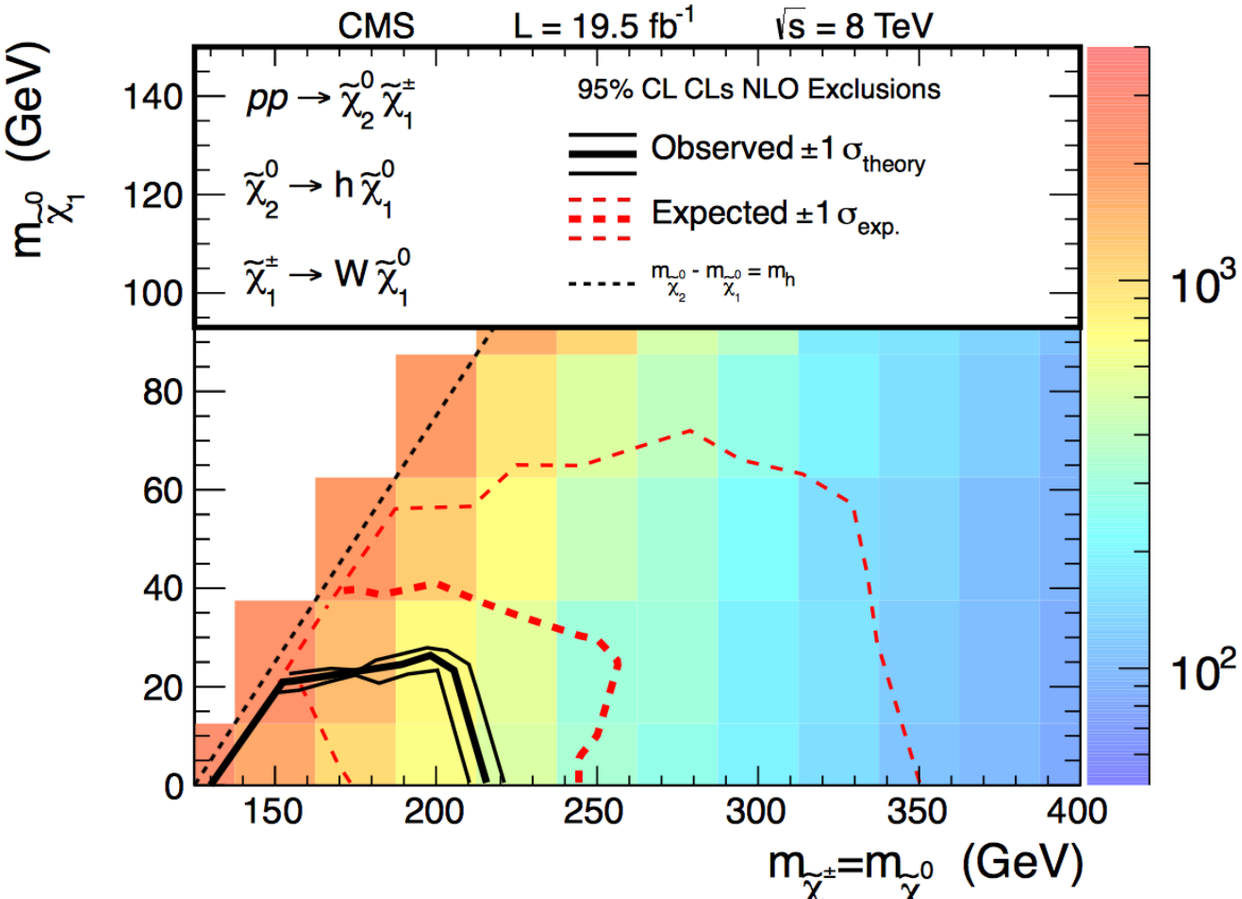


ll+2jet final state

Results and Interpretation

- Combined limit plot including ATLAS 3-lepton searches result. arXiv:1402.7029 - JHEP
- 95% CL exclusion region extends to 250 GeV for $m_{\tilde{\chi}_1^0} = 0$.





CMS SUS-14-002 - PRD

Similar Search from CMS collaboration, the observed limit is 210 GeV.

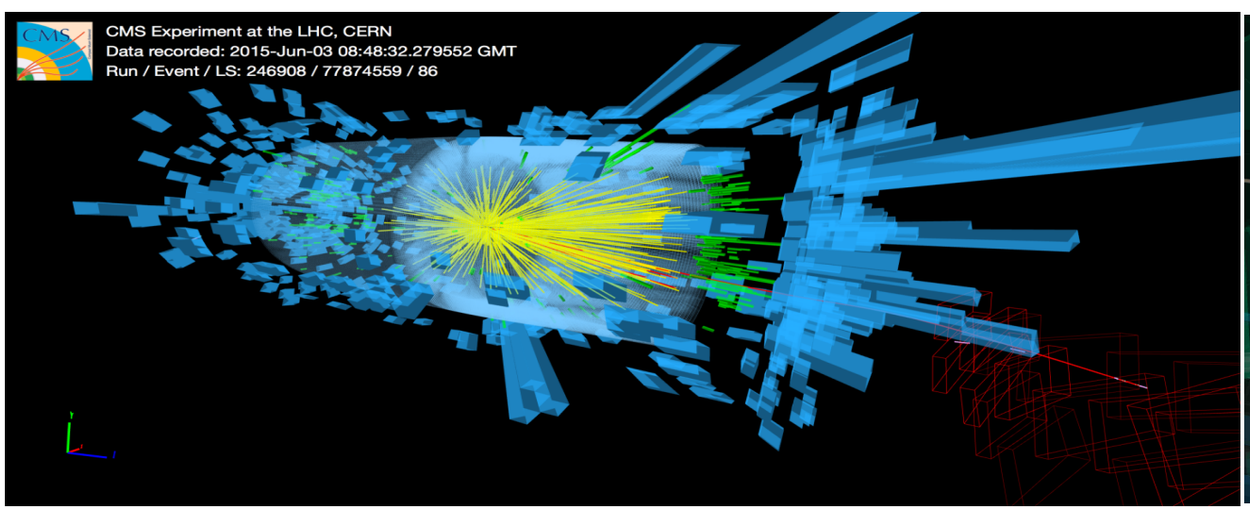
Summary

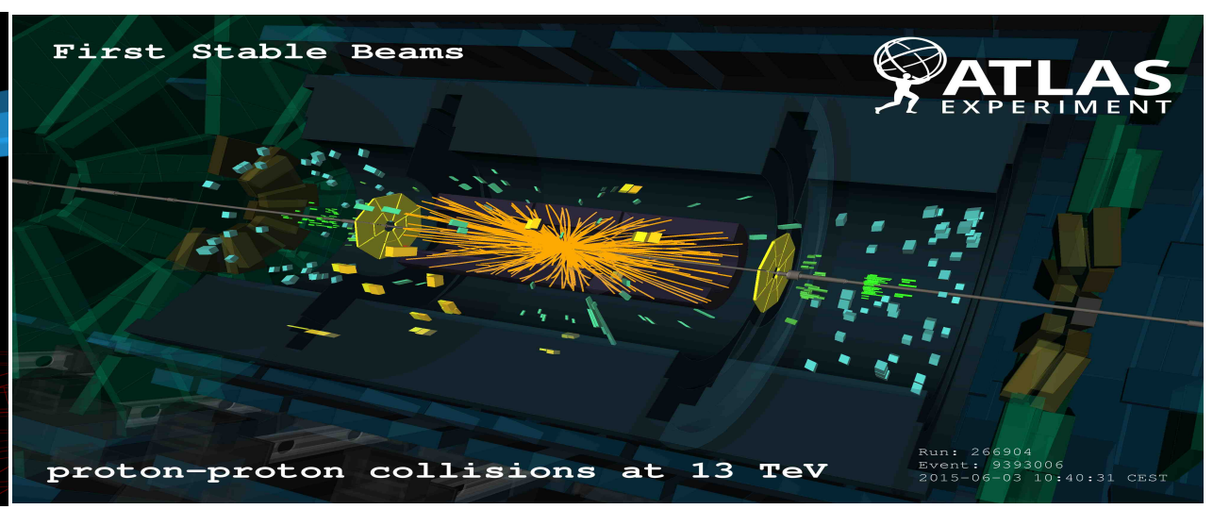
- ATLAS and CMS has variety of searches in EWK SUSY sector.

  CMS:https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

  ATLAS:https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
- Presented some of recent results from both experiments.
- Small excesses observed in some of channels (not significant yet).
- Limit on the chargino masses up to ~700 GeV.
- LHC Run2 already started. Both experiments started collecting 13 TeV data.

Stay tuned for interesting results !!!!



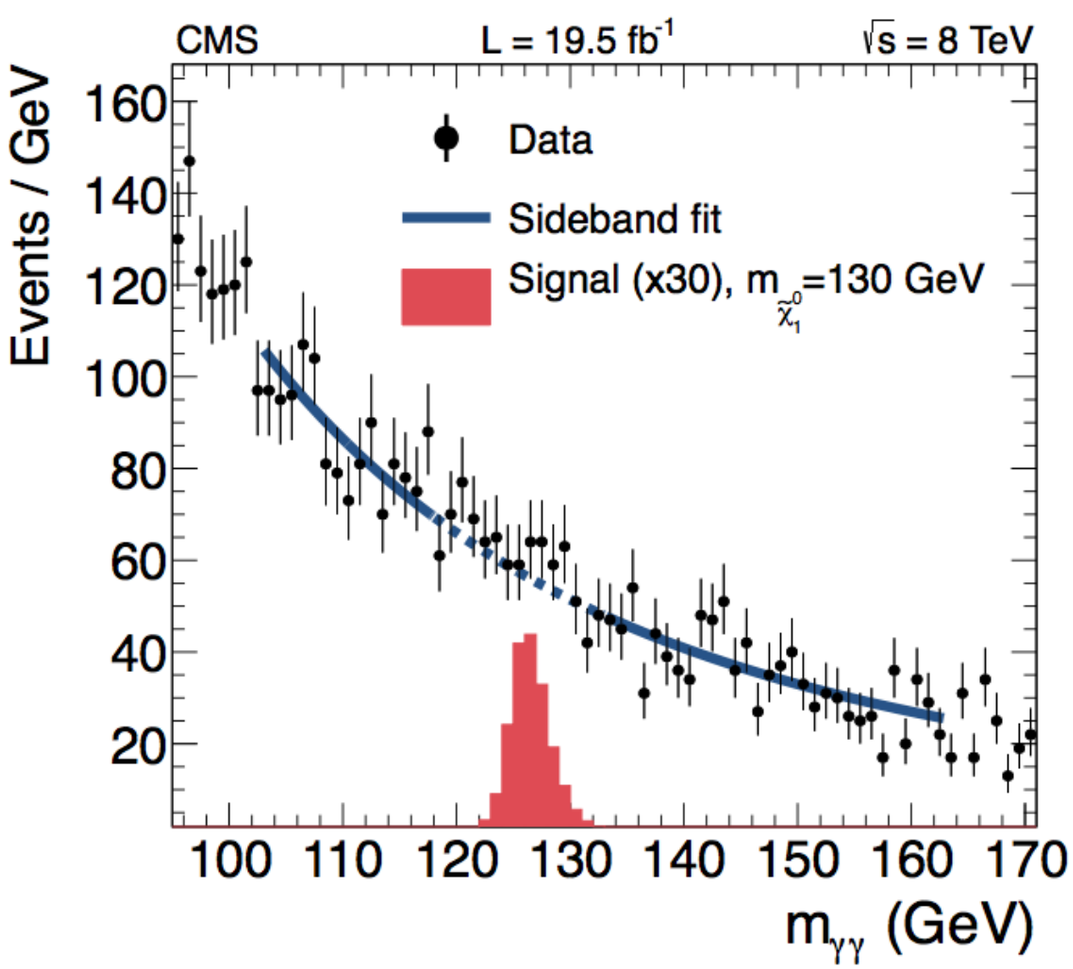


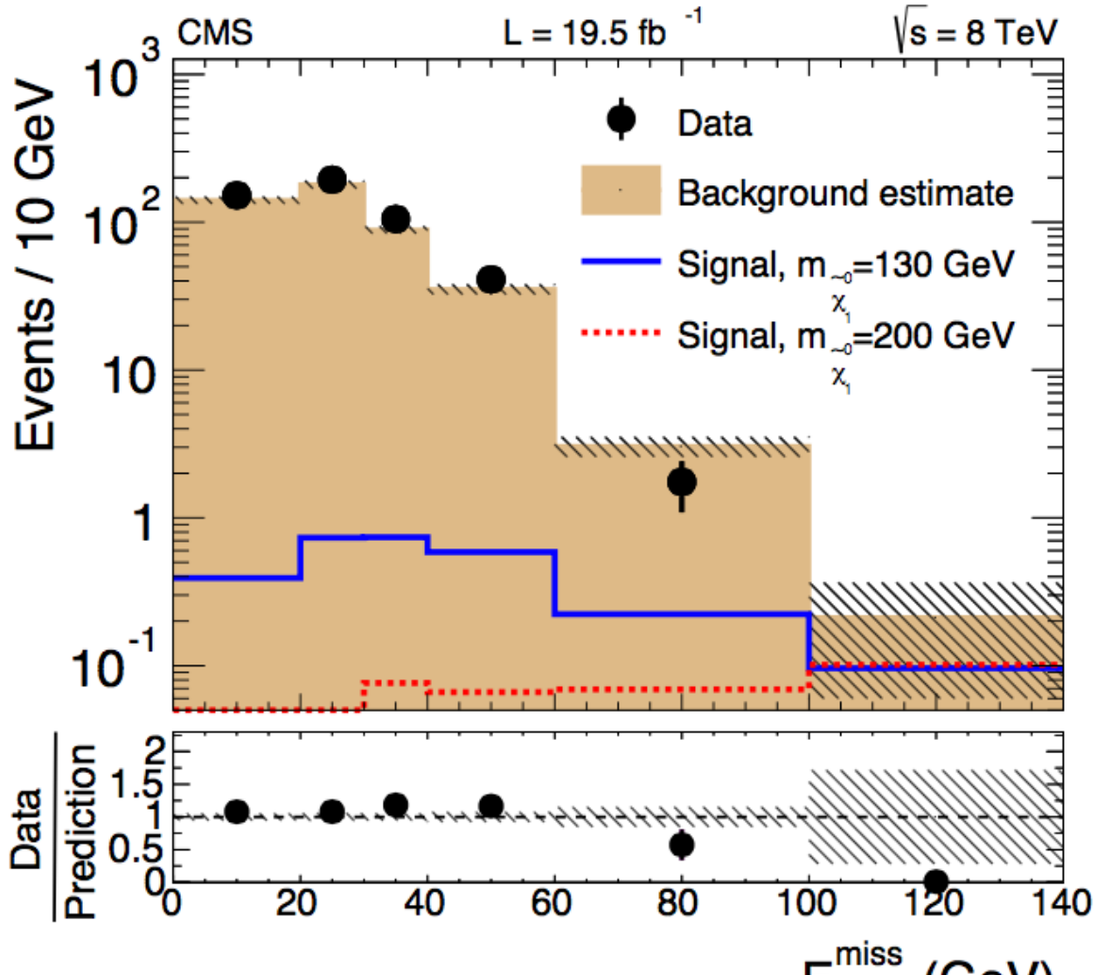
Supporting Material

hZ/hW → γγ + 2 jets

- dijet mass m_{jj} is (70,100) GeV.
- isolated lepton veto.
- event rejected if $m_{b\bar{b}}$ (95,155) GeV.
- Discriminating Variable : E_T^{miss}
- scaled E_T^{miss} distributions from 2 sidebands are consistent within their uncertainties.

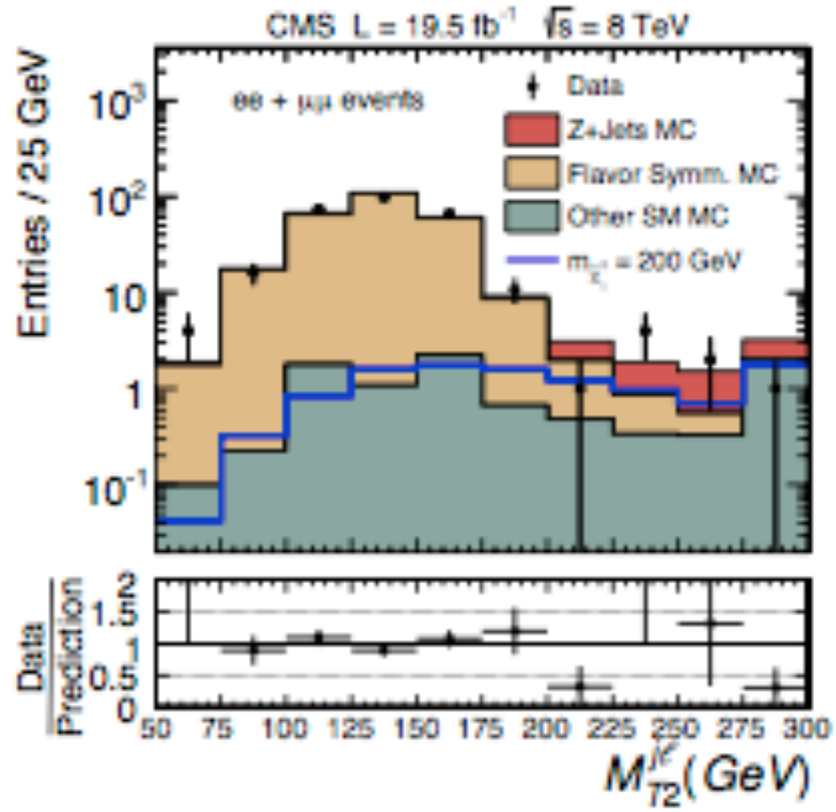
E_T^{miss} (GeV)	SM background	Data	hZ events, $m_{\tilde{\chi}_1^0} = 130$ GeV
0-20	288 ± 15	305	0.76 ± 0.03
20-30	183 ± 10	195	0.71 ± 0.03
30-40	91.1 ± 4.7	105	0.72 ± 0.03
40-60	72.0 ± 5.0	82	1.14 ± 0.04
60-100	12.5 ± 1.9	7	0.87 ± 0.03
>100	0.96 ± 0.61	0	0.37 ± 0.02





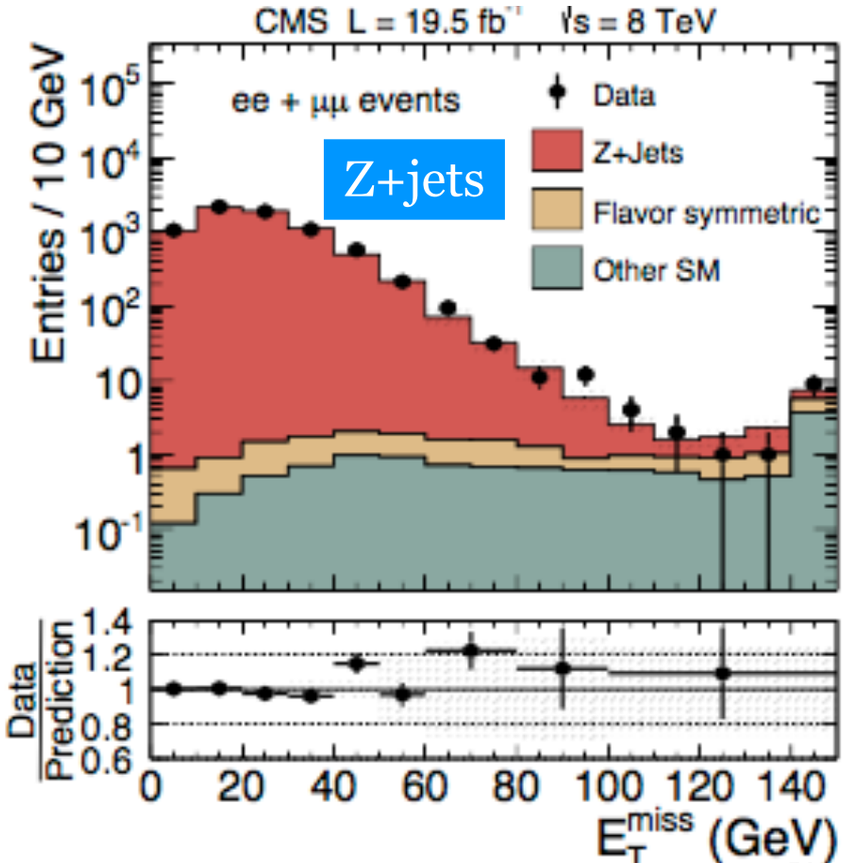
h(→bb̄) Z(→l⁺l⁻)

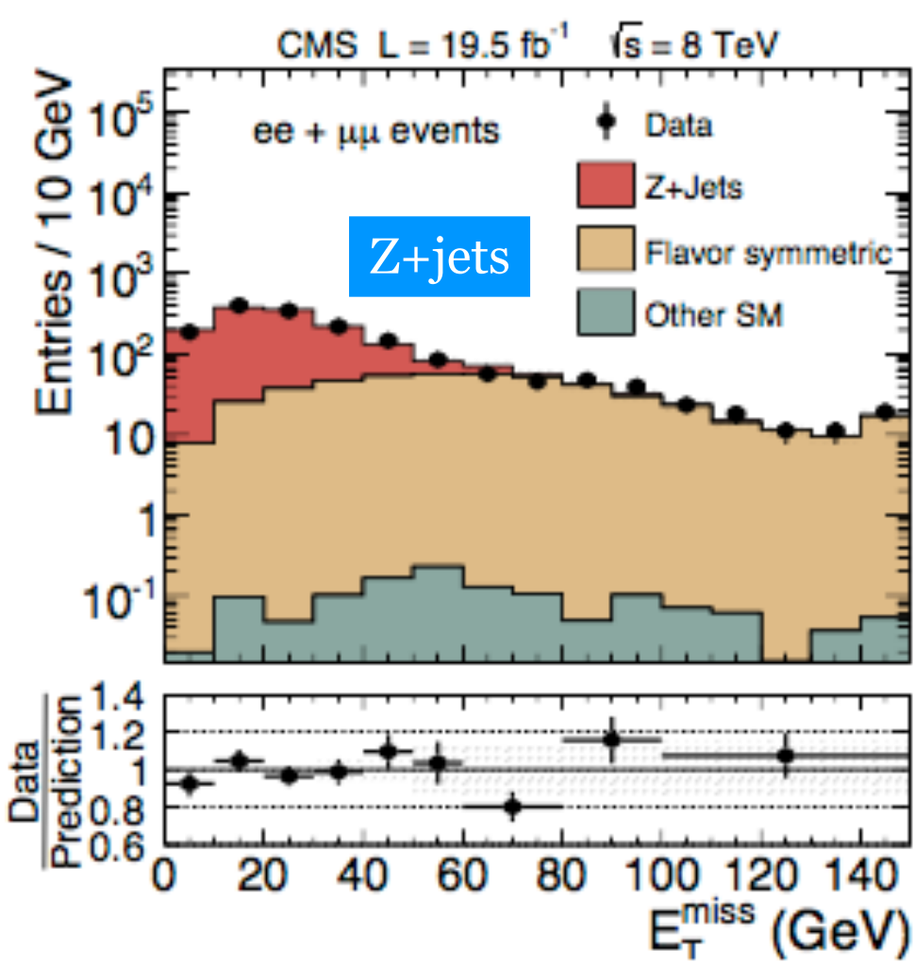
- leptons can be electrons/muons.
- leptons with p_T > 20 GeV and |η| < 2.4
- p_T > 30 GeV for jets with |η| < 2.5, b-jets.
- exactly one lepton pair with 81<m_{ll} < 101 GeV.
- no third lepton and tau candidate.
- ≥ 2 b-jets with 100< $m_{bb̄}$ < 150 GeV.
- BG: Z+jets, FS(W+W-,ττ,ttbar,tW), Others (ZW,ZZ, ttbarV,VV V)
- M_{T2}^{jl} > 200 GeV, E_T^{miss}

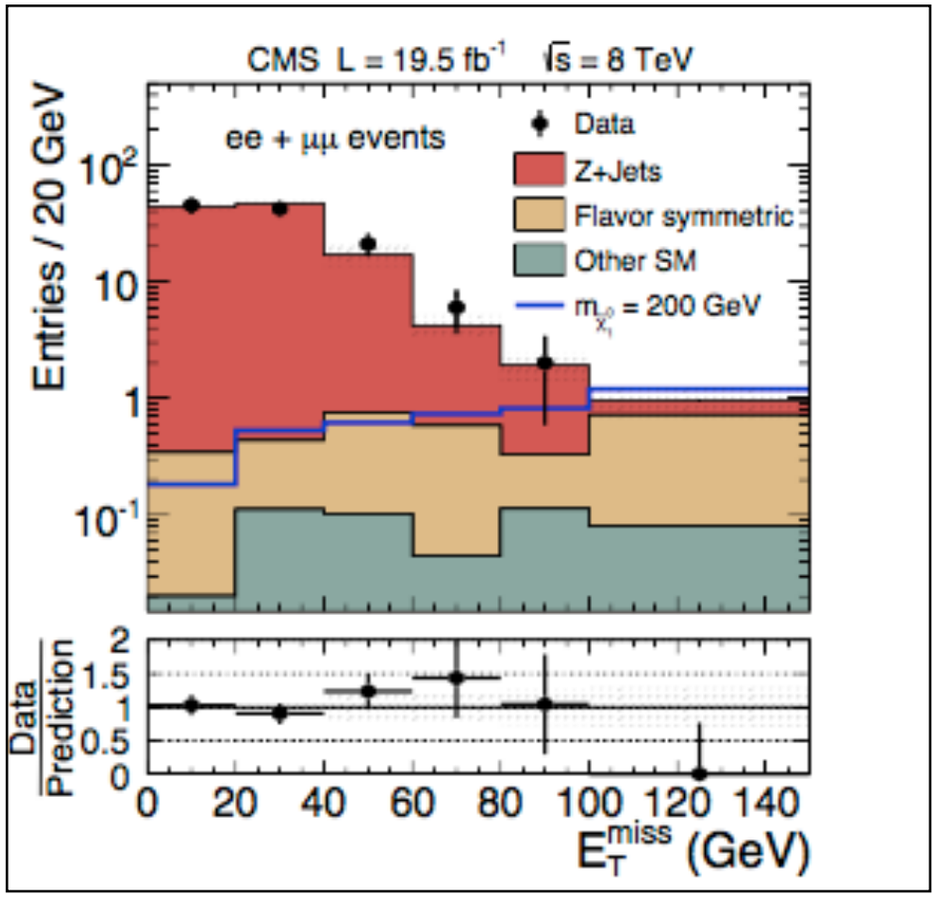


BG Estimation

- For Z+jets estimation, γ+jets template is used.
- Contribution of BG other than Z+jets is reduced by taking low E_T^{miss} < 50 GeV.
- FS BG is estimated from eμ CR (81<$m_{eμ}$ < 101 GeV).
- BG procedures are validated using Data CR enriched with that BG.
- For Z+jets CR, no b-jets are required.
- For ttbar enriched region, M_{T2}^{jl} requirement is inverted.







no excess over SM prediction

	$E_T^{miss} < 25$ GeV	$25 < E_T^{miss} < 50$ GeV	$50 < E_T^{miss} < 60$ GeV
Z+jets background	56.7 ± 1.9	43.3 ± 2.3	5.7 ± 1.2
Flavor symmetric background	0.4 ± 0.3	0.4 ± 0.3	0.4 ± 0.3
Other SM background	<0.1	0.1 ± 0.1	0.1 ± 0.1
Total SM background	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 background	5.7 ± 1.8	2.2 ± 0.9	0.6 ± 0.3
Flavor symmetric background	2.4 ± 0.9	1.8 ± 0.7	1.6 ± 0.6
Other SM background	0.3 ± 0.2	0.3 ± 0.2	0.2 ± 0.1
Total SM background	8.5 ± 2.0	4.3 ± 1.2	2.4 ± 0.7
Data	8	2	0
hZ events			
$m_{\tilde{\chi}_1^0} = 130$ GeV	5.4 ± 0.1	3.1 ± 0.1	1.7 ± 0.1
$m_{\tilde{\chi}_1^0} = 150$ GeV	5.3 ± 0.1	3.3 ± 0.1	2.0 ± 0.1
$m_{\tilde{\chi}_1^0} = 200$ GeV	4.7 ± 0.1	4.2 ± 0.1	3.3 ± 0.1
$m_{\tilde{\chi}_1^0} = 250$ GeV	3.5 ± 0.1	3.2 ± 0.1	2.8 ± 0.1

multilepton search

- three or more lepton searches are sensitive to hh and hZ channels (for low values of higgsino mass)
- atleast 3 charged leptons including one τ_h candidate.
- Exclusive SR Categories are based on
- Number and flavor of leptons.
- presence or absence of OSSF lepton pair.
- Consistency of invariant mass of OSSF pair with Z boson.
- b-jets or no b-jets.
- E_T^{miss} and H_T .
- For interpretation of results,ordering of channels by their sensitivity.

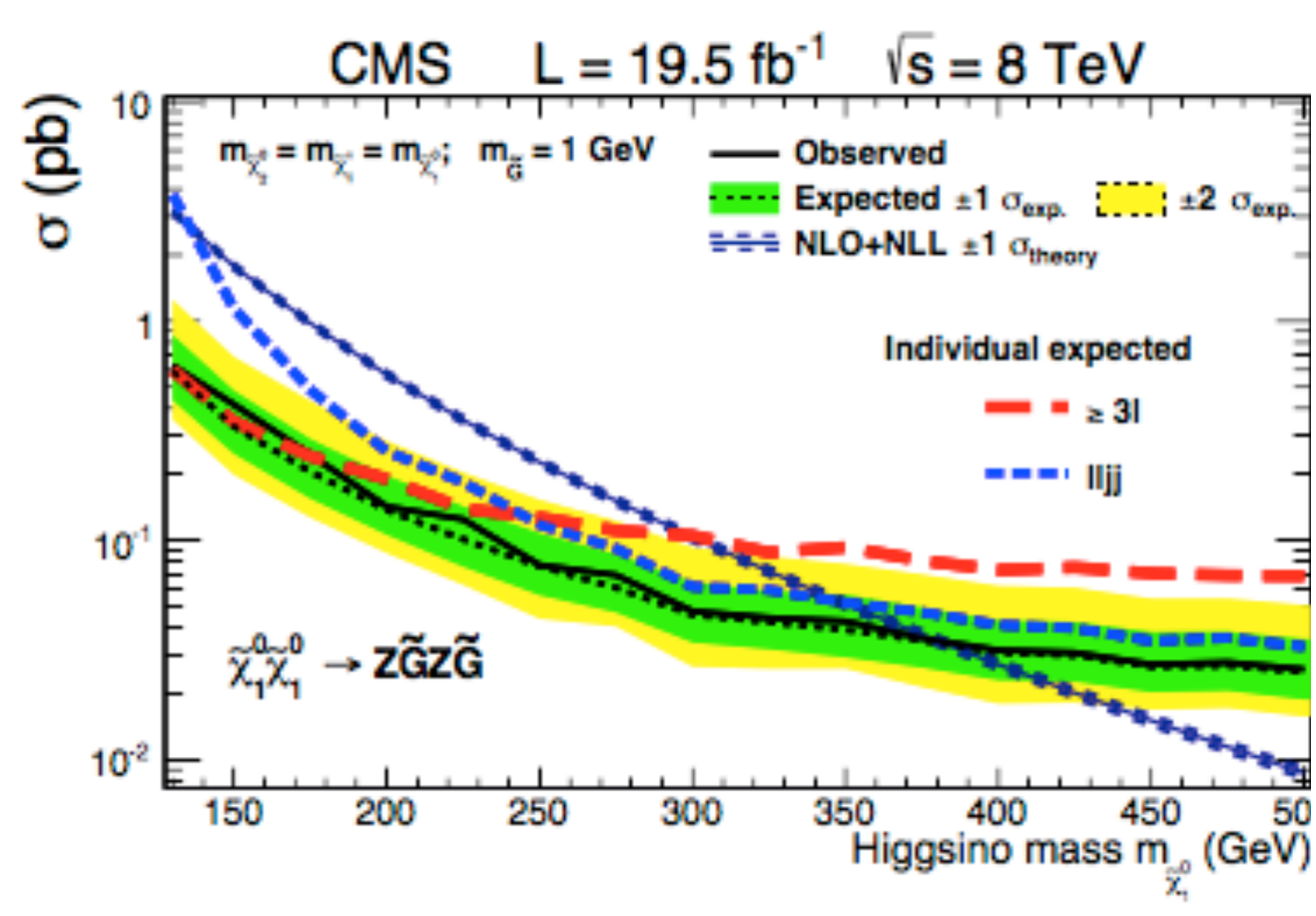
CMS-SUS-13-002
PRD

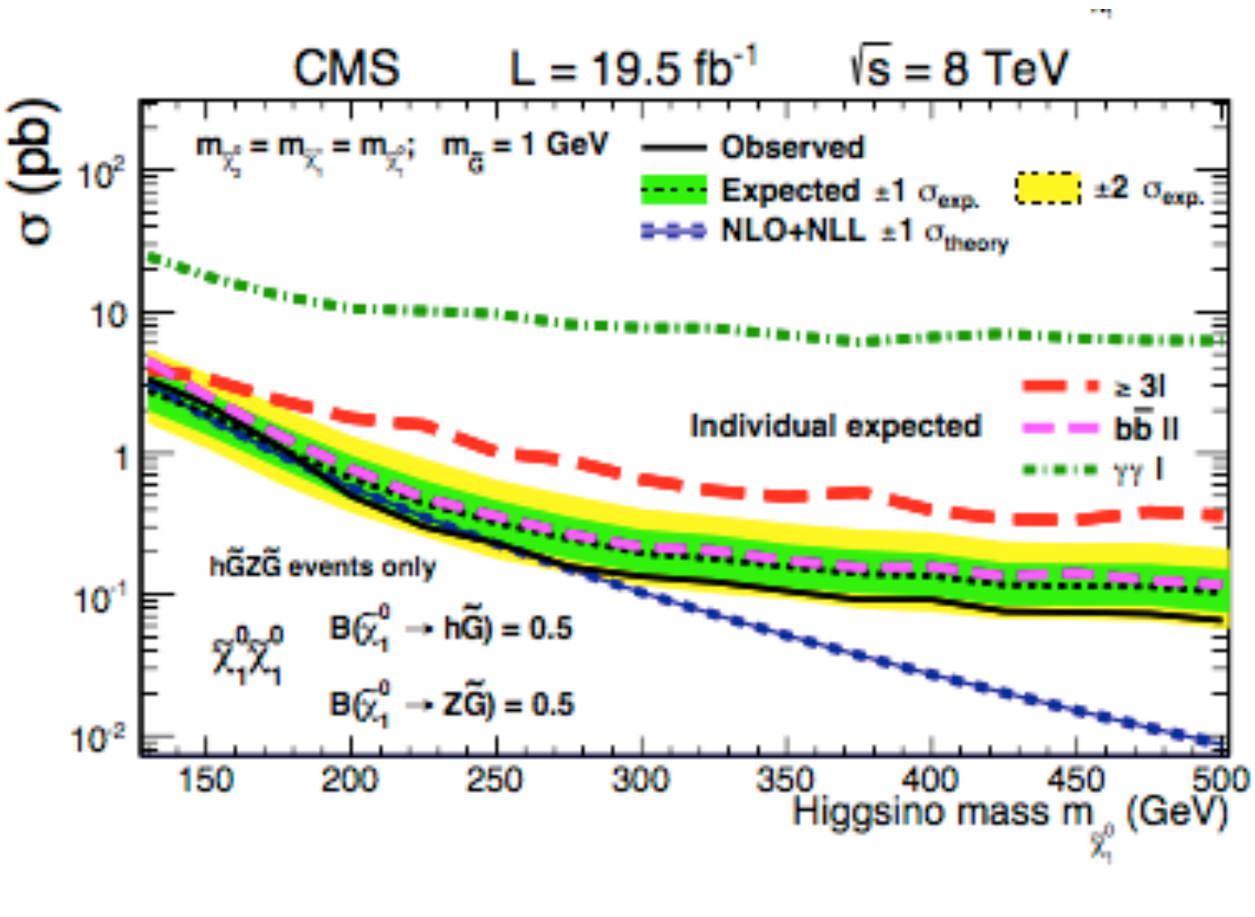
N_ℓ	N_{τ_h}	N_{OSSF}	$m_{\ell\ell}$ range	E_T^{miss} (GeV)	SM background	Data	hh events, $m_{\tilde{\chi}_1^0} = 150$ GeV
3	0	0	—	0-50	51 ± 11	53	3.1 ± 0.6
3	0	0	—	50-100	38 ± 15	35	2.7 ± 0.6
3	0	1	Below Z	50-100	130 ± 27	142	7.4 ± 1.6
3	1	0	—	50-100	400 ± 150	406	8.0 ± 1.4
4	0	1	Off Z	50-100	0.2 ± 0.1	0	0.5 ± 0.2
4	1	1	Off Z	0-50	7.5 ± 2.0	15	0.8 ± 0.2
4	1	1	Off Z	50-100	2.1 ± 0.5	4	0.7 ± 0.2

Combined local excess is 2.6σ and is consistent within statistical fluctuation for large number of search channels (look-else where effect)

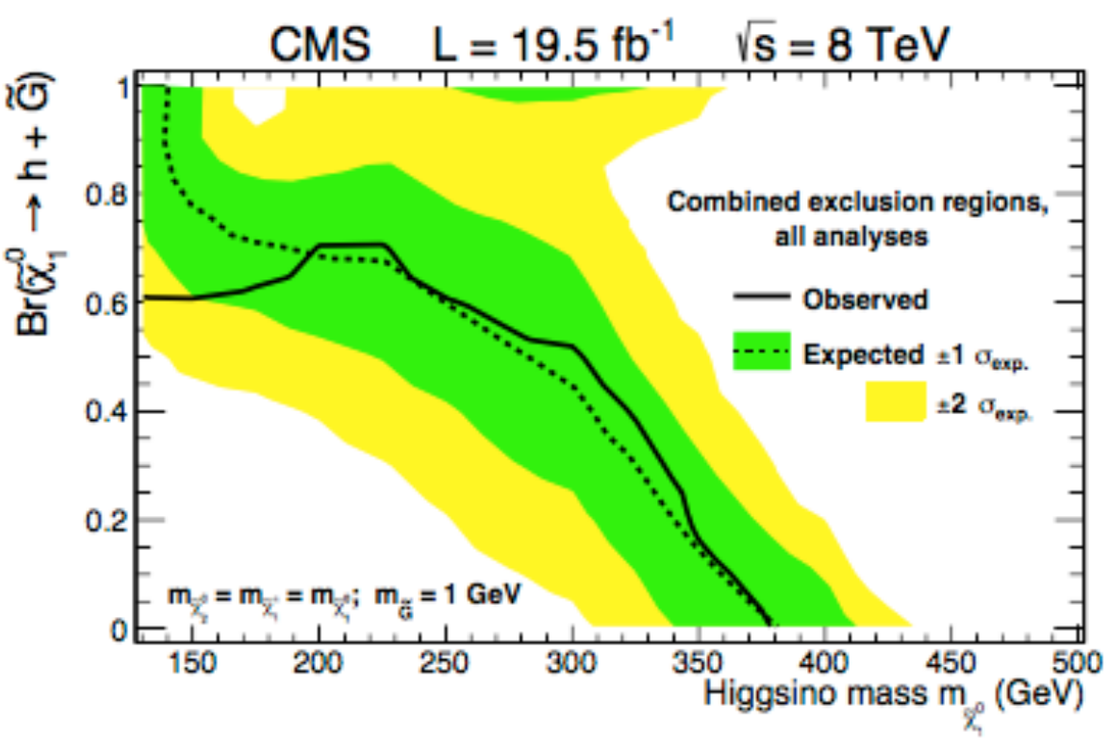
$ZZ \rightarrow l^+l^- + 2jets$

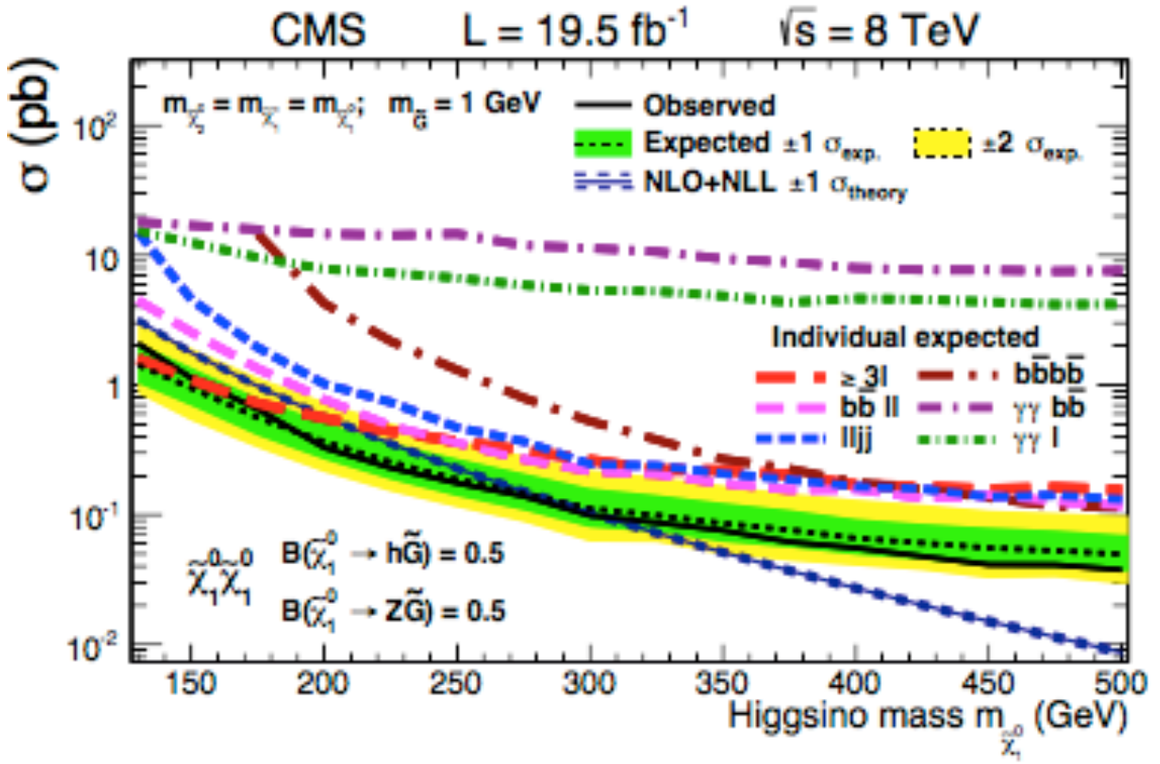
- most sensitive to SUSY ZZ channel.
- atleast one e^+e^- or $\mu^+\mu^-$ pair.
- no other lepton and b-jets.
- large E_T^{miss}
- atleast 2 jets.
- dilepton and dijet invariant mass consistent with Z

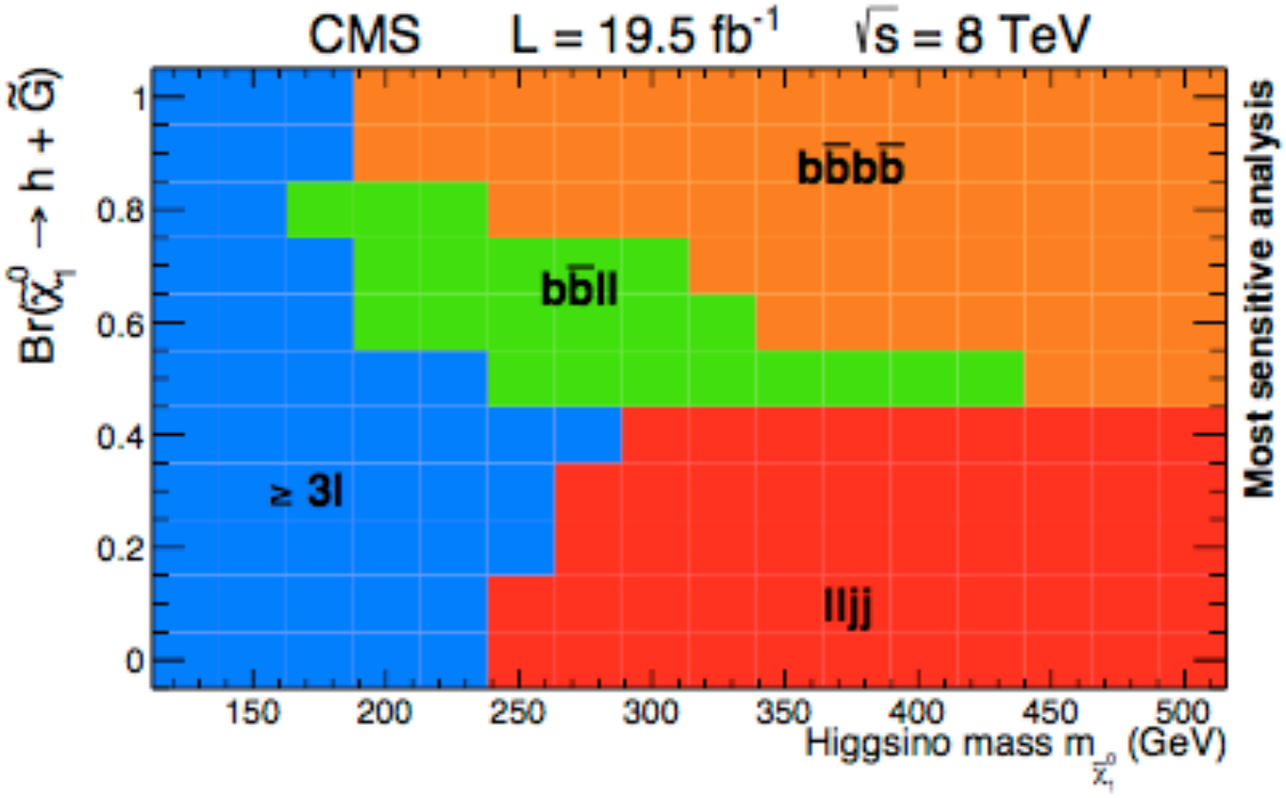




2 D exclusion limit and Analysis sensitivity

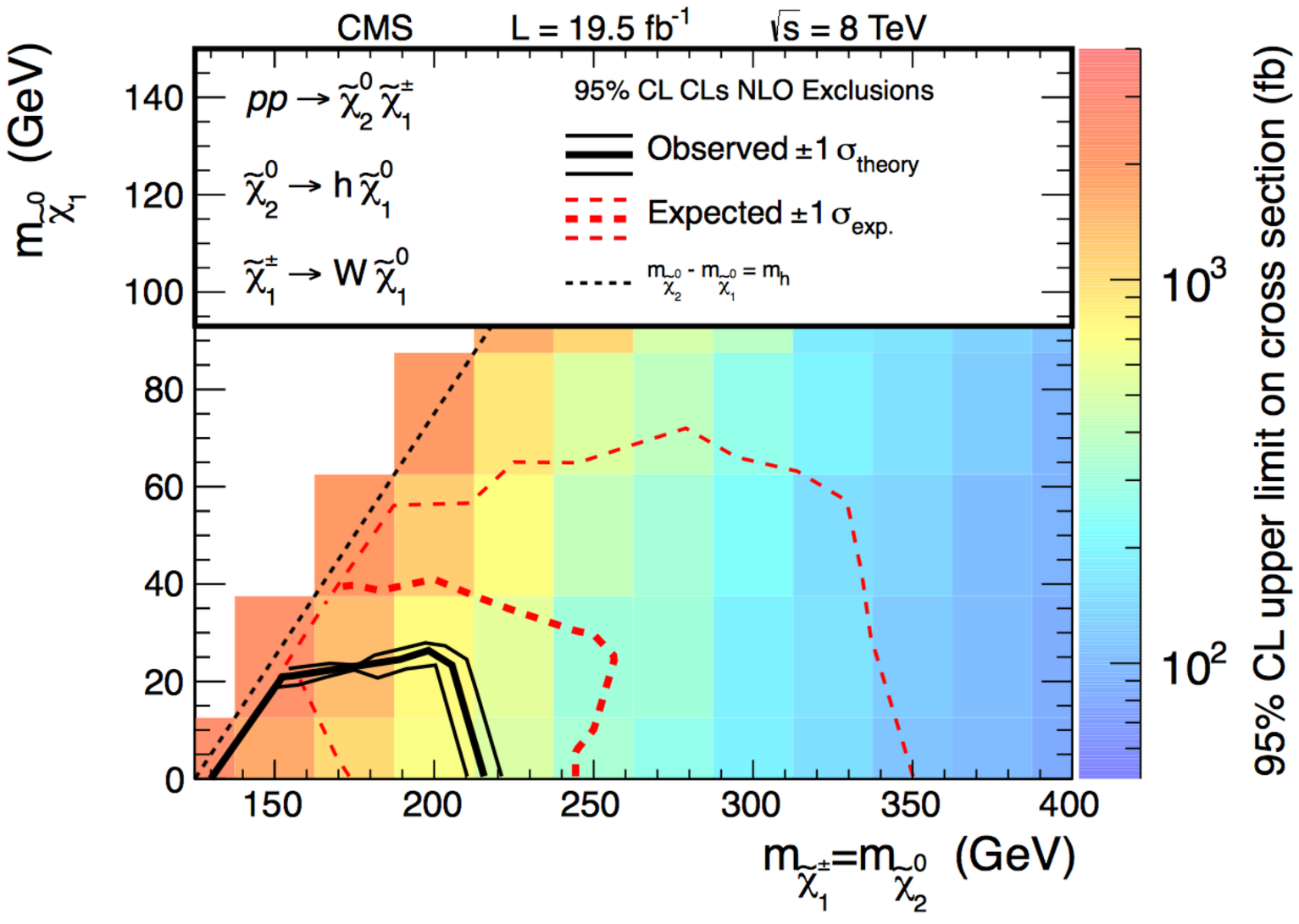




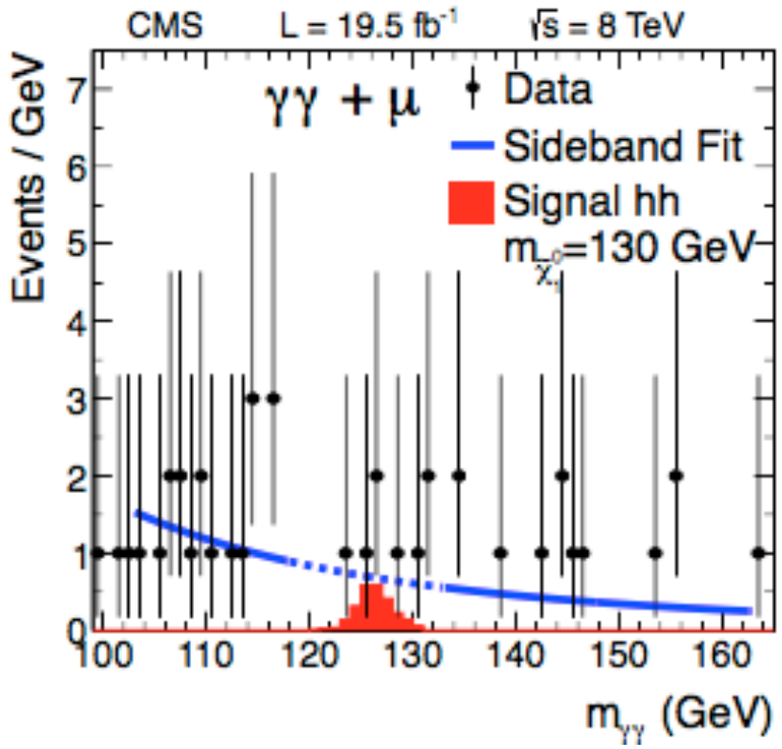


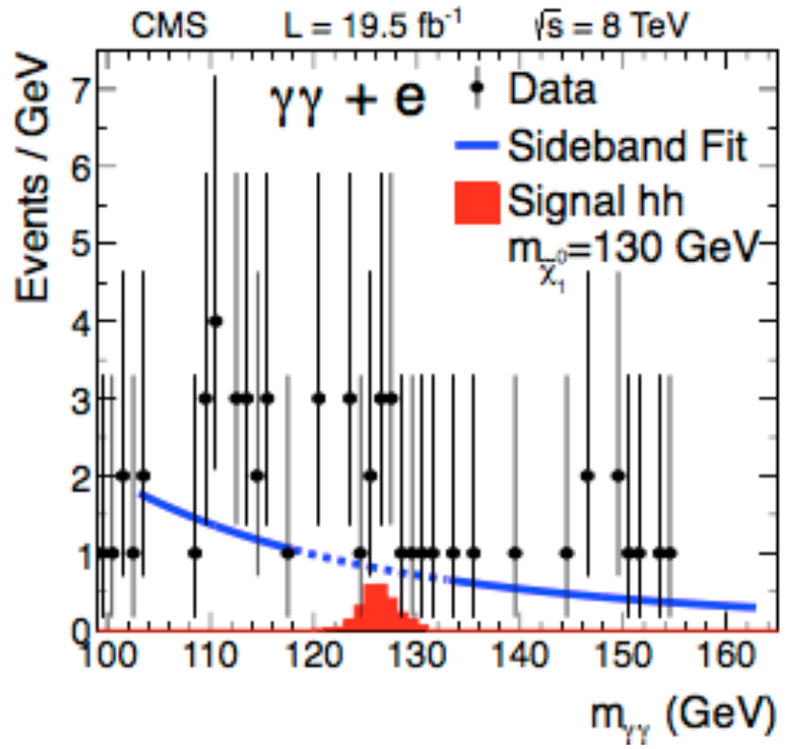
hW topology

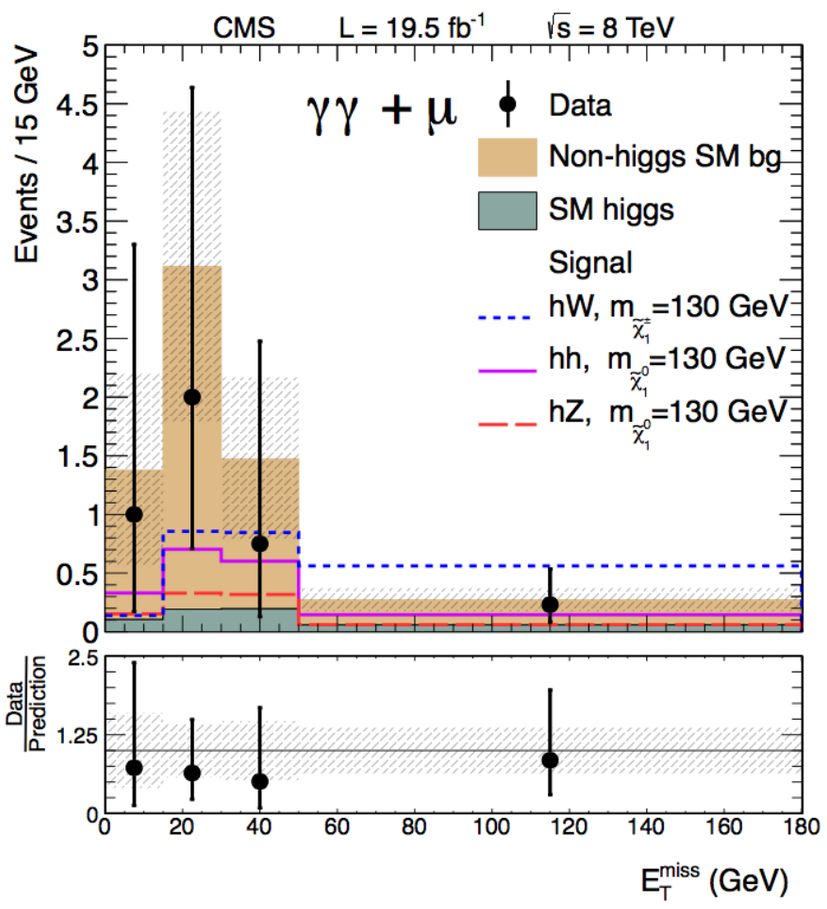
- Event signature:
  single electron/muon and bb̄ pair.
  same-sign ee,eμ,μμ pair (no third lepton)
  3or more leptons.
- h(→bb̄) W(→lν), h(→ZZ,WW,τ τ) W(→lν), h(→ γγ) W(→lν)

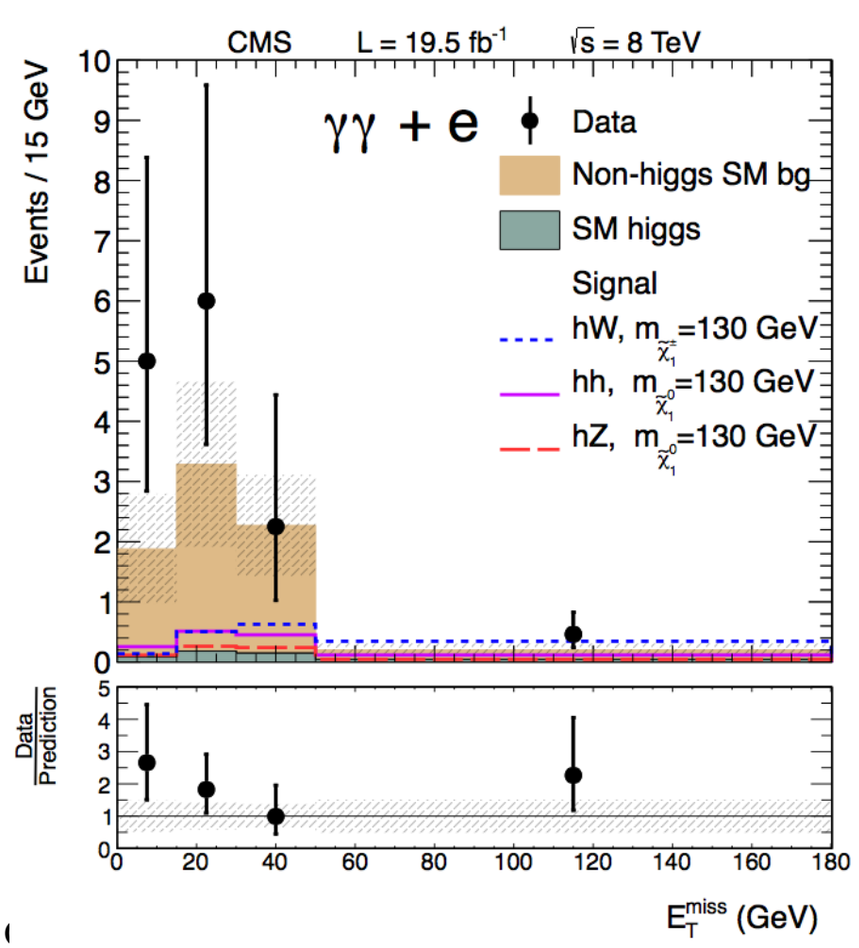


hh (WW/ZZ/$\tau\tau$) , hZ , hW → γγ + l± (e,μ)

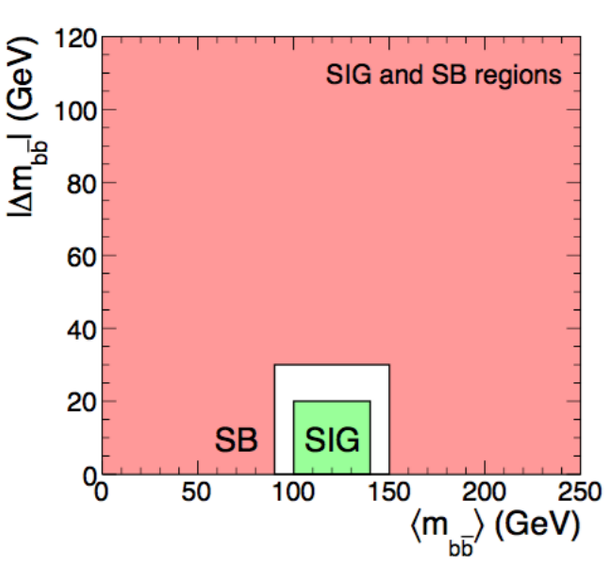


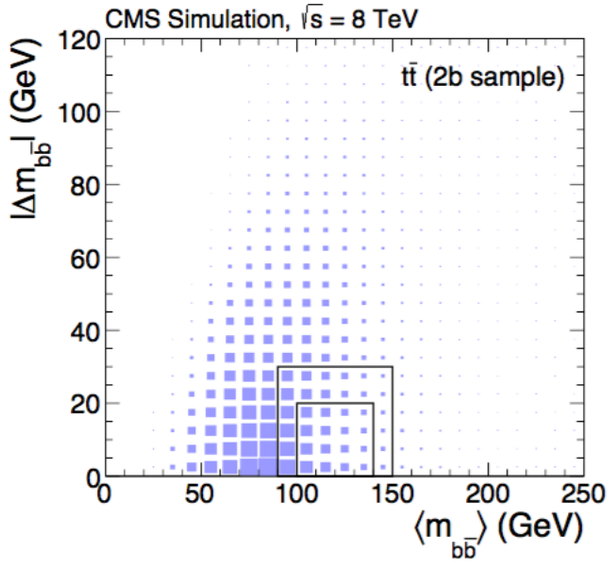


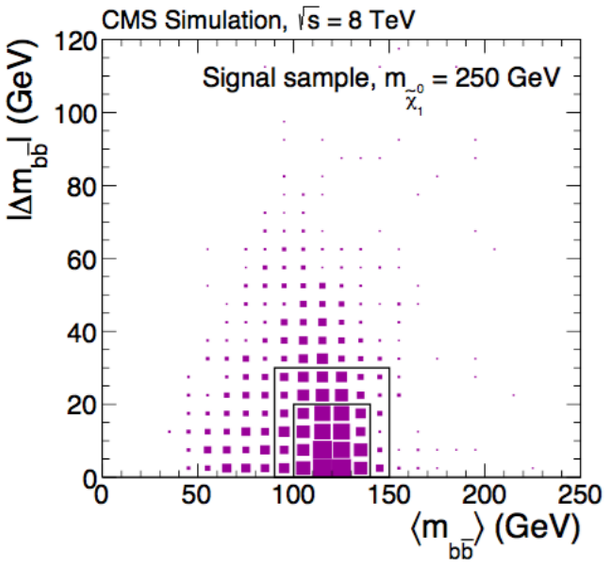


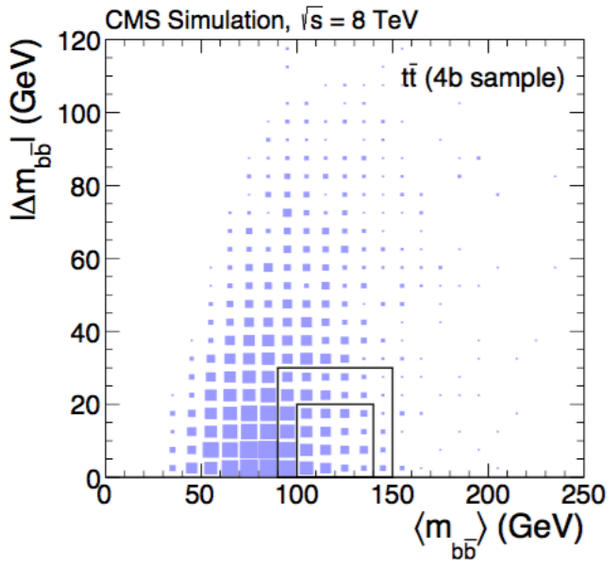


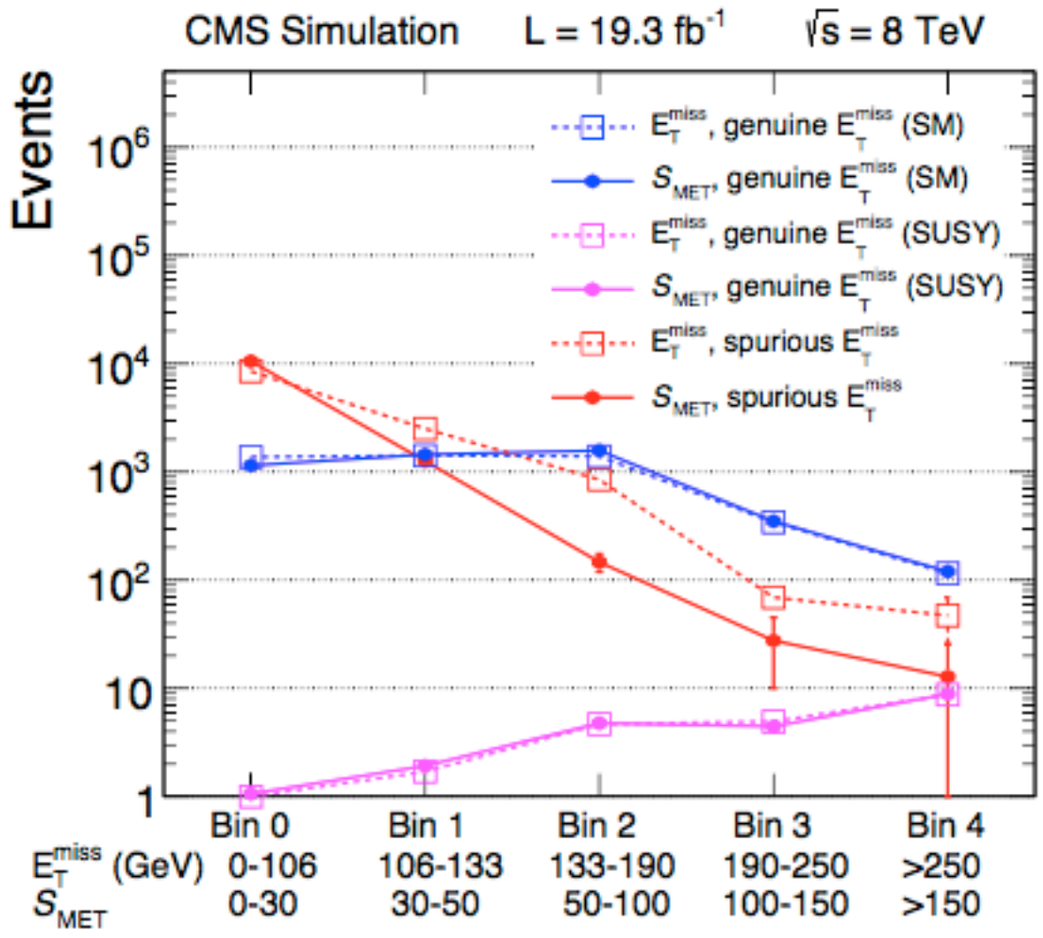
Searches via h(→bb̄) h(→bb̄)











Searches with h→ γγ decay

CMS SUS-14-002 - PRD

- Criteria for h → γγ selection:
  - 2 γ's with $p_T > 40$, 25 GeV and $|\eta| < 1.44$ with $120 < m_{\gamma\gamma} < 131$ GeV (higgs tag region)
- Common BG estimate
  - Fit $m_{\gamma\gamma}$ distribution in side bands excluding tag region with power law function.
  - Integrate power-law function in higgs tag region to normalize continuum non-h SM BG.
  - BG shape in **"discriminating variable"** taken from average of lower and upper $m_{\gamma\gamma}$ sidebands.
  - BG from SM-Higgs added then.

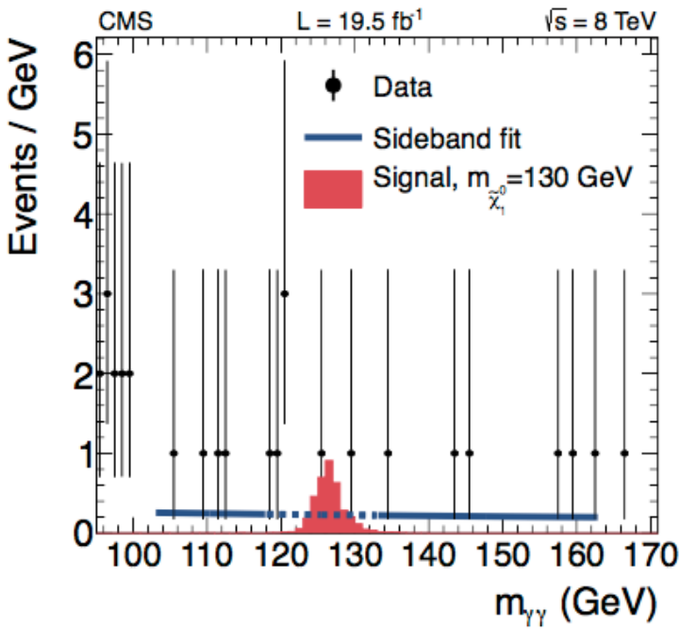
h(→bb̄) h(→ γγ)

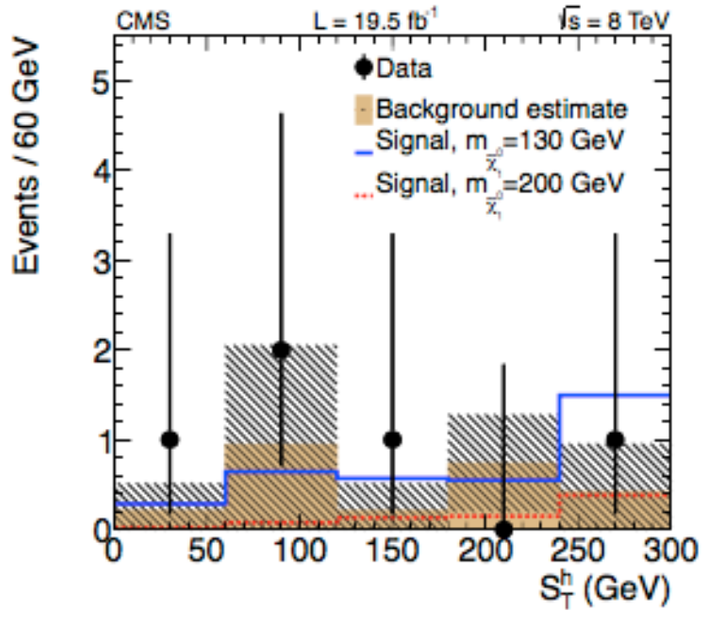
- required exactly 2 b-jets, p_T (jets) > 30 GeV
- no identified, isolated lepton
- ΔR(γ, j) > 0.5
- 95< $m_{b\bar{b}}$ < 155 GeV

"Discriminating Variable"

$$S_T^h = p_T^{h\to\gamma\gamma} + p_T^{h\to b\bar{b}}$$

extends to higher value for signal





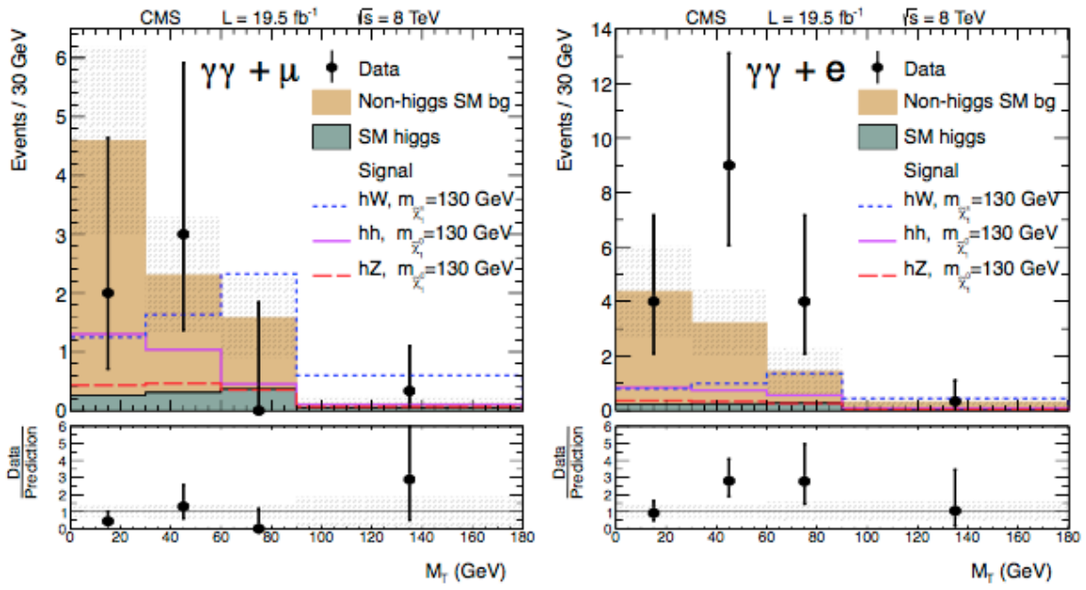
no excess over SM prediction

hh (WW/ZZ/$\tau\tau$) , hZ , hW → γγ + $l^{\pm}$ (e,μ) CMS SUS-14-002 - PRD

- required ≤ 1 b-jet (avoid overlap to h → bb̄ final state)
- ≥ 1μ or 1 e with p_T > 15 GeV and ΔR(l,γ) > 0.5
- rejects e faking γ by vetoing near m_Z (86-96) GeV

"Discriminating Variable"

$$M_T = \sqrt{2E_T^{miss} p_T^l (1 - cos(\Delta\phi_{l,E_T^{miss}}))}$$



excess is seen (2.1 σ), consistent with in statistical fluctuations

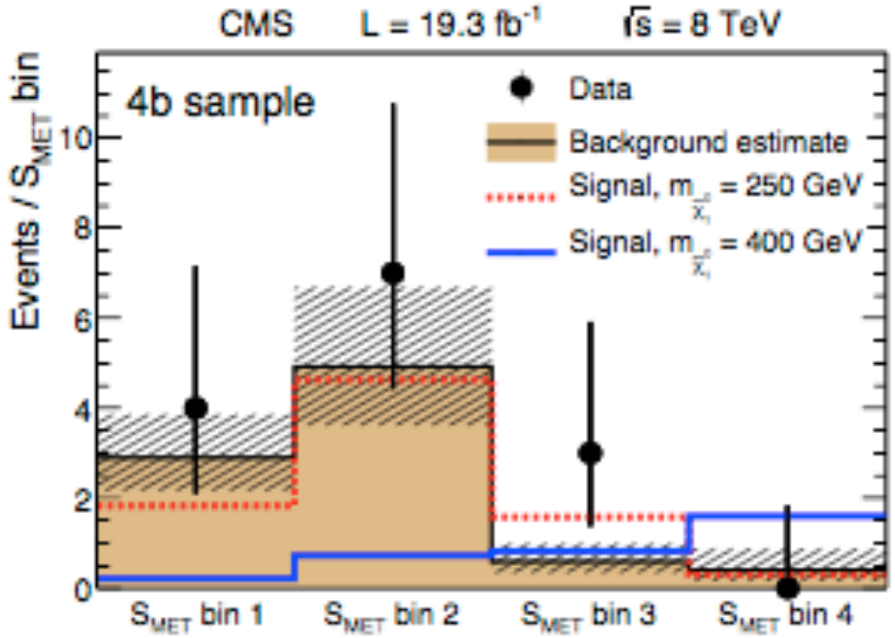
Searches via h(→bb̄) h(→bb̄) CMS SUS-14-002 - PRD

Signal Selections

- 4 or 5 jets with p_T > 20 GeV (including b-jets)
- no identified lepton
- E_T^{miss} significance S_{MET} > 30
- $|\Delta m_{b\bar{b}}|$<20 GeV
- max(ΔR(j,j)) < 2.2 (to reject ttbar)
- 100<⟨$m_{b\bar{b}}$⟩ < 140 GeV

Background Estimation

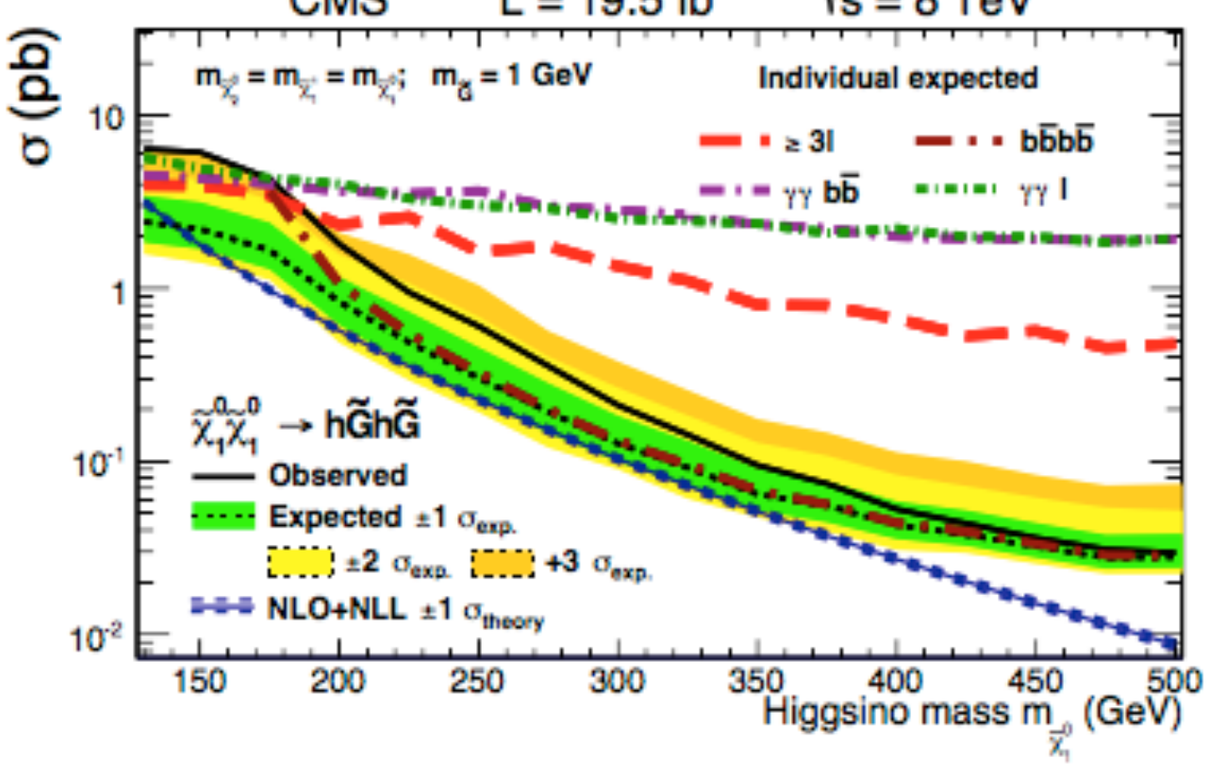
- 3 control samples: 2b-jets, 3b-jets and 4 b-jets.
- Sample having 2b-jets only (region dominated by BG)
- Side Bands (SB) having $|\Delta m_{b\bar{b}}|$<30 GeV and 100<⟨$m_{b\bar{b}}$⟩ < 140 GeV.
- ABCD method is used to calculate number of events in regions 3 b and 4b using SIG/SB ratio from 2b sample.



$\mathcal{S}_{MET}$ bin	$\mathcal{S}_{MET}$ 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

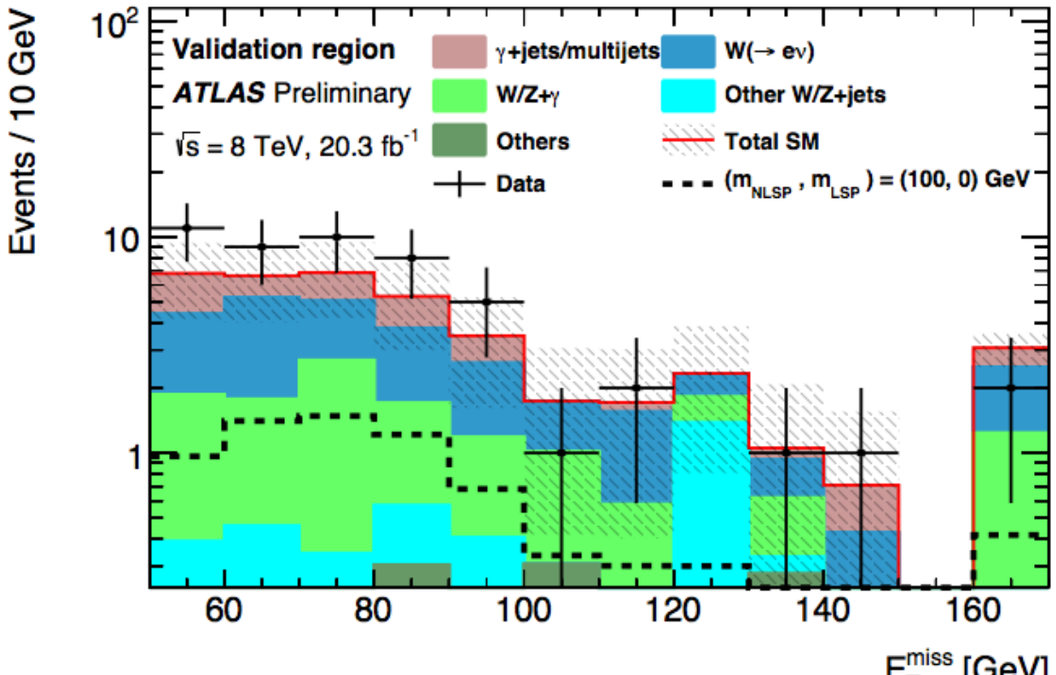
no significant excess observed over SM prediction

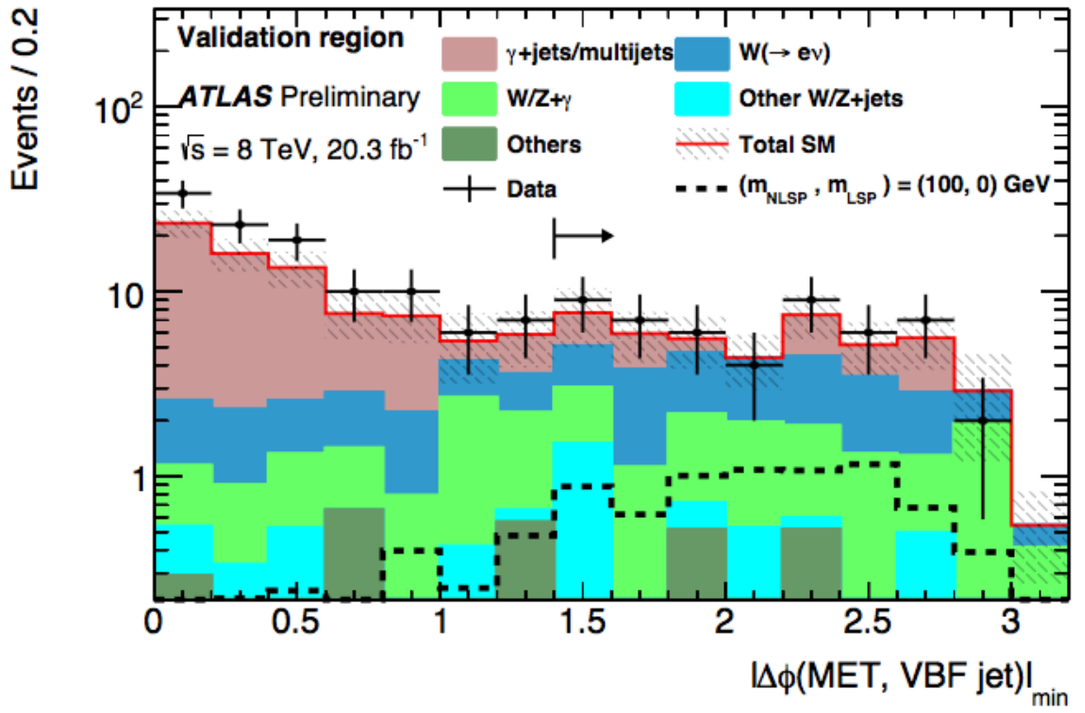
- Scenarios with $\mathrm{Br}(\tilde{\chi}_1^0 \rightarrow \mathrm{h}\tilde{G}\ ) = 1$
- $hh \rightarrow b\bar{b}b\bar{b}$ is more sensitive for masses above 200 GeV and loses sensitivity below 200 GeV (S_{MET} spectrum become SM-like) .
- Multileptons and $\gamma\gamma$ are more sensitive at low higgsino mass.
- 3σ excess at masses below 170 GeV is mostly provided by multilepton analysis.

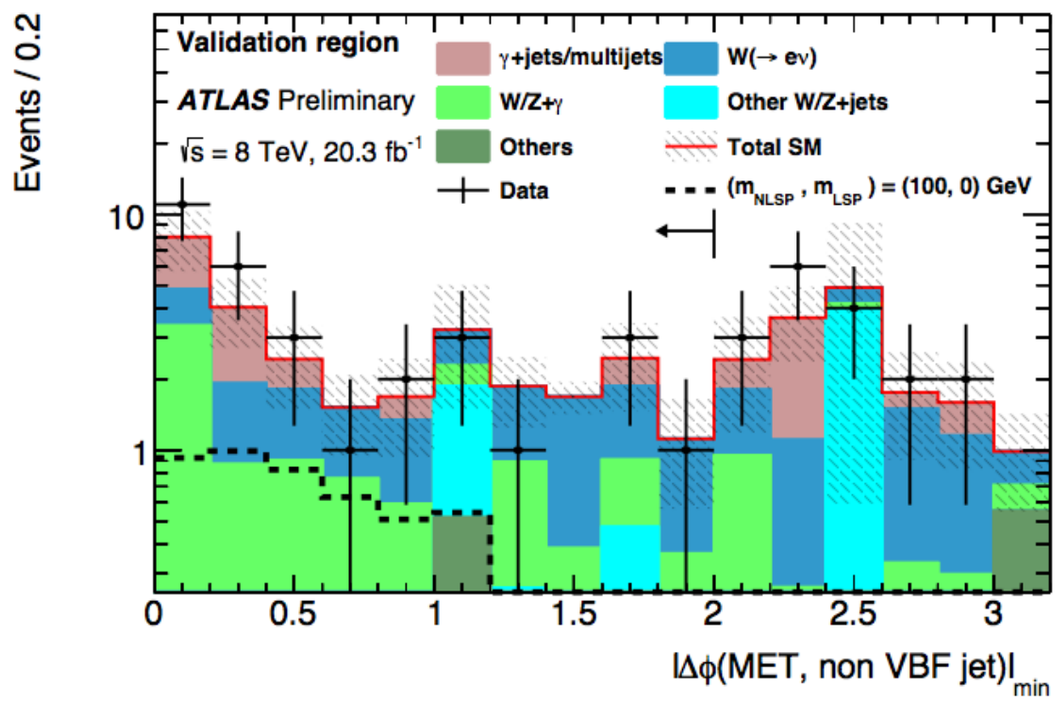


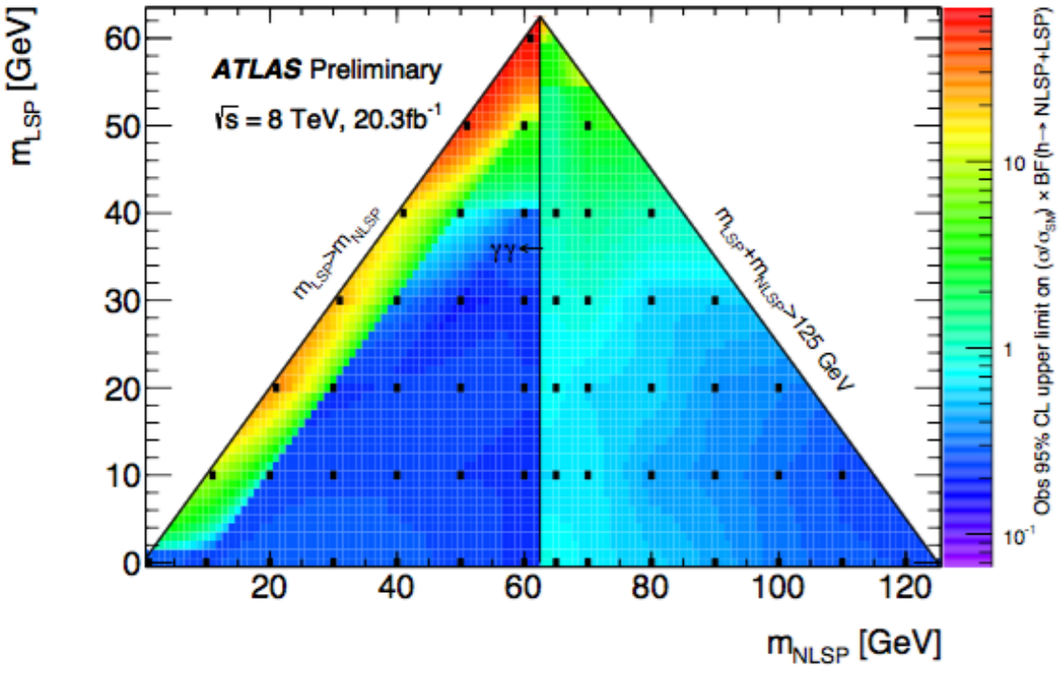
Searches via exotic higgs decaying to γ(γγ)+ LSP

ATLAS-CONF-2015-001









Background	Distributions	Normalization
$W(\rightarrow e\nu)$	$W(\rightarrow e\nu)$ MC with $e \rightarrow \gamma$ misidentification rate from data	Data CR
W/Z + jets	W/Z + jets MC with jet$\rightarrow \gamma$ misidentification rate from MC	Data CR
$W\gamma/Z\gamma$	MC	Data CR
Top and diboson	MC	MC
γ + jets and multijet	Data CR	Data CR

Requirements	Main analysis	Electron CR	$l\nu\gamma$ CR	γ+jets VR
EM object(s)	Photon	Electron	Photon + lepton	Photon
$\lvert\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, VBF\,jet)\rvert_{min}$	> 1.4	> 1.4	> 1.4	≤ 1.4
$m_{jj} \leq 600$ GeV or $\lvert\Delta\eta_{jj}\rvert \leq 4.0$, $\lvert\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \gamma)\rvert \leq 1.8$	B	e B	$l\nu\gamma$ B	γ+jets B
$m_{jj} > 600$ GeV, $\lvert\Delta\eta_{jj}\rvert > 4.0$, OPV, $p_T^{TOT} \geq 50$ GeV and $\lvert\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \gamma)\rvert \leq 1.8$	A	e A	$l\nu\gamma$ A	γ+jets A

Systematic	$Z(\rightarrow \nu\nu)\gamma$	$W(\rightarrow l\nu)\gamma$	$Z(\rightarrow \nu\nu)$	$Z(\rightarrow \tau\tau)$	$W(\rightarrow e\nu)$	$W(\rightarrow \mu\nu)$	$W(\rightarrow \tau\nu)$	Others	γ+jets	Signal
W/Z+jets norm.	0	0	0.02	0.01	0.64	0.01	0.25	0	0.28	0
W/Z+γ norm.	0.19	2.2	0	0	0	0	0	0	0.28	0
$e \rightarrow \gamma$ misid. rate	0	0	0	0	0.54	0	0	0	0	0
jet$\rightarrow \gamma$ misid. rate	0	0	0.28	0.24	0	0.01	0.42	0	0	0
MC γ rate	0	0	0	0	0	0.2	0.17	0	0	0
Trigger efficiency	0.01	0.14	0.01	0	0.21	0	0.08	0.01	0	0.29
ABCD	0	0	0	0	0	0	0	0	3.5	0
Jet energy resolution	0.03	0.22	0.28	0	0.43	0.09	0.18	0.14	0.28	0.58
Jet energy scale	0.02	0.5	0.28	0.02	1.2	0.08	0.17	0.22	0.14	1.0
γ energy resolution	0.01	0.07	0	0	0	0	0.19	0	0	0.15
γ energy scale	0.02	0.22	0.01	0	0	0	0.19	0	0	0.15
Cross section	0	0	0	0	0	0	0	0	0	0.8
Total	0.2	2.3	0.48	0.24	1.5	0.24	0.65	0.26	3.5	1.2

Searches via h(→bb̄) W(→lν)

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- jets with p_T > 25GeV , exactly 2 b-jets
- BG: ttbar, W+jets, tW, other rare SM
- Discrimination variables : E_T^{miss} , m_{CT} , m_W
- Signal is defined in 5 bins of $m_{bb̄}$ (47-75-**105-135**-165-185)

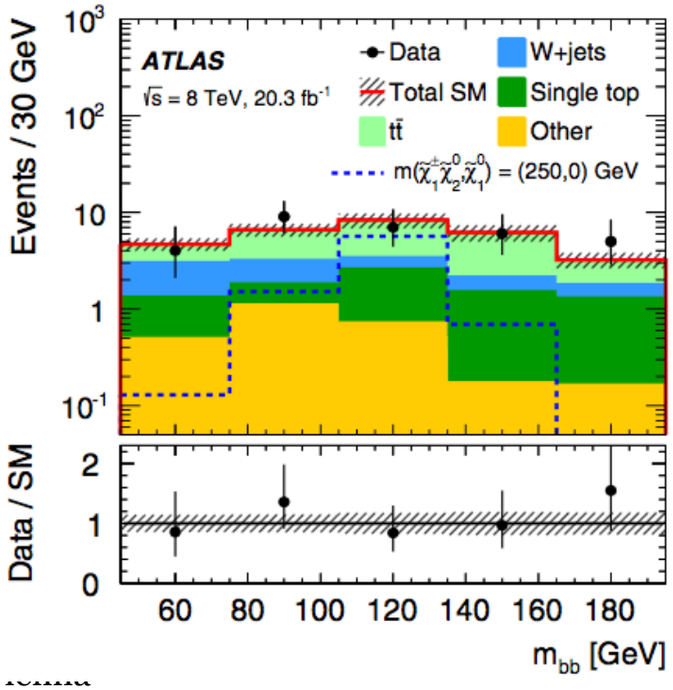
arXiv:0802.2879 [hep-ph]

$$m_{\mathrm{CT}} = \sqrt{(E_{\mathrm{T}}^{b_1} + E_{\mathrm{T}}^{b_2})^2 - |\mathbf{p}_{\mathrm{T}}^{b_1} - \mathbf{p}_{\mathrm{T}}^{b_2}|^2},$$

Selection Criteria in SR, CR and VR

	SRℓbb-1	SRℓbb-2	CRℓbb-T	CRℓbb-W	VRℓbb-1	VRℓbb-2
n_{lepton}	1	1	1	1	1	1
n_{jet}	2–3	2–3	2–3	2	2–3	2–3
$n_{b-\mathrm{jet}}$	2	2	2	1	2	2
$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	>100	>100	>100	>100	>100	>100
m_{CT} (GeV)	>160	>160	100–160	>160	100–160	>160
m_{T}^{W} (GeV)	100–130	>130	>100	>40	40–100	40–100

- BG are estimated from MC but the normalization factors are estimated by back-ground only fitting to data in CRlbb-T and CRlbb-W.
- BG modelling is validated from VRlbb-1 and VRlbb-2 using background only fit.



Searches via h(→ γγ) W(→lν)

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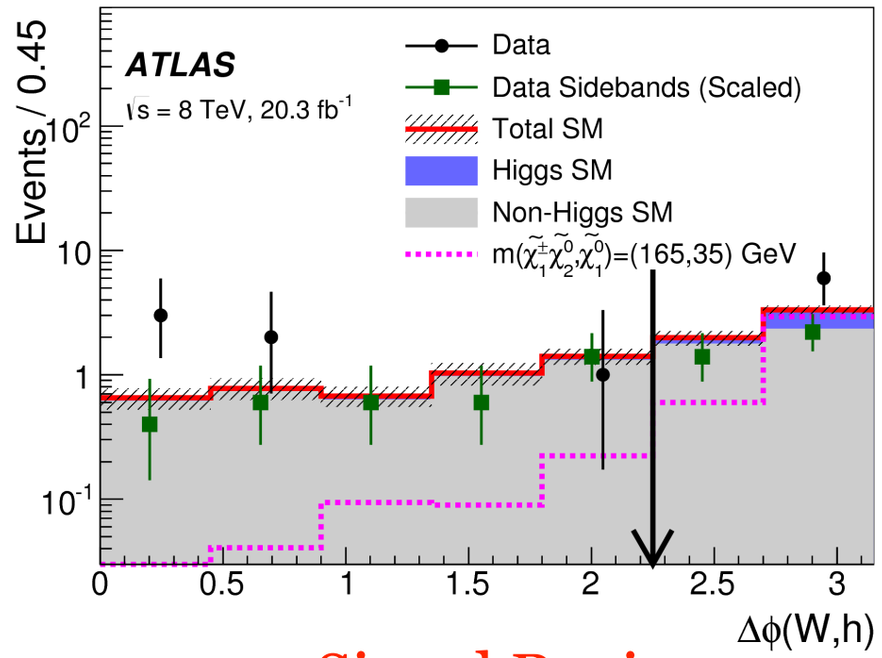
Signal Regions

	SRℓγγ-1	SRℓγγ-2	VRℓγγ-1	VRℓγγ-2
n_{lepton}	1	1	1	1
n_γ	2	2	2	2
$E_{\text{T}}^{\text{miss}}$ (GeV)	>40	>40	<40	–
$\Delta\phi(W, h)$	>2.25	>2.25	–	<2.25
$m_{\text{T}}^{W\gamma_1}$ (GeV)	>150	<150		
	and	or	–	–
$m_{\text{T}}^{W\gamma_2}$ (GeV)	>80	<80		

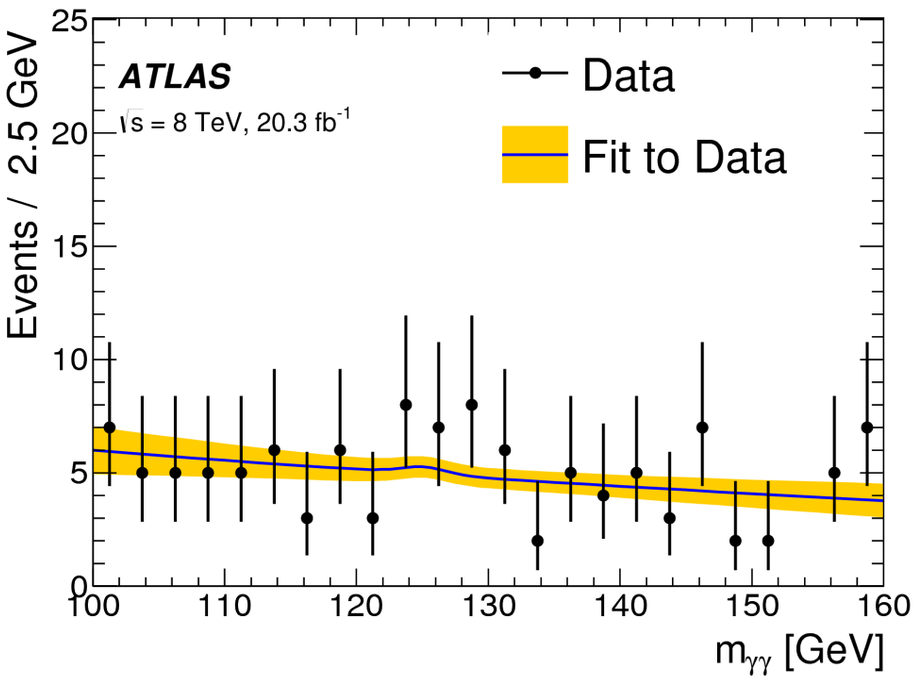


Signal Region

- Signal region higgs mass window (120-130) GeV
- major BG : multijets and Zγ
- contribution of non-higgs BG , modeled as exp(- α $m_{\gamma\gamma}$) ,is obtained from sidebands fitting $m_{\gamma\gamma}$ distribution (100-160) GeV excluding higgs window.
- SM processes with Higgs are estimated from simulation.

Observed and expected rate in SR & VR

	SRℓγγ-1	SRℓγγ-2	VRℓγγ-1	VRℓγγ-2
Observed events	1	5	30	26
SM expectation	1.6 ± 0.4	3.3 ± 0.8	30.2 ± 2.3	20.4 ± 1.9
Non-Higgs	0.6 ± 0.3	3.0 ± 0.8	29.2 ± 2.3	19.8 ± 1.9
Wh	0.85 ± 0.02	0.23 ± 0.01	0.71 ± 0.02	0.29 ± 0.01
Zh	0.04 ± 0.01	0.02 ± 0.01	0.14 ± 0.02	0.05 ± 0.01
$t\bar{t}h$	0.14 ± 0.01	0.02 ± 0.01	0.11 ± 0.01	0.25 ± 0.01



BG only fit to observed $m_{\gamma\gamma}$ in VR : VRlγγ-2

Searches via h(→ WW→ l±ν + jets) W(→l±ν)

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- 2 leptons with p_T > 30 GeV (or 20 GeV) with no third lepton
- 1,2 or 3 central jets with p_T > 20 GeV (no b-jets)
- BG: WW, WZ, ZZ, and backgrounds with non-prompt leptons (from heavy flavoured decays, γ conversions, misID jets)

6 SR (lepton flavour and N_{jets})

	SRee-1	SRee-2	SR$\mu\mu$-1	SR$\mu\mu$-2	SR$e\mu$-1	SR$e\mu$-2
Lepton flavours	ee	ee	$\mu\mu$	$\mu\mu$	$e\mu$	$e\mu$
n_{jet}	1	2 or 3	1	2 or 3	1	2 or 3
Leading lepton p_T (GeV)	>30	>30	>30	>30	>30	>30
Sub-leading lepton p_T (GeV)	>20	>20	>20	>30	>30	>30
$\lvert m_{\ell\ell} - m_Z \rvert$ (GeV)	>10	>10	–	–	–	–
$\Delta\eta_{\ell\ell}$	–	–	<1.5	<1.5	<1.5	<1.5
$E_T^{\text{miss,rel}}$ (GeV)	>55	>30	–	–	–	–
m_{eff} (GeV)	>200	–	>200	>200	>200	>200
m_T^{max} (GeV)	–	>110	>110	–	>110	>110
$m_{\ell j}$ or $m_{\ell jj}$ (GeV)	<90	<120	<90	<120	<90	<120

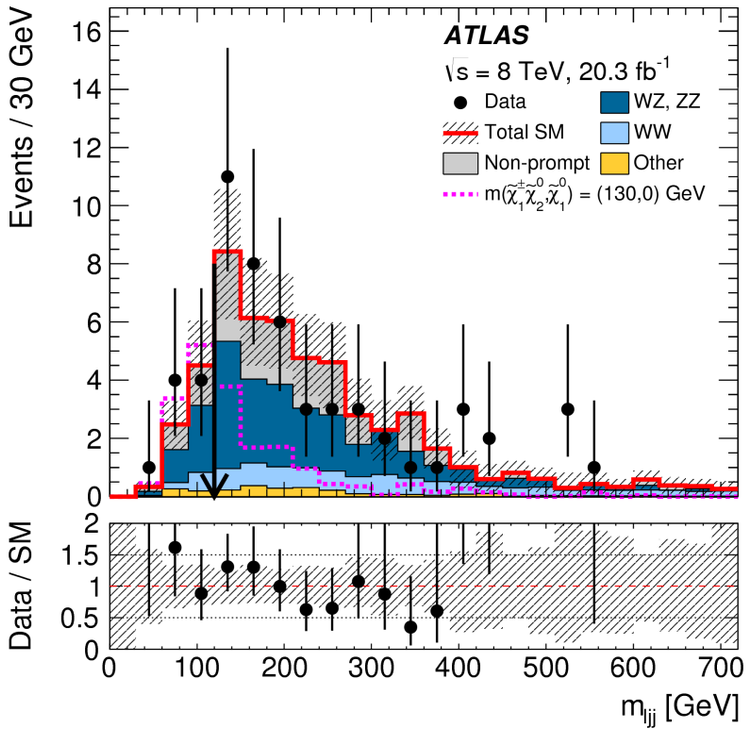
Validation regions having lepton p_T and N_{jets} only , m_{lj} > 90 and m_{llj} > 120 GeV

Background Estimation

arXiv:1403.5294

- Dibosons are estimated from simulation.
- matrix element method is used to estimate non-prompt backgrounds.
- Efficiencies for prompt and non-prompt leptons passing signal lepton requirements are calculated as function of p_T and η of leptons for each process in control regions.
- Contribution from each BG used to calculate weighted average efficiency.
- Charge mismeasurement probability measured in data and is < 1% (for ee).
- BG estimation tested in validation regions.

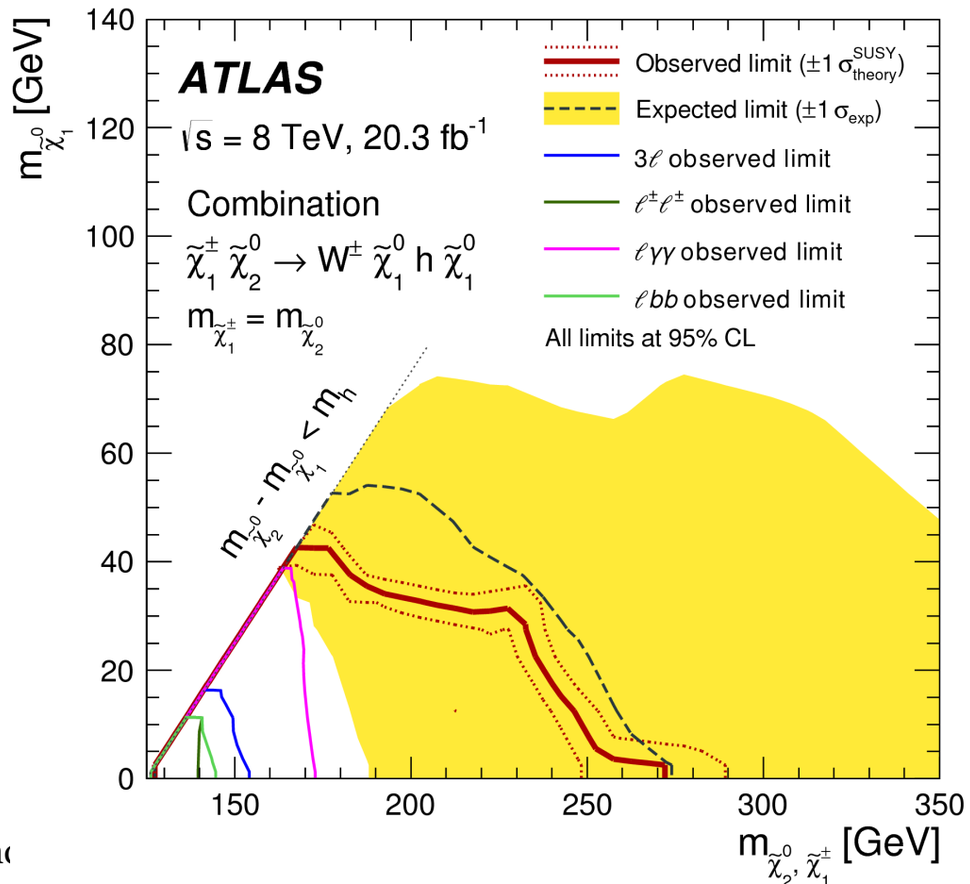
Signal Region



	SRee-1	SRee-2	SR$\mu\mu$-1	SR$\mu\mu$-2	SR$e\mu$-1	SR$e\mu$-2
Observed events	2	1	6	4	8	4
SM expectation	6.0 $\pm$1.2	2.8 $\pm$0.8	3.8 $\pm$0.9	2.6 $\pm$1.1	7.0 $\pm$1.3	1.9 $\pm$0.7
Non-prompt	3.4 $\pm$1.0	1.6 $\pm$0.5	0.00 $\pm$ 0.20	0.3 $\pm$0.4	3.0 $\pm$0.9	0.48 $\pm$ 0.28
WZ, ZZ	2.2 $\pm$0.6	0.7 $\pm$0.4	3.4 $\pm$0.8	1.8 $\pm$0.9	3.3 $\pm$0.8	1.1 $\pm$0.5
WW	0.33 $\pm$ 0.31	0.22 $\pm$ 0.23	0.24 $\pm$ 0.29	0.4 $\pm$0.5	0.4 $\pm$0.4	0.23 $\pm$ 0.26
Other	0.13 $\pm$ 0.13	0.31 $\pm$ 0.31	0.14 $\pm$ 0.14	0.06 $\pm$ 0.06	0.19 $\pm$ 0.17	0.09 $\pm$ 0.08

Table showing BG yield and Data in different Signal Regions (consistent with SM prediction)

- Combined limit plot including ATLAS 3-lepton searches result. arXiv:1402.7029 - JHEP
- 95% CL exclusion region extends to 250 GeV for $m_{\tilde{\chi}_1^0} = 0$.



Searches via h(→ WW→ l± + jets) W(→l±ν)

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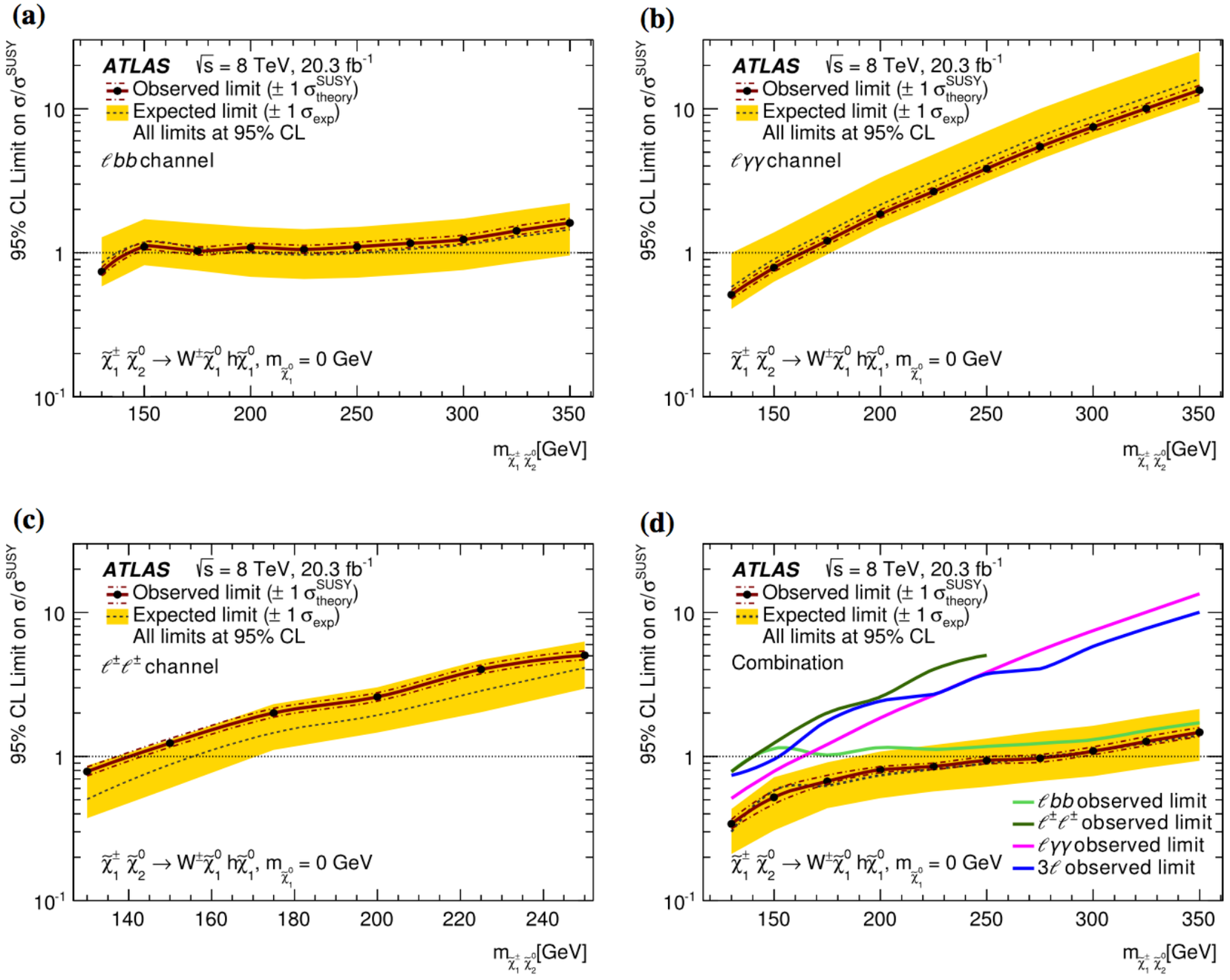

Fig. 7 Observed (*solid line*) and expected (*dashed line*) 95 % CL upper limits on the cross section normalised by the simplified model prediction as a function of the common mass $m_{\tilde{\chi}_1^\pm \tilde{\chi}_2^0}$ for $m_{\tilde{\chi}_1^0} = 0$. The combination in **d** is obtained using the result from the ATLAS three-lepton search [21] in addition to the three channels reported in this paper. The *dash-dotted lines* around the observed limit represent the results obtained when changing the nominal signal cross section up or down by the $\pm 1\sigma_{\text{theory}}^{\text{SUSY}}$ theoretical uncertainty. The *solid band around the expected limit* represents the $\pm 1\sigma_{\text{exp}}$ uncertainty band where all uncertainties, except those on the signal cross sections, are considered. **a** One lepton and two *b*-jets channel, **b** one lepton and two photons channel, **c** same-sign dilepton channel, **d** combination

Searches via h(→ WW→ l± + jets) W(→l±ν)

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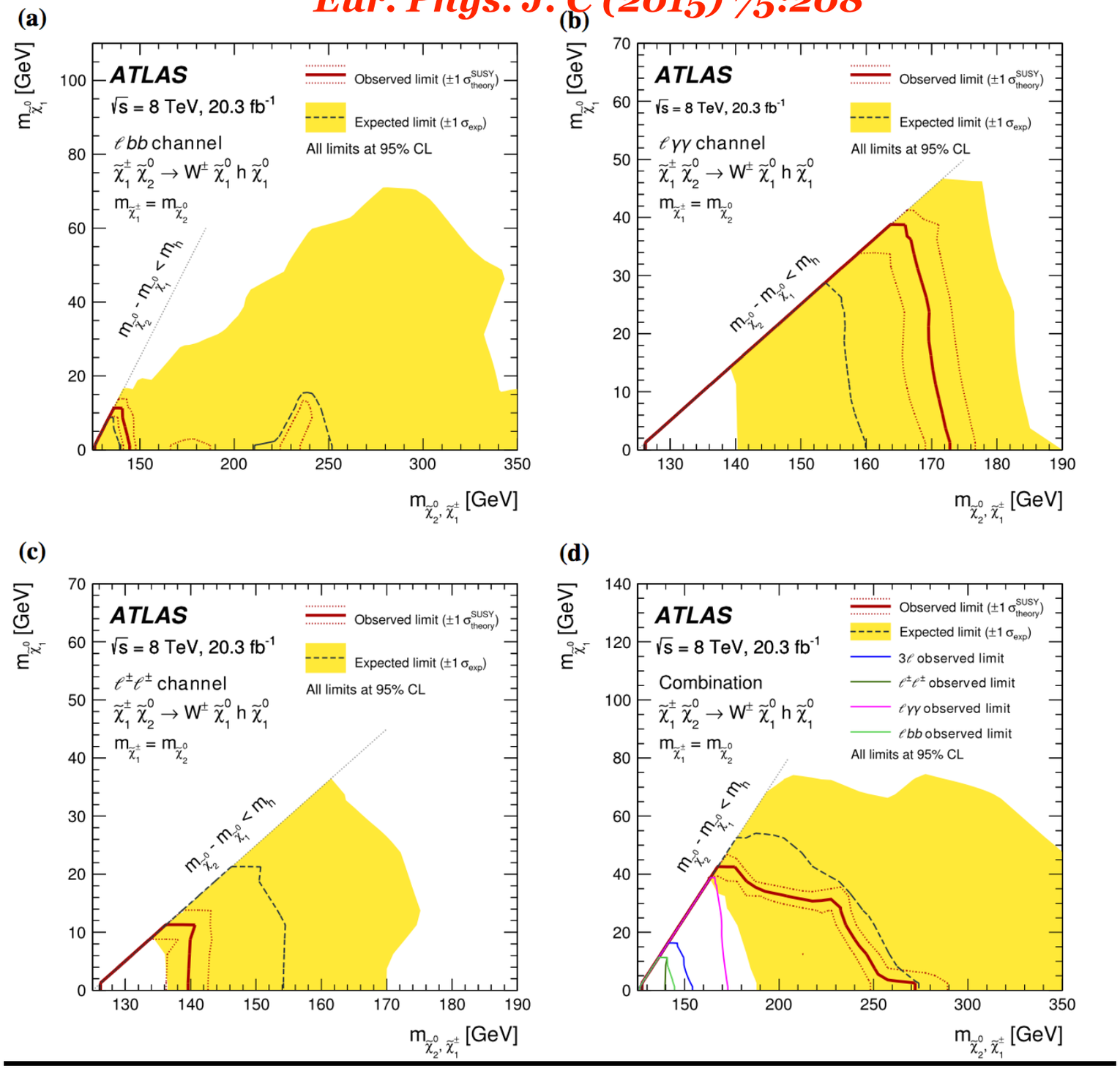

Searches via h(→ WW→ l± + jets) W(→l±ν)

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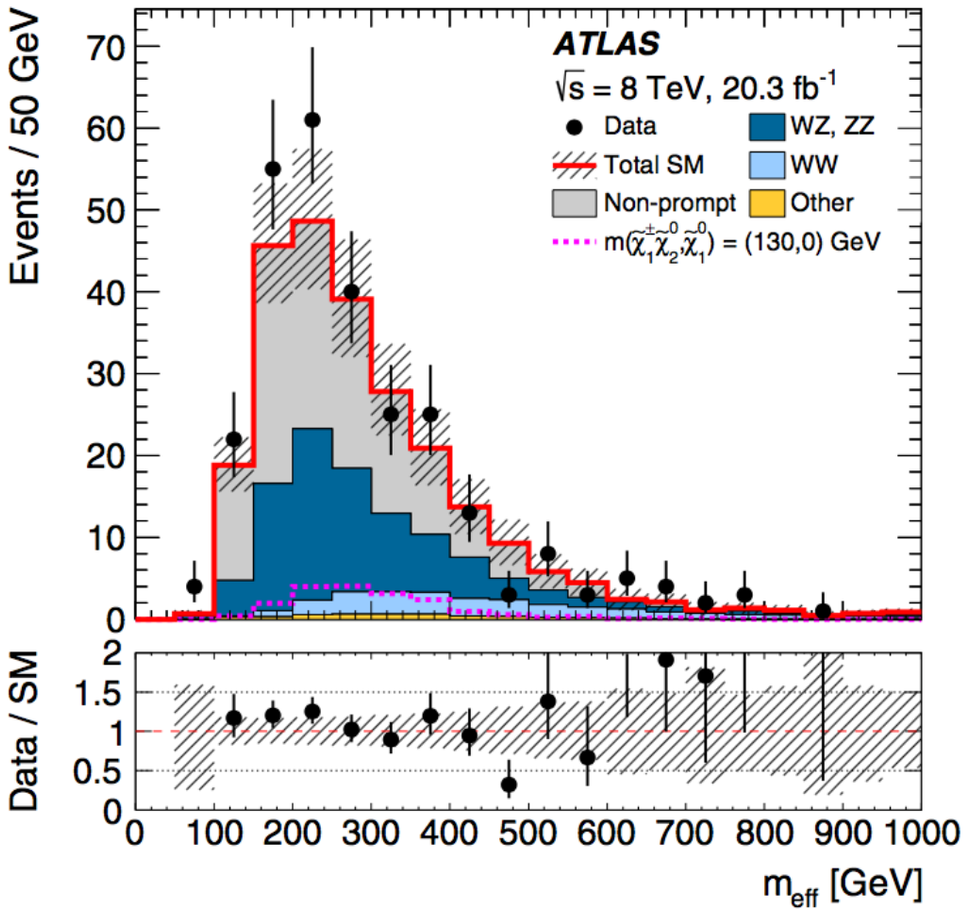
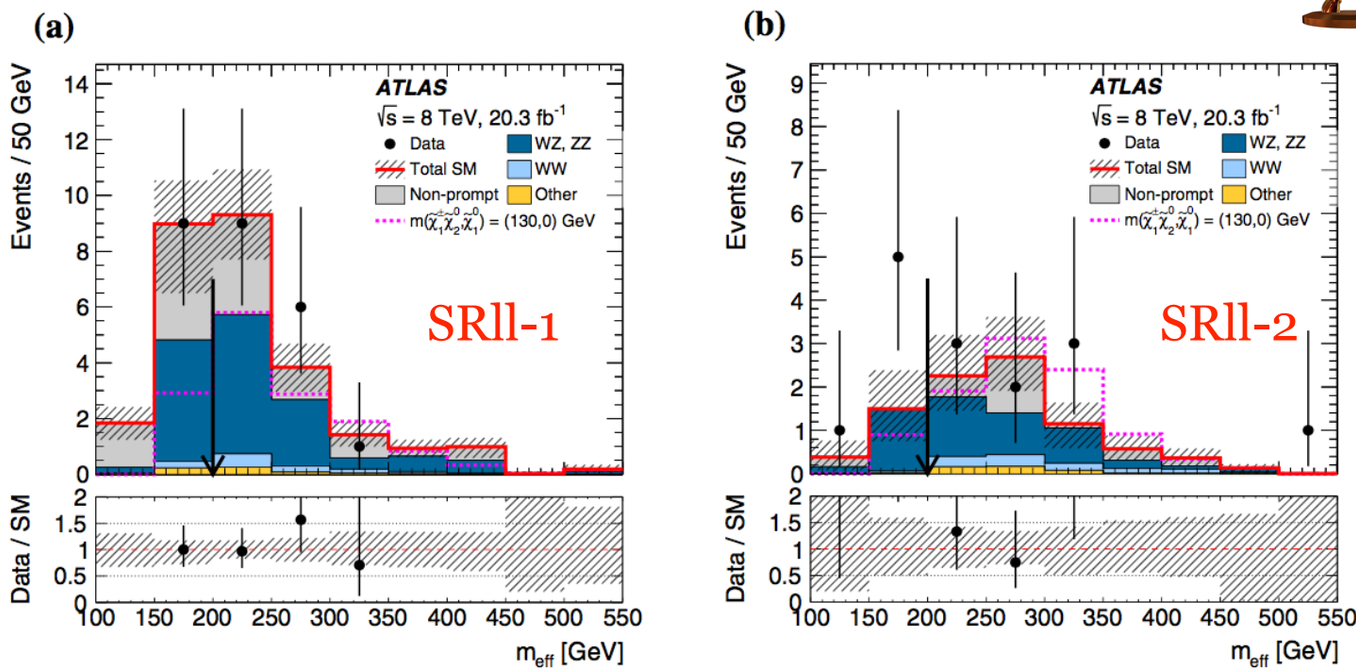
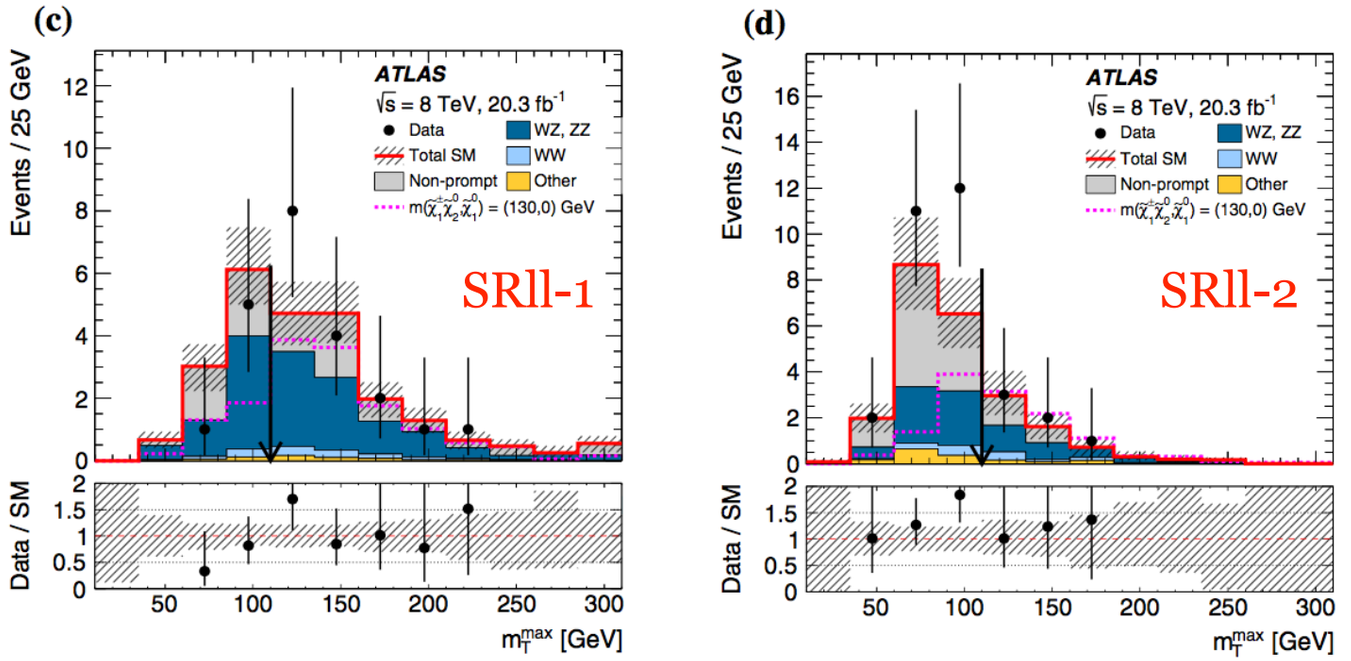


Data-MC agreement in VR of same-sign eμ region



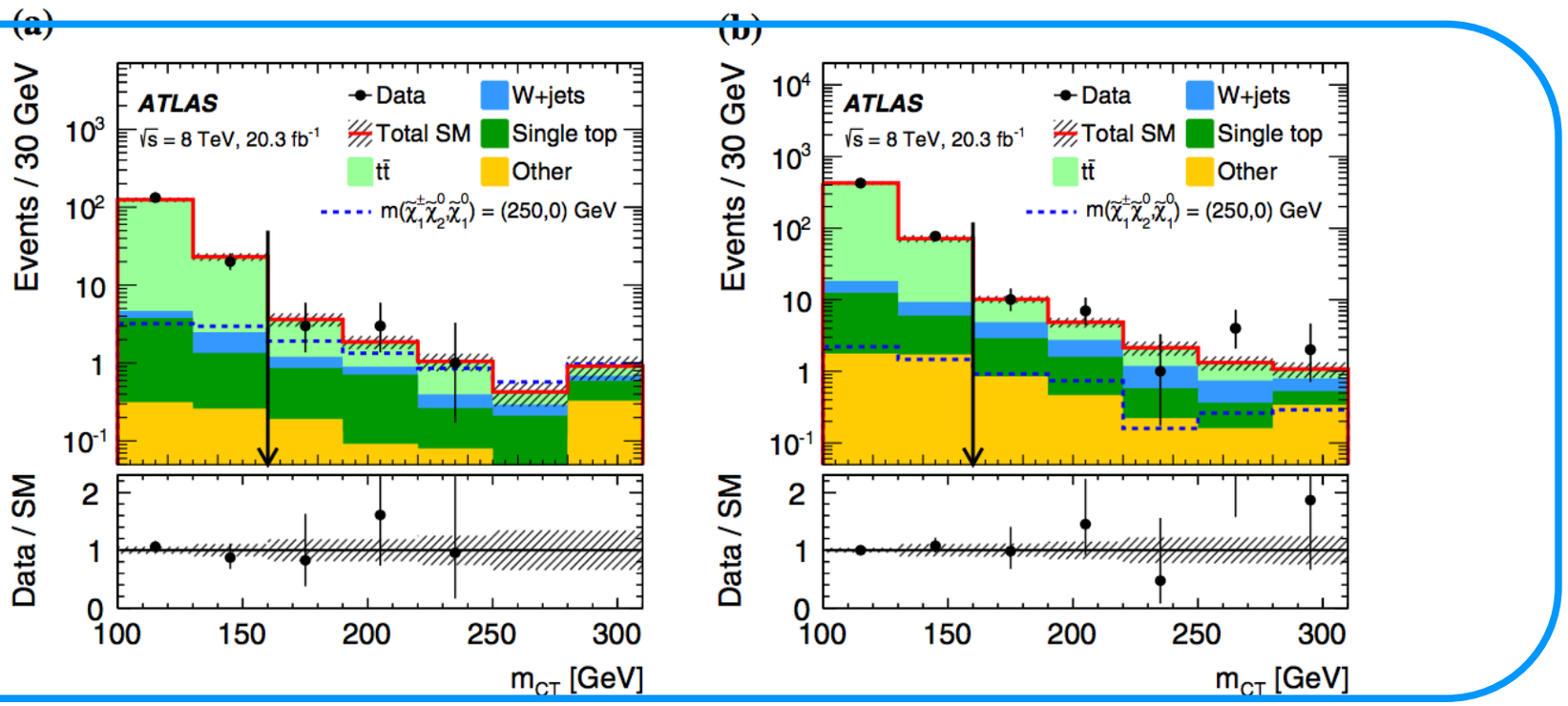


Distributions in SR for same-sign lepton search

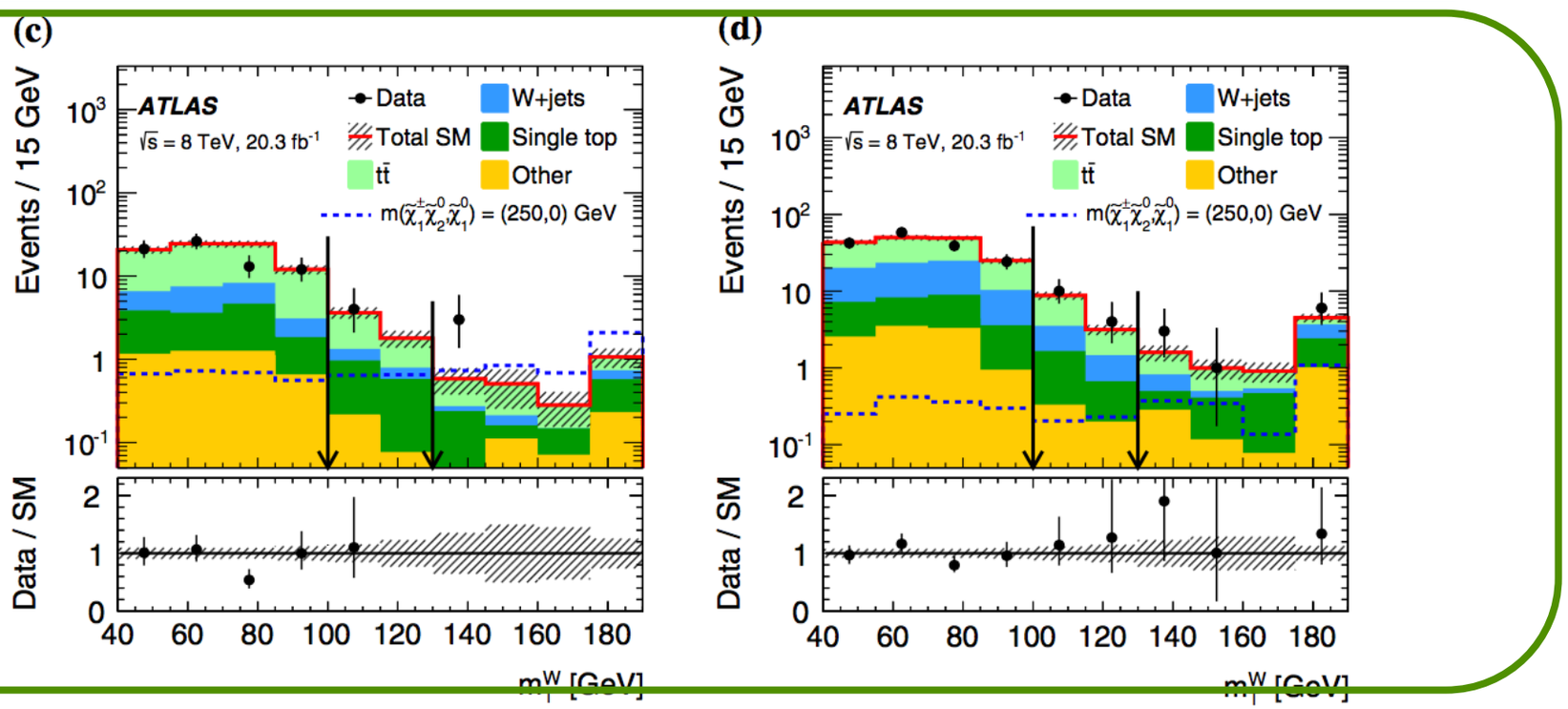
Searches via h(→bb̄) W(→lν)

m_{bb} central bins **m_{bb} side bands**

CRlbb-T, SRlbb-1, SRlbb-2



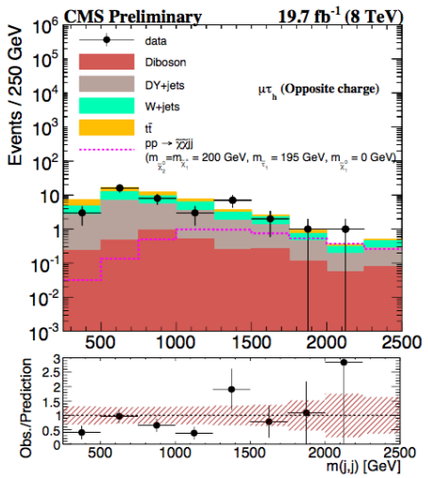
VRlbb-2, SRlbb-1, SRlbb-2

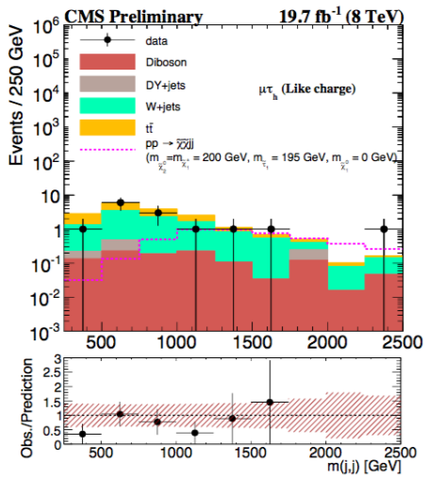


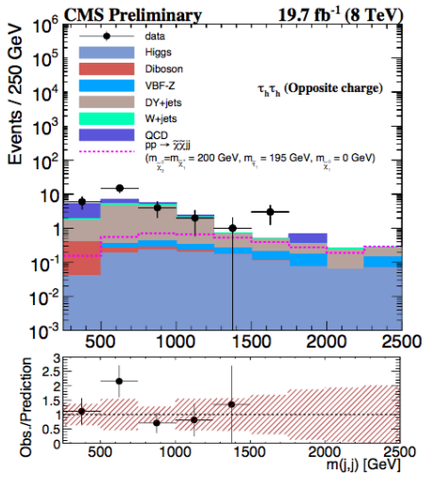
Searches via VBF process with ≥ 2 leptons

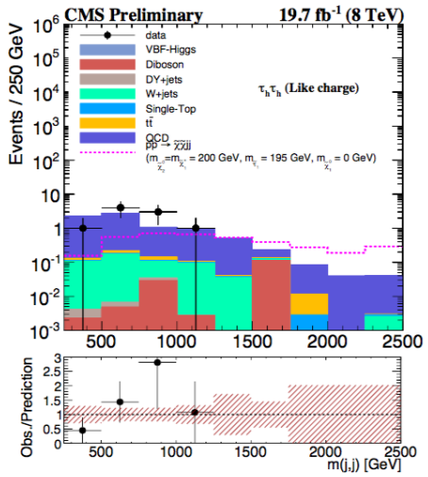
CMS PAS SUS-14-005

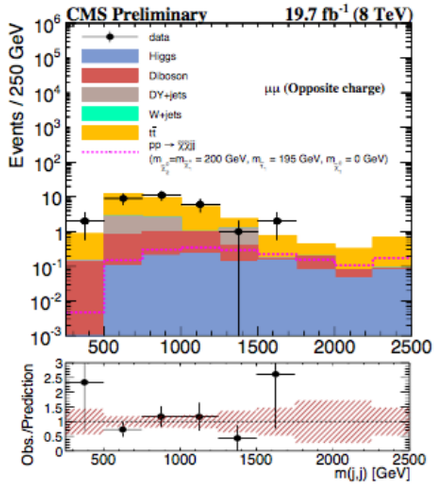
mjj plots in individual channels

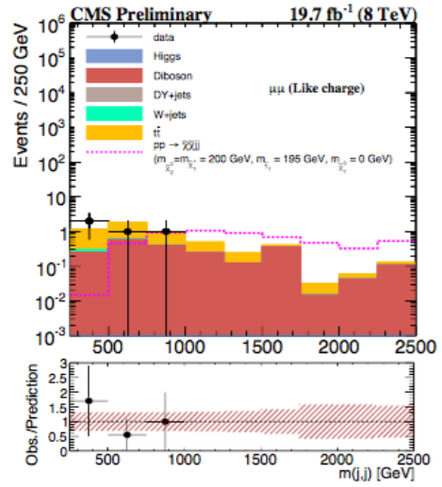


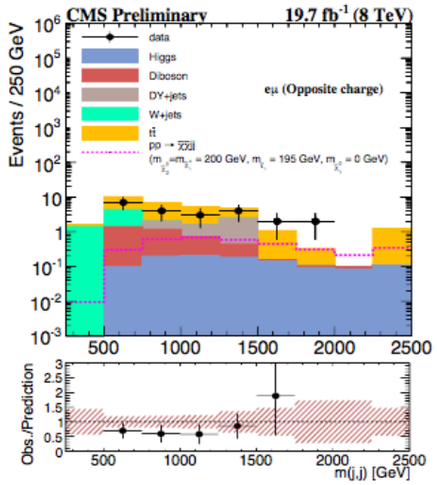


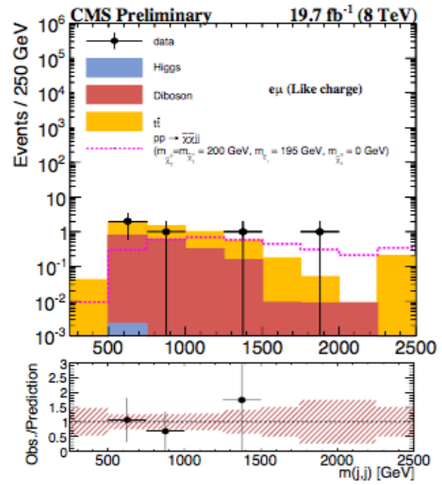












Searches via VBF process with ≥ 2 leptons

CMS PAS SUS-14-005

Table 3: Cumulative signal acceptance for $m_{jj} > 250$ GeV.

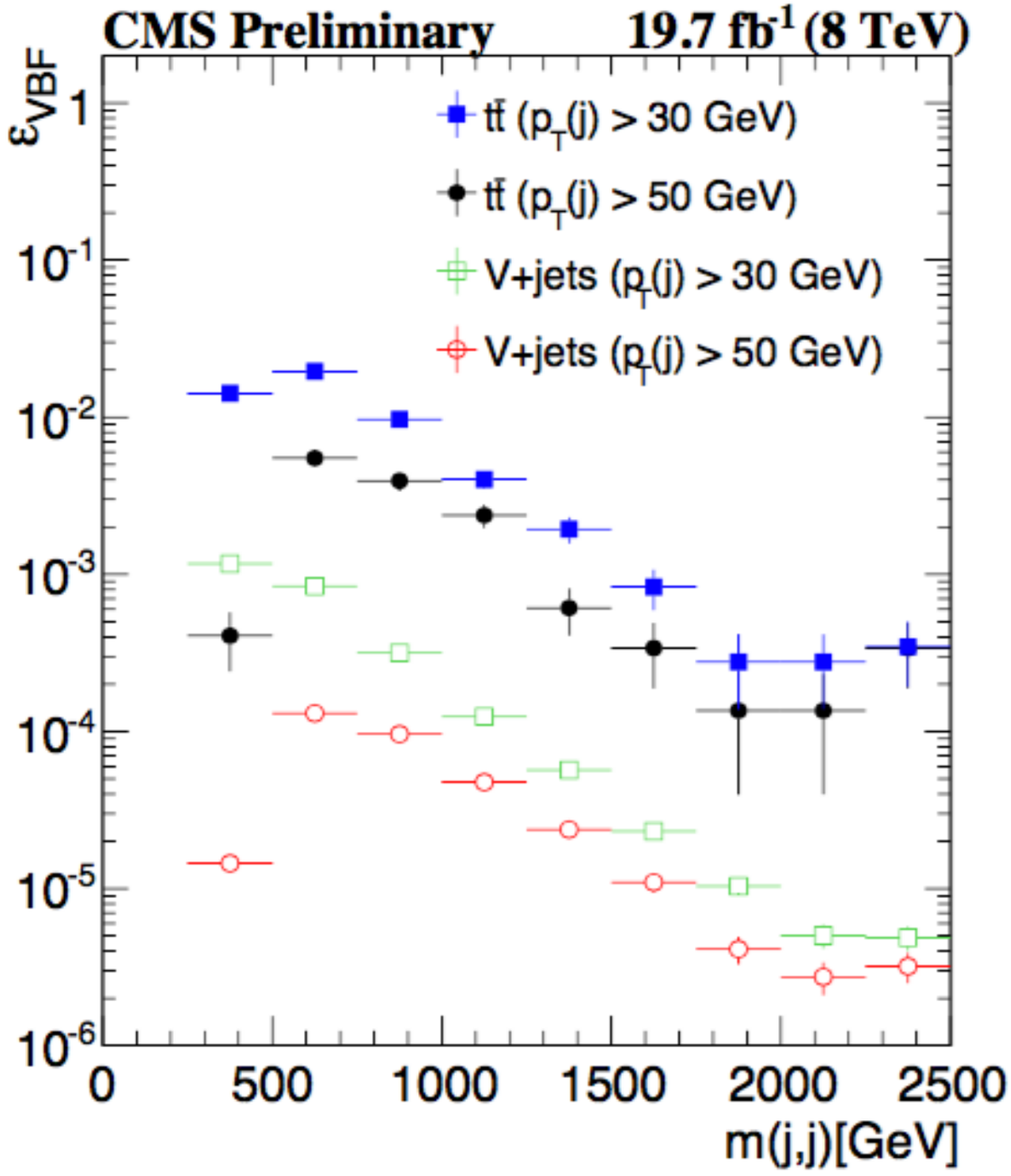
channel	BR($\geq 1\ell_1$ & $\geq 1\ell_2$)	ll+MET	VBF
$\mu^+\tau_h^-$ ($\mu^\pm\tau_h^\pm$)	0.399	0.0197 (0.0196)	0.0075 (0.0074)
$e^+\mu^-$ ($e^\pm\mu^\pm$)	0.152	0.0367 (0.0373)	0.0140 (0.0140)
$\tau_h^+\tau_h^-$ ($\tau_h^\pm\tau_h^\pm$)	0.717	0.0098 (0.0097)	0.0092 (0.0093)
$\mu^+\mu^-$ ($\mu^\pm\mu^\pm$)	0.081	0.0181 (0.0180)	0.0070 (0.0172)

Table 4: Simulated yield of signal events. The terms in only curly brackets, $\{m_{\tilde{\chi}_1^\pm}, m_{\tilde{\tau}}\}$, represent the scenarios where $\Delta m(\tilde{\chi}_1^\pm, \tilde{\tau}) = 5$ GeV, while the terms in parenthesis, $(\{m_{\tilde{\chi}_1^\pm}, m_{\tilde{\tau}}\})$, are for scenarios where $m(\tilde{\tau}_1) = \frac{1}{2}m(\tilde{\chi}_1^0) + \frac{1}{2}m(\tilde{\chi}_1^\pm)$.

$\{m(\tilde{\chi}_1^\pm), m(\tilde{\tau})\}$ [GeV]	$\mu^\pm\mu^\pm jj$ (Loose)	$\mu^\pm\mu^\mp jj$ (Tight)	eμjj	$\mu\tau_h jj$	$\tau_h\tau_h jj$
$m(\tilde{\chi}_1^0) = 0$ GeV					
{100, 95} ({100, 50})	16.22(28.94)	6.61(11.79)	13.21(23.57)	7.10(9.36)	8.65(10.73)
{200, 195} ({200, 100})	5.42(9.67)	1.76(3.14)	3.52(6.28)	4.53(5.97)	3.76(4.67)
{300, 295} ({300, 150})	2.27(4.05)	0.68(1.21)	1.37(2.44)	1.85(2.54)	1.53(2.04)
{400, 395} ({400, 200})	0.57(1.02)	0.17(3.03)	0.35(0.62)	0.46(0.63)	0.38(0.51)
$m(\tilde{\chi}_1^0) = 50$ GeV					
{100, 95} ({100, 75})	5.66(2.21)	3.30(1.29)	6.60(2.58)	4.34(1.51)	2.07(0.41)
{200, 195} ({200, 125})	3.03(5.41)	1.11(1.98)	2.21(3.94)	3.06(4.04)	2.41(2.99)
{300, 295} ({300, 175})	1.27(2.27)	0.60(1.07)	1.19(2.12)	1.66(2.28)	1.40(1.86)
{400, 395} ({400, 225})	0.34(0.61)	0.16(0.29)	0.32(0.57)	0.43(0.59)	0.36(0.48)
$\Delta m(\tilde{\chi}_1^\pm - \tilde{\chi}_1^0) = 50$ GeV					
{200, 195} ({200, 175})	1.38(0.54)	0.85(0.33)	1.65(0.65)	0.99(0.35)	0.46(0.09)
{300, 295} ({300, 275})	0.47(0.18)	0.28(0.11)	0.58(0.23)	0.40(0.14)	0.20(0.04)
{400, 395} ({400, 375})	0.12(0.05)	0.08(0.03)	0.15(0.06)	0.10(0.03)	0.05(0.01)

Searches via VBF process with ≥ 2 leptons

CMS PAS SUS-14-005



10.1103/PhysRevD.87.035029

VBF topology cuts