Searches for Electroweak SUSY Production with Higgs Bosons at CMS

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on behalf of the CMS collaboration

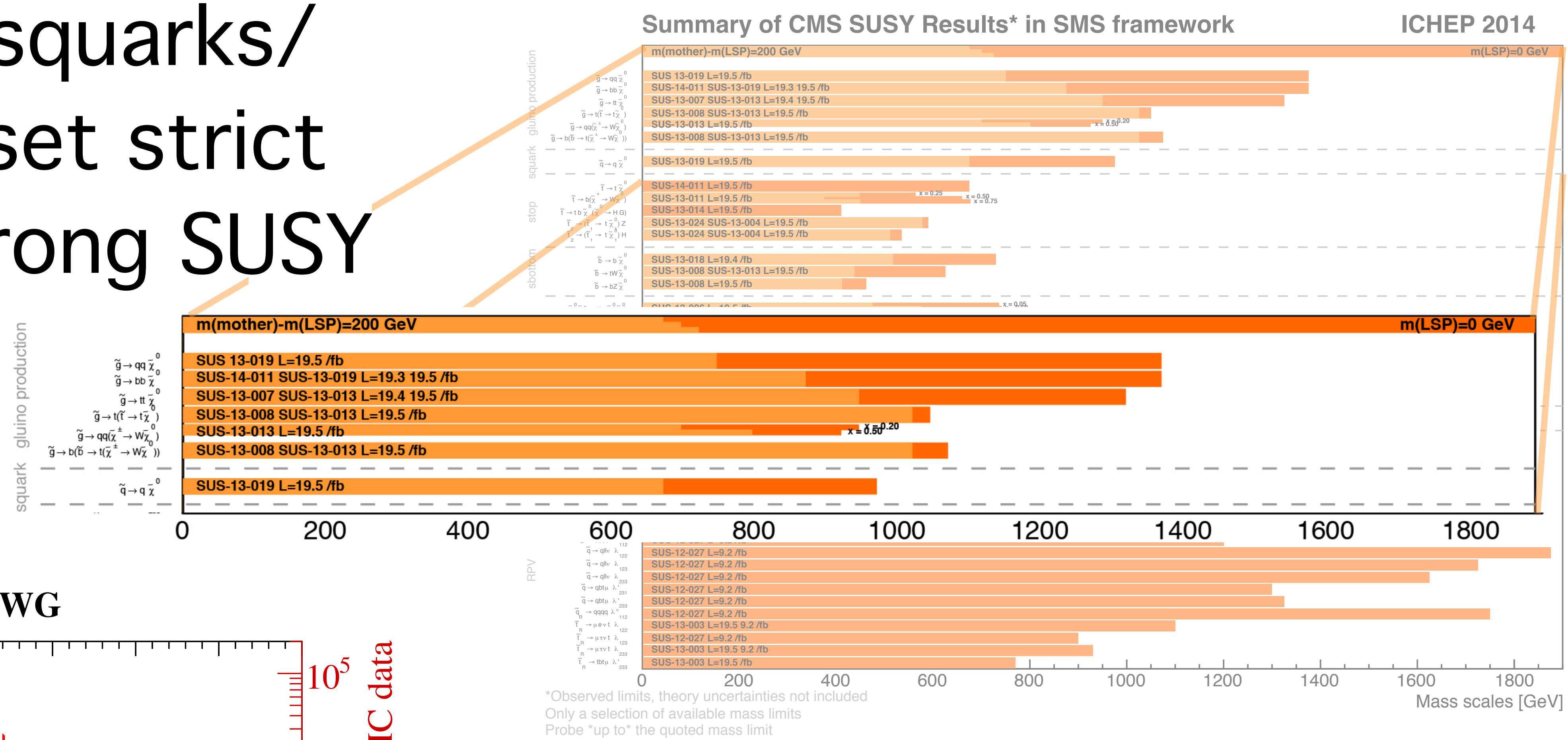
Northeastern

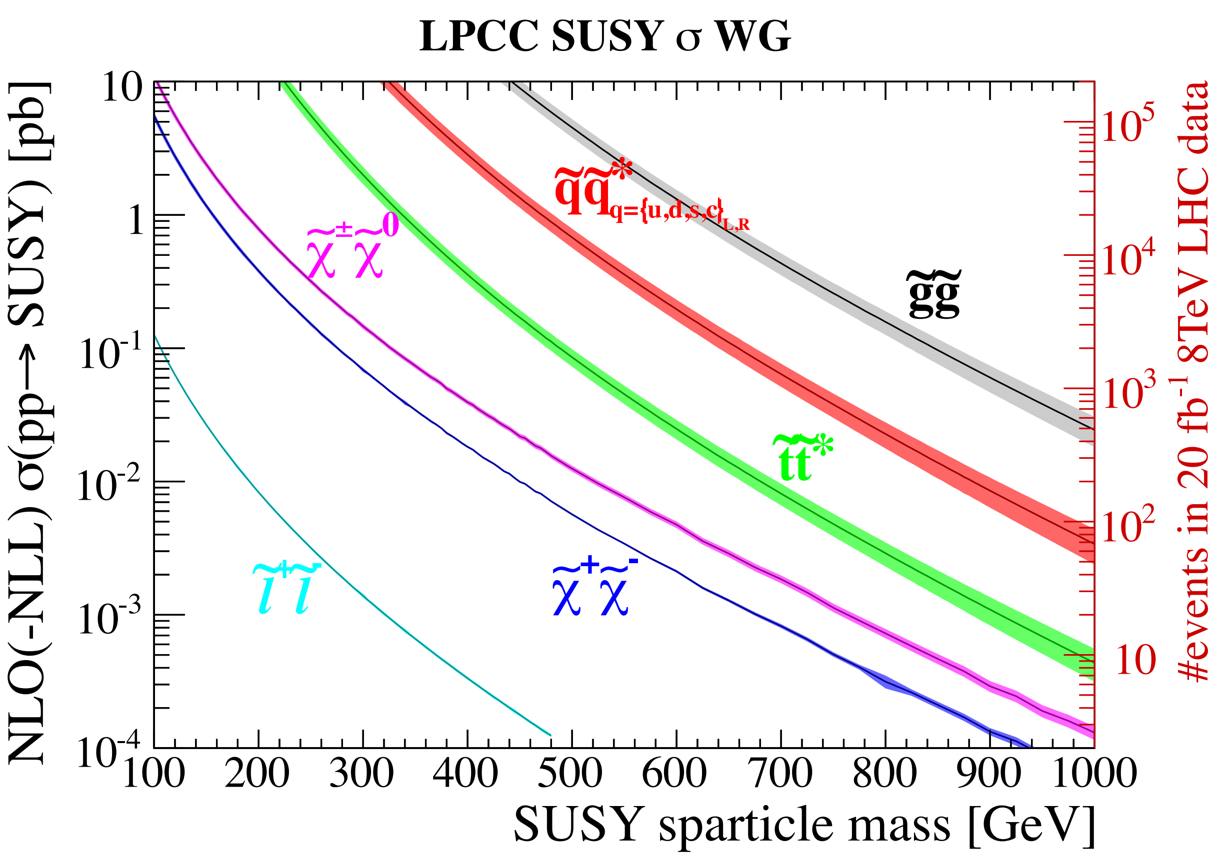
Kruger 2014

Discovery Physics at the LHC

Electroweak SUSY

Searches for squarks/ gluinos have set strict bounds on strong SUSY production





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

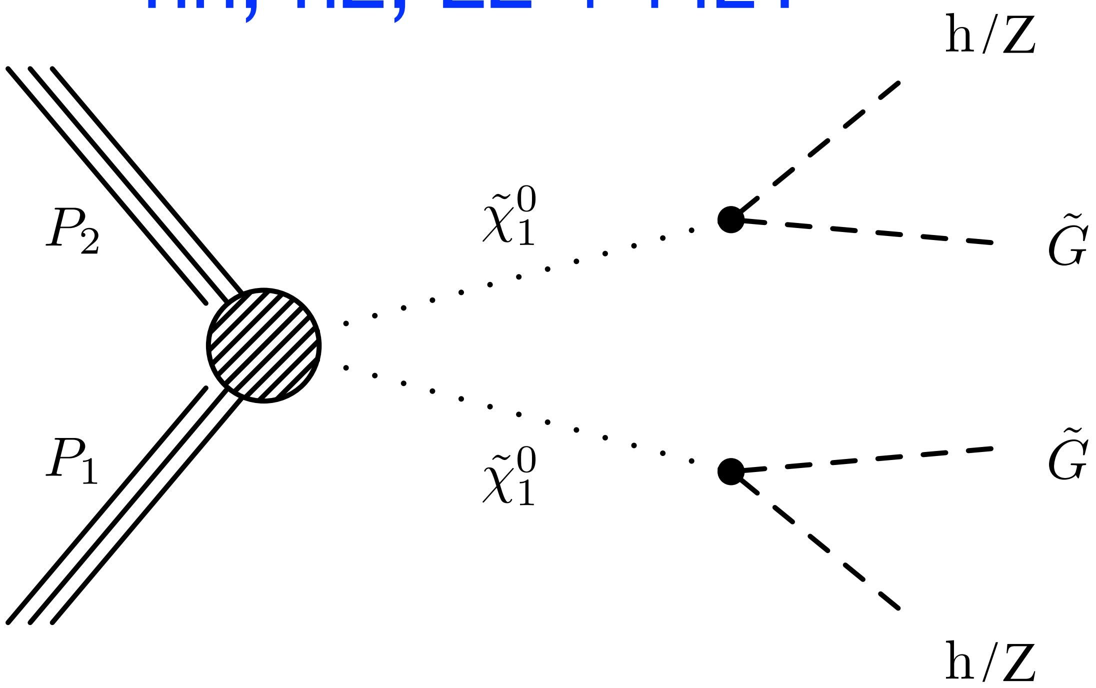
Direct electroweak production of charginos / neutralinos has smaller cross sections and lower jet multiplicities

Electroweak Signatures

2 main models, many final states

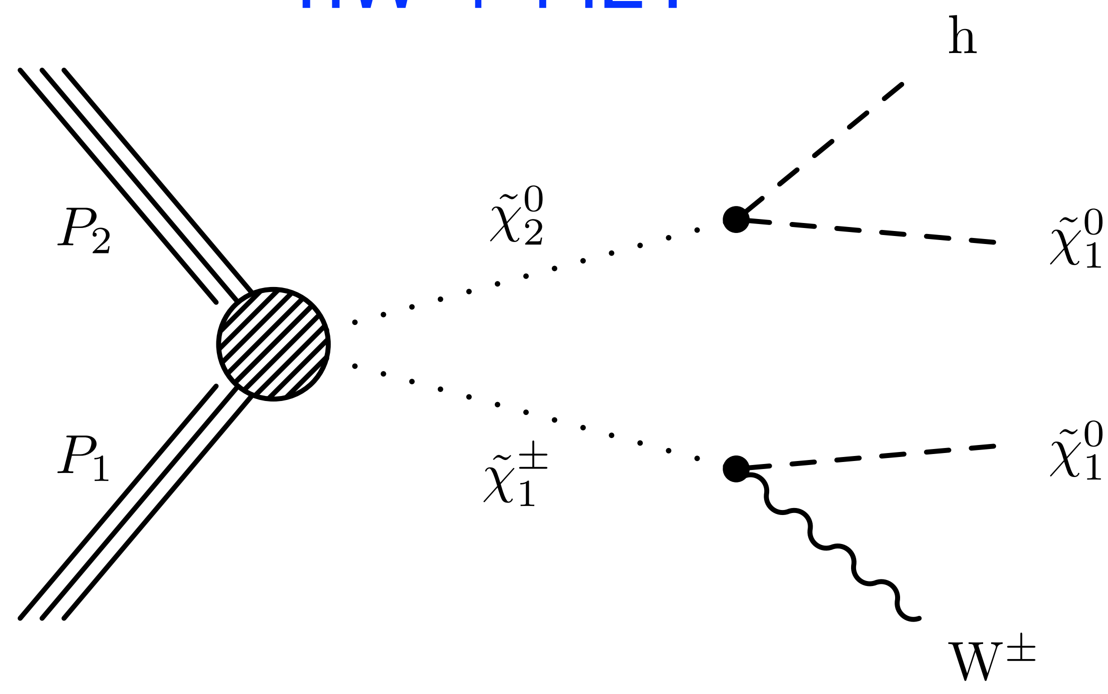
– GMSB model with Higgsino NLSP and ~massless $\tilde{G}$ LSP

- hh, hZ, ZZ + MET



– Chargino/neutralino co-NLSP with massive $\tilde{\chi}_1^0$ LSP

- hW + MET



Discovery of ~125 GeV Higgs Boson provides new SUSY search handle: “higgs tagging”

Here h is lightest SUSY CP-even higgs, which can be SM-like, if other higgs-es are heavy

Channels & Documentation

- Search Channels
  - h(γγ)+hadrons. SUS-14-002
  - h(γγ)+leptons. SUS-14-002
  - h(bb)Z(ll) SUS-14-002
  - hh→4b SUS-13-022
  - Inclusive multi leptons. . . SUS-13-002 arXiv:1404.5801 accepted by PRD
  - Z(ll)Z(jj) . . . . SUS-13-006 arXiv:1405.7570 Eur. Phys. J. C 74 (2014) 3036

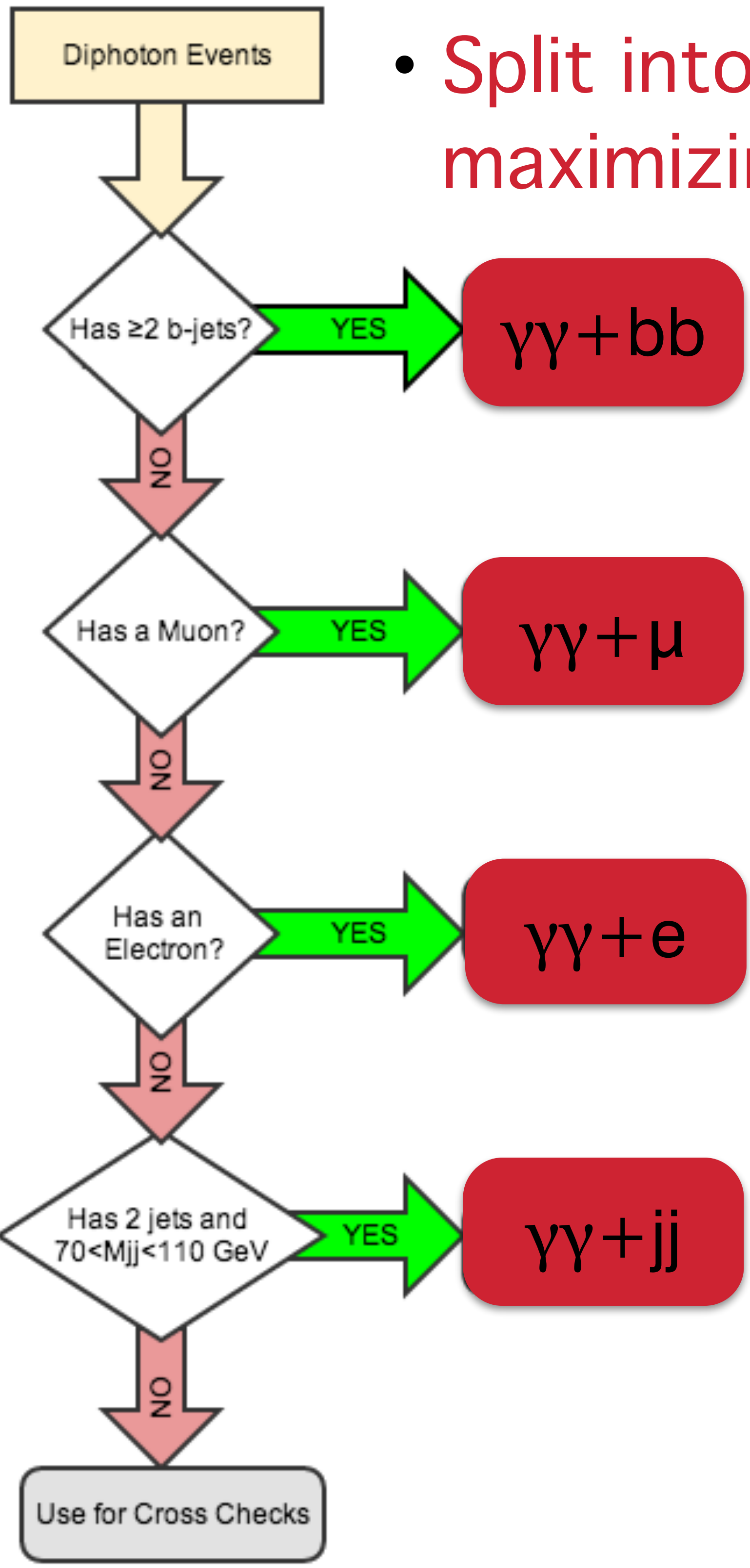
All results use 19.5 fb^{-1} @ $\sqrt{s}$=8 TeV

- hW+MET reinterpretation of SUS-13-017 with addition of h→γγ channels. SUS-14-002
- Higgsino Combination & Interpretation SUS-14-002

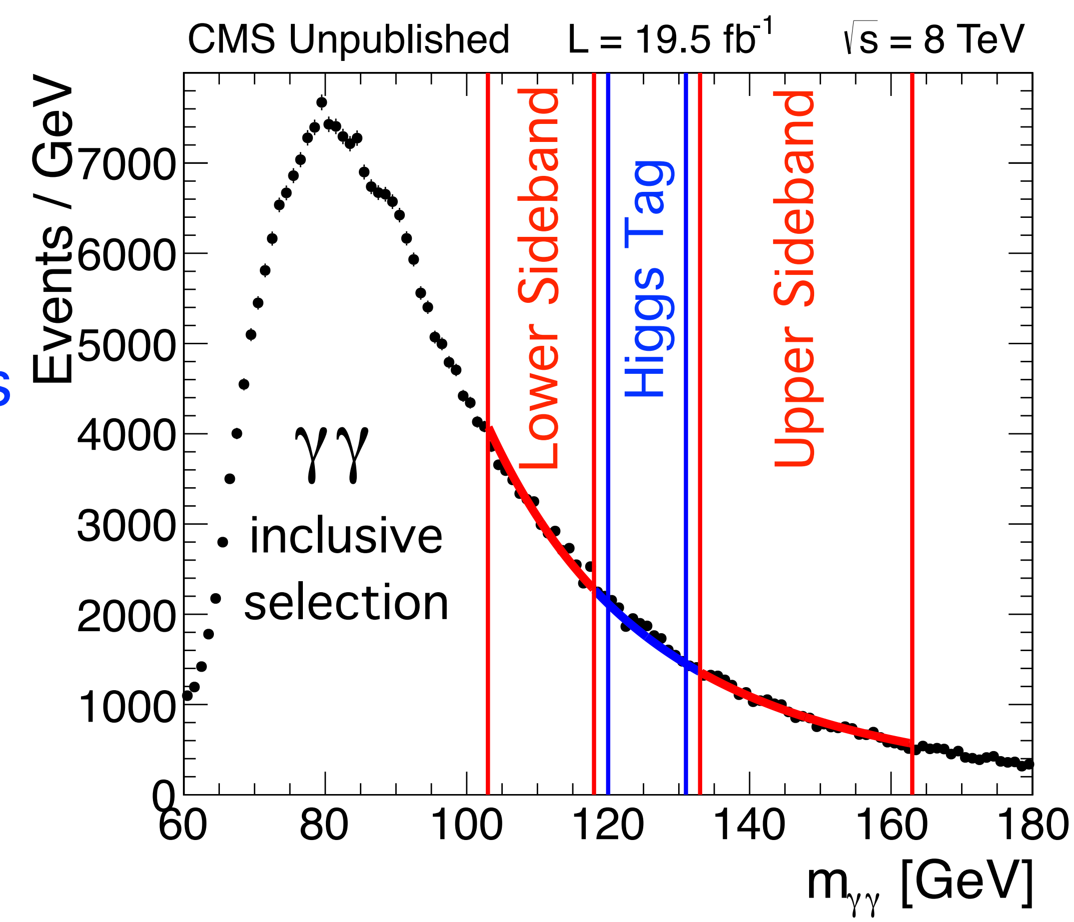
arXiv:1409.3168
Phys. Rev. D 90 (2014) 092007

https://twiki.cern.ch/twiki/bin/viewauth/CMSPublic/PhysicsResultsSUS14002

$\gamma\gamma$+X



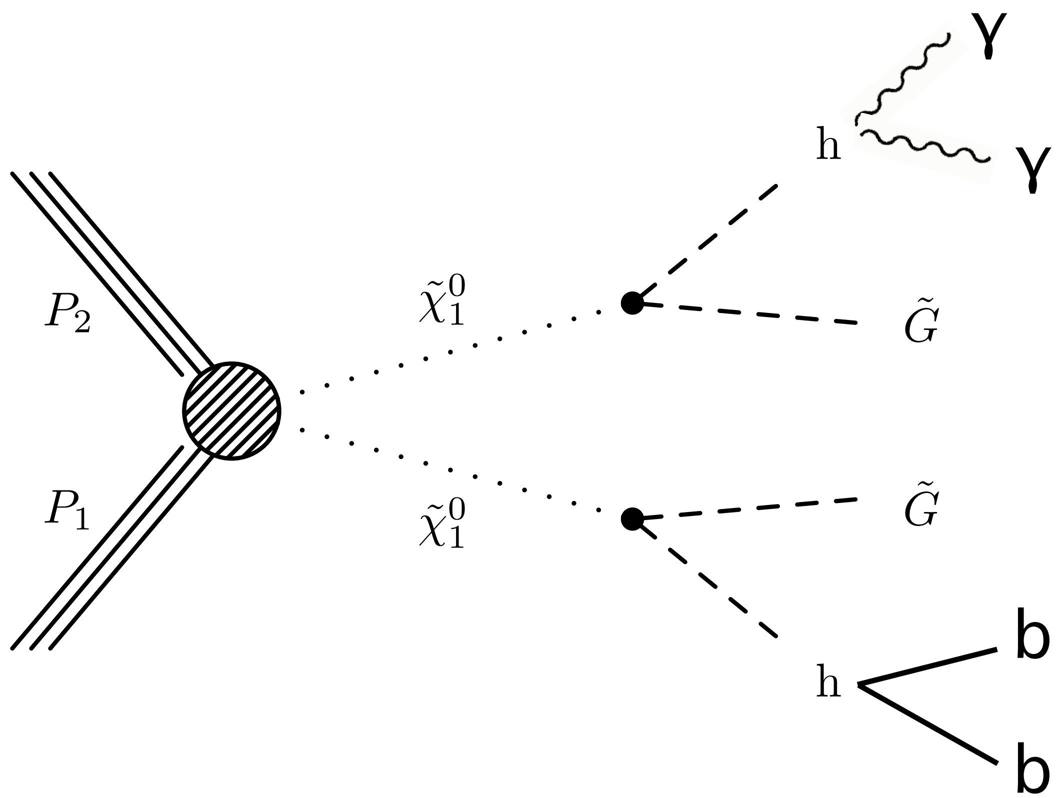
- Split into 4 orthogonal channels, preferentially maximizing sensitivity and purity



1. Make $\gamma\gamma$+X selection
2. SM non-Higgs background estimated using sidebands of Higgs mass window
    - Kinematic shapes taken from lower and upper sidebands
    - Each channel makes a power law fit to the invariant mass distribution, excluding the Higgs Tag window
    - Extrapolation into Higgs Tag window gives normalization of non-Higgs SM backgrounds
3. SM Higgs background estimated from simulation
4. Compare data in Higgs Tag window with SM background expectation in a sensitive variable

γγ+bb - 2 Higgs Channel

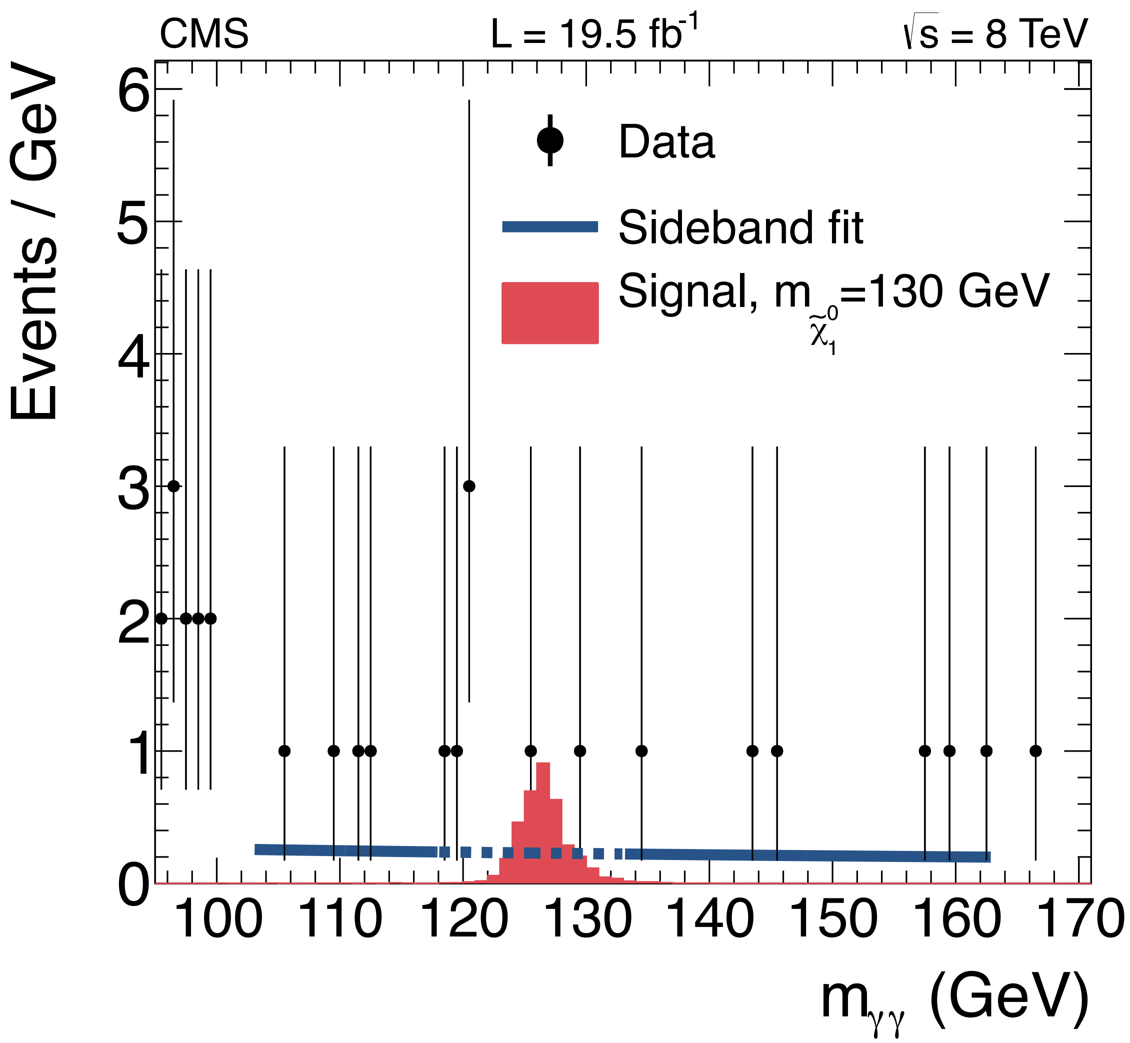
- Targets higgsino model, hh production with h(γγ)h(bb)
  - Require exactly 2 b-jets in Higgs mass window
  - Discriminating variable: $\text{Higgs } S_T = \left(\vec{p}_{\gamma 1} + \vec{p}_{\gamma 2}\right)_T + \left(\vec{p}_{b1} + \vec{p}_{b2}\right)_T$
  - SM Higgs contribution negligible

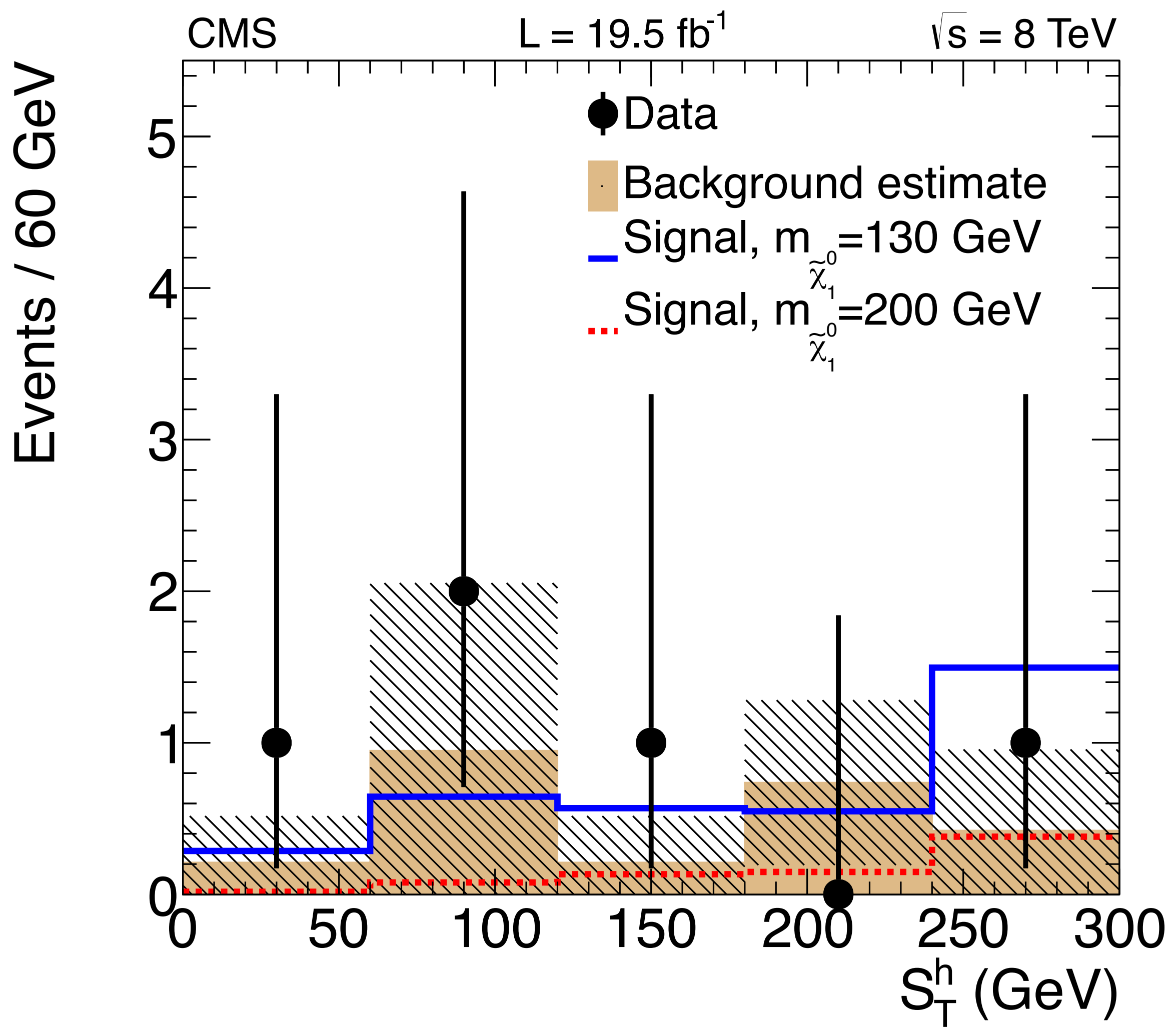


- All channels use identical photon selection and background estimation methods
  - 2 barrel photons, |η|<1.4442
  - Leading (trailing) photon E_T>40 (25)
  - $\Delta R(\gamma_1,\gamma_2)>0.5$, $\Delta\Phi(\gamma_1,\gamma_2)>0.05$

γγ+bb Results

S_T^h bin (GeV)	SM background	Data	hh events, $m_{\tilde{\chi}_1^0} = 130\,\text{GeV}$
0–60	$0.21^{+0.28}_{-0.21}$	1	0.28 ± 0.03
60–120	$0.95^{+0.99}_{-0.95}$	2	0.63 ± 0.04
120–180	$0.21^{+0.29}_{-0.21}$	1	0.55 ± 0.04
180–240	0.74 ± 0.38	0	0.53 ± 0.04
>240	$0.42^{+0.49}_{-0.42}$	1	1.46 ± 0.06

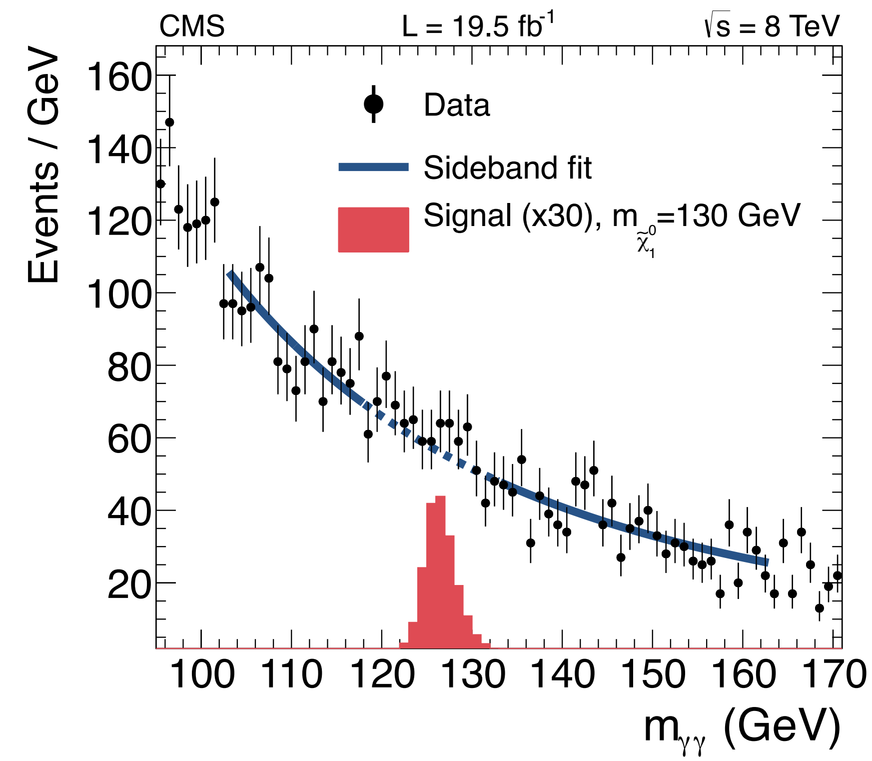


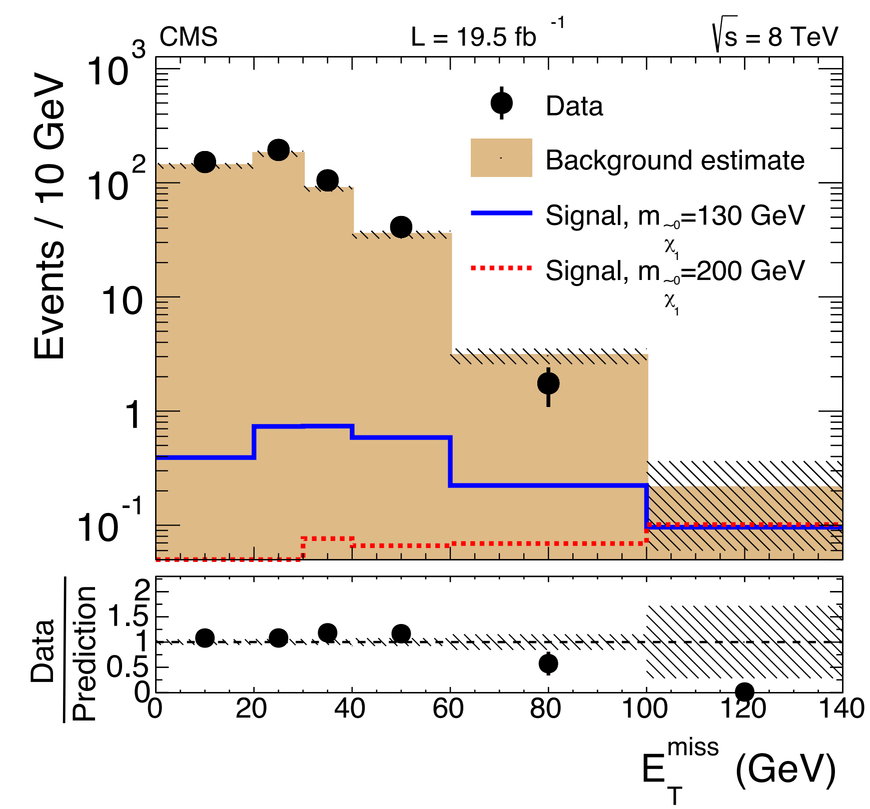


γγ+jj

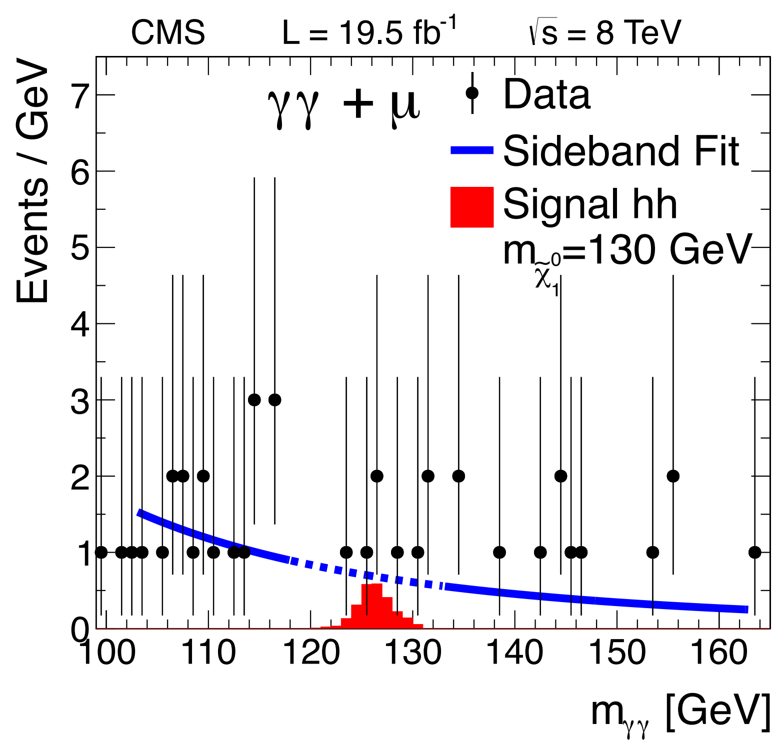
- Targets hV production with h(γγ)W/Z(jj)
  - –Veto events with ≥1 medium ID b-jet or ≥2 loose ID b-jets
  - –Veto events with ≥1 muon/electron
  - –Require jets in W/Z mass window $65<M_{jj}<120$ GeV
  - –MET is discriminating variable

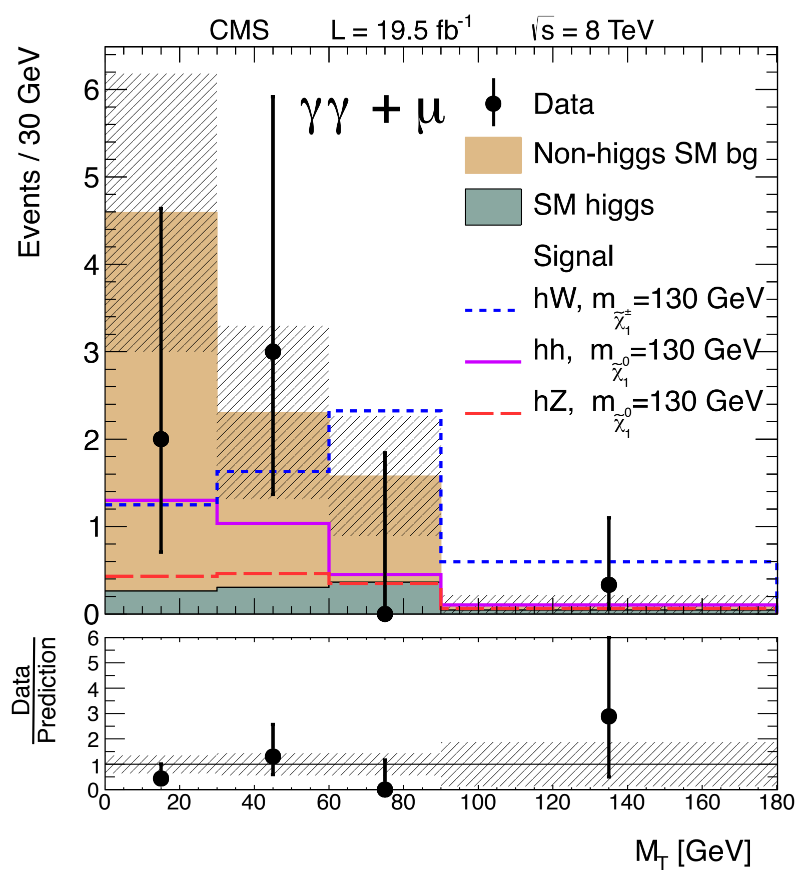
E_T^{miss} (GeV)	SM background	Data	hZ events, $m_{\tilde{\chi}_1^0} = 130$ GeV
0-20	282 ± 15	305	0.76 ± 0.03
20-30	180 ± 10	195	0.71 ± 0.03
30-40	89.0 ± 4.7	105	0.72 ± 0.03
40-60	70.8 ± 5.0	82	1.14 ± 0.04
60-100	12.2 ± 1.9	7	0.87 ± 0.03
>100	0.85 ± 0.61	0	0.37 ± 0.02





γγ+Muon





- Targets hh, hZ, hW
- Requires ≤1 b-jet, ≥1 muon
  - lepton p_T>15
  - $\Delta R(\ell,\gamma)>0.3$

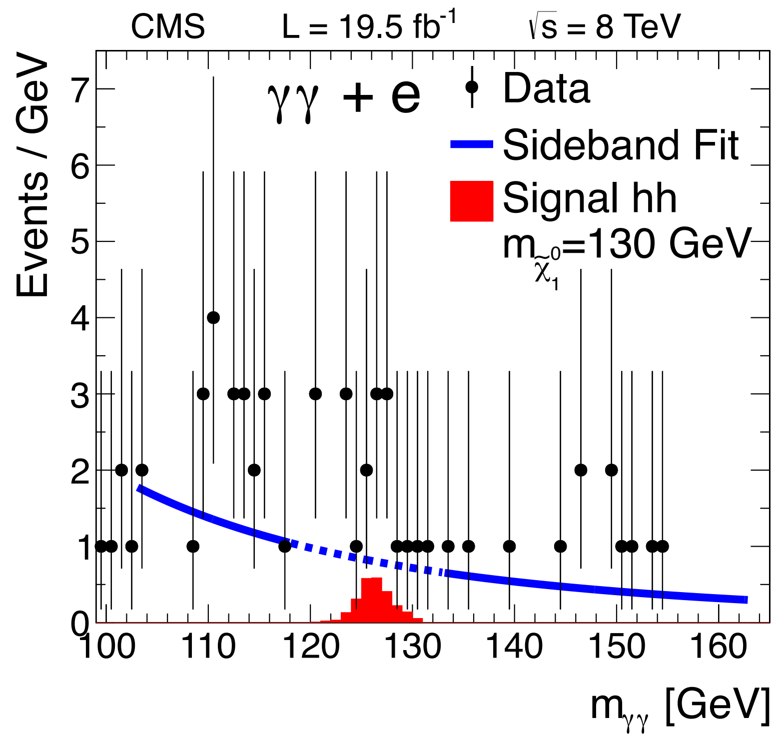
same for γγ+electron

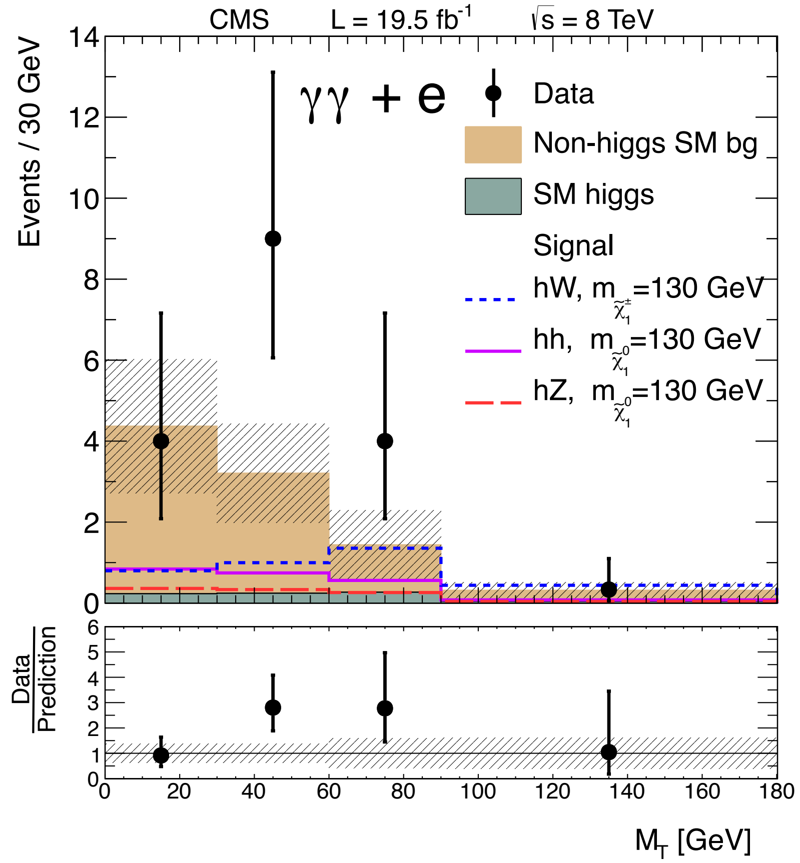
- Discriminating variable is transverse mass of lepton and missing energy

$$M_T = \sqrt{2E_T^{lepton}E_T^{miss}\left(1-\cos\left(\Delta\phi_{lepton,\,E_T^{miss}}\right)\right)}$$

	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

γγ+Electron



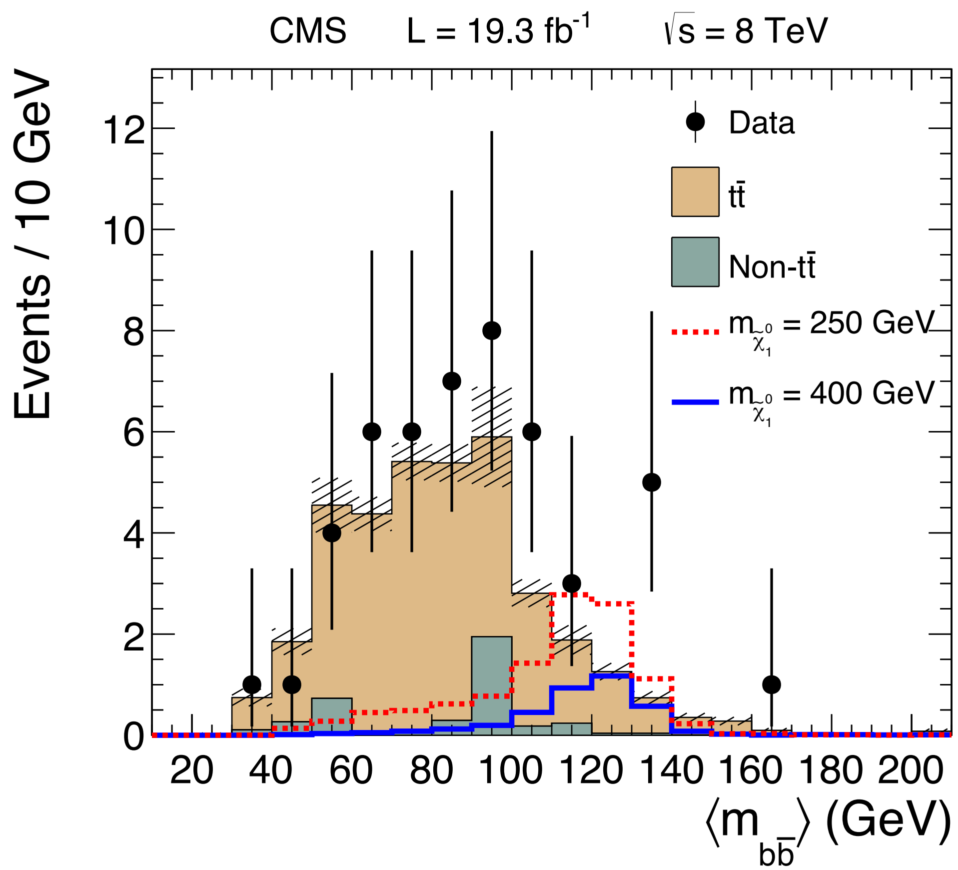


- Targets hh, hZ, hW
- Requires ≤1 b-jet, 0 muons, ≥1 electron
  - Veto $86<M_{e\gamma}<96$ to avoid Z contamination through e→γ mis-id
- Broad 2.1σ excess in electron channel
  - Excess events not signal-like (low MET)
  - Many checks to validate robustness of fit and background estimate
  - Consistent with statistical fluctuation

	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

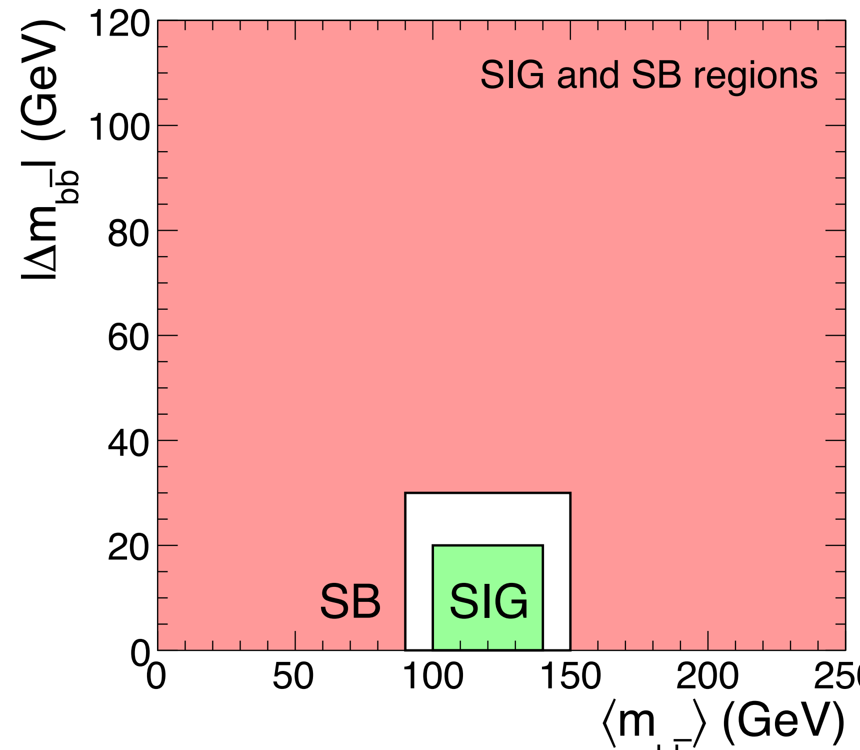
hh→4b

- Benefits from largest higgs branching fraction BR(h→bb)≈56%
- Selects exactly 4 or 5 jets, 2 of which have tight b-tags
  - 4 highest b-tag value jets are selected
  - Double Higgs reconstruction chosen to minimize $|\Delta m_{jj}| \equiv |m_{jj,1} - m_{jj,2}|$



- ALL SM backgrounds ($t\bar{t}$, single top, Vjets, QCD) estimated with ABCD method
  - Sidebands in <M_{bb}>and ΔM_{bb}
  - Background extrapolated from 2b sample

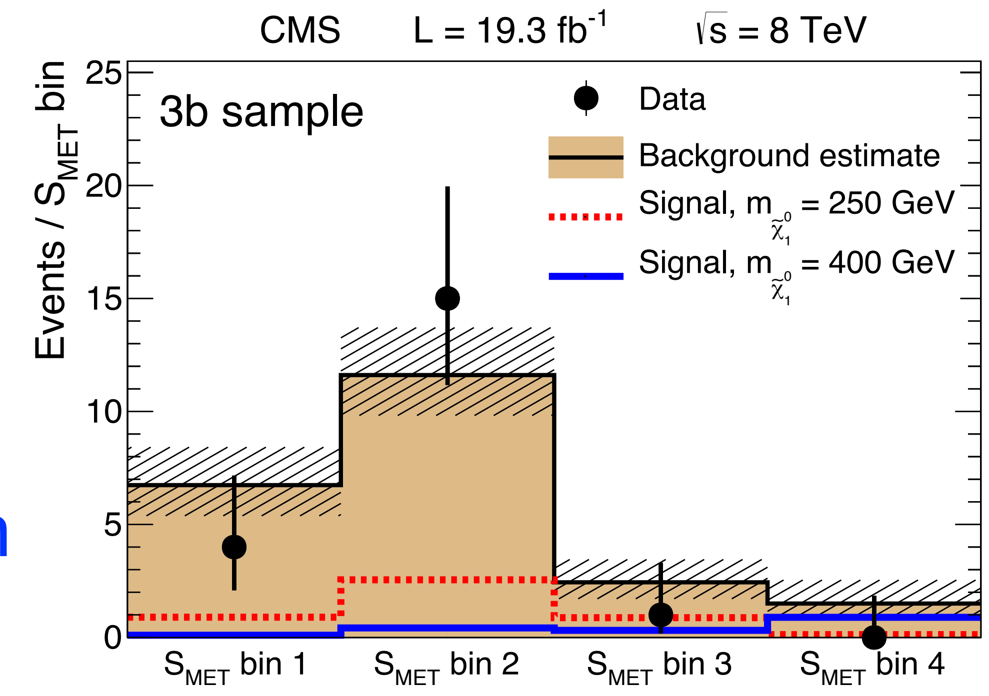
$$4b\_SIG = \frac{2b\_SIG}{2b\_SB} 4b\_SB$$

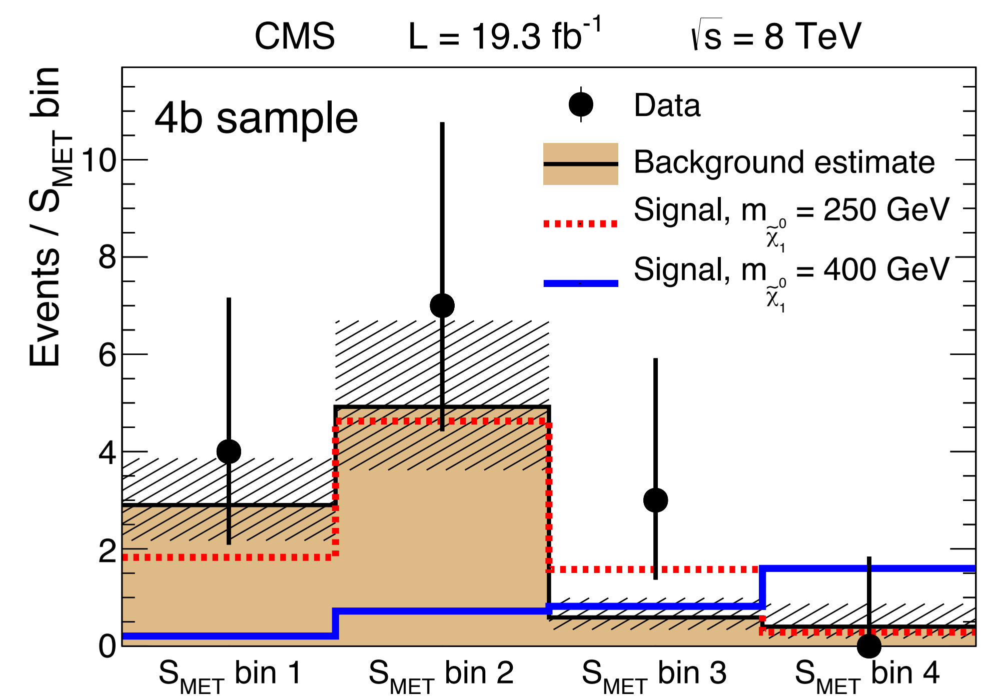


hh→4b

- Search performed in MET significance S_{MET}
  - Accounts for jet resolution on event by event basis
  - Better rejection of fake MET, discrimination between signal and background
- Data Consistent with background estimate

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

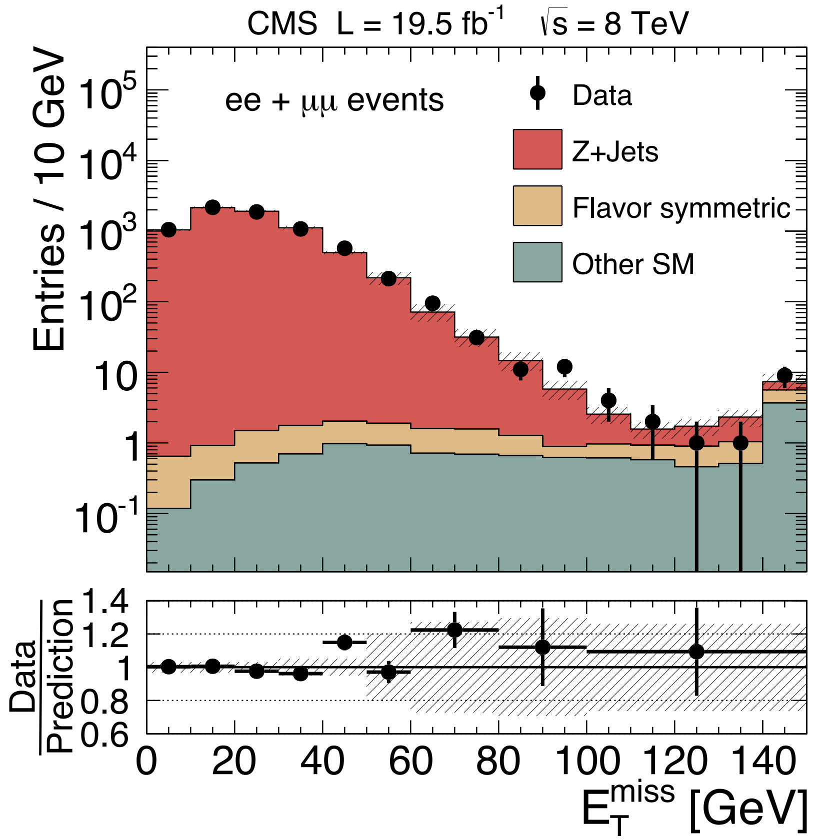




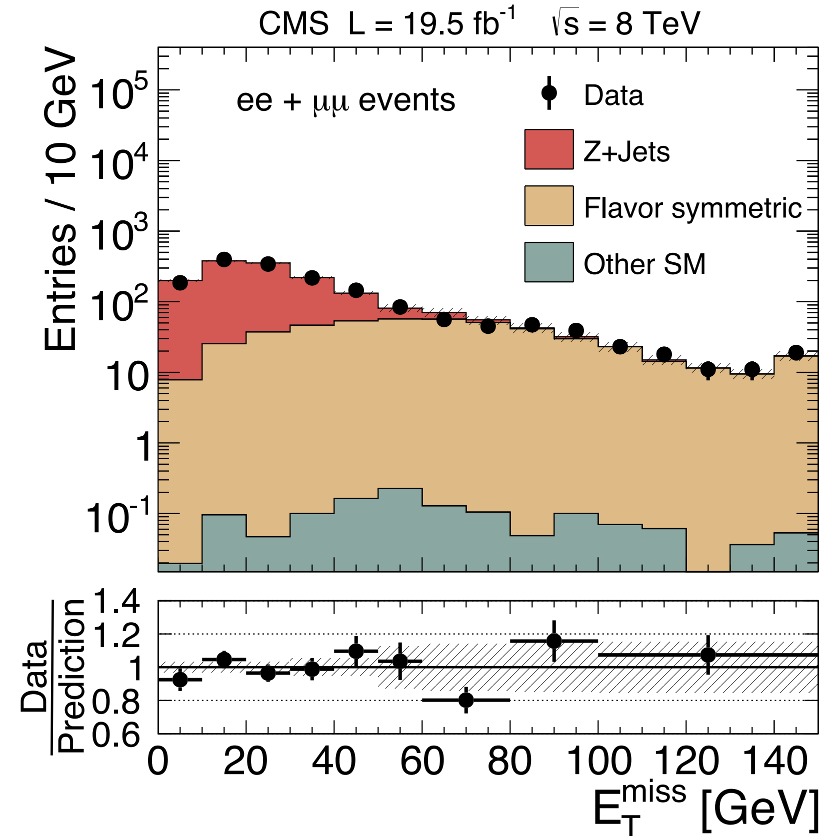
hZ→2b2ℓ

- Higgs-tagging: Two most b-like jets in the event must be reconstructed in the Higgs window $100<m_{bb}<150$
- Z-tagging: Require exactly 1 e^+e^- or $\mu^+\mu^-$ pair with $81<m_{\ell\ell}<101$
- Veto 3rd lepton and hadronic taus to avoid overlap with other searches

Z+Jets enriched control sample



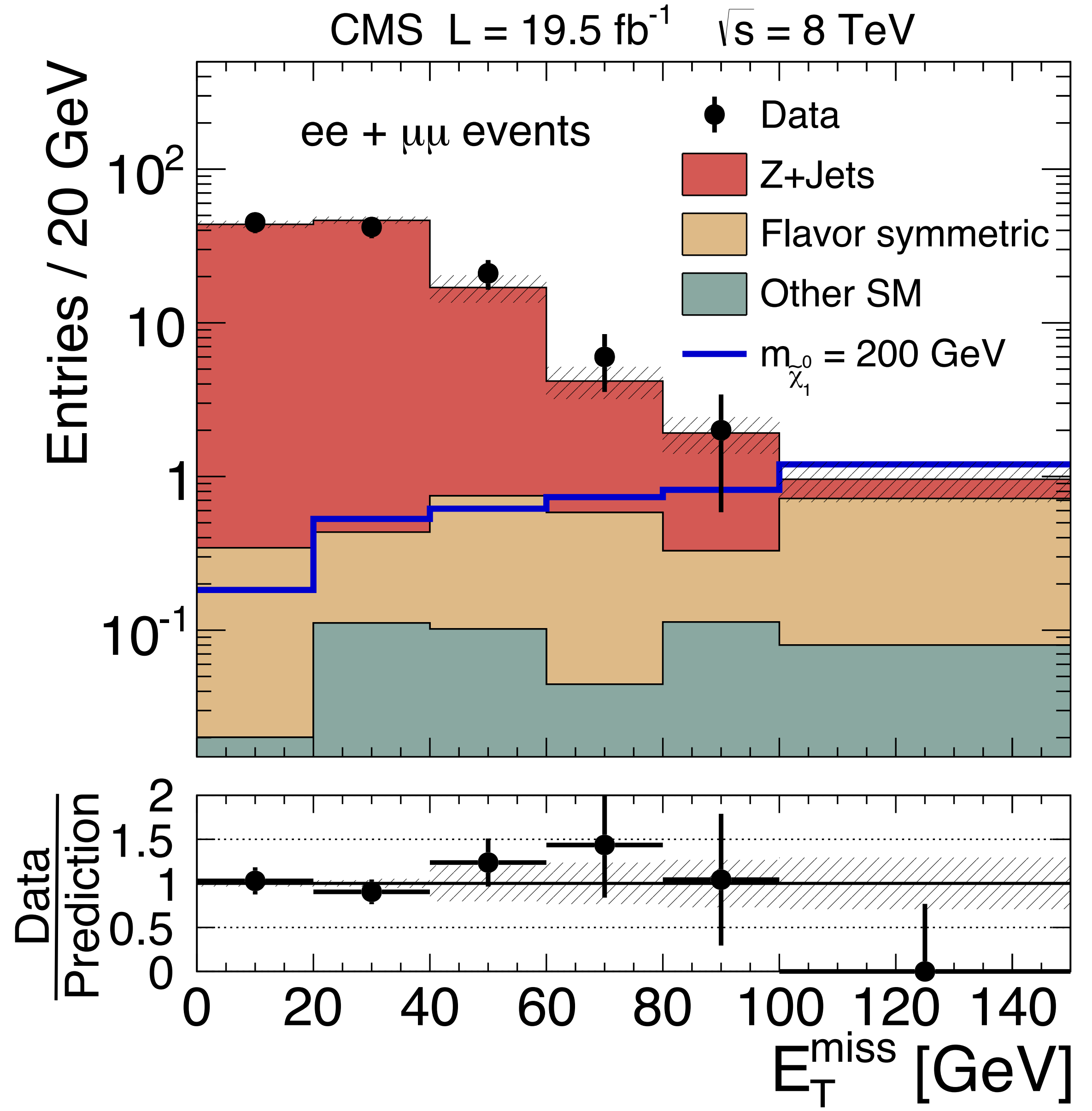
$t\bar{t}$ enriched control sample



hZ→2b2ℓ

- Z+Jets shape estimated using MET template using γ+Jets control sample, normalized to data yield in MET<50
- Flavor symmetric ($t\bar{t}$, WW, ττ, tW) MET shape template and normalization from eμ sample
- Other SM background estimated from simulation
- Data consistent with background estimate

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



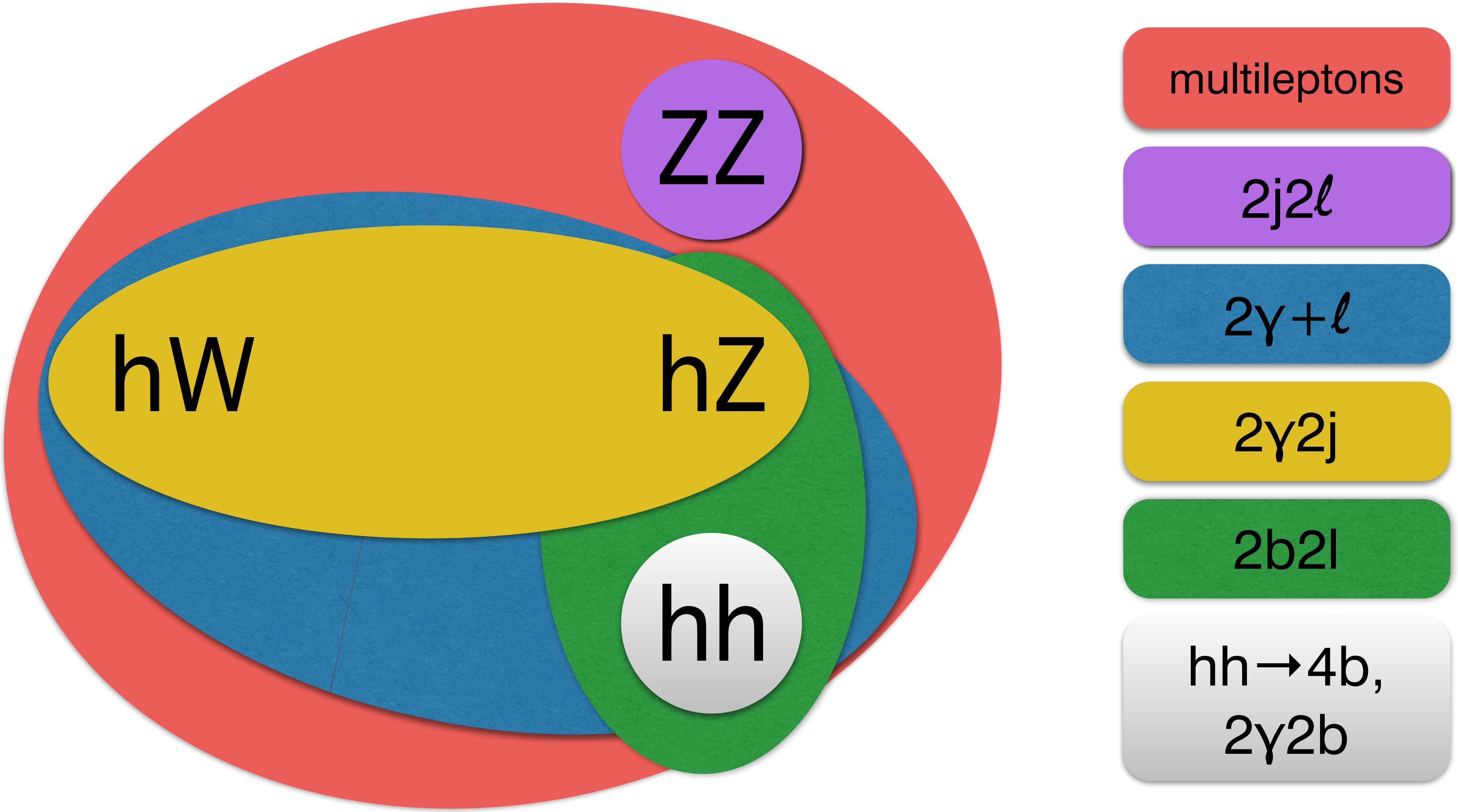
Multilepton & ZZ Searches

- ZZ→2ℓ2j CMS-SUS-13-006 arXiv:1405.7570 Eur. Phys. J. C 74 (2014) 3036
  - –di-lepton pair and di-jet pair in Z window
  - –MET is discriminating variable
- Multileptons CMS-SUS-13-002 arXiv:1404.5801 accepted by PRD
  - –Searches with at least 3 leptons, including up to 1 hadronic tau
  - –Channels binned in N_{lep}, N_{τ}, N_{OSSF} lepton pairs, $m_{\ell\ell}$, $N_{b\text{-jets}}$, H_T, MET
  - –tt, di-boson and rare SM backgrounds taken from simulation
  - –fake taus, fake electrons, photon conversion backgrounds from data driven methods
  - –Excess over SM background expectation in 1 channel, local significance: 2.6σ
    - Many studies performed, believed to be statistical fluctuation

N_{ℓ}	N_{τ_h}	N_{OSSF}	$m_{\ell\ell}$ range	E_T^{miss} (GeV)	SM background	Data	hh events, $m_{\tilde{\chi}_1^0} = 150\,\text{GeV}$
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

Interpretations

- Interpretations made in all allowed combinations of di-boson final states

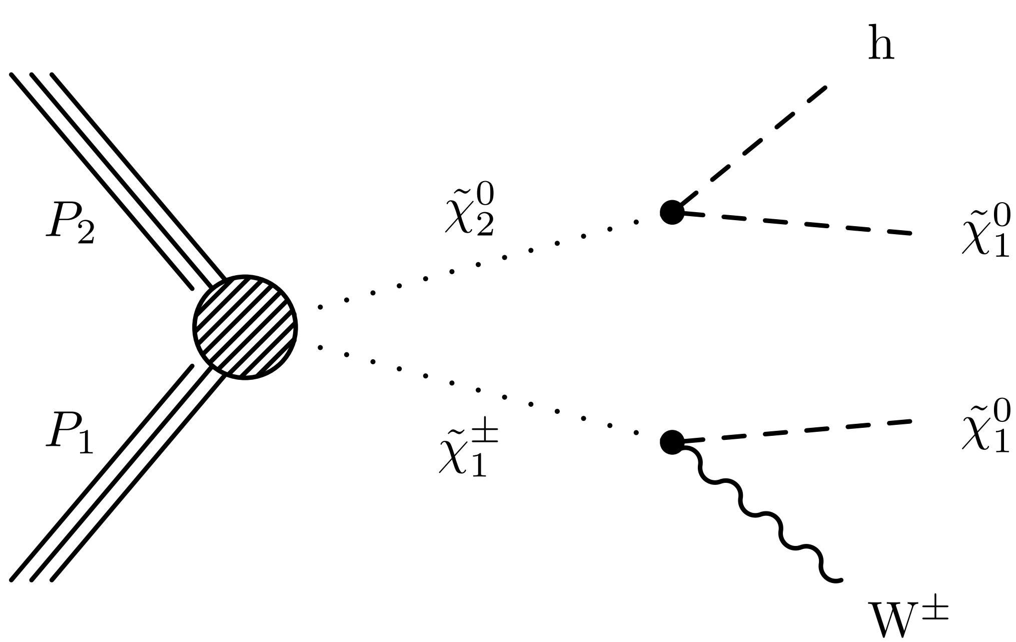


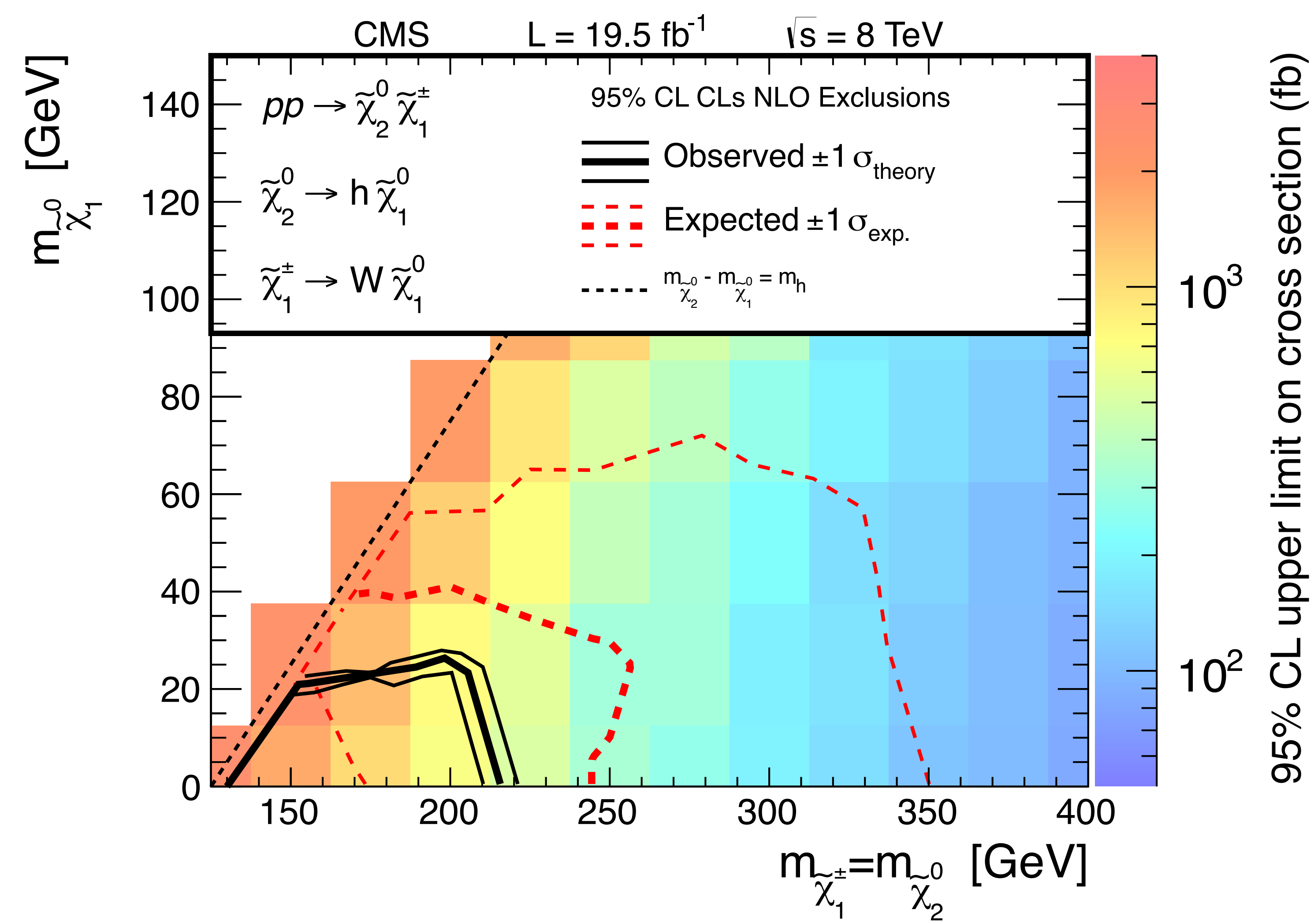
Chargino/Neutralino Production

Mass degenerate Chargino/ Neutralino production

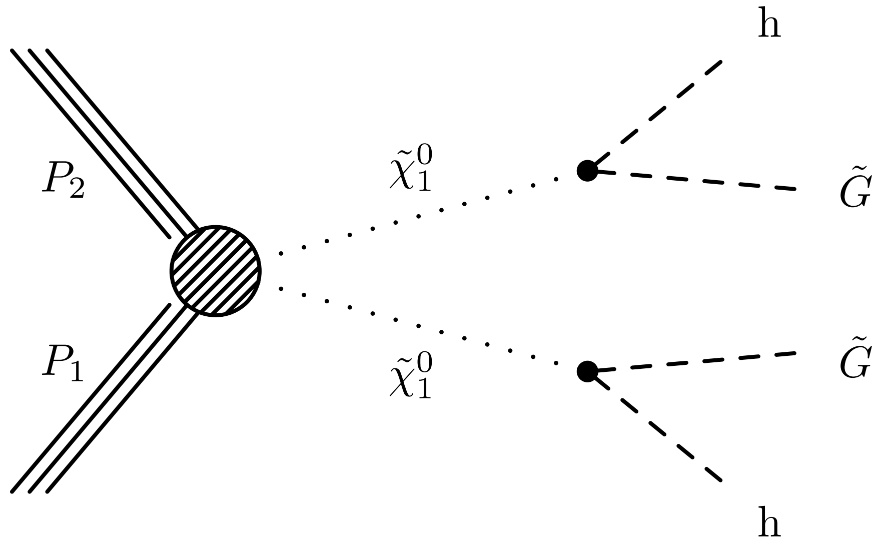
hW

- single lepton, SS di-lepton, multilepton
- h(γγ) channels added

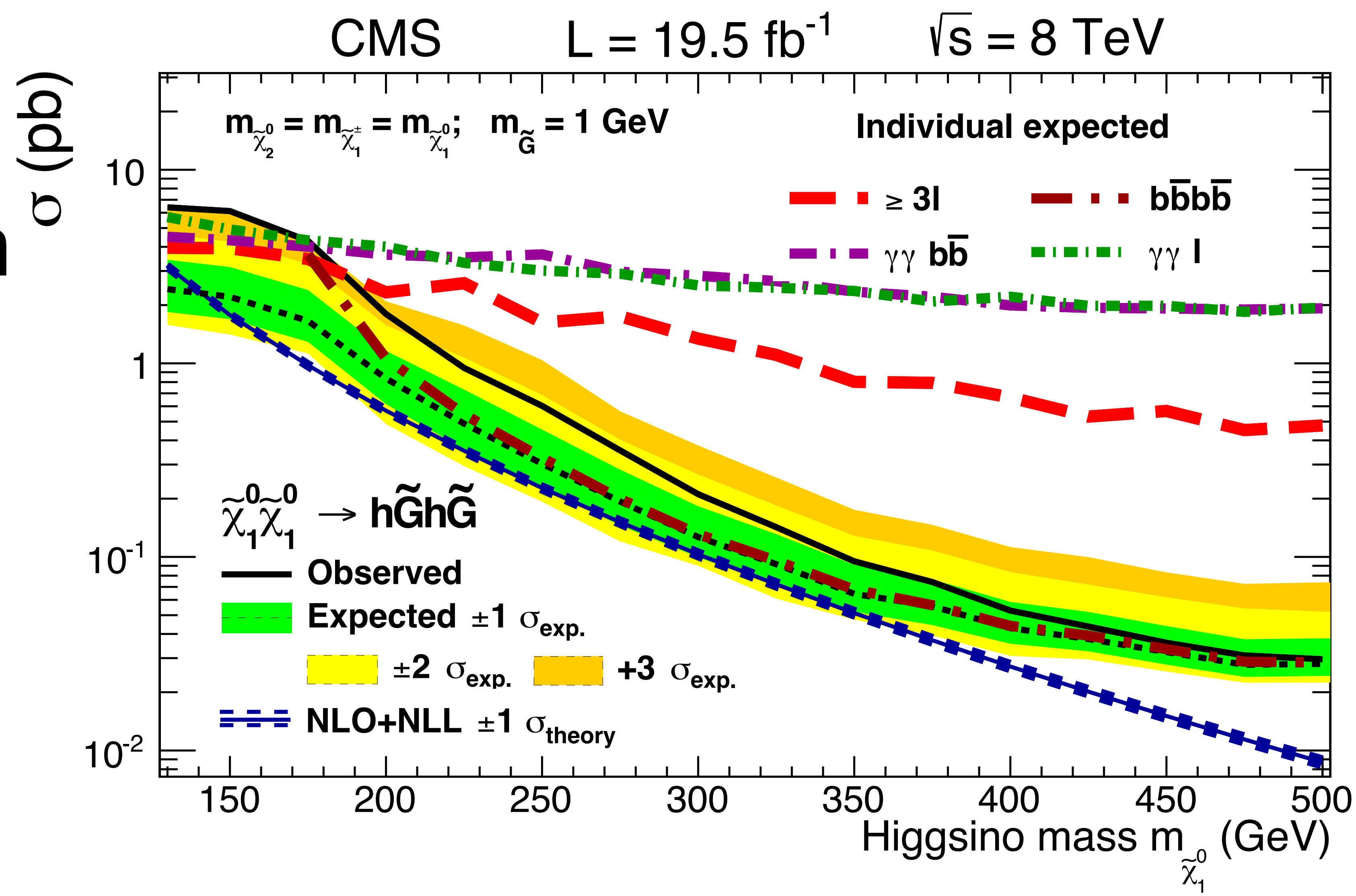




Higgsino Production



- GMSB model with higgsino NLSP
- hh final state
- LSP is 1 GeV $\tilde{G}$



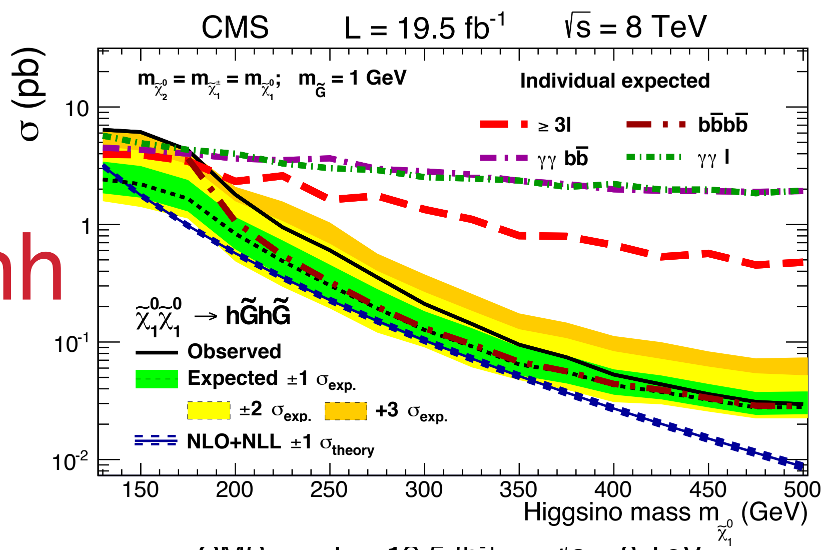
- This interpretation assumes

$$\mathrm{BR}(\tilde{\chi}_1^0 \to h + \tilde{G}) = 1$$

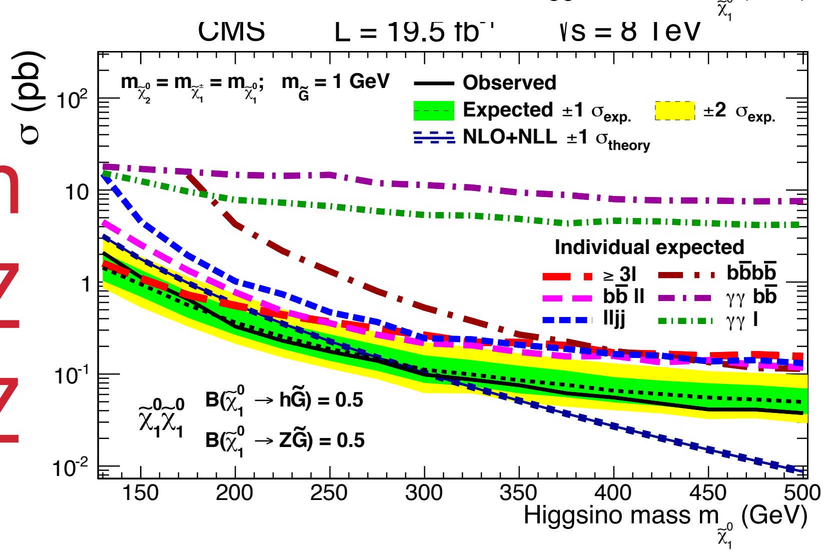
- Can also move to more general higgsino case…

Higgsino Production

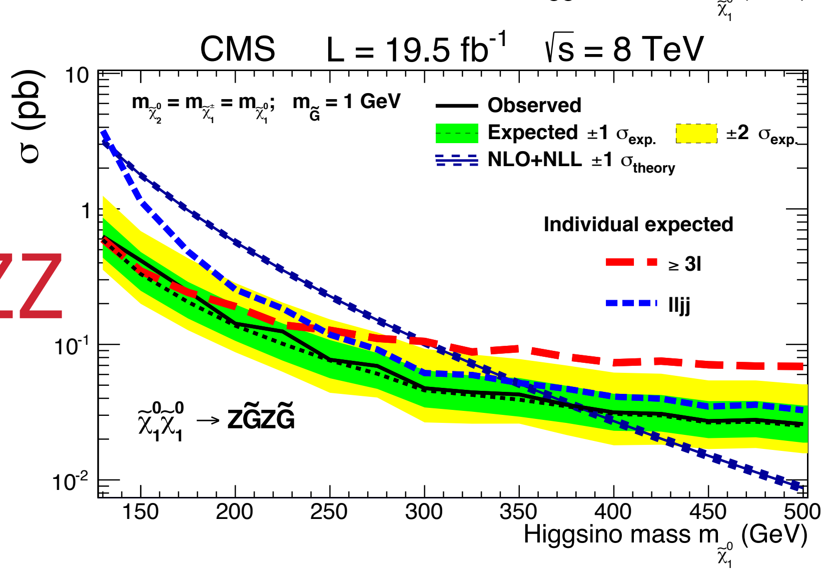
100% hh



25% hh
50% hZ
25% ZZ

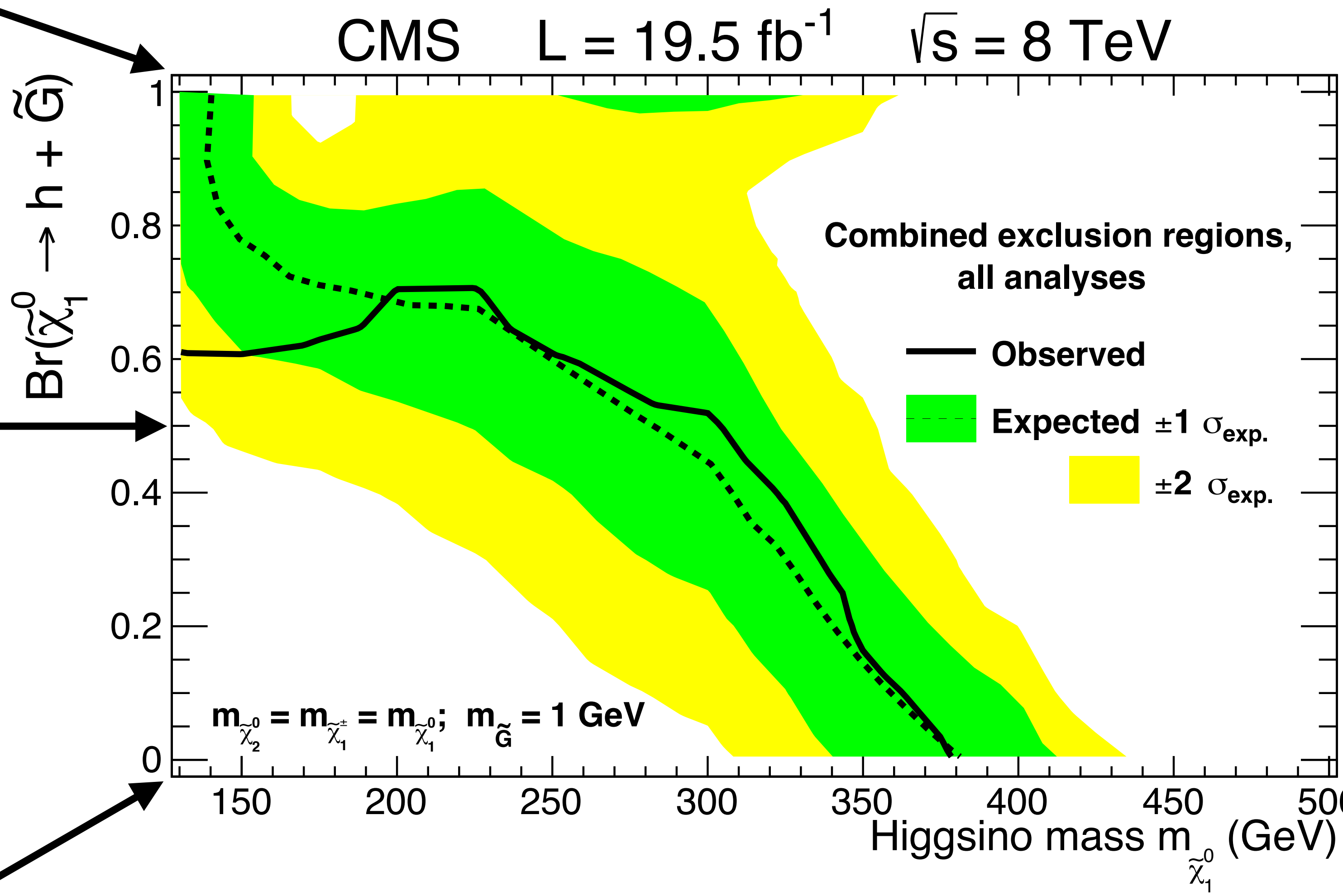


100% ZZ



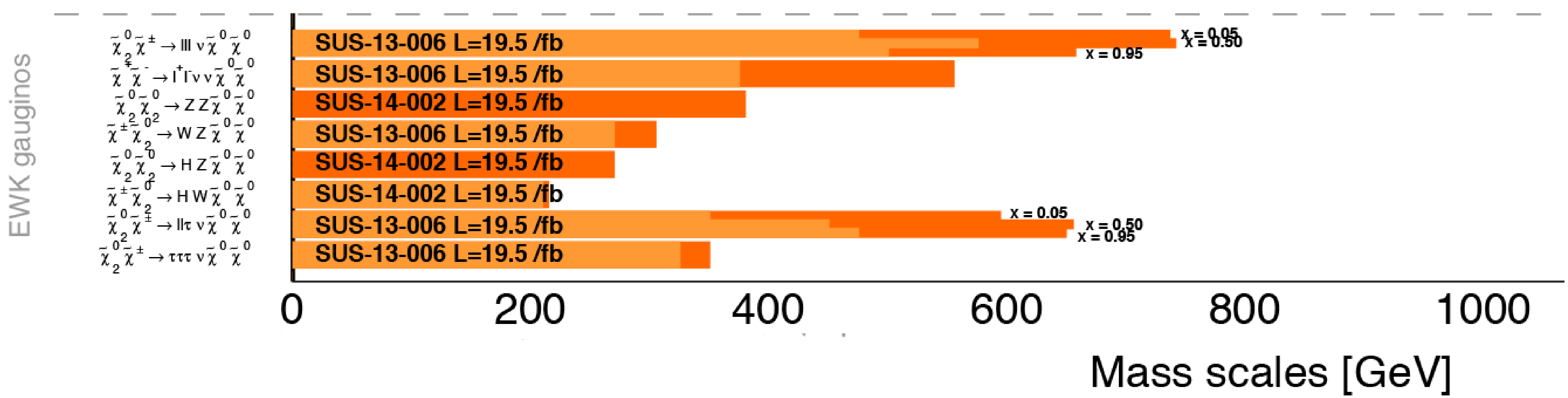
2D Exclusion as a function of

$$BR(\tilde{\chi}_1^0 \to h + \tilde{G})$$



Summary

- Electroweak SUSY searches provide an important counterpart to strong production searches
  - –Even more so if present strong production bounds are pushed even higher
- New techniques such as higgs-tagging are available
- CMS has performed searches for electroweak production of SUSY in many final states



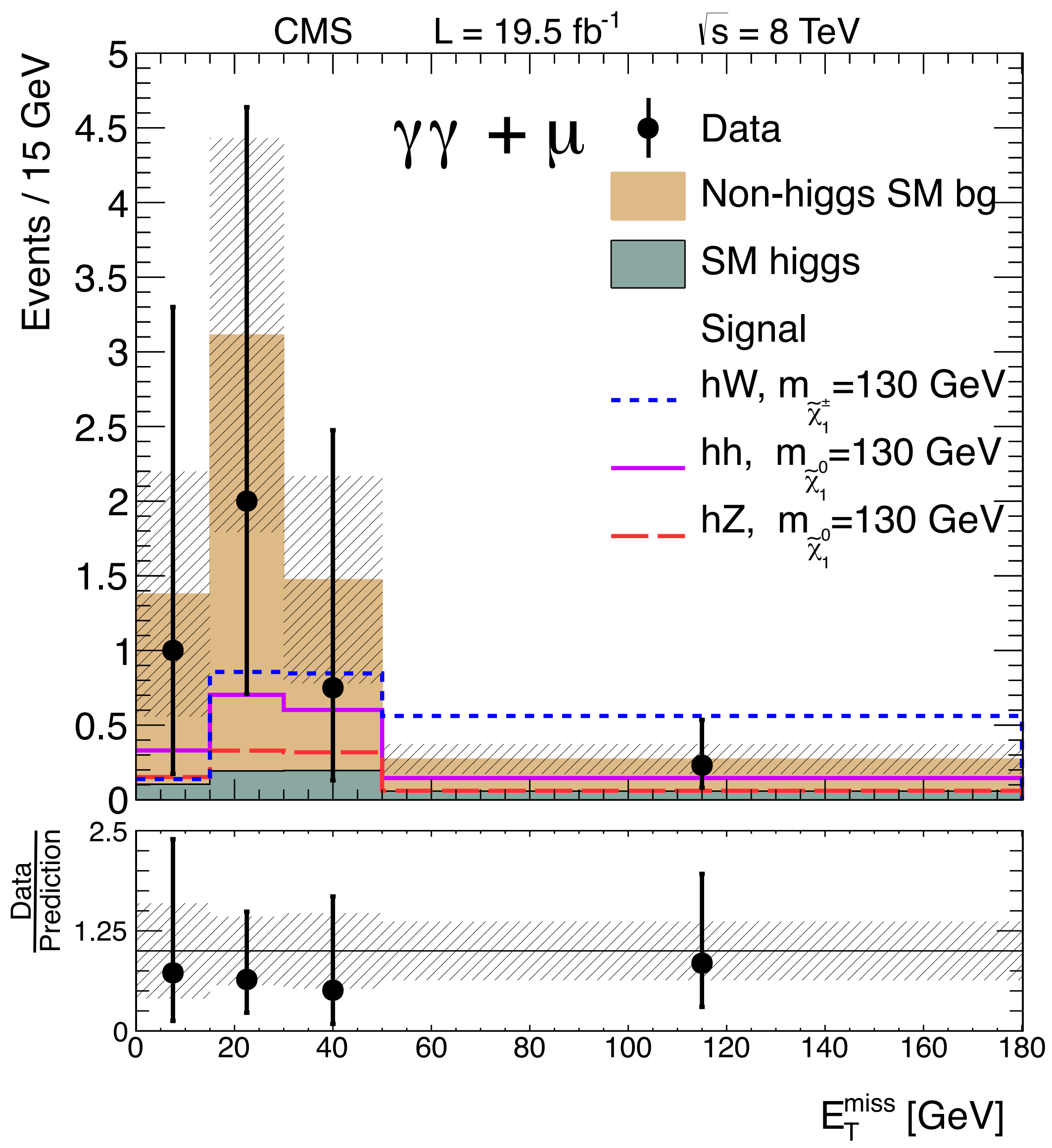
Outlook

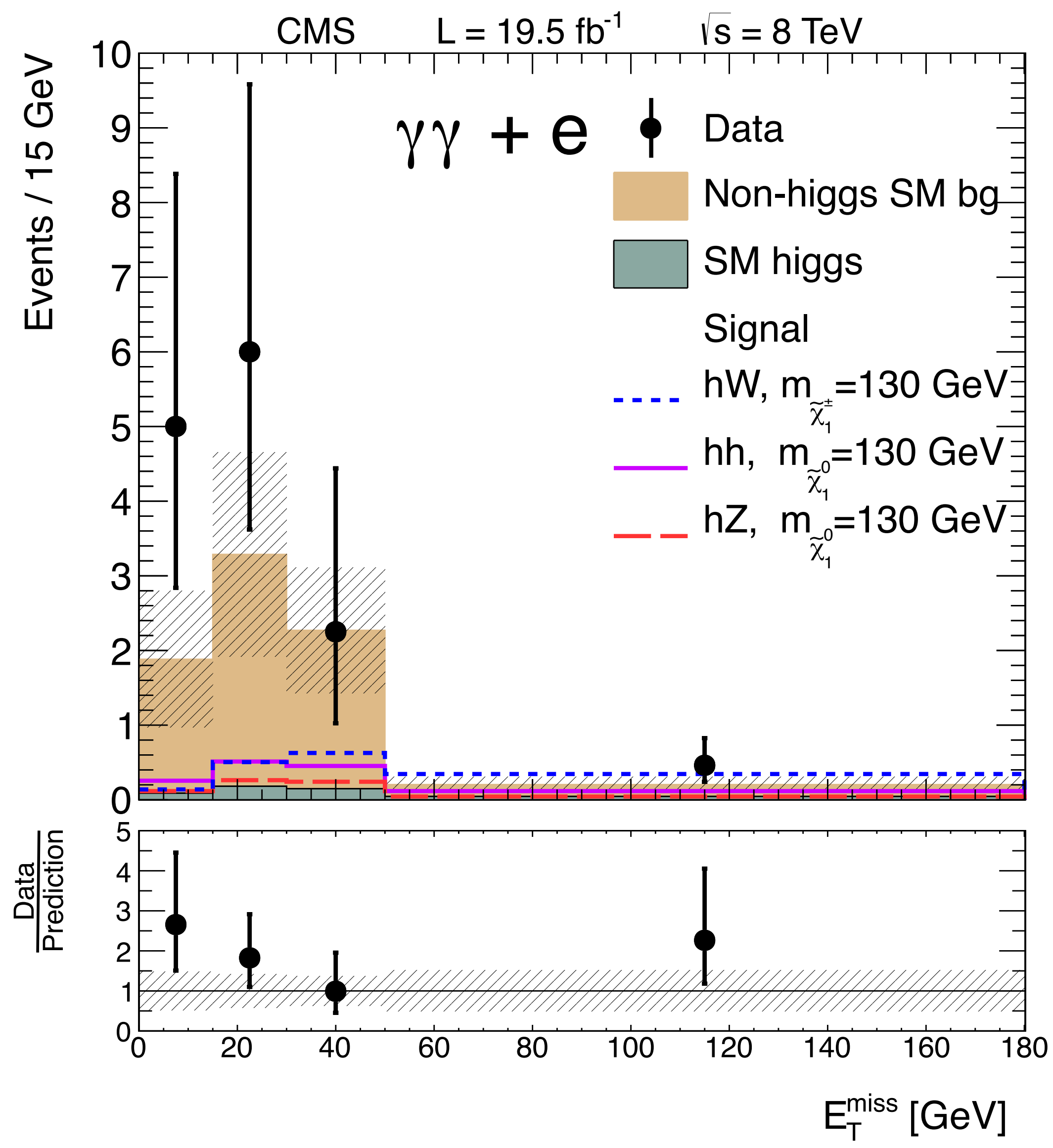
Searching for low rate processes can be like finding a needle in a haystack - or a leopard in the bush. But it can be done!

13TeV searches will extend the reach of these analyses, with signal production outpacing increases in SM backgrounds, especially at high sparticle mass. There is a challenging but exciting time ahead!

BACKUP

γγ+Lepton MET





γγ+Electron Excess

- 2.1σ excess at medium values of M_T
  - 18 events in Higgs tag window vs. 10.0 ± 2.3 predicted from SM background
- Checks performed:
  - Comparison of M_T in upper and lower sidebands to check for SM processes which die off in invariant mass spectrum
    - Upper and lower sidebands show good agreement
  - Look at MET instead of M_T
    - Clustered at low values, non-signal like
  - Tried other fit functions
    - exponential, 3rd/5th order polynomials, Bernstein polynomial all agree within errors
  - Fit stability
    - Threw 10,000 toys using fit results, then fit resulting distributions to study effect of low statistics on the fit - stable within ~1σ
    - Variance of sideband ranges to check fit integral stability in both sidebands and Higgs tag window - stable within ~1σ
- Find no evidence that disagreement is caused by experimental method or systematic problem

Multilepton Excess

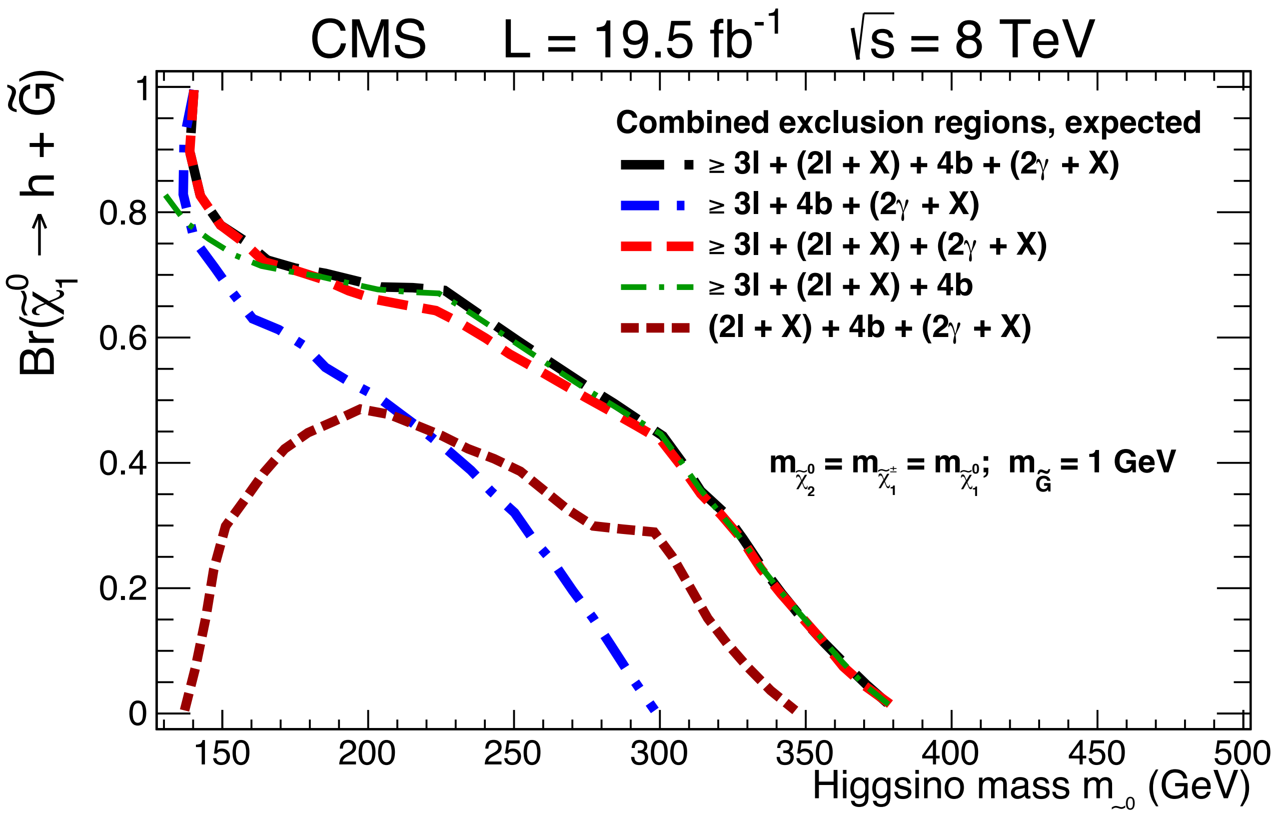
- Excess seen in one channel
  - 22 data events, background prediction 10.1±2.4
  - 64 channels total, each with 3 MET bins

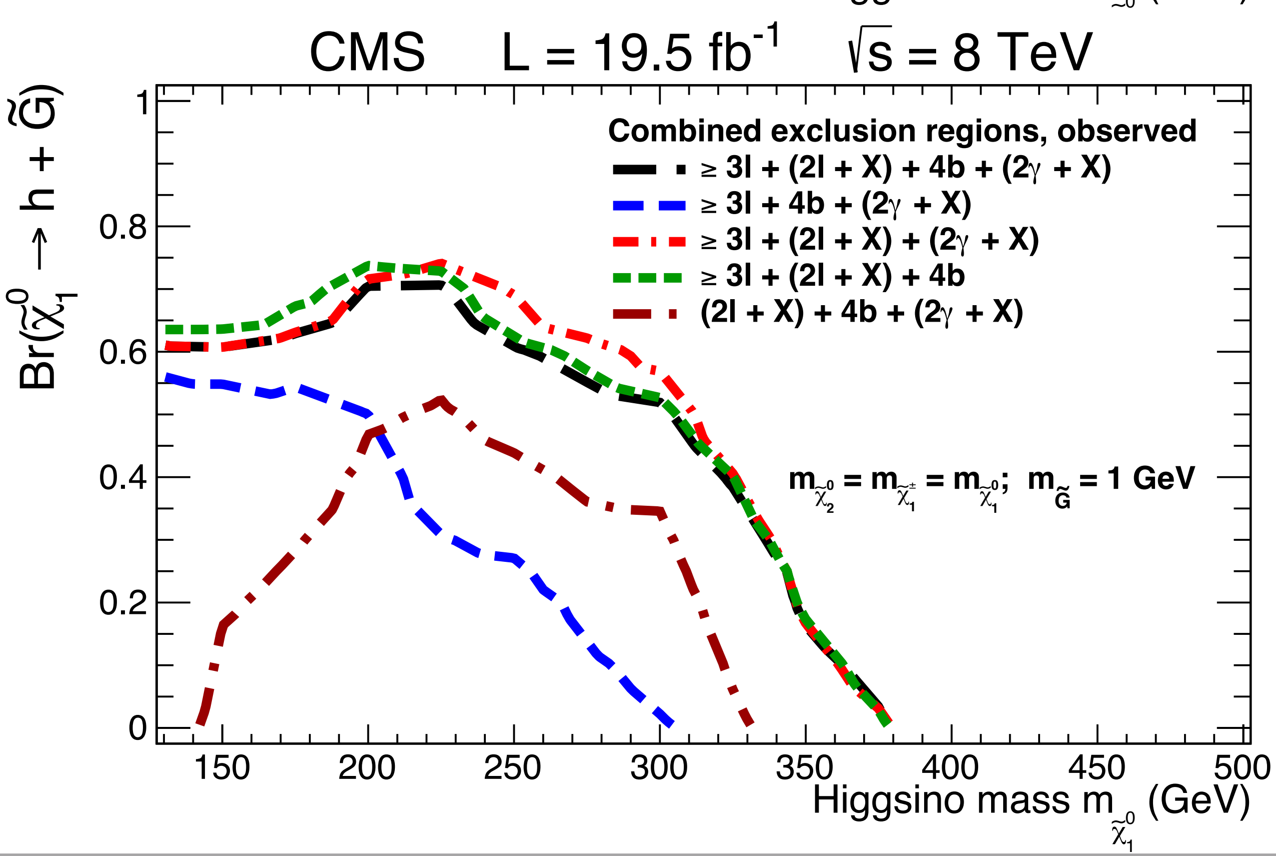
- Chance of seeing a 2.6σ fluctuation in 64 channels ~50%

≥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.	$c_{\tau_h} = 0, N_b \geq 1$ Obs.	Exp.	$N_{\tau_h} = 1, N_b \geq 1$ Obs.	Exp.
OSSF0	—	(100, ∞)	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, ∞)	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, ∞)	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, ∞)	0	$0.01^{+0.02}_{-0.01}$	—	—	0	$0.01^{+0.06}_{-0.01}$	—	—
OSSF2	On-Z	(100, ∞)	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, ∞)	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, ∞)	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, ∞)	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, ∞)	0	0.04 ± 0.03	—	—	0	0.05 ± 0.04	—	—
OSSF2	On-Z	(100, ∞)	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	—	—

Individual 2D Higgsino Limits





h(γγ) &
multileptons

Most Sensitive Analysis