

Searches for SUSY with photons in the final state in CMS

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on behalf of the CMS collaboration

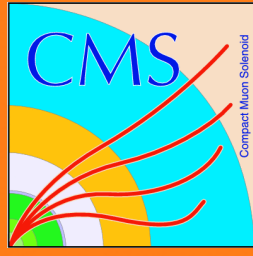


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Motivation



- SUSY with photons in the final state are well motivated:
GMSB gluino / squark production
- Higgs discovery \rightarrow exciting new direction in SUSY
searches involving decays to H
- $H \rightarrow \gamma\gamma$ is a very clean and effective tag signature for
Higgs
- I will discuss both types of searches at CMS
including new result on inclusive higgs-aware ($H \rightarrow \gamma\gamma$)
search using razor variables



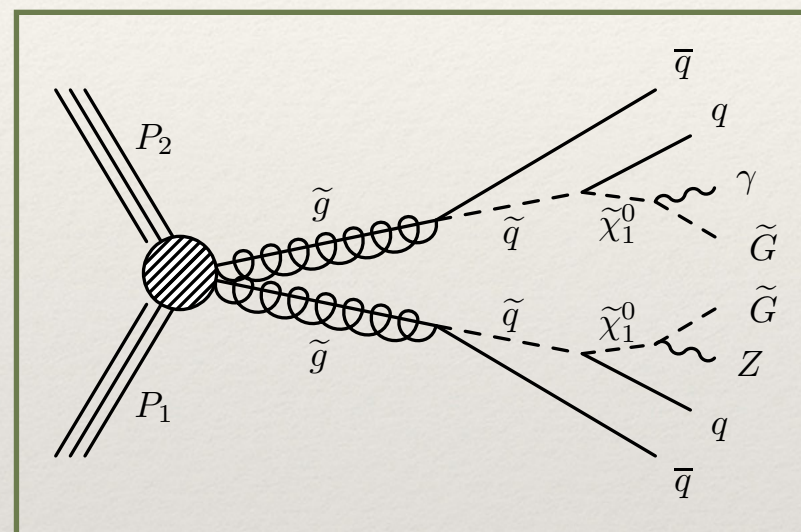
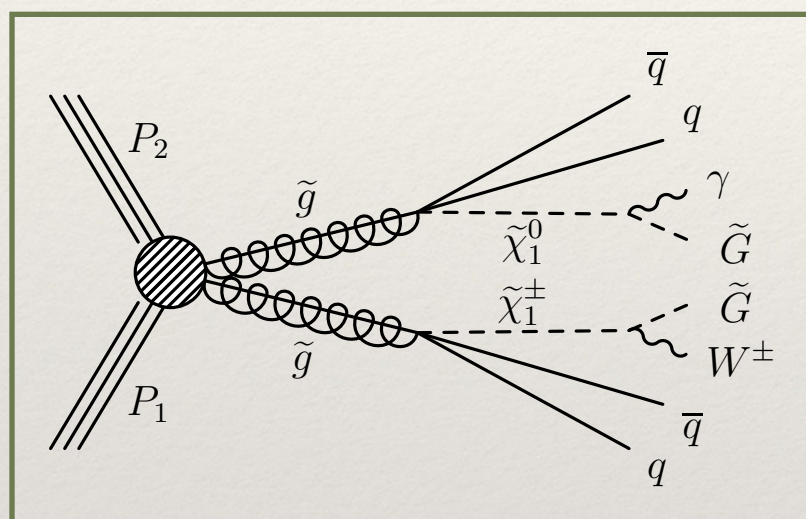
Gauge Mediated SUSY



- SUSY with gauge-mediated symmetry breaking
- Gravitino is the LSP. Stable if R-parity is conserved
- If NLSP is a neutralino (bino/wino), photons with large p_T may be produced

CMS-SUS-14-004, PRD 1507.02898

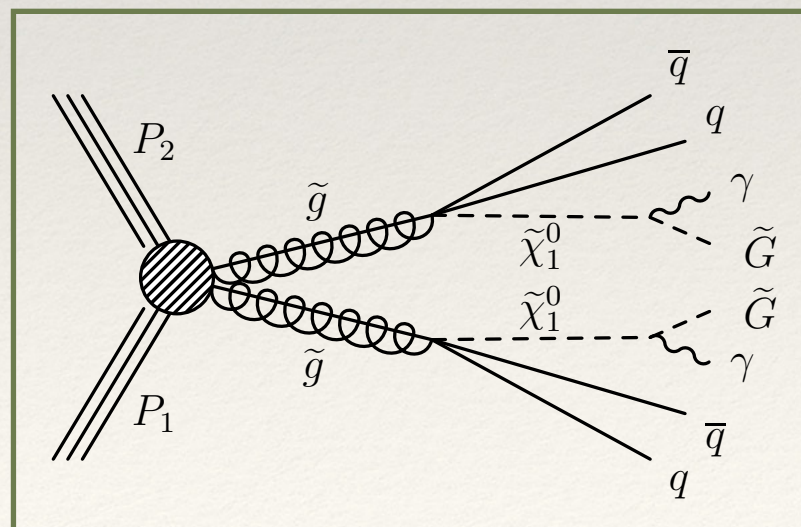
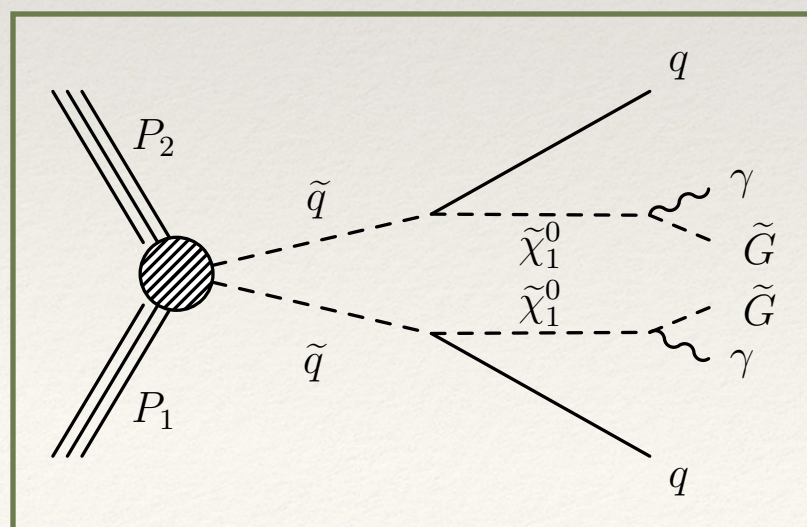
Single Photon Final State



- At least one photon (γ)
- Jets
- Missing E_T

discriminating variable: E_T^{miss}

Double Photon Final State



- At least two photon (γ)
- Jets
- Missing E_T

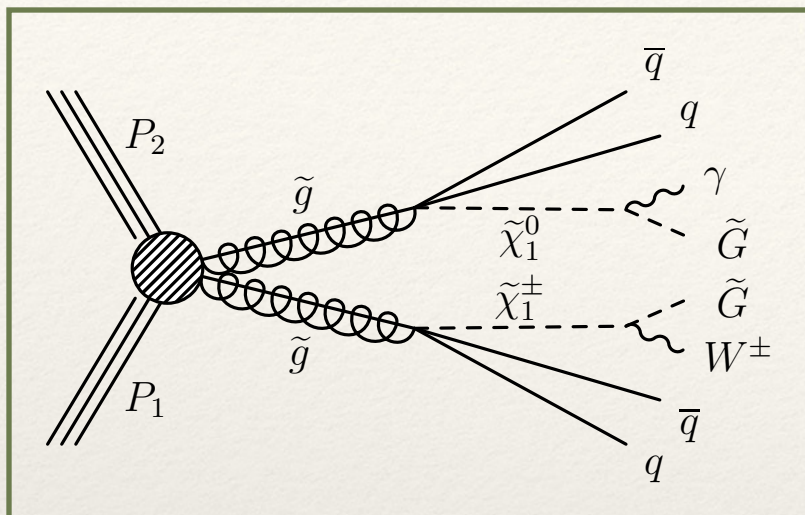
discriminating variable: Razor



Single Photon Analysis



CMS-SUS-14-004, PRD 1507.02898



• Selection:

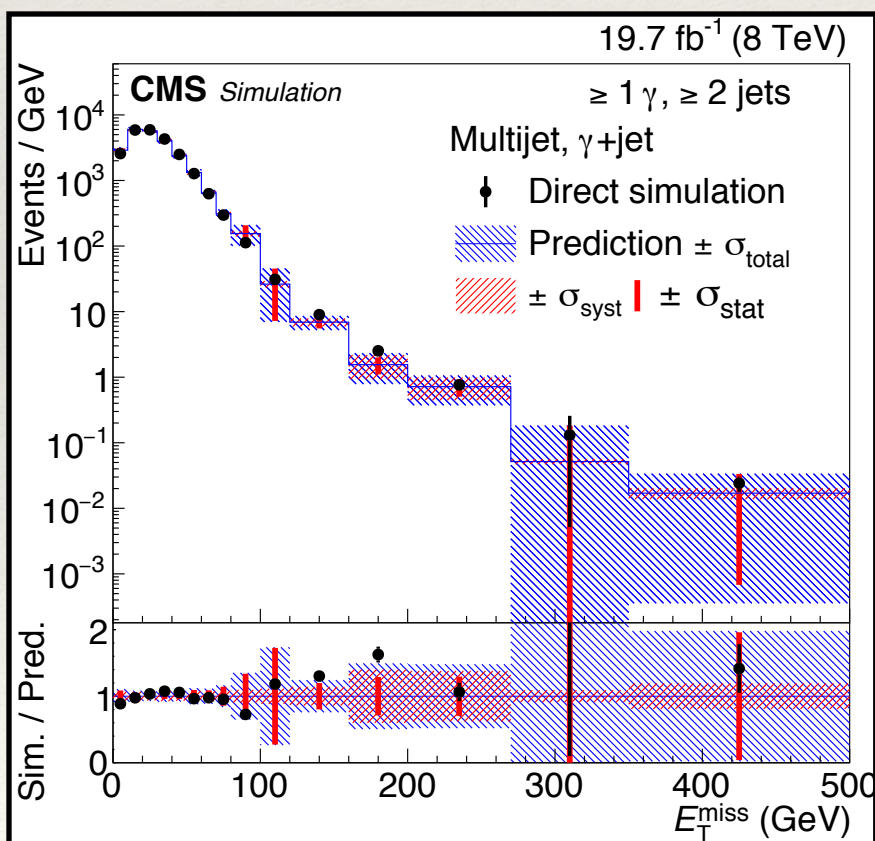
- At least one photon (γ): $P_T^* > 110 \text{ GeV}$
- At least two jets: $P_T > 30 \text{ GeV}$
- $H_T^* > 500 \text{ GeV}$ (including γ)

• SM backgrounds

- *QCD multijet + γ +jets events*
- *W+jets and tt + jets (EW): real E_T^{miss} , $e \rightarrow \gamma$*
- *γ W+jets, γ Z+jets, γ tt + jets*

• Discriminating variable

- $E_T^{\text{miss}} > 100 \text{ GeV}$, 6 bin categories

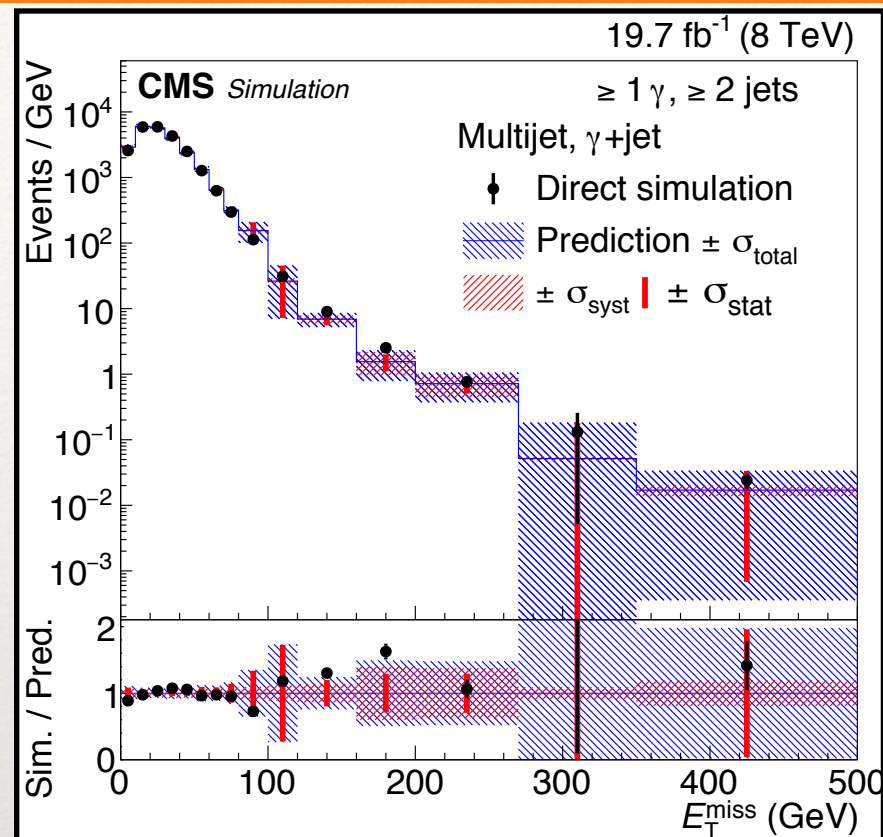




Single Photon Analysis

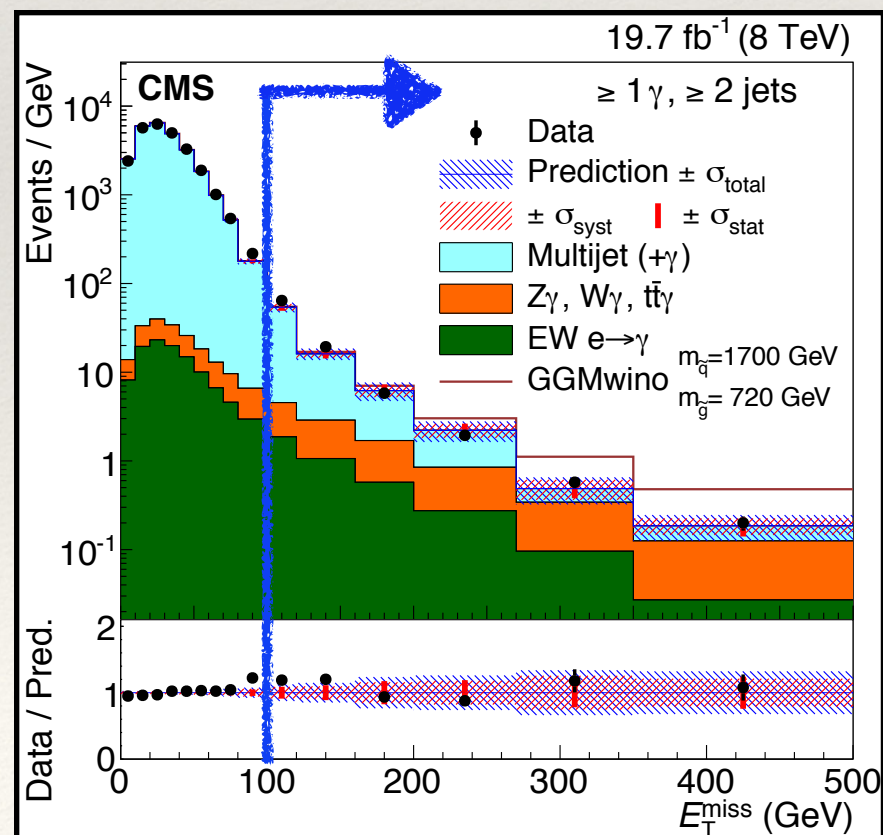


CMS-SUS-14-004, PRD 1507.02898



Background Prediction

- Use a γ^{loose} (relax isolation) control sample.
Obtain correction factors for $E^{\text{miss}}_{\text{T}}$.
Predict Multijet and γ +jet
- Use a γ^{pixel} (pixel seed match) control sample.
Predict EW scaling $E^{\text{miss}}_{\text{T}}$ distribution by $f_{e \rightarrow \gamma}$



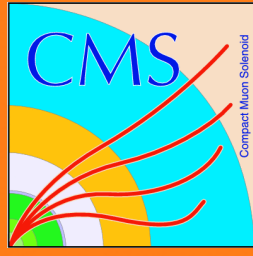
Results

- Obtain Full background prediction
- Search $E^{\text{miss}}_{\text{T}} > 100$ GeV in 6 bins.
- Look for excesses in the tail of $E^{\text{miss}}_{\text{T}}$

No excess found in any $E^{\text{miss}}_{\text{T}}$ bin



Single Photon Analysis



*CMS-SUS-14-004,
PRD 1507.02898*

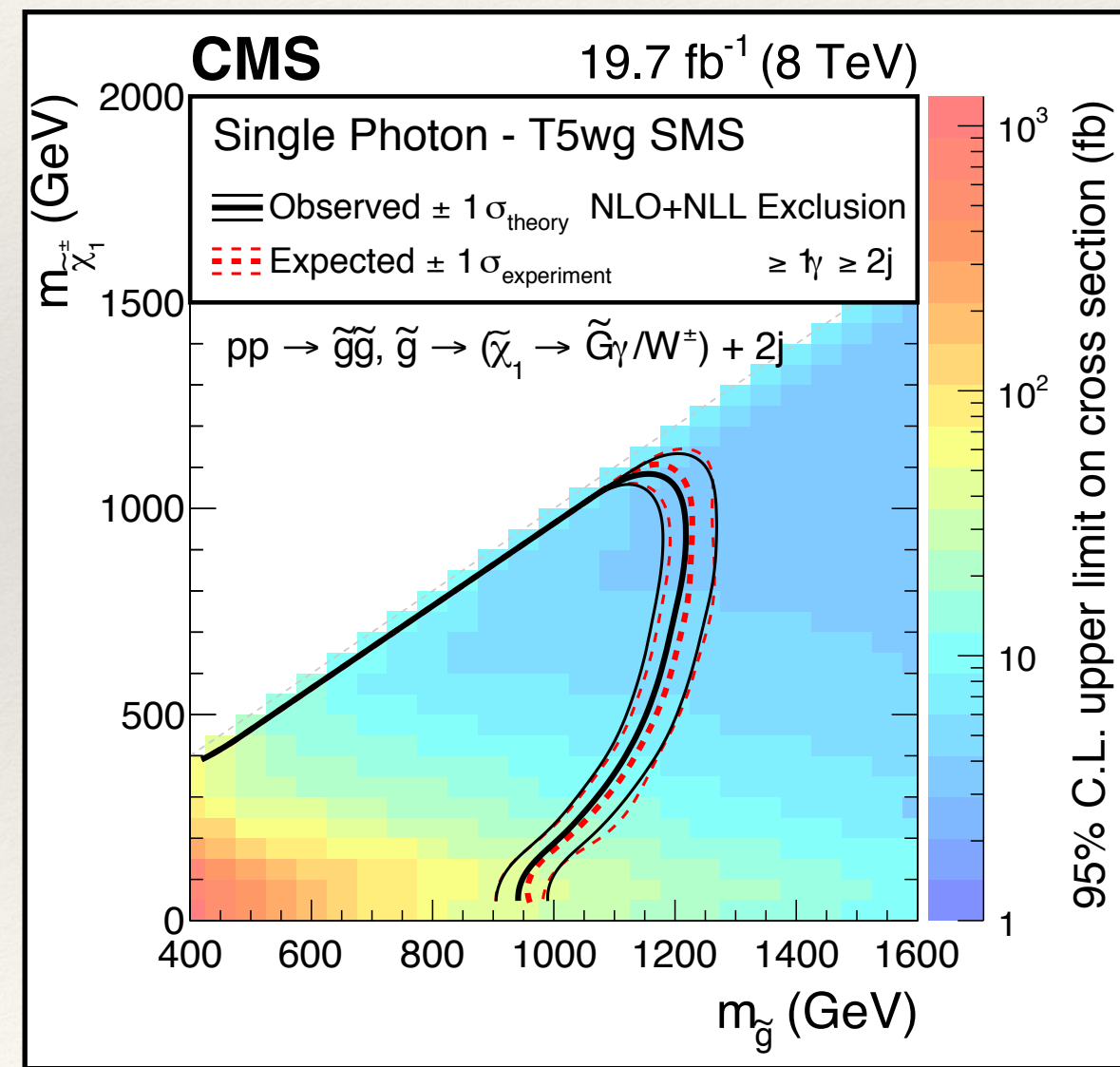
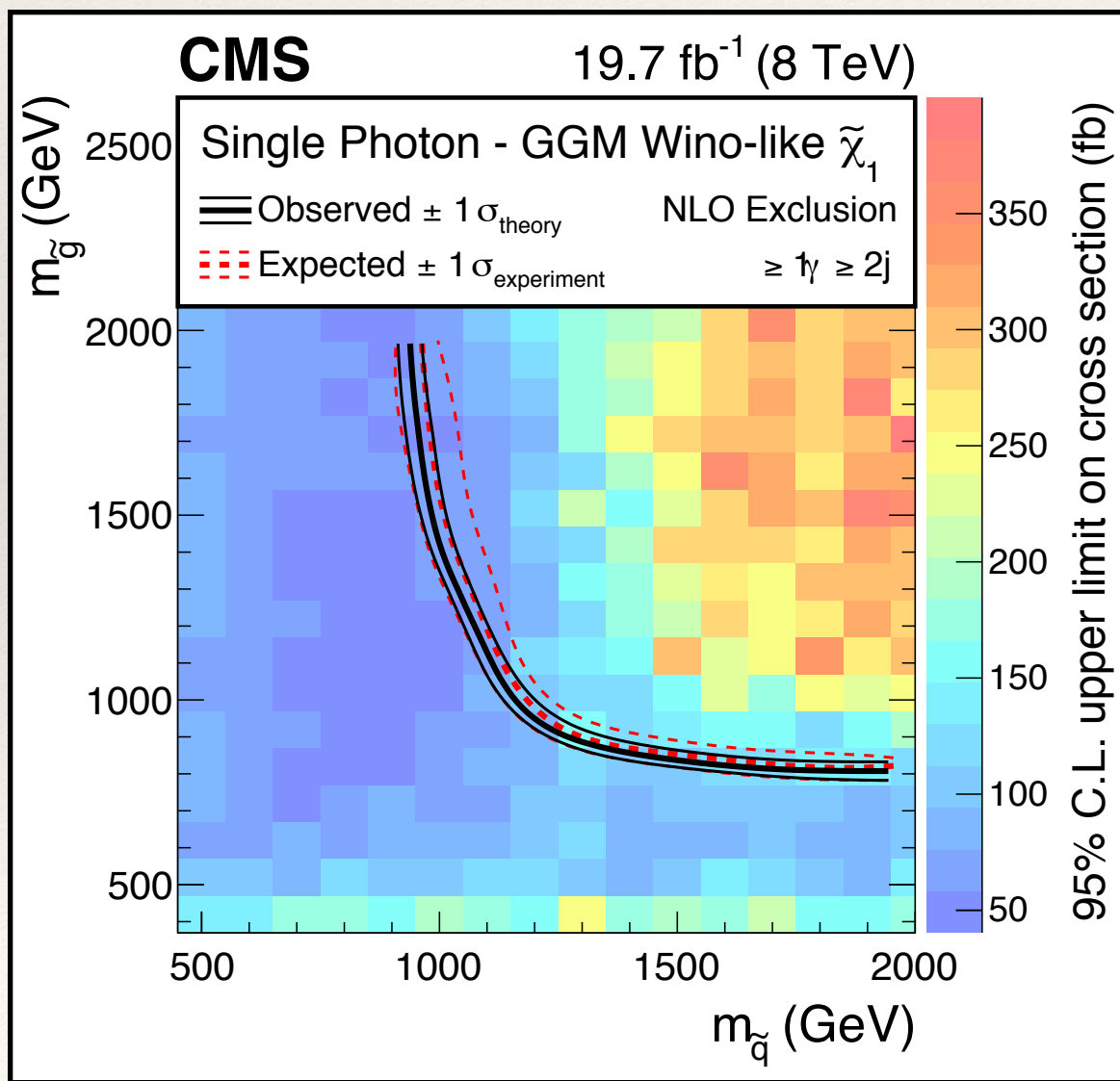
- No observed excess
- Multi-channel counting exp.
- We set 95% CLs limits

• *GGM-Wino*

• $m_{\text{gluino}} > \sim 1 \text{ TeV}$, $m_{\text{squark}} > \sim 0.8 \text{ TeV}$

• *SMS T5wg*

• $m_{\text{gluino}} > \sim 1 \text{ TeV}$

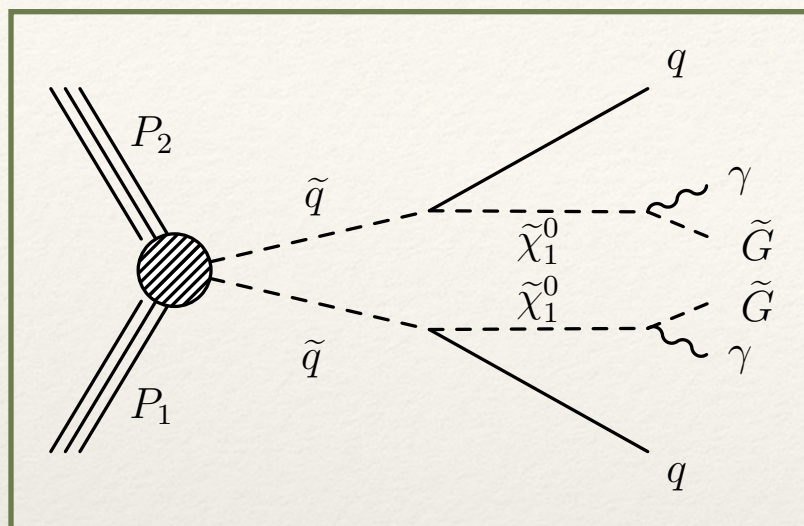




Double Photon Analysis



CMS-SUS-14-004, PRD 1507.02898



- Selection:

- At least two photons (γ): $P_{\text{lead}_T} > 30$, $P_{\text{sublead}_T} > 22$ GeV
- At least one jet: $P_T > 40$ GeV, $|\eta| < 2.5$, $\Delta R(\gamma_{(1,2)}, j_i) > 0.5$

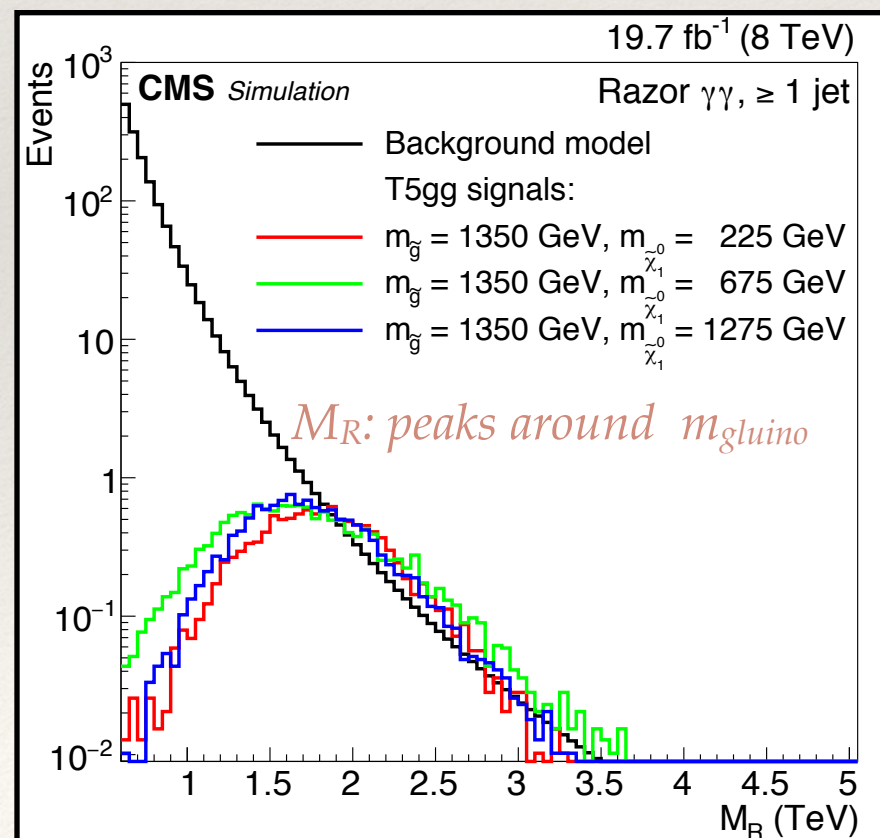
- Standard Model backgrounds

- QCD multijet, γ +jets events
- W+jets and tt + jets (EW): real E_{miss_T} , $e \rightarrow \gamma$ (*negligible*)

- Discriminating variables

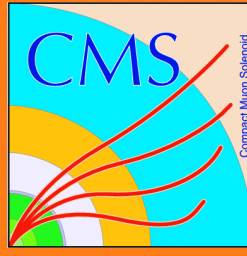
- Razor variables: M_R (mass scale) and R^2 (energy imbalance)

- Search region: $M_R > 600$ GeV && $R^2 > 0.2$ (*high R^2*)

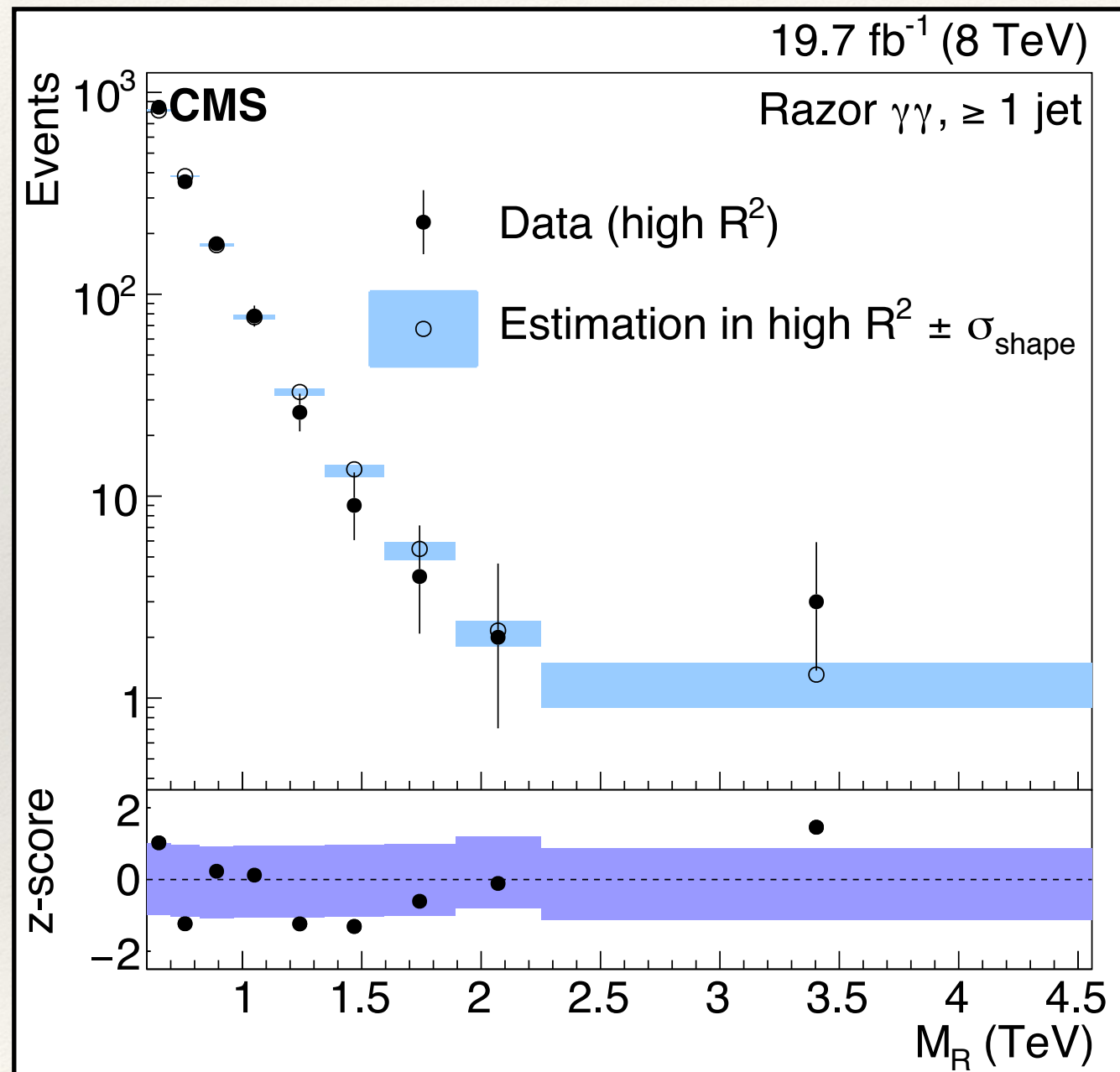




Double Photon Analysis



CMS-SUS-14-004,
PRD 1507.02898



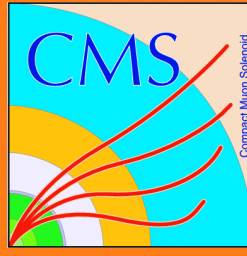
Results

- Extrapolate fit shape to signal region
- Look for excess in $M_R > 600$ GeV

No excess in any M_R bin.



Double Photon Analysis

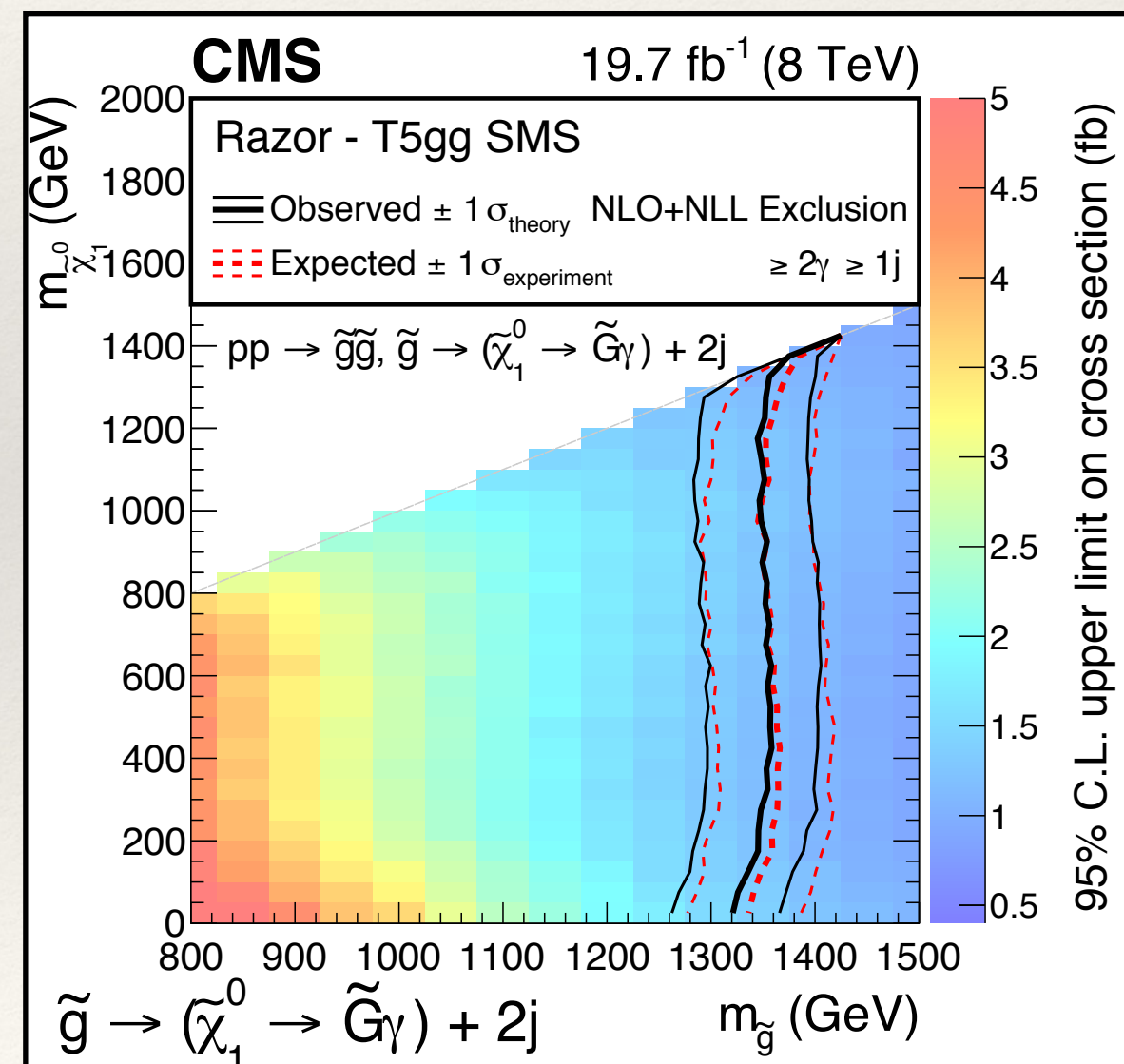
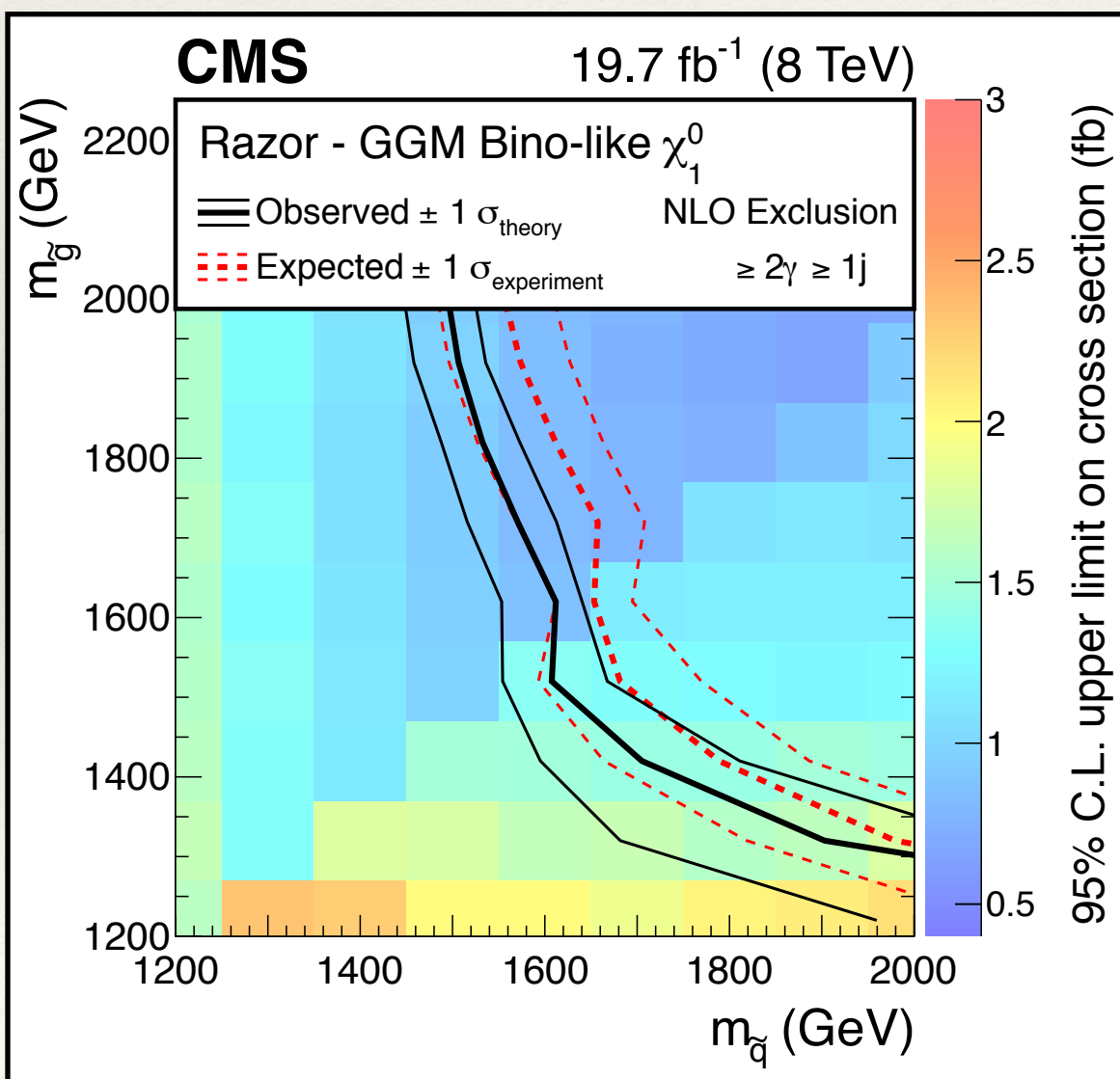


- No observed excess
- multi-channel counting exp.
- We set 95% CLs limits

*CMS-SUS-14-004,
PRD 1507.02898*

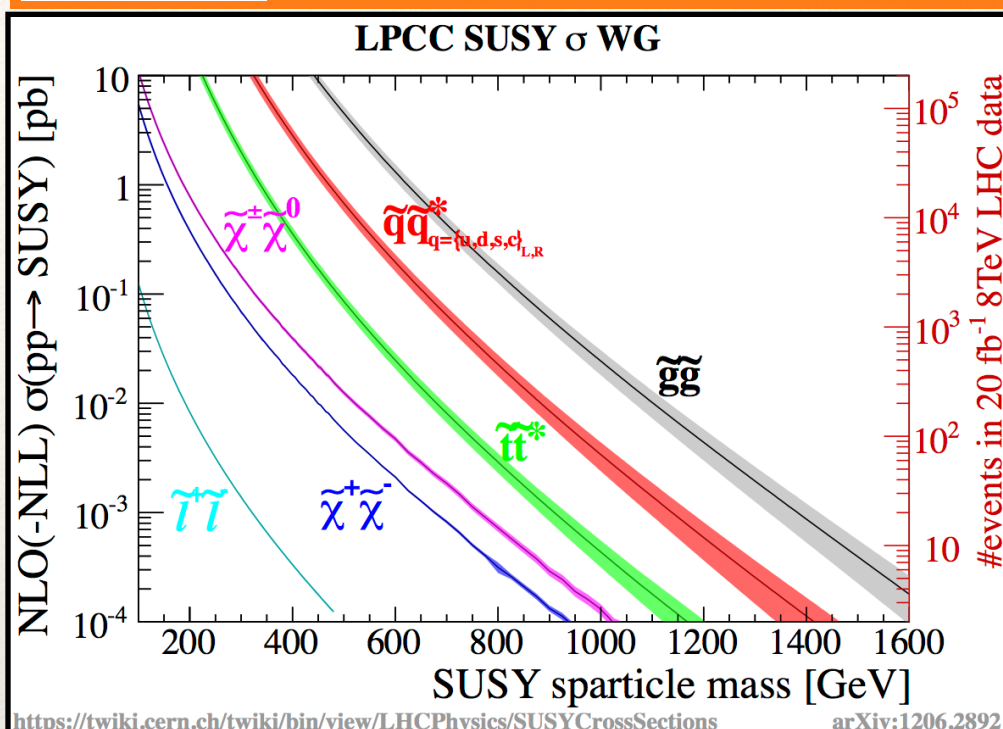
- *GGM-Bino*
- *$m_{\text{gluino}} > \sim 1.5 \text{ TeV}$, $m_{\text{squark}} > \sim 1.4 \text{ TeV}$*

- *SMS T5gg*
- *$m_{\text{gluino}} > \sim 1.3 \text{ TeV}$*



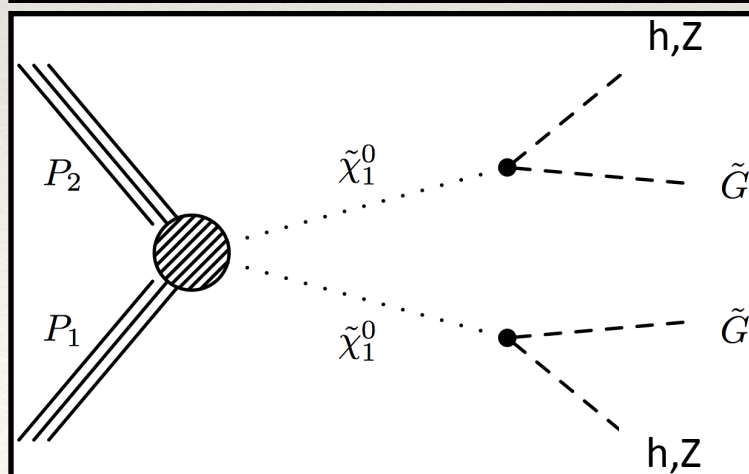
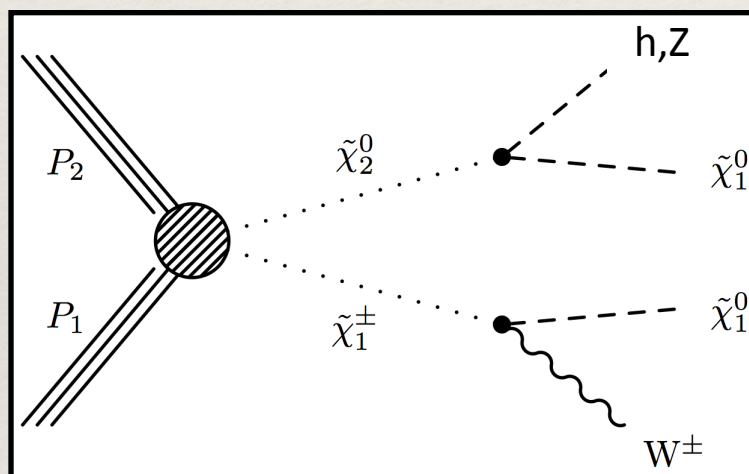


Higgs Aware SUSY



Discovery of the higgs boson enhances the LHC SUSY program

- Search for electroweak SUSY production complements typical searches for strongly produced SUSY
- Characterized by: fewer jets & more W, Z, Higgs in decay chain
- $h \rightarrow \gamma\gamma$ is particularly interesting : a narrow resonance
- *Final state: photons, jets and/or leptons*





Electroweak SUSY Searches ($h \rightarrow \gamma\gamma$)



CMS-SUS-14-002, PRD 90, 092007 (2014)

- Selection:

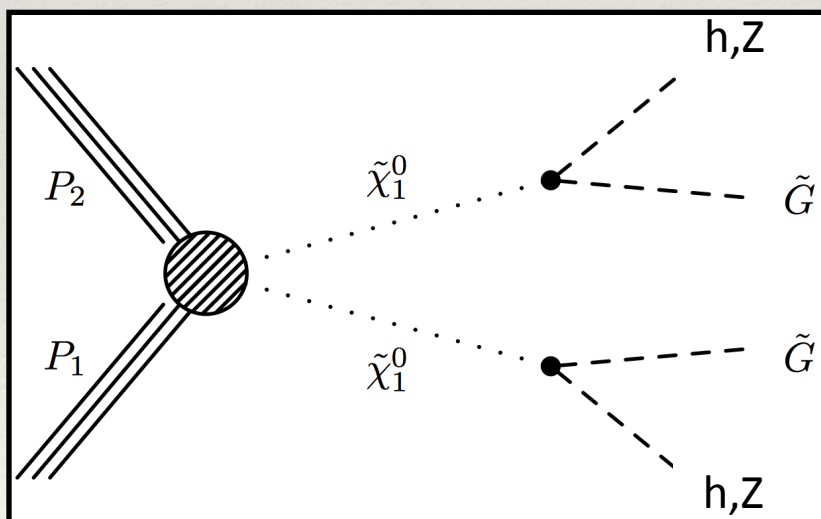
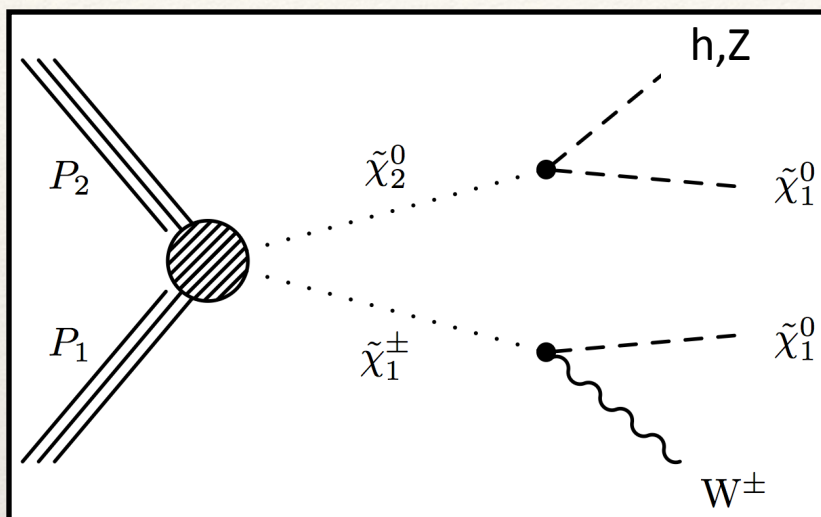
- At least two photons (γ): $P_{\text{lead}}^T > 40$, $P_{\text{sublead}}^T > 25$ GeV
- Both photons in ECAL barrel, i.e. $|\eta| < 1.44$
- Two highest P_T photons form higgs candidate

- SM backgrounds

- QCD multijet events: mismeasured E_{miss}^T + fakes
- QCD multijet + $\gamma/\gamma\gamma$: mismeasured E_{miss}^T (*dominant*)
- SM-higgs: real E_{miss}^T , (*sub-leading*)

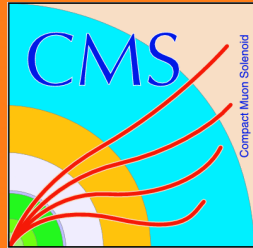
- Discriminating variables

- Depends on the final state:
 - $hh \rightarrow \gamma\gamma bb$, S_T^h : scalar sum of higgs cand. P_T
 - $hZ, hW \rightarrow \gamma\gamma + 2\text{jets}$: E_{miss}^T
 - $hZ, hW \rightarrow \gamma\gamma + \text{leptons}$: missing transverse mass M_T

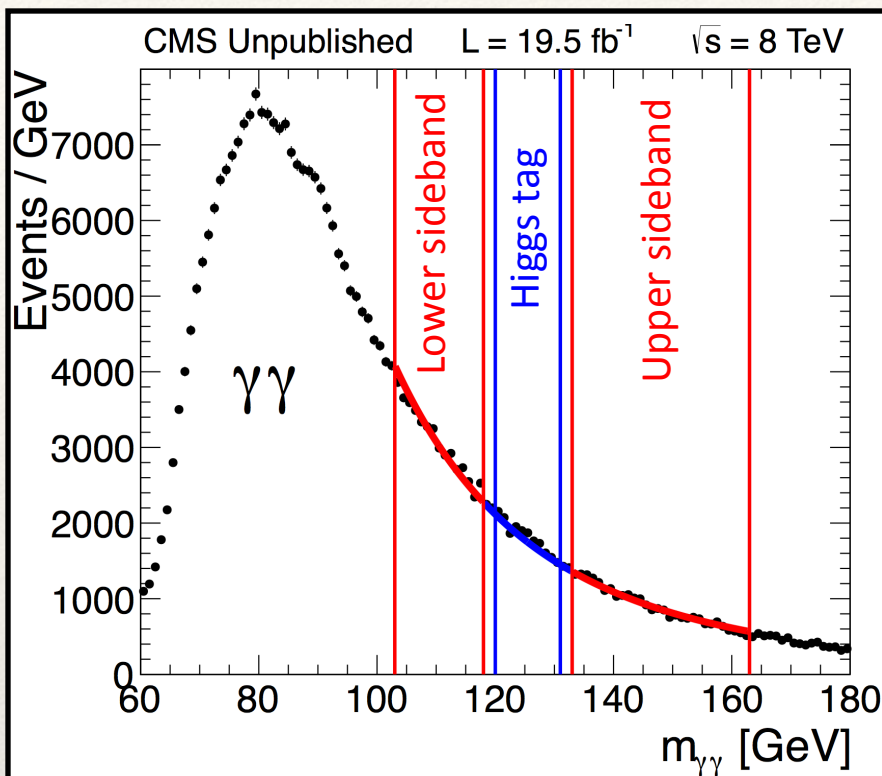




Electroweak SUSY Searches ($h \rightarrow \gamma\gamma$)

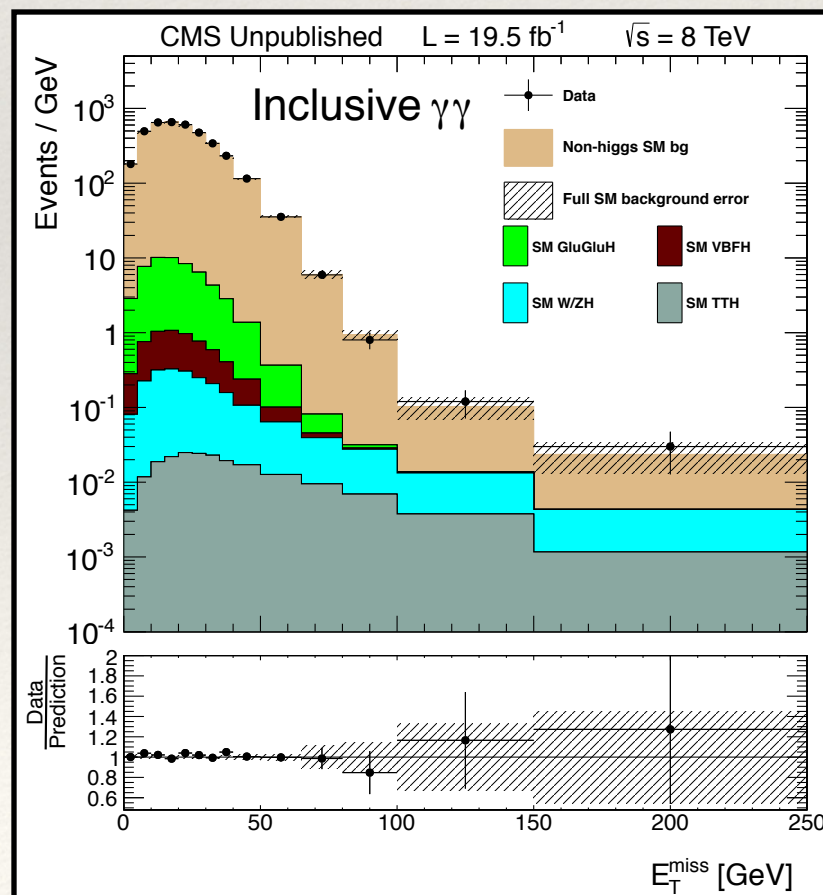


CMS-SUS-14-002, PRD 90, 092007 (2014)



Background Prediction

- Define sideband region:
 $m_{\gamma\gamma} \ni [\{103-118\}, \{133-163\}] \text{ GeV}$
- Fit sidebands with a power law function
- Use fit to extrapolate from the sidebands to the signal region
- *Extrapolate chosen search variable distribution in sidebands to signal region*
- Estimate SM-Higgs using Monte Carlo





Electroweak SUSY Searches ($hh \rightarrow \gamma\gamma bb$)

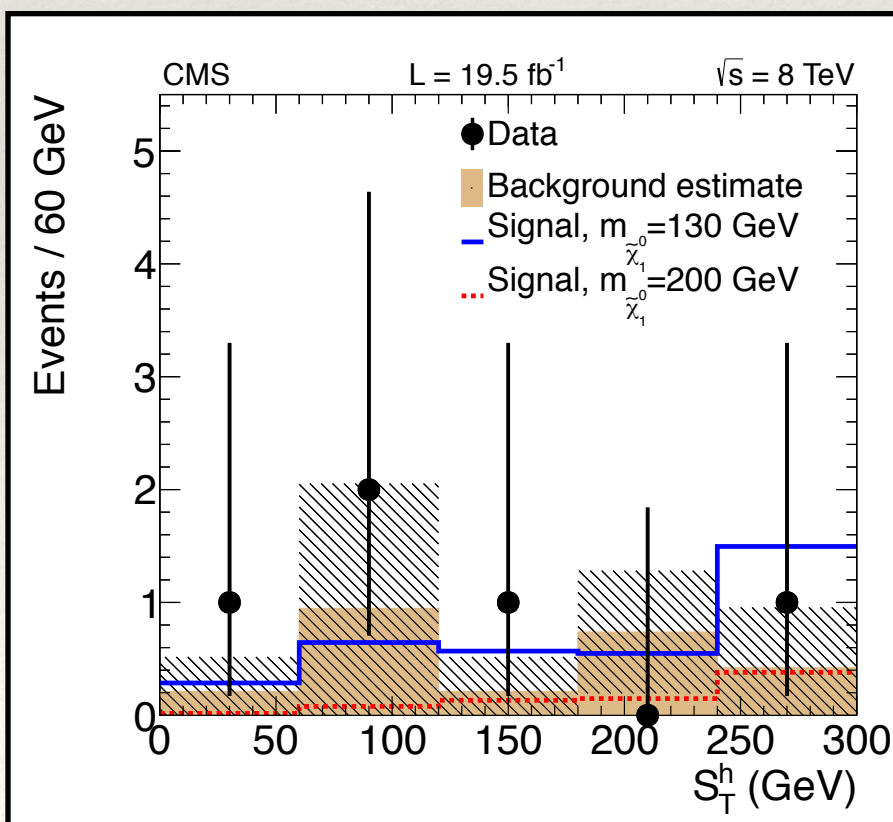
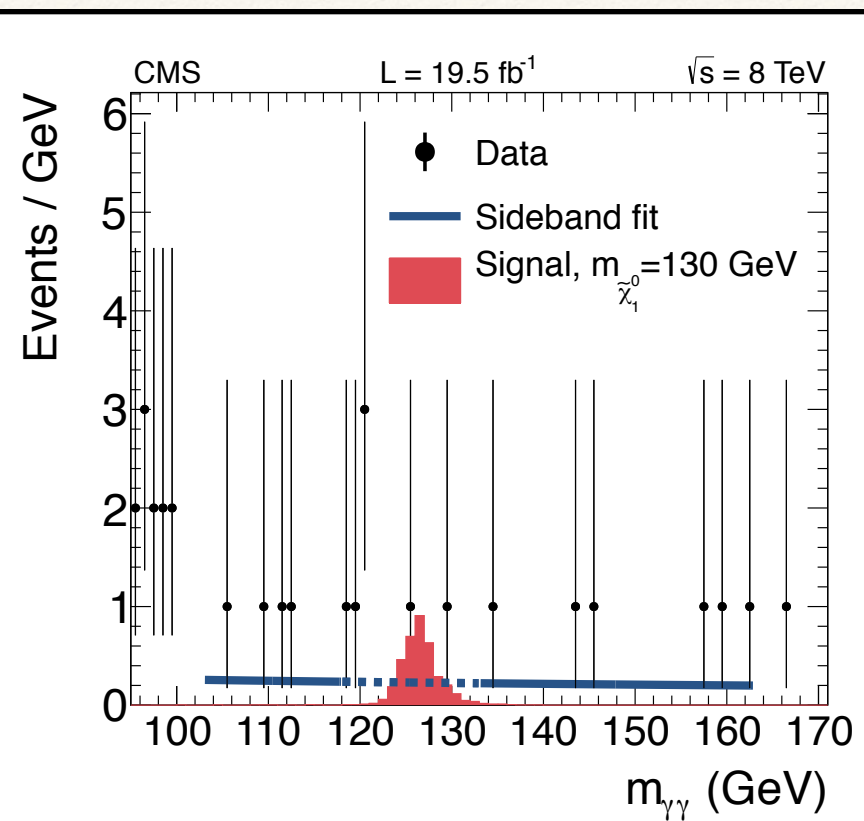
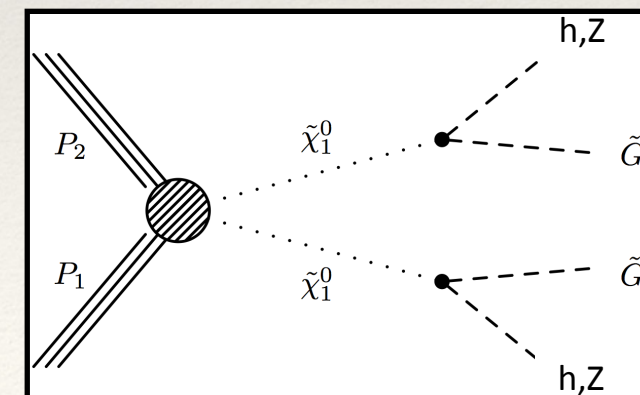


CMS-SUS-14-002, PRD 90, 092007 (2014)

Search for double higgs production

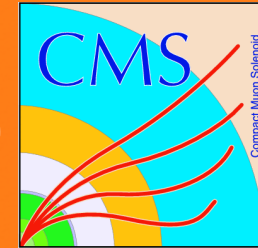
- Reconstruct one higgs candidates through:
 - $h \rightarrow \gamma\gamma$ decay, $m_{\gamma\gamma} \ni [103-163]$ GeV
 - $h \rightarrow bb$ decay, $m_{bb} \ni [95-155]$ GeV
- Construct S^h , scalar sum P_T of the two h 's
- *Background prediction by extrapolating from $m_{\gamma\gamma}$ sidebands.*

No significant excess observed
SM-Higgs background from MC: negligible





Electroweak SUSY Searches ($hZ/W \rightarrow \gamma\gamma 2j$)



CMS-SUS-14-002, PRD 90, 092007 (2014)

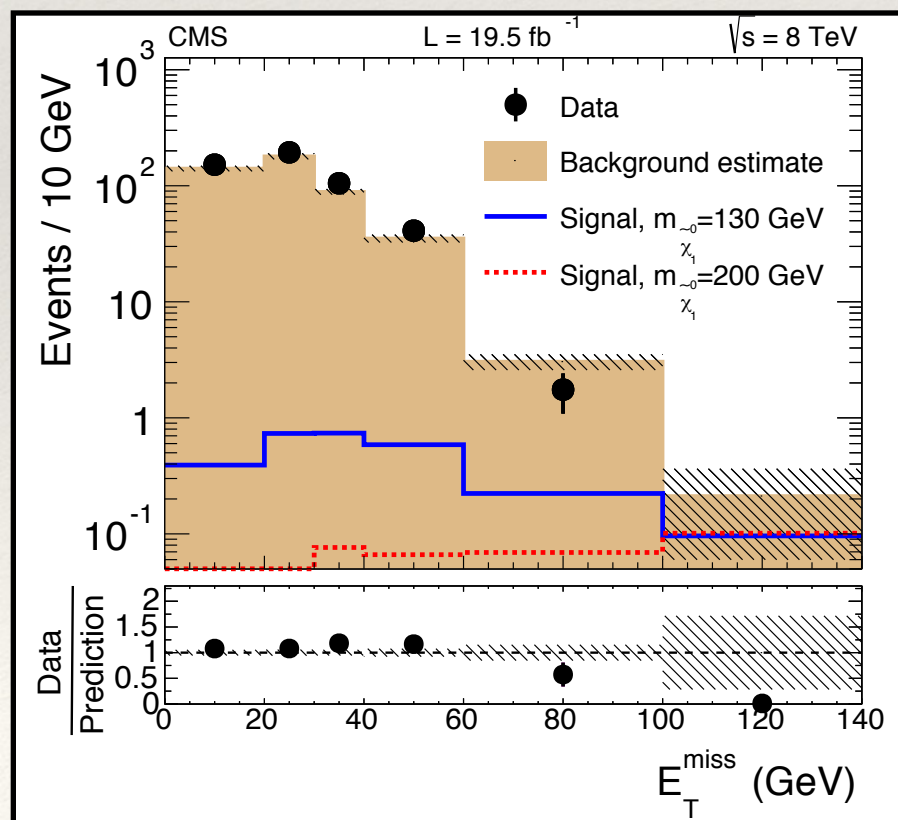
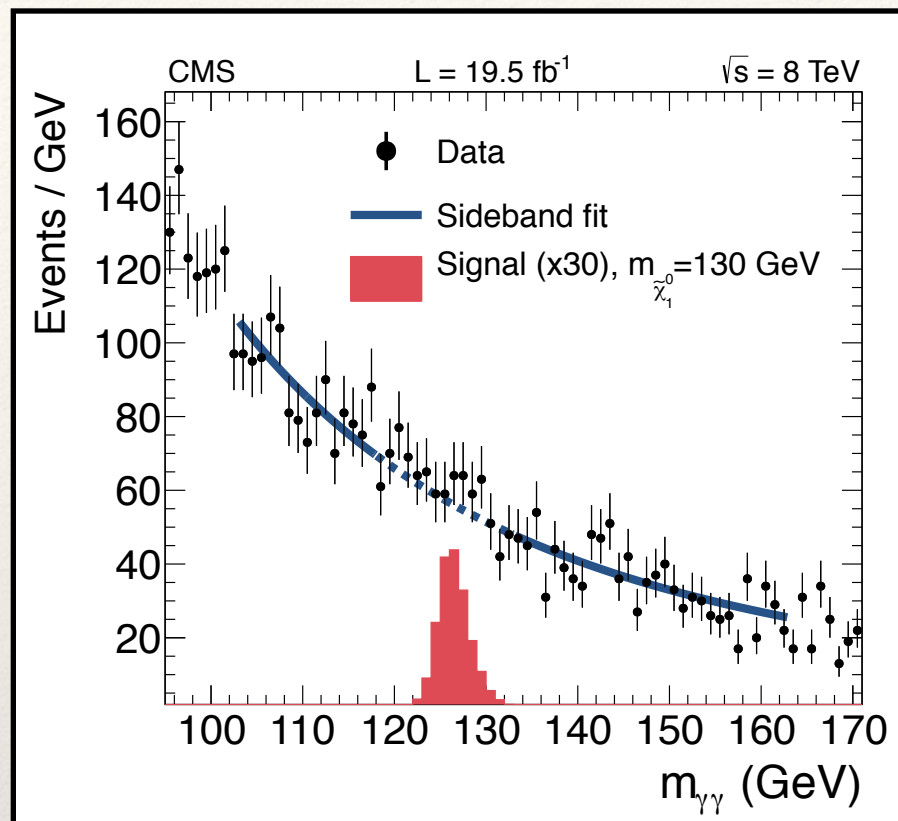
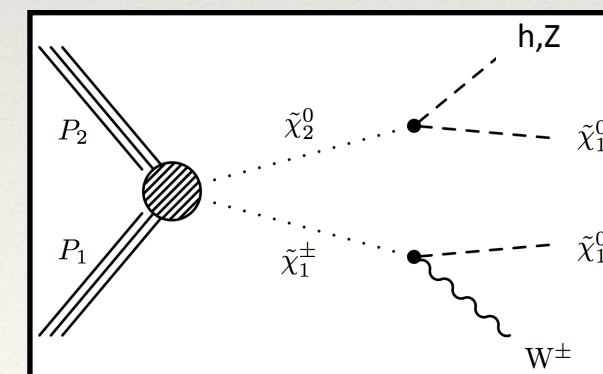
Search for higgs + V(Z,W) production

- Reconstruct higgs through: $h \rightarrow \gamma\gamma$ decay
- Reconstruct V through hadronic decay:
 $m_{jj} \ni [70-110] \text{ GeV}$
- Discriminating variable E^{miss}_T

- *Background prediction by extrapolating from $m_{\gamma\gamma}$ sidebands.*

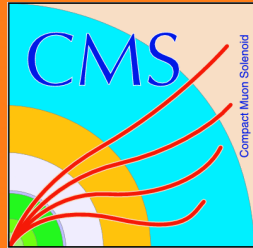
No significant excess observed

SM-Higgs background from MC: 30% uncertainty





Electroweak SUSY Searches ($h(h,V) \rightarrow \gamma\gamma\text{leptons}$)



CMS-SUS-14-002, PRD 90, 092007 (2014)

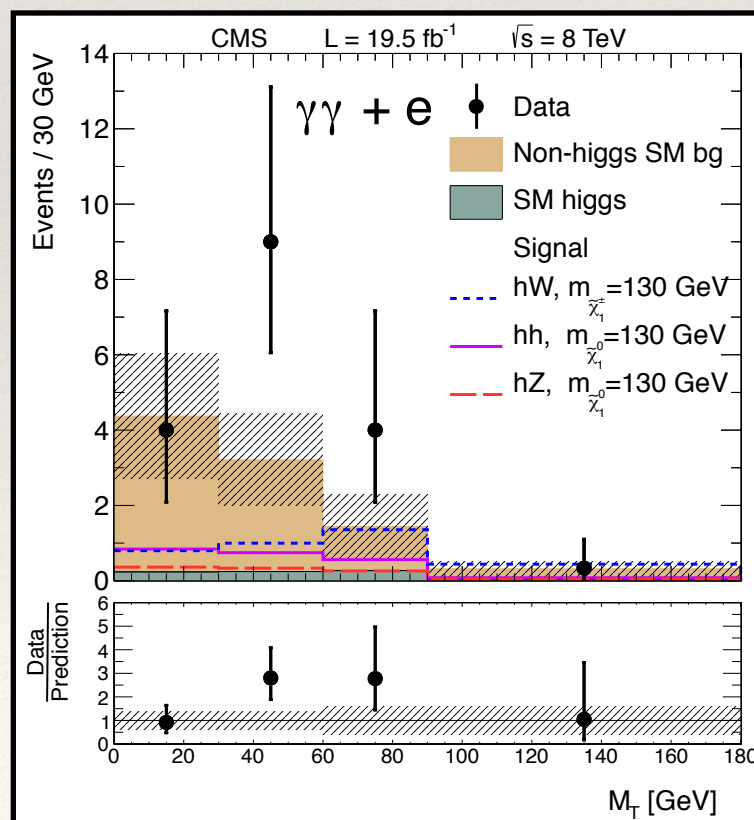
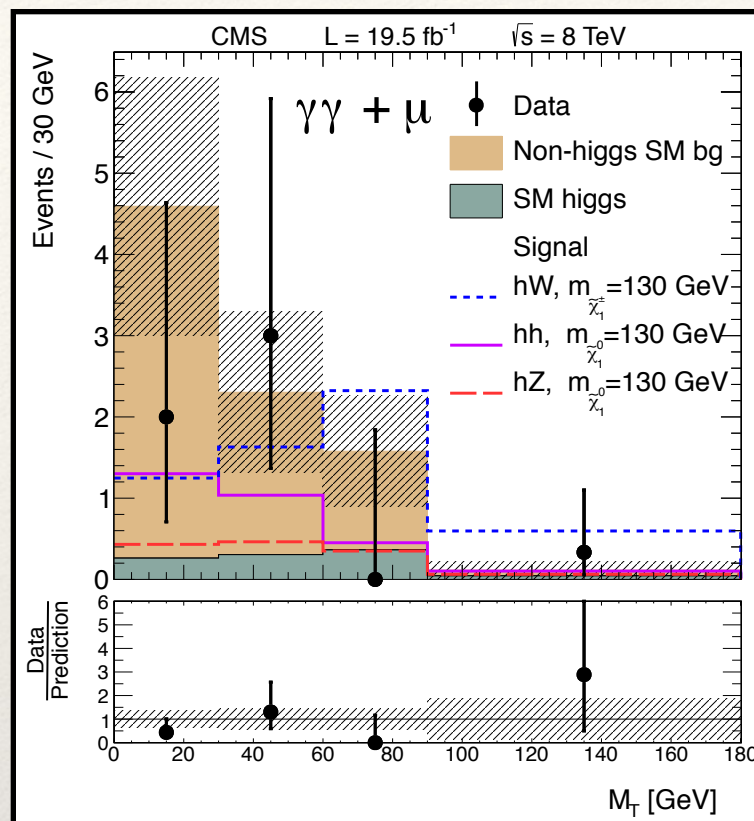
Search for higgs + (h,V) production

- Reconstruct higgs through: $h \rightarrow \gamma\gamma$ decay
- Tag second boson by requiring at least one (e/ μ)
- At least one electron, at least one muon
- *Discriminating variable: transverse mass (M_T)*

- *Background prediction by extrapolating from $m_{\gamma\gamma}$ sidebands.*

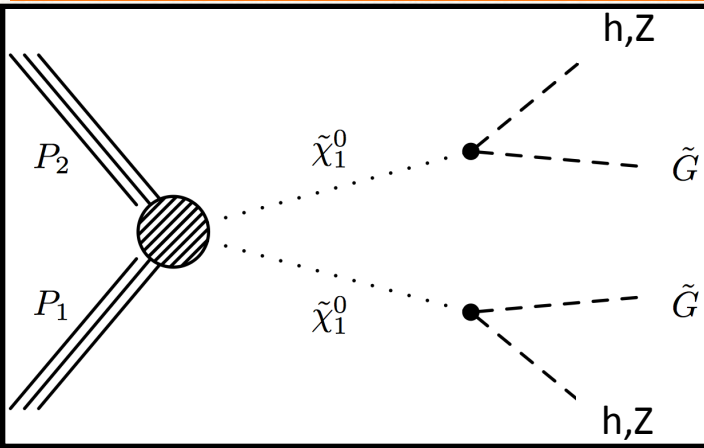
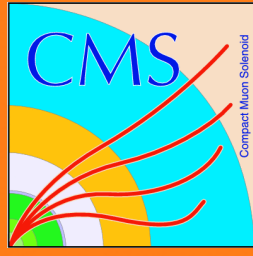
Largest excess observed is 2.1σ in electron sample

SM-Higgs background from MC: 30% uncertainty

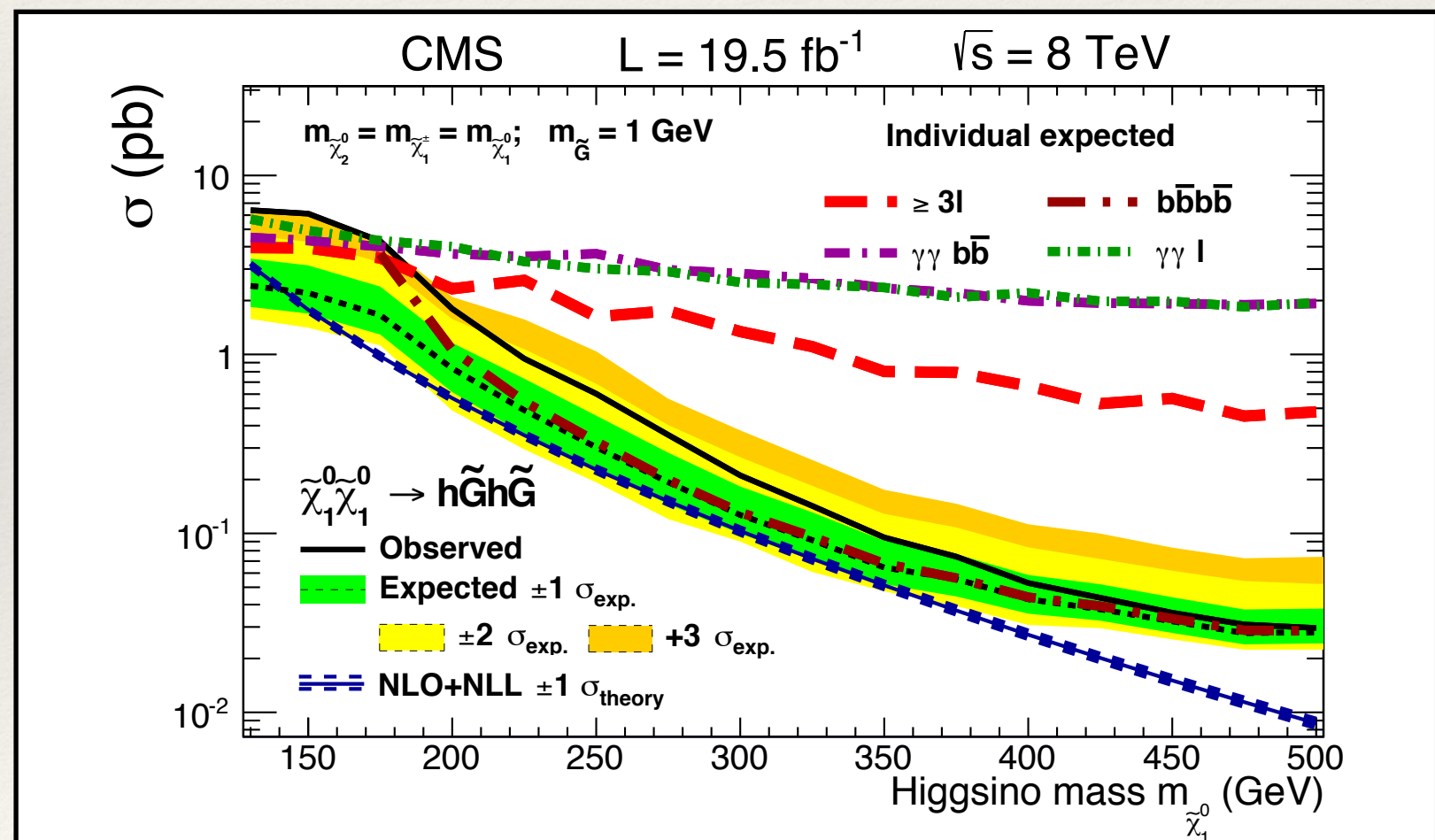




Electroweak SUSY Searches



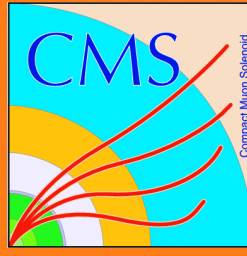
- Set limits for electroweak GMSB hh production
 - $hh \rightarrow \gamma \gamma bb$
 - $hh \rightarrow \gamma \gamma + \text{lepton}$
- *Expected sensitivity can rule out neutralino at 150 GeV, but observation does not.*



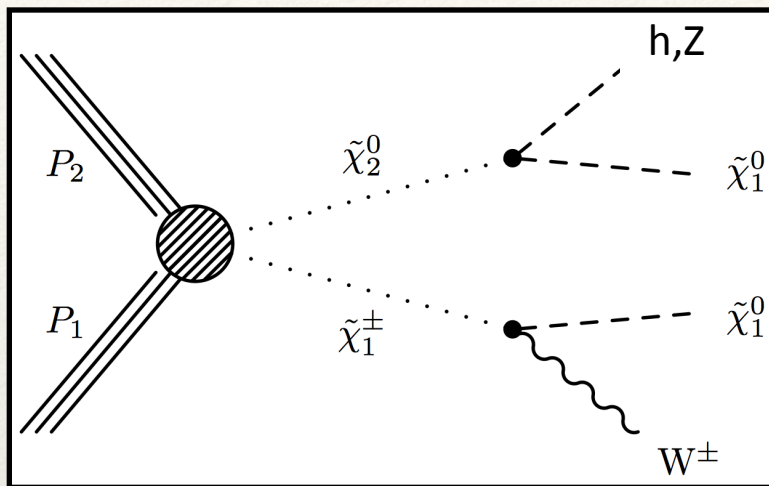
CMS-SUS-14-002, PRD 90, 092007 (2014)



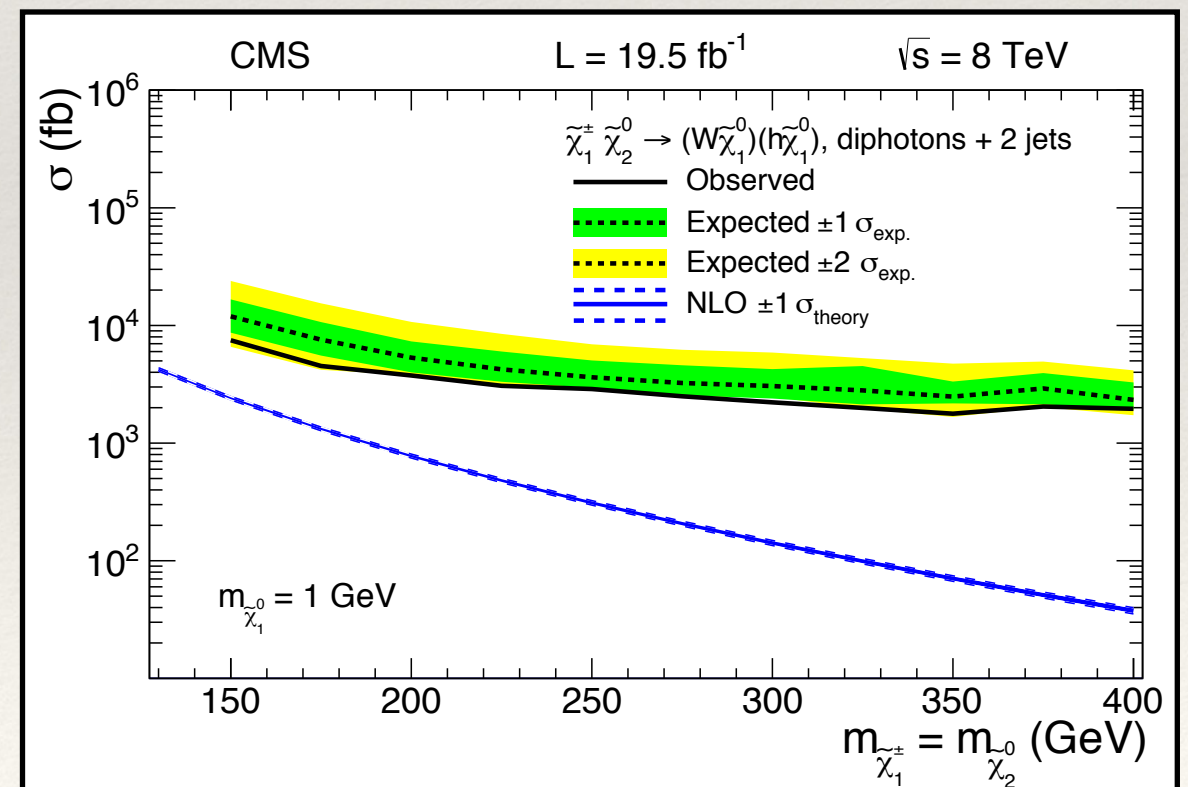
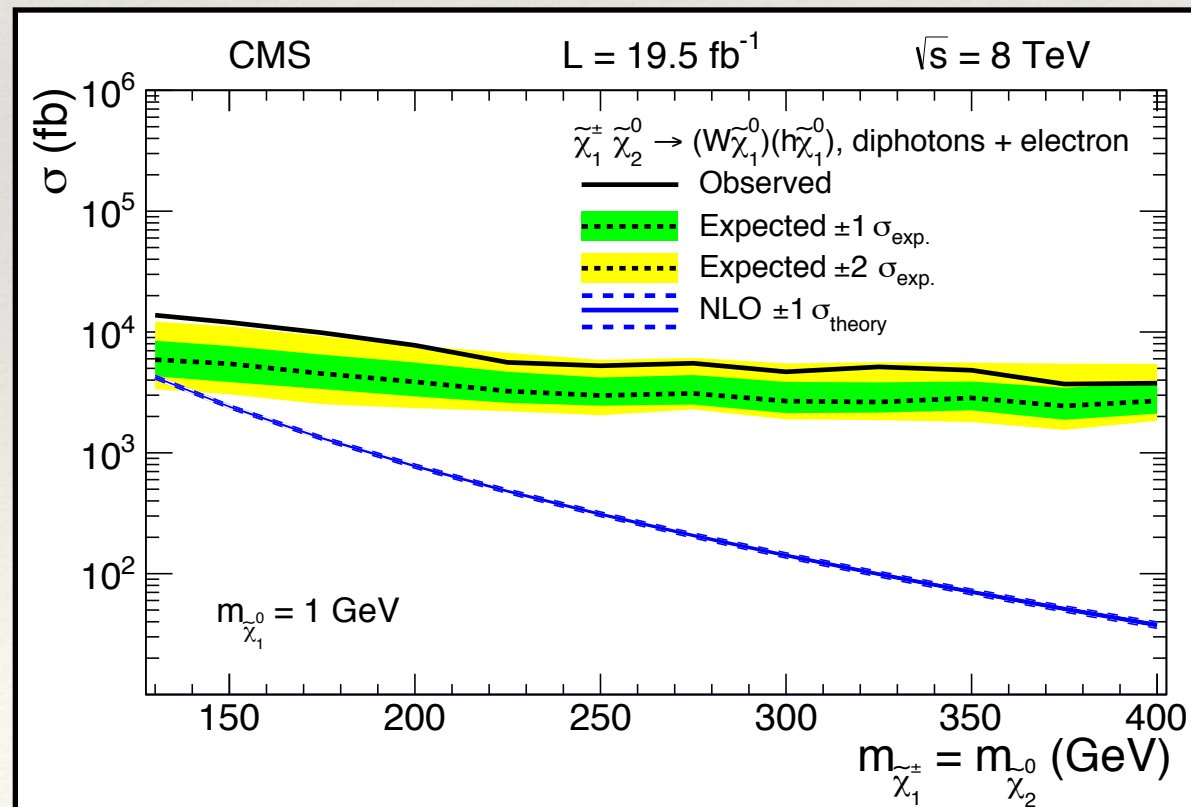
Electroweak SUSY Searches



CMS-SUS-14-002, PRD 90, 092007 (2014)



- Set limits for electroweak hW production
 - $hh \rightarrow \gamma \gamma + 2\text{jets}$
 - $hh \rightarrow \gamma \gamma + \text{leptons}$
- Current sensitivity from combination of channels is close to theoretical cross section at 130 GeV





Inclusive Higgs-aware Search



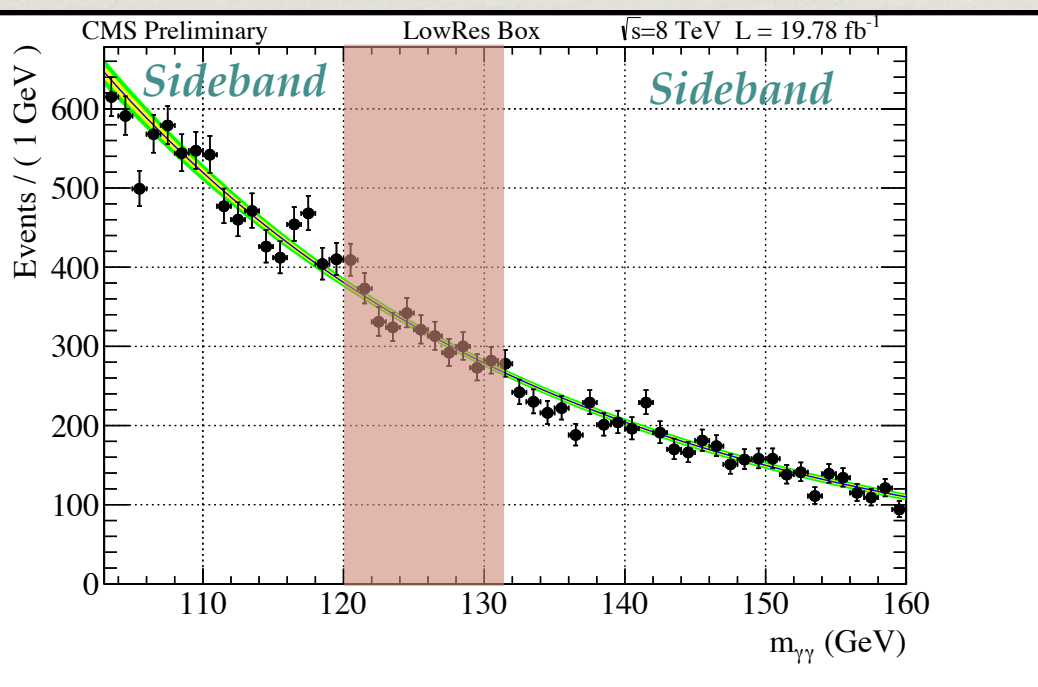
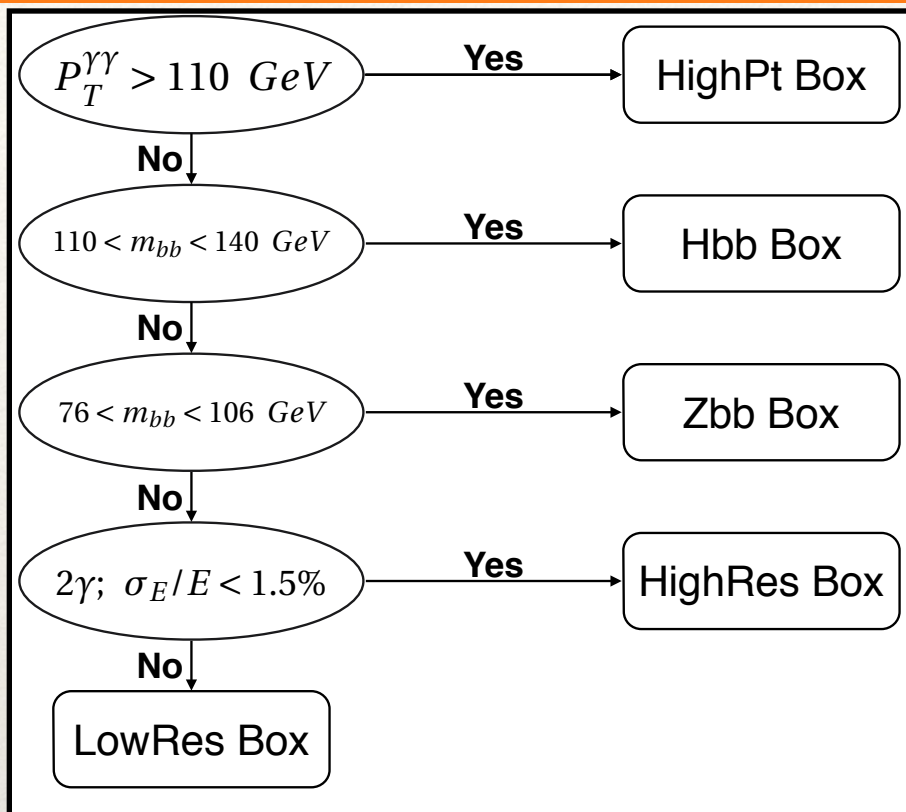
CMS-SUS-14-017: New Result



Inclusive Search for SUSY with Higgs

- Selection:
 - Tag higgs using: $h \rightarrow \gamma\gamma$
 - Categorize using higgs P_T and photon resolution
- Discriminating variables: M_R and R^2

Analysis Event Category Workflow



- *Background prediction by extrapolating from $m_{\gamma\gamma}$ sidebands.*

$m_{\gamma\gamma} \ni \{103-118\}, \{133-163\} \text{ GeV}$



Inclusive Higgs-aware Search

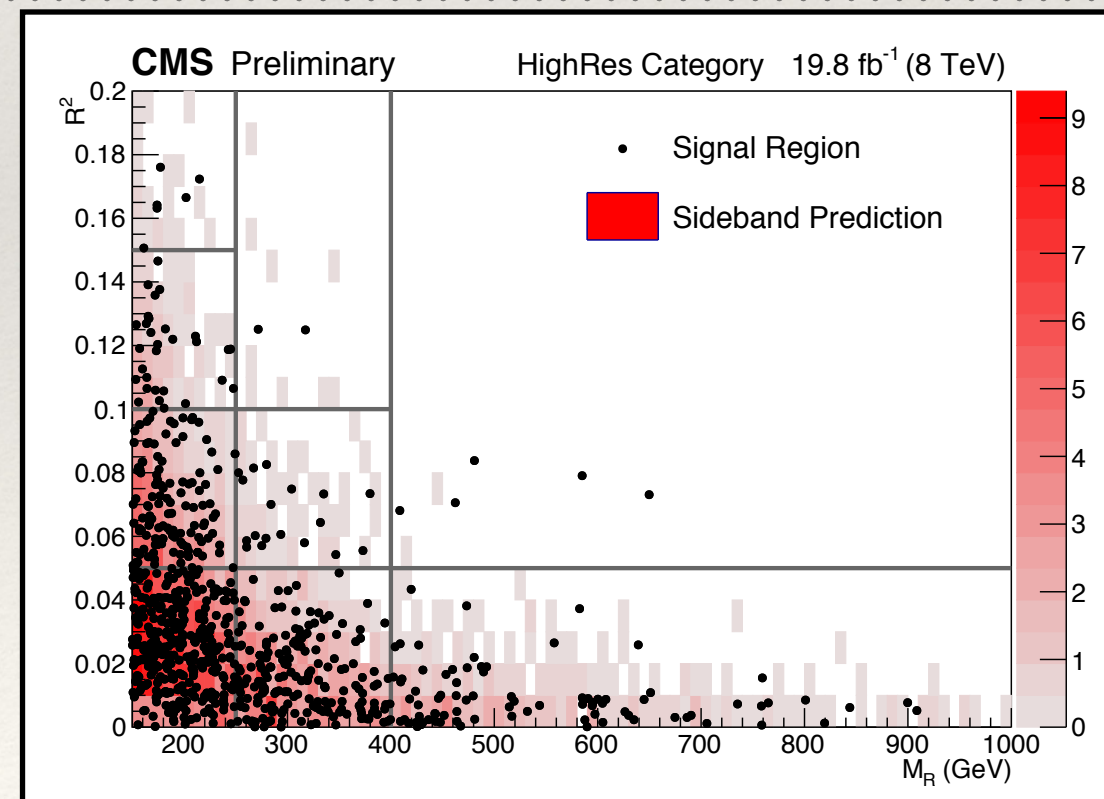
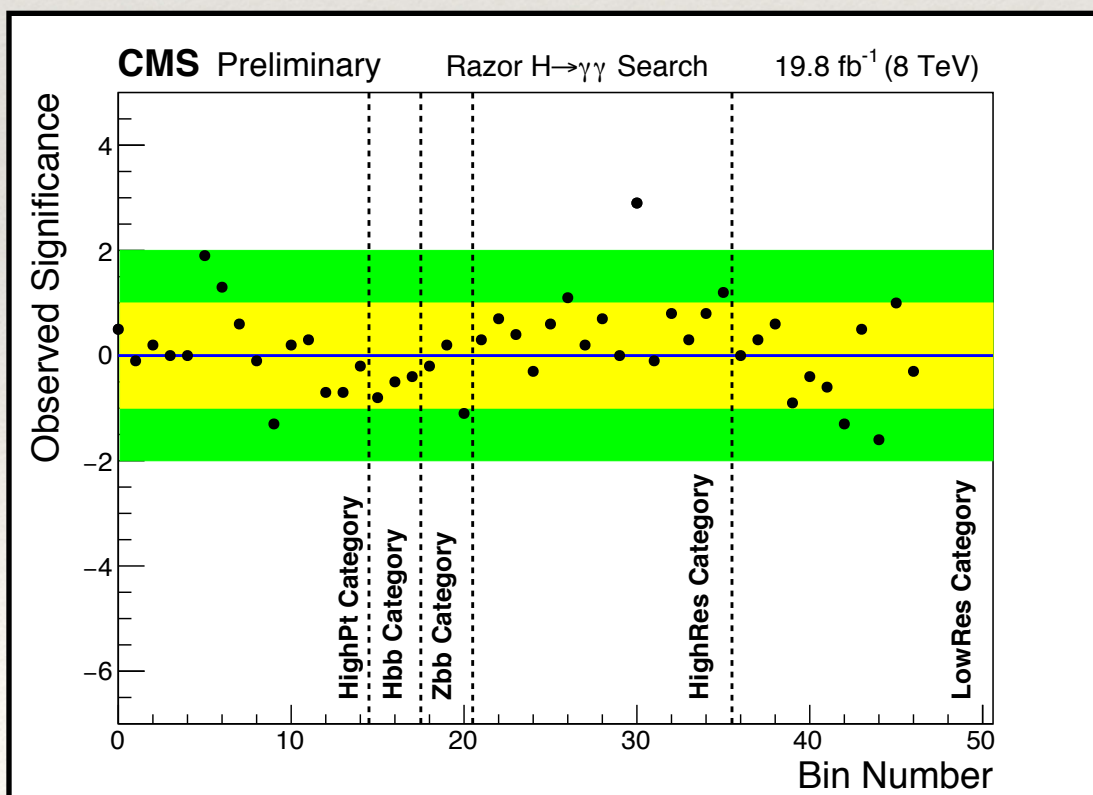


HighRes Event Category Results

CMS-SUS-14-017:
New Result

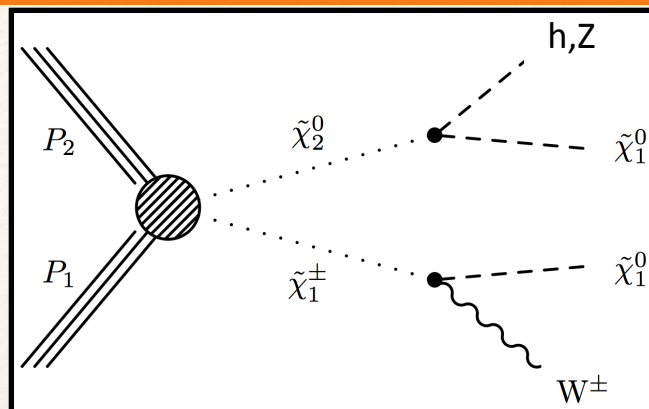
*excess is 1.6 σ
after look
elsewhere effect*

M_R region	R^2 region	observed events	expected background	p-value	significance (σ)
150 - 250	0.00 - 0.05	363	$357.6^{+9.6}_{-9.4}$ (syst.)	0.40	0.3
150 - 250	0.05 - 0.10	149	$139.4^{+5.6}_{-5.4}$ (syst.)	0.23	0.7
150 - 250	0.10 - 0.15	35	$32.5^{+3.4}_{-3.1}$ (syst.)	0.34	0.4
150 - 250	0.15 - 1.00	7	$8.0^{+1.7}_{-1.4}$ (syst.)	0.40	-0.3
250 - 400	0.00 - 0.05	218	$207.9^{+7.0}_{-6.8}$ (syst.)	0.27	0.6
250 - 400	0.05 - 0.10	20	$14.7^{+2.5}_{-2.1}$ (syst.)	0.13	1.1
250 - 400	0.10 - 1.00	3	$2.7^{+0.8}_{-0.6}$ (syst.)	0.43	0.2
400 - 1400	0.00 - 0.05	109	$101.6^{+5.0}_{-4.8}$ (syst.)	0.26	0.7
400 - 1400	0.05 - 1.00	5	$0.5^{+0.4}_{-0.2}$ (syst.)	0.002	2.9
1400 - 3000	0.00 - 1.00	0	$0.9^{+0.5}_{-0.3}$ (syst.)	0.44	-0.1

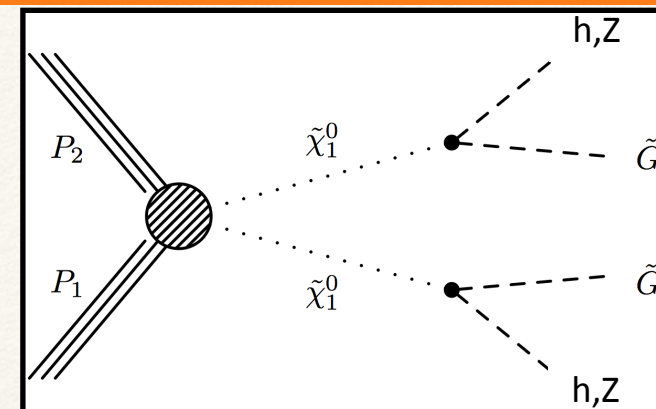




Inclusive Higgs-aware Search

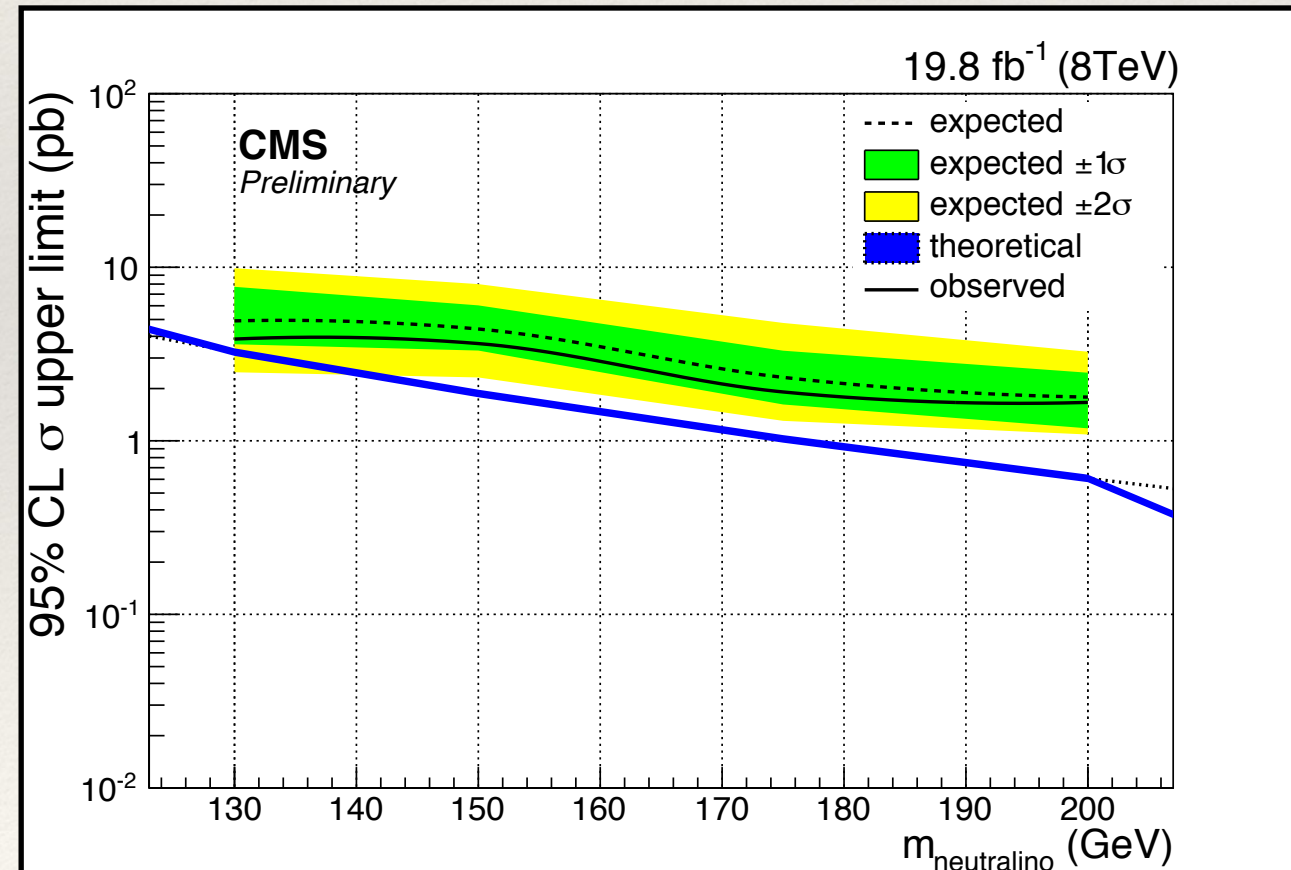
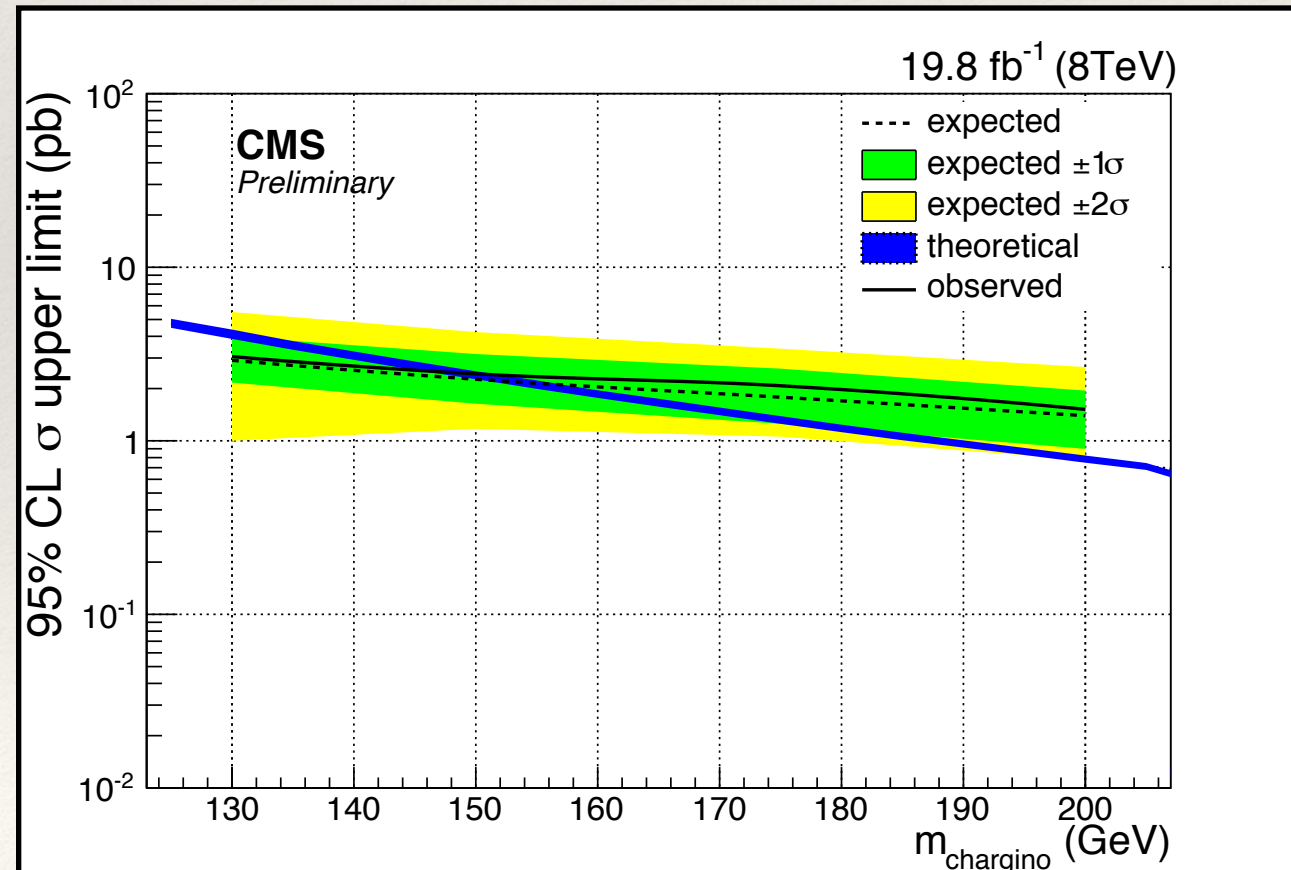


*CMS-SUS-14-017:
New Result*



- hW electroweak production
- *Exclude a 130-150 GeV neutralino/ chargino*

- hh electroweak production
- *Sensitivity close to exclude a 130 GeV neutralino*

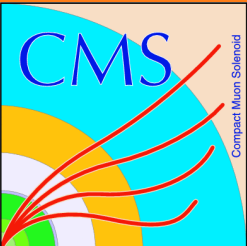




Summary



- CMS searches for GMSB SUSY gluino/squark production
 - *single and diphoton final state, no excesses found*
 - *Exclude gluino at 1.0 TeV and squark at 0.8 TeV (wino case)*
 - *Exclude gluino at 1.5 TeV and squark at 1.4 TeV (bino case)*
- CMS searches for GMSB SUSY EW production
 - *Use SM h ($h \rightarrow \gamma\gamma$) as a tool to look for SUSY*
 - *New analyses improve sensitivity to hh , hW electroweak production. hW , chargino/neutralino excluded at 150 GeV*
- New higgs-aware search: does not depend on a particular SUSY model. Enhances possible discovery.
- Interesting results. Stay tuned for 13 TeV photon updates



Backups



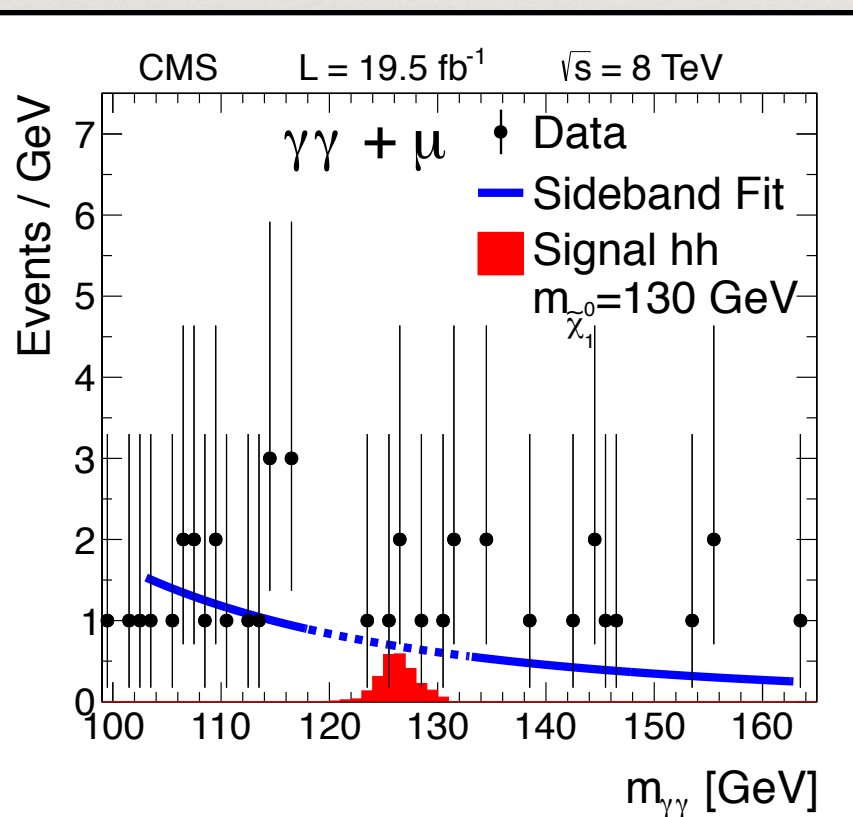
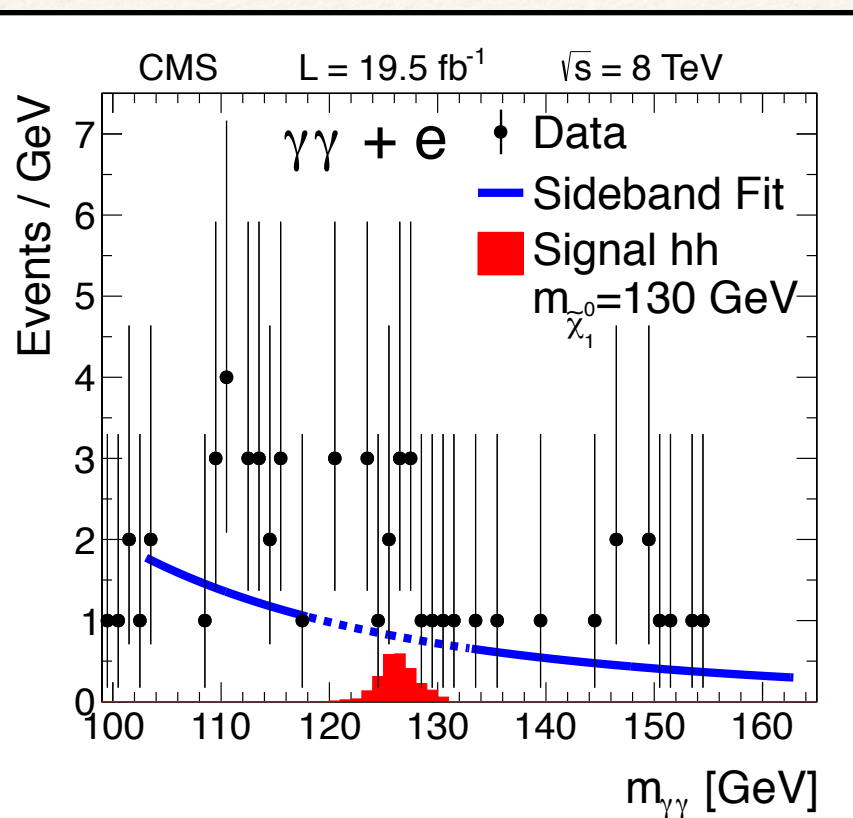
CMS-SUS-14-002, PRD 90, 092007 (2014)

Search for higgs + (h,V) production

- Apply standard photon selection
- Reconstruct one higgs candidate by its $\gamma\gamma$ decay
 - $m_{\gamma\gamma} \ni [103-163]$ GeV
- Tag second boson by requiring at least one (e/ μ)
 - Isolated Leptons, $P_T > 15$ GeV, $|\eta| < 2.4$
 - $\Delta R(\gamma_{(1,2)}, \text{lepton}) > 0.3$
 - $m_{e\gamma} \ni [86-96]$ GeV
- Two search samples:
 - At least one electron, at least one muon
- *Look for excess in the transverse mass M_T distribution*
- *Fit $m_{\gamma\gamma}$ in sidebands. Use fit result to scale the M_T sideband distribution to the expected signal region.*

*2.1 standard deviations excess in electron sample.
cross checks suggest consistent with background
fluctuation*

SM-Higgs background from MC: 30% uncertainty

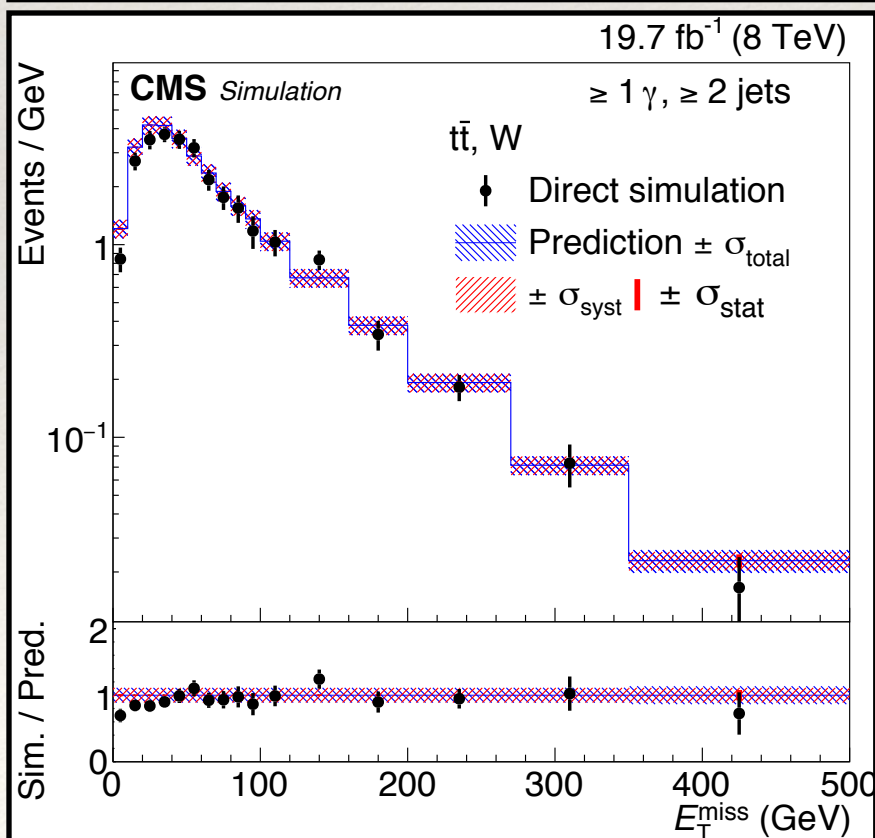
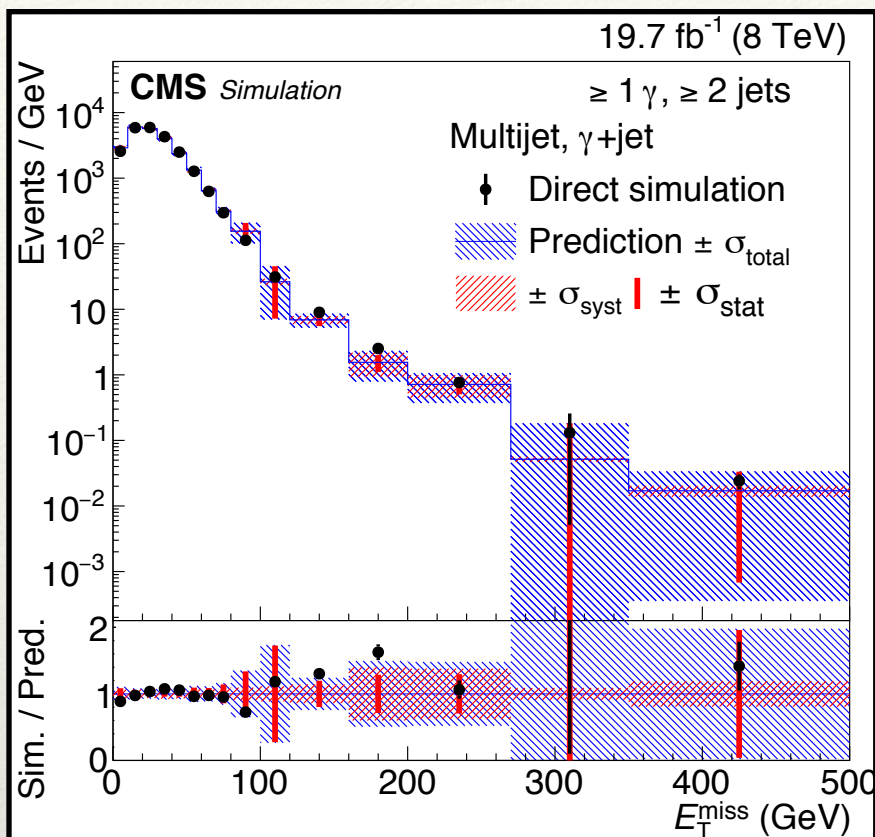




Single Photon Analysis



CMS-SUS-14-004, PRD 1507.02898



- **Selection:**

- At least one photon (γ): $P_T^* > 110$ GeV
- At least two jets: $P_T > 30$ GeV, $|\eta| < 2.5$, $\Delta R(\gamma, j_i) > 0.3$
- $H_T^* > 500$ GeV (including γ)

- **SM backgrounds**

- QCD multijet events: mismeasured E_T^{miss} + fakes
- QCD multijet + γ: mismeasured E_T^{miss}
- W+jets and tt + jets (EW): real E_T^{miss} , $e \rightarrow \gamma$
- γW+jets, γZ+jets, γtt + jets

- **Discriminating variable**

- $E_T^{\text{miss}} > 100$ GeV, 6 bin categories

- **Background estimation**

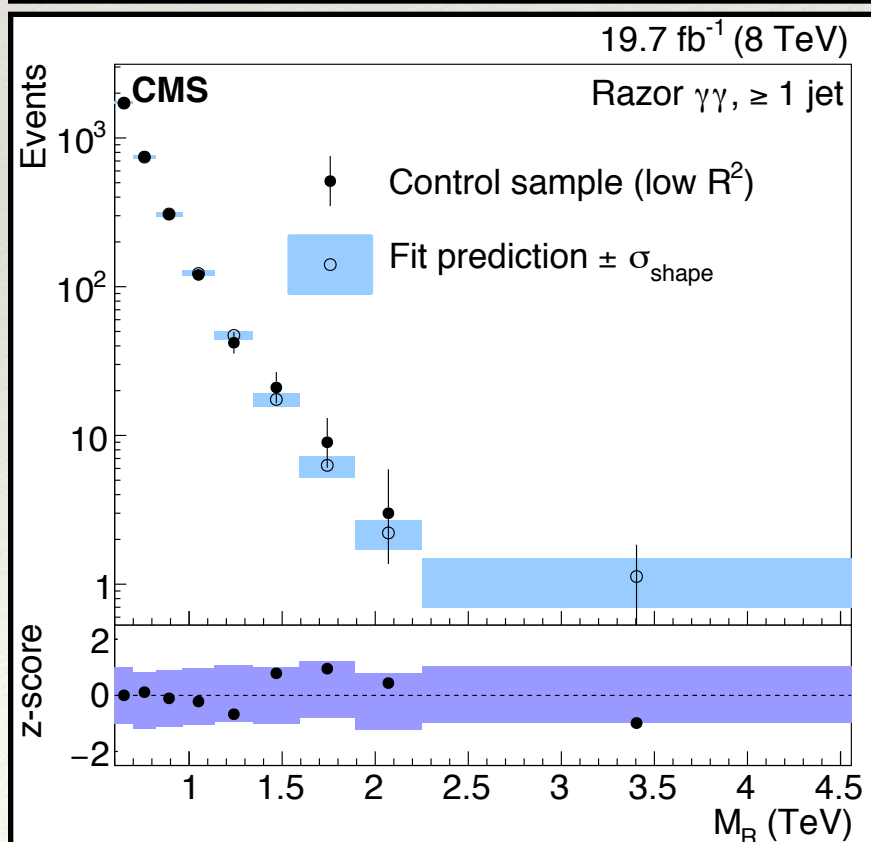
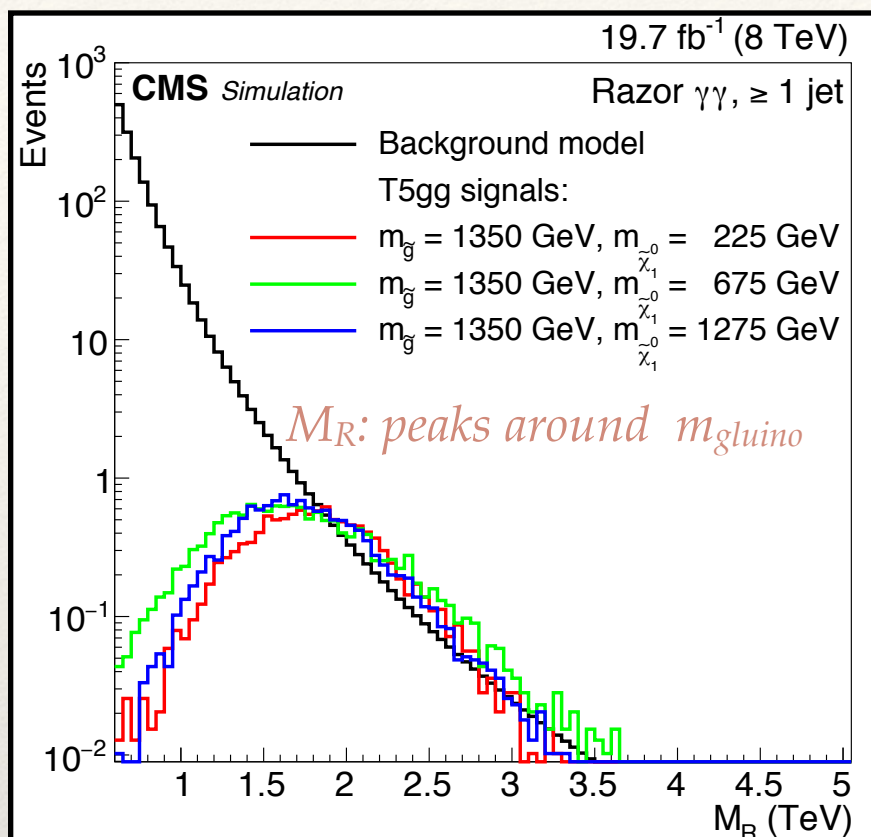
- Use a γ^{loose} (relax isolation) control sample. Obtain correction factors for E_T^{miss} . *Predict Multijet and γ+jet*
- Use a γ^{pixel} (pixel seed match) control sample. *Predict EW scaling E_T^{miss} distribution by $f_{e \rightarrow \gamma}$*



Double Photon Analysis



CMS-SUS-14-004, PRD 1507.02898



• Selection:

- At least two photons (γ): $P_{\text{lead}_T} > 30$, $P_{\text{sublead}_T} > 22$ GeV
- At least one jet: $P_T > 40$ GeV, $|\eta| < 2.5$, $\Delta R(\gamma_{(1,2)}, j_i) > 0.5$

• SM backgrounds

- QCD multijet events: mismeasured E_{miss_T} + fakes
- QCD multijet + γ : mismeasured E_{miss_T} (*dominant*)
- W+jets and tt + jets (EW): real E_{miss_T} , $e \rightarrow \gamma$ (*negligible*)

• Discriminating variable

- Razor variables: M_R (*mass scale*) and R^2 (*energy imbalance*)

• Background estimation

- Define control region $M_R > 600$ GeV && $0.01 < R^2 < 0.02$.

Fit M_R with $P(M_R) \propto e^{-k(M_R - M_R^0)^{\frac{1}{n}}}$

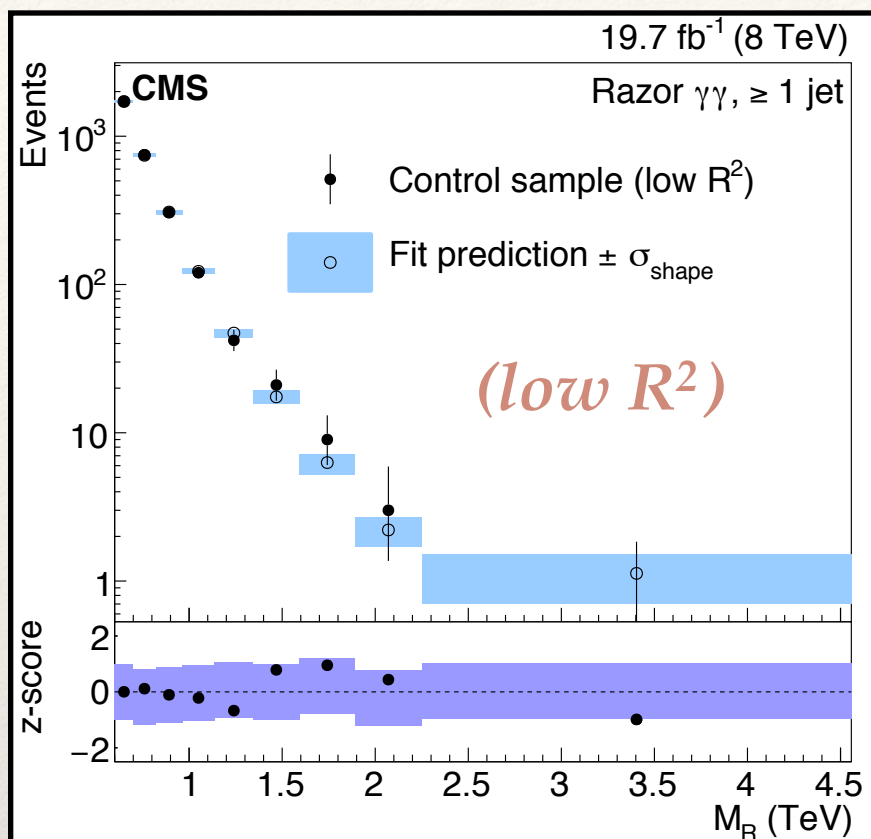
- Use fit shape normalize to the total number of events as background prediction in signal region

Fit to control sample:

bottom panel z-score (number of Normal standard deviation)



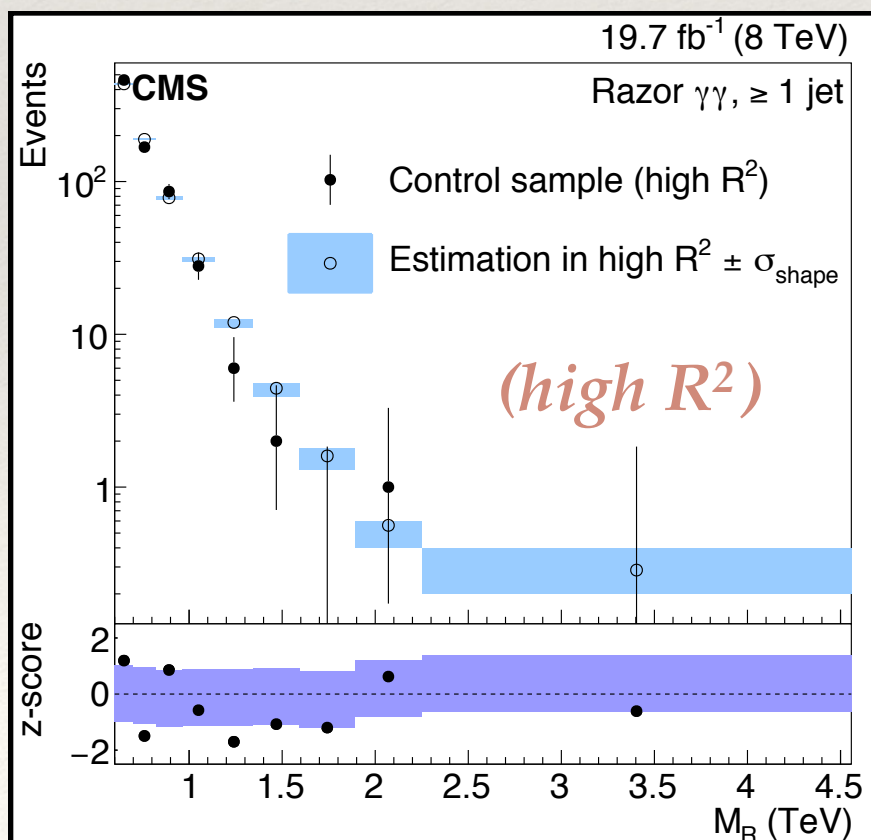
Double Photon Analysis



Background Prediction

- Define control region $M_R > 600$ GeV && $0.01 < R^2 < 0.02$.
Fit M_R with $P(M_R) \propto e^{-k(M_R - M_R^0)^{1/n}}$ *(low R^2)*
- Normalize to the total yield as background prediction in signal region

CMS-SUS-14-004,
PRD 1507.02898

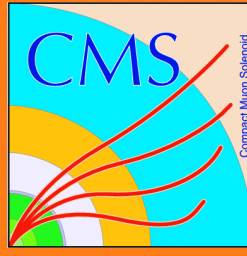


Background Prediction Validation

- Search region: $M_R > 600$ GeV && $R^2 > 0.2$ (high R^2)
- Control sample in high R^2 kinematic region with photons failing isolation/cluster shape
- No observed systematic deviation.*
within one standard deviation

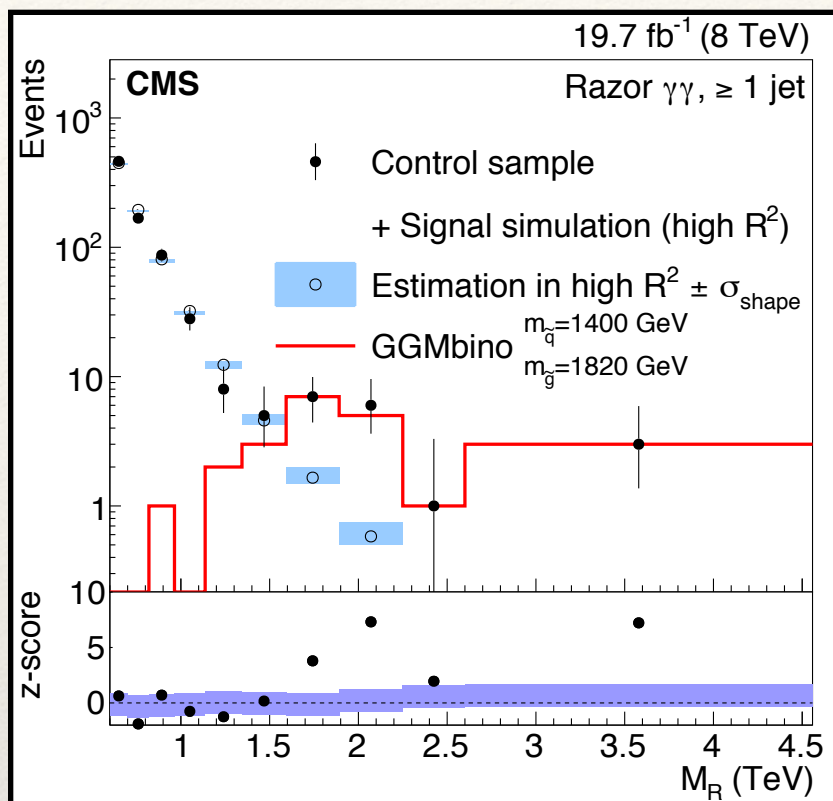


Double Photon Analysis



Signal Injection Test

CMS-SUS-14-004,
PRD 1507.02898

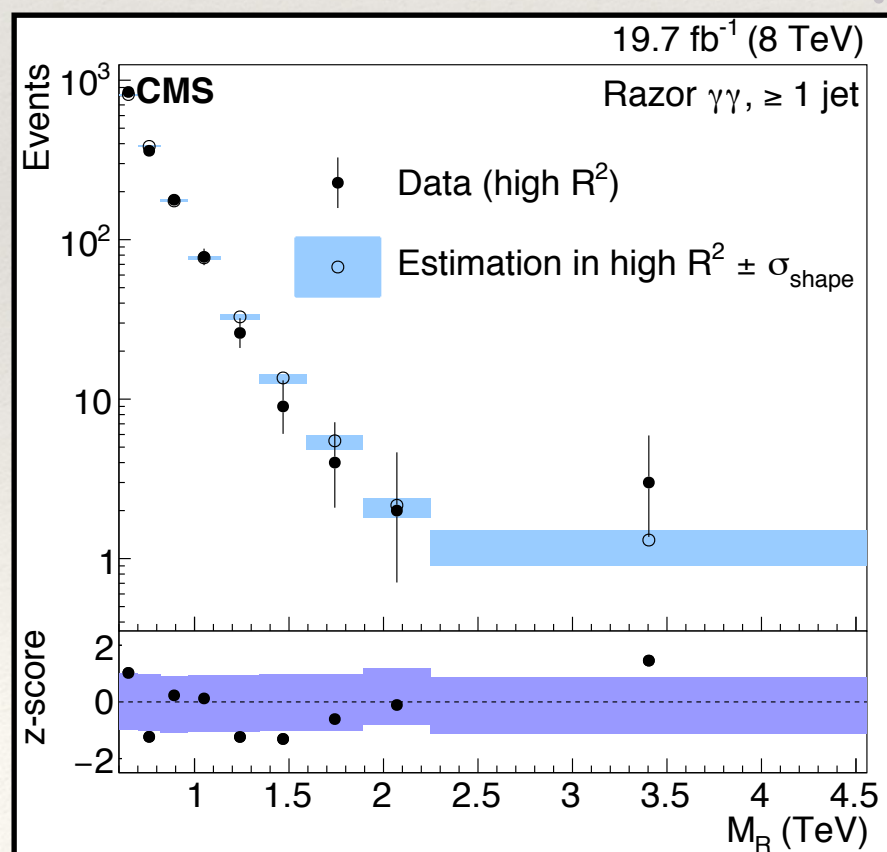


- Inject signal events to the control sample
 - $m_{\text{gluino}} = 1820$ GeV, $m_{\text{squark}} = 1400$ GeV (GGMbino)
- Clear excess at $M_R \approx 2$ TeV. This is how an signal would show up. *Analysis works as designed*

Results

- Extrapolate fit shape to signal region
- Look for excess in $M_R > 600$ GeV

No excess in any M_R bin.

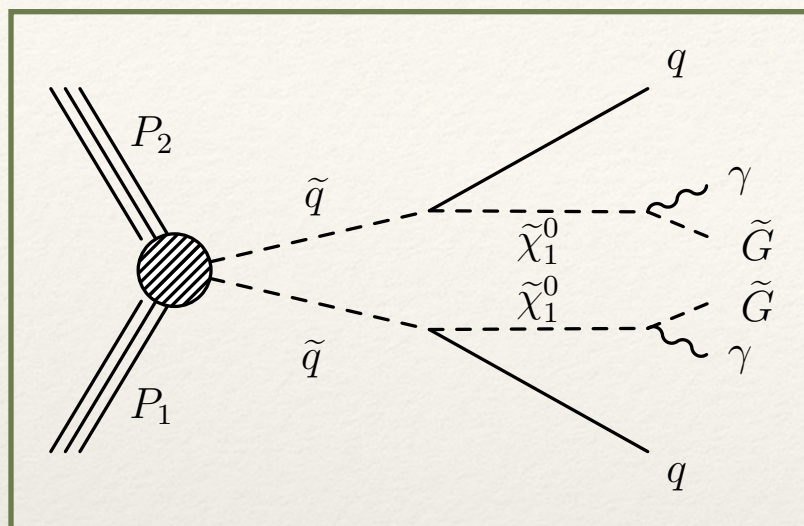




Double Photon Analysis



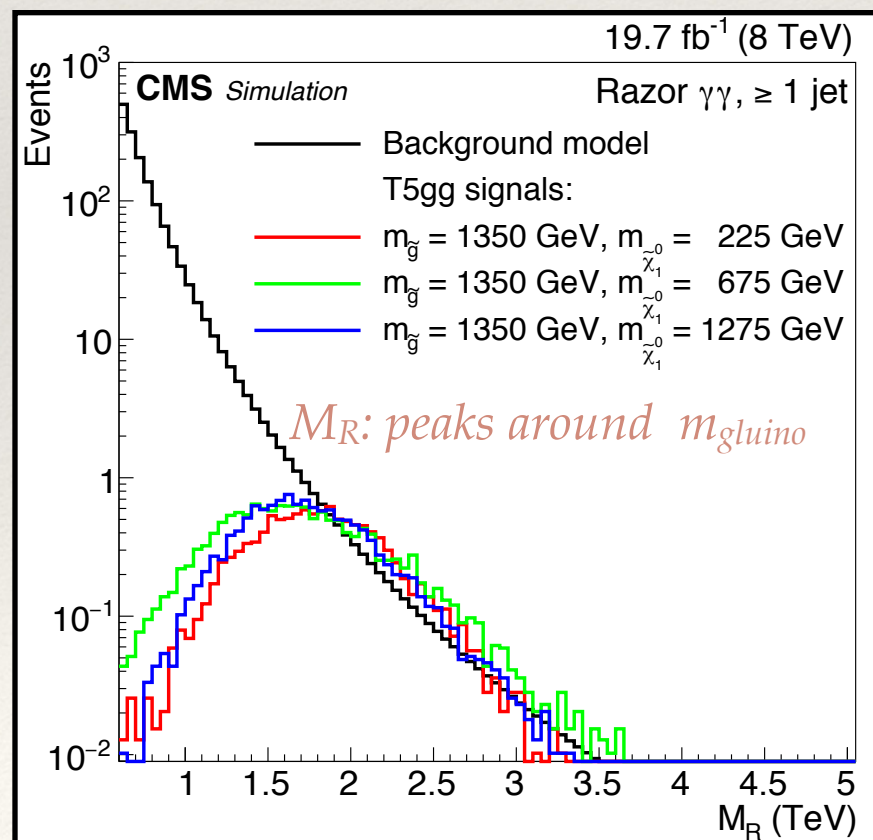
CMS-SUS-14-004, PRD 1507.02898



$$M_R \equiv \sqrt{(|\vec{p}^{j1}| + |\vec{p}^{j2}|)^2 - (p_z^{j1} + p_z^{j2})^2},$$

$$R^2 \equiv \left(\frac{M_T^R}{M_R} \right)^2,$$

$$M_T^R \equiv \sqrt{\frac{E_T^{\text{miss}} (p_T^{j1} + p_T^{j2}) - \vec{p}_T^{\text{miss}} \cdot (\vec{p}_T^{j1} + \vec{p}_T^{j2})}{2}}.$$





Double Photon Analysis



- Search region: $M_R > 600 \text{ GeV}$ && $R^2 > 0.2$ (*high R^2*)
- Define a control sample in the high R^2 kinematic region with photons failing isolation/cluster shape

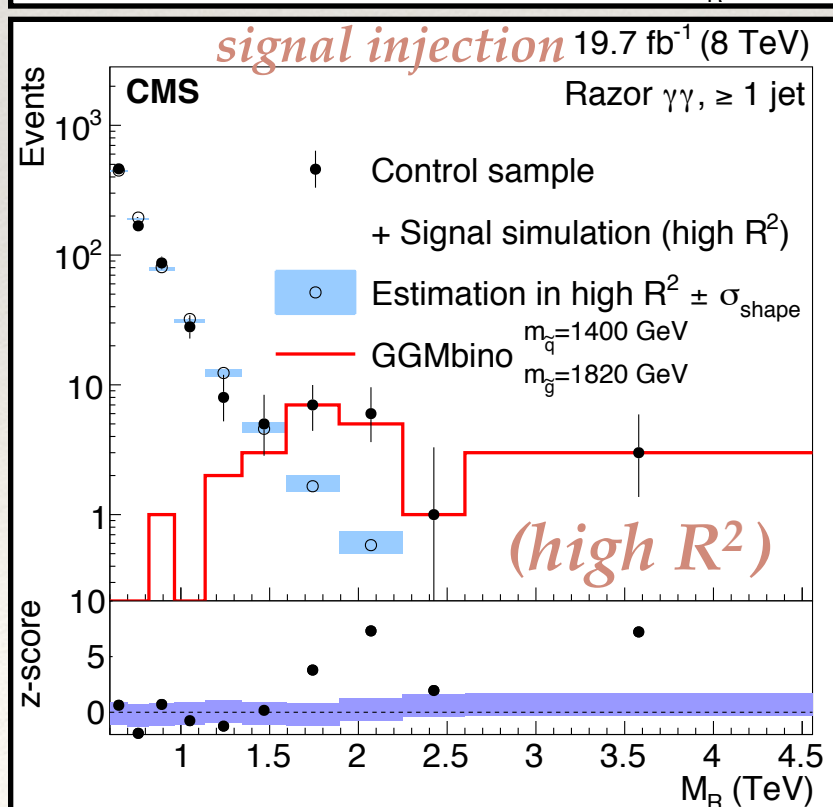
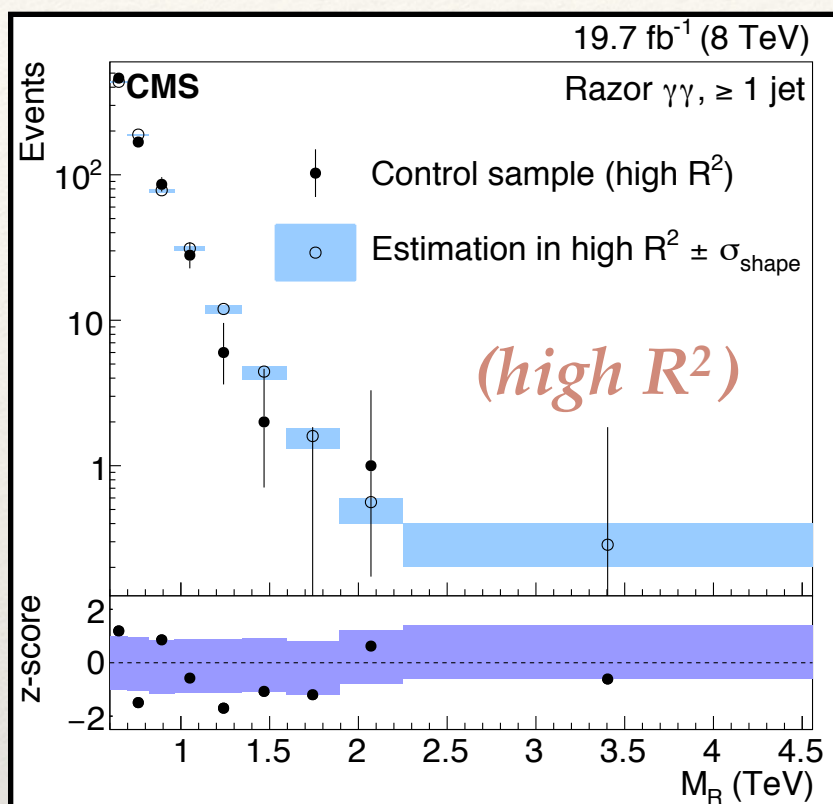
Background Prediction Validation

- Test background prediction technique in this control sample
- Normalize obtained fit shape $P(M_R) \propto e^{-k(M_R - M_R^0)^{\frac{1}{n}}}$ to observed yield in control sample (high R^2)
- *No observed systematic deviation. Most deviations are within one standard deviation*

Signal Injection Test

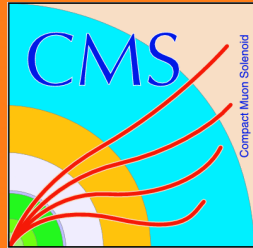
CMS-SUS-14-004,
PRD 1507.02898

- Test analysis sensitivity/behavior
- Inject signal events to the control sample data
 - $m_{\text{gluino}} = 1820 \text{ GeV}$, $m_{\text{squark}} = 1400 \text{ GeV}$ (GGMbino)
- Use same prediction as in the background prediction validation
- Clear excess at $M_R \approx 2 \text{ TeV}$. This is how an signal would show up. *Analysis works as designed*





Electroweak SUSY Searches ($h(h,V) \rightarrow \gamma\gamma\text{leptons}$)



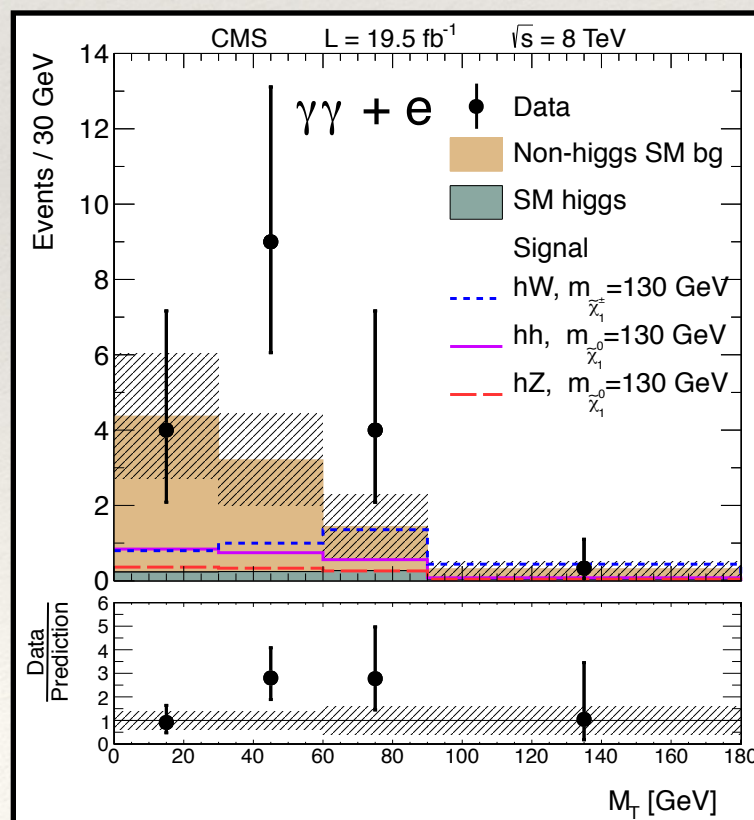
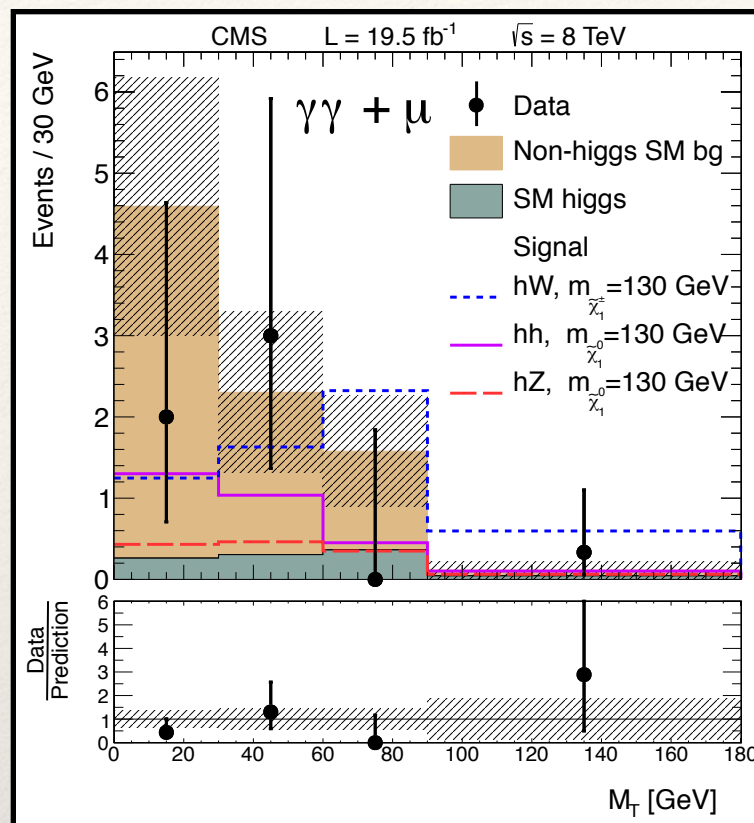
CMS-SUS-14-002, PRD 90, 092007 (2014)

Search for higgs + (h,V) production

- Apply standard photon selection
- Reconstruct higgs through: $h \rightarrow \gamma\gamma$ decay
- Tag second boson by requiring at least one (e/ μ)
 - Isolated Leptons, $P_T > 15$ GeV, $|\eta| < 2.4$
 - $\Delta R(\gamma_{(1,2)}, \text{lepton}) > 0.3$
 - $m_{e\gamma} \notin [86-96]$ GeV
- Two search samples:
 - At least one electron, at least one muon
- *Look for excess in the transverse mass M_T distribution*
- *Fit $m_{\gamma\gamma}$ in sidebands. Use fit result to scale the M_T sideband distribution to the expected signal region.*

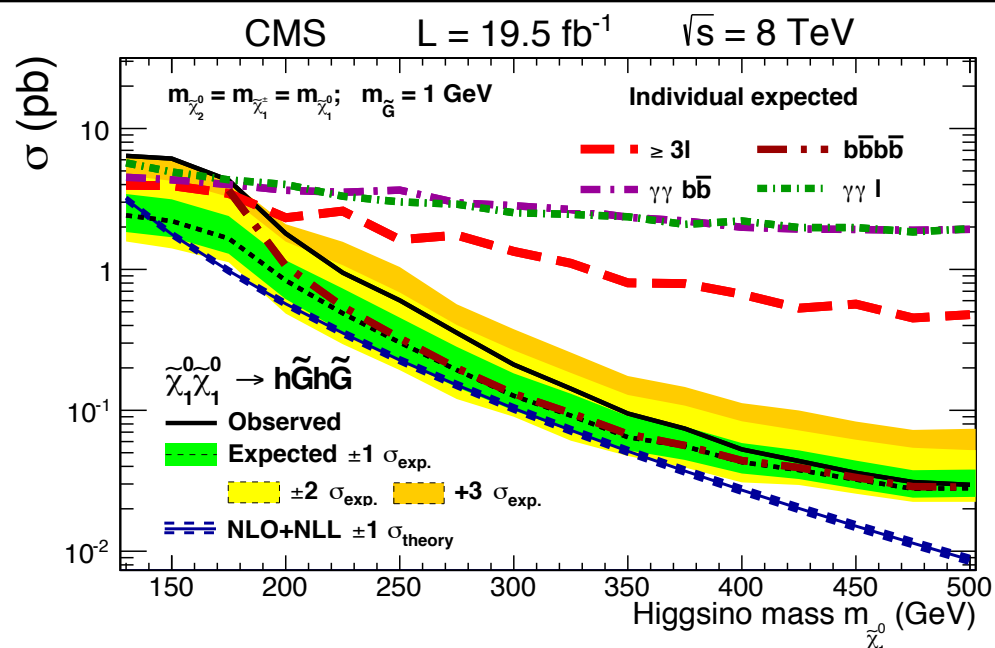
*2.1 standard deviations excess in electron sample.
cross checks suggest consistent with background fluctuation*

SM-Higgs background from MC: 30% uncertainty

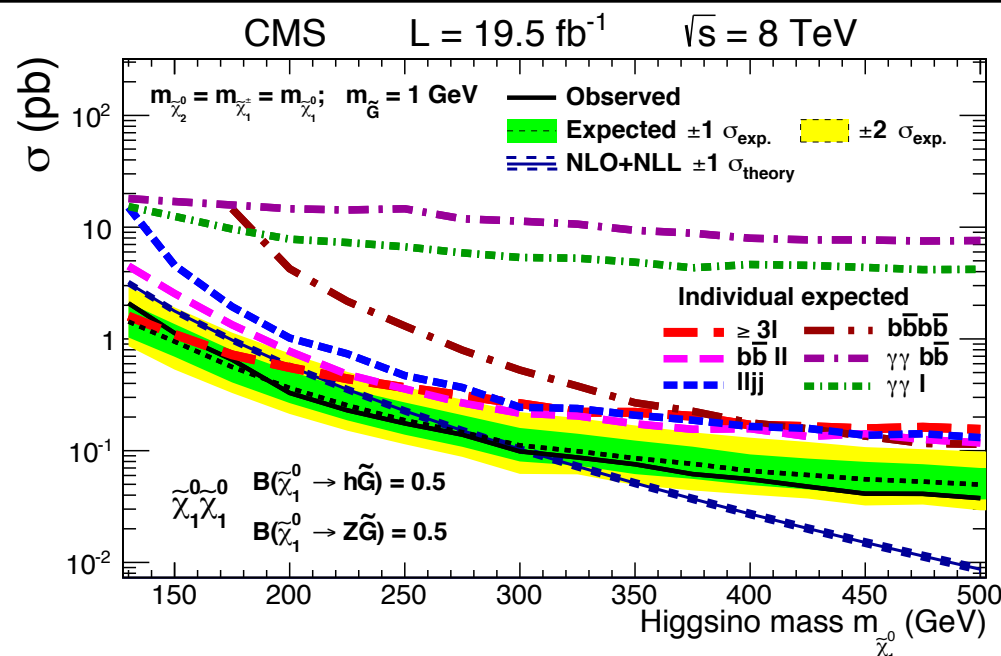




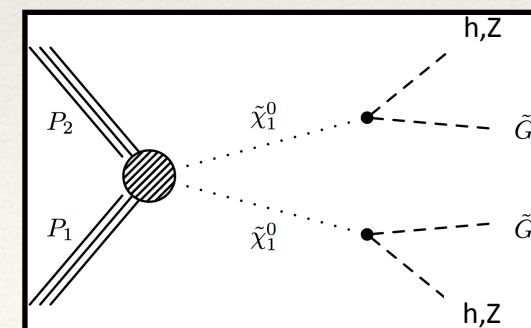
Electroweak SUSY Searches



- Set limits for electroweak GMSB hh production
- hh production In this talk
 - $hh \rightarrow \gamma \gamma bb$
 - $hh \rightarrow \gamma \gamma + \text{lepton}$
- Not enough sensitivity to exclude any neutralino mass yet
- Expected sensitivity could rule out a 150 GeV neutralino



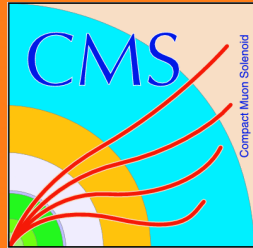
- Set limits for electroweak GMSB h h,Z production
- 50% BR to $\chi^1 \rightarrow ZG$
- hh production In this talk
 - $hh \rightarrow \gamma \gamma bb$
 - $hh \rightarrow \gamma \gamma + \text{lepton}$
- Combination excludes neutralinos at ~ 290 GeV



CMS-SUS-14-002, PRD 90, 092007 (2014)



Razor $h \rightarrow \gamma\gamma$

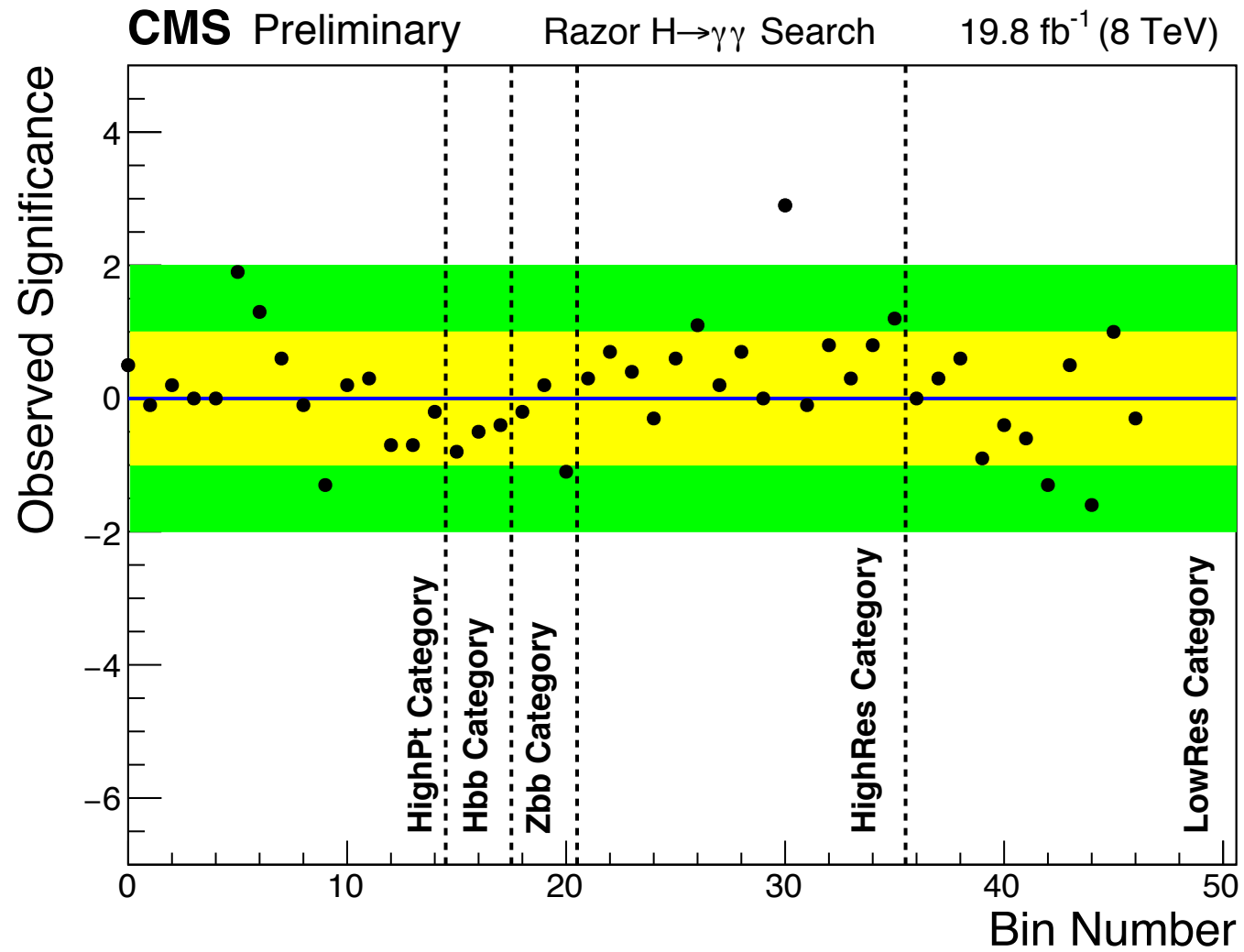
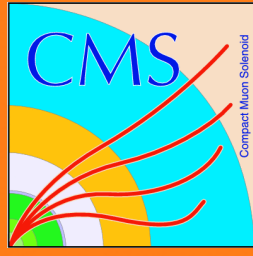


Event Category	Background Prediction Transfer Factor
HighPt	0.162 ± 0.004
Hbb	0.212 ± 0.049
Zbb	0.204 ± 0.032
HighRes	0.162 ± 0.002
LowRes	0.259 ± 0.002

MC normalization systematic uncertainties		
Source	value	target
luminosity	2.5%	Signal Models, SM Higgs boson MC
trigger efficiency	5%	Signal Models, SM Higgs boson MC
Higgs boson theory	2% – 8%	SM Higgs boson MC
signal theory x-sec uncertainty	$\approx 13\%$	
Object-level systematic uncertainties		
jet energy scale	shape (3%)	Signal Models, SM Higgs boson MC
photon energy and resolution	shape (1%)	Signal Models, SM Higgs boson MC
b-tagging ID	shape (0 – 4%)	Signal Models, SM Higgs boson MC
σ_E/E uncertainty	shape	Signal Models, SM Higgs boson MC
Normalization & shape systematic uncertainties		
background prediction uncertainty	1% – 50%	background shape
sideband yields	1 – 100%	low event yields in the data sidebands
fit choice	$\approx 1\%$	background normalization
MC statistics	varies	statistics in SM Higgs boson and SMS MC

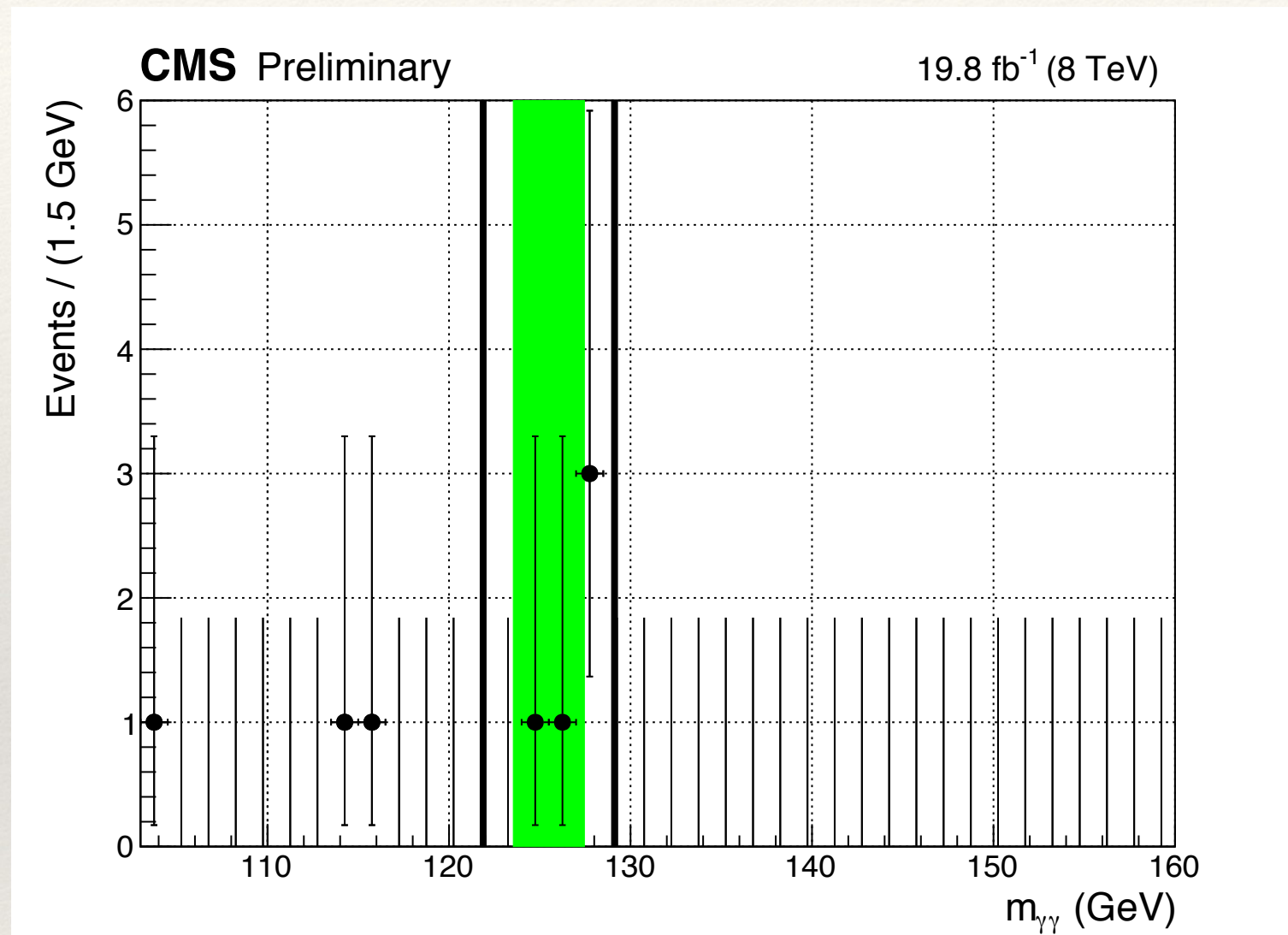
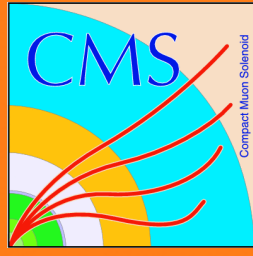


Razor $h \rightarrow \gamma\gamma$





Razor $h \rightarrow \gamma\gamma$





Razor $h \rightarrow \gamma\gamma$

