Search for supersymmetry in final states with photons at CMS

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for the CMS collaboration

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Outline

Introduction to supersymmetry (SUSY)

Experimental aspects

- Simplified SUSY models
- Important variables

3 recent CMS SUSY results with photons

- CMS-SUS-16-046 electroweak SUSY productions with photons
- CMS-SUS-16-047 strong SUSY productions with photons
- CMS-SUS-16-045 $H \to \gamma\gamma$ in electroweak and strong SUSY productions

Introduction to Supersymmetry

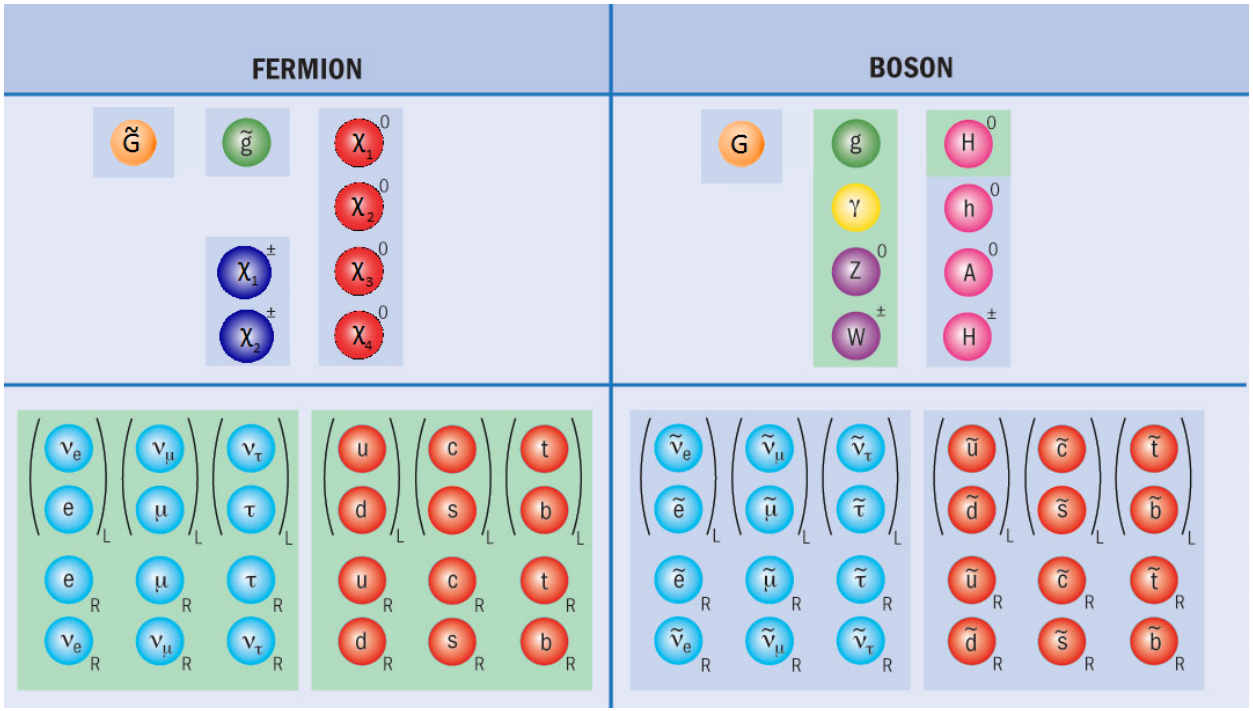
What is SUSY? – *Extension to the Standard Model (SM)*

- **Symmetry** between **fermions** and **bosons**

Why SUSY? – *Helps to solve problems of SM*

- **Dark matter**: Lightest SUSY Particle (**LSP**) if neutral and weakly interacting
- **Hierarchy problem**: cancel unnaturally big quantum corrections to m_H
- **Gauge unification**: EM, weak and strong forces unify at $\approx 10^{16}\,GeV$

New particles predicted



SUSY particles not seen at low energy → supersymmetry **broken**

- Minimal Supergravity (mSUGRA)
- **Gauge Mediated Supersymmetry Breaking (GMSB)**
  - General Gauge Mediation (GGM)

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- Multiplicative quantum number, +1 for SM, -1 for SUSY
- R-parity conserved → SUSY particles pair-produced, **LSP stable**

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Neutralinos ($\widetilde{\chi}_i^0$) & **charginos** ($\widetilde{\chi}_i^\pm$)

- Superpartners of EW bosons: Higgsinos ($\widetilde{H}_i$), winos ($\widetilde{W}_i$) and bino ($\widetilde{B}$)
- Symmetry breaking→these mix together to form mass eigenstates: neutralinos ($\widetilde{\chi}_1^0, \widetilde{\chi}_2^0, \widetilde{\chi}_3^0, \widetilde{\chi}_4^0$) and charginos ($\widetilde{\chi}_1^\pm$, $\widetilde{\chi}_2^\pm$)
- Decays into SM boson $W^\pm/Z/\gamma/H$, and lighter SUSY particle

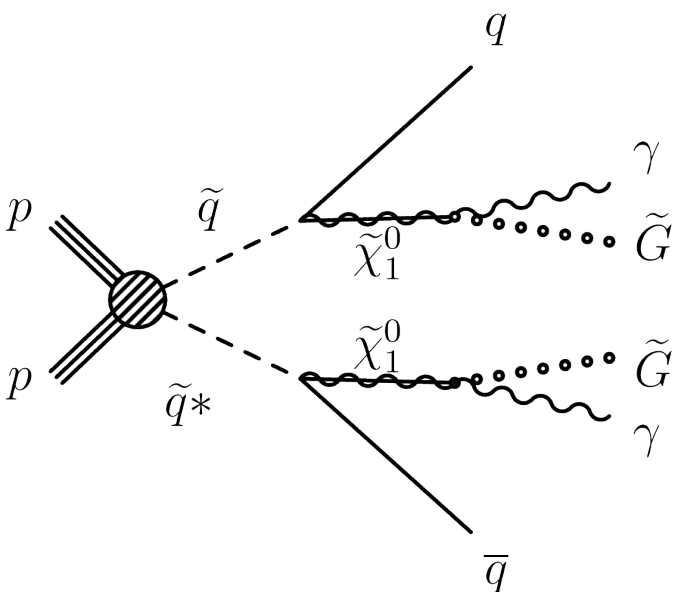
GMSB: **gravitino** ($\widetilde{G}$) LSP, frequently **neutralino** ($\widetilde{\chi}_1^0$) Next-to-LSP (NLSP)

Simplified SUSY models

- SUSY models depend on many parameters
- Simplified models: *bridge between theory and experiment*
- Low number of new particles and interactions
- Few parameters related to collider physics
  - Particle masses
  - Production cross-sections
  - Branching factions
- Easy to simulate (MadGraph, Pythia)
- Limits apply to general models with same topologies

$pp \to \widetilde{q}\widetilde{q},\ \widetilde{q} \to q\widetilde{\chi}_1^0$

$\widetilde{\chi}_1^0 \xrightarrow{100\%} \gamma\widetilde{G}$



$pp \to \widetilde{\chi}_1^0\widetilde{\chi}_1^\pm$

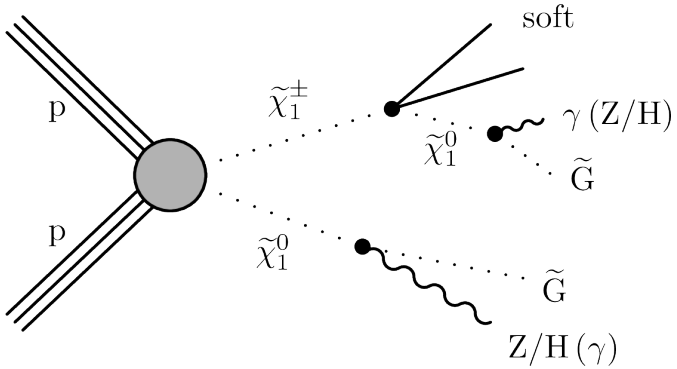
$\widetilde{\chi}_1^\pm \to soft + \widetilde{\chi}_1^0$

$m_{\widetilde{\chi}_1^\pm} \gtrapprox m_{\widetilde{\chi}_1^0}$

$\widetilde{\chi}_1^0 \xrightarrow{50\%} \gamma\widetilde{G}$

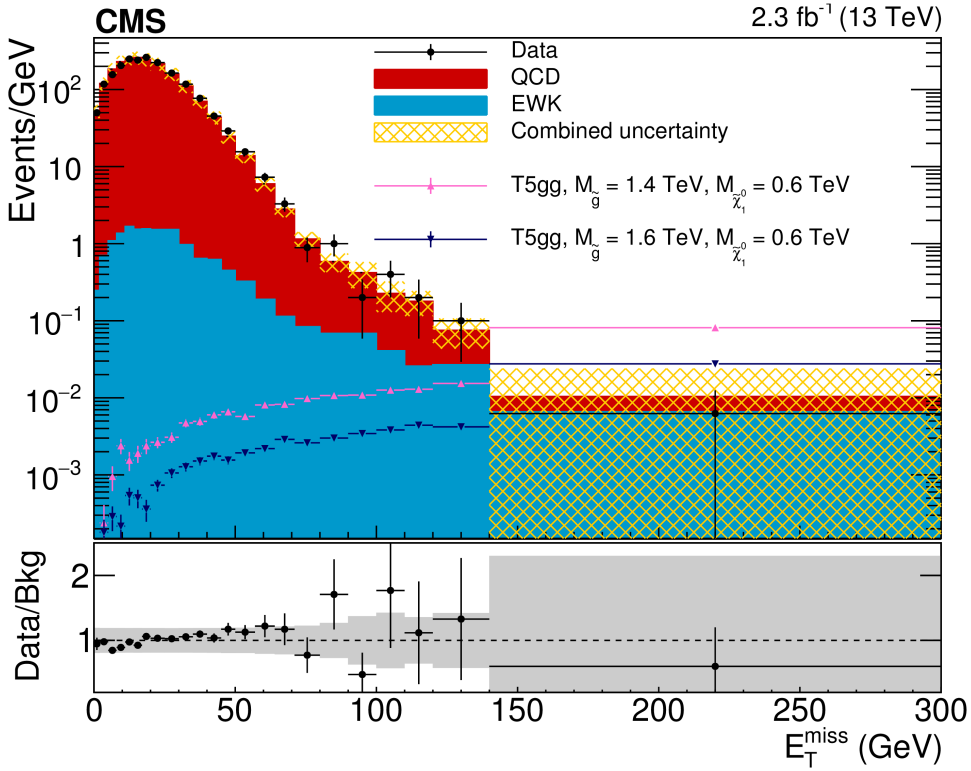
$\widetilde{\chi}_1^0 \xrightarrow{25\%} Z\widetilde{G}$

$\widetilde{\chi}_1^0 \xrightarrow{25\%} H\widetilde{G}$



Important variables

- Missing E_T (MET): $E_T^{miss} = |\vec{p}_T^{miss}| = |-\sum_i \vec{p}_T(i)|$, i =all objects
  - Important signal of LSP
- Transverse mass (M_T): $M_T^2(\gamma, p_T^{miss}) = 2p_T^{miss} E_T^{\gamma}[1 - \cos\Delta\phi(\vec{p}_T^{miss}, \gamma)]$
  - $M_T \approx m_{NLSP}$, when $\tilde{\chi}_1^0 \to \gamma\tilde{G}$
  - Reduce process $W \to e\nu$ (e misindentified as γ)
- $S_T^{\gamma} = p_T^{miss} + \sum_i E_T^{\gamma_i}$
- $H_T^{\gamma} = \sum p_T^{jets} + \sum_i E_T^{\gamma_i}$



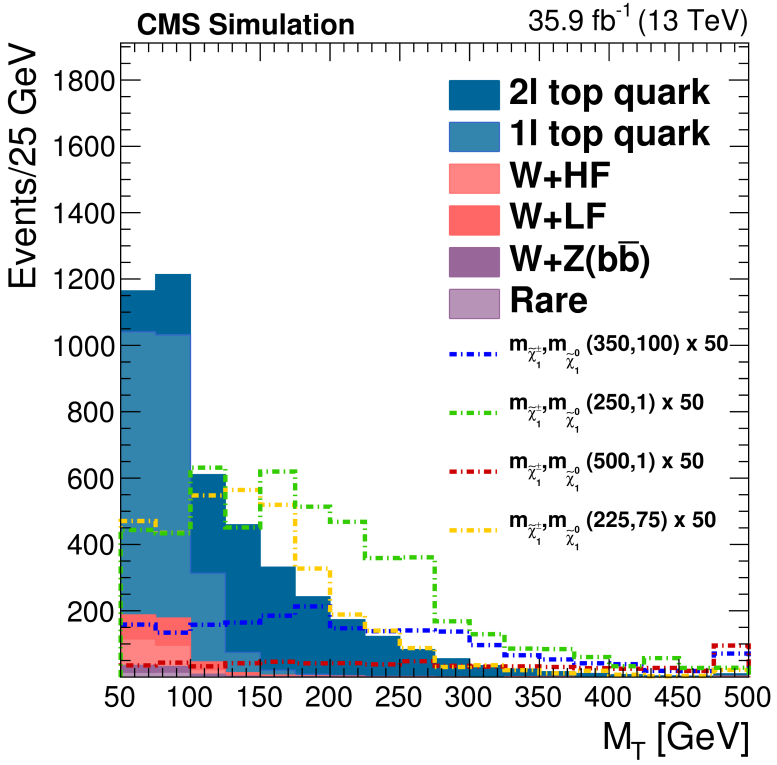
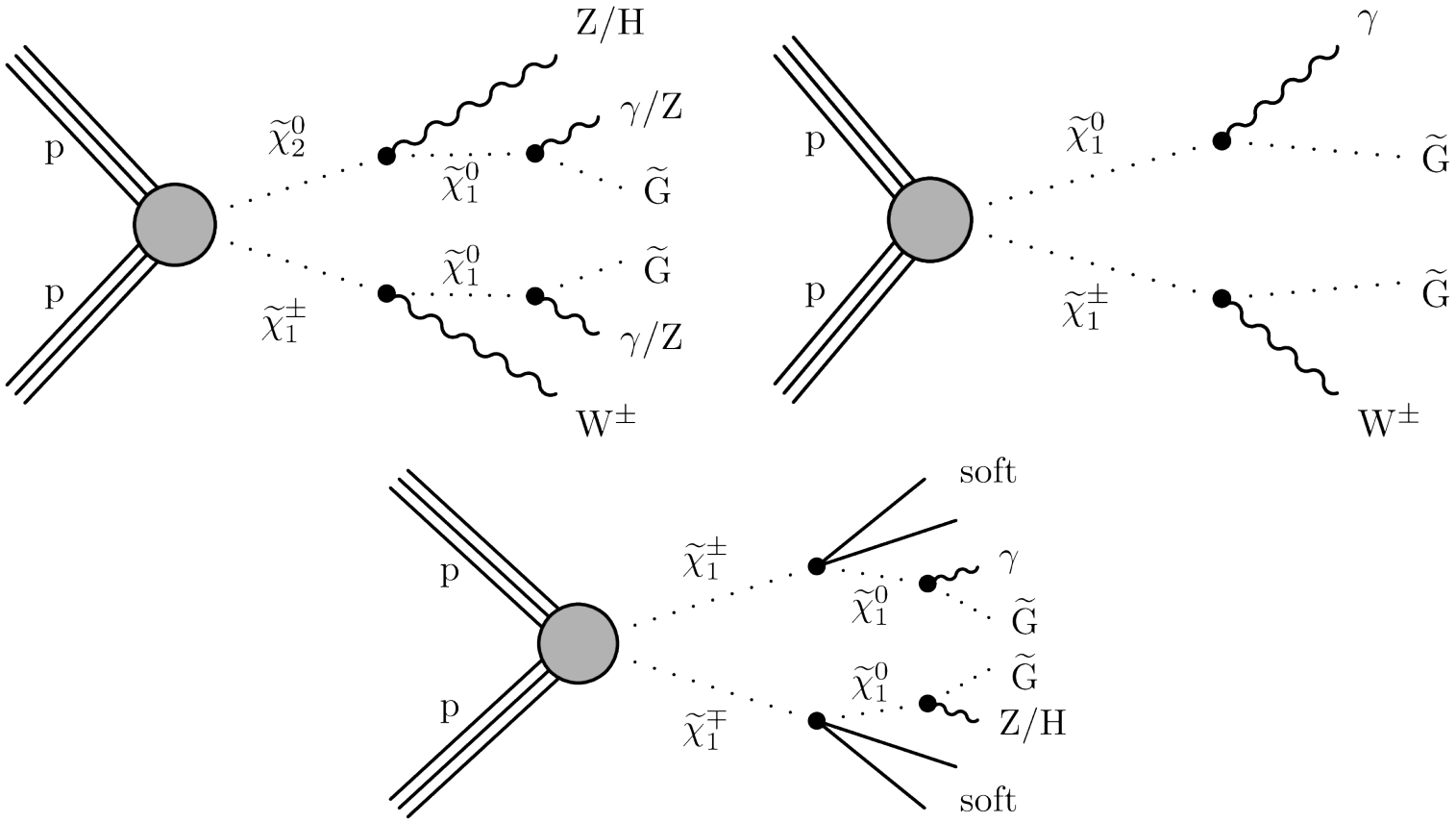


Figure: CMS-SUS-15-012, CMS-SUS-16-043

γ+MET+S_T^γ in EWK production CMS-SUS-16-046

$N_\gamma \geq 1$, $E_T^\gamma > 180$ GeV, $|\eta| < 1.44$
$p_T^{miss} > 300$ GeV
$M_T(\gamma, \vec{p}_T^{miss}) > 300$ GeV
$\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{jet}) > 0.3$ if $p_T^{jet} > 100$ GeV
$S_T^\gamma > 600$ GeV



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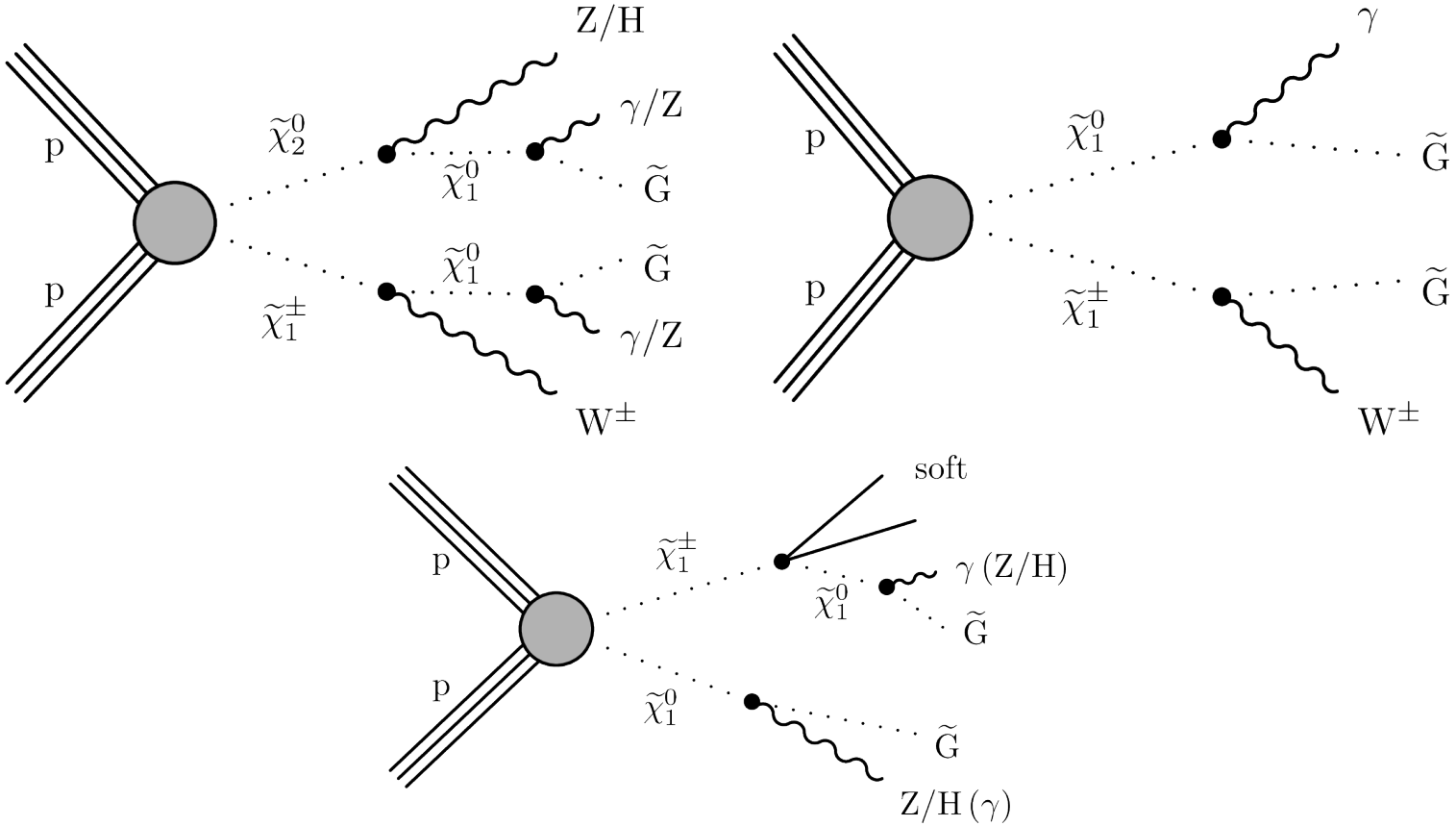
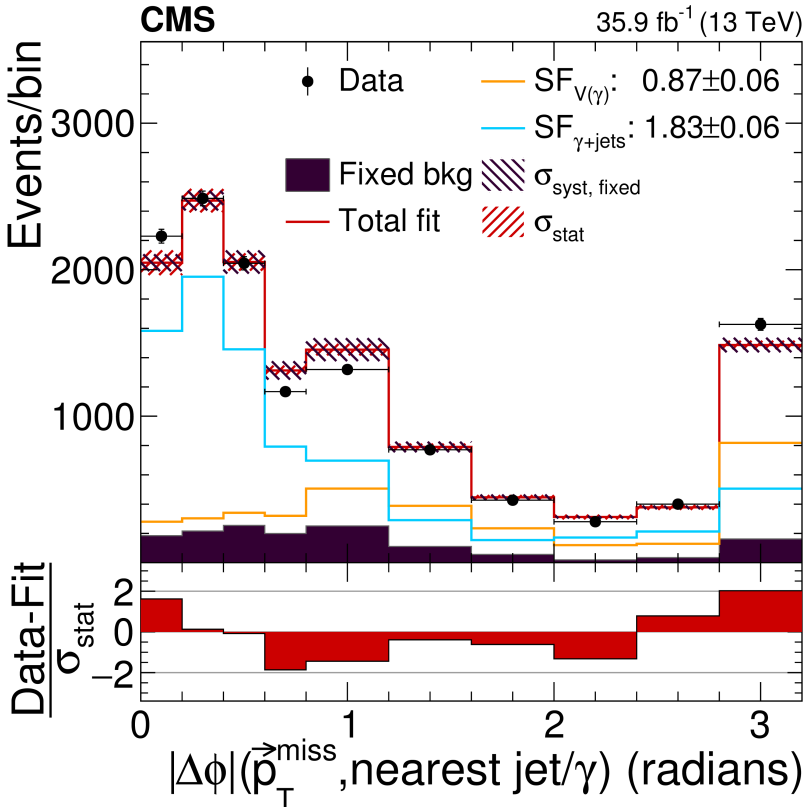
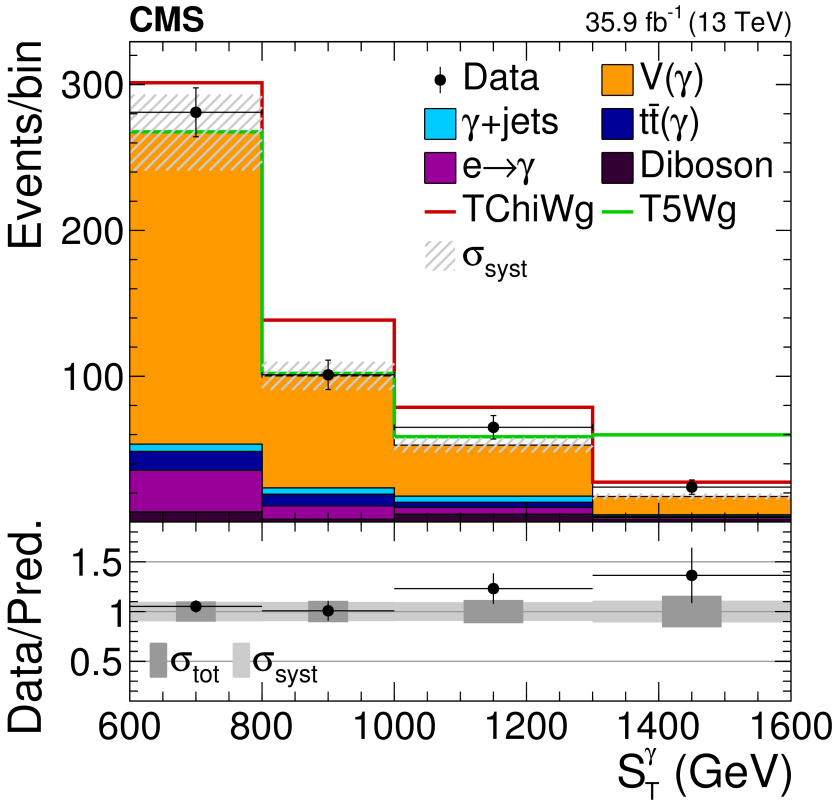


γ+MET+S_T^γ in EWK production CMS-SUS-16-046

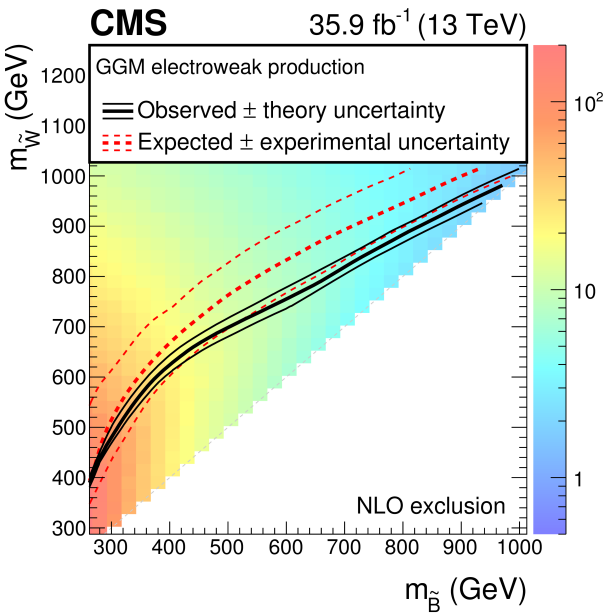
- Dominant background: Vγ+jets, γ+jets, $e \to \gamma$
- Background prediction: semi data-driven
  Derive scale factor from fit of MC to data in low p_T^{miss} and/or M_T CR
  Use scale factor on MC in SR
  $e \to \gamma$: $Z \to ee/Z \to e\gamma$ tag-and-probe
- Binning in S_T^γ

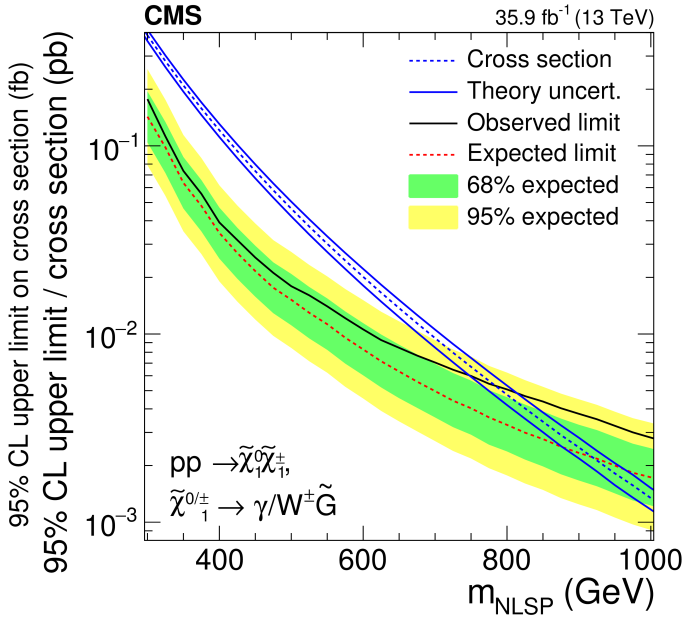


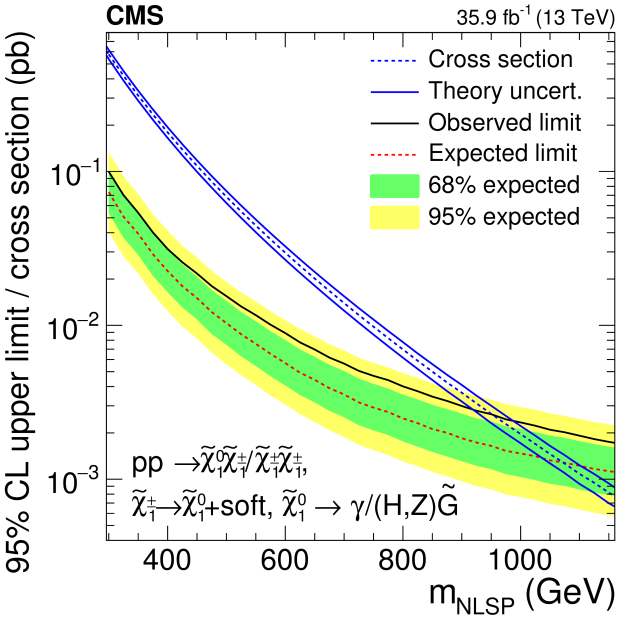


γ+MET+S_T^γ in EWK production CMS-SUS-16-046

- $m_{\widetilde{B}} \approx m_{\widetilde{W}} > 900$ GeV
  GGM interpretation
- $\widetilde{\chi}_1^0\widetilde{\chi}_1^\pm \to \gamma W^\pm \widetilde{G}$
  $m_{NLSP} > 780$ GeV
- $\widetilde{\chi}_1^0\widetilde{\chi}_1^\pm \to \gamma/H/Z\widetilde{G}$
  $m_{NLSP} > 950$ GeV



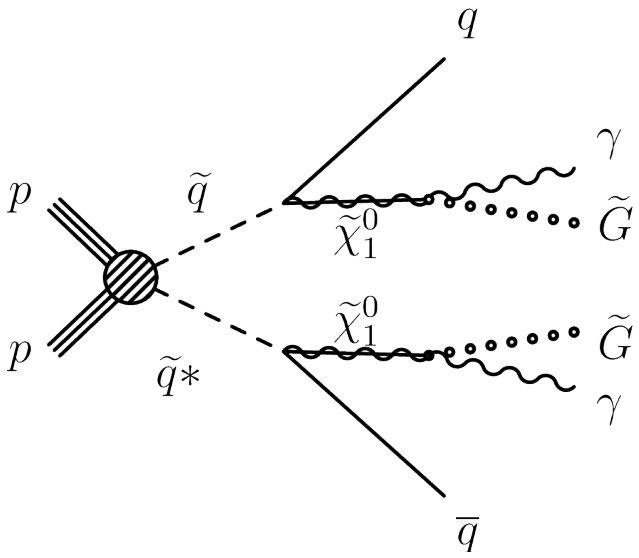


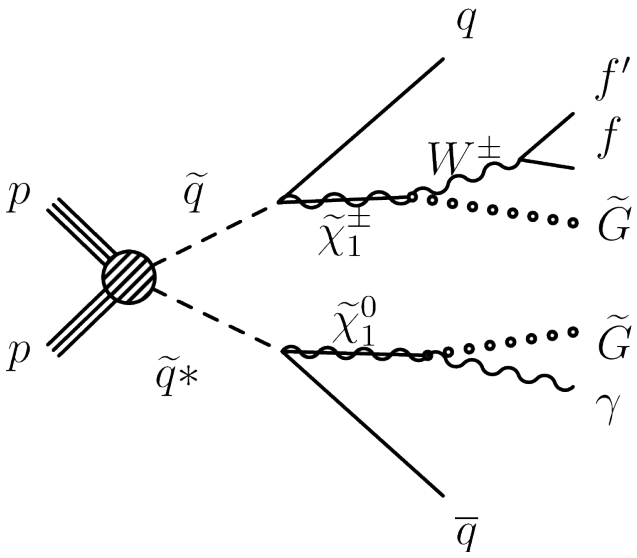


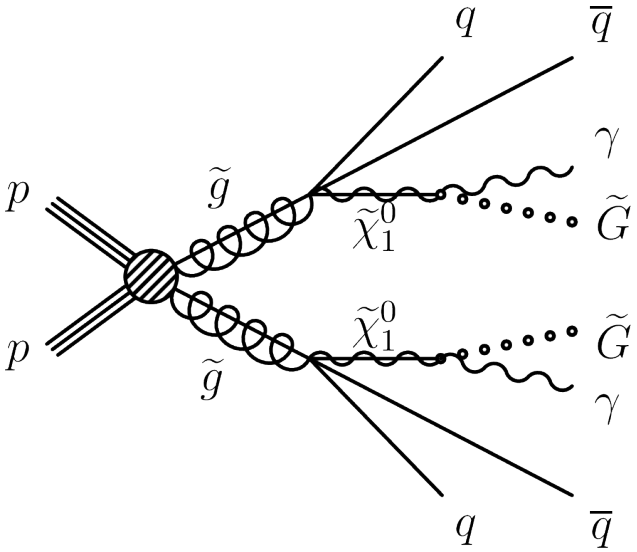
Also interpreted in strong productions, but better results are from next analysis

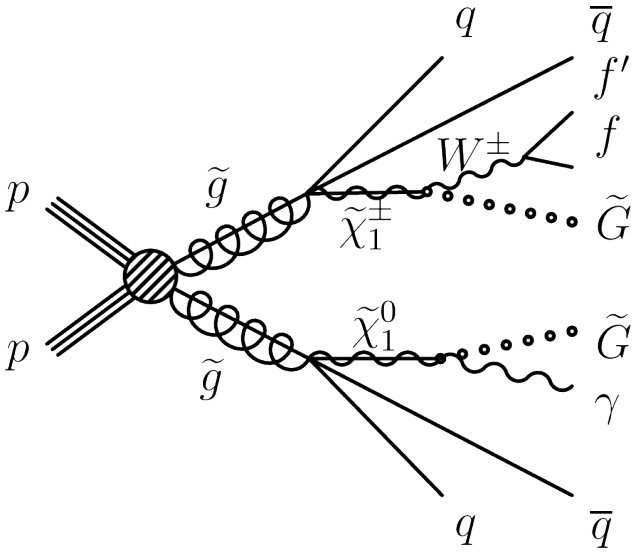
γ+MET+H_T^γ in strong production CMS-SUS-16-047

$N_\gamma \geq 1$, $E_T^\gamma > 100$ GeV
$|\eta| < 1.44$
$p_T^{miss} > 300$ GeV
$\Delta\phi(\pm\vec{p}_T^{miss}, \vec{p}_T^\gamma) > 0.3$
$H_T^\gamma > 700$ GeV



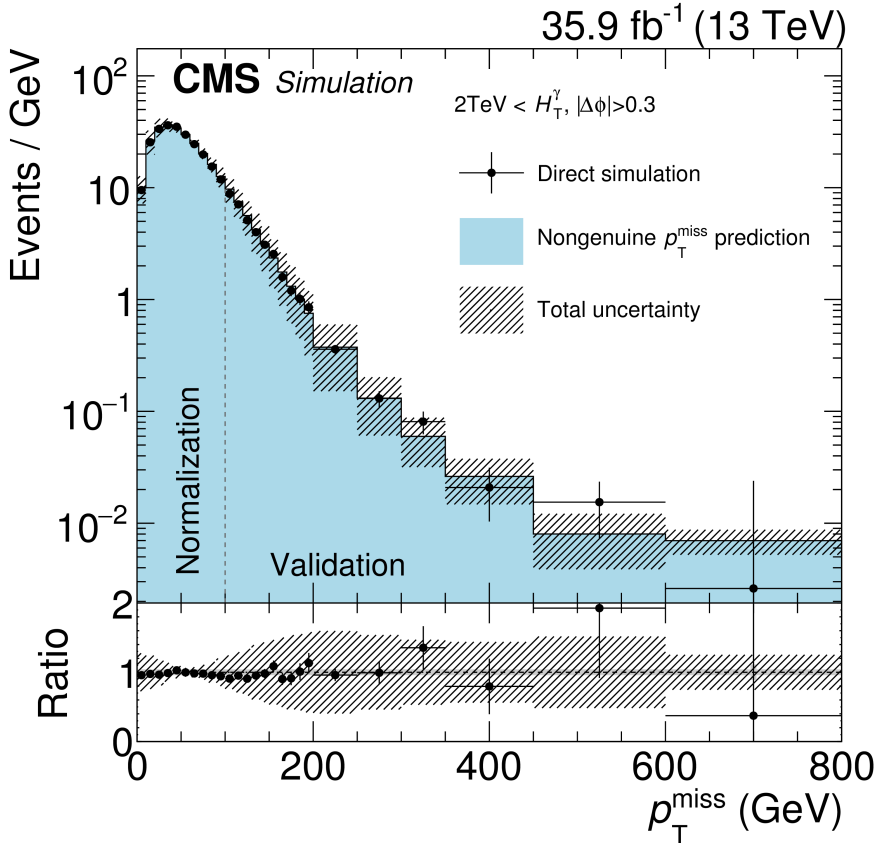


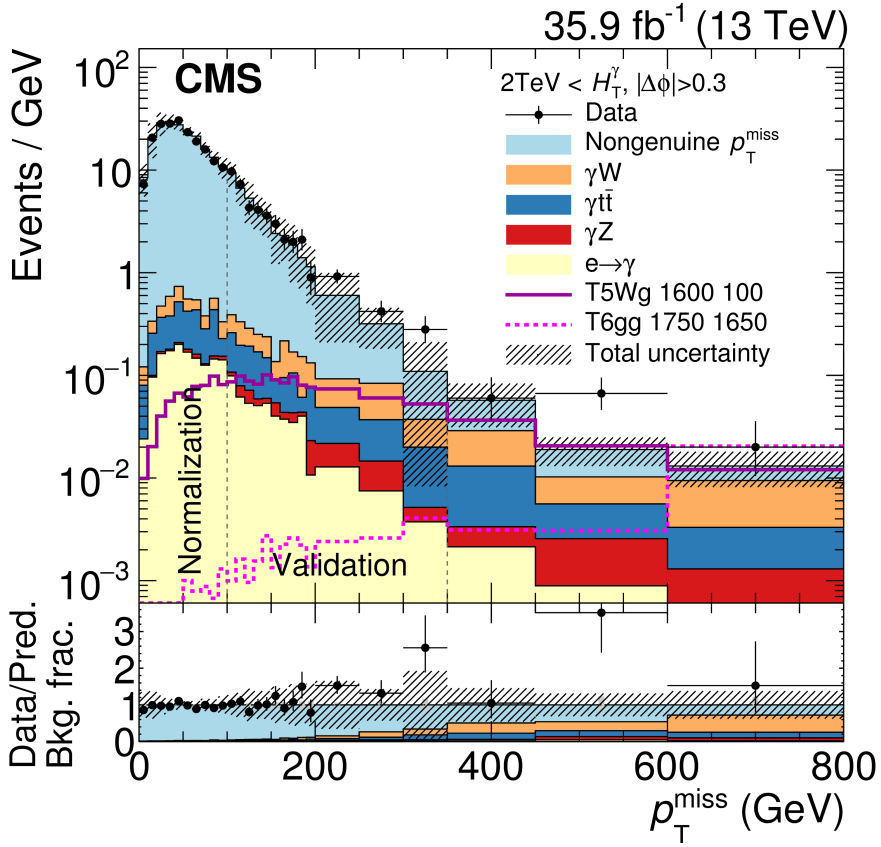




γ+MET+H_T^γ in strong production CMS-SUS-16-047

- Dominant background: γ+jets, $e \to \gamma$
- Background prediction: data-driven
  QCD: Estimate from zero-photon CR normalized by low p_T^{miss} CR
  $e \to \gamma$: $Z \to ee/Z \to e\gamma$ tag-and-probe
- Binning in H_T^γ and p_T^{miss}

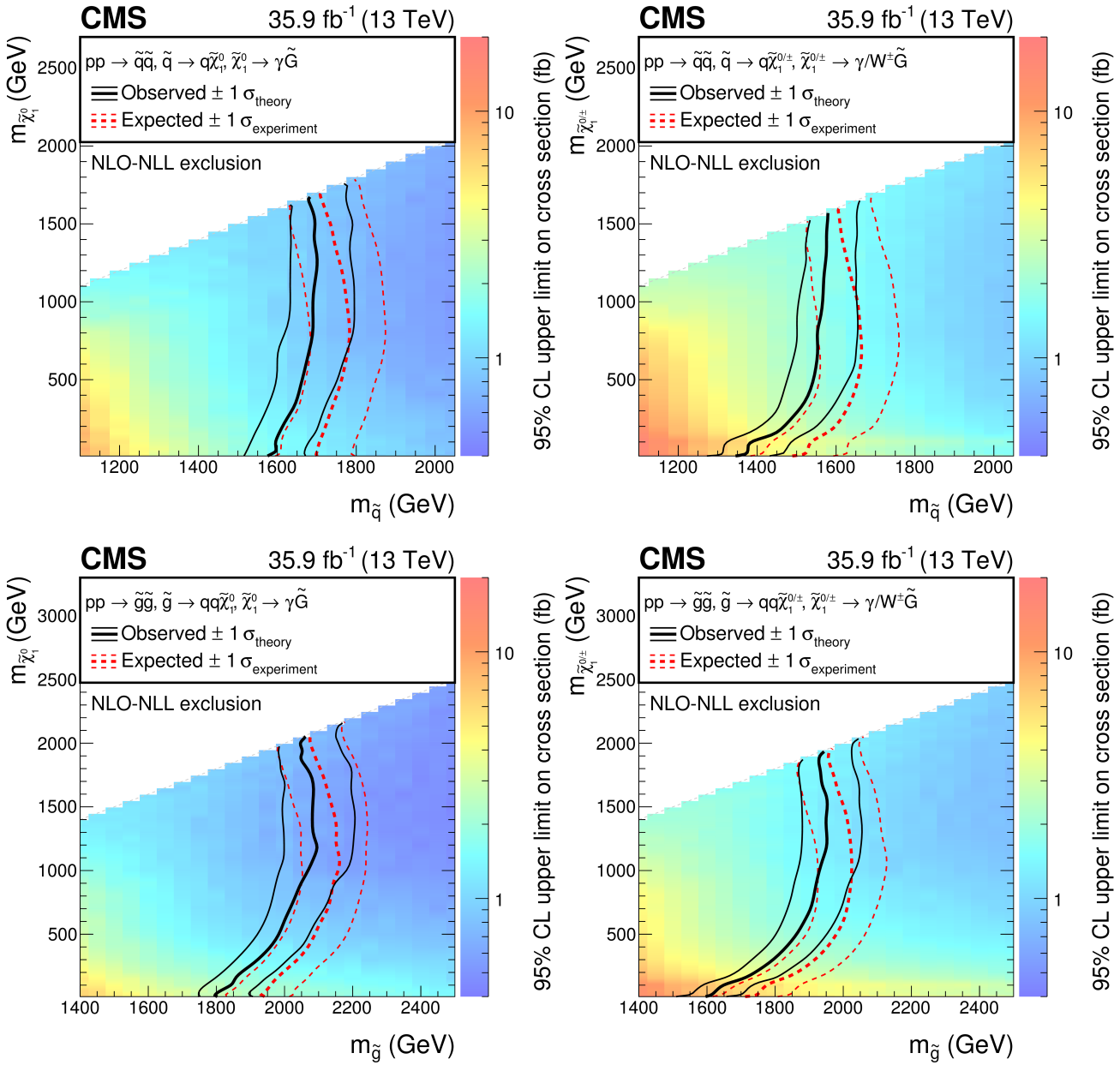




γ+MET+H_T^γ in strong production CMS-SUS-16-047

Results implemented in 4 simplified models

- $\tilde{q} \to q\tilde{\chi}_1^0 \to \gamma\tilde{G}$
  $m_{\tilde{q}} > 1650$ GeV
- $\tilde{q} \to q\tilde{\chi}_1^0/\tilde{\chi}_1^\pm \to \gamma/W^\pm\tilde{G}$
  $m_{\tilde{q}} > 1550$ GeV
- $\tilde{g} \to qq\tilde{\chi}_1^0 \to \gamma\tilde{G}$
  $m_{\tilde{g}} > 2000$ GeV
- $\tilde{g} \to qq\tilde{\chi}_1^0/\tilde{\chi}_1^\pm \to \gamma/W^\pm\tilde{G}$
  $m_{\tilde{g}} > 1900$ GeV



Razor variables

- Based on pair production of two heavy particles
- Decaying to undetected particle + visible products
- All events treated like di-jet event
- Reconstructed objects → two megajets j_1, j_2

$$M_R = \sqrt{(|\vec{p}^{j_1}| + |\vec{p}^{j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

$$M_R \approx \frac{m_{\tilde{g}}^2 - m_{LSP}^2}{2m_{\tilde{g}}}$$

$$M_T^R = \sqrt{\frac{p_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \vec{p}_T^{miss}(\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}$$

$$R^2 = (\frac{M_T^R}{M_R})^2$$

- SM background exponentially falling
- SUSY signals large values of M_R, R^2

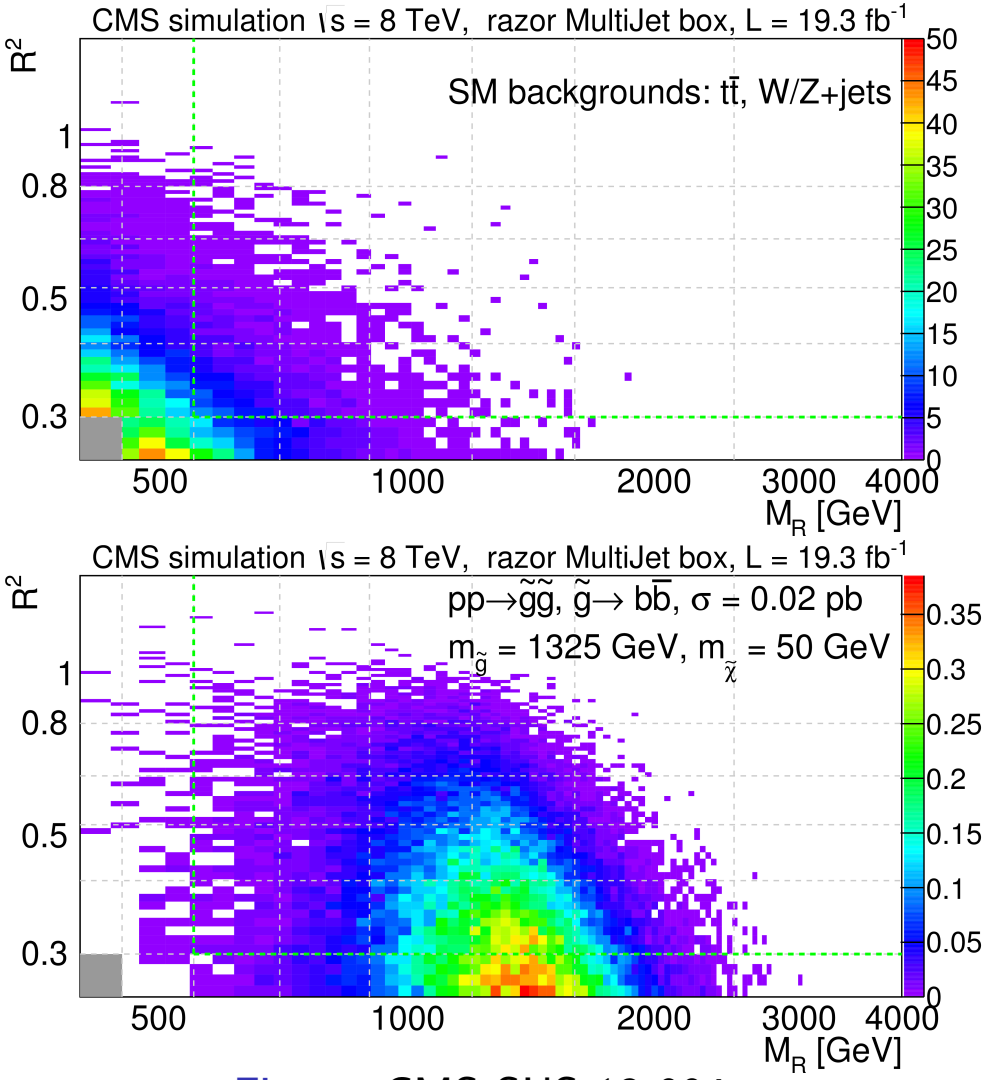
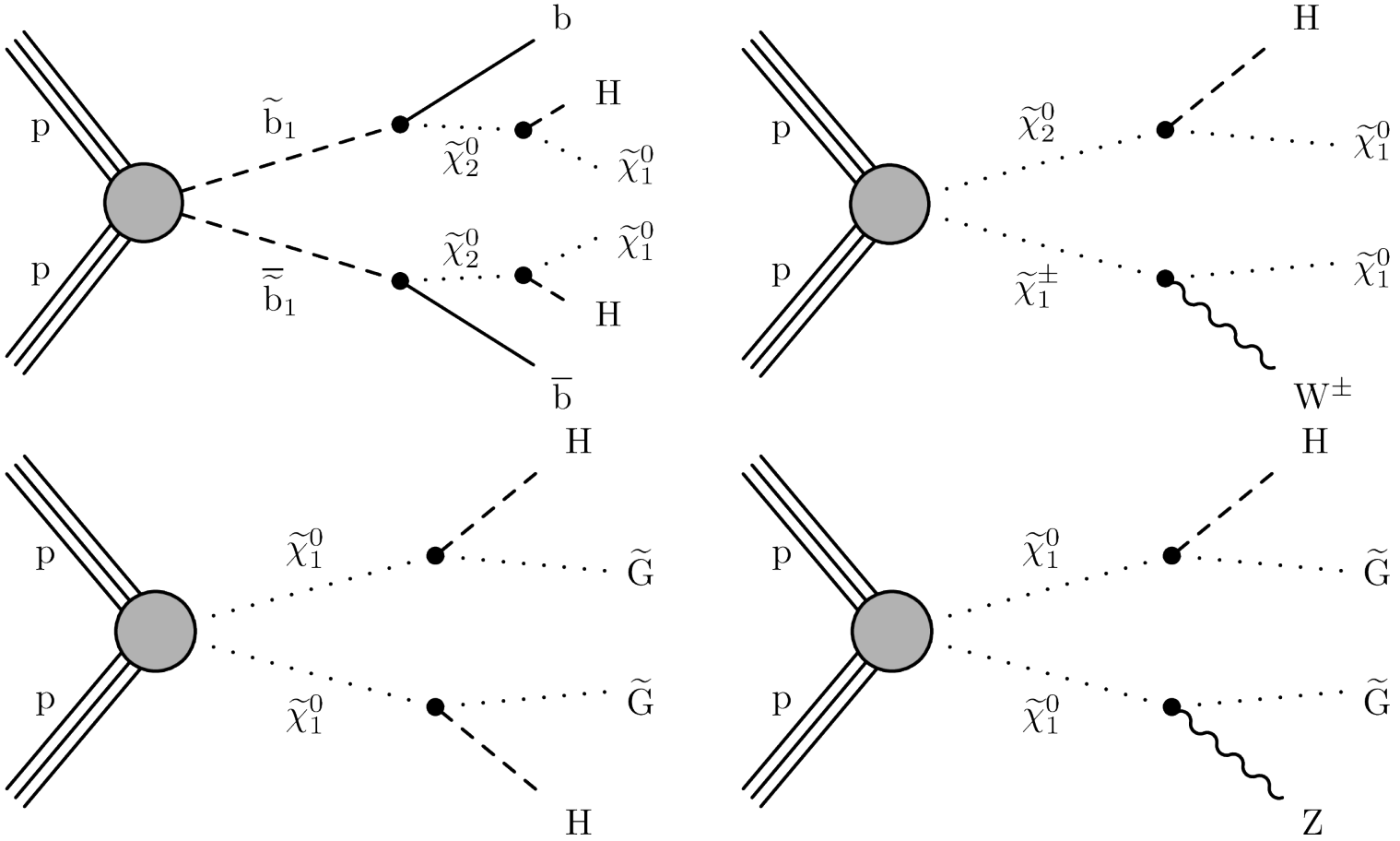


Figure: CMS-SUS-13-004

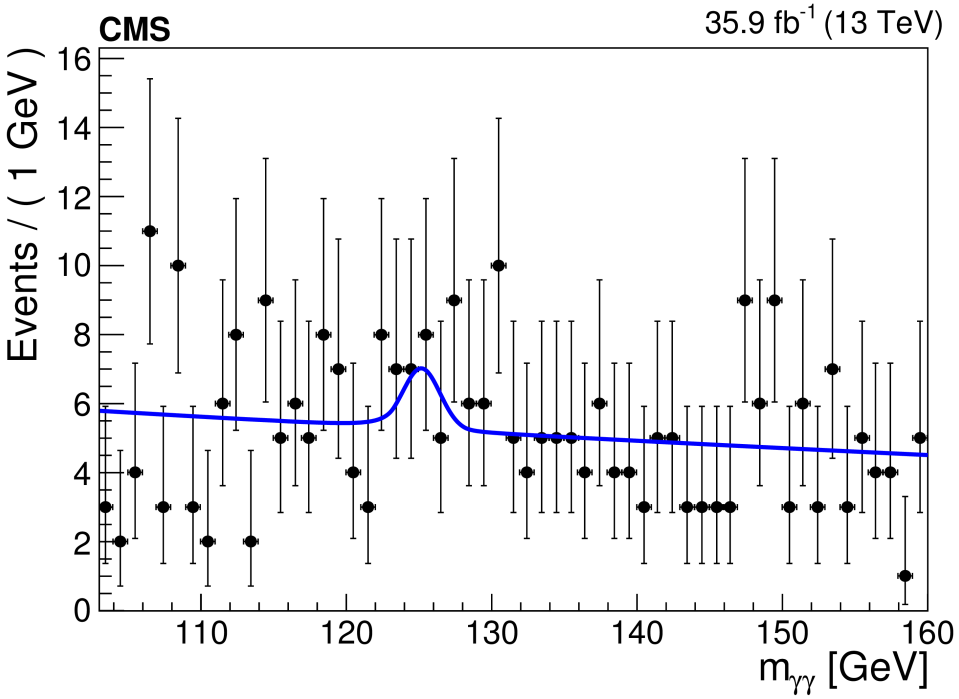
Higgs→ $\gamma\gamma$+X with razor variables CMS-SUS-16-045

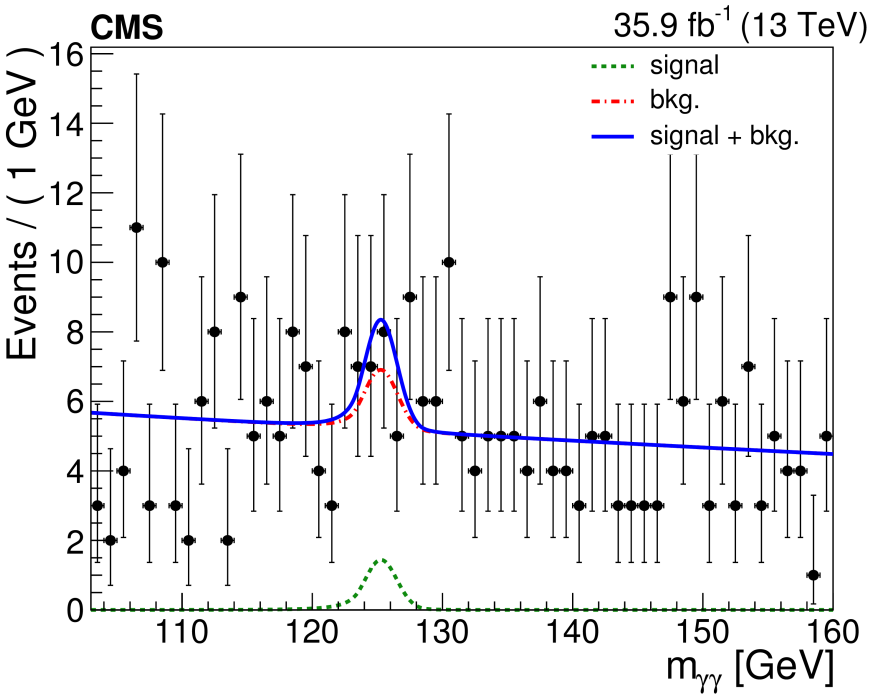
$N_\gamma \geq 2$, $m_{\gamma\gamma} \approx 125$ GeV
$|\eta| < 1.44$
$M_R > 150$ GeV



Higgs→ $\gamma\gamma$+X with razor variables CMS-SUS-16-045

- Dominant background:
  $\gamma\gamma$+jets, γ+jets, SM Higgs boson
- Background prediction: data-driven+MC
  QCD: fit $m_{\gamma\gamma}$ spectrum
  SM Higgs: MC prediction
- Binning in M_R, R^2 in 4 categories (HighPt, $H(\gamma\gamma) - HZ(bb)$, HighRes, LowRes)





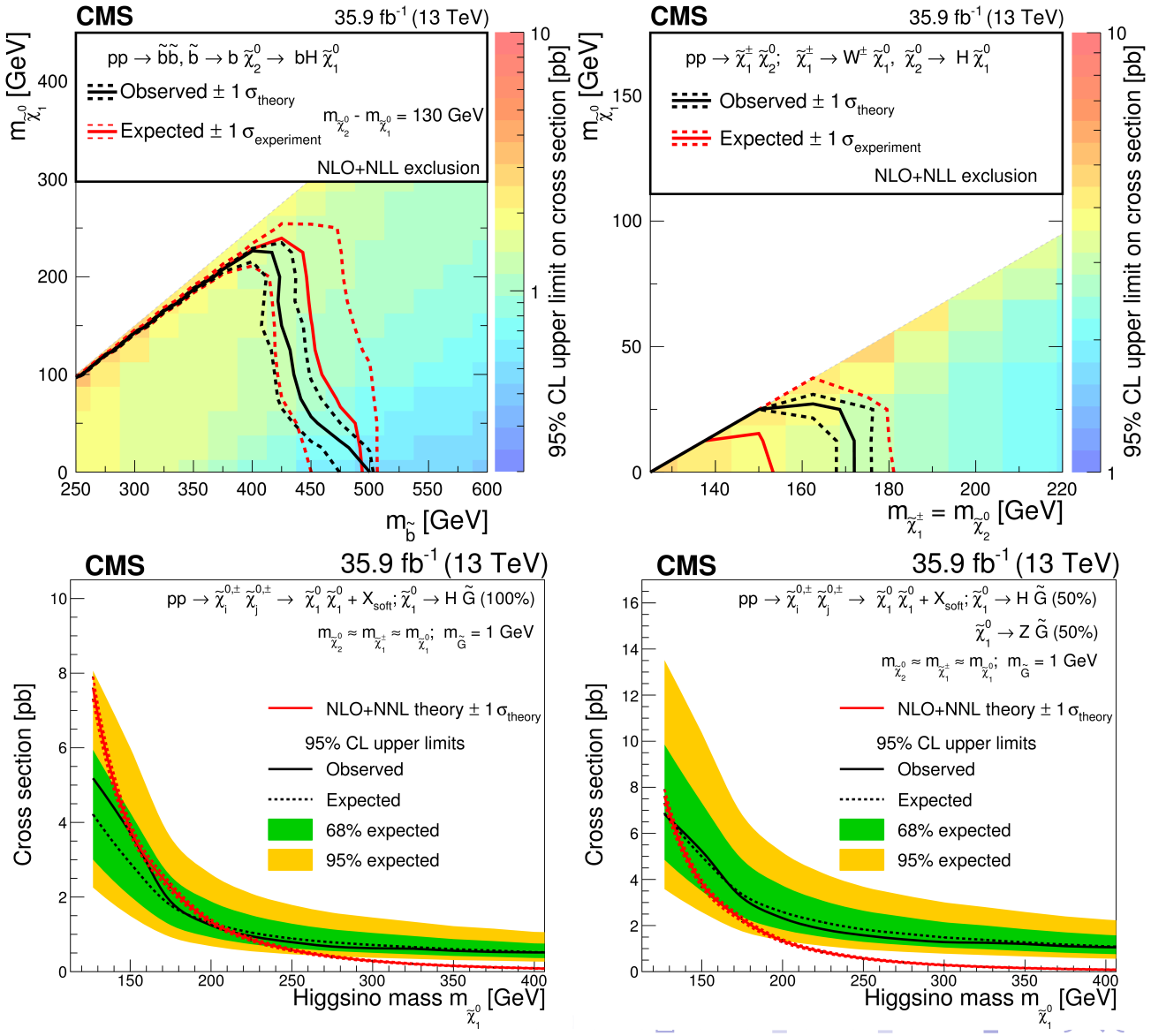
Higgs→ $\gamma\gamma$+X with razor variables CMS-SUS-16-045

Results implemented in 4 simplified models

- $\tilde{b} \to b\tilde{\chi}_2^0 \to H\tilde{\chi}_1^0$
  $m_{\tilde{b}} > 450$ GeV
- $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to W^\pm H\tilde{\chi}_1^0$
  $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0} > 150$ GeV

GMSB:

- $\tilde{\chi}_1^0 \to H\tilde{G}$
  $m_{\tilde{\chi}_1^0} > 205$ GeV
- $\tilde{\chi}_1^0 \to H/Z\tilde{G}$
  $m_{\tilde{\chi}_1^0} > 130$ GeV



Summary

- Photonic SUSY searches important for GMSB

- 3 analysis shown, extending limits in EWK and strong productions
- EWK: $m_{NLSP} \gtrsim 800$ GeV
- Strong: $m_{\tilde{q}} \gtrsim 1600$ GeV, $m_{\tilde{g}} \gtrsim 2000$ GeV

- Many ongoing searches in GMSB sector
  - Expect stronger limits on models
  - Or a discovery ... ☺