Searches for supersymmetry in final states with photons with CMS

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on behalf of the CMS collaboration

RWTH Aachen University

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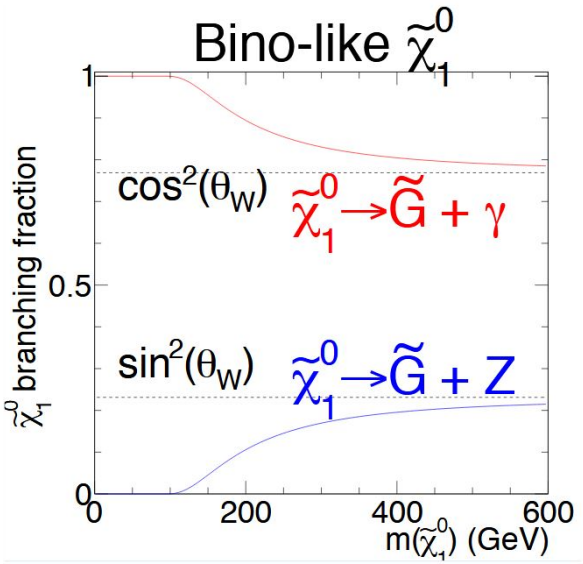
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Motivation and overview

$\gamma + p_T^{miss}$ final states well motivated in **gauge-mediated supersymmetry breaking** scenarios:

- Gravitino $\widetilde{G}$ (essentially massless) is LSP
- $\widetilde{\chi}_1^0$ is NLSP and promptly decaying
- Esp. **bino** NLSPs decay with high probability to $\widetilde{\mathbf{G}} + \gamma$
- **R-Parity conservation** $\rightarrow$ stable LSPs lead to p_T^{miss}



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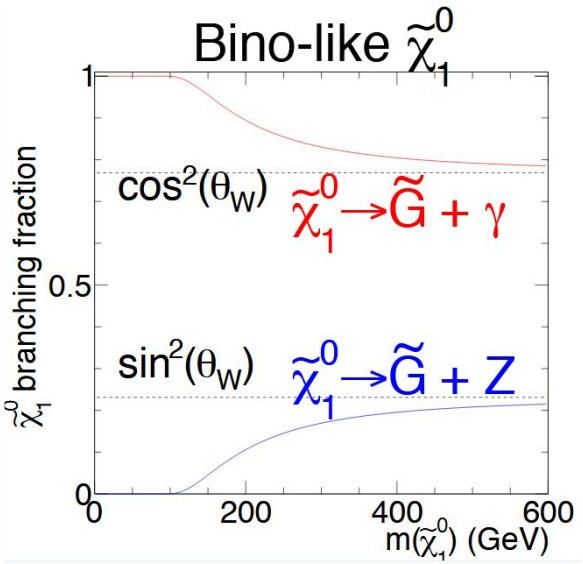

Latest SUSY photon results:

Reference	Title	Journal (*presented at*)
SUS-17-012	Search for SUSY using events with a photon, a lepton, and missing transverse momentum in pp collisions at 13 TeV	approved, target JHEP (*SUSY2018*)
SUS-16-046	Search for gauge-mediated SUSY in events with at least one photon and missing transverse momentum in pp collisions at 13 TeV	PLB 780 (2018) 118 *(SUSY2018)*
SUS-16-045	Search for SUSY with Higgs boson to diphoton decays using the razor variables at 13 TeV	PLB 779 (2018) 166 *(SUSY2018 poster poster by Jiajing Mao)*
SUS-16-047	Search for SUSY in events with at least one photon, missing transverse momentum, and large transverse event activity in pp collisions at 13 TeV	JHEP 12 (2017) 142 (*SUSY2018*)
SUS-15-012	Search for SUSY in events with photons and missing transverse energy	PLB 769 (2017) 391 (*SUSY2016*)
SUS-14-016	Search for SUSY in electroweak production with photons and large missing transverse energy in pp collisions at 8 TeV	PLB 759 (2016) 479 (*SUSY2016*)

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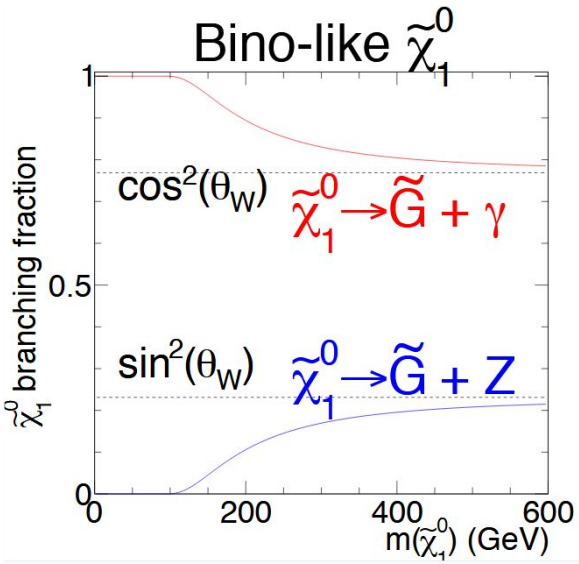

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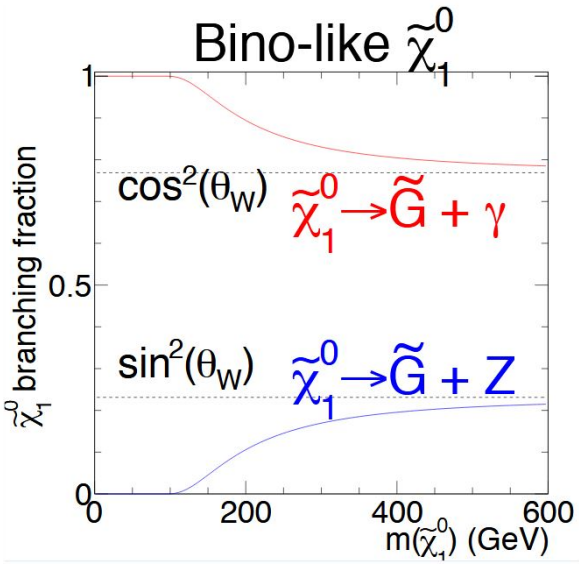

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Data set and background overview

Data set:

- 2016 data set with 35.9 fb^{-1} at 13 TeV

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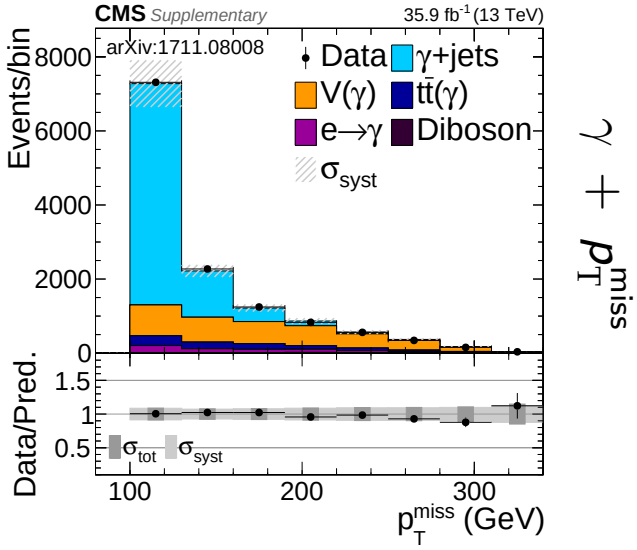
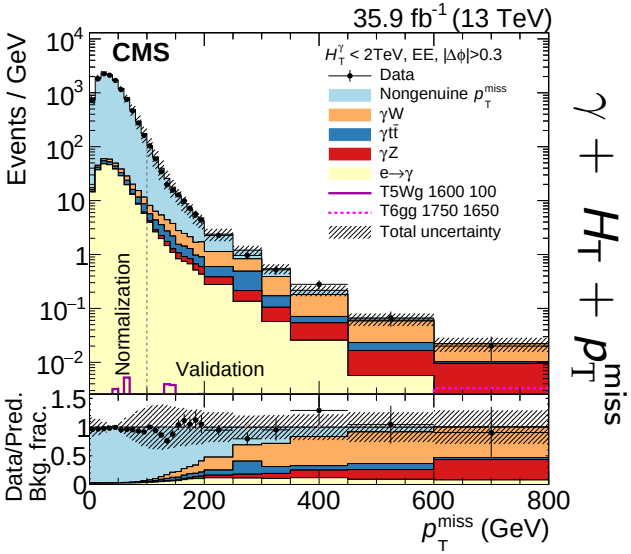
Overview over contributing backgrounds:

$\gamma + p_T^{miss}$	$\gamma + H_T + p_T^{miss}$	$\gamma + l + p_T^{miss}$
$\mathbf{V}(\gamma)^*$	$\mathbf{V}\gamma^*$	$\mathbf{V}\gamma^*$
$\gamma +$ jets	**Nongenuine** p_T^{miss}	fake leptons
		j$\rightarrow \gamma$ fake
$e \rightarrow \gamma$	$e \rightarrow \gamma$	$\mathbf{e \rightarrow \gamma}$
$t\bar{t}(\gamma)$	$t\bar{t}\gamma$	$\mathbf{t\bar{t}\gamma}$
Diboson	-	$\mathbf{WW\gamma}$, $\mathbf{WZ\gamma}$

*V = W, Z





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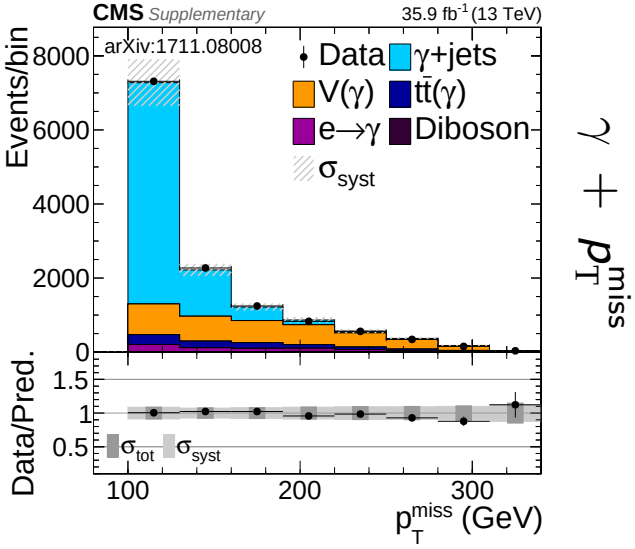
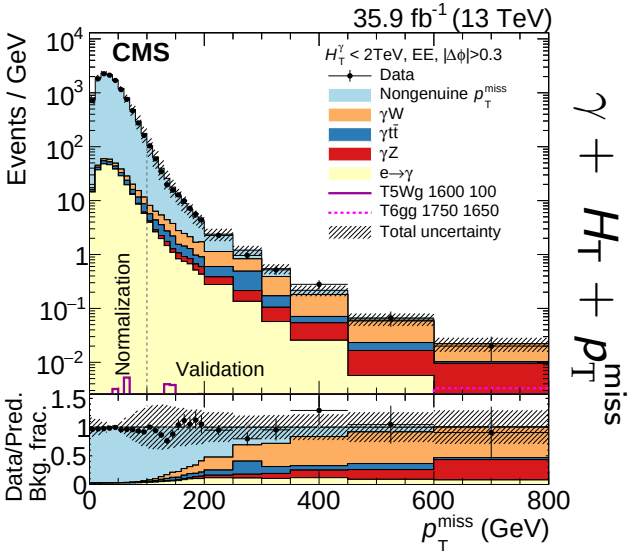
Estimation method:

- simulation





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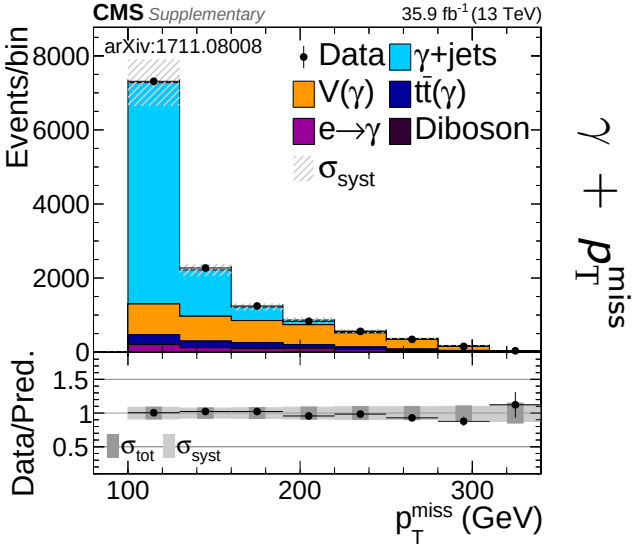

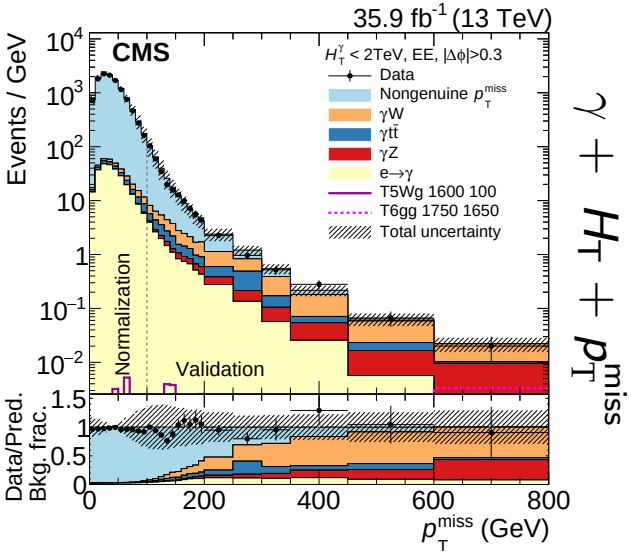

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Estimation method:

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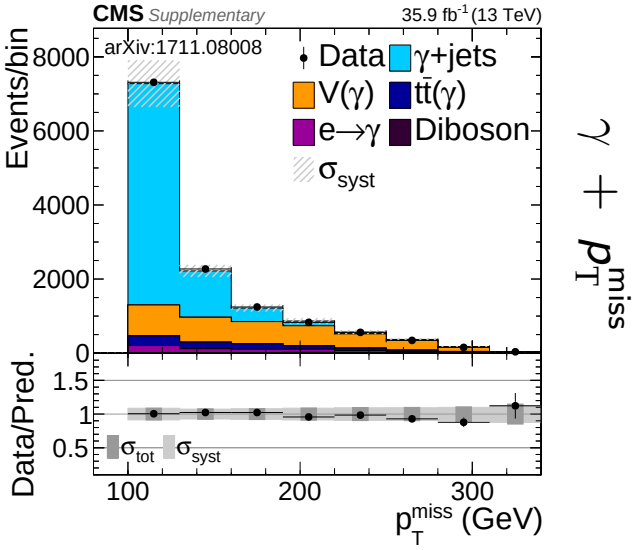
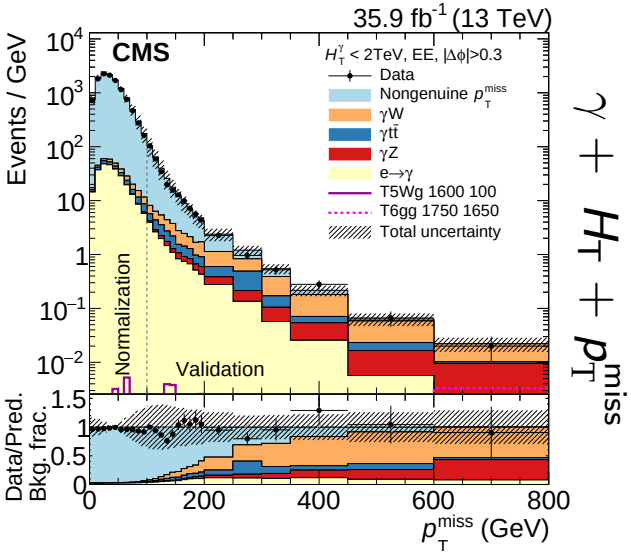
- data driven estimate

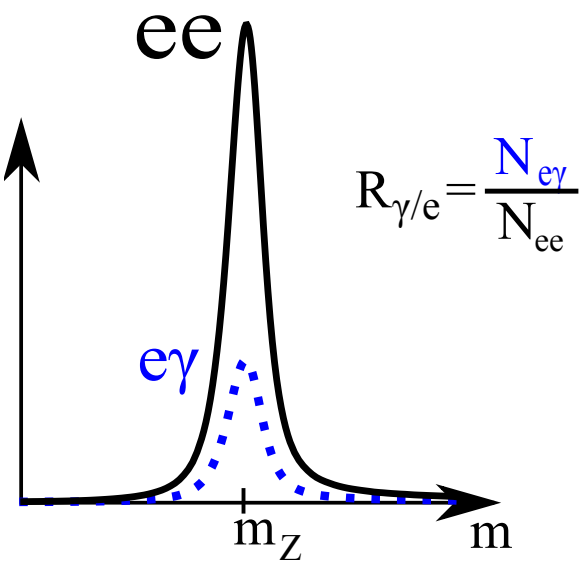




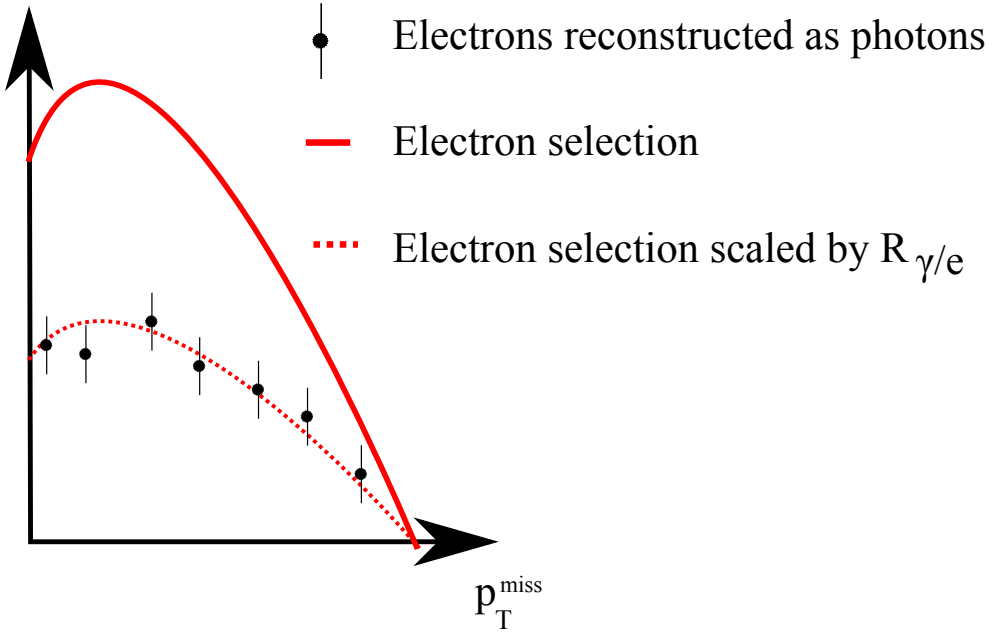
e→ γ background estimation

Method

- electron-like object: photon candidate definition but **with** matching cluster of hits in pixel detector
- determine probability $R_{\gamma/e}$ that an electron-like object is misidentified as a photon
- select control sample with electron-like objects and same selection criteria
- scale control sample with misidentification probability



$$R_{\gamma/e} = \frac{N_{e\gamma}}{N_{ee}}$$

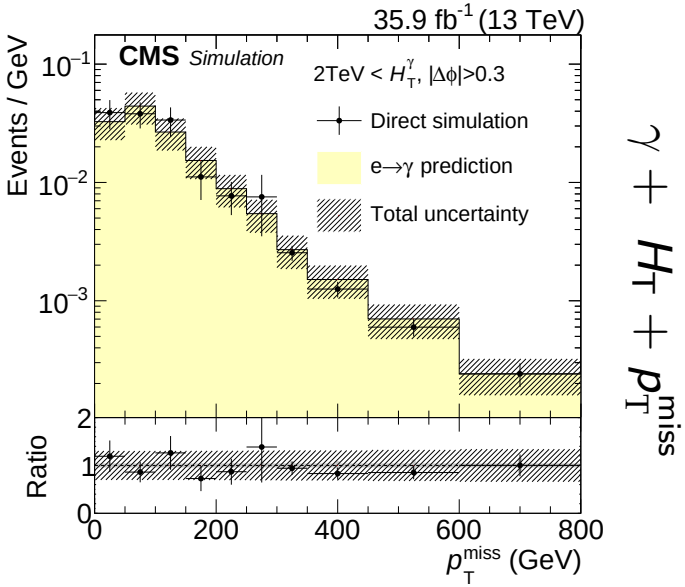


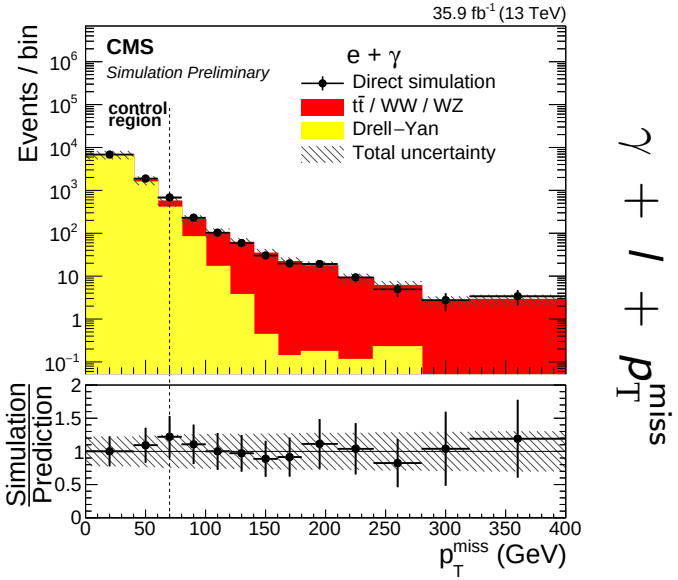
e→ γ background estimation

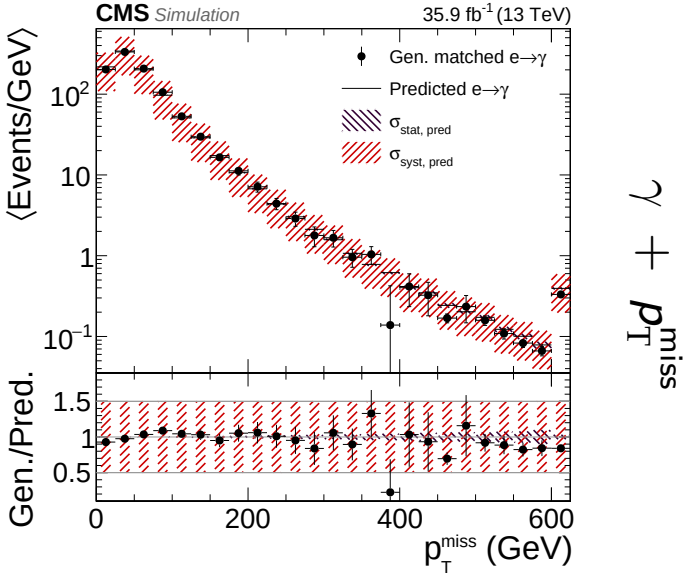
Validation

- Generated electron matched to reconstructed photon compared to prediction

- Similar procedure for j $\rightarrow \gamma$ background in $\gamma + l + p_T^{miss}$ analysis







Fit of Vγ and (γ + jets/ fake leptons) background

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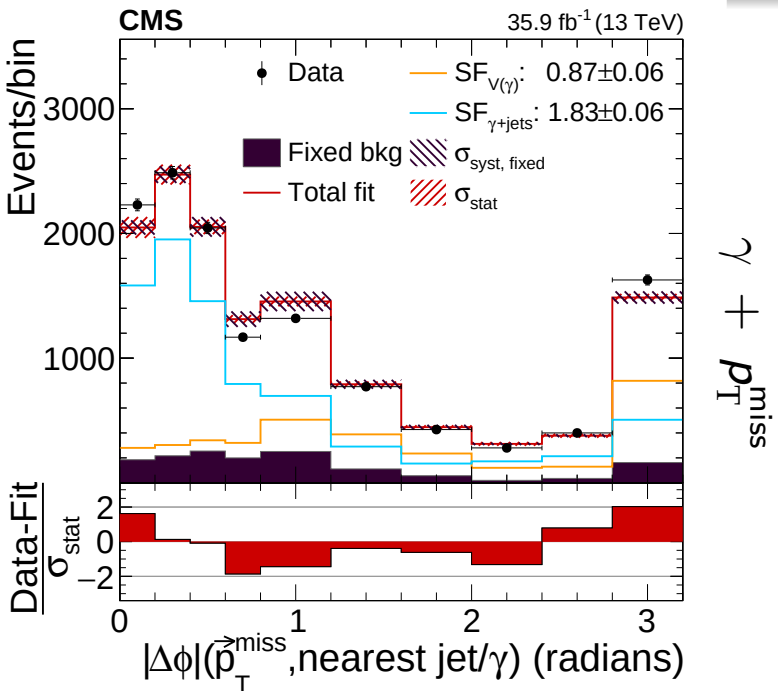
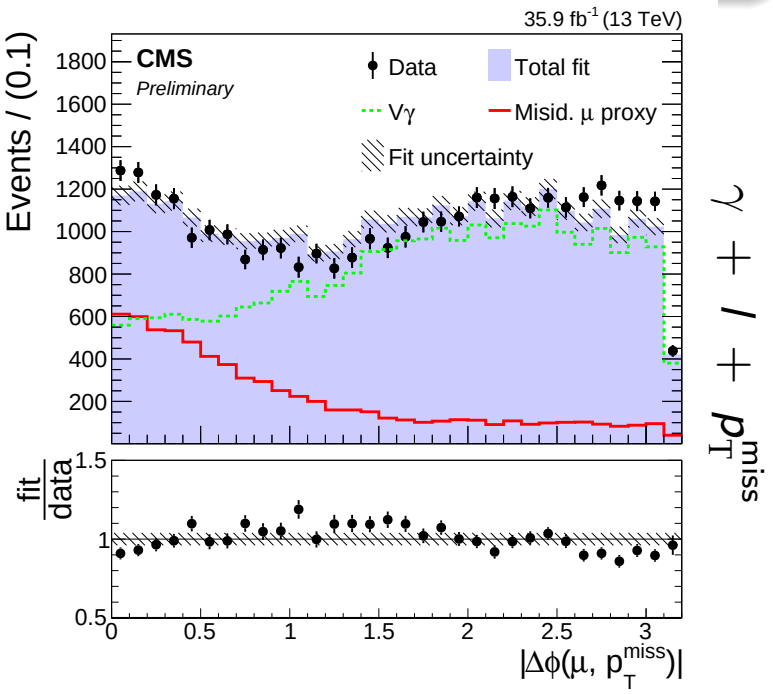
- Fitting MC simulation of two backgrounds Vγ and (γ + jets/ fake leptons) to data in control region
- remaining subdominant backgrounds fixed / subtracted
- template variable needs to separate the shapes of the two fit components
- uncertainties in normalization are canceled, simulated shape uncertainties remain





Signal region selections

$\gamma + l + p_T^{miss}$

- $p_T(\gamma) > 35$ GeV
- $1l$, either e or μ with $p_T > 25$ GeV
- $\Delta R(\gamma, l) > 0.8$
- if eγ channel: $M_{e\gamma} > M_Z + 10$ GeV
- $M_T(\vec{p}_T(l), \vec{p}_T^{\,miss}) > 100$ GeV
- $p_T^{miss} > 120$ GeV

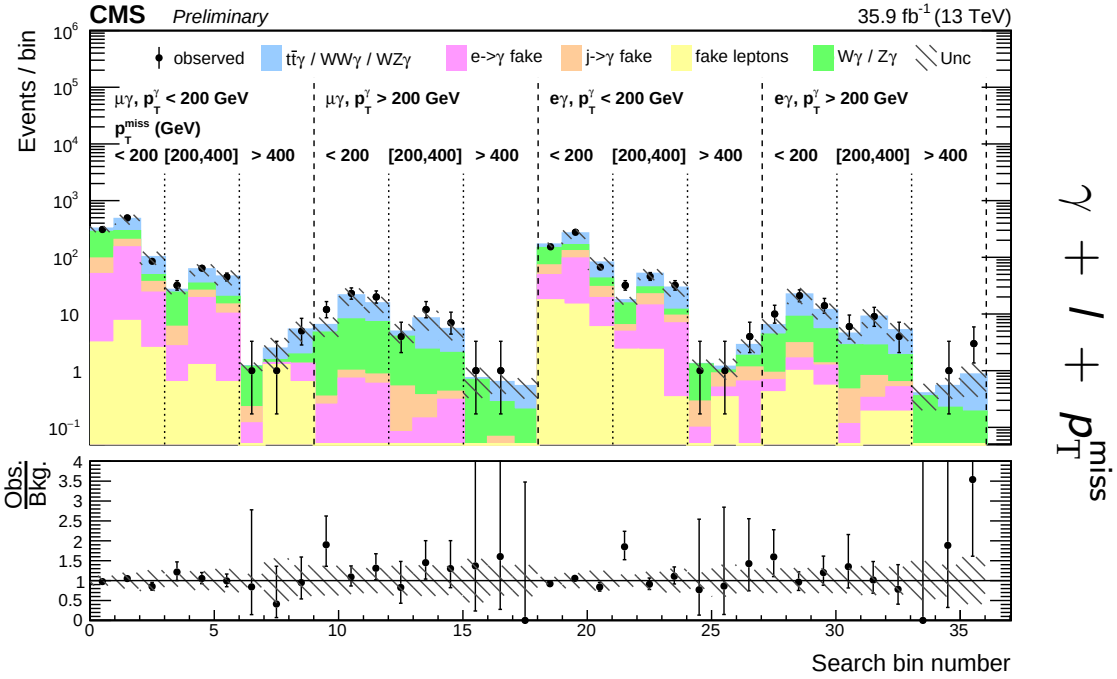
$\gamma + H_T + p_T^{miss}$

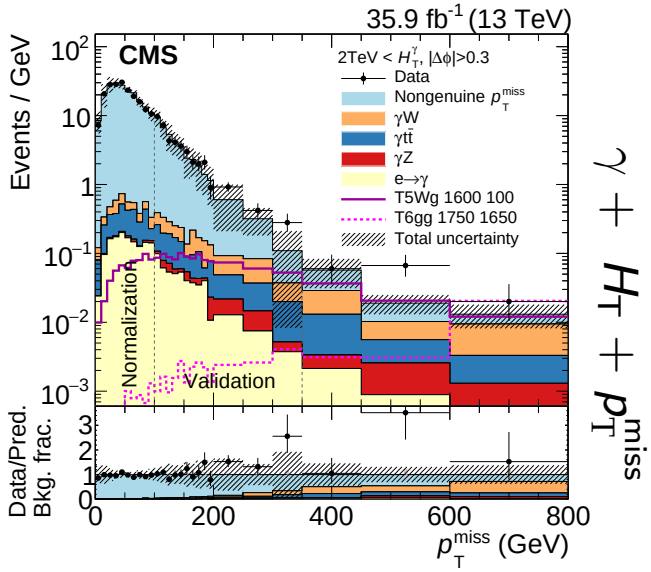
- $p_T(\gamma) > 100$ GeV
- $|\Delta\phi(\gamma, p_T^{miss})| > 0.3$
- $p_T^{miss} > 350$ GeV
- $H_T^{\gamma} = p_T(\gamma) + H_T > 700$ GeV

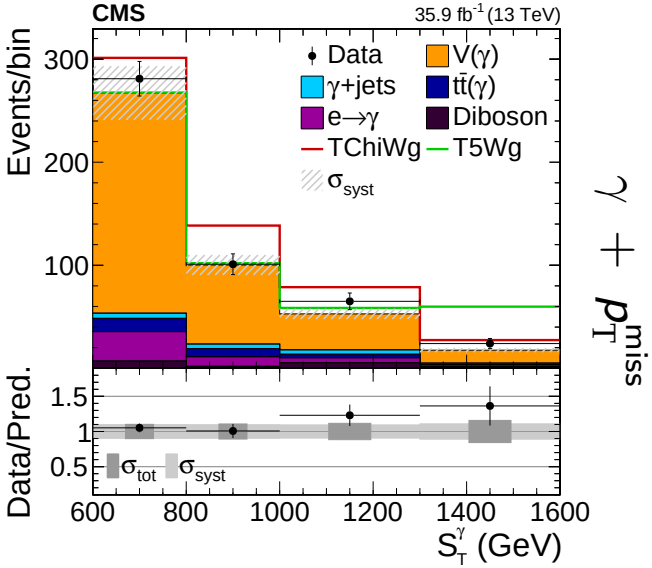
$\gamma + p_T^{miss}$

- $p_T(\gamma) > 180$ GeV
- $\Delta\phi(p_T^{miss}, \text{jet}) > 0.3$, if p_T (jet) > 100 GeV
- $M_T(\vec{p}_T(\gamma), \vec{p}_T^{\,miss}) > 300$ GeV
- $p_T^{miss} > 300$ GeV
- $S_T^{\gamma} = \sum_i^{N_\gamma} p_T(\gamma_i) + p_T^{miss} > 600$ GeV

Results

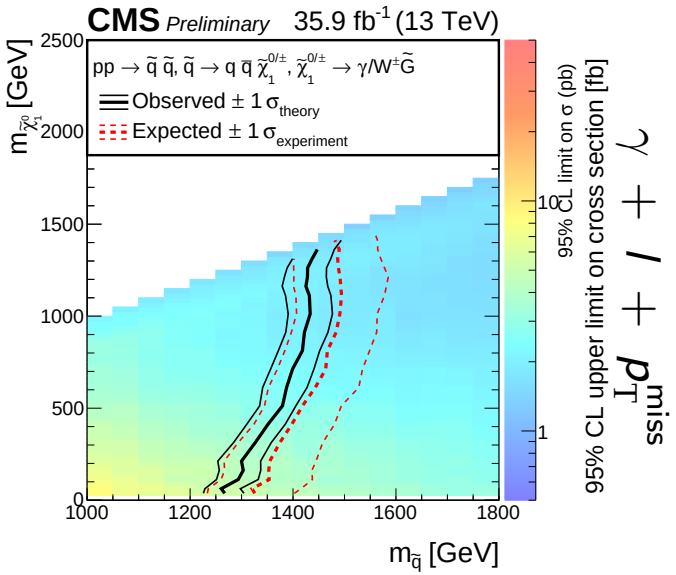


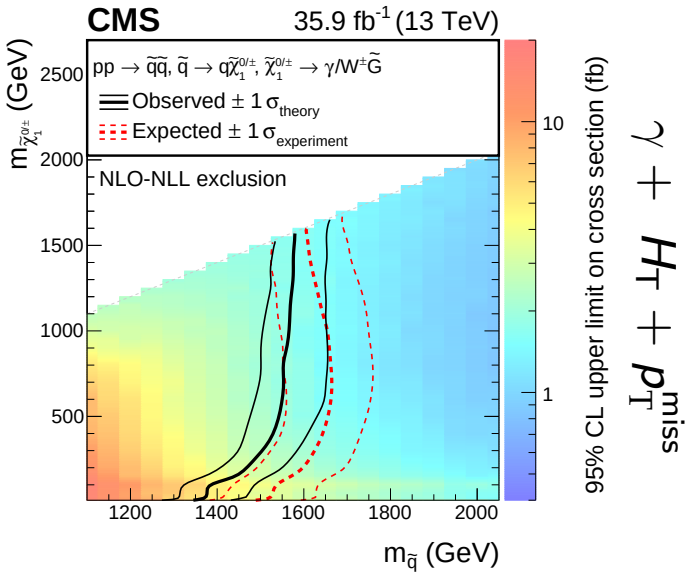


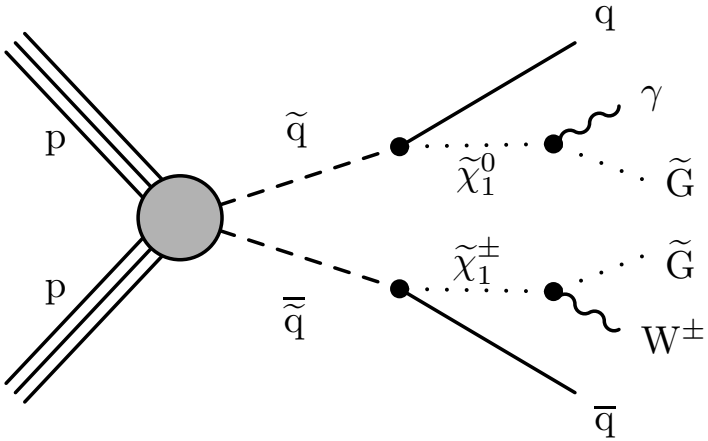


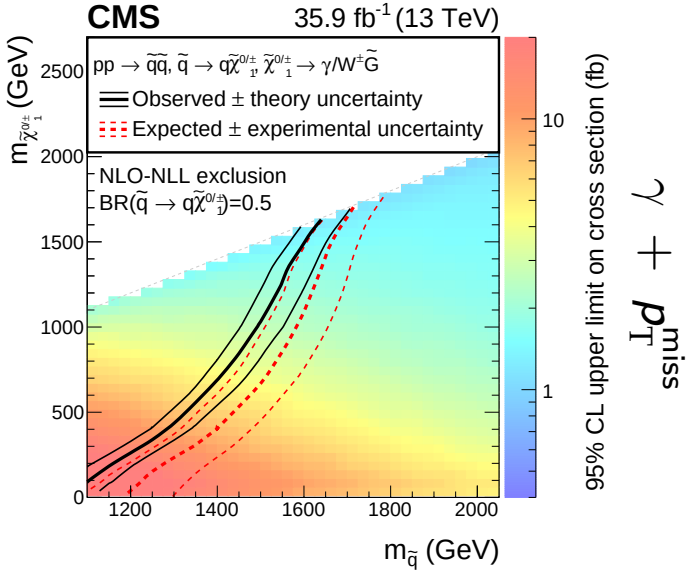
- $\gamma + l + p_{\mathrm{T}}^{\mathrm{miss}}$: 36 search regions
- $\gamma + H_{\mathrm{T}} + p_{\mathrm{T}}^{\mathrm{miss}}$: 6 search regions
- $\gamma + p_{\mathrm{T}}^{\mathrm{miss}}$: 4 search regions
- Overall good agreement

Interpretation - strong production - T6Wg









T6Wg: up to $M_{\tilde{q}} \lesssim 1.65$ TeV excluded

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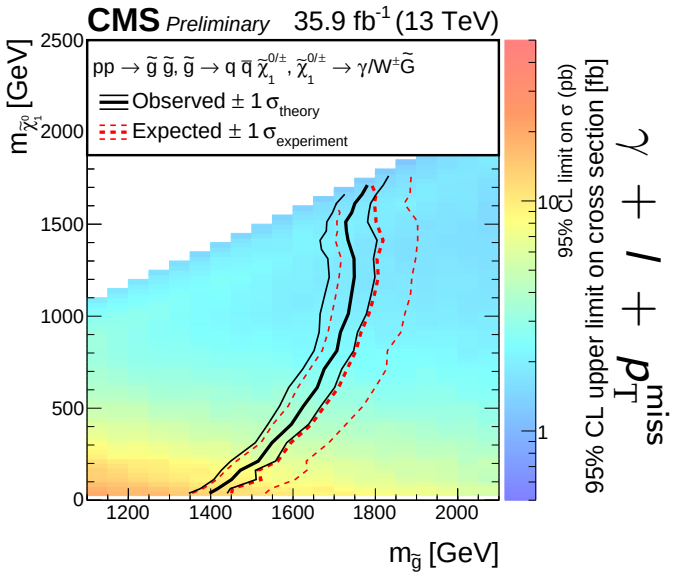
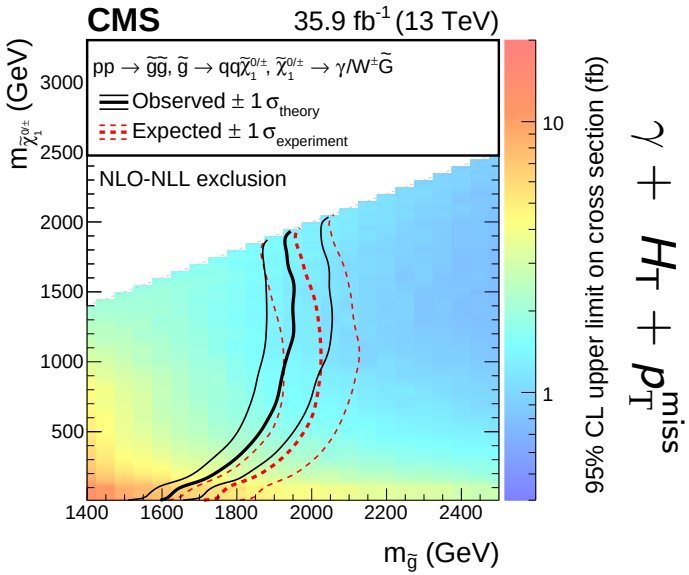
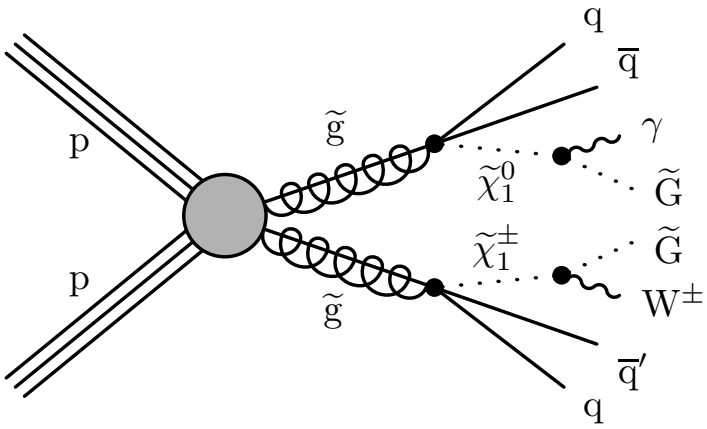
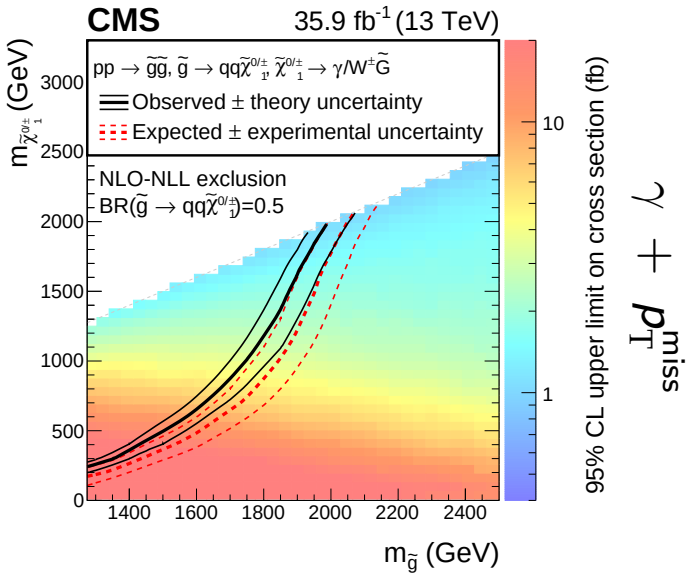


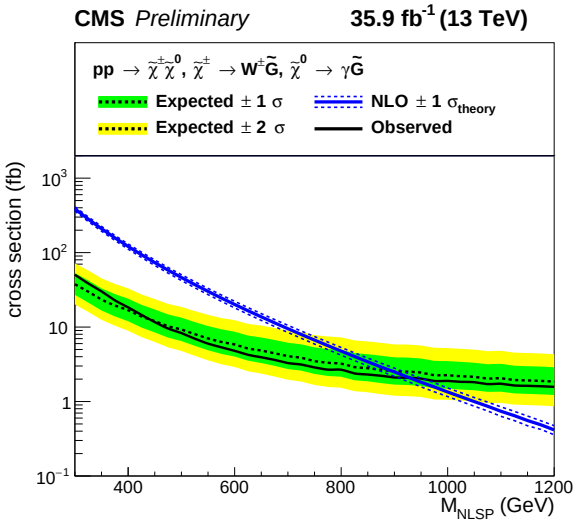




T5Wg: up to $M_{\tilde{g}} \lesssim 2$ TeV excluded



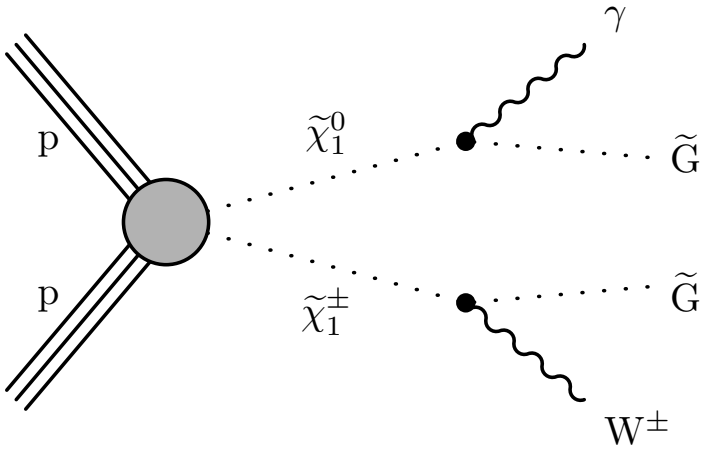
Interpretation - electroweak production - TChiWg



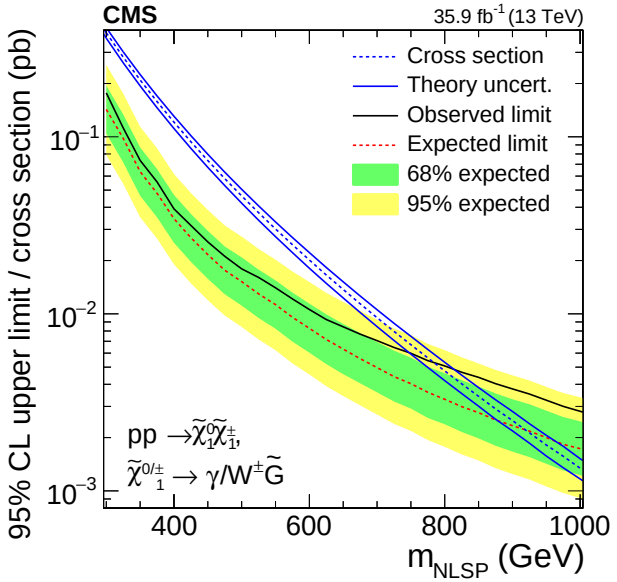
$\gamma + l + p_T^{miss}$

backup

- $m_{\mathrm{NLSP}} \lesssim 0.95$ TeV in electroweak **TChiNg** model with $\gamma+$ H/Z final states set by $\gamma + p_T^{miss}$



TChiWg: up to $m_{\mathrm{NLSP}} \lesssim 0.9$ TeV excluded

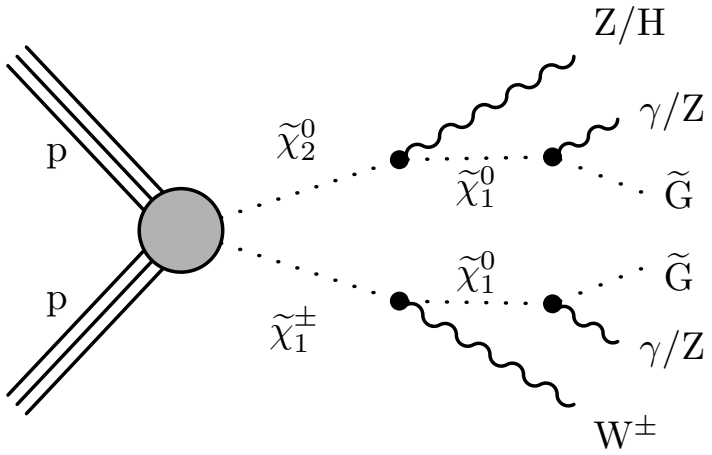


$\gamma + p_T^{miss}$

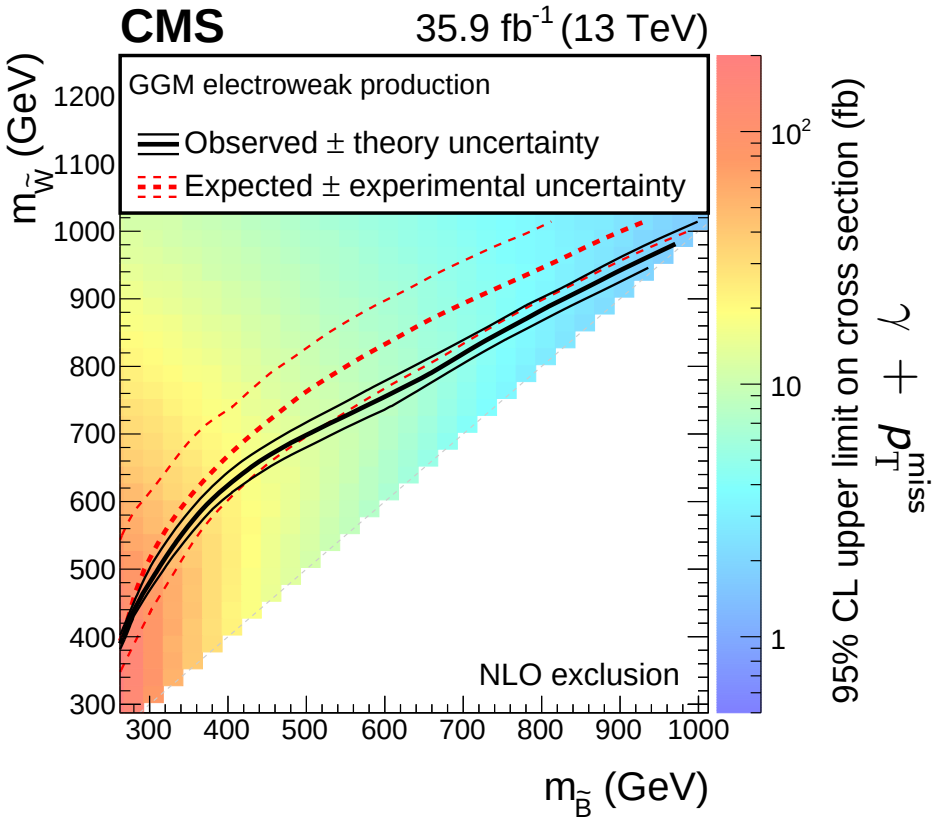
Interpretation - electroweak production - GGM

full model based on gauge mediation

- full set of processes contribute to signal point
- bino mass $m_{\tilde{B}} = M_{\tilde{\chi}_1^0}$
- wino mass $m_{\tilde{W}} = M_{\tilde{\chi}_2^0} = M_{\tilde{\chi}_1^\pm}$



GGM: up to $m_{\mathrm{NLSP}} \lesssim 0.98$ TeV excluded



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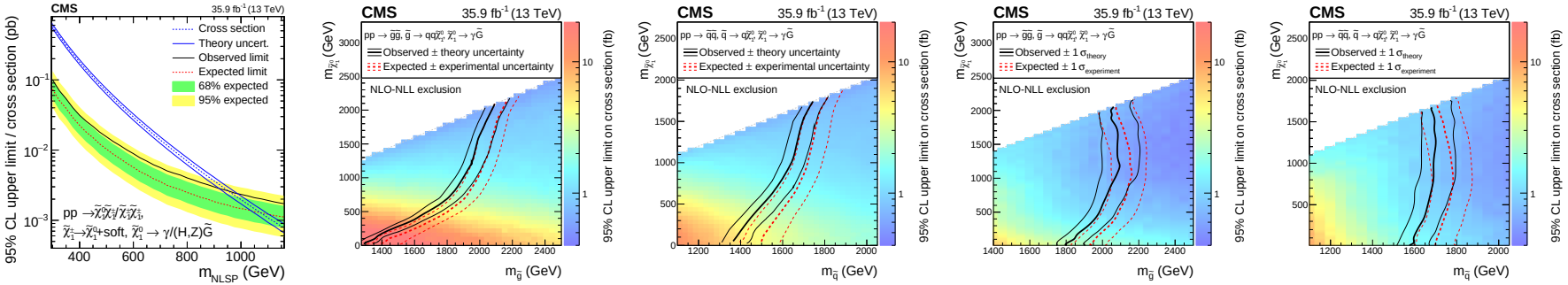

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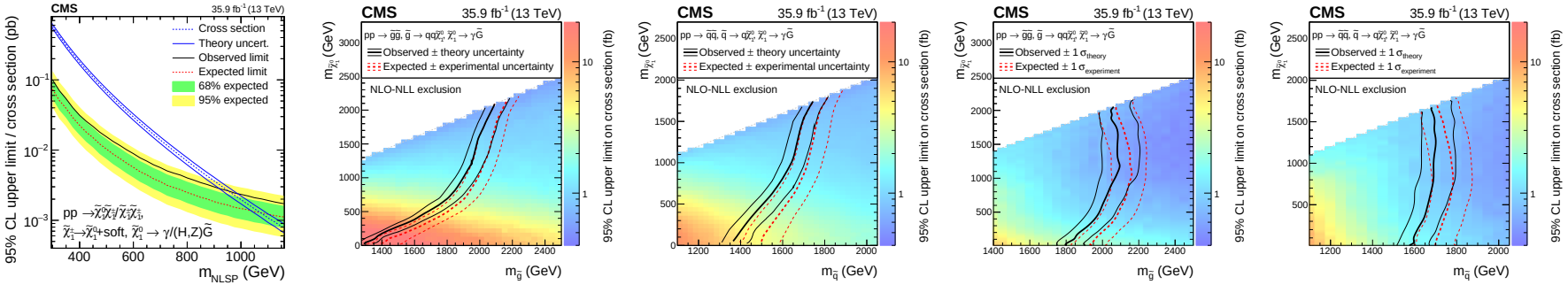
- limits in scenarios of **electroweak** production of charginos and neutralinos reach **1 TeV** threshold

There is more:

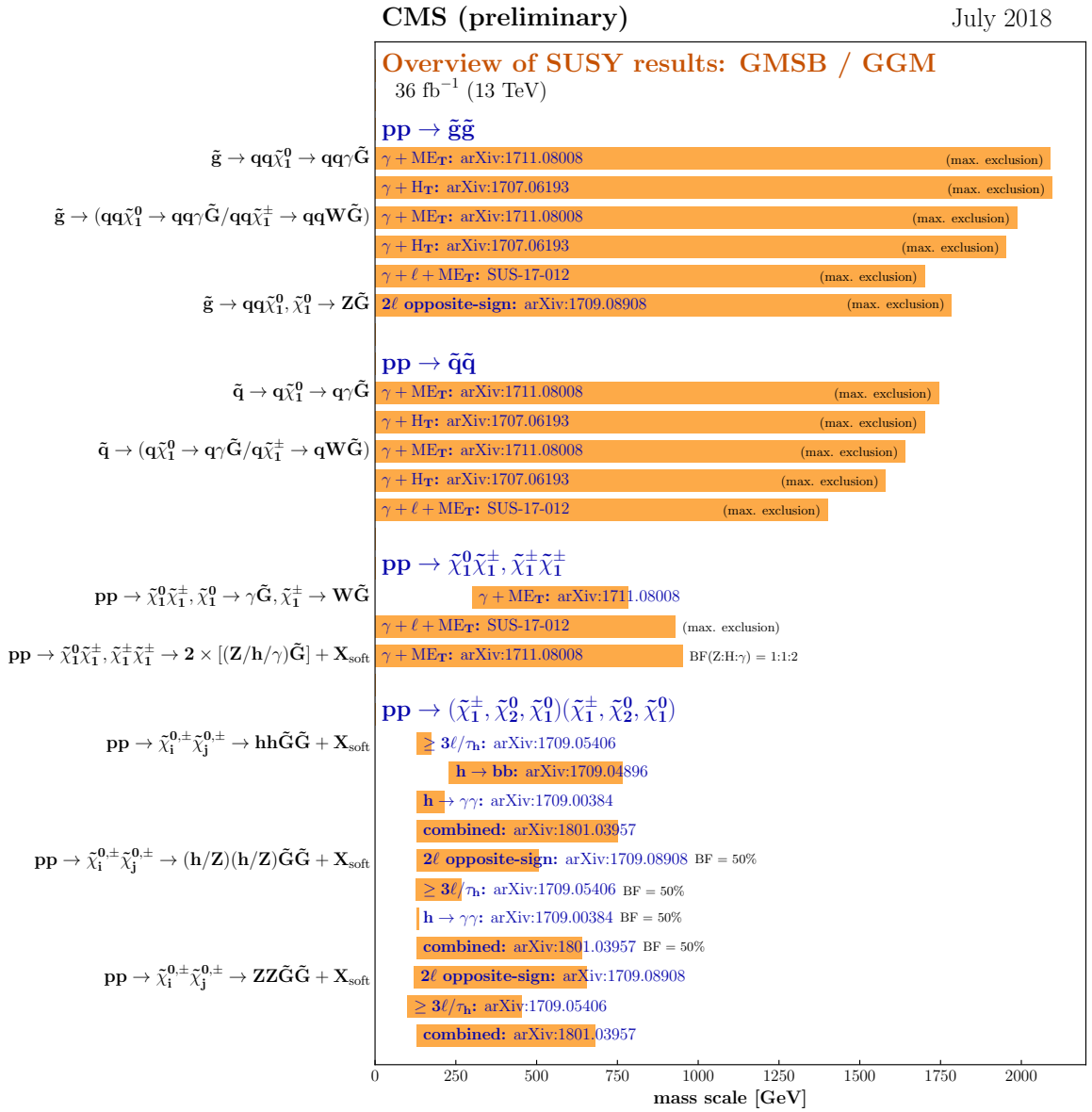


And that's not all:

- Several CMS SUSY photon analyses in preparation:
  - $2\gamma + p_{\mathrm{T}}^{\mathrm{miss}}$: pre-approved
  - $\gamma + b$ jets: approval talk next week
  - further analyses in development
- **combination** of photon analyses in preparation including two new full SUSY models

BACKUP

Interpretations



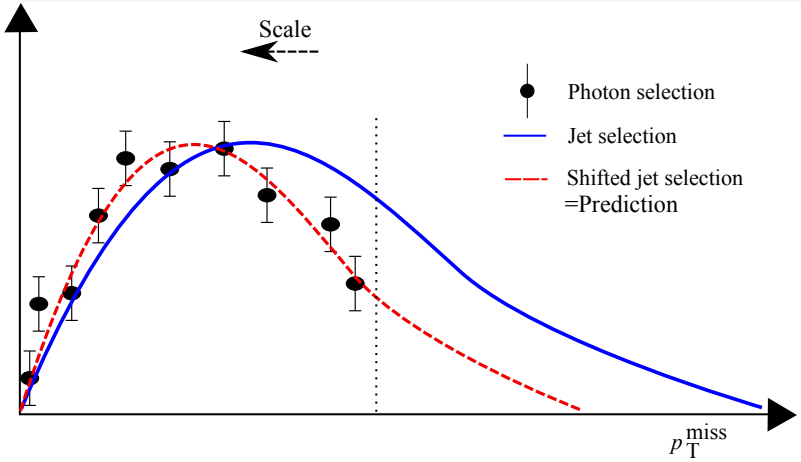
Non-genuine p_T^{miss} background estimation

Jet control region

- no photon, H_T trigger
- EM$H_T > 700/2000$ GeV

Estimation method

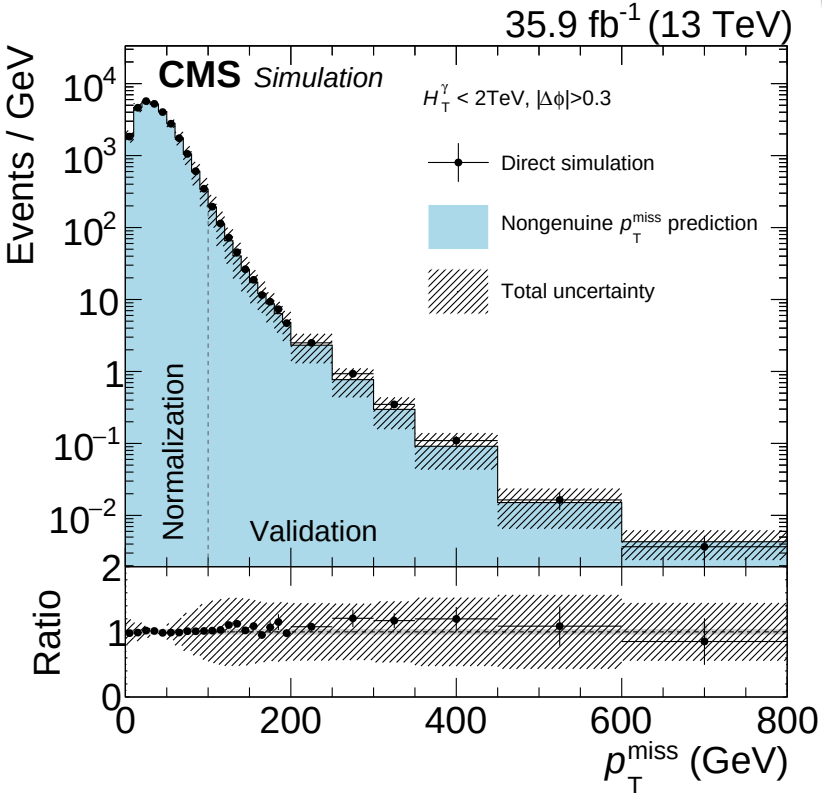
- use p_T^{miss} shape of jet control region
- correct shape for difference in photon and jet selection:
  p_T^{miss} (jet selection) $\rightarrow$ p_T^{miss} (jet selection) $\cdot$ scale
- normalized to photon selection in $p_T^{miss} < 100$ GeV region

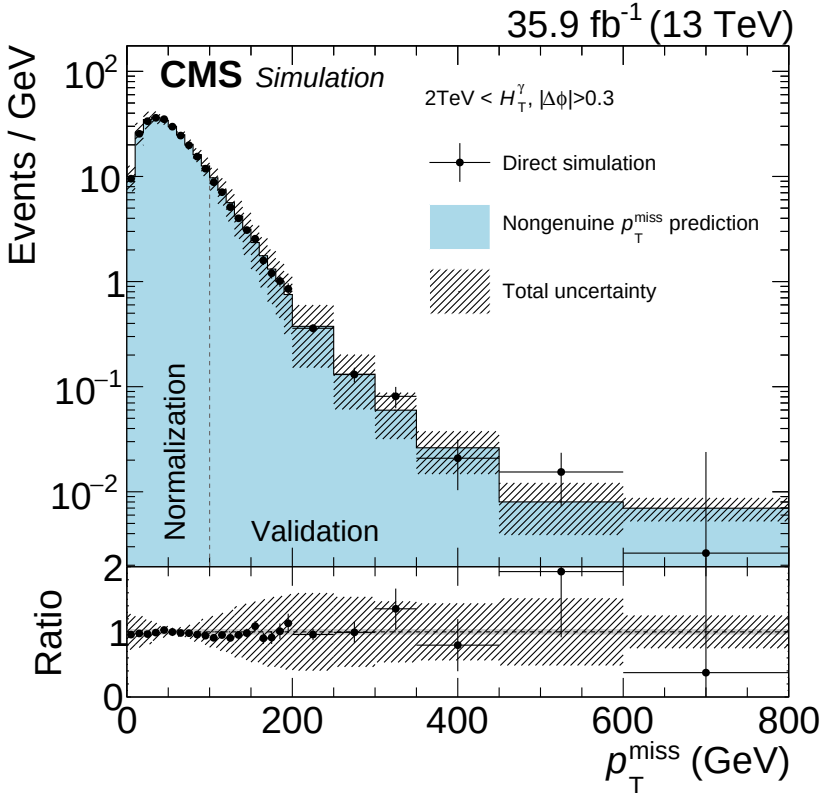


Nongenuine p_T^{miss} background estimation

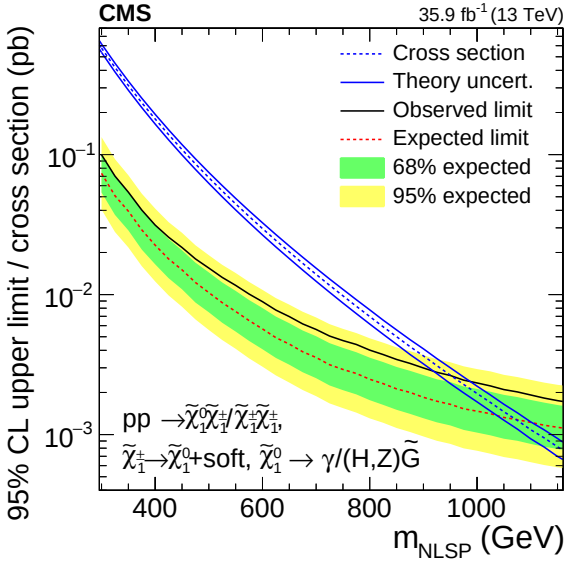
Validation

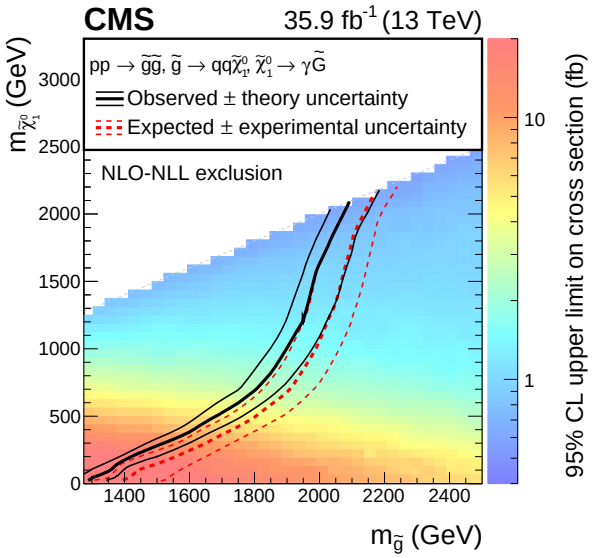
- direct γ + jets and QCD multijet simulation
- compared to method applied to simulation
- left: low EMH_T, right: high EMH_T

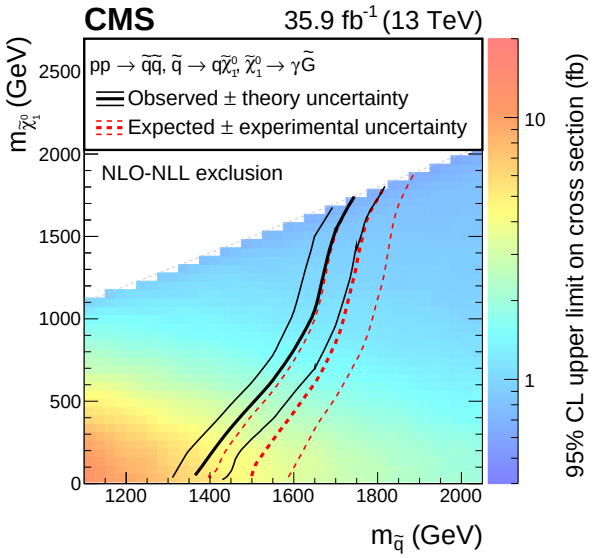


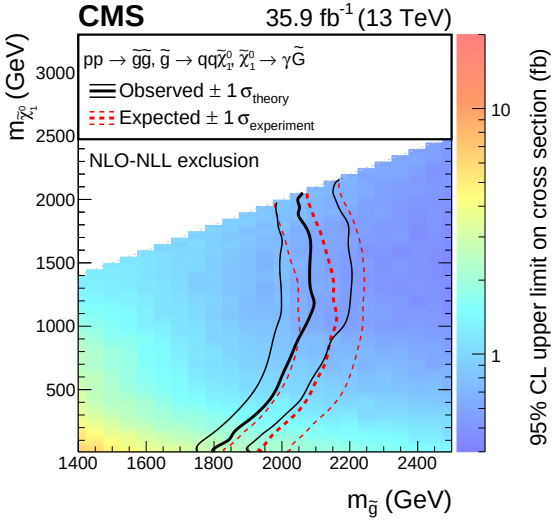


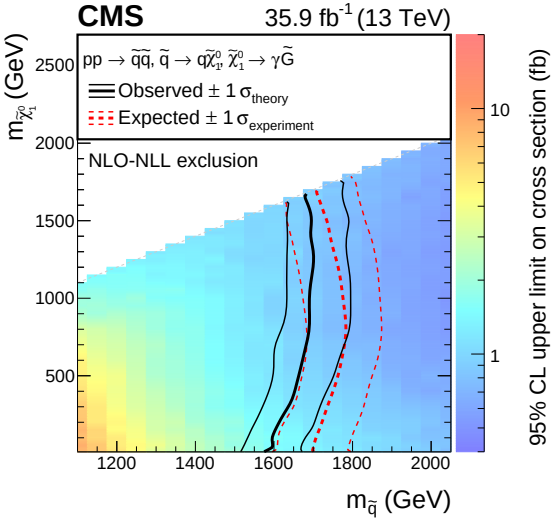
Interpretations



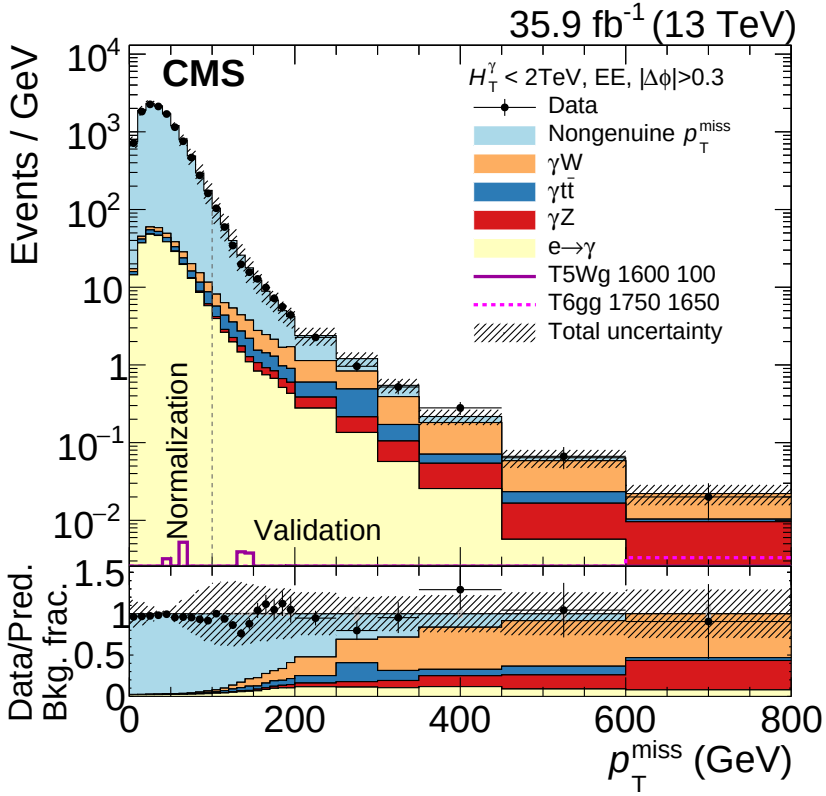


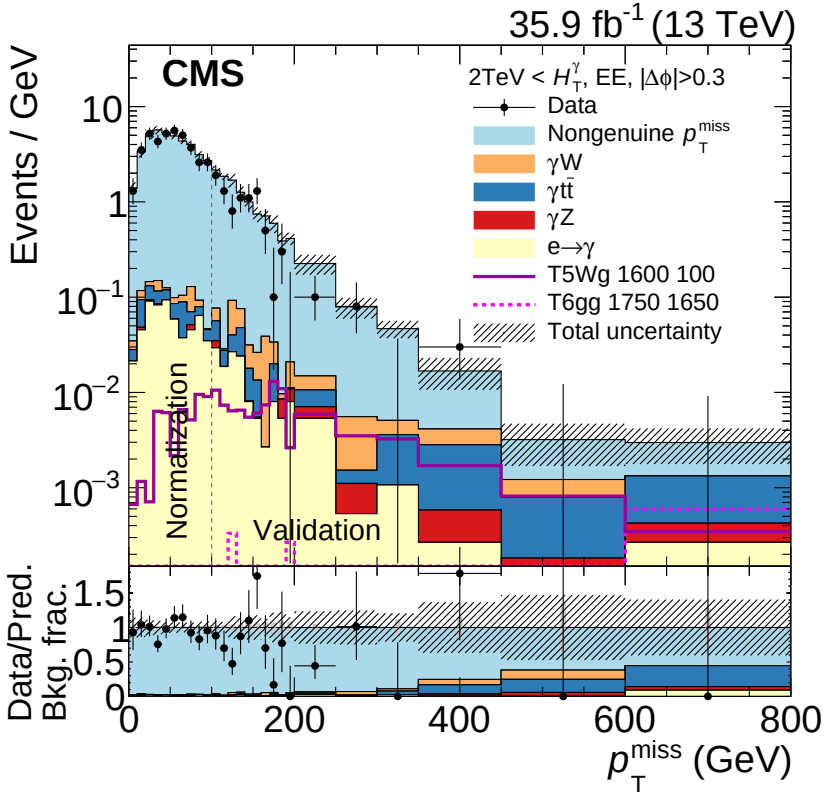




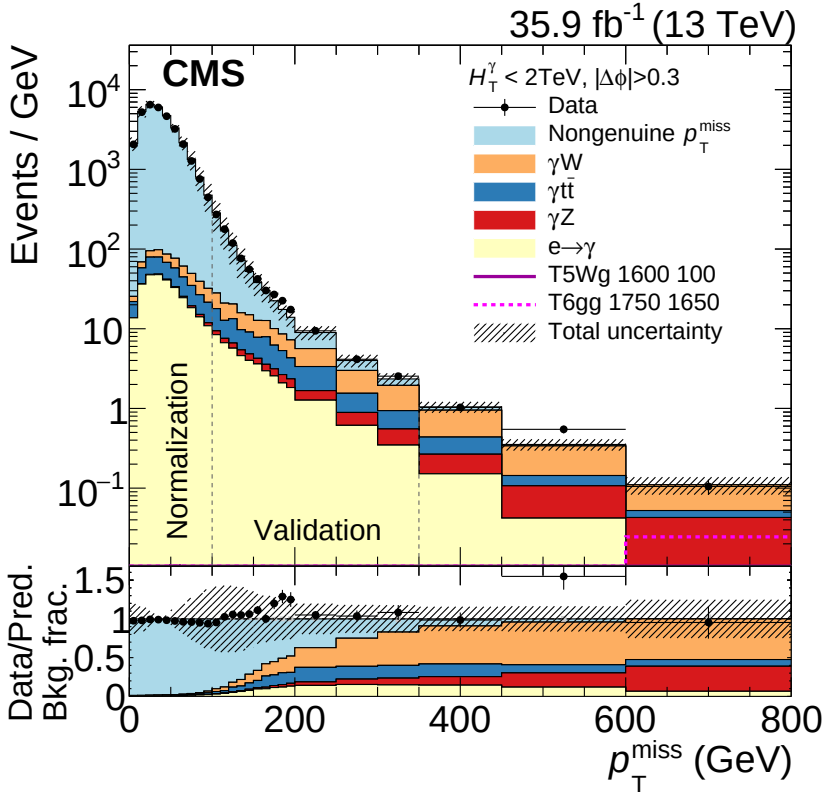


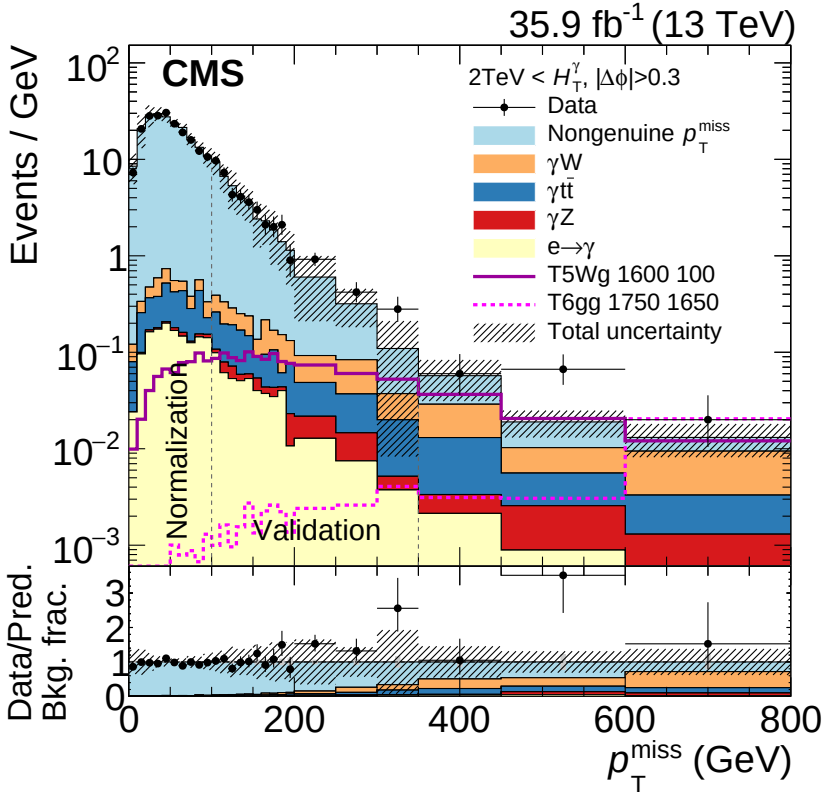
Validation SUS-16-047





Results SUS-16-047





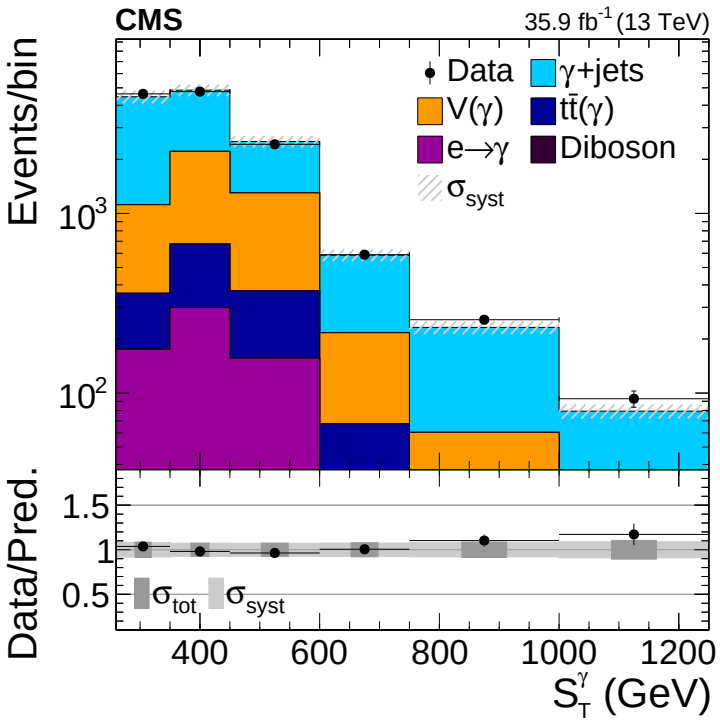
Uncertainties SUS-16-047

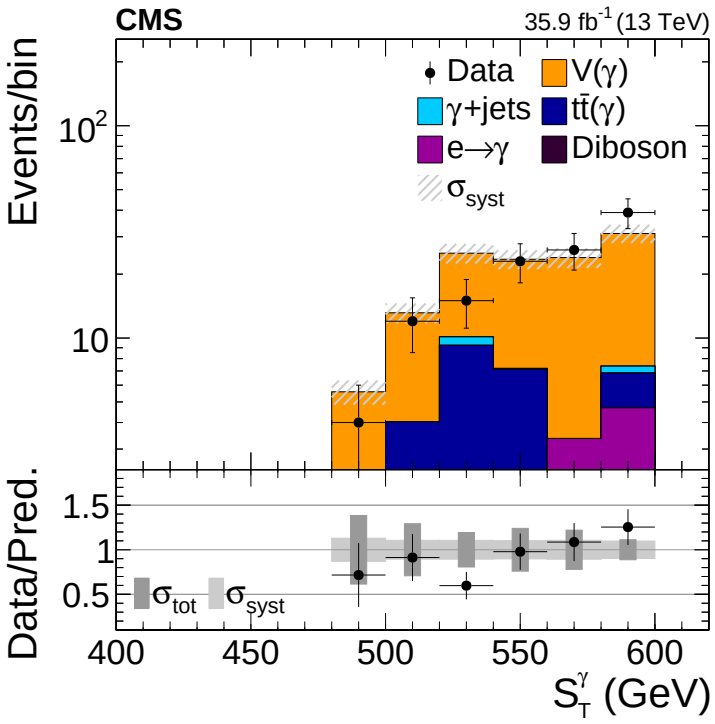
Source	Relative uncertainty (%) background	signal
Nongenuine $p_{\mathrm{T}}^{\mathrm{miss}}$	14–250	
$\mathrm{e} \to \gamma$	30	
Integrated luminosity	2.5	2.5
Photon scale factors	2	2
Trigger	4	4
PDFs	5–10	
Renormalization/factorization scales	16–27	0–1
Jet energy scale and resolution	2–20	1–6
Pileup	0.2–6	0.2–10
ISR		0–10
Fast simulation $p_{\mathrm{T}}^{\mathrm{miss}}$ modelling		0.5–6

Results SUS-16-047

H_T^γ (GeV)	<2000			>2000		
p_T^{miss} (GeV)	(350, 450)	(450, 600)	>600	(350, 450)	(450, 600)	>600
Nongenuine p_T^{miss}	$9.6^{+11.1}_{-9.6}$	$2.2^{+5.5}_{-2.2}$	< 0.1	2.83 ± 2.51	1.31 ± 0.74	$0.73^{+0.86}_{-0.73}$
γW	51.3 ± 9.7	29.1 ± 5.5	11.6 ± 2.5	1.58 ± 0.58	0.70 ± 0.37	1.23 ± 0.43
$\gamma t\bar{t}$	17.1 ± 5.4	5.6 ± 2.6	1.9 ± 0.4	0.97 ± 0.38	0.45 ± 0.29	0.40 ± 0.22
γZ	11.5 ± 2.4	9.7 ± 1.8	7.1 ± 1.4	0.12 ± 0.07	0.25 ± 0.11	0.21 ± 0.10
$e \to \gamma$	15.1 ± 4.6	6.3 ± 1.9	1.4 ± 0.5	0.21 ± 0.10	0.13 ± 0.07	0.05 ± 0.04
Total bkg.	104.6 ± 16.5	53.0 ± 8.6	22.0 ± 3.0	5.72 ± 2.60	2.84 ± 0.89	2.62 ± 0.99
Data	103	82	21	6	10	4
T5Wg 1600 100	0.4 ± 0.1	0.8 ± 0.1	0.7 ± 0.1	3.66 ± 0.40	3.09 ± 0.40	2.41 ± 0.32
T6gg 1750 1650	0.5 ± 0.1	0.8 ± 0.1	4.9 ± 0.4	0.31 ± 0.04	0.46 ± 0.07	4.12 ± 0.32

Validation SUS-16-046





Selection SUS-16-046

Region	Selection
Preselection	p_T^{miss} filters At least one reconstructed vertex At least one photon with $p_T > 180\,\text{GeV}$ $\Delta R(\gamma, \text{jet}) > 0.5$ $\Delta\phi(\vec{p}_T^{miss}, \text{jet}) > 0.3\,\text{rad}$, if $p_T(\text{jet}) > 100\,\text{GeV}$
Control region	Preselection $p_T^{miss} > 100\,\text{GeV}$ $M_T(\gamma, \vec{p}_T^{miss}) > 100\,\text{GeV}$ $p_T^{miss} < 300\,\text{GeV}$ or $M_T(\gamma, \vec{p}_T^{miss}) < 300\,\text{GeV}$
Validation region	Preselection $p_T^{miss} > 300\,\text{GeV}$ $M_T(\gamma, \vec{p}_T^{miss}) > 300\,\text{GeV}$ $S_T^{\gamma} < 600\,\text{GeV}$
Signal region	Preselection $p_T^{miss} > 300\,\text{GeV}$ $M_T(\gamma, \vec{p}_T^{miss}) > 300\,\text{GeV}$ $S_T^{\gamma} > 600\,\text{GeV}$

Uncertainties background SUS-16-046

	$V(\gamma)$	γ+jets	$e \to \gamma$	$t\bar{t}(\gamma)$	Diboson
Fit uncert. of statistical origin	6.9	3.3	–	–	–
Scale uncertainty in shape	3.8–9.0	2.8–7.1	–	–	–
PDF uncertainty in shape	1.6–3.8	1.9–8.2	–	–	–
JES uncertainty in shape	5.0–5.9	0.9–32	–	–	–
Tag-and-probe fit	–	–	50	–	–
Cross section, PDF, scales	–	–	–	30	30
Integrated luminosity	–	–	–	2.5	2.5
Photon eff. scale factor	–	–	–	2.0	2.0
Trigger efficiency	–	–	–	0.4	0.4

Uncertainties signal SUS-16-046

Source	Signal scenario EWK	Signal scenario Strong production
Statistical MC precision per signal region	1−28	2−50
Fast simulation uncertainty in $p_{\mathrm{T}}^{\mathrm{miss}}$	<0.1−5	<0.1−25
Scale uncertainty in shape	<0.1−1.8	<0.1−1.2
Integrated luminosity	2.5	2.5
Trigger efficiency	0.4	0.4
Photon scale factor	2.0	2.0
Pileup	<0.1−0.4	<0.1−2.1
ISR reweighting	0.6−3.0	–

Results SUS-16-046

S_T^γ: 600−800 GeV

	Yield	σ_{stat}	σ_{syst}
$V(\gamma)$	213	4.4	21.3
γ+jets	5	1.1	0.5
$t\bar{t}(\gamma)$	13	5.7	3.9
$e \to \gamma$	29	0.9	14.2
Diboson	7	2.8	2.1
Total	267	7.9	26.0
Data	281		

S_T^γ: 800−1000 GeV

	Yield	σ_{stat}	σ_{syst}
$V(\gamma)$	76.8	1.9	8.1
γ+jets	4.4	1.2	0.4
$t\bar{t}(\gamma)$	8.0	3.8	2.4
$e \to \gamma$	9.2	0.5	4.6
Diboson	1.9	1.7	0.6
Total	100.2	4.7	9.7
Data	101		

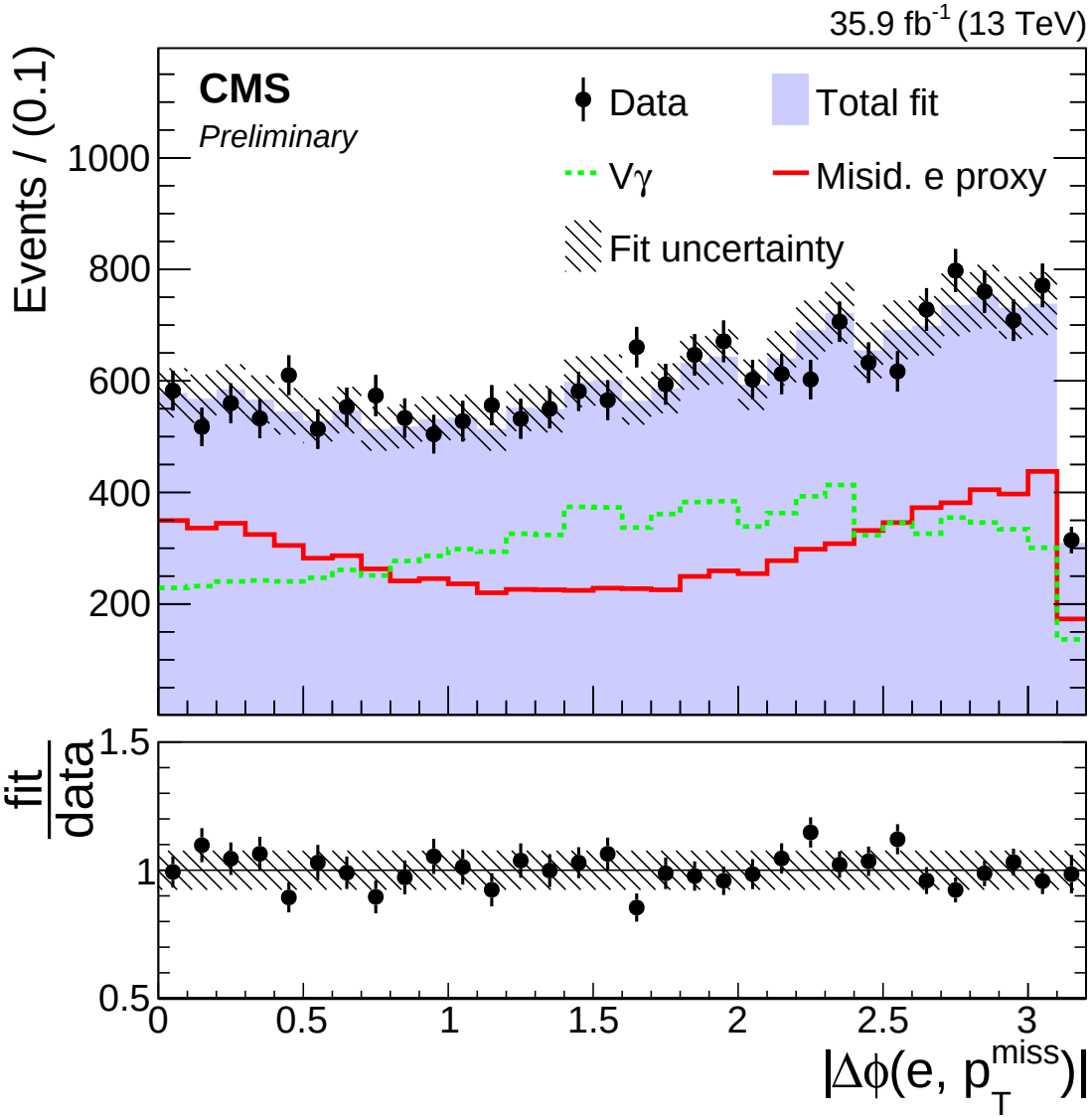
S_T^γ: 1000−1300 GeV

	Yield	σ_{stat}	σ_{syst}
$V(\gamma)$	35.0	1.3	3.9
γ+jets	4.2	1.3	0.4
$t\bar{t}(\gamma)$	3.5	0.9	1.1
$e \to \gamma$	4.7	0.4	2.3
Diboson	5.4	3.0	1.6
Total	52.8	3.6	5.0
Data	65		

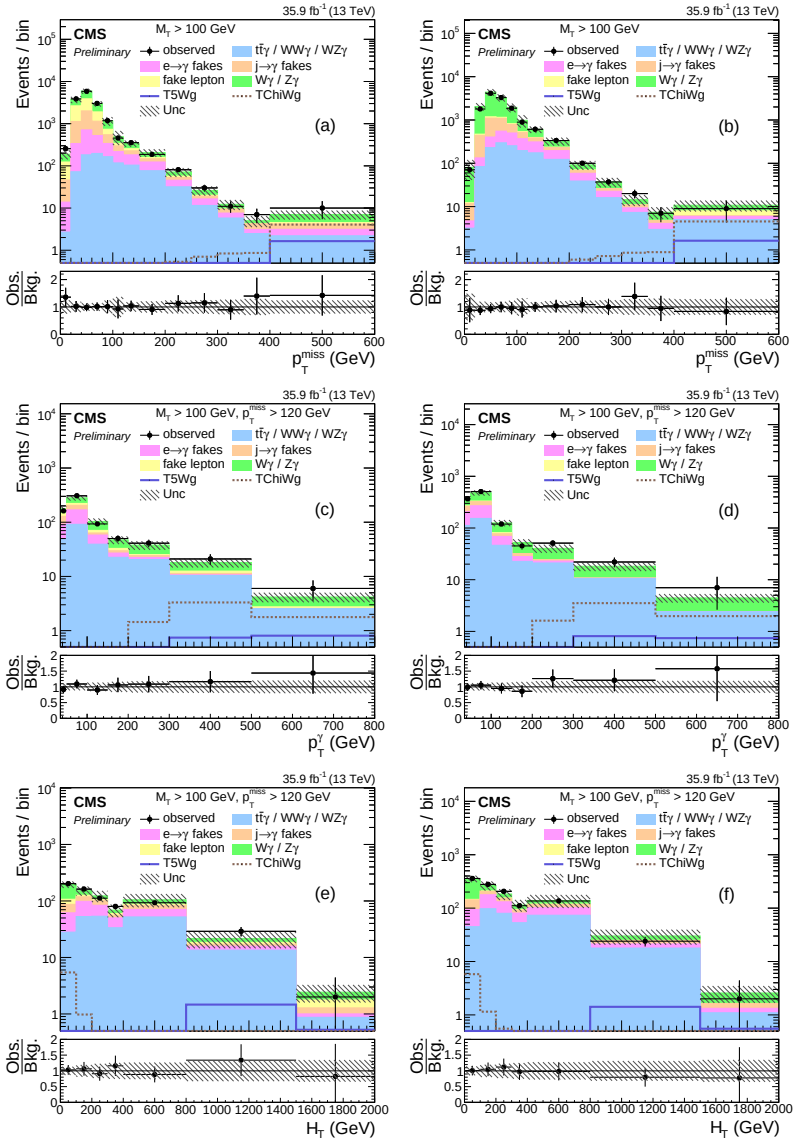
S_T^γ: >1300 GeV

	Yield	σ_{stat}	σ_{syst}
$V(\gamma)$	12.6	0.7	1.6
γ+jets	1.1	0.5	0.4
$t\bar{t}(\gamma)$	0.7	0.5	0.2
$e \to \gamma$	1.5	0.2	0.8
Diboson	1.7	1.7	0.5
Total	17.6	2.0	1.9
Data	24		

Fit electron channel SUS-17-012



Results SUS-17-012



Uncertainties SUS-17-012

Source of uncertainty	SUSY signal	$e \to \gamma$ fakes	jet$\to \gamma$ fakes	jet$\to \ell$ fakes	$V + \gamma$	rare EWK
Jet energy scale	$0 - 10$	–	–	–	$0 - 15.6$	$0 - 22.5$
Jet energy resolution	$0 - 10$	–	–	–	$0 - 13.6$	$0 - 23$
ID and trigger efficiency	4	–	–	–	$1.4 - 6.5$	$1.3 - 6.5$
Cross section	$4.3 - 36.8$	–	–	–	–	50
e-faking-photon shape	–	$8.0 - 50.5$	–	–	–	–
Jet-faking-photon shape	–	–	$8.1 - 56.1$	–	–	–
Fake-lepton shape	–	–	–	$0 - 42.4$	–	–
ISR corrections	–	–	–	–	$2.6 - 57.8$	–
Normalization scale	–	–	–	20	20	–
Pileup uncertainty	$2 - 10$	–	–	–	–	–
Integrated luminosity	2.6	–	–	–	–	2.6