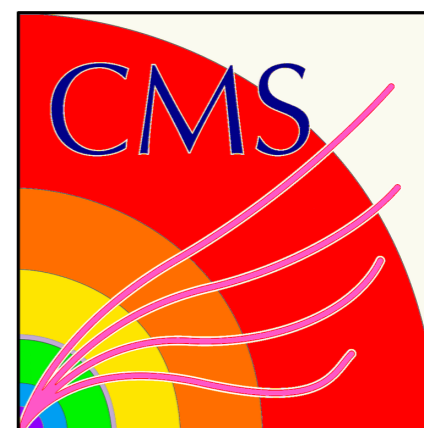


# Searches for new physics in CMS in events with jets, leptons, and photons in the final state

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Devin Mahon  
on behalf of the CMS Collaboration  
34<sup>th</sup> Rencontres de Blois  
18 May 2023



# Outline

- SUSY Search in 1 photon + jets +  $p_T^{\text{miss}}$  Events
- Stealth SUSY Search in 2 photon + jets Events
- Search for dark matter in  $W^+W^- + p_T^{\text{miss}}$  Events
- Low-mass Dimuon Resonance Search

Huge diversity within CMS in...  
phenomenologies  
motivating models  
advanced analysis techniques

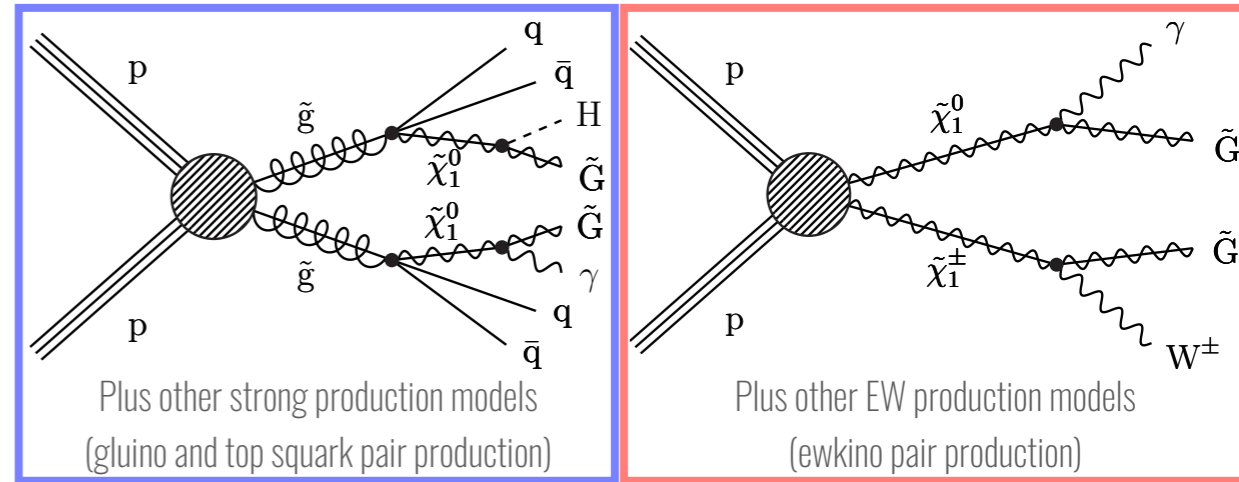


Many brand new Run 2 results  
and much more in the works!

See also Soham Bhattacharya's upcoming talk  
on CMS LLP & unconventional searches

# SUSY Search in 1 Photon + Jets + $p_T^{\text{miss}}$ Events: Strategy

- Targets both strong and electroweak (EW) SUSY production of neutralinos and charginos
  - Considers several models of squark- and gluino-mediated production
  - High  $N_{\text{jets}}$  final states with GMSB decay  $\tilde{\chi}_{1/2}^0 \rightarrow \gamma \tilde{G}$
- Analysis regions defined by  $p_T^{\text{miss}}$ , b/V/H-tag,  $N_{\text{jets}}$  bins
  - 37 SRs + 8 CRs optimized for strong and EW production, all orthogonal
- Data-driven background estimation using ABCD method or transfer factors (TFs)



**Baseline Selections**  
 $p_T^{\text{miss}} > 300 \text{ GeV}$   
 $N_{\text{jets}} \geq 2, N_\gamma \geq 1, N_l = 0$   
 $S_T (\sum_{j,\gamma} p_T) \geq 300 \text{ GeV}$

**Additional Strong Selections**  
No V- or H-tag

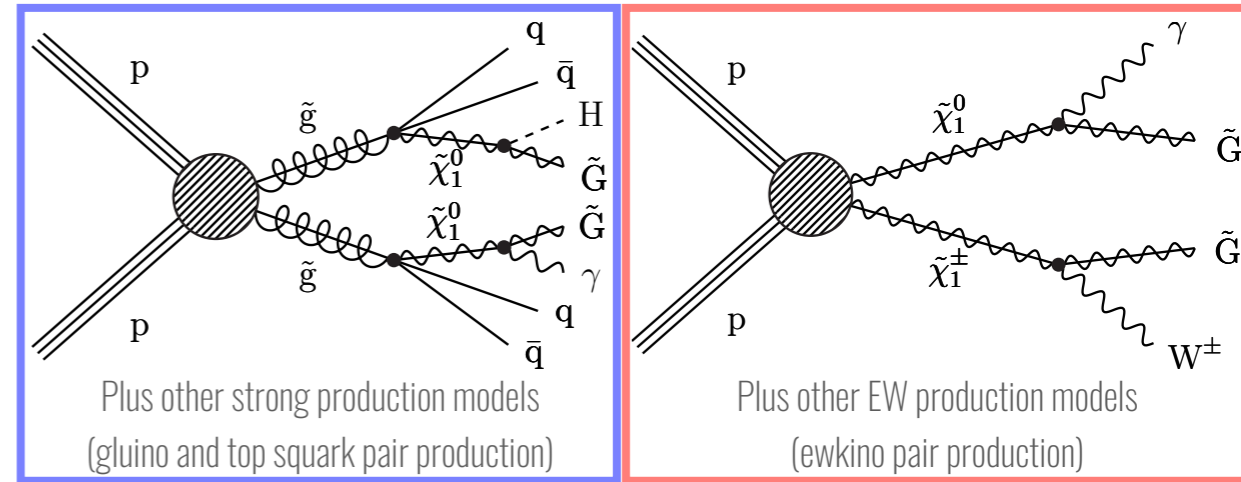
$N_{\text{jets}}^{\text{b-tags}}$	$N_{\geq 7}^0$	29	30	31	32	33		
	$N_{5-6}^0$	24	25	26	27	28		
	$N_{2-4}^0$	19	20	21	22	23		
	$N_{\geq 7}^0$	14	15	16	17	18		
	$N_{5-6}^0$	8	9	10	11	12	13	
	$N_{2-4}^0$	1	2	3	4	5	6	7
		200	300	370	450	600	750	900
		$p_T^{\text{miss}}$ (GeV)						

**Additional EW Selections**  
 $2 \leq N_{\text{jets}} < 6$   
 V- or H-tag

H-tag	40	41	42	43	44	45
V-tag	34	35	36	37	38	39
	200	300	370	450	600	750
	$p_T^{\text{miss}}$ (GeV)					

# SUSY Search in 1 Photon + Jets + $p_T^{\text{miss}}$ Events: Strategy

- Targets both strong and electroweak (EW) SUSY production of neutralinos and charginos
  - Considers several models of squark- and gluino-mediated production
  - High  $N_{\text{jets}}$  final states with GMSB decay  $\tilde{\chi}_{1/2}^0 \rightarrow \gamma \tilde{G}$
- Analysis regions defined by  $p_T^{\text{miss}}$ , b/V/H-tag,  $N_{\text{jets}}$  bins
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**Baseline Selections**

$p_T^{\text{miss}} > 300 \text{ GeV}$

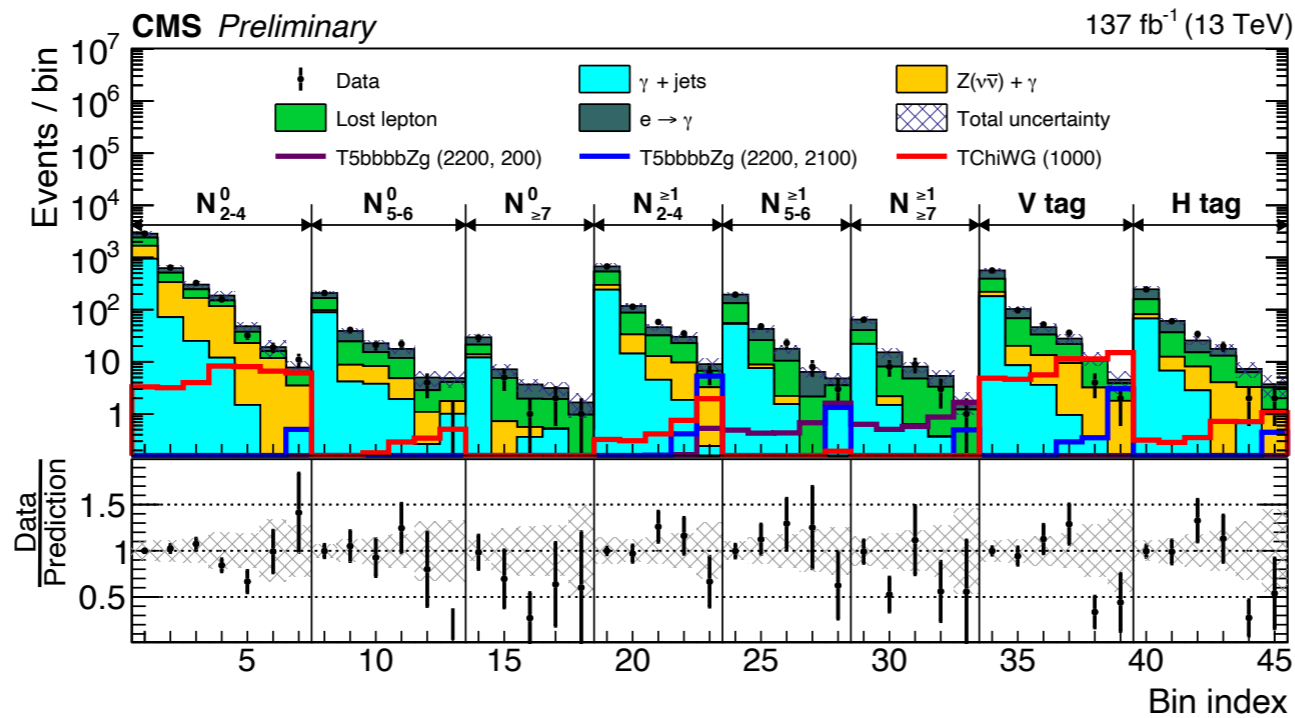
$N_{\text{jets}} \geq 2, N_\gamma \geq 1, N_l = 0$

$S_T (\sum_{j,\gamma} p_T) \geq 300 \text{ GeV}$

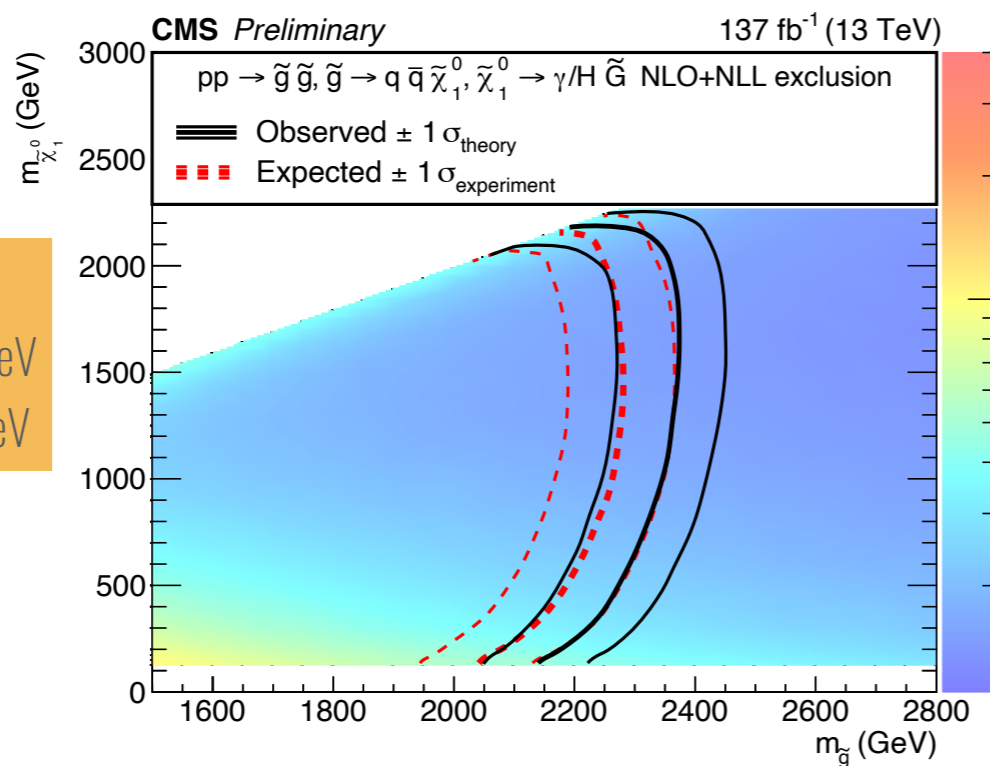
## Major Backgrounds

	$W\gamma + \text{jets}$ $t\bar{t}\gamma + \text{jets}$	$W + \text{jets}$ $t\bar{t} + \text{jets}$	$Z(\nu\nu)\gamma + \text{jets}$	$\gamma + \text{jets}$ QCD multijet
Process				
Phenomenology	decay where lepton is "lost"	electron mid-ID'd as photon	irreducible	$p_T^{\text{miss}}$ from mismeasurement jet mid-ID'd as photon (QCD)
Estimation Method	TF from 1 $l$ CRs	TF from 1 $e, 0\gamma$ CRs	TF from Z(11) $\gamma$ CRs	ABCD method: $\Delta\phi(j, p_T^{\text{miss}})$ vs. $p_T^{\text{miss}}$

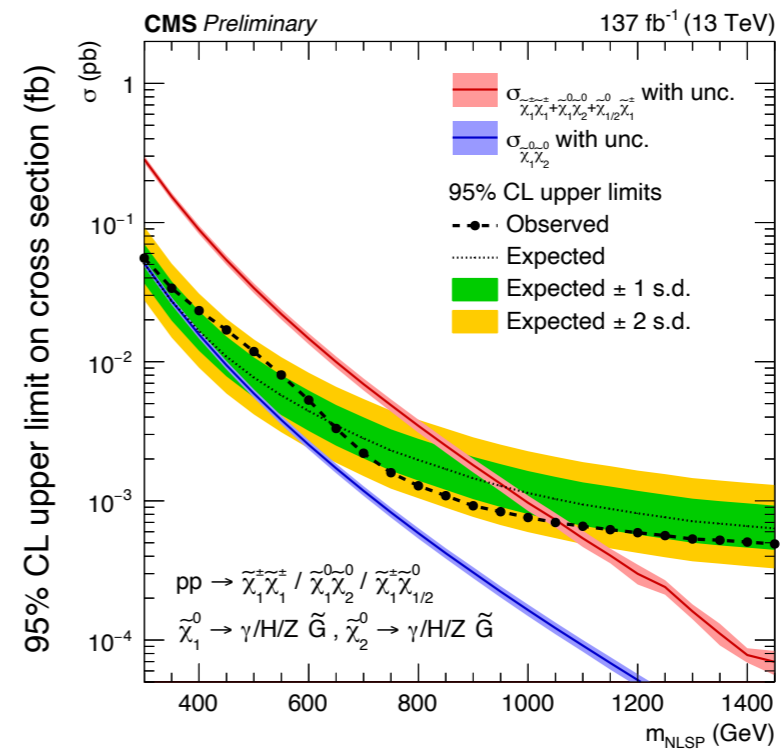
# SUSY Search in 1 Photon + Jets + $p_T^{\text{miss}}$ Events: Results



No excess observed



**Strong Production**  
 $g\tilde{g}$  excluded up to 2.35 TeV  
 $\tilde{\tau}$  excluded up to 1.43 TeV



**EW Production**  
 Wino-like ewkinos excluded up to 1.30 TeV  
 Higgsino-like ewkinos excluded up to 1.05 TeV

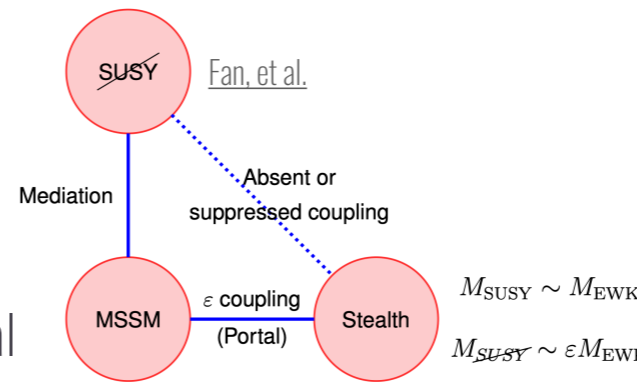
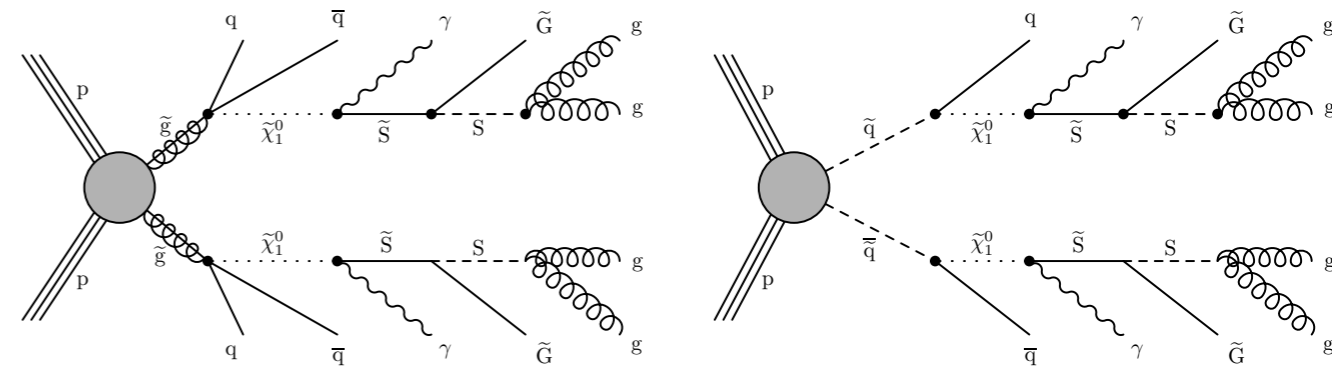
# SUSY Search in 2 Photon + Jets Events: Strategy

## Stealth SUSY:

- Stealth sector of light particles coupled to MSSM with absent/weak couplings to SUSY breaking sector
- Hidden sector singlino  $\tilde{S}$  decays to nearly mass degenerate scalar singlet  $S$  and light LSP  $\tilde{G}$  (carries away little  $p_T^{\text{miss}}$ )
- Strong production decaying via ewkinos yields 2 photons, high  $N_{\text{jets}}$

## Data-driven background estimation:

- Dominant background: QCD multijet with 2 photons in initial scatter
- Relies on invariance of  $S_T$  after jet fragmentation above a threshold to make  $S_T$  shape independent of  $N_{\text{jets}}$
- $S_T$  shape derived from  $N_{\text{jets}} = 2$  sideband, normalization from  $1200 \leq S_T \leq 1300$  GeV sideband
  - Modeled using adaptive Gaussian kernel (AGK)
  - MC-based correction to shape for selection efficiency biases
- Fits performed in  $N_{\text{jets}}$  bins (4, 5,  $\geq 6$ )



**Event Selections**

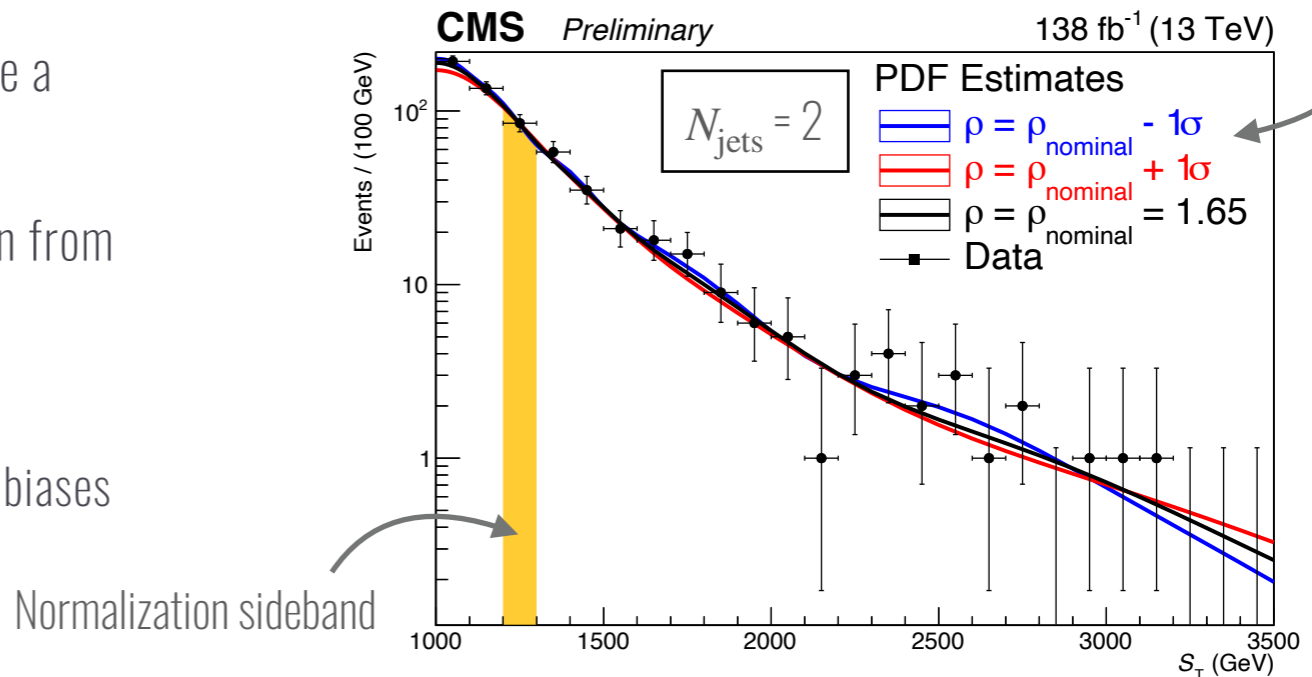
$N_{\text{jets}} \geq 4$

$N_\gamma = 2, m_{\gamma\gamma} > 90$  GeV

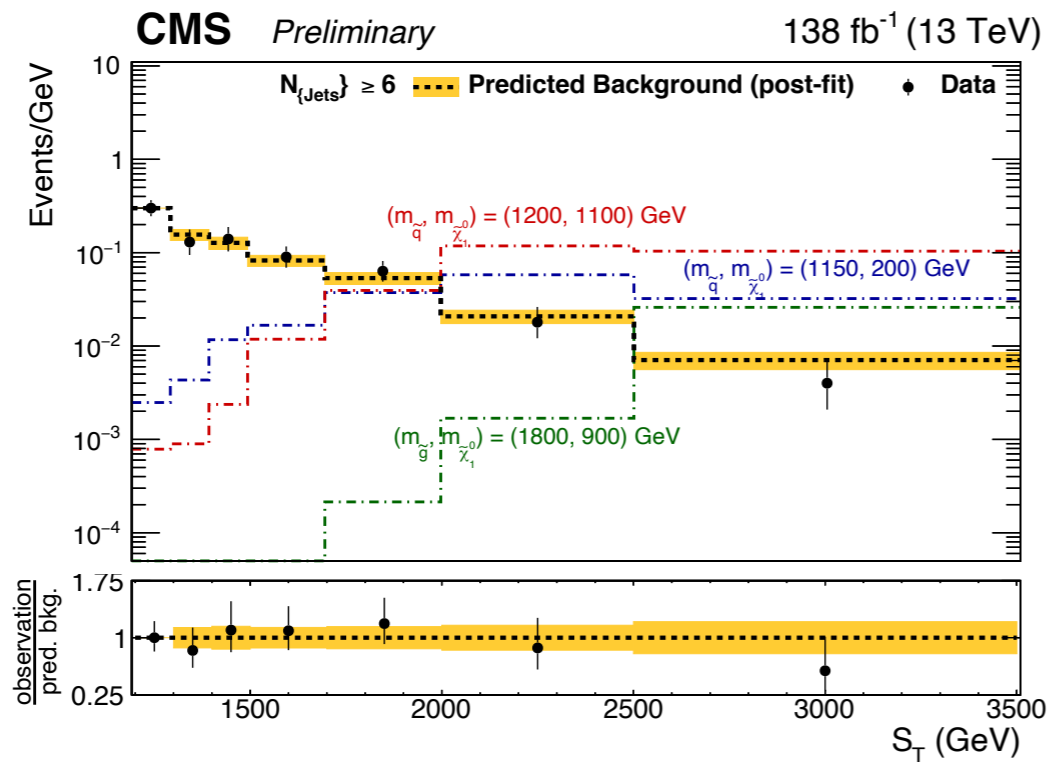
$S_T (\sum_{j,\gamma} p_T^{\text{miss}}) \geq 1300$  GeV

No  $p_T^{\text{miss}}$  requirement

Kernel bandwidth parameter  $\rho$

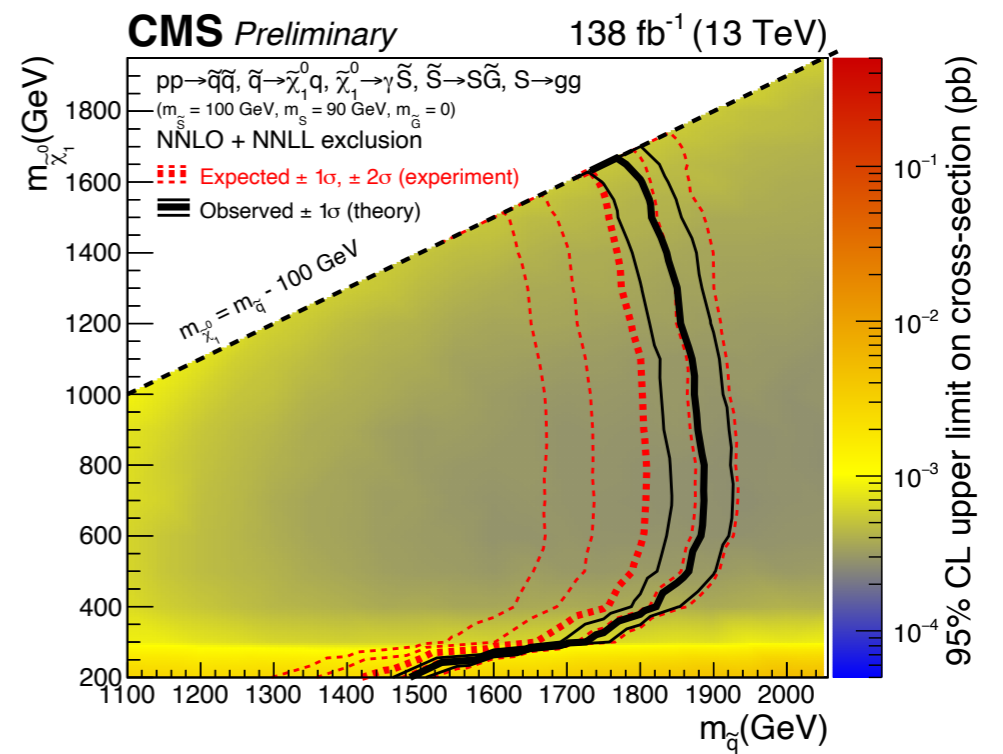
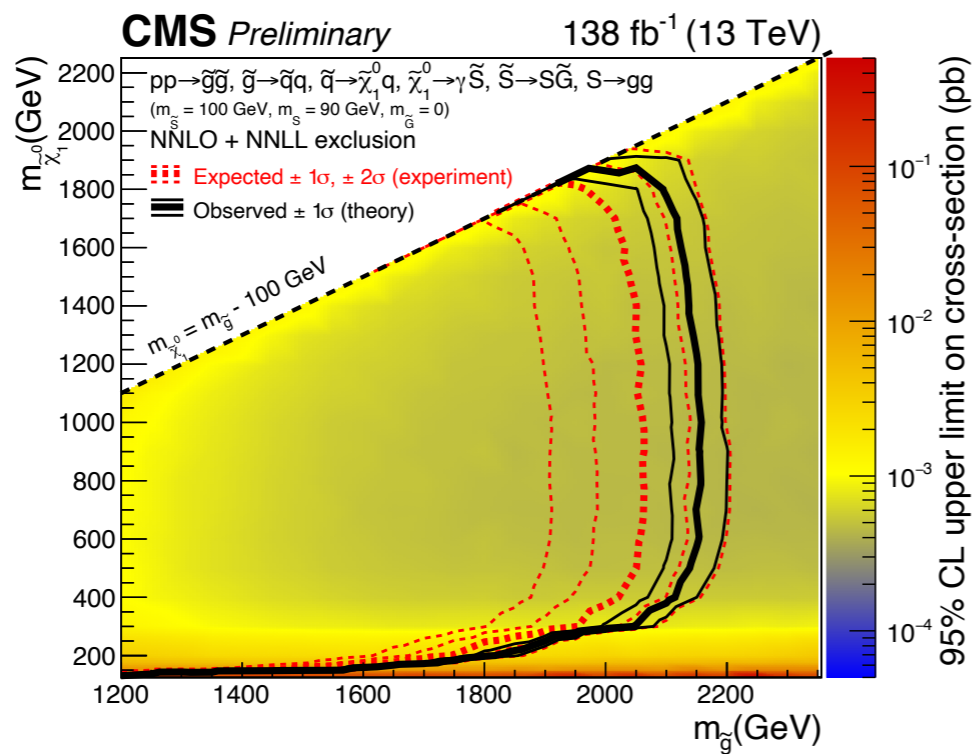


# SUSY Search in 2 Photon + Jets Events: Results



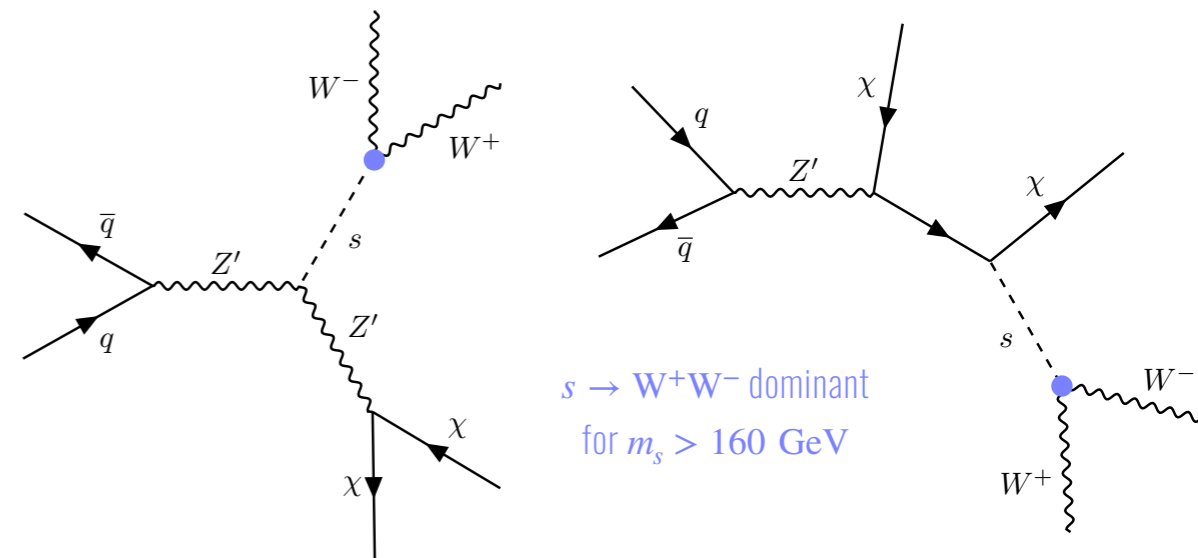
No excess observed

$\tilde{g}$  excluded up to 2.15 TeV  
 $\tilde{q}$  excluded up to 1.85 TeV  
 Strongest available limits for these models



# Dark Matter Search in $W^+W^- + p_T^{\text{miss}}$ Events: Strategy

- Dark Higgs model with new U(1) gauge symmetry:
  - Higgs singlet  $s$
  - Majorana dark matter (DM) particle  $\chi$ , whose mass can be generated via Higgs mechanism
  - Massive spin-1 vector boson mediator  $Z'$
  - $s$  can be lighter than  $\chi$ 
    - New annihilation channels accessible
    - DM freeze-out relic abundance can readily match observations



- Two final state channels based on  $W^+W^-$  decays:
  - Di-leptonic: 2D profiled fit to  $m_T(l_2, p_T^{\text{miss}})$  and  $m_{ll}$
  - Semi-leptonic: 1D binned fit of BDT score, based on lepton and  $p_T^{\text{miss}}$  kinematic variables

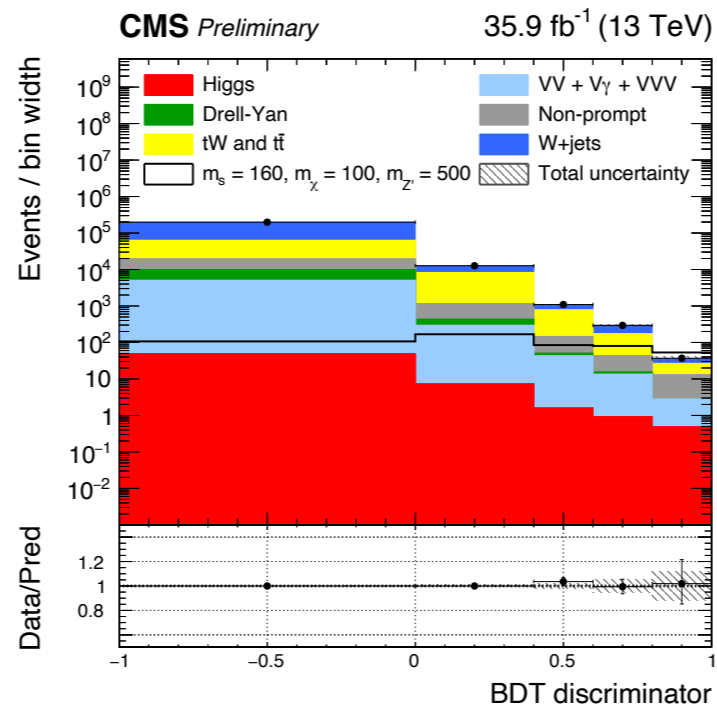
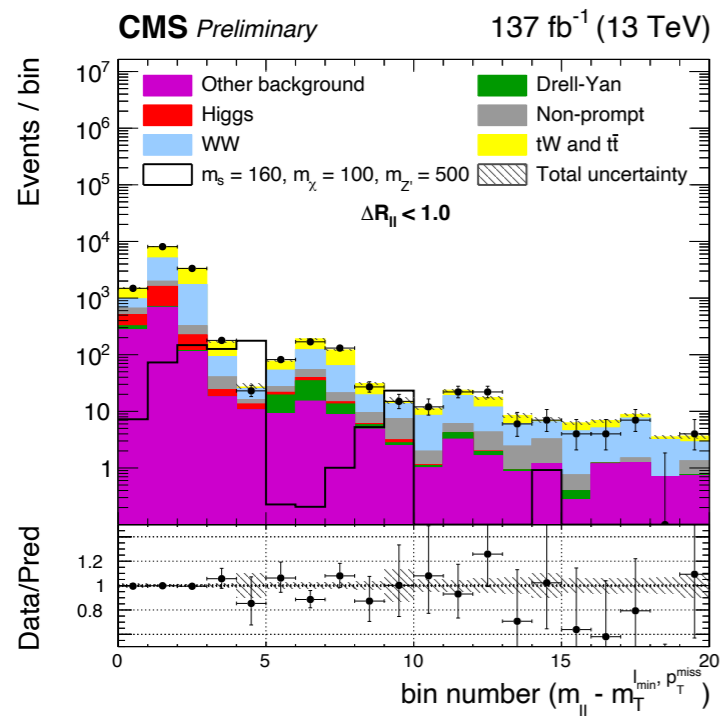
- Backgrounds modeled by MC, normalizations from independent data CRs

- Main di-leptonic bkg:  $tW$ ,  $t\bar{t}$ ,  $W^+W^-$ , and Drell-Yan
- Main semi-leptonic bkg:  $tW$ ,  $t\bar{t}$ , and  $W + \text{jets}$

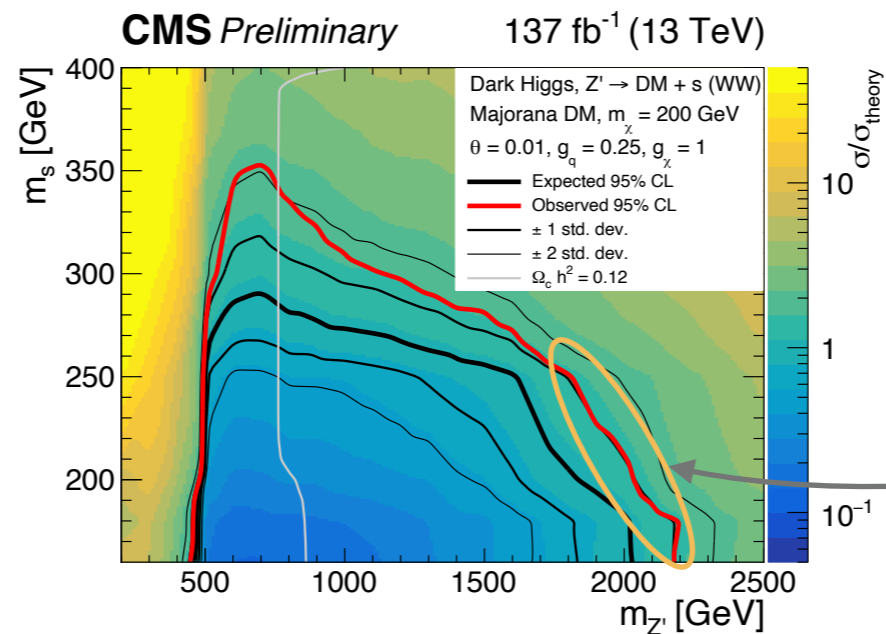
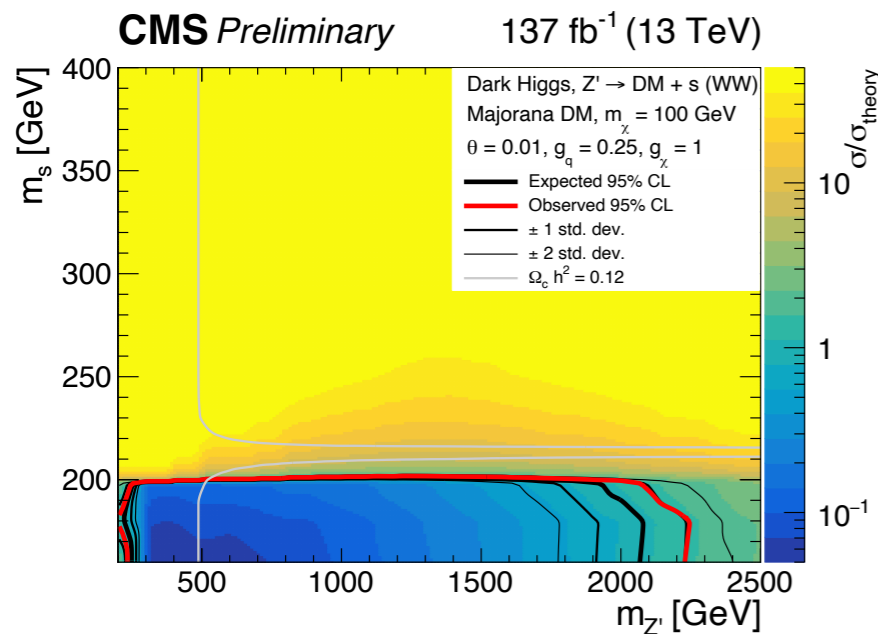
	Di-leptonic Channel	Semi-leptonic Channel
$N_l / N_j$	$N_l = 2$	$N_l = 1, N_j = 2$
Lepton Flavor	$e\mu, \mu e$	$e/\mu$
Lepton Charge	Opposite	N/A
$p_T^{\text{miss}}$	$>20$ GeV	$>60$ GeV
b-tagged jets	0	0 (from non W candidate)
Angular cuts	$\Delta R_{ll} < 2.5$	$\Delta R_{l,jj} < 3$ $\Delta \phi_{l,jj} < 1.8$
	3 SRs by dark Higgs boost: $\Delta R_{ll} = 0-1$ (high), 1-1.5 (medium), 1.5-2.5 (low)	$\Delta R_{l,p_T^{\text{miss}}} > 2$



# Dark Matter Search in $W^+W^- + p_T^{\text{miss}}$ Events: Results



No excess observed

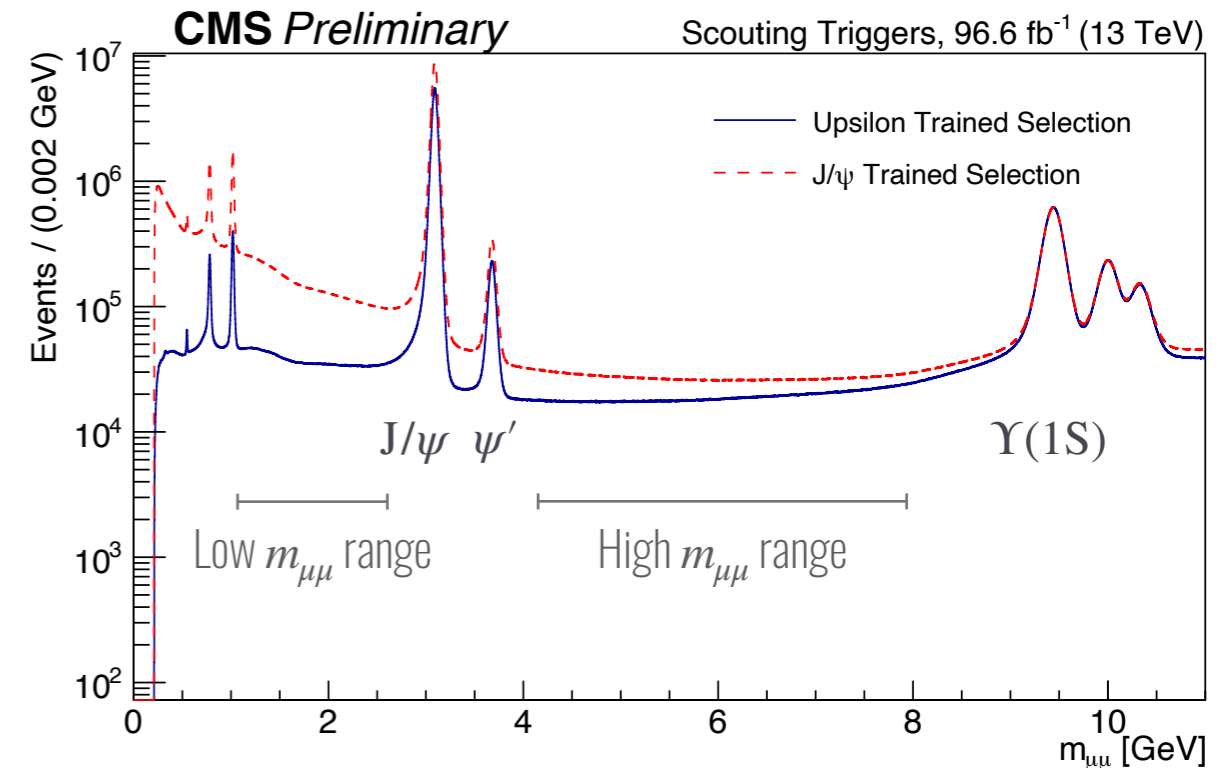
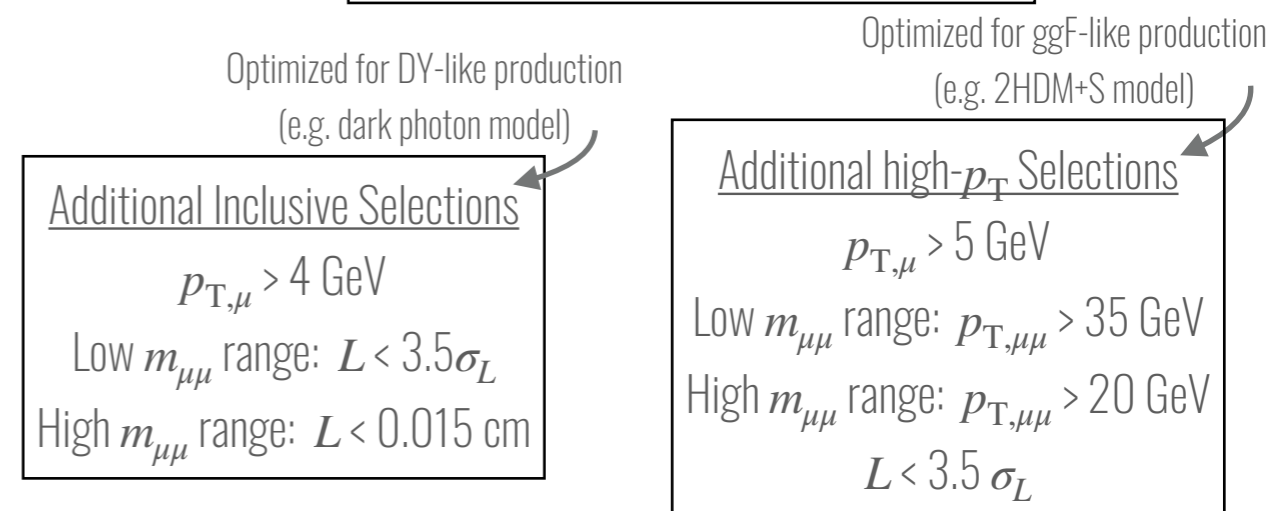


First CMS limits on dark Higgs to  $W^+W^-$   
Extends range of  $m_{\text{DM}}$  in available searches to  
100-300 GeV  
Extends limits on  $m_{Z'}$  for  $m_{\text{DM}} = 200$  GeV

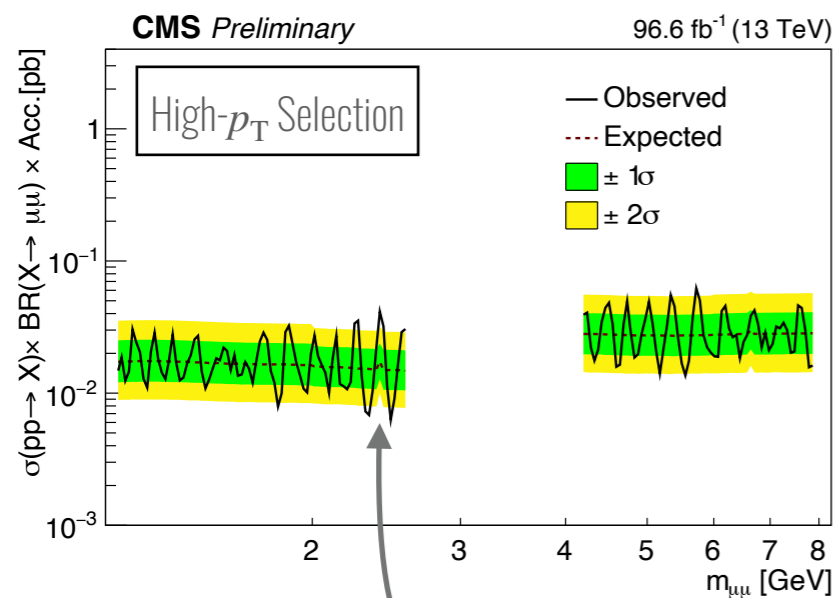
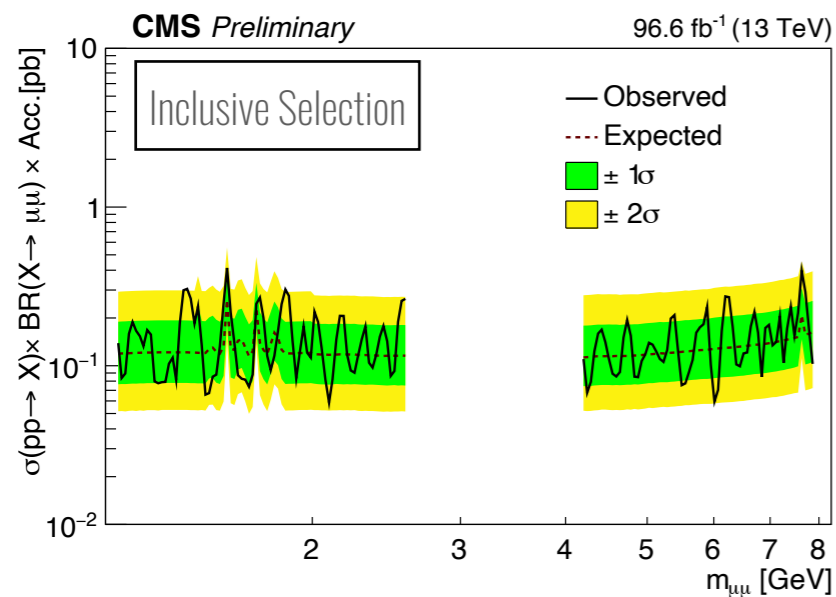
# Low-Mass Dimuon Resonance Search: Strategy

- Search for light BSM mediator with dimuon decay
  - Two motivating models:
    - Dark photon  $Z_D$  with kinetic mixing  $\epsilon$
    - Two-Higgs-doublet model + complex scalar singlet (2HDM+S)
  - Narrow-resonance from primary vertex (PV) in 2 discrete  $m_{\mu\mu}$  ranges: 1.1-2.6 GeV (low) and 4.2-7.9 GeV (high)
    - Excludes  $J/\psi$ ,  $\psi'$ ,  $\Upsilon(1S)$  resonances
- Using data scouting: reduced event information, lower trigger thresholds
  - Scouting trigger: 2 muons with  $p_T > 3$  GeV
- Dedicated muon ID using two BDTs
  - Trained with  $J/\psi$  and  $\Upsilon(1S)$  samples
- Component added to bkg fit for  $D \rightarrow KK(K\pi)$  decays that are ID'd as dimuon pairs with resonances at 1.58 (1.72) GeV
  - Using MC, get PDF and transfer factor from high- $\sigma_L$  CR to SR
- Fit to  $m_{\mu\mu}$  spectrum in windows  $\pm 5x$  detector resolution ( $\approx 1.3\%$ )

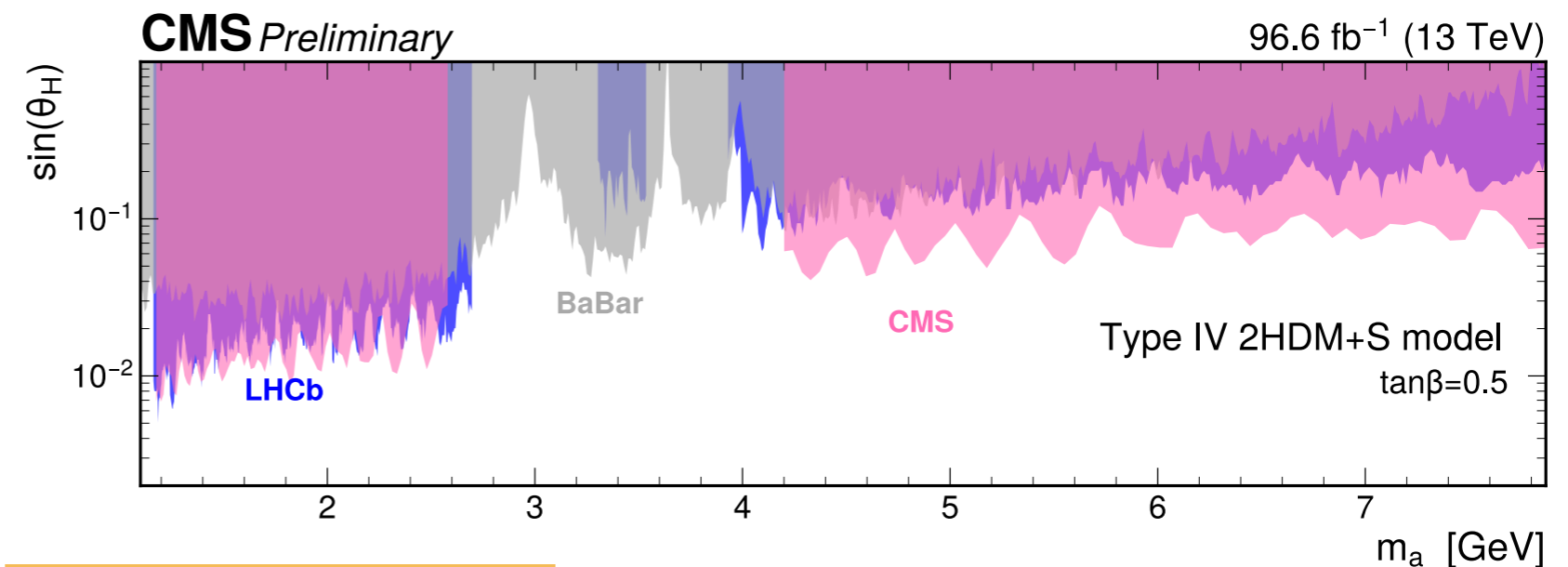
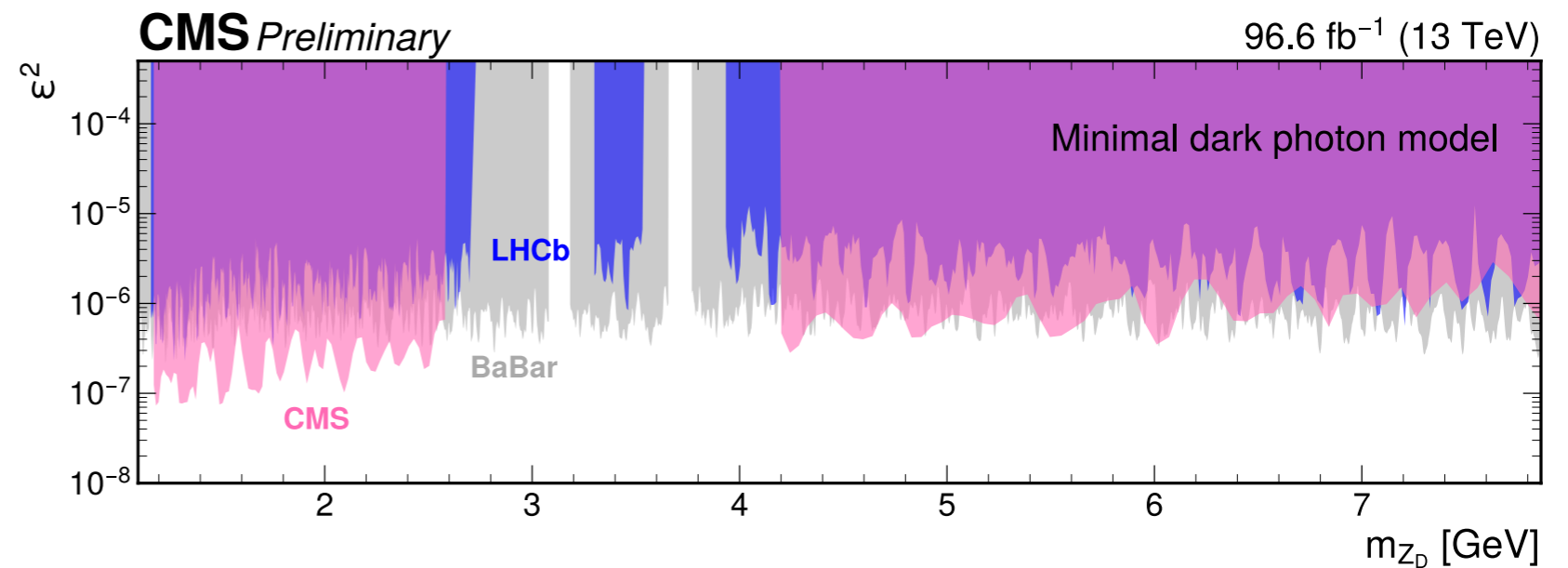
**Baseline Selections**  
 Two oppositely-charge muons,  $|\eta_\mu| < 1.9$   
 $L < 0.2$  cm ( $|\vec{P}\vec{V}_T - \vec{B}\vec{e}\vec{a}\vec{m}\vec{S}\vec{p}\vec{o}\vec{t}_T|$ )



# Low-Mass Dimuon Resonance Search: Results



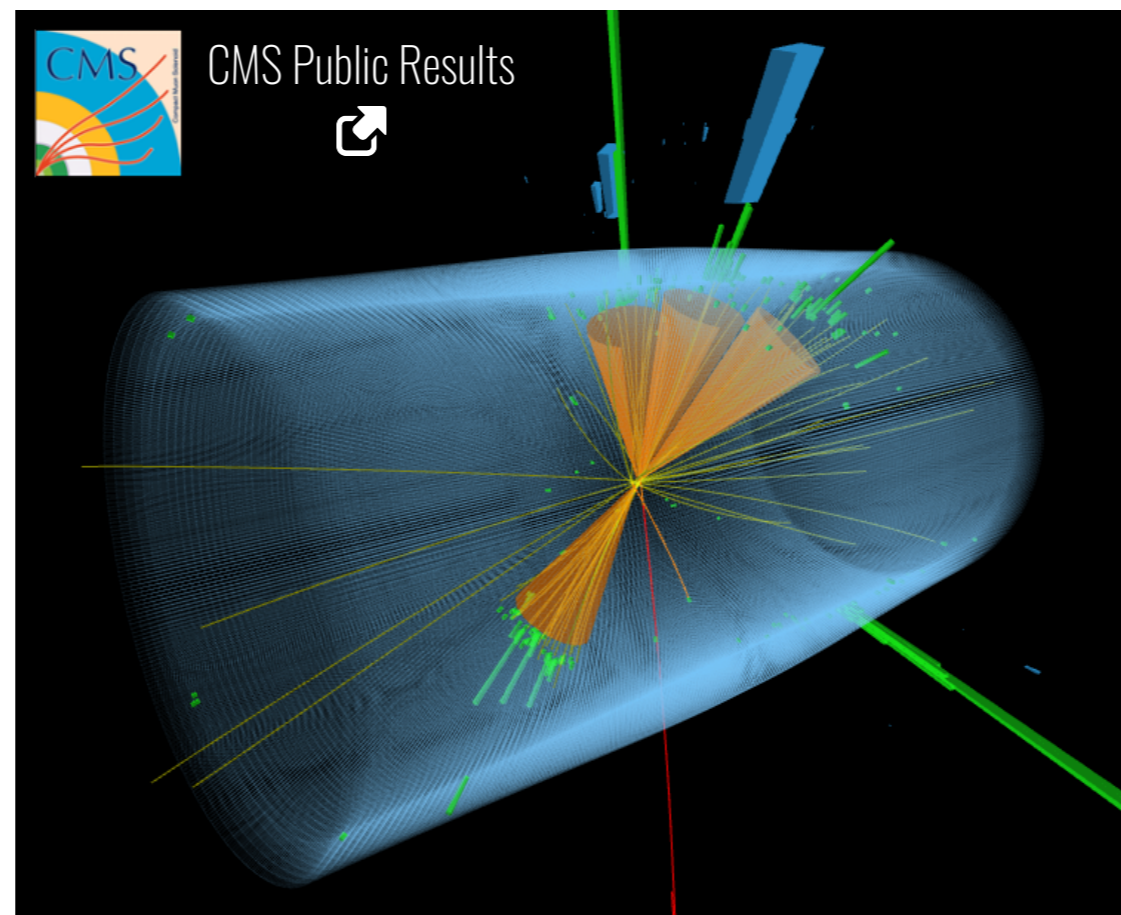
Largest excess at 2.41 GeV  
3.2σ local, 1.3σ global



LHCb observes excess at 2.42 GeV  
in comparable X + b search  
3.1σ local, <1σ global

# Conclusions

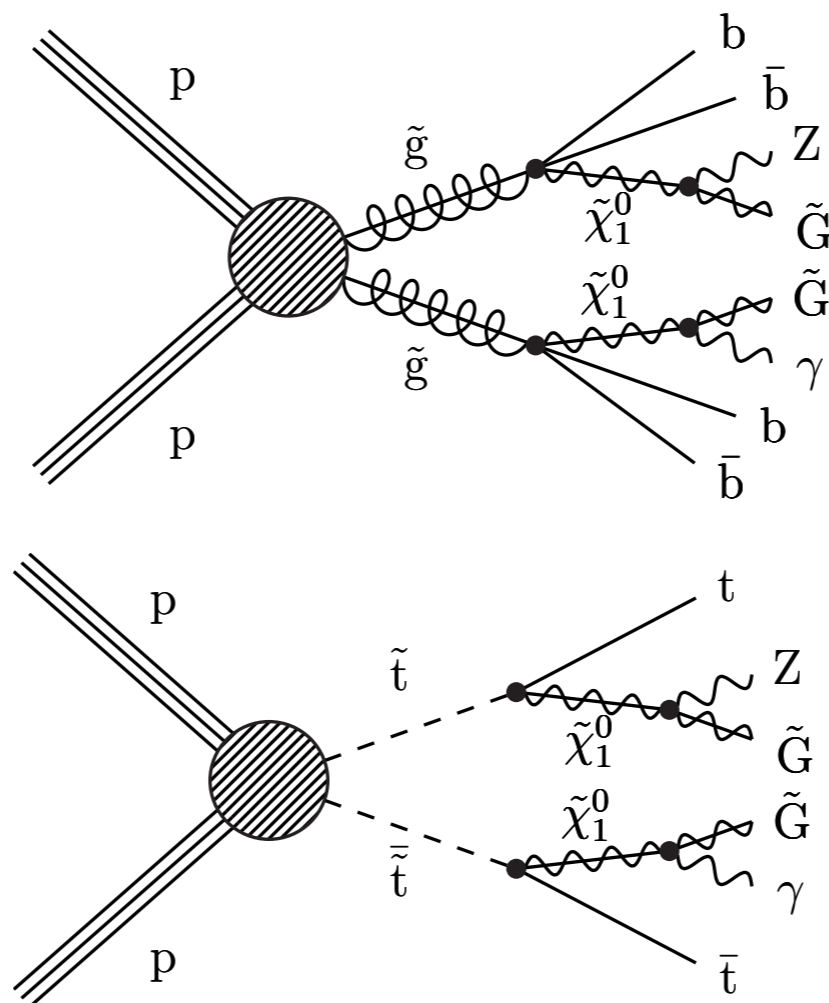
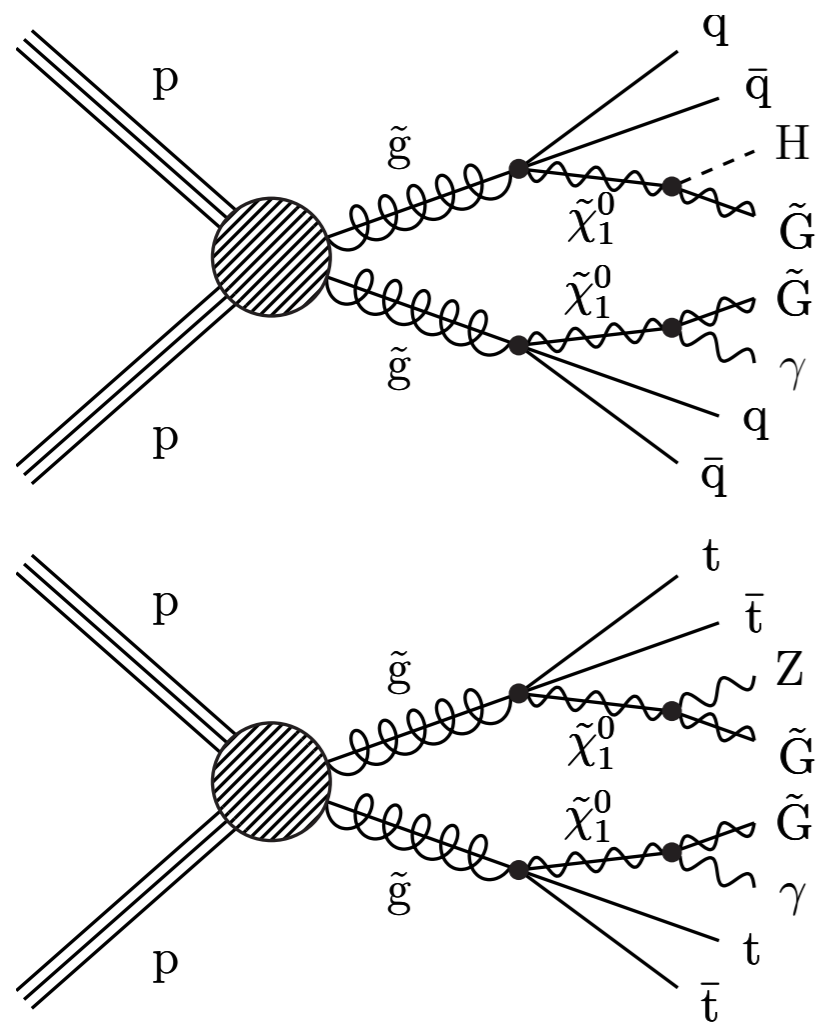
- Highlighted a sampling of recent CMS searches with jets, leptons, and photons
  - Wide variety of signatures, models, and advanced techniques
  - All push the boundaries of explored phase space
- Many more results—including Run 3 searches—to come, stay tuned!



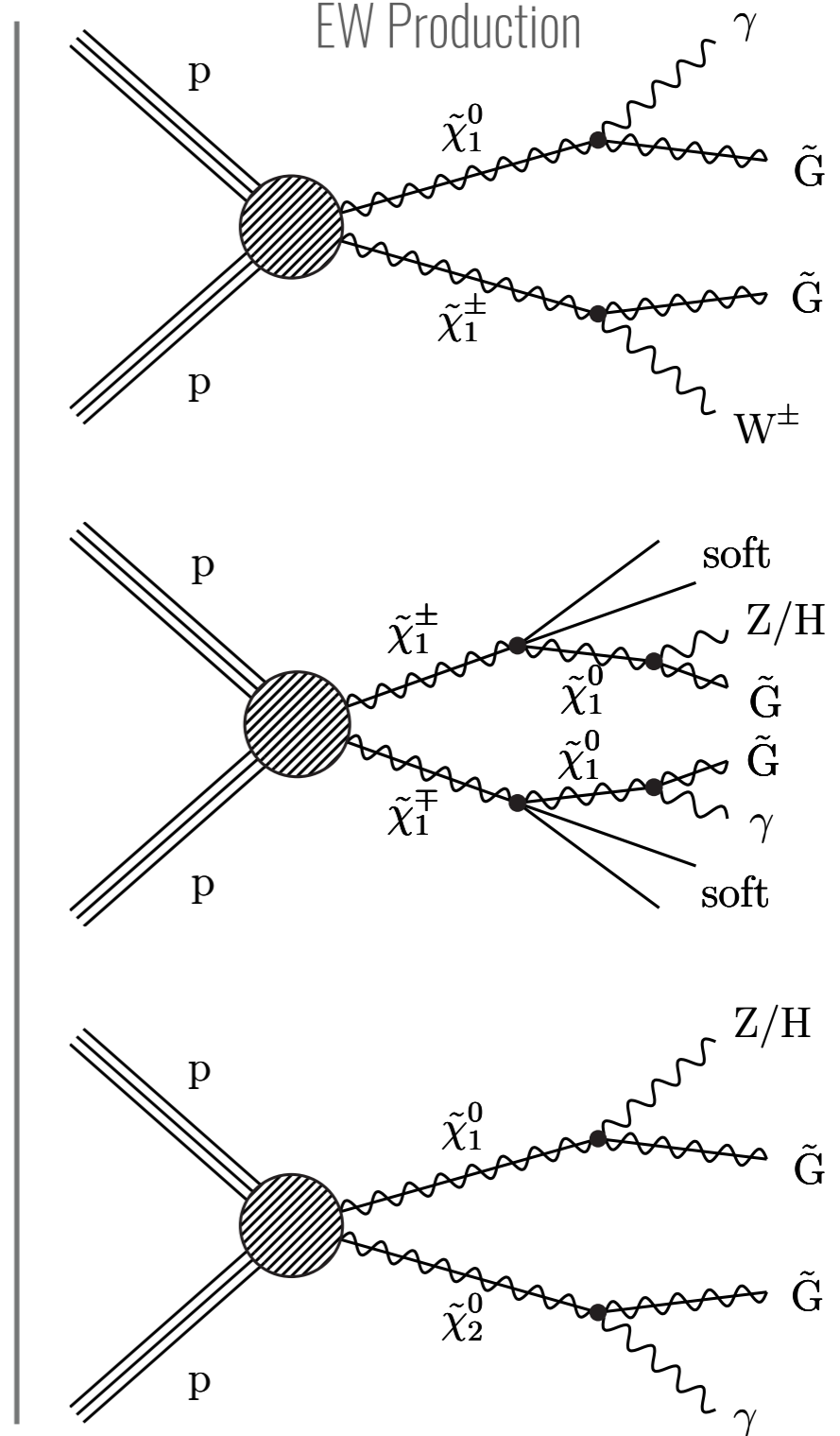
Backup

# SUSY Search in 1 Photon + Jets + $p_T^{\text{miss}}$ Events: Models

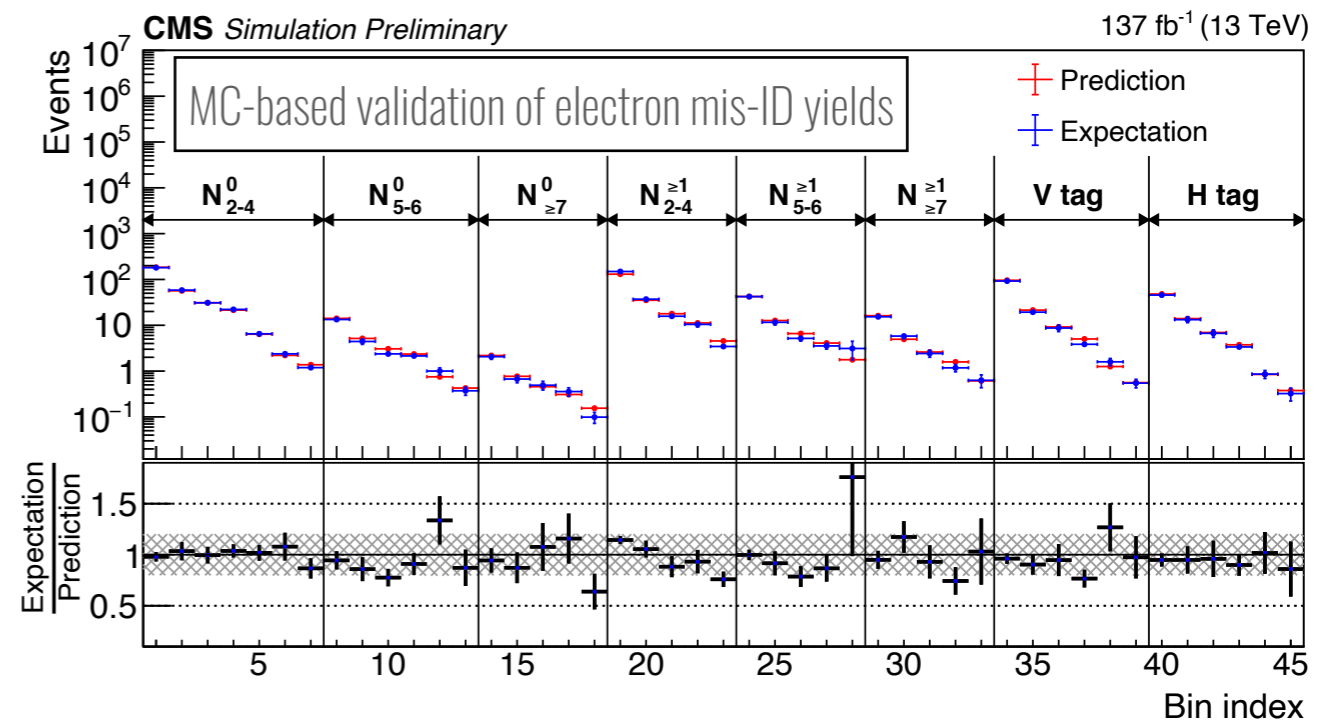
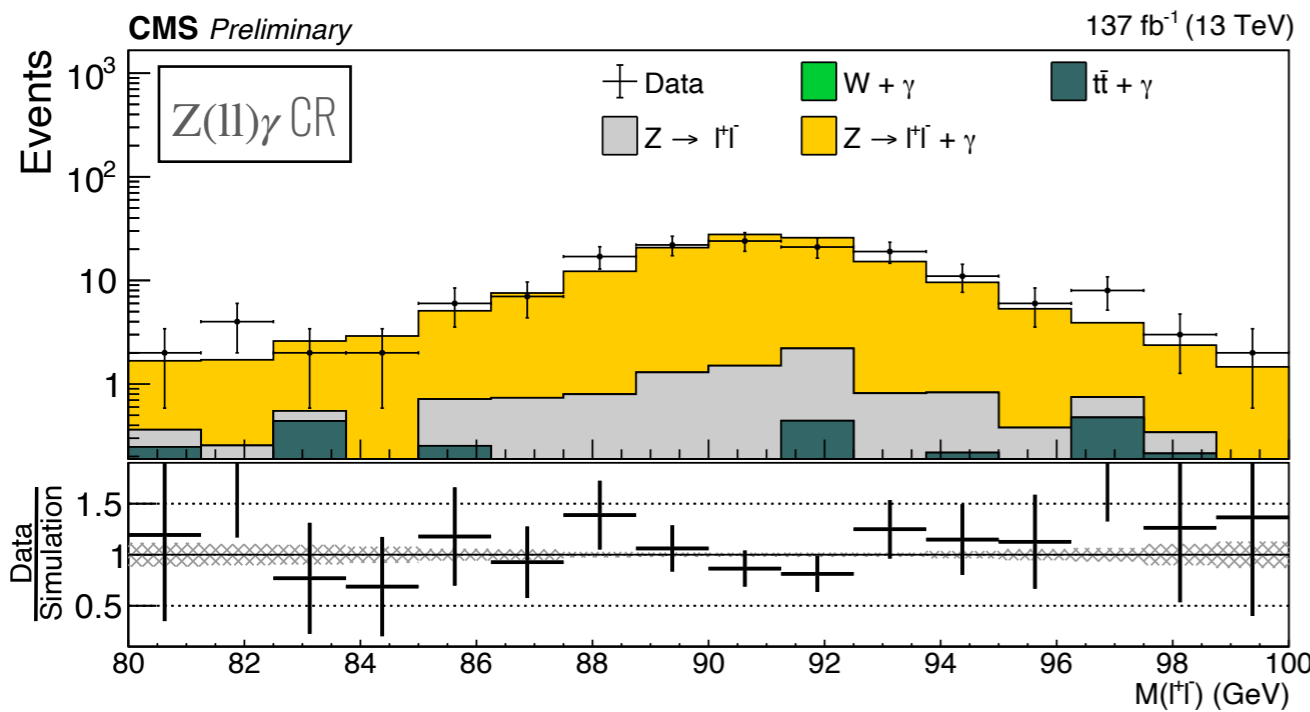
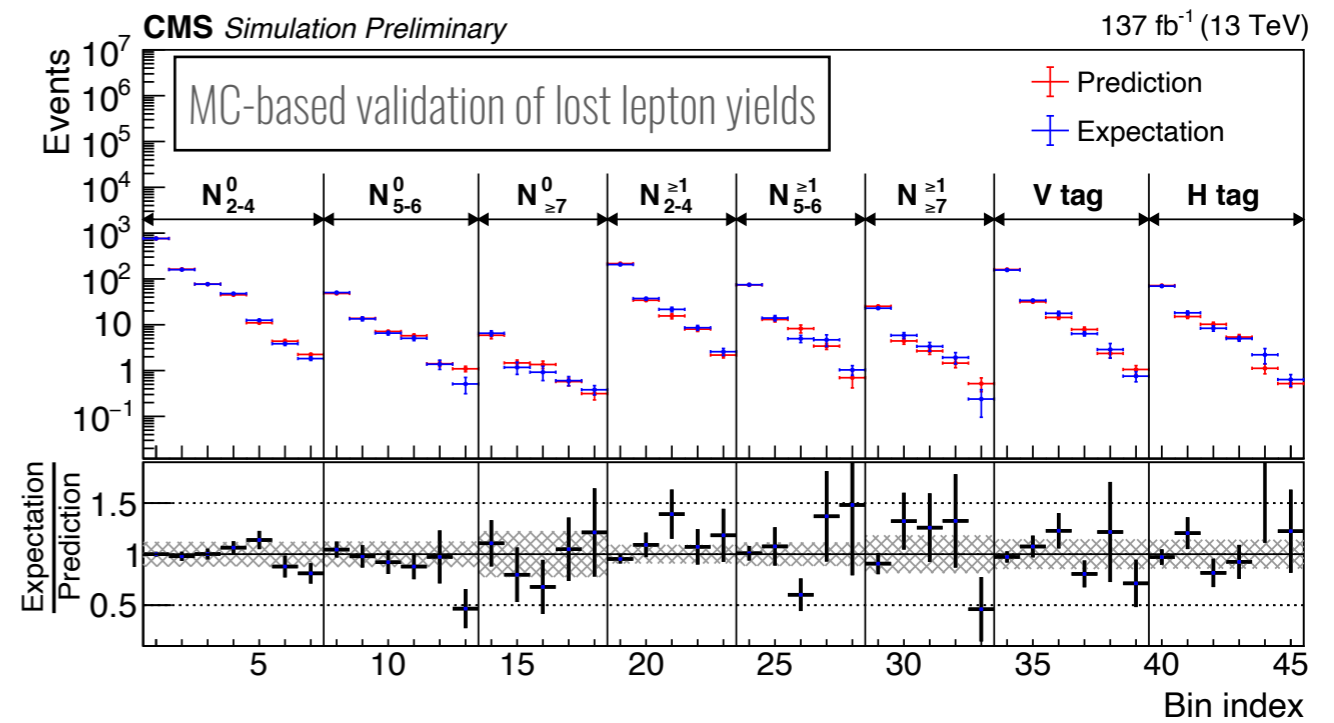
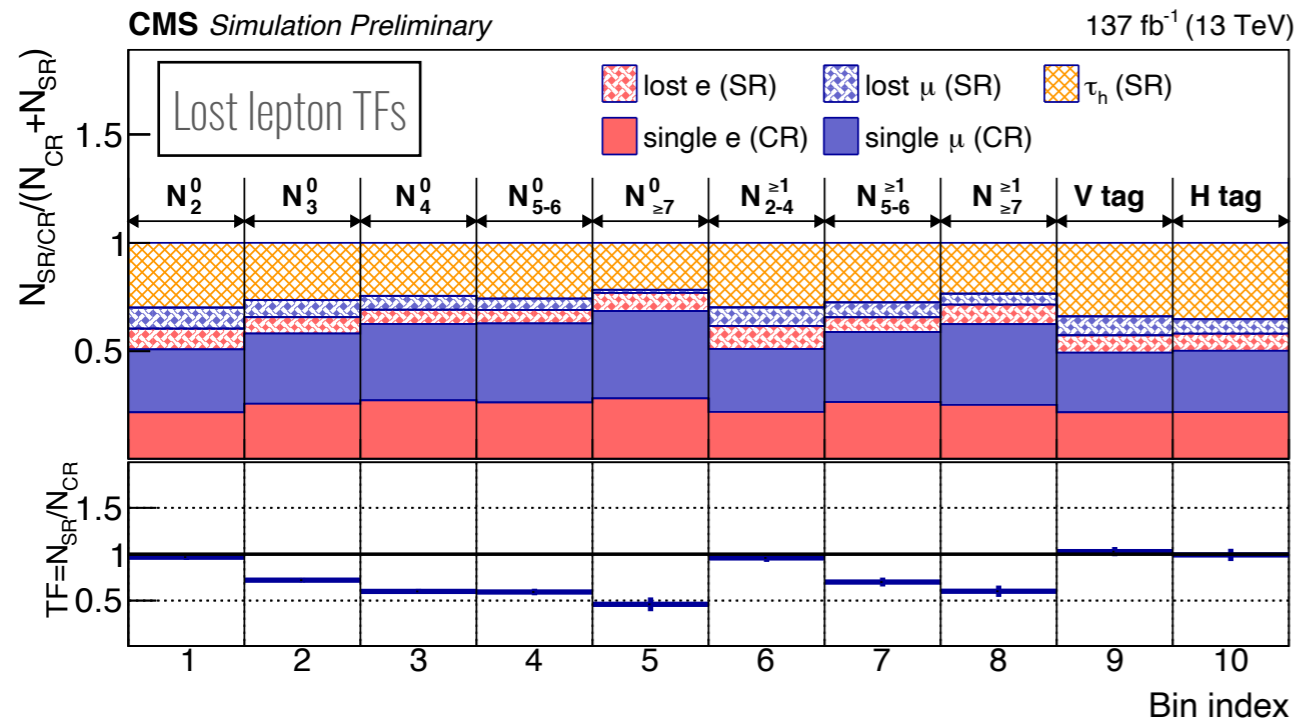
Strong Production



EW Production



# SUSY Search in 1 Photon + Jets + $p_T^{\text{miss}}$ Events: CRs & TFs



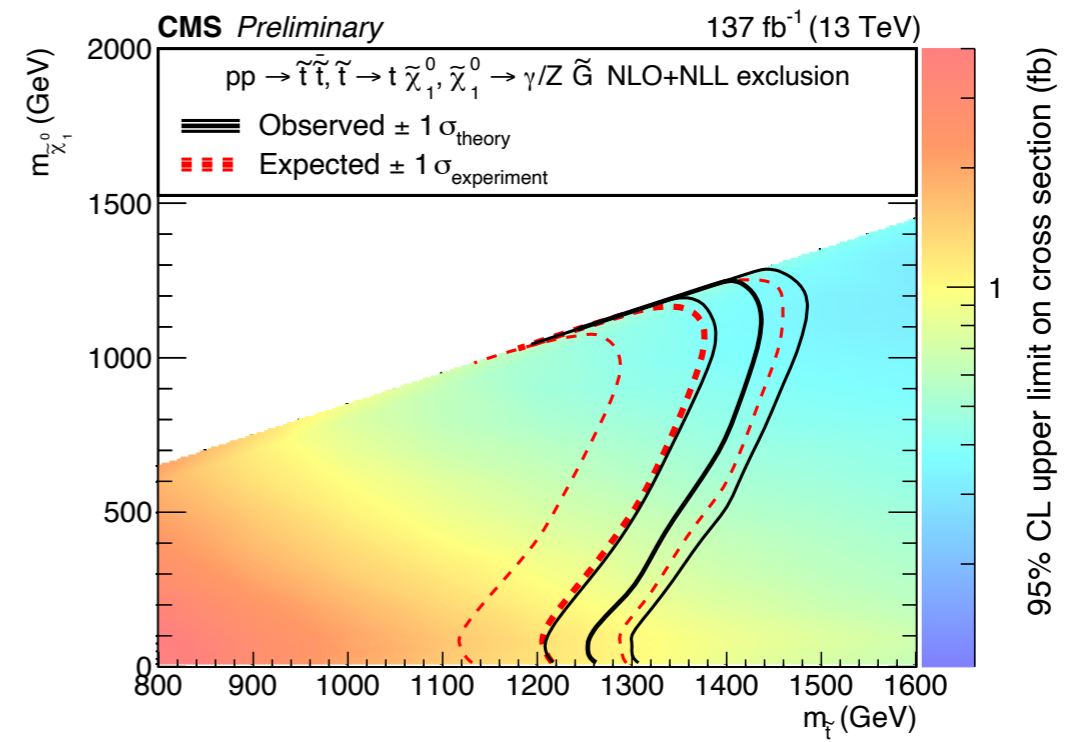
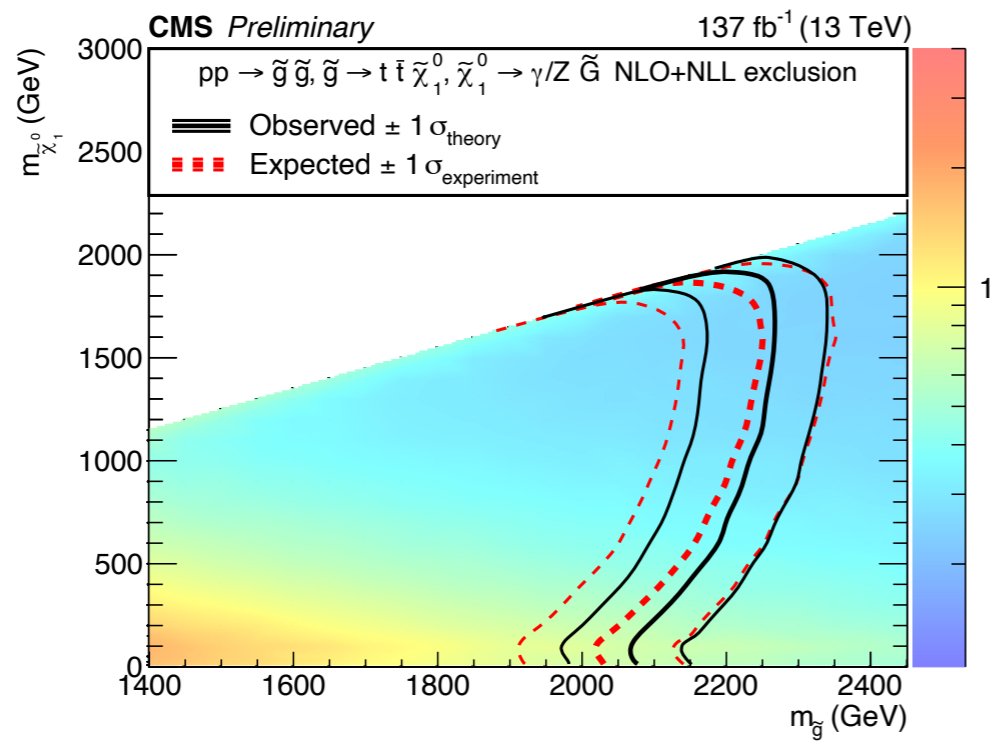
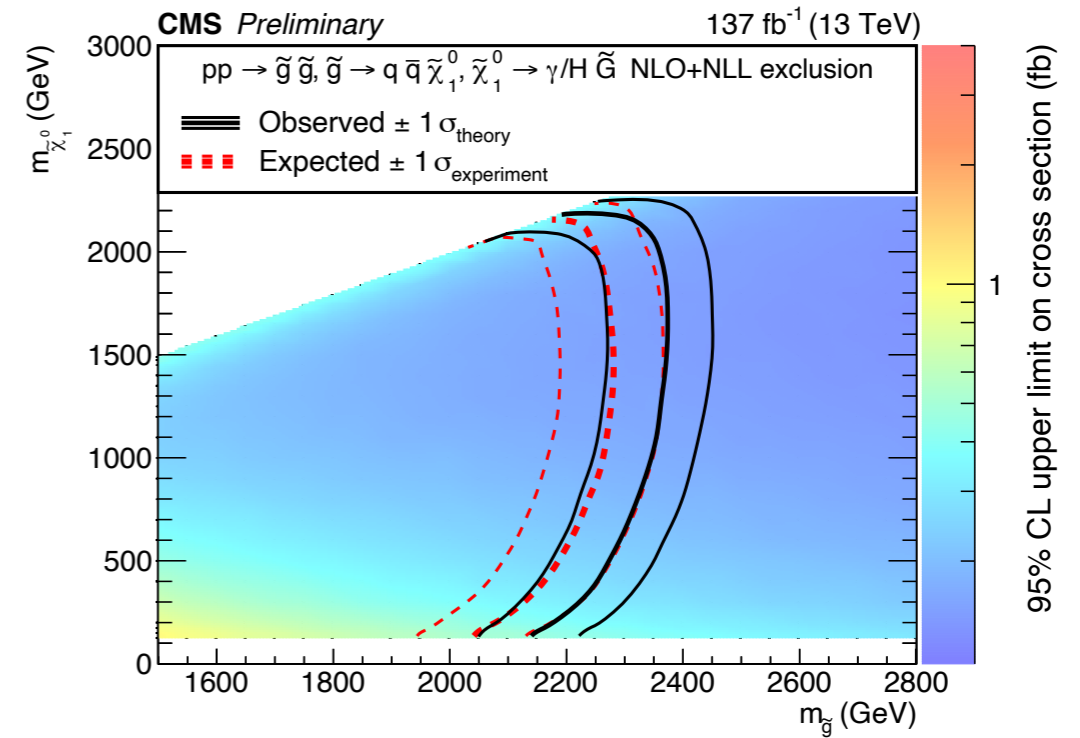
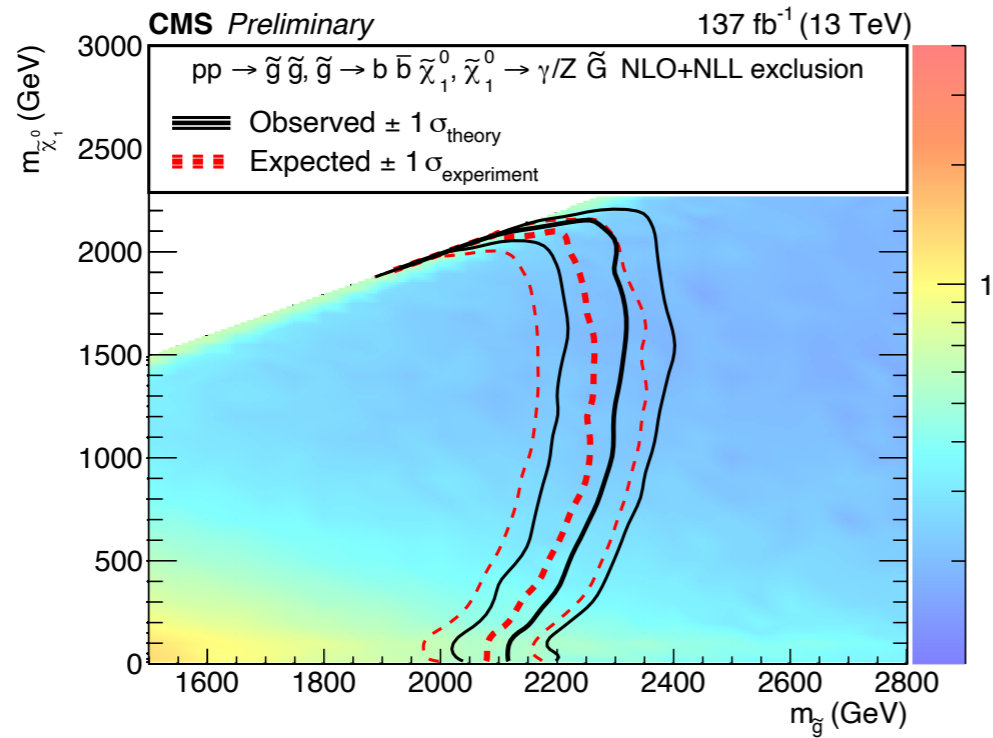
# SUSY Search in 1 Photon + Jets + $p_T^{\text{miss}}$ Events: Systematics

Table 2: The systematic uncertainties in the predicted background and signal event yields (in %). A dash (—) indicates that the source of uncertainty is not applicable or negligible.

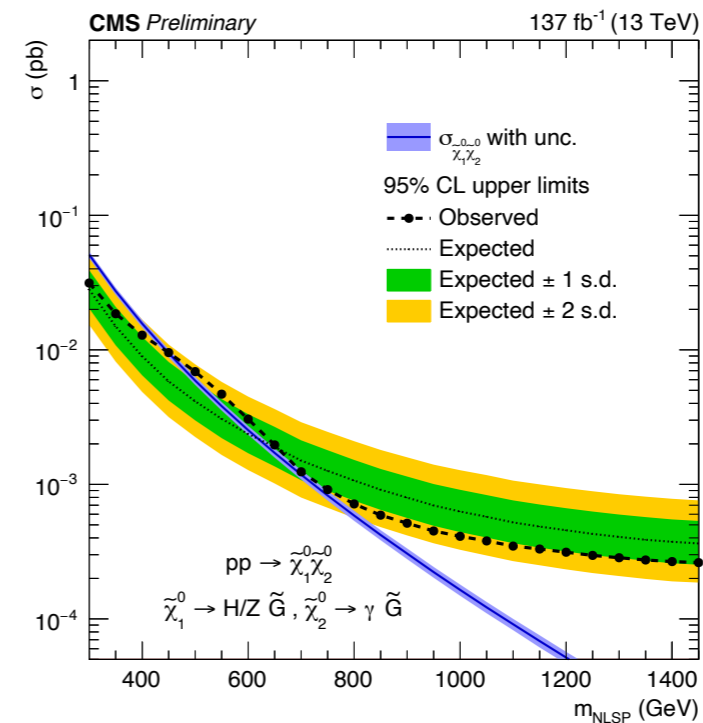
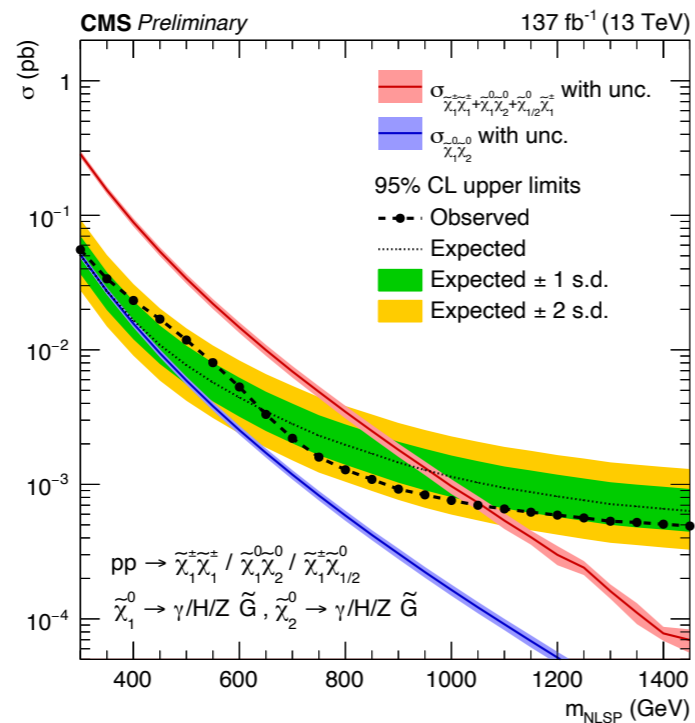
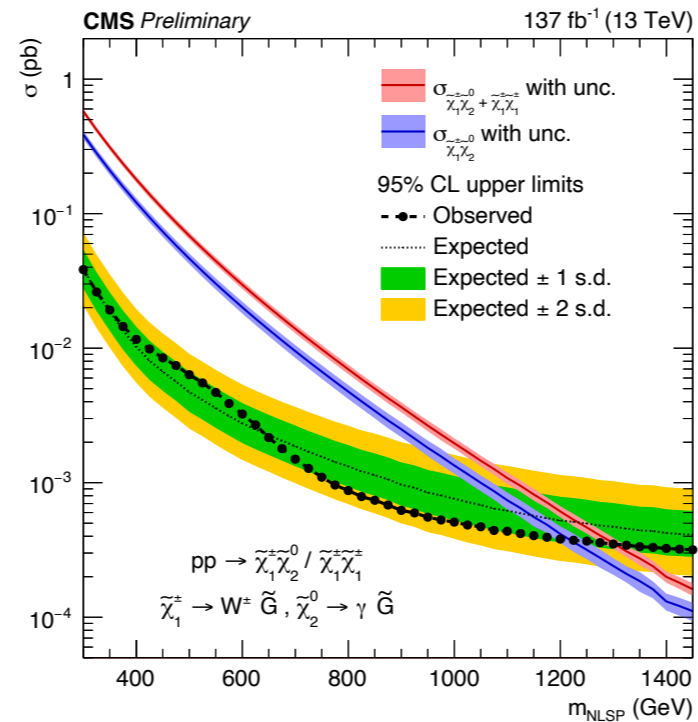
Source	Lost lepton	Misidentified e	Z( $\nu\nu$ ) $\gamma$	Multijet+ $\gamma$	Signal
Luminosity	—	—	—	—	1.6
Limited number of CR events	3–100	5–20	8–28	2–100	—
Limited number of simulated events	2–10	2–20	2–70	10–50	0.7–38
b tagging	0–1	0–1	—	—	0–10
PDF	3	—	—	—	1–2
$\mu_R$ and $\mu_F$ scales	2	—	—	—	0.3–5
JEC	0–6	0–3	—	—	1–2
JER	0–6	0–4	—	—	1–2
Pileup	—	—	—	—	0.1–0.3
Trigger efficiency	—	—	—	—	3–10
Collinear $\gamma$	4	—	—	—	—
$\alpha$	—	20	—	—	—
Modeling of $\gamma p_T$	—	—	18–40	—	—
$\kappa$ modeling	—	—	—	10–36	—
low- $p_T^{\text{miss}}$ C/A data stat.	—	—	—	10–50	—
Isolated track veto	—	—	—	—	2
Jet ID	—	—	—	—	1



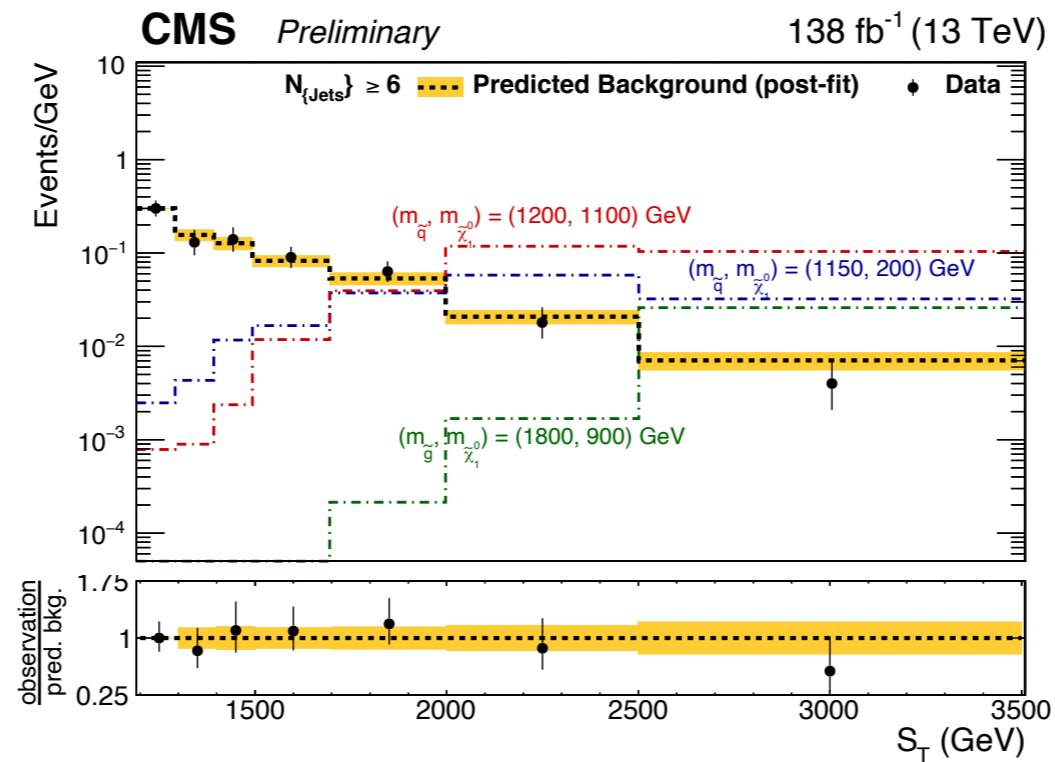
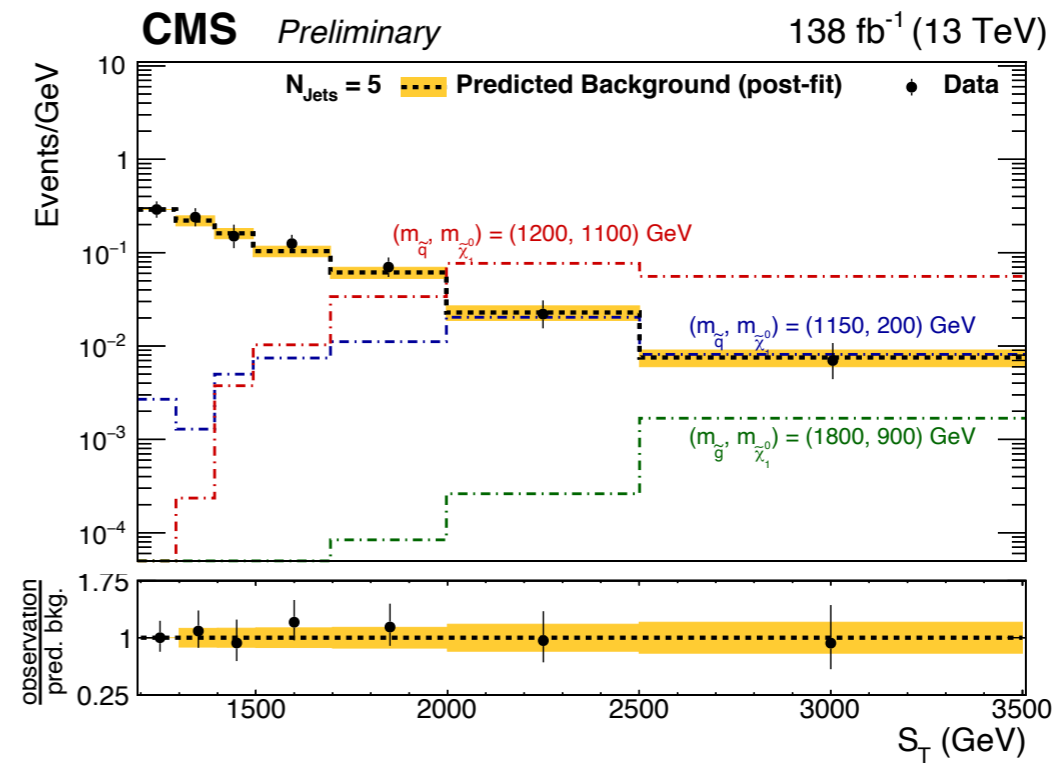
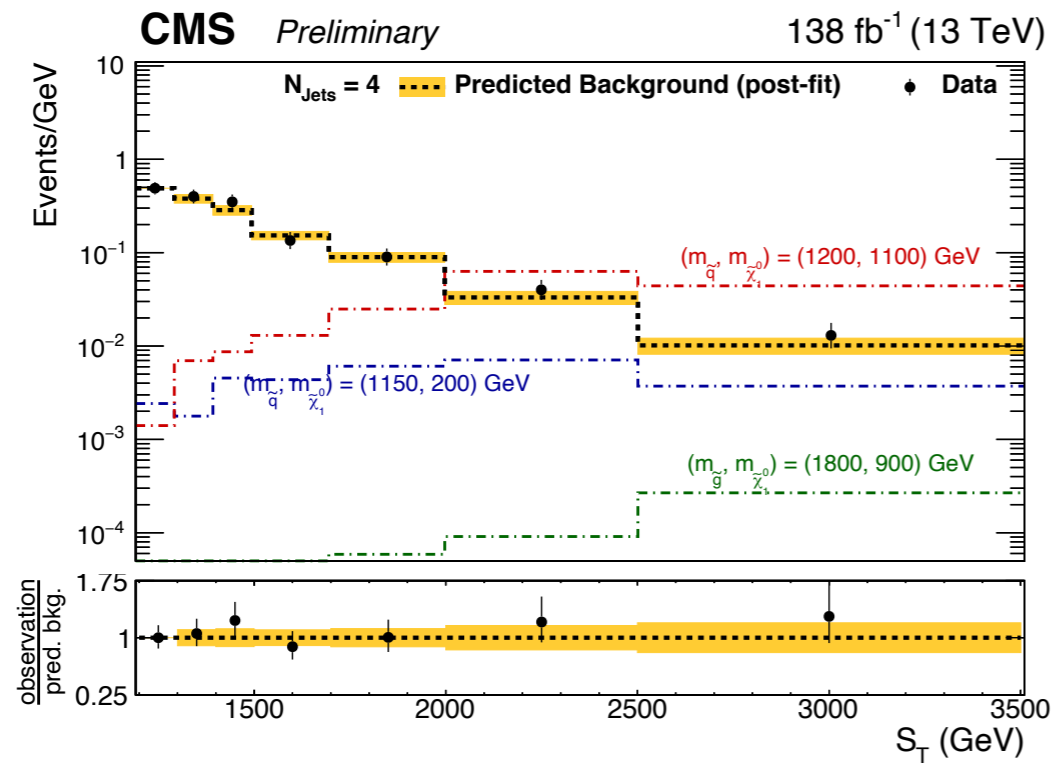
# SUSY Search in 1 Photon + Jets + $p_T^{\text{miss}}$ Events: Limits



# SUSY Search in 1 Photon + Jets + $p_T^{\text{miss}}$ Events: Limits



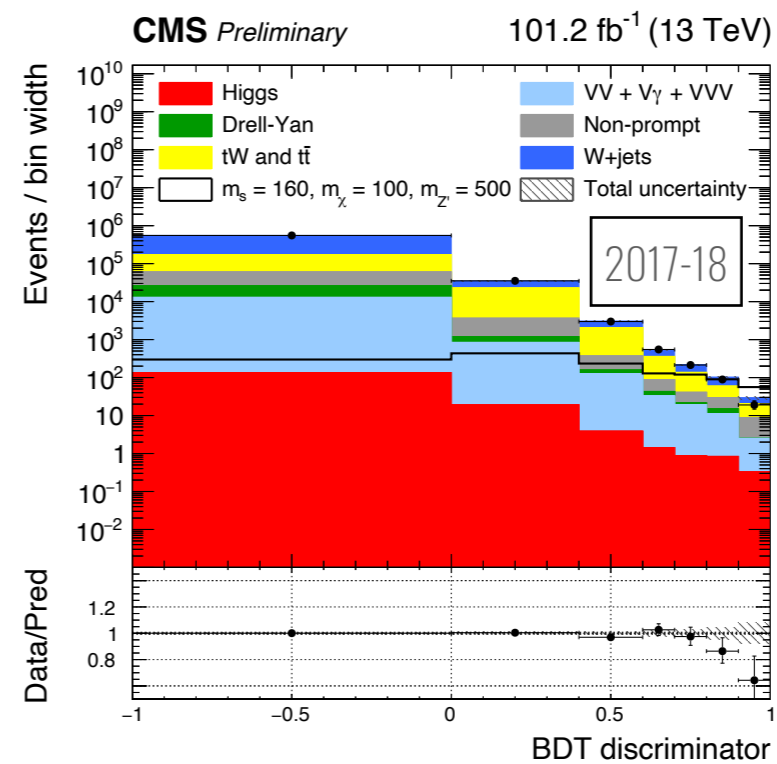
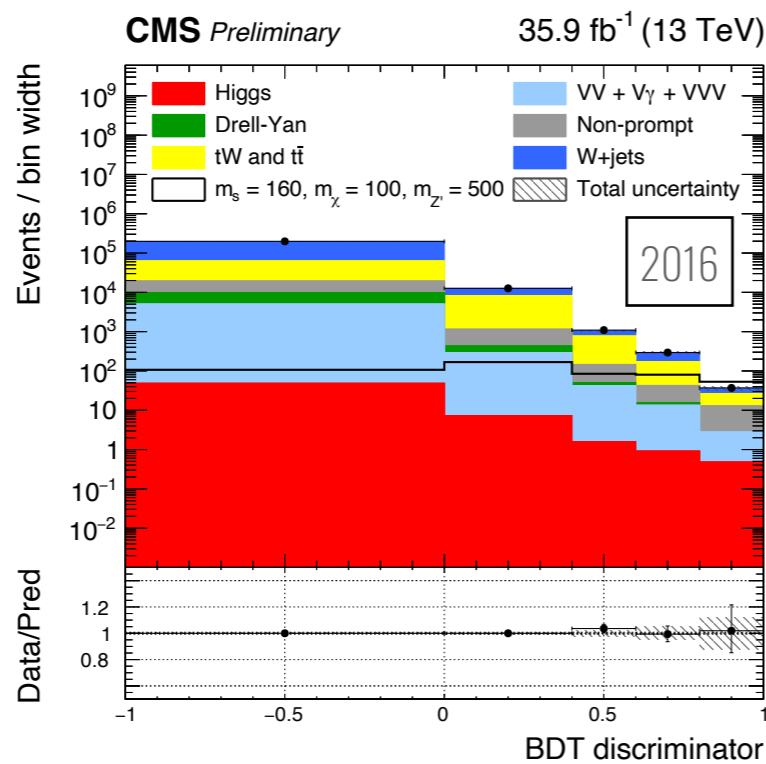
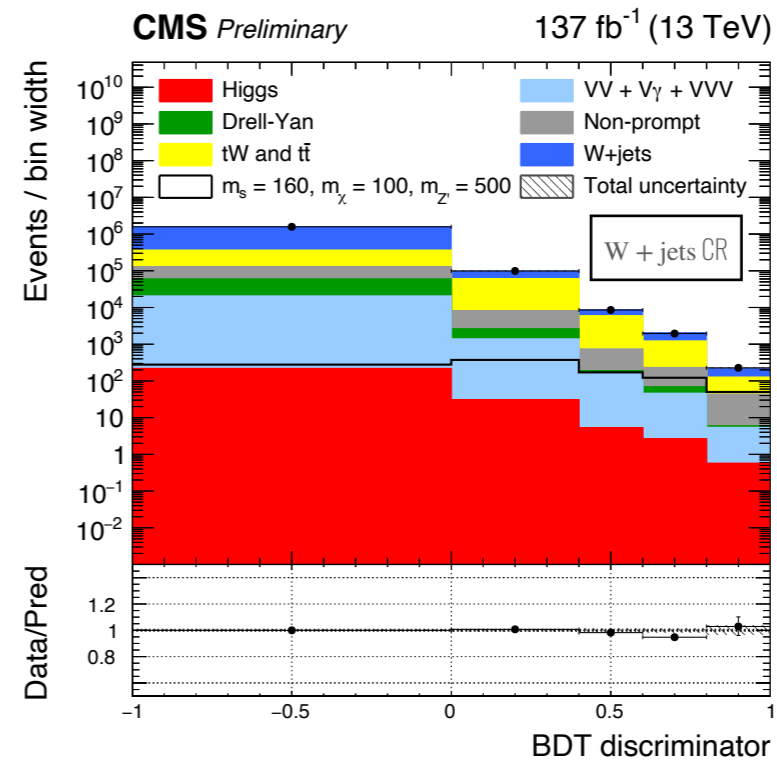
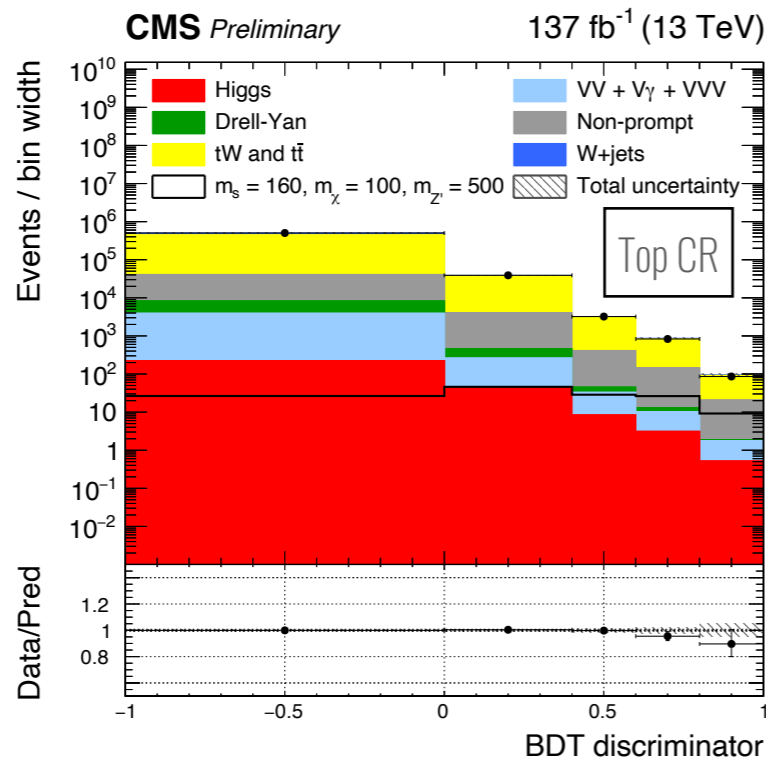
# SUSY Search in 2 Photon + Jets Events: $S_T$ Fits



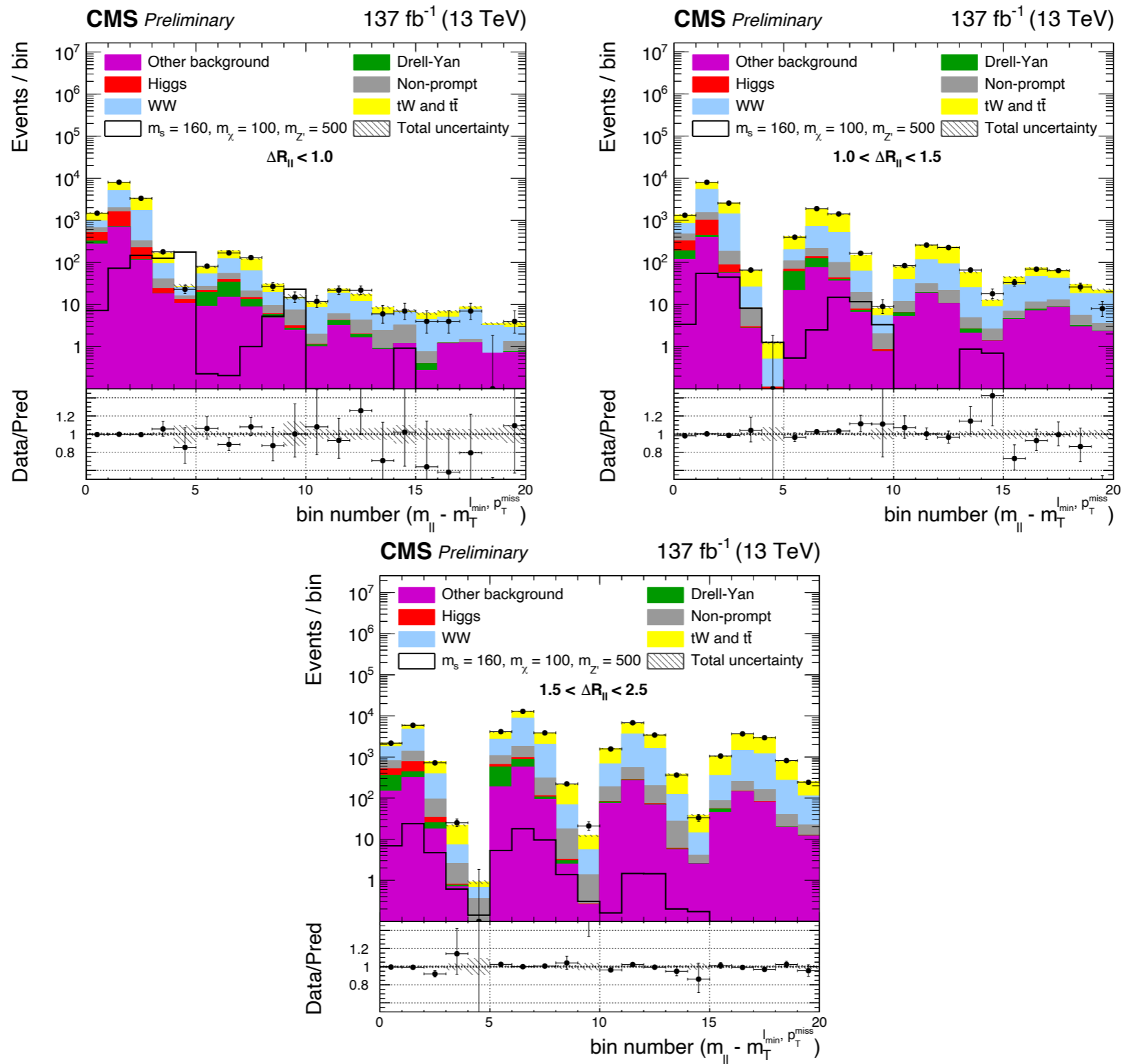
# Search for Dark Matter in $W^+W^- + p_T^{\text{miss}}$ Events: CRs

- **tW and  $t\bar{t}$  CR:** ● ●
    - Reversed b-tag requirement ( $>0$ )
  - **$W^+W^-$  CR:** ●
    - Reversed  $\Delta R_{ll}$  requirement ( $\Delta R_{ll} > 2.5$ )
  - **Drell-Yan CR:** ●
    - Inverted  $m_T(ll, p_T^{\text{miss}})$  requirement ( $m_T(ll, p_T^{\text{miss}}) < 50$  GeV)
  - **W + jets CR:** ●
    - Inverted  $m_{jj}$  requirement ( $65 \text{ GeV} < m_{jj} < 105 \text{ GeV}$ )
- Semi-leptonic channel
- Di-leptonic channel

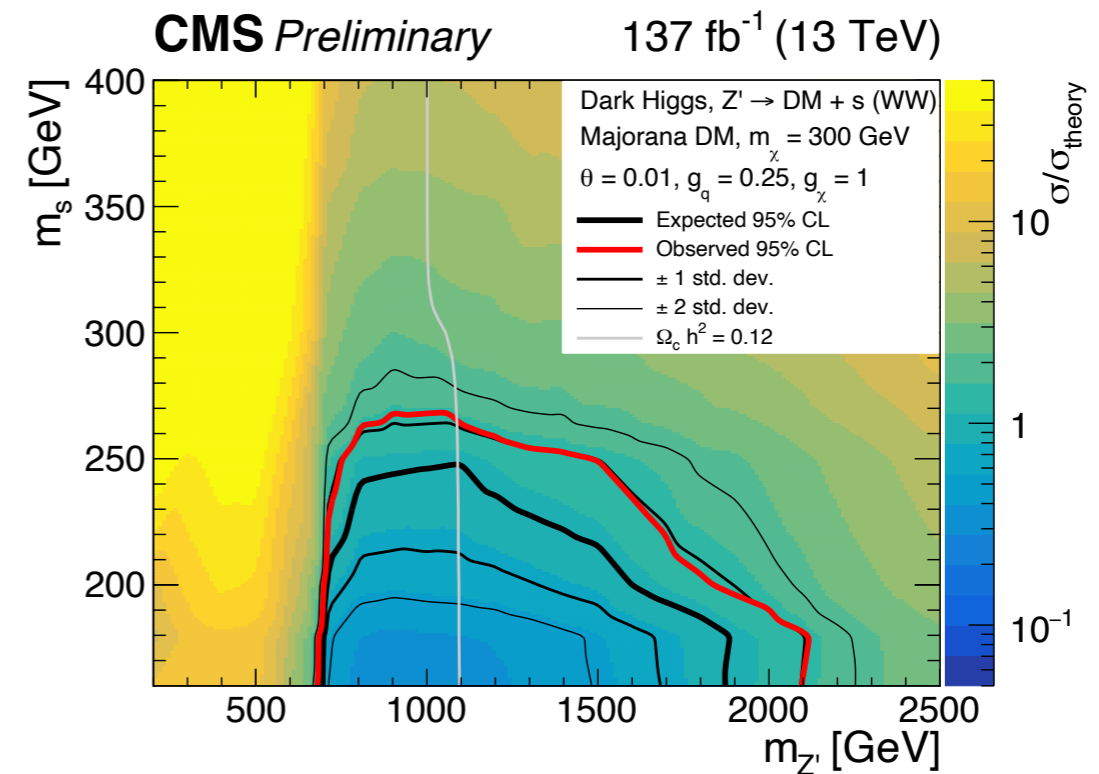
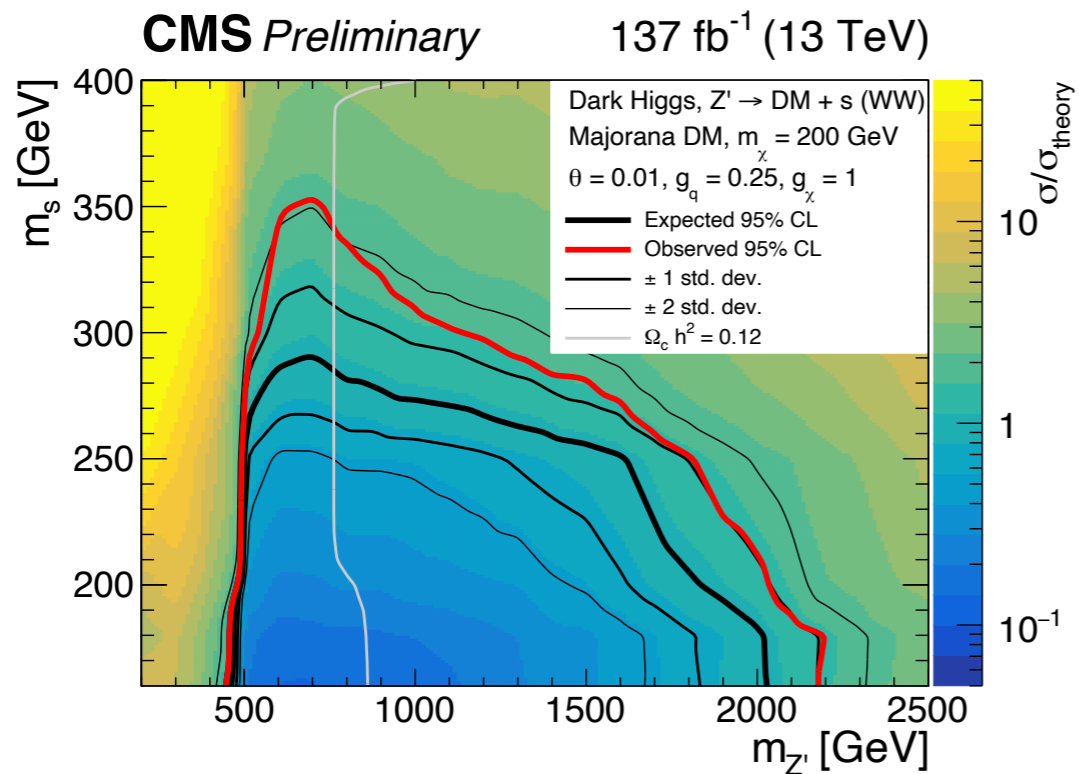
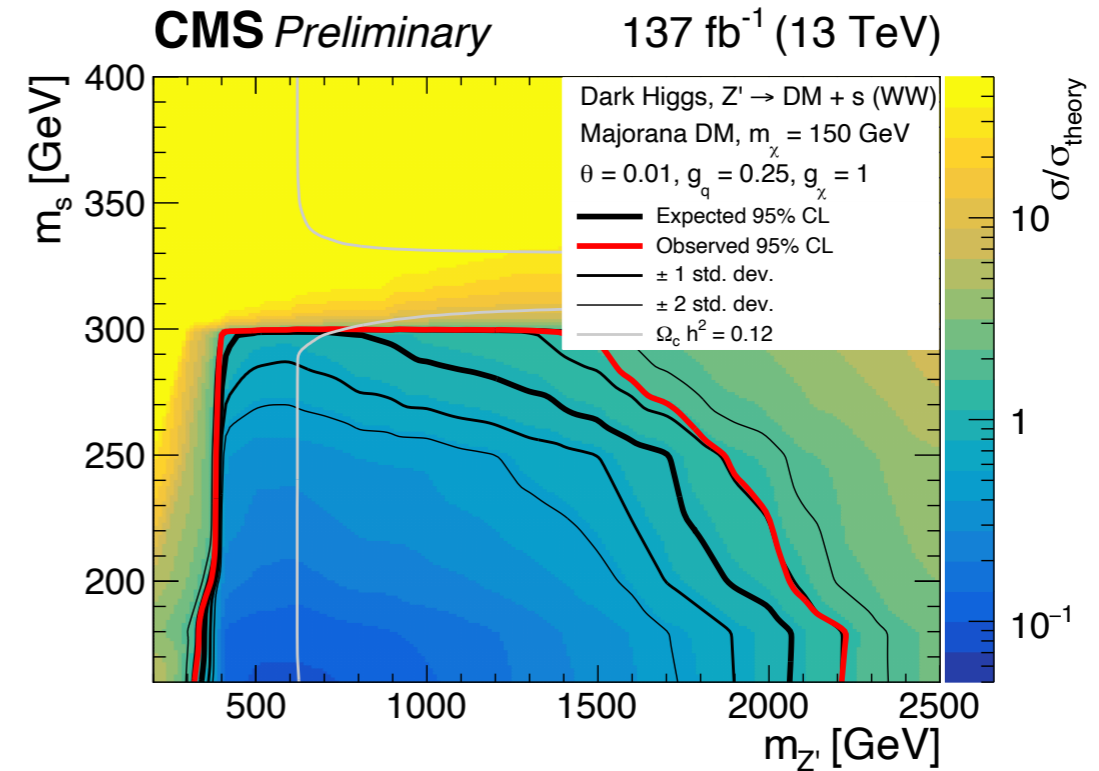
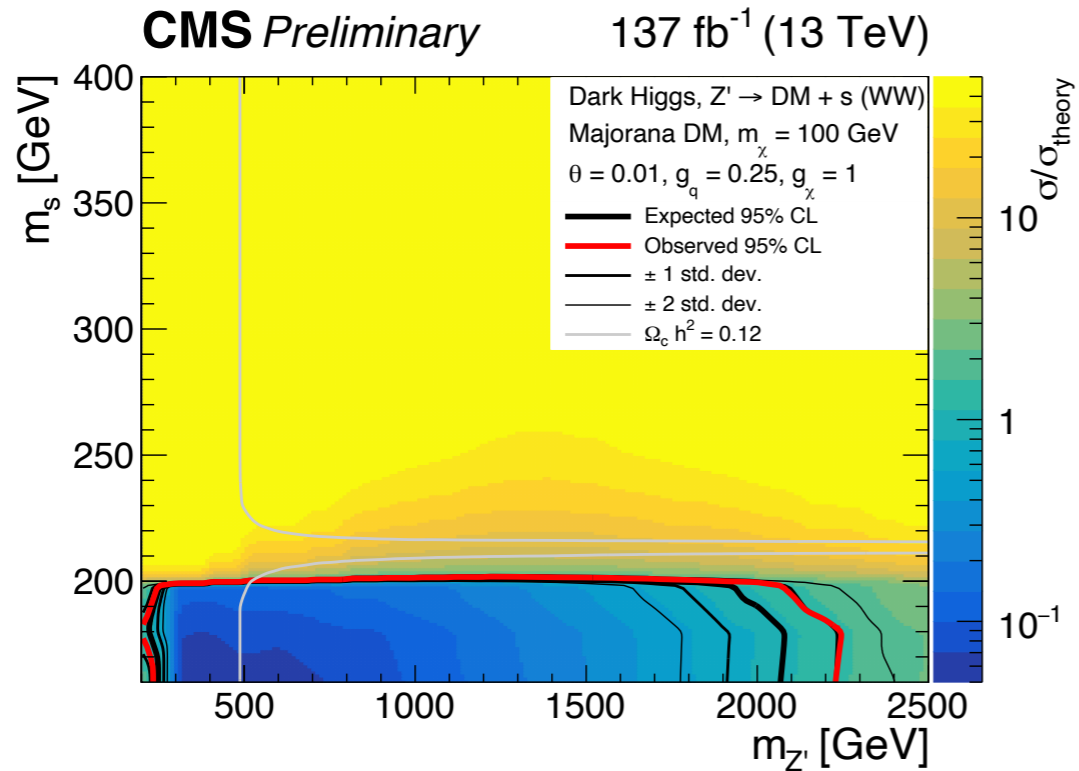
# Search for Dark Matter in $W^+W^- + p_T^{\text{miss}}$ Events: 1 $\ell$ Fits



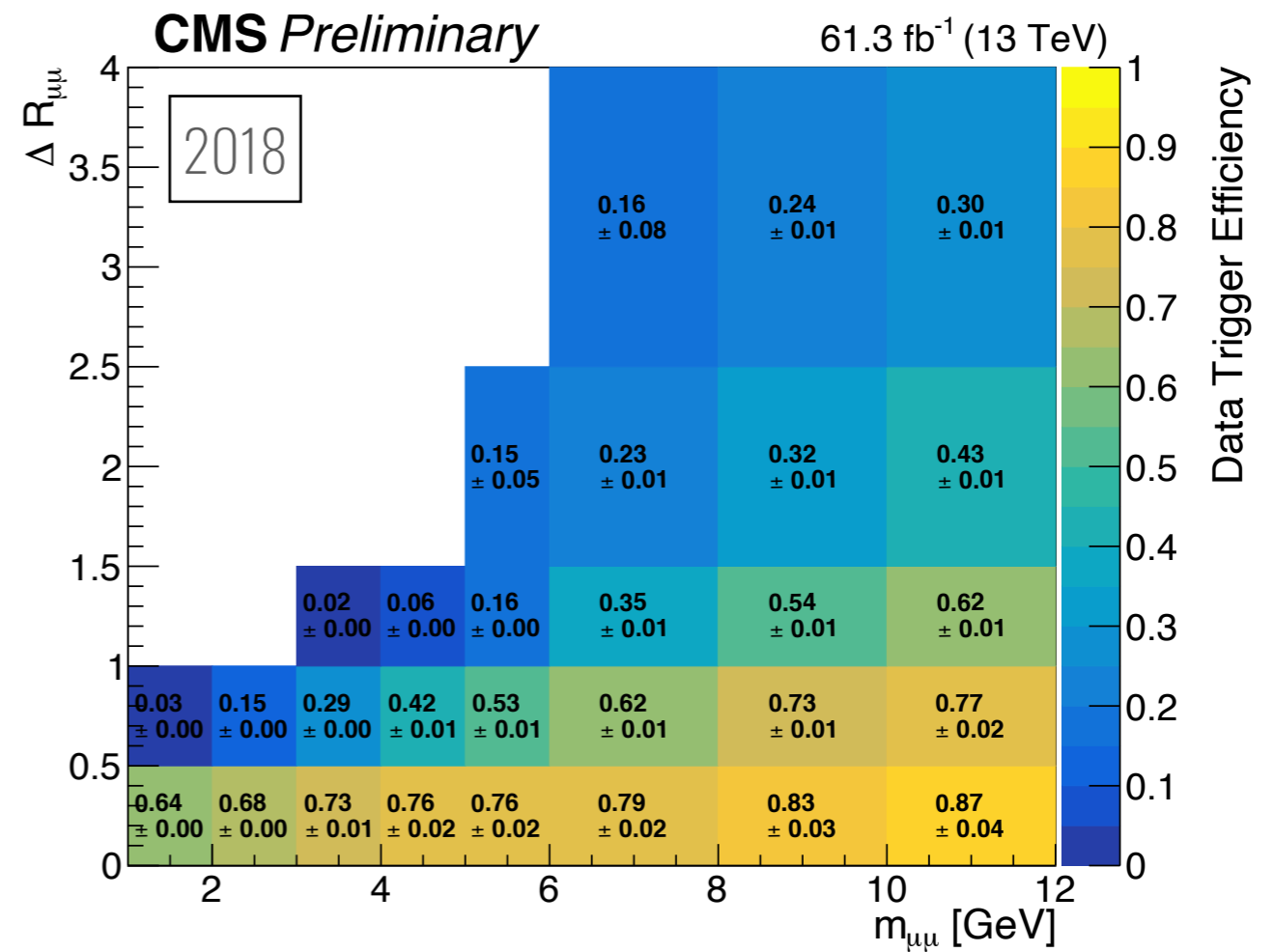
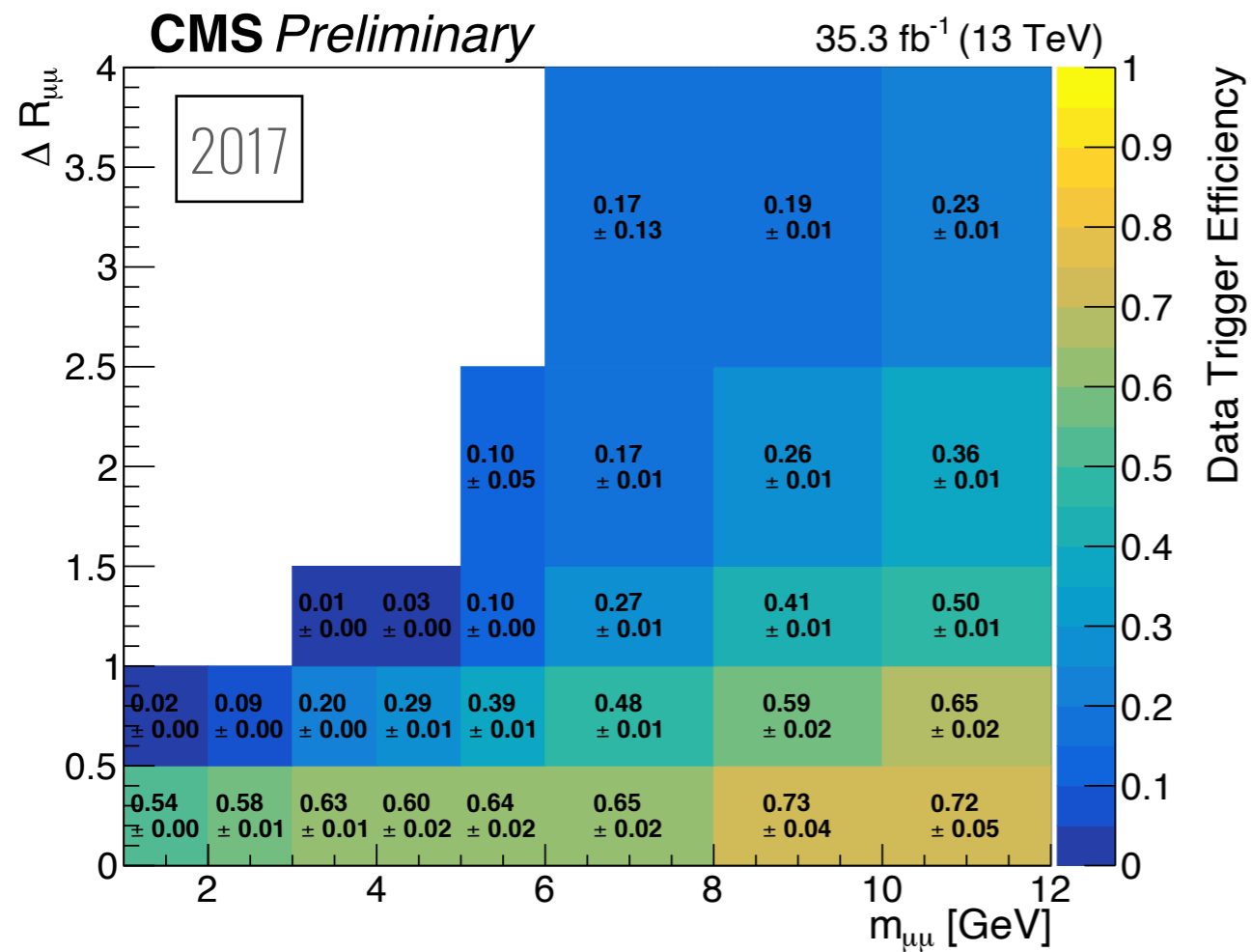
# Search for Dark Matter in $W^+W^- + p_T^{\text{miss}}$ Events: 21 Fits



# Search for Dark Matter in $W^+W^- + p_T^{\text{miss}}$ Events: Limits



# Low-Mass Dimuon Resonance Search: Scouting Trigger Efficiencies





# Low-Mass Dimuon Resonance Search: Overall Efficiencies

