# Search for new massive scalars at CMS

LHCP2024 (3-7 Jun 2024)

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# Introduction



Searches for heavy scalars are motivated by many BSM models including theories with extended Higgs sectors

- Minimal extension: two-Higgs-doublet models (2HDMs) ← MSSM
  - Introduce an adddional Higgs doublet
  - Predict 5 Higgs bosons: CP-even $\mathrm{h}^0$, $\mathrm{H}^0$, CP-odd A, $\mathrm{H}^{\pm}$
- Next-to-minimal extensions: 2HDM+Singlet, Higgs triplet, ...

CMS is broadening the searches for new scalars

- New signals, modern techniques, ...
- Results are interpreted in the context of BSM models

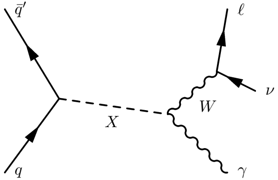
This talk summarizes some of the latest CMS searches with Run II data:

| | |
|---|---|
| $X^{\pm} \to W^{\pm}\gamma$ | CMS-PAS-EXO-21-017 |
| X$\to \phi\phi \to 4\gamma$ | arXiv:2405.00834 |
| $\mathrm{A} \to \mathrm{Z}(\ell\ell)\mathrm{H}(\mathrm{t}\bar{\mathrm{t}})$ | CMS-PAS-B2G-23-006 |
| $\mathrm{H}^{\pm} \to \mathrm{H}^0\mathrm{W}$, $\ell\tau_\mathrm{h}(\tau_\mathrm{h})$ | JHEP09(2023)032 |
| $\mathrm{W}\phi$, $\mathrm{Z}\phi, \mathrm{t}\bar{\mathrm{t}}\phi$ $(\mathrm{X}\phi)$, multilepton | arXiv:2402.11098 |

## $W^{\pm}\gamma$ signatures in final states with $\ell$, $\gamma$, $p_T^{miss}$

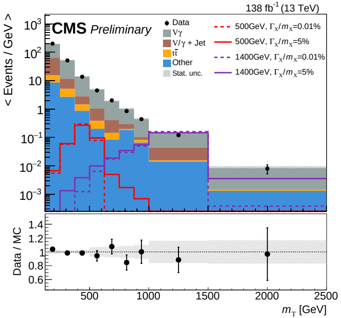
- Search for bump in data $m_T$

$$m_T^2 = \left(E_T(\gamma) + E_T(\ell) + p_T^{miss}\right)^2 - |\vec{p}_T(\gamma) + \vec{p}_T(\ell) + \vec{p}_T^{miss}|^2$$

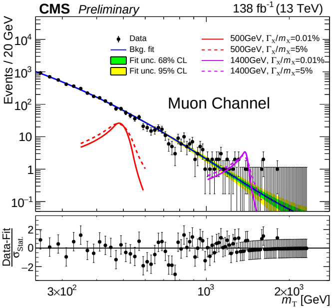



## Background: From data, with analytic functions

Main bkg: $V\gamma$, $V/\gamma$+jets, $t\bar{t}$




Background-only fit

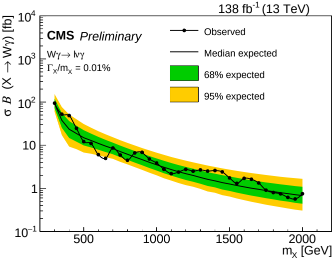


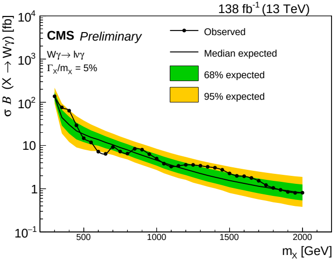

$$p_0 x^{\sum_{i=1}^{N} p_i \log^{i-1}(x)},$$

$$p_0 \frac{(1-x)^{p_1}}{x^{\sum_{i=2}^{N} p_i \log^{i-2}(x)}},$$

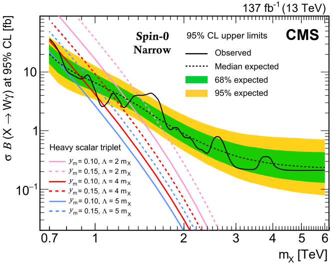
$$p_0 e^{p_1 x} x^{\sum_{i=2}^{N} p_i \log^{i-2}(x)},$$

## Leptonic $W^{\pm}\gamma$

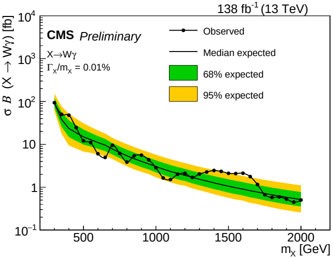



## Hadronic - PLB 826(2022) 136888

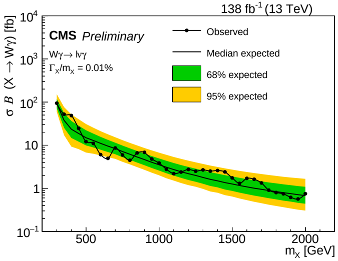


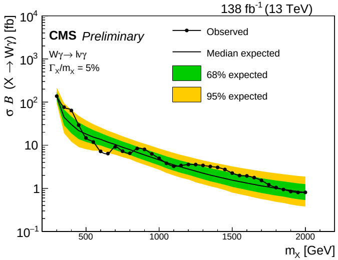

## Combination - narrow signal

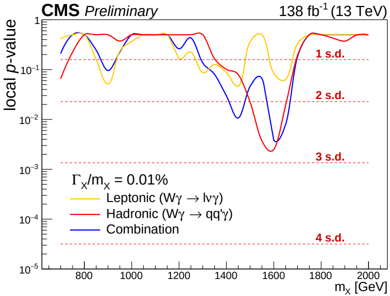


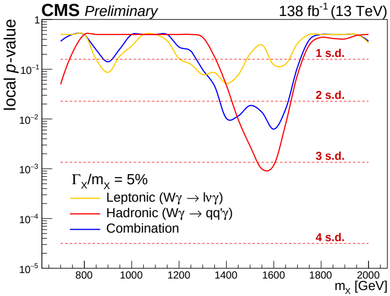

- Combination with CMS hadronic results
- Excess at 1.58 TeV not confirmed

## Leptonic $W^{\pm}\gamma$

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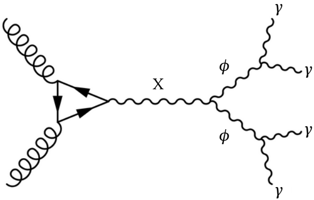
## Extended Higgs sectors with X, $\phi$ scalars

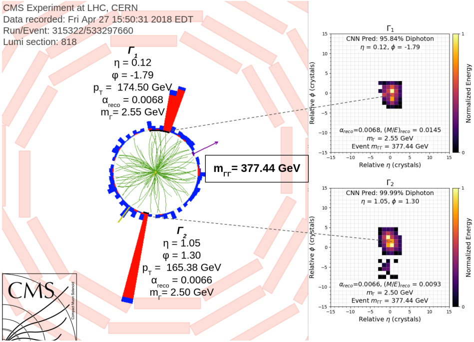
- $X \to \phi\phi$ kinematically allowed for $m_\phi < 2m_{bb/cc}$
- Highly boosted $\phi$ for $m_X >> m_\phi$ - **merged diphotons**



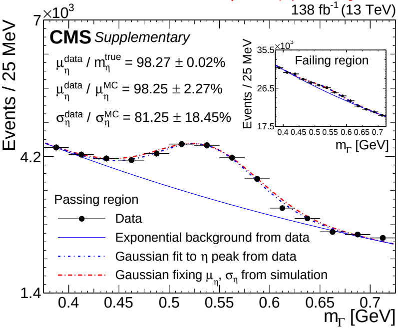

## Merged diphoton ($\Gamma = \gamma\gamma$) reconstruction

- Convolutional neural network (CNN) using clusters from ECAL
- Classification: "$\gamma\gamma$", "$\gamma$", "hadron"
- Regression: m/E of the $\gamma\gamma$ clusters

ECAL cluster image recognition




Validation in $\eta \to \gamma\gamma$ decays



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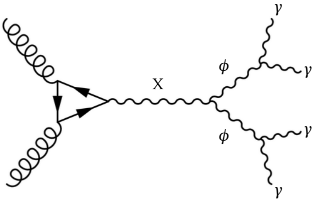



## Analysis strategy

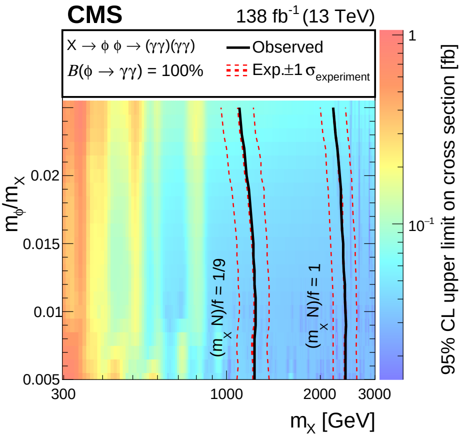
- Two Γ clusters ($\text{CNN}_{\gamma\gamma}$)
- Search for excess in data $M_{\Gamma\Gamma}$
- Data binned in slices of $\alpha^{reco} = \hat{m}_\Gamma / M_{\Gamma\Gamma}$

## Background estimation

- Fit of falling $M_{\Gamma\Gamma}$ in data

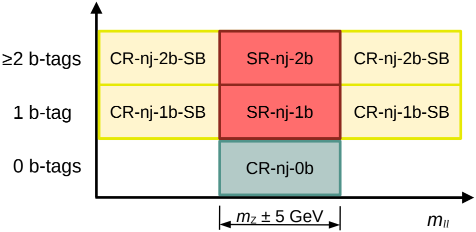
## Fit of background + signal to data

- Largest Excess at $m_X = 720$ GeV, $m_\phi/m_X = 7\%$ ($m_\phi \approx 5$ GeV): $3.57\sigma$ local/ $1.07\sigma$ global significance



## Search for signatures with $Z \rightarrow \ell\ell$ and fully hadronic $t\bar{t}$

- Event categorization based on $\ell$ flavor, $n_{jet}$, $n_{bjet}$, $m_{\ell\ell}$

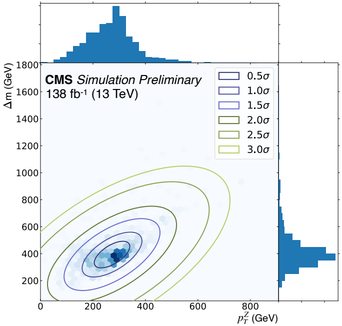



with n = 5, ≥6

- SR: signal regions
- Z sidebands: $t\bar{t}$ normalization
- 0b CR: DY normalization

## Fit discriminant: $p_T^Z \times \Delta m$

- $p_T^Z = p_T^{\ell\ell}$
- $\Delta m = m_{t\bar{t}Z}$-$m_{t\bar{t}} \approx m_A$ - $m_H$
- Better experimental resolution compared to $m_{t\bar{t}Z}$ and $m_{t\bar{t}}$
- Concentric elliptical bins in $(\Delta m,\ p_T^Z)$



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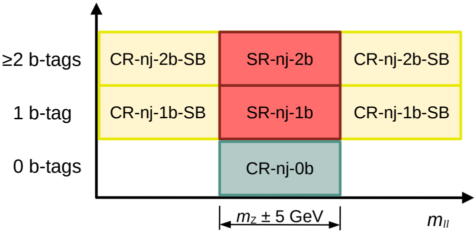


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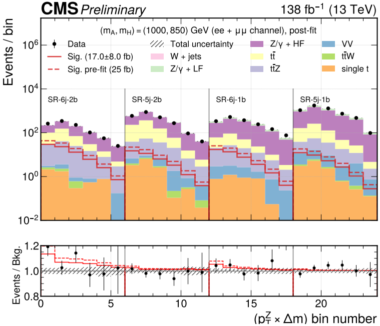
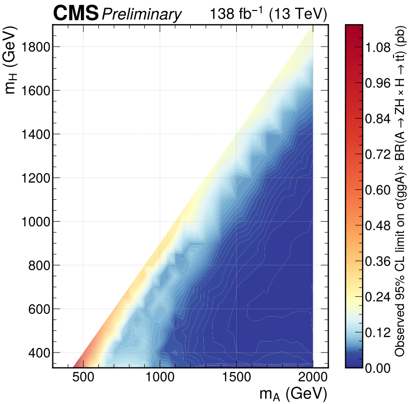
$p_T^Z \times \Delta m$ bins



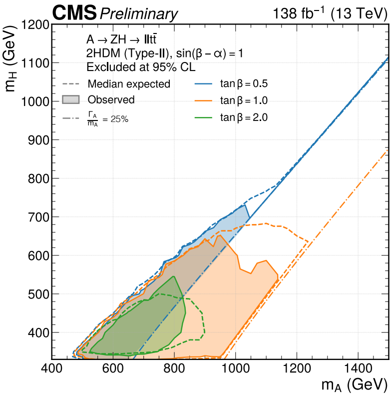
## Simultaneous fit of signal and background

### Model-independent observed limits




- No significant signal excess observed
- Results do not confirm the excess reported by ATLAS @ $(m_A, m_H) \approx (650, 450)$ GeV

### Interpretation in type-II 2HDM




- Exclusion region vs $\tan\beta$

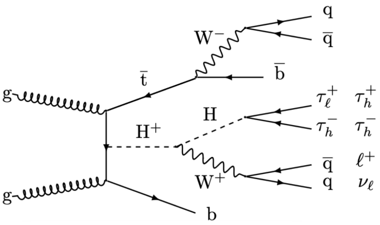
Search for $H^{\pm} \to H^0 W$ in ditau final states: $e\tau_h$, $\mu\tau_h$, $e\tau_h\tau_h$, $\mu\tau_h\tau_h$

$\ell\tau_h$: Large $\mathcal{BR}$

- 1 $\ell$ + 1 $\tau_h$ (SS or OS)
- $\geq$ 3 jets ($\geq$ 1 b jet)
- large $p_T^{miss}$
- Resolved t candidates: custom MVA ($t^{res}$)

$\ell\tau_h\tau_h$: Clean signature

- 1 $\ell$, 2 $\tau_h$ (OS)
- $\geq$ 2 jets ($\geq$ 1 b jet)
- large $p_T^{miss}$, $S_T$




Dominant background ($t\bar{t}$, V+jets) can be decomposed to:

- Genuine $\tau_h$ ← **SIMULATION**
- $\ell$ misidentified as $\tau_h$ ($\ell \to \tau_h$) ← **SIMULATION**
- jet misidentified as $\tau_h$ ($j \to \tau_h$) ← **DATA DRIVEN**

$j \to \tau_h$ background measured from data with fake factor method

- Estimate $\tau_h$ fake rates in control regions
- Fake rates applied in a region with anti-isolated $\tau_h$

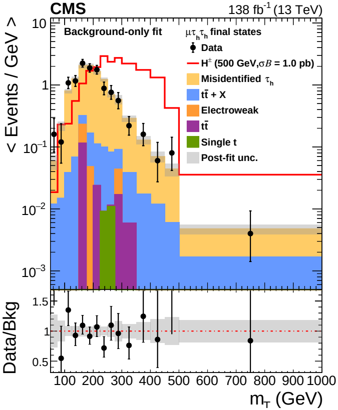
## Signal extraction:

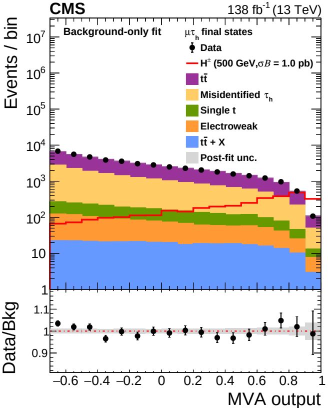
$\ell\tau_h\tau_h$: $H^{\pm}$ transverse mass ($m_T^{H^{\pm}}$)

- $m_T^{H^{\pm}} = m_T(\tau_h^+, \tau_h^-, \ell, \nu_\ell)$

$\ell\tau_h$: BDT event discriminant

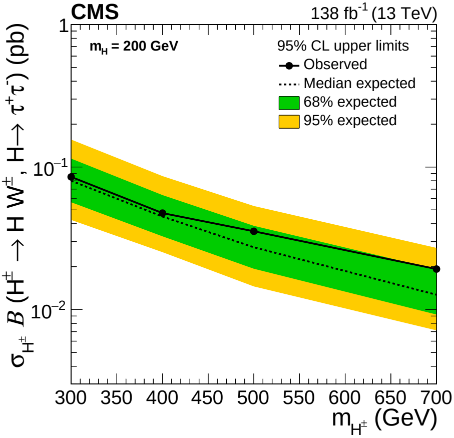
- Combinatorial-jet background goes into $m_T^{H^{\pm}} = m_T(\ell, \tau_h, j_1, j_2, \nu_\ell)$
- Enhance sensitivity with MVA
- 12 inputs including $m_T$, $N_{t^{res}}$, $p_T^{miss}$



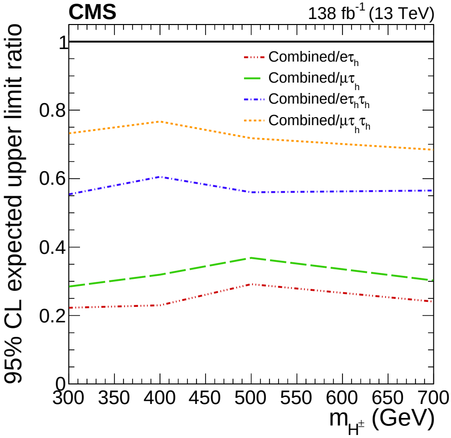



## Simultaneous fit to data in all SRs:

### Model-independent limits

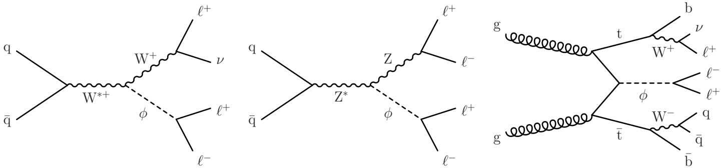



### Relative expected limits



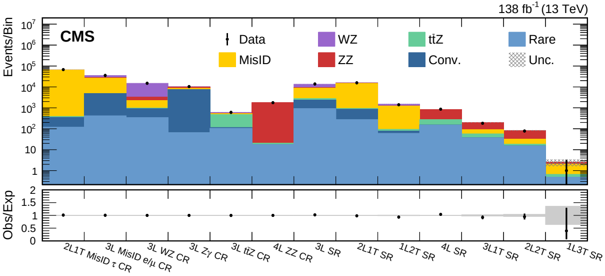

- $\ell\tau_h\tau_h$ most sensitive; $\ell\tau_h$ improves sensitivity by 20-35%
- First search of the process at the LHC

## Dilepton resonances in events with $3\ell$, $4\ell$




- Seven final states based on the number of light $\ell$, $\tau_h$
- Model-independent selections to constrain SM background
  - $N_b$, OSSF$_n$, $M_{OSSF}$, $p_T^{\mathrm{miss}}$, $M_T$

Control regions (CR) and Signal regions (SR)

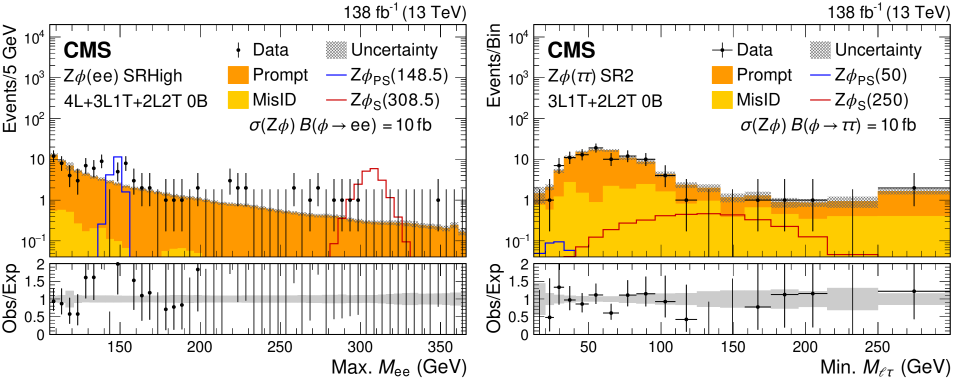



### Main background:

- **WZ, ZZ, $t\bar{t}Z$, Z$\gamma$:** from simulation, normalized in control regions
- **MisID $\ell$:** Data-driven using the matrix method

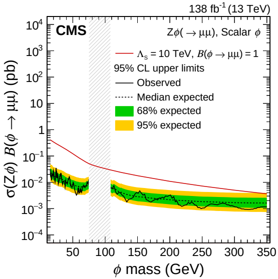
## Analysis strategy

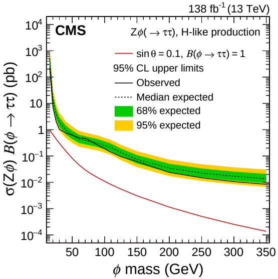
- $X\phi \rightarrow e^+e^-/\mu^+\mu^-$:
  - low- (high-) mass $\phi$ with mass below (above) the Z mass
  - Fit discriminant: min/max $M_{\ell\ell}$
- $X\phi \rightarrow \tau^+\tau^-$:
  - Search for $e\mu$, $\ell\tau_h$, $\tau_h\tau_h$ decays
  - Fit discriminant: min $M_{e\mu}$, $M_{\ell\tau_h}$, $M_{tau_h\tau_h}$

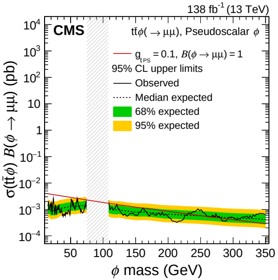


# $W\phi$, $Z\phi$, $t\bar{t}\phi$ ($X\phi$), multilepton arXiv:2402.11098

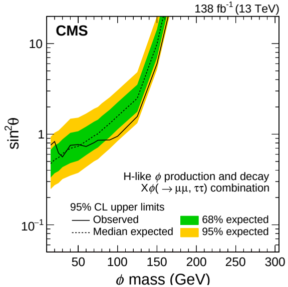
## Model-independent results: scalar, pseudoscalar, H-like $\phi$

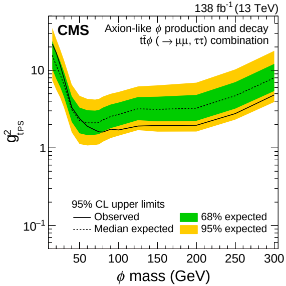



## Model-dependent results: Dilaton-like, Axion-like, H-like $\phi$



# Summary



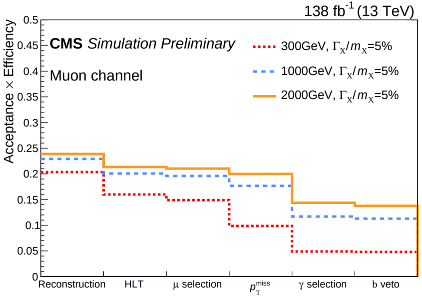
Presented latest searches for additional scalar bosons with CMS

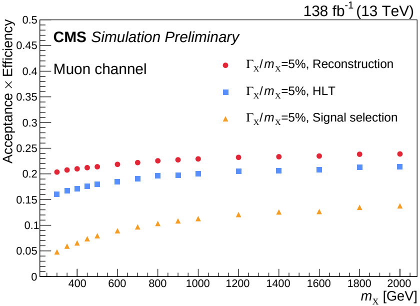
- New unexplored signal signatures
- Advanced techniques, event categorization
- No evidence for BSM physics observed

- More results to come with Run II and Run III data!

# BACKUP

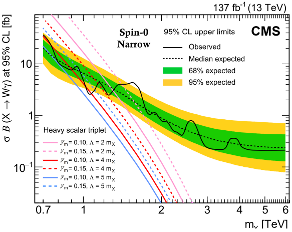
| Selections | Electron channel | Muon channel |
|---|---|---|
| Lepton $p_T$ | $> 35\,\text{GeV}$ | $> 30\,\text{GeV}$ |
| $m_{\ell\gamma}$ mass | $\lvert m_{e\gamma} - 91.0 \rvert > 20\,\text{GeV}$ | — |
| Lepton ID | Tight | |
| Photon $p_T$ | $0.4 m_T < p_T(\gamma) < 0.55 m_T$ | |
| $p_T^{miss}$ | $p_T^{miss} > 40\,\text{GeV}$ | |
| Photon $\eta$ | $\lvert \eta \rvert < 1.44$ | |
| b jet veto | 0 medium-tagged b jets | |

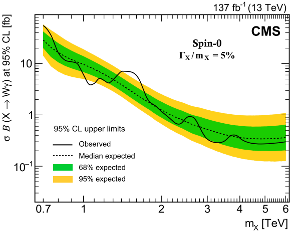


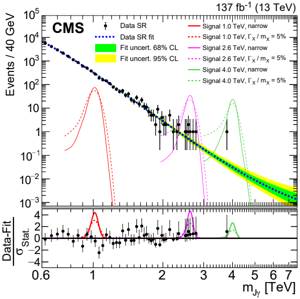
## $X \to W^{\pm}\gamma$ in final state with $\gamma$, large-R jet

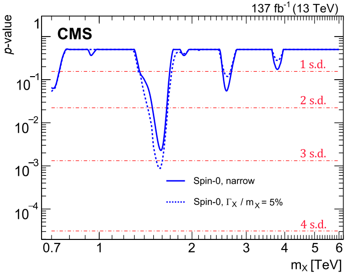
- W-tagged jet ($\tau_2/\tau_1$, $m_{SD}$)
- Search for bump in data X reconstructed mass: $m_{J\gamma}$



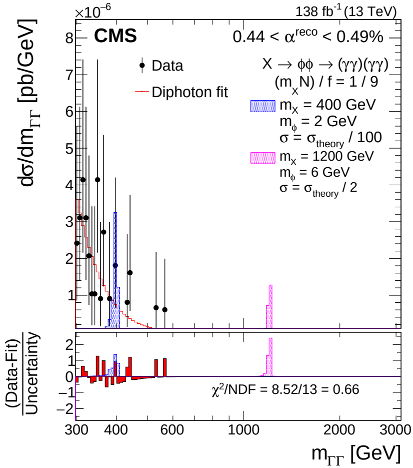

Background-only fit

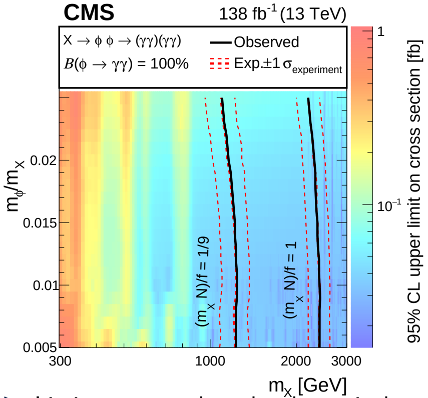


# Fit of background function + signal shape to data

Background-only fit




- Limits compared to the theoretical estimates for a set of $(m_X N/f)$ values.
- $N$ flavors of new Dirac fermion quarks that receive their mass from the X vev $f$