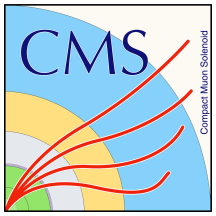


Searches for new physics in events with leptons in the final state in CMS

Jie Xiao, PKU & MIB
on behalf of the CMS collaborations

Pheno2021: Phenomenology 2021 Symposium, 24-26 May 2021

Outline

Many new physics models are expected to manifest themselves in the final states with leptons and photons. This talk presents searches in CMS for new phenomena in the final states that include leptons (and photons), focusing on the recent results obtained using the full Run-II data-set collected at the LHC in following areas:

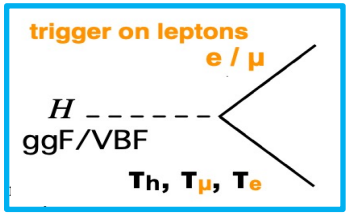
- The Higgs Sector
- Exotic Heavy Resonances
- Exotic Dark Matter
- Supersymmetry

The Higgs Sector

Lepton Flavor Violating Decays: H → eτ/μτ

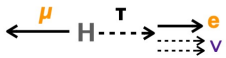
CMS-PAS-HIG-20-009

- **Lepton flavor violating (LFV)** decays of the Higgs are forbidden in the SM
- Higgs production mechanisms: gluon fusion (**ggH**), vector boson fusion (**VBF**)
- Search for $H \to e\tau$ and $H \to \mu\tau$ in 4 channels: $\mu\tau_h$, $\mu\tau_e$, $e\tau_h$, $e\tau_\mu$
  - τ_h reconstructed with the standard HPS algorithm



- **Main backgrounds**: $Z \to \tau\tau$, top-quark processes, backgrounds from mis-identified objects
- Train **BDTs** in each channel separately
  - e.g. input variables in H →μτe

m_{col} = collinear mass
- estimate m_H assuming the momentum of neutrinos (ν) collinear with the visible tau decay product(s)



$$p_T^{\mu}, p_T^{e}, m_{col}, m_T(\mu, \vec{p}_T^{miss}), m_T(e, \vec{p}_T^{miss}), \Delta\phi(e,\mu), \Delta\phi(\mu, \vec{p}_T^{miss}), \Delta\phi(e, \vec{p}_T^{miss})$$

m_T = transverse mass
- discriminate against W→ ℓ ν background

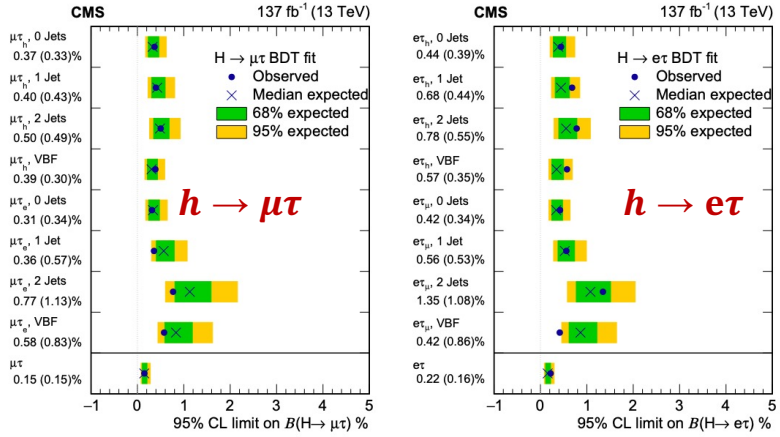
$$m_T(\ell) = \sqrt{2|\vec{p}_T^{\ell}||\vec{p}_T^{miss}|(1-\cos\Delta\phi_{\ell,\vec{p}_T^{miss}})}$$

Lepton Flavor Violating Decays: H → eτ/μτ

CMS-PAS-HIG-20-009

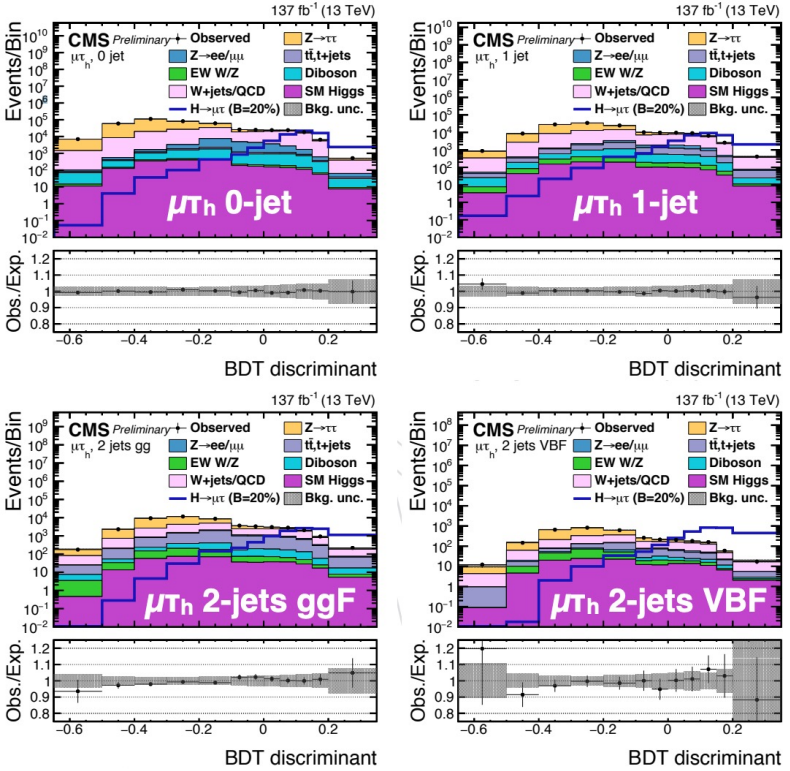
- Each channel divided into **4 event categories** to enhance different Higgs production mechanisms
- Fit to BDT distributions performed simultaneously over all channels and categories

95% C.L. Obs. (Exp.) upper limits on the branching fractions



< 0.15 (0.15) %

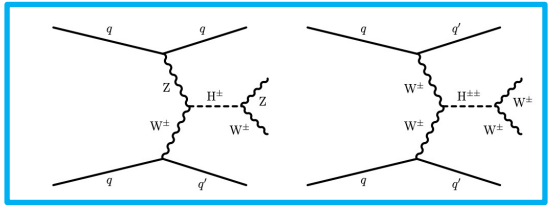
< 0.22 (0.16)%

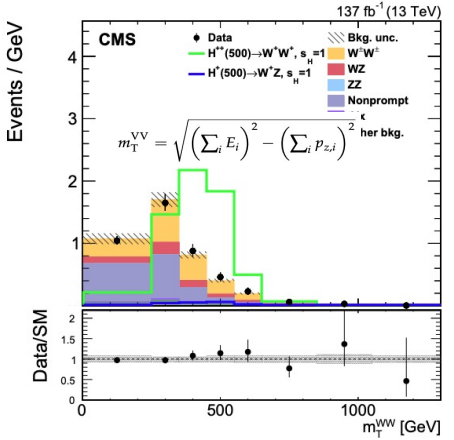


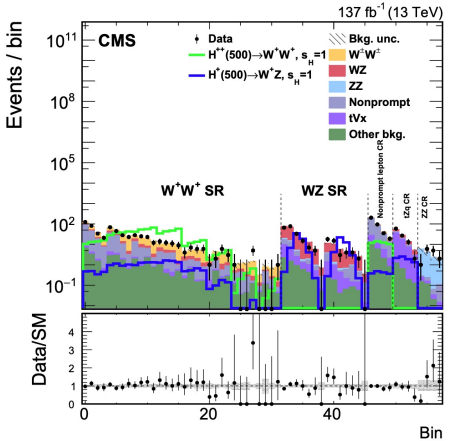
Search for VBF $H^{\pm}$ and $H^{\pm\pm}$

CMS-PAS-HIG-20-017

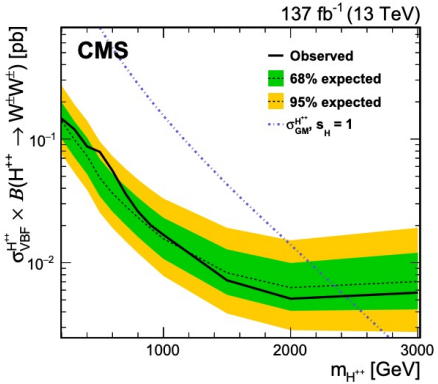
- In **Georgi-Machacek model**, extended Higgs sectors give rise to **charged Higgs bosons** with couplings to W and Z
- Search for **VBF $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ and $H^{\pm} \rightarrow W^{\pm}Z$** in fully leptonic ($e/\mu$) decays
- Main backgrounds: **diboson**, **non-prompt lepton**
- **m_T^{VV}** and **m_{jj}** effective in **discriminating** between signal and background



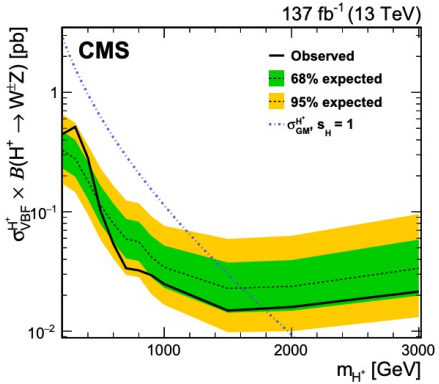




Expected and observed exclusion limits at 95% CL



$\sigma_{VBF}(H^{\pm\pm})\,\mathcal{B}(H^{\pm\pm} \rightarrow W^{\pm}W^{\pm})$



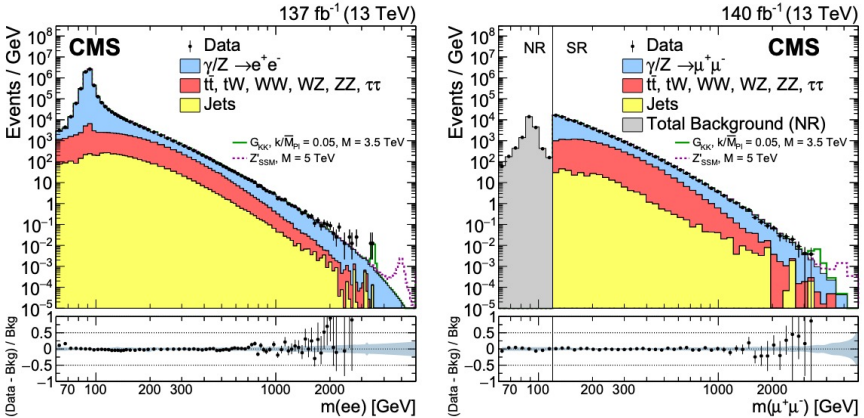
$\sigma_{VBF}(H^{\pm})\,\mathcal{B}(H^{\pm} \rightarrow WZ)$

Exotic Heavy Resonances

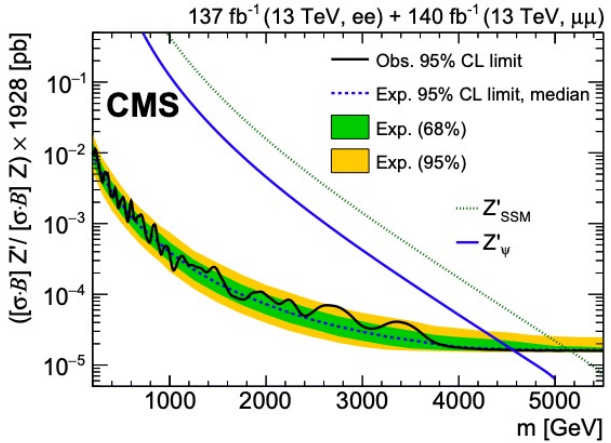
Di-Lepton Resonances

CMS-PAS-EXO-19-019

- Simple signature: **Z' → ll**
- Multiple theory models
  - E.g., Spin-1 resonances in a sequential **SM (SSM)** and a superstring-inspired model: **Z'_{SSM}** or **Z'_{ψ}**
- Lepton backgrounds from high order simulation with Z peak used to normalize. Jet backgrounds estimated from data



ee channel **μμ channel**



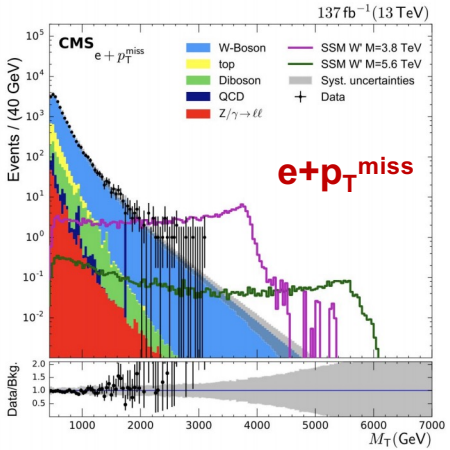
Limits for a spin-1 narrow resonance with an intrinsic width of 0.6%

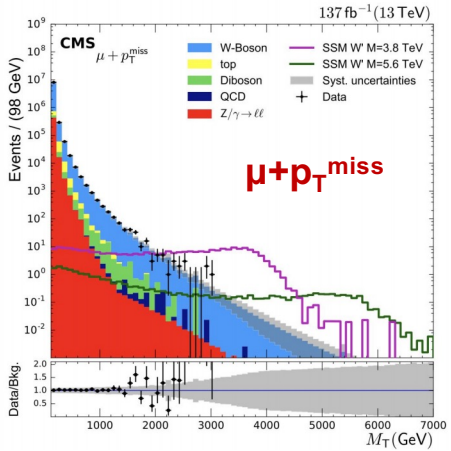
Lepton + MET Resonances

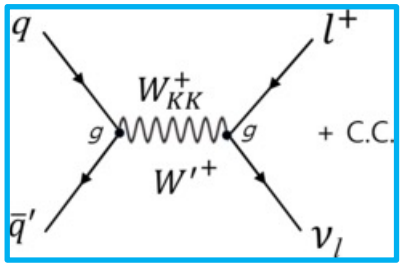
CMS-PAS-EXO-19-017

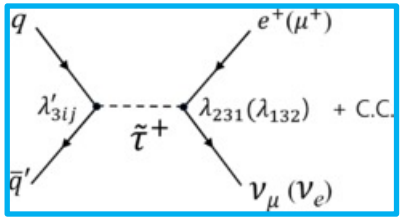
- **W' → lν** : high pT lepton and "nothing else" (pT miss), inclusive in number of jets
  - Equivalent **SSM** interpretation
  - Split-Universal Extra Dimension (**split-UED**) model, Kaluza-Klein (KK) partner: $W_{KK}^{(n)}$
  - R-parity Violating (**RPV**) Supersymmetry model
- Study based on a binned fit in the discriminant variable $\mathbf{M_T}$

$$M_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell}\ p_{\mathrm{T}}^{\mathrm{miss}} \left(1 - \cos[\Delta\phi(\ell, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})]\right)}$$





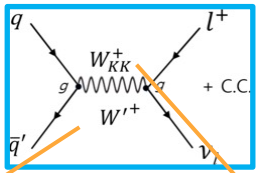


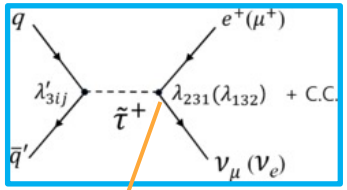


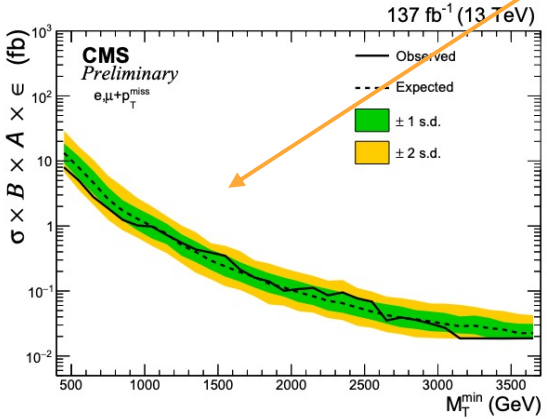
Lepton + MET Resonances

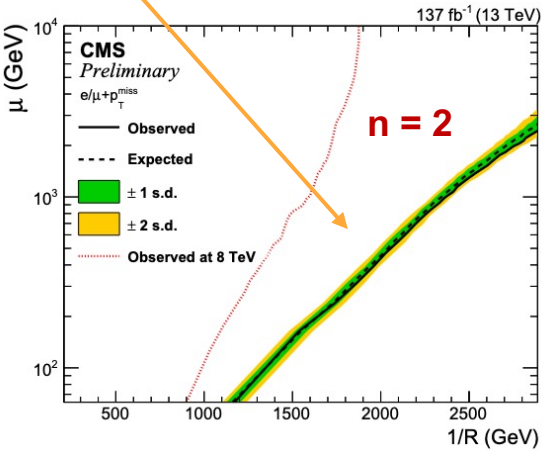
CMS-PAS-EXO-19-017

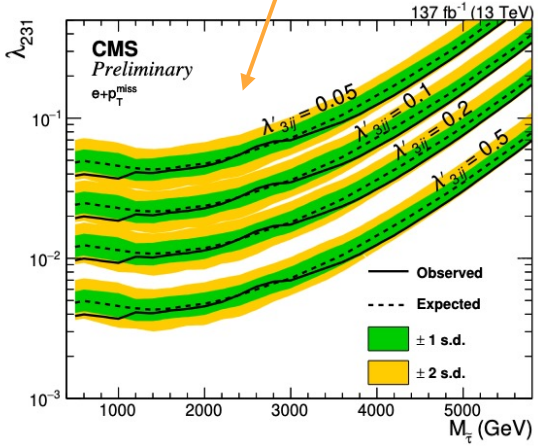
- **Cross-section limits** set as a function of transverse mass
- In **split-UED** model, **R** (the extra dimension radius) vs. **μ** (the bulk mass parameter of the five dimensional fermion field)
- Can also scan in **RPV Slepton mass** vs. **coupling** plane









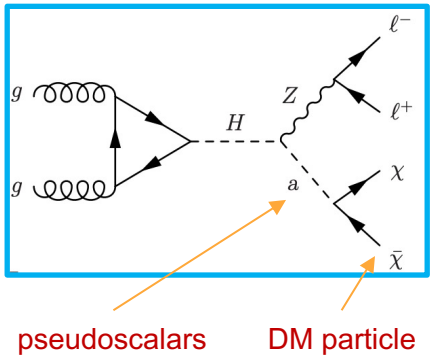


Exotic Dark Matter

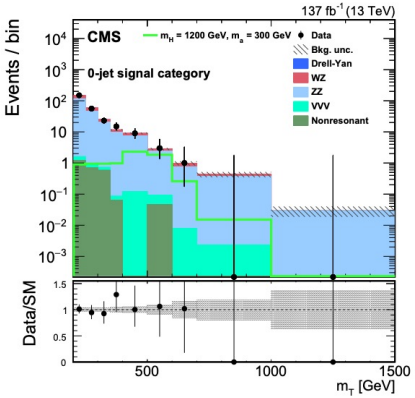
Dark matter produced in association with Z boson

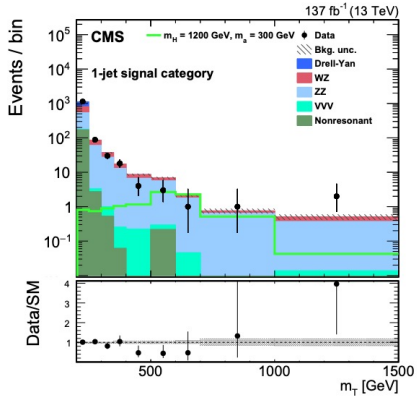
EPJC 81 13 (2021)

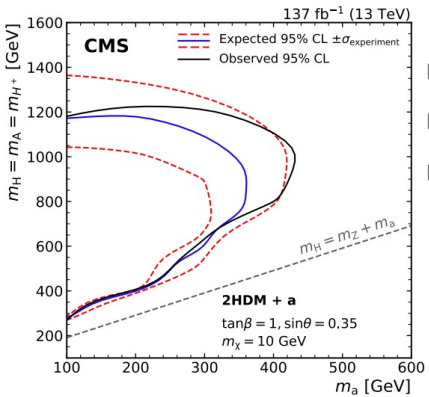
- Several models are considered including Two-Higgs-doublet model + pseudoscalars (**2HDM+a**), **simplified DM**, **invisible Higgs** and **Graviton**
- **"mono-Z"** scenario: a Z boson produced in pp collisions, recoils against **DM** or other **BSM invisible particles**
- Baseline selections require same flavor oppositely charged lepton pair within Z mass window, (b)-jet veto and additional lepton veto, and p_T^{miss} and m_T
- Fit either $\mathbf{p_T^{miss}}$ or $\mathbf{m_T}$ distribution to data ($\mathbf{m_T}$ is used for **2HDM+a**)



$$m_T = \sqrt{2 p_{\ell\ell}^T p_T^{miss} [1 - \cos \Delta\phi(\vec{p}_T^{\ell\ell}, \vec{p}_T^{miss})]}$$







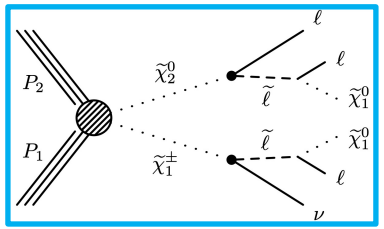
- Categorize the signal regions by **0 or 1 jet**
- Limits are set on the $\mathbf{m_a}$ at 95%
- $\mathbf{m_a}$ up to 440 GeV is excluded for m_H=1 TeV

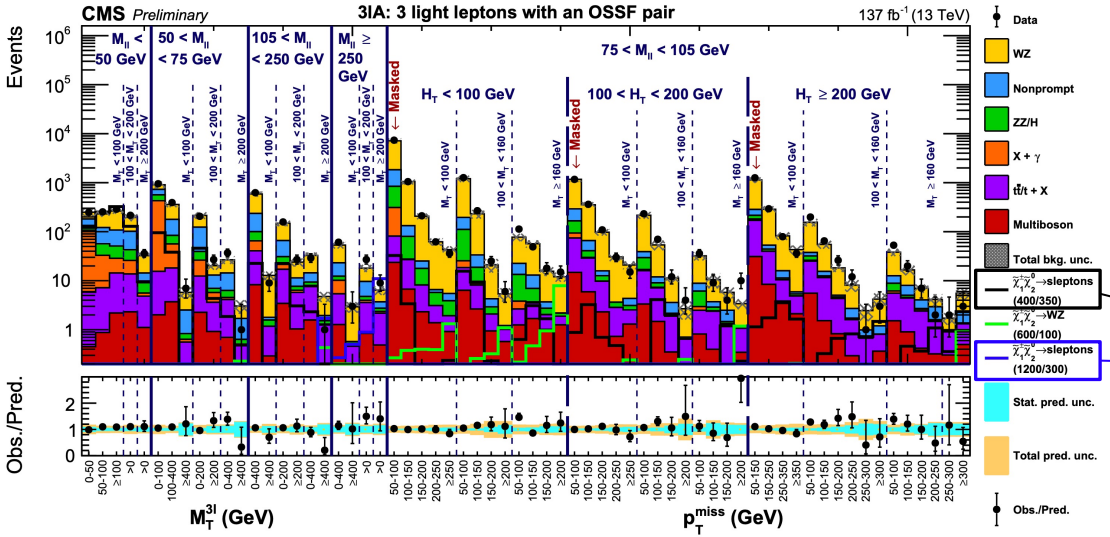
Supersymmetry

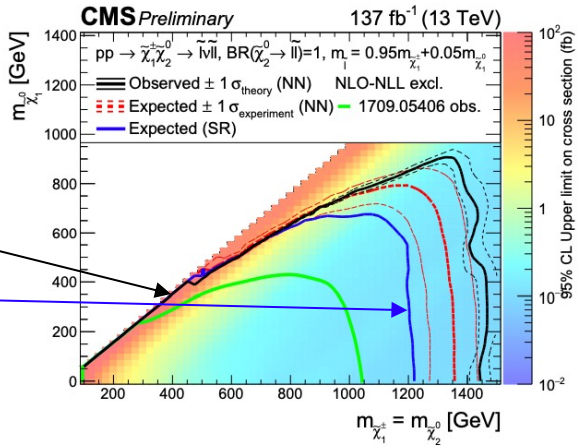
EWK SUSY production in multilepton final states

CMS-PAS-SUS-19-012

- Decay chains in electroweak SUSY production naturally yield leptonic final states, the unknown nature of “True SUSY” means it could be anywhere
- Search exhaustively: look at up to **13** different leptonic final states
- A glance of the **3 leptons channel**

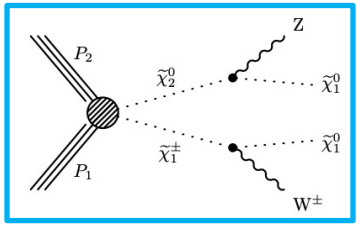






EWK SUSY production in multilepton final states

- A glance of the **2 same-sign leptons channel**



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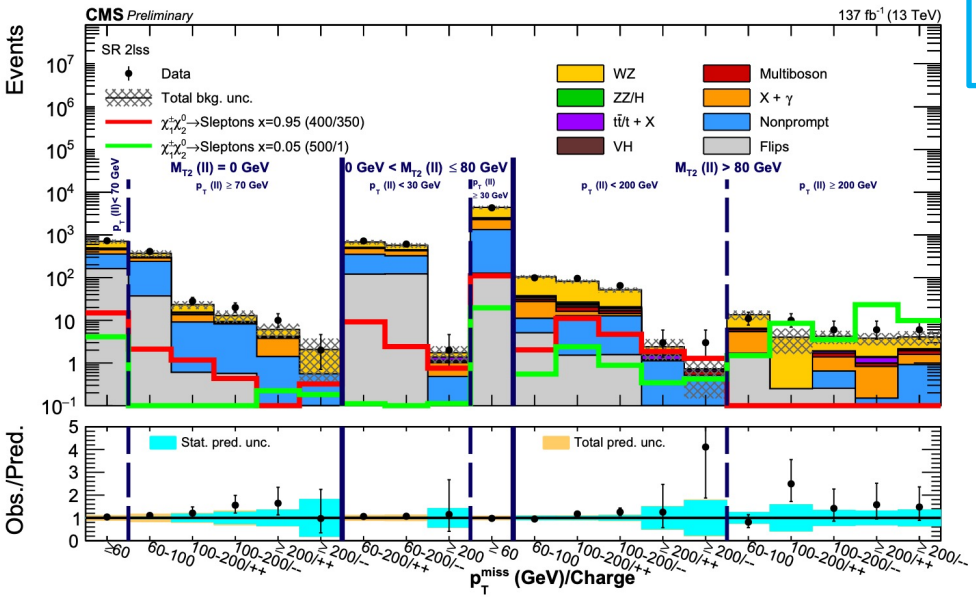

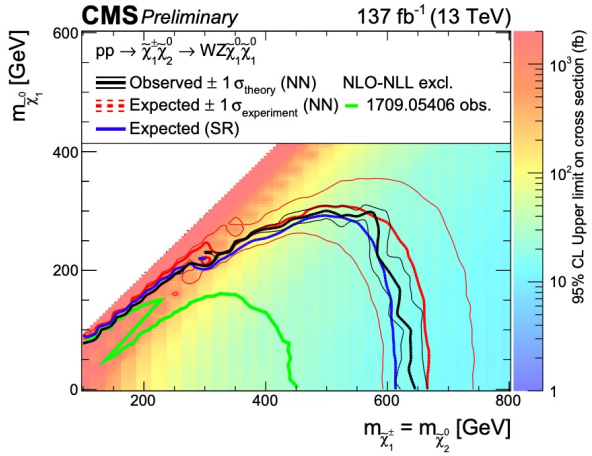

- Final states with a ss lepton pair are quite clean SM-wise, and can be home to more compressed SUSY
- The problem is dealing with “non-prompt” leptons: use a dedicated and precise data-driven estimation

Summary and Outlook

- CMS is highly active in BSM searching with leptons and photons
- Many BSM models are explored, e.g., the Higgs sectors, exotic heavy resonances, extra dimensions, supersymmetric theories, and dark sector extensions, …
- Limits can often be easily reinterpreted between several BSM models
- No significant deviation from SM expectation is observed
- Still many degrees of freedom left to explore!
- Run III offers the chance to search for new models, update background methods and tools!

Backup

Dark photon: VBF + Higgs ($\gamma\gamma_D$)

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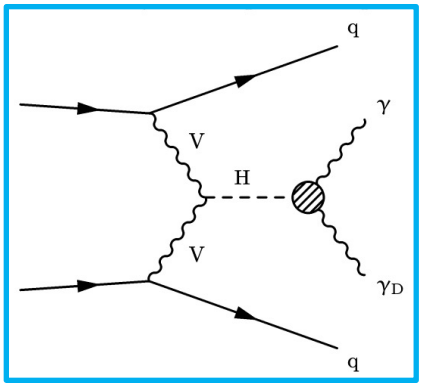
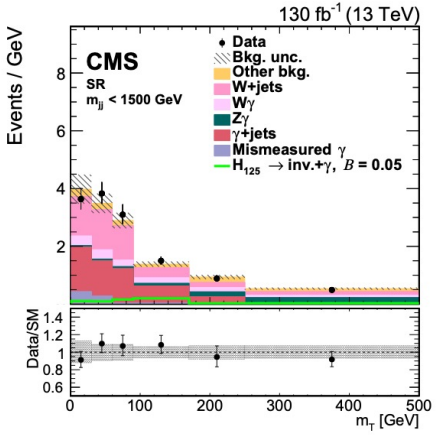
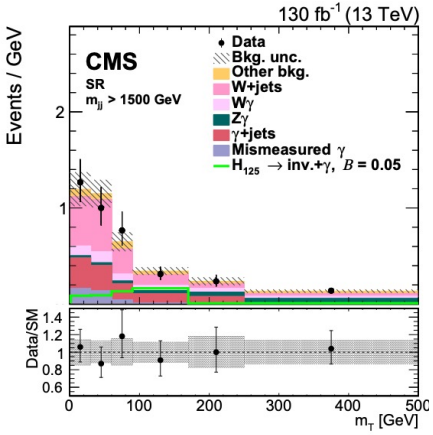
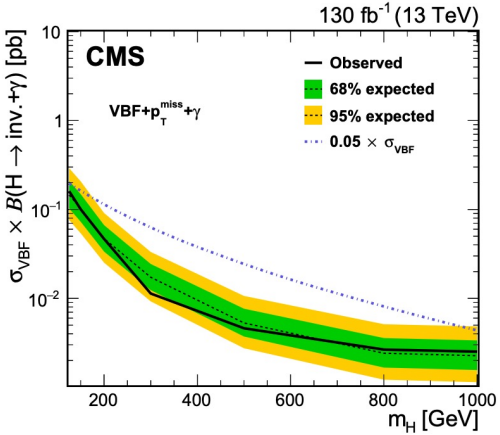
- The final-state quarks (q) arise from the **VBF** process and γ_D is a **massless dark photon** that couples to the Higgs boson through a dark sector
- Signal region requires **VBF, lepton veto, jet multiplicity**, and **geometrical cut** between and jets
- Divide the regions by : **< 1500 GeV** and **> 1500 GeV**



$$m_{\mathrm{T}} \equiv \sqrt{2p_{\mathrm{T}}^{\mathrm{miss}} p_{\mathrm{T}}^{\gamma}[1-\cos(\Delta\phi_{\vec{p}_{\mathrm{T}}^{\mathrm{miss}},\vec{p}_{\mathrm{T}}^{\gamma}})]}$$







- Upper limits at 95% CL on the product of σ_{VBF} and B(H → inv. + γ) as a function of m_H
- From 160 to 2 fb, for m_H within 125 GeV and 1000 GeV

Two-Higgs-doublet model: H→ aa→μμττ

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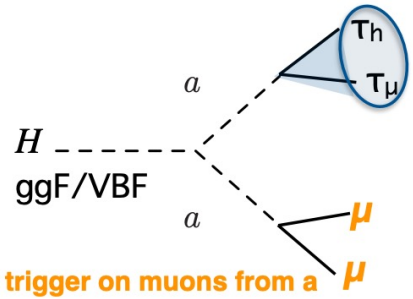
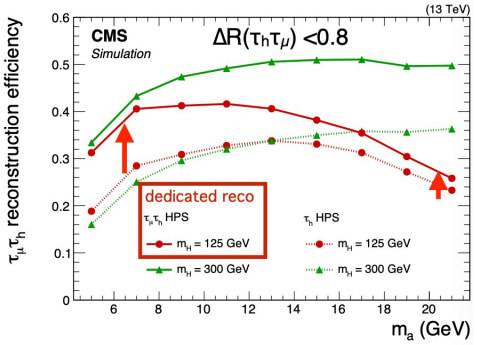
- Two-Higgs-doublet model are simple extensions of the SM
- Further extension 2HDM+S: possible search for $h \rightarrow aa$ (a pseudoscalar)
  - $\tau_h\tau_\mu$ final state chosen for high reco efficiency and a low misidentification probability
  - 3.6<ma[GeV]<21

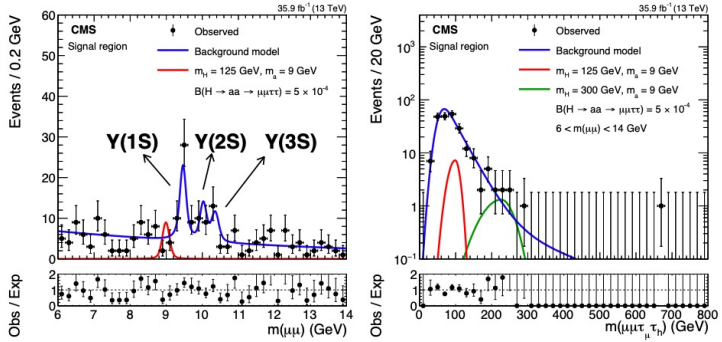


- Background constrained in a 2D unbinned fit to $m_{\mu\mu}$ vs $m_{\mu\mu}\tau_h\tau_\mu$ in 3 $m_{\mu\mu}$ fit
- Limits are set at 95% C.L., as a function of m_a, on the branching fraction ($\mathcal{B}$) for H → aa → *μμττ*

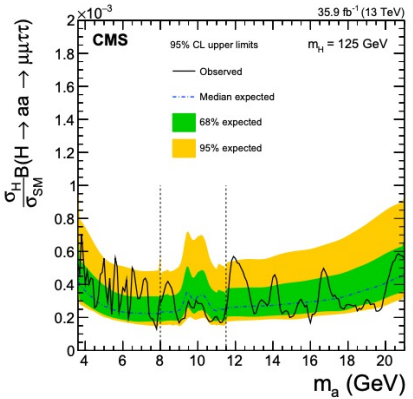
Dedicated reconstruction method



Background constrained



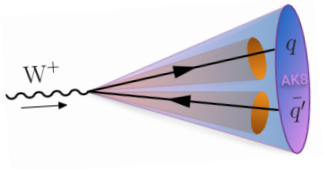
Limits are set at 95% C.L.

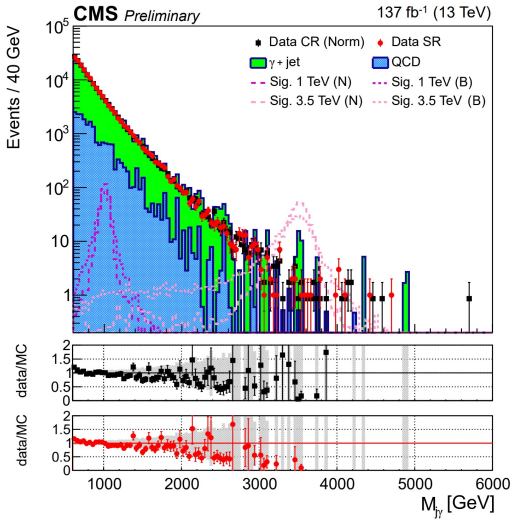


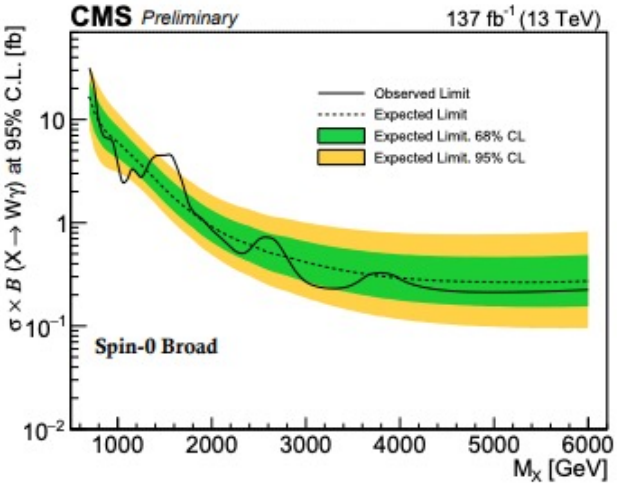
Wγ Resonances

CMS-PAS-EXO-20-001

- **X/W' → Wγ:** appears in many different models
  - Spin 0 or 1; narrow or 5% broad resonances
- Hadronic decay of the W identified with jet substructure
- $\mathbf{m_{jγ}}$ distribution fitted by the parametric function
- Limits set on σ × B(X → Wγ): 0.11–35 fb





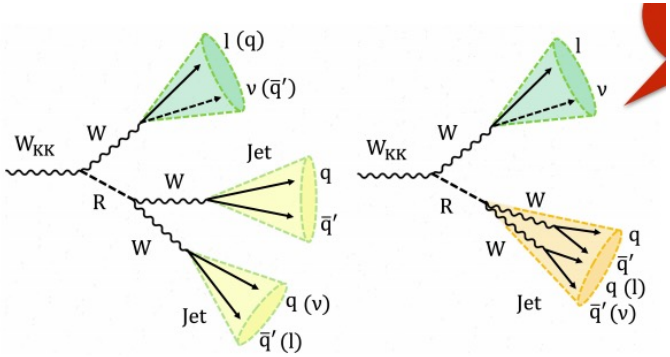


Other heavy resonance

CMS-PAS-B2G-20-001

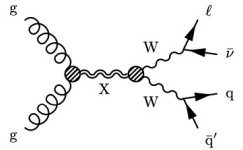
- **First triboson resonance search (WWW)**

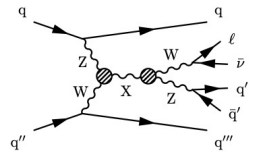
See Xudong's Talk

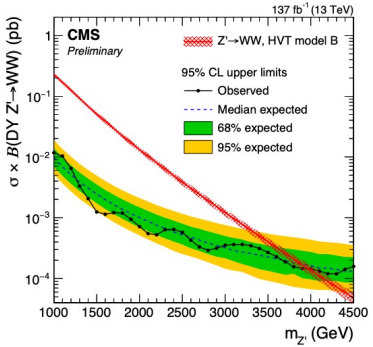


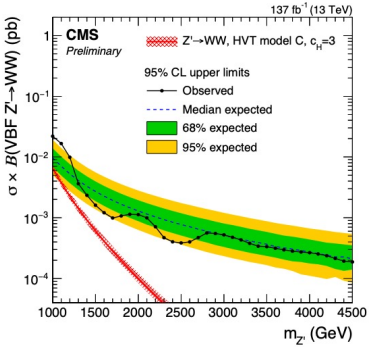
CMS-PAS-B2G-19-002

- **X → W V/H → lν qq/bb**
- 2-dimensional fit in hadronic V/H jet mass and W+V invariant mass distributions





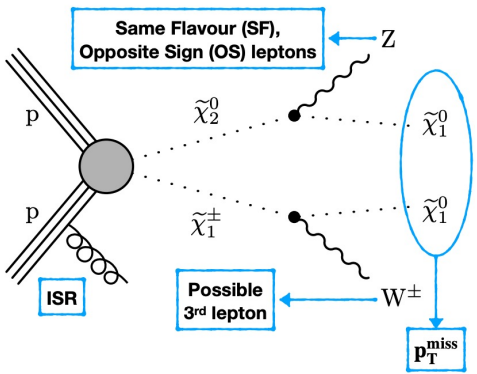




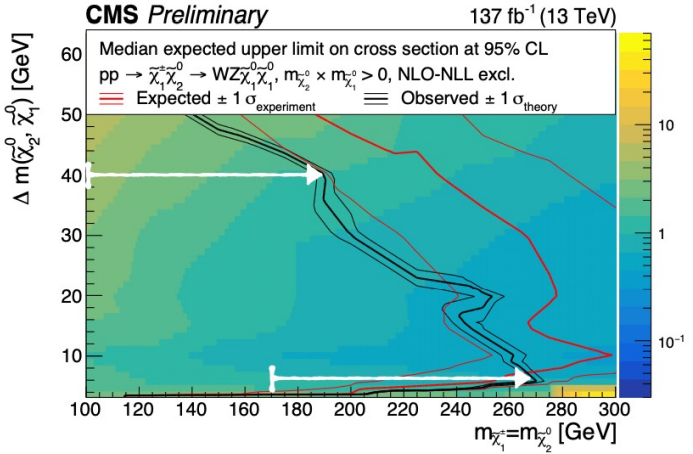
Compressed SUSY models in leptonic final states

CMS-SUS-PAS-18-004

- Soft 2ℓOS & 3ℓ Final States
- Signal
  - ISR jet: Boost to final state objects
  - Z*/W* leptonic decays
  - Isolated, tight-IP, soft leptons
  - $M_{\ell\ell}$ down to 1 GeV



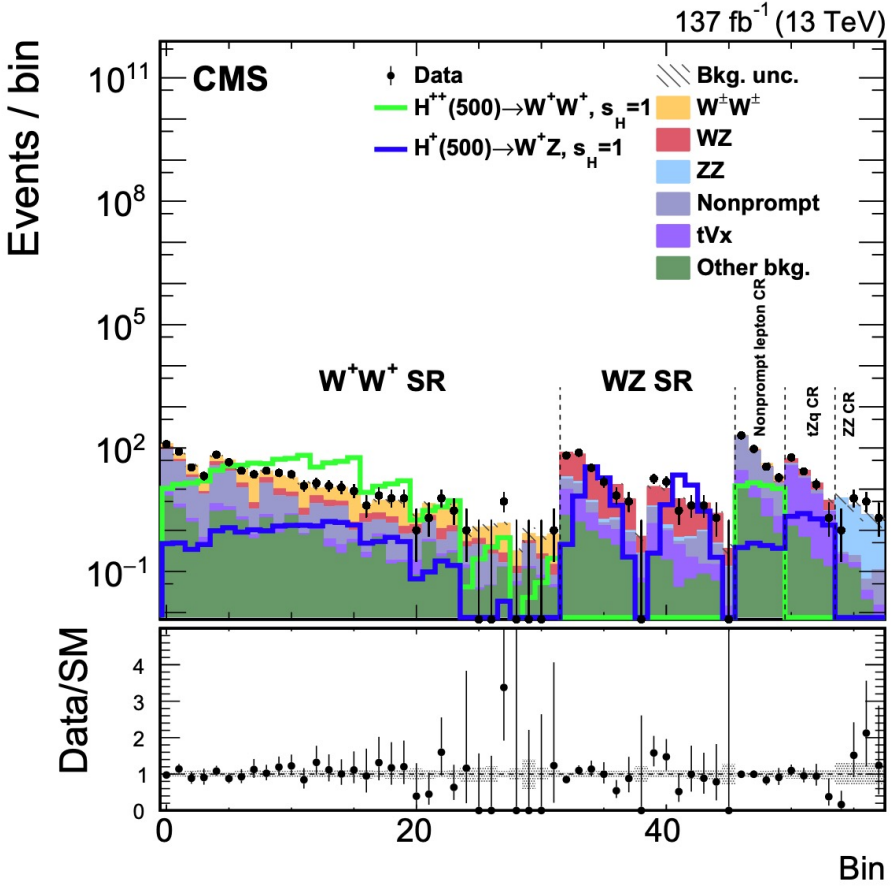
- **Wino/Bino Interpretation**
- Increased low-$M_{\ell\ell}$ acceptance: sensitivity down to **Δm~3 GeV**
- Optimization + Maximum acceptance: sensitivity up **m(χ_2^0) to ~300 GeV @ Δm~10 GeV**
- **3ℓ** complements the 2ℓ to **higher Δm**



Search for VBF $H^{\pm}$ and $H^{\pm\pm}$

CMS-PAS-HIG-20-017

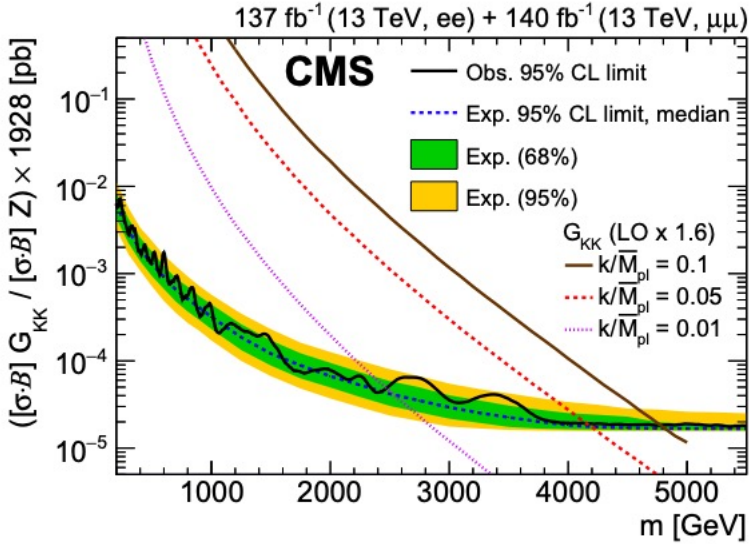
- $W^{\pm}W^{\pm}$ SR (2D)
  - 8 bins in m_T^{VV} ([0, 250, 350, 450, 550, 650, 850, 1050, ∞]
  - 4 bins in m_{jj} ([500, 800, 1200, 1800, ∞] GeV)
- WZ SR (2D)
  - 7 bins in m_T^{VV} ([0, 325, 450, 550, 650, 850, 1350, ∞] GeV)
  - 2 bins in m_{jj} ([500, 1500, ∞] GeV)
- CRs
  - 4 bins in m_{jj} ([500, 800, 1200, 1800, ∞] GeV)



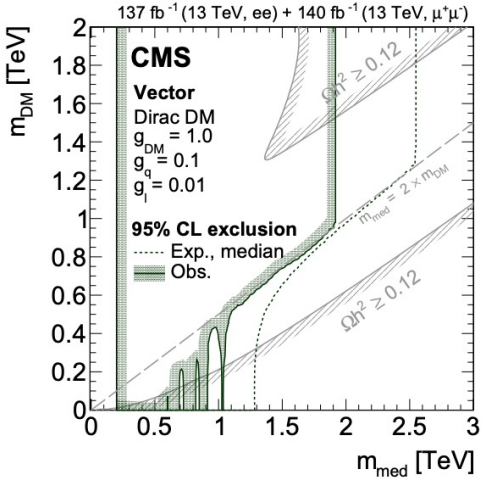
Di-Lepton Resonances

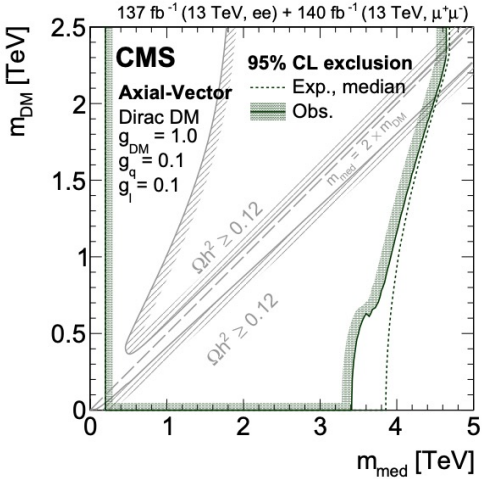
CMS-EXO-19-019

Upper limits for **a spin-2 graviton** resonances in the **Randall–Sundrum model** of extra dimensions



Exclusion limits in the mass plane of the **mediator** and **DM particles**

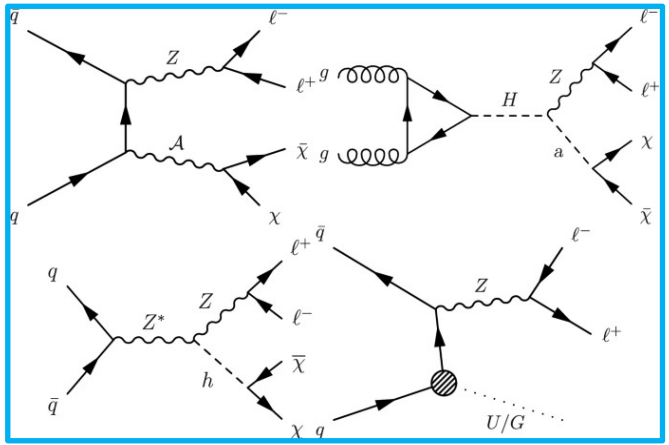


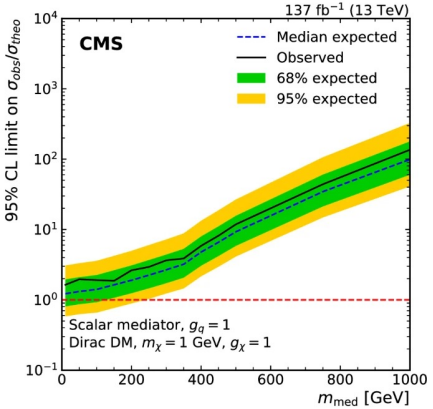


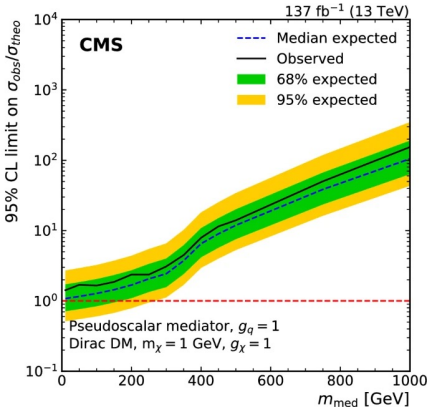
Dark matter produced in association with Z boson

EPJC 81 13 (2021)

- Several models are considered including Two-Higgs-doublet model + pseudoscalars (**2HDM+a**), **simplified DM**, **invisible Higgs** and **Graviton**







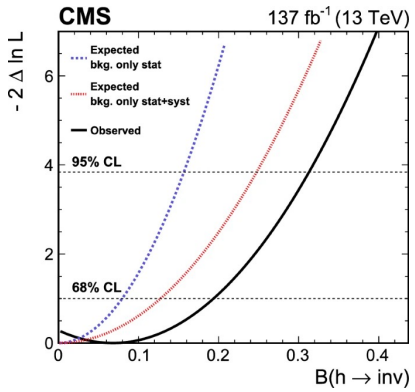
- 95% CL upper limits on the cross section for simplified DM models with scalar (upper) and pseudoscalar (lower) mediators.
- The coupling to quarks is set to g_q=1, the coupling to DM is set to g_χ=1 and the DM mass is $m\chi$=1GeV

Dark matter produced in association with Z boson

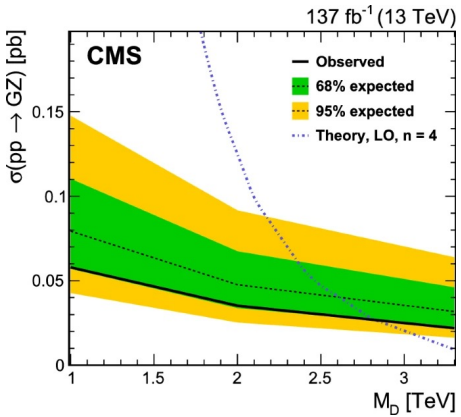
EPJC 81 13 (2021)

- Several models are considered including Two-Higgs-doublet model + pseudoscalars (**2HDM+a)**, **simplified DM**, **invisible Higgs** and **Graviton**

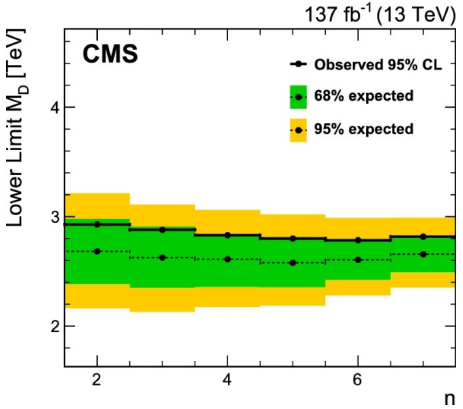
- Upper limits of branching fraction of the Higgs boson invisible decay



- The 95% CL cross section limit in the ADD* scenario as a function of M_D for n=4



- 95% CL expected and observed exclusion limits on M_D as a function of the number of extra dimensions *n*



***Arkani-Hamed–Dimopoulos–Dvali (ADD)** model of large extra dimensions. which is motivated by the disparity between the electroweak (EW) unification scale and the Planck scale. This model predicts graviton (G) production