



SUSY / BSM related searches and hints / anomalies in CMS

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National and Kapodistrian University of Athens
on behalf of the CMS Collaboration

The 30th International Conference on Supersymmetry and Unification of
Fundamental Interactions

University of Southampton, 17-21 July 2023

Outline

- Introduction
- Searches with hadronic final states
- Searches using heavy object taggers
- Searches with leptonic final states (e, μ)
- Searches with τ leptons
- Searches for unconventional signatures
- Search combinations
- Conclusions

BSM physics

- Despite its spectacular success, the Standard Model (SM) of elementary particles is believed to be only an effective low-energy theory
 - Unexplained phenomena: gravity, dark matter, dark energy, neutrino masses, matter-antimatter asymmetry
 - Unsolved theoretical problems: mass hierarchy, strong CP problem, quantum triviality, large number of free parameters

BSM physics

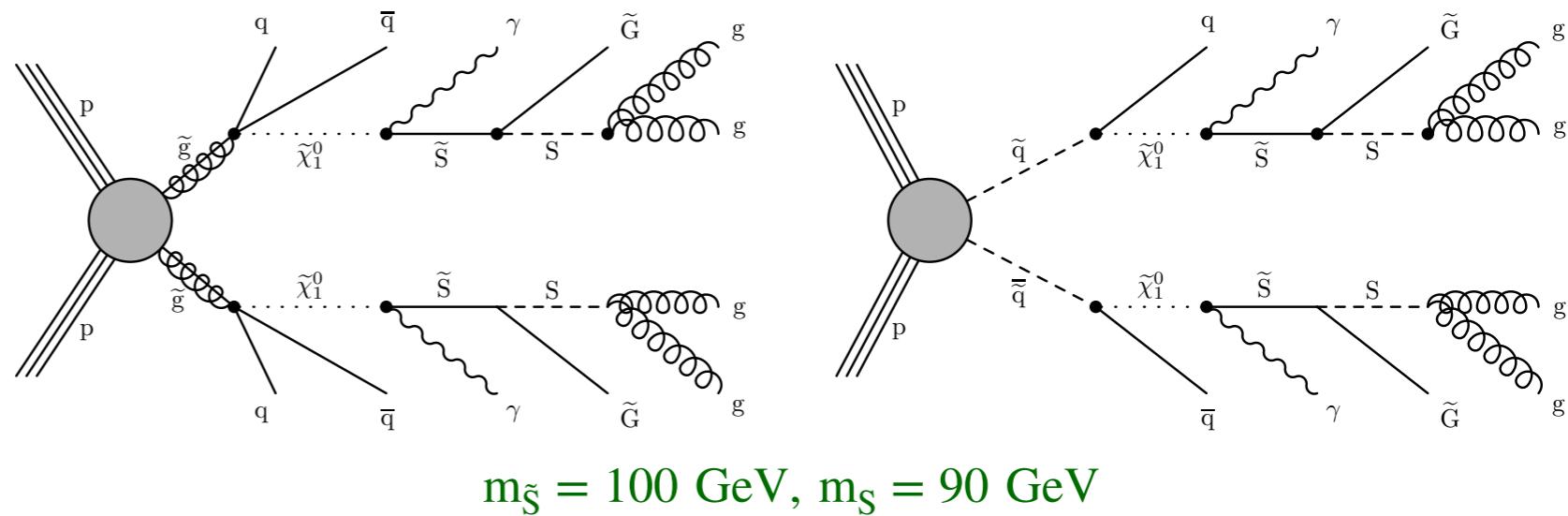
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 - ▶ SM extensions: supersymmetry, extended gauge or scalar sector, new fermions, axions, compositeness
 - ▶ New frameworks: extra dimensions, GUTs, strings, M-theory

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 - ▶ New frameworks: extra dimensions, GUTs, strings, M-theory
- CMS is pursuing an intensive program of BSM physics searches since the start of LHC operations
- The large dataset collected with CMS during Run 2 offers exciting opportunities to extend this program to more complex signatures and larger regions of the parameter space

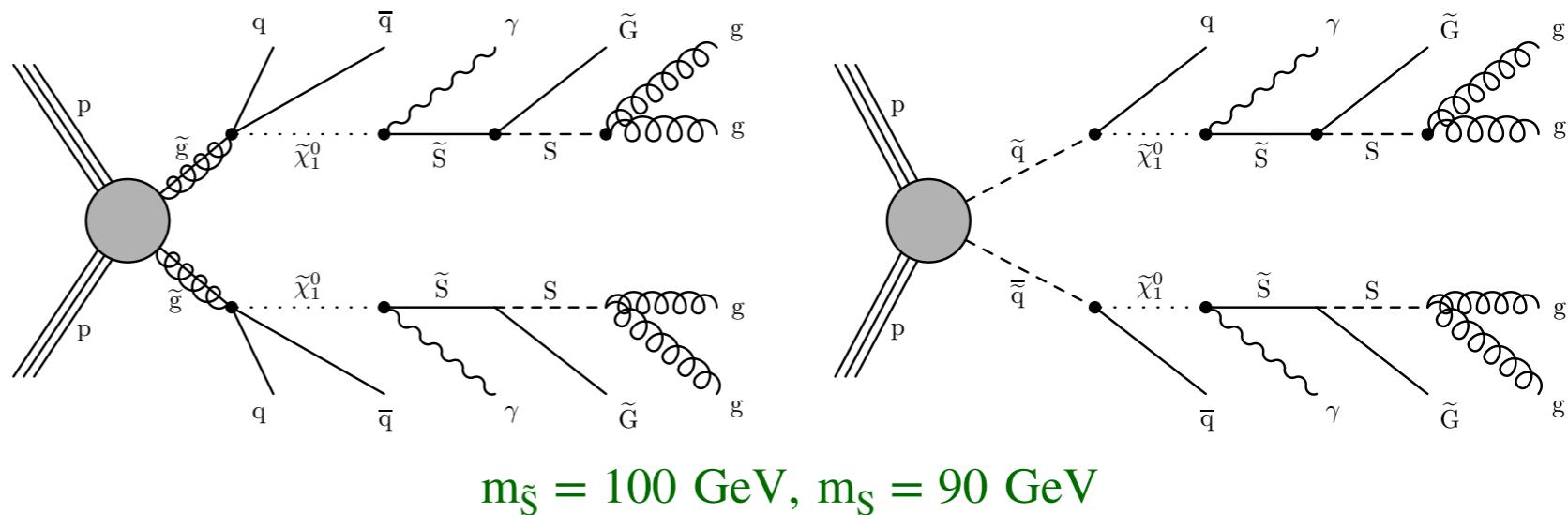
Jets and photons

- Sensitive to minimal extension of MSSM with a scalar singlet S and its super-partner \tilde{S} (singlino)
- GMSB scenario (\tilde{G} as LSP)
- $|m_{\tilde{S}} - m_S|$ small \Rightarrow no MET requirement (“stealth” SUSY)
- Extension of similar Run 1 search

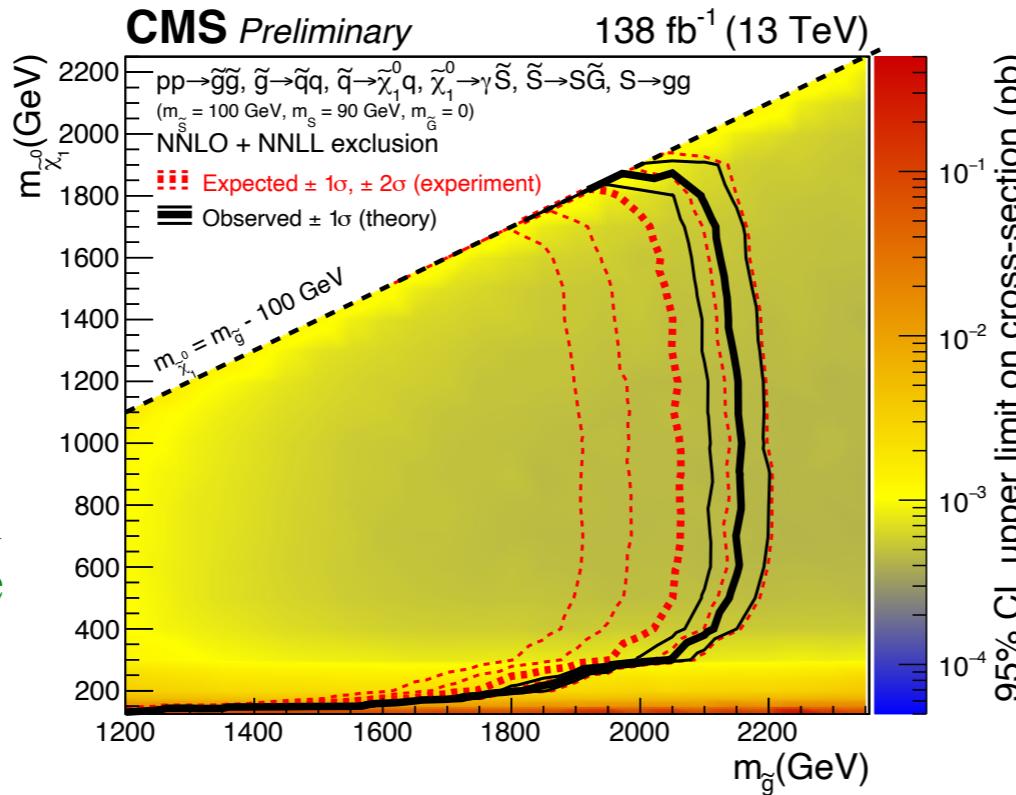


Stealth SUSY in diphoton+jets final states

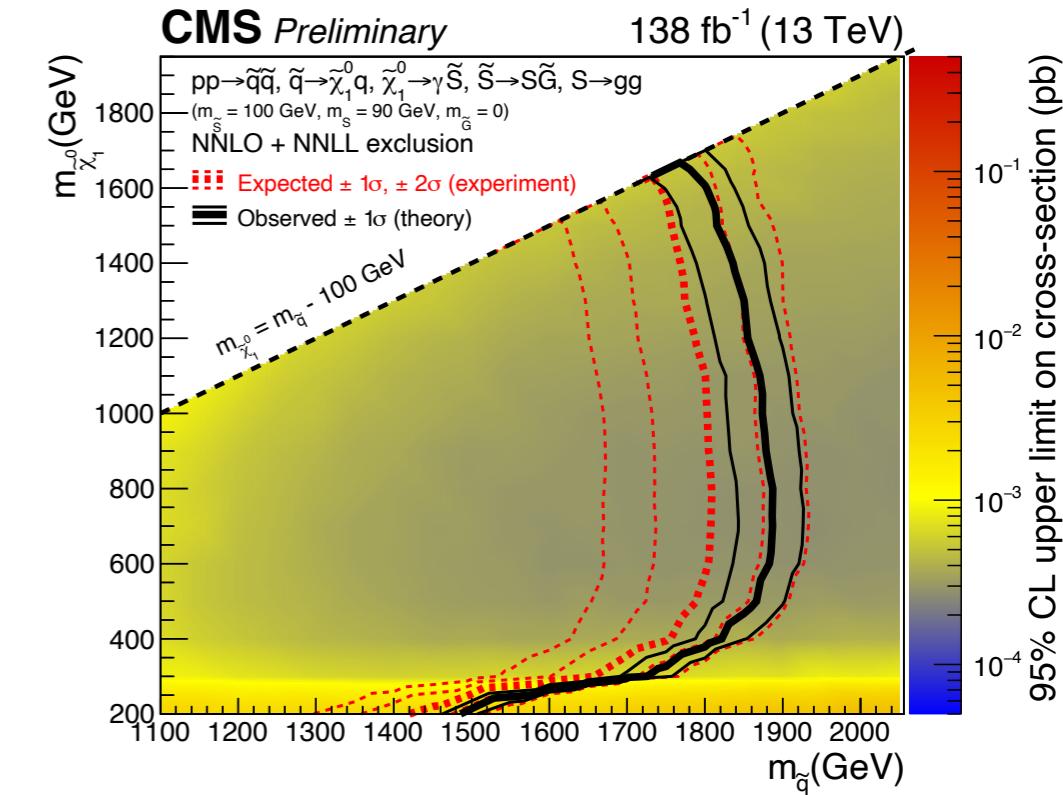
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- Exclude $m_{\tilde{g}} (m_{\tilde{q}}) < 2.15 (1.85) \text{ TeV}$
- $\sim 70\%$ improvement in the reach of the exclusion contour in the $(m_{\tilde{q}}, m_{\tilde{\chi}_1^0})$ space



Most stringent limits on these models

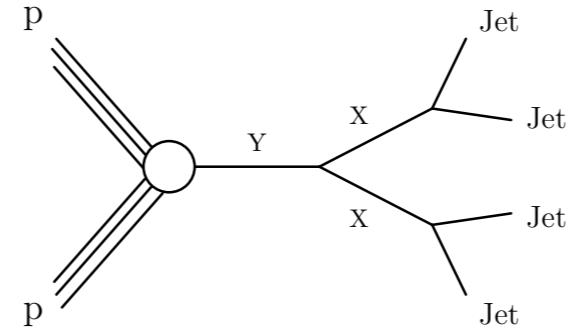


Dijet resonance pairs

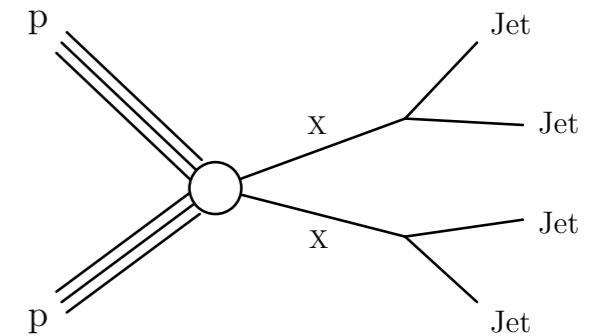
EXO-21-010

First search for resonant production of dijet resonances

Empirical QCD background functions and simulated shapes of resonance signals are fit to observed m_{4j} and m_{2j} distributions in bins of $\alpha = \bar{m}_{2j}/m_{4j}$ to eliminate correlations



Diquark benchmark model
 $uu \rightarrow S \rightarrow \chi\chi \rightarrow (ug)(ug)$



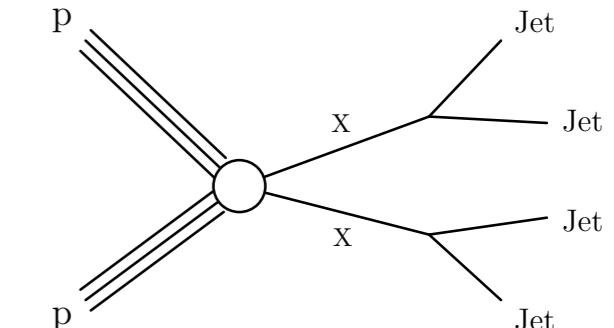
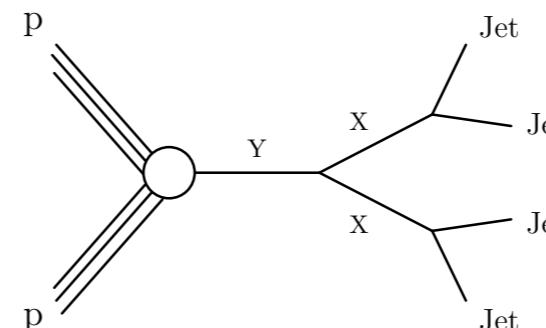
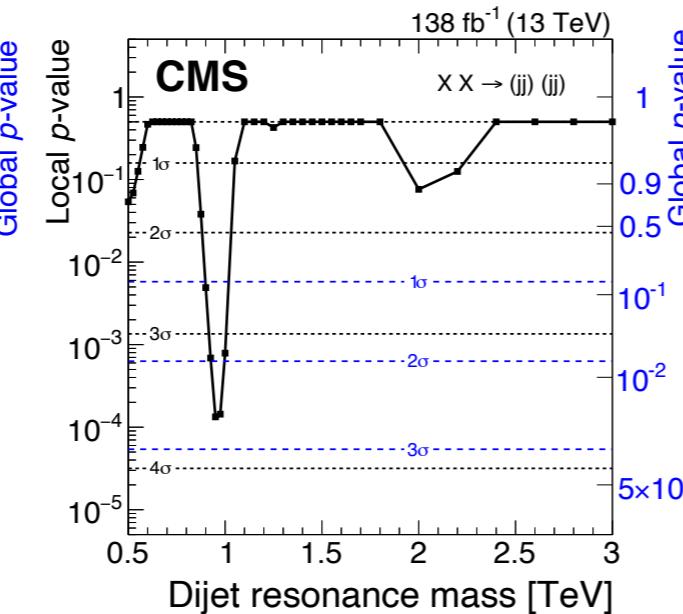
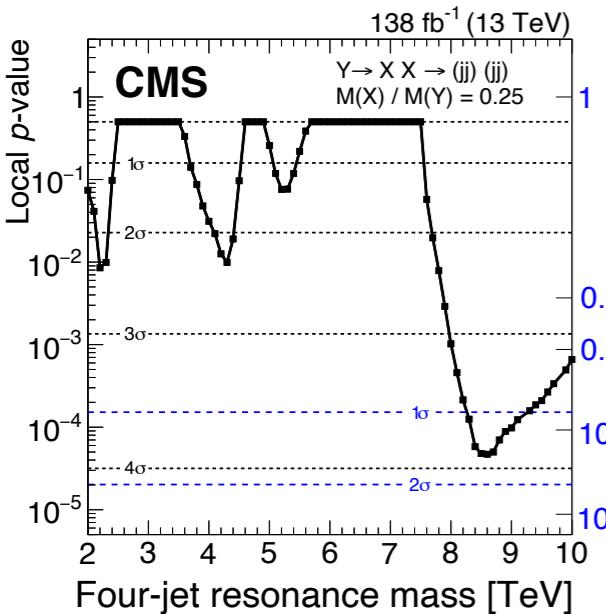
RPV SUSY benchmark model
 $pp \rightarrow \tilde{t}\tilde{t}^* \rightarrow (\bar{d}\bar{s})(ds)$

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[EXO-21-010](#)

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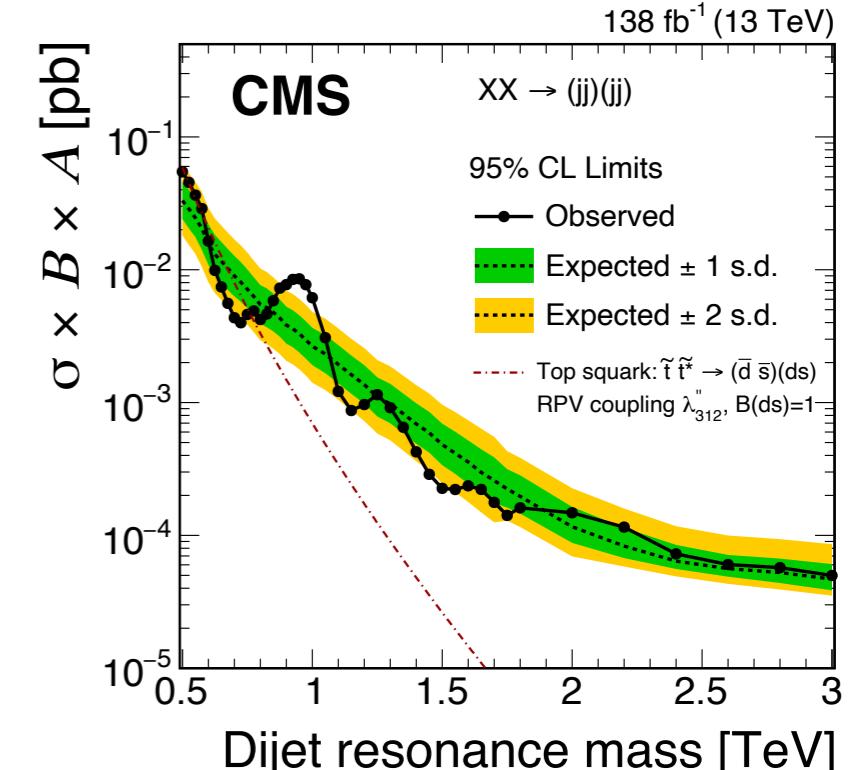
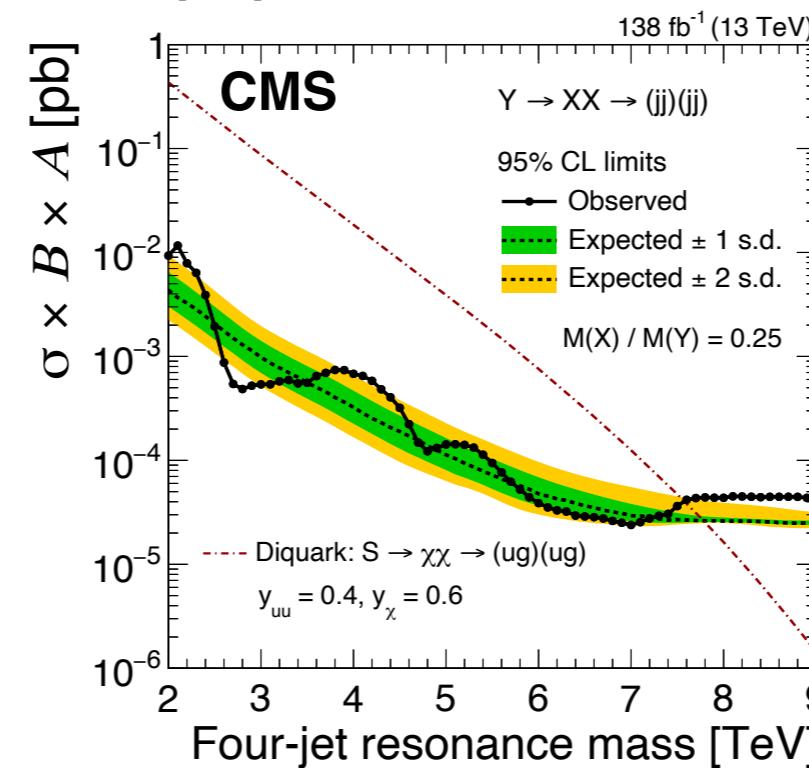
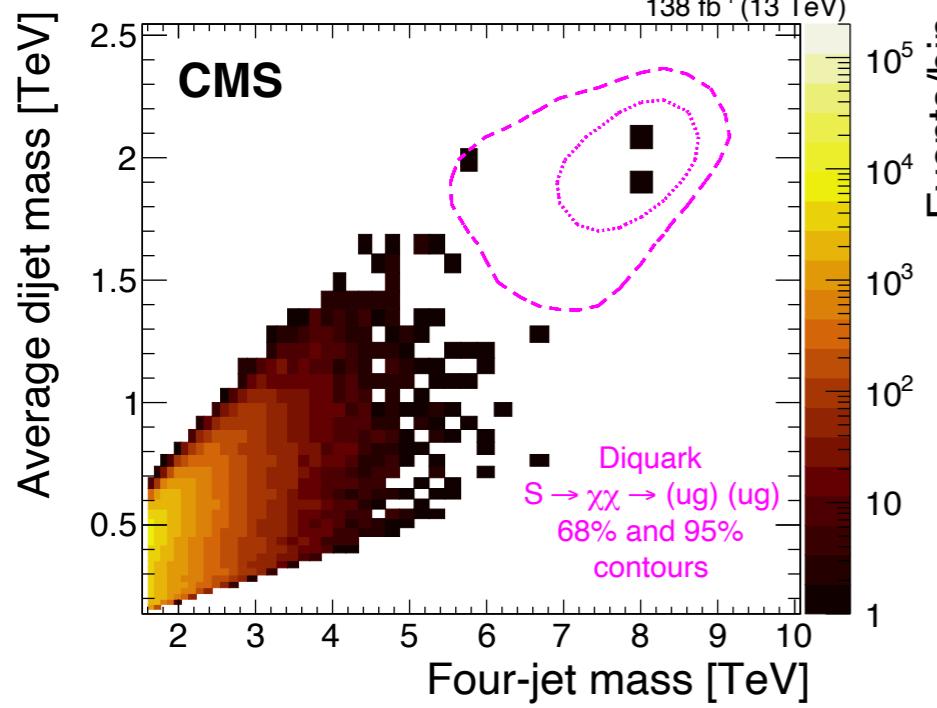
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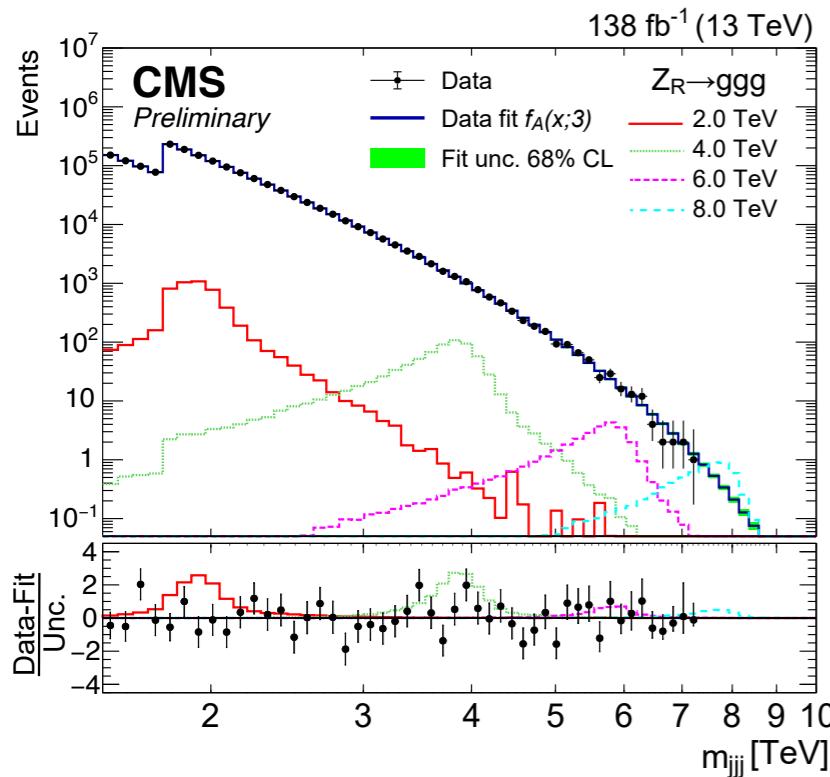
RPV SUSY benchmark model
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2 events with $m_{4j} = 8$ TeV and average $m_{2j} = 2$ TeV
result in a **3.9 (1.6) σ local (global) significance**
when interpreted as a $(m_{4j}, m_{2j}) = (8.6, 2.15)$ TeV
resonance signal → **more data needed**



First search for high-mass narrow resonances into 3 resolved jets at LHC

- Employ standard dijet resonance search techniques
- Use 2016 data up to $m_{jjj} = 2$ TeV and 2016-2018 data in $m_{jjj} \in [2, 9]$ TeV, due to higher trigger thresholds in 2017-2018
- Interpret the results in the context of $Z_R \rightarrow ggg$, $G_{KK} \rightarrow \varphi(gg)g$, and $q^* \rightarrow V(q\bar{q})q$



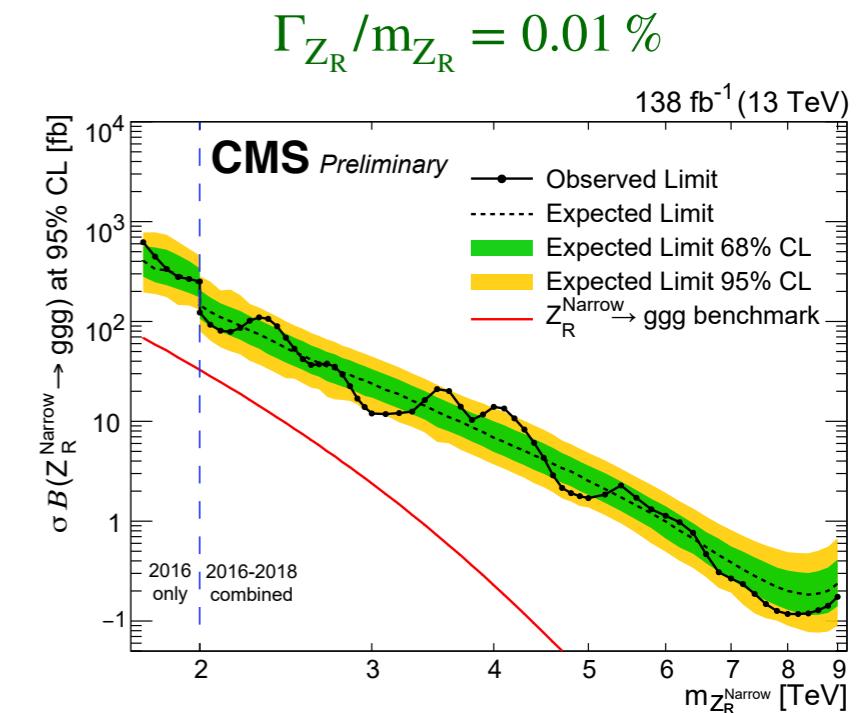
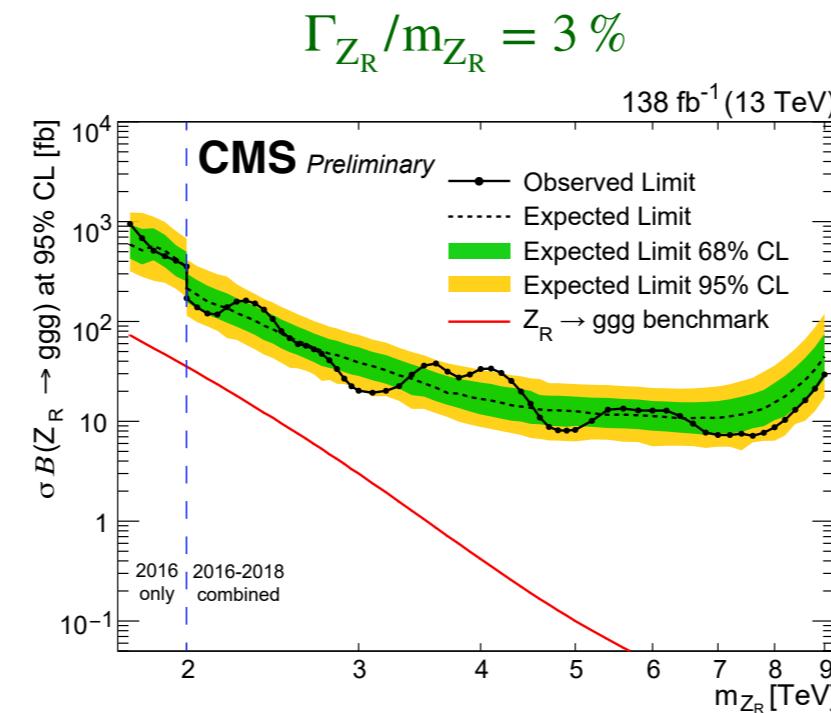
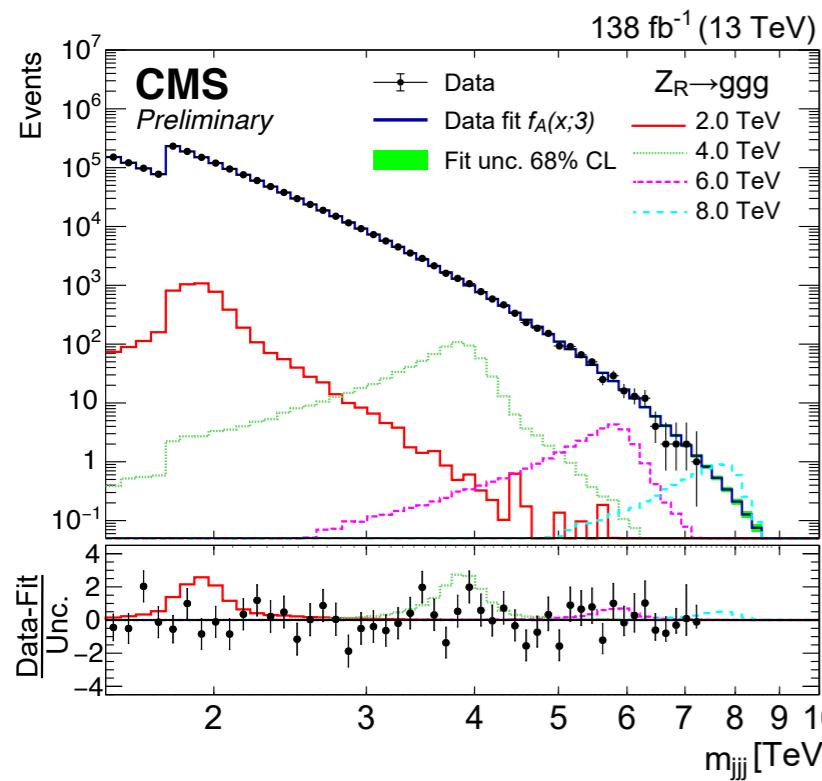
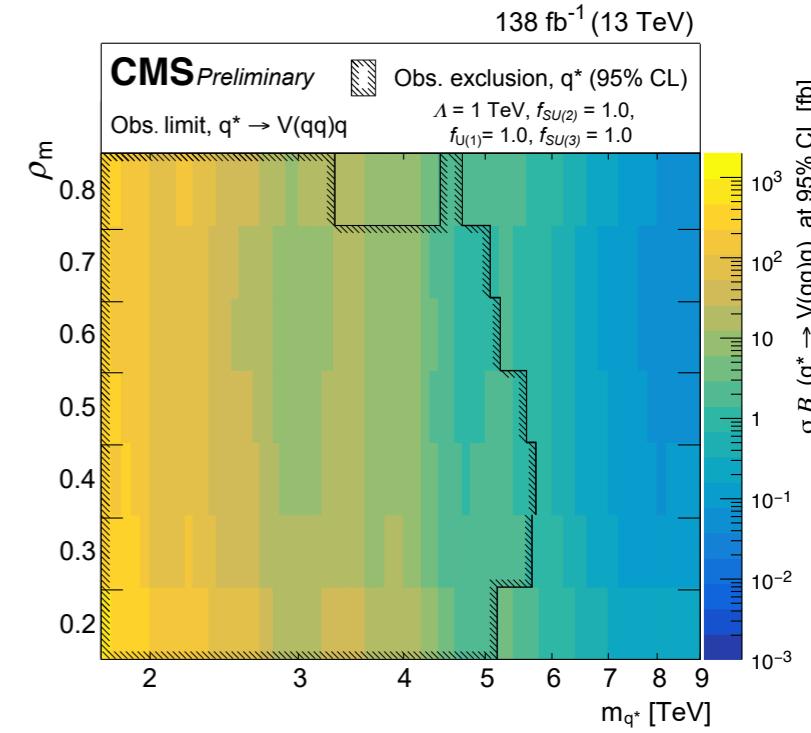
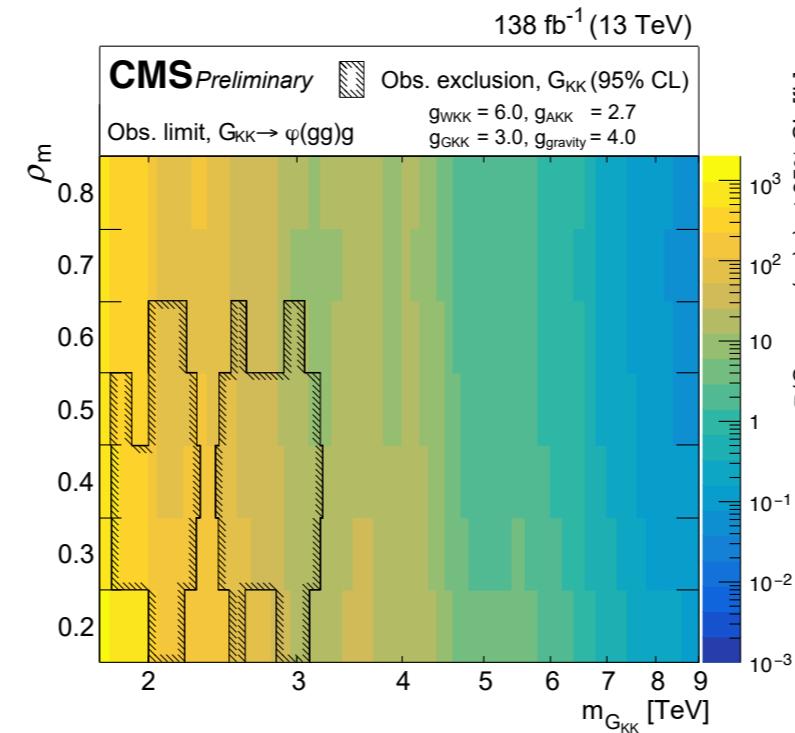
Trijet resonances

EXO-22-008

First search for high-mass resonances into 3 resolved jets at the LHC

- Employ standard dijet resonance search techniques
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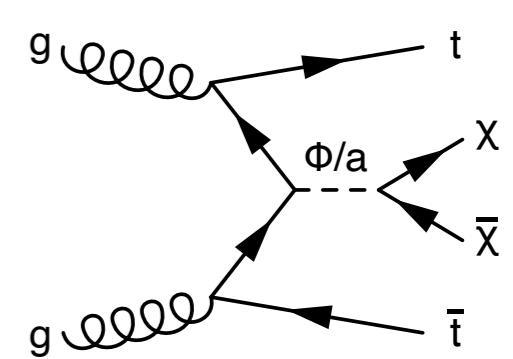
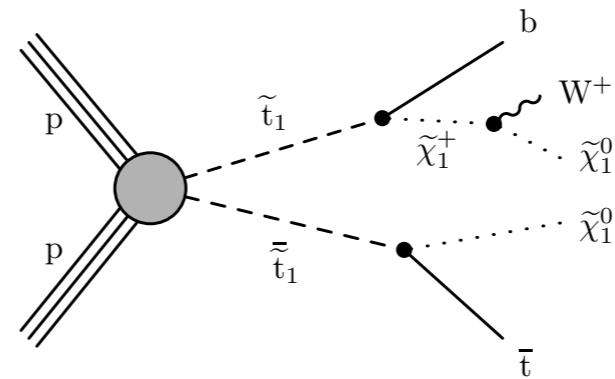
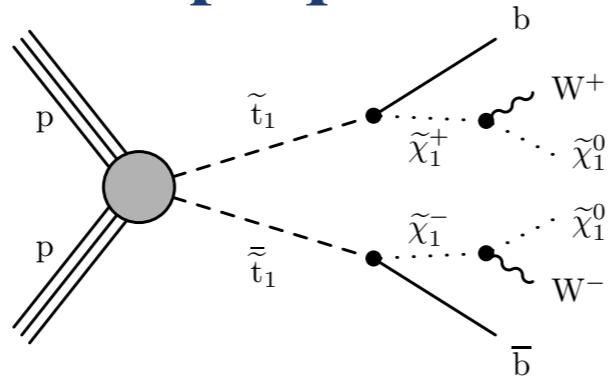
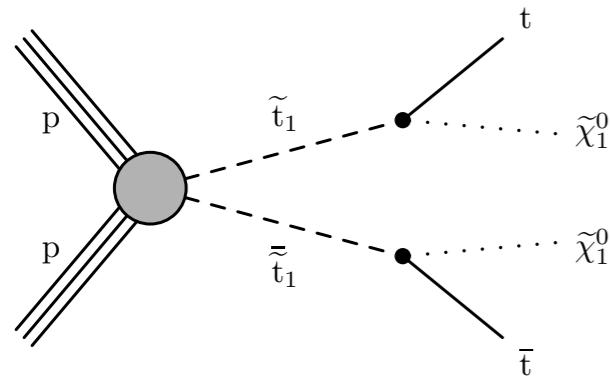
$$\rho_m = m_\varphi/m_{G_{\text{KK}}} \text{ or } m_V/m_{q^*}$$



Heavy object taggers

SUS-20-002

Top squarks “in the corridor”

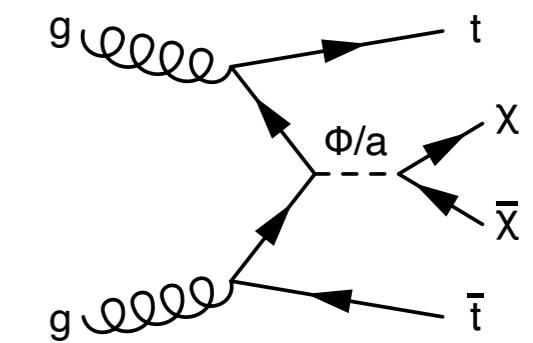
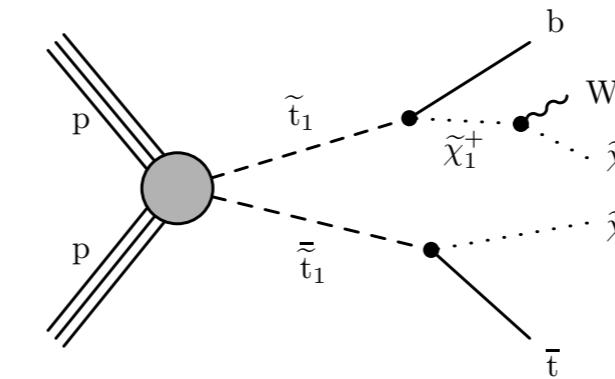
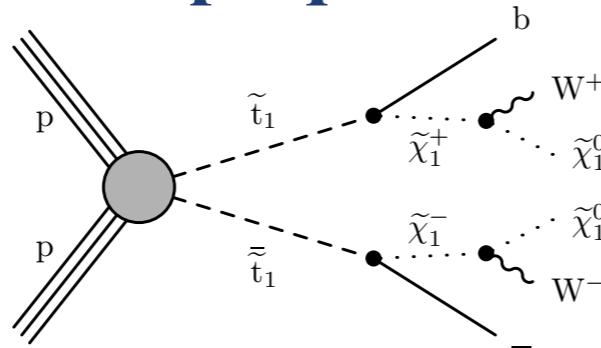
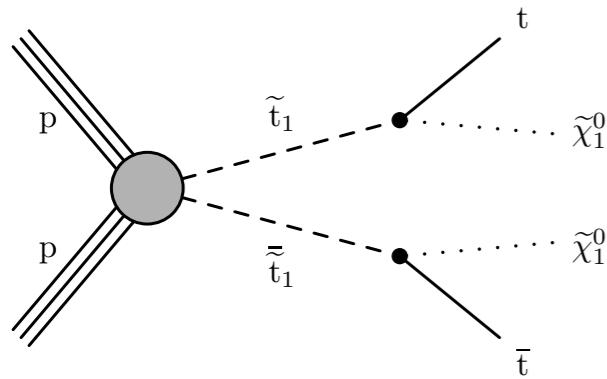


- Combination of previous searches in final states with 0, 1, 2 leptons + new search in the “corridor”* ($m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \sim m_t$), with opposite-sign dilepton final states, kinematically very similar to SM $t\bar{t}$ events
- Employ a DNN to discriminate signal in the corridor from SM $t\bar{t}$ events
- Explore alternative model $gg \rightarrow t\bar{t}\chi\bar{\chi}$ with a DM spinor χ ($m_\chi = 1$ GeV) and a (pseudo) scalar mediator ϕ (a) with couplings $g_{SM} = g_{DM} = 1$ to both visible (t) and dark (χ) sectors

* Defined with boundaries $\Delta m_{Corr} = |\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) - m_t| < 30$ GeV and $m_{\tilde{\chi}_1^0} < 275$ GeV, assuming $m_t = 175$ GeV

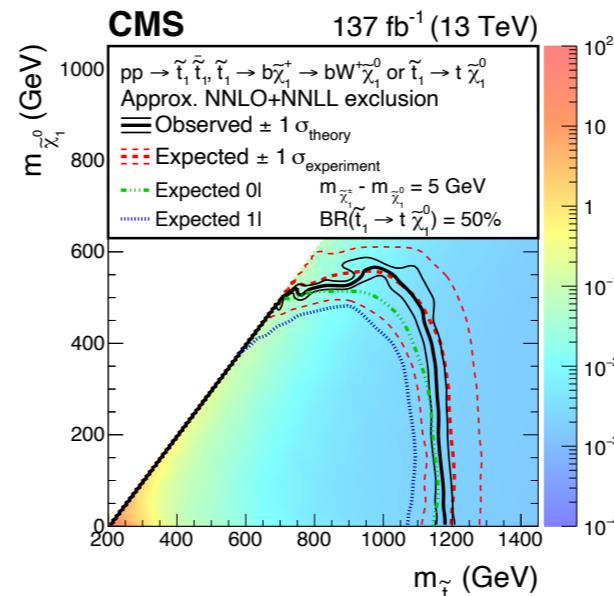
SUS-20-002

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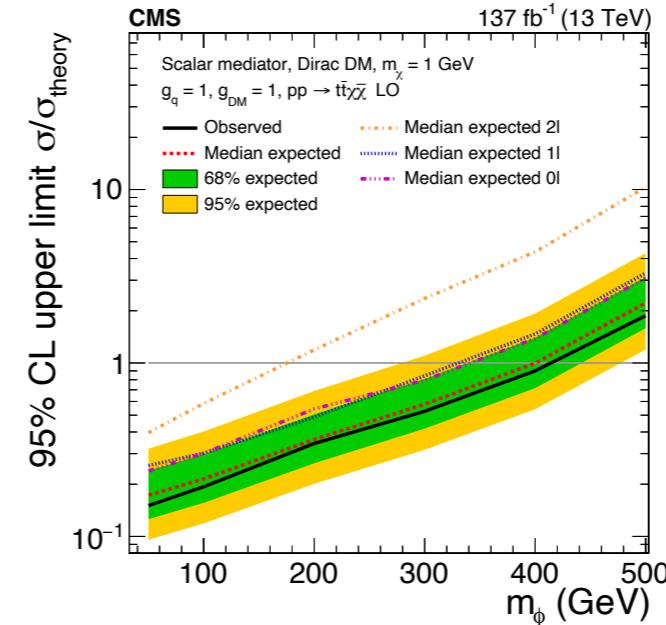
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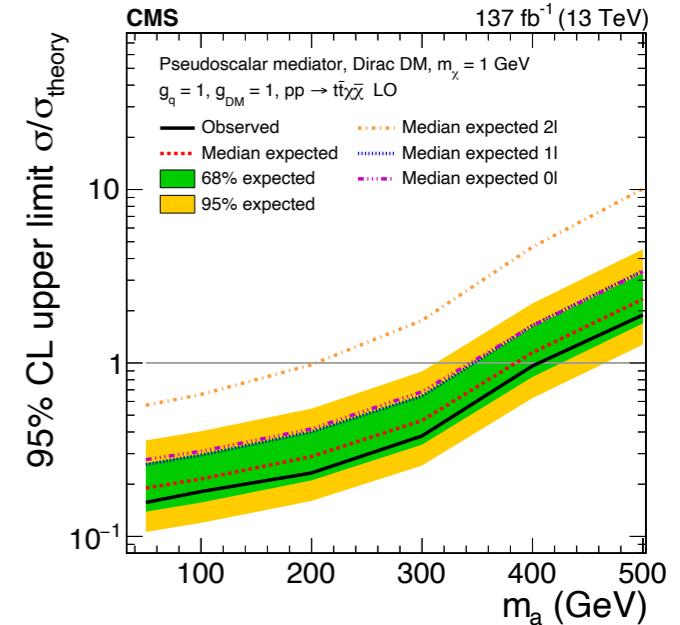


Exclude $m_{\tilde{t}_1} < 1325$ GeV ($m_{\tilde{\chi}_1^0} = 0$), $m_{\tilde{\chi}_1^0} < 700$ GeV ($m_{\tilde{t}_1} = 1150$ GeV) (combined search)

Exclude $145 < m_{\tilde{t}_1} < 295$ GeV, $0 < m_{\tilde{\chi}_1^0} < 100$ GeV in corridor, **first time with CMS data**



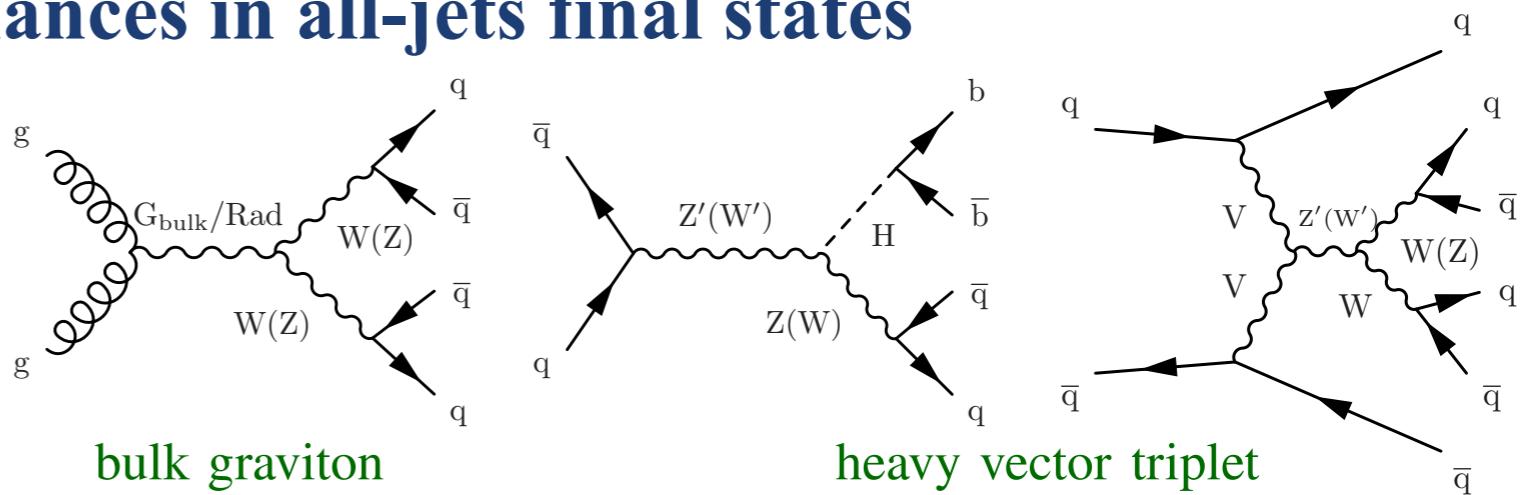
Exclude DM model for mediator masses up to 420 GeV



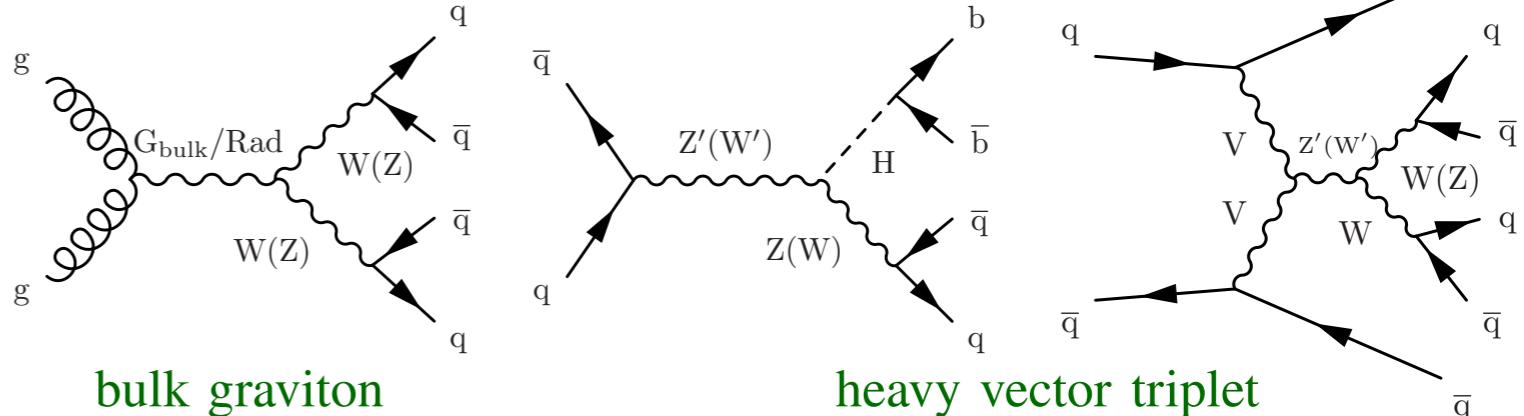
Costas Vellidis

VV / VH resonances in all-jets final states

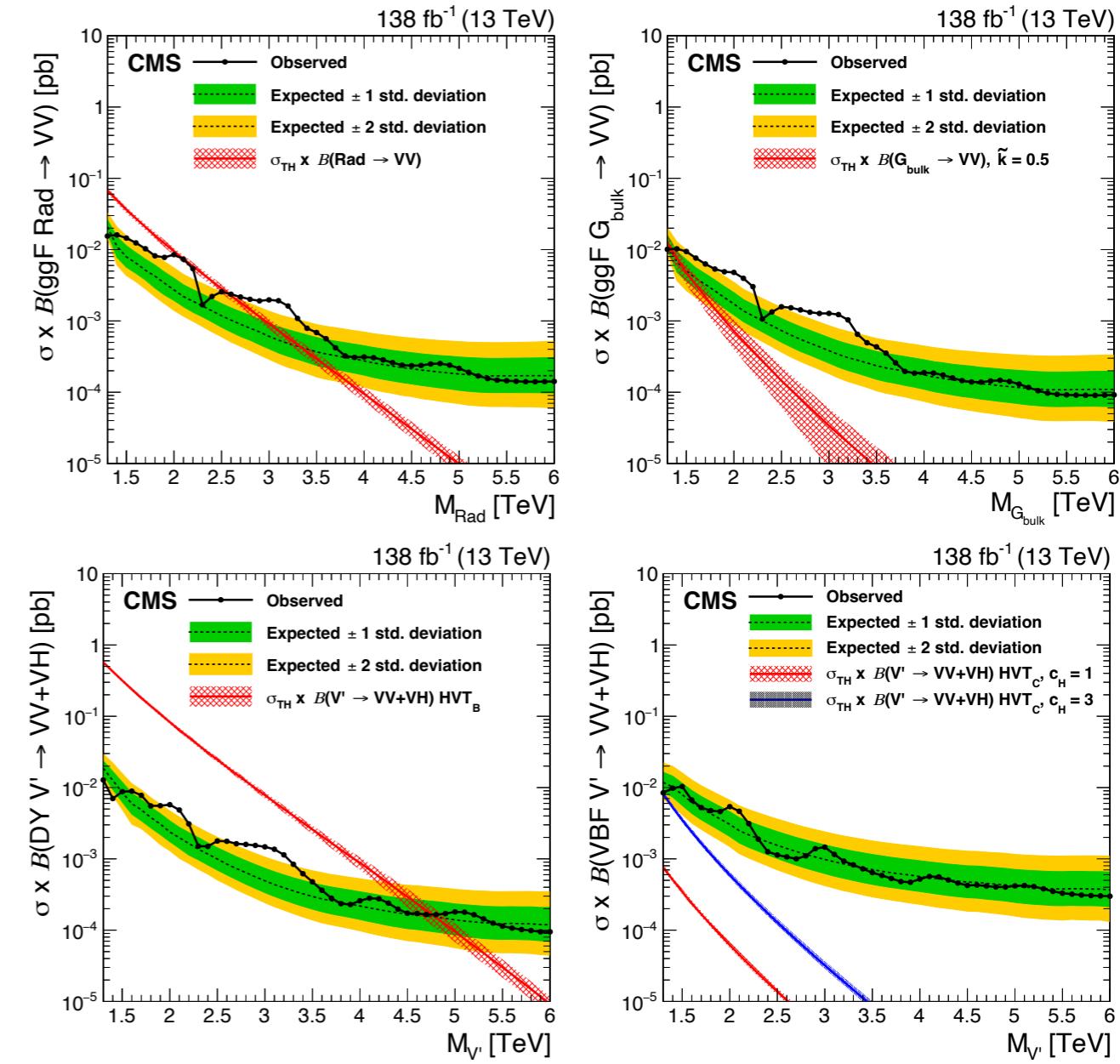
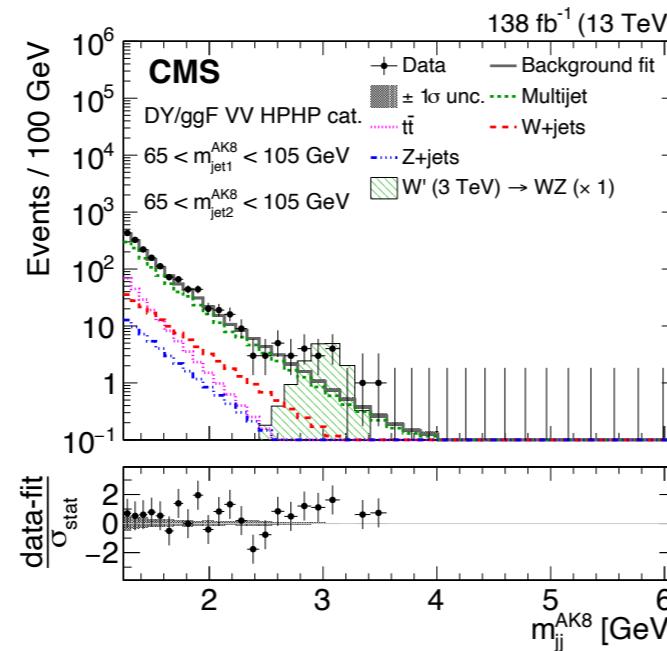
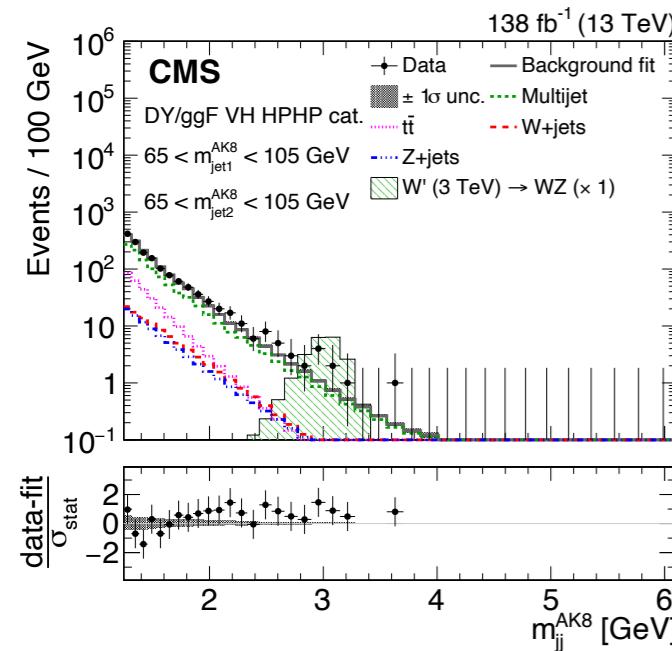
- Search sensitive to resonances with mass > 1.3 TeV, decaying to highly boosted bosons identified as fat jets with the DeepAK8 tagger
- 3D fit of signal and background templates to data in (m_{jj}, m_{j1}, m_{j2}) space reconstructed from the lepton and MET



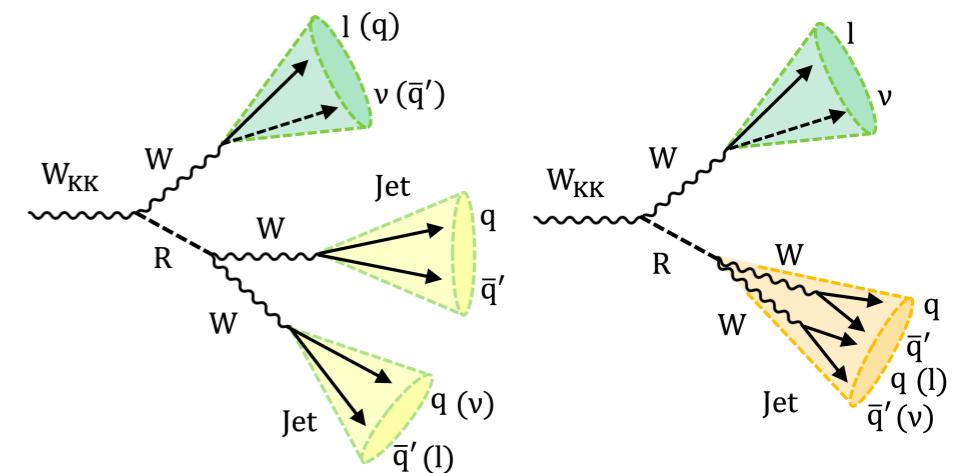
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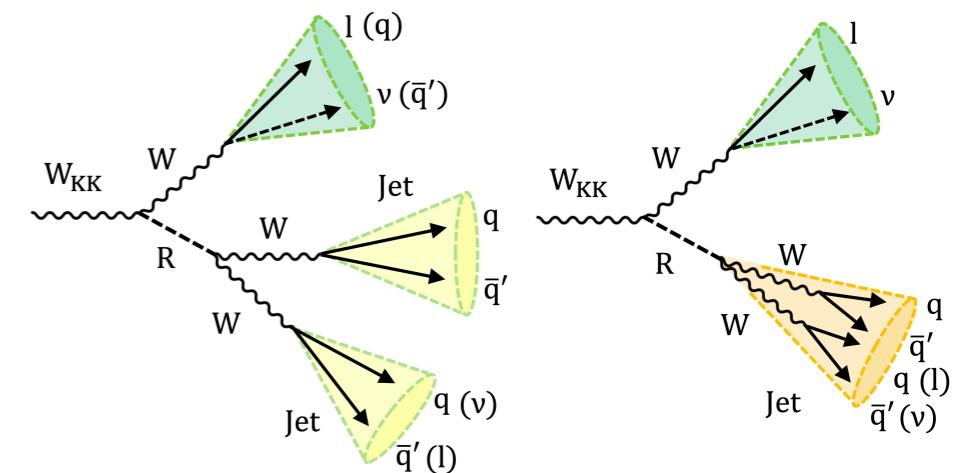
- Excess of **3.9 (2.3) σ** local (global) significance observed in the data at $m_{jj} = 2.1$ and 2.9 TeV, **not observed in semi-leptonic final states**
- Exclude $m_{V'} < 4.8$ TeV, $m_G < 1.4$ TeV, $m_{Rad} < 2.7$ TeV, and VBF resonance production cross section $\sigma > 0.1$ fb



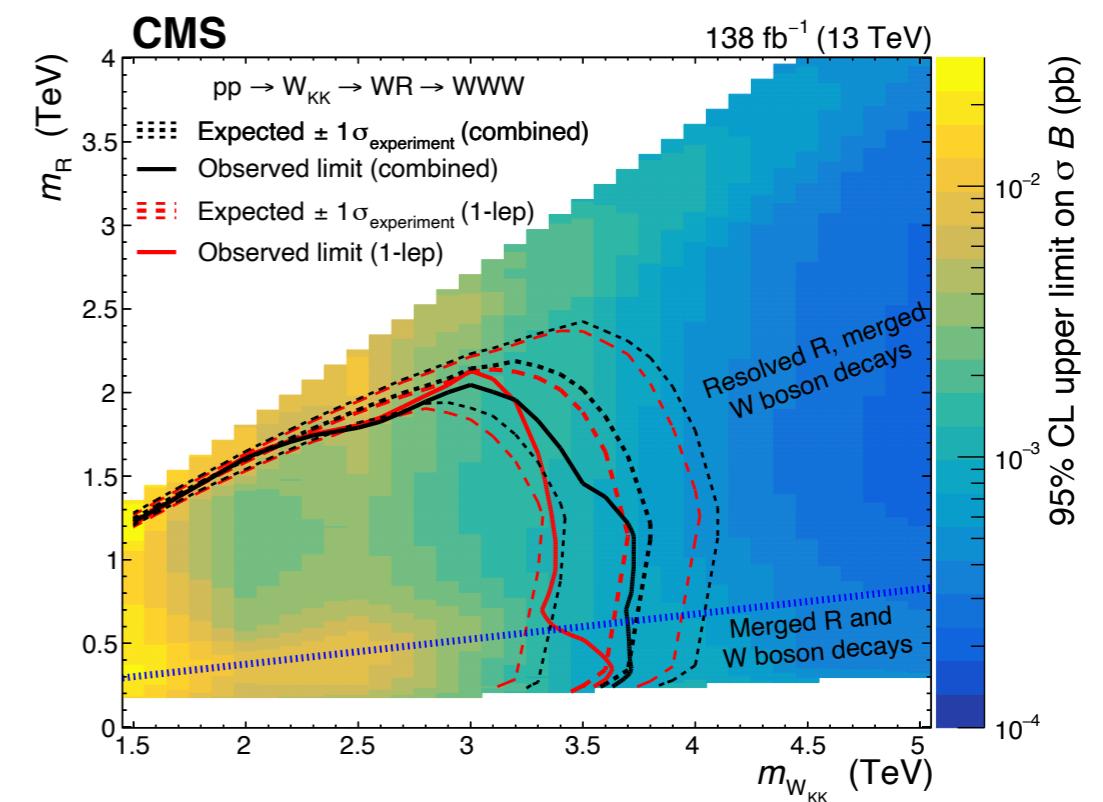
- First search for massive resonances decaying to 3 highly boosted W bosons in cascade through $W_{KK} \rightarrow WR$ and $R \rightarrow WW$
- W bosons identified as fat jets of 2 or 4 partons, with one boson decaying leptonically
- Substructure of fat jets analysed using the DeepAK8 tagger into resolved and merged $R \rightarrow WW$ decays
- Results combined with analysis of fully hadronic states ([B2G-21-002](#))



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- Data excess around $m_{jjl\nu} = 3.5$ TeV in SR6 \Rightarrow weaker than expected observed limit for the resolved signal
- The novel radion identification and calibration techniques are also applicable to boosted H decays



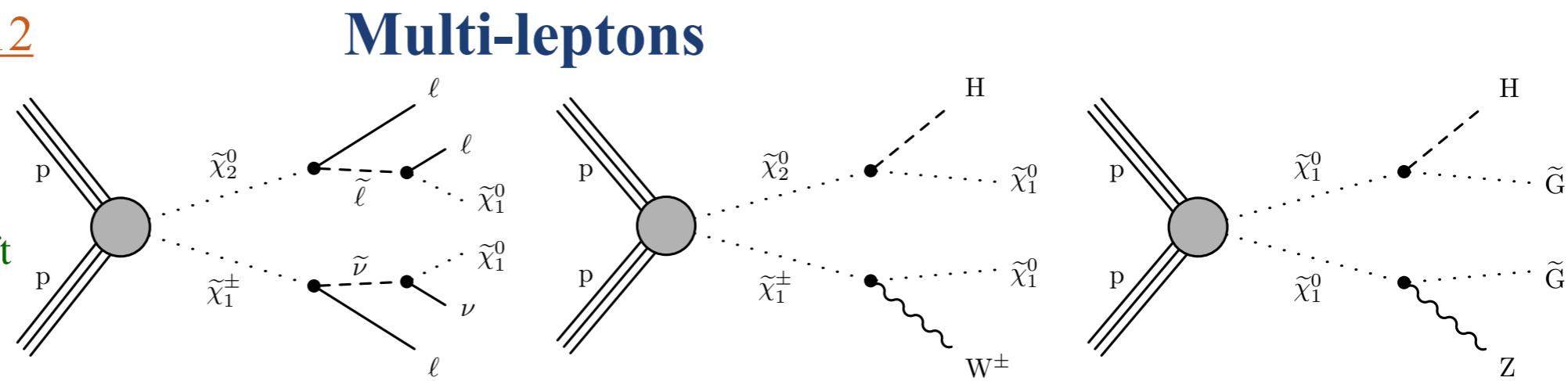
Electrons and muons

SUS-19-012

$$m_{\tilde{\ell}} = x m_{\tilde{\chi}_2^0} + (1 - x) m_{\tilde{\chi}_1^0}$$

$x = 0.5 \Rightarrow$ identical ℓ spectra

$x = 0.05$ or $0.95 \Rightarrow$ one ℓ soft



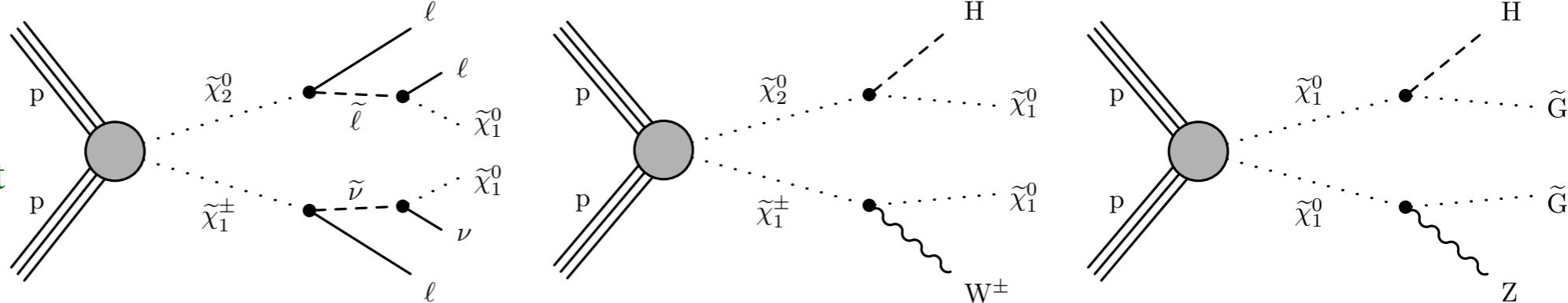
Search optimized in event categories with 2, 3, 4 leptons based on sign and flavour

Sensitive to mass-degenerate wino- or higgsino-like chargino-neutralino and to neutralino-neutralino (GMSB) production

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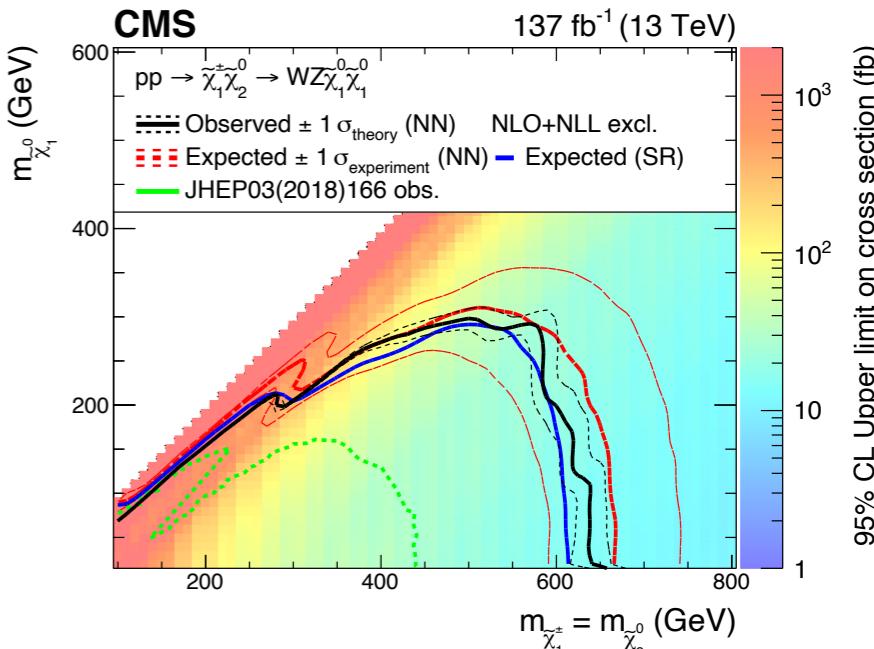
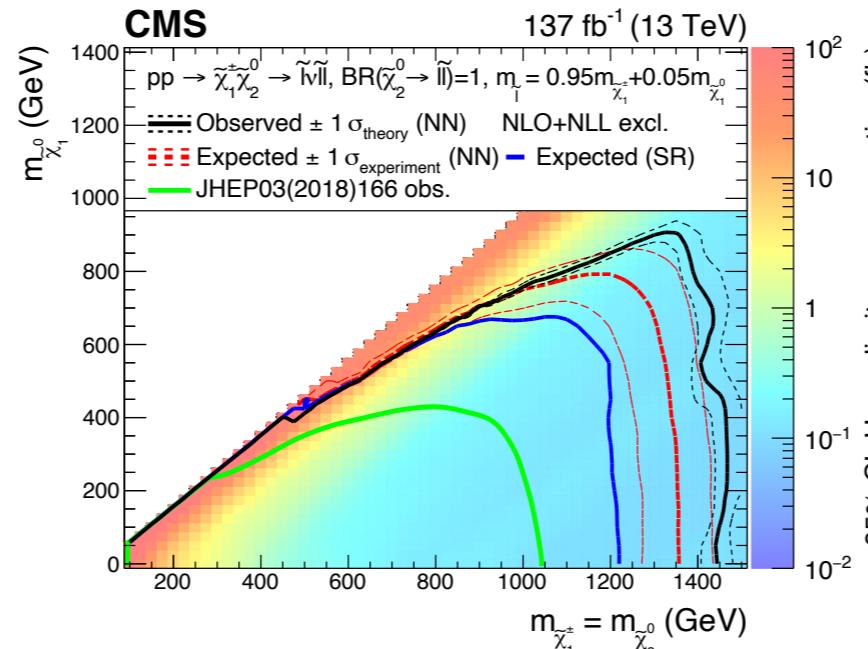
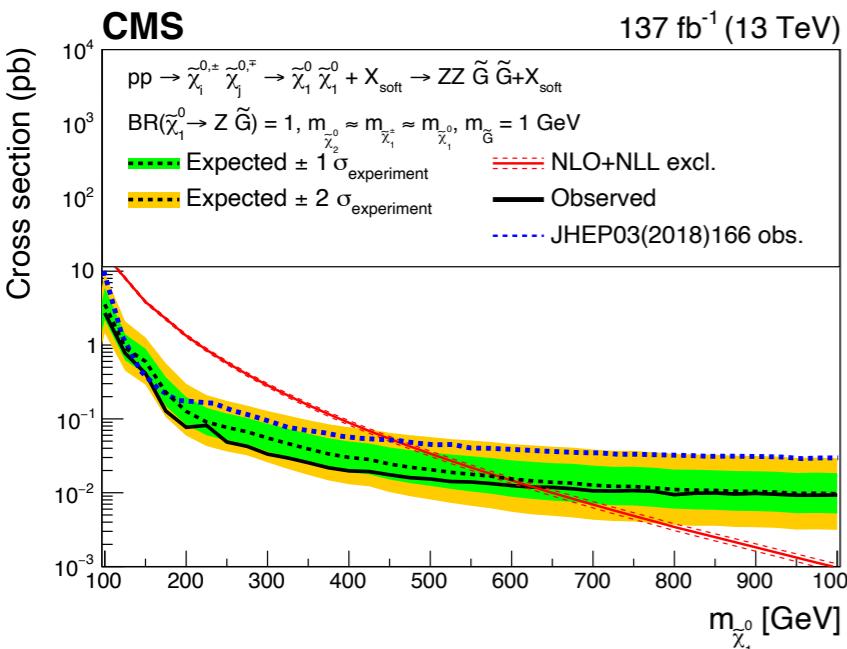
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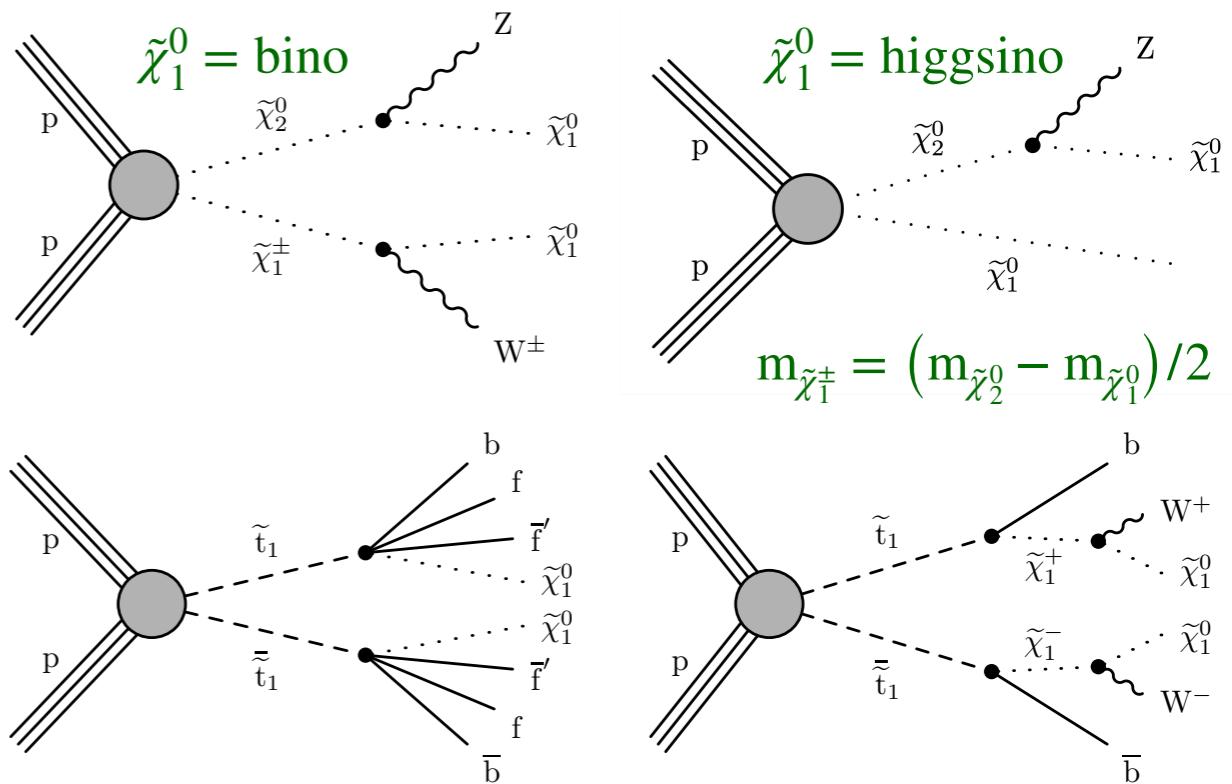


- Exclude $m_{\tilde{\chi}_1^\pm} < 1450$ GeV in 3ℓ events using parametric NN
- Exclude $m_{\tilde{\chi}_1^\pm} < 970$ GeV in 3τ events for right-handed sleptons
- Exclude $m_{\tilde{\chi}_1^\pm} < 650$ (250) GeV in events with WZ (WH) pair in final state
- Exclude $m_{\tilde{\chi}_1^0} < 600$ GeV in events with Z or H bosons in final state

Most stringent $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production limits for $m_{\text{NLSP}} - m_{\text{LSP}} \sim m_Z$

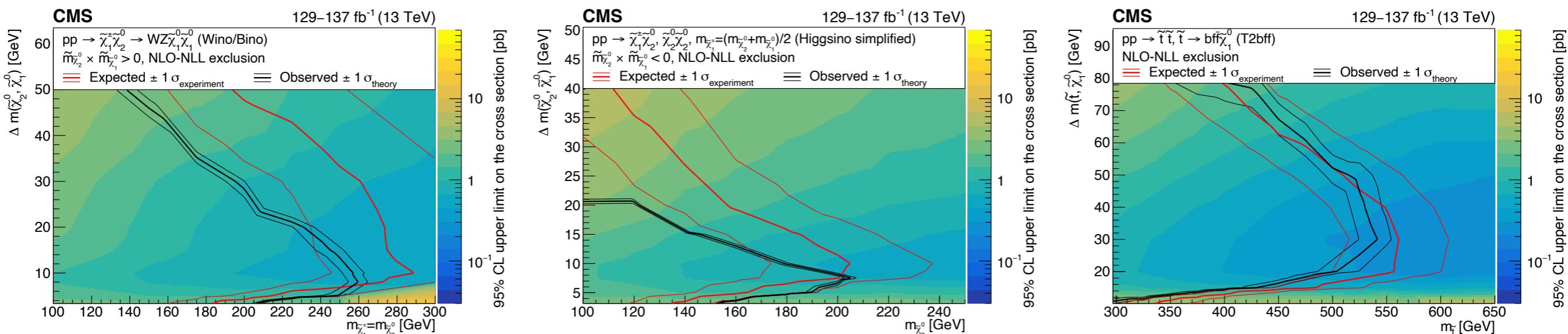
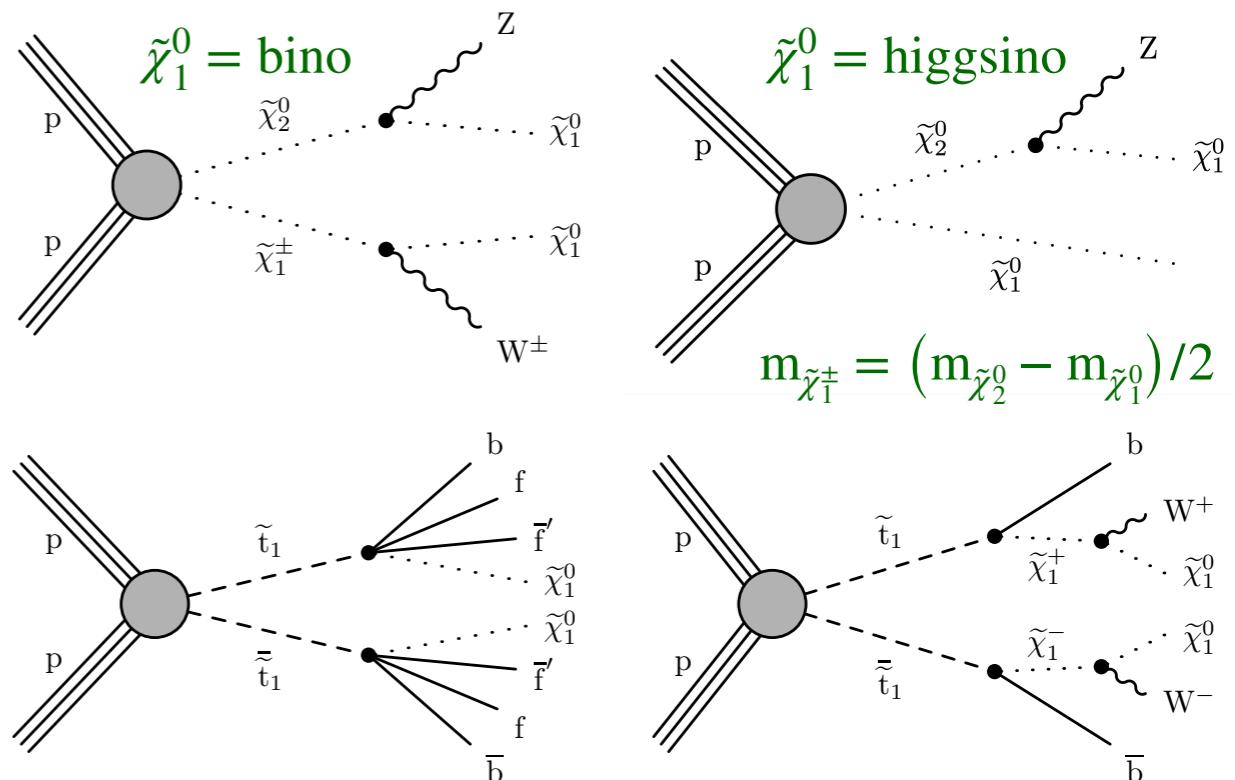
Soft opposite-sign leptons

- Search sensitive to compressed mass spectra in electroweakino and stop pair production
- Include 3ℓ final state w.r.t. previous iteration of the analysis by CMS (2016 data)
- Require 2 or 3 e (μ) in the event with $5(3.5) < p_T < 30$ GeV, including one OS pair
- Search variables: $m_{\ell\ell}$ in electroweakino production and $p_{T,\max}^\ell$ in \tilde{t} production



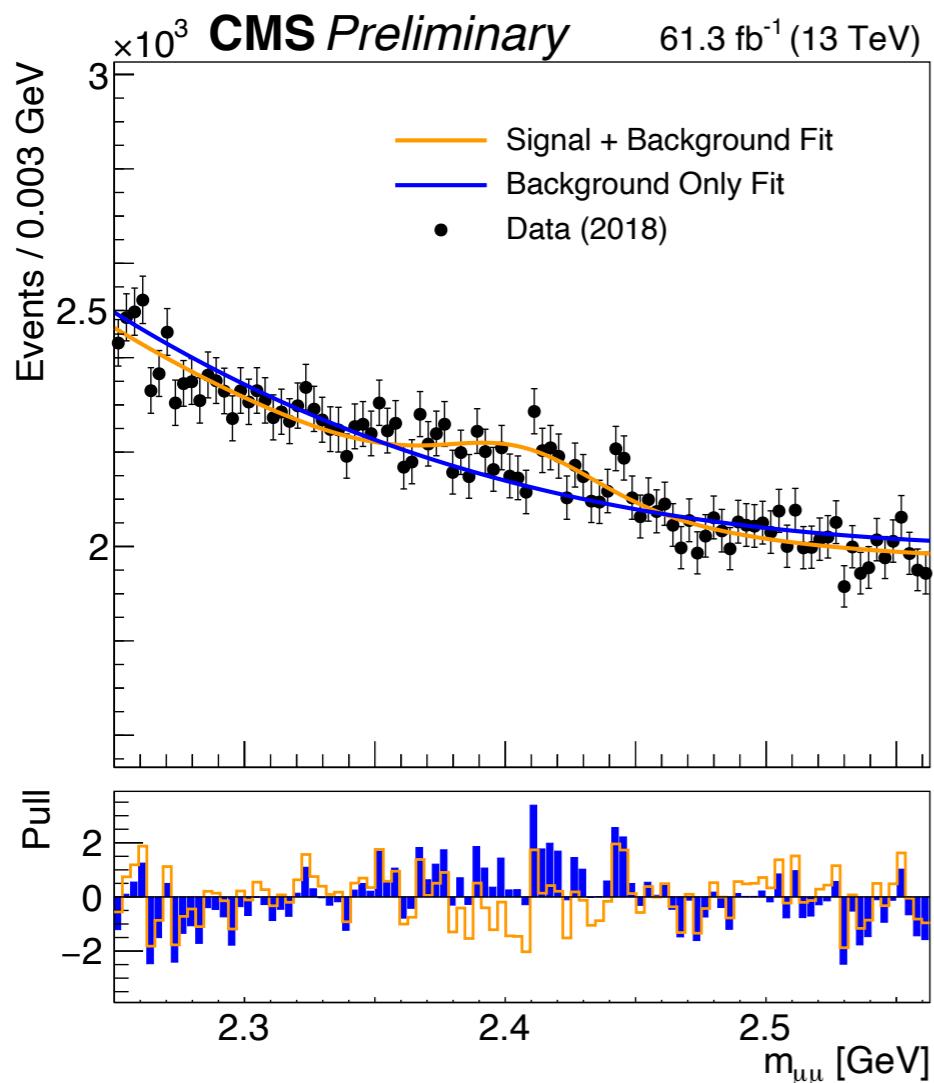
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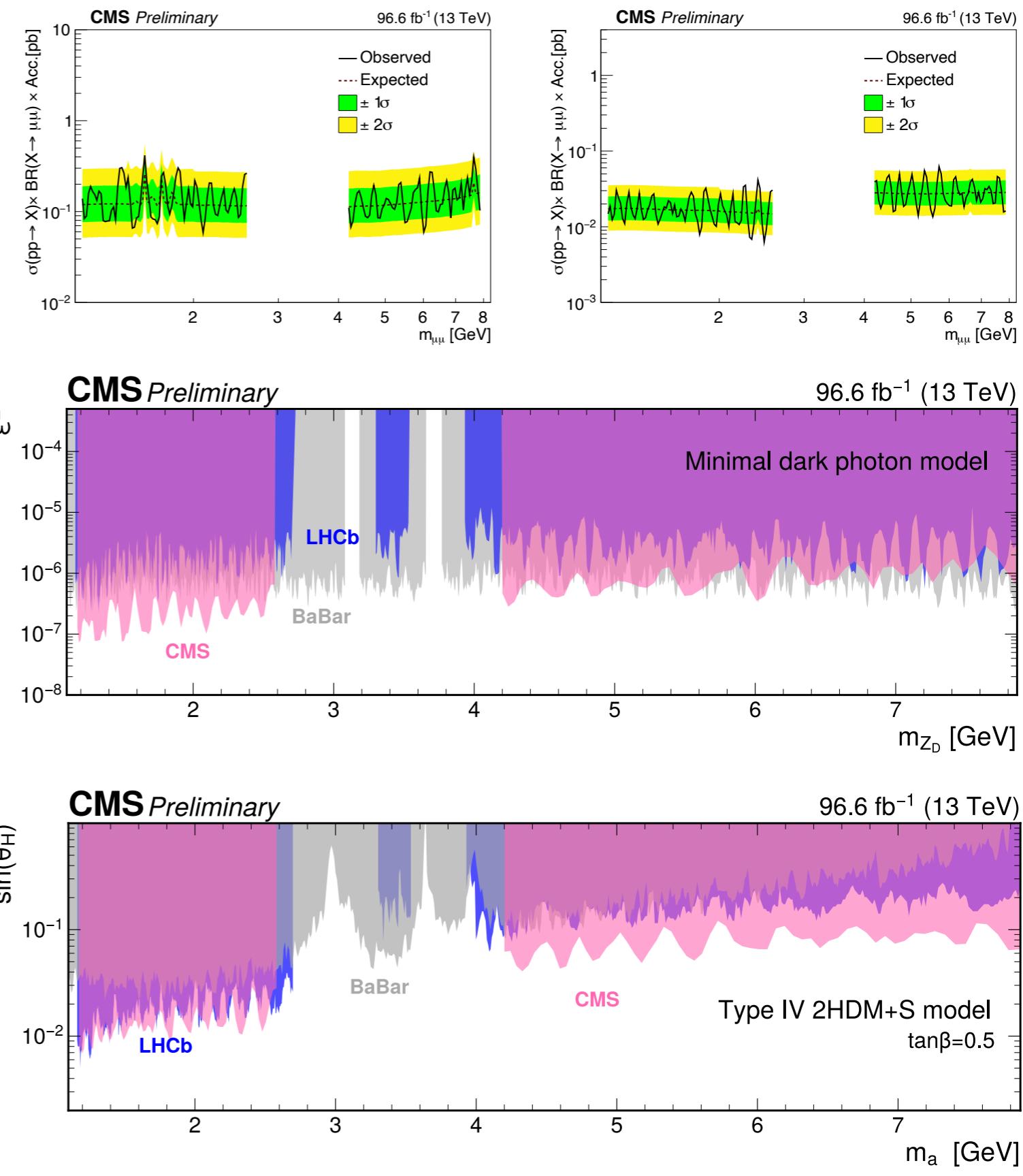
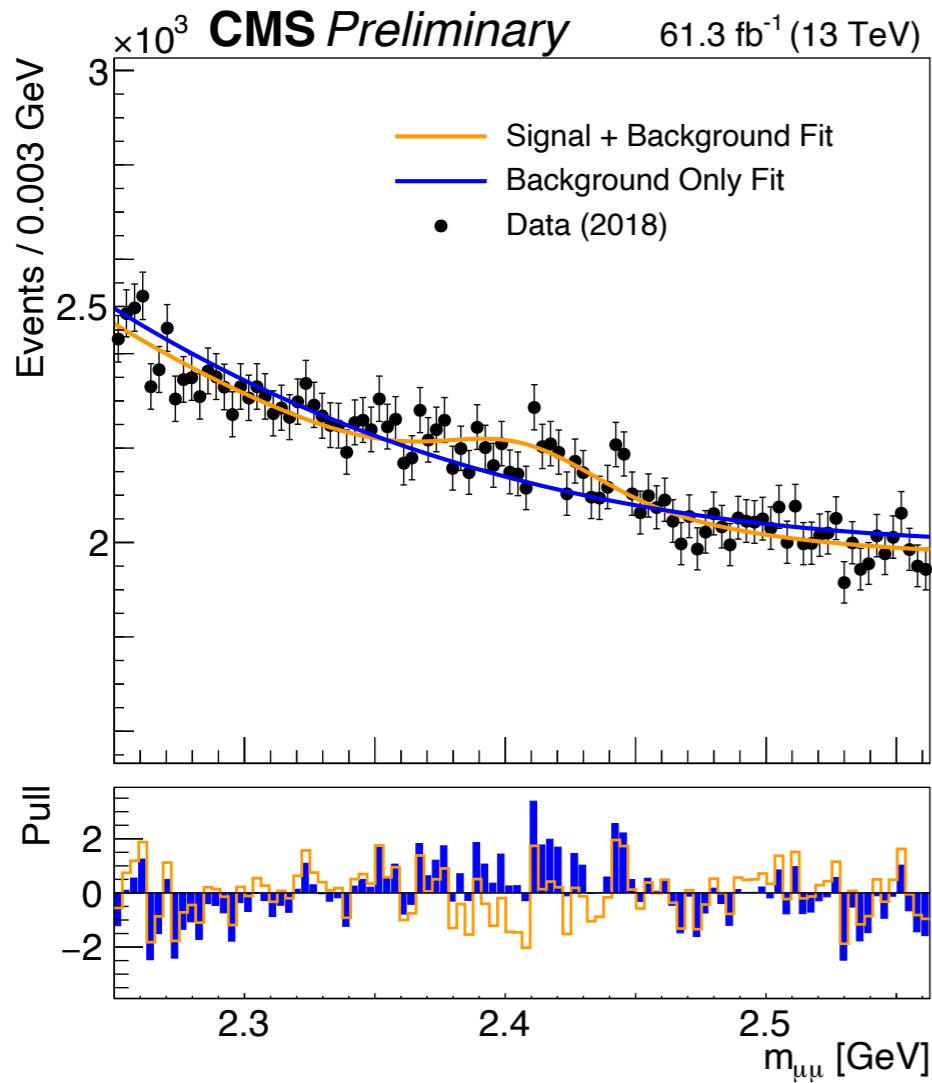
- Exclude $m_{\tilde{\chi}_2^0/\tilde{\chi}_1^\pm} < 275$ GeV for $\Delta m = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 10$ GeV (wino-bino)
- Exclude $m_{\tilde{\chi}_2^0/\tilde{\chi}_1^\pm} < 205 (150)$ GeV for $\Delta m = 7.5 (3)$ GeV (higgsino)
- Exclude $m_{\tilde{t}} < 540 (480)$ GeV for $\Delta m = 30$ GeV in 4-body decays

- Search for prompt narrow resonances in the range $[1.1, 2.6] \cup [4.2, 7.9]$ GeV decaying to a pair of muons
- Use scouting data collected during 2017-2018
- Select muons with MVA improving sensitivity
- Interpret the results model-independently and in the context of minimal dark photon and 2HDM + scalar models



Dimuon resonances

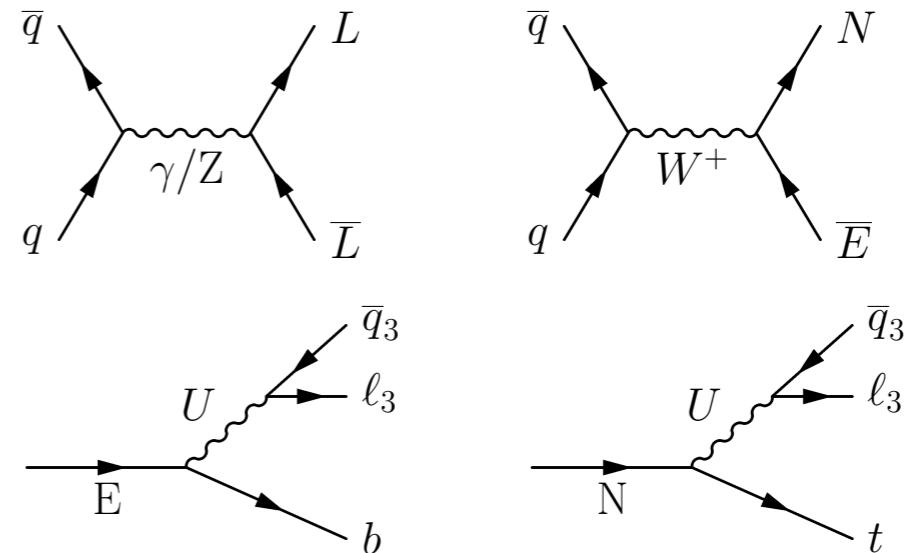
- Search for prompt narrow resonances in the range $[1.1, 2.6] \cup [4.2, 7.9]$ GeV decaying to a pair of muons
- Use scouting data collected during 2017-2018
- Select muons with MVA improving sensitivity
- Interpret the results model-independently and in the context of minimal dark photon and 2HDM + scalar models



Tau leptons

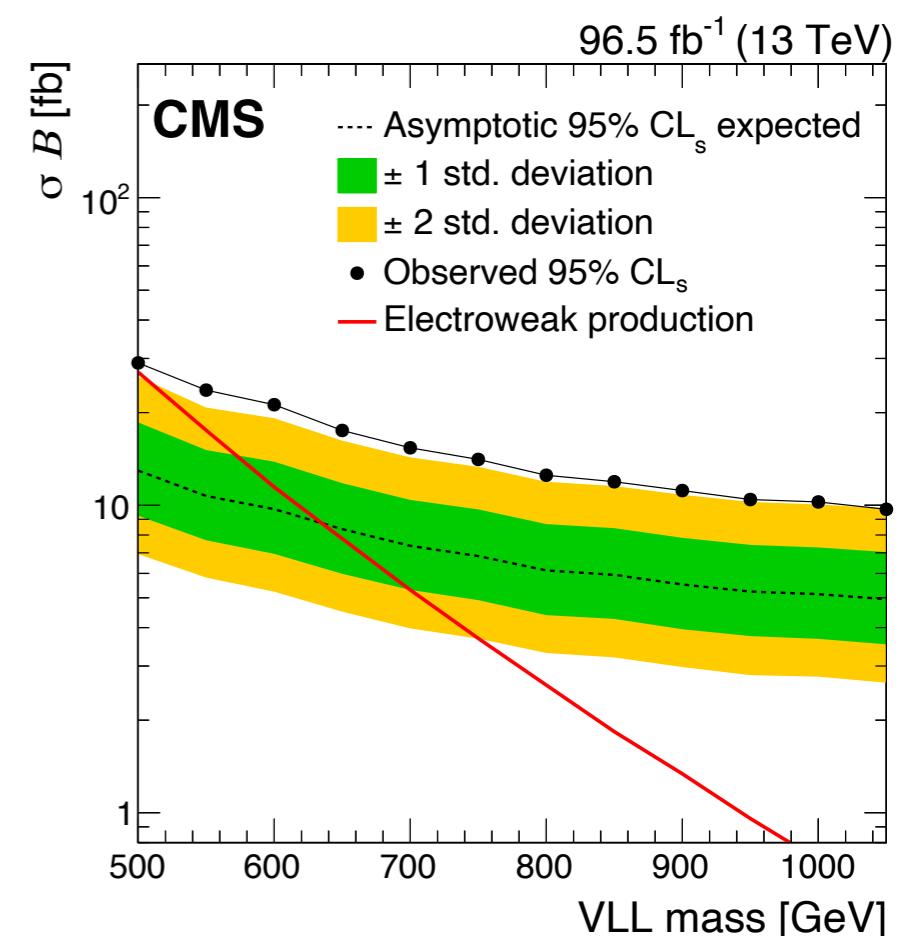
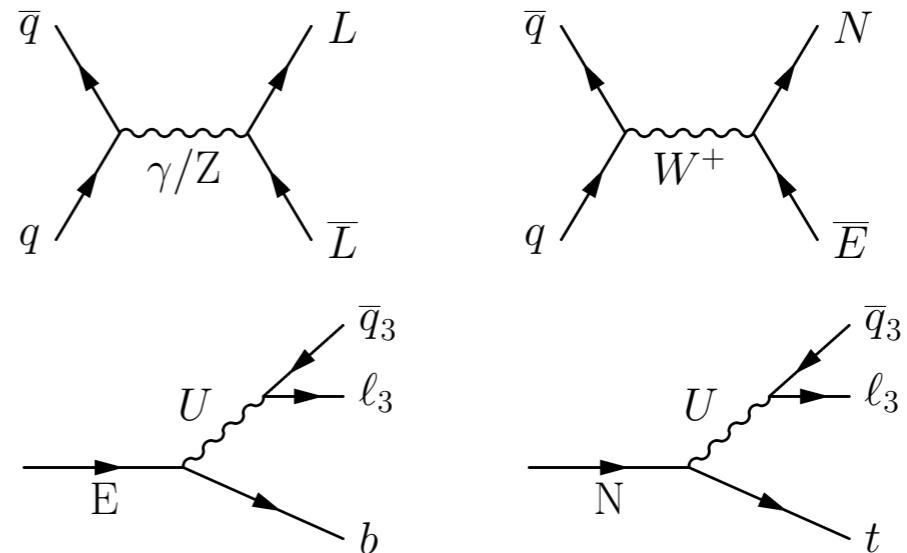
Vector-like lepton pair production

- Search sensitive to VLL pair production in the “4321” model $SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$
- Possibly explains flavour-nonuniversal results while respecting results in agreement with SM
- VLLs are non-chiral and decay via leptoquarks U to 2 quarks and 1 lepton, predominantly in 3rd generation to explain B-physics anomalies

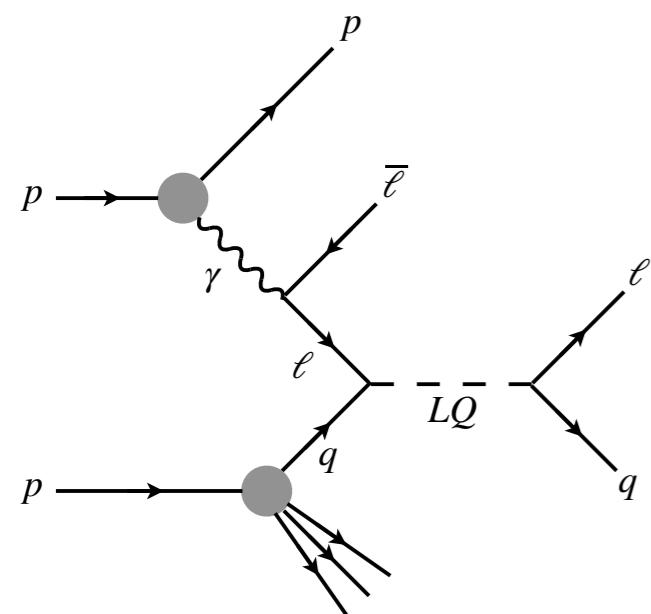


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- Focusing on fully hadronic final states: b-jets and hadronic tau's, identified using DeepJets and DeepTau taggers, respectively
- Event selection using DNN_{QCD} and $DNN_{t\bar{t}}$ for signal discrimination from the dominant QCD (0- τ channel) and $t\bar{t}$ background (1- τ and 2- τ channels), respectively
- **Observed data show consistent excesses in highest $DNN_{t\bar{t}}$ bins for both 1- τ and 2- τ channels $\Rightarrow 2.8 \sigma$ excess at representative VLL mass of 600 GeV**
- Tests show the results hold when including Z' production of VLL pairs

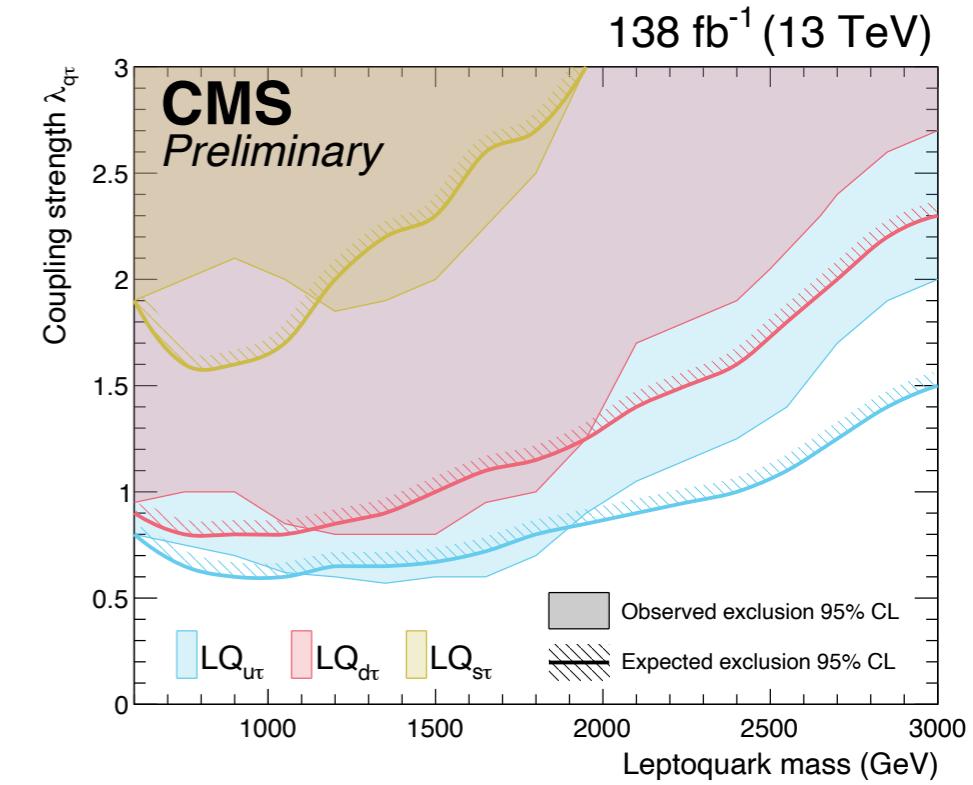
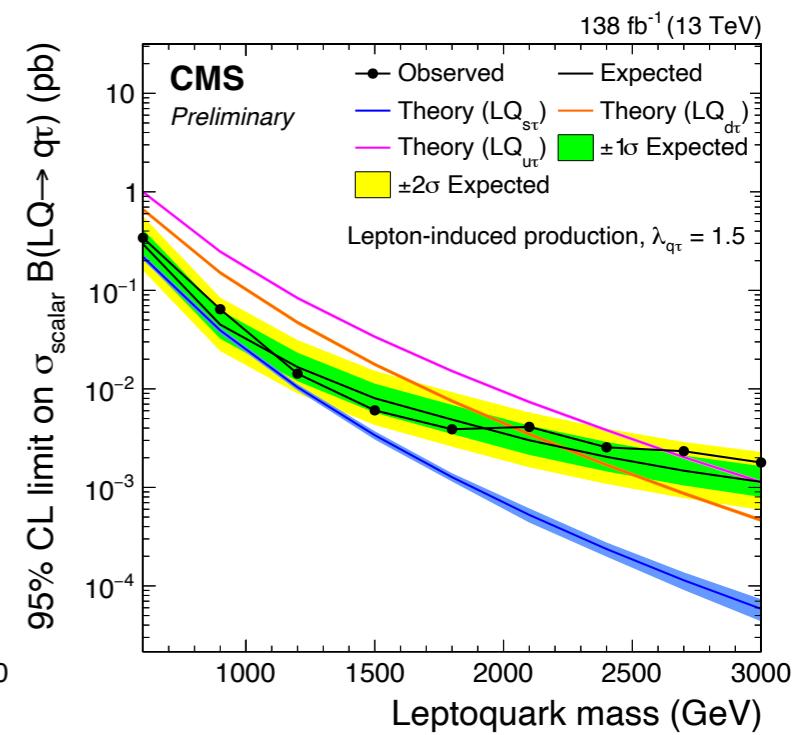
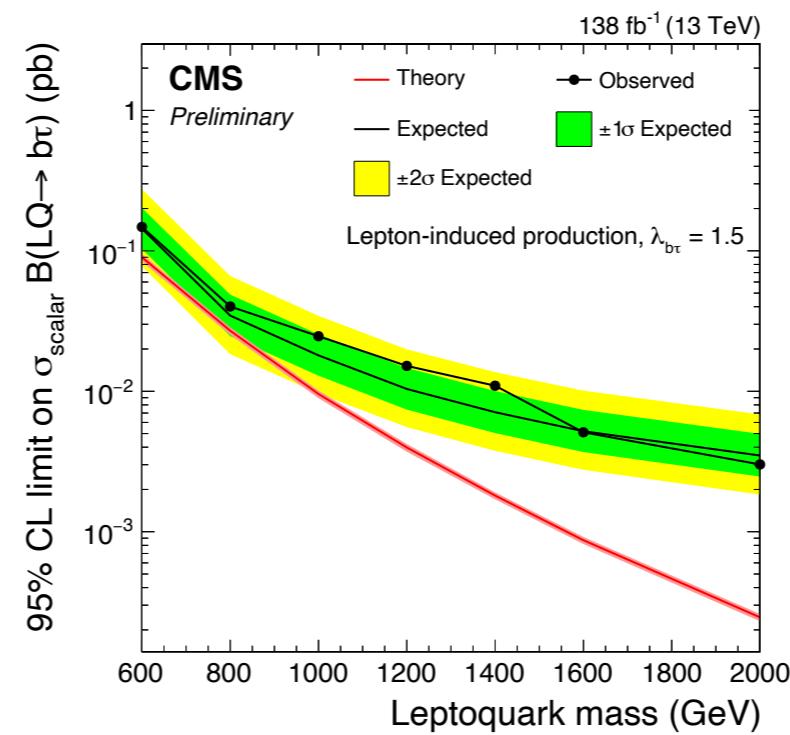
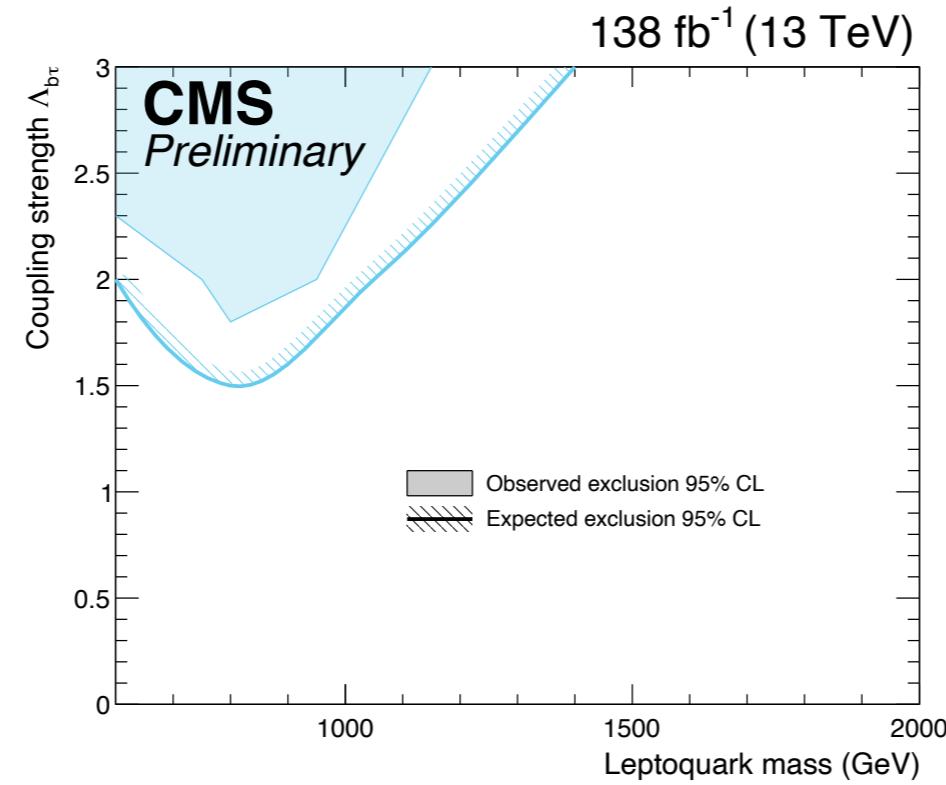
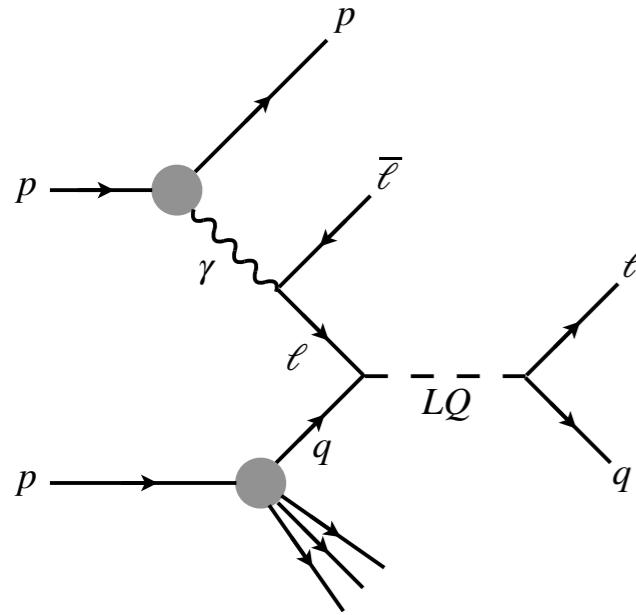


- Select final states with a jet, significant MET, and a hadronic or leptonic τ lepton
- Search for leptoquark decays to $b\tau$ and $q\tau$, where $q = u, d, s$



Lepto-quarks coupling to τ leptons

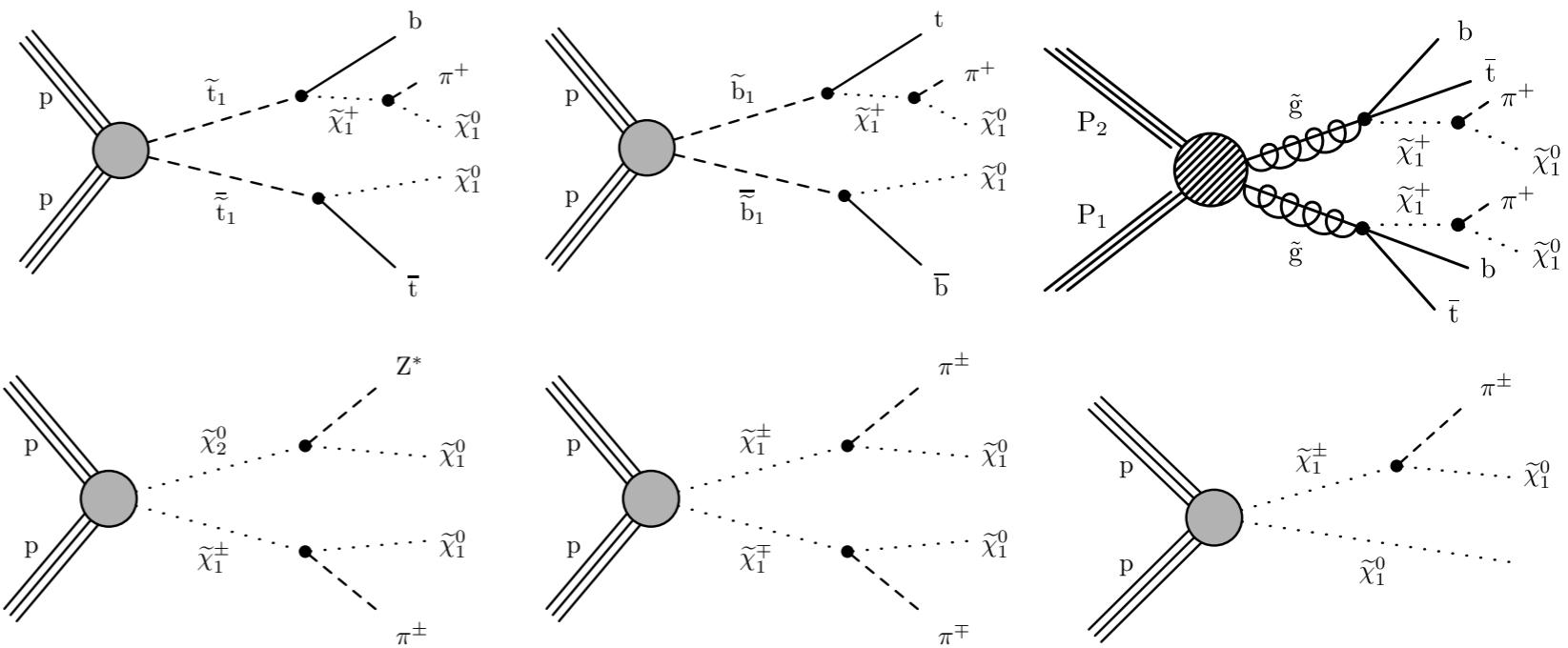
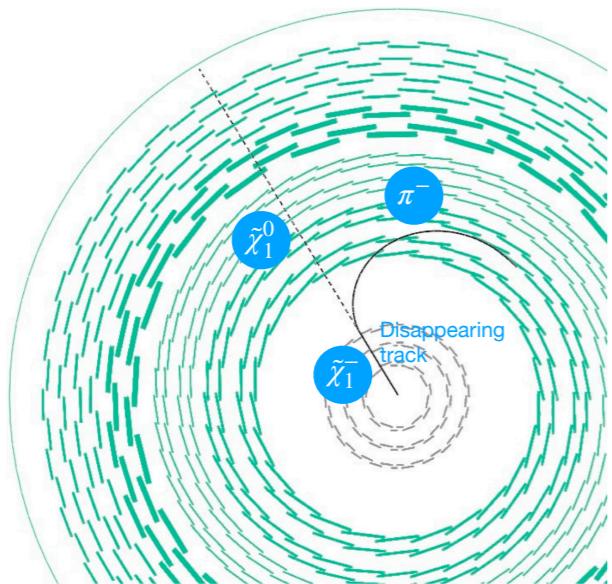
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Unconventional signatures

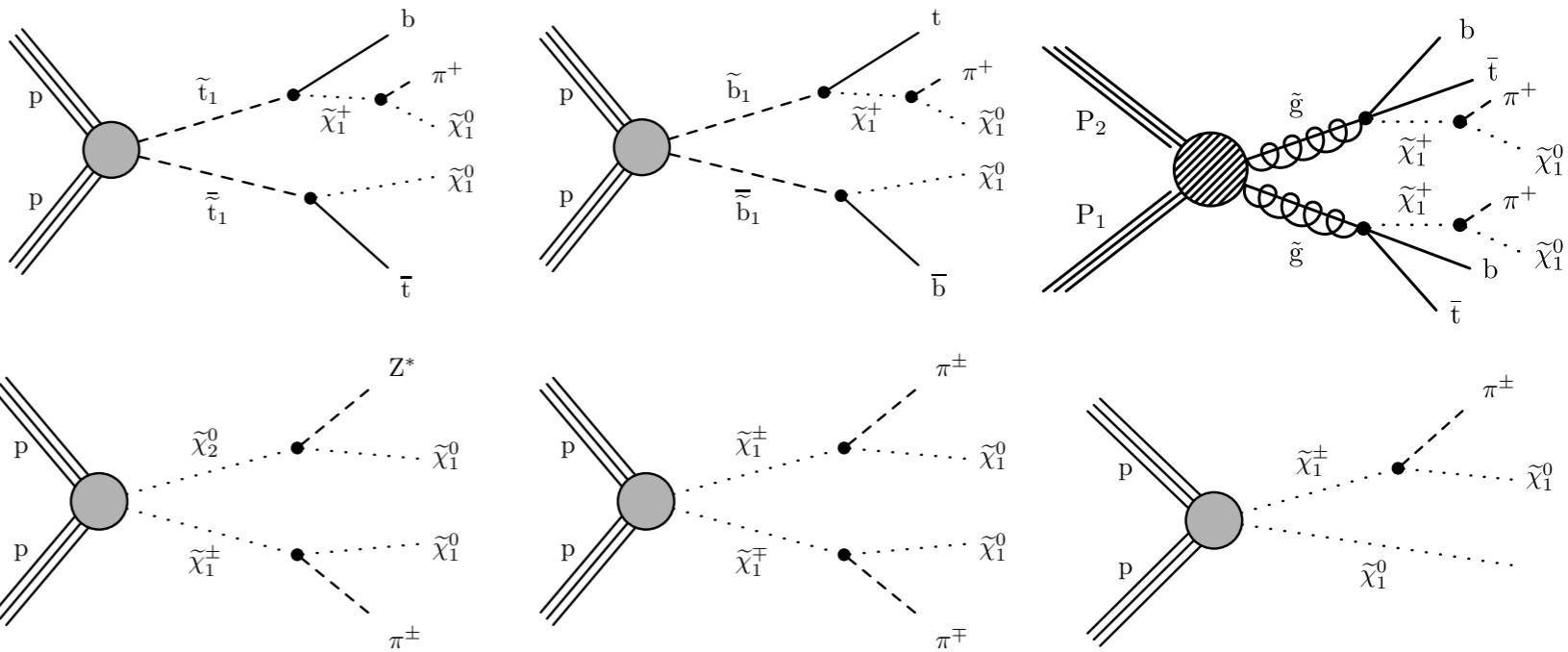
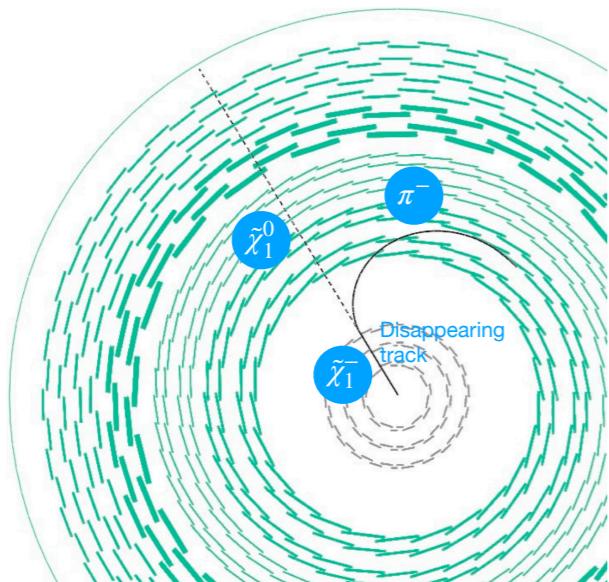
Long-lived charginos as disappearing tracks

- $\tilde{\chi}_1^\pm \rightarrow \pi^\pm \tilde{\chi}_1^0$ with $\Delta m_{\tilde{\chi}_1^\pm \tilde{\chi}_1^0} < 1 \text{ GeV} \Rightarrow c\tau_{\tilde{\chi}_1^\pm} \sim \text{O}(1 \text{ cm}) - \text{O}(1 \text{ m})$
- BDT-based selection of short (pixel-only hits) and long (pixel+strips) disappearing tracks (DTk) associated with e, μ, jets

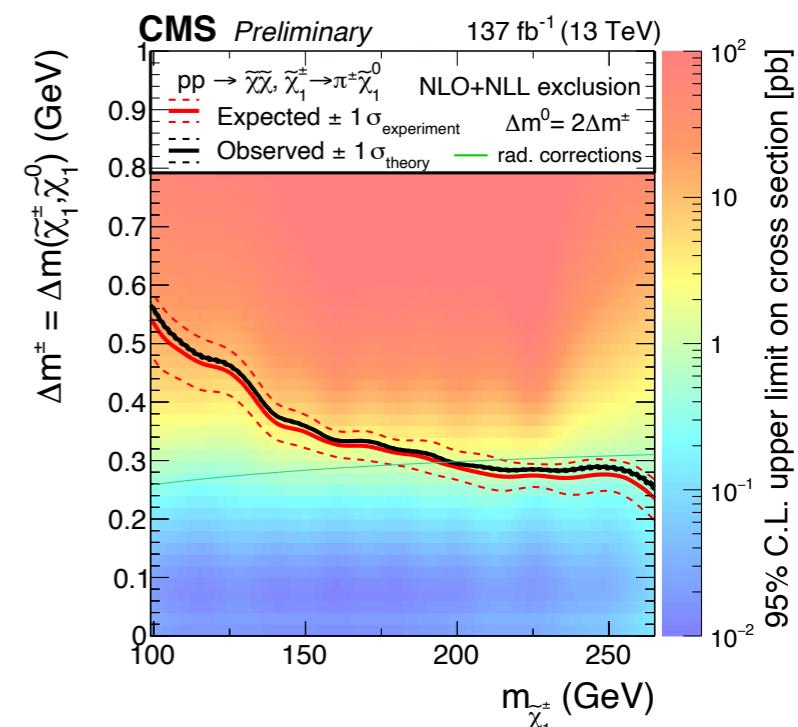
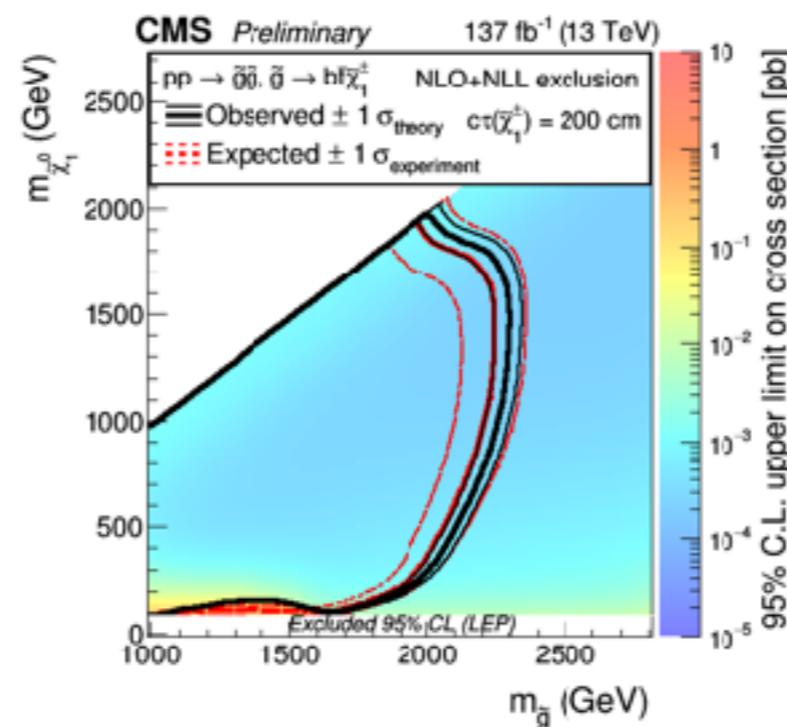
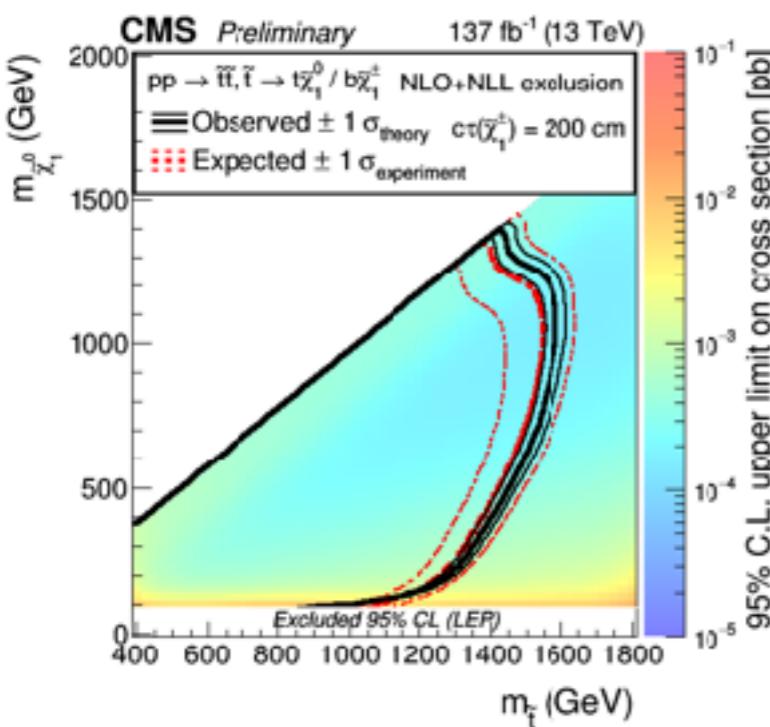


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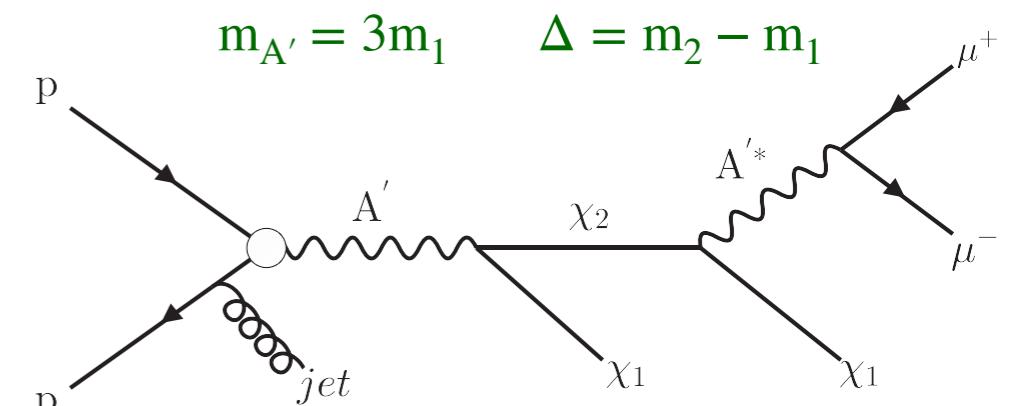
Extend previous CMS limits by hundreds of GeV



Inelastic dark matter with displaced muon pair signature

First dedicated collider search for IDM

- 2 nearly mass-degenerate DM states χ_1 and χ_2 couple to a dark photon A' kinetically mixed with SM hypercharge \Rightarrow accounts for thermal relic abundance
- For small Δ , χ_2 travels a measurable distance before decay
- Extend sensitivity in DM mass of $\lesssim 1$ GeV, from re-interpretation of previous results, into the range of $3 - 80$ GeV

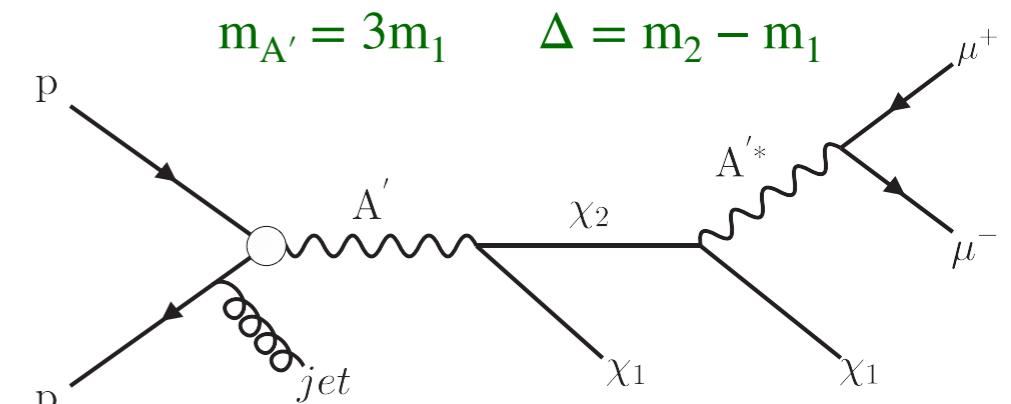


EXO-20-010

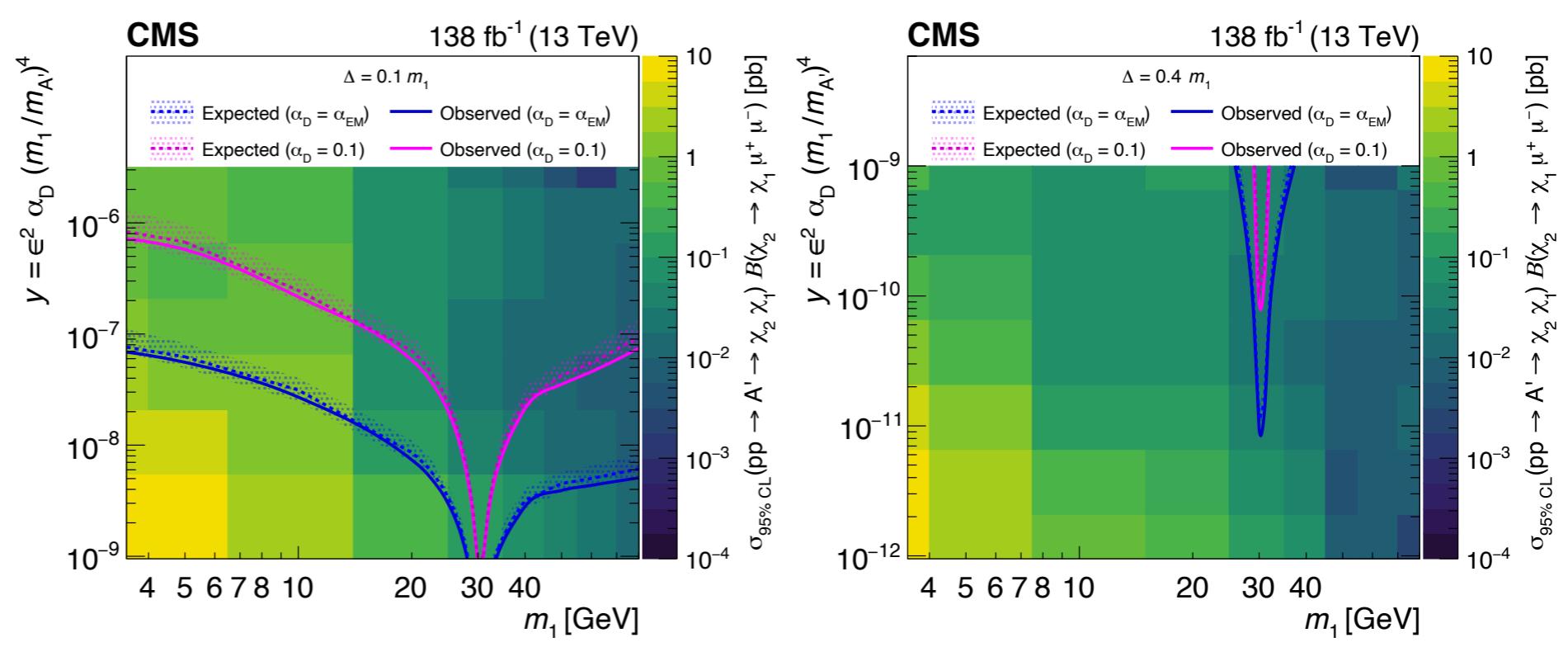
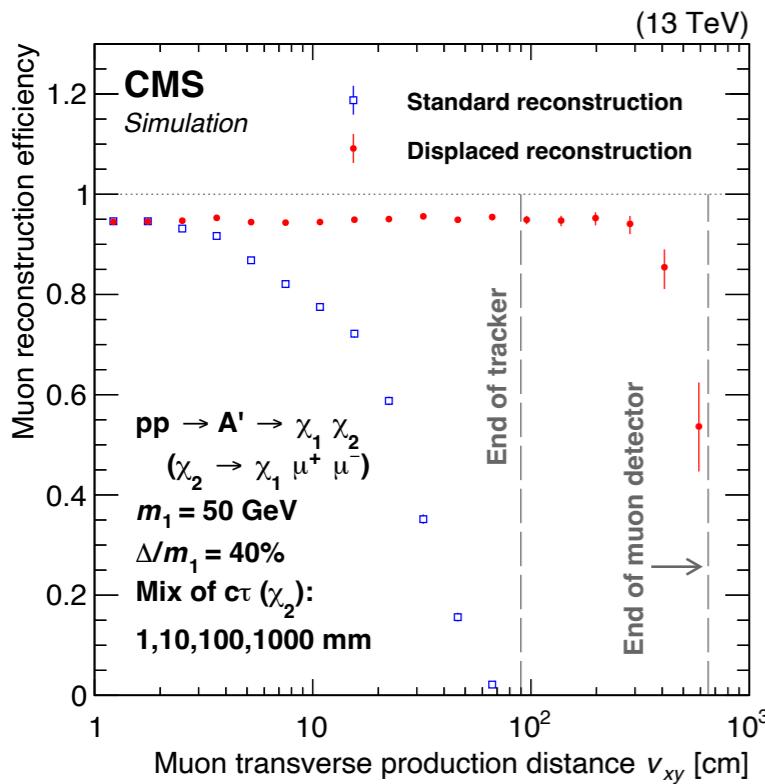
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- 2 muons reconstructed with **special displaced standalone algorithm (DSA)** using only information from the muon detectors and not requiring muons to originate from the interaction point
- Resonant enhancement in the exclusion limit from mixing between A' and Z when $m_{A'} \approx m_Z$

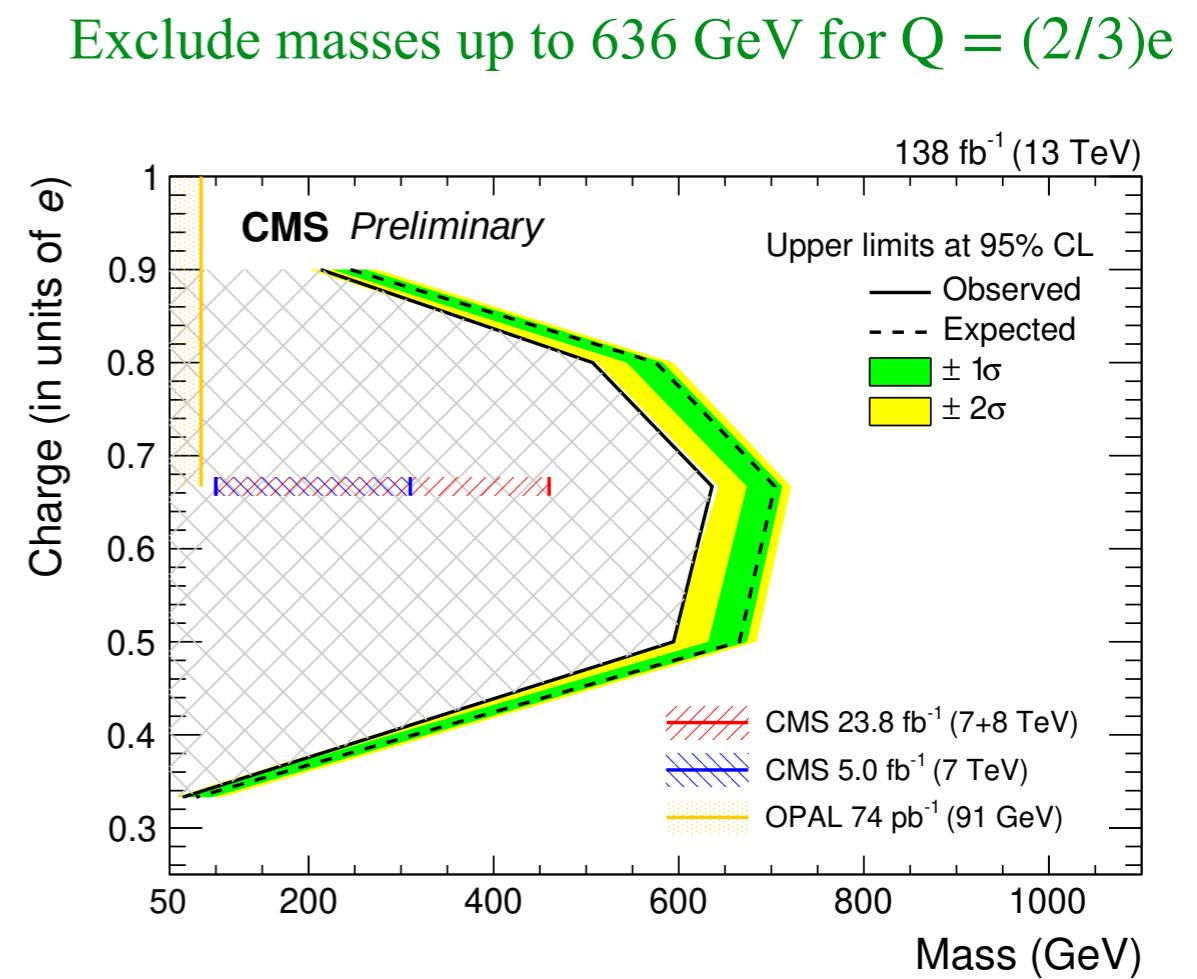
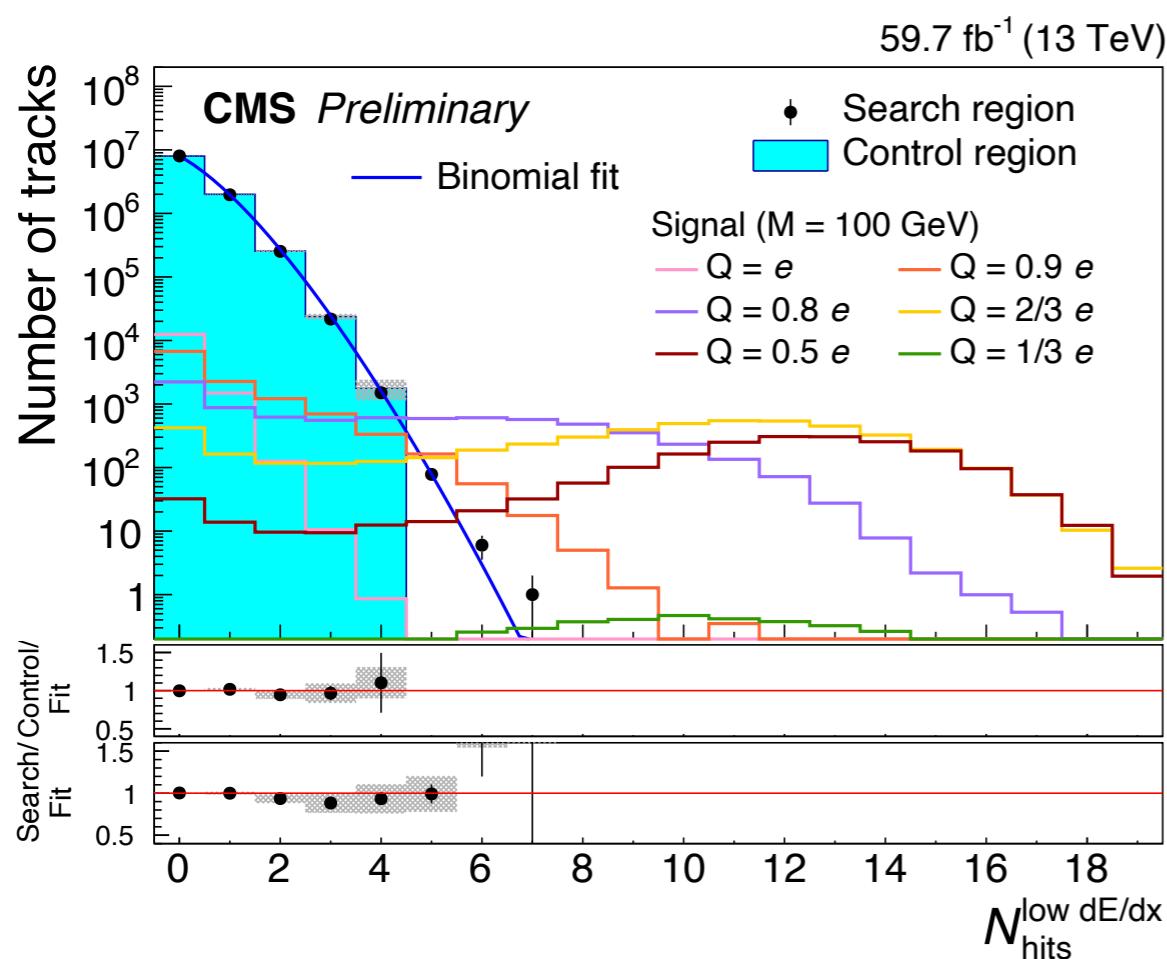


EXO-20-010



- Adding a hidden U(1) gauge field in the hypercharge portal scenario coupled to a new heavy Dirac fermion, kinetic mixing between SM and new gauge field leads to the new fermion acquiring a fractional charge $Q = \epsilon e$
- Measure track ionisation loss ($\propto Q^2$) in the tracker assuming DY-like produced FCP pairs
- Search region: 1 track or 2 tracks with $m_{\text{pair}} \notin [80, 100] \text{ GeV}$
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- Count number of tracks in bins of low-dE/dx hits distribution

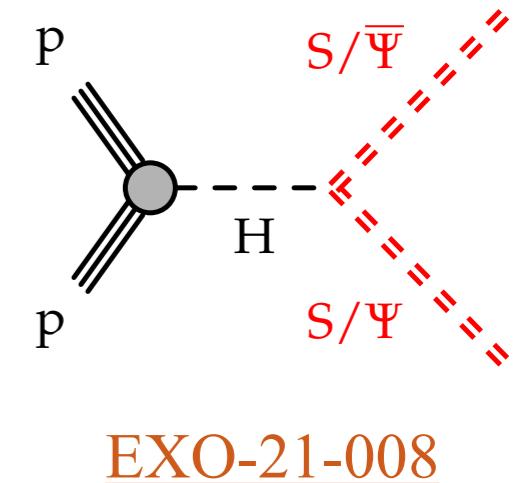
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Long-lived particle decays producing muon showers

- Thick shielding ($12\text{-}27 \chi_{\text{rad}}$) of CMS allows for using muon chambers as calorimeters
- Search for clusters of ≥ 50 hits within $\Delta R = 0.2$ in the muon chambers
- Interpret results in the context of 2 benchmark models:
 - ▶ $H \rightarrow SS$ with $S \rightarrow b\bar{b}$, $d\bar{d}$, $K\bar{K}$, $\pi\pi$, $\gamma\gamma$, ee , $\tau\tau$ and $m_S \in [0.4, 55] \text{ GeV}$
 - ▶ $H \rightarrow \Psi\bar{\Psi}$ with $\Psi \rightarrow$ dark LLP \rightarrow SMP and $m_{\text{LLP}} \in [2, 20] \text{ GeV}$ **first time at LHC**

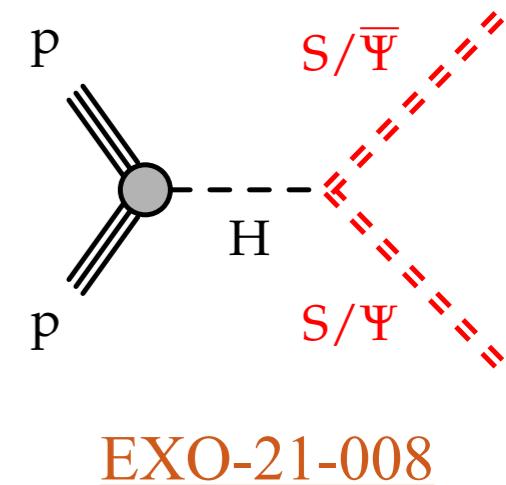
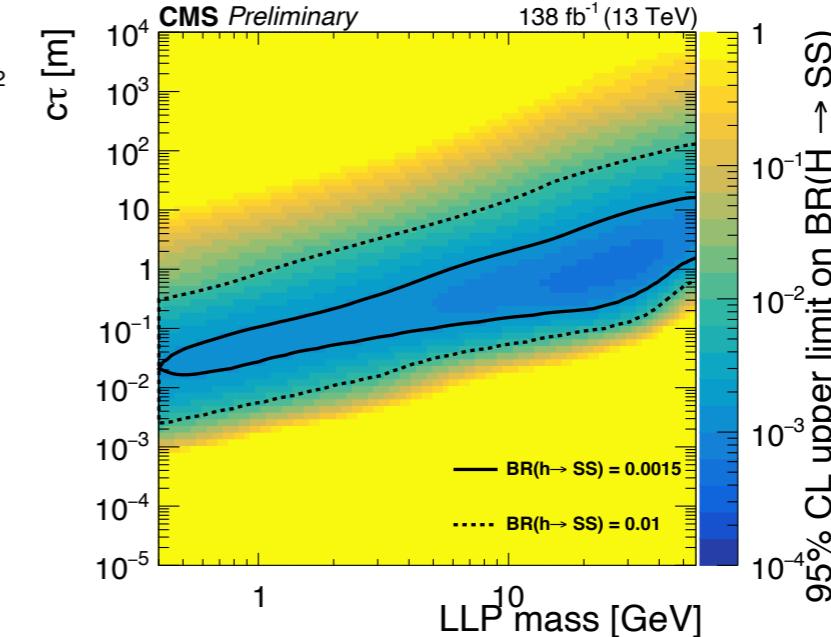
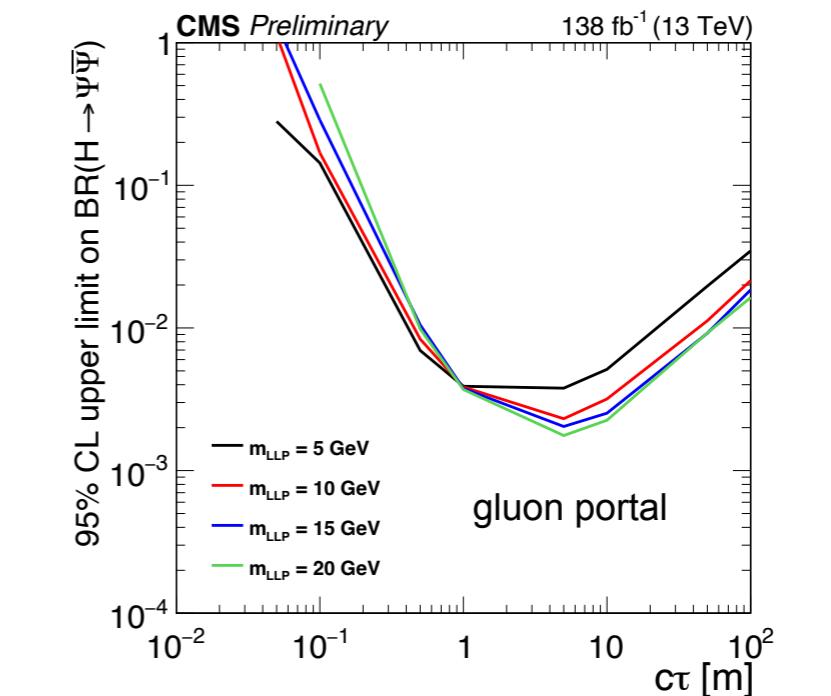
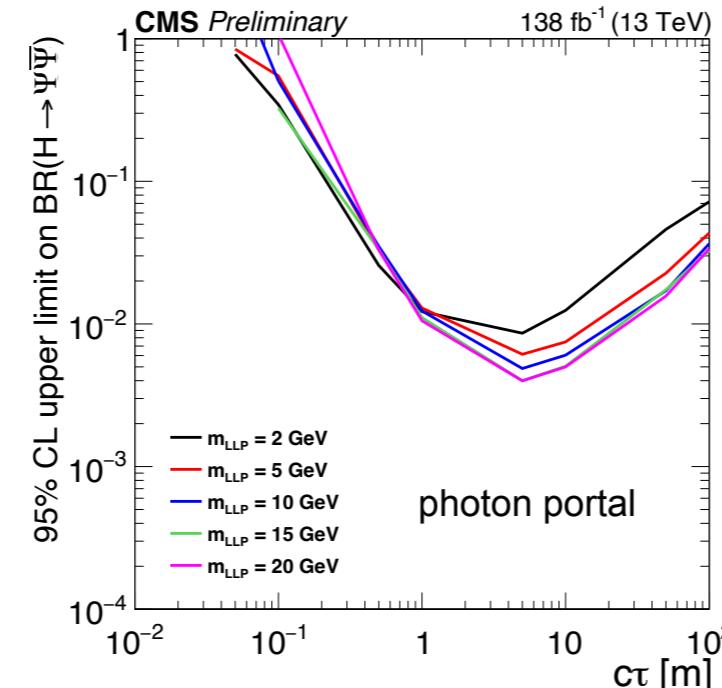
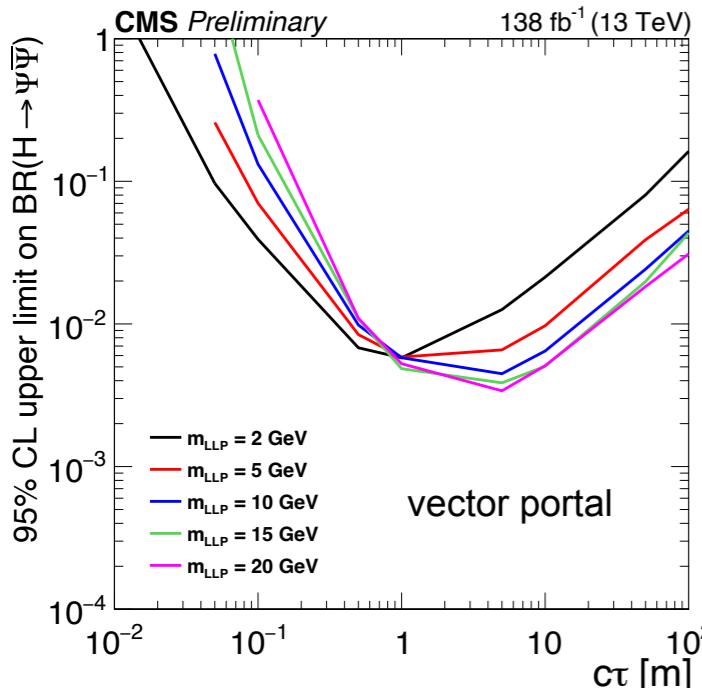
Sensitive to a broad range of LLP decay modes,
reaching $m_{\text{LLP}} < 1 \text{ GeV}$ and $c\tau \in [1 \text{ mm}, 10 \text{ m}]$



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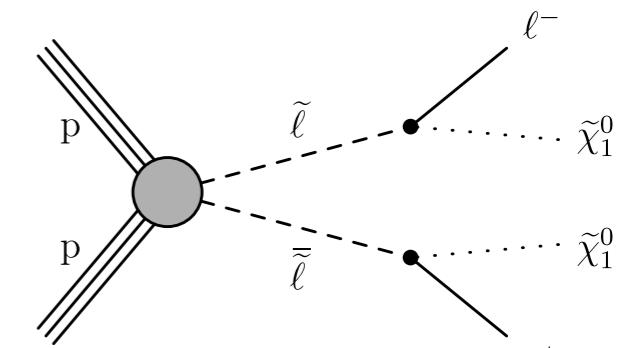
Most stringent limits for

- $c\tau$ in 0.04-0.4 m and > 4 m assuming LLP mass of 15 GeV
- $c\tau$ in 0.3-0.9 m and > 3 m assuming LLP mass of 40 GeV
- $c\tau > 0.8$ m assuming LLP mass of 55 GeV

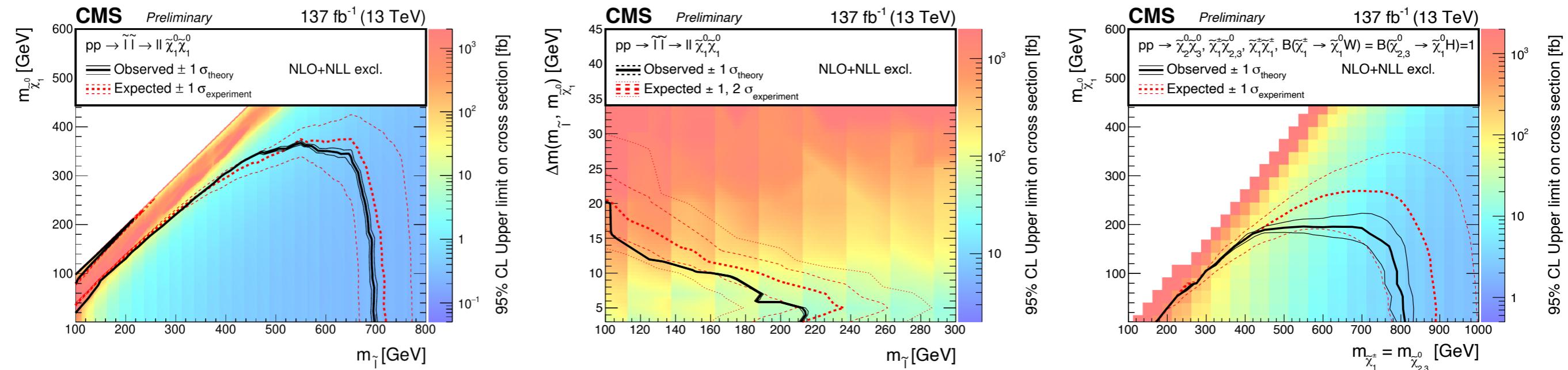
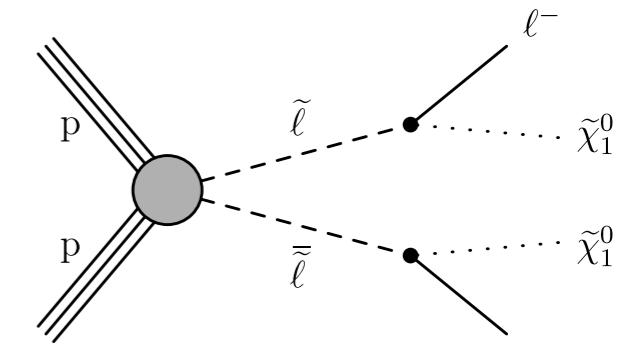
First LHC limits on $\text{BR}(H \rightarrow \text{dark quarks})$ down to 10^{-3}

Combinations

- Combine exclusion limits from all searches for electroweakino and slepton production with the full Run 2 sample
- Include limits on
 - gaugino-like chargino-neutralino production
 - higgsino-like neutralino pair production in a GMSB scenario
 - higgsino-bino interpretation
 - slepton pair production
- Added interpretation of soft opposite-sign dilepton analysis with a slepton pair production model
First search of slepton pair production in the compressed mass scenario



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- For $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0) = 5$ GeV, exclude $m_{\tilde{\ell}} < 215$ GeV in SOS analysis
- Combination excludes $m_{\tilde{\ell}} < 700$ GeV for $m_{\tilde{\chi}_1^0} < 50$ GeV

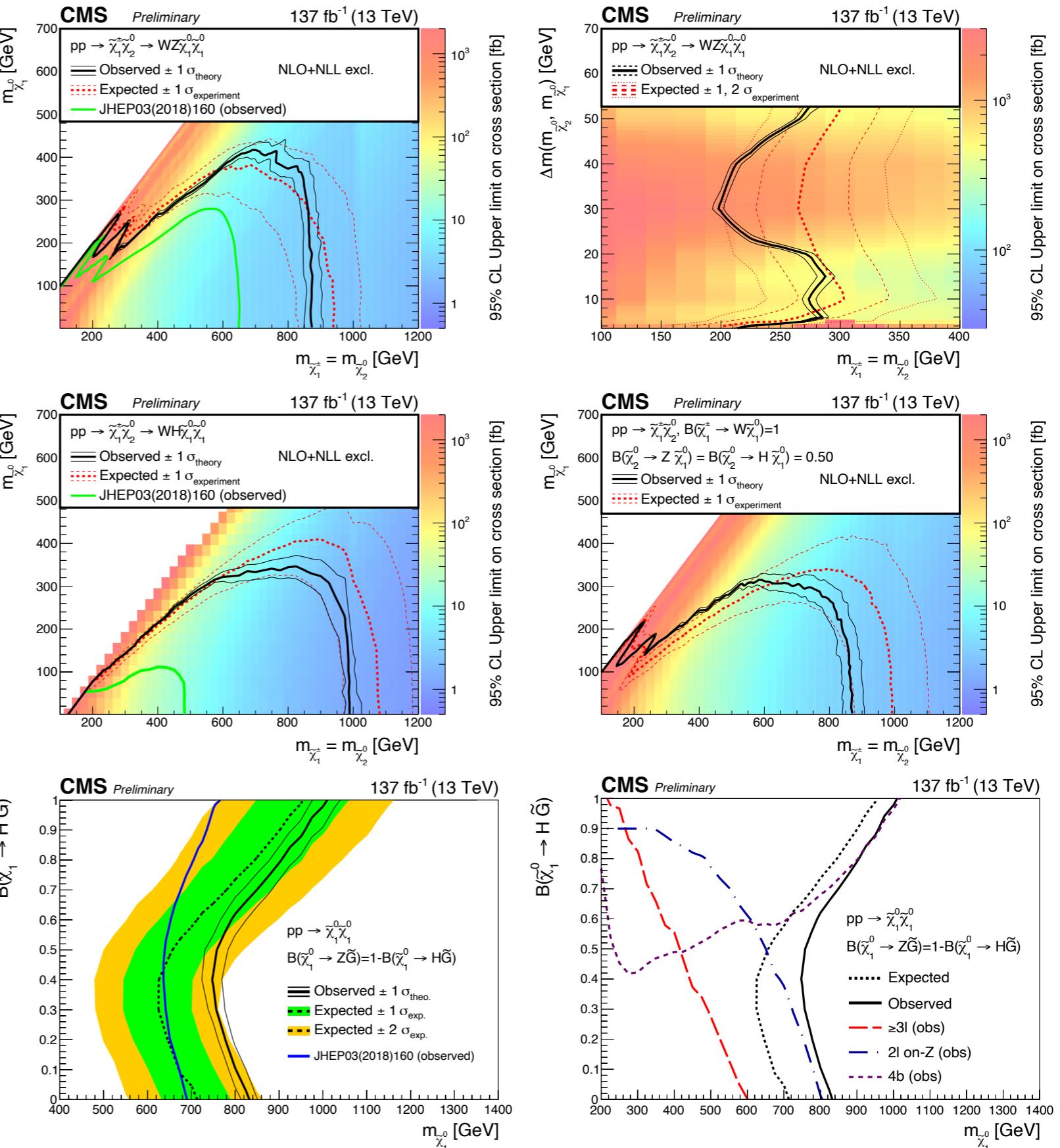
Higgsino-bino interpretation

- Exclude $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0} < 800$ GeV for $m_{\tilde{\chi}_1^0} < 50$ GeV

Combination of electroweak SUSY searches

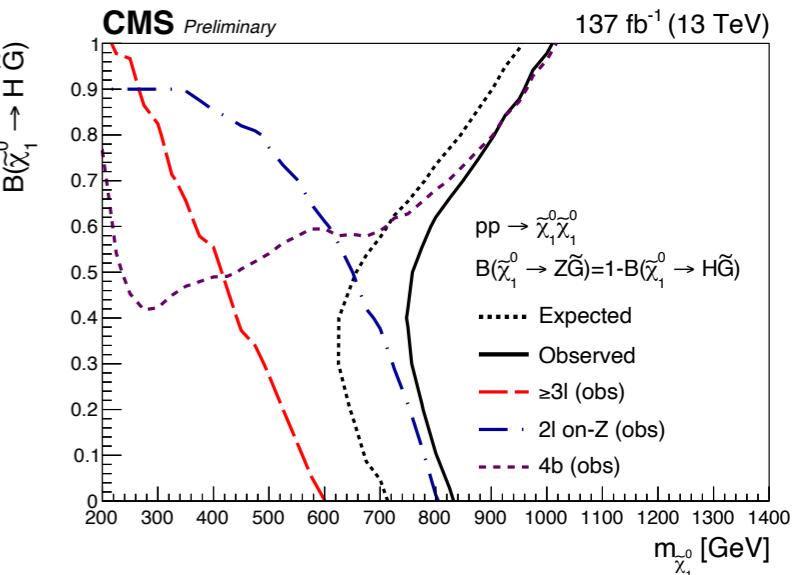
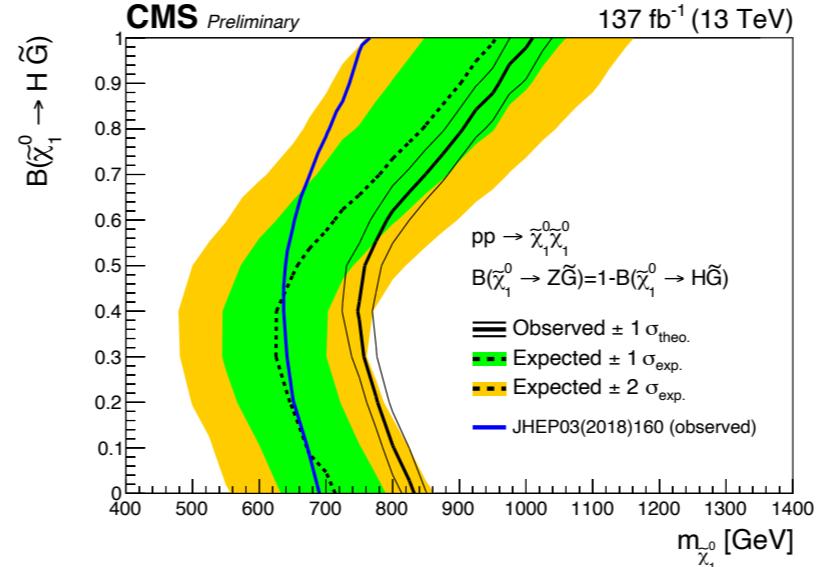
Chargino-neutralino production:

- Exclude $m_{\tilde{\chi}_1^\pm} < 875, 990, 875$ GeV with $m_{\tilde{\chi}_1^0} < 50$ GeV in the WZ, WH, and mixed final state
- Extend previous CMS limits by 225, 510, and 340 GeV, respectively



Neutralino pair production:

- For nearly massless LSP, exclude $m_{\text{NLSP}} < 750$ GeV independently of $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H\tilde{G})$
- Extend previous CMS limit by 100 GeV



Further reading:

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS>

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G>

<https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS/index.html>

<https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO/index.html>

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Conclusions: the way ahead

- Great progress in BSM searches achieved by CMS using the Run 2 sample
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- Where to look for BSM next
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 - ▶ Unconventional signatures (e.g.: disappearing or low-dE/dx tracks, displaced μ 's, μ -showers)
- Double data sample from LHC Run 3 will improve sensitivity
- High-Luminosity LHC: a whole new era of searches, with sample size, detector & trigger technology, and analysis power advanced to a substantially higher level

Backup

Dijet resonance pairs: the two outlier events

