CMS SUSY and Exotica results

Tribeni Mishra

National Institute of Science Education and Research, India

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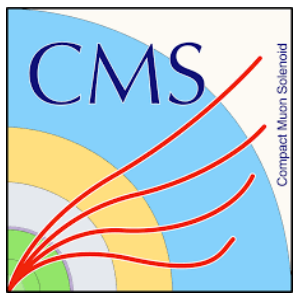
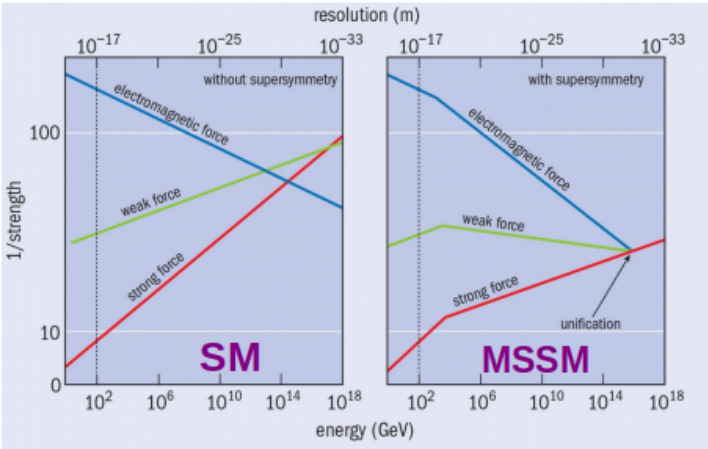


Why look for Beyond Standard Model?

Standard model successfully explains the structure of matter and the forces acting between them. Still, it fails to answer many important questions.

Gauge couplings :

Unification of coupling constant at a single scale



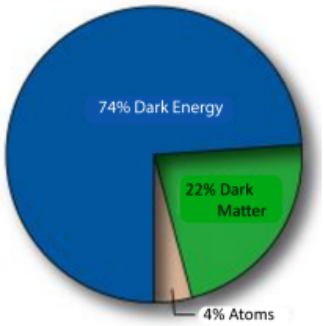
Gravity:

Standard Model doesn't include Gravity

Hierarchy problem :

- Divergence in Higgs mass due to divergent terms from couplings to massive particles

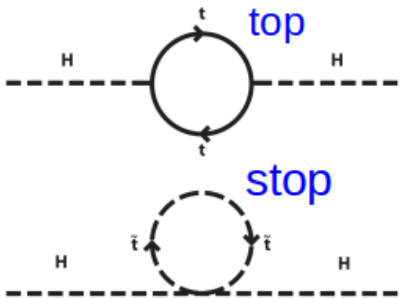
Higgs mass stabilisation against loop correction



Dark Matter:

- No candidate in Standard Model

Lightest SUSY particle (LSP) is a possible candidate



$$\Delta m_H^2 = -\frac{\lambda_f}{8\pi^2}\lambda_V^2 + \ldots\ldots$$

$$\Delta m_H^2 = \frac{\lambda_s}{16\pi^2}\lambda_V^2 + \ldots\ldots$$

Overall recent CMS SUSY and Exotics program

Aim to give you a feeling of the breadth of the LHC search program, focus on very new results.

Recent CMS SUSY results

- Gluino/squark searches

  SUS-19-010 Hadronic final state
- Third generation squark searches

  SUS-20-002 Stop searches
- Electroweak searches (charginos/neutralinos, sleptons)

  SUS-21-002 Hadronic final state
  SUS-20-004 With Higgs signature
  SUS-19-012 Multi-lepton final state
  SUS-21-001 Direct Stau production

Recent CMS B2G results

Recent CMS Exotica results

- Long lived particle (LLP) Searches

  EXO-20-003 Z+displaced jets
- Resonance Searches

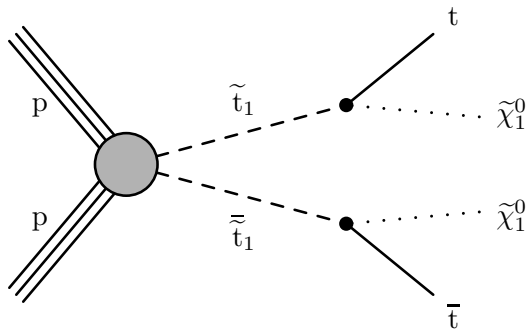
  EXO-20-007 Tri-jet resonances
  B2G-21-002 Tri-boson resonances
  B2G-20-010 Heavy b* resonance
- Heavy gauge bosons

  EXO-19-017 $\ell\nu$ final state
  B2G-19-002 Semi-leptonic channel
- excludes Dark Matter searches (covered by Mariia Savina)

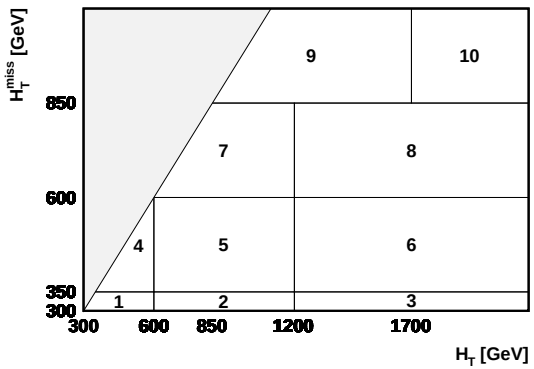
General search strategy

- Select data using trigger based on the final state of targeted signals.
- Identify the SM processes having similar final state as of the signal. SM backgrounds : $t\bar{t}$, W/Z +jets, QCD,..
- Build search variables sensitive to the targeted signals.
  N_{jets} = Jet multiplicity
  $H_T^{miss} = |-\sum_{jets} \vec{p_T}|$, $H_T = \sum_{jets} p_T$,
  MET/p_T^{miss} = $|-\sum_{particles} \vec{p_T}|$,
- Select search variables to design search region (SR)
- Estimate the contribution SM backgrounds, find the cases where observed data is more than predicted backgrounds.
- Look for the discrepancy, or
  set limit on BSM processes at a given Confidence Level

Example :
A SUSY signal



Final state :
Jets and missing energy

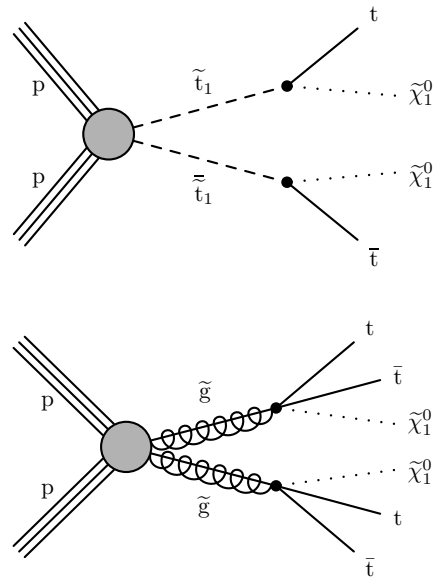


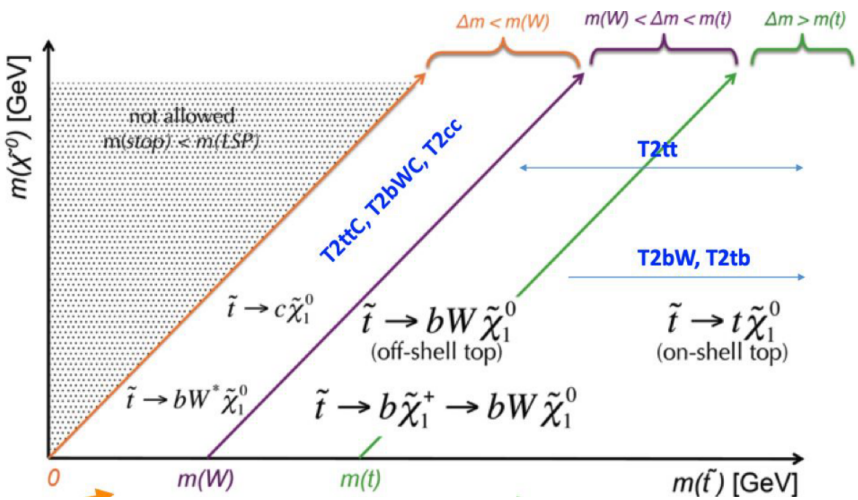
Search Region

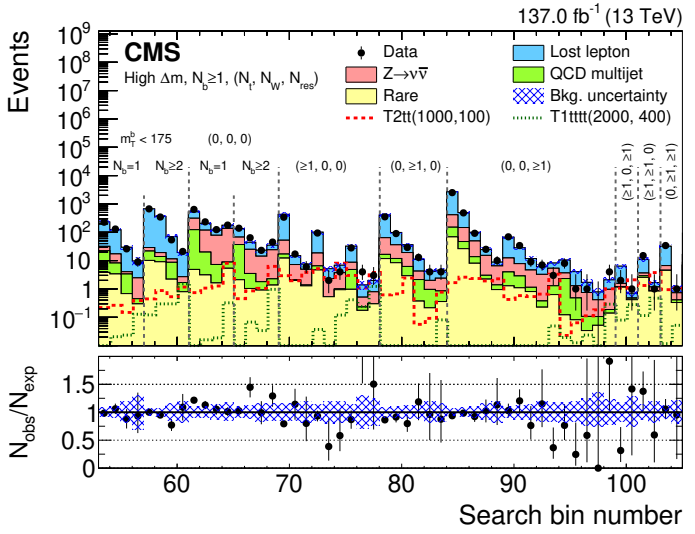
Gluino/squark searches: hadronic final state

SUS-19-010

- Targets stop and gluino production
- Final state : multiple jets, high p_T^{miss}
- Two SRs sensitive to different signals corresponding to the high and low $\triangle$m ($= m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$) values
- Merged tagging algorithm for boosted tops
- Deep Neural Network (DNN) based Resolved tagger for low p_T tops.
- Use of W tagger and soft b tagger



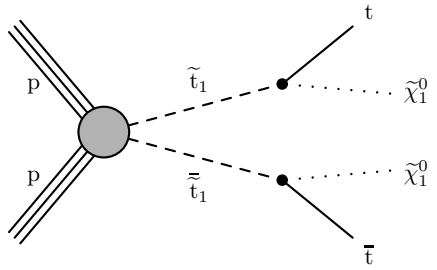




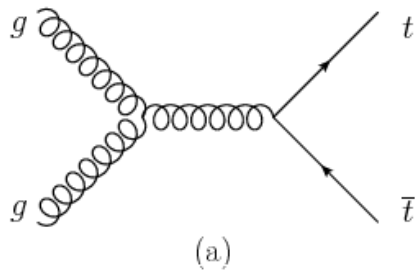
Stop searches: top corridor

- Probe stop in the top corridor region with di-lepton final state.
- Final state: di-lepton with p_T^{miss} and at least two jets.
- Challenging as the signal (T2tt) and SM background ($t\bar{t}$) have similar kinematics.
- Major SM backgrounds : $t\bar{t}$ (91% of total), tW, Drell-Yan
- DNN is used to separate signal from background.

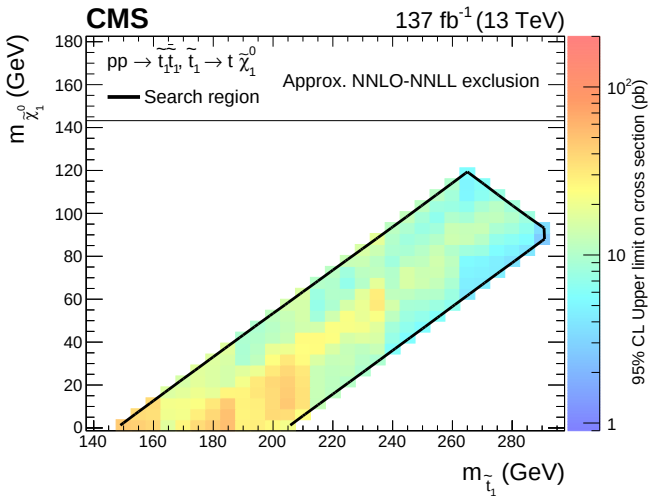
SUS-20-002



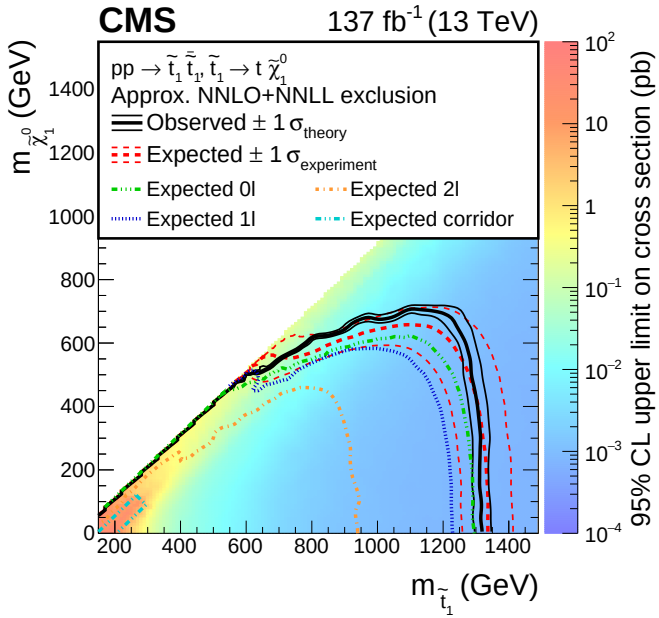
$\triangle m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \simeq m_t$



$t\bar{t}$ production

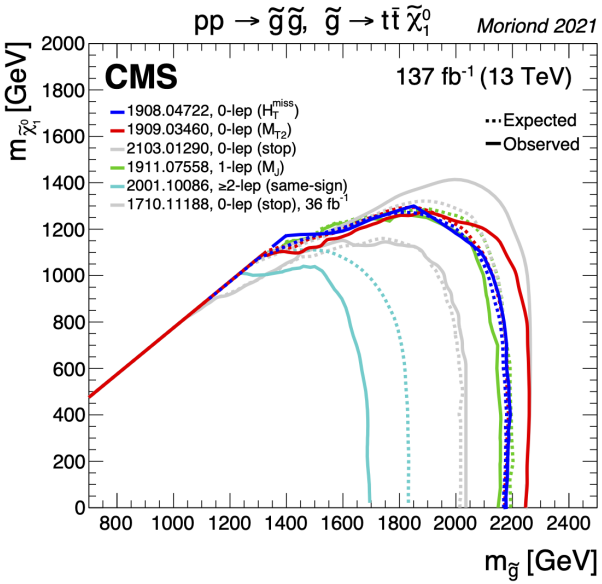


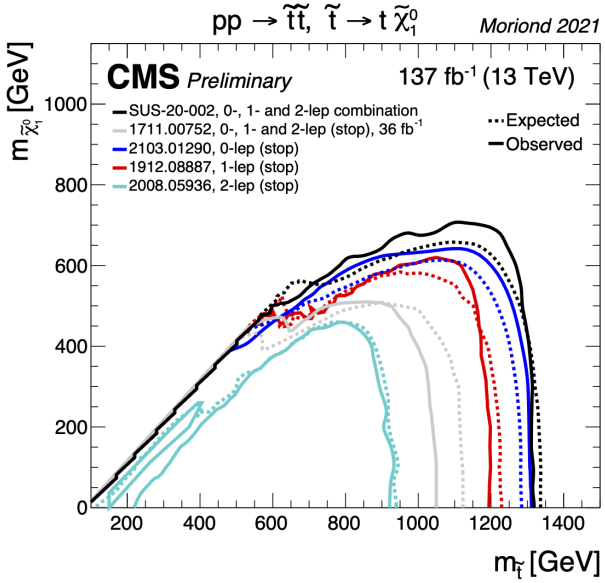
Full top corridor region excluded!

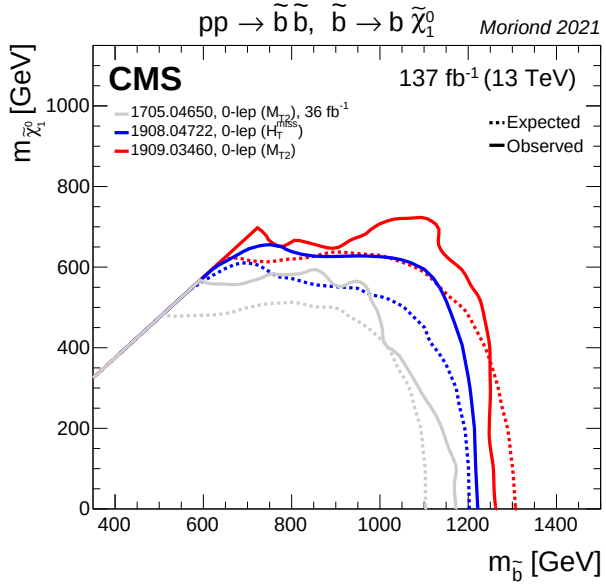


Unblinded top corridor

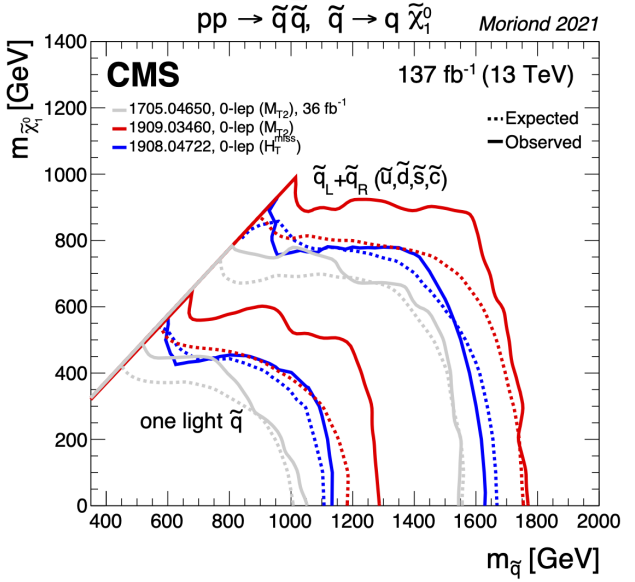
Gluino/squark Searches: Summary







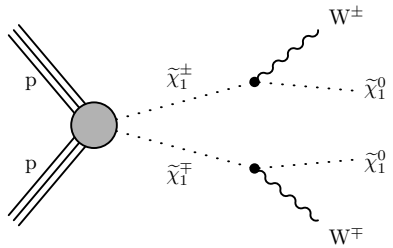
- Gluino masses excluded up to 2.3 TeV.
- Stop masses excluded up to 1.3 TeV.
- Sbottom masses excluded up to 1.25 TeV.
- Single (degenerate) squark masses excluded up to 1.3 (1.8) TeV.

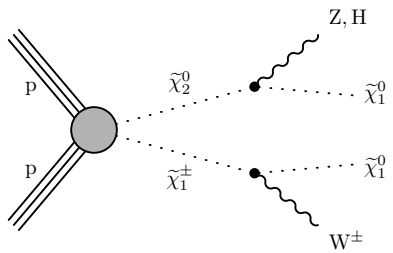


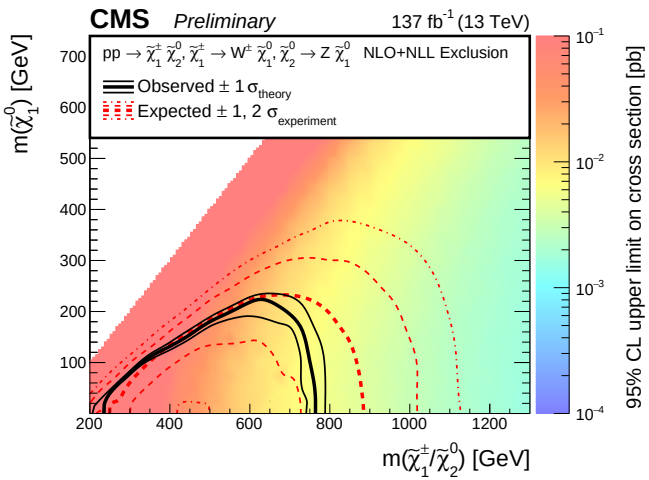
Electroweakino searches: all hadronic final states

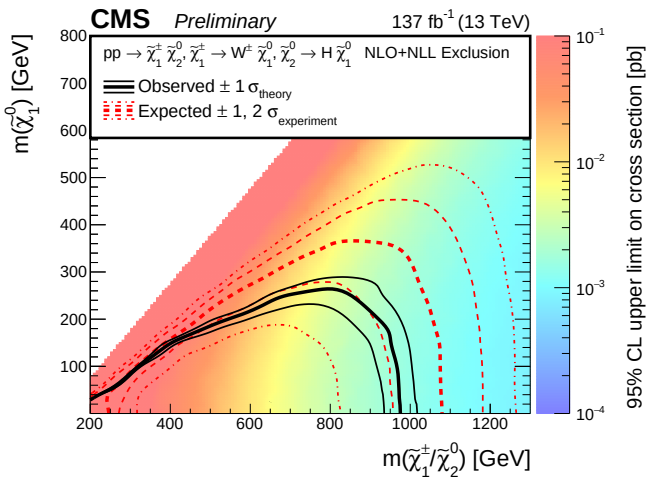
SUS-21-002

- Hadronically decaying WW, WZ, WH in the final states
- Anti-k_T jets with clustering size, R = 0.8 for reconstruction of W/Z/H.
- W taggers for tagging W bosons and bb-vs-light tagger for tagging H/Z bosons decaying into $b\bar{b}$
- Search region is defined based on the number of b-tagged jets and W and H boson candidate.
- For nearly massless $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ masses excluded up to 760 and 970 GeV in case of $\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \rightarrow H\tilde{\chi}_1^0$, respectively.





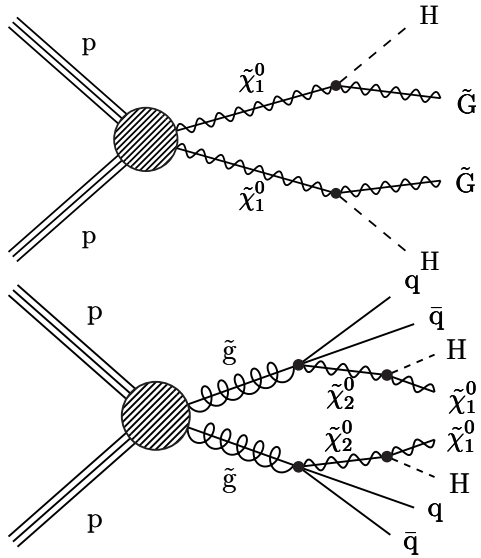




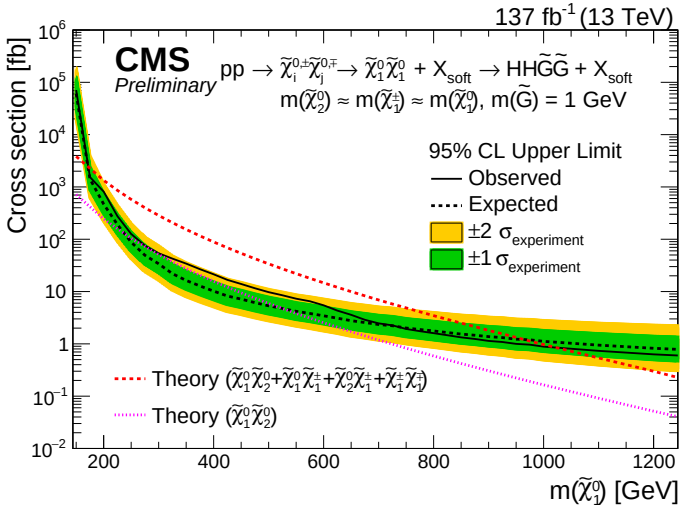
Electroweakino searches: HH final states

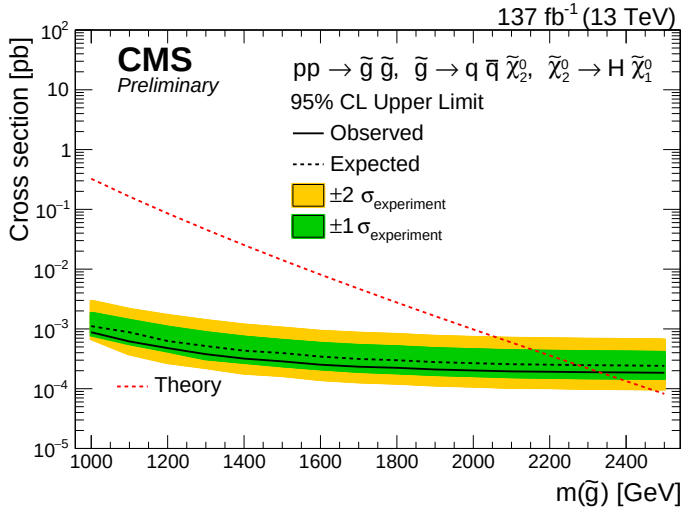
SUS-20-004

- Two Higgs boson decaying to $b\bar{b}$ in the final state.
- A combined phase space
- Resolved region : Higgs contained in 2 AK4 jets
  $p_T^{miss} > 150$ GeV, 4-5 AK4 jets, $\geq$2 b-jets,
  $100 < m_{bb} < 140$ GeV.
- Boosted region : Higgs contained in a single AK8 jet
  $p_T^{miss} > 300$ GeV, $\geq$ 2 AK8 jets, $95 < m_{jet} < 145$ GeV



- For electroweak production, neutralino masses is excluded from 175 to 1025 GeV.
- For strong production, gluino masses is excluded up to 2330 GeV.

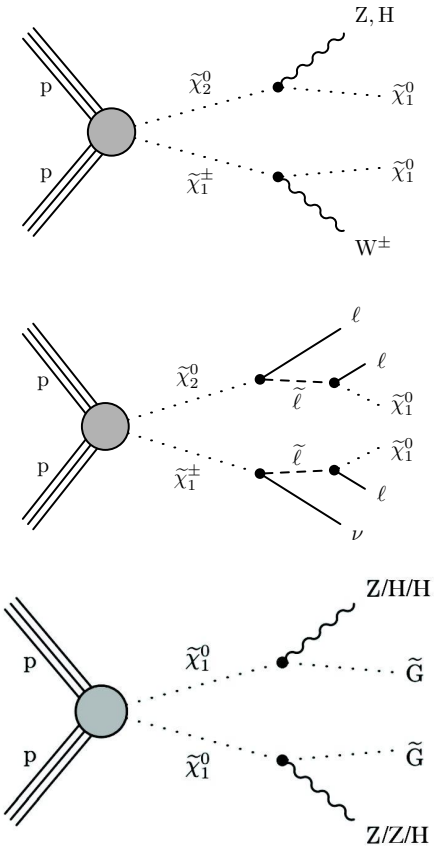


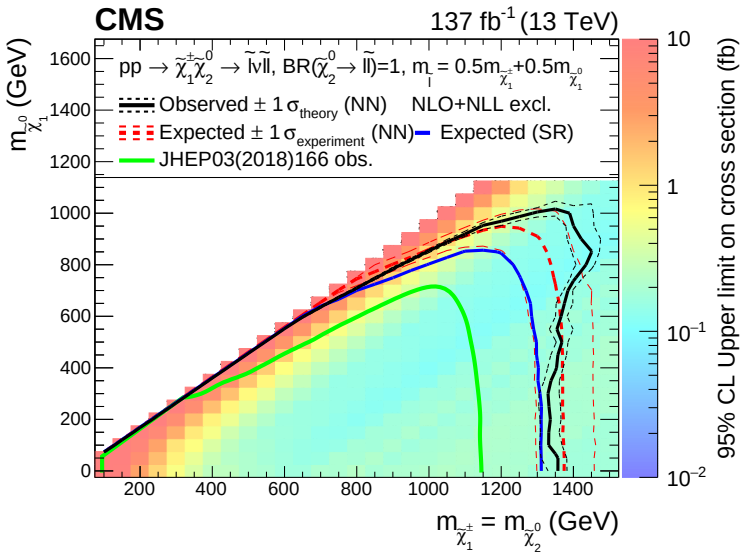


Electroweakino searches: multi-lepton final states

- Pair production of chargino/neutralino
- Consider three decay topology : direct decay, mediated by sleptons, and Gauge mediated decay with gravitino as LSP.
- Final state has 3-4 leptons, with up to $2\tau_h$
- Search region is binned in terms of di-lepton p_T, p_T^{miss} and m_{T2}
- DNN with parameter $\triangle M = m_{NLSP} - m_{LSP}$ is trained to increase search sensitivity.
- Excludes electroweakinos up to 1.4 TeV.

SUS-19-012





Slepton searches

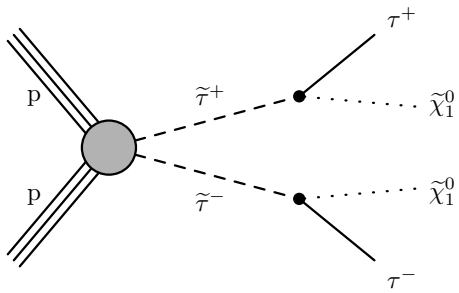
Direct stau($\tilde{\tau}$) pair production

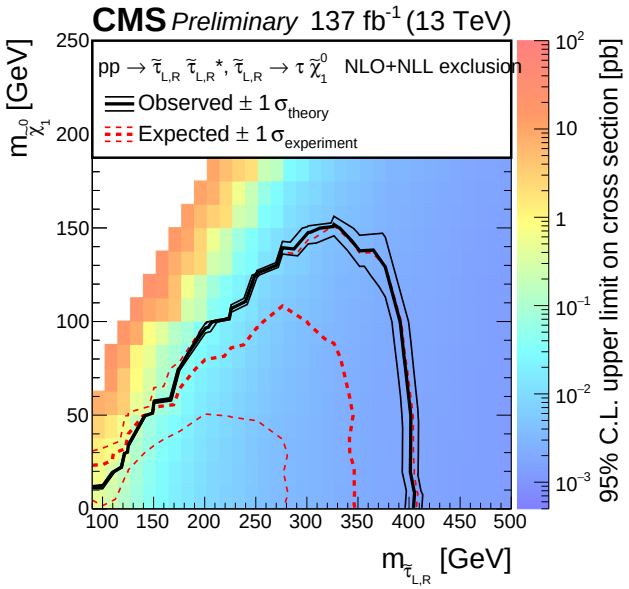
- consider different mixtures of left and right handed $\tilde{\tau}$
- consider $\tilde{\tau}$ to be long-lived
  decay length $c\tau(\tilde{\tau})$ is 0.01 - 10mm
- Final state: two hadronic τ + large MET from LSP
- Uses DNN based "DeepTau" algorithm to tag hadronically decaying τ
- Search region is binned in $N_{jets}, p_T, m_{T2}, m_T$
- Excluded m($\tilde{\tau}$) up to $\sim$ 400 GeV.

e, μ slepton pair production SUS-20-001

- Final state : OS SF leptons and large MET
- Excluded slepton masses up to $\sim$ 700 GeV

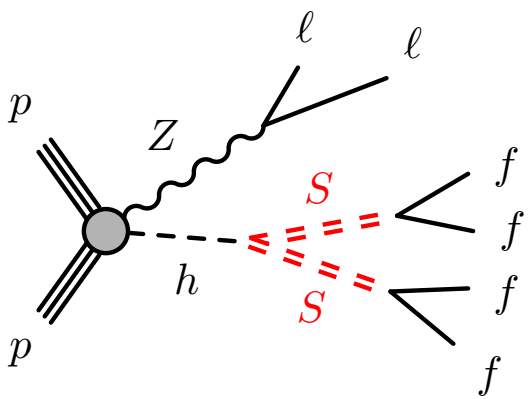
SUS-21-001





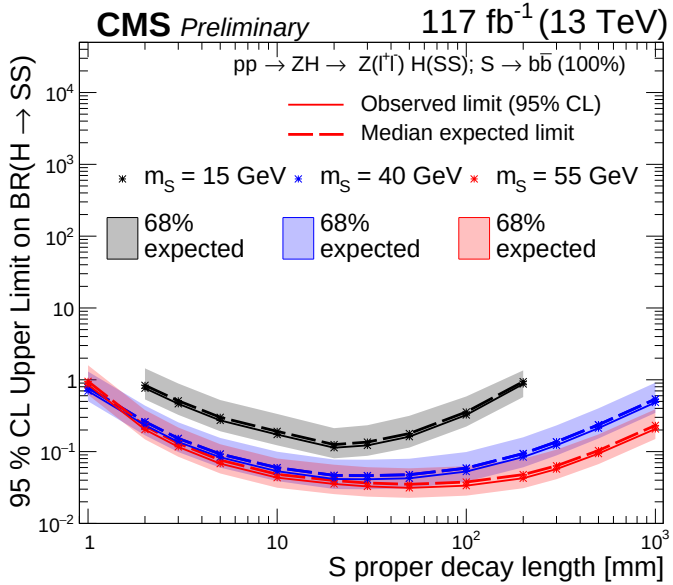
LLP Searches: Z with displaced jets in final state

- Search for SM-like Higgs boson decaying to LLPs in association with a Z boson.
- Z decays to ee or $\mu\mu$ providing sensitivity to light (< 15 GeV) LLPs.
- Cut-based displaced-jet tagging using the properties of the tracks associated with each jet.
- Look for events with prompt dilepton with ≥ 2 displaced jets.
- No significant deviation from SM backgrounds is observed.
- $H \to SS$ branching ratio is constrained to be below 5-10% for proper decay lengths of 10-100 mm and masses between 40 and 55 GeV.



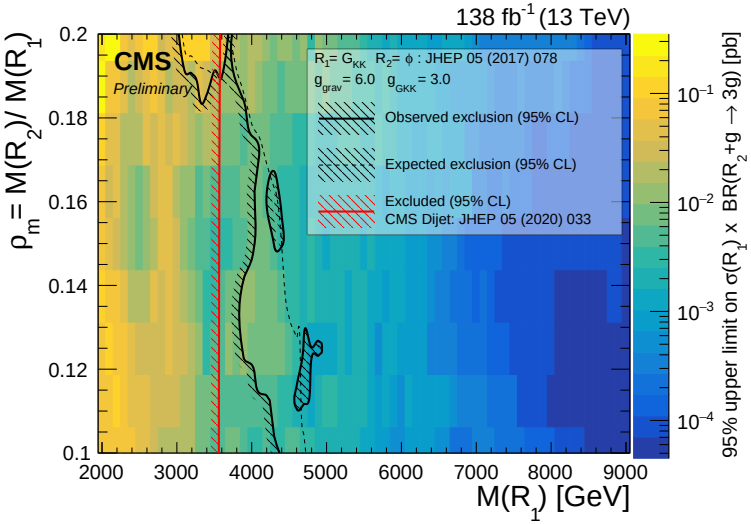
EXO-20-003

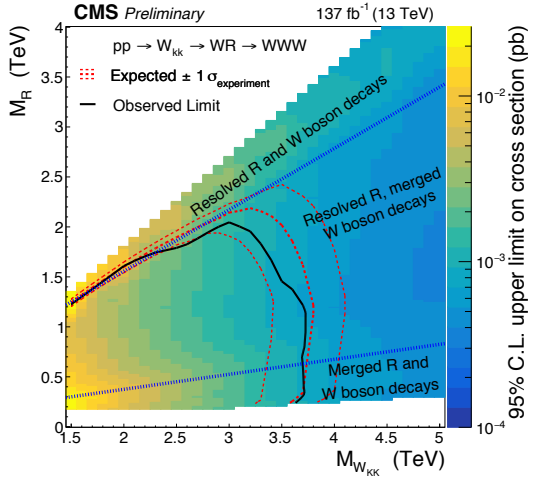
Z + displaced jets final state



Three body Resonance Searches

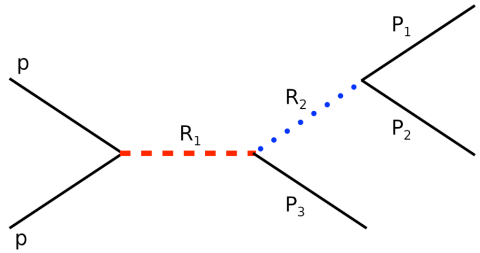
- First tri-jet and tri-boson searches at LHC.
- Tri-jet :
  Kaluza-Klein (KK) gluon (R_1) decaying to SM gluons (P_1, P_2) via radion (R_2)
  $G_{KK} \rightarrow \phi g \rightarrow ggg$
  Double resonance and jet substructure
- Tri-boson :
  KK excited massive W, $W_{KK} \rightarrow WR \rightarrow WWW$





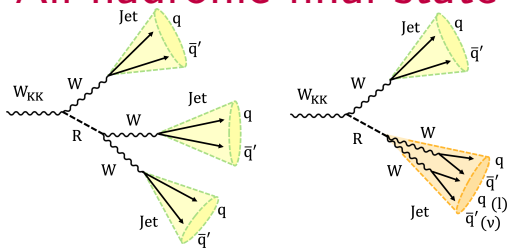
EXO-20-007

Tri-jet final state



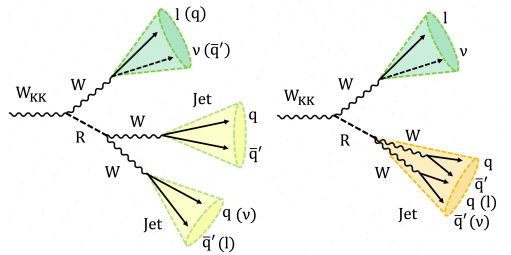
B2G-21-002

All hadronic final state



B2G-20-001

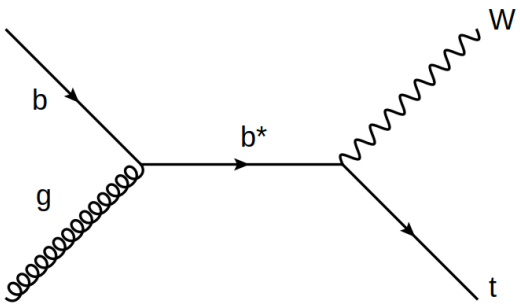
Lepton + large R jets



Heavy b* resonance

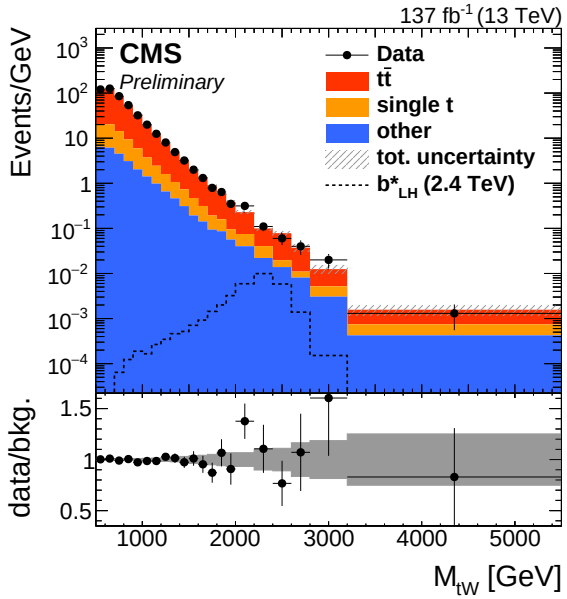
- Search for heavy resonance decaying to tW
- Search in single-lepton final state : $b^* \rightarrow tW \rightarrow t\ell\nu$
- Reconstruct top quark using top tagging with HOTVR (Heavy Object Trigger with Variable Radius) algorithm
- Large H_T (>200 GeV) and S_T (>400 GeV)
- M_{tW} used as observational variable
- Results combined with all-hadronic analysis.

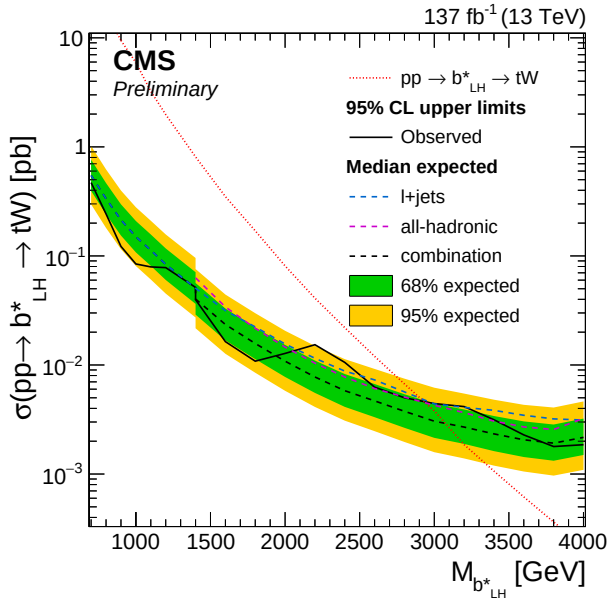
  The b^* is excluded up to masses of 2.95, 3.03, 3.22 TeV for the LH, RH and VL couplings.



B2G-20-010
Lepton+jets final state

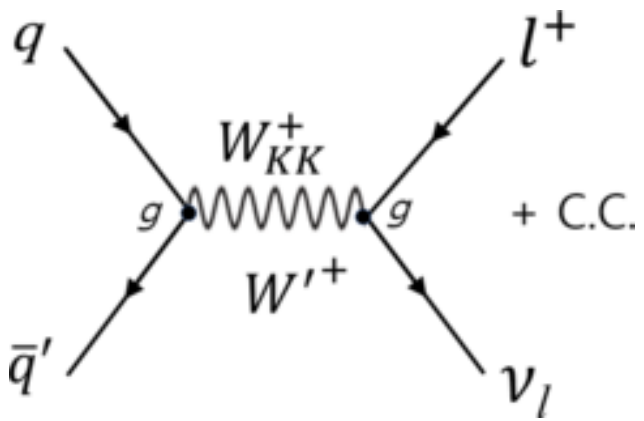
B2G-19-003
fully hadronic final state



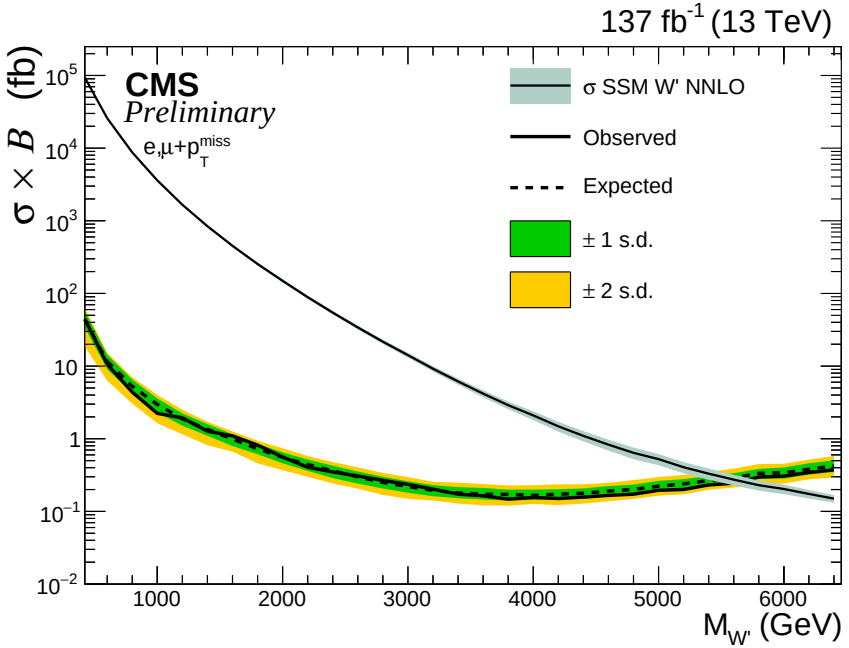


Heavy Gauge Bosons : $\ell + p_T^{miss}$ final state

- Search for Sequential Standard Model (SSM) $W^{'}$ boson $W^{'} \rightarrow \ell\nu$ decays
- The transverse mass distribution of the lepton-neutrino system, $m_T(\ell, p_T^{miss})$ is used as the discriminating variable.
- Mass of SSM $W^{'}$ boson is excluded up to 5.7 TeV with SM like coupling by combining e and μ decay channels.

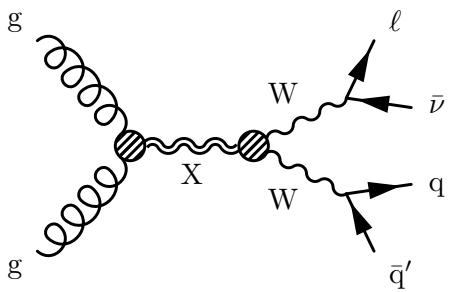


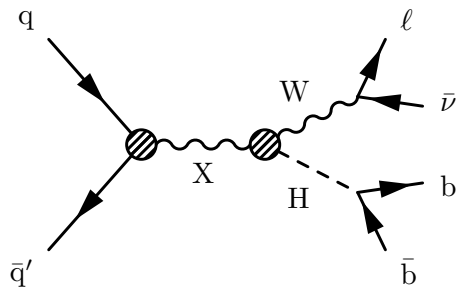
EXO-19-017



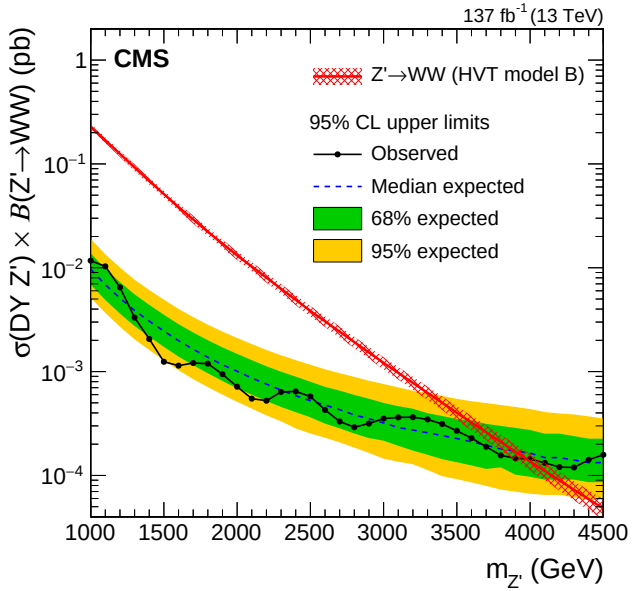
Heavy Gauge Bosons : semi-leptonic channel

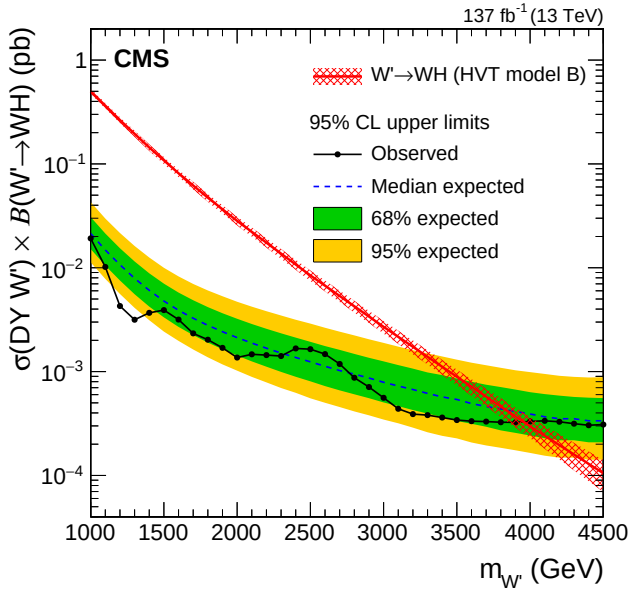
- Search for resonance in semi-leptonic channel
  $Z^{'} \rightarrow WW \rightarrow \ell\nu q\bar{q}$
  $W^{'} \rightarrow WH \rightarrow \ell\nu b\bar{b}$
- Collimated decay products
  $\rightarrow$ large R jets, substructure
- Higgs tagging with double b-tagger
- No significant excess is observed above the estimated background.
- The analysis adds a lot to the sensitivity since the 2016 result.





[B2G-19-002]



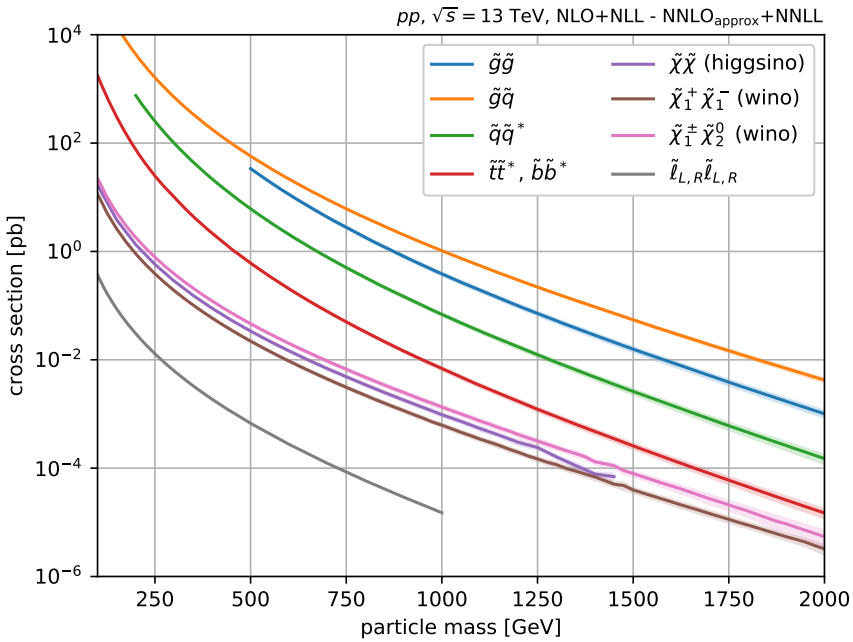


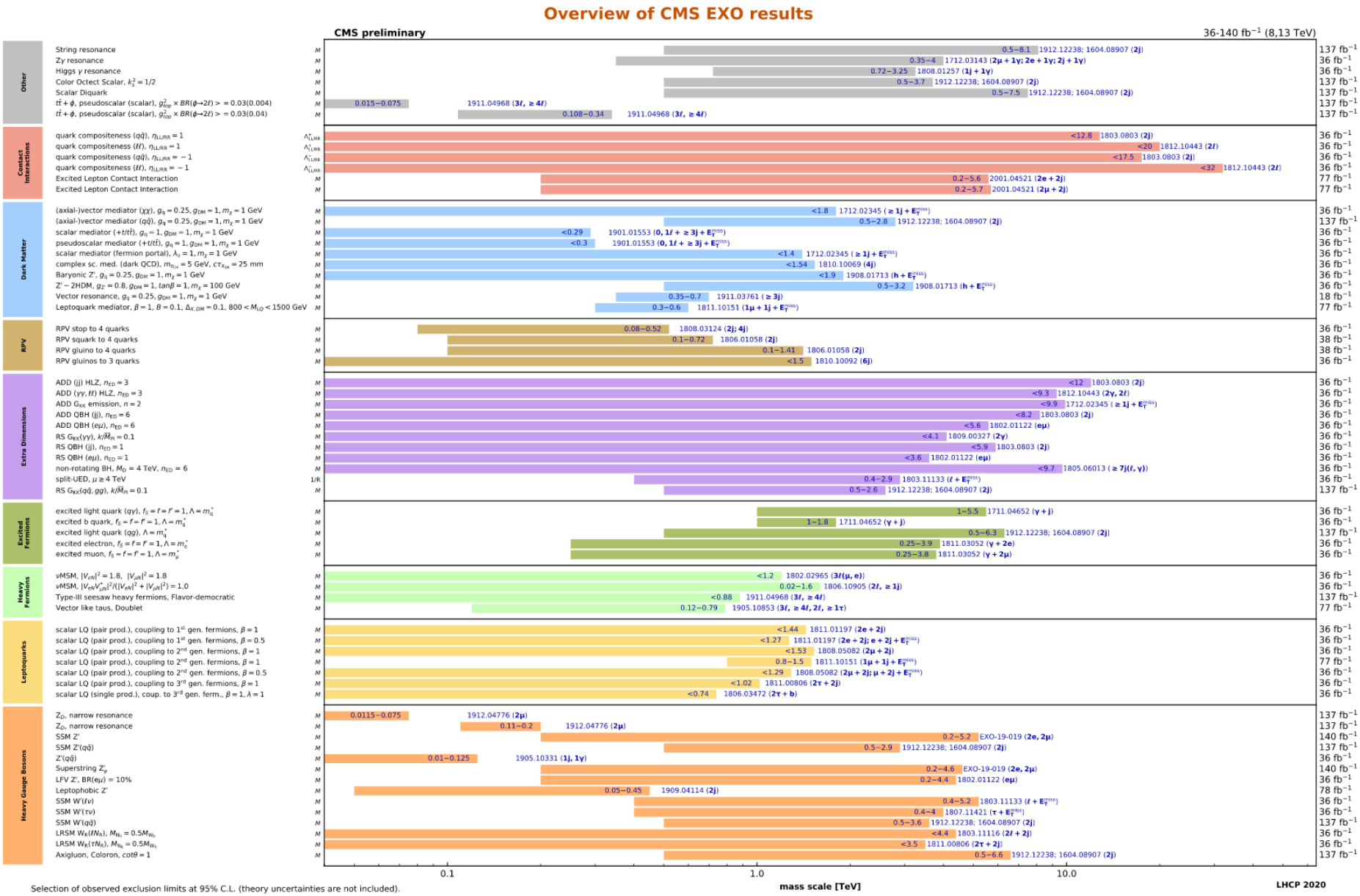
Summary and outlook

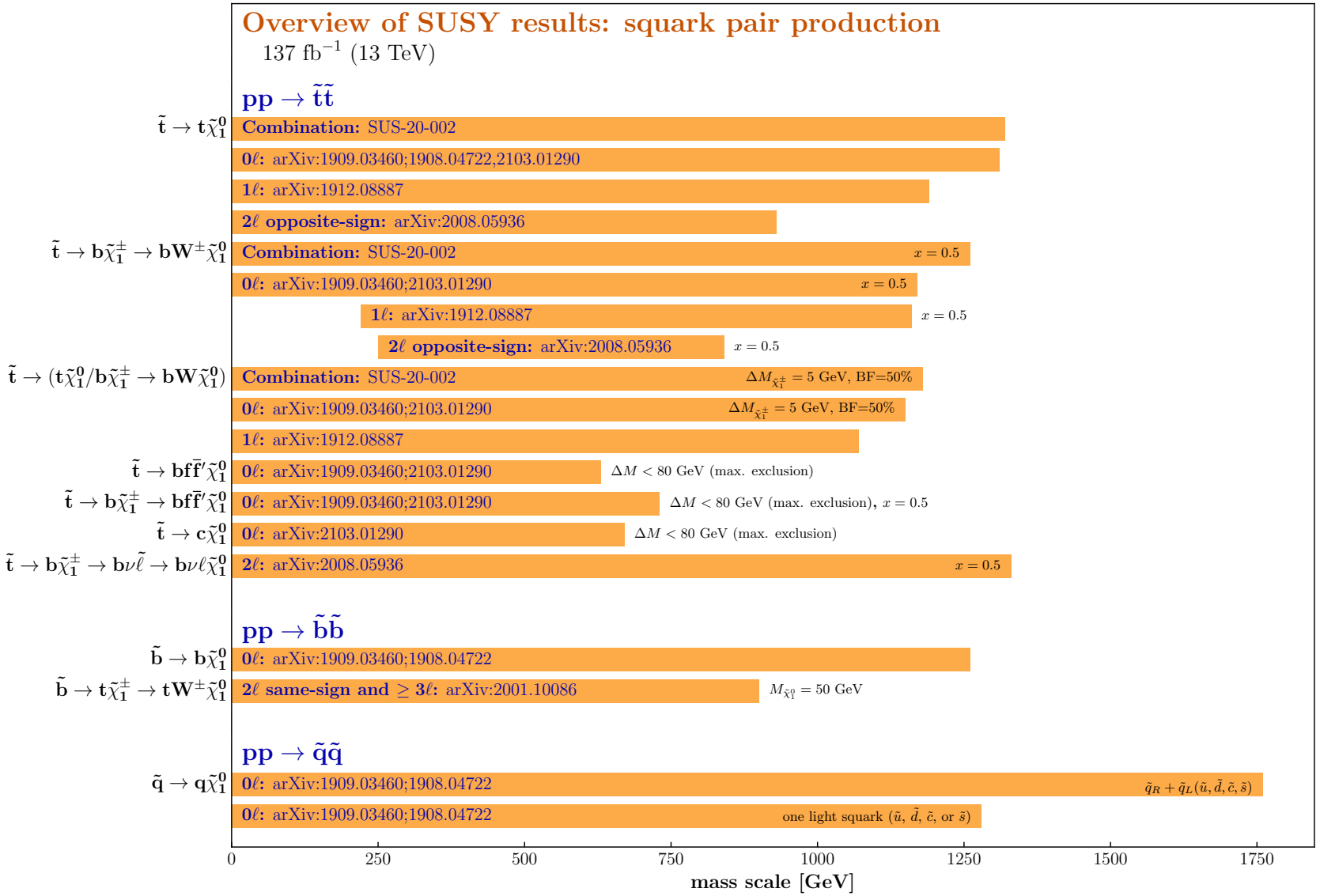
- Many new full Run2 results are already public, more to come in the near future.
- Cannot do justice to all results – only highlighted a few recent ones. Full list here :
  Recent CMS SUSY, Exotica, B2G results
- Unfortunately, no obesrvation of BSM signature yet, only limits are being pushed further.
- Preparations for Run 3 in full swing.
- Exciting times ahead!

Additional slides

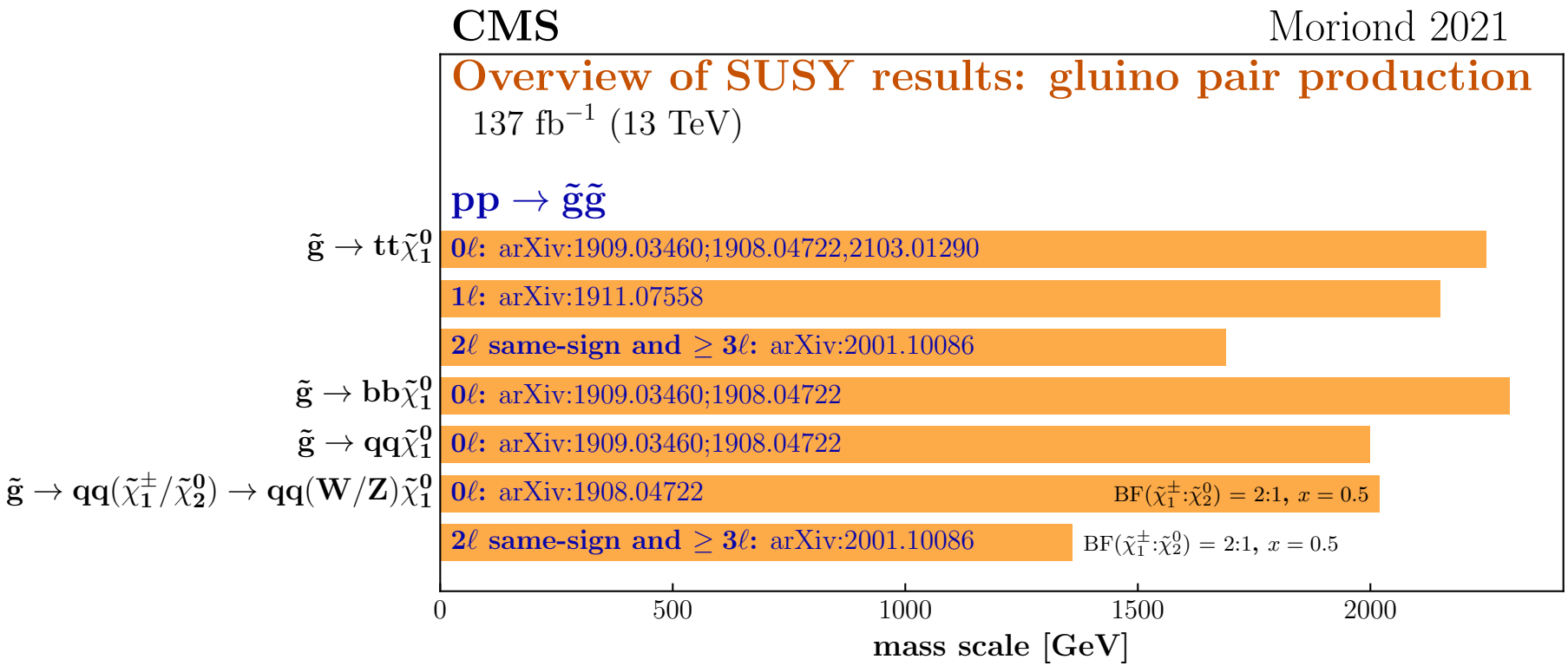
- **gluino/squark production :**
  Largest cross section, Events with many jets in the final state.
- **third generation quarks :**
  Intermediate cross sections favoured for naturalness
- **Electroweak production :**
  Lower cross section
  clean signature with leptons.



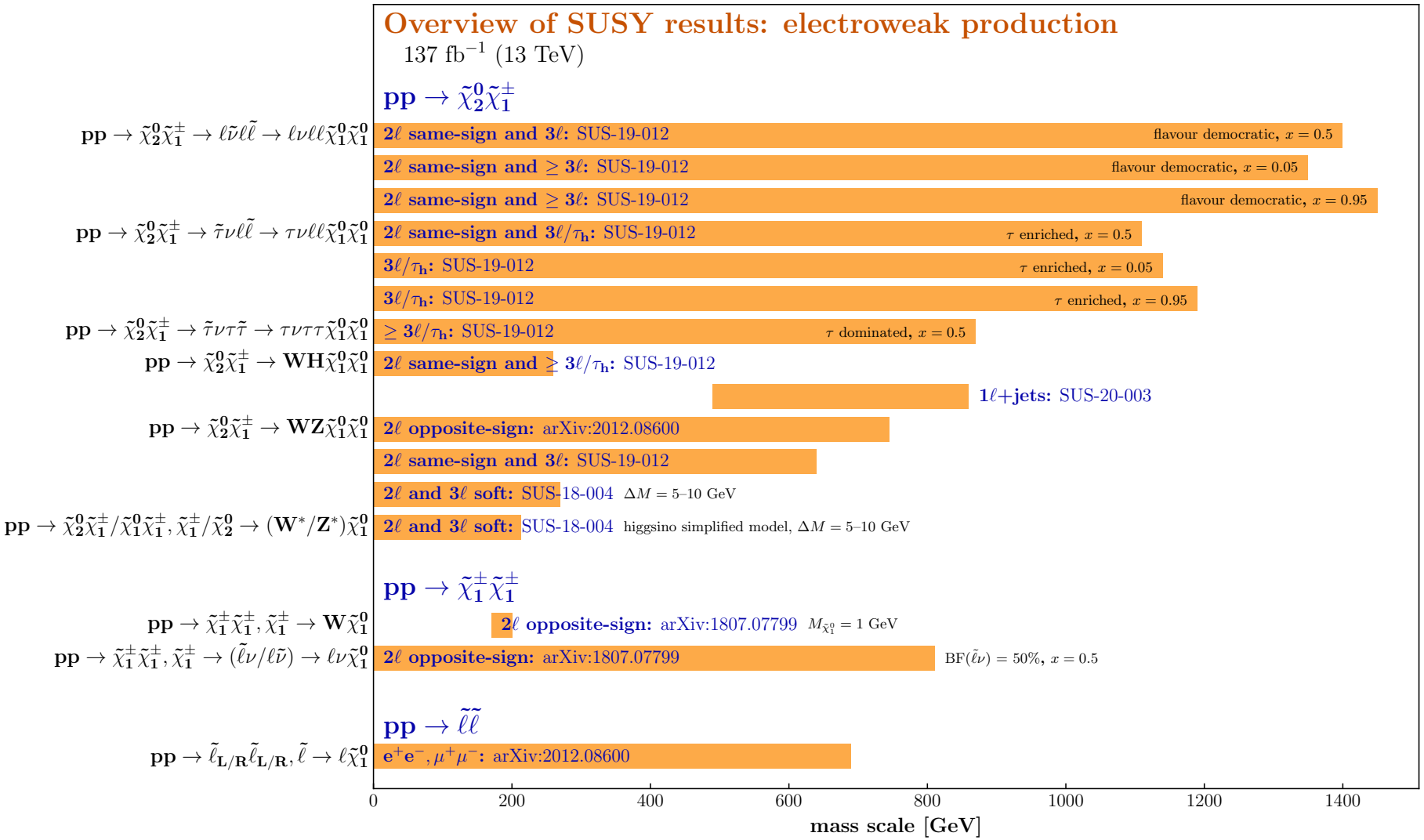

Overview of CMS EXO results
CMS preliminary
36-140 fb^{-1} (8,13 TeV)
Other
String resonance
Zγ resonance
Higgs γ resonance
Color Octect Scalar, $k_c^2 = 1/2$
Scalar Diquark
$t\bar{t}+\phi$, pseudoscalar (scalar), $g_{top}^2 \times BR(\phi \to 2\ell) > = 0.03(0.004)$
$t\bar{t}+\phi$, pseudoscalar (scalar), $g_{top}^2 \times BR(\phi \to 2\ell) > = 0.03(0.04)$
0.5−8.1 1912.12238; 1604.08907 (2j)
0.35−4 1712.03143 (2μ + 1γ; 2e + 1γ; 2j + 1γ)
0.72−3.25 1808.01257 (1j + 1γ)
0.5−3.7 1912.12238; 1604.08907 (2j)
0.5−7.5 1912.12238; 1604.08907 (2j)
0.015−0.075 1911.04968 (3ℓ, ≥ 4ℓ)
0.108−0.34 1911.04968 (3ℓ, ≥ 4ℓ)
137 fb^{-1}
36 fb^{-1}
36 fb^{-1}
137 fb^{-1}
137 fb^{-1}
137 fb^{-1}
137 fb^{-1}
Contact Interactions
quark compositeness ($q\bar{q}$), $\eta_{LLRR} = 1$
quark compositeness ($\ell\ell$), $\eta_{LLRR} = 1$
quark compositeness ($q\bar{q}$), $\eta_{LLRR} = -1$
quark compositeness ($\ell\ell$), $\eta_{LLRR} = -1$
Excited Lepton Contact Interaction
Excited Lepton Contact Interaction
<12.8 1803.0803 (2j)
<20 1812.10443 (2ℓ)
<17.5 1803.0803 (2j)
<32 1812.10443 (2ℓ)
0.2−5.6 2001.04521 (2e + 2j)
0.2−5.7 2001.04521 (2μ + 2j)
36 fb^{-1}
36 fb^{-1}
36 fb^{-1}
36 fb^{-1}
77 fb^{-1}
77 fb^{-1}
Dark Matter
(axial-)vector mediator ($\chi\chi$), $g_q = 0.25$, $g_{DM} = 1$, $m_\chi = 1$ GeV
(axial-)vector mediator ($q\bar{q}$), $g_q = 0.25$, $g_{DM} = 1$, $m_\chi = 1$ GeV
scalar mediator ($+t/t\bar{t}$), $g_q = 1$, $g_{DM} = 1$, $m_\chi = 1$ GeV
pseudoscalar mediator ($+t/t\bar{t}$), $g_q = 1$, $g_{DM} = 1$, $m_\chi = 1$ GeV
scalar mediator (fermion portal), $\lambda_u = 1$, $m_\chi = 1$ GeV
complex sc. med. (dark QCD), $m_{\pi_{DC}} = 5$ GeV, $c\tau_{\pi_{DC}} = 25$ mm
Baryonic Z′, $g_q = 0.25$, $g_{DM} = 1$, $m_\chi = 1$ GeV
Z′ − 2HDM, $g_{Z'} = 0.8$, $g_{DM} = 1$, $tan\beta = 1$, $m_\chi = 100$ GeV
Vector resonance, $g_q = 0.25$, $g_{DM} = 1$, $m_\chi = 1$ GeV
Leptoquark mediator, $\beta = 1$, $B = 0.1$, $\Delta_{\chi,DM} = 0.1$, $800 < M_{LQ} < 1500$ GeV
<1.8 1712.02345 (≥ 1j + E_T^{miss})
0.5−2.8 1912.12238; 1604.08907 (2j)
<0.29 1901.01553 (0, 1ℓ + ≥ 3j + E_T^{miss})
<0.3 1901.01553 (0, 1ℓ + ≥ 3j + E_T^{miss})
<1.4 1712.02345 (≥ 1j + E_T^{miss})
<1.54 1810.10069 (4j)
<1.9 1908.01713 (h + E_T^{miss})
0.5−3.2 1908.01713 (h + E_T^{miss})
0.35−0.7 1911.03761 (≥ 3j)
0.3−0.6 1811.10151 (1μ + 1j + E_T^{miss})
36 fb^{-1}
137 fb^{-1}
36 fb^{-1}
36 fb^{-1}
36 fb^{-1}
36 fb^{-1}
36 fb^{-1}
36 fb^{-1}
36 fb^{-1}
18 fb^{-1}
77 fb^{-1}
RPV
RPV stop to 4 quarks
RPV squark to 4 quarks
RPV gluino to 4 quarks
RPV gluinos to 3 quarks
0.08−0.52 1808.03124 (2j; 4j)
0.1−0.72 1806.01058 (2j)
0.1−1.41 1806.01058 (2j)
<1.5 1810.10092 (6j)
36 fb^{-1}
38 fb^{-1}
38 fb^{-1}
36 fb^{-1}
Extra Dimensions
ADD (jj) HLZ, $n_{ED} = 3$
ADD (γγ, ℓℓ) HLZ, $n_{ED} = 3$
ADD G_{KK} emission, $n = 2$
ADD QBH (jj), $n_{ED} = 6$
ADD QBH (eμ), $n_{ED} = 6$
RS $G_{KK}(\gamma\gamma)$, $k/\bar{M}_{Pl} = 0.1$
RS QBH (jj), $n_{ED} = 1$
RS QBH (eμ), $n_{ED} = 1$
non-rotating BH, $M_D = 4$ TeV, $n_{ED} = 6$
split-UED, $\mu \geq 4$ TeV
RS $G_{KK}(q\bar{q}, gg)$, $k/\bar{M}_{Pl} = 0.1$
<12 1803.0803 (2j)
<9.3 1812.10443 (2γ, 2ℓ)
<9.9 1712.02345 (≥ 1j + E_T^{miss})
<8.2 1803.0803 (2j)
<5.6 1802.01122 (eμ)
<4.1 1809.00327 (2γ)
<5.9 1803.0803 (2j)
<3.6 1802.01122 (eμ)
<9.7 1805.06013 (≥ 7j(ℓ, γ))
0.4−2.9 1803.11133 (ℓ + E_T^{miss})
0.5−2.6 1912.12238; 1604.08907 (2j)
36 fb^{-1}
36 fb^{-1}
36 fb^{-1}
36 fb^{-1}
36 fb^{-1}
36 fb^{-1}
36 fb^{-1}
36 fb^{-1}
36 fb^{-1}
36 fb^{-1}
137 fb^{-1}
Excited Fermions
excited light quark (qγ), $f_s = f = f' = 1$, $\Lambda = m_{q^*}$
excited b quark, $f_s = f = f' = 1$, $\Lambda = m_{q^*}$
excited light quark (qg), $\Lambda = m_{q^*}$
excited electron, $f_s = f = f' = 1$, $\Lambda = m_{e^*}$
excited muon, $f_s = f = f' = 1$, $\Lambda = m_{\mu^*}$
1−5.5 1711.04652 (γ + j)
1−1.8 1711.04652 (γ + j)
0.5−6.3 1912.12238; 1604.08907 (2j)
0.25−3.9 1811.03052 (γ + 2e)
0.25−3.8 1811.03052 (γ + 2μ)
36 fb^{-1}
36 fb^{-1}
137 fb^{-1}
36 fb^{-1}
36 fb^{-1}
Heavy Fermions
νMSM, $|V_{eN}|^2 = 1.8$, $|V_{\mu N}|^2 = 1.8$
νMSM, $|V_{eN}V_{\mu N}^*|^2/(|V_{eN}|^2 + |V_{\mu N}|^2) = 1.0$
Type-III seesaw heavy fermions, Flavor-democratic
Vector like taus, Doublet
<1.2 1802.02965 (3ℓ(μ, e))
0.02−1.6 1806.10905 (2ℓ, ≥ 1j)
<0.88 1911.04968 (3ℓ, ≥ 4ℓ)
0.12−0.79 1905.10853 (3ℓ, ≥ 4ℓ, 2ℓ, ≥ 1τ)
36 fb^{-1}
36 fb^{-1}
137 fb^{-1}
77 fb^{-1}
Leptoquarks
scalar LQ (pair prod.), coupling to 1st gen. fermions, $\beta = 1$
scalar LQ (pair prod.), coupling to 1st gen. fermions, $\beta = 0.5$
scalar LQ (pair prod.), coupling to 2nd gen. fermions, $\beta = 1$
scalar LQ (pair prod.), coupling to 2nd gen. fermions, $\beta = 1$
scalar LQ (pair prod.), coupling to 2nd gen. fermions, $\beta = 0.5$
scalar LQ (pair prod.), coupling to 3rd gen. fermions, $\beta = 1$
scalar LQ (single prod.), coup. to 3rd gen. ferm., $\beta = 1$, $\lambda = 1$
<1.44 1811.01197 (2e + 2j)
<1.27 1811.01197 (2e + 2j; e + 2j + E_T^{miss})
<1.53 1808.05082 (2μ + 2j)
0.8−1.5 1811.10151 (1μ + 1j + E_T^{miss})
<1.29 1808.05082 (2μ + 2j; μ + 2j + E_T^{miss})
<1.02 1811.00806 (2τ + 2j)
<0.74 1806.03472 (2τ + b)
36 fb^{-1}
36 fb^{-1}
36 fb^{-1}
77 fb^{-1}
36 fb^{-1}
36 fb^{-1}
36 fb^{-1}
Heavy Gauge Bosons
Z_D, narrow resonance
Z_D, narrow resonance
SSM Z′
SSM Z′($q\bar{q}$)
Z′($q\bar{q}$)
Superstring Z'_ψ
LFV Z′, BR(eμ) = 10%
Leptophobic Z′
SSM W′(ℓν)
SSM W′(τν)
SSM W′($q\bar{q}$)
LRSM $W_R(\ell N_R)$, $M_{N_\ell} = 0.5 M_{W_R}$
LRSM $W_R(\tau N_R)$, $M_{N_\tau} = 0.5 M_{W_R}$
Axigluon, Coloron, $cot\theta = 1$
0.0115−0.075 1912.04776 (2μ)
0.11−0.2 1912.04776 (2μ)
0.2−5.2 EXO-19-019 (2e, 2μ)
0.5−2.9 1912.12238; 1604.08907 (2j)
0.01−0.125 1905.10331 (1j, 1γ)
0.2−4.6 EXO-19-019 (2e, 2μ)
0.2−4.4 1802.01122 (eμ)
0.05−0.45 1909.04114 (2j)
0.4−5.2 1803.11133 (ℓ + E_T^{miss})
0.4−4 1807.11421 (τ + E_T^{miss})
0.5−3.6 1912.12238; 1604.08907 (2j)
<4.4 1803.11116 (2ℓ + 2j)
<3.5 1811.00806 (2τ + 2j)
0.5−6.6 1912.12238; 1604.08907 (2j)
137 fb^{-1}
137 fb^{-1}
140 fb^{-1}
137 fb^{-1}
36 fb^{-1}
140 fb^{-1}
36 fb^{-1}
78 fb^{-1}
36 fb^{-1}
36 fb^{-1}
137 fb^{-1}
36 fb^{-1}
36 fb^{-1}
137 fb^{-1}
0.1
1.0
10.0
mass scale [TeV]
LHCP 2020
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.