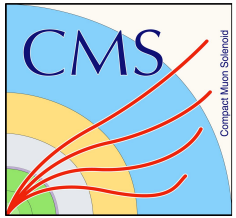


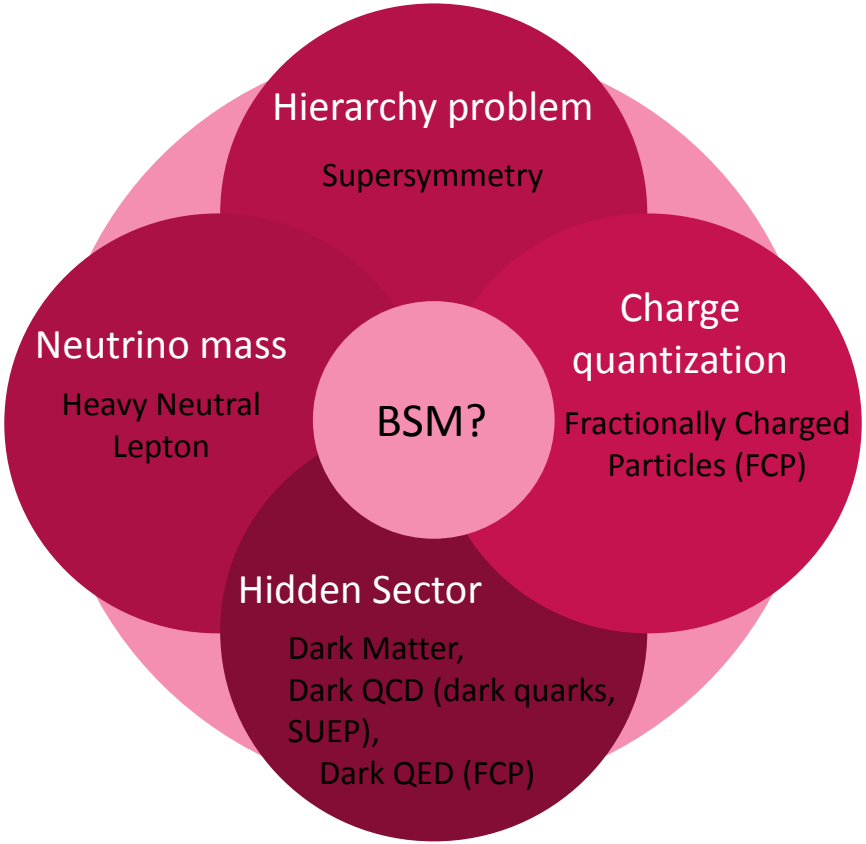
Exotic searches at the LHC

Report from the CMS and ATLAS collaborations

La Thuile 2024
Les Rencontres de Physique de la Vallée d'Aoste

David Vannerom, March 8th, 2024

Big questions



New analyses presented today (CMS, ATLAS)

Analysis	Data set	Probe object(s)	Reference
R-parity-violating SUSY in final states containing many jets	Full Run 2	Multiple jets	arXiv:2401.16333
New phenomena with top-quark pairs and large missing transverse momentum	Full Run 2	ttbar + MET	arXiv:2401.13430
Search for invisible particles produced in association with single top quarks	Full Run 2	Mono-top	arXiv:2402.16561
Prompt HNLs decaying to e, mu and tau	Full Run 2	e, mu, tau (hadronic)	arXiv:2403.00100
Nearly mass-degenerate higgsinos using low momentum mildly displaced tracks	Full Run 2	Displaced tracks	arXiv:2401.14046
LLP using displaced vertices and missing transverse momentum	Full Run 2	Displaced vertices	arXiv:2402.15804
Fractionally charged particles	Full Run 2	Low dE/dx hits in tracker	arXiv:2402.09932
Search for light LL neutral particles from Higgs boson decays via VBF	Full Run 2	Dark photon jets	arXiv:2311.18298
Resonant production of Dark Quarks in the dijet final state	Full Run 2	Dijets (non-standard topology)	arXiv:2311.03944
Emerging jets	Full Run 2	Emerging jets	arXiv:2403.01556
Soft unclustered energy patterns	Full Run 2	Dijets (non-standard topology)	CMS-PAS-EXO-23-002
Long-lived HNLs decaying in the CMS muon detectors	Full Run 2	Shower in muon detectors	arXiv:2402.18658

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Standard objects

Exotic signatures

Search for RPV Supersymmetry in events with many jets

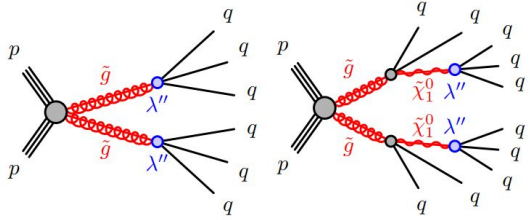
2401.16333

SUSY

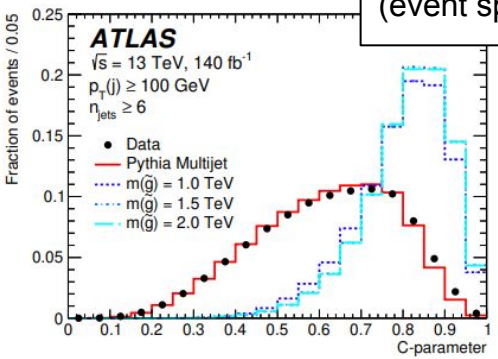
2 methods:

Jet counting

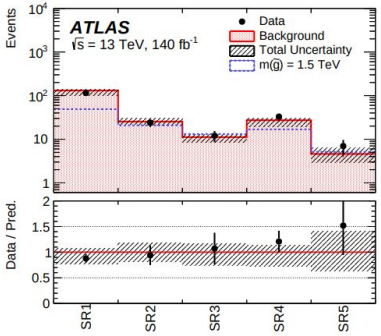
Mass resonance

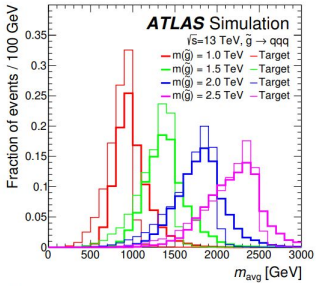


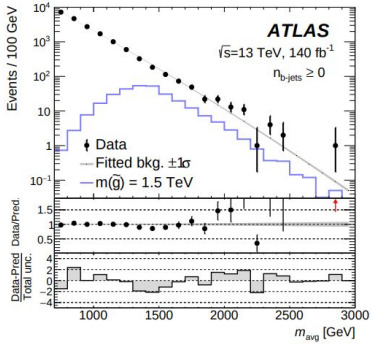
Shape variable C (event sphericity)

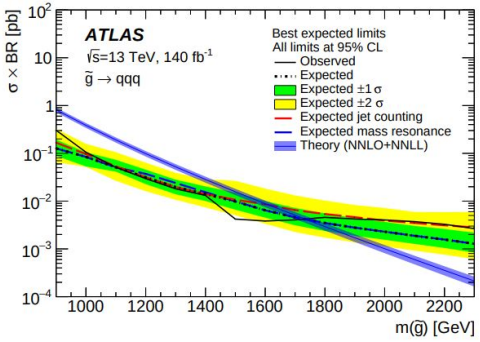


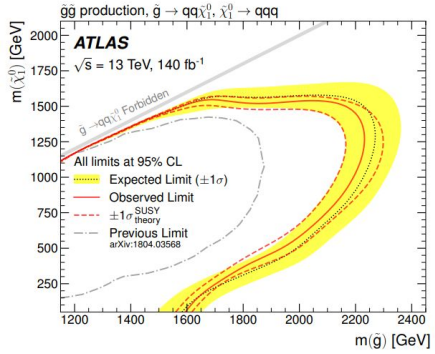
	n_{jets}	$p_{\text{T}}(j)$ [GeV]	C	$n_{b-\text{jets}}$
SR1	≥ 7	≥ 180	≥ 0.90	–
SR2	≥ 7	≥ 220	≥ 0.90	–
SR3	≥ 7	≥ 240	≥ 0.90	–
SR4	≥ 8	≥ 180	≥ 0.85	–
SR5	≥ 8	≥ 210	≥ 0.85	–
SR1bj	≥ 7	≥ 180	≥ 0.85	≥ 2
SR2bj	≥ 8	≥ 180	≥ 0.85	≥ 2







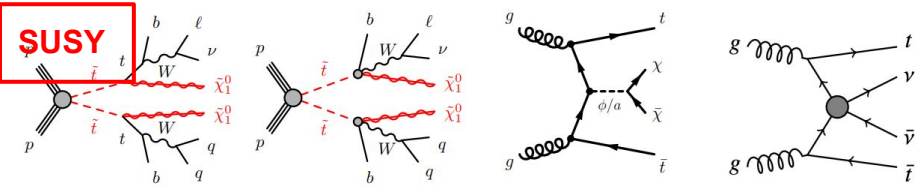




Search for Supersymmetry in events with ttbar + E_T^{miss}

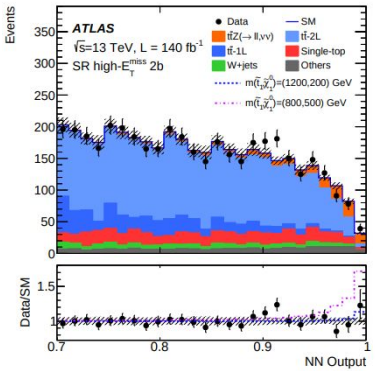
2401.13430

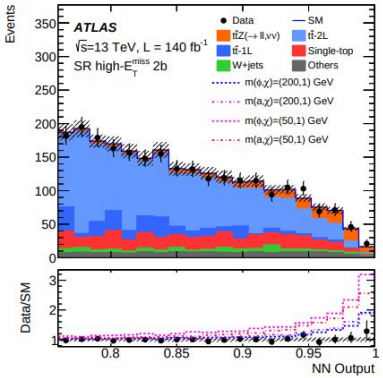
SUSY

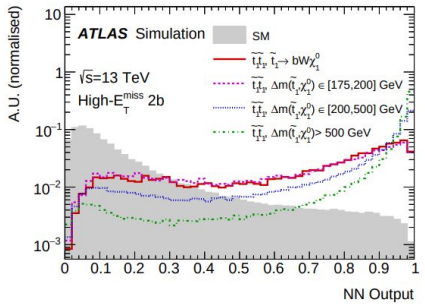


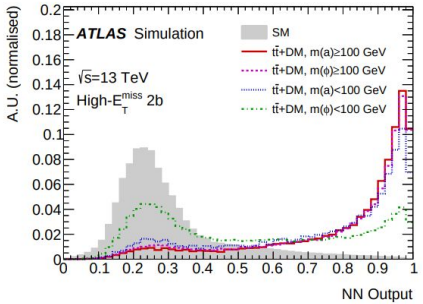
(a) $\tilde{t}_1\tilde{t}_1$ in two-body decays (b) $\tilde{t}_1\tilde{t}_1$ in three-body decays (c) $t\bar{t}$ + DM (d) $t\bar{t}\nu\bar{\nu}$ CI

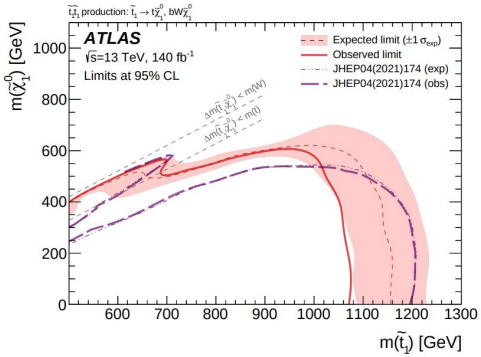
Analysis Category	High-E_T^{miss} 1b	High-E_T^{miss} 2b	Boosted 1b-lep-0t	Boosted 1b-had-0t	Boosted 2b-0t	Boosted 1b-lep-1t	Boosted 1b-had-1t	Boosted 2b-1t
$N(lR$ jet, $p_T > 600$ GeV)	0		≥ 1					
N(top-tagged lR jet)	-		0			≥ 1		
$N_{b-\text{jet}}$ with $\Delta R(b, lR\text{ jet}) < 1.1$	-		0	≥ 1	≥ 1	0	≥ 1	≥ 1
$N_{b-\text{jet}}$ with $\Delta R(b, lR\text{ jet}) > 1.1$	-		≥ 1	0	≥ 1	≥ 1	0	≥ 1
top-NN-tagged multiplet	✓		-					
$N_{b-\text{jet}}$	1	≥ 2	-					
$N_{\text{light-jet}}$	≥ 2	≥ 1	-					
top_{had} candidate	top-NN multiplet		lR jet					
top_{lep} candidate	$\ell + j$	$\ell + b$	$\ell + b$	ℓ(+j)	$\ell + b$	$\ell + b$	ℓ(+j)	$\ell + b$

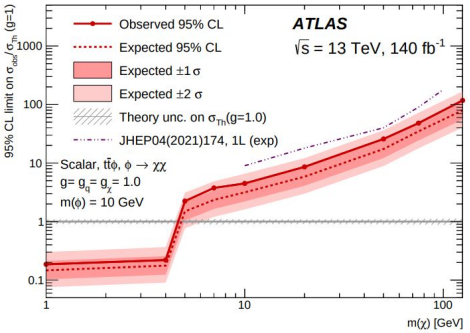








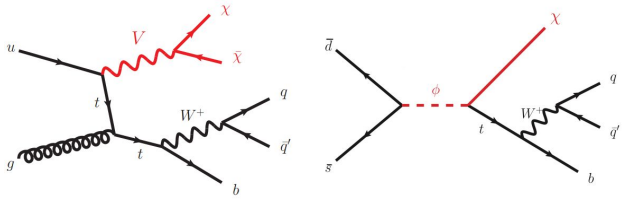




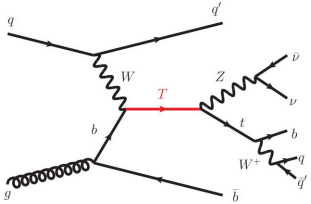
Search for invisible particles + single top quarks

2402.16561

Dark Matter interpretation (vector/scalar)



Vector-like quarks interpretation



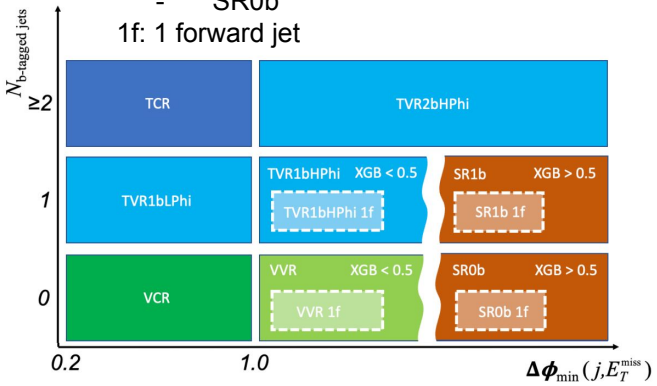
Event selection:

- Trigger on MET (offline > 250 GeV)
- Lepton veto
- ≥ 1 large-R jet (boosted top)
  - top-tagged
  - 2.5 TeV > pT > 350 GeV

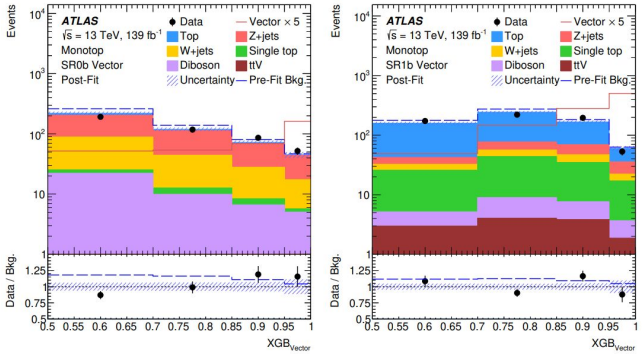
XGBoost classifier to define SR:

- SR1b
- SR0b

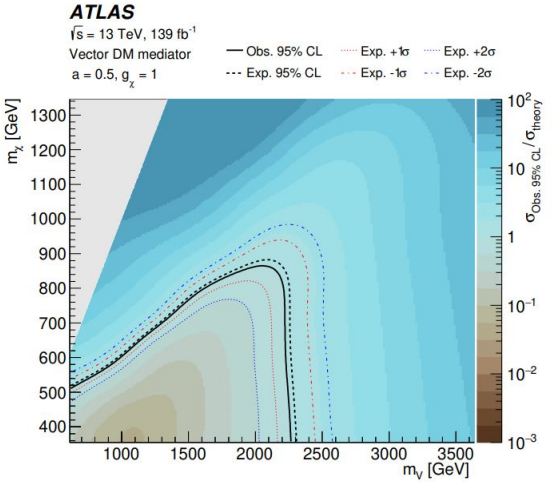
1f: 1 forward jet



DM (vector)

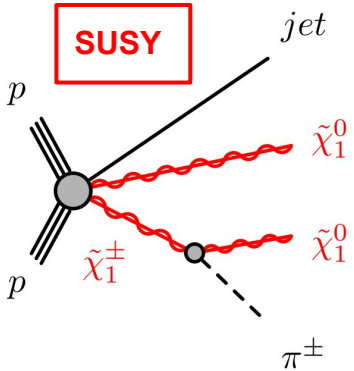


DM (vector): previous exclusion at 2 TeV on the mediator mass



Search for higgsinos using displaced tracks

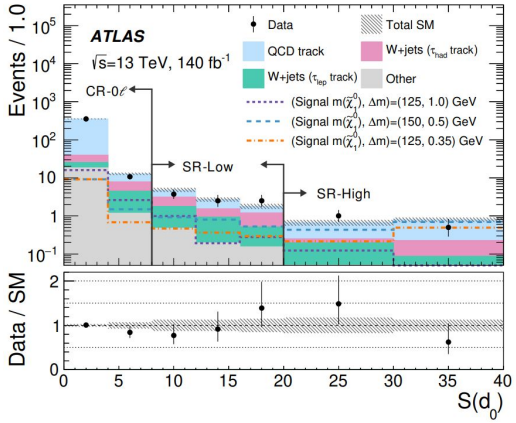
2401.14046



$\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \approx 0.3\text{–}1$ GeV

⇒ decay flight length ~ 0.1 - 1 mm

	SR-Low	SR-High
Observed data	35	15
SM prediction	37 ± 4	14.8 ± 2.0
QCD track	14.0 ± 1.7	10.0 ± 1.6
$W(\rightarrow \tau_\ell \nu)$+jets	9.6 ± 1.6	2.0 ± 0.6
$W(\rightarrow \tau_h \nu)$+jets	10.6 ± 2.0	1.9 ± 0.8
Others	3.2 ± 0.7	0.8 ± 0.4
$\langle \epsilon\sigma \rangle^{95}_{\text{obs}}$ [fb]	0.10	0.07
S^{95}_{obs}	13.5	9.9
S^{95}_{exp}	$15.1^{+6.3}_{-4.2}$	$9.6^{+4.4}_{-2.8}$



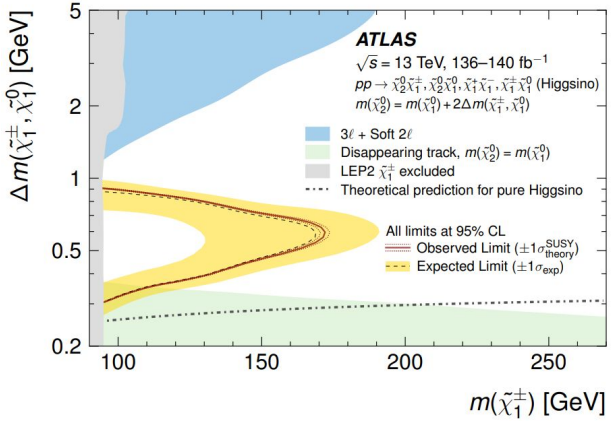
The transverse impact parameter significance:

$$S(d_0) = |d_0|/\sigma(d_0)$$

is relevant to isolate signal events

Event selection:

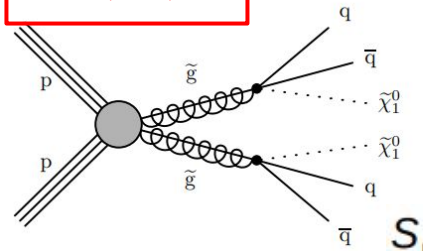
- Trigger on MET (from ISR jet + invisible higgsinos)
- Tracks pT < 5 GeV
  - Reduces leading W($\tau\nu$)+jets background
- Track pT > 2 GeV
  - Reduces subleading Z/W+jets background



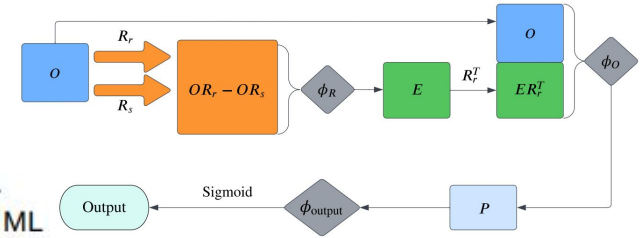
Search for LLPs using displaced vertices

2402.15804

SUSY, HV, …

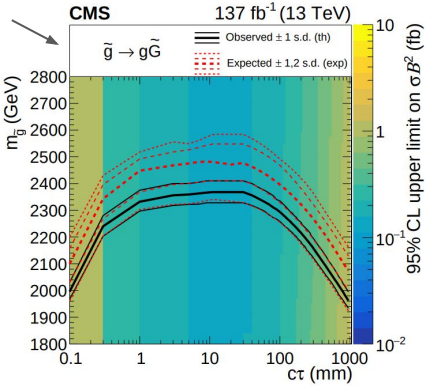


Interaction Network (graph NN)

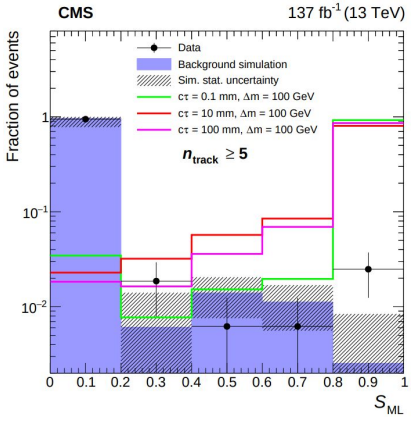


S_{ML}

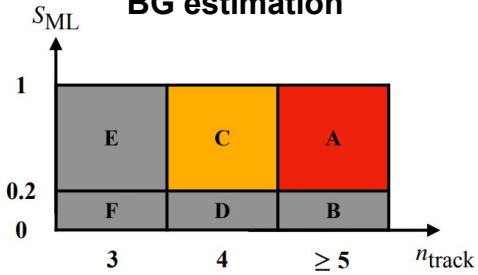
GMSB SUSY

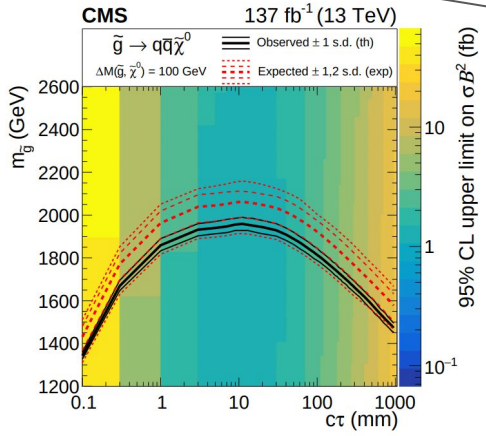


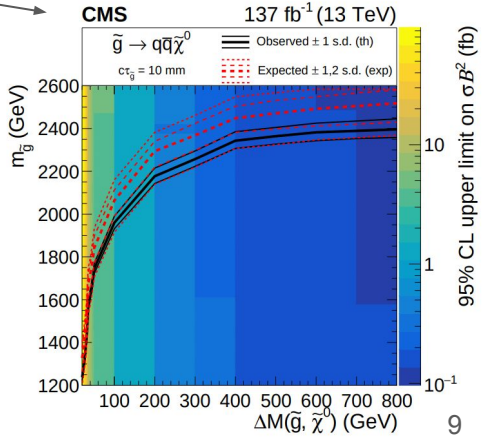
split-SUSY



BG estimation







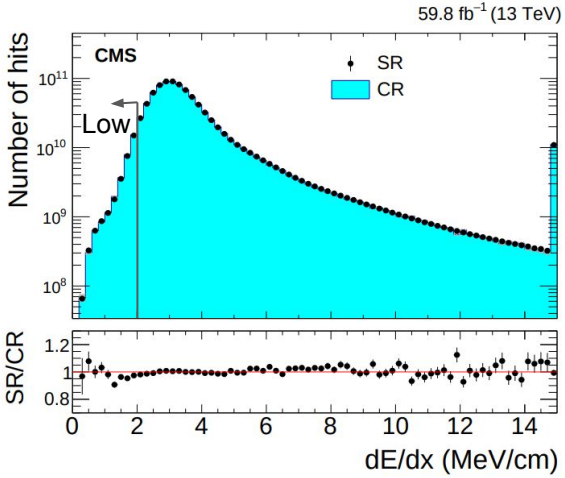
Search for Fractionally Charged Particles (FCPs)

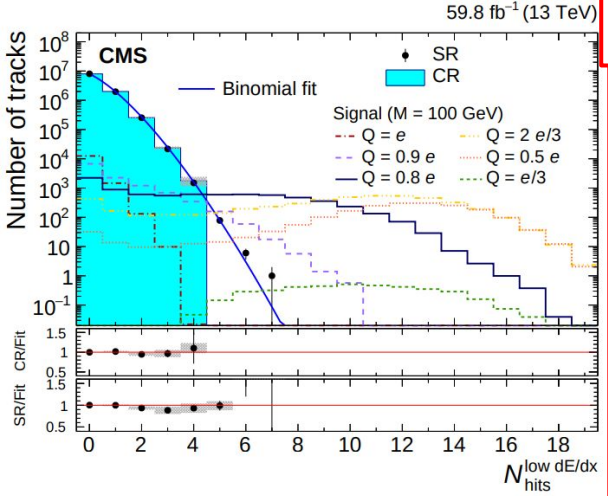
2402.09932

Dark QED (hidden U(1)):
⇒ kinematically mixing with SM hypercharge

FCP ionize feebly the silicon tracker
⇒
The number of tracker hits with dE/dx < ~2 MeV/cm ($N_{\text{hits}}^{\text{low } dE/dx}$) is:

- **Large** for FCPs (signal)
- **Low** for muons (BG)



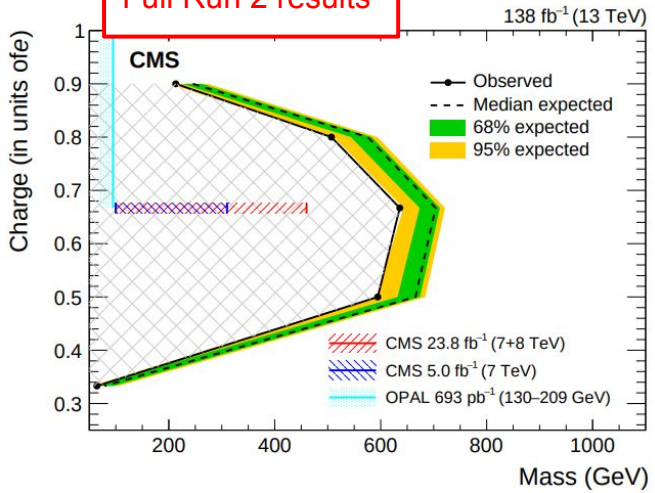


N^{observed}	1
$N_{\text{BG}}^{\text{expected}}$	0.09
Fit function	±19%
Fit range	±28%

	$Q = 2e/3$	$Q = e/3$
$N_{\text{signal}}^{\text{expected}}$	3622	3.51
L1 trigger inefficiency	5%	5%
Muon system energy loss simul.	+4%/−3%	75%
Muon detector inefficiency	3%	15%
Integrated luminosity	2.5%	2.5%
Selection	2.0%	2.0%
dE/dx corrections	1.7%	2.3%
Limited signal sample	<1%	1.8%

Results for 2018 data

Full Run 2 results

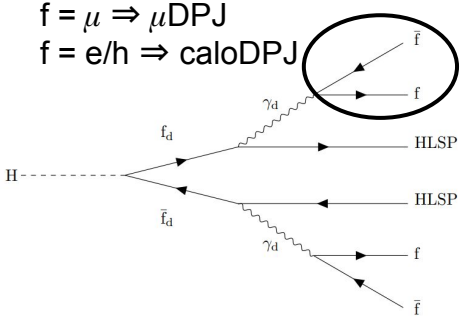


Search for LL neutral particles from Higgs decays via VBF

2311.18298

Dark QED (hidden U(1)):
⇒ Dark photons kinematically mixing with SM hypercharge

Dark photon jet (DPJ):
- f = μ ⇒ μDPJ
- f = e/h ⇒ caloDPJ

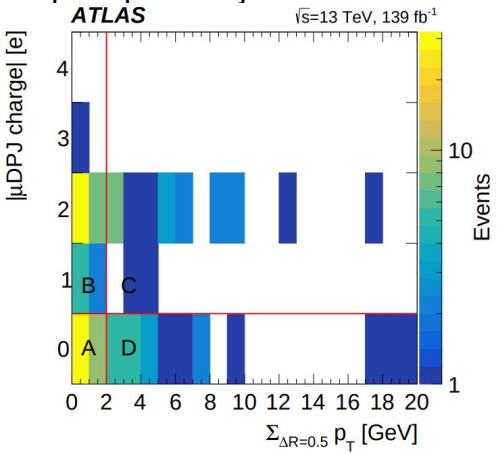


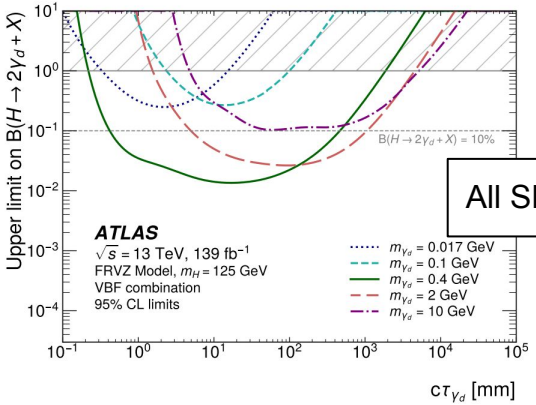
DPJ definition:
1. μDPJ:
   a. ≥ 2 muon tracks
   b. No closeby jet
2. caloDPJ
   a. EM energy fraction < 0.4
   b. Prompt jet tagger veto

Event selection

Requirement / Region	SR_μ	$SR_c^{L/H}$
Number of DPJs	≥ 1	≥ 1
Leading DPJ type	μDPJ	caloDPJ
Trigger	E_T^{miss} Tri-muon MS-only Muon narrow-scan	E_T^{miss}
p_T(jet) [GeV]	> 30	> 30
N_{jet}	≥ 2	≥ 2
m_{jj} [GeV]	≥ 1000	≥ 1000
$\lvert\Delta\eta_{jj}\rvert$	> 3	> 3
$\lvert\Delta\phi_{jj}\rvert$	< 2.5	< 2.5
N_ℓ	0	0
$N_{b\text{-jet}}$	0	0
C_{DPJ}	> 0.7	-
$\Delta\phi_{min}$	-	> 0.4
E_T^{miss} [GeV]	> 100	SR_c^L: [100, 225] SR_c^H: > 225
$\lvert\mu$DPJ charge$\rvert$	0	-
caloDPJ tagger	-	> 0.9
$\sum_{\Delta R=0.5} p_T$ [GeV]	< 2	< 2

Main BG: misidentified prompt QCD jets
⇒ ABCD method



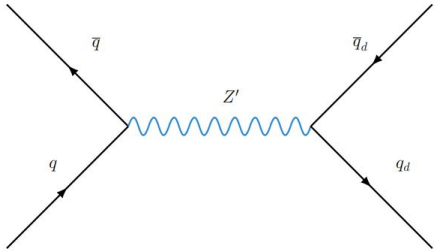


All SR combined

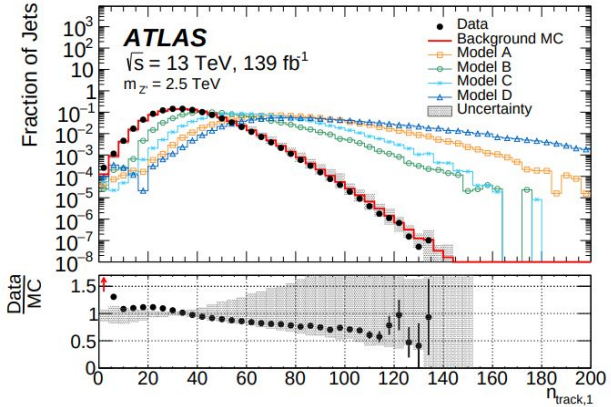
Search for resonant production of dark quarks (dijet)

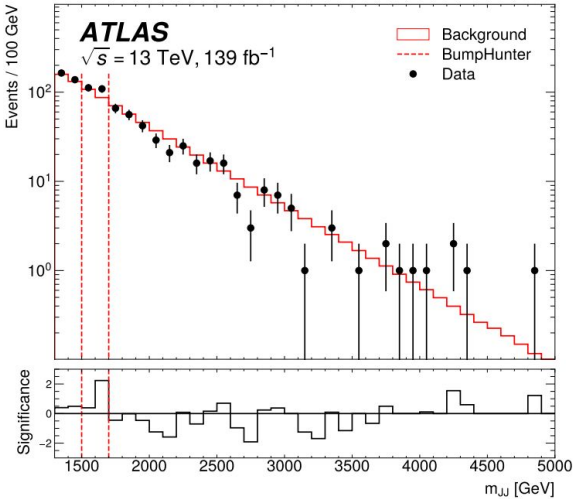
2311.03944

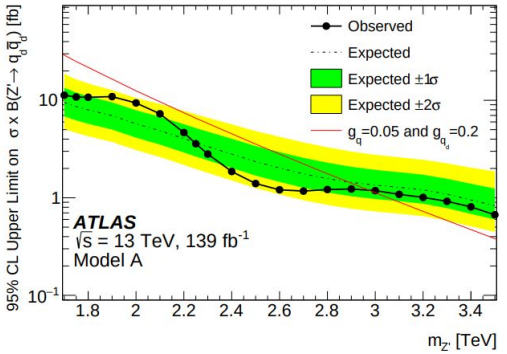
Dark QCD (hidden SU(3)):
- Dark quarks q_{dark}



Model	n_f	Λ_d (GeV)	$\tilde{m}_{q'}$ (GeV)	m_{π_d} (GeV)	m_{ρ_d} (GeV)	π_d decay mode
A	2	15	20	10	50	$\pi_d \to c\bar{c}$
B	6	2	2	2	4.67	$\pi_d \to s\bar{s}$
C	2	15	20	10	50	$\pi_d \to \gamma'\gamma'$ with $m_{\gamma'} = 4.0$ GeV
D	6	2	2	2	4.67	$\pi_d \to \gamma'\gamma'$ with $m_{\gamma'} = 0.7$ GeV







Hadronization in a 2-stage process
1. Dark quark to dark hadrons
2. Dark hadrons to SM hadrons

⇒ Wider jets

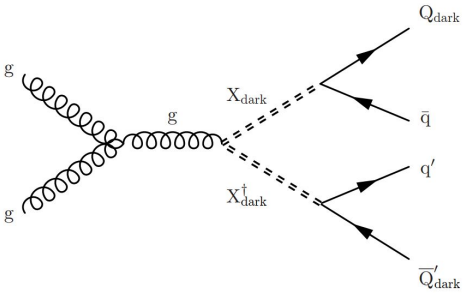
⇒ Larger number of constituents

⇒ Complementary with "standard" dijet resonant search

Search for new physics with emerging jets

2403.01556

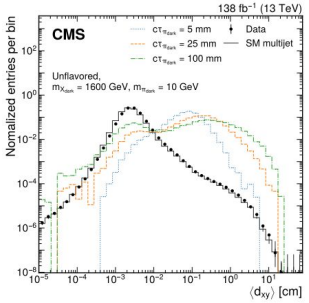
Dark QCD (hidden SU(3)):
- Scalar mediator X_{dark}
- Dark quarks Q_{dark}

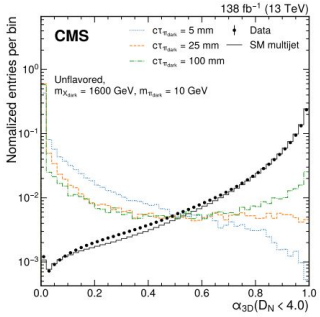


Event selection:
- Jet pT / HT triggers
- ≥ 4 jet with pT ≥ 100 GeV
- High HT

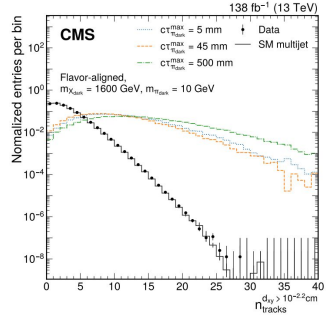
EJ tagging

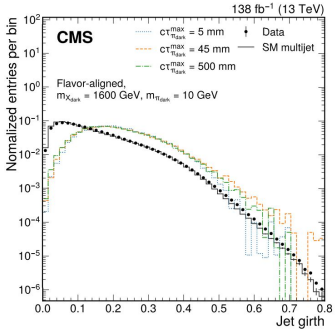
Model-agnostic



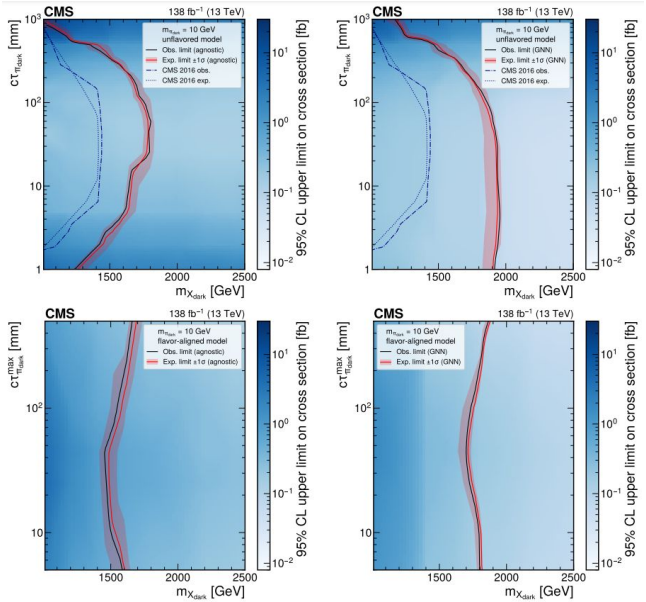


ML-based





Up: results for unflavored with model-agnostic (left) and ML (right)
Down: results for flavor-aligned with model-agnostic (left) and ML (right)



Search for Soft Unclustered Energy Patterns (SUEPs)

EXO-23-002

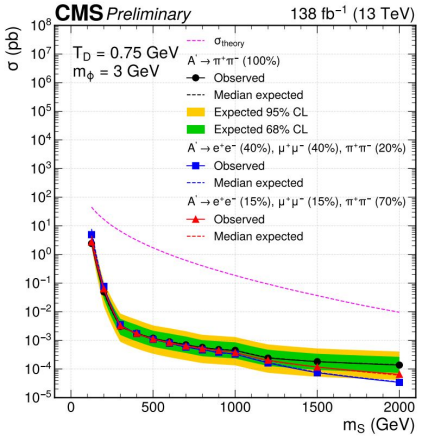
Dark QCD (hidden SU(3)):

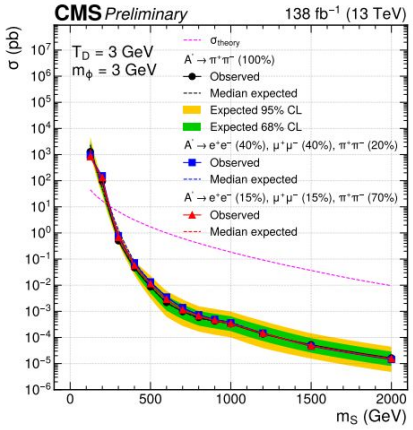
Dark quarks ⟶ showering to dark mesons (mass m_ϕ)

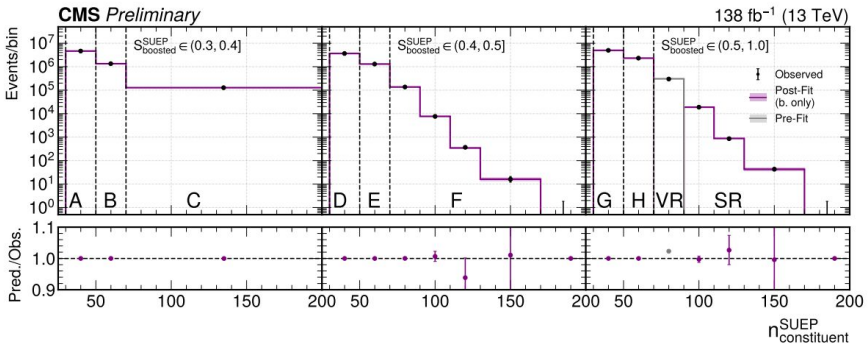
p_T spectrum: Boltzmann with temperature T_D

Event selection:

1. H_T > 1200 GeV
2. Lepton veto
3. # wide jets ≥ 2
   a. Highest p_T: SUEP jet
   b. 2nd highest p_T: ISR jet
4. $S^{SUEP}_{boosted}$: sphericity of SUEP jet constituents

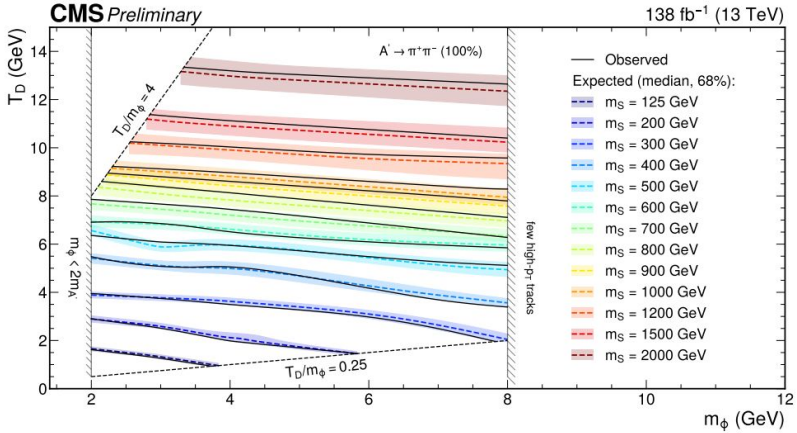






Main background from QCD:

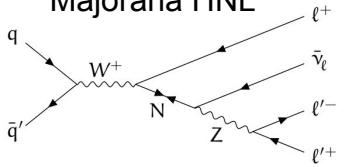
⇒ Data driven "extended" ABCD method



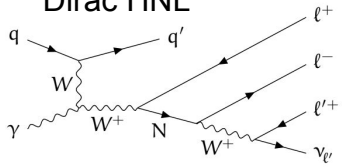
Search for HNLs decaying to e, mu, and tau (hadronic)

2403.00100

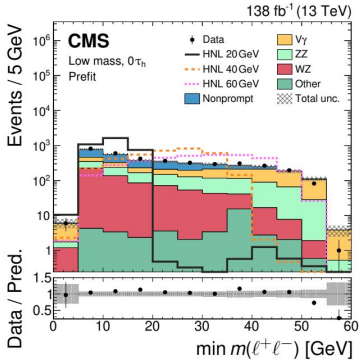
DY, Z-mediated, Majorana HNL



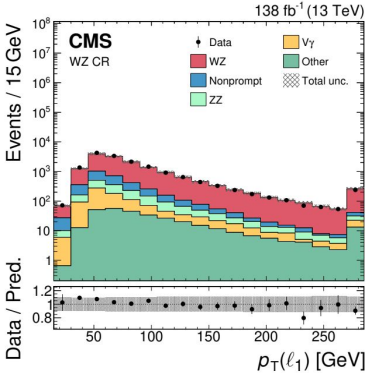
VBF, W-mediated, Dirac HNL



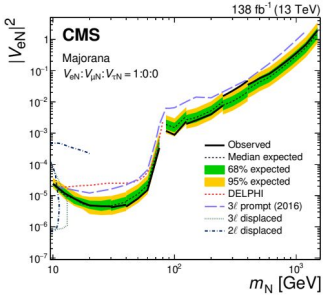
BDT used for signal extraction.
Example of input variable:

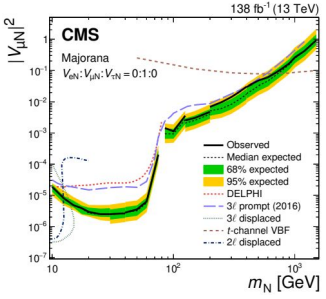


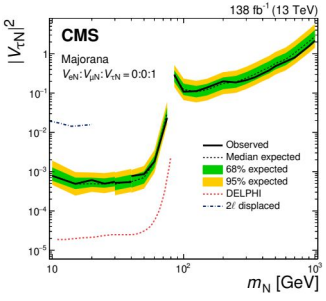
BG estimation partly from data CR (**WZ**, ZZ, $Z\gamma$):



Results:
very complementary to the next HNL search







Search region definitions

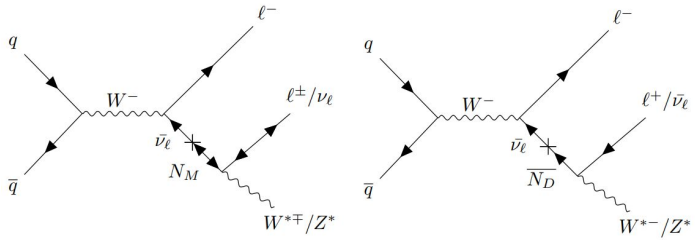
OSSF pair	$p_T(\ell_1)$ (GeV)	$m(3\ell)$ (GeV)	min $m(\ell^+\ell^-)$ (GeV)	m_T (GeV)	SR name
Low-mass selection					
No	<30	<80	<10	any	La1
			10–20		La2
			20–30		La3
			>30		La4
	30–55	<80	<10	any	La5
			10–20		La6
			20–30		La7
			>30		La8
Yes	<30	<80	<10	any	Lb1
			10–20		Lb2
			20–30		Lb3
			>30		Lb4
	30–55	<80	<10	any	Lb5
			10–20		Lb6
			20–30		Lb7
			>30		Lb8

OSSF pair	$p_T(\ell_1)$ (GeV)	$m(3\ell)$ (GeV)	min $m(\ell^+\ell^-)$ (GeV)	m_T (GeV)	SR name
High-mass selection					
No	>55	<100	any	<100	Ha1
				>100	Ha2
		>100	<100	<100	Ha3
				100–150	Ha4
				150–250	Ha5
				>250	Ha6
			100–200	<100	Ha7
				>100	Ha8
			>200	any	Ha9
Yes	>55	<75	any	<100	Hb1
				100–200	Hb2
				>200	Hb3
		>105	<100	<100	Hb4
				100–200	Hb5
				200–300	Hb6
				300–400	Hb7
				>400	Hb8
			100–200	<100	Hb9
				100–200	Hb10
				200–300	Hb11
				>300	Hb12
			>200	<100	Hb13
				100–200	Hb14
				200–300	Hb15
				>300	Hb16

Search for HNLs decaying in the muon detector

2402.18658

Majorana (left), Dirac (right) HNL

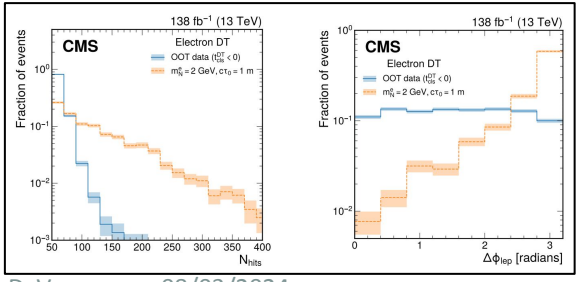


Basic event selection targeted at W boson production:

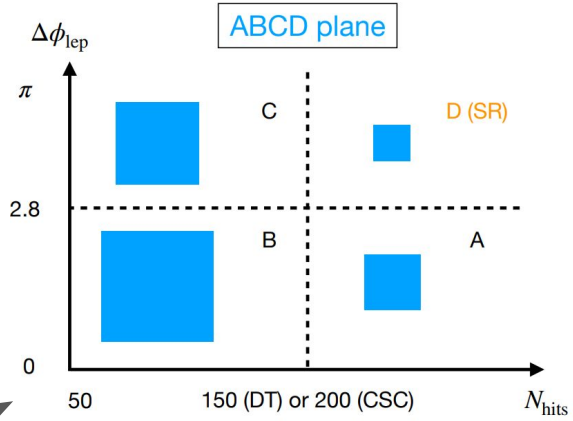
1. High-p_T electron or muon (trigger on the prompt lepton)
2. $E_T^{miss} \geq 30$ GeV (discard QCD background)

Muon detector shower (MDS) clusters:

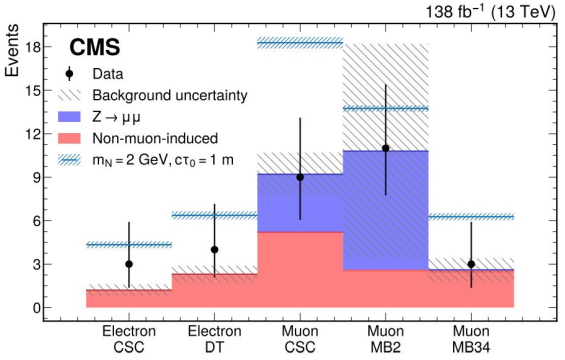
1. DBSCAN clustering algorithm
2. $N_{hits} \geq 50$ (per cluster)

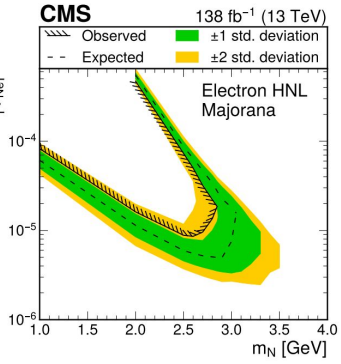


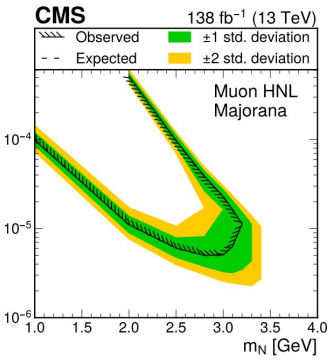
BG estimation

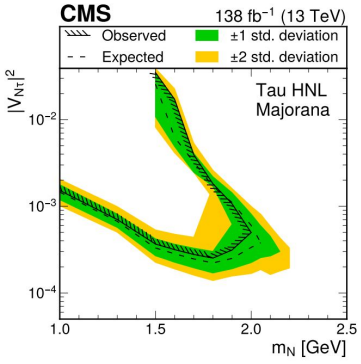


Results





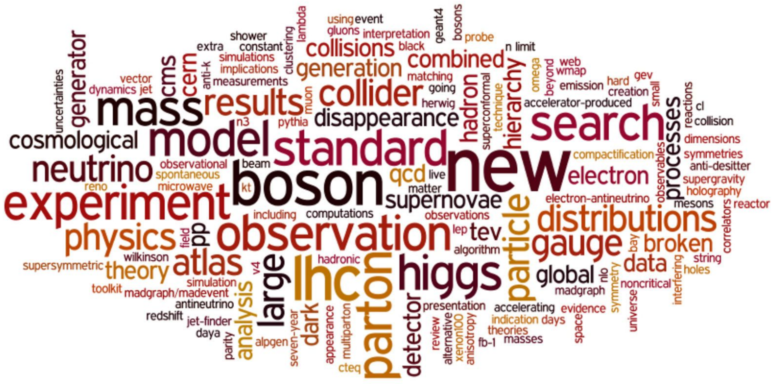




Outlook

New physics is being hunted in every possible corner!

- New exotic signatures are being probed:
  - Displaced vertices/tracks
  - Emerging jets
  - Exotic charge - dE/dx
  - Delayed decay (HNLs)
  - SUEP
  - Dark jets
- New tools are constantly being developed:
  - Machine Learning algorithm
    - (Graph) Neural Networks
    - DBSCAN clustering
  - Extended ABCD methods



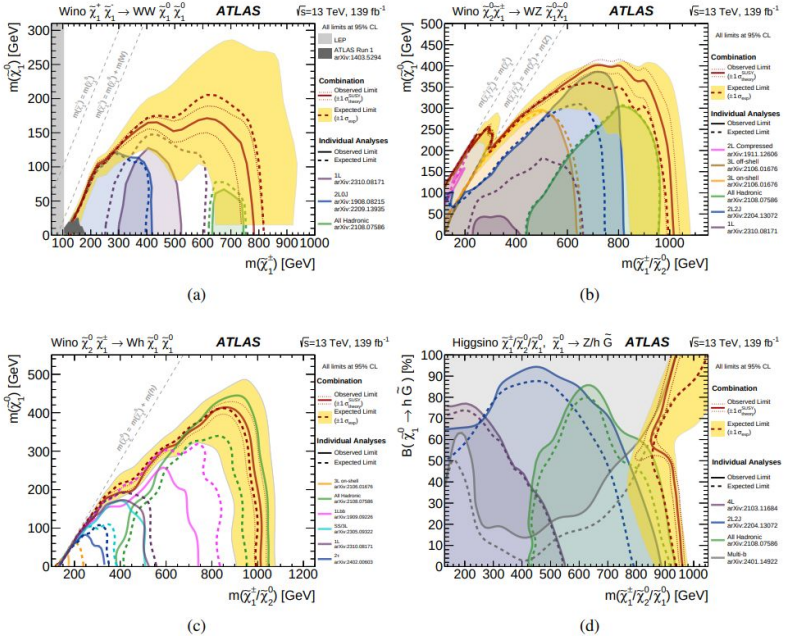
Stay tuned for what’s coming!

Backup

SUSY combination papers

2402.08347

Production mode	Wino $\tilde{\chi}_1^+\tilde{\chi}_1^-$	Wino $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$	Wino $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$	Higgsino GGM $\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^\pm\tilde{\chi}_{1,2}^0, \tilde{\chi}_1^0\tilde{\chi}_2^0$
Decay mode	$\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$	$\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$ $\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$	$\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$ $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$	$\tilde{\chi}_1^0 \to Z/h\tilde{G}$
Searches				
All Hadronic [24]	✓	✓	✓	✓
1L [25]	✓	✓		
1Lbb [26]			✓	
2L Compressed [27]		✓		
2L0J $\Delta m > m(W)$ [28]	✓			
2L0J $\Delta m \sim m(W)$ [29]	✓			
2L2J [30]		✓		✓
2τ [31]			✓	
3L [32]		✓	✓	
SS/3L [33]		✓	✓	
4L [34]				✓
Multi-b [35]				✓



SUSY combination papers

2402.01888

Search	Wino-bino WZ	Wino-bino WH	GMSB ZZ	GMSB HZ	GMSB HH	Higgsino-bino WW	Higgsino-bino HH	Higgsino-bino WH	Sleptons $\ell^+\ell^-$
$2/3\ell$ soft [72]	all								2ℓ soft
2ℓ on-Z [70]	EW		EW	EW					
2ℓ nonres. [70]									Slepton
2SSℓ / $\geq 3\ell$ [73]	SS, A(NN)	SS, A–F	all	all	all			SS, A–F	
1ℓ2b [71]		all						all	
4b [74]					all		3-b, 4-b, 2-bb		
Hadr. WX [75]	all	all				ex H		ex H