Recent updates of BSM searches at CMS and future prospects at HL-LHC

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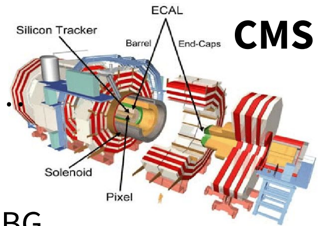
on behalf of the CMS Collaboration

8-11 July 2024, LCWS2024 - Tokyo, Japan

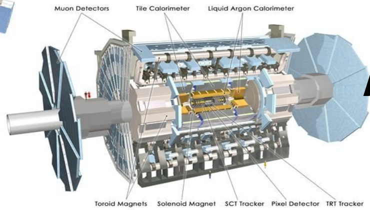
BSM Searches at the LHC

- **LHC** is the world's most powerful discovery machine
  - Aiming to find hints of BSM physics through direct searches and precise measurements
- **Physics program** at LHC driven by
  - BSM Theories : Explaining fundamental mysteries in universe
    ⇒ Hierarchy problem, Unification, Dark matter, neutrino mass, Matter-antimatter asymmetry …
  - Experimental measurements :
    ⇒ μ g-2, B-anomalies, DM detection, cosmological constraints, neutrino oscillation etc…
  - Exotic detector signatures :
    ⇒ Very high-p_T/boosted particles, Long-lived particles …
- **Advancements in analysis techniques**
  - Trigger, Reconstruction, ID algorithm play a vital role in SIG vs. BG
  - Improving techniques (ML) to explore more exotic world
    - Enabling to test unconventional signature, more sensitivity

CERN 70th Anniversary in 2024



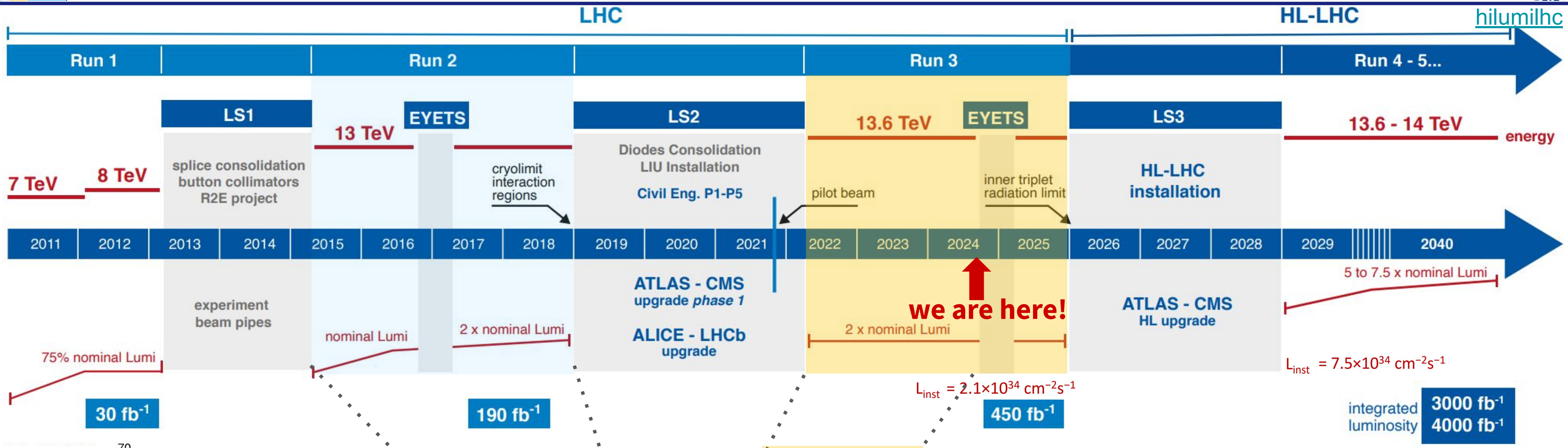
CMS

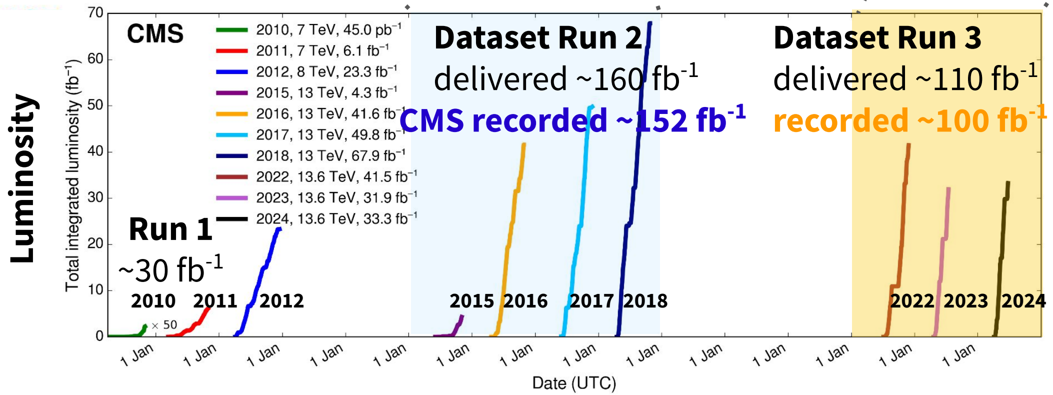


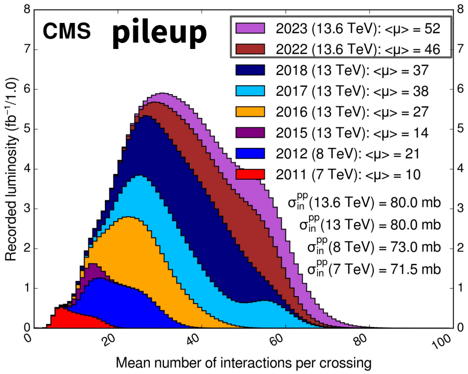
ATLAS

LHC & HL-LHC timeline

hilumilhc







CMS Luminosity

Run 3 (2022-2025) expected to yield tot. of ~**260 fb^{-1}**
⇒ Total Run1+2+3 **450 fb^{-1}**

Overview of this talk

- <u>Only a small subset of most recent results</u> will be showing.
  - **Search for new Bosons/interactions**
  - **Search for Dark Sector**
  - **Search for new Fermions (HNL,VLQ)**
  - **Search for Long-Lived Particles**
  - **BSM Prospects for the HL-LHC**

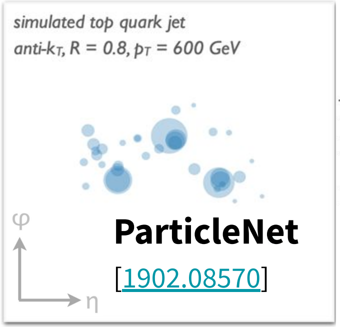
Run-2 (Search for new Bosons/interactions, Dark Sector, new Fermions)

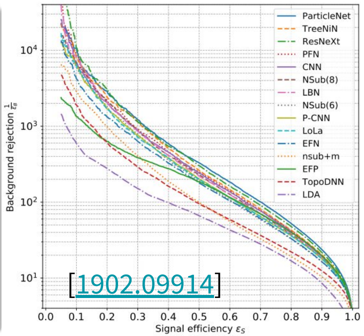
Run-3 (Search for Long-Lived Particles)

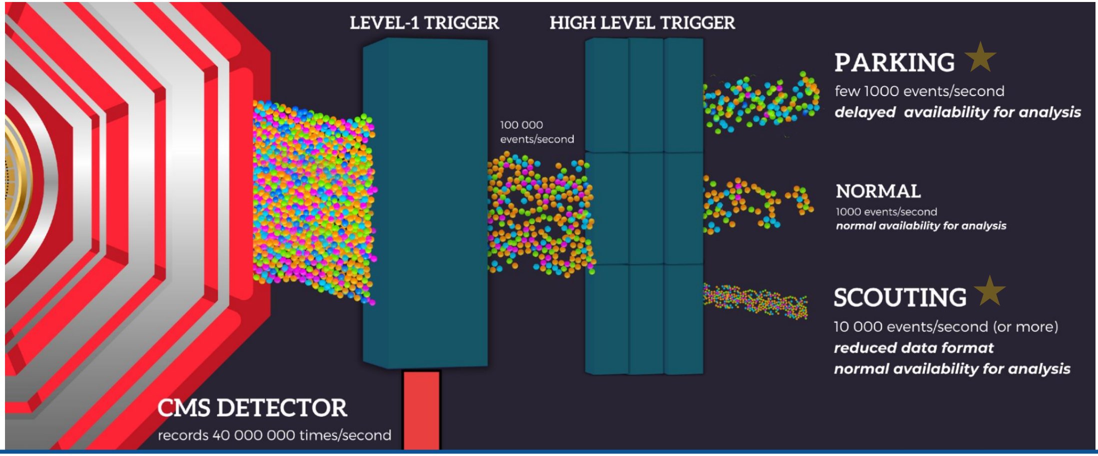
Recent CMS Review articles UPDATE
all submitted to Phys. Rept.

- 🏆 2405.13778 : **Dark Sector** searches
- 🏆 2405.17605 : Searches for **VLQs, VLLs,** and **HNLs**
- 🏆 2403.16926 : **Heavy resonances with Higgs**
- 🏆 2403.16134 : **Data Scouting** and **Parking technique**

- Improvement of Analysis techniques
  - Novel data-taking paradigm, Trigger strategies
  - Improvement on ID Tagging using ML



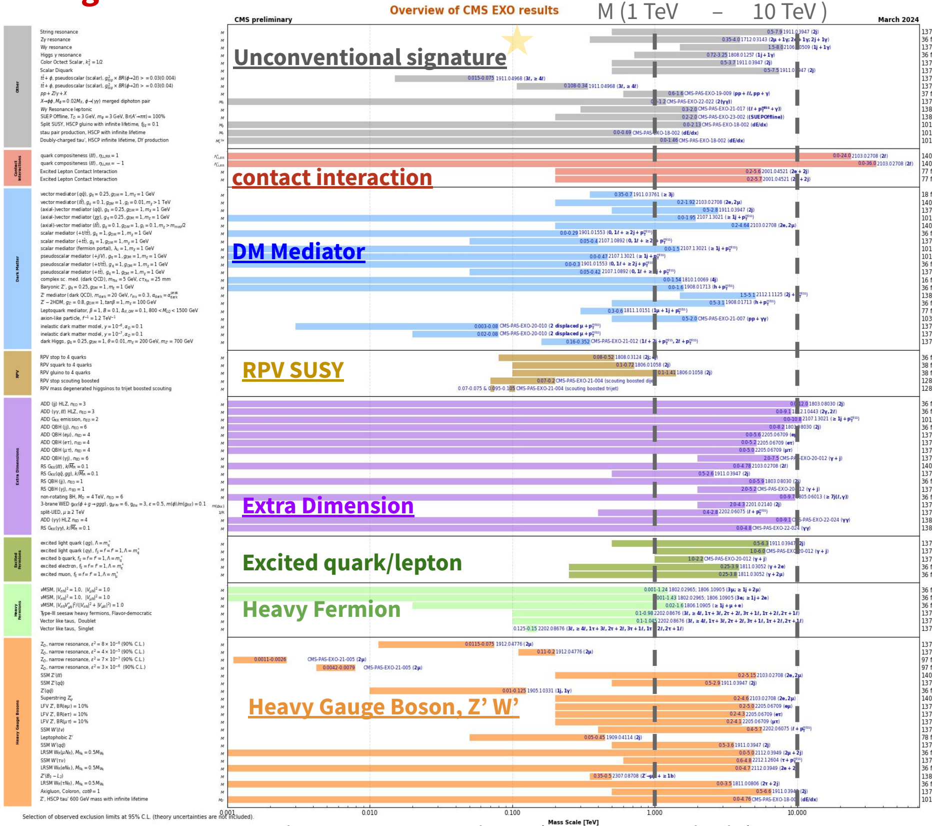




Search for New Resonances at CMS

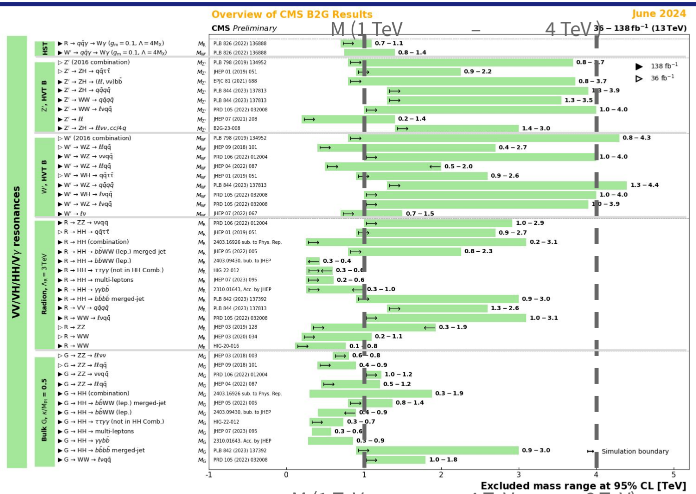
BSM Signatures

BSM scenarios



x-axis : Mass Exclusions (Observed Limit)

Diboson Resonance



HVT(Vγ)

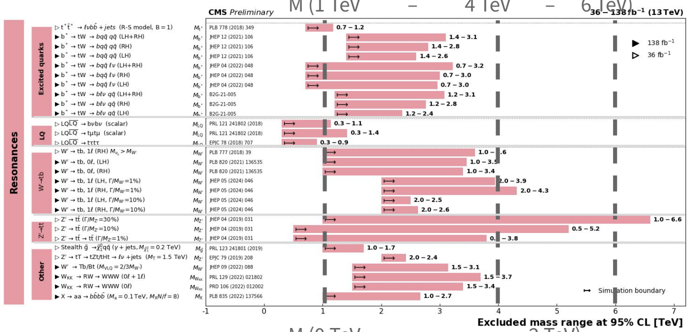
HVT B (Z')

HVT B (W')

Radion→VV

Graviton→VV

Heavy Flavour



Excited q

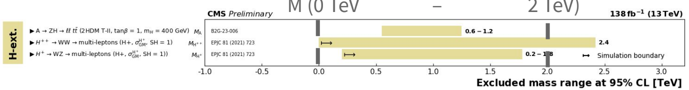
Leptoquark

W' → tb

Z' → tt

Other

2HDM

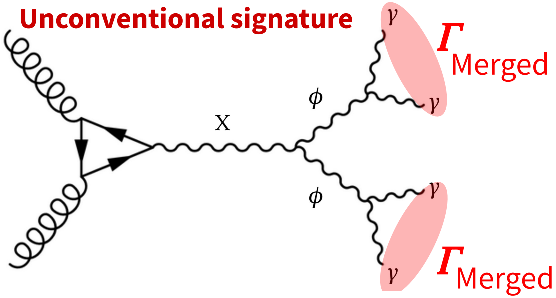


A, H^{++}, H^{+}

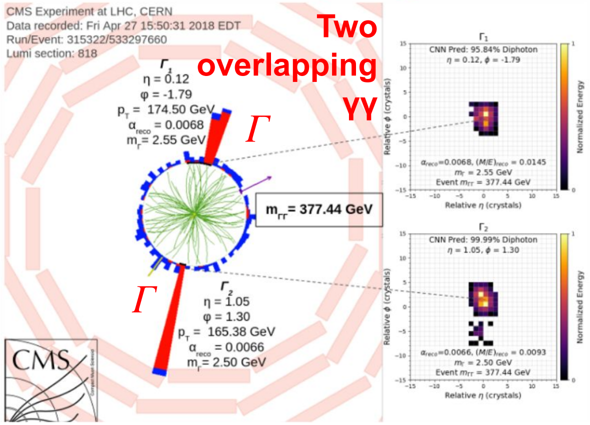
arxiv:2405.00834

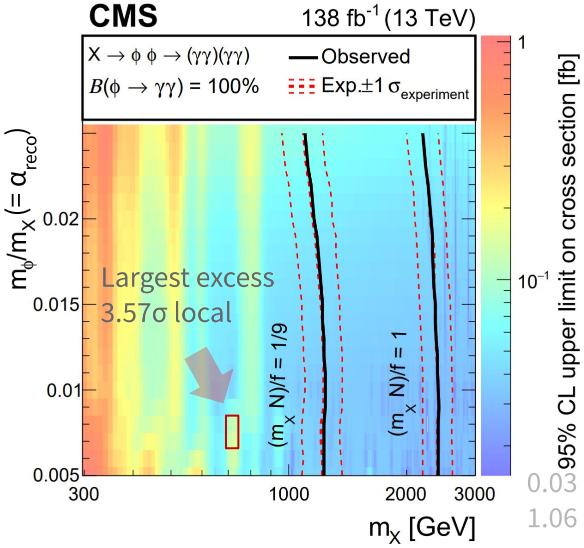
- Search for X, ϕ scalars in the extended Higgs Sector
  - X $\to \phi\phi$ kinematically allowed for m(ϕ) < 2m(bb/cc)
  - Highly boosted ϕ for m(X) >> m(ϕ) ⇒ merged diphoton Γ(= γγ)
- Analysis strategy:
  - Exploiting CNN to classify events with two Γ clusters
  - Data binned in slices of $\alpha_{reco} = m(\Gamma)/M(\Gamma\Gamma)$ = [0.5% ~ 2.5%].
  - Search for excess in data M($\Gamma\Gamma$)
- Background estimation
  - parametrized fit of falling M($\Gamma\Gamma$) in data
- Result
  Largest excess at m(X) = 720 GeV, α = 0.7% (m(ϕ) ~ 5 GeV)
  ⇒ local (global) significance of 3.57σ (1.07σ)

First time!
Unconventional signature



ECAL cluster image recognition

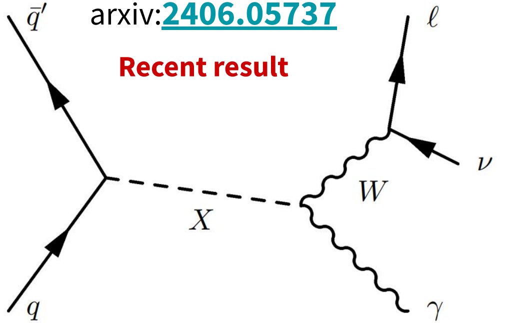




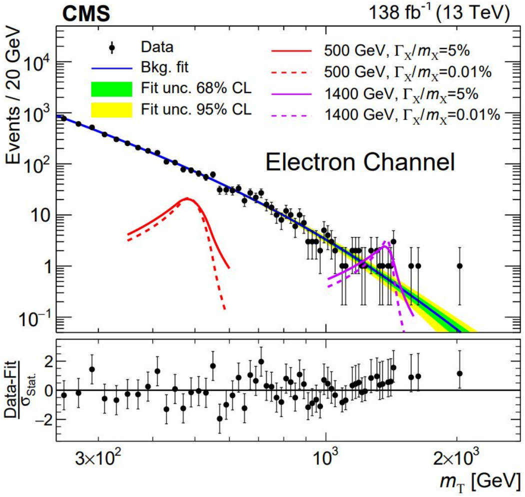
New Resonance Search in W γ

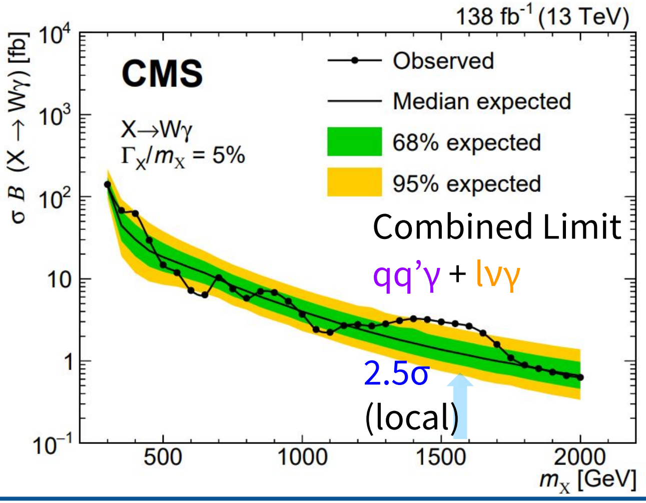
arxiv:[2406.05737]

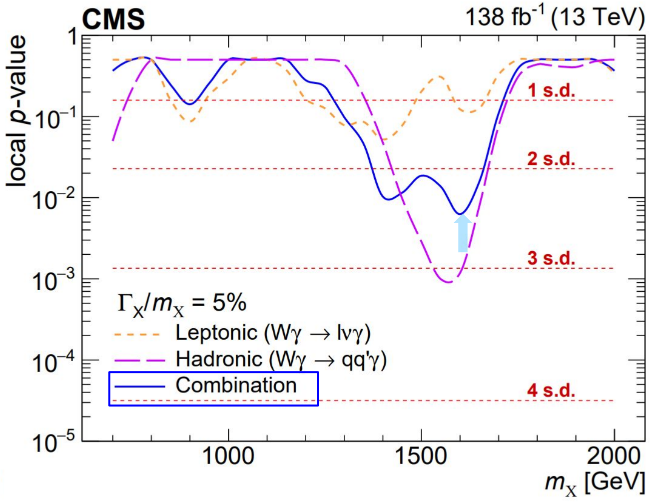
Recent result



- New charged X boson (M_X = 0.3 - 2 TeV) → Wγ in leptonically (eν, μν)
  - Complements previous Wγ analysis in hadronic (CMS PLB & ATLAS JHEP)
- Analysis strategy:
  - Kinematic cut : $0.4m_T < p_T^\gamma < 0.55m_T$, $|\eta^\gamma| < 1.44$, Z veto, b-veto
  - Bump Hunt over the $m_T(l\nu\gamma)$ spectrum → $(m_T)^2 = \left(E_T(\gamma) + E_T(\ell) + p_T^{miss}\right)^2 - |\vec{p}_T(\gamma) + \vec{p}_T(\ell) + \vec{p}_T^{miss}|^2$
  - Background Fit on m_T in data
- By combining Wγ both qq'γ + lνγ channels :
  - Largest local significance 3.1σ , 1.7σ reduced to 2.5σ for broad signal-width scenario

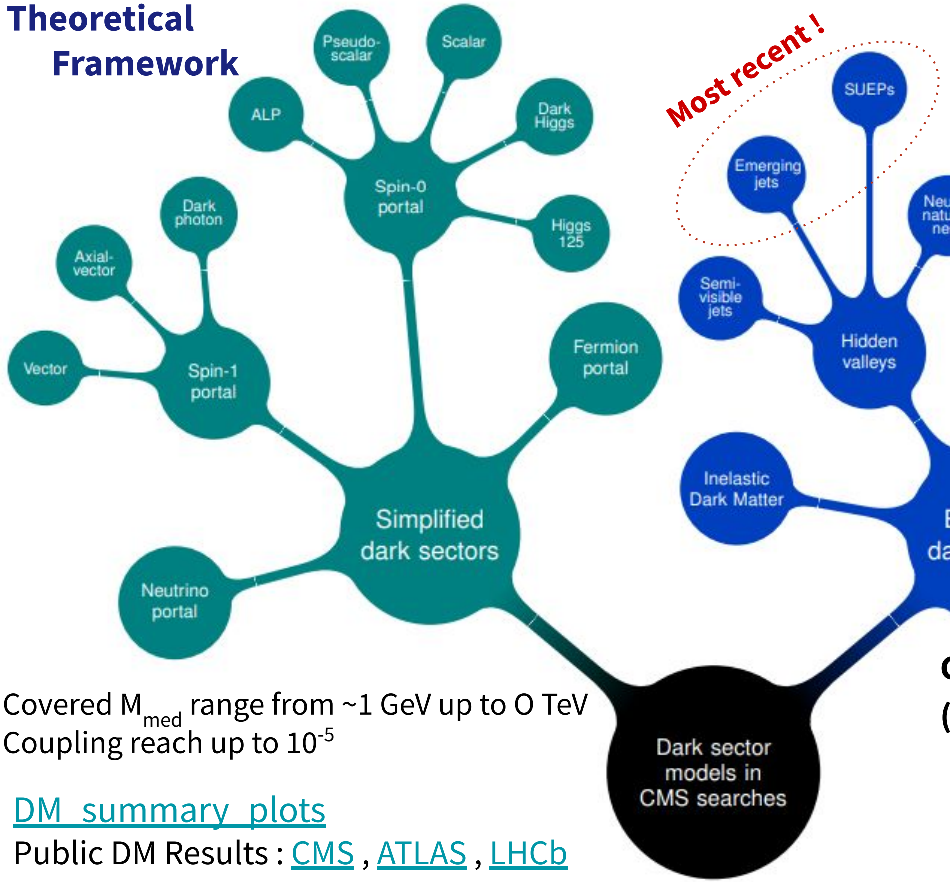






Rich Dark Sector Searches at CMS

Theoretical Framework

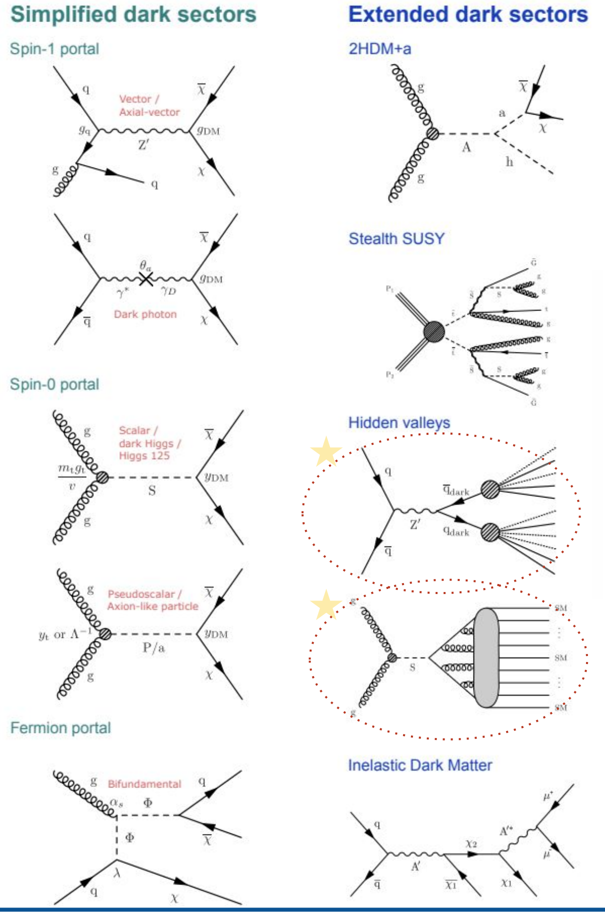


Covered M_{med} range from ~1 GeV up to O TeV
Coupling reach up to 10^{-5}

DM_summary_plots

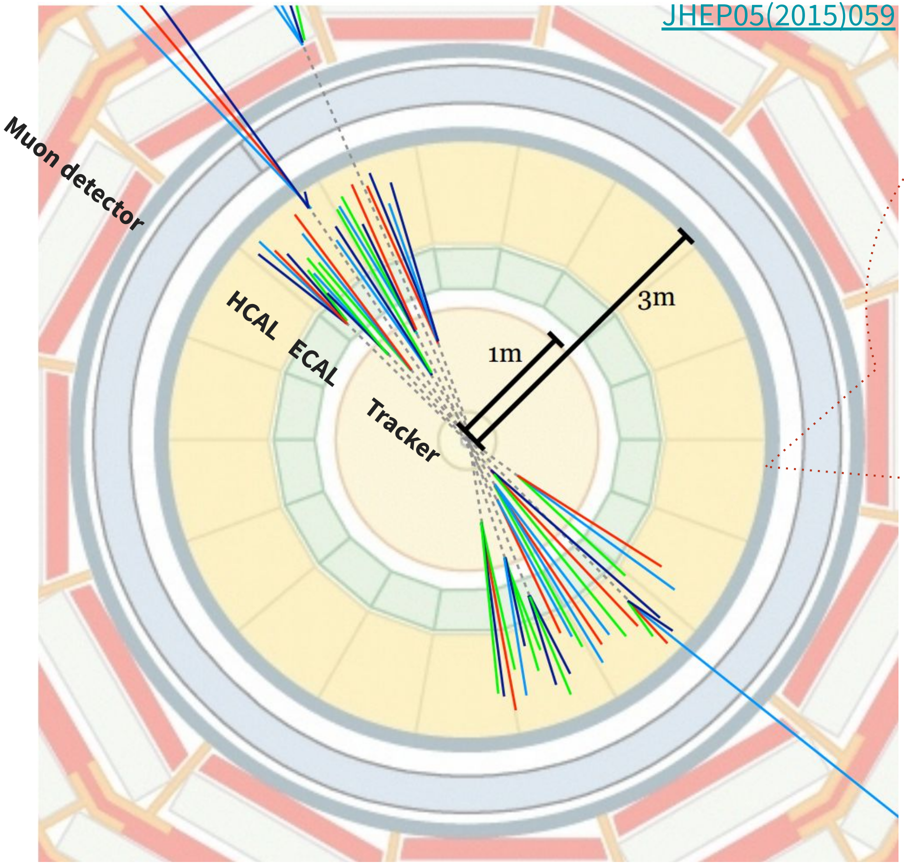
Public DM Results : CMS , ATLAS , LHCb

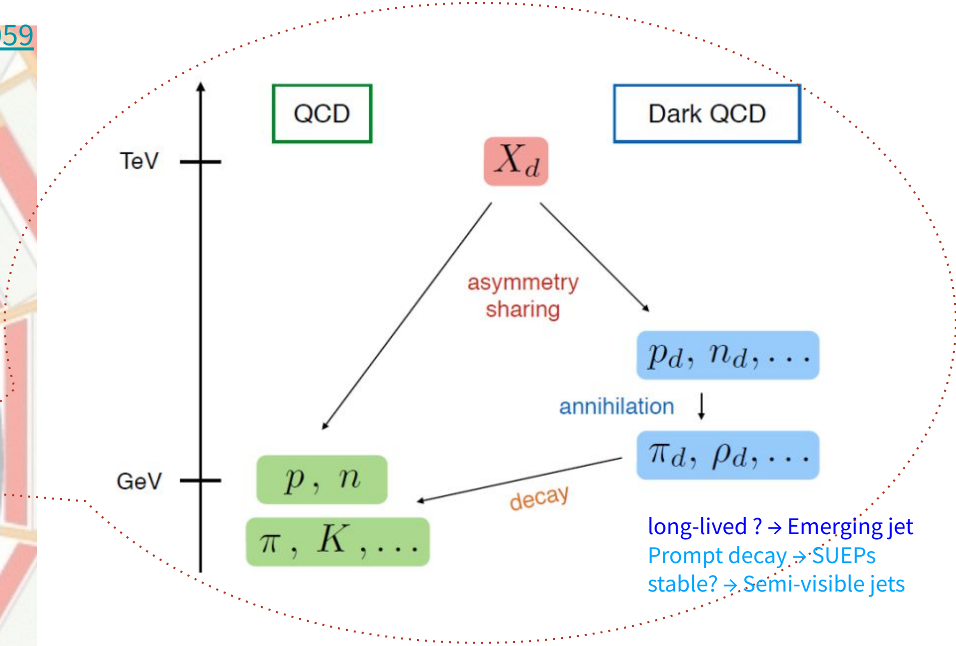
CMS Dark sector review (2405.13778)



Dark Shower : Emerging Jets

JHEP05(2015)059





- Unique DM-targeted signatures → Probing **dark QCD within HV model → Dark showers**
- Tracks start near the edge of the tracker, in the ECAL and HCAL, and even in the muon stations.

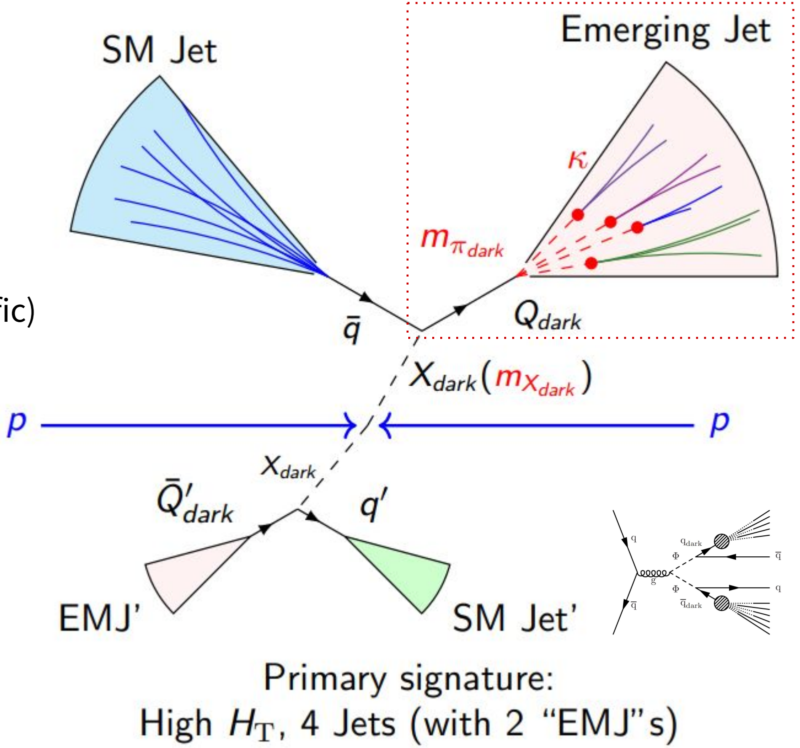
New Emerging Jets in Tracker

arxiv:2403.01556

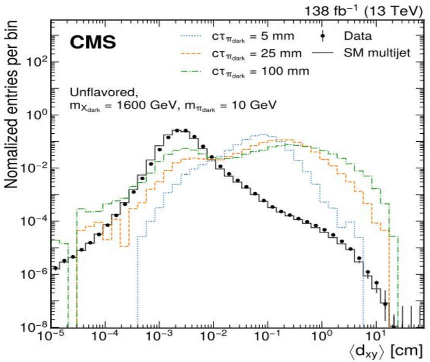
- This search examines a dark QCD sector (dark quark Q_{dark}) that couples to the SM through scalar mediator X_{dark}
- Dark quarks hadronizes into a long-lived dark pion (π_{dark})

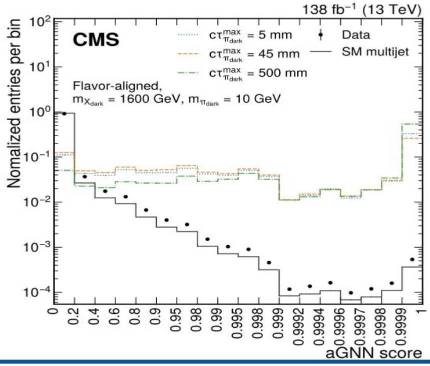
  ⇒ Emerging jets (multiple displaced vertices)

- Two signal dark sector model
  - New Unflavored scenario : Q_{dark} couples to d quark (generic)
  - Flavor-aligned scenario : Q_{dark} couples to d-type quarks (specific)
  - Free parameters : $m(X_{dark})$, $m(\pi_{dark})$, and $c\tau(\pi_{dark})$
- Event selection in Cut Based vs. GNN(ParticleNet) method



Primary signature:
High H_T, 4 Jets (with 2 "EMJ"s)

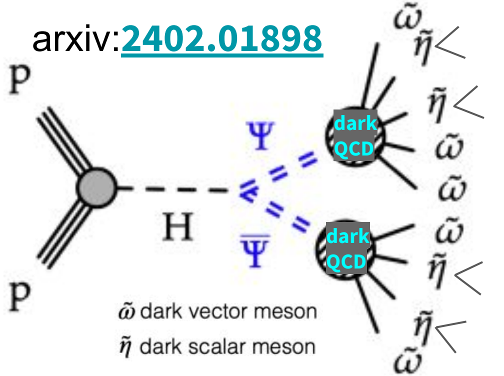


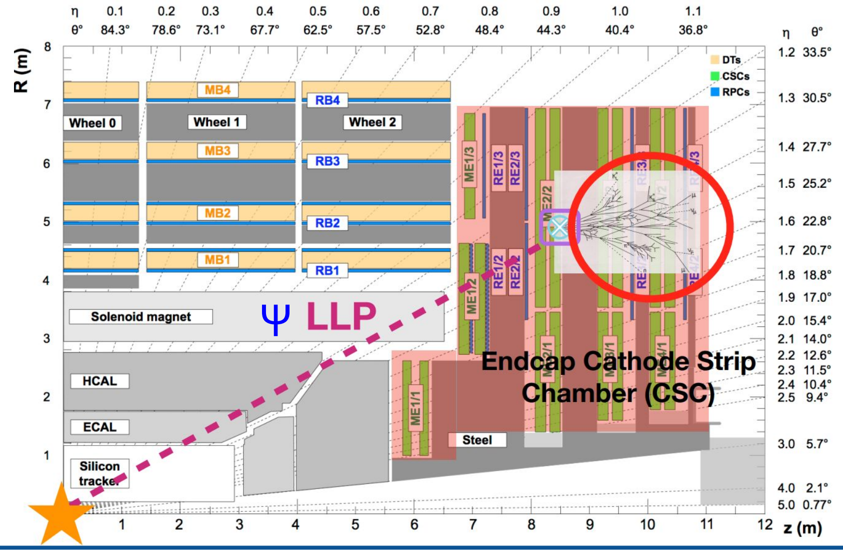


Emerging Jets in Muon detector

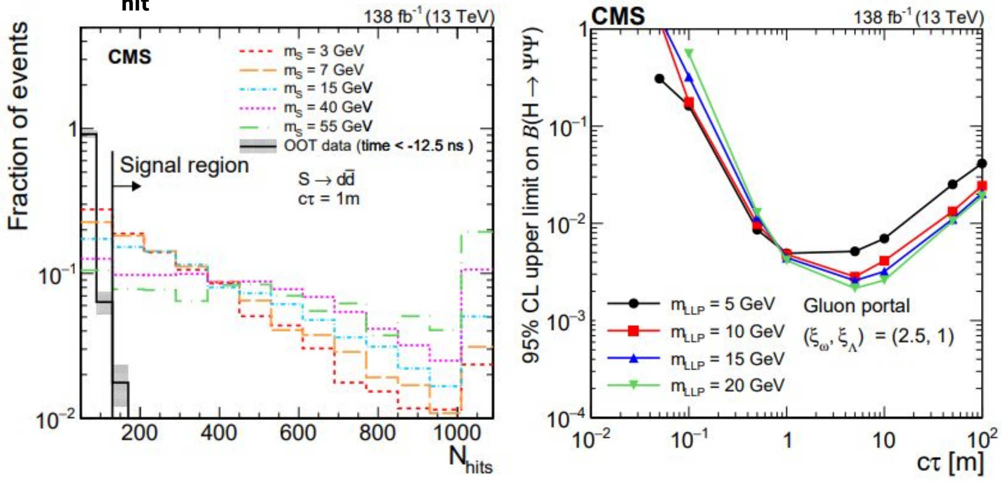
- Complementary to track-based search
- Experiment Signature: **Muon detector shower (MDS)**
  - Large cluster of hits (>130 hits) in the muon system with no jets or tracks
- Excellent background suppression from shielding material
  ⇒ Unique signature due to the presence of steel in the CMS muon system
- Upper limits on the BR, cross-section were set for various LLP M and cτ

arxiv:2402.01898





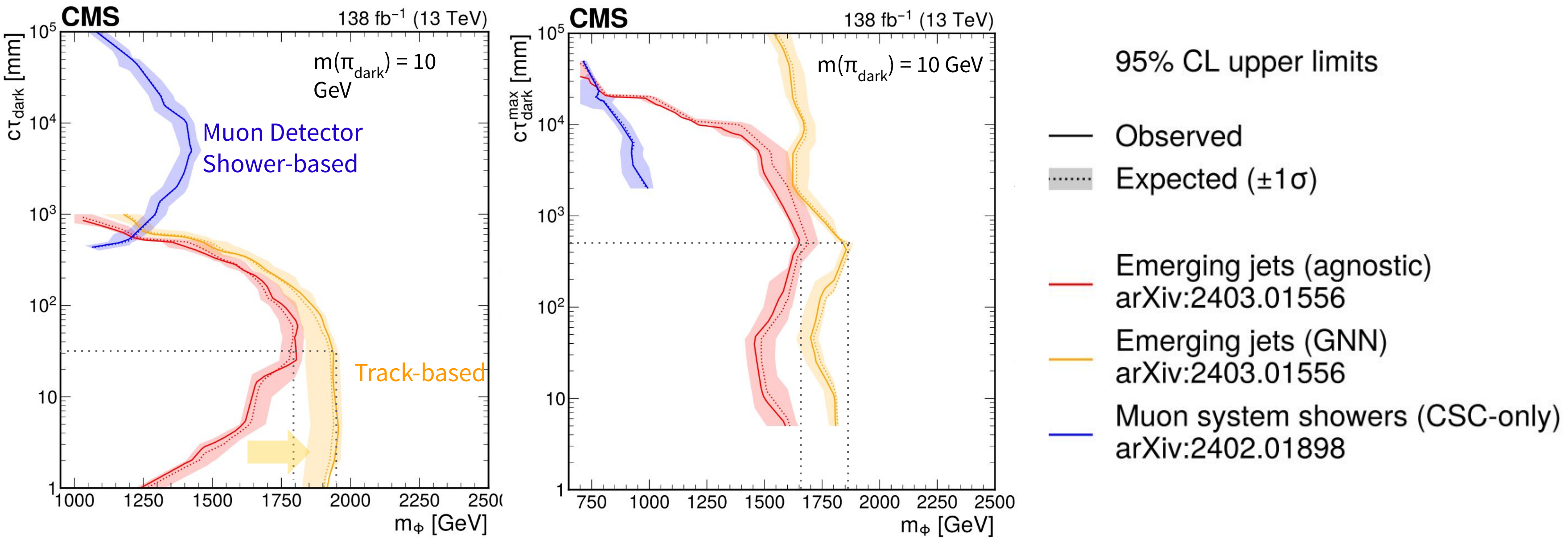
N_{hit} : Main discriminator



Emerging Jets summary plots in Run-2

Unflavored model

New model
Flavor-aligned model



- The most stringent limits to date & first limit on the flavor-aligned scenario.
- Unflavored model : $m(\phi = X_{dark})$ excluded at 1950 GeV at $c\tau(\pi_{dark})$ ~ 10 mm.
- Flavor-aligned model : $m(\phi = X_{dark})$ excluded at 1850 GeV at $c\tau(\pi_{dark})$ ~ 500 mm.

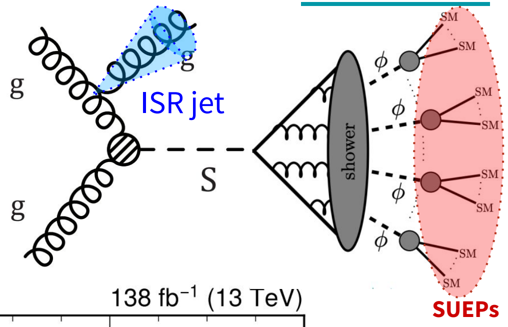
arxiv:2403.01556
arxiv:2402.01898

Emerging_Jet_Summary_Plot

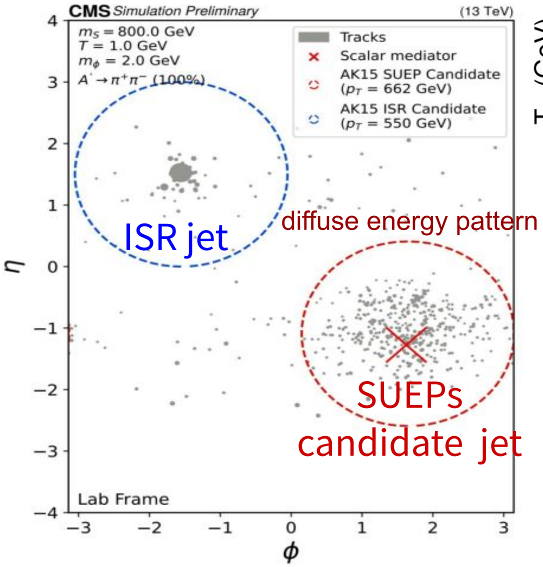
Soft Unclustered Energy Patterns (SUEPs)

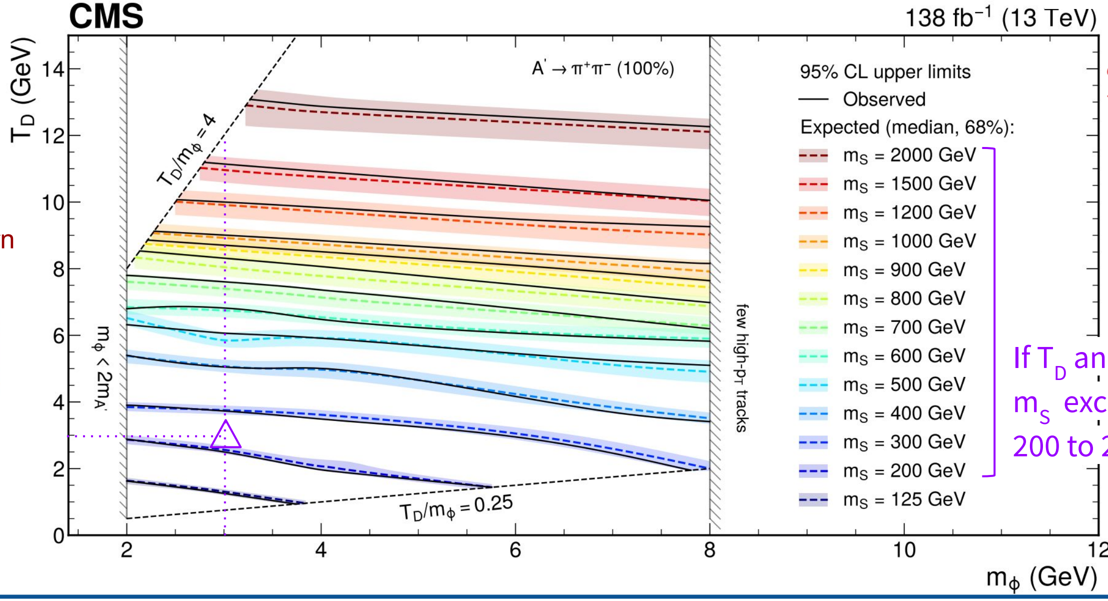
arxiv:2403.05311

- New type of unconventional signature in dark QCD :
  - Heavy S decays into many light dark mesons ⇒ Diffuse energy pattern
  - Challenging to detect : High multiplicity, Spherically distributed low-p_T Tracks
- In HV model, the most interesting case appear at large ‘t Hooft coupling scenario : large angle emission + number of particles produced.
  - Focus on boosted scenario : mediator S recoils against ISR jet ⇒ dijet system



ϕ promptly decay to SM particles

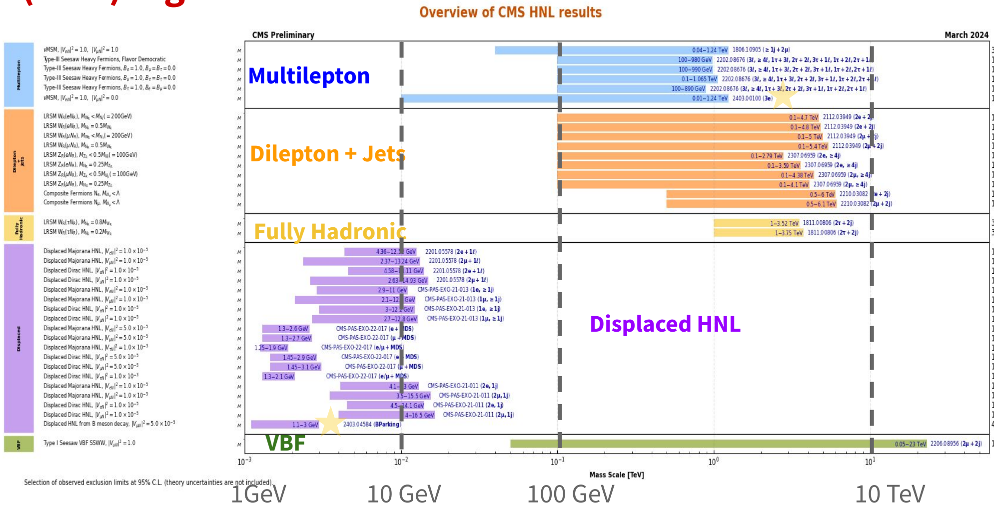




If T_D and m_ϕ = 3 GeV m_S excluded from 200 to 2000 GeV

New Fermions Searches at CMS

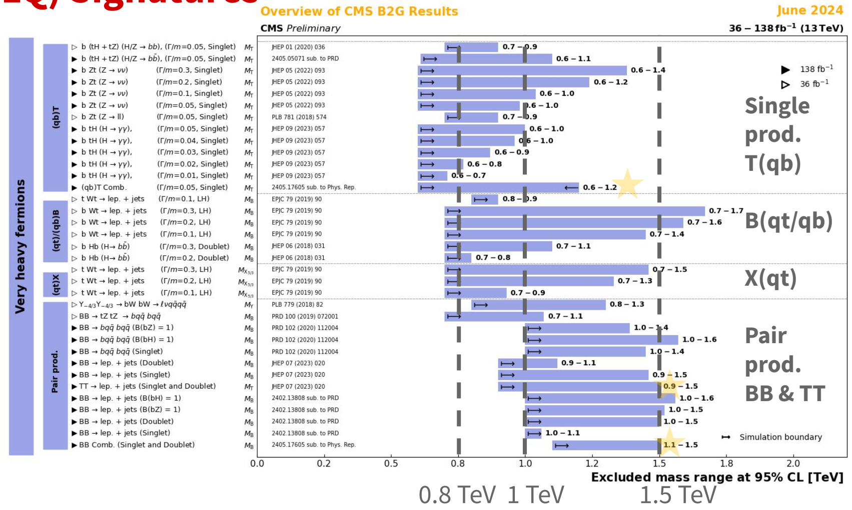
Heavy Neutral Lepton (HNL) Signatures



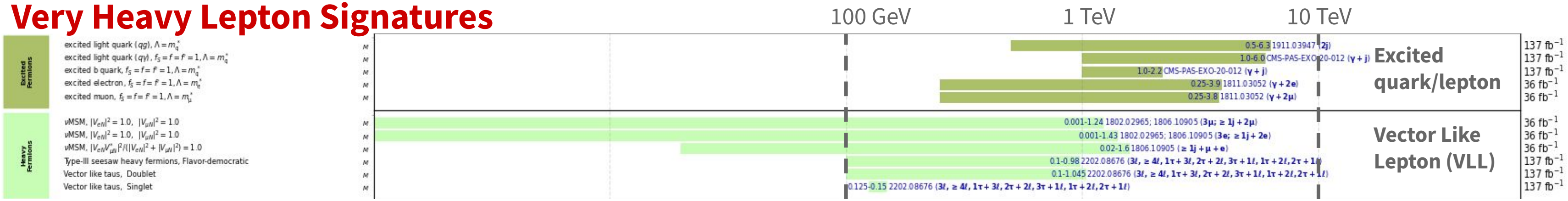
Vector Like Quark (VLQ) Signatures

CMS Review of New Fermion

[2405.17605](2405.17605)



Very Heavy Lepton Signatures

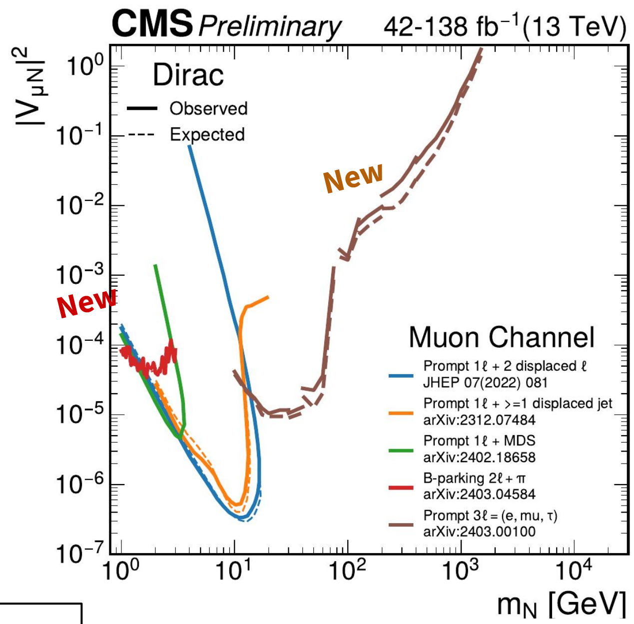


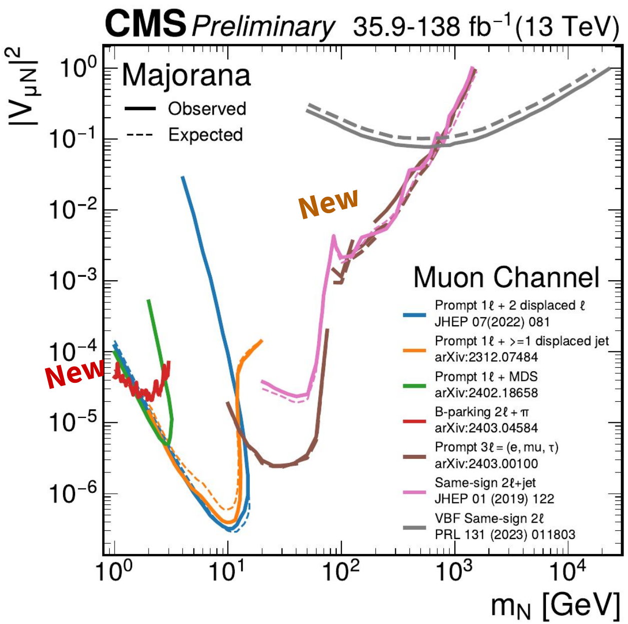
x-axis : Mass Exclusions (Observed Limit)

Heavy Neutral Lepton Search in Run-2

2405.17605 : Review of searches for vector-like quarks, vector-like leptons, and heavy neutral leptons at the CMS experiment

HNL in the Type-I seesaw model





$$\tau \sim \frac{1}{m_N^5 \, |V_{\ell N}|^2}$$

HNL lifetime (τ) depends on the mass (m_N) and mixing matrix ($|V_{lN}|$)

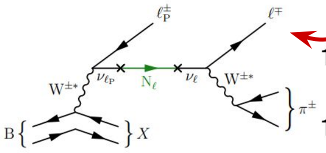
HNL_Summary_Plot

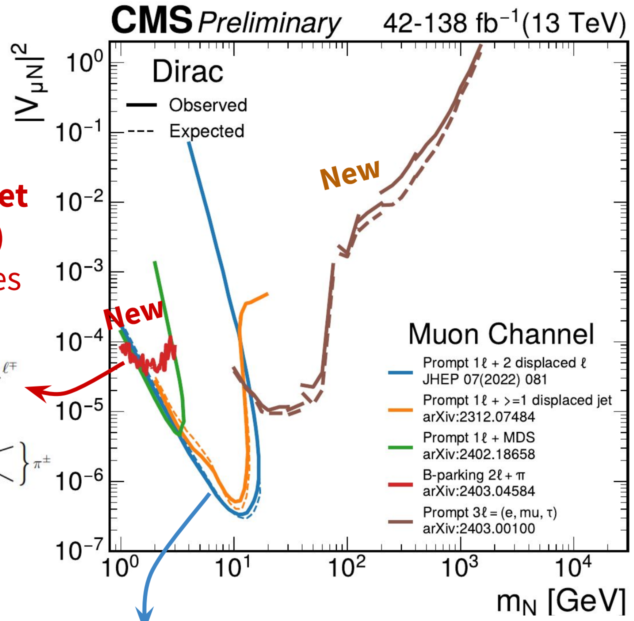
Heavy Neutral Lepton Search in Run-2

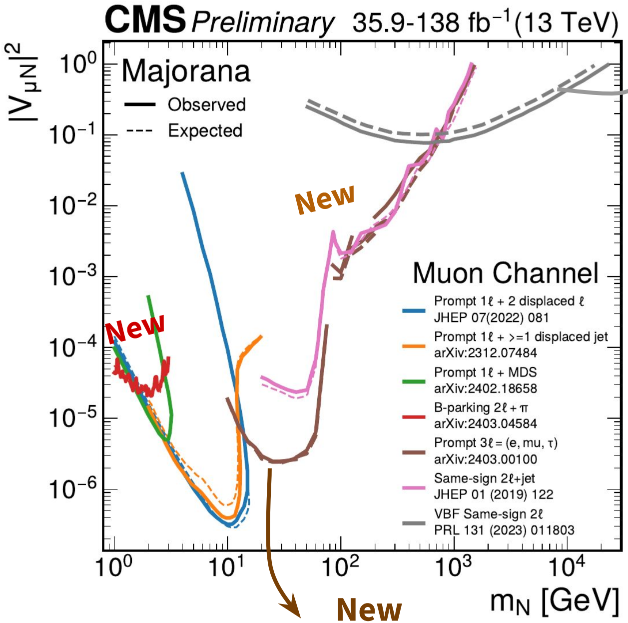
2405.17605 : Review of searches for vector-like quarks, vector-like leptons, and heavy neutral leptons at the CMS experiment

HNL in the Type-I seesaw model

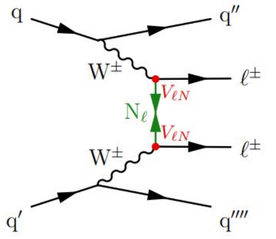
New
B-parking dataset
(10^{10} $b\bar{b}$ events)
displaced vertices
+ π meson



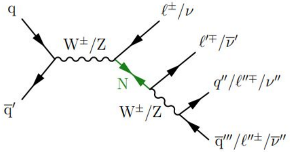




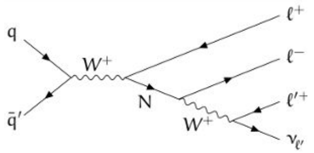
ββ0ν process with VBF same-sign lepton pair



Prompt lepton + displaced dilepton
displaced vertices/jets



New
Prompt 3 leptons
Same-sign lepton/jet pair

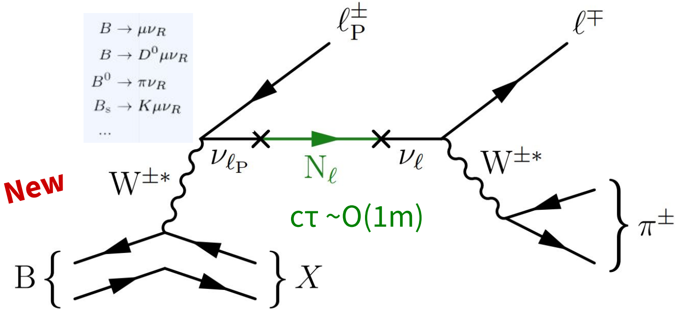


HNL Summary Plot

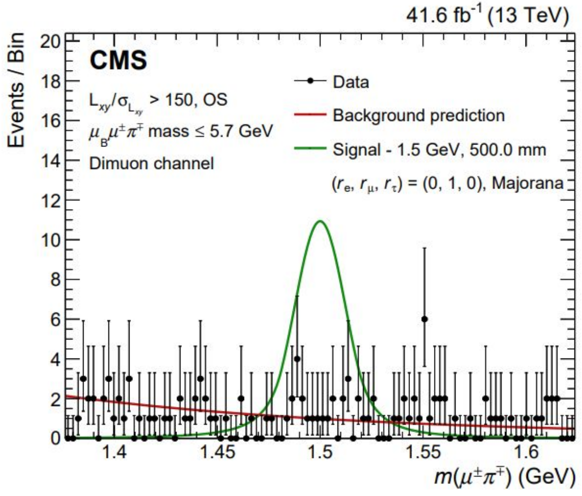
New Low mass HNL in B-meson Decay

- Experimental signature : Displaced l (e, μ) and $\pi^{\pm}$ tracks
- Use special B-parked data in 2018 ⇒ recorded O(10B) $b\bar{b}$ events
- Event Categorized with lepton flavor, m(l $\pi^{\pm}$), tracker info
- Utilize parametric Neural Network (pNN) to enhance sensitivity
- Collider best limits on $|V_N|^2$ at **$1 < m_N < 1.7$ GeV** to date.
    - Outperform previous Belle (LHCb) results by a factor of 2 (10)

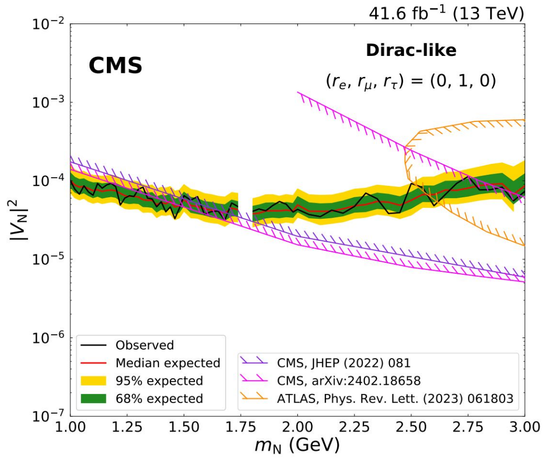
New

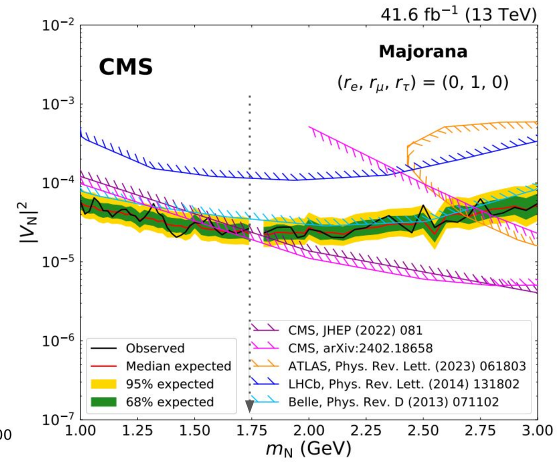


arxiv:2403.04584
Sterile-Neutrino.org



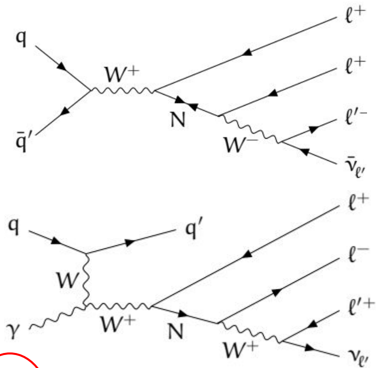
Exclusive μ mixing scenario





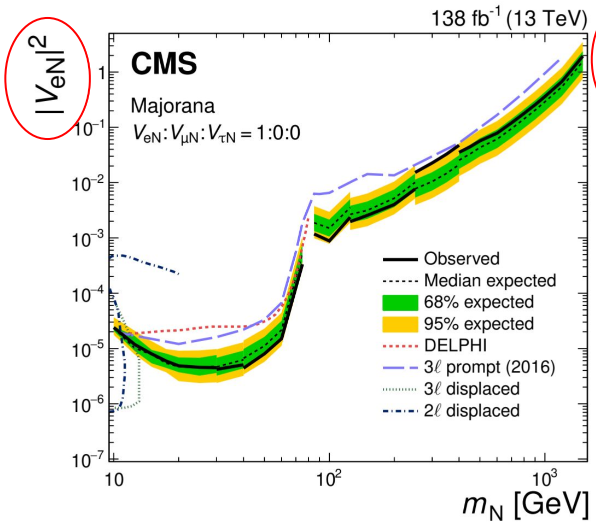
New HNL with prompt 3 leptons

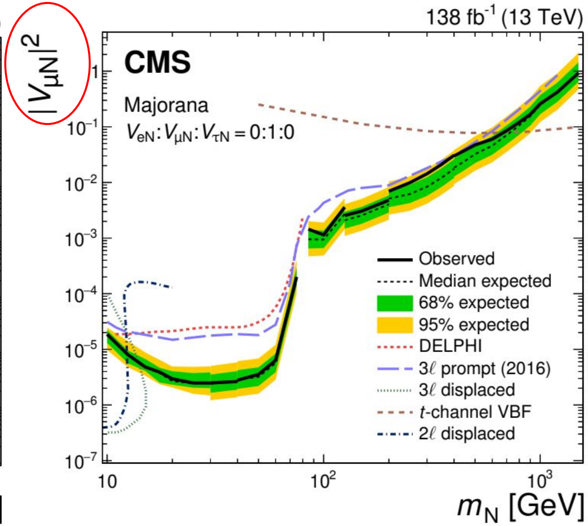
- Search for HNL with short lifetimes & various M_N (10 GeV – 1.5 TeV)
- Final state leptons : e, μ, and τ (eee, μμμ, μμe, eeμ, eeτ, μμτ, and eμτ)
- Event selection:
  - Multiple event categorization and ML-based BDT discriminants
- Upper limits on mixing matrix for HNL mass [10 GeV - 1.5 TeV]
- First limits on exclusive τ neutrino coupling m_N > W mass at LHC

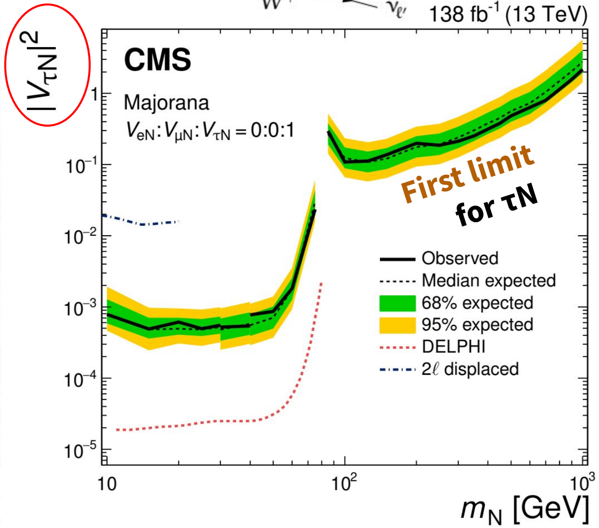


New

arxiv: 2403.00100





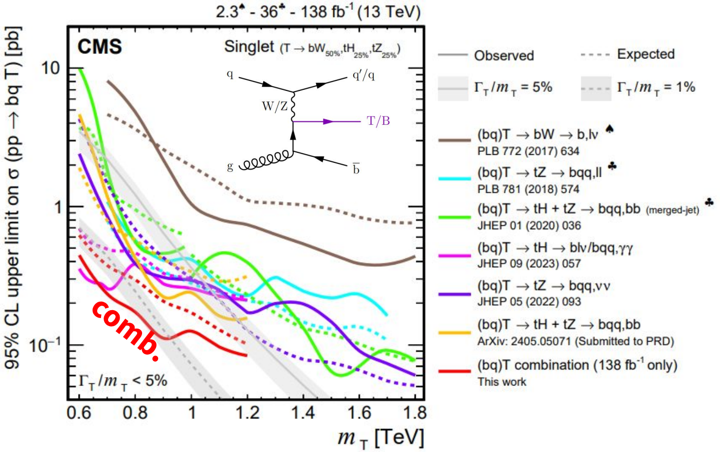


Combined limits for VLQ Search at CMS

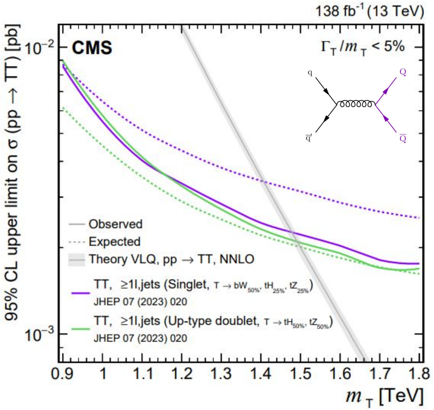
- A complete overview of final states is provided together with their complementarity and partial combination in benchmark scenario
  - Singlet : Br(W) 50% & Br(Z/H) 25%
- Statistical combination pushes sensitivity!

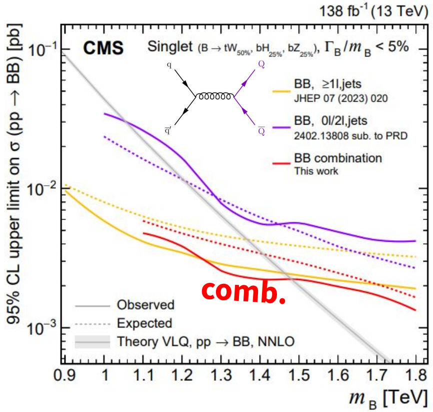
CMS Heavy Fermion review
(2405.17605)

Combined limit on σ(pp → bqT) Single T

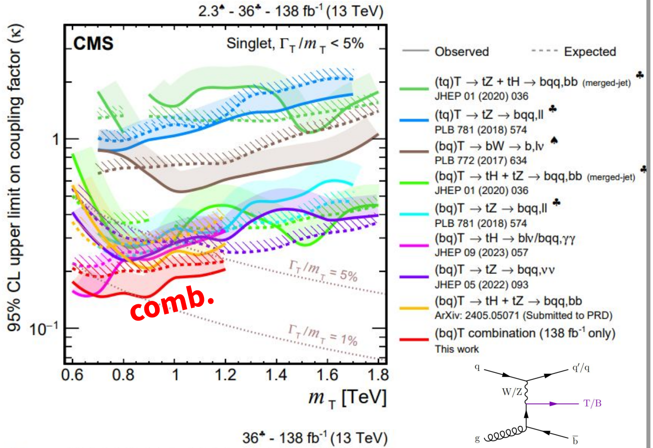


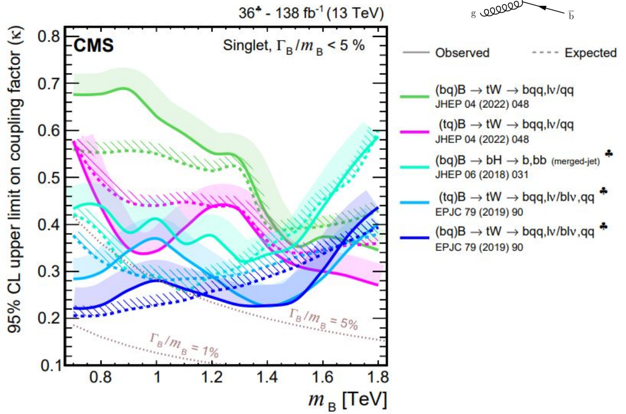
Comb. limit on σ(pp → TT/BB)





Comb. limit on the coupling for single T/B

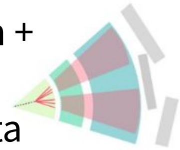


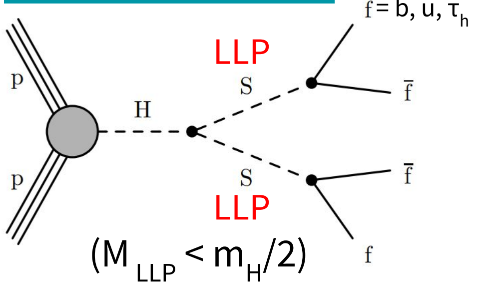


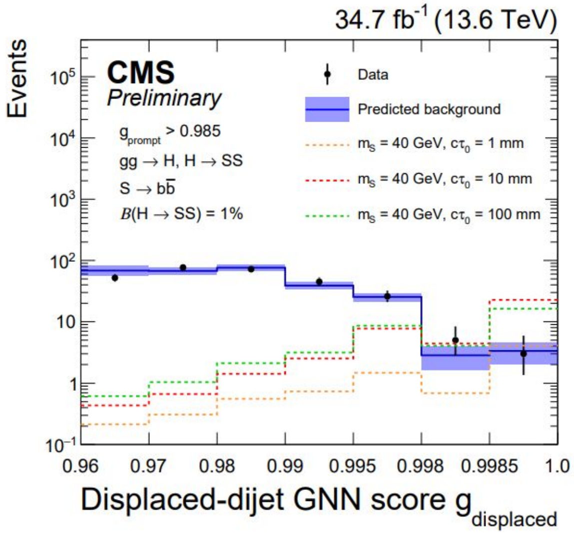
New Run3 LLPs to displaced jet pair in Run-3

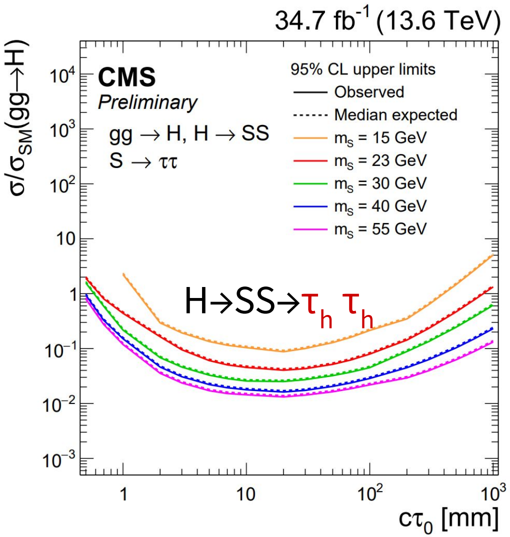
CMS-PAS-EXO-23-013

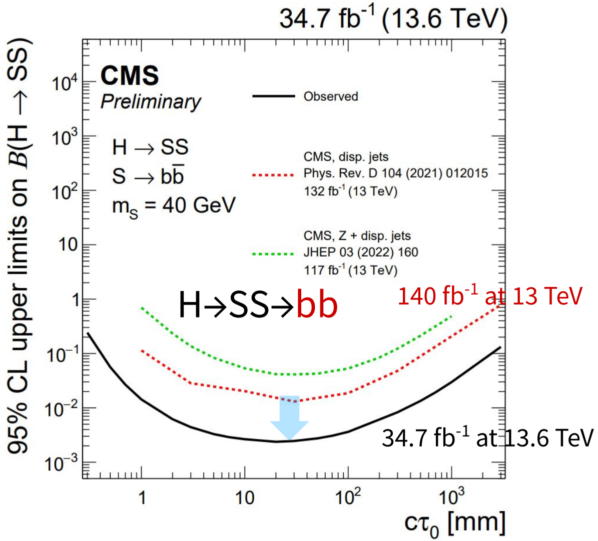
- With 2022 data at 13.6 TeV, Search for LLP to displaced jet
- To enhance sensitivity, novel displaced-jet trigger* + reconstruction + Graph-NN LLP taggers (displaced/prompt GNN) were developed.
  - Outperforming (x10) full Run2 result with fraction of Run3 data
  - First limit on (tracker-based) displaced τ_h channel at LHC
- The best limits to date are set on H→SS with M_S > 16 GeV with cτ smaller than 10^3 mm.









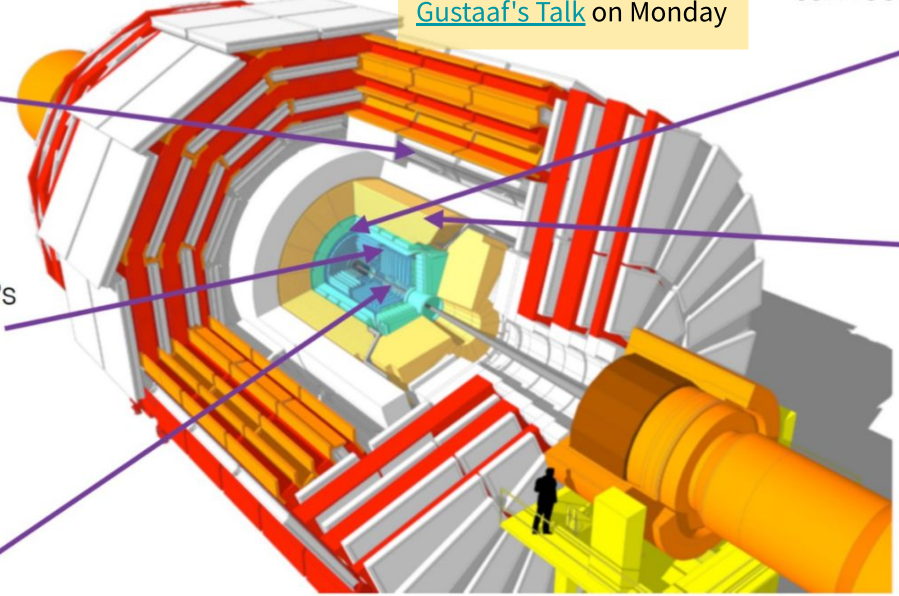


HL-LHC: The CMS Detector Upgrade

Improved muon coverage and trigger
increased RPC coverage (1.5 < |η| < 2.4)
new electronics
CMS-TDR-016

Gustaaf's Talk on Monday

New endcap calorimeters
high granularity
can reconstruct showers in 3D
CMS-TDR-019



New precision timing detector
Timing resolution of 30-40 ps for MIPs
full coverage of |η| < 3.0
CMS-TDR-020

Updates to calorimeter and trigger
higher granularity
electronics for trigger
CMS-TDR-015

Level-1 : CMS-TDR-021
DAQ&HLT : CMS-TDR-022

New inner tracker
all silicon tracker
4 layers of pixels
5 layers of strips
coverage to |η| < 4
CMS-TDR-014

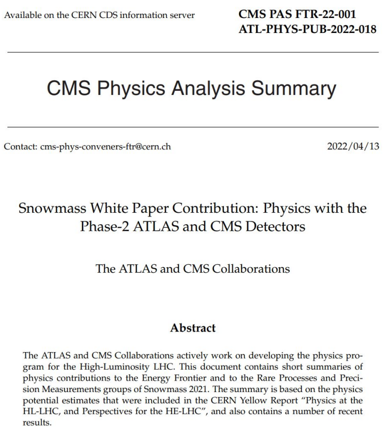
Beam Radiation Instrumentation and Luminosity Detectors
CMS-TDR-023

Upgrade to trigger and DAQ
L1 rate increased to 750 kHz
High Level trigger rate to 7.5 kHz
Track information at L1

HL-LHC BSM Physics Studies at CMS

- Dedicated studies to explore the full potential of the HL-LHC and upgraded detectors
  - Continue and improve current searches to extend sensitivity
  - Design new searches exploiting the new detector improvements
  - Develop new analysis strategies to access scenarios with lower x-sections and acceptance to open new search channels

Snowmass White Paper


Available on the CERN CDS information server

CMS PAS FTR-22-001
ATL-PHYS-PUB-2022-018

CMS Physics Analysis Summary

Contact: cms-phys-conveners-ftr@cern.ch 2022/04/13

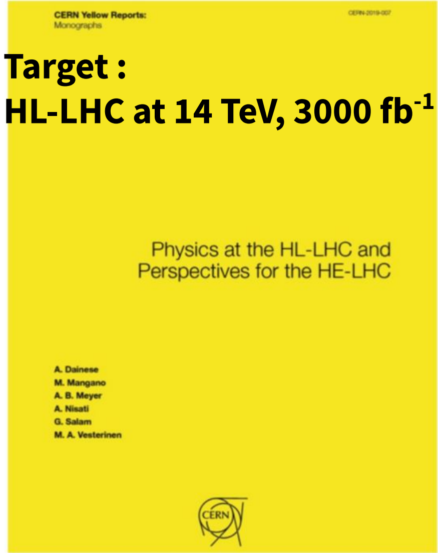
Snowmass White Paper Contribution: Physics with the Phase-2 ATLAS and CMS Detectors

The ATLAS and CMS Collaborations

Abstract

The ATLAS and CMS Collaborations actively work on developing the physics program for the High-Luminosity LHC. This document contains short summaries of physics contributions to the Energy Frontier and to the Rare Processes and Precision Measurements groups of Snowmass 2021. The summary is based on the physics potential estimates that were included in the CERN Yellow Report "Physics at the HL-LHC, and Perspectives for the HE-LHC", and also contains a number of recent results.

HL-LHC Yellow Report (2018)


CERN Yellow Reports: Monographs

CERN-2019-007

Physics at the HL-LHC and Perspectives for the HE-LHC

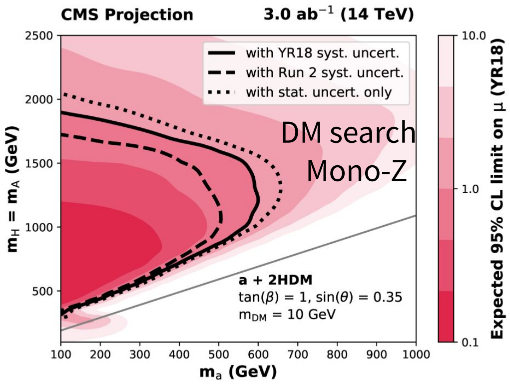
A. Dainese
M. Mangano
A. B. Meyer
A. Nisati
G. Salam
M. A. Vesterinen

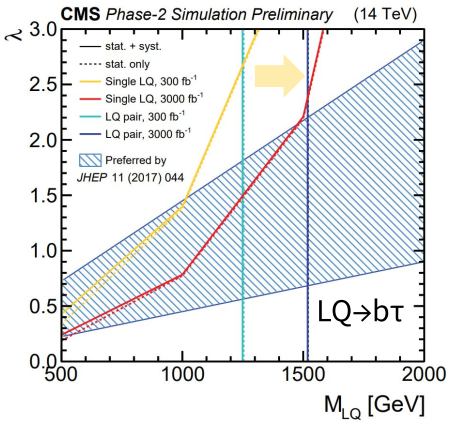
Target :
HL-LHC at 14 TeV, 3000 fb^{-1}

- **Model specific explorations**
  - SUSY
  - Leptoquark
  - 4 top quarks in 2HDM+a
  - Leptophobic Z'
  - Seesaw model
- **More general explorations**
  - Compositeness
  - New gauge bosons
  - Long-lived particle
- **Dark matter at colliders**
  - Mono-X (X=jet,γ,t,Z, VBF ..)
  - Dark photon

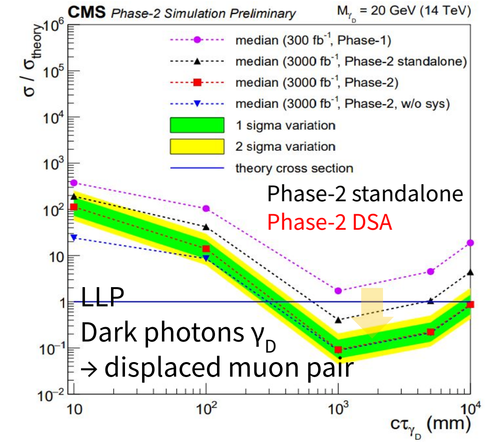
BSM Searches at HL-LHC

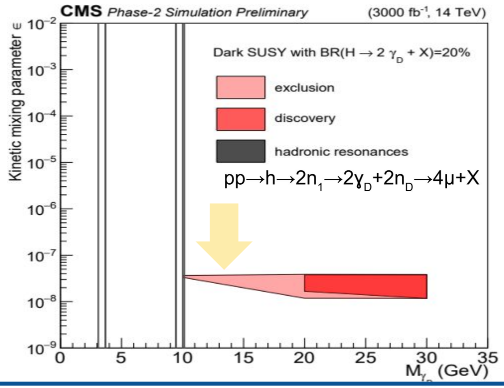
Probing Higher Masses



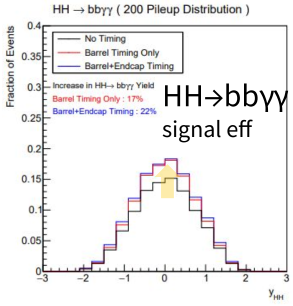


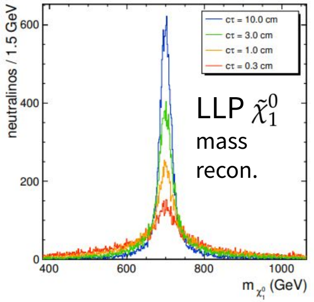
Probing Lower couplings

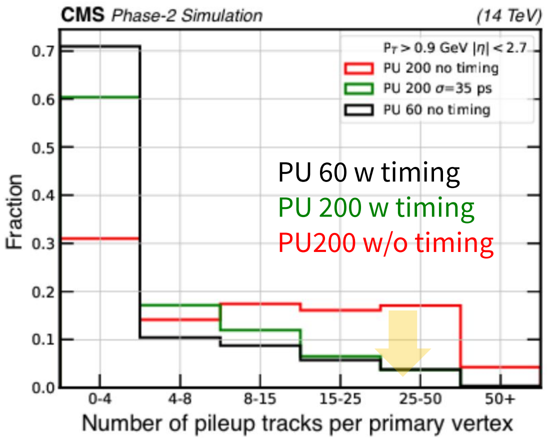




Physics Benefics from Precision timing



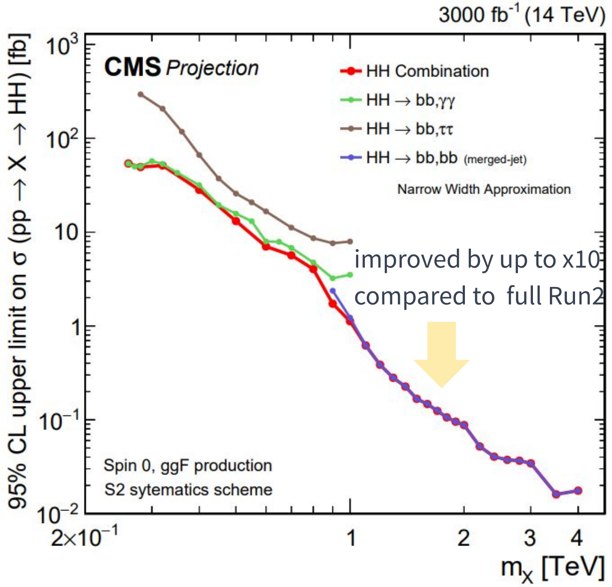




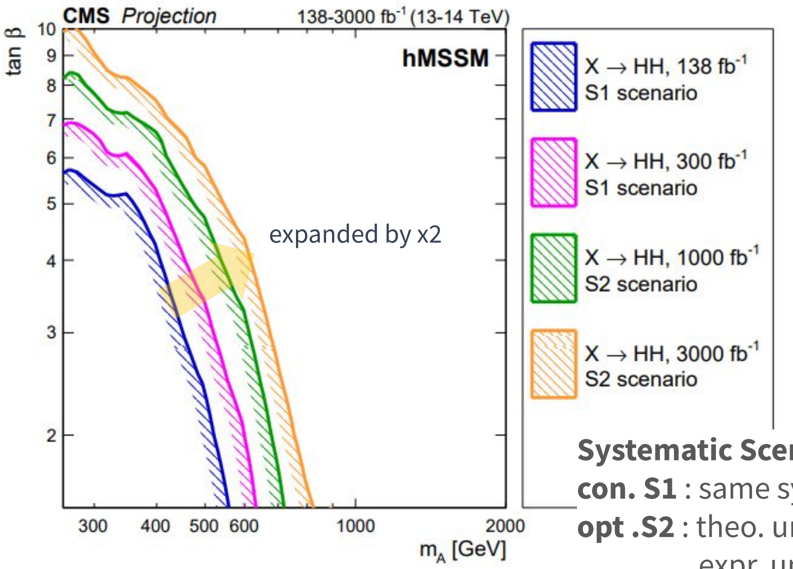
Many more in Snowmass White Paper , sys

Projection for X →HH search at HL-LHC

Discovery potential for X →HH



Projection in Benchmark: hMSSM



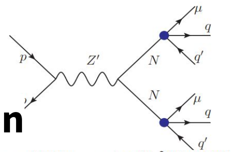
Systematic Scenarios:
con. S1 : same sys. as Run-2
opt .S2 : theo. uncert are halved
expr. uncert from YR18

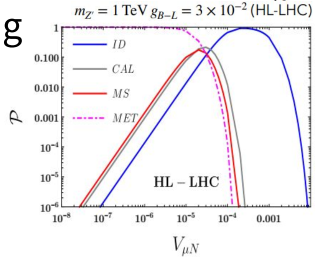
- The expected upper limits for resonant HH production for the HL-LHC scenario
  - Range from about 50 fb at a resonance mass of 300 GeV to nearly 0.01 fb for M > 3 TeV.
- The exclusions in terms of tan β in the hMSSM and $M^{125}_{h,EFT}$ scenarios for HL-LHC scenario
  - Expanded by almost a factor of 2 compared to the Run 2 data (138/fb) set.
- More projections can be found in CMS review (2403.16926 : **Heavy resonances with h)**

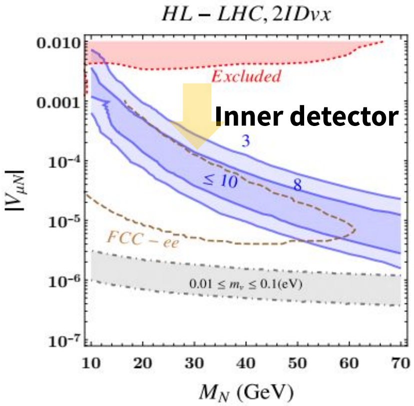
Projection for HNL at HL-LHC

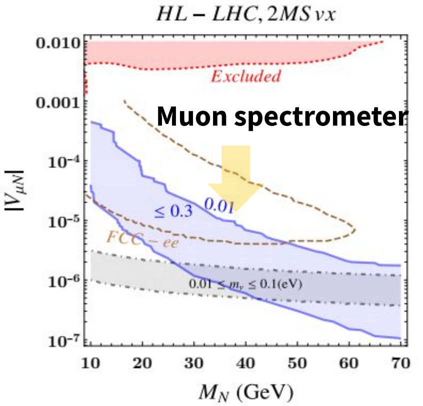
- **Highly boosted LL HNLs via a B−L Z’ boson**
- HL-LHC can be sensitive to small mixing $|V_{\mu N}|>10^{-6}$ with the N_{evt} reaching O(10)

EPJC82(2022)858







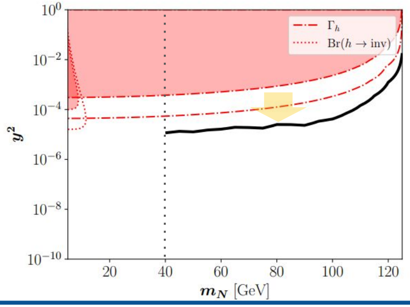


- **HNL from Higgs bosons** (h → Nν, N → νff) ⇒ Using Yukawa coupling to h
- This new decay mode contributes to total Γ_h

2311.18033

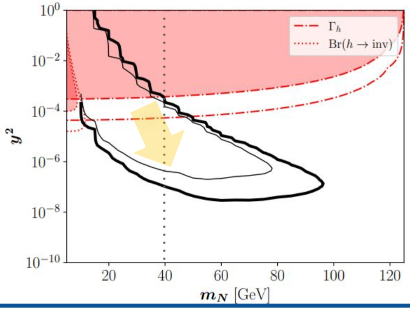
Prompt Decays (PD)

cτ < 1 mm



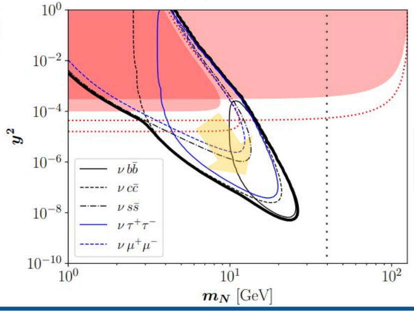
Displaced Vertices (DV)

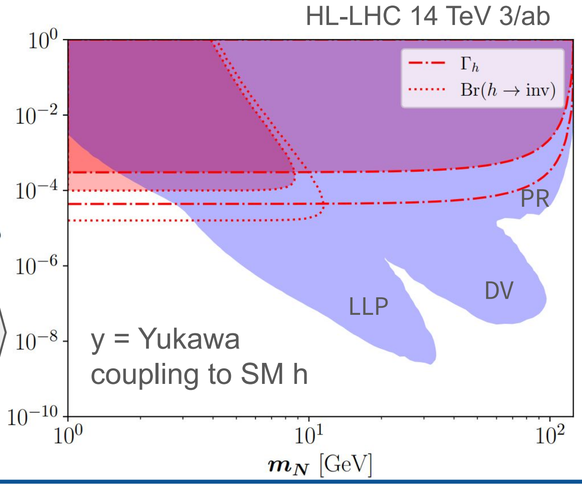
O(1) mm < cτ < O(1) m



Long-lived particle (LLP)

O(1) m < cτ





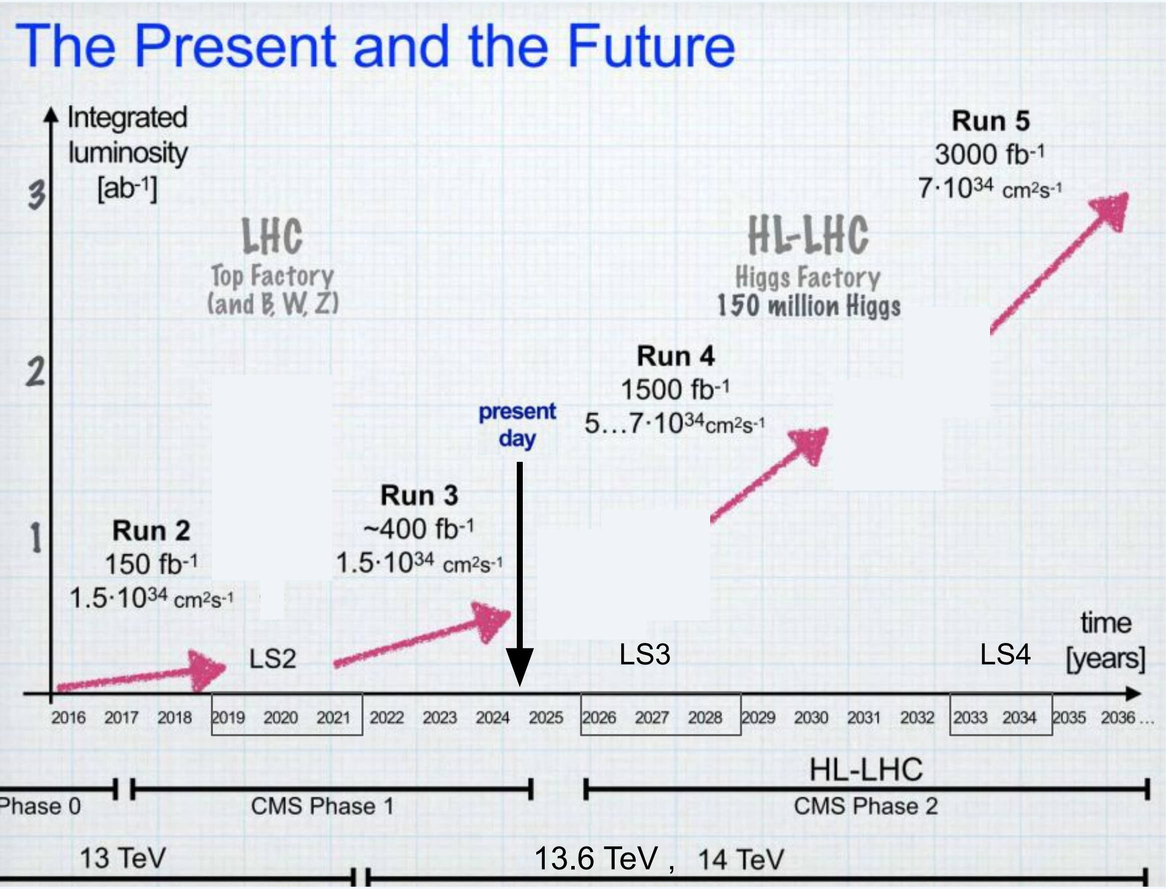
Summary

- Large number of BSM scenarios and signatures explored with Run-2 & Run-3 data.
  - Sensitivity significantly improved with new reconstruction & analysis techniques.
  - Several new models/unconventional signatures explored for the first time !
  - Actively advancing LLP lifetime frontier by using CMS detectors in new ways.

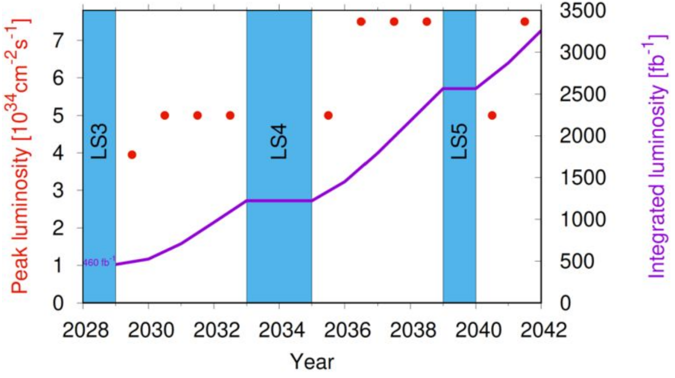
- No clear evidence has been found yet, but significantly extended our exclusion range. Continue with more data to come!

- HL-LHC to yield the largest pp dataset so far ⇒ Rich physics program
  - Sensitivity to BSM searches to be much advanced
  - hope to see many new ideas to be born and realized in near future.

- Please Stay Tuned!   Thank you for your attention

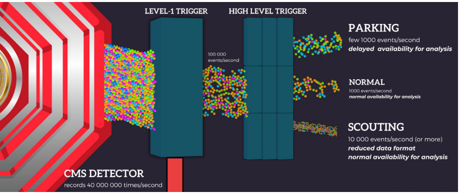


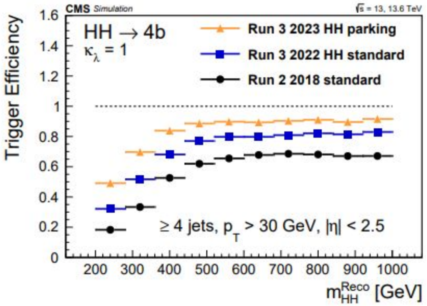
Prospected evolution of integrated luminosity in the HL-LHC

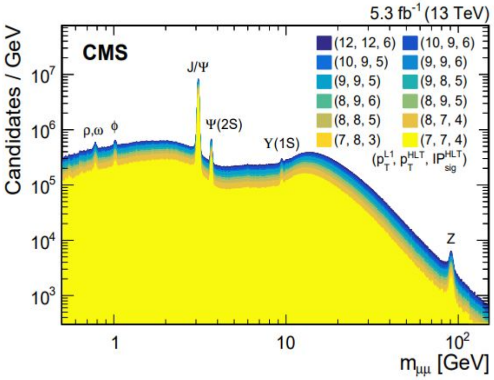


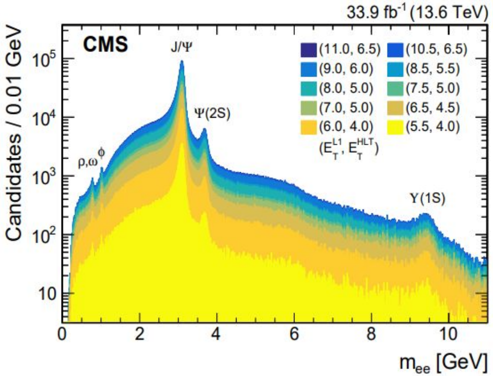
Year	ppb $[10^{11}]$	Virtual lumi. $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Days in physics	θ [μrad]	β^*_{start} [cm]	β^*_{end} [cm]	CC	Max. PU
2029	1.8	4.4	90	380	70	30	exp	116
2030	2.2	9.7	120	500	100	30	on	132
2031	2.2	11.3	160	500	100	25	on	132
2032	2.2	13.5	160	500	100	20	on	132
2033-34	Long shutdown 4							
2035	2.2	13.5	140	500	100	20	on	132
2036	2.2	16.9	170	500	100	15	on	132
2036	2.2	16.9	200	500	100	15	on	200

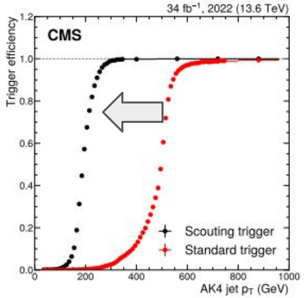
Data Parking & Scouting Run-3

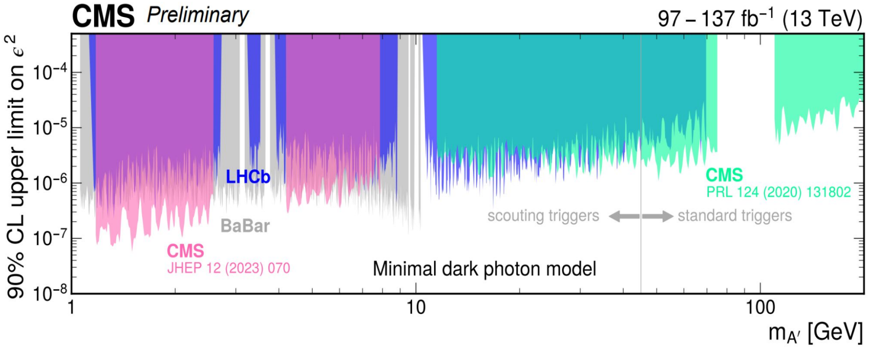


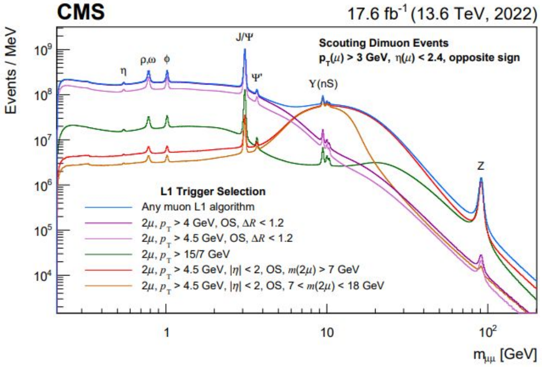


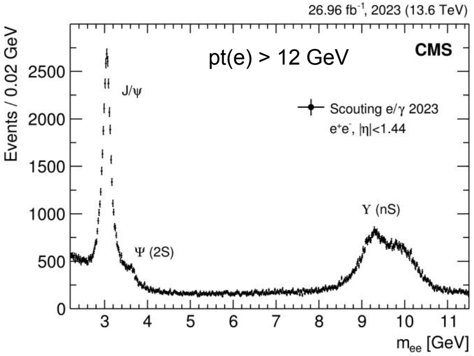




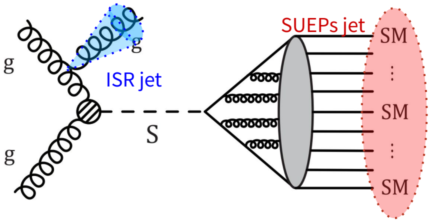


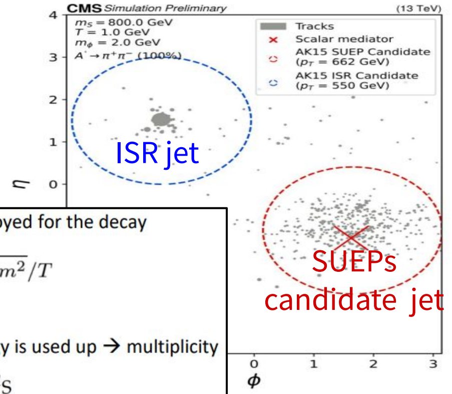






arxiv:2403.05311





LO Boltzmannian thermal model is employed for the decay

$$\frac{dN_\phi}{dp} \propto e^{-\sqrt{p^2+m^2}/T}$$

Keep sampling distribution until all energy is used up → multiplicity related by:

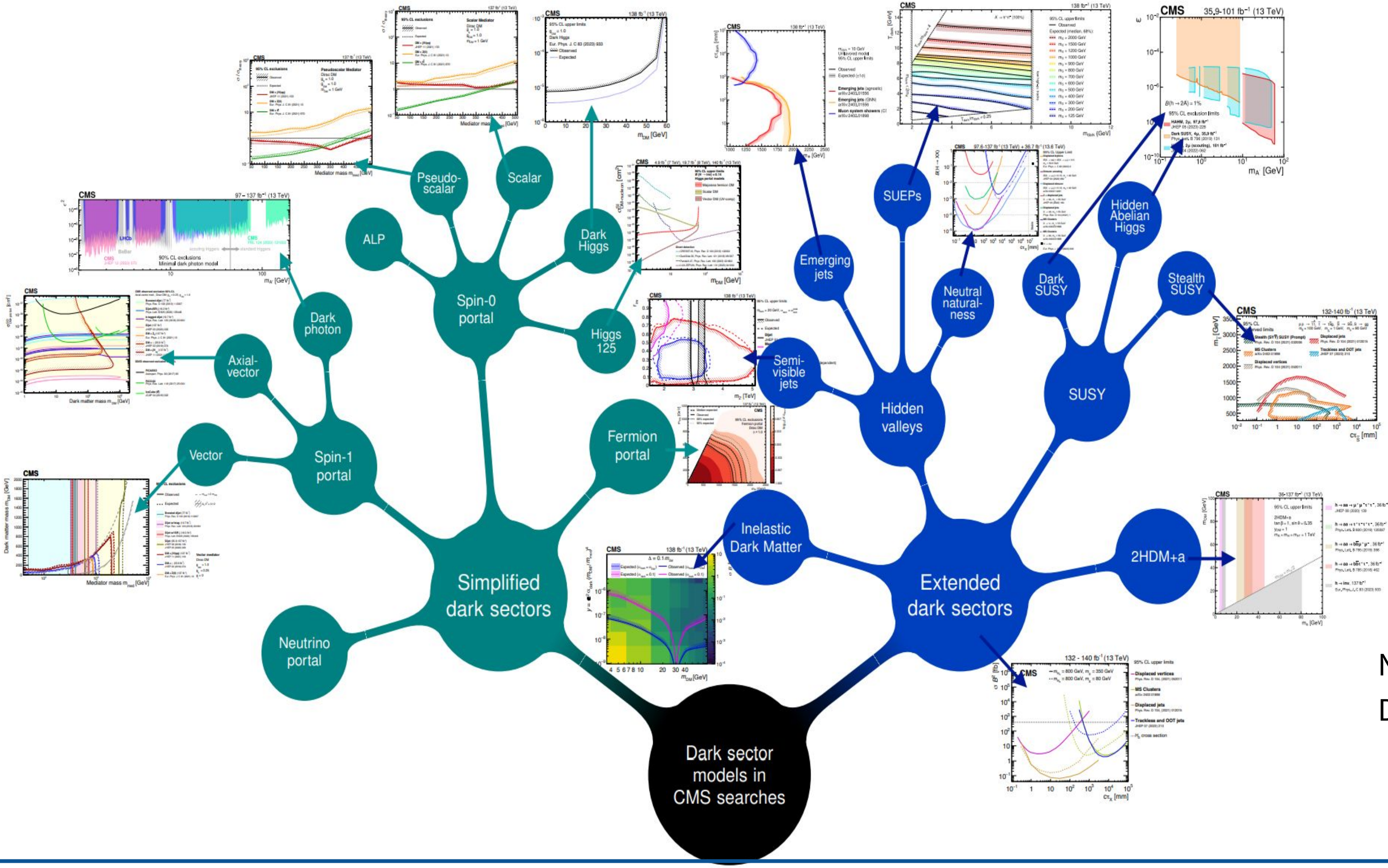
$$N \sim \frac{m_S}{m_\phi} \sim \frac{m_S}{T}$$

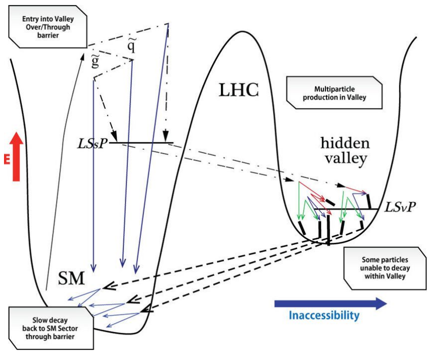
- **Trigger & HT:**
  - PFHT900 (2016), PHT1050 (2017, 2018)
  - HT > 1200 GeV (offline)
- **Lepton Veto:**
  - Orthogonality to associated production (W/Z)
  - No leptons with pT > 25.
- **Track Selection:**
  - packedPFCandidates matched to tracks + lost tracks
  - Track cleaning:

$$|\eta| < 2.4$$
$$\text{fromPV} > 1$$
$$p_T > 0.75\,\text{GeV}$$
$$|dz| < 10\text{ cm}$$
$$|dz_{err}| < 0.05\text{ cm}$$

- SUEP candidate definition:
  - Used Fastjet to cluster our selected tracks to form clusters with anti-kt algorithm with dR = 1.5.
  - SUEP-ISR system defined to be two highest p_T clusters.
  - SUEP candidate defined as cluster with most **constituents** of the two.
- Boosting
  - Calculate **Sphericity** (r=1) in boosted frame of the SUEP candidate of the tracks corresponding to the candidate's cluster.

Dark Sector Report map



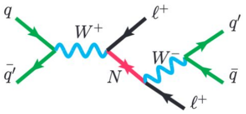


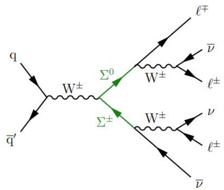
Hidden Valley model

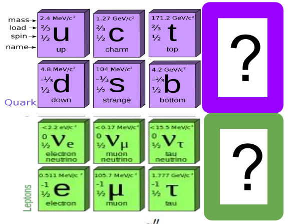
Nice CMS Review article of Dark sector (2405.13778)

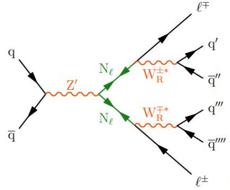
HNL, VLQ/L Searches

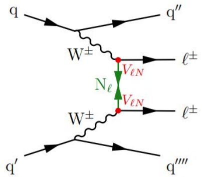
- Heavy Neutral Lepton (**HNL**) or Heavy Neutrino
  - Potential BSM solutions for neutrino mass
    - **Type-I Seesaw models** : HNL mix with SM ν
    - **Type-III Seesaw models** : $SU(2)_L$ triplet $\Sigma^0, \Sigma^+, \Sigma^-$ heavy leptons
    - **Left-Right Symmetry model** (LRSM) : W_R, Z' along with 3 HN_R
    - **Composite model**
  - If HNL is Majorana neutrino, Lepton Number Violation is possible





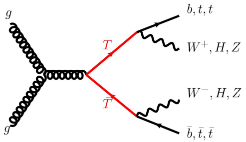


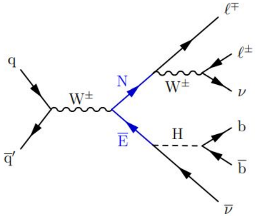




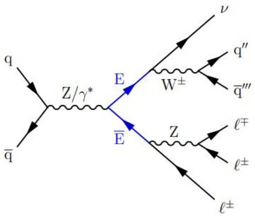
- Vector-like fermions (**VLQ, VLL**)
  - **VLQ**s are colored spin ½ fermions ;
  - L/R-handed transform identically under EW symmetry
  - Can mix with SM quarks to regulate Higgs mass
    - Extra dimensions, composite Higgs models etc..
  - **VLL**s are color singlet counterparts of the VLQs
    - Minimal Model, 4321 Model (UV); Z', vector LQ

Pair Prod. (QCD)
Dominant at low M (<TeV)



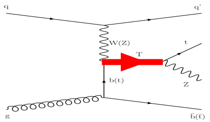


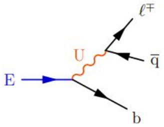
VLL Doublet

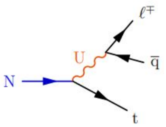


VLL Doublet/Singlet

Single Prod. (EWK)
Enhance at high M
but model dependent

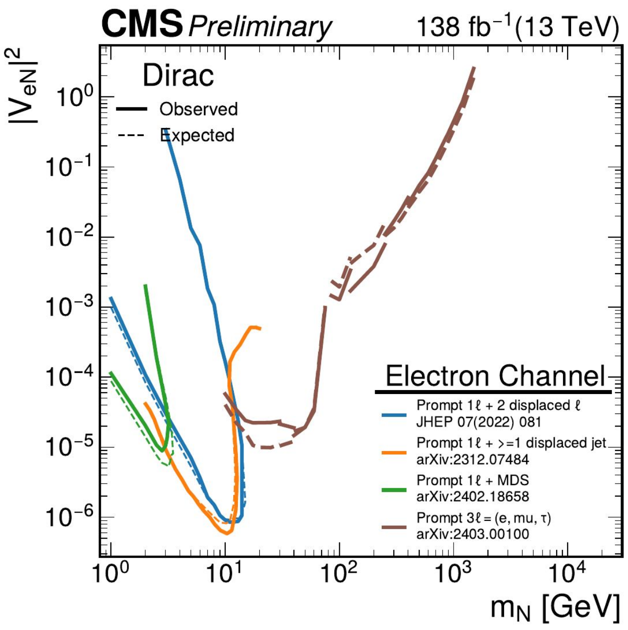


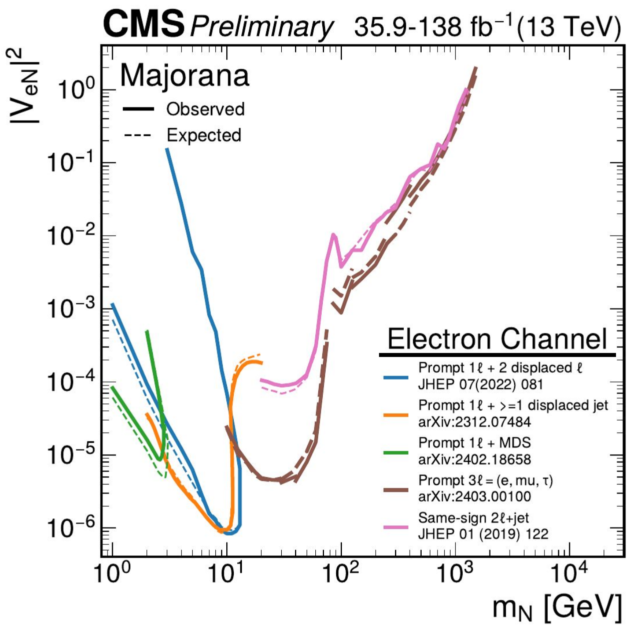


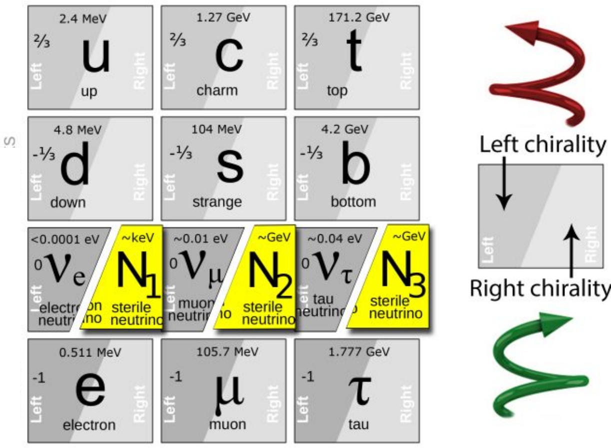


Heavy Neutral Lepton Search in Run-2

HNL in the Type-I seesaw model (Electron Mixing)





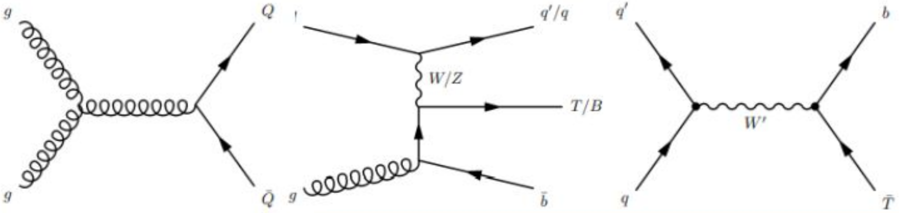


HNL_Summary_Plot

VLQ, VLL decay modes

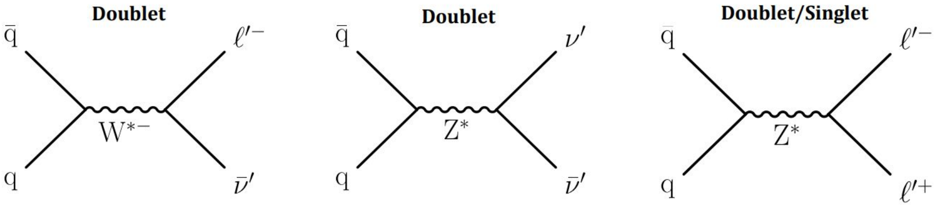
Production mode	Decay mode	Channel	Section	Refs.
$T\bar{T}$	bW, tH, tZ	$0\ell, 1\ell$, OS 2ℓ, SS $2\ell, 3\ell$	6.2.2	[137–140]
$B\bar{B}$	tW, bH, bZ	$0\ell, 1\ell$, OS 2ℓ, SS $2\ell, 3\ell$	6.2.3	[139–141]
$X_{5/3}\bar{X}_{5/3}$	tW	1ℓ, SS 2ℓ	6.2.1	[142]
$Y_{4/3}\bar{Y}_{4/3}$	bW	1ℓ	6.2.2	[137]
T	tZ	$bqq\,\ell\ell$, bqq bb, $bqq\,\nu\nu$	6.3.1	[143–145]
	tH	$bqq\,\gamma\gamma$, bqq bb	6.3.2	[144, 146, 147]
	bW	$b\,\ell\nu$	6.3.3	[148]
B	bH	b bb	6.3.4	[149]
	tW	$bqq\,\ell\nu$, $b\ell\nu$ qq, bqq qq	6.3.4	[150–152]
$X_{5/3}$	tW	$bqq\,\ell\nu$, $b\ell\nu$ qq, bqq qq	6.3.4	[150, 152]
$Y_{4/3}$	bW	$b\,\ell\nu$	6.3.3	[148]
$Z' \to T\bar{T}$	bW	0ℓ	6.4.1	[153]
	tH, tZ	1ℓ		[154]
$W' \to Tb$	tH, tZ	0ℓ	6.4.2	[155, 156]
$W' \to Bt$	bH, bZ	0ℓ		[155, 156]

VLQ

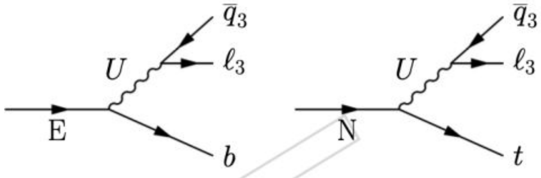


Benchmark	BR(W)	BR(Z)	BR(H)
Singlet	50%	25%	25%
Doublet	--	50%	50%
1 Decay	100% (or 0)	100% (or 0)	100% (or 0)

VLL



Doublet decays	Singlet decays
$\ell' \to Z\ell$	$\ell' \to Z\ell$
$\ell' \to H\ell$	$\ell' \to H\ell$
$\nu' \to W\ell$	$\ell' \to W\nu$

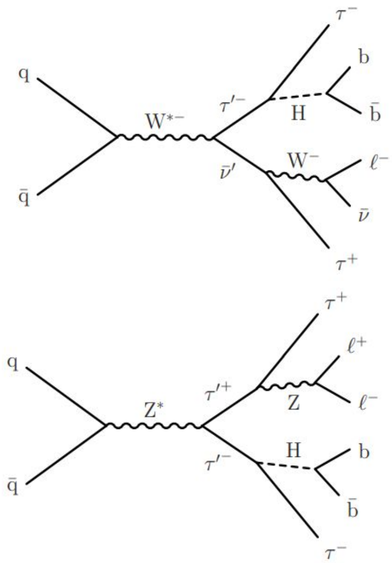


⇒ In 4321 model connect with vector V', LQ

⇒ In minimal model

Vector-Like Lepton Search

- Vector-like fermions are hypothetical particles whose L and R-handed components transform under conjugate representations of the SM gauge symmetries, and hence their masses are independent of the SM Higgs mechanism and are not constrained by ew precision measurements



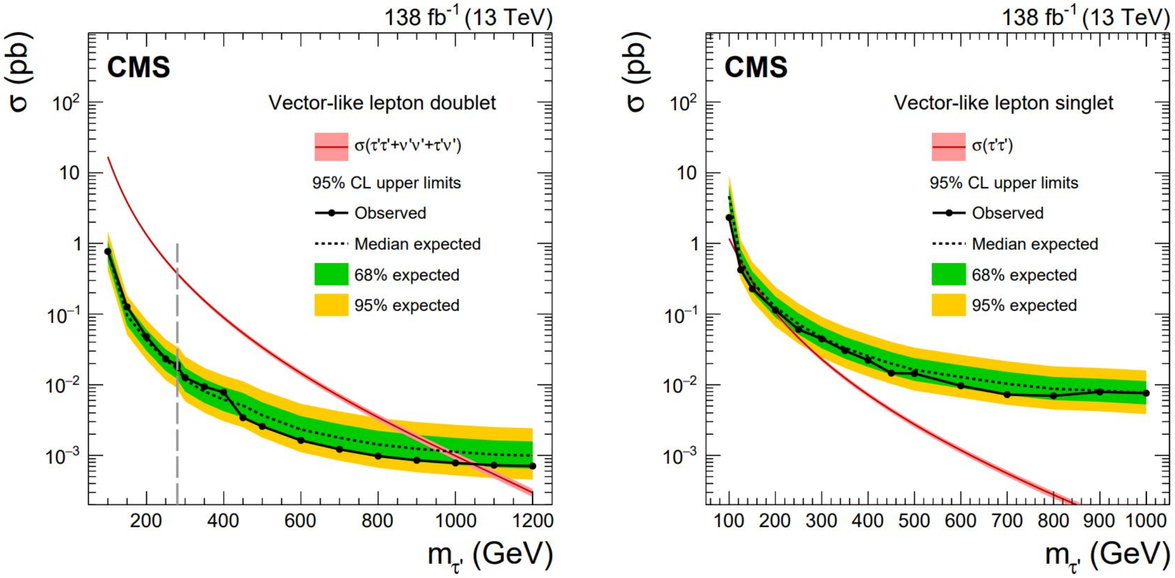
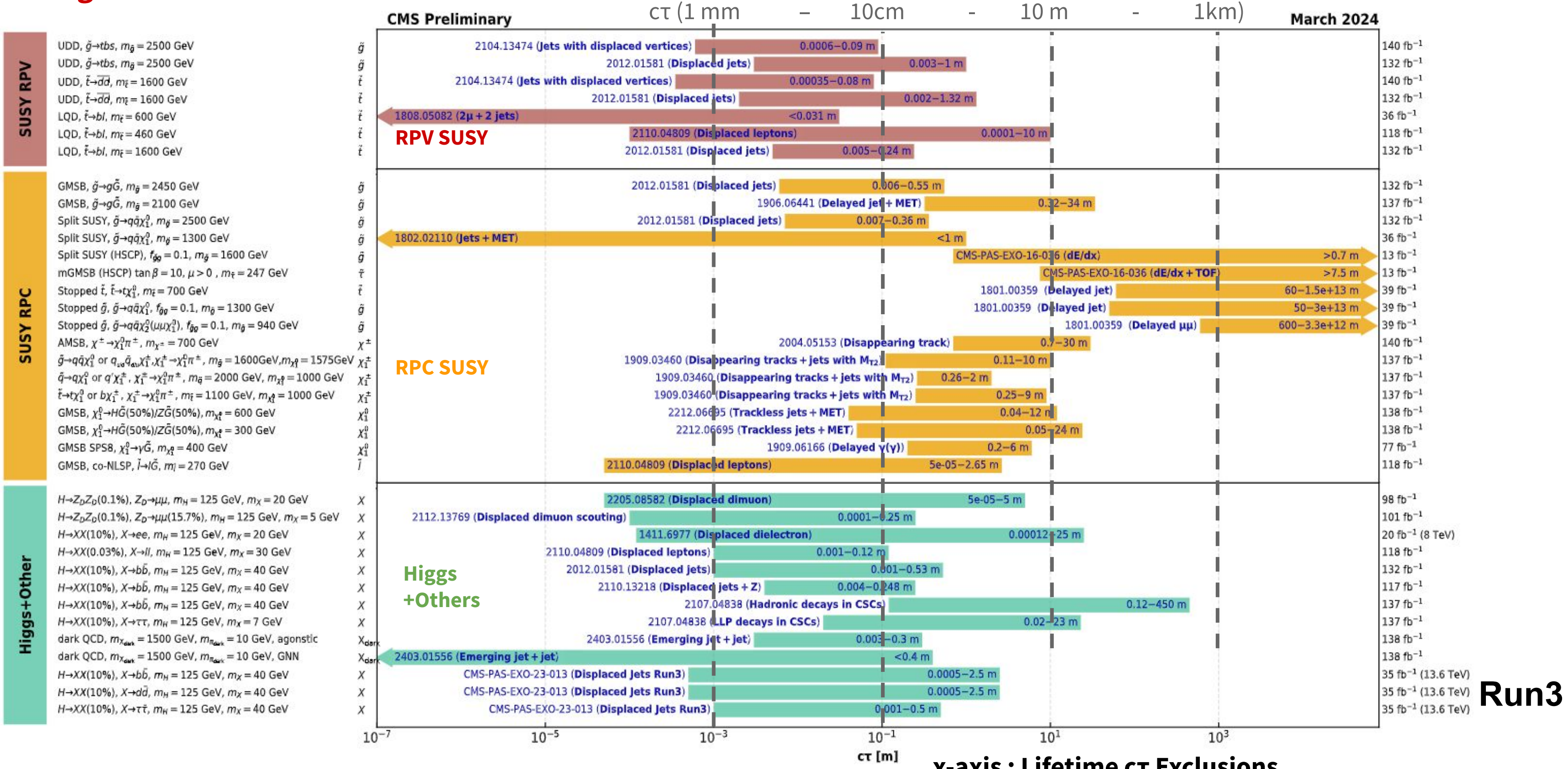


Figure 26: Observed and expected upper limits at 95% CL on the production cross section for the vector-like τ leptons: doublet model (left), and singlet model (right). For the doublet vector-like lepton model, to the left of the vertical dashed gray line, the limits are shown from the advanced S_T table, while to the right the limits are shown from the BDT regions. For the singlet vector-like lepton model, the limit is shown from the advanced S_T table for all masses.

Search for LLP in Run-3

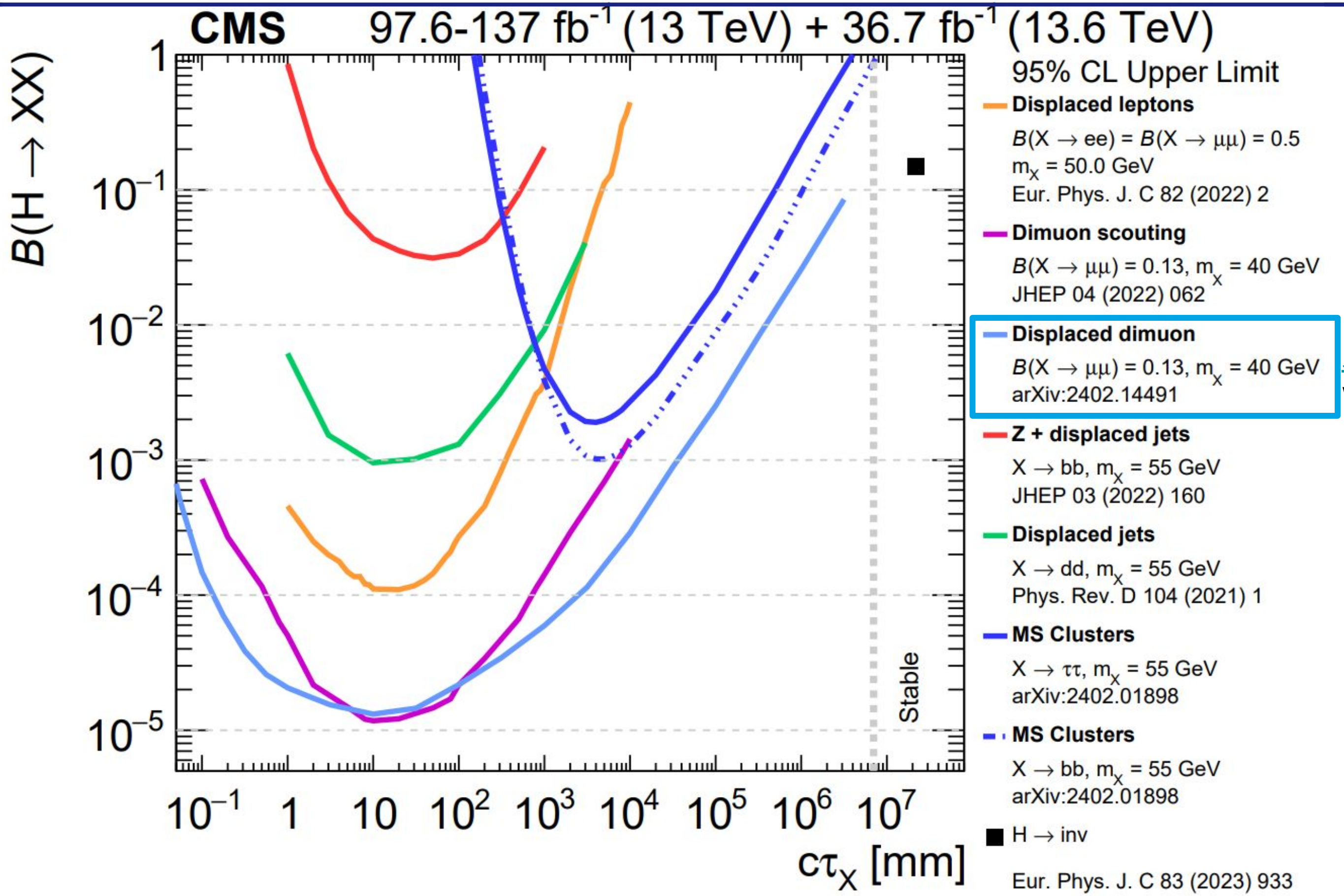
LLP Signatures

Overview of CMS long-lived particle searches



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

Summary plot for BR(h →LLPs)

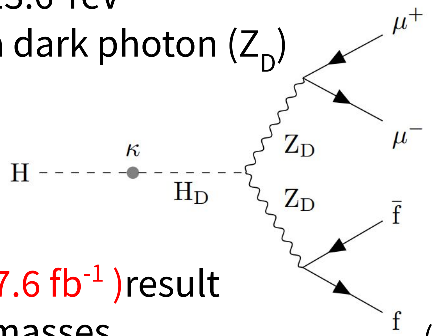


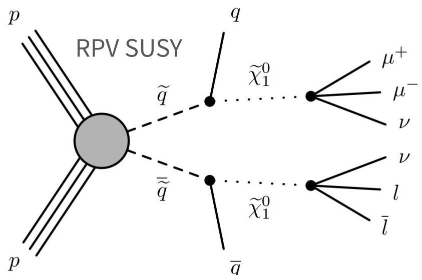
JHEP05(2024)047 with early Run-3 data

LLPs to displaced μ pair in Run-3

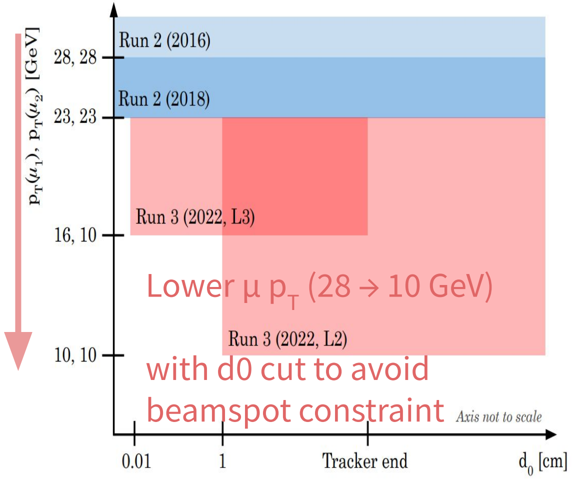
JHEP05(2024)047

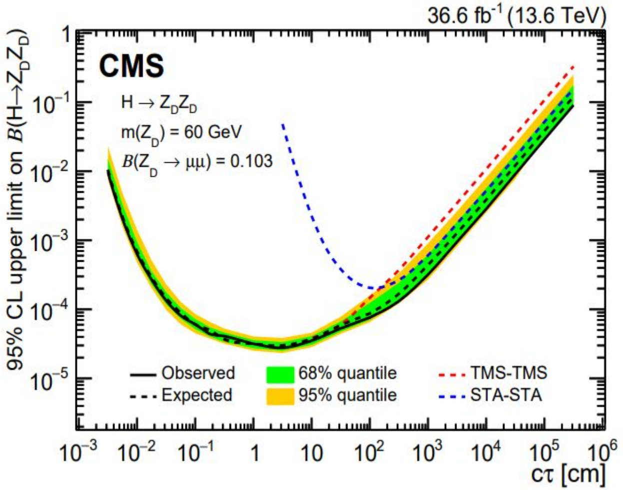
- Search for LLP decays to displaced vertex of dimuon at 13.6 TeV
- Dark Higgs (H_D) mixed with Higgs boson, decay to SM via dark photon (Z_D)
- New dedicated trigger for displaced-dimuon
- Two categories based on μ reconstruction:
  - using both tracker & muon spectrometer (TMS)
  - standalone muon spectrometer (STA)
- partial Run-3 (36.6 fb^{-1})result competitive with Run-2 (97.6 fb^{-1})result
- Run-3 analysis better for length > 100 cm for various Z_D masses

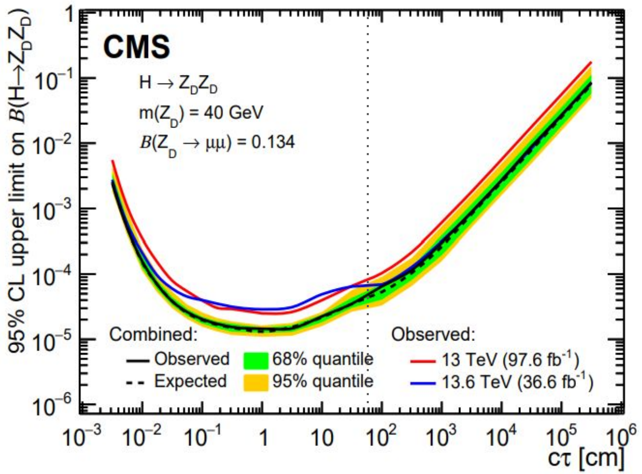




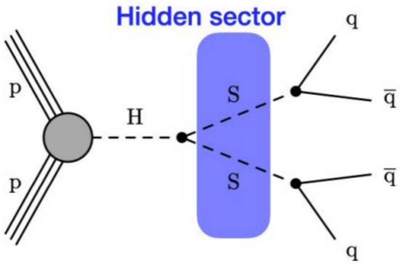
($m_{LLP} < m_H/2$)



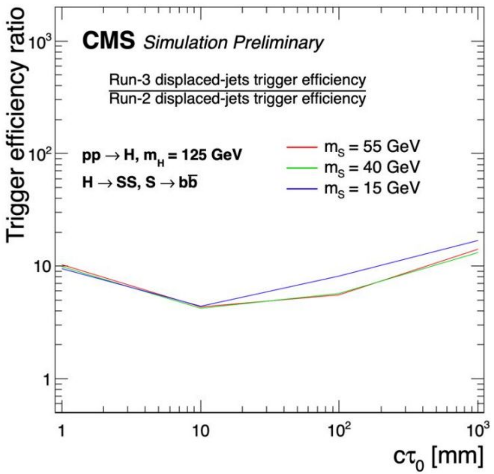




LLP trigger: displaced j/ μ

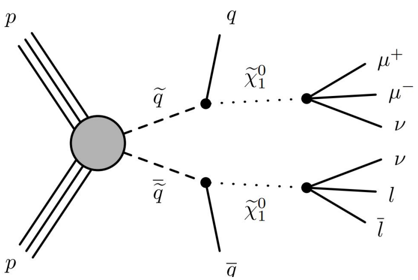


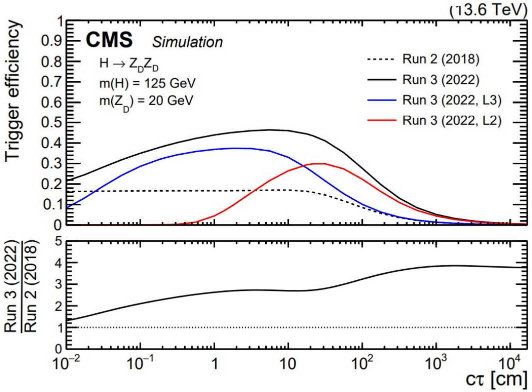
Run-2 vs. Run-3



- The ratio between the Run 3 displaced-jets trigger efficiency and the Run 2 displaced-jets trigger efficiency for a 125 GeV H→SS,S→bb signal model
- The efficiency ratios are shown for different scalar masses m_S and proper decay lengths $c\tau_0$
- Run 3 trigger efficiencies are higher than the Run 2 trigger efficiencies by a factor of 4 to 11 for m_S between 10 and 60 GeV, and $c\tau_0$ between 1 and 1000 mm
- The trigger rate is ~26 Hz at instantaneous luminosity of 2×10^{34} cm^{-2} s^{-1}

*CMS-DP-2023-043

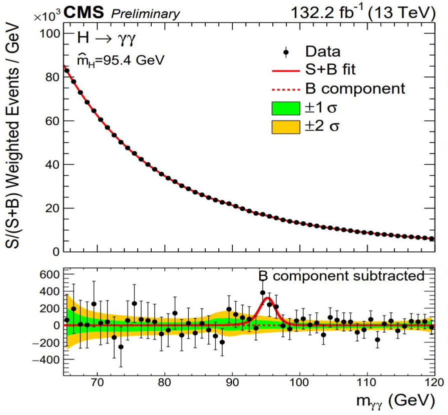




JHEP05(2024)047

Highlights of BSM Higgs Searches at CMS

Low mass H→γγ



m_H = 70 – 110 GeV

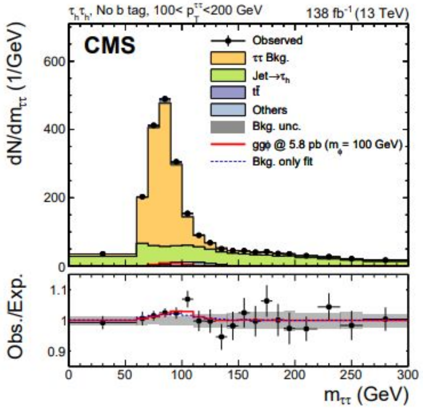
CMS-PAS-HIG-20-002

ATLAS-CONF-2023-035

PLB 793 (2019) 320–347
(CMS 2012+2016)

H(ϕ)→ττ

μτh, eτh, τhτh, and eμ



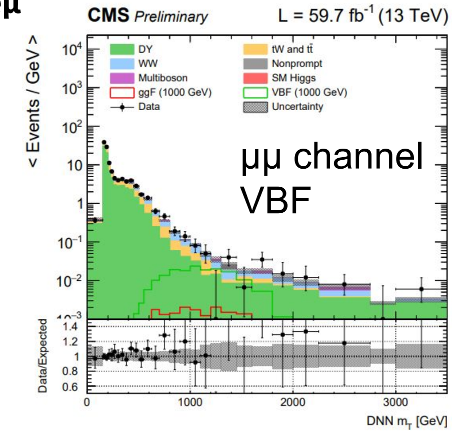
m_H = 60 – 3500 GeV

ATLAS >200 GeV

CMS JHEP07(2023)073

ATLAS PRL125(2020)051801

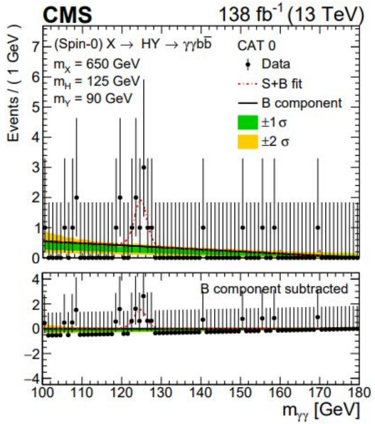
H→WW(2l2ν)



m_H = 115 – 5000 GeV

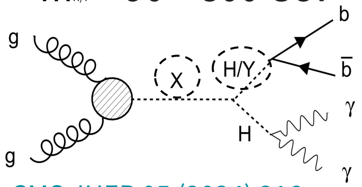
CMS-HIG-20-016 (di-lep)
CMS-HIG-23-008 (semi-lep)
will be updated.

X→HY→γγbb



m_X = 300 – 1000 GeV

$m_{H/Y}$ = 90 – 800 GeV

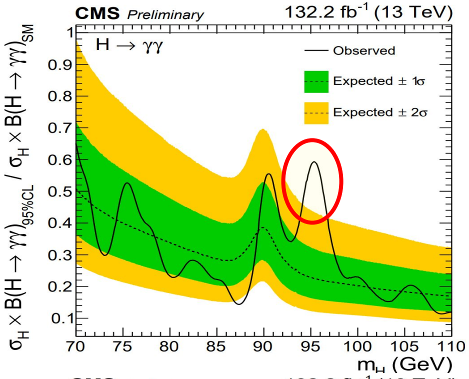


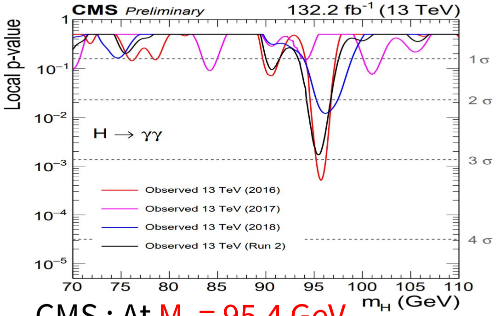
CMS JHEP 05 (2024) 316
CMS-HIG-20-012 (4b) ongoing.

All results in full Run-2 (138/fb)

Intriguing excess of BSM Higgs

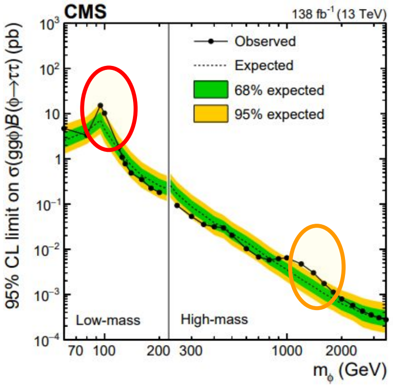
Low mass H→γγ





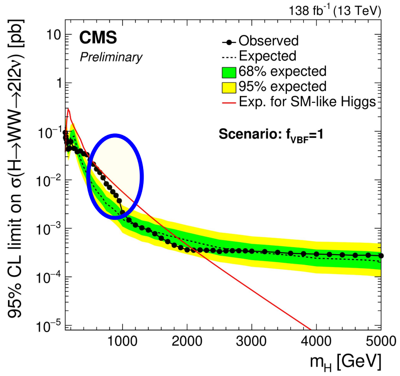
CMS : At M_H= 95.4 GeV,
a largest significance local (global)
2.9 (1.3) σ is observed.
(ATLAS : at same M_H local 1.7σ)

H(ϕ)→ττ



At M_H= 95, 1200 GeV
the largest significance local (global) 2.6 (2.3) σ, 2.8 (2.2) σ are observed.

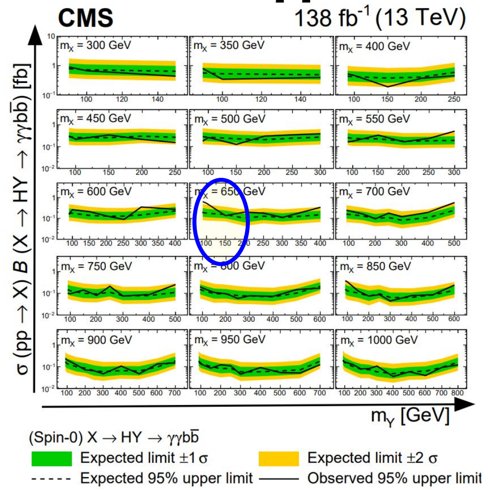
H→WW(2l2ν)



Scenario	Mass [GeV]	local	global σ
SM f_{VBF}	800	3.2	1.7 ± 0.2
$f_{VBF}=1$	650	3.8	2.6 ± 0.2
$f_{VBF}=0$	950	2.6	0.4 ± 0.6
floating f_{VBF}	650	3.8	2.4 ± 0.2

At M_H= 650 GeV,
the largest significance local (global) 3.8 (2.6) σ is observed in the VBF mode.

X→HY→γγbb



At M_X= 650 GeV and M_Y= 90 GeV,
the highest significance local (global) 3.8 (2.8) σ is observed.

More data are needed to clarify the origin of these deviations !

BSM Interpretation of excess

- 2HDM+S a good description of the excess : Yukawa types II and IV in T. Biekötter, Sven.H., G. Weiglein 2306.03889

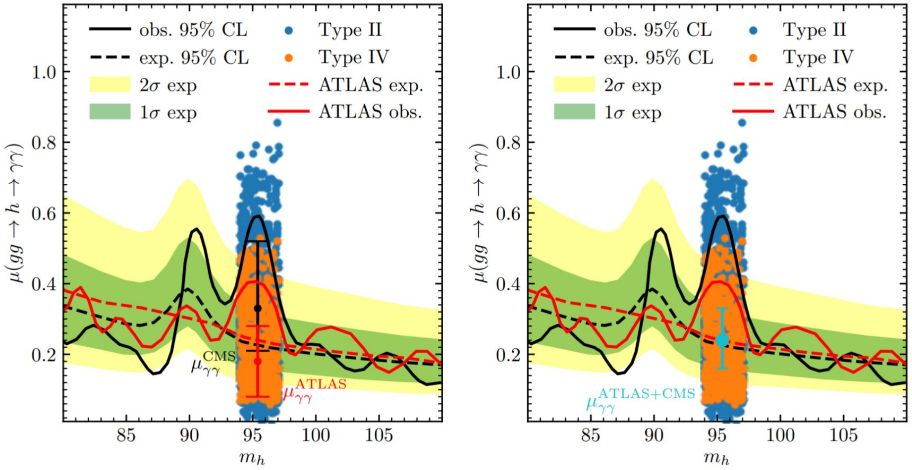


Figure 1: S2HDM parameter points passing the applied constraints in the $(m_{h_1}, \mu_{\gamma\gamma})$ plane for the type II (blue) and the type IV (orange). The expected and observed cross section limits obtained by CMS are indicated by the black dashed and solid lines, respectively, and the 1σ and 2σ uncertainty intervals are indicated by the green and yellow bands, respectively. Overlaid in red are the expected and observed limits from ATLAS [14]. The values of $\mu_{\gamma\gamma}^{ATLAS}$, $\mu_{\gamma\gamma}^{CMS}$ and $\mu_{\gamma\gamma}^{ATLAS+CMS}$ and their respective uncertainties are indicated by the red, black (left plot) and cyan (right plot) error bars at 95.4 GeV.

Combination: $\mu_{\gamma\gamma}^{ATLAS+CMS} = 0.24^{+0.09}_{-0.08}$ corresponding to an excess of 3.1σ

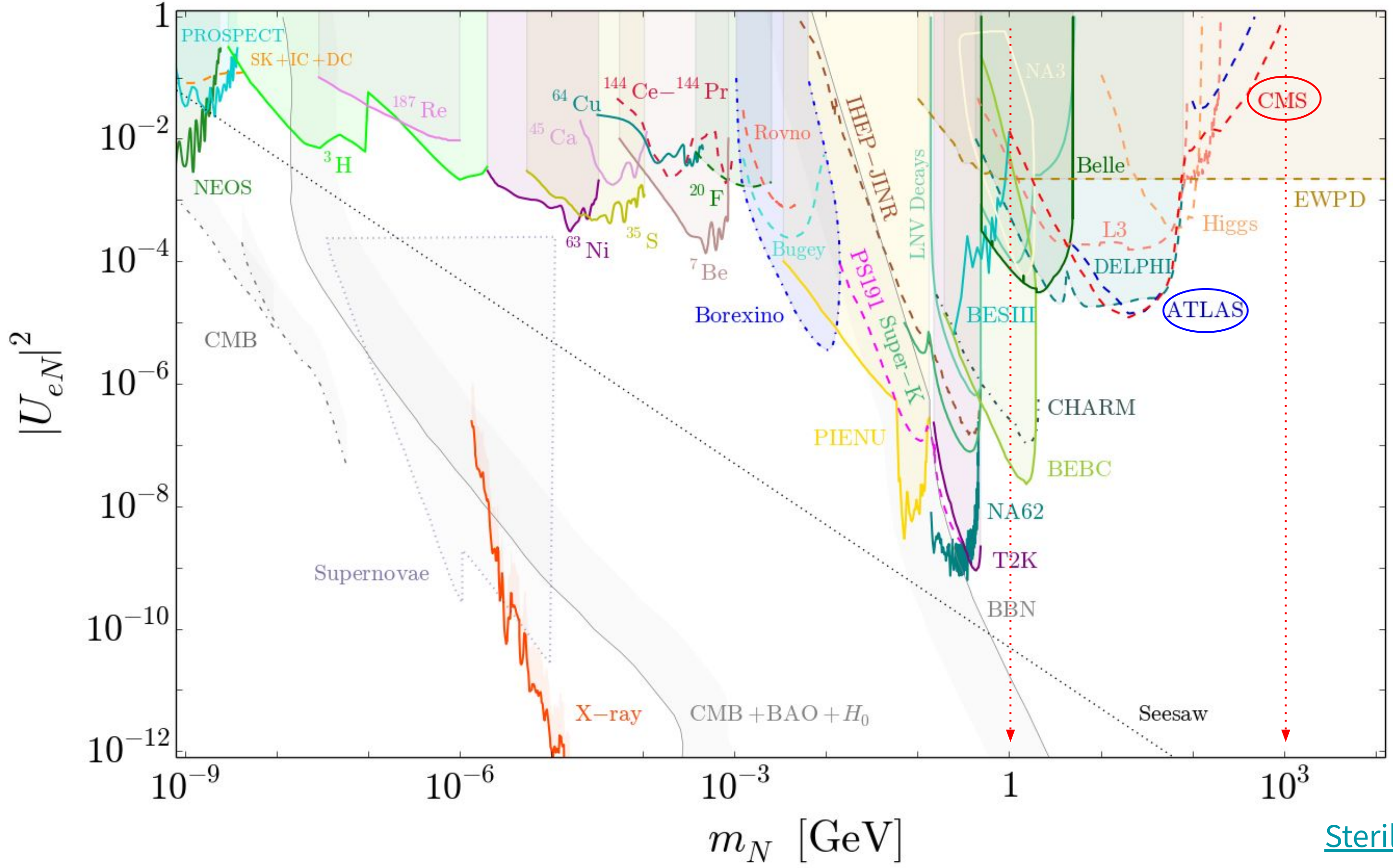
.

From Thomas Biekötter at the "Collider Crosstalk at CERN" (Sept. 2023)

Authors	Model	arXiv	Excesses	Comments
Cao, Guo, He et al.	nNMSSM	1612.08522	$b\bar{b}+\gamma\gamma$	
Fox, Weiner	2HDM + VL	1710.07649	$b\bar{b}+\gamma\gamma$	
Haisch, Malinauskas	2HDM	1712.06599	$b\bar{b}+(\gamma\gamma)$	
TB, Heinemeyer, Muñoz	$\mu\nu$SSM	1712.07475	$b\bar{b}+\gamma\gamma$	EW seesaw
Liu, Liu, Wagner, Wang	$U(1)_{L_\mu-L_\tau}$	1805.01476	$b\bar{b}+\gamma\gamma$	B-anomalies
Domingo, Heinemeyer, Paßehr, Weiglein	NMSSM	1807.06322	$b\bar{b}+\gamma\gamma$	
Hollik, Liebler, Moortgat-Pick et al.	μNMSSM	1809.07371	$b\bar{b}+\gamma\gamma$	Inflation
TB, Chakraborti, Heinemeyer	N2HDM	1903.11661	$b\bar{b}+\gamma\gamma$	
Cline, Toma	pNG + squarks	1906.02175	$b\bar{b}+\gamma\gamma$	DM
Choi, Hui Im, Sik Jeong et al.	gNMSSM	1906.03389	$b\bar{b}+\gamma\gamma$	
Cao, Jia, Yue et al.	nNMSSM	1908.07206	$b\bar{b}+\gamma\gamma$	Type-I seesaw
Aguilar-Saavedra, Joaquim	SM + $U(1)_{Y'}$	2002.07697	$b\bar{b}+\gamma\gamma$	
TB, Olea-Romacho	S2HDM	2108.10864	$b\bar{b}+\gamma\gamma$	DM, GC excess
TB, Grohsjean, Heinemeyer et al.	NMSSM	2109.01128	$\gamma\gamma$	400 GeV excess
Heinemeyer, Lika, Moortgat-Pick et al.	2HDM+s	2112.11958	$b\bar{b}+\gamma\gamma$	
TB, Heinemeyer, Weiglein	N2HDM	2203.13180	$b\bar{b}+(\tau\tau)+\gamma\gamma$	
TB, Heinemeyer, Weiglein	N2HDM	2204.05975	$b\bar{b}+(\tau\tau)+\gamma\gamma$	CDF M_W
Benbrik, Boukidi, Moretti et al.	A2HDM-III	2204.07470	$b\bar{b}+\gamma\gamma$	LFV
TB, Heinemeyer, Weiglein	S2HDM	2303.12018	$b\bar{b}+(\tau\tau)+\gamma\gamma$	DM
Azevedo, TB, Ferreira	C2HDM	2305.19716	$b\bar{b}+\tau\tau+\gamma\gamma$	
Bonilla, Carcamo, Kovalenko et al.	Left-Right model	2305.11967	$\gamma\gamma$	DM
TB, Heinemeyer, Weiglein	S2HDM	2306.03889	$b\bar{b}+(\tau\tau)+\gamma\gamma$	ATLAS-$\gamma\gamma$
Escribano, Martin Lozano, Vicente	Scotogenic	2306.03735	$b\bar{b}+\gamma\gamma$	DM, ν masses
Belyaev, Benbrik, Boukidi et al.	A2HDM	2306.09029	$b\bar{b}+(\tau\tau)+\gamma\gamma$	
Ashanuman, Banik, Coloretti et al.	$Y=0$ triplet	2306.15722	$\gamma\gamma$	CDF M_W
Aguilar-Saavedra, Camara, Joaquim et al.	UN2HDM	2307.03768	$(\tau\tau)$, $\gamma\gamma$	

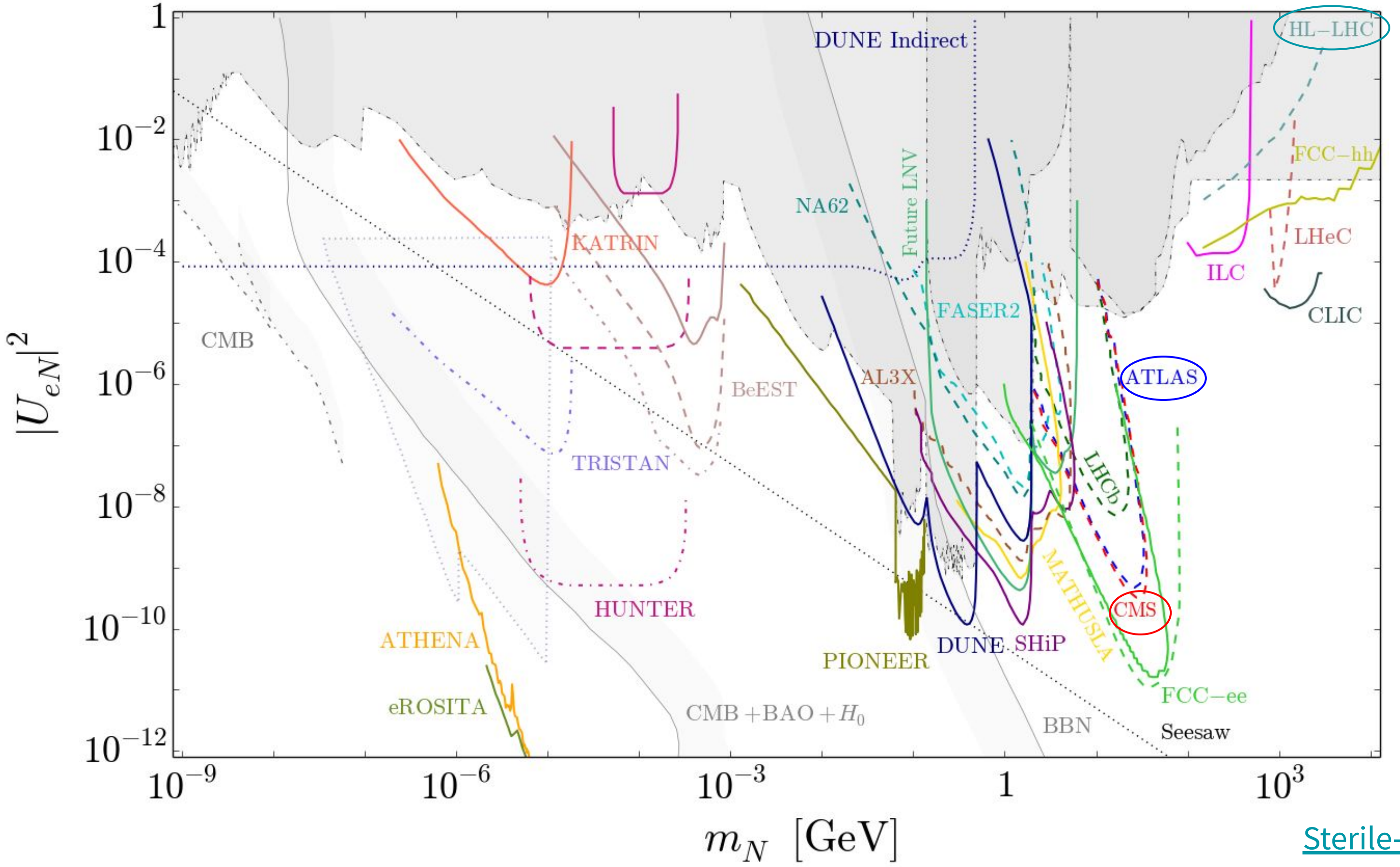
Green: 2HDM(+X); Blue: Susy; Red: Extra charged fields 7

Current Constraints- Electron Mixing



Sterile-Neutrino.org

Future projection- Electron Mixing



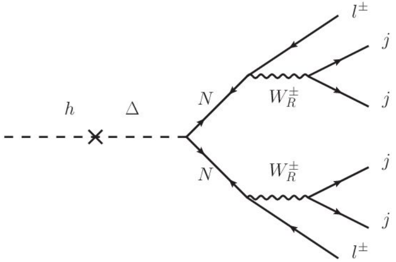
Sterile-Neutrino.org

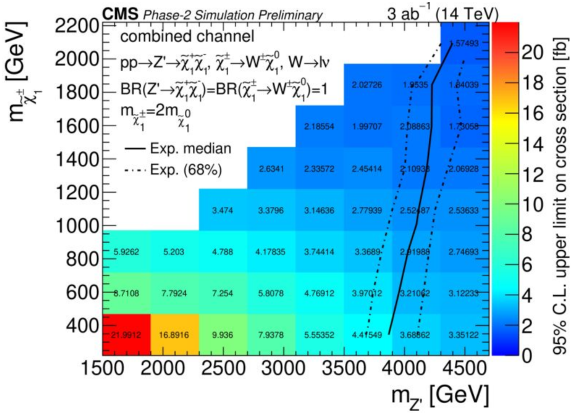
HL-LHC BSM Physics Studies at CMS

$$Z' \to \tilde{\chi}^+\tilde{\chi}^- \to W^+\tilde{\chi}^0_1 W^-\tilde{\chi}^0_1$$

- **Leptophobic Z' to Charginos in dilepton+MET**
  - Leptophobic Z' in U(1)'-extended minimal SUSY (UMSSM) scenario
  - **Low BR (order of percent)**
    ⇒ would highly benefit from the HL-LHC
  - With 3ab^{-1} ⇒ exclude M(Z') up to 4.4 TeV

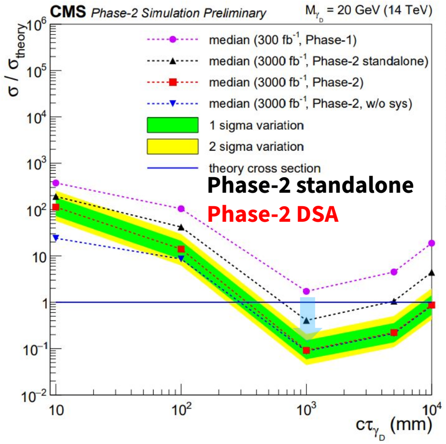
LNV Higgs decay

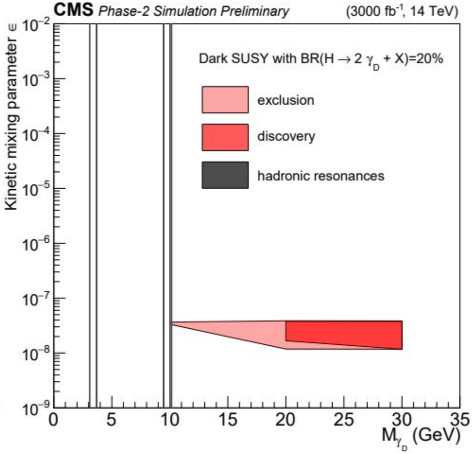




$$pp \to h \to 2n_1 \to 2\gamma_D + 2n_D \to 4\mu + X$$

- **Dark photons γ_D to displaced muon pair**
  - Signal : SM h→ MSSM-like lightest neutralino (n_1) pair, n_1 → dark sector neutralino(n_D) + dark photon (γ_D)
  - Final states: **displaced muon pair + large MET**
  - Phase-2 searches are **sensitive to higher M(γ_D) and lower values of ϵ**, which corresponds to longer lifetimes.





Many more studies in Snowmass White Paper

Precision timing for CMS in HL-LHC

LHCC-P-009

- CMS Phase-2 upgrade aims to achieve High Precision Timing Measurements
  - **In ECAL barrel**: new electronics to achieve **~30 ps** resolution for photon/electron
  - **In HGCal**: design to **~50 ps** timing resolution per layer in EM showers, multiple layers can be combined
  - **MIP timing detector (MTD)**: cover up to **|η|<3.0** to time stamp charged particles in the event: **~30 psec** timing resolution
    - **LYSO + SiPM** layer in the barrel & **Low Gain Avalanche Detector (LGAD**) layer in the endcap

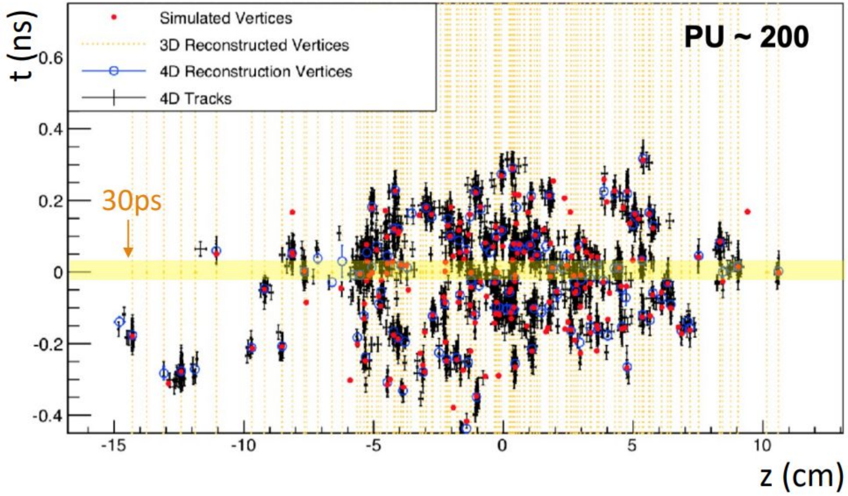


Table 1.1: Representative signals for Higgs boson measurements and SUSY searches used to map each specific detector requirement into the relative performance gain at the analysis level (analysis impact) and in the measured physical quantity (physics impact).

Signal	Detector requirement	Analysis impact	Physics impact
$H \to \gamma\gamma$	30 ps photon and track timing • barrel: central signal • endcap: improved time-zero and acceptance	$S/\sqrt{B}$: +20% - isolation efficiency +30% - diphoton vertex	+25% (statistical) precision on cross section
VBF+ $H\to\tau\tau$	30 ps track timing • barrel: central signature • endcap: forward jet tagging • hermetic coverage: optimal p_T^{miss} reconstruction	$S/\sqrt{B}$: +30% - isolation efficiency +30% - VBF tagging +10% - mass (p_T^{miss}) resolution	+20% (statistical) precision on cross section (upper limit or significance)
HH	30 ps track timing • hermetic coverage	signal acceptance : +20% b-jets and isolation efficiency	Consolidate HH searches
$\chi^{\pm}\chi^0 \to W^{\pm}H+p_T^{miss}$	30 ps track timing • hermetic coverage: p_T^{miss}	$S/\sqrt{B}$: +40% - reduction of p_T^{miss} tails	+150 GeV mass reach
Long-lived particles	30 ps track timing • barrel: central signature	mass reconstruction of the decay particle	unique sensitivity to split-SUSY and SUSY with compressed spectra