Gaps, overlaps, and complementarity in recent LLP searches

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11th LLP Community workshop

Gaps, overlaps, and complementarity

This talk will focus on **my view on the topic**, focusing on recent results at the LHC

- I find the (expanding) LLP search program impressive and full of creativity and brilliant ideas!
  - Boost in the past years in the number of H → XX and HNL searches
  - Recently, plenty of new results in direct searches for LLPs

At the same time, I tried to address

- Where can we do better? Is there room for improvement?

Heavy Neutral Leptons (HNLs)

2204.11988 (ATLAS)

2201.05578 (CMS)

Eur. Phys. J. C 81 (2021) 248 (LHCb)

Heavy Neutral Leptons

Existing LLP searches for HNL (N) target W → lN production:

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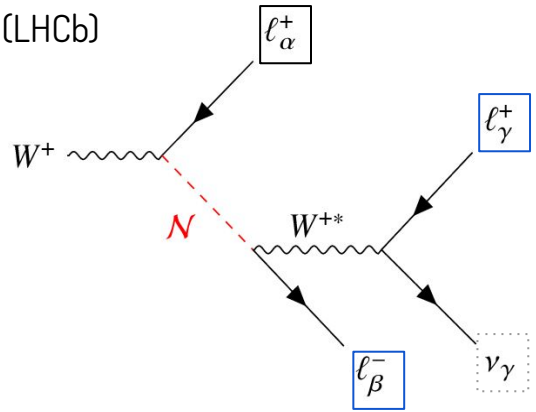
- 2201.05578 (CMS)
- Eur. Phys. J. C 81 (2021) 248 (LHCb)



N decaying in tracker

μ-$\mu\mu$, μ-μe, μ-ee, e-ee (ATLAS+CMS)

e-$\mu\mu$, e-μe (ATLAS-only)

μ-μqq (LHCb)

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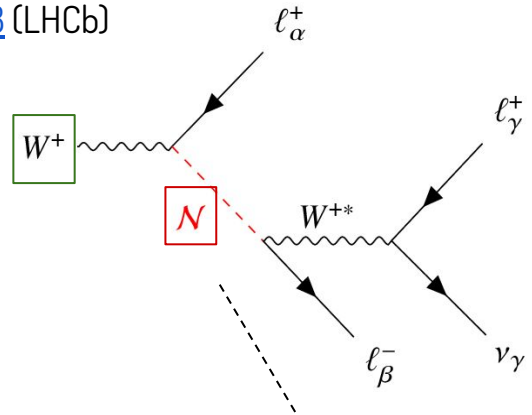


N decaying in tracker

μ-$\mu\mu$, μ-μe, μ-ee, e-ee (ATLAS+CMS)

e-$\mu\mu$, e-μe (ATLAS-only)

μ-μqq (LHCb)

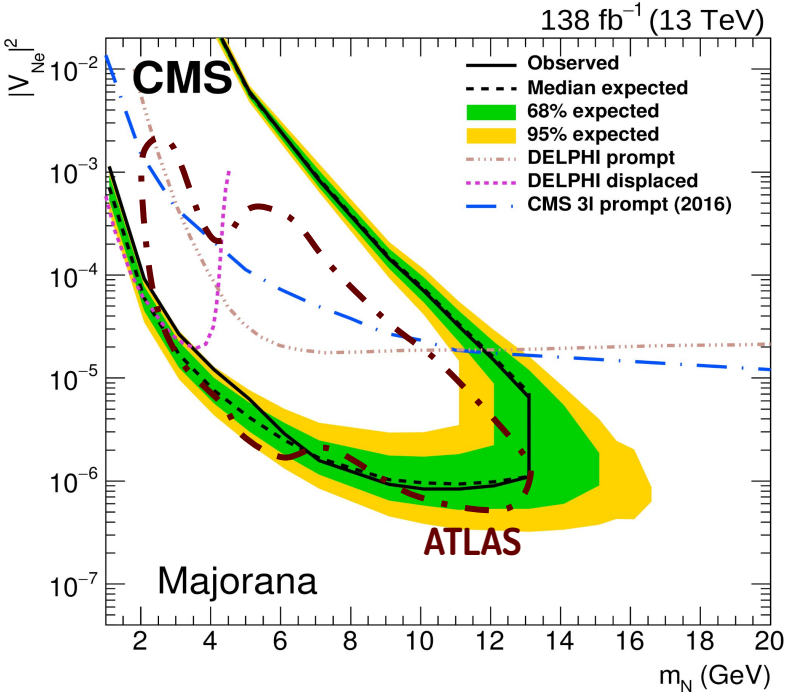
Expand to other production mechanism, e.g K^+, B decays, H (even BSM, e.g Z')

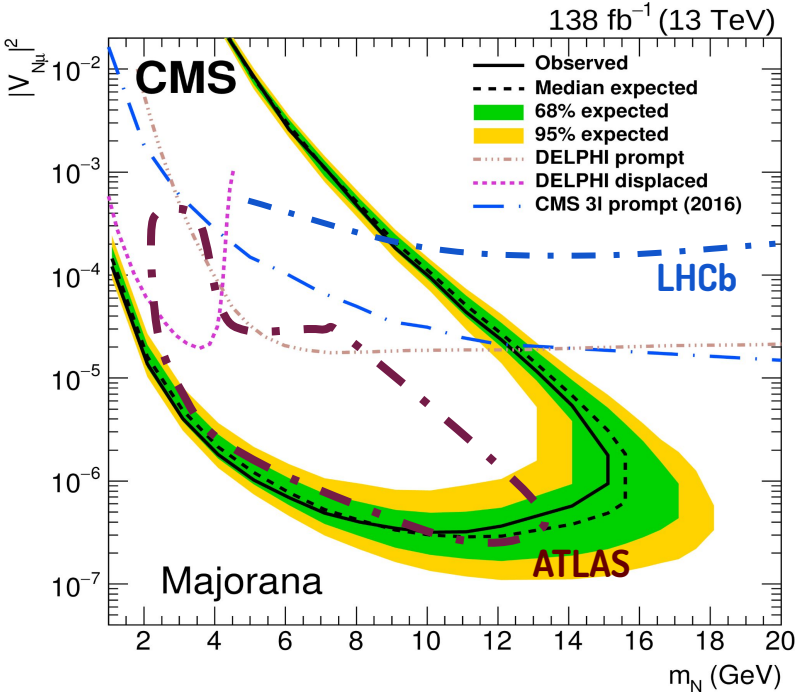
- No prompt leptons to trigger

Expand to other N decay modes (e.g lW*(qq), νZ*(qq), τ_{had}'s ...)

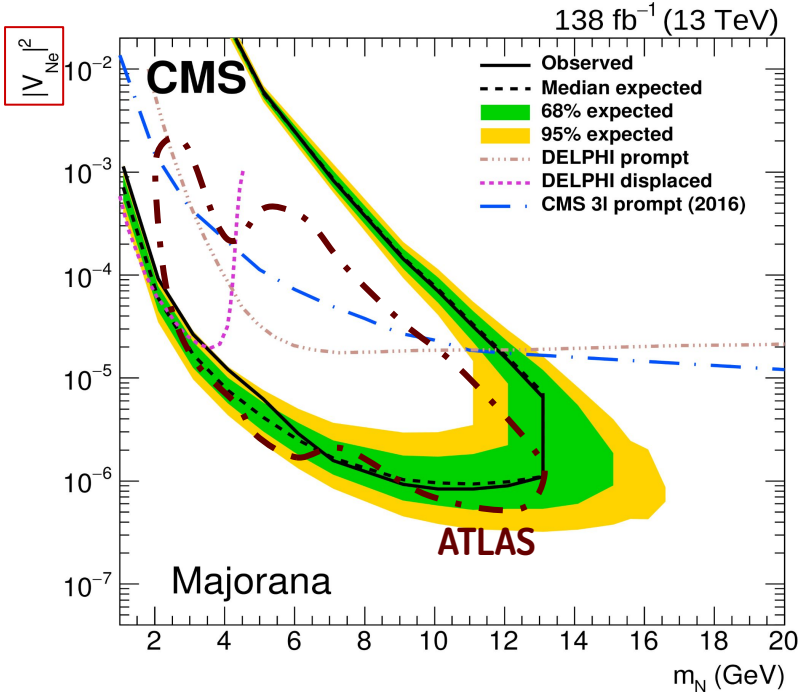
Heavy Neutral Leptons

Hand-drawn comparison between **ATLAS**, **CMS**, **LHCb**, and DELPHI results

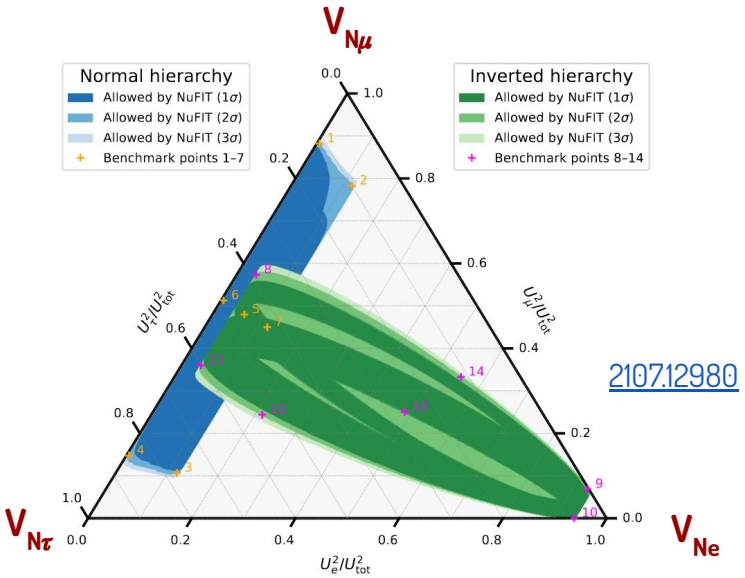




Heavy Neutral Leptons



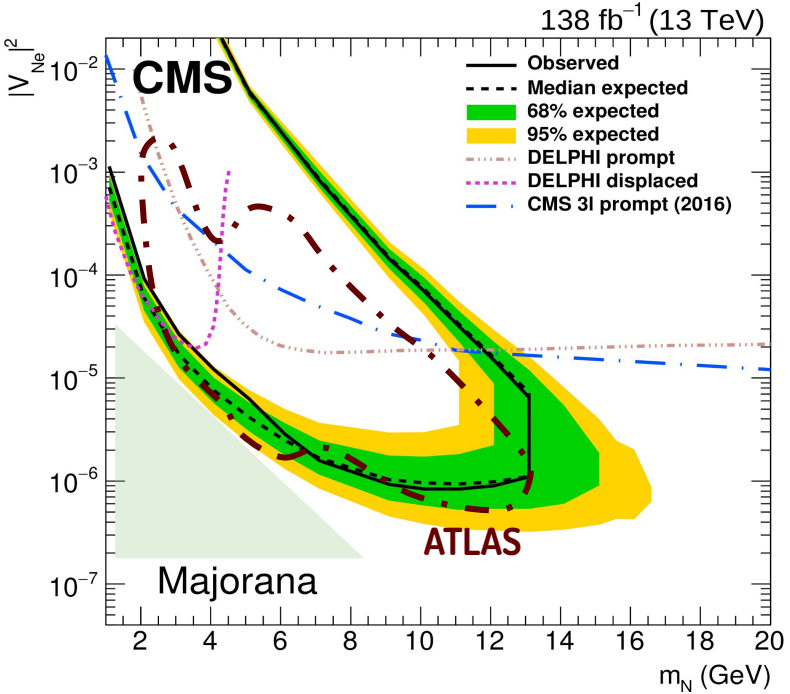
Possible extensions:



2107.12980

Scan the different combinations of mixing angles, and connect with realistic scenarios

Heavy Neutral Leptons



Possible extensions:

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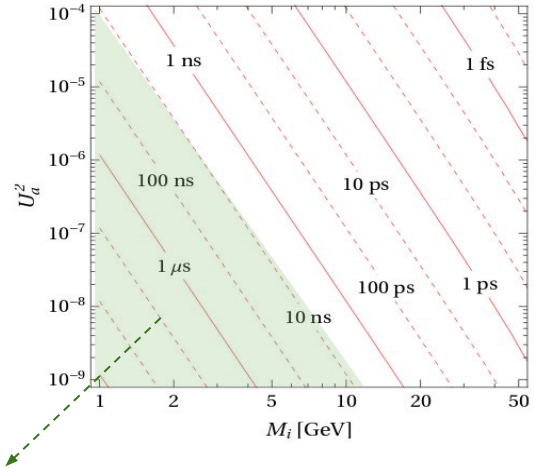
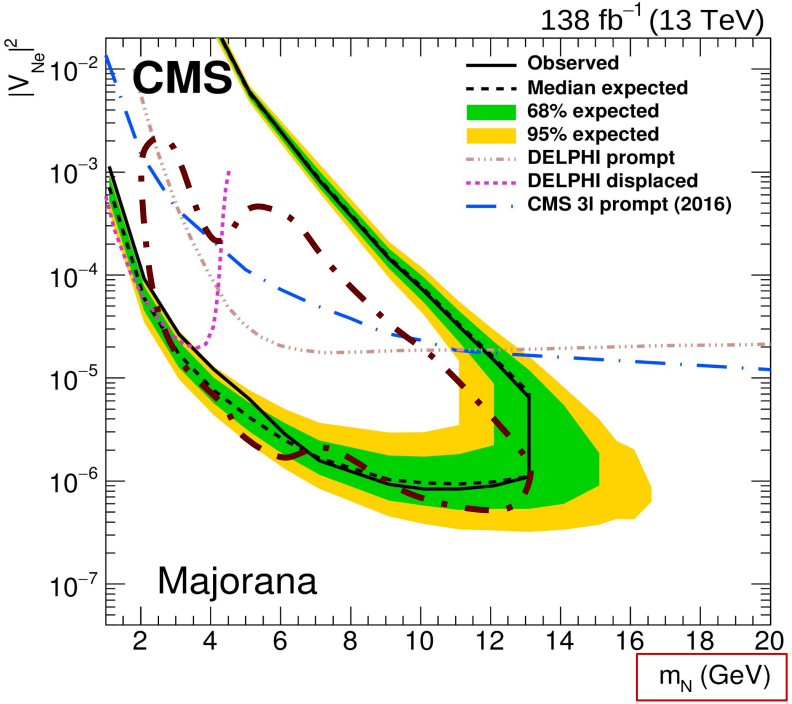


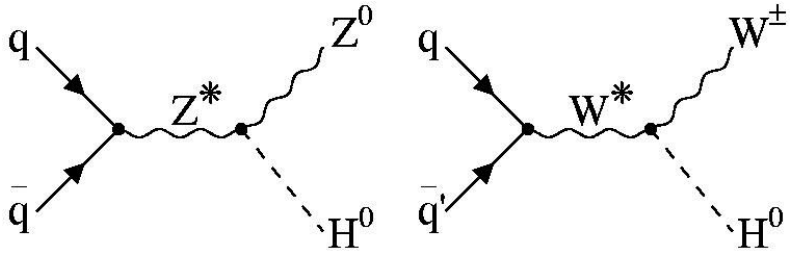
Small m_{HNL} and HNL decays beyond tracker

- Trigger directly on displaced decay products (e.g displaced leptons) for HNLs produced in B decays
- HNL decays beyond detectors

Heavy Neutral Leptons



Possible extensions:



HNLs searches could have sensitivity to other low mass LLP scenarios (e.g VH; H → XX production).

- So far no interpretation beyond HNL

H → XX: Hadronic final states

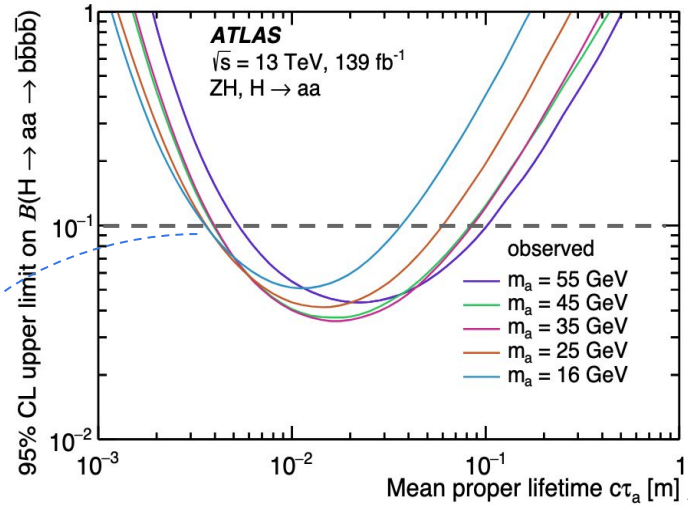
- Tracker
- Muon system
- HCAL

JHEP 11 (2021) 229 (ATLAS)
JHEP 03 (2022) 160 (CMS)
Phys. Rev. D 104, 012015 (2021) (CMS)
Eur. Phys. J. C77 (2017) 812 (LHCb)

2203.00587 (ATLAS)
Phys. Rev. Lett. 127.261804 (CMS)
2203.01009 (ATLAS)
ATLAS-CONF-2022-001 (ATLAS)

H → XX (hadronic): Tracker

At the shortest lifetimes (decays in tracker), associated production (VH) is a powerful handle to probe low mass, X → qq



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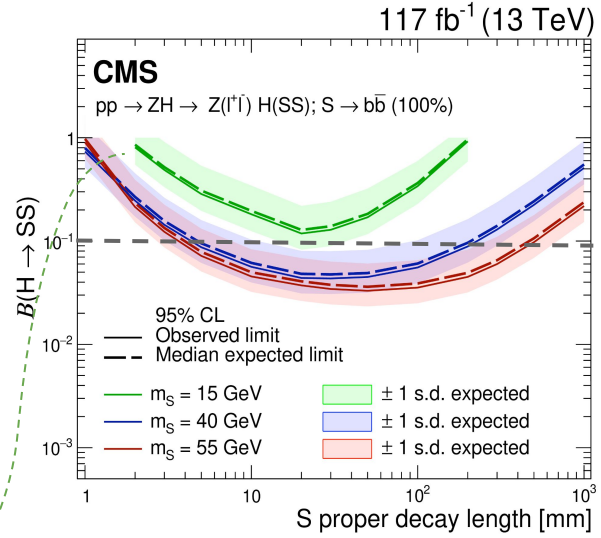

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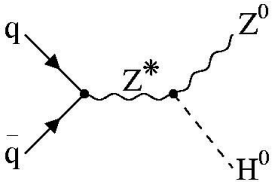
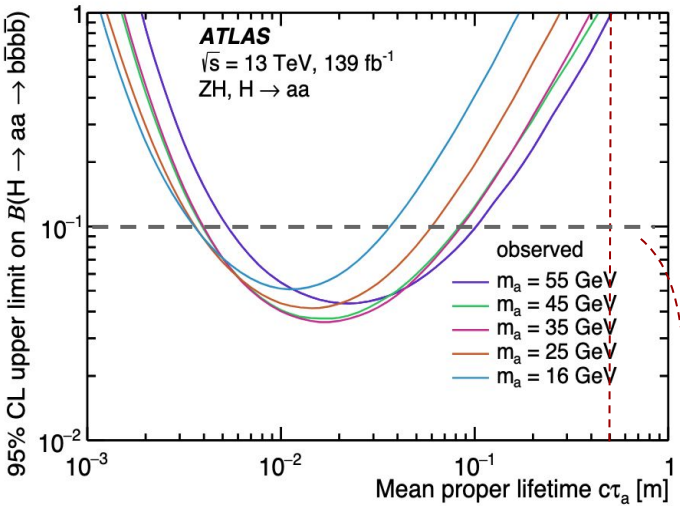


ATLAS better at low masses (m_S ~ 15/16 GeV)

H → XX (hadronic): Tracker

At the shortest lifetimes (decays in tracker), associated production (VH) is a powerful handle to probe low mass, X → qq



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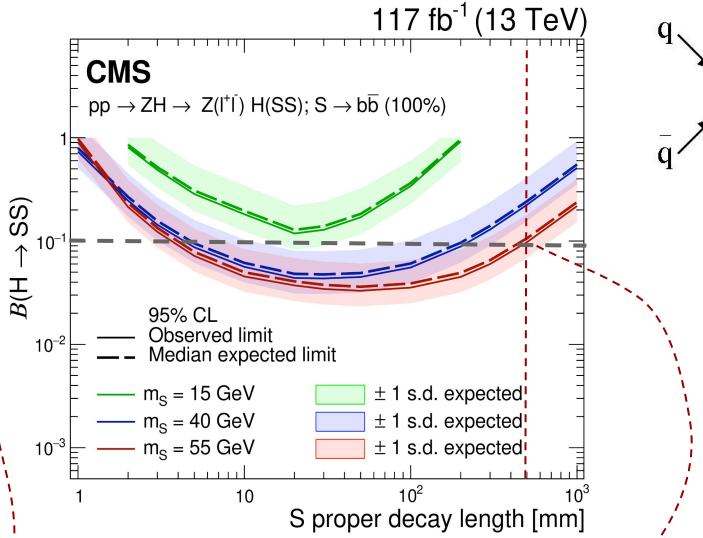

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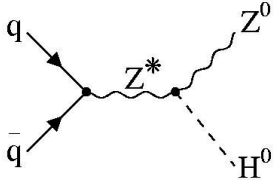
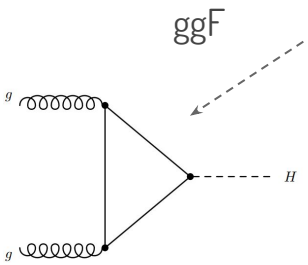
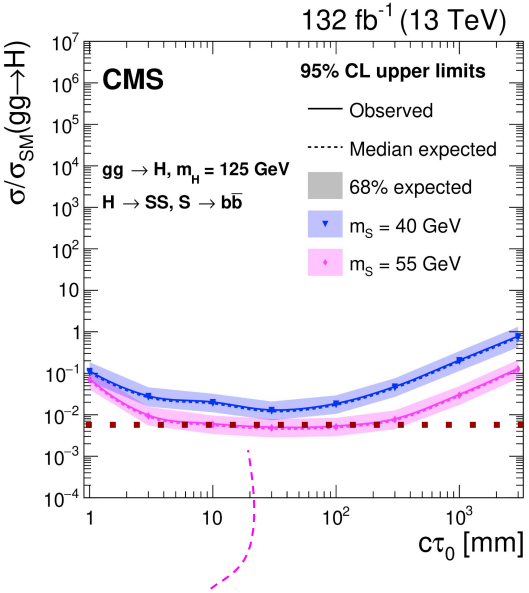


CMS better at higher lifetimes (m_S = 55 GeV)

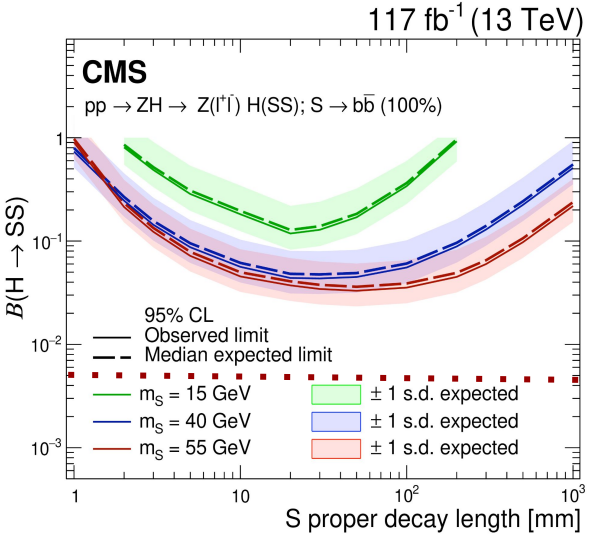
H → XX (hadronic): Tracker

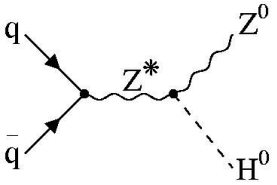
Phys. Rev. D 104, 012015 (2021) (CMS)





JHEP 03 (2022) 160 (CMS)



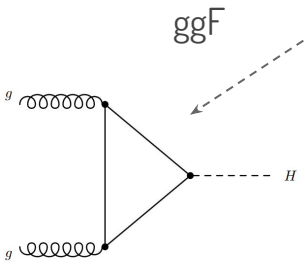


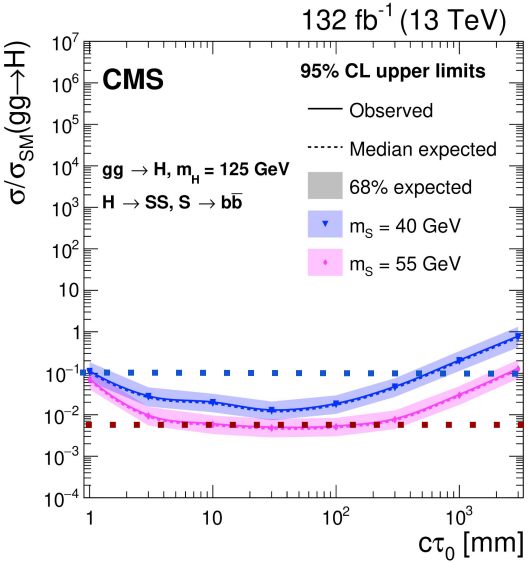
At high masses (m_S~55 GeV), CMS search in ggF is more powerful (no equivalent ggF interpretation from ATLAS)

- ZH could expand to lower masses (m_S < 15 GeV), and new final states (e.g $\tau_{had}\tau_{had}$)
- So far no associated searches beyond Z→ll (e.g W, VBF, tt...)

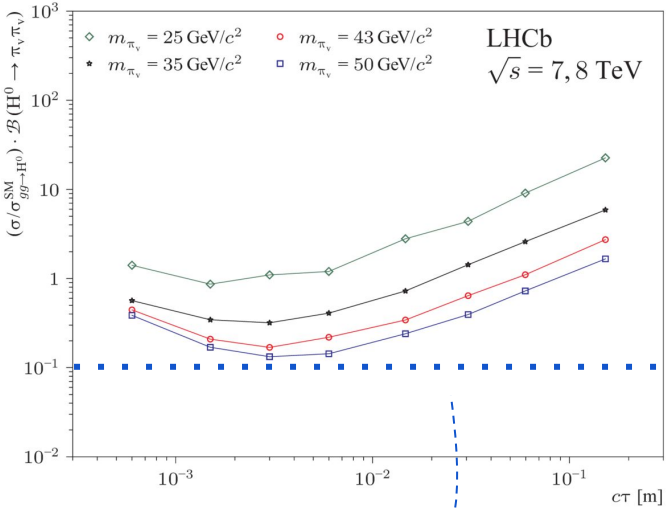
H → XX (hadronic): Tracker

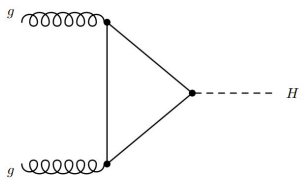
Phys. Rev. D 104, 012015 (2021) (CMS)





Eur. Phys. J. C77 (2017) 812 (LHCb, from **2017**)



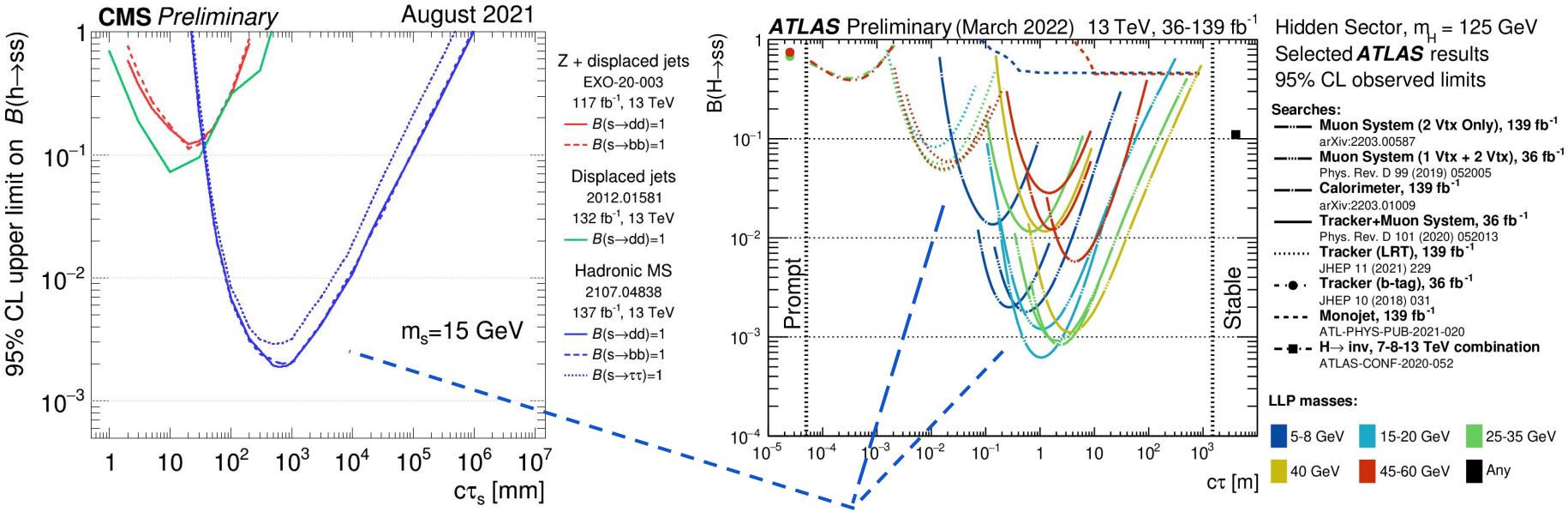


At high masses (m_S~55 GeV), CMS search in ggF is more powerful than LHCb search (ggF)

- Room for improvement at low masses in LHCb (e.g. at m = 25 GeV, B(H→XX) > 1)

H → XX (hadronic): Tracker vs Muon system

SummaryPlotsEX013TeV ATL-PHYS-PUB-2022-007



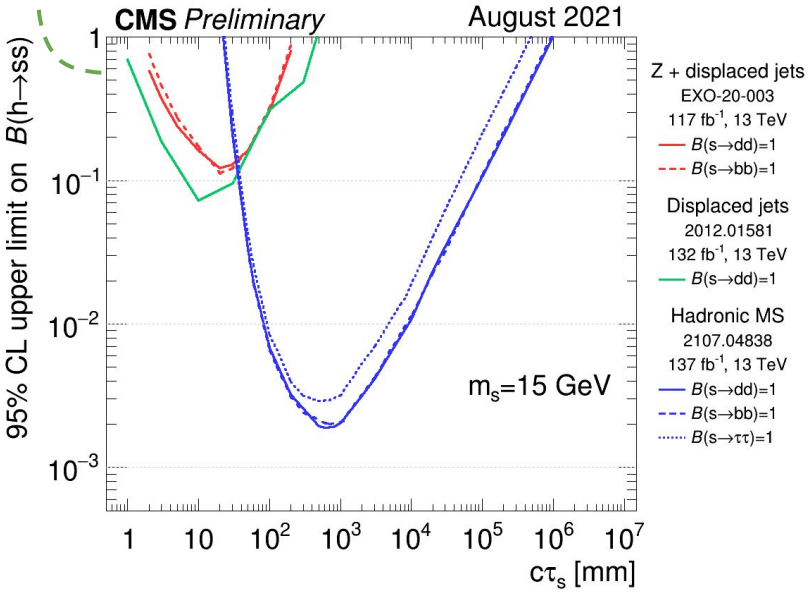
At higher lifetimes, ggF searches in the HCAL/Muon systems (MS) expand the cτ coverage (including low mass)

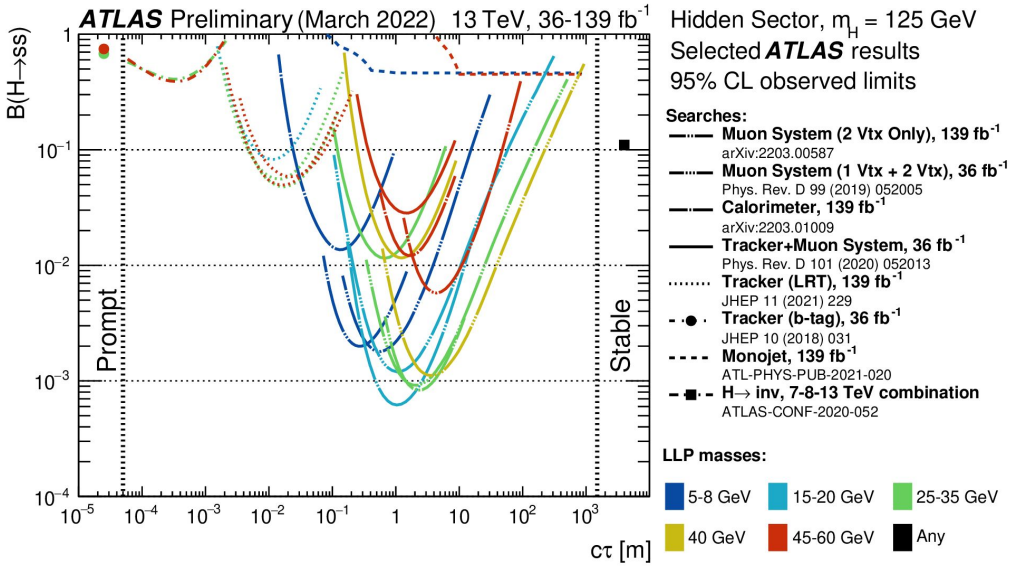
H → XX (hadronic): Tracker vs Muon system

SummaryPlotsEX013TeV ATL-PHYS-PUB-2022-007

Room for improvement in low mass LLP searches with tracker lifetimes using dedicated triggers/ML

- Final states with $\tau_{had}\tau_{ha}$, and compressed/boosted less explored (challenging)





H → XX (hadronic): Muon system

Different strategies between ATLAS and CMS for searches in the MS

ATLAS search for displaced **vertices** in the muon system

2203.00587

- Dedicated trigger in MS for this signature
- Two vertices isolated from hadronic and inner detector activity

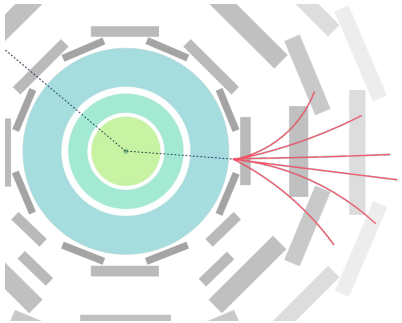
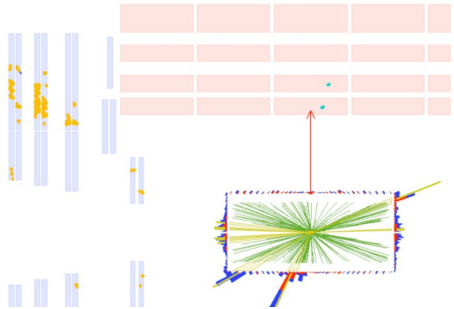


figure credit

CMS search for **hadronic showers** in muon system

Phys. Rev. Lett. 127.261804

- E_T^{miss} trigger (calorimeter)
- Larger hit multiplicity in Cathode Strip Chamber (CSC)



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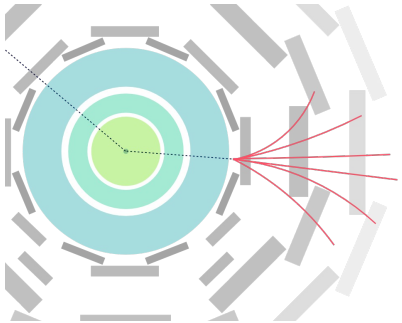
Expand to E_T^{miss} trigger



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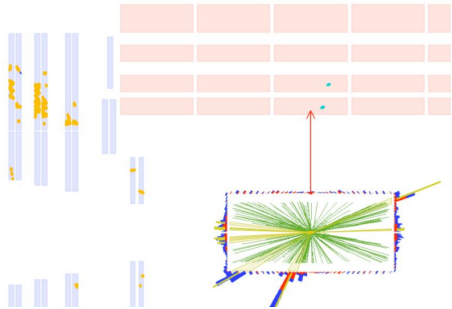
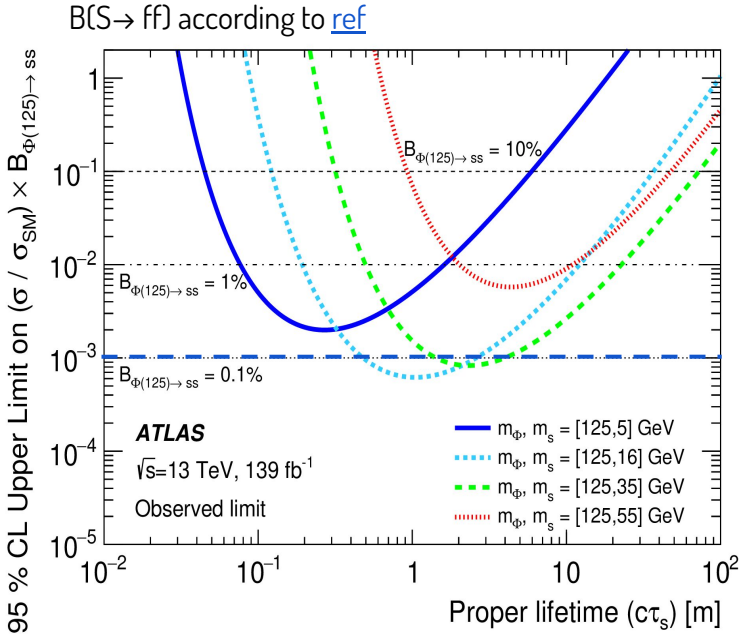
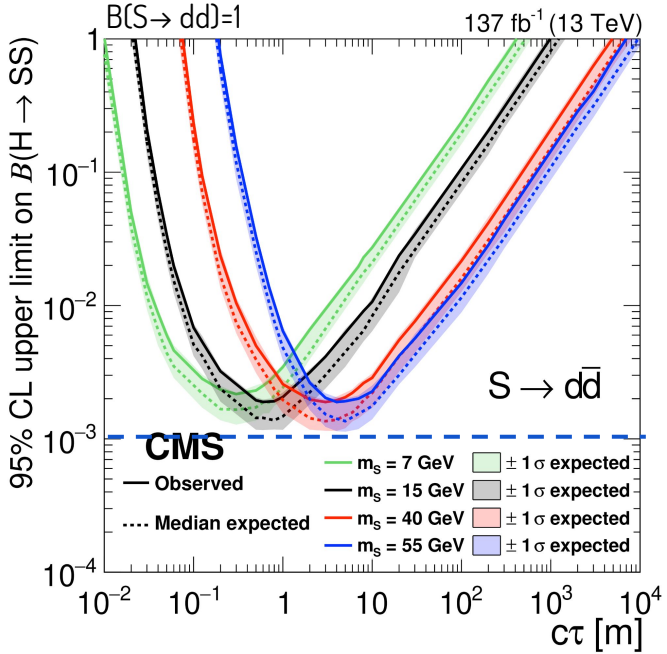


Expand to dedicated trigger in MS

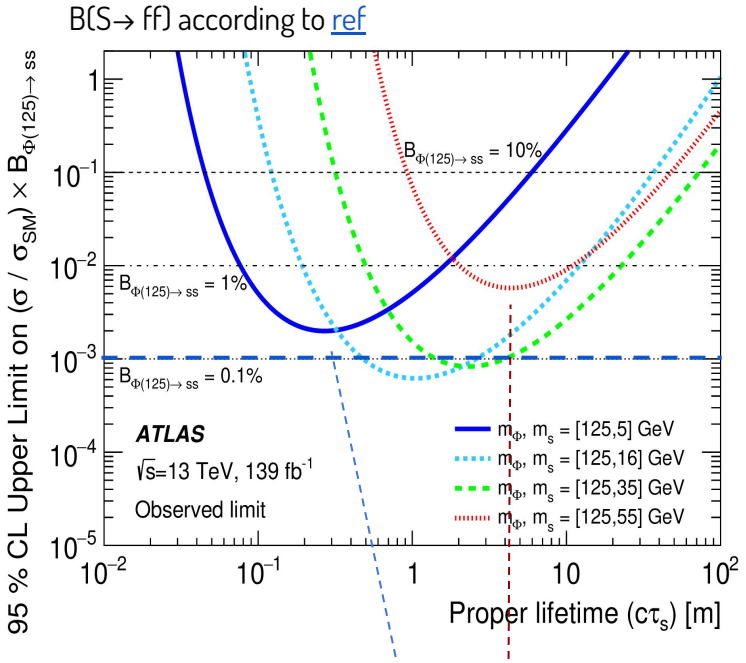
H → XX (hadronic): Muon detectors

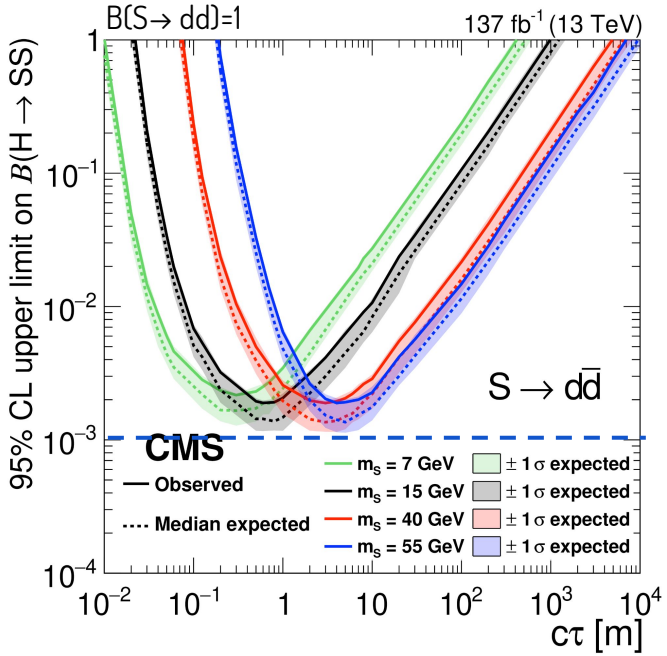
Different strategies between ATLAS and CMS for searches in the MS (with comparable sensitivity)





H → XX (hadronic): Muon detectors





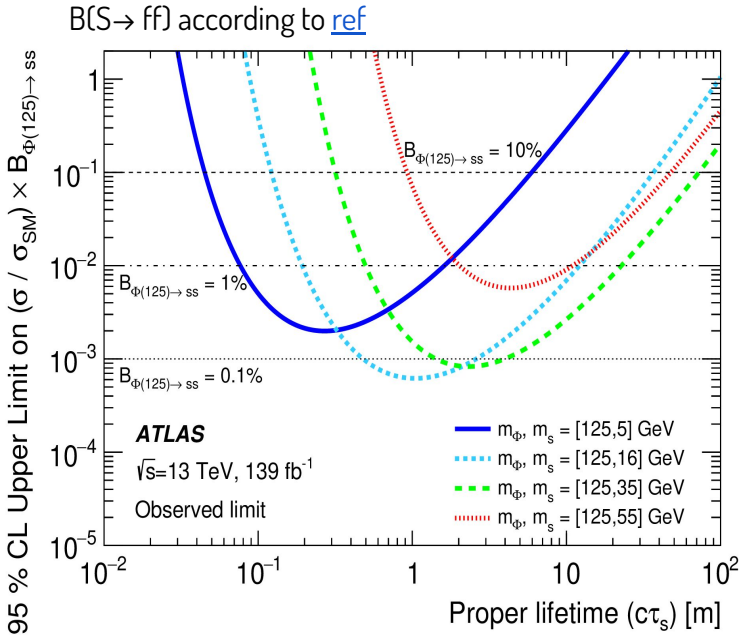
Degradation in sensitivity for low/compressed masses, no $\tau_{had}\tau_{had}$ interpretation

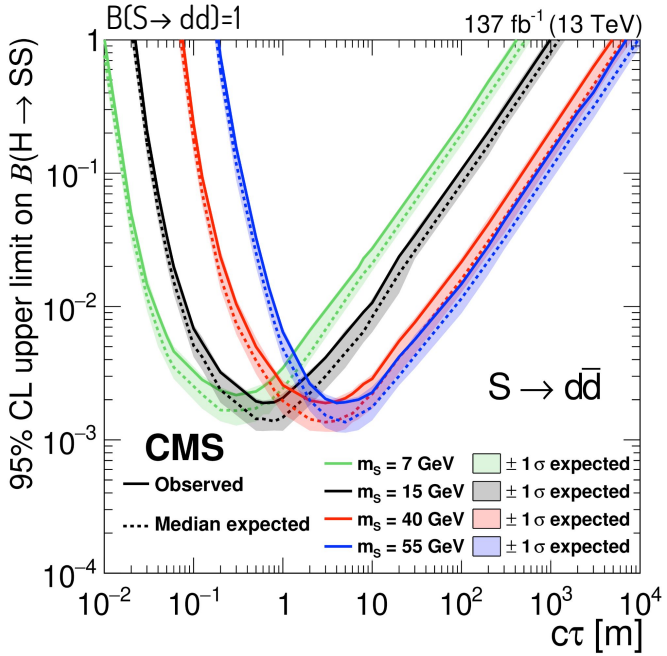
Acceptance could increase with SR with 1 vtx

No BSM Higgs interpretation

Acceptance could increase with decays in barrel or HCAL

H → XX (hadronic): Muon detectors



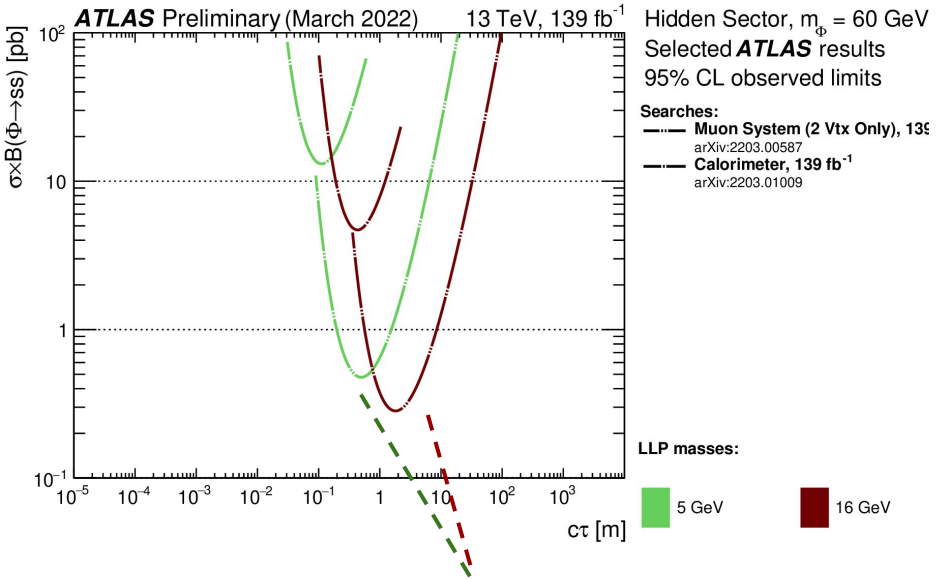


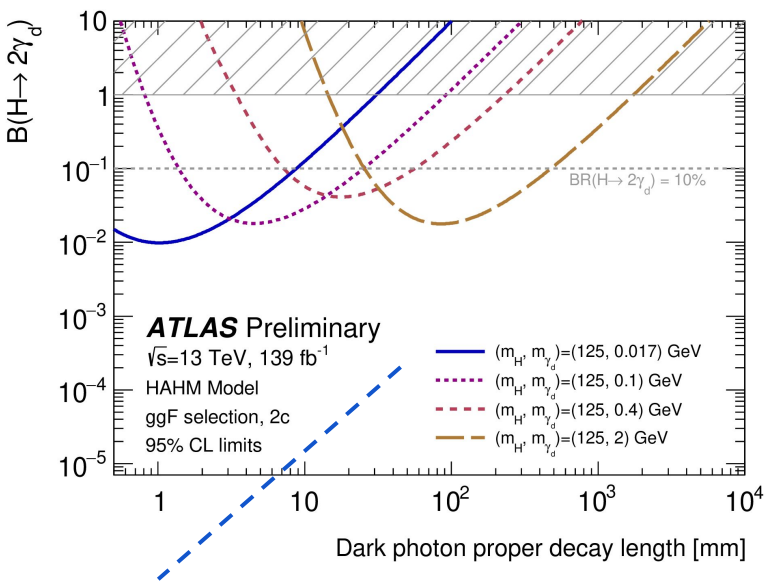
- Complementarity with H→invisible (at high $c\tau$)
- Signal regions with prompt objects (e.g target very long-lived HNLs)
- Searches could be sensitive to other LLPs scenarios: dark shower/emerging jets, Split/RPV SUSY ...

H → XX (hadronic): Hadronic Calorimeter (HCAL)

ATLAS also search for LLPs decays in HCAL with dedicated CalRatio trigger

2203.01009 (ATLAS)
ATLAS-CONF-2022-001 (ATLAS)





Difficult to compete with searches in MS

- Important channel in case of excess (no CMS equivalent)

Powerful strategy to search for collimated electrons/light hadrons (at extremely low masses)

H → XX, Non-Hadronic final states:

- Displaced dilepton vertex
- Low mass (m < 10 GeV)
- Delayed, non-pointing photons in ECAL

Phys. Rev. D 99, 012001 (2019) (ATLAS)

2205.08582 (CMS)

JHEP 04 (2022) 062 (CMS)

ATLAS-CONF-2022-001 (ATLAS)

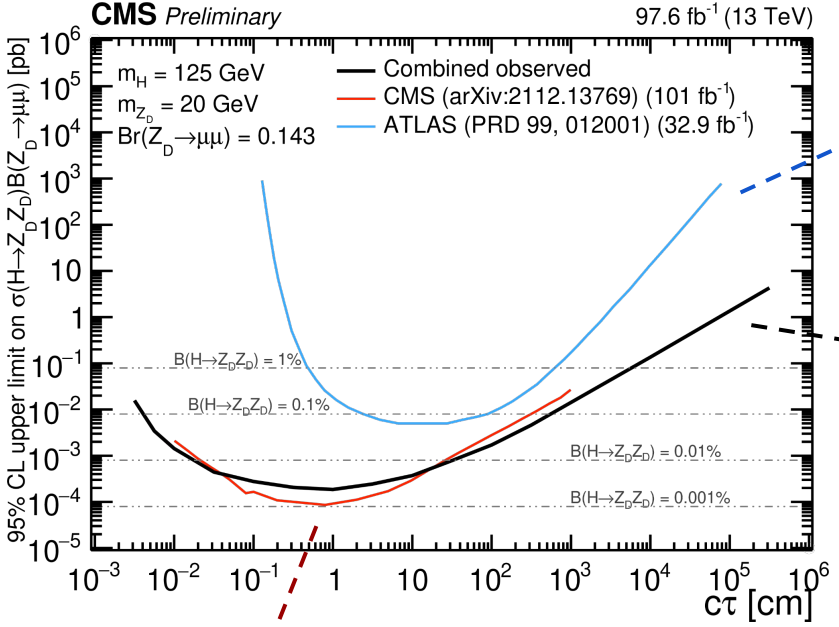
JHEP 10 (2020) 156 (LHCb)

EXOT-2022-017 (ATLAS)

Phys. Rev. D 100 (2019) 112003 (CMS)

H → XX (non-hadronic): Displaced dilepton vertex

Generic signature well motivated in many BSM scenarios (e.g H → XX, X → ll).



$\mu\mu$ in Tracker (101 fb^{-1}, CMS Scouting data) JHEP 04 (2022) 062 (CMS)

Strong constraints for $c\tau$ ~ tracker

- Limited to dimuon vertices within pixel tracker

$\mu\mu$ in Muon System (32.9 fb^{-1})

Search sensitive to $c\tau \gtrsim 0.1$ cm

- Limited to small $\Delta R_{\mu\mu}$ (due to trigger)

Phys. Rev. D 99, 012001 (2019) (ATLAS)

$\mu\mu$ Tracker+Muon System (97 fb^{-1})

Wide range of $c\tau$ from μm to km

- Limited by trigger efficiency

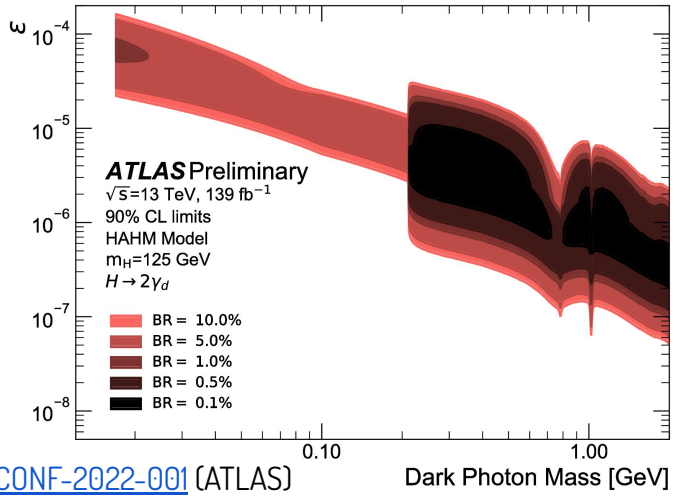
2205.08582 (CMS)

No analogous result (common vertex) for X → ll (l=e or τ_{had}) at 13 TeV

In all cases, room for improvement with improved lepton triggers

H → XX (non-hadronic): Low mass (m < 10 GeV)

Collimated fermions (μ, e or q in MS or HCAL)

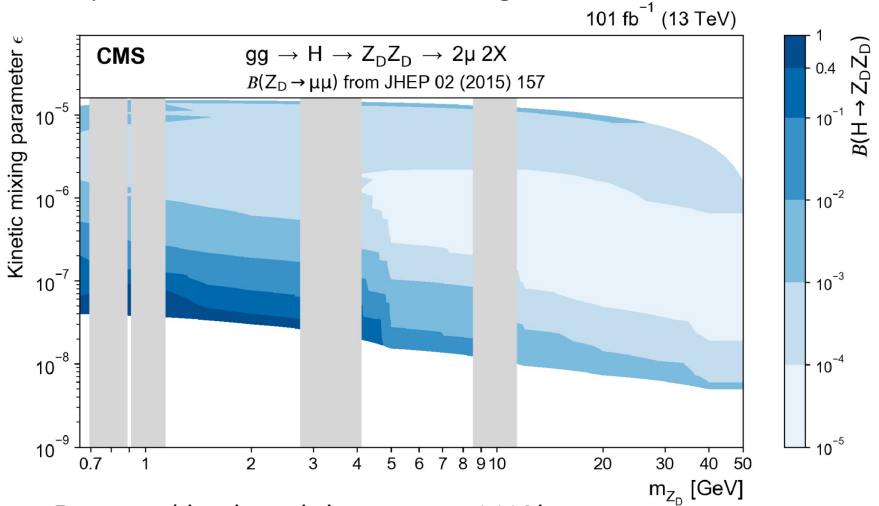


ATLAS-CONF-2022-001 (ATLAS)

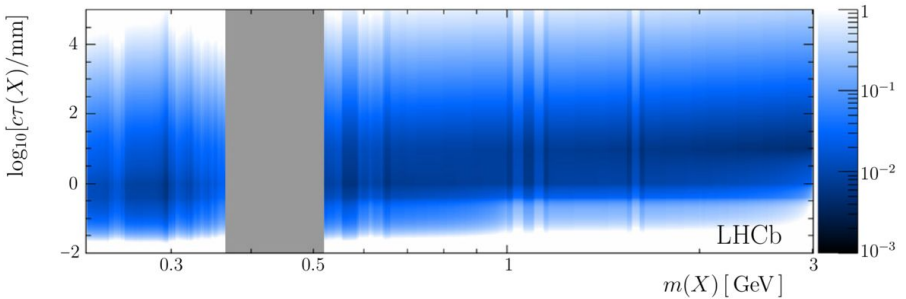
Small overlap in mass coverage.

- m < 210 MeV only probed by ATLAS
  - Promising prospects for A' → ee at LHCb
- ATLAS targets the smallest ϵ (HAHM model)
  - Different prod. mode for LHCb

Displaced dimuons with Scouting JHEP 04 (2022) 062 (CMS)



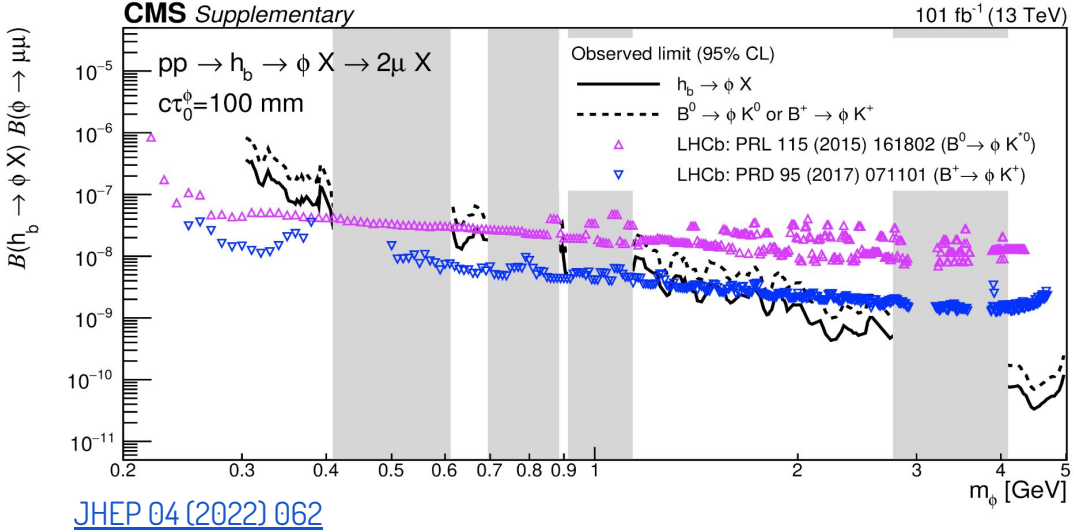
Prompt/displaced dimuons in LHCb JHEP 10 (2020) 156 (LHCb)



H → XX (non-hadronic): Low mass (m < 10 GeV)

An interesting (and challenging) scenario is the production of displaced vertices in heavy flavor decays

- Probed in CMS and LHCb with dimuons, no ATLAS equivalent.



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Additional interpretations would facilitate the comparison between experiments

- e.g. H → XX for LHCb, A' → ff for ATLAS/CMS (no Higgs mediator), heavy flavor decays for ATLAS...

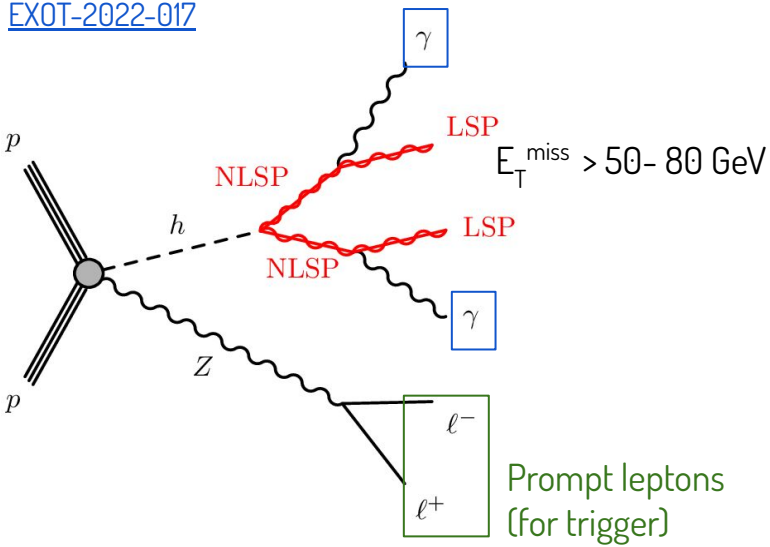
Low mass searches could be made sensitive to HNLs (sensitivity is unknown)

H → XX (non-hadronic): Delayed/non-pointing photons in ECAL

Different strategies between ATLAS and CMS in searches for LLPs in ECAL

ATLAS targets GMSB SUSY via H → NLSP NLSP

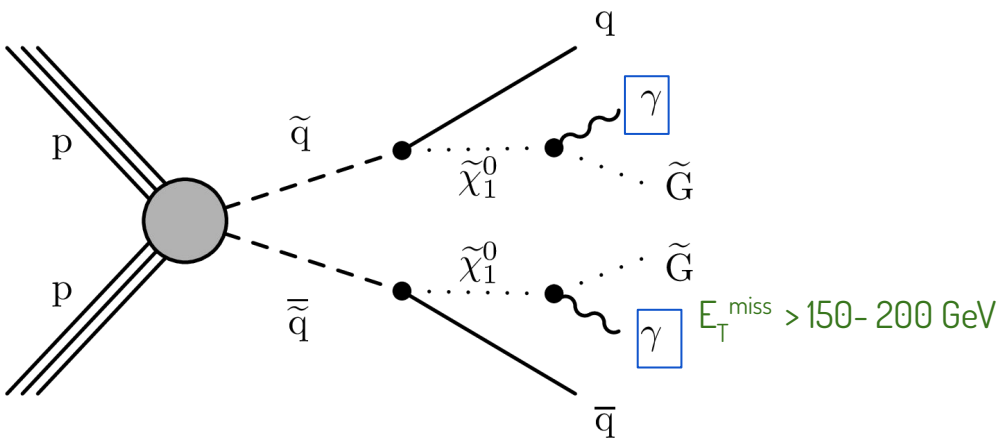
EXOT-2022-017



Trigger: single lepton trigger (e, μ)

CMS targets GMSB SUSY via SPS8

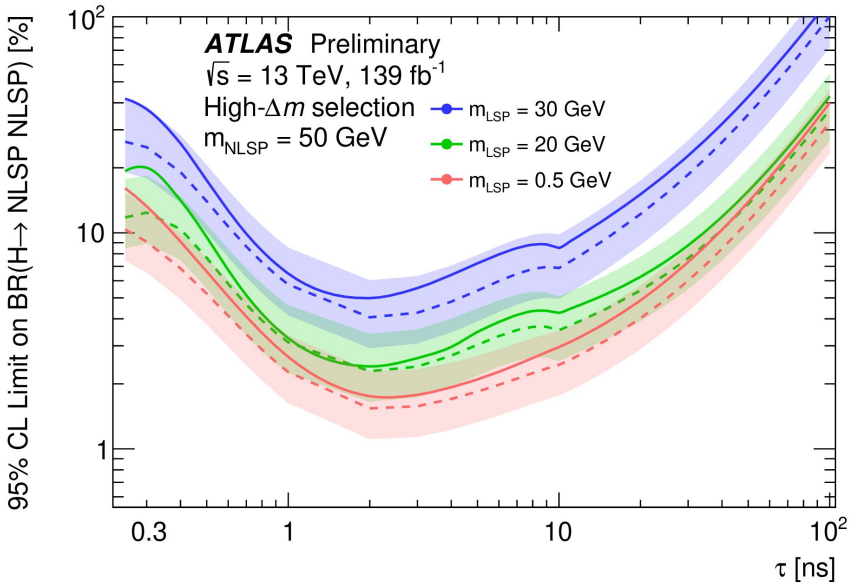
Phys. Rev. D 100 (2019) 112003

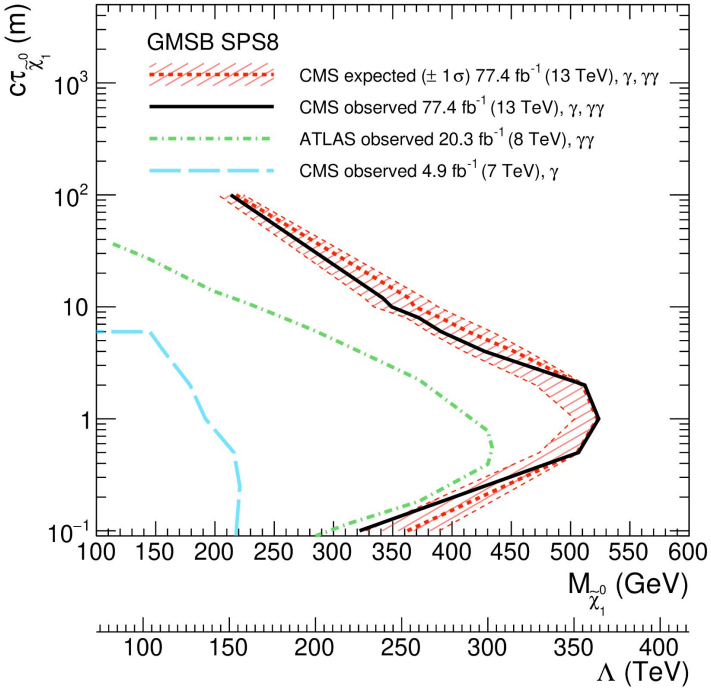


Trigger: non-pointing photon (with H_T > 350 GeV)

H → XX (non-hadronic): Delayed/non-pointing photons in ECAL

Different strategies between ATLAS and CMS in searches for LLPs in ECAL



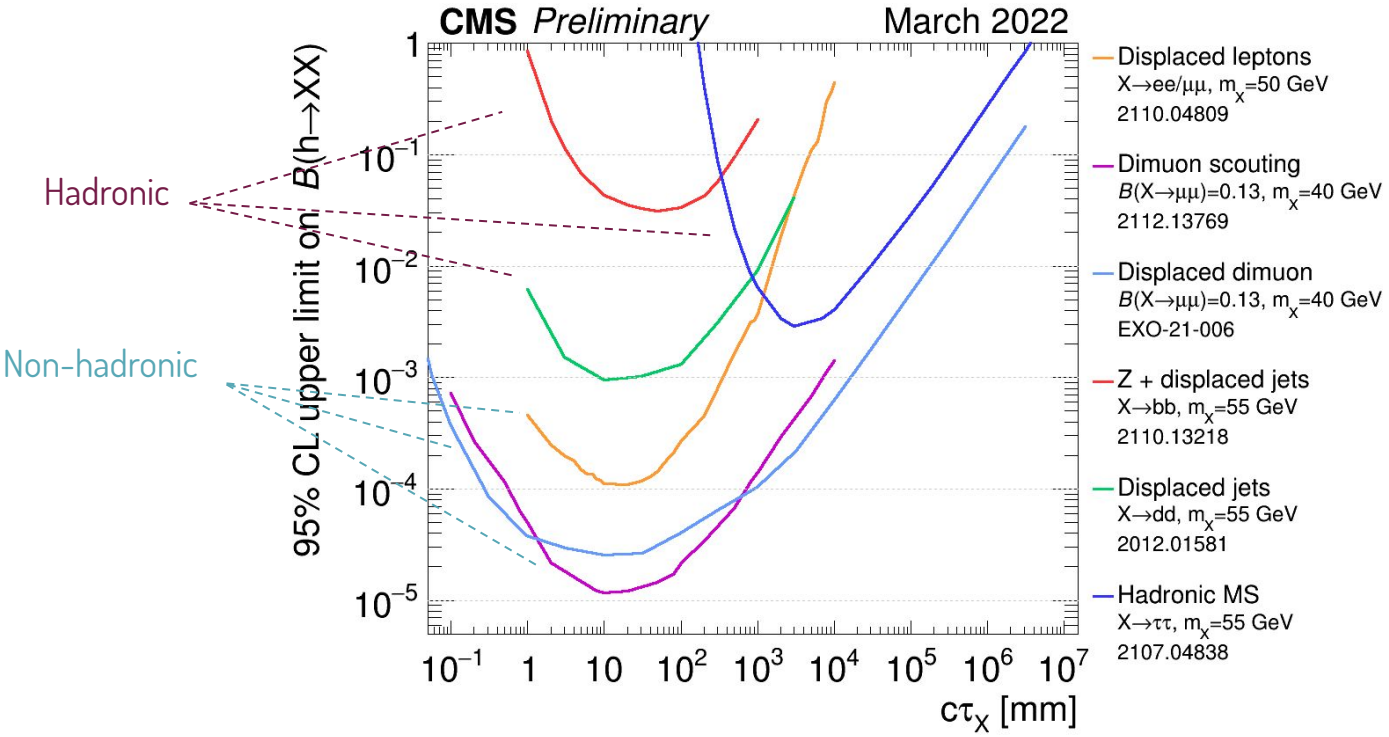


... and comparison is not easy due to different production mechanism

H → XX Hadronic vs Non-hadronic

SummaryPlotsEX013TeV

If B(X → qq) ~ B(X → ll), non-hadronic searches set stronger constraints than hadronic searches (depending on B(X)).



But B(X → qq) >> B(X → ll) often in BSM models → **complementarity and coverage is the key**

SUSY and charged LLPs

- Indirect detection:
  - Semileptonic decays
  - Displaced leptons (without common vertex)
- Direct detection
  - dE/dX
  - Complementarity

Phys. Rev. D 102, 032006 (2020) (ATLAS)

Phys. Rev. D 104, 012015 (2021) (CMS)

Eur. Phys. J. C 82 (2022) 153 (CMS)

2110.07293 (LHCb)

Phys. Rev. Lett. 127, 051802 (2021) (ATLAS)

2205.06013 (ATLAS)

ATLAS-CONF-2022-034 (ATLAS)

Phys. Lett. B 806 (2020) 135502 (CMS)

2201.02472 (ATLAS)

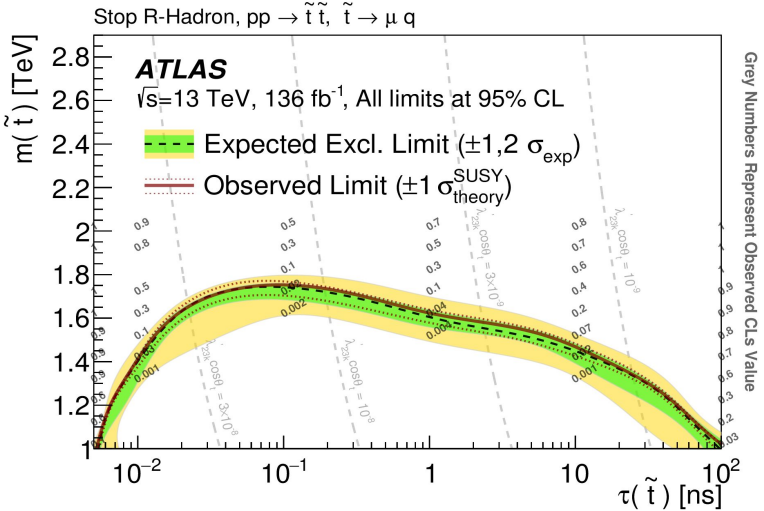
JHEP 07 (2021) 173 (ATLAS)

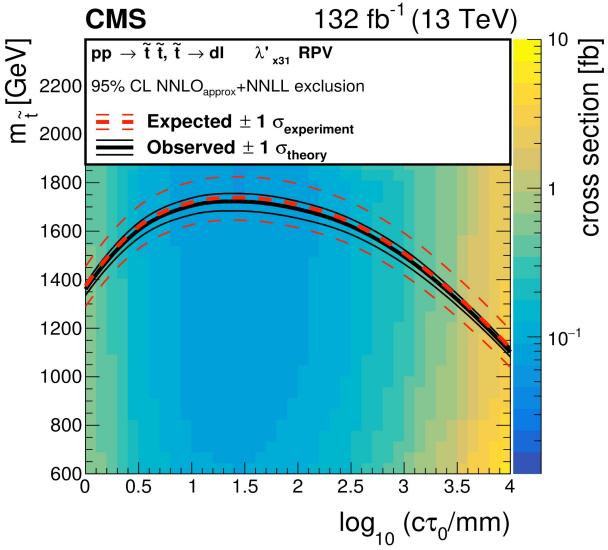
CMS-PAS-EXO-16-036 (CMS)

SUSY: Semileptonic decays, X → lqq

Well motivated signature, e.g. in RPV-SUSY $\tilde{t} \rightarrow lq$

- **ATLAS** search for RPV stop in semileptonic decays (Phys. Rev. D 102, 032006 (2020))
- **CMS** search for RPV stop in displaced jets (Phys. Rev. D 104, 012015 (2021)), and leptons (Eur. Phys. J. C 82 (2022) 153)





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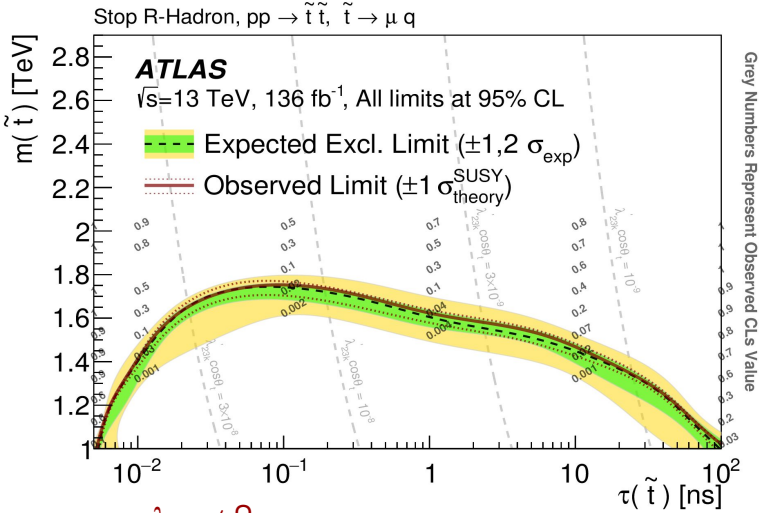
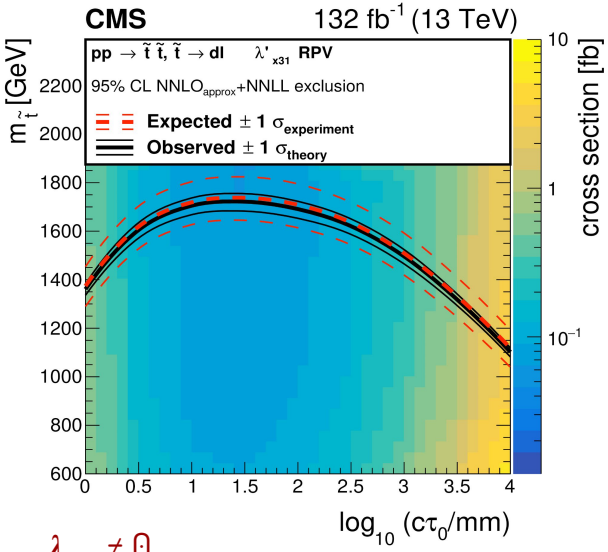


$\lambda_{23X} \neq 0$

B(stop → μq) = 100%



$\lambda_{X3X} \neq 0$

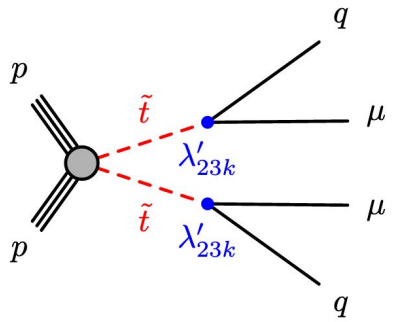
B(stop → lq) with l=e, μ, τ (flavor democratic)

Unfortunately, out of the box direct comparison is not possible (CMS approach is more inclusive)

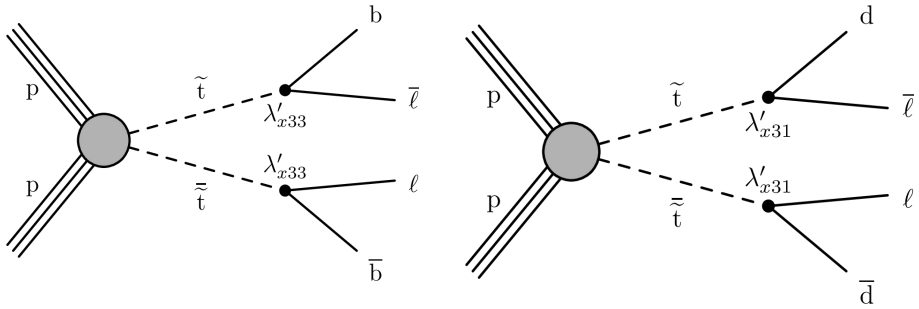
RPV SUSY: Interpretations

In general, different benchmark RPV SUSY interpretations in related LLP searches (e.g semileptonic decays)

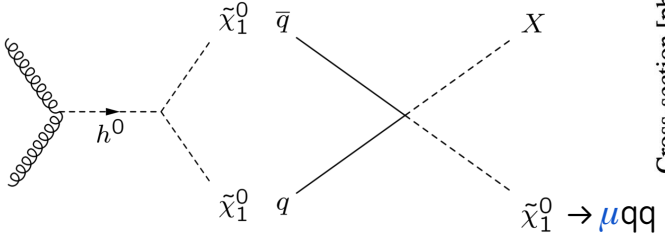
Phys. Rev. D 102, 032006 (2020) (ATLAS)

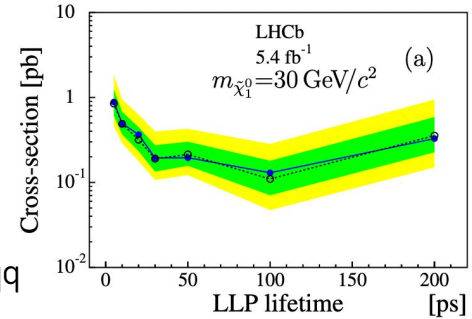


Phys. Rev. D 104, 012015 (2021) and Eur. Phys. J. C 82 (2022) 153 (CMS)



and 2110.07293 (LHCb)





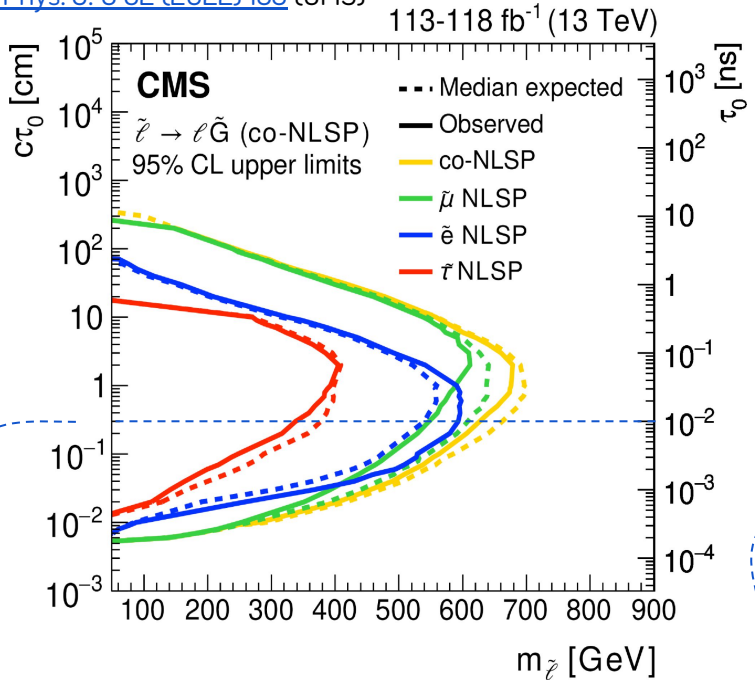
Need for a more systematic approach to the RPV SUSY coverage to facilitate comparisons between experiments (e.g by defining benchmark scenarios)

- E.g "RPV meets RPC", ATLAS-CONF-2018-003

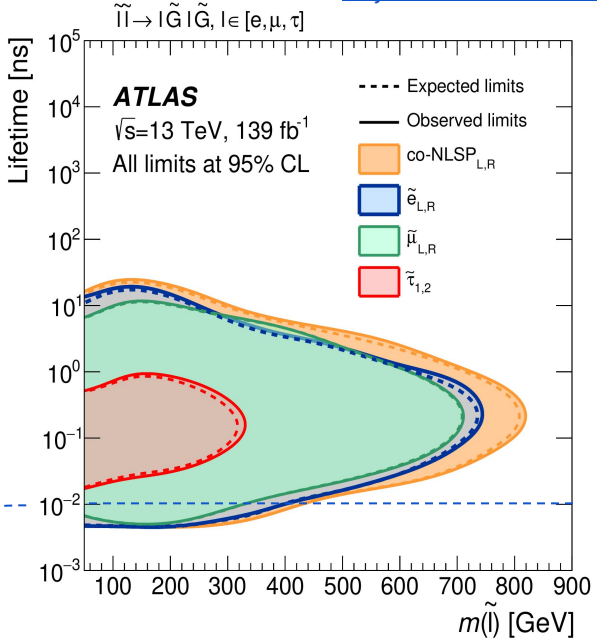
SUSY: Displaced leptons (without common vertex)

Inclusive signature sensitive to a broad class of BSM scenarios, e.g. GMSB SUSY $\tilde{l} \rightarrow l + \tilde{G}$

Eur. Phys. J. C 82 (2022) 153 (CMS)



Phys. Rev. Lett. 127, 051802 (2021) (ATLAS)



CMS is stronger at shorter lifetimes (0.1 < d0 < 100 mm)

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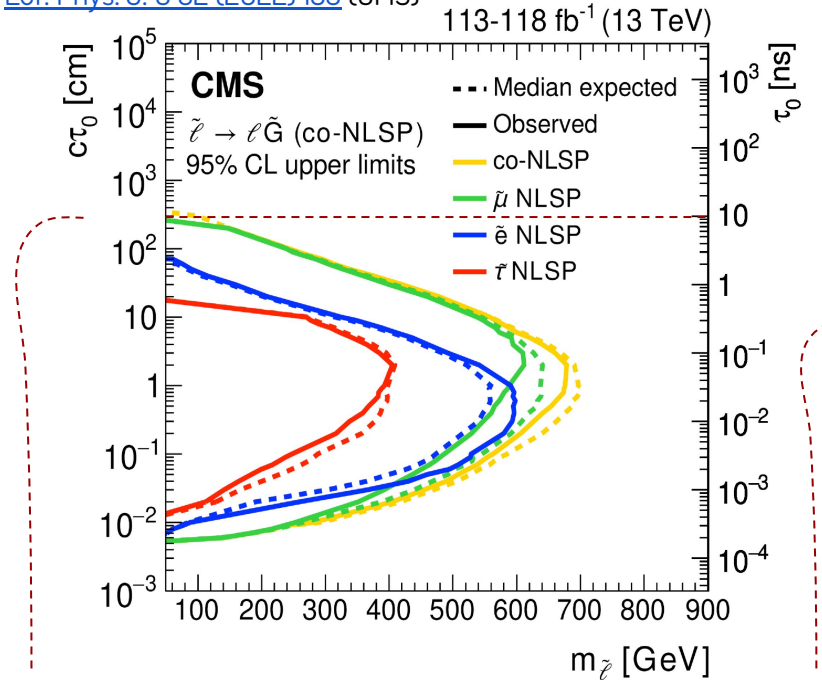
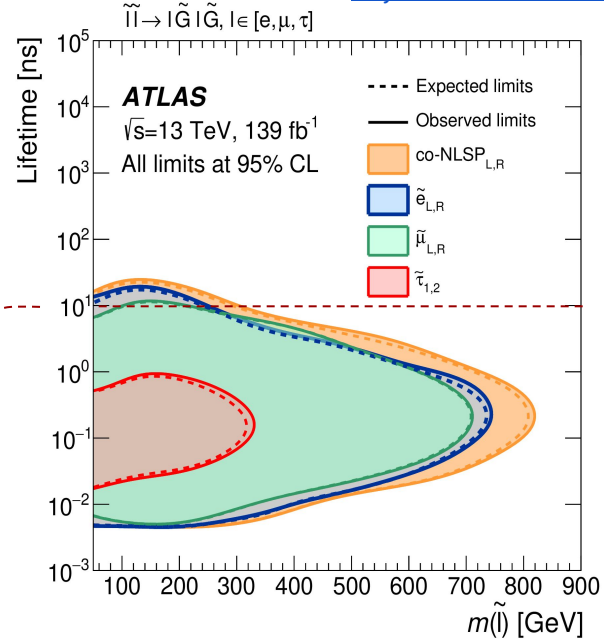
Eur. Phys. J. C 82 (2022) 153 (CMS)



Phys. Rev. Lett. 127, 051802 (2021) (ATLAS)



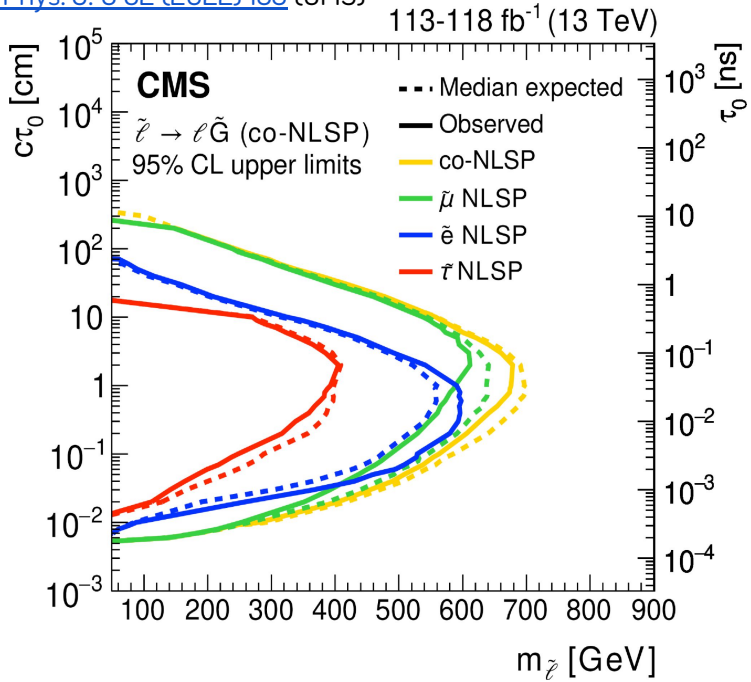
ATLAS at higher lifetimes (3 < d0 < 300 mm), esp. with electrons.

- Possibility to extend to leptons produced beyond tracker (or non-isolated displaced leptons)

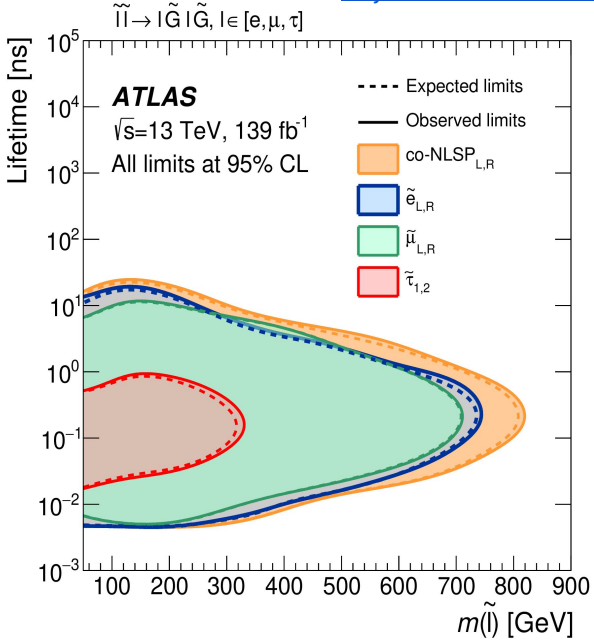
SUSY: Displaced leptons (without common vertex)

Inclusive signature sensitive to a broad class of BSM scenarios, e.g. GMSB SUSY $\tilde{l} \rightarrow l + \tilde{G}$

Eur. Phys. J. C 82 (2022) 153 (CMS)



Phys. Rev. Lett. 127, 051802 (2021) (ATLAS)



Lepton (e, μ) p_T requirements (> 30 - 60 GeV) too tight to probe low mass LLPs

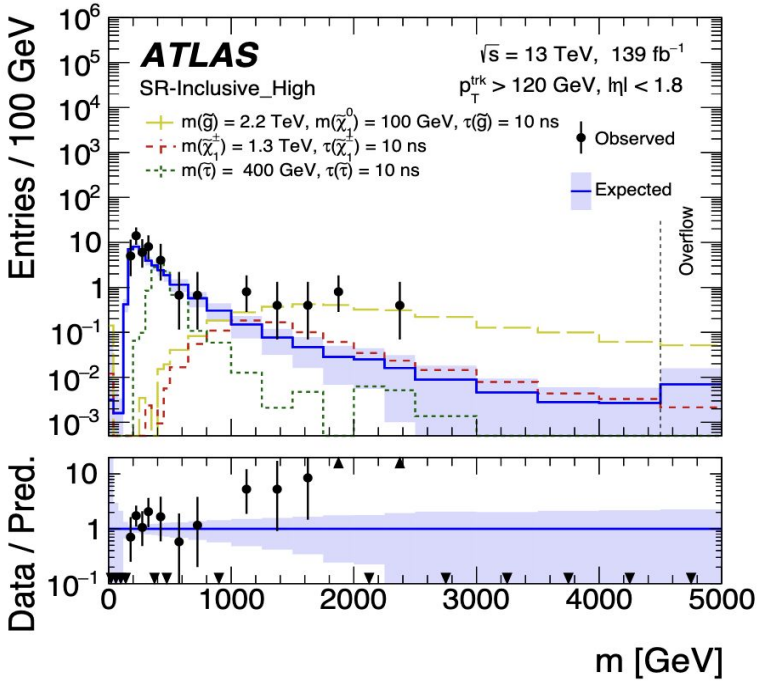
- Possibility to lower the p_T thresholds to with improved triggers
- So far no final states with displaced τ_{had} (important to probe staus)

Direct detection: Charged LLPs, dE/dX

16:45 → 19:05 **New LLP search results at the LHC: That dE/dx excess ;)**

Conveners: Karri Folan Di Petrillo (Fermi National Accelerator Lab. (US)), Margaret Susan Lutz (Tel Aviv University (IL))

Hot-topic, triggered by search for anomalously high dE/dX in pixel tracker 2205.06013 (ATLAS)



Excess of events at high <dE/dX>.

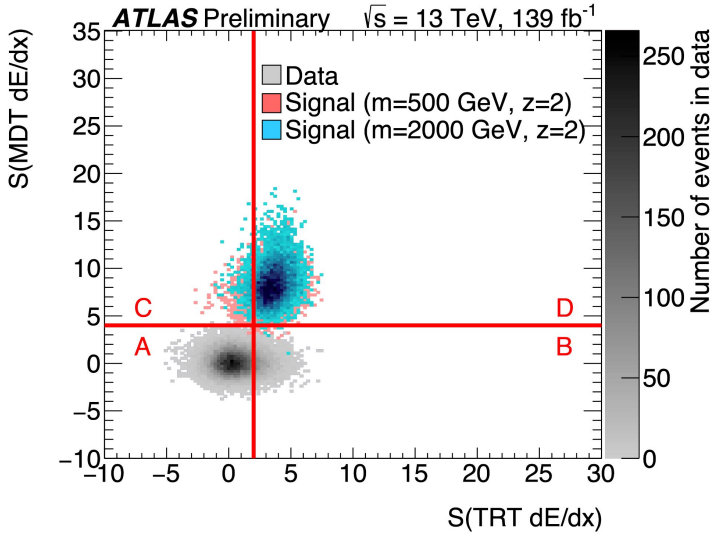
- 3.6 (3.3) local (global).
  - β~[0.62,0.52] from <dE/dX>
- β~1 from time-of-flight measurement from calorimeter and muon system

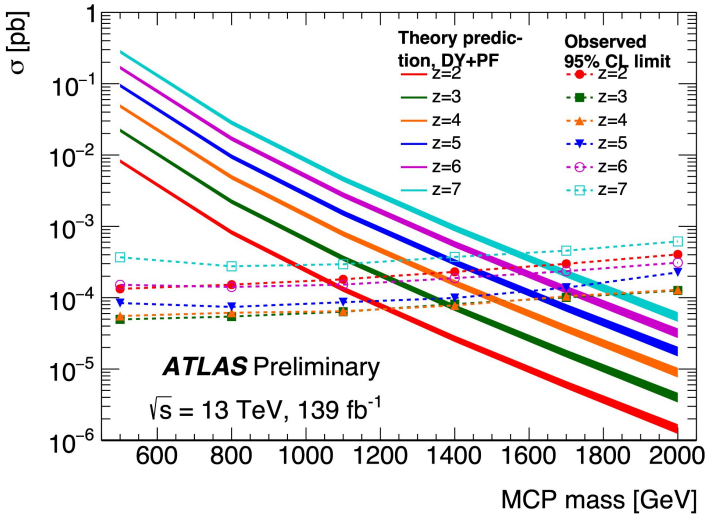
Excess not compatible with considered LLP signals

Direct detection: Complementarity

Potential complementary signatures related to the excess (all with anomalous dE/dX)

- **If Q>ze,** could show up in multi-charged particle search
- If $\tau \lesssim 10$ ns, could show up as disappearing/kinked track search
- If $\beta < 1$ and stable, could show up in stopped particle or tracker+time-of-flight searches
- ...





ATLAS-CONF-2022-034 (ATLAS)

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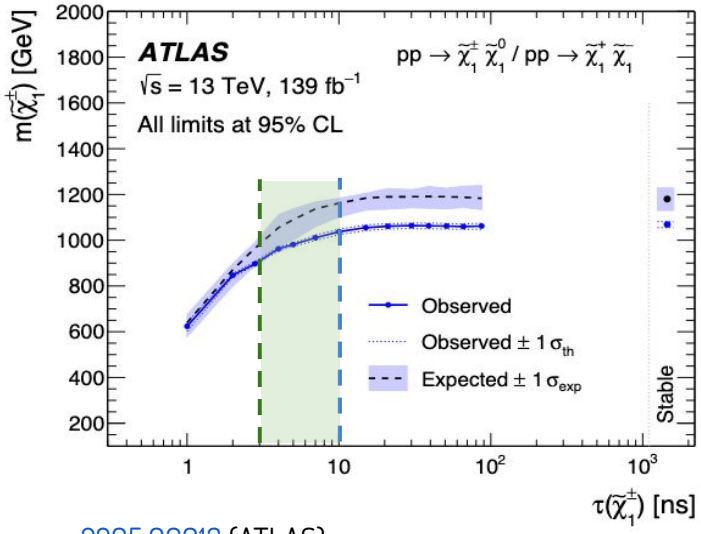
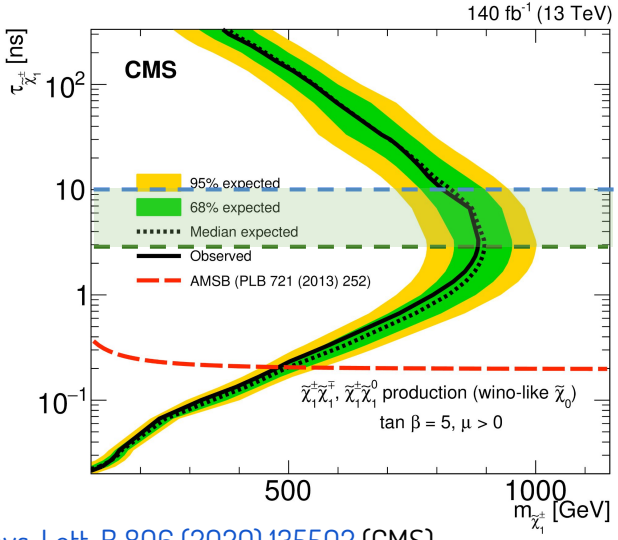


2205.06013 (ATLAS)



Phys. Lett. B 806 (2020) 135502 (CMS)

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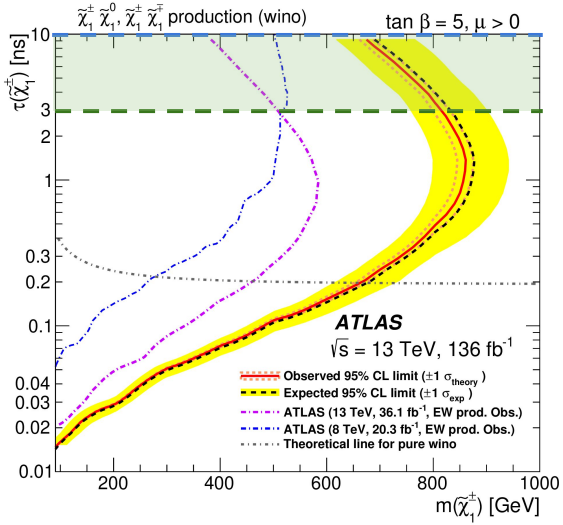
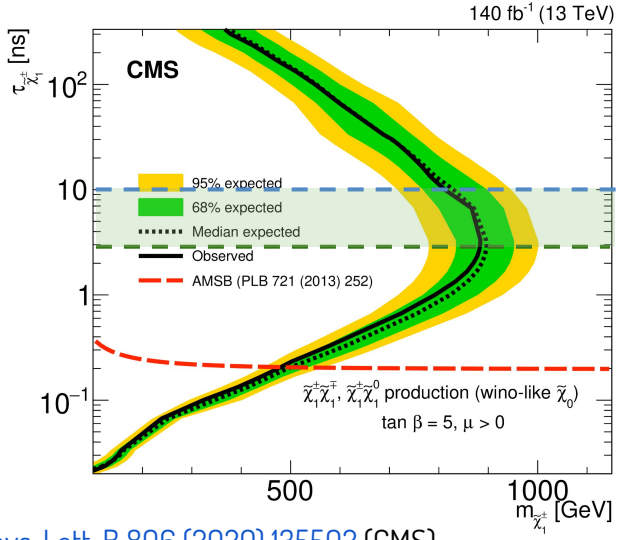


2201.02472 (ATLAS)



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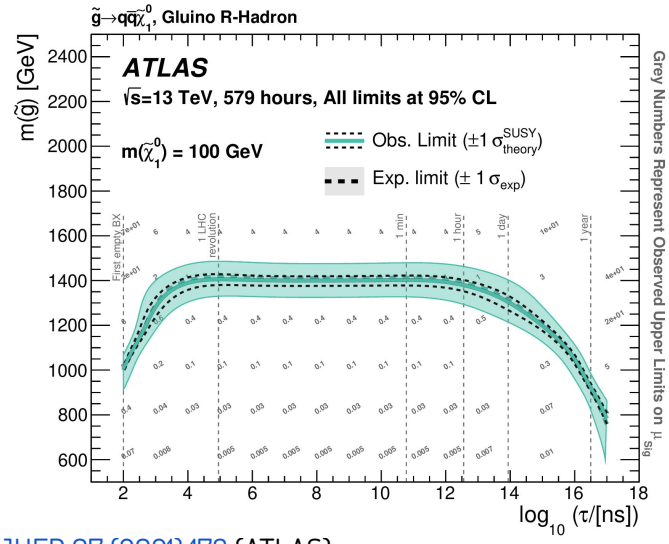
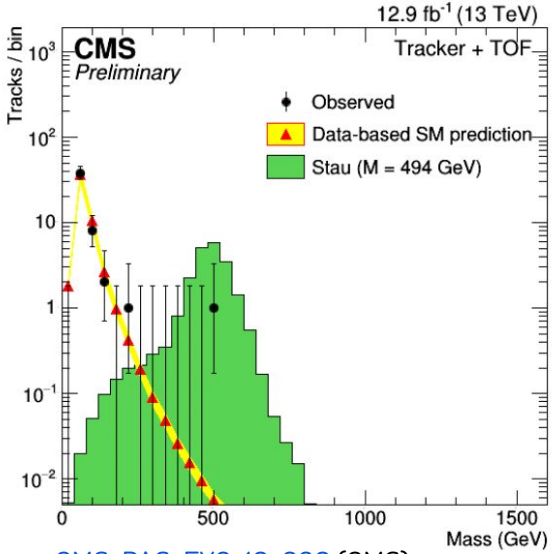


JHEP 07 (2021) 173 (ATLAS)



CMS-PAS-EXO-16-036 (CMS)

… or in RICH detector at LHCb, Eur. Phys. J. C 75 (2015) 595

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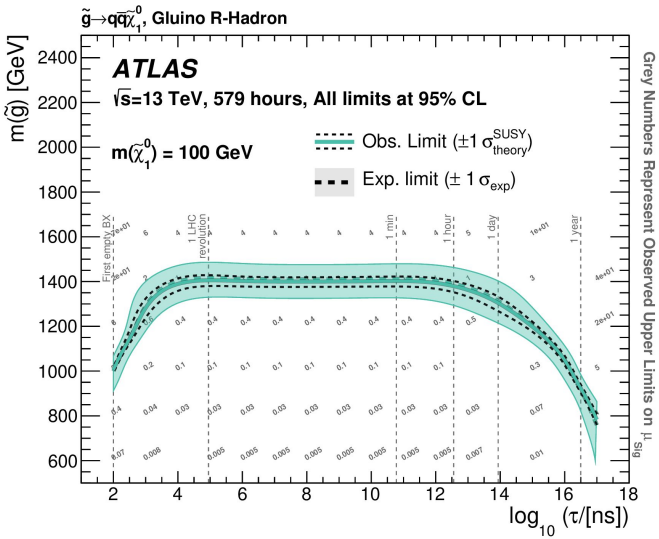
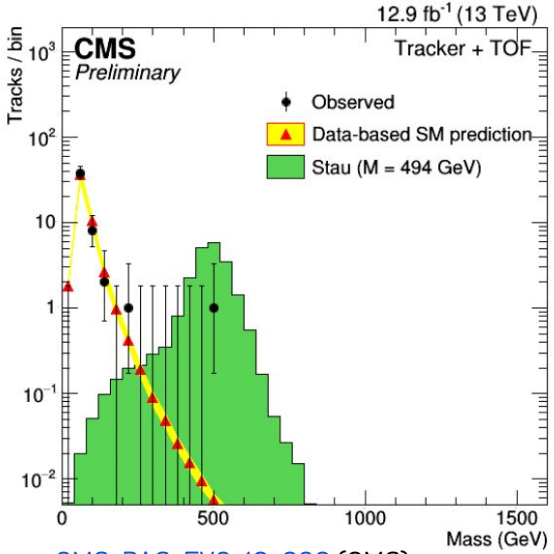


JHEP 07 (2021) 173 (ATLAS)



CMS-PAS-EXO-16-036 (CMS)

So far, no excess in any other direct detection search

Summary and outlook

Impressive neutral LLP search program at the LHC

- Room for improvement in most challenging regions of the phase space
- Comparison between experiments (sometimes) possible in benchmark models (e.g H→XX, HNLs)

Direct searches for LLPs are highly motivated (regardless of the dE/dX excess)

- Complementary signatures (in other subdetectors) vital to confirm a possible LLP observation

I expect massive gains in sensitivity in Run 3 LLP searches (wrt Run 2) thanks to (novel) trigger developments and improved analysis techniques

- Data taking is around the corner!