Searches with displaced particles

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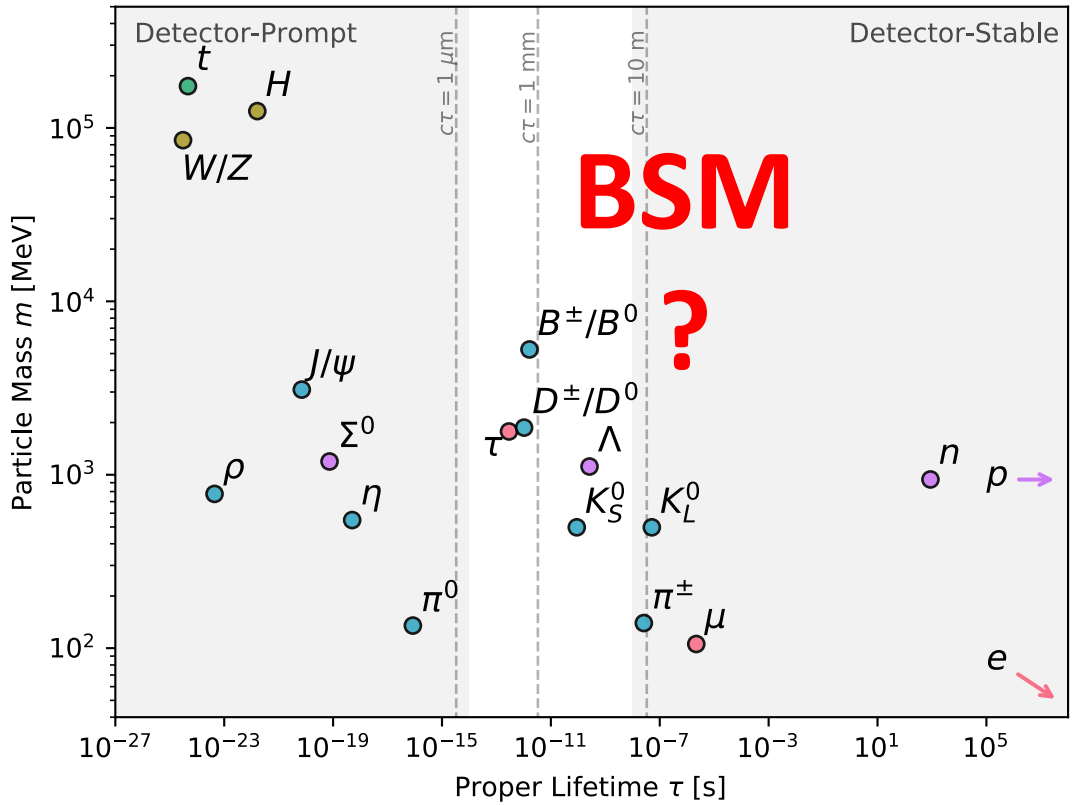
EPFL

on behalf of ATLAS, CMS, LHCb, NA62 & FASER Collaborations

Long-lived particles at the LHC



- LLPs exist in the SM and are taken into account in particle detectors design
- but SM LLPs have relatively short travel distance in the LHC detectors
- BSM models with
  - (nearly) degenerate mass spectra
  - small couplings
  - highly virtual intermediate states

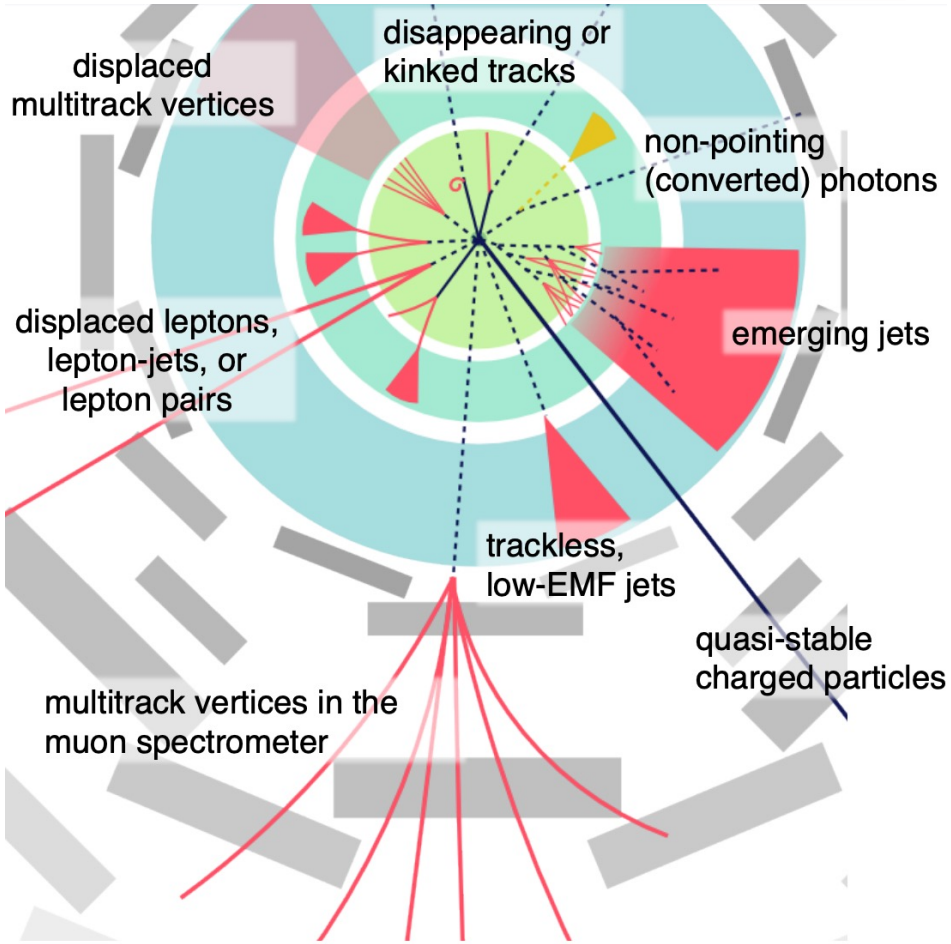
  can populate lifetime space void of expected signatures in the SM
- require creativity and effort in data reconstruction and analysis to recover sensitivity to such scenarios

arXiv:1810.12602

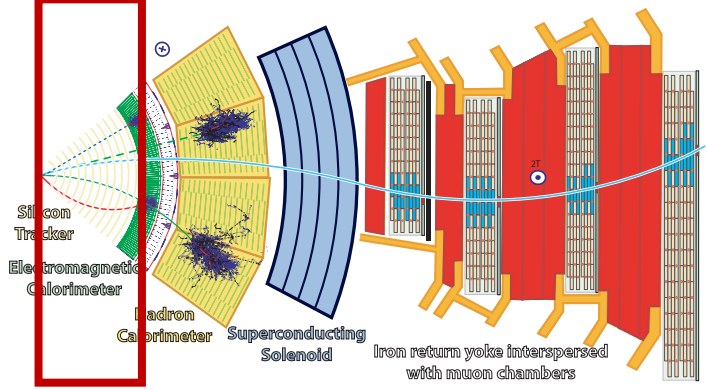
New venues explored with novel approaches

- Pushing tracking capabilities:
  - Disappearing tracks: CMS-PAS-SUS-21-006
  - Displaced jets: CMS-PAS-EXO-21-013
  - Displaced vertices: arXiv:2301.13866 (ATLAS)
  - Displaced dimuons: JHEP 10 (2020) 156 (LHCb)
  - Slightly displaced muons: arXiv:2305.02005 (ATLAS)
- Exploiting muon system:
  - Very displaced muons: arXiv:2305.11649 (CMS)
- ECAL timing information:
  - Out-of-time jets: arXiv:2212.06695 (CMS)
  - Displaced EM objects: arXiv:2304.12885 (ATLAS)
- Checking dE/dx in multiple subdetectors:
  - Multicharged particles: arXiv:2303.13613 (ATLAS)
  - Fractionally charged particles: CMS-PAS-EXO-19-006

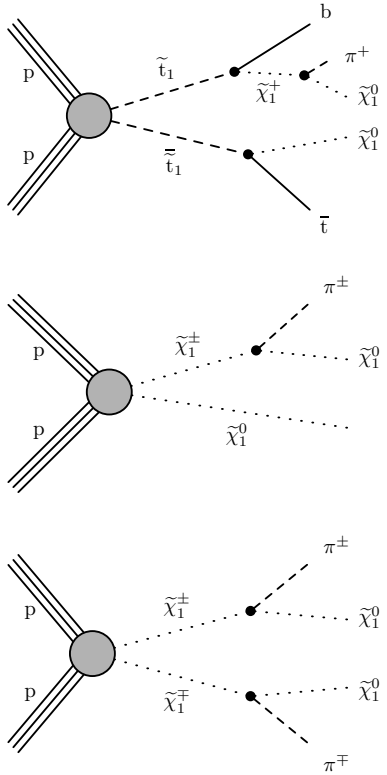
credits: Heather Russel



Disappearing tracks



Trigger:
p_T^{miss} > 120 GeV;
prompt e or μ

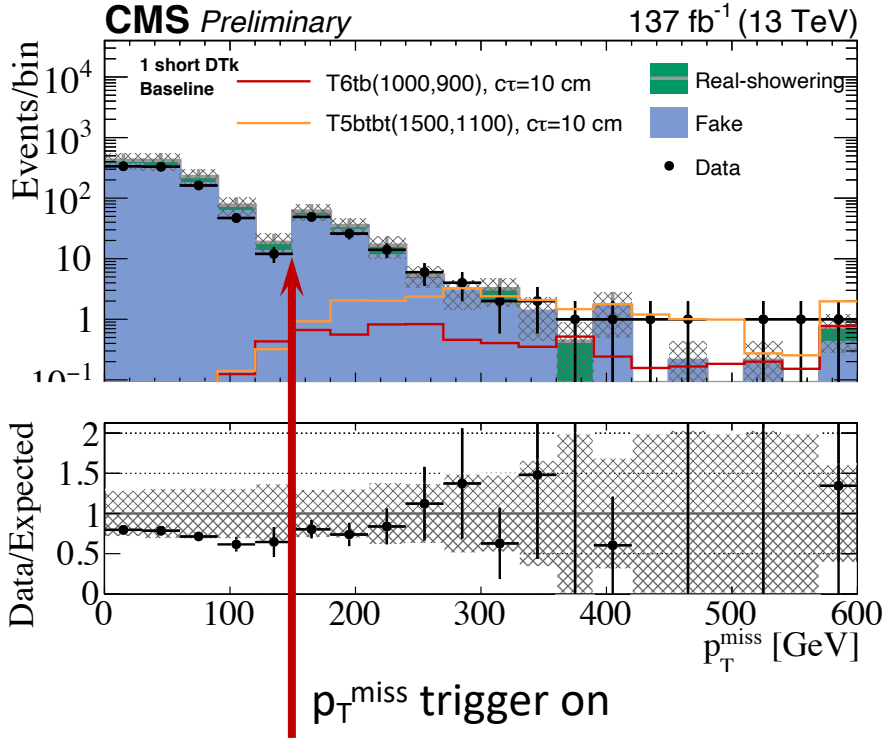


Innovation:
short and long disappearing tracks (DTk) with dedicated BDT-classifier
target $\chi^\pm \rightarrow \chi^0$ + soft $\pi^\pm$ (undetected)

Calibration: rerun reconstruction on muon tracks with artificially removed hits; consistent with simulation with 10% unc.

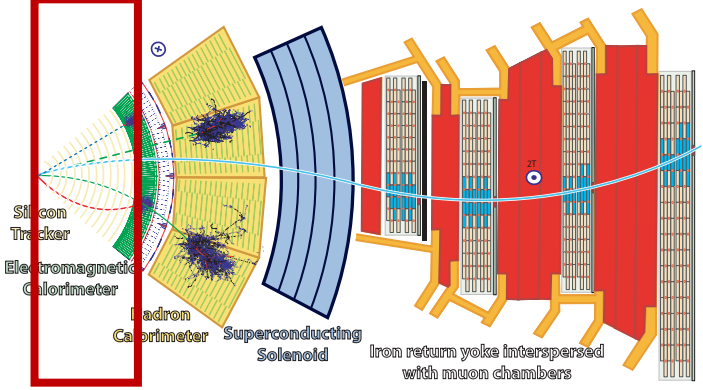
- 3 channels: hadronic, e or μ
- 49 search bins in p_T^{miss}, number of (b)jets and DTk, pixel dE/dx
- backgrounds from poorly reconstructed tracks or random hit alignments: estimated from data with ABCD method

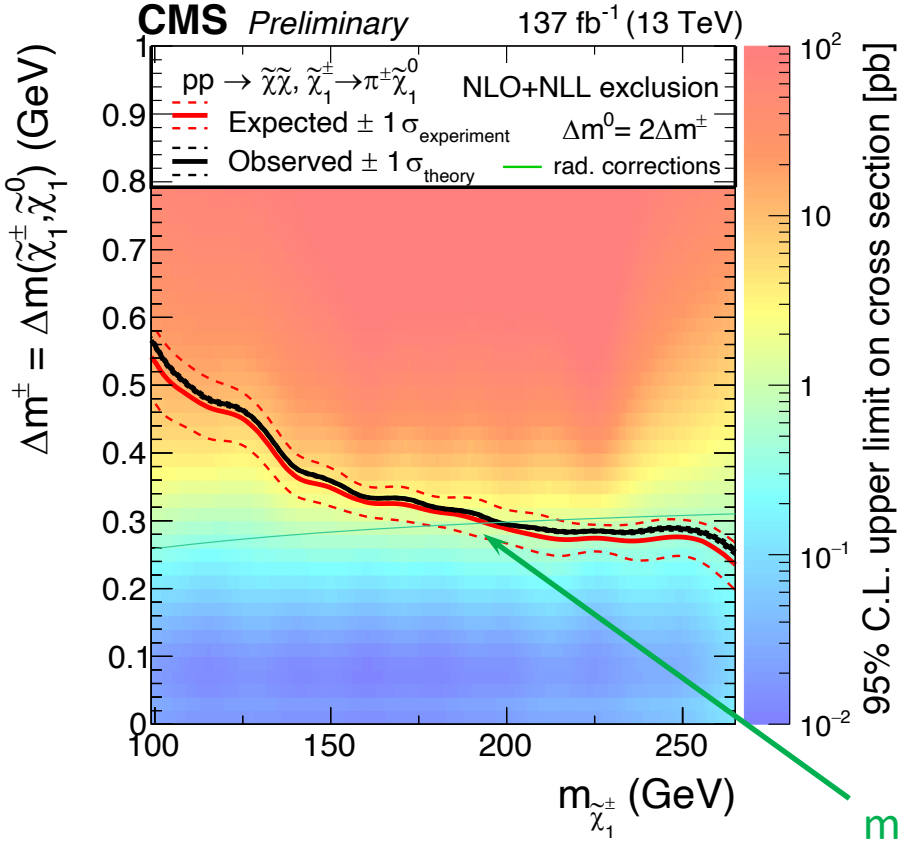
Inclusive short-track category



[CMS-PAS-SUS-21-006]

Example SUSY sensitivity

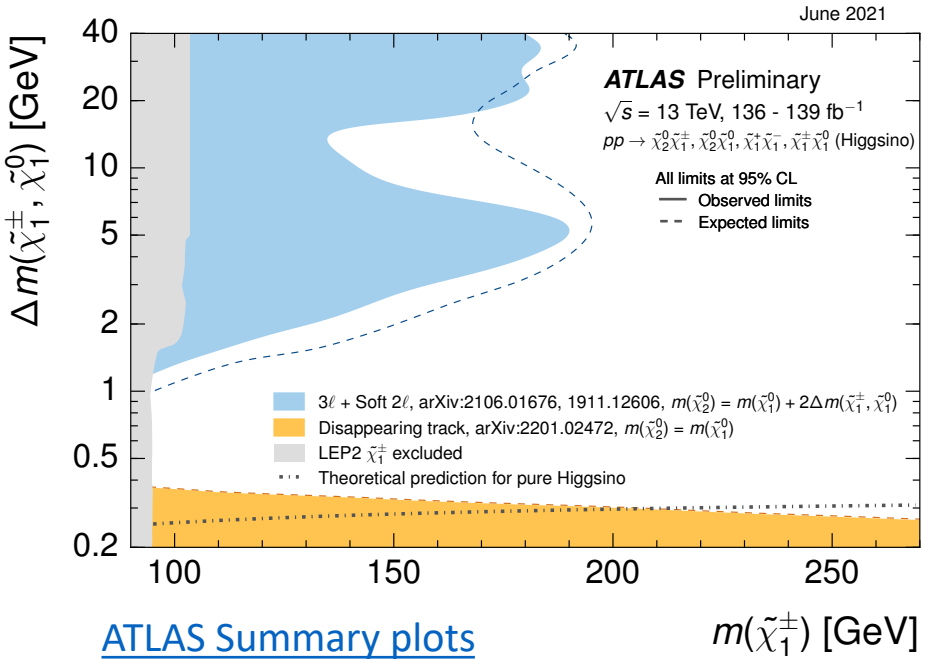




- pure Higgsino model: mass-degenerate χ_1^0, χ_2^0, $\chi_1^{\pm}$
- exclude $\chi_1^{\pm}$ up to ~200 GeV
- similar to the sensitivity obtained by ATLAS

mass splitting due to EWK radiative corrections
arXiv:1703.09675

Higgsinos with prompt and displaced signatures

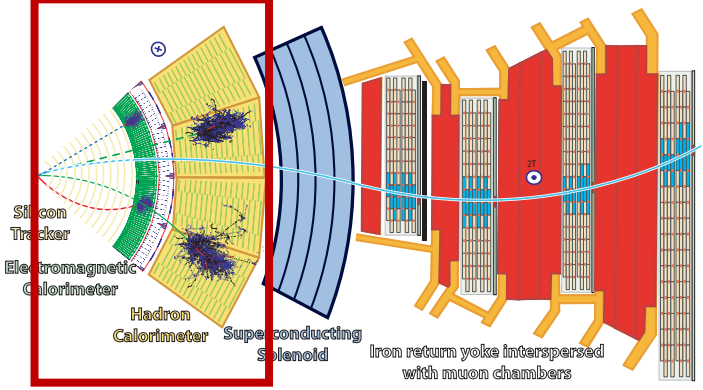


ATLAS Summary plots

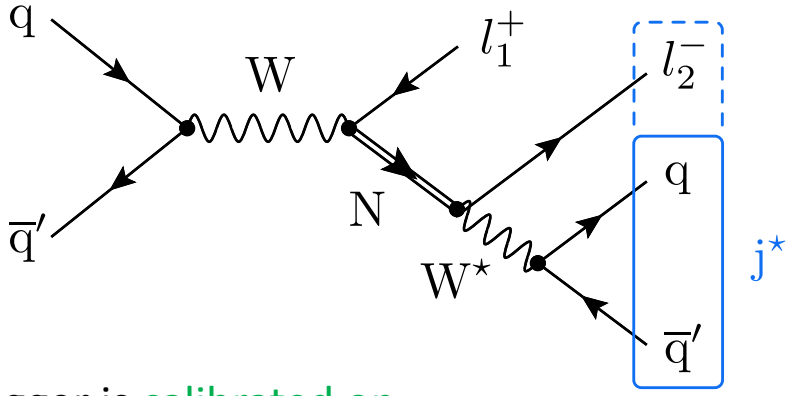
Talk by Sezen Sekmen on Wed

CMS-PAS-SUS-21-006

Displaced jet substructure



Trigger:
prompt e or μ

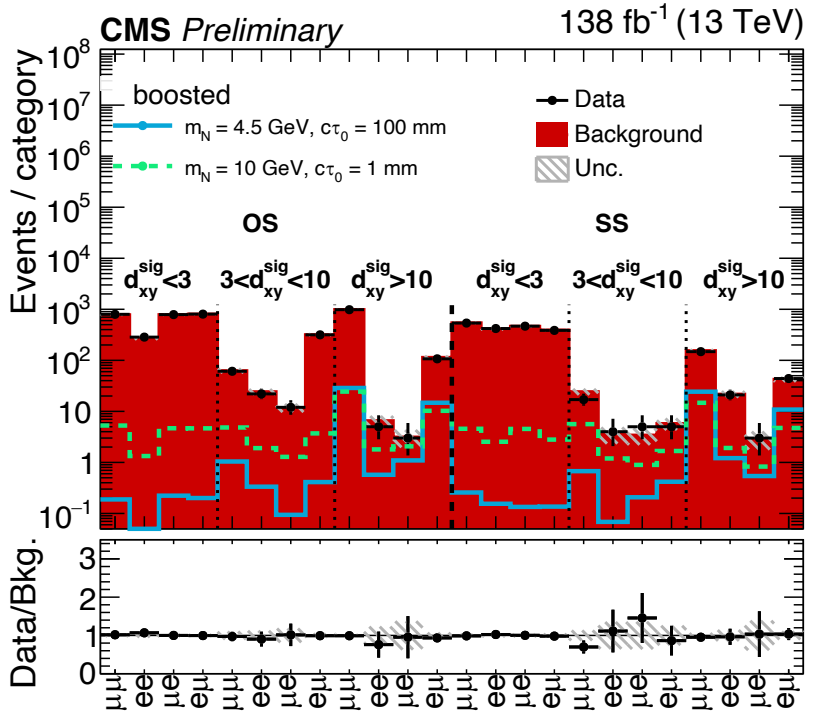


Jet tagger is calibrated on displaced tracks in ttbar-enriched region; corrections are within 10-20%

Innovation:
DNN-based jet tagger
arXiv:1912.12238

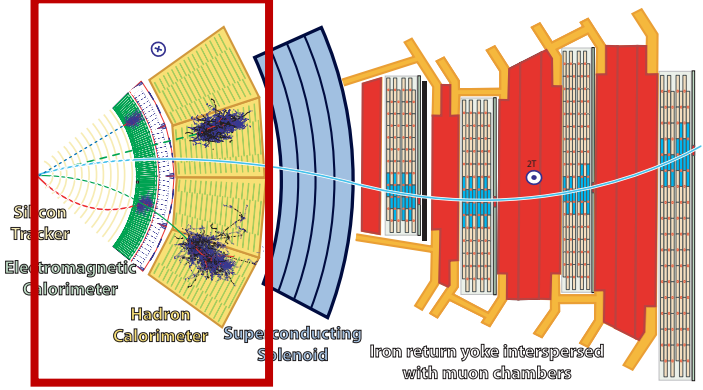
SM bkg are determined from data with ABCD method on W-candidate mass and jet tagger score variables

- Trained on HNL decays with d_{xy}>100 μm
- No explicit selection on jet displacement
- Categorization of events in ℓ_2 displacement significance d_{xy}^{sig} and closeness of ℓ_2 and the jet

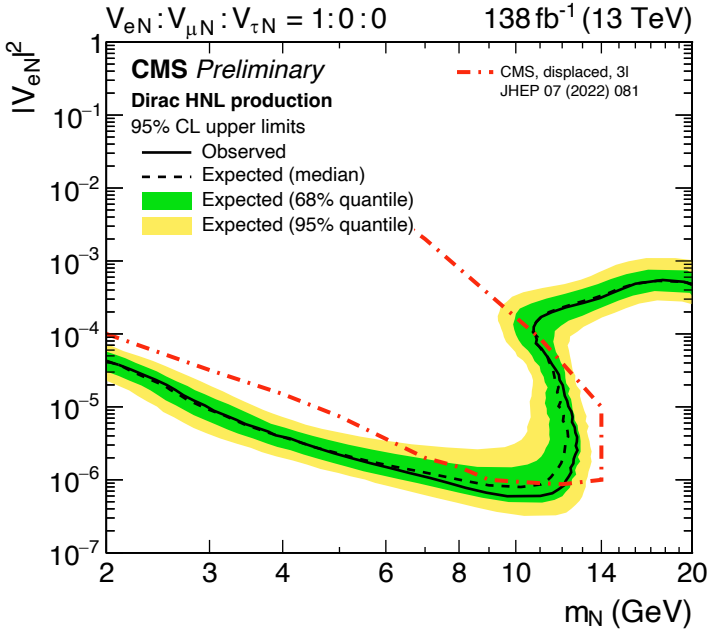


CMS-PAS-EXO-21-013

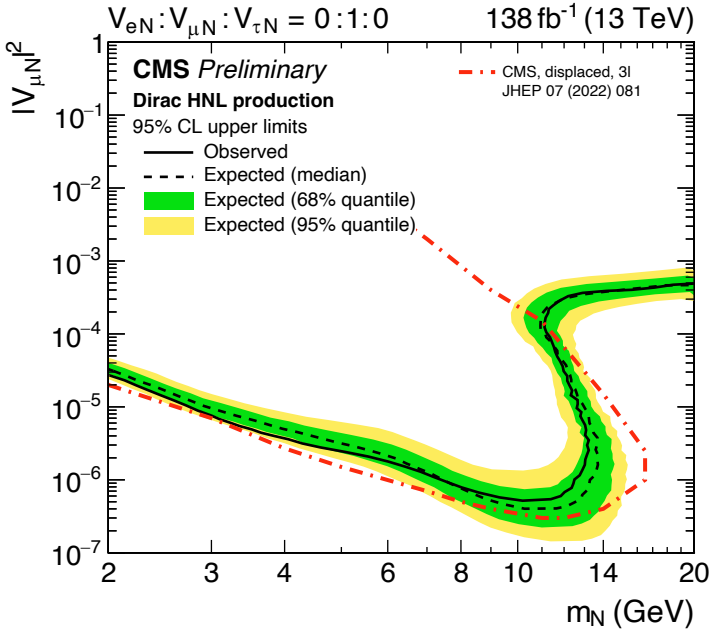
New HNL sensitivity



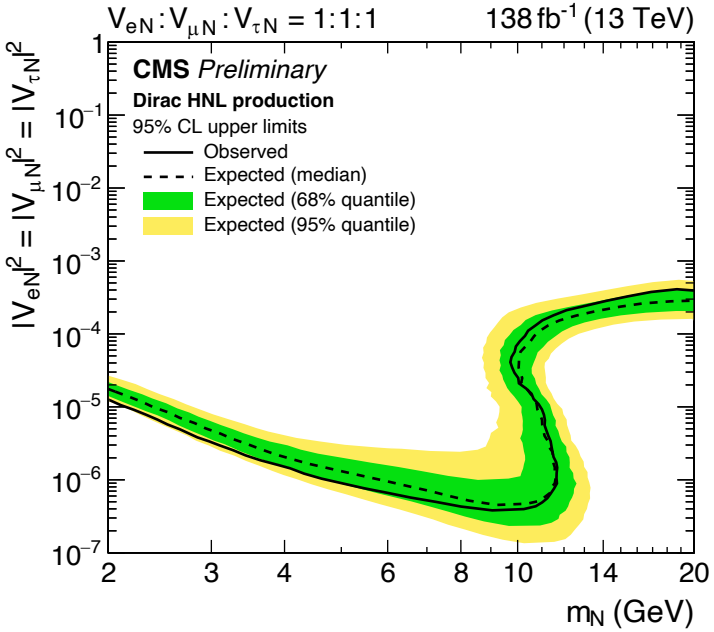
Electron dominance



Muon dominance



Democratic coupling

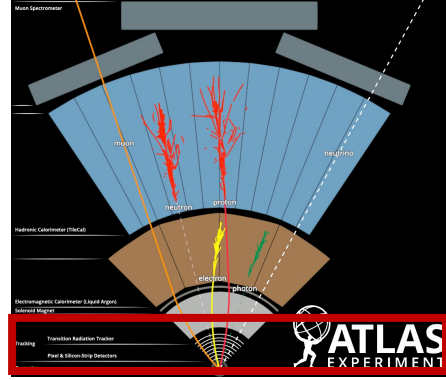


First sensitivity to scenarios with τ-dominance!

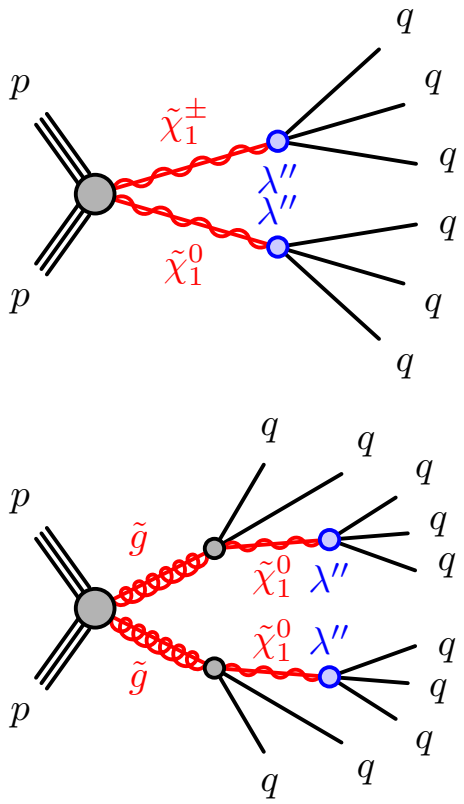
[Talk by Raffaella Tramontano](#) on Mon

[CMS-PAS-EXO-21-013](#)

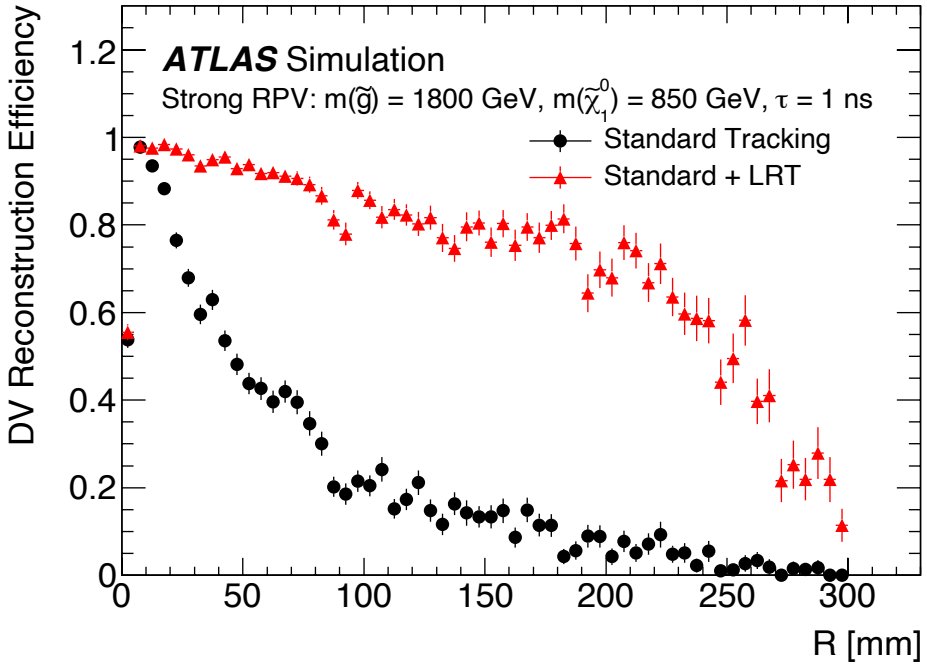
Displaced vertices and jets



Trigger:
multijet

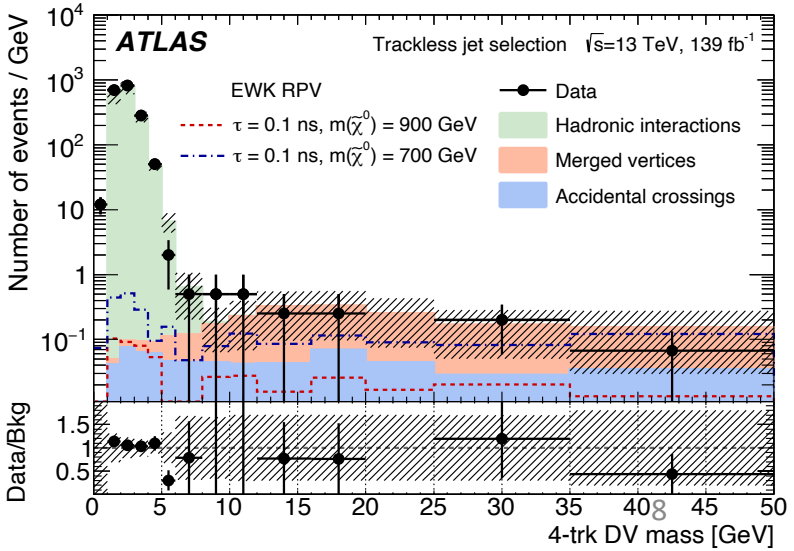


Innovation:
large-radius tracking (LRT)
to recover very displaced vertices;
calibrated with K_S in data and MC



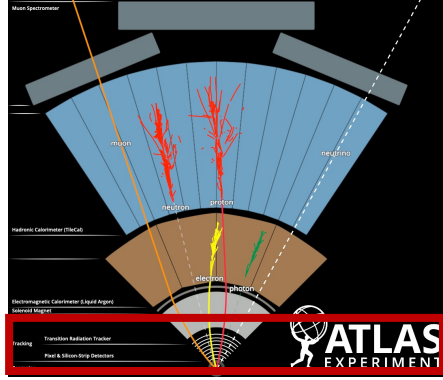
drop at small R due to displacement requirement;
for R>30 cm – due to minimum N_{hit} requirement

- require several jets and at least one displaced vertex (of at least 5 tracks, m>10 GeV) inconsistent with detector material map
- two different data-driven methods for backgrounds from hadronic interactions, merged vertices and accidental crossings

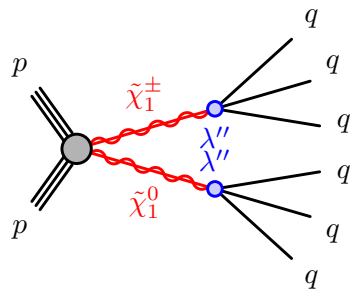


arXiv:2301.13866

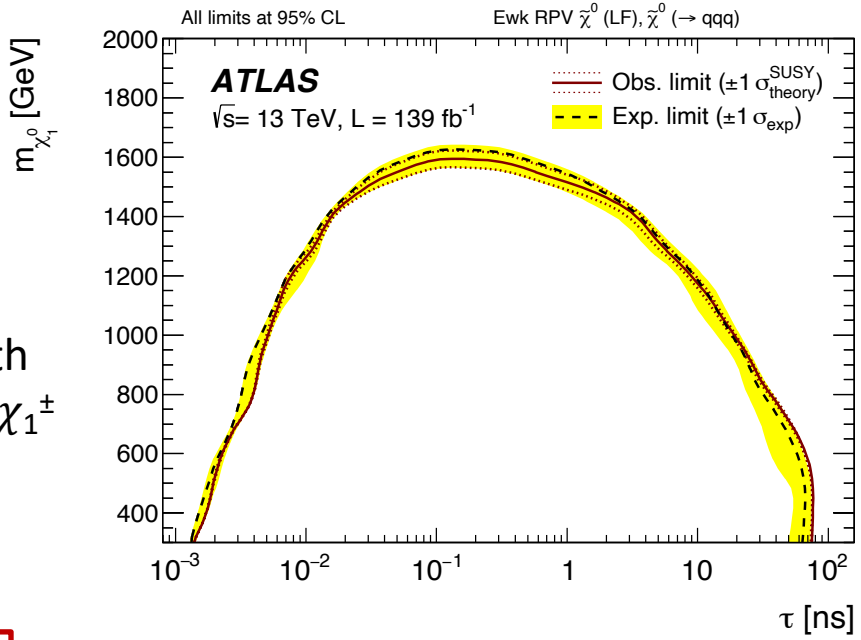
RPV SUSY sensitivity

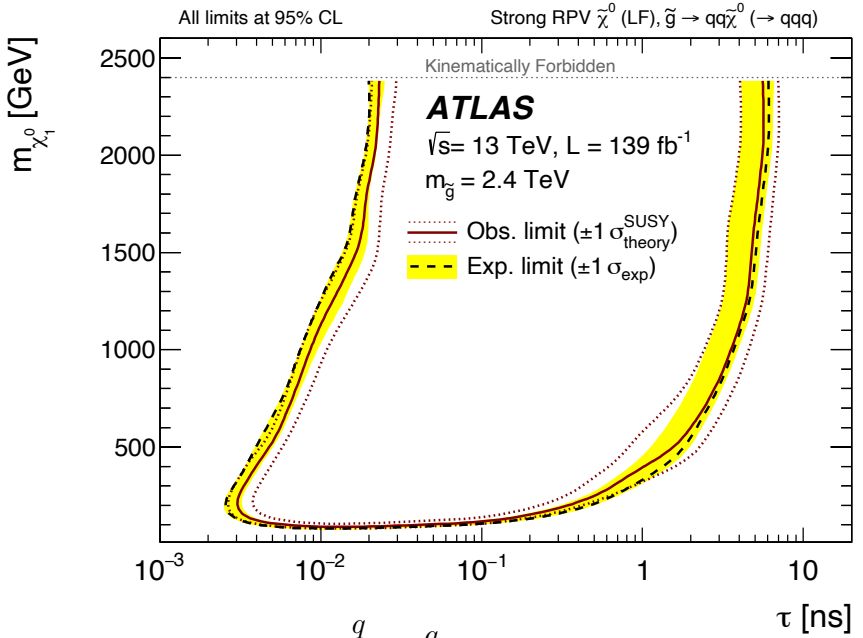


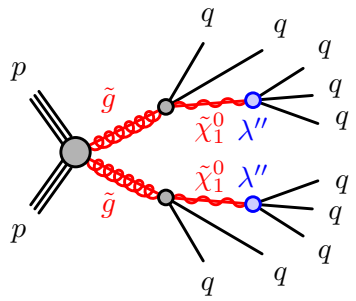
Signal Region	Observed	Expected	S^{95}_{obs}	S^{95}_{exp}	$\langle\sigma_{vis}\rangle^{95}_{obs}$ [fb]
High-p_T jet SR	1	$0.46^{+0.27}_{-0.30}$	3.8	$3.1^{+1.0}_{-0.1}$	0.027
Trackless jet SR	0	$0.83^{+0.51}_{-0.53}$	3.0	$3.4^{+1.3}_{-0.3}$	0.022



Assume pure Higgsinos with mass-degenerate χ_1^0, χ_2^0, $\chi_1^{\pm}$



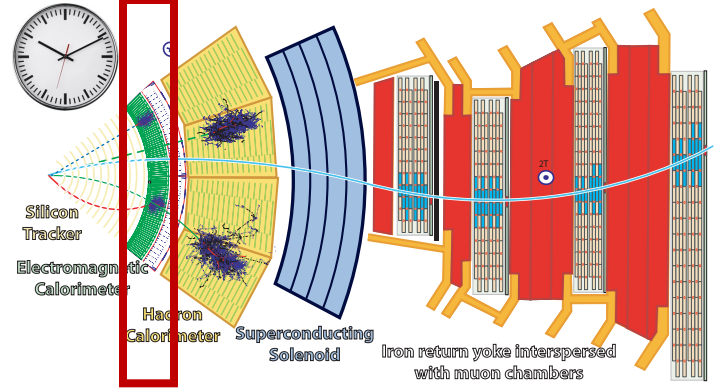




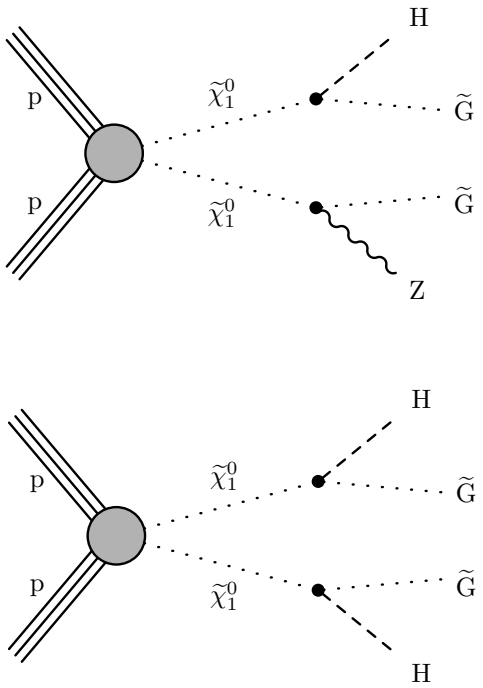
[Talk by Mohsen Naseri](#) on Mon

[arXiv:2301.13866](#)

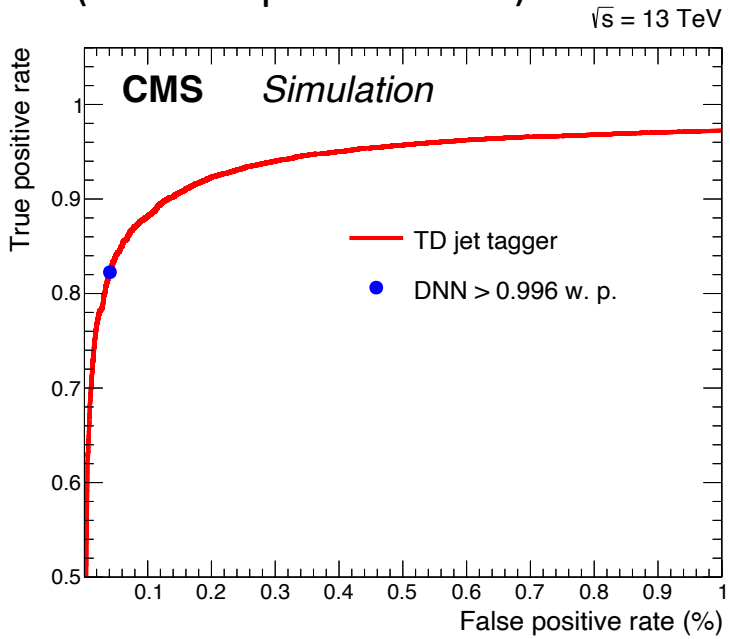
Out-of-time trackless jets



Trigger:
p_T^{miss} > 120 GeV

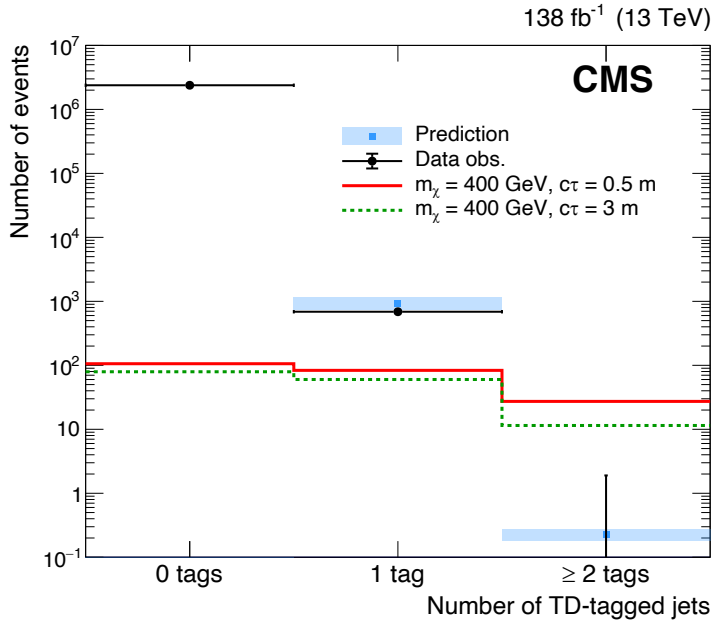


Innovation:
trackless delayed jet tagger
DNN with 22 input features, including ECAL timing (400-600 ps resolution)



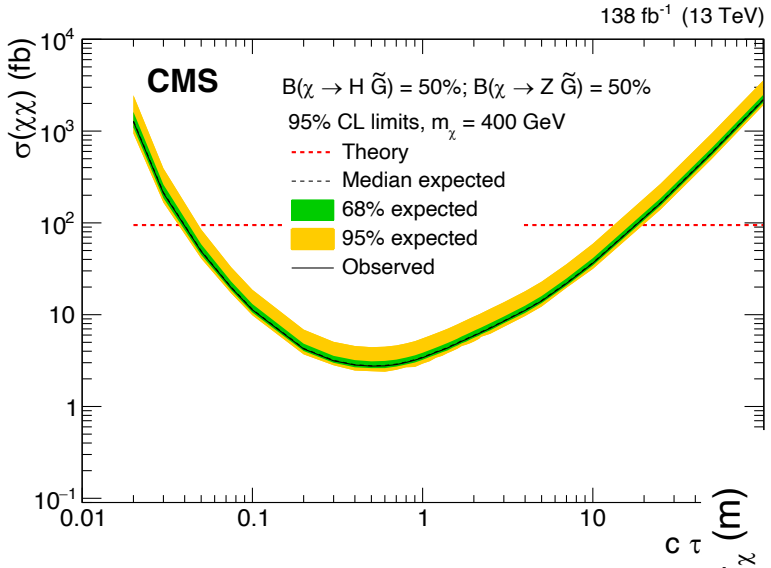
Calibrated on Z→ℓℓγ, W→eν events with artificially added 1-2 ns delay

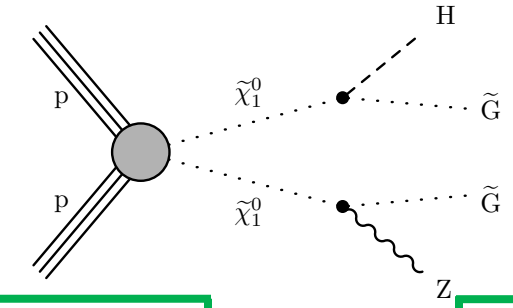
- require at least two TD-tagged jets and p_T^{miss} > 200 GeV
- cosmic ray muon and beam halo veto
- data-driven matrix method for bkg estimation with misID probability measured in a data control region

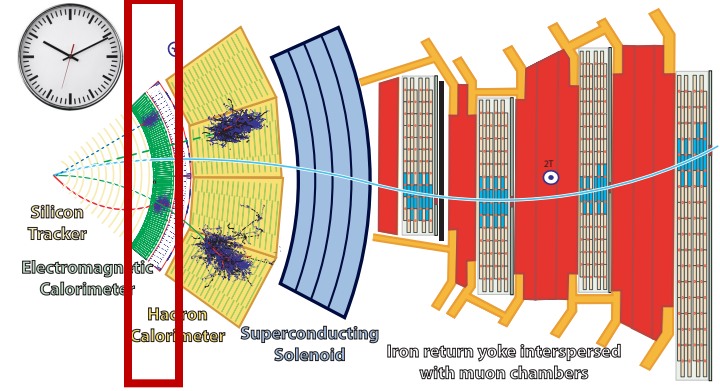


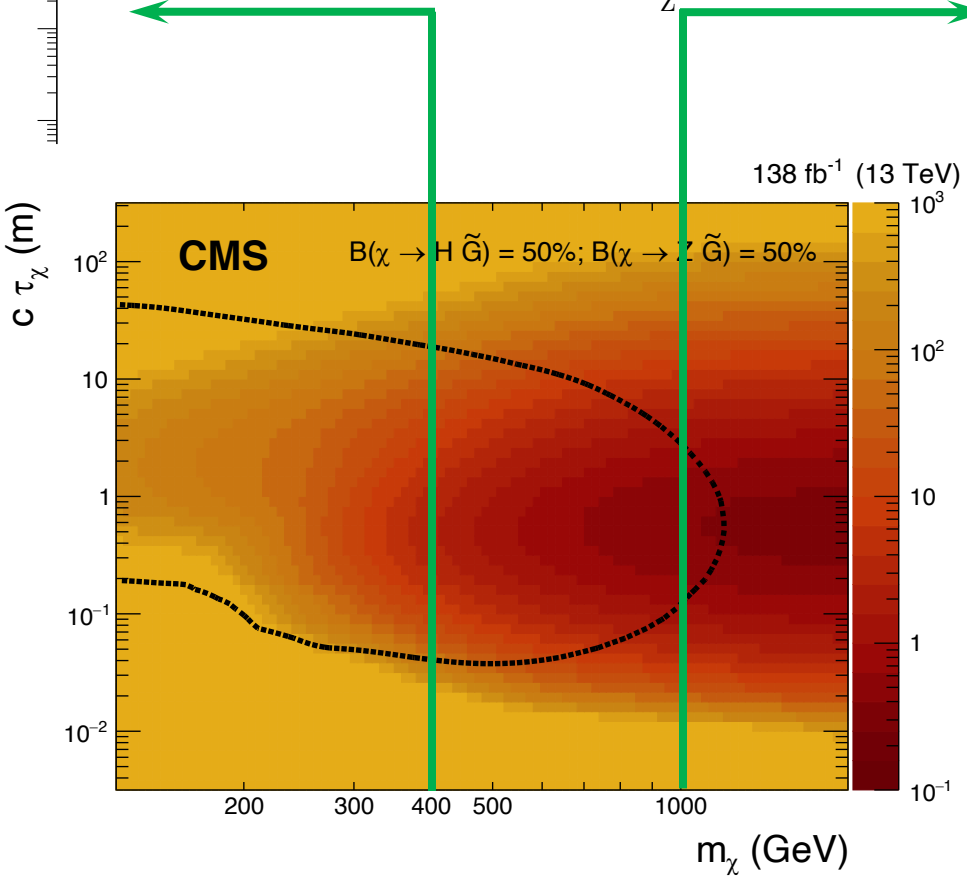
arXiv:2212.06695

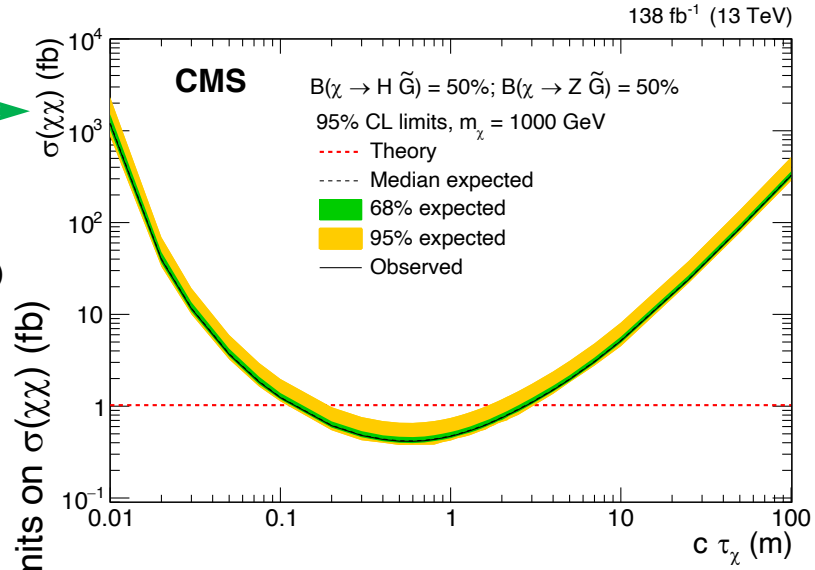
Electroweak SUSY sensitivity









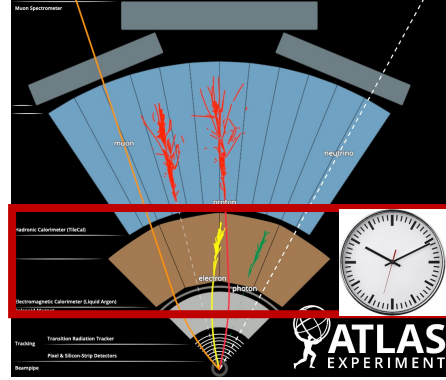


Assume pure Higgsinos with mass-degenerate χ_1^0, χ_2^0, $\chi_1^{\pm}$

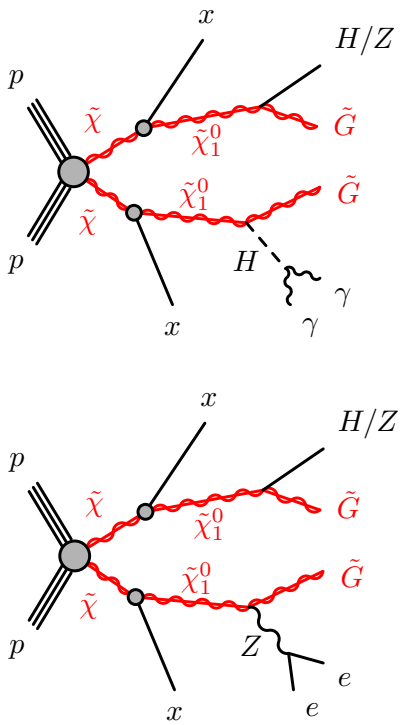
[Talk by Ang Li](#) on Mon

arXiv:2212.06695

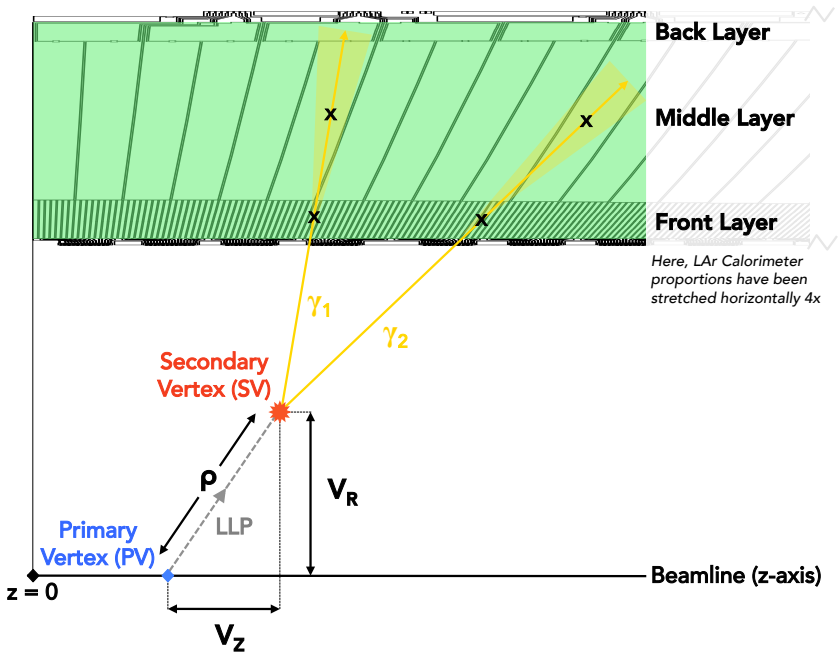
Displaced EM objects



Trigger:
two high-p_T photons

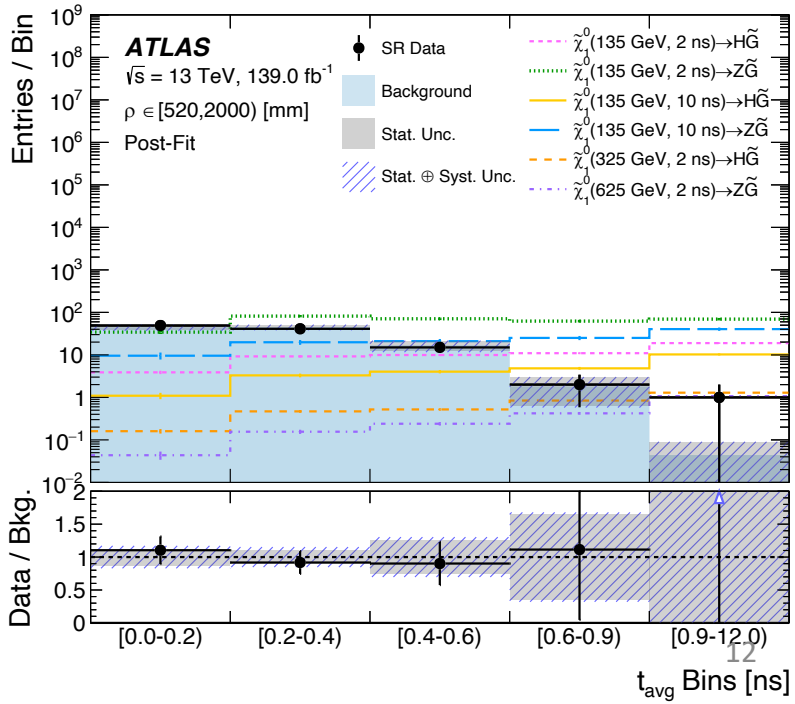


Innovation:
displaced diphoton vertex (DDV)
using precise LAr timing (σ~200 ps)
and pointing capabilities (σ~15 mm)



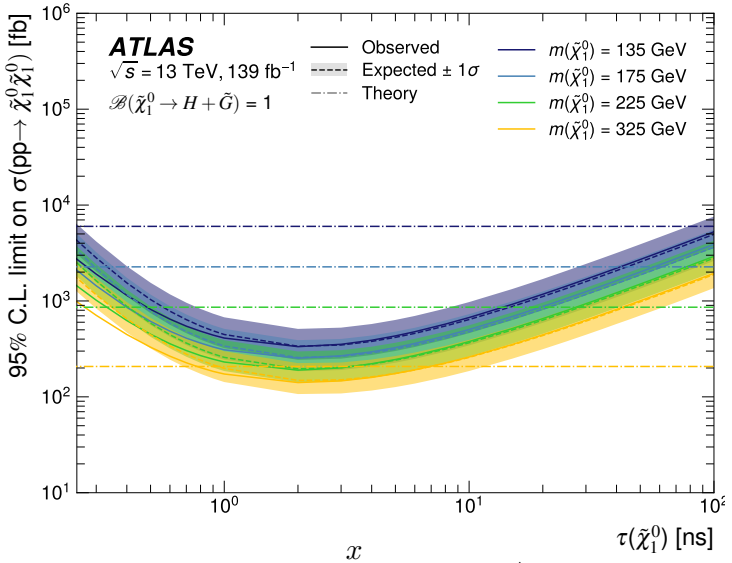
Calibrated on W→eν, Z→ee events

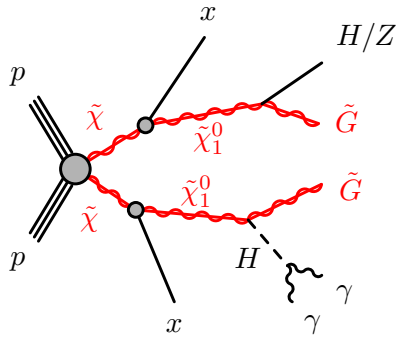
- require two photons ($0 < t_\gamma < 12$ ns) forming a DDV and $p_T^{miss} > 30$ GeV
- data-driven method to measure time templates for DDV with real and misidentified photons

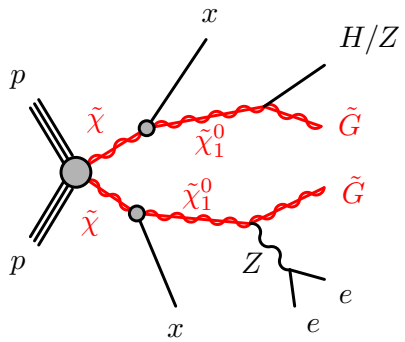


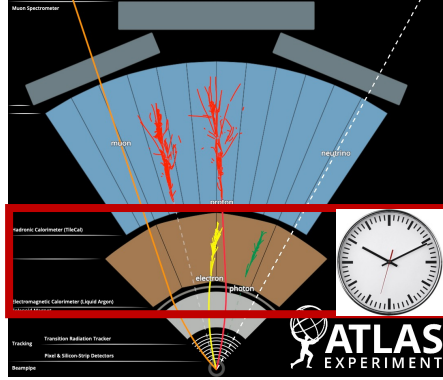
arXiv:2304.12885

Electroweak SUSY sensitivity

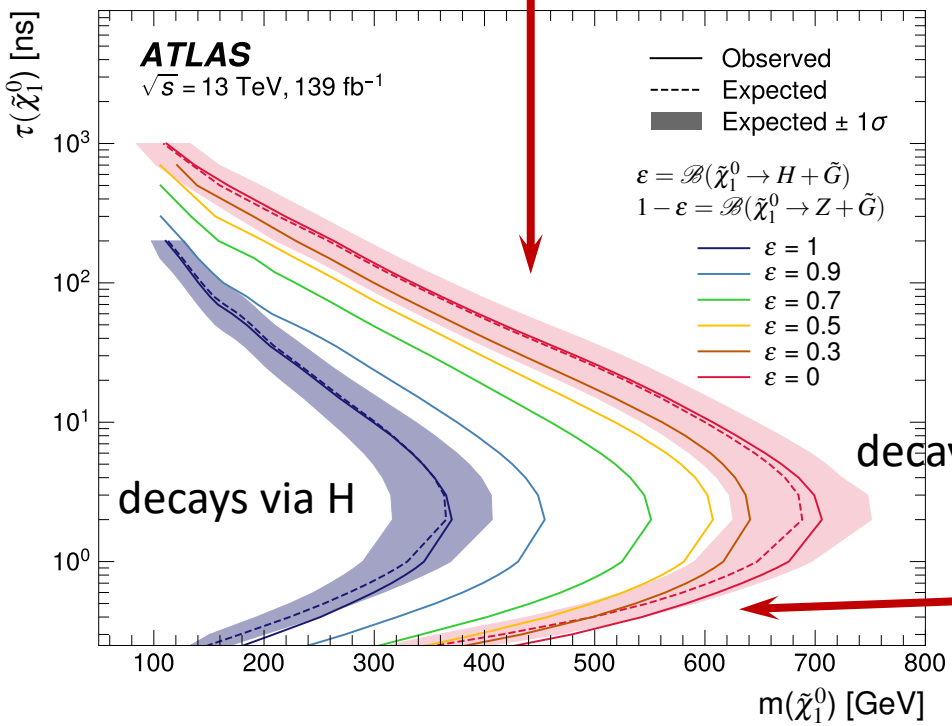


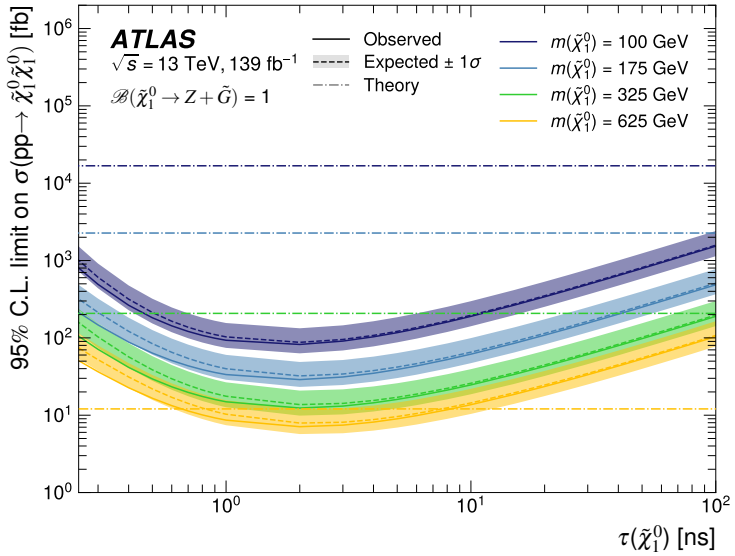






higgsino decays outside the detector



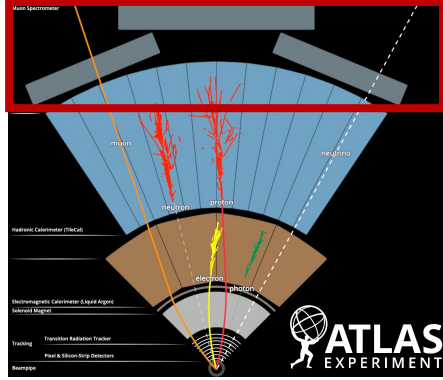


higgsino lifetime too short

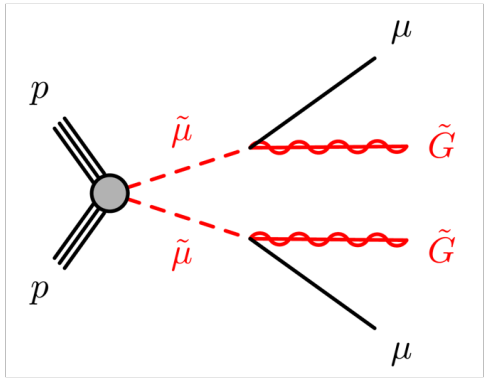
[Talk by Mohsen Naseri](#) on Mon

arXiv:2304.12885

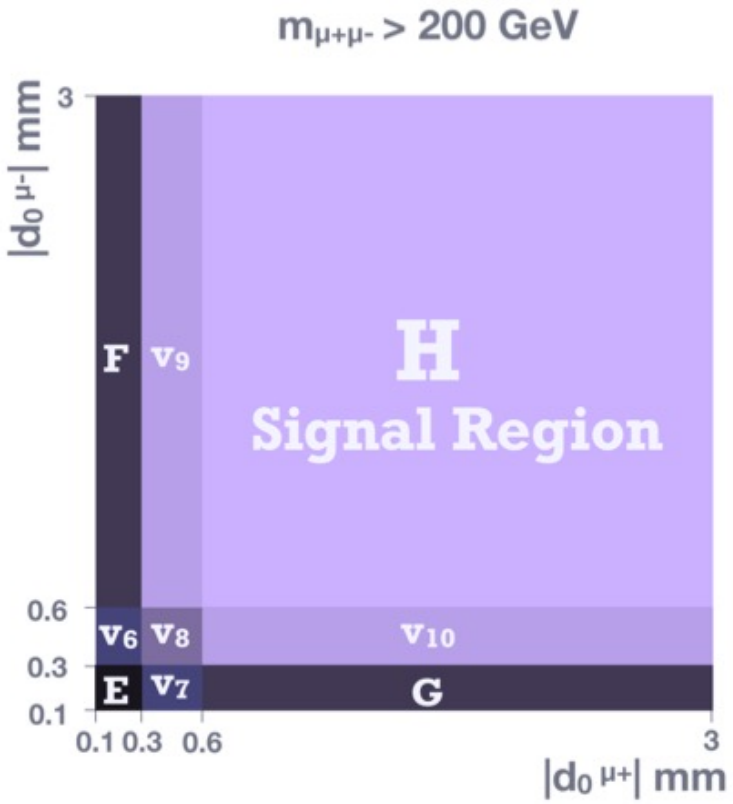
Slightly displaced muons



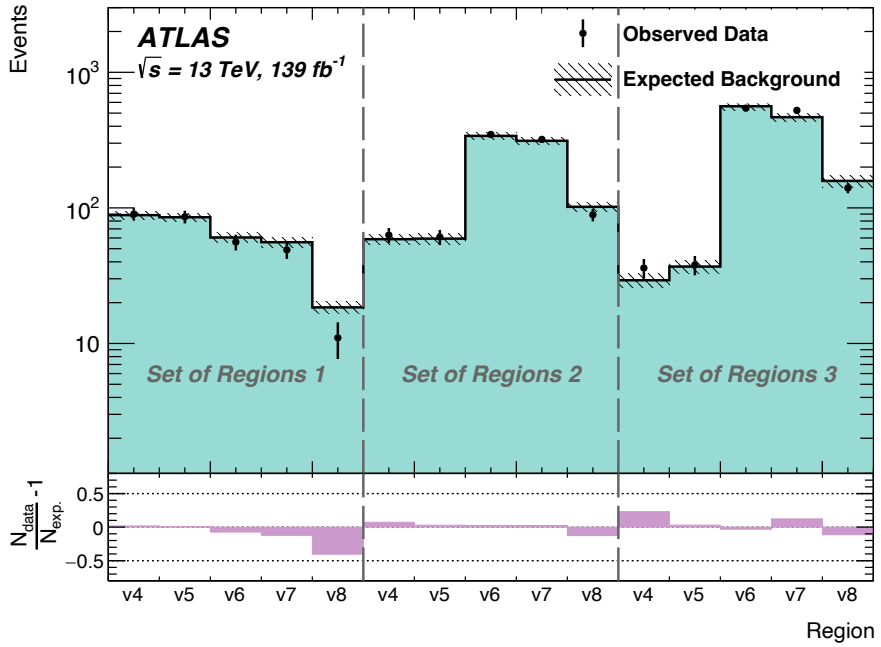
Trigger:
regular dimuon



Innovation:
target blind spot of previous searches by concentrating on small displacements

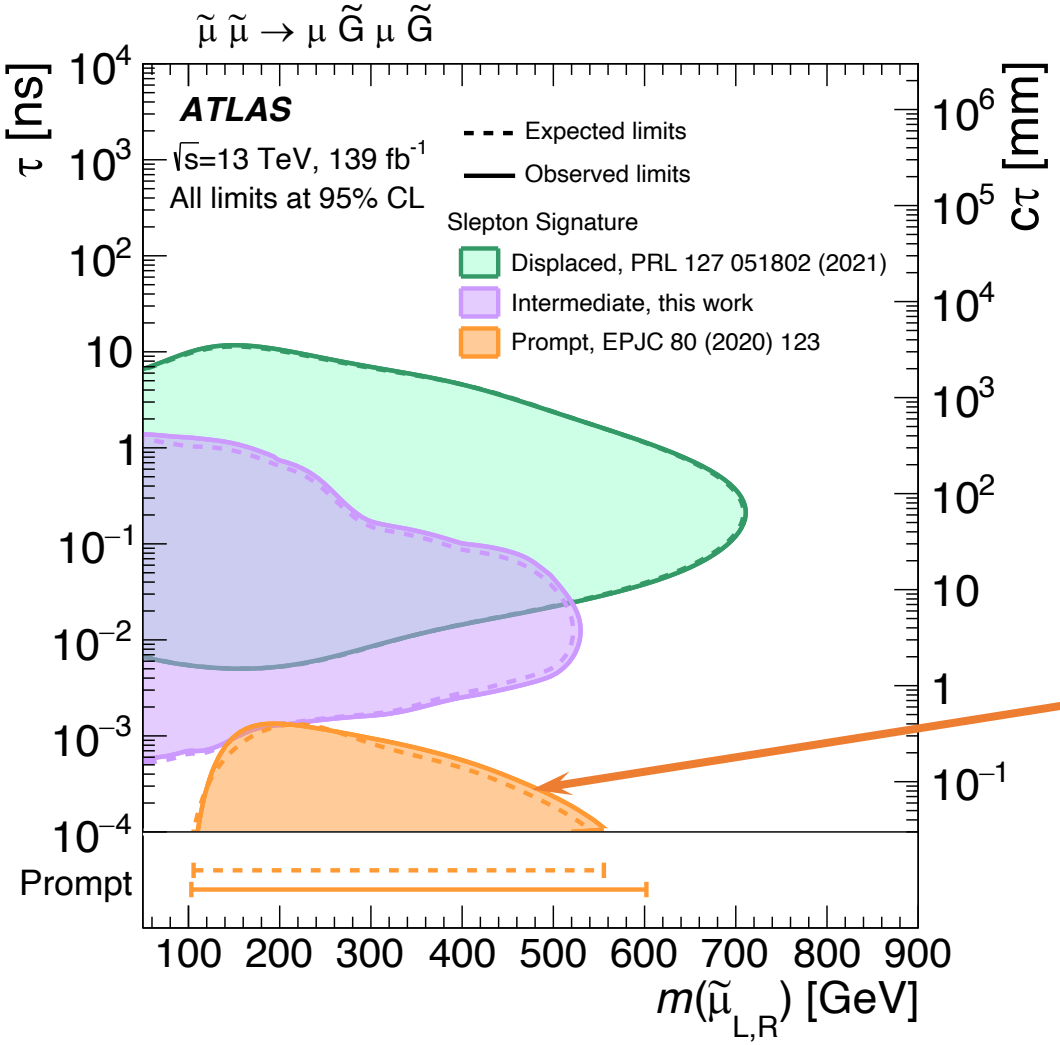


- require two displaced muons ($0.6 < d_0 < 3$ mm) with m(μμ) > 200 GeV
- data-driven ABCD method with d_0 and m(μμ) to estimate SM background



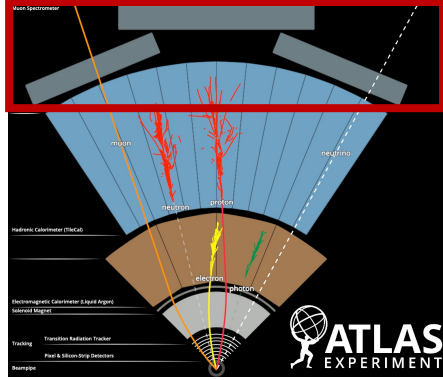
arXiv:2305.02005

Sensitivity to smuons



- Closes the gap between the reinterpreted prompt and large-d_0(> 3mm) searches

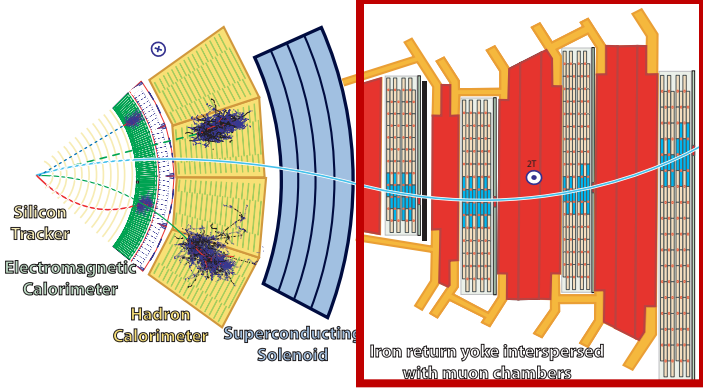
the first explicit reinterpretation of a search with prompt leptons into the long-lived regime



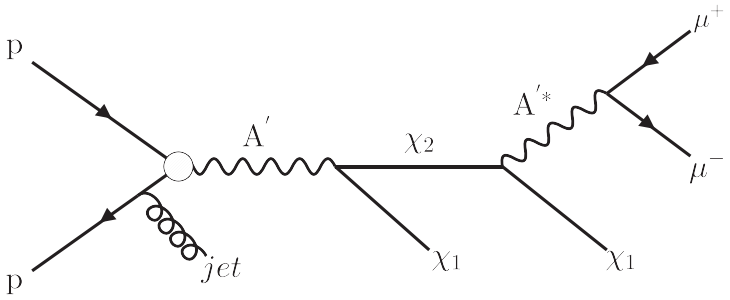
Talk by Mohsen Naseri on Mon

arXiv:2305.02005

Very displaced muons

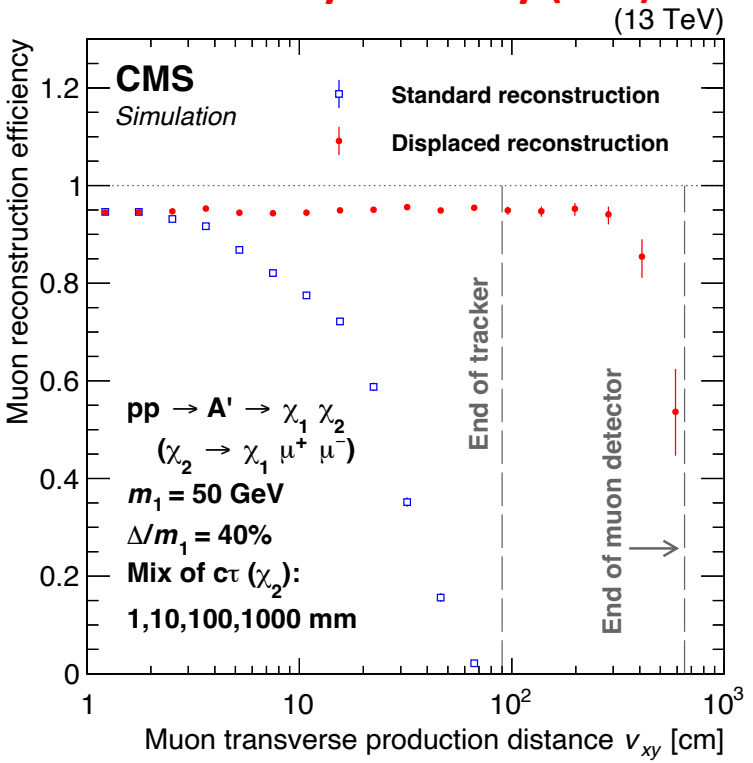


Trigger:
p_T^{miss} > 120 GeV



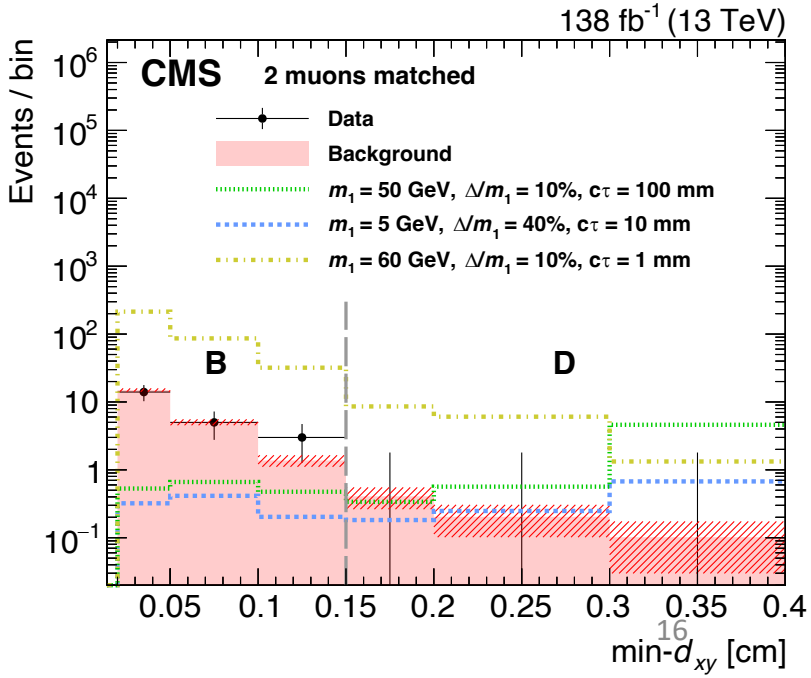
Model:
Inelastic dark matter production and decay

Innovation:
displaced muon reconstruction with muon system only (dSA)



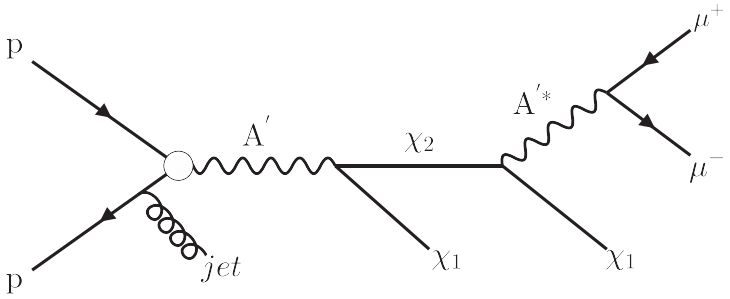
Calibrated with cosmic muons, Z→μμ and J/ψ→μμ events

- require two collimated dSA muons, p_T^{miss} > 200 GeV and 1-2 jets
- data-driven ABCD method with min-d_{xy} and muon isolation for SM background



arXiv:2305.11649

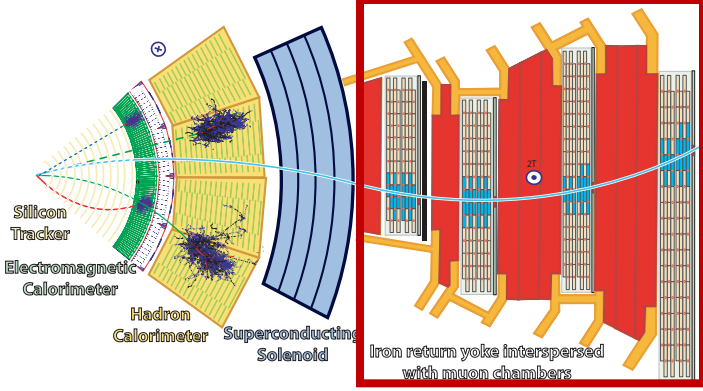
Sensitivity to DM



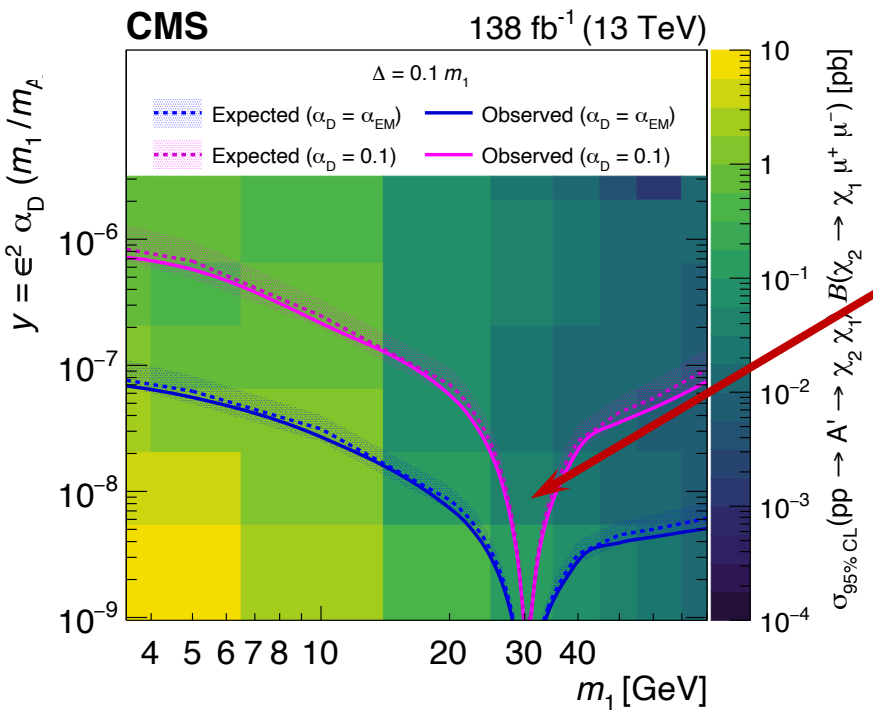
$\Delta = m(\chi_2) - m(\chi_1)$

$m(A) = 3m_1$

y – "interaction strength"

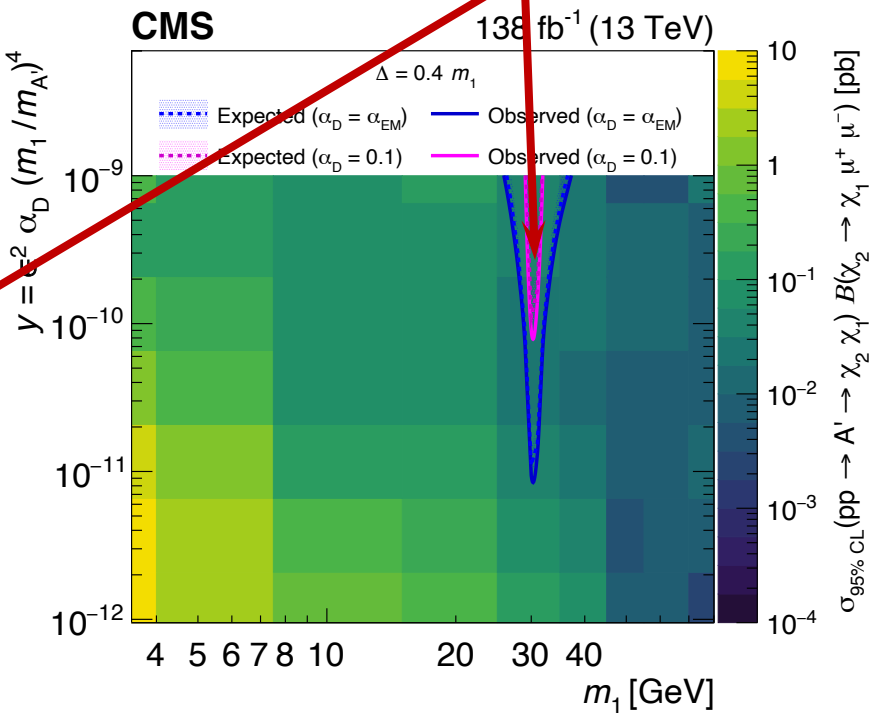


Low Δ



High Δ

m(A')~90 GeV

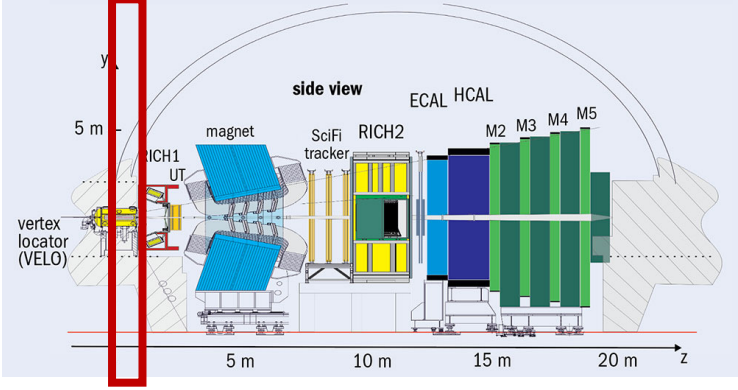


Weaker exclusion as $\sigma \sim 1/\Delta^5$

Talk by Ang Li on Mon

arXiv:2305.11649

Dark photon→$\mu\mu$ @ LHCb

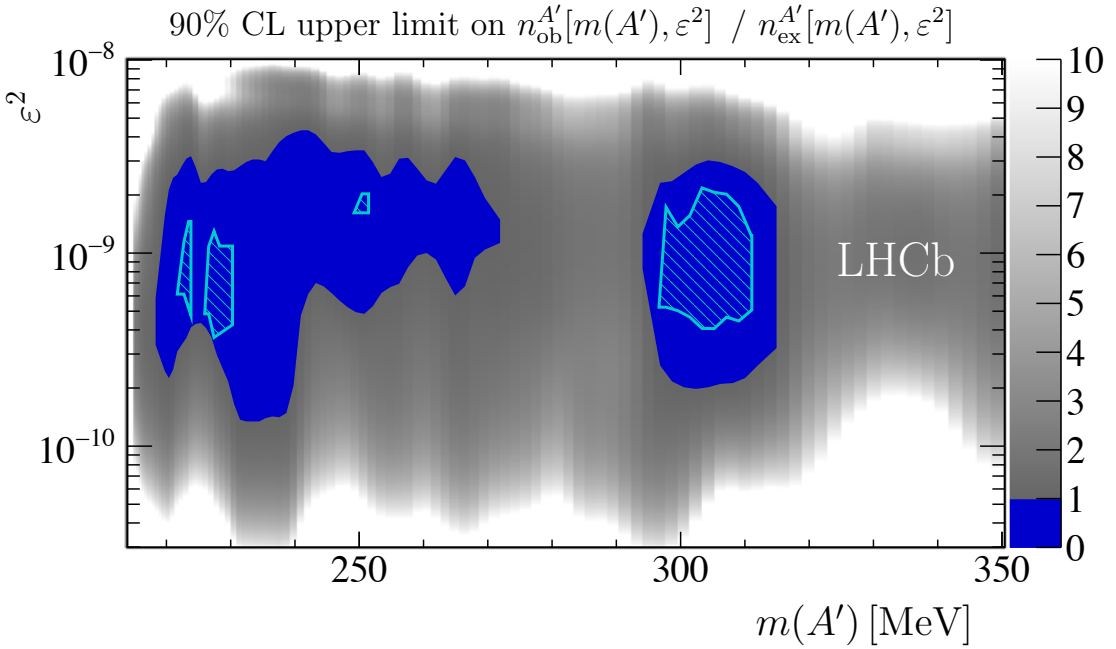


Innovation:

dedicated dimuon trigger

material map veto to suppress conversion

- target 214 < m(A') < 350 MeV region
- require muons inconsistent with originating from PV, with p_T > 0.5 GeV and p > 10 GeV
- A' should be consistent with originating from a PV and be isolated from other tracks
- veto material interactions and stay below K_S mass
- veto events selected by inclusive heavy-flavor software trigger
- signal extraction using mass bump-hunt, scanning both mass and lifetime variables



the only displaced dark photon search at the LHC!

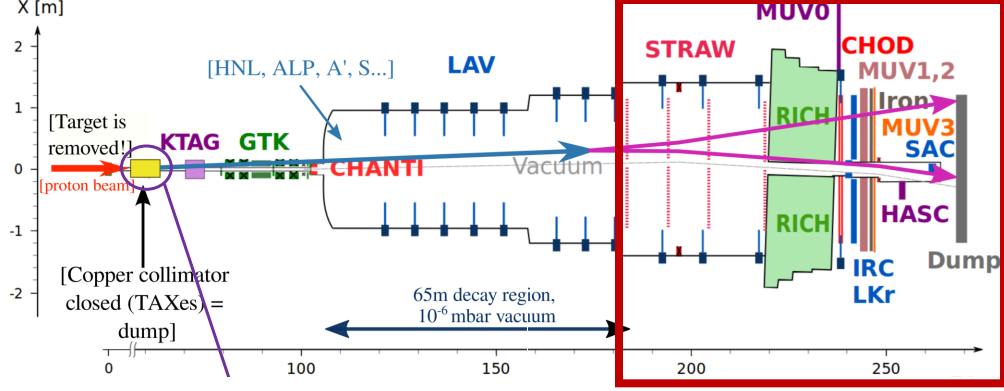
PRL 124 (2020) 041801

Dedicated LLP experiments @ CERN

NA62 @ SPS for kaon physics

FASER @ LHC for LLP searches

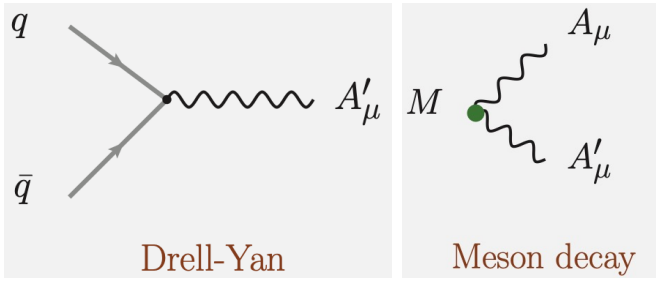
Dark photons @ NA62



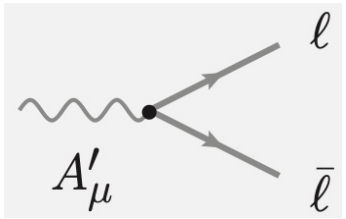
Innovation:

Running in beam-dump mode

Production:



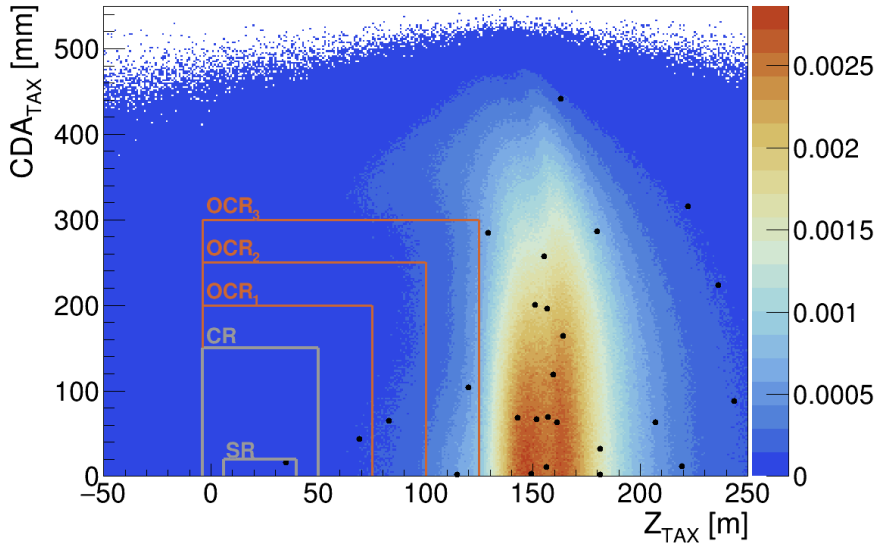
Decay:



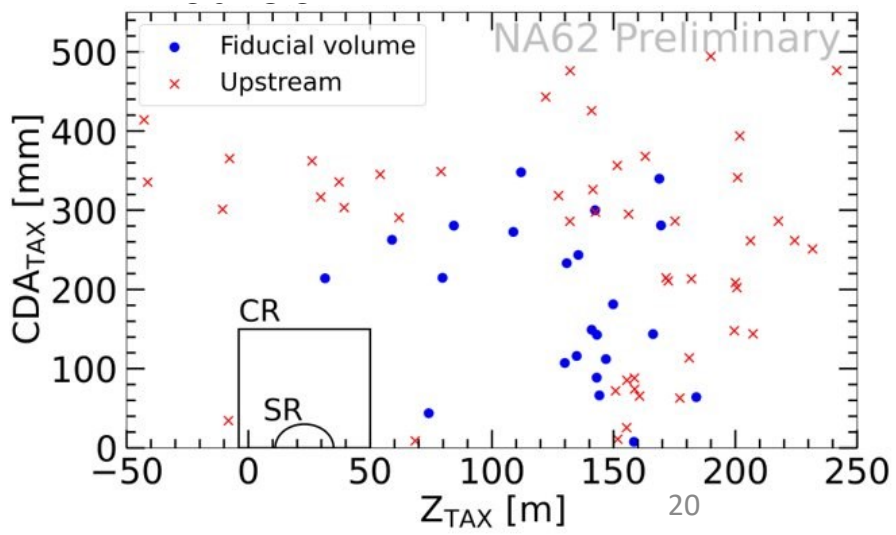
- require dilepton vertex with A' flight vector pointing back to the target
- track timing coincidence with the trigger
- no in-time activity at large angle veto detectors

- combinatorial background from mixing single-track events in data
- prompt background by muon secondaries from simulation corrected with data

muons



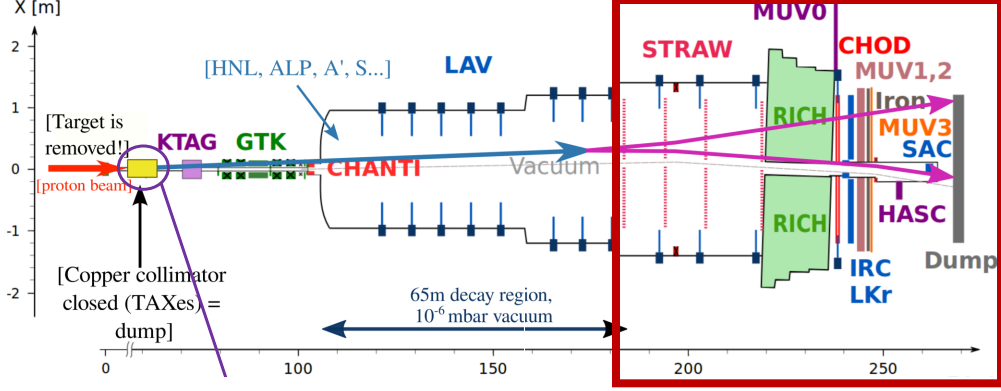
electrons

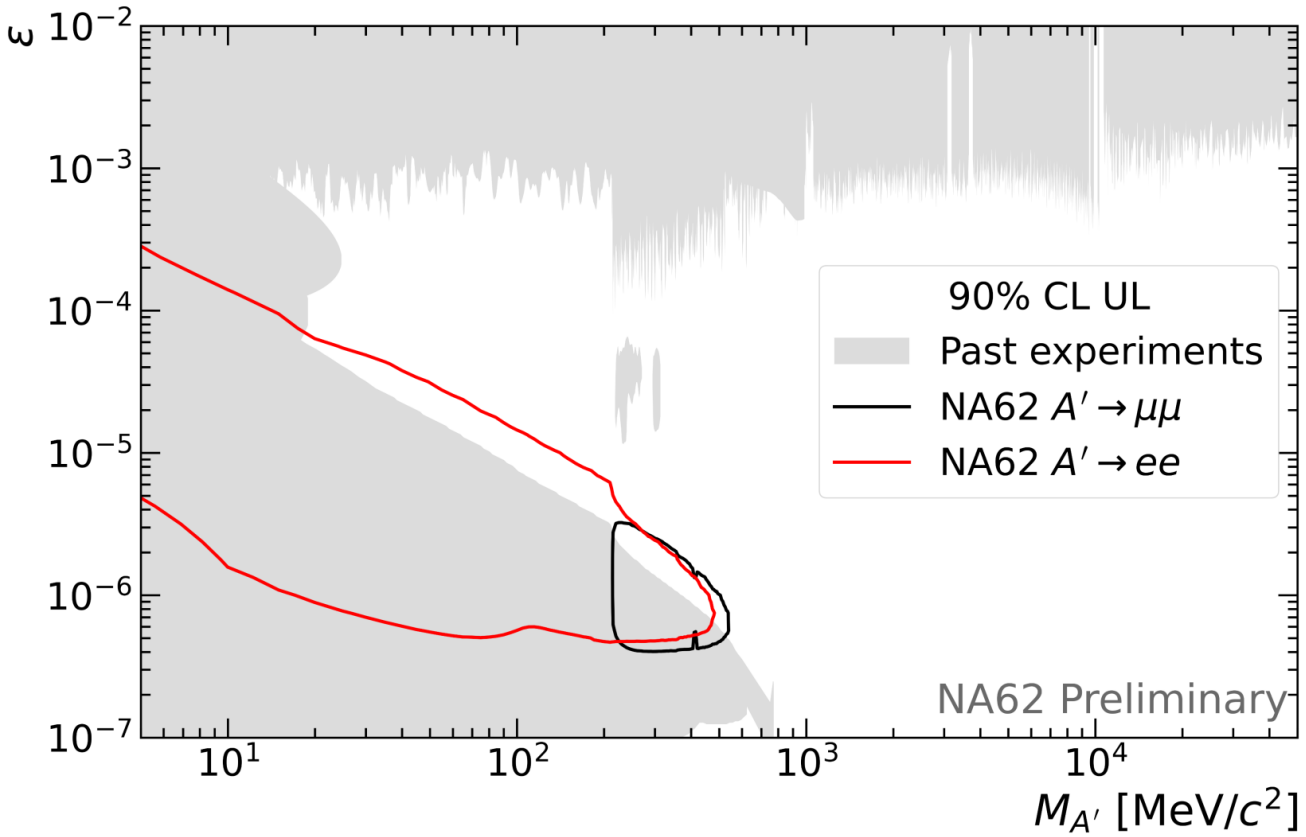


arXiv:2303.08666

A. Kleimenova @ La Thuile

Dark photons @ NA62



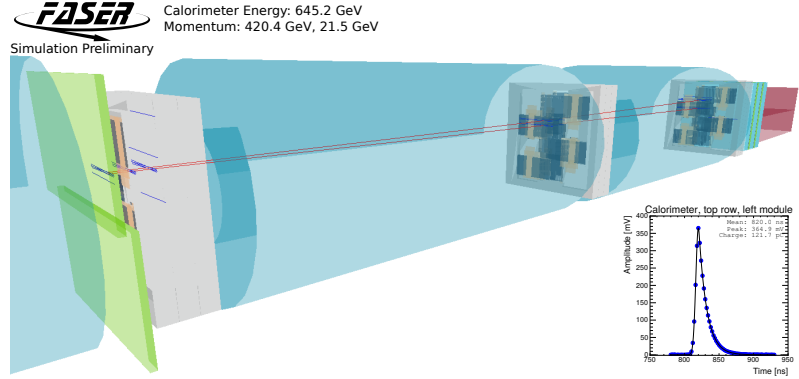


- results based on full 2021 dataset of $(1.4 \pm 0.3)\times10^{17}$ POT
- plan to collect 10^{18} POT in 2022-2025
- other final states ($\gamma\gamma$, $\pi^+\pi^-\gamma$) are being explored

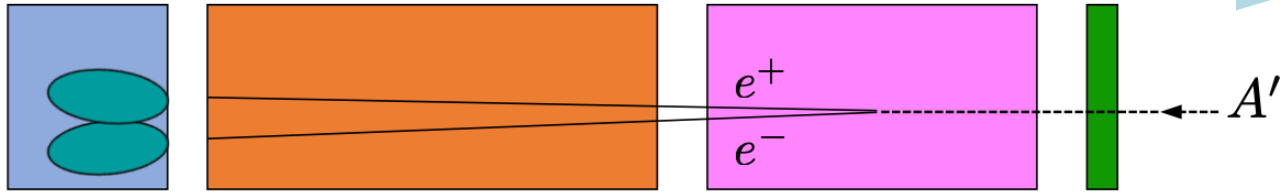
More in a talk by Slava Duk on Fri

arXiv:2303.08666 A. Kleimenova@La Thuile

Dark photons @ FASER



Innovation:
New experiment!

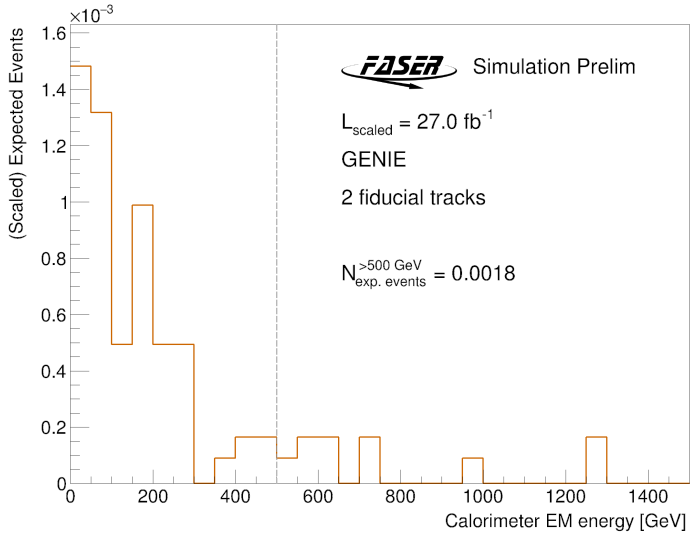


Energy measurement | Tracking | Decay volume | Scintillator veto

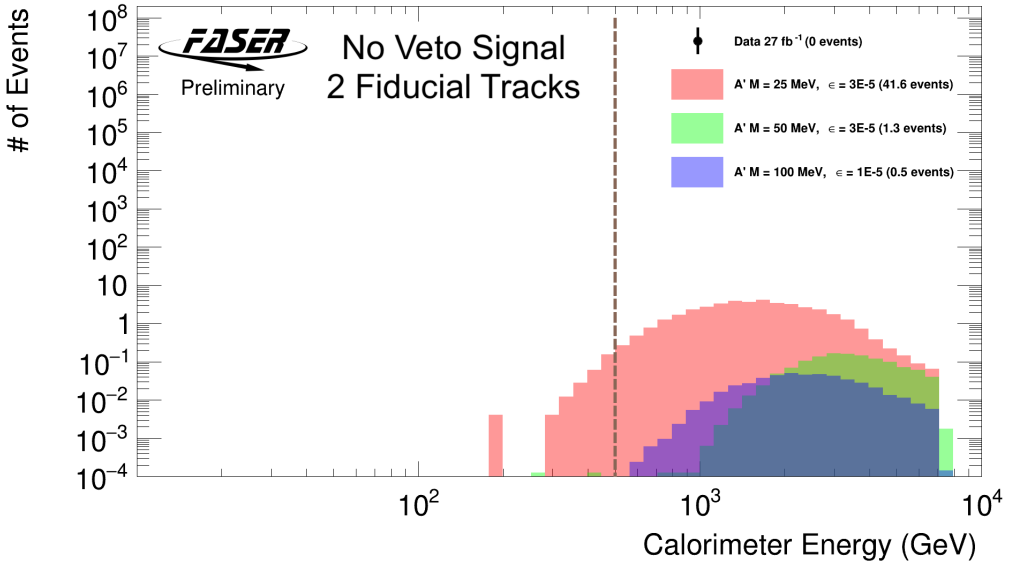
located 480 m away from ATLAS IP
shielded by 100 m of rock

- two good tracks and high energy deposit in ECAL, nothing in Veto detectors
- noncollision background from noncolliding bunches or runs w/o a beam
- neutrino background from simulation
- expect 0.0020±0.0024 events

Expected ν background

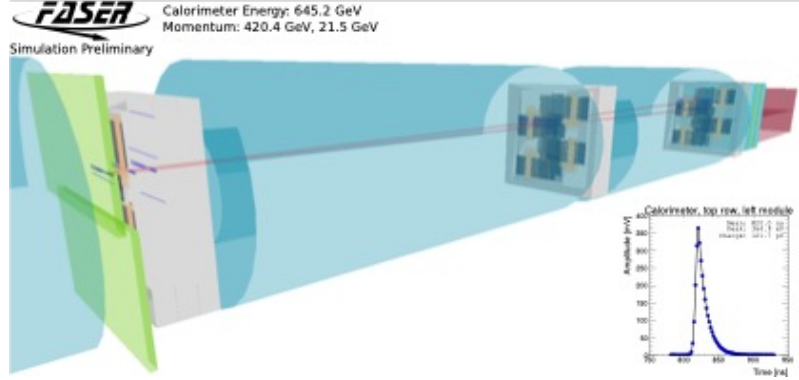


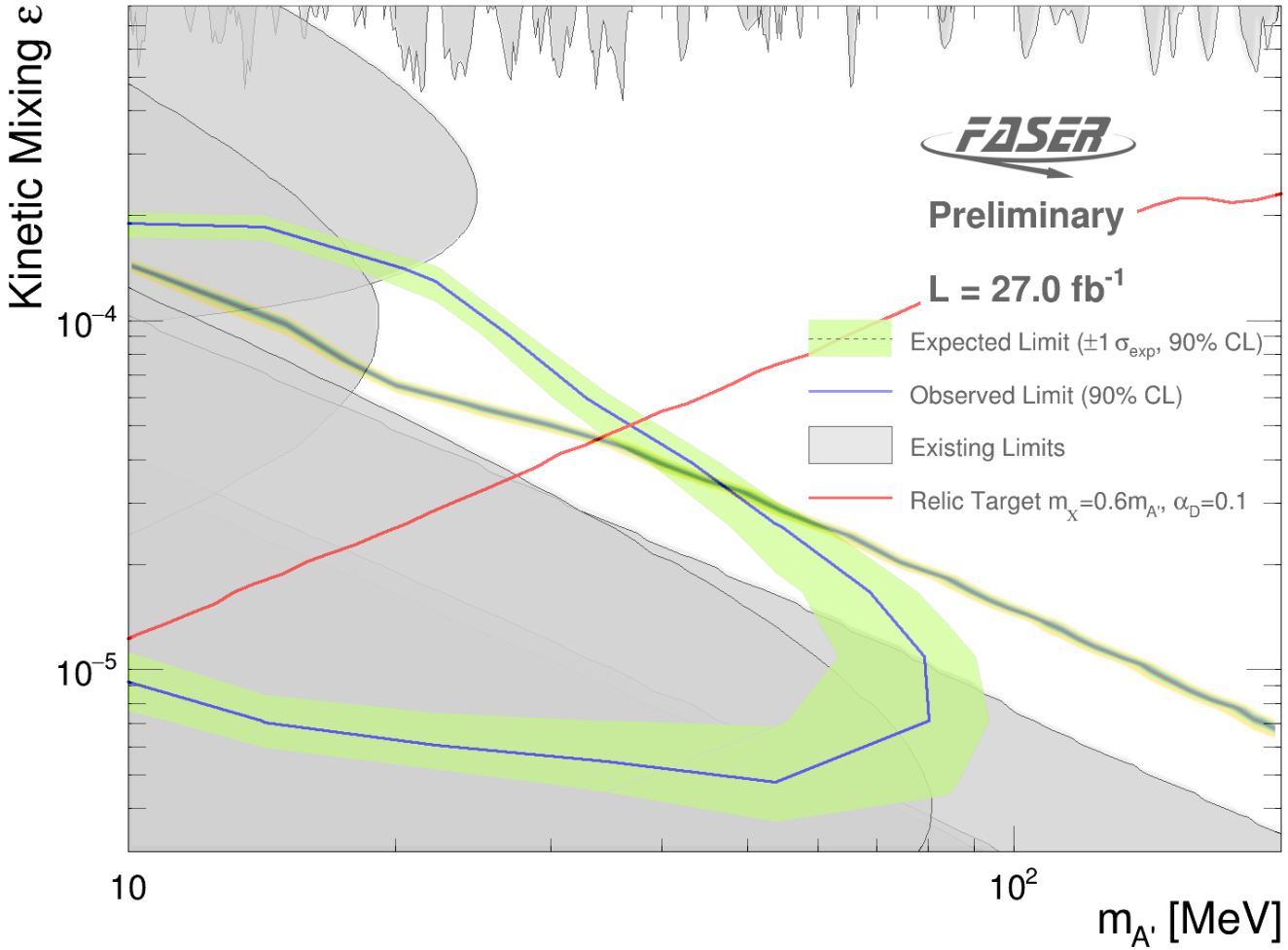
Signal region: 0 events observed



CERN-FASER-CONF-2023-001

Dark photons @ FASER





- Better sensitivity at lower masses compared to NA62
- FASER sensitivity is in the region motivated by the dark matter thermal relic density (red line, model-dependent):
  - chosen parameters lead to visible dark photon decays
  - region below the line leads to an over-abundance of DM and would be excluded cosmologically

NA62 result overlaid

More in a talk by Noshin Tarannum on Tue

CERN-FASER-CONF-2023-001

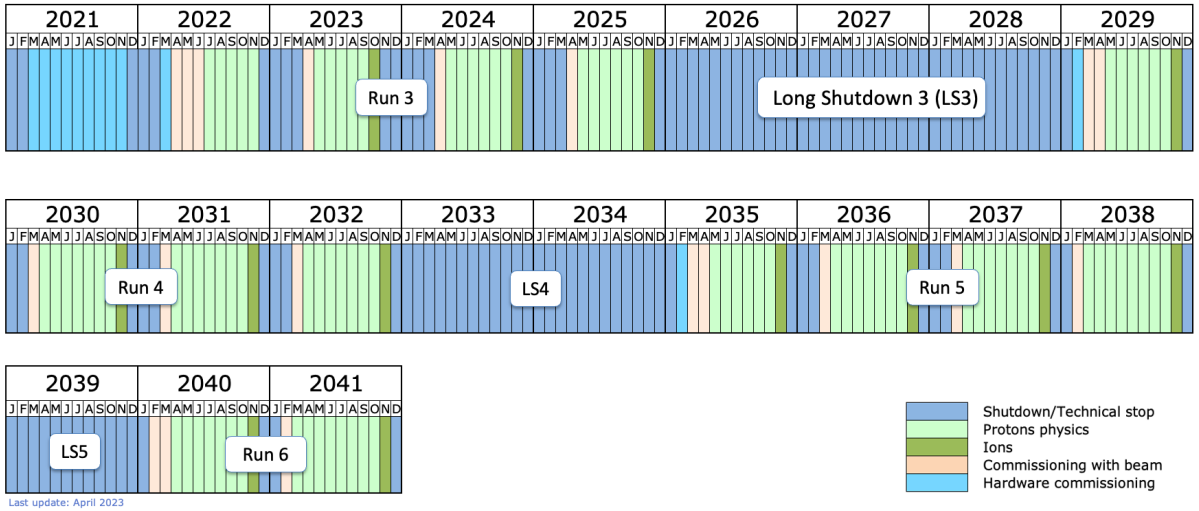
Future prospects: less model-dependence

crazy reconstruction ideas *triggers*

- Yesterday's ~~Nobel prizes~~ are today's ~~calibration channels~~
  - ATLAS/CMS/LHCb Run 3 review: arXiv:2110.14675
- New Run 3 hardware-stage (L1) trigger features:
  - ATLAS/CMS: **HCAL** timing (0.6/1 ns resolution)
  - ATLAS/CMS: ECAL/HCAL ratio (already exists in ATLAS Run 2) + timing
  - ATLAS/CMS: displaced **muon** (remove pp vertex constraint)
  - ATLAS/CMS: **showers** in muon system (target neutral LLPs decays)
  - LHCb: fully software trigger, 30 MHz event reconstruction
- HL-LHC: track trigger will allow to have track displacement in L1
  - ATLAS-TDR-029: "Technical Design Report for the Phase-II Upgrade of the ATLAS TDAQ System"
  - CMS-TDR-021: "The Phase-2 Upgrade of the CMS Level-1 Trigger"

Outlook

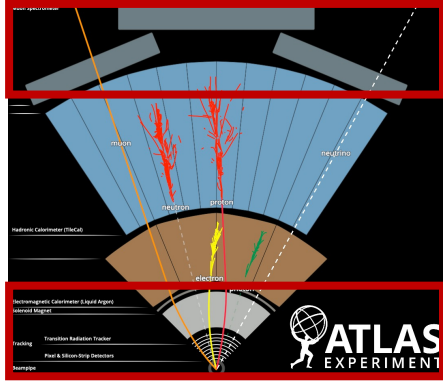
- Run 3 is an imminent testing ground for many new ideas from Run 2
- LLP program is continuous burst of creativity in data-handling:
  - non-conventional signatures require non-conventional detector usage
- It benefits from 3 ab^{-1} being collected over a decade:
  - can expect many new ideas to be born and realized during HL-LHC
  - proposed Forward Physics Facility (FPF) could house several new experiments for LLP searches in the forward region for the HL-LHC



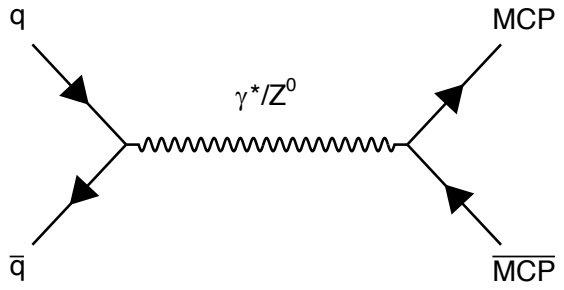
More in a talk by Roshan Mammen Abraham on Tue

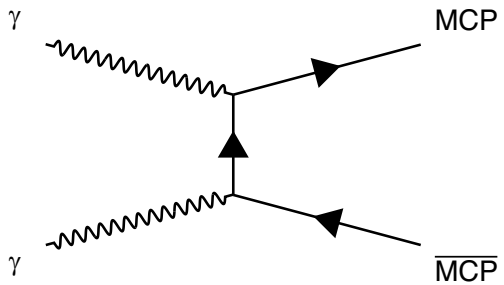
Extra

Multicharged particles

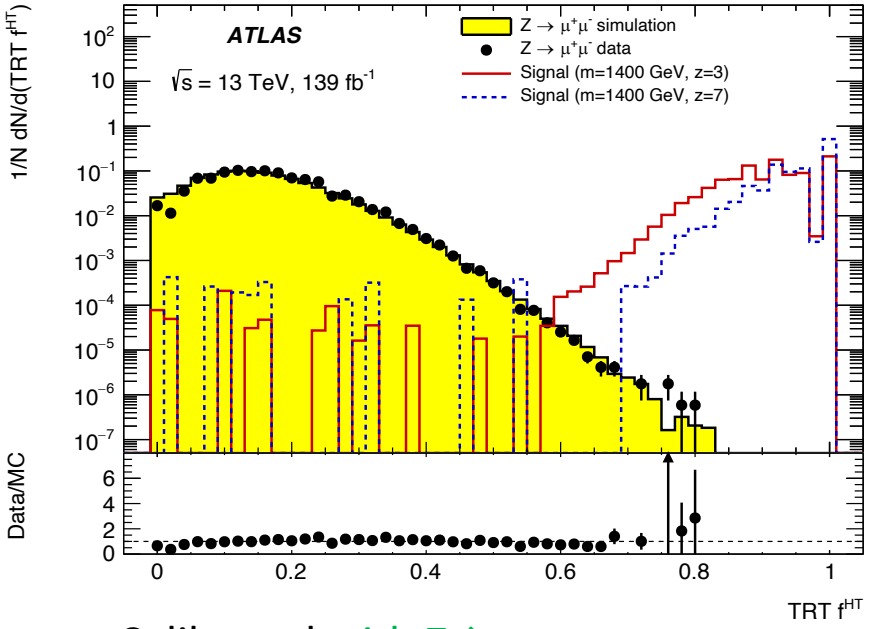


Triggers:
single muon;
p_T^{miss} > 90/110 GeV;
late-muon trigger



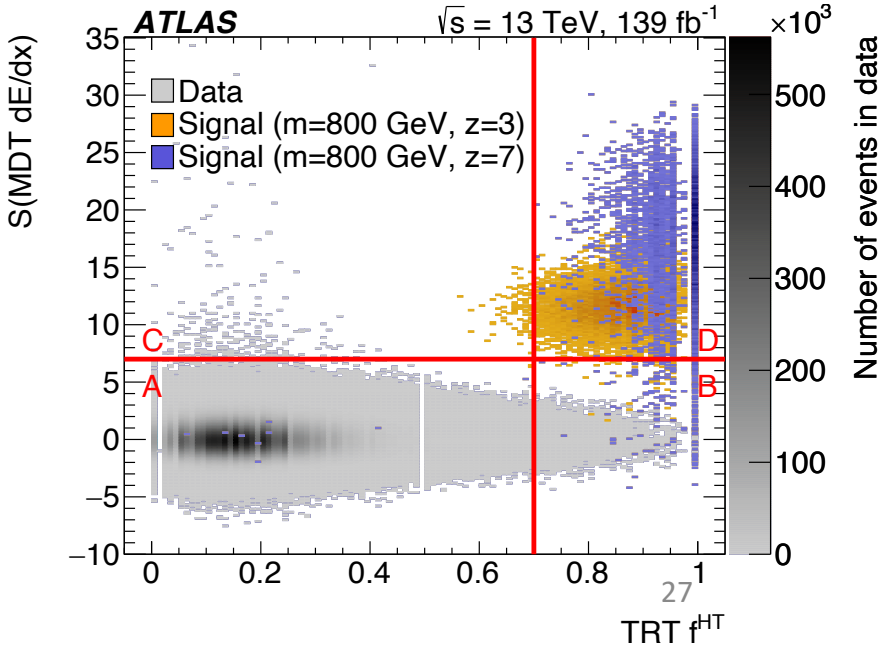


Innovation:
anomalous dE/dx in pixel, transition radiation tracker or muon system



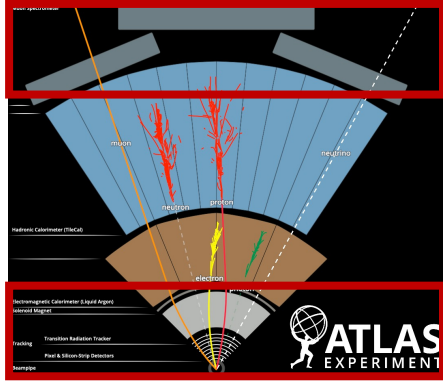
Calibrated with Z→μμ events;
trigger efficiency is corrected for possible late arrival to muon system

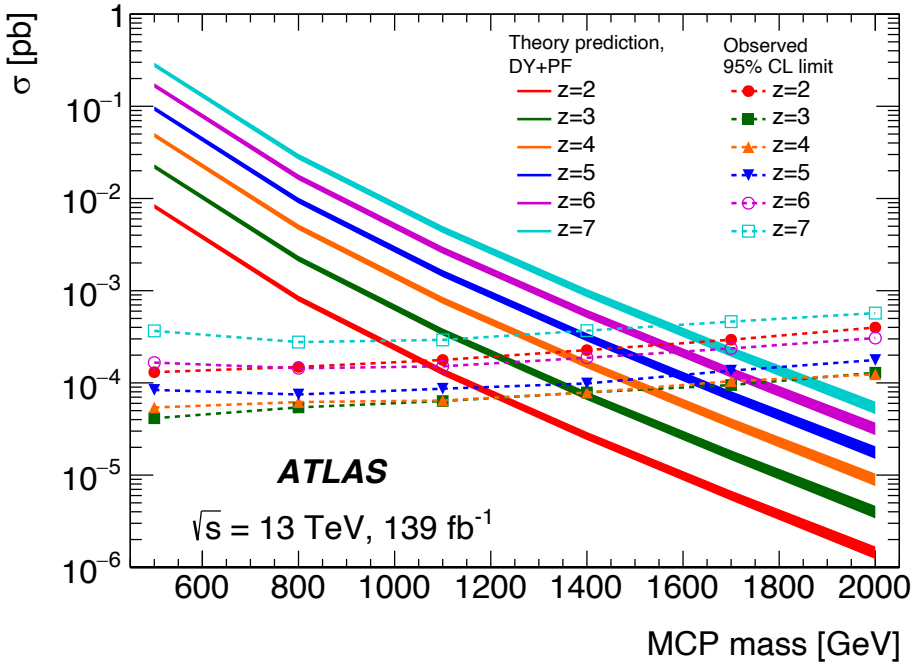
- require at least one "combined" muon with high dE/dx in the pixel, TRT or muon system
- main bkg from muons with high ionization due to occupancy effects
- estimated from data with ABCD method

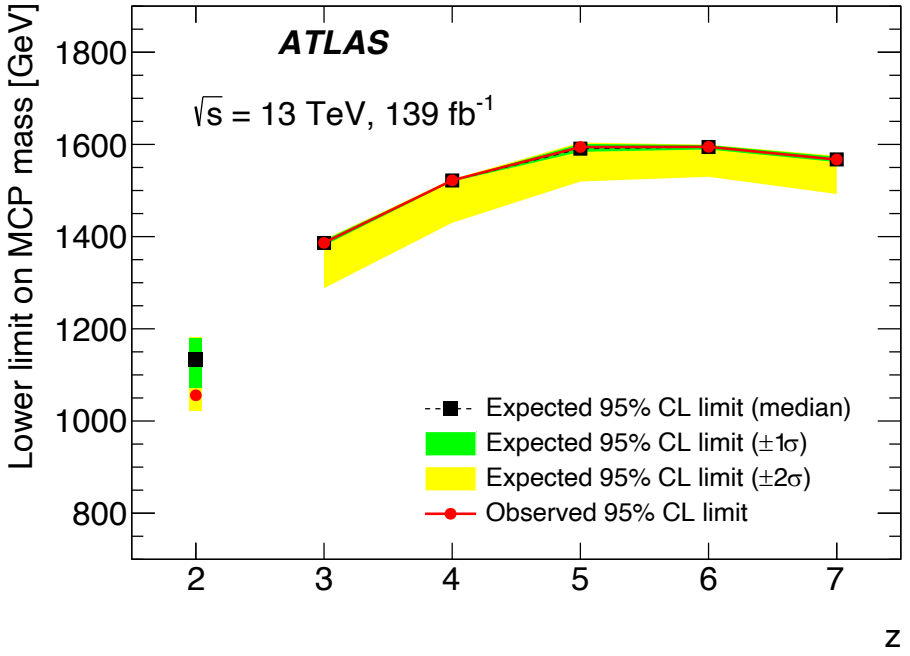


arXiv:2303.13613

Multicharged particles





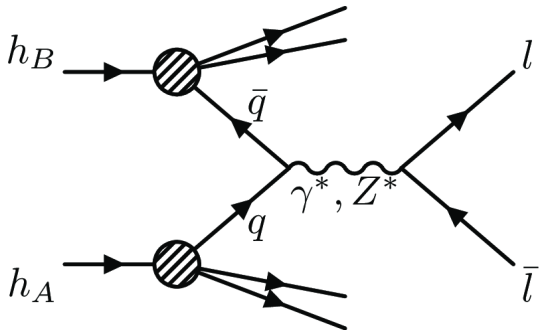


- 4 events observed in the z=2 search region with 1.6 ± 0.4 (stat) ± 0.5 (syst) expected
- No events observed in the z>2 search with 0.034 ± 0.002 (stat) ± 0.004 (syst) expected

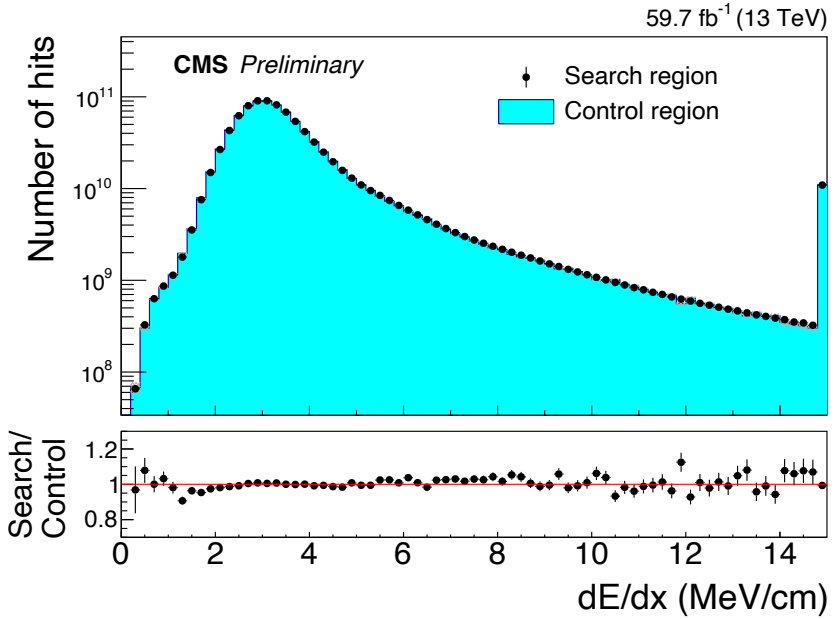
arXiv:2303.13613

Fractionally charged particles

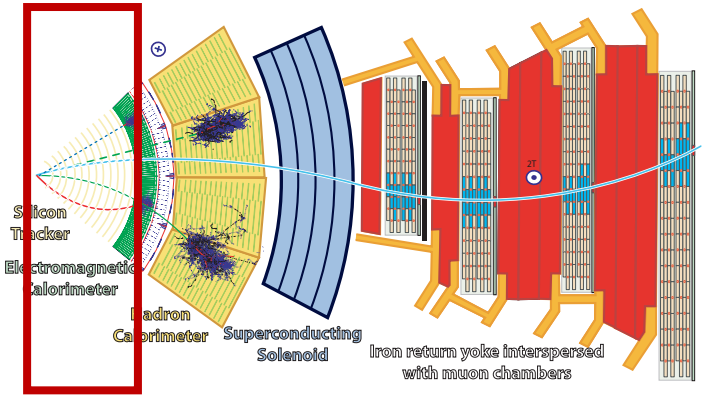
Trigger:
single muon



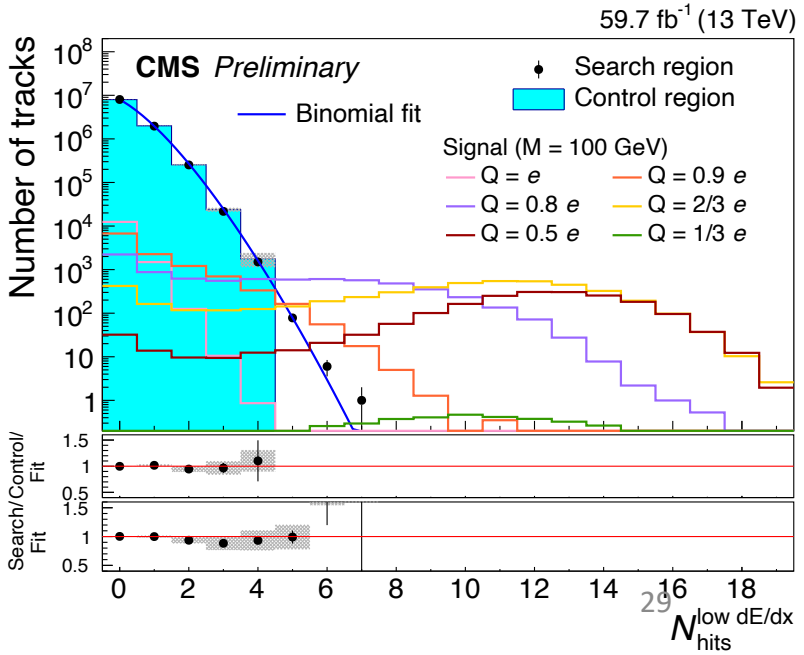
Innovation:
dE/dx measurement in the tracker



Calibrated with Z→μμ events

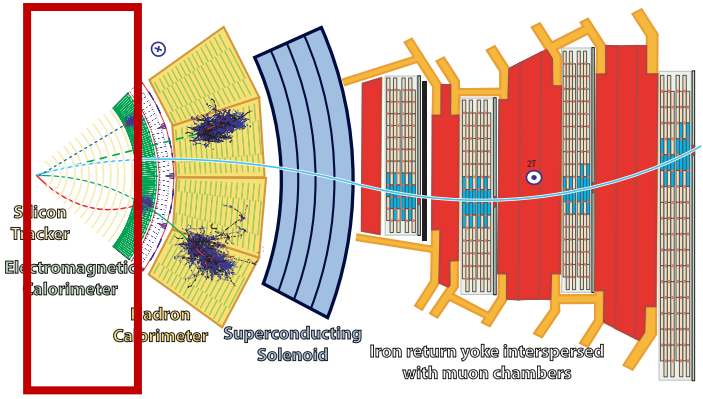


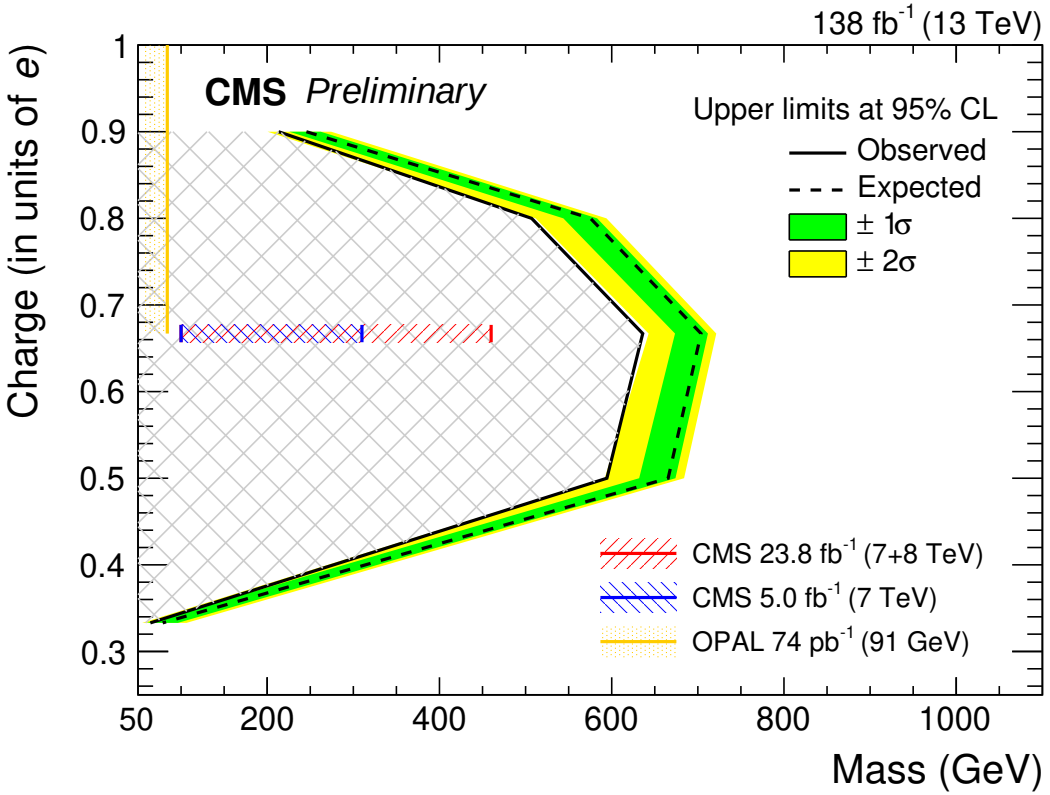
- require one or two (outside of Z peak) tracks with a number of hits with low dE/dx value
- veto tracker regions affected by radiation damage
- estimate bkg by extrapolating from control region with binomial fit



[CMS-PAS-EXO-19-006]

Fractionally charged particles





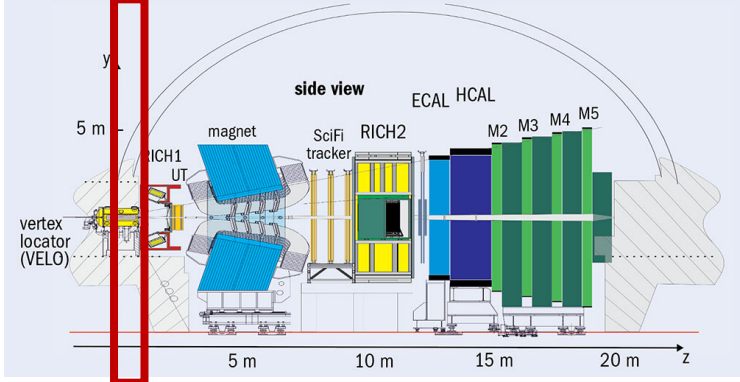
- For too low charges energy deposits in the tracker often fall below the readout threshold leading to loss of the signal efficiency
- Significant increase of sensitivity compared to previous searches

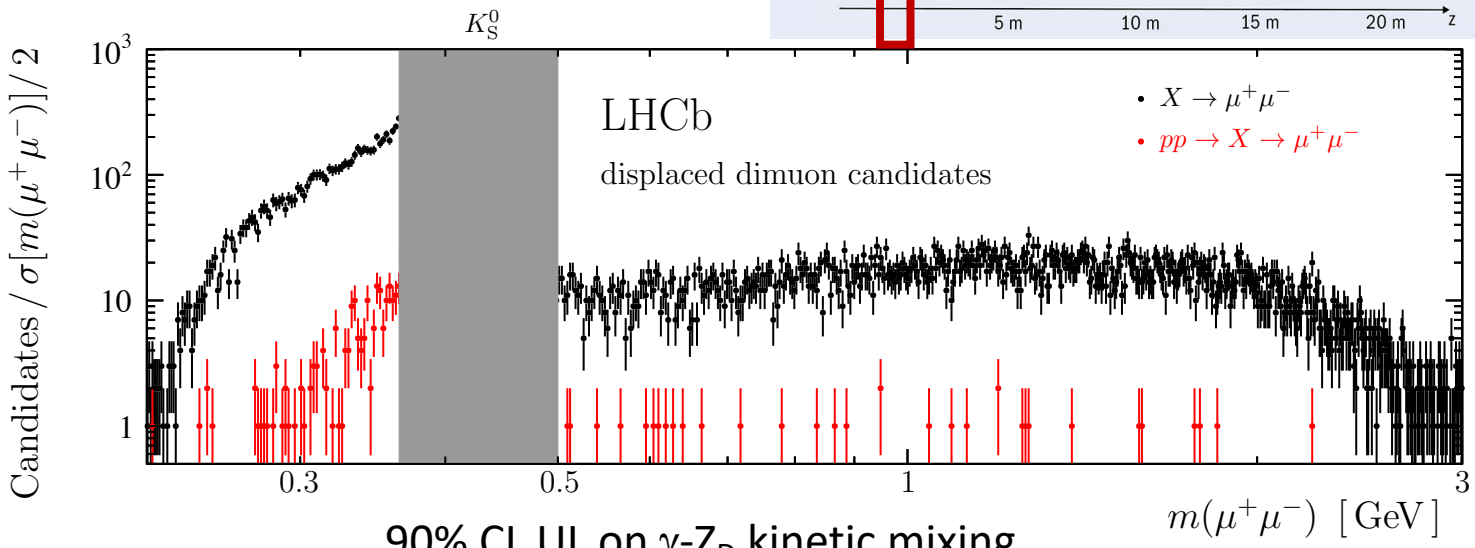
CMS-PAS-EXO-19-006

Displaced dimuons

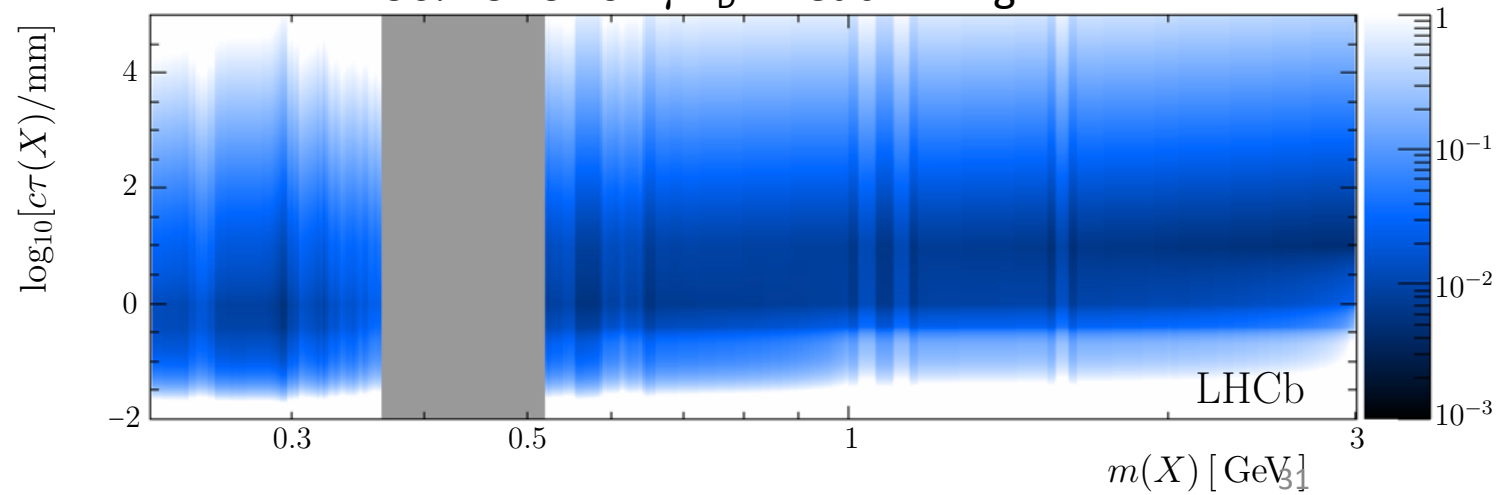
Innovation:
dedicated dimuon trigger
material map veto to suppress conversion

- require dimuon pair with SV transverse displacement between 12 and 30 mm
- new resonance X should be consistent with originating from PV
- veto material interactions and K_S
- interpreted in wide range of X lifetimes





90% CL UL on γ-Z_D kinetic mixing



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