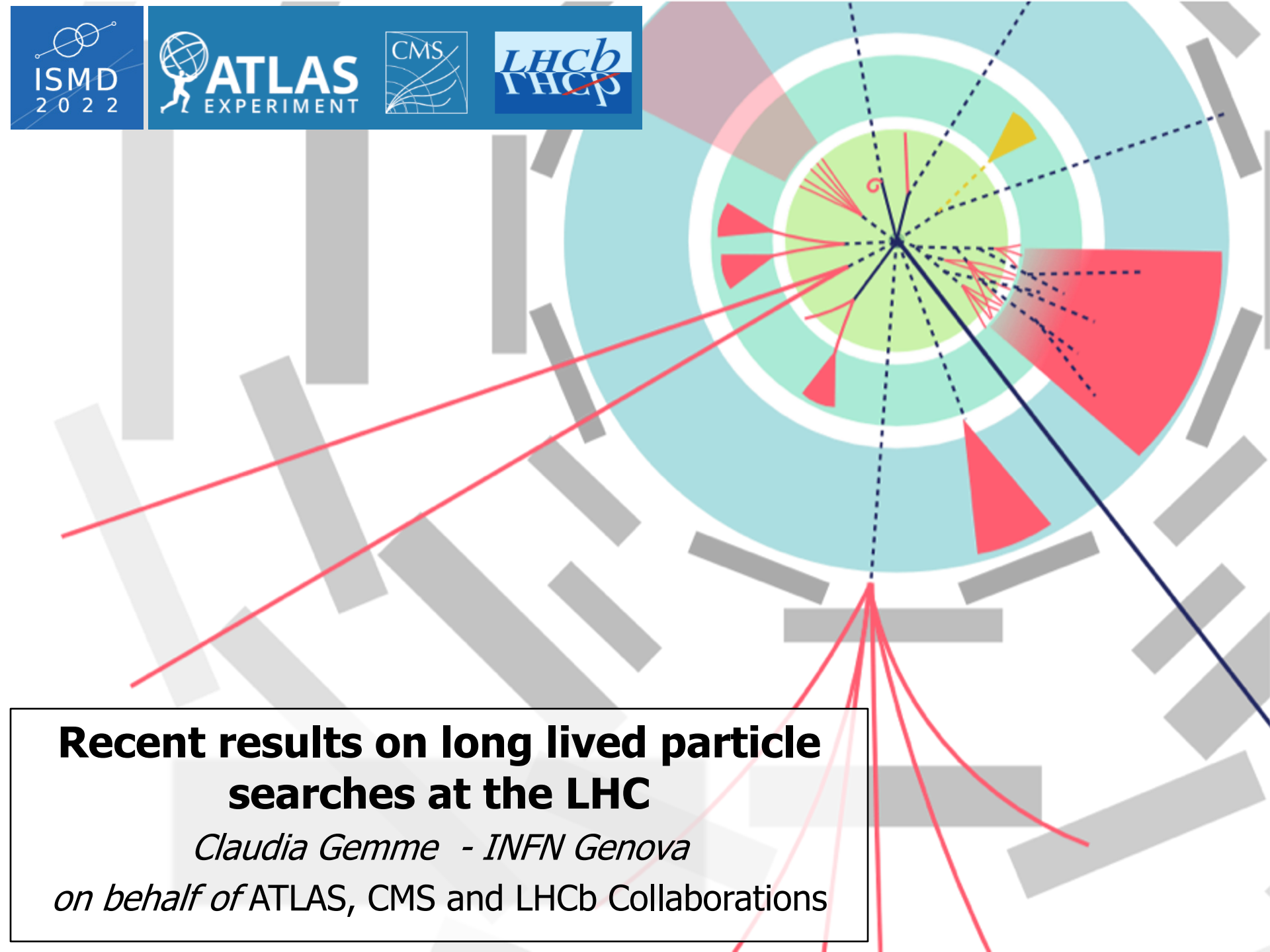


Recent results on long lived particle searches at the LHC

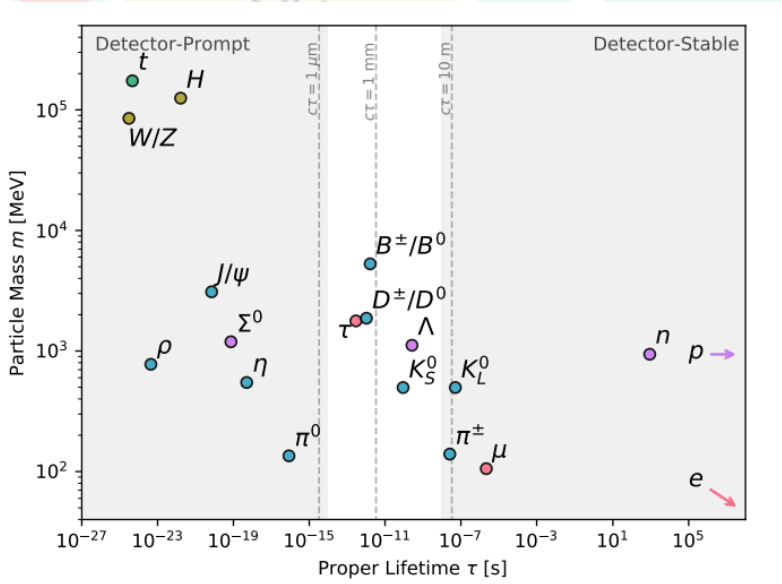
Claudia Gemme - INFN Genova

on behalf of ATLAS, CMS and LHCb Collaborations

Why *LLPs searches?*

- Long Lived Particles (LLPs) are BSM particles that decay inside the detector or, if charged, that are stable within the detector acceptance.
- LLPs do exist! New long-lived particles are both theoretically and experimentally motivated
  - small couplings
  - phase-space suppression
  - conserved (or nearly conserved) symmetries

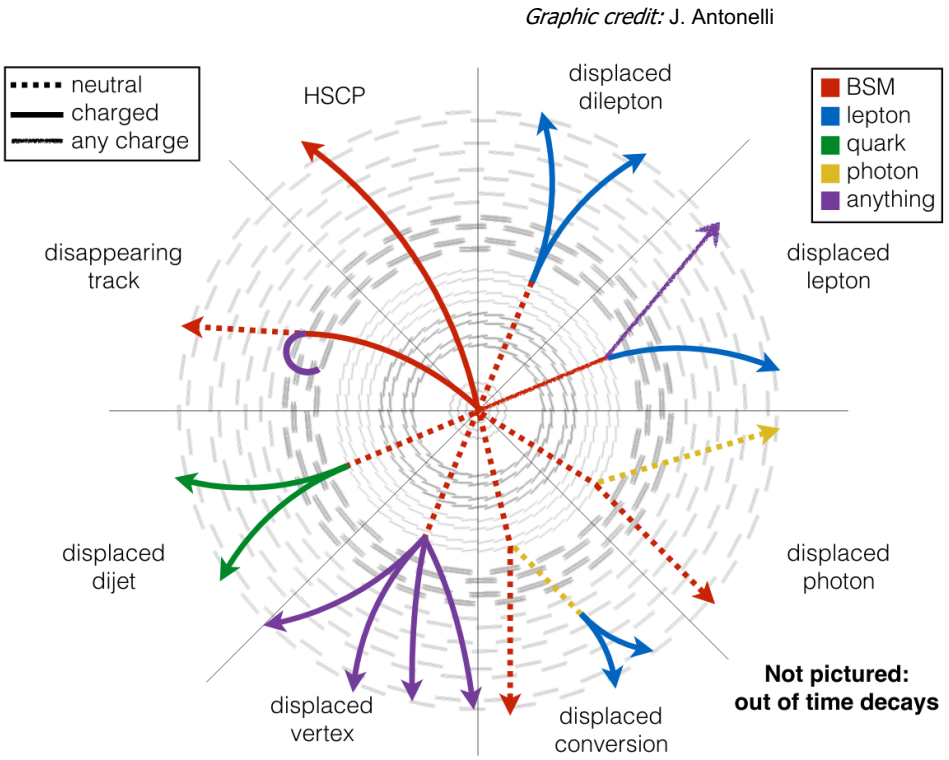
arXiv:1810.12602



- There is a strong increasing interest in BSM LLPs as our current extensive look at 13 TeV data yields impressive agreement with Standard Model expectations.
- Detectors upgrades are now using also these channels as benchmarks. It was not the case for the original construction.

How *to find LLPs?*

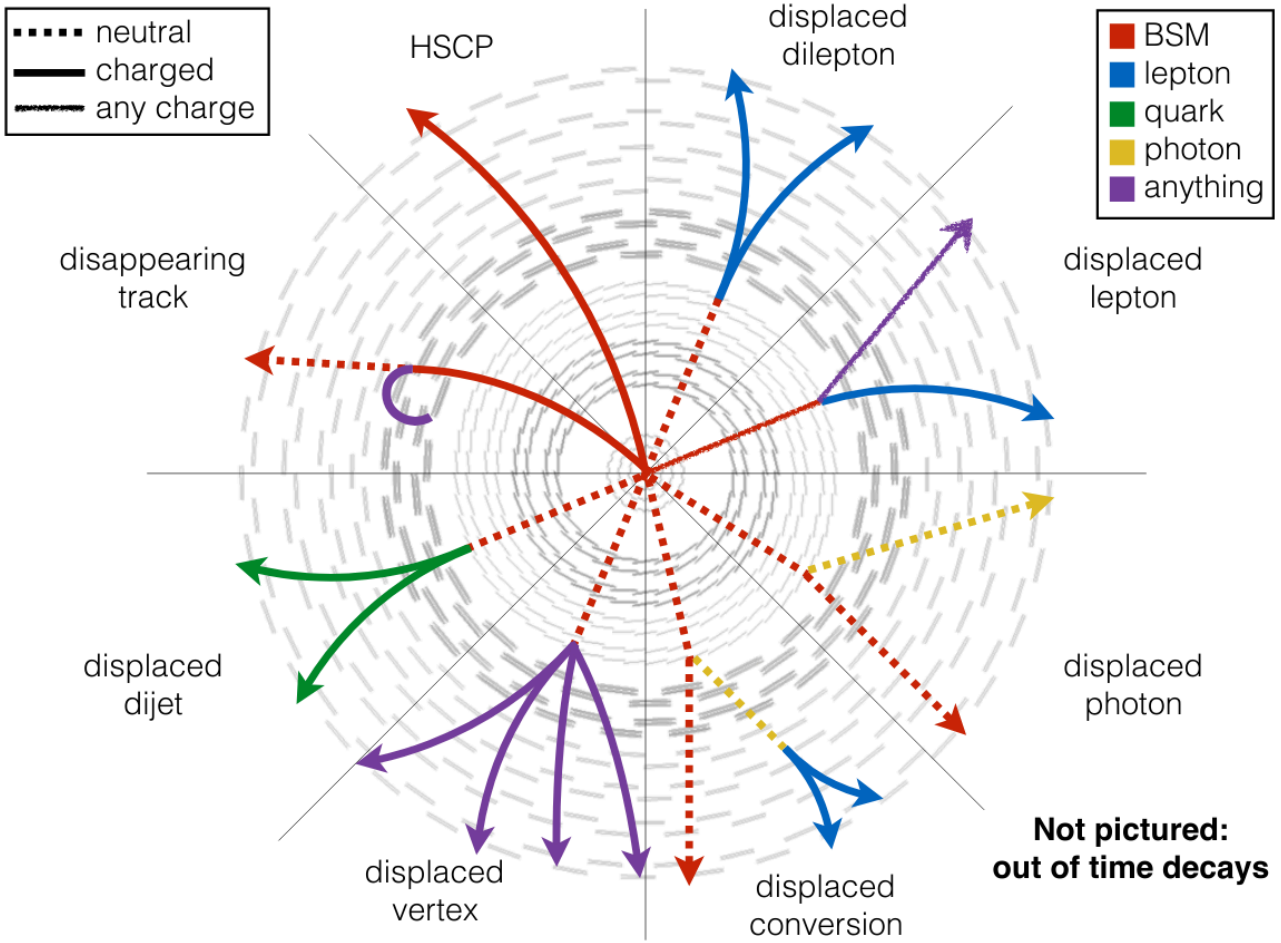
- Rather than theory driven LLP searches are signature driven. Multiple scenarios are then possible:
  - They can be light or heavy, can travel fast or slow.
  - They can decay to quarks, leptons, gluons... or even to invisible particles, leaving missing transverse momentum.
- Anomalous ionization, displacements and lifetime are the key signatures.



- Despite the different signatures, BSM LLPs have one thing in common: they are atypical topologies that offer appealing and challenging searches where algorithms, triggers and tools can be improved, as:
  - The estimation of non-standard backgrounds,
  - Loss of efficiency in reconstruction,
  - Reduced trigger performance.

Recent results

- A lot of searches in this area! Difficult to fit in a single talk!
- In the following few examples based on signatures.
  - In the backup, links to more measurements and overviews,

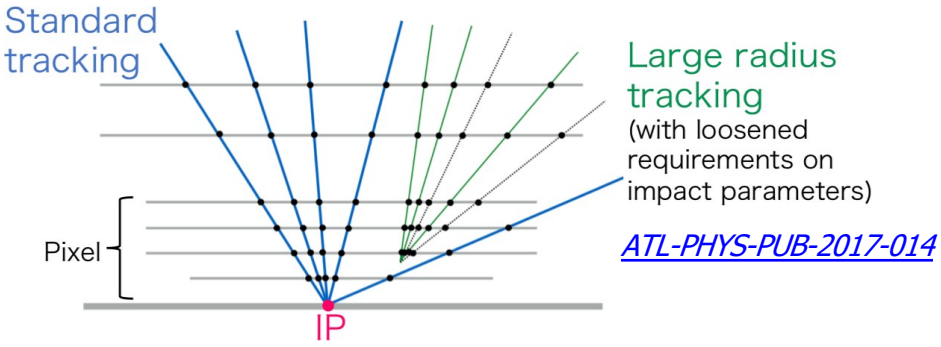


Jets + Displaced Vertices

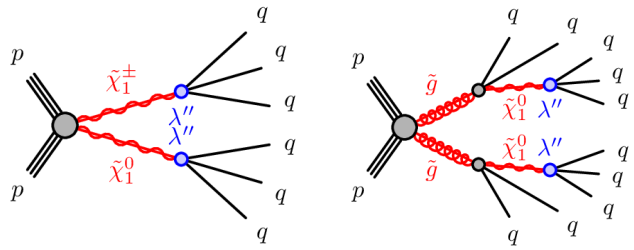
ATLAS

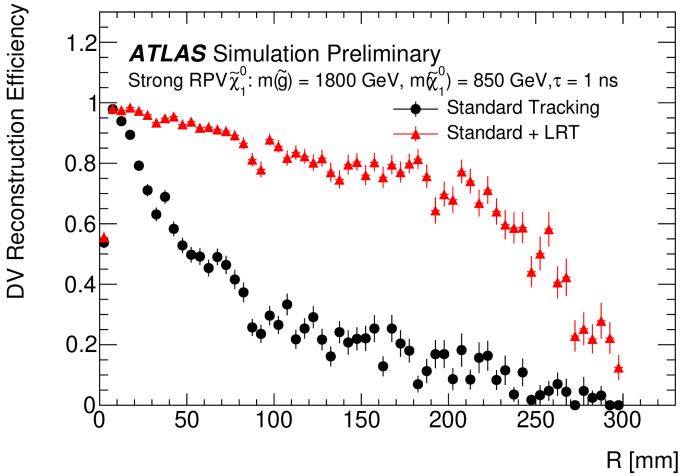
ATLAS-CONF-2022-054

- **Target**: General search for heavy LLPs decaying in the Inner Detector in hadrons
- **Signature**: Looking for an excess in multi-jet events with Displaced Vertices with high mass and multiplicity.
- **Algorithm:** Displaced Vertex reconstruction possible up to 300 mm thanks to Large Radius Tracking → Example of how algorithms improves for the LLP searches.



ATL-PHYS-PUB-2017-014





- Two cut-and-count SRs, one targeting trackless jets (for ewkinos) and the other targeting high p_T jets (for gluinos).

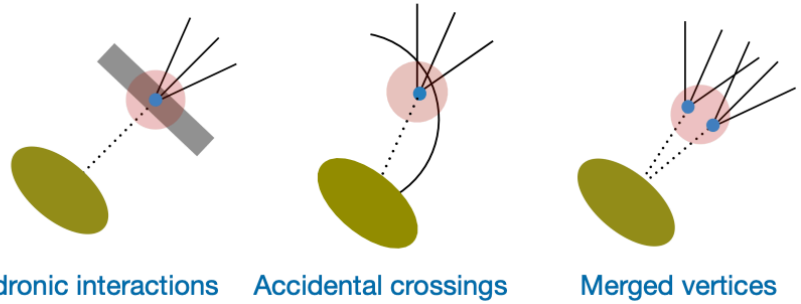
  Sensitivity to the EWK production is reached for the first time in this analysis!

Jets + Displaced Vertices

ATLAS

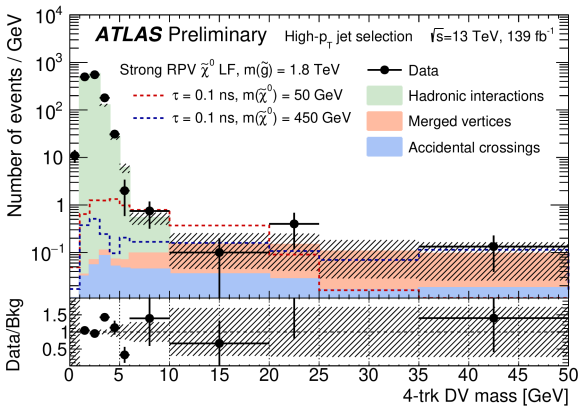
[ATLAS-CONF-2022-054]

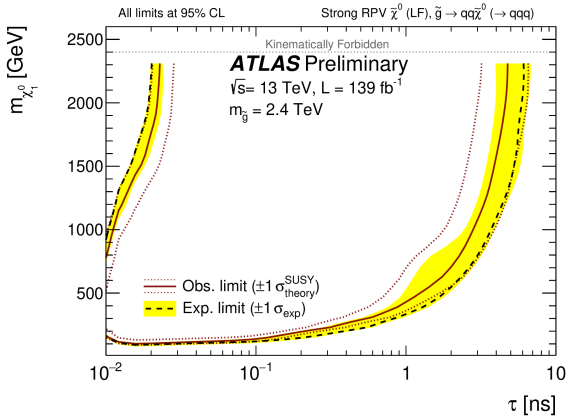
- Background: rare hadronic events, accidental track-crossing and close-by secondary vertices

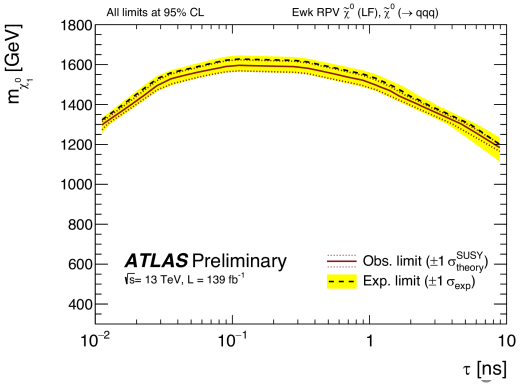


- Jet-DV correlation is measured in a signal-free CR and used to estimate the background in the SR
- No excess → limits are set on the SUSY benchmark models. At 95% CL, values up to 1.58 TeV for = 0.1 ns excluded, and the limit surpasses 1.5 TeV for all lifetimes in the range from 0.03 ns to 1 ns

	Expected	Observed
High-p_T SR	$0.46^{+0.27}_{-0.30}$	1
Trackless-jets SR	$0.83^{+0.51}_{-0.53}$	0





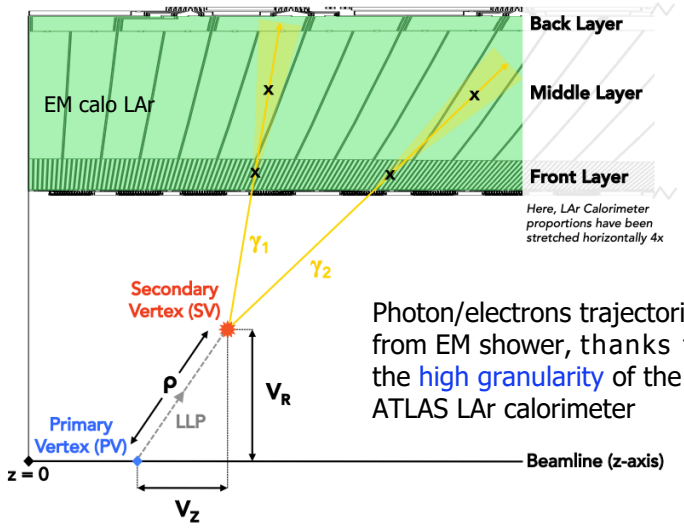


Displaced di-photon vertex

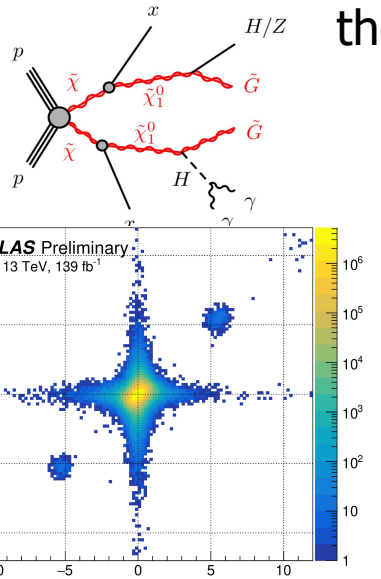
ATLAS

ATLAS-CONF-2022-051

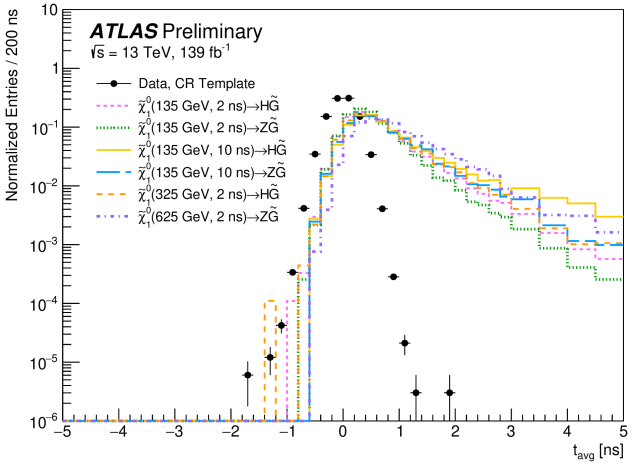
- **Target**: long lived heavy particles, originating displaced H→γγ or Z→ee decays
- **Signature**: Exploit LAr arrival time (t_{avg}) as well as the mass and 2D position (ρ) of the Displaced vertex.
- **Benchmark** model: gauge-mediated SUSY breaking model, LLP pair produced, then decaying into H or Z.



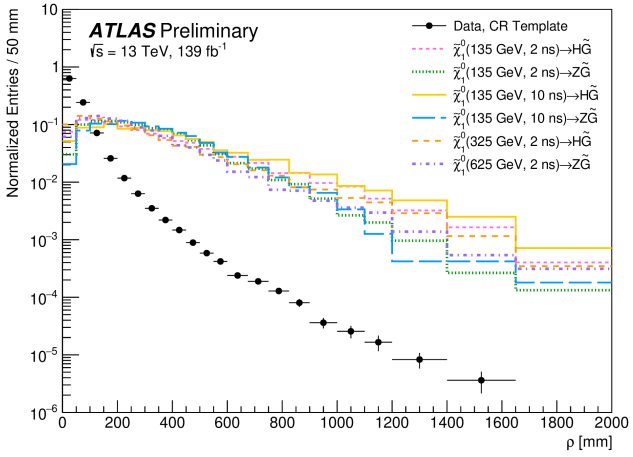
Photon/electrons trajectories from EM shower, thanks to the high granularity of the ATLAS LAr calorimeter



electron LAr timing, satellite collisions are visible



AArrival timing for the bkg in the SR +signals



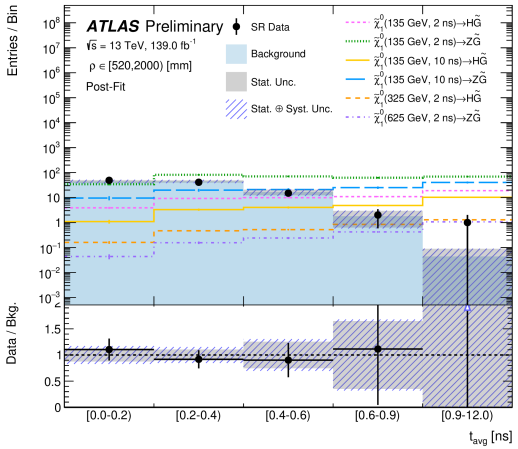
Displacement for the bkg in the SR +signals

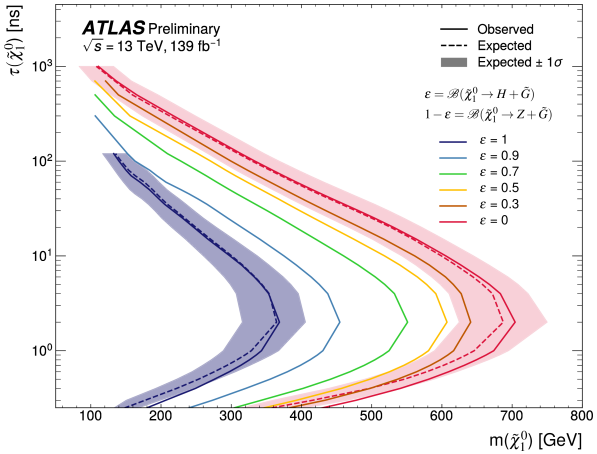
Displaced di-photon vertex

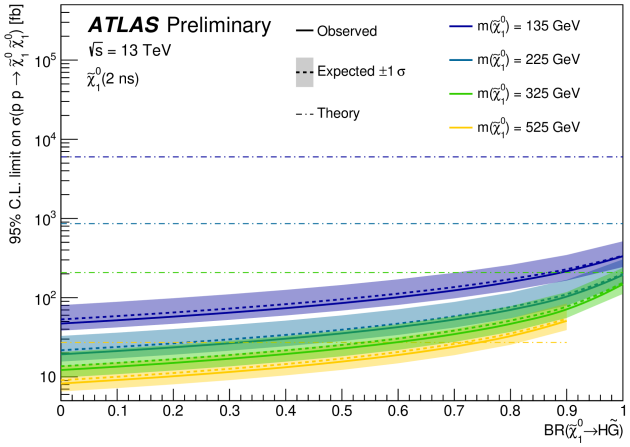
ATLAS

ATLAS-CONF-2022-051

- Background: due to fake and mis-measured photons
- Likelihood fit of t_{avg} in different bins of ρ, background estimated from t_{avg} templates from CR
- No disagreement with S M observed → strong limits on neutralino masses and lifetimes







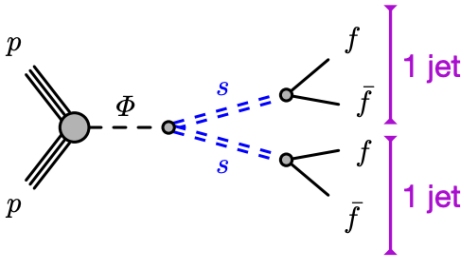
Backup: Similar analisis with displaced photons, w/o vertex request: ATLAS-CONF-2022-017

Displaced Jets in Hadronic Calo

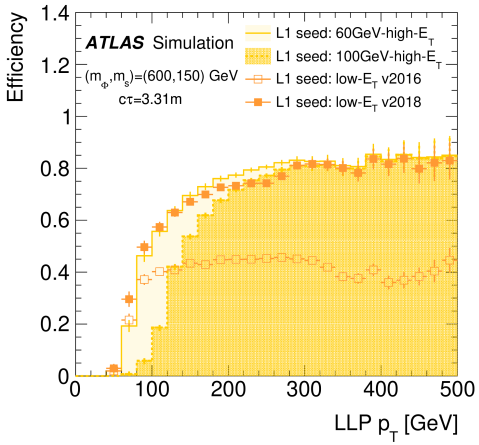
ATLAS

EXOT-2019-29
JHEP 06 (2022) 005

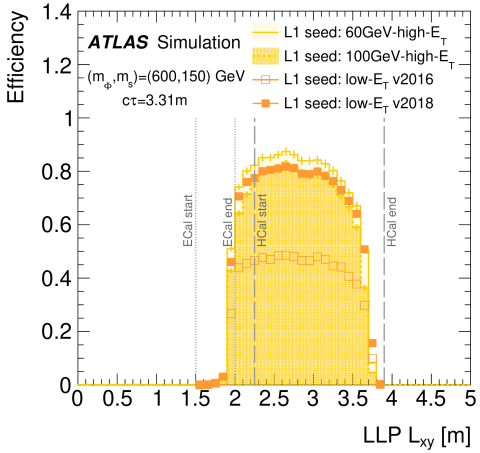
- **Target:** pairs of neutral long-lived particles decaying to SM fermions in the Calorimeter
- **Benchmark** model: Hidden Sector with a heavy neutral boson, ϕ, decaying to two long-lived neutral scalars, *s*, that decay to pairs of SM fermions
- **Signature**: two narrow single jets, trackless and with an unusually high proportion of energy in the hadronic calo.
- **Trigger**: Dedicated CalRatio* triggers specifically designed for this search.



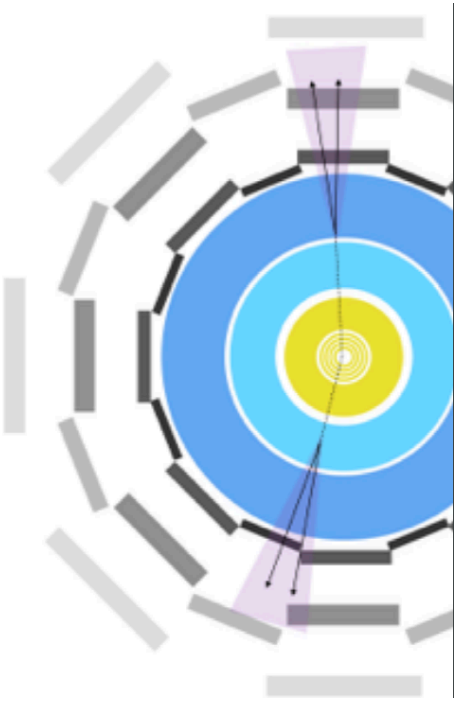
- Two search regions are defined for different LLP kinematic regimes.



Trigger efficiency for simulated signal events as a function of the LLP p_T



Trigger efficiency for simulated signal events as a function of the LLP Lxy



** logR = $log_{10}(E_H/E_{EM})$*

Displaced Jets in Hadronic Calo

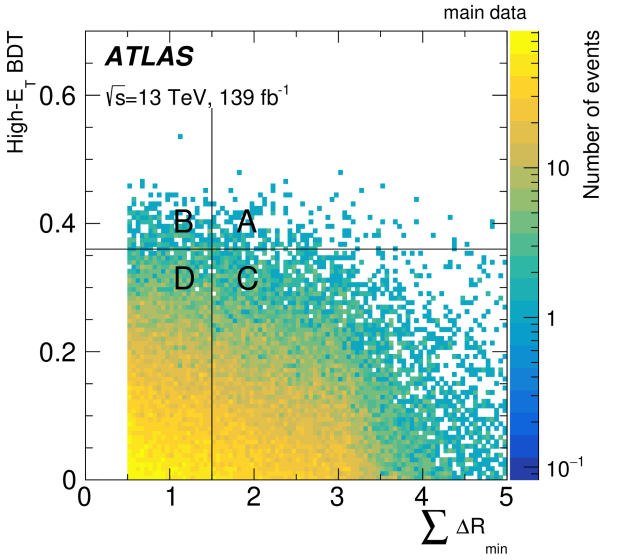
ATLAS

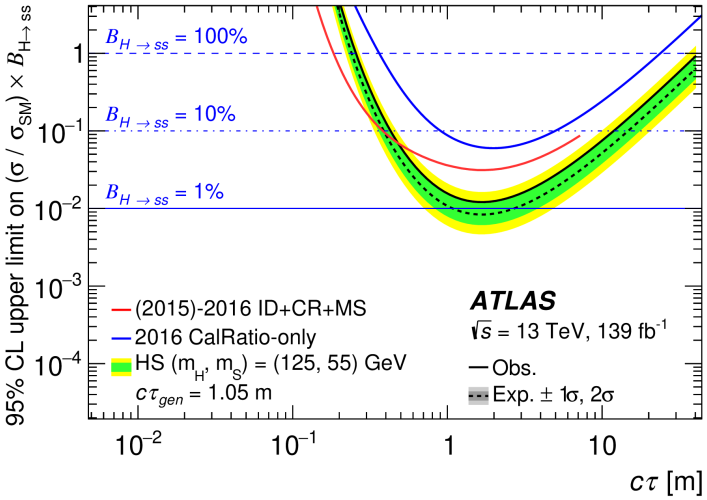
EXOT-2019-29
JHEP 06 (2022) 005

- Backgrounds:
  - Dominant is multi-jets: low probability to mimic signal, but dominant due to high cross-section → estimated using data-driven methods.
  - Subdominant: beam-induced background (BIB) and cosmic muons
- Use innovative ML techniques for signal-jet identification
- No disagreement with S M observed

→ For a SM Higgs boson with a mass of 125 GeV, branching ratios above 10% are excluded at 95% confidence level for values of ct between 20mm and 10m depending on the model.

→ Upper limits are also set on the cross-section times branching ratio for scalars with a mass of 60 GeV and for masses between 200 GeV and 1TeV.



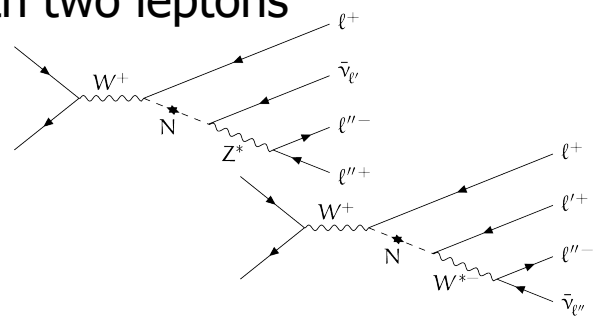


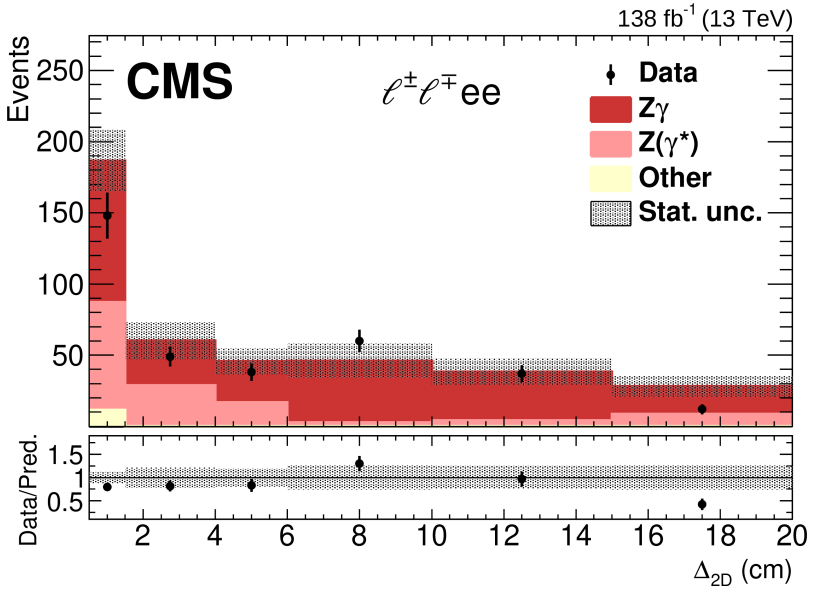
Displaced Heavy Neutral Leptons

CMS

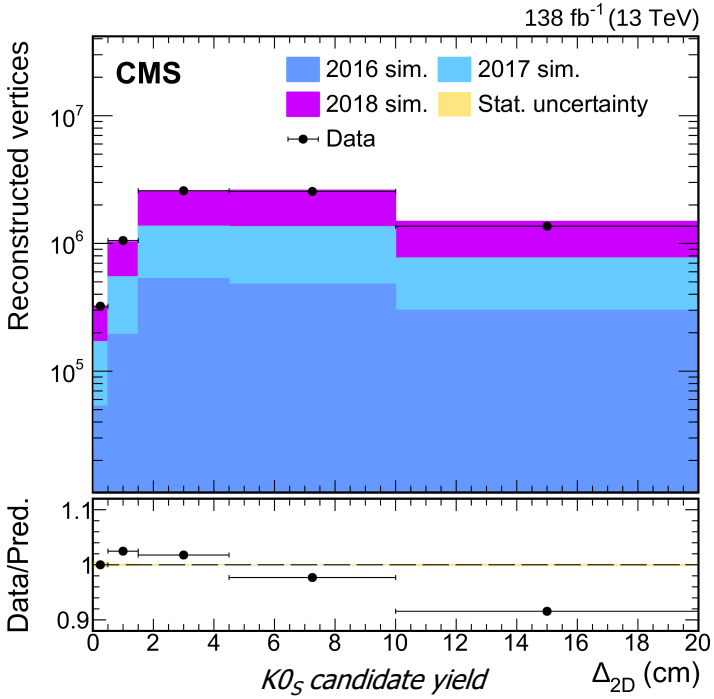
CMS-EXO-20-009

- ✓ **Target:** search for LL Heavy Neutral Leptons (N)
- ✓ **Benchmark** model: right-handed Dirac or Majorana neutrinos, mix to SM-υ
- ✓ **Signature**: Prompt lepton and displaced vertex with two leptons
  - Needed well reconstructed displaced leptons
  - Reconstruct vertex from displaced lepton pair
  - Validation of displaced reconstruction
    - Displaced electrons: asymmetric photon conversions
    - Displaced muon: J/ψ from B, and K_S decays





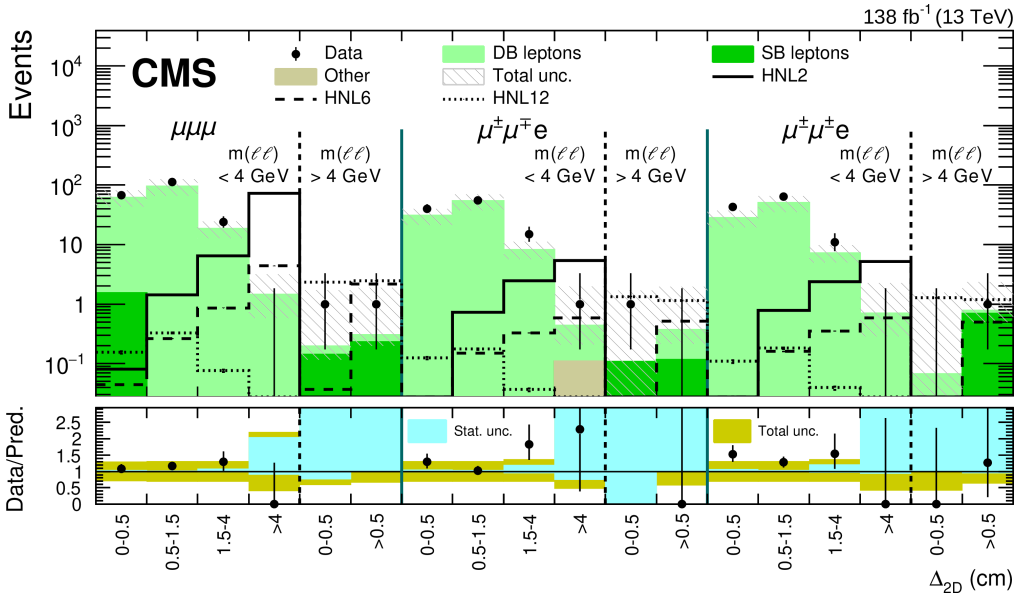
Events are selected in the final states with four leptons, with one (or two) of the leptons identified as displaced electron(s). The distribution of the Δ2D variable is presented (transverse displacement of vertex).



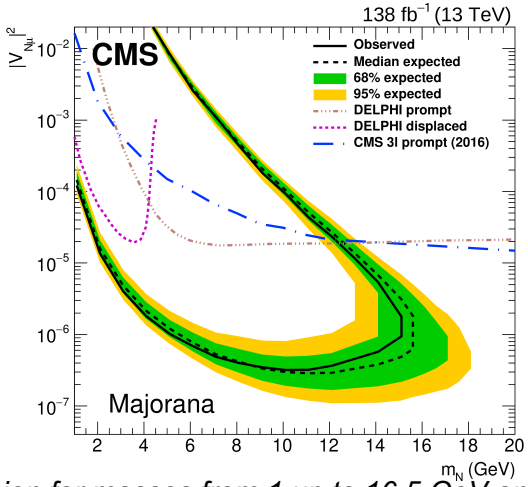
Displaced Heavy Neutral Leptons

CMS [CMS-EXO-20-009]

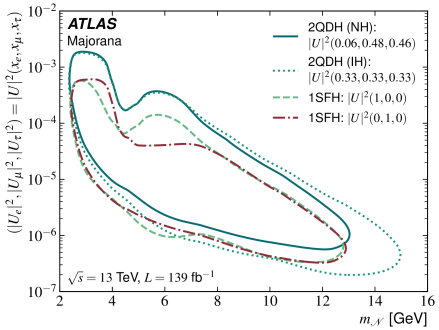
- Data-driven Bkg Estimation
  - Tight-to-loose ratio with lepton isolation. Two main type of bkg: Single Background (SB) leptons = uncorrelated sources for the leptons or Double Background (DB) leptons = leptons produced in same decay chain.
- Results
  - No significant excess observed
  - Constraints are derived for models with a single HNL generation of Majorana or Dirac nature, coupled exclusively to electrons or muons.
- *Similar analysis in ATLAS arXiv:2204.11988 and in LHCB https://arxiv.org/pdf/2011.05263.pdf*



Search regions for the μμX final states. Predictions for signal events are shown for several benchmark hypotheses for Majorana HNL production.



ATLAS arXiv:2204.11988



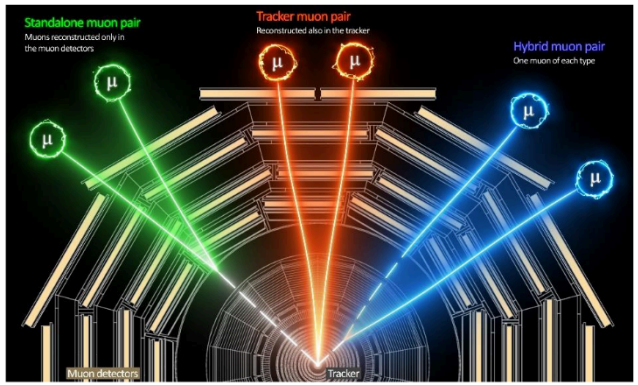
Exclusion for masses from 1 up to 16.5 GeV and squared mixing parameters as low as 3.2 × 10−7 ,

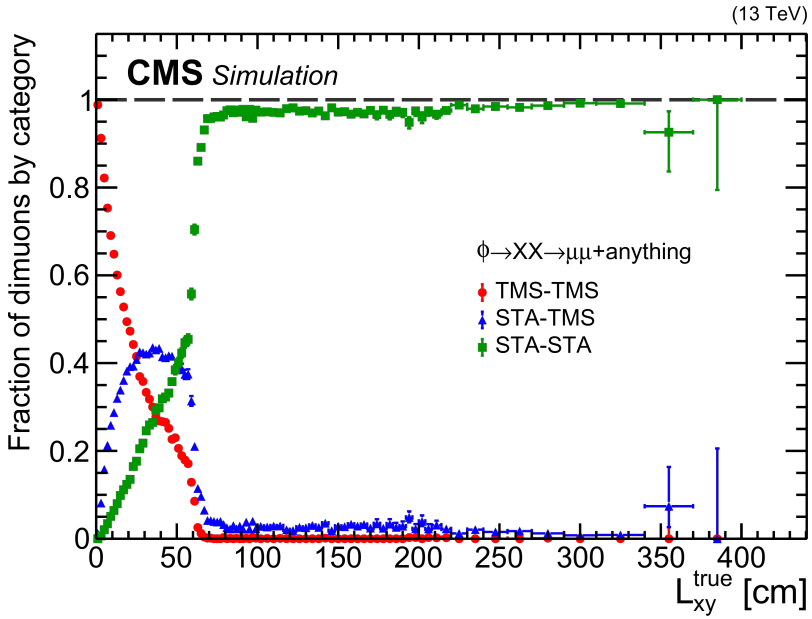
Displaced di-muon vertex

CMS

CMS-EXO-21-006
2205.08582 (JHEP)

- **Target**: long lived particles decaying to muons at distances ranging from few tens of um to several meters
- **Signature**: pair of OS charged muons originating from a common displaced vertex.
  - Splitted in three categories that are optimized separately
- Triggered with muons only in muon chambers (no vertex constraint).
- Background:
  - Cosmics, multijets, low-mass… suppressed with selection.
  - Prompt misreconstruction estimated from control region with $|\Delta\Phi(p_T\mu\mu, L_{xy})| > 3\pi/4$.
  - Non prompt estimated from control region with SS dimuon vertices.

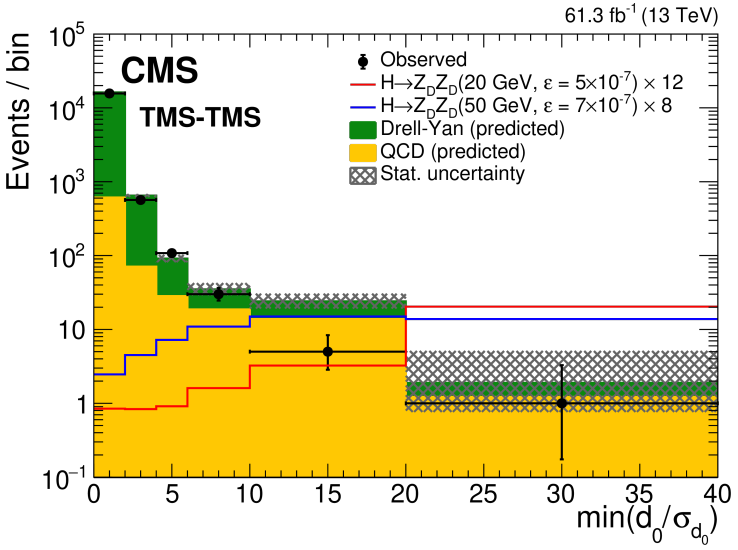


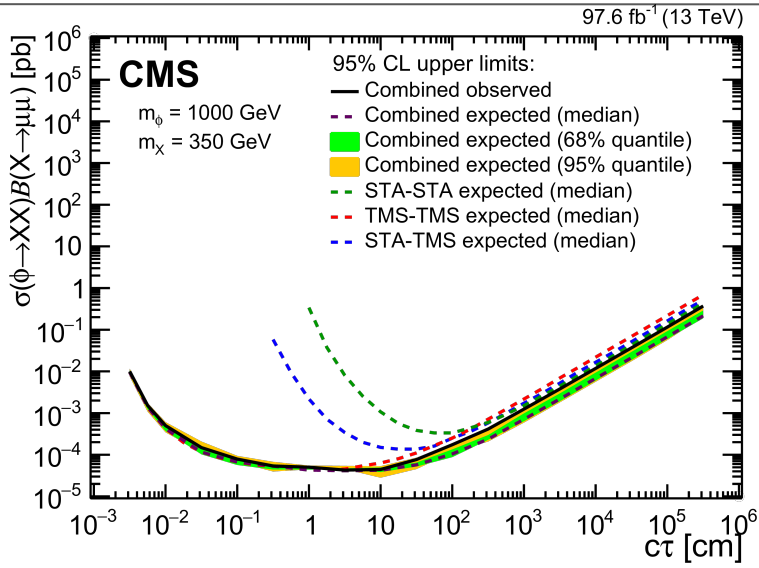


Displaced di-muon vertex

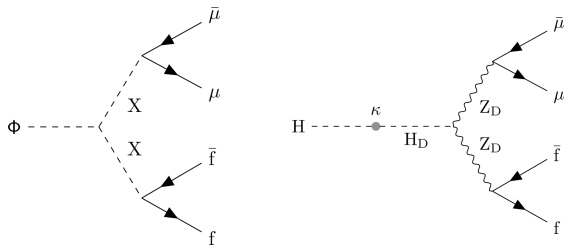
CMS

CMS-EXO-21-006
2205.08582 (JHEP)

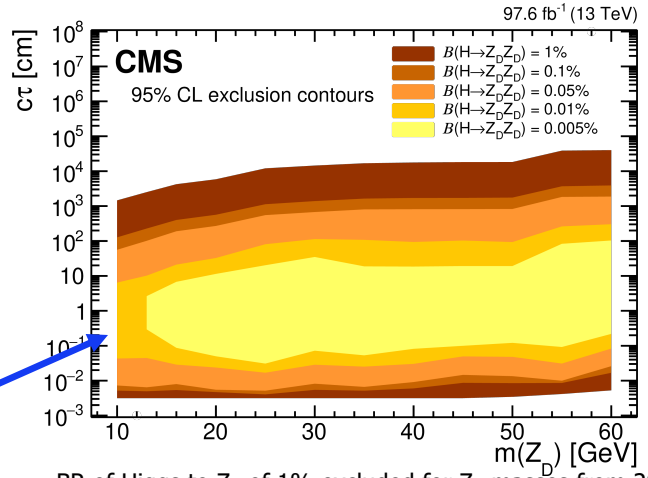




No excess observed → Exclusion limits set on a model with BSM heavy scalar decaying to LLPs and on a Hidden Abelian Higgs Model (HAHM) with dark photons Z_D:



Complemented with a scouting search based by a dimuon trigger stream with low transverse momentum thresholds, to explore otherwise inaccessible phase space at low dimuon mass and nonzero displacement from the primary interaction vertex: *EXO-20-014*, *JHEP 04 (2022) 062*



BR of Higgs to Z_D of 1% excluded for Z_D masses from 20 to 60 GeV and lifetimes from few tens of μm to 100 m

Pixel dE/dx

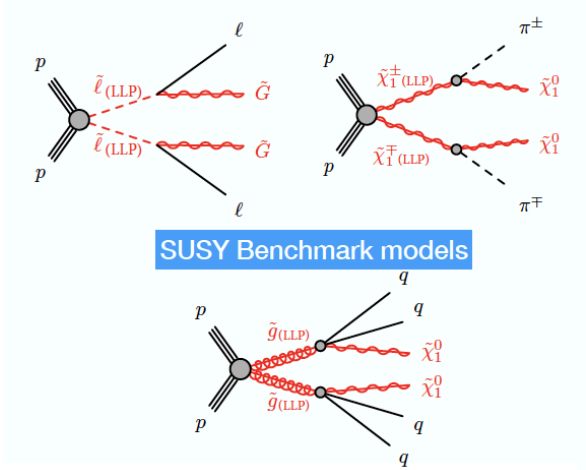
ATLAS

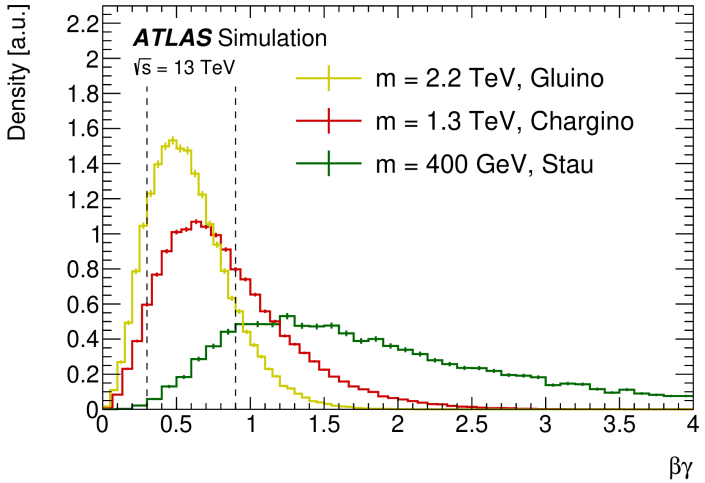
arXiv:2205.06013

- **Target**: massive charged LLPs, having Low β → Large ionization.
- **Signature**: Selection exploiting missing E^T and well-isolated track or muon with large pT and with large dE/dx
- From Pixel dE/dx → Bethe-Bloch → βɣ
  - Mass estimate from βɣ and momentum

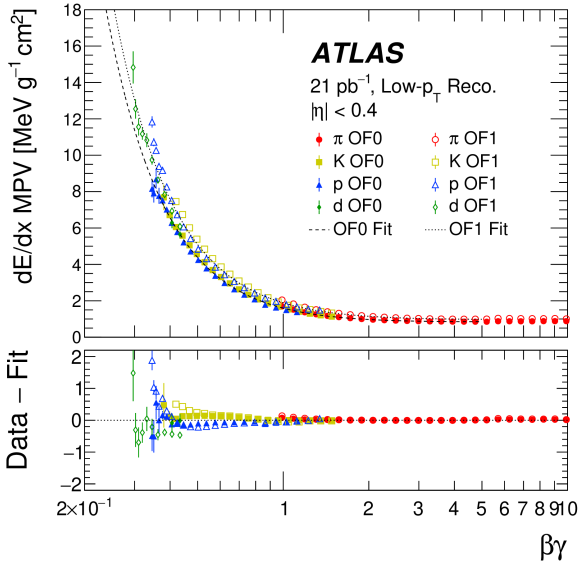
$$m_{\mathrm{d}E/\mathrm{d}x} = \frac{p_{\mathrm{tracker}}}{\beta\gamma_{\langle \mathrm{d}E/\mathrm{d}x \rangle}}$$

- 8 signal regions targeting different LLP masses and lifetime regimes
- Fully data-driven background estimation (based on pseudo-data generation from CRs)





The ranges 0.3<βγ<0.9 indicated by vertical dashed lines approximately correspond to the acceptance of this search from the dE/dx



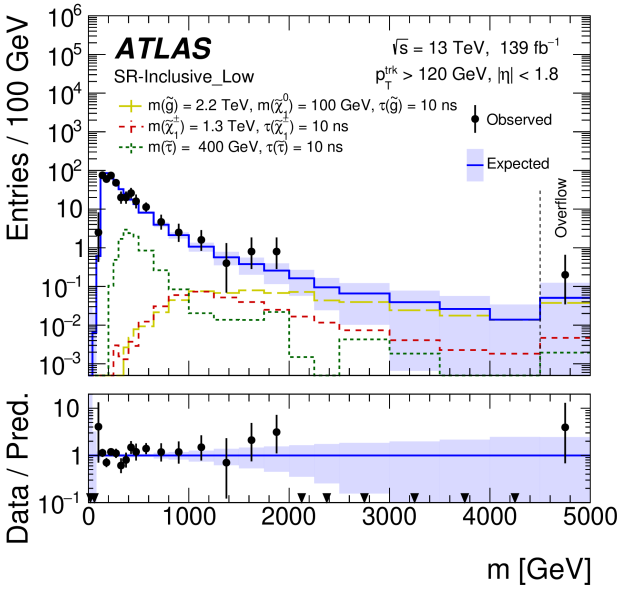
Bethe-Bloch calibration using special low u runs, with pT>100MeV reconstruction

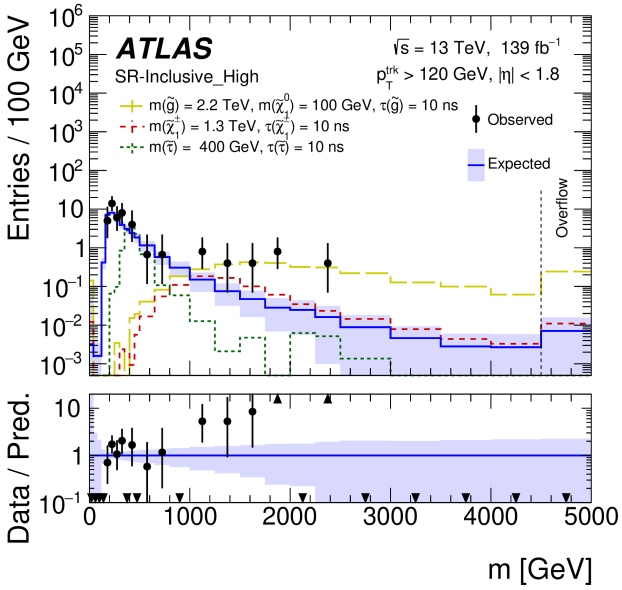
Pixel dE/dx

ATLAS

arXiv:2205.06013

- For most of the SR, the observed data agrees well with the predicted background.





Largest significance of 3.6σ is observed for a mass window [1.1, 2.8] TeV in high-dE/dx SR: in this window, 0.7 ± 0.4 events are expected and 7 events are observed.
Global significance: 3.3σ.

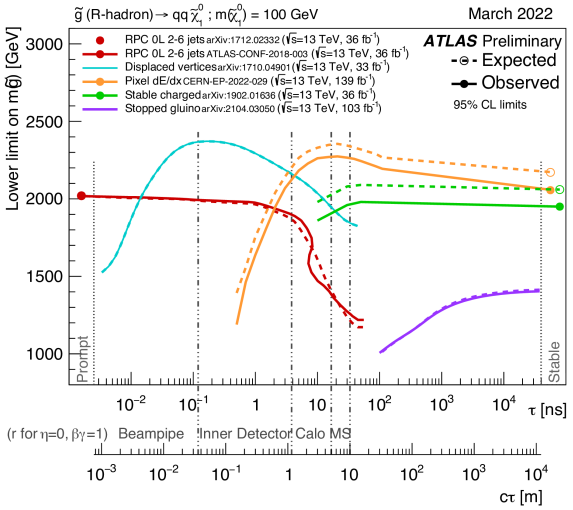
- **No instrumental pathologies** were found in the observed tracks and individual pixel cluster shapes.
- **Crosscheck of momentum** reconstruction between ID and MS for muon candidate tracks.
- **Time-of-flight** measurements of these excess event were also extracted from muon and calorimeter systems. → All of excess events candidate tracks were observed to be **well consistent** with $\beta = 1$ within the data-driven timing resolution.
- The excess events are **not compatible** with the benchmark signal models considered in this search.

Pixel dE/dx

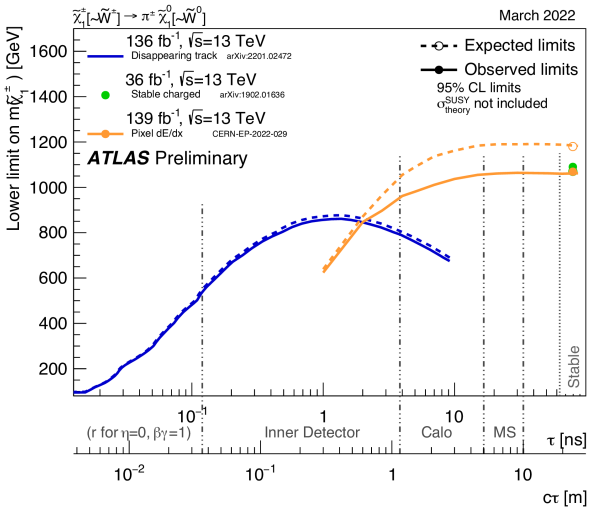
ATLAS

arXiv:2205.06013

- For most of the SR, the observed data agrees well with the predicted background.

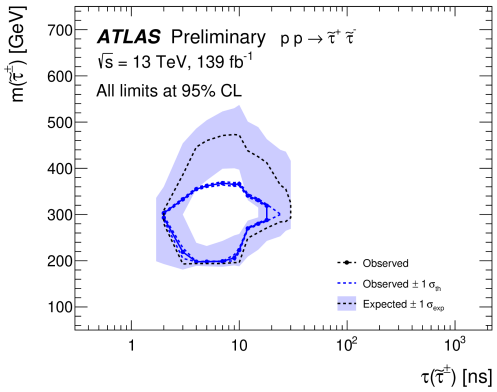


τ = 20 ns, Gluino = 2.27 TeV



τ = 30 ns, Chargino (Wino) = 1.07 TeV

Complementarity with disappearing track search arXiv:2201.02472



τ = 10 ns, Stau = 200-300 GeV

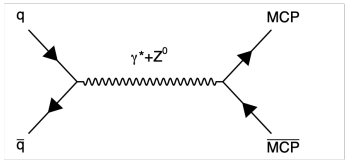
- Results: unique and stringent limits to gluino R-hadrons, chargino (wino) and sleptons for lifetime > a few ns. Well complementary to the "disappearing Track" search that is instead looking for short tracks.
  - Due to the presence of the excess, the observed limit is weaker than expected.

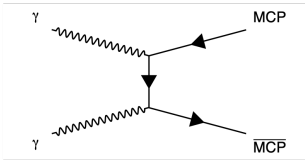
Ionization

Multi-charged particles

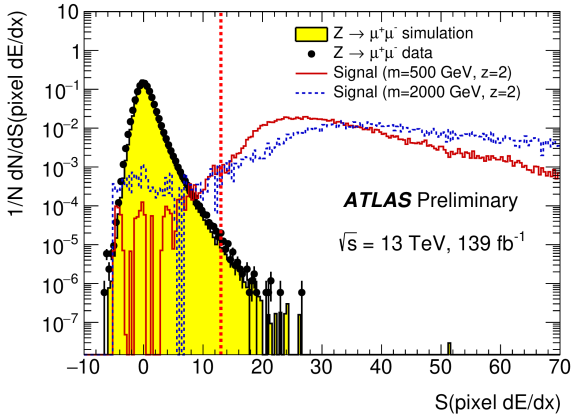
ATLAS

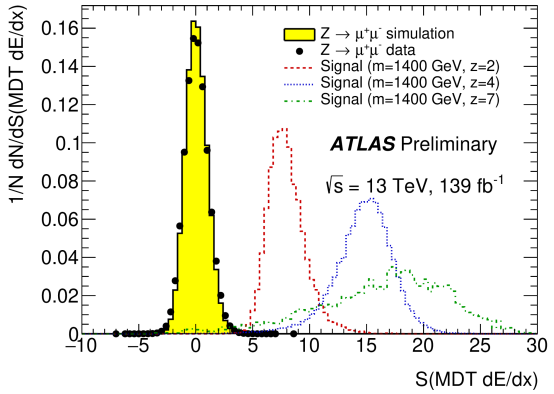
ATLAS-CONF-2022-034

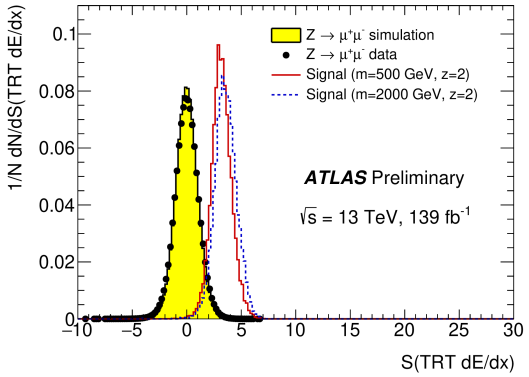


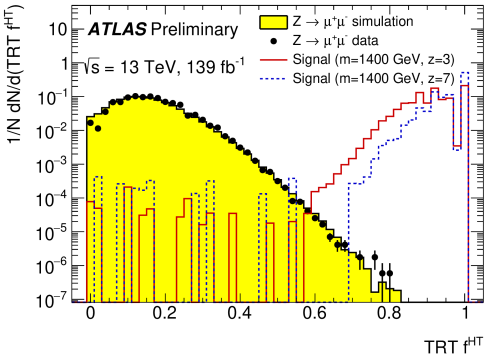


- **Target**: Long lived Multi-Charged Particles.
- **Benchmark** model: MCP produced in pairs via Drell-Yan or photon-fusion processes. Exotic heavy fermions with high electric charge (z=2 and $3 \leq z \leq 7$)
- **Signature**: hits in the ID + MS → reconstructed as muons, with anomalously large dE/dx significance in multiple subsystems (Pixel, TRT, MDT) and/or fraction of high-threshold TRT hits.
  - Missing E^T, single muon and late-muon triggers for maximum signal acceptance









$$S(dE/dx) = \frac{dE/dx_{candidate} - \langle dE/dx_{muon} \rangle}{\sigma(dE/dx_{muon})}$$

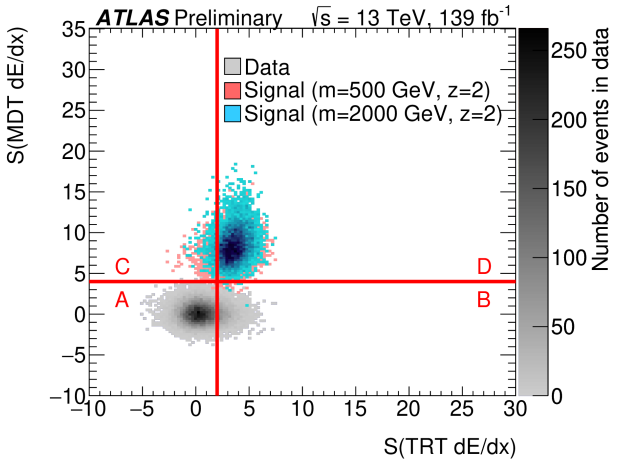
- Require at least one track with $p_T/z > 50\text{GeV}$ in $|\eta| < 2.0$ identified as an isolated muon.
- Require anomalously large $S(dE/dx)$ in multiple subsystems:
  - $z = 2$: S (dE/dx, pixel) > 13.0, then
    $S(dE/dx, \text{TRT}) > 2.0$ &
    $S(dE/dx, \text{MDT}) > 4.0$
  - $z > 2$: TRT high-threshold hits fraction (f_{HT}) > 0.7 & S (dE/dx, MDT) > 7.0

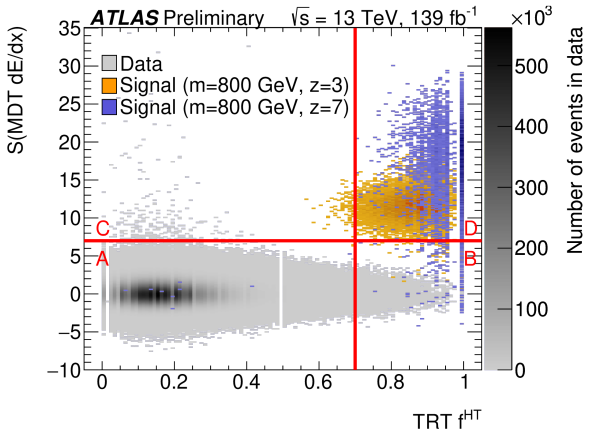
Multi-charged particles

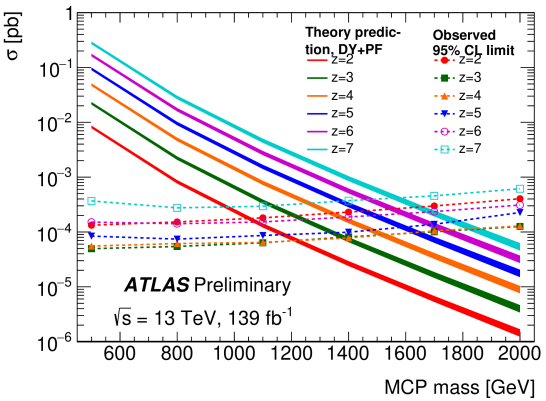
ATLAS [ATLAS-CONF-2022-034]

- Background due to random fluctuations of the energy loss
- Data driven (ABCD) background estimation, assuming two final discriminants are ore orthogonal each other
  - $z = 2$: $\mathcal{S}(\mathrm{d}E/\mathrm{d}x, \mathrm{TRT})$ & $\mathcal{S}(\mathrm{d}E/\mathrm{d}x, \mathrm{MDT})$
  - $z > 2$: f_{HT} & $\mathcal{S}(\mathrm{d}E/\mathrm{d}x, \mathrm{MDT})$
- No excess! → Limits set on MCP production cross section for MCP mass up to ~1.7 TeV

Selection	$N^{\mathrm{A\ observed}}_{\mathrm{data}}$	$N^{\mathrm{B\ observed}}_{\mathrm{data}}$	$N^{\mathrm{C\ observed}}_{\mathrm{data}}$	$N^{\mathrm{D\ expected}}_{\mathrm{data}}$	$N^{\mathrm{D\ observed}}_{\mathrm{data}}$
$z = 2$	24 294	4039	9	1.5 ± 0.5 (stat.) ± 0.5 (syst.)	4
$z > 2$	192 036 934	15 004	441	0.034 ± 0.002 (stat.) ± 0.004 (syst.)	0





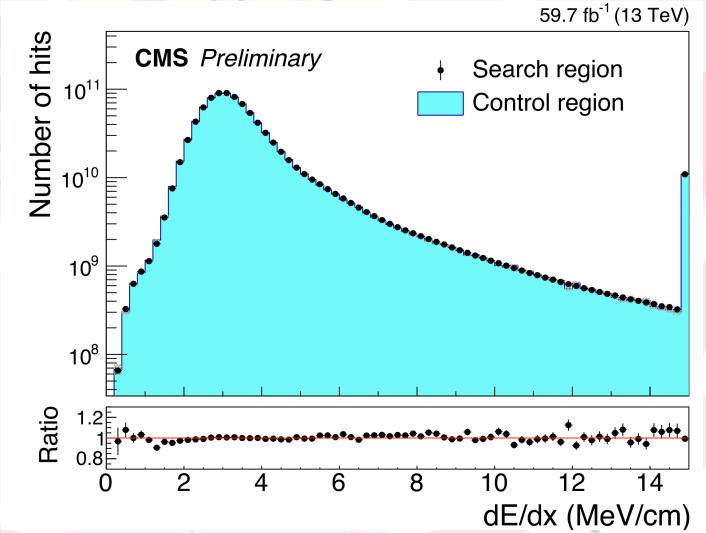


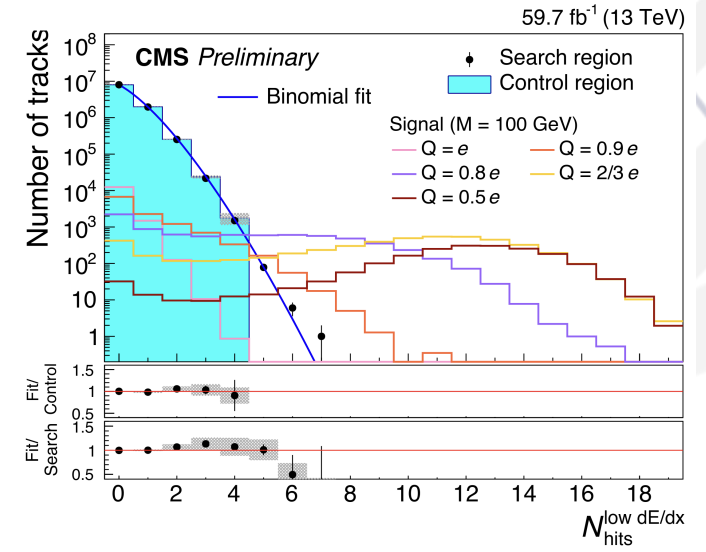
Fractional-charged particles

CMS

CMS-EXO-19-006

- **Target:** Long lived Fractional Charge Particles (FCP)
- **Signature**: High p_T track matched to a muon track
  - The number of tracker hits with low dE/dx $N_{hits}^{low\_dE/dx}$ is expected to be higher and it is used as main discriminant
- Background arises mainly from muons from W or Z decays:
  - Detector effects (radiation damage, pixel inefficiencies, edge hits…) mitigated with track/hit selection
  - Modelled with a fitted binomial distribution to extrapolate bkg from low to high $N_{hits}^{low\_dE/dx}$



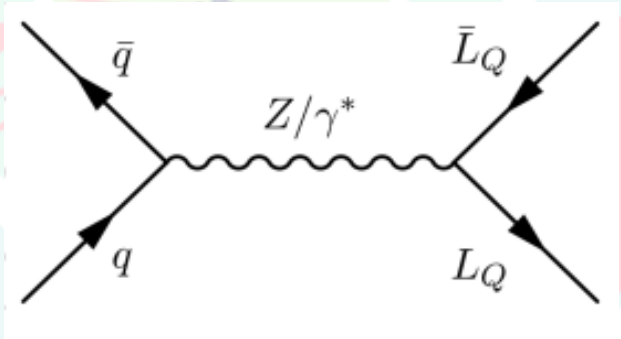


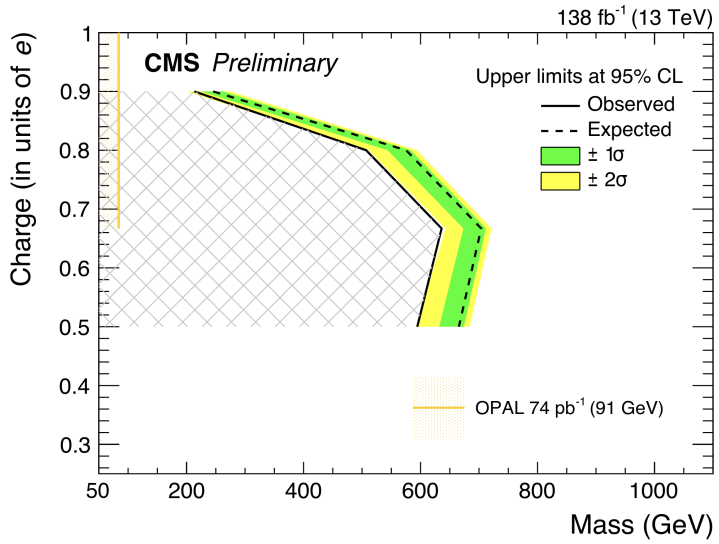
Fractional-charged particles

CMS

CMS-EXO-19-006

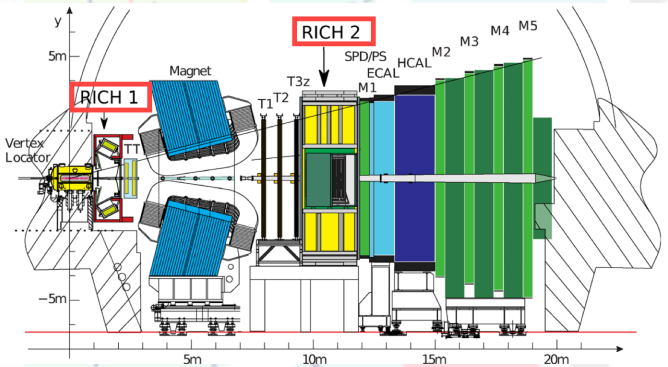
- ✓ Exclusion limits set on the cross-section of FCPs production in Drell-Yan:
  - Best limits are obtained for intermediate charges. Excluded 2/3e for σ above 0.283 fb and masses of 636 GeV

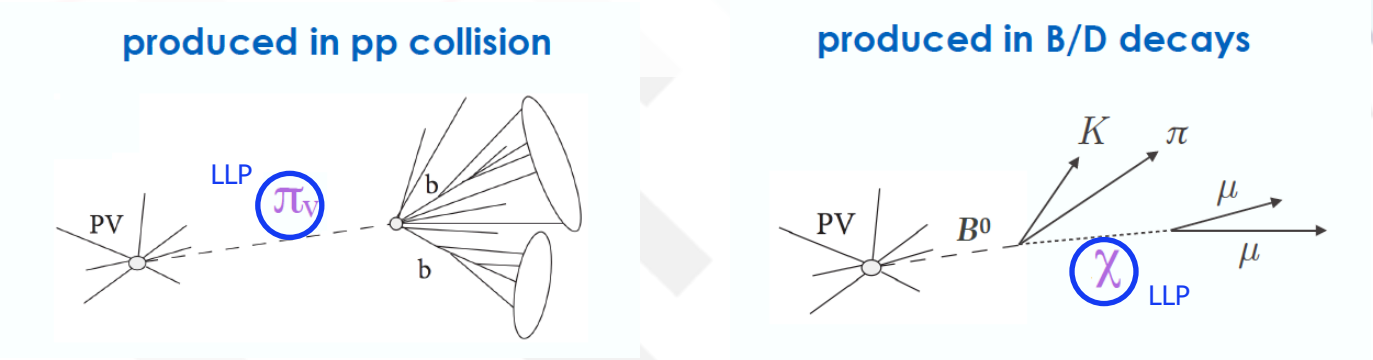




LHCb

- LHCb provides unique coverage complementary to ATLAS and CMS. The detector is actually designed to reconstruct "displaced" vertices from B-meson decays.
  - This has been successfully adapted for LLP searches.
  - LHCb proved to be competitive in many signatures. low masses, low lifetimes and LLP from B/D decays





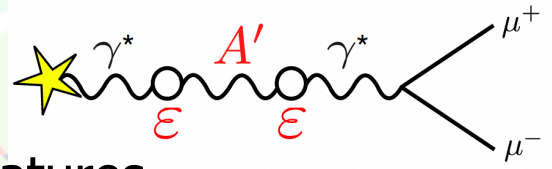
- Moreover: via the RICH detector LHCb is sensitive to tag charged particles slower than speed of light by O(%) to O(per mill).
  - Tracks are reconstructible for $\beta \gtrsim 0.8$ and get full-efficient for $\beta > 0.95$

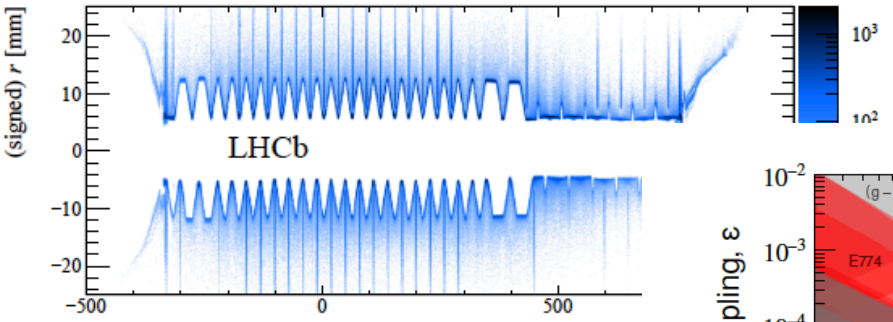
✓ Recent publication for massive LLP decaying semileptonically in LHCb ***ARXIV:2110.07293*** → ***BACKUP***

Displaced leptons from dark photon

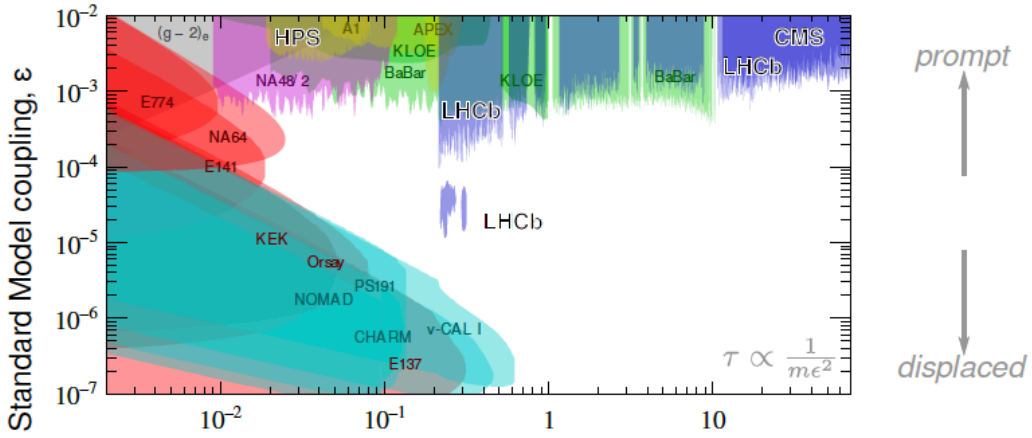
LHCb

- Minimal model parameterised by $m_{A'}$ and mixing strength ϵ.
- LHCb $\sigma(\tau) = 50$ fs: 'prompt' vs 'displaced' signatures
- Displaced signature:
  - A' radial flight distance > 5mm: ~ no prompt background
  - Background: from photon conversions in the first detector layers
  - Special beam-gas runs: high-precision material map to veto





arXiv:JINST 13 P06008



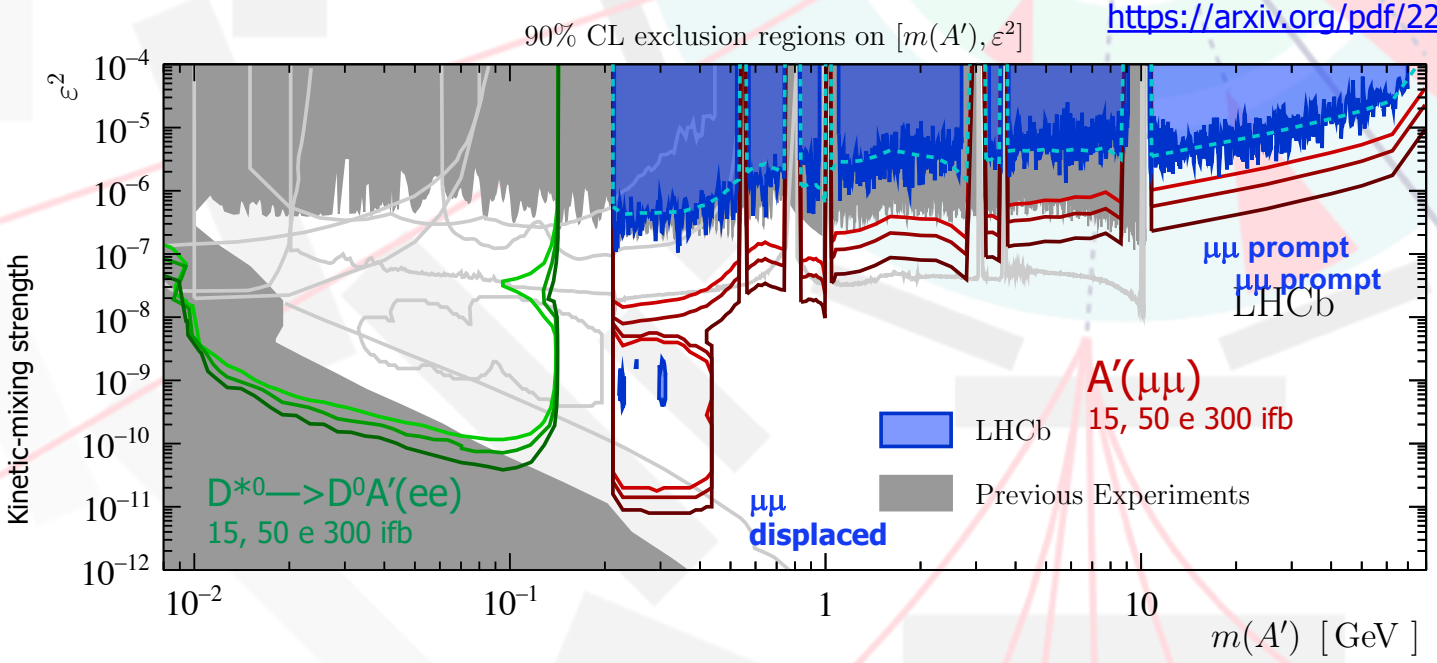
arXiv:PRL 124041801

Displaced leptons, other perspectives

LHCb

- In LHC-Run 3, just started, expected exceptional sensitivity to low-mass displaced dilepton signatures thanks to mass resolution, excellent vertexing and online selection allowed by trigger-less readout.
  - Extend reach for dark photon A′→μμ & new feasibility to probe radiative charm decay.

https://arxiv.org/pdf/2203.07048.pdf



- Dimuon search (prompt and displaced) also targets low-mass resonances, decaying promptly or displaced. Limits set up to 3 GeV

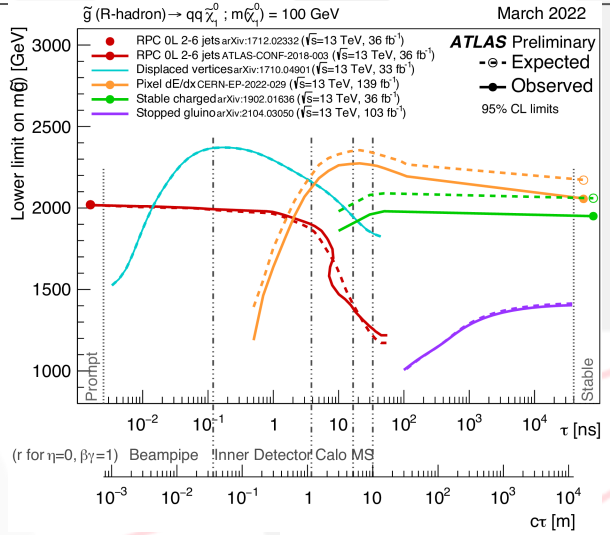
https://arxiv.org/pdf/2007.03923.pdf

Conclusions

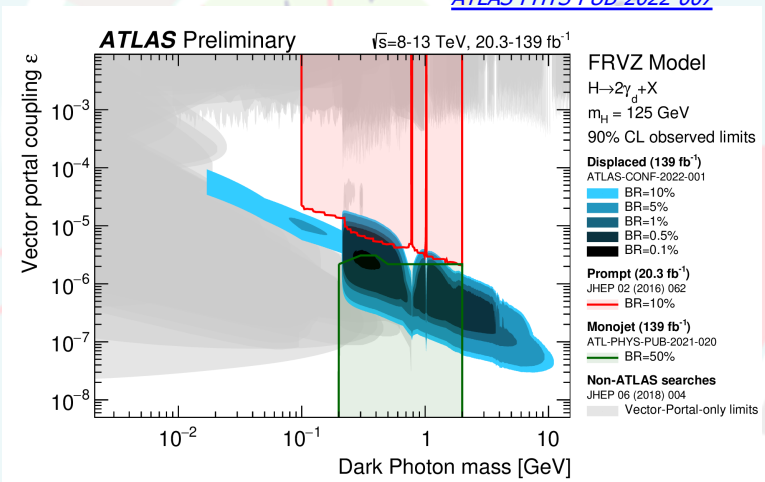
- There is a strong increasing interest in BSM LLPs as our current extensive look at 13 TeV data yields impressive agreement with Standard Model expectations.
- As LLP show atypical signatures, ad-hoc algorithms are coming, allowing to explore a variety of searches in a model-independent manner.
  - Just few of them have been shown here.
- While results are still coming from the previous data-taking, Run 3 will give an opportunity to boost even further these searches with new triggers(*) deployed and Phase-1 detector upgrade.
  - New ideas(*), such as CODEX-b, Mathusla and FASER, involve also far-away extension of the detectors coverage and may provide additional information on longer lived particles.

(*) Back-up slides

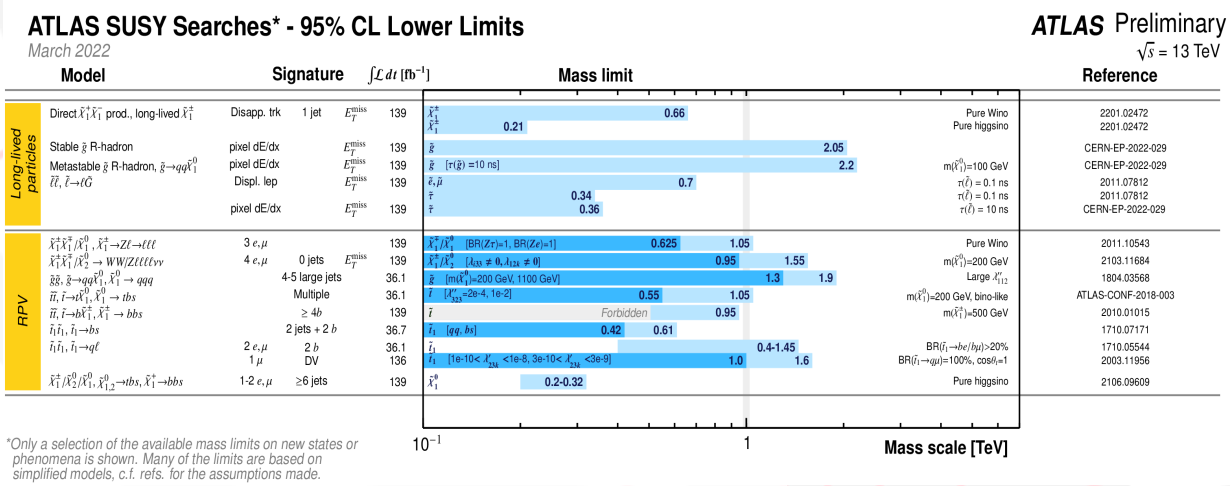
ATLAS Summary Plots



ATLAS-PHYS-PUB-2022-007



ATLAS-PHYS-PUB-2022-013



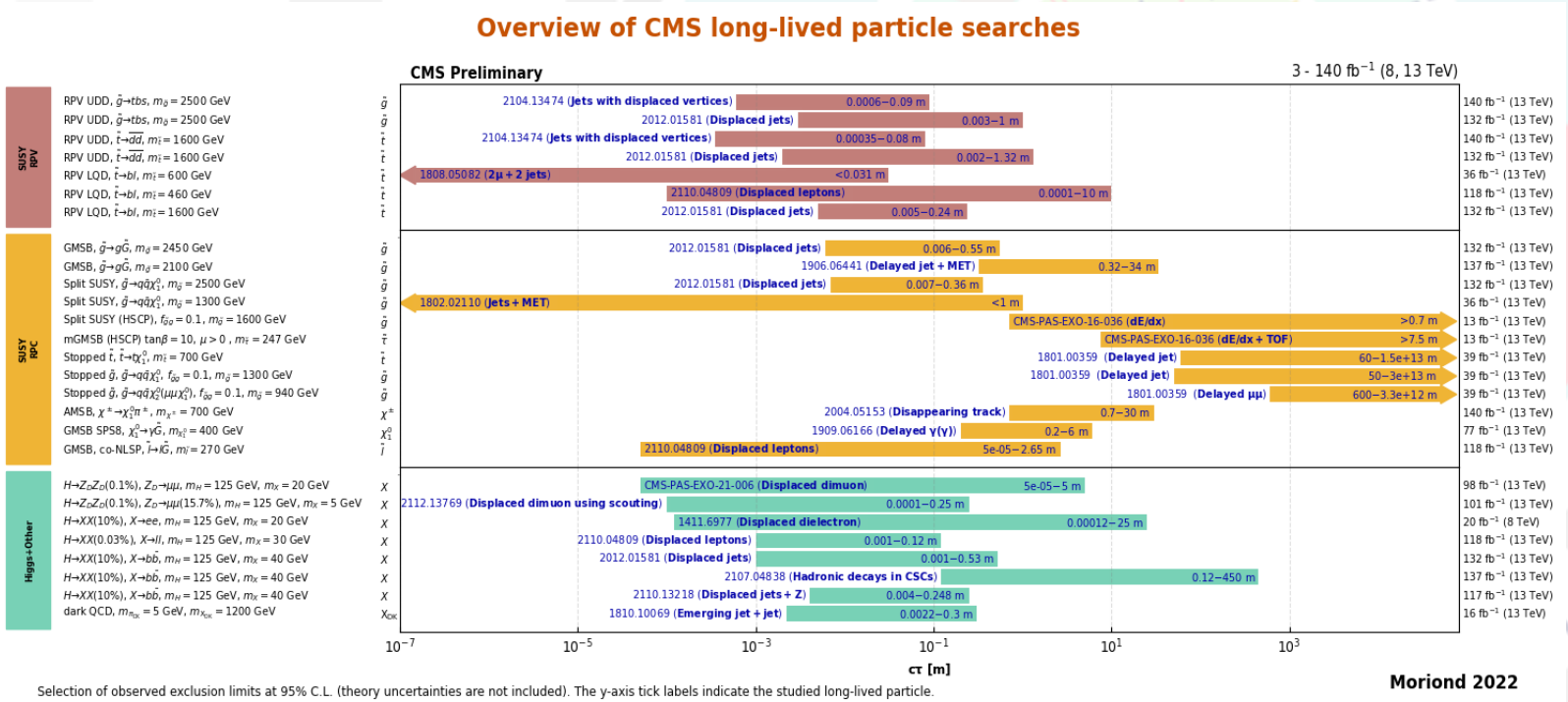
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Recent searches

- displaced Heavy Neutral Leptons EXOT-2019-29
- displaced jets in the hadronic calorimeter EXOT-2019-23
- displaced jets in the Muon Spectrometr EXOT-2019-24
- displaced lepton jets based on dark photon model EXOT-2019-05

CMS Summary Plots

[Long Lived summary plot]

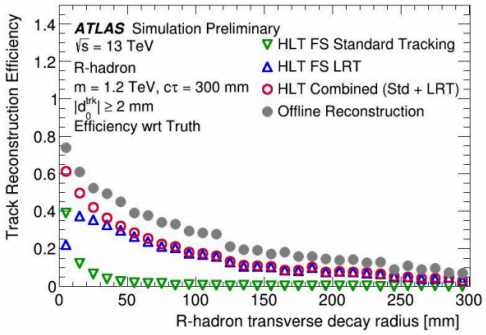


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

Analysis	Signature	Displacement	Mass
CMS-EXO-18-003	Displaced (di)leptons	Within pixel tracker	> 30 GeV
CMS-EXO-20-014	Displaced dimuon (with vertex)	Within pixel tracker	> 200 MeV
CMS-EXO-21-006	Displaced dimuon (with vertex)	Tracker + muon system	> 10 GeV
CMS-EXO-20-003	Displaced jets + Z	Within tracker	> 15 GeV
CMS-EXO-19-006	Low ionizing particles	Outside of CMS	> 100 GeV

Trigger: Extending the searches to LLP

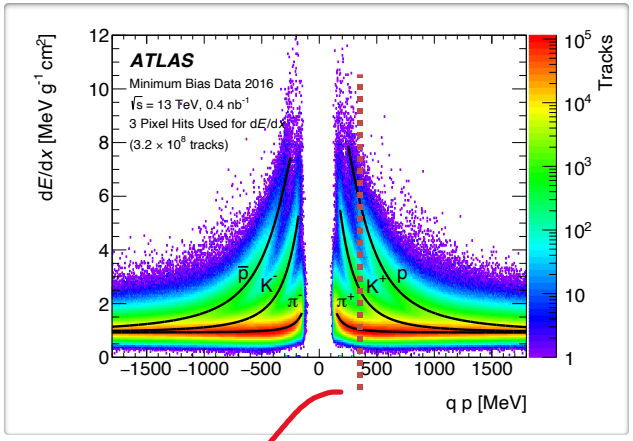
- ✓ Long-lived particles (LLP) can have unique signatures and track-shapes inside the ATLAS detector , and existing conventional ATLAS triggers can become a limiting factor
- ✓ As of Run-3, the ATLAS collaboration have implemented new tracking algorithms for the High Level Trigger (HLT). This was made possible with advancement in ATLAS algorithms and CPU technologies.
  - Full detector tracking (without a need for region of interest) will be available at O(10kHz). ATL-COM-DAQ-2021-003
  - LRT tracks are reconstructed either: **ATL-COM-DAQ-2022-023**
    - 1) Globally: From hits that are not associated to prompt tracks.
    - 2) In an RoI seeded by a muon, electron or jet particle type in the trigger.
  - Disappearing track trigger to identify Charged LLP particles that decay inside the tracker

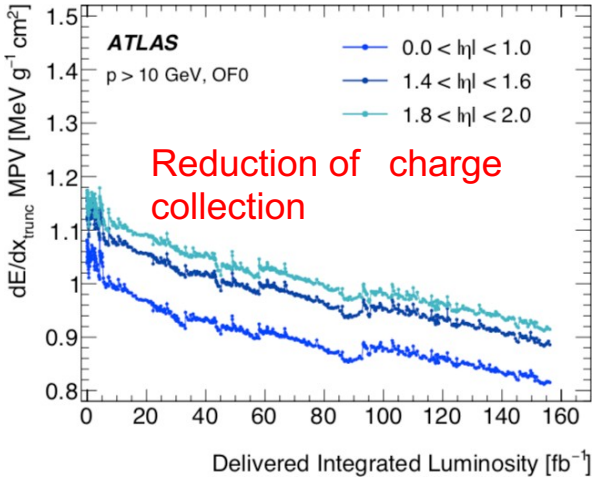


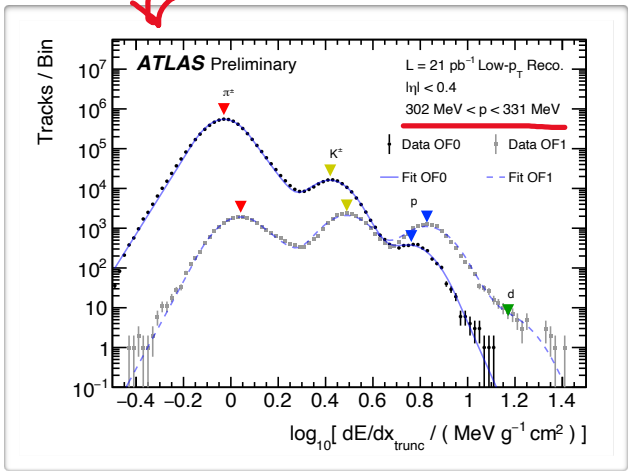
Pixel dE/dx - Calibration

ATLAS

- Time-over-threshold from pixel sensors → **charge** measurement
- dE/dx corrected to account for radiation damage and η dependence
- **Average dE/dx** is evaluated from all the sub-leading pixel clusters







- **Calibration** performed in a special dataset with reconstructed tracks down to p_T>100 MeV (standard is > 500 MeV).
- Fitted MPV of dE/dx for known particle species → Calibrated MPV-βγ relation

$$\mathrm{MPV}_{dE/dx}(\beta\gamma) = \frac{1+(\beta\gamma)^2}{(\beta\gamma)^2}\left(c_0 + c_1 \log_{10}(\beta\gamma) + c_2 \left[\log_{10}(\beta\gamma)\right]^2\right)$$

Pixel dE/dx - Background

ATLAS

arXiv:2205.06013

Basic assumption for data-driven estimation:

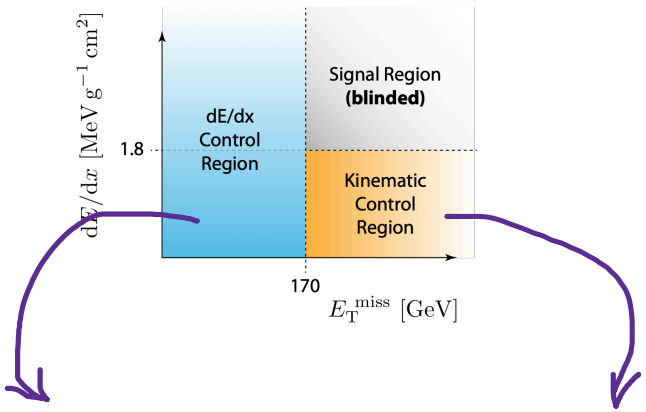
SM particles are ~MIP.

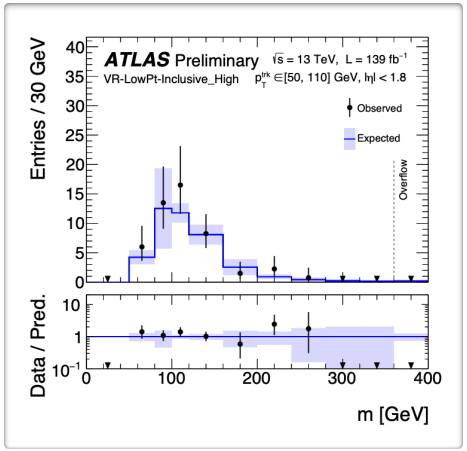
→ Kinematics and dE/dx response are independent.

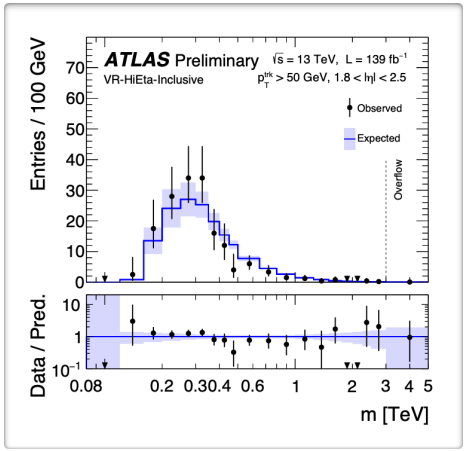
(1) Random picking of (pT,eta) from the kinematic template.

(2) Random picking of dE/dx from the same eta of the dE/dx template.

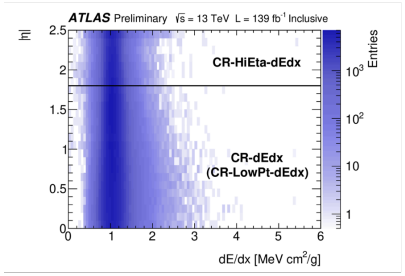
(3) Construct mass and normalize events at m<160 GeV.



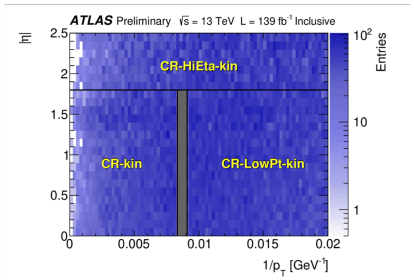




Good prediction closure in VRs.



Extract dE/dx response



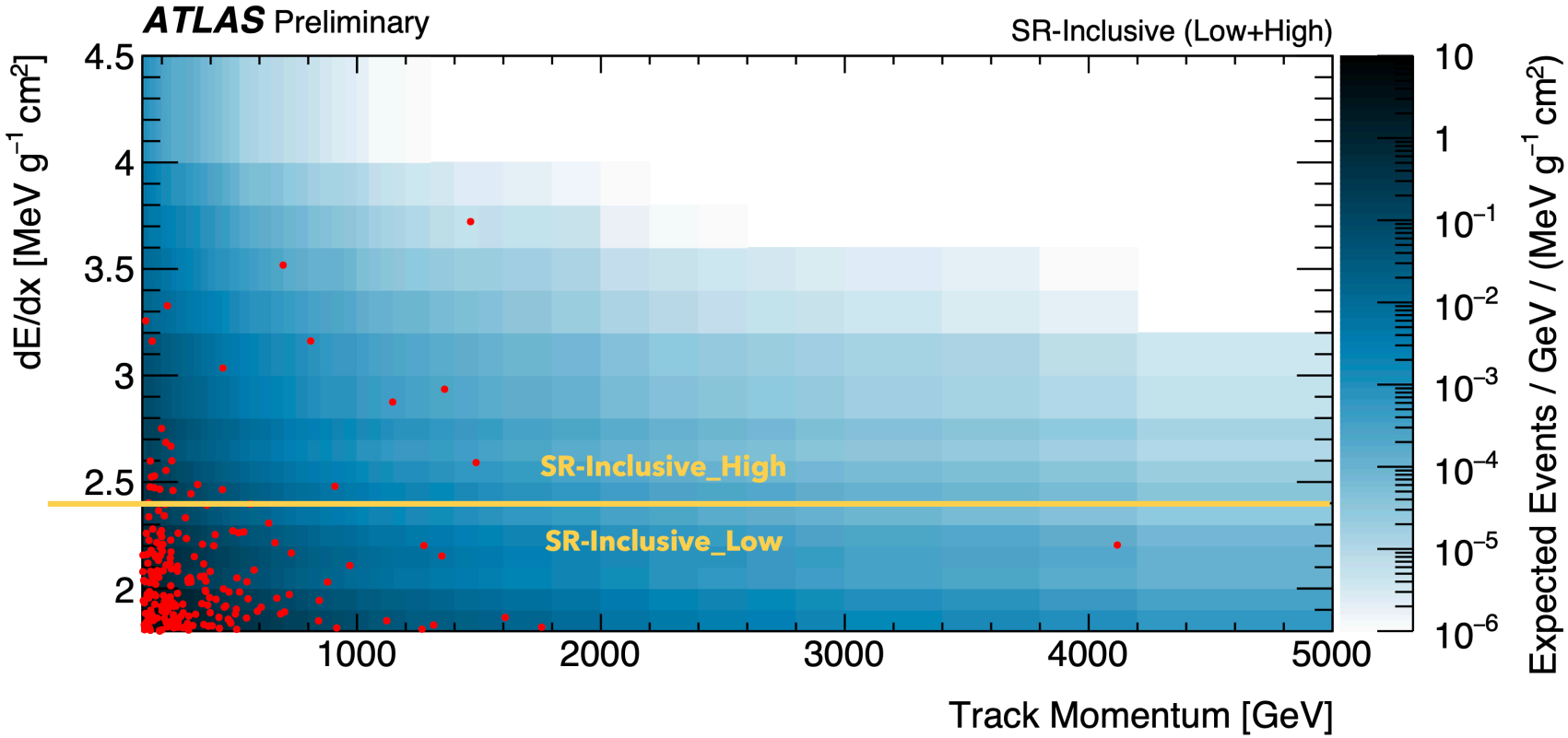
Extract 1track kinematic (pt,eta)

Ionization

Pixel dE/dx - Checks

ATLAS

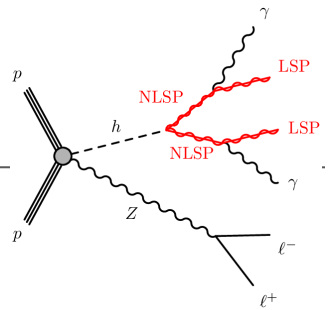
arXiv:2205.06013



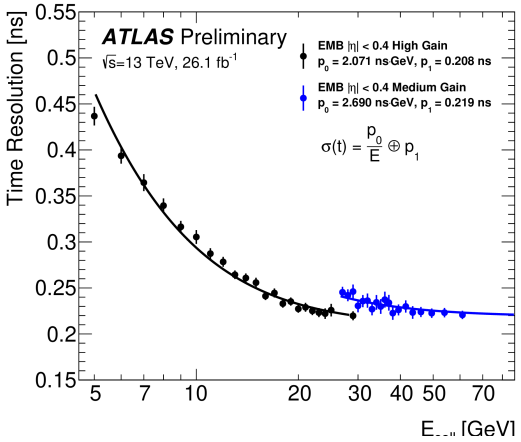
Displaced photons

ATLAS

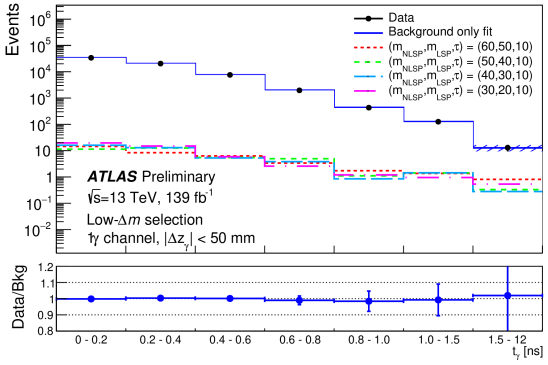
ATLAS-CONF-2022-017

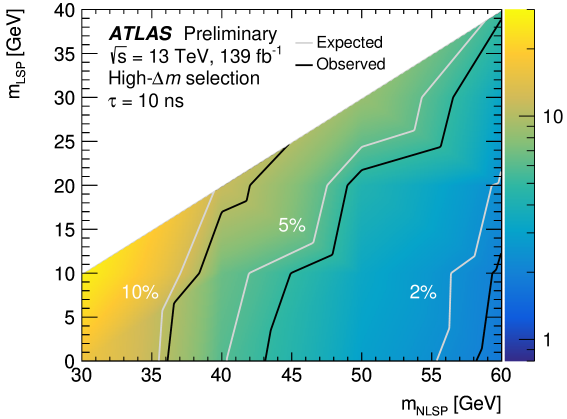


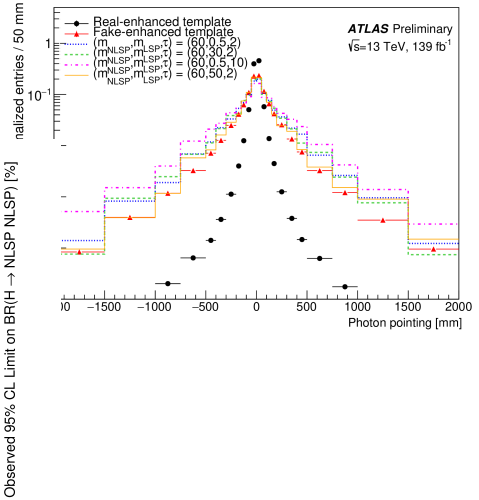
- Target: Similar to the diphoton analysis except that the photons are not required to originate from the same vertex → search is performed for delayed and non-pointing photons originating from the displaced decay of a neutral long-lived particle.
  - Electromagnetic calorimeter is exploited to precisely measure the arrival time (t_{avg}) and trajectory of photons.
- Benchmark model: scenario where the LLPs are pair-produced in exotic decays of the 125 GeV Higgs boson, and each LLP subsequently decays to a photon and a particle that escapes direct detection.



Region	Requirements	Expected	Observed	σ^{95}_{vis} [fb]
1γ	$1.5 < t_\gamma < 12$ ns, $\lvert\Delta z_\gamma\rvert > 300$ mm	3.8 ± 1.6	4	0.042
$\geq 2\gamma$	$1.0 < t_\gamma < 12$ ns, $\lvert\Delta z_\gamma\rvert > 300$ mm	0.28 ± 0.04	0	0.022
$\geq 1\gamma$		4.1 ± 1.7	4	0.041







Massive LLP, semileptonic decay

LHCb, Run2

ARXIV:2110.07293

- Search addresses a subset of models featuring massive long-lived particles with a measurable flight distance, decaying semi-leptonically.
  - The LLP signature is a displaced vertex accompanied by an isolated muon with high transverse momentum. The LLP lifetime range is from 5 ps to 200 ps.

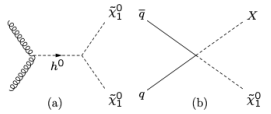
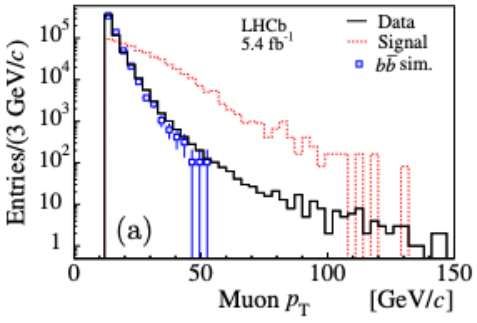
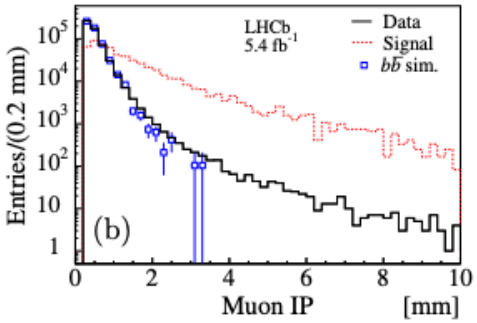
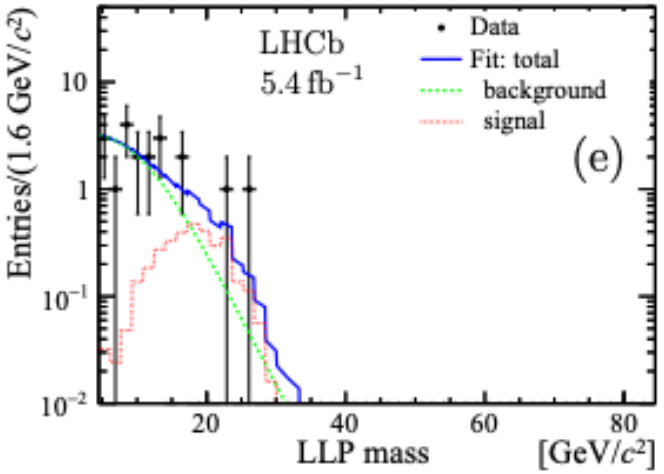


Figure 1: LLP production processes considered in this paper, where the $\tilde{\chi}_1^0$ represents the LLP: (a) di-LLP production via a scalar particle h^0; (b) non-resonant, direct LLP production from quark interactions, where X is a stable particle, with mass identical to the LLP. The LLP decays into a muon and two quarks: $\tilde{\chi}_1^0 \to \mu^+ q_i q_j (\mu^- \bar{q}_i \bar{q}_j)$.

- This study benefits from the excellent VELO vertex reconstruction and by the low pT threshold of the muon trigger.
- Background is dominated by bb events and is reduced by tight selection requirements, including a dedicated multivariate classifier.
- **NO EXCEES IS FOUND:** upper limits at 95% CL set on the cross-section times branching fractions.





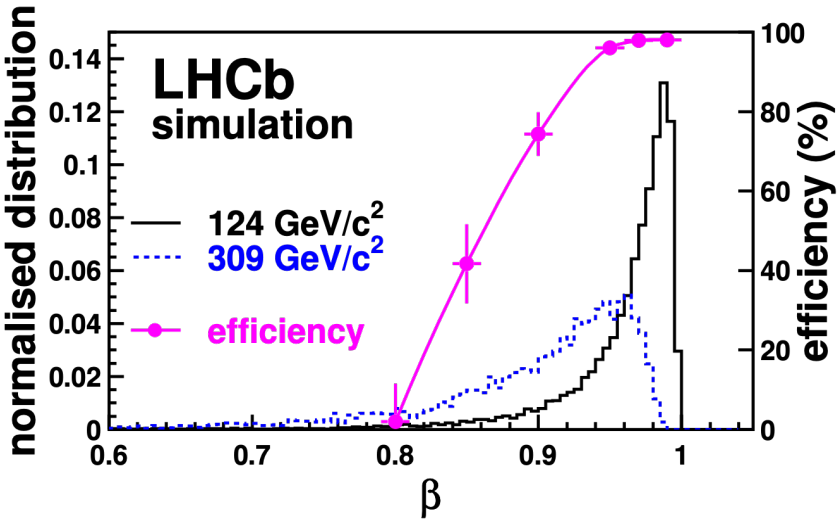


Charged Massive LLP

LHCb, Run1

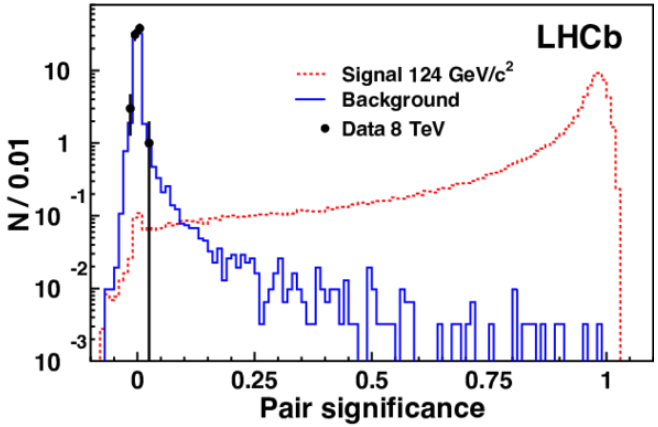
LHCb-PAPER-2015-002, EUR. PHYS. J. C75 (2015) 595

- LHCb can exploit the RICH detector: sensitive to tag charged particles slower than speed of light
  - Tracks are reconstructible for $\beta \gtrsim 0.8$ and get full-efficient for $\beta > 0.95$
  - → based on the response of the ring imaging Cherenkov detectors to distinguish the heavy, slow-moving particles from muons.



Selection

- Events triggered by a single muon of $p_{\mathrm{T}} > 15\mathrm{GeV}$ in $1.8 < \eta < 4.9$.
- Requires to have an opposite-charged dimuon from IP, with $m_{\mu\mu} > 100\mathrm{GeV}$.
  - → Invariant-mass-dependent momentum threshold for accepting $\beta > 0.8$ signals.
- Signal Selection via a ANN trained per track
  - Energy deposits in detector subsystems in VELO, ECal, HCal.
  - **A likelihood variable constructed from RICH information.**
    → **DLLx**: Delta of log-likelihood (DLL) for particle hypothesis changed from $\pi^{\pm}$ to μ, e, K, p.
- The Bkg. sample is taken from simulation.
- The product of the score for the dimuon system (**pair significance**) is used as the discriminant, reducing the SM dimuon background by a factor of 10^{-5}.



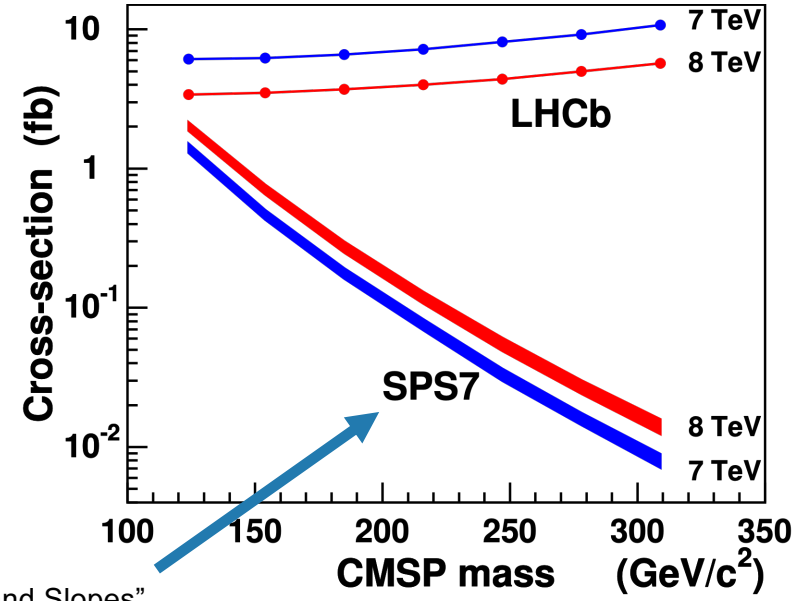
Charged Massive LLP

LHCb, Run1

LHCb-PAPER-2015-002, EUR. PHYS. J. C75 (2015) 595

- Data in $\sqrt{s} = 7{,}8\text{TeV}$ with integrated luminosity of 3.0fb^{-1}.
- Estimated background events in SR: ~0.02 events.
- Observed 0 events.

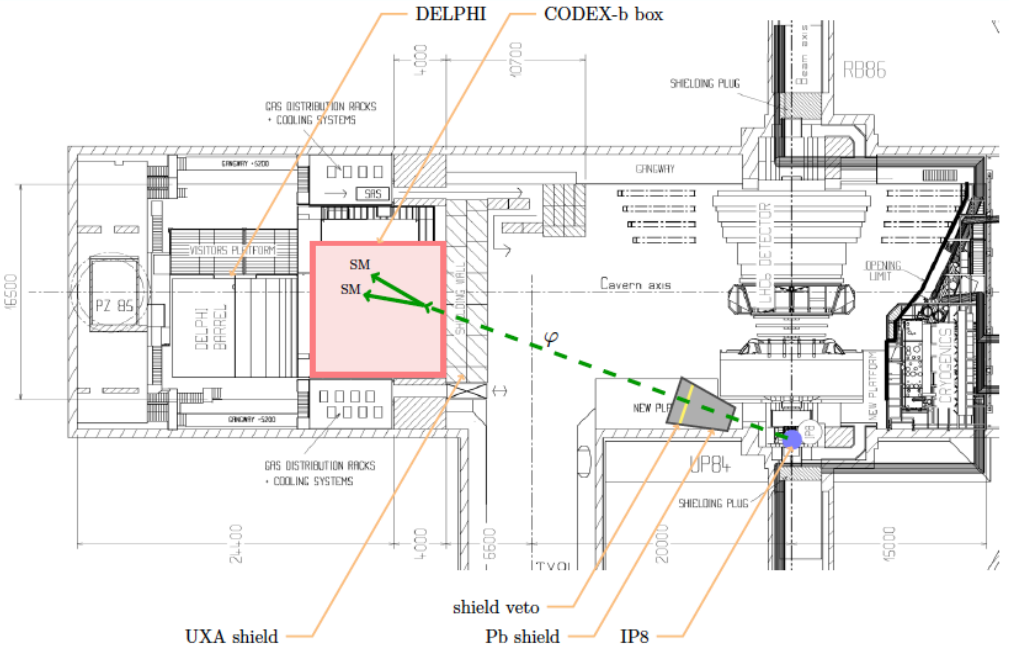
- 95% CL cross-section upper limits set for stable charged particle mass in [124, 309] GeV for $\sqrt{s} = 7\text{TeV}$ and 8TeV individually.
  - 7 TeV: 6.1 fb — 10.7 fb
  - 8 TeV: 3.4 fb — 5.7 fb



2002 “Snowmass Points and Slopes” benchmark points for GMSB Stau
arXiv:hep-ph/0202233

Extending the searches to ULLP

- ✓ CODEX-b to search for decays-in-flight of LLPs generated at IP8.
  - 10x10x10m^3 box, around 25 m from IP, 1% angular coverage
  - Tracking detectors → feasibility based on RPC with 1 cm2 granularity and 50- 100 ps timing resolution
  - Extra shield close to IP8 to attenuate muon and neutral hadrons. Thin active veto for secondaries inside the shield.



b→sφ Higgs-scalar mixing

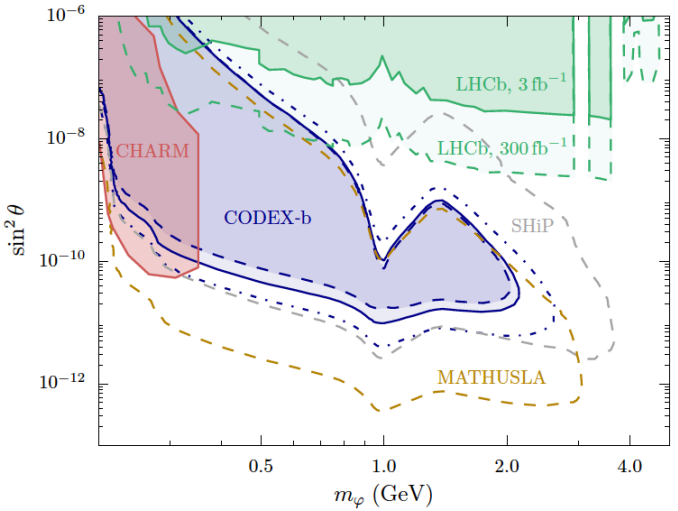
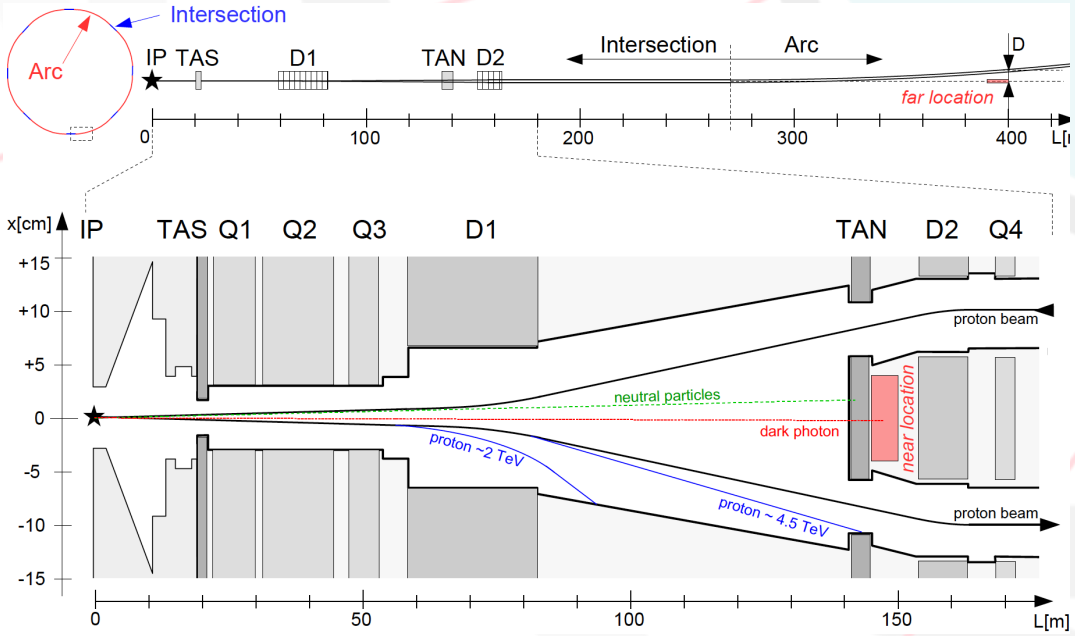


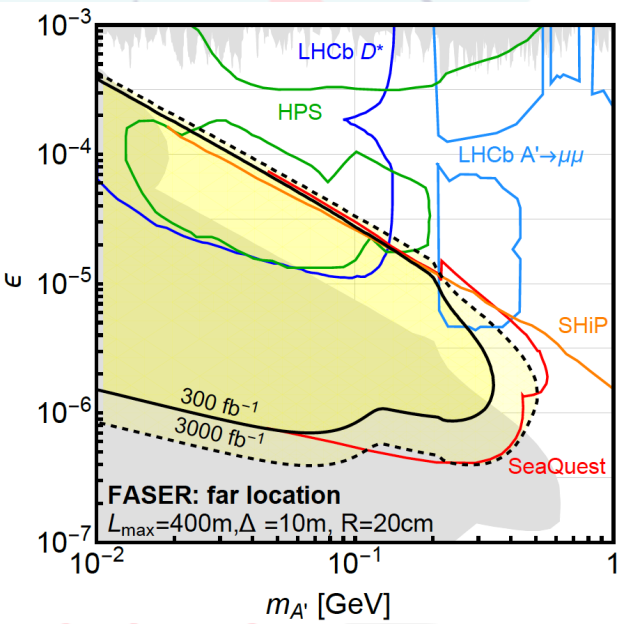
FIG. 3. CODEX-b reach for $B \to X_s\varphi$ in the s_θ^2–m_φ plane. Solid (dashed) blue line assumes 100% (Tab. I) tracking efficiency. Dot-dashed line indicates the reach for $\mathcal{L} = 1\,\text{ab}^{-1}$.

arXiv:1708.09395

Extending the searches to ULLP

- ✓ FASER is a small to be placed in the very forward region of ATLAS/CMS, a few 100m downstream of the IP, to search for new light and weakly interacting particles
  - Dark photon searches either produced in meson decays ($\pi^0 \rightarrow A'\gamma$), trough dark bremsstrahlung $pp \rightarrow pA'X$ and durect QCD $qq \rightarrow A'X$

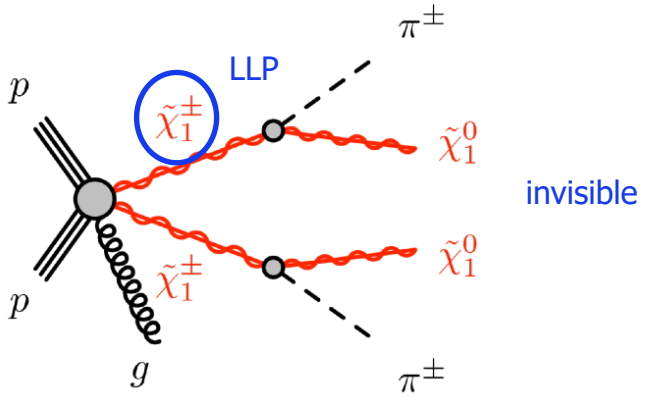




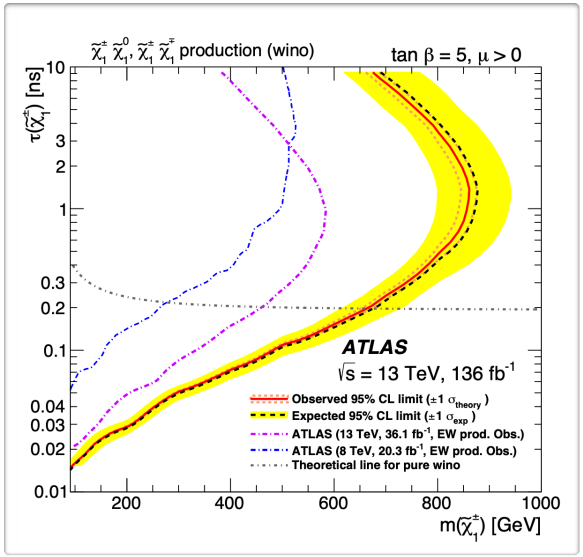
arXiv:1708.09389

Disappearing Track (ATLAS, Full Run2)

pure wino or pure higgsino SUSY LSP, in which case the lighest chargino is the LLP

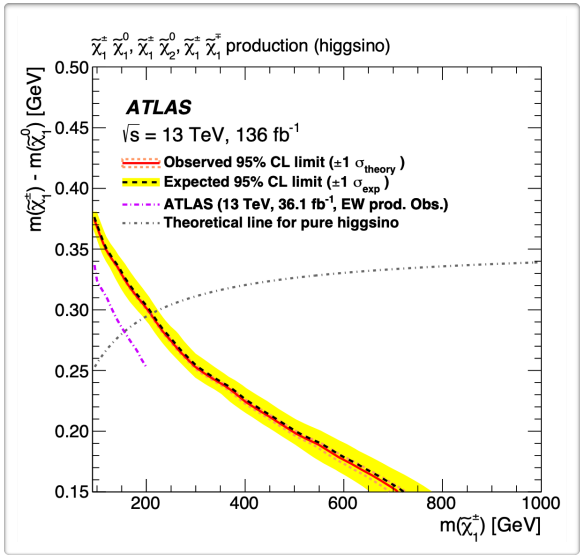


EWK Production (Pure-Wino/AMSB)



Excluded <660 GeV Wino

EWK Production (Pure-Higgsino)

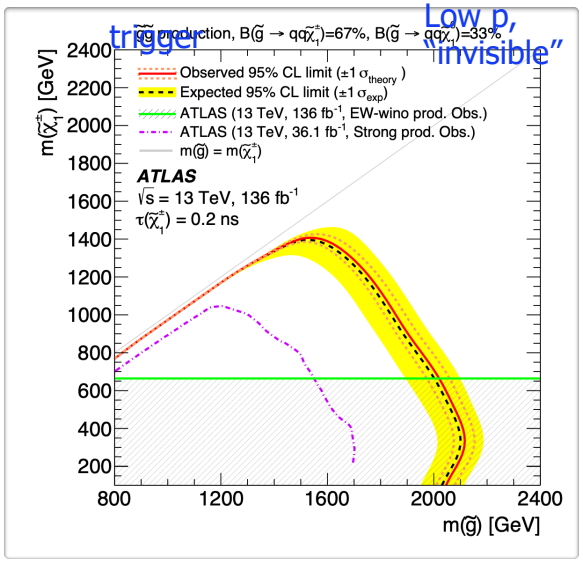


Excluded <210 GeV Higgsino

Strong Production

trigger

Low p, "invisible"



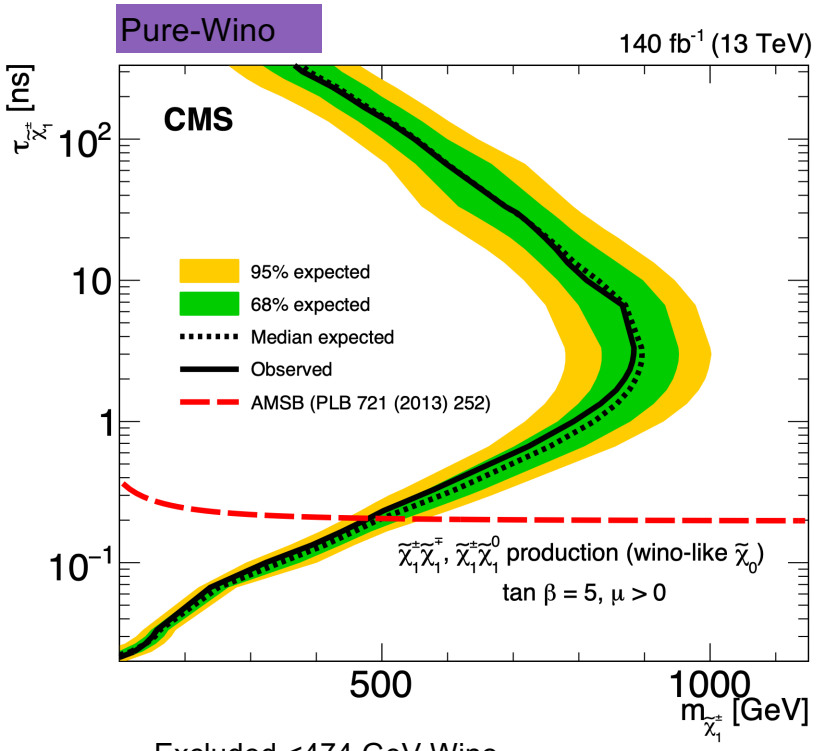
Excluded <2.1 TeV gluino for 300 GeV chargino

- Stringent limits to well-inspired DM scenarios by a dedicated search!

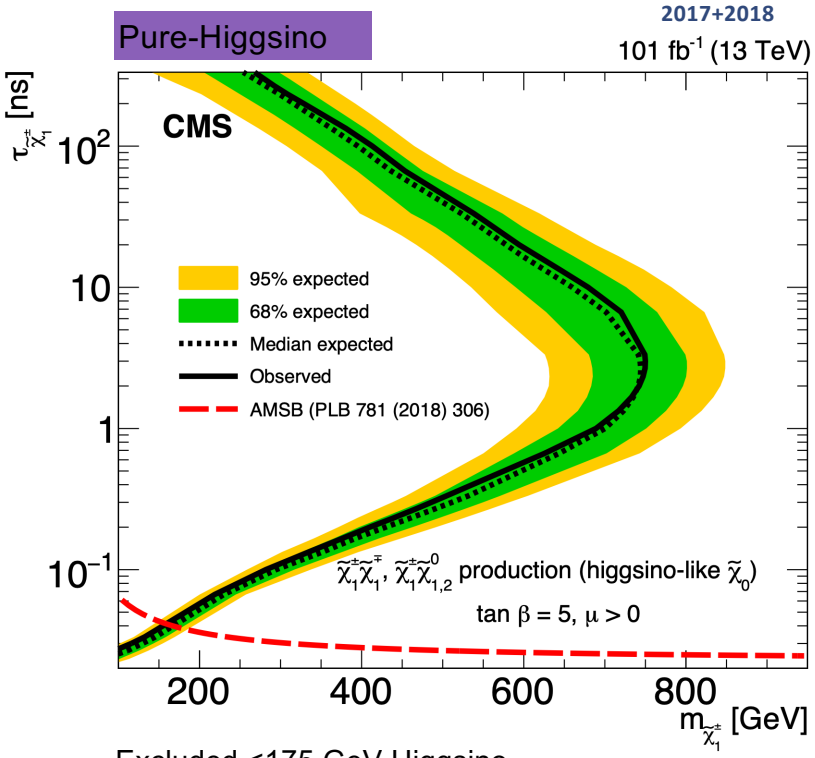
ATLAS-SUSY-2018-19, arXiv:2201.02472

Disappearing Track (CMS, Full Run2)

CMS-EXO-19-010, PLB 806 (2020) 135502



Excluded <474 GeV Wino



Excluded <175 GeV Higgsino