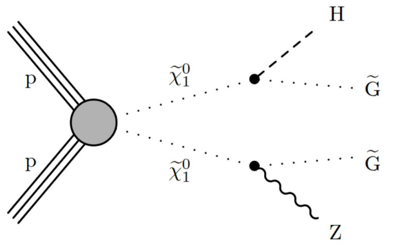
Searches for long-lived particles at the LHC

Lisa Benato (HEPHY, Austrian Academy of Sciences)
on behalf of the CMS, ATLAS, LHCb collaborations

35th Rencontres de Blois on “Particle Physics and Cosmology”
21 October 2024

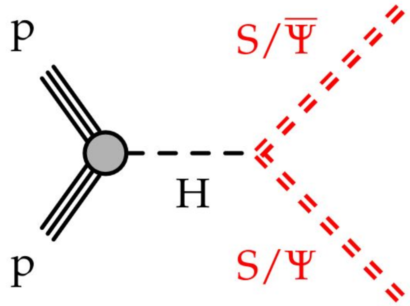
Introduction: LLP searches @ LHC

https://arxiv.org/abs/1810.12602



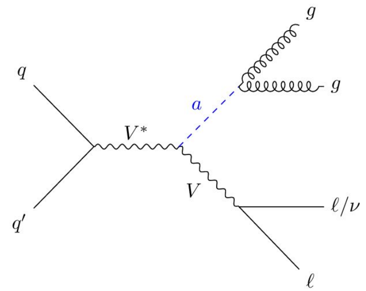
SUSY

- Standard Model doesn’t answer all the questions about matter and its interactions
- Extensions of SM can predict new particles that are long-lived if:
  - Small couplings
  - Suppressed phase space
  - Highly virtual intermediate states



Dark sectors

- Some examples:
  - Partners of SM particles (SUSY) → dark matter candidates
  - Dark sectors communicating with SM via Higgs boson/Dark photons → Higgs mass hierarchy problem
  - Axion-like particles (ALPs) → strong CP problem



ALPs

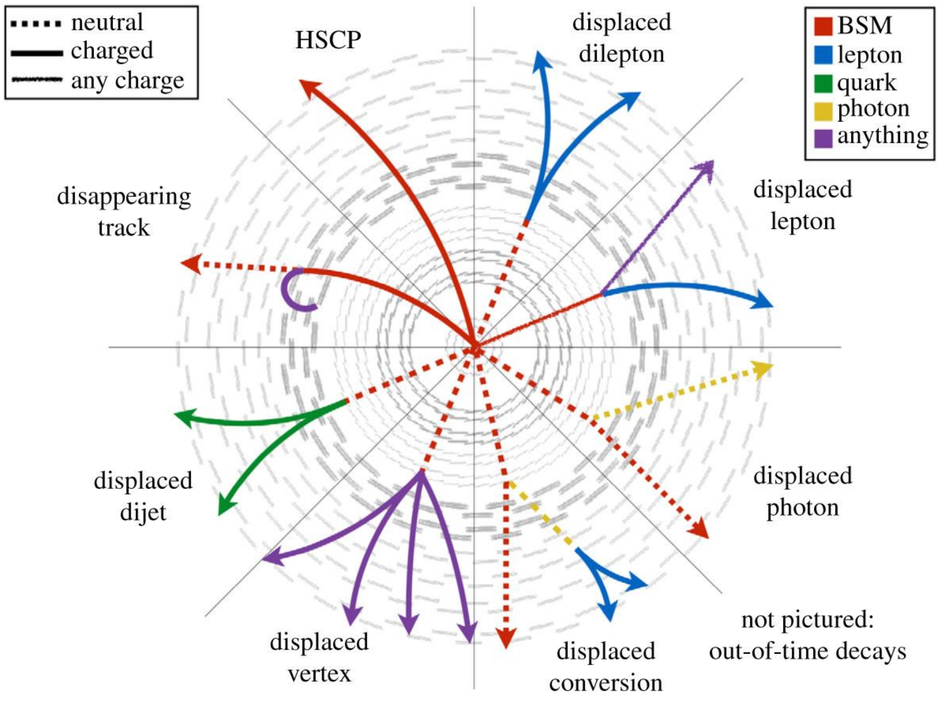
Introduction: LLP searches @ LHC

Very broad (and growing) long-lived particles (LLPs) search program at the LHC!

- LLP searches are **challenging**: detectors not designed for these signatures!
- …but they give **unique opportunities** for R&D
- New ideas applied at **any level** (reconstruction, trigger, analysis techniques, machine learning)

Challenges:
- Non-standard use of the detector
- Non-standard data formats
- Non-standard backgrounds

Unexplored phase-space: new physics in already collected data!



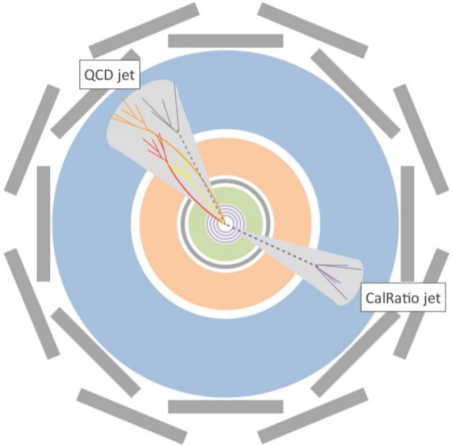
J. Antonelli

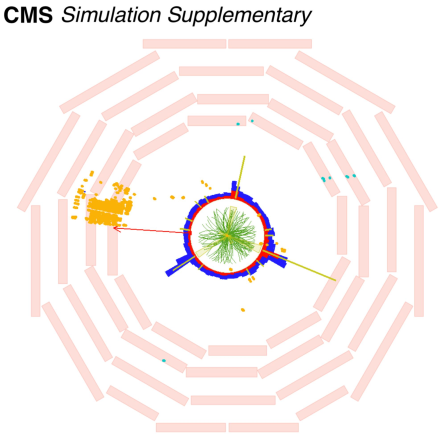
Introduction: LLP searches @ LHC

In this presentation:

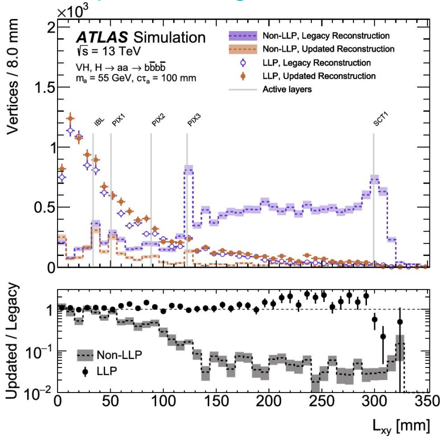
- Recent results @ ATLAS, CMS, LHCb
  - LHC proton-proton collisions at
    13 TeV (**Run 2**: 2016-2018)
    13.6 TeV (**Run 3**: 2022-2025)
- Focus on **long decay lengths:**
  - LLP searches with calorimeters
  - With muon systems

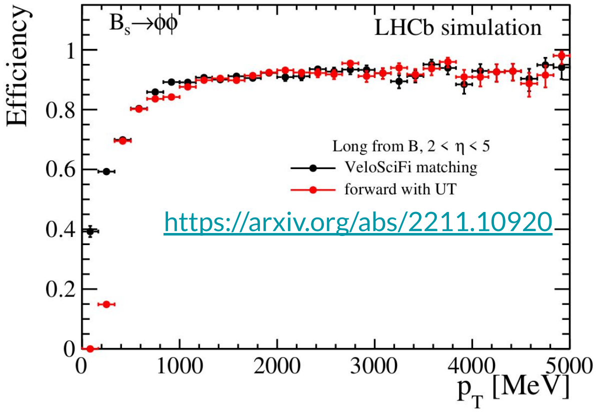
- New Run3 developments @ LHC experiments
- New ideas for the future





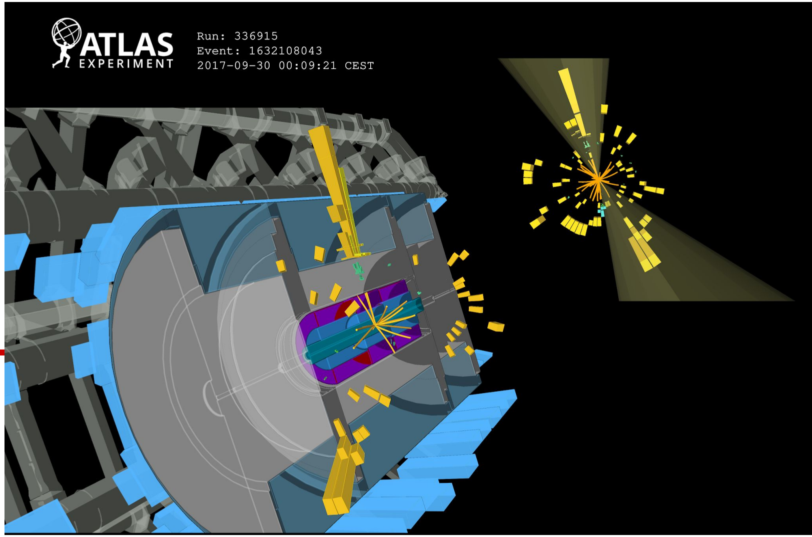
https://arxiv.org/abs/2304.12867





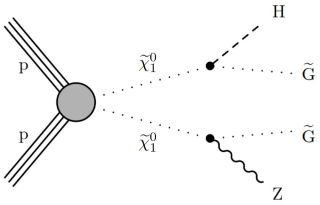
https://arxiv.org/abs/2211.10920

LLP searches with calorimeters



CMS: trackless and out-of-time jets

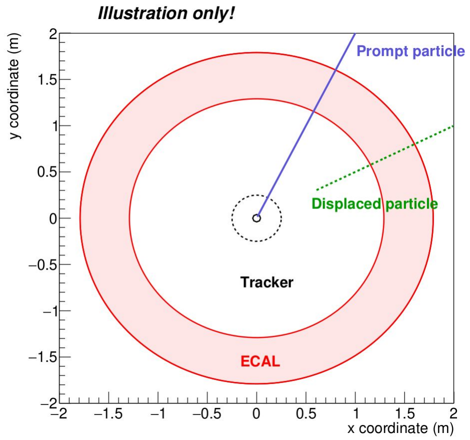
https://arxiv.org/abs/2212.06695



- SUSY neutralino X → GH(Z)
- $c\tau_X$ ~ 1 m (outer tracker/electromagnetic calorimeter ECAL)
- G (LSP) creating missing transverse energy → trigger
- H(Z) to hadrons → jets

Trackless-ness:

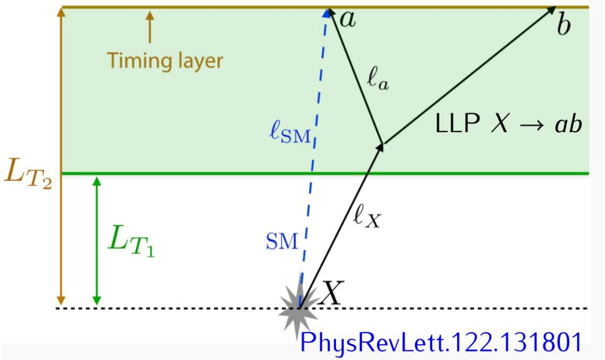
- Tracking efficiency decreases with displacement
- Jets appear as trackless



prompt = produced at collision point

Delay:

- Slow-moving LLPs and/or path length increase due to displacement → jets are delayed wrt p-p collision!
- Timing layer: $PbWO_4$ ECAL scintillating crystals



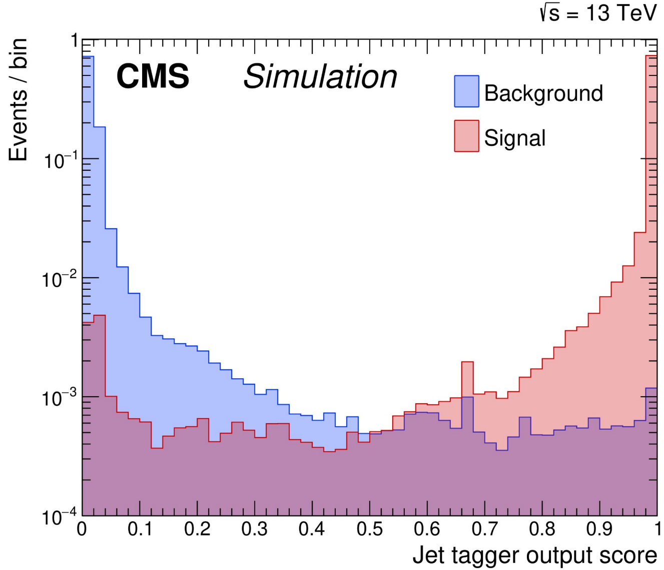
$$\Delta t_a = \frac{l_X}{\beta_X} + \frac{l_a}{\beta_a} - \frac{l_{SM}}{\beta_{SM}}$$

https://arxiv.org/abs/2212.06695

CMS: trackless and out-of-time jets

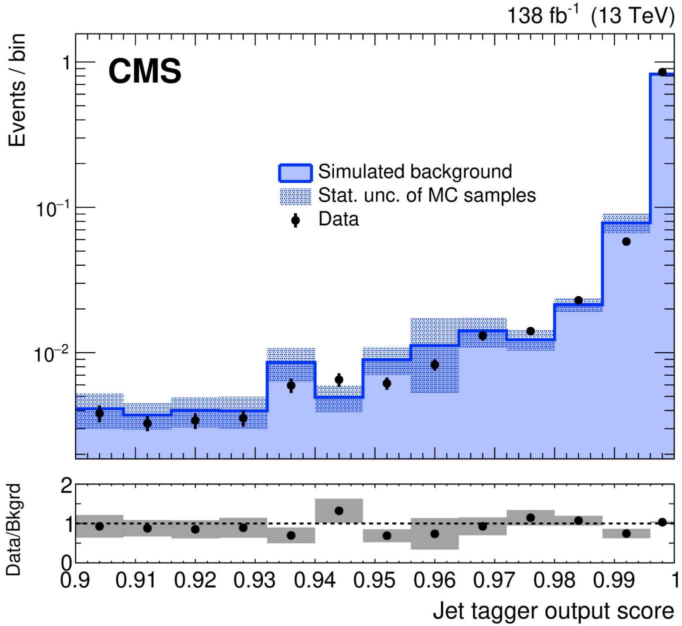
Trackless and OOT jet DNN tagger:

- Combine features of
  - ECAL crystals (time, multiplicity)
  - Tracks associated to a jet
- Strong background rejection
- Signal Region (SR): at least 2 tagged jets



Study of the **DNN response in MC/data:**

- DNN inputs corrected in MC to match data in CR
- Good data/MC agreement after corrections applied

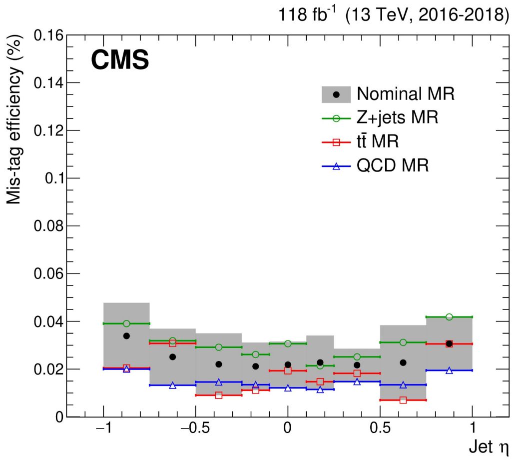


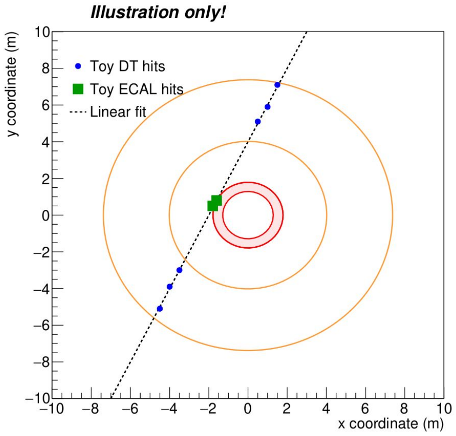
CMS: trackless and out-of-time jets

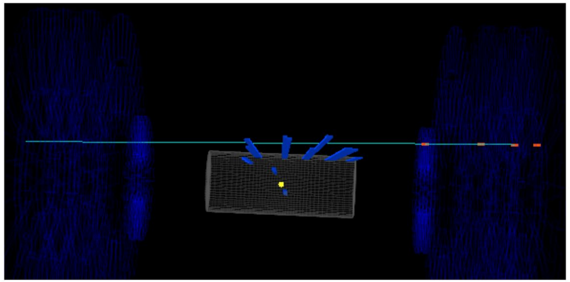
https://arxiv.org/abs/2212.06695

Collision background:
- Prompt jets misidentified as trackless and delayed
- Misidentification rate evaluated in CRs in data
- Background predicted with matrix method

Noncollision backgrounds:
- Cosmic muons and beam induced backgrounds (beam halo) creating ECAL deposits without associated tracks
- Dedicated vetoes (geometry + physics)



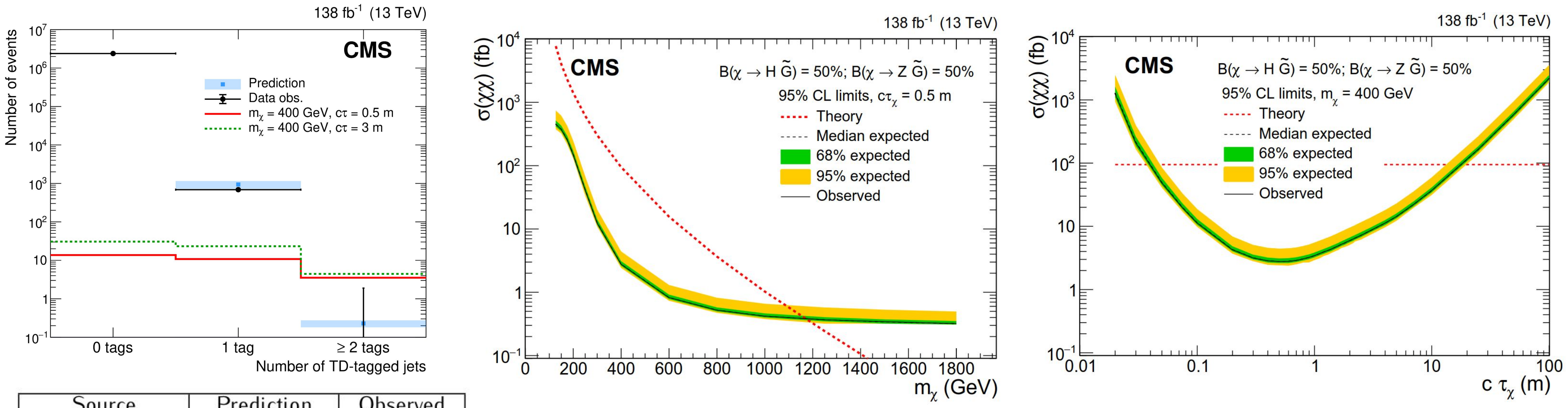




https://twiki.cern.ch/twiki/bin/view/CMSPublic/SWGuideEJTermBeamHaloId

CMS: trackless and out-of-time jets

https://arxiv.org/abs/2212.06695



Source	Prediction	Observed
Mistag	0.15 ± 0.08	
Cosmic muons	0.03 ± 0.02	
Beam halo	0.05 ± 0.05	
Tot. Run 2	0.23 ± 0.10	0

Results:

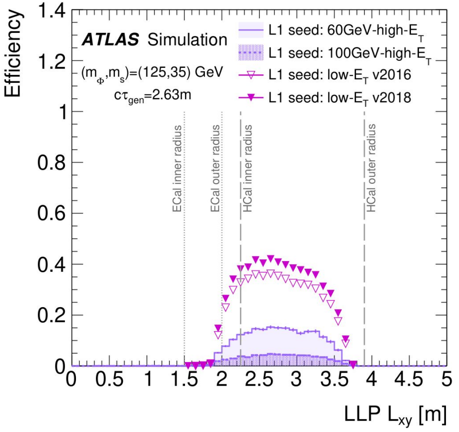
- Expected <1 events (DNN), 0 observed
- Limits at 1 fb level for m_χ > 550 GeV, exclude m_χ up to 1.18 TeV at cτ = 0.5 m

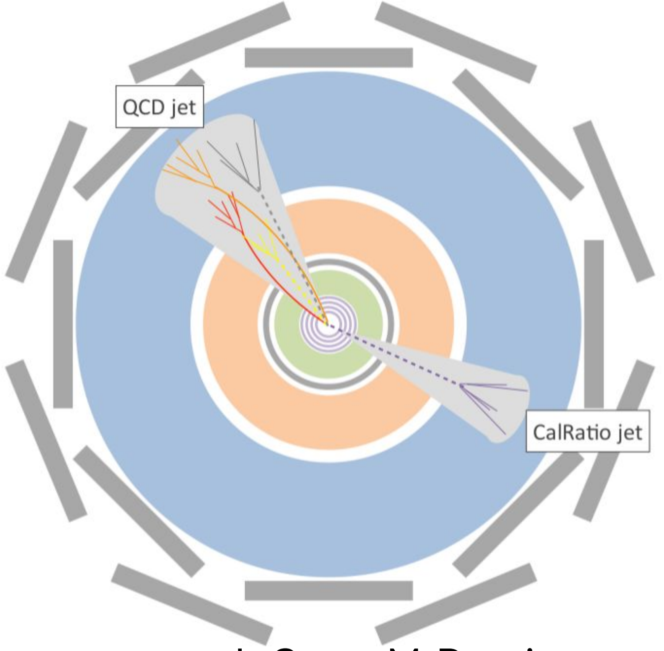
https://arxiv.org/abs/2203.01009

ATLAS: calorimeter-ratio search

LLP decays in hadronic calorimeter (HCAL):
- Trackless jets
- Low energy fraction in ECAL:
  CalRatio = E_{HCAL}/E_{ECAL}

CalRatio trigger:
- CalRatio triggers: low E_T & high E_T
- 2 search regions: low- (≤200 GeV) and high-mass (>200 GeV)
- Can access lower masses wrt CMS!





L. Corpe, M. Danninger

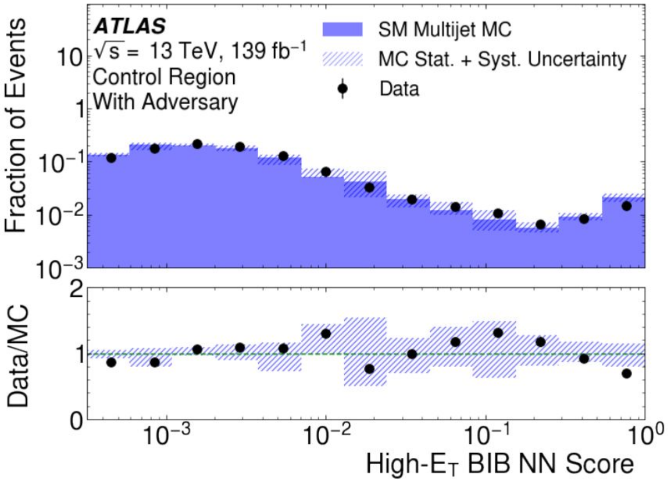
Backgrounds:
- Multijets (strong interaction) with mis-reconstructed tracks/neutral hadron abundance
- Noncollision backgrounds:
  - Beam induced backgrounds (BIB) ~ beam halo in CMS
  - Cosmic muons showering in HCAL
  - Reduced to negligible levels after final selections

https://arxiv.org/abs/2203.01009

ATLAS: calorimeter-ratio search

DNN jet tagger:

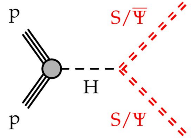
- Input variables: features of tracks, calo deposits, muon segments inside a jet
- Adversarial Network to mitigate MC mis-modelling (calo cluster timing)



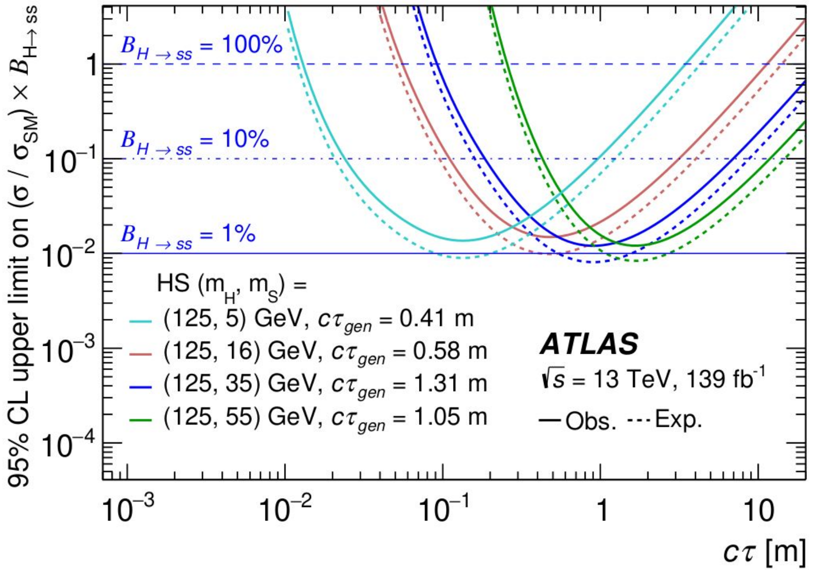
Event BDT:

- 2 CalRatio jets DNN scores
- Event-level variables

Results:



- Data-driven background estimation, ABCD
- Limits on $H \to SS \to 4f$, m_H=125 GeV
- Branching ratios BR>10% excluded for 20 mm < $c\tau$ < 10 m



EXOT-2022-04

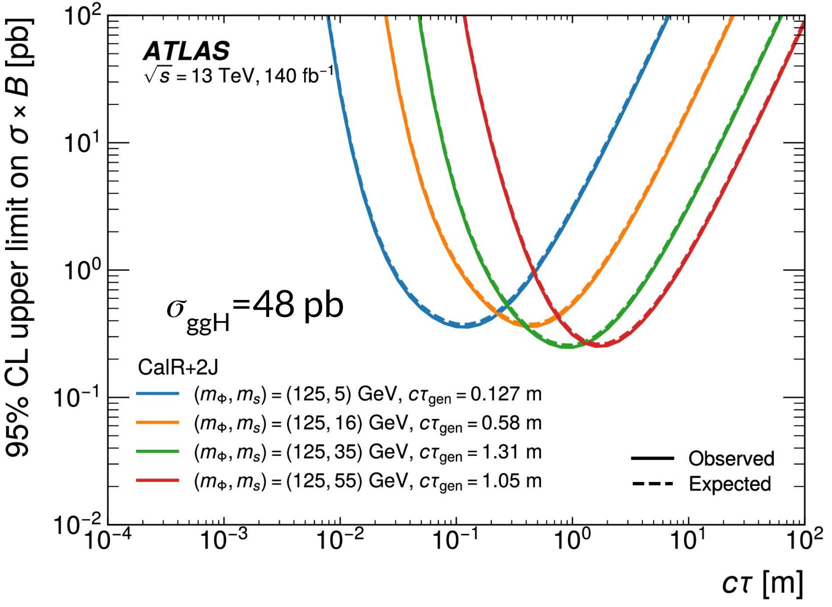
New!

ATLAS: calorimeter-ratio search

More details: Ian's talk
(on Wed, Collider BSM parallel)

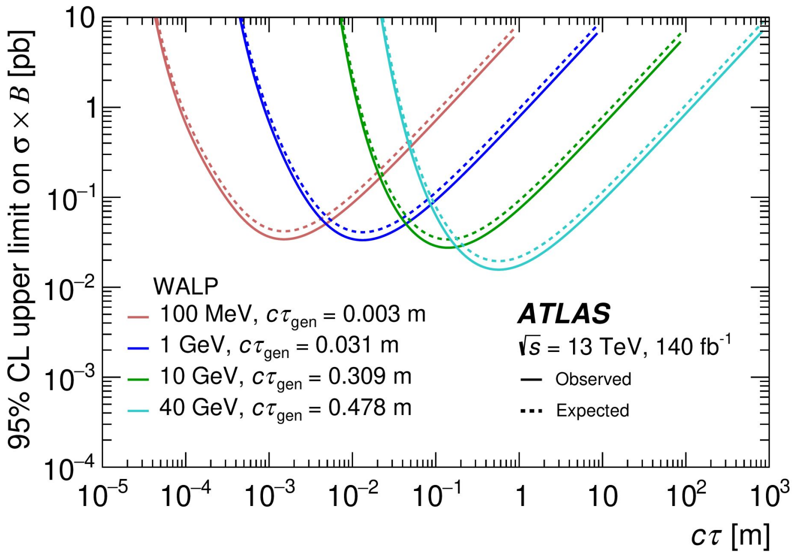
Pair-produced LLPs: "merged + resolved"

- 1 CalRatio jet + 2 trackless jets: CalRatio trigger
- ABCDisco: per-event NN, decorrelated with variable measuring trackless-ness of jets
- 3x improvement w.r.t. 2 CalRatio jets 2203.01009

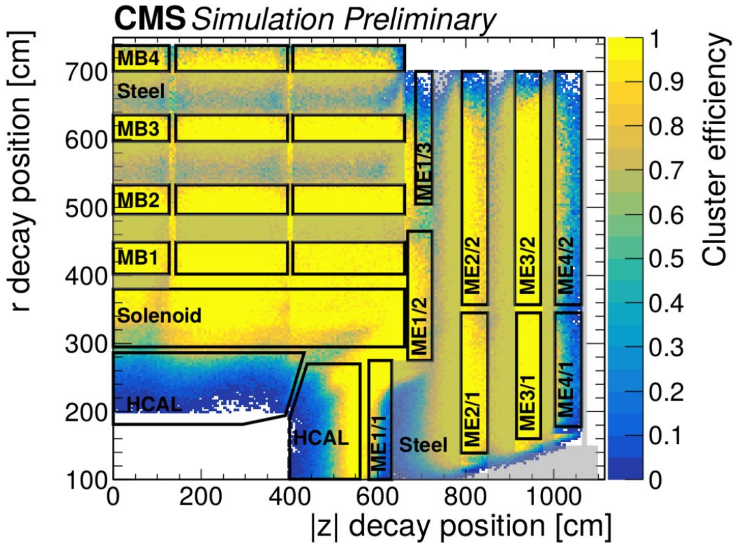


LLP (1 CalRatio jet) + SM W/Z:

- W/Z: lepton triggers
- LLP + W/Z: new interpretations (photo-phobic ALPs)



LLP searches with muon systems



ATLAS: displaced vertices in MS

https://arxiv.org/abs/2203.00587

ATLAS **Muon System (MS)**

- Big volume, shielded by calorimeters
- Tracking capability in Monitoring Drift Tubes (MDT)

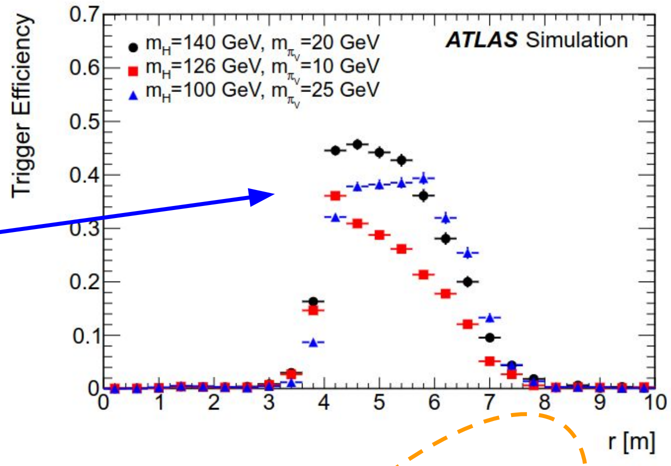
Muon RoI cluster trigger (arxiv 1305.2284)

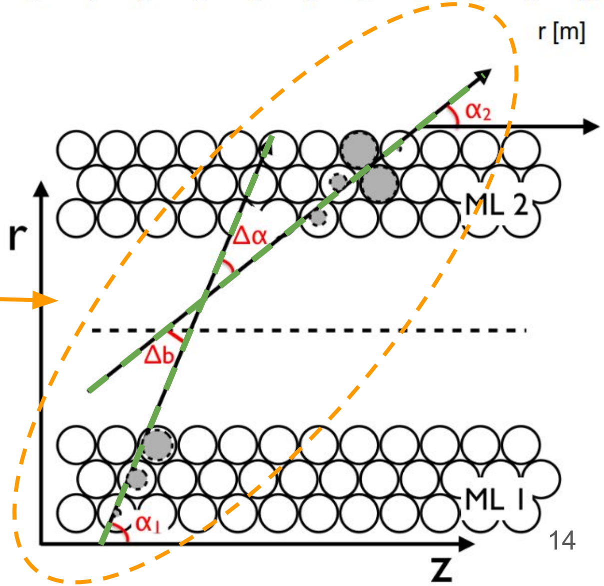
- Muon hardware trigger (L1) **RoI**: coincidence of hits in MS trigger detectors
- Software trigger (HLT) **RoI cluster**: a $\Delta R=0.4$ region containing at least 3 (4) L1 RoIs in the barrel (endcaps)

MS vertex algorithm (arxiv 1311.7070):

- Uses spatial separation of multilayers (ML) inside MDT
- Single ML hits form segments
- ML segments form tracklets
- MS vertex (η, ϕ) position reconstructed with at least 3 (4) tracklets in the barrel (endcaps)

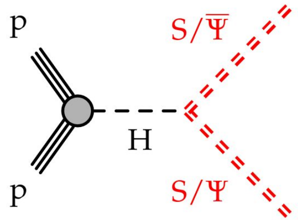
- SR: 2 MS vertices matched to HLT RoI clusters (at least 1)





https://arxiv.org/abs/2203.00587

ATLAS: displaced vertices in MS

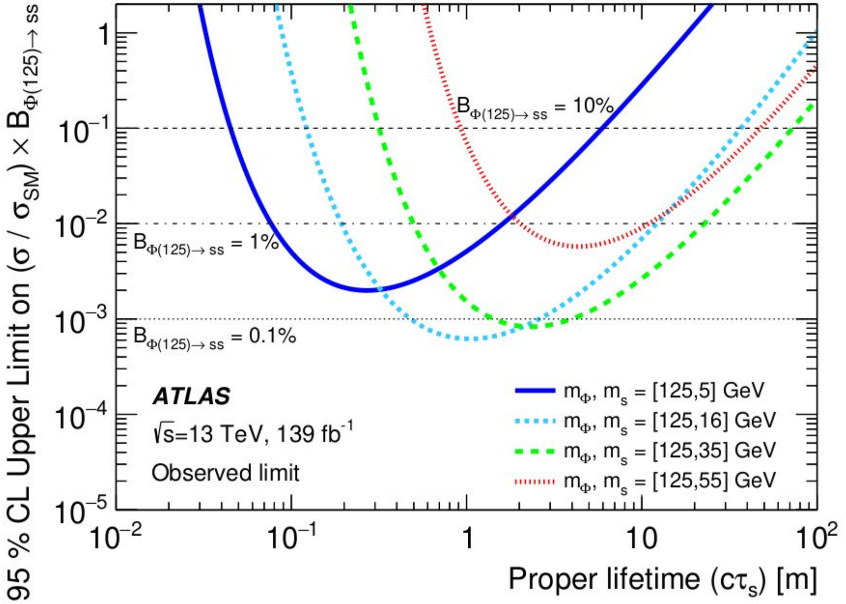


Backgrounds

- Punch-through jets showering in MS
- Noncollision (electronic noise, cosmic muons, BIB)

Results

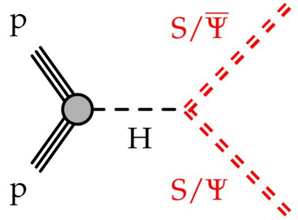
- Expected 0.32 ± 0.05 events, 0 observed
- Excluded H→SS→4f BR<0.1%
- BR>10% excluded for LLP 4 cm < $c\tau$ < 72.4 m

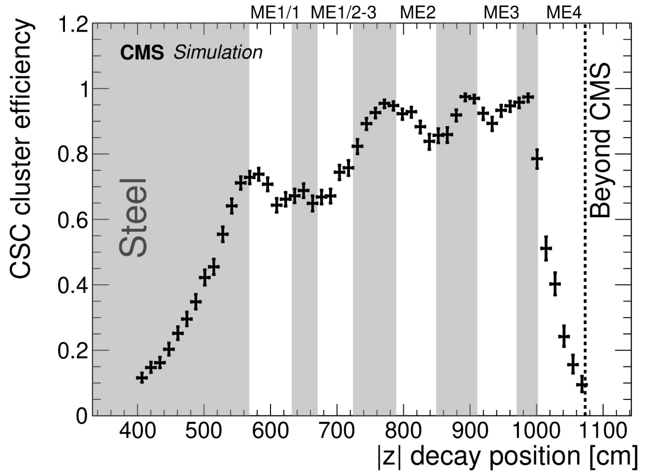


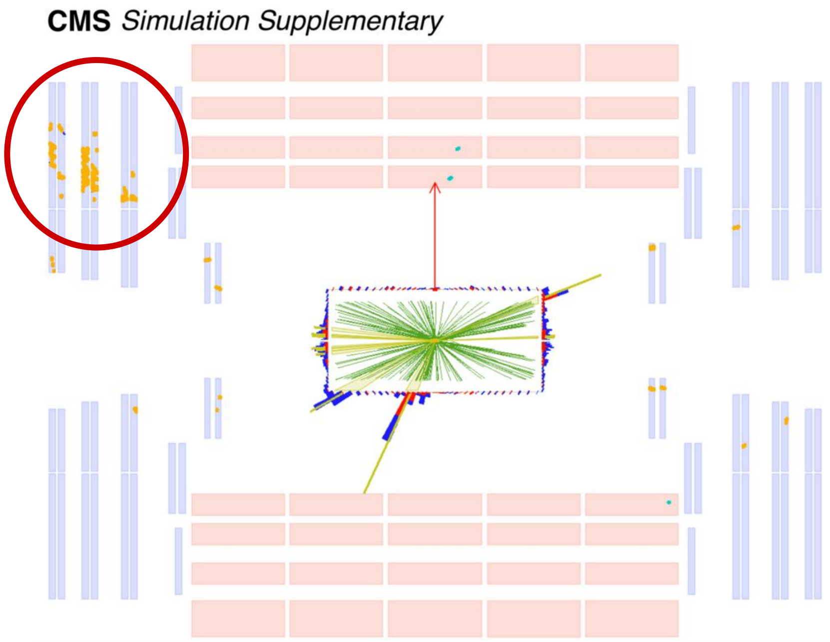
https://arxiv.org/abs/2402.01898

CMS: muon detector showers (MDS)

- Neutral LLP ($c\tau$>1 m) → decay products ionize gas in **CSCs (endcap)**/**DTs (barrel)**
- Passive material (iron/steel) + muon chambers: sampling calorimeter → a shower develops → high multiplicity of hits: **muon detector shower (MDS)**
- Sensitivity to any LLP decay (except muons)
  - Also light (O(100) MeV) particles → poor sensitivity in tracker/calorimeter (background too high!)
- Trigger: missing energy → pair of LLPs, one out of CMS
- First CMS result using CSCs: PRL.127.261804







CMS: searches for LLPs with MDS

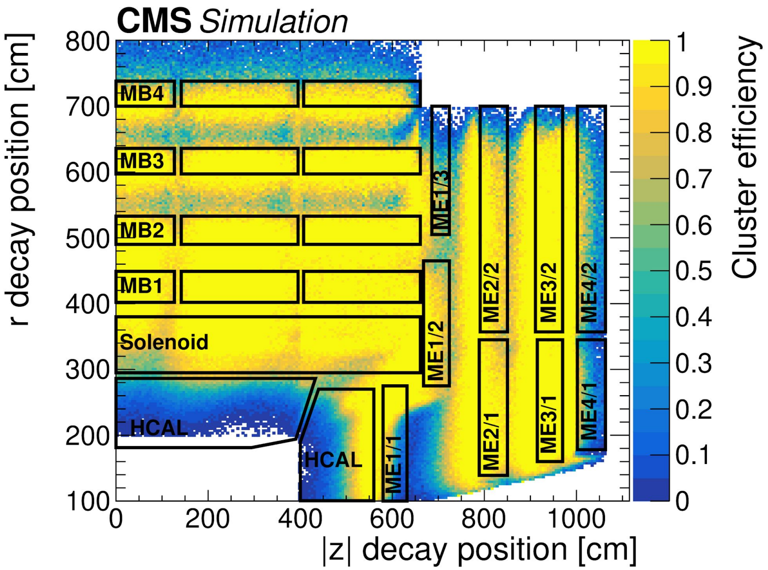
https://arxiv.org/abs/2402.01898

MDS in CSC+DT:

- Muon hits clustered with DBSCAN
- High efficiency throughout the detector

Backgrounds:

- Punch-through jets, low-p_T pileup particles
- Suppressed by vetoing high background regions (inner DT/CSC chambers)



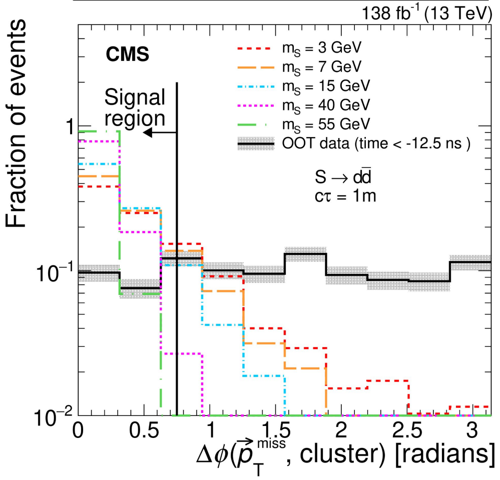
Exclusive categories: 1 CSC, 1 DT, 2 clusters

- Data-driven ABCD background prediction
- 1 cluster ABCD plane: n. hits, Δφ (cluster,MET)
- 2 clusters ABCD plane: n. hits in each cluster

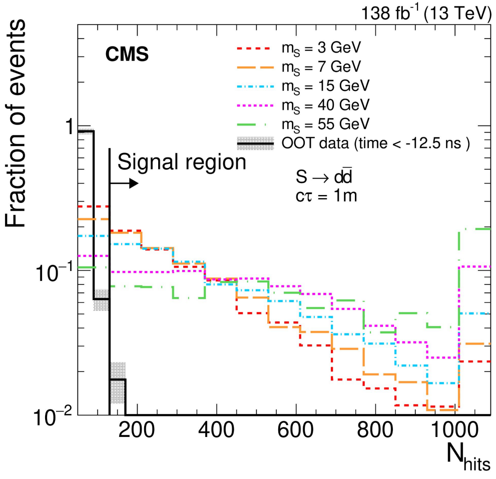
Advantage wrt ATLAS:

- More shielding material → less background → can use 1 cluster category to increase sensitivity!

Angular separation missing p_T and cluster



N_{hits} in cluster: most discriminating variable

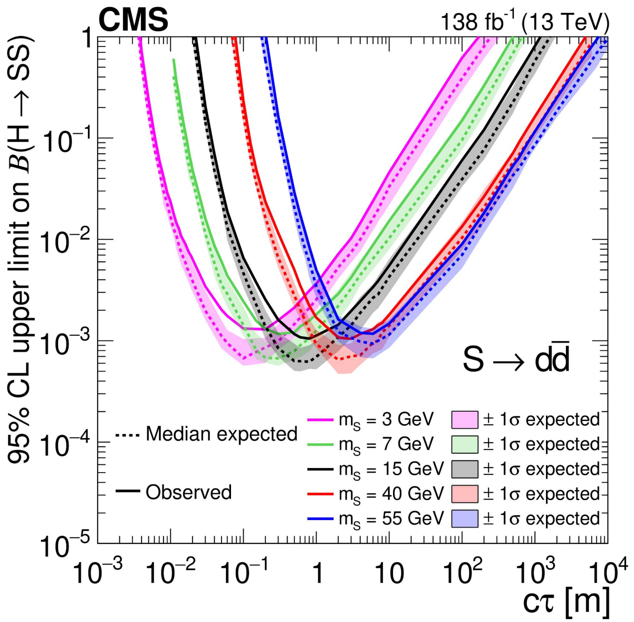


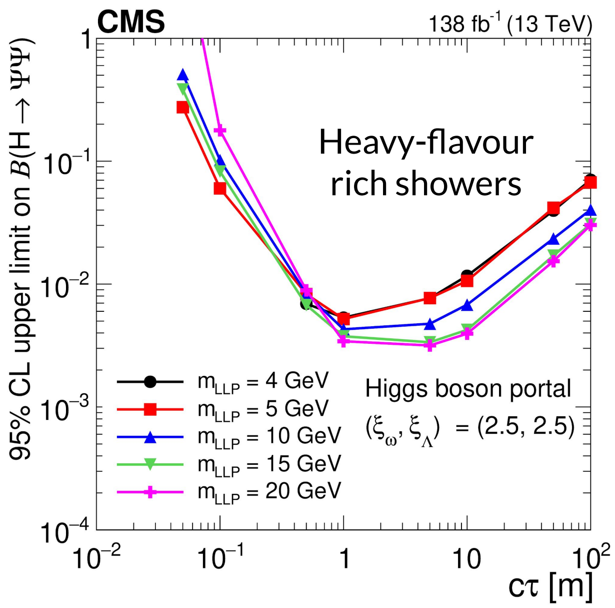
https://arxiv.org/abs/2402.01898

CMS: searches for LLPs with MDS

Results:

- $H \to SS \to 4f$: 9 decay modes with hadronic shower (bb, dd, K^+K^-, K^0K^0, $\pi^+\pi^-$), EM ($\pi^0\pi^0$, γγ, e^+e^-), or both ($\tau^+\tau^-$)
- Same sensitivity for same shower type independent of masses
- First sensitivity to sub-GeV mass LLPs at BR = 0.1% level
- Best limits to date on Twin Higgs model:
  0.04–0.40 m and above 5 m for 15 GeV LLP; 0.3–0.9 m and above 3 m for 40 GeV LLP; and above 0.9 m for 55 GeV LLP
- First sensitivity @ LHC to dark showers model produced from Higgs decay





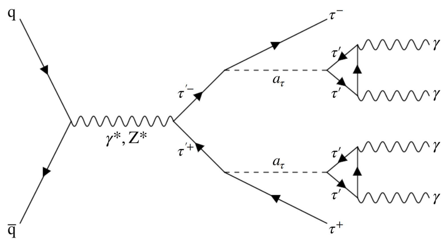
CMS: searches for VLLs with MDS

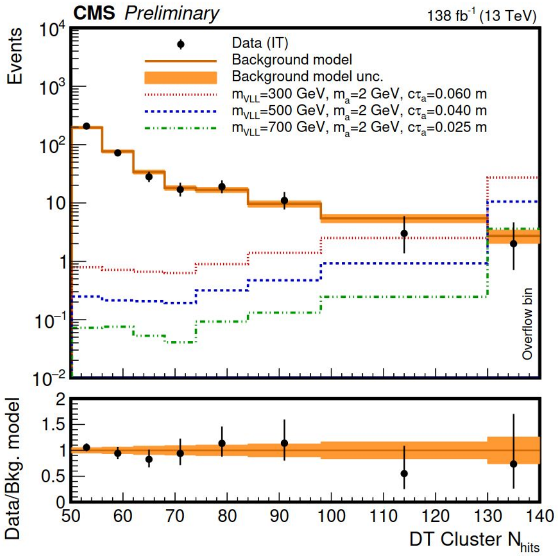
CMS-PAS-EXO-23-015

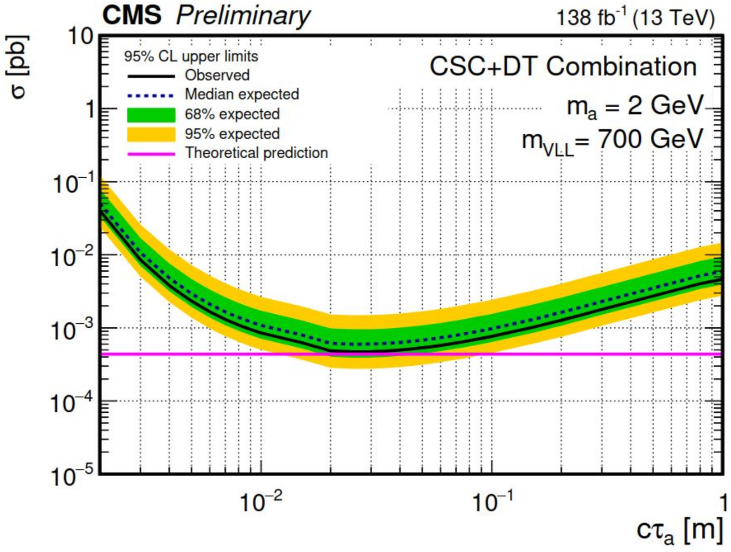
New!

Vector-like lepton (VLL): $\tau' \to \tau\ a_\tau$

- Prompt τ lepton + a_τ light pseudoscalar, long-lived → electromagnetic shower as **MDS**
- N. hits predicted from data events failing τ identification
- Validated in out-of-time data







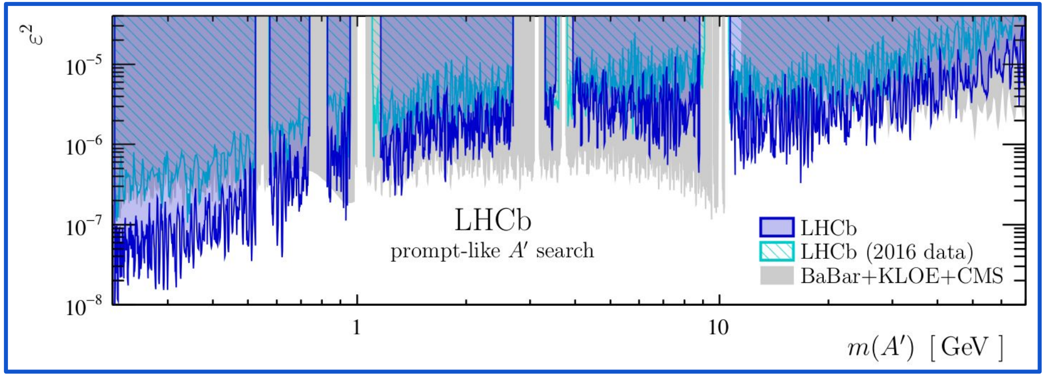
m(VLL) excluded up to 690 GeV for $m(a_\tau)$ = 2 GeV

https://arxiv.org/abs/1910.06926

LHCb: dark photons to dimuons

A' → $\mu^+\mu^-$, full Run2 (5.5 fb^{-1})

- Prompt (m(A')<70 GeV)

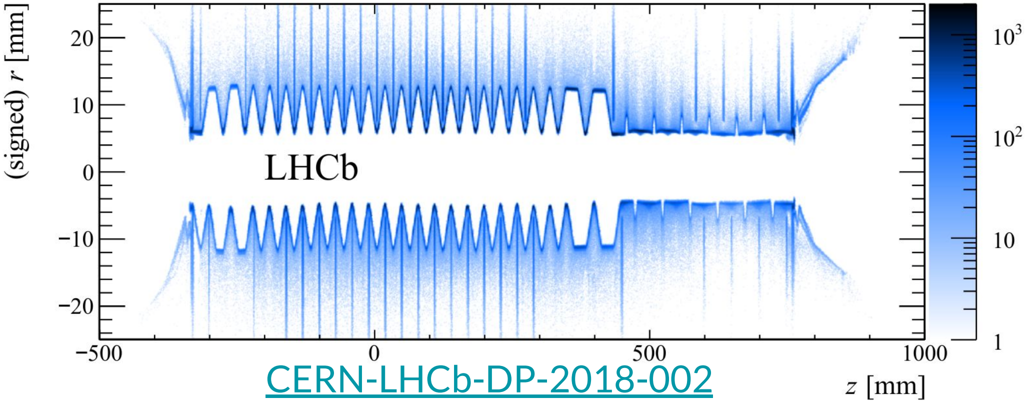


Displaced analysis:

- Software trigger: dimuons forming good quality displaced vertex → suppress prompt background

Backgrounds:

- Photon conversions in Vertex Locator detector (VELO) → determined with a precise 3D material map
- b-hadrons → reduced with BDT (isolation) + veto on heavy-flavour software trigger
- Low mass tail of $K_S^0 \to \pi^+\pi^-$



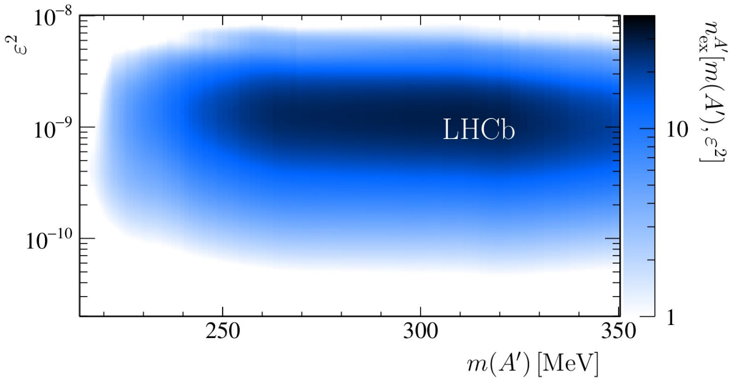
CERN-LHCb-DP-2018-002

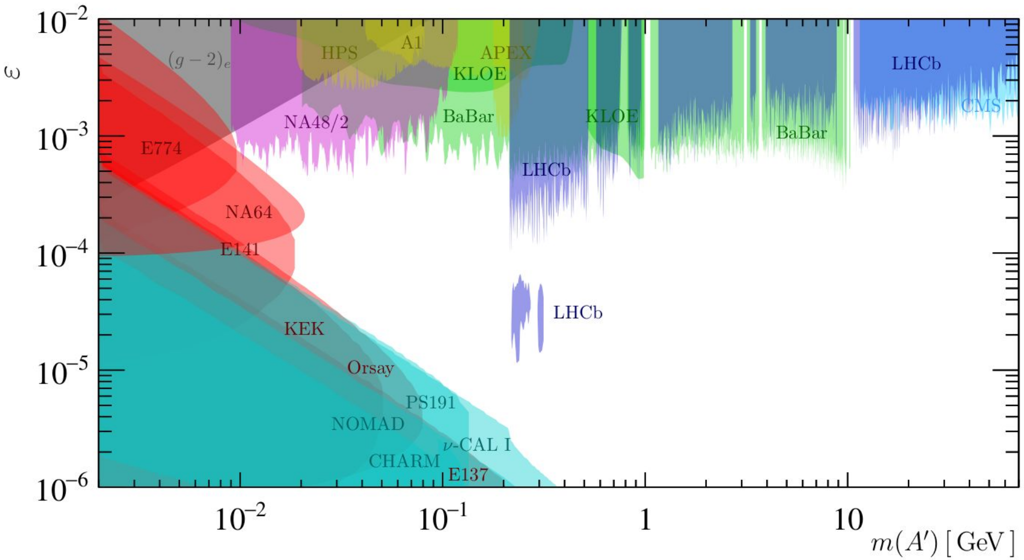
https://arxiv.org/abs/1910.06926

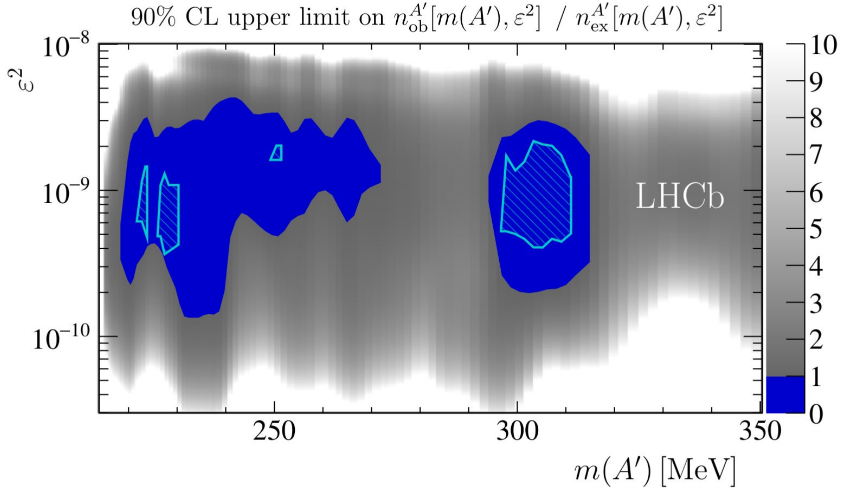
LHCb: dark photons to dimuons

Results:

- Signal yield dependency on displacement corrected by resampling prompt $\gamma^* \rightarrow \mu^+\mu^-$ in data
- No excess, exclude large portion of [m(A'), ε^2] plane
  - ε^2 : A' kinetic mixing to SM photon (related to τ(A'))

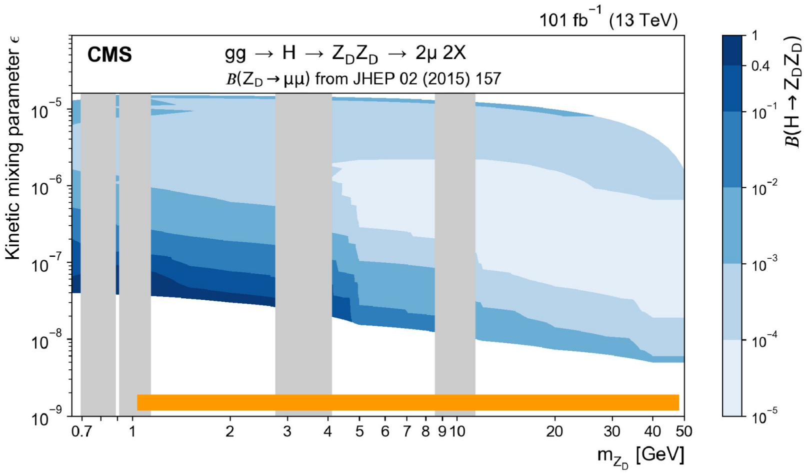




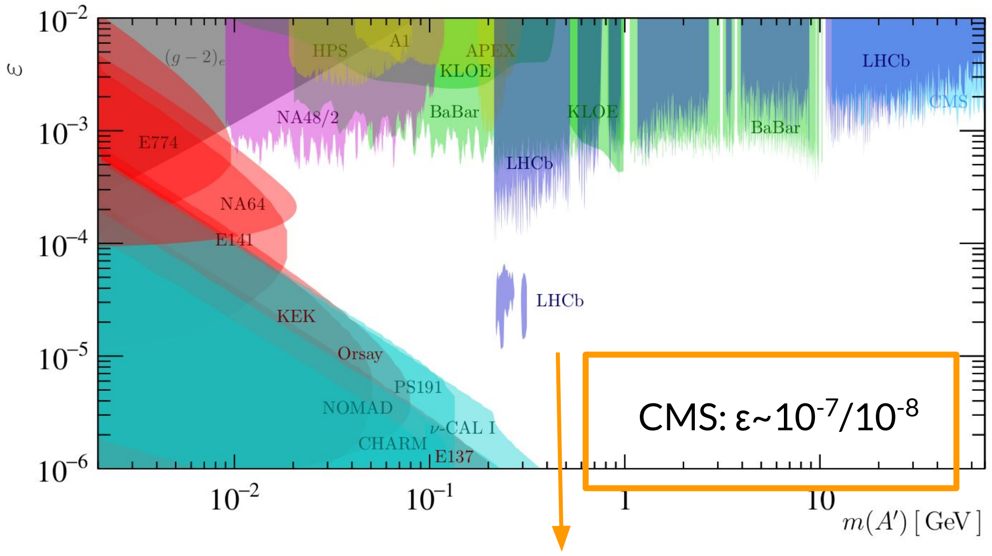


https://arxiv.org/abs/1910.06926

LHCb - CMS: dark photons to dimuons



CMS-EXO-20-014

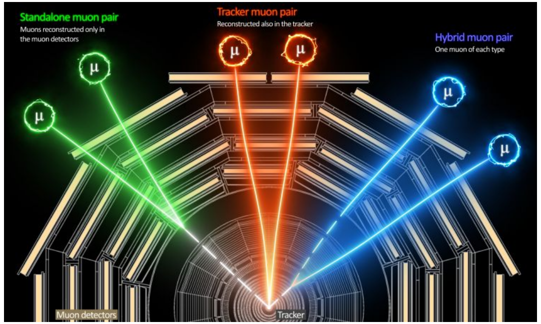


Analogous CMS analysis:

- H → A' A' → 2μ X
- Special CMS data stream called "scouting" [2403.16134]: store only limited event information but can loosen trigger thresholds
- Clear complementarity!

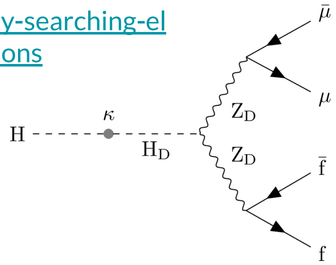
CMS: displaced dimuons with Run3 data

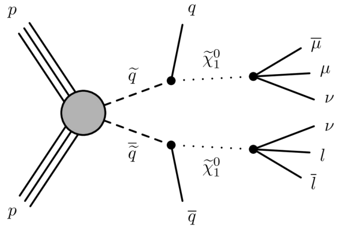
https://arxiv.org/abs/2402.14491



https://cms.cern/news/detector-far-far-away-searching-elusive-long-lived-travellers-tracing-pairs-muons

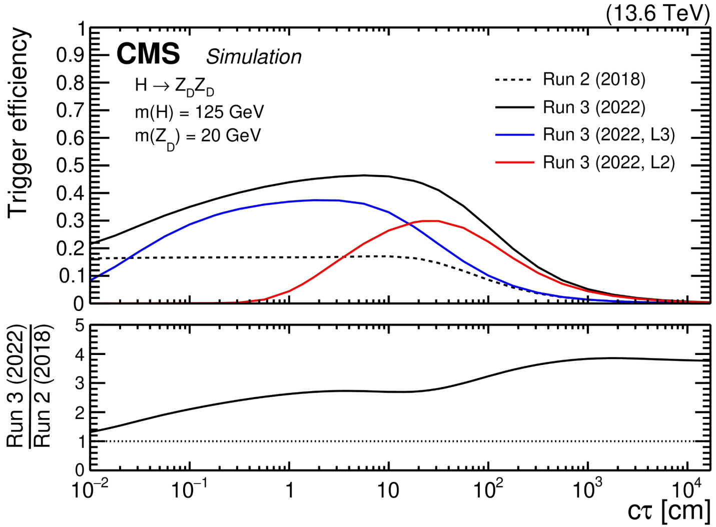
First Run3 CMS search!





Run 3 key development: trigger

- New L1 algorithm to assign p_T to μ from displaced vertex
- Improved HLT algos:
  Recovers efficiency for shorter μ tracks,
  x2 better @ cτ = 1 cm
  Discard prompt μ → improves at larger displacement,
  x3 efficiency @ cτ = 1 m

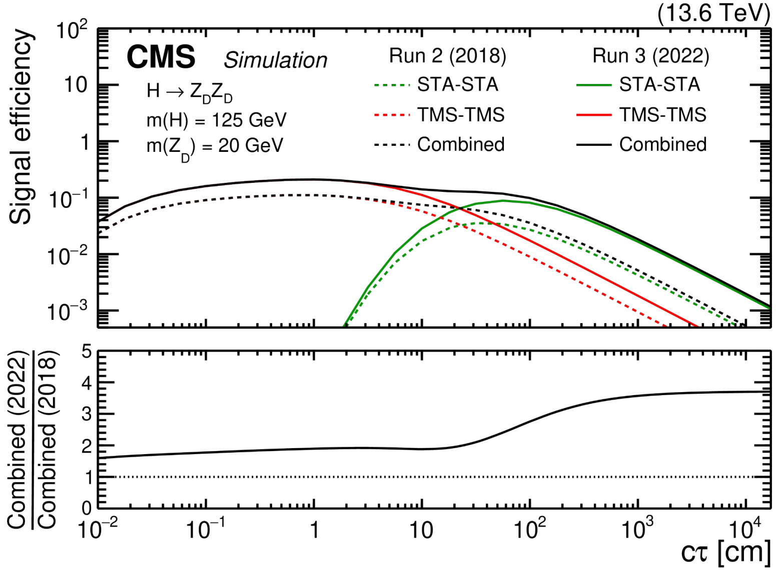


CMS: displaced dimuons with Run3 data

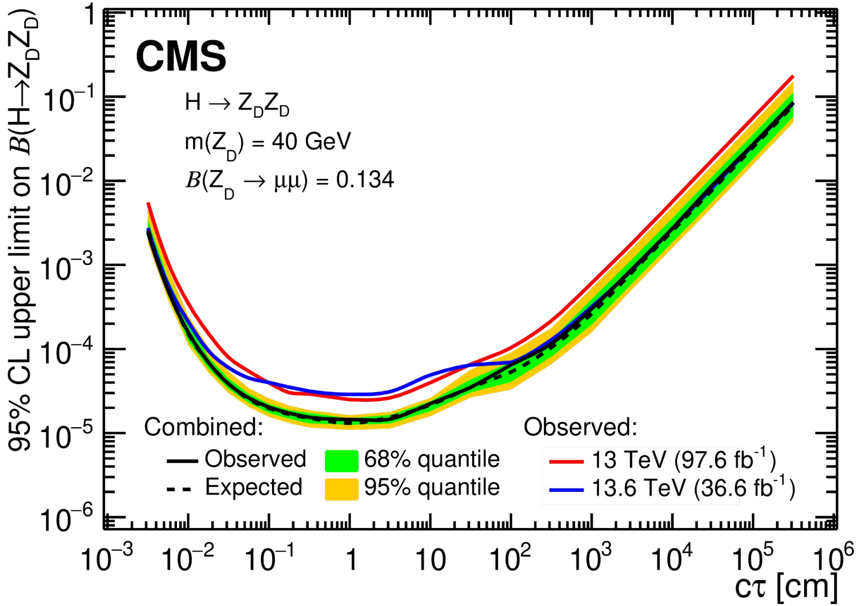
https://arxiv.org/abs/2402.14491

Displaced dimuons reconstruction:

- As global μ (with tracker): better at lower displacement
- As standalone μ (muon system only): better at higher displacement

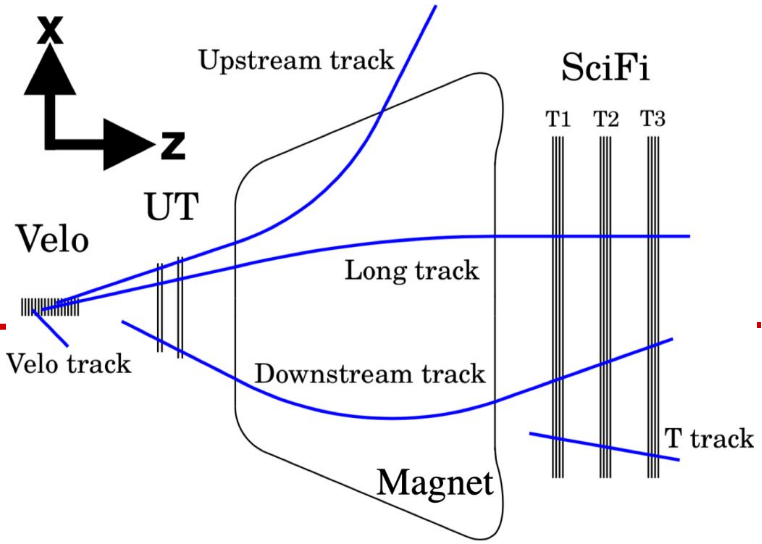


Achieved similar sensitivity to Run 2 data with only ⅓ of the luminosity in Run 3 (2022)



More LLP Run 3 results:
Daniele's talk (on Tue, plenary)

Run3 developments



ATLAS Run3 upgrades

https://arxiv.org/abs/2305.16623

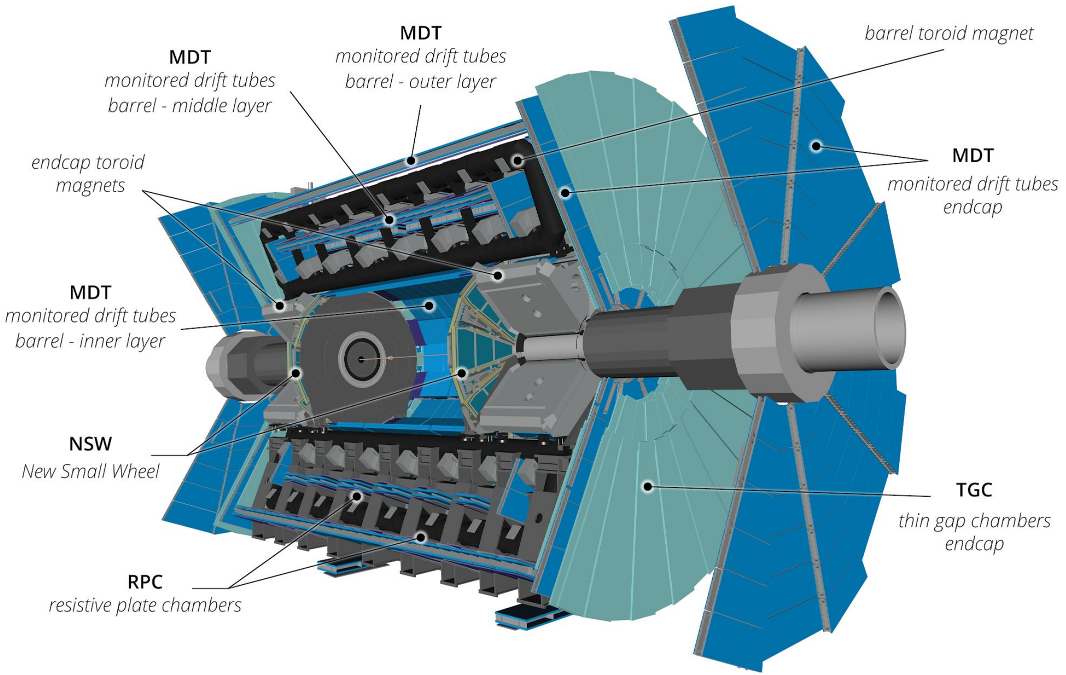
- **ECAL LAr** electronics: finer granularity inputs to trigger, better control of rates (better resolution, rejection of pileup)
- **HCAL TileCal**: more robust against radiation (extended coverage of scintillation counters)

→CalRatio!

- MS: New Small Wheel (**NSW**) detectors installed in endcaps innermost stations, $1.3 < |\eta| < 2.7$
- Small-strip TGCs and micro-mesh gaseous structure (Micromegas) detectors: fast trigger, precision tracking

→Muon Displaced Vertices!

- Upgraded HLT and DAQ



ATLAS: large radius tracking

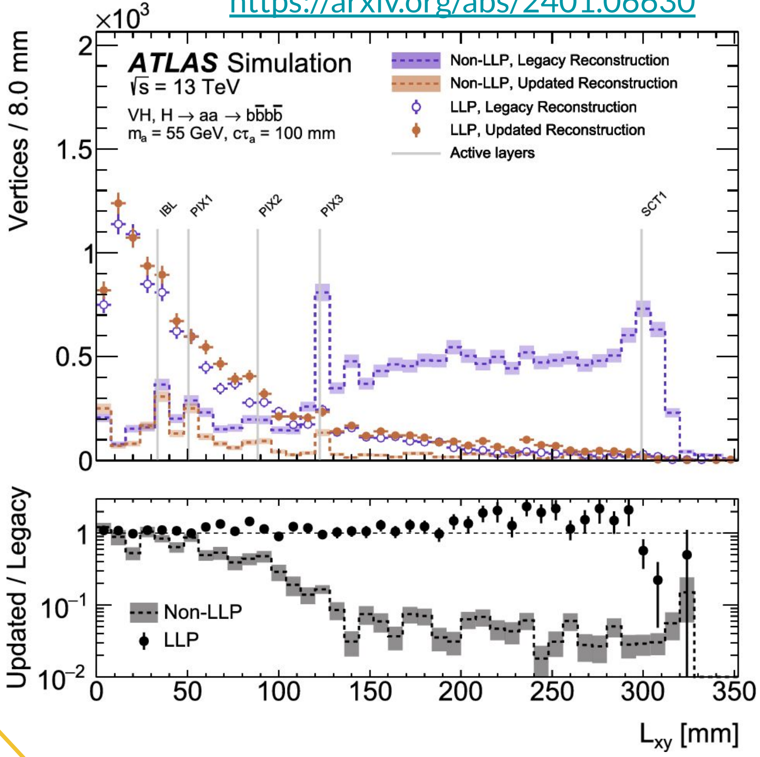
https://arxiv.org/abs/2304.12867
https://arxiv.org/abs/2401.06630

LRT:

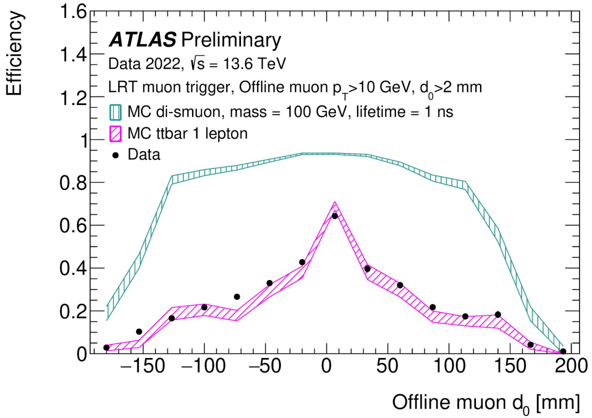
- Deploys unused hits after standard tracking
- Optimized for LLP decays:
  - $|d_0|$ 5-300 mm, $|z_0|$ 200-500 mm

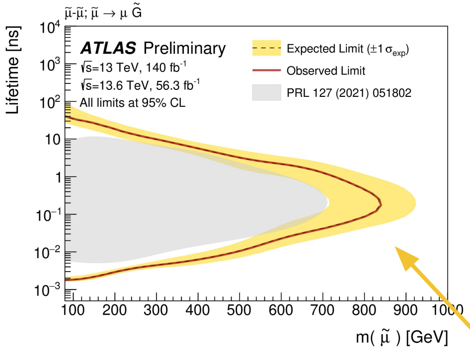
Run3 LRT:

- Tighten selections to reduce fake rate and PU-dependency
- Commissioned studying K^0, excellent data-MC agreement
- Deployed to trigger on displaced jets/taus/leptons



https://cds.cern.ch/record/2875779/





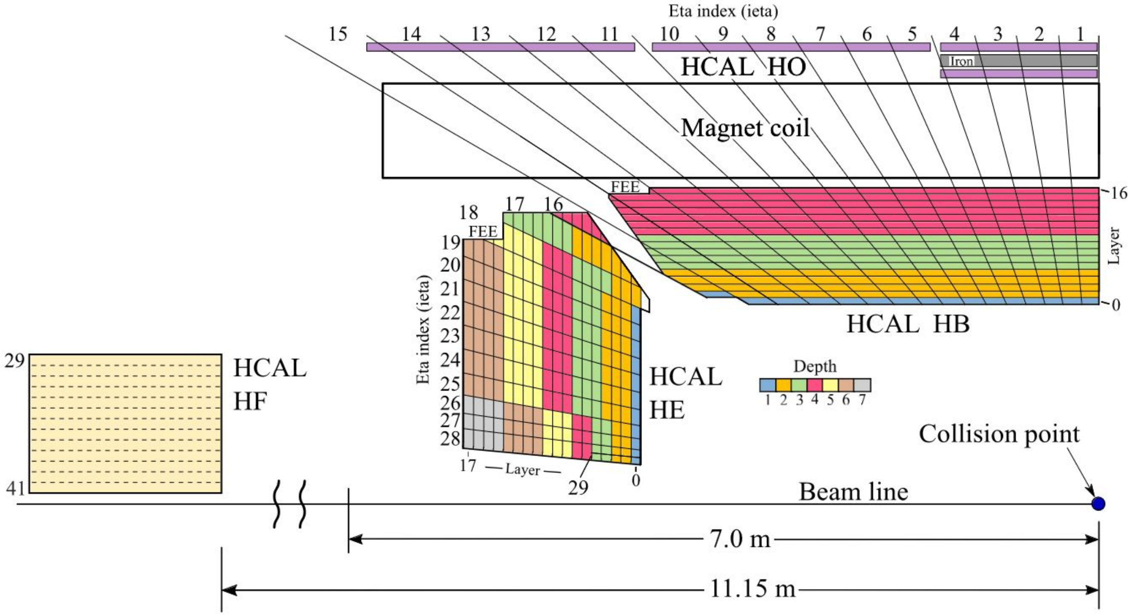
See Ben's talk (earlier today)

LRT: used in the new Run2+3 displaced leptons search! ATLAS-CONF-2024-011

CMS Run3 upgrades

http://arxiv.org/abs/arXiv:2309.05466

- Innermost tracker layer replaced (radiation damage)
- **HCAL**: enhanced readout granularity and shower depth (4 barrel layers)
- Installed first stations the Gas Electron Multiplier (GEM) for HL-LHC
- CSC electronic replacement (in view of HL)
- HLT farm equipped with GPUs to accelerate reconstruction



CMS trigger developments: delayed jets

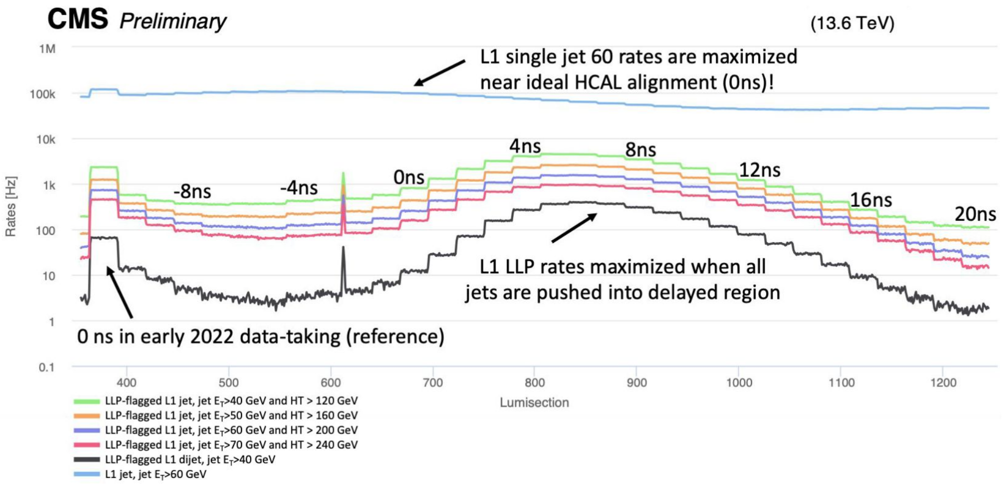
DP-2023-043

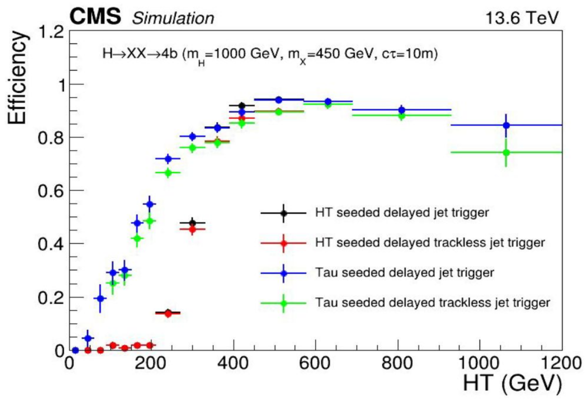
Delayed and displaced jets in HCAL trigger:

- L1 algorithm: identifies HCAL trigger towers with significant energy in higher depths or pulses at late times
- x4 efficiency @ LLP cτ = 3 m
- Signature currently not covered at CMS, analogous to ATLAS CalRatio!

Delayed jets in ECAL trigger:

- ECAL timing + trackless jet @ HLT
- Improved p_T/H_T reach (300 GeV w.r.t 1 TeV in Run2) → more competitive wrt ATLAS

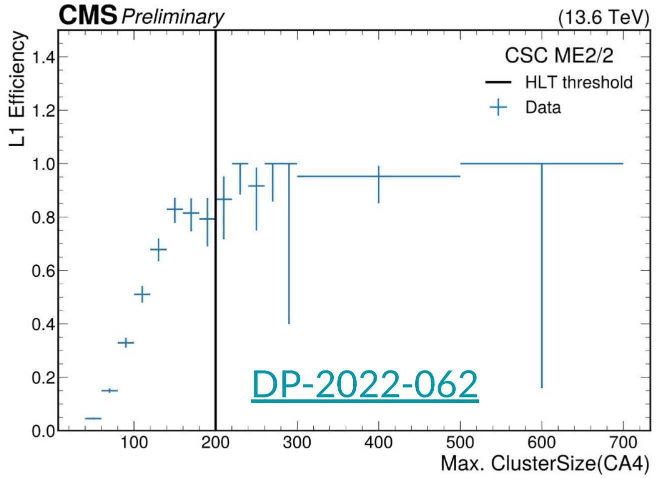




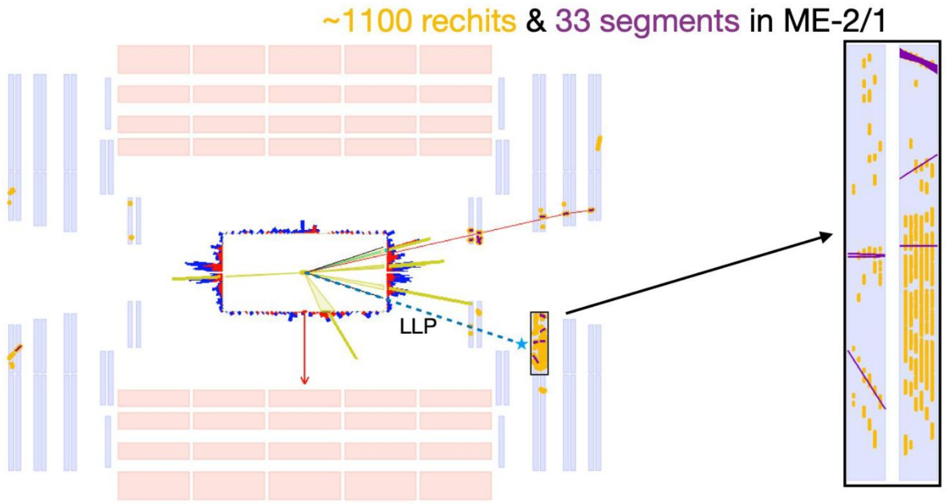
CMS trigger developments: muon showers

Muon detector shower trigger:

- L1 algorithm: counts if CSC hits in a chamber above a configurable threshold
- 20x better acceptance wrt Run2 unspecific trigger (MET)



DP-2022-062

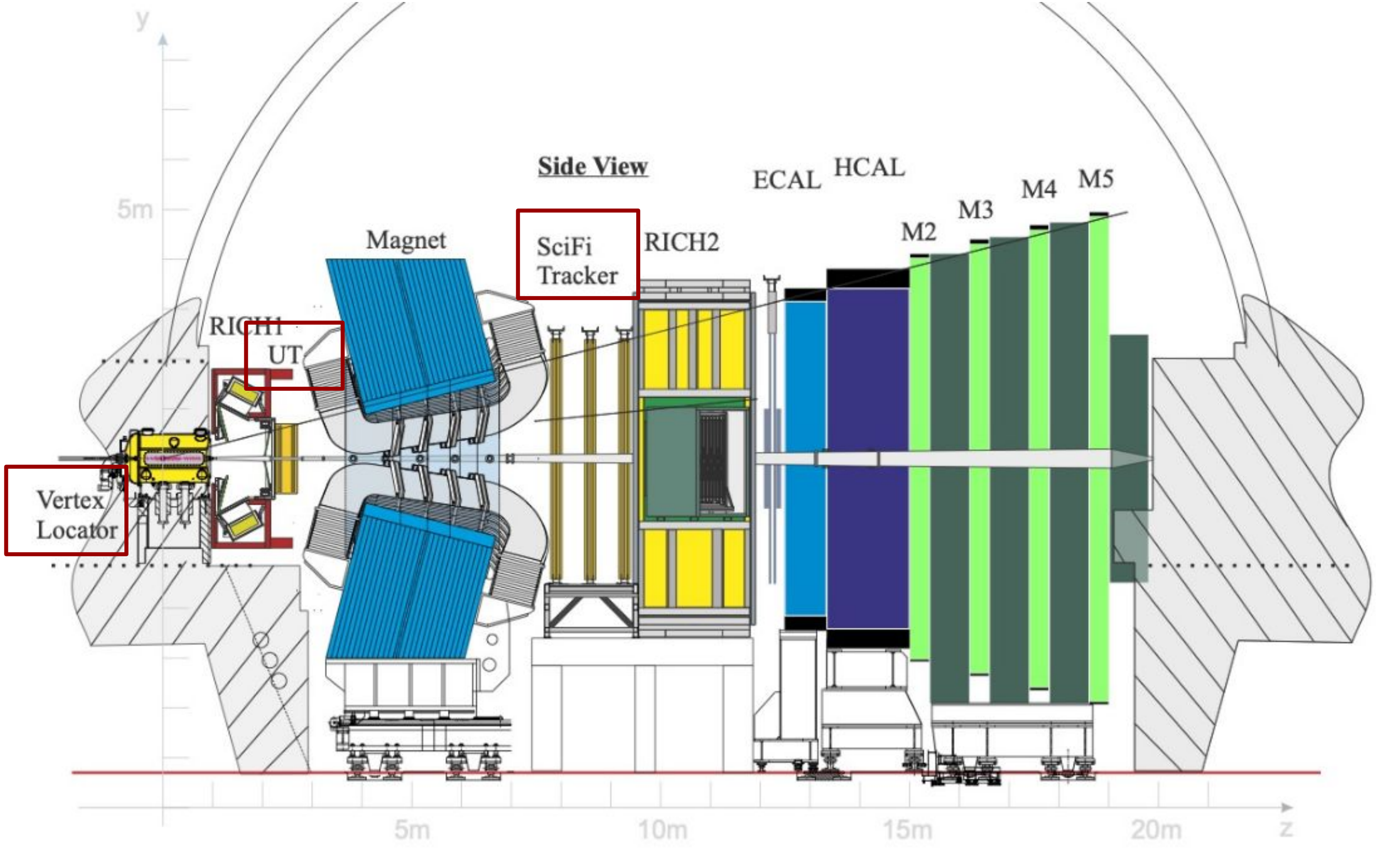


https://arxiv.org/abs/2305.10515

LHCb detector upgrade

Detector upgrade for Run3

- **VELO**: new silicon pixel, placed closer to beam
- RICH: new optics/PM
- **UT**: new high granularity upstream tracker
- **SciFi**: 3 new scintillating fibre tracking stations
- Full replacement of FE and DAQ
- **Full software trigger**
- HLT1 on GPUs
- HLT2 on CPUs
- Full detector readout at 40 MHz!
- New data centre



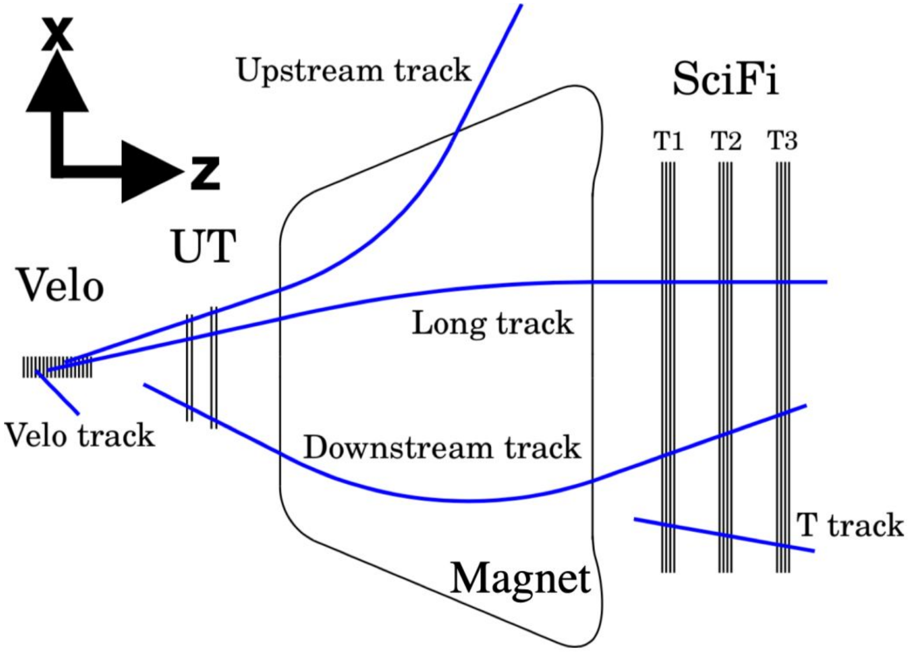
LHCb tracking for LLPs

Long tracks:
- Standard approach
- All tracker detectors

Downstream tracks:
- UT + SciFi matching without VELO

T-tracks:
- Using SciFi only

Challenges:
- Low momentum resolution (lower magnetic field), extrapolation over long distance, low vertex reconstruction efficiency (ghost vertices)



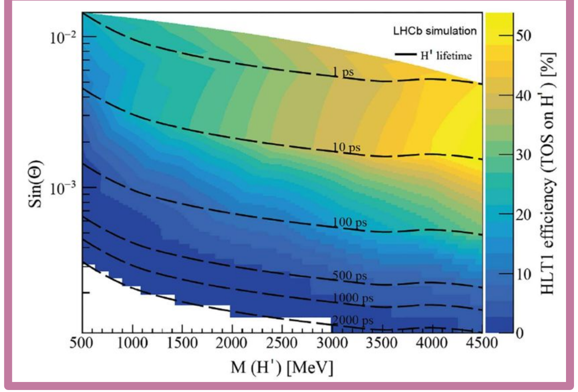
https://arxiv.org/abs/2305.10515

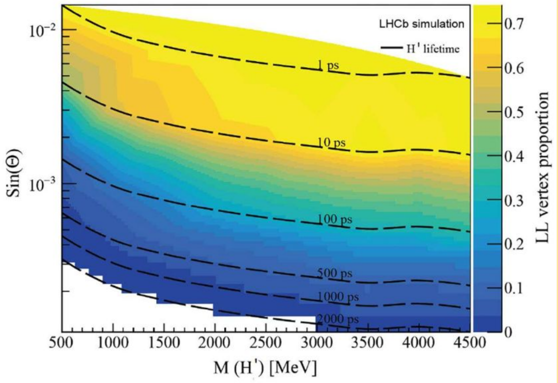
LHCb tracking for LLPs

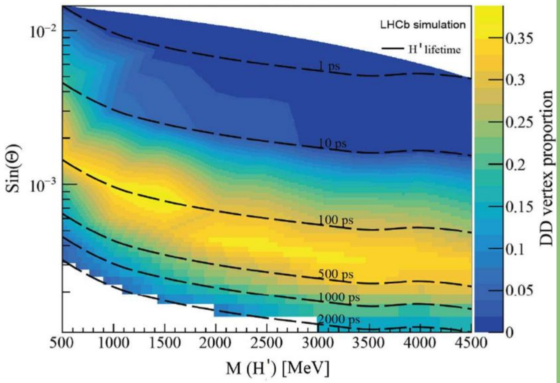
https://www.frontiersin.org/articles/10.3389/fdata.2022.1008737/full#F10

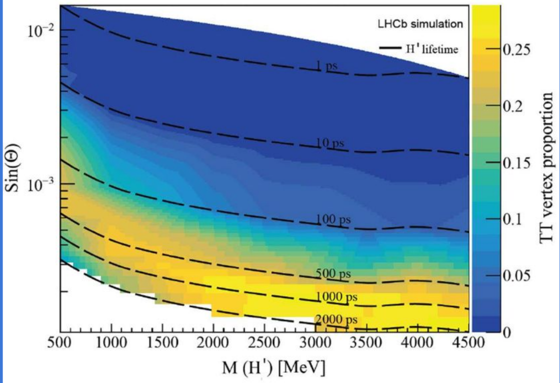
Case study: Higgs portal to DM; $B \rightarrow H' (\rightarrow \mu^+\mu^-)K$

- Mixing of SM H and light H′ produced in B decays
- Reconstructability of the decay vertex ($H' \rightarrow \mu^+\mu^-$) as a function of $M_{H'}$ and lifetimes:
  - 2 Long tracks
  - 2 Downstream tracks
  - 2 T-tracks
- To be compared to current HLT capabilities with long tracks only!

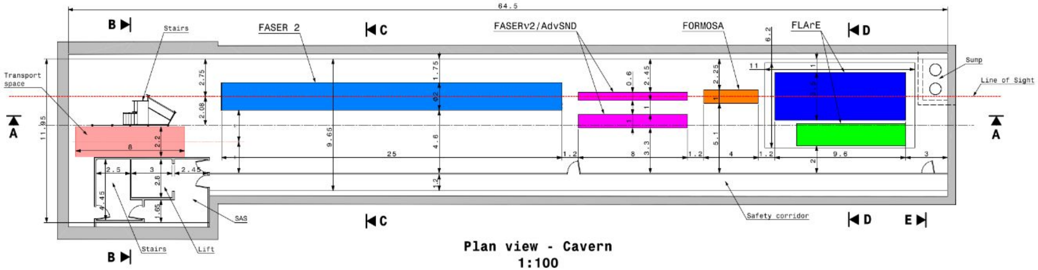








LLP detectors @ LHC

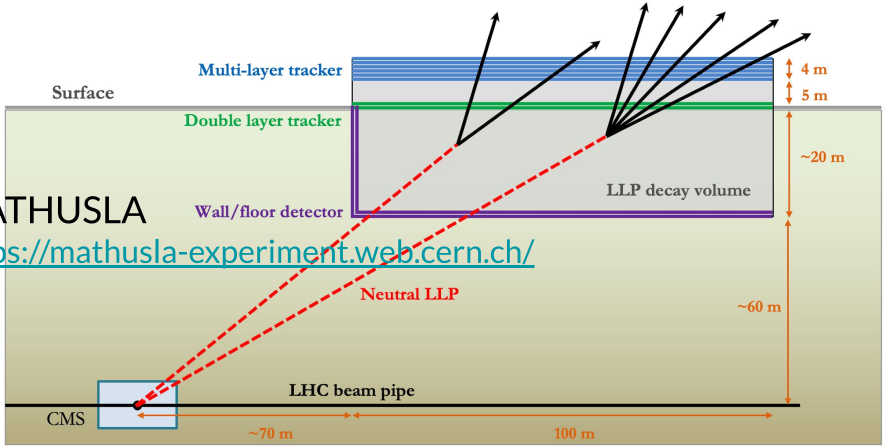


LLP transverse detectors

- Target LLPs in large mass range (GeV-TeV)
- Increase lifetime coverage wrt ATLAS/CMS/LHCb

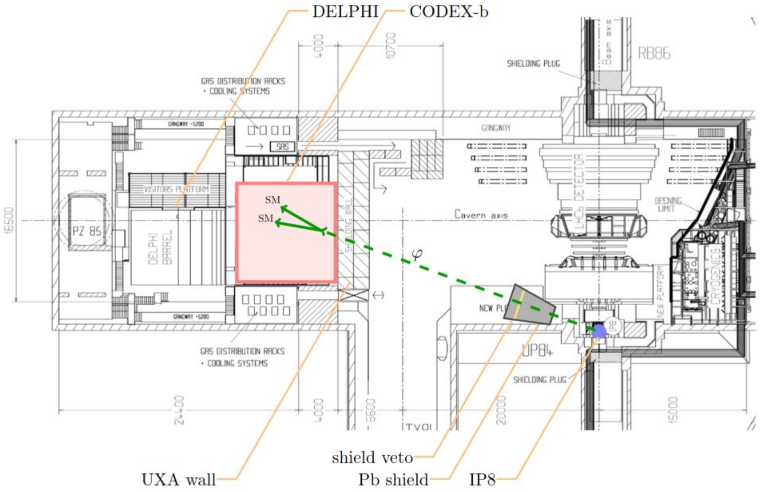
MATHUSLA

https://mathusla-experiment.web.cern.ch/



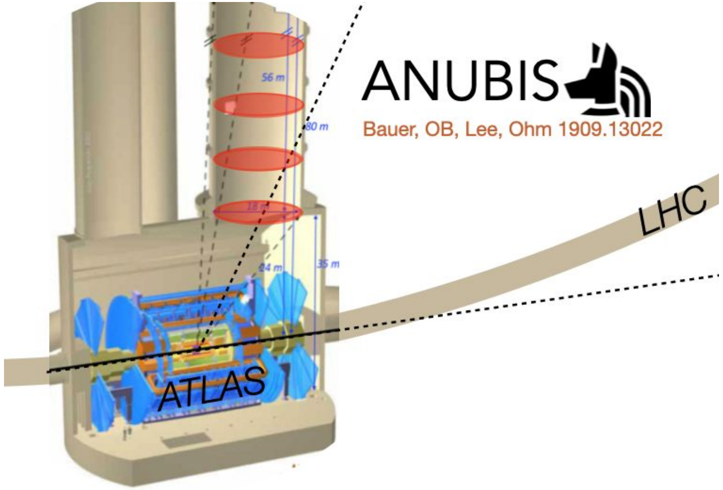
CODEX-b

https://link.springer.com/article/10.1140/epjc/s10052-020-08711-3



ANUBIS

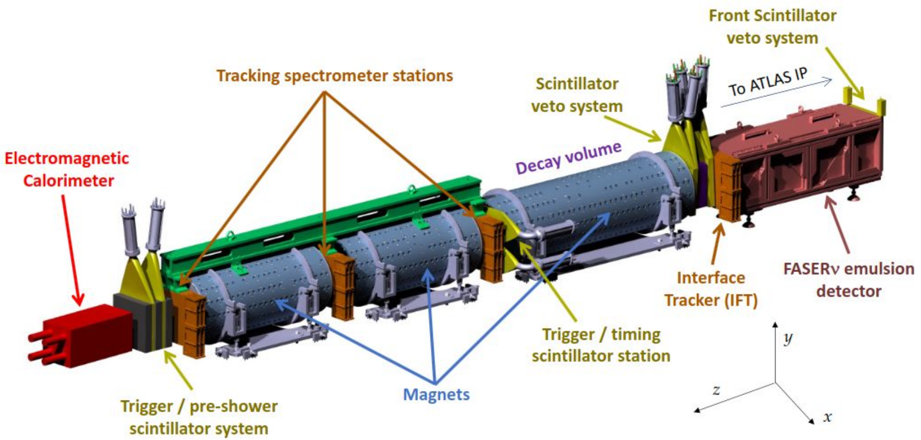
https://twiki.cern.ch/twiki/bin/view/ANUBIS/

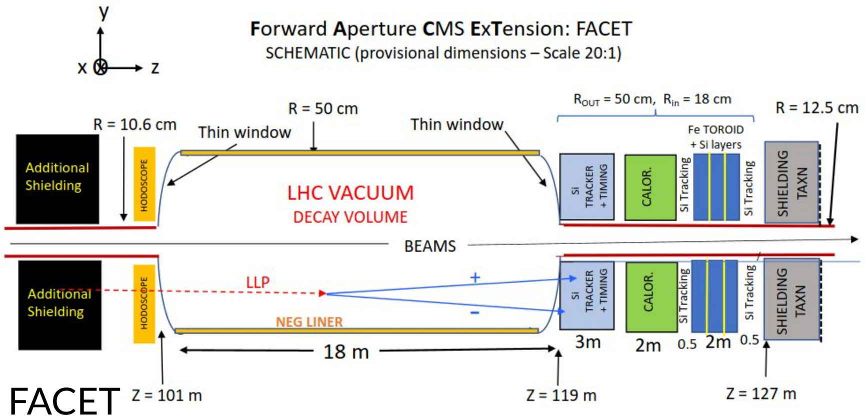


LLP forward detectors

- Target lighter LLPs mass range (<GeV) more likely to be produced forward

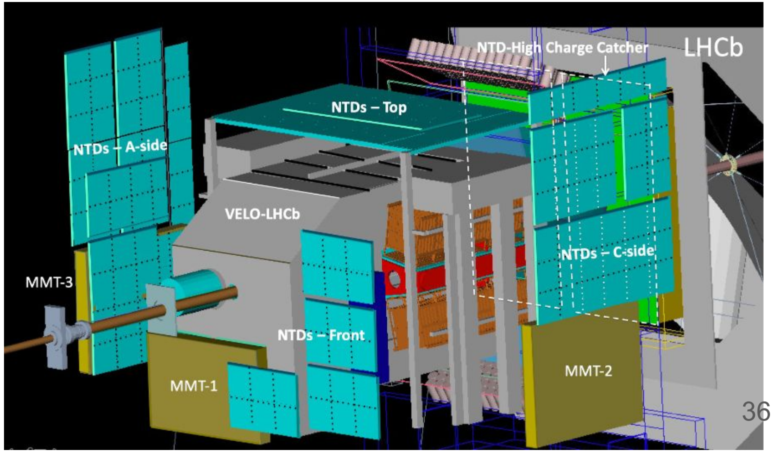
FASER
https://faser.web.cern.ch/
Search for dark photons A' → e^+e^- (2022 data)
https://arxiv.org/abs/2308.05587
Search for ALPs → γγ (2022+2023 data)
https://arxiv.org/abs/2410.10363





FACET
https://arxiv.org/abs/2201.00019

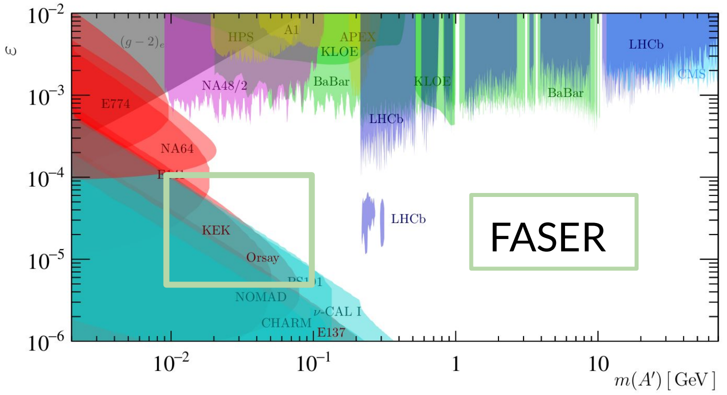
MoEDAL-MAPP
http://dx.doi.org/10.1142/S0217751X14300506



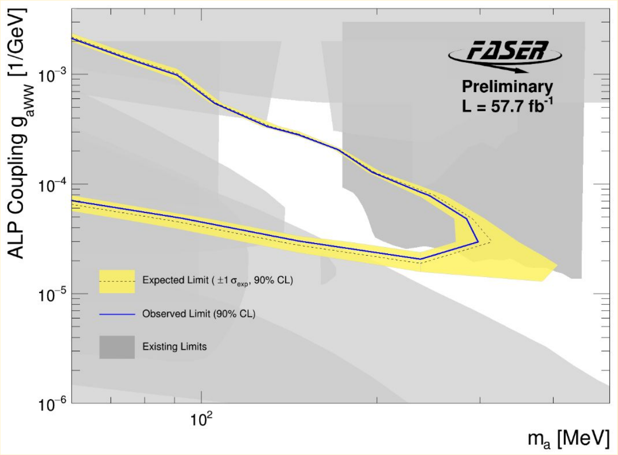
LLP forward detectors

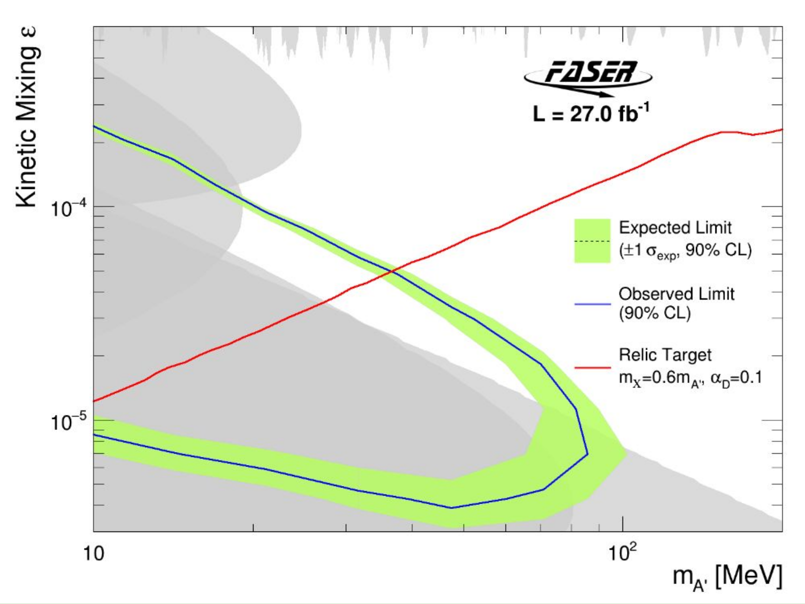
- Target lighter LLPs mass range (<GeV) more likely to be produced forward

Run3 searches!



FASER
https://faser.web.cern.ch/
Search for dark photons A' → e^+e^- (2022 data)
https://arxiv.org/abs/2308.05587
Search for ALPs → γγ (2022+2023 data)
https://arxiv.org/abs/2410.10363





LLP Community Workshop

State-of-the-art: **LLP Community Workshop**

LLP2025 in Valencia:
https://indico.cern.ch/event/1441321/
2-6 June 2025!

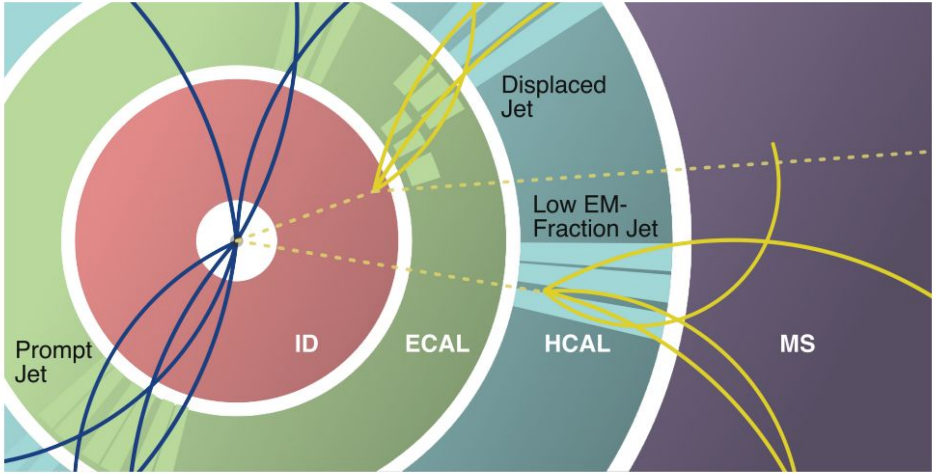
LLP2024 in Tokyo:
https://indico.cern.ch/event/1381368/

Summary

https://arxiv.org/abs/1810.12602

LLP searches: a very vibrant field!

- Many opportunities for R&D and new ideas at any level
  - reconstruction
  - trigger
  - analysis techniques
  - machine learning for classification/regression
- We may have collected new physics already!

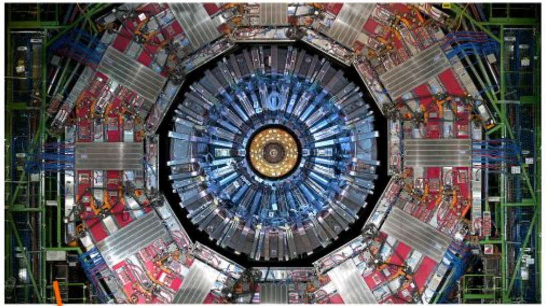


LHC community strongly involved in LLP searches:

- Already achieved high impact publications
- Many more in the pipeline
- Several new ideas for the future…
- …and also several more LLP experiments!

Backup

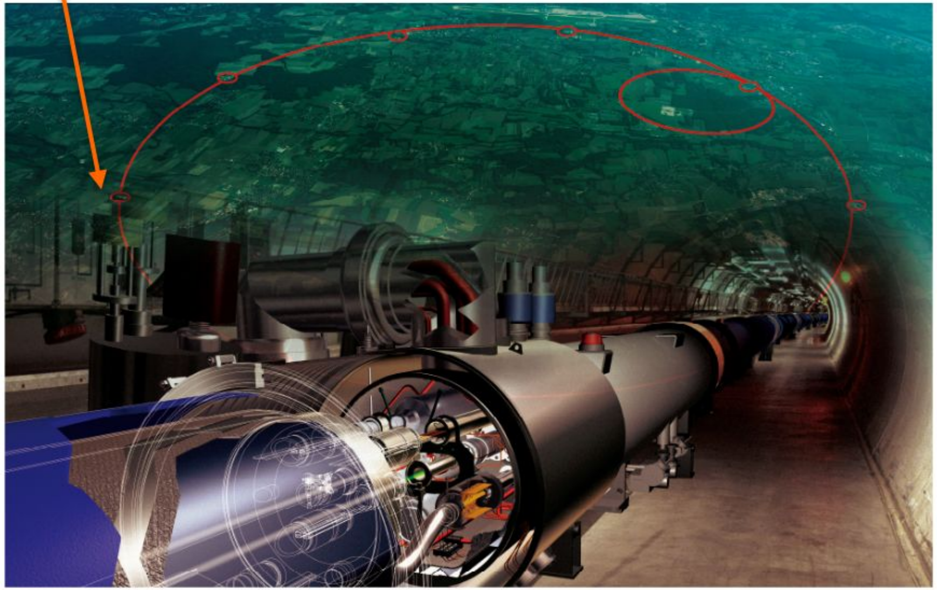
Introduction: LLP searches @ LHC

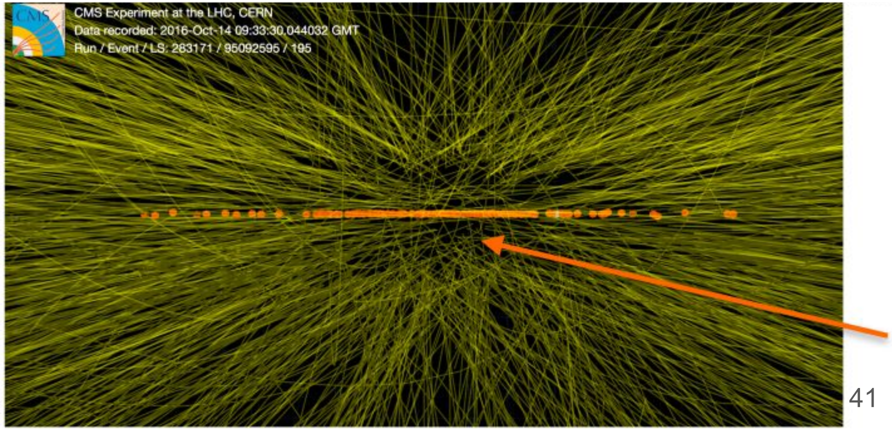


LHC: proton-proton collisions at

- 13 TeV (Run 2: 2016-2018)
- 13.6 TeV (Run 3: 2022-2025)

- momentum of quarks/gluons unknown → hard to precisely model
- beam organised in bunches of 10^{11} protons: multiple collisions at each crossing (pile-up), up to ~80

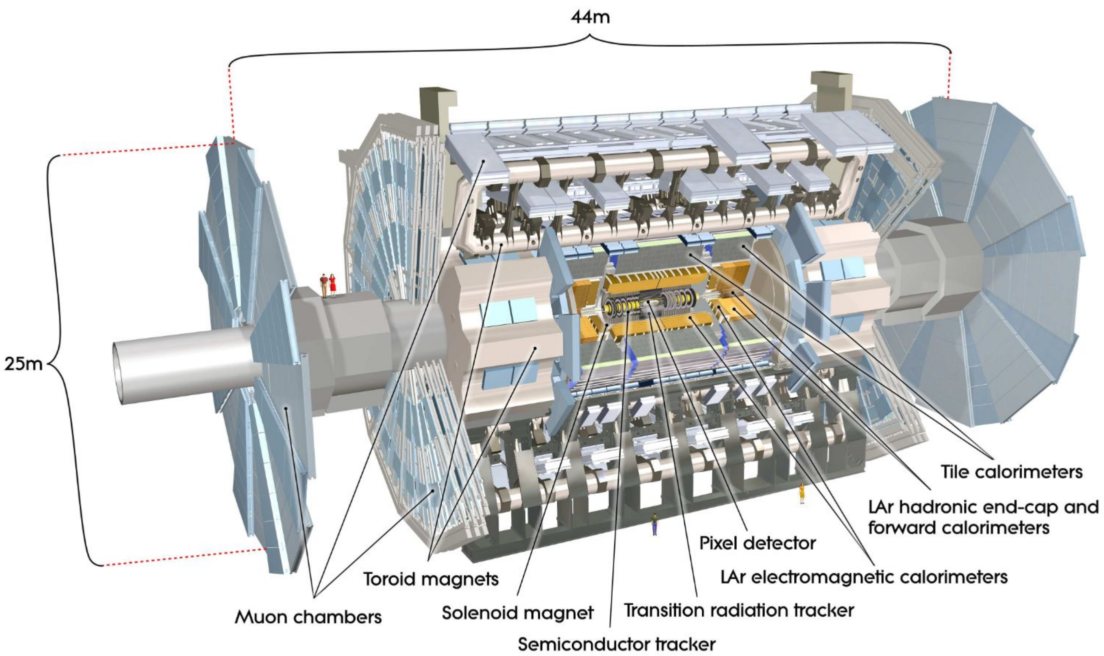




10.1088/1748-0221/3/08/S08003

ATLAS

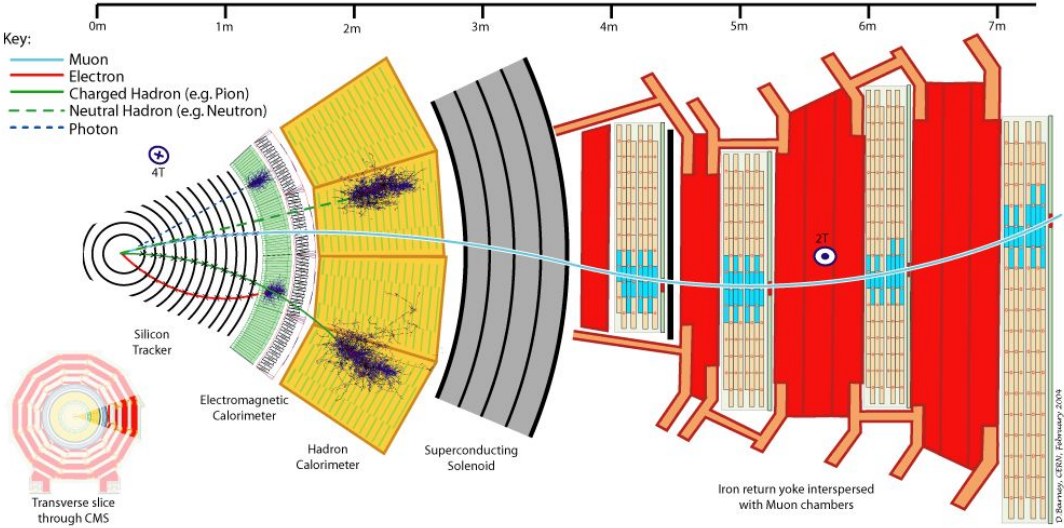
- **Tracking inner detector**
- **Solenoid magnet** 2 T
- **ECAL**: liquid argon (LAr) with lead absorbers
- **HCAL**: steel/scintillator-tile
- **Muon system** (MS):
  3 stations trigger + tracking
  - **Trigger: RPC + TGC**
  - **Tracking:**
    - Monitored Drift Tube (MDT)
    - Cathode Strip Chambers (CSC)
  - Each MDT: 2 Multi Layers (ML) with 3/4 DT
- **3 toroidal magnets**, each 8 coils
- **L1 hardware trigger, HLT software trigger**



10.1088/1748-0221/3/08/S08004

CMS

- **Tracking**: silicon pixel and strip detectors
- **Solenoid magnet** 3.8 T
- **ECAL**: $PbWO_4$ scintillating crystals
- **HCAL**: brass+scintillator sampling calorimeter
- **Muon system (MS)**:
  3 gas detectors
  - **Drift Tubes** in barrel
  - **Cathode Strip Chambers** in endcaps
  - **Resistive Plate Chambers**, timing assignment (trigger)
- **L1 hardware trigger, HLT software trigger**



https://arxiv.org/abs/2305.10515

LHCb

LHCb: forward single-arm spectrometer:

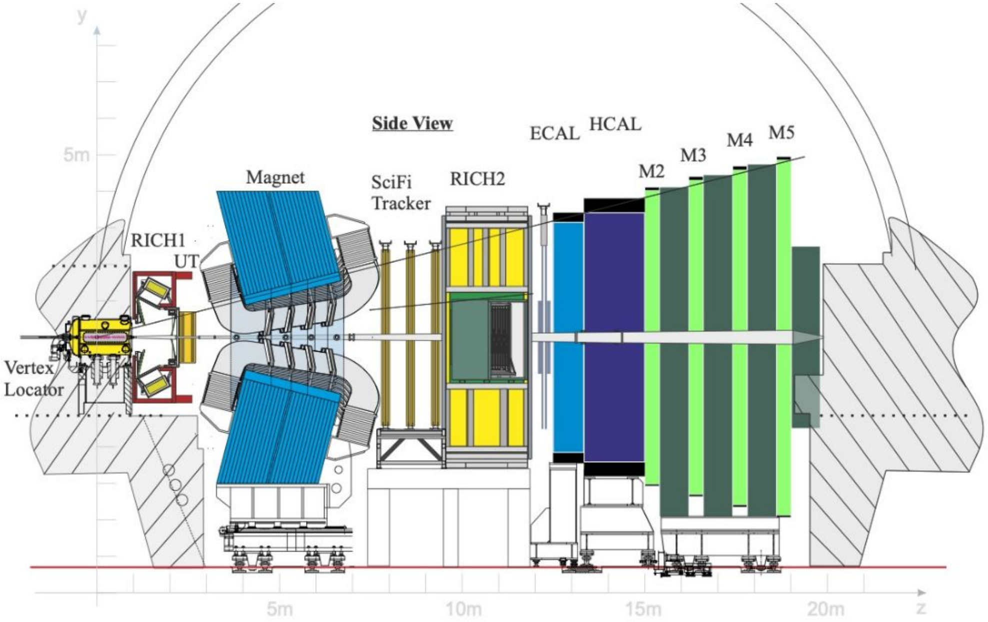
- **Tracking system**: excellent momentum and (displaced) vertex identification: **VErtex LOcator** (VELO)
- **Ring Imaging Cherenkov Detectors**: Particle IDentification (PID)
- **Calorimeters**: γ and π^0
- **Muon chambers**

Advantages:

- Very forward ($2 < \eta < 5$), complementary to ATLAS/CMS
- Low p_T (0.5 GeV) tracking
- Can probe lighter LLPs that are boosted, tracking system covers large decay volumes
- Better PID with RICH (separate π, K, p) w.r.t. ATLAS/CMS

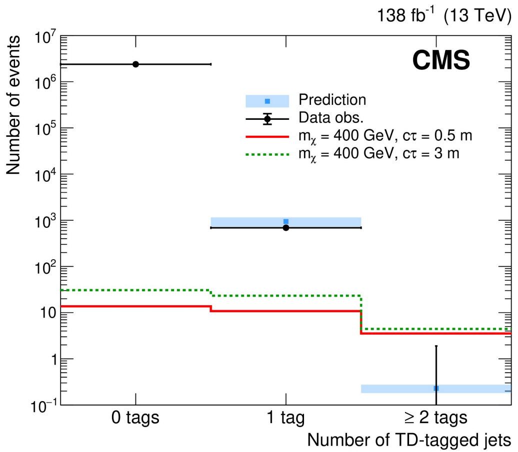
Disadvantage:

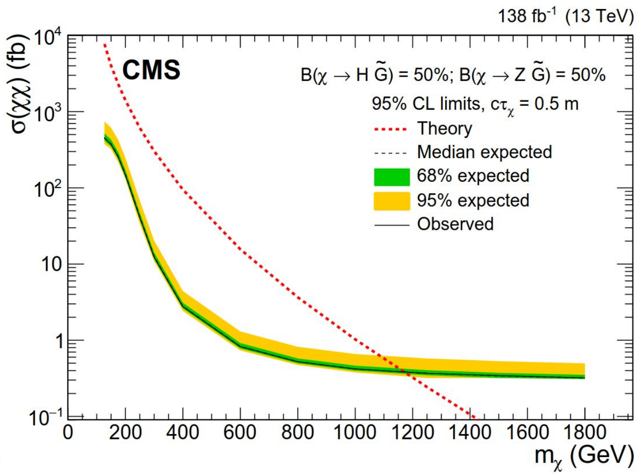
- Lower luminosity

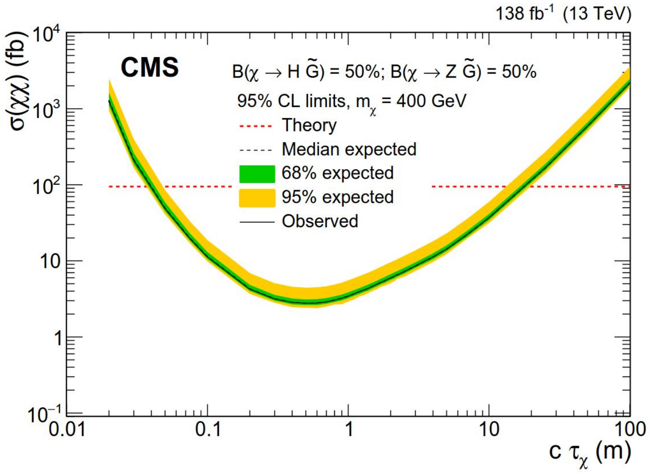


CMS: trackless and out-of-time jets

https://arxiv.org/abs/2212.06695







Source	Prediction	Observed
Mistag	0.15 ± 0.08	
Cosmic muons	0.03 ± 0.02	
Beam halo	0.05 ± 0.05	
Tot. Run 2	0.23 ± 0.10	0

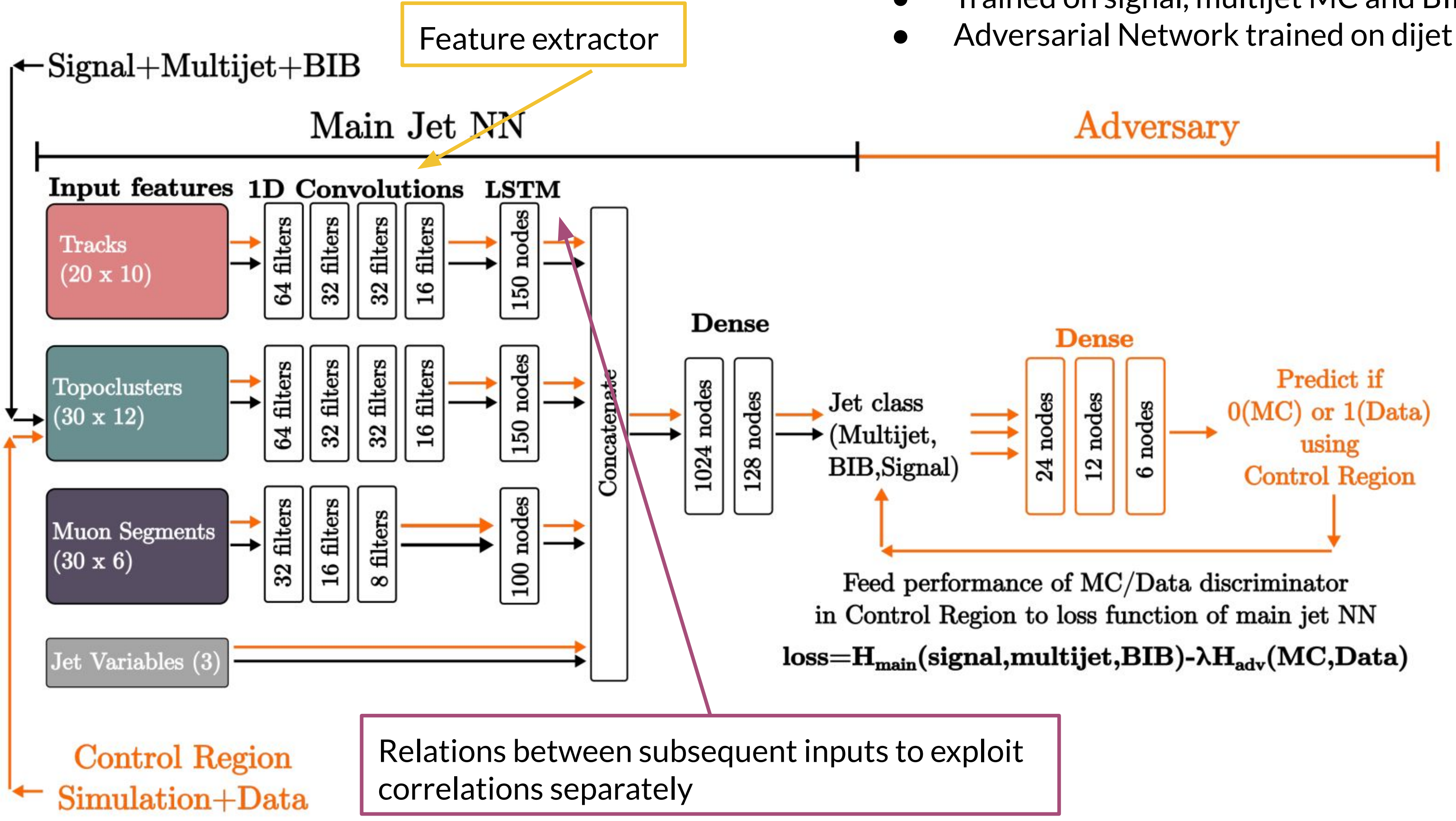
Results:

- Expected <1 events (DNN), 0 observed
- Limits at 1 fb level for m_χ > 550 GeV, exclude m_χ up to 1.18 TeV at cτ = 0.5 m
- Complementary to prompt analysis (https://arxiv.org/abs/1709.04896), up to x20 better sensitivity at lower masses

https://arxiv.org/abs/2203.01009

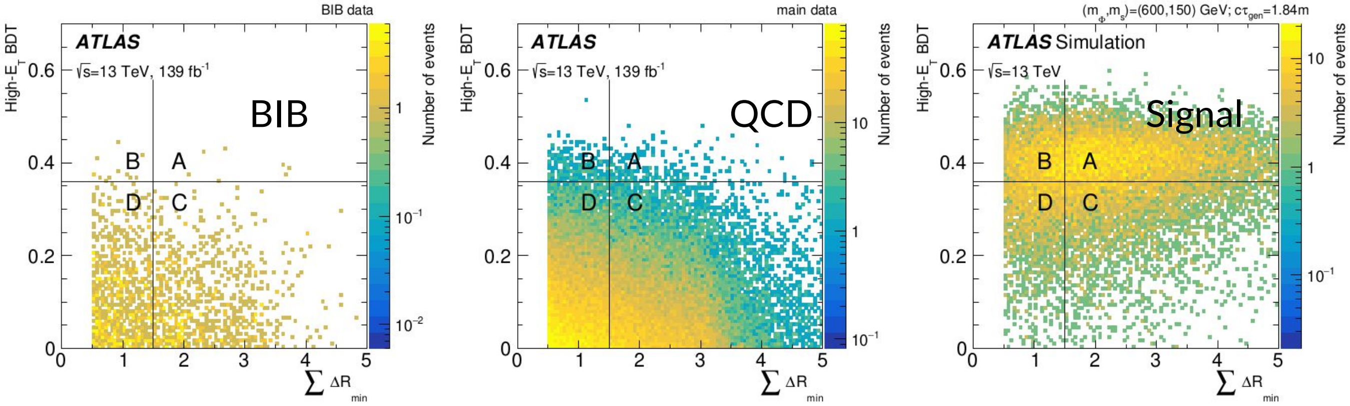
ATLAS: Calorimeter-ratio search

- Trained on signal, multijet MC and BIB data
- Adversarial Network trained on dijet data/MC

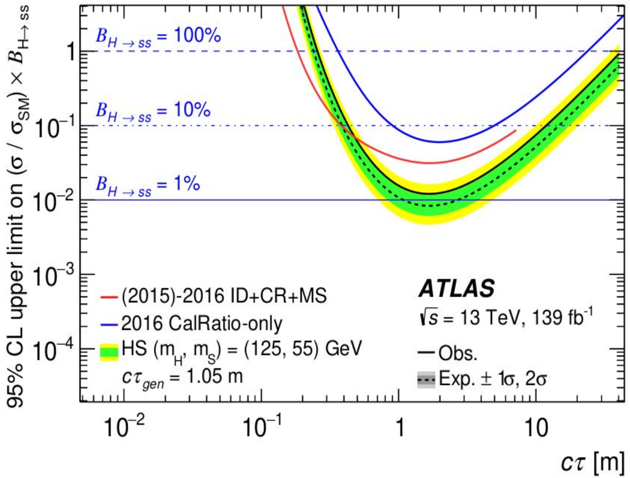


https://arxiv.org/abs/2203.01009

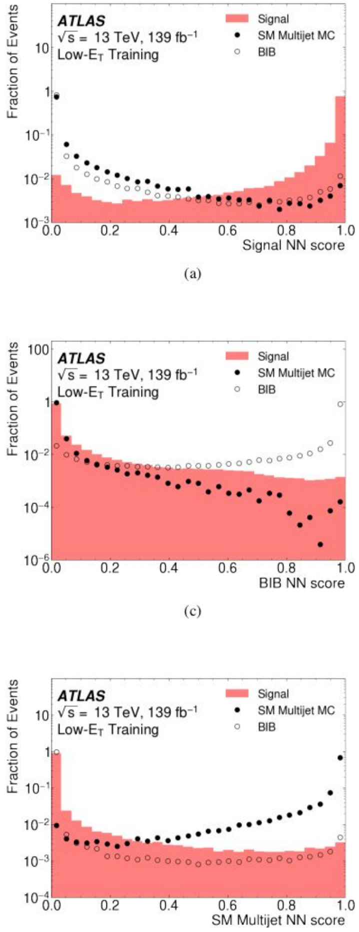
ATLAS: Calorimeter-ratio search



$\Delta R_{\min}$ (jet, tracks)



$\Sigma\,\Delta R_{\min}$: sum over jets min angular distance wrt tracks



EXOT-2022-04

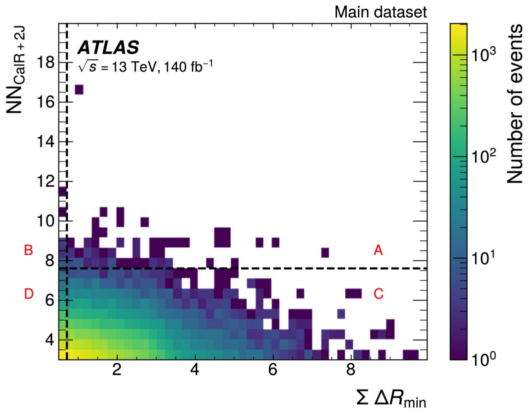
ATLAS: calorimeter-ratio search

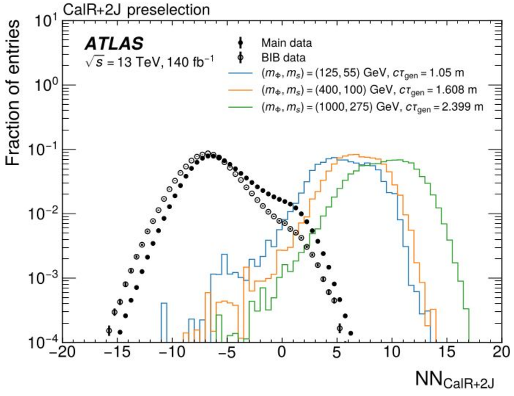
CalR + 2J:

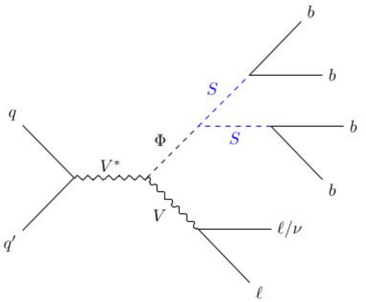
- Select 3 jets with highest signal score, 1 being CalR, and build a per-event DNN decorrelated from $\Sigma \Delta R_{min}$ → only multijet bkg left
- Inputs: per-jet NN scores, kinematics, width, time; scalar sum hadronic energy of all jets, angular separations, missing transverse energy
- Per-jet NN mismodelling: up to 5%
- Improvement: relaxing requirement on signal-like jets, exploiting additional jet information → bkg reduction

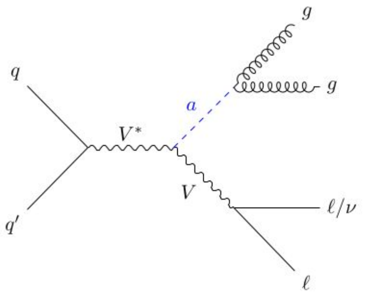
CalW/CalZ:

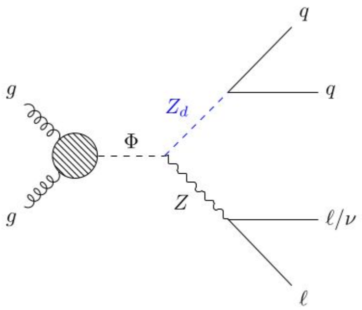
- Improvement: luminosity and stronger DNN-jet rejection
- ALP masses 0.1-4 GeV
- Dark photon (Z_d) model with mediator mass 250-600 GeV, m(Z_d) 5-400 GeV









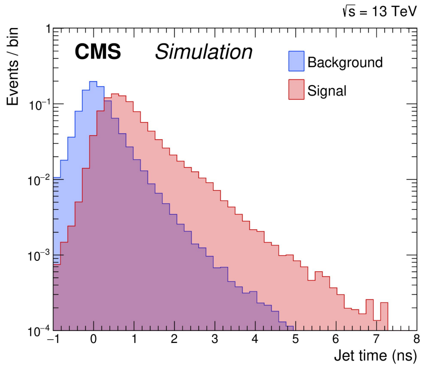


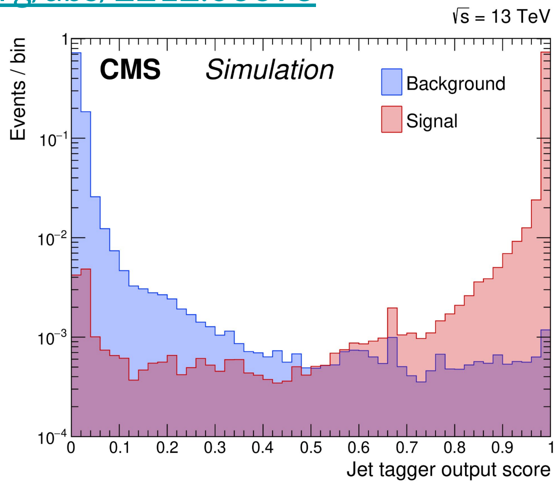
https://arxiv.org/abs/2212.06695

CMS: trackless and out-of-time jets

Trackless and OOT jet DNN tagger:

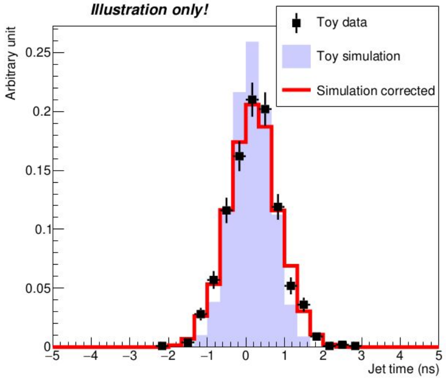
- Combine features of
  - ECAL crystals (time, multiplicity)
  - Tracks associated to a jet
- Strong background rejection
- SR: at least 2 tagged jets

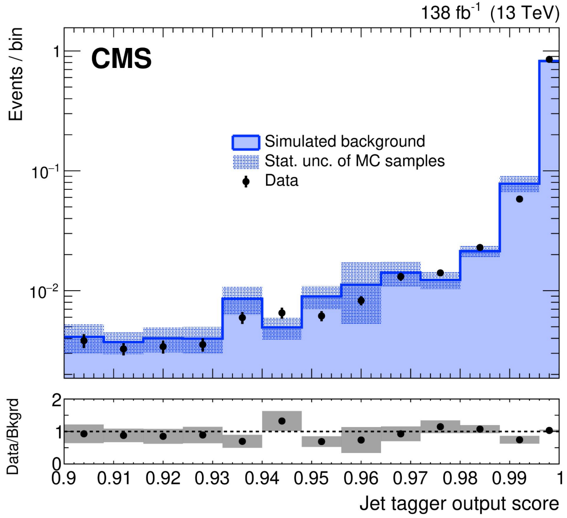




Study of the DNN response in MC/data

- DNN inputs well modelled in MC except jet time
- Correct MC jet time to match data in CR
- Good data/MC agreement after corrections applied





ATLAS: displaced vertices in MS

https://arxiv.org/abs/2203.00587

ATLAS Muon System (MS)

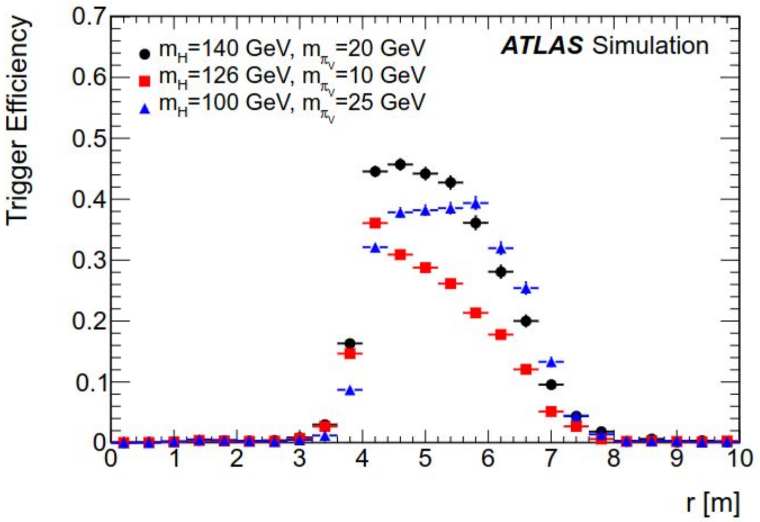
- Big volume, shielded by calorimeters
- Tracking capability

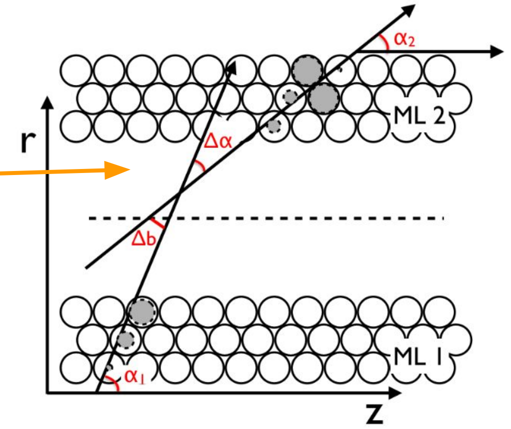
Muon RoI cluster trigger (arxiv 1305.2284)

- Muon **L1 RoI**: coincidence of hits in at least 3 of 4 layers of the 3 inner RPC planes for the barrel, 2 outer TGC planes for the end-caps
- L1 seed: 2 Muon RoI with pT>10 GeV
- **HLT RoI cluster**: a DR=0.4 region containing at least 3 (4) RoIs in the barrel (endcaps)

MS vertex algorithm (arxiv 1311.7070):

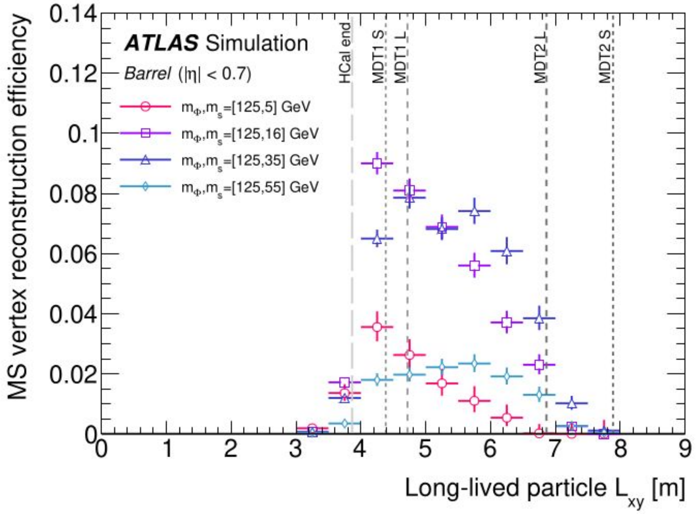
- Uses spatial separation of ML inside MDT (no CSC!)
- MDT hits form tracklets
- Reconstruct vertices with at least 3 (4) tracklets in the barrel (endcaps)
- Vertices matched to trigger RoI clusters

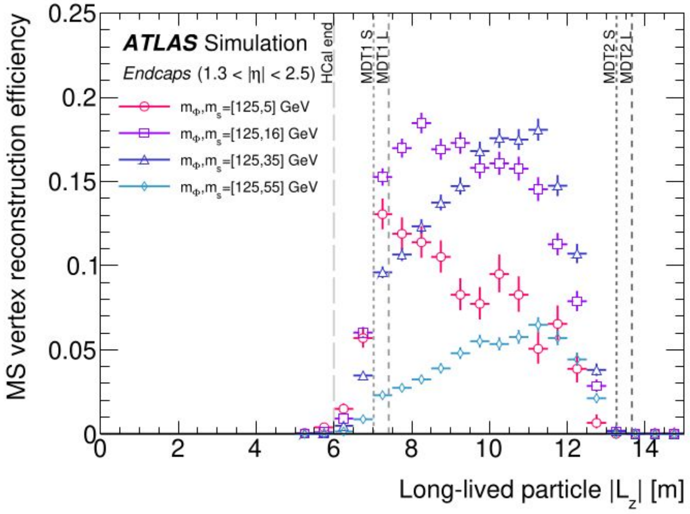




https://arxiv.org/abs/2203.00587

ATLAS: displaced vertices in MS





- MS barrel: vertex reco eff. O (2−15)% near the outer edge of the hadronic calorimeter ($r \approx 4$ m) and decreases as decay closer to middle stations ($r \approx 7$ m) → charged hadrons and photons not spatially separated and overlap when traversing middle stations → less efficient tracklet reco
- MS endcaps: higher reco eff (40%) due to more efficient selection and vertex reconstruction: magnetic field here is weak, looser tracklets curvature constraints wrt barrel → vertex reco uses straight-line fits → low-momentum tracks are not rejected
- MS barrel: curvature plus combinatorics provide better rejection of misreconstructed tracks
- Vertex reco in endcaps: more efficient for signal, but less robust in rejecting background

https://arxiv.org/abs/2203.00587

ATLAS: displaced vertices in MS

Backgrounds

- Punch-through jets showering in MS
- Noncollision (electronic noise, cosmic muons, beam induced background BIB)

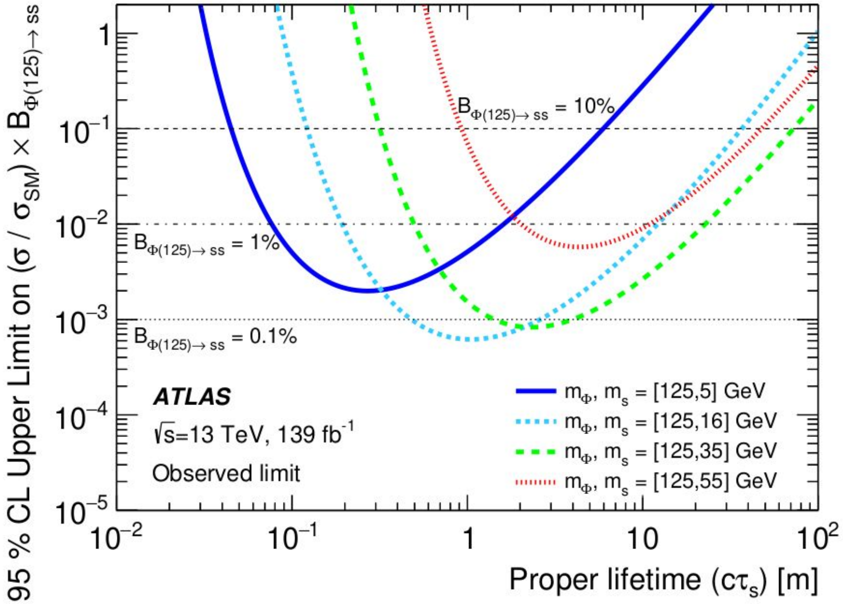
$$N_{2\mathrm{Vx}} = N^{1\mathrm{cl}} \cdot \underbrace{P^{\mathrm{Vx}}_{\mathrm{noMStrig}}}_{\text{Zero bias}} + N^{2\mathrm{cl}}_{1\mathrm{UMBcl}} \cdot P^{\mathrm{Vx}}_{\mathrm{Bcl}} + N^{2\mathrm{cl}}_{1\mathrm{UMEcl}} \cdot P^{\mathrm{Vx}}_{\mathrm{Ecl}} = 0.32 \pm 0.05$$

Cluster: trigger object
Vertex: offline object

- Excluded H→SS→4f BR<0.1%
- BR>10% excluded for LLP 4 cm < $c\tau$ < 72.4 m

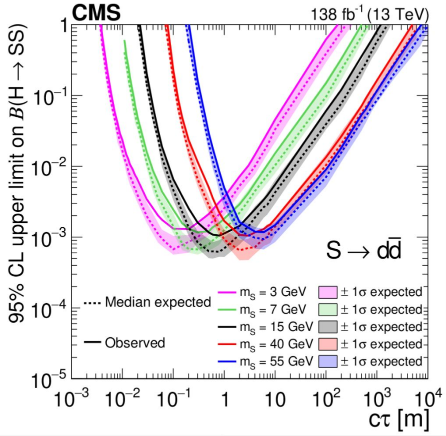
Systematic uncertainties:

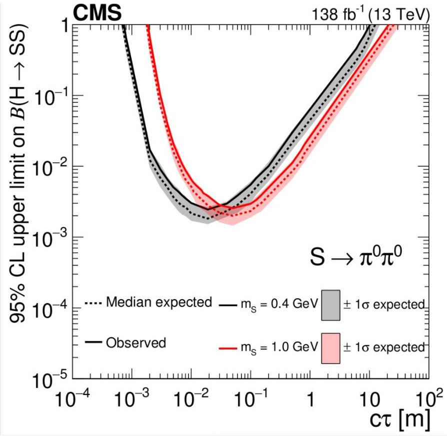
- 20-24% trigger efficiency (MC)
- 11-13% vertex reco mismodelling
- Up to 30% signal stat unc.

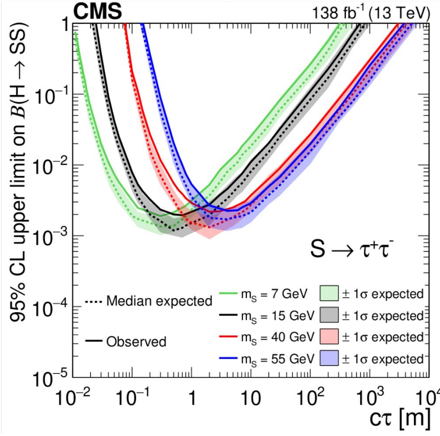


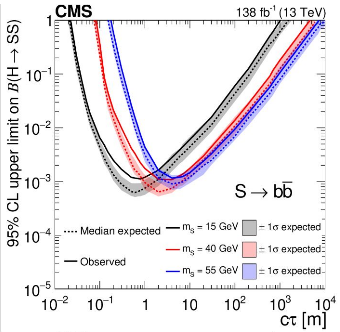
https://arxiv.org/abs/2402.01898

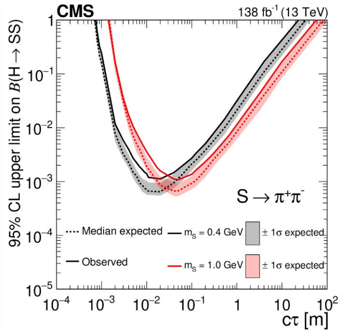
CMS: searches for LLPs with MDS

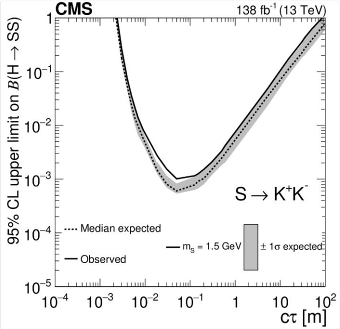


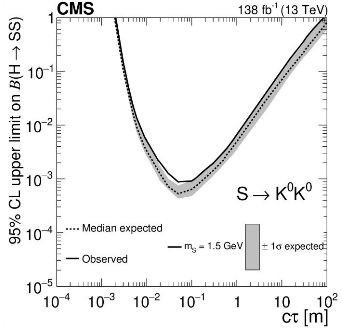


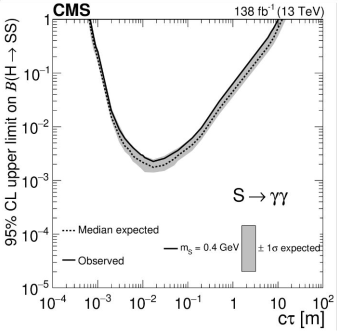


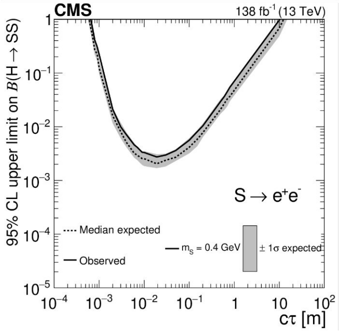






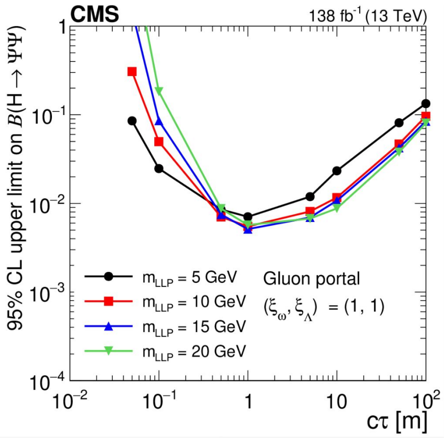


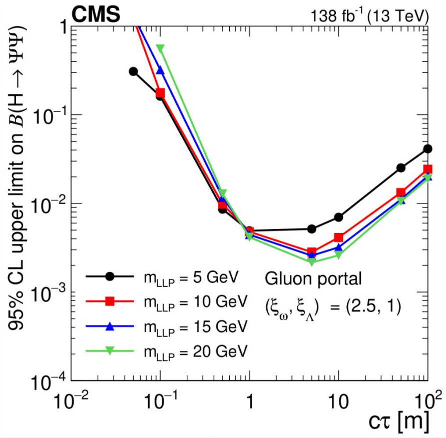


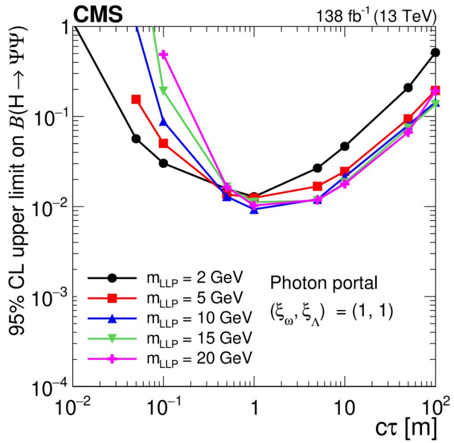


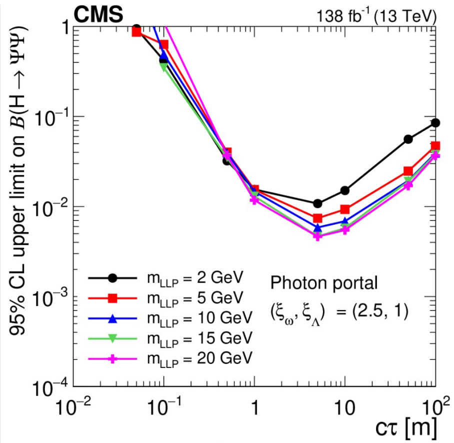
https://arxiv.org/abs/2402.01898

CMS: searches for LLPs with MDS

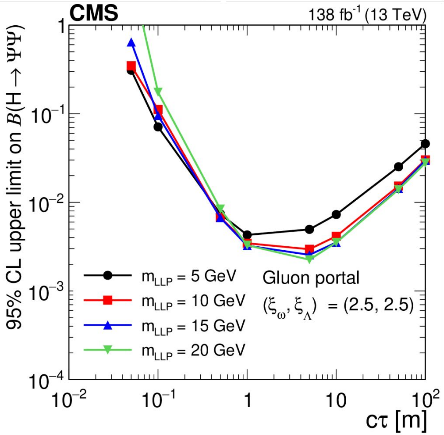




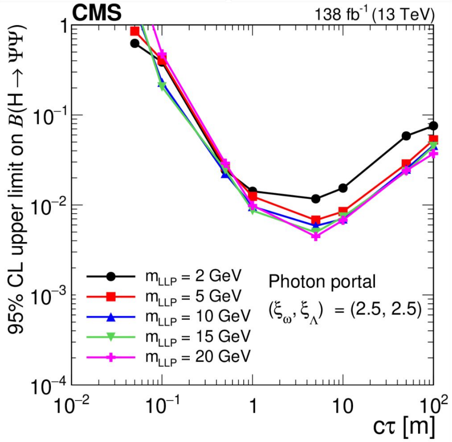




Hadron rich showers

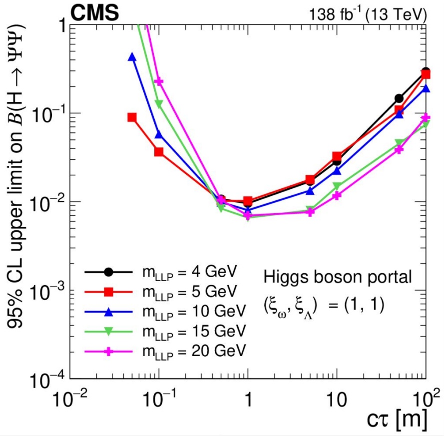


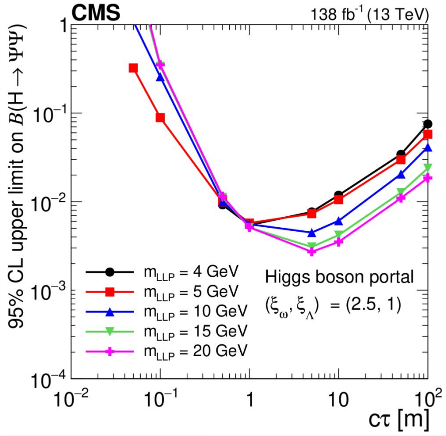
Photon rich showers

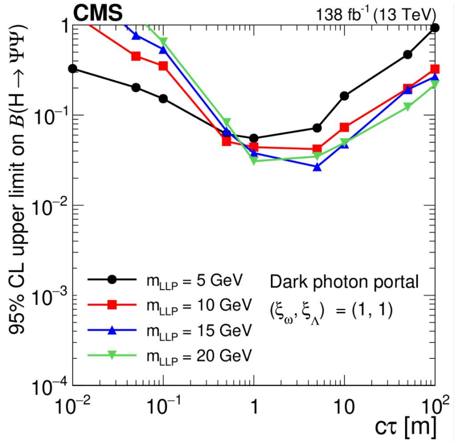


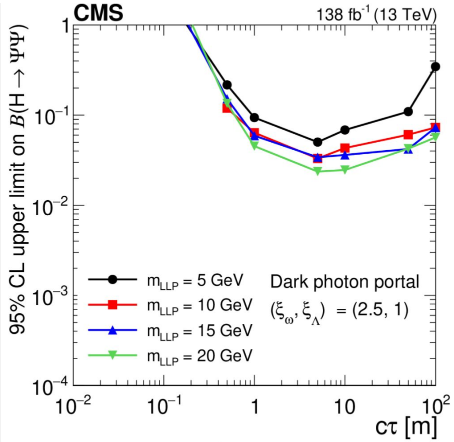
https://arxiv.org/abs/2402.01898

CMS: searches for LLPs with MDS

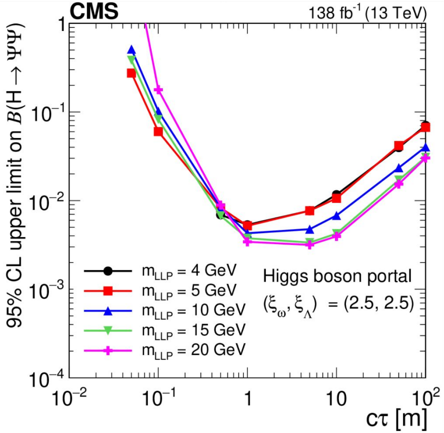




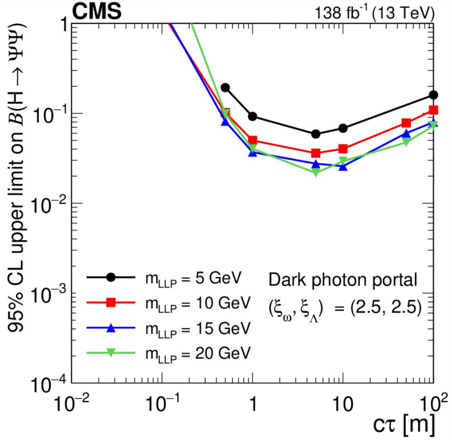




Heavy-flavour rich showers

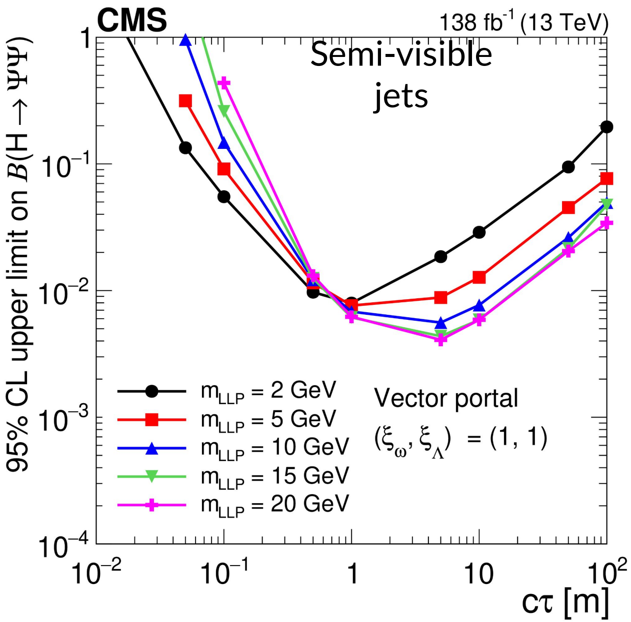


Lepton rich showers



https://arxiv.org/abs/2402.01898

CMS: searches for LLPs with MDS



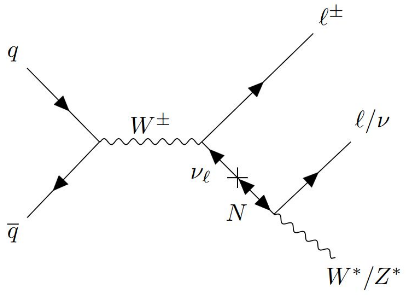
https://arxiv.org/abs/2402.18658

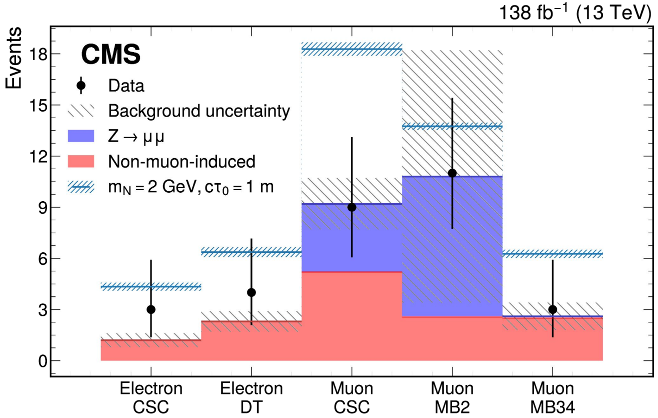
CMS: searches for LLPs with MDS

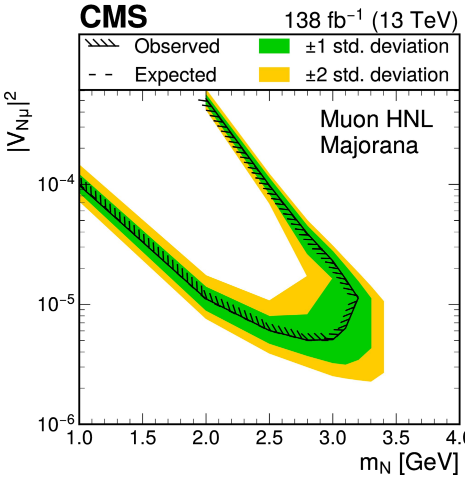
Search for HNLs in the muon system
- Majorana/Dirac HNLs with cτ > 1 m
- Trigger on associated prompt e/μ
- HNL decay reconstructed as 1 muon hits cluster

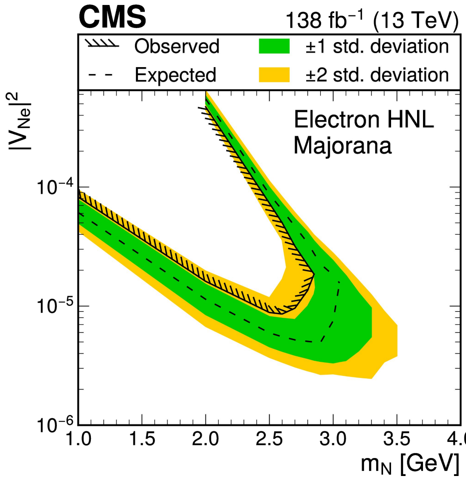
Background:
- W + jets or hadrons from pileup, Z→μμ
- ABCD plane:
  # cluster hits, Δφ (cluster, prompt e/μ)

Results:
- Limits to 3 lepton generations
- Best limits in the range 2-3 GeV!









CMS: searches for VLLs with MDS

CMS-PAS-EXO-23-015

Vector-like lepton (VLL): $\tau' \rightarrow \tau\, a_\tau$

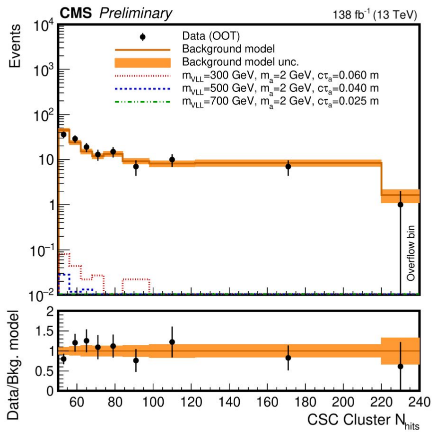
- a_τ Yukawa interaction with weak singlet VLL
- Heavy physical VLL (τ') mixing with τ
- a_τ VEV and CP-odd component lighter than τ'
- $m(a_\tau)$ = 2 GeV → decay to photons via τ' loop

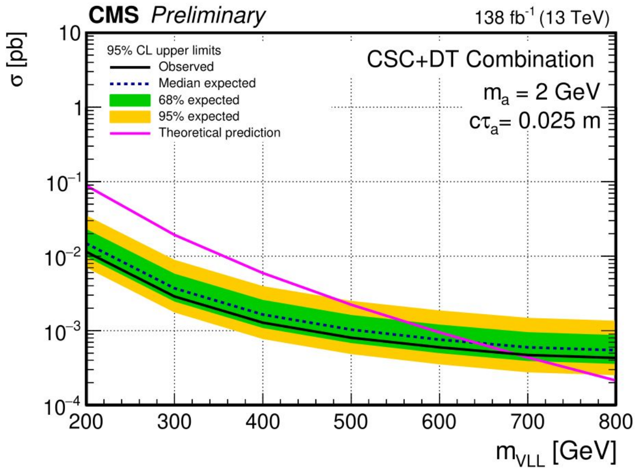
- EM MDS mostly contained in 1 station, stopped by steel
- CSC cluster efficiency: 35%
- DT cluster efficiency: 45%
- missing momentum efficiency: 6-62%
- τh efficiency: 50-85%

Backgrounds:

- Punch-through jets
- Muons undergoing bremsstrahlung
- Isolated hadrons from PU or UE
- Cosmic muons showering

OOT validation



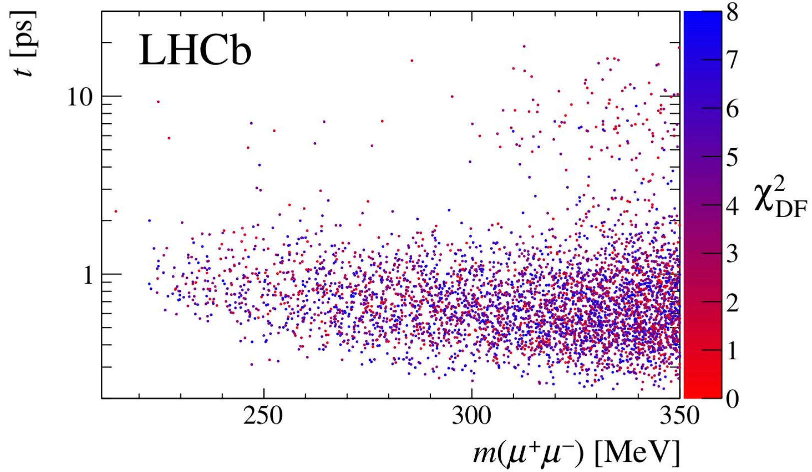


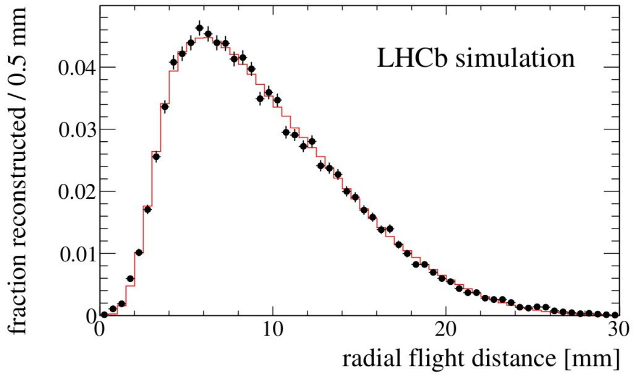
https://arxiv.org/abs/1910.06926

LHCb: dark photons to dimuons

- Fit to [m($\mu^+\mu^-$), decay length, χ^2(decay fit)]
- Mass binning depend on m(A’) σ[m($\mu^+\mu^-$)]/2
- 8 t bins (0.2, >10 ps)
- Signal: small χ^2_{DF} values, 50% (80%) having χ^2_{DF} < 2 (4)
- b-hadron: small t region, uniformly distributed in χ^2_{DF}
- K_S^0: signal-like in χ^2_{DF} and uniformly distributed in t
- Photon conversions yield: from n. candidates rejected by conversion criterion
- b- and K_S^0 modeled by second-order polynomials of the energy released in the decay: sqrt(m(μ+ μ−)^2 − 4m(μ)^2)
- Contributions validated in data control sample

- Hardware trigger: muon p_T>1.8 GeV or dimuon pair, or high-p_T hadron
- 214 < m(A’) < 350 MeV

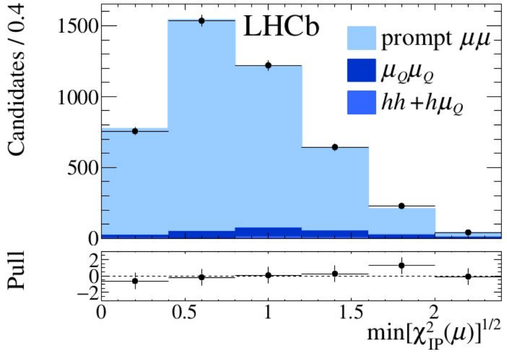


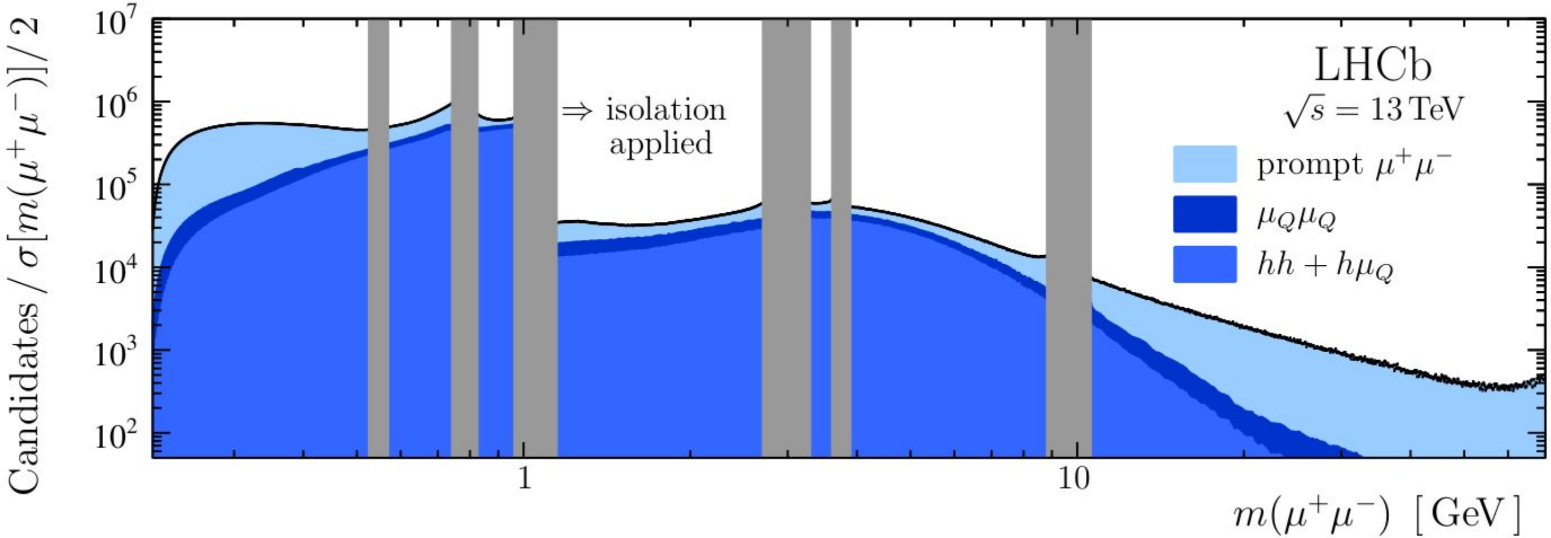


https://arxiv.org/abs/1910.06926

LHCb: dark photons to prompt dimuons

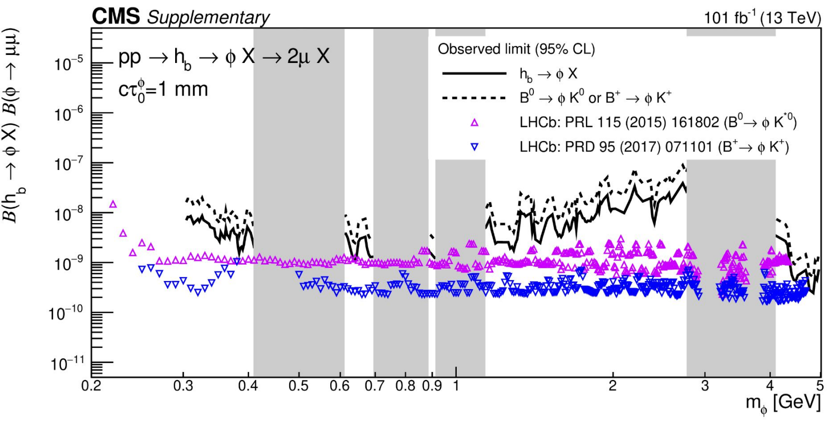
- Prompt $\mu^+\mu^-$: PDFs from data at m(J/ψ) and m(Z)
- $\mu_Q\mu_Q$ from heavy flavour: from min[χ^2_{IP}(μ)] fit on simulation
- χ^2_{IP} (μ): difference in χ^2_{VF} (PV) when PV is reconstructed with and without the muon track
- hh + $h\mu_Q$: from same sign μμ

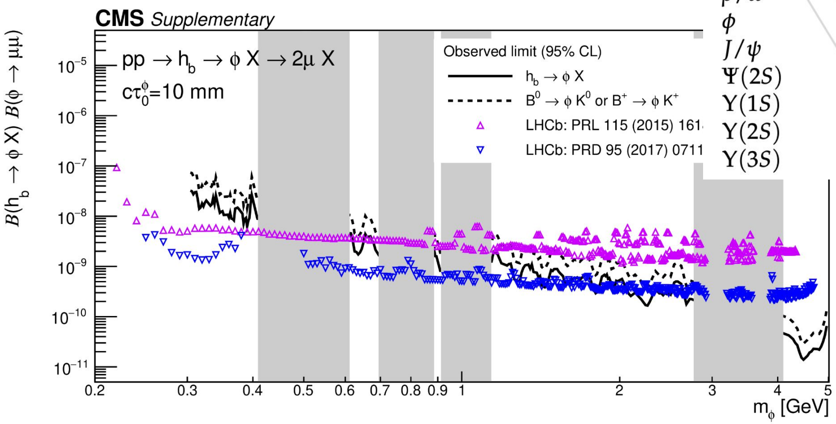


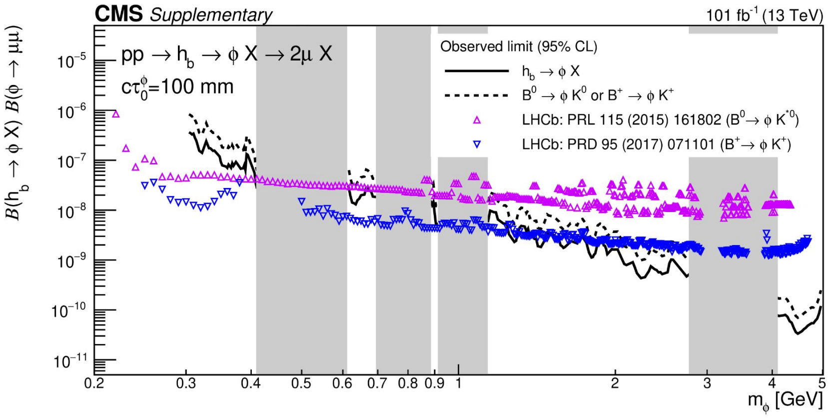


LHCb - CMS: LL scalar ϕ→2μ from b hadron

Resonance	Mean mass [GeV]
K_S	0.46
η	0.55
ρ/ω	0.78
ϕ	1.02
J/ψ	3.09
$\Psi(2S)$	3.68
$\Upsilon(1S)$	9.43
$\Upsilon(2S)$	10.00
$\Upsilon(3S)$	10.32







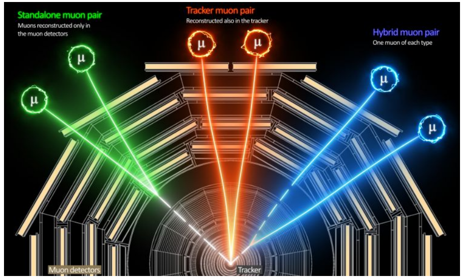
L1 trigger (2017 and 2018)
- 2 OS muons with opposite charges (OS), pT > 4 GeV (2017) or 4.5 GeV (2018) and ΔR(μ1, μ2) < 1.2;
- 2 OS muons with |ημ | < 1.4 and ΔR(μ1, μ2) < 1.4;
- 2 L1 muons with pμ1T > 15 and pμ2T > 7 GeV.

HLT:
- 2 OS muons with pμT > 3 GeV and |ημ | < 2.4

[CMS-EXO-20-014]

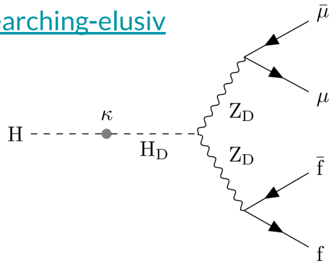
CMS: displaced dimuons with Run3 data

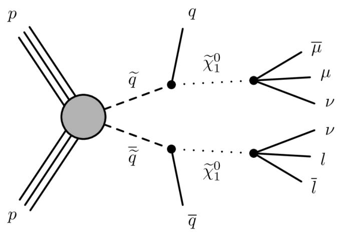
https://arxiv.org/abs/2402.14491



https://cms.cern/news/detector-far-far-away-searching-elusive-long-lived-travellers-tracing-pairs-muons

First Run3 CMS search!

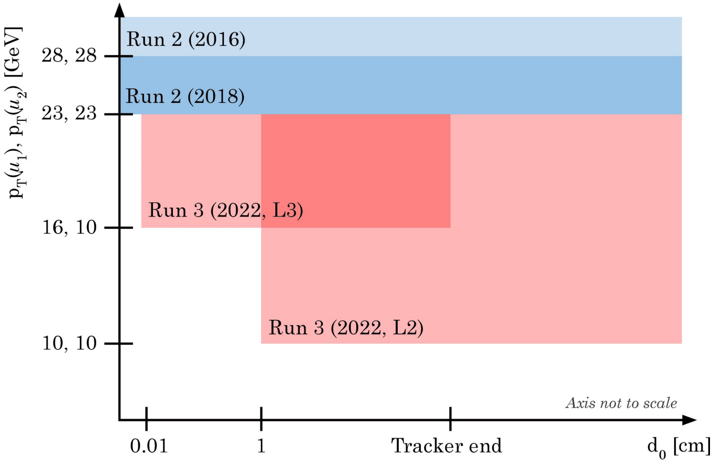




Displaced dimuons

- Achieved similar sensitivity to Run 2 data with only ⅓ of the luminosity in Run 3 (2022)

- Key development: trigger
  - New L1T algo to assign p_T to μ from displaced vertex
  - Improved HLT algos:
    Recovers efficiency for shorter μ tracks,
    x2 better @ cτ = 1 cm
    Discard prompt μ → improves at larger displacement,
    x3 efficiency @ cτ = 1 m



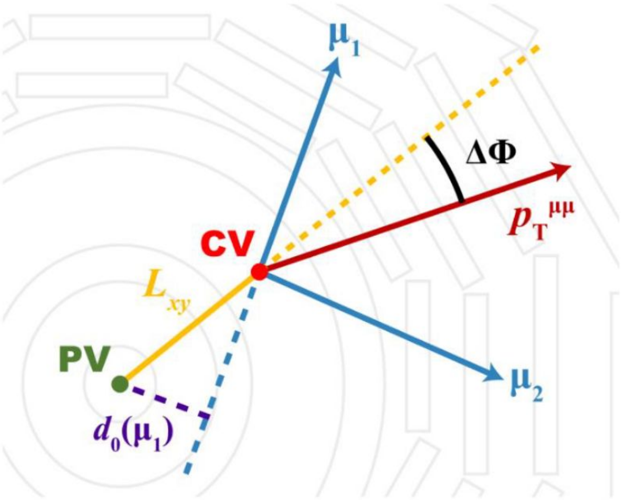
CMS: displaced dimuons with Run3 data

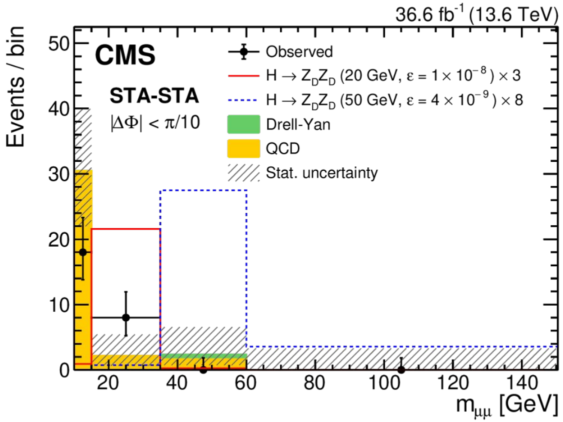
https://arxiv.org/abs/2402.14491

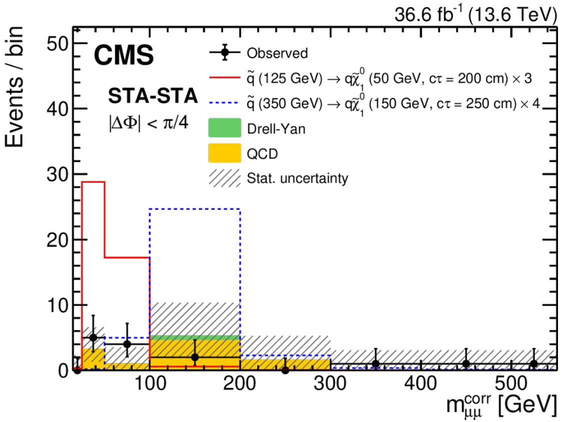
R. Dasgupta, A . E. Del Valle, M. Iqbal

Transverse collinearity angle |ΔΦ| between Lxy and pTμμ :

- |ΔΦ| < π/4 → signal (SR)
  - Expected to be aligned (OS muons)
- |ΔΦ| symmetric around π/2 → DY-like background
  - Prompt μ with large mismeasured Lxy
  - Estimated in control region CR with large |ΔΦ| > 3π/4
- |ΔΦ| asymmetric and small → QCD-like background
  - Mismeasured pμμ (low-mass resonances, jets)
  - Mostly rejected by mμμ > 10 GeV
  - Estimated in SS / non-isolated μ CR





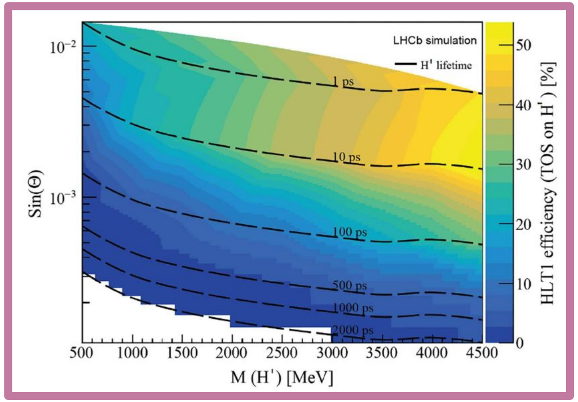


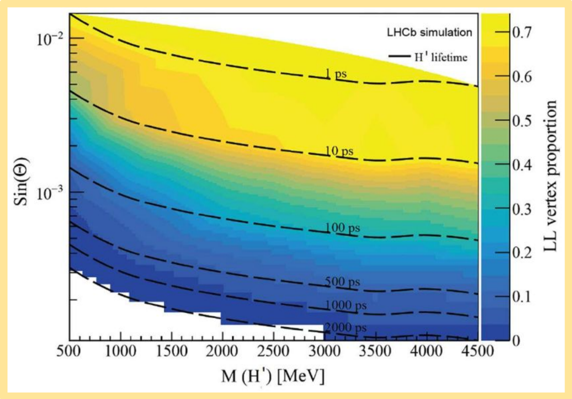
LHCb tracking for LLPs

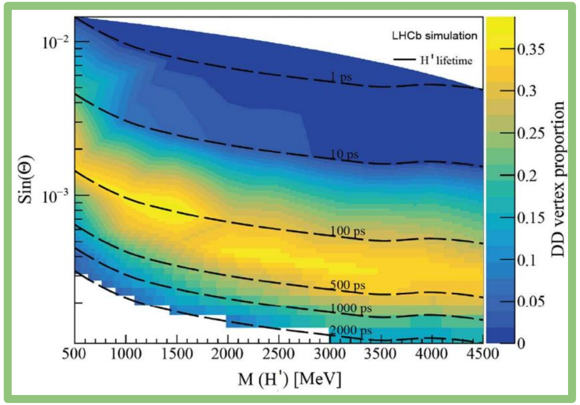
https://www.frontiersin.org/articles/10.3389/fdata.2022.1008737/full#F10

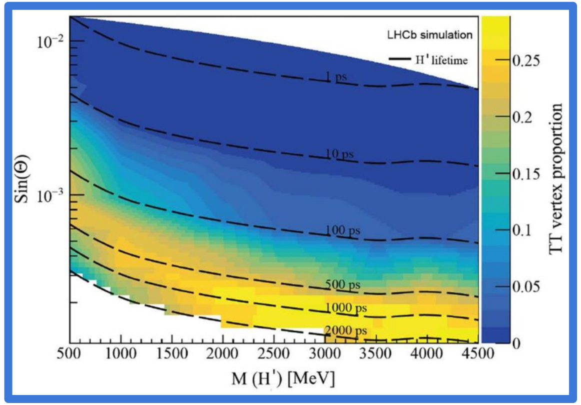
Case study: Higgs portal to DM; B → H′ (→$\mu^+\mu^-$)K

- Mixing of SM H and light H': h = H cos θ − H′ sin θ
- 0.5 < $M_{H'}$ < 4.5 GeV, B → H′ (→$\mu^+\mu^-$)K
- Reconstructability of the decay vertex H′→$\mu^+\mu^-$ as a function of $M_{H'}$ and lifetimes
  - 2 Long tracks
  - 2 Downstream tracks
  - 2 T-tracks
- To be compared to current HLT capabilities with long tracks only!



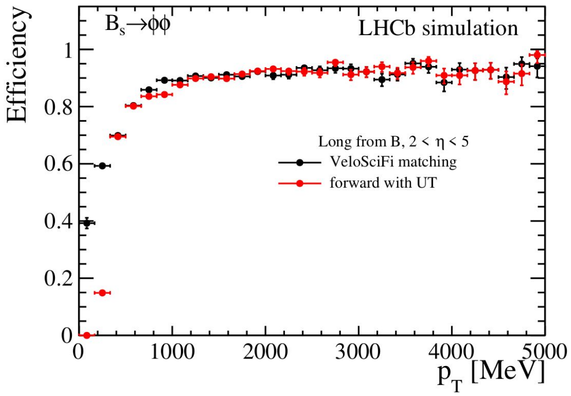




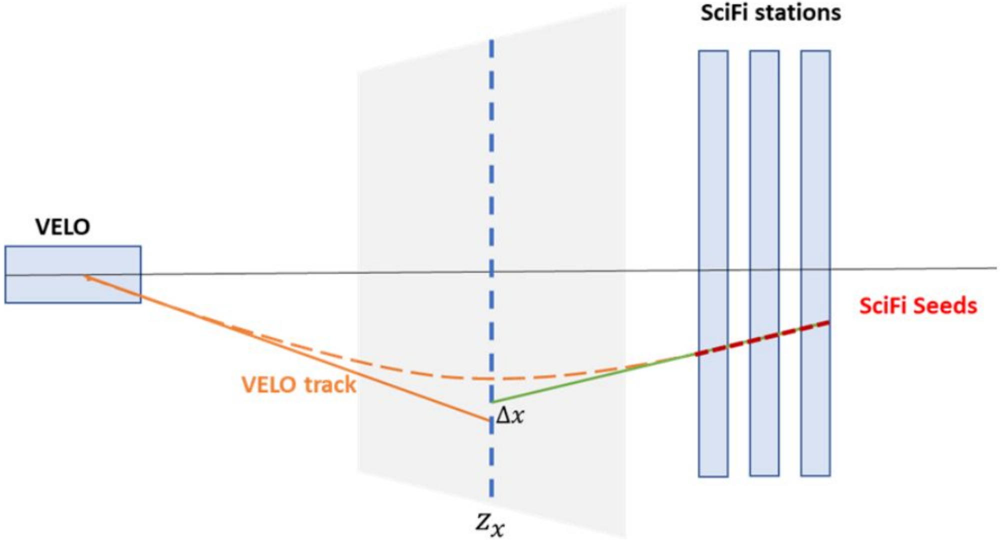


LHCb upgraded tracking

https://cds.cern.ch/record/2826068/



https://cds.cern.ch/record/2811214



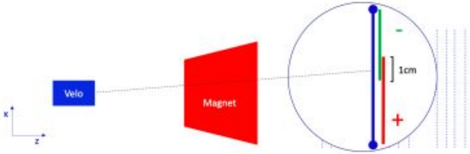
Tracking algorithms @ upgraded HLT1 (GPU)

- Long tracks: VELO + SciFi (no UT)
- Individual reconstruction + matching algorithm
- Ability to improve low p_T tracks performances w.r.t standard algorithm (“forward”)

HLT1 - long tracks

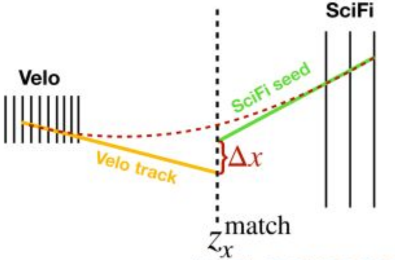
Forward tracking

- double sided search window for p>5GeV & p_T>1GeV

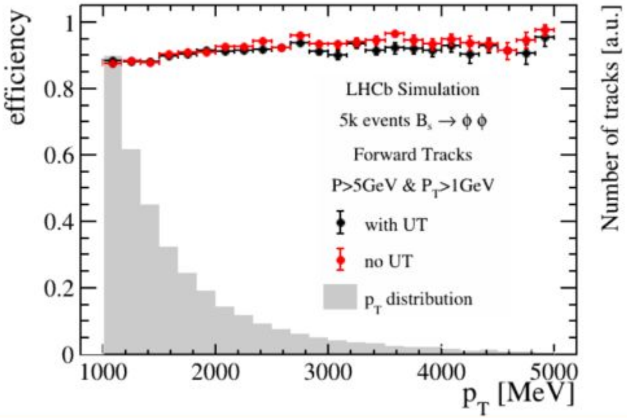


VELO-SciFi matching

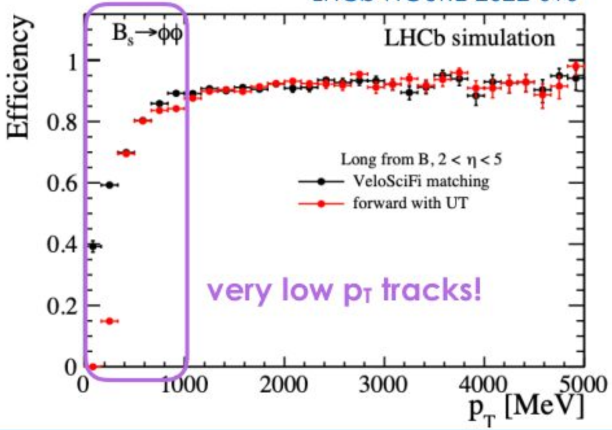
- VELO & SciFi seeds extrapolated as straight lines to matching position



LHCb-FIGURE-2022-007



LHCb-FIGURE-2022-010

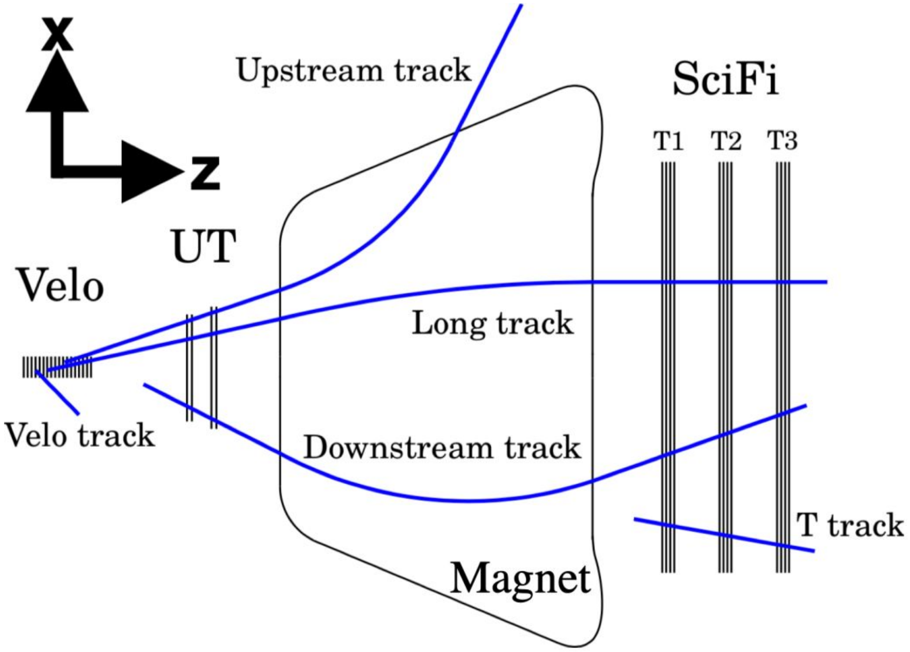


E. Dall'Occo talk @ LLP12
https://indico.cern.ch/event/1166678/timetable/#40-whats-new-for-run-3-for-llp

LHCb tracking for LLPs

Downstream tracks:

- UT + SciFi matching
- Good efficiency but high rates
- Downstream tracking: from SciFi upstream the magnet
- Better performance, possibly more restrictions on momentum



https://arxiv.org/abs/2305.10515

T-tracks:

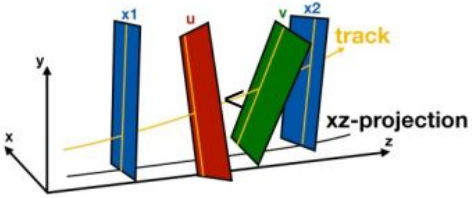
- Using SciFi only
- Low momentum resolution (lower magnetic field), extrapolation over long distance, low vertex reconstruction efficiency (ghost vertices)
- Possibility to add PID (RICH) or kinematical info
- Studied on SM LLPs (Λ and K0)

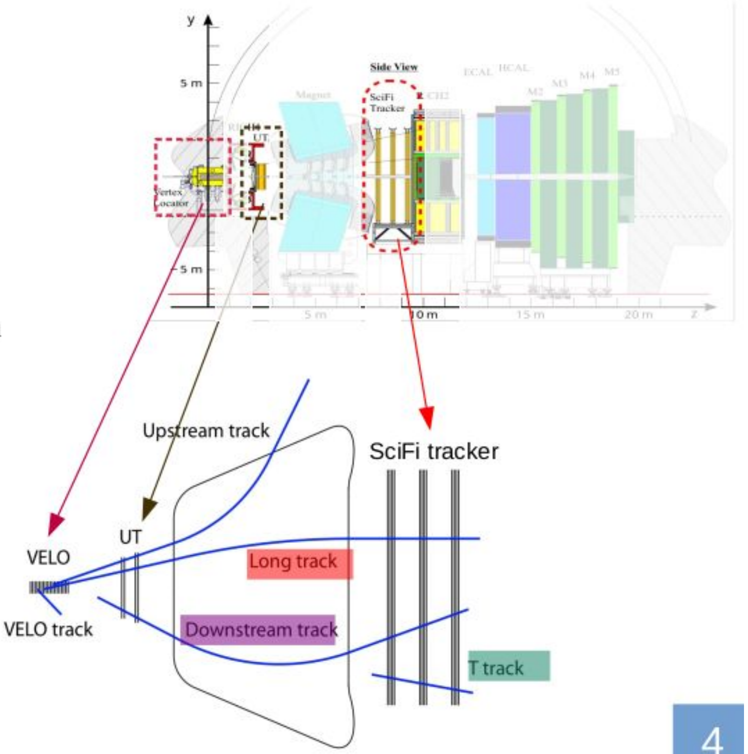
https://arxiv.org/abs/2211.10920

D. Mendoza talk @ LLP12
https://indico.cern.ch/event/1166678/timetable/#53-impact-of-the-high-level-tr

LHCb tracking system and track types

- ✗ Three sub-detectors: VELO, UT and SciFi + magnet
  - Estimation of particle momentum and track origin
- ✗ Main track types for physics analysis:
  - Long: signal in VELO and SciFi (minimum) + UT (full)
  - Downstream: signal in UT and SciFi
  - T: hits only in SciFi
- ✗ In simulations, reconstructible tracks meet certain threshold in each subsystem:
  - VELO: 3 pixel sensors with 1 digit each
  - UT: two clusters from layers 1-2 and 3-4
  - SciFi: 1 hit per cluster and 1 stereo cluster per station



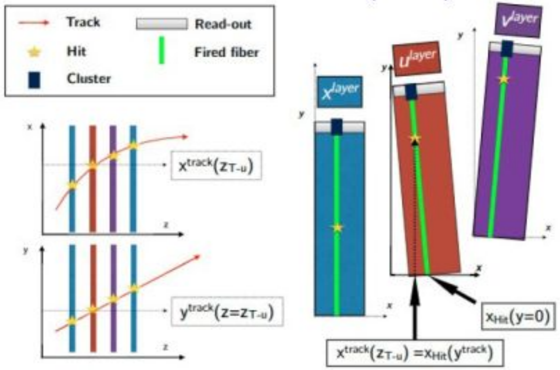


4

D. Mendoza talk @ LLP12
https://indico.cern.ch/event/1166678/timetable/#53-impact-of-the-high-level-tr

The Hybrid Seeding strategy

Aiola et al. (2021)

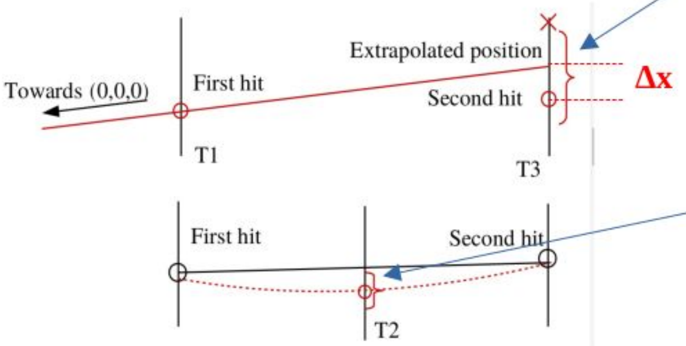


- ✗ An iterative reconstruction algorithm to reconstruct track segments
- ✗ SciFi: three stations with x-u-v-x geometry

  u and v layers titled by +/- 5° stereo angle
- ✗ X-Z plane: parabolic trajectory with cubic correction
- ✗ Residual B_y field: easier to get y trajectory (straight line)
- ✗ **Seeding in XZ:**

  First assumption: origin in (0,0,0) and infinite momentum

  Open search windows in T3 from a hit in T1: tolerance window around the projected position



But second hit is not aligned with first hit and (0,0,0)

⇩

Δx allows to estimate charge and momentum

⇩

narrower window to look for 3rd hit in T2

At least 5 hits to provide a track candidate (many ghosts!)

16

D. Mendoza talk @ LLP12
https://indico.cern.ch/event/1166678/timetable/#53-impact-of-the-high-level-tr

The Hybrid Seeding strategy

Aiola et al. (2021)

✗ X-Z trajectories provide x(z) track equations. How to find y coordinate?

✗ **U/V layers:**

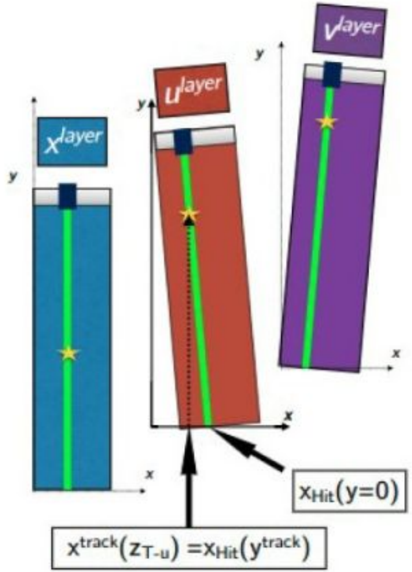
Estimate of x-position in the first U layer from x(z) trajectory

Assumption: trajectories coming from the origin ⇨ define $\mathbf{t_y}$ slope

Open search window in next U/V layer

For each combination found, new hits are seek in further layers

Minimum of 10 hits for track candidate



Good quality tracks are used for further tracking, matching with:

VELO segments
Long tracks

UT hits
Downstream tracks

… or to construct T-tracks (remaing tracklets)

In development

17

LLP detectors at FPF

https://cds.cern.ch/record/2851822

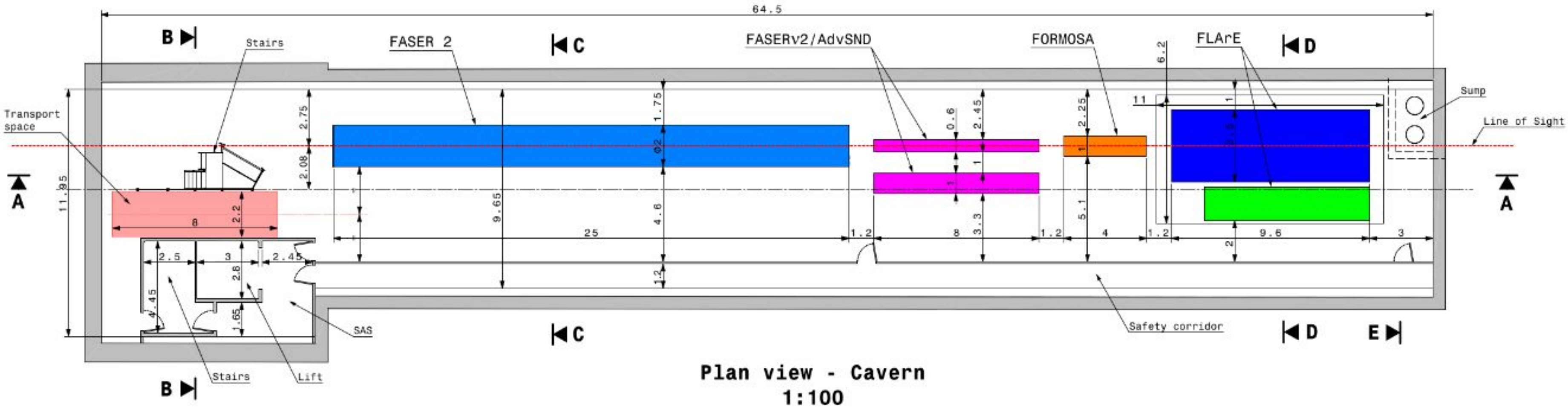
- Forward Physics Facility: 65 m cavern
- Host large volume detectors 600 m from ATLAS
- Detectors dedicated to BSM and neutrino physics

Physics case summary Oct 2024

FASER2: magnetized spectrometer for LLP, quirks

FASERNu2: neutrino emulsion detector

FORMOSA: plastic scintillator array mCPs



AdvSND: electronic neutrino

FLArE: liquid Argon TPC neutrino detector

FASER: search for dark photons with 2022 data

- Search for dark photons $A' \to e^+e^-$: https://arxiv.org/abs/2308.05587
- Dark photons in light mesons decays (pions → photon + A')
- Electrons reconstructed in tracking stations and calorimeters
- Backgrounds:
  - Veto inefficiency + muons missing veto → negligible (evaluated from scintillator efficiency + MC)
  - Noncollision (cosmics, beam induced) → negligible (evaluated in non-colliding bunches)
  - Neutrinos → (1.8 +- 2.4) 10^{-3} (from MC)
  - Neutral hadrons → (2.2+-3.1) 10^{-4} (data driven)
  - Expected 0.0020 +- 0.0024 events, observed 0

FASER: search for ALPs with 2022+2023 data

- Search for ALPs → γγ: https://arxiv.org/abs/2410.10363
- Produced from photons (Primakoff) or mesons (B)
- Photons reconstructed in calorimeter and scintillation layers
- Backgrounds:
  - Irreducible neutrino background from light/charm (evaluated from MC, large flux uncertainties)
  - Validation regions depending on where the neutrino interacts
  - Expected 0.44 +- 0.39 events, observed 1

MoEDAL - MAPP

Phase-0: MoEDAL deployed for LHC Run1-2 (2010 - 18) and Phase-1: Run-3 (2022 -)

- Nuclear Track Detector, plastic array
- Trapping detector array (1 T of Aluminium) to trap Highly Ionizing Particles
- Timepix array: digital camera for real time radiation monitoring
- No trigger, no bkg, permanent record
- Search for monopoles (best limits!), dyons (e and magnetic charge), HECOs (done!)
- Charged SUSY particles (looser requirement), multiply charged particles

Phase-1 - MAPP-1 upgrade deployed: Run3 (2022-)

- 400 scintillator bars (10 x 10 x 75 cm3) in 4 sections readout by PMTs - hermetic VETO counter
- Millicharged particles

Phase-2 - MAPP-2 upgrade to be deployed for HL-LHC (2027-)

- Detector extended in UGC1 gallery, enhanced technology and resolution
- HIPs, FIPs and LLPs → charged particles and photons

FACET

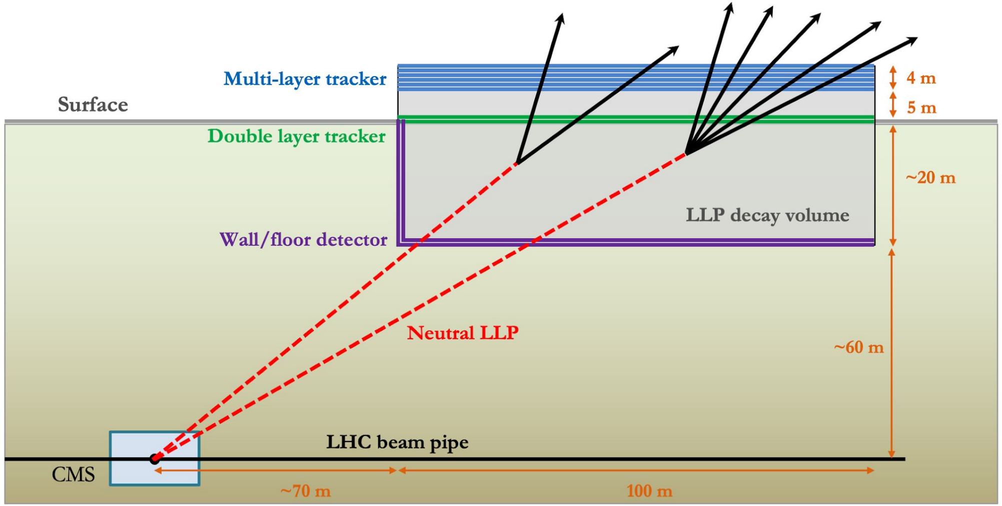
- Proposal: 100 m from CMS
- Forward direction (7.6 > h > 6.2)
- Large decay volume (D= 1m, L = 18 m, 14 m3)
- High vacuum (10-10 mbar) ≈ low background
- Forward direction 6.2 < η < 7.6
- Shielding upstream ≈ 35 – 50 m of iron
- Detector design: CMS Phase-2 technology
- High precision Si - tracking, high granularity calorimeter/hodoscopes
- Detect neutral particles $\rightarrow$ 2 charged/photons
- LLPs: dark photons, HNLs, ALPs, dark Higgs
- Lifetime sensitivity $\gamma c\tau$ ≈ 10 – 10,000 m, peak ≈ 100m
- Evaluating possible configurations

Codex-b

- 10 m cube of 500 RPC triplet modules, 4 internal faces
- Near 0 background, active and passive shielding
- Design needs to accommodate LHCb needs for Run4 (currently ongoing)
- Backgrounds: neutrons and KL at IP → active veto, secondary interaction producing KS
- CODEX-beta demonstrator: 2 m cube, 14 RPC triplet modules
- Validate bkg, integrate with LHCb DAQ, validate mechanical support
- RPC: modules from HL-ATLAS, timing resolution O(100 ps), spatial resolution O(1 mm)
- Commissioning with cosmic muons
- Full installation in YETS (December 2024 - March 2025)
- Data taken for remainder of Run 3

Mathusla

- Massive timing Hodoscope for ultra stable neutral particles
- Sensitivity to ct~0.1 s (BBN limit)
- Operation in HL-LHC, prototype in progress
- 80 m of rocks shielding
- Walls/floor scintillator to veto LHC muons
- Tracking scintillators + timing to separate upward/downward muons



https://indico.cern.ch/event/1216822/contributions/5449253/attachments/2671677/4631782/Mathusla_13LHCLLP_June2023.pdf

- Modular design, 100 modules 9x9 m2, decay volume 100 x 100 x 25 m3, 20 m underground
- Each layer has 4 sub-planes with 8 adjacent modules with 32 scintillator bars
- 4D tracking and vertexing to reduce background
- SiPM, goal 1 ns and 1 cm transverse hit resolution
- Trigger: able to trigger CMS readout!
- Feasibility study using FPGAs, signals propagation times are important

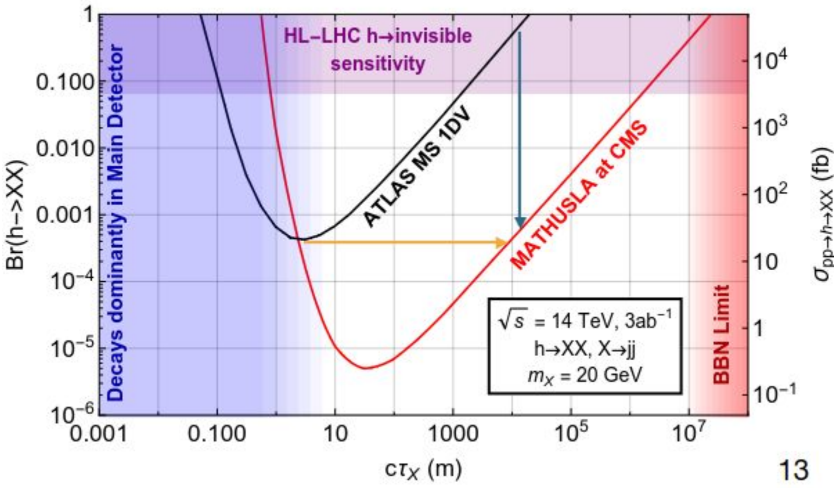
Mathusla

https://indico.cern.ch/event/1216822/contributions/5449253/attachments/2671677/4631782/Mathusla_13LHCLLP_June2023.pdf

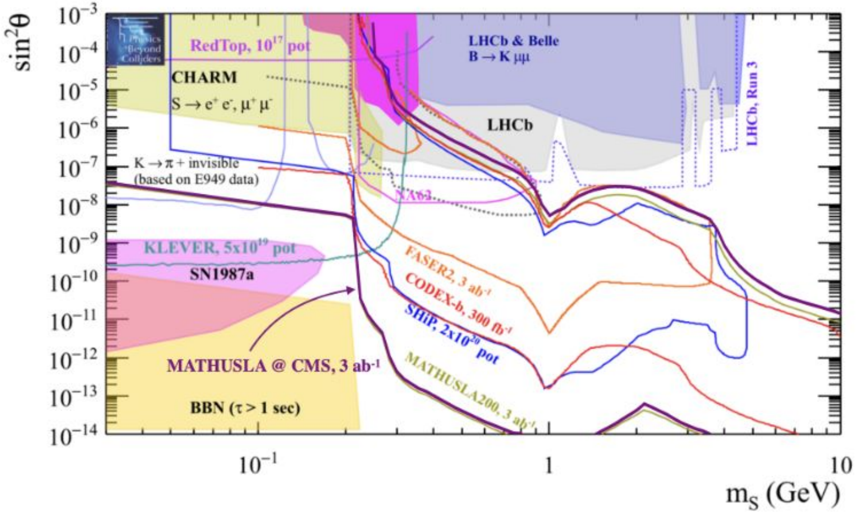
Backgrounds:

- QCD (punch-through jets) killed by rock
- Space-time resolution: reject 1.7 MHz cosmics
- Tracking: reject 10 Hz muons from CMS
- More challenging: neutrino scattering (no signal on walls) from LHC and atmosphere → non pointing vertices, similar to a LLP decay

H→SS→ hadrons: factor 3 in cau and sensitivity
https://arxiv.org/abs/1806.07396



Complementary to FASER (similar masses but shorter lifetimes)



MATHUSLA

- P5: does not recommend full 100mx100m → rescope at smaller size
- Updated design: 40 m x 40 m x 17 m, no excavation, 1/10 signal acceptance
- Test stand above ATLAS, 2 layers of scintillator
- RPC for tracking
- Took cosmic data and LHC-on
- Upward tracks: LHC + inelastic backscattering
- Some early demonstrators underground for muon tomography
- 2 new test stands currently assembled: 4 layers, 1mx1m

- Proposal for Mathusla-10: 10mx10m, to be placed above CMS, needed to understand beam-associated backgrounds
- Mathusla FastSim implemented and GEANT4 in progress
- Reconstruction: Kalman filter based track and vertex under development

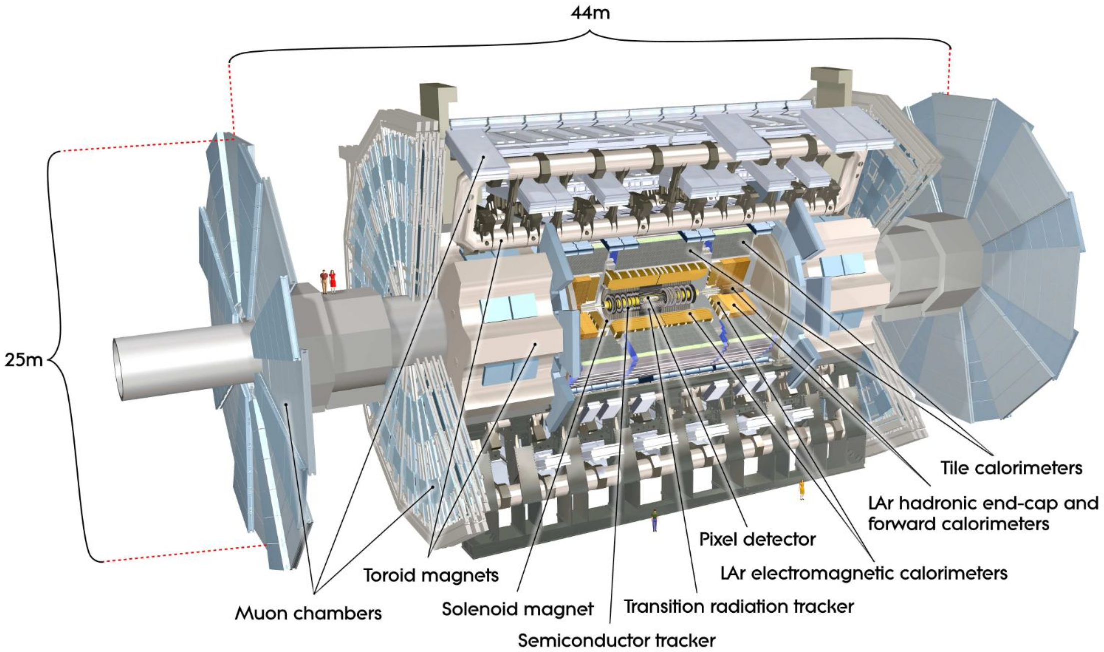
ANUBIS

- ATLAS cavern: large solid angle with minimal SM backgrounds, ATLAS can veto collision products
- Transverse position: higher-mass LLP (>1 GeV), EW-scale+ mediators.
- RPC: large instrumented area at low cost: 3 chambers separated by air gaps
- BIS78 RPC technology for HL-ATLAS MS: reduces cost/effort
- proANUBIS prototype: single 3-RPC module, constructed in 2022, installed March 2023
- Goals: validate detector performance, synchronize timing with ATLAS, combine particle reconstruction with ATLAS, measure punch-through + hadronic interactions in air
- Re-commissioning in February 2024 to upgrade trigger system (issues with signal polarity)
- Early data: correlation of proANUBIS with ATLAS luminosity (~1 hz with beam off and O(~few kHz) during collisions)
- Data analysis ongoing: RPC track reconstruction, timing, cosmic runs show data/MC agreement
- To do: LHC clock synchronization → punch-through events
- 2026: ANUBIS engineering and commissioning
- Run4 + Run5: ATLAS+ANUBIS data taking

10.1088/1748-0221/3/08/S08003

ATLAS

- **Tracking inner detector** ID, $|\eta| < 2.5$
- **Solenoid magnet** 2 T
- **ECAL**: liquid argon (**LAr**) with lead absorbers.
  $1.5 < r < 2.0$ m; $3.6 < |z| < 4.25$ m
- **HCAL**: **steel/scintillator-tile**, segmented in 3 barrel structures $|\eta| < 1.7$ + 2 copper/LAr endcaps ($1.5 < |\eta| < 3.2$)
  $2.25 < r < 4.25$ m; $4.3 < |z| < 6.05$
- **Muon system** (MS):
  3 stations trigger + tracking
  - **Trigger: RPC + TGC**, $|\eta| < 2.4$
  - **Tracking: monitored drift tube (MDT) - cathode strip chambers (CSC)** in endcaps, $|\eta| < 2.7$
  - Each MDT: 2 ML with 3/4 DT
- **3 toroidal magnets**, each 8 coils
- **L1 hardware trigger, HLT software trigger**



10.1088/1748-0221/3/08/S08004

CMS

- **Solenoid magnet** 3.8 T
- **Tracking**: silicon pixel and strip detectors, $|\eta| < 2.5$, $r < 1.16$ m
- **ECAL**: PbWO4 scintillating crystals $1.29 < r < 1.52$ m, time resolution 100 ps per hit
- **HCAL**: brass+scintillator sampling calorimeter, $1.77 < r < 2.95$ m
- **Muon system (MS)**: 3 gas detectors
  - **Drift Tubes** in barrel, $|\eta| < 1.4$, $4 < r < 7.5$ m
  - **Cathode Strip Chambers** in endcaps, $0.9 < |\eta| < 2.4$, $6 < |z| < 10.5$ m
  - **Resistive Plate Chambers**, good timing assignment (trigger), $|\eta| < 1.6$