Searches for BSM physics using challenging and long-lived signatures with the ATLAS detector

Alexander Lory on behalf of the **ATLAS collaboration**

SUSY 2024 - Madrid

ATLAS EXPERIMENT

FSP ATLAS
Erforschung von Universum und Materie

LMU
LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

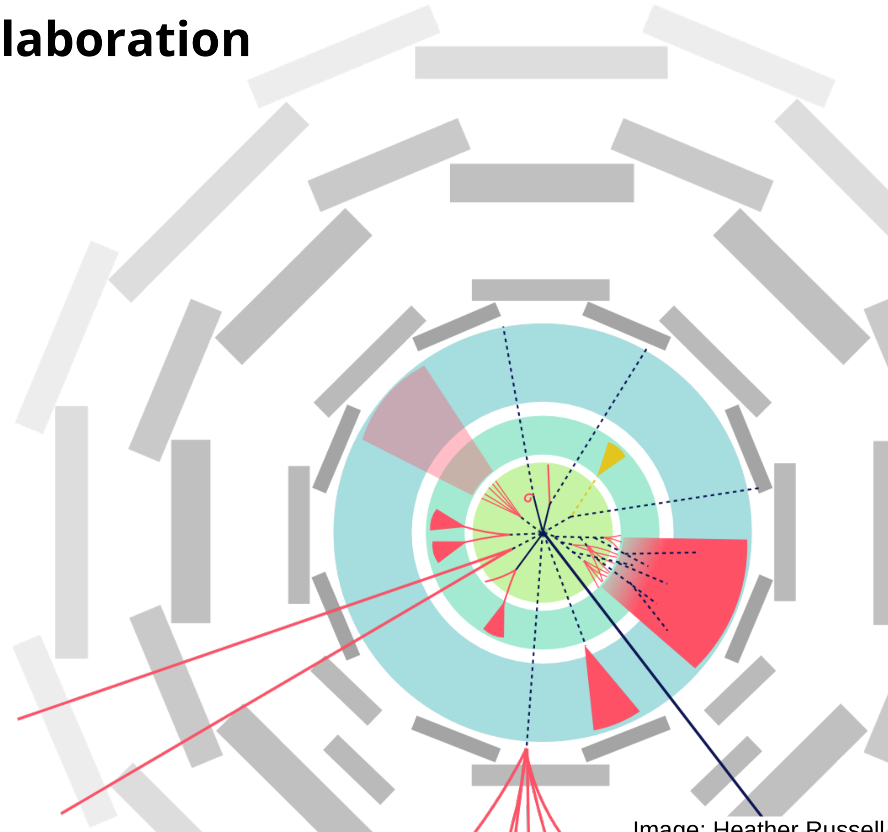
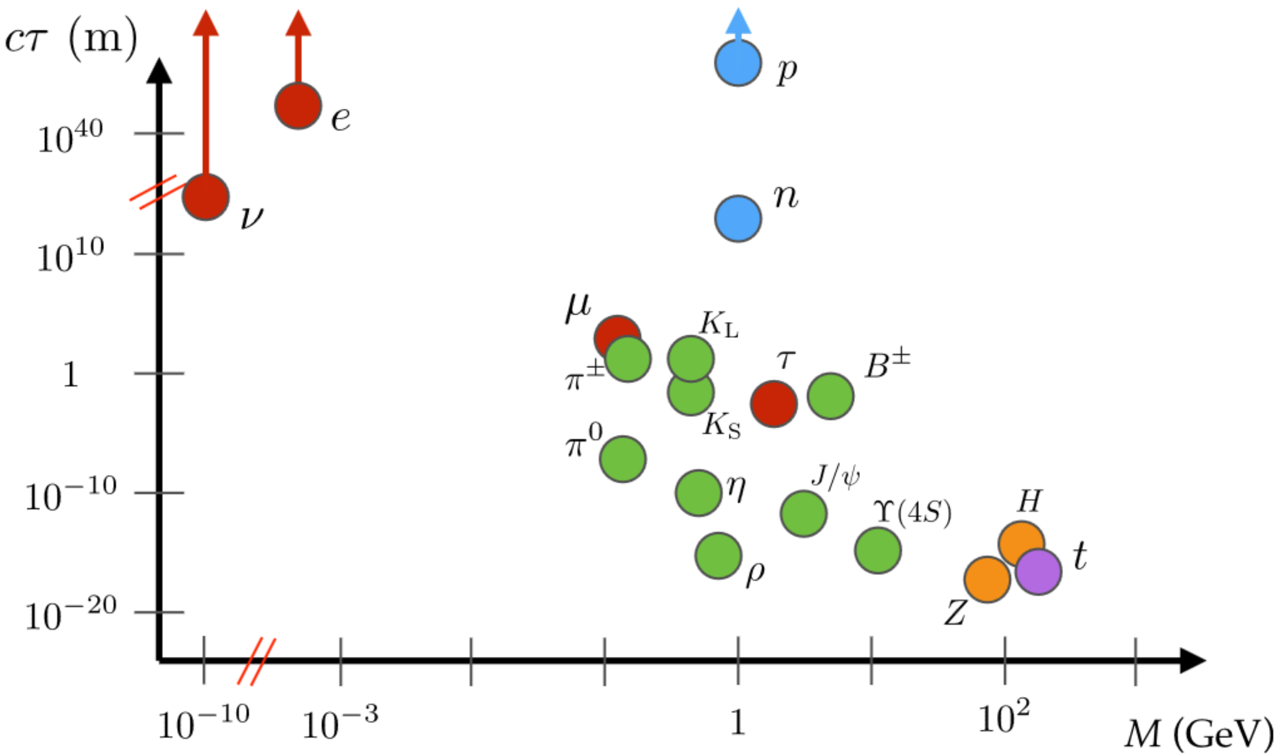


Image: Heather Russell

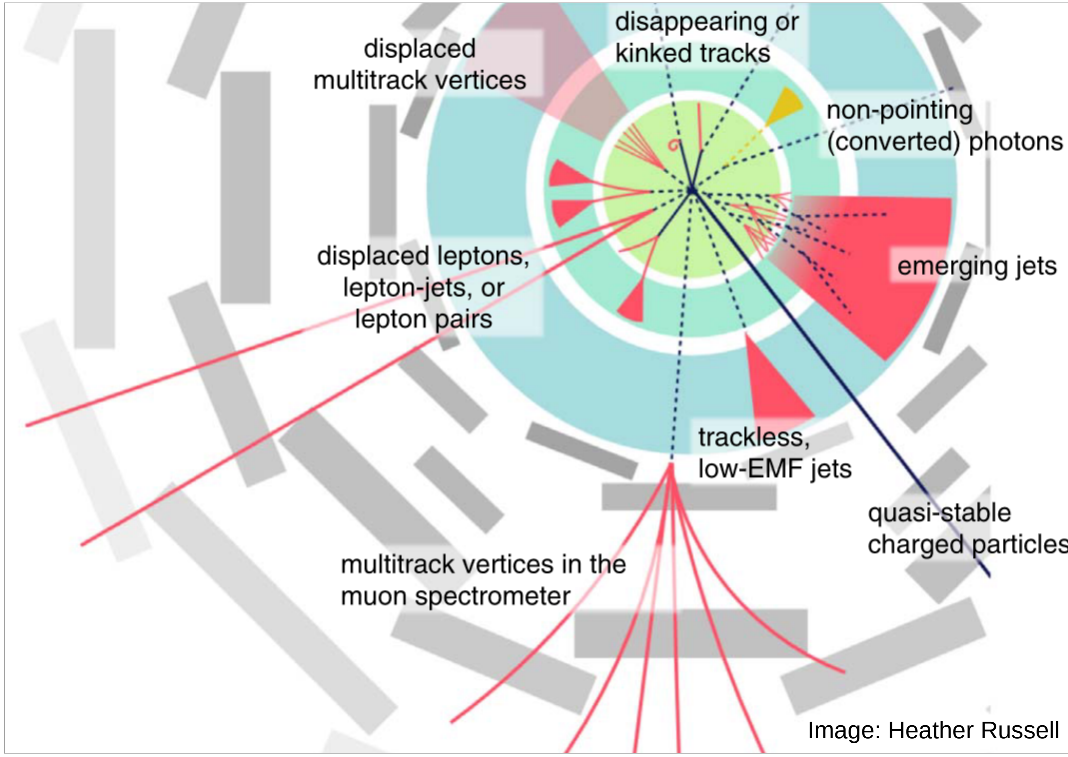
- Particles of the SM have lifetimes and masses spanning large ranges
- Same for BSM models!
  - Long lifetimes:
    - Small couplings
    - Approximate symmetries
    - Suppressed phase space available for decays



J. Phys. G 47 (2020) 090501

- Striking, exotic signatures are expected if LLP particles decay to SM at detector-scale distances

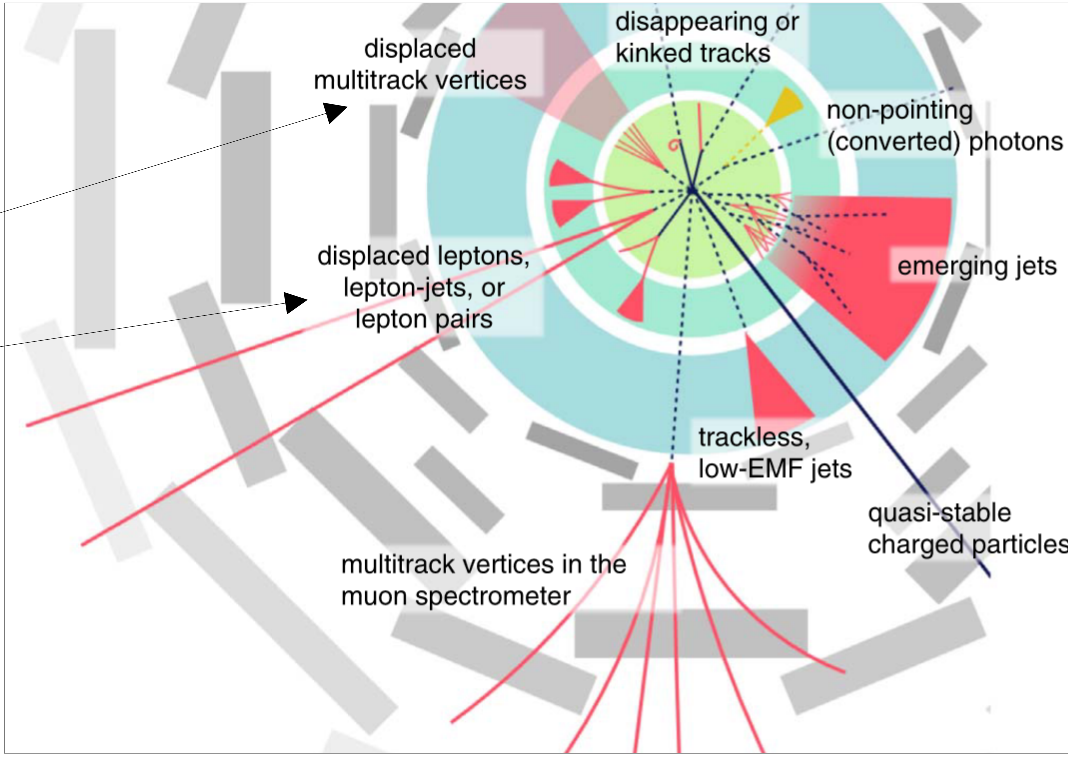
- However, the ATLAS detector, triggers, simulations, reconstruction techniques, … are typically optimised for signatures observed in the SM



- Long-lived signatures require dedicated / unconventional / challenging
  - Triggers
  - Reconstruction algorithms
  - Background estimates (often data-driven)
  - Signal simulations

Outline

- Focus on new results from two analyses:
  - Displaced vertices in the ID
    arXiv:2403.15332
  - Displaced lepton jets
    CERN-EP-2023-226

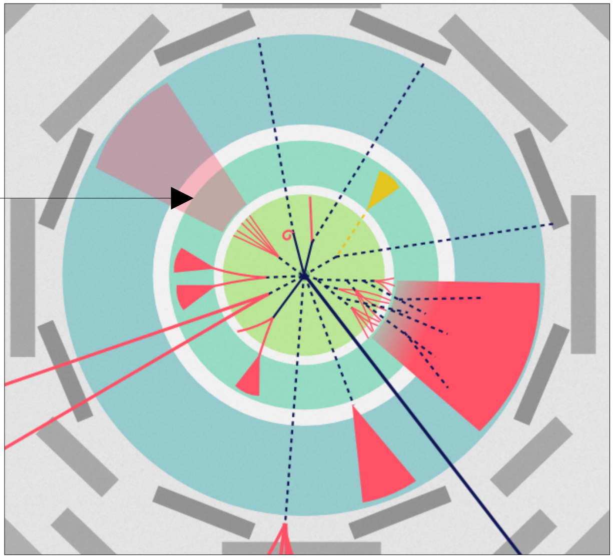


- For an overview of **ATLAS SUSY LLP** searches see [Recent results on long-lived particles in ATLAS - Dr. Vasiliki Mitsou]() in the SUSY parallel session

Search for light long-lived particles in pp collisions at 13 TeV using displaced vertices in the ATLAS inner detector

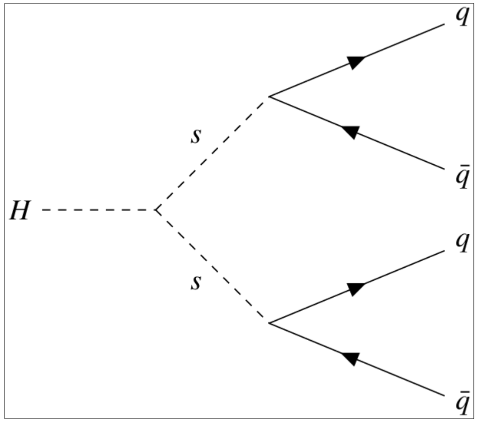
arXiv:2403.15332

- Search for neutral LLP decaying hadronically in the ID
  - displaced jets
  - displaced vertices in the inner detector

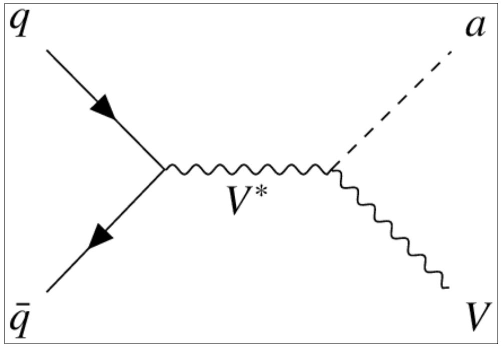


- First direct application of improved large radius tracking (LRT) Eur. Phys. J. C 83, 1081 (2023)

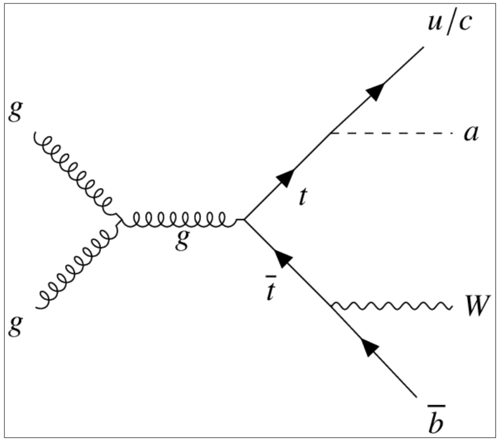
- Targetting 3 benchmark models:
  - Higgs portal



  - Axion-like particle (ALP) coupling to gluons / vector bosons

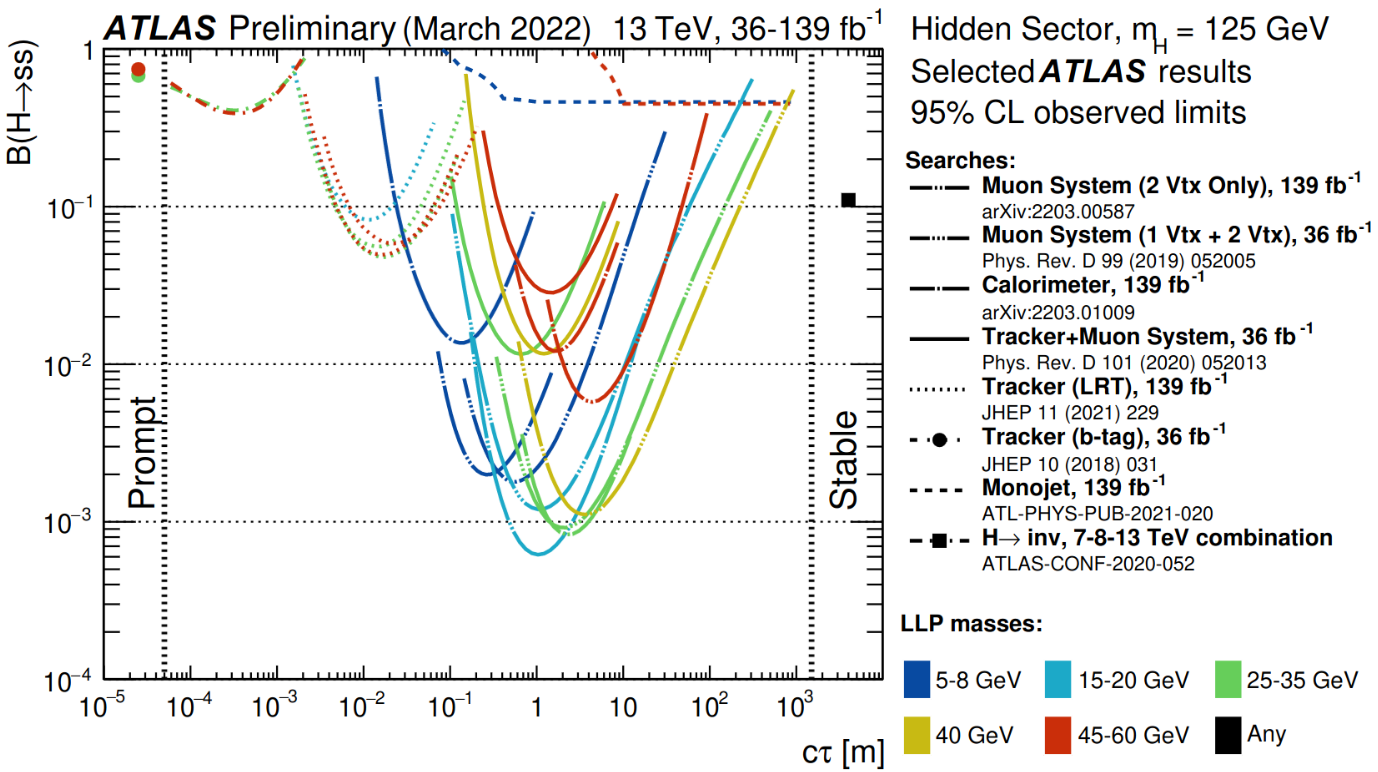


  - ALP coupling to up-type quarks leading to exotic top decay



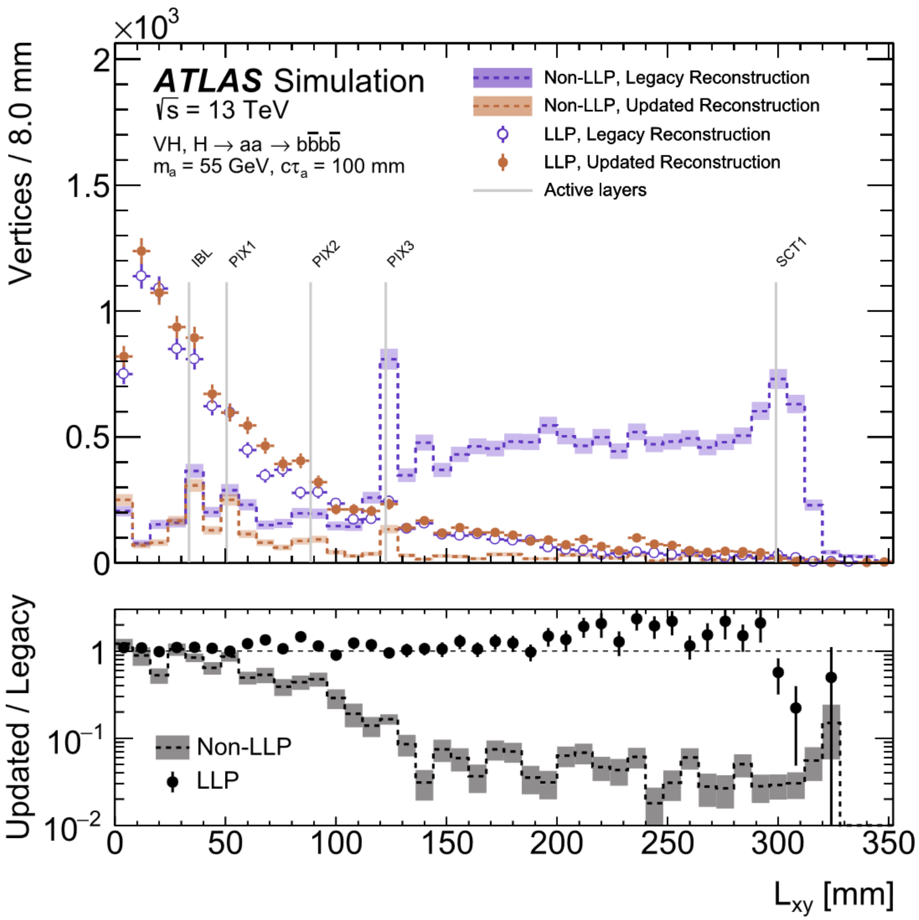
Displaced vertices in the ID

- Previous ATLAS searches



- In the ID:
  - No dedicated trigger available
  - LRT computationally expensive and high fake rate
    - Restricted to ZH production
    - Required at least two displaced vertices due to large background from fake tracks

- This new search uses updated LRT Eur. Phys. J. C 83, 1081 (2023) :
  - Significantly reduced rate of fake tracks
  - LRT can be applied to each event
  - WH and VBF productions now also probed (and topologies used for triggering)

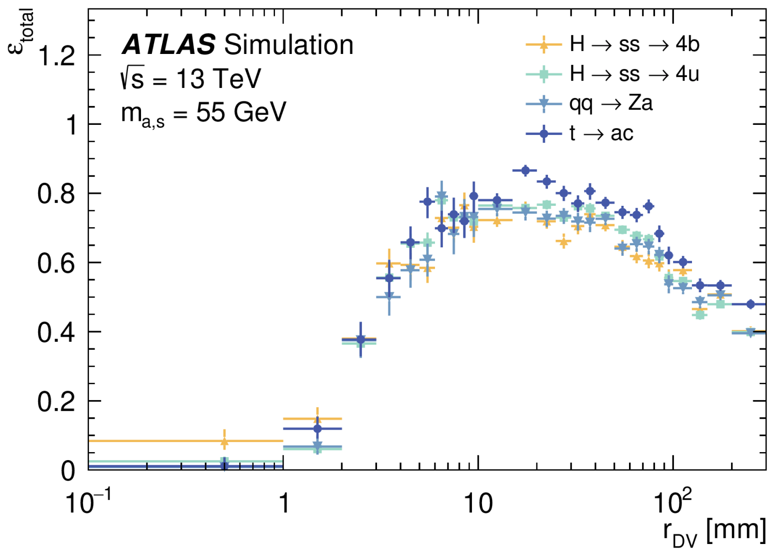


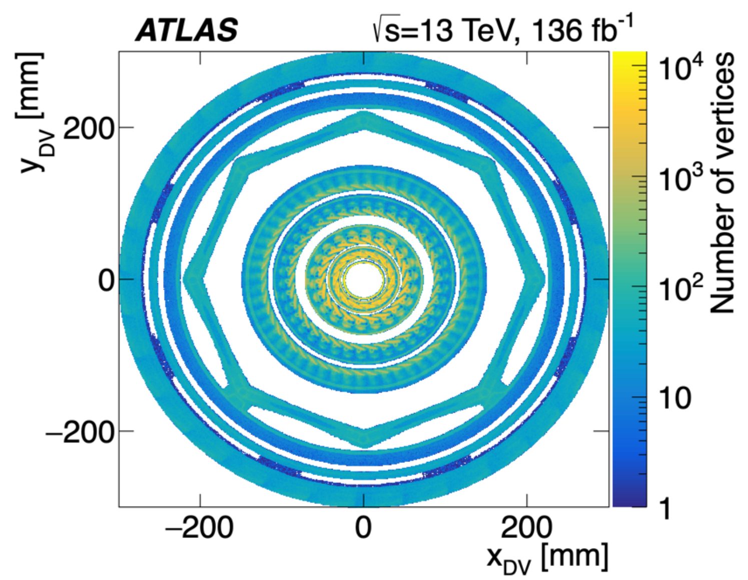
- Displaced vertices ATL-PHYS-PUB-2019-013
  - Dedicated algorithm for LLP searches
  - Using both standard tracks and LRTs
  - Efficient from 2 mm to 300 mm displaced decays
- Main background:
  - Interaction of SM particle with detector material

    → veto vertices on location of detector material
  - 3D map of material is built by reconstructing DVs in a data sample

    → not well applicable to simulation

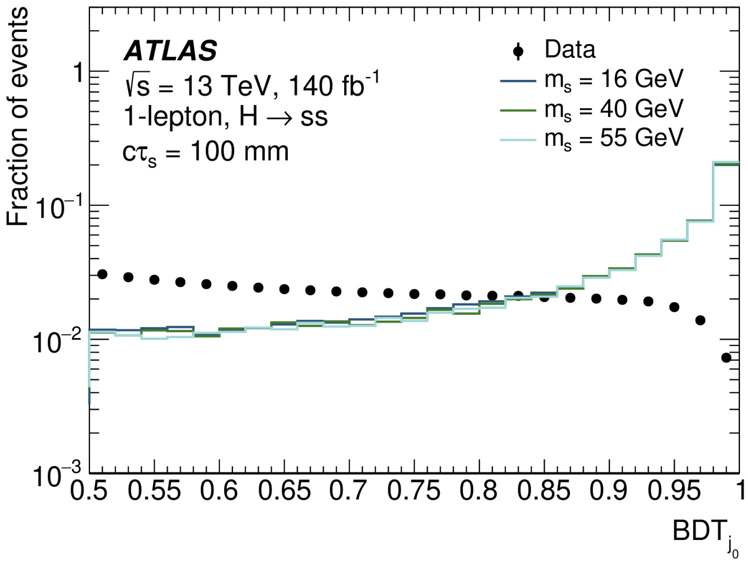
    → search uses data-driven background estimate

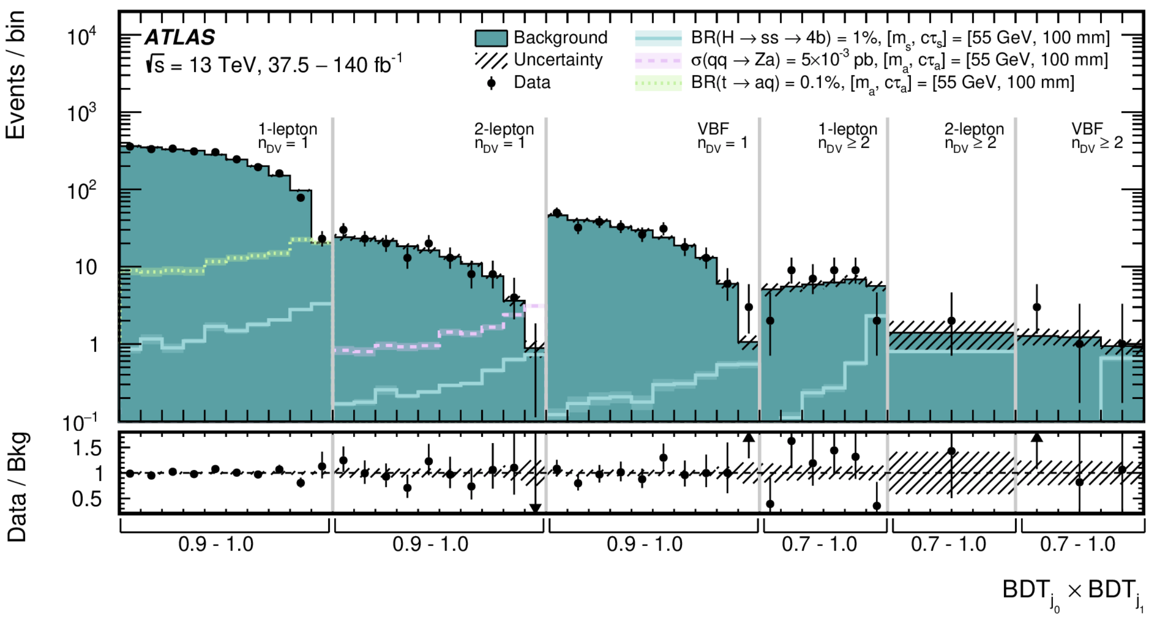




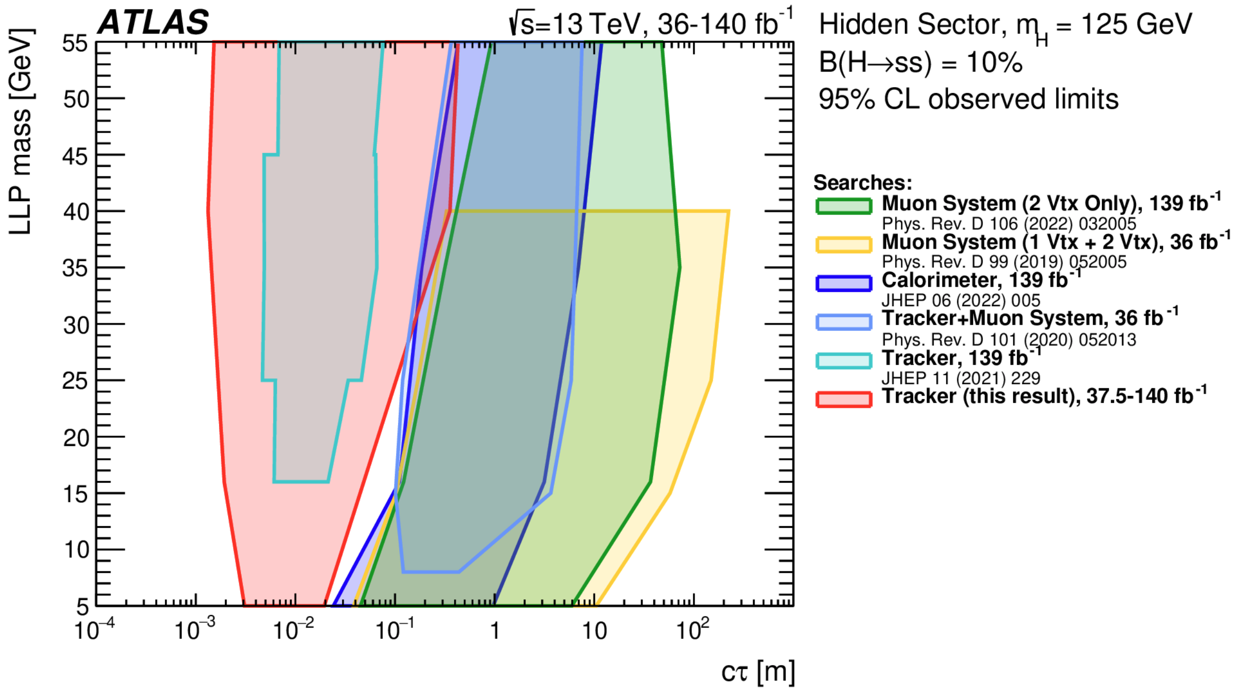
Displaced vertices in the ID

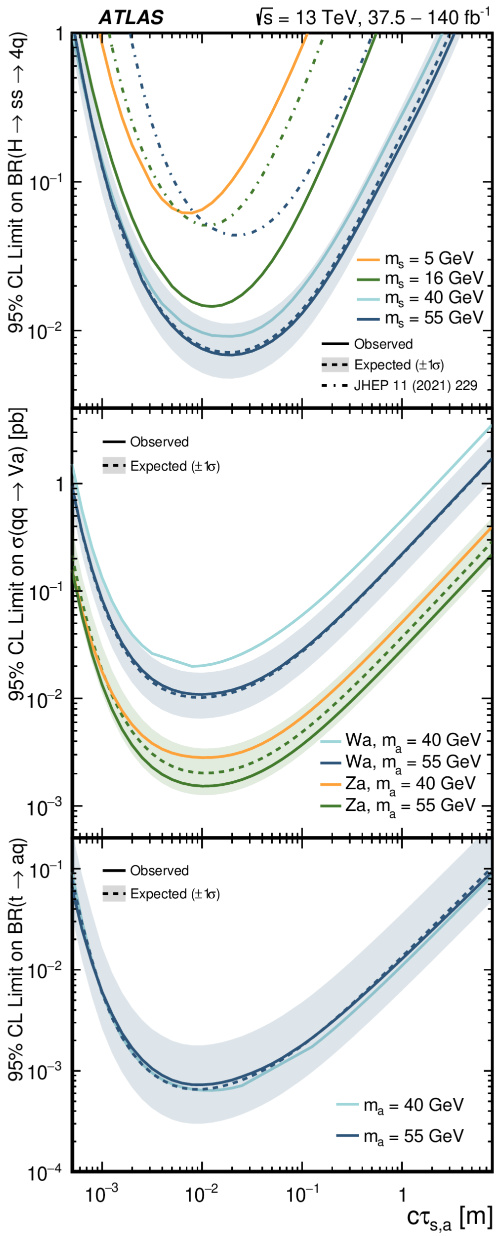
- Displaced jet reconstruction:
  - BDT trained using 5 jet-level features related to the displacement of tracks within jets
- Events categorized based on $\mathrm{BDT}_{j_0} \times \mathrm{BDT}_{j_1}$, n_{DV}
  - SR exactly one, or at least two DVs
- Background estimate:
  - Fully data-driven
  - In CR, measure probability for a DV to be reconstructed in the vicinity of a DJ, as a function of DJ characteristics
  - Compute probabilities to obtain given DV mutliplicity in each event based on present DJs
  - Applying these probabilities as event weightsin an inclusive data selection gives the expected number of events in the SRs





Displaced vertices in the ID



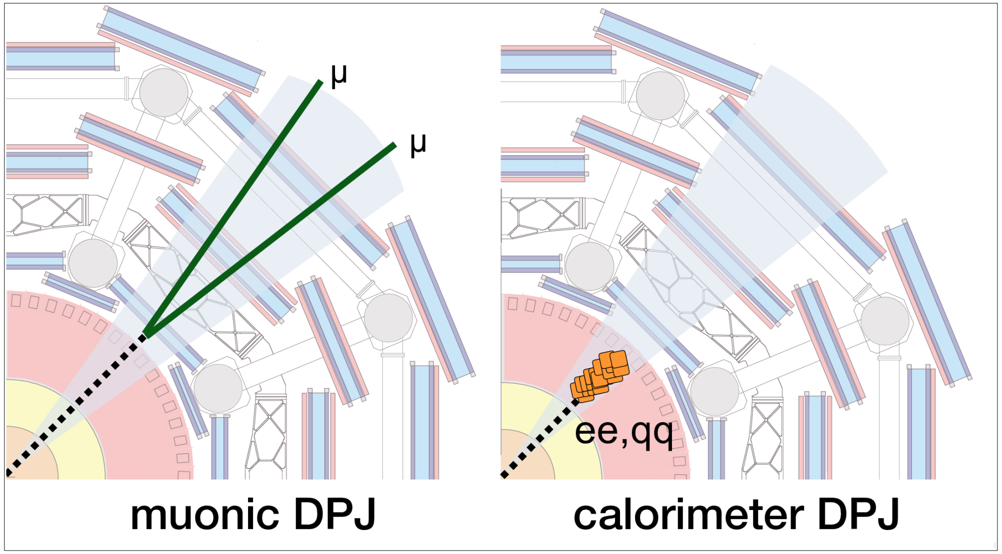


Search for light long-lived neutral particles from Higgs boson decays via vector-boson-fusion production from pp collisions at s=13 TeV with the ATLAS detector

CERN-EP-2023-226

- Search for a hidden sector with light, long lived dark photons

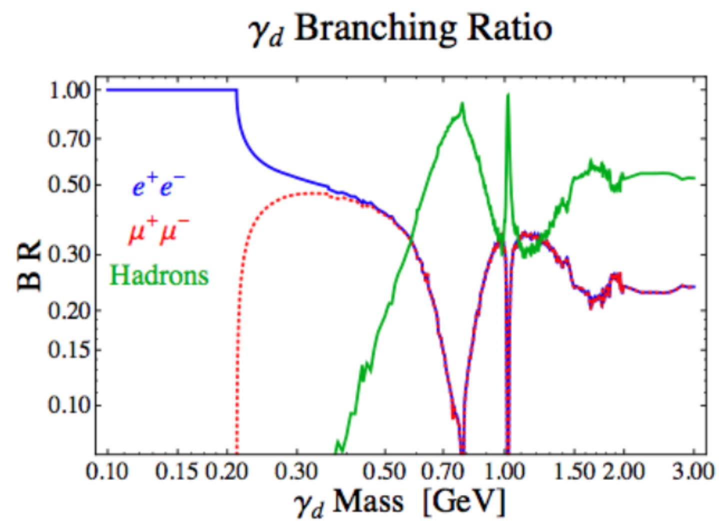
  → displaced decays of collimated leptons or light hadrons in the calorimeters and MS
  Dark photon jets (DPJs)



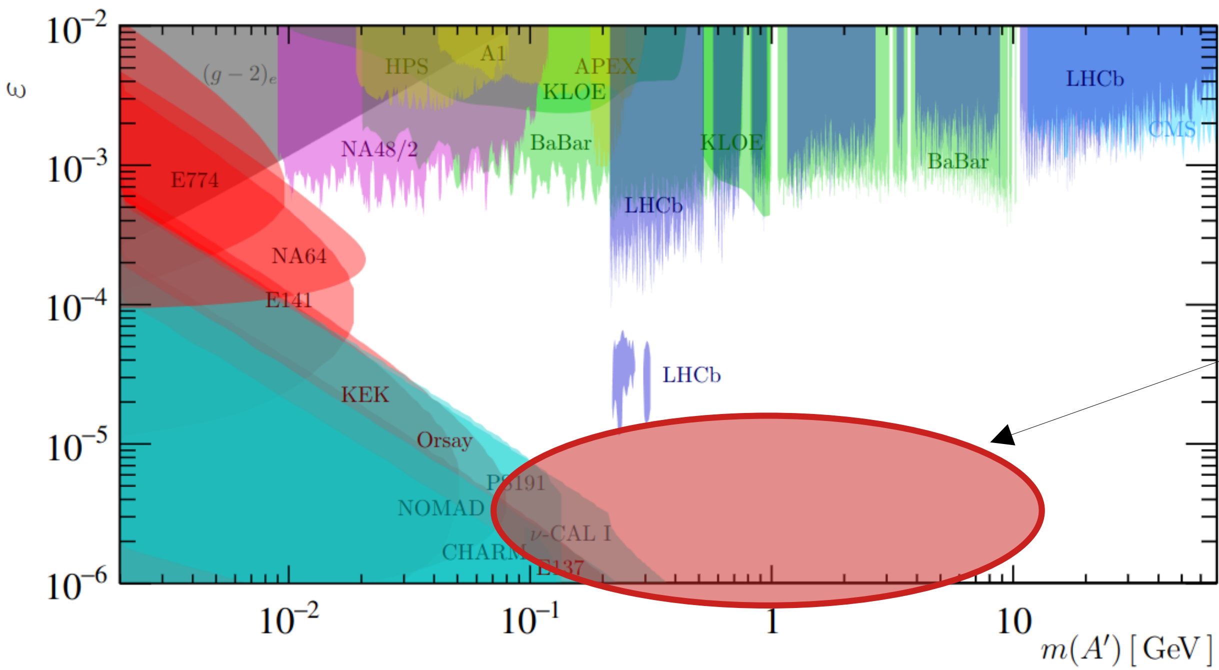
- Dark photons
  - Kinetic mixing with SM photon with mixing term ε, related to lifetime

$$\tau \propto \left(\frac{10^{-4}}{\varepsilon}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_{\gamma_d}}\right)^2 [\mathrm{s}]$$

  - Constrains: JHEP 06 (2018) 004



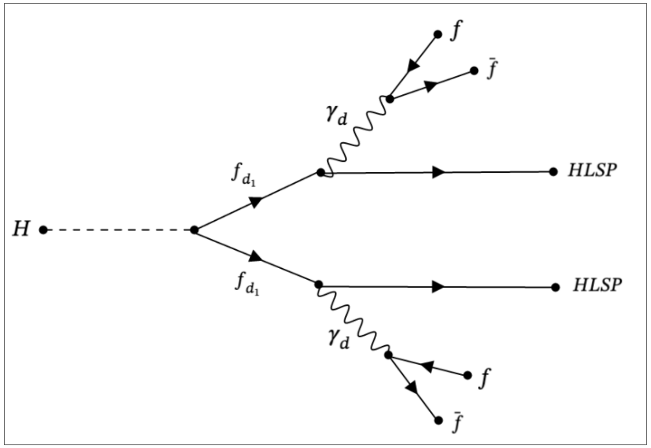
JHEP 05 (2010) 077



Targetted by this analysis (lifetimes 5 mm – 1 m)

Displaced lepton jets

- Targetted signal model
  - Falkowski–Ruderman–Volansky–Zupan (FRVZ) model
  - A hidden sector with dark fermions reached with exotic decay of H
  - Decay to dark photons + hidden lightest stable particle (HLSP)
    → ETmiss
  - Dark photons are light (0.017 – 15 GeV)
    - Collimated decay products
  - Higher dark photon masses (20 – 60 GeV) probed by the displaced dimuon search
    Phys. Rev. D 99 (2019) 012001

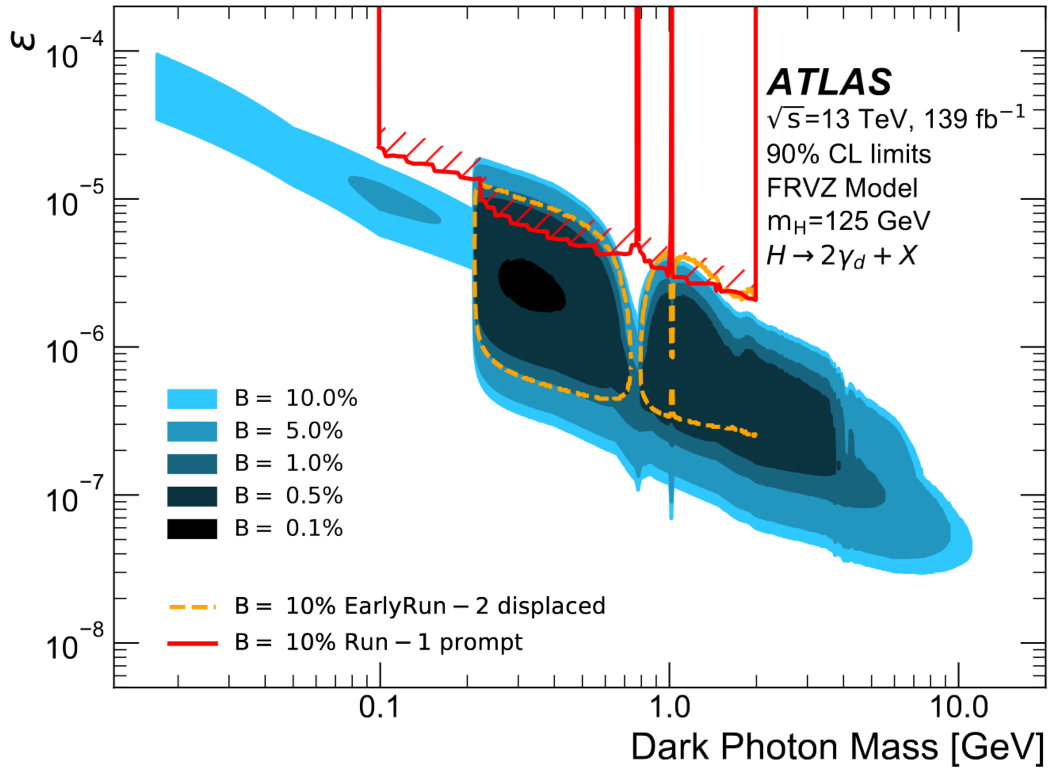


Displaced lepton jets

- Previous ATLAS searches
  - **Red**: Run – 1 prompt JHEP 02 (2016) 062
  - **Orange**: EarlyRun – 2 displaced Eur. Phys. J. C 80 (2020) 450
  - **Blue**: Run – 2 displaced (ggH + WH) J. High Energ. Phys. 2023, 153 (2023)

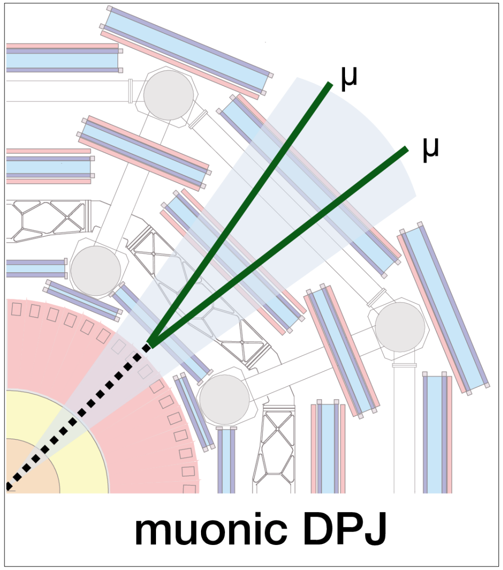
- This search extends Run – 2 ggH + WH
  - Targets also VBF

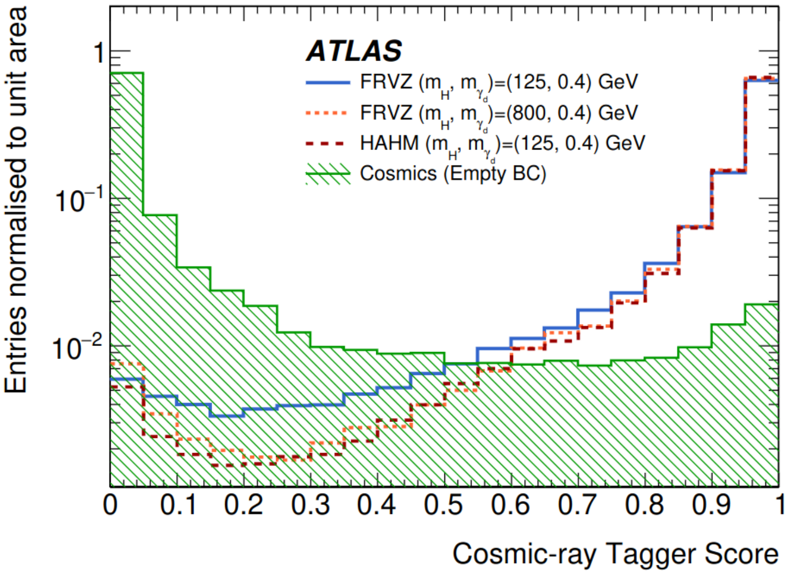
- Triggering
  - Dedicated LLP muon triggers JINST 8 (2013) P07015
  - Missing transverse energy



Muonic dark photon jets (μDPJ)

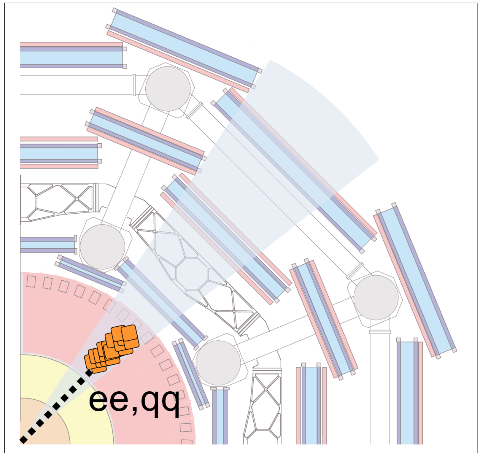
- Dark photons decaying outside the ID into 2 or more collimated muons
- Muons reconstructed using only MS are clustered using a Cambridge–Aachen algorithm
- Main backgrounds:
  - Cosmic :
    → rejected by DNN which uses
    - Impact parameter z
    - Track direction
    - Timing measurements
  - Rare QCD punch-through



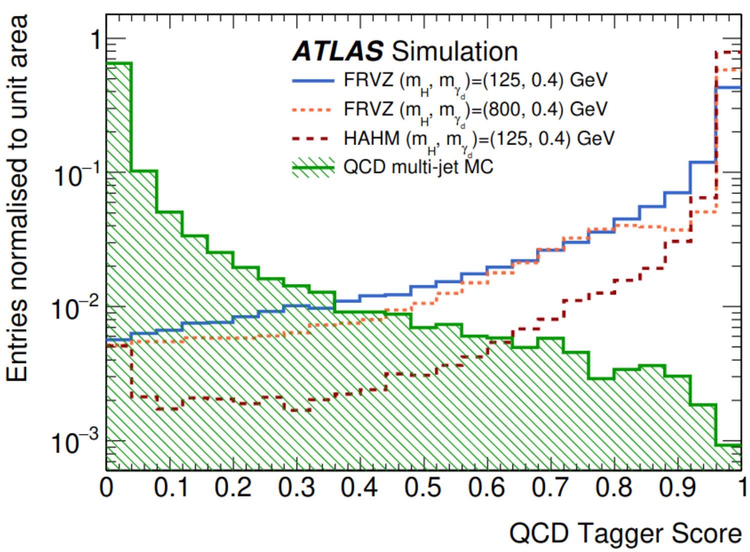


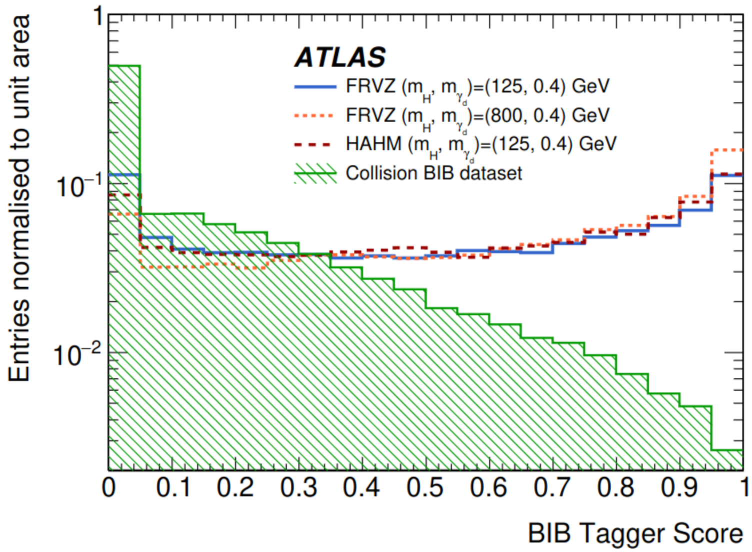
Calorimeter dark photon jets

- Dark photons decaying to electrons or quark pairs in the HCAL
- Standard jets, but with low EM fraction
- Veto jets with > 40% matched tracks compatible with PV
- Timing measurements used to reject cosmic and beam-induced bkgs
- 2 CNNs using calorimeter cell information used to reject
  - Fakes from prompt QCD jets
  - Beam induced background



calorimeter DPJ

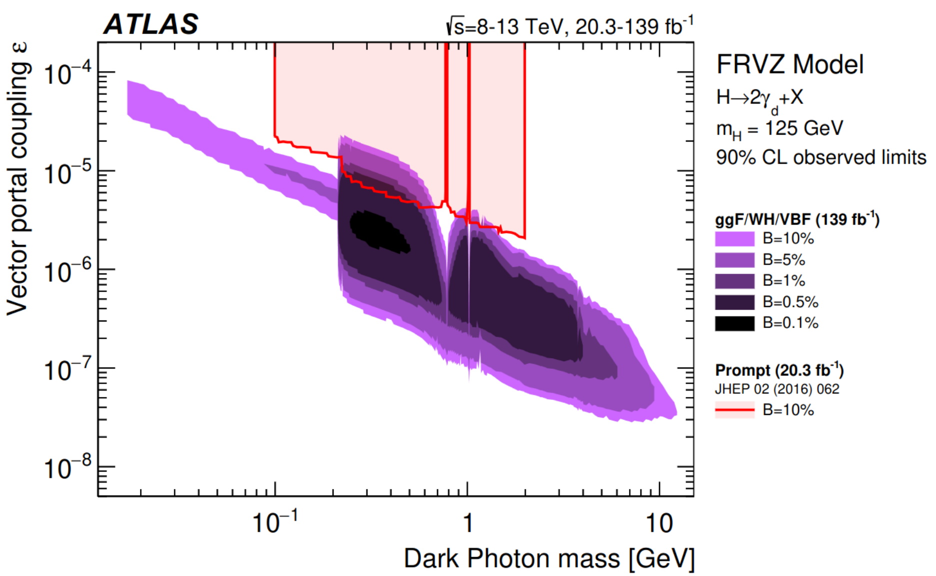




- Main background (QCD jets) estimated with ABCD method
- No deviations from the background expectations were observed

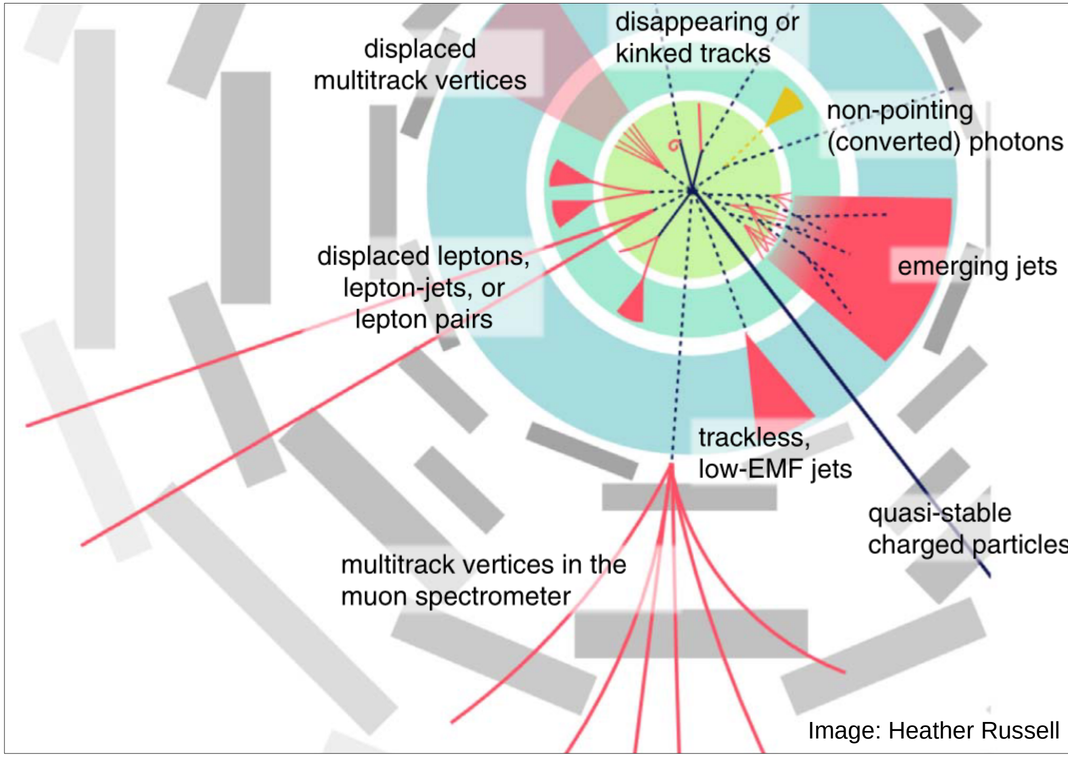
Selection	CRB	CRC	CRD	SR expected	SR observed
SR_{μ}	44	22	21	42 ± 14	41
SR_c^L	224	256	1123	983 ± 95	923
SR_c^H	9	11	35	29 ± 14	46

- Results are combined with the ggH + WH search



Conclusion

- No new physics has been found in signatures of displaced jets and displaced lepton jets
- Reconstruction techniques and analysis strategies still improving to uncover more phase space with Run – 2 data
- What else to search for?



Backup

Displaced vertices in the ID

- Main background for DVs:
  - Interaction of SM particle with detector material

    → veto vertices on location of detector material
  - 3D map of material is built by reconstructing DVs in a data sample

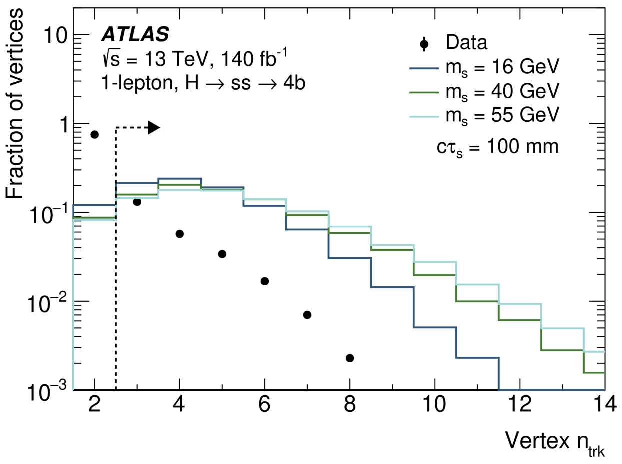
    → not well applicable to simulation

    → search uses data-driven background estimate
- Remaining background:
  - Light hadron decays (mostly 2 prong)

    → require at least 3 tracks

- Main background for DVs:
  - Interaction of SM particle with detector material
    → veto vertices on location of detector material
  - 3D map of material is built by reconstructing DVs in a data sample
    → not well applicable to simulation
    → search uses data-driven background estimate
- Remaining background:
  - Light hadron decays (mostly 2 prong)
    → require at least 3 tracks
- Additional requirements reject
  - Light hadron decays with random crossing
  - Heavy flavour decays

Parameter	Value
Material veto	True
Max. χ^2/n_{DoF}	5
Max. $\lvert z_{\mathrm{DV}}\rvert$	300 mm
Min. n_{trk}	3
Min. $m/\Delta R_{\mathrm{max}}$	4 GeV
Min. H_{T}	10 GeV
Min. $d_{0,\mathrm{max}}$	3 mm
Min. $d_{0,\mathrm{min}}$	0.1 mm
Max. ΔR_{jet}	0.6



Triggers:

- Dedicated triggers for LLPs: JINST 8 (2013) P07015
  - Tri-muon MS-only:
    - 3 muons at L1 (6 GeV)
    - confirmed at HLT using only MS
    - Limited sensitivity to collimated leptons
  - Muon narrow-scan:
    - 1 L1 muon (20 GeV)
    - Scan for a second muon within dR = 0.4 at HLT
    - Not required to be matched to ID tracks
- ETmiss (70 – 110 GeV)

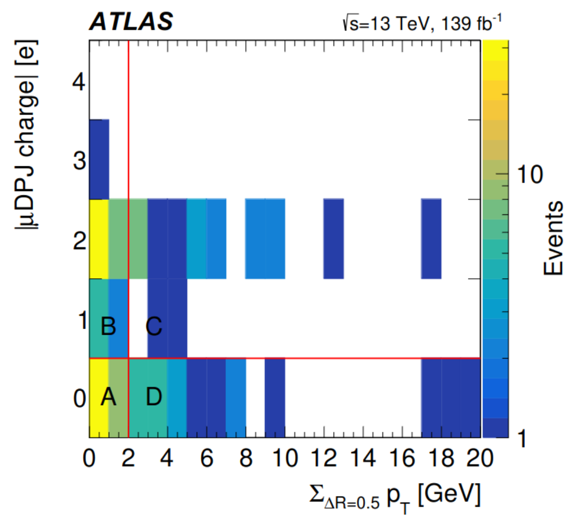
Events categorized base on type of the leading DPJ

- Muonic DPJ:
  - Tri-muon, muon narrow scan, and ETmiss triggers
- Calo DPJ:
  - ETmiss trigger only
- Event selection requirements target VBF production topology and reject QCD background with fake ETmiss from mismeasured jet energies.

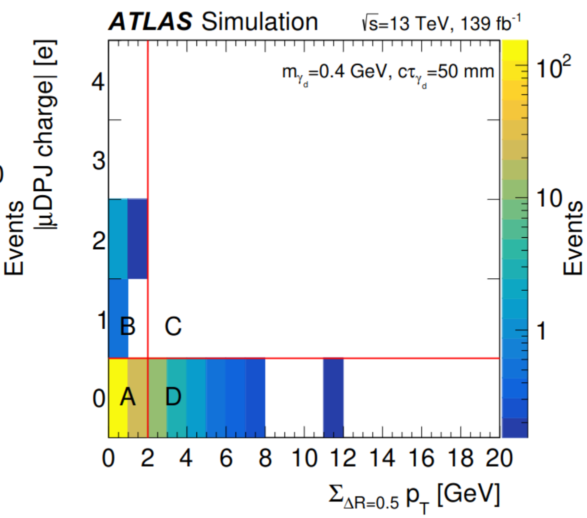
Requirement / Region	SR_{μ}	$SR_c^{L/H}$
Number of DPJs	≥ 1	≥ 1
Leading DPJ type	μDPJ	caloDPJ
Trigger	E_T^{miss} Tri-muon MS-only Muon narrow-scan	E_T^{miss}
p_T(jet) [GeV]	> 30	> 30
N_{jet}	≥ 2	≥ 2
m_{jj} [GeV]	≥ 1000	≥ 1000
$\lvert\Delta\eta_{jj}\rvert$	> 3	> 3
$\lvert\Delta\phi_{jj}\rvert$	< 2.5	< 2.5
N_{ℓ}	0	0
$N_{b\text{-jet}}$	0	0
C_{DPJ}	> 0.7	-
$\Delta\phi_{min}$	-	> 0.4
E_T^{miss} [GeV]	> 100	SR_c^L: [100, 225] SR_c^H: > 225
$\lvert\mu$DPJ charge$\rvert$	0	-
caloDPJ tagger	-	> 0.9
$\sum_{\Delta R=0.5} p_T$ [GeV]	< 2	< 2

- 2 channels:
  - Calo DPJ
  - Muonic DPJ
- Main backgrounds:
  - QCD jets

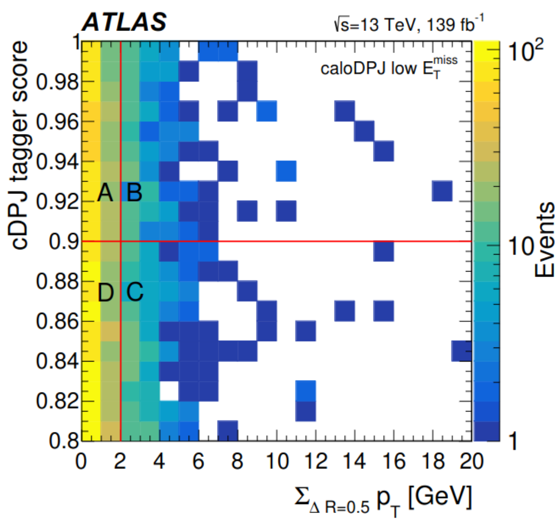
Data



Signal



Data



Signal