Long lived dark photon searches at ATLAS

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Dark Interactions
BNL
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UNIVERSITY of WASHINGTON

ATLAS EXPERIMENT

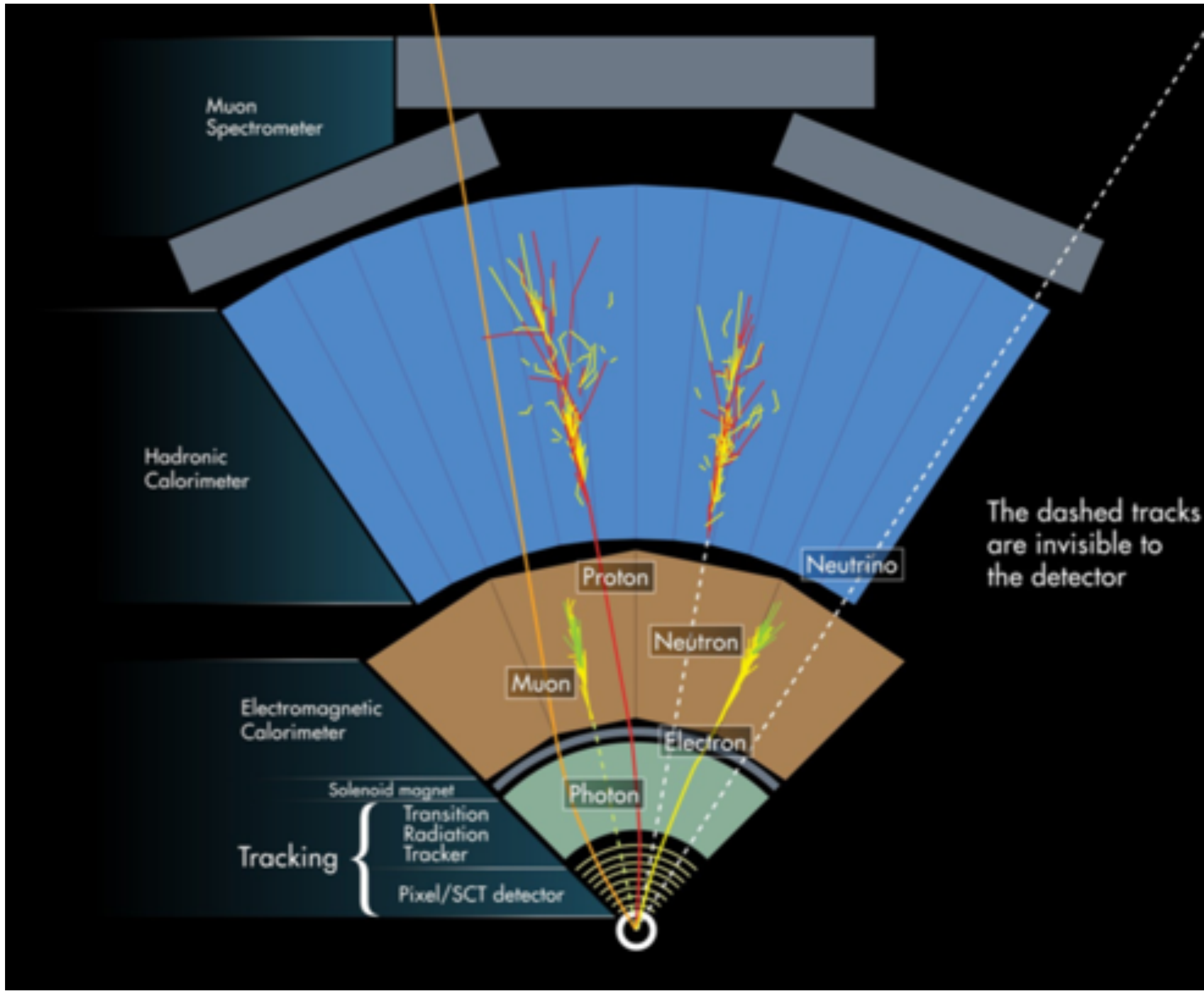
LLP searches in ATLAS

- In many models of BSM physics there are free parameters that influence the lifetimes of the new particle states, with no strong motivation for assuming that all the particles decay promptly

- New particles will either be
  - Prompt decaying
  - Semi-stable Long-Lived Particles (LLPs), decay in the detector ← we need to make sure we have sensitivity to these too!
  - Detector-stable, decay outside the detector
  - Stable

  - ATLAS and CMS are designed to optimize object identification for (prompt) SM particles

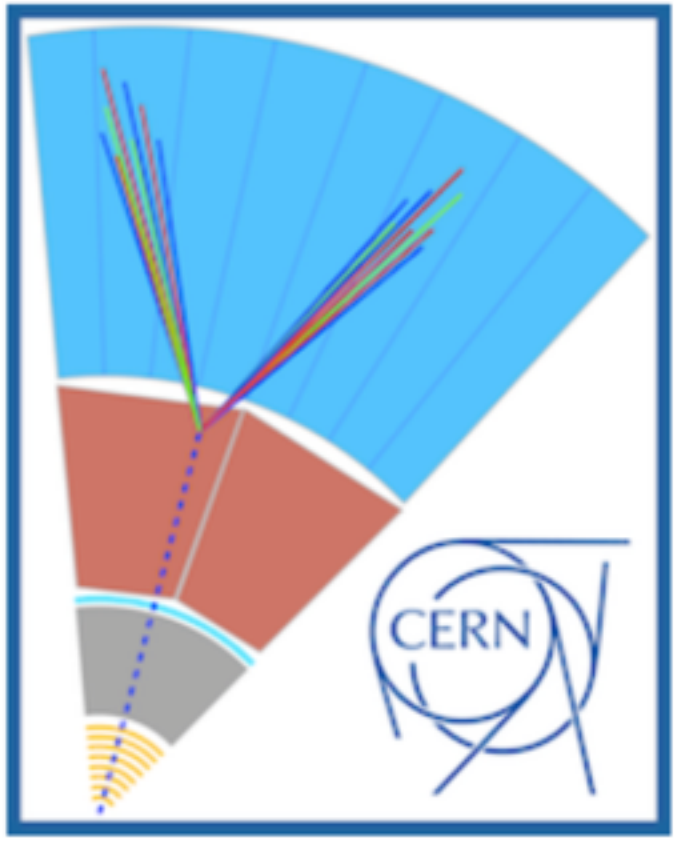
  - Standard object ID algorithms don't usually have good efficiency for LLP reconstruction



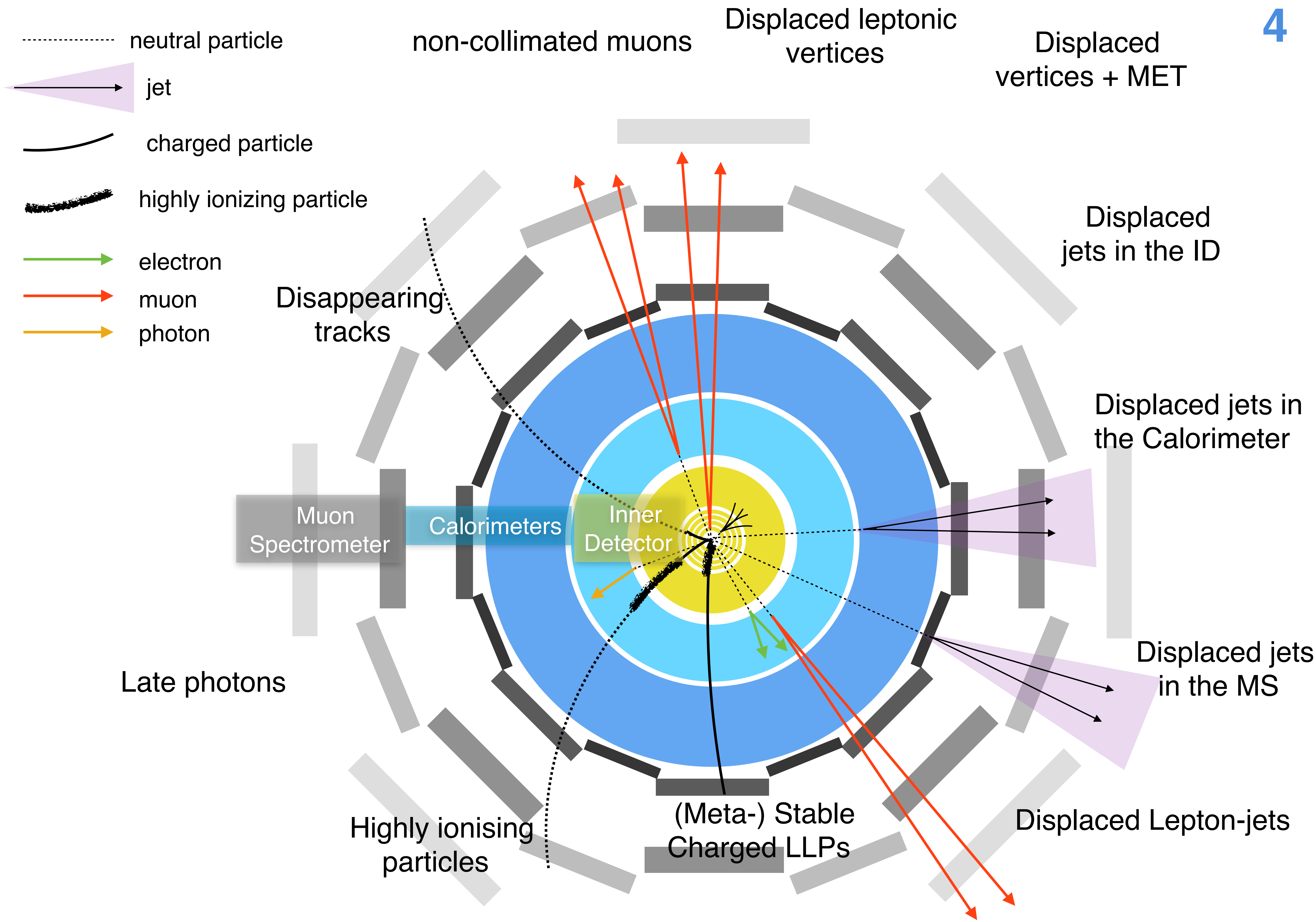
- Then, can we look for LLPs in ATLAS?

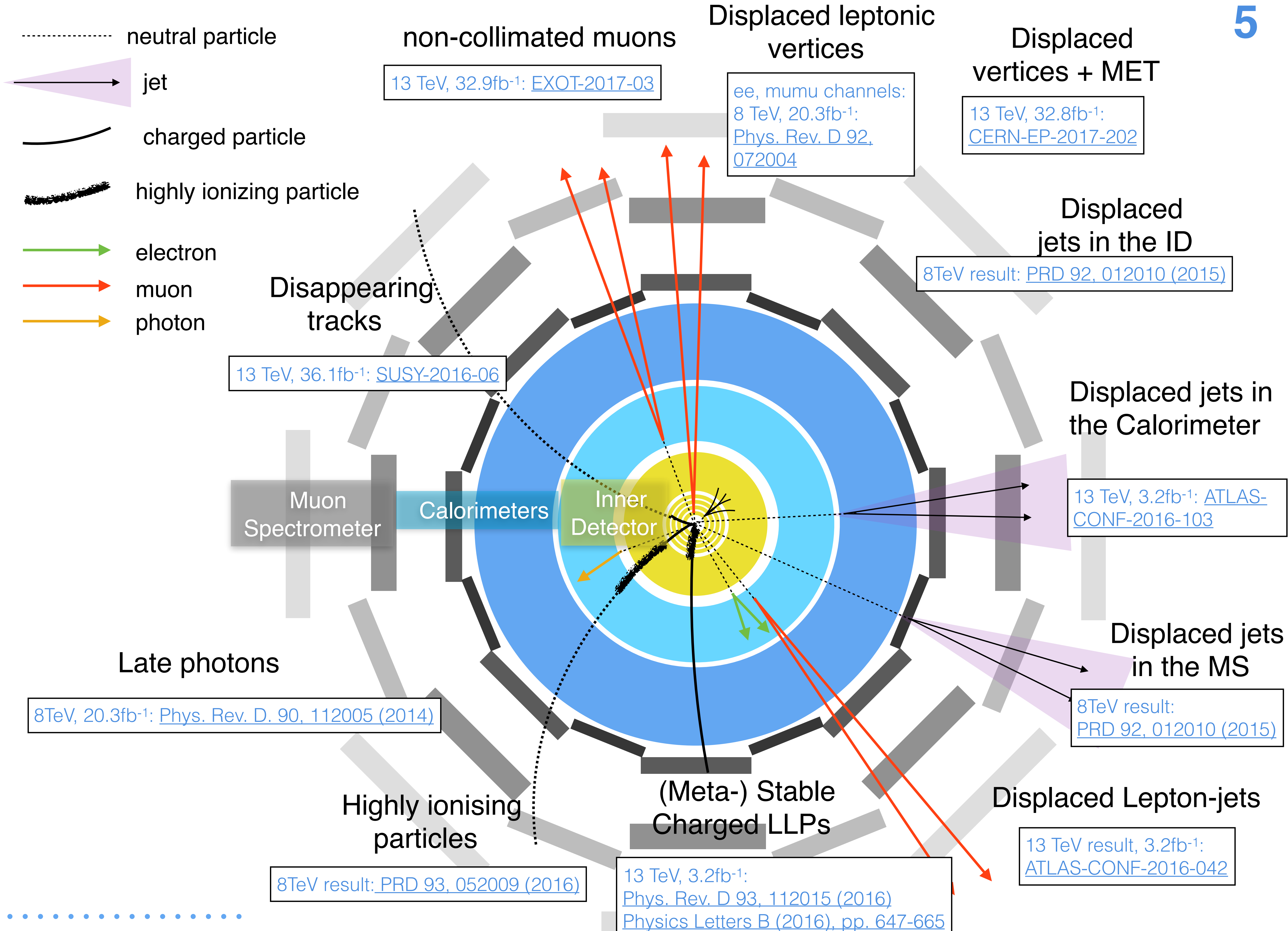
LLP searches in ATLAS

- Yes! ATLAS is well suited for these searches
  - large integrated luminosity
  - excellent tracking, vertexing, calorimetry, muon ID but standard tools need to be adjusted



- So, where should we look?
  - Many different signal models predict LLP
  - The strategy is to organize searches according to final states.
  - Searches as model independent as possible
  - Use several models for selection optimization, if necessary define several SRs
  - Give all possible information for recasting


neutral particle
jet
charged particle
highly ionizing particle
electron
muon
photon
non-collimated muons
Displaced leptonic vertices
Displaced vertices + MET
Displaced jets in the ID
Disappearing tracks
Displaced jets in the Calorimeter
Muon Spectrometer
Calorimeters
Inner Detector
Displaced jets in the MS
Late photons
Displaced Lepton-jets
Highly ionising particles
(Meta-) Stable Charged LLPs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13 TeV, 32.9fb-1: EXOT-2017-03
Displaced leptonic vertices
ee, mumu channels: 8 TeV, 20.3fb-1: Phys. Rev. D 92, 072004
Displaced vertices + MET
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Displaced jets in the ID
8TeV result: PRD 92, 012010 (2015)
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13 TeV, 36.1fb-1: SUSY-2016-06
Displaced jets in the Calorimeter
13 TeV, 3.2fb-1: ATLAS-CONF-2016-103
Muon Spectrometer
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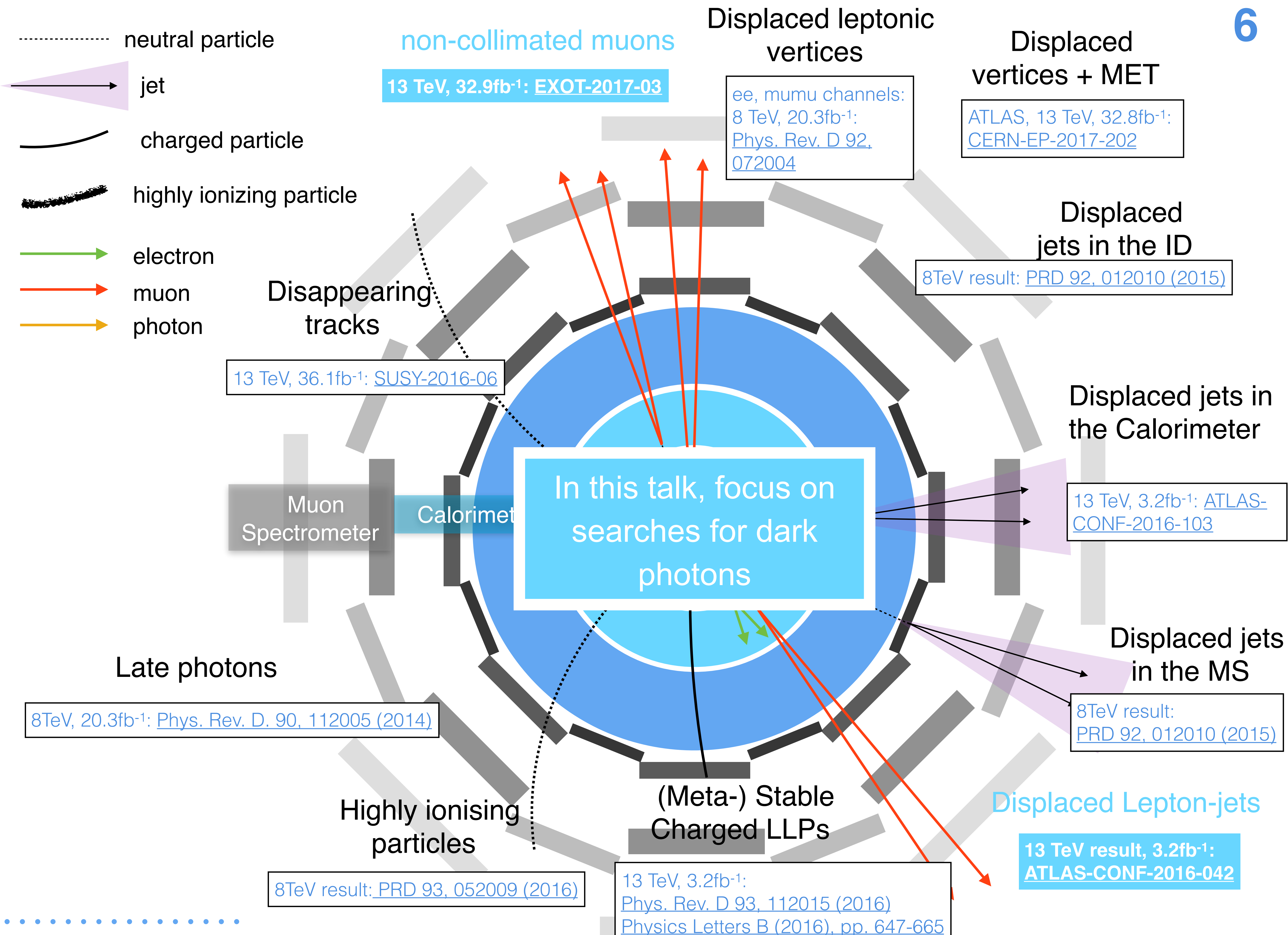
(Meta-) Stable Charged LLPs
13 TeV, 3.2fb-1: Phys. Rev. D 93, 112015 (2016) Physics Letters B (2016), pp. 647-665
Displaced Lepton-jets
13 TeV result, 3.2fb-1: ATLAS-CONF-2016-042



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Muon Spectrometer
Calorimet
In this talk, focus on searches for dark photons
Displaced jets in the MS
8TeV result: PRD 92, 012010 (2015)
Late photons
8TeV, 20.3fb-1: Phys. Rev. D. 90, 112005 (2014)
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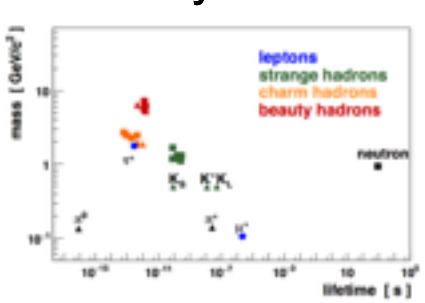
13 TeV result, 3.2fb-1: ATLAS-CONF-2016-042

Challenges in LLP searches

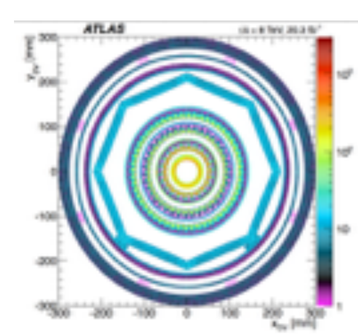
- Trigger: combination of hardware + software that must decide very quickly whether to save an event or lose it forever
  - First step in every search for LLPs: make sure that interesting events are saved!
    1. In associated production, trigger on prompt particle (Eg. WH prod. trigger on mu; ISR trigger on MET)
    2. Design and develop a new trigger. Need to keep trigger rates under control and within budget

- Object identification algorithms assume prompt particles. Need to adapt them
- Backgrounds: SM backgrounds usually small but instrumental background such as miss-identified leptons (“fakes”) and non-collision backgrounds (NCB) have to be taken into account

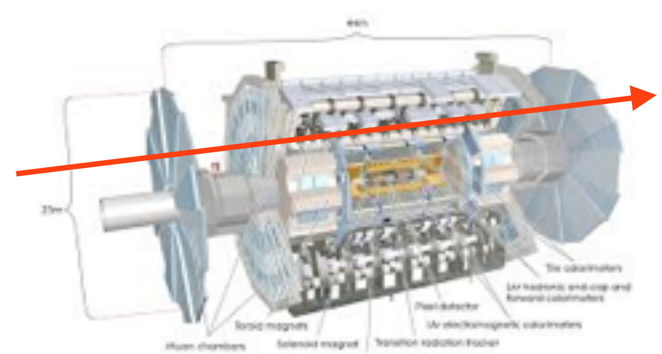
weak decays of heavy flavour



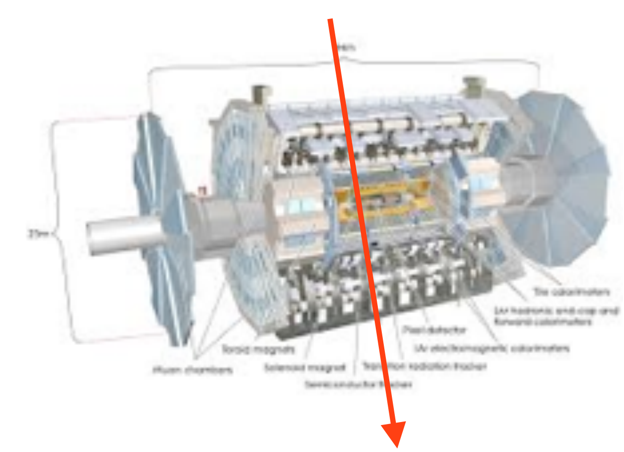
material interactions



beam halo muons

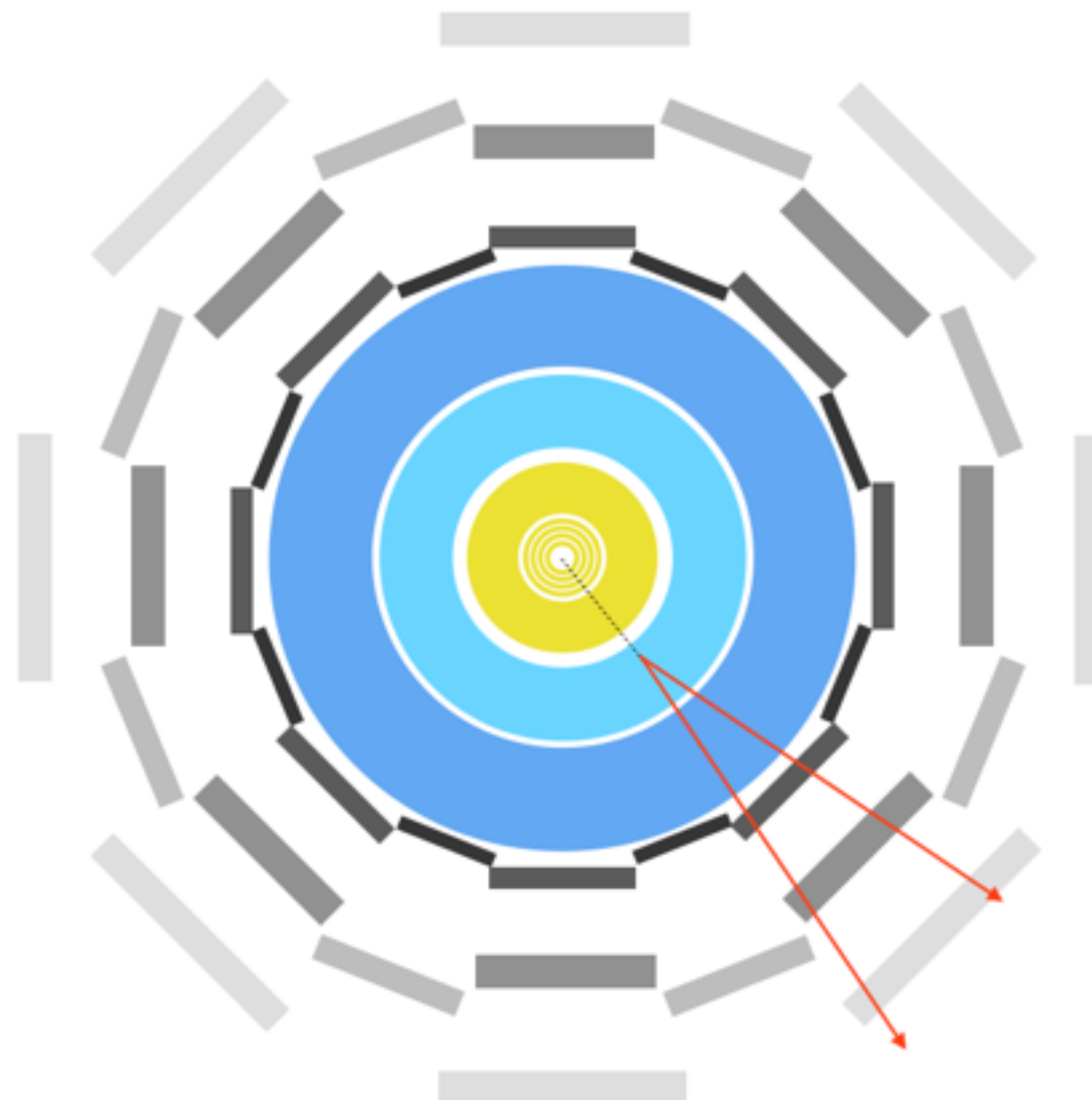


cosmic muons



- Systematic uncertainties: can’t use standard recommendations for object reconstruction nor trigger

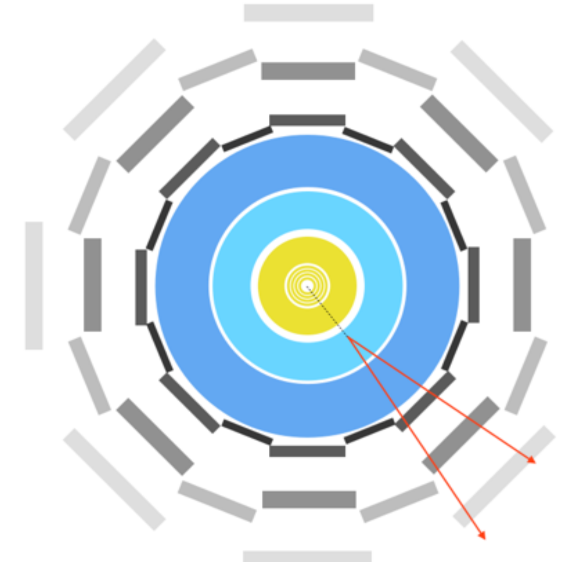
Non-collimated muons search



13 TeV, 32.9fb^{-1}: EXOT-2017-03

32.9 fb^{-1}
13 TeV (2015-2016 data)

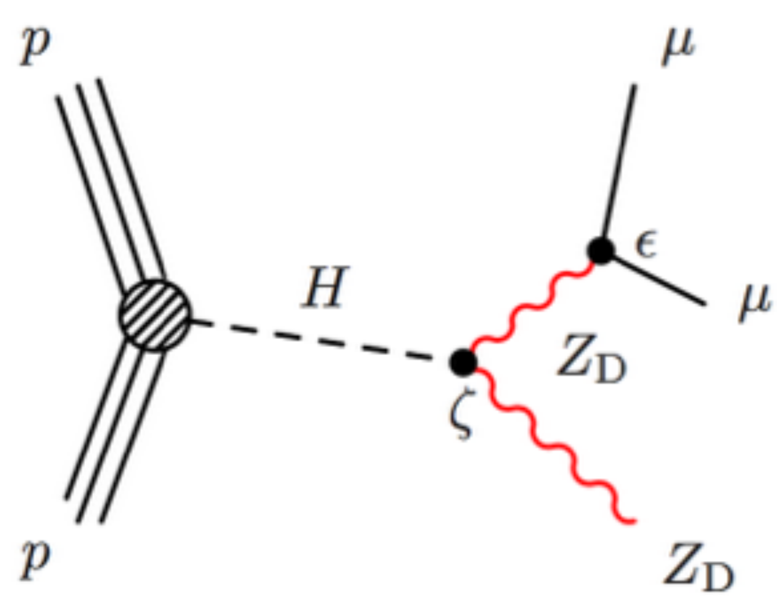
Non-collimated muons
Benchmark models



- Search for pairs of muons with opposite-sign electric charge, $\mu^+\mu^-$, not originating from the IP

- "Higgs portal" models:
  - $U(1)_D$ symmetry in the dark sector
  - the dark photon Z_D, is given mass via a singlet scalar field H_D, analogous to the Higgs field H in the visible SM sector

- (+ SUSY GGM model)



m_{Z_D} [GeV]	$c\tau_{Z_D}$ [cm]	$B(Z_D \to \mu^+\mu^-)$
20	50	0.1475
40	50	0.1370
40	500	0.1370
60	50	0.1066
60	500	0.1066

Non-collimated muons

Selection

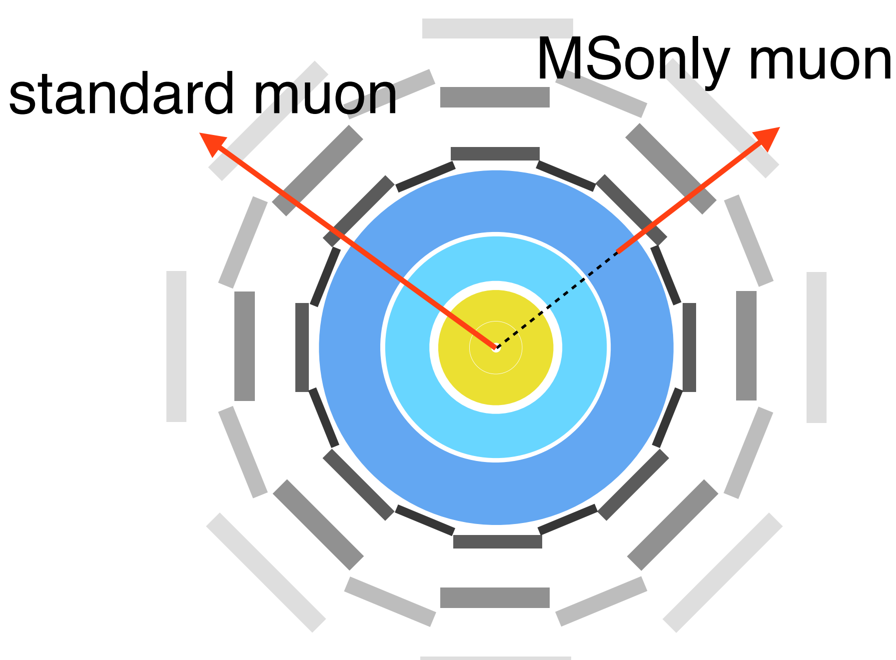
- Designed to
  - strongly suppress background
  - efficiently accepting signal events over a wide range of LLP masses, lifetimes and velocities.
  - minimal requirements are placed on other aspects of the event, to retain the greatest possible model independence

- Trigger on MSonly muons

Signal type	Trigger	Description	Thresholds
High mass	E_T^{miss} single muon	missing transverse momentum single muon restricted to the barrel region	$E_T^{miss} > 110$ GeV muon $\lvert\eta\rvert < 1.05$ and $p_T > 60$ GeV
Low mass	collimated dimuon trimuon	two muons with small angular separation three muons	p_T of muons > 15 and 20 GeV and $\Delta R_{\mu\mu} < 0.5$ $p_T > 6$ GeV for all three muons

- All three of the muon triggers use only measurements in the MS to identify muons.

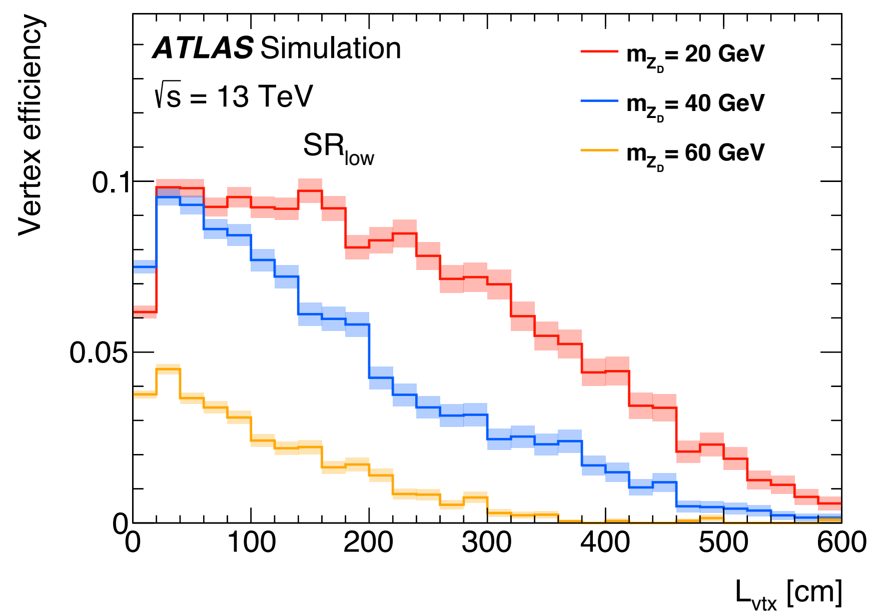
- Muon reconstruction:
  - "standard" muons: matching between a track in the Muons System (MS) and a track in the Inner Detector (ID)
  - muon from LLP: track in the MS with no matching in the ID
- This analysis searches for pairs of MSonly muons



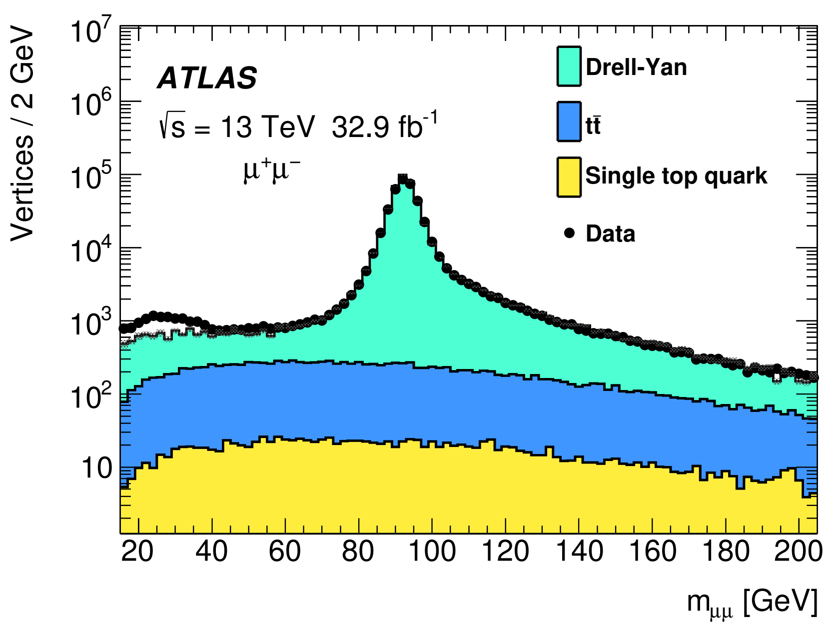
Non-collimated muons

Backgrounds

- Vertexing:
  - for every pair of MSonly muons, extrapolate tracks to IP and find point of closest approach
  - efficiency decreases with decay position



- Two kinds of backgrounds:
  - non-prompt background: cosmic muons + beam-induced background + pions/kaons
    - leave signal in the MS only -> can be reconstructed as MS only muons
    - pair of muons doesn't have charge correlation —> estimated using a CR with SS muons
  - prompt backgrounds: from SM processes (DY, Z+jets) where
    - jets are misidentified as muons
    - jets punch-through
    - reduced by requiring muon isolation from jets and ID tracks
    - $m_{\mu\mu}$ >15 GeV to avoid low-mass resonances
    - estimated with data-driven method

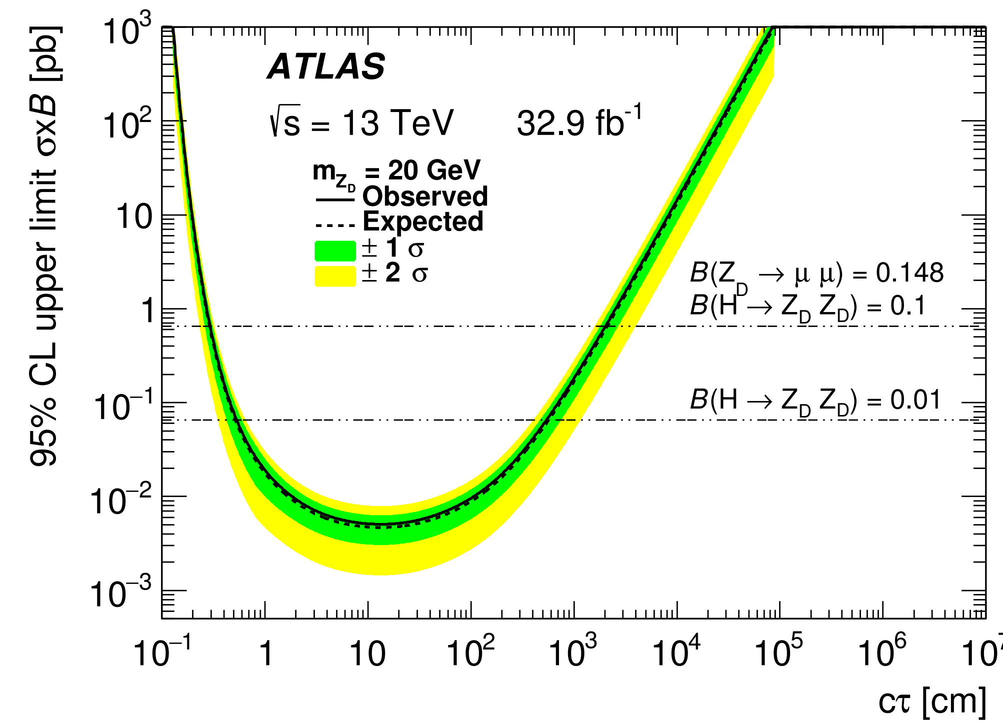


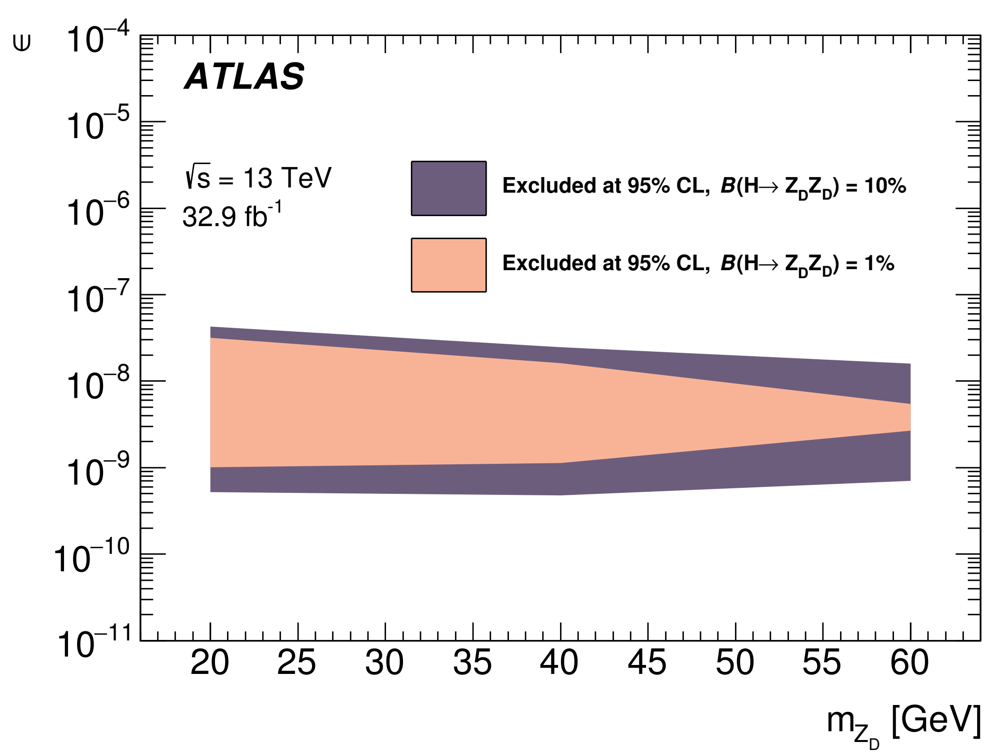
Non-collimated muons

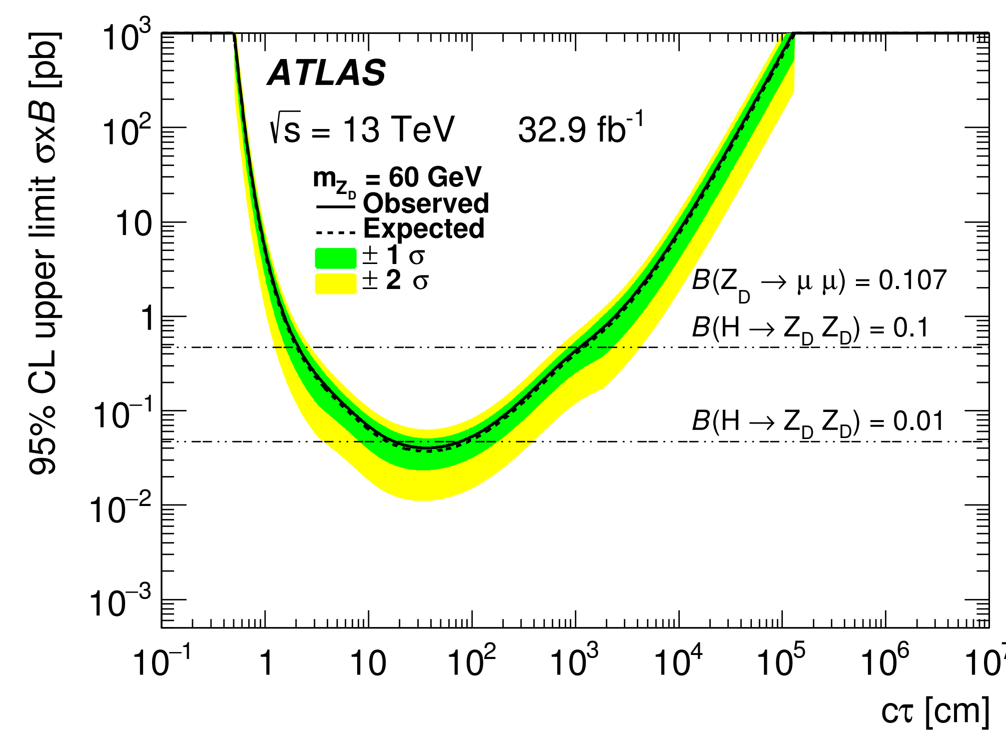
Results

- Background estimation in agreement with observation

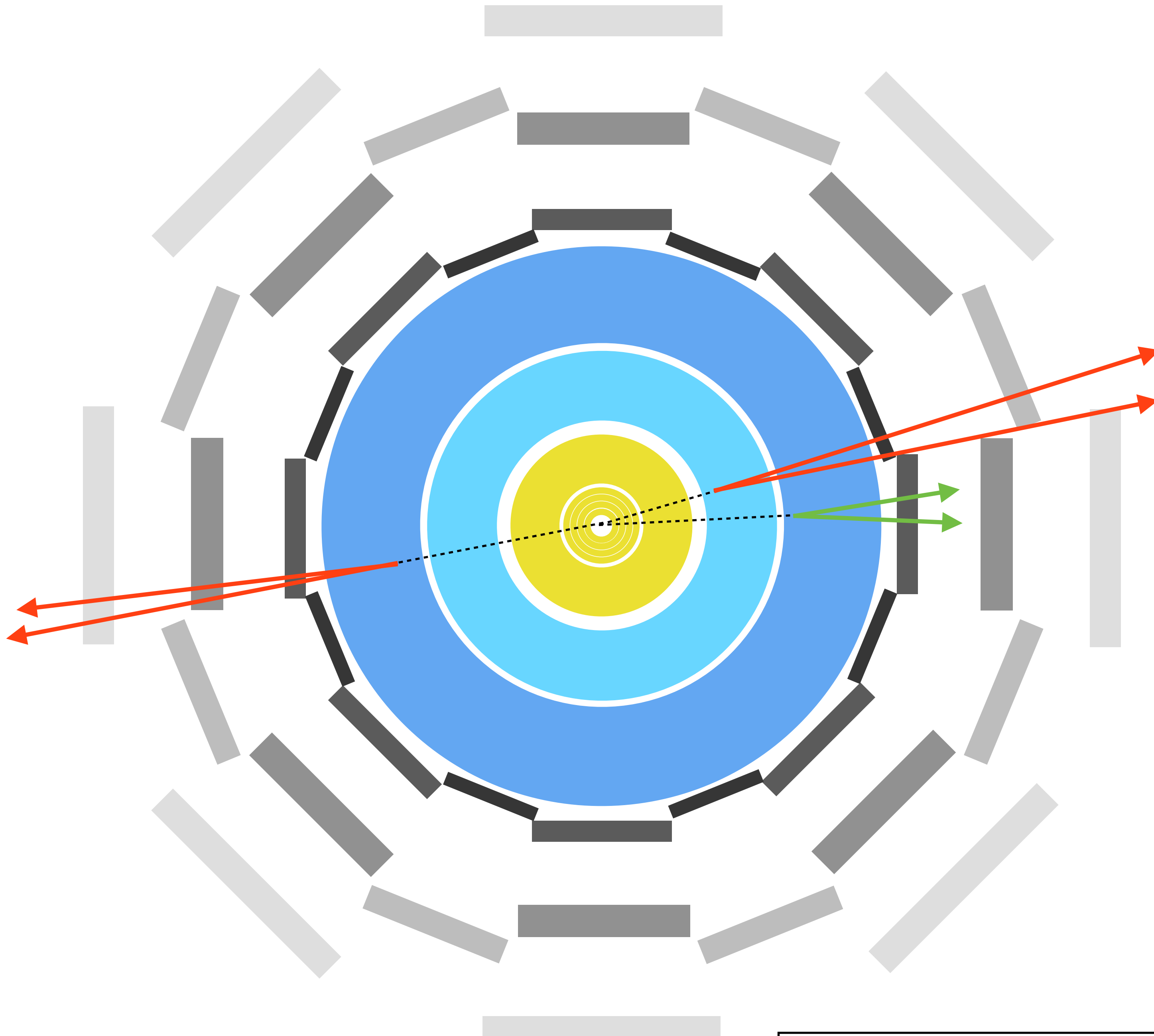
Yield	$\mathrm{SR}_{\mathrm{low}}$	$\mathrm{SR}_{\mathrm{high}}$
$N^{\text{non-prompt}}$	13.6 ± 4.9	$0.0\ ^{+1.4}_{-0.0}$
N^{prompt}	0.1 ± 0.2	0.50 ± 0.07
N^{bkgd}	13.8 ± 4.9	$0.50\ ^{+1.42}_{-0.07}$
N^{obs}	15	2







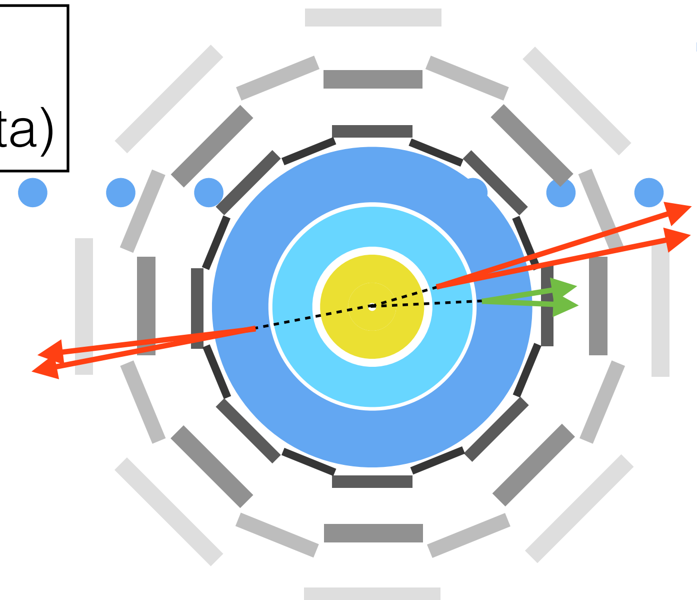
Displaced Lepton-jets search



13 TeV result, 3.2fb^{-1}:
ATLAS-CONF-2016-042

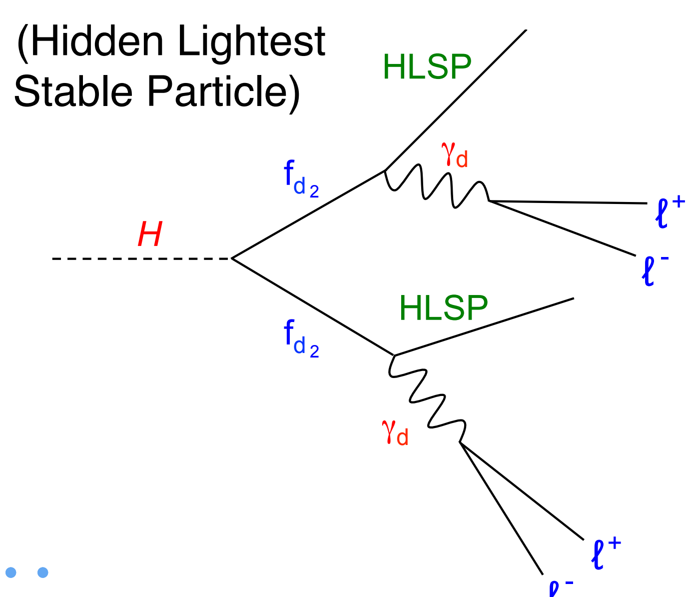
Lepton-jets
Benchmark models

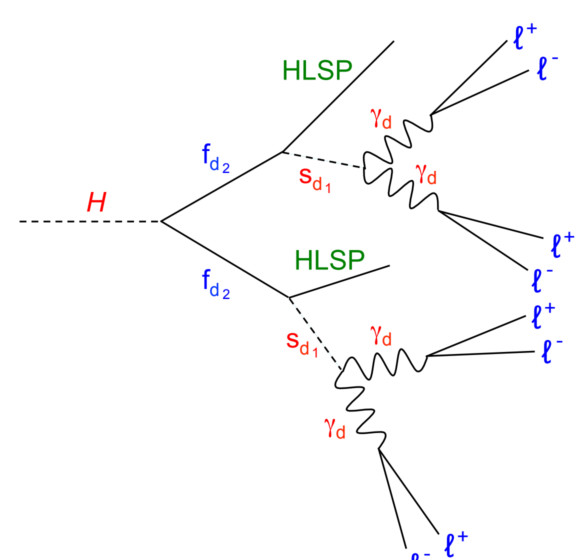
3.4 fb^{-1}
13 TeV (2015 data)



- Search for pairs of collimated muons or low EMF jets

- Falkowsky-Ruderman-Volansky-Zupan (FRVZ) models:
  - Higgs boson decays to a pair of hidden fermions f_{d_2} which produce two (four) γ_d
  - A low-mass dark photon mixing kinetically with the SM photon will decay mainly to leptons and possibly light mesons
  - The γ_d decay lifetime, controlled by the kinetic mixing parameter, ε, is a free parameter.
  - At the LHC, these dark photons would typically be produced with large boost, due to their small mass,
    —> collimated jet-like structures containing pairs of leptons and/or light hadrons (lepton-jets, LJs)

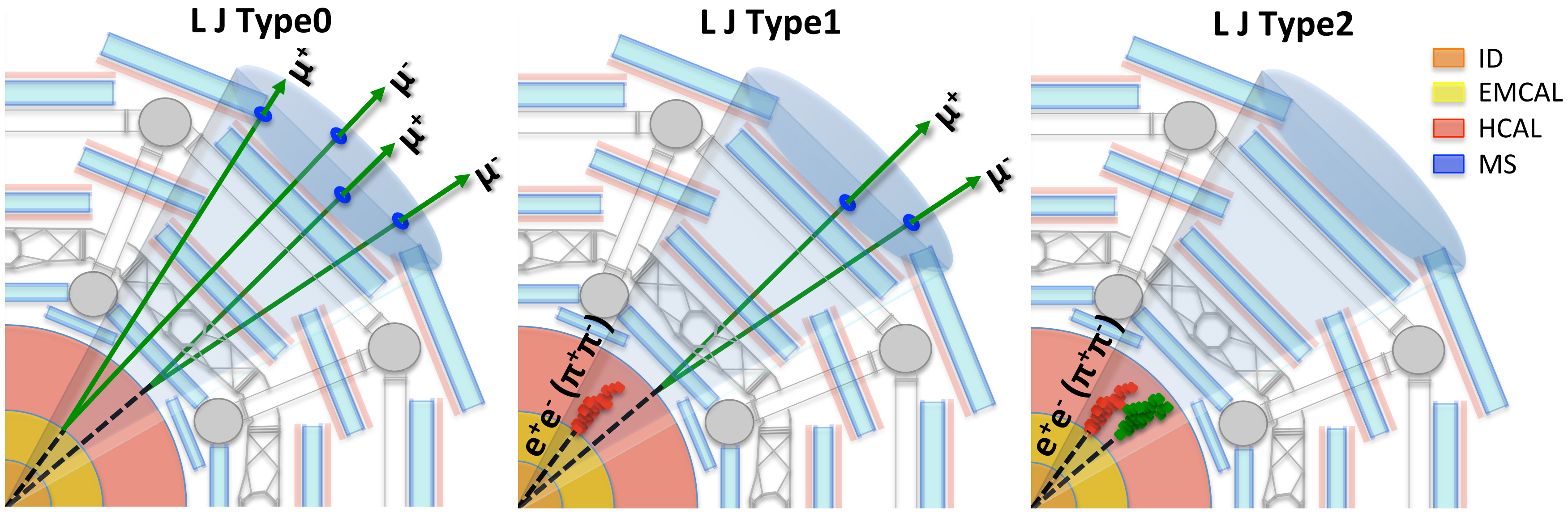




Benchmark model	m_H [GeV]	$m_{f_{d_2}}$ [GeV]	m_{HLSP} [GeV]	$m_{s_{d_1}}$ [GeV]	m_{γ_d} [GeV]	$c\tau_{\gamma_d}$ [mm]
2 γ_d	125	5.0	2.0	-	0.4	47.0
4 γ_d	125	5.0	2.0	2.0	0.4	82.40
2 γ_d	800	5.0	2.0	-	0.4	11.76
4 γ_d	800	5.0	2.0	2.0	0.4	21.04

Lepton-jets: Selection

- The analysis divides the various LJs into categories based on the species of the constituent particles.



at least two muons and no jets

at least two muons and only one jet in the cone

no muons

- Triggering for the low-masses is difficult
- Trigger efficiency (%):

Trigger	Higgs → $2\gamma_d + X$ m_H = 125 GeV	Higgs → $2\gamma_d + X$ m_H = 800 GeV	Higgs → $4\gamma_d + X$ m_H = 125 GeV	Higgs → $4\gamma_d + X$ m_H = 800 GeV
Tri-muon MS-only	2.0	2.4	4.9	7.8
Narrow-Scan	10.6	23.0	8.3	38.4
CalRatio	0.3	9.7	0.1	7.4
OR of all	11.9	32.0	11.8	44.8

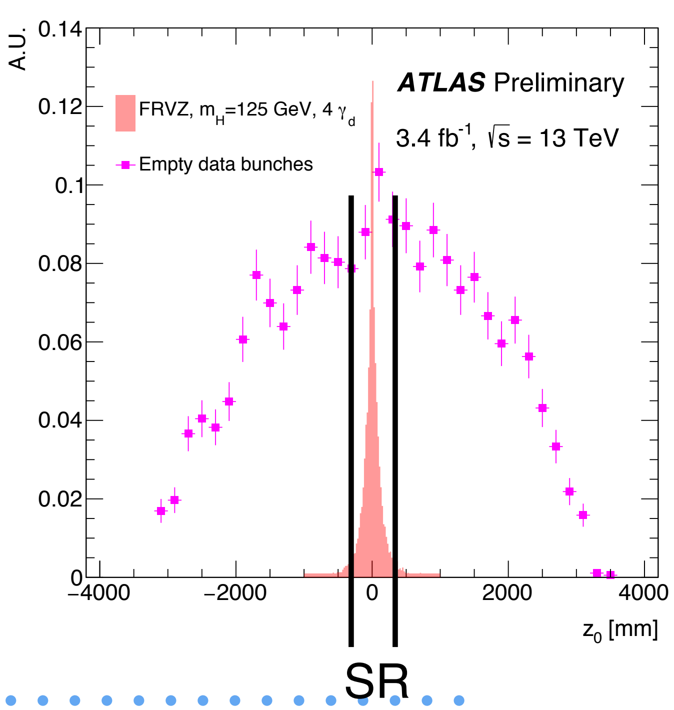
same as in the non-collimated muons search

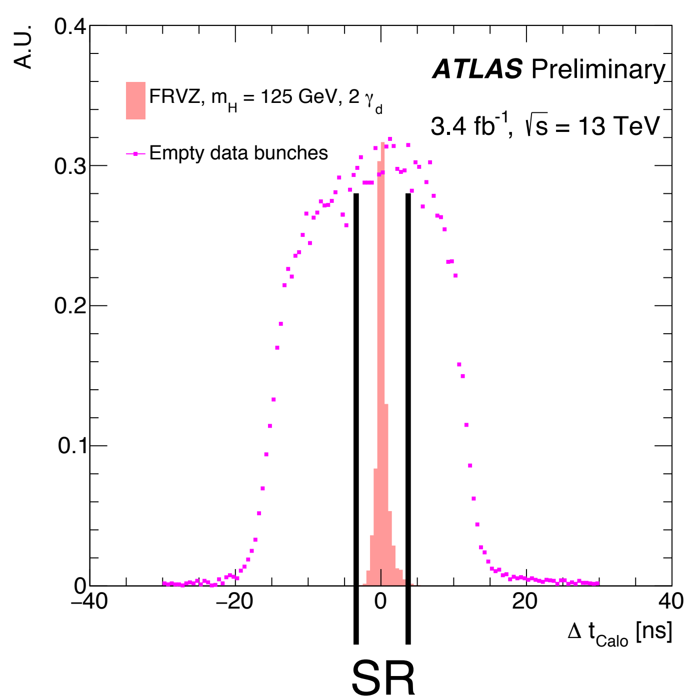
trackless low-EMF jets

- Muon reconstruction:
  - MSonly muons
  - clustering algorithm that combines all the muons lying within a cone
- Jet reconstruction
  - LJs produced by a single dark photon decaying into an electron/pion pair
  - expected to be reconstructed as a single jet due to their large boost.

Lepton-jets: Backgrounds

- Type 2 Lepton-jets (hadronic)
  - SM multijets
    - reduced with selection:
      - EM fraction < 0.1
      - jet width < 0.058
      - jet vertex fraction < 0.56
    - Final estimation with data-driven methods
  - Beam-induced-background
    - reduced with BIB-tagging using low EMF jets and MS end-cap information
- Type 0 Lepton-jets (muonic)
  - Cosmic-ray muons:
    - studied in events collected in empty bunch-crossings
    - rejected with cuts in z0 and t



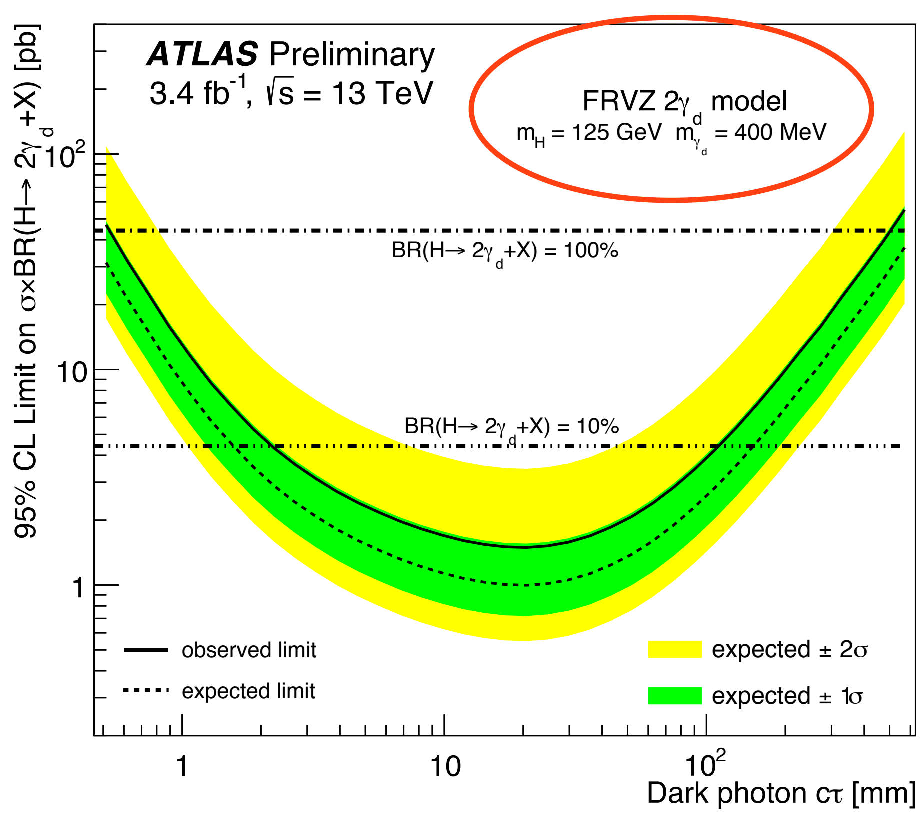


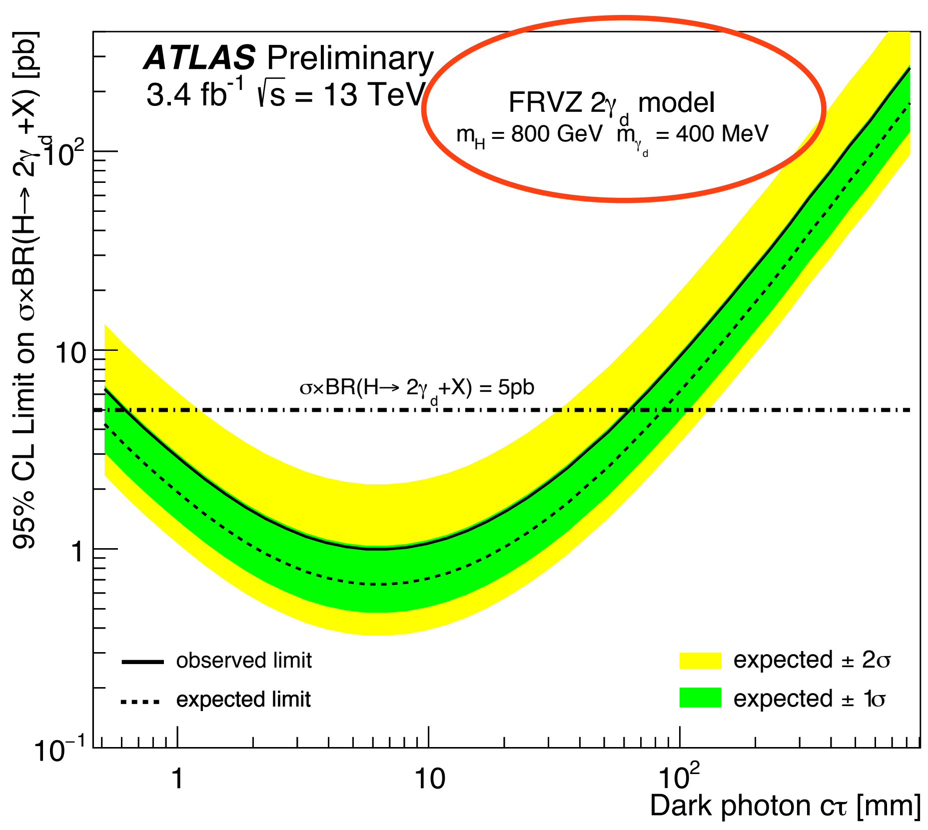
- Other SM processes (*W*+jets, *Z*+jets, $t\bar{t}$, single-top, *WW*, WZ, and *ZZ)*
- can lead to real prompt muons and muons plus jets) that could fake displaced muons
  - studied in MC
  - negligible after requiring MSonly muons

Lepton-jets: Results

- Background estimation in agreement with observation

Category	Observed events	Expected background
All events	285	231 ± 12 (stat) ± 62 (syst)
Type2–Type2 excluded	46	31.8 ± 3.8 (stat) ± 8.6 (syst)
Type2–Type2 only	239	241 ± 41(stat) ± 65(syst)





Lepton-jets: Plans

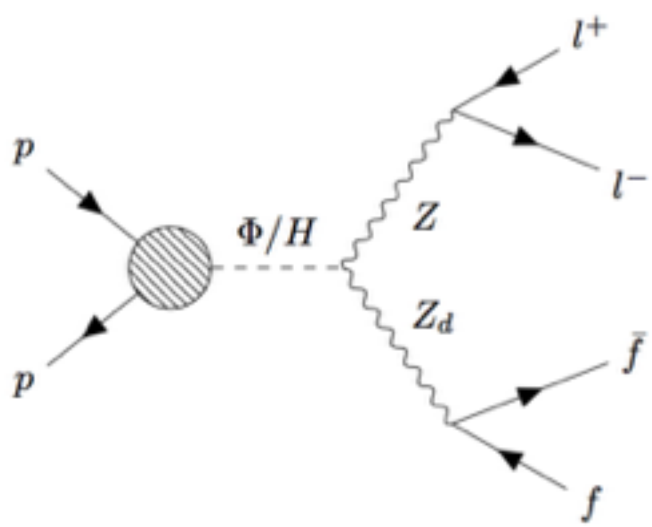
- This talk shows the 2015 dataset results
- dLJ analysis ongoing with 2015+2016 dataset
  - Several improvements:
    - updated triggers for the muon channel (Trigger is still one of the main difficulties, especially for low pt)
    - ML techniques to identify dLJ
  - plans to include other production modes
  - search for mono-LJ + X

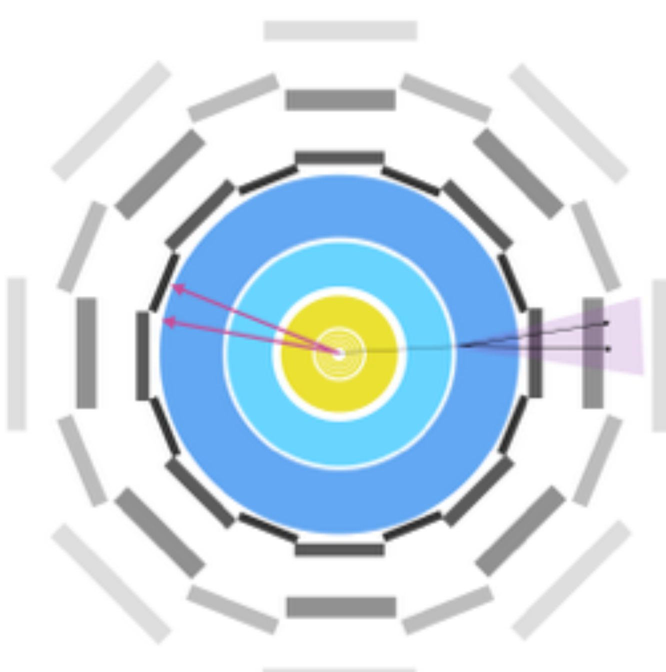
- search for same models in the prompt LJ version ongoing

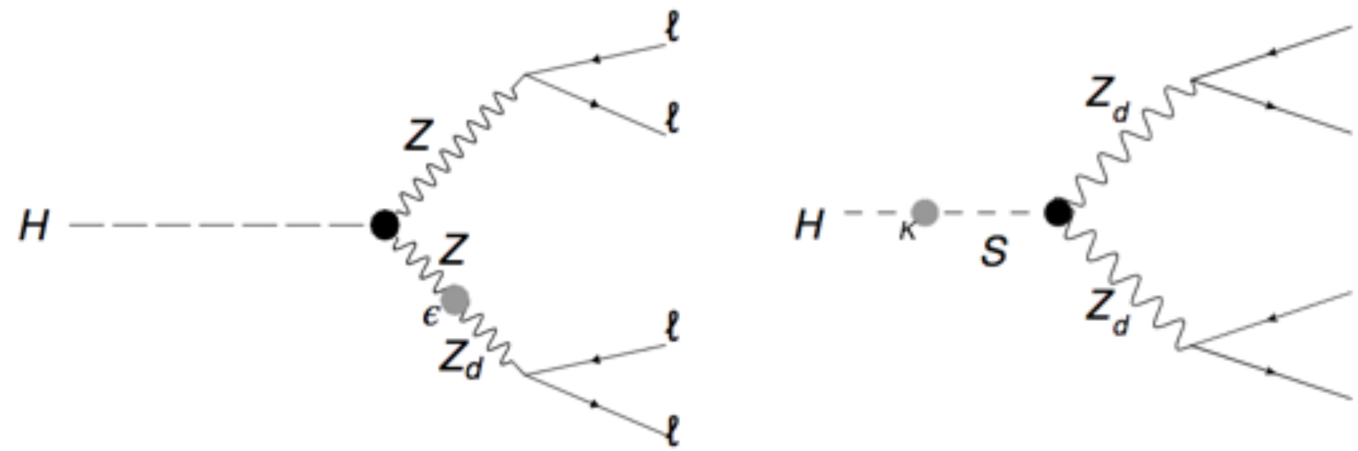
Other searches for dark photons

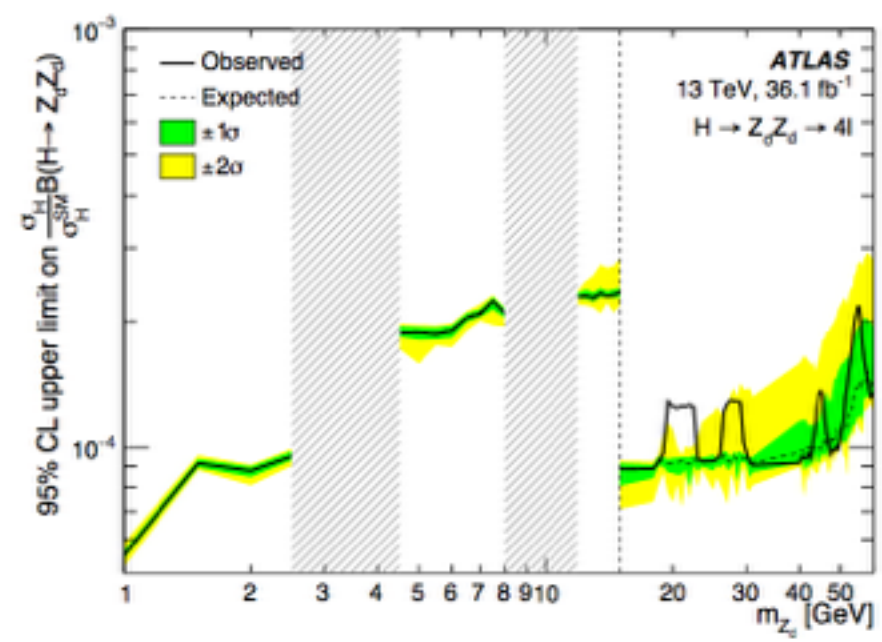
- Search for Z+Long-lived dark photon decaying in the calorimeter
  - ongoing for 2015+2016 dataset
  - first time done in ATLAS
  - will be published soon

- prompt ZdZd -> 4 leptons
  - considers models similar to the non-collimated muons search
  - see talk by Diallo





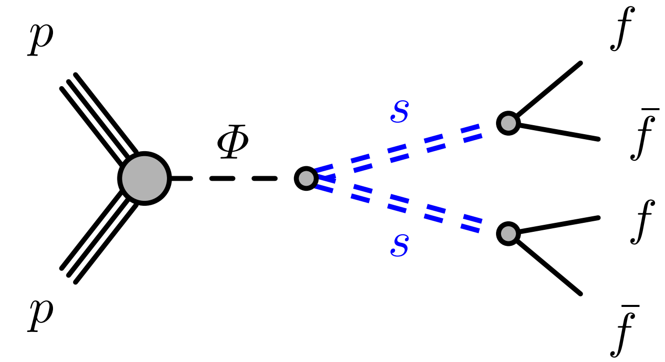




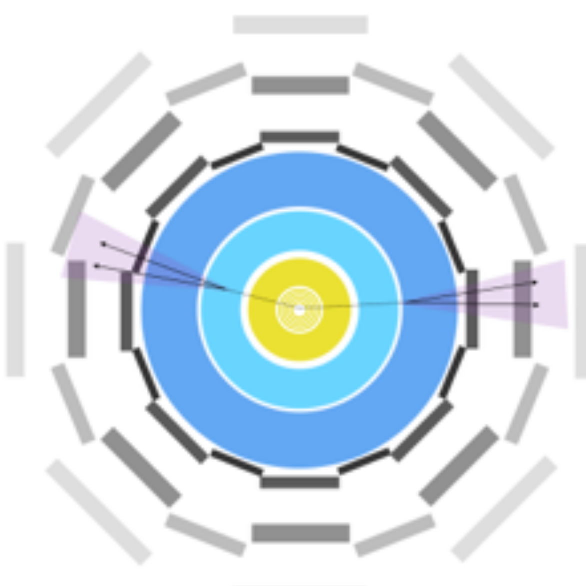
(a) $H \to Z_d Z_d$

Other searches for dark sectors

- Heavy boson in the dark sector decaying to pair of (long-lived) scalars, eventually decaying to SM fermions
  - Several versions of the search depending on where the LLP decays in ATLAS
  - Decays in the MS: 2 MS vtx, 1 MS vtx + MET, 1 MS vtx + 2jets

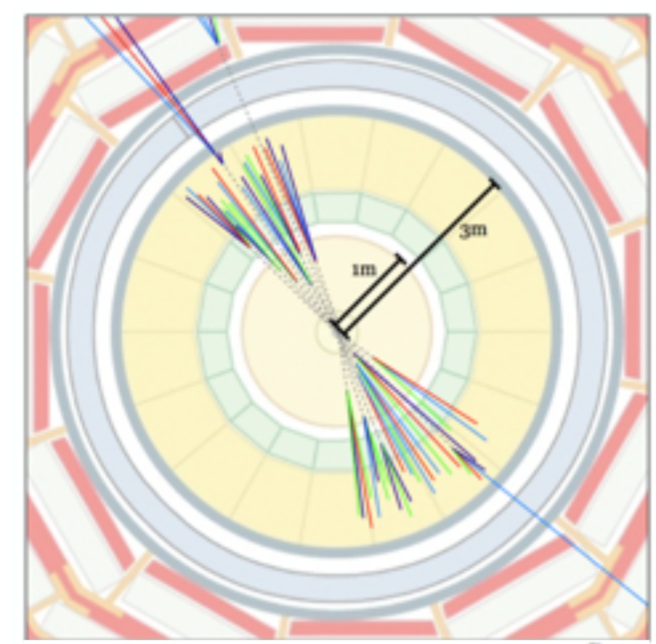


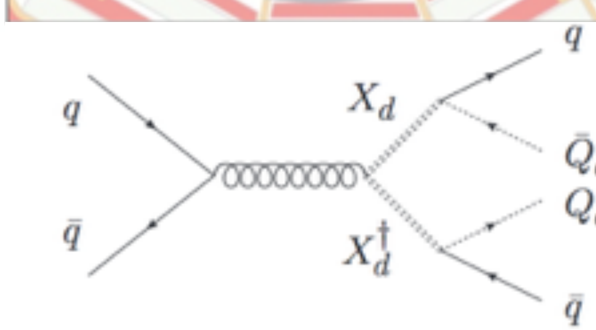
- Decays in the calorimeter: 2 low EMF jets



- Combined decays: 1MS vtx, 1ID vtx

- Emerging jets (dark QCD) : 2 QCD jets + n ID vtx

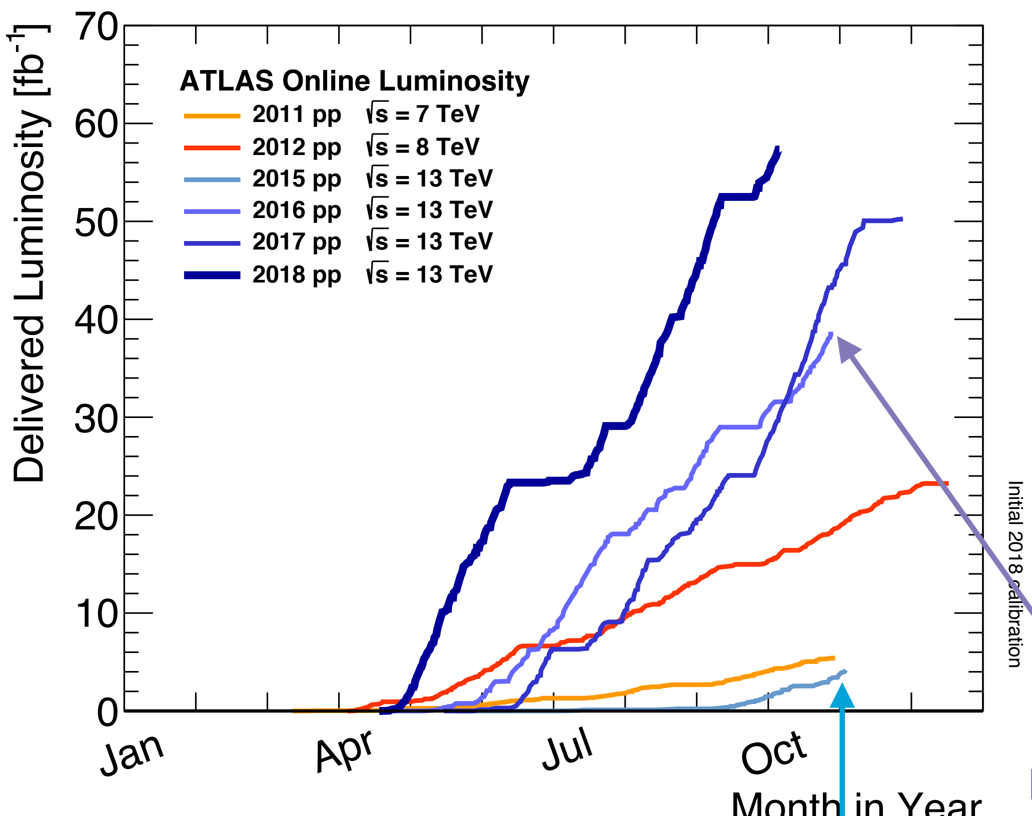




Conclusion

- Lacking any evidence for New Physics in any of the searches finalized so far, unconventional signatures are gaining in popularity

- ATLAS has a complete program to search for long-lived particles in many different signatures
  - Wide variety of searches
  - Very challenging, pushing the detector for searches it was not designed to perform
  - Many analysis working on improvements with the full 13 TeV dataset



non-collimated muons results shown here

displaced lepton jets results shown here

- No discovery so far but…

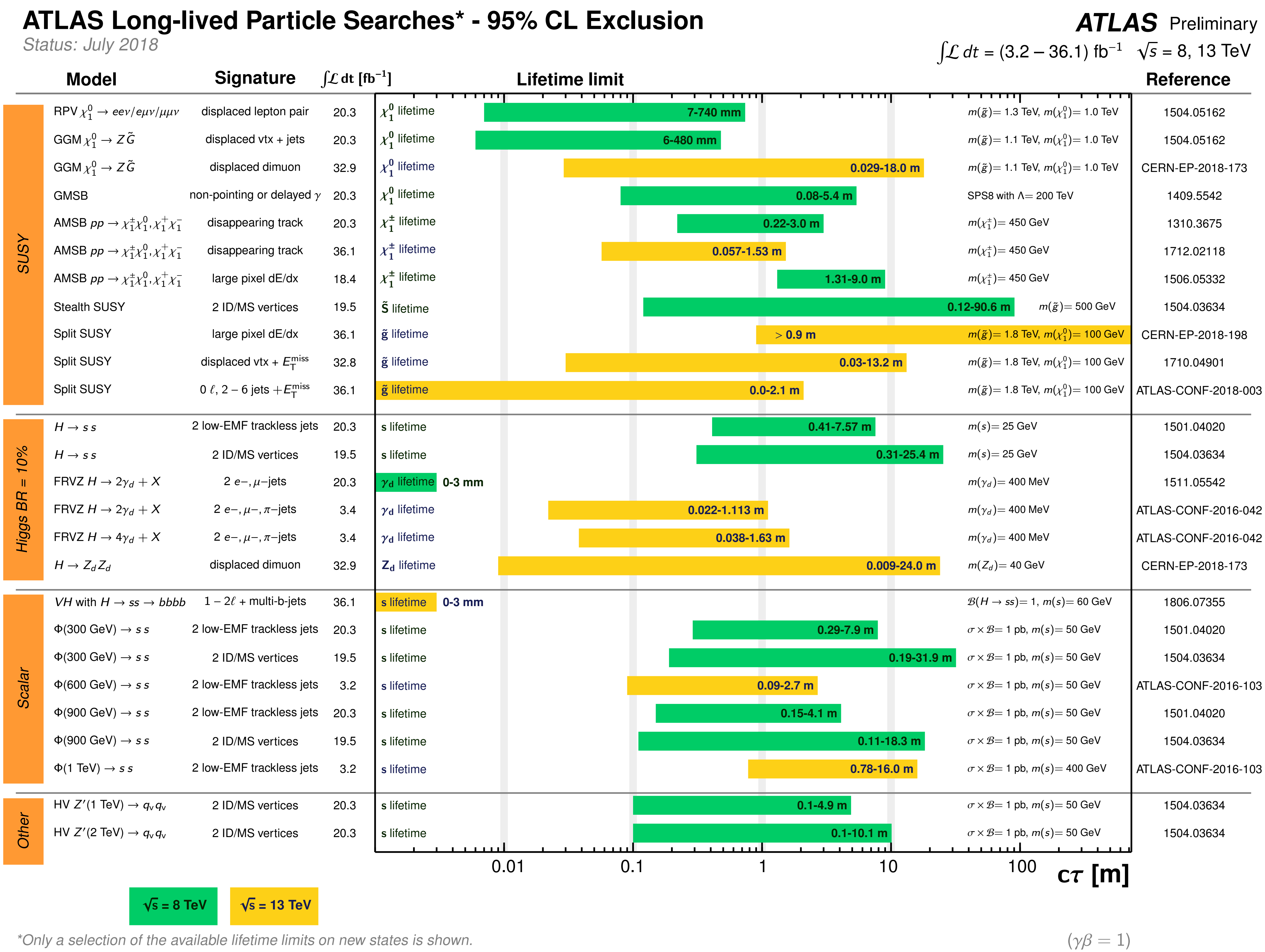
- 2017+2018 datasets to be studied yet!

- Most analyses developing new techniques for better identification

- Looking forward to seeing first significant deviations from the SM predictions!!

Backup

Summary plots



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/ATLAS_Exotics_LLP_Summary/ATLAS_Exotics_LLP_Summary.pdf

ATLAS public results

- All ATLAS public results:
- ATLAS: https:/twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome

- EXOTICS specific results:
- ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

- SUSY specific results:
- ATLAS: https:/twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults