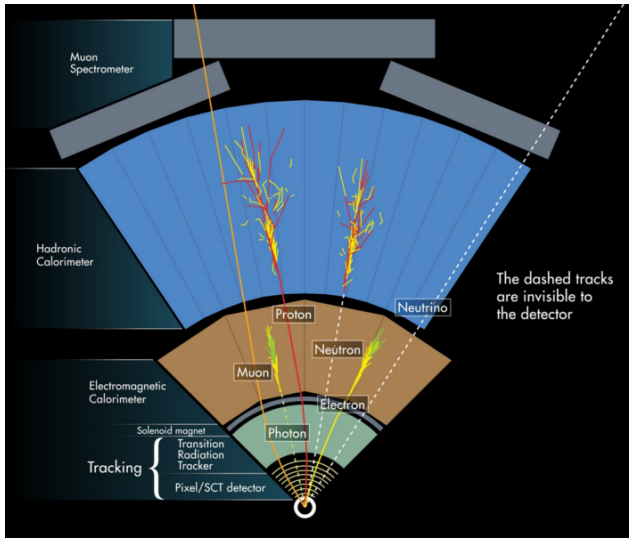
Search for New Physics through the Reconstruction of Challenging Signatures with the ATLAS detector

Shohei Shirabe (Kyushu University)

on behalf of the ATLAS collaboration

We still haven't found BSM yet...

- LHC-Run2 data provide us a great potential to find BSM.
- Most of particles searched by ATLAS are assumed to be:
  - generated and decaying at the interaction point
  - going through the detectors with speed of light (β = 1)



Many BSM models predict particles with long lifetime and we could miss such long-lived particles by the conventional searches.

How to be long-lived particles?

- Taking an example from $\pi^{\pm}$ decay ($c\tau \sim 7.8$ m)

Small coupling constant

Helicity suppression

$$\frac{\hbar}{\tau} = \frac{f_\pi^2}{256\pi m_\pi}\left[\frac{g^2}{M_W^2}\frac{m_\mu}{m_\pi}(m_\pi^2 - m_\mu^2)\right]^2$$

Heavy intermediate particle

Small mass difference

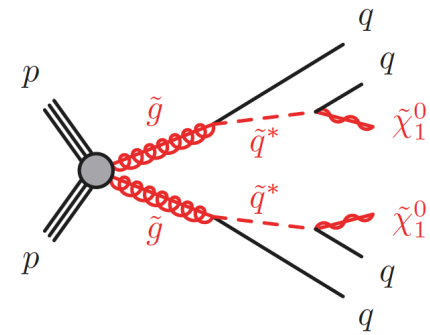
Effects shown above appear in various physics.

Physics behind long-lived particles

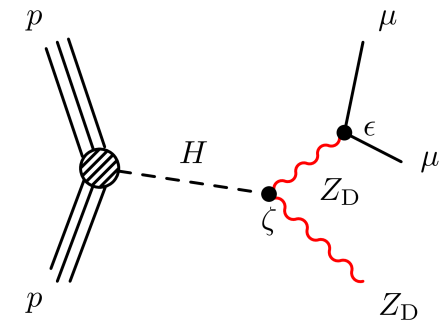
- SUSY
  - Long-lived gluino : Heavy squark, Gluino-Bino co-annihilation
  - Long-lived $\chi^{\pm}$: Wino/Higgsino LSP
  - Long-lived χ^{0} : Gravitino LSP, R-parity violation Wino-Bino co-annihilation
- Hidden/dark sector scenario
  - Long-lived dark photon : Higgs portal
- Others
  - Long-lived right-handed neutrino : vMSM
  - Long-lived multi-charged particle : Monopole, Micro black hole, Q-ball

And many more!!

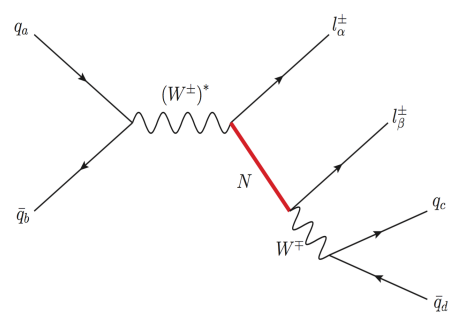
Long-lived gluino



Long-lived dark photon

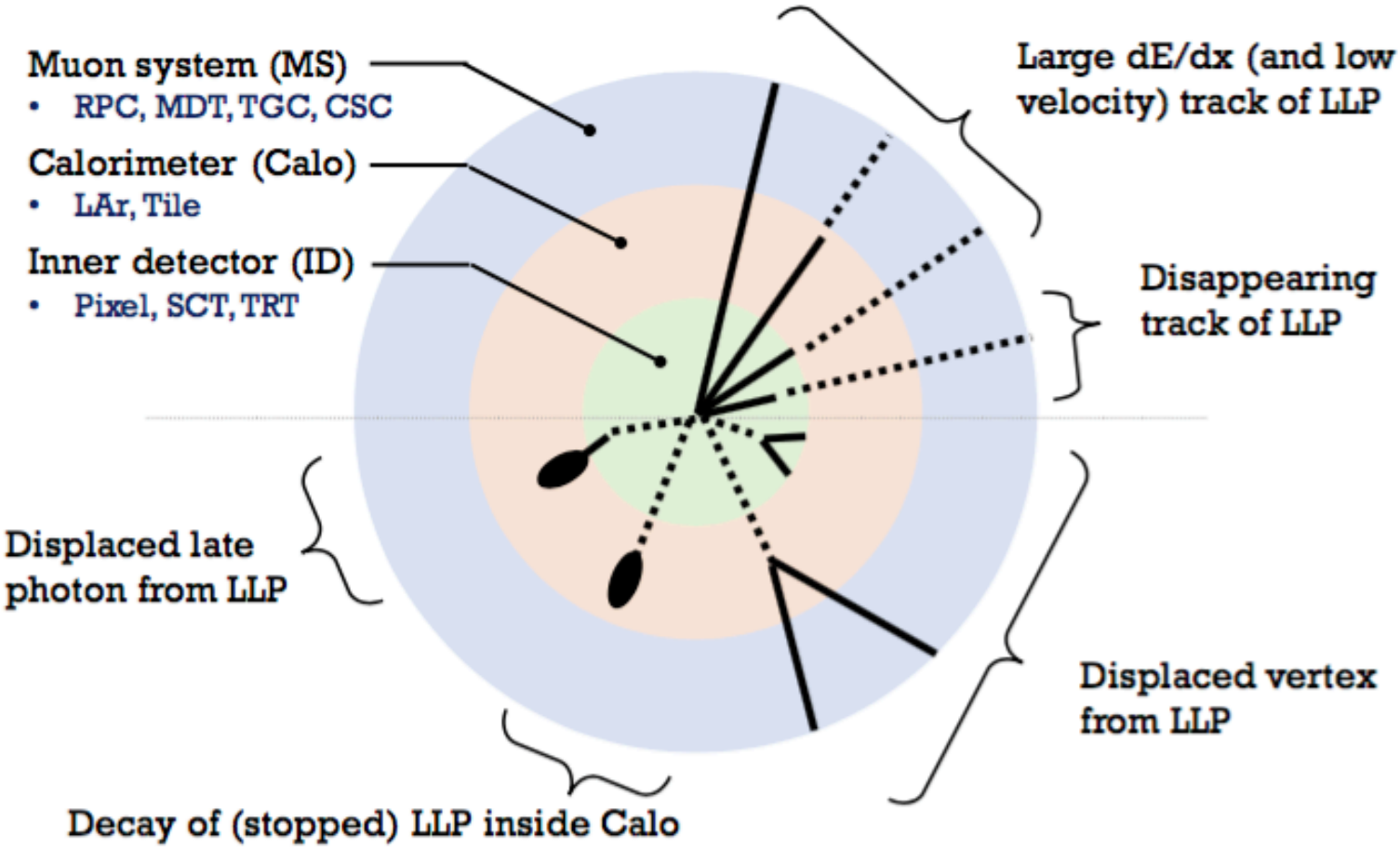


vMSM



Signatures of long-lived particles

Various types of signatures require dedicated non-standard reconstruction methods!!



Signatures of long-lived particles

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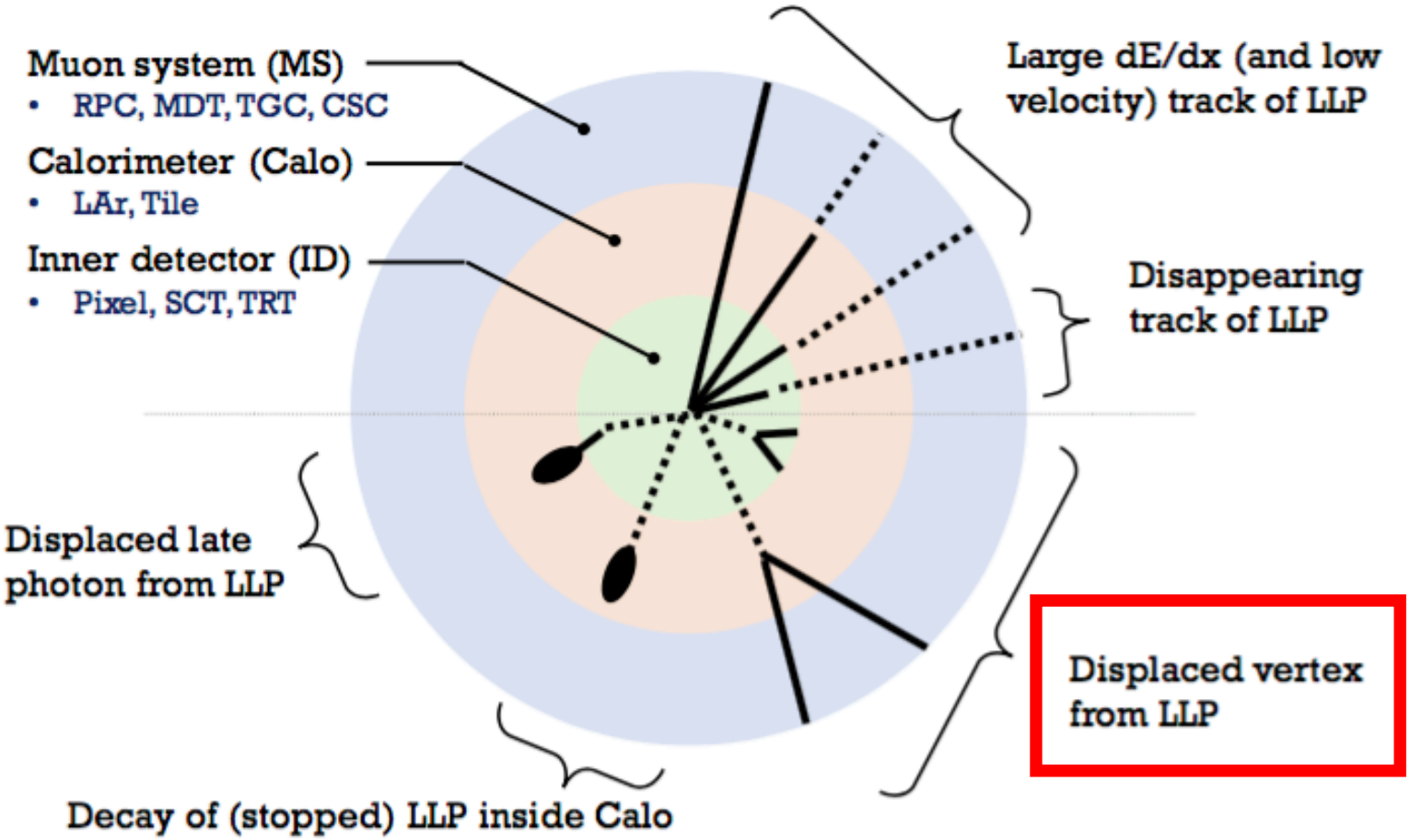
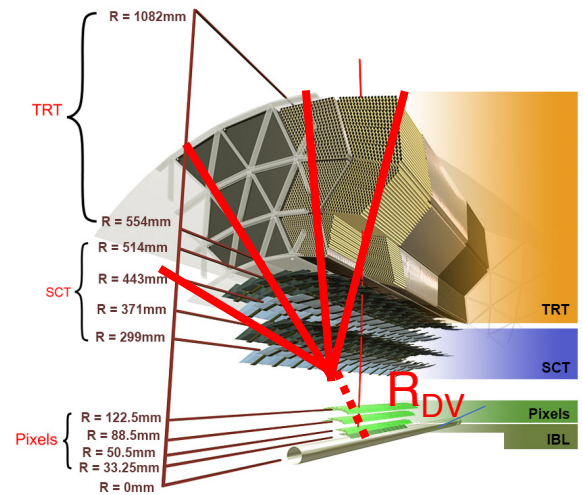
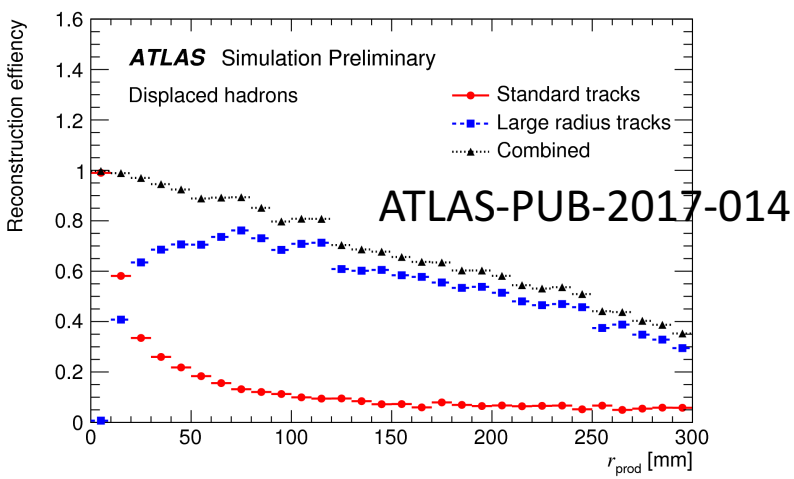


Decays within the inner detector

- The particle decaying within the ID can be reconstructed as a Displaced Vertex (DV)
  - Such tracks are not reconstructed by standard tracking.
    - Standard tracking aims to tracks from IP.
  - Reconstruction of displaced vertex has been developed.
    - There is special re-tracking for tracks which have large impact parameter.

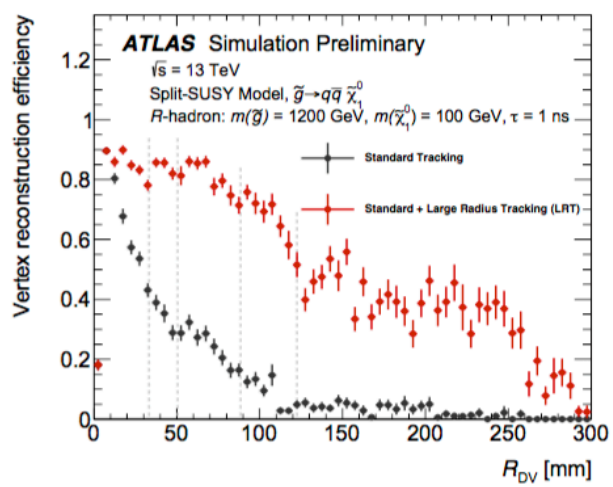


Track Reconstruction Efficiency



ATLAS-PUB-2017-014

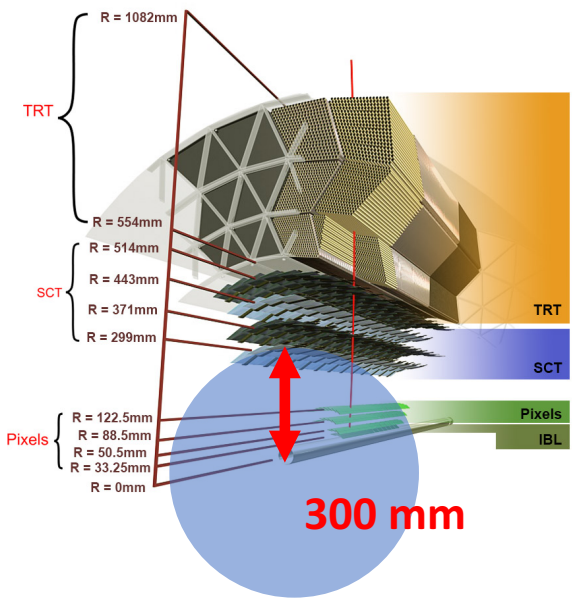
Vertex Reconstruction Efficiency



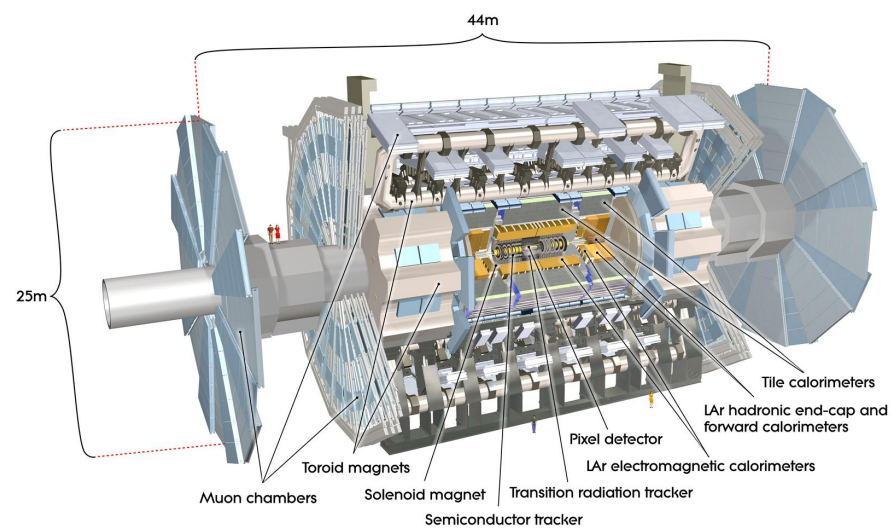
Decays after the inner detector

- The particle decaying after the ID also can be reconstructed by other subdetectors.
  - Muon Subsystems (MS) can detect such a tracks.
  - Look for MS tracks which have no ID matched tracks

ATLAS Inner Detector



ATLAS Detector



Displaced vertex search using ID has no efficiency outside the first SCT layer.

Using MS allows us more acceptance.

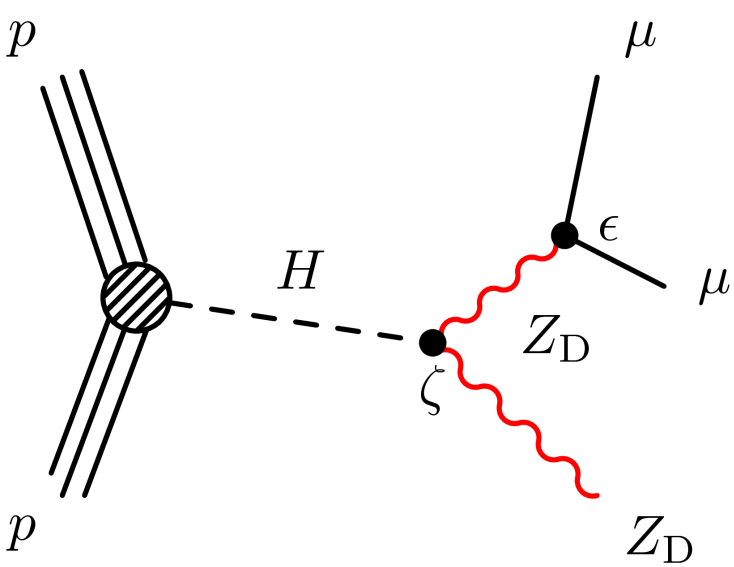
Search for LLP with di-muon DV

ATLAS-EXOT-2017-03

- Target : specific BSM physics models

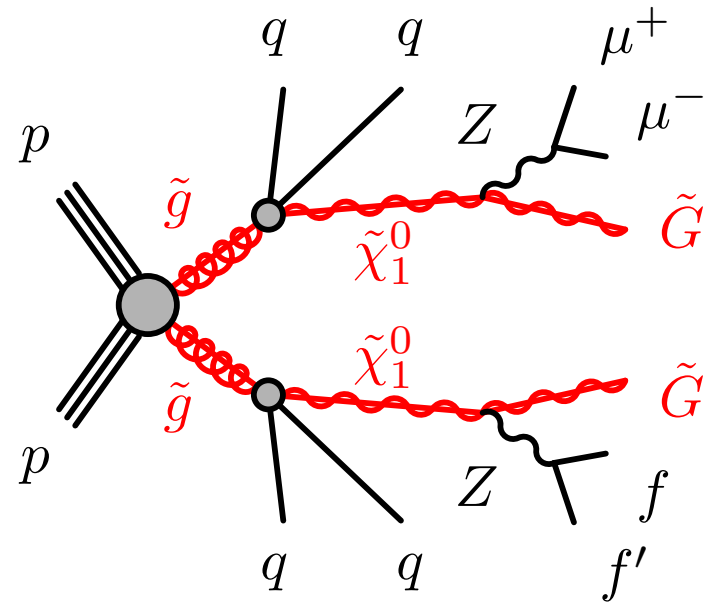
Focus on new results!!

Dark-sector gauge boson



- Low mass (< 60 GeV)
- Small Z-Z_D coupling: long-lived
- low p_T muons

Gauge-mediated supersymmetry

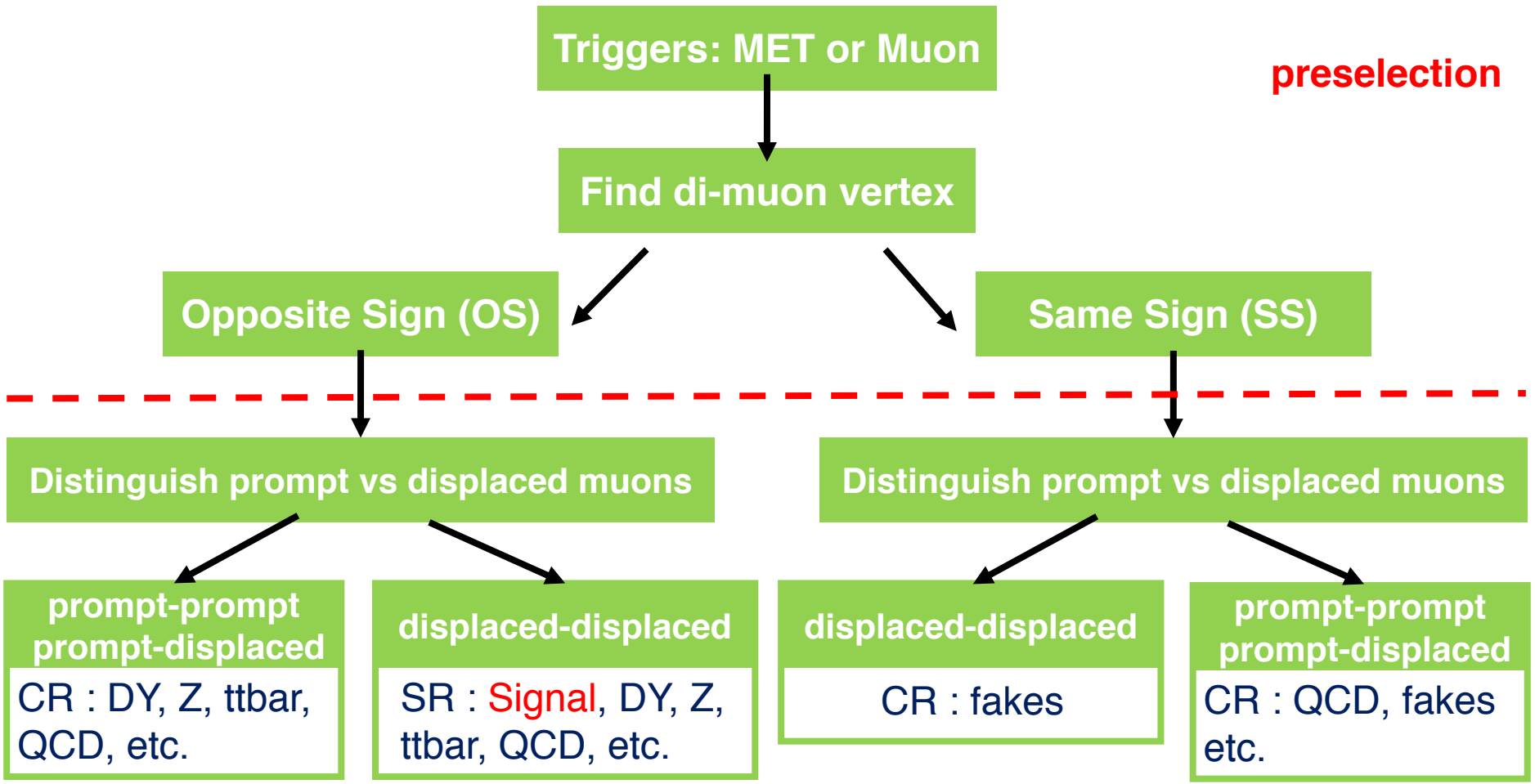


- High mass (> 60 GeV)
- Neutralino NLSP: long-lived
- high p_T muons

Event Selection Flow

ATLAS-EXOT-2017-03

- All region separated into low mass (< 60 GeV) and high mass (> 60 GeV) region



Background Estimation

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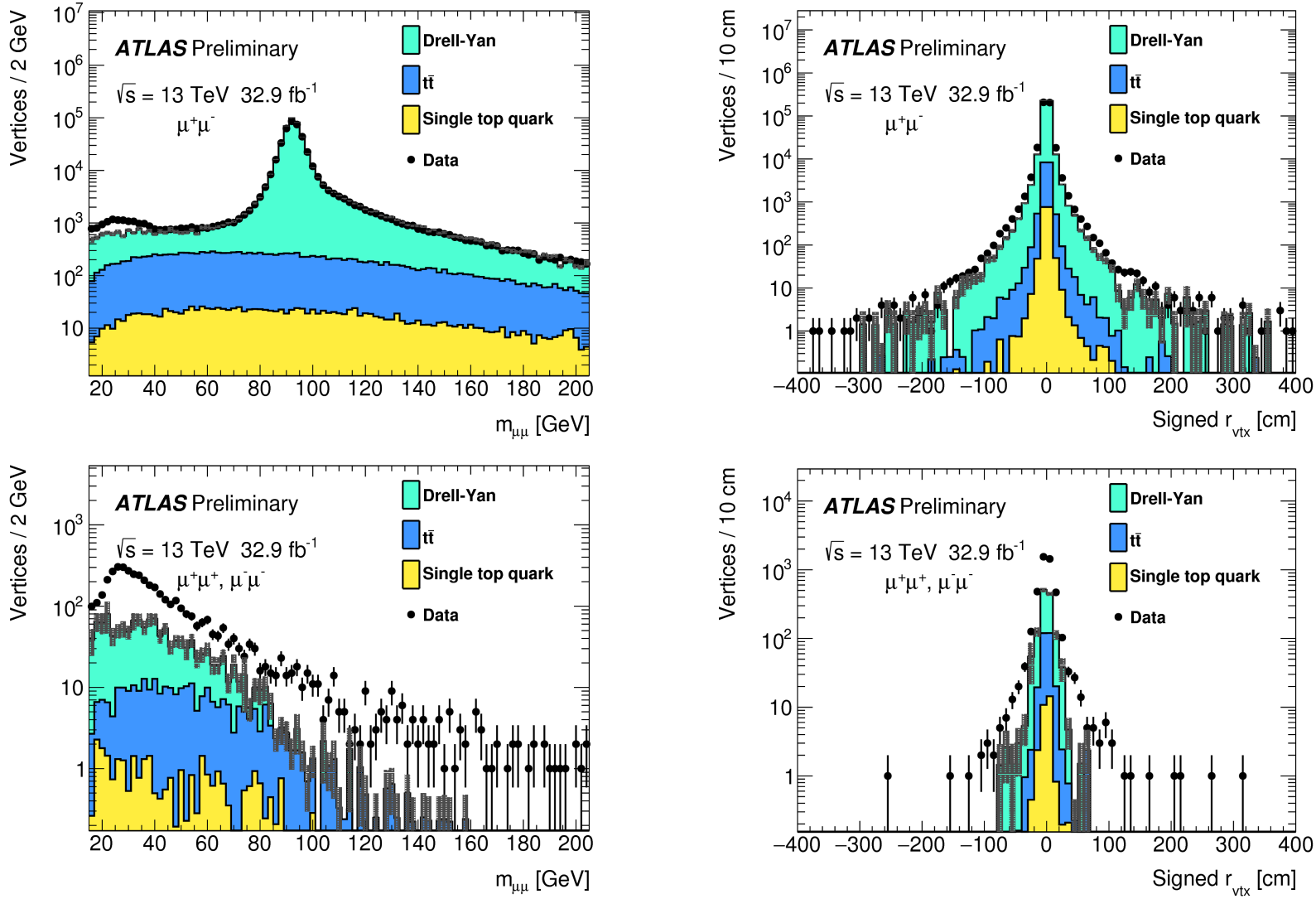
$m_{\mu\mu}$ and r_{vtx} distribution after preselection

OS

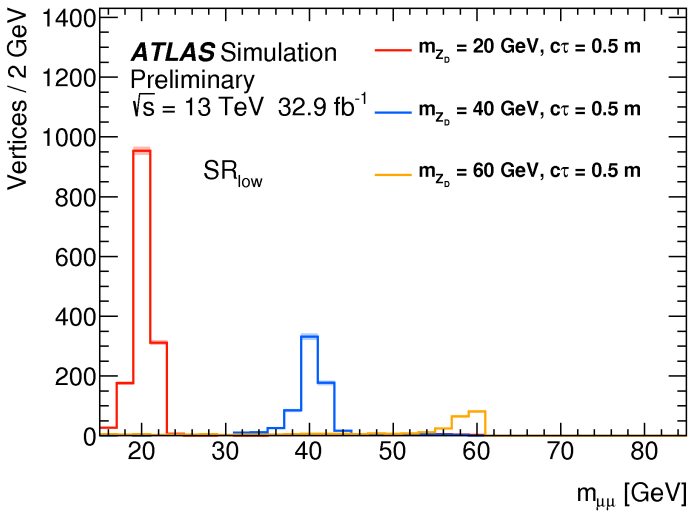
SS



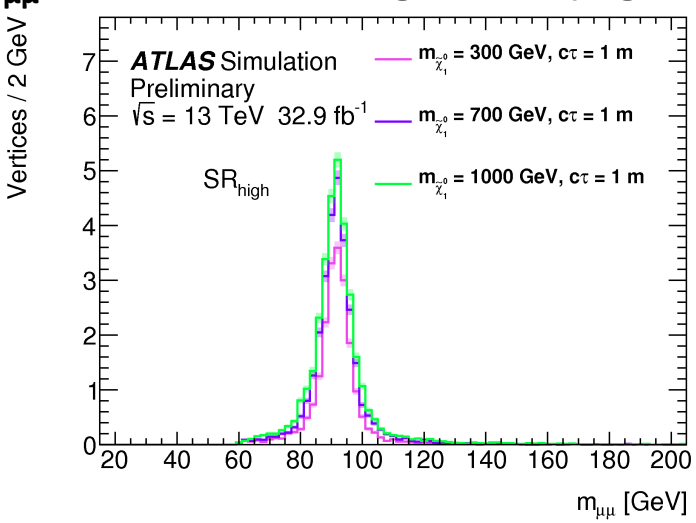
$m_{\mu\mu}$ distribution for MC and Data

ATLAS-EXOT-2017-03

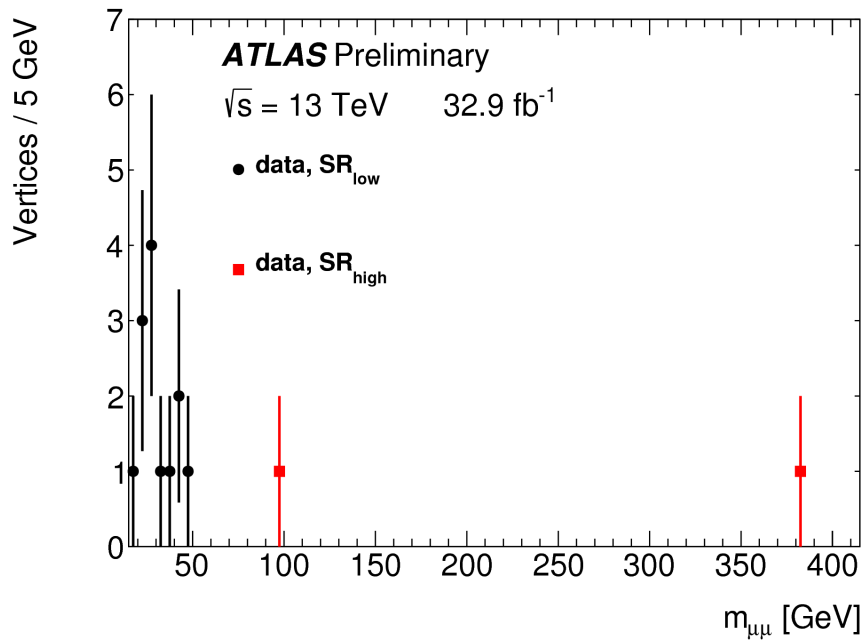
$m_{\mu\mu}$ distribution for signal MC (low mass)



$m_{\mu\mu}$ distribution for signal MC (high mass)



$m_{\mu\mu}$ distribution for data

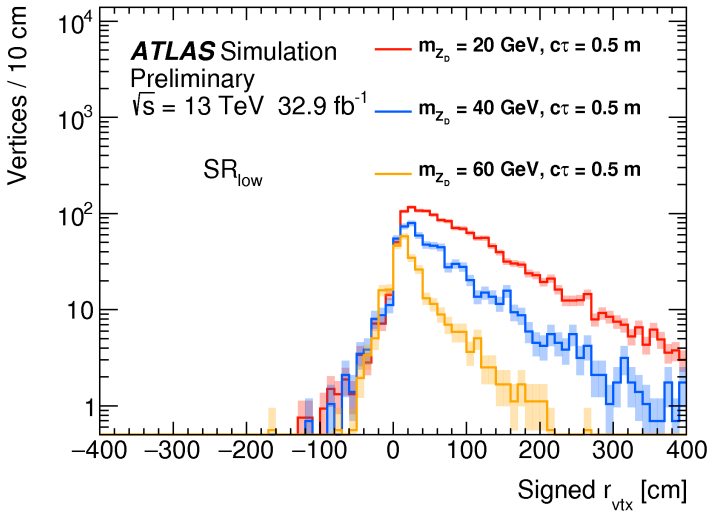


There are no signal like events.

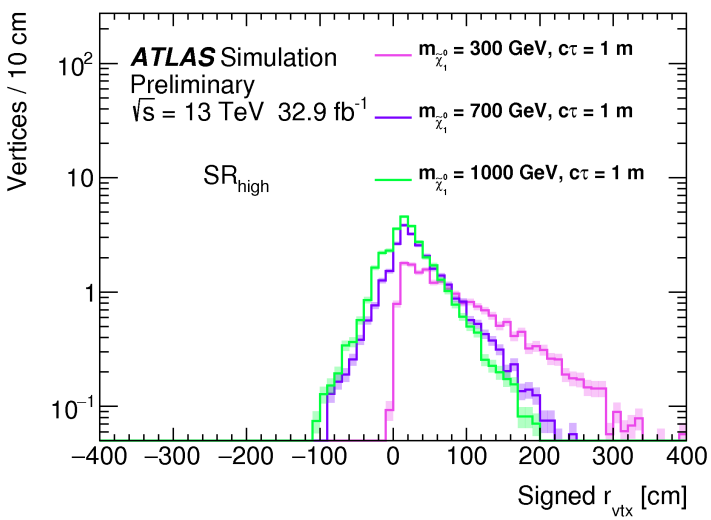
r_{vtx} distribution for MC and Data

ATLAS-EXOT-2017-03

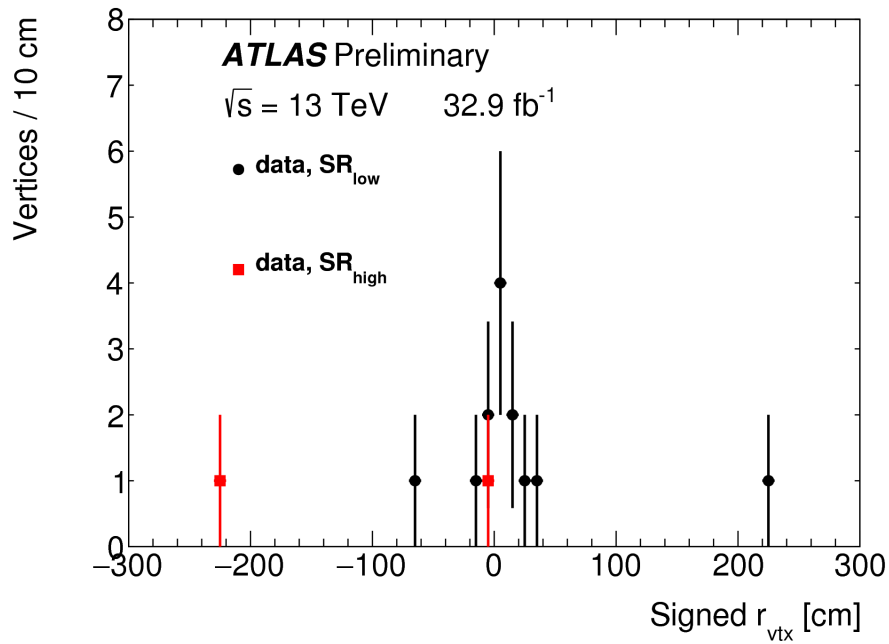
r_{vtx} distribution for signal MC (low mass)



r_{vtx} distribution for signal MC (high mass)



r_{vtx} distribution for data



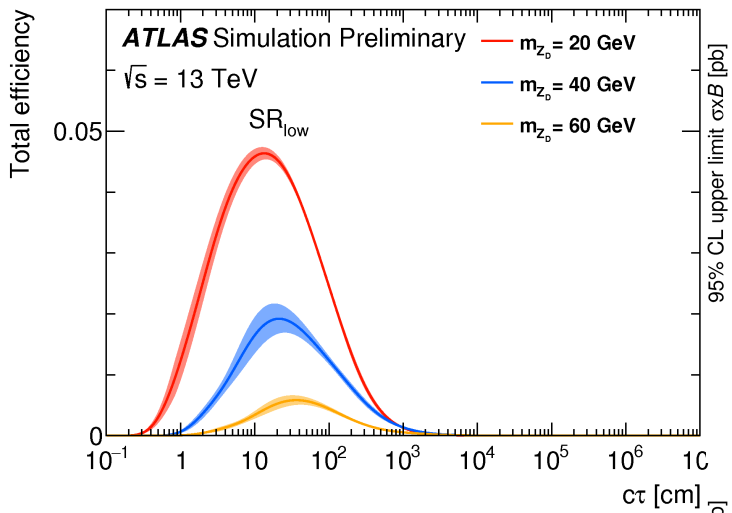
There are no signal like events.

Sensitivities and Results for low mass region

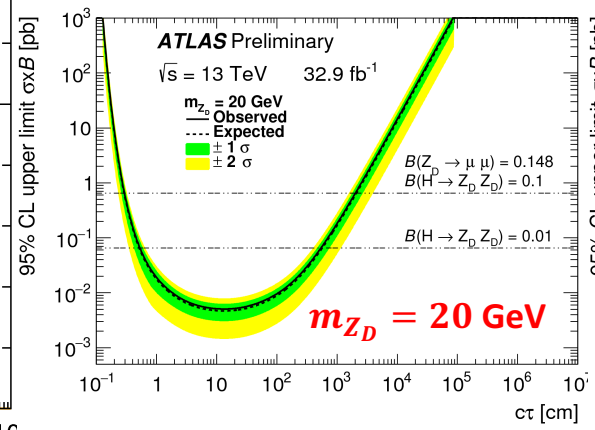
ATLAS-EXOT-2017-03

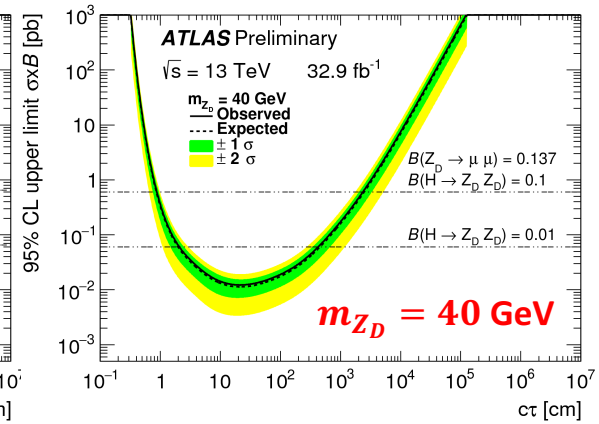
Sensitivities and Results for low mass region

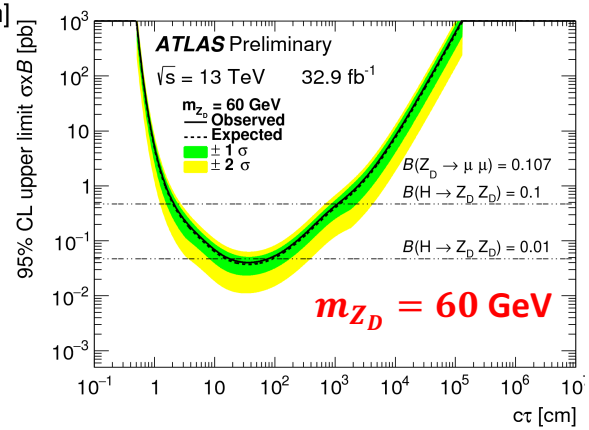
Event-level efficiencies

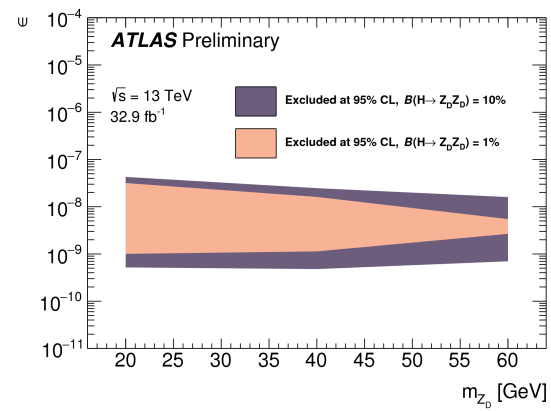


The observed and expected 95% CL upper limits









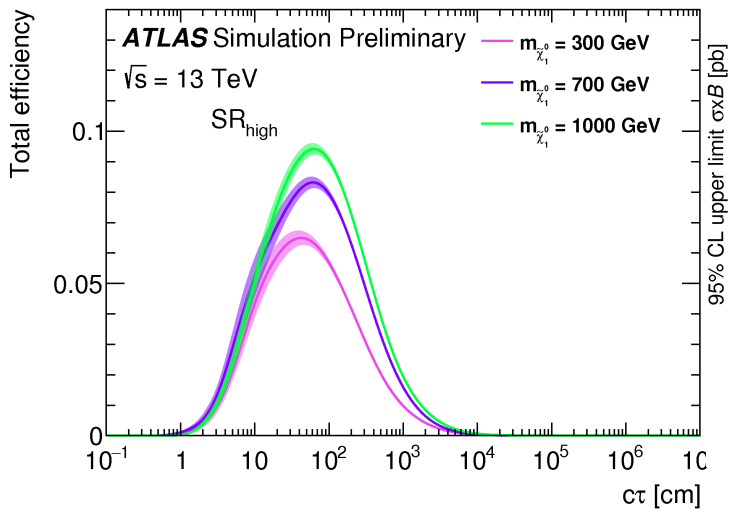
Yield	SR_{low}
$N^{non\text{-}prompt}$	13.6 ± 4.9
N^{prompt}	0.1 ± 0.2
N^{bkgd}	13.8 ± 4.9
N^{obs}	15

Sensitivities and Results for high mass region

ATLAS-EXOT-2017-03

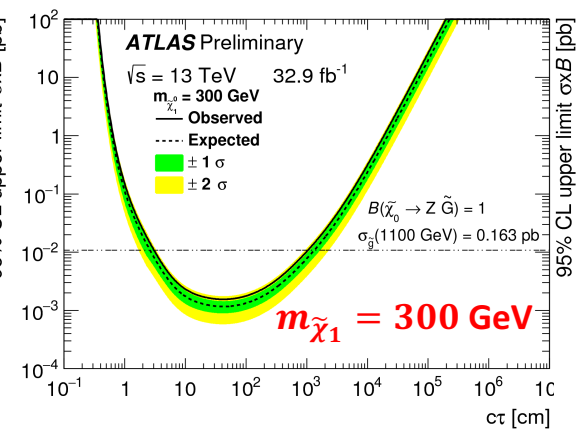
Sensitivities and Results for high mass region

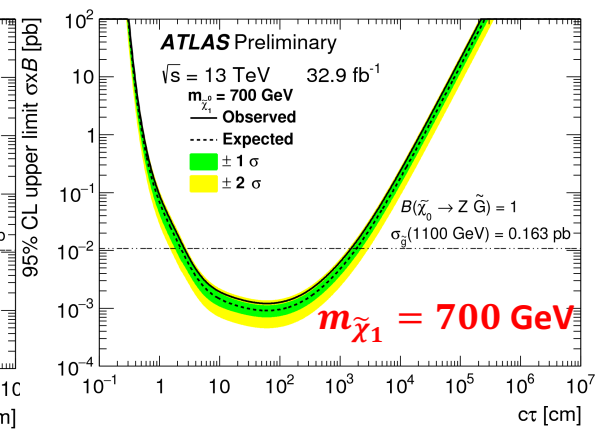
Event-level efficiencies

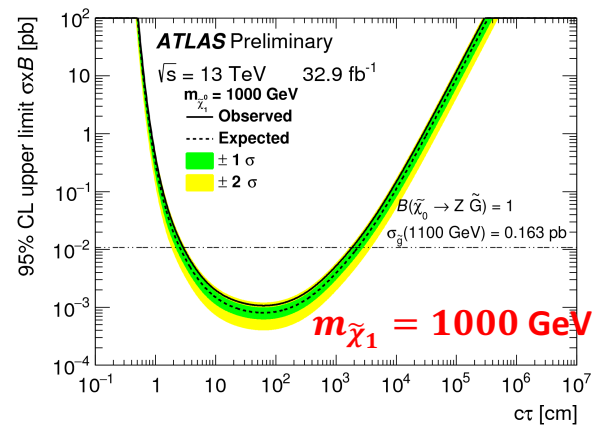


Yield	SR_{high}
$N^{non\text{-}prompt}$	$0.0^{+1.4}_{-0.0}$
N^{prompt}	0.50 ± 0.07
N^{bkgd}	$0.50^{+1.42}_{-0.07}$
N^{obs}	2

The observed and expected 95% CL upper limits

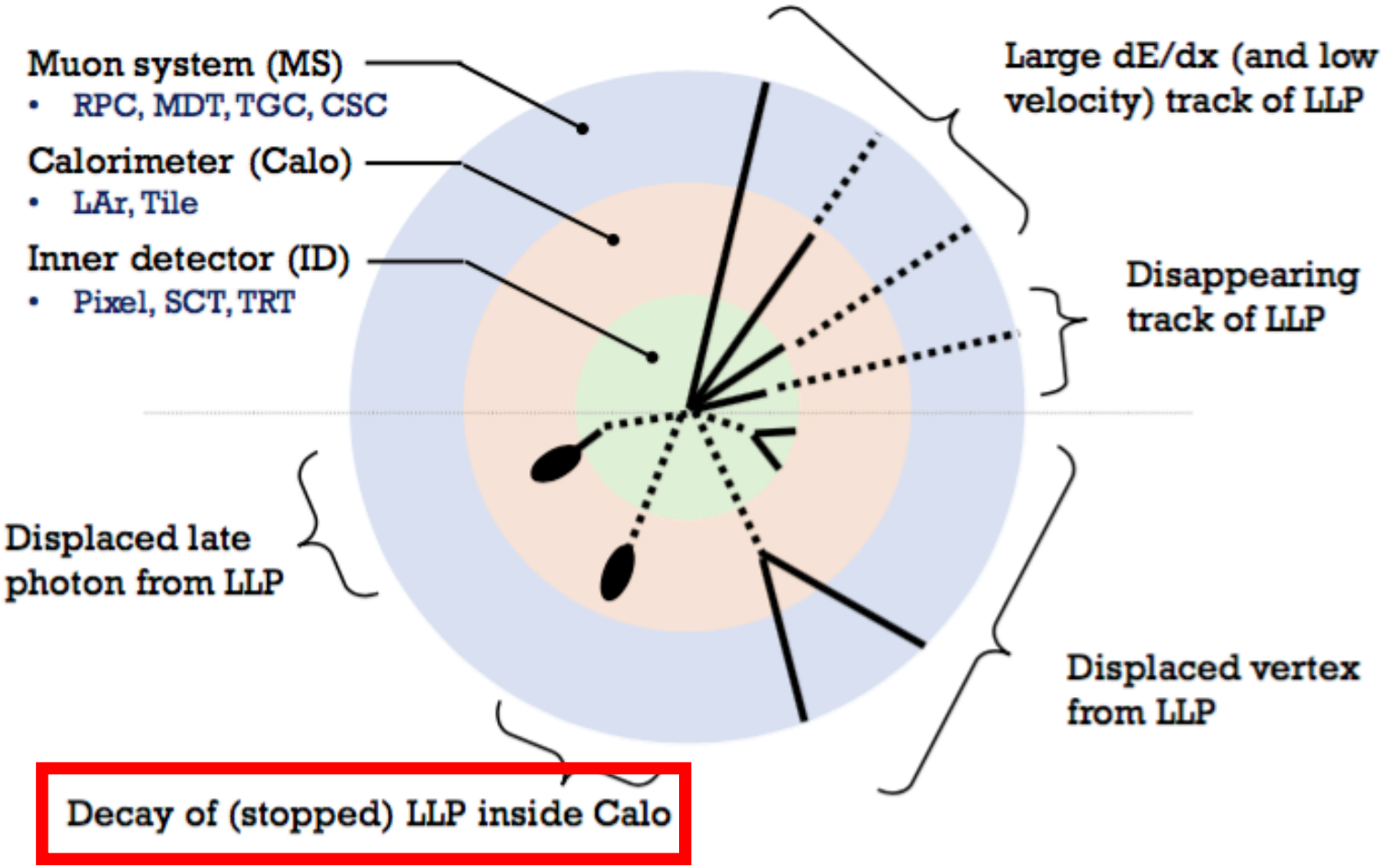






Signatures of long-lived particles

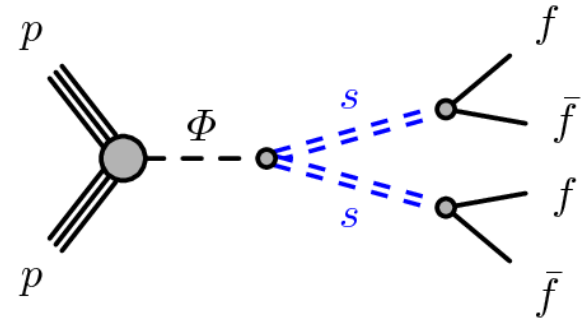
Various types of signatures require dedicated non-standard reconstruction methods!!

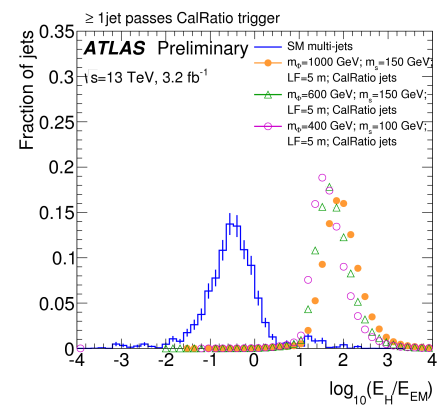


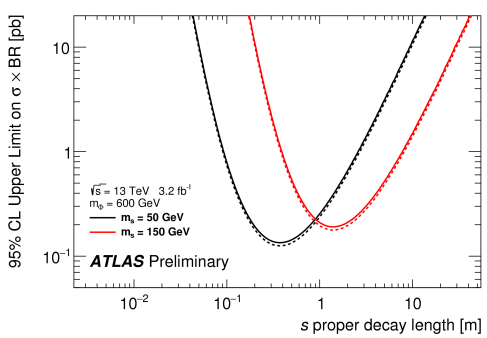
Search for LLP decaying in Calo

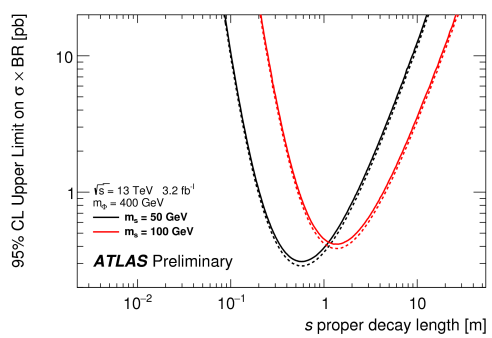
ATLAS-CONF-2016-103

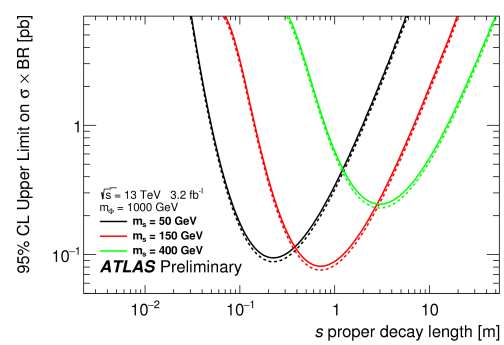
- Target : Hidden sector models
  - a dark sector weakly coupled with the SM through a heavy neutral boson ϕ
- Signature
  - LLP decays within the hadronic calorimeter
  - two jets which has high Ehad/Ecal, no track associated, small width
- Dedicated CaloRatio trigger
  - Compare the energy deposit in Hadron calo and EM calo
- No excess observed…







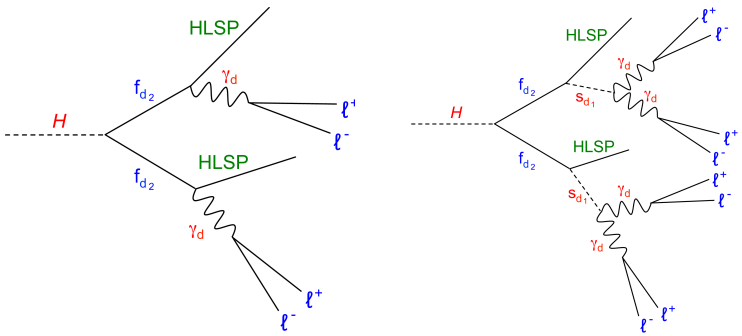


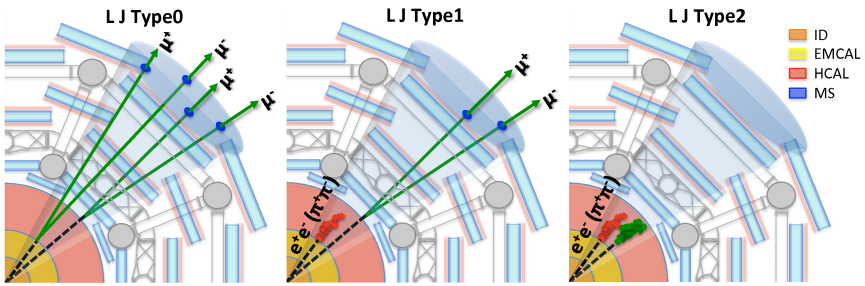


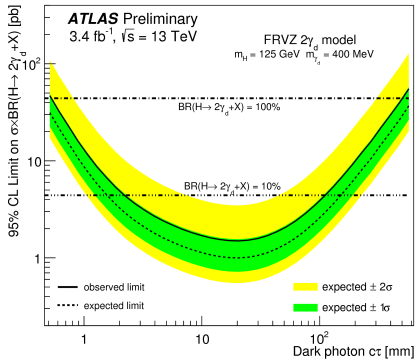
Search for LLP decaying to lepton-jets

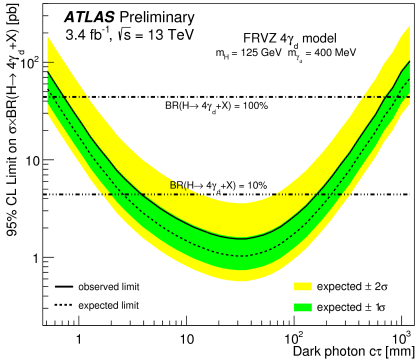
ATLAS-CONF-2016-042

- Target : Hidden sector models
  - dark photons mixed with SM photon
- Signature
  - displaced lepton jets of leptons and/or light hadrons
  - μ pair : reconstructed only by Muon system
  - e/π pair : no activity preceding Tile Calorimeter
- Dedicated collimated muon trigger
  - narrow scan muon
- No excess observed…

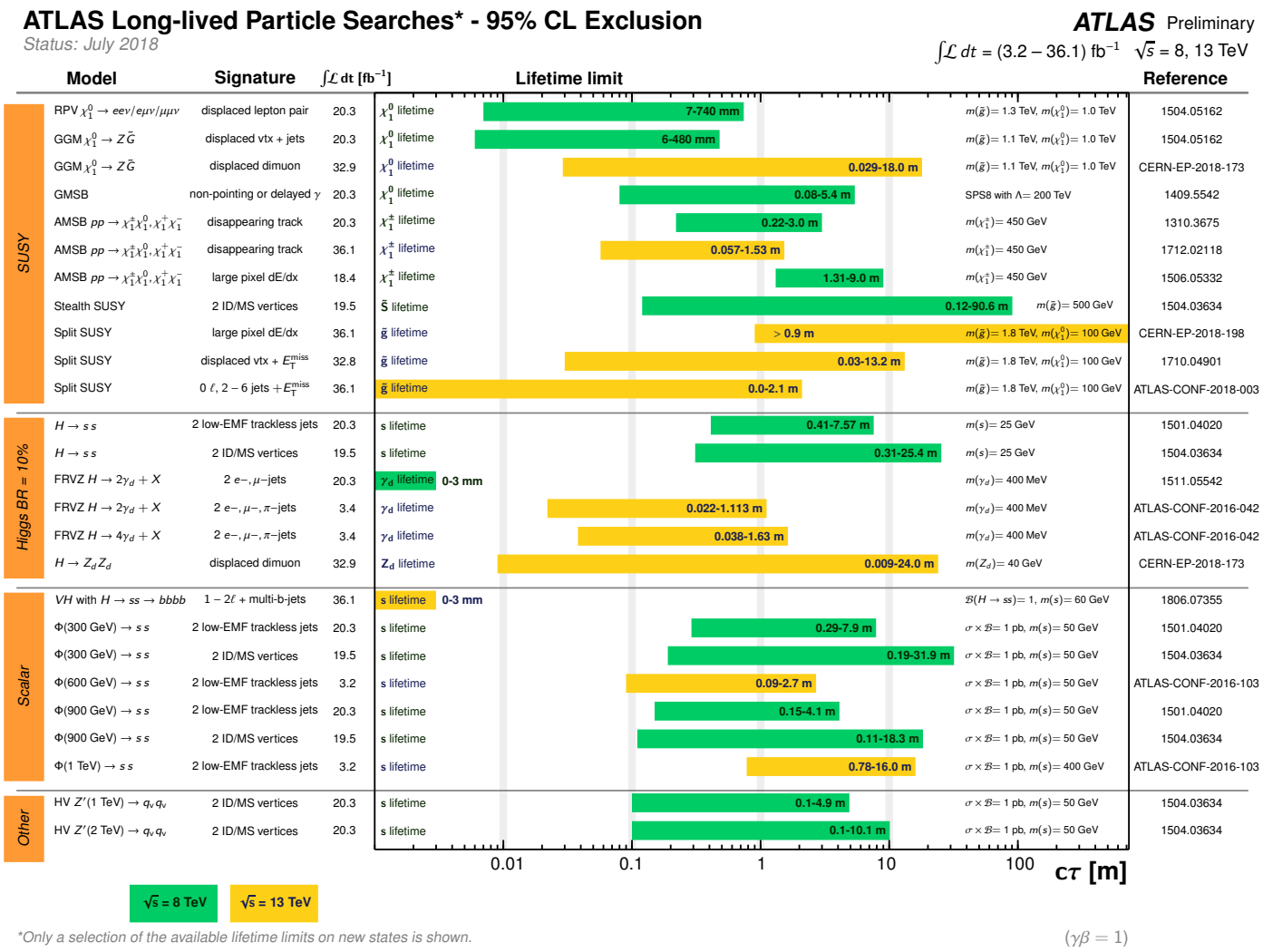








LLP summary


ATLAS Long-lived Particle Searches* - 95% CL Exclusion
Status: July 2018
ATLAS Preliminary
$\int \mathcal{L}\, dt$ = (3.2 – 36.1) fb^{-1} $\sqrt{s}$ = 8, 13 TeV
Model
Signature
$\int \mathcal{L}\, dt$ [fb^{-1}]
Lifetime limit
Reference
SUSY
RPV $\chi_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$ displaced lepton pair 20.3 χ_1^0 lifetime 7-740 mm $m(\tilde{g})$= 1.3 TeV, $m(\chi_1^0)$= 1.0 TeV 1504.05162
GGM $\chi_1^0 \to Z\tilde{G}$ displaced vtx + jets 20.3 χ_1^0 lifetime 6-480 mm $m(\tilde{g})$= 1.1 TeV, $m(\chi_1^0)$= 1.0 TeV 1504.05162
GGM $\chi_1^0 \to Z\tilde{G}$ displaced dimuon 32.9 χ_1^0 lifetime 0.029-18.0 m $m(\tilde{g})$= 1.1 TeV, $m(\chi_1^0)$= 1.0 TeV CERN-EP-2018-173
GMSB non-pointing or delayed γ 20.3 χ_1^0 lifetime 0.08-5.4 m SPS8 with Λ= 200 TeV 1409.5542
AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$ disappearing track 20.3 $\chi_1^\pm$ lifetime 0.22-3.0 m $m(\chi_1^\pm)$= 450 GeV 1310.3675
AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$ disappearing track 36.1 $\chi_1^\pm$ lifetime 0.057-1.53 m $m(\chi_1^\pm)$= 450 GeV 1712.02118
AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$ large pixel dE/dx 18.4 $\chi_1^\pm$ lifetime 1.31-9.0 m $m(\chi_1^\pm)$= 450 GeV 1506.05332
Stealth SUSY 2 ID/MS vertices 19.5 $\tilde{S}$ lifetime 0.12-90.6 m $m(\tilde{g})$= 500 GeV 1504.03634
Split SUSY large pixel dE/dx 36.1 $\tilde{g}$ lifetime > 0.9 m $m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV CERN-EP-2018-198
Split SUSY displaced vtx + E_T^{miss} 32.8 $\tilde{g}$ lifetime 0.03-13.2 m $m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV 1710.04901
Split SUSY 0 ℓ, 2 – 6 jets + E_T^{miss} 36.1 $\tilde{g}$ lifetime 0.0-2.1 m $m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV ATLAS-CONF-2018-003
Higgs BR = 10%
$H \to ss$ 2 low-EMF trackless jets 20.3 s lifetime 0.41-7.57 m $m(s)$= 25 GeV 1501.04020
$H \to ss$ 2 ID/MS vertices 19.5 s lifetime 0.31-25.4 m $m(s)$= 25 GeV 1504.03634
FRVZ $H \to 2\gamma_d + X$ 2 $e-,\mu-$jets 20.3 γ_d lifetime 0-3 mm $m(\gamma_d)$= 400 MeV 1511.05542
FRVZ $H \to 2\gamma_d + X$ 2 $e-,\mu-,\pi-$jets 3.4 γ_d lifetime 0.022-1.113 m $m(\gamma_d)$= 400 MeV ATLAS-CONF-2016-042
FRVZ $H \to 4\gamma_d + X$ 2 $e-,\mu-,\pi-$jets 3.4 γ_d lifetime 0.038-1.63 m $m(\gamma_d)$= 400 MeV ATLAS-CONF-2016-042
$H \to Z_d Z_d$ displaced dimuon 32.9 Z_d lifetime 0.009-24.0 m $m(Z_d)$= 40 GeV CERN-EP-2018-173
Scalar
VH with $H \to ss \to bbbb$ 1 – 2ℓ + multi-b-jets 36.1 s lifetime 0-3 mm $\mathcal{B}(H \to ss)$= 1, $m(s)$= 60 GeV 1806.07355
Φ(300 GeV) $\to ss$ 2 low-EMF trackless jets 20.3 s lifetime 0.29-7.9 m $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV 1501.04020
Φ(300 GeV) $\to ss$ 2 ID/MS vertices 19.5 s lifetime 0.19-31.9 m $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV 1504.03634
Φ(600 GeV) $\to ss$ 2 low-EMF trackless jets 3.2 s lifetime 0.09-2.7 m $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV ATLAS-CONF-2016-103
Φ(900 GeV) $\to ss$ 2 low-EMF trackless jets 20.3 s lifetime 0.15-4.1 m $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV 1501.04020
Φ(900 GeV) $\to ss$ 2 ID/MS vertices 19.5 s lifetime 0.11-18.3 m $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV 1504.03634
Φ(1 TeV) $\to ss$ 2 low-EMF trackless jets 3.2 s lifetime 0.78-16.0 m $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 400 GeV ATLAS-CONF-2016-103
Other
HV Z'(1 TeV) $\to q_v q_v$ 2 ID/MS vertices 20.3 s lifetime 0.1-4.9 m $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV 1504.03634
HV Z'(2 TeV) $\to q_v q_v$ 2 ID/MS vertices 20.3 s lifetime 0.1-10.1 m $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV 1504.03634
0.01
0.1
1
10
100
$c\tau$ [m]
$\sqrt{s}$ = 8 TeV
$\sqrt{s}$ = 13 TeV
*Only a selection of the available lifetime limits on new states is shown.
($\gamma\beta = 1$)

Conclusion

- Long-lived particles appear in various physics models.
  - They make many kinds of unconventional signatures.
  - Some creative analysis techniques are developed in ATLAS.
  - Analysis using displaced vertex, Calo-ratio and lepton-jet have been reviewed.
- No significant excess have not been observed so far.
  - But we still have many things to be done!!