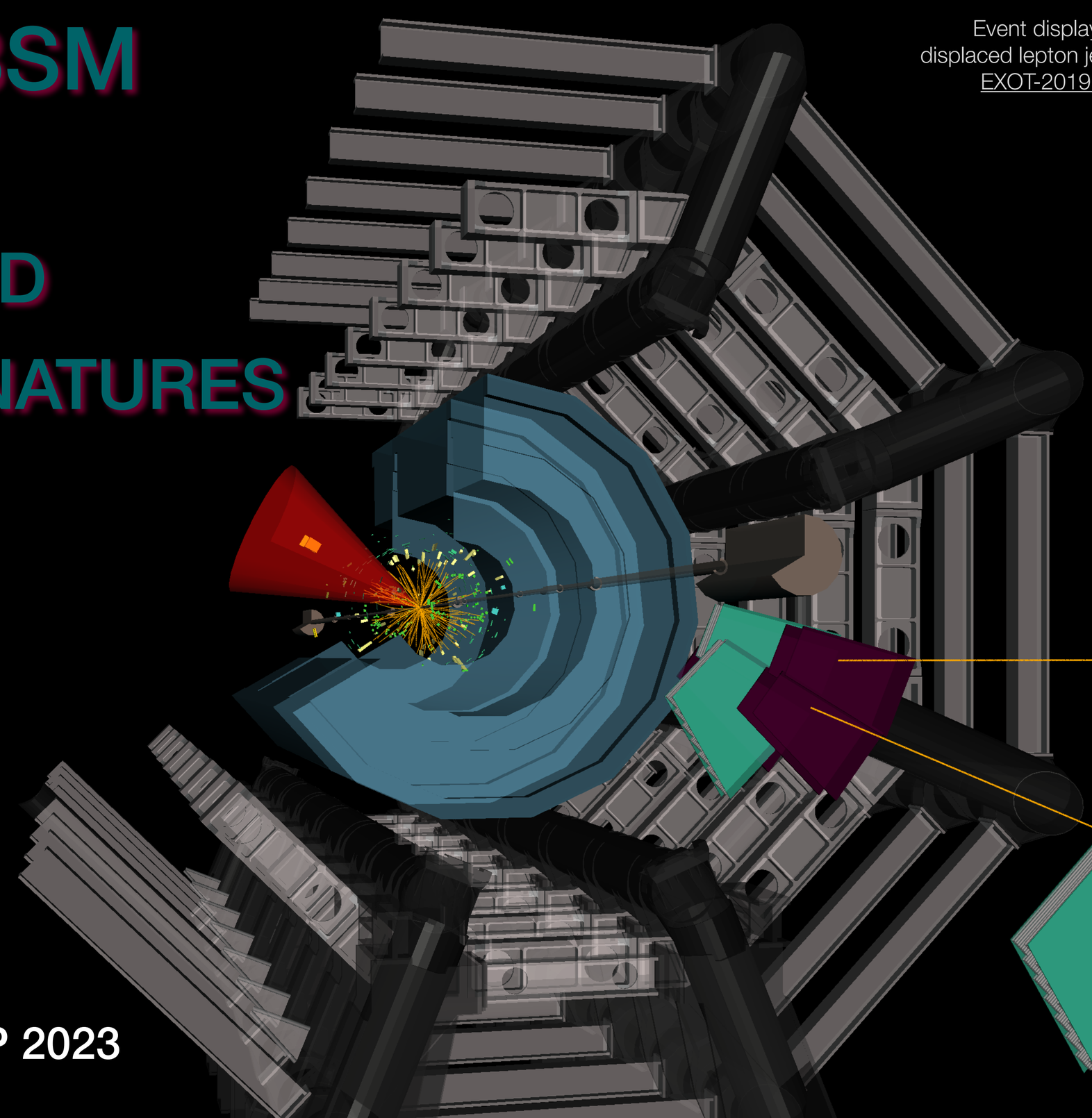
Searches for BSM Physics Using Challenging and Long-Lived Signatures with the ATLAS Detector

Stefanie Morgenstern (CERN)
on behalf of the
ATLAS Collaboration



Event display of displaced lepton jets, EXOT-2019-05

EPS-HEP 2023

Long-Lived Particles in Theory

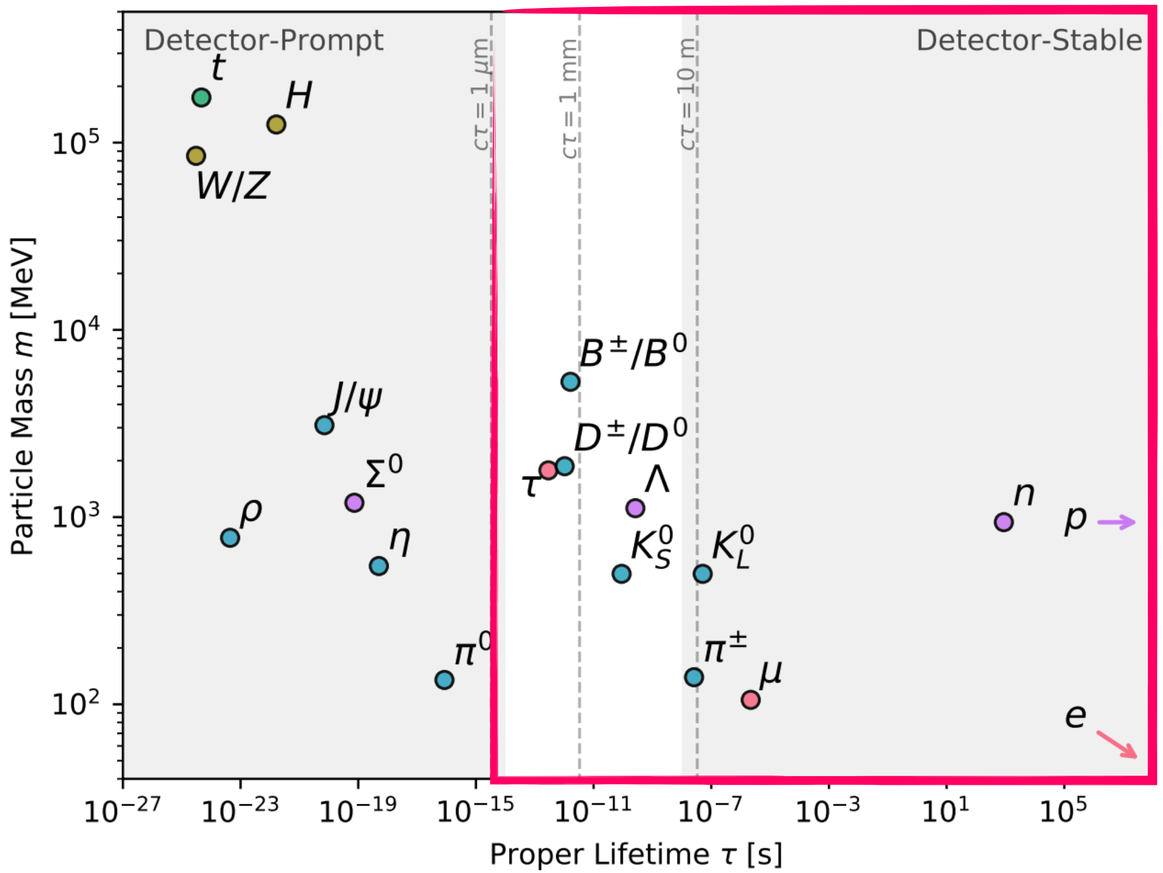
- **Standard Model**: a very successful theory
  - But also leaves some **questions unanswered**: Dark Matter, neutrino mass, matter-antimatter asymmetry, …

- **Long-lived particles** are predicted by many **BSM** theories:
  - Hidden sector, SUSY, Portal models, Leptogenesis, Neutral Naturalness, HECO and monopoles, …

- Long-lifetimes due to **small couplings**, **small phase space**, or **off-shell decays**

- Not so unconventional: many **long-lived particles** exist in the **Standard Model**
  - But …

JPPNP 3695 (2019)

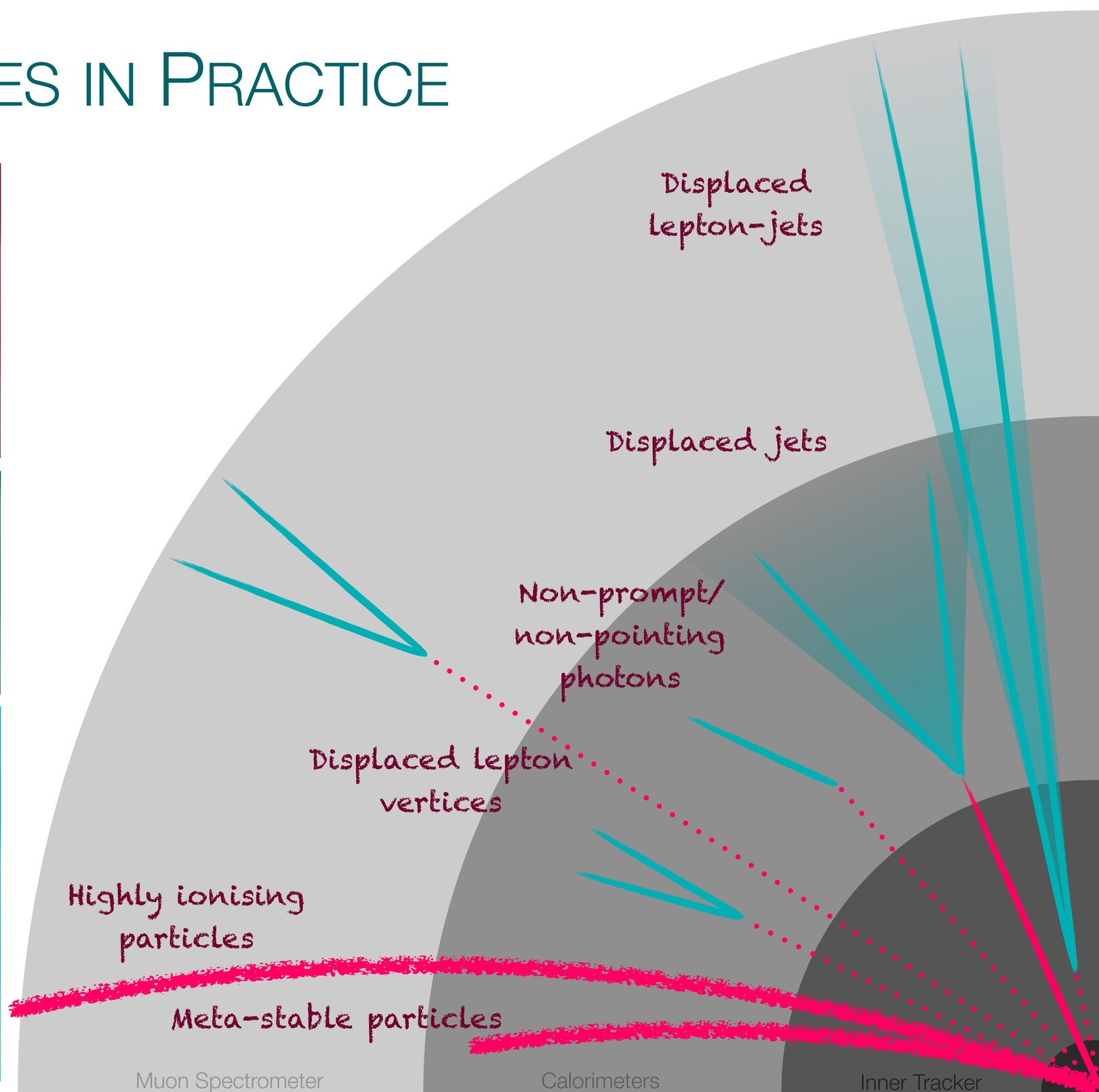


Long-Lived Particles in Practice

- Detector signatures are **unconventional, delayed and displaced**
- Often similar to noise, pile-up, mis-reconstruction
- Dependent on LLP mass, $c\tau$, $\langle\beta\gamma\rangle$ and decay channel

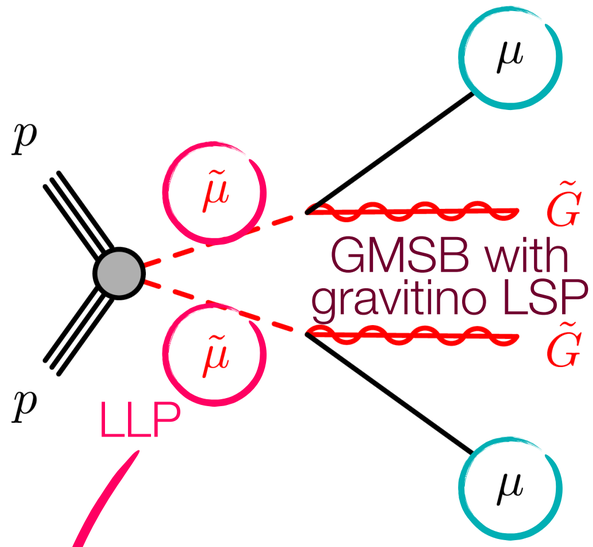
- **Innovative** trigger strategies
- **Custom** reconstruction and identification methods
- **Sophisticated** ML techniques

- **Small or non-standard backgrounds**
  - SM particles with long lifetime
  - Material interactions
  - Beam-induced background
  - Cosmic-induced background
- Fully **data-driven** background estimation approaches



arXiv:2305.02005

Micro-Displaced Muons



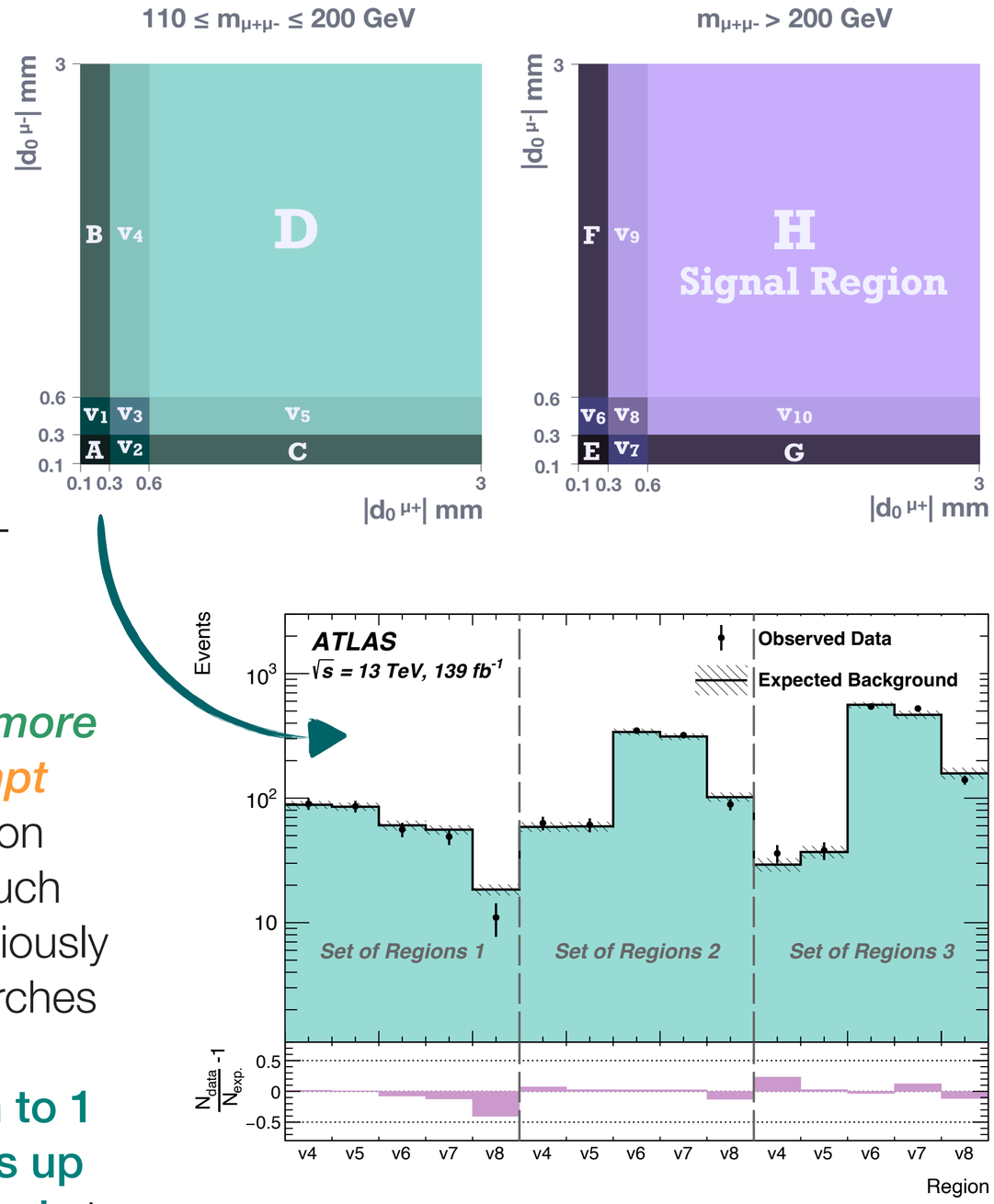
slightly displaced muons in ID tracker

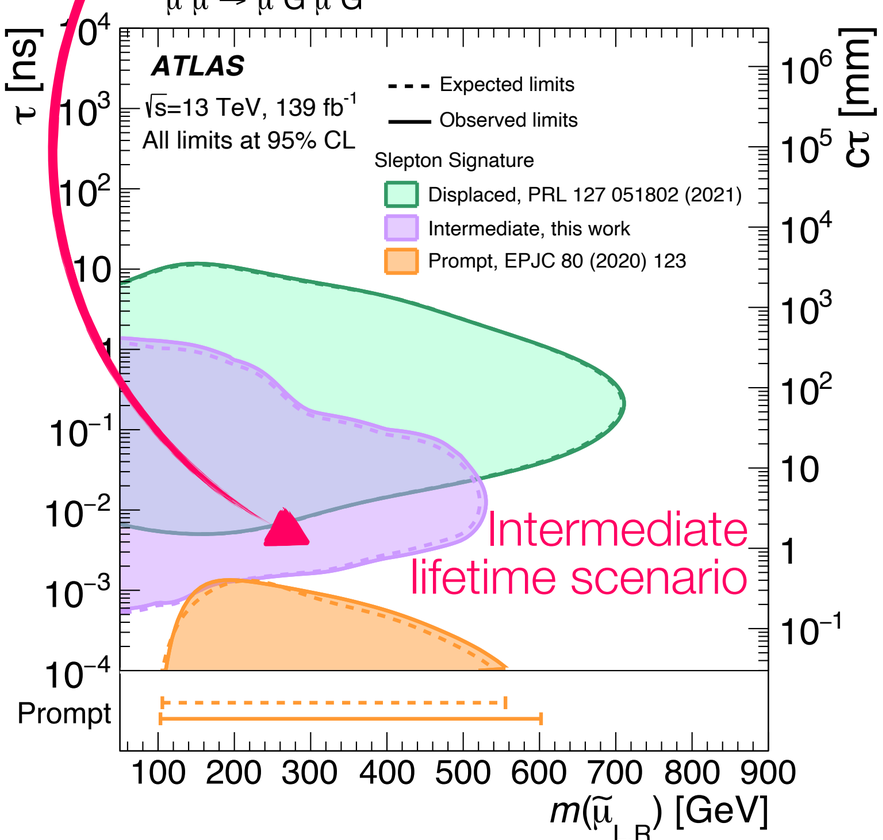
Extended ABCD background estimation method

- based on charge and transverse impact parameter of each muon and invariant muon pair mass
- discriminate against B-hadron decays

Bridges gap between ***more displaced*** and ***prompt*** *(reinterpretation)* lepton analysis accessing much lower lifetimes than previously targeted by ATLAS searches

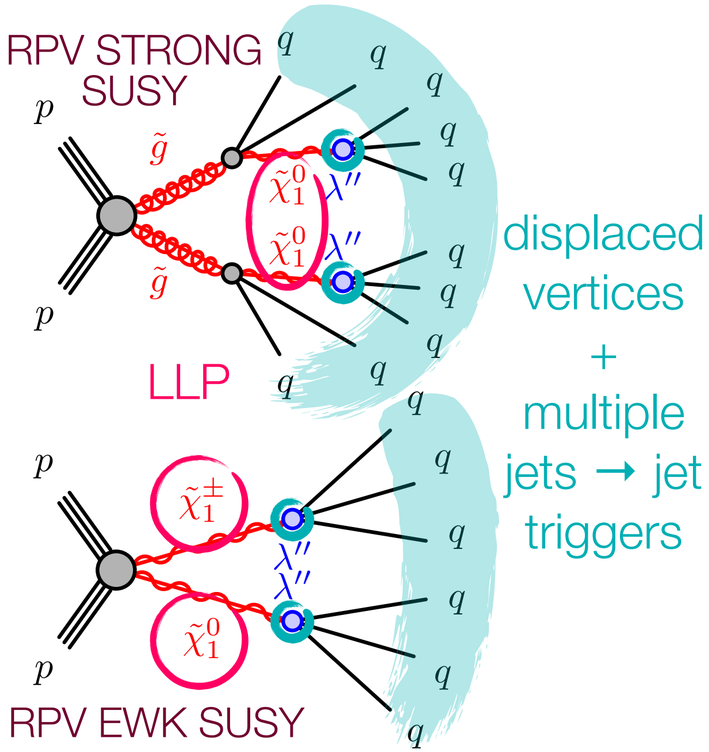
smuon lifetimes down to 1 ps and **smuon masses up to 520 GeV are excluded** at 95% CL





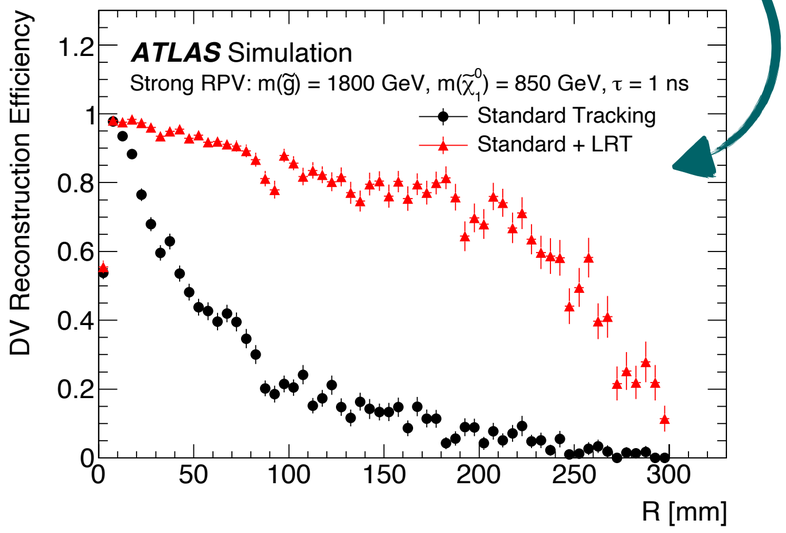
arXiv:2301.13866

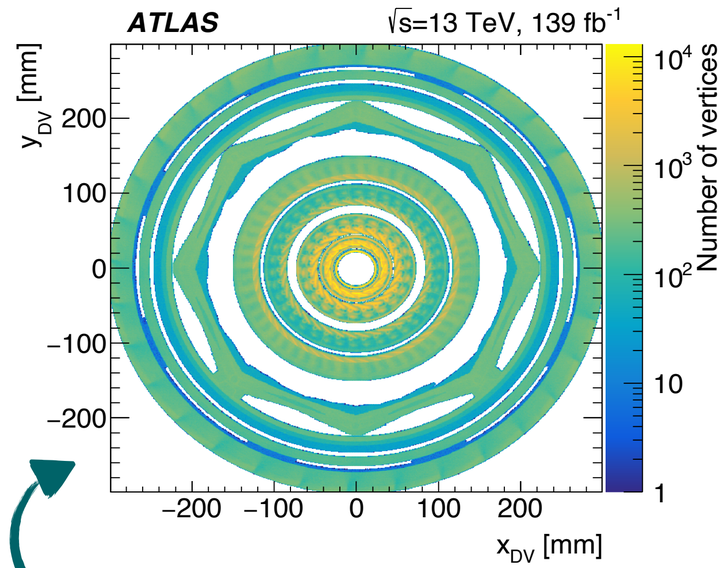
DISPLACED VERTICES + JETS



displaced vertices + multiple jets → jet triggers

Dedicated secondary-vertex reconstruction for DVs benefitting from **dedicated track reconstruction** for non-prompt particles (Large Radius Tracking)





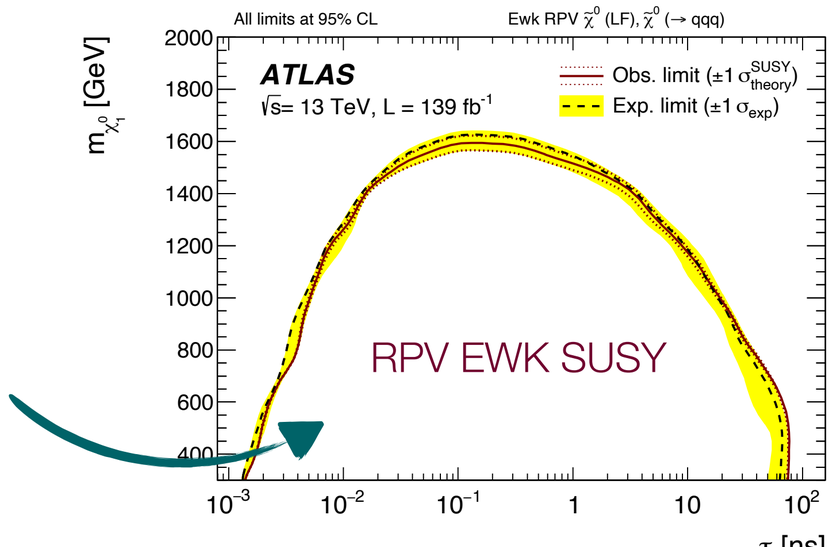
Material map veto removes 48% of the fiducial volume

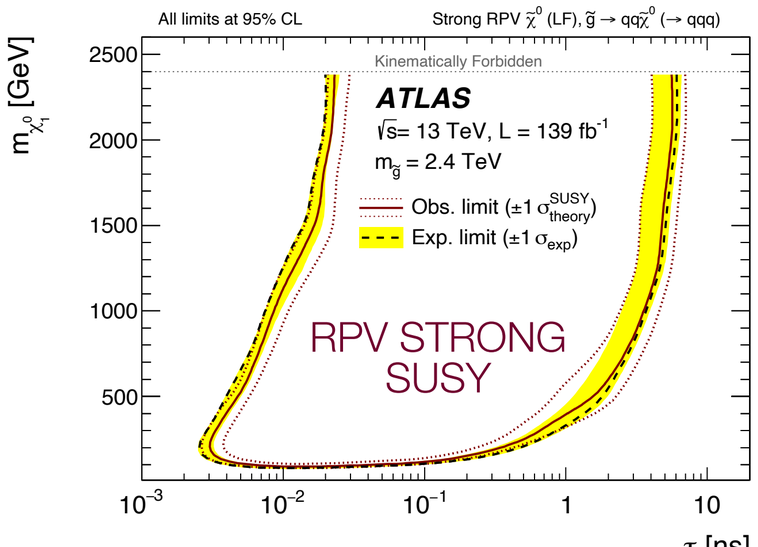
High-p_T jet SR and **trackless-jet SR**

- Targeting strong and electroweak scenarios, respectively

First limits on RPV EWK SUSY LLP production in ATLAS

Electroweakino masses up to 1.58 TeV are excluded for lifetimes of 0.1 ns



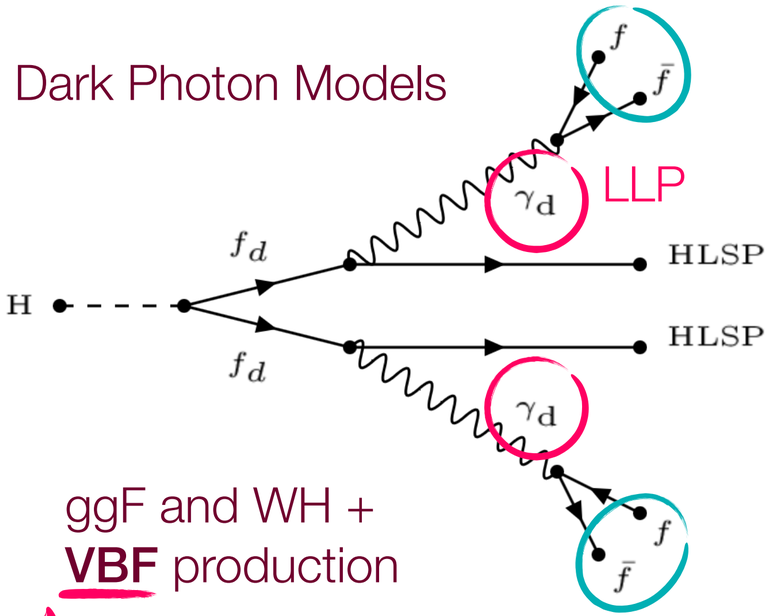


NEW

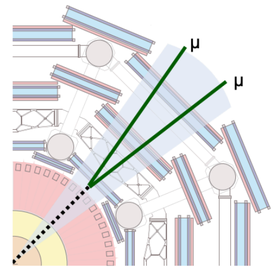
Displaced Lepton Jets

arXiv:2206.12181, ATLAS-CONF-2023-051

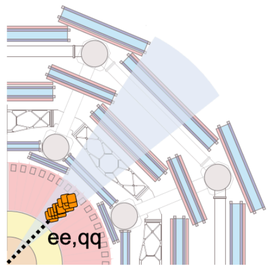
Dark Photon Models



ggF and WH + **VBF** production



muonic DPJ

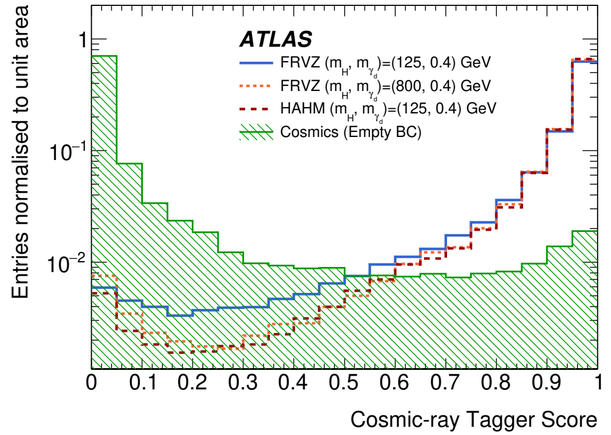


calorimeter DPJ

collimated fermion pairs

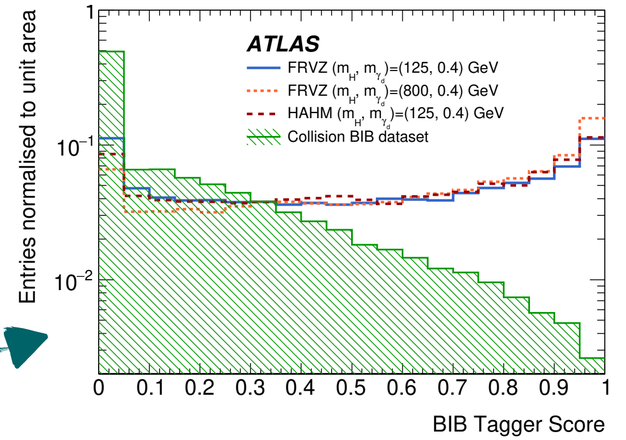
Cosmic ray tagger: dense neural network

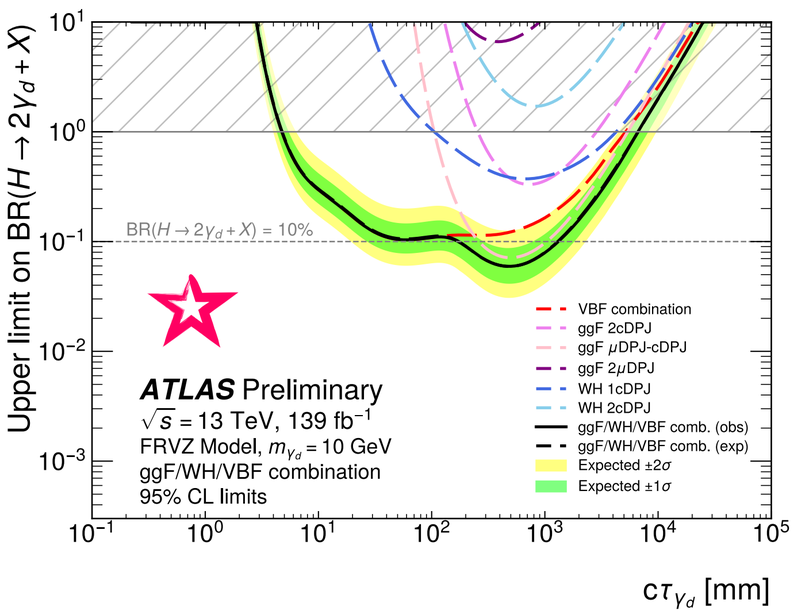
- Timing, impact parameter and angular direction



BIB and QCD tagger: convolutional neural network

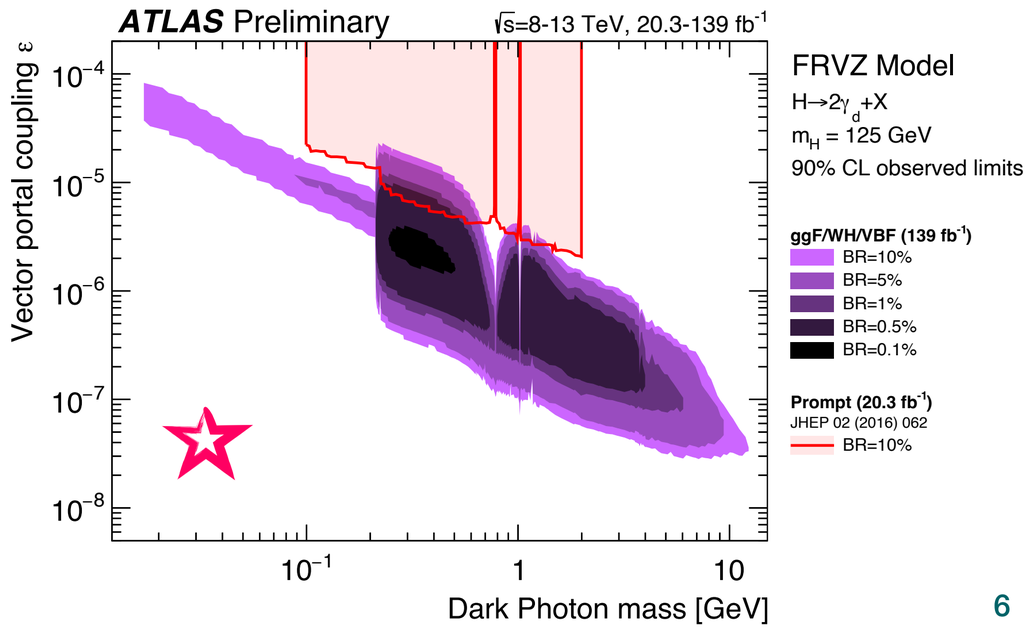
- Topology of the energy deposits





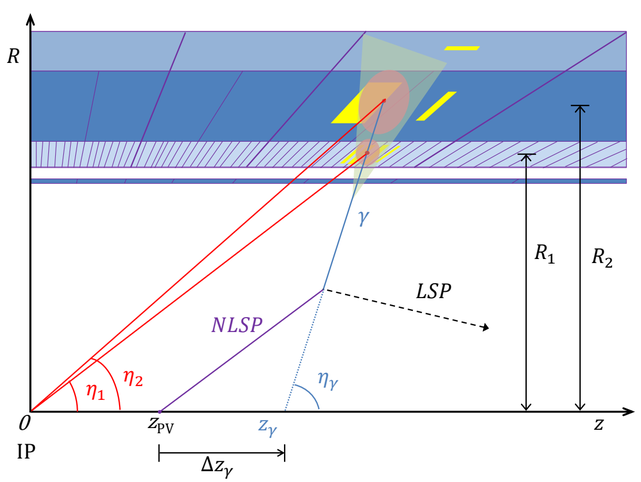
Sensitivity of previous ATLAS searches significantly extended

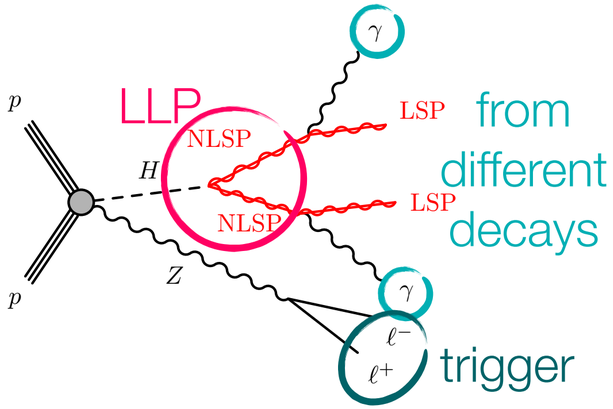
Branching fractions above 10% are excluded for Higgs decays to two dark photons with mean proper decay length of ~~[10,250]mm~~ → *[0.5,3000] mm* and mass between 0.4 GeV and 2 GeV



arXiv:2209.01029, arXiv:2304.12885

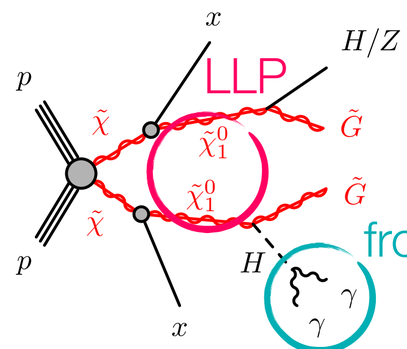
NON-POINTING & NON-PROMPT PHOTONS





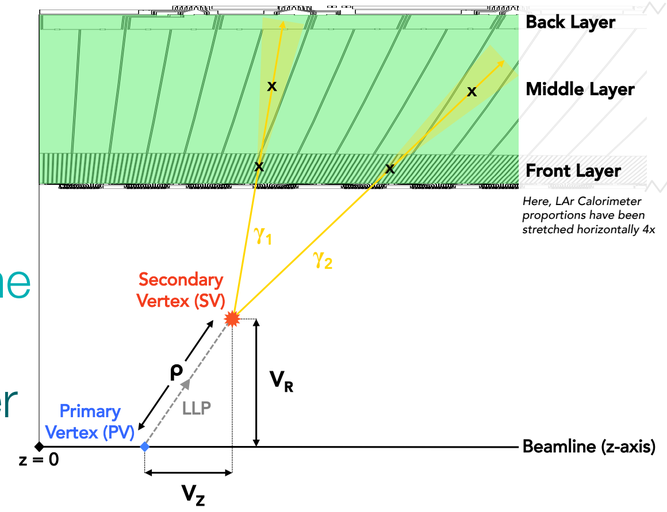
from different decays

trigger



from same decay → trigger

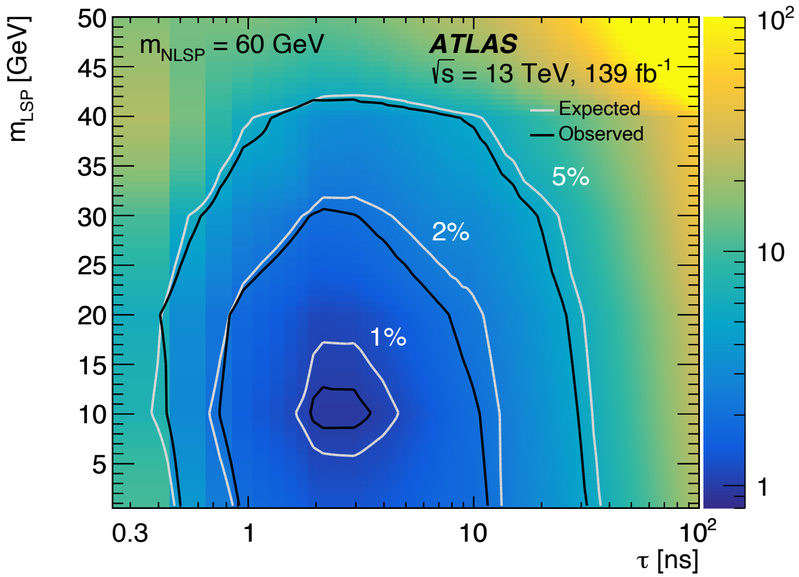
(also sensitive to displaced electrons)

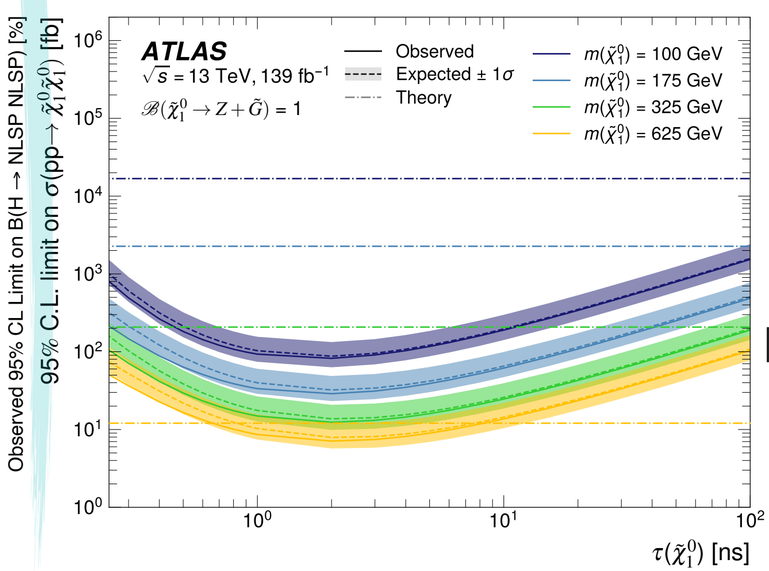


Exploit the **precise spatial and timing capabilities of the ATLAS LAr calorimeter** of *O*(10 mm) and ~0.2 ns resolution, respectively, to **determine pointing and timing of photons**

Most stringent limits for lifetimes of 2-3 ns

A model-independent limit is set on the production of photons with large values of displacement and time delay





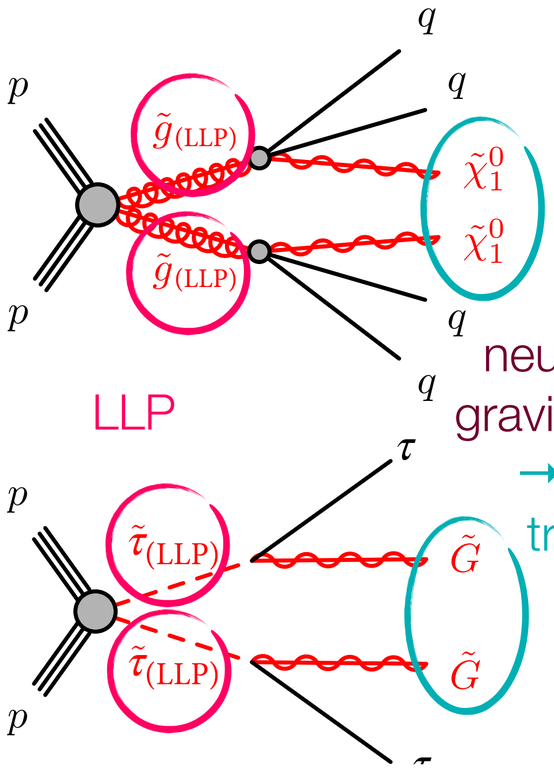
Limits set as function of m_{LLP} and τ for various BR compositions, and cross section for LLP pair-production with 100 GeV < m < 705 GeV and 0.25 ns < τ < 1000 ns

NEW

ATLAS-CONF-2023-044

LARGE dE/dx

→ Poster by Martina Ressegotti

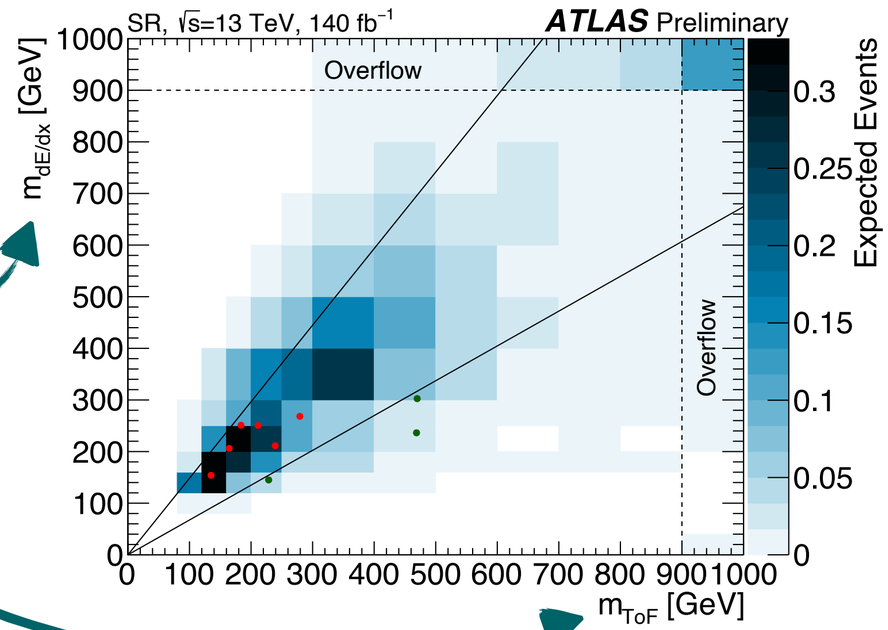


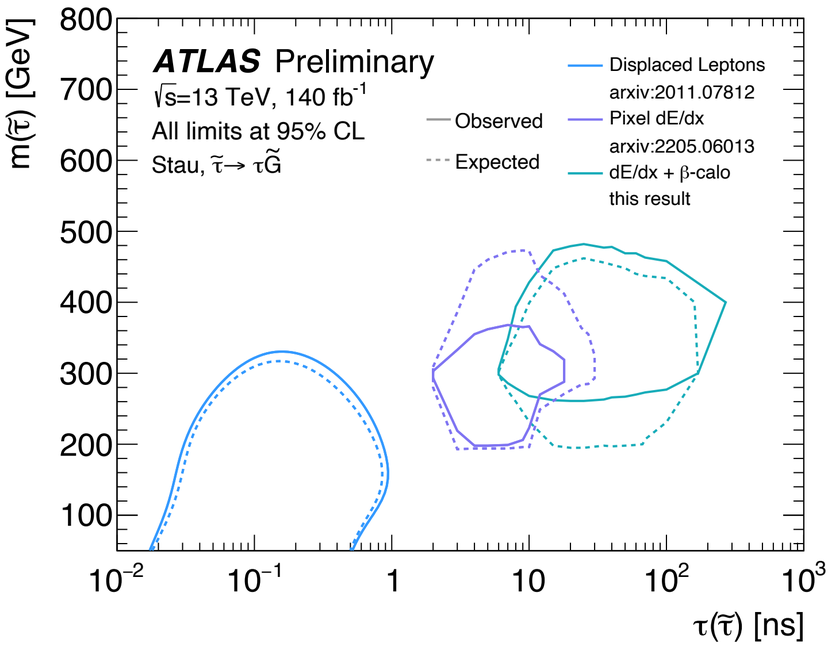
LLP

neutralino/ gravitino LSP → MET trigger

Targeting **massive charged slow particles**: m > 100 GeV, τ > 3 ns

- Exploits the measurement of the anomalously **large ionisation energy loss** (dE/dx) in the ID tracker
- Improved previous search by including **Time-of-Flight** (ToF) measured by the hadronic calorimeter

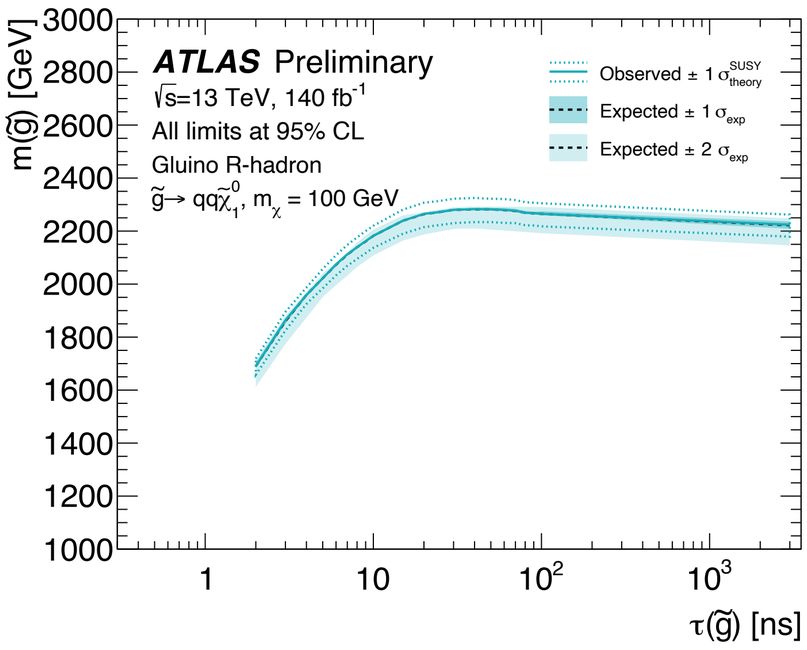




Agreement with background expectation

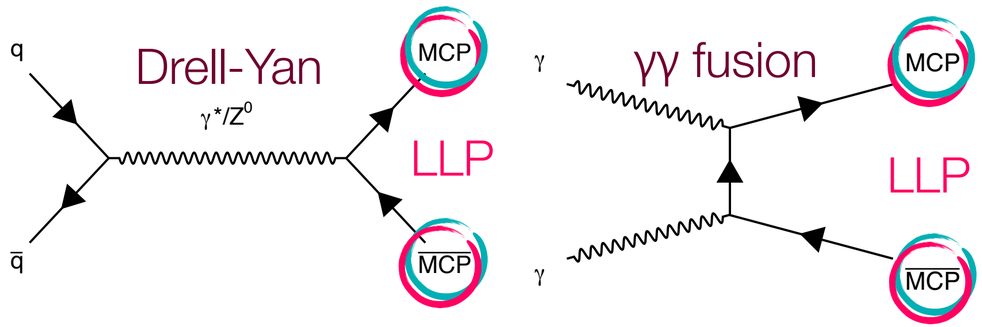
observed 6 events in SR,
expected 5.1±0.5 background events

Highest sensitivity is reached for LLPs with τ > 10 ns



arXiv:2303.13613

MULTI-CHARGED PARTICLES



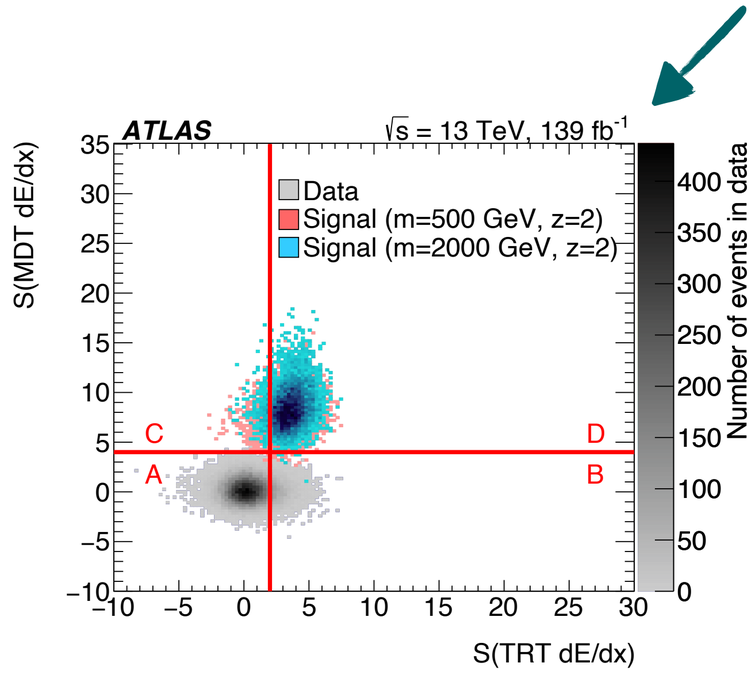
Search for **heavy long-lived multi-charged particles** (MCPs):
$|q| \leq ze$, $2 \leq z \leq 7$

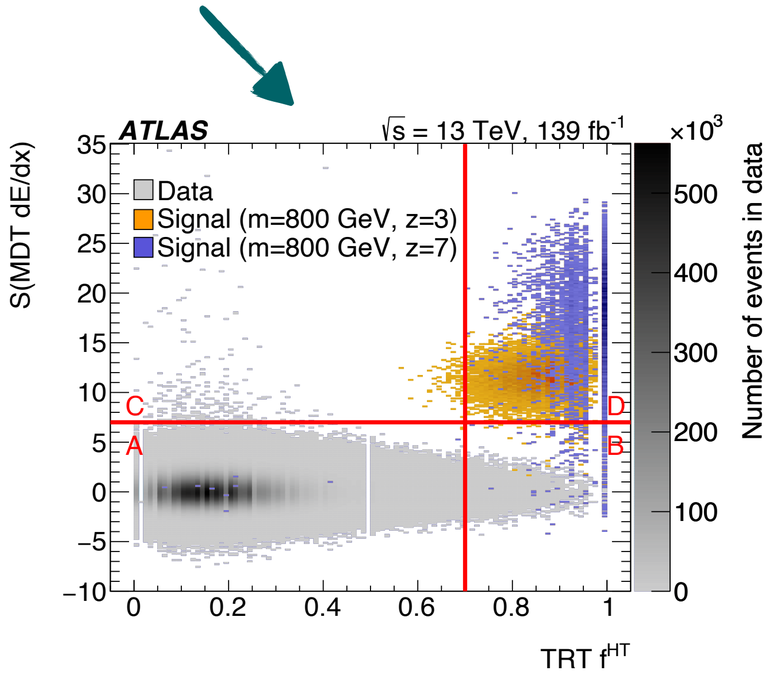
- **Traversing the entire ATLAS detector** without decaying
- Exploiting MET, prompt muon and novel late-muon triggers

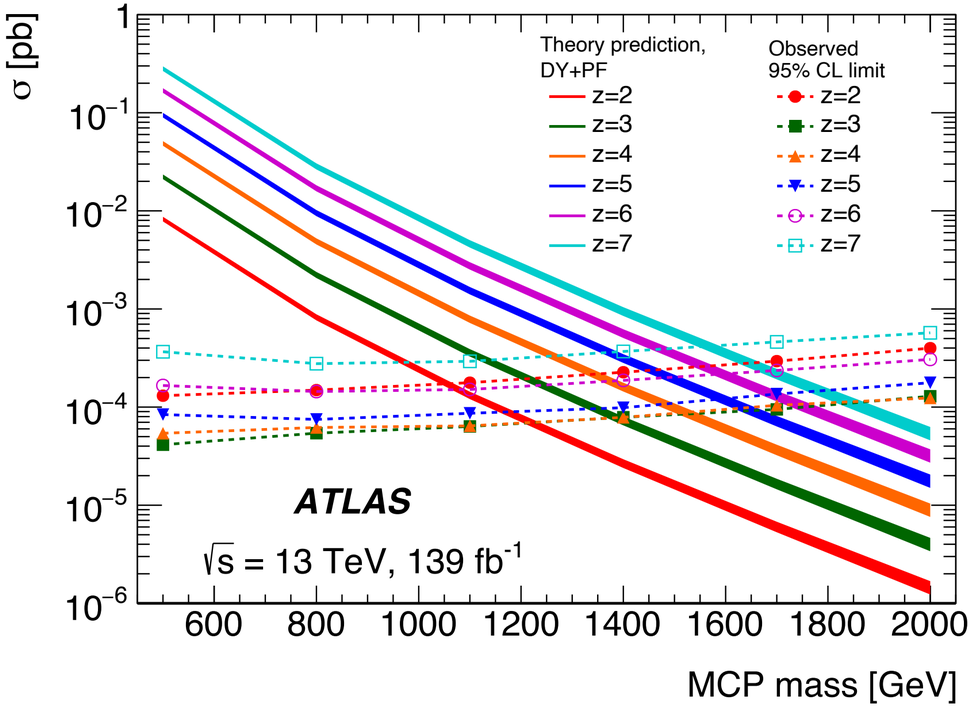
Targeting high-p_T muon-like signatures with **high dE/dx values in several sub-detectors**: ID Pixel, TRT, MS MDT

- Fraction of **high-threshold TRT hits**, **Pixel, TRT and MDT dE/dx**

Different selections optimised for **z = 2** and **z > 2**





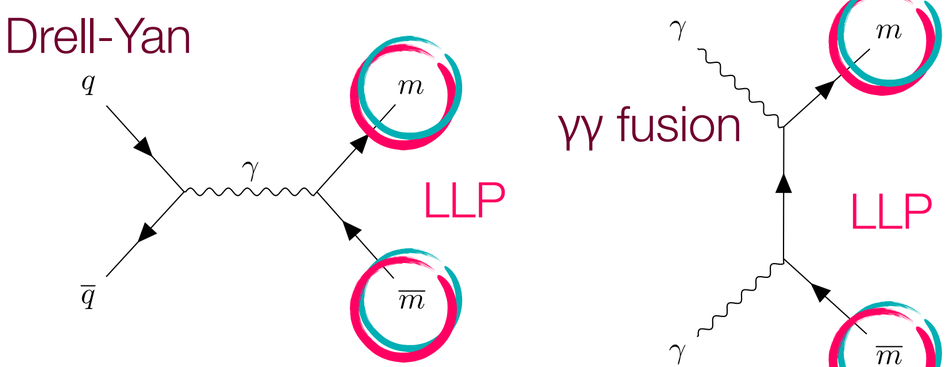


Upper limits **exclude muon-like MCPs with masses from 500 GeV to 1060 GeV (z = 2) and 1600 GeV (z = 6)**

NEW

arXiv:2308.04835

MAGNETIC MONOPOLES/HECOS/HIPS



Highly Ionising Particles:

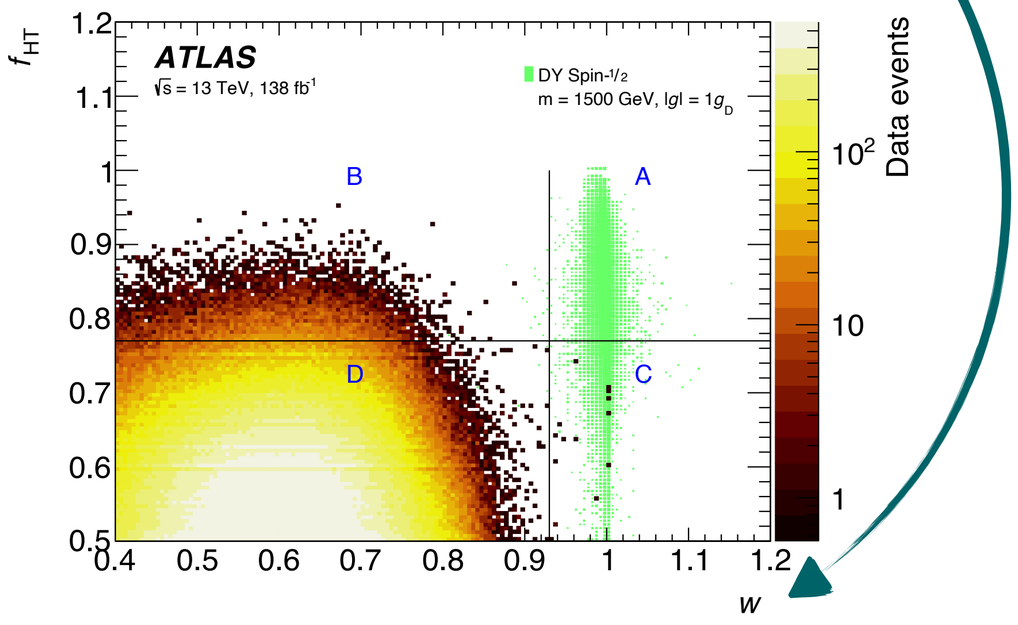
Magnetic monopoles of charge $1g_D$ and $2g_D$ and **high-electric-charge objects** $20 \leq |z| \leq 100$

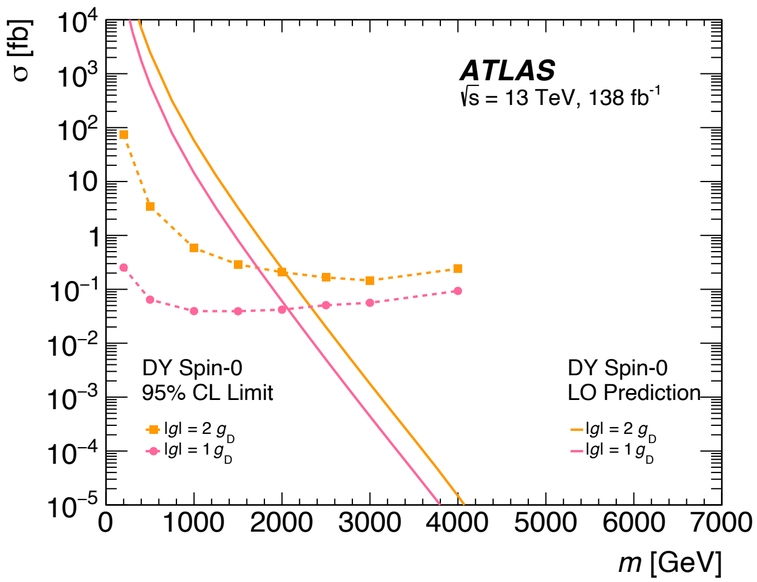
- δ-rays produced in TRT
- EM deposits with low lateral dispersion, no HCAL deposits

} **dedicated HIP trigger**

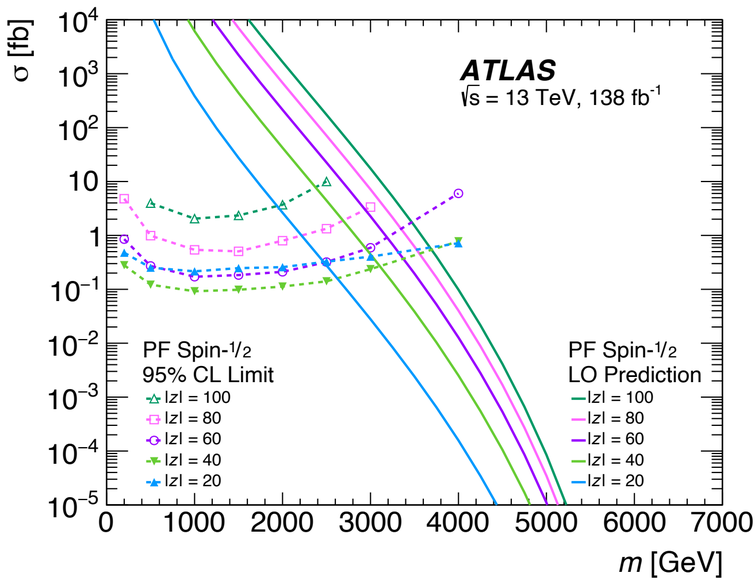
ABCD background estimation method exploiting

- fraction of **high-threshold TRT hits** and
- **lateral dispersion of the EM clusters**





Cross-section limits on the Drell-Yan production of magnetic monopoles **improved by a factor ~3**



First ATLAS limits on the γγ fusion production of magnetic monopoles and HECOs

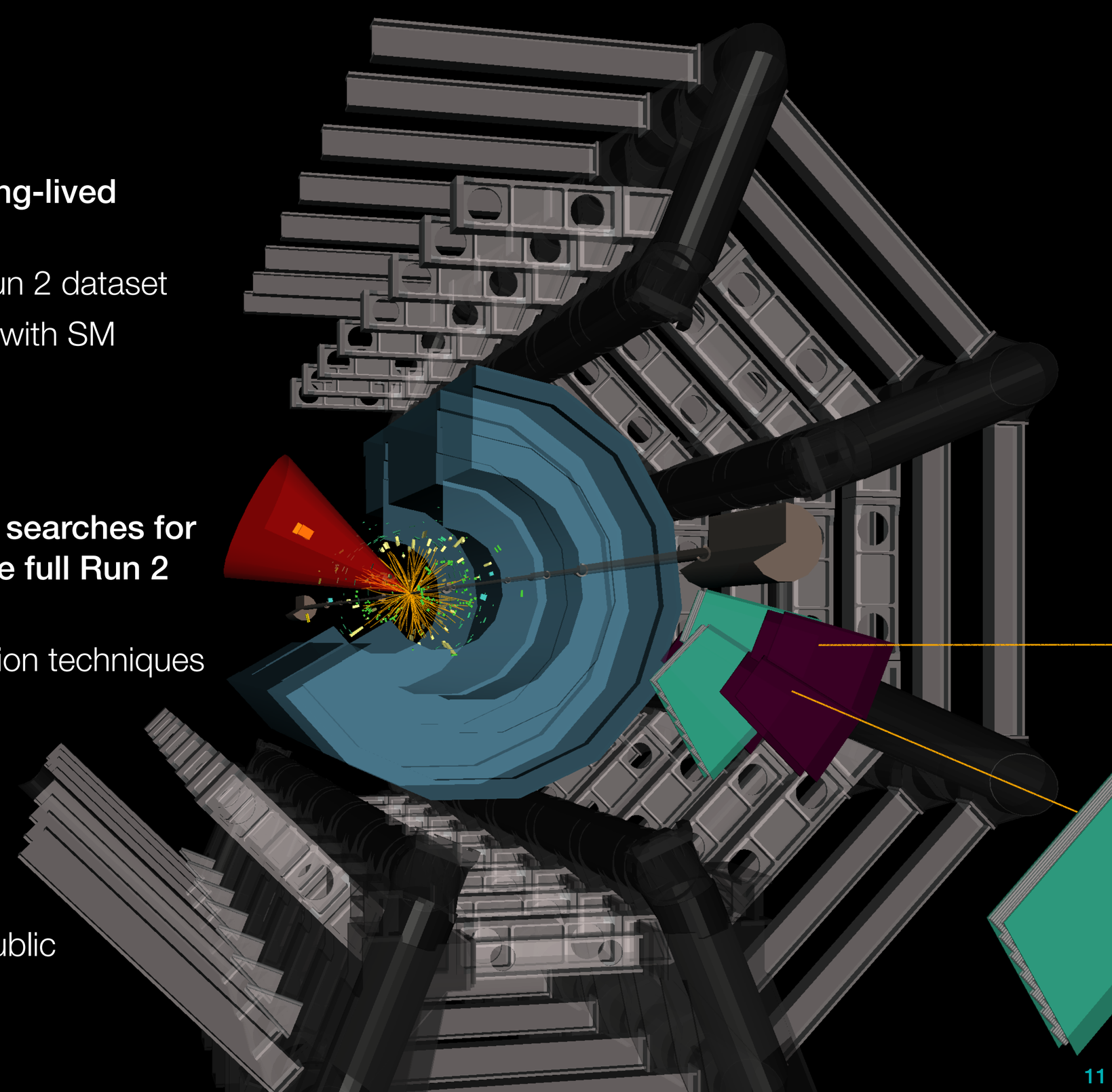
Conclusion

- **New and updated BSM searches for long-lived particles**
  - Exploring the large and high quality Run 2 dataset
  - For now the data remains compatible with SM predictions
  - Stringent limits set in various models

- **Many new and updated results of BSM searches for long-lived particles yet to come with the full Run 2 dataset**
  - Benefitting from improved reconstruction techniques

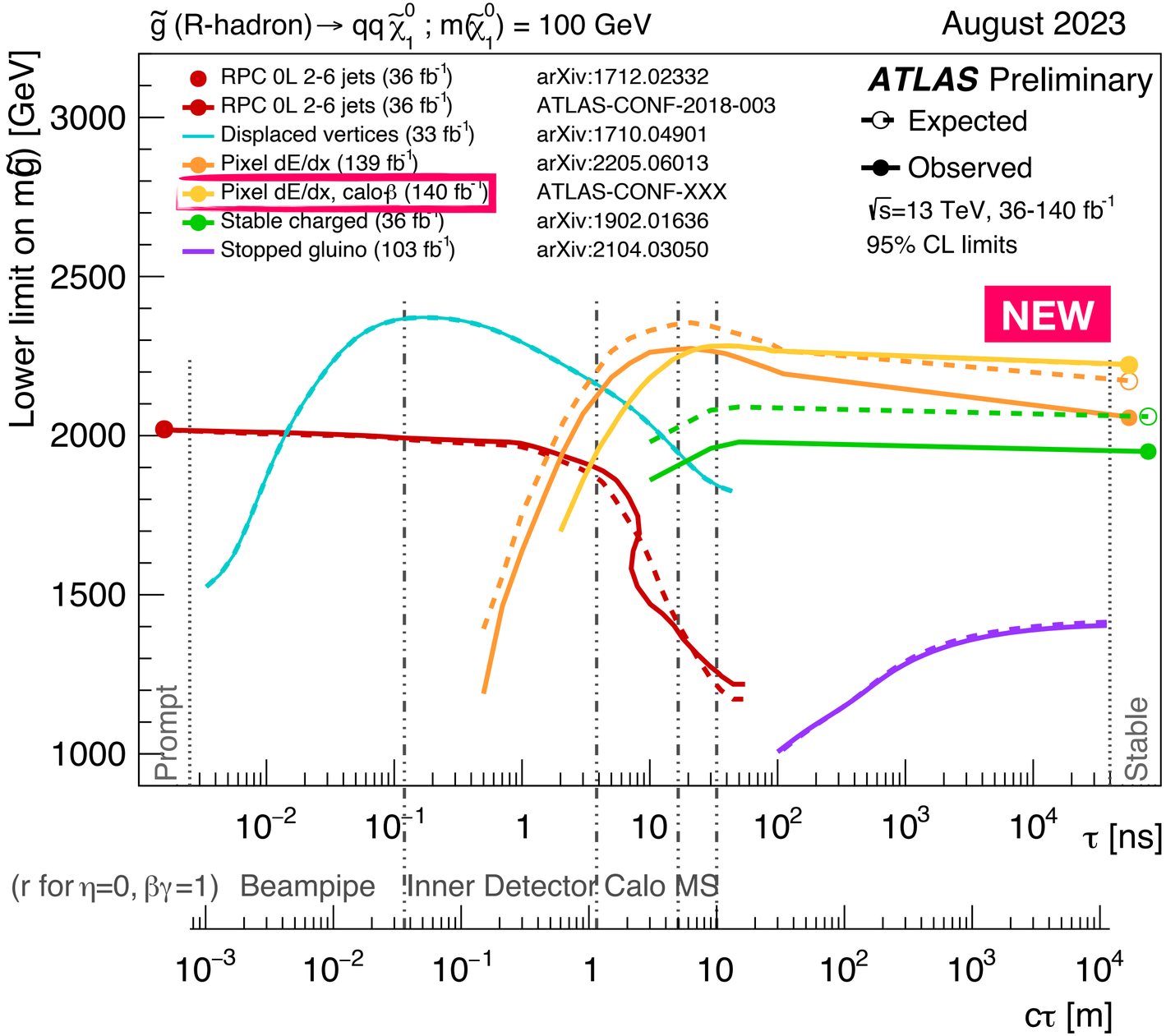
- **Stay tuned for the first Run 3 results utilising novel trigger and analysis approaches**

- More results: ATLAS Exotics and SUSY public results

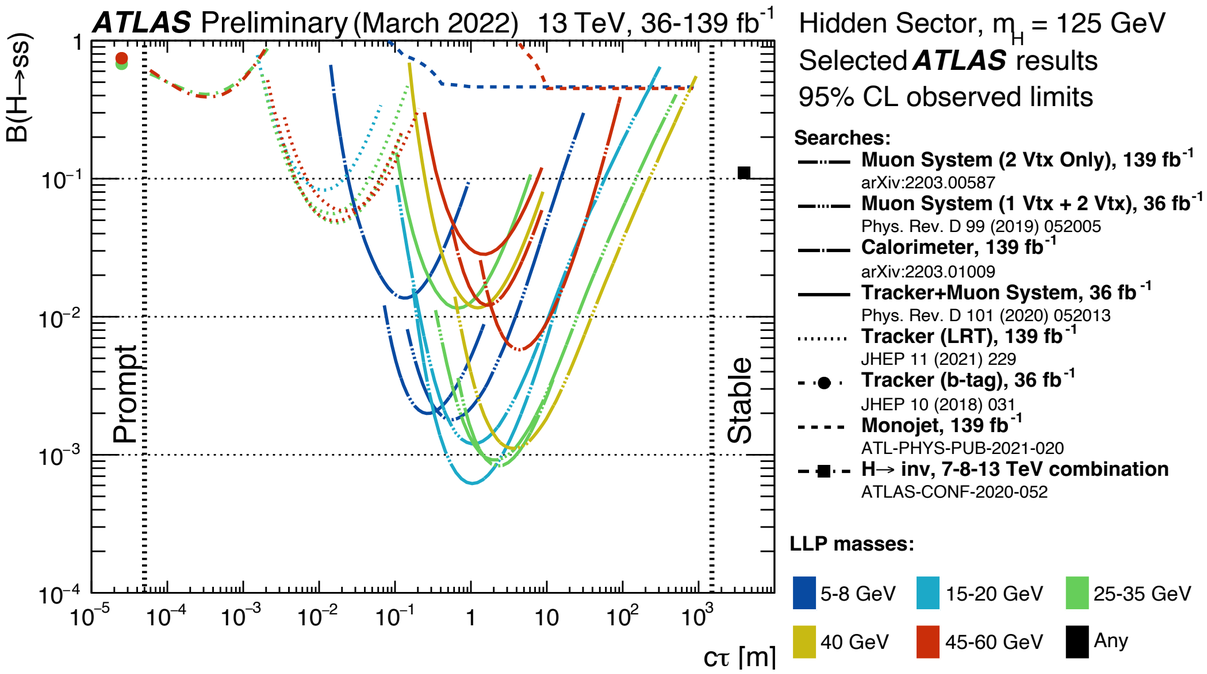


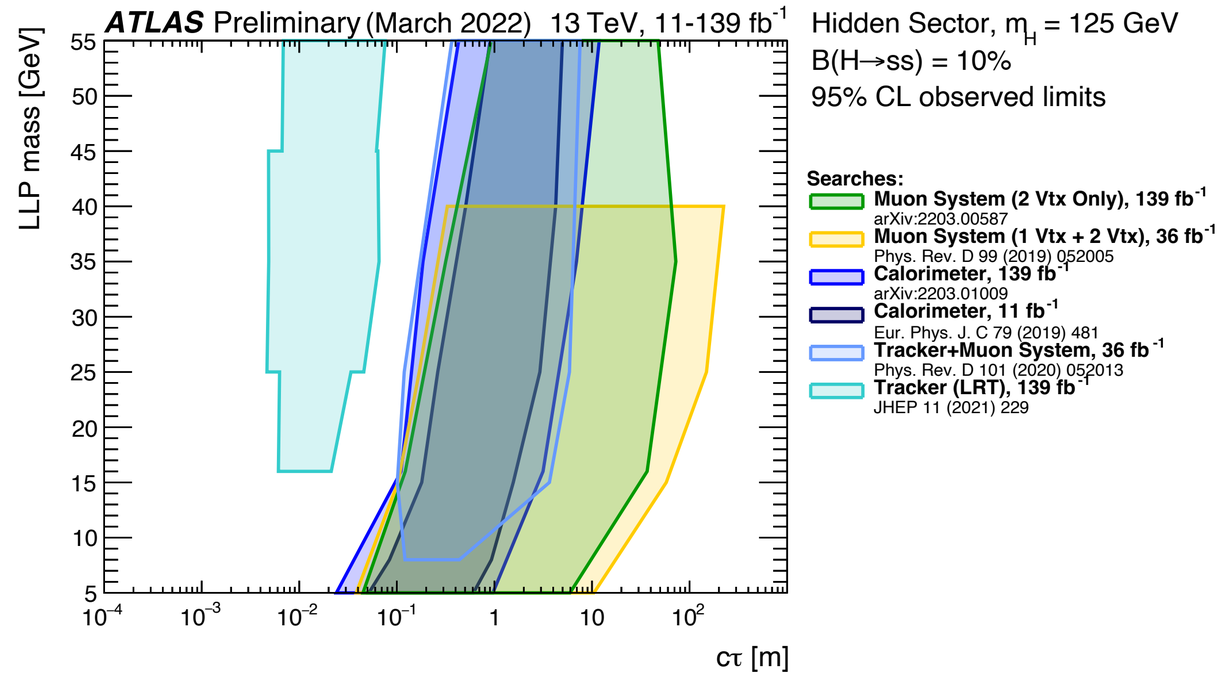
backup

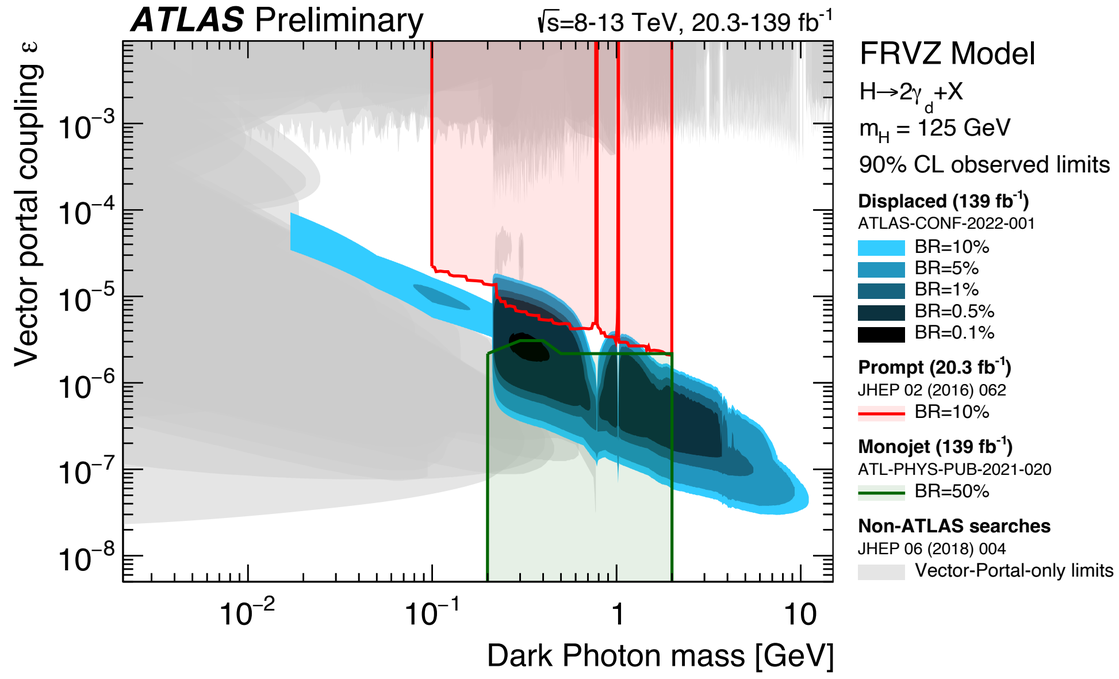
SUMMARY PLOTS - SUSY



SUMMARY PLOTS - HIDDEN SECTOR & DARK PHOTONS





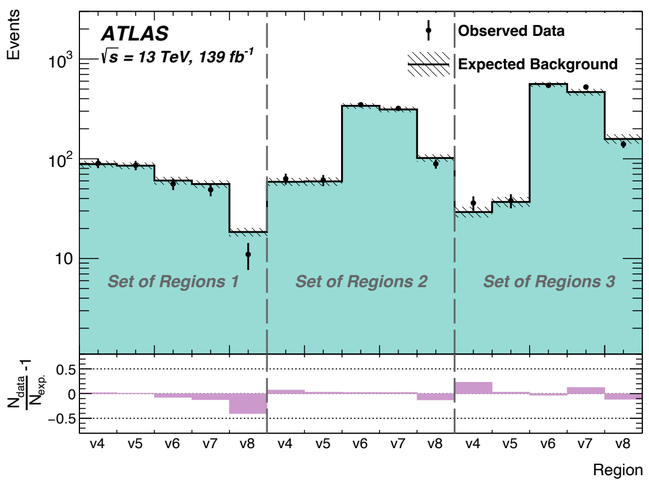


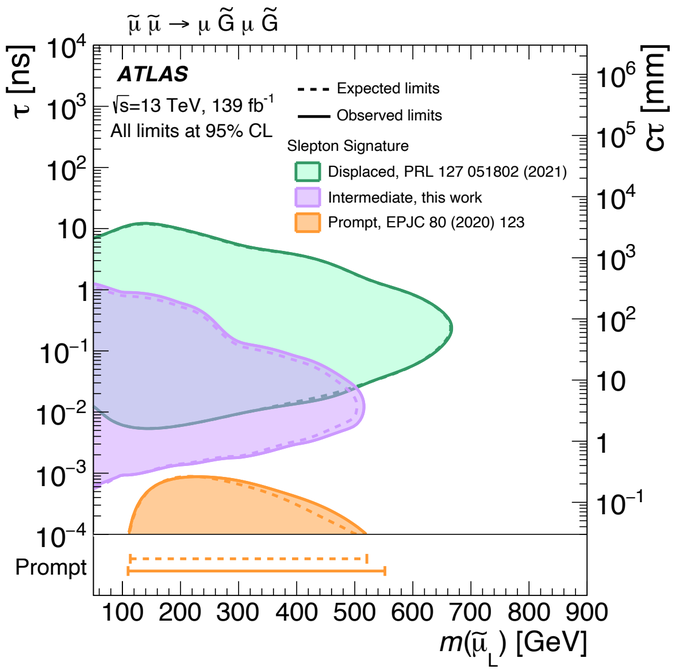
bonus plots

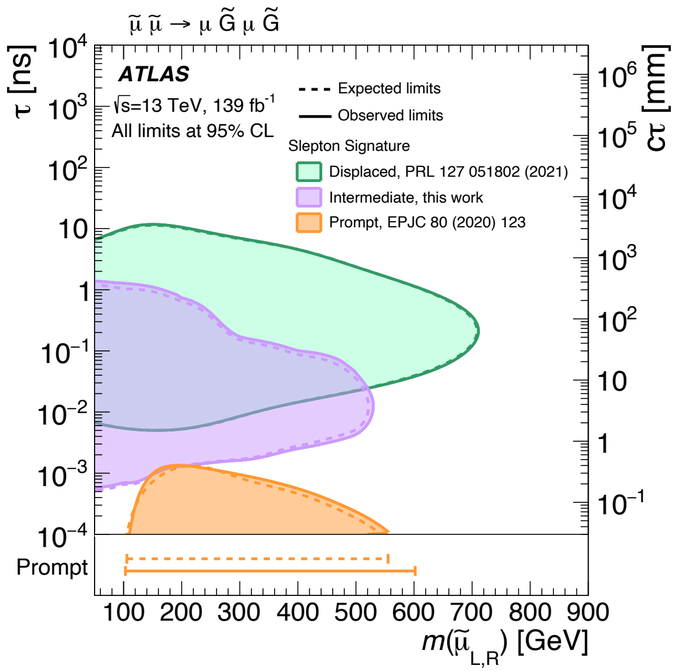
Micro-Displaced Muons

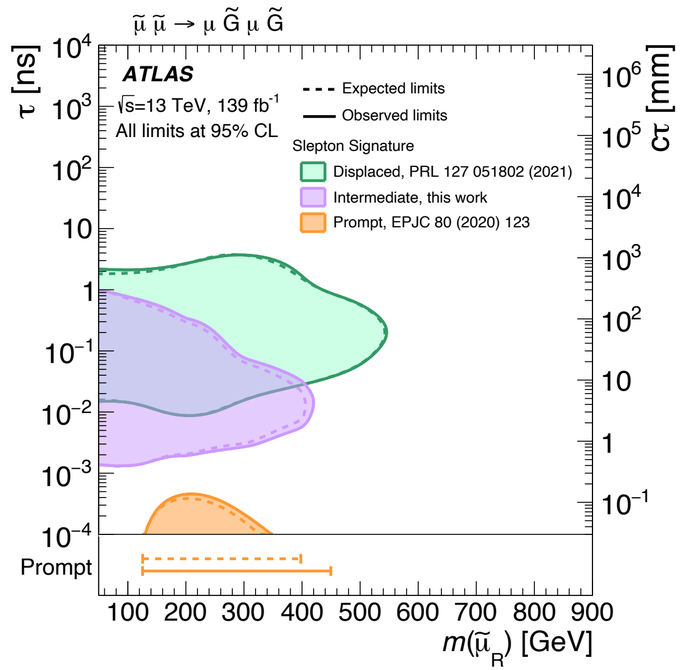
Set of Regions	Lower displacement region	Higher displacement region	Threshold $m_{\mu^+\mu^-}$	Additional cut
1	$0.1 \leq \lvert d_0 \rvert < 0.3$	$0.6 \leq \lvert d_0 \rvert < 3$ mm	200 GeV	-
2	$0.1 \leq \lvert d_0 \rvert < 0.3$	$0.6 \leq \lvert d_0 \rvert < 3$ mm	140 GeV	-
3	$0.1 \leq \lvert d_0 \rvert < 0.3$	$0.6 \leq \lvert d_0 \rvert < 1.3$ mm	125 GeV	$\Delta R_{\mu^+\mu^-} > 3$ rad.

Set of Regions	Expected N_H^{bkg}	Observed N_H^{data}	$\langle A\epsilon\sigma \rangle_{\text{obs}}^{95}$[fb]	S_{obs}^{95}	S_{exp}^{95}	CL_B	$p(s=0)$ (Z)
1	2.1 ± 0.8	1	0.02	3.3	$4.2^{+2.5}_{-1.4}$	0.27	0.50 (0.00)
2	12.5 ± 5.2	7	0.04	5.2	$8.5^{+4.0}_{-2.7}$	0.08	0.50 (0.00)
3	17.2 ± 7.4	14	0.06	8.9	$10.5^{+5.0}_{-3.1}$	0.26	0.50 (0.00)

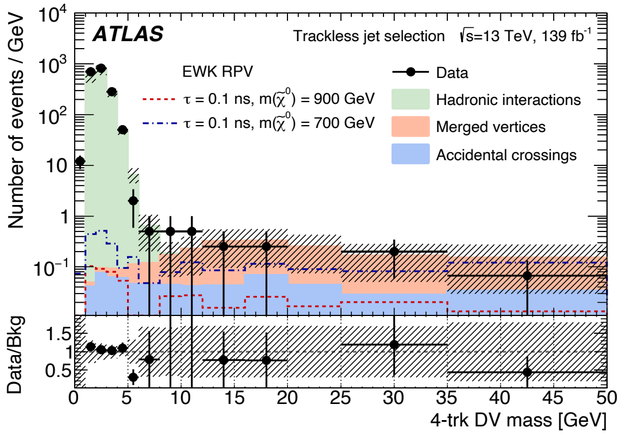


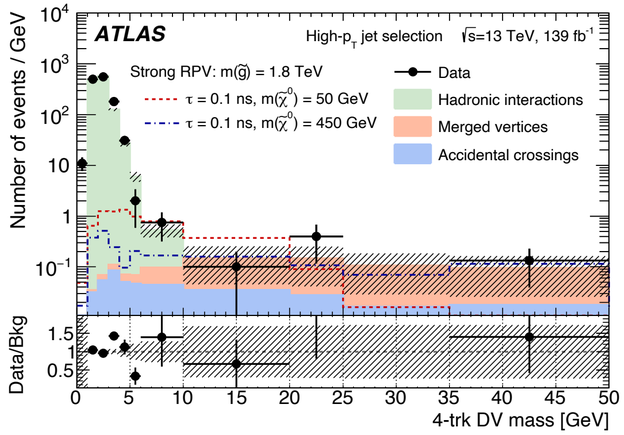


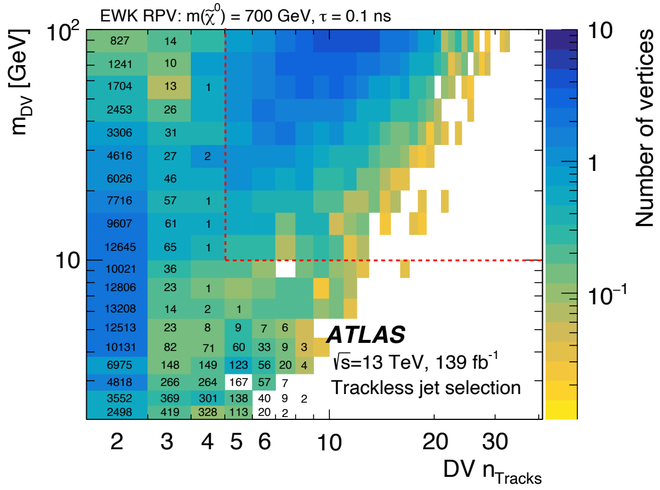


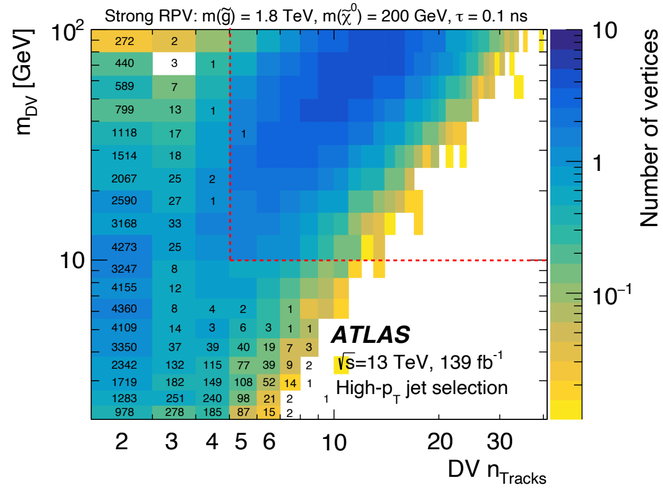


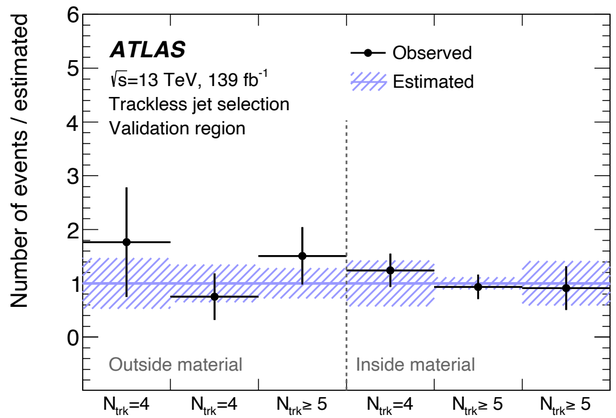
DISPLACED VERTICES + JETS

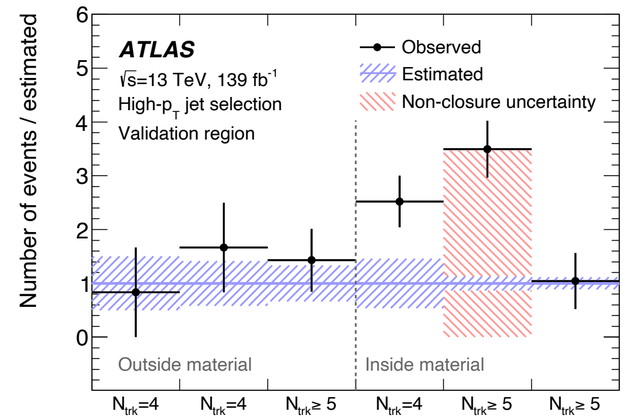




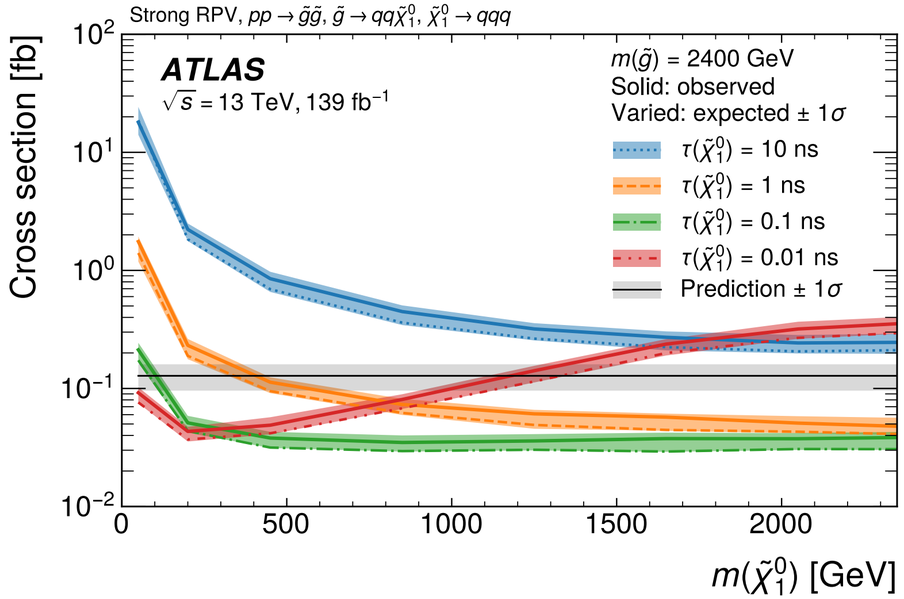


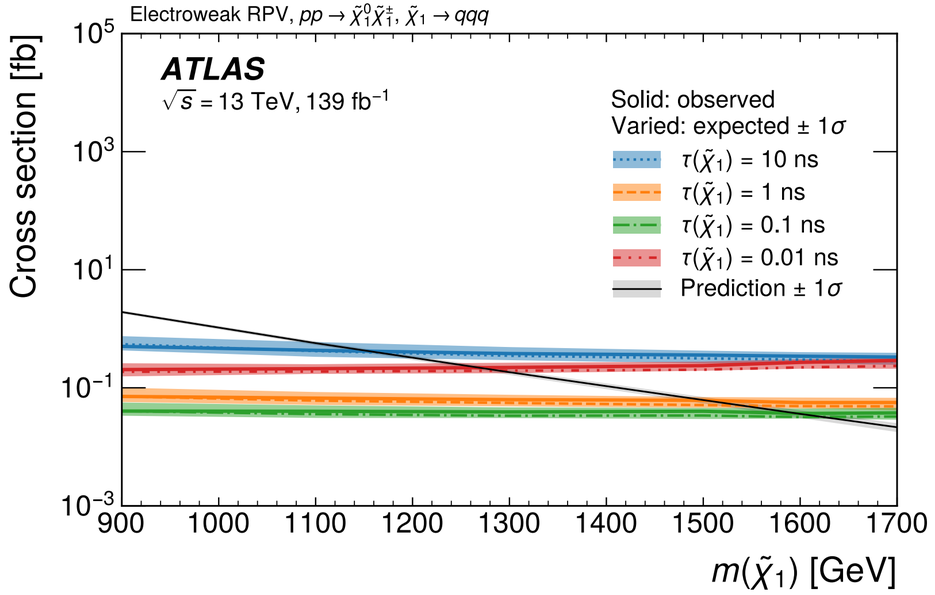




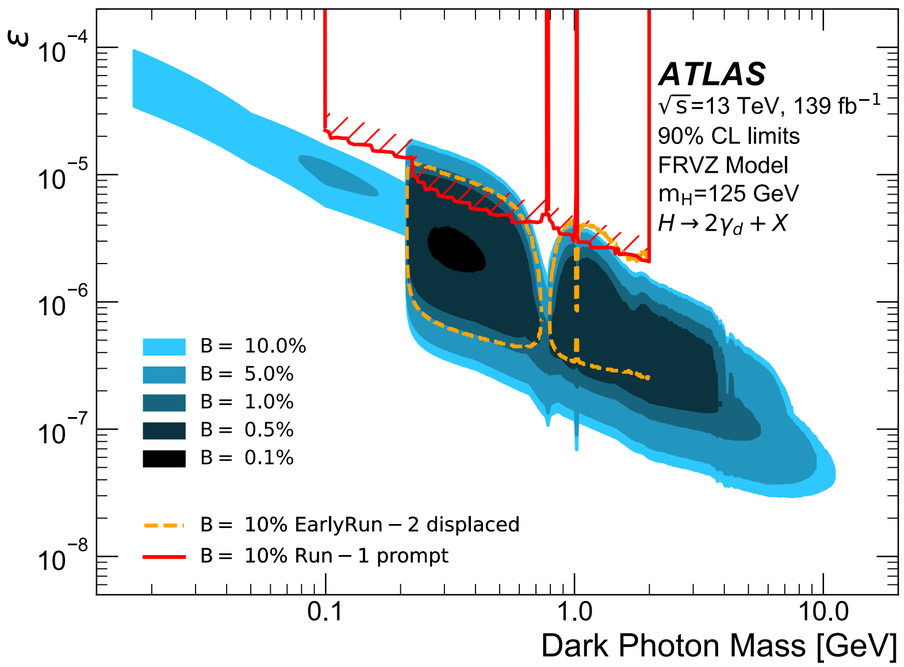


Signal Region	Observed	Expected	S^{95}_{obs}	S^{95}_{exp}	$\langle\sigma_{\text{vis}}\rangle^{95}_{\text{obs}}$ [fb]
High-p_{T} jet SR	1	$0.46^{+0.27}_{-0.30}$	3.8	$3.1^{+1.0}_{-0.1}$	0.027
Trackless jet SR	0	$0.83^{+0.51}_{-0.53}$	3.0	$3.4^{+1.3}_{-0.3}$	0.022

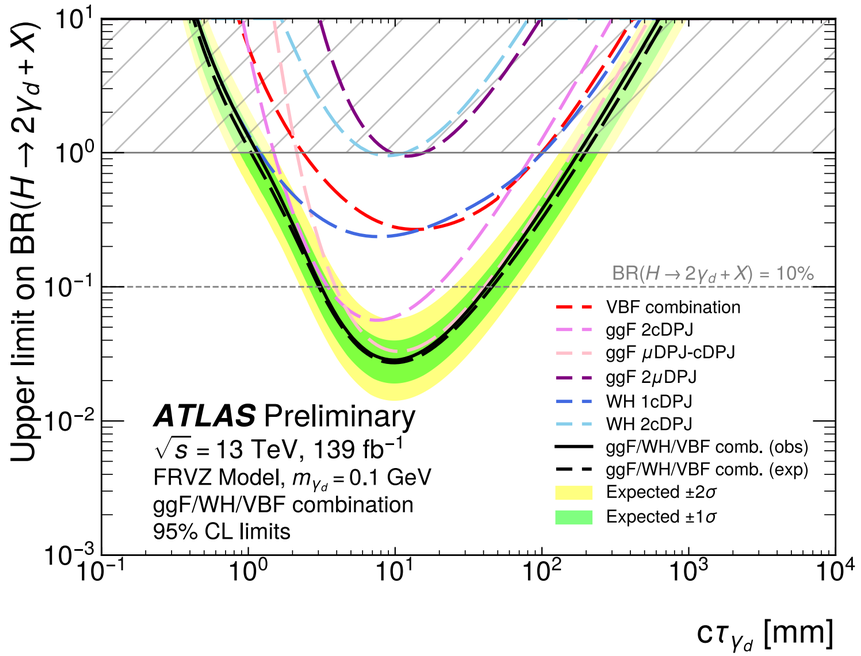


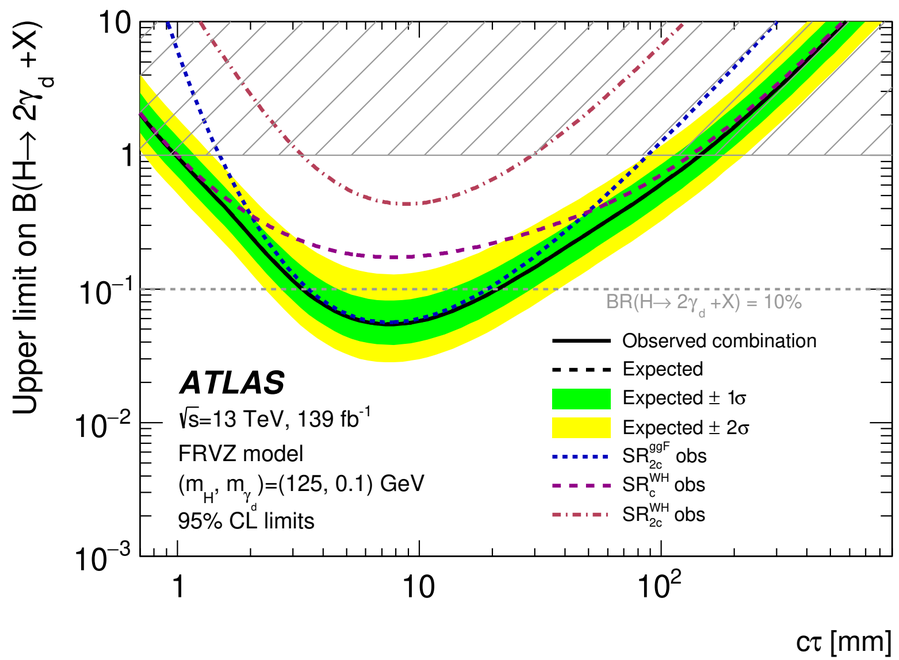


DISPLACED LEPTON JETS

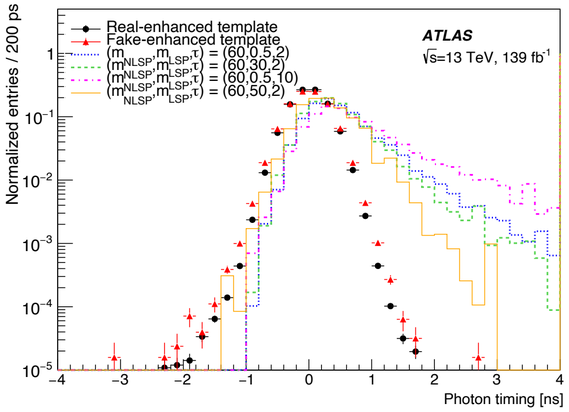


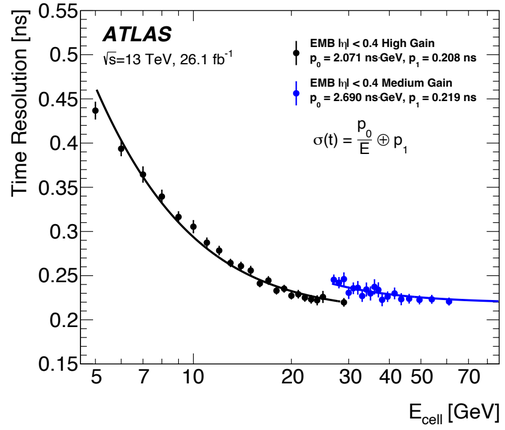
Requirement / Region	muonic SR_{μ}	calo $SR_{c}^{L/H}$
Number of DPJs	≥ 1	
Leading DPJ type	μDPJ	caloDPJ
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$ Tri-muon MS-only Muon narrow-scan	$E_{\mathrm{T}}^{\mathrm{miss}}$
$p_{\mathrm{T}}(\mathrm{jet})$ $[GeV]$	> 30	
N_{jet}	≥ 2	
m_{jj} $[GeV]$	≥ 1000	
$\lvert\Delta\eta_{\mathrm{jj}}\rvert$	> 3	
$\lvert\Delta\phi_{\mathrm{jj}}\rvert$	< 2.5	
N_{ℓ}	0	
$N_{b\text{-jet}}$	0	
C_{DPJ}	> 0.7	-
$\Delta\phi_{\mathrm{min}}$	-	> 0.4
$E_{\mathrm{T}}^{\mathrm{miss}}$ $[GeV]$	> 100	SR_{c}^{L}: $[100, 225]$ SR_{c}^{H}: > 225

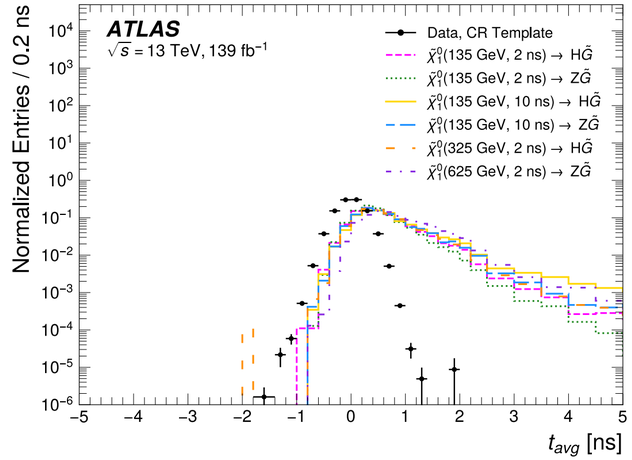


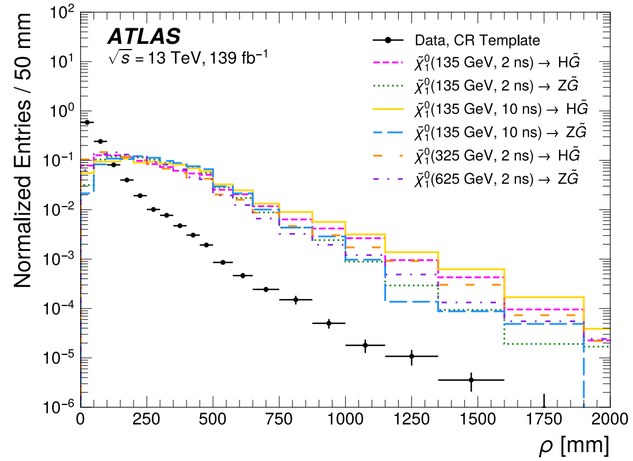


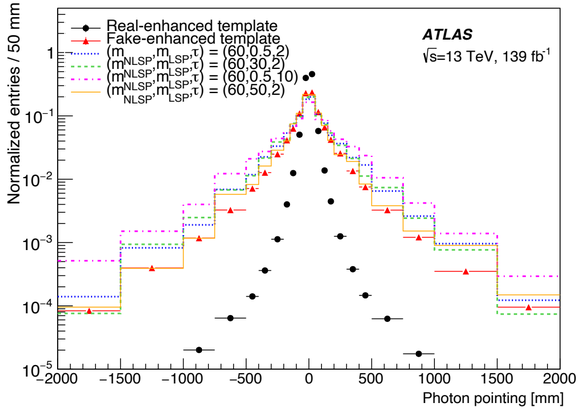
NON-POINTING & NON-PROMPT PHOTONS

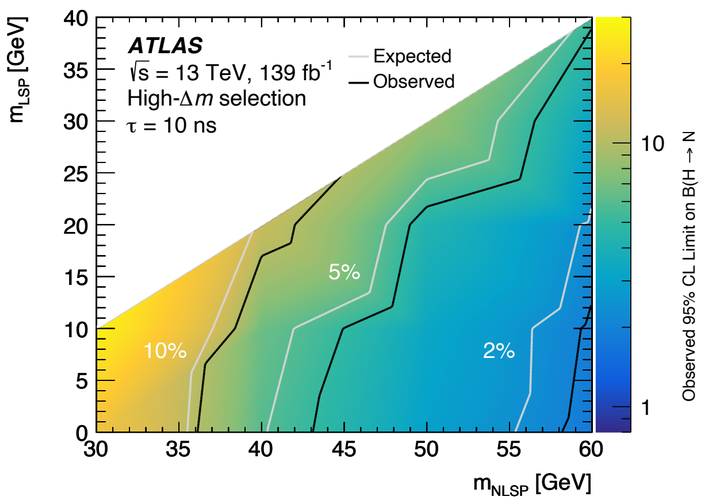


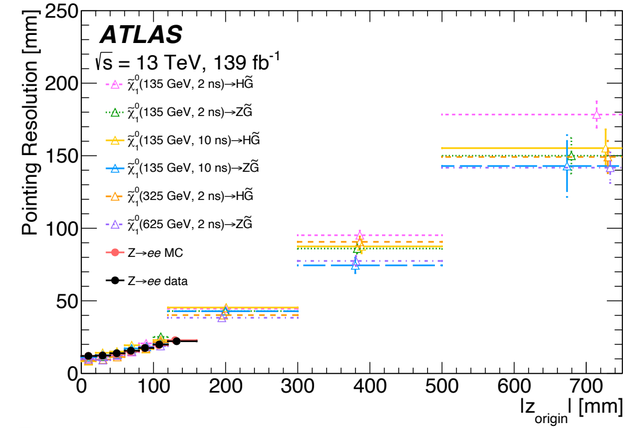


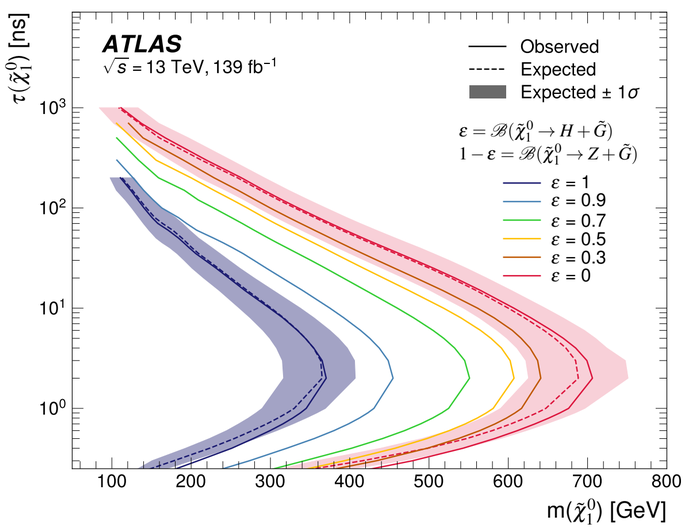




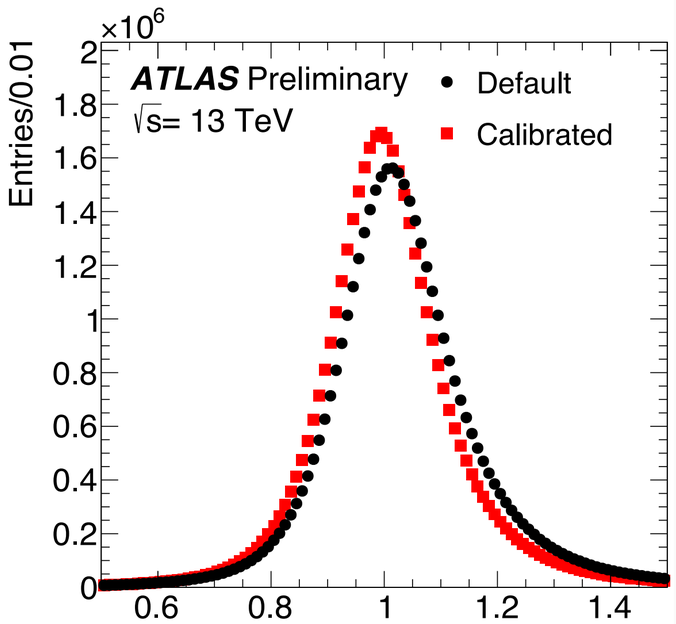


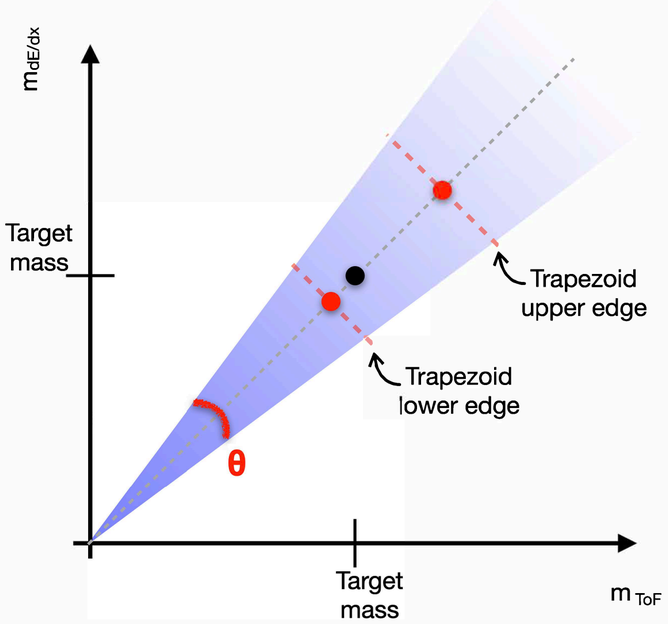


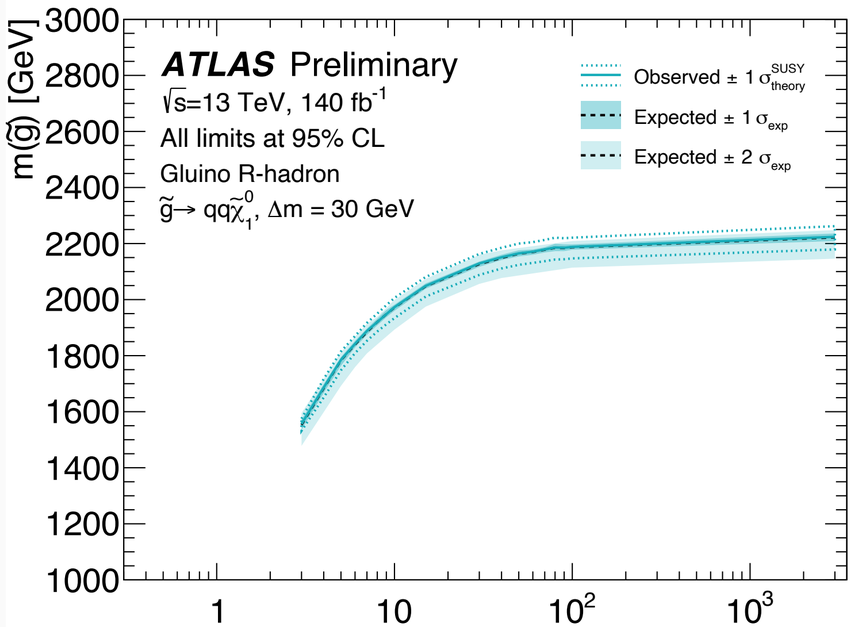


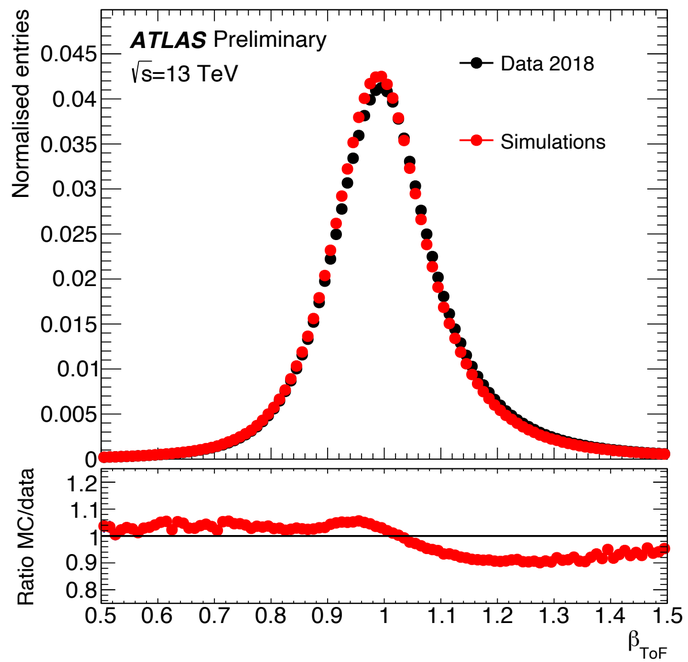


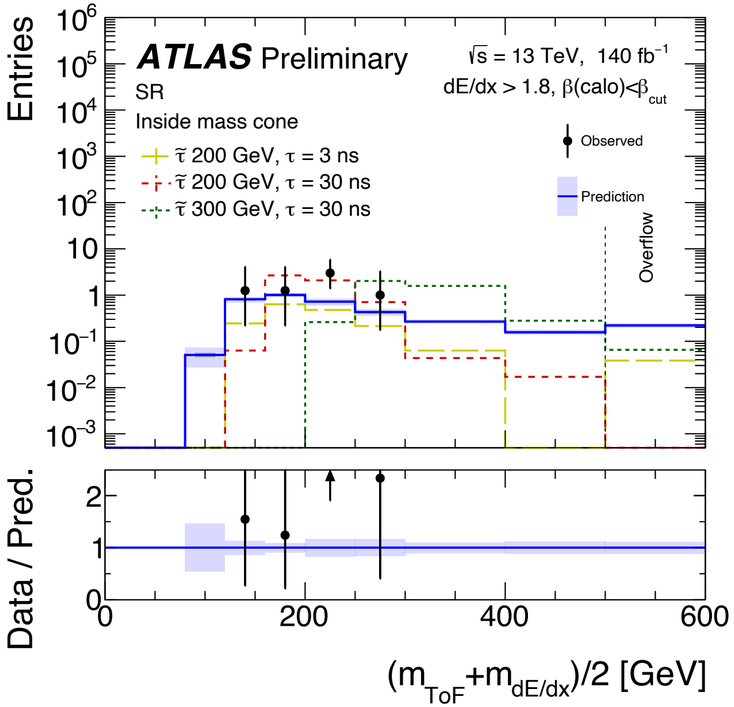
LARGE dE/dx

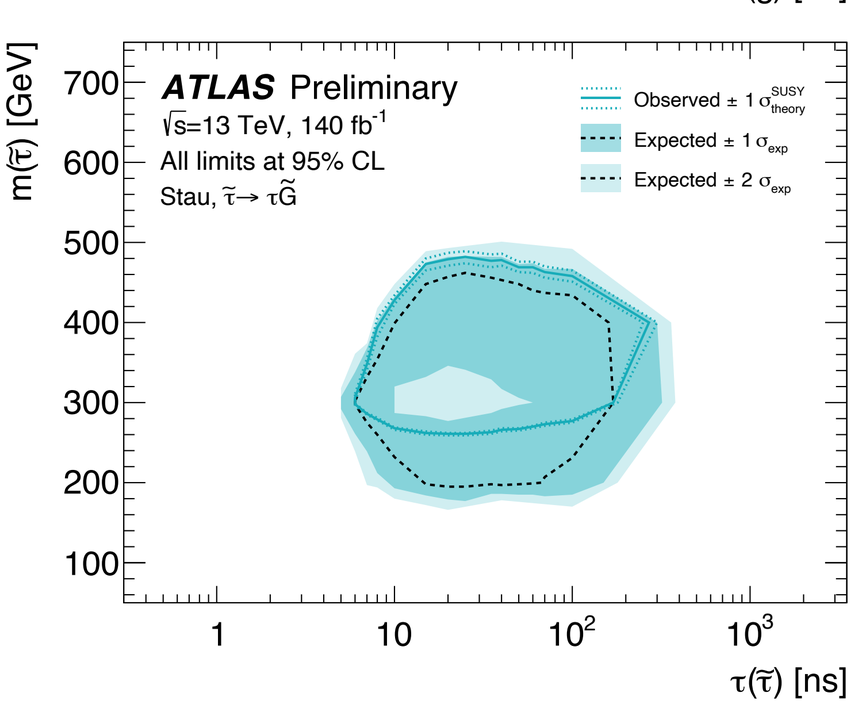






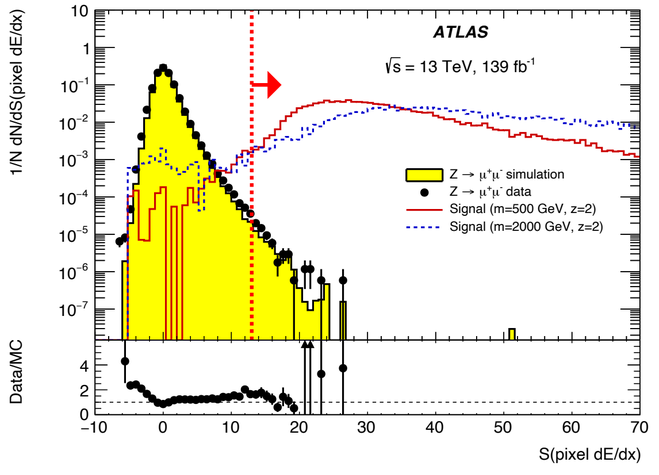


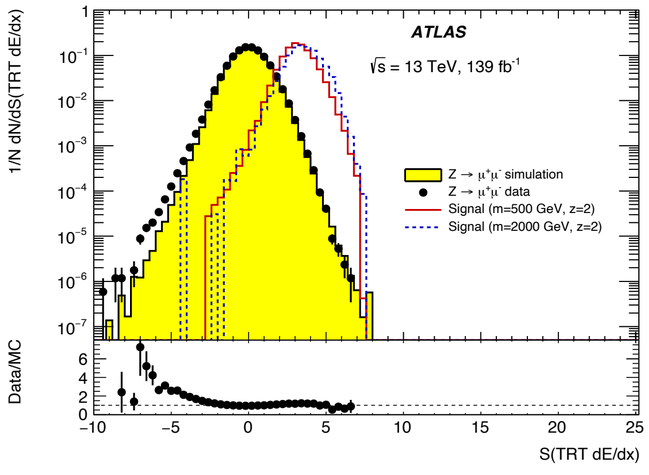


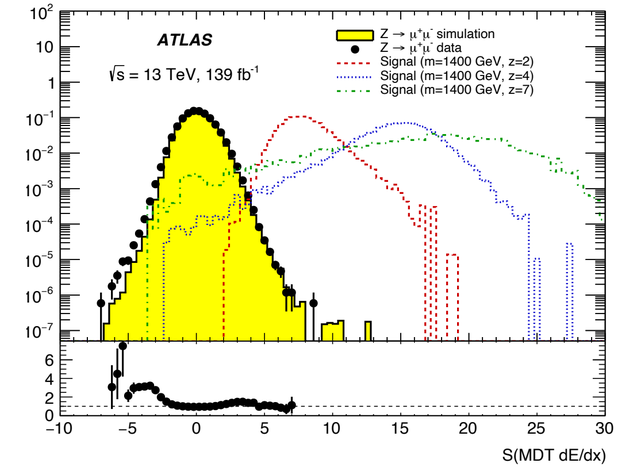


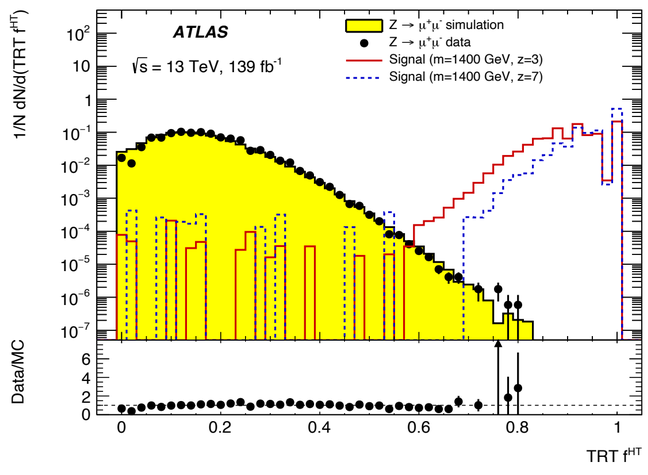
τ(g̃) [ns]

MULTI-CHARGED PARTICLES

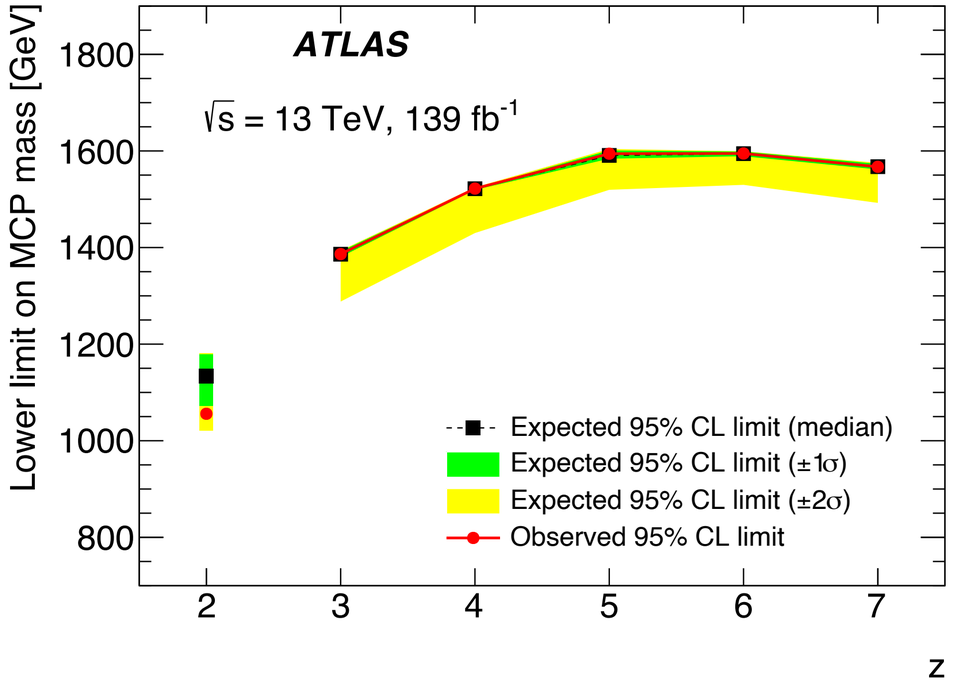




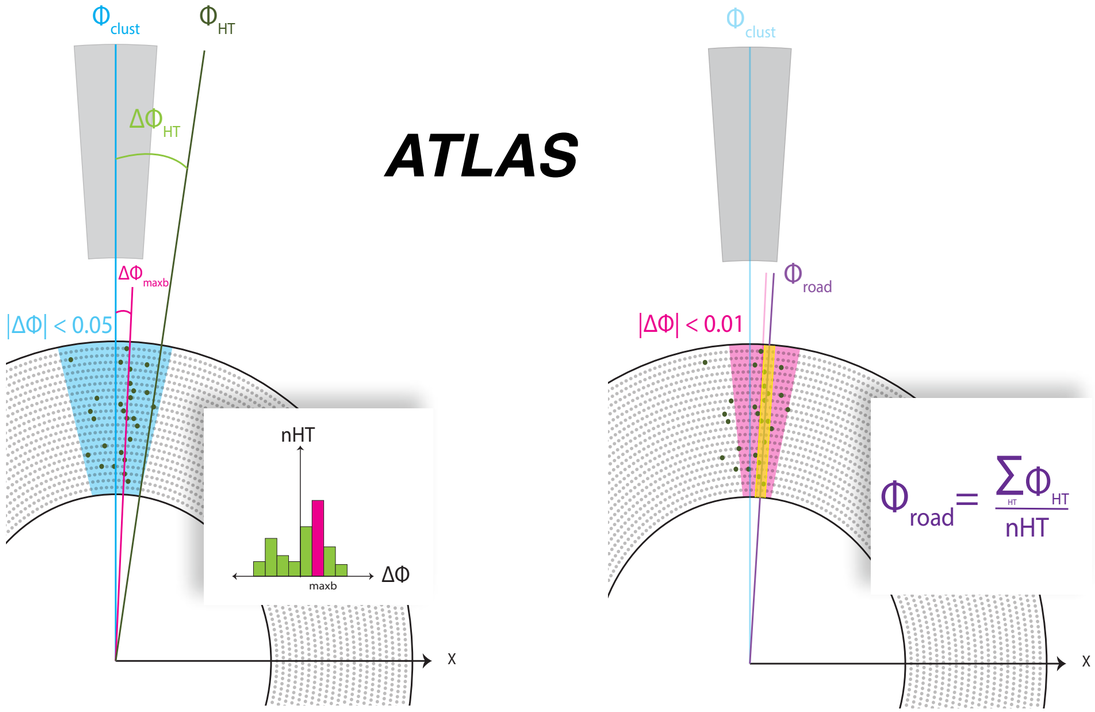


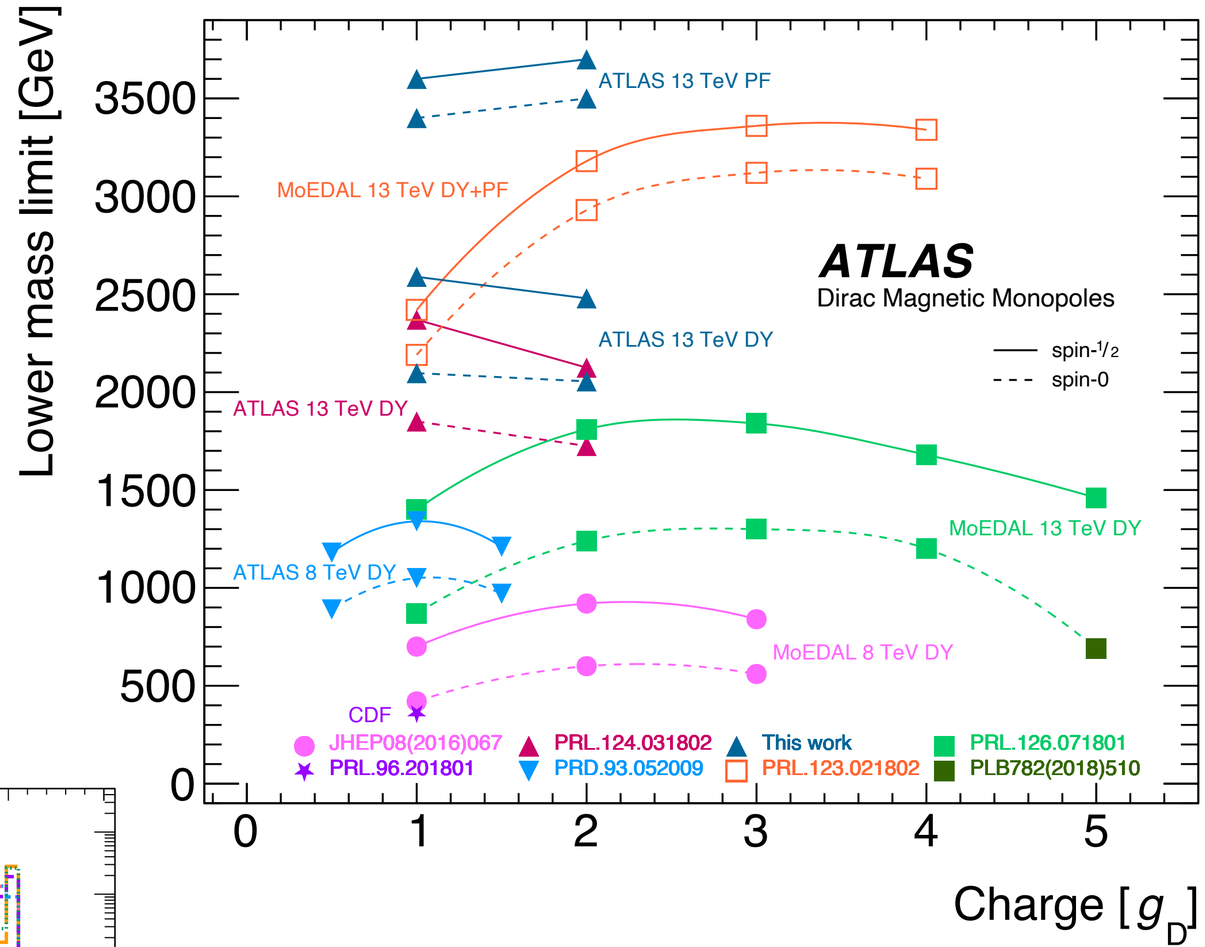


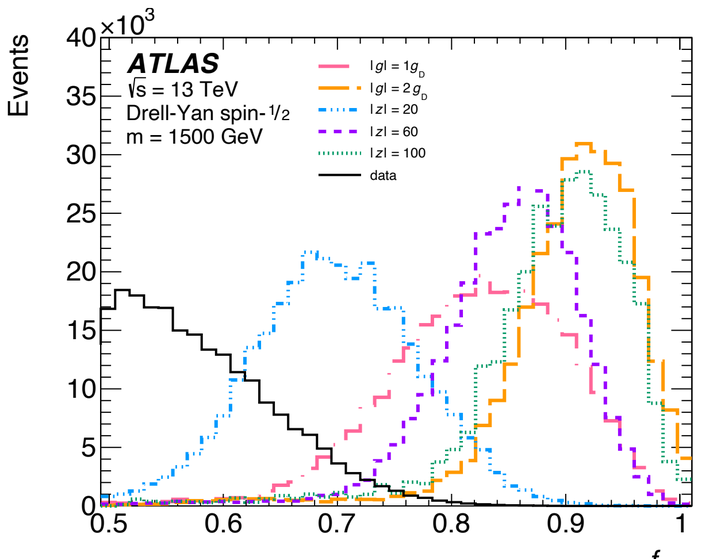
Search category	Preselection	Tight selection	Final selection
$z = 2$	Combined muon with: 'medium' identification criteria, $p_{\mathrm{T}}^{\mu}/z > 50\,\mathrm{GeV}$, $p_{\mathrm{T}}/z > 10\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.0$, no other particles with $p_{\mathrm{T}}/z > 0.5\,\mathrm{GeV}$ within $\Delta R = 0.01$	Preselected candidate with $S(\text{pixel } dE/dx) > 13$	Tightly selected candidate with: $S(\text{TRT } dE/dx) > 2$, $S(\text{MDT } dE/dx) > 4$
$z > 2$		–	Preselected candidate with: TRT $f^{\mathrm{HT}} > 0.7$, $S(\text{MDT } dE/dx) > 7$

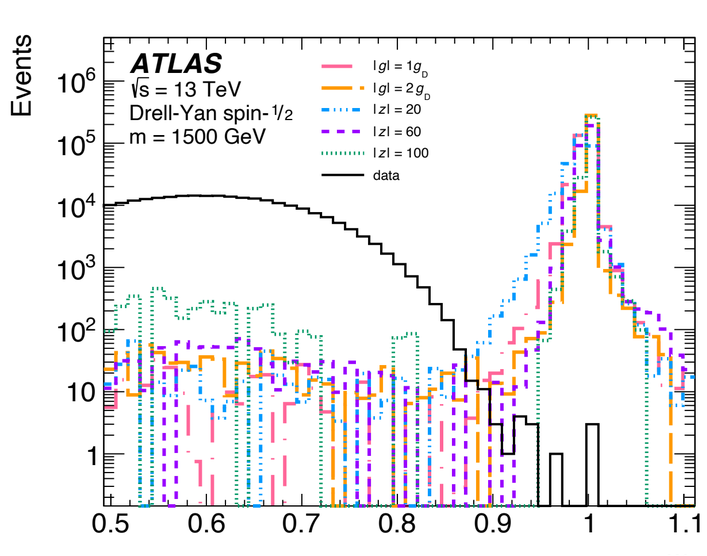


MAGNETIC MONOPOLES/HECOS/HIPS





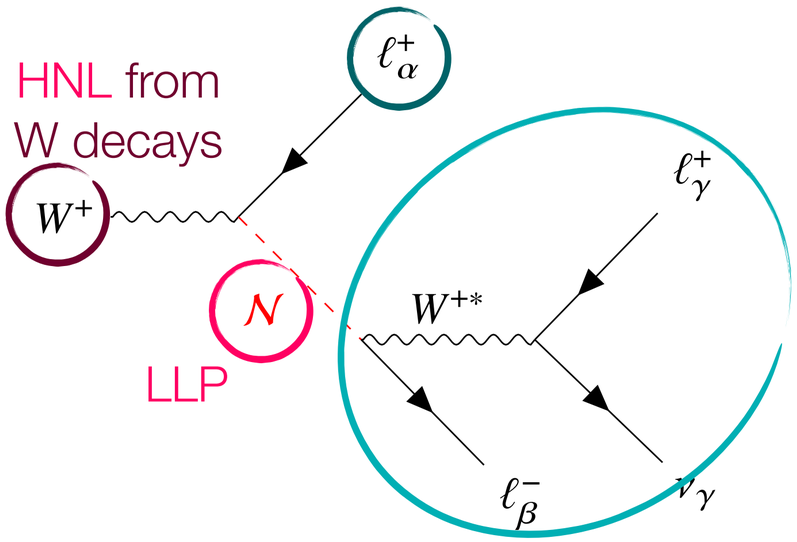




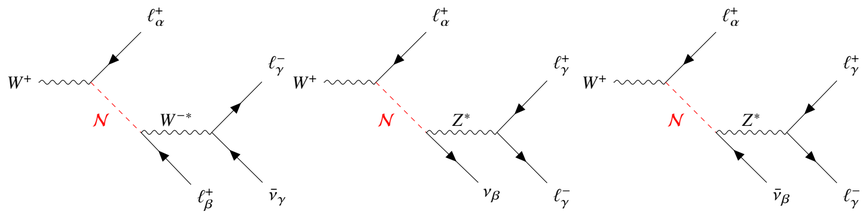
bonus analyses

arXiv:2204.11988

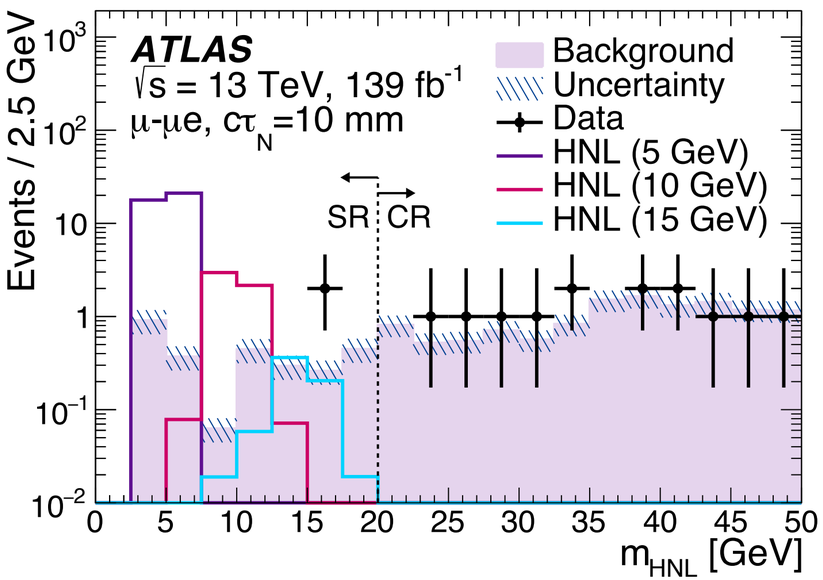
Displaced Heavy Neutral Leptons



Events must contain a **prompt lepton (trigger)** and a **DV comprising a pair of leptons with opposite-sign**



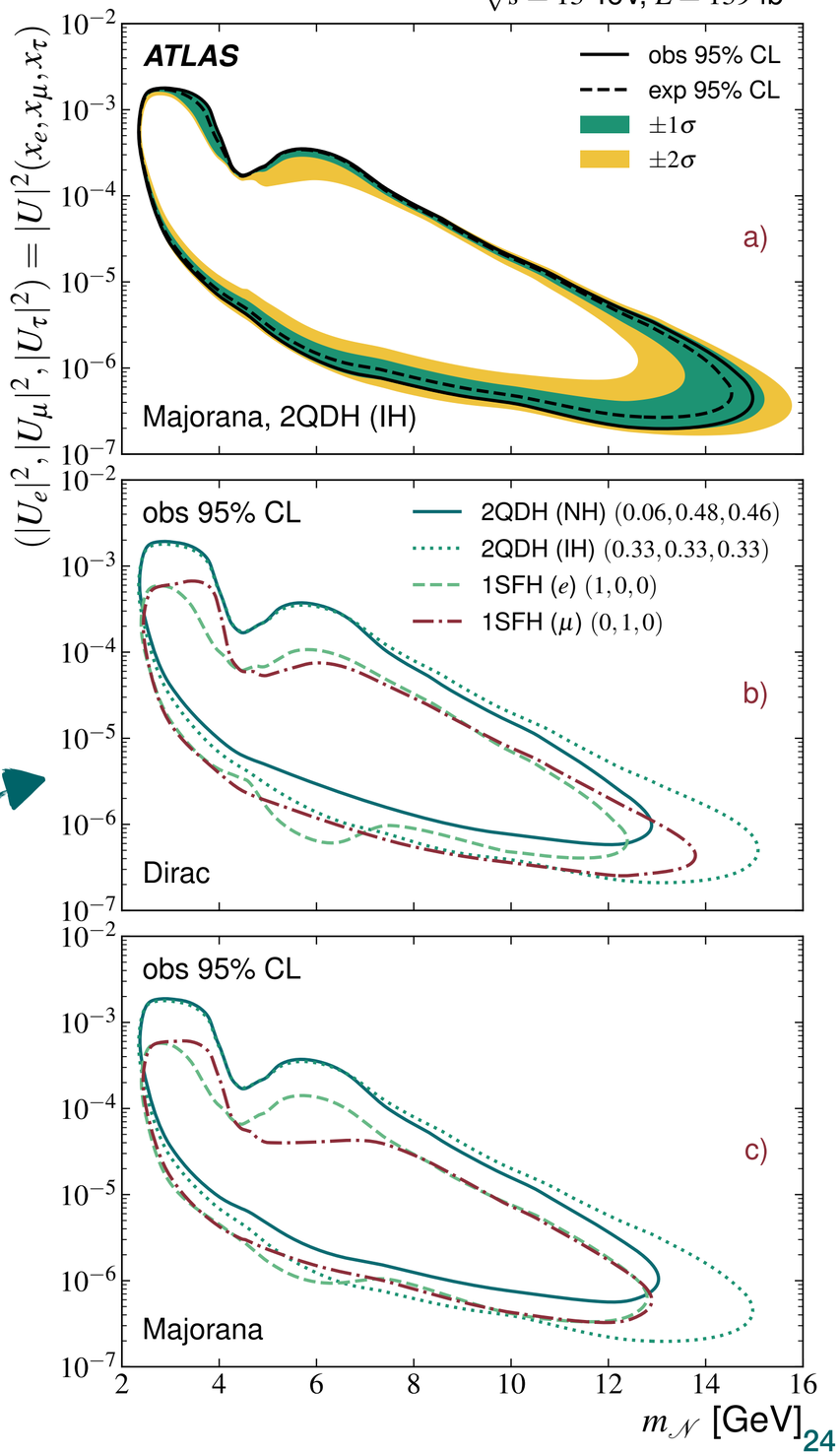
- Backgrounds from material interactions, $Z \to ll$, cosmics
- **Dedicated track reconstruction** for non-prompt particles (Large Radius Tracking)
- Final SR selection **targeting $m_{HNL} < 20$ GeV**



Limits are set on squared mixing parameters of HNL with left-handed neutrino

Observed limits **exclude a region with wider ranges of $|U_\mu|^2$ and m_N than previously excluded by ATLAS**

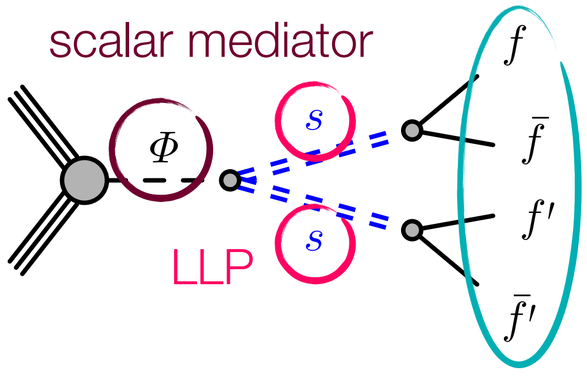
Limits on $|U_e|^2$ are novel in ATLAS



arXiv:2203.01009

DISPLACED HADRONIC JETS IN THE CALORIMETER

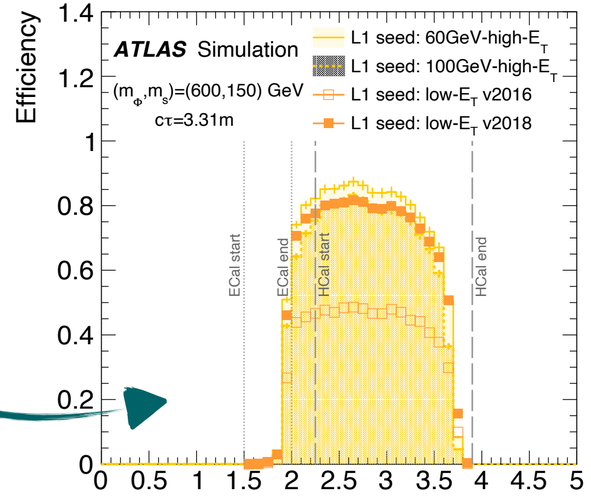
Hidden sector with scalar mediator

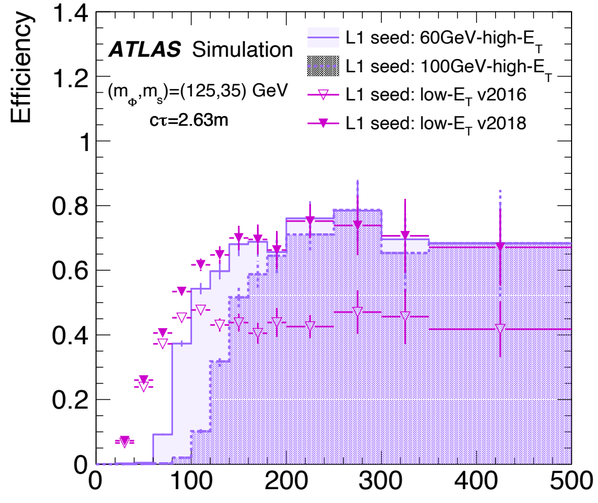


four fermion final state

Dedicated trigger

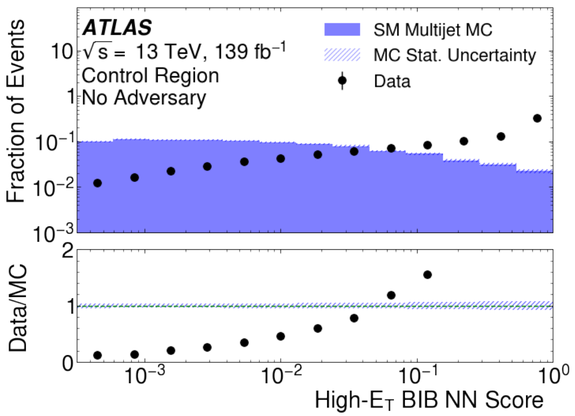
- narrow jets
- imbalanced energy deposits
- track isolation

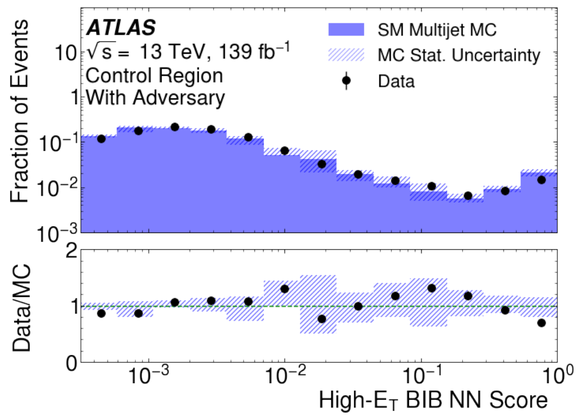


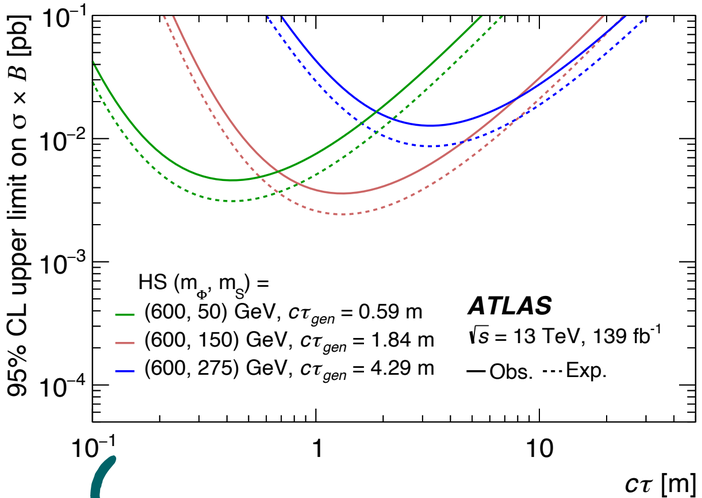


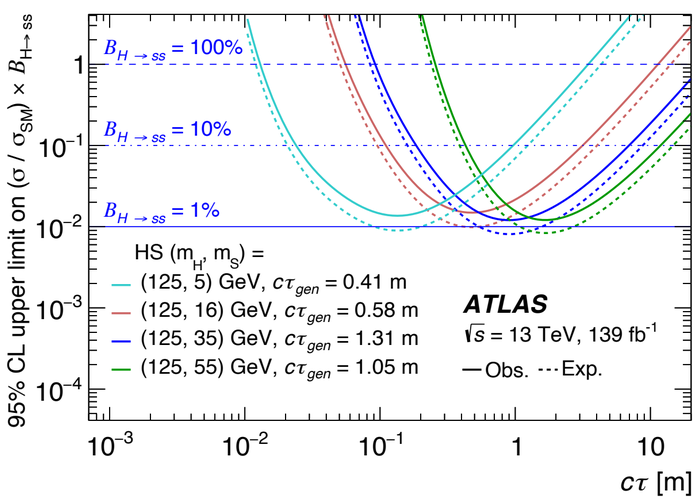
Displaced-jet tagger based on Neural Network (NN) discriminating against multi-jet and beam-induced background

- **Adversary NN** to mitigate data-MC mis-modelling





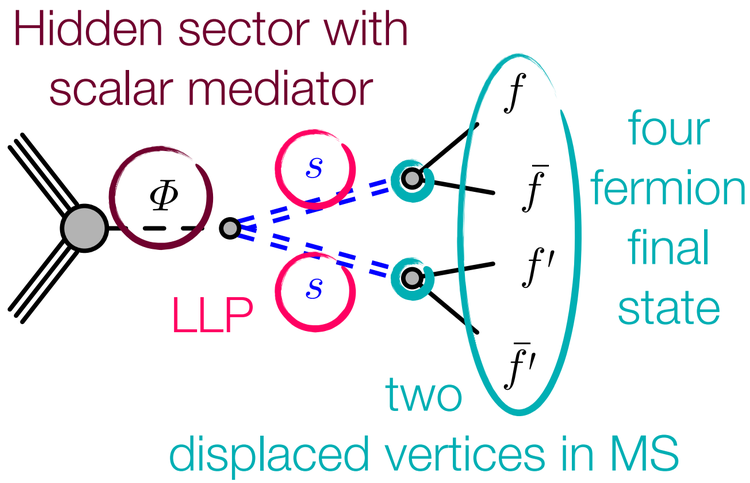




Limits are set on HS benchmark models with **mediator masses** ranging from **60 GeV to 1 TeV** and **LLP scalar masses** ranging from **5 GeV to 475 GeV**

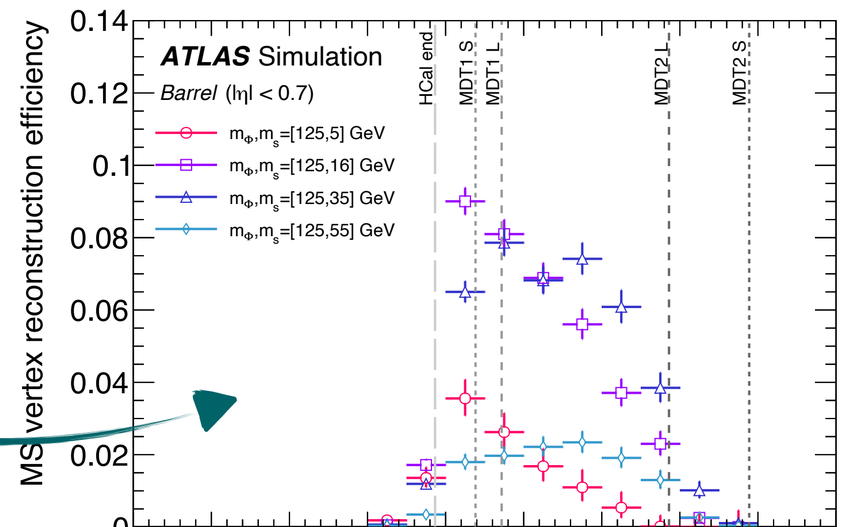
arXiv:2203.00587

DISPLACED HADRONIC JETS IN MUON SPECTROMETER



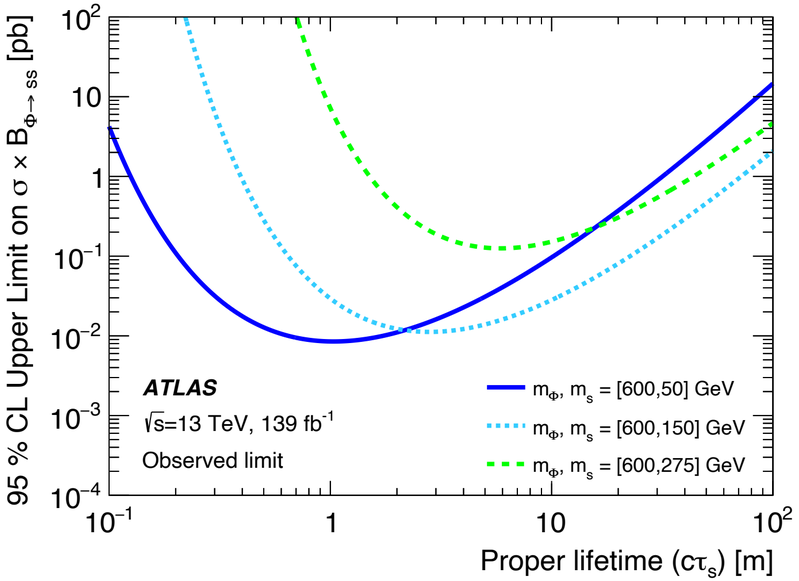
Dedicated trigger on Muon Cluster activity

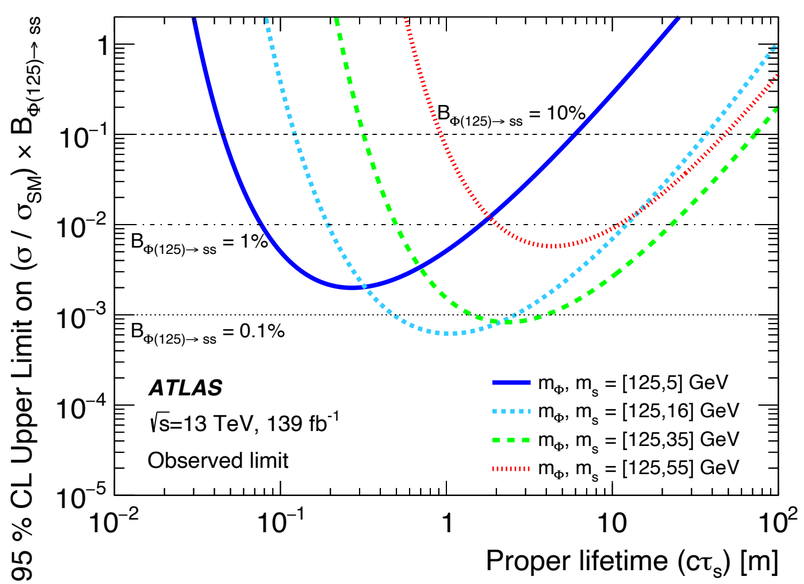
+ **Dedicated algorithm to reconstruct DVs** with low-momentum tracks in a busy environment



Main backgrounds: **punch-through jets** and **non-collisions backgrounds**

- Veto activity in Calorimeters and ID tracker
- Require two DVs per event





For mediator mass, $m_H = 125$ GeV:
first exclusion limits for branching fractions below 0.1%

Branching fractions above 10% are excluded at 95% CL for **LLP mean proper lifetimes ranging from 4 cm to 72.4 m**