Searches For Beyond The Standard Model Physics Using Challenging And Long-lived Signatures With The ATLAS Detector

35th Rencontres De Blois

Ian Ramirez-Berend

On Behalf Of The ATLAS Collaboration

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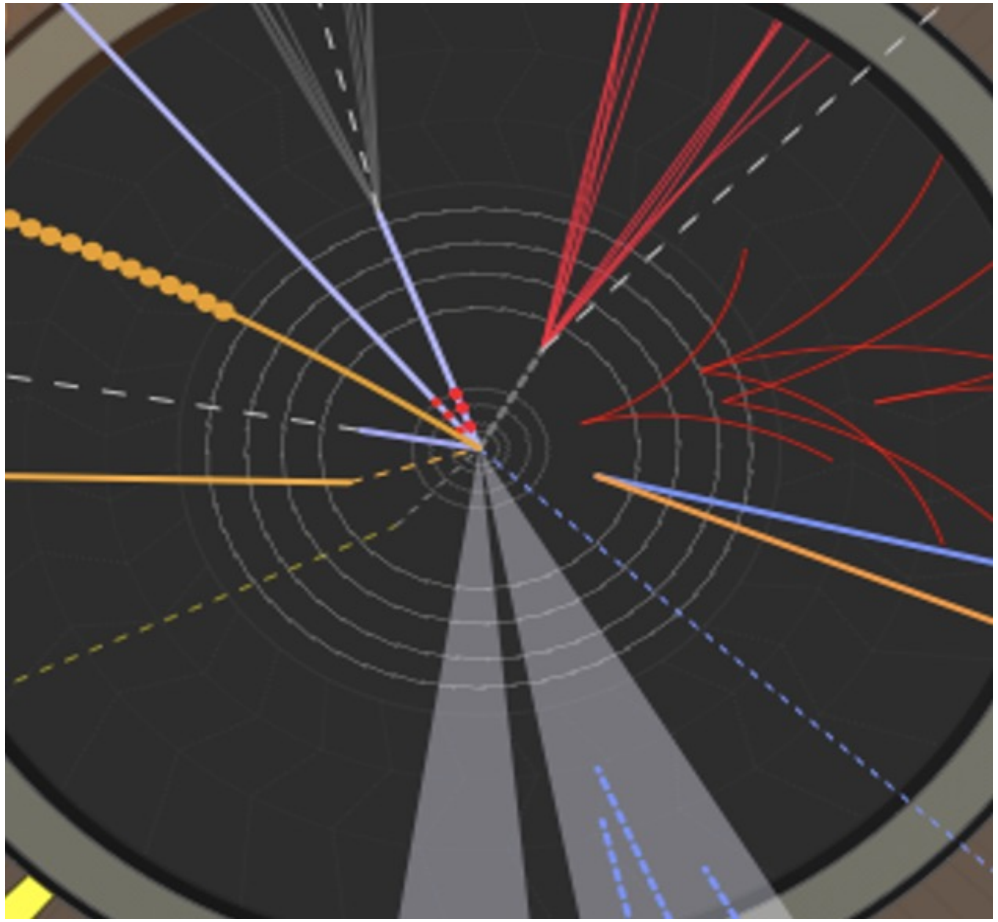
OVERVIEW

- Long-Lived (talks from Ben, Lisa, and Daniele) and Exotics event signatures serve as exciting and rich opportunities to probe Beyond the Standard Model (BSM) physics
- ATLAS searches for a wide variety of new physics scenarios, each one with unique event signatures and challenges
- 3 recent ATLAS results covered here

Carleton ATLAS



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INCLUDED ANALYSES

1. *Search for displaced leptons in 13 TeV and 13.6 TeV pp collisions with the ATLAS detector*
   CONF Note: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2024-011/
   Full Run 2 (140 fb^{-1}) + Partial Run 3 (56.3 fb^{-1})

2. *Search for neutral long-lived particles that decay into displaced jets in the ATLAS calorimeter in association with leptons or jets using pp collisions at $\sqrt{s} = 13$ TeV*
   Submitted to JHEP, arXiv: 2407.09183
   Full Run 2 (140 fb^{-1})

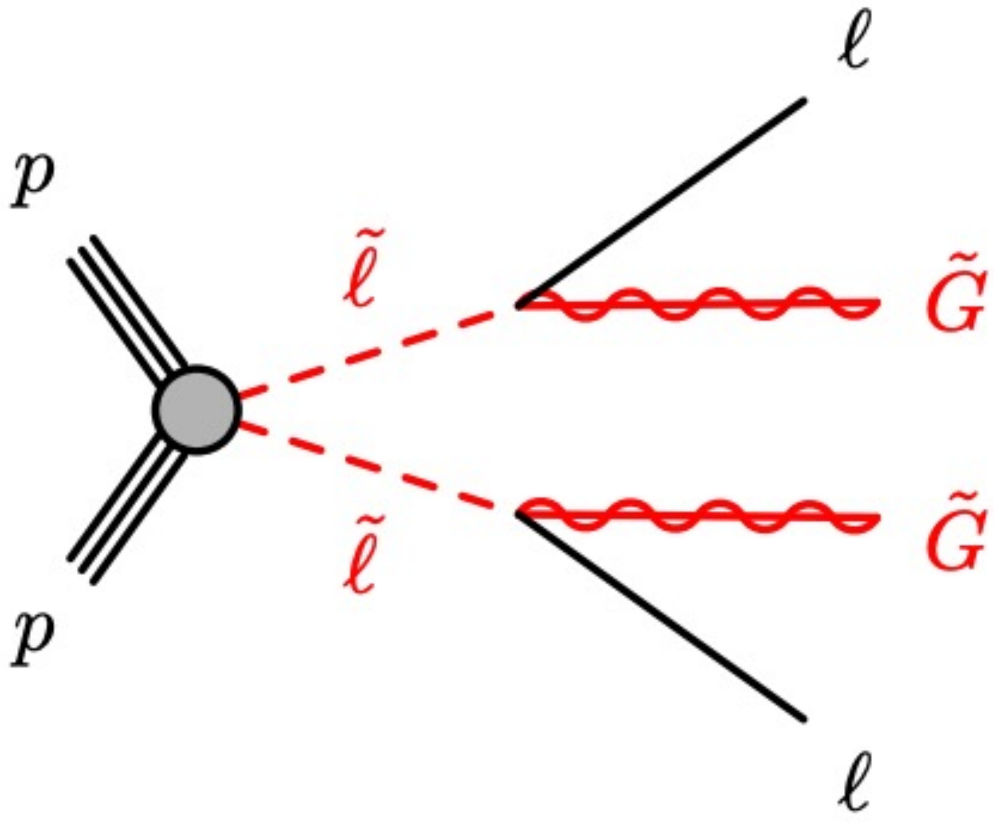
3. *Search for light neutral particles decaying promptly into collimated pairs of electrons or muons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*
   Submitted to EPJC, arXiv: 2407.09168
   Full Run 2 (140 fb^{-1})

Search For Displaced Leptons In 13 TeV And 13.6 TeV *pp* Collisions With The ATLAS Detector

BASELINE EVENT SIGNATURE

Two light leptons (electrons/muons) which are displaced from the initial interaction

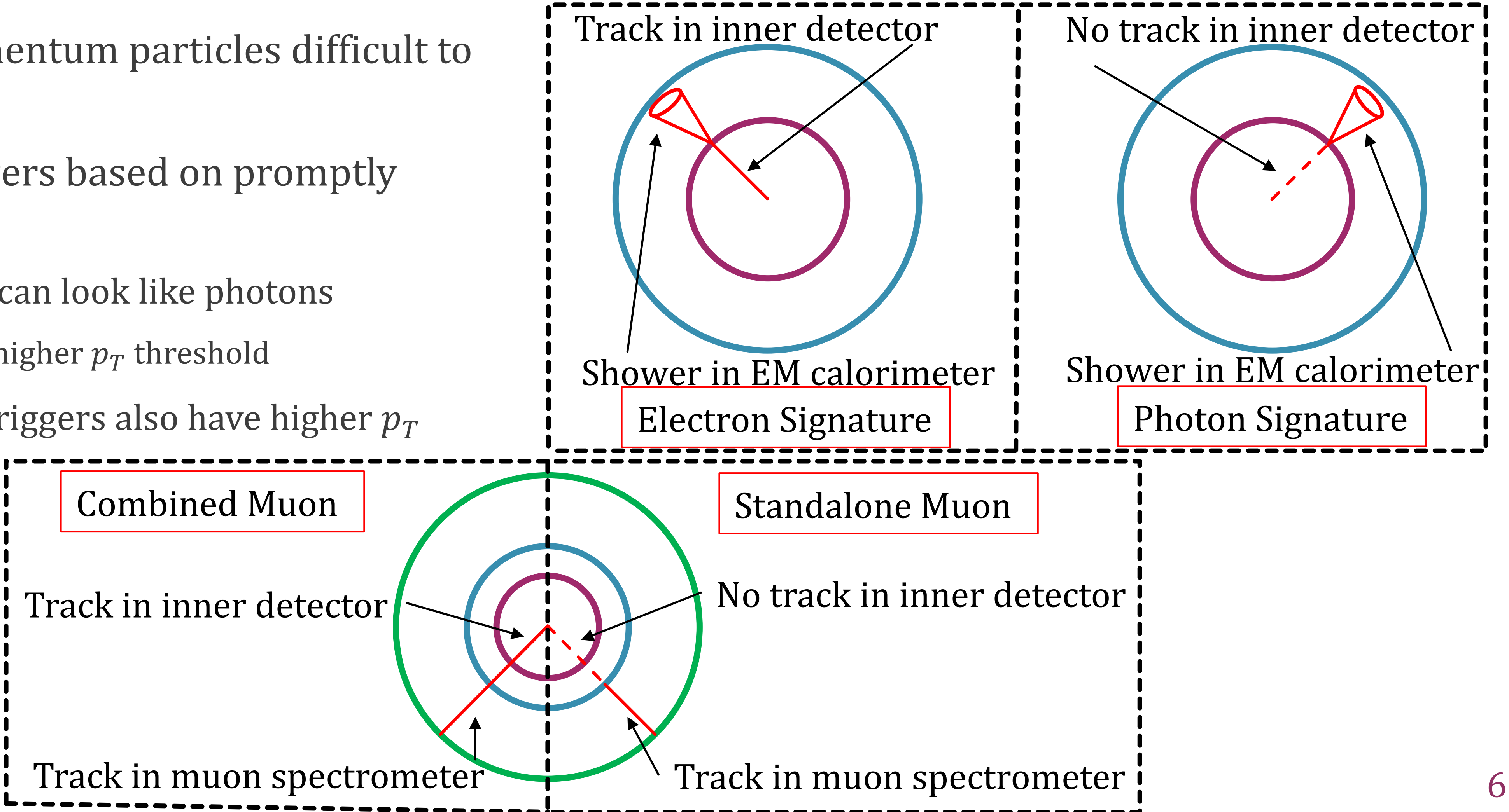
- Pair produced LLPs; decay to lepton + invisible
- Benchmark model: Gauge-Mediated SUSY Breaking (GMSB)
  - LLP is second lightest SUSY particle: slepton ($\tilde{e}, \tilde{\mu}, \tilde{\tau}$)
  - lightest SUSY particle is Gravitino ($\tilde{G}$) → invisible in detectors
- slepton is long-lived due to weak gravitational coupling



Carleton ATLAS

SIGNATURE CHALLENGE

- Displaced + low momentum particles difficult to trigger + reconstruct
- Standard lepton triggers based on promptly decaying particles
  - Displaced electrons can look like photons
    - Photon trigger has higher p_T threshold
  - 'Standalone' muon triggers also have higher p_T threshold

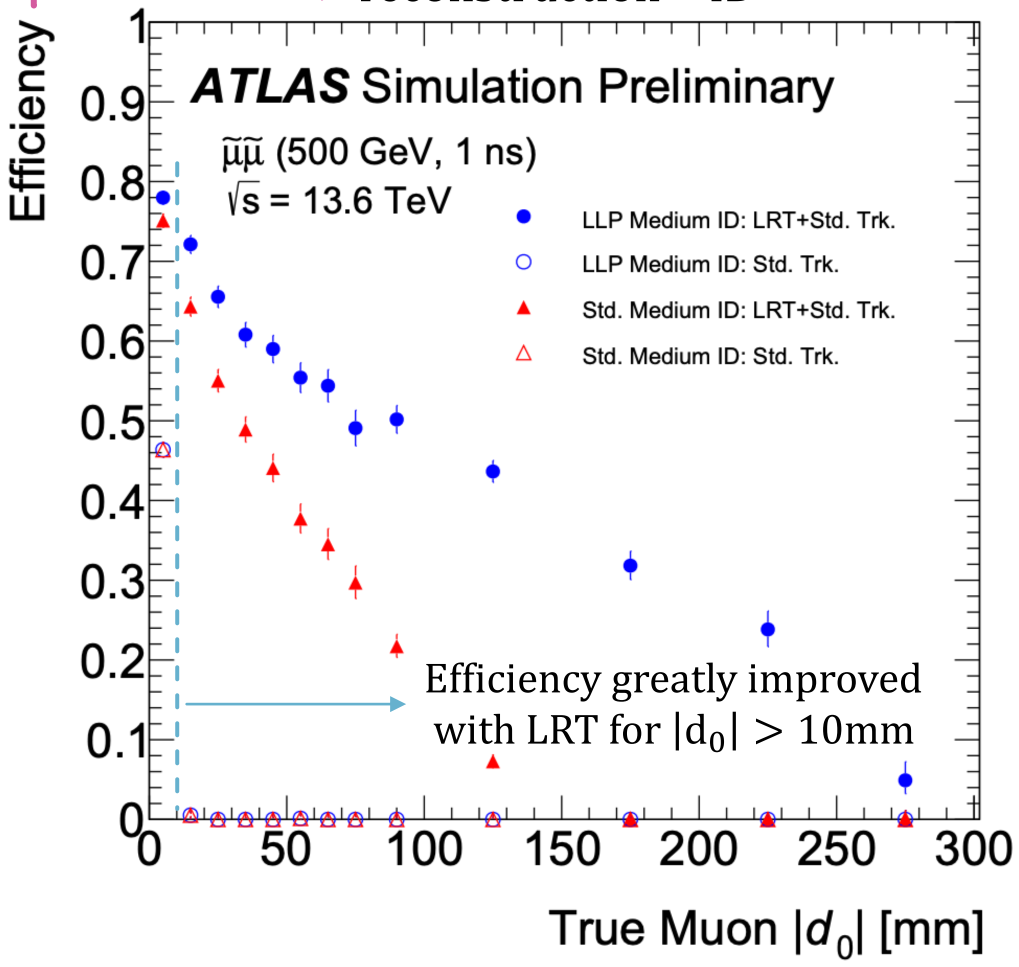


IMPROVED TOOLS FOR DISPLACED SIGNATURES

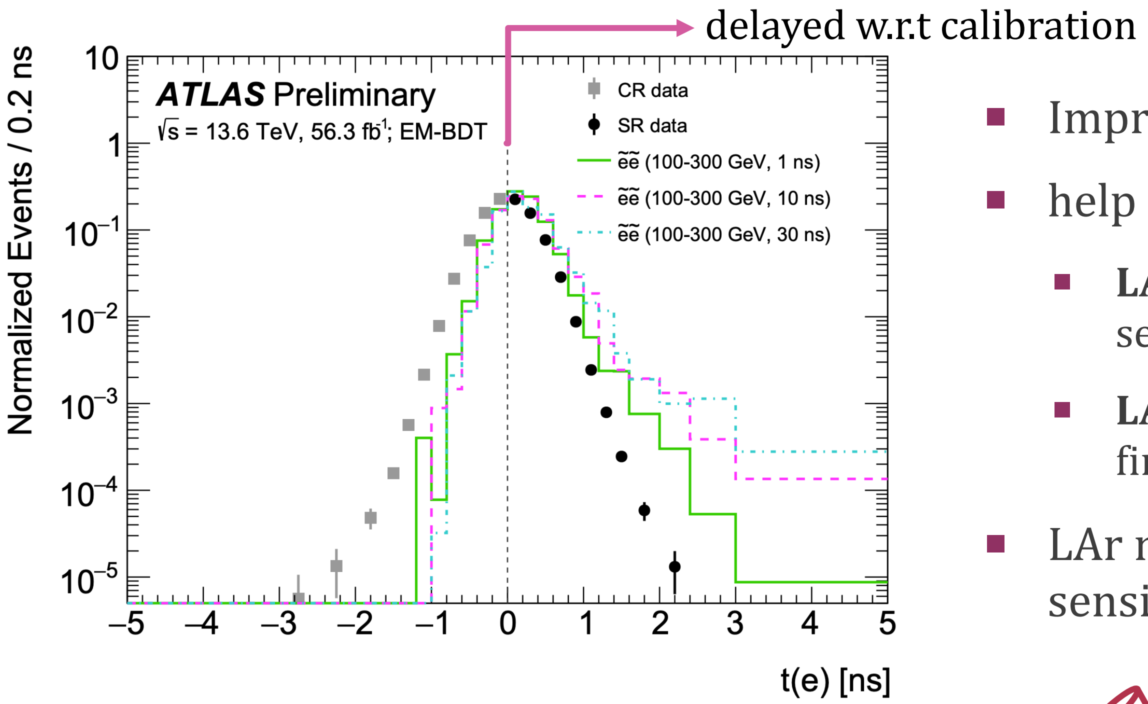
Large Radius Tracking (LRT)

- Standard tracking: prompt particles coming from interaction point
  - Low transverse impact parameter (d_0) w.r.t. the primary vertex (PV)
- LRT: secondary tracking for displaced signatures ($\sim$2mm $< |d_0| <$ 300mm)
  - Improved LRT for Run; 3 included in trigger chain
- LRT-based lepton triggers for displaced leptons:
  - lower p_T threshold than in Run2

reconstruction + ID

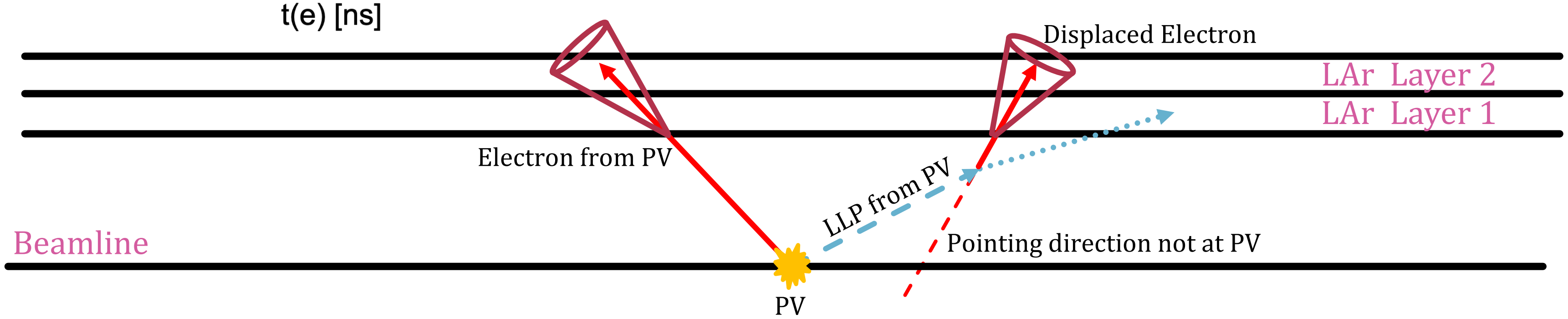


IMPROVED TOOLS FOR DISPLACED SIGNATURES [CONT.]

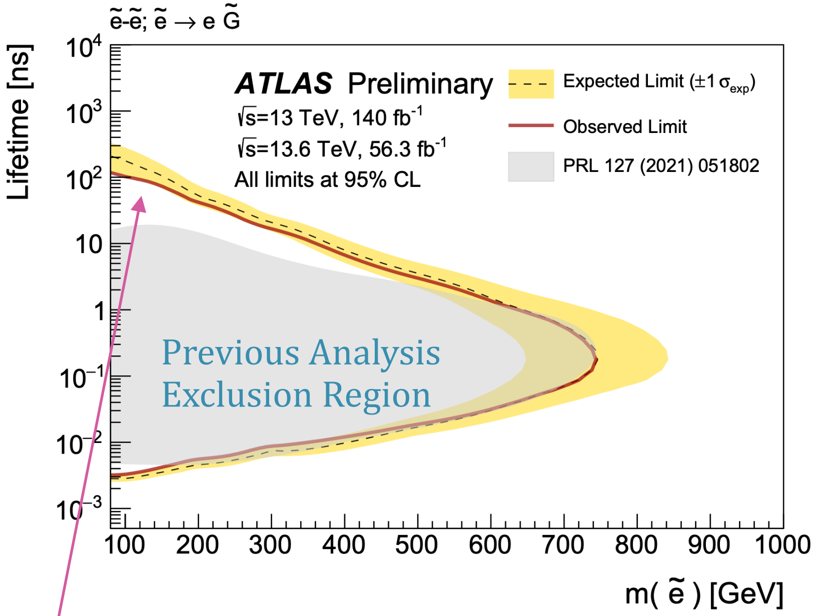


Liquid Argon (LAr) EM Calorimeter

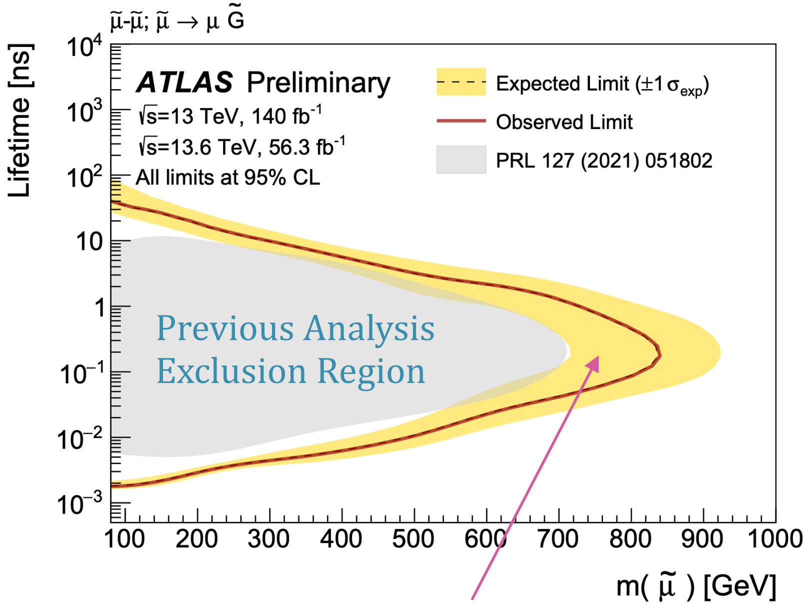
- Improved Run 3 electronics give better granularity + fast readout
- help with displaced signatures:
  - **LAr Arrival Timing**: when the EM shower starts based on deposits in second layer
  - **LAr Pointing**: the direction of the EM shower based on deposits in first two layers
- LAr measures used in Boosted Decision Tree (BDT) extend sensitivity to very displaced ($|d_0| > 300\text{mm}$) electron signatures



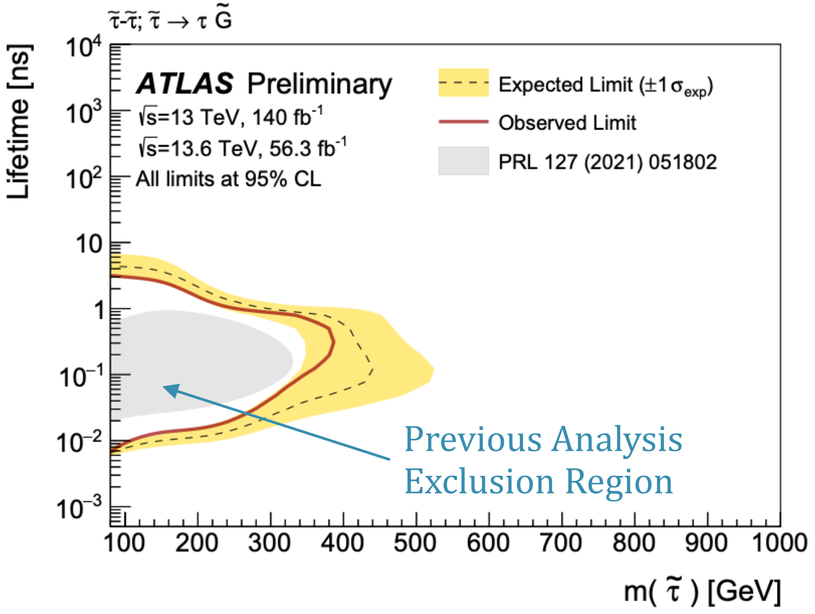
RESULTS



Selectron limits extended to higher lifetimes



Smuon limits extended to higher masses



Stau limits improved overall

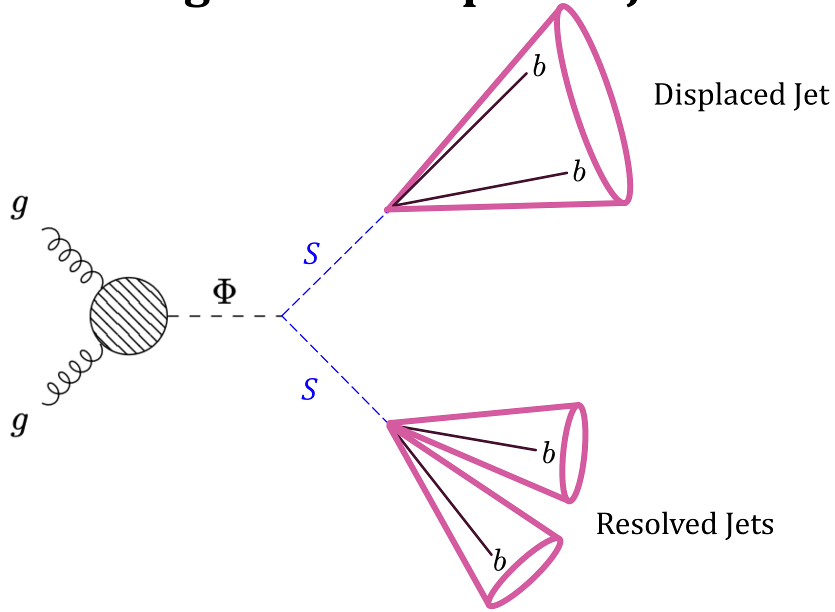
No significant excess above SM expectation found

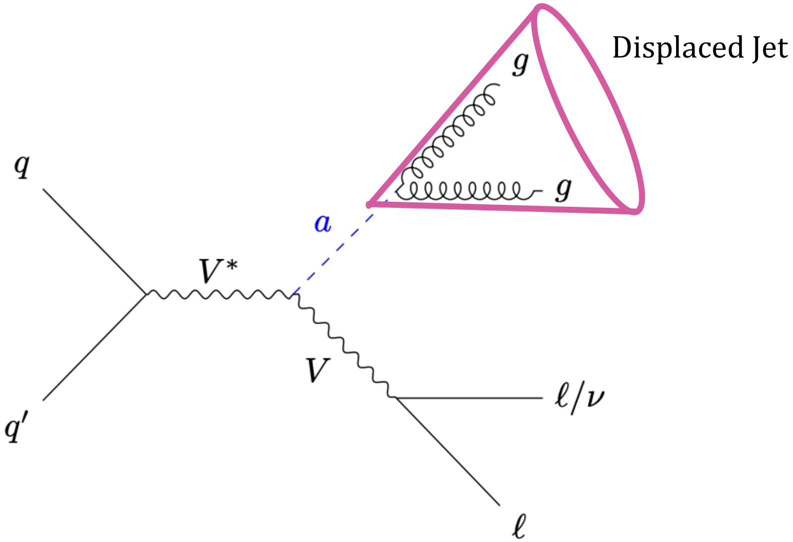
Additional Reinterpretation: arXiv:2410.16835 [hep-ex] (Very New Results!)

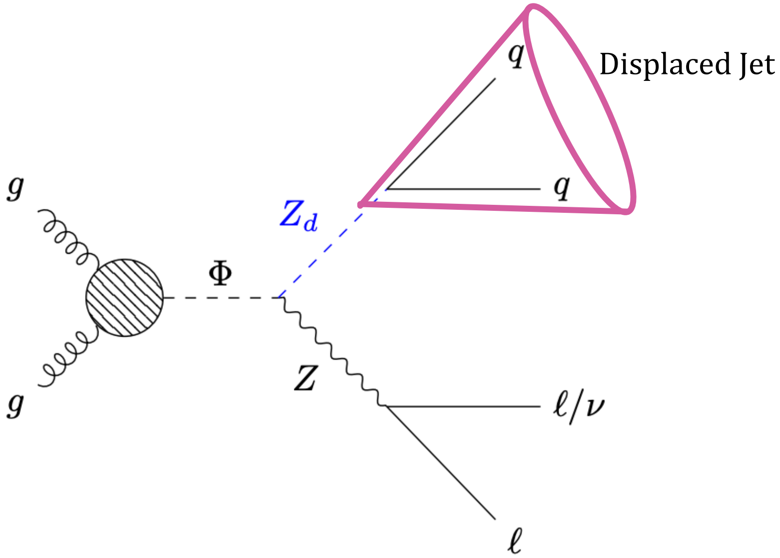
Search For Neutral Long-lived Particles That Decay Into Displaced Jets In The ATLAS Calorimeter In Association With Leptons Or Jets Using pp Collisions At $\sqrt{s} = 13$ TeV

THREE EVENT SIGNATURES

Baseline Signature: displaced jet in hadronic calorimeter (HCal) + another event-level object to trigger on





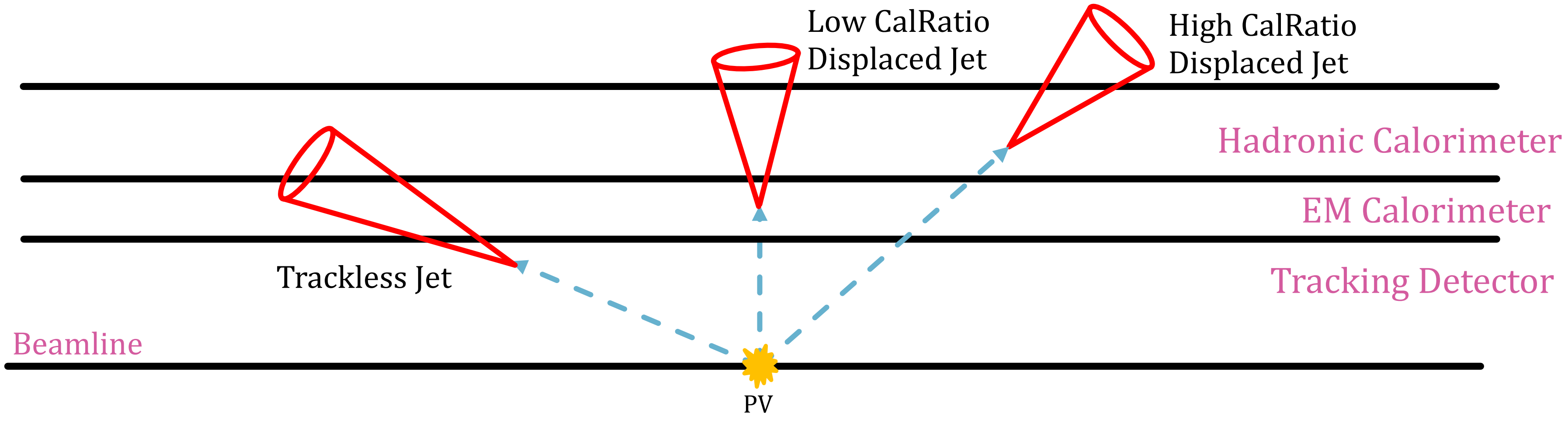


- Pair-produced neutral LLPs; 1 decays before HCal, produces two additional jets (may be trackless)
- Axion-Like Particle (ALP) LLP produced with leptonically decaying vector boson (W/Z)
- Dark-Photon LLP produced with leptonically decaying Z boson

CALORIMETER RATIO (CalRatio) AND SIGNATURE CHALLENGE

- $CalRatio = \frac{E_{HCal}}{E_{EM}}$: ratio of energy deposited in the HCal to the energy deposited in the EM calorimeter
  - Should be ~ 0.5 for SM jets: 2/3 in EM, 1/3 in Hcal
- For LLPs decaying in the HCal, expect large CalRatio

- Displaced jets alone can be difficult to trigger
  - Use other detector objects:
    - Trigger on prompt leptons
    - Additional reconstructed objects (other jets, leptons)
  - Use dedicated CalRatio Trigger; max ~6% of jet energy in EM calo.



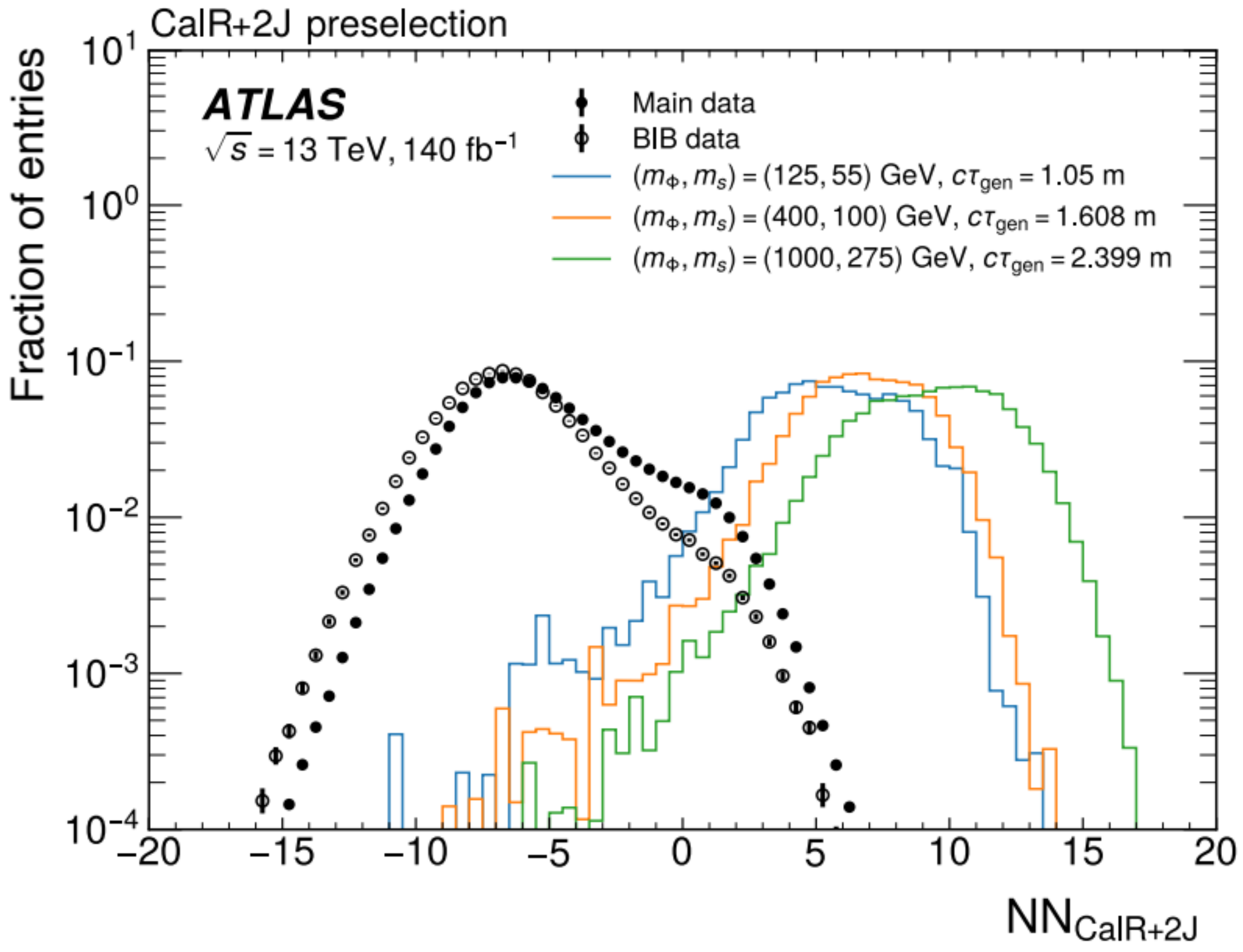
ANALYSIS STRATEGY

Baseline Strategy

- All channels use jet-level neural network (NN):
  - Separate signal-like displaced jets from background
  - Beam induced background (BIB) + SM multijet
- Additional ML tools used in each channel

Displaced jet + two resolved jets (CalRatio + 2J):

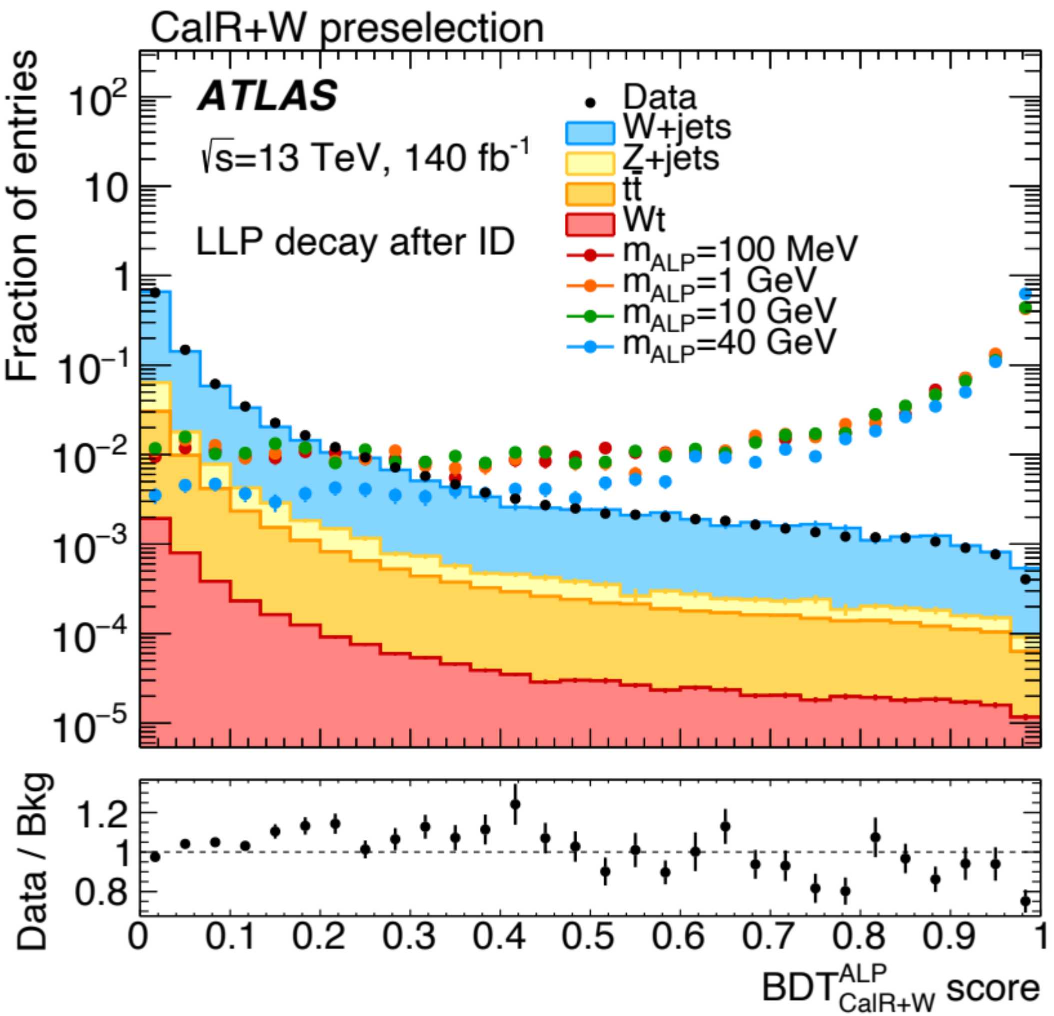
- Event-Level NN is trained to remove BIB events, leave only SM multijet



Carleton ATLAS

DISPLACED JET + $W^{\pm} \rightarrow \ell^{\pm}\nu$(CALRATIO + W):

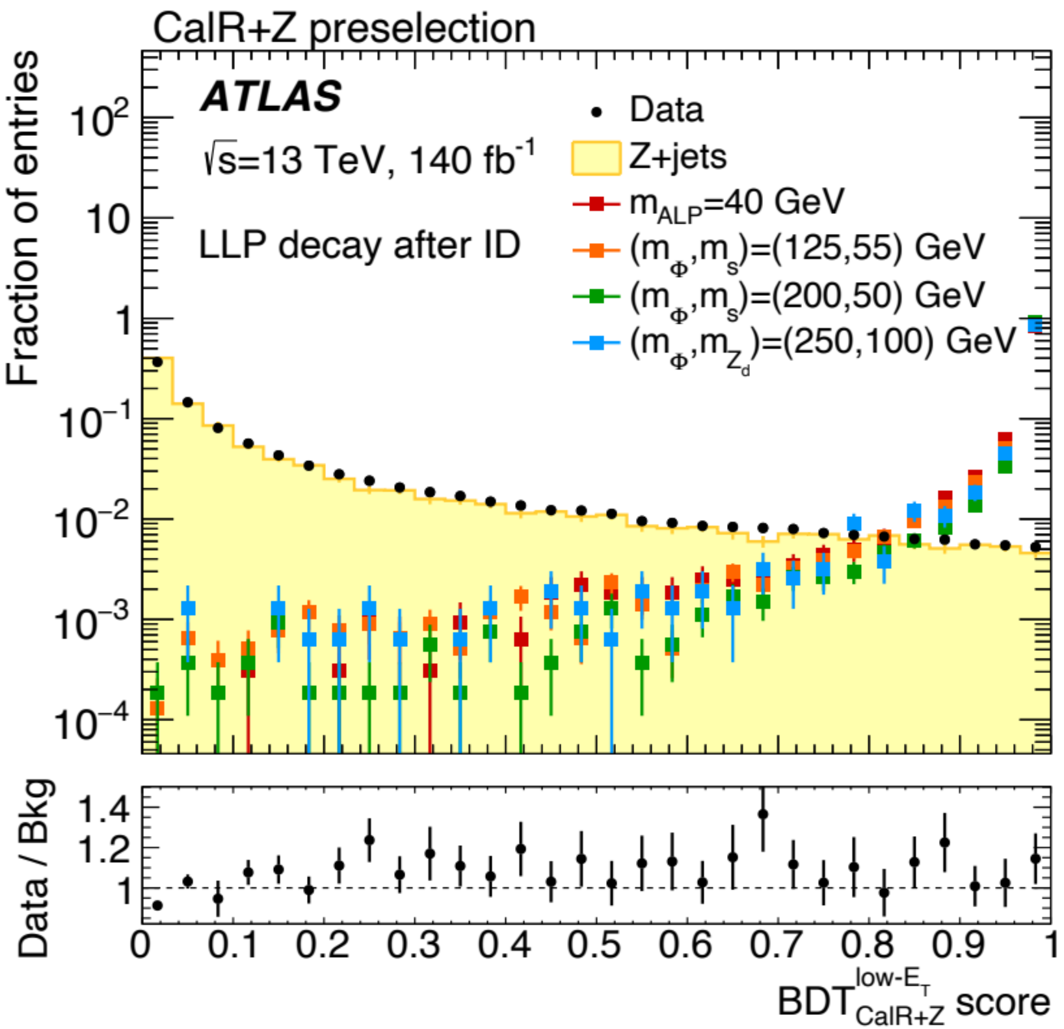
- Single lepton trigger (no additional leptons)
- Lepton requirement also removes BIB events
- Event-Level BDT to separate from SM $\ell + \text{jet}$ backgrounds
  - Trained on jet + lepton information
  - Missing E_T from the neutrino



Carleton ATLAS

DISPLACED JET + Z → $\ell^+\ell^-$ (CALRATIO + Z):

- Dilepton Trigger:
  - Removes BIB events
  - Reconstructs Z mass
- Event-Level BDT to separate from Z + jet backgrounds
  - Trained on jet + dilepton information
  - Reconstructed kinematics of the Z



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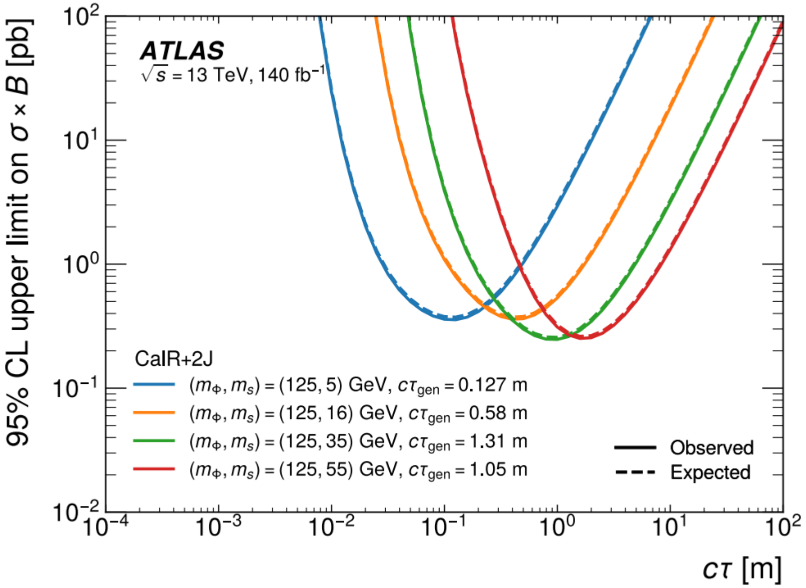
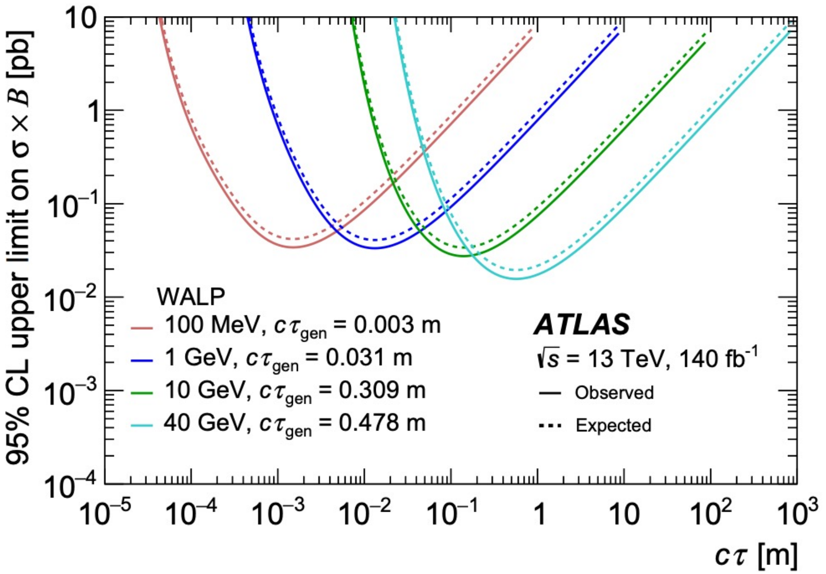
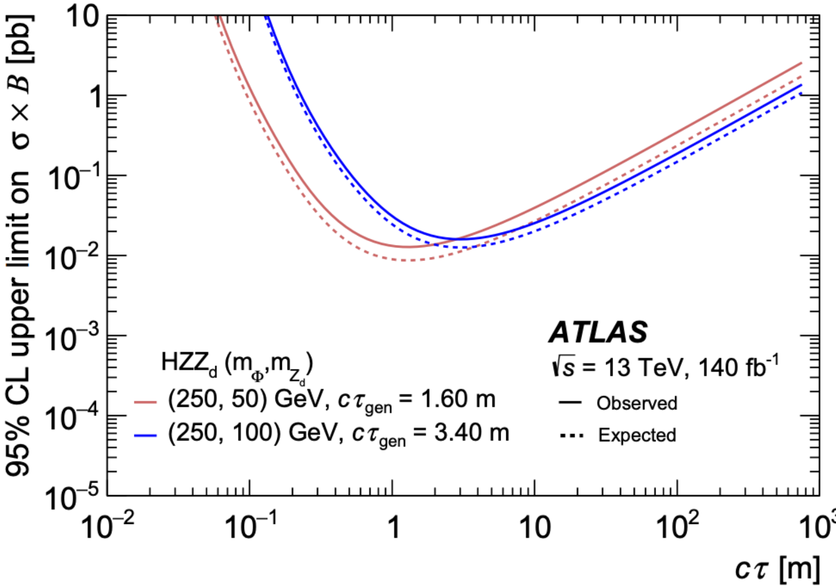


3x improvement LLP $\Phi \rightarrow 2J$
(Higgs Boson portal)
CalRatio+2J scenario



First LLP Axion-Like → Jets limits in ATLAS
CalRatio+W/Z scenarios



10x improvement LLP Z_d → Jets
CalRatio+Z scenario

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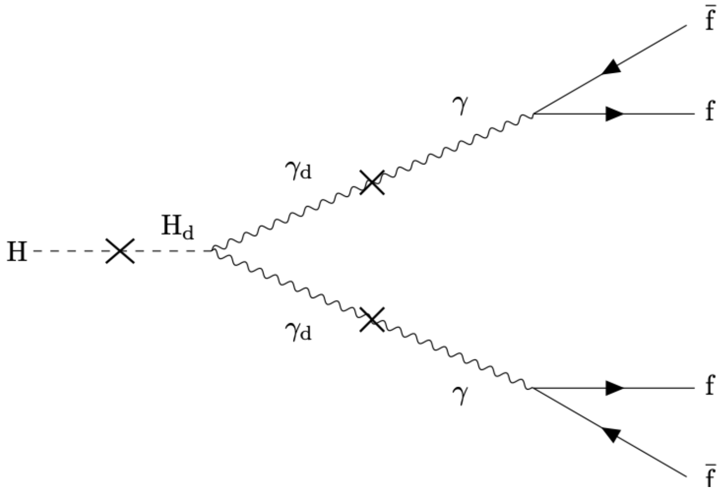
No significant excess above SM expectation found

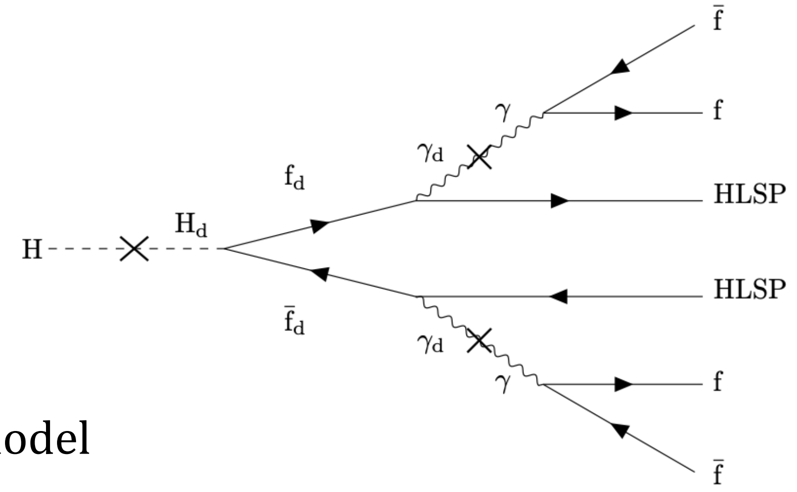
Search For Light Neutral Particles Decaying Promptly Into Collimated Pairs Of Electrons Or Muons In *pp* Collisions At $\sqrt{s} = 13$ TeV With The ATLAS Detector

BASELINE EVENT SIGNATURE

Two highly-collimated lepton pairs (e^+e^- or $\mu^+\mu^-$) which are reconstructed as a Lepton-Jet (LJ)

- Dark photon (γ_d) + dark Higgs (H_d) extensions with two benchmark models:
  - HAHM: γ_d couples directly with H_d
  - FRVZ: H_d decays to dark fermions which then decay to γ_d and Hidden Lightest Stable Particle (HLSP) [invisible in detectors]
- $m_{\gamma_d} \ll m_H$ → causes collimated lepton pairs
- Pair-produce γ_d → require two LJs in final state

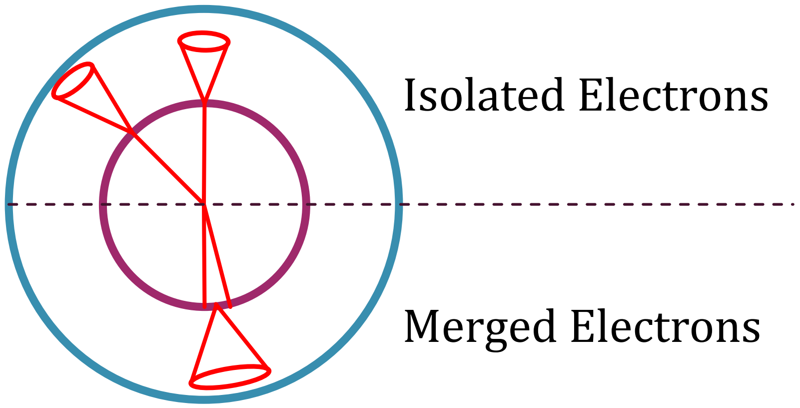


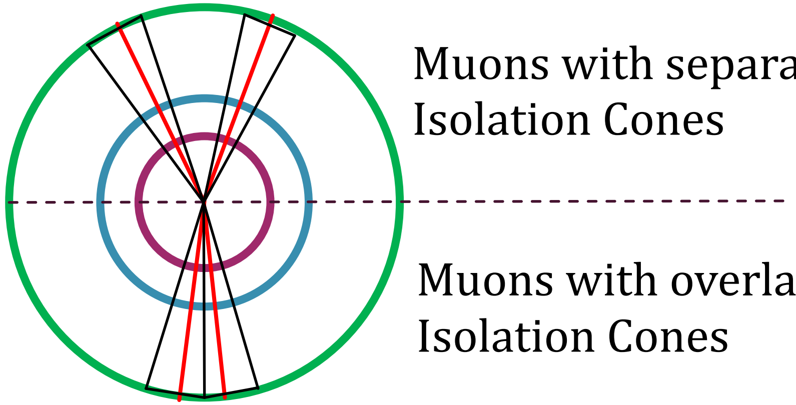


HAHM: Hidden Abelian Higgs Model
FRVZ: Falkowski-Ruderman-Volansky-Zupan model

SIGNATURE CHALLENGE

- Standard lepton (e, μ) reconstruction generally targets isolated leptons
- Electrons from γ_d decays tend to merge showers in EM calo., with two associated tracks → reconstructed as 1 electron
- Standard muons must be isolated from both tracks and calo deposits → require modified isolation to reconstruct $\gamma_d \rightarrow 2\mu$





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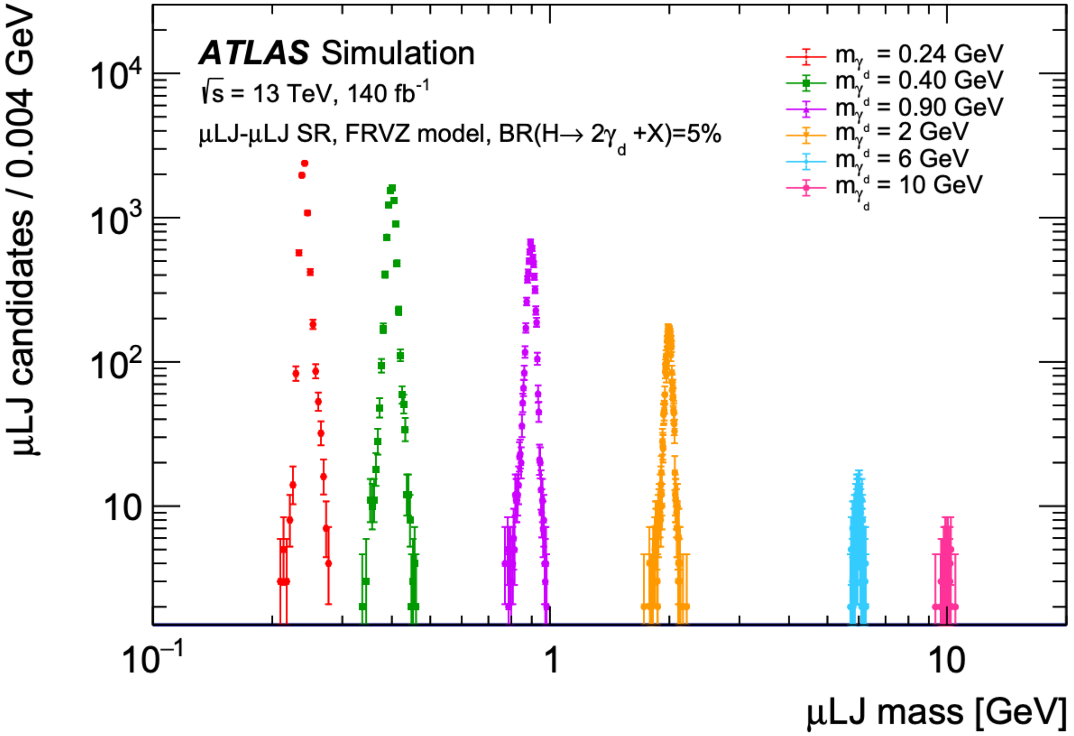
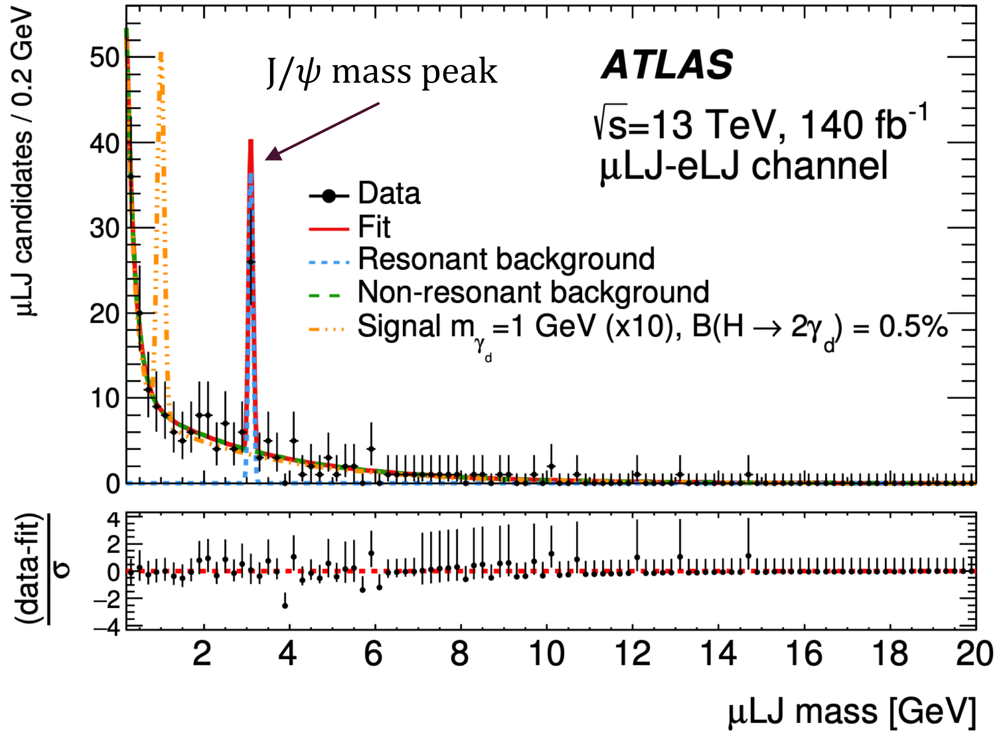
ANALYSIS STRATEGY: BUMP HUNT

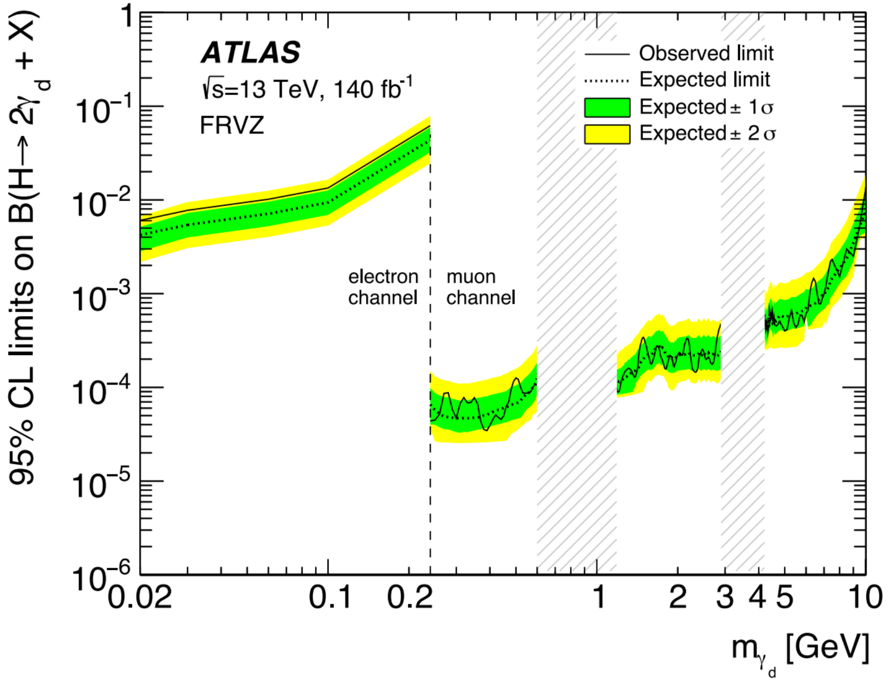




- Reconstructed LJ masses give clear resonance peaks at m_{γ_d}
- Easily distinguished from background: smoothly falling + known resonance peaks

RESULTS

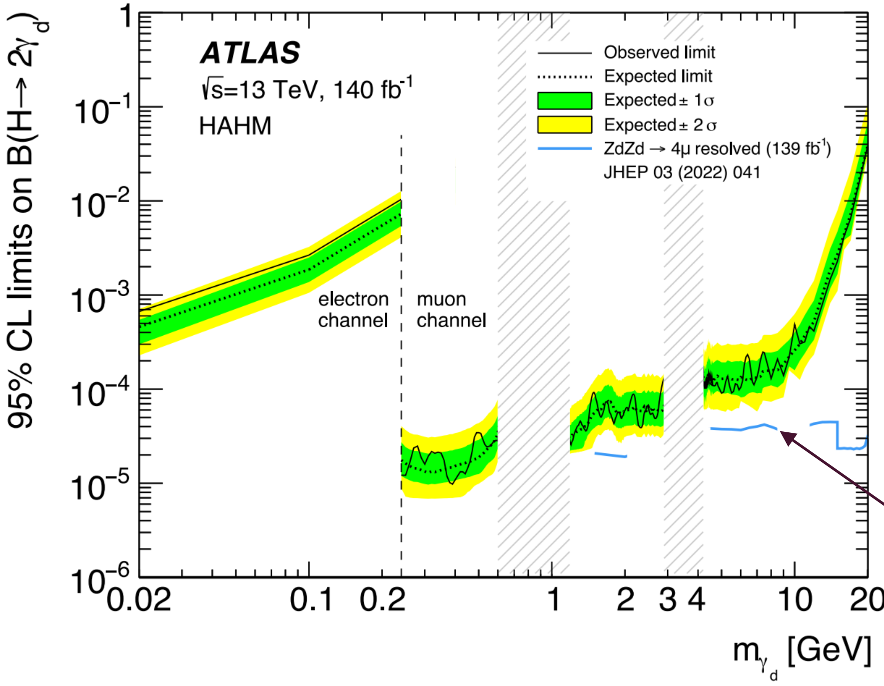
FRVZ Model ($H \to 2\gamma_d(\to \ell\ell) + 2HLSP$)



50x improvement on previous FRVZ search

improvement from better LJ mass fit

HAHM ($H \to 2\gamma_d(\to \ell\ell)$)



Limits from 4 isolated muons

First results for the HAHM search

Stricter limits than FRVZ due to harder γ_d spectrum

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No significant excess above SM expectation found

CONCLUSIONS

- Unique signatures provide handles to probe Beyond the Standard Model physics
- ‘Smoking gun’ type events require non-standard techniques to detect:
  - Detector improvements, machine learning, and reconstruction techniques all help push further into the vast phase-space of new physics
- 3 new ATLAS results have all set strict and competitive limits on their respective processes, allowing us to constrain the allowed possibilities

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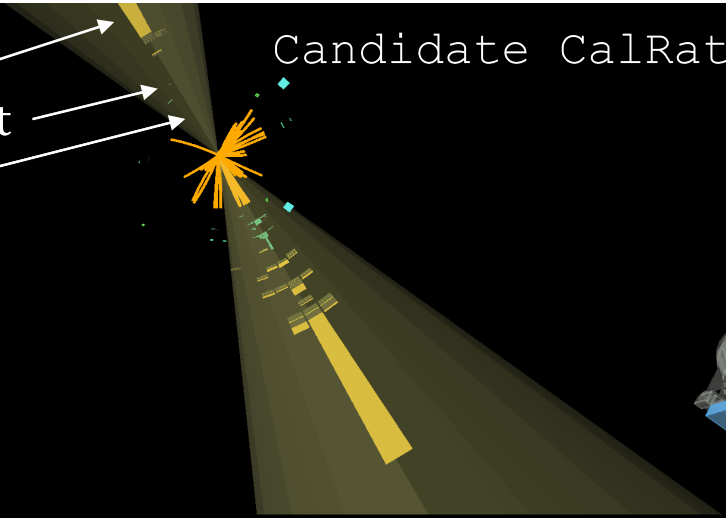

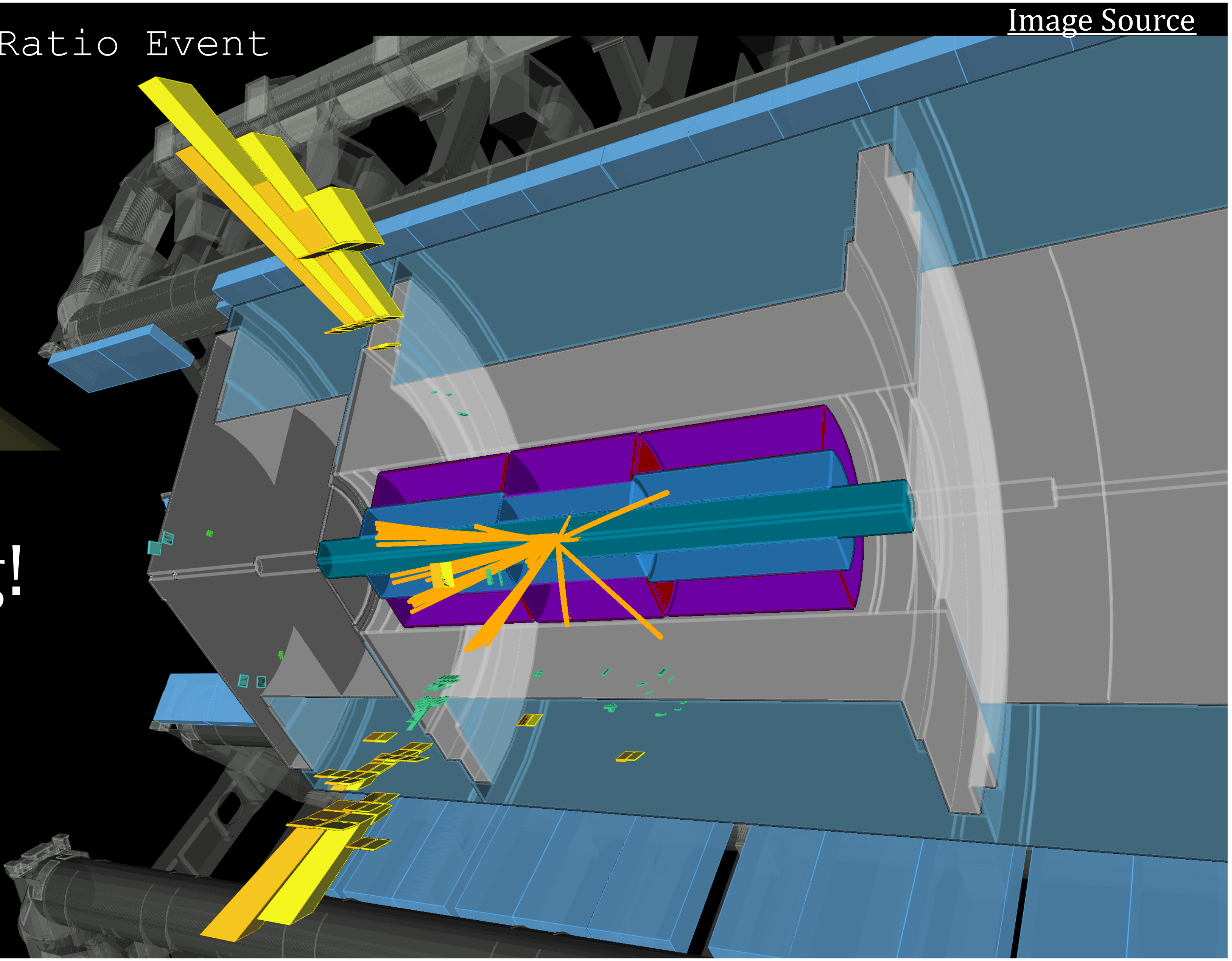

Thank you for listening!
Any Questions?