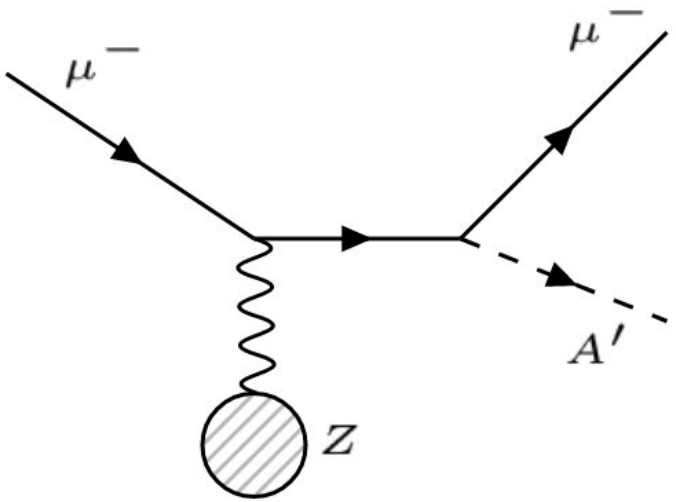
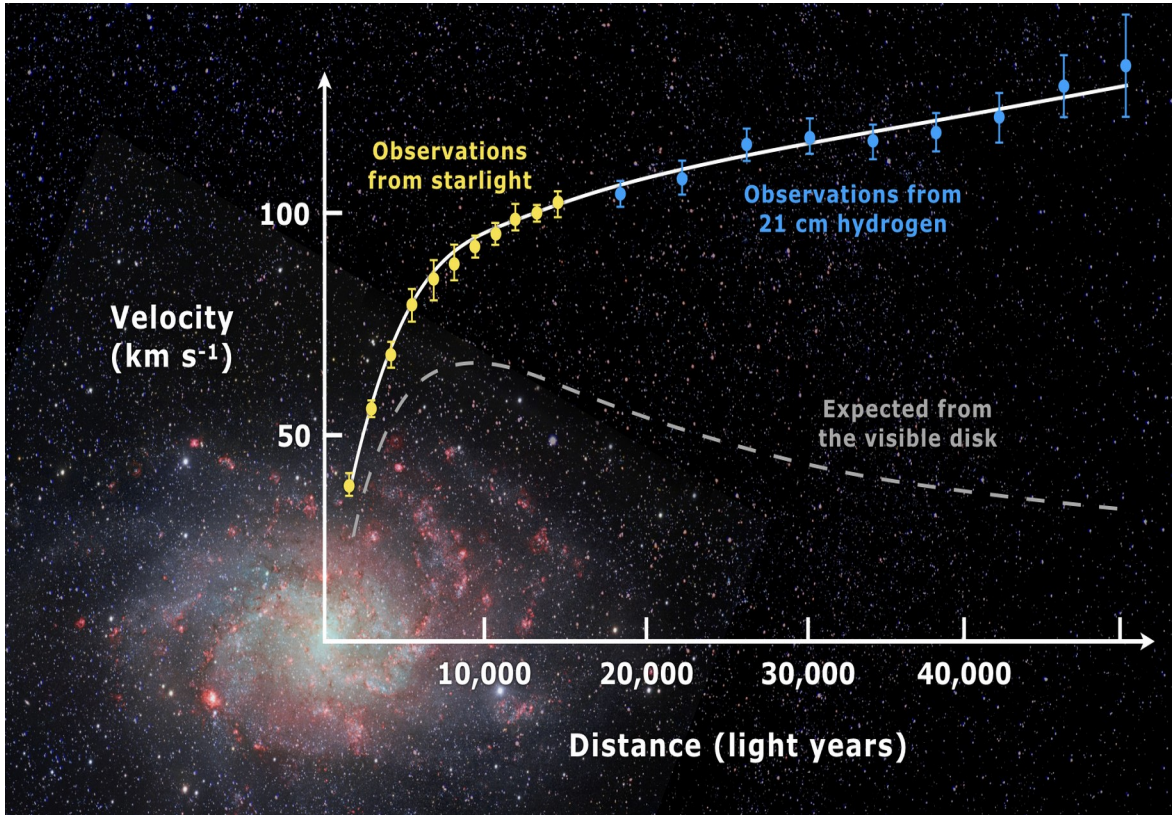
# A Search for Dark Matter via Disappearing Muons in the CMS Hadronic Calorimeter

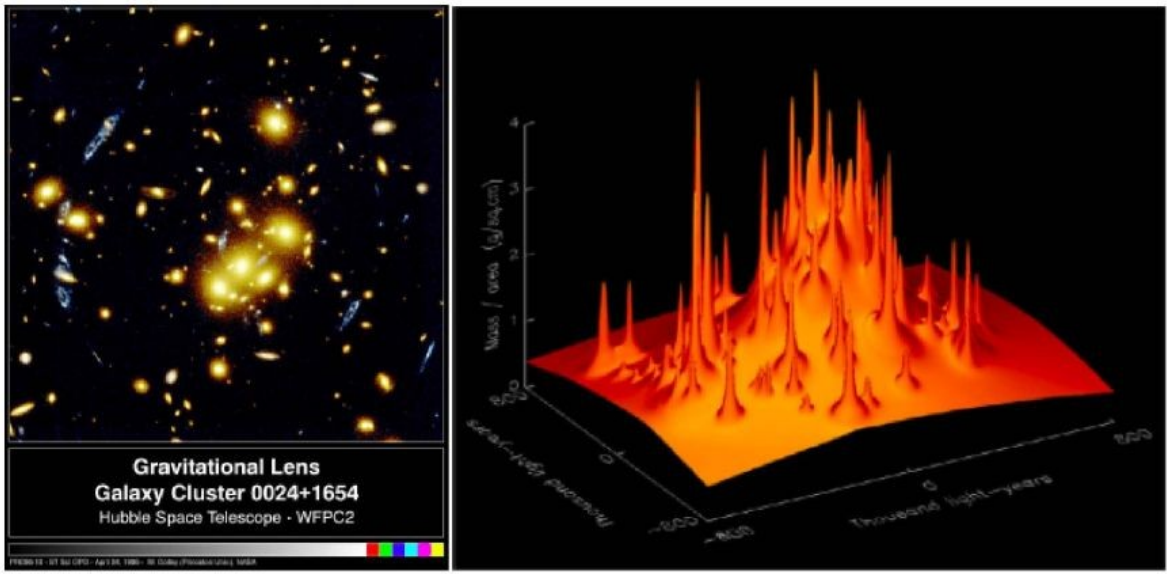


# A Brief Look at Dark Matter

- First observed by Knut Lundmark in Sweden in the 1930's and later Fritz Zwicky at Caltech using galaxies in the Coma Cluster.
- Later, Ford and Rubin show that these unexplained rapid orbits were seen in *every* galaxy.

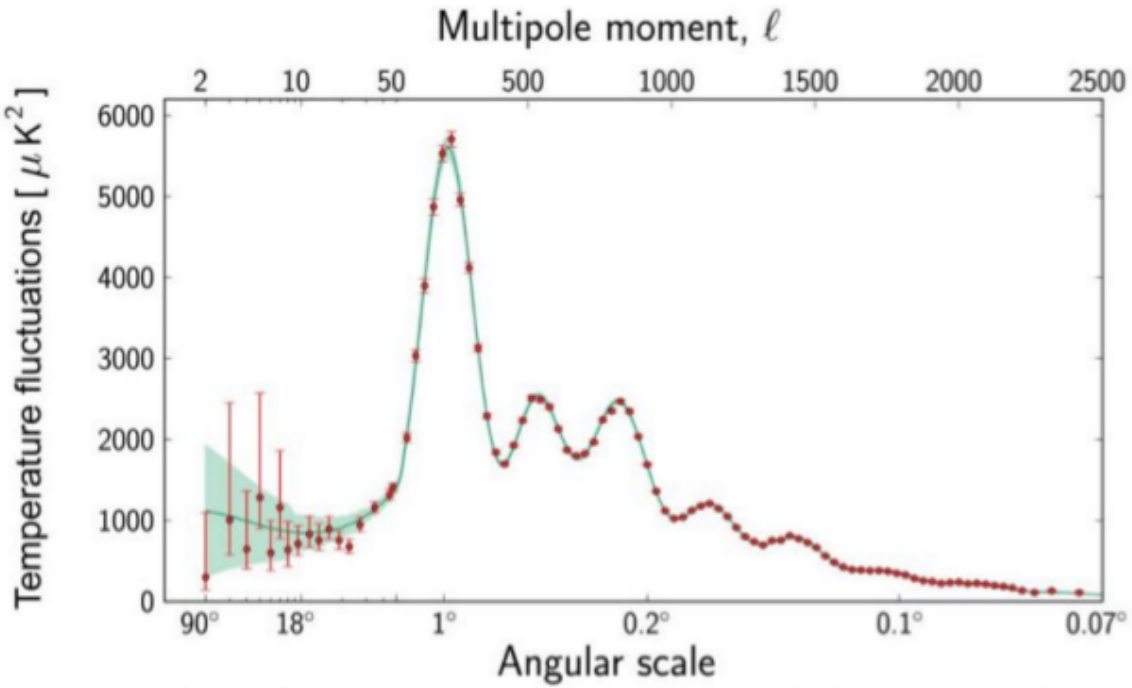


# Why are we so convinced that it is a new particle?

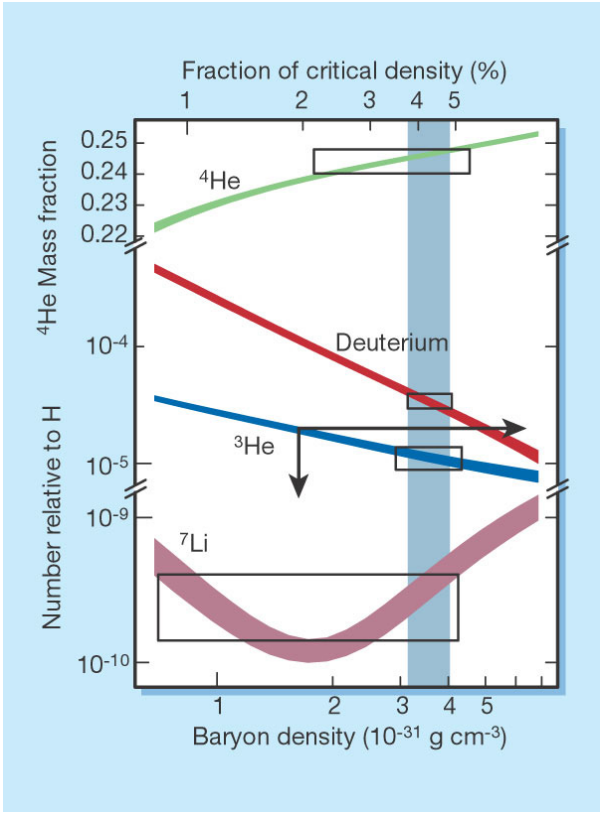



*Left: The foreground cluster gravitationally lenses the blue background galaxy into multiple images.*

*Right: The Bullet Cluster*
*X-ray image (pink) superimposed over visible light (galaxies) and gravitational lensing data (blue).* [2]



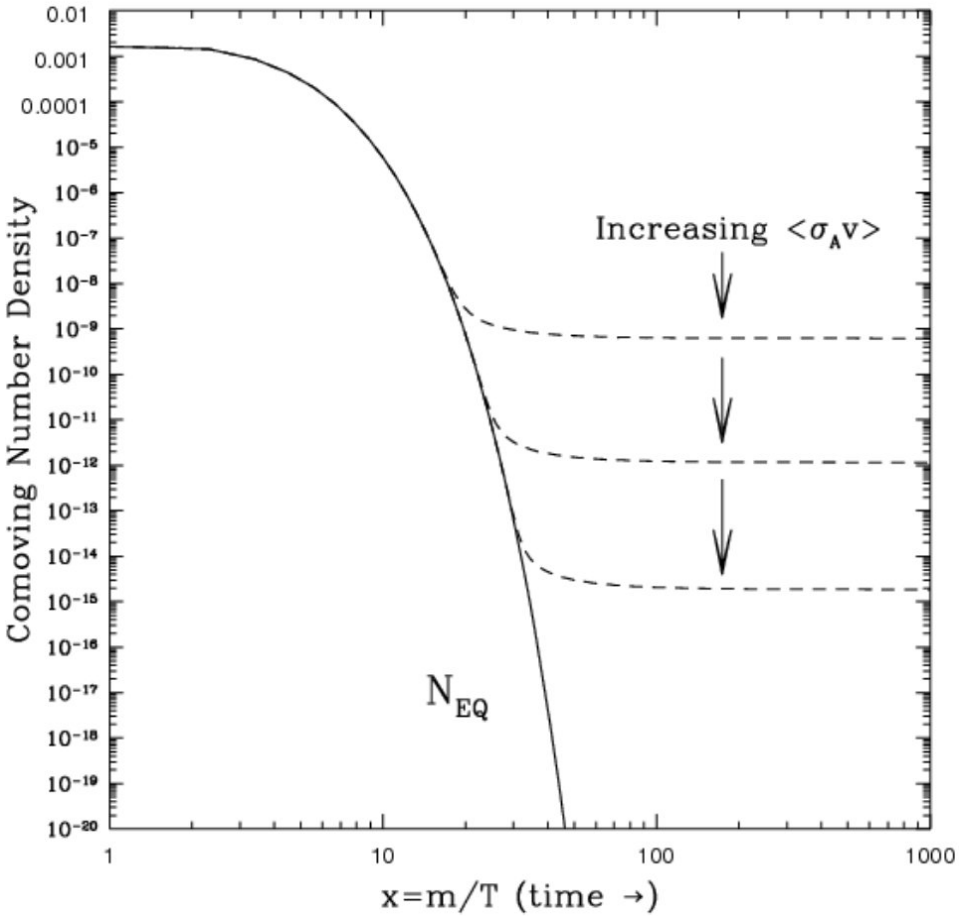

*Planck's Power Spectrum of the Cosmic Microwave Background.*



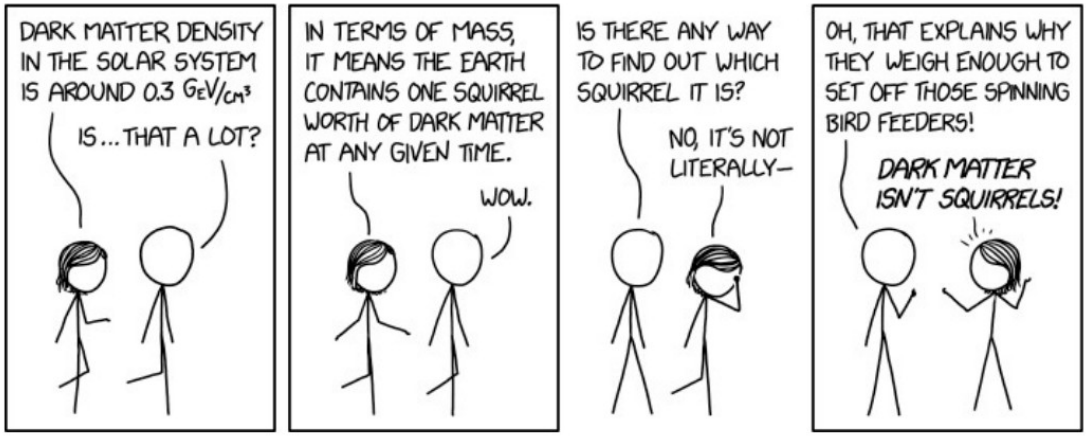

*Relative abundances produced in primordial nucleosynthesis as a function of Baryon density.*

- Results from CMB measurements and observed relative abundances are both incompatible with baryonic dark matter.

# Thermal Dark Matter




*Thermal dark matter freeze out for different annihilation cross sections.* [1]

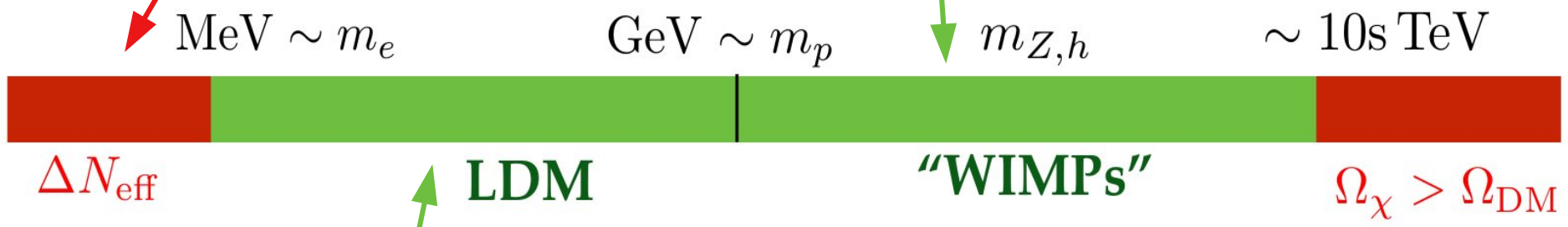



- CMB sets DM mass density.
- Freeze out and mass density connect cross section to DM mass.
- **Lower mass → Lower Cross section.**

# “Light” Dark Matter

-DM Freezes out after neutrinos

-Can be charged under weak force
-Well explored phase space

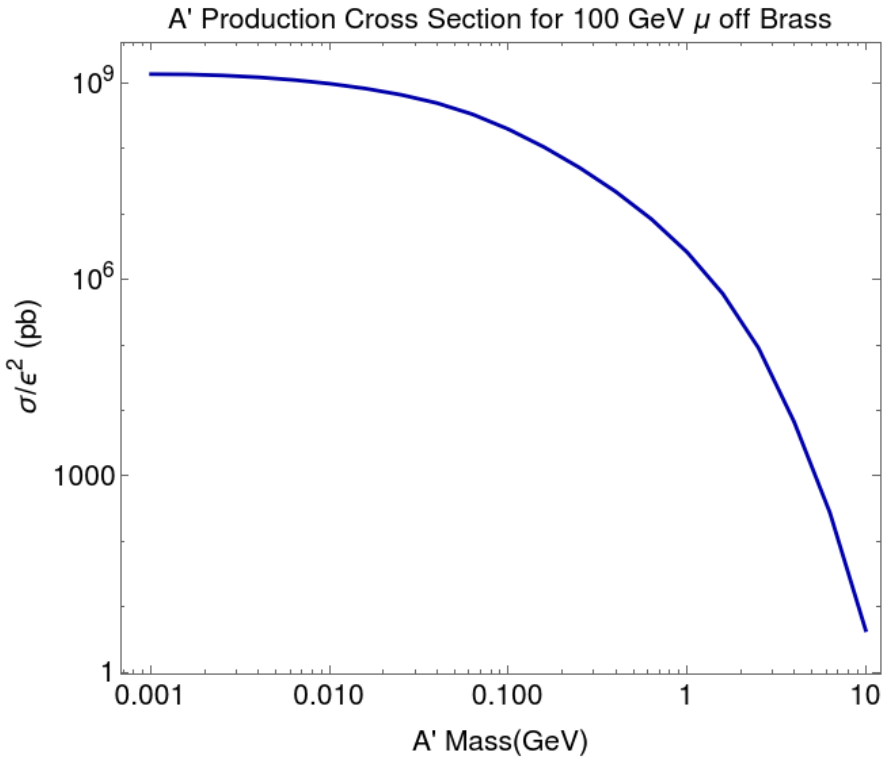


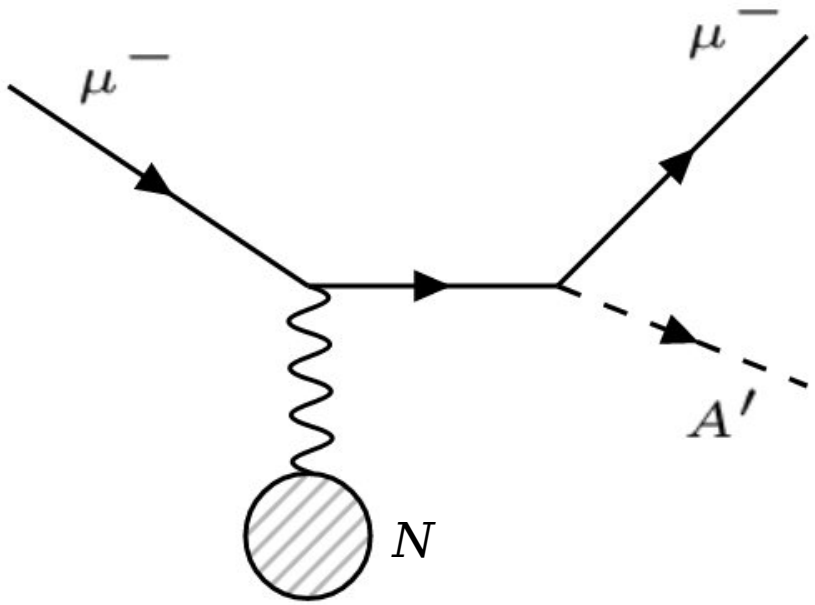

-Difficult to observe with traditional searches

-Mass too high to produce relic abundance

# Dark Bremsstrahlung

- Rate is proportional to $\varepsilon^2$
- We use a dark photon (A') for demonstration, signal is largely model independent.



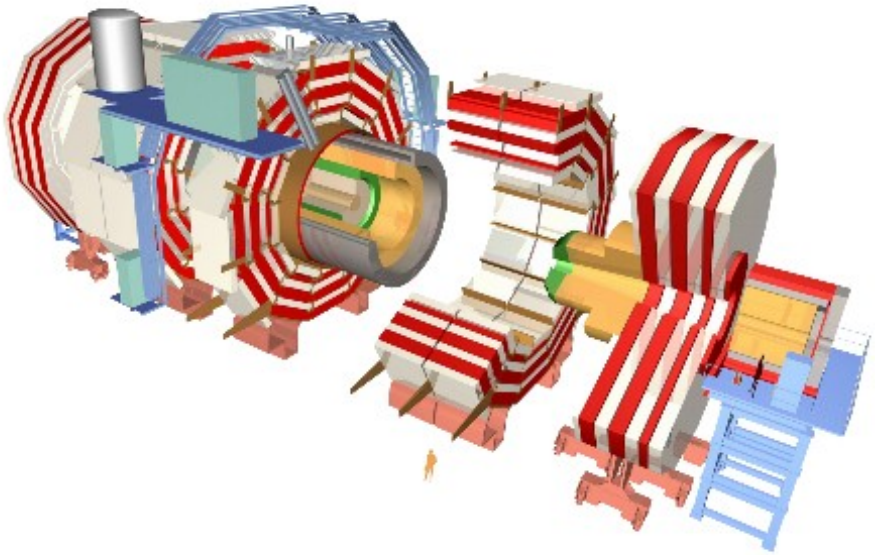



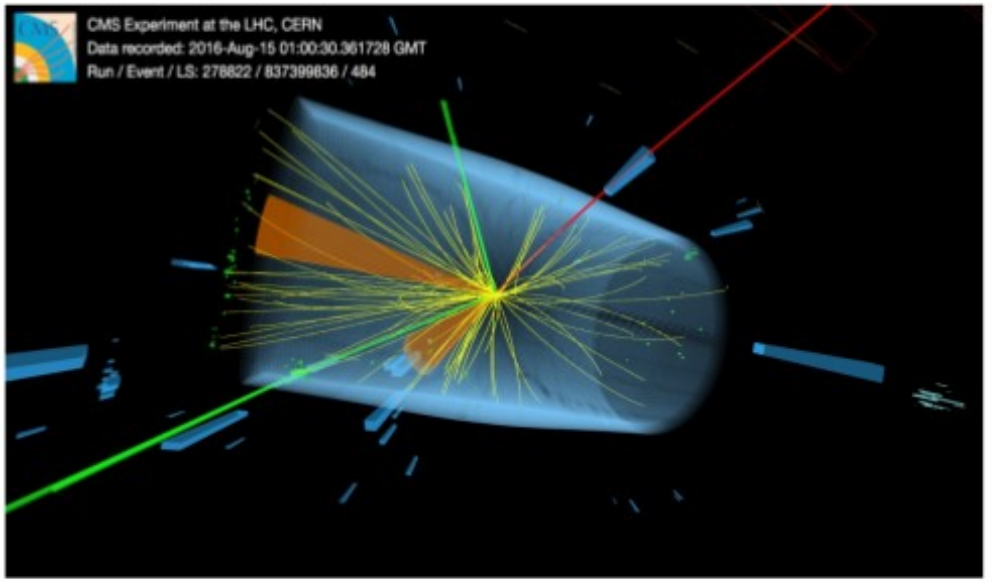

**Event Signature**

- Large muon energy loss.
- High muon angular deviation.
- No additional visible particles.

# Using CMS to find Dark Matter

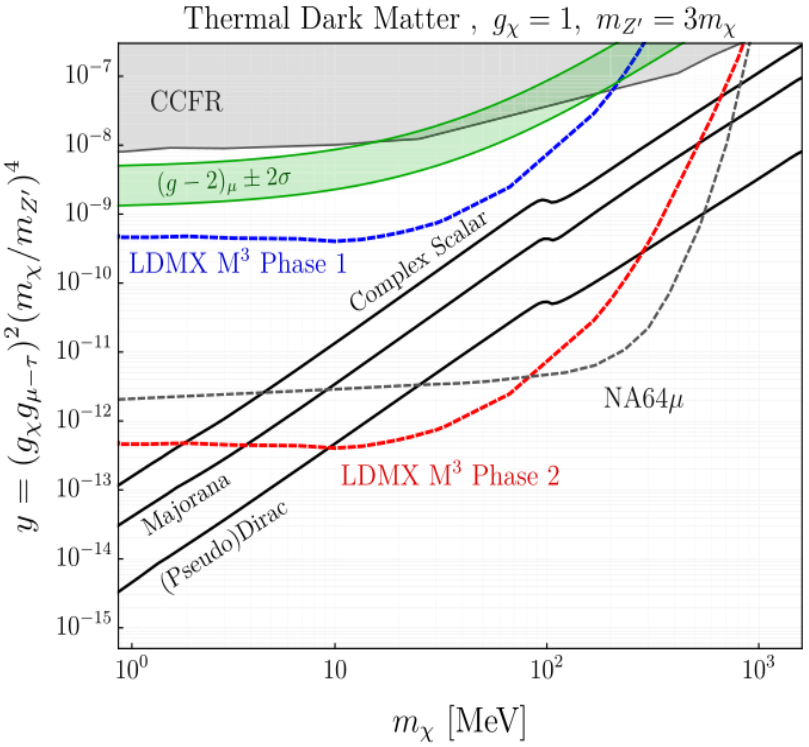
- CMS is a *collider* experiment.
- Need to use secondary particles produced in a collision instead of direct from a beam.

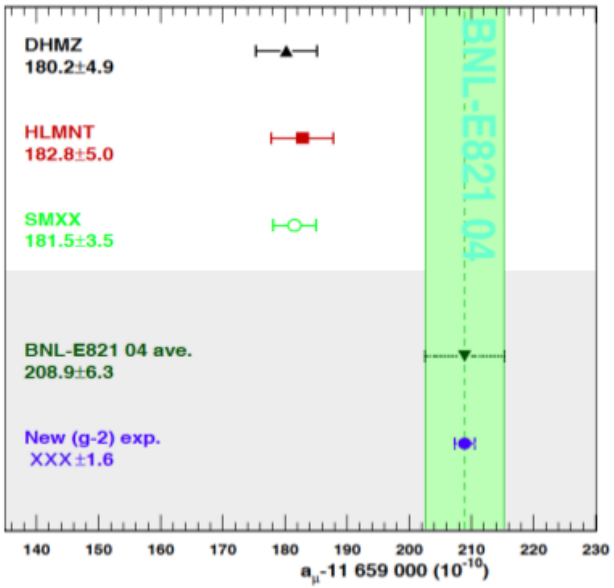




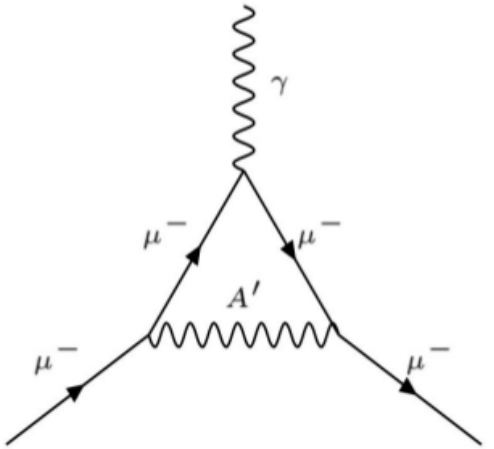
# What do we actually gain by using CMS?

- CMS *already exists*
- We can use muons as our incident particle




*Limits on the muon anomalous magnetic dipole moment.*

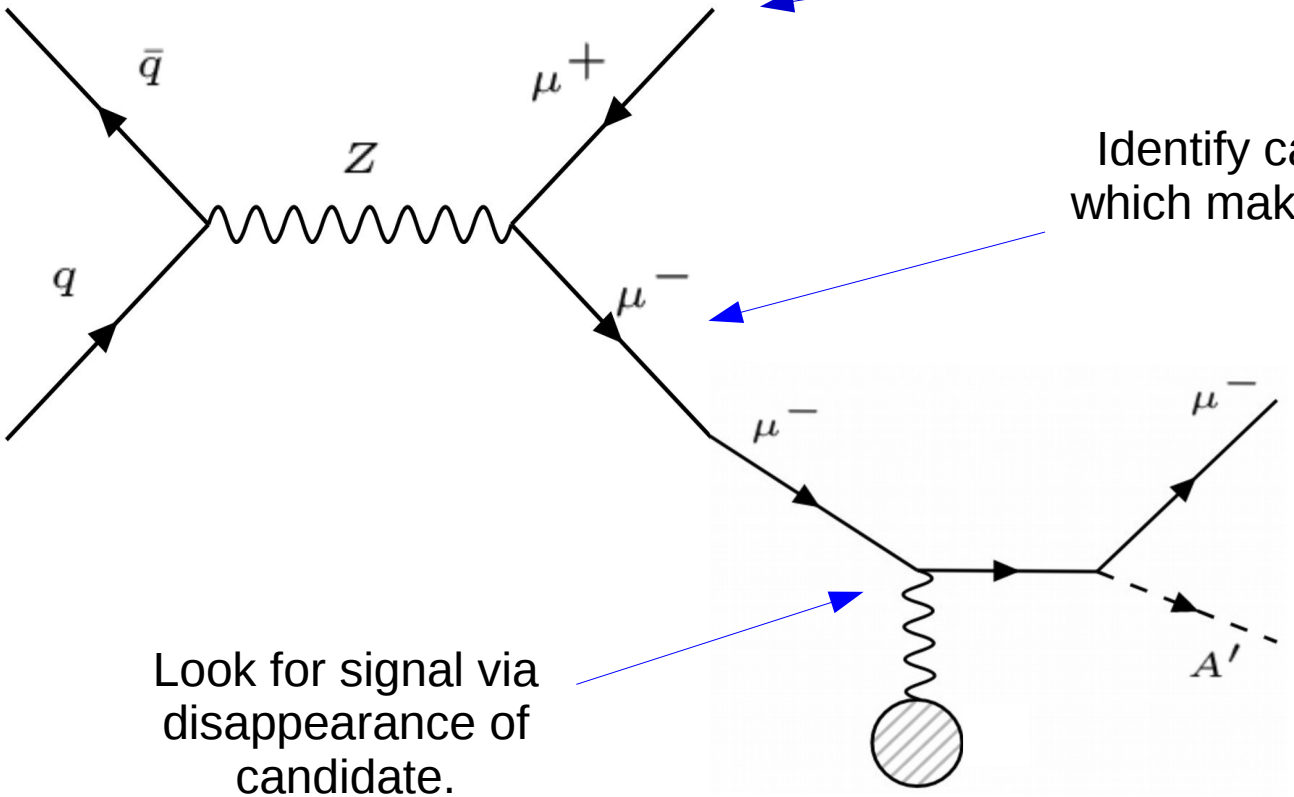


# Selecting Muons

Look for Z→μμ events

Trigger using fully reconstructed muon.

Identify candidate muon via track which makes invariant mass near Z peak.

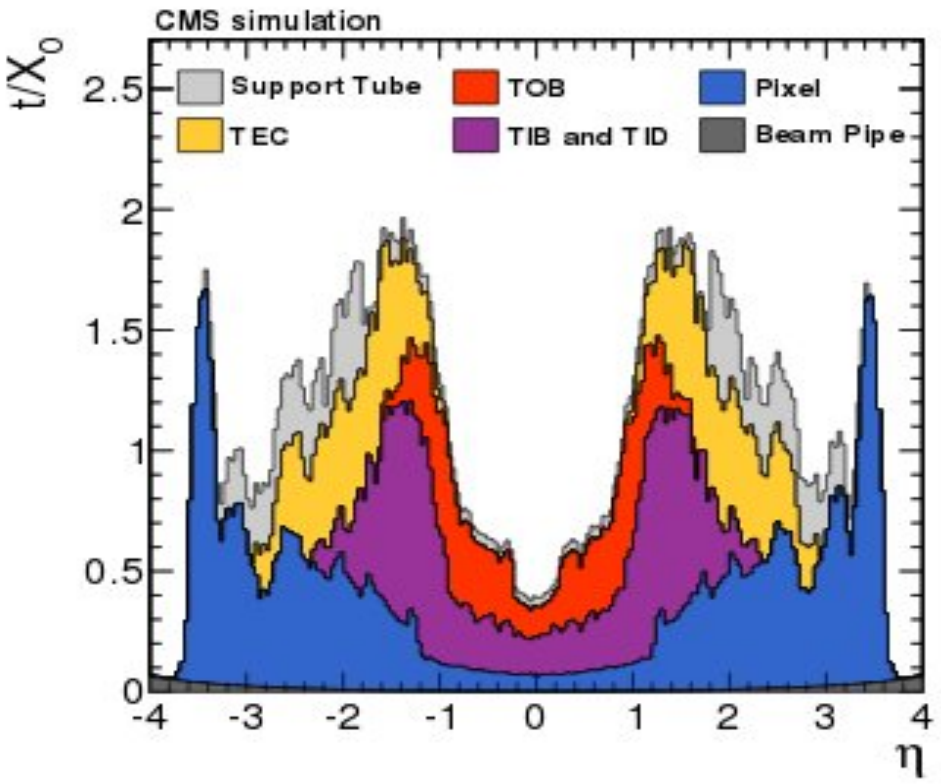



Look for signal via disappearance of candidate.

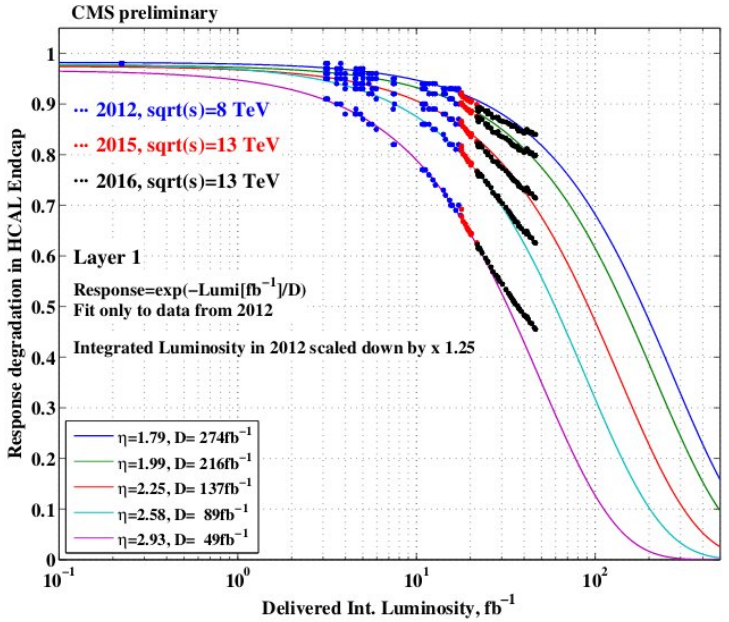
# Why look in the Calorimeter?

- Previously attempted to reinterpret result from CMS tracker.
- Low tracker thickness resulted in weak limit.
- HE thickness (~100 $X_0$ >> ~0.7 $X_0$ for tracker.

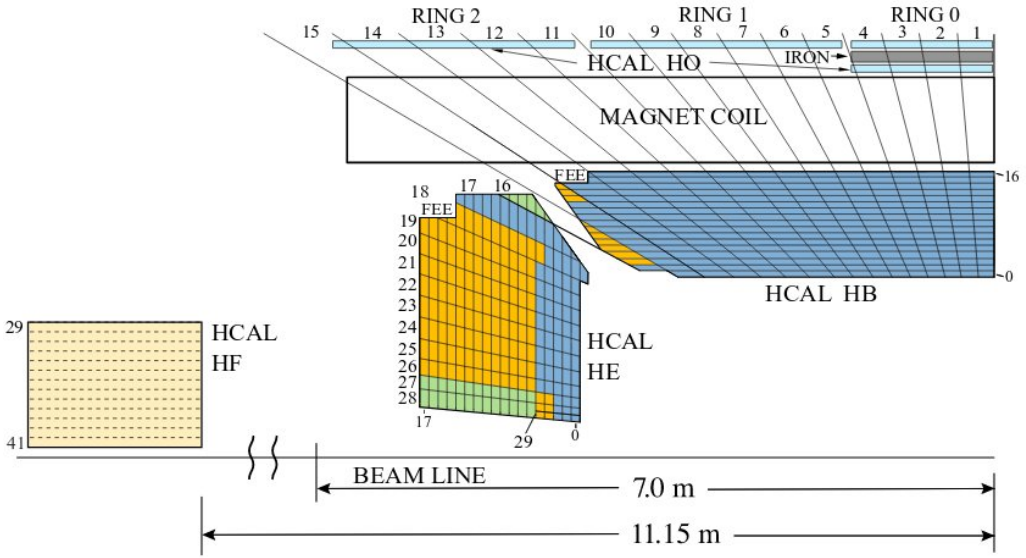
$$\mathcal{L}_{FT} = \Phi \rho_T l$$



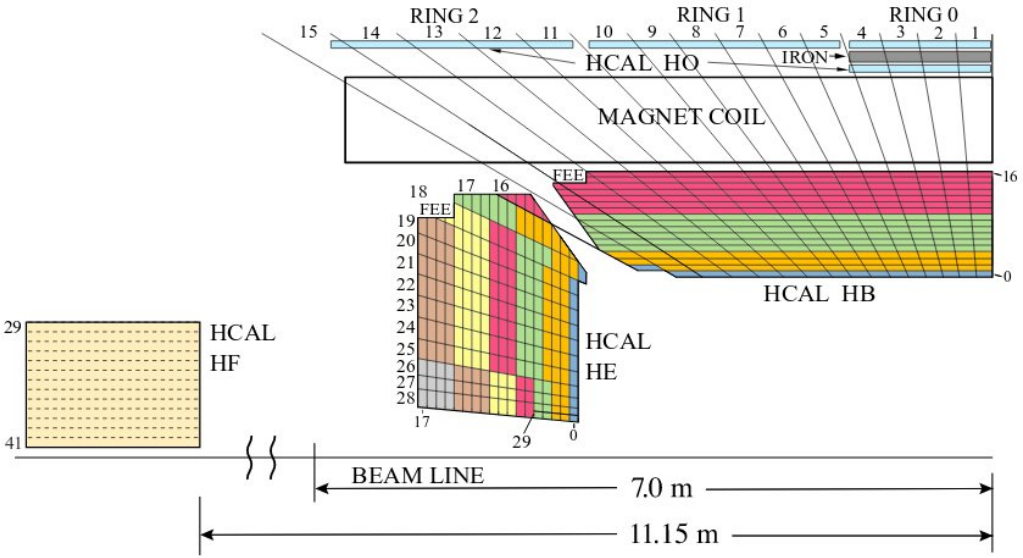
# 2018 HCAL Endcap (HE) Upgrade




- Photodiodes in endcap replaced with Silicon Photomultipliers.
- New SiPMs add necessary depth segmentation and signal resolution.
- Only endcaps were upgraded for 2018 data, barrel will be available for run 3.




*Pre-upgrade HCAL depth segmentation[4]*

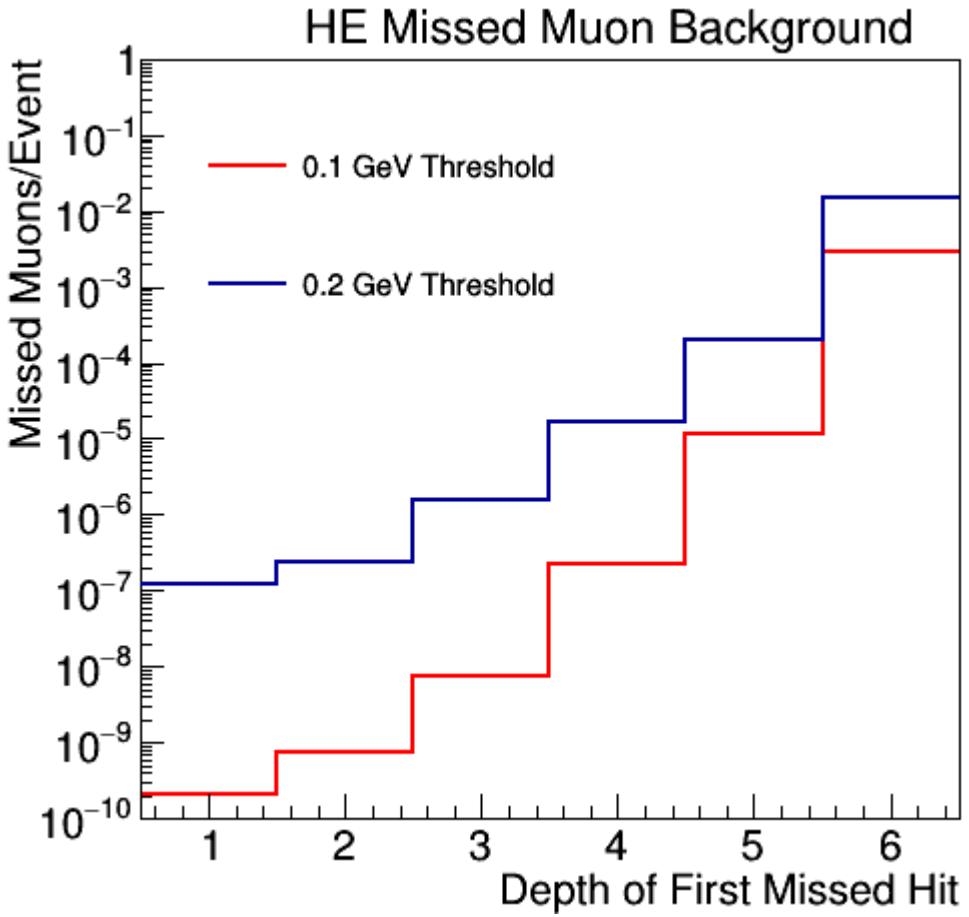



*Post-upgrade HCAL depth segmentation[4]*

# Backgrounds

## Missed Muons

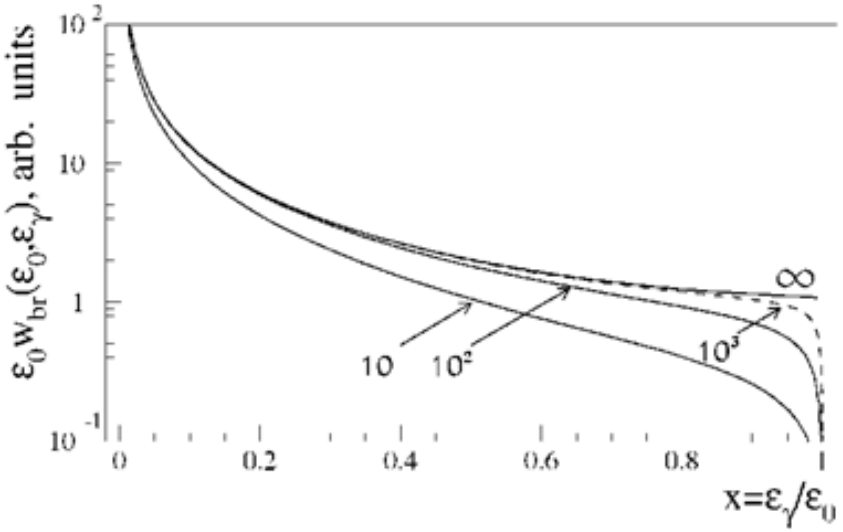
- Muons pass fully through HE and muon chambers, pass below threshold for multiple depths.
- Study with control regions with muon hits in the CSCs.



# Backgrounds

## Hard Bremsstrahlung

- Veto using additional energy deposits from photon.
- Can estimate contribution using Monte Carlo.
- Validate with data control regions containing photon deposits.

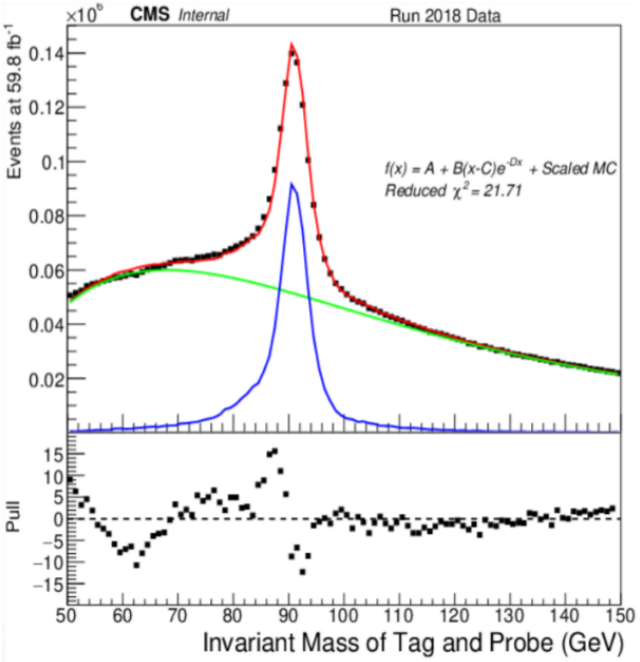


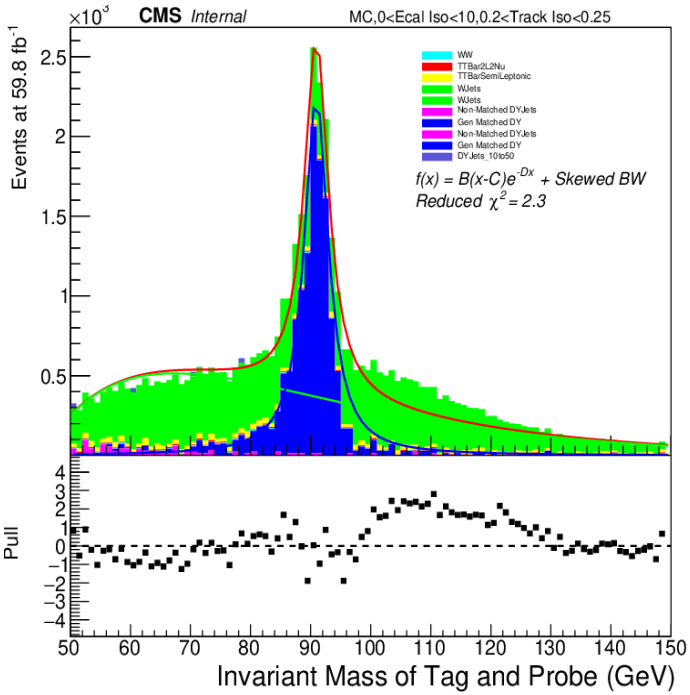

*Bremsstrahlung differential cross section for several different beam energies. Note that the axis is final photon energy, where earlier graphs where final lepton.*

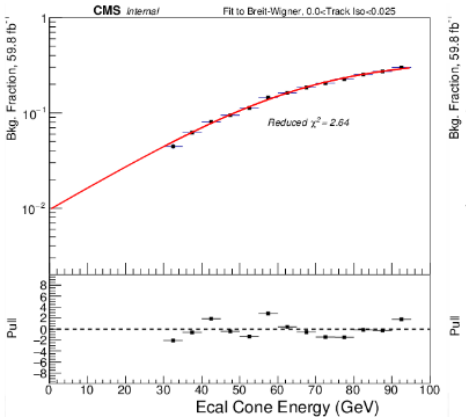
# Backgrounds

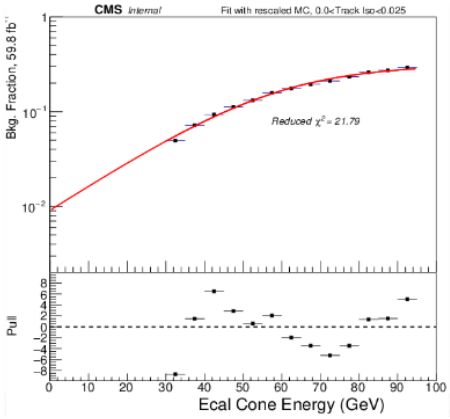
## μ+X

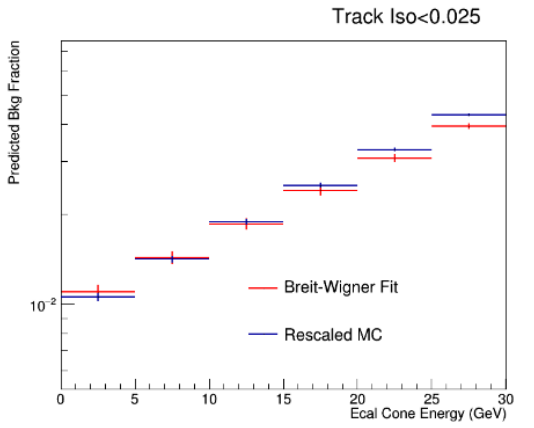
- Events where the selected probe track doesn't originate from a real muon.
- Study with control region with poor isolation.



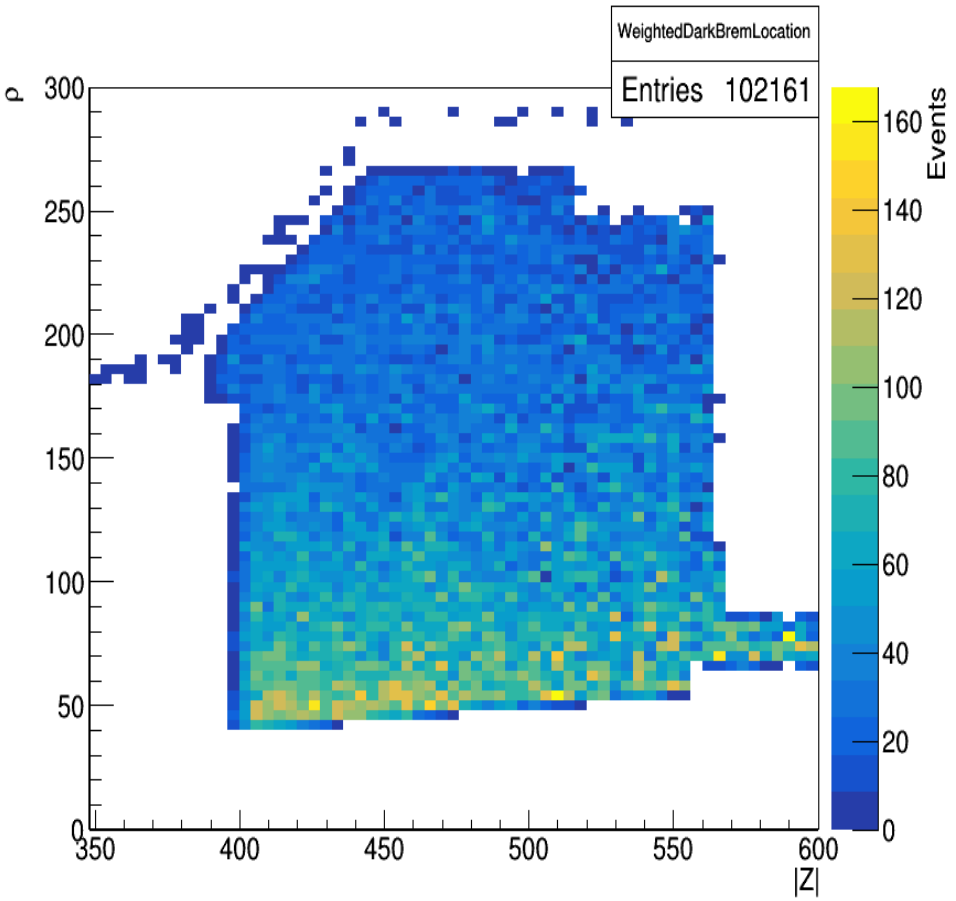



# Signal Simulation




*Locations of Simulated Dark Bremsstrahlung interactions in CMSSW*

- Unique challenge for this type of analysis.
- Muon energy loss before DM interaction can change kinematics.
- Signal implemented in GEANT, imported into CMSSW.
- Modified Custom Physics list, all other changes performed via plugins.

# Outlook

- Studying how pileup effects our signal selection efficiencies.
- Upgrade of HE provides a unique opportunity to look for a well motivated DM signal in a relatively open phase space.
- Many potential ways to improve the study with future detector upgrades.