ML applications in searches for long-lived particles at CMS

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Workshop on Machine Learning and High-Energy Physics
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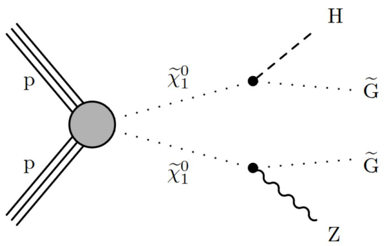
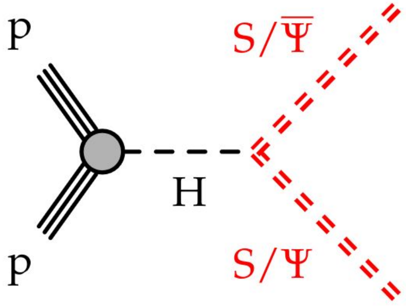
Introduction: LLP searches

- Standard Model doesn't answer all the questions about matter and interaction (dark matter candidates, Higgs mass hierarchy problem, neutrino masses, strong CP problem)

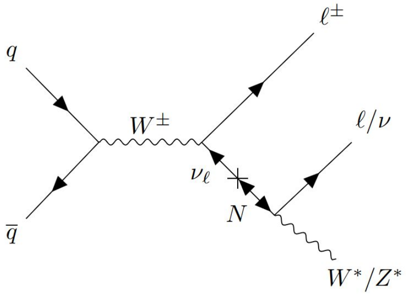
- Extensions of SM predict new particles that can be produced at LHC and are long-lived:
  - Partners of SM particles (SUSY)
  - Dark sectors communicating with SM via Higgs boson
  - Heavy neutral leptons (HNLs)
  - Axion-like particles (ALPs)
  - …many, many more!



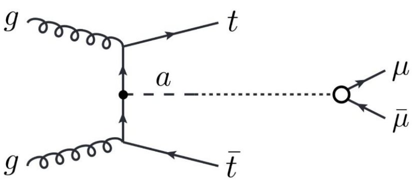
SUSY



Dark sectors



HNLs

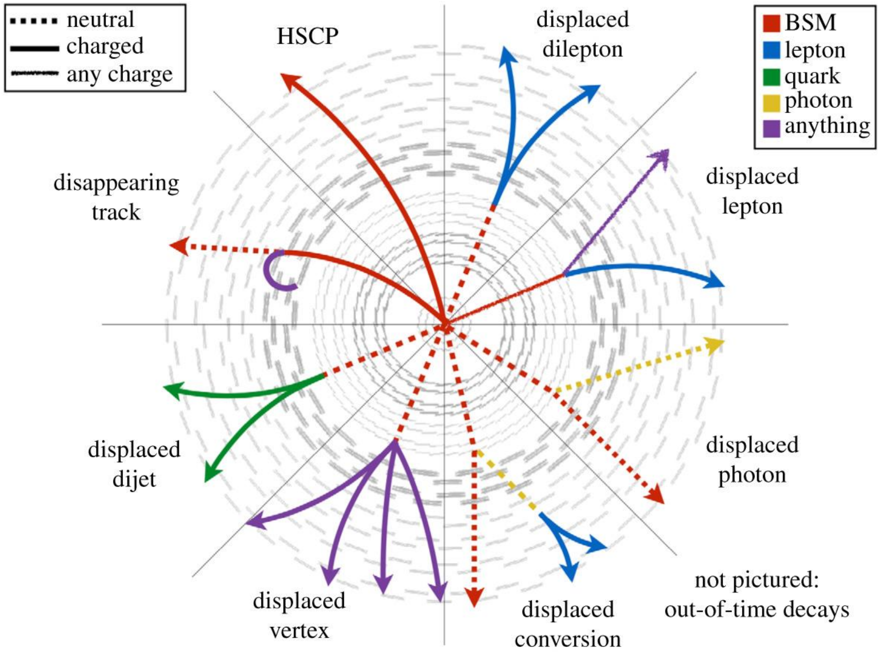


ALPs

Introduction: LLP searches @ CMS

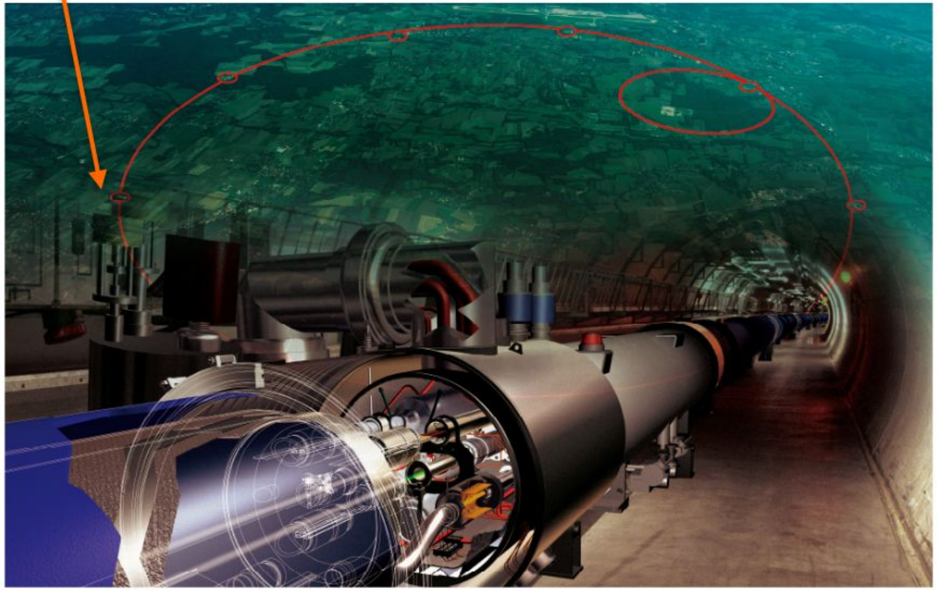
Very broad (and growing) LLP program at CMS!

- LLP searches are **challenging**
- …but they give **unique opportunities** for R&D
- New ideas applied at **any level** (reconstruction, trigger, analysis techniques, machine learning)
    - Creativity (non-standard use of the detector) and detector knowledge
    - Computing efforts (non-standard data formats)
    - Coordination

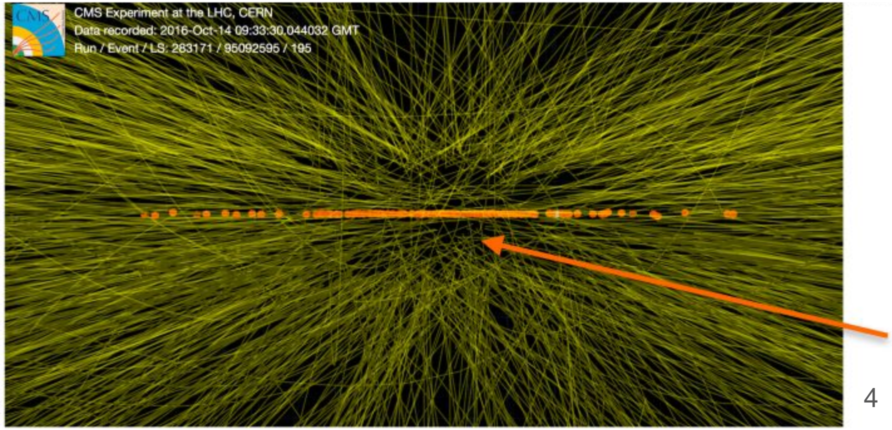


J. Antonelli

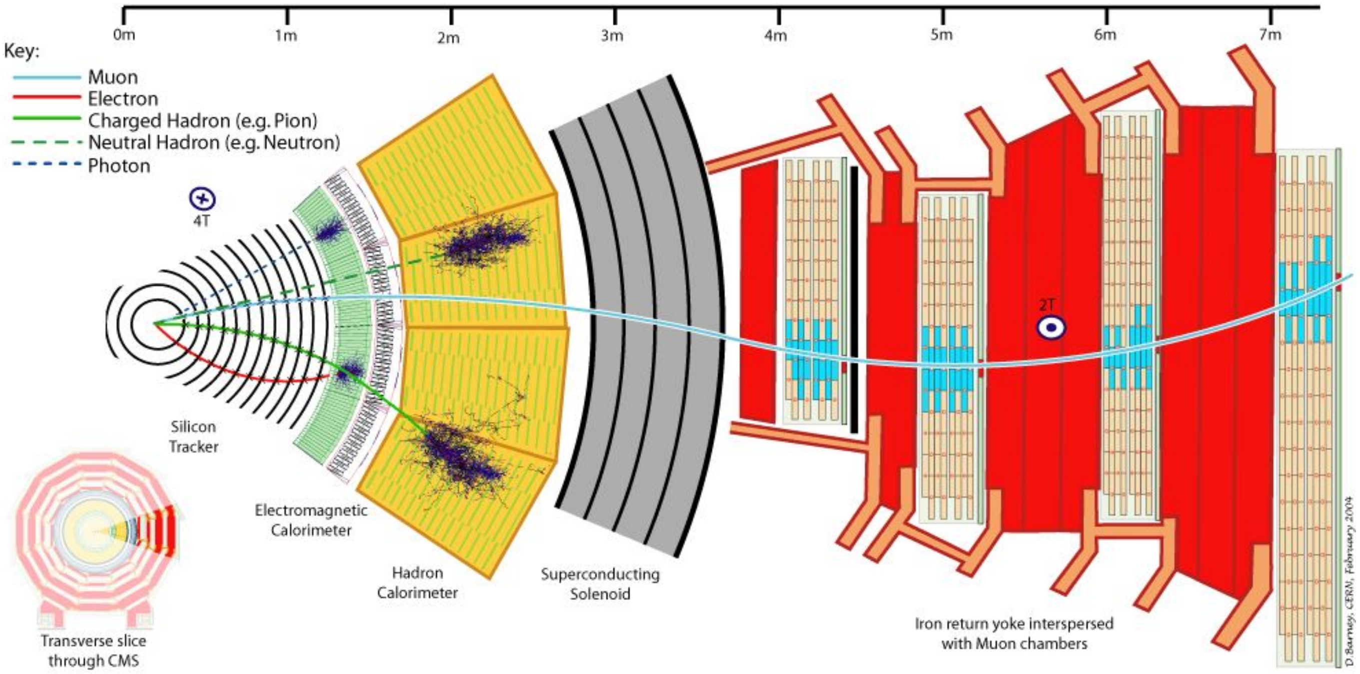
Introduction: LHC and CMS



- LHC: proton-proton collisions at 13/13.6 TeV (Run2, Run3)
  - momentum of quarks/gluons unknown → hard to precisely model what happens
  - bunch crossing at 40 MHz (25 ns): fast decision → sophisticated trigger systems @ experiments
  - beam organised in bunches of 10^{11} protons: multiple collisions at each crossing (pile-up), up to ~80

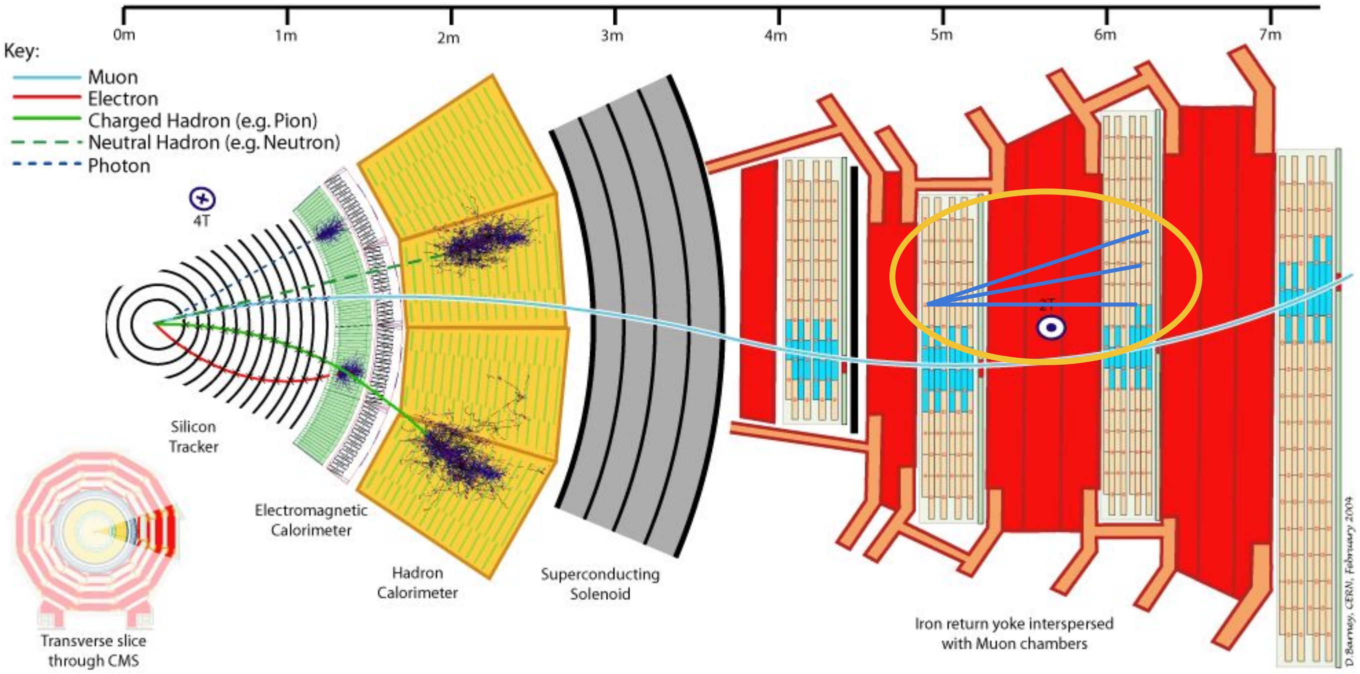


Introduction: CMS



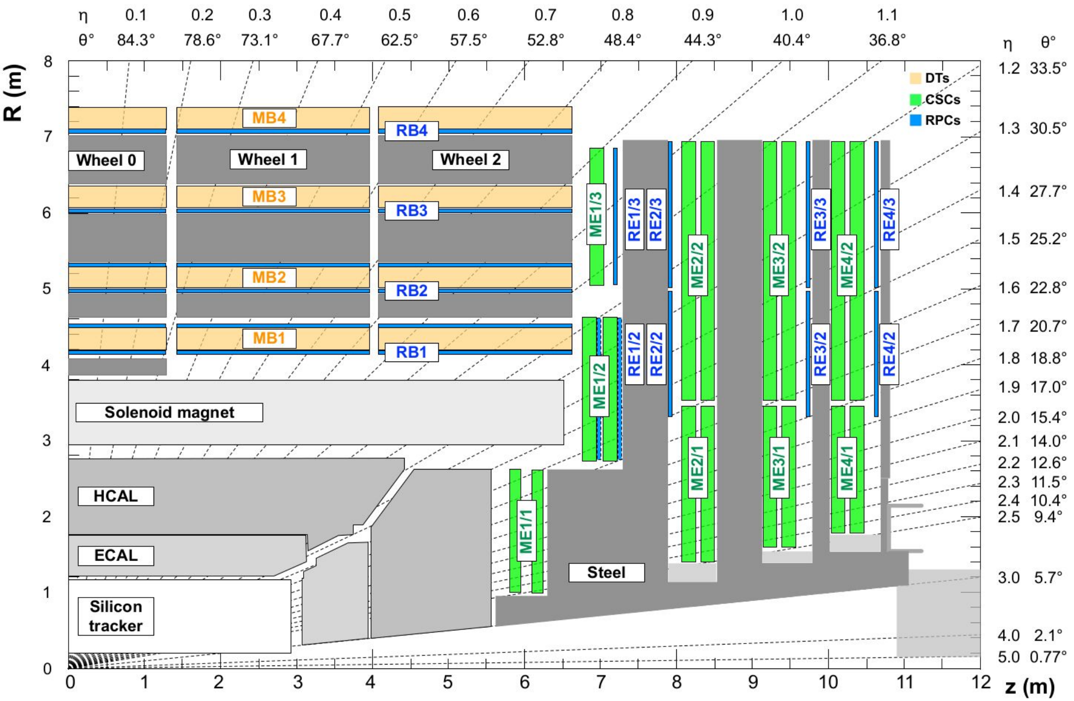
- CMS organized in layers to detect different particles
- Particle Flow algorithm connects info from sub detectors → precise momentum measurements and particle identification
- But… standard algorithms not designed for LL signatures!

LLPs decaying in the muon system



- What if a LLP travels through CMS without interacting, and decays to hadrons in the muon system?
  - Hadronization processes do not behave as a muon!
  - A “jet” in the muon system!
  - Currently no standard CMS algorithm to deal with this signature!

CMS muon system at work



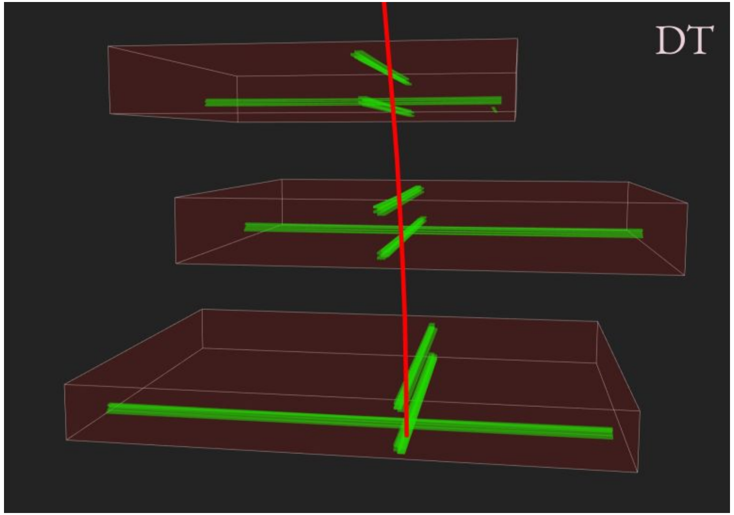
- Muon system: gas detectors and iron/steel (passive material + return yoke)
- Drift tubes (DTs) in barrel:
  - Anode wire in gas mixture
  - Uniform magnetic field, low rate
  - Very good spatial resolution (~100 μm) and time resolution (5 ns)
- Cathode strip chambers (CSCs) in endcaps:
  - Multi wire proportional chambers
  - Non uniform magnetic field, high rate
  - Fast time response (short drift path) and very good resolution (3 ns)
- Time information
  - Ability to trigger

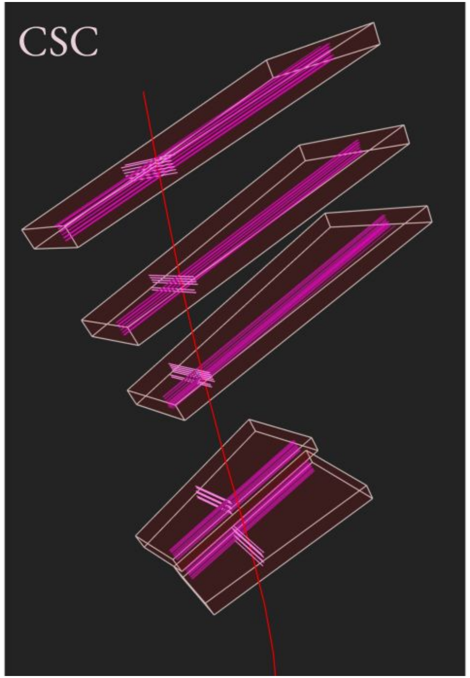
CMS muon system at work

Standard muon reconstruction

- Basic objects: hits
- Position in DT: time of arrival of ionization electrons collected by anode wire
- Position in CSC: intersection points of cathode strips and anode wire groups
- Hits combined to form segments (straight lines), 1 hit per layer
- Segments fit to determine muon trajectory and momentum

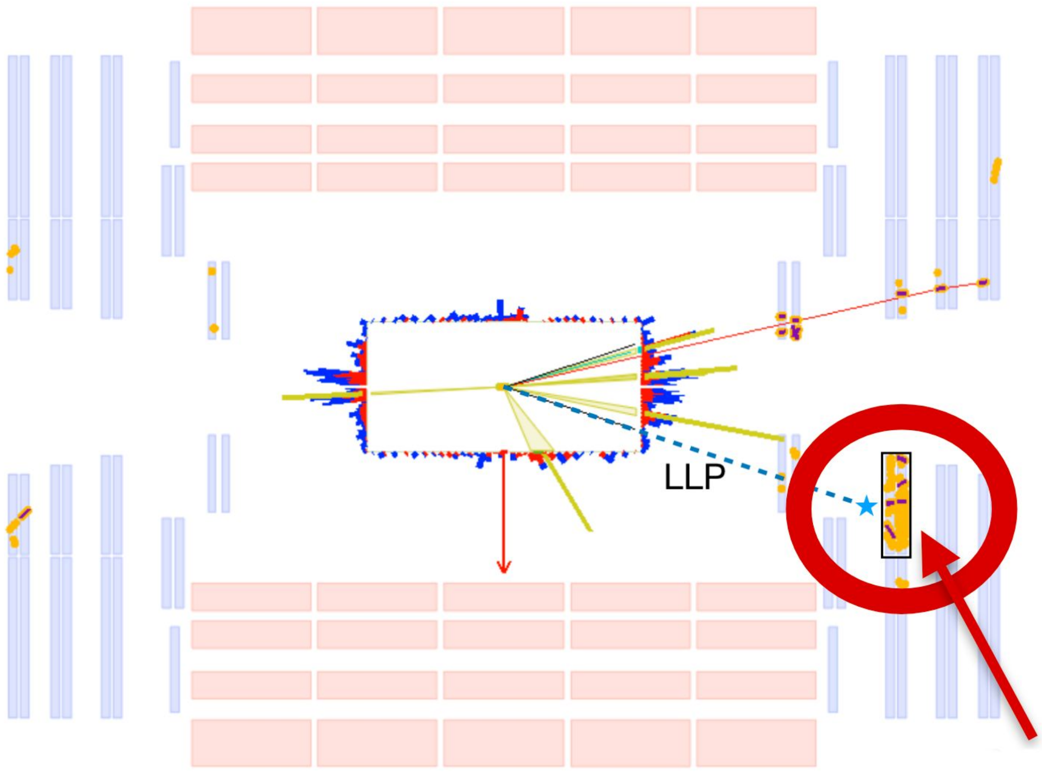
- These assumptions may not hold when dealing with hadrons!





M. Osherson's seminar

LLP decays in muon system



- Neutral LLPs (cτ > 1 m) hadronic decays: no tracks, no jets, but showers in muon system
- Muon detectors (steel/iron interleaved with gas chambers) act as a sampling calorimeter
- Hadrons ionize gas in muon chambers
- Signature: high multiplicity of hits
- Iron: suppresses punch through jet → very small background

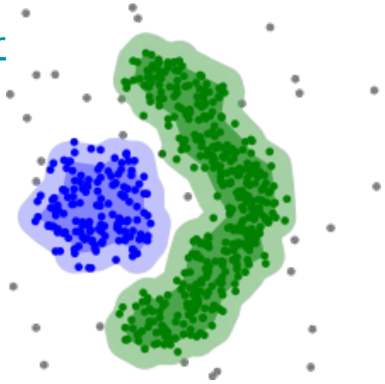
Muon detector shower

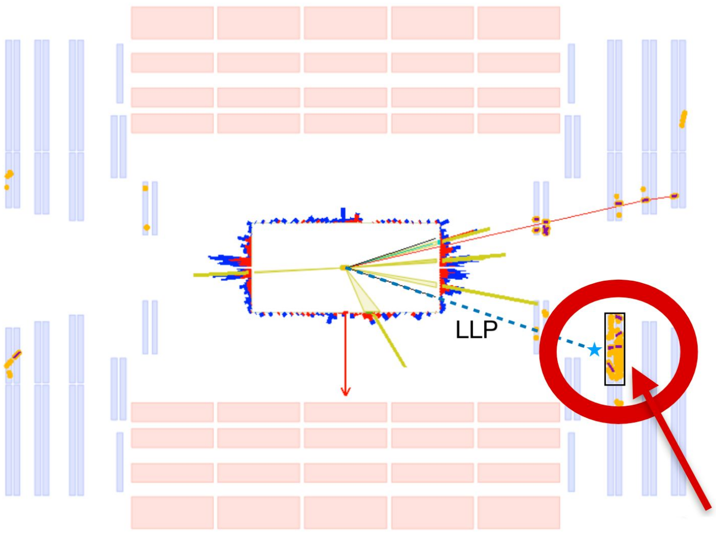
LLP decays in muon system

Current reconstruction: muon detector showers (MDS)
- Hits clustered with geometrical clustering algorithms

1. DBSCAN
- Density-based, non-parametric algorithm: groups together points that are closely packed together (points with many nearby neighbors), marking as outliers (noise) points that lie alone in low-density regions (whose nearest neighbors are too far away)
- Robust against outliers, can find arbitrarily shaped clusters
- Can’t handle well very different density regions
- Clustering parameter distance based on physics arguments (distance among layers in muon system; DR<0.2)

https://en.wikipedia.org/wiki/DBSCAN





https://ar5iv.labs.arxiv.org/html/0802.1189

LLP decays in muon system

Current reconstruction: muon detector showers (MDS)

- Hits clustered with geometrical clustering algorithms

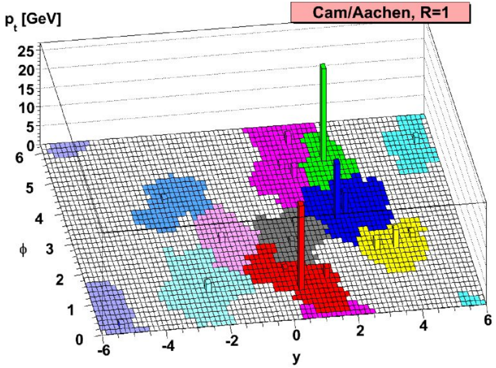
2. Jet clustering techniques

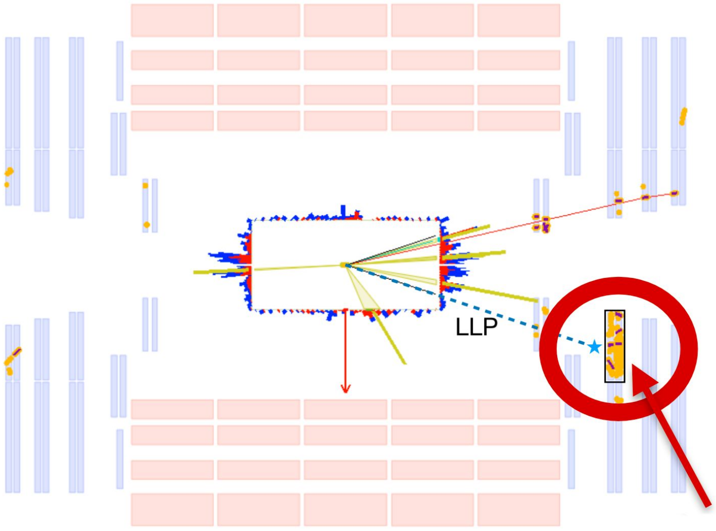
- Cambridge-Aachen, a=0

$$d_{ij} = \min\left(p_{T,i}^{2a} p_{T,j}^{2a}\right) \frac{R_{ij}^2}{R_0^2},$$

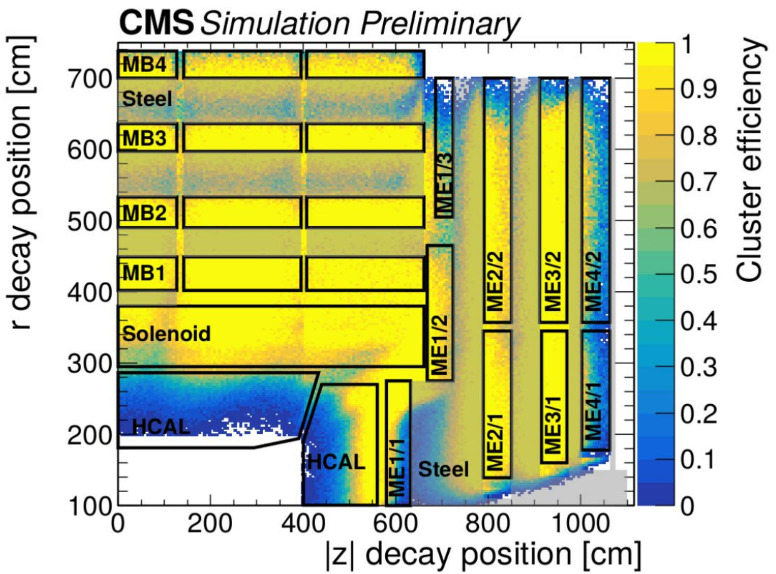
$$d_{iB} = p_{T,i}^{2a},$$

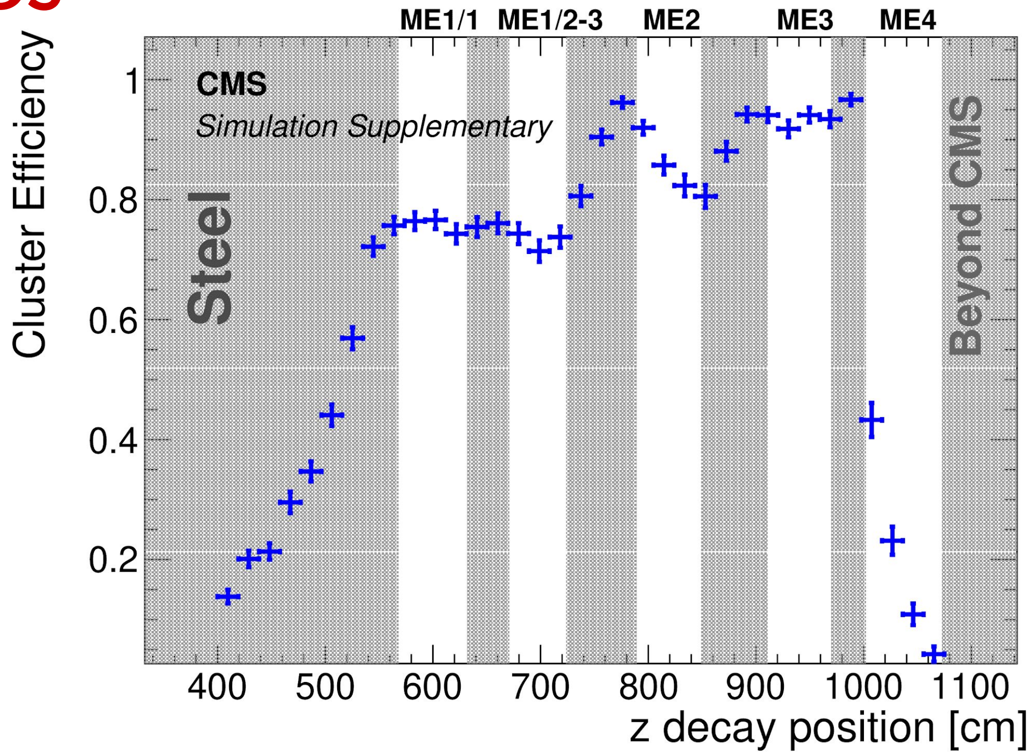
- Largely deployed at CMS, easy to implement
- Currently adopted at trigger level (MDS trigger introduced in Run3)
- Similar performances as DBSCAN





Searches for LLPs with MDS





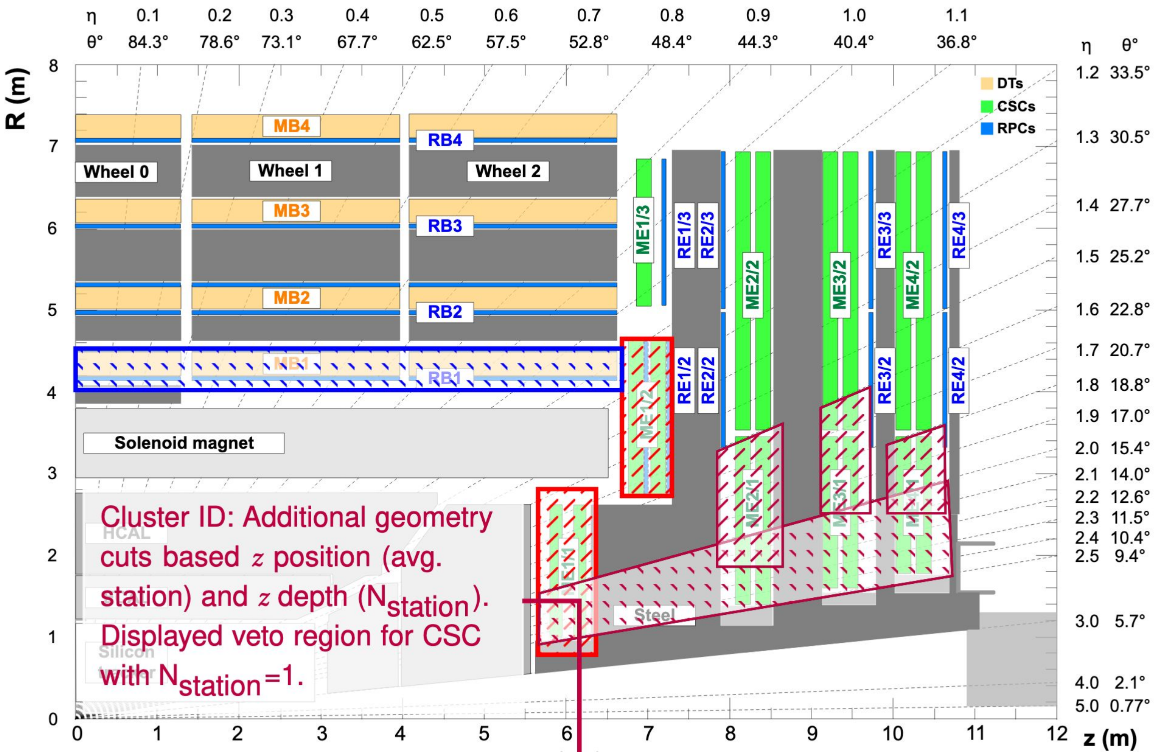
Search strategy:

- Look for 1 or 2 MDS (1 per LLP decay) → sensitivity to every particle decay except muons!
- Electromagnetic energy easily stopped by steel
- Hadronic energy punches through

Searches for LLPs with MDS

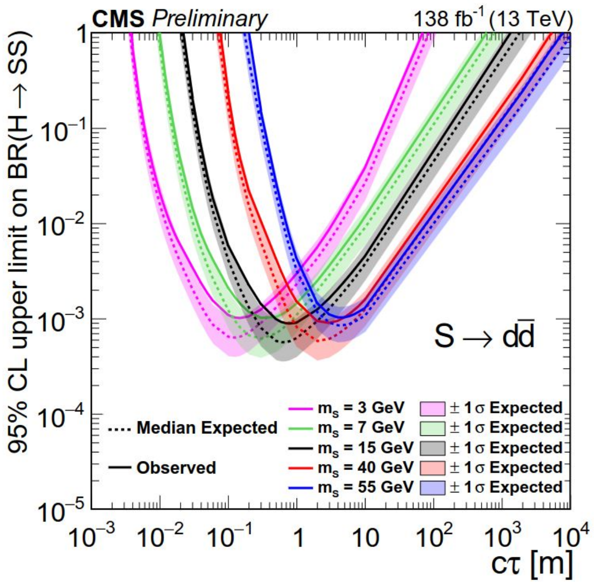
Backgrounds:

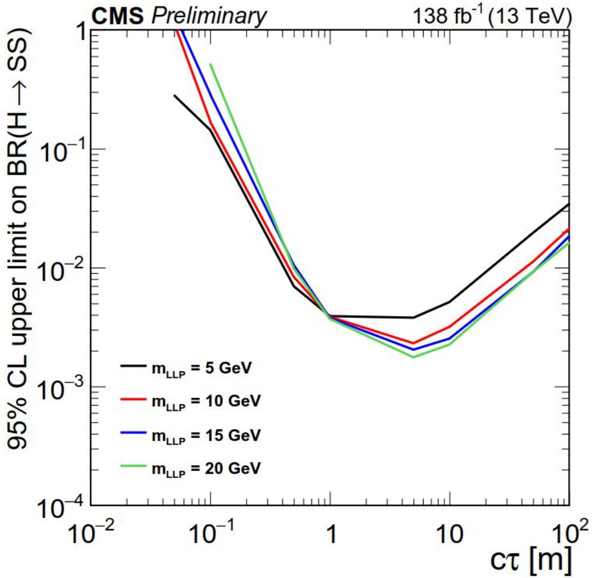
- Punch-through jets, low-p_T pileup particles (pions, kaons)
- Mostly suppressed by vetoing high background regions (inner DT/CSC chambers)
- Dedicated vetoes for cosmic muons, beam induced backgrounds

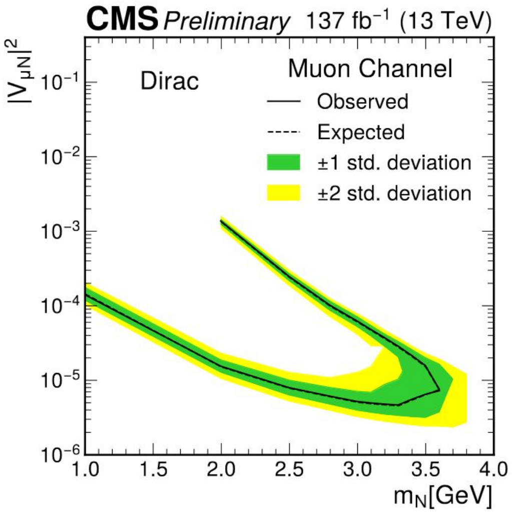


Searches for LLPs with MDS

- MDS provide sensitivity to any LLP decay (except muons)
  - Also light (O(100) MeV) particles → non reconstructable in tracker/calorimeter
- First CMS result using CSCs: PRL.127.261804
- Close to publishing CSC+DT combination (PAS-EXO-21-008)
- Best limits to date on Twin Higgs model!
- First limits @ LHC on Dark showers model!
- Close to publishing search for heavy neutral leptons (PAS-EXO-22-017)





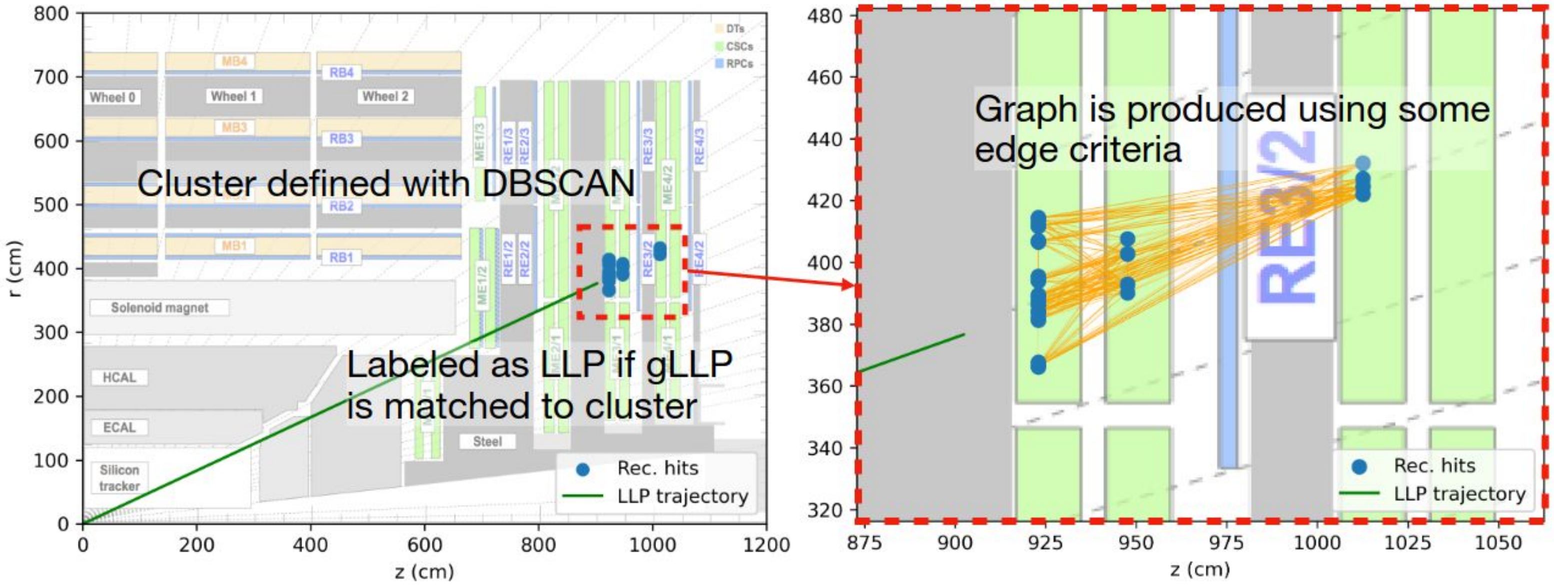


Improving MDS

MDS as geometrical clustering of hits:

- No pT/energy measurement, only position and hit multiplicity
- No identification of the particle initiating the shower
    - But we have seen that EM showers are “smaller”!
- Muon system hits based on some assumptions (dealing with muons)
- How can we improve this?

A. Aportela
J. Duarte



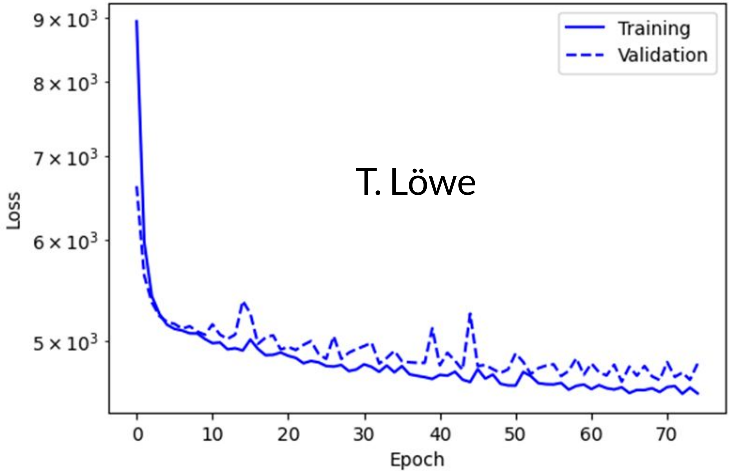
MDS energy regression

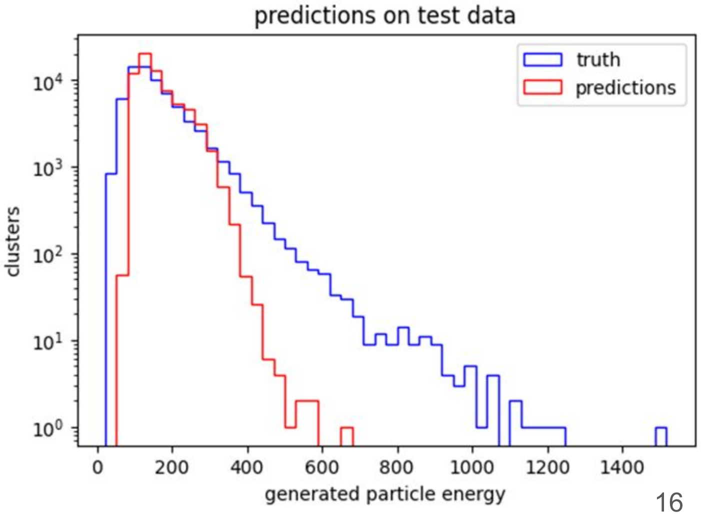
Information we can currently access at MDS level:

- Centroid position of hits (x, y, z, eta, phi)
- Average chamber/layer (quantify decay distance)
- Time w.r.t. proton-proton collision
- Some measurements of the shower spread (skewness, kurtosis, major/minor axes)

Ongoing effort:

- Very first attempts at energy regression
- Simple FCN architecture
- Size of the cluster seems the most important variable
- Looking at individual hits inside the cluster?





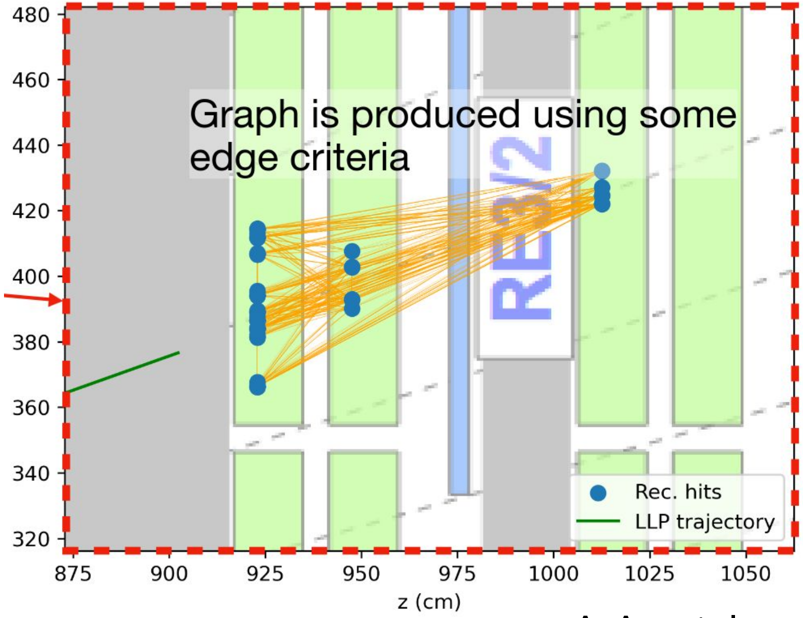
GNN applied to MDS

Graph neural networks:

- **Node features** include hit level info (position, time)
- **Graph features** include cluster level info (position, time, spread, ...)
- **Edge connections** represent some relationship between nodes:
  - Spatial relation or something more abstract e.g. deltaR threshold or k-nearest neighbors

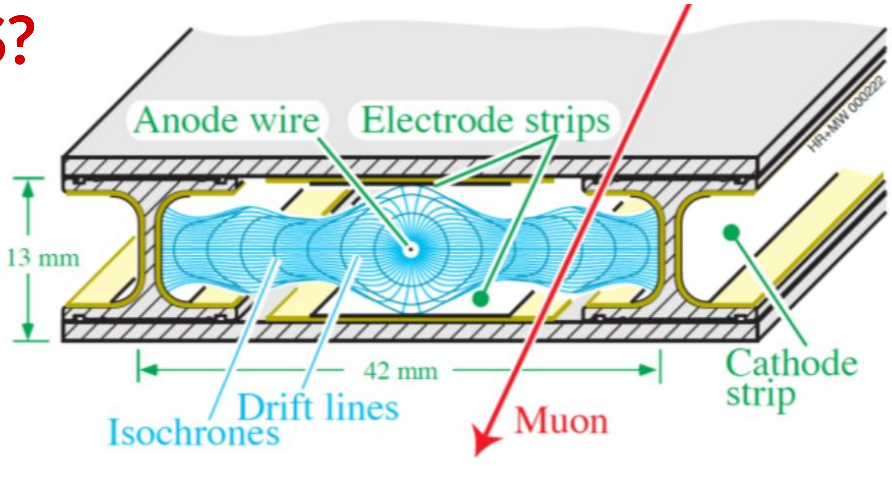
Ongoing efforts:

- Classification task S vs B
- Transformers vs GNN?



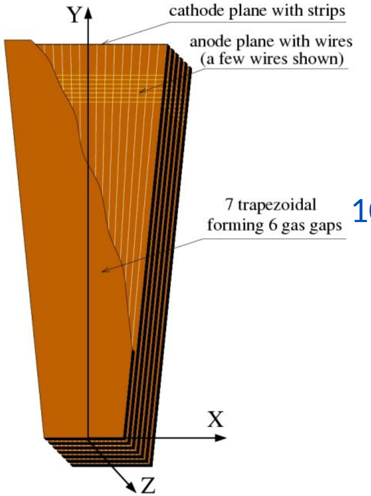
A. Aportela
J. Duarte

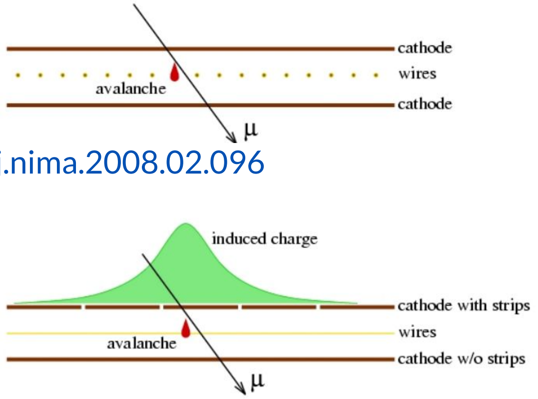
A novel algorithm to build MDS?



Build a MDS from very first principles:

- Hits contain some assumptions on the trajectory of a muon → can be biased in some way
- Use lower level detector information
  DT: charge deposited in anodes and TDC signal
  CSC: charge and signal pulse deposited in anodes/cathodes;
- It looks like a point cloud type of problem → graphs?



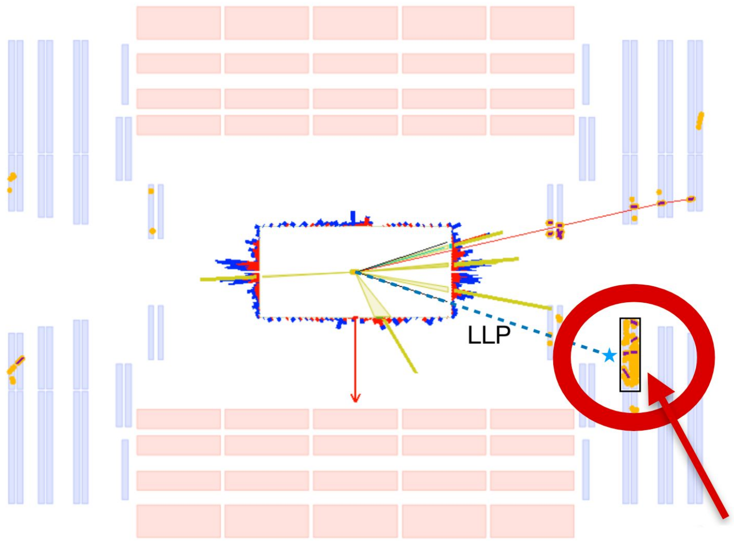


10.1016/j.nima.2008.02.096

Summary

- Developed a new tool to search for LLP decays
- MDS currently based on geometrical clustering
- Very powerful but still so much to learn/improve!

- Goal: calorimetry with muon system, NOT designed for this scope
- Perform energy measurement and particle identification
- We can access very low level detector information
- Would like to use ML to develop some more advanced reconstruction
- Any suggestion or future discussion would be extremely welcome!

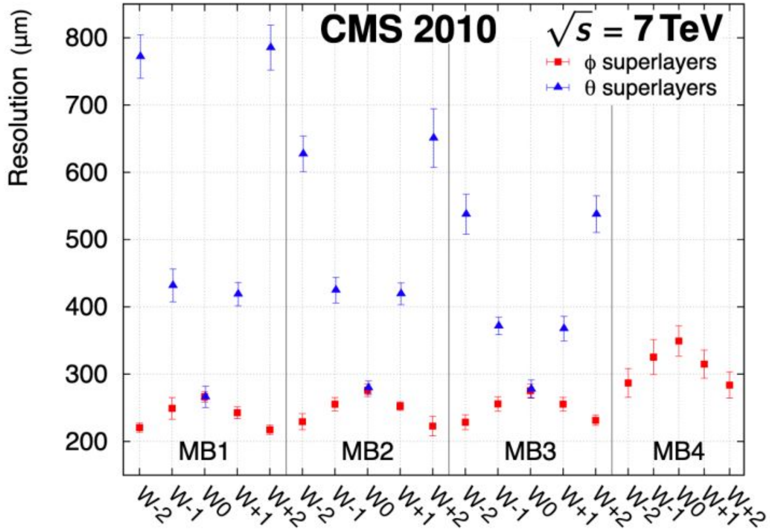


Backup

DTs

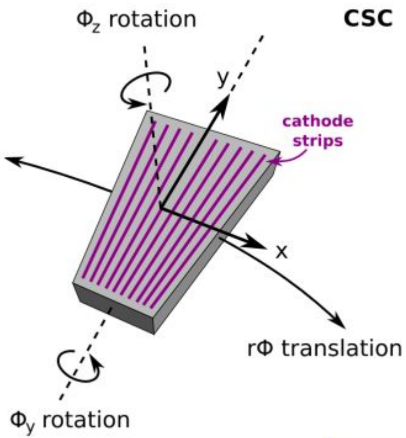
- DT cell: 42×13 mm2, gas mixture (85% argon, 15% CO2)
- Ionisation electrons drift to the 50 μm thick steel anodic wire, in the center. Signal induced in aluminiom cathode strips
- Electric field: electron drift speed uniform, muon position from drift time
- Cells oriented with wire along z → measure φ; wire along r → measure z
- Resolution: 100 μm in (r,φ) plane, 1 mrad in φ, 150 μm in longitudinal z coordinate
- Arranged in 4 stations, 5 wheels

arXiv:1306.6905



CSCs

- Anodic wires in 6 planes, measure r
- Perpendicular cathodic strips (along r) measure φ
- Ionisation electrons migrate to anodes, inducing a charge distribution on cathodes → azimuthal coordinate
- Resolution: 75 – 150 μm in (r,φ) plane



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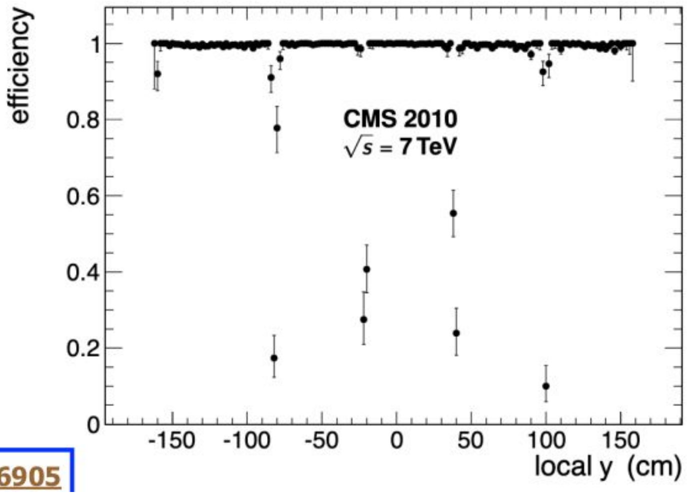

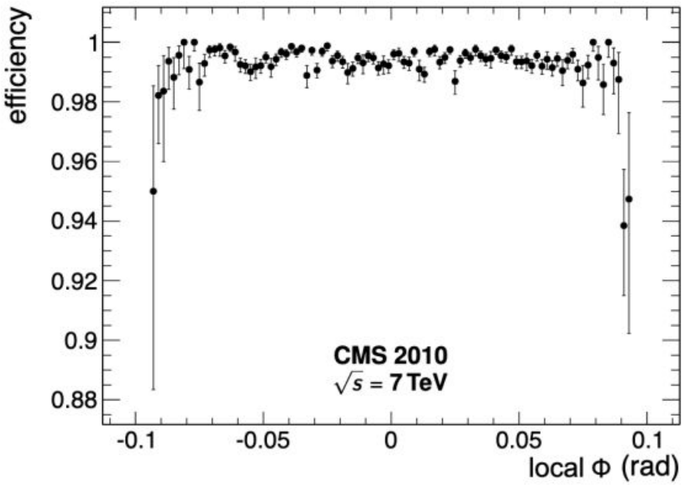

RPCs

- Resistive Plate Chambers both in barrel and endcaps
- Charged at high voltages, work in avalanche ionisation mode
- Plastic resistive plates equipped with readout strips
- Spatial resolution low (1-2 cm), but fast timing response (2-3 ns) and good time resolution (1 ns) → additional triggering system + precise measurement of bunch-crossing time