# Experimental aspects of Long-lived particle searches at the LHC

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Frontiers in Particle Physics

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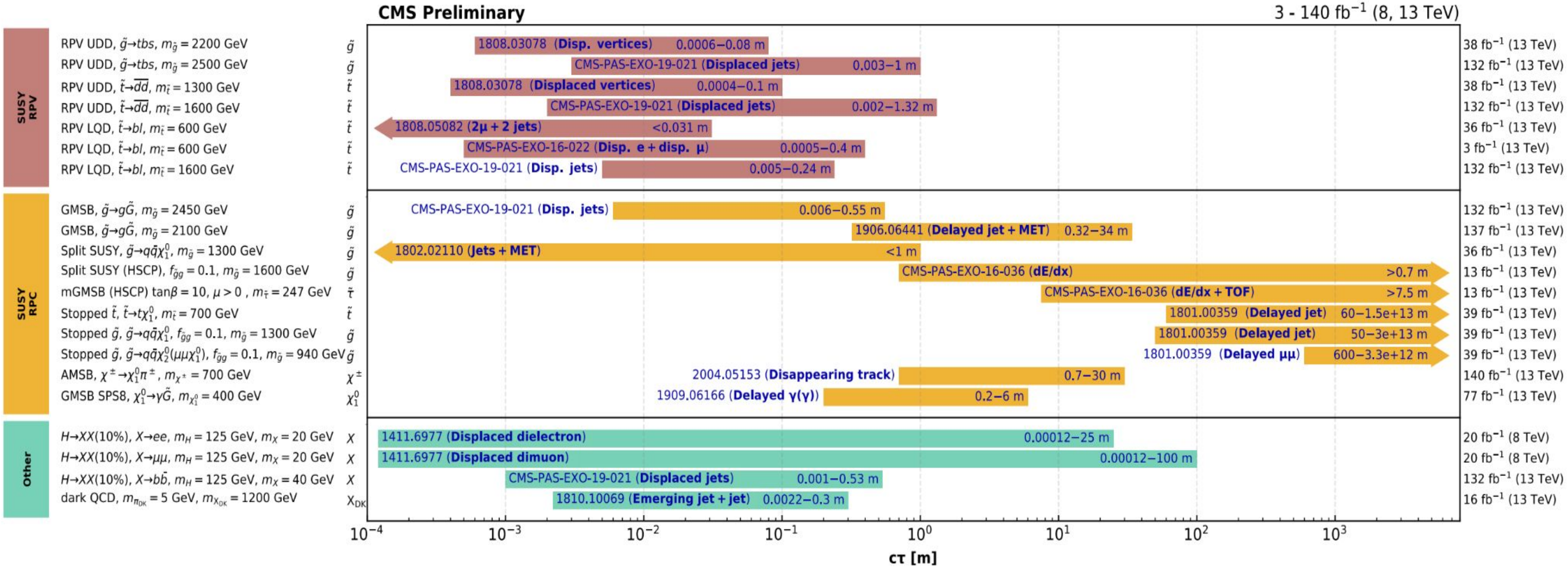
# Overview of CMS long-lived particle searches

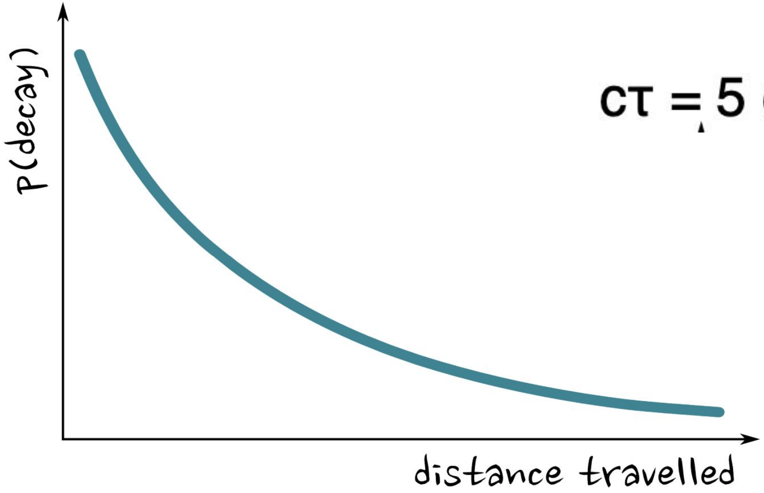



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

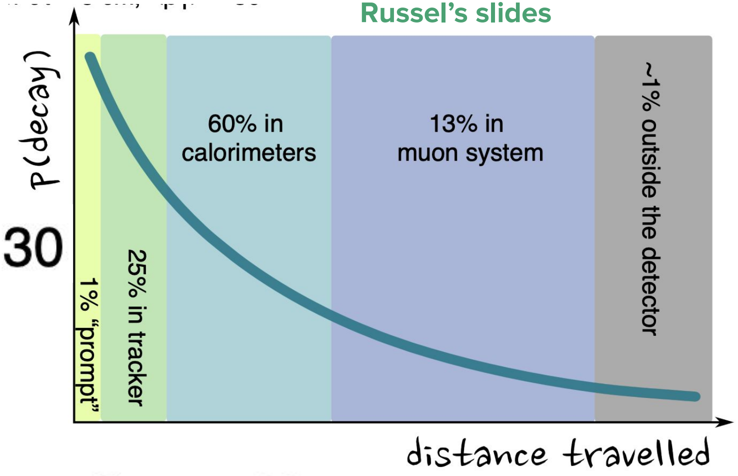
- Spectrum of LLP searches in CMS - similar in ATLAS

# Why are there so many different searches for LLPs?

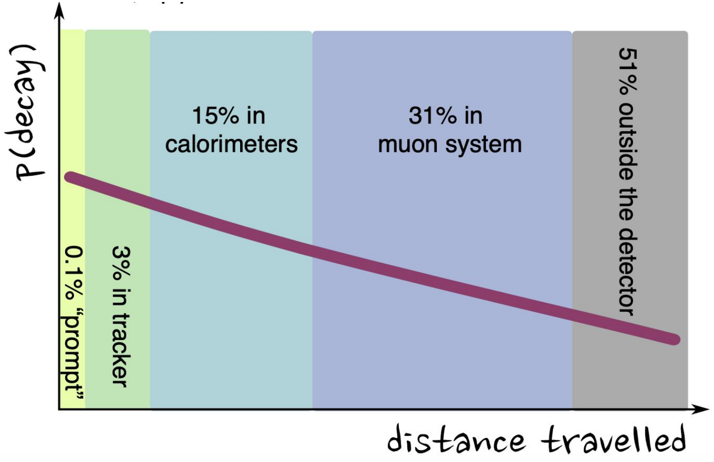
Pictures taken from Heather Russel's slides




cτ = 5 cm, <βγ> ~ 30



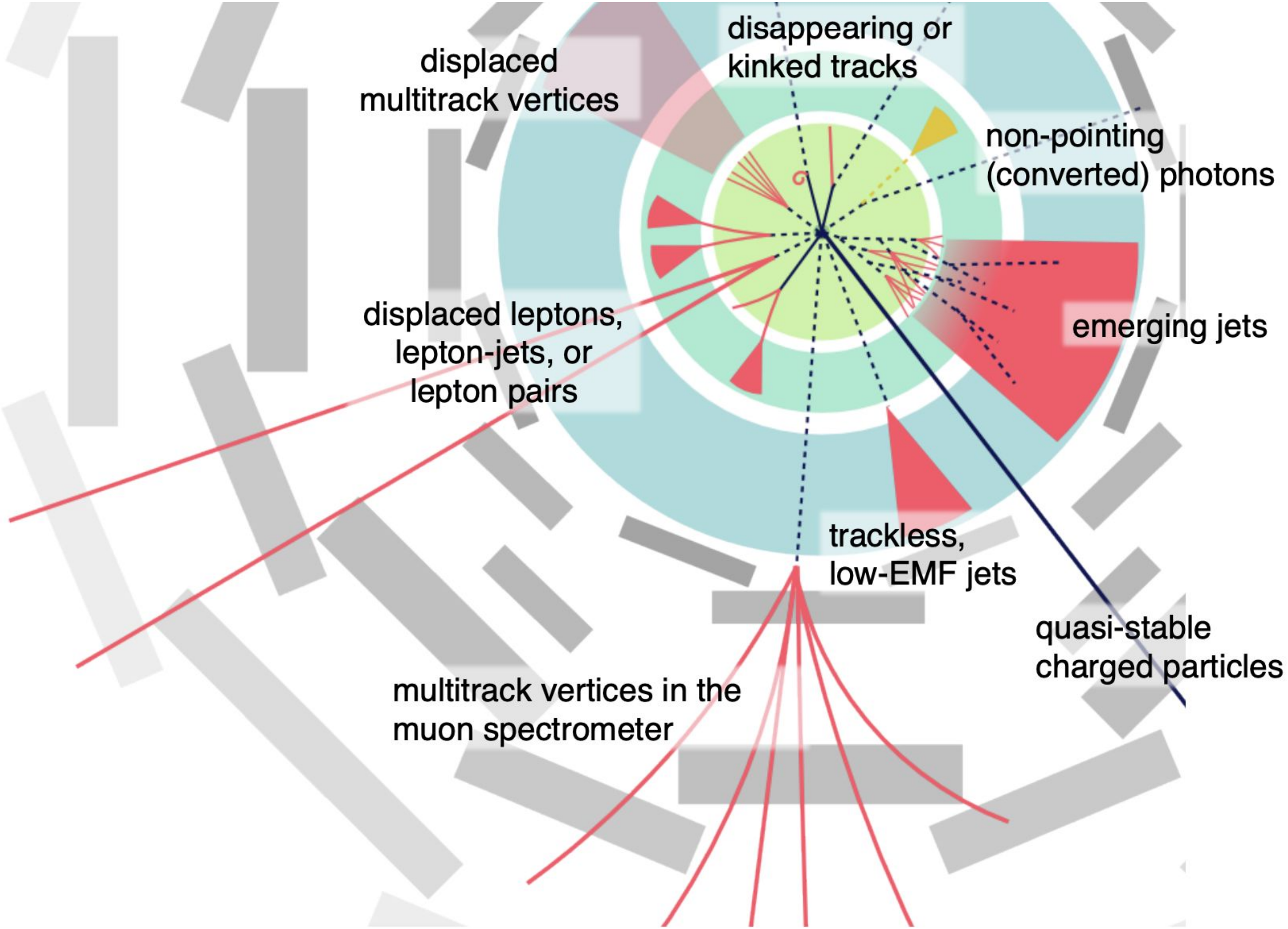

cτ = 50 cm, <βγ> ~ 30



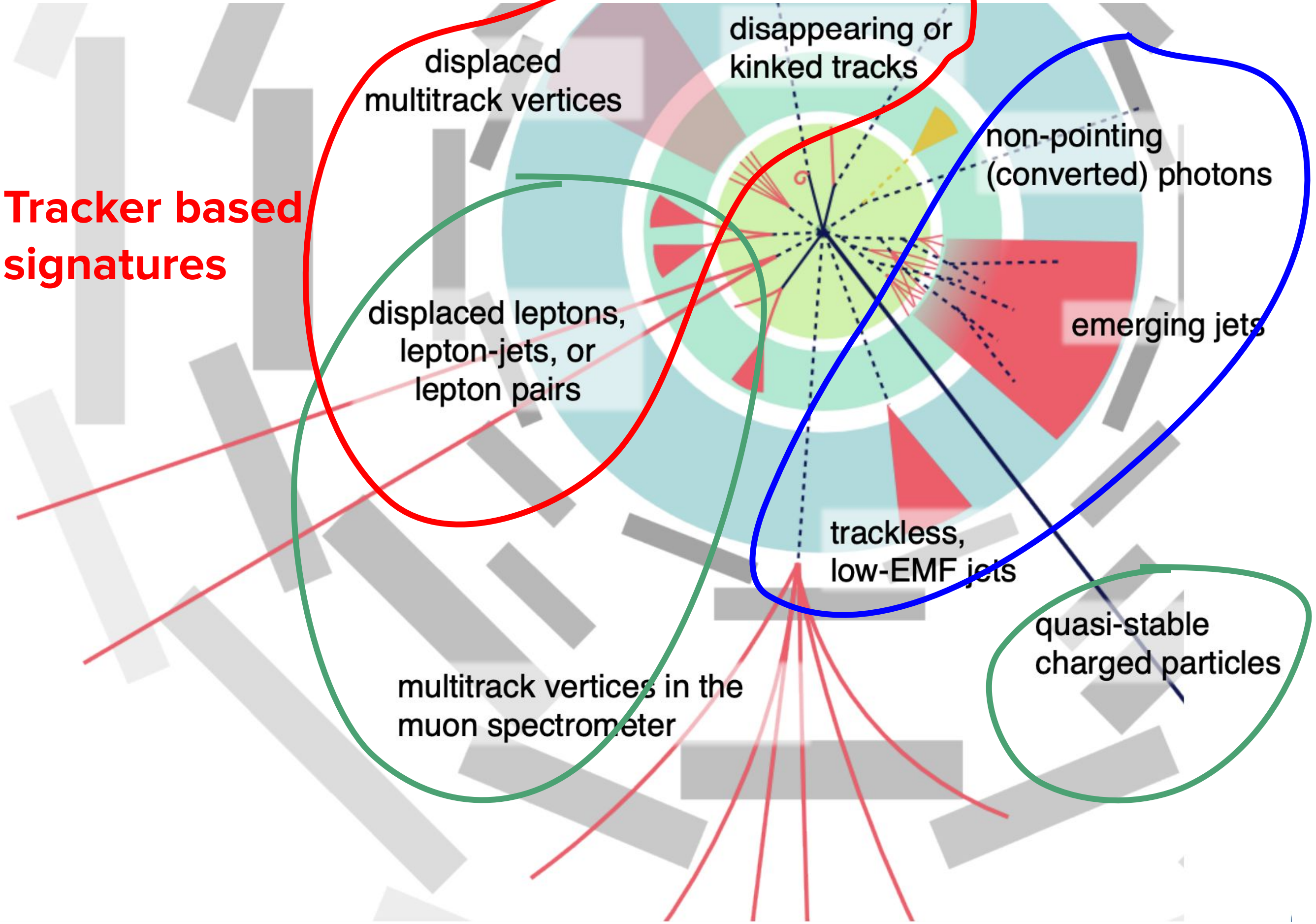

- A given particle's  time is sampled from an exponential distribution
- Depending on its proper lifetime (lifetime in its rest frame) and the boost, it can travel different distances in the lab frame before decaying ➔ **Different signatures in the detector**

# Signatures of LLPs

Pictures taken from Heather Russel's slides



# Signatures of LLPs categorized by detectors




Calorimetric based signatures

Muon spectrometer based signatures

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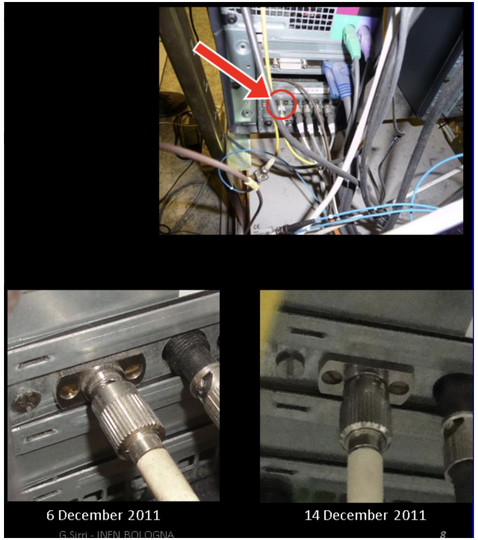
# Challenges in the LLP searches

- Reconstruction is usually tuned to detect standard signatures
  - E.g. Electron reconstruction is ideal either for prompt production or pair production via photon interaction with the tracker material
- Understanding and modeling the backgrounds are the biggest challenge
  - The sources are usually not the ones that are encountered in the standard searches
  - These can arise from various sources, e.g. cosmics, non-collisions backgrounds, algorithmic sources etc

# History shows us why understanding the sources is important

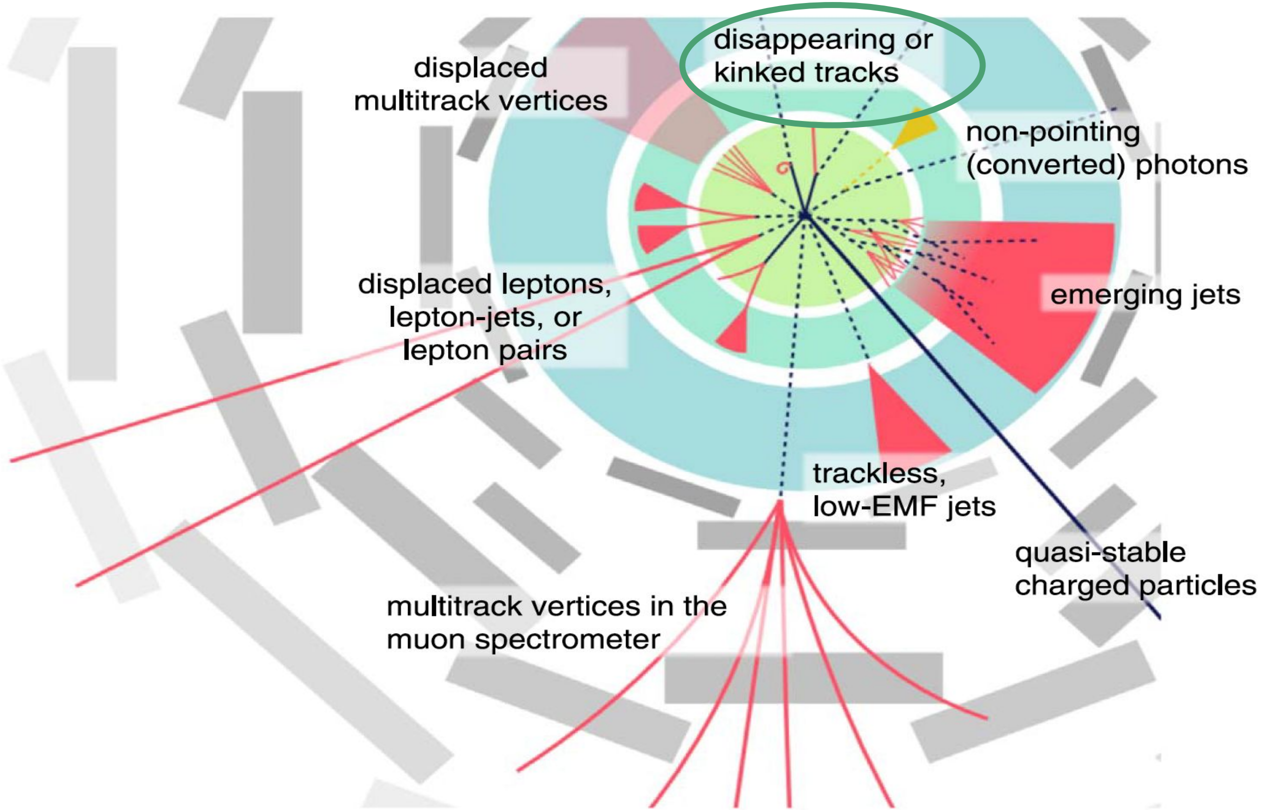
- There are many examples of mis-understanding of the background sources
- OPERA experiment at Gran Sasso made an announcement of neutrinos traveling faster than the speed of light - It was a 6σ effect in 2011!!!
- However, after investigation of all the possible sources, it was found out that the optical fiber that sent timing signal to the master clock was not screwed in properly.



- In the next slides, using some of the LLP searches, my main focus will be on the challenges (mostly on understanding the background sources) faced by these various searches according to their decay signatures

# Signatures inside the tracker

# Disappearing tracks

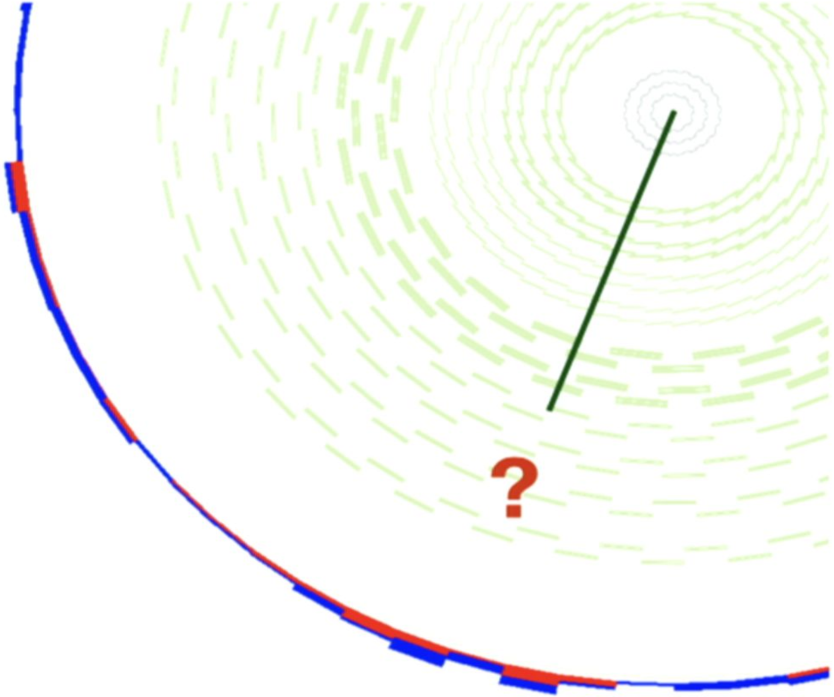



**CMS: PLB 806 (2020)**
**(EXO-19-010)**

# Distinctive Experimental Signature

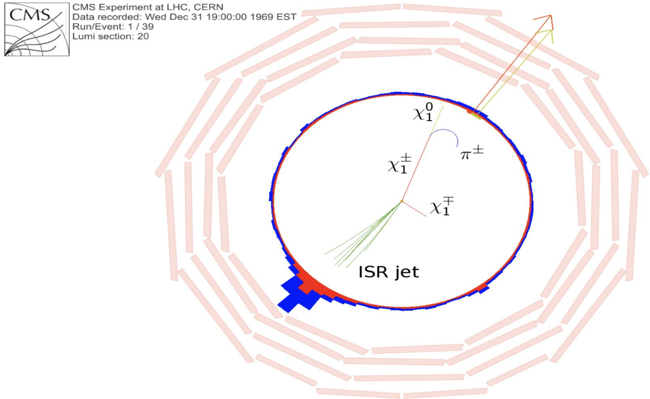
**+Some calorimetric deposit**

- LLP decays in the tracker
- Signature is a “Disappearing track”
  - Hits stop midway in the tracker
  - Produced by charged BSM particle if decay products are undetected because they are low-momentum or neutral/weakly-interacting



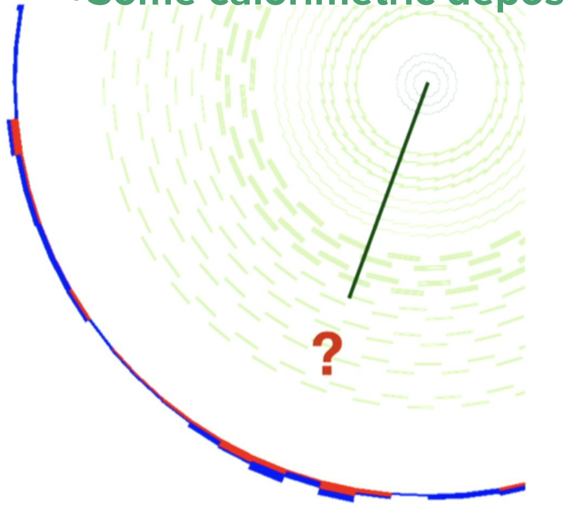
# Usual Signal Benchmark

- Anomaly-mediated supersymmetry breaking (AMSB) can give rise to such signatures
- AMSB predicts particle mass spectrum in which there is a small mass splitting between lightest chargino ($\chi^{+/-}_1$) and neutralino ($\chi^0_1$ - LSP)
- Decay looks like (100% BR) : $\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^{0} \pi^{\pm}$.
- In such a scenario, chargino has a lifetime of the order of 1ns, and the daughter pion has low momentum (~100 MeV)
    - Typically small and hence pion is not reconstructed as a track

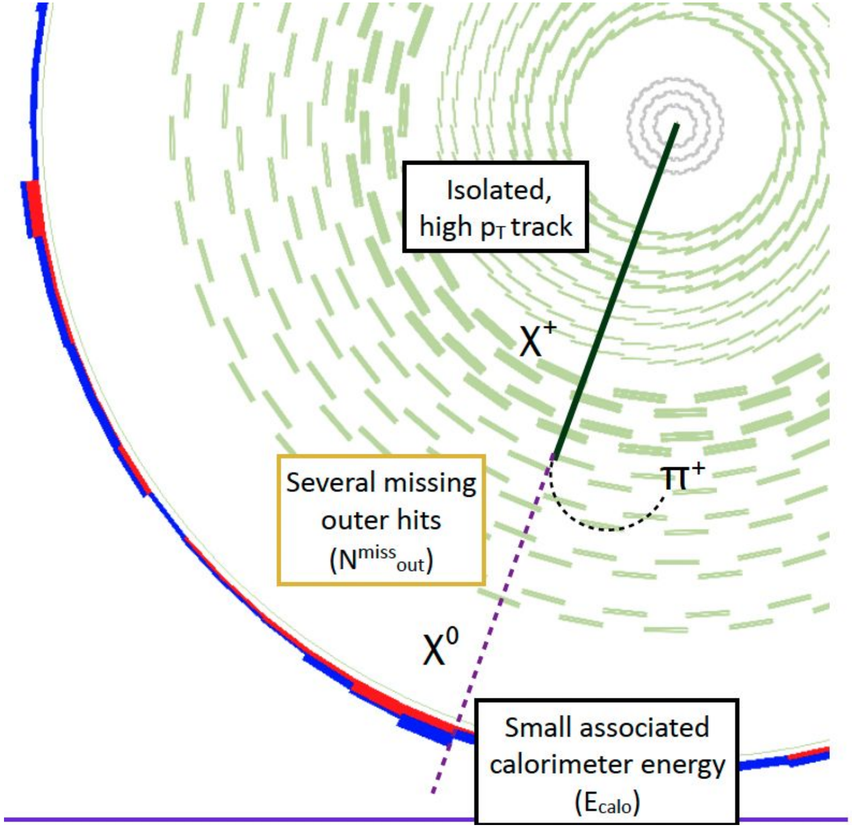



Signature in the detector

+Some calorimetric deposit



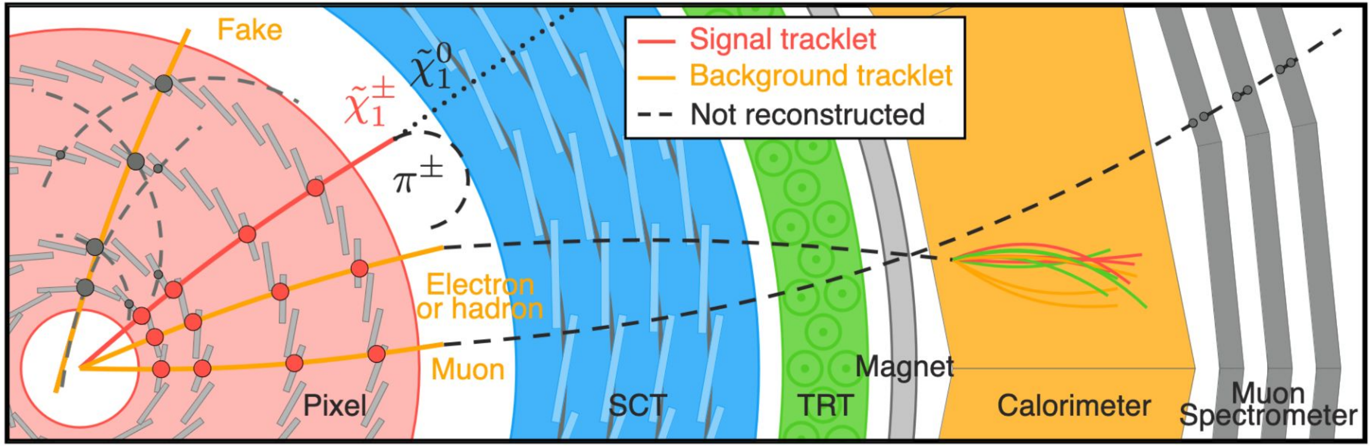
# Event topology




- Such signatures have:
  - Isolated high pT track
  - Several missing hits in the outer layers of the tracker
  - Small energy deposits in the calorimeter - usually coming as a recoil from an ISR jet
  - MET in the system

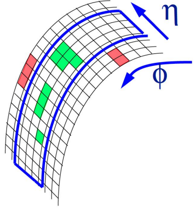
# Characteristics of the Background

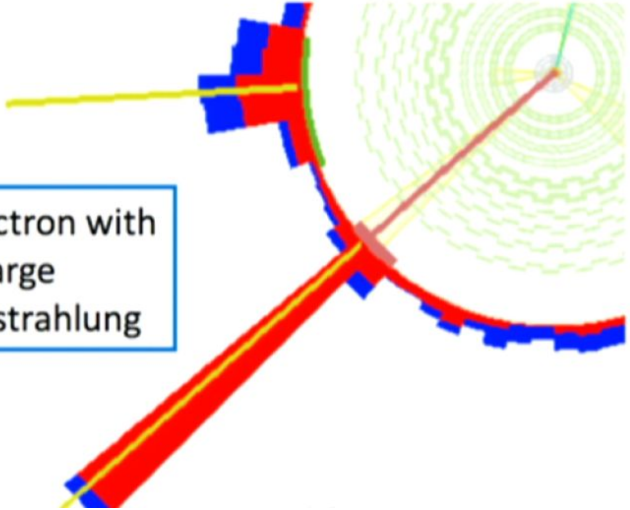
- Instrumental effects, interactions with the detector and failure of pattern recognition algorithm in track reconstruction
  - Muon: If it has no recorded hit in the muon system (decays in flight, or produces a EM shower) or traverses a gap or a problematic chamber in the muon system
  - Electrons: E.g. If tracks are directed towards a dead channel or strong brem that makes it lose its hits in the outer tracker
  - Tau:
    - If pions in $\tau \to \pi\nu$ decays has pT which has been mis-measured
    - Nuclear interaction of the pion with the material of the detector




Taken from ATLAS-CONF-2021-015

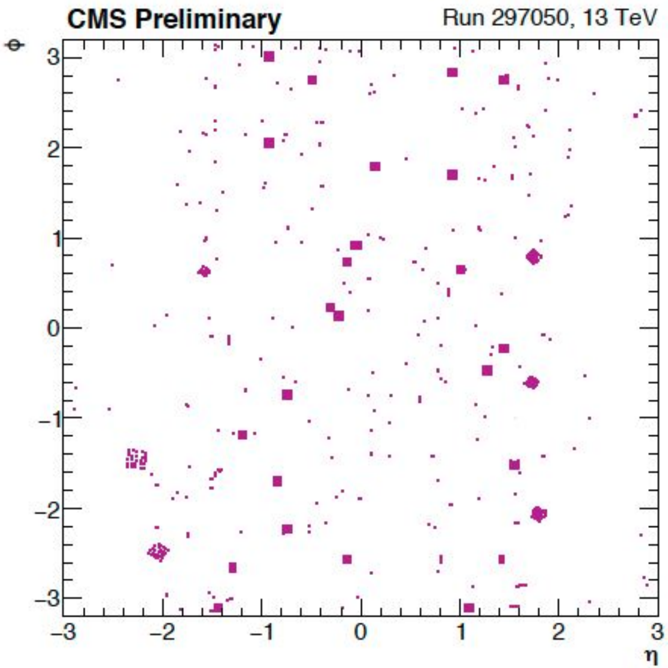
# Electron as fakes



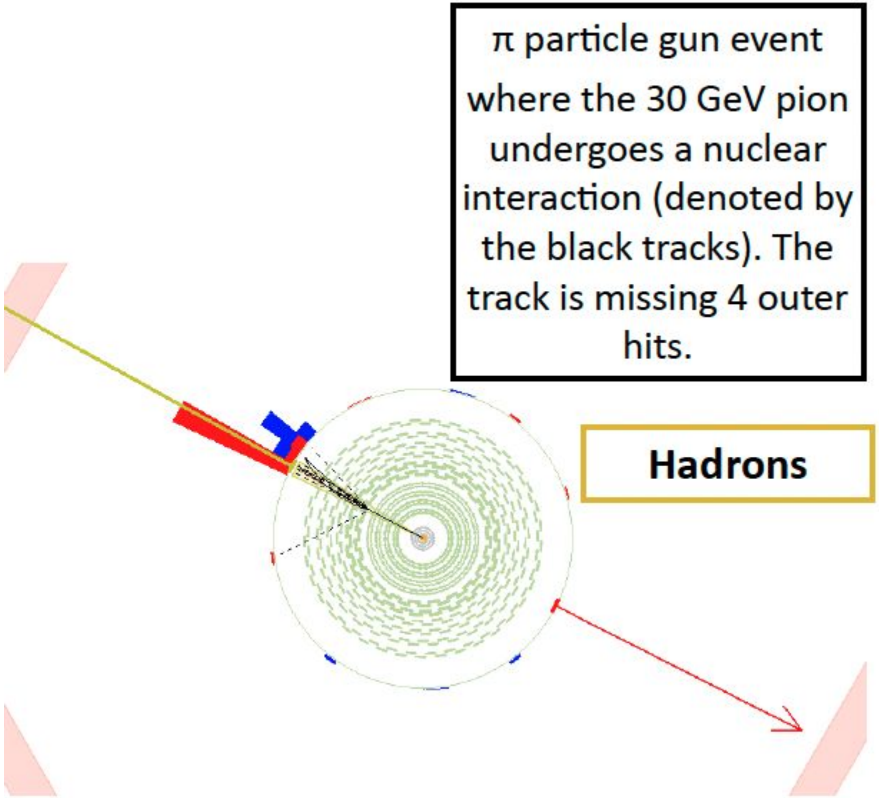
E.g. electron with large bremsstrahlung

Rejected by applying $E_{ECAL} < 10$ GeV in a cone of 0.5 around the track




Tracks falling within a certain dR of these noisy or dead  channels can fake the signal

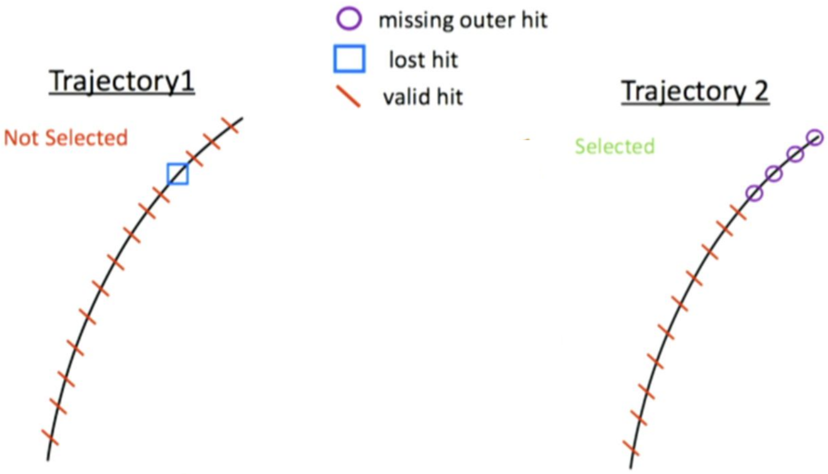
# Tau as fake

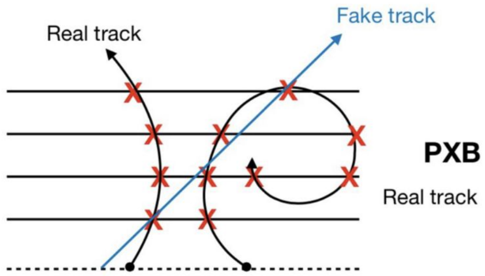



- Pion from tau decay undergoes nuclear interaction
  - $\pi^{+/-} + n \rightarrow \pi^0 + p$
- A very small background

# Algorithmic sources and fake tracks

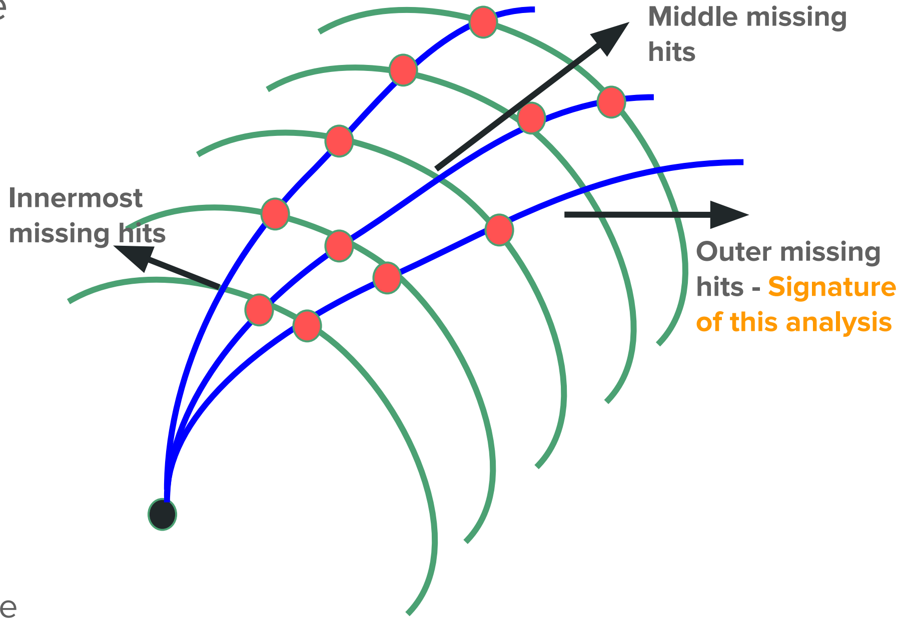
- Reconstructed tracks in CMS are chosen from various possibilities based on which has the highest quality score.
- This score depends on the number of lost hits
- As an example, if a track has a lost hit in between, it can be assigned lower quality score



# Selections

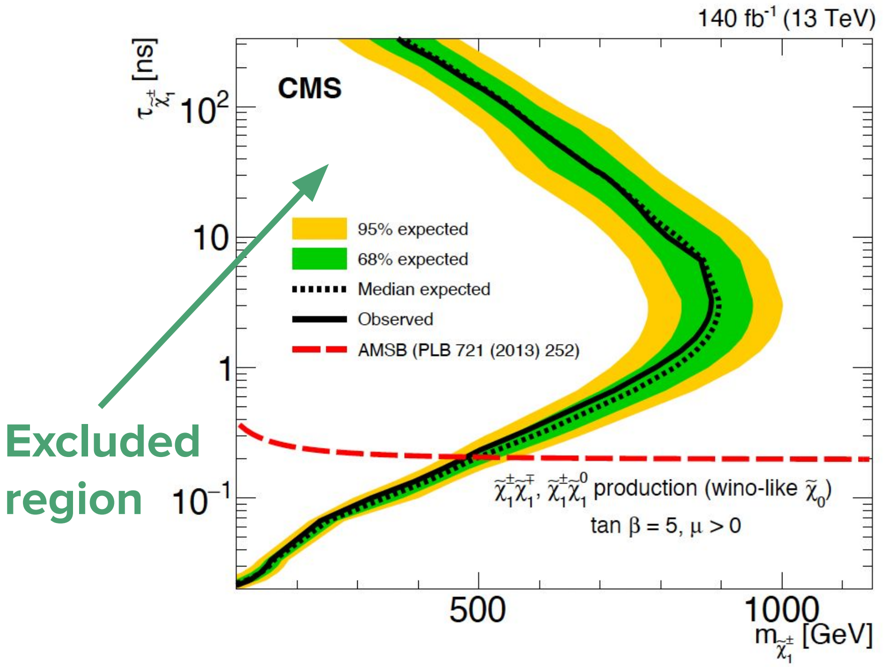
- Trigger on MET which appears because of the recoil of the χχ system against the ISR jet
  - MET > 105 GeV
  - pT of the isolated track > 50 GeV
  - At least 5 associated tracker hits
- Baseline offline selection
  - **MET** > 120 GeV, **at least one jet** with pT > 110 GeV
  - Δφ(jet, MET) > 0.5 radians to avoid MET due to mis-measurement of JEC
  - **Isolated tracks** with pT > 55 GeV
- Additional offline criteria on missing hits to reject background:
  - Usually track reconstruction algorithm allows for innermost missing hits to improve the track reconstruction efficiency but in this case can give rise to fake background
- Selection of disappearing tracks
  - Must have at least 3 missing outer hits
  - Sum of all associated calorimeter energy within ΔR < 0.5 must be < 10 GeV




Require tracks to have no missing inner or middle hits

# Interpretation

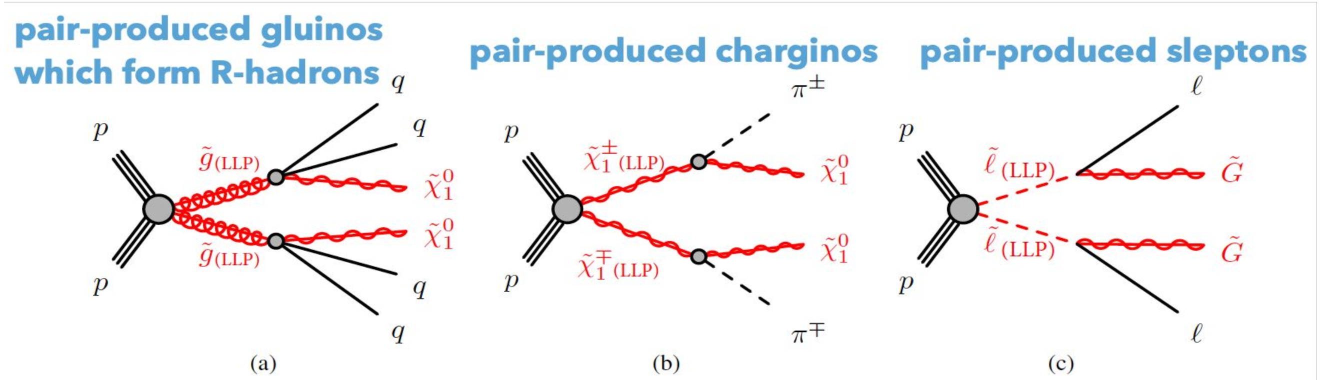
- Spurious track due to algorithmic error contributes to ~85% of the background in this analysis
- Remaining is due to fake lepton track reconstruction
- Observe a total of 48 events in 2018 with an expectation of 47.8 +/- 2.7 +/- 8.1
- Chargino mass for a purely wino-like neutralino:
  - Excluded below 884 GeV for τ = 3 ns
  - Excluded below 474 GeV for τ = 0.2 ns




Purely Wino LSP in AMSB

# Search for Heavy charged LLP with heavy ionization

**Another complementary approach**




R-parity conserving

Small phase space

Couplings between status and Gravitinos is weak

- **Interpretation for pair-production of R-hadrons, charginos and staus**
- Massive, long-lived charged particles. These move slower than the speed of light

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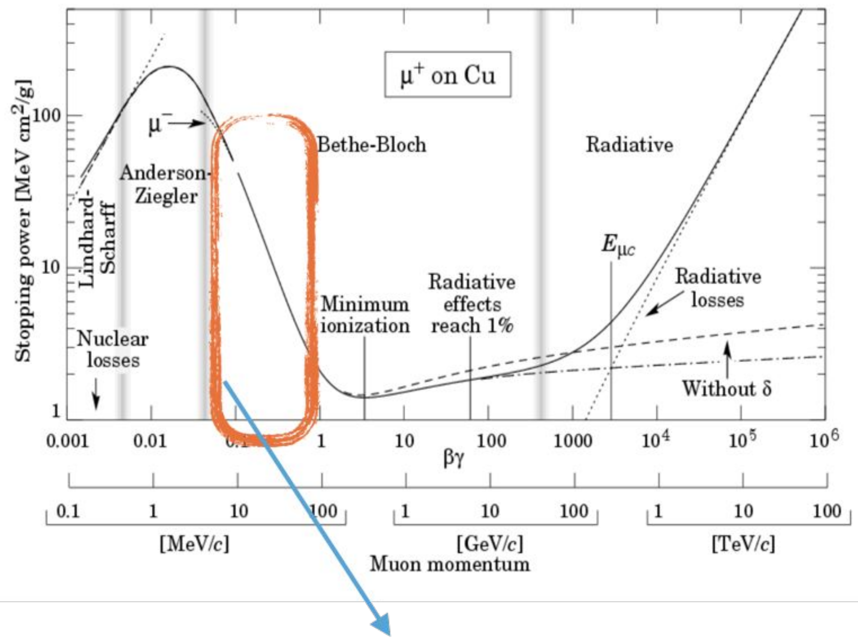
# Search for Heavy charged LLP with heavy ionization

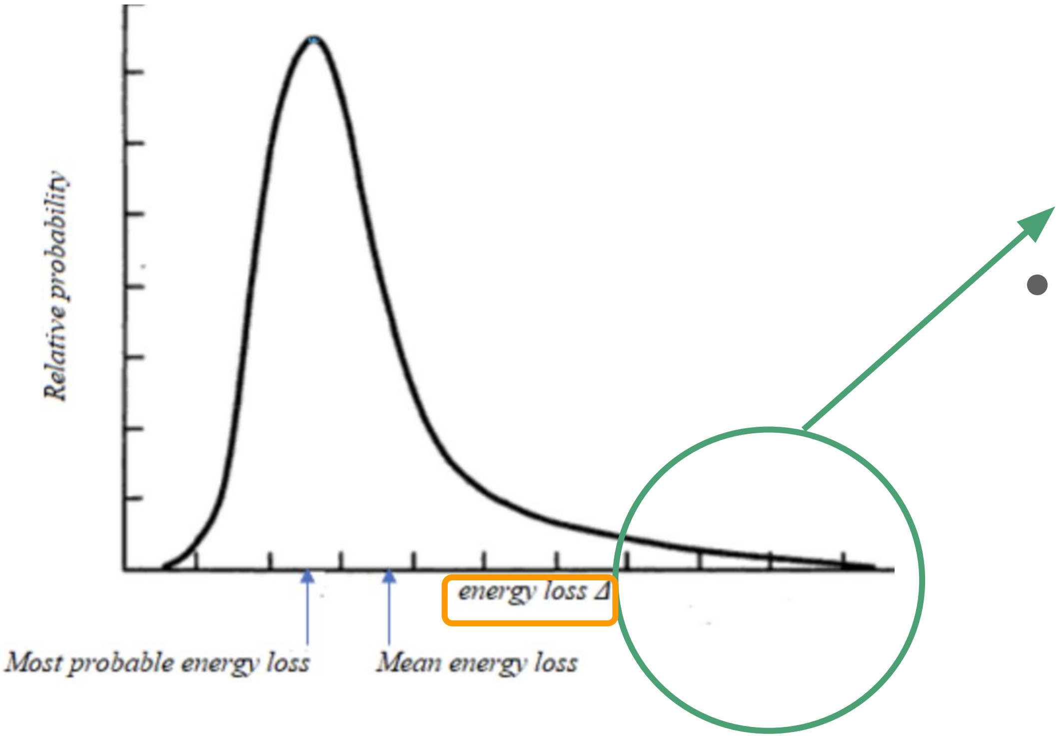
**Bethe Bloch curve**




**Energy deposited by LLPs**

- Massive, long-lived charged particles. These move slower than the speed of light
  - Lose energy in the tracker via ionization loss and hence high dE/dx following Bethe Bloch relation
- Trajectories are solely reconstructed by inner tracking system
  - **dE/dX measurement provided by pixel detector layers** and hence agnostic to the decay activity
- **This identification method does not depend on the way LLP interacts in the calorimeters**
  - **Universal handle for charged LLPs**
  - **results valid for any other LLP model**

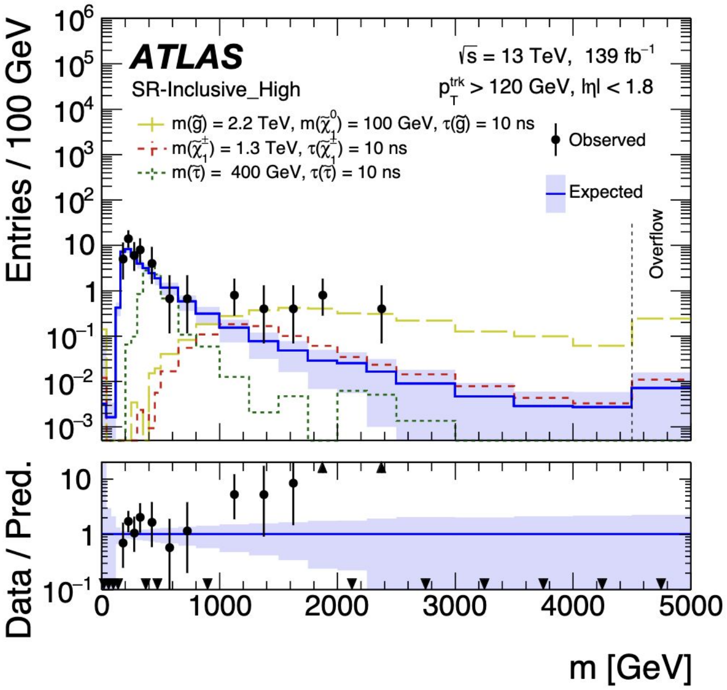
# Major backgrounds



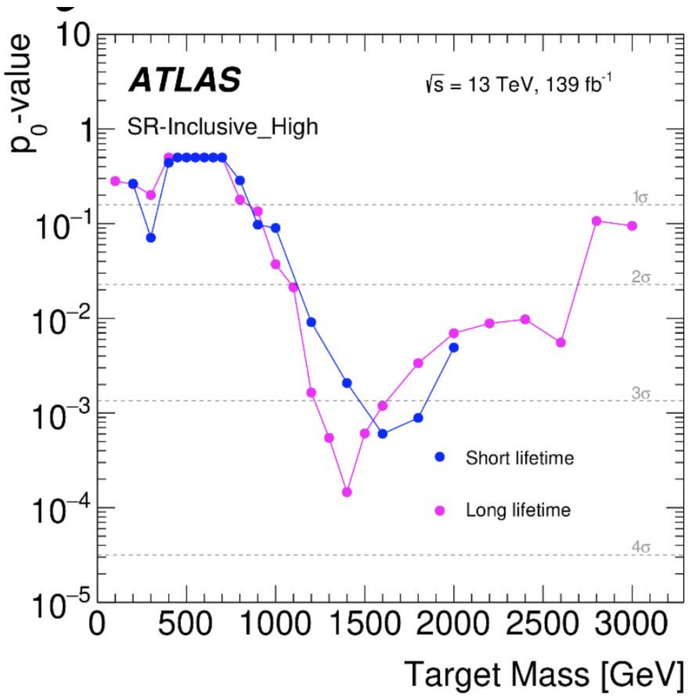

- The background is mostly due to the SM processes generating high pT tracks with a large dE/dx that is randomly produced according to the Landau distribution of MIPs
- While such fluctuations do not usually turn out as background in other analyses, **this becomes the most important background for this kind of LLP analysis**

# Heavy LLPs in ATLAS

- Trigger on $p_T^{miss}$ (from neutralinos or gravitinos)
- Require at least on high-$p_T$ track with various quality and background rejection requirements
- Measure dE/dx (in MeV $g^{-1}$ $cm^2$) using inner detector:
  - Reconstruct track mass: $m_{dE/dx} = p_{reco}/\beta\gamma$ (<dE/dx>corr)
  - Signal regions: low (1.8 <= dE/dx <=2.4), high (dE/dx > 2.4)
  - Done for particles with 0.3 <= βγ <= 0.9;
    - Low threshold is the noise threshold that is used in the tracker reconstruction for readout (355 eh pairs)
    - Higher threshold is just below the regime of MIP (where dE/dX becomes quasi independent of βγ)



# Statistical Analysis




- 7 excess events with 1100 < m < 2800 GeV (expected 0.7 +/- 0.4). p-value ~3.6σ for signal mass = 1.4 TeV(global is ~3.3σ)

# Very Late decays - not in the bunch crossing

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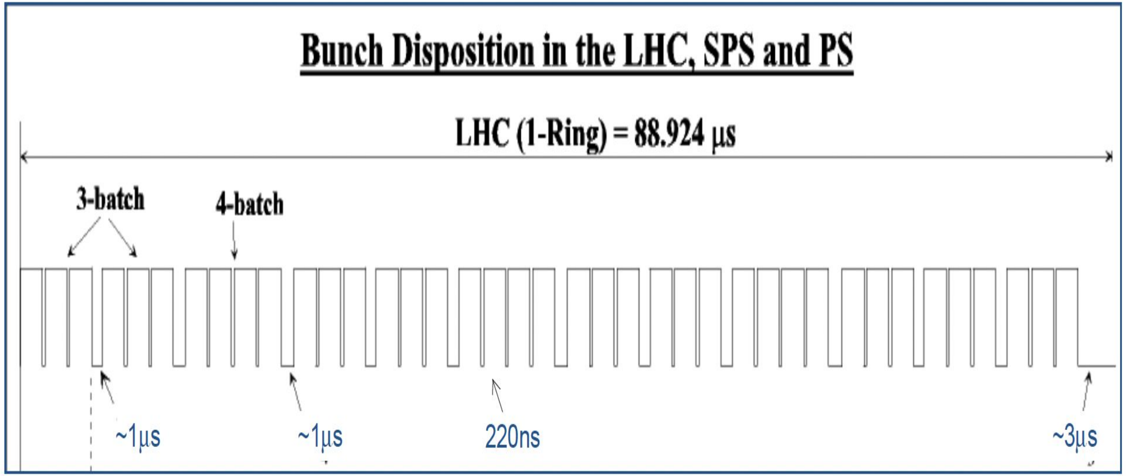
# Stopped exotic LLPs

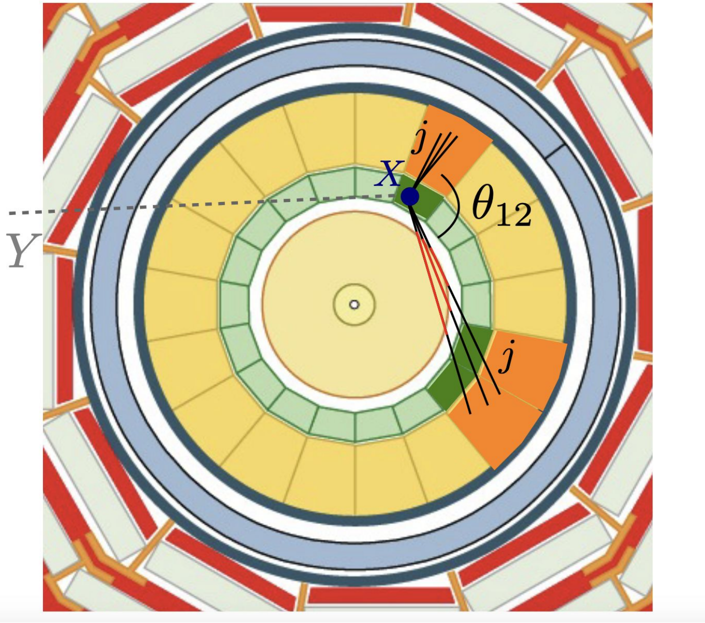
- This search is designed for LLPs with very long life-time - decay from several ns (~50 ns) to several weeks
- **Their decays would be reconstructed as separate events unrelated to their production**
- If such LLPs move slowly (typically ~0.5c) and deposit all their K.E inside the calorimeter, they can come to stop inside the detector
- To identify their decay products cleanly and clearly, **collect events when pp collisions do not happen!**




Events are triggered in between the gaps when bunches are not present ( > 2x25 ns)

# Stopped exotic LLPs

- Such LLPs come to stop in the densest part of the detectors
  - ECAL, HCAL and iron return yokes of the CMS
  - Large energy deposit in the calorimeters or hits in the muon chambers
- Scenarios considered:
  - Split SUSY
    - $\tilde{g} \to g\tilde{\chi}^0$
  - 3 body decays of gluino: $\tilde{g} \to q\bar{q}\tilde{\chi}^0$
- This analysis in CMS targets decays in the $\tilde{g} \to q\bar{q}\tilde{\chi}_2^0, \tilde{\chi}_2^0 \to \mu^+\mu^-$
  - The HCAL or
  - The muon chambers to pair of muons

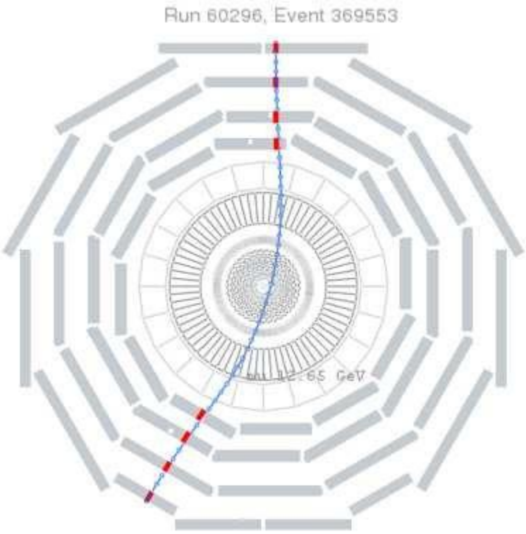


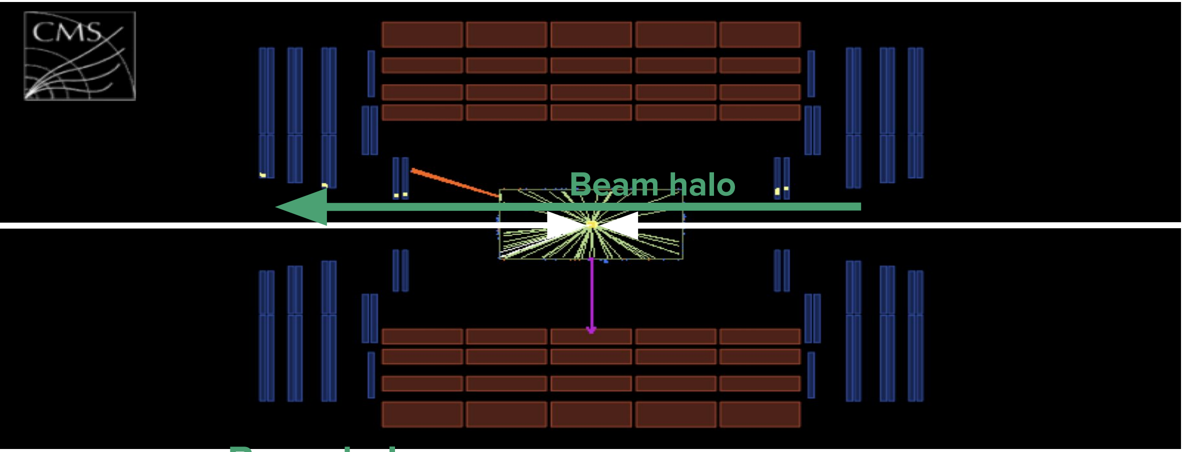

Signature in the HCAL

# Typical backgrounds

- Since the data is collected when there are no pp collisions in the detector, the background can come from
    - Cosmic muons - due to bremsstrahlung photon
    - Beam halo - due to bremsstrahlung photon
    - Noise in the HCAL - unrelated to any physical interaction with the particles produced in the detector. Rate drops with the jet energy

**Cosmic muon**



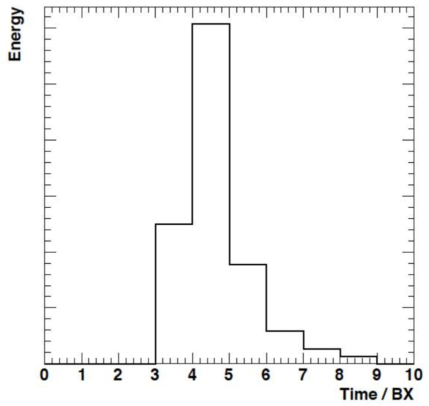




**Beam halo**

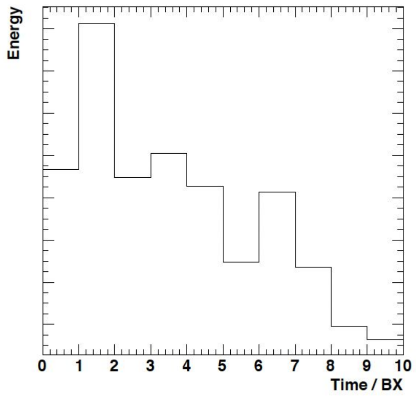
# Event selection for Calorimeter search

- HCAL noise rejection:
  - Calorimeter based jet energy > 70 GeV
  - In addition use information from analog pulse shapes
- Cosmic muon rejection:
  - Reject events with hits in the muon outermost or second outermost chambers (DT)
  - Two DT segments with large separation in φ (φ > π/2)
  - DT segments in the muon chambers having large φ with the jet
- Beam halo rejection
  - Reject events that have at least 5 reconstructed hits in the CSCs (EE muon stations)

**HCAL pulse shape for real energy deposit**

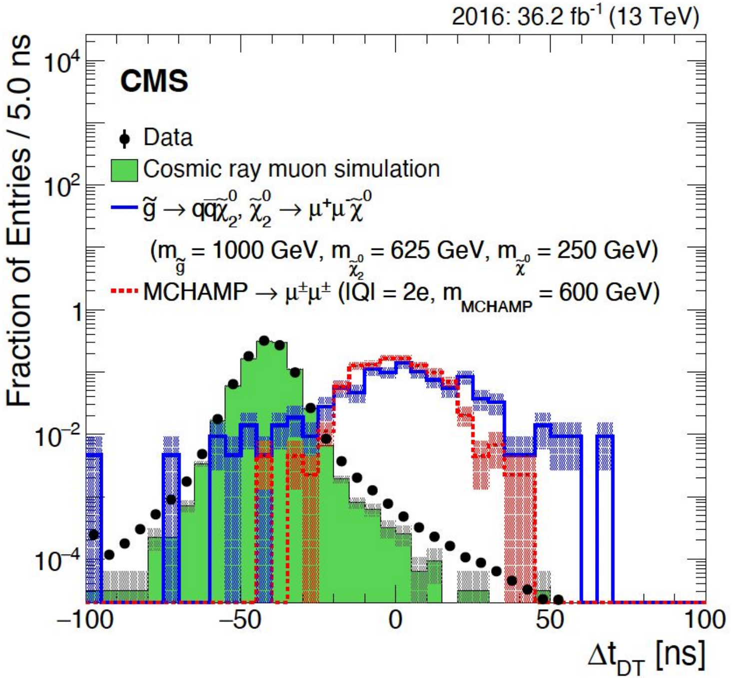



**HCAL pulse shape for noise**



# Event selection for Muon search

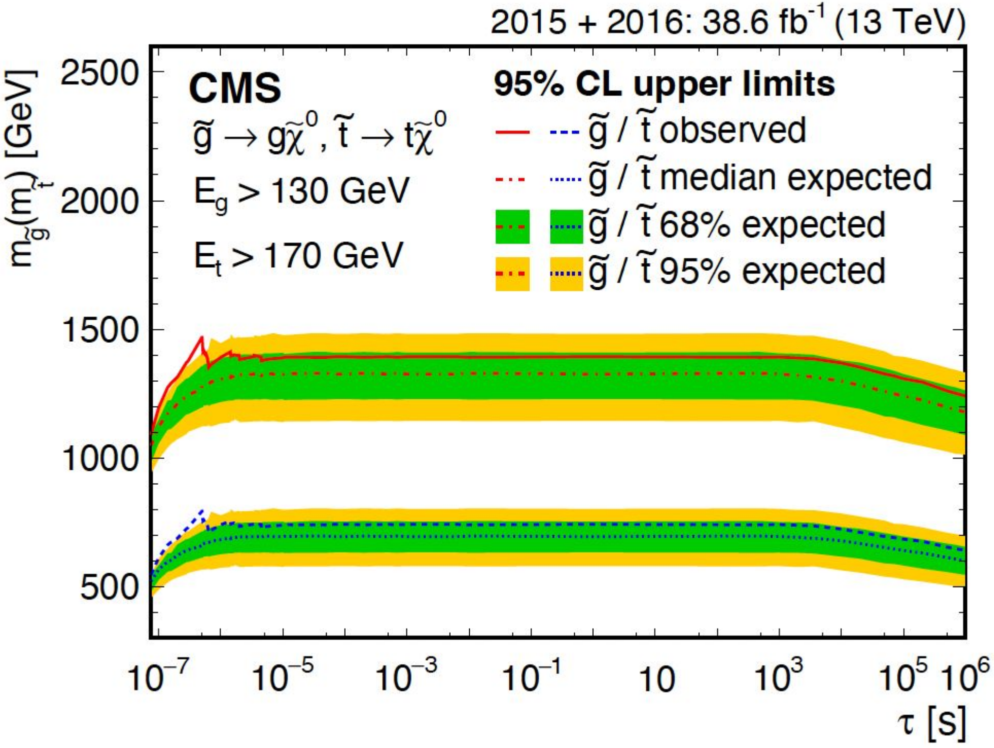
- This search uses special reconstruction of muons that is not restricted to the origin from the interaction point
- Muon detector noise:
  - Select two muons with pT > 40 GeV
- Cosmic muon rejection:
  - Two DT segments with large separation in φ (φ > π/2)
  - Use timing information from RPCs and DTs as well - cosmic muons arrive 40-50 ns early in the upper hemisphere
- Beam halo rejection
  - Reject events that have at least 5 reconstructed hits in the CSCs (EE muon stations)




**Using timing information from Drift chambers to reject cosmich muons**

# Statistical analysis

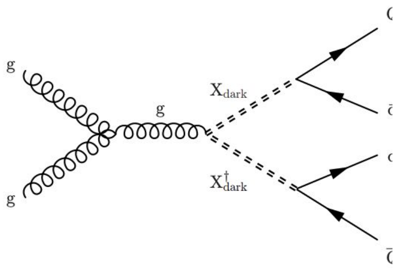
- It is a counting experiment
- Count the number of observed events for signal lifetime hypothesis ranging from 0.1 µs to $10^6$ s (~12 days)
- 2015:
  - Observed: 4
  - Expected: 4.1 + 3.0 - 1.0
- 2016:
  - Observed: 13
  - Expected: 11.4 + 10.3 - 3.1
- Excluded gluinos with m < 1385 GeV that decay via gluino→$g\chi_0$ and top quarks with m < 744 GeV for 10µs <τ < 1000s

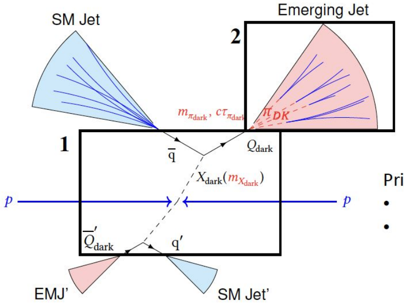


# Very recent highlights on LLPs

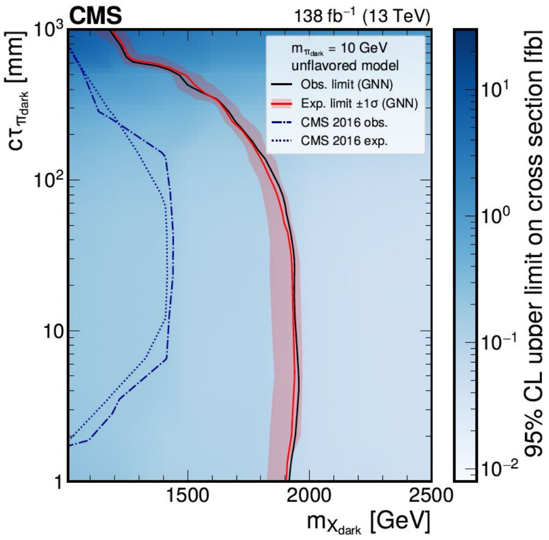
# Emerging jets at 13 TeV

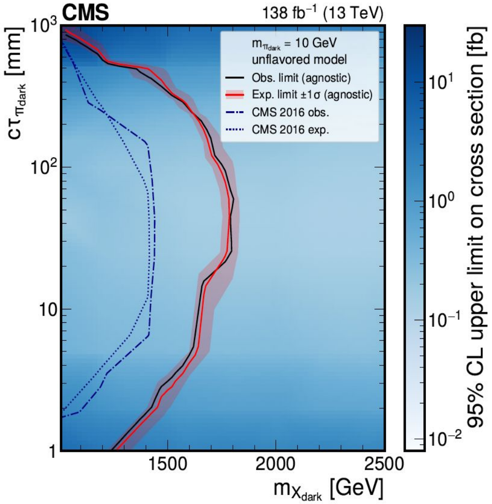
- Emerging jets
- Both **flavour-aligned** (dark sector couples only to the d quark) and **unflavoured** (dark sector couples to d-type quarks) scenarios considered
- To tag and EMJ, both high level variables (model agnostic) and GNN (model dependent) based analysis considered ➔ several times improvement by using GNN



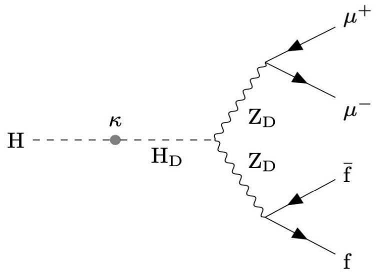

Primary signature:
- High $H_T$
- 4 high $p_T$ jets (2 EMJ, 2 SM jets)



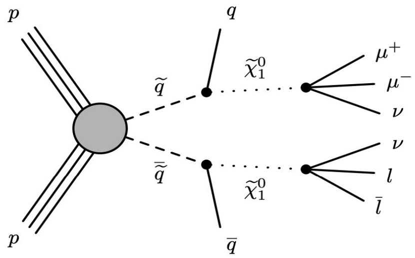



# LLPs ➔ di-muons at 13.6 TeV

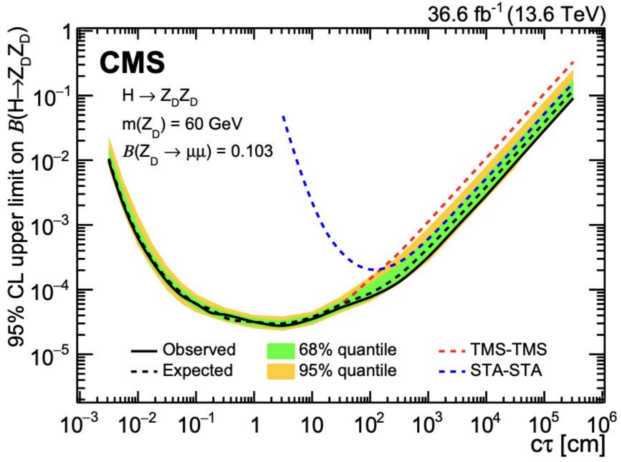
[Link]

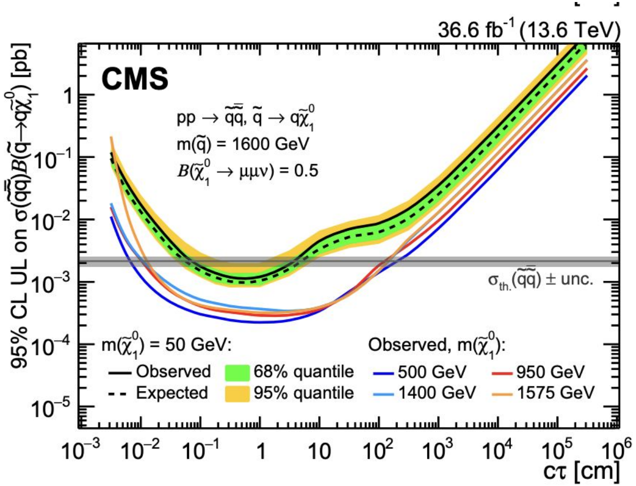



**Hidden Abelian Higgs Model**



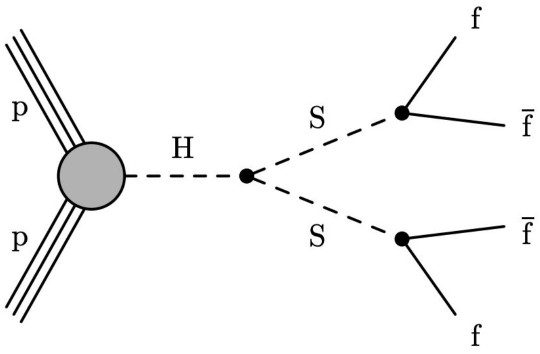

**R-parity violating SUSY**



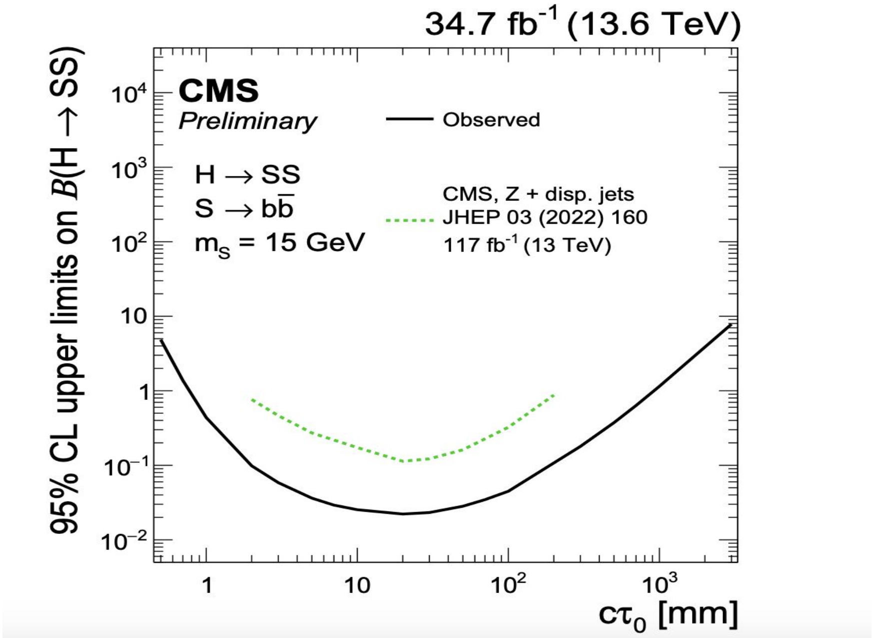




- This search benefits from the latest development at HLT – displaced muon algorithm is in place
- For $B(H \to Z_D Z_D)$ = 1% is excluded in the range of proper decay length $c\tau(Z_D)$ from a few tens of μm to 30 m (700 m) for $m(Z_D)$ = 10 GeV (60 GeV).
- In the framework of the R-parity violating supersymmetry model at a squark mass of 1.6 TeV, the results exclude mean proper neutralino decay lengths between 0.07 and 4 cm for a 50 GeV neutralino and between 70 μm and 2 m for a 500 GeV neutralino.

# LLPs ➜ displaced jets at 13.6 TeV




Exotic Higgs decays to 2 scalaer particles S



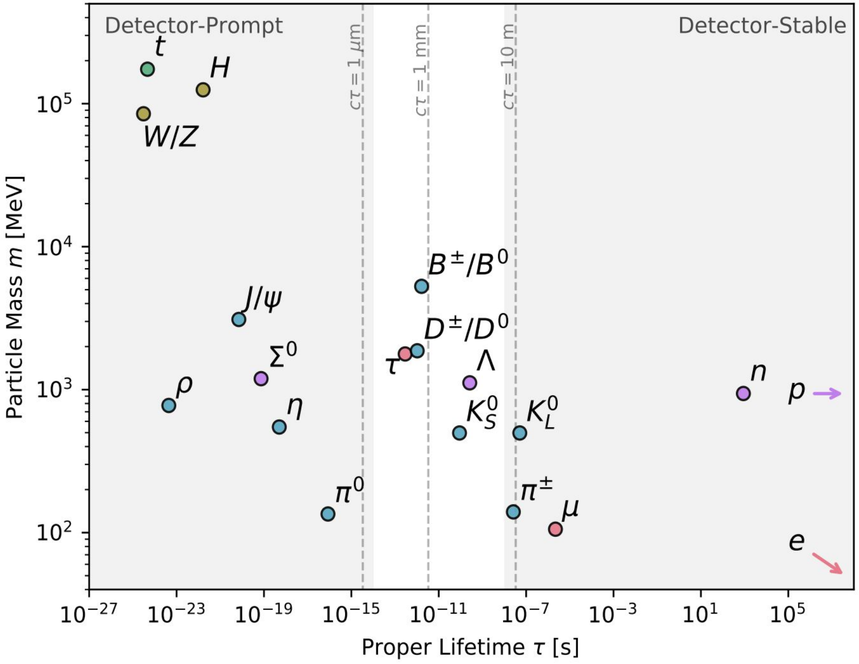

- This search benefits from the latest development at HLT – displaced muon algorithm is in place
- Novel trigger, reconstruction and ML techniques employed (GNN to identify displaced jets) - up to a factor of 10 improvement is achieved

# Discussion

# Backup slides

# What are long lived particles?

- Prompt particles: If the distance between the particle's production and decay point is smaller or comparable to the spatial resolution of the detector
- Long-lived particle (LLP) is an unstable particle with sizeable lifetime
  - Sizeable enough to be detected within the experimental setup
- These are not new!
- Many particles in Standard Model are long-lived



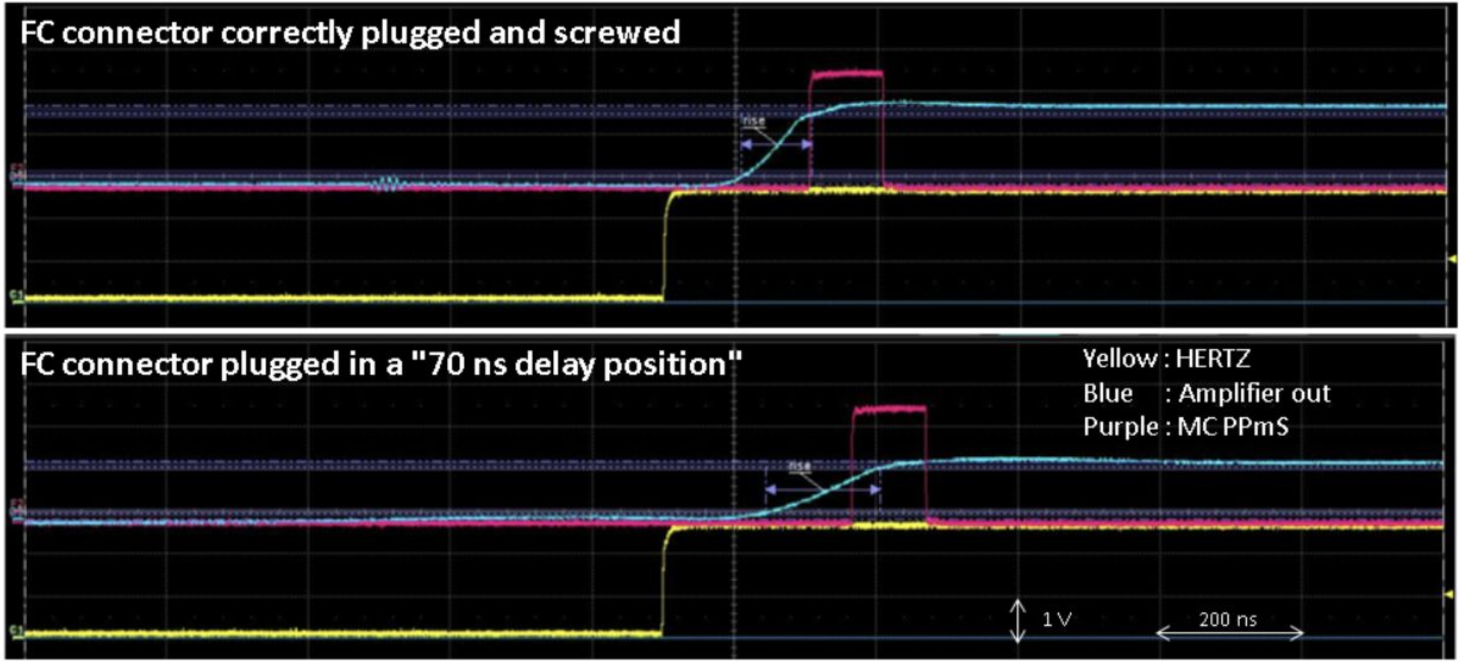
# What causes a particle to be LLP?

$$\tau^{-1} = \Gamma = \frac{1}{2m_X} \int d\Pi_f |\mathcal{M}(m_X \to \{p_f\})|^2$$

- Either the matrix element is small ➜ may be due to small broken symmetry which makes the coupling values small
- Small phase space
- Coupling constant is suppressed by the power of scales ($\Lambda >> m_X$)

**More in Shankha's slides**

## Delay measured at an early stage of the amplifier circuit

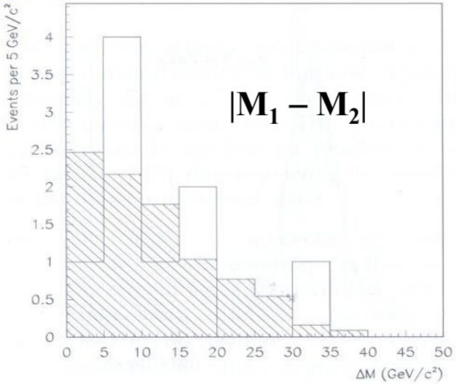



The effect is related to the charging up of the photodiode capacitance.

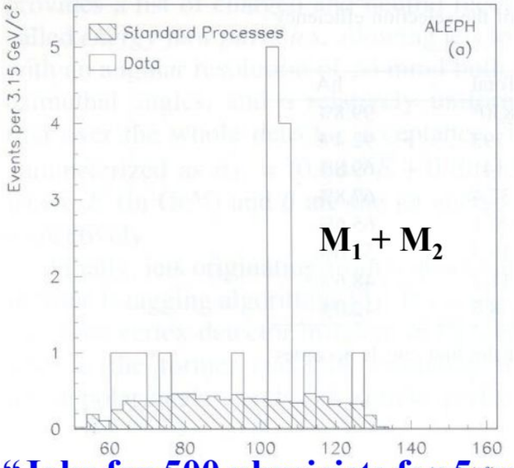
# ALEPH four jet events

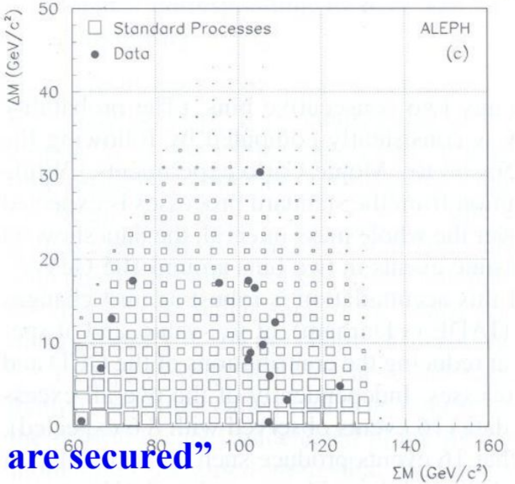
- Motivation was for $e^+e^- \to Z^* \to hA \to b\bar{b}b\bar{b}$ search
- Two masses from four jets (Durham algorithm w $y_{cut}$ = 0.008, JADE with $y_{cut}$=0.022)
- Use energy-momentum conservation to correct 4- vector of jets
- There are three combinations
  - Sum of the dijet mass for the combination with smallest mass difference

Z. Phys. C71 (1996) 179




No B-tag



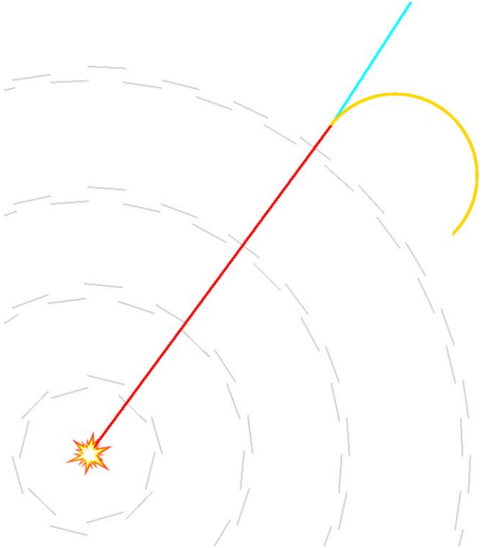

S. Mangla : “Jobs for 500 physicists for 5 years are secured”

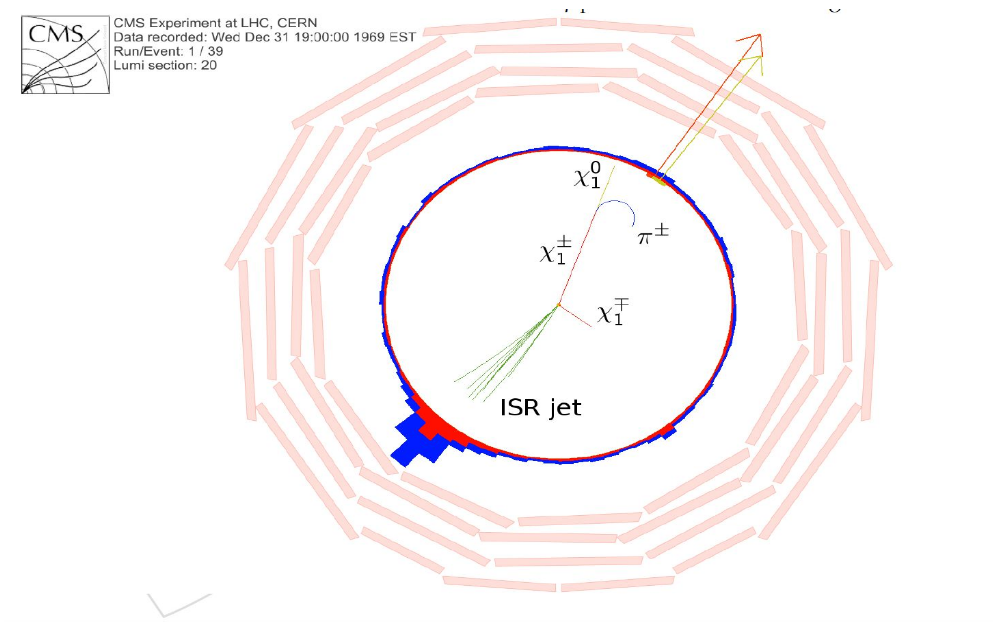
16

Slide from Gobinda Majumder

# Disappearing tracks

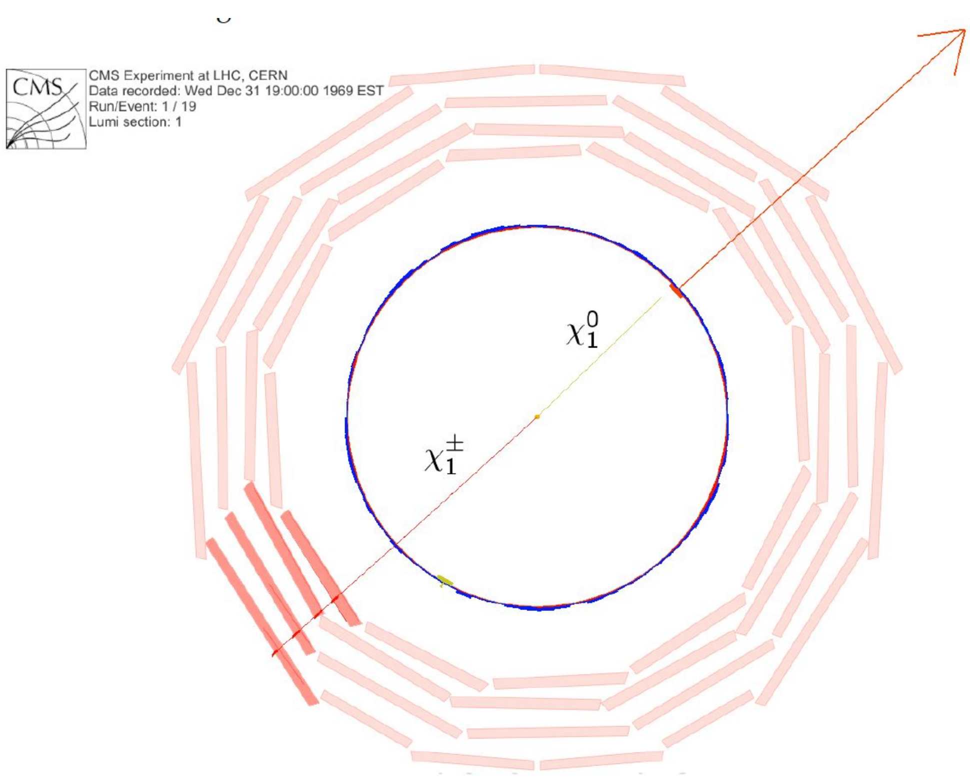
# Event topology





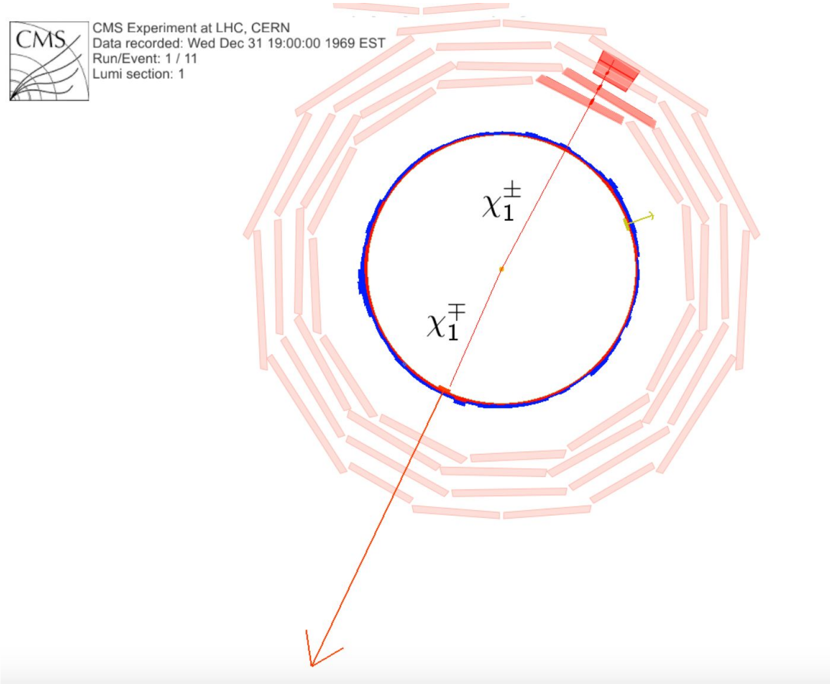

$\tilde{\chi}^\pm \rightarrow \pi^\pm \chi^0$

# Signature 1



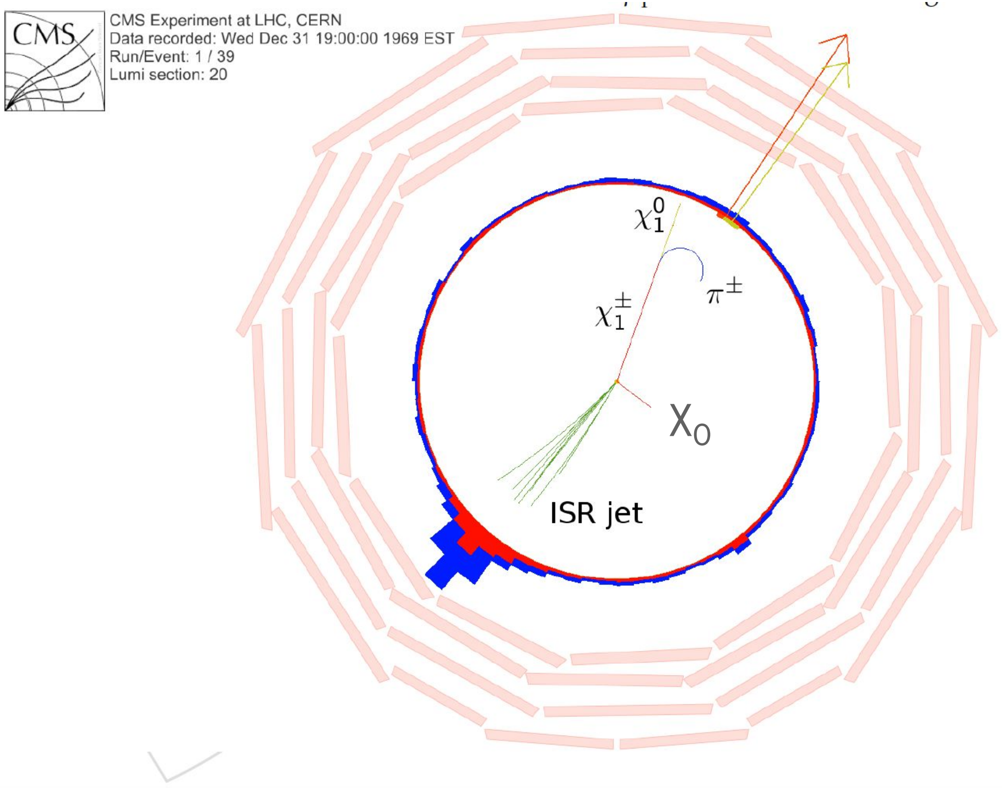

- MET is due to undetected neutralino

# Signature 2




- MET is due to undetected chargino

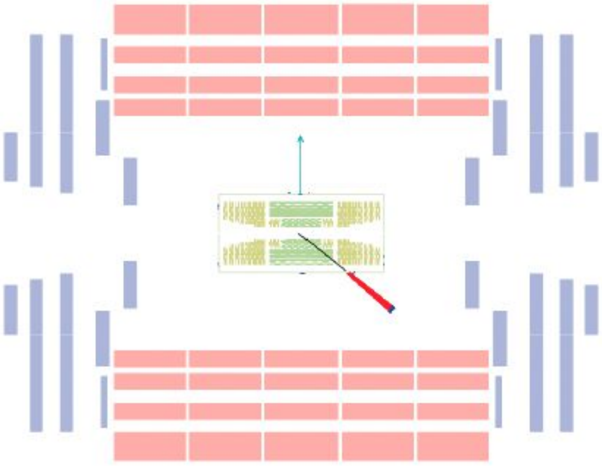
# Signature 3



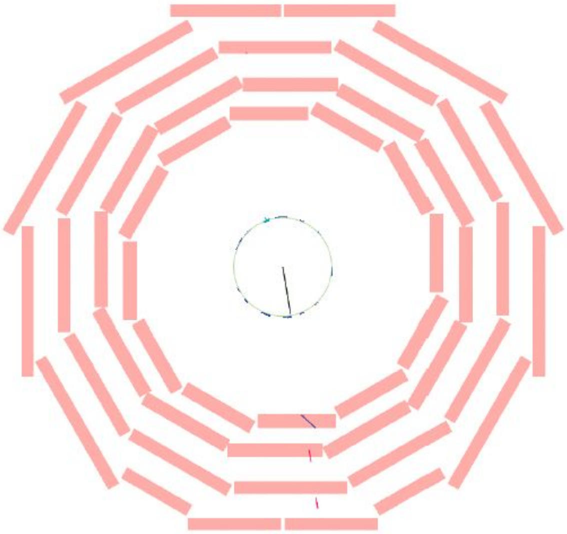

Targeted in the analysis

Missing hits and MET due to recoil against ISR JET and undetected chargino

# Muon as fake



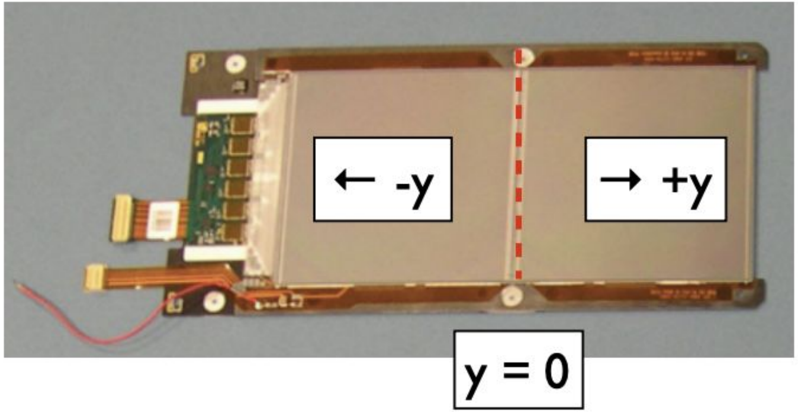
Muon decay → electron produces EM showers in the ECAL



Muon fails the matching criteria of the hits in the muon chamber and the tracker layer

- Brem and no matching hit: Very rare. Probability is ~$6.8 \times 10^{-5}$

CMS silicon strip module




- Observed in CMS disappearing track search in Run 1
- Since the analysis requires several missing hits in the outer tracker layers, many of the “signal-like” events came from the glue joint between two Si strip modules
- It was not there in the track reconstruction code

# Lepton Background estimation

- A lepton can appear as a disappearing track if:
  - It leaves track in the tracker, still fails to be reconstructed as a lepton
  - The MET resulting from this reconstruction failure is enough to pass the offline criteria
  - The resulting MET is enough to pass the HLT requirement
- Each step is estimated as the conditional probability

$$N^{l}_{\mathrm{estimate}} = N^{l}_{\mathrm{ctrl}} \, P_{\mathrm{veto}} \, P_{\mathrm{offline}} \, P_{\mathrm{trigger}}$$

Single lepton control region

Probability to pass lepton veto
Measured with tag-and-probe

Probability to pass online/offline MET cuts

# $P_{veto}$, $P_{off}$ and $P_{trig}$

- $P_{veto}$:
  - Using tag and probe method
  - Require tag to pass tight criteria and probe disappearing track criteria
- $P_{off}$: Probability of event passing MET > 140 GeV given that the lepton did not get reconstructed
  - Collect data from single electron dataset
  - Assume that the unreconstructed lepton contains no calorimeteric energy
  - Calculate the modified MET removing the lepton
  - $|\vec{E}_T^{\text{miss}} + \vec{p}_T^{\,l}| > 120\ \text{GeV}$
- $P_{trig}$:
  - Probability for a lepton, already passing lepton veto and MET > 120 GeV to fire HLT
  - Use single lepton dataset
  - Multiply the bin-by-bin modified MET spectrum above (Poffline) with the trigger efficiency
  - The fraction of events in single lepton control region with $|\vec{E}_T^{\text{miss}} + \vec{p}_T^{\,l}| > 120\ \text{GeV}$ gives the required number

# Fake track background estimate

- It is not a real track but a fake track due to pattern recognition algorithm
- Though the requirement of zero missing inner and middle hits greatly suppress this background, but there can be a non-zero contribution
- Estimated in Z→μμ and Z→ee samples where no such tracks are expected where a track has disappeared
    - Criteria applied so that it does not overlap with the signal region
    - Number of tracks in these regions passing the disappearing track criteria gives the probability of such events happening

$$N^{fake} = N^{kin} P^{fake}$$

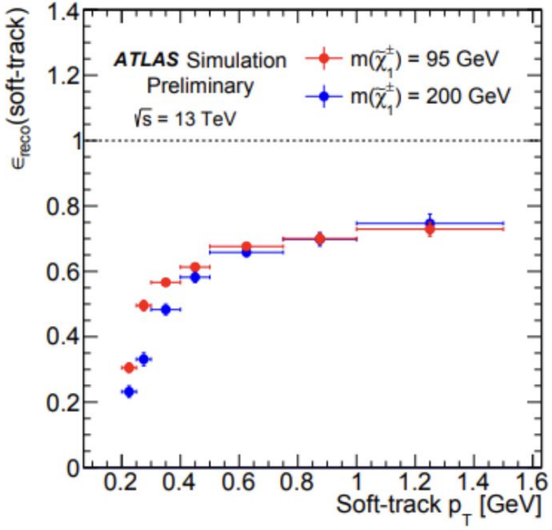
$N^{kin}$: number of events that pass the MET and jet cuts (search selection without track criteria)

$P^{fake} = N^{fake}_{ctrl}/N^{kin}_{ctrl}$:

- $N^{kin}_{ctrl}$ = # events in Z→μμ control sample
- $N^{fake}_{ctrl}$ : # events in Z→μμ control sample that additionally have a track that passes the disappearing track criteria

# Possible run 3 improvements

ATLAS-PHYS-PUB-2019-011

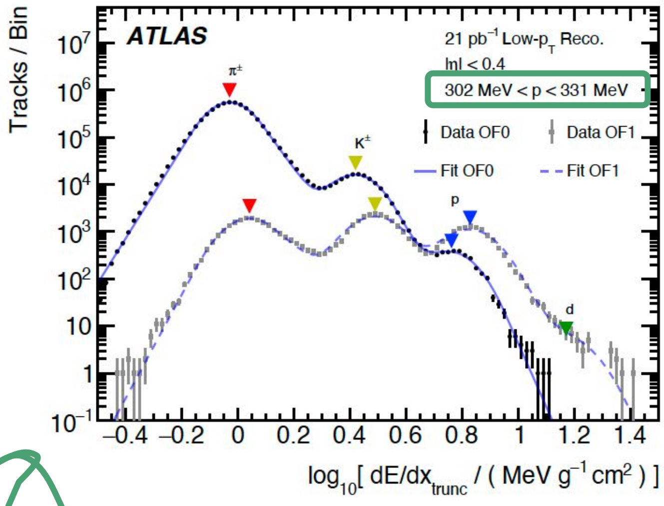


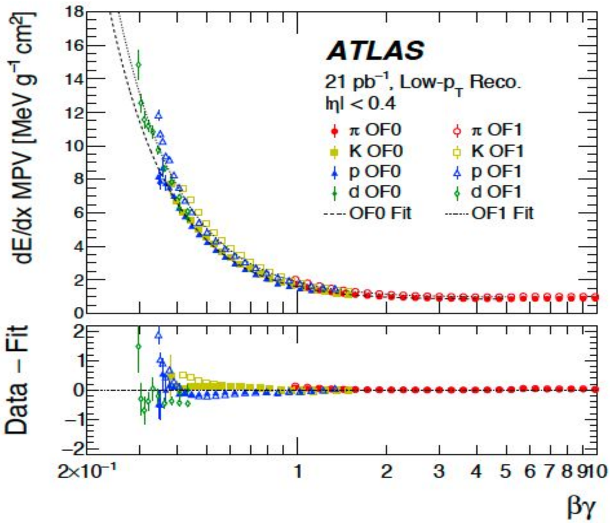

- Soft pion tagging techniques
  - Use the hits that are not used in the standard tracking algorithm
- NN based fake track classifier

# dEdX from ATLAS

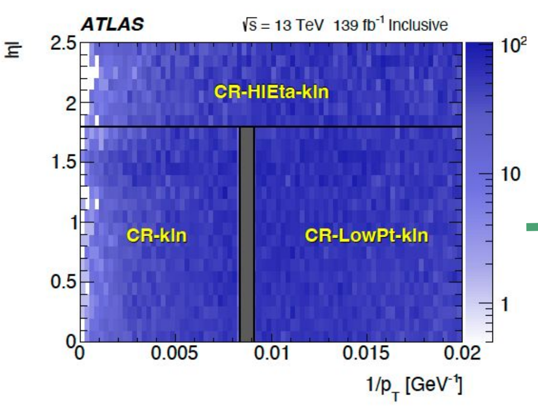
# dE/dx Measurement, and βγ mapping

- Done in low PU dataset where even 100 MeV of tracks can be reconstructed
- When charged particles pass through the inner detector layer, they deposit energy and multiple pixel hits across a pixel layer are recorded
- The dE/dx measurement of an individual track is calculated by averaging the individual clusters that are associated with the tracks
- A mapping of βγ to dEdx is extracted in the low pile-up runs (to go as low in pT as possible ~100 MeV) in narrow momentum slice and are then used for extracting the βγ of each individual track by using m = p/βγ where m is known because of the peaks

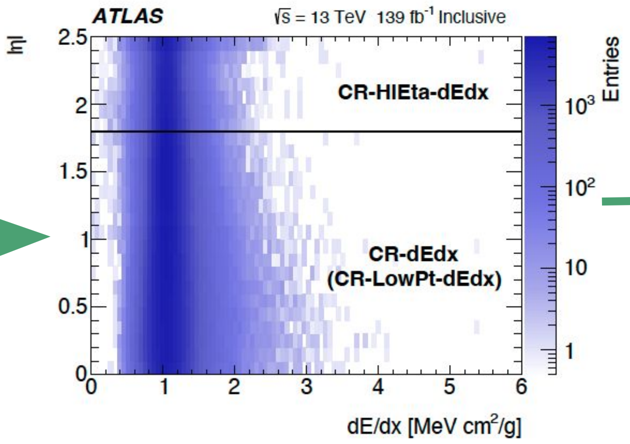


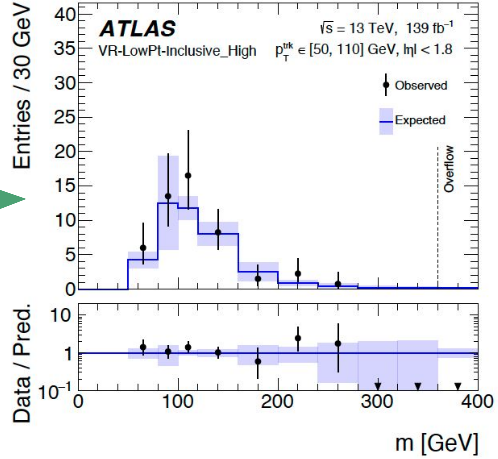
# Background estimation




(a) Kinematic control regions

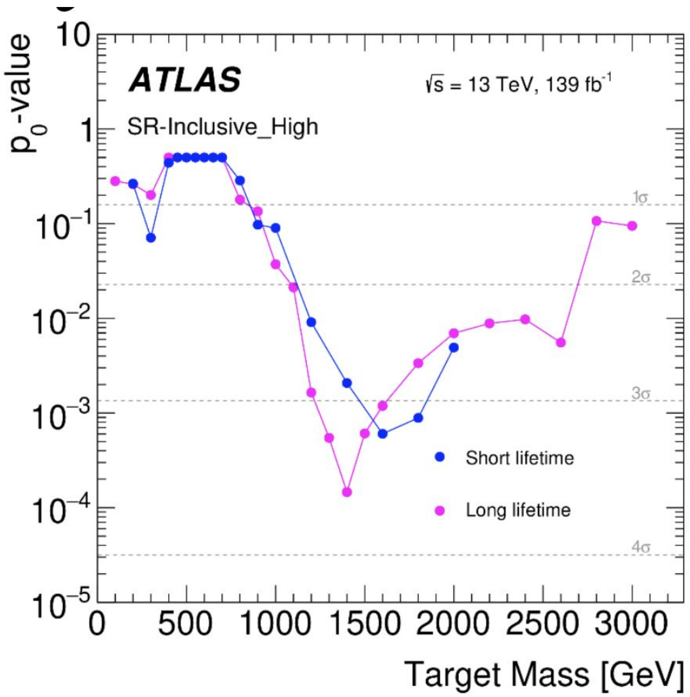



(b) $\mathrm{d}E/\mathrm{d}x$ control regions



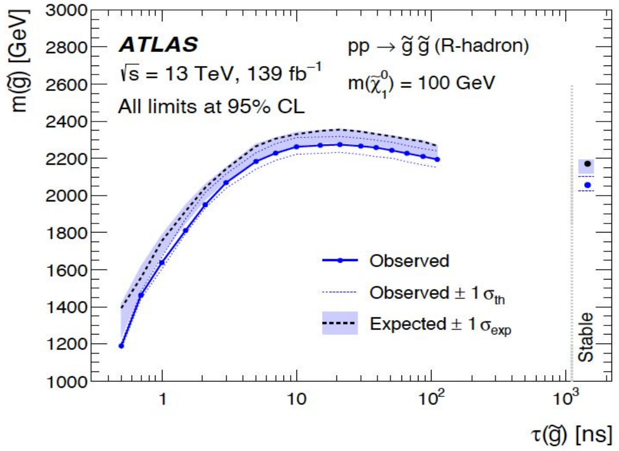

- Background estimation based on random toy tracks:
  - Sample (1/pT, η) values from a region representing the kinematic profile of the Signal region
  - Sample dE/dX value from the corresponding region representing the dEdX profile of the signal region in that η eta bin
  - Calculate the mass of the toy track from the selected value using $m_{dE/dx} = p_{reco}/\beta\gamma$
  - This is repeated millions of times
  - The distribution is normalized to the data

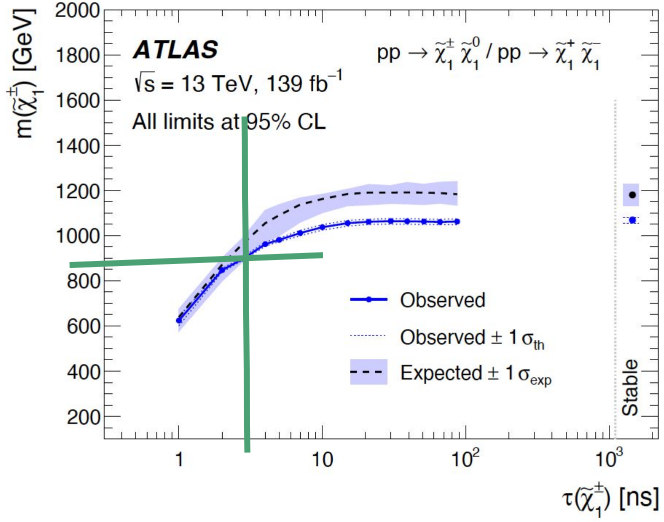
# Statistical Analysis

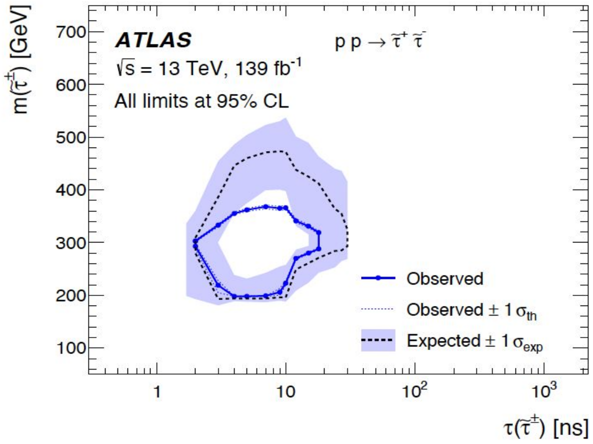



- 7 excess events with 1100 < m < 2800 GeV (expected 0.7 +/- 0.4). p-value ~3.6σ  for signal mass = 1.4 TeV(global is ~3.3σ)
  - 2.4 <= dE/dx <= 3.7 MeV $g^{-1}cm^2$
    - Predicted β = 0.5—0.6, but measured β ~ 1 (from ToF, MS, Calo)
  - Not consistent with the heavy (and hence slow) LLP hypothesis

# dEdX search from ATLAS



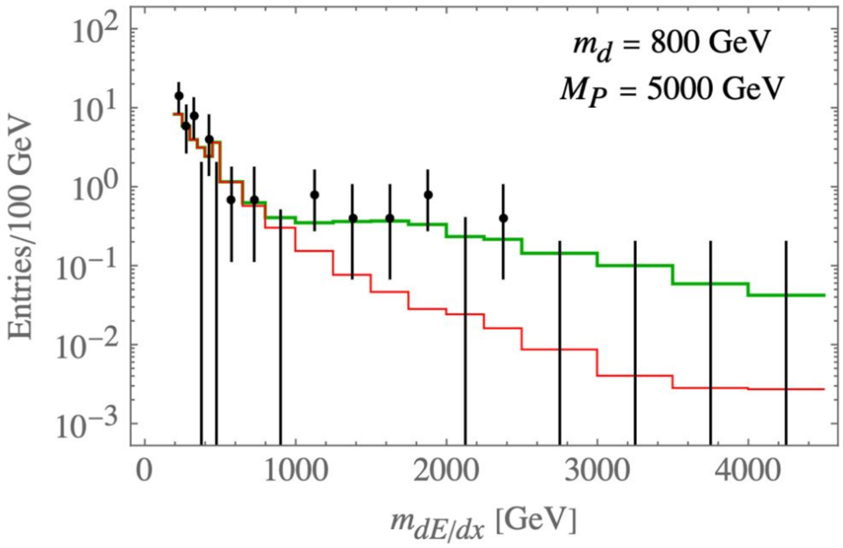



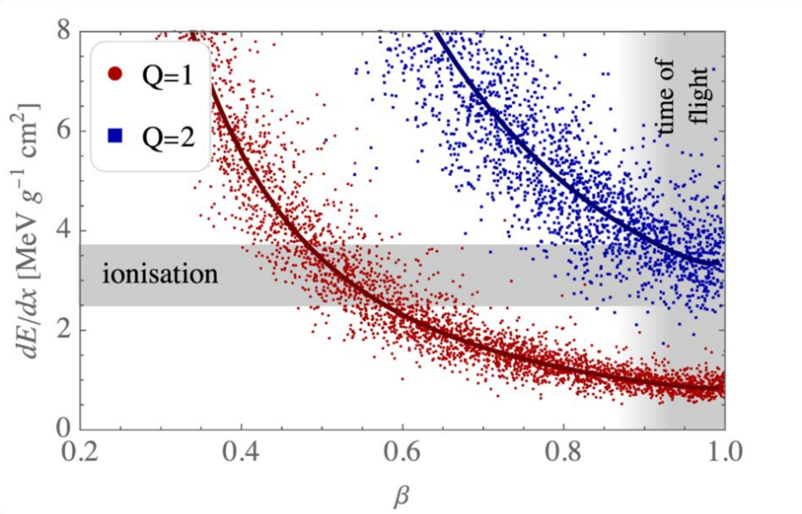




- Masses smaller than 2.27 TeV are excluded at the 95% confidence level for gluino *R*-hadrons (10-30 ns)
- Masses below 1.07 TeV for charginos and in the range 220–360 GeV for staus are excluded for lifetimes of 30 ns and 10 ns
- 

# Another interpretation

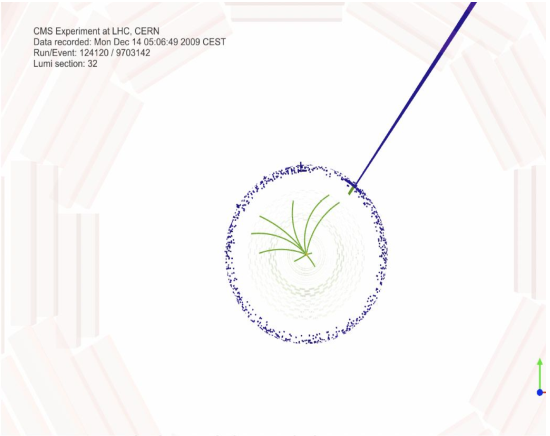
- Doubly-charged LLPs have β values compatible with measured dE/dx!
- Resonant production of relatively light daughter particles d from massive particle P —> boosted
- Good match for kinematic properties of excess events



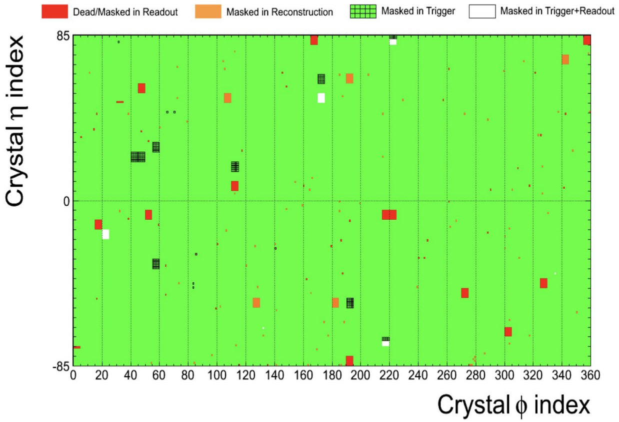



# MET due to anomalous effects

- Arise due to reconstruction failures, malfunctioning detectors or non-collision backgrounds
- ECAL:
  - Spikes → localized energy deposit (mostly) in a single crystal
  - Dead cells → underestimation of energy and hence high fake MET
  - Noise in the EE crystals due to transparency loss

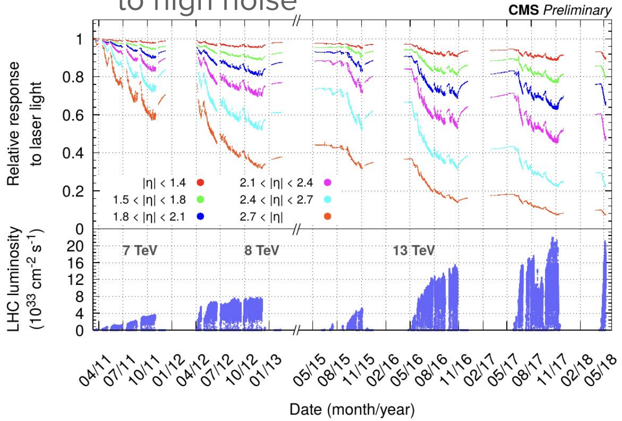



Spikes




Example of dead channel map from Run 1

Low transparency in the EE leads to high noise




Transparency profile

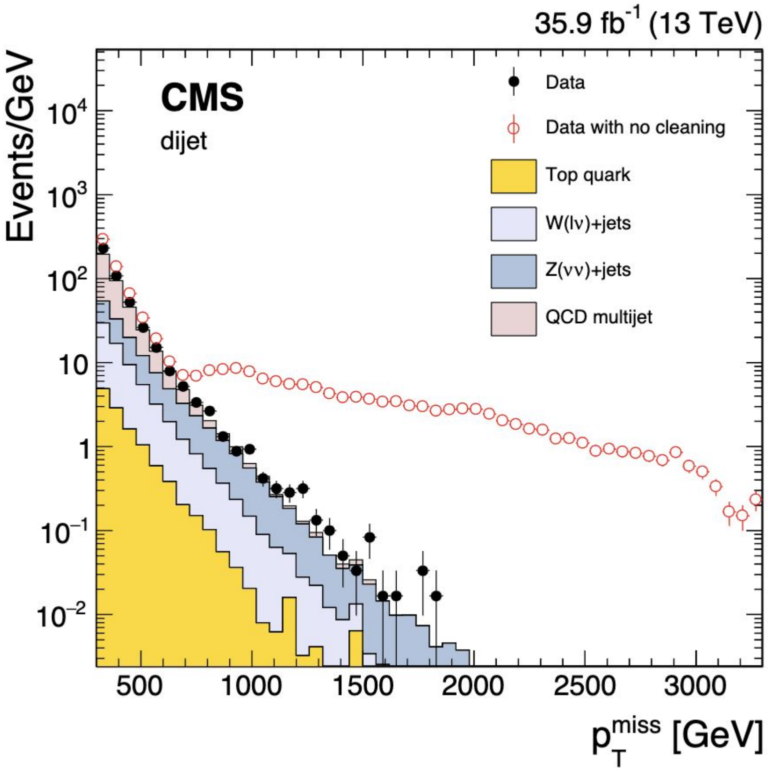
# Mis-reconstruction of energy due to missing readout channels

- In this analysis, major background in this category comes from non-functionality of the ECAL detector readouts
- Reconstructed jet may overlap with such readout units ➔ giving rise to MET in the direction of the jet
- Appear as localized excesses in η-φ plane
- Remove it
  - $\Delta R(\mathrm{j}_{1,2}, c_{\mathrm{nonfunctional}}) < 0.1.$

# MET due to anomalous effects

arXiv

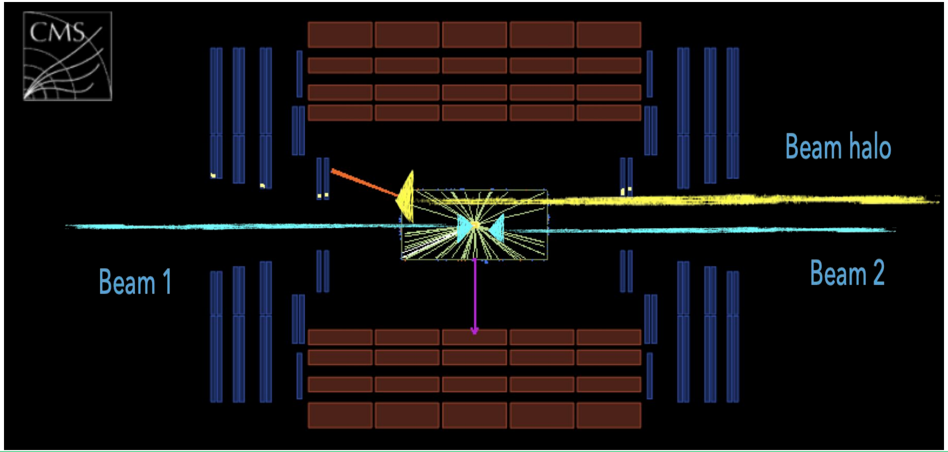
- Arise due to reconstruction failures, malfunctioning detectors or non-collision backgrounds
- ECAL:
  - Spikes
  - Dead cells → underestimation of energy and hence high fake MET
  - Noise in the EE crystals due to transparency loss
- HCAL:
  - HB/HE: Persistently hot channels, noise
  - HF: Particle interaction with the light guides and PMTs

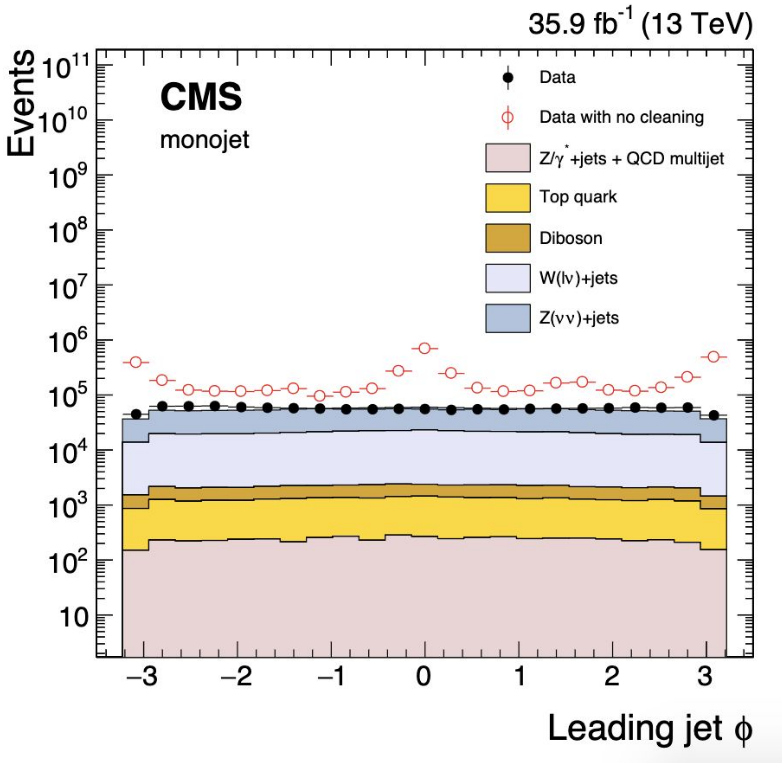


# MET due to anomalous effects

arXiv

- Arise due to reconstruction failures, malfunctioning detectors or non-collision backgrounds
- ECAL:
  - Spikes
  - Dead cells → underestimation of energy and hence high fake MET
  - Noise in the EE crystals due to transparency loss
- HCAL:
  - HB/HE: Noise in the detector readout units
  - HF:  Particle interaction with the light guides and PMTs
- Non-collision background due to beam halo in the ECAL and HCAL



# MET scale and resolution

- Estimated using Z+jet and γ+jet events
- Expect $\vec{q}_T + \vec{u}_T + \vec{E}_T = 0.$

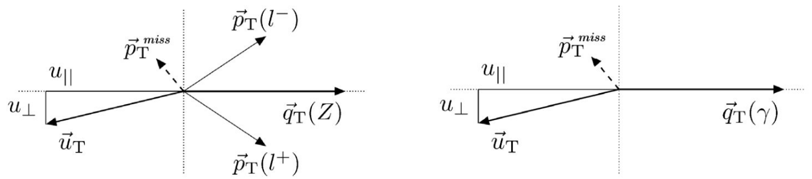
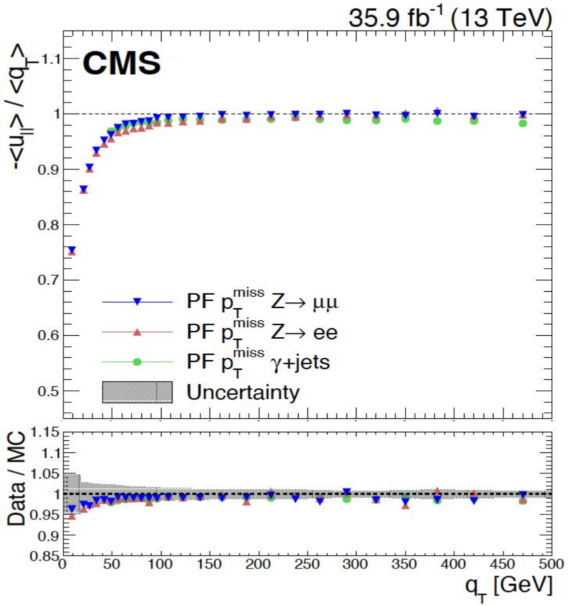
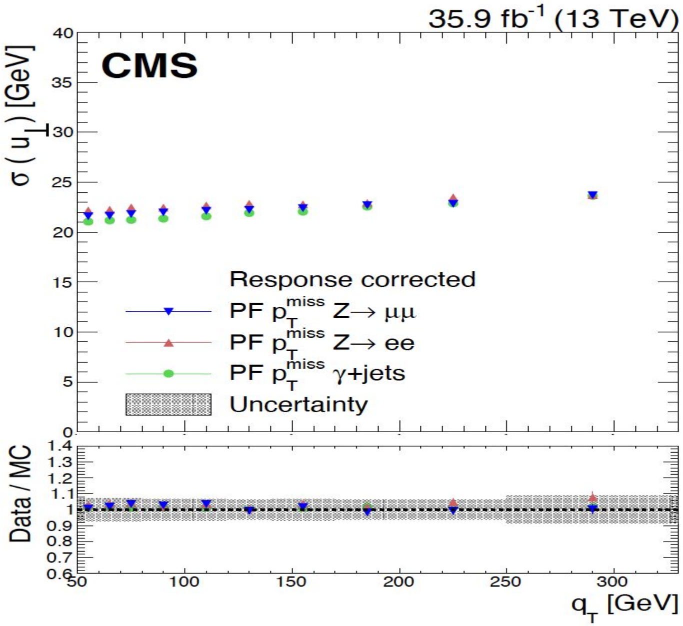


Figure 6: Illustration of the Z boson (left) and photon (right) event kinematics in the transverse plane. The vector $\vec{u}_T$ denotes the vectorial sum of all particles reconstructed in the event except for the two leptons from the Z decay (left) or the photon (right).



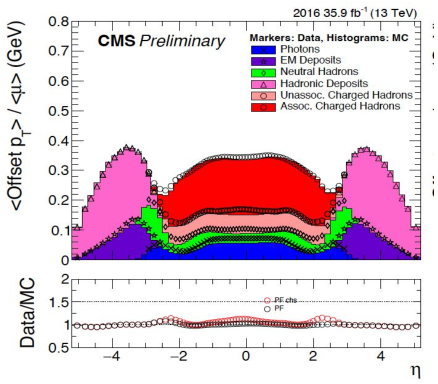



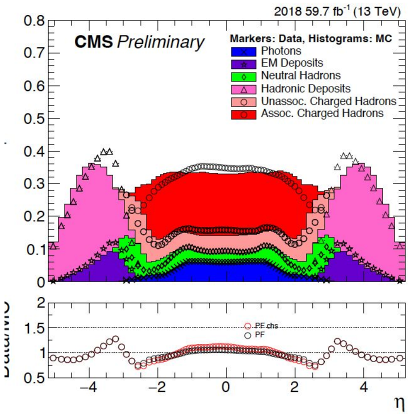

Resolution ~ 9% for $q_T$ > 200 GeV

# How well do we know Jet energy scale?

# Jet energy calibraion

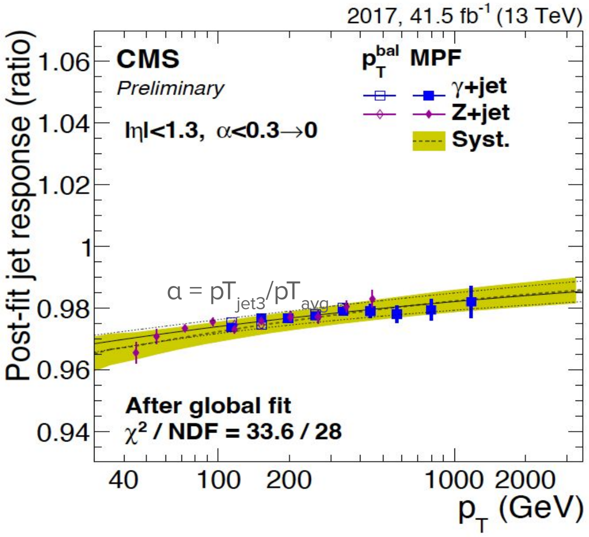
- Jet energy measurement is affected:
  - Pile-up: Dedicated corrections applied to mitigate the effect of pile-up
  - Non-uniformity of the detector response in pT and η: Hadronic shower development is a complex process, EM component is a function of pT
  - Noise from the detector
- Calibrate jets for the above effects in this order
  - Pileup corrections to account for the energy coming from PU
    - Data also corrected for residual differences in data and simulation
  - Simulation based corrections to address non-uniformity of detector response in pT and η
    - Small residual corrections to data to address the differences between data and simulation using techniques like pT balancing topologies e.g. dijet and multijet, Z+jets, γ+jet

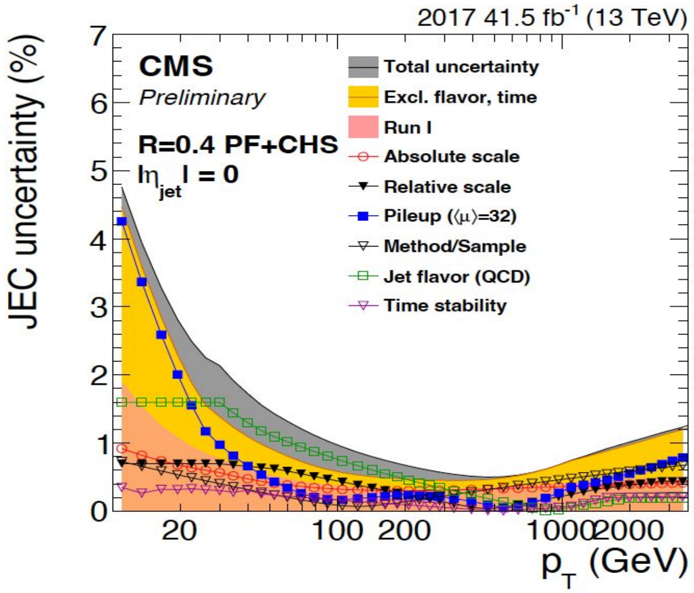



Dedicated corrections for every year. As an example, left plots show the PU corrections applied to simulation and data for each year separately

# Performance of jet energy scale (JES)



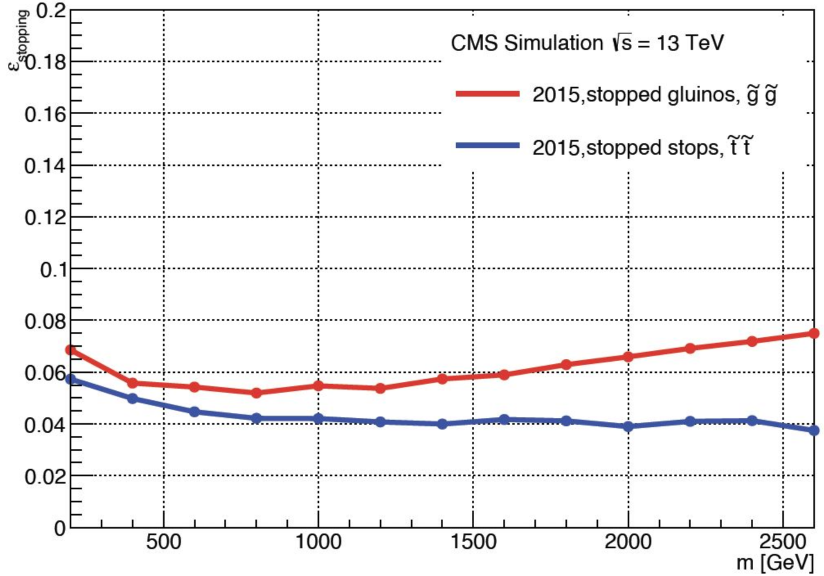



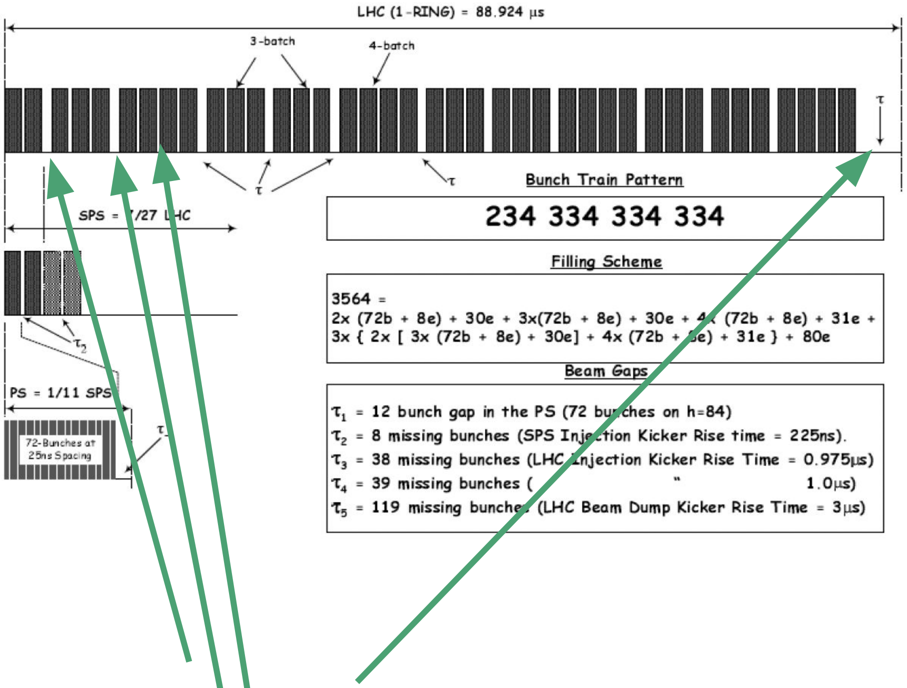

- Left: Energy scale difference between data and simulation after all the steps.
  - The ratio on the y-axis are applied to data
- Right: Uncertainty on JES due to all the sources in the calibration chain
  - 1% - 5%

# Very long lived - out of BX

# Stopped exotic LLPs

- Gluino R-hadrons are more likely to be doubly charged compared to stop R-hadron



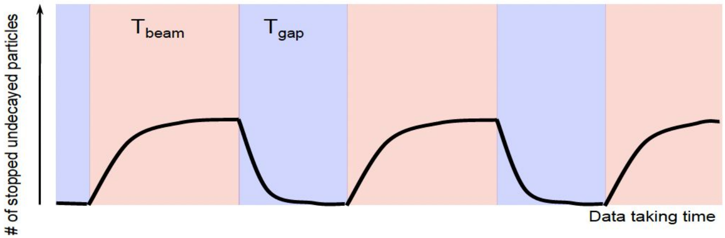




Events are triggered in between the gaps when bunches are not present

# Simulation of stopped searches

- Phase I: Obtain the stopping map as to where in the detector do they come to stop after their production
- Phase II: Simulation of their decays: Place the particle gun of that LLP at that point in the stop map
- Phase III: Simulation of beam tree structure

$$\text{For } \tau \ll T_{beam},\ \sigma_{effective} = (\sigma_{prod} \times \varepsilon_{stop}) \times \varepsilon_{reco} \times \frac{\tau}{T_{beam} + T_{gap}} \times (1 - e^{-T_{gap}/\tau})$$



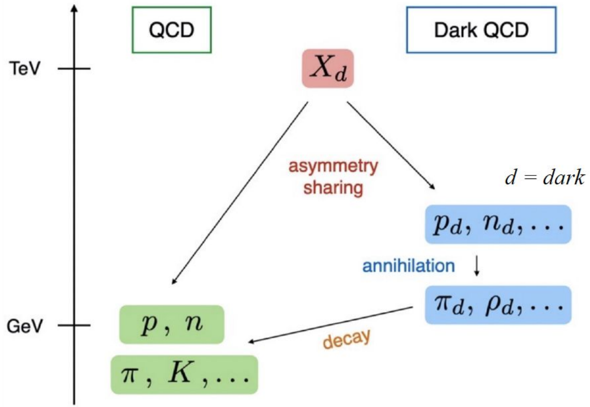

Ref: Internal note (AN-2009-005)

# Background estimation

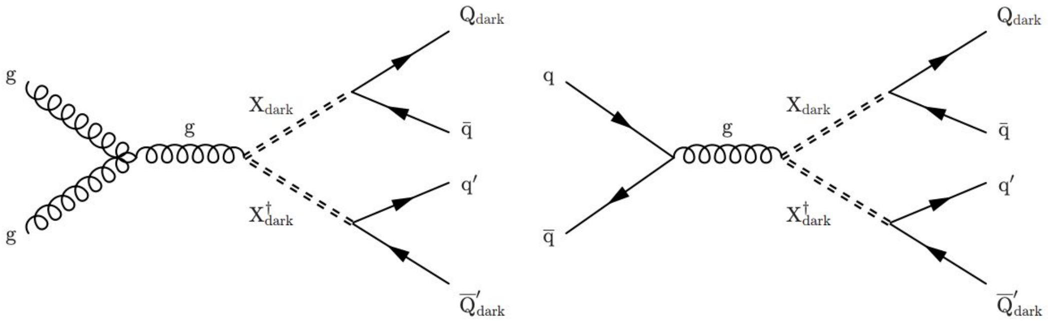
- This estimation is essentially related to the inefficiency of the criteria for these backgrounds
- Cosmic muons: Use MC to determine the inefficiency of the cosmic muons to pass the selections and apply that to the data. Estimate: 8.8 +/- 1.3 (stat) +/- 2.8 (sys)
- Beam halo: From a control sample in data (which passes beam halo filter selection of CMS), check how many of them pass the analysis selection. Estimate: 2.6 +/- 0.1 (stat) +/- 0.1 (sys)
- Noise estimate: Using cosmic runs when there is only cosmic and noise. Subtract the contribution of cosmics from the total so the remaining is the noise. Estimate: 0.0 + 9.8 - 0.0. The uncertainty is larger because the trigger livetime of the cosmic runs is 60% smaller than the pp collisions and the 2016 trigger livetime in collision runs is larger than that in 2015 collision runs so the uncertainty is scaled by a bigger factor

# Emerging jets

# Theoretical introduction

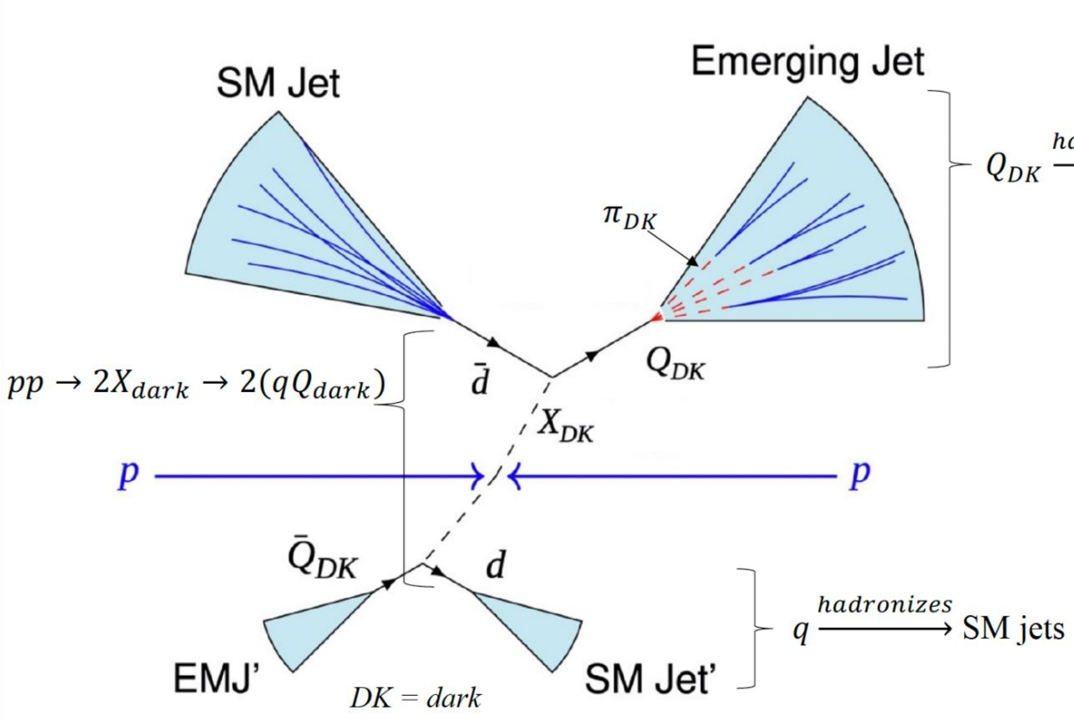



Taken from theory paper




- Dark matter model == QCD like hidden model
- Dark hadrons with $\lambda_{dark}$ (GeV), dark pion unstable: $m_{\pi dark} < \lambda_{dark}$
- Heavy mediator particles couples to both dark and SM sector

# EMJs in CMS detector



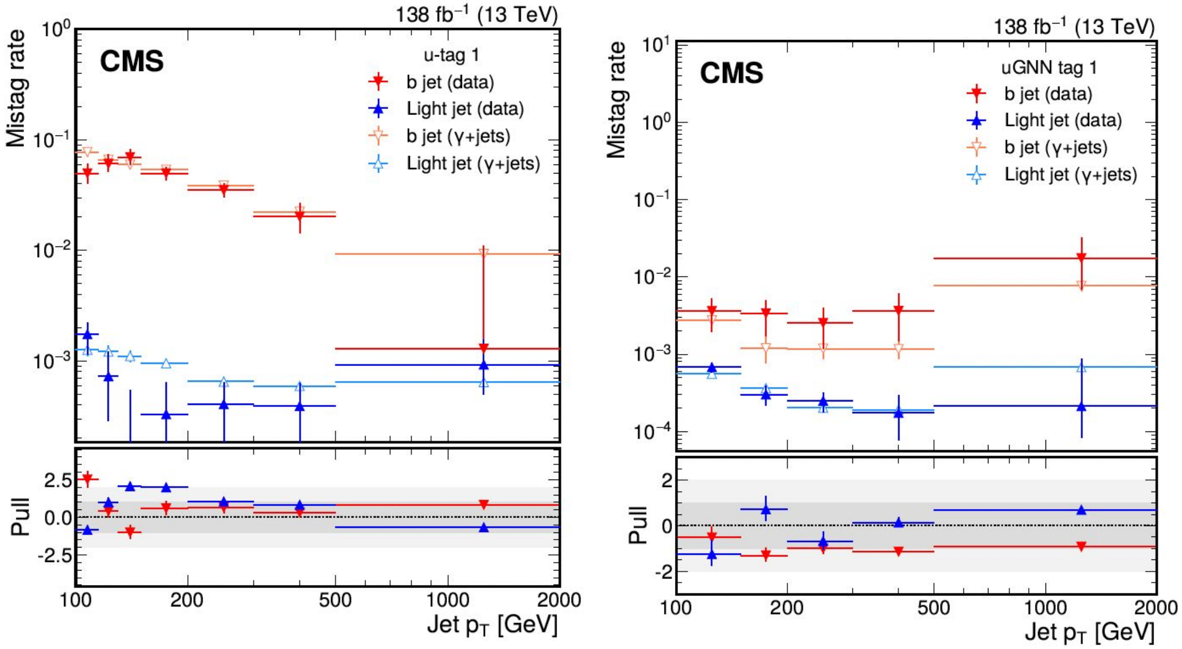

Primary signature:

- High $H_T$
- 4 high $p_T$ jets (2 EMJ, 2 SM jets)

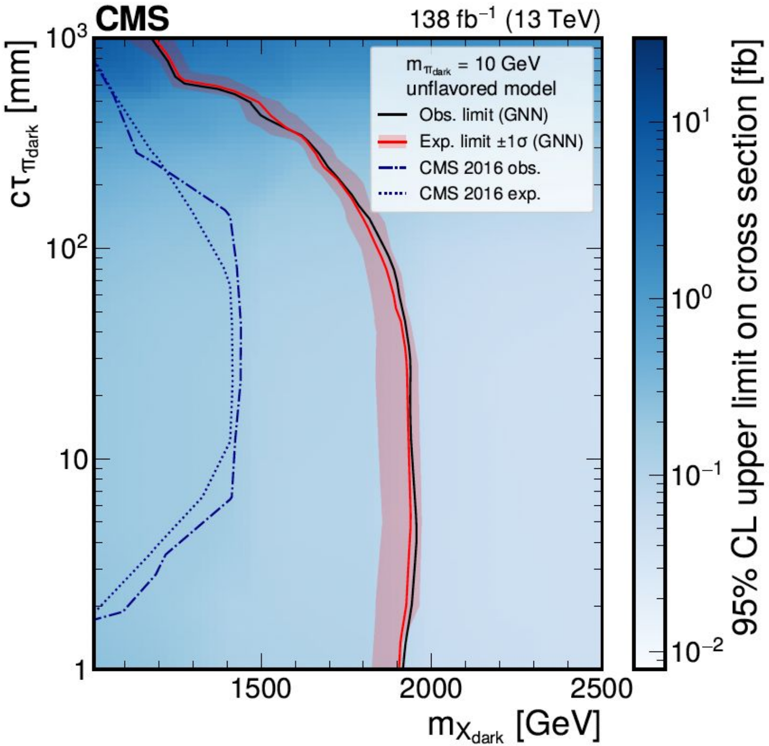
Picture credits: CMS internal talk

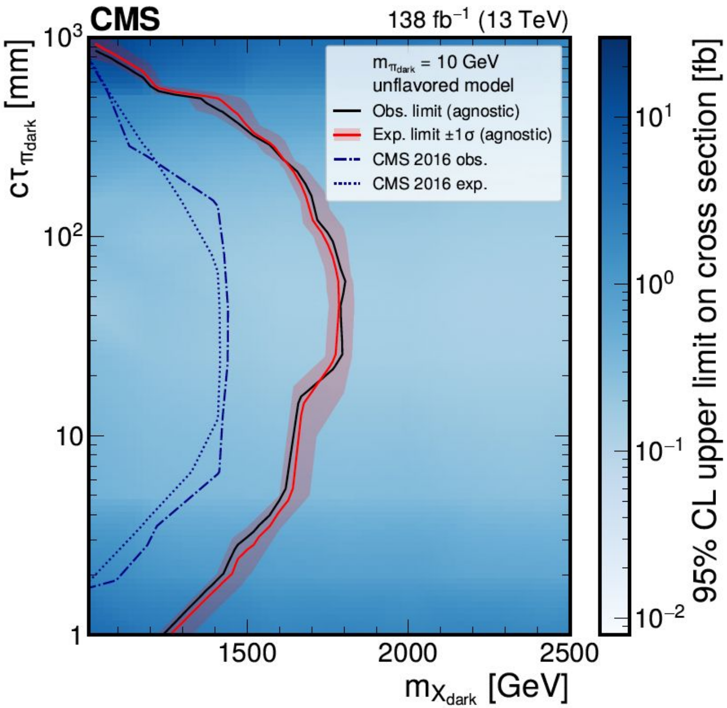
# EMJ tagging

- Model agnostic
  - Jet level variables are used for selecting EMJs e.g. avg dxy of tracks inside it
  - Can be used to re-interpret other models
- Selection based on GNN
  - Classify EMJs from SM jets
  - Not generalizable



# Results


CMS
138 fb$^{-1}$ (13 TeV)
$m_{\pi_{dark}}$ = 10 GeV
unflavored model
Obs. limit (GNN)
Exp. limit ±1σ (GNN)
CMS 2016 obs.
CMS 2016 exp.
$c\tau_{\pi_{dark}}$ [mm]
$m_{X_{dark}}$ [GeV]
95% CL upper limit on cross section [fb]


CMS
138 fb$^{-1}$ (13 TeV)
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Obs. limit (agnostic)
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