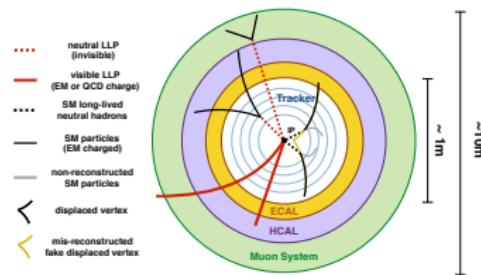


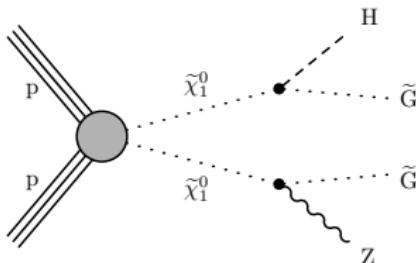
Search for long-lived particles decaying into displaced jets using a trackless and out-of-time jet tagger



Pheno 2023, 08 May – 10 May 2023

Lisa Benato on behalf of the CMS Collaboration
lisa.benato@cern.ch

Introduction

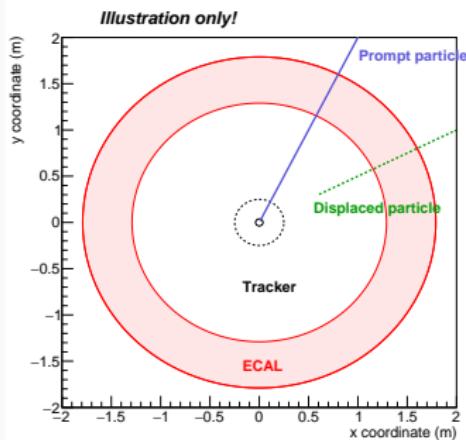


- New CMS result!
EXO-21-014 <http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-21-014/>
- Search for long-lived GMSB SUSY neutralino $\chi \rightarrow \tilde{\chi}^0_1 H(Z) \rightarrow b\bar{b}(q\bar{q})$
- Gravitino \tilde{G} (LSP) light and undetected, provides $\vec{p}_T^{\text{miss}} \rightarrow \vec{p}_T^{\text{miss}}$ trigger
- Targeting neutralino lifetimes $O(1)$ m
 - Shorter lifetimes: tracker-based analysis
 - Longer lifetimes: muon system-based analysis
 - This analysis: covering the gap!
- Unexplored phase-space → CMS prompt neutralino analysis <https://arxiv.org/abs/1709.04896> has no sensitivity

Introduction

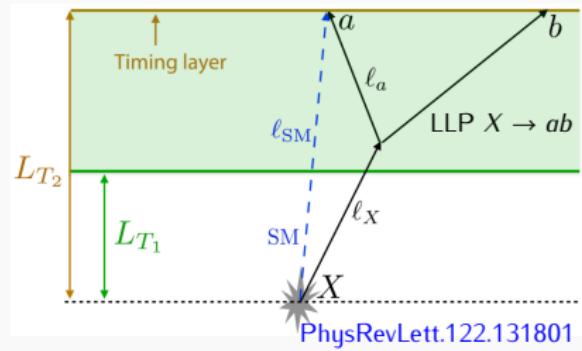
Tracklessness

- CMS tracking efficiency decreases with displacement
- Jets appear as trackless, mostly consisting of neutral components (not actually neutral!)



Delay

- Delay: slow-moving LLPs and/or path length increase due to displacement
- Excellent timing layer at CMS: ECAL $PbWO_4$ scintillating crystals



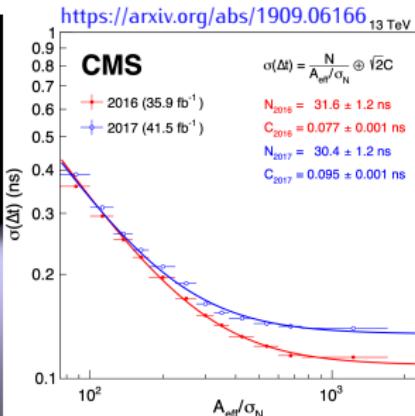
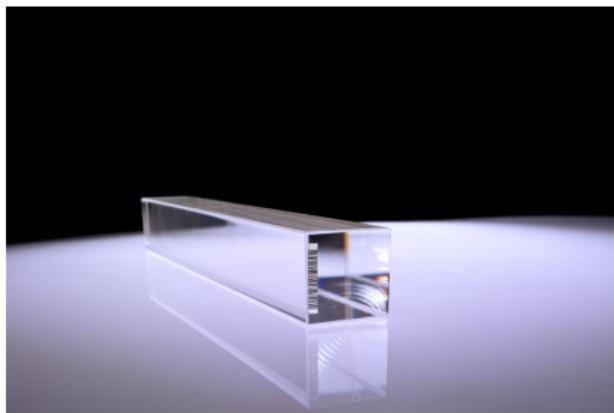
$$\Delta t_a = \frac{l_X}{\beta_X} + \frac{l_a}{\beta_a} - \frac{l_{SM}}{\beta_{SM}}$$

- Increase sensitivity (lower masses) combining ECAL delay with track information in a new DNN jet tagger

Event selections



- Data collected with missing momentum triggers ($\vec{p}_T^{\text{miss}} > 120 \text{ GeV}$)
- AK4 jets $p_T > 30 \text{ GeV}$, $|\eta| < 1$
- Jet time: energy weighted time of ECAL crystals associated to jet

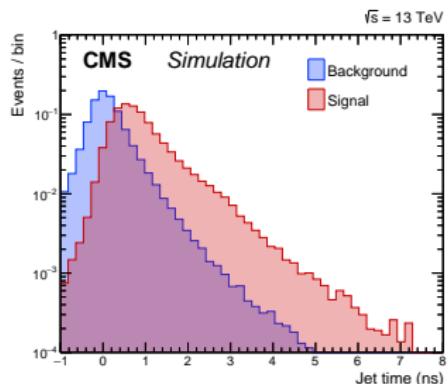
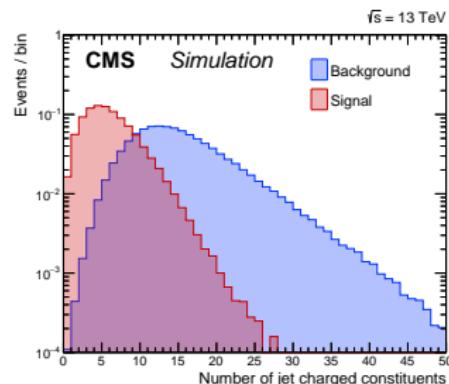
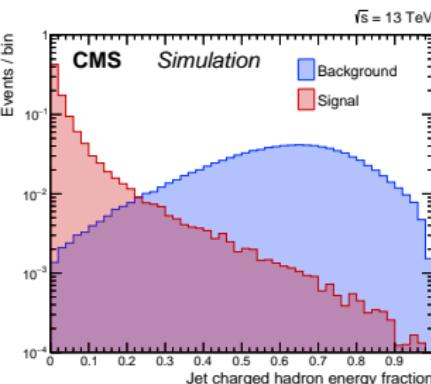


Trackless and delayed jet tagger



Input variables (21 in total):

- Jet composition (neutral/charged hadron, $e/\mu/\gamma$ energy fractions)
- Features of tracks associated to jet
- Features of ECAL crystals associated to jet (energy weighted time stamp)



Trackless and delayed jet tagger

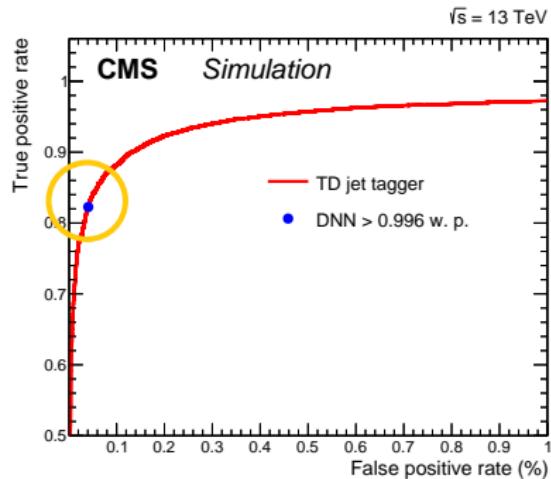
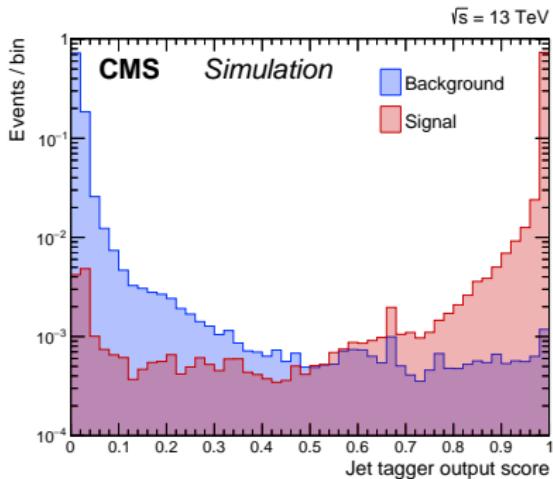


DNN architecture

- 5 fully connected layers (64, 32, 16, 8 and 1 node)
- Supervised training on mixture of simulated signals vs simulated background

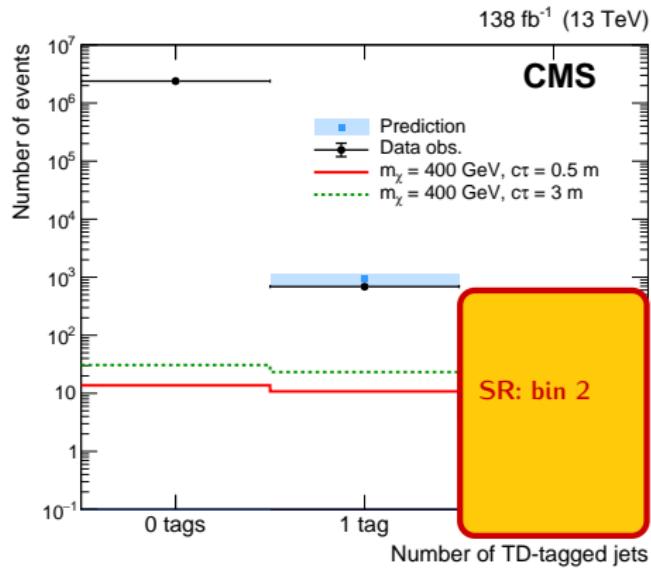
Performances

- At background rejection 4×10^{-4}
- Tagger: 82% signal efficiency



Signal region definition

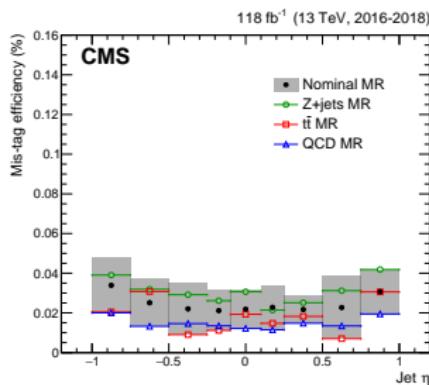
- Background: Z+jets (64%), W+jets (29%), multijet (3%), top (3%), dibosons (1%)
- SR definition optimised in order to have $\lesssim 1$ background event
 - **SR: $n_{\text{tags}} \geq 2$**
- Data-driven approach to predict bin 2: mistag efficiency in control regions (matrix method)



Collision background estimation



1. Compute tag efficiency vs η ¹



2. Prediction from bin 1

- Main background prediction
- Consider events with 1 tagged jet (bin 1)
- Loop on remaining untagged jets and compute probability of having 1 additional tagged jet

$$N_{\geq 2\text{-tag bkg}} = \sum_{k=1}^{N_{1\text{-tag}}} \left(\sum_{i=1}^{N_{\text{untagged}}} \epsilon_{\text{bkg}}(\eta_{\text{jet } i}) \right)$$

- Ansatz: mistag for each jet is independent to other jets, verified with closure tests

¹ Updated plot resubmitted to JHEP, differs from <https://arxiv.org/abs/2212.06695v1>

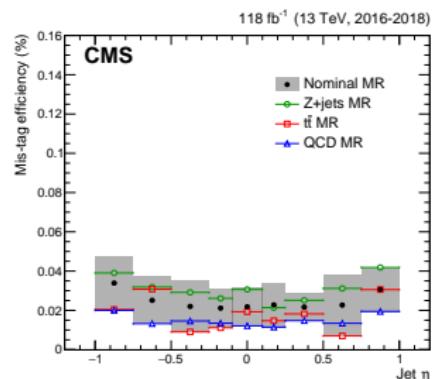
Mistag in control regions

Measurement region (MR): $W \rightarrow \ell\nu$

- 1 lepton (trigger), no signal contamination
- Includes true \vec{p}_T^{miss} (like SR)
- High statistics
- Mistag rate used to predict bin 2 SR yield ²

Alternative measurement regions

- Potential systematic uncertainty: process/jet composition dependence
- Measurement performed in alternative samples
 - $Z \rightarrow \ell\ell$ as a proxy for $Z \rightarrow \nu\nu$
 - $e\mu$ as a proxy for $t\bar{t}$
 - Single jet trigger + $\vec{p}_T^{\text{miss}} < 25 \text{ GeV}$ as a proxy for multijet background
- Discrepancies w.r.t. MR taken as background composition uncertainty



²Updated plot resubmitted to JHEP, differs from <https://arxiv.org/abs/2212.06695v1>

Collision background estimation method uncertainty



Prediction from bin 0

- Alternative prediction from bin 0:

$$N'_{\geq 2\text{-tag bkg}} = \sum_{k=1}^{N_{0\text{-tag}}} \left(\sum_{i=1}^{N_{\text{untagged}}^k} \sum_{j>i}^{N_{\text{untagged}}^k} \epsilon_{\text{bkg}}(\eta_{\text{jet } i}) \epsilon_{\text{bkg}}(\eta_{\text{jet } j}) \right)$$

- Predict bin 2: difference w.r.t main bin 2 prediction as **method systematic uncertainty**

Non-collision background sources



Two non-collision backgrounds (not included in MC sample) potentially affecting bin 2

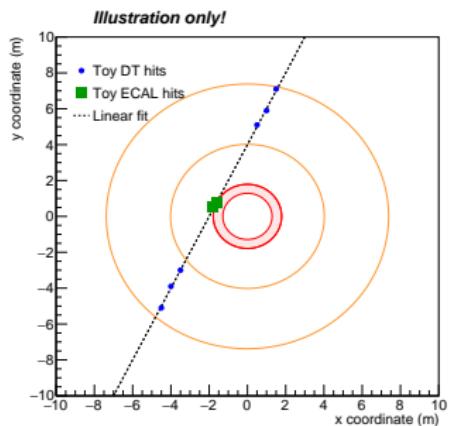
- **Cosmic muons** tangentially grazing the calorimeter
- **Beam halo** particles grazing the calorimeter tangentially along beam line

Cosmic muon background



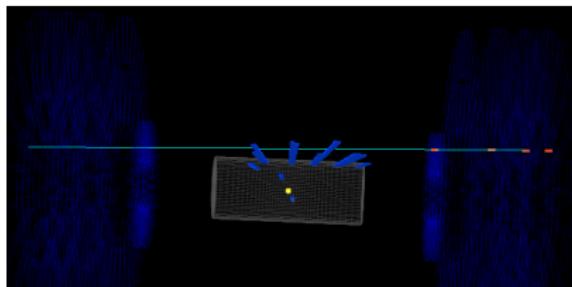
Cosmic veto design

- A cosmic muon that hits the surface of the ECAL can mimic a trackless jet
- Observed hits in Drift Tubes (barrel muon detector) line up with trajectory of cosmic muons
- Simple geometric approach based on cosmic muon distance to the ECAL
 - Reconstruct each cosmic leg by clustering DT hits (segments) with DBSCAN
 - Linear fit in 3D of DT hits
 - If $\text{dist}_{\text{ECAL,cosmic}} < 0.5 \text{ m}$, reject the event



Beam halo (BH) background

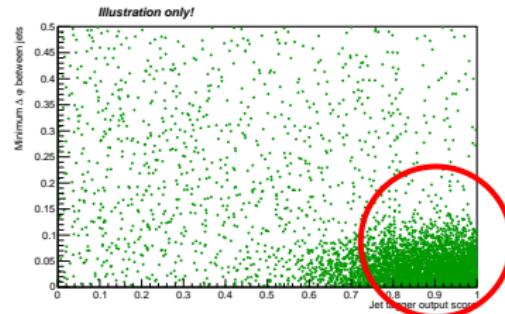
- Beam halo particles (proton collisions with material or beam gas) mostly parallel to the beam direction can generate calo clusters
- Standard CMS-BH filter associates calorimeter patterns to Cathode Strip Chambers hits (forward muon detector) → some events can escape!



<https://twiki.cern.ch/twiki/bin/view/CMSPublic/SWGuideEJTermBeamHaloid>

Beam halo (BH) veto design

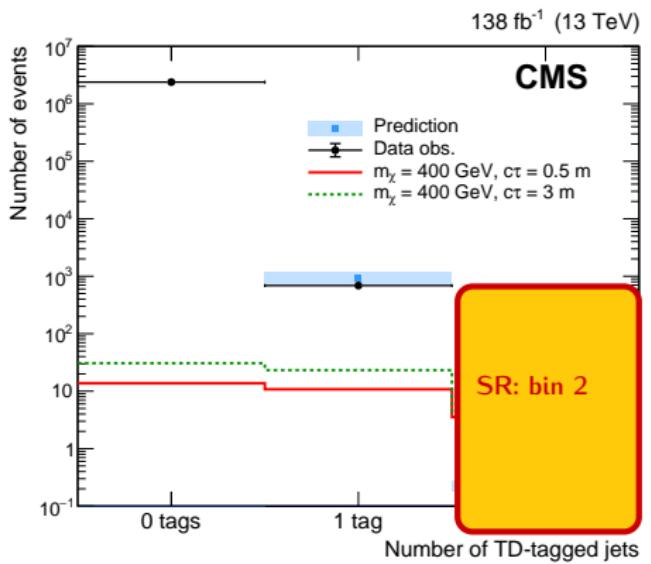
- BH deposits: soft jets, $\varphi \sim 0, \pi$, few ECAL deposits
- Correlation between jets close in φ and their DNN score (not present in collision data!)
- Additional custom BH veto: $\min\Delta\varphi(\text{tag jets}) < 0.05$ & low ECAL crystals multiplicity



Background yield



- Final background prediction, collision and non-collision



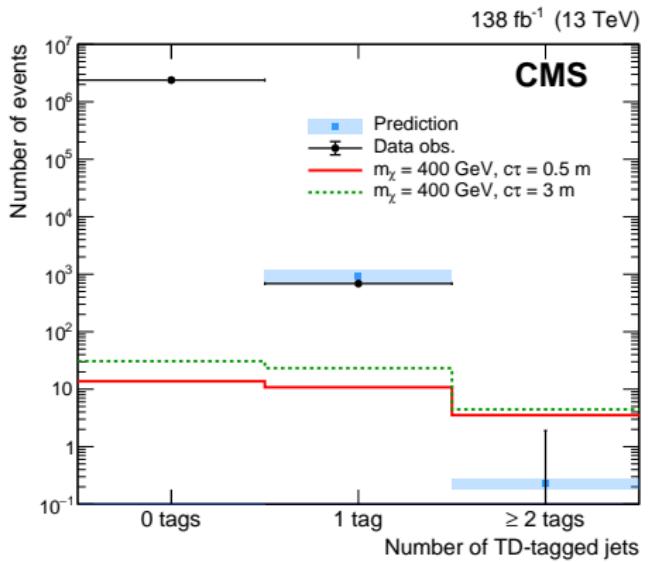
Source	Prediction	Observed
Mistag	0.15 ± 0.08	
Cosmic muons	0.03 ± 0.02	
Beam halo	0.05 ± 0.05	
Tot. Run 2	0.23 ± 0.10	

Background yield



- Final background prediction, collision and non-collision

Source	Prediction	Observed
Mistag	0.15 ± 0.08	
Cosmic muons	0.03 ± 0.02	
Beam halo	0.05 ± 0.05	
Tot. Run 2	0.23 ± 0.10	0

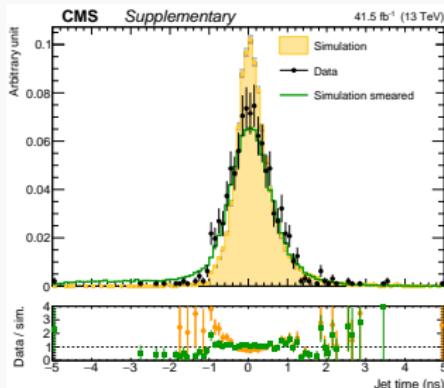


Data/MC modeling of DNN



$t\bar{t} \rightarrow e\mu + X$ control region

- $t\bar{t} \rightarrow e\mu + X$ control region to study DNN input variables in MC:
 - All well modeled except jet time



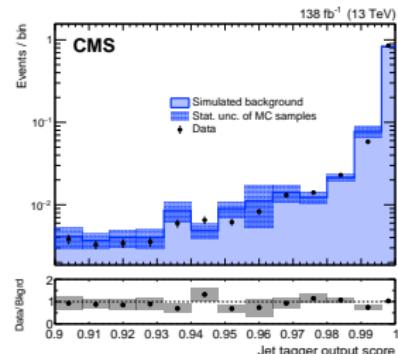
- Correct/smear MC jet time (mean/width) and recompute DNN output after smearing

Photon proxy object

- Photon: SM object that resembles LLP trackless jet
- Good for modeling low- p_T jets

Electron proxy object

- Electrons are signal-like jets if we remove their track
- Good for modeling high- p_T jets
- Data/MC mistag ratio: SF to correct jets in MC (signal)
- Data/corrected MC jet DNN score: excellent agreement



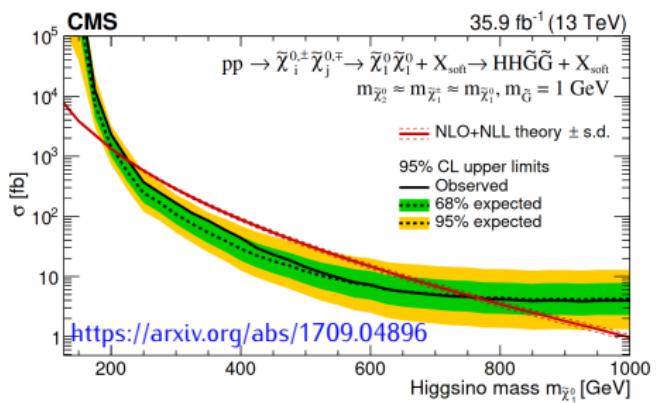
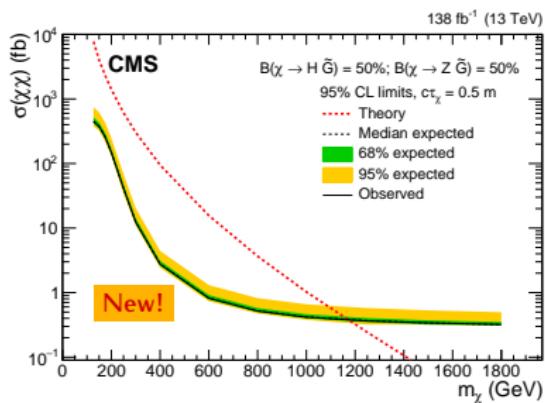
Uncertainties



Uncertainty source	Process	Uncertainty size [%]
Background MR sample size	Background	4
Jet tagger misidentification process dependence	Background	30
Background estimation method	Background	13
Non-collision background	Background	23
Jet tagger efficiency modeling	Signal	8–29
Jet energy scale	Signal	0.1–11
Jet energy resolution	Signal	0.2–10
PDFs	Signal	1–16
Missing higher-order QCD corrections	Signal	4–15
Pileup	Signal	0.3–6.3
Luminosity	Signal	2.5
Signal sample size	Signal	5–8
Lepton and photon veto efficiency	Signal	< 1

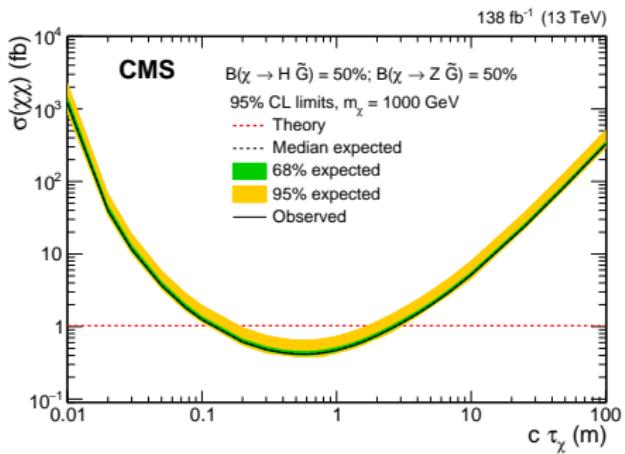
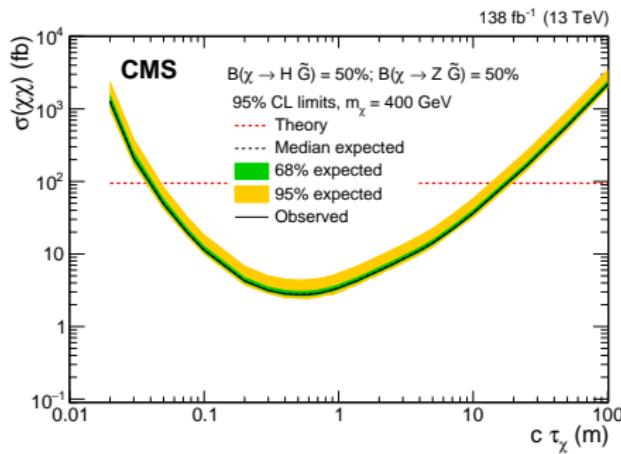
Exclusion limits vs m_{χ}

- Combination of Run 2 data
- Limits at 1 fb level for $m_{\chi} > 550$ GeV
- Complementary to prompt analysis, big improvement at lower masses!
- Exclude m_{χ} up to 1.18 TeV at $c\tau = 0.5$ m



Exclusion limits vs $c\tau_\chi$

- Peak sensitivity for 0.03–15 (0.1–3) m lifetimes at $m_\chi = 400$ (1000) GeV



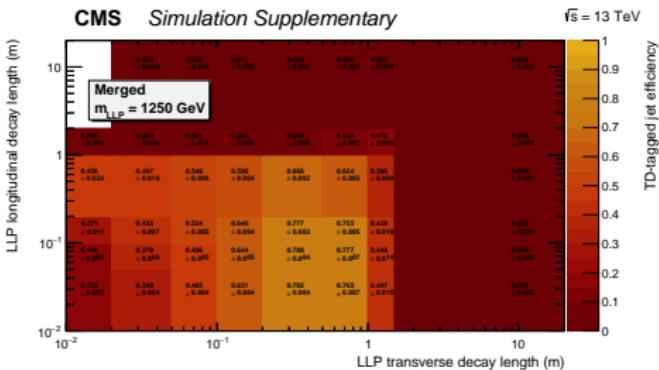
Re-interpretation material

```

def resolved_sq1(r, LLP_r, quark1_pt, quark1_eta, quark1_phi, quark2_pt, quark2_eta, quark2_phi):
    """
    Function that takes as input the LLP r and z in meters, the quarks pt in GeV, and the quarks eta and phi.
    It returns the probability that the LLP has a resolved topology, with both quarks in acceptance.
    It accepts the LLP r and z satisfying the resolved topology requirement, with both quarks in acceptance.
    More details on the HEPData entry:
    https://www.hepdata.net/record/ins2613855
    """
    deltaq = abs(quark1_eta, quark1_phi, quark2_eta, quark2_phi)
    resolved = (deltaq <= 0.005)
    LLP_r_00 = np.logical_and(
        LLP_r >= 0.005,
        np.logical_and(quark1_pt >= 0, abs(quark1_eta) <= 1),
        np.logical_and(quark2_pt >= 0, abs(quark2_eta) <= 1),
    )
    resolved = resolved & LLP_r_00 & LLP_r <= r
    return resolved

def predict(LLP_r, LLP_z, r_eff, m_llp):
    """
    Function that predicts the probability that the LLP decays生成 one out-of-time trackless jet.
    It takes as input the LLP decay position z and r in m, and the corresponding efficiency map (TH2D root histogram).
    It also takes the LLP mass m in GeV and the uncertainty as decay arrays.
    More details on the HEPData entry:
    https://www.hepdata.net/record/ins2613855
    """
    weights = []
    weights_mc = []
    for i in range(len(LLP_r)):
        r_eff_i = r_eff[LLP_z[i]]
        weights.append(r_eff_i * mc_efficiency(i))
        weights_mc.append(r_eff_i * mc_efficiency_mc(i))
    weights = np.array(weights)
    weights_mc = np.array(weights_mc)
    return weights, weights_mc

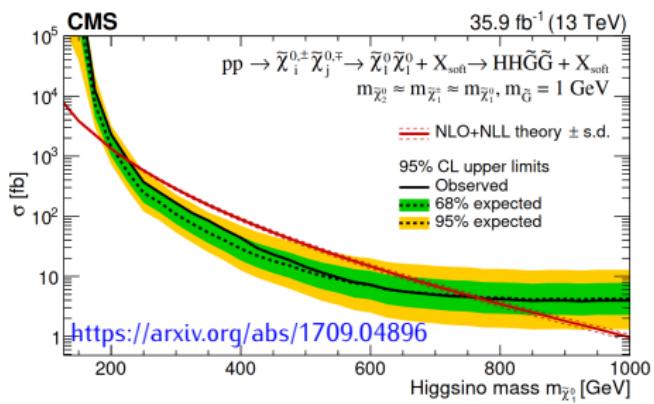
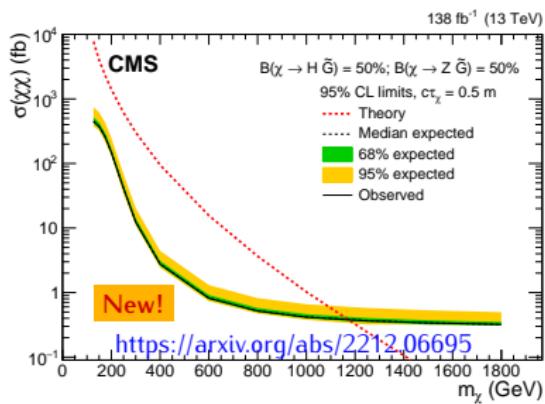
```



- We provide signal efficiency maps (ROOT histograms) as a function of the LLP transverse and longitudinal decay lengths (r, z)
- Dedicated functions compute the topology, load the efficiency maps, perform the prediction
- Material and detailed instructions available in:
 - HEPData <https://www.hepdata.net/record/ins2613855>
 - <http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-21-014/>

Summary

- We presented a search for long-lived particles with trackless and out-of-time jets
- Achieved very strong background suppression by using a DNN tagger
- Observe 0 events, in agreement with prediction
- Compared to previous searches for promptly decaying χ , sensitivity 20–10 times better at $m_\chi = 400\text{--}600 \text{ GeV}$
- Exclude m_χ up to 1.18 TeV
- Plenty of ideas and opportunities for Run 3!



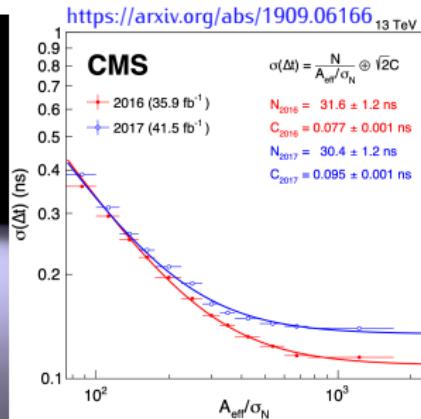
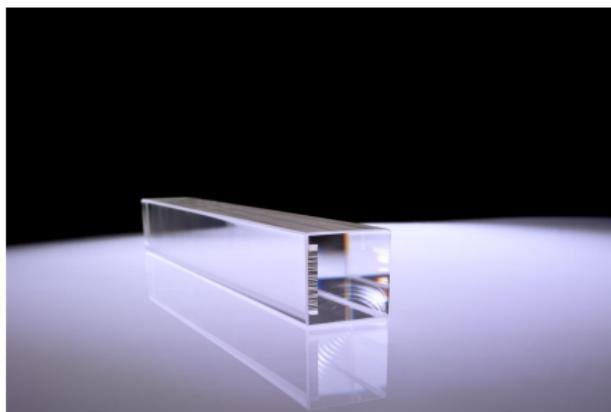


Backup slides

Event selections



- Data collected with missing momentum triggers ($\vec{p}_T^{\text{miss}} > 120 \text{ GeV}$)
- AK4 jets $p_T > 30 \text{ GeV}$, $|\eta| < 1$ (better ECAL time calibration and tracking efficiency)
- Jet time: energy weighted time of ECAL crystals associated to jet

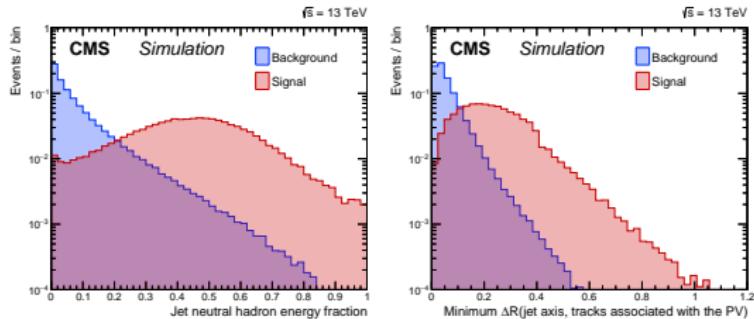


- Veto electrons, muons, taus: to suppress $W+jets$ and $t\bar{t}$
- Veto photons (fake trackless jets)
- Require minimum $\Delta\varphi(\text{jets}, \vec{p}_T^{\text{miss}}) > 0.5$ to suppress multijet background
- Generator level matching: LLP decay within calorimeter volume: $30 < r < 184 \text{ cm}$

Trackless and delayed jet tagger

Input variables (21 in total):

- Jet composition (neutral/charged hadron, ele/mu/photon energy fractions)
- Tracking variables (α , β , γ max) comparing p_T of tracks associated to jet w.r.t. jet energy/ p_T
- ΔR between a track (associated to a PV), and the jet itself
- Number of charged constituents
- Associated ECAL rec-hits in a cone $\Delta R < 0.4$ w.r.t. jet:
 - Multiplicity, relative energy and time stamp (weighted with rec hit energy)



Trackless and delayed jet tagger

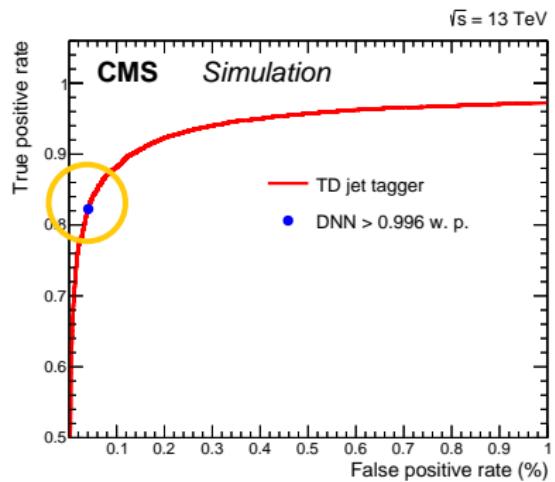
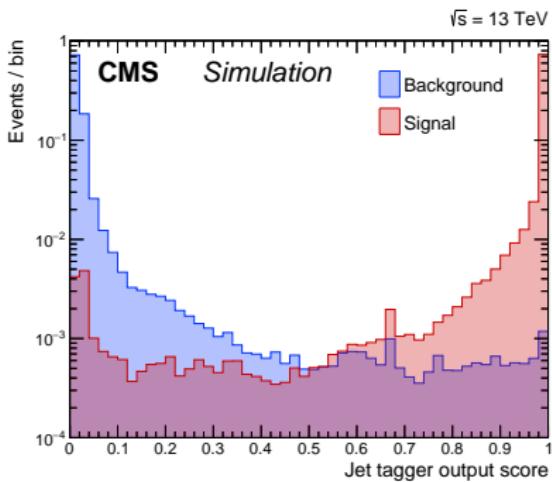


DNN architecture

- 5 fully connected layers (64, 32, 16, 8 and 1 node)
- Training 1000 epochs on SM background processes and $m_\chi = 400$ GeV, $c\tau = 1$ m signal, 2.5 M events (S/B = 1/8)

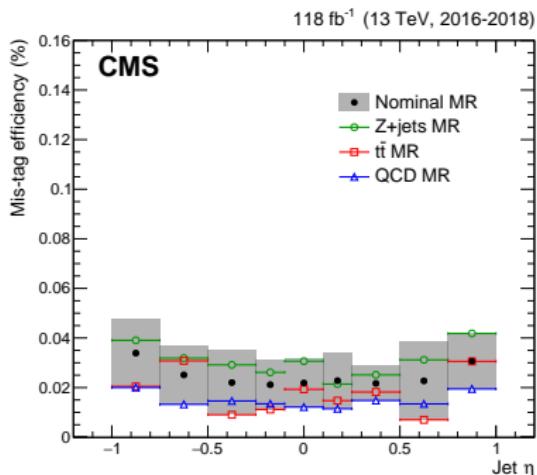
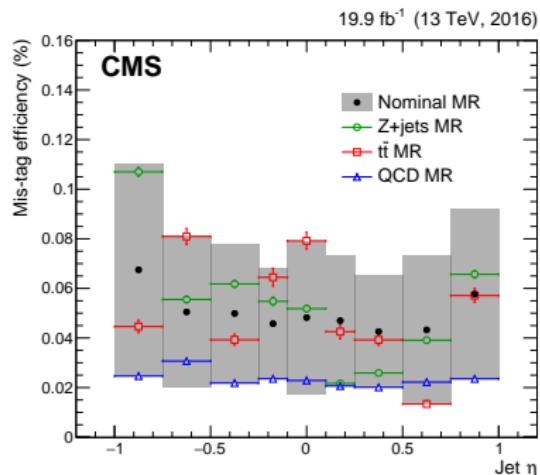
Performances

- At background rejection 4×10^{-4}
- Tagger: 82% signal efficiency
- Jet is trackless and delayed if DNN score > 0.996



Mistag in control regions

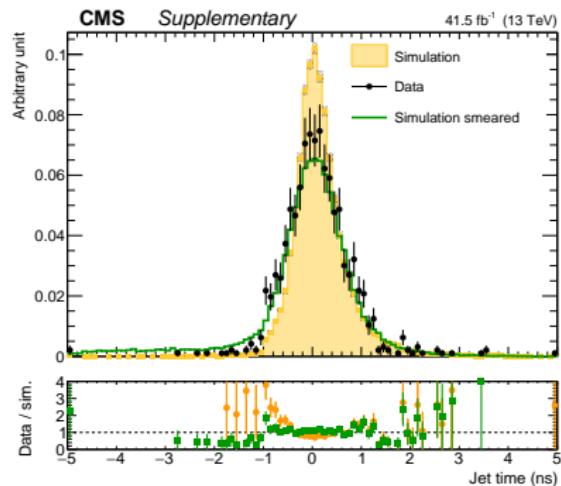
- Mistag in 2016 B-F (left); in 2016 H - 2018 (right)³



³Updated plots resubmitted to JHEP, differ from <https://arxiv.org/abs/2212.06695v1>

Data/MC modeling of DNN input variables

- $t\bar{t} \rightarrow e\mu + X$ control region to study DNN input variables in MC:
 - All well modeled except jet time



- Perform a crystal ball fit on data/MC
- Correct/smear MC jet time (mean/width) and recompute DNN output after smearing

Data/MC modeling of DNN score: photon and electron proxy objects

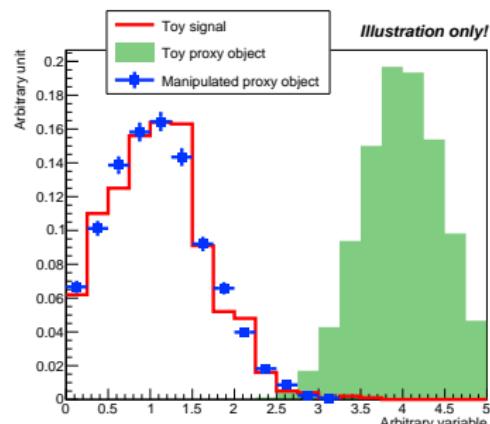


Photon proxy object

- SM photon: object that closely resembles LLP signal jet
- Define region $Z \rightarrow \ell\ell\gamma$
- Require 1 photon faking a trackless jet
 - Tracking variables close to signal
 - Jet composition and ECAL variables different
- Produce a trackless + delayed jet sample by shifting/smearing DNN inputs to match signal
- Good for modeling low- p_T jets

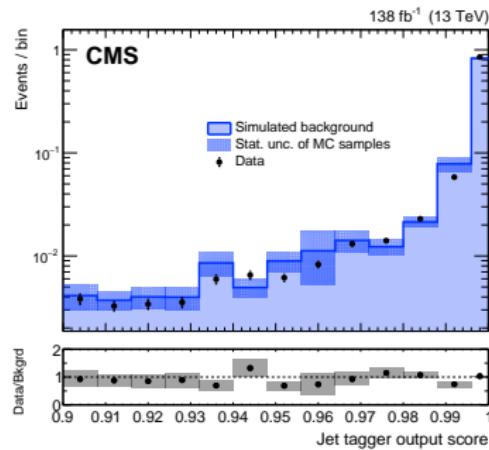
Electron proxy object

- Electrons as a proxy for high- p_T signal-like jets if we pretend the electron is a photon
- Require 1 electron faking 1 jet → manipulation to make the jet trackless
 - Same approach as photon proxy object
- Good for modeling high- p_T jets

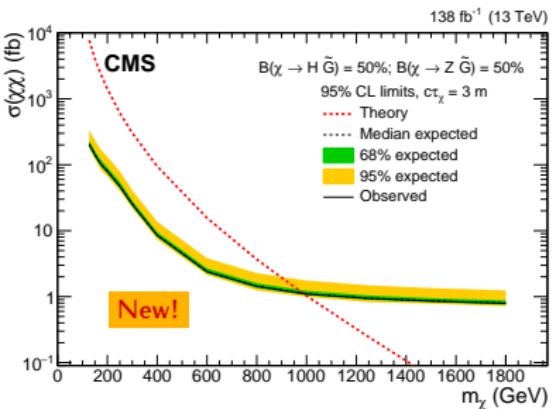
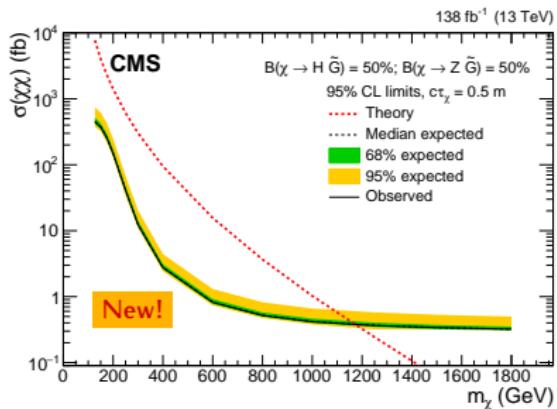


Data/MC modeling DNN score

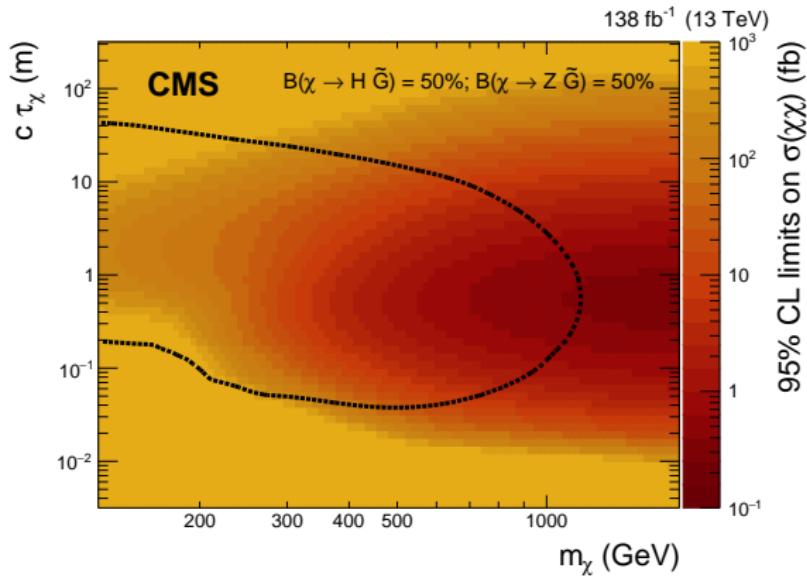
- Data/MC mistag ratio as SF used to correct jets in signal
 - if jet $p_T < 70$ GeV: use photon SF
 - if jet $p_T > 70$ GeV: use electron SF
- SF flat vs η and p_T , and they agree within uncertainty
- Evaluate data/MC jet tagger score for electron proxy objects (after corrections on inputs in MC), very good agreement



Exclusion limits vs m_χ



Exclusion limits



Residual cosmic background

1. Cosmic veto efficiency estimation:
 - Use non-collision cosmic data to measure cosmic veto efficiency $\epsilon_{\text{cosmic veto}}$
2. Cosmic reconstruction inefficiency due to gaps in DT muon system
 - Use cosmic MC to estimate the cosmic muon leg reconstruction efficiency $\epsilon_{\text{cosmic muon reco MC}}$

Residual cosmic background in SR:

$$\text{cosmic bkg} = \frac{(1 - \epsilon_{\text{cosmic veto}}) \cdot n_{\text{obs}}(\text{events rejected by cosmic veto})}{\epsilon_{\text{cosmic muon reco MC}}}$$

N. of vetoed events	Cosmic background prediction
6	0.034 ± 0.018

Residual beam halo (BH) background

1. Custom BH veto efficiency estimation:
 - Measure custom BH veto inefficiency for tagged jet pairs close in φ in BH enriched sample $\epsilon_{\text{BH veto}}$
2. BH filter inefficiency due to gaps in CSC muon system:
 - Estimate CSC-BH filter inefficiency in BH enriched sample $\epsilon_{\text{CSC-BH filter}}$

Residual beam halo background in SR:

$$\text{beam halo bkg} = \frac{(1 - \epsilon_{\text{BH veto}}) \cdot n_{\text{obs}}(\text{events rejected by beam halo veto})}{\epsilon_{\text{CSC-BH filter}}}$$

N. of vetoed events	Beam halo background prediction
1	0.05 ± 0.05