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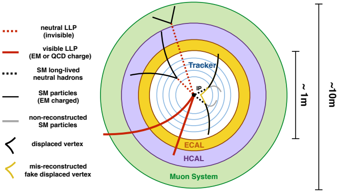
FSP CMS
Erforschung von Universum und Materie

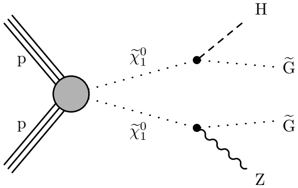
Search for long-lived particles decaying into displaced jets using a trackless and delayed jet tagger



LLP 12 workshop, 31 Oct. – 4 Nov. 2022

Lisa Benato on behalf of the CMS Collaboration

Introduction

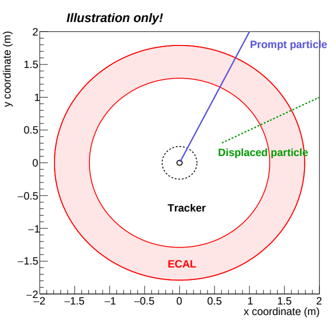


- **New CMS result!** (EXO-21-014 http://cds.cern.ch/record/2839046)
- Search for long-lived GMSB SUSY neutralino $\chi \rightarrow \tilde{G}H(Z) \rightarrow b\bar{b}(q\bar{q})$
- Gravitino $\tilde{G}$ (LSP) light and undetected, provides $\vec{p}_T^{miss} \rightarrow \vec{p}_T^{miss}$ trigger
- Targeting neutralino lifetimes $O(1)$ m
  - Shorter lifetimes: tracker-based analysis
  - Longer lifetimes: muon system-based analysis
  - This analysis: covering the gap!
- Unexplored phase-space → prompt neutralino analysis https://arxiv.org/abs/1709.04896 has no sensitivity

Introduction

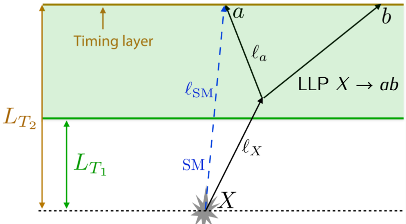
Tracklessness

- 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



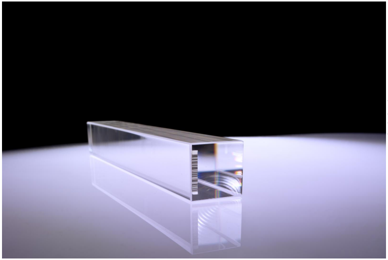
PhysRevLett.122.131801

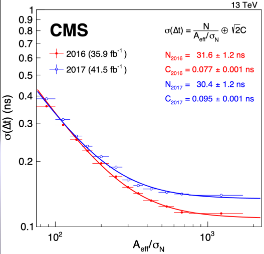
$$\Delta t_a = \frac{l_X}{\beta_X} + \frac{l_a}{\beta_a} - \frac{l_{SM}}{\beta_{SM}}$$

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

Event selections

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



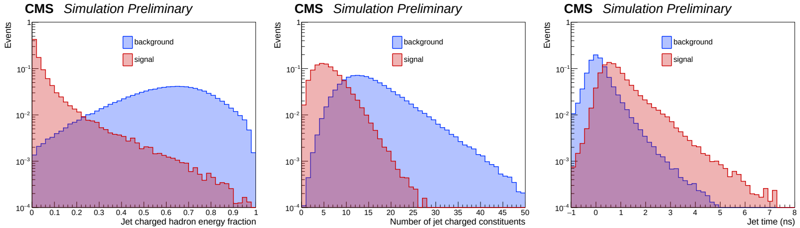


- Veto electrons, muons, taus: to suppress W+jets and $t\bar{t}$
- Veto photons (fake trackless jets)
- Require minimum $\Delta\varphi(\mathrm{jets}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) > 0.5$ to suppress multijet background
- Generator level matching: LLP decay within calorimeter volume: $30 < r 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

Trackless and delayed jet tagger

Input variables (21 in total):

- Jet composition (neutral/charged hadron, $e/\mu/\gamma$ energy fractions)
- Tracking variables comparing p_{T} of tracks associated to jet w.r.t. jet energy/p_{T}
- Minimum ΔR between a track and the jet itself
- Number of charged constituents
- Associated ECAL crystals in jet cone:
  - Multiplicity, relative energy and time stamp (energy weighted)



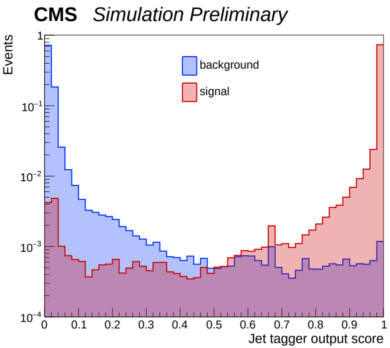
Trackless and delayed jet tagger

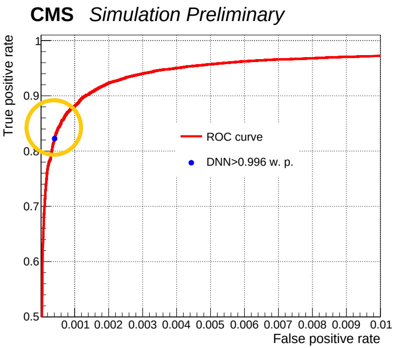
DNN architecture

- 5 fully connected layers (64, 32, 16, 8 and 1 node)
- Training 1000 epochs on SM background processes and $m_\chi = 400$ GeV, $c\tau_0 = 1$ m signal, 2.5 M events (S/B = 1/8)

Performances

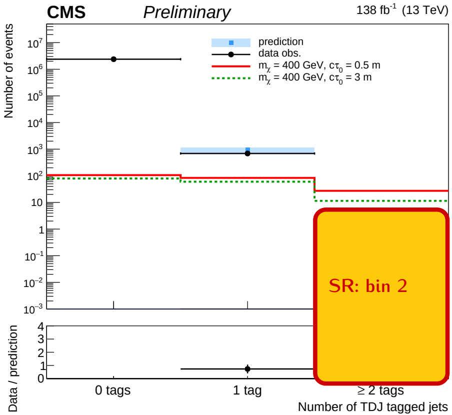
- At background rejection 4×10^{-4}
- Tagger: 82% signal efficiency
- Jet is trackless and delayed if DNN score > 0.996





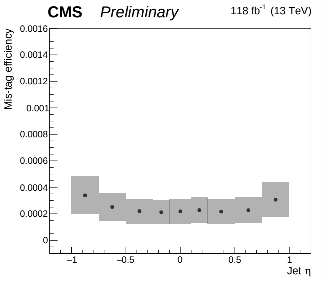
Signal region definition

- 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



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

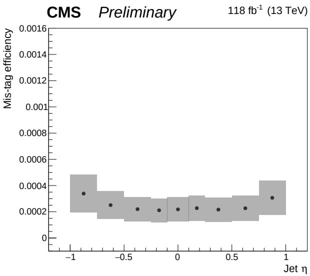
$$p_2 = \sum_{i \in \text{untagged j bin1}} \epsilon(\eta_i | \text{1 j tagged})$$

- Probability → event weight → predict bin 2 yield
- Ansatz: mistag for each jet is independent to other jets, verified with closure tests (in simulation and data control regions)

Mistag in control regions

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

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



Alternative measurement regions

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

Collision background estimation method uncertainty

Prediction from bin 0

- Alternative prediction to extract **method systematic uncertainty**

$$p_2 = \sum_{(i,j) \in \text{untagged j bin0}} \epsilon(\eta_i) \cdot \epsilon(\eta_j)$$

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

Non-collision background sources

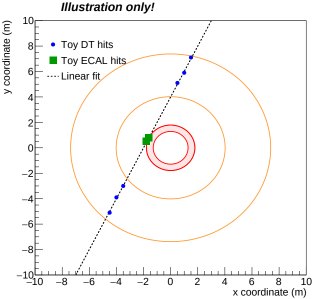
Two non-collision backgrounds (not included in MC sample) potentially affecting bin 2

- **Cosmic muons** tangentially grazing the calorimeter
- **Beam halo** particles grazing the calorimeter tangentially along beam line
- In both cases: trackless jets, large time delay $\rightarrow$ large DNN score

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 $\text{dist}_{\text{ECAL,cosmic}} < 0.5$ m, reject the event

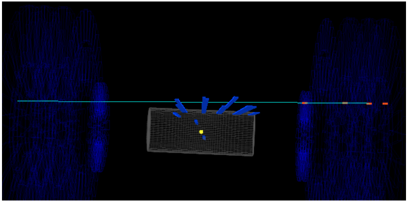


Residual cosmic background

- We measure cosmic veto efficiency and cosmic reconstruction inefficiency due to gaps in DT muon system in control regions → correction factor F_{cosmic}
- Residual cosmic background in SR: cosmic bkg $= F_{\text{cosmic}} \cdot n_{\text{obs}}($ events rejected by cosmic veto)

Beam halo background

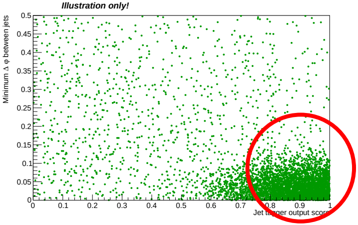
- Beam halo particles (proton collisions with material or beam gas) mostly parallel to the beam direction can generate calo clusters
- Standard CMS-BH filter associates calorimeter patterns to Cathode Strip Chambers hits (forward muon detector) → some events can escape!



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



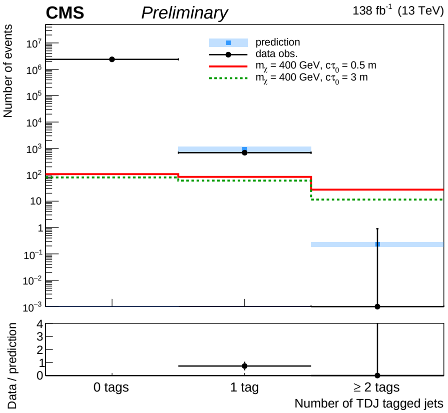
Residual beam halo background

- We measure custom BH veto efficiency and inefficiency due to gaps in CSC muon system in BH enriched sample → correction factor F_{BH}
- Residual beam halo background in SR: BH bkg $= F_{\text{BH}} \cdot n_{\text{obs}}$(events rejected by BH veto)

Background yield

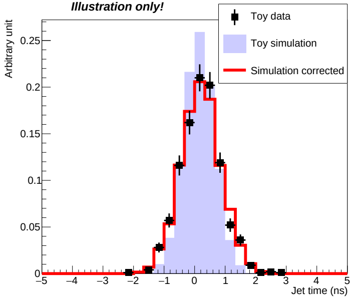
- Final background prediction, collision and non-collision

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 input variables

- $t\bar{t} \to e\mu + X$ 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

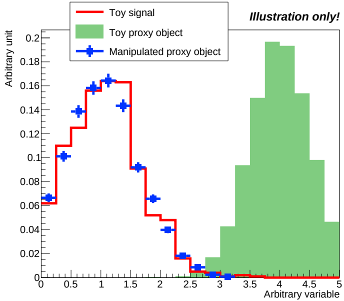
- SM photon: object that closely resembles LLP signal jet
- Define region $Z \to \ell\ell\gamma$
- Require 1 photon faking a trackless jet
  - Tracking variables close to signal
  - Jet composition and ECAL variables different

→ Produce a trackless + delayed jet sample by shifting/smearing DNN inputs to match signal

- Good for modeling low-p_T jets

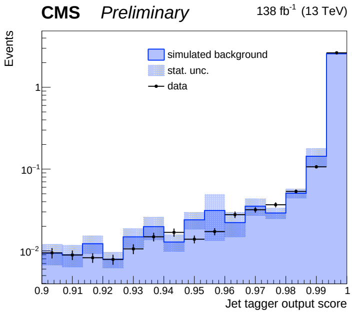
Electron proxy object

- 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

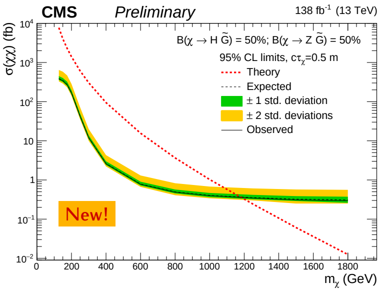


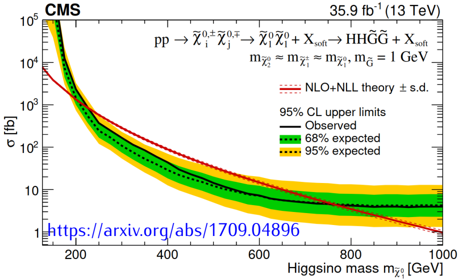
Uncertainties

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

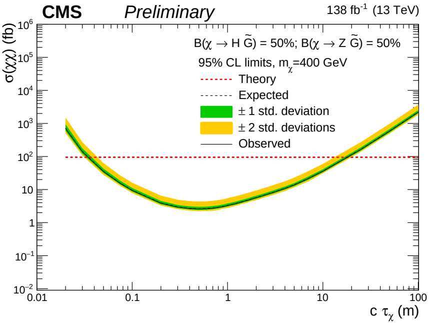
- Combination of Run 2 data
- Branching ratio scan of the neutralino decay modes; limits compatible within 10%
- Limits at 1 fb level for $m_\chi > 550$ GeV
- Complementary to prompt analysis, big improvement at lower masses!
- Exclude m_χ up to 1.18 TeV at $c\tau_0$ =0.5 m

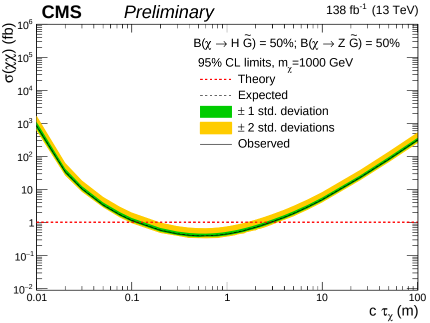




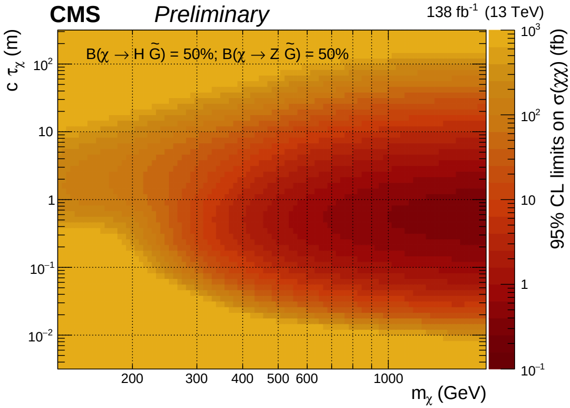
Exclusion limits vs $c\tau$

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



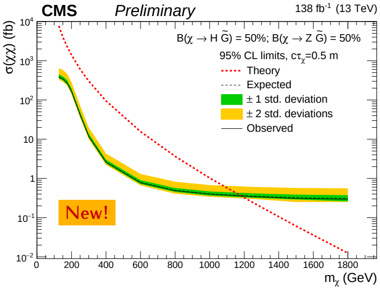


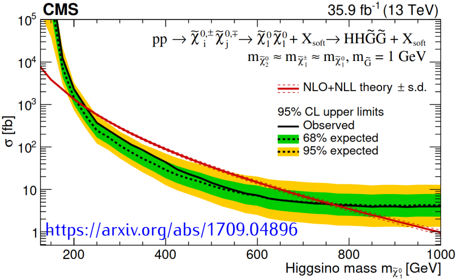
Exclusion limits



Summary

- We presented a search for long-lived particles with trackless and delayed 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 $m_\chi = 400$–600 GeV
- Exclude m_χ up to 1.18 TeV
- Plenty of ideas and opportunities for Run 3!



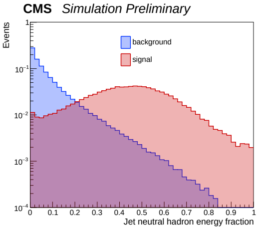


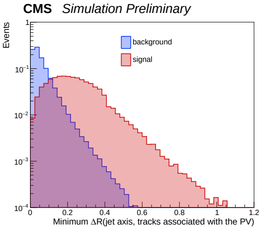
Backup slides

Trackless and delayed jet tagger

Input variables (21 in total):

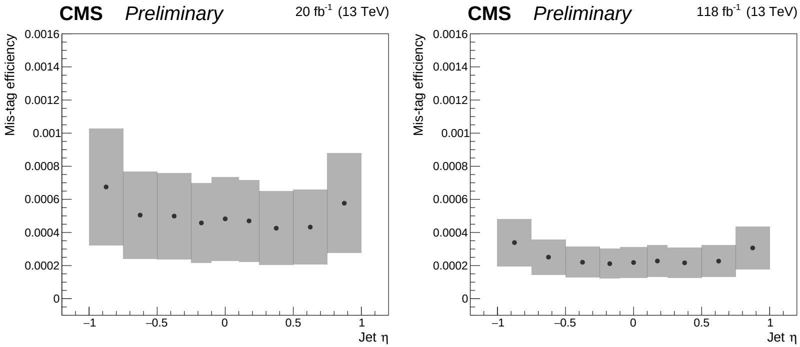
- Jet composition (neutral/charged hadron, ele/mu/photon energy fractions)
- Tracking variables (α, β, γ max) comparing p_T of tracks associated to jet w.r.t. jet energy/p_T
- ΔR between a track (associated to a PV), and the jet itself
- Number of charged constituents
- Associated ECAL rec-hits in a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



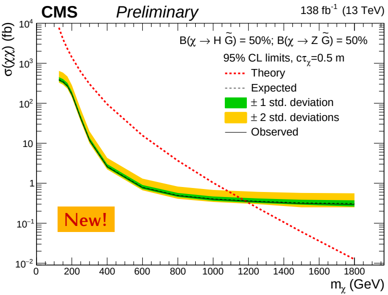


Mistag in control regions

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



Exclusion limits vs m_χ



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:

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

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:

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

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