

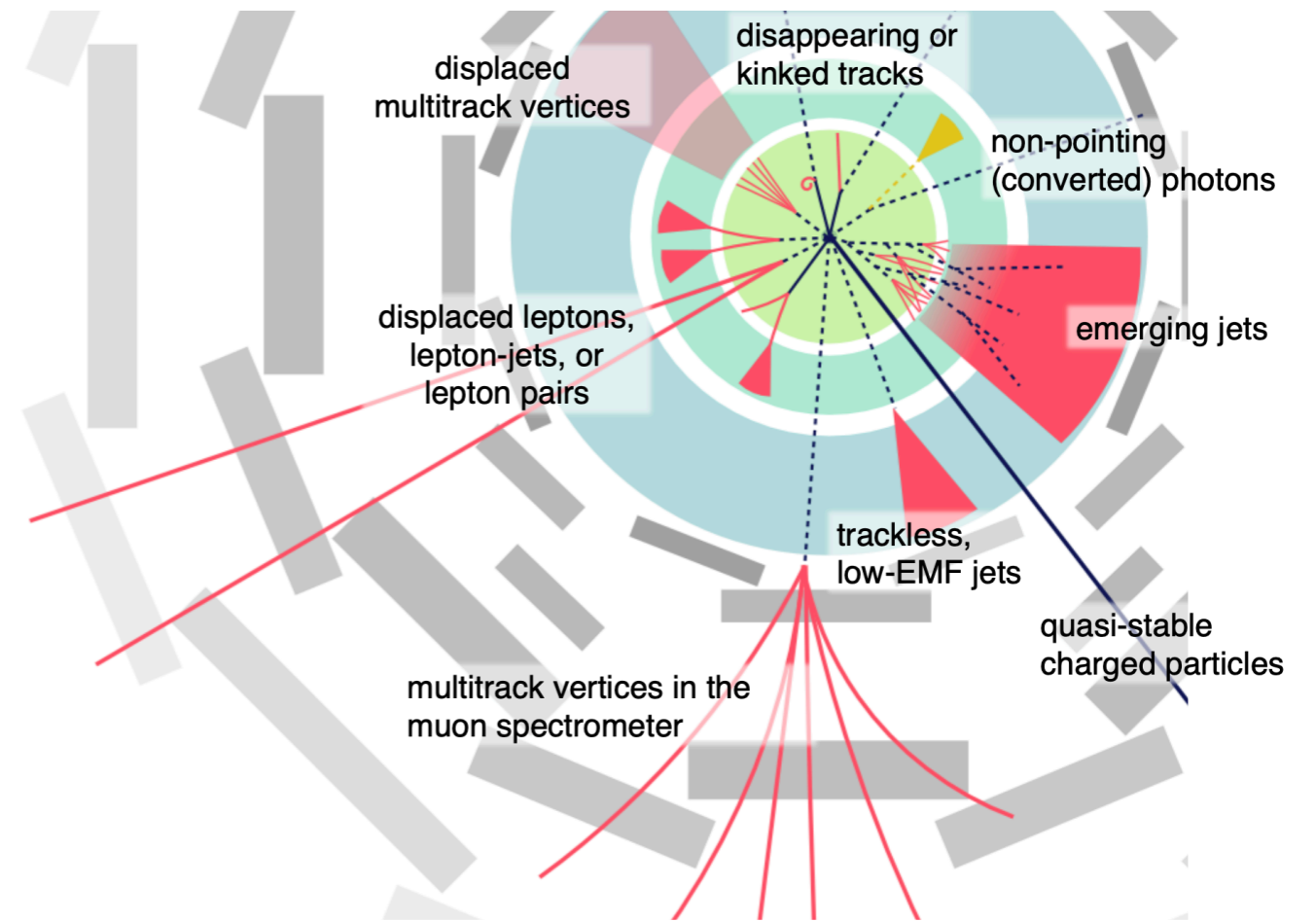
# Long-Lived Particle Results in CMS

**11th Large Hadron Collider Physics Conference  
Belgrade, 22-26 May, 2023**

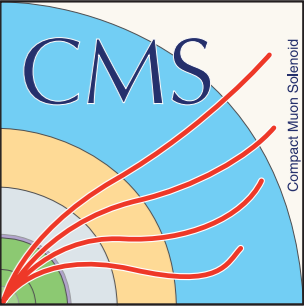
**Ang Li  
on behalf of the CMS Collaboration**

# Introduction

- Long-lived particles (LLPs) are theoretically well-motivated given a wide range of beyond-the-standard-model (BSM) physics that predict them
  - Approximate symmetries
  - Small couplings
  - Suppressed phase space
- The long lifetimes of LLPs create **unique signatures** in the detector
  - Harder to reconstruct
  - Removes most of the SM background
- Many searches focus on the long-lived signatures
  - Can be interpreted to different BSM theories



[[arXiv:1903.04497](https://arxiv.org/abs/1903.04497)]



# Recent CMS results

- Inelastic dark matter [[CMS-EXO-20-010](#)]
- Long-lived particles with delayed trackless jets [[arXiv:2212.06695](#)]
- Fractionally charged particles [[CMS-PAS-EXO-19-006](#)]
- Long-lived particles decaying to a pair of muons [[arXiv:2205.08582](#)]

# Inelastic dark matter

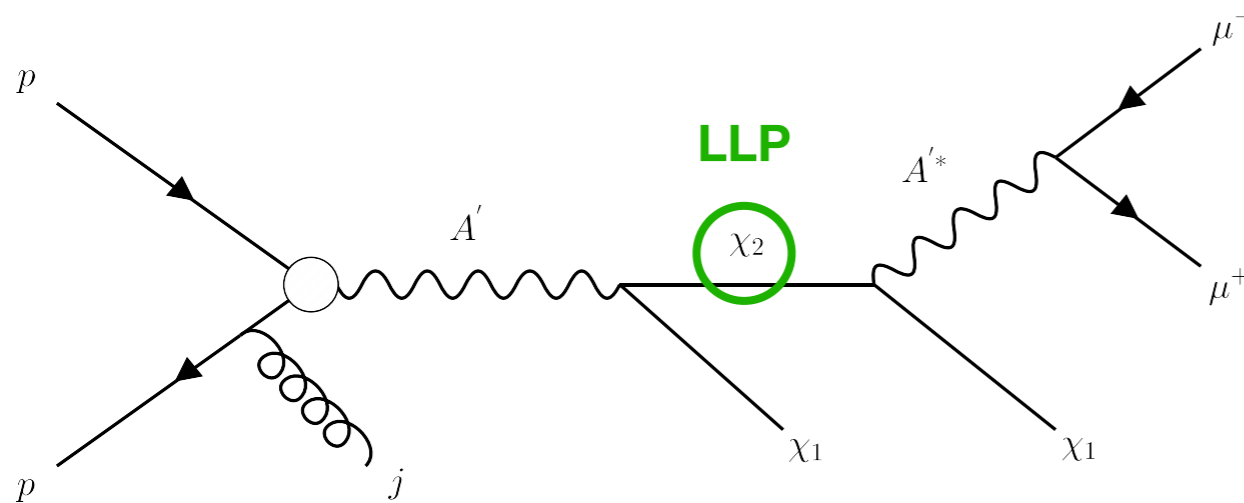
CMS-EXO-20-010

- **Dark matter off-diagonal interactions**
  - Interactions between different mass eigenstates  $\chi_1$  and  $\chi_2$
  - Small mass splitting between  $\chi_1$  and  $\chi_2$ 
    - **Compressed** scenario
    - **Long lifetime** of heavy state  $\chi_2$
- **Dark photon  $A'$  mix with  $\gamma/Z$ :  $\epsilon \rightarrow$  SM decay products**

$$y \equiv \epsilon^2 \alpha_D \left( \frac{m_1}{m_{A'}} \right)^4 \quad \text{Interaction strength}$$

↓

$$\Gamma_{\chi_2} \sim \frac{\epsilon \alpha_D \Delta^5}{m_{A'}^4} \quad \text{Lifetime}$$

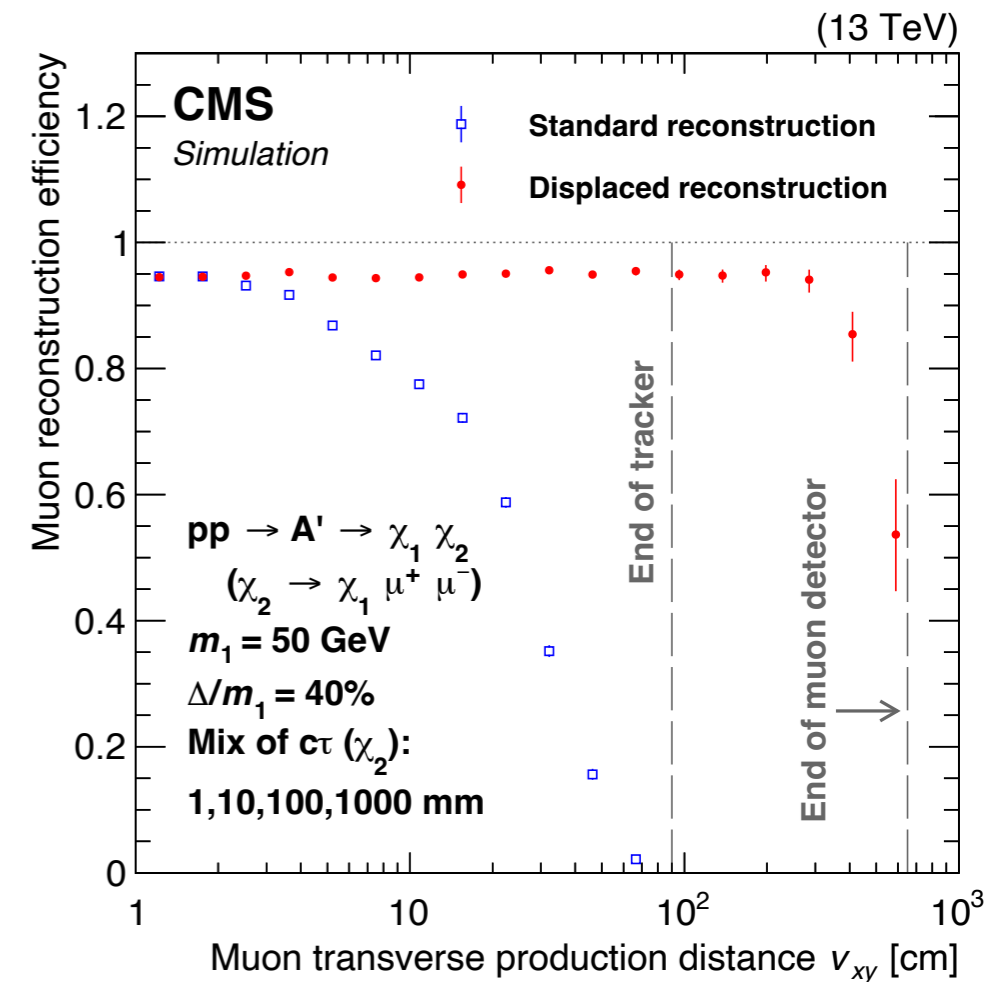
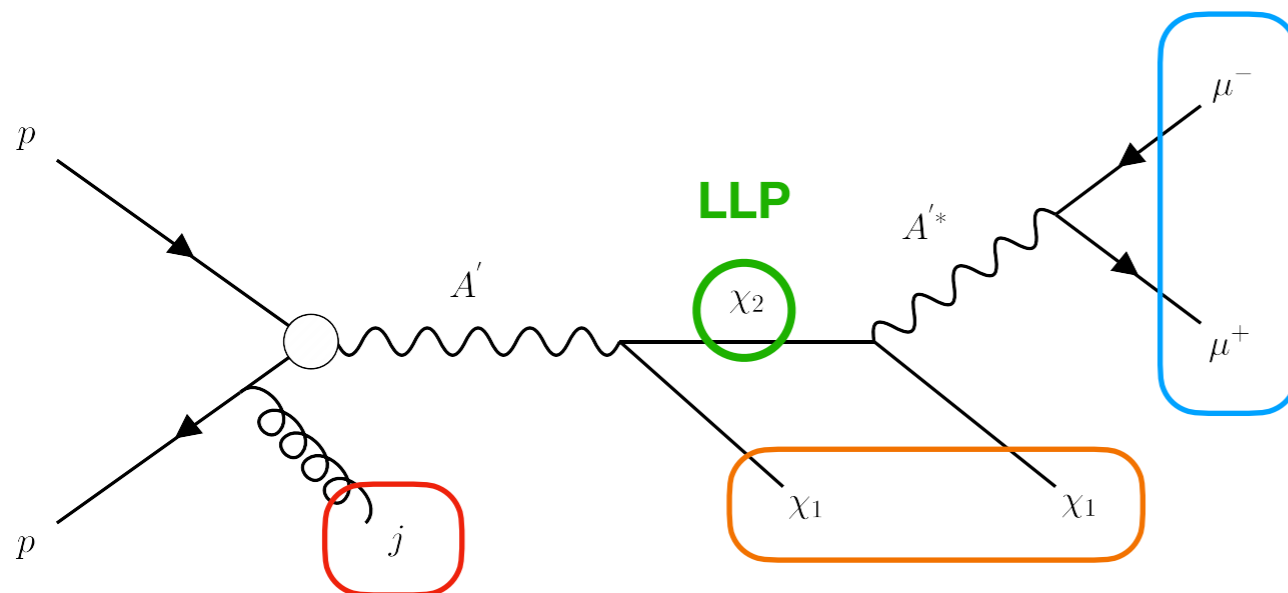


- $\chi_1$  mass:  $m_1$
- Mass splitting:  $\Delta$
- $\chi_2$  lifetime:  $c\tau$
- $A'$  mass:  $m_{A'} = 3m_1$
- Dark gauge coupling:  $\alpha_D$
- Kinematic mixing:  $\epsilon$

# Inelastic dark matter

CMS-EXO-20-010

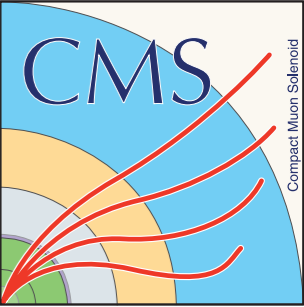
- First dedicated collider search for iDM
- Search for dark matter using **displaced muons**
- Signature:
  - ▶ Pair of soft, displaced, collimated muons
  - ▶ Significant MET collimated with muons
  - ▶ Energetic recoiling jet opposite DM system



## Dedicated displaced muon reconstruction (dSA)

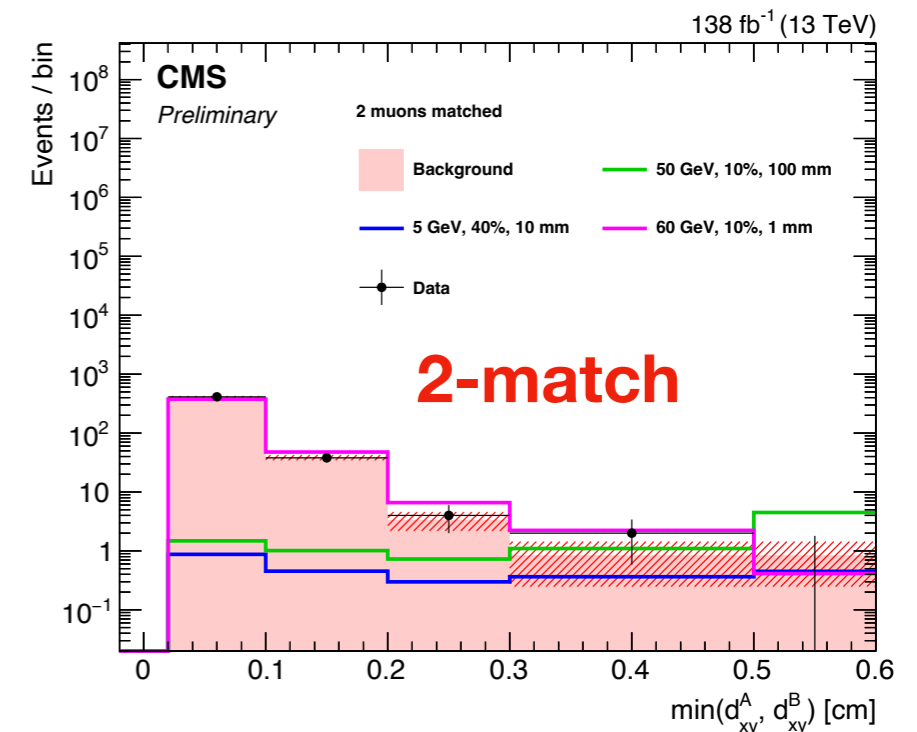
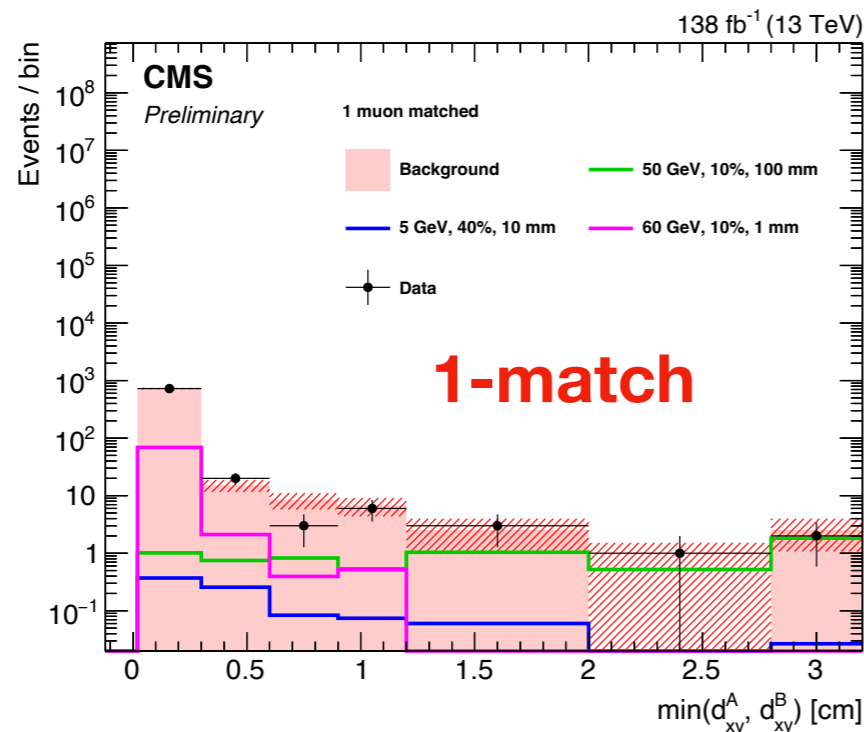
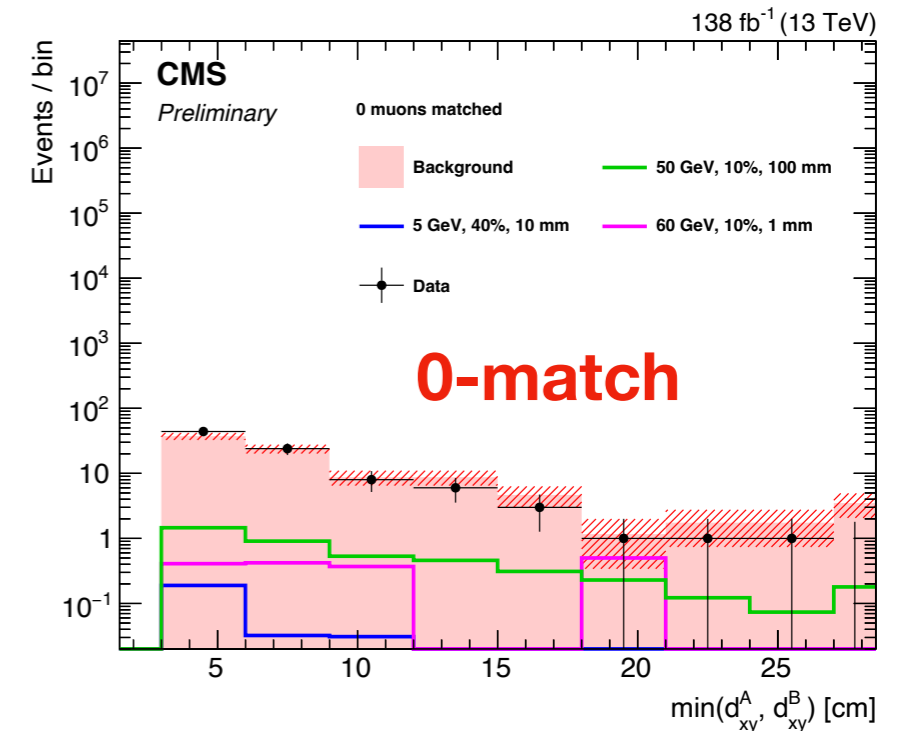
- High efficiency at large displacement
- Worse pt and dxy resolution

# Inelastic dark matter

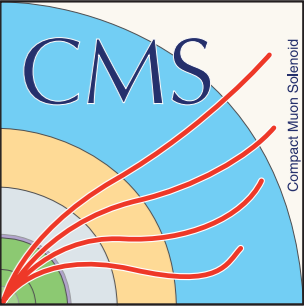


CMS-EXO-20-010

- Categorize events based on the **number of dSA matched with PF muons**
- **Data-driven background estimation using modified ABCD method**
  - ▶ **0-match:**  
**muon displacement** and **MET-dimuon collimation**
  - ▶ **1- and 2- match:**  
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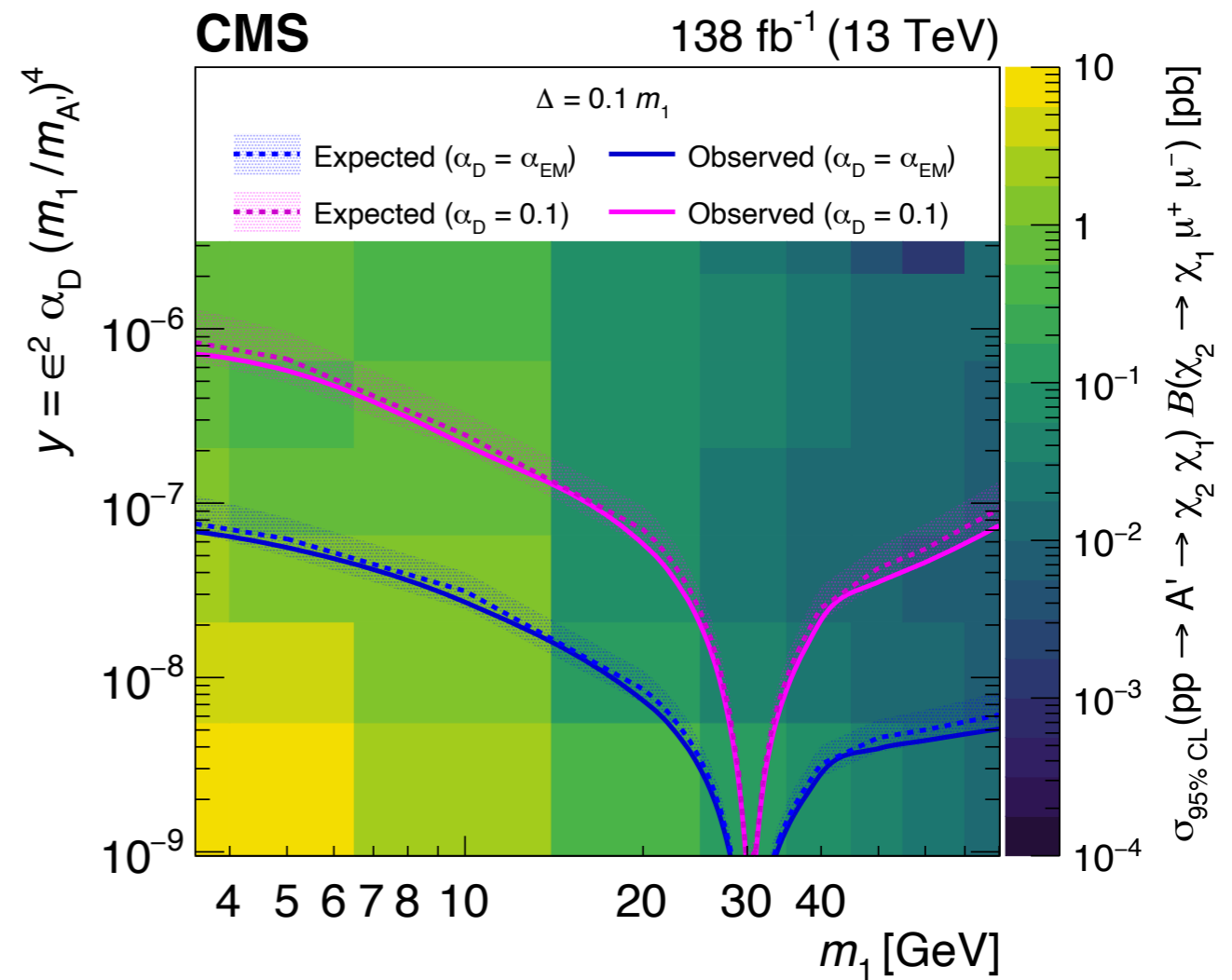
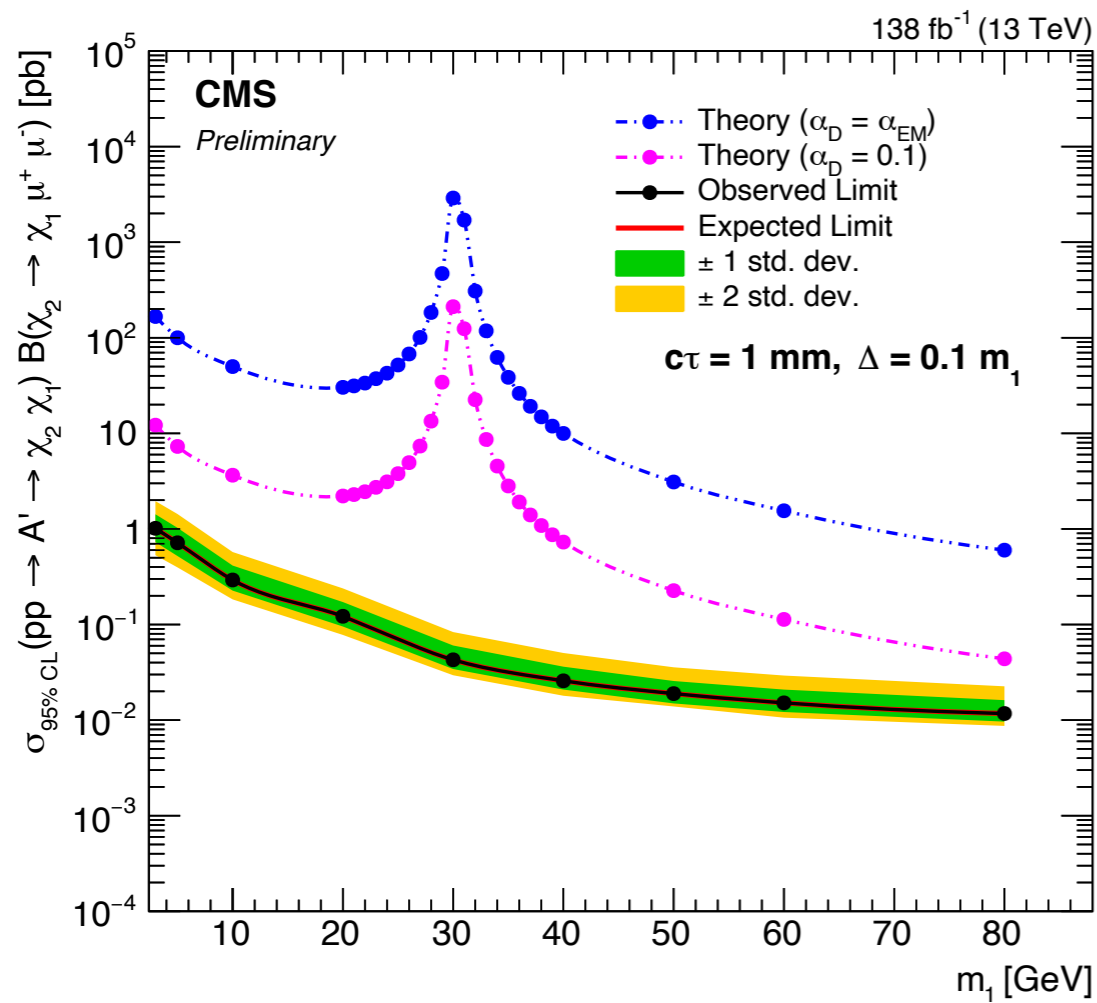


# Inelastic dark matter



CMS-EXO-20-010

- Limits on interaction strength  $y$  and lighter DM state  $m_1$



# LLPs with delayed trackless jets

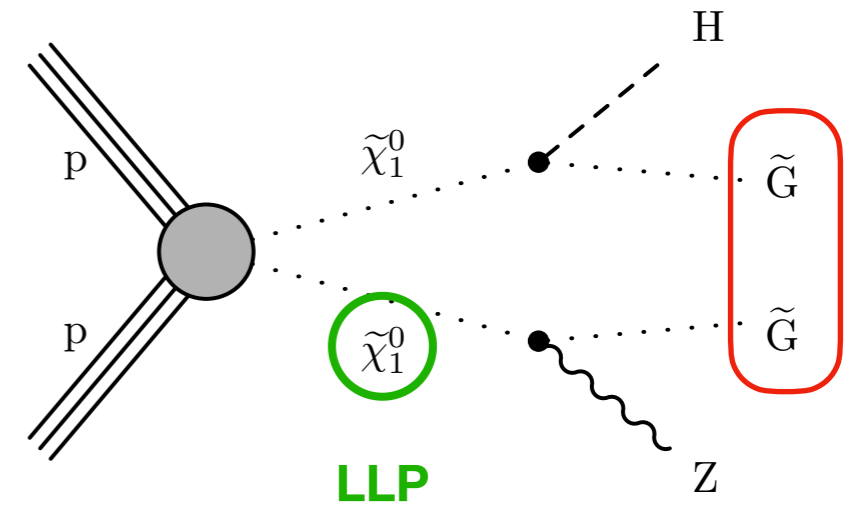
[arXiv:2212.06695](https://arxiv.org/abs/2212.06695)

- Search for long-lived GMSB SUSY

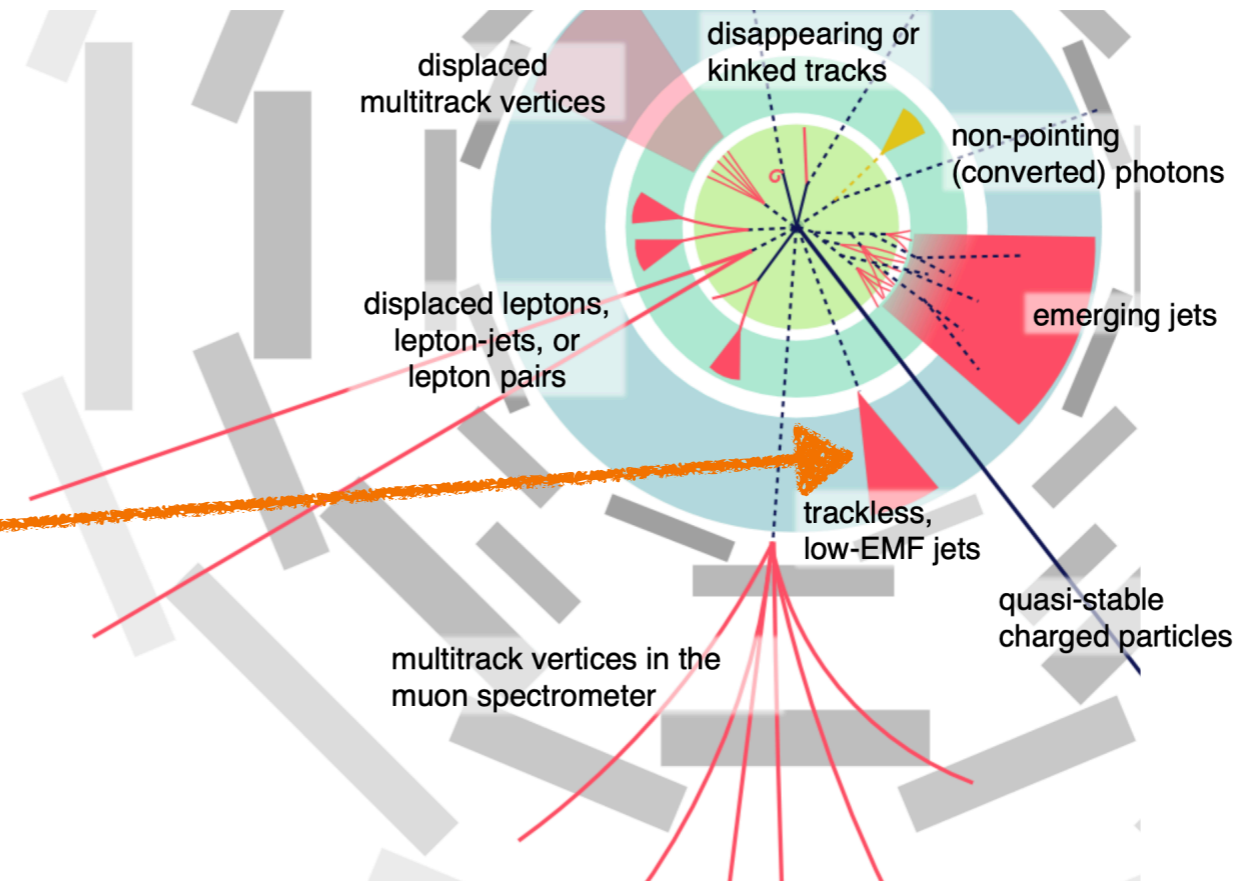
$$\chi \rightarrow H(Z) \rightarrow b\bar{b}(q\bar{q})$$

- Signature:

- ▶ MET
- ▶ Trackless and delayed jets



**Trackless jets**





# LLPs with delayed trackless jets

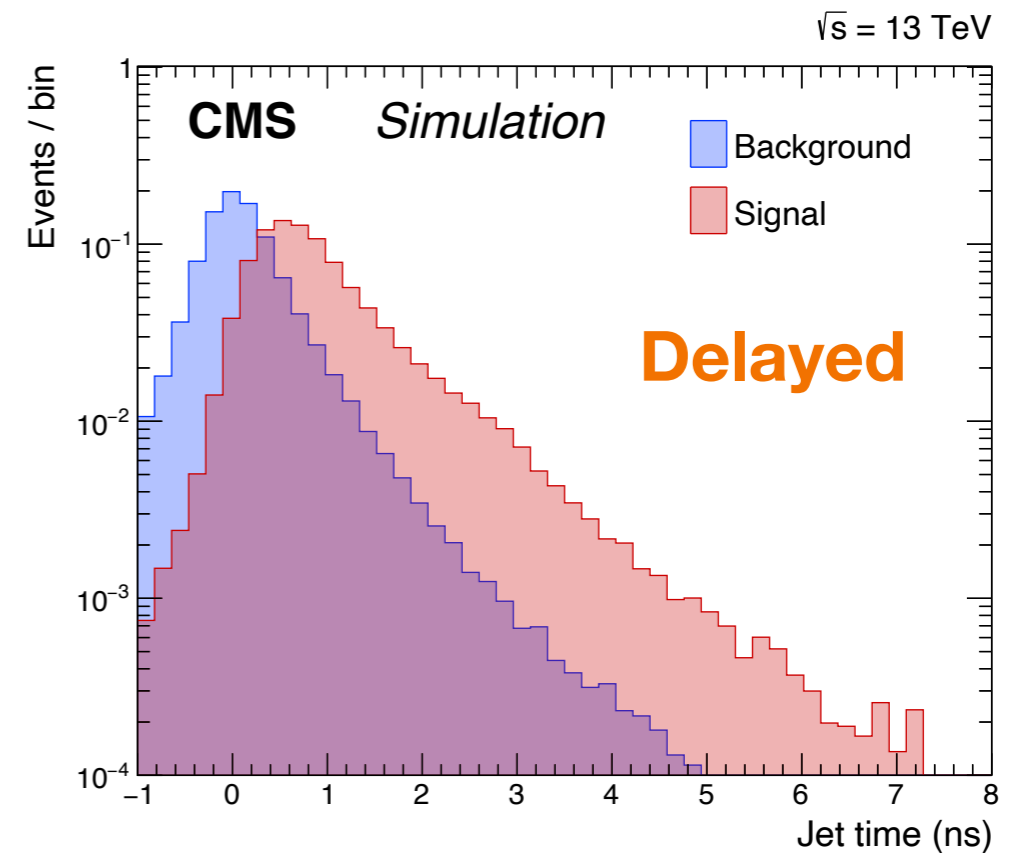
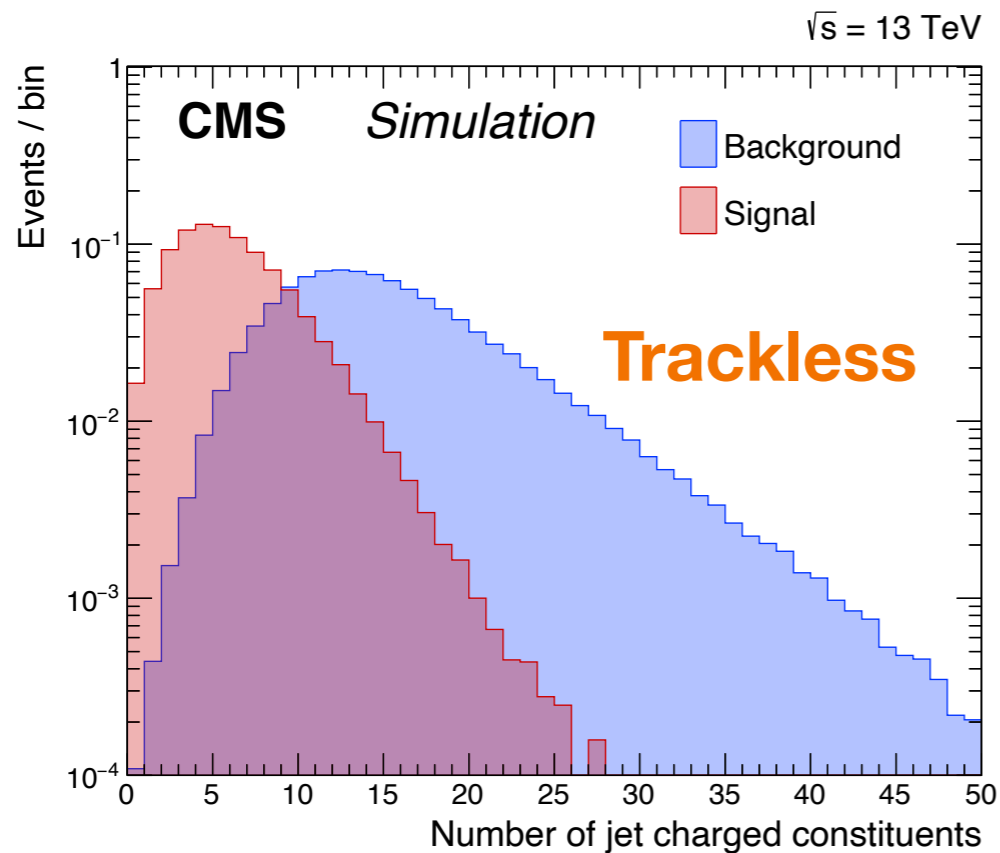
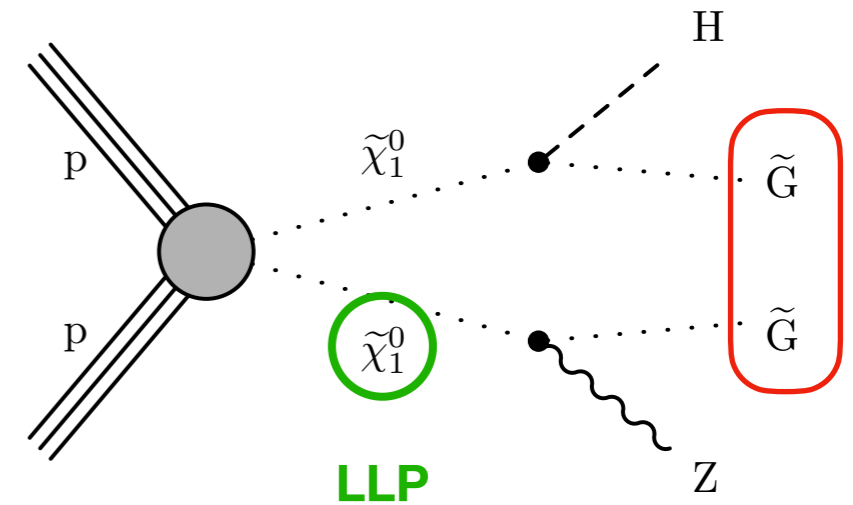
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- Signature:

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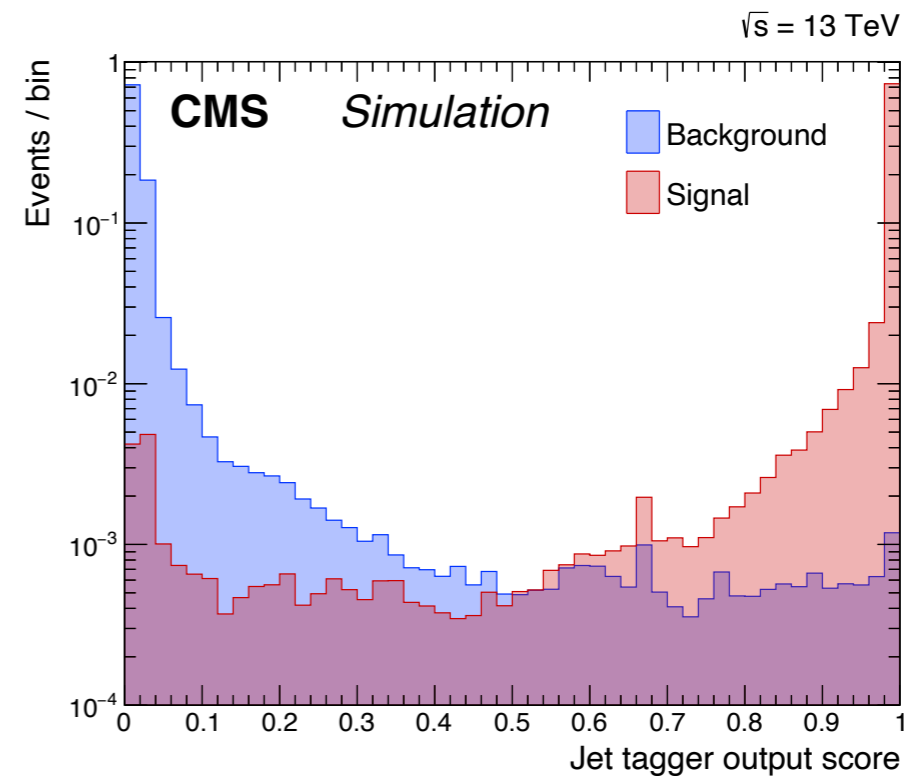


# LLPs with delayed trackless jets

[arXiv:2212.06695](https://arxiv.org/abs/2212.06695)

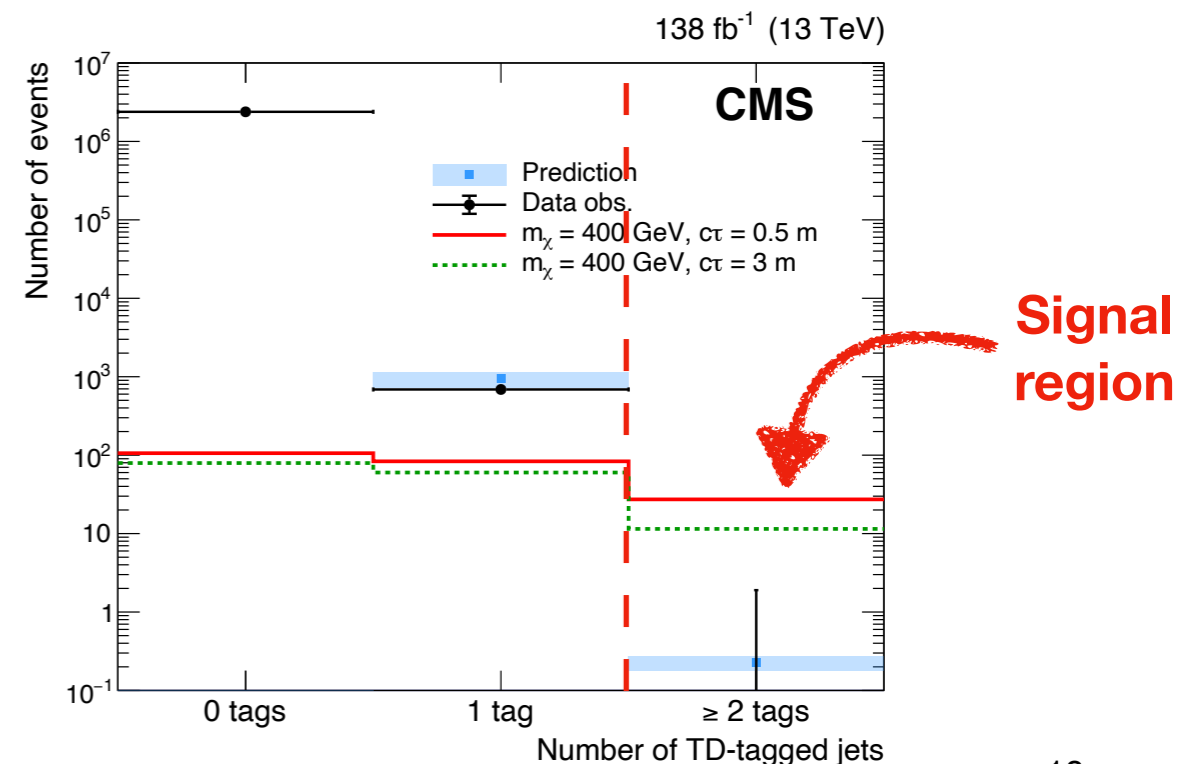
- **DNN jet tagger**

- ▶ Combine **timing information** from ECAL with **track information**
- ▶ 82% signal efficiency at background rejection  $4 \times 10^{-4}$

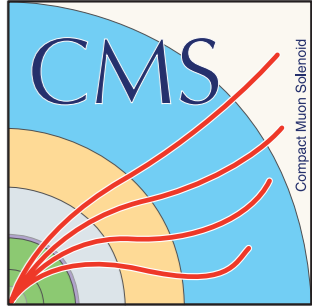


- **Signal region:**  $n_{tags} \geq 2$

- **Estimate background using mistag rate measured in lepton + jet control region**

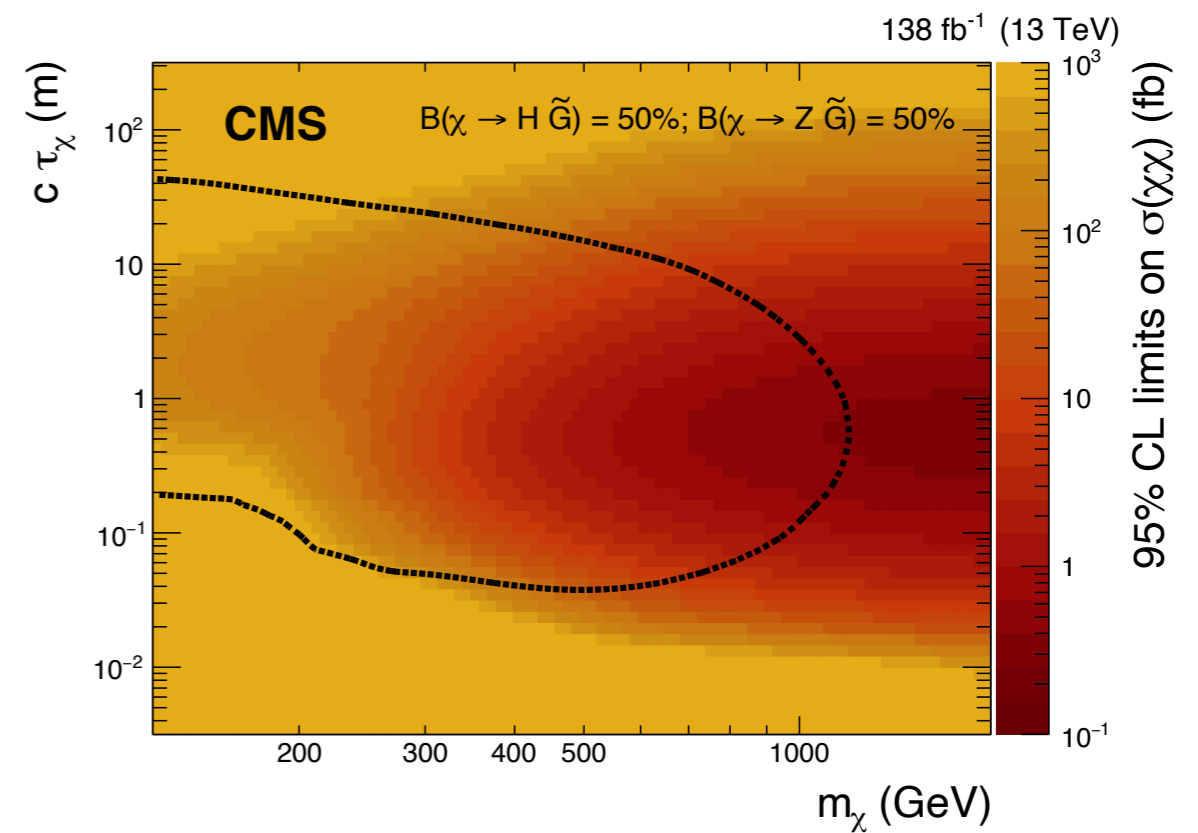
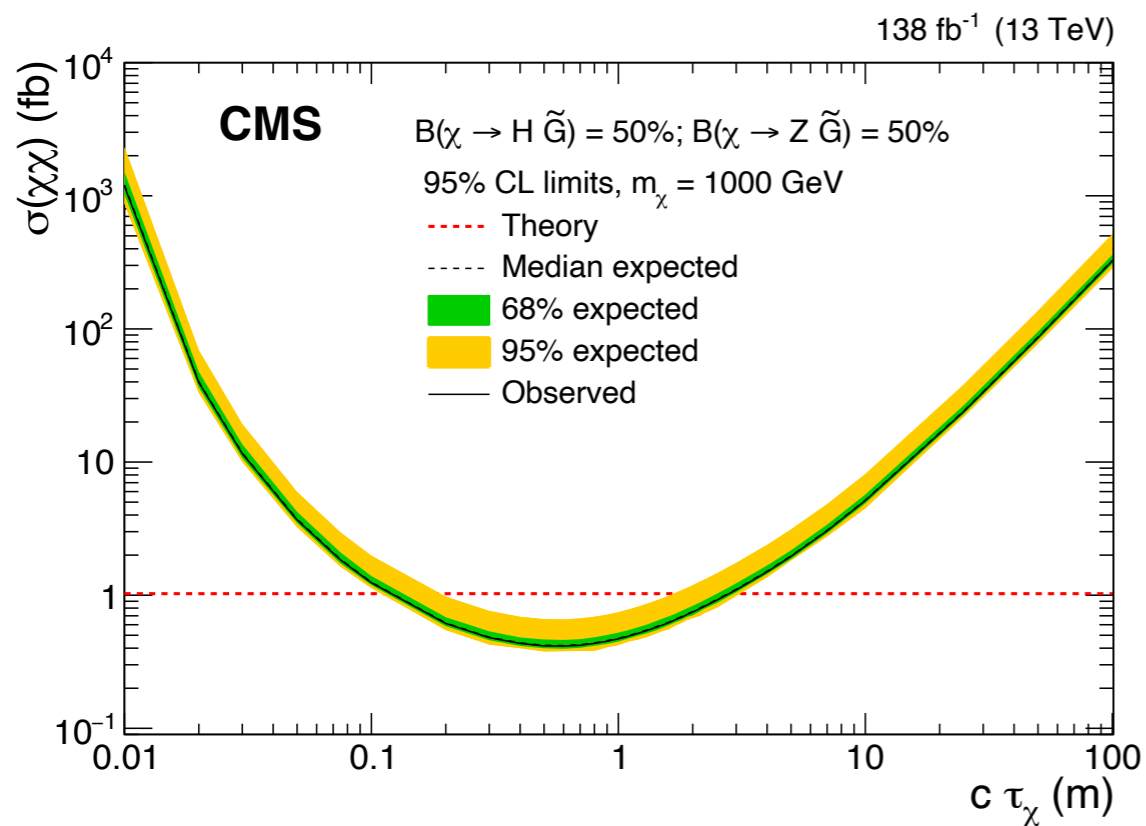


# LLPs with delayed trackless jets



[arXiv:2212.06695](https://arxiv.org/abs/2212.06695)

- Upper limit set on  $m_\chi$  and  $c\tau$
- Exclude  $m_\chi$  up to 1.18 TeV (990 GeV) at  $c\tau_0 = 0.5$  (3.0) m



# Fractionally charged particles

[CMS-PAS-EXO-19-006](#)

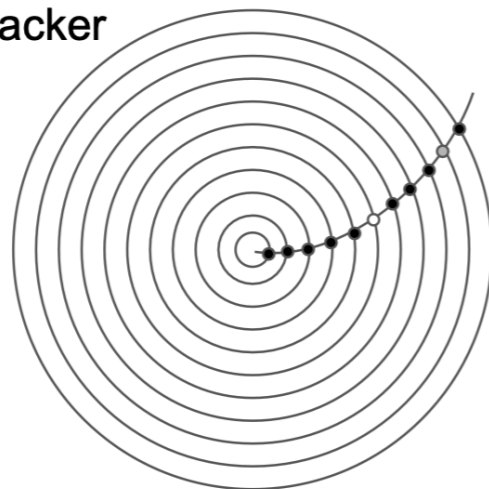
- Low charge particles -> less energy deposited in the tracker

$$-\left\langle \frac{dE}{dx} \right\rangle = K Q^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \left( \frac{2m_e (c\beta\gamma)^2 T_{max}}{I^2} \right) - \beta^2 \right]$$

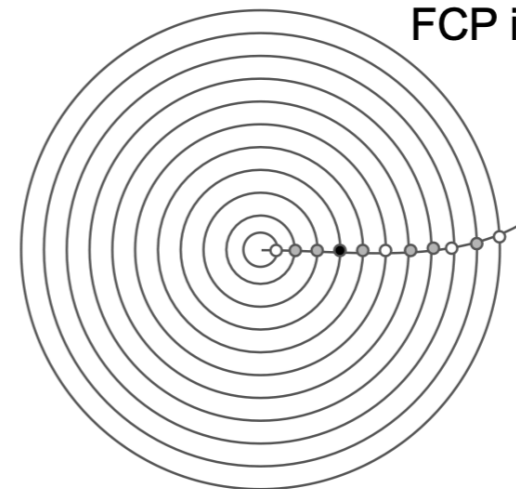
- Signature:

- Tracks with large number of **low dE/dx hits**

Muon in silicon tracker



FCP in silicon tracker

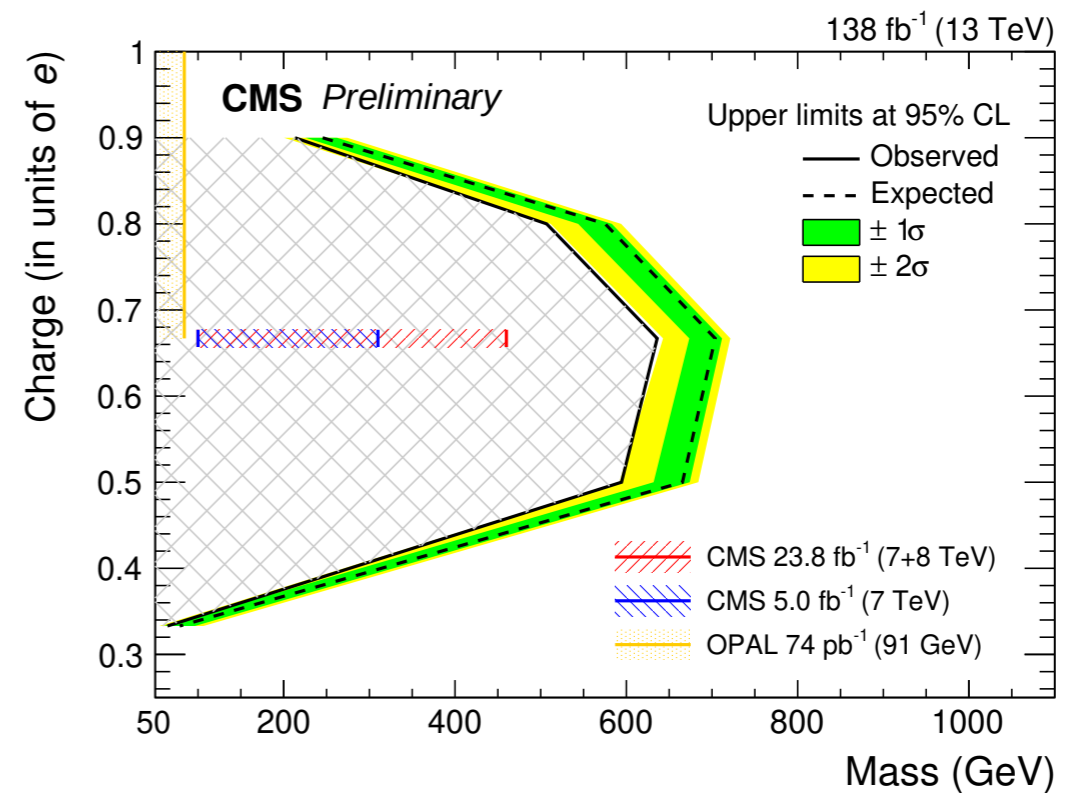
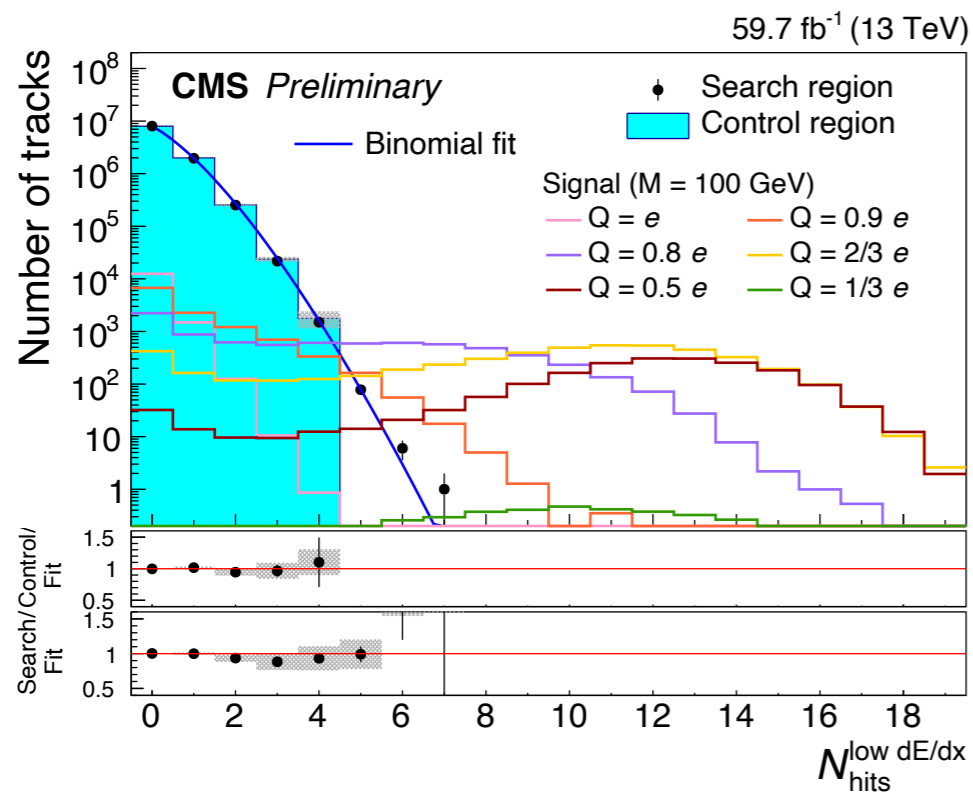


- Hit from significant energy loss:  $dE/dx > 3 \text{ MeV/cm}$
- Hit from feeble energy loss:  $dE/dx < 3 \text{ MeV/cm}$
- Missing hit:  $dE/dx \ll \text{threshold}$

# Fractionally charged particles

CMS-PAS-EXO-19-006

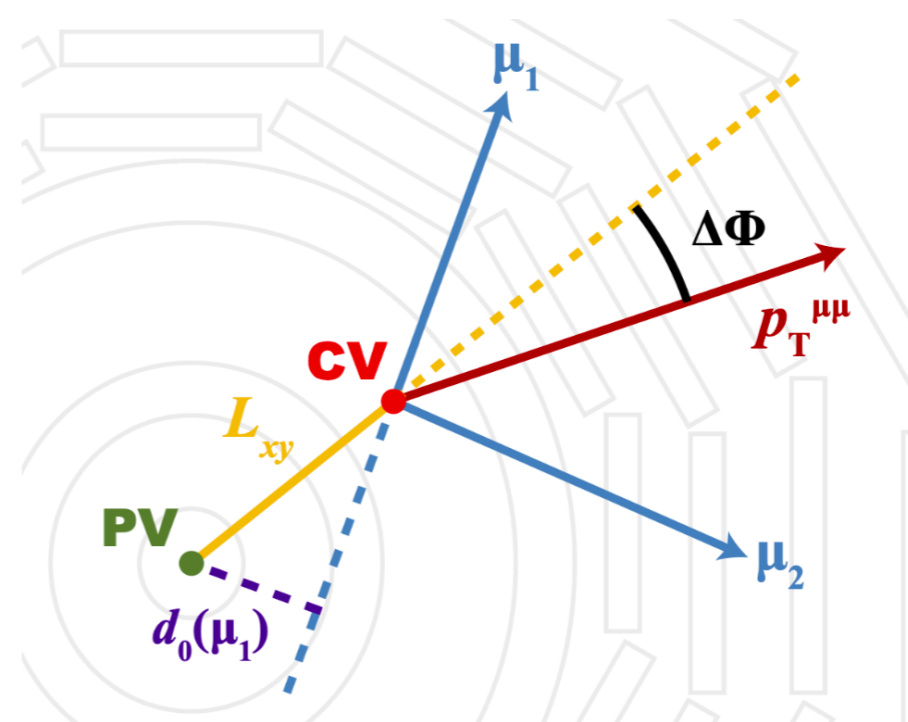
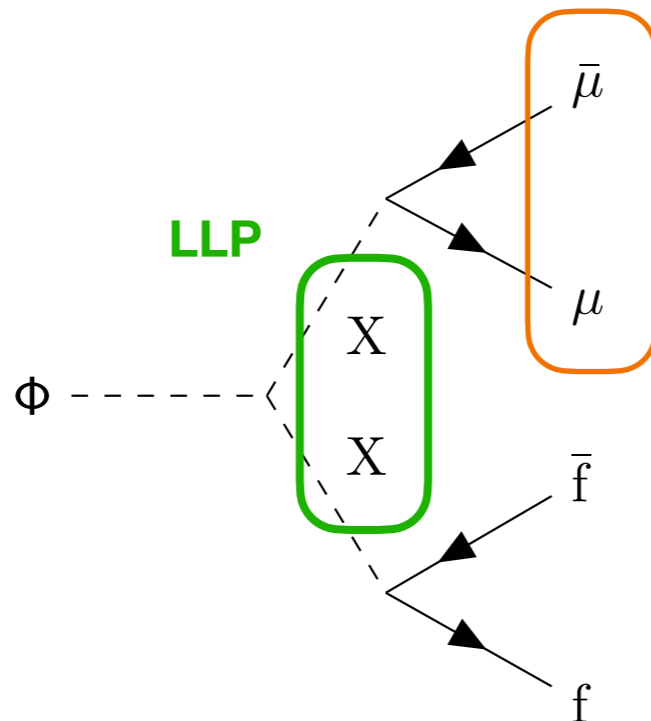
- **Signal selection:**
  - Events with 1 track or 2 tracks with  $m < 80$  GeV or  $m > 100$  GeV
- **Estimate background by fitting  $N_{hits}^{low dE/dx}$  distribution using events dominated by **Z boson candidates****
- **The best limits on this particular new-physics signature in the considered phase space**



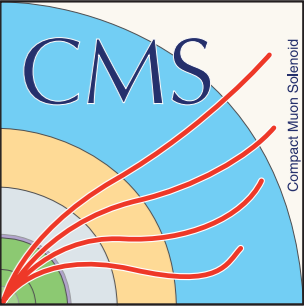
# LLPs decaying to a pair of muons

[arXiv:2205.08582](https://arxiv.org/abs/2205.08582)

- **Signature: displaced dimuons**
  - Large displacement:  $L_{xy}$ ,  $d_0$
  - $\Delta\Phi$  between the  $L_{xy}$  vector and dimuon  $p_T$  near 0
- **Customized trigger** that looks for two moderate  $p_T$  muons
- Use both **track based muons (TMS muon)** and **muon system based muons (STA muon)**

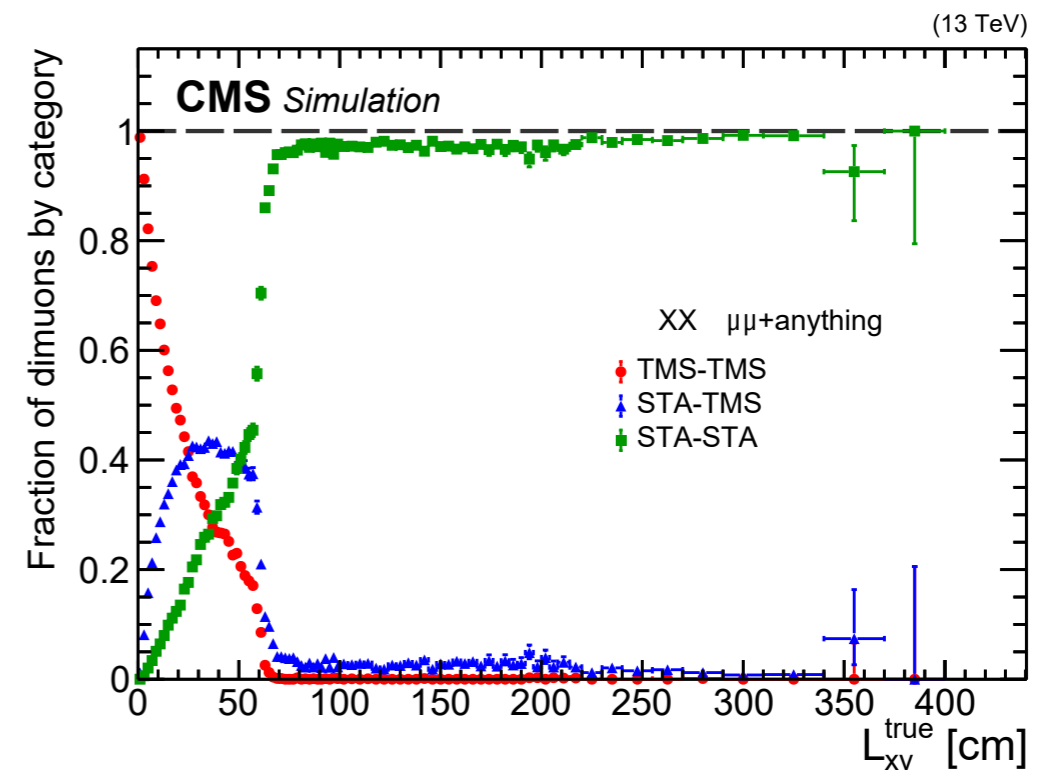
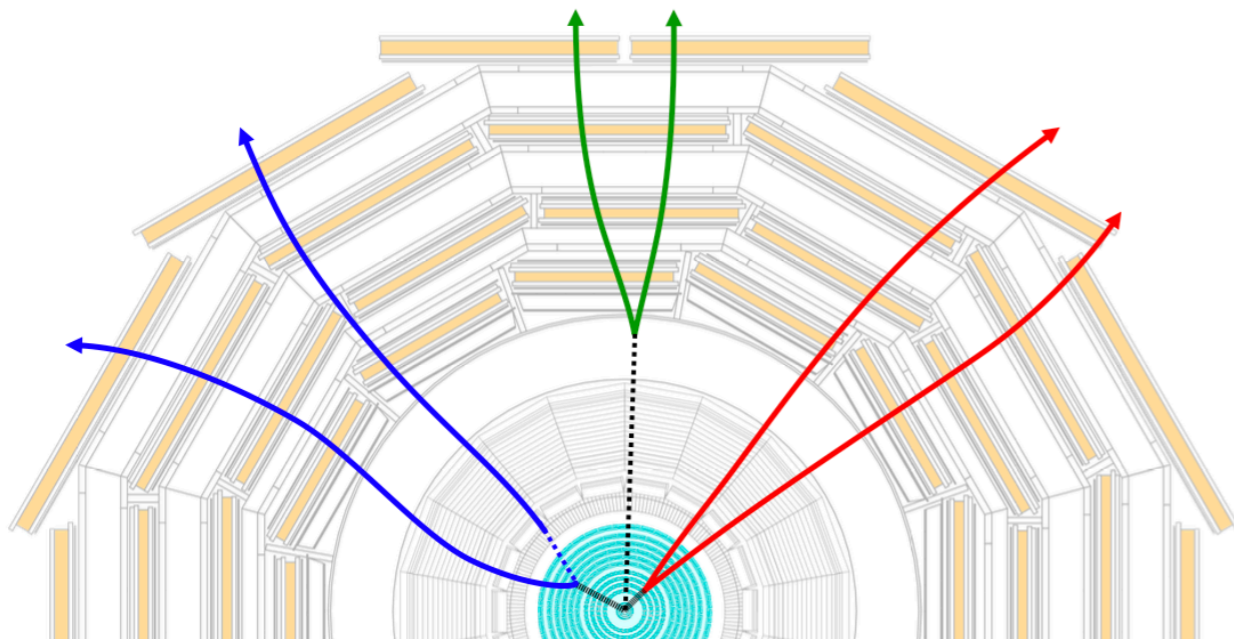


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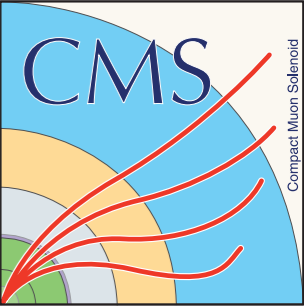


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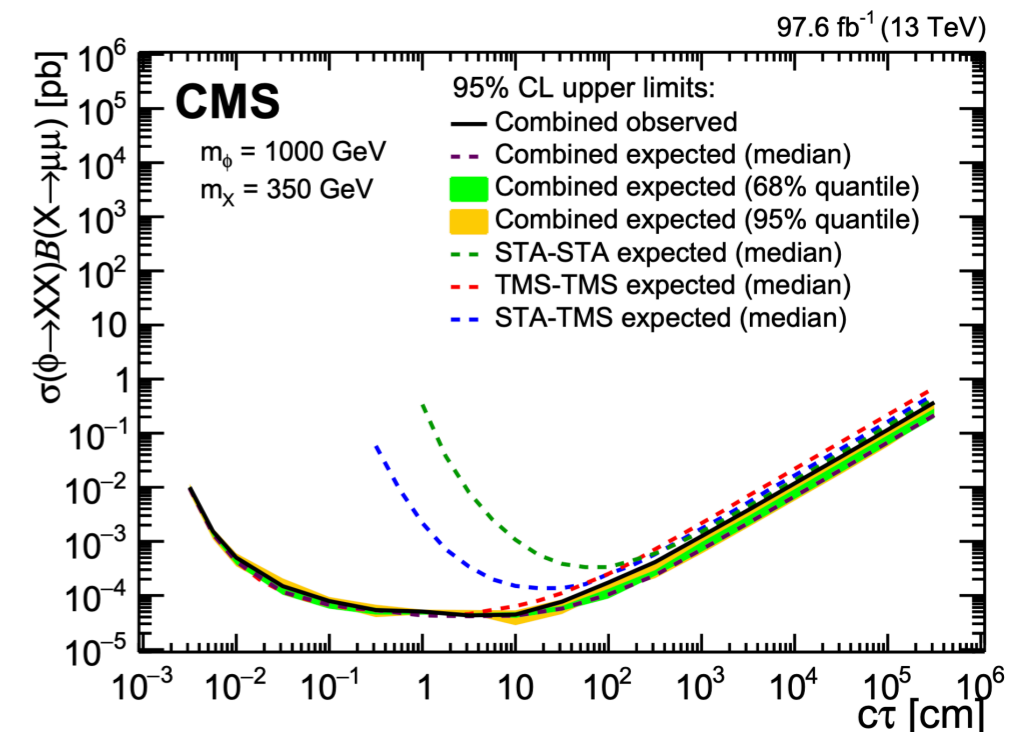
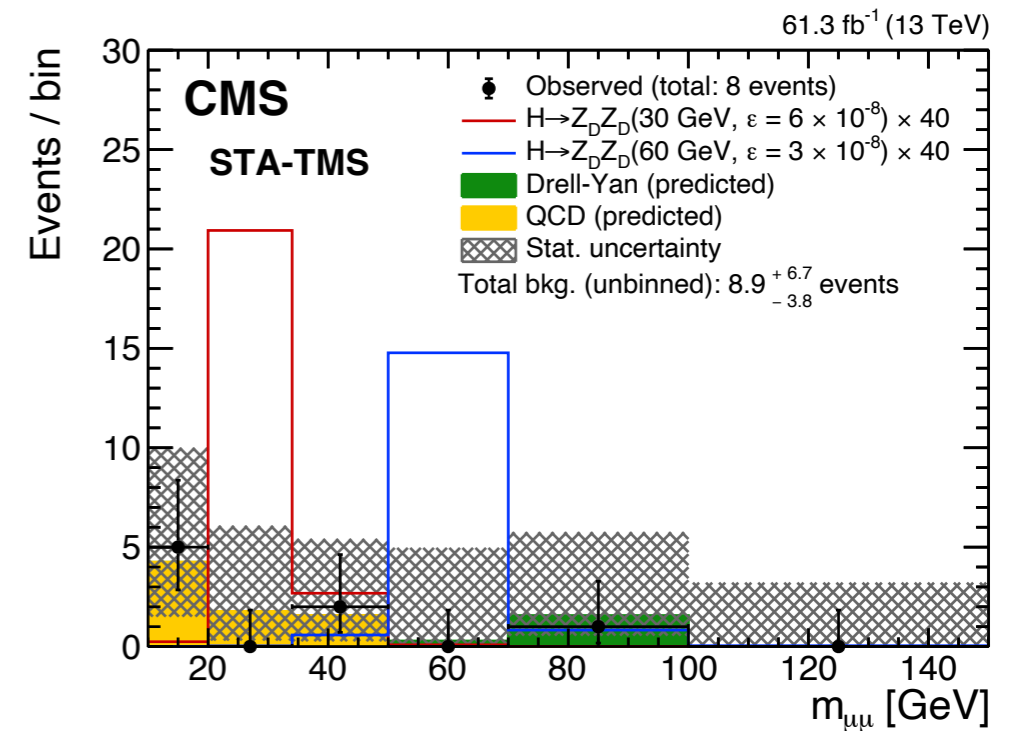


# LLPs decaying to a pair of muons



arXiv:2205.08582

- Background results from instrumental/reconstruction mistakes
- Data-driven background estimation based on ABCD method
  - Regions defined based on  $\Delta\Phi$  and whether the dimuon is same-sign or opposite-sign
- Sensitive to a broad range of  $c\tau$  from 30  $\mu\text{m}$  to more than 1 km
- Smallest value excluded is 0.05 fb, at  $m_X = 350$  GeV and  $c\tau$  between 0.3 and 30 cm





# Summary

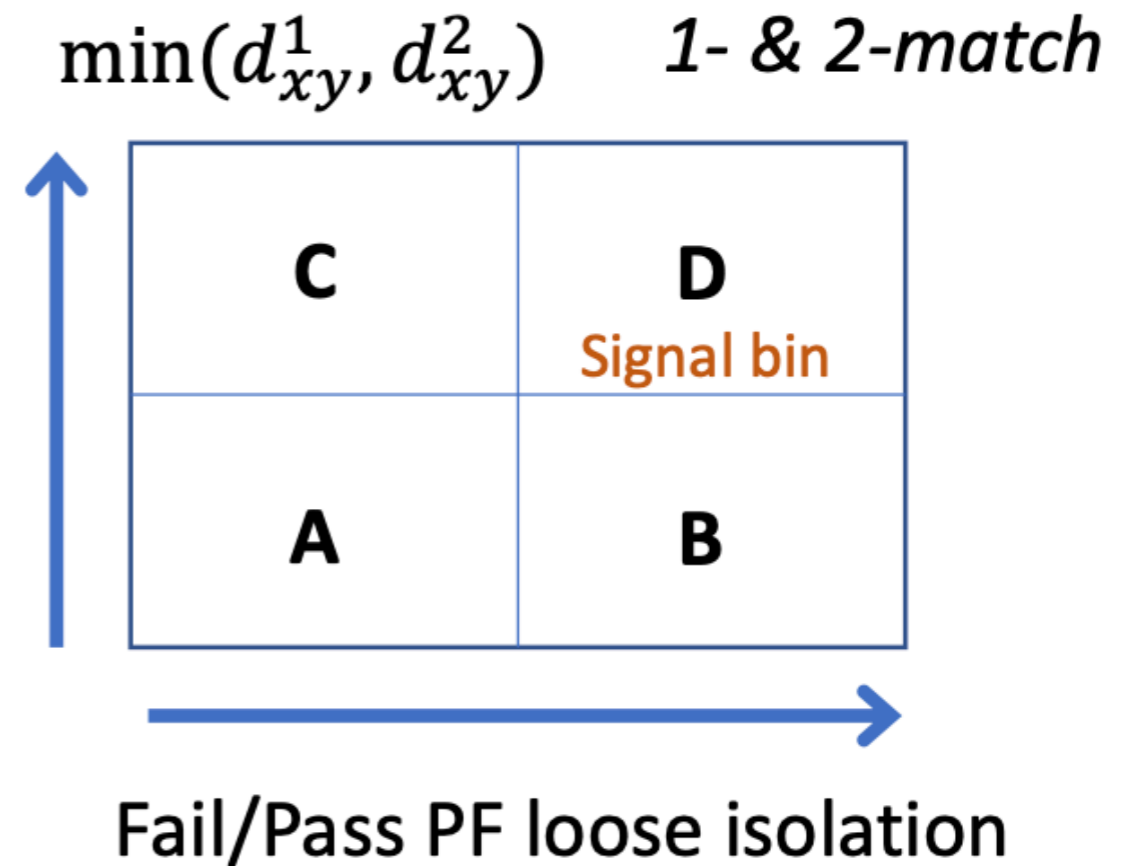
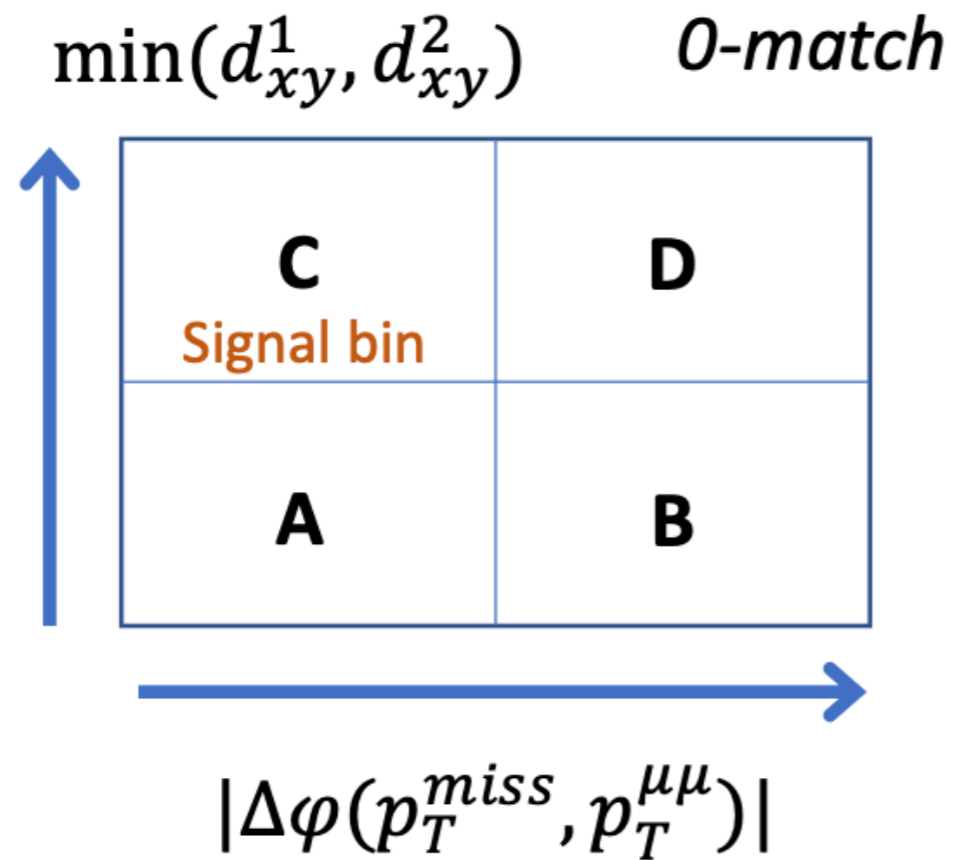
- LLPs are **well-motivated** and **challenging** to search for
- **Many CMS searches target LLPs**
  - Explored a variety of **long-lived signatures**
  - Can be **reinterpreted** into new physics theories
- **Opportunities is waiting ahead**
  - More **signatures** and **techniques** to be explored
  - More **data** to be analyzed in Run 3 and HL-LHC
  - New **triggers** and **detectors** dedicated for LLP searches

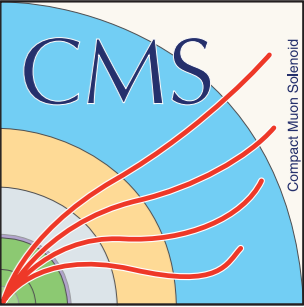
**Thanks!**

**Backup**

# Inelastic dark matter

- ABCD regions

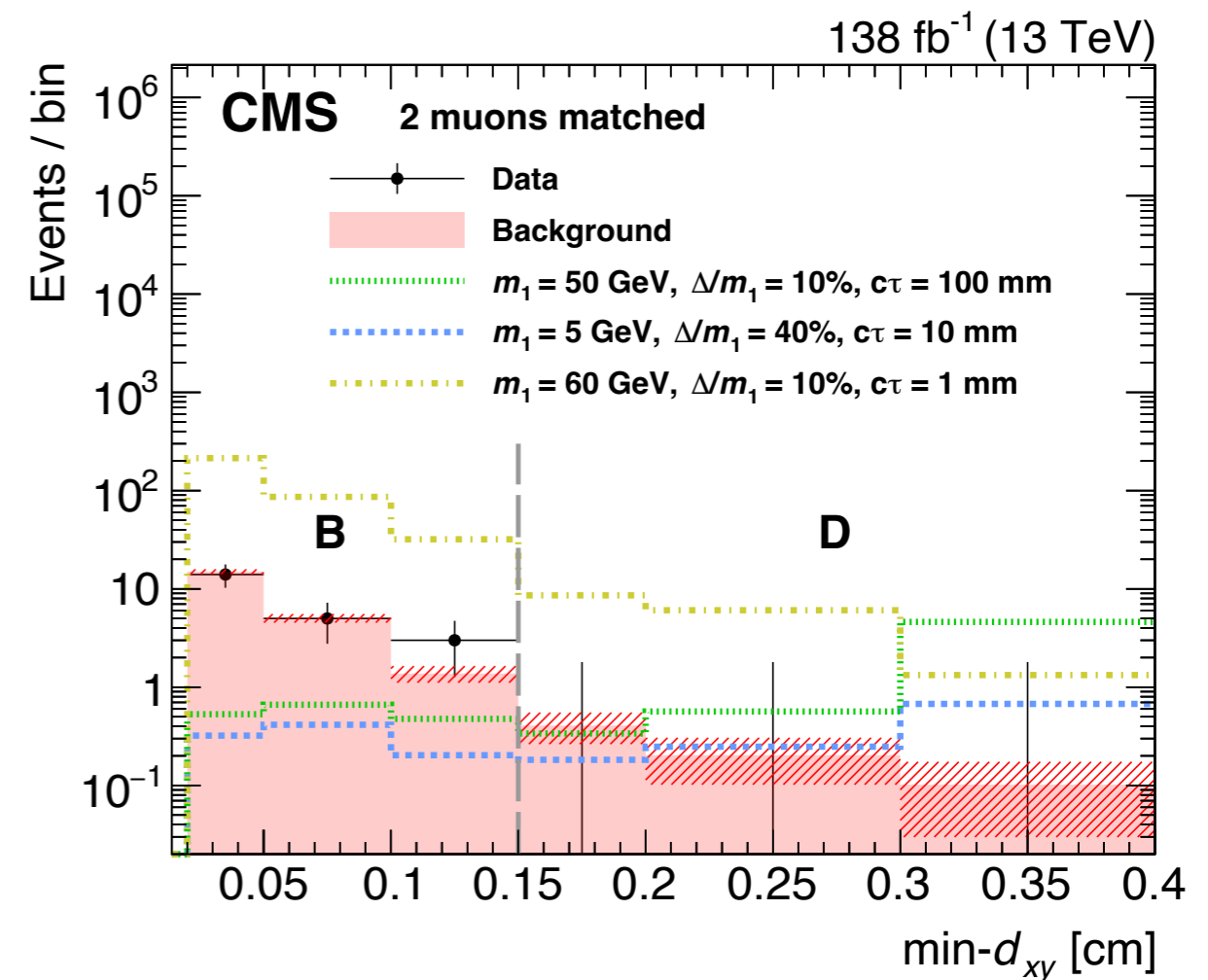


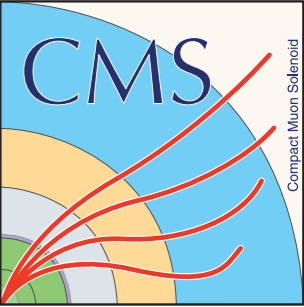


# Inelastic dark matter

CMS-EXO-20-010

- Categorize events based on the **number of dSA matched with PF muons**
- **Data-driven background estimation using modified ABCD method**
  - ▶ **0-match:**  
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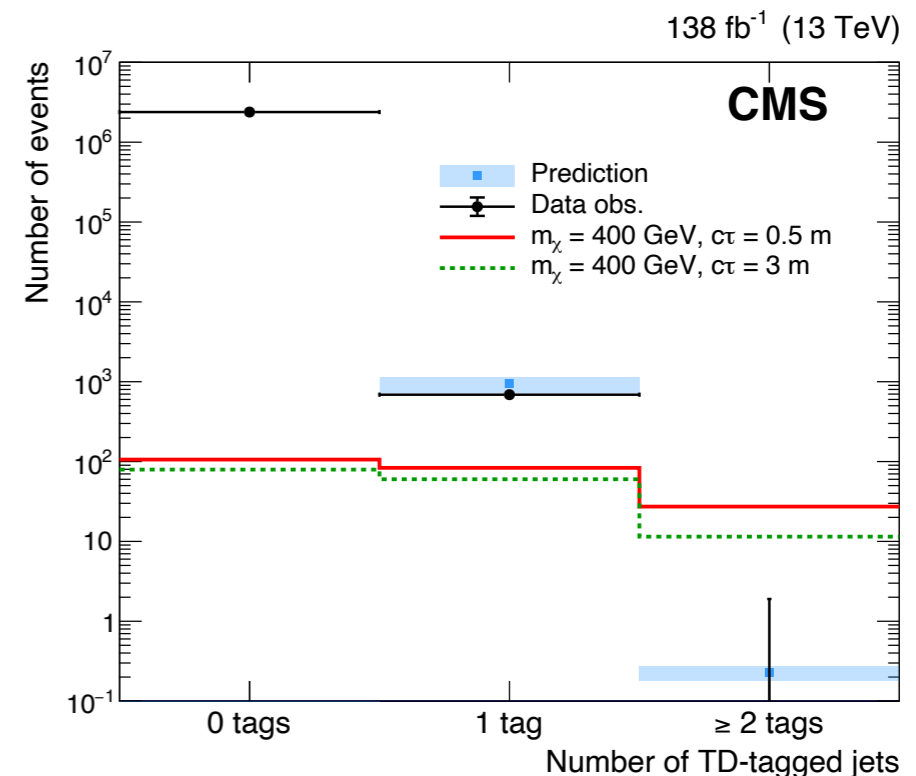
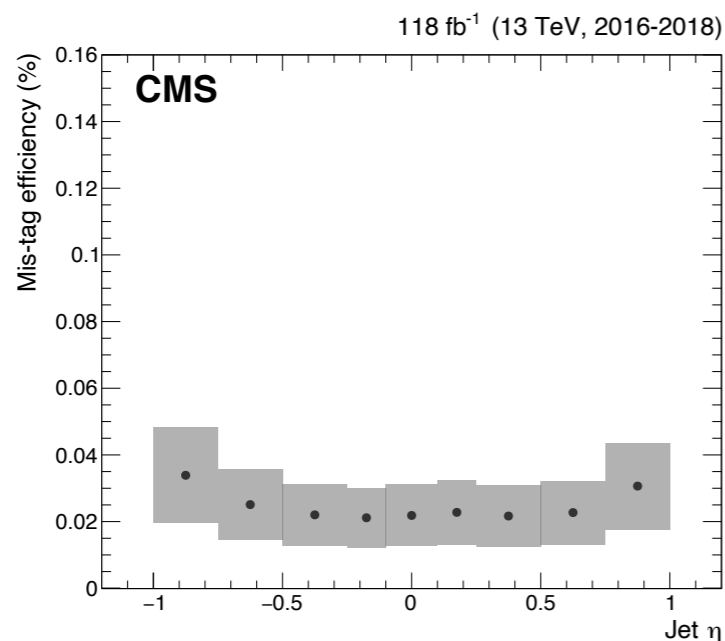
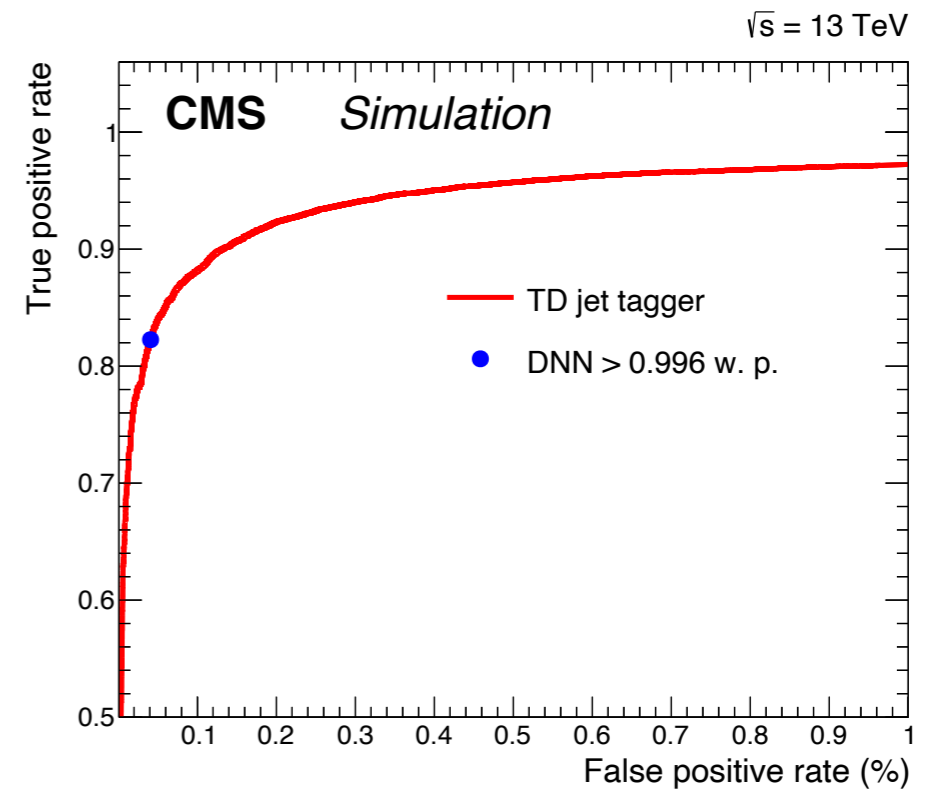




# LLPs with delayed trackless jets

- **ROC curve of the DNN**
- **Measure mistag rate in the region dominated by  $W \rightarrow l\nu$** 
  - 1 isolated signal lepton
- **Background prediction**

$$p_2 = \sum_{i \in \text{untagged } j \text{ bin } 1} \epsilon(\eta_i | 1 \text{ } j \text{ tagged})$$
- **Non-collision background:**
  - Contribute to trackless jets, out of time -> high DNN score
    - Cosmic muons
    - Beam halo



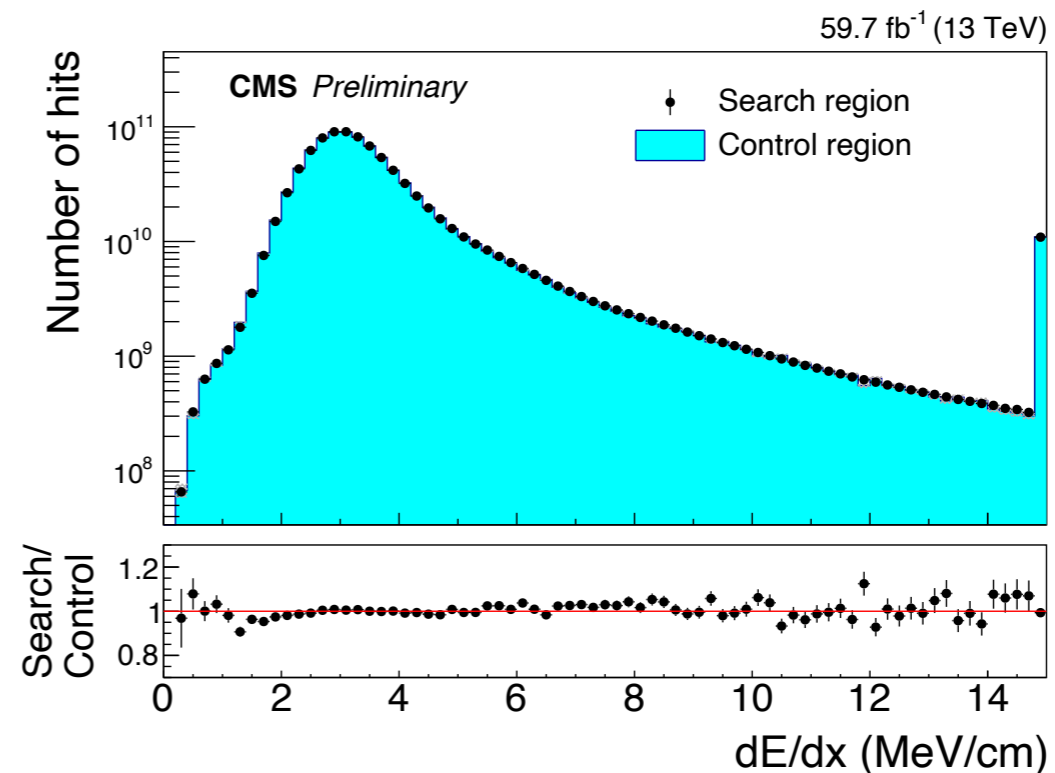
# Fractional charged particles

- Bethe relation -> energy deposit related to charge

$$-\left\langle \frac{dE}{dx} \right\rangle = K Q^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \left( \frac{2m_e (c\beta\gamma)^2 T_{max}}{I^2} \right) - \beta^2 \right]$$

- Region definition:

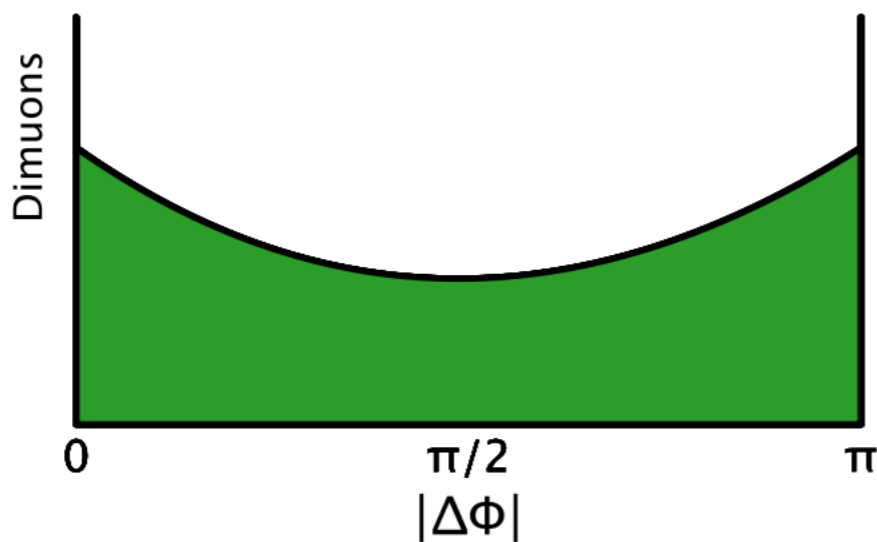
- ▶ Search region: events with one track or two tracks with invariant mass smaller than 80GeV or greater than 100GeV
- ▶ Control region: events with two tracks with invariant mass in 80-100GeV -> dominate by Z boson candidates



# LLPs decaying to a pair of muons

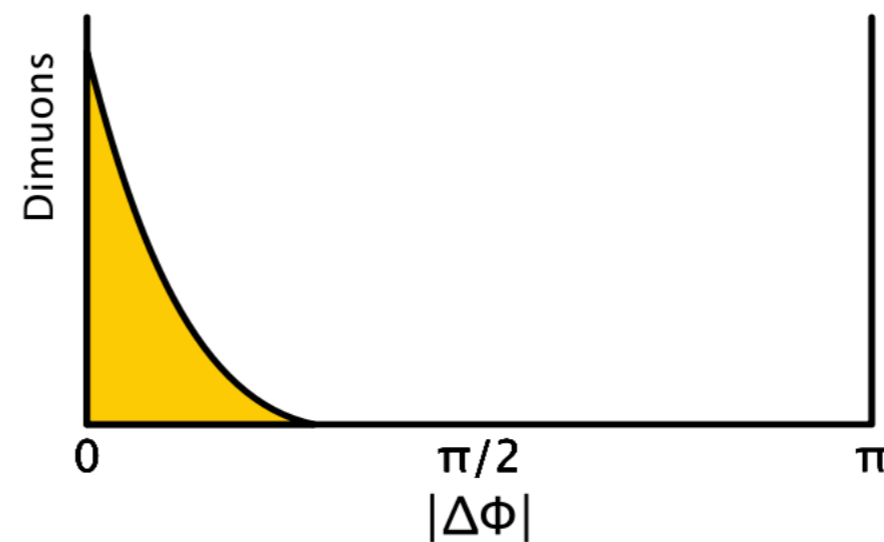
## Symmetric

- Mismeasured (**prompt**) Drell-Yan (DY),  $t\bar{t}$ , dibosons...
- Cosmic ray muons
- Unrelated jets /  $W$  + jets

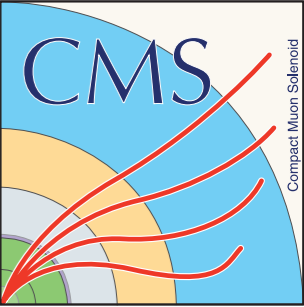


## Asymmetric

- Mismeasured low-mass **non-prompt** resonances (e.g.  $J/\Psi$ )
- Cascade decays resulting in 2+ muons (e.g. from  $B$  mesons)







# LLPs decaying to a pair of muons

- Background estimation

