# Recent Results on Long-Lived Particles with (Semi)Leptonic Final States in CMS

**LHCP2024 Conference, Boston**

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On behalf of the CMS collaboration

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# Context

- **Long-lived particles (LLPs)** produced at the LHC travel a macroscopic distance before decaying
    - Unique experimental signature, ideal as a **probe for new physics**
    - Several **experimental challenges**: trigger, event reconstruction, background estimation,…
- LLPs are predicted by many extensions of the SM

| **Neutrino sector** | **Hidden Sector** | **SUSY sector** | … |
|---|---|---|---|
| Neutrino minimal SM, … | Hidden Abelian Higgs, Dark showers, … | R-parity violating SUSY, … | |

- Different types of particles in the final state: both hadronic and leptonic signatures in the CMS detector
- Different approaches: model-dependent and inclusive searches

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- Different types of particles in the final state: both hadronic and leptonic signatures in the CMS detector
- Different approaches: model-dependent and inclusive searches

**In this talk**:
- Overview of (semi)leptonic LLP searches (at least one lepton from the LLP decay)
- Focus on inclusive approaches

*See the [talk from R. Haberle] for an overview of LLP searches with hadronic final states*

# LL HNLs with Semileptonic Final States

**Model-dependent analyses:** Heavy Neutral Lepton (HNL) Searches

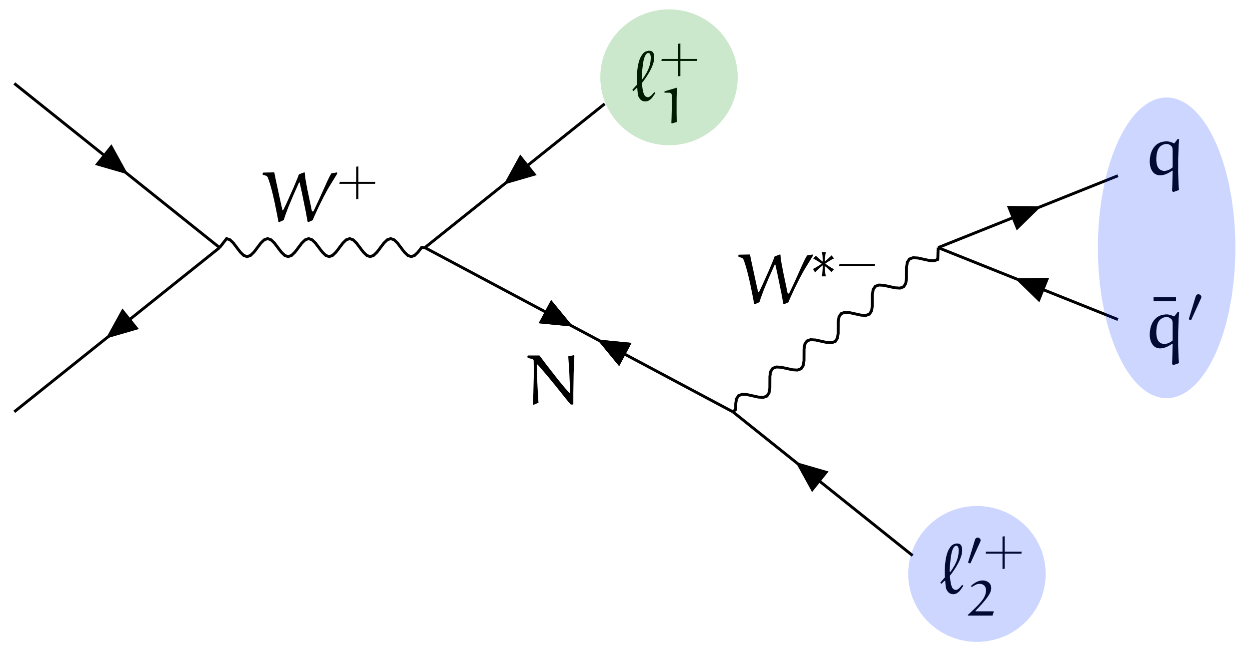
- Target: **long-lived HNLs** decaying semileptonically
- Displaced signature gives access to low HNL mass and low coupling values
- In most cases, rely on the **prompt lepton** for **triggering**

*See the talk from L. Lunerti for an overview of HNL searches*

[CMS-PAS-EXO-21-011]

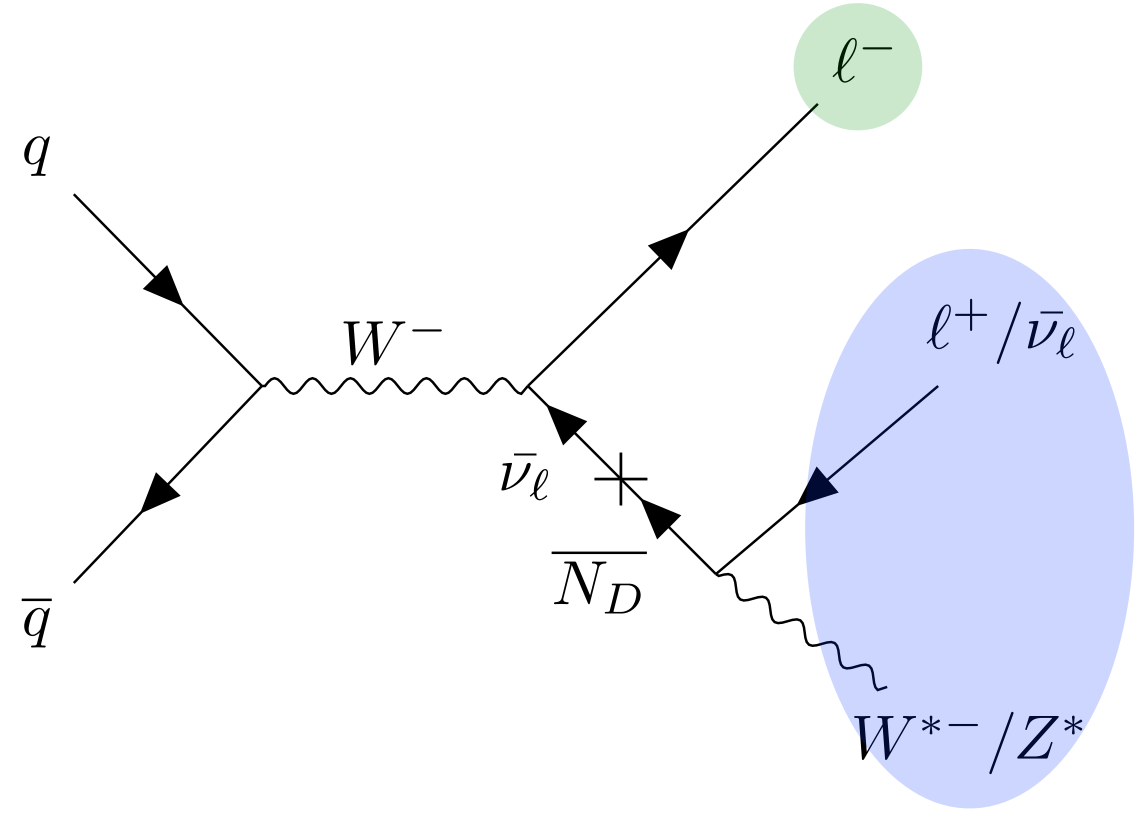
[JHEP03(2024)105]

- 1 displaced lepton + ≥1 jet



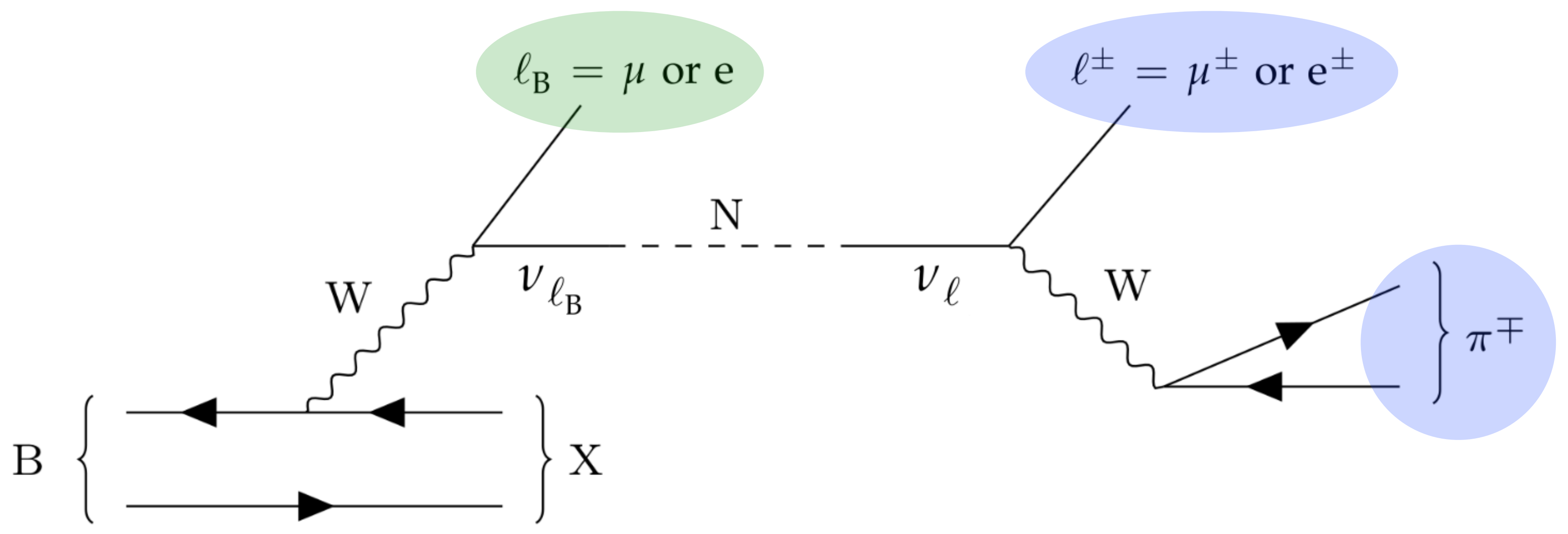

[arXiv:2402.18658v1]

- Cluster of hits in the muon system




[arXiv:2403.04584v1]

- HNL from a B-meson decay
- 1 displaced lepton + 1 displaced pion



# Inclusive LLP Searches

### Model-independent analyses

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- Give access to a **wide range of BSM scenarios**
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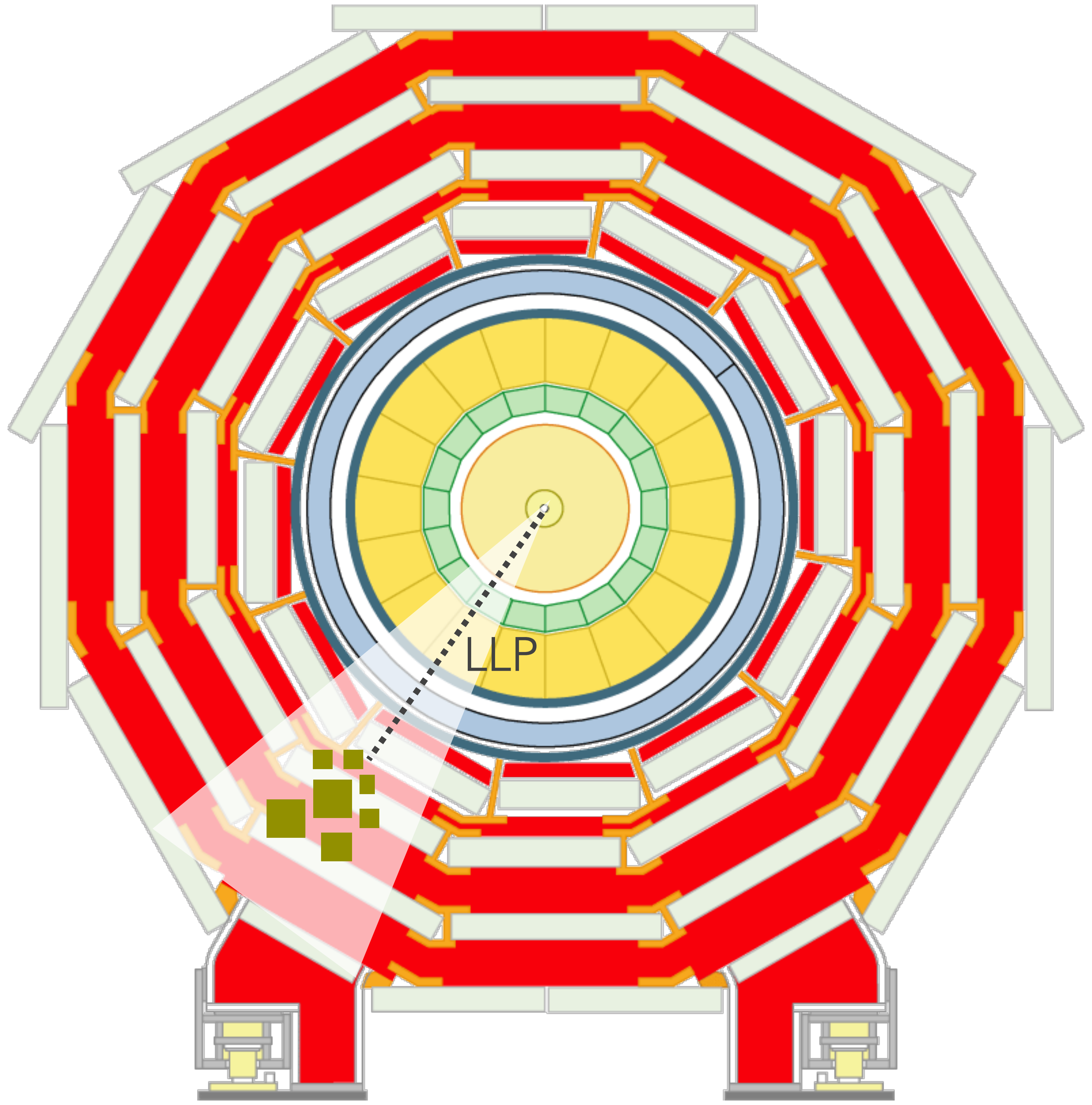
- Signature: particle showers in the muon detectors not associated to inner tracks



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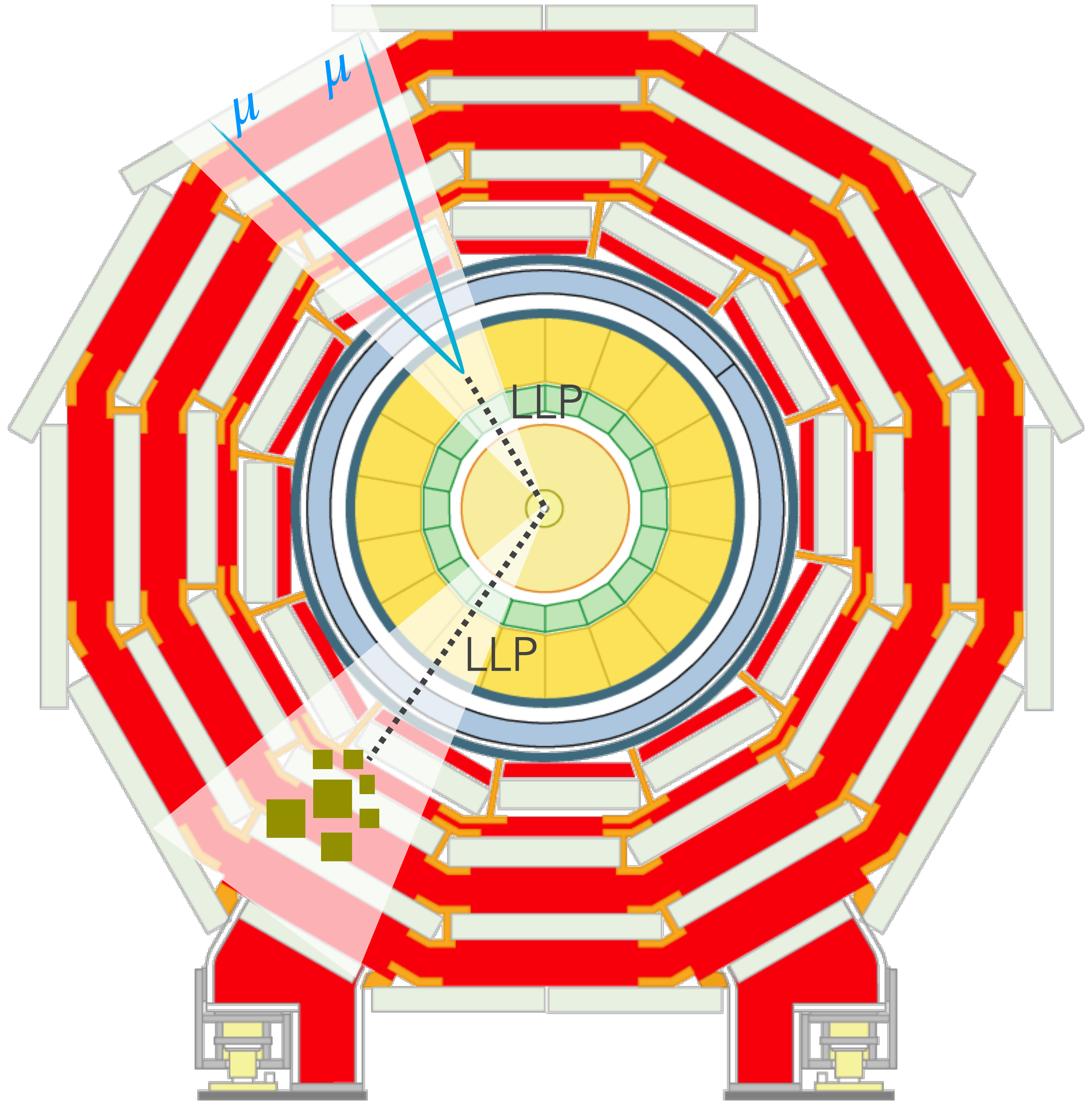
[JHEP05(2024)047]

*Search for long-lived particles decaying to final states with a pair of muons in proton-proton collisions at* $\sqrt{s} = 13.6~\mathrm{TeV}$

- Signature: pair of oppositely-charged muons originated from a displaced common vertex (CV)



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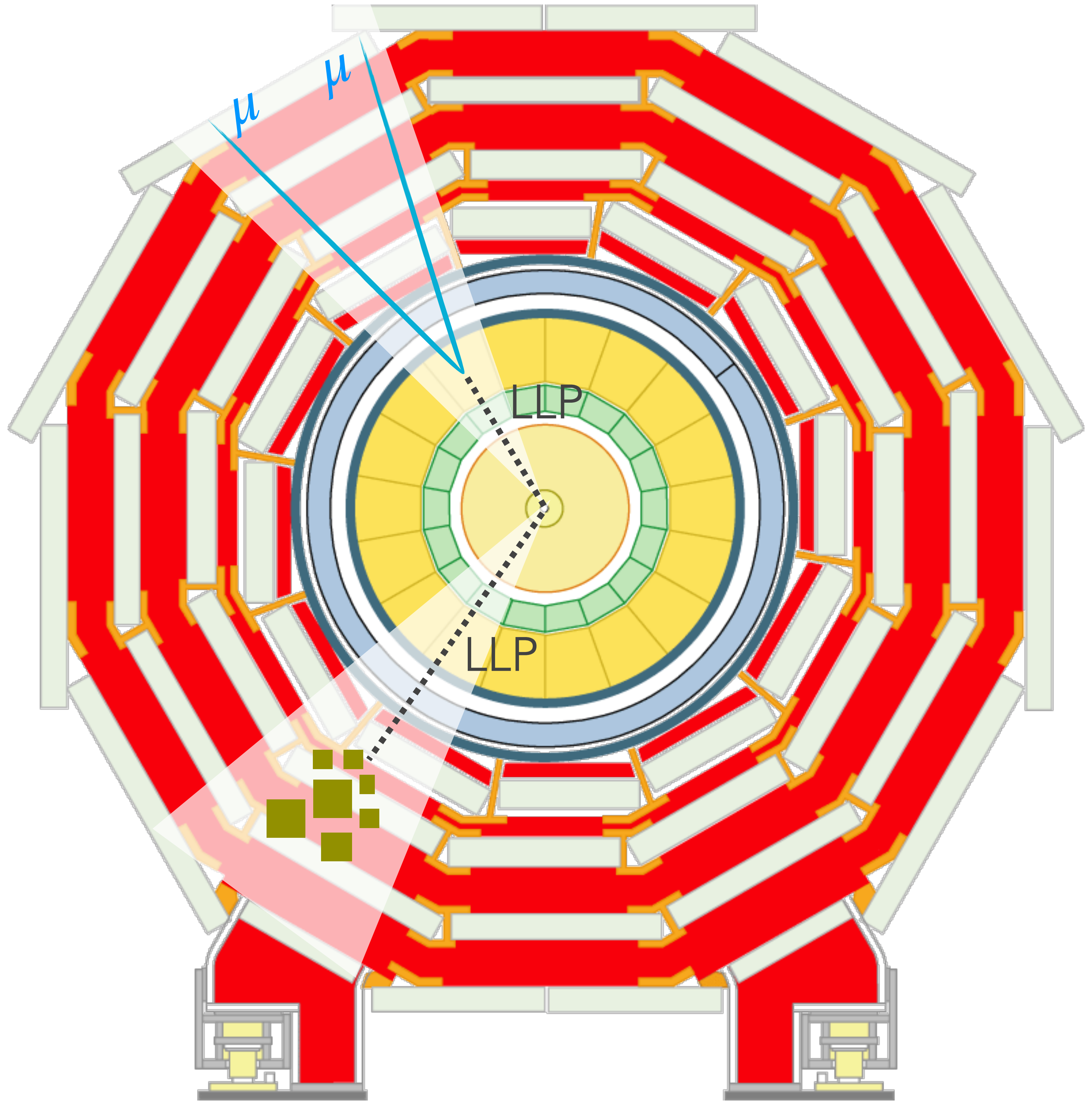
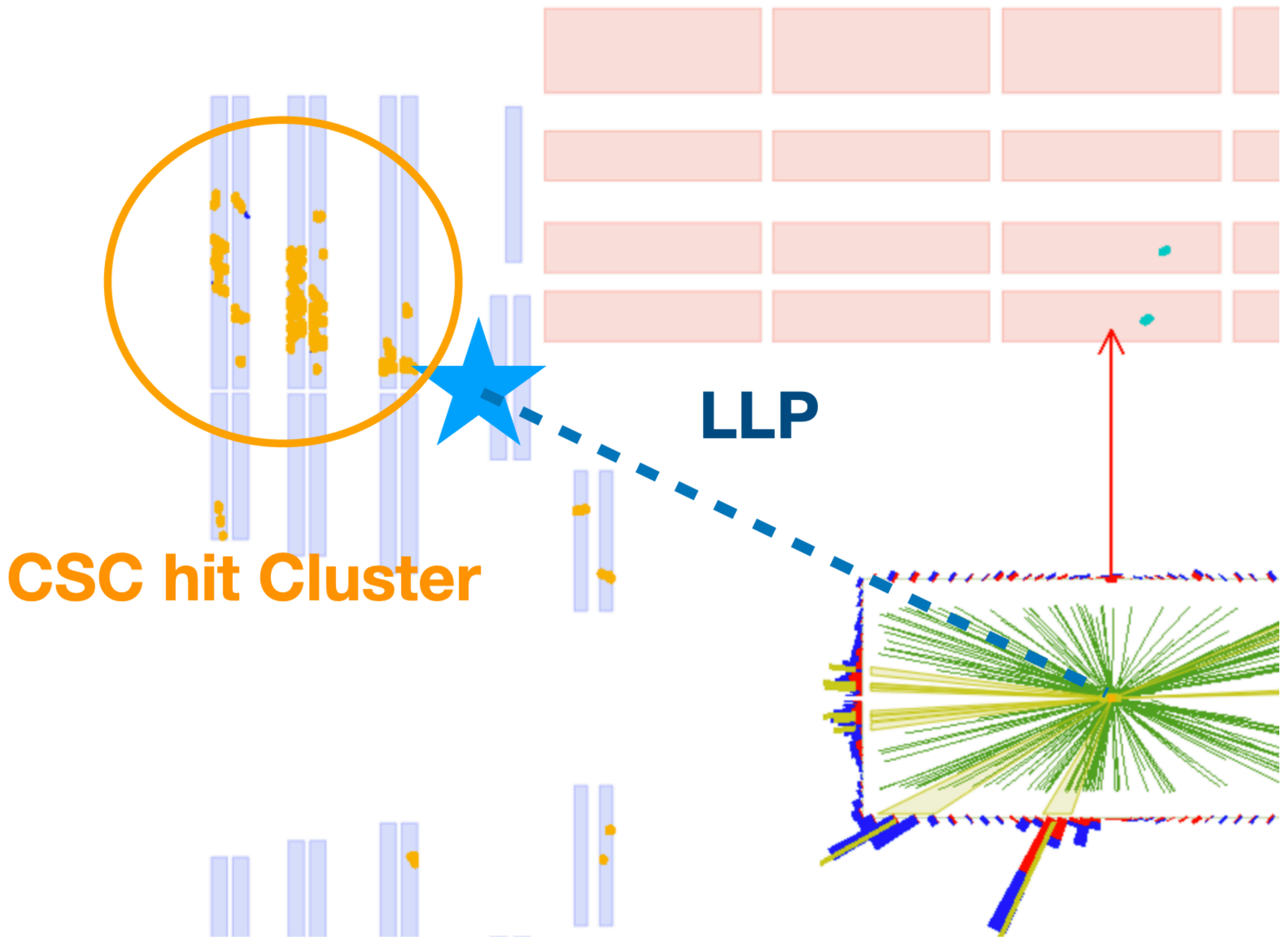


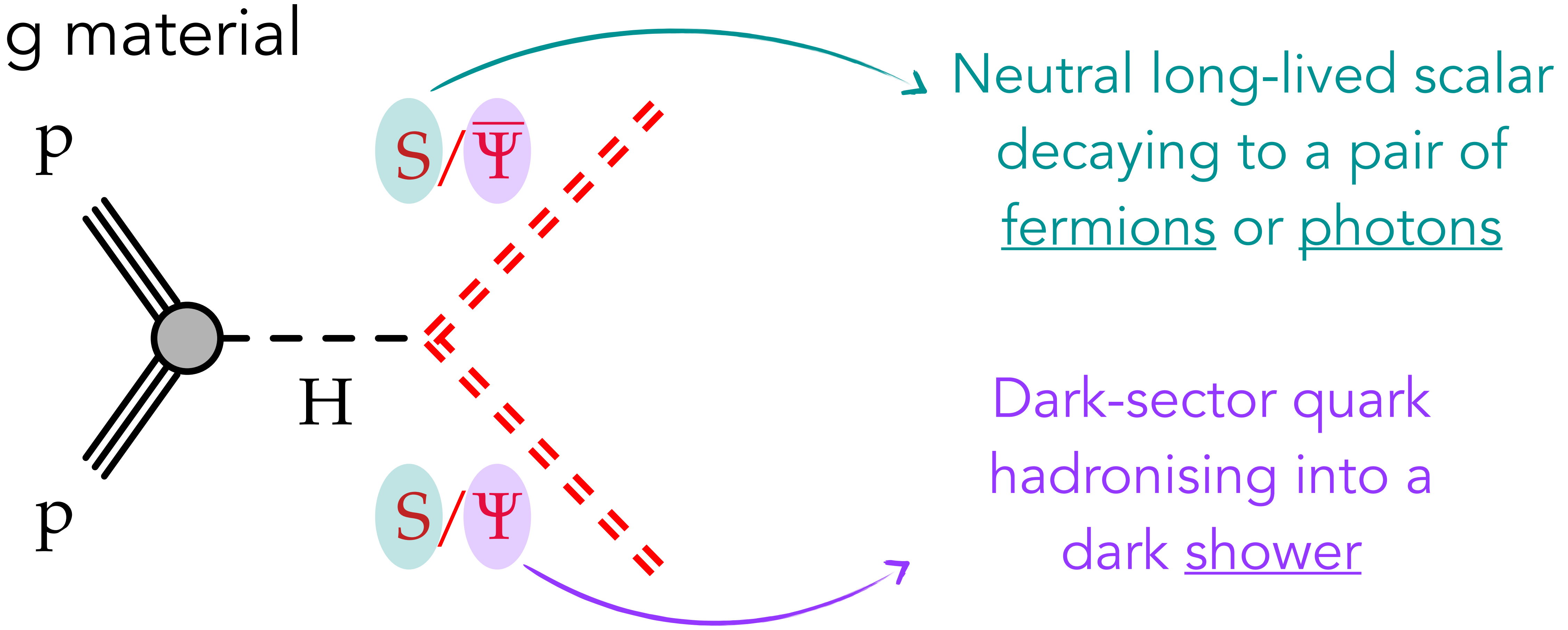

*Focus of the rest of this talk*

# LLPs Decaying in the Muon Detectors

arXiv:2402.01898

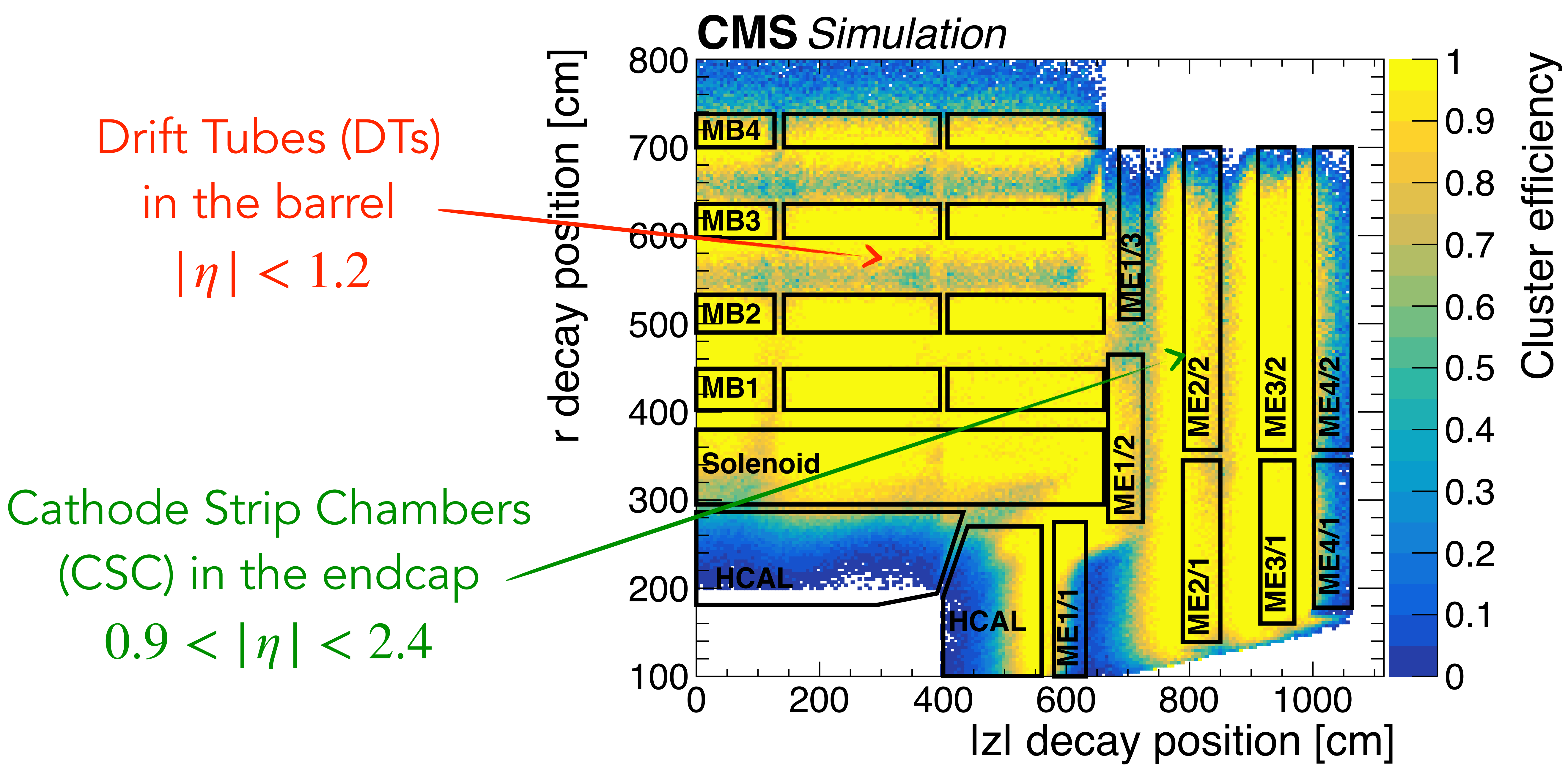
- Inclusive search of LLPs using the **muon system** as a **sampling calorimeter**
  - Sensitive to a **broad range of decays**: quarks, taus, photons, electrons,…
- Signature:
  - **Large cluster of hits in the muon system** (**M**uon **D**etector **S**hower) not associated to jets or tracks
  - Missing transverse momentum
- High **background suppression** thanks to the shielding material
- Results interpreted for two signal models
  - Twin Higgs scenario: $\mathrm{H} \to \mathrm{SS}$
  - Dark shower models: $\mathrm{H} \to \Psi\overline{\Psi}$



# LLPs Decaying in the Muon Detectors: Strategy

- Run 2 analysis: 138 fb$^{-1}$ of data collected between 2016 and 2018
- Selection of events with high **missing transverse momentum**: $p_T^{miss} > 200$ GeV (Trigger: $p_T^{miss} > 120$ GeV)
- Hits in high-intensity regions grouped into **clusters** separately in **barrel (DT)** and **endcap (CSC)** detectors
  - $N_{hits} > 50$ for clustering to reject minimum-ionising muons




- Categories based on the number of clusters and their location:
  - Single DT cluster
  - Single CSC cluster
  - Double cluster: DT-DT, DT-CSC, CSC-CSC
- Signal region definition and background estimation separately optimised for each category

# **LLPs Decaying in the Muon Detectors**: Backgrounds

- Main backgrounds: punch-through jets (jets "surviving" up to the muon system), bremsstrahlung muons, isolated hadrons (pileup, recoils, underlying events)

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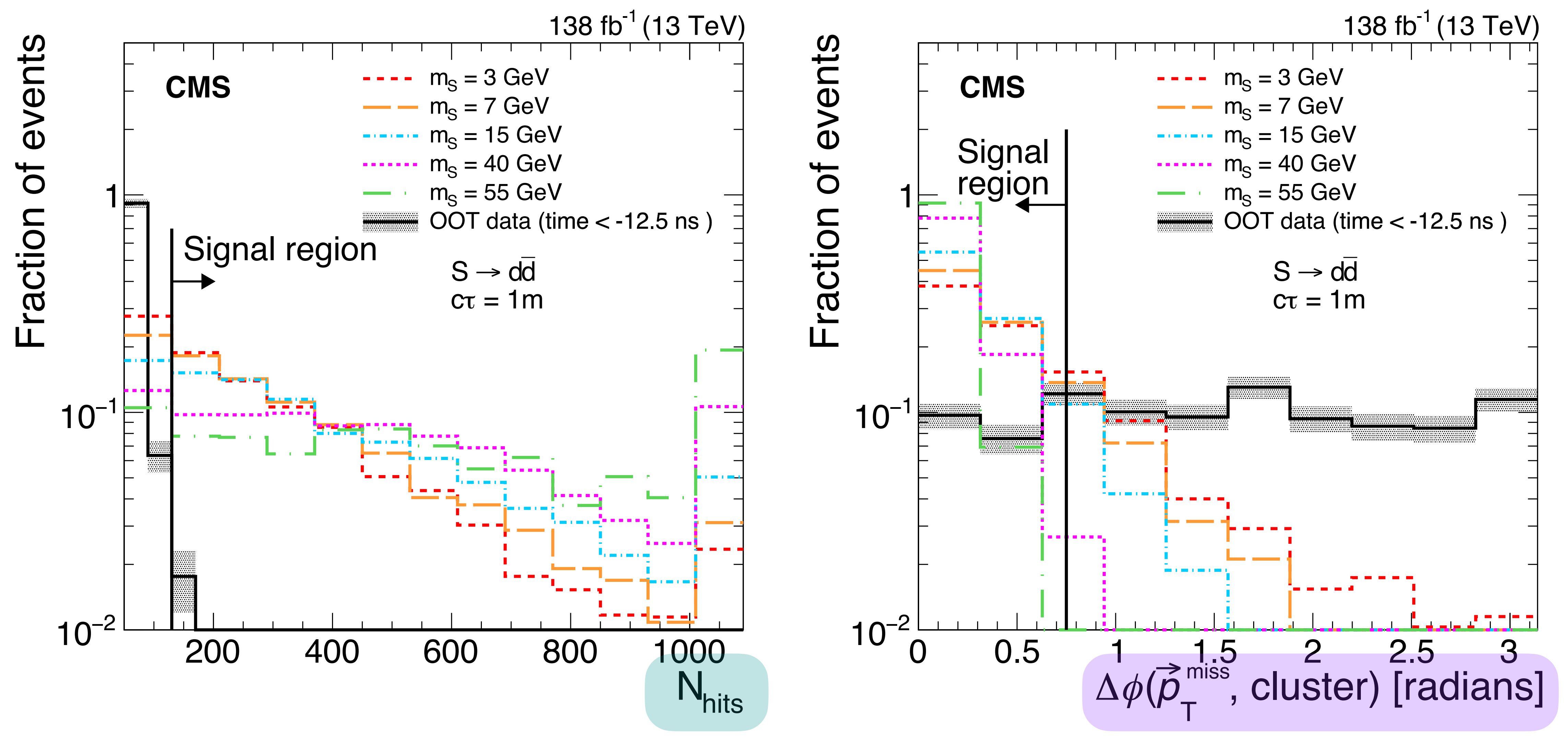
- Main **discriminating variables**
  - Number of hits in the cluster $N_{hits}$
  - Angular difference between $\vec{p}_T^{miss}$ and the cluster $|\Delta\phi(\vec{p}_T^{miss}, \text{cluster})|$




Signal: High number of cluster hits and significant correlation between $\vec{p}_T^{miss}$ and the cluster position

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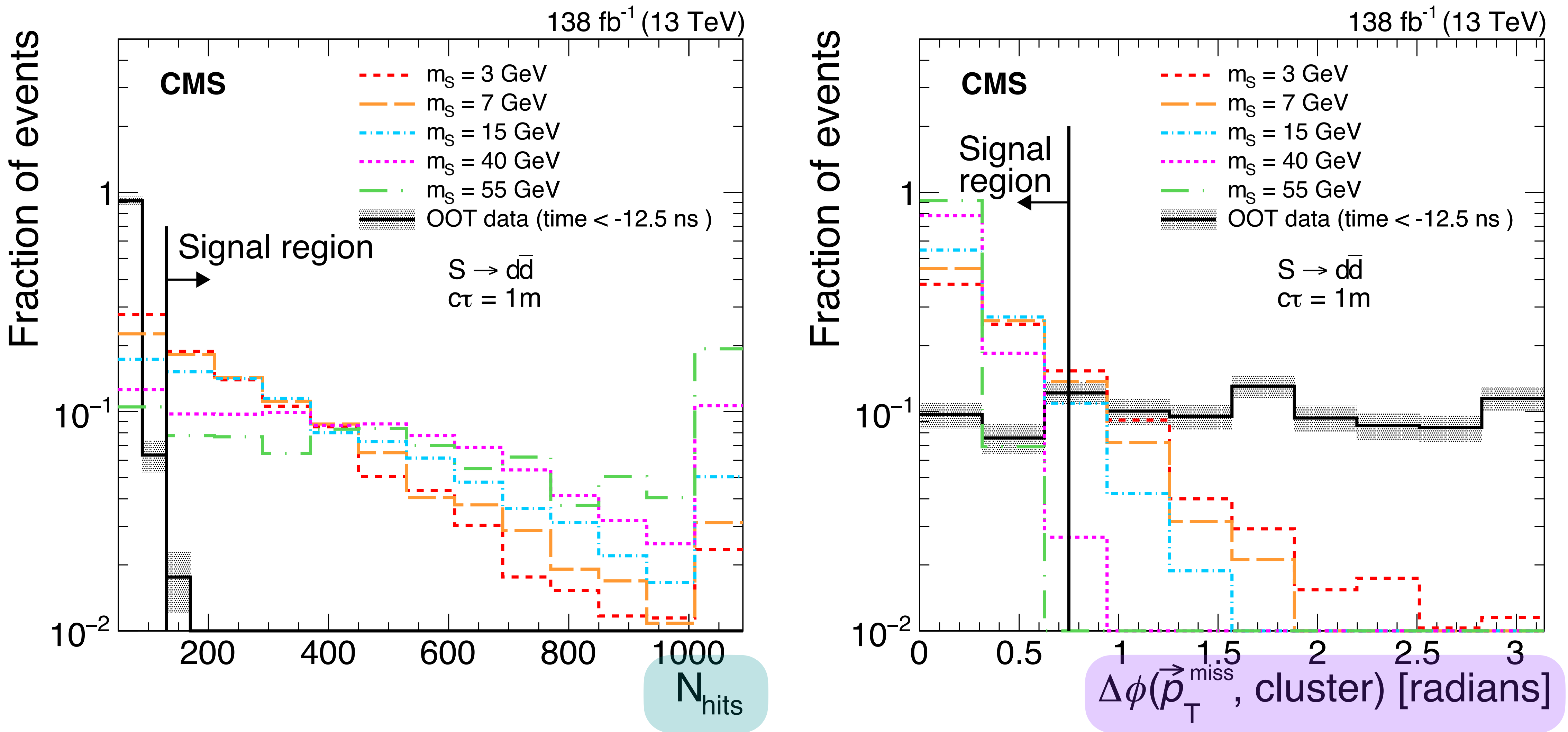
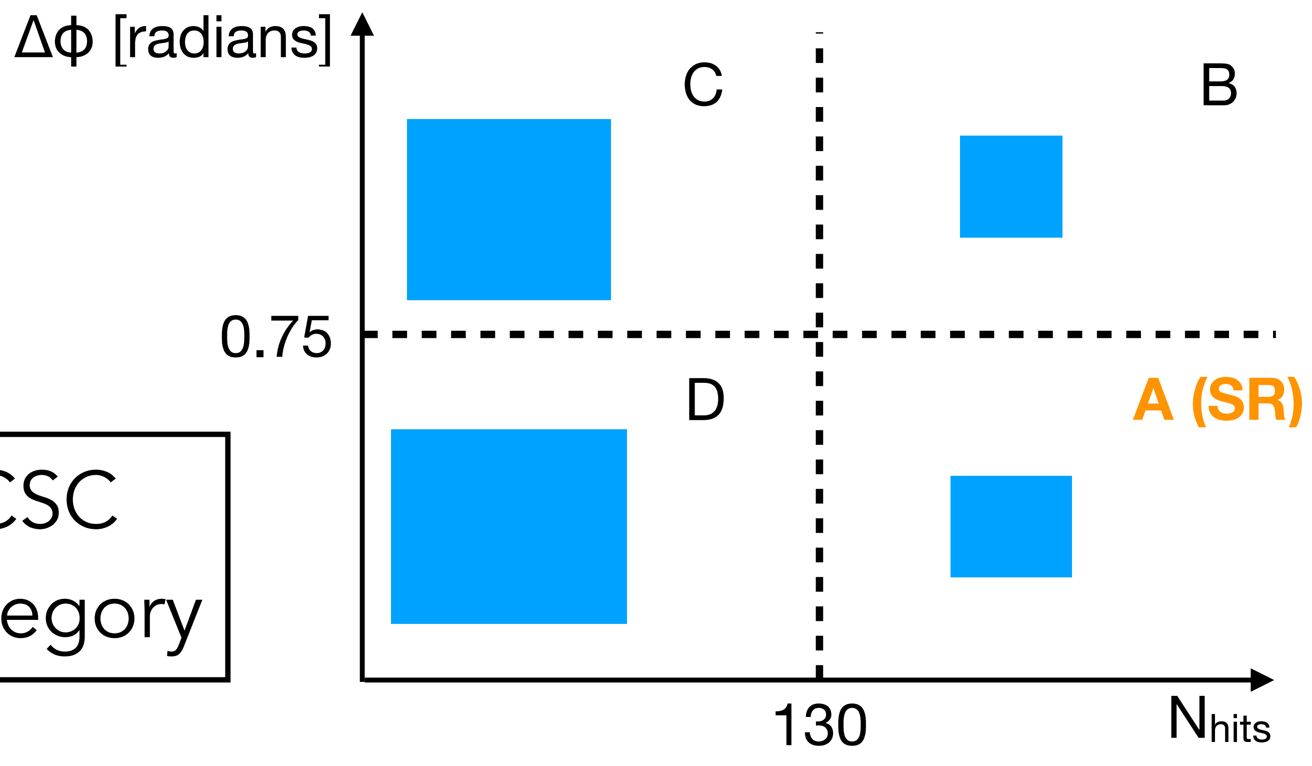



Used to define the signal region and estimate pileup-like background

→ **Data-driven ABCD methods**

Single CSC cluster category

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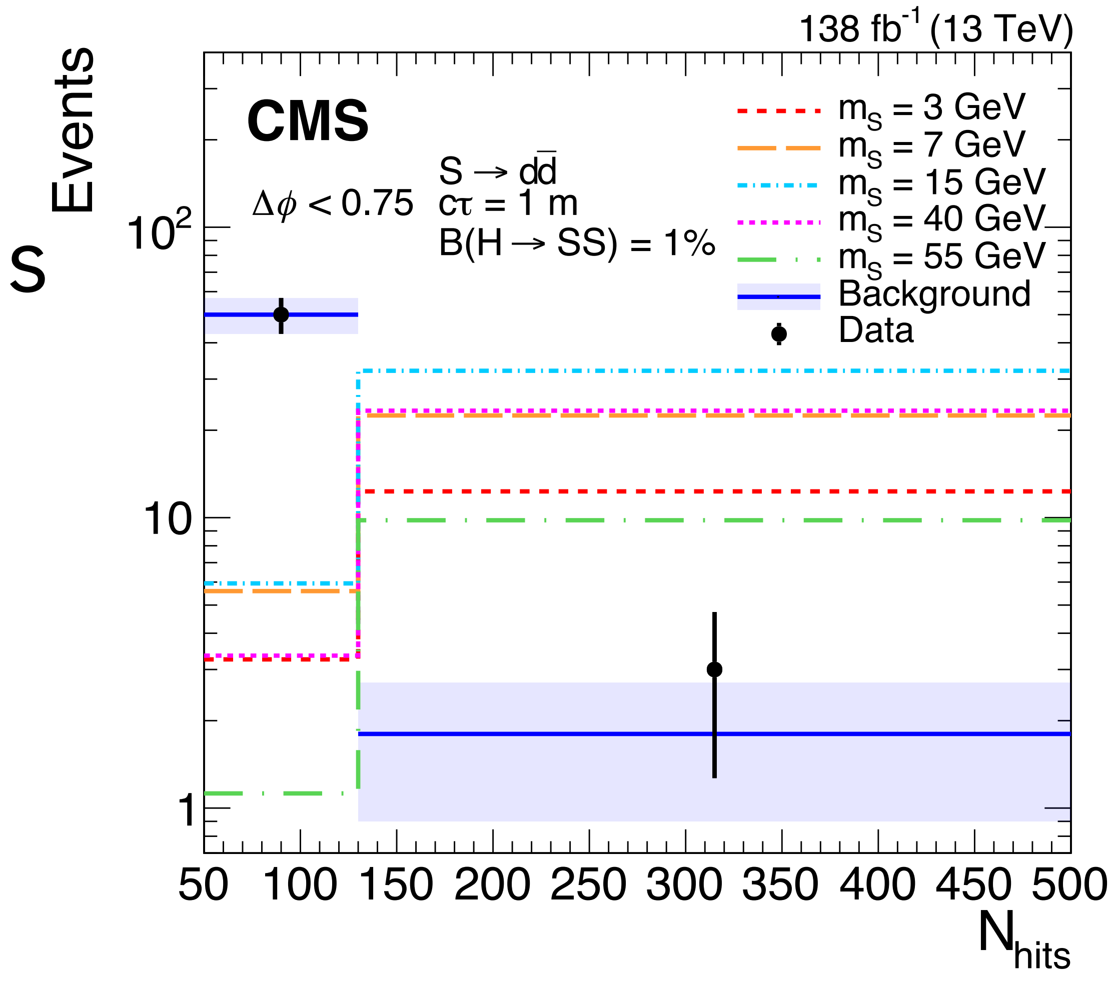
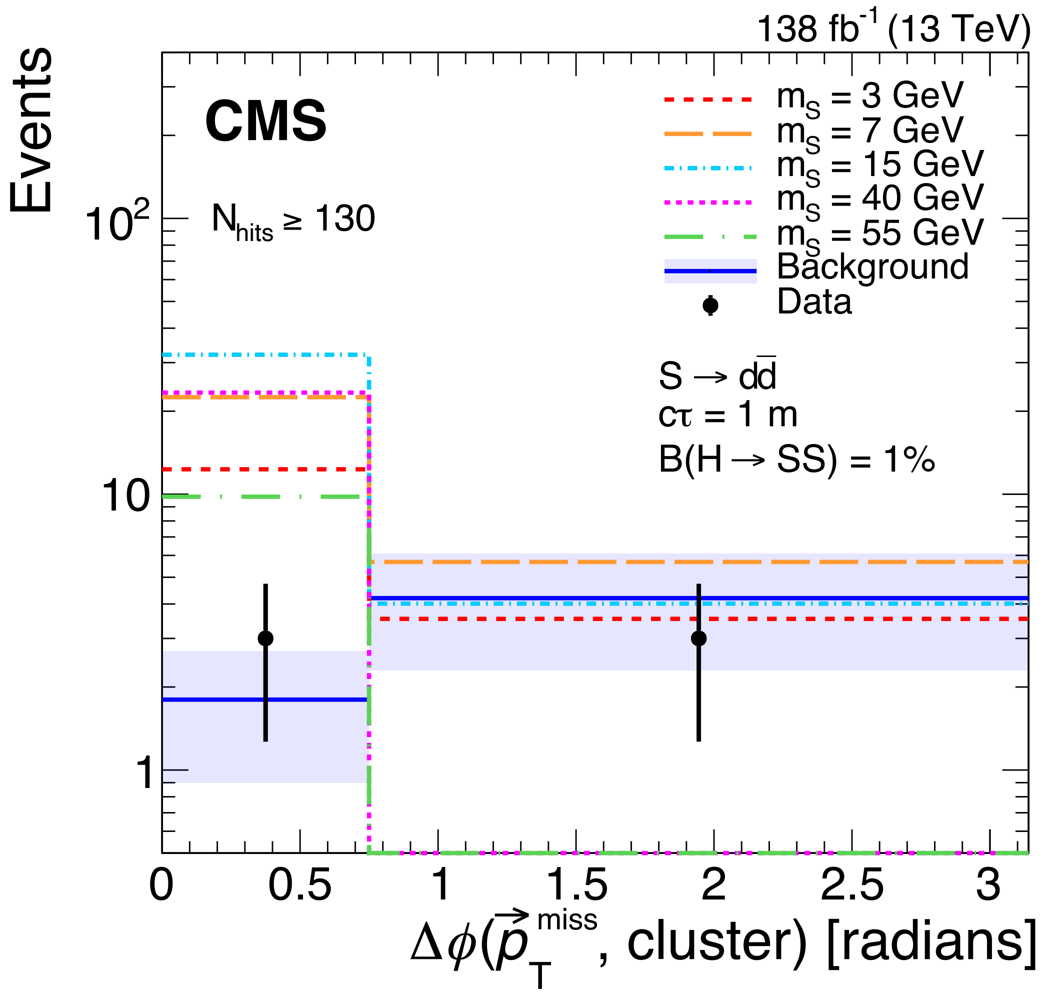
- No significant excess over the SM observed
- Results interpreted in terms of the two benchmark models



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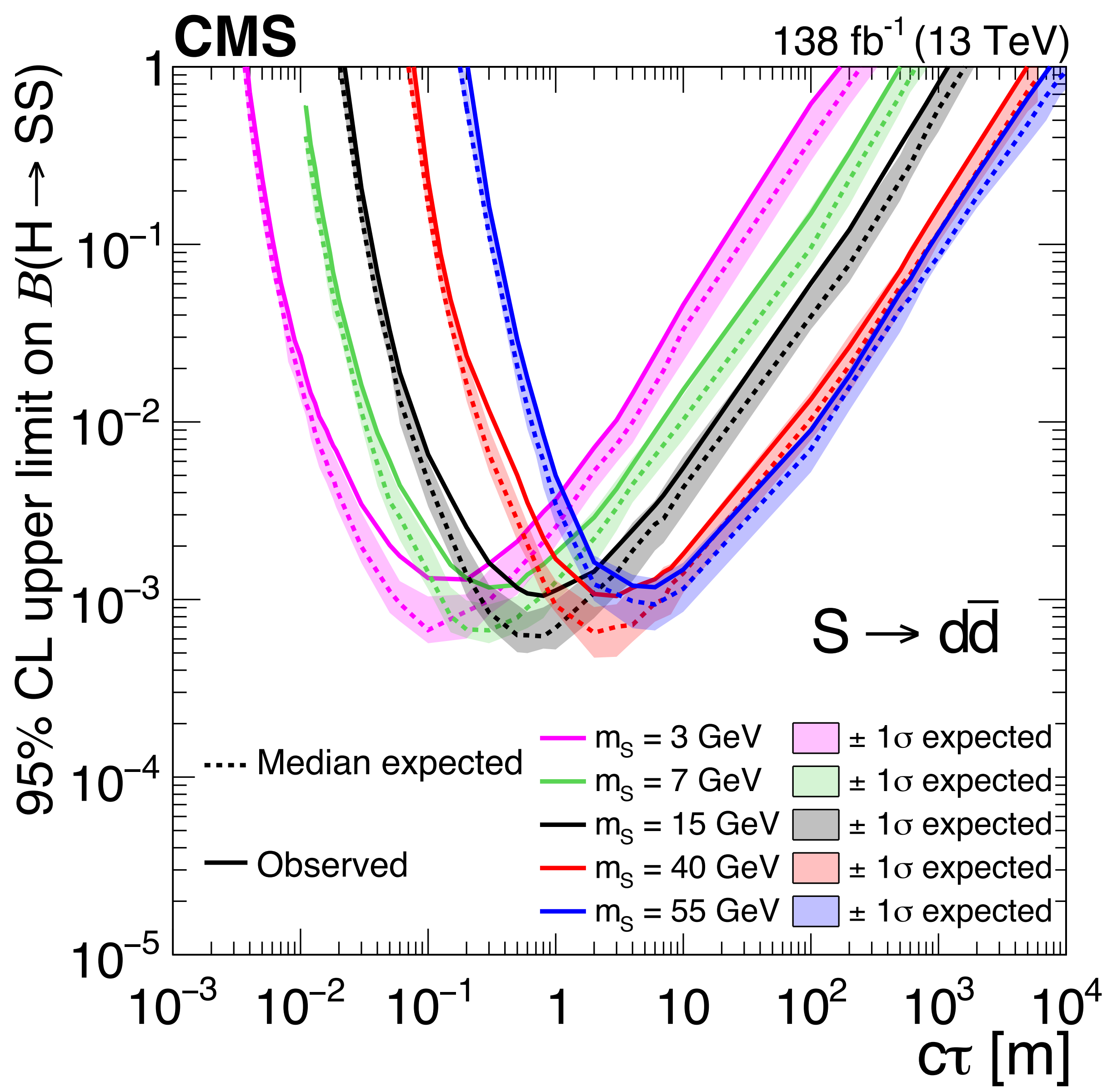


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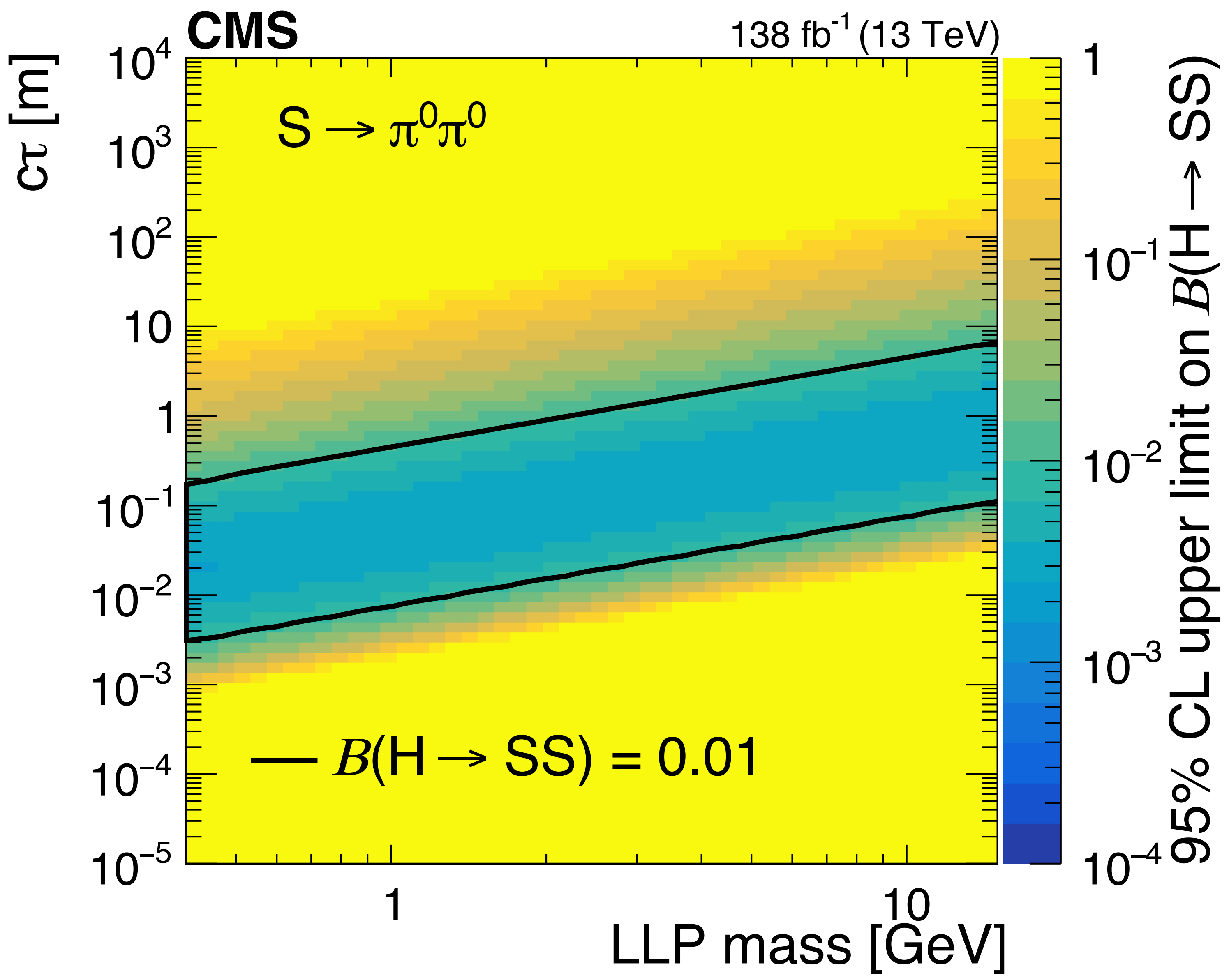

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- First LHC limits set on the dark-shower model

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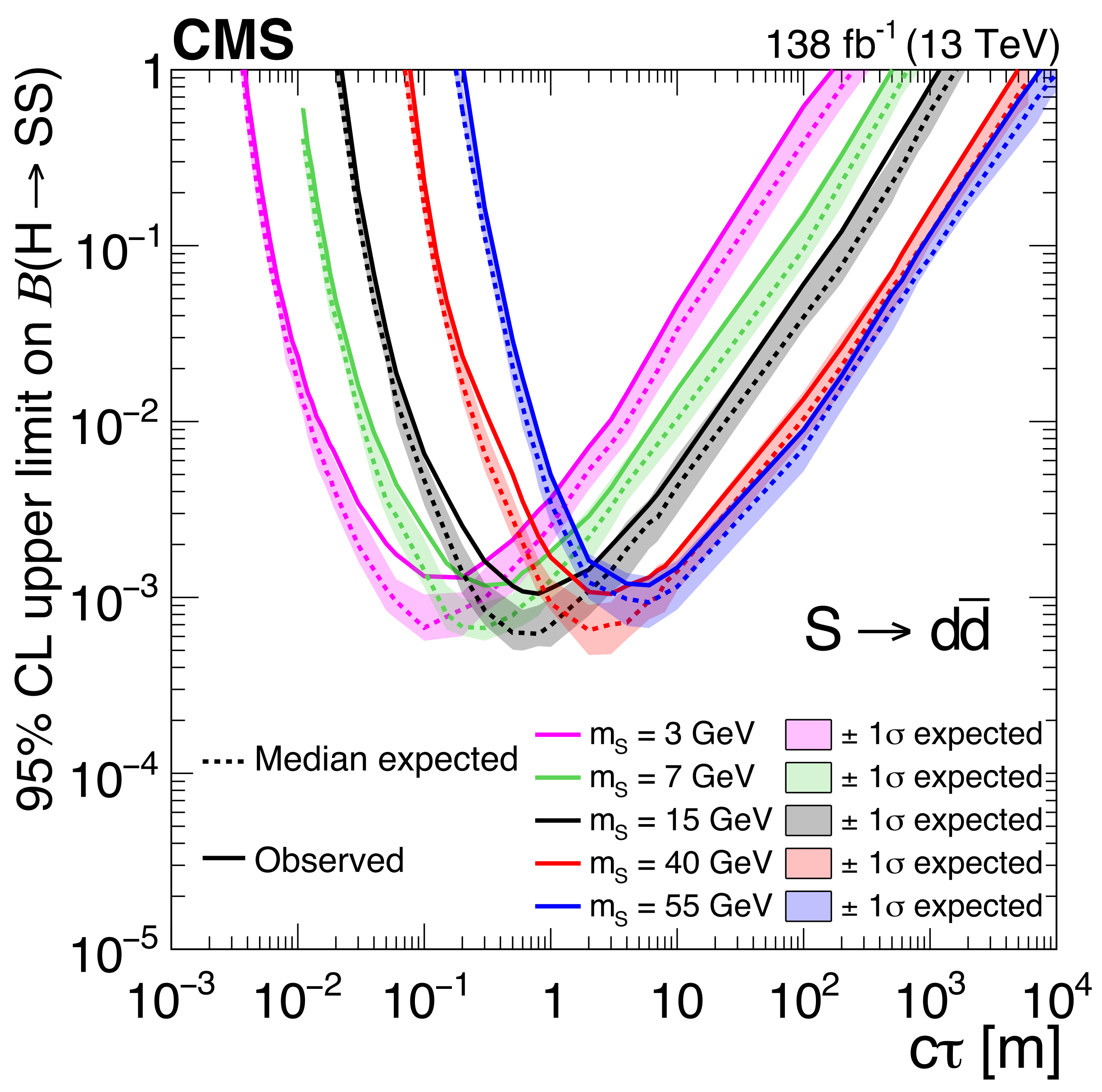


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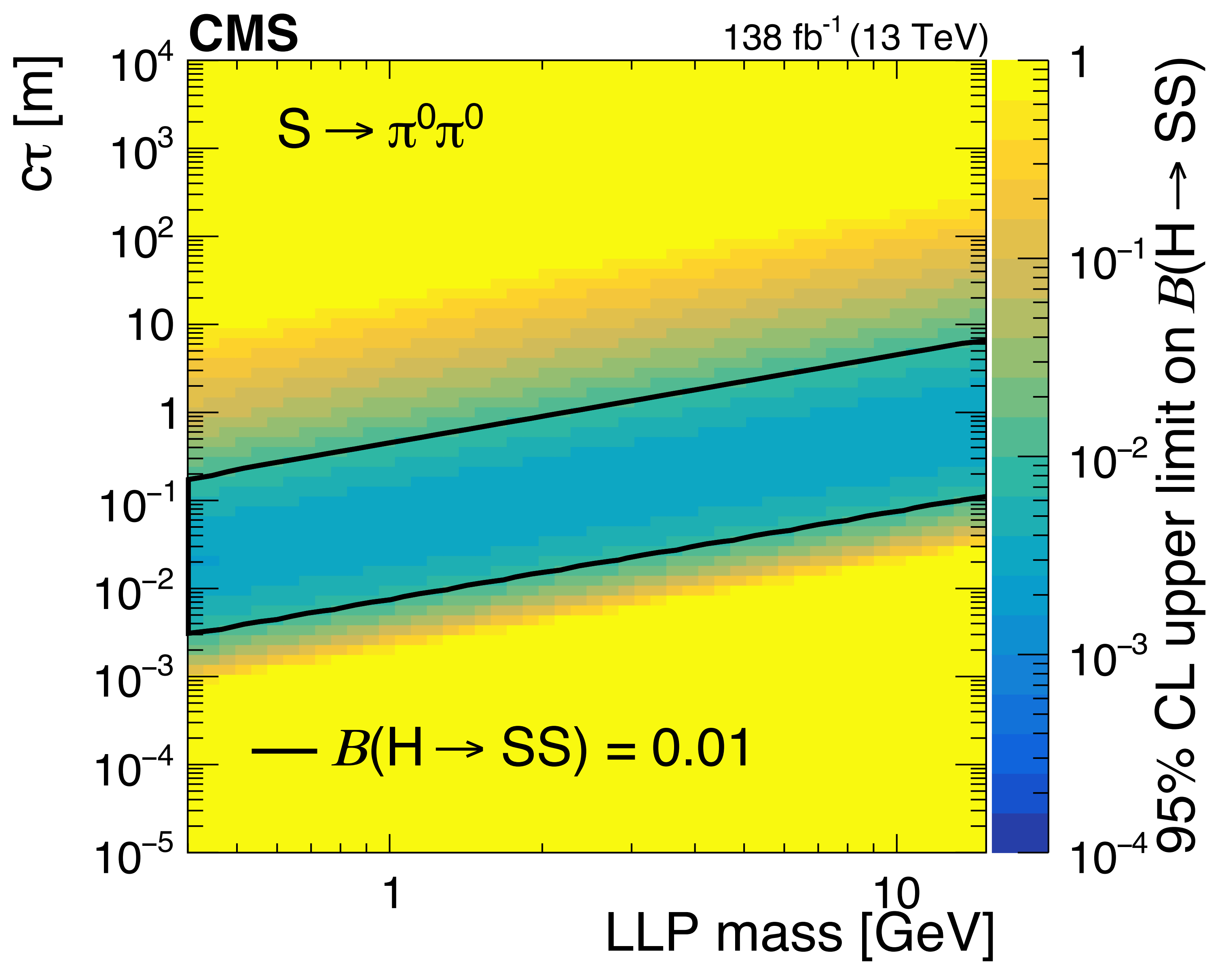
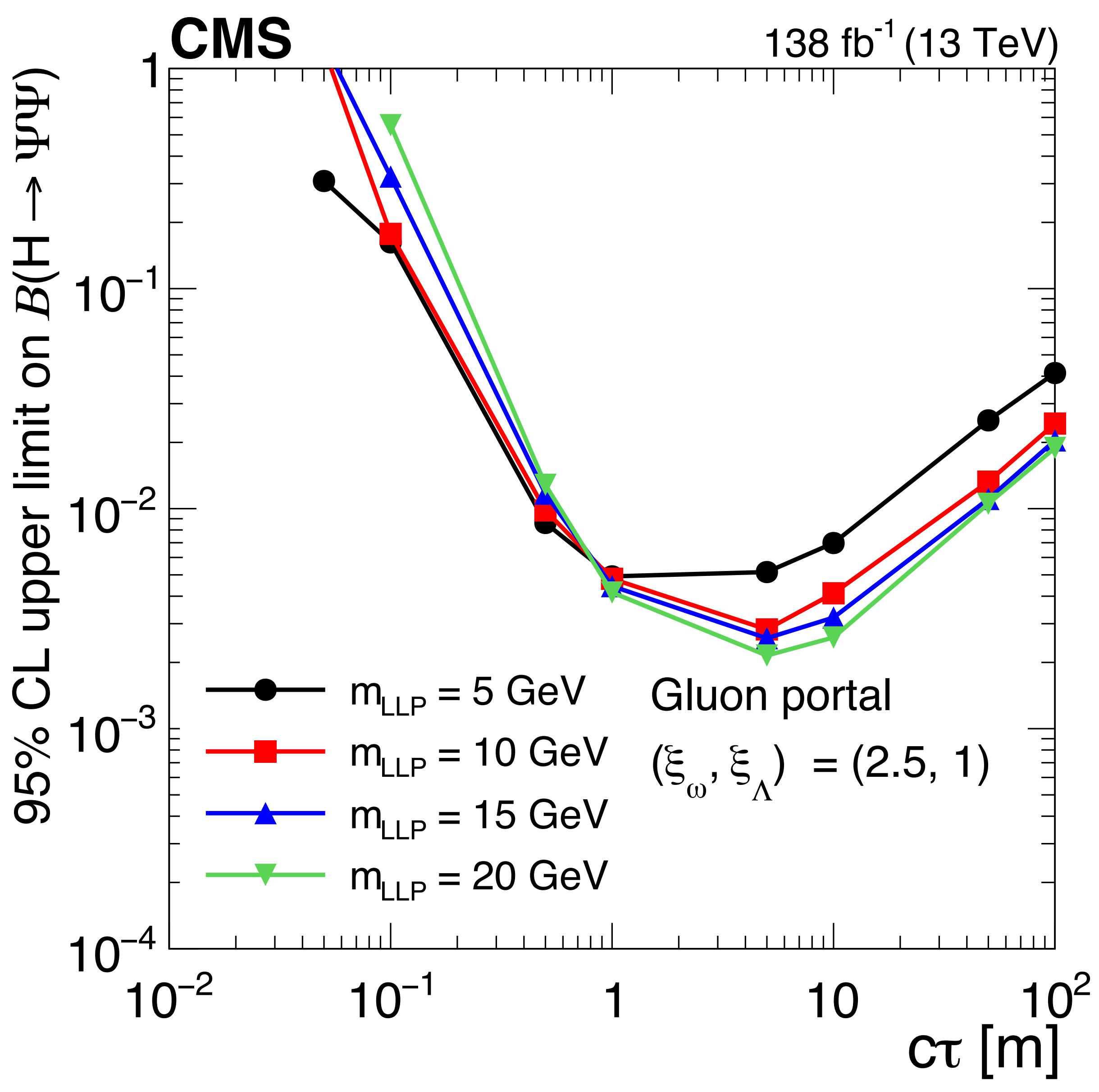


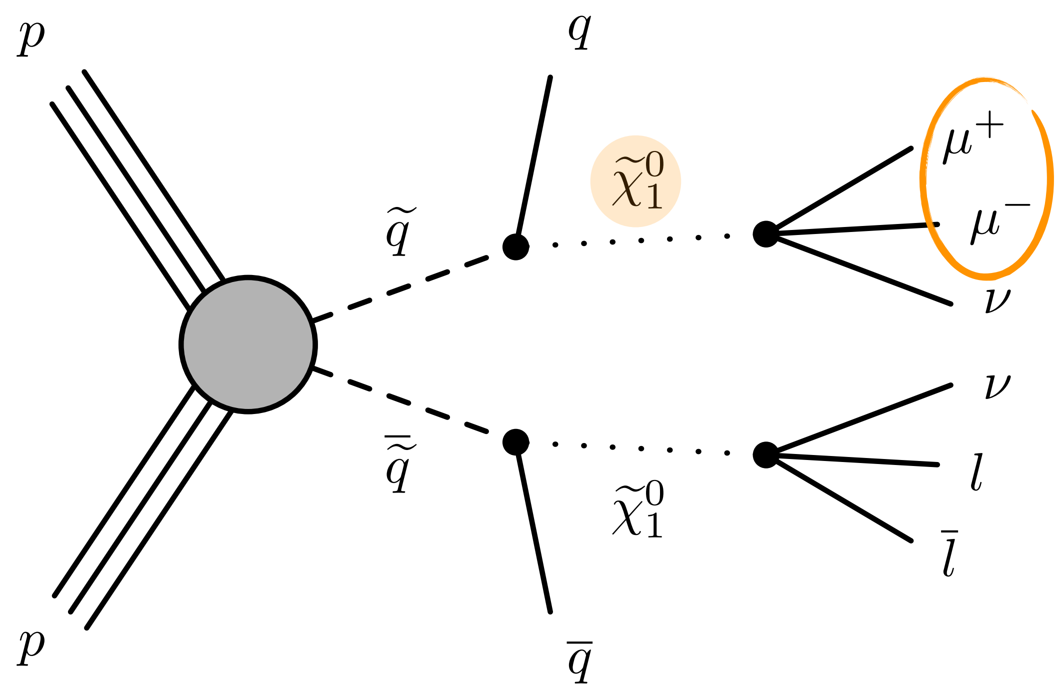

**Dark-shower model** (gluon portal)



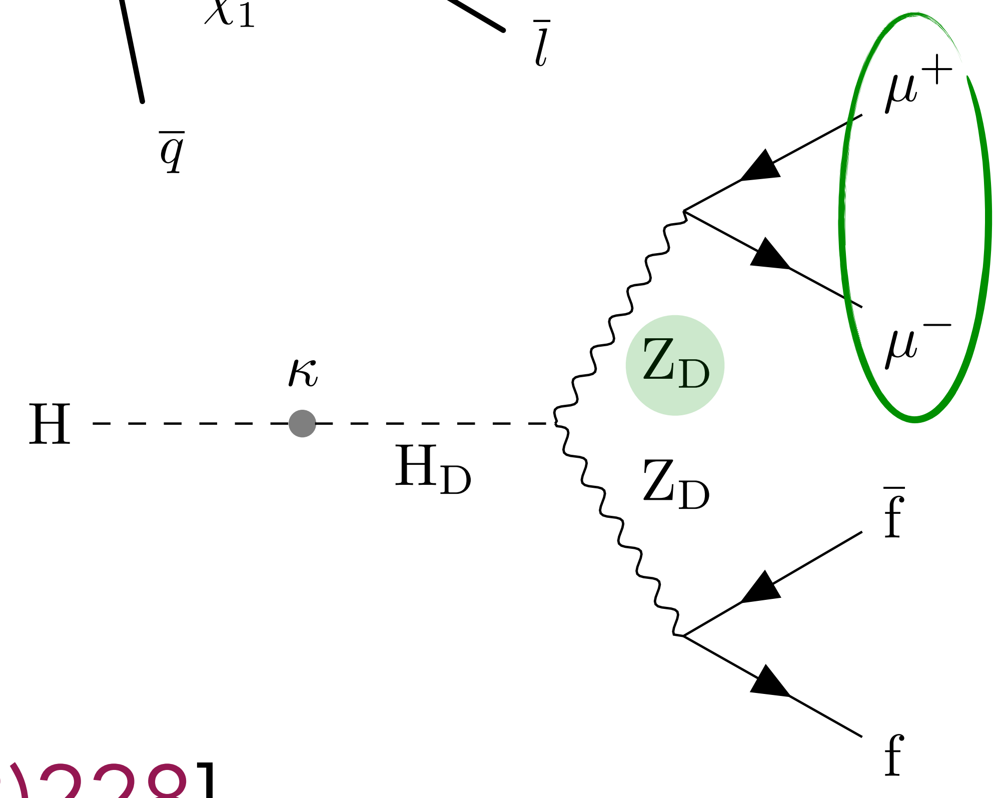
# LLPs to Muon Pairs

JHEP05(2024)047

- Inclusive search for long-lived particles decaying into pairs of oppositely-charged muons (**displaced dimuons**)
- Results benchmarked for two BSM models
  - R-parity violating SUSY model ($\tilde{q} \rightarrow q\tilde{\chi}^0_1, \tilde{\chi}^0_1 \rightarrow \mu\mu\nu$)
  - Dark photon model ($H \rightarrow Z_D Z_D, Z_D \rightarrow \mu\mu$)
- Early Run 3 search
  - With **36.7 fb**$^{-1}$ of data collected in 2022 at $\sqrt{s} = 13.6$ TeV
  - **Following the strategy** of a similar search **in Run 2** [JHEP05(2023)228]
  - Comparable or better sensitivity than Run 2 obtained with only 38% of the data → Improved signal efficiency thanks to **new trigger developments**




Non-resonant neutralino decay

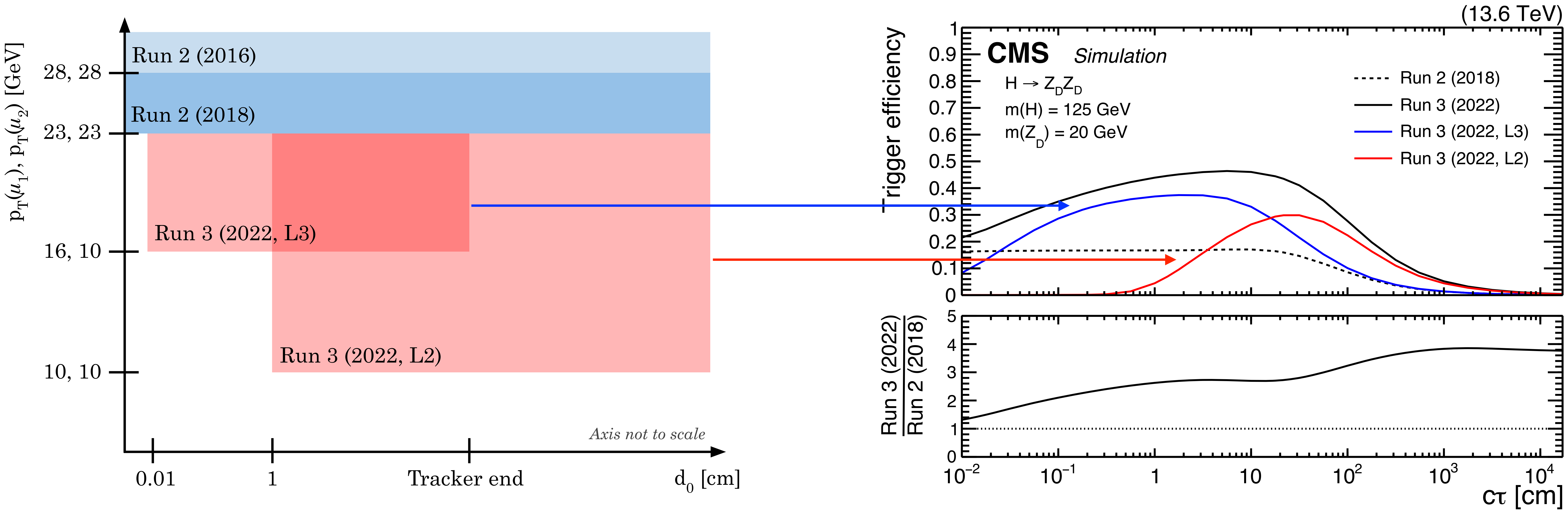



Resonant dark photon decay

# Double-muon Trigger Improvements in 2022

Improved LLP triggers at both L1 (hardware) and HLT (software)

- New **L1** algorithms:
  - Double-muon triggers with lower $p_T$ thresholds
  - $p_T$ reconstruction without beam-spot constraint
- New **HLT** algorithms: higher thresholds on the impact parameter to allow lower $p_T$ thresholds

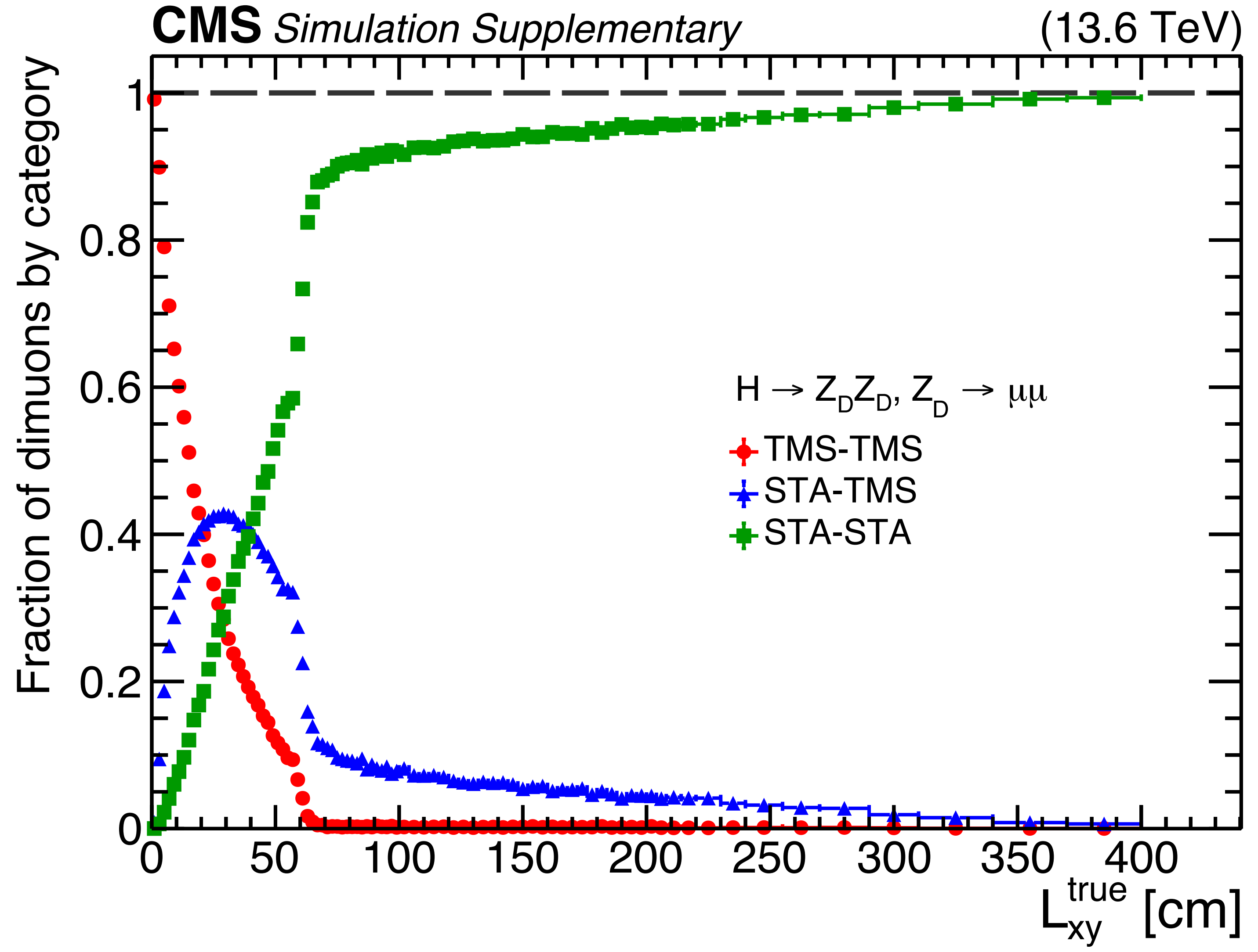



Efficiency improves up to a factor 4 at high lifetimes

# LLPs to Muon Pairs: Strategy

- Two types of muon reconstruction in CMS:
  - STA: Displaced STand-Alone (muon system only)
  - TMS: Tracker + Muon System (better track, vertex and mass resolution)

  Two **dimuon categories**: TMS-TMS and STA-STA allow to cover a high range of displacements beyond the tracker
- Dimuons fitted to a common vertex



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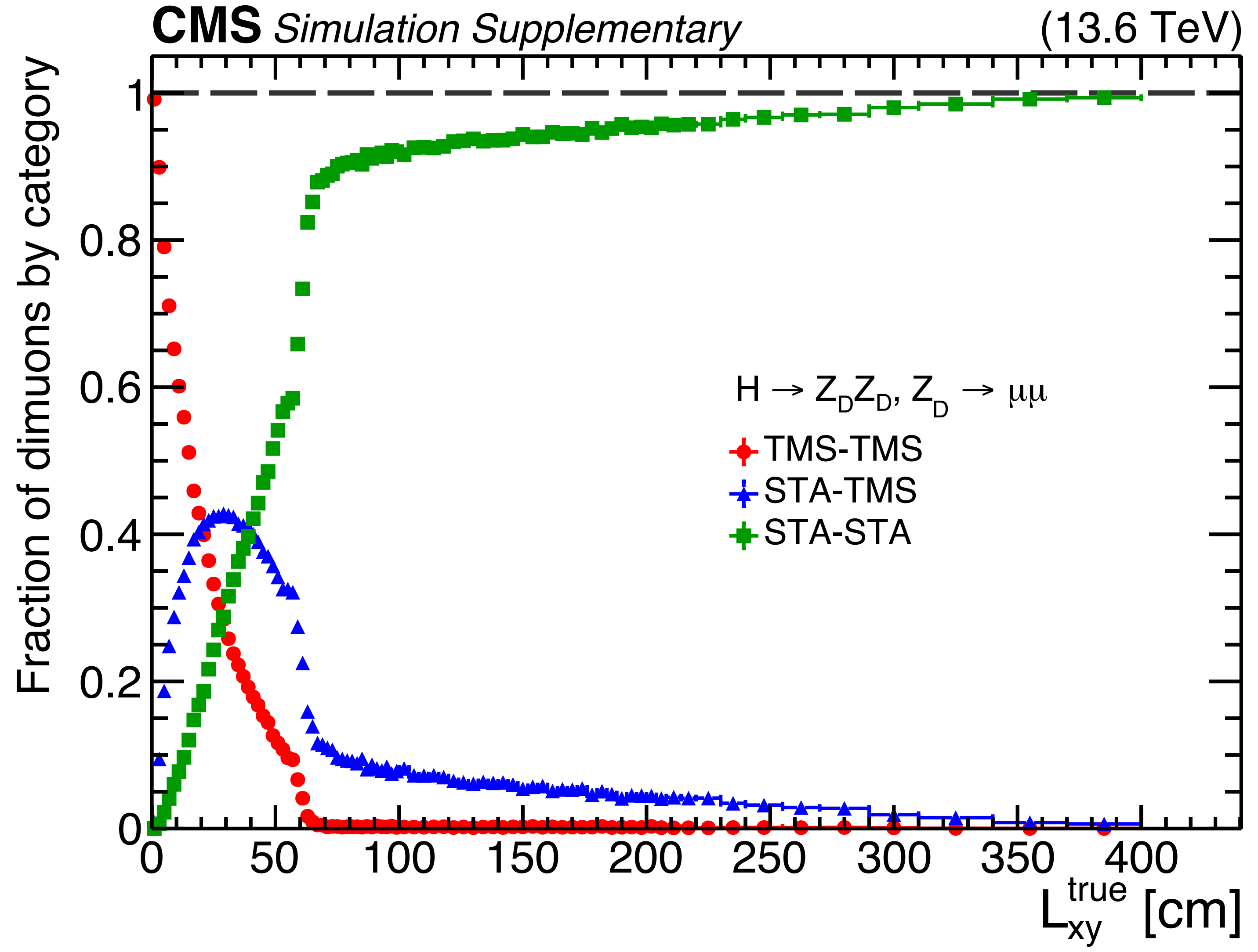
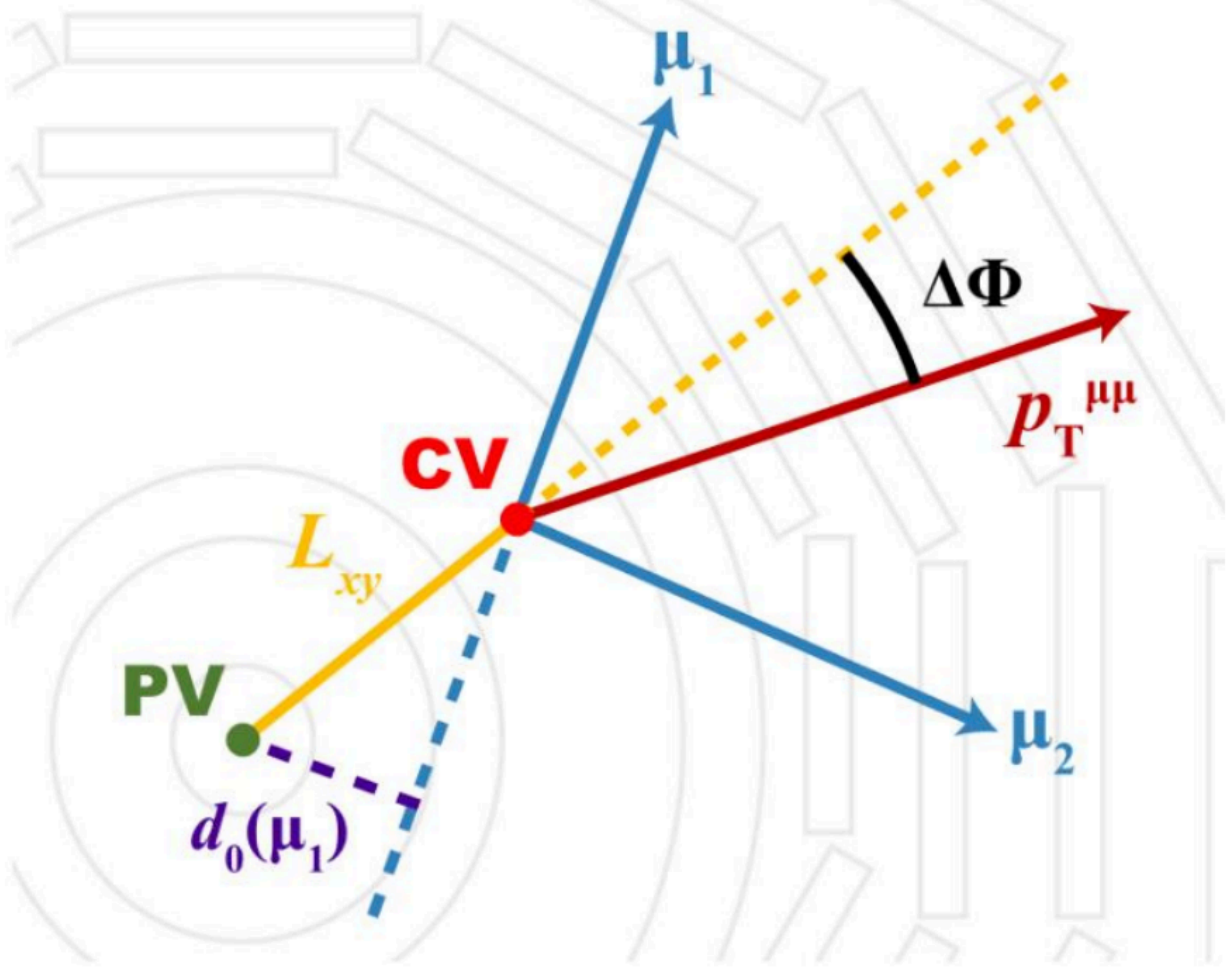



### Main discriminating variables

- Transverse decay length ($L_{xy}$) and its significance ($L_{xy}/\sigma_{L_{xy}}$)
- Transverse impact parameter ($d_0$) and its significance ($d_0/\sigma_{d_0}$)
- Transverse collinearity ($|\Delta\phi|$) → Small for signal




LLP candidates selected with upper cuts on $|\Delta\phi|$ and lower cuts on $L_{xy}/\sigma_{L_{xy}}$ and $d_0/\sigma_{d_0}$

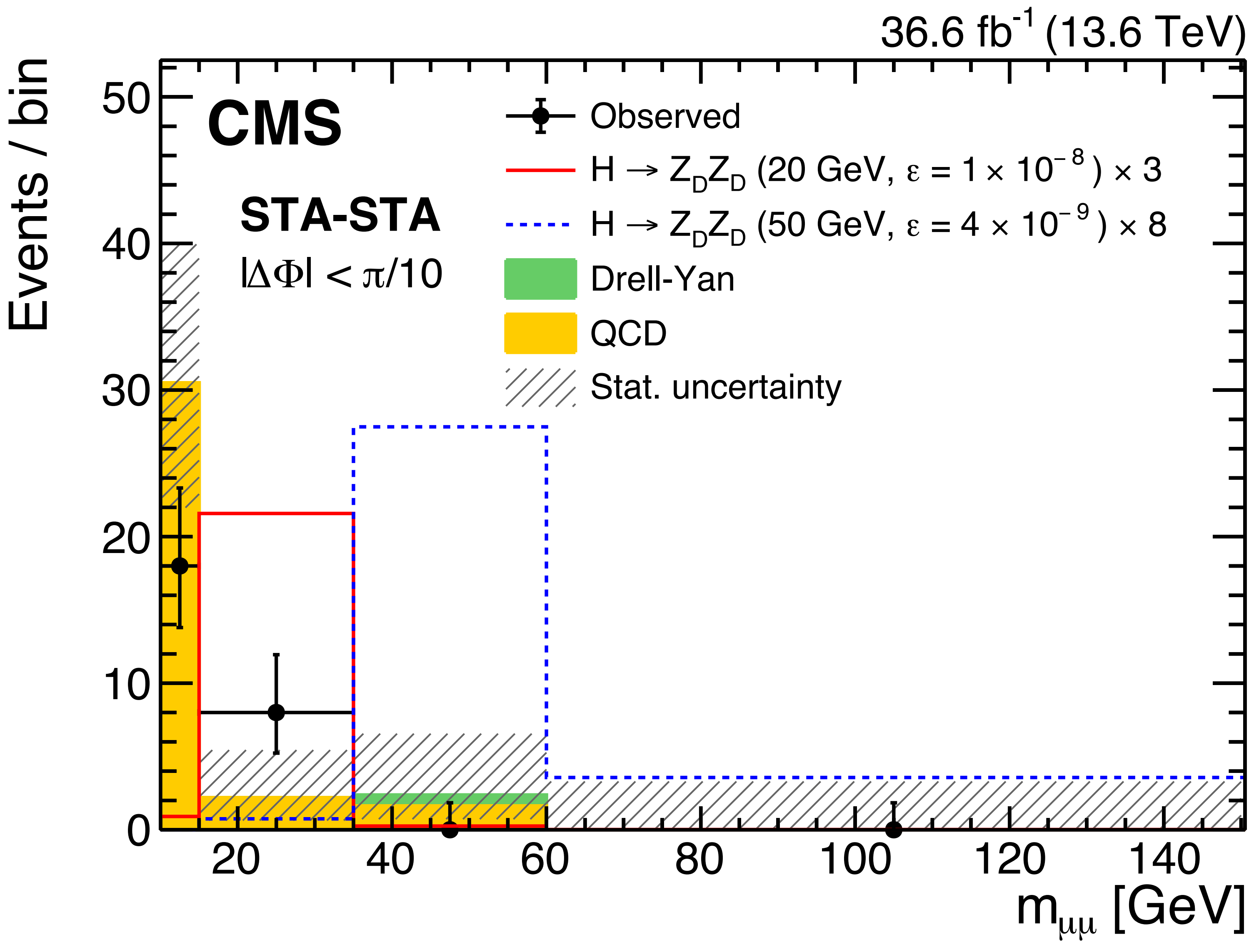
# LLPs to a Muon Pairs: Strategy

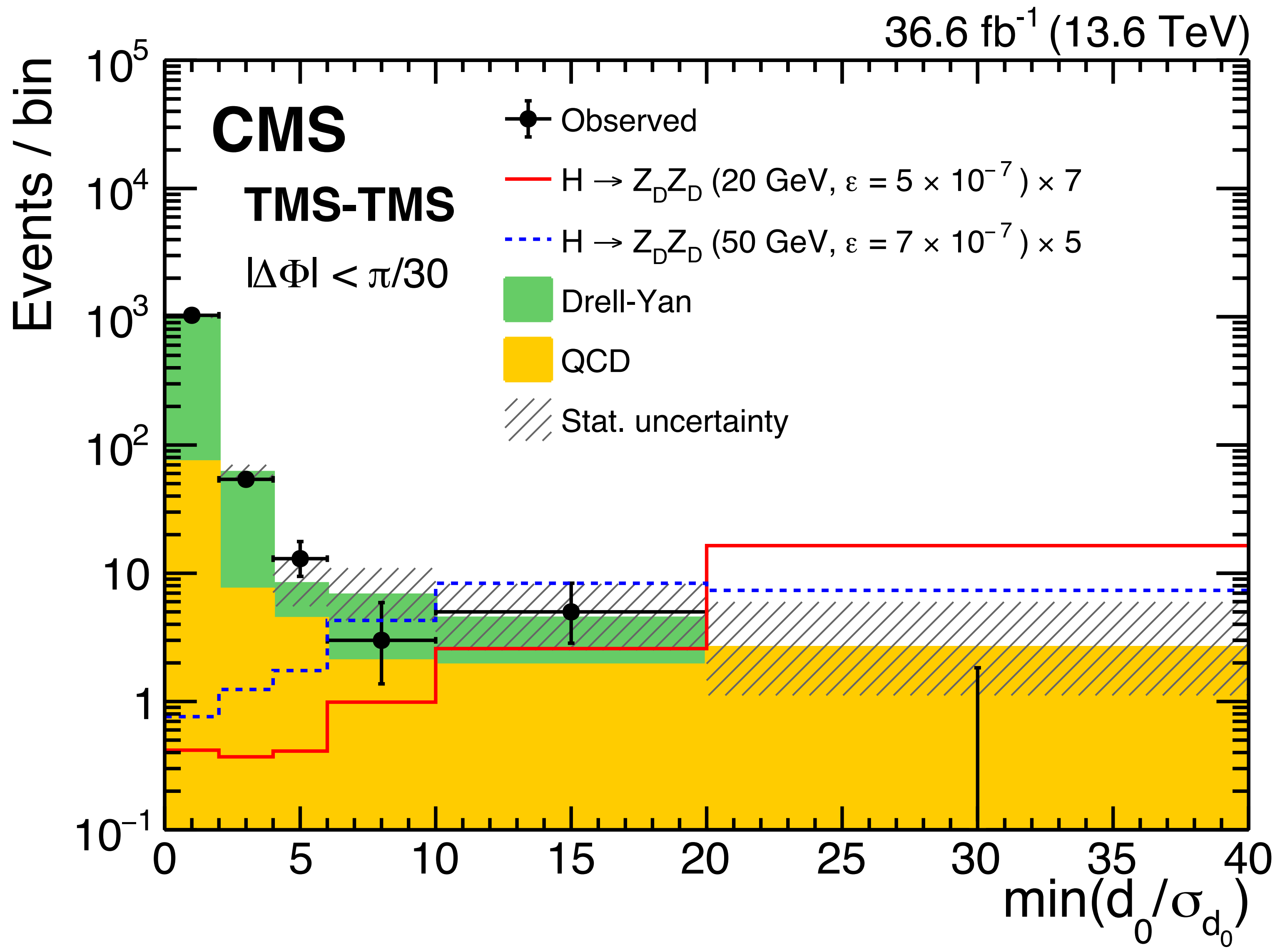
Background due to instrumentation/reconstruction mistakes ⟶ Data-driven estimation

- QCD-like: low mass resonances, cascade decays (e.g. from B hadrons)
- Drell-Yan-like : (misreconstructed) prompt dimuons from Drell-Yan, $t\bar{t}$ and dibosons

Search regions:

- Separate $m_{\mu\mu}$ interval for each mass hypothesis
- Binning in $d_0/\sigma_{d_0}$ in the TMS-TMS category



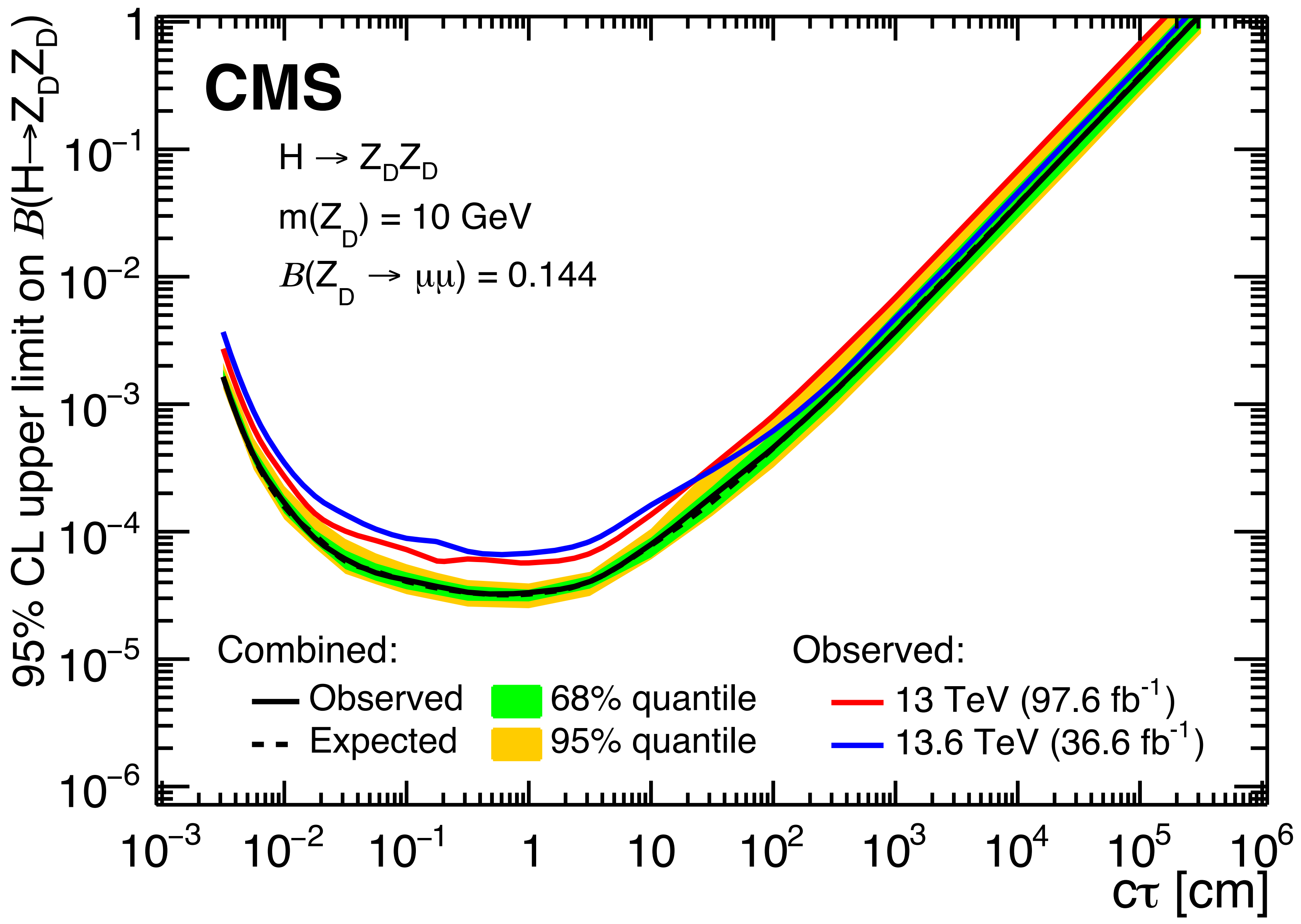




Observed data **consistent with SM predictions** in all search regions

# **LLPs to Muon Pairs**: Results

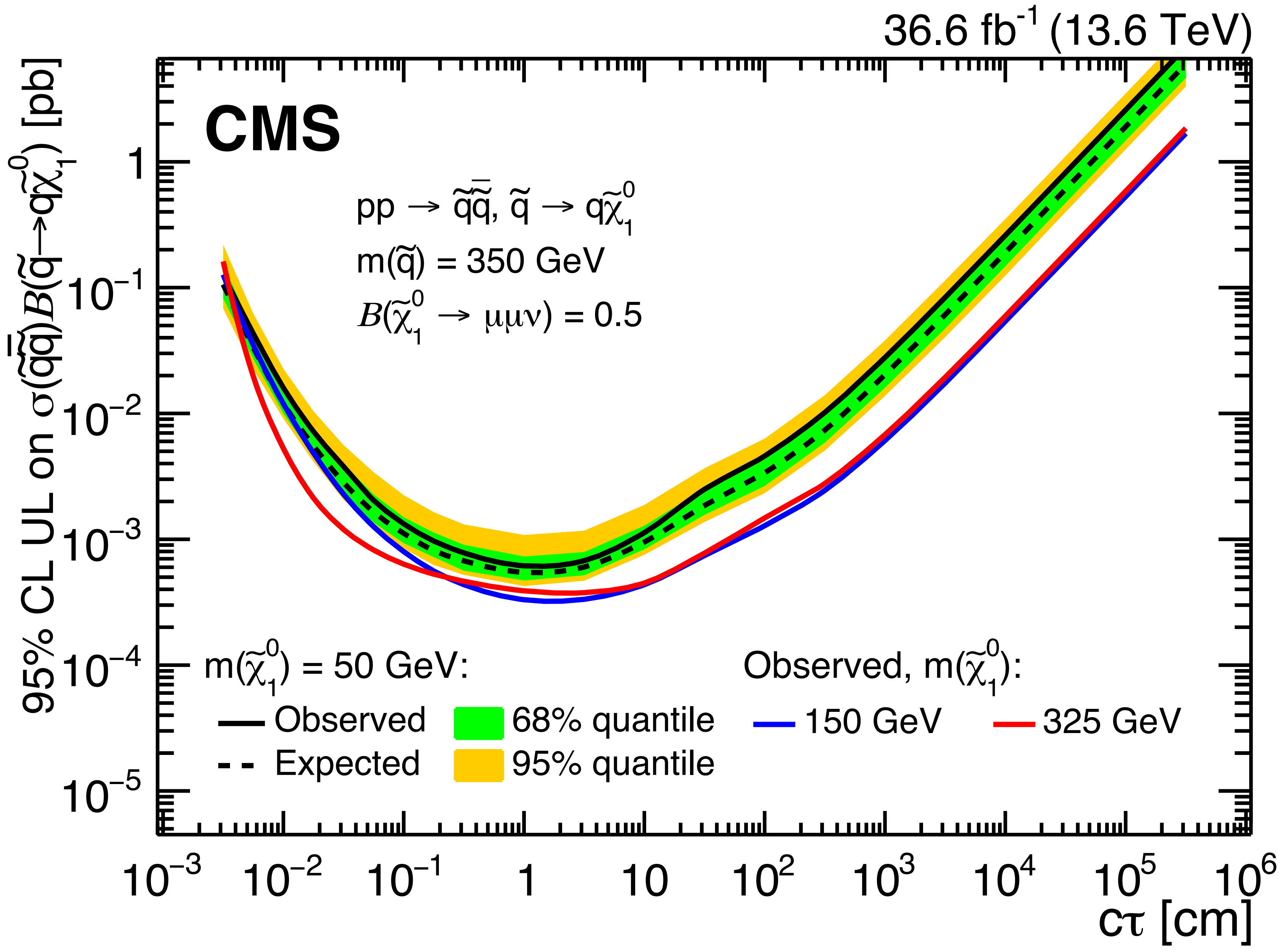
- Results interpreted in terms of the two benchmark models
- Improved sensitivity on both models compared to existing results in a wide region of the parameter space
- (Partial) Run 3 results competitive or better (at high displacement) than Run 2

**Dark-photon model -** Combined with Run 2




- Run 2 (97.6 $fb^{-1}$)
- Run 3 (36.6 $fb^{-1}$)

**RPV-SUSY model -** New in Run 3



# Summary

- Inclusive searches of LLP give access to a broad range of new physics models
- The presented results improve existing limits in wide regions of the parameter space for different BSM scenarios
- Large ongoing effort in CMS to improve LLP searches
  - Trigger developments
  - Reconstruction of Long-lived objects
  - Innovative (data-driven) background estimation methods
  - …
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The future for LLP searches at CMS looks promising and many more (Run 3) results are on the way… Stay tuned!

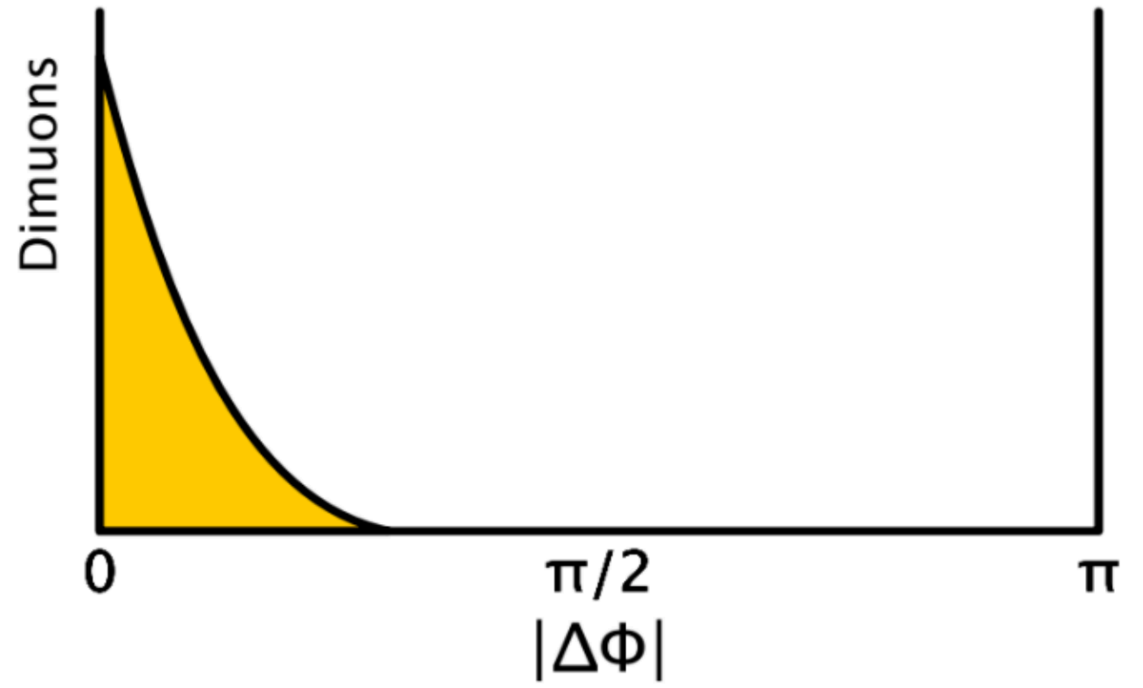
# Backup

# **LLPs decaying to a pair of muons**: Backgrounds

No genuine LLPs with $\mathrm{m}_{\mu\mu} > 10$ GeV in the SM
→ backgrounds are due to **instrumentation/reconstruction mistakes**

**$|\Delta\phi|$ - asymmetric (QCD)**

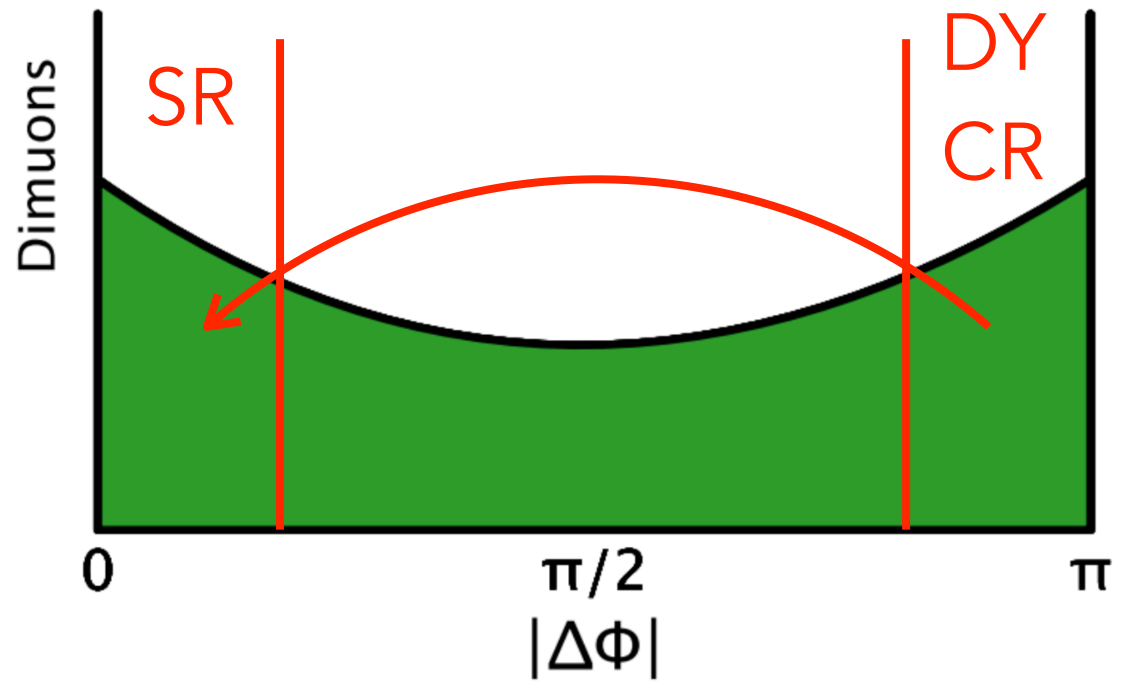
- Low mass resonances
- Cascade decays (e.g. from B hadrons)



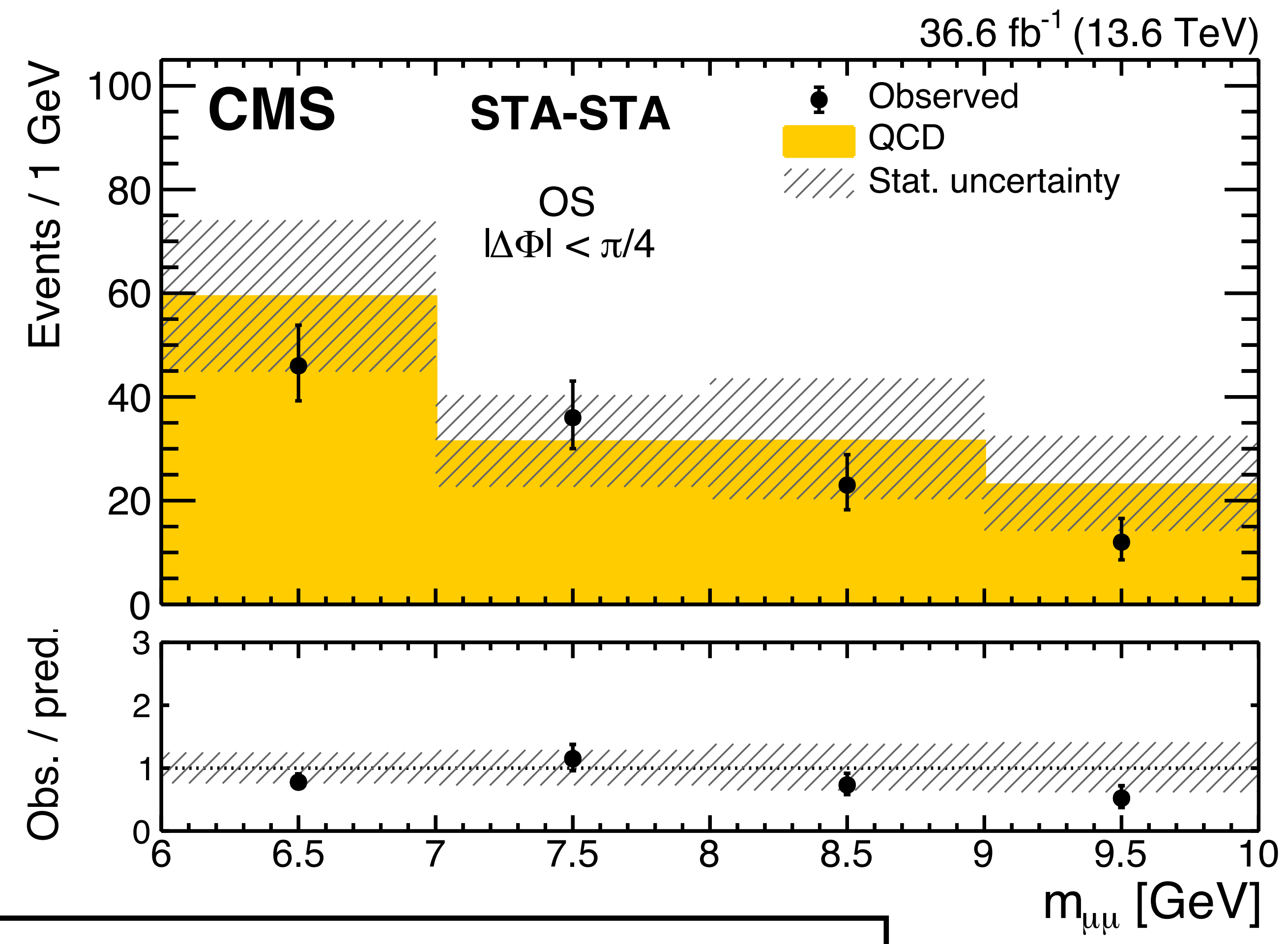

Estimated in data control regions with Same-Sign (SS) muons and non-isolated muons

**$|\Delta\phi|$ - symmetric (DY)**

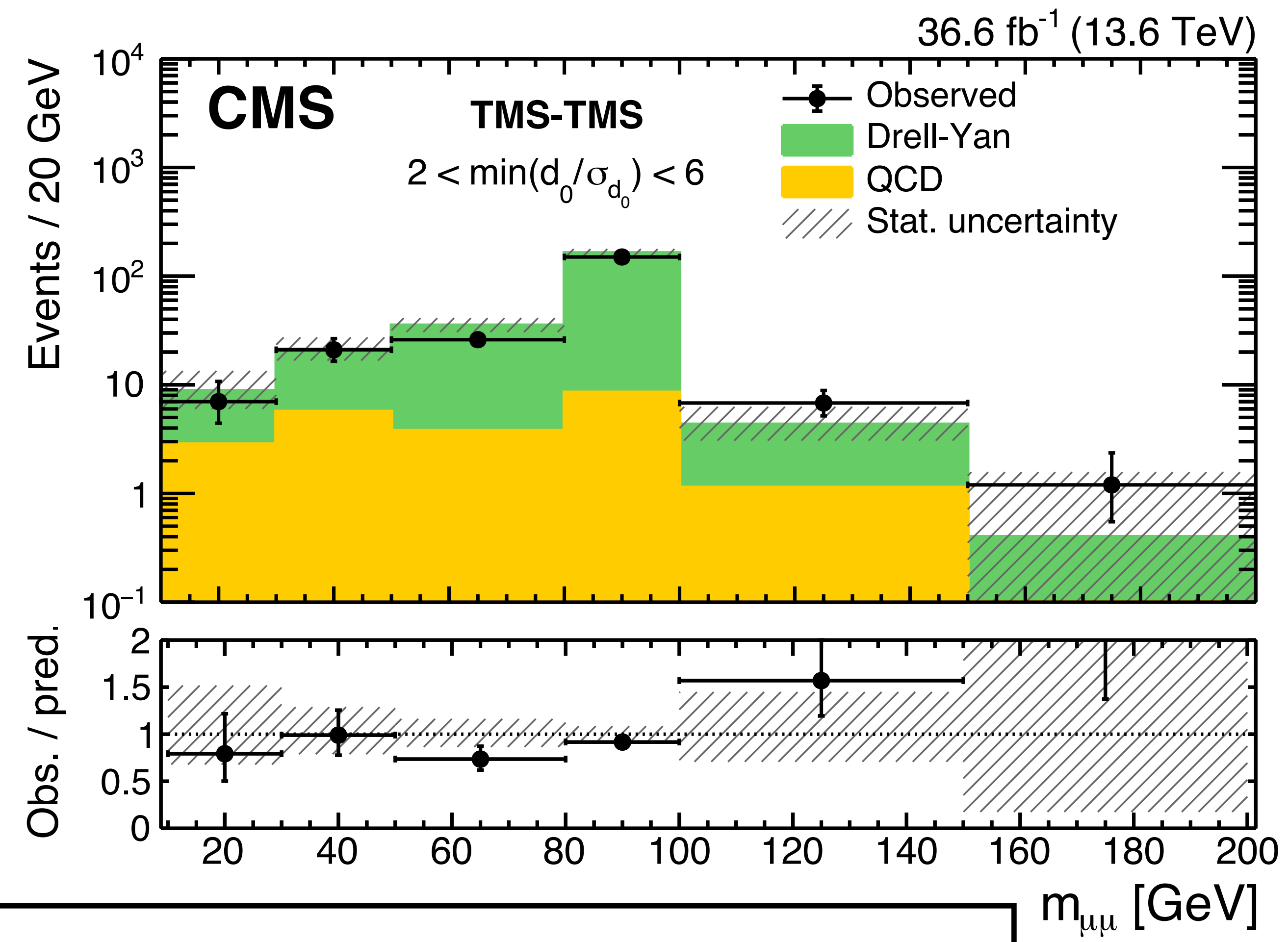
- Prompt dimuons from Drell-Yan (DY), $t\bar{t}$ and dibosons
- Cosmic rays, …




Evaluated from opposite, symmetric $|\Delta\phi|$ data control region




Low mass validation region




Low $\min(\mathrm{d}_0/\sigma_{\mathrm{d}_0})$ validation region