FERMILAB-SLIDES-26-0066-CMS

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CMS

May 11, 2026

# Recent Highlights of Dark Matter Searches from CMS

**Murtaza Safdari,** for the CMS Collaboration
Pheno 2026 Symposium, University of Pittsburgh
Dark Matter Theory and Detection: *Link to Indico*

Φαινό 2026
**The 2026 Phenomenology Symposium**
*An odyssey through particle physics and related encounters in astrophysics and cosmology*

U.S. DEPARTMENT of ENERGY
Fermi National Accelerator Laboratory is managed by FermiForward for the U.S. Department of Energy Office of Science

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# Why look for Dark Matter at Colliders?

Comprehensive coverage for DM searches using all available tools

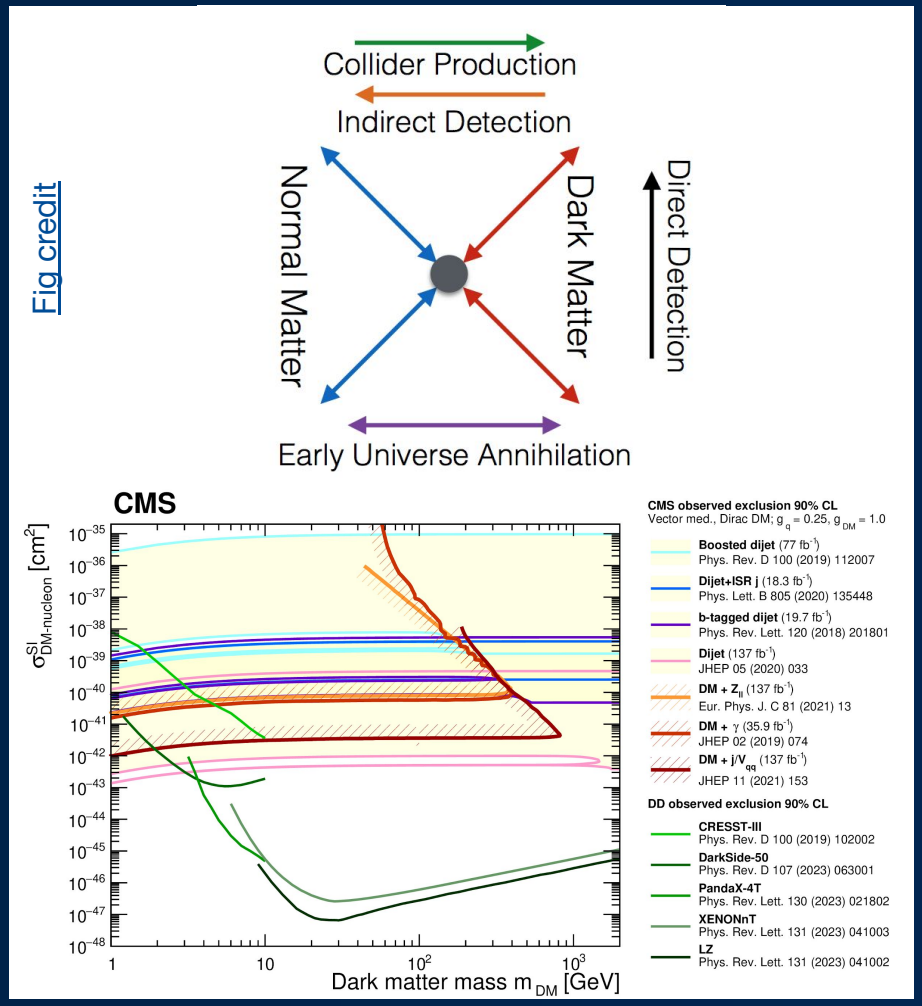
**Complementarity to the Broader Program**

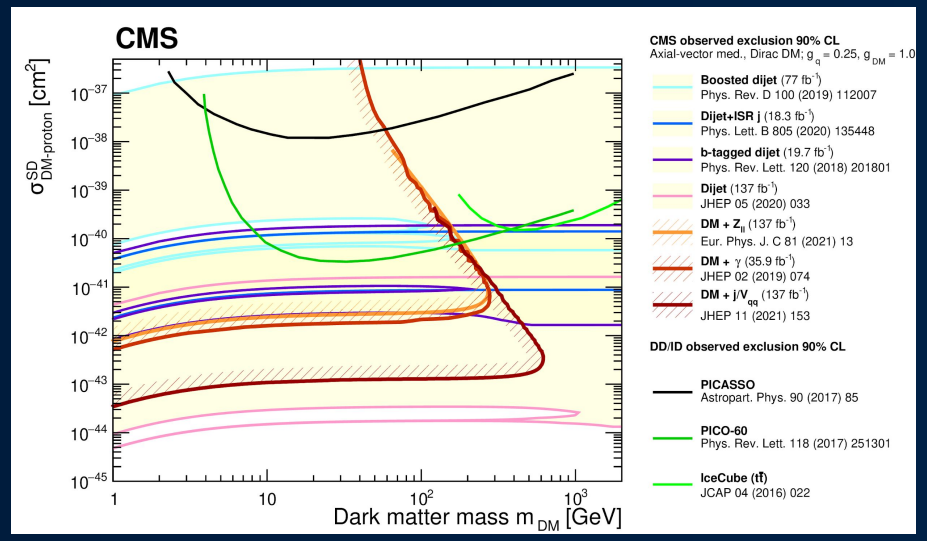
**Direct Access to Mediators**

**Insensitivity to Cosmological Assumptions**

**Probing the Low-Mass Regime**

**Mapping Complex Dark Sectors**



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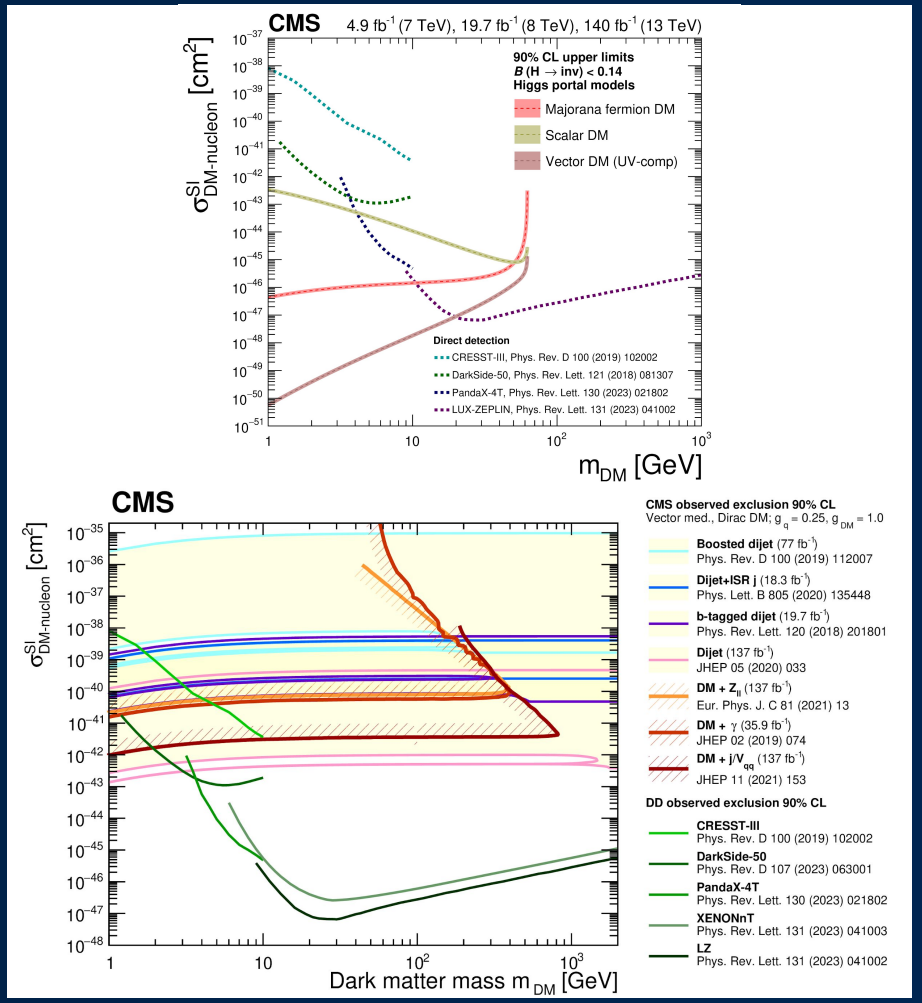


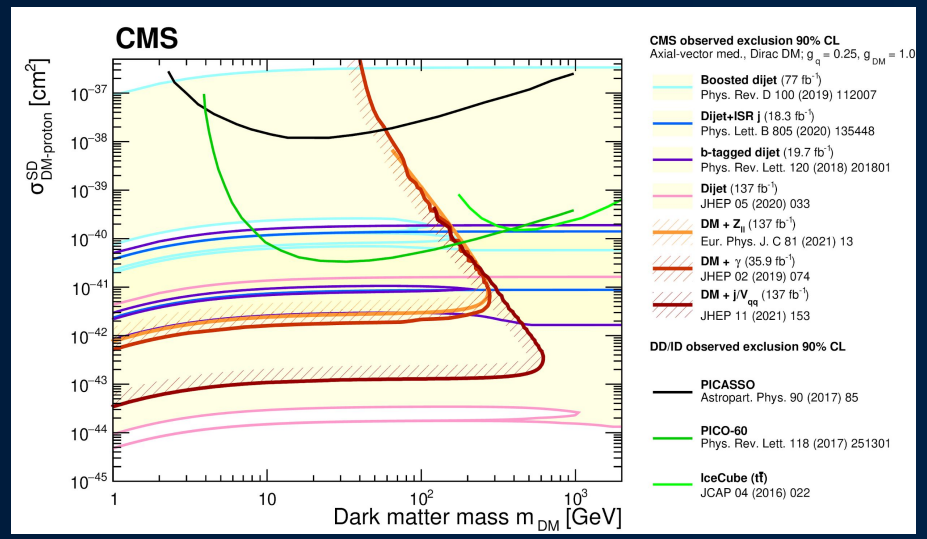

# The CMS Experiment

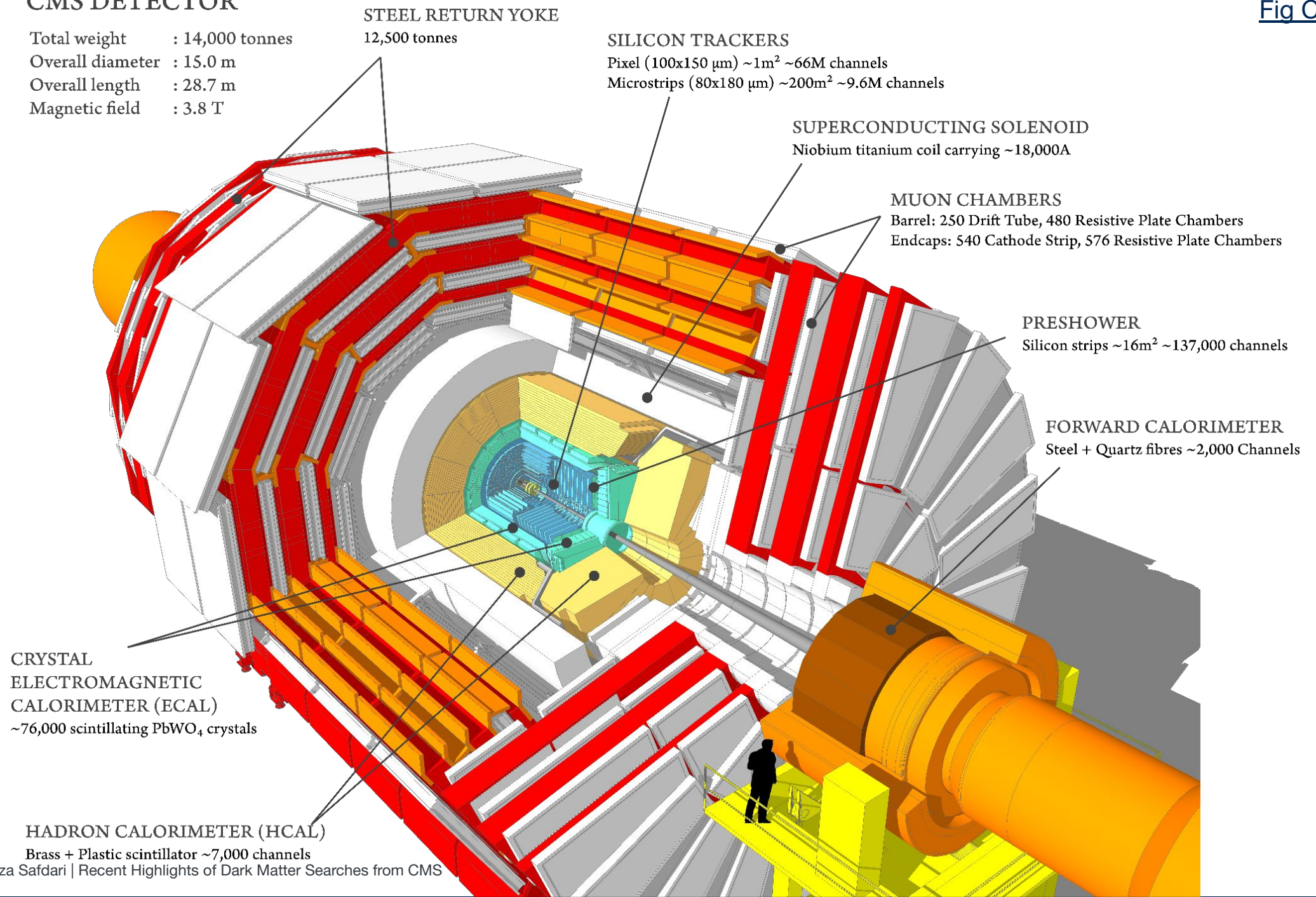


Fig Credit

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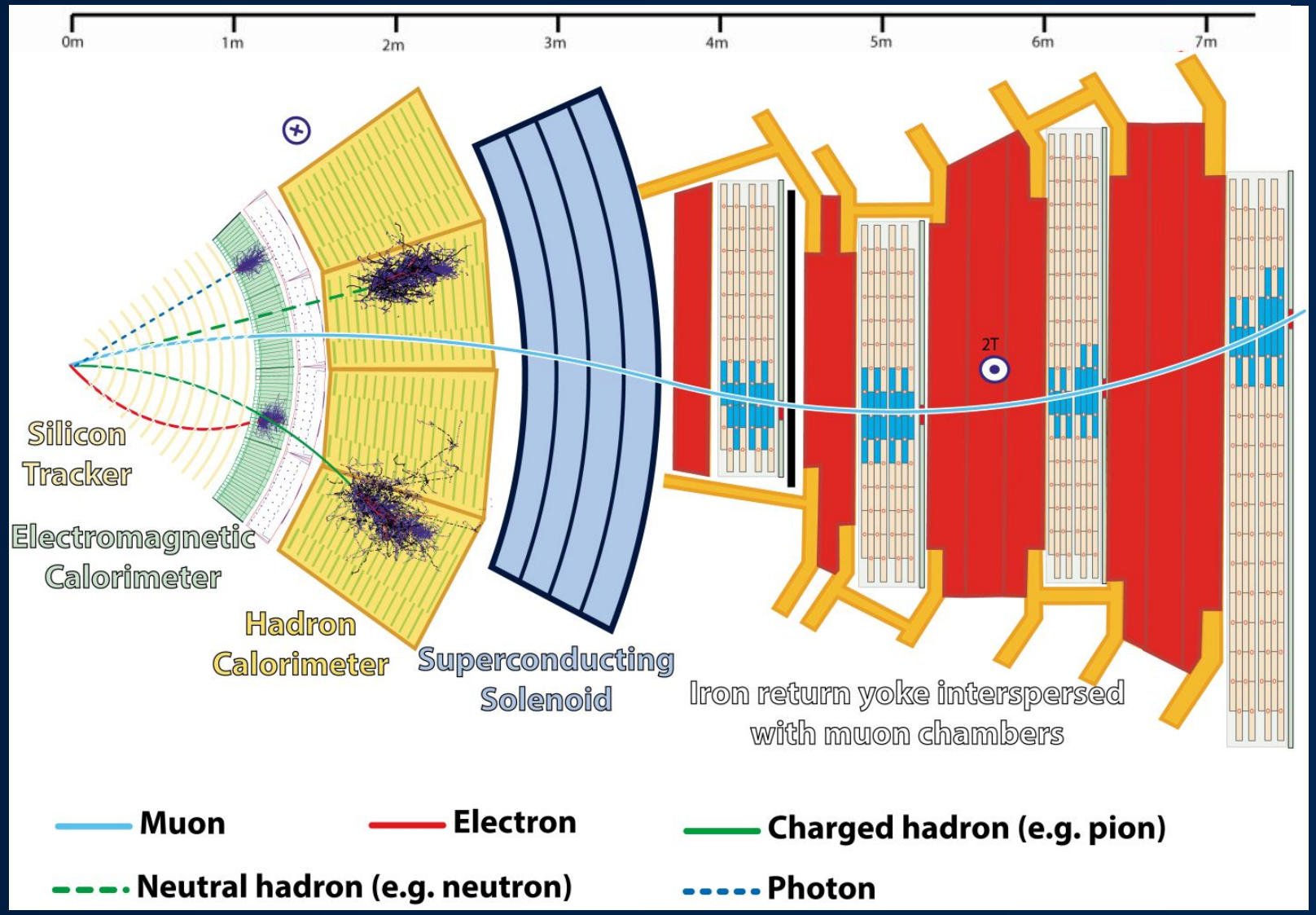

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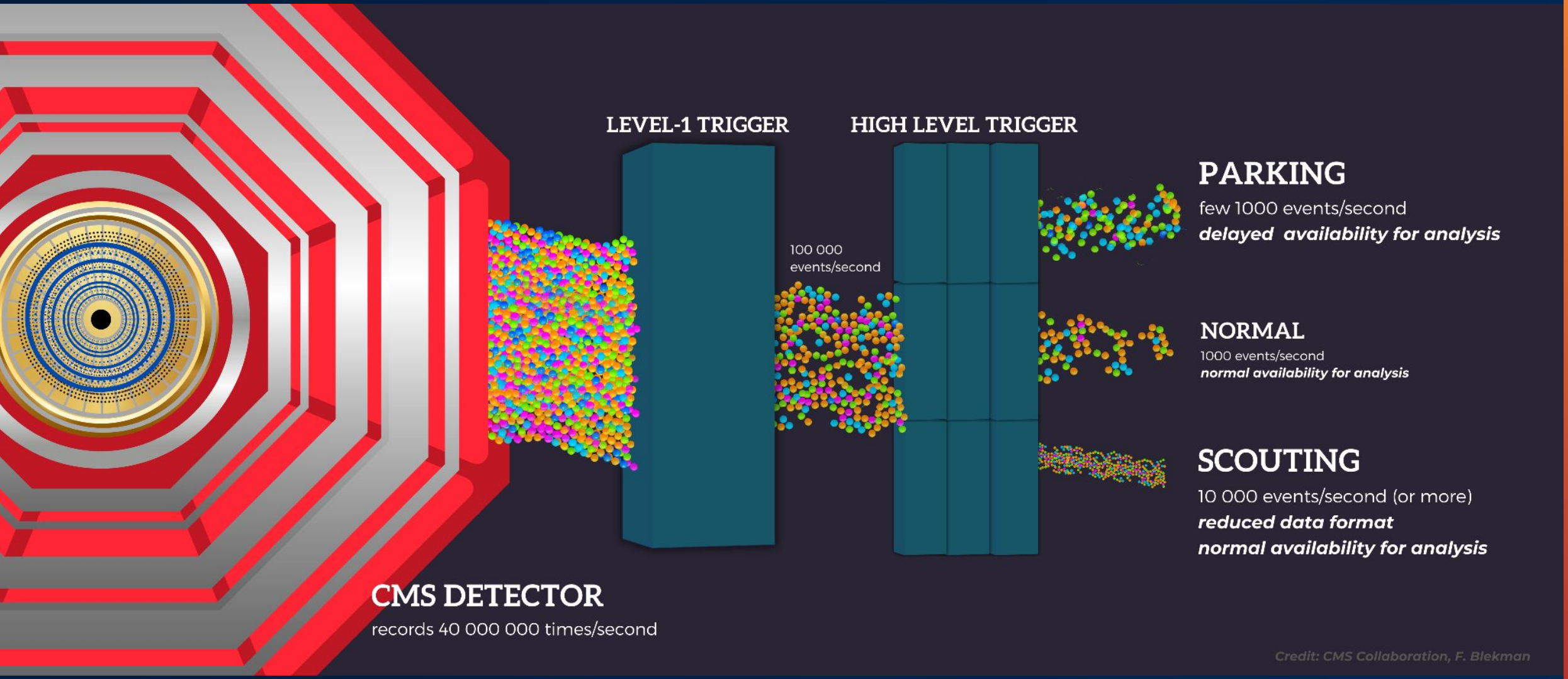


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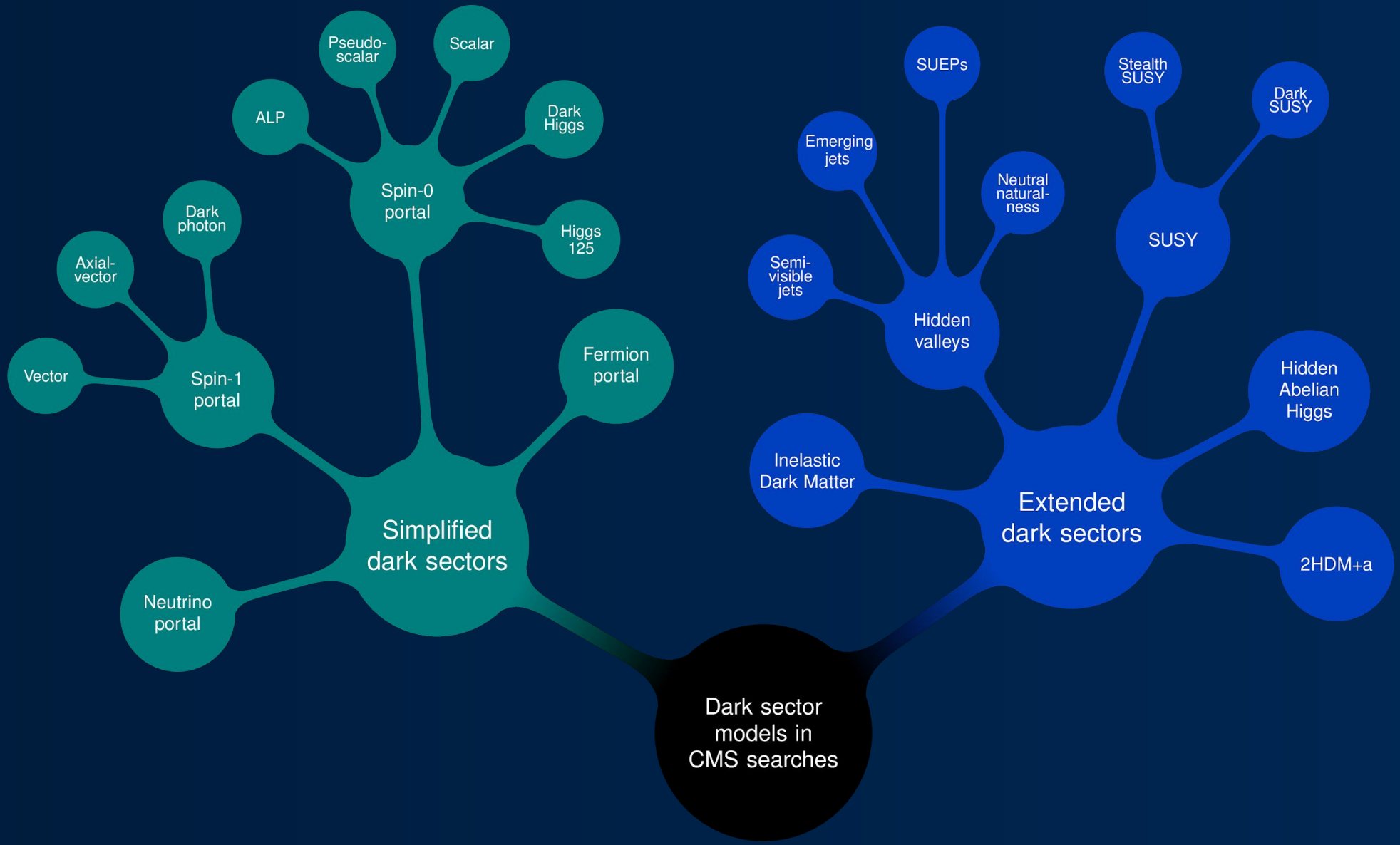
CMS EXO-23-005

# CMS Dark Matter Horizon

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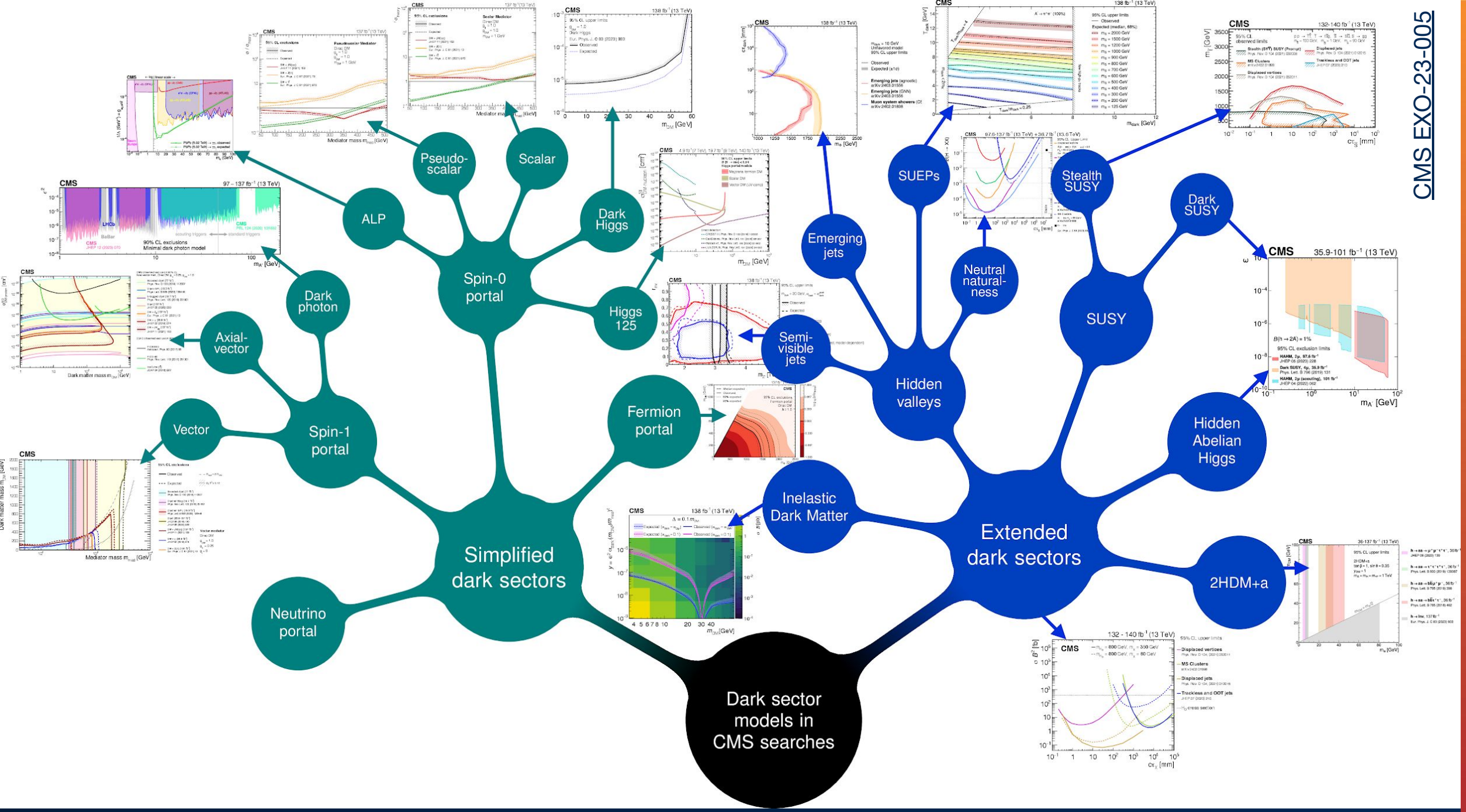

Dark sector models in CMS searches
Simplified dark sectors
Spin-0 portal
Pseudo-scalar
Scalar
ALP
Dark Higgs
Higgs 125
Spin-1 portal
Dark photon
Axial-vector
Vector
Fermion portal
Neutrino portal
Extended dark sectors
SUEPs
Emerging jets
Neutral natural-ness
Hidden valleys
Semi-visible jets
Inelastic Dark Matter
SUSY
Stealth SUSY
Dark SUSY
Hidden Abelian Higgs
2HDM+a
CMS EXO-23-005

# High pT / MET Searches

- Search for new charged gauge bosons in the e/μ + $p_T^{miss}$ channel
- Search for dark matter produced in association with a Higgs boson decaying to bottom quarks
- Search for dark matter produced in association with a dark Higgs boson decaying into a bottom quark pair

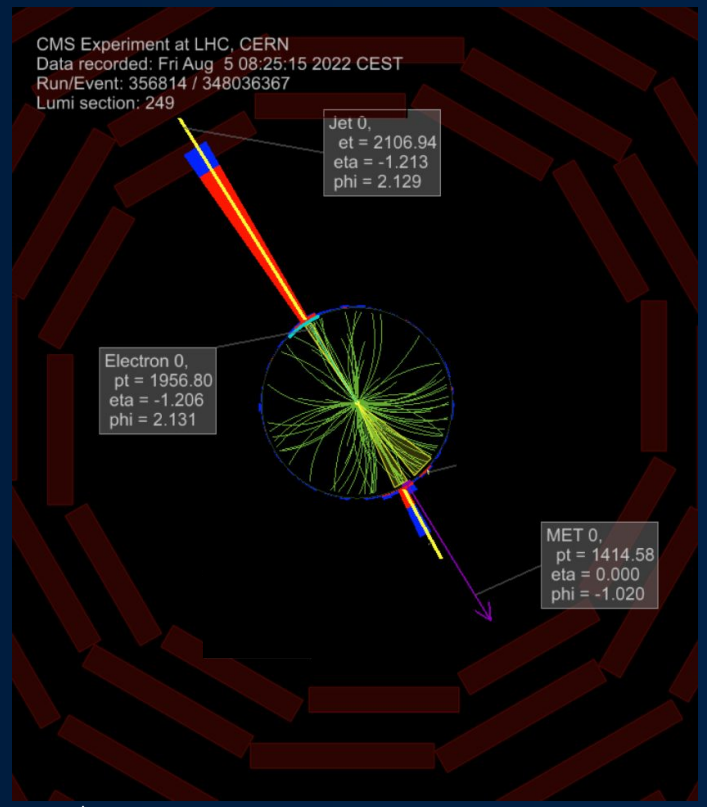
# High Energy pp→W′→lν

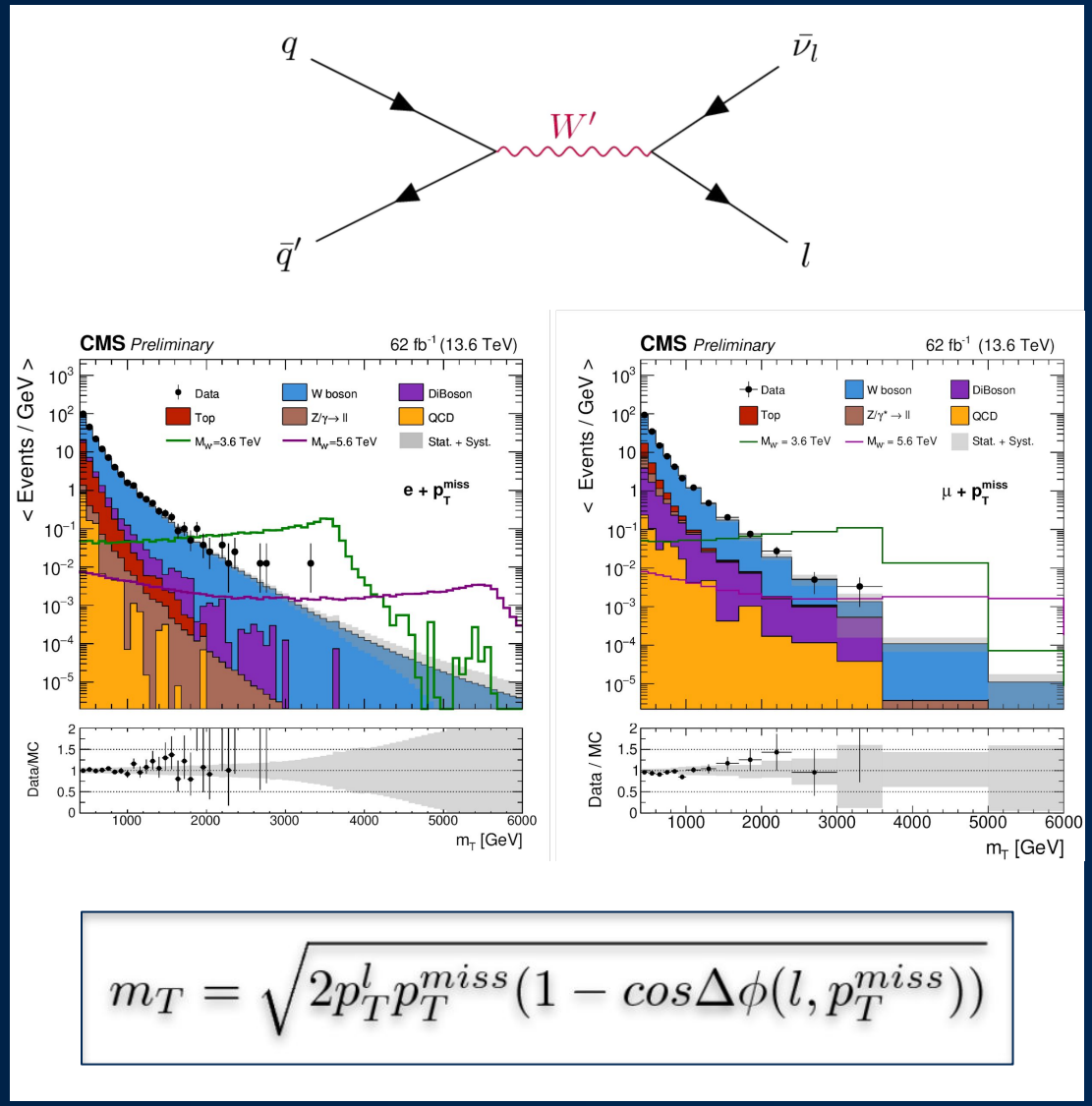
## Search for new charged gauge bosons in the e/μ + pTmiss channel

**Dataset & Triggers:** 62 1/fb of Run 3 data at s=13.6 TeV (2022-2023). Events are captured using single high-pT electron (ET>115 GeV) and muon (pT>50 GeV) triggers.

**Topology:** Heavy mediator W′→ℓν (High-pT lepton + aligned pTmiss)

**Methods:** Requires a highly energetic lepton & kinematics must be balanced (0.4<pTℓ/pTmiss<1.5) and back-to-back (Δϕ(ℓ,pTmiss)>2.5).




$$m_T = \sqrt{2p_T^l p_T^{miss}(1 - cos\Delta\phi(l, p_T^{miss}))}$$

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**Methods:** Requires a highly energetic lepton & kinematics must be balanced (0.4<pTℓ/pTmiss<1.5) and back-to-back (Δϕ(ℓ,pTmiss)>2.5).

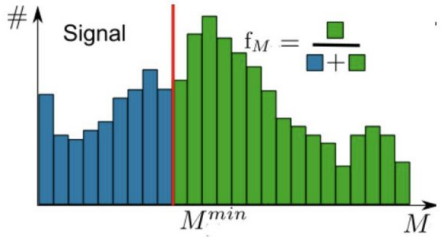
**Background:** Irreducible off-shell SM W→ℓν (Precision modeling via NNLO QCD + NLO EW K-factors).

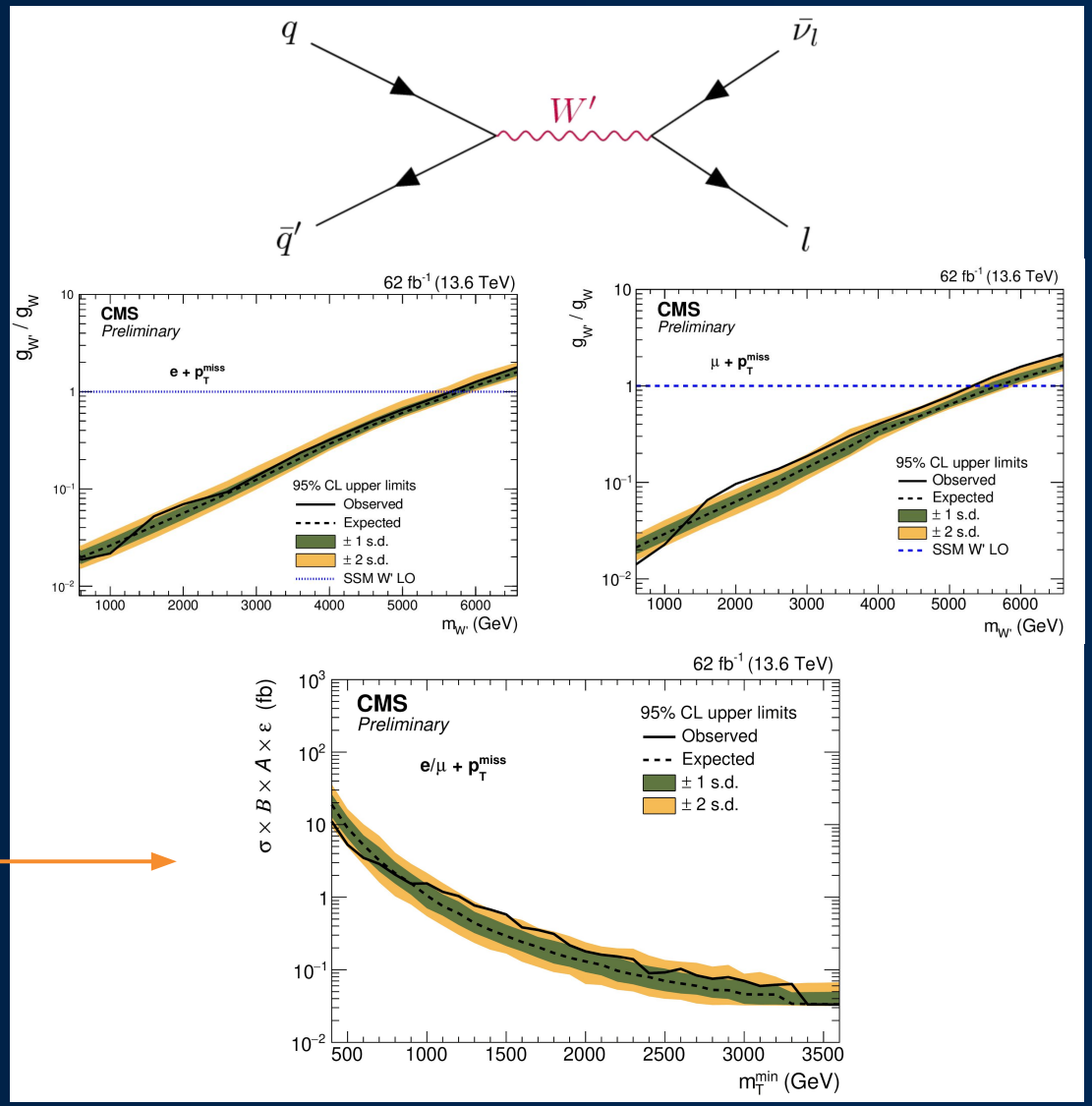
**Results:** Data consistent with SM out to mT>4 TeV (mild 2.6$\sigma$ local fluctuation at 2 TeV)

**Impact:** Excludes W′ up to 5.9 TeV; provides model-independent limits for direct dark sector reinterpretation.

### *Model Independent (MI) Limit*

- Using a single bin approach integrating $m_T$ from $m_T^{min}$ to infinity
- Set limit on $\sigma \times \mathcal{B} \times A \times \varepsilon$



# pp→Z′/A→χχh

## Search for dark matter produced in association with a Higgs boson decaying to bottom quarks

**Dataset:** 138 1/b (Full Run 2 Combination) via high-ptmiss triggers

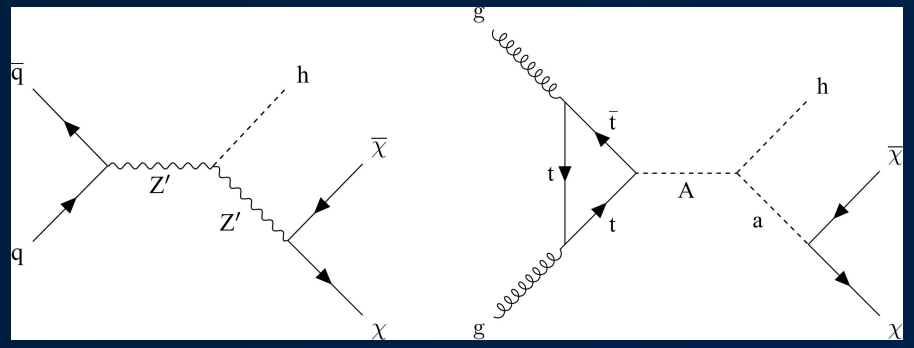
**Topology:** 125 GeV SM Higgs (h→bb) produced in association with escaping Dark Matter (ptmiss). Probes Baryonic-Z' and 2HDM+a models by using the SM Higgs as the bridge to the dark sector.

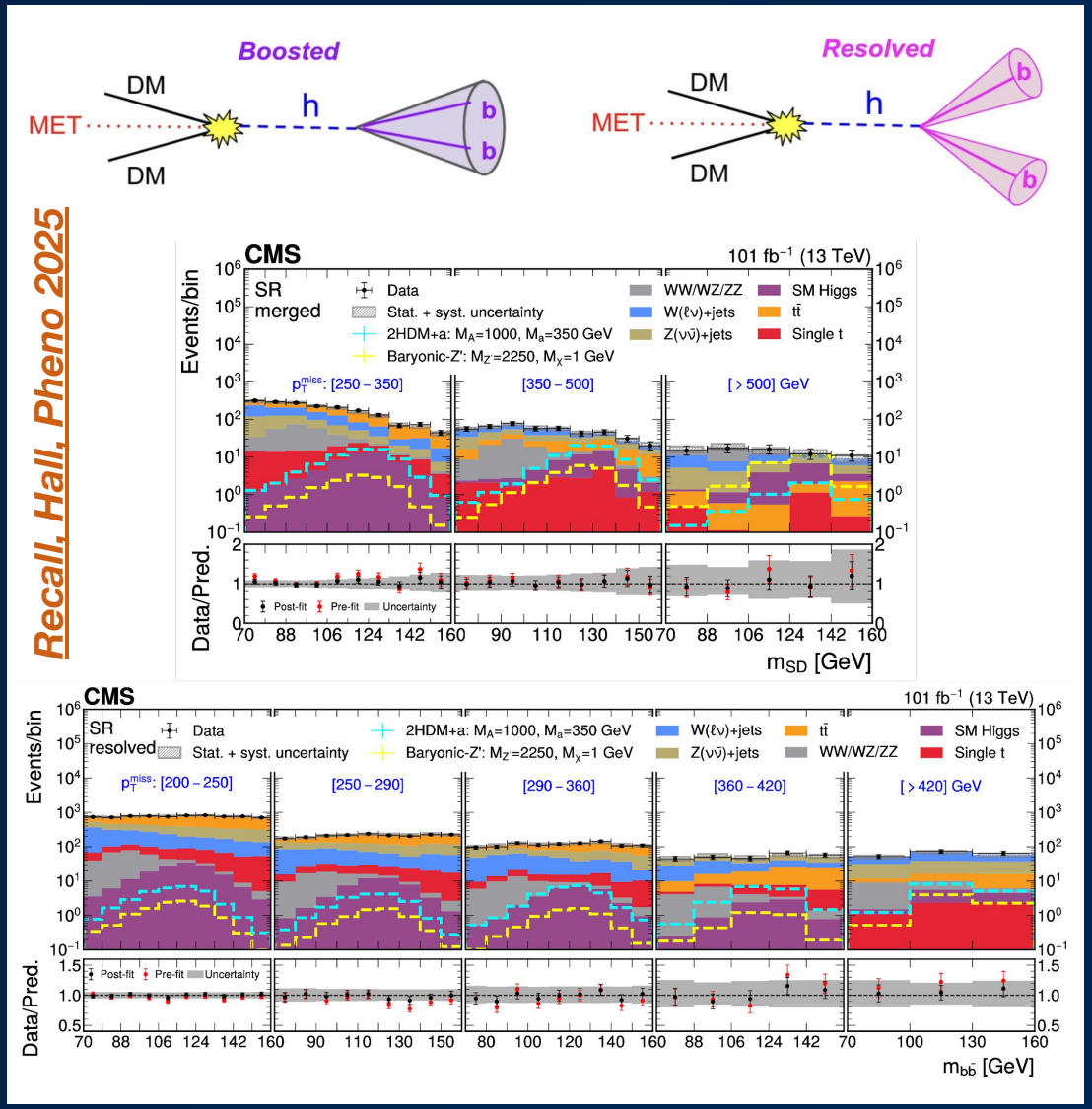
**Methods:** Categorized by Lorentz boost:

- **Merged:** 1 AK8 fat jet (ParticleNet-MD double-b tag)
- **Resolved:** 2 AK4 jets (DeepJet b-tag)

**Background:** Irreducible tt and Zνν+jets (Simultaneous binned-likelihood fit of the h-mass across ptmissand lepton CRs)

**Results:** Data consistent with the SM background model
**Impact:** Excludes Baryonic-Z' up to 2.1 TeV; tight constraints placed on 2HDM+a parameter space



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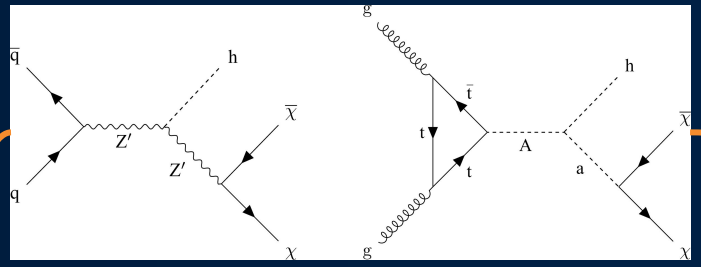
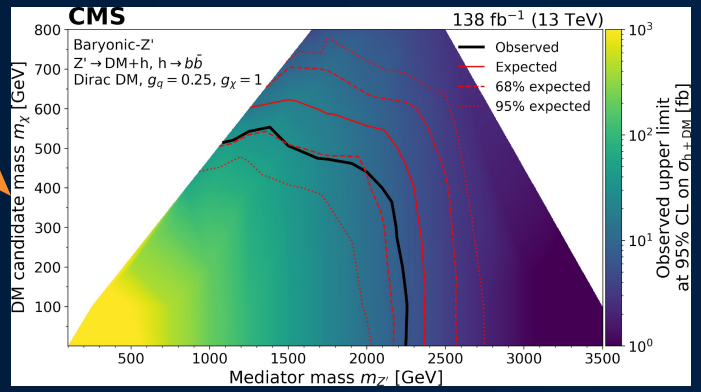
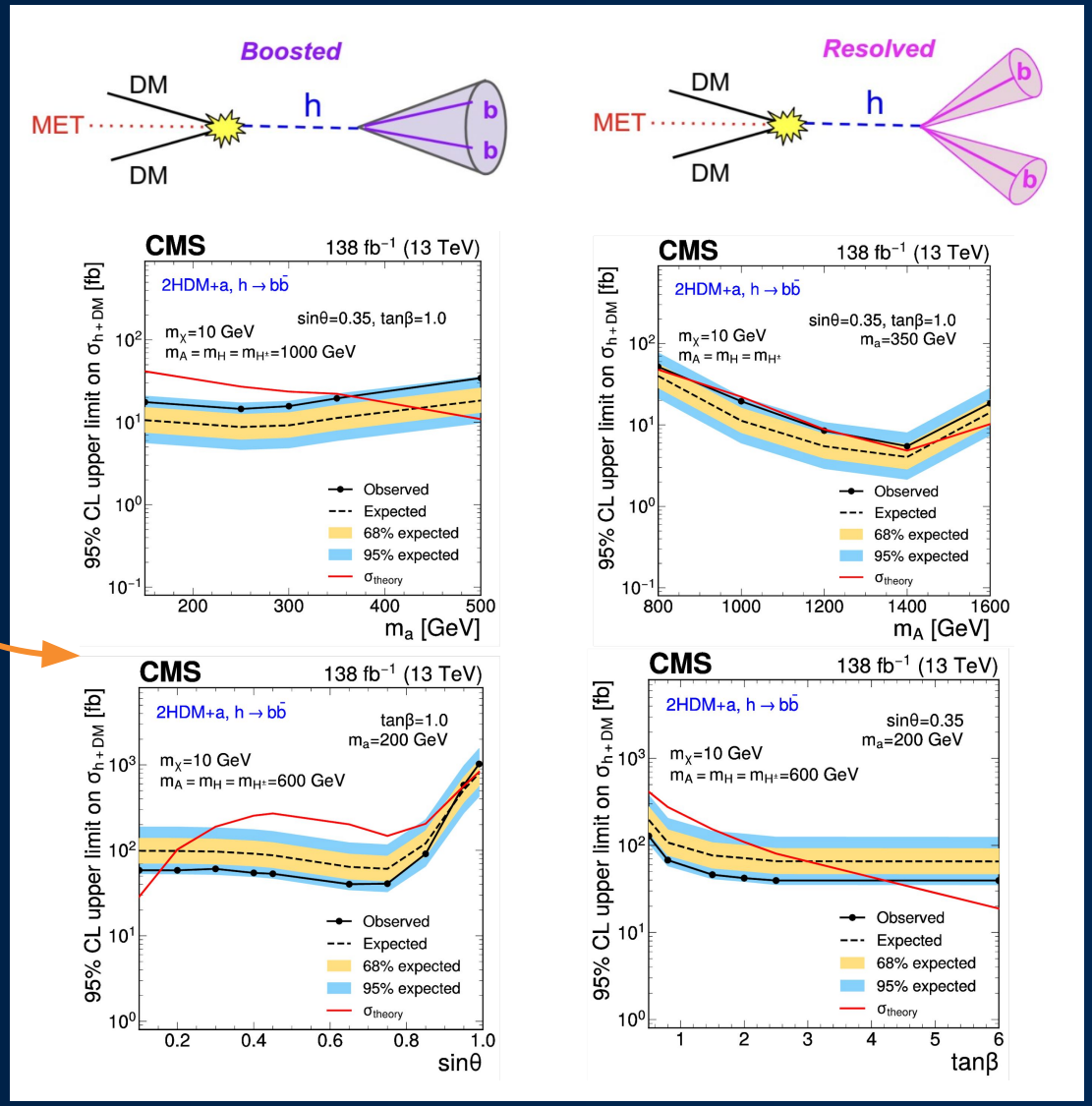


# $pp \to Z' \to \chi\chi s$, with $s \to b\bar{b}$

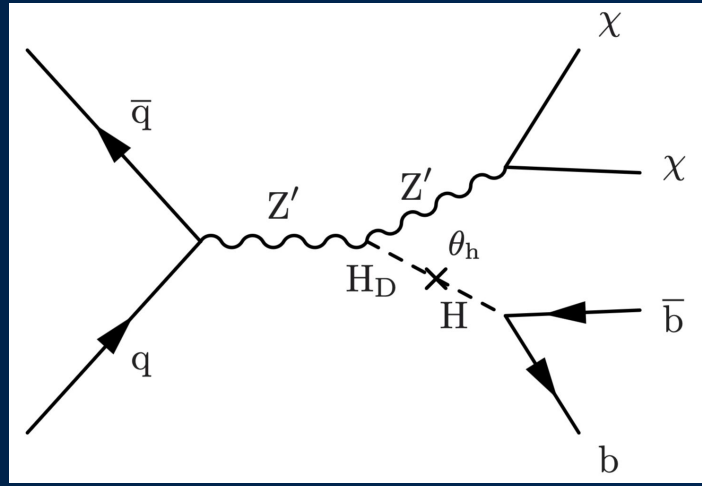
## Search for dark matter produced in association with a dark Higgs boson decaying into a bottom quark pair

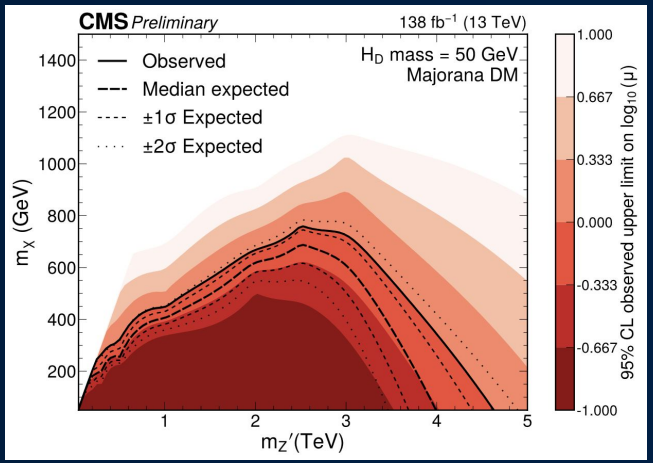
**The Physics Model:** Targets a vector mediator (Z′) that decays to dark matter (χ) while radiating a Dark Higgs ($s \to b\bar{b}$). Probes complex dark sectors that feature their own internal mass-generation mechanism, communicating back to our world via mixing with the Standard Model Higgs.

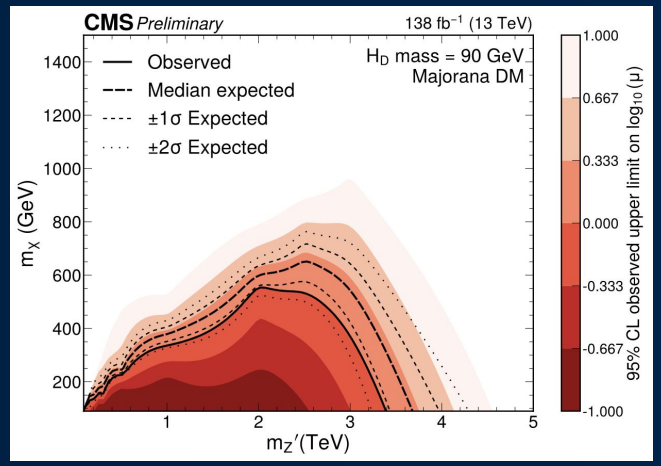
**The Observable:** Signal extraction relies on a 2D fit of the missing transverse momentum (pTmiss) and the invariant mass of the Dark Higgs candidate

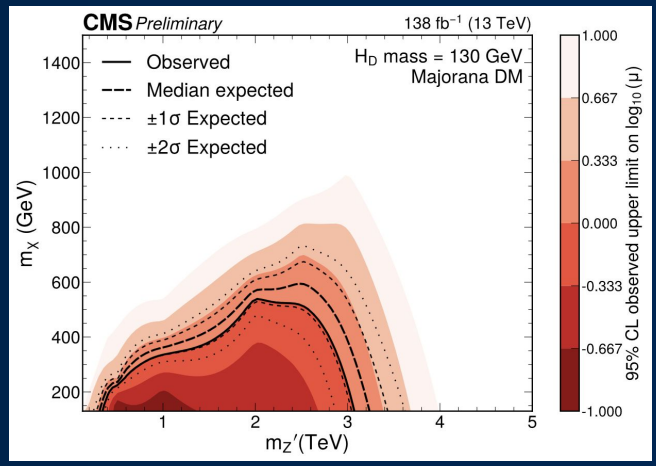
**The Results:** No significant localized excess is observed in the mbb spectrum across either the resolved or boosted regimes.

Stay tuned for the next talk by Erdem!



# Kinematic Blind Spots

- Search for soft unclustered energy patterns using CMS data scouting
- Search for soft unclustered energy patterns produced in association with a W/Z boson
- Search for dark matter produced in association with a boosted large-radius jet
- Search for s-channel production of τ-enriched semivisible jets

# Soft Showers - Hidden valley models

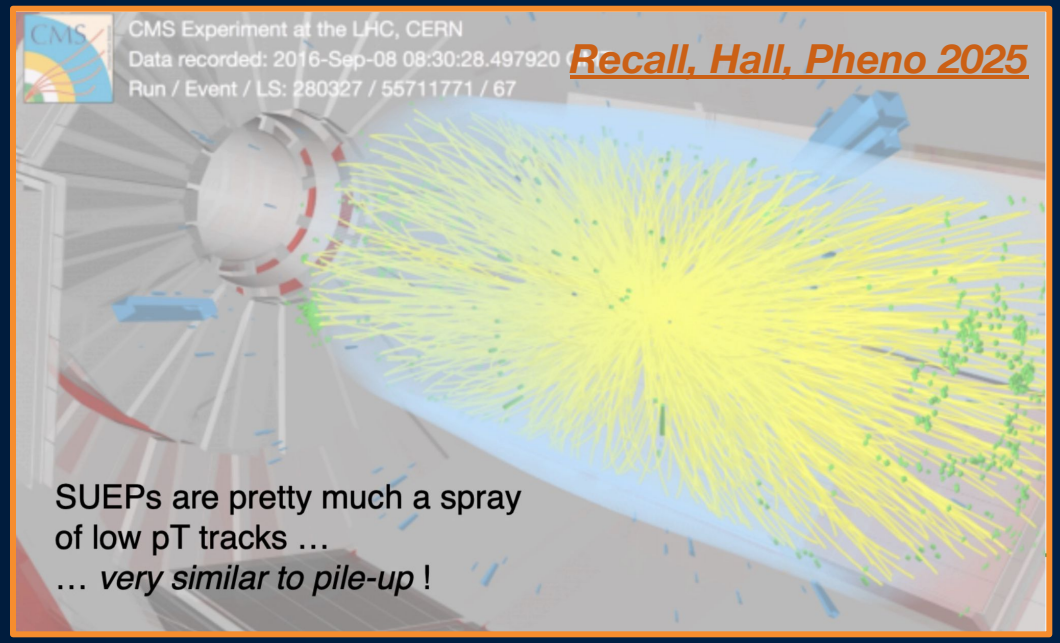
## Search for soft unclustered energy patterns using CMS data scouting

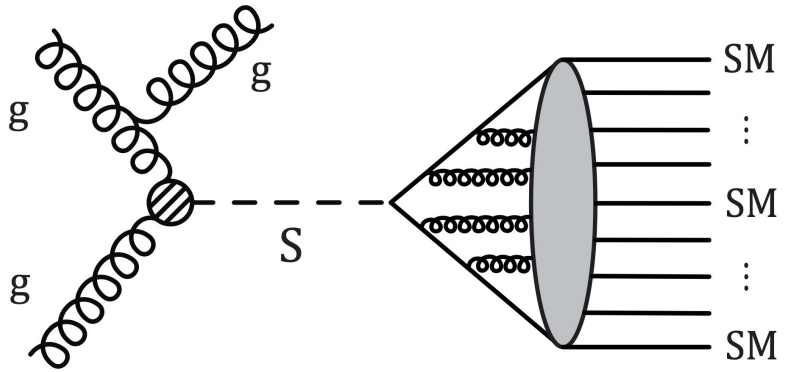
**Dataset & Triggers:** 127 1/fb of Run 2 data using the **CMS Data Scouting stream**. By bypassing offline reconstruction, the HT trigger threshold was lowered from 1200 GeV down to 410 GeV.

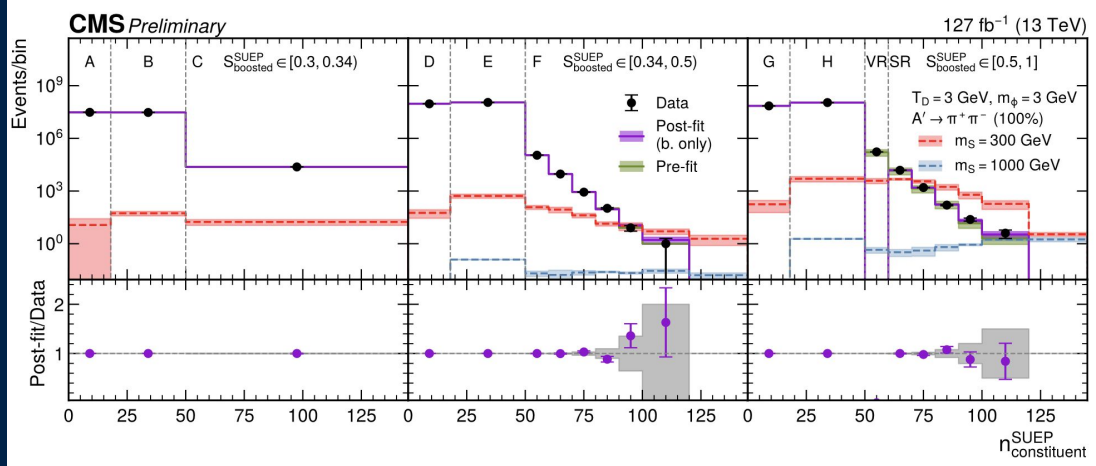
**Topology:** Heavy scalar → Hidden Valley (Visible soft SUEP + Escaping Dark Matter)

**Methods:** Massive AK15 jets (wide-cone) to capture diffuse, high-multiplicity, spherical tracks, recoiling against ISR jet

**Background Estimation:** The QCD multijet background is estimated with data-driven **9-region extended ABCD method**.




**Observables:** Signal extraction relies on two key variables: the track multiplicity within the SUEP cone, and the boosted sphericity (event shape) of the tracks.

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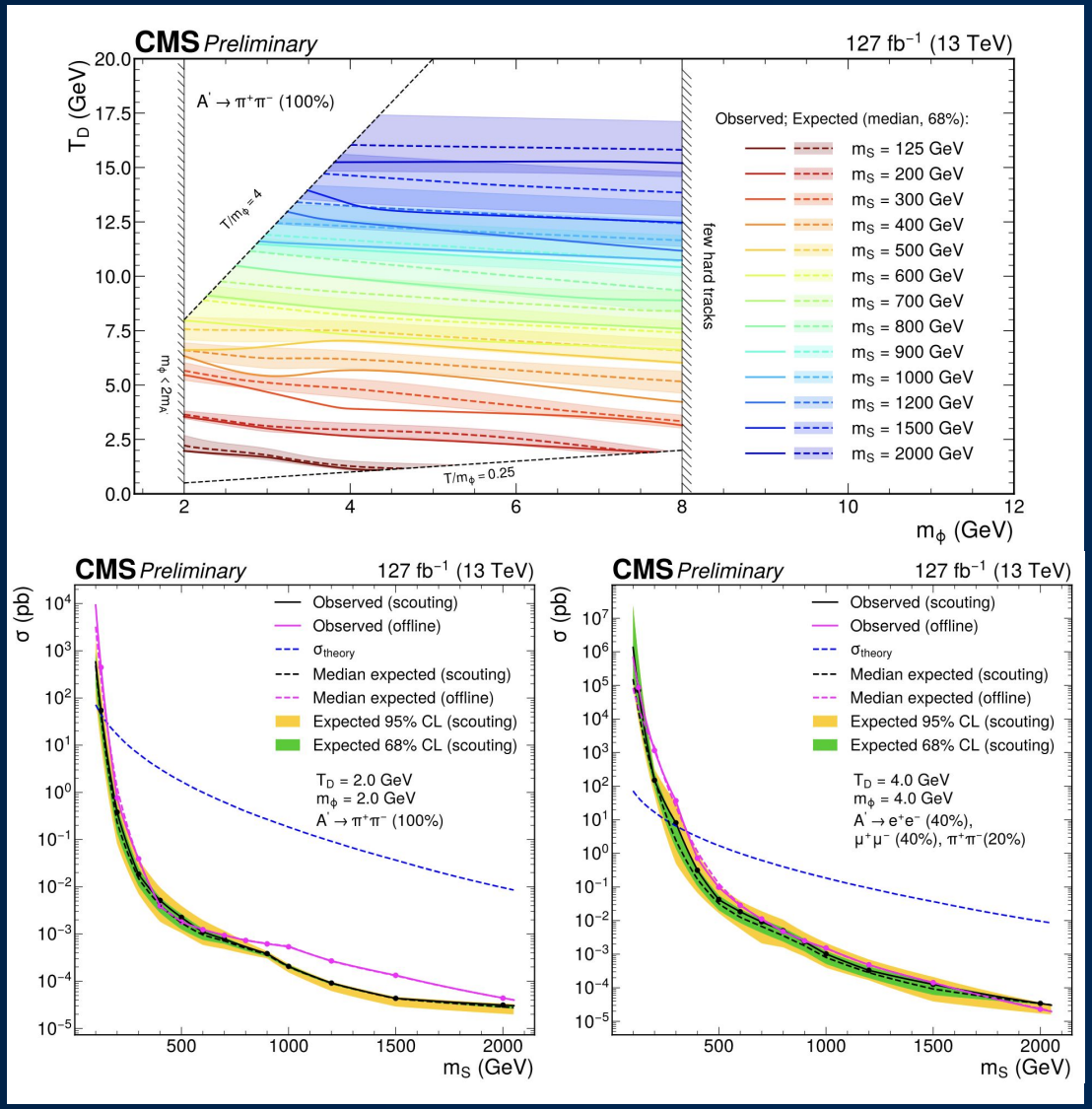
**Background Estimation:** The QCD multijet background is estimated with data-driven **9-region extended ABCD method**.

**Results:** Data perfectly matches SM background in high-sphericity signal region

**Impact:** Most stringent limits to date; Scouting trigger recovers massive low-HT phase space

Tune into Gianfranco's talk for more on the CMS SUEP analyses



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**Dataset & Triggers:** 138 1/fb Run 2 dataset. Highly efficient single and double electron/muon triggers.

**Topology:** Associated production (VH), testing the 125 GeV Higgs as the Dark Sector portal

**Methods:** Tag high-pT V-boson leptons → search recoiling system for soft, spherical SUEP

**Background Estimation:** The V+jets and $t\bar{t}$ backgrounds are estimated via extended data-driven ABCD method.

**Results:** Unblinding the highly spherical, high-multiplicity regions shows no significant deviation from the Standard Model V+jets prediction.

**Limits:** Provides constraints on the Higgs-to-SUEP branching fraction, digging deeper into the low-mass mediator parameter space than previously possible.

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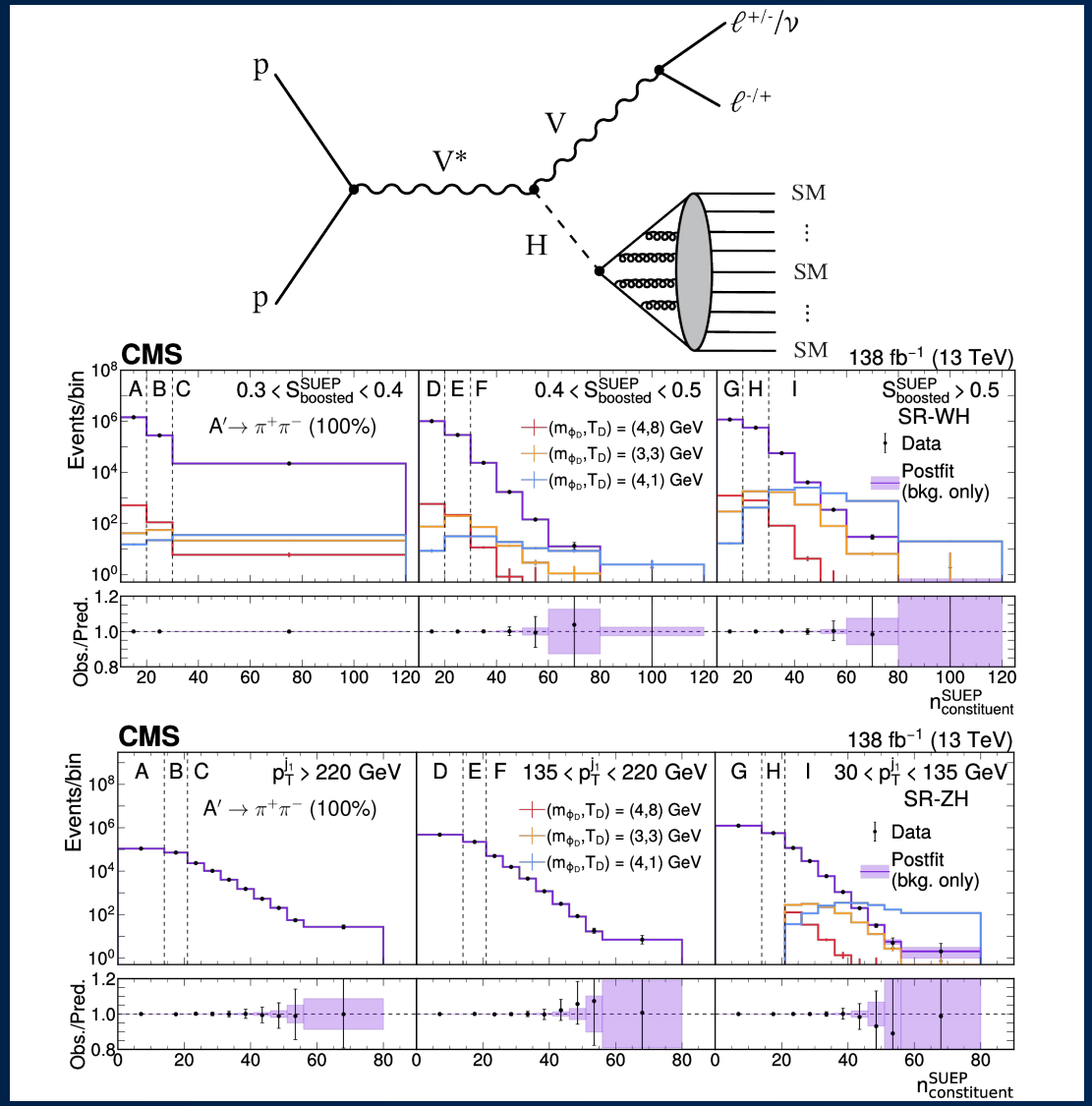

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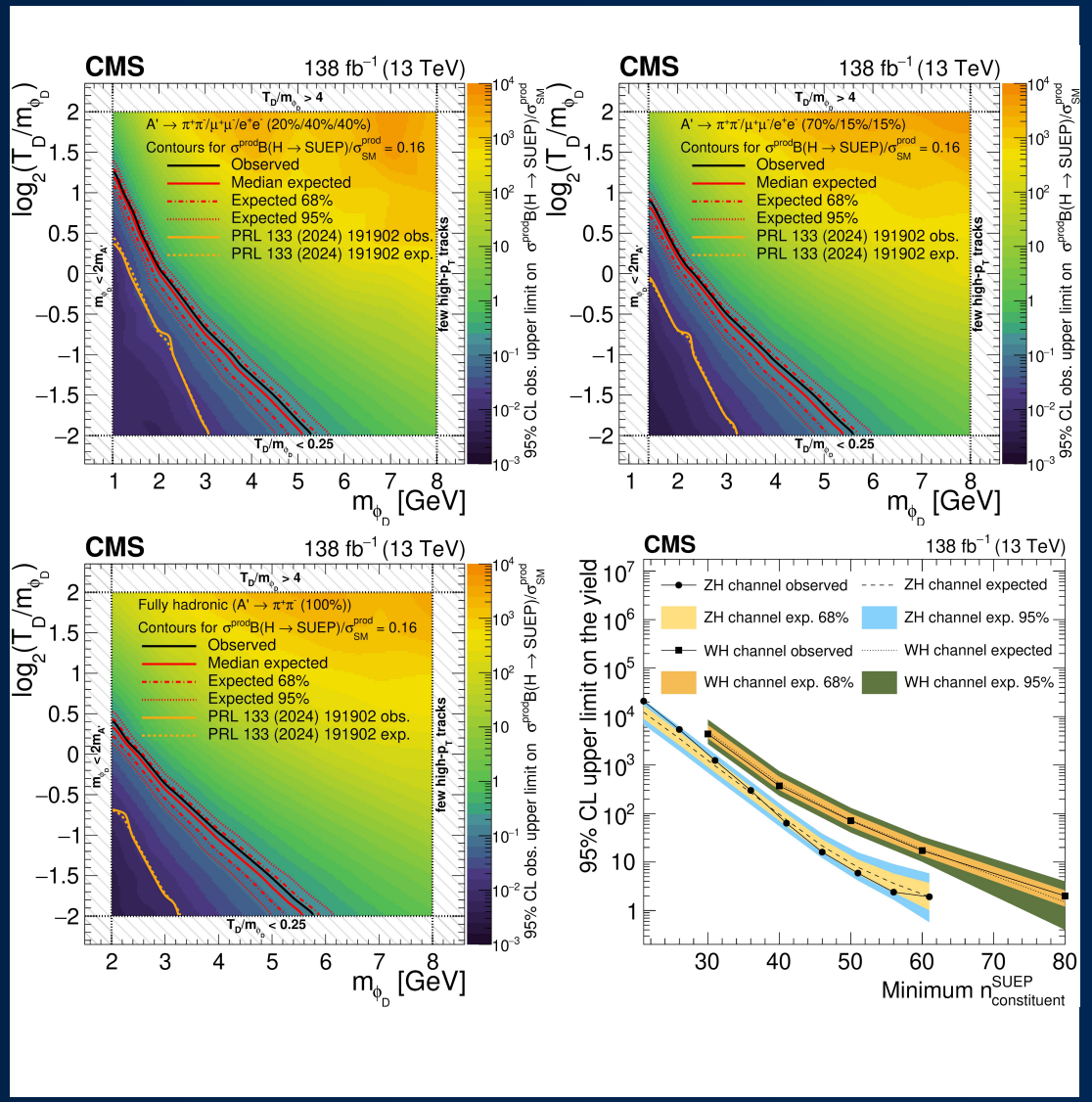


# Dark Matter hiding inside jets - iDM

## Search for dark matter produced in association with a boosted large-radius jet

**Dataset:** 138 1/fb data from(Run 2 via high-HT and AK8 jet triggers

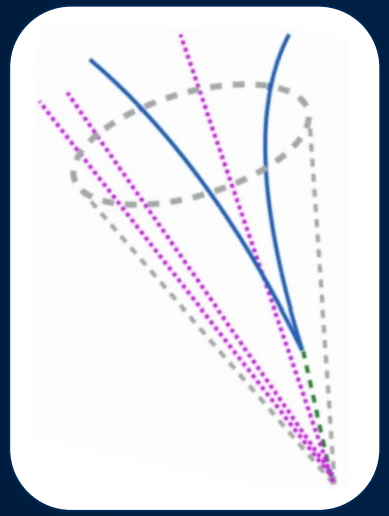
**Topology:** Inelastic DM (χ2→stable χ1+qq̄) overlapping inside a single boosted AK8 jet

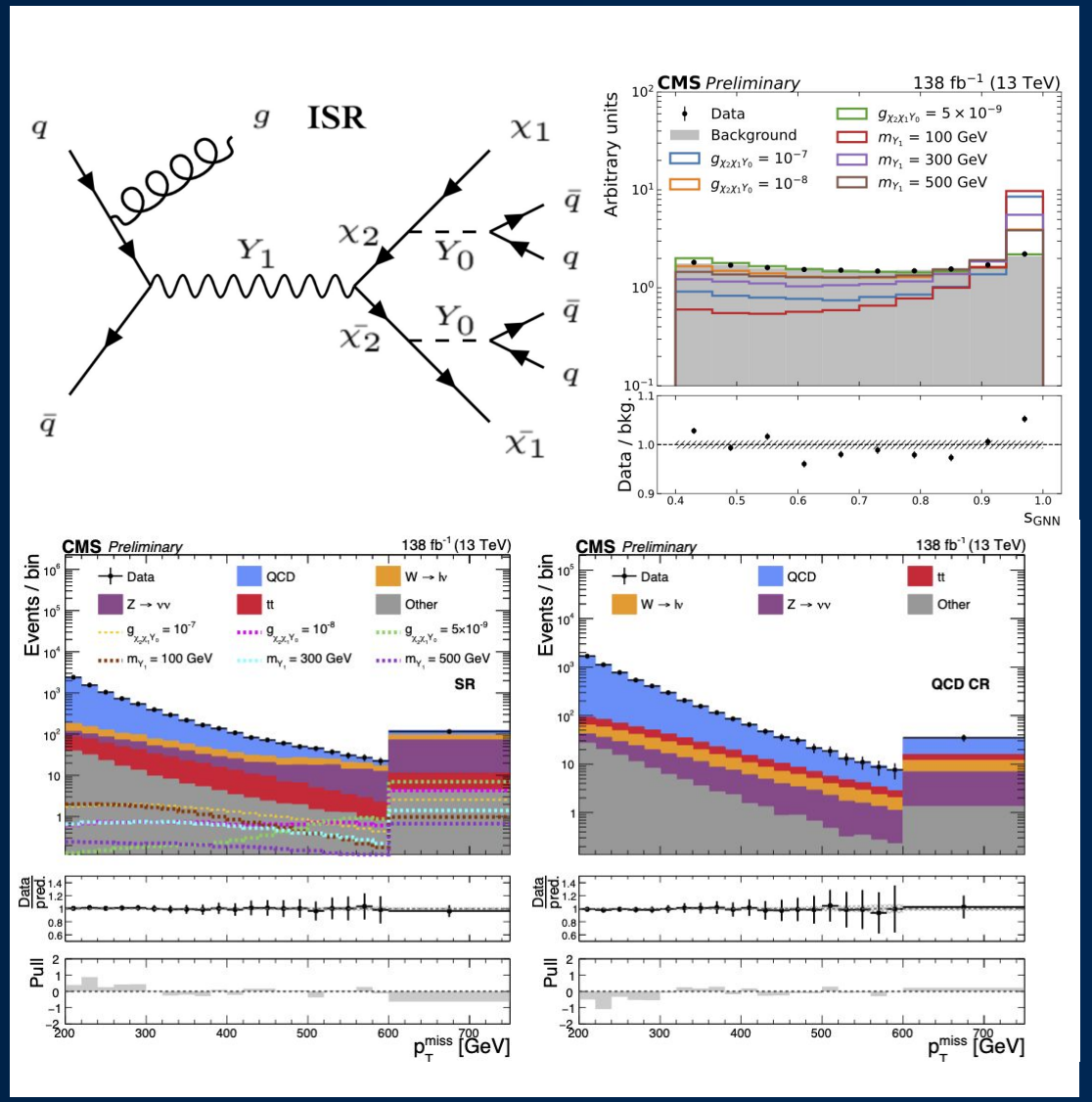
**Methods:** Interaction Network GNN targeting 13 Secondary Vertex features

**Background:** QCD, W+jets, Z→νν (Estimated via data-driven Transfer Factors)

**Observable:** Shape fit of the pTmiss spectrum in a high-GNN signal region

**Impact:** Stringent constraints on light vector mediators (100–500 GeV) and dark couplings





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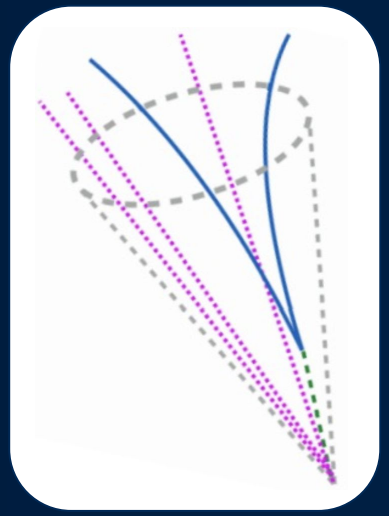
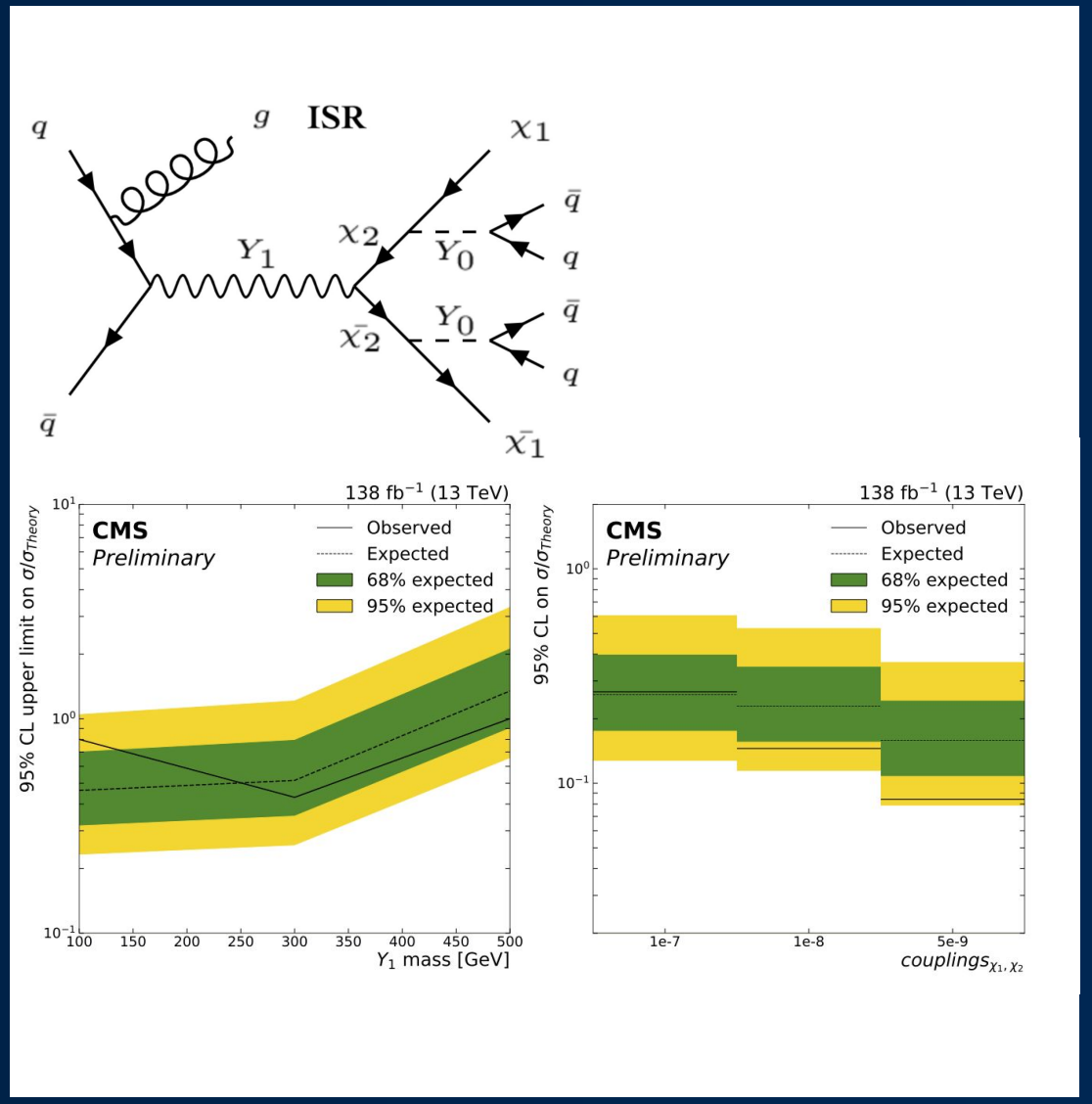




# Dark Matter hiding inside jets - DS

## Search for s-channel production of τ-enriched semivisible jets

**Dataset:** 138 1/fb of Run 2 data  via high-HT and single high-pT jet triggers

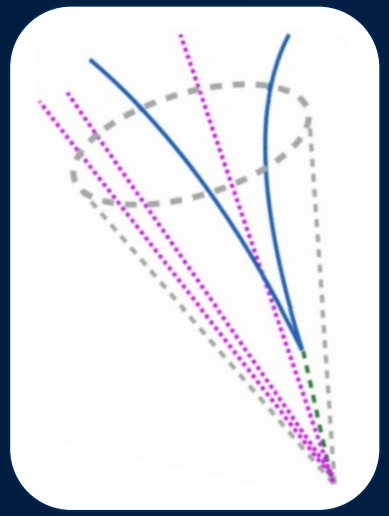
**Topology:** Resonant Z′→ Dark Shower (Stable DM + unstable mesons →τ leptons)

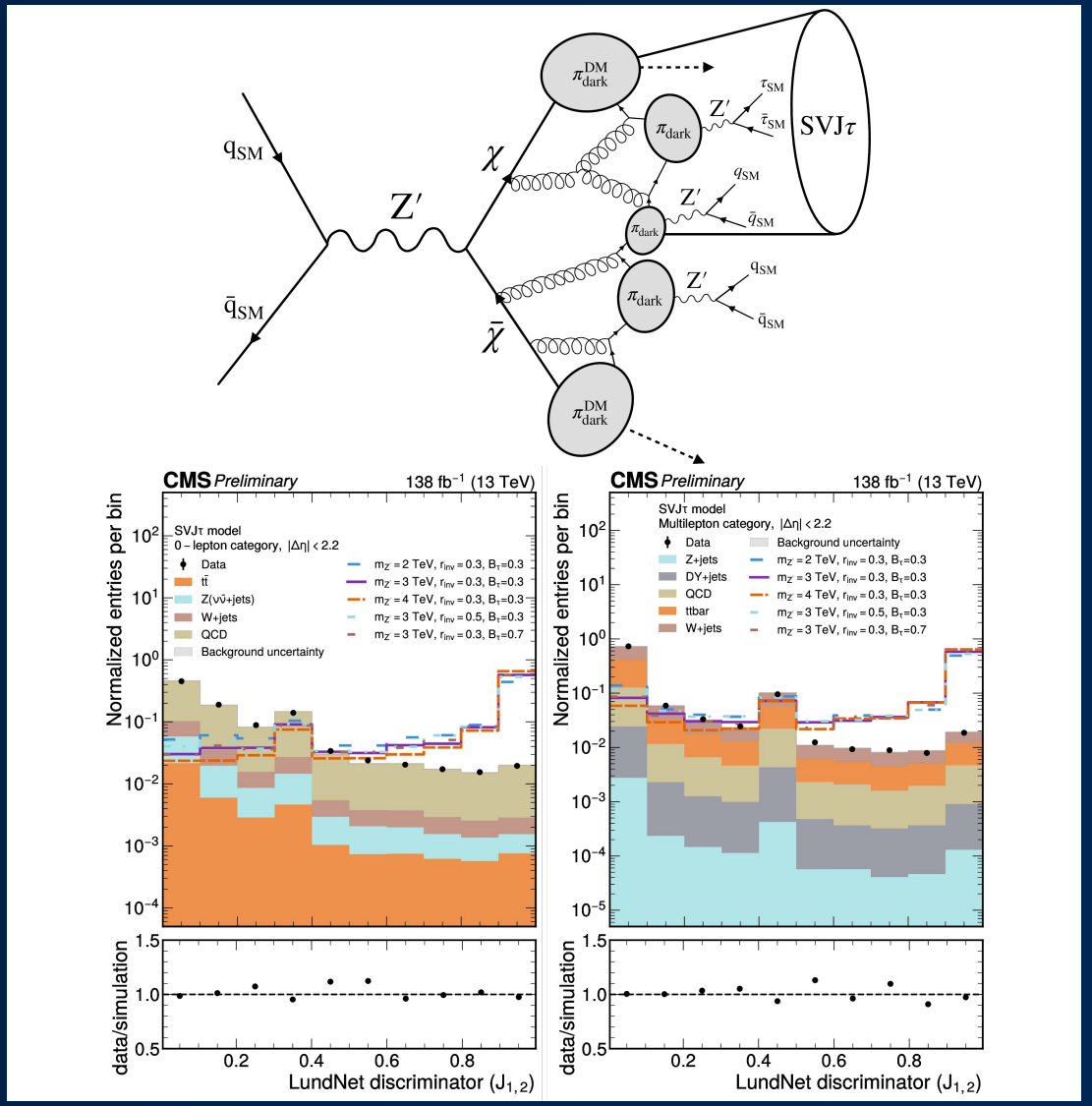
**Methods: LundNet GNN** leveraging declustering history and energy fractions

**Background: MD-ABCDisCoTEC** (Data-driven DNNs using Distance Correlation)

**Observable:** Shape analysis on the dijet transverse mass (mT)

**Impact:** First-ever collider constraints on τ-enriched SVJs (Z′ excluded 1.8–3.5 TeV)





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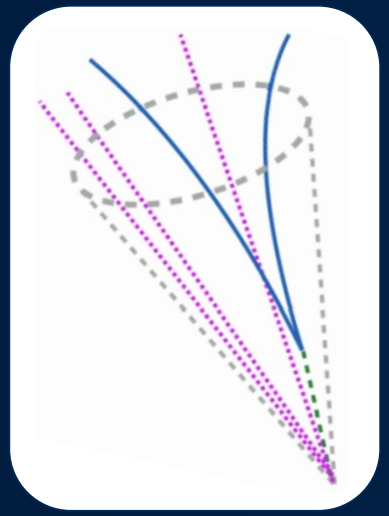
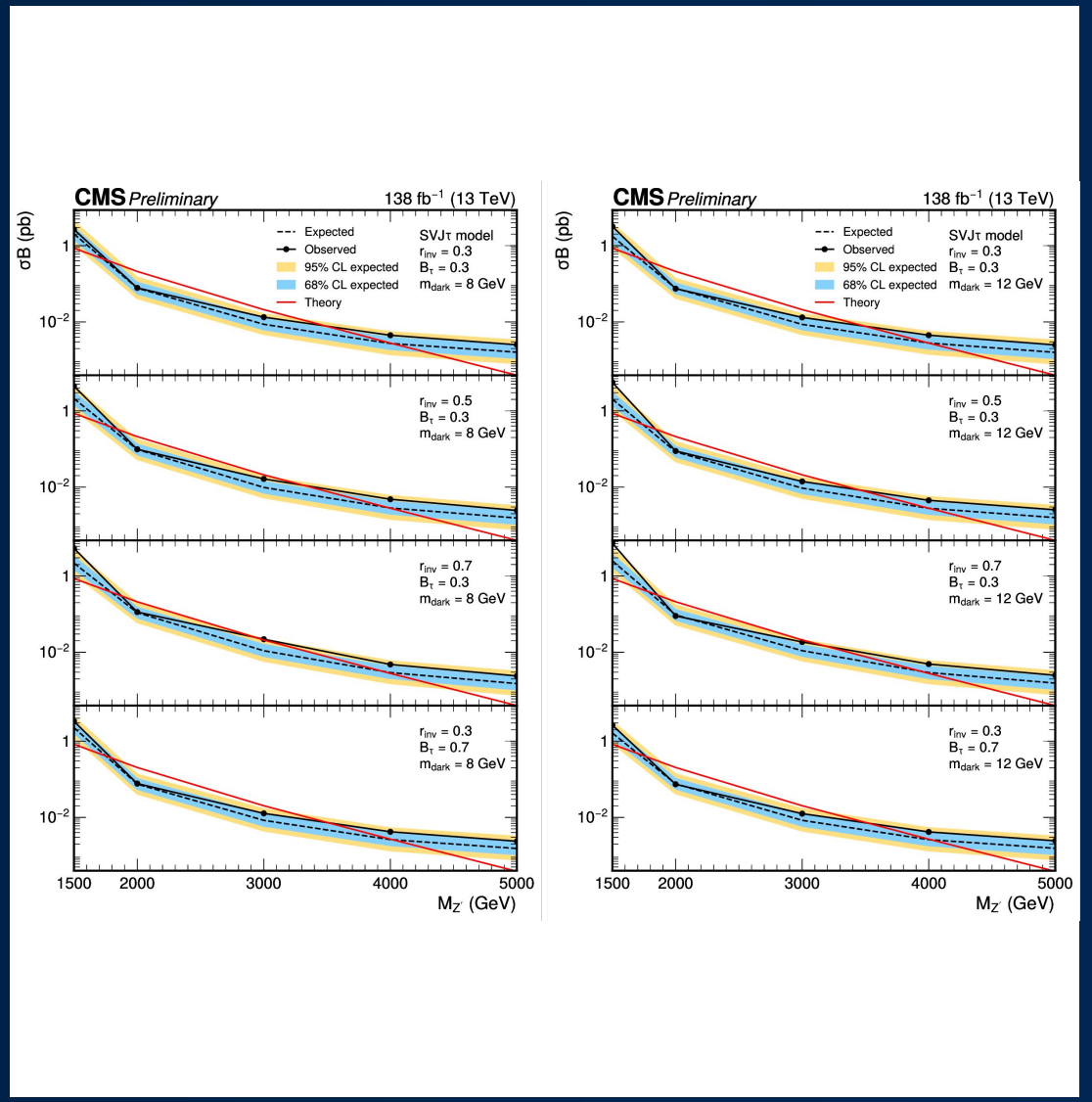




# Displaced Frontier

- Search for the pair production of long-lived supersymmetric partners of the tau lepton

# Delayed Dark Matter Long - Lived Staus

## Search for the pair production of long-lived supersymmetric partners of the tau lepton

**Dataset:** 138 1/fb of Run 2 data via pTmiss > 120 GeV triggers

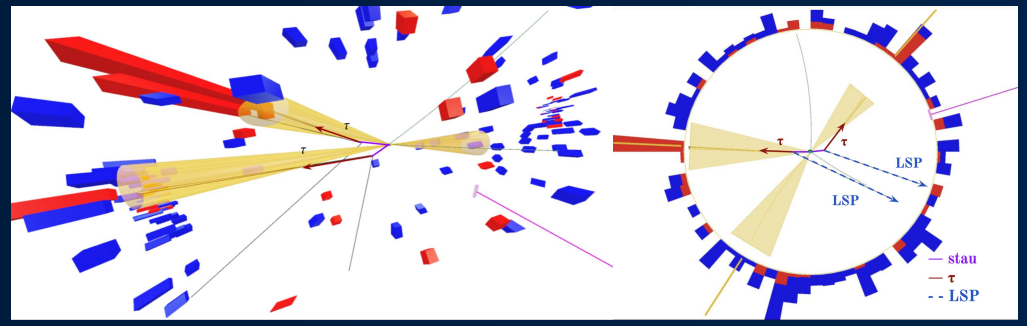
**Topology:** GMSB Long-Lived Staus (τ~→τ+stable G~ DM) decaying inside the tracker

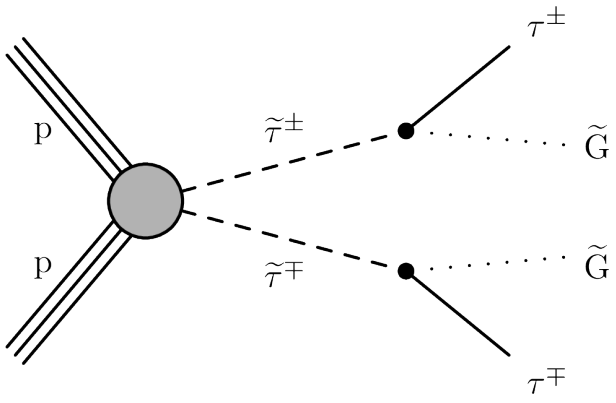
**The Innovation: DisTau** (ParticleNet-based GNN) treats jet constituents as a point cloud, recovering displaced tau efficiency up to 500 mm

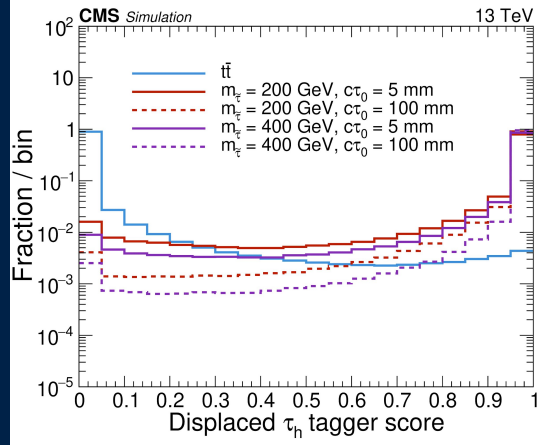
**Background:** Irreducible QCD fake-taus estimated via data-driven fake-rate method (from W/Z control regions)

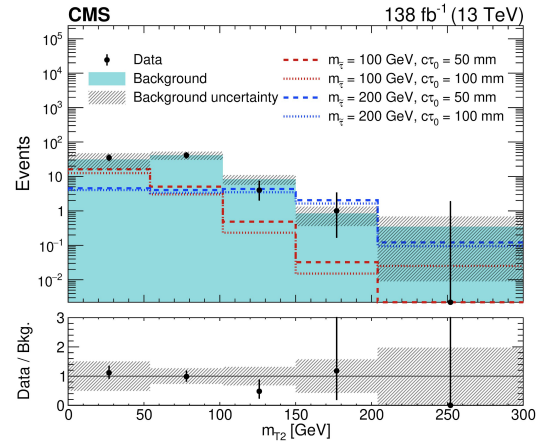
**Categorization:** 8 signal bins based on mT2, pTmiss, subleading τ pT

**Results:** Data consistent with SM background model. In the mass-degenerate scenario, stau masses up to 450 GeV (for cτ0=100 mm) and lifetimes up to 390 mm (for mτ~=200 GeV) are excluded




**Observable:** Stransverse mass (mT2) isolates the pair-produced invisible gravitinos

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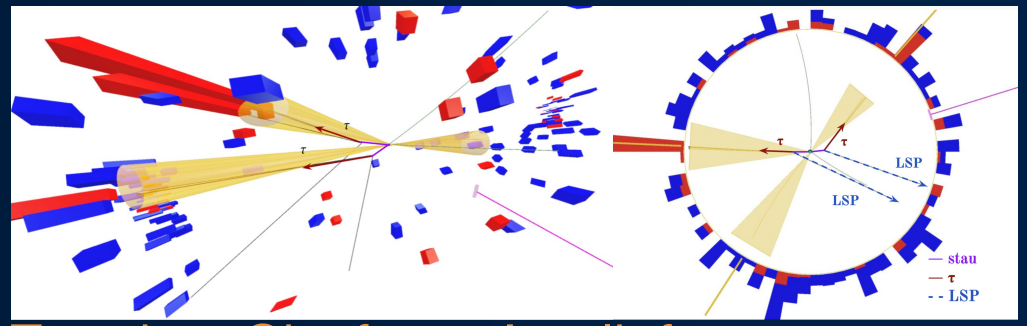
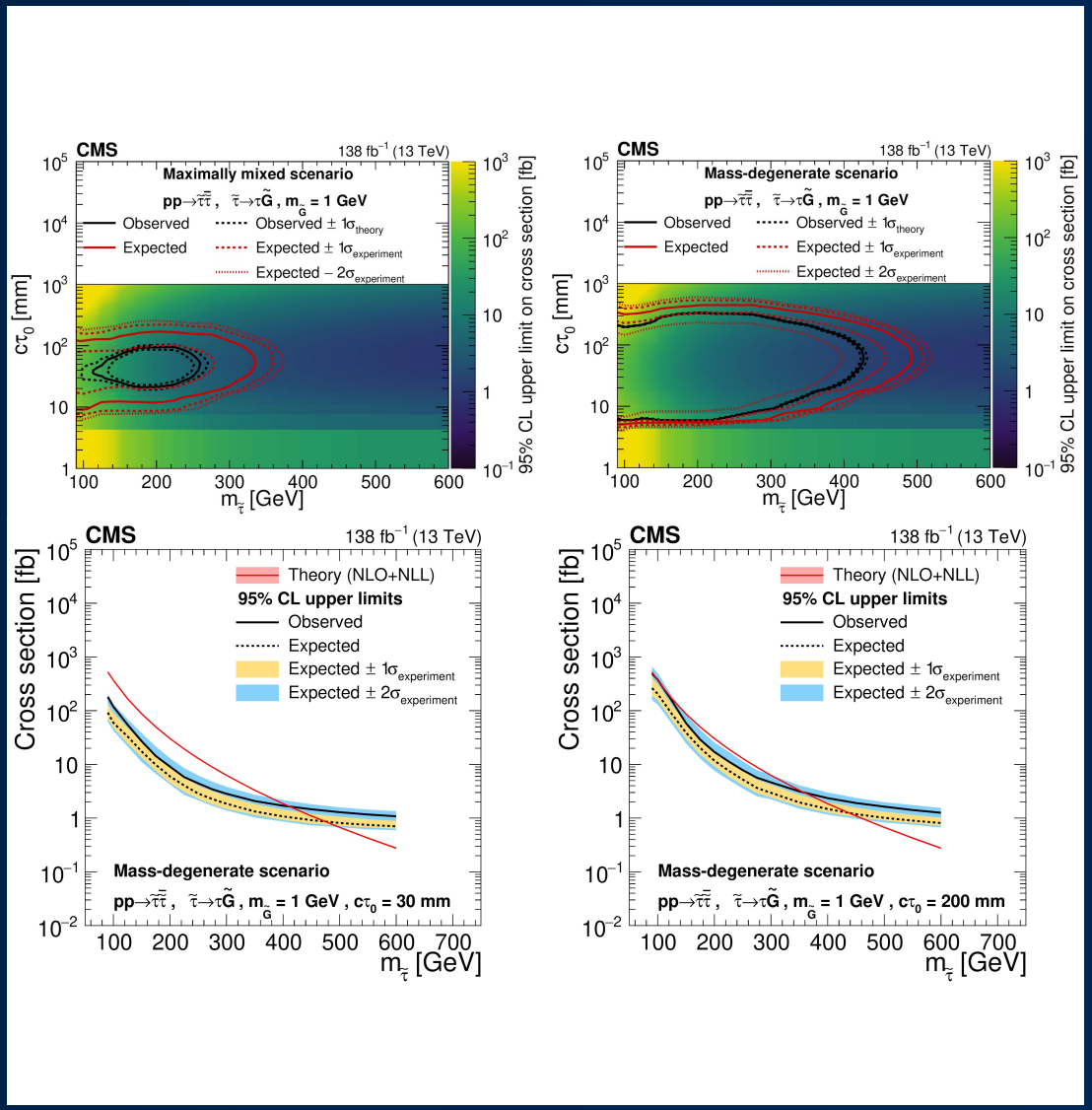


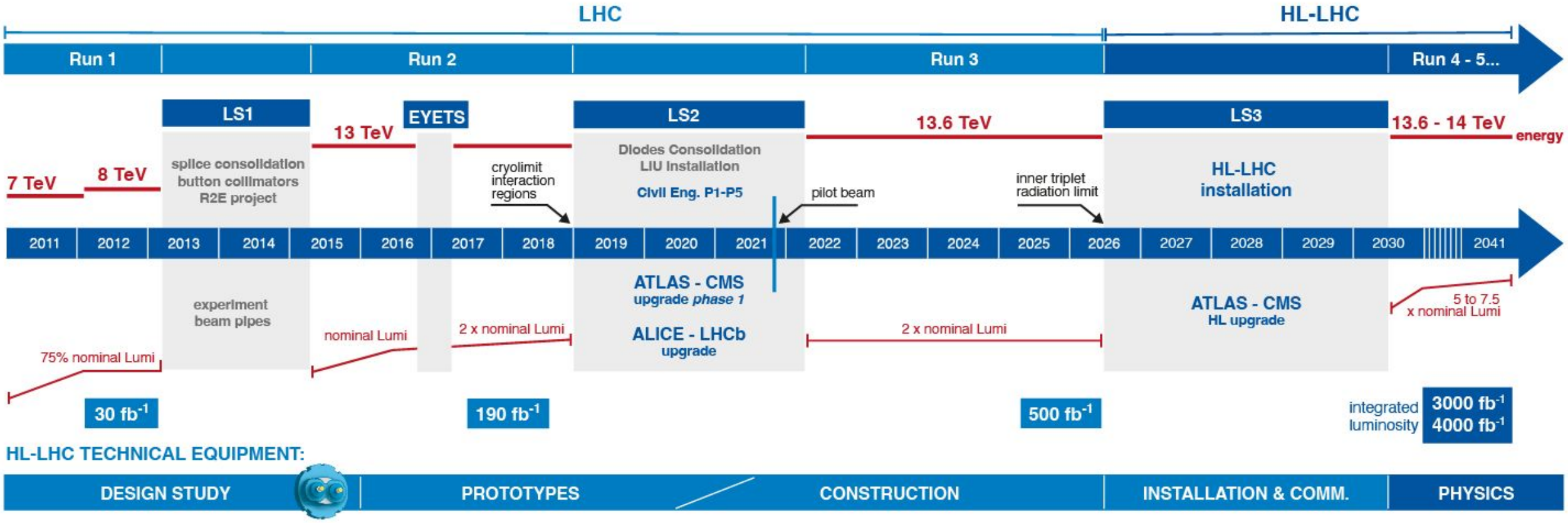

Tune into Gianfranco's talk for more on the CMS LLP analyses



# High-Luminosity LHC

- 3000-4000 1/fb awaits!

# LHC / HL-LHC Plan



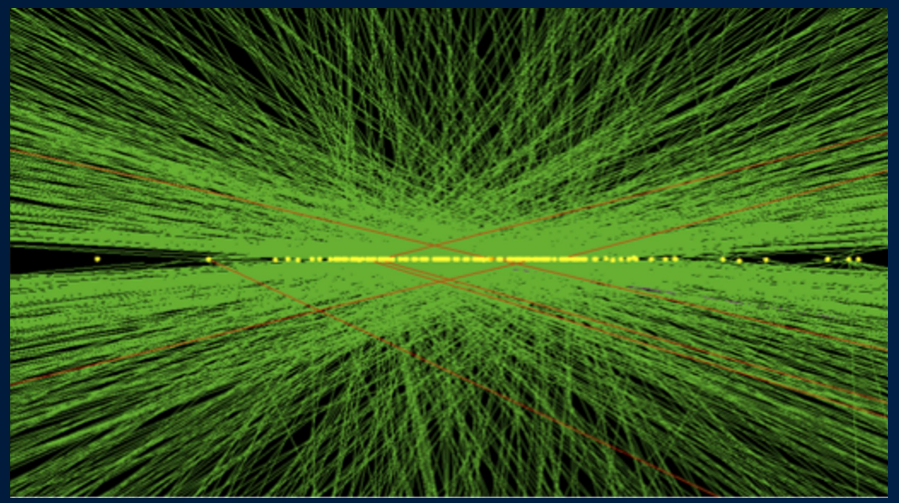

HL-LHC TECHNICAL EQUIPMENT:

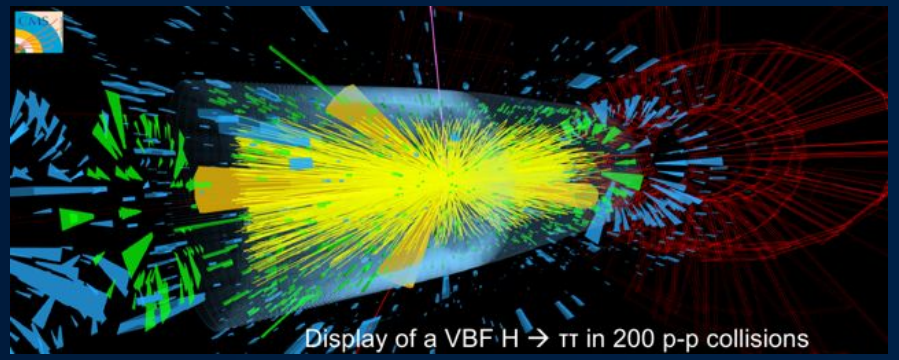
| DESIGN STUDY | PROTOTYPES | CONSTRUCTION | INSTALLATION & COMM. | PHYSICS |
|---|---|---|---|---|

HL-LHC CIVIL ENGINEERING:

| DEFINITION | EXCAVATION | BUILDINGS | CORES |
|---|---|---|---|

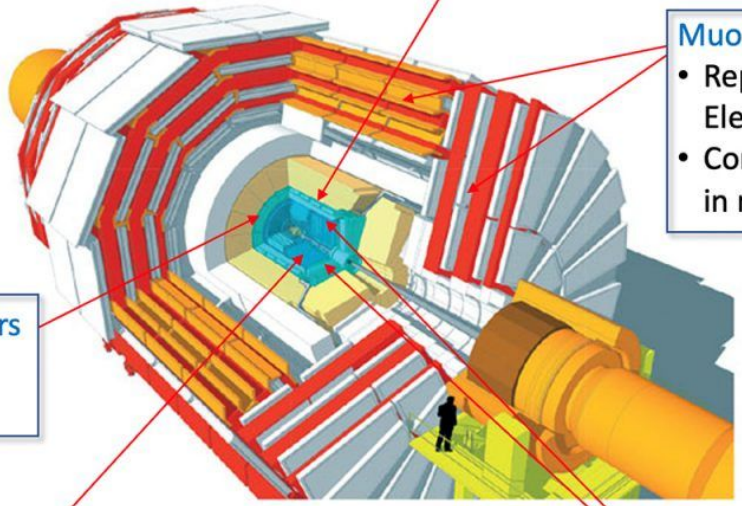
# Completely upgraded CMS to handle HL-LHC






**Trigger/HLT/DAQ**
- Track information in L1-Trigger
- L1-Trigger: 12.5 μs latency – output 750 kHz
- HLT output 7.5 kHz

**Barrel ECAL/HCAL**
- Replace FE/BE electronics
- Lower ECAL operating temp. (8 °C)



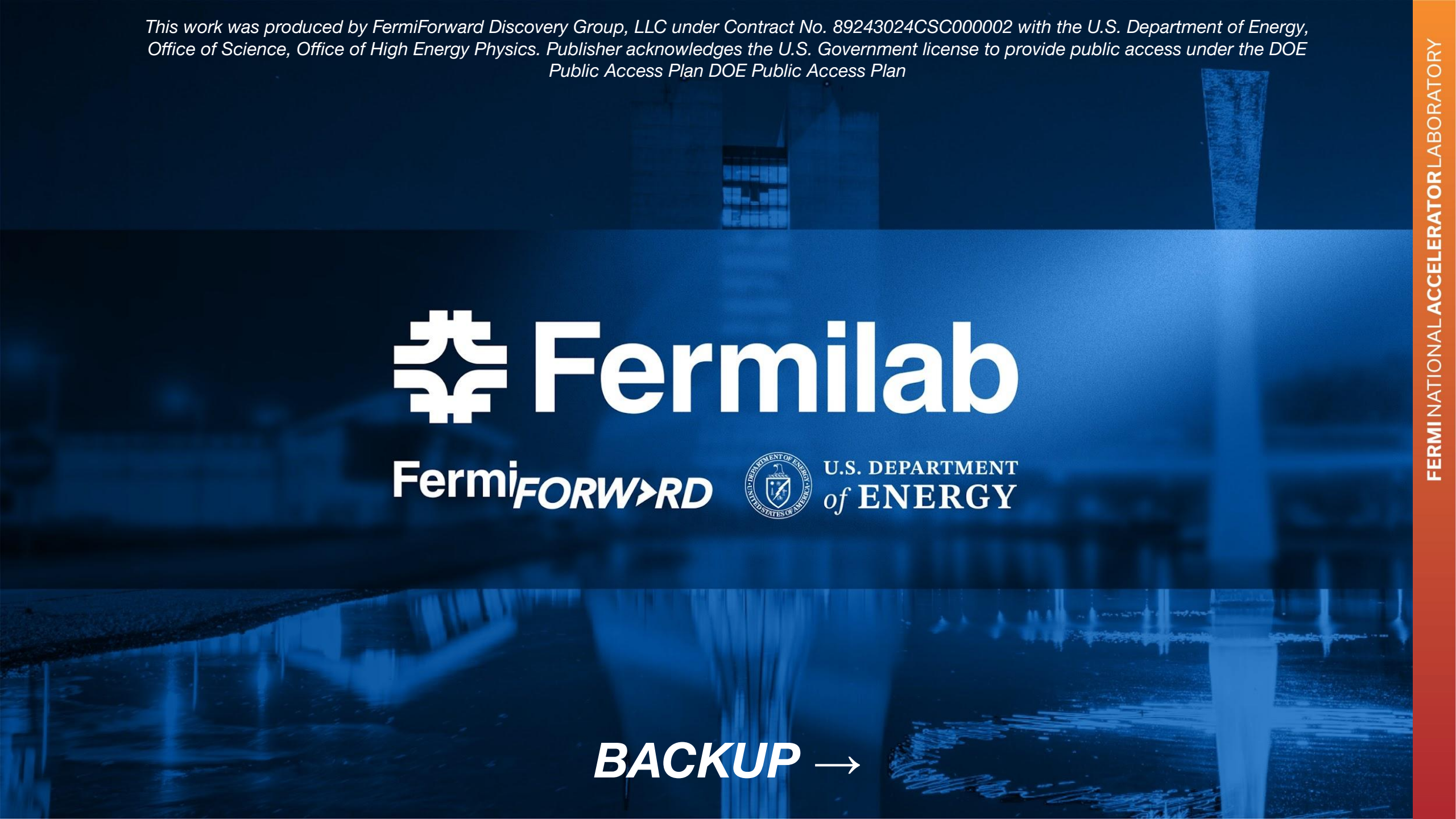
**Muon Systems**
- Replace DT & CSC FE/BE Electronics
- Complete Muon coverage in region $1.5<\eta<2.4$

**New Endcap Calorimeters**
- High granularity
- 3D capable

**New Tracker**
- Rad. tolerant – high granularity – significant less material
- 40 MHz selective readout ($p_T$>2 GeV) in Outer Tracker for L1 -Trigger
- Extended coverage to $\eta$=4

**New Precision Timing Detector**
- Barrel: Crystal +SiPM
- Endcap: Low Gain Avalanche Diodes

*This work was produced by FermiForward Discovery Group, LLC under Contract No. 89243024CSC000002 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. Publisher acknowledges the U.S. Government license to provide public access under the DOE Public Access Plan DOE Public Access Plan*



# Dark Matter hiding inside jets - DS

## Search for s-channel production of τ-enriched semivisible jets

**Dataset:** 138 1/fb of Run 2 data  via high-HT and single high-pT jet triggers

**Topology:** Resonant Z′→ Dark Shower (Stable DM + unstable mesons →τ leptons)

**Methods: LundNet GNN** leveraging declustering history and energy fractions

**Background: MD-ABCDisCoTEC** (Data-driven DNNs using Distance Correlation)

**Observable:** Shape analysis on the dijet transverse mass (mT)

**Impact:** First-ever collider constraints on τ-enriched SVJs (Z′ excluded 1.8–3.5 TeV)