SEARCHING FOR A DARK SECTOR IN ATLAS AND CMS

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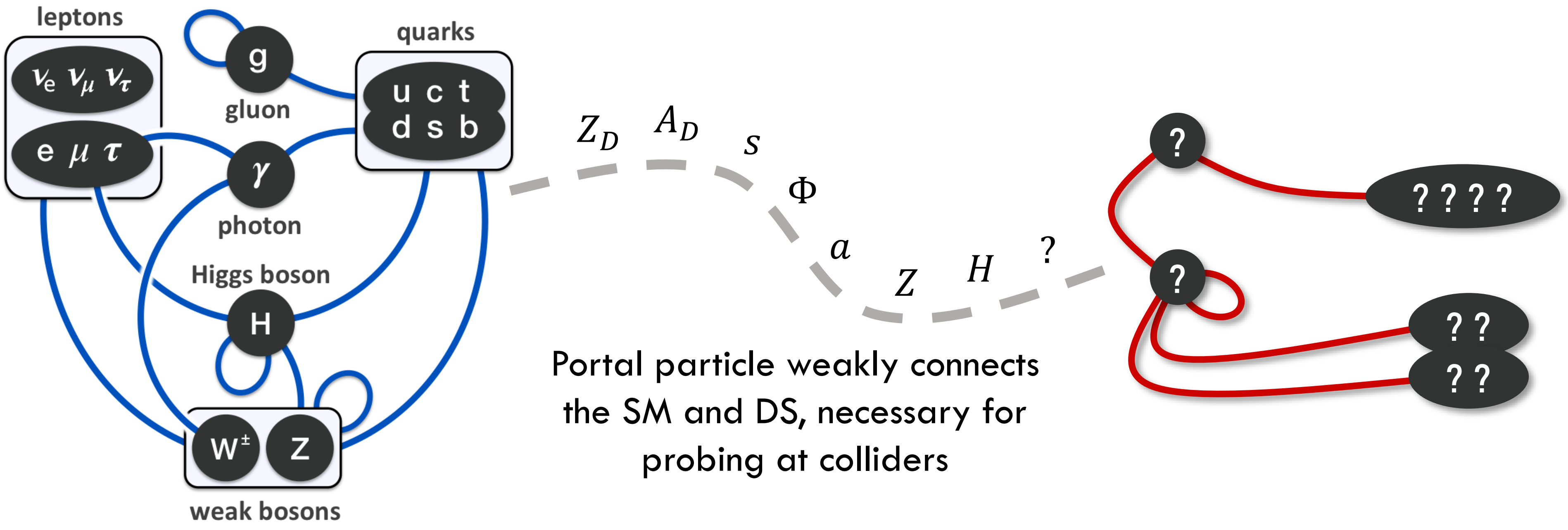
On behalf of the ATLAS and CMS Collaborations

WE KNOW IT'S OUT THERE, BUT NOT WHAT IT IS

A VERY BROAD CONCEPT

In a nutshell: any piece of Nature's lagrangian that is (mostly) decoupled from the Standard Model (SM)

Motivated mainly by evidence for dark matter (DM), which we assumes makes up the dark sector (DS)



Portal particle weakly connects the SM and DS, necessary for probing at colliders

DS can have its own gauge structure and particle content

DISCLAIMER

- **Making justice to the dark matter programs of ATLAS and CMS in 20’ is arguably impossible**
- **I will instead try to achieve two tings:**
  1. Give you a picture of the landscape, leaving most details for you to discover
  2. Highlight some (subjectively picked) interesting new ideas and techniques in the field
- Helped greatly by the recently-released reviews by both collaborations [1, 2]

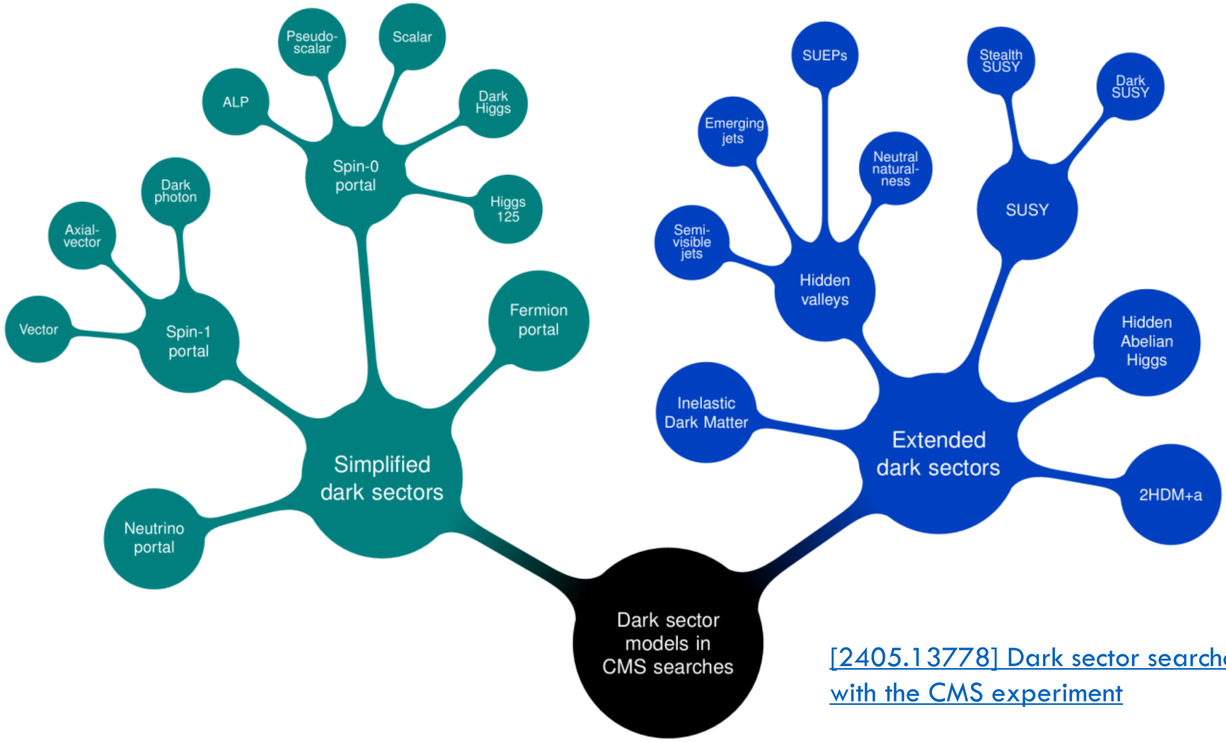
WE WILL NEED A COMPASS, OR TWO

WHERE DO YOU START?

How do you navigate a possible model space so big? Two complementary approaches

Simplified approach:

- Specify type of portal interaction
- Consider only one DS state (usually a fermion)

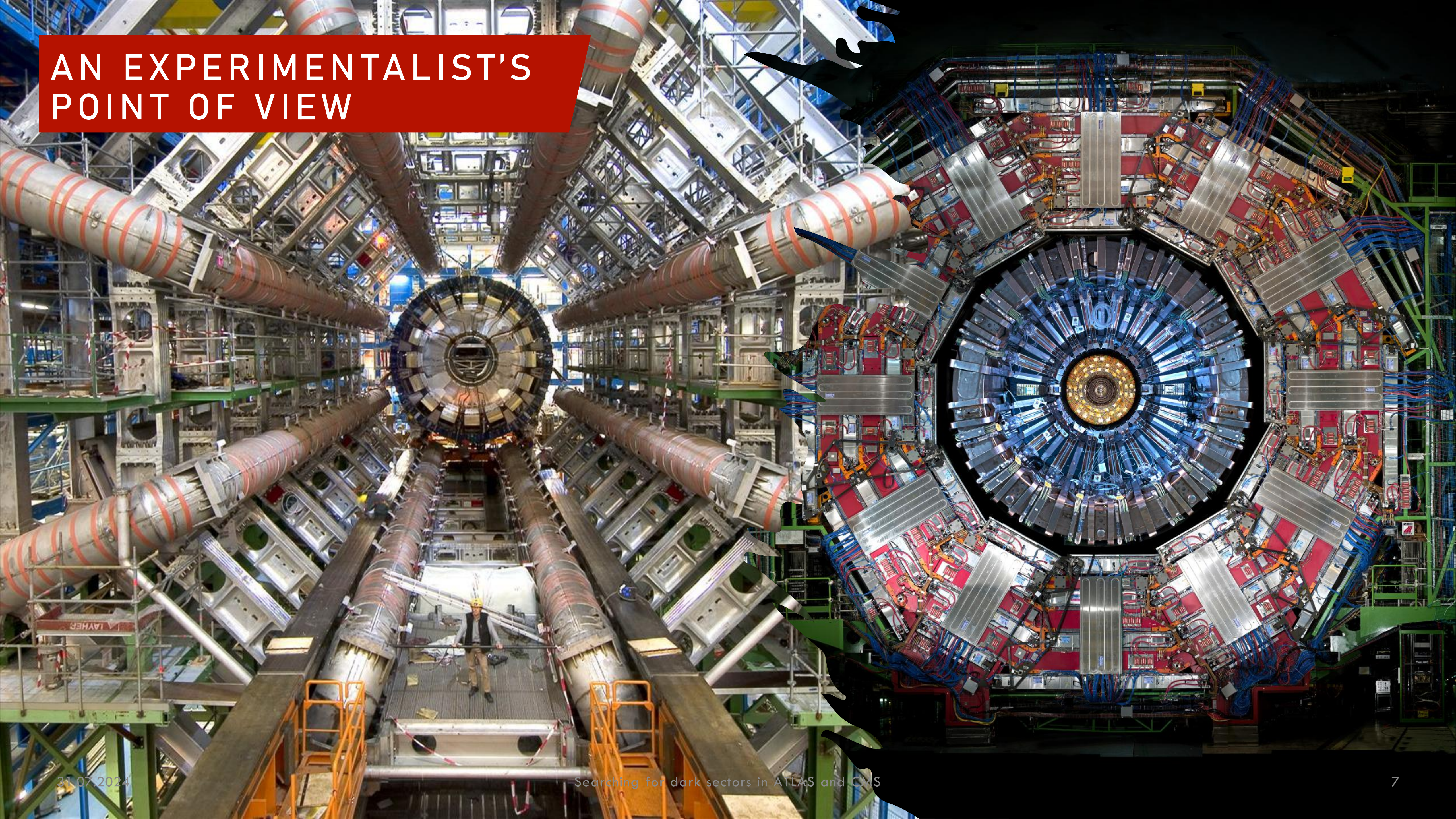


[2405.13778] Dark sector searches with the CMS experiment

Extended approach:

- More structured DS with rich dynamics
- Targeted searches with higher sensitivity, but less generality
- **Exotic final states can evade searches targeting the "simplified" approach**

AN EXPERIMENTALIST'S POINT OF VIEW



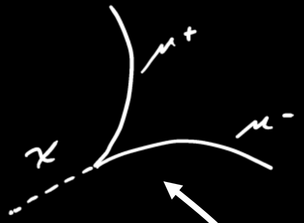
WHAT WOULD A DS LOOK LIKE IN ATLAS/CMS?

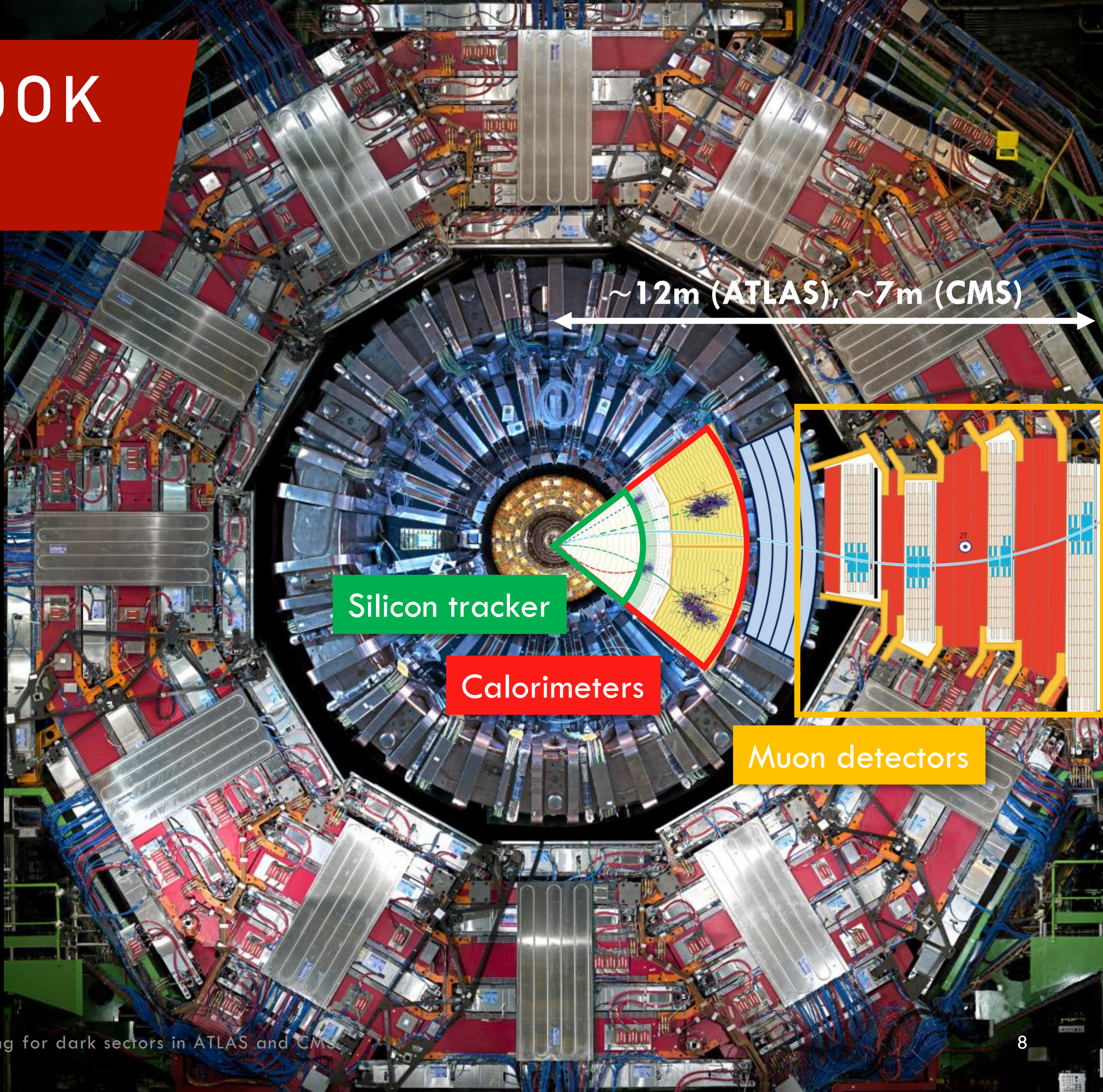
- By definition, DS states don't interact with matter
- Must detect decay products or particles produced in association

Lifetime $c\tau$

Detector volume

Invisible	ISR+p_T^{miss} → «Mono» searches
Displaced	Tracks not pointing to IP
Prompt	Resonances

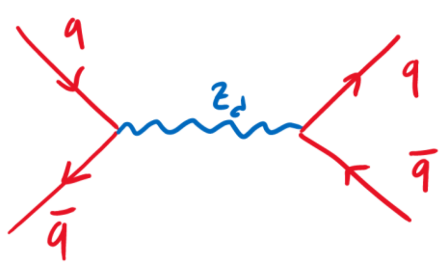




VISIBLE, INVISIBLE, OR…IN BETWEEN?

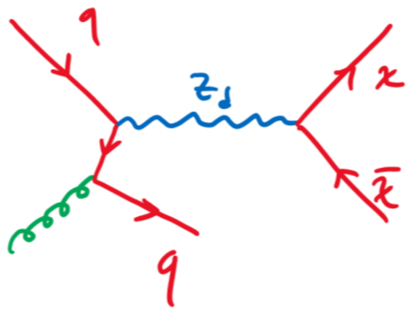
Consider as an example a simplified DS model with a vector portal Z_D and a dark fermion χ

- If $qq \to Z_D$, then $Z_D \to qq$



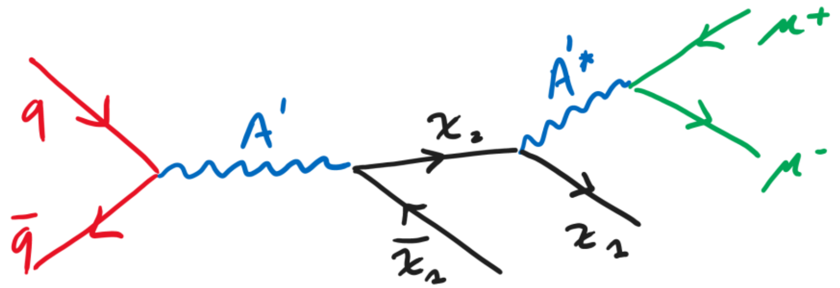
- Search for new dijet/dilepton resonances
- TLA/scouting* for low masses (more on that later)

- χ is detector-stable



- Exploit recoil against γ/jet/V/H and look for p_T^{miss}
- «Mono» or «DM+X» searches

- What if the DS is more complicated?

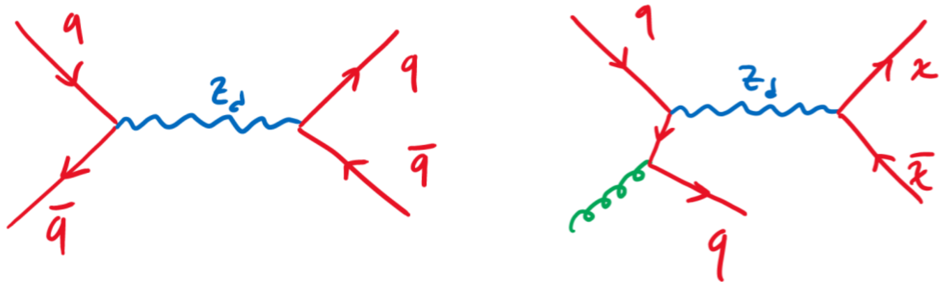


- Meta-stable states can result in displaced tracks
- Confining forces in the DS can lead to dark showers
- **Such signatures would escape "traditional" searches**

WE HAVE OUR MAP, LET'S DIVE IN

LET'S START GENERAL

- Little assumptions on the makeup of the DS → space for different interpretations



- Benchmark models common between ATLAS and CMS e.g., for a polar vector Z_d:

$$g_\ell = 0.01, g_q = 0.1, g_\chi = 1$$
$$g_\ell = 0, g_q = 0.25, g_\chi = 1$$

- Both ATLAS and CMS cover this space extensively

CMS

Boosted dijet search [3]
B-tagged dijet search [4]
Dijet+ISR with scouting* [5]
High-mass dijet [6]

Mono-j/Mono-V(jj) [7]
Mono-γ [8]
Mono-V($\ell\ell$) [9]
Dilepton search [10]

ATLAS

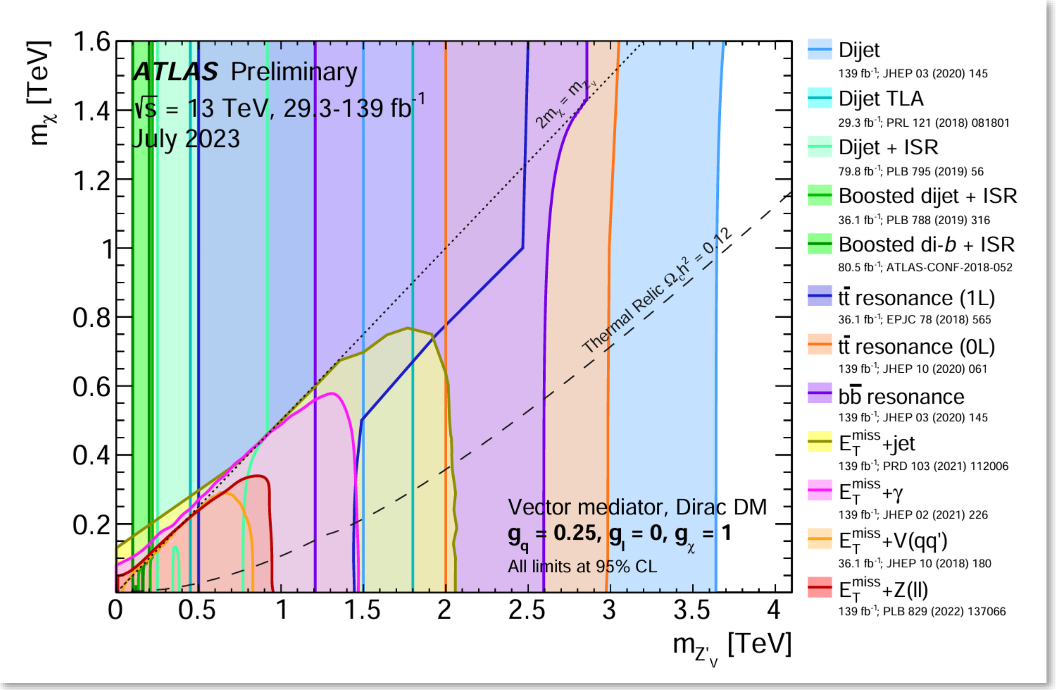
(b-tagged) dijet search [10]
Dijet search with TLA* [11]
Dijet+ISR (resolved) [12]
Dijet+ISR (boosted) [13]
$t\bar{t}$ resonances [14, 15]

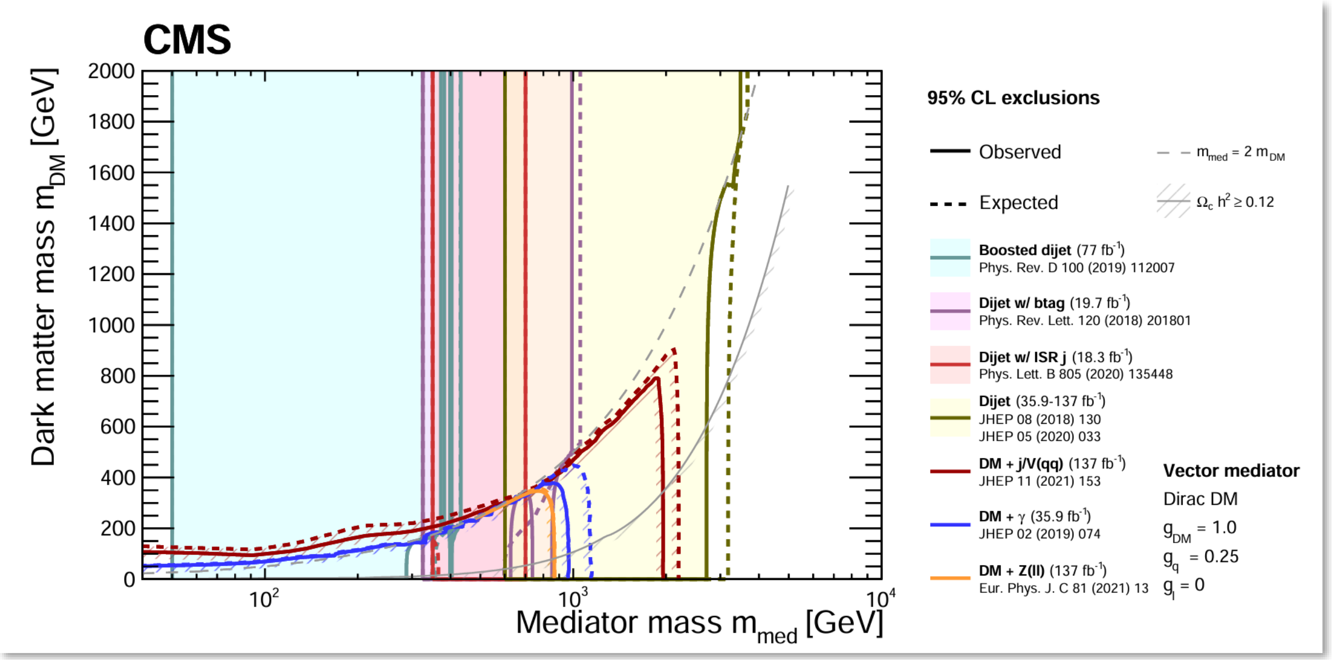
Mono-j [16]
Mono-γ [17]
Mono-V(jj/$\ell\ell$) [18, 19]
Dilepton search [21]

LIMITS ON POLAR VECTOR PORTALS

High intensity frontier

High energy frontier





- Other interpretations in the backup

BREAKING THE LOW MASS FRONTIER

- When the resonance mass becomes too low, the **trigger system** becomes a limit
- Overwhelming background rates (driven by dominant QCD cross section) → an online selection of potentially interesting events is required → trigger
- E.g., dijet analyses limited to resonance masses of ~1.5 TeV in CMS/ATLAS
- **So how do we go lower?**

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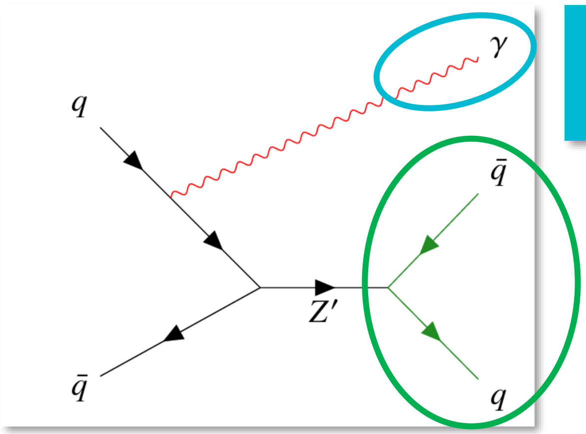
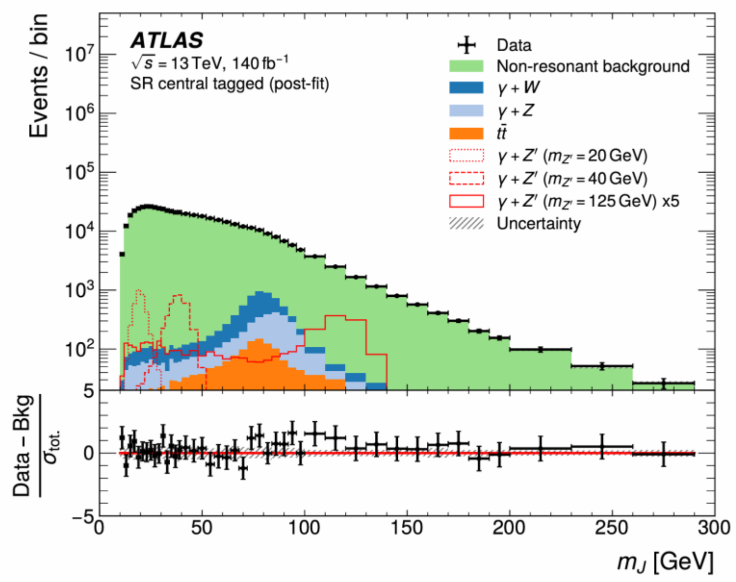
- **So how do we go lower?**
- Let ISR help → boosted topologies, e.g.:
- **ATLAS DM+ISR photon search probes mediators down to 20 GeV**

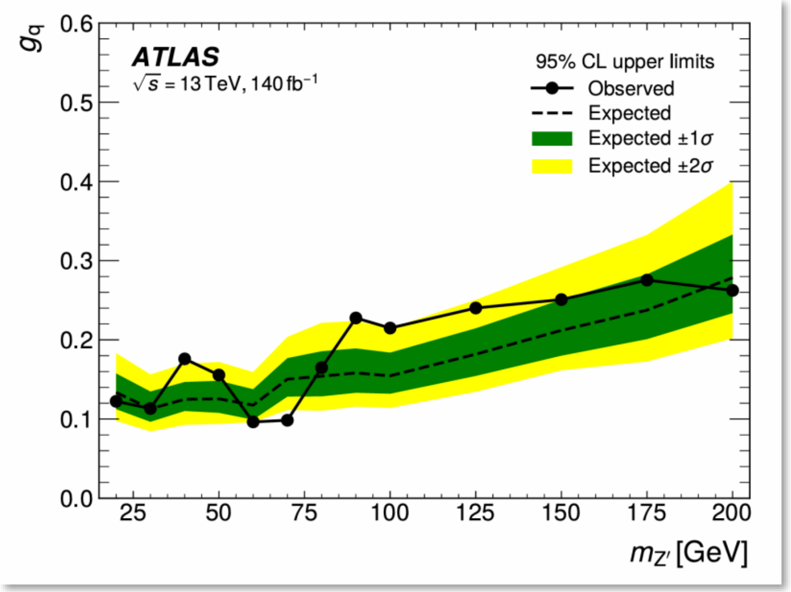


Leverage hard ISR for triggering

Boosted jet with two-pronged structure

10.48550/arXiv.2408.00049





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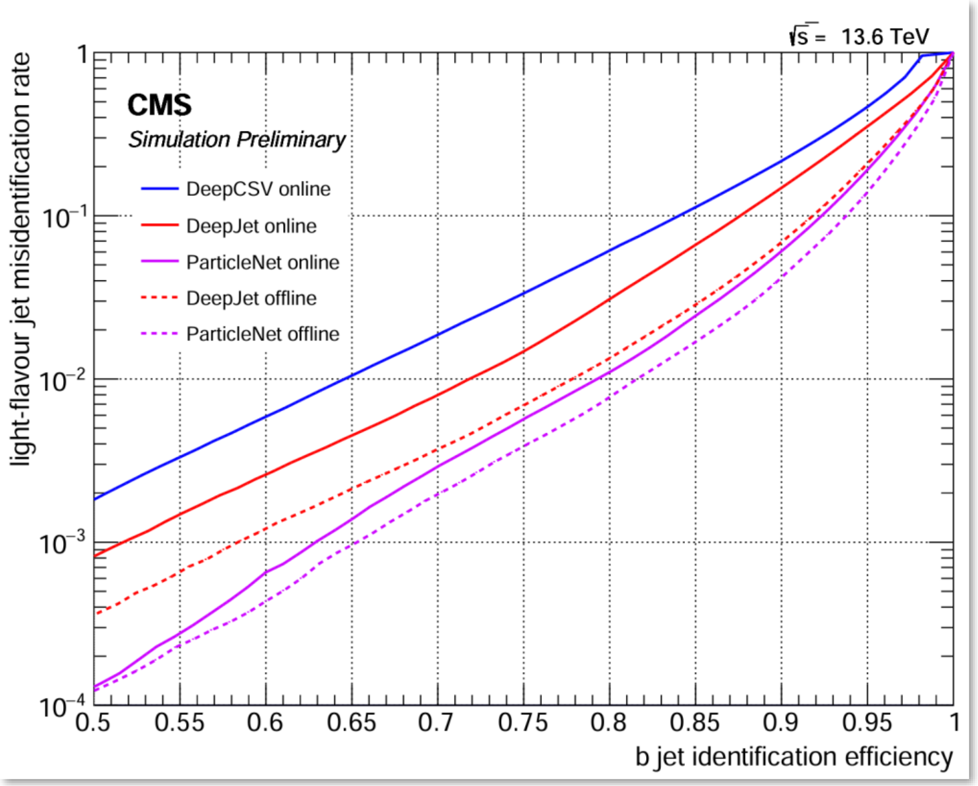
- **So how do we go lower?**
- Exploit jet substructure in the trigger
- Greatly suppresses QCD → higher rates

CERN-CMS-DP-2023-021



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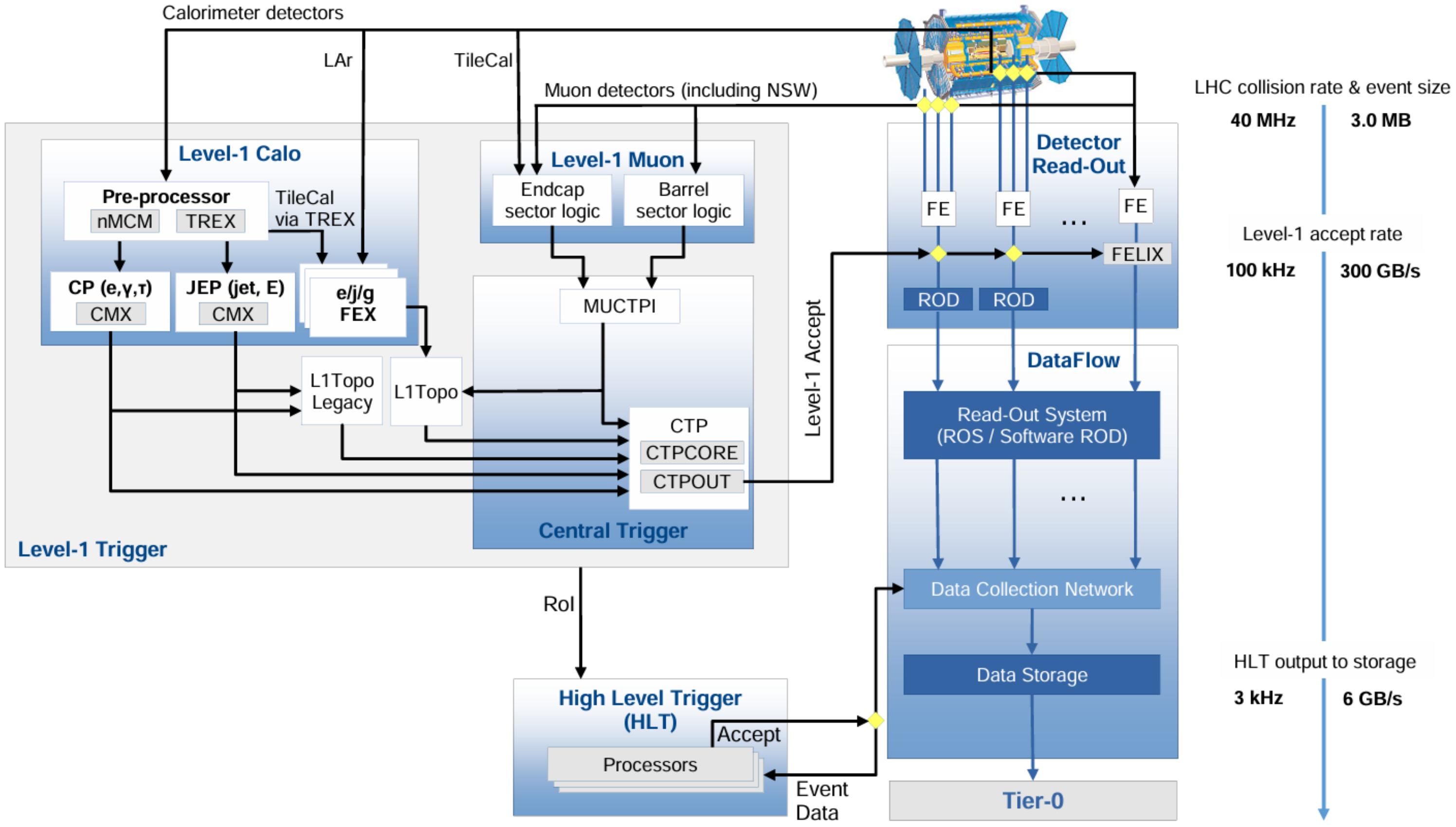
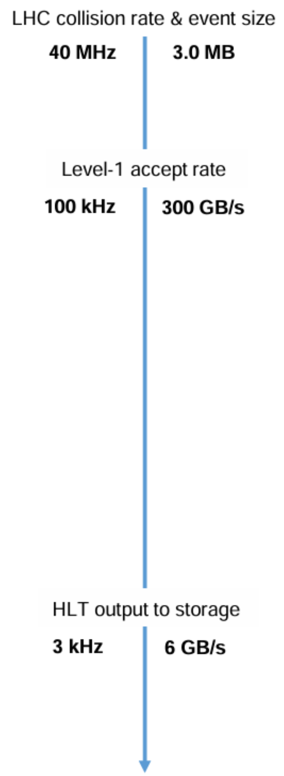
- **So how do we go lower?**
- Look closer to what is actually limiting the trigger rate



BREAKING THE LOW MASS FRONTIER

[ATLAS trigger operations public results](#)

- Look closer to what is actually limiting the trigger rate!



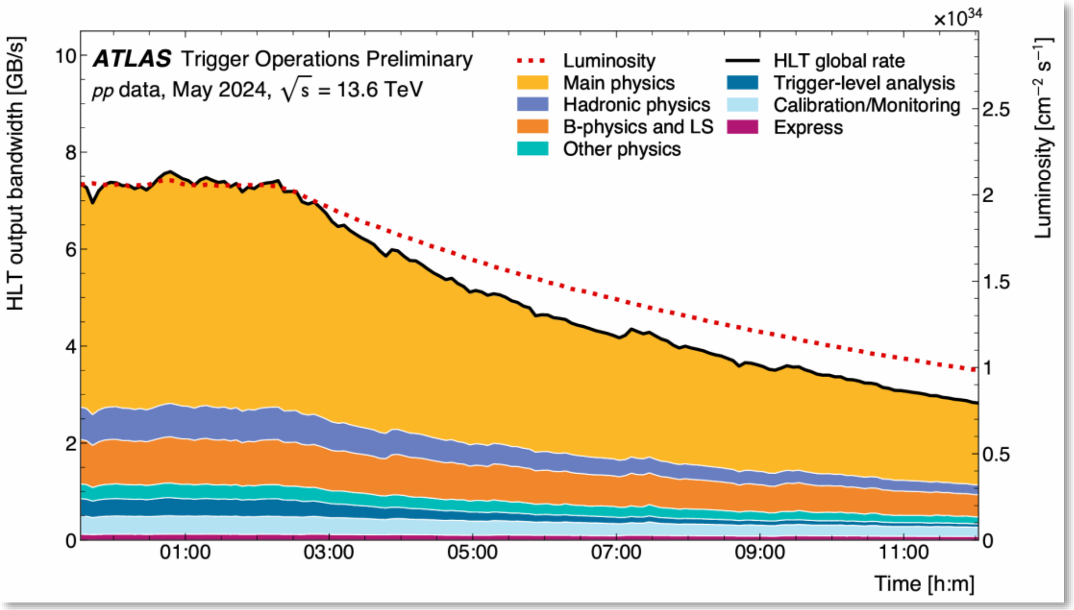
The limit of the trigger is not rate, it's bandwidth

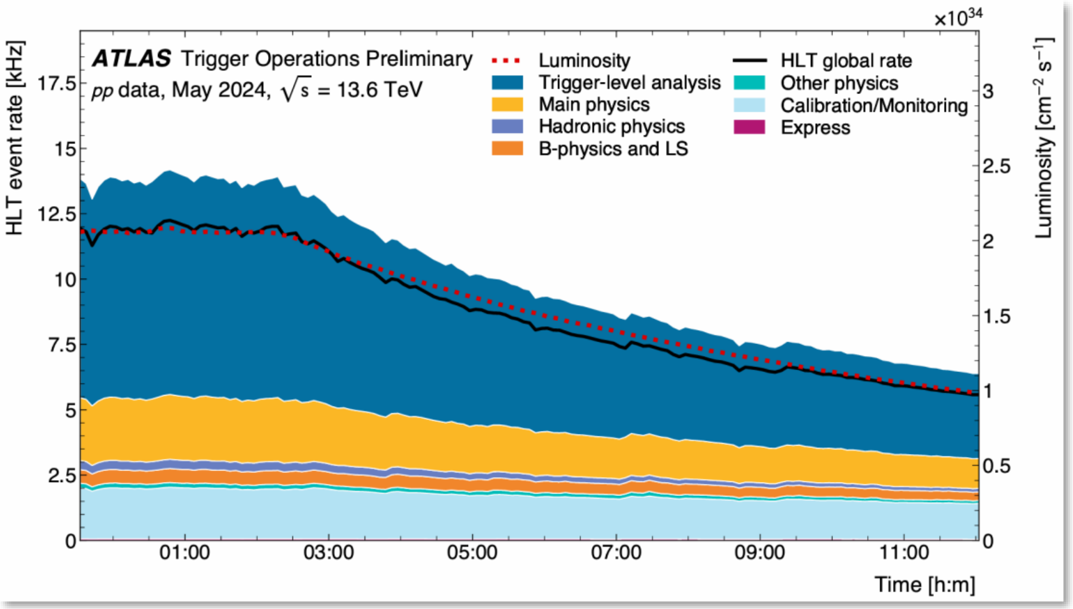
↓

The HLT does an almost complete reconstruction of all events from L1, but we then throw it away

↓

Scouting (CMS)/Trigger Level Analysis (TLA, ATLAS) → store much lighter HLT info





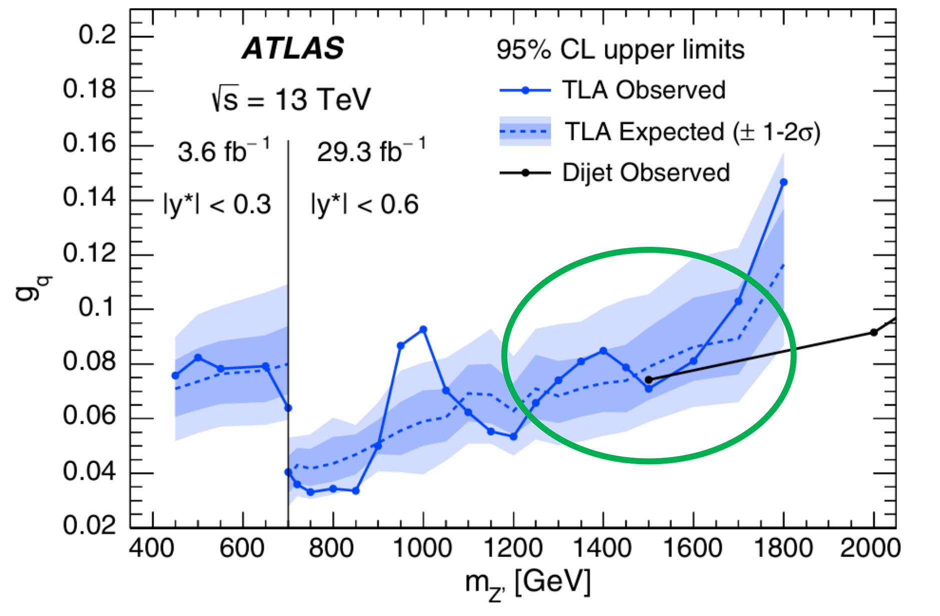
LET'S SEE IT IN ACTION

- To give but two examples of how this strategy can unlock a whole new level of potential sensitivity:

10.1103/PhysRevLett.121.081801

ATLAS TLA dijet search

- Record all events containing a L1 jet with $E_T > 100$ GeV (29.3 fb^{-1})
- Subset of data with eve looser $E_T > 75$ GeV requirement (3.6 fb^{-1})
- Store jet 4-momentum (+a few quality variables) → 0.5% of size w.r.t. full event info
- **Fully efficient for offline $p_T > 220$ GeV**



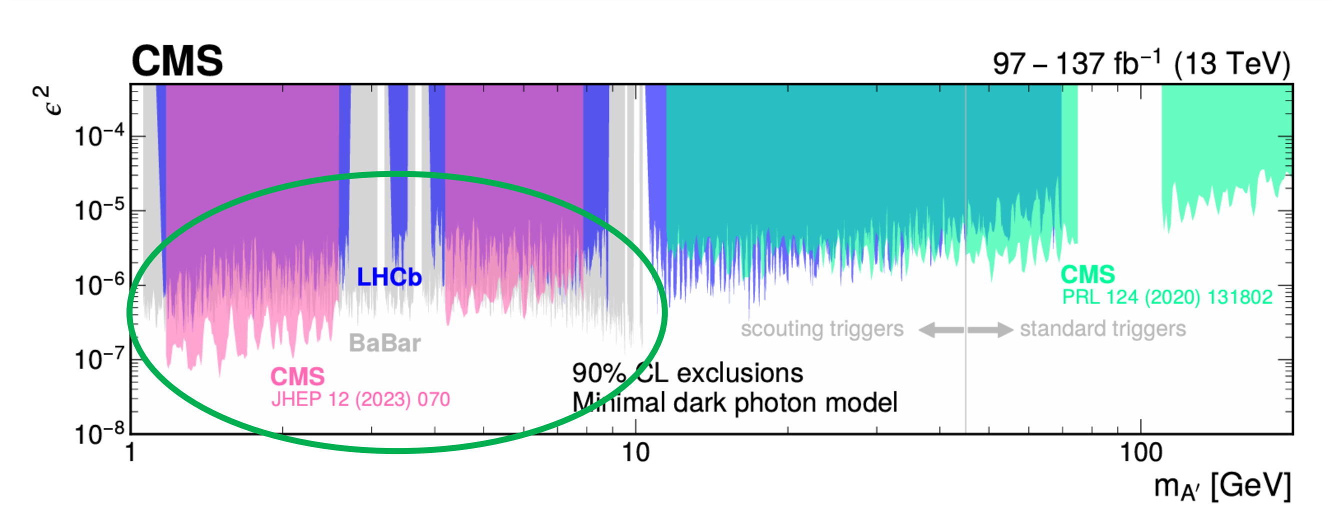
LET'S SEE IT IN ACTION

- To give but two examples of how this strategy can unlock a whole new level of potential sensitivity:

CMS scouting dimuon search

- Record all L1 events with two muons having $p_T > 3$ GeV
- Active in 2017 and 2018 for 97 fb^{-1} of lumi
- Store hits in tracker/muon system and calorimeter clusters
- Event size: ~1 MB (offline) → ~8 kB (scouting)
- Event rate: 450 Hz (offline) → 2 kHz (scouting)

10.1007/JHEP12(2023)070

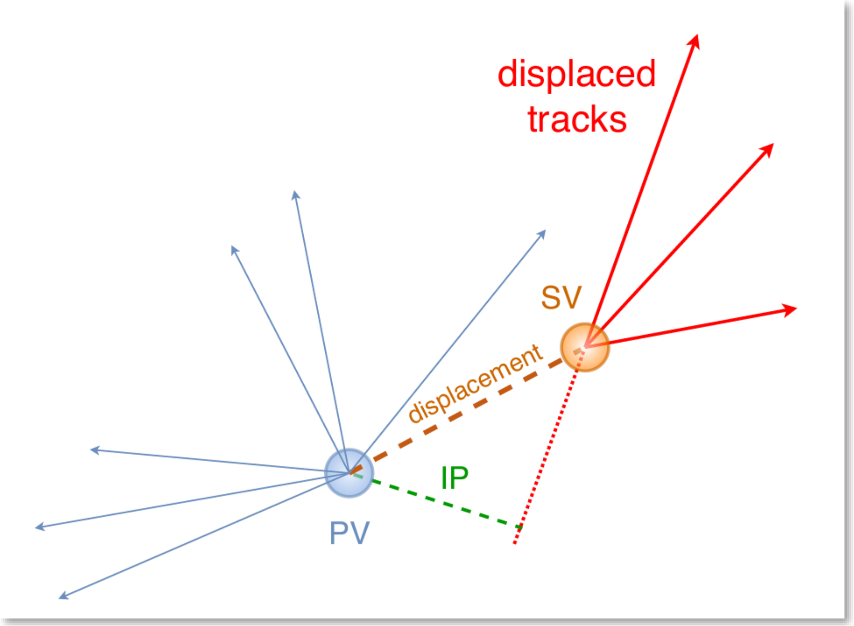


Enabling some of the most stringent limits to date!

COVERING OUR BLIND SPOTS

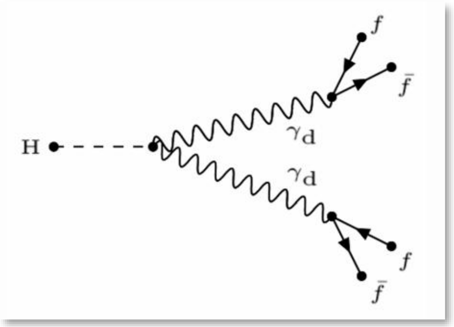
DISPLACED SIGNATURES

- The general approach to DS searches I discussed up to now is powerful, but it has failure modes
- Common reconstruction and analysis pipelines in ATLAS and CMS designed for prompt objects, but
- If DS states are meta-stable → displaced objects
- Require rethinking most of the criteria in reconstructing objects
- Powerful tool to extend reach of DS searches, but also new and challenging backgrounds to fight
- Will only give a few examples in the interest of time, much more in [1, 2]

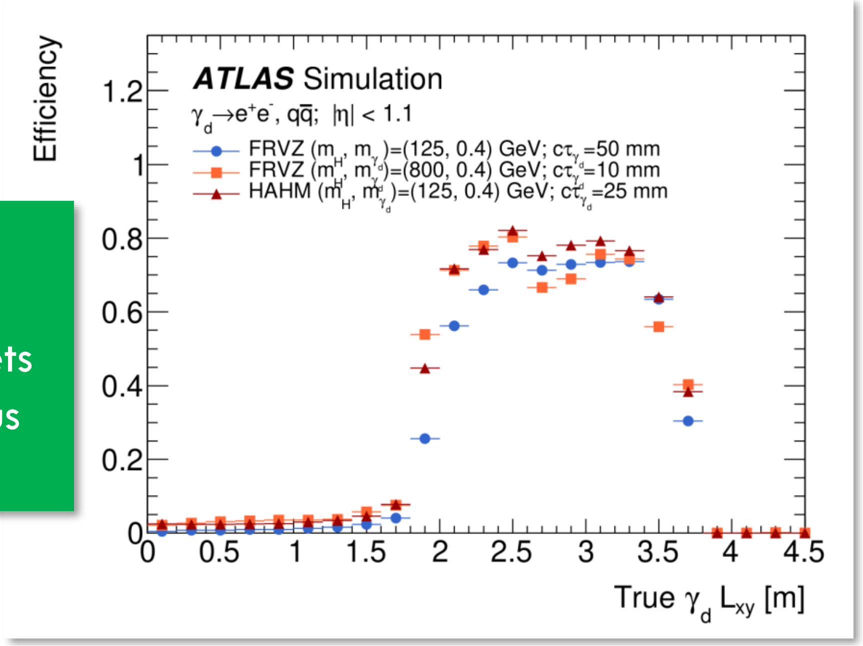


DARK-PHOTON JETS IN ATLAS

- Beautiful ATLAS searches considering different potential long-lived signatures
- Very different signature depending on dark photon lifetime

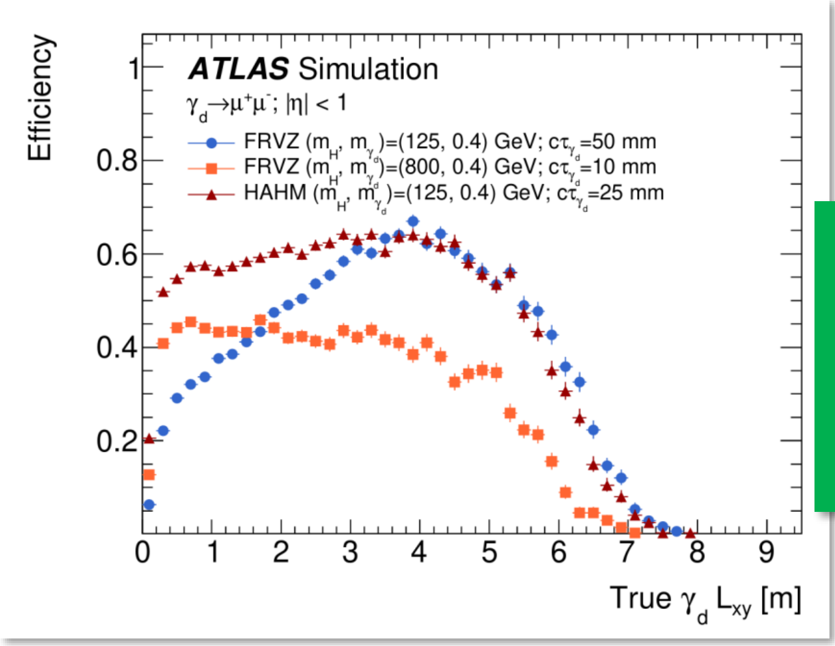


[10.1007/JHEP06(2023)153](https://doi.org/10.1007/JHEP06(2023)153)



- Decays in the calorimeter
- Detected as jets with anomalous EM fraction

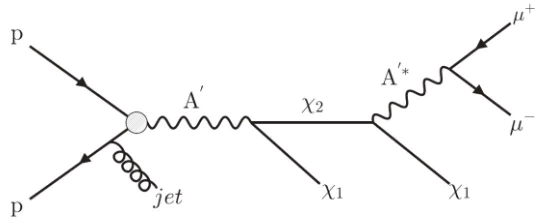
[10.1007/JHEP06(2023)153](https://doi.org/10.1007/JHEP06(2023)153)



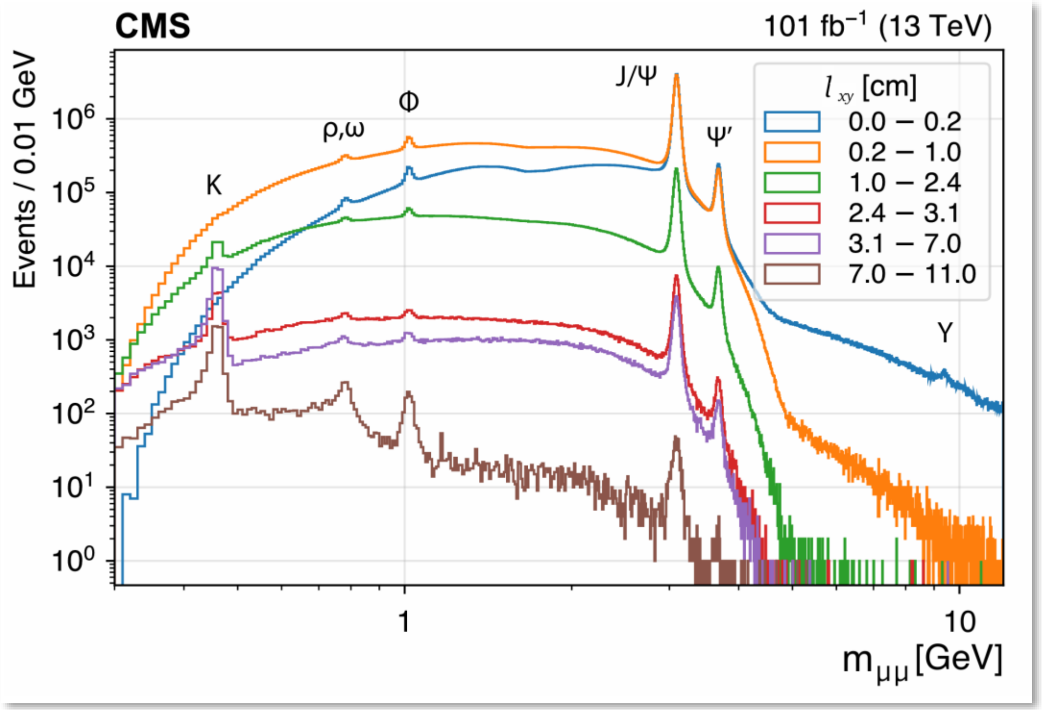
- Decays in the muon system
- Clusters of standalone muon-system tracks

DISPLACED DIMUONS IN CMS

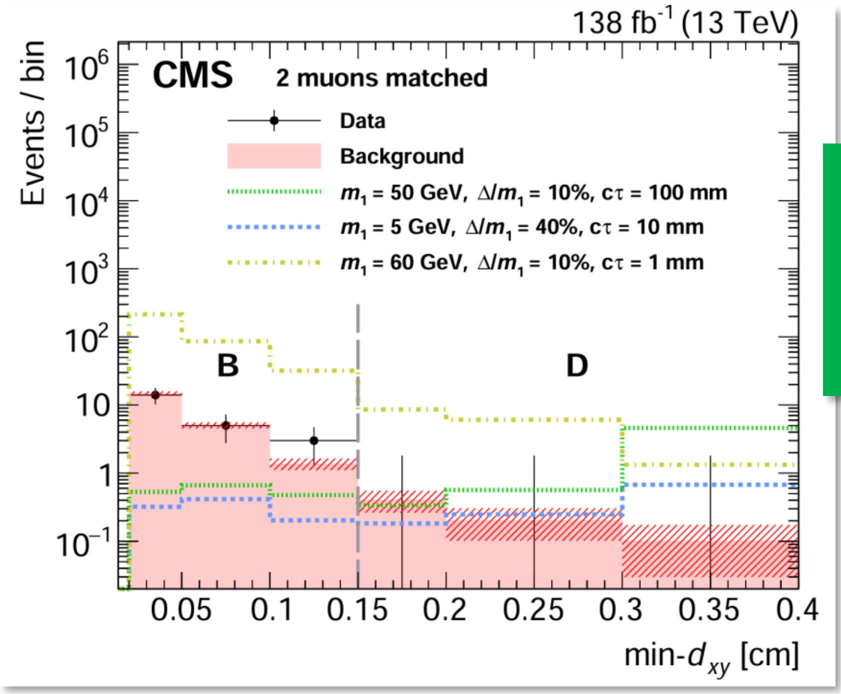
- Leveraging scouting data, displaced dimuons down to invariant masses of O(1) GeV
- Search for inelastic DM with displaced dimuons + p_T^{miss}



10.48550/arXiv.2403.16134

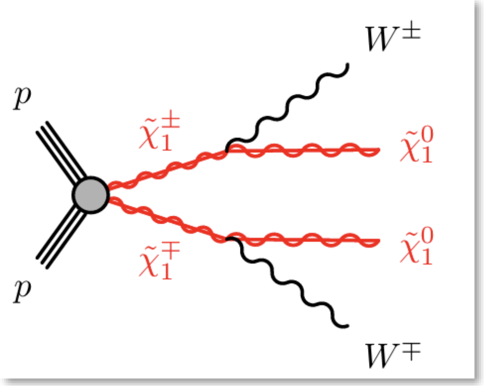


10.1103/PhysRevLett.132.041802



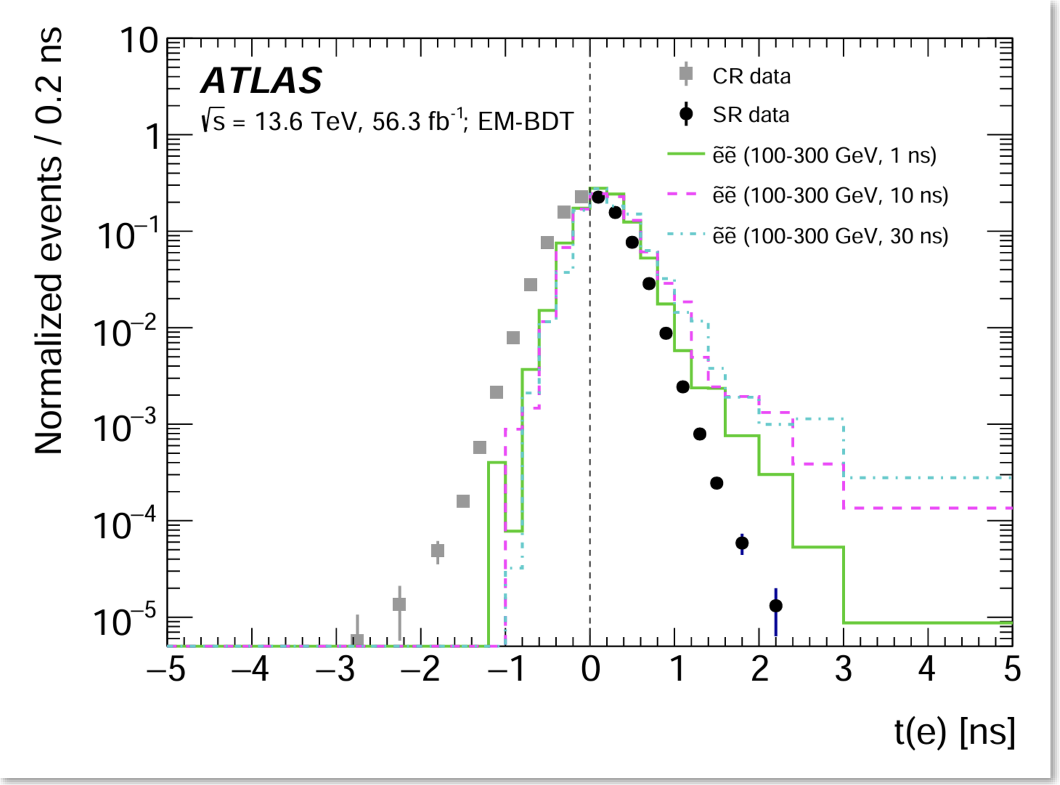
Use both tracks in muon system only as well as matched to inner tracker

DISPLACED LEPTONS IN ATLAS



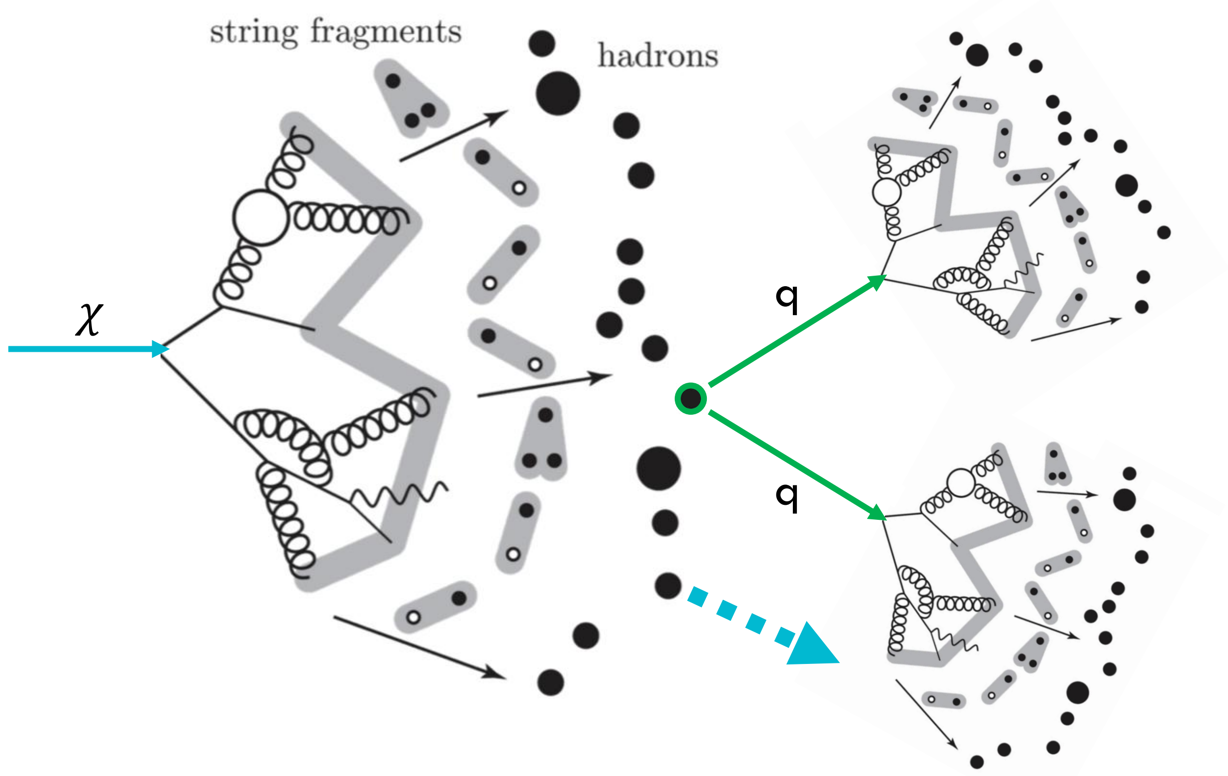
10.48550/arXiv.2410.16835

- New for Run 3: exploit large radius tracking (LRT) directly in the trigger
- Exploit the capabilities of the ATLAS LAr EM calorimeter
- Two BDTs are built by using timing and pointing info from the LAr EM calo
- Discriminate displaced electrons reconstructed as either electrons or photons from prompt objects

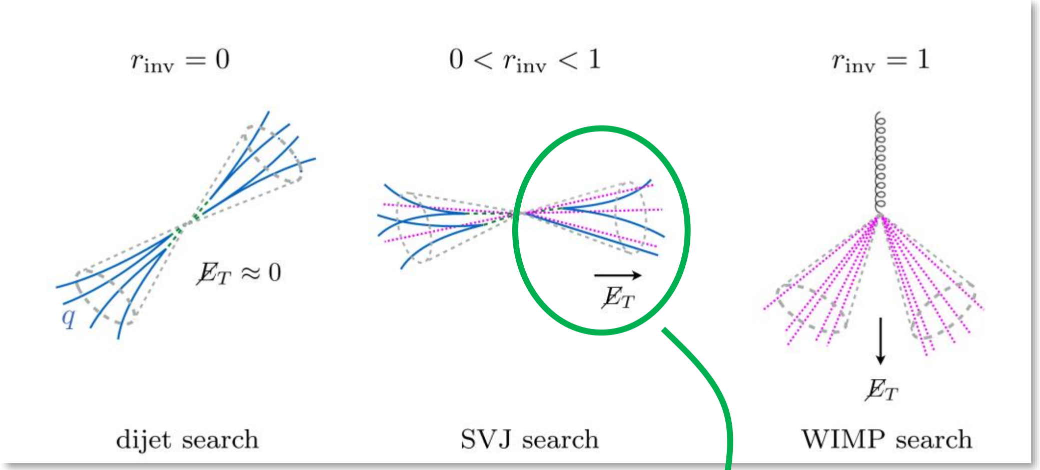


DARK QCD - SVJS

- If the DS is subject to a confining force, interesting signatures can arise
- Dark quarks shower and hadronized in DS → "dark" jet → stable dark hadrons decay back to SM → semivisible jets



r_{inv}: fraction of stable dark hadrons

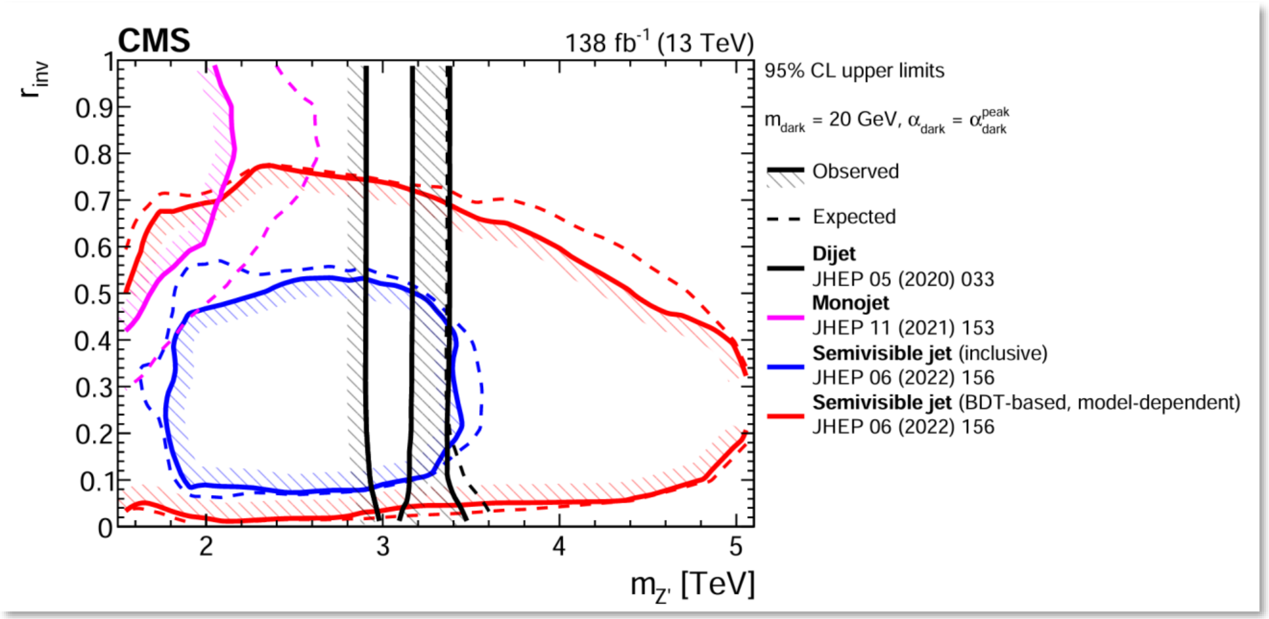


Explicitly vetoed by most DS searches

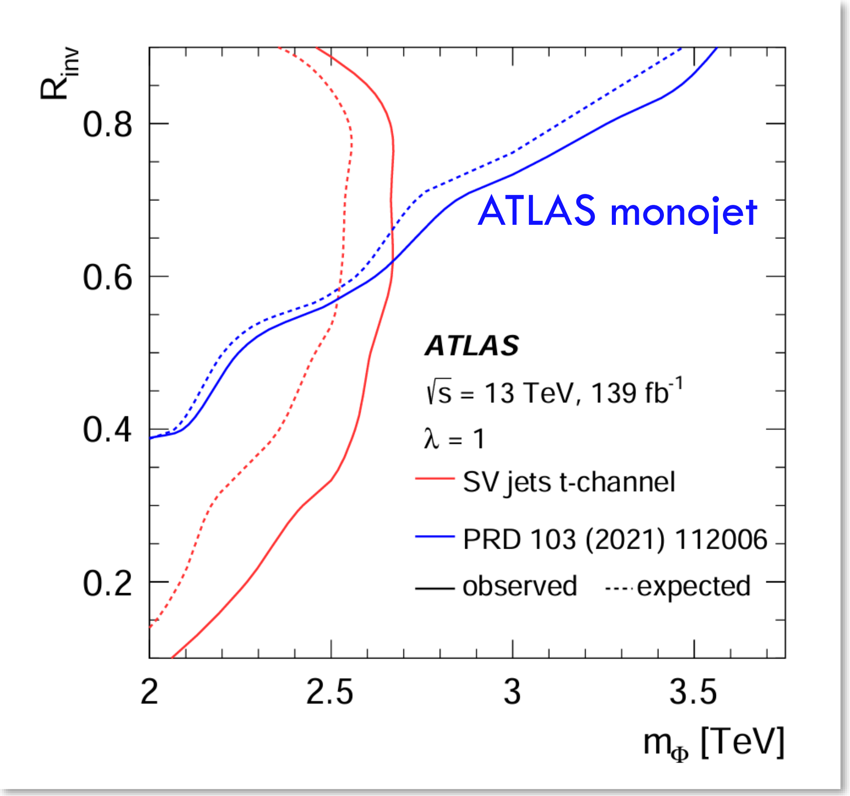
DARK QCD - SVJS

- First search by CMS for vector mediator (s-channel), first search by ATLAS for bi-fundamental mediator (t-channel)

[10.1007/JHEP06(2022)156](https://doi.org/10.1007/JHEP06(2022)156)

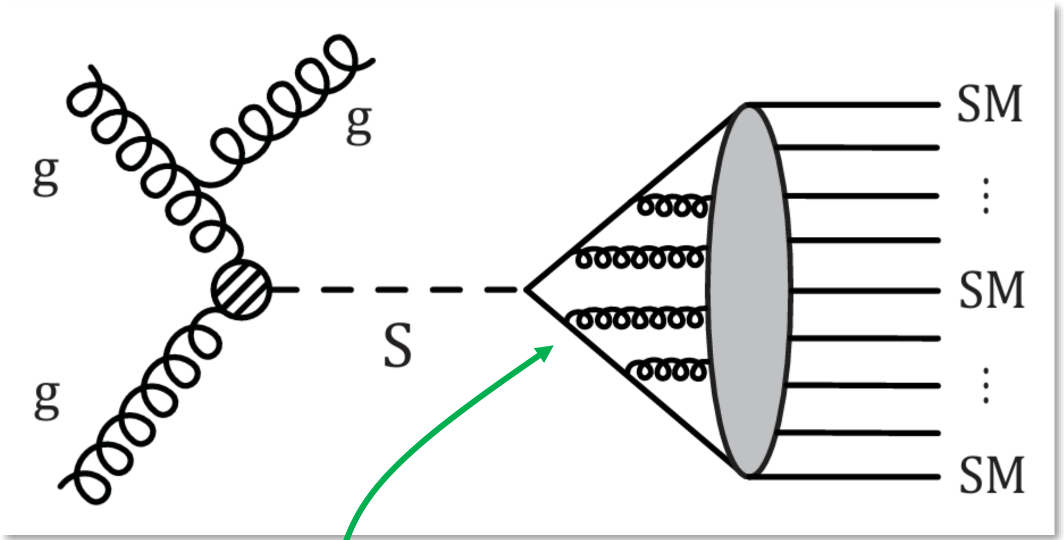


[10.1016/j.physletb.2023.138324](https://doi.org/10.1016/j.physletb.2023.138324)

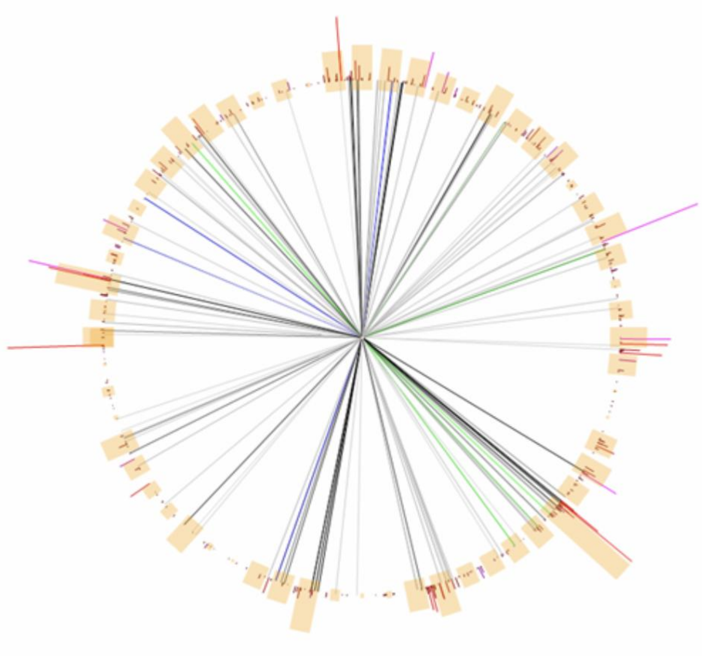


DARK QCD – SUEPS

- Who says dark QCD should behave like SM QCD?
- In the large t' Hooft coupling regime you don't get jets anymore



Quasi-isotropic radiation pattern in CoM frame of S

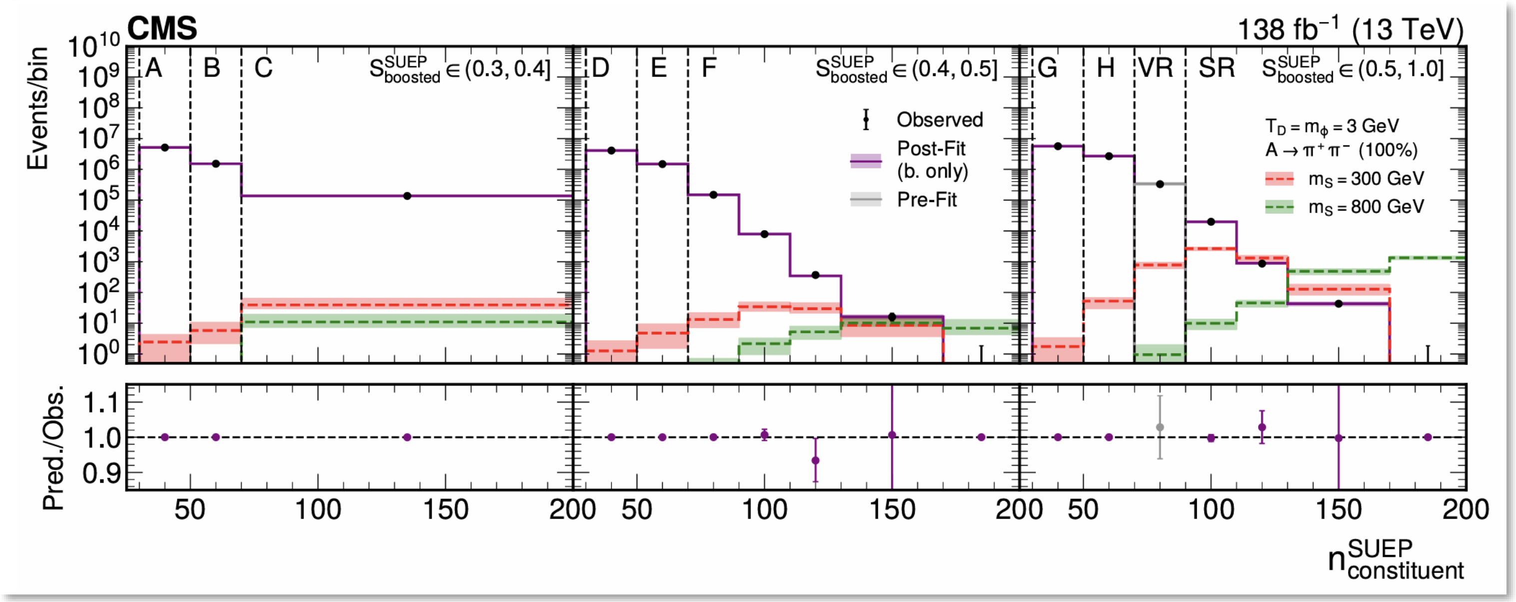


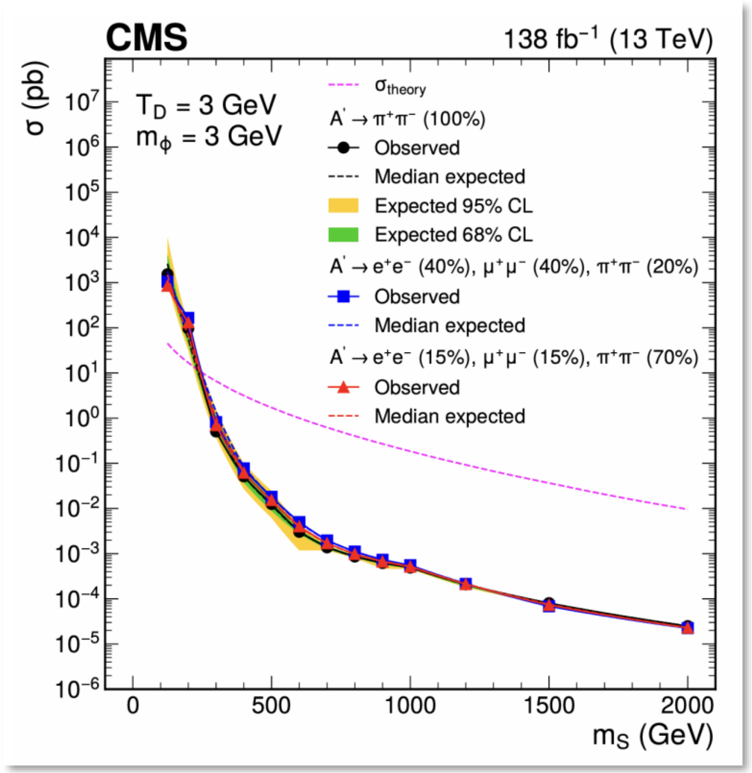
Easily lost in the PU sea

DARK QCD – SUEPS

- First search for such signatures released by CMS

10.1103/PhysRevLett.133.191902



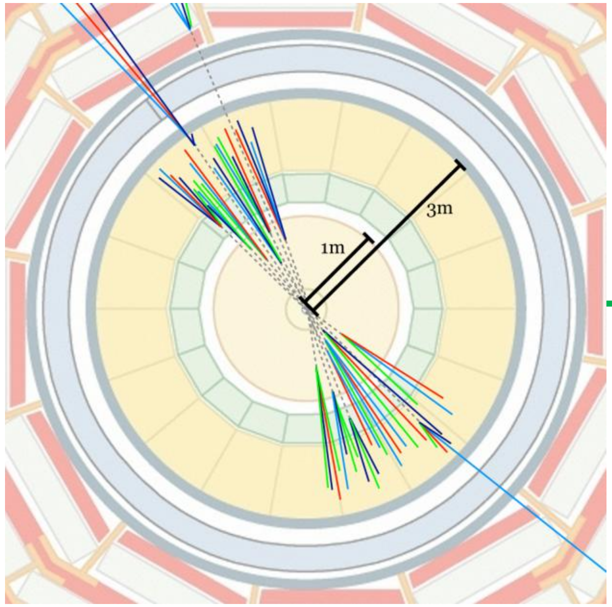


- Fully data-driven background estimation via extended ABCD, fit on $n_{constituents}$

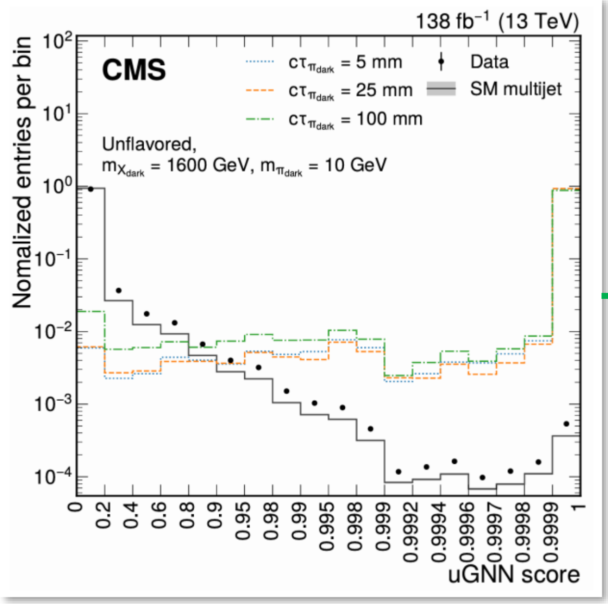
DARK QCD

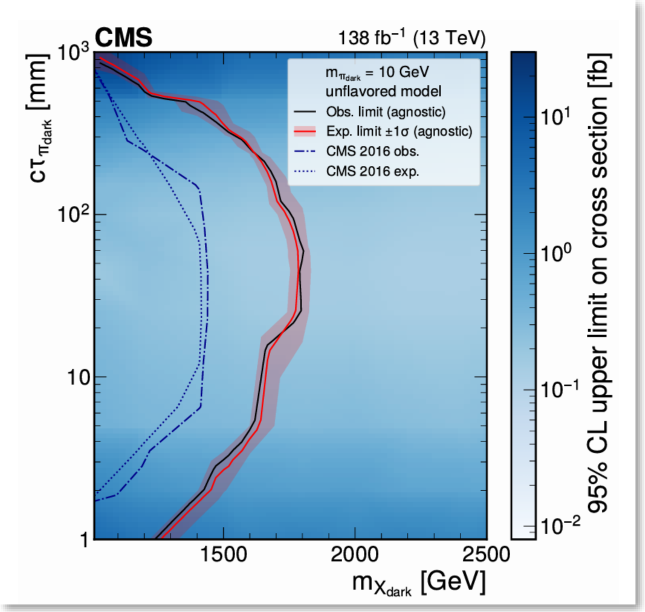
- If we allow dark hadrons to be long lived → emerging jets

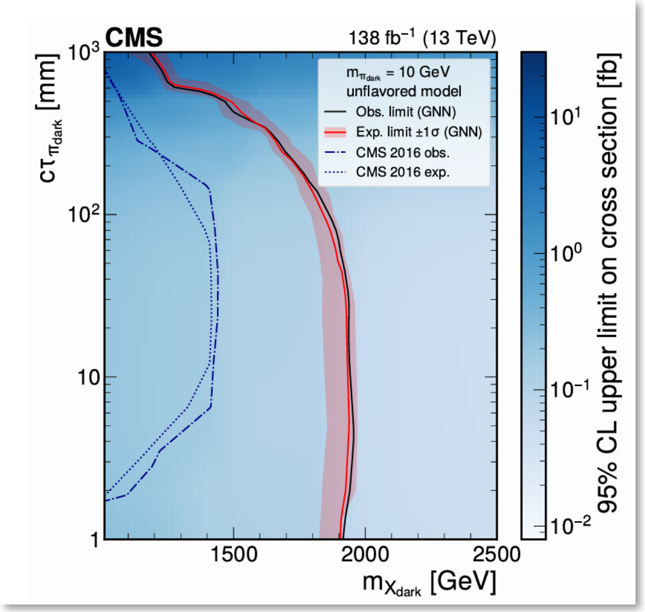
10.1007/JHEP05(2015)059



10.1007/JHEP07(2024)142





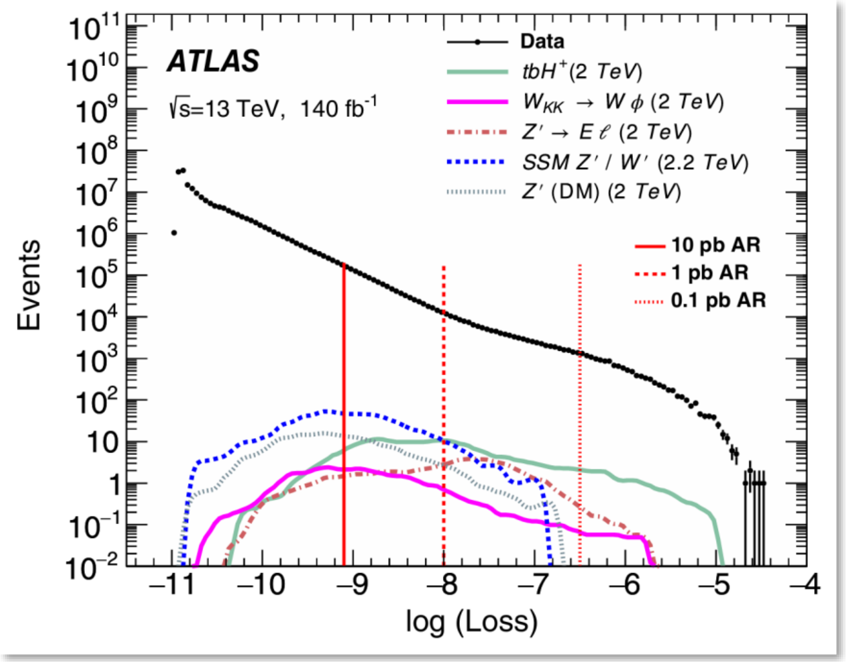


Tracks in each jet are fed to a graph neural network

ANOMALY DETECTION

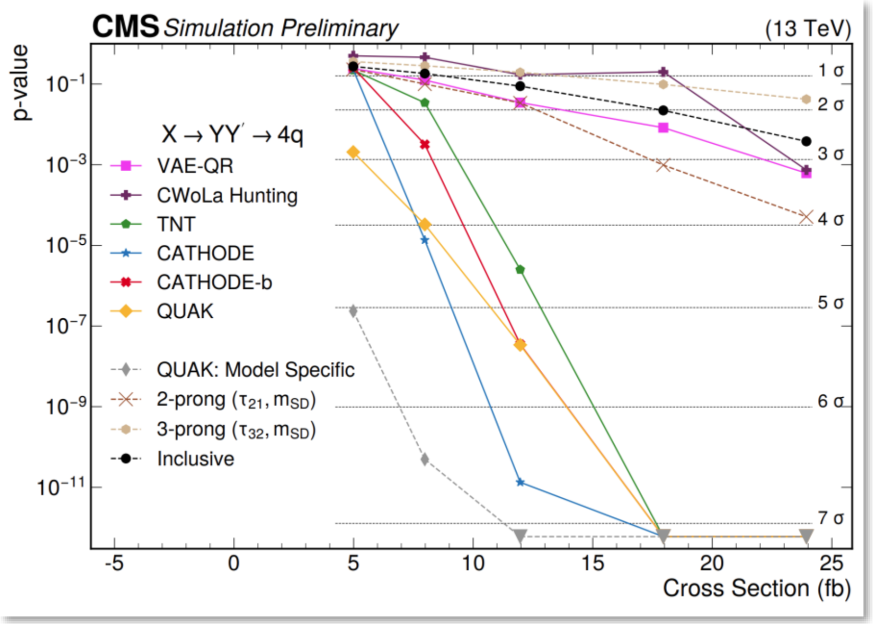
- Train a model to learn what the background looks like → tag potentially anomalous data

10.1103/PhysRevLett.132.081801



Autoencoder trained on data represented as a rapidity-mass matrix

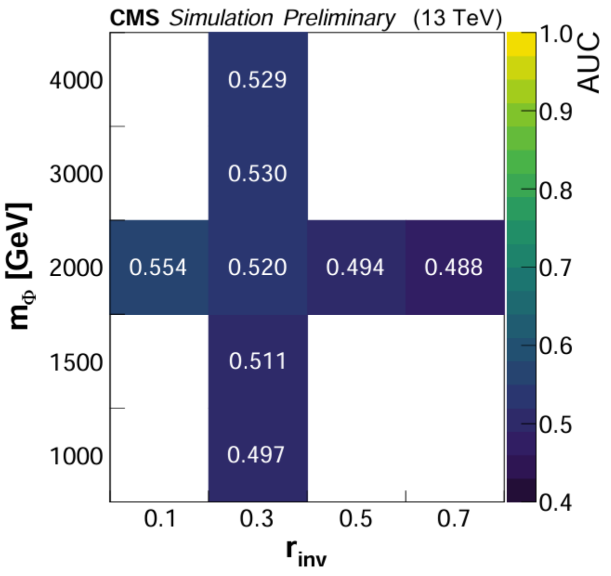
CMS-PAS-EXO-22-026



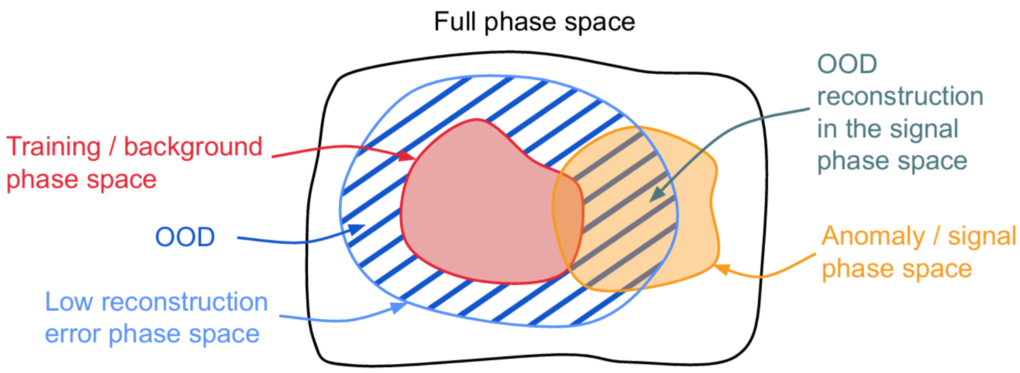
Various techniques, including variational autoencoders and normalizing-flow-based setups

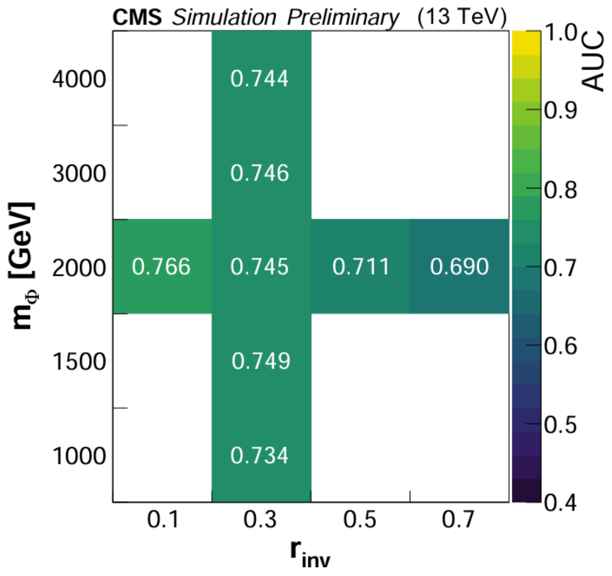
ANOMALY DETECTION

- Train a model to learn what the background looks like → tag potentially anomalous data
- Can also be powerful to reduce dependency of more targeted searches
- E.g.: Wasserstein Normalized Autoencoders for semivisble jet tagging

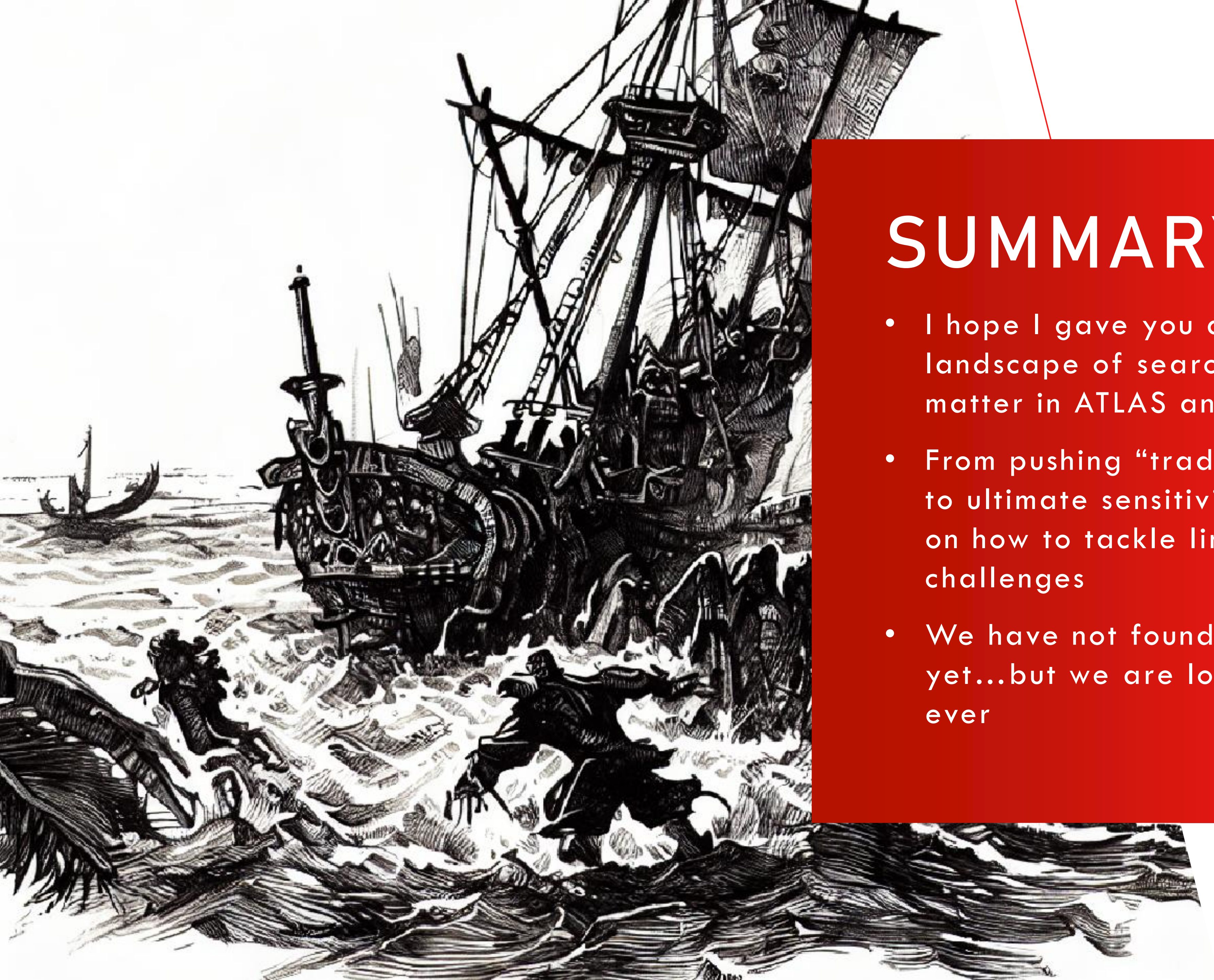


CMS-PAS-MLG-24-002





Force an autoencoder to only learn the background without showing it the signal



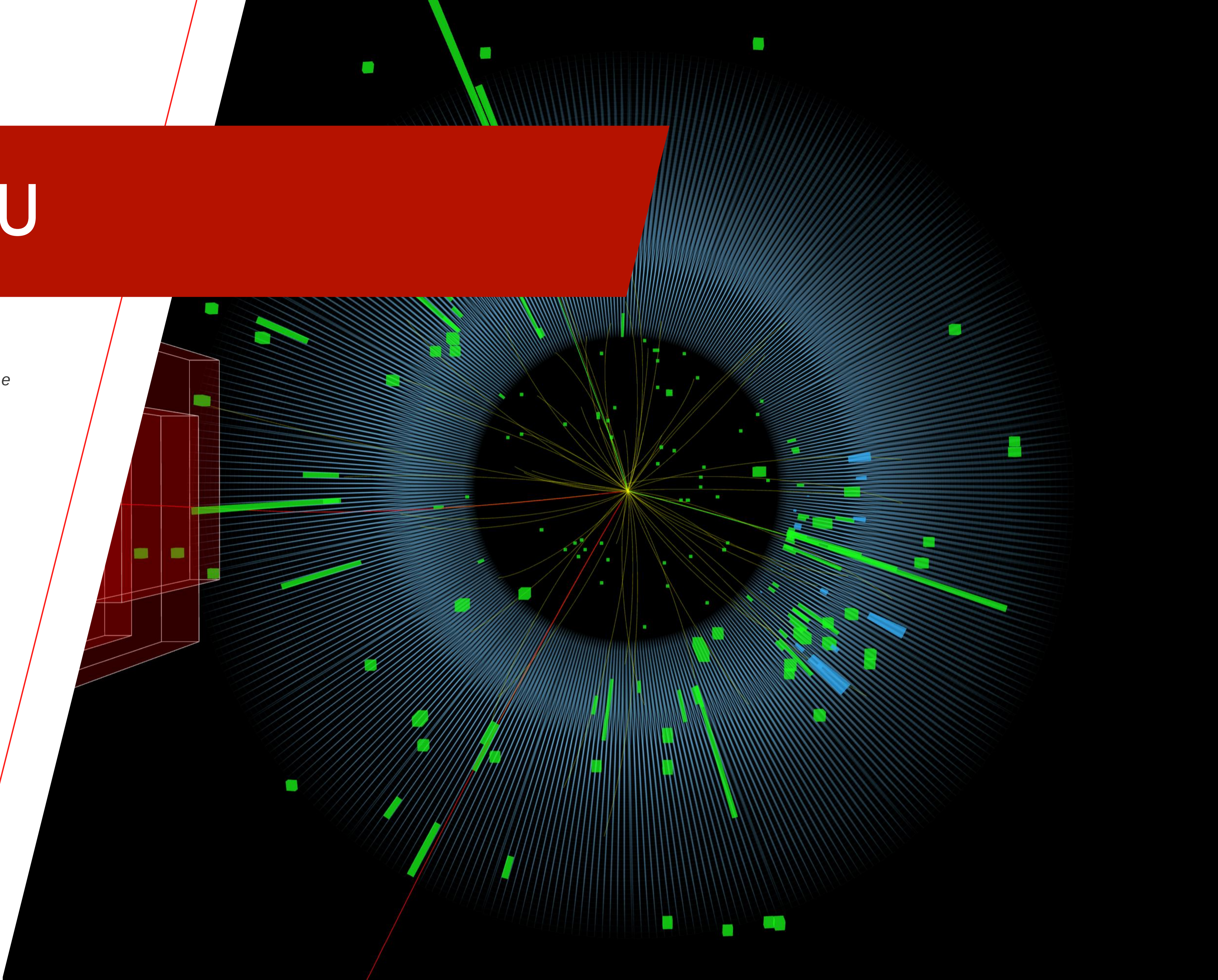
SUMMARY

- I hope I gave you an idea of the landscape of searches for dark matter in ATLAS and CMS
- From pushing “traditional” methods to ultimate sensitivity, to new ideas on how to tackle limits and challenges
- We have not found dark matter yet…but we are looking closer than ever

THANK YOU

« Ce qui est admirable, ce n'est pas que
le champ des étoiles soit si vaste,
c'est que l'homme l'ait mesuré. »

Jacques Anatole François Thibault



BACKUP

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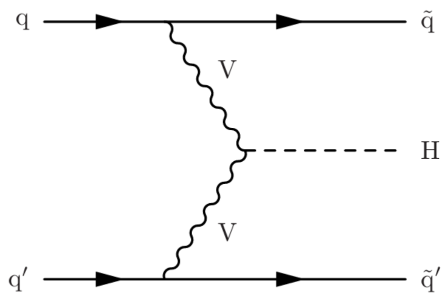
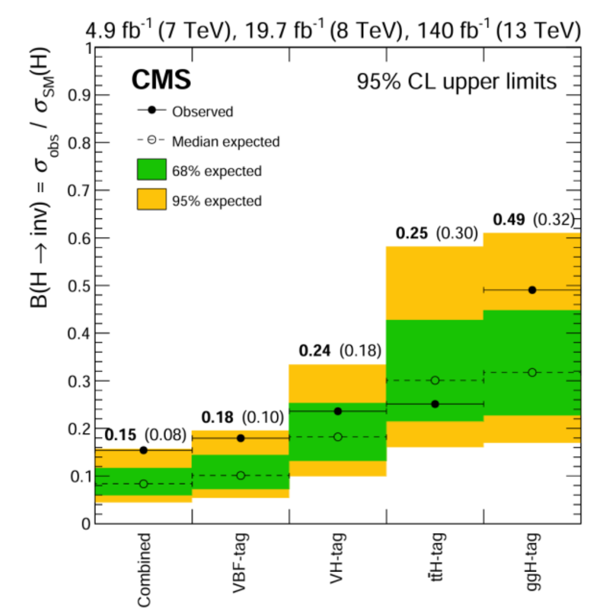
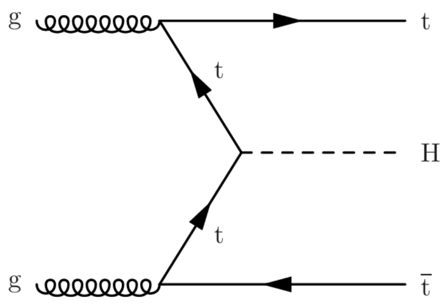
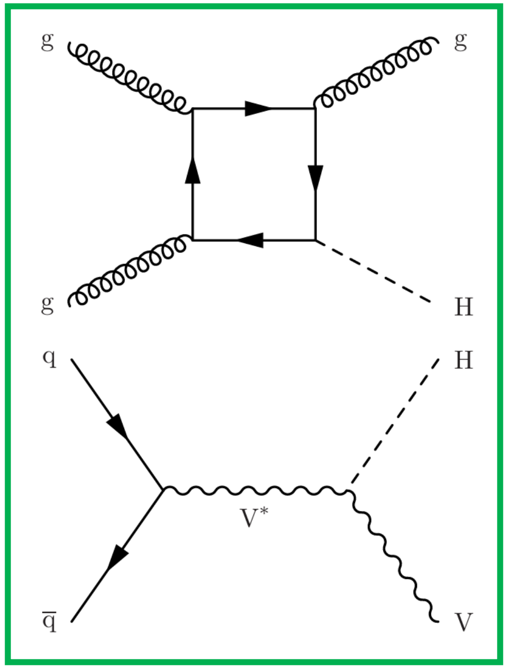
THE HIGGS BOSON AS A DARK SECTOR PROBE

- We discovered the Higgs boson, why not start using it as a probe?
- In the SM, the Higgs boson can decay invisibly via $H \rightarrow ZZ \rightarrow 4\nu$
- Once $H \rightarrow ZZ$ and $Z \rightarrow \nu\nu$ branching fractions are known, searches for generic $H \rightarrow invisible$ events are powerful probes for DSs

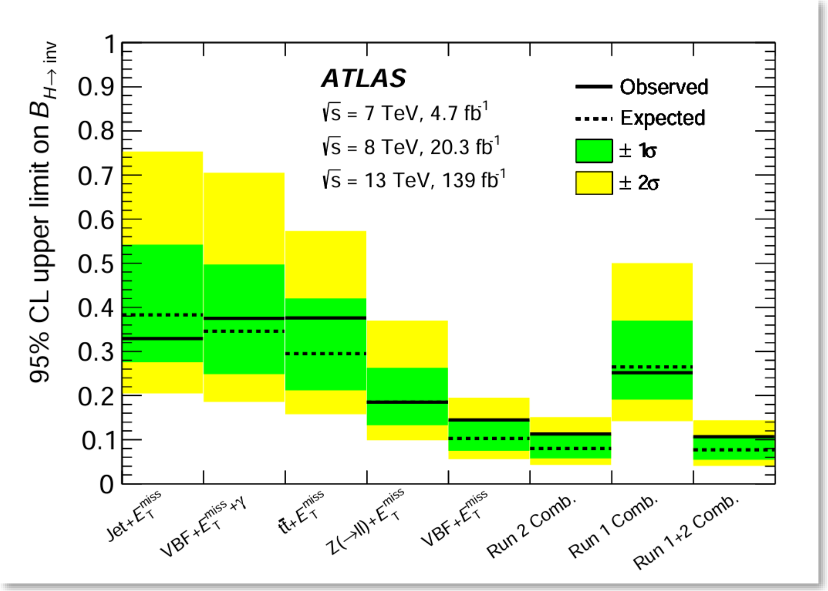




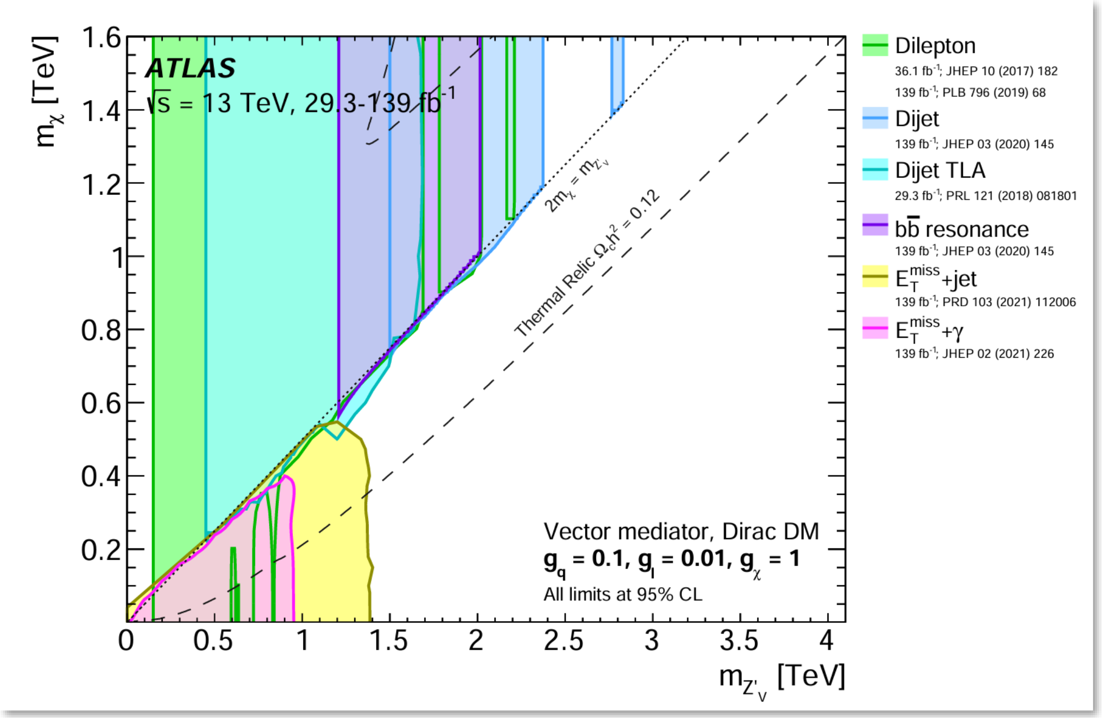


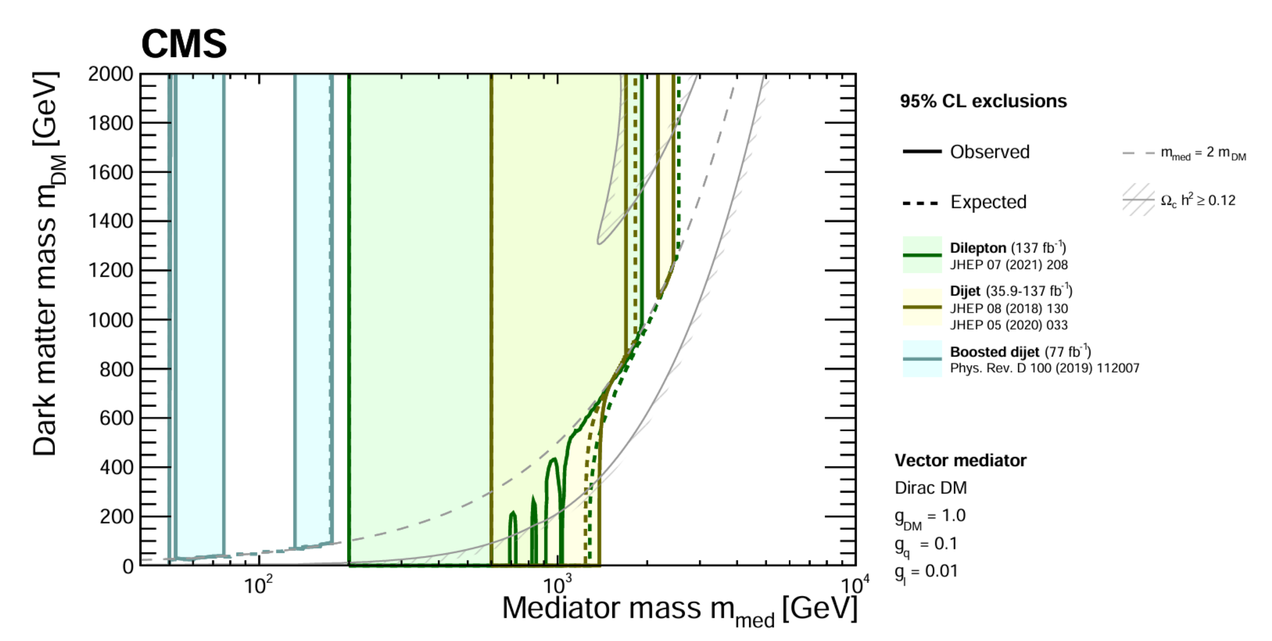


Covered by mono searches



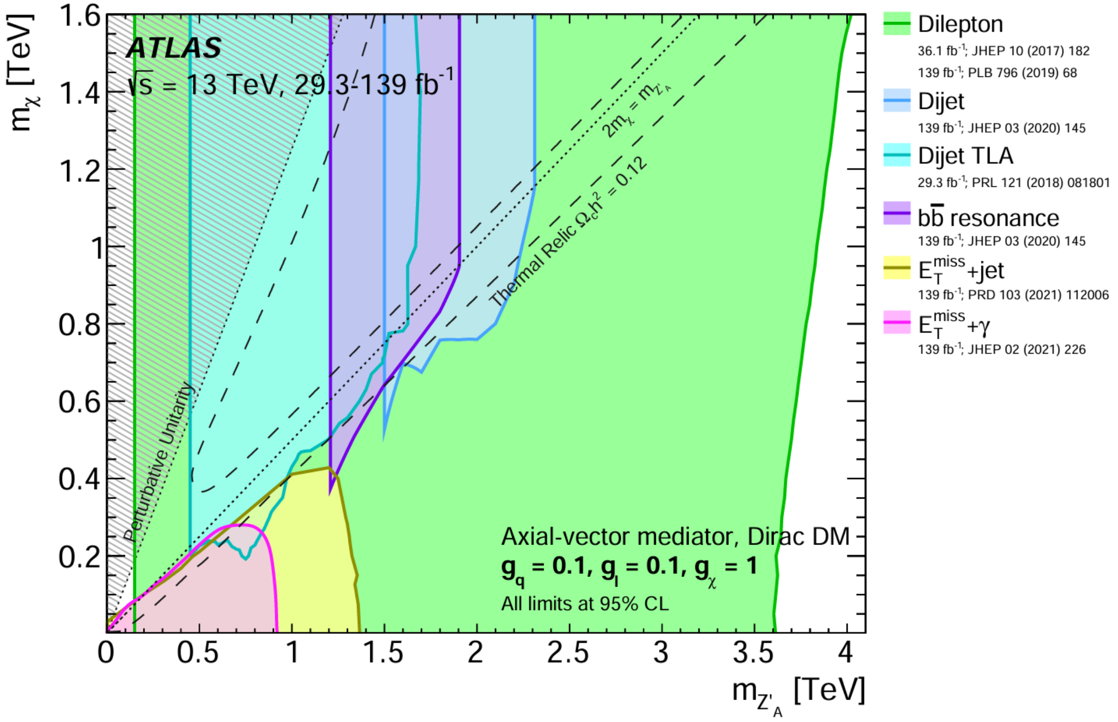
VECTOR PORTAL LIMITS

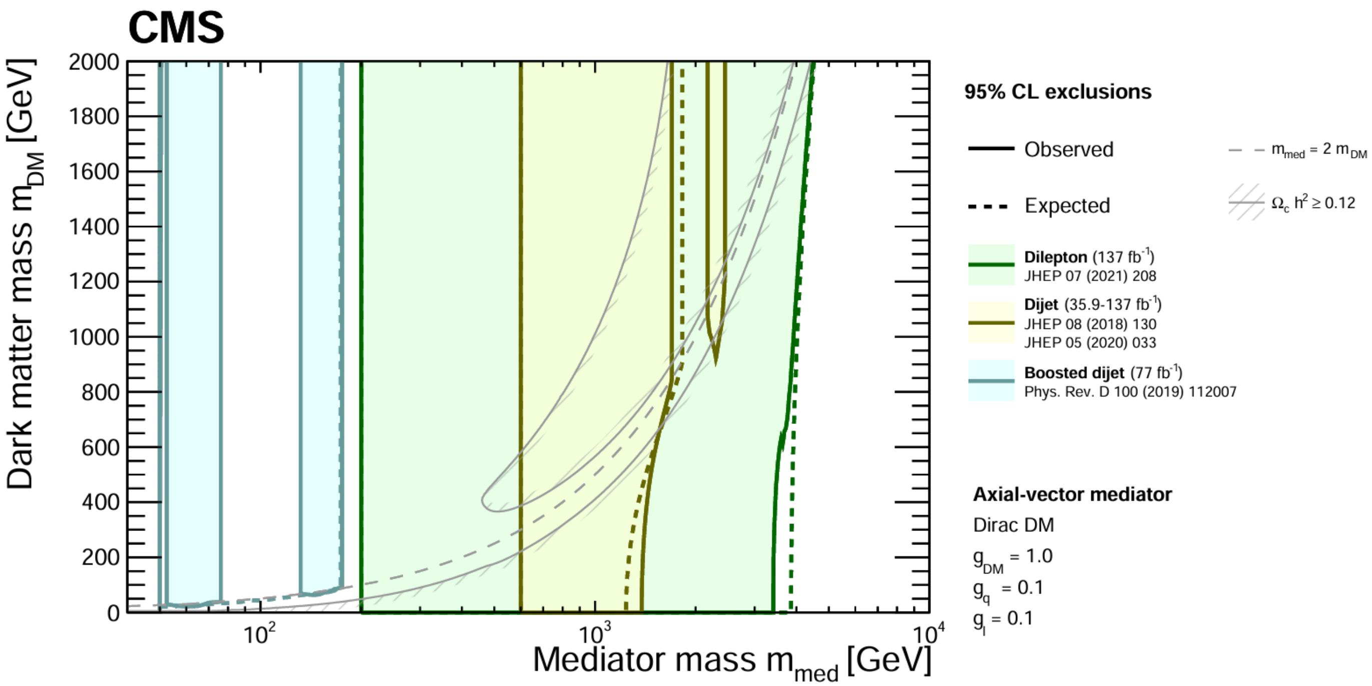




- Limits mostly dominated by dilepton searches if portal is allowed lepton couplings
- Lower masses can be reached by ISR+dijet searches or TLA/scouting (more on those later)

AXIAL VECTOR PORTAL LIMITS





LEPTOPHOBIC AXIAL VECTOR PORTAL LIMITS