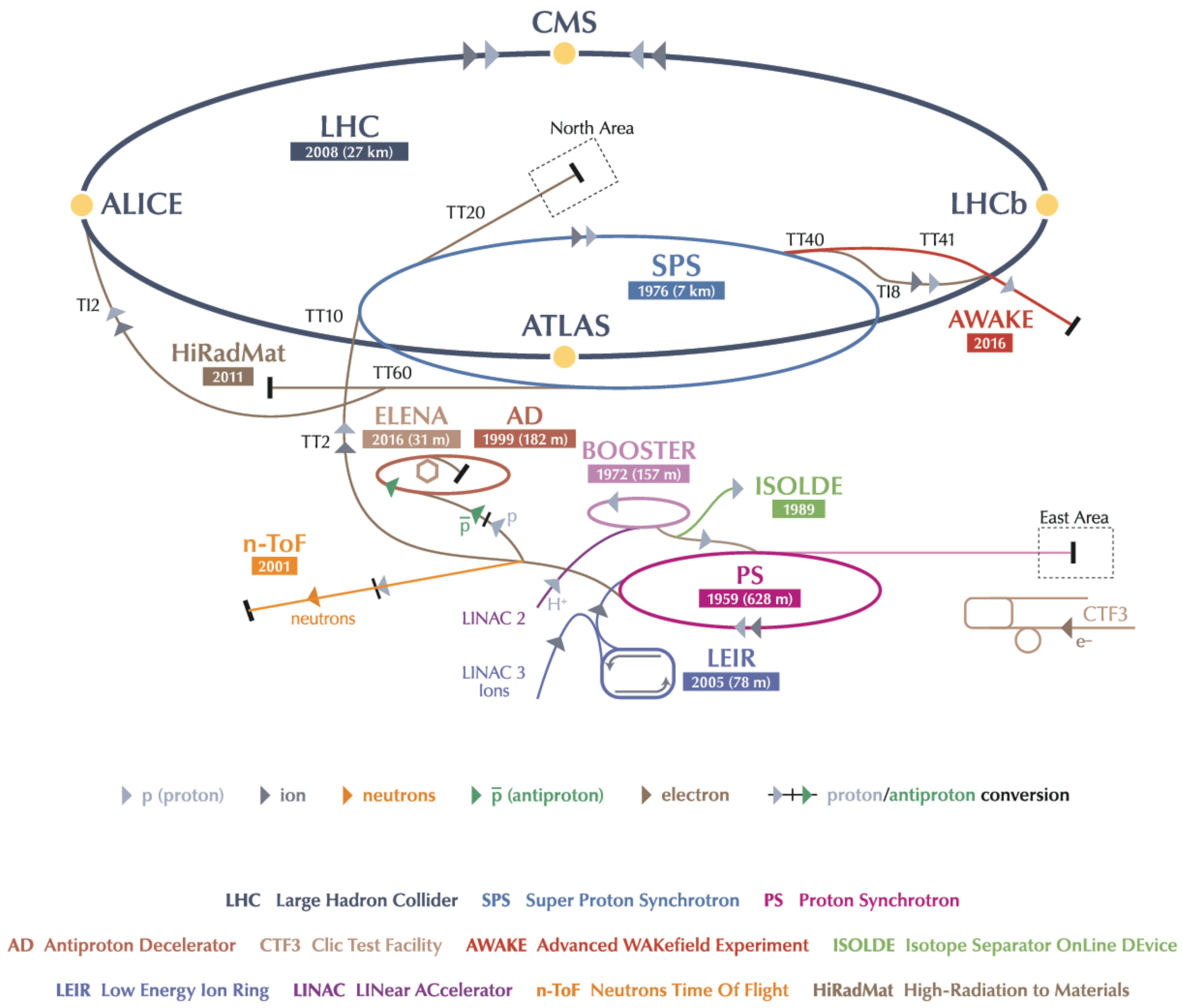
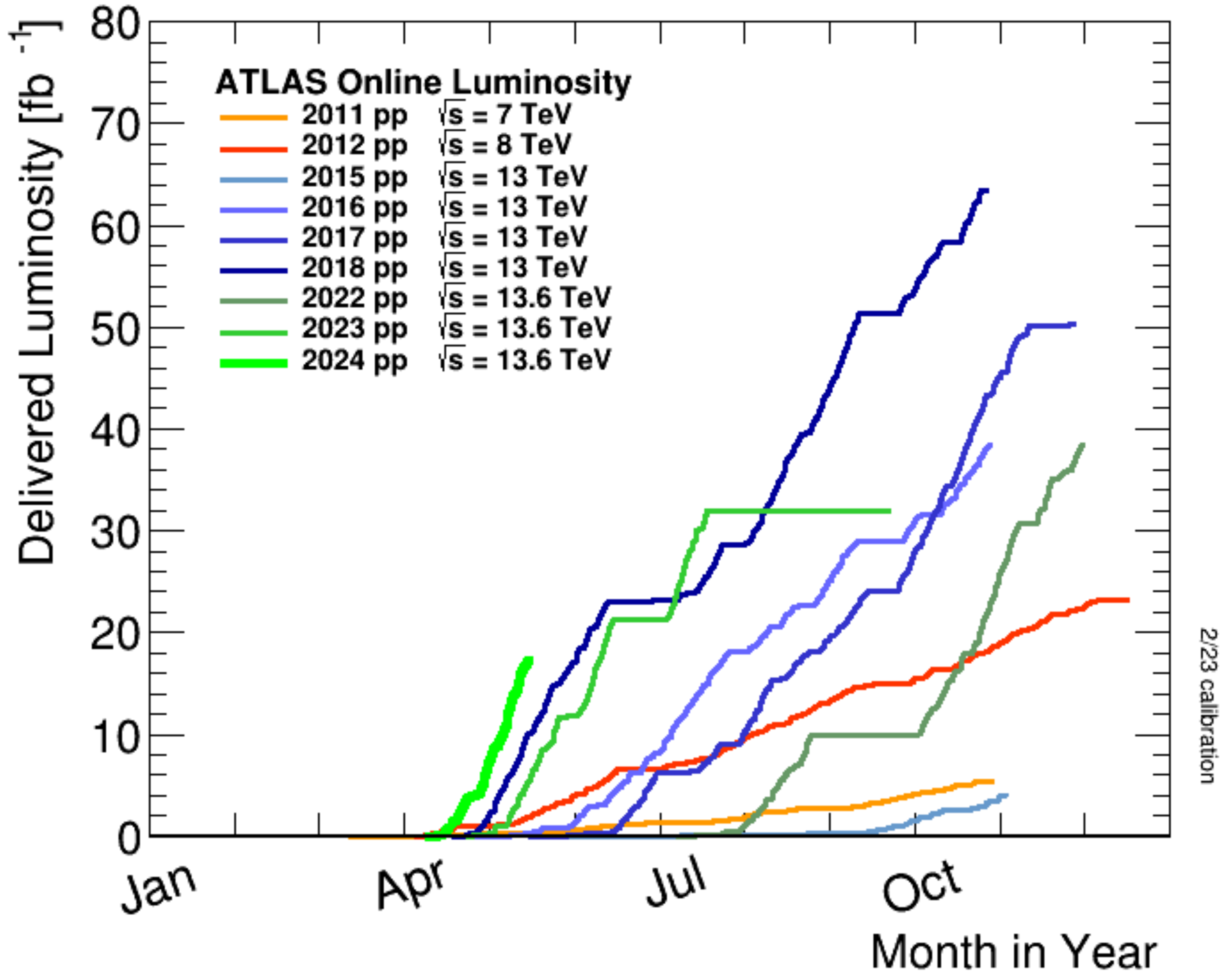
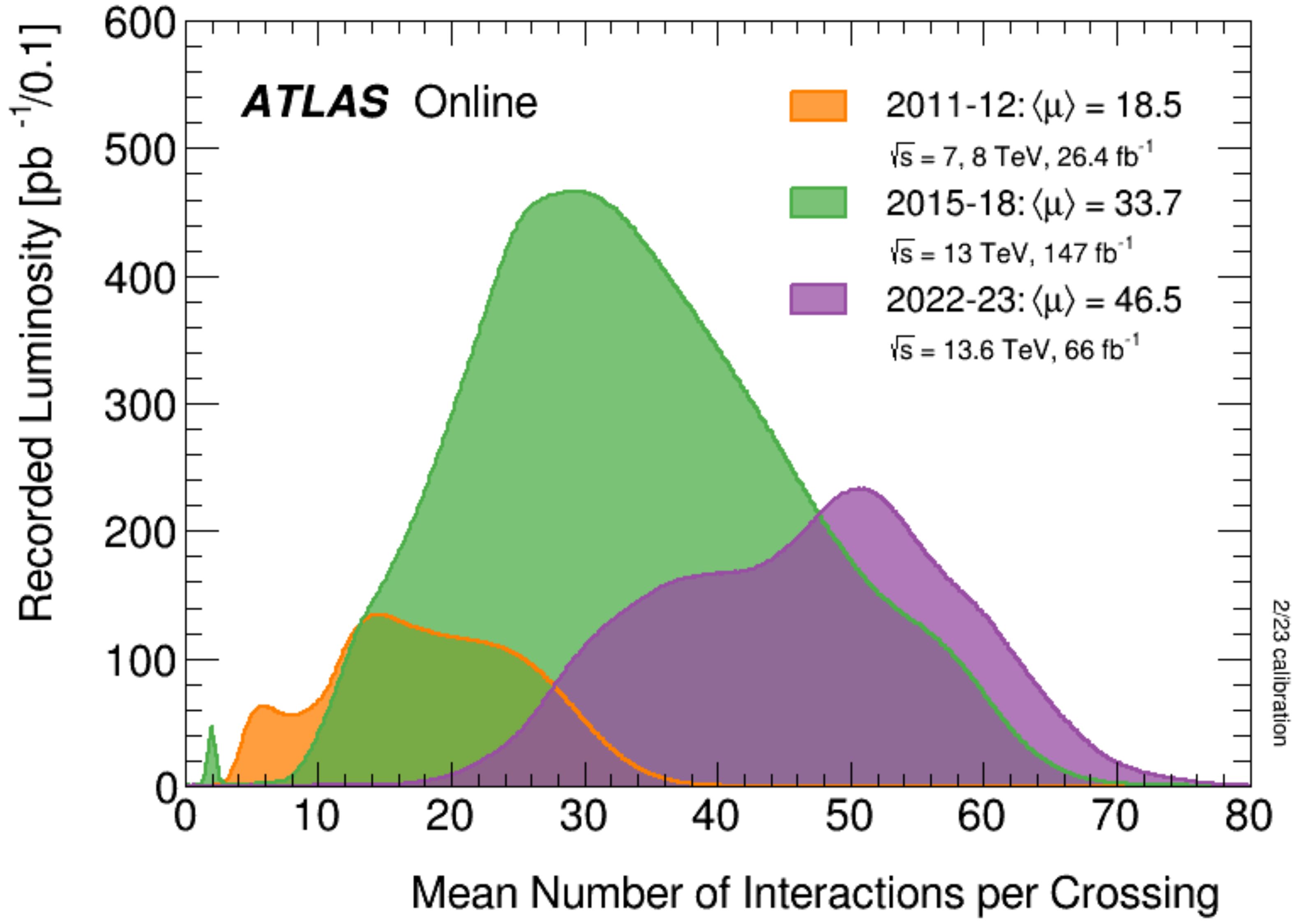
Search for exotic physics with long-lived particles at ATLAS

Cristiano Sebastiani
17 May 2024, University of Liverpool

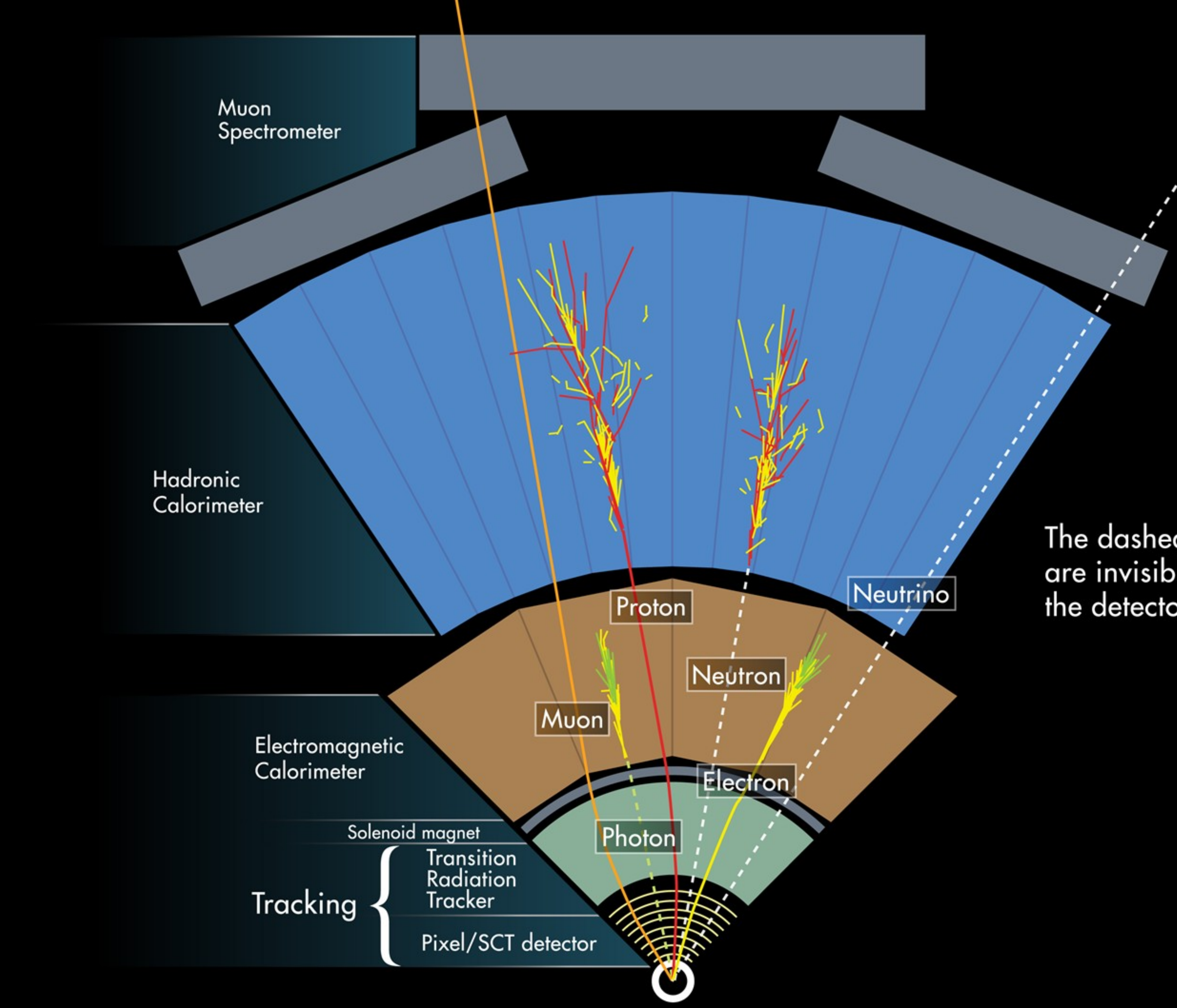
Large Hadron Collider



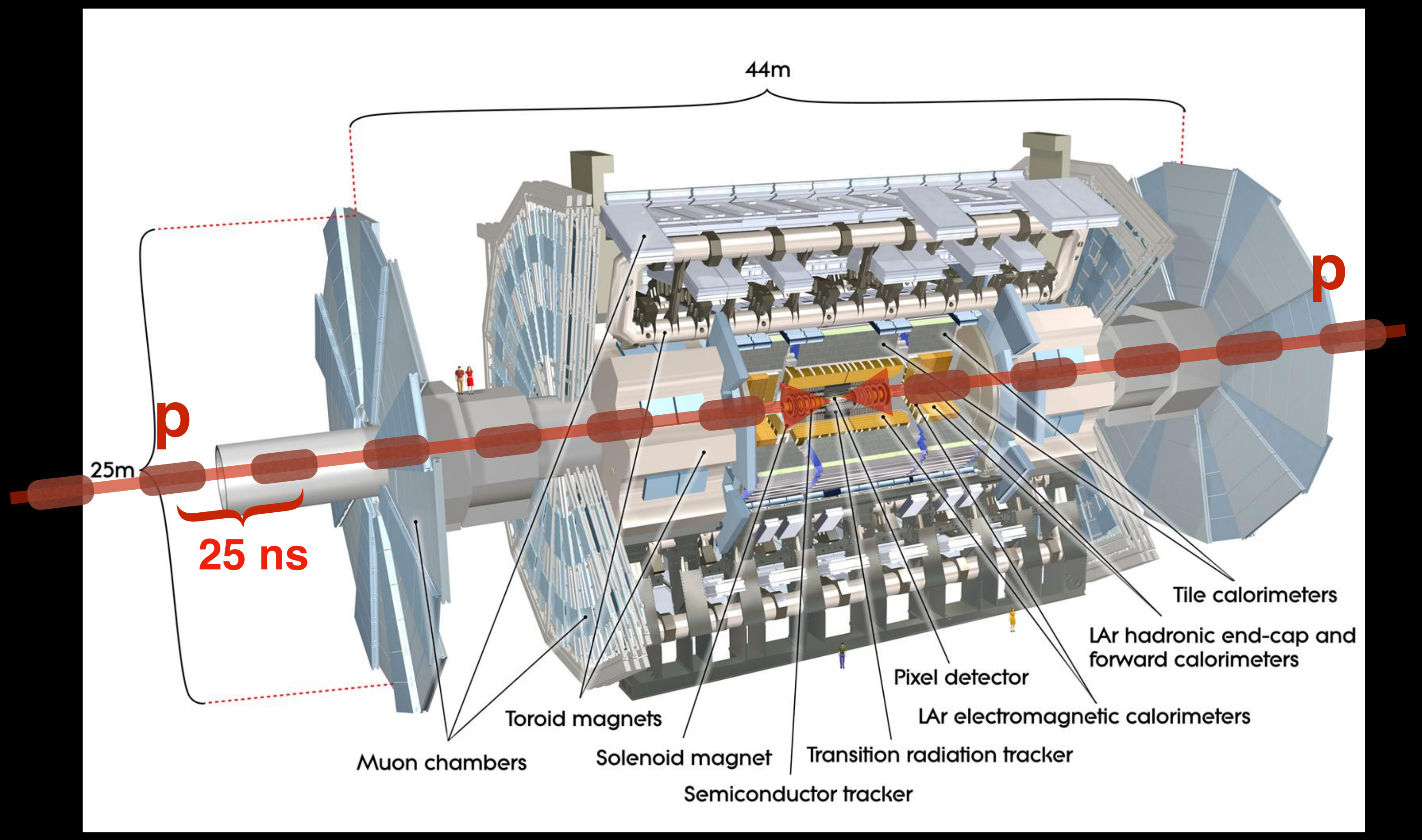




ATLAS@LHC



The dashed tracks are invisible to the detector



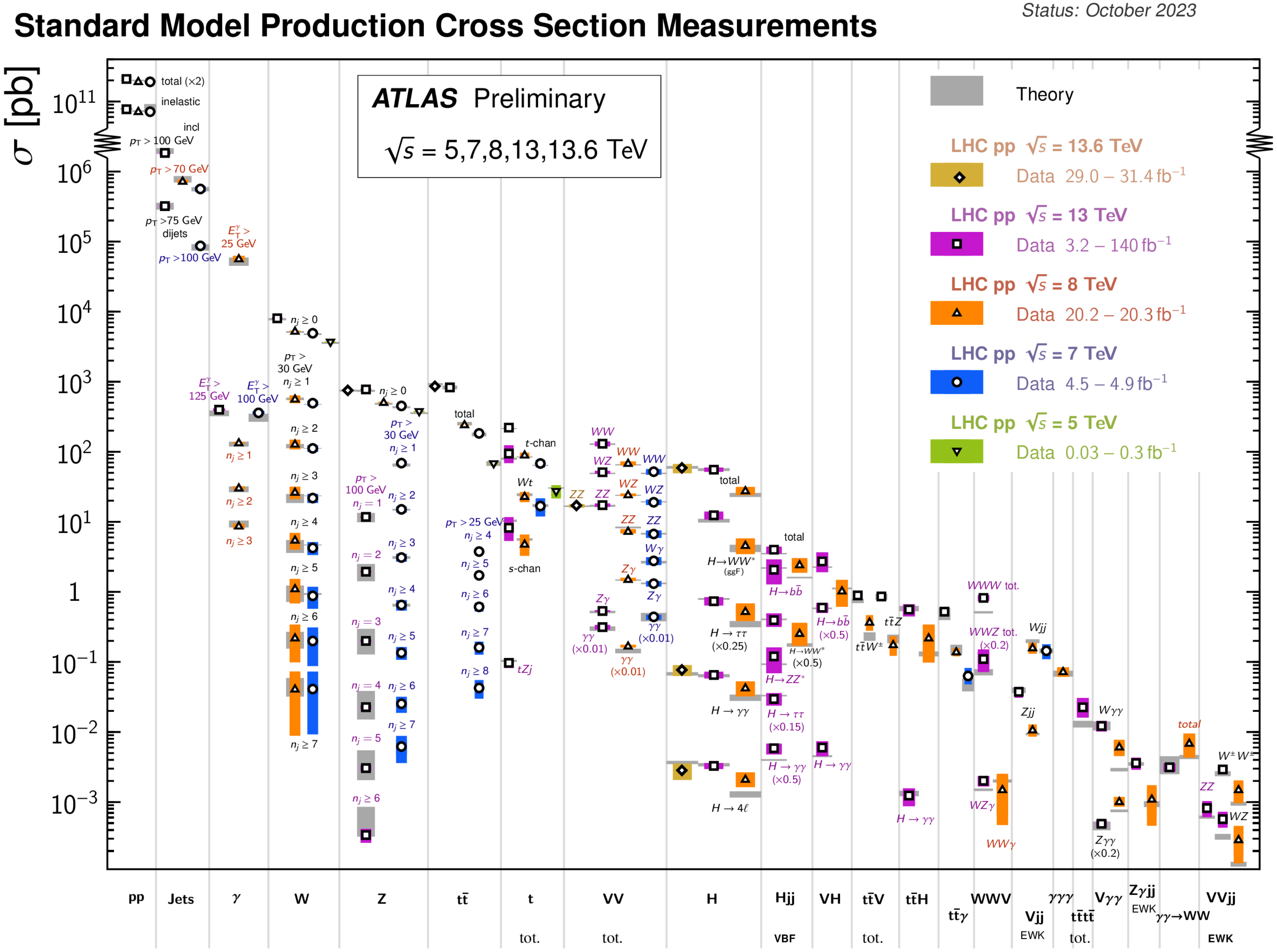
Standard Model

All about discovering new physics:

- ATLAS extensive measurements programme can still be considered as searches

- Almost all collider measurements to date, across 14 orders of magnitude, agree with its predictions

… no new physics so far…



DM signatures

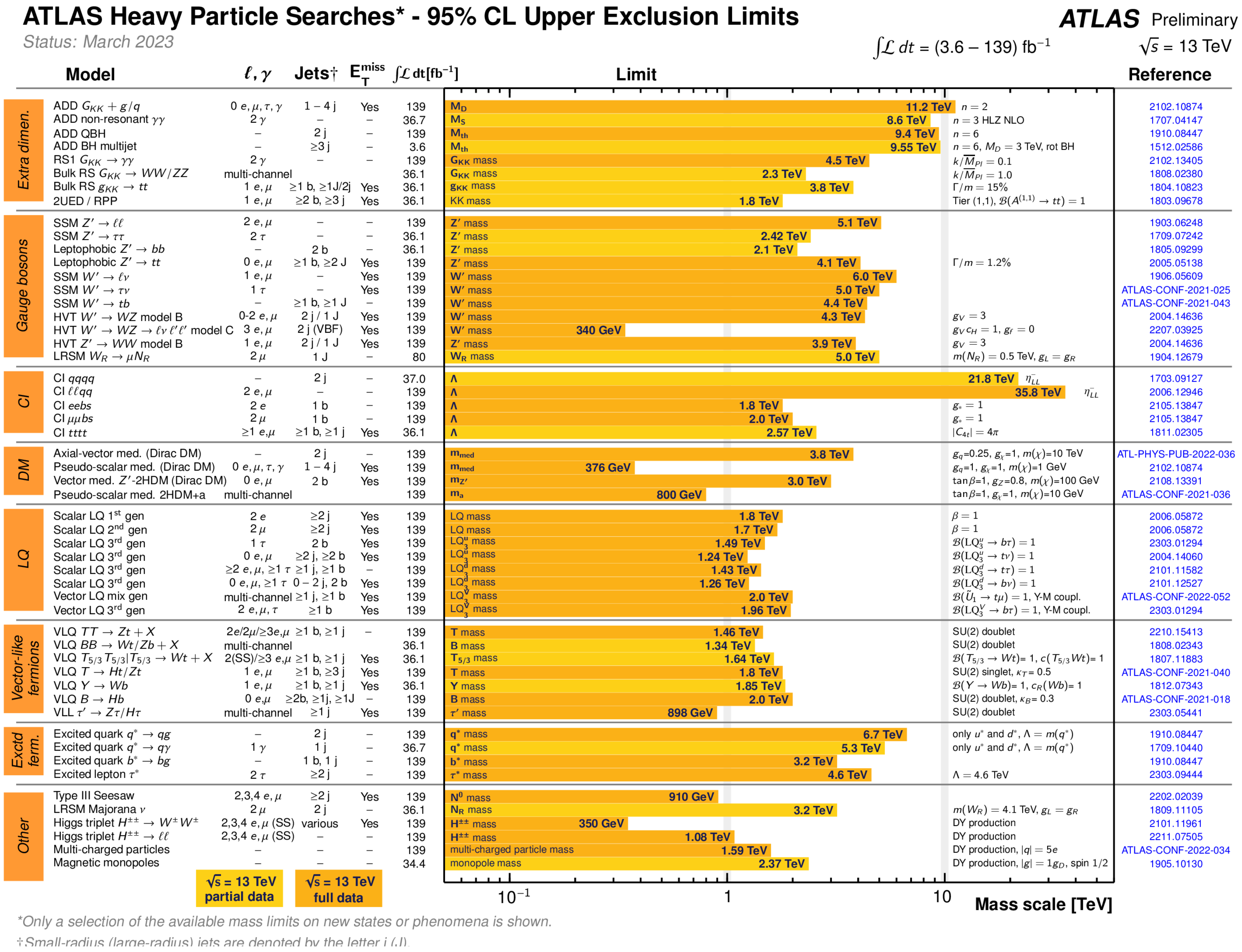
Signature based searches:

- Many expected SUSY and WIMP particles to follow shortly after the Higgs, but now increasingly disfavoured

- No hint for new discoveries to be made at the energy scales accessible to the LHC

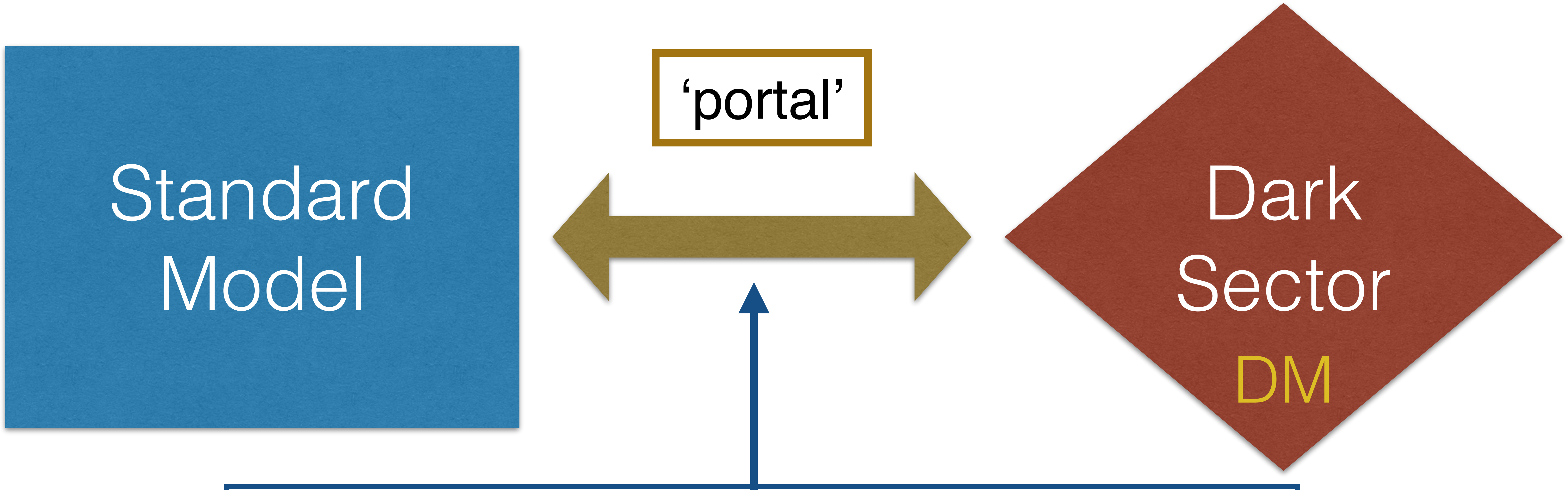
Are there underlying assumptions in our research programme which are preventing a discovery?

it's time to explore new ideas!



A new perspective

New Physics can be decoupled from electroweak scale in Dark Sector models, requiring additional low-mass mediators to explain the observed relic density with light DM (sub-GeV)



Shift the focus from the Dark Matter sector composition to the new mediator itself

Dark Sector portals

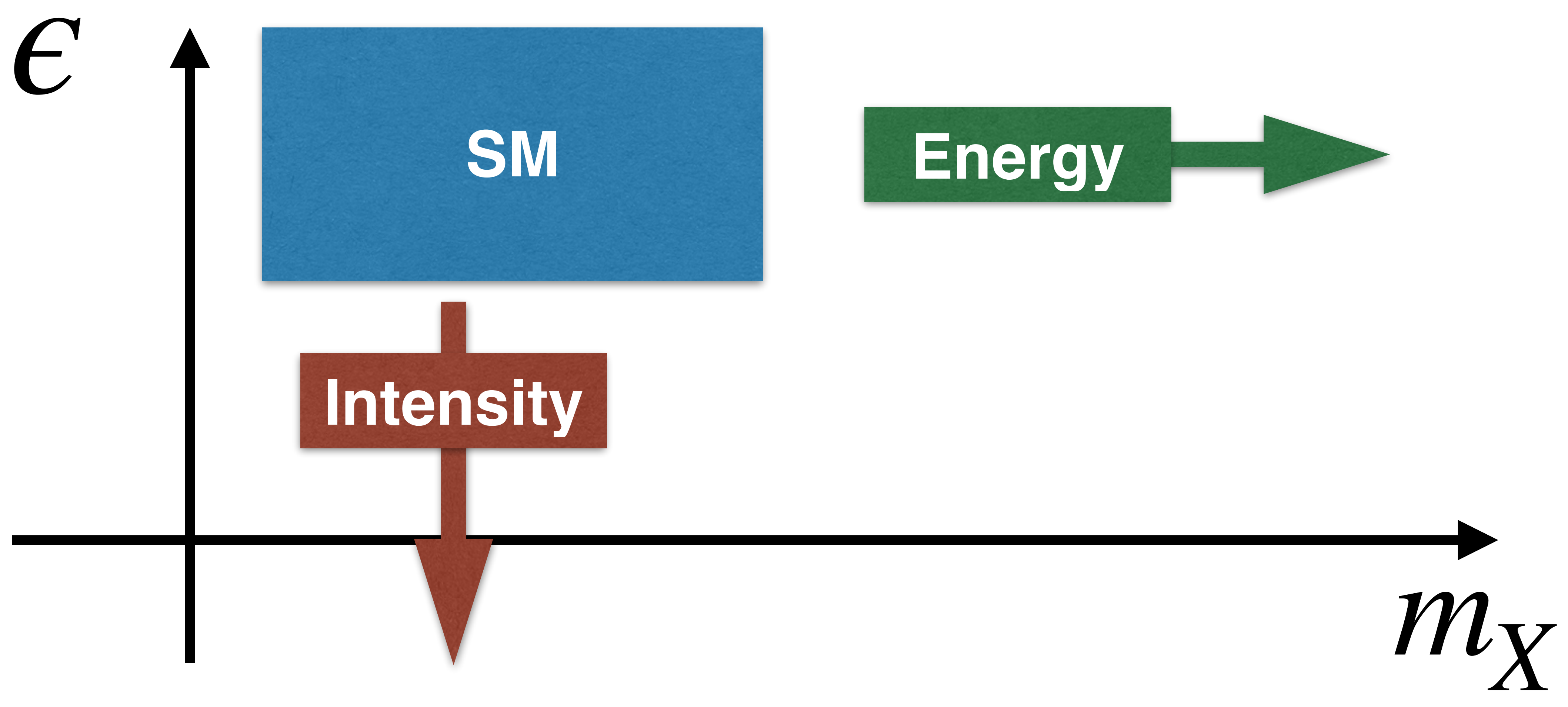
Light mediators, HNL and ALPs must be SM singlets: options limited by SM gauge invariance

Pseudoscalar portal: $\delta_\mu \bar{\psi}\gamma^\mu\gamma^5\psi \; , \; \frac{a}{f_a}F'_{\mu\nu}\tilde{F}^{\mu\nu}$ **axions/ALPs**

Vector portal: $\epsilon F^{\mu\nu}F'_{\mu\nu}$ **'dark' vector boson (A', γ_d, Z_d) which mixes with SM photon**

Higgs portal: $\kappa H^2 S^2 + \mu H^2 S$ **'dark' scalar boson (S) —> exotic Higgs decays**

Neutrino portal: $\kappa(HL)N$ **no more sterile neutrino**



Feebly interacting particles are well motivated but their mass scale is unknown and are very difficult to probe at particle colliders, often lead to unconventional signatures!

Dark Sector portals

Light mediators, HNL and ALPs must be SM singlets: options limited by SM gauge invariance

Today's study case

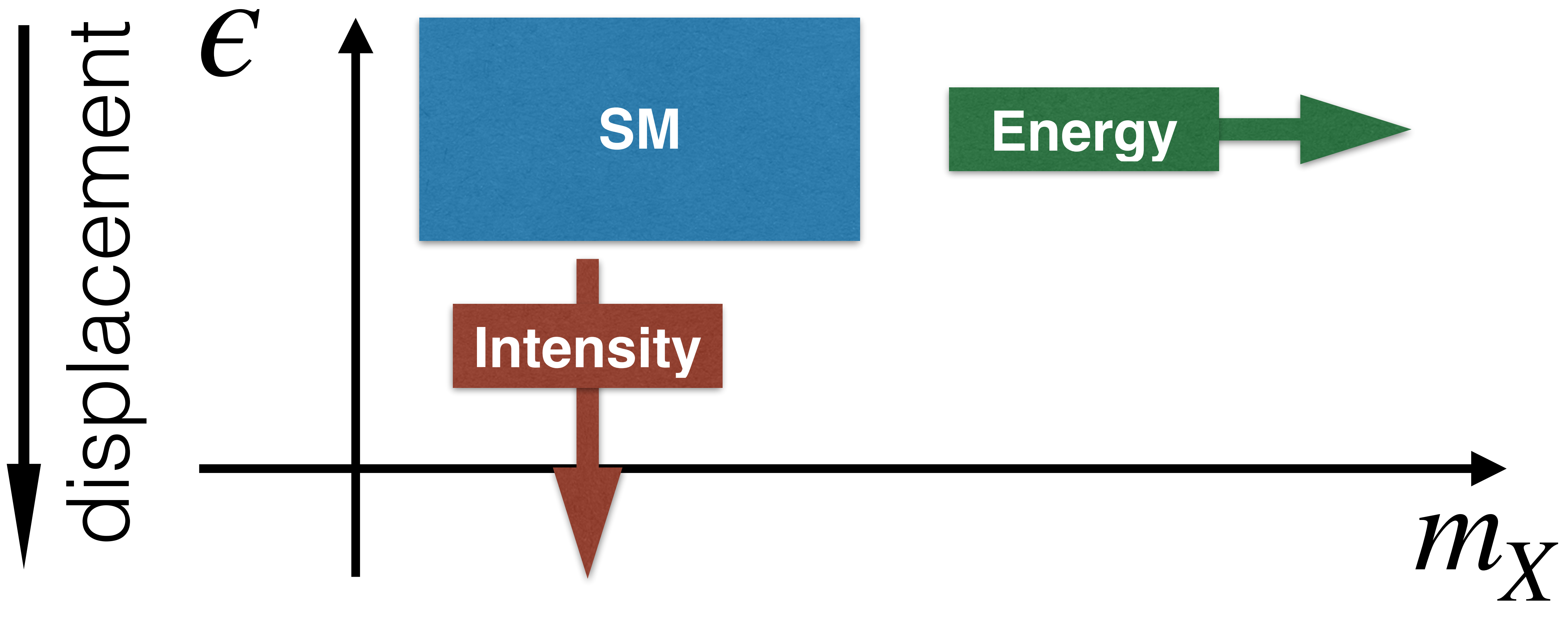
Pseudoscalar portal: $\delta_\mu \bar{\psi}\gamma^\mu\gamma^5 \ldots$ ALPs

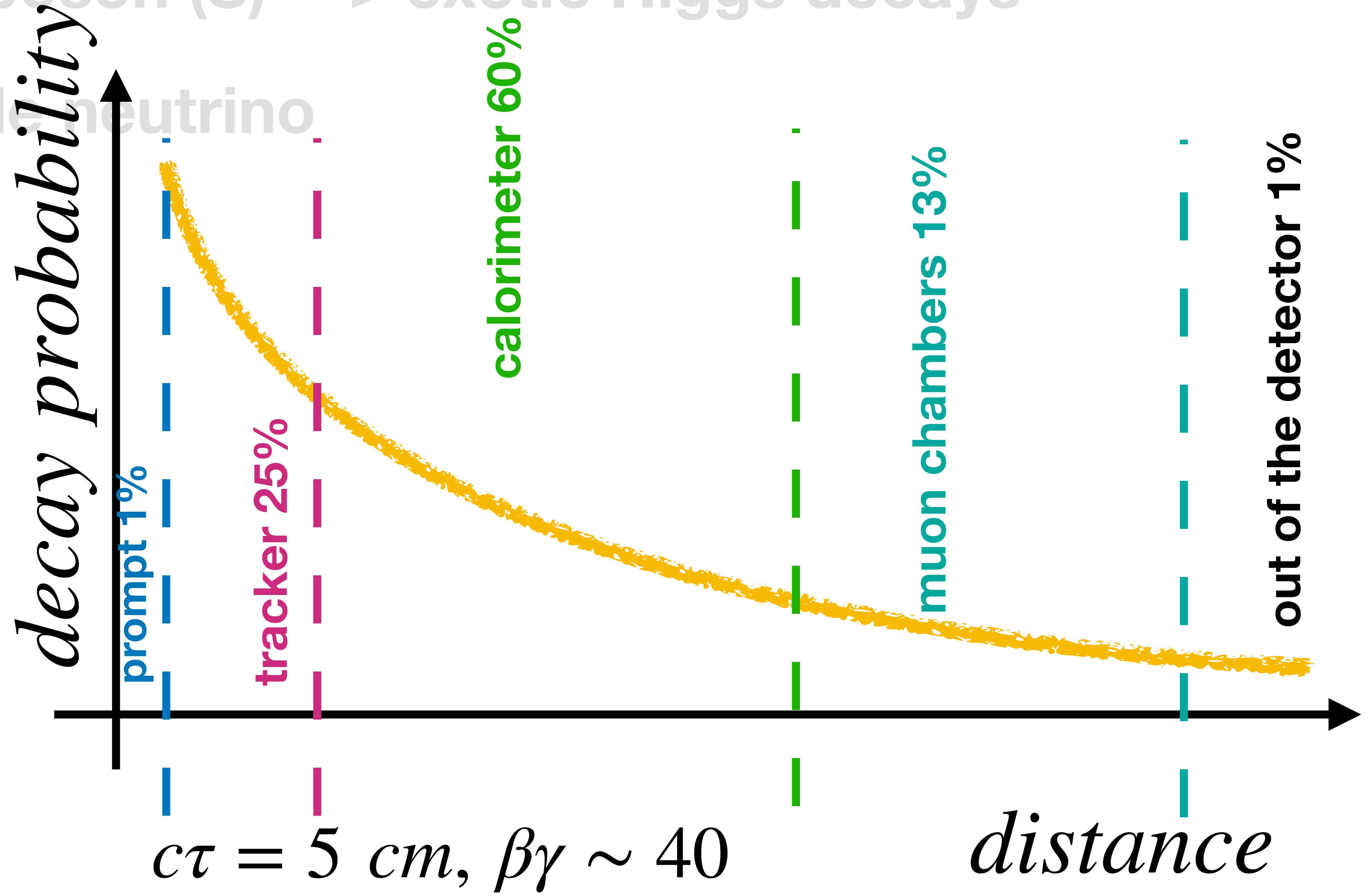
Vector portal: $\epsilon F^{\mu\nu} F'_{\mu\nu}$ **'dark' vector boson (A', γ_d, Z_d) which mixes with SM photon**

Higgs portal: $\kappa H^2 S^2 + \mu H^2 S$ 'dark' scalar boson (S) —> exotic Higgs decays

Neutrino portal: $\kappa (HL) N$ no more sterile neutrino

New particles can be long-lived: observed lifetime is governed by an exponential defined by the proper lifetime cτ





Exotic among exotics?

Search for new BSM physics at LHC with exotic signatures:

- Standard decays
- **Unconventional signatures**: long time-of-flight, anomalous energy deposits, displaced secondary vertices…
- Detector-stable particles

ATLAS and CMS are not optimised for this kind of signals

Unusual and unique signatures are extremely challenging to probe:

TRIGGER	RECONSTRUCTION	NON-COLLISION BACKGROUND
Anomalous signatures not associated with standard activity in the detector require the development of dedicated triggers!	Object identification and reconstruction algorithms are to be updated to include non-standard tracks and energy deposits	Unconventional signatures have unconventional backgrounds, from detector noise to non-collision physics events

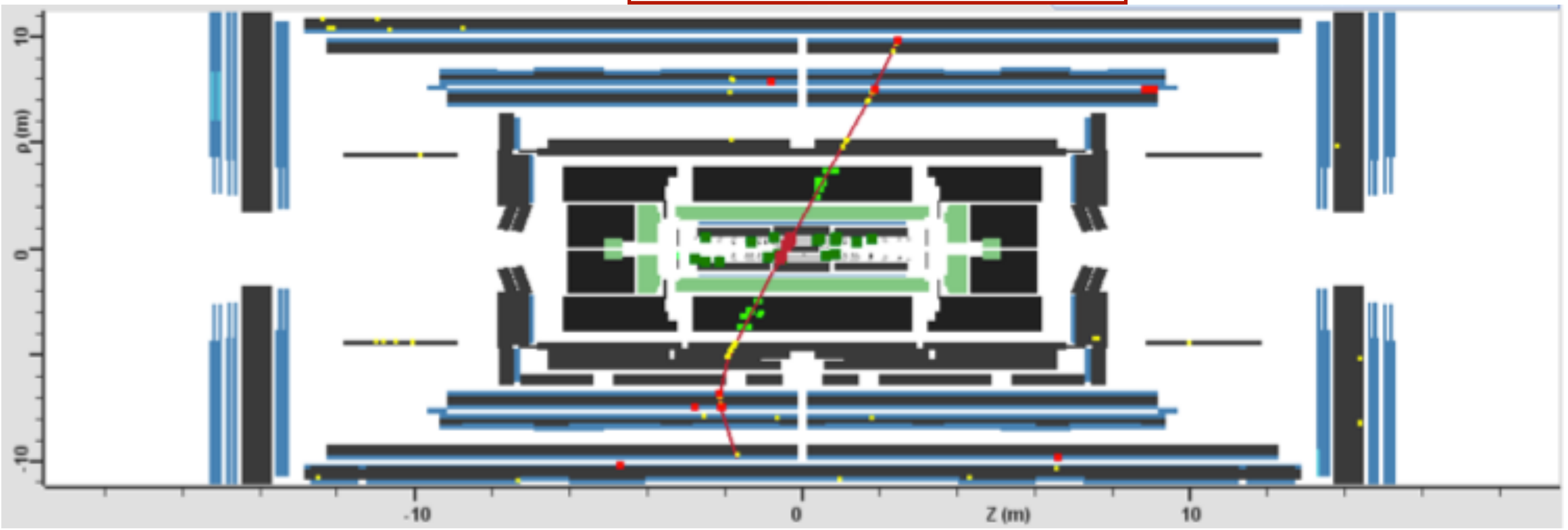
Unconventional backgrounds

Develop new techniques and ideas to reduce very unconventional background sources

Cosmic muons

- Muon bundles from cosmic-ray that cross the detector in-time with the *pp* collision event

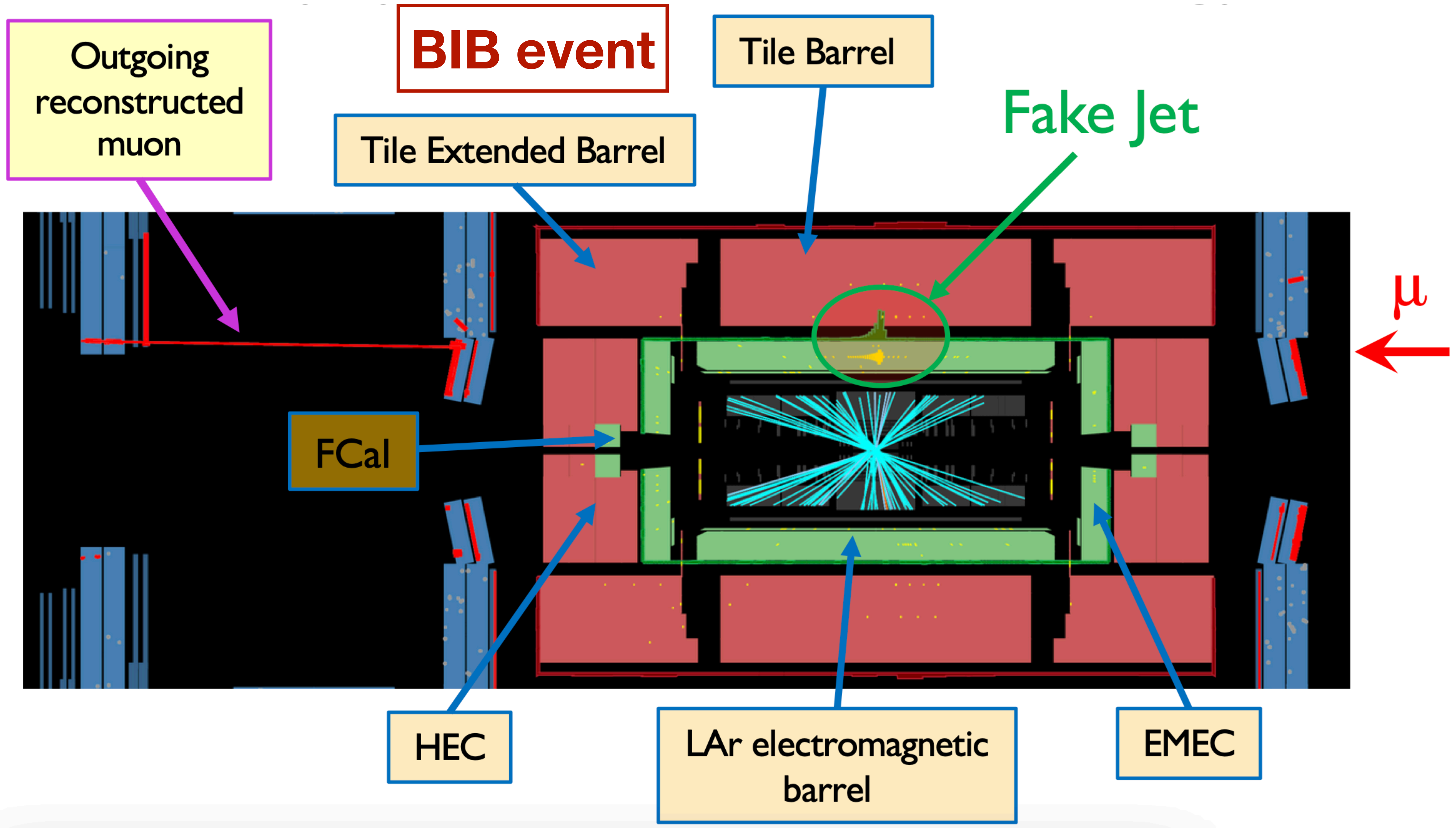
Cosmic-ray event



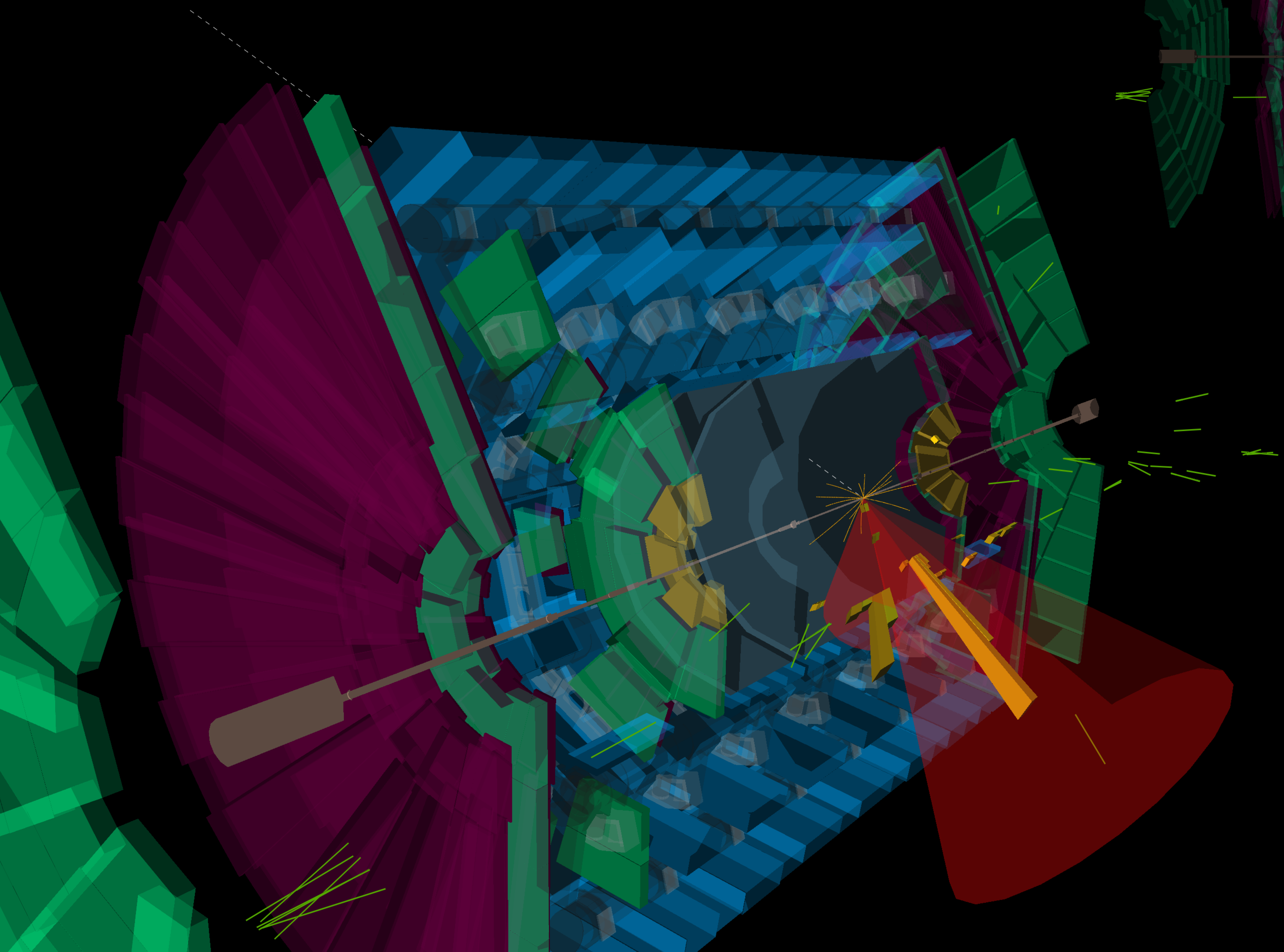
Beam induced background (BIB)

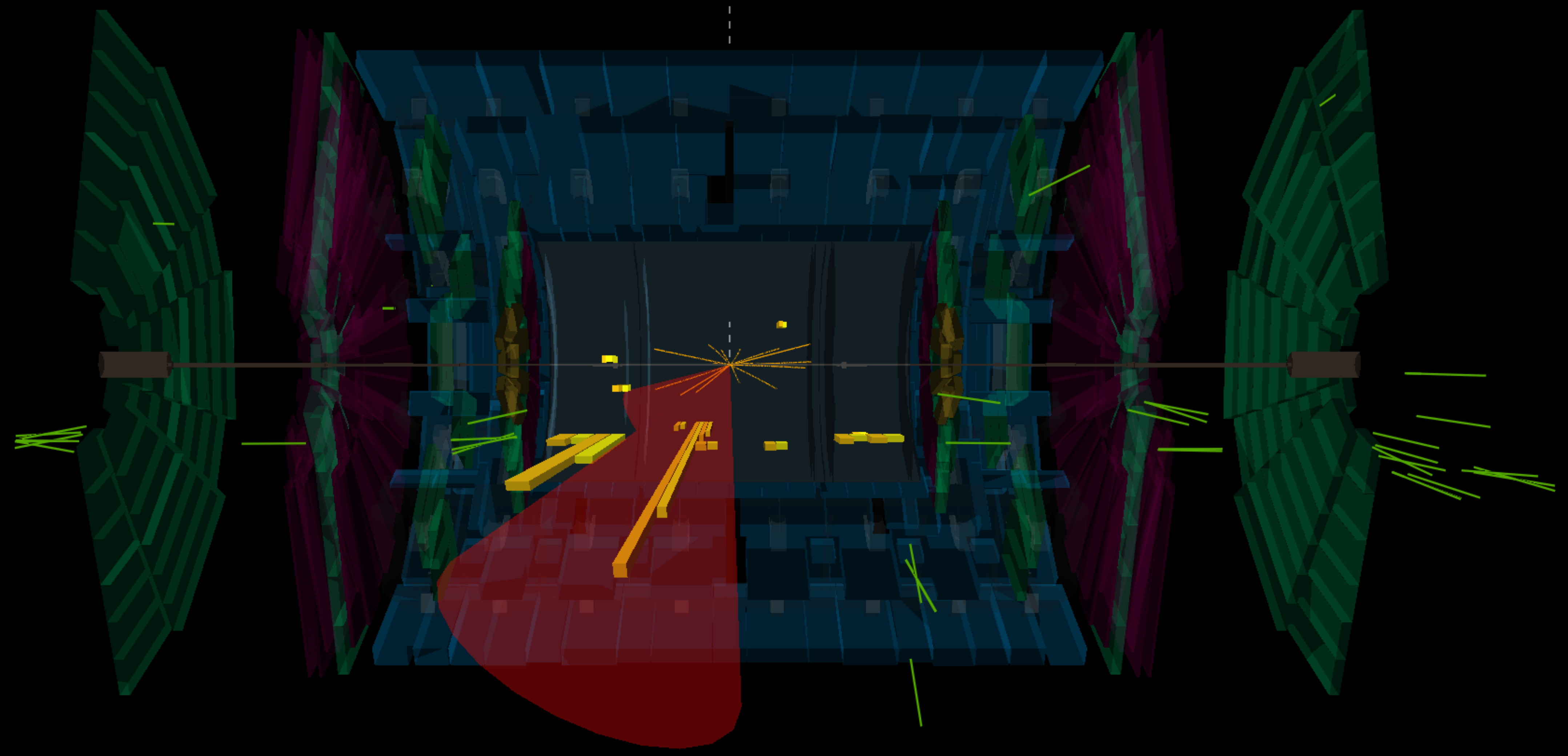
- Machine/beam-induced backgrounds from upstream proton losses in the LHC, from inelastic collisions with residual gas, beam halo cleaning losses or beam-gas scattering

BIB event



BIB event





ATLAS EXPERIMENT

Run: 300487
Event: 445566353
2016-05-30 00:29:53 CEST

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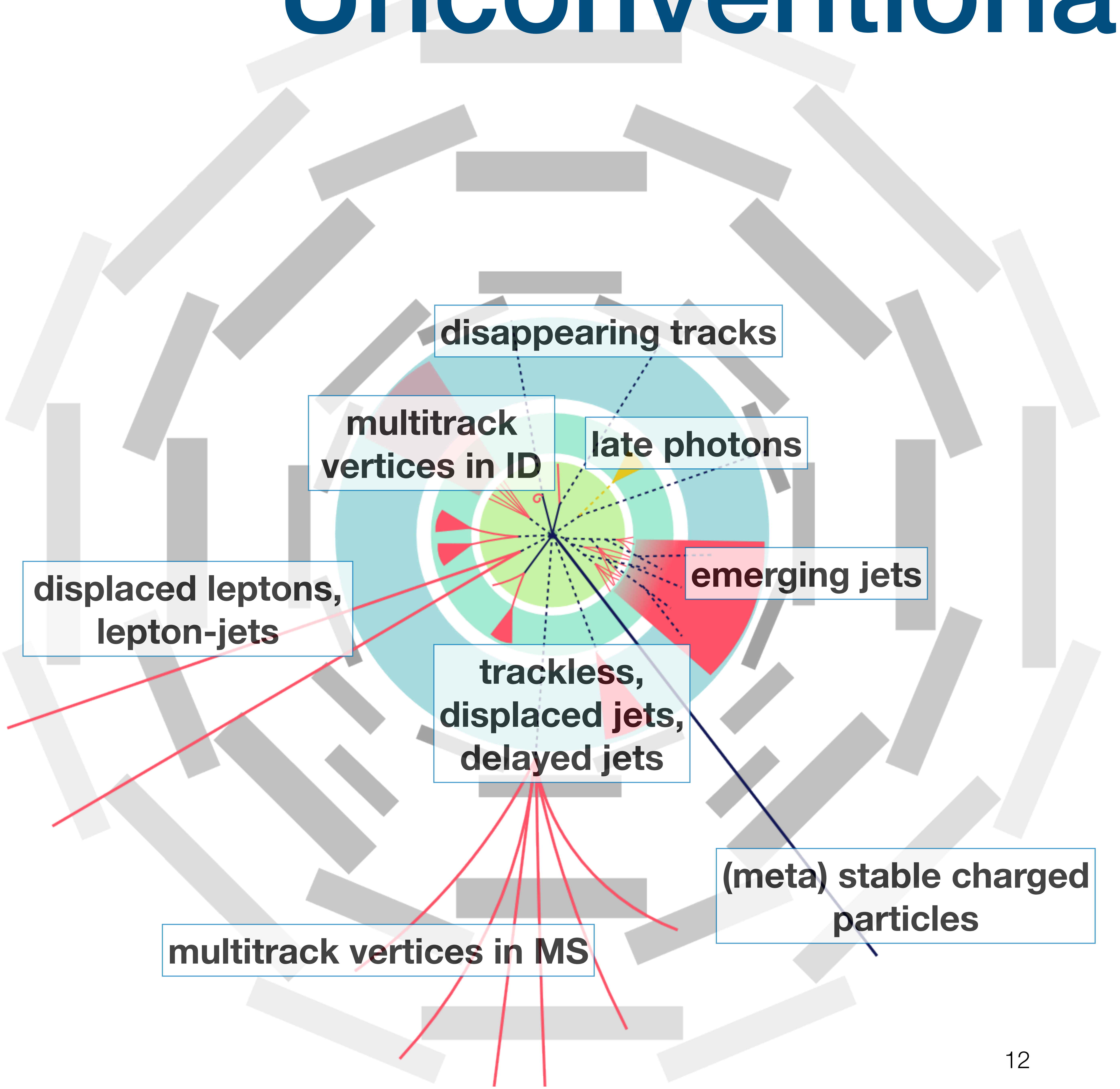
Unconventional signatures



LLPs could lead to a plethora of new signatures. Experimental approach depending on…

- Charge and decay products
- Interaction with specific sub-detector
- Displacement of the decay

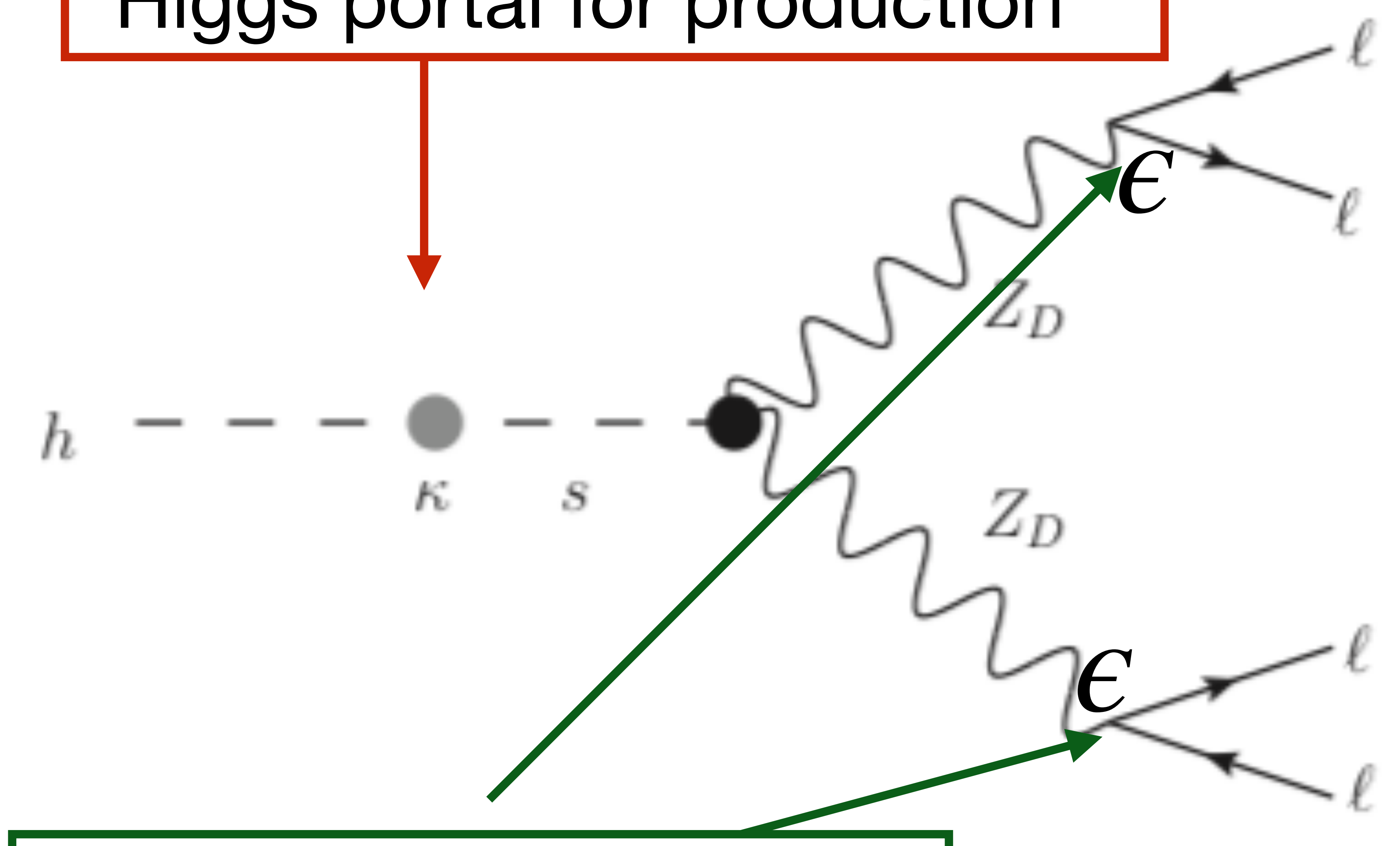
LLP guidebook

- Find a new signature yet unexplored in ATLAS broad LLP programme
- Interaction with the LHC community and theorists to exchange ideas
- Use the detector at its best: bespoke strategies for triggers, reconstruction and calibration objects
- Exploit new state of the art techniques, like Machine Learning tools
- Enjoy the journey :)

A long-lived dark photon search

Exploit 'large' Higgs cross-section to probe events with very small epsilon values —> Long-lived particles (LLP)

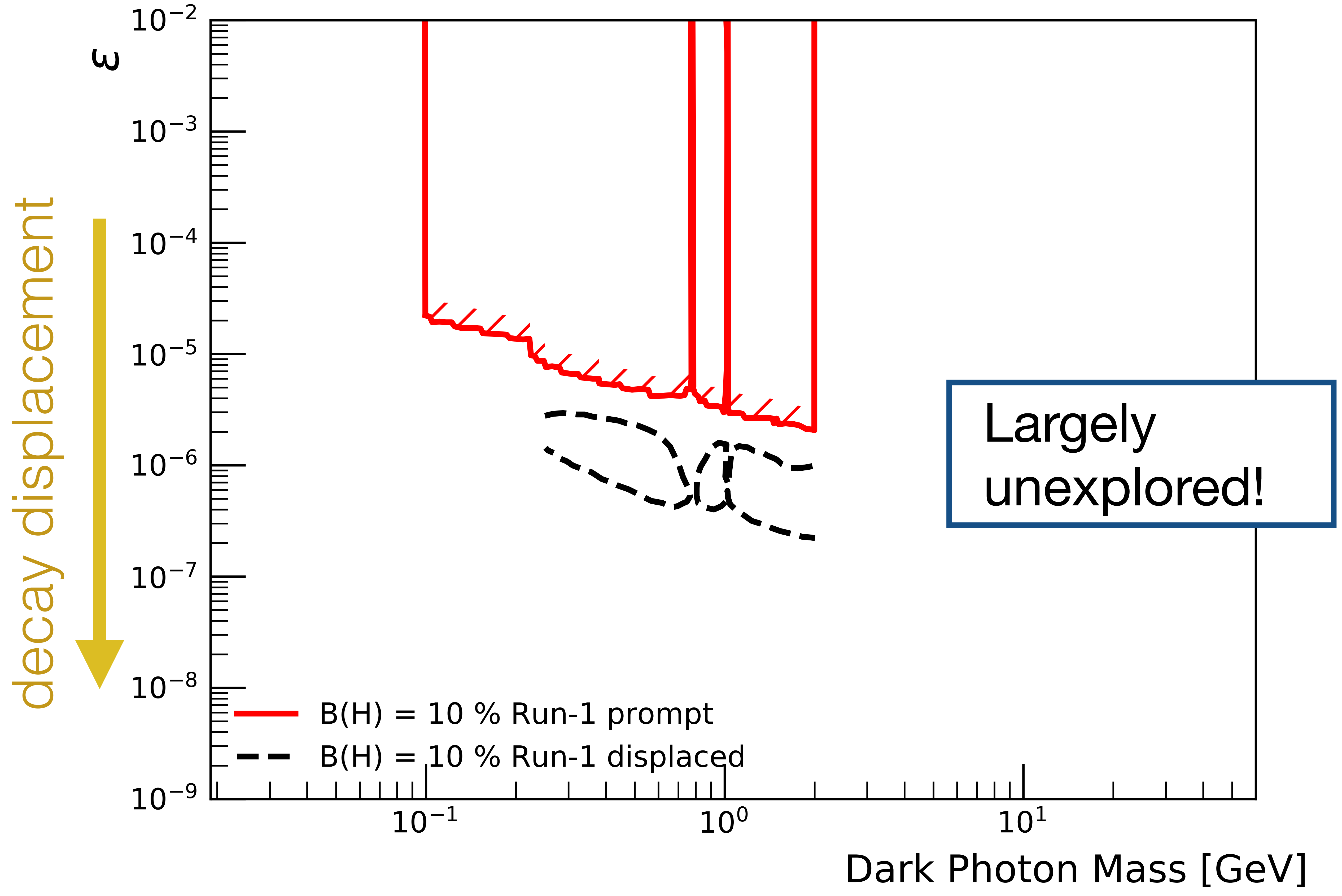
Higgs portal for production



Vector portal for decay

$$h \rightarrow Z_d Z_d \rightarrow 4l$$

ATLAS Higgs portal constraints

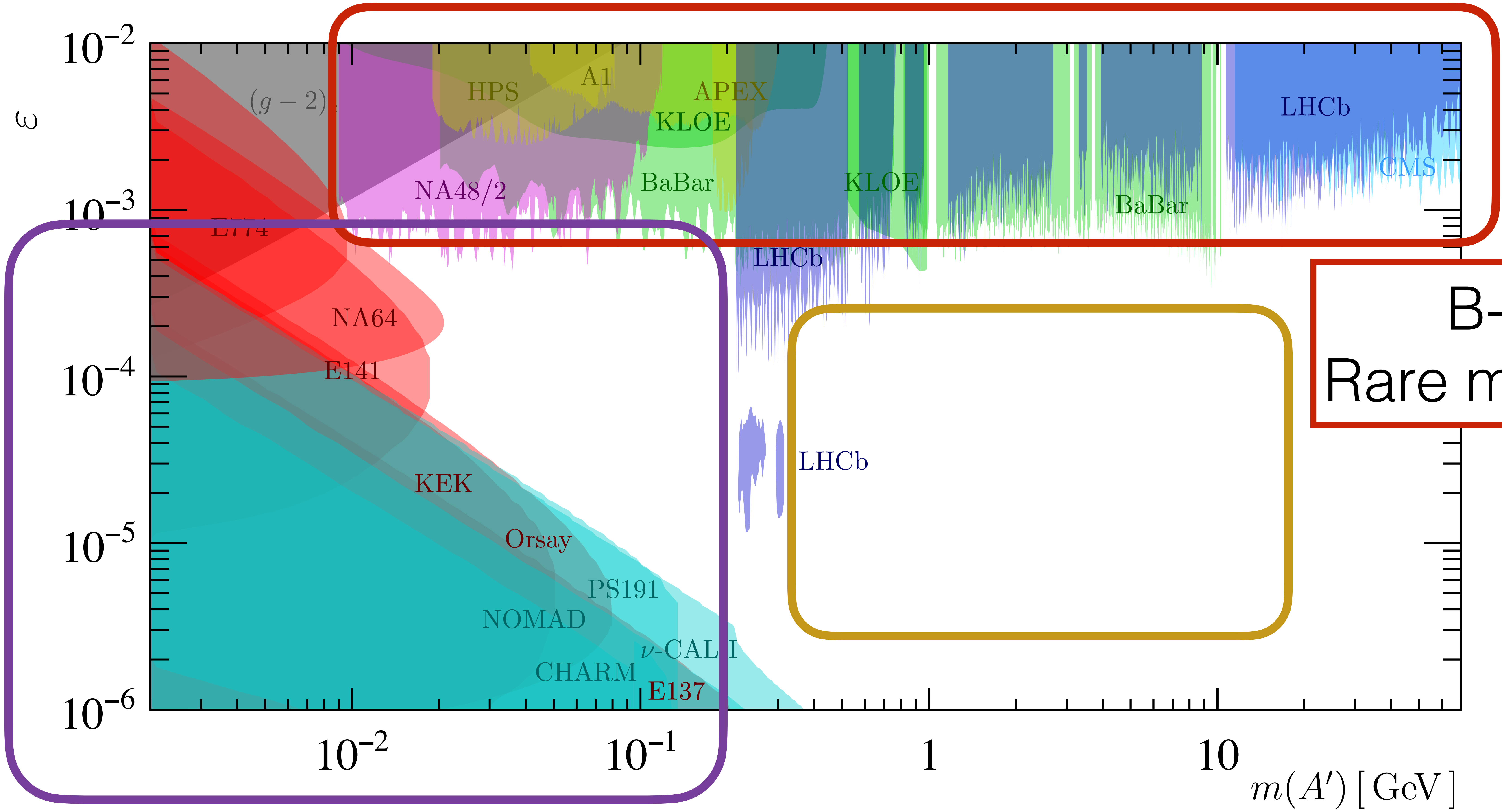


Largely unexplored!

Current constraints

Constraints on visible dark photon decays are expressed in the parameter space epsilon ε versus dark photon mass m(A')

e/p beam dump



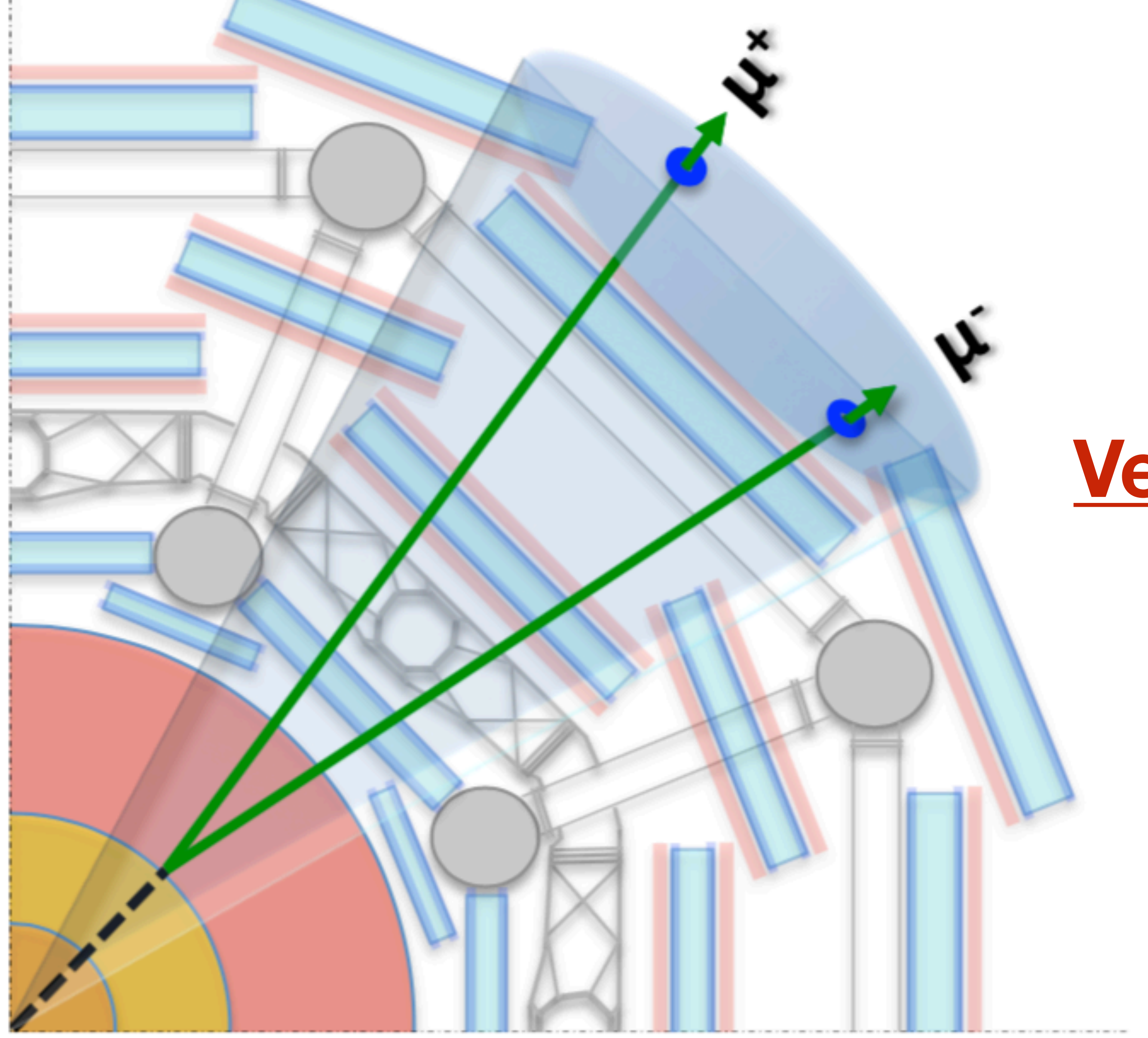
B-factories
Rare meson decays

Region explorable at particle colliders via Higgs portal

Search for long-lived dark photons

Search for light long-lived neutral particles decaying into collimated jet structures of leptons or light hadrons

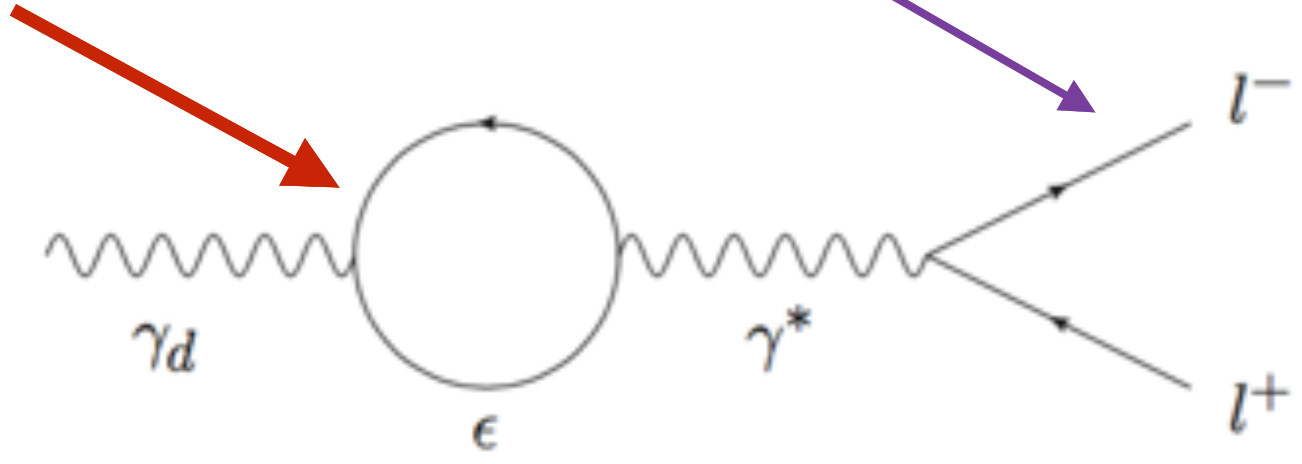
Muonic



$$\Delta\Phi \simeq \frac{m_{\gamma d}}{E_{\gamma d}} << 1$$

Outgoing products may be collimated

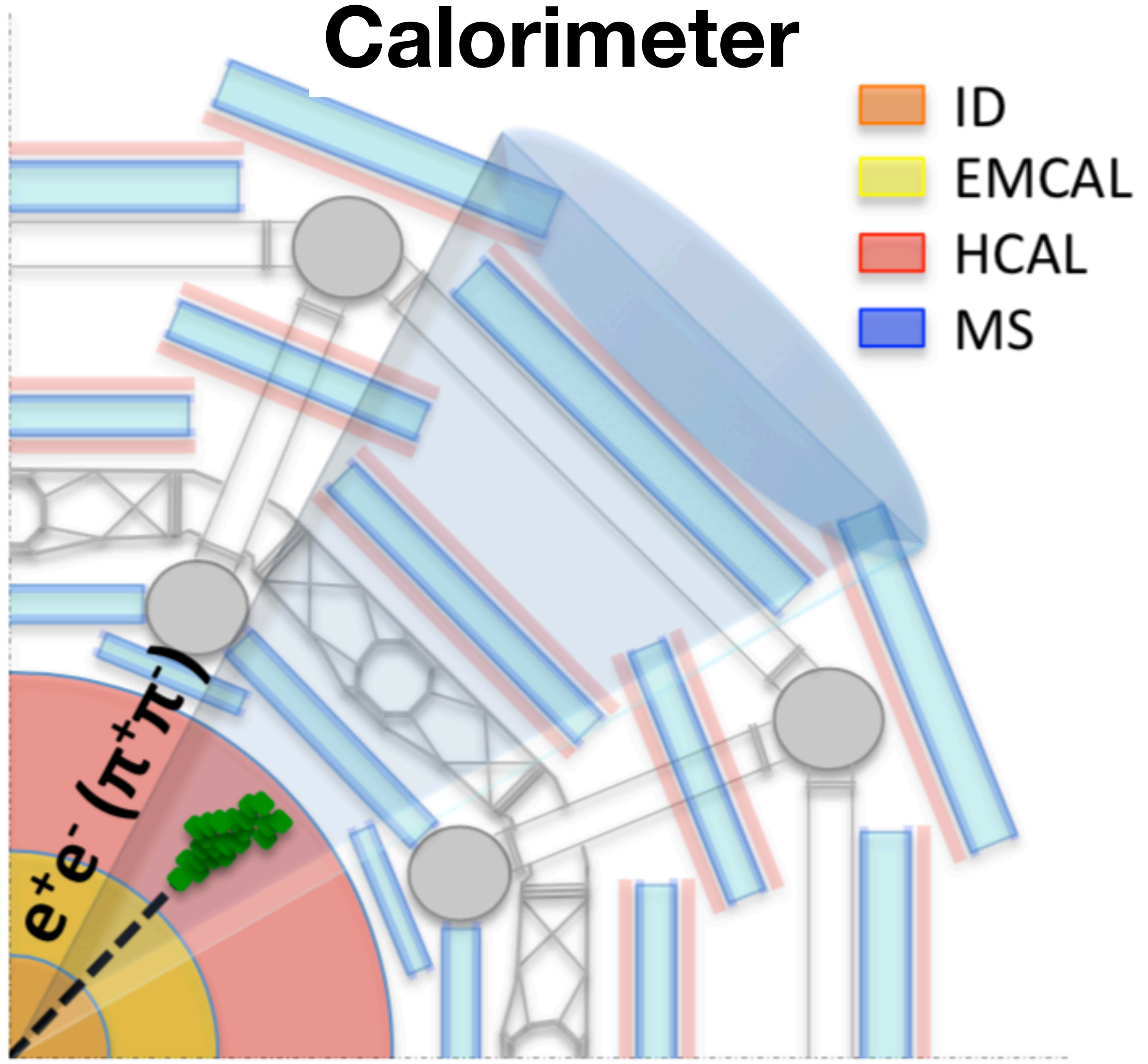
Vector portal



For small couplings very displaced decays

$$c\tau = \frac{1}{\Gamma_{tot}} \propto \frac{1}{\epsilon^2}$$

Calorimeter



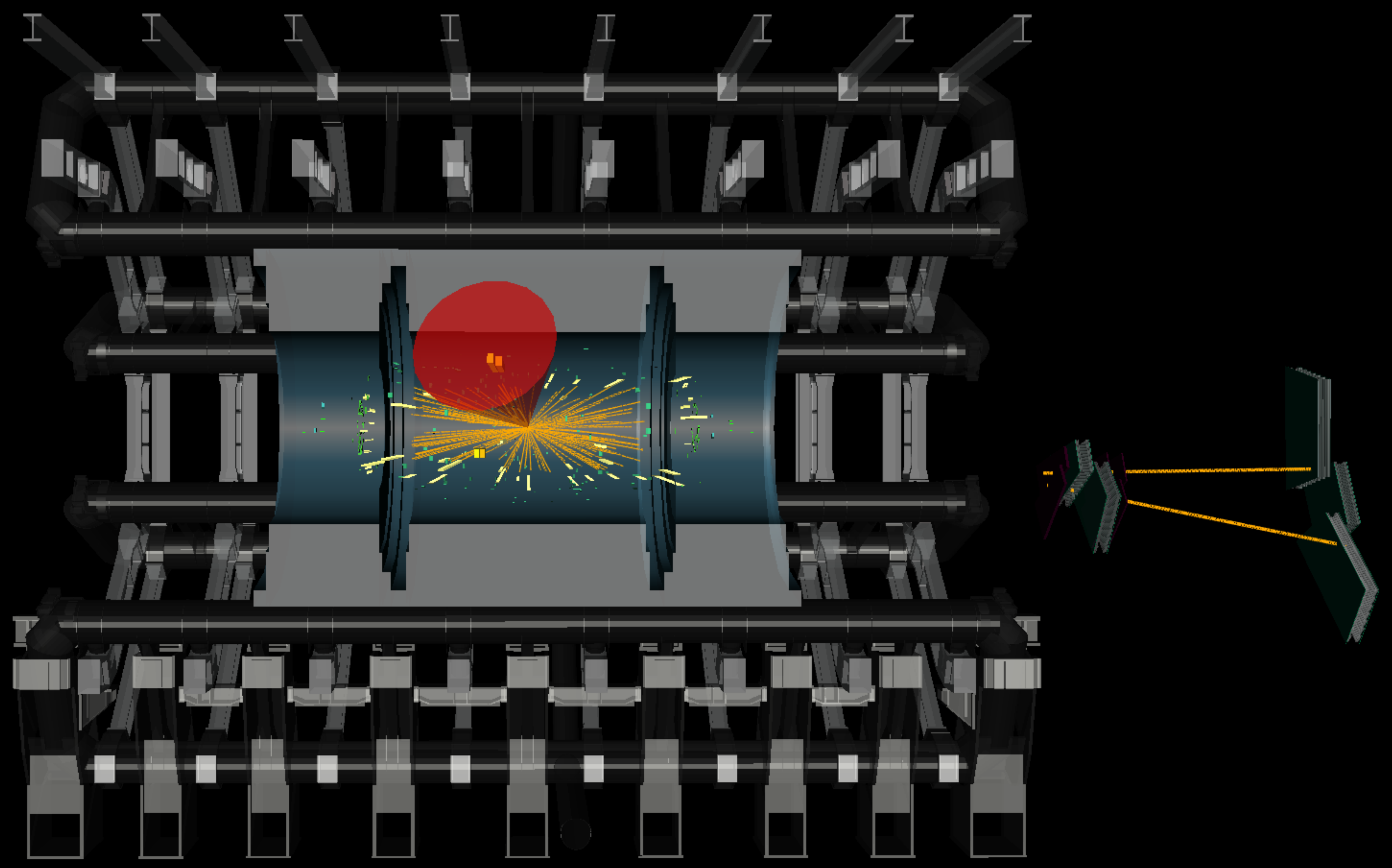
Muonic decay
Collimated bundle of muon without track in the inner detector (no jets)

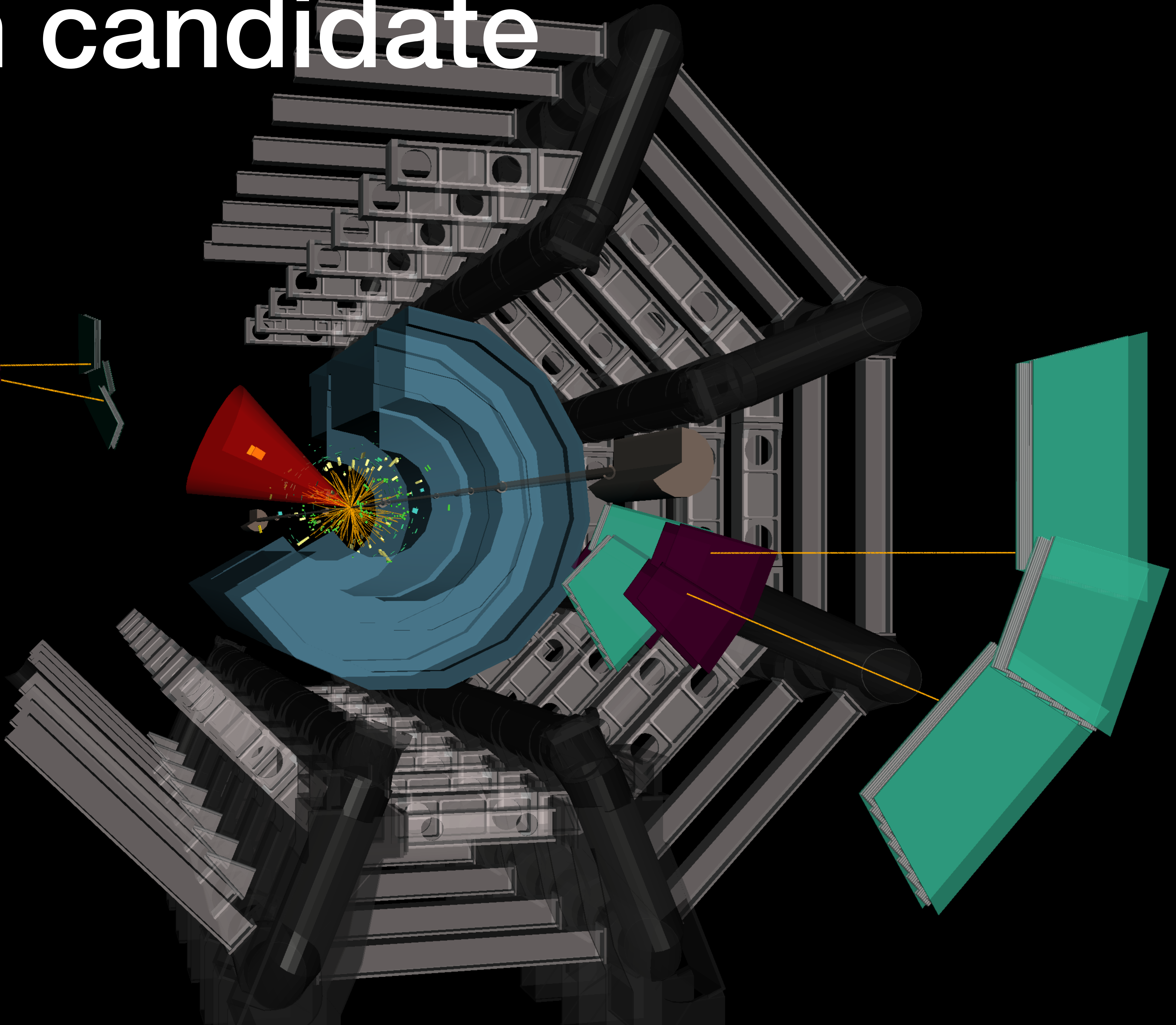
Difficult to trigger: low-pt muon
Cosmic-ray muons background

Calorimeter decay
Displaced jet with most of energy deposit in the HCAL (no muons)

Very high background from rare QCD events and few handles to play with

Dark-photon candidate



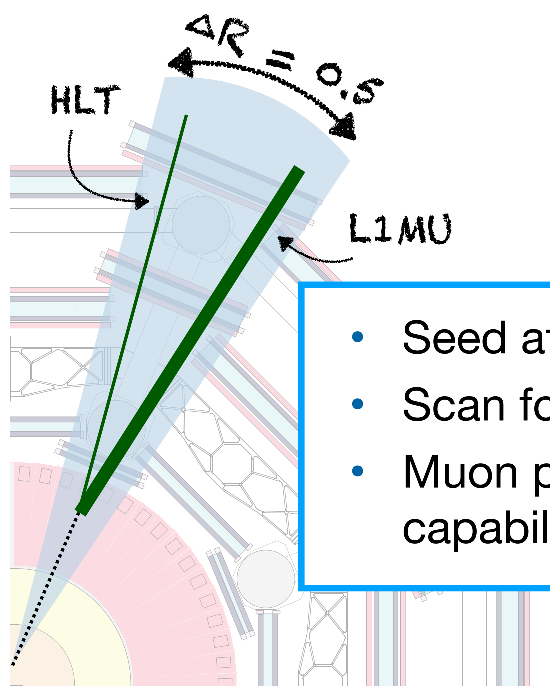


ATLAS EXPERIMENT

Run: 303266
Event: 1584619053
2016-07-04 04:57:58 CEST
[JHEP 06 (2023) 153]

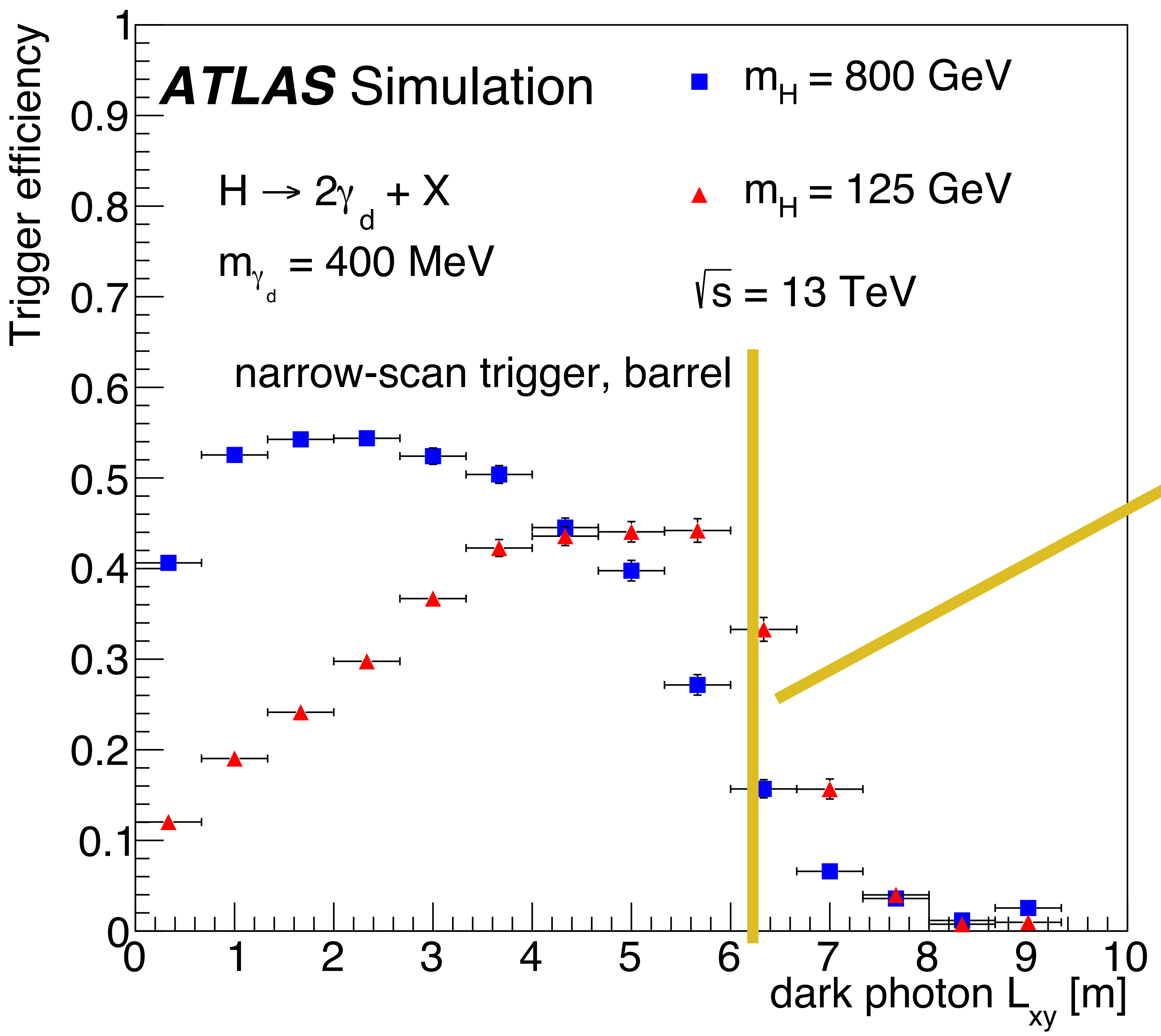
Trigger for muonic dark-photon

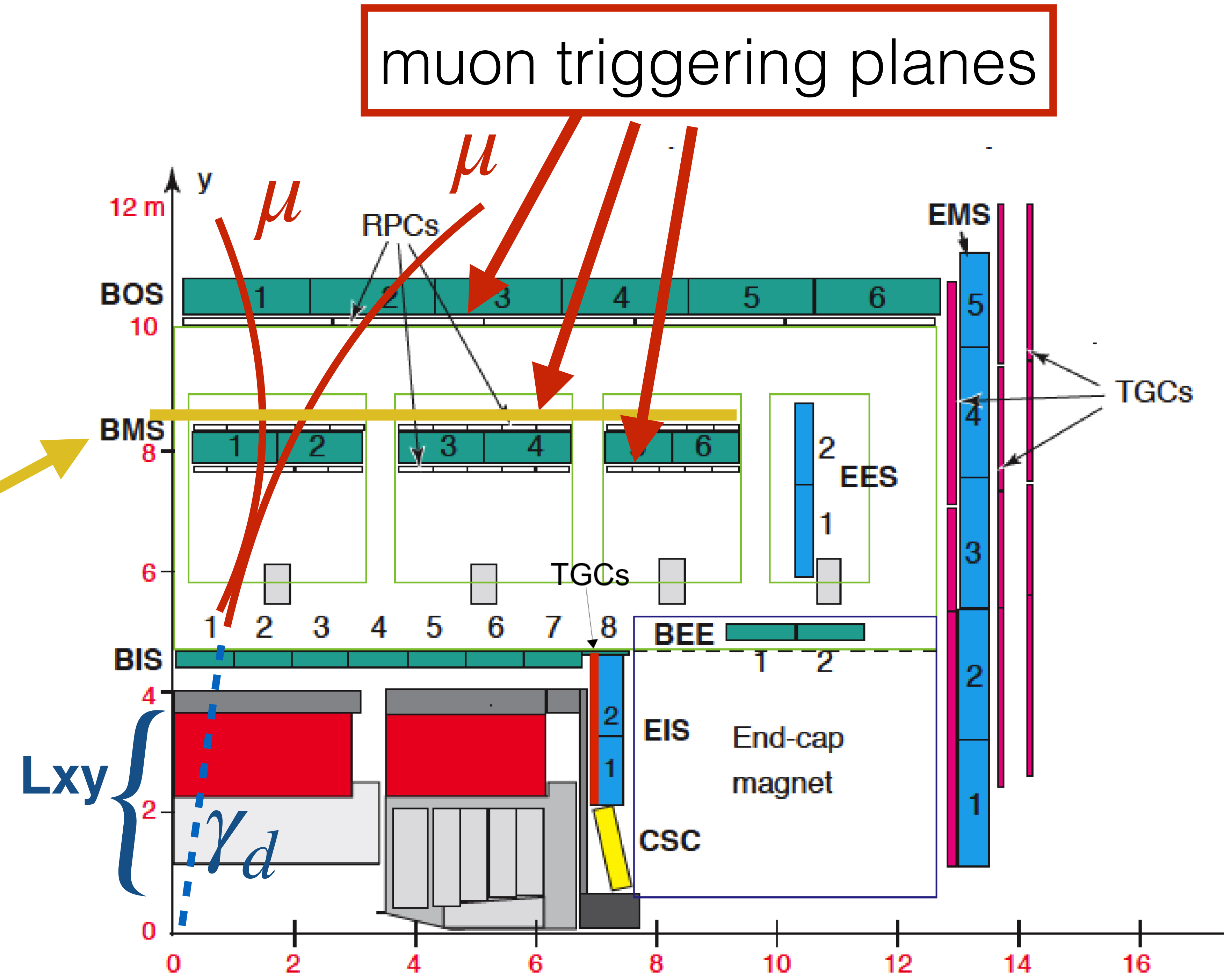
Dedicated triggers are used to select events with highly collimated muons with low activity in the ID



Narrow-Scan

- Seed at L1 by MU20
- Scan for a 2nd muon at HLT (CPU-consuming)
- Muon p_T threshold determined by the rate capabilities





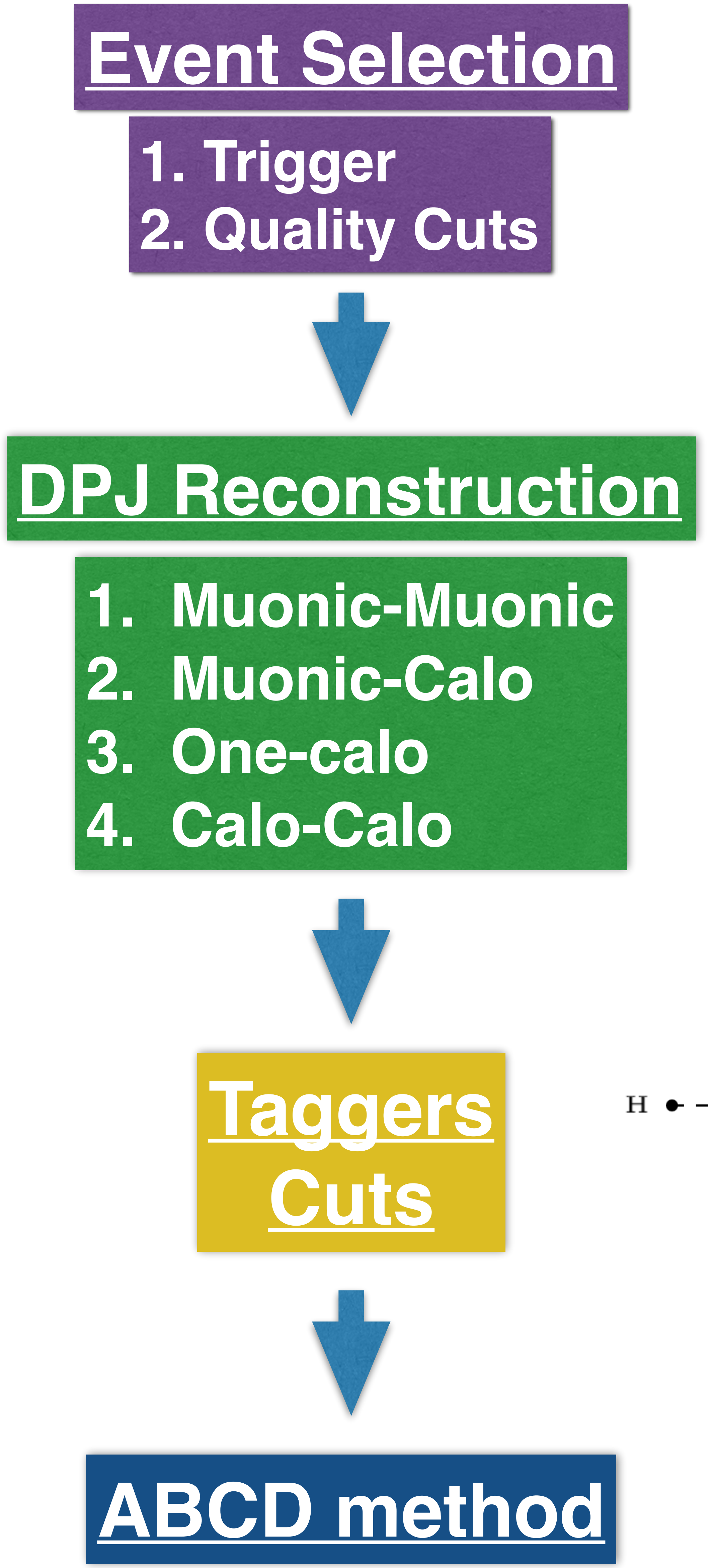
Analysis strategy

- Dedicated triggers: NarrowScan (muonic) and CaloRatio (hadronic)

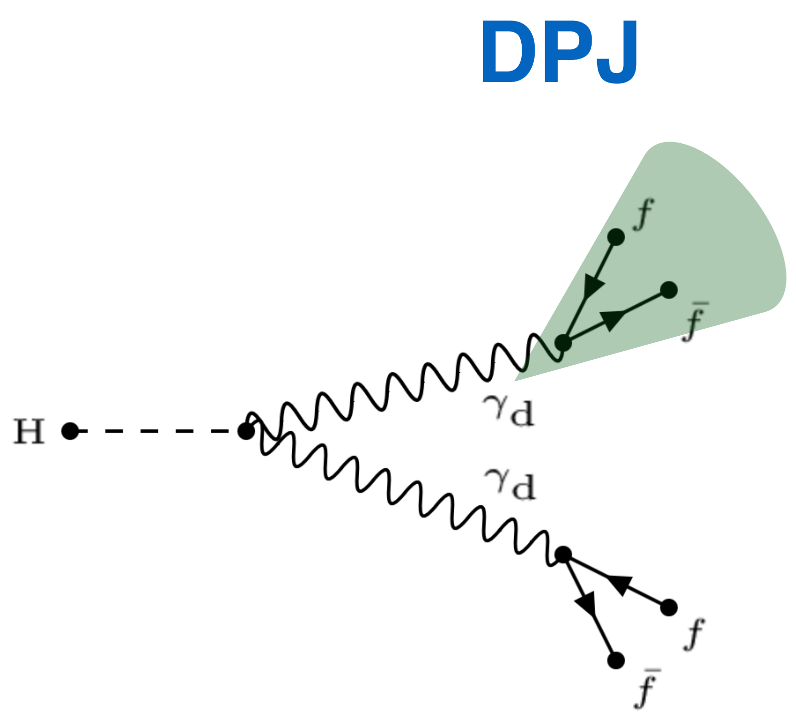
- Two production modes: ggH and WH
  - Six channels: muonic-muonic (ggH), muonic-calo (ggH+WH), one-calo exclusive (WH) and calo-calo (ggH+WH)

- Backgrounds: rare QCD events, cosmic-ray muons and beam induced background (BIB)
  - Advanced NN-based taggers according to DPJ type

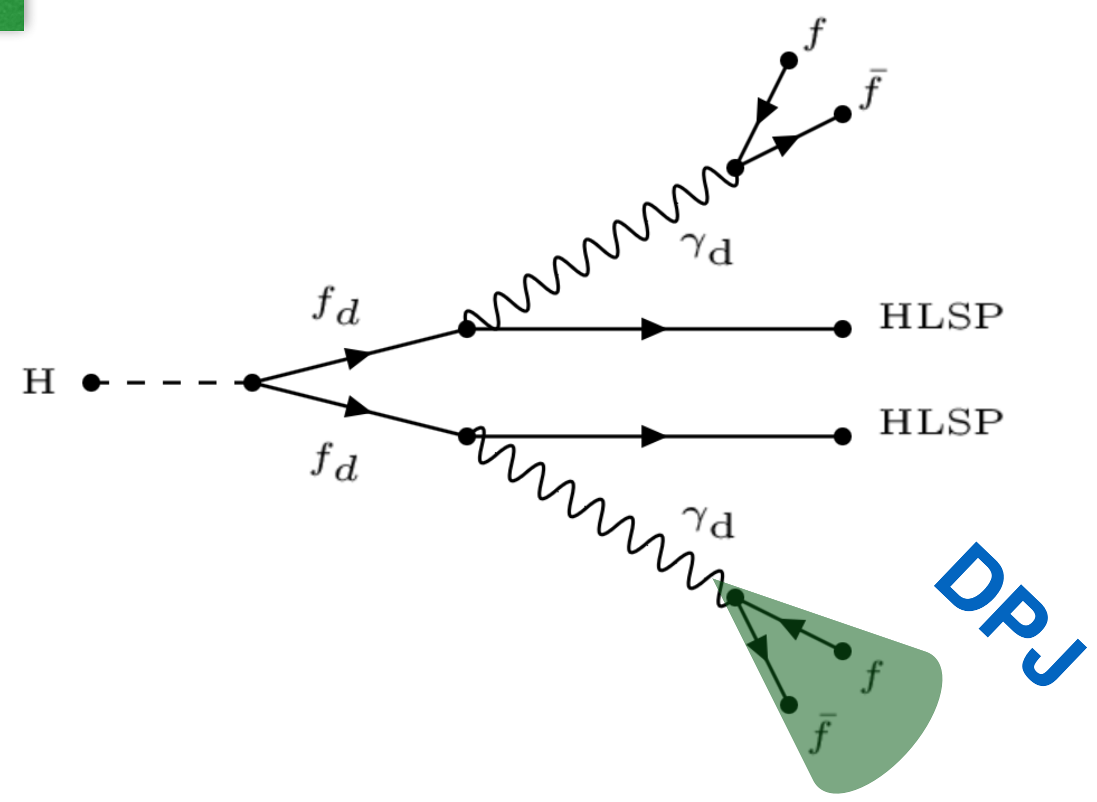
- Data-driven ABCD method to estimate dominant QCD background in the signal regions



Benchmark models



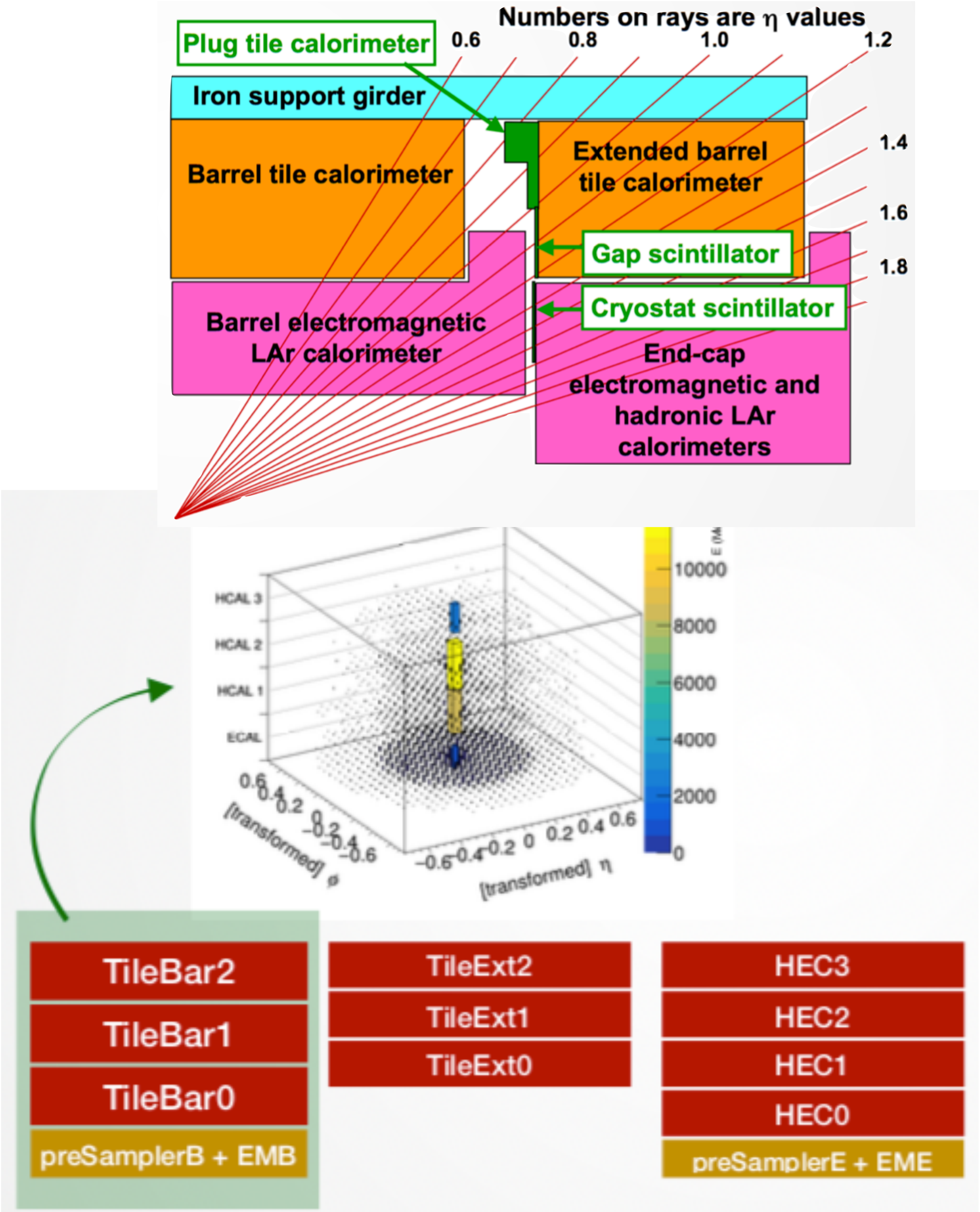
Hidden Abelian Higgs Model [HAHM] arXiv:1312.4992



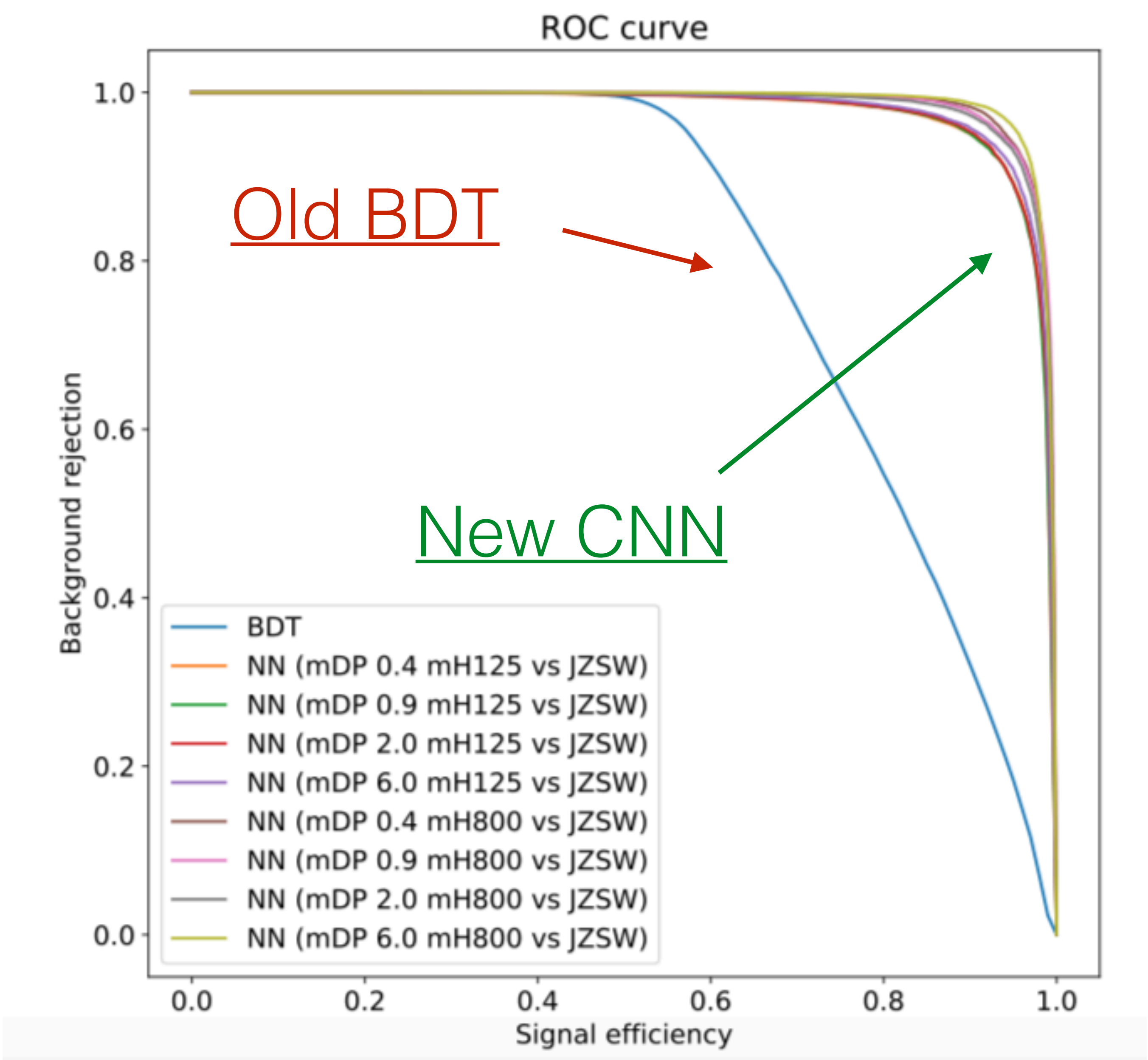
Falkowsky, Ruderman, Volansky, Zupan [FRVZ] arXiv:1002.2952

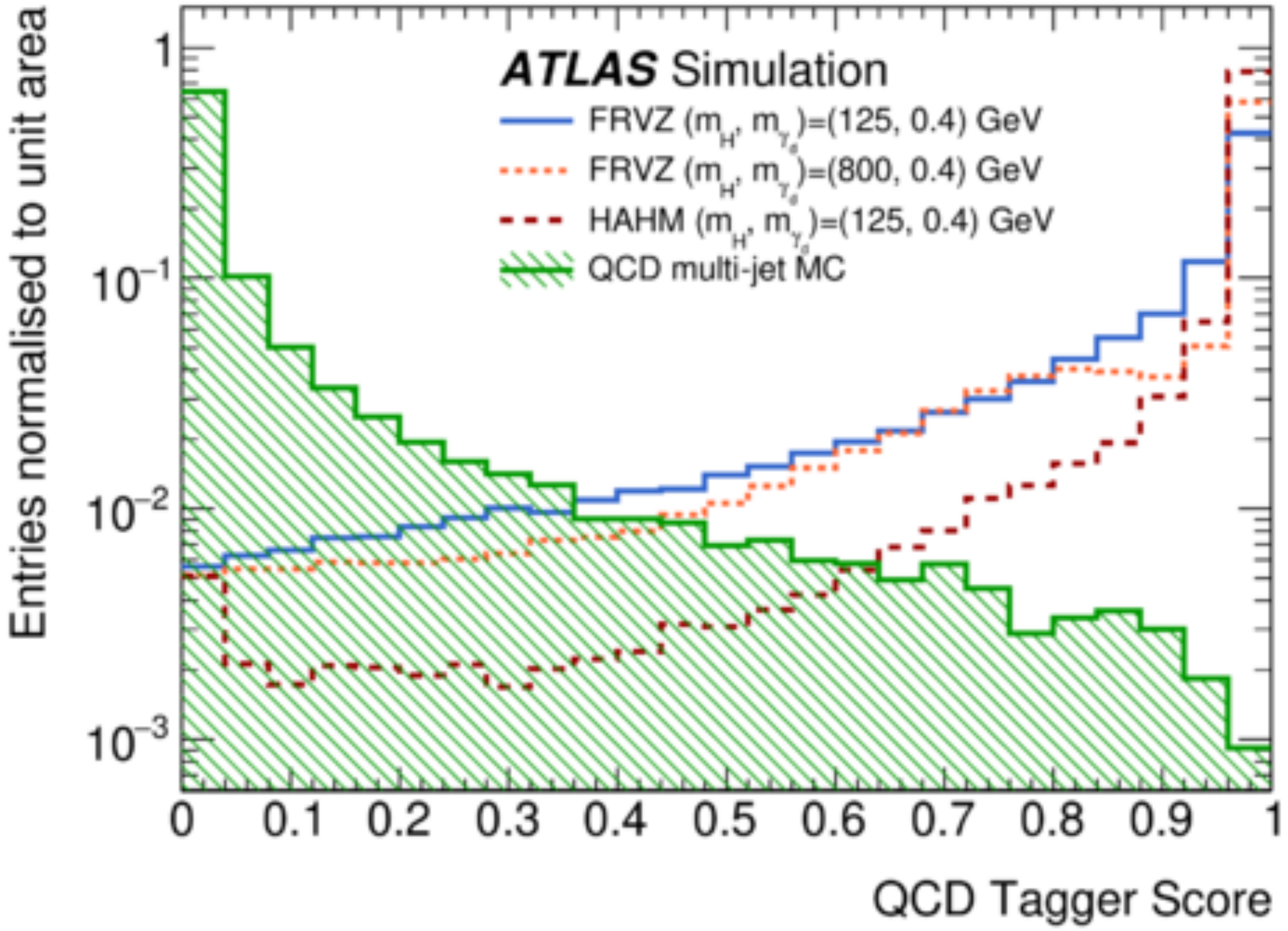
A low-level input NN

Extract low level information from the ATLAS calorimeter from a single jet in either 3D images or graphs



Calorimeter sampling is sensitive to the dark photon displacement

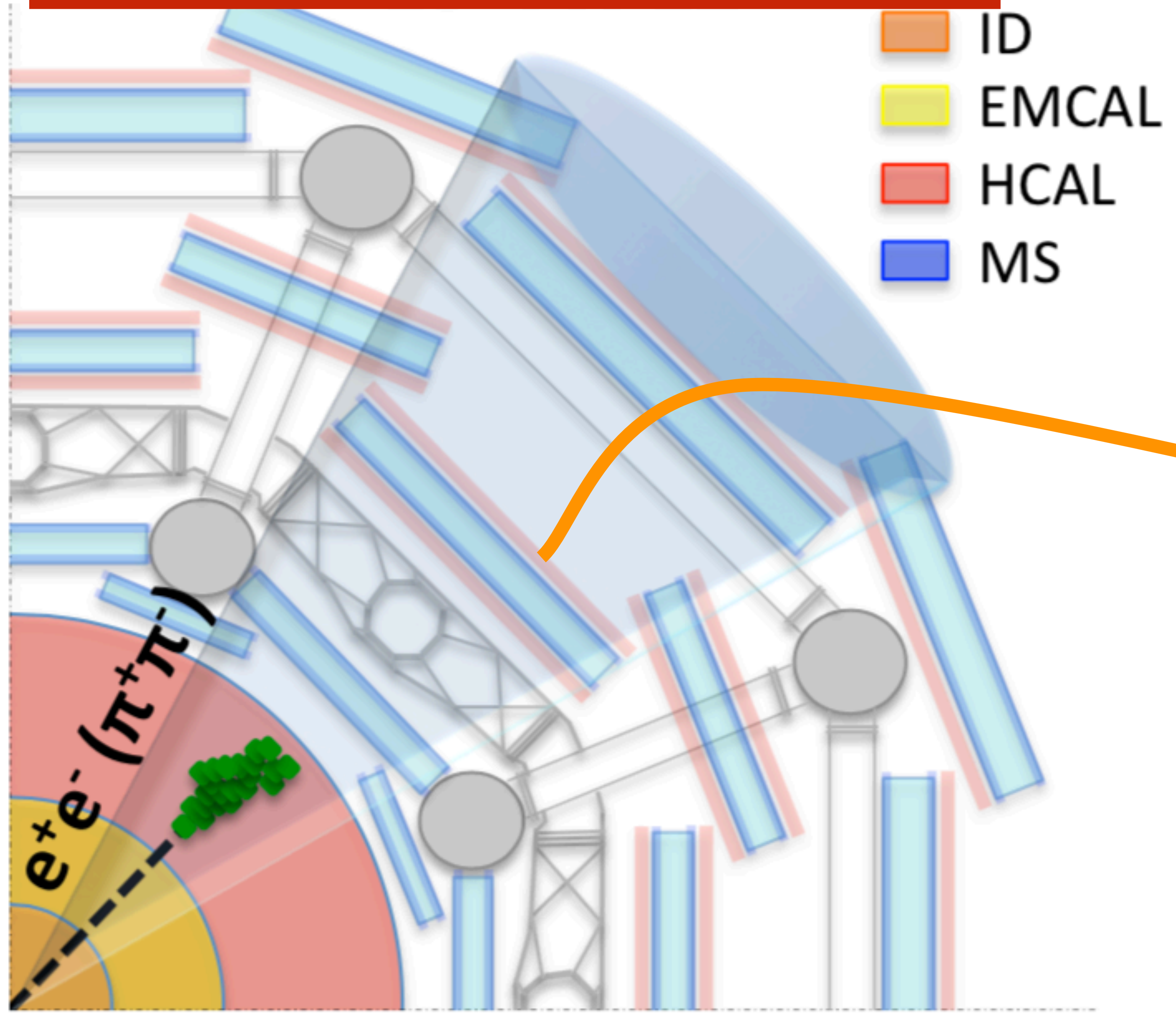


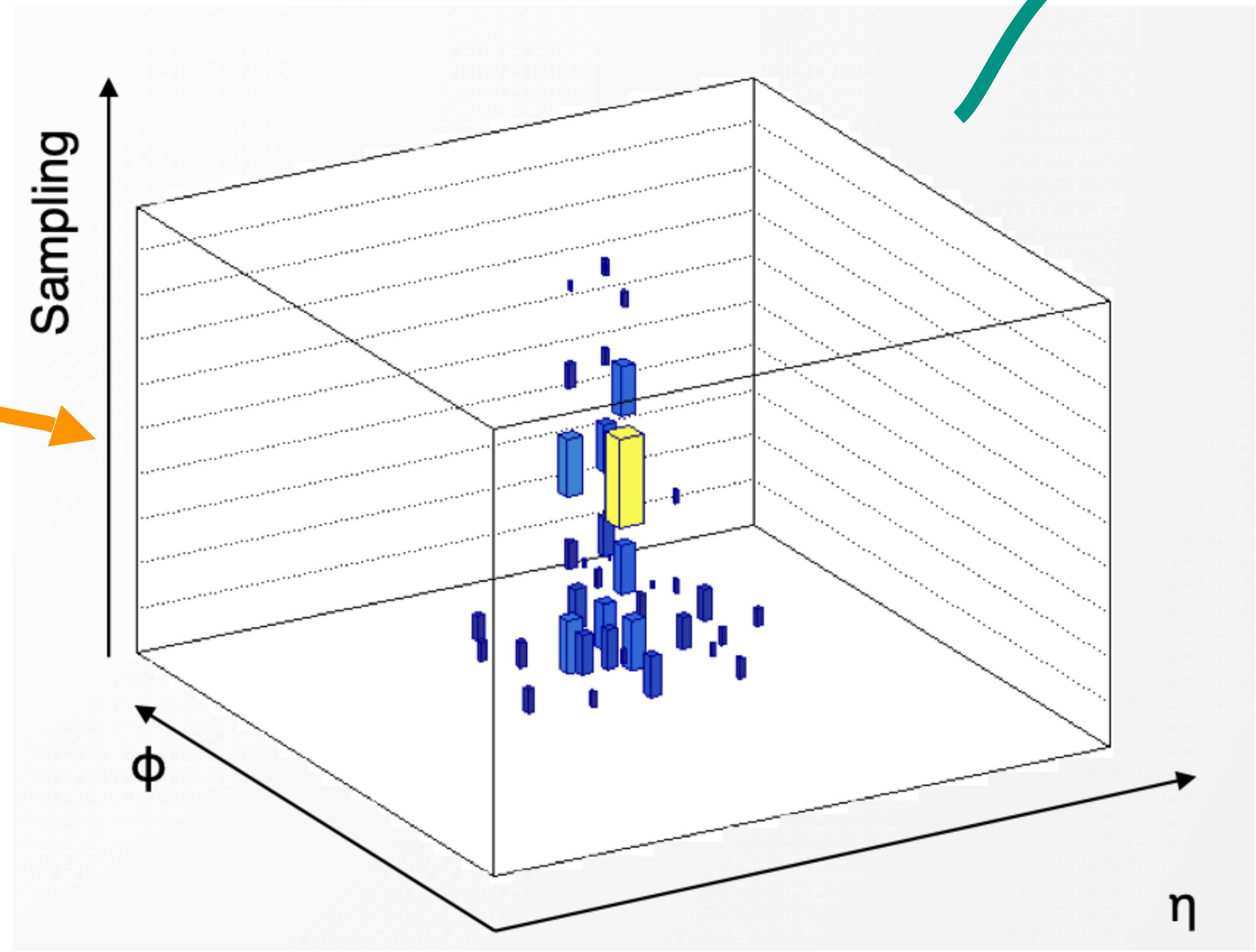


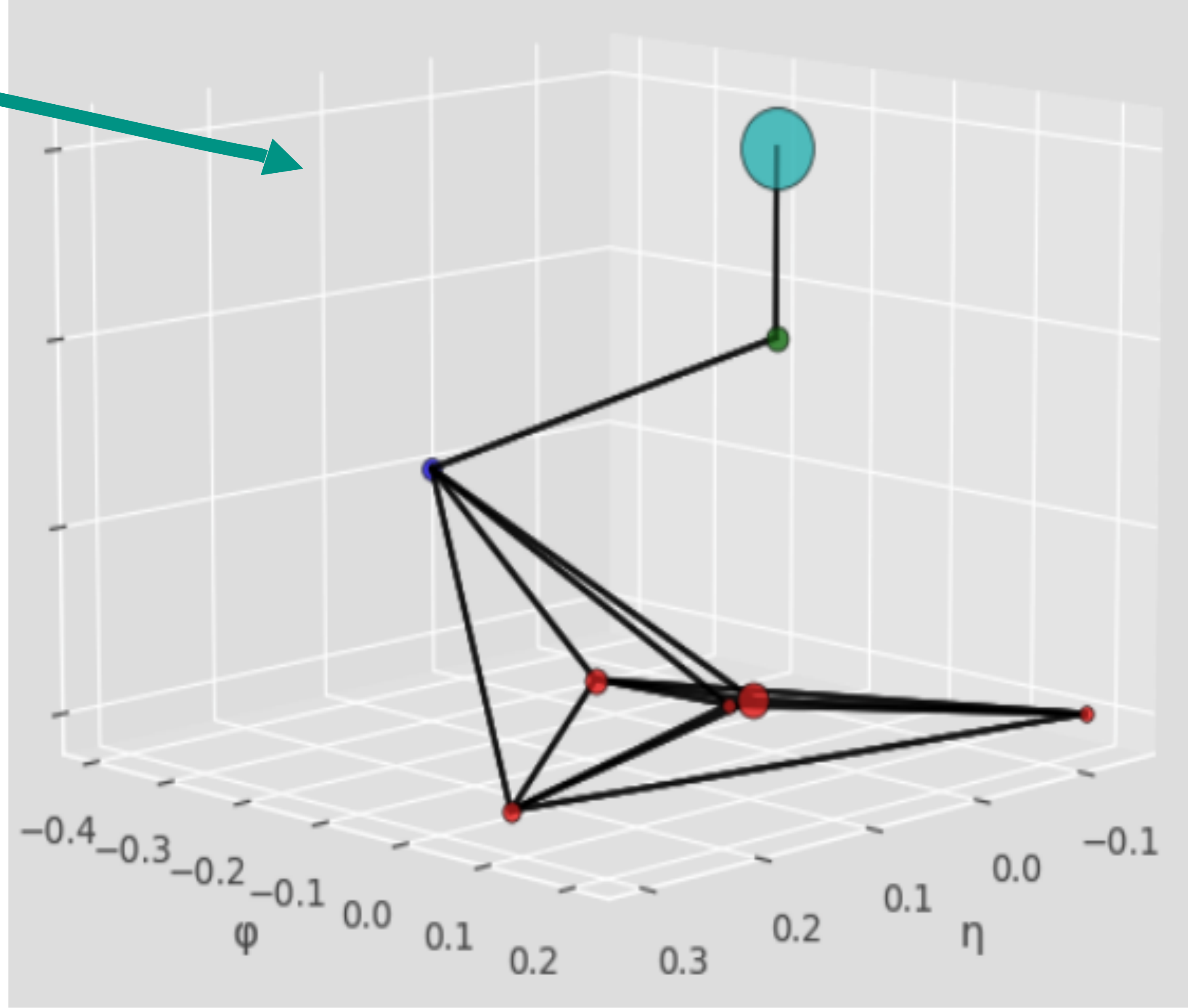
Tool to reject QCD main background, will allow an exclusion on hadronic-LJ channels!

A closer look on NN methods

The ATLAS detector orthogonal view







Let's exploit the calorimeter granularity to parametrise the energy deposits: x, y, z, energy

3D jet images:
- Train a CNN
- Very sparse images -> sub-optimal

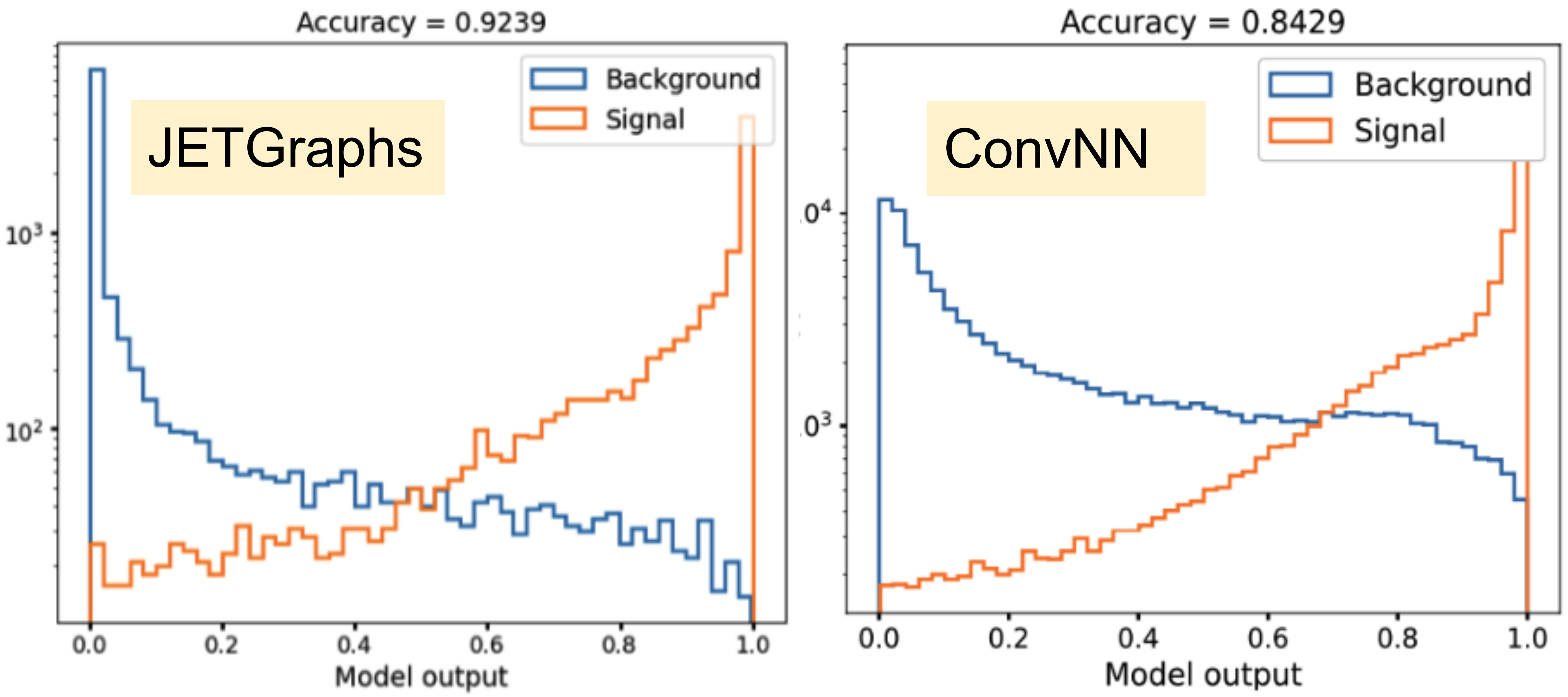
Graphs:
- Train a fully optimised GNN
- Small cloud space objects
- Efficient and easy to manipulate

Additional higher level variable can can be added as features to further improve the network performance, although the goal is to have them already 'learned' by the network by using only the low level inputs

Project developed within the **MUCCA** consortium - Multi-disciplinary Use Cases for Convergent new Approaches to AI explainability, with M. D'Onofrio (PI) and J. Carmignani —> for more info: [intro-video]

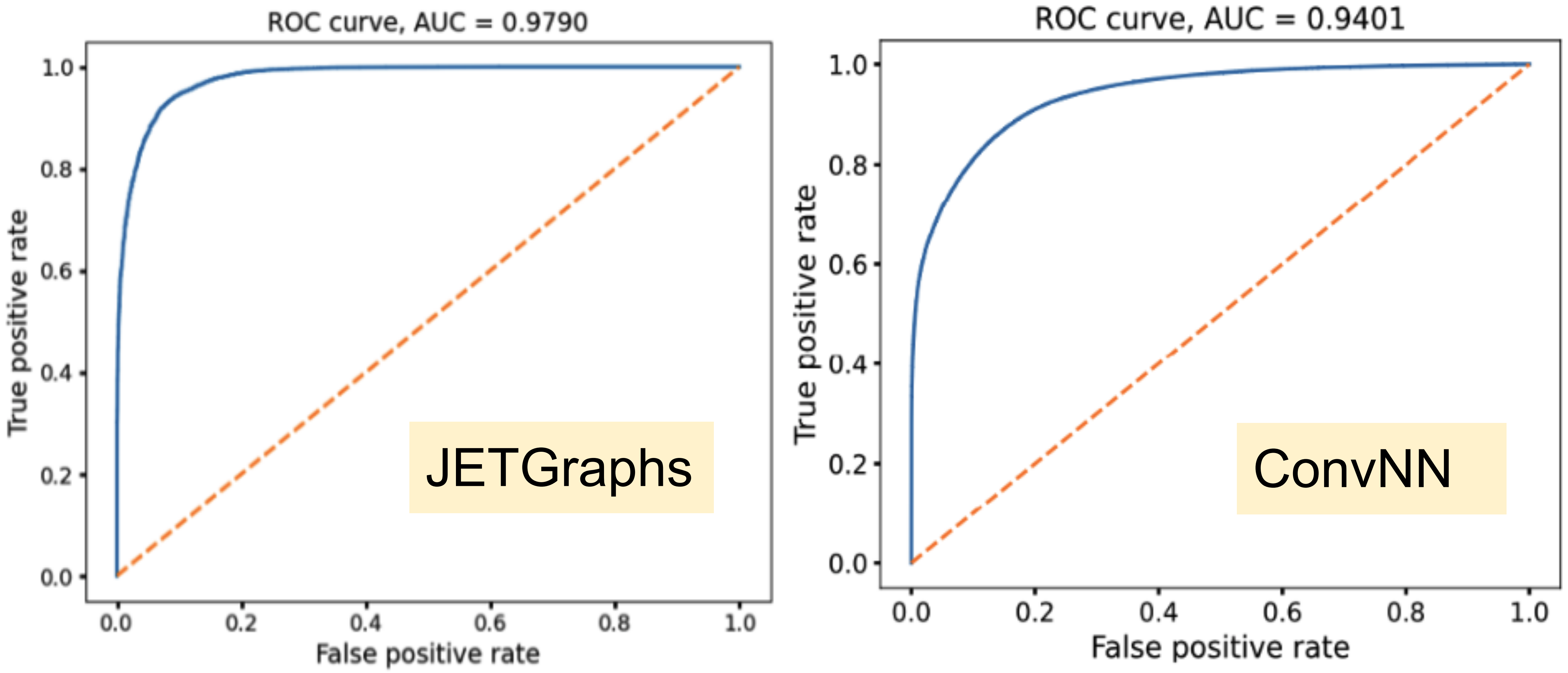
Performances

The GNN model out-performed the CNN model on all **performance metrics** tested at same signal efficiency score



Classification Accuracy

Area Under ROC Curve



As expected graph dataset are proven very effective for classification of sparse image of HEP calorimeter detectors! GNN will be used in Run3 searches!

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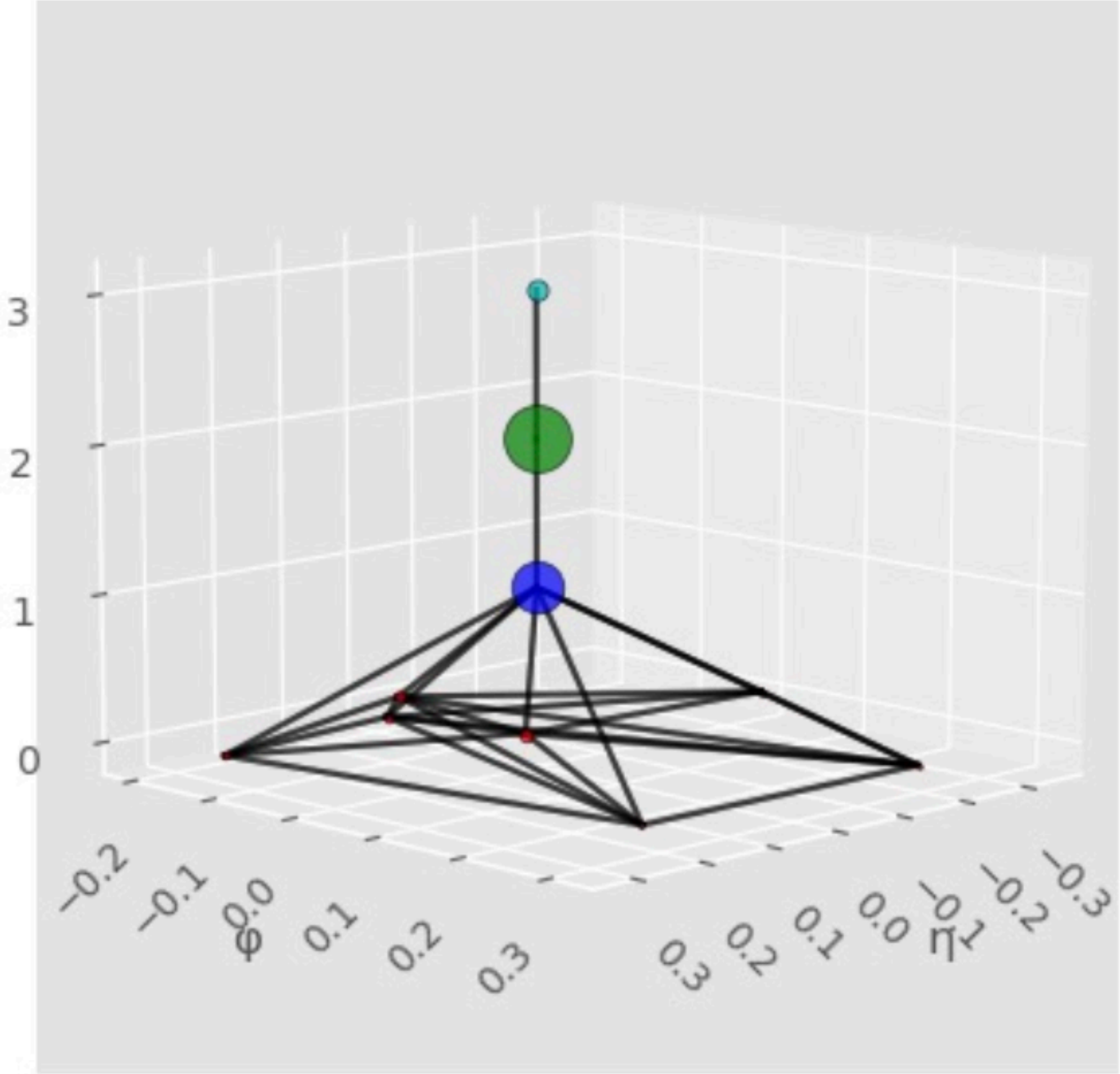
Dark-photon explainability

- How does a signal look like?

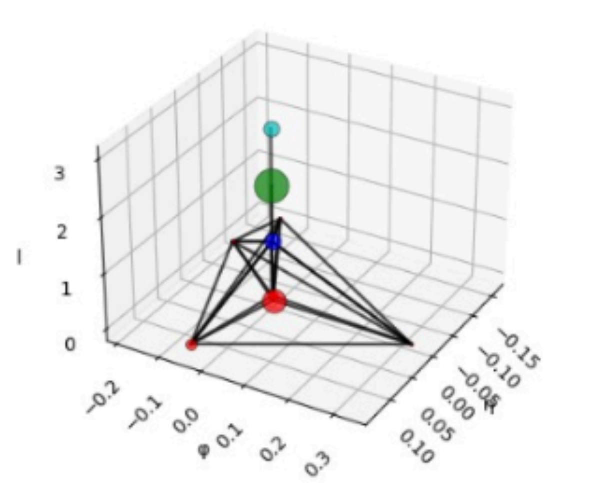


- How does the NN understands true positive (signal), true negative or false positive ?

Stay tuned… paper out very soon :)

(True Negative)

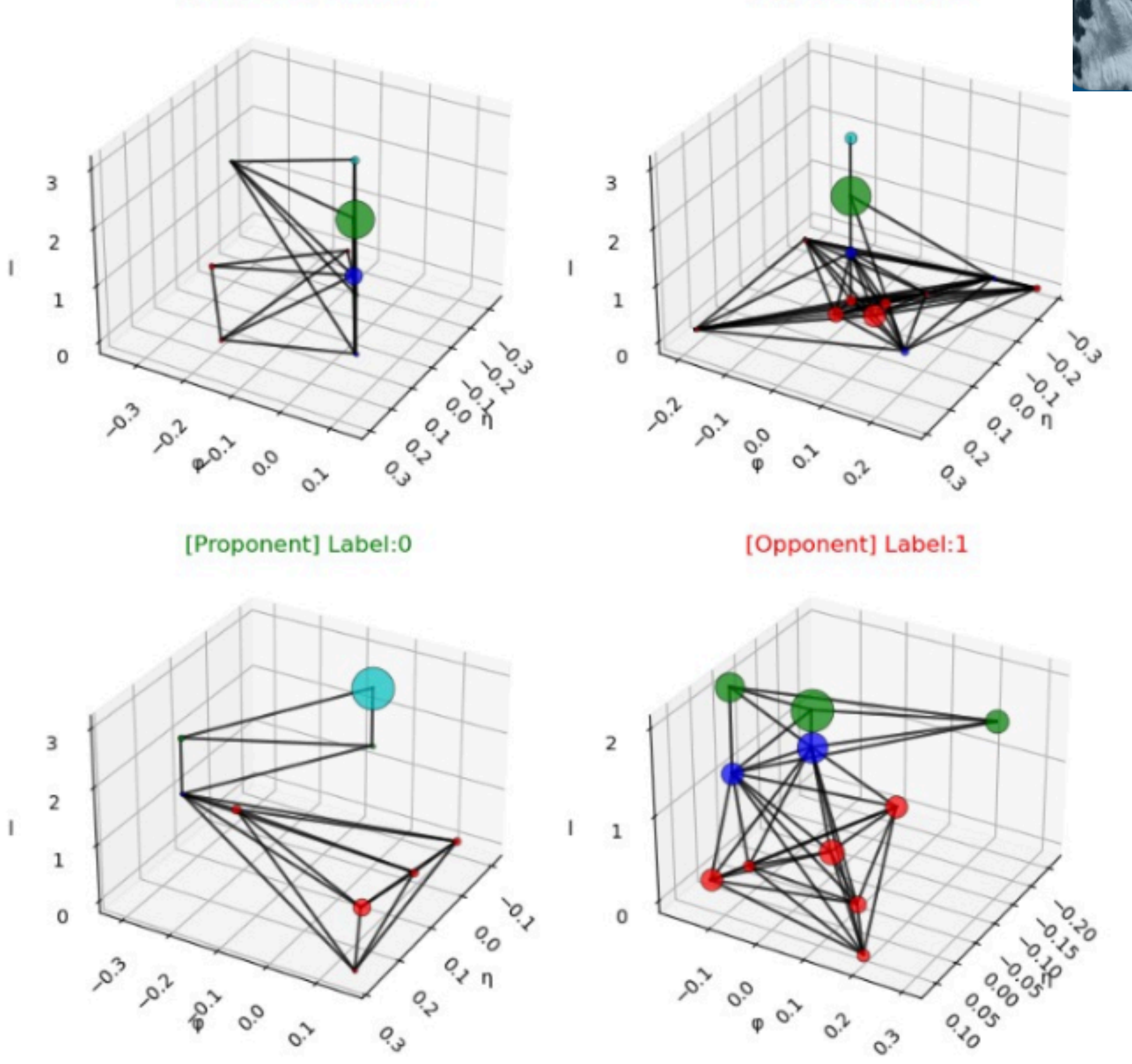
- Sig 1 Bkg 0



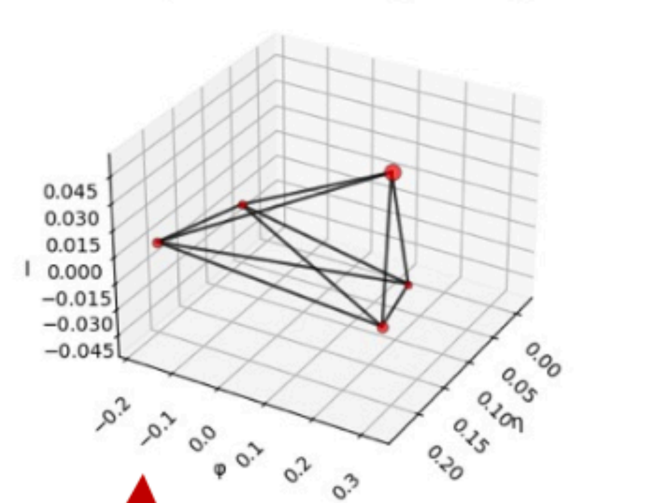
Input Graph

- Proponents for Bkg while opponents for Sig which is sensibly expected

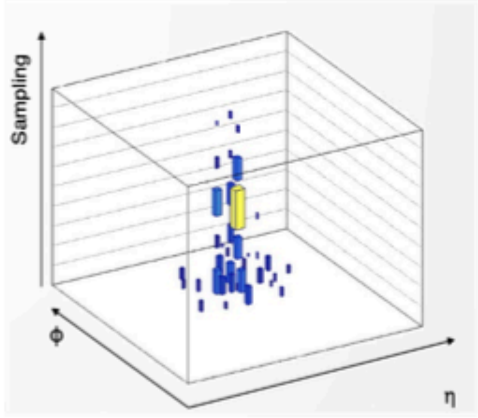
Trac-In



(False Positive)

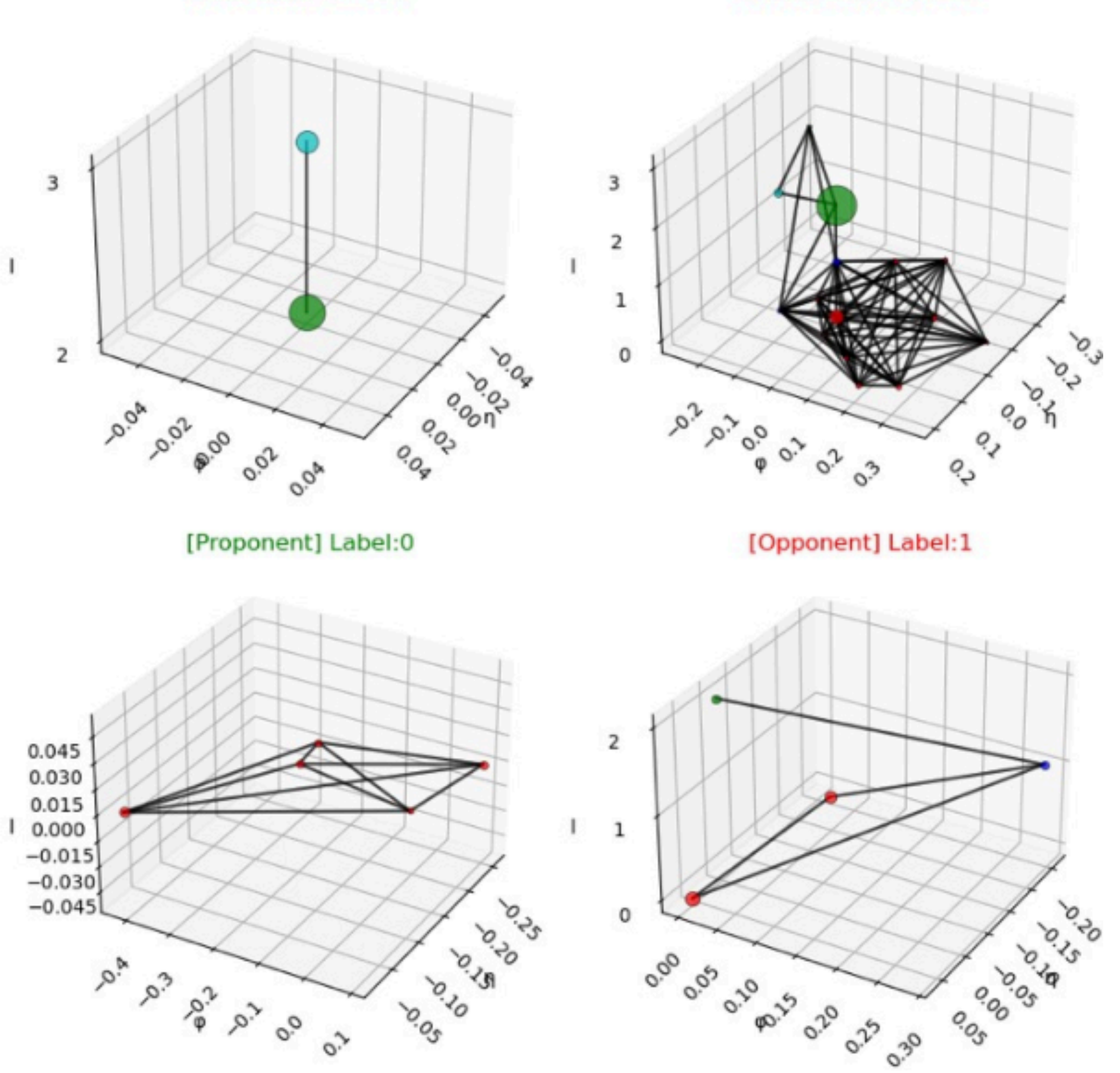


Input Graph



- Still trying to understand the Physics of Failure

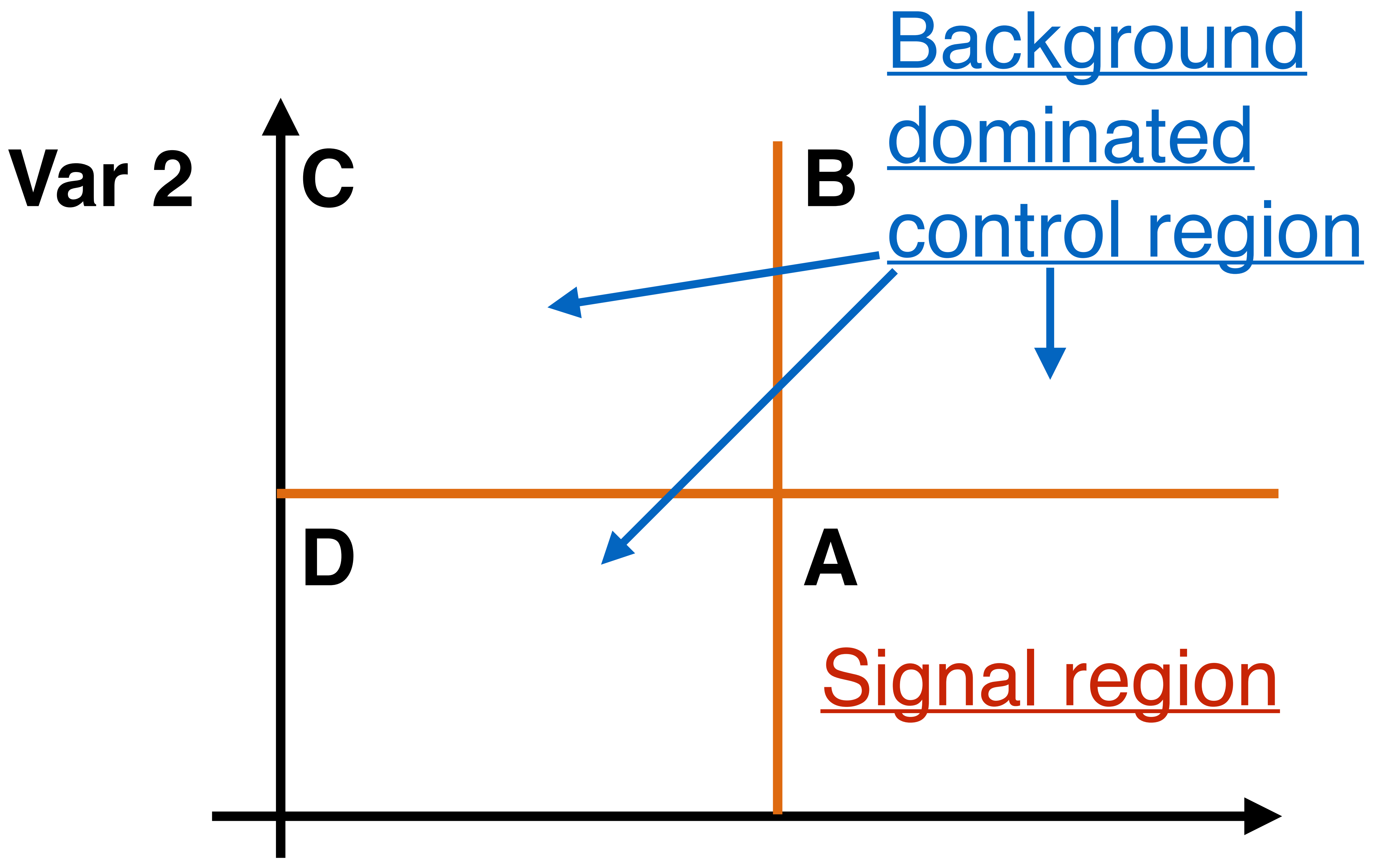
Trac-In



Background estimation

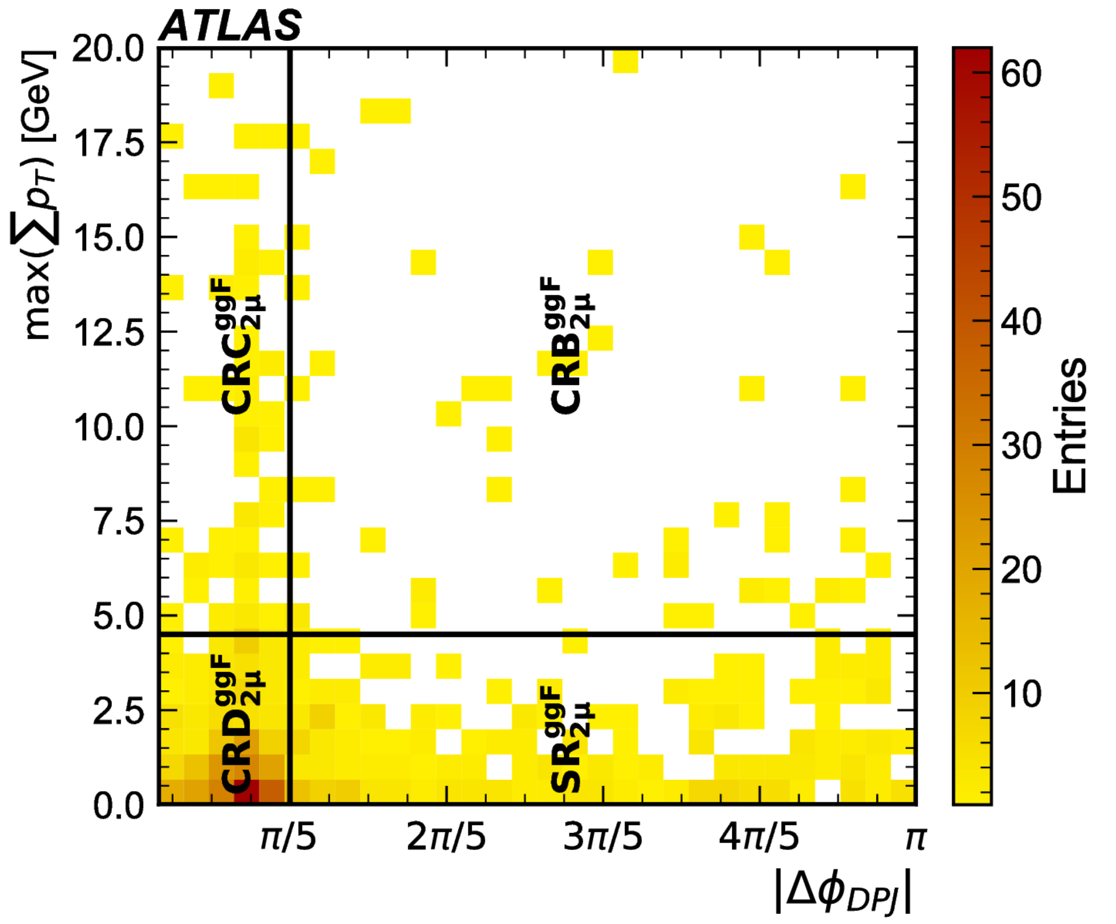
Data-driven estimation of residual multi-jet background events in signal region defined by a pair of cuts of two uncorrelated variables for the background

- Single source of background (remove all BIB and Cosmics, leave only rare QCD events)
- No correlation between variables
- Small signal contamination in CRs

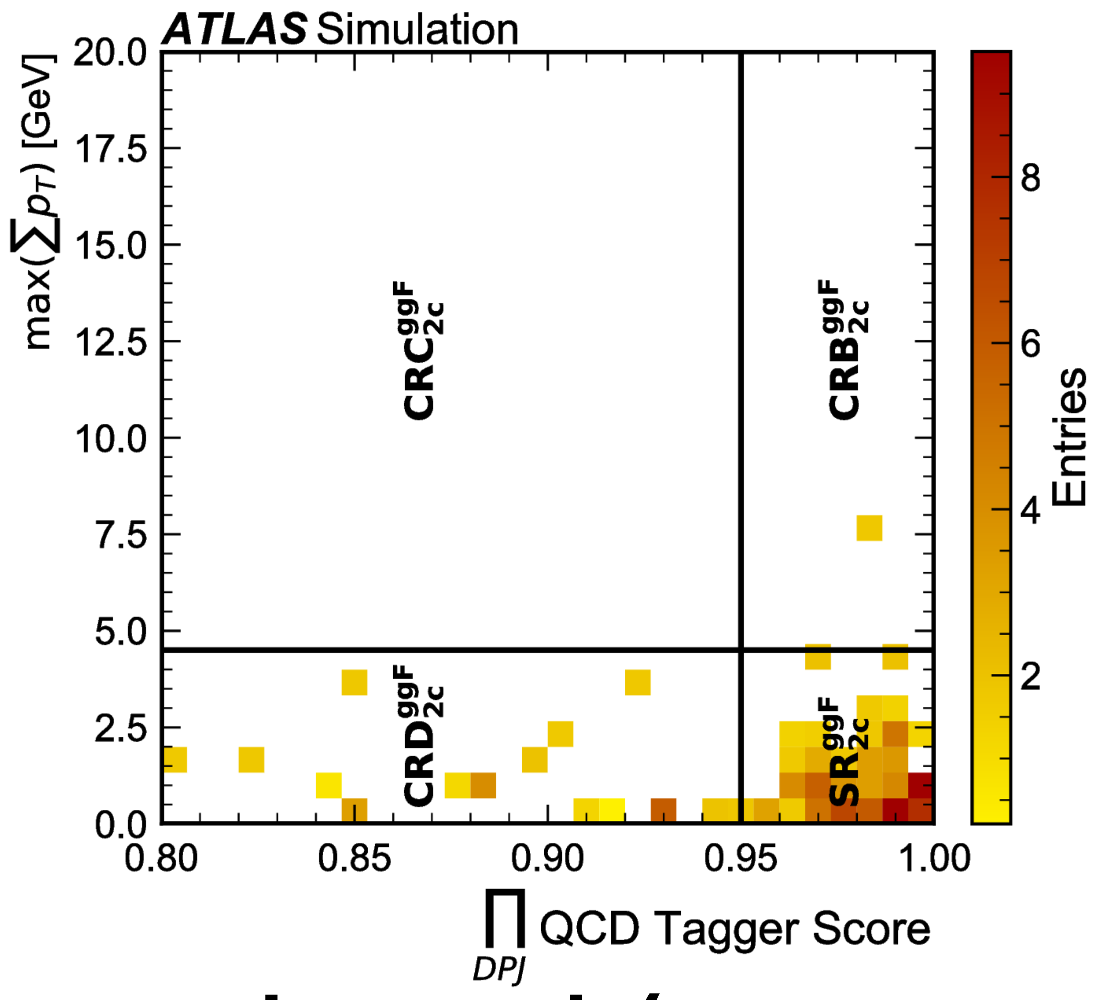


$$N_A^{exp} = \frac{N_D \cdot N_B}{N_C}$$

data



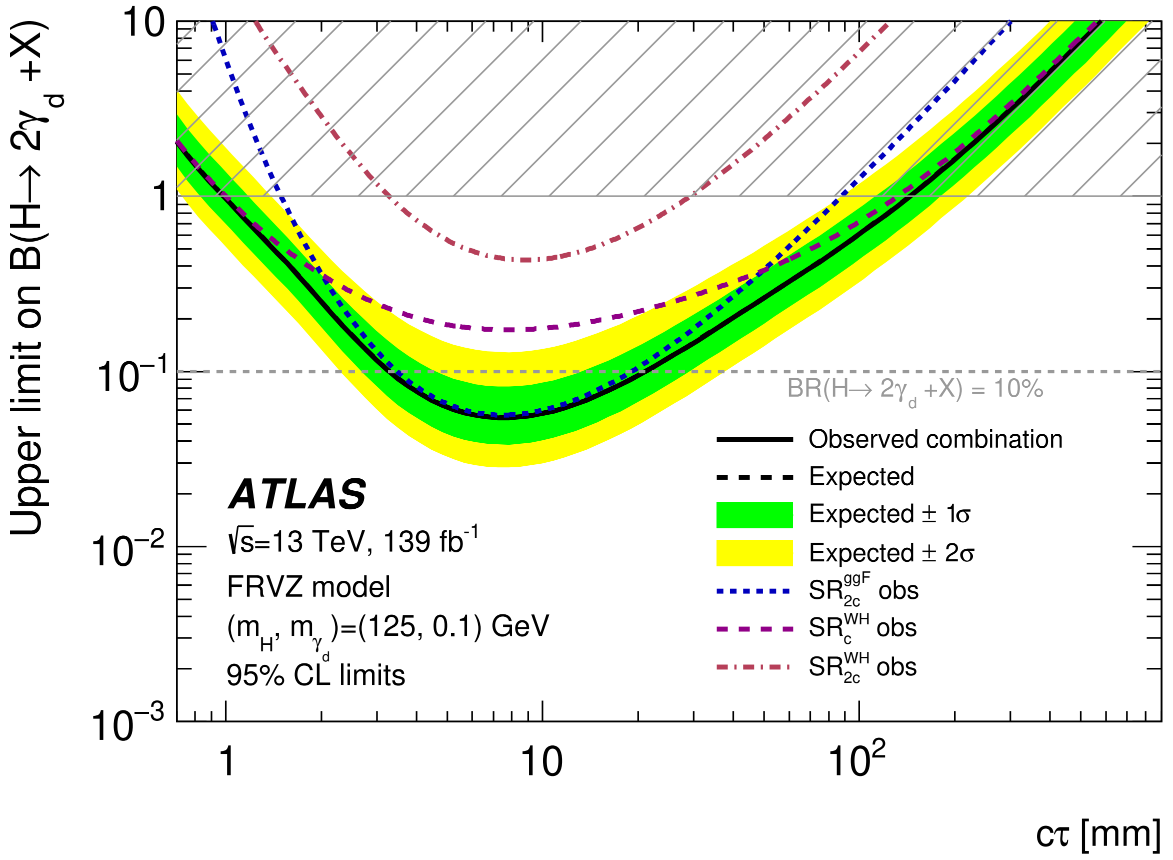
signal



No significan excess was observed :(

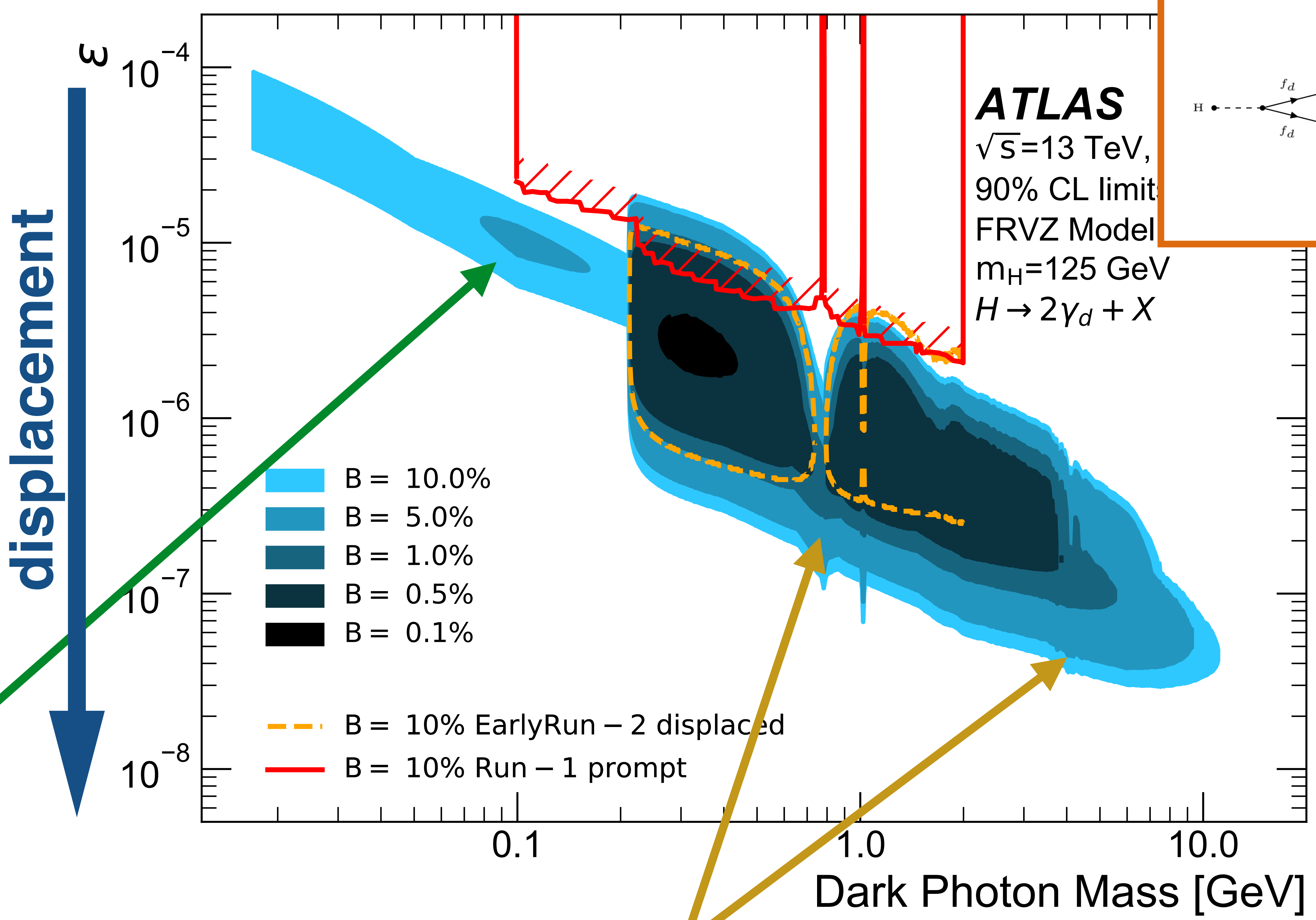
Results

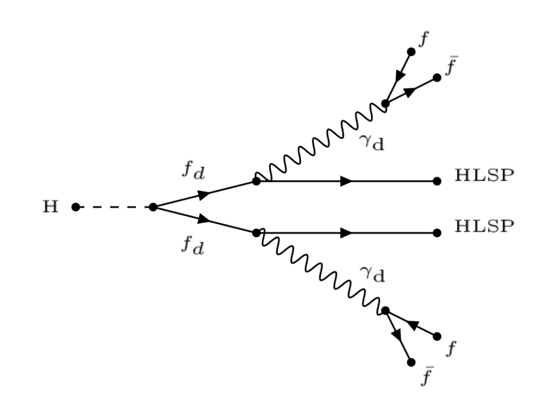
No excess found! Exclusion limits are presented as exclusion regions in the (ε,mγd) plane in the context of the Vector portal model as a function of BR (h→ dark sector)



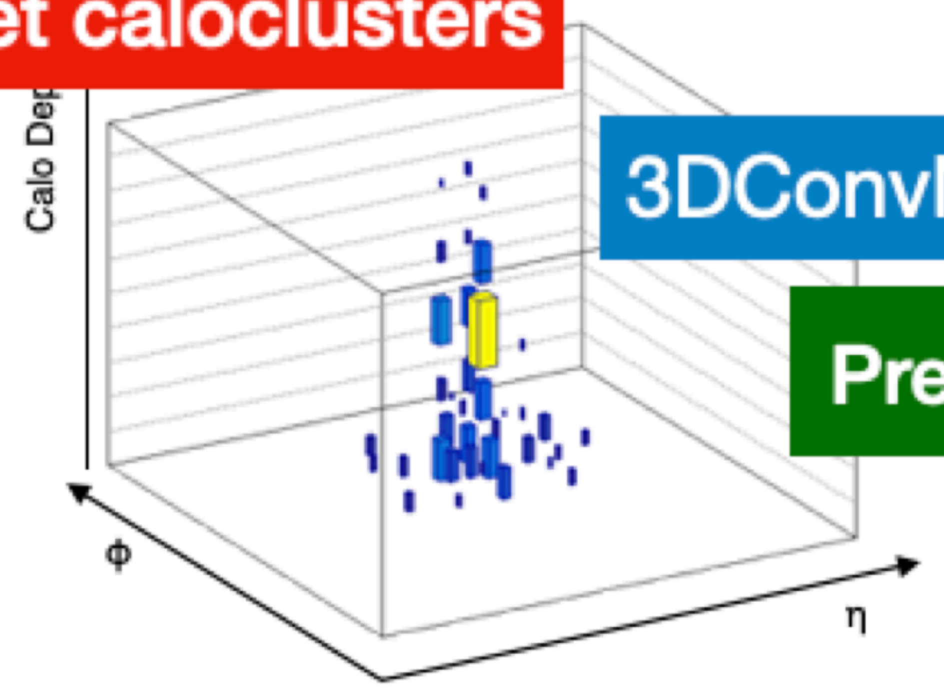
Combination of ggH and WH hadronic channels to improve results!

Muonic exclusion of Br(h->dark sector) down to 0.1%!
—> Br(h->4v) ~0.1%!





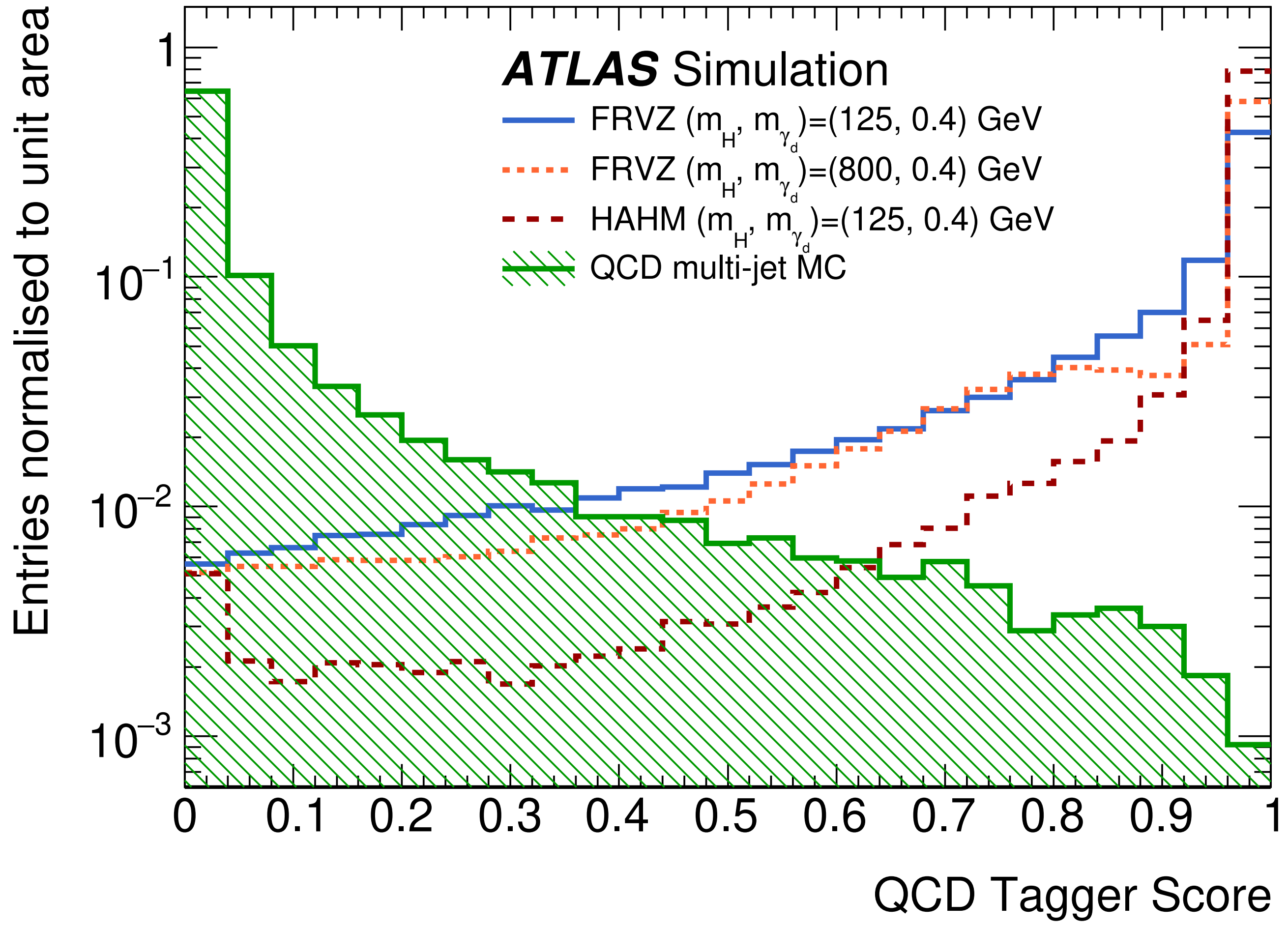
Jet caloclusters



3DConvNet

Prediction

First use in ATLAS searches of a Convolutional Neural Network based tagger trained on low-level inputs (3D jet images from calorimetric clusters)



First time exclusion in the fully electron channel

Significant analysis improvements (CNN taggers) and new topologies (WH) allowed for an exclusion of hadronic decays

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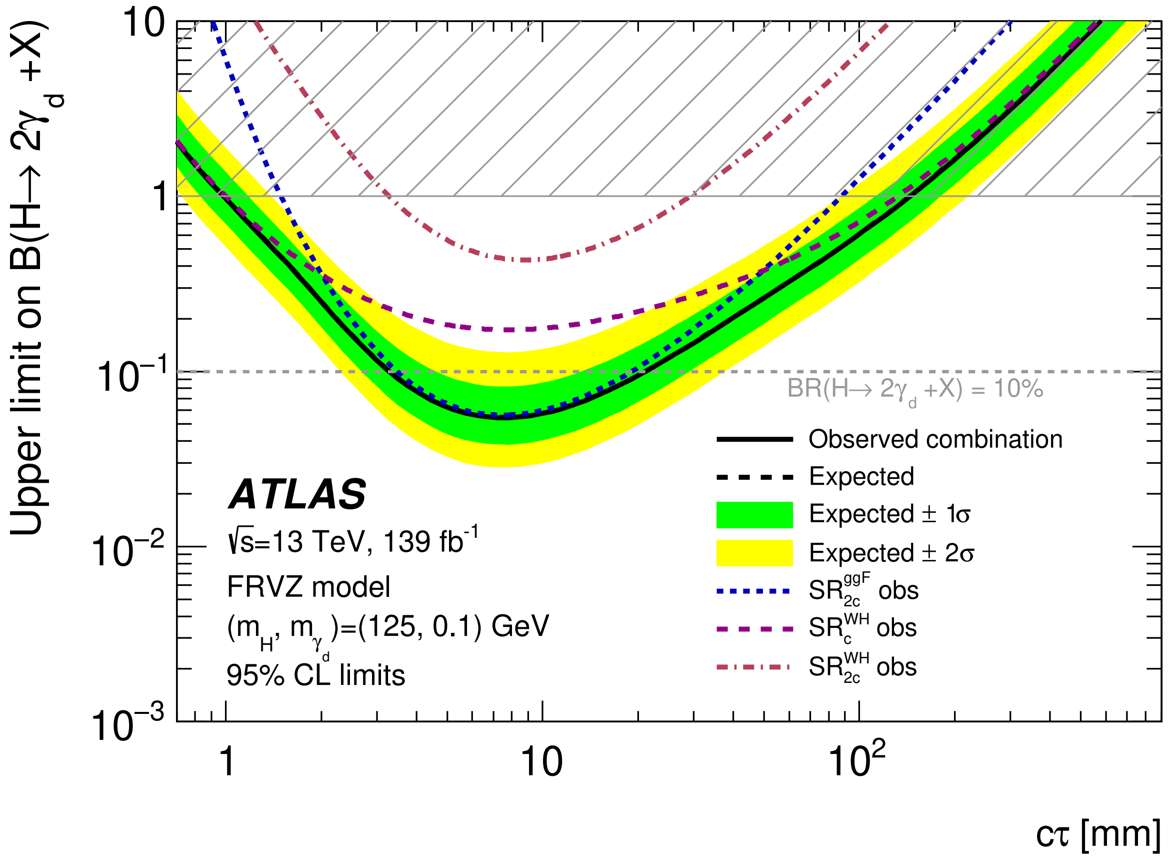

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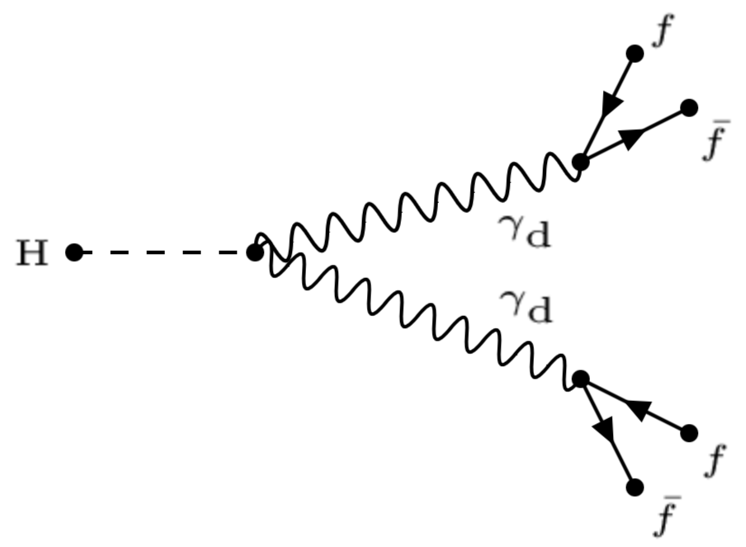
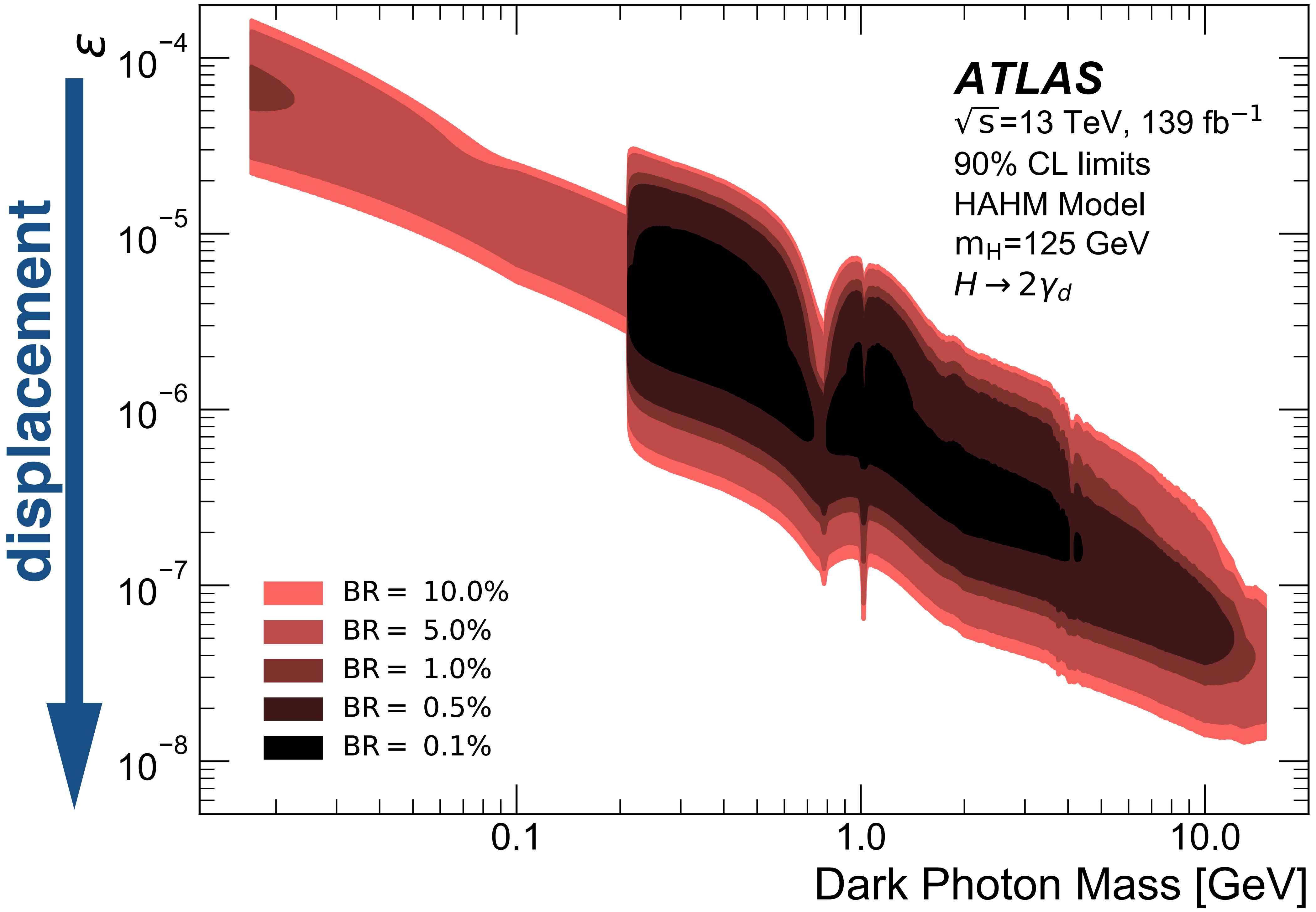
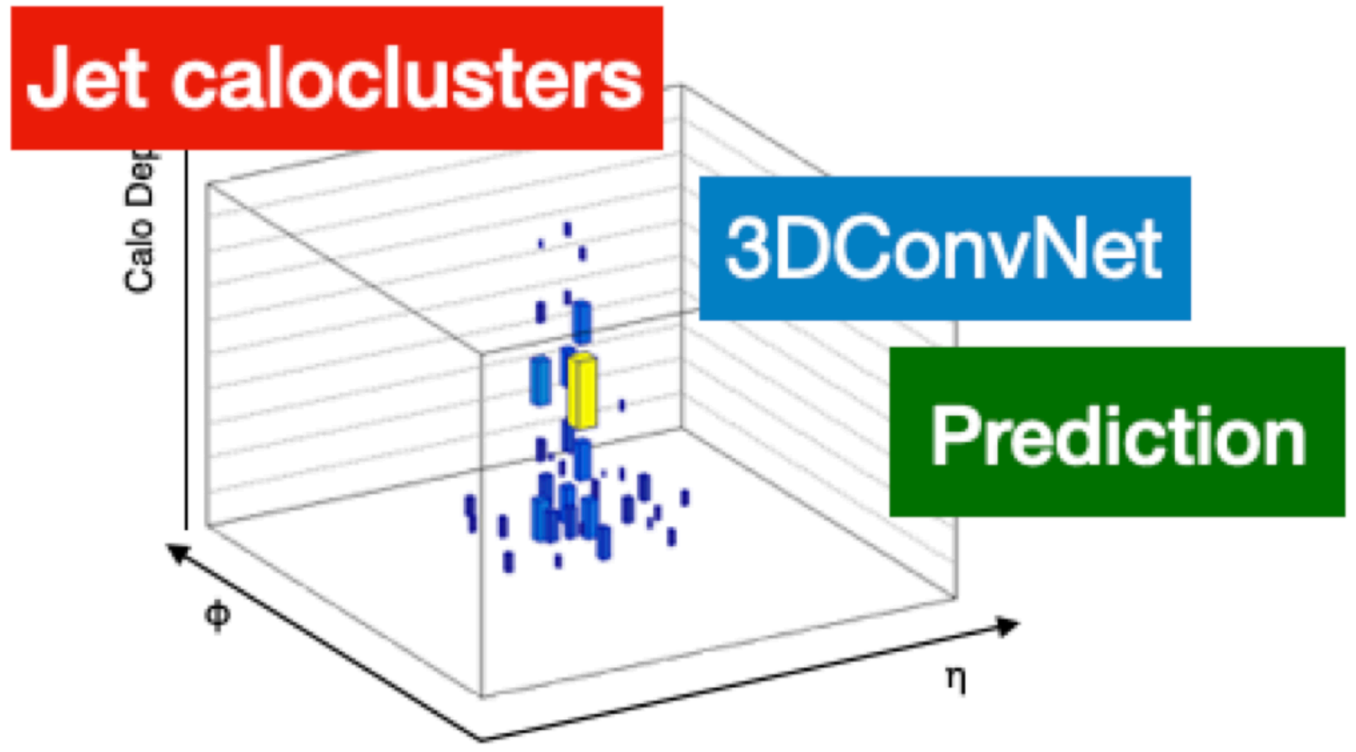


Analysis reinterpreted in HAHM model

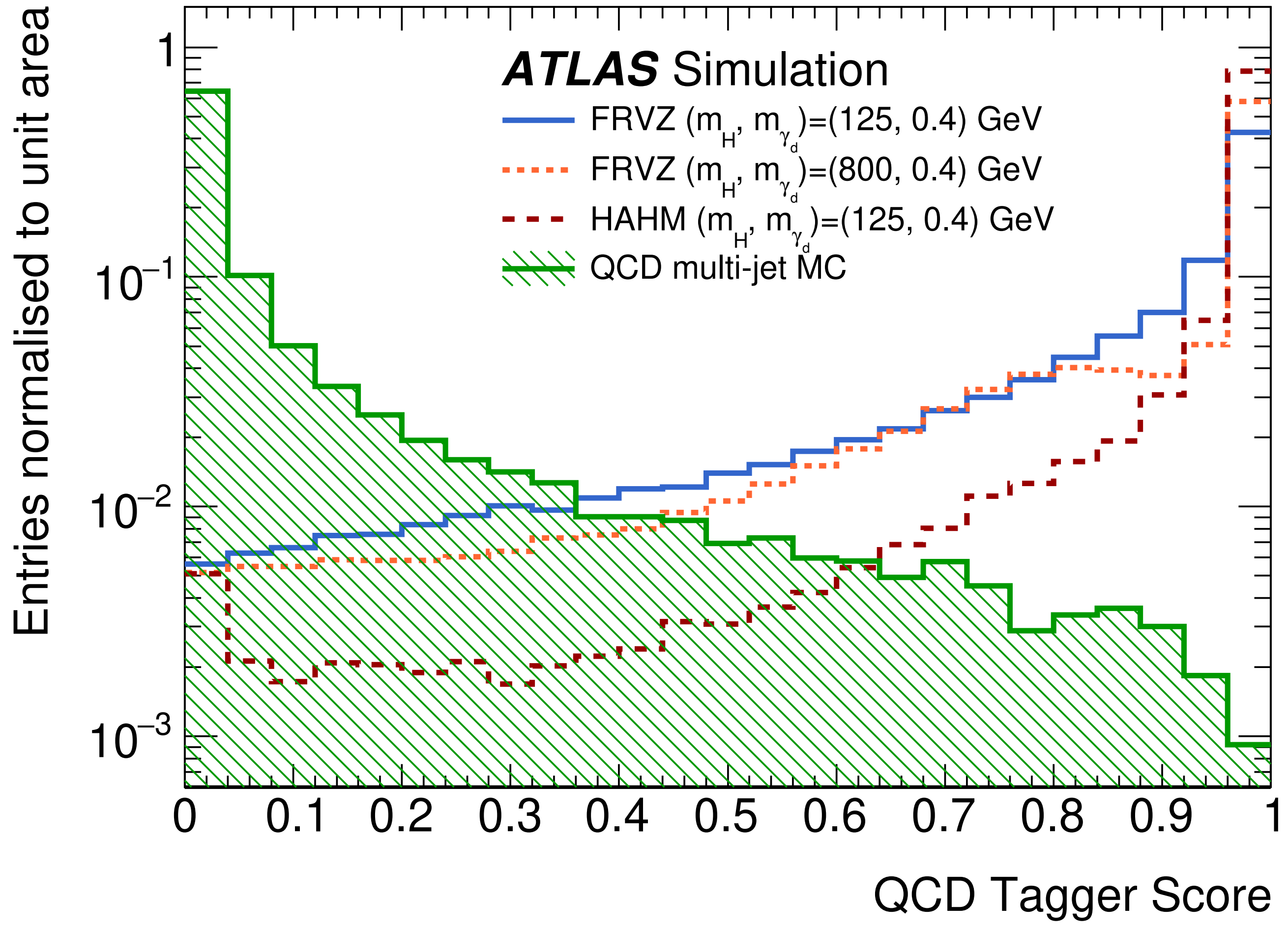
Muonic exclusion of Br(h->dark sector) down to 0.1%! —> Br(h->4v) ~0.1%!



First time exclusion of HAHM model with dark-photon jet signature



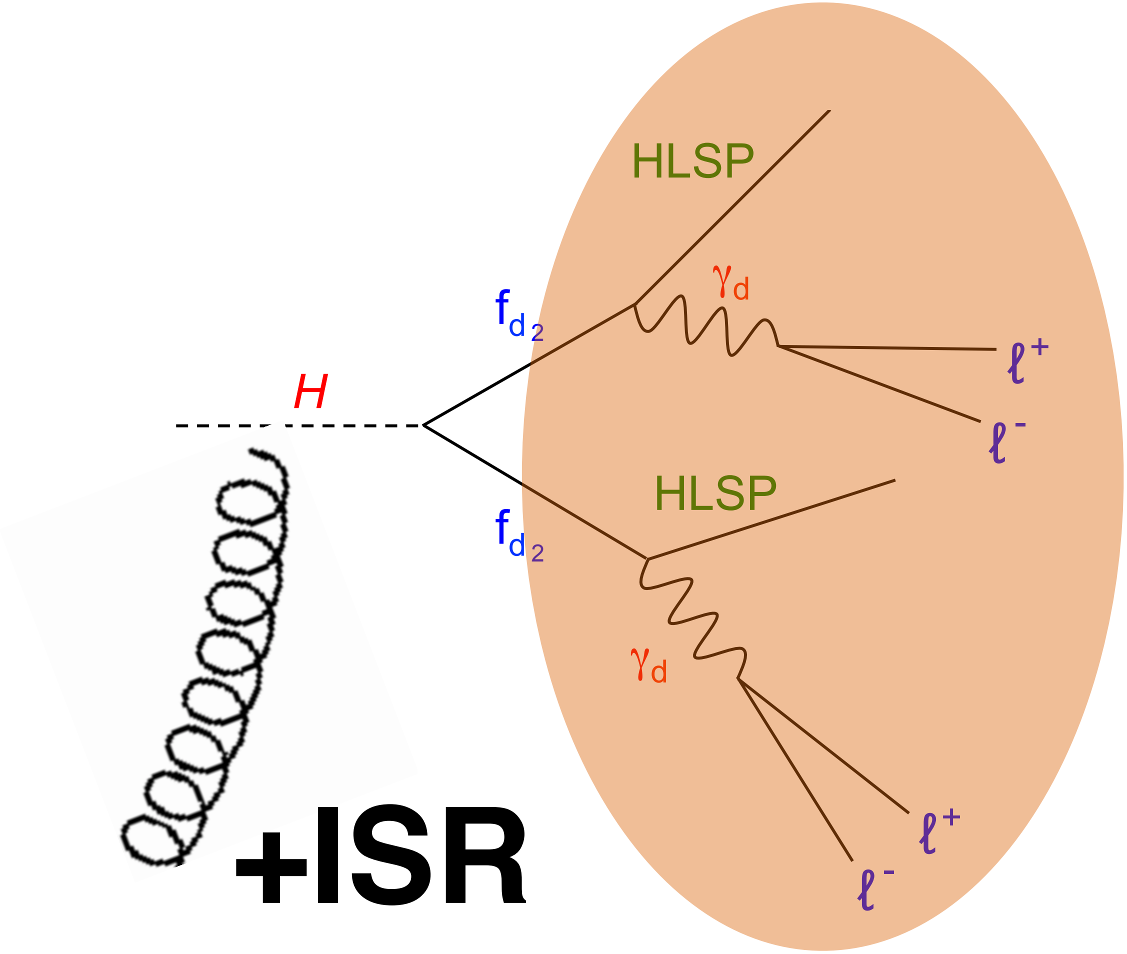
First use in ATLAS searches of a Convolutional Neural Network based tagger trained on low-level inputs (3D jet images from calorimetric clusters)



mono-jet reinterpretation

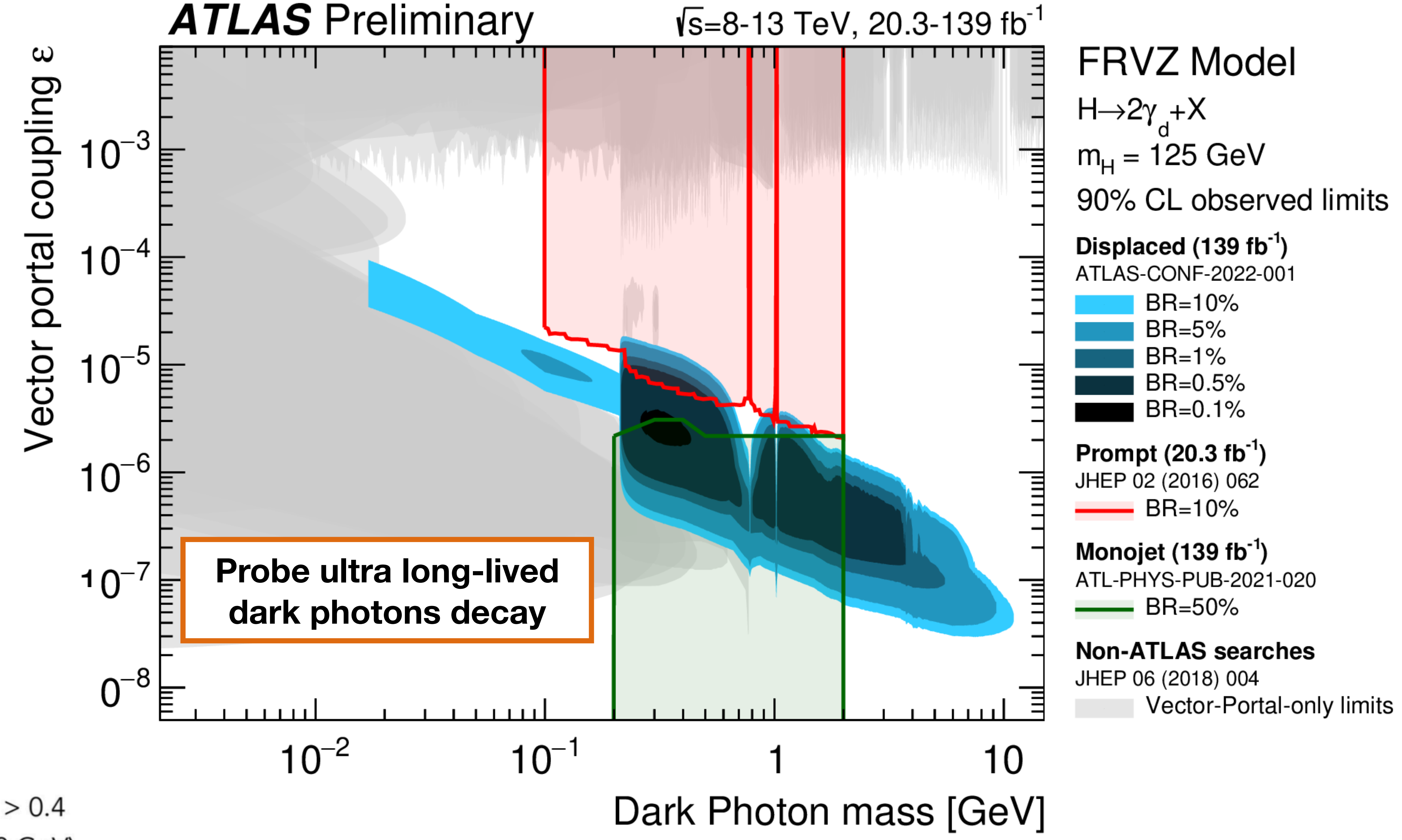
Both dark photons can decay outside ATLAS…

ATL-PHYS-PUB-2021-020

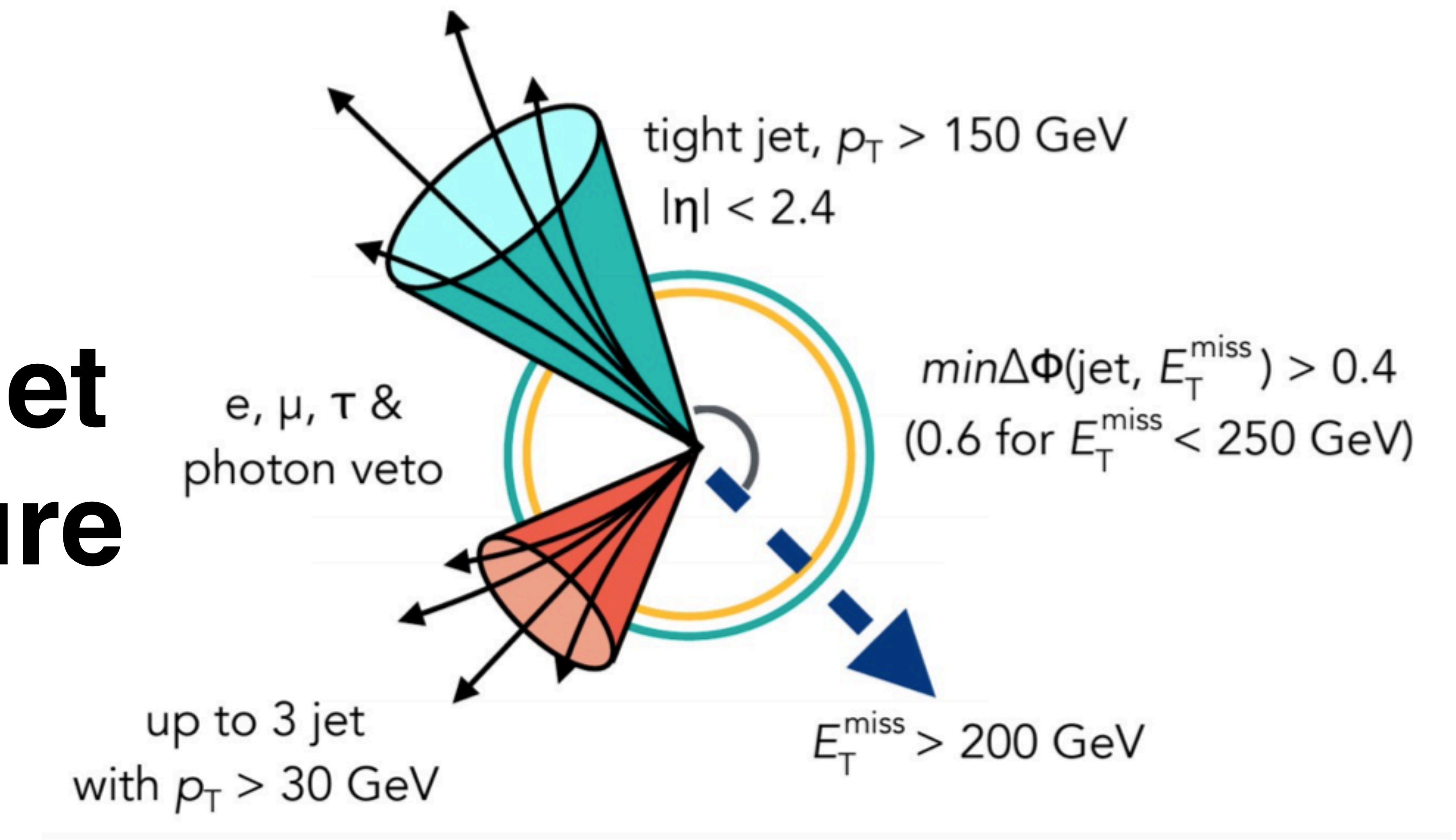


MET

+ISR



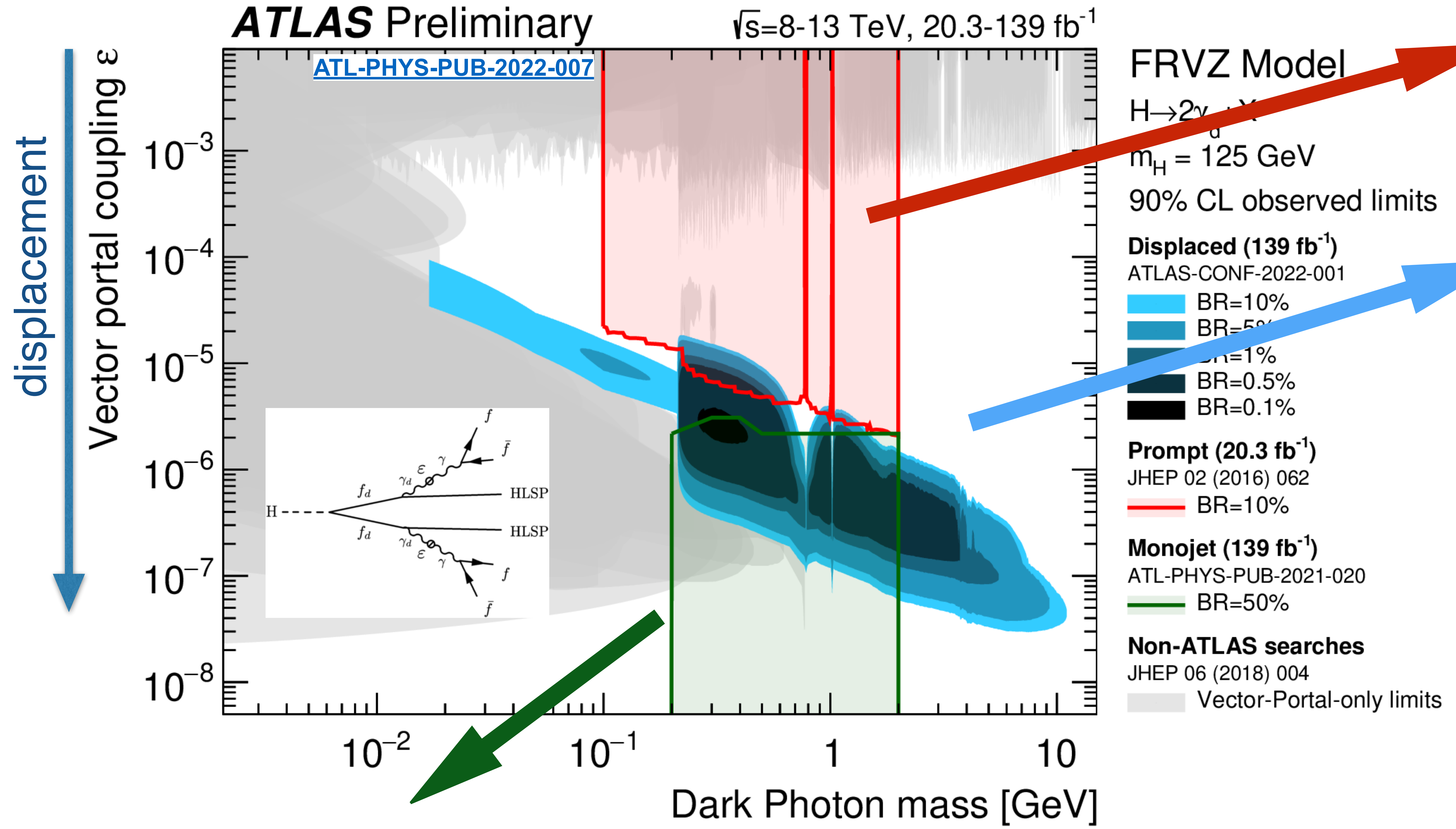
mono-jet signature



Monojet is becoming a precision measurement with a huge interpretation potential:

- Model-independent limits on visible cross-section
- Higgs to invisible BR upper limit (95%CL obs. 0.50)
- Countless possible NP interpretations

Where to go now?



Full Run2 prompt analysis:
- Extend m_yd mass range to [0.01;10] GeV

Explore VBF signature (EXOT-2022-15):
- Significantly improve ele results ($m_{\gamma d}$ < 280 MeV)

Final combination of prompt and displaced (ggF+WH+VBF)!
Prepare a Run2 legacy result of FRVZ and HAHM models

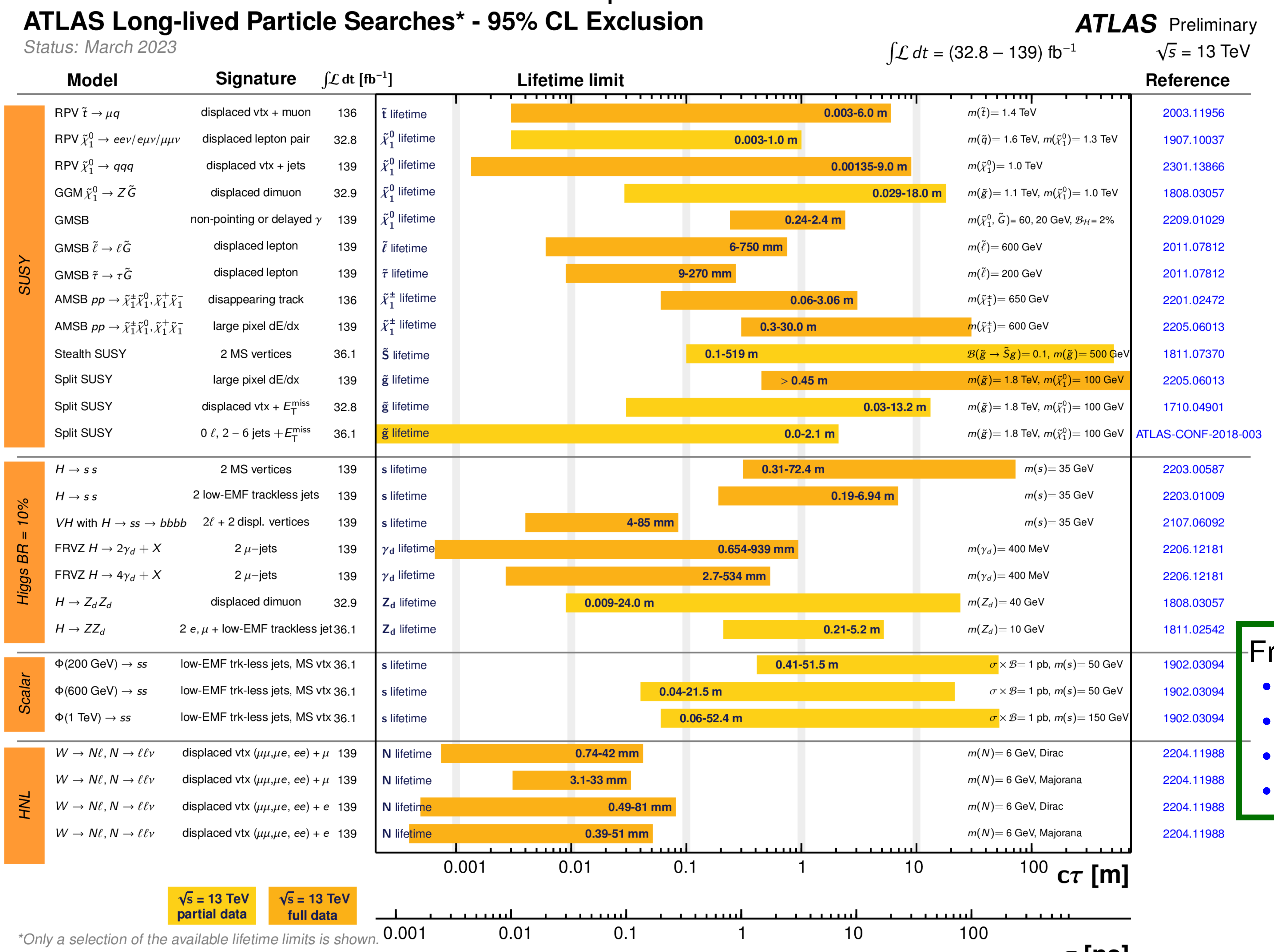
Where to go in Run3:
- Go TLA+PEB for muonic signature
- Additional Higgs productions mechanism for prompt analysis
- Explore mono-LJ (LJ + MET) signature to fill the gaps between prompt and combined

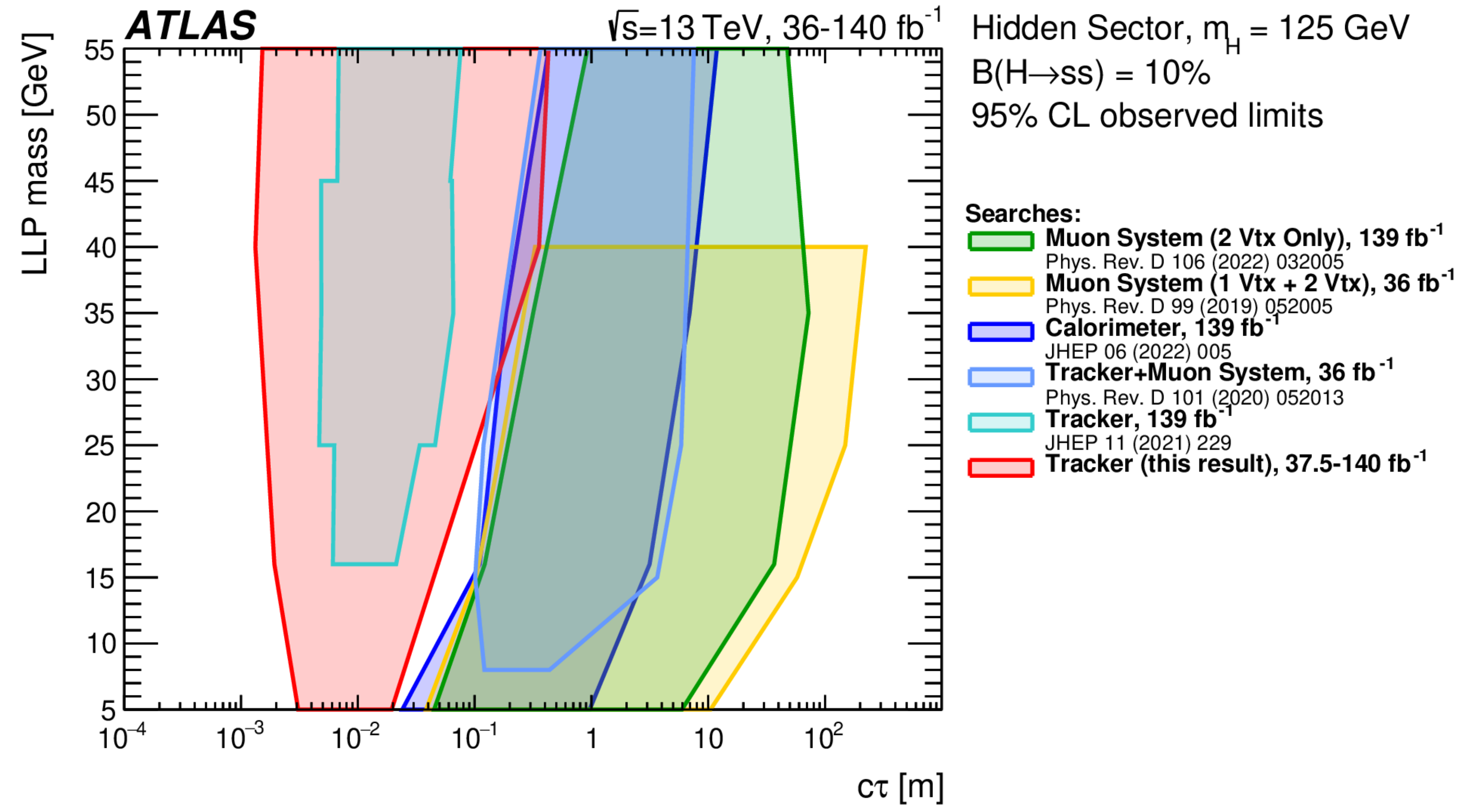
Very displaced region: mono-jet search reinterpretation
ATL-PHYS-PUB-2021-020

Could benefit from a VBF+MET (+y) reinterpretation

Not only dark-photons in ATLAS…

Snapshot of the most recent ATLAS LLP results..





From the past year…

- (May 24) CERN-EP-2023-226 VBF displaced dark photon
- (Mar 24) CERN-EP-2024-086 Displaced vertices
- (Nov 23) JHEP 11 (2023) 112 Highly ionising particles
- (Mar 23) Phys. Lett. B 847 (2023) 138316 Multi-charged particles

Analyses reach into the lifetime space

Dark Sector portals

Light mediators, HNL and ALPs must be SM singlets: options limited by SM gauge invariance

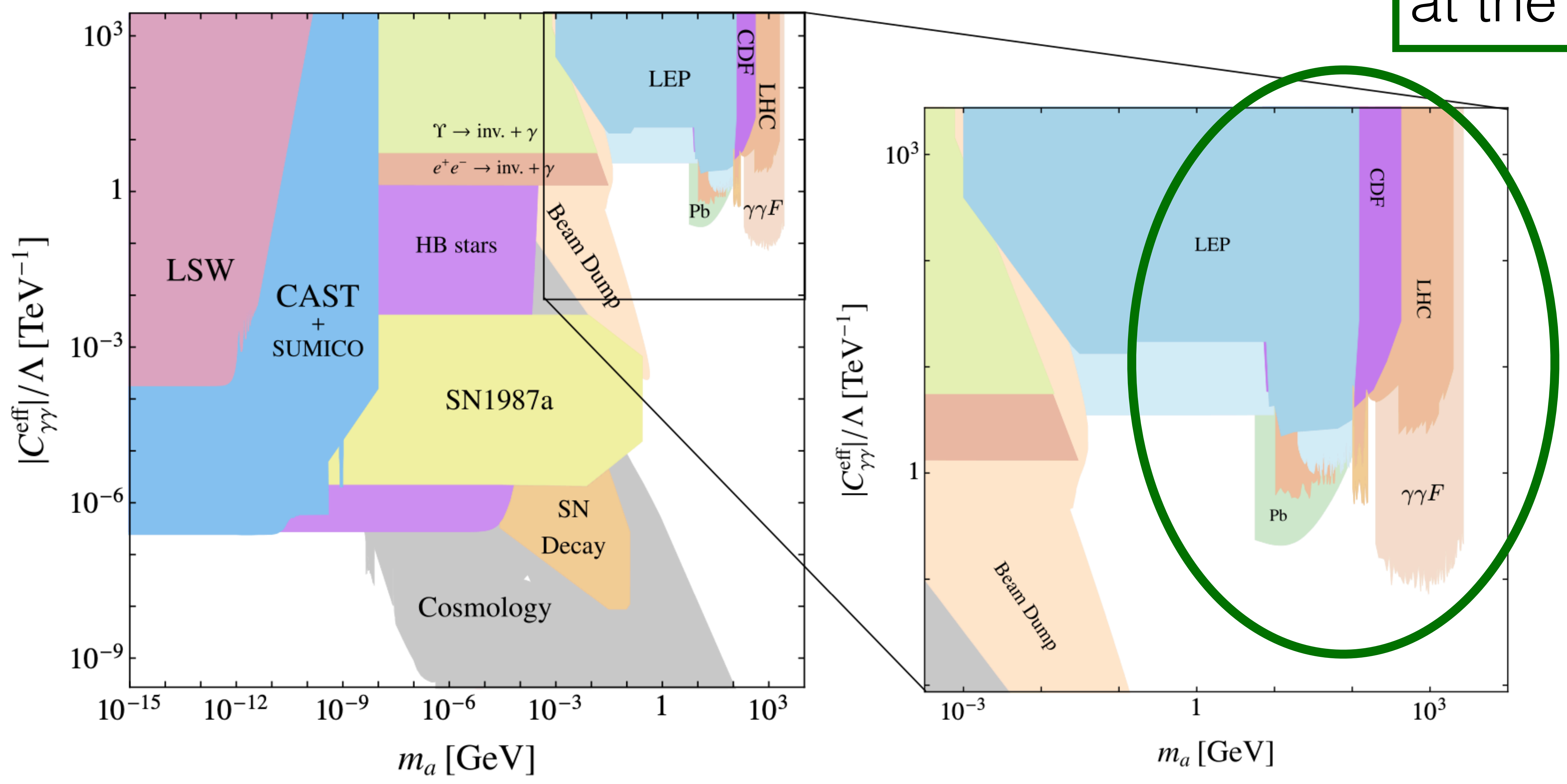
Pseudoscalar portal: $\delta_\mu \bar{\psi}\gamma^\mu\gamma^5\psi \; , \; \frac{a}{f_a} F'_{\mu\nu}\tilde{F}^{\mu\nu}$ **axions/ALPs**

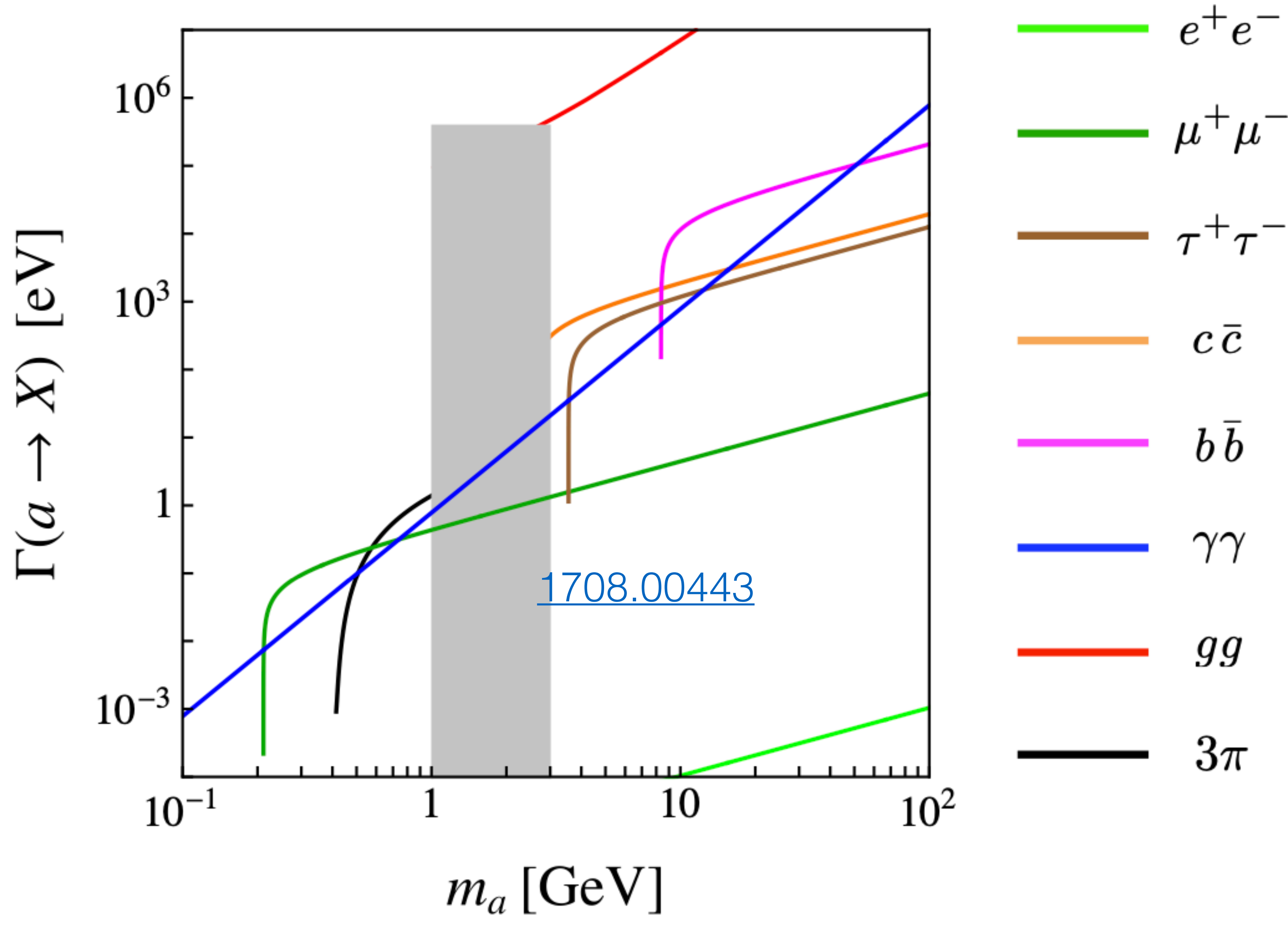
'dark' vector boson (A', γ_d

What about axions…

Are we covering the whole phase space accessible at the LHC?

Decay rates for a NP scale at 1 TeV and effective coefficients set to 1





Nice complementarity between LHC, beam-dump and astrophysics boundaries. Together they can explore a large fraction of the axion regions

Prompt axion searches

Many searches looking for prompt ALPs in a great effort to systematically cover all production and decay channels!

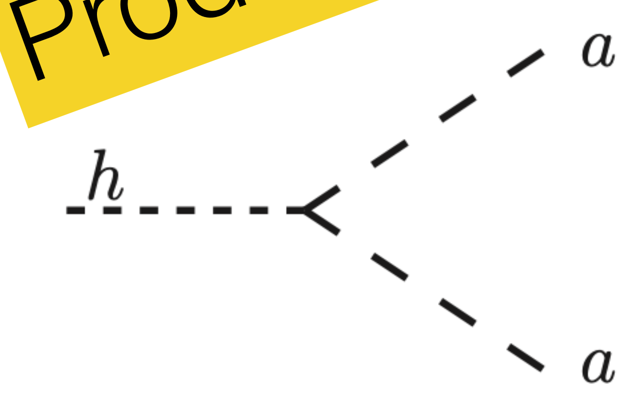
COVERED | UNEXPLORED

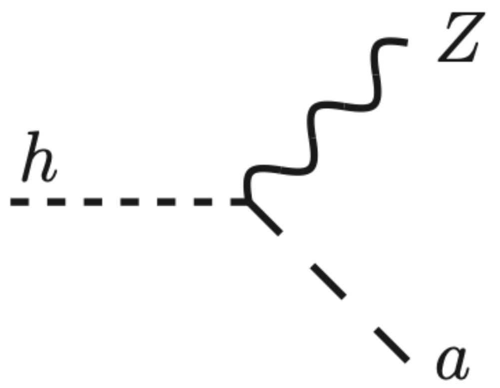
aa—> XX/YY	e	mu	tau	γ	j	b
e	COVERED					
mu	COVERED	COVERED				
tau	UNEXPLORED	UNEXPLORED	COVERED			
γ	UNEXPLORED	UNEXPLORED	COVERED	COVERED		
j	COVERED	COVERED	UNEXPLORED	COVERED	COVERED	
b	COVERED	COVERED	COVERED	UNEXPLORED	UNEXPLORED	COVERED

tta—> XX	tt
e	UNEXPLORED
mu	COVERED
tau	COVERED
γ	UNEXPLORED
g	UNEXPLORED
b	COVERED
MET	COVERED

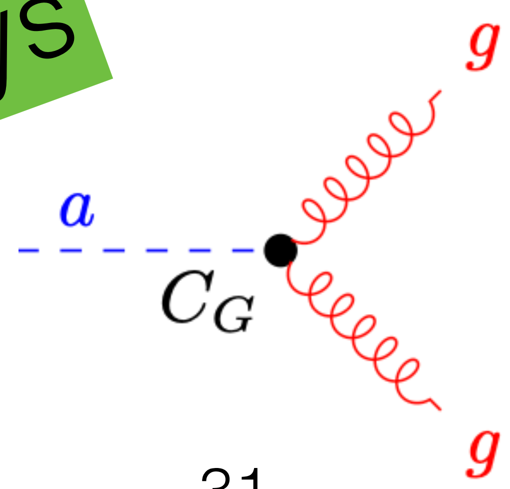
Za—> ll XX	ll
e	COVERED
mu	COVERED
tau	UNEXPLORED
y	COVERED
g	COVERED
b	COVERED

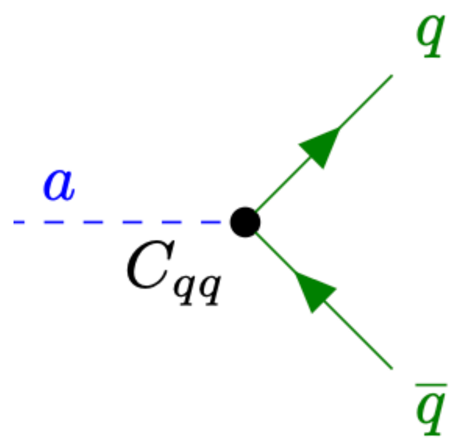
Production

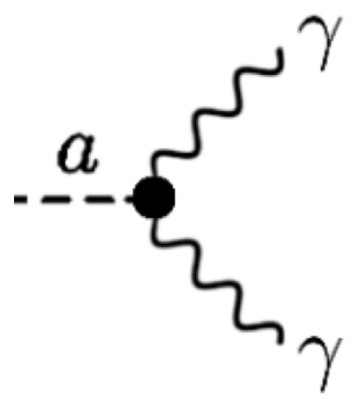


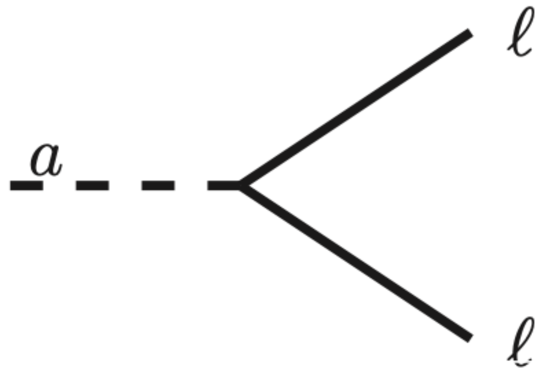


Decays









Displaced axion searches

Still plenty of unexplored displaced ALP scenarios, many possibilities for synergies and reinterpretations

COVERED | UNEXPLORED | REINTERPRETATION ONLY

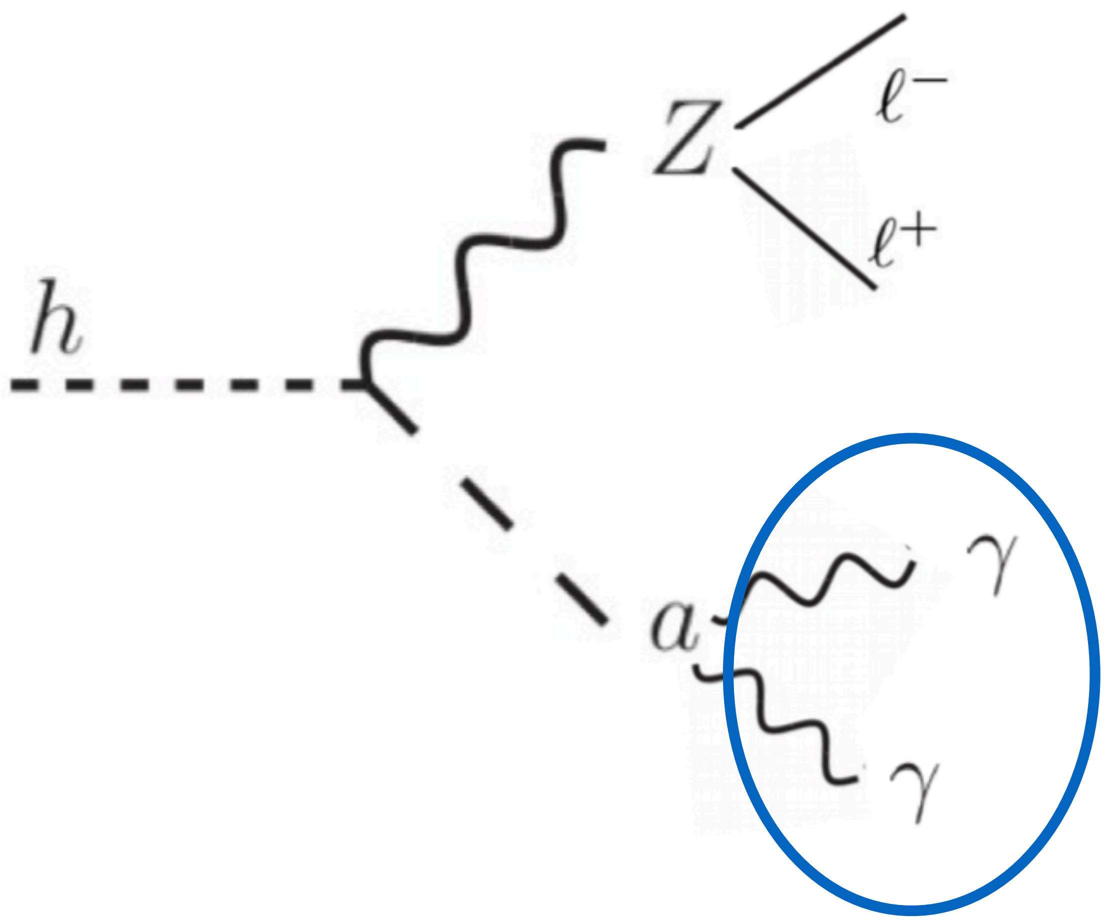
aa—> XX/YY	e	mu	tau	γ	j	b
e						
mu						
tau						
γ						
j						
b						

Za—> ll XX	ll
e	
mu	
tau	
y	
g	
b	

It’s time to develop new ideas and explore all blind spot left in the ATLAS LLP programme!

New idea: a search for long-lived axions

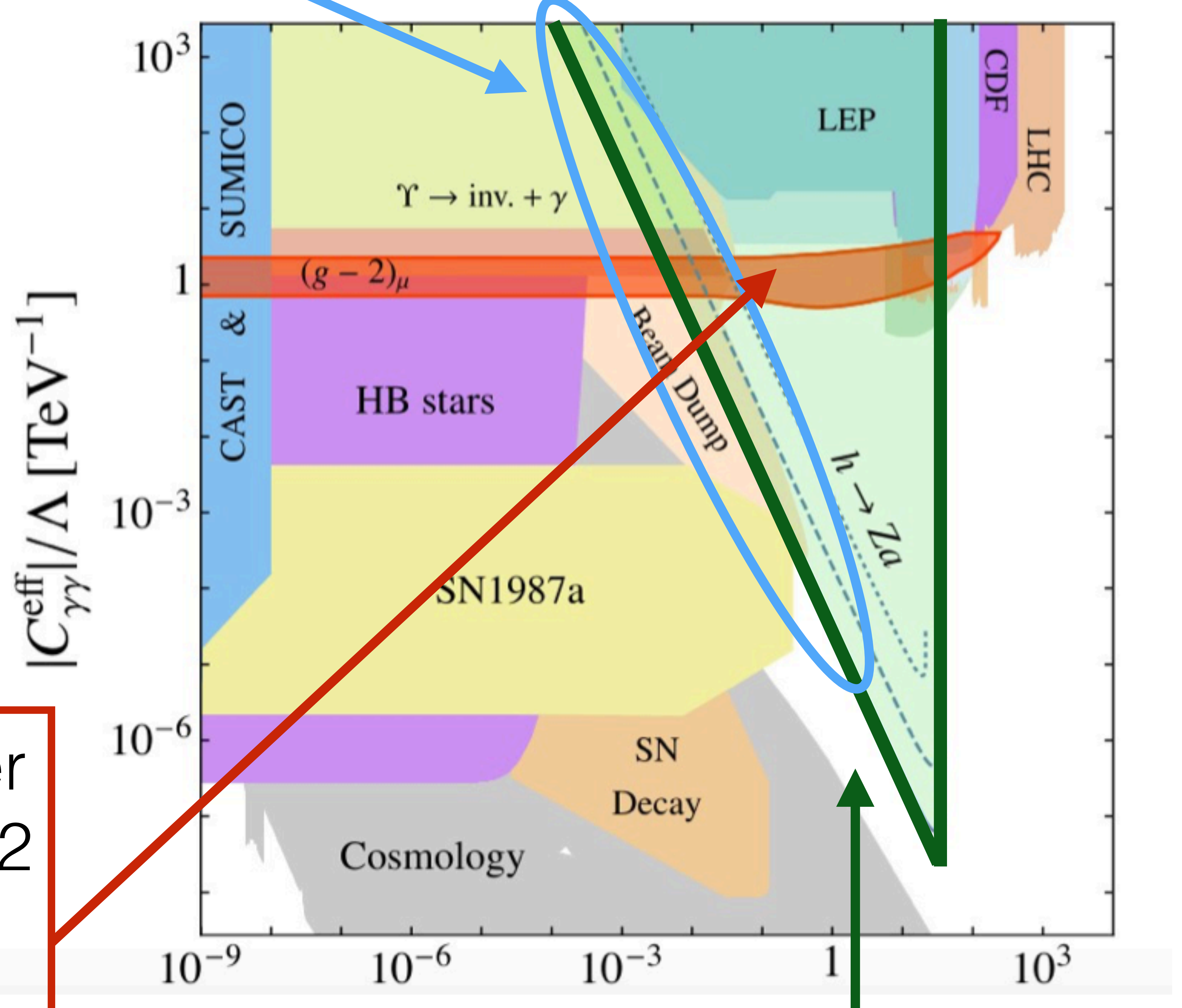
- Axion particle produced in association with a Z boson from Higgs decay
- Signature with two leptons and two collimated photons (one if signal photons are collimated enough)
- Main backgrounds from Z+jet and Zy



2 close-by photons

axion displaced region
From few mm to stable

arXiv:1708.00443



preferred parameter space where mu g-2 anomaly can be explained

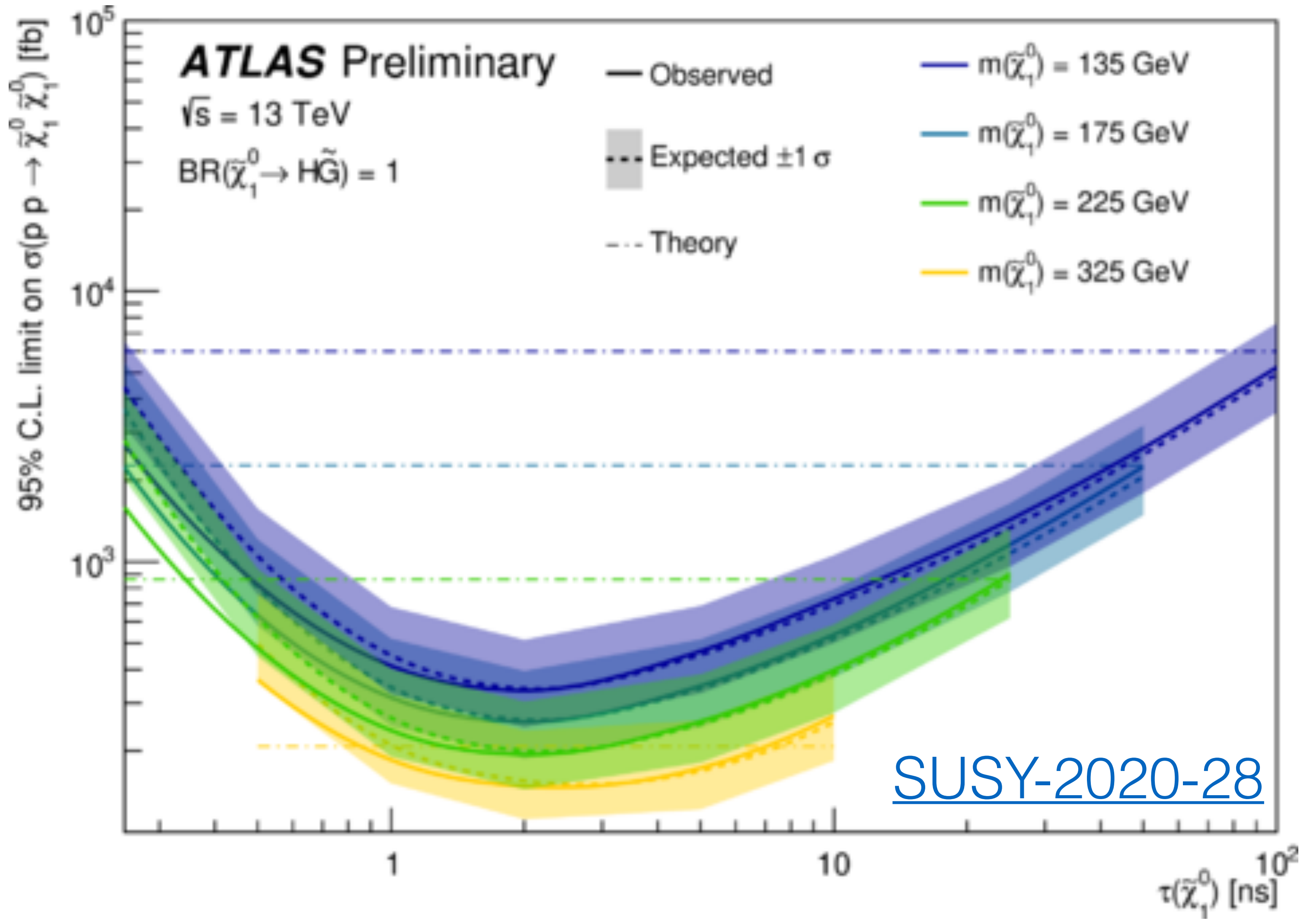
axion decay rate:

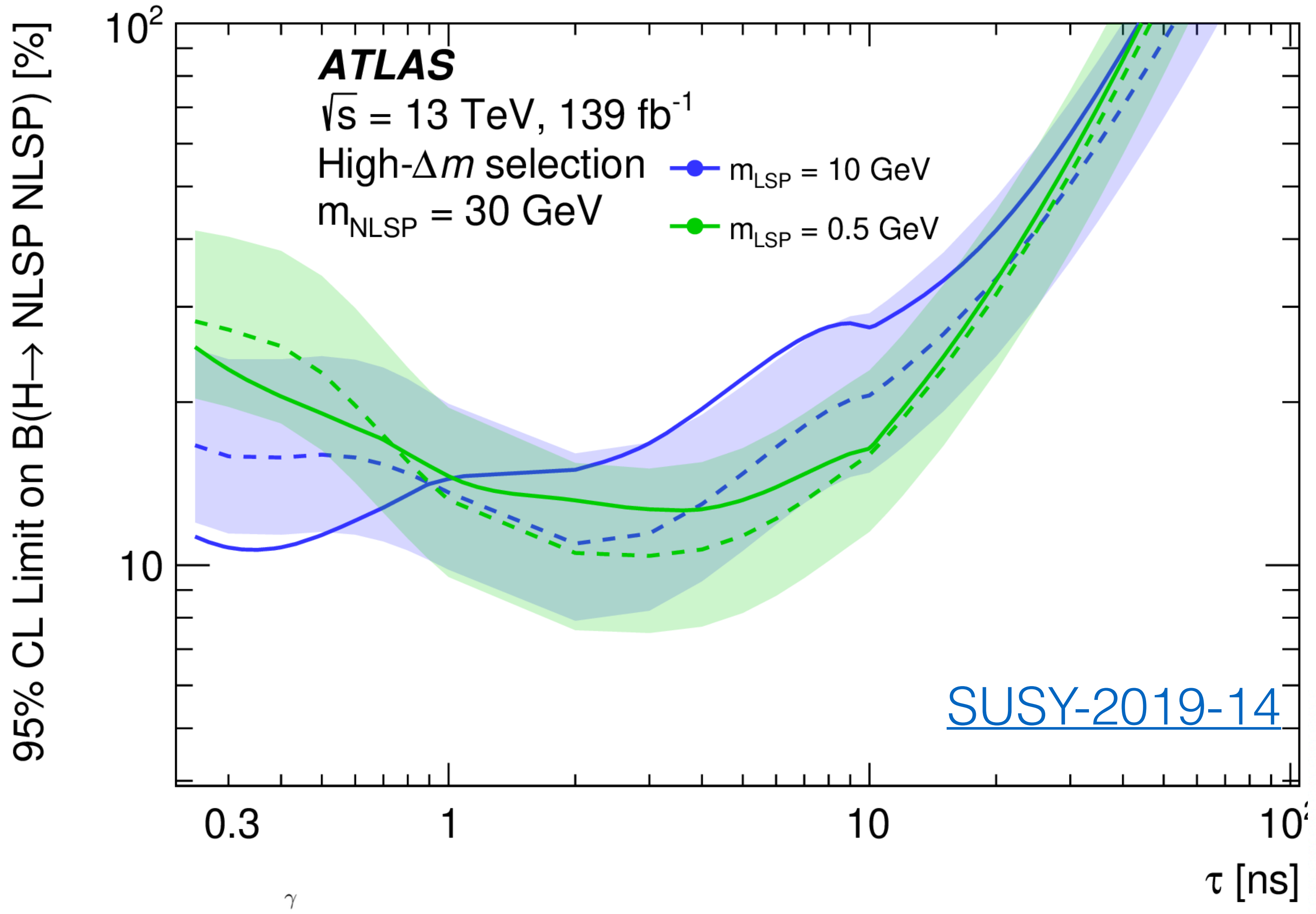
$$\Gamma(a \to \gamma\gamma) \equiv \frac{4\pi\alpha^2 m_a^3}{\Lambda^2} \left|C_{\gamma\gamma}^{\rm eff}\right|^2$$

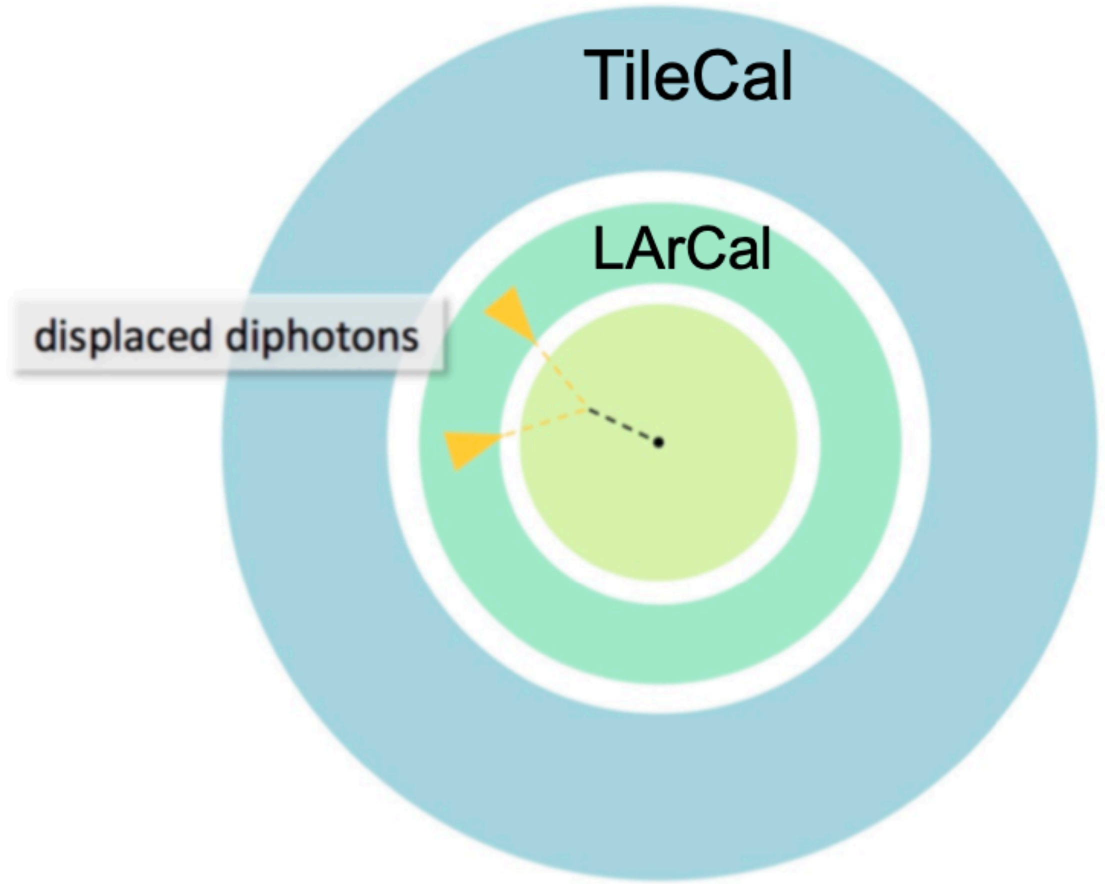
ALPs pseudo-scalar particles: mass range 0.1-35 GeV.

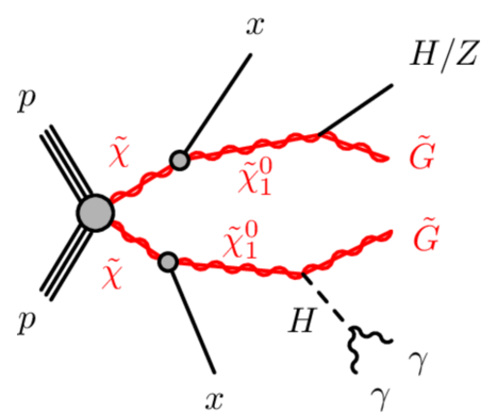
Current searches

Non-pointing photon search Phys. Rev. D 108 (2023) 032016
with ID di-photon vertexing Phys. Rev. D 108 (2023) 012012

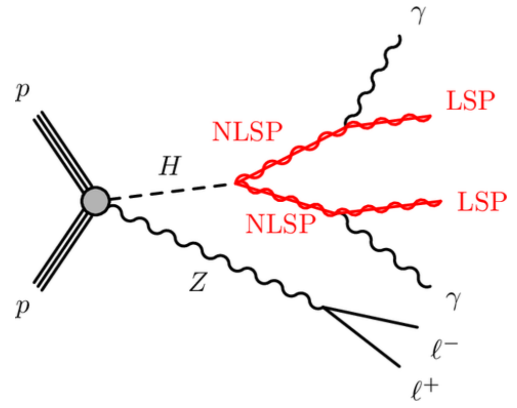




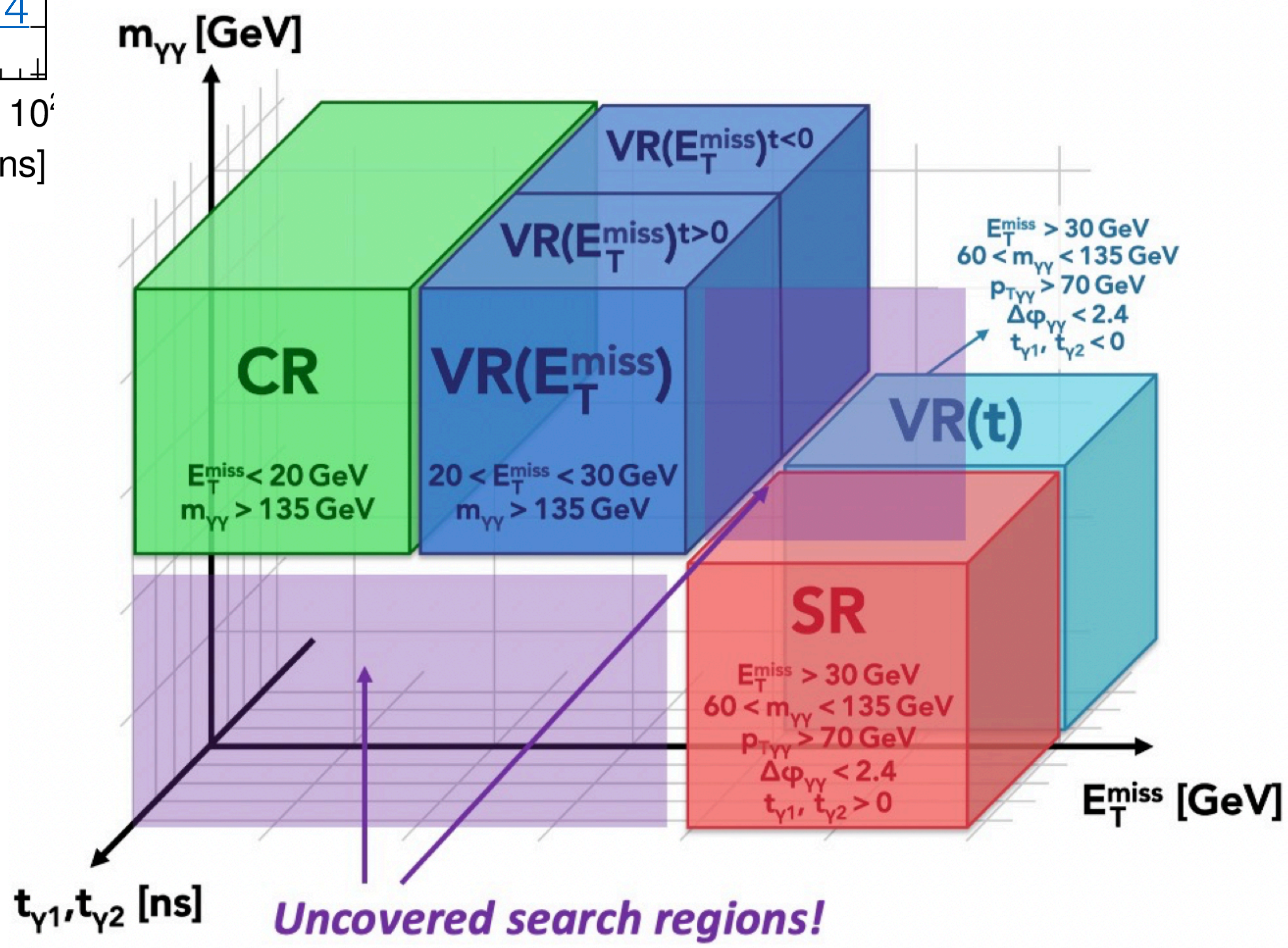




GMSB susy model



Possible reinterpretation in LLP axions

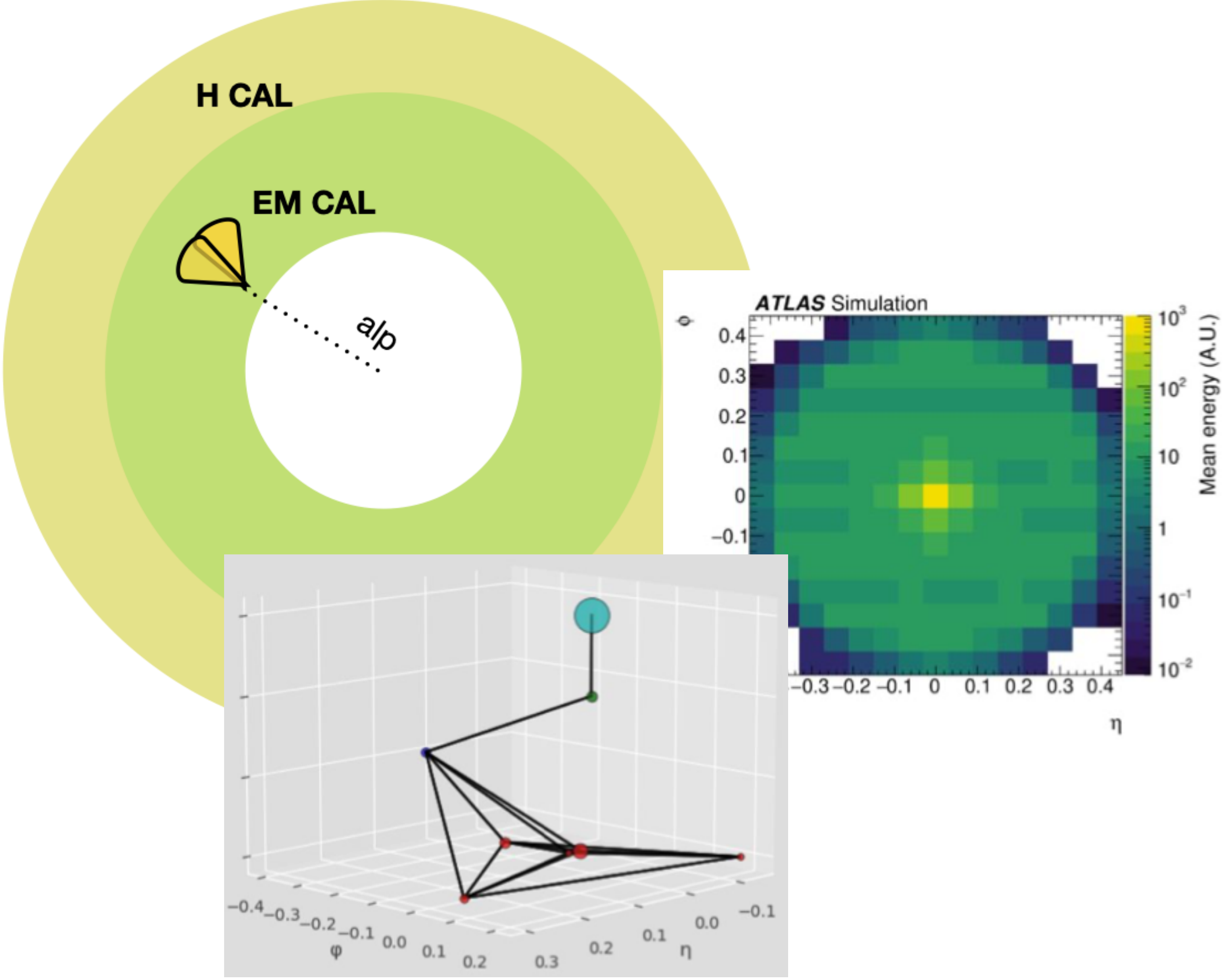


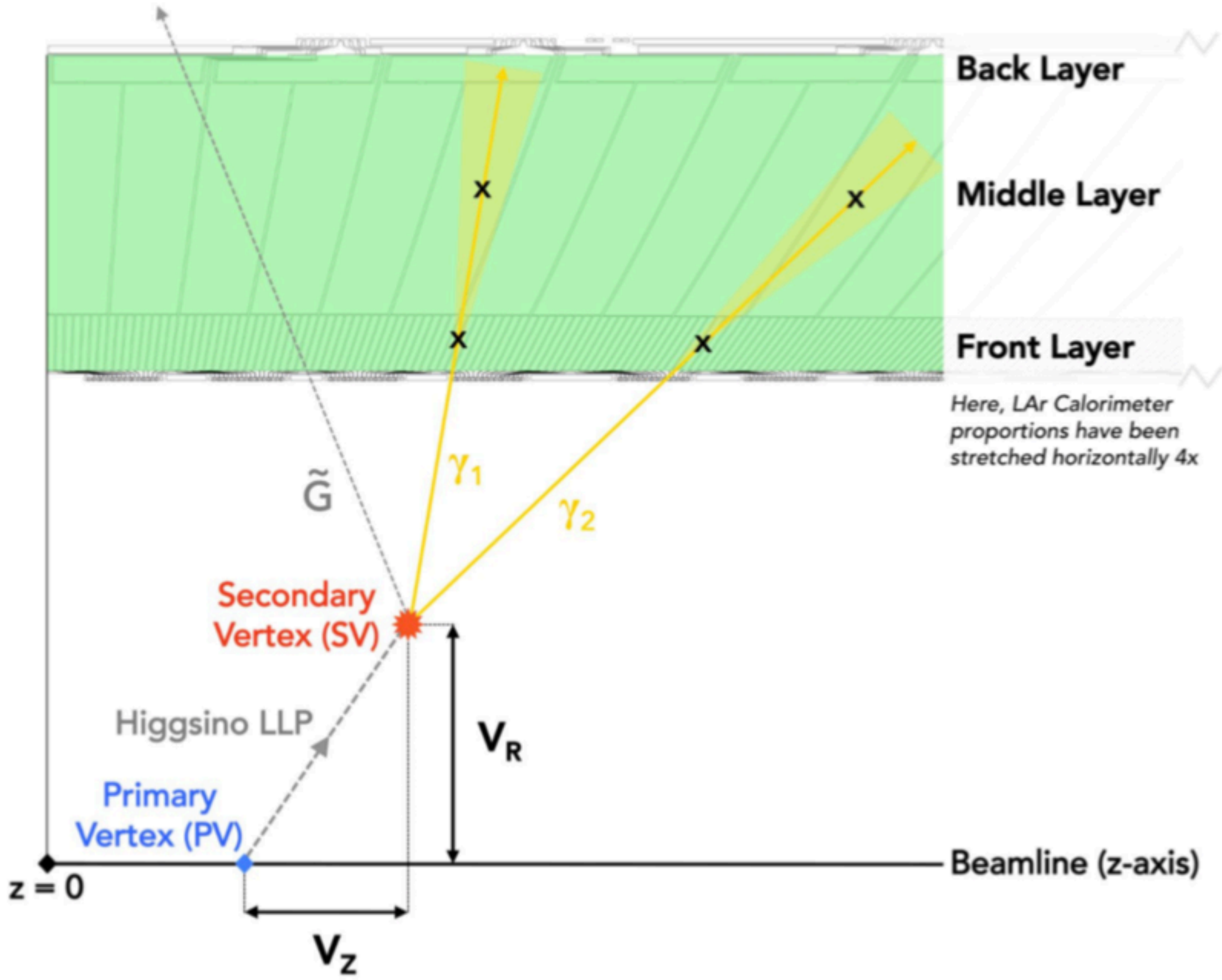
- Analysis optimised for **high-mass** LLP mediator that decays before **ECAL** with a MET signature
- New search plans to target **low-mass** LLP mediator that decays within **ECAL** or **HCAL**

Probing displaced photons

Target key discriminants for long-lived photons: anomalous shower shape, delayed timing and secondary vertices.

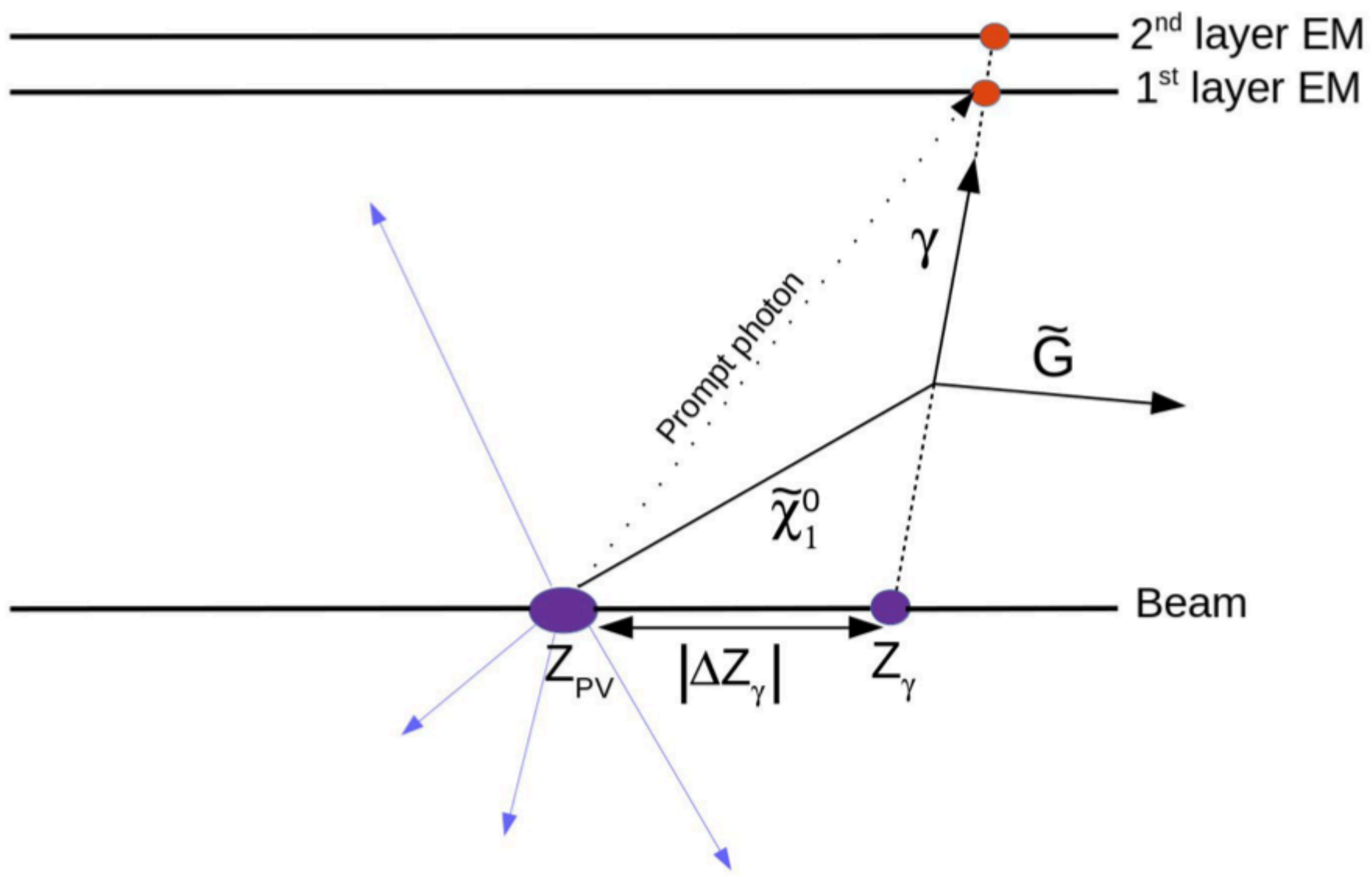
Calo images and graph to reconstruct decays within calorimeter from shower shapes





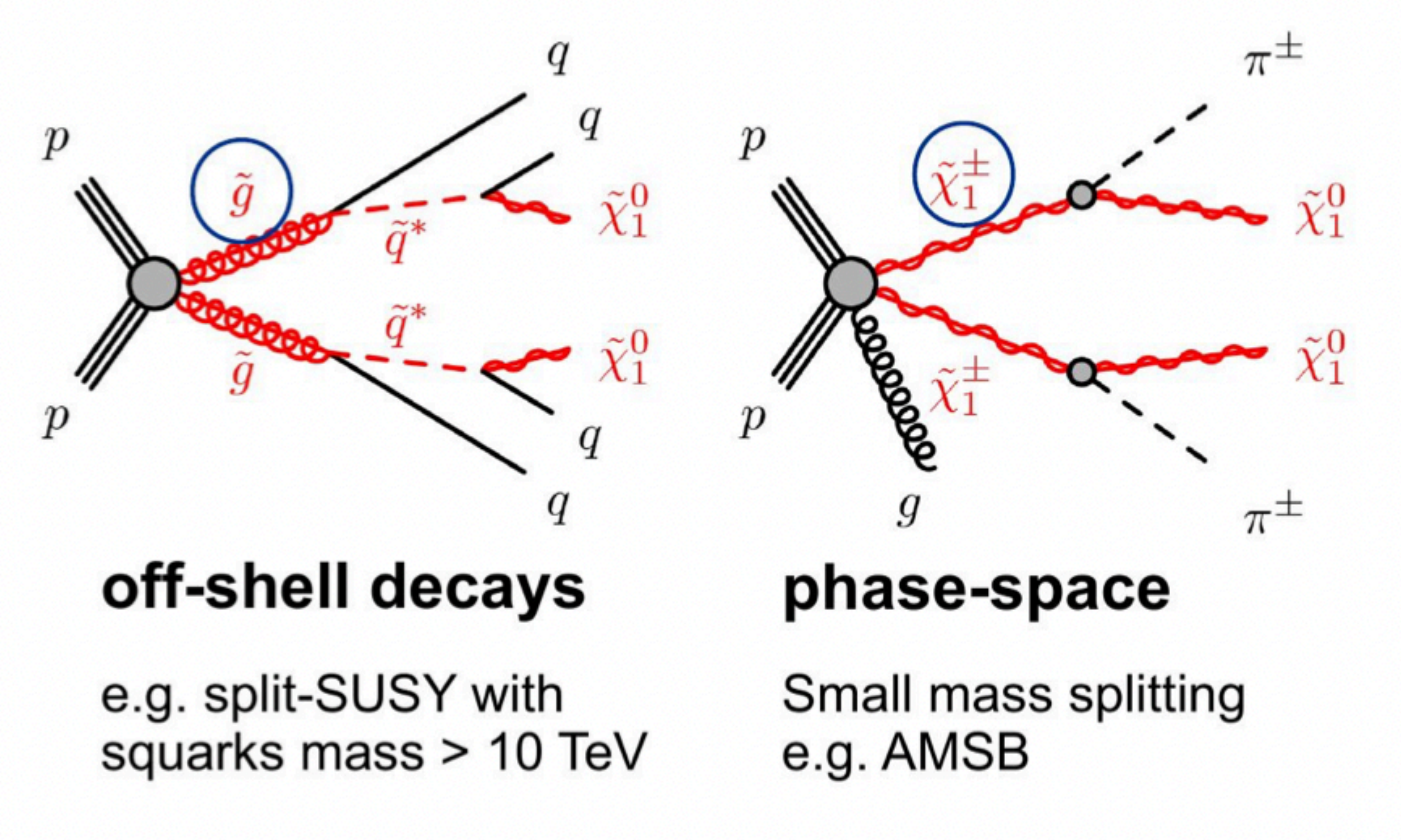
Calo vertexing to reconstruct secondary vertex within the ID

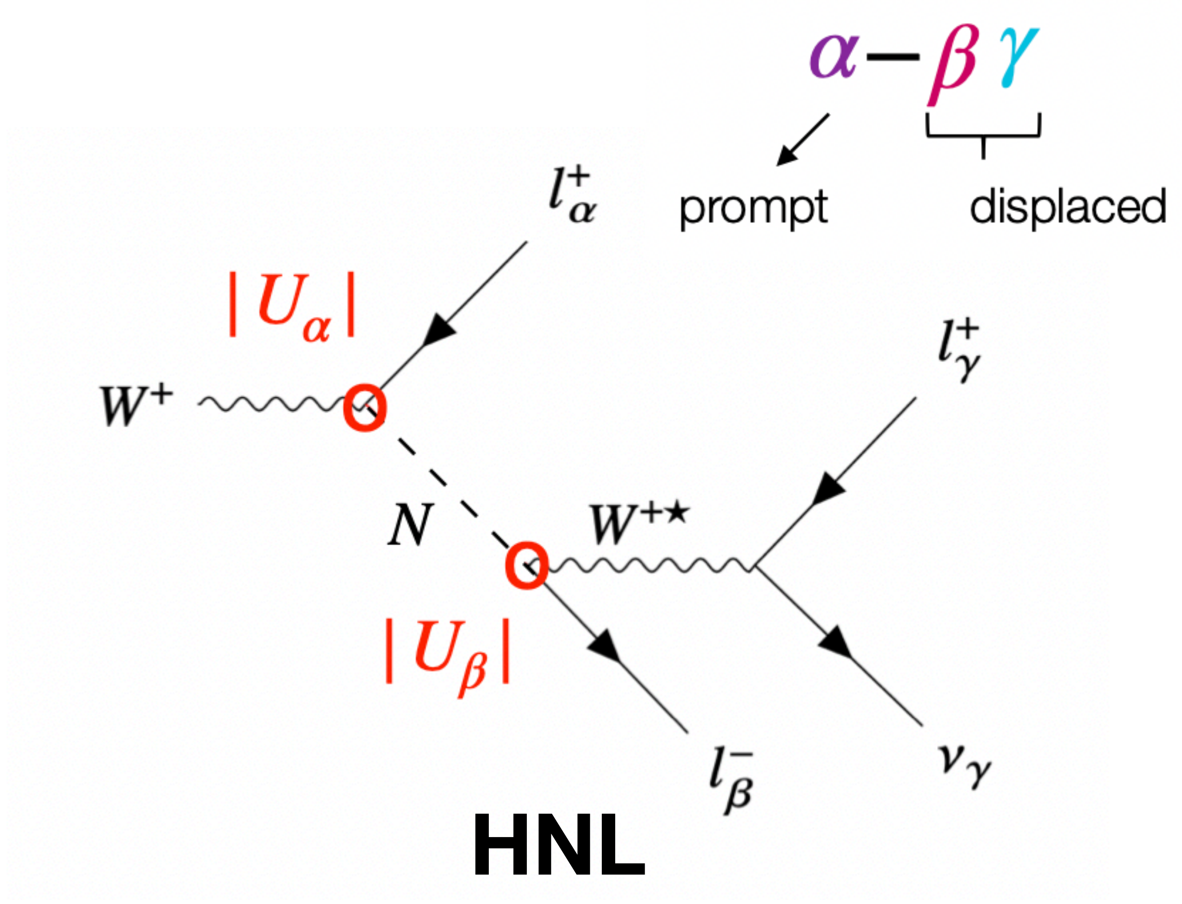
Photon timing to target non-pointing photons



Also more complete models

Long-lived particles are present in many BSM theories like SUSY and heavy neutrinos





Long-lived sterile neutrino

Specific theories can suggest new signatures to explore. LLPs are well-motivated in many BSM models (due to weak couplings or small mass splitting).
Results are presented for representative benchmark scenarios, giving the possibility to reinterpret in a different model.

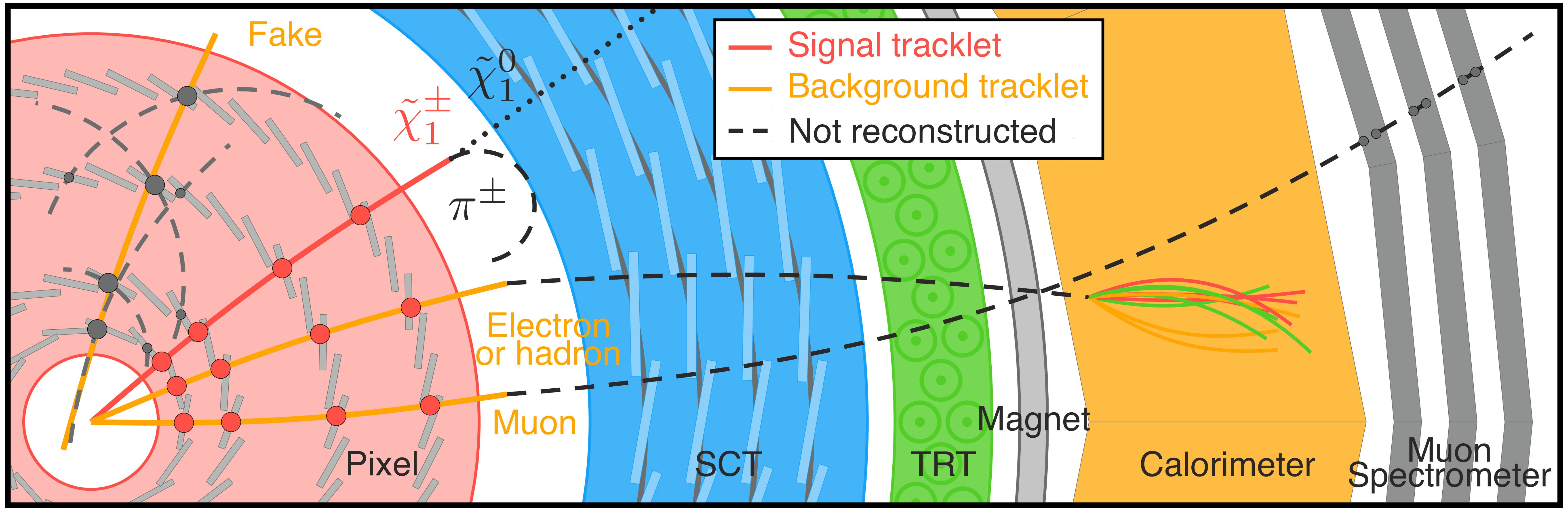
Unconventional SUSY models

Disappearing tracks: Search for long-lived particle decaying within the inner tracker

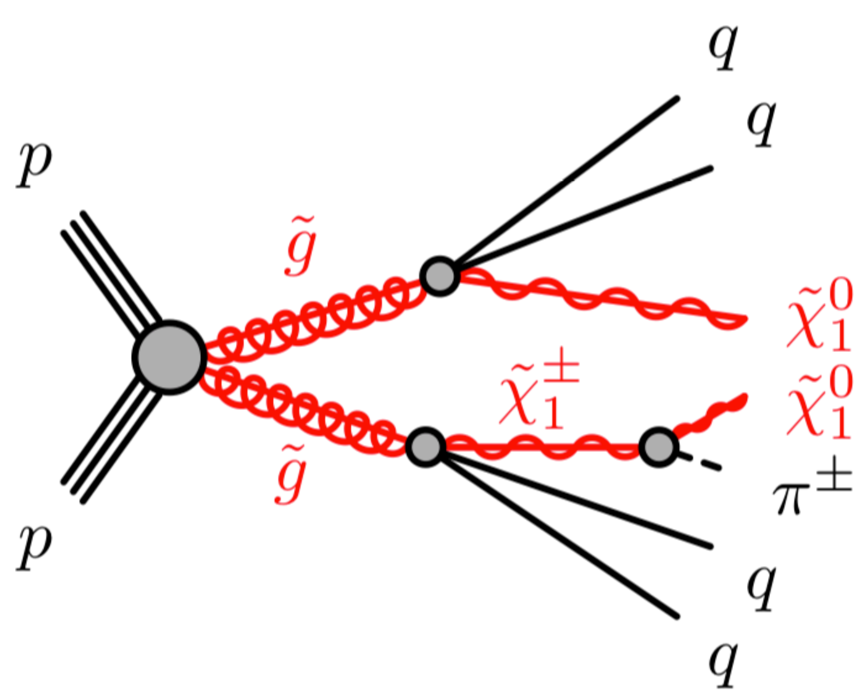
- MET trigger to select events with jets and ‘disappearing tracks’ (due to suppressed interaction or low-pT)

- ‘Disappearing track’: 4-hit pixel tracks with no hits in the silicon traker (SCT) and < 5 GeV of energy deposits in calo dR < 0.2

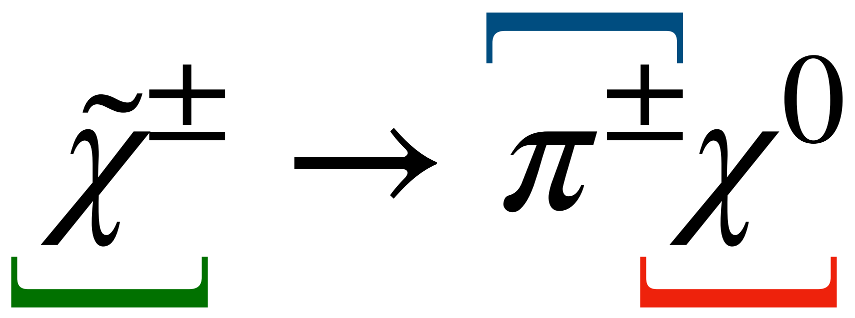
- Rare SM backgrounds from charged lepton scattering and combinatorial fakes

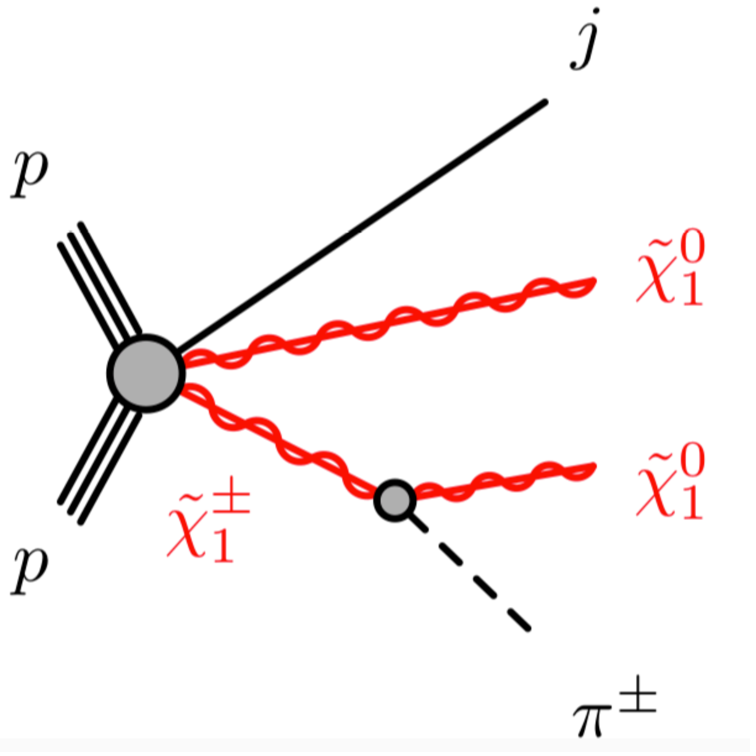


Targets very compressed SUSY scenarios (…and various DM models)



Electroweak (EWK) production



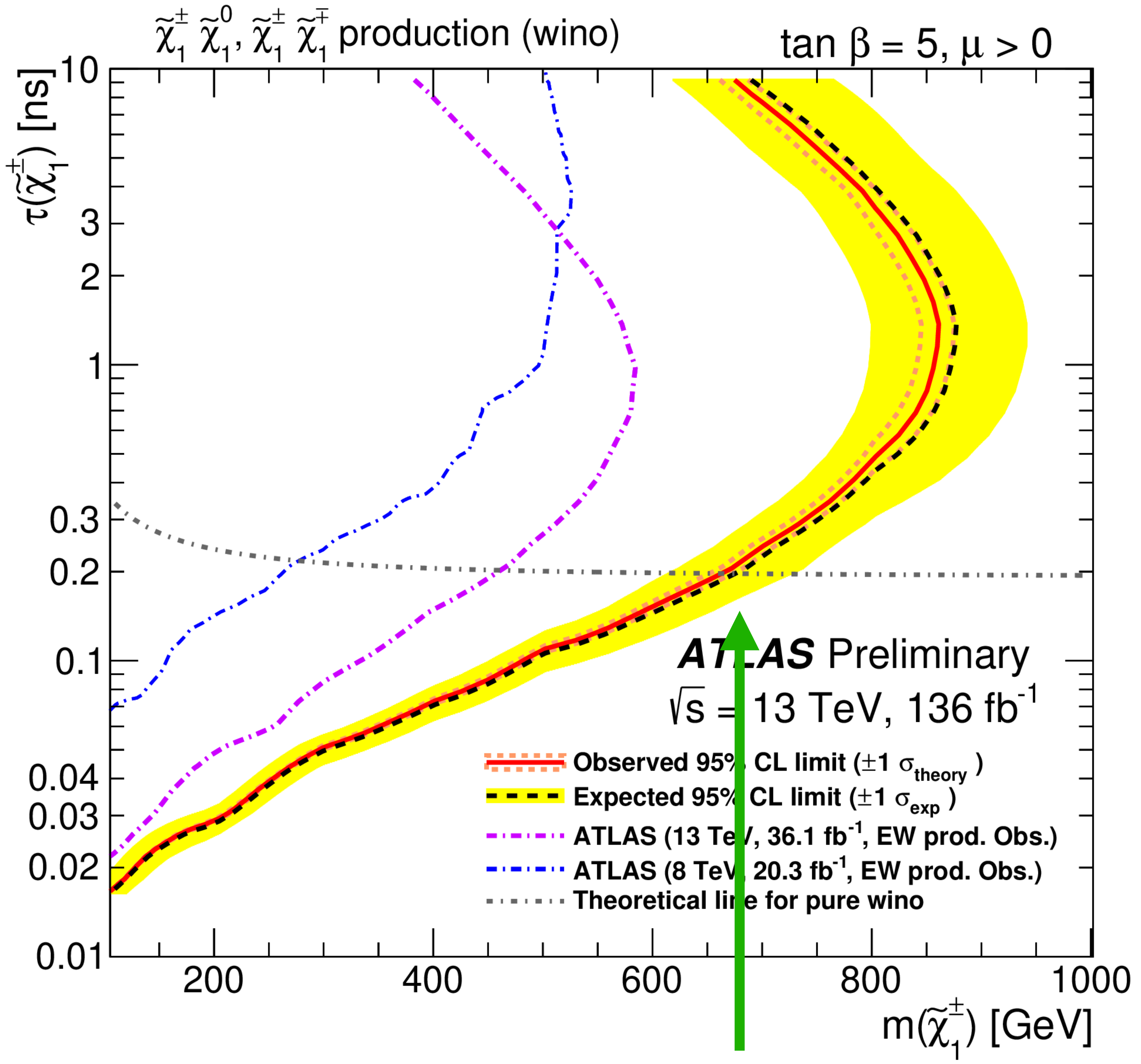


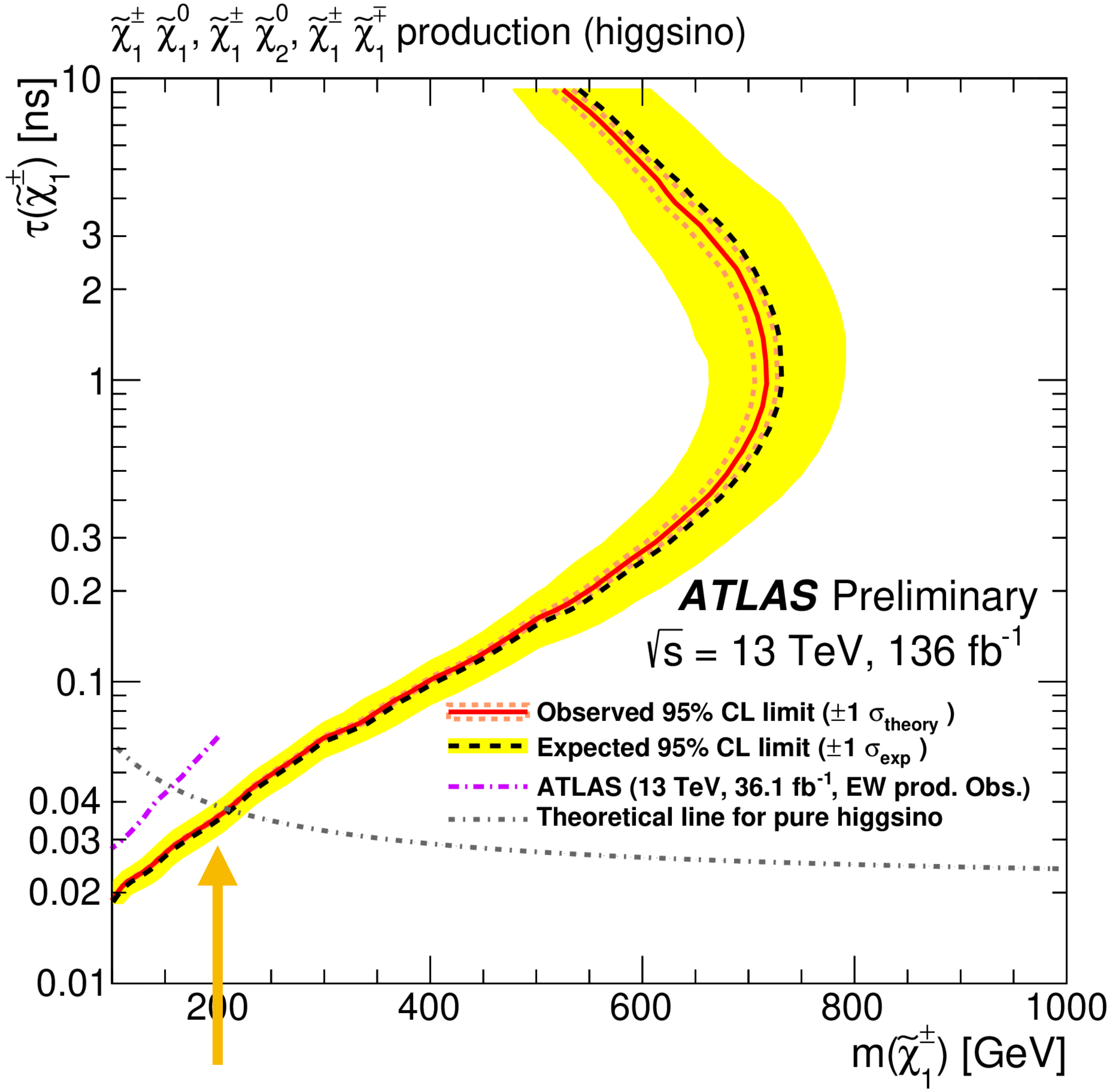
Strong production

[Eur. Phys. J. C 82 (2022) 606]

Disappearing tracks

Exclusion limits at 95% CL for the EWK channel fo the AMSB model, neutralino mass vs lifetime





Exclusion for 660 GeV wino, best limit for wino-like neutralino (460 GeV in early Run2)

Exclusion for 210 GeV Higgsino, best limit for higgsino-like neutralino (155 GeV in early Run2)

Outlook

- Long-lived particle searches have been so far discontinuous in ATLAS: from the portal framework we can identify benchmark models for a systematic investigation of the hidden sectors

- A snapshot of the most recent results from ATLAS have been shown, but many more analyses in progress using the full Run-2 dataset

- Run3 with a larger dataset and new exciting improvements will enhance the discovery potential for Long-lived signatures

- Many unexplored synergies and overlaps across searches that could be exploited
  - Harmonise common models where possible or promote multiple interpretations
  - Encourage combinations and summary plots to spot uncovered regions