Search for long-lived particles at ATLAS & CMS

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on behalf of the ATLAS and CMS Collaborations

IPA2022 — Interplay between Particle and Astroparticle physics

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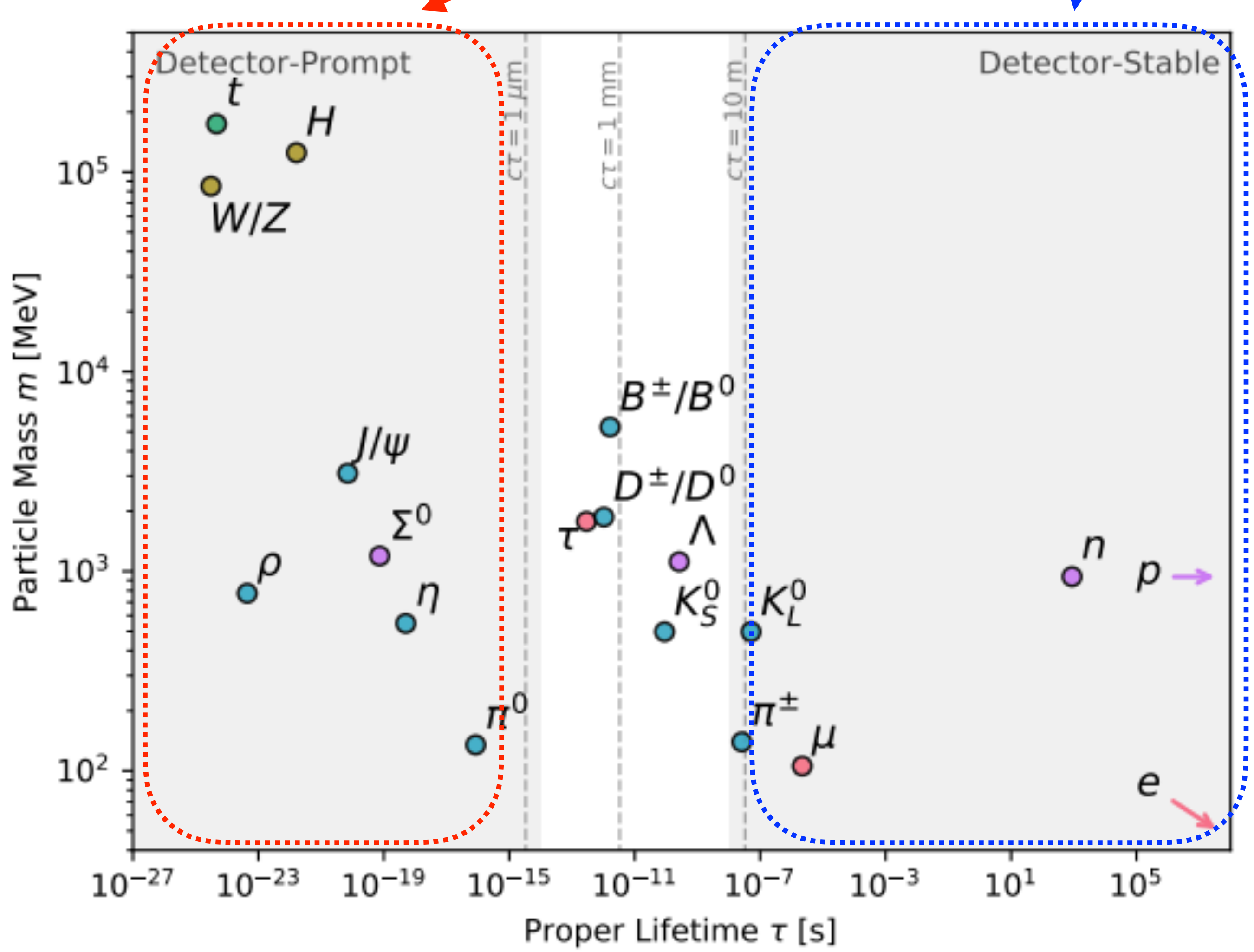
Why long-lived particles?

- In the first years of the LHC, new physics searches focused mostly on particles
  - **quasi-stable**, decaying outside the detector → $c\tau \gtrsim 10$ m
  - **promptly** decaying near the interaction point (IP) → $c\tau \lesssim 1$ μm

  ⇒ ***optimal performance:*** *use of all sub-detectors, best efficiency and resolution, IP constraints*



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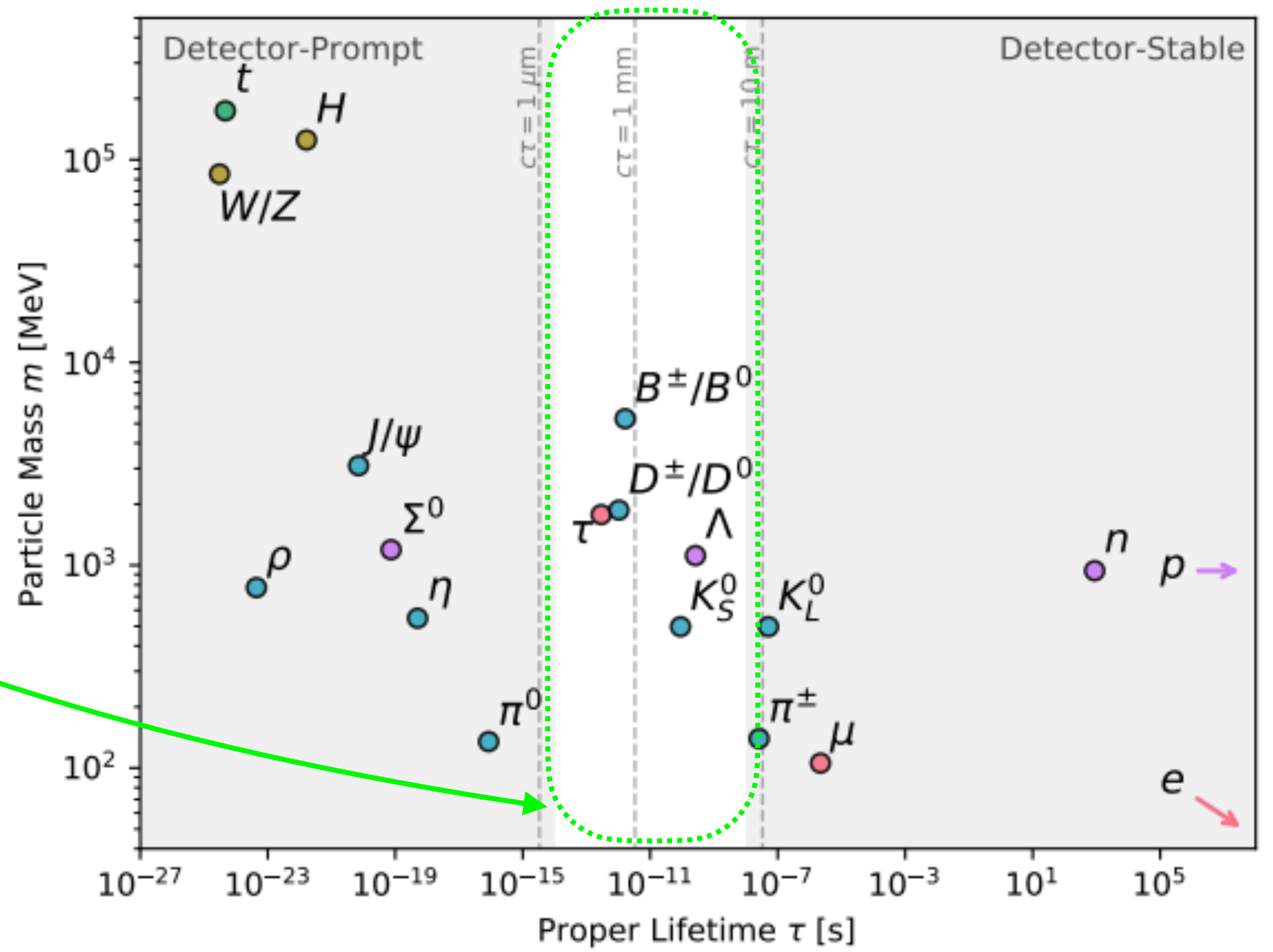
- However, numerous theories predict particles with $c\tau \sim \mathcal{O}(\mathrm{mm–m})$ that can decay halfway through the detector

  ⟹ **long-lived particles** (LLPs)



Benchmark models

- Models with quasi-degenerate mass states, small couplings, or highly virtual mediators can lead to LLPs, e.g.:
  - **SUSY:** RPV models, split SUSY, GMSB, AMSB, etc.
  - **Hidden sectors:** scalar portal, dark photon, ALPs, heavy neutrinos, etc.
  - Magnetic monopoles

- Typical benchmark models used to interpret LHC results
  - **SM-like or BSM Higgs:** $H \to XX \to 4f$ with scalar or vector X
  - **SUSY:** electroweakino/gluino/slepton/squark pair production
  - **Heavy neutral leptons** (HNL) with (semi-)leptonic decays

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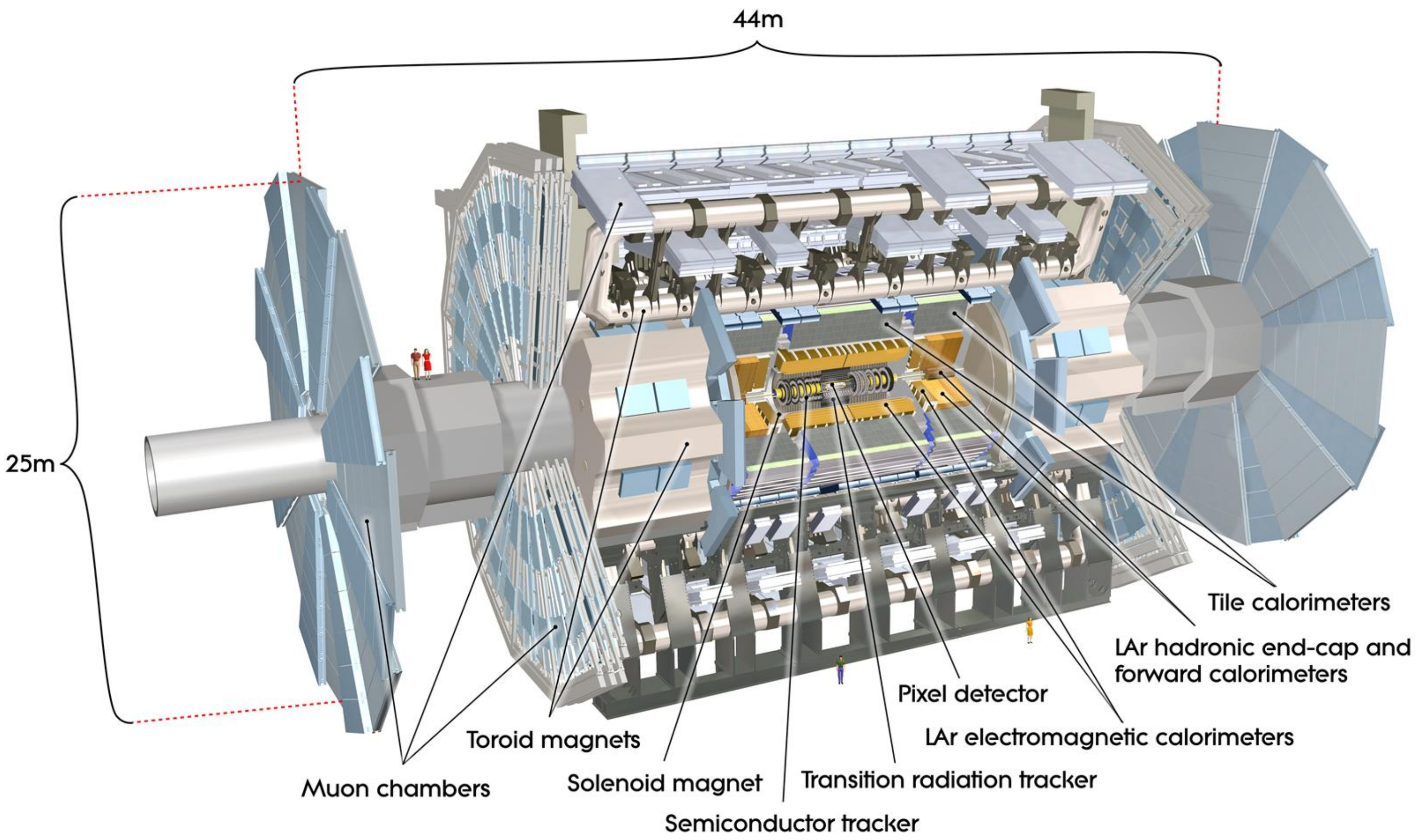
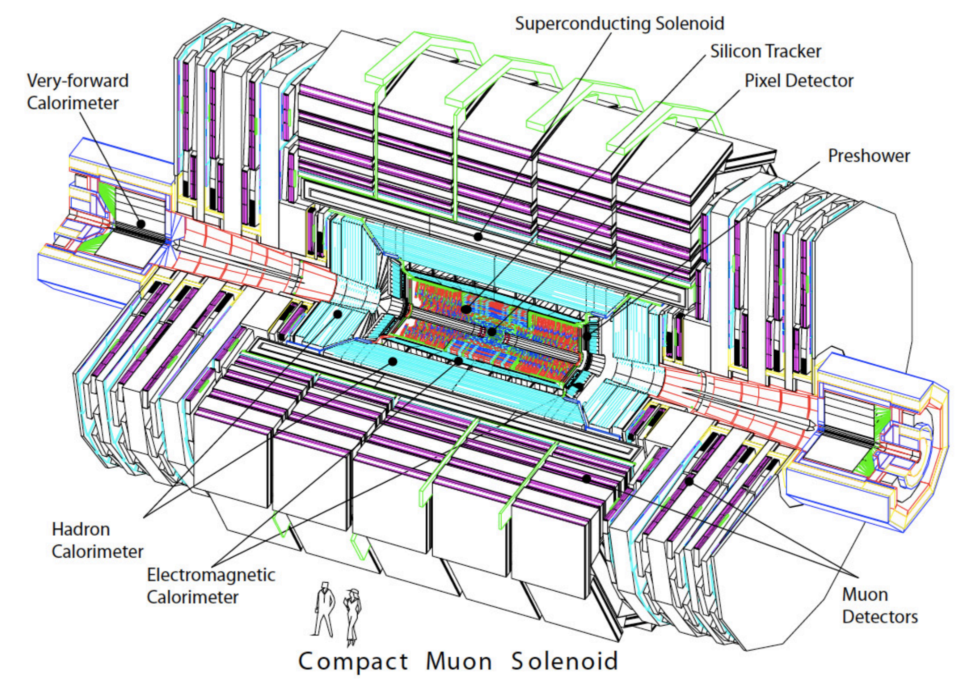
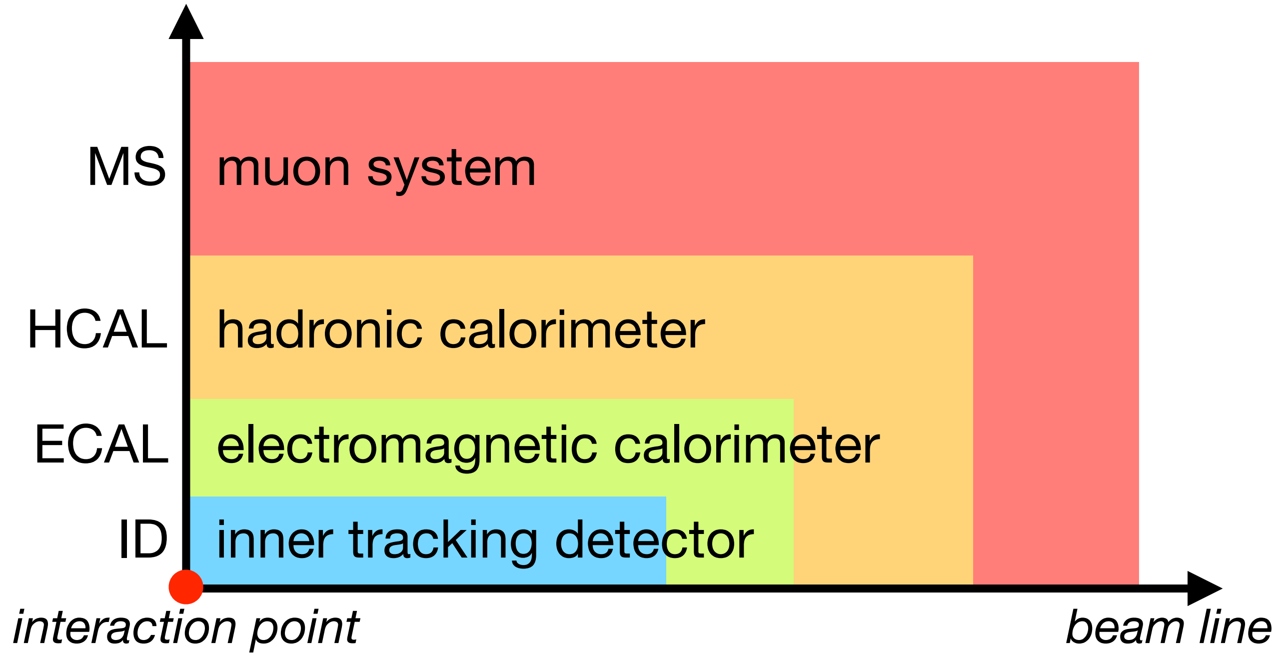
*Searches will be presented following a **signature-driven** (rather than **model-driven**) criterion*

The ATLAS & CMS detectors

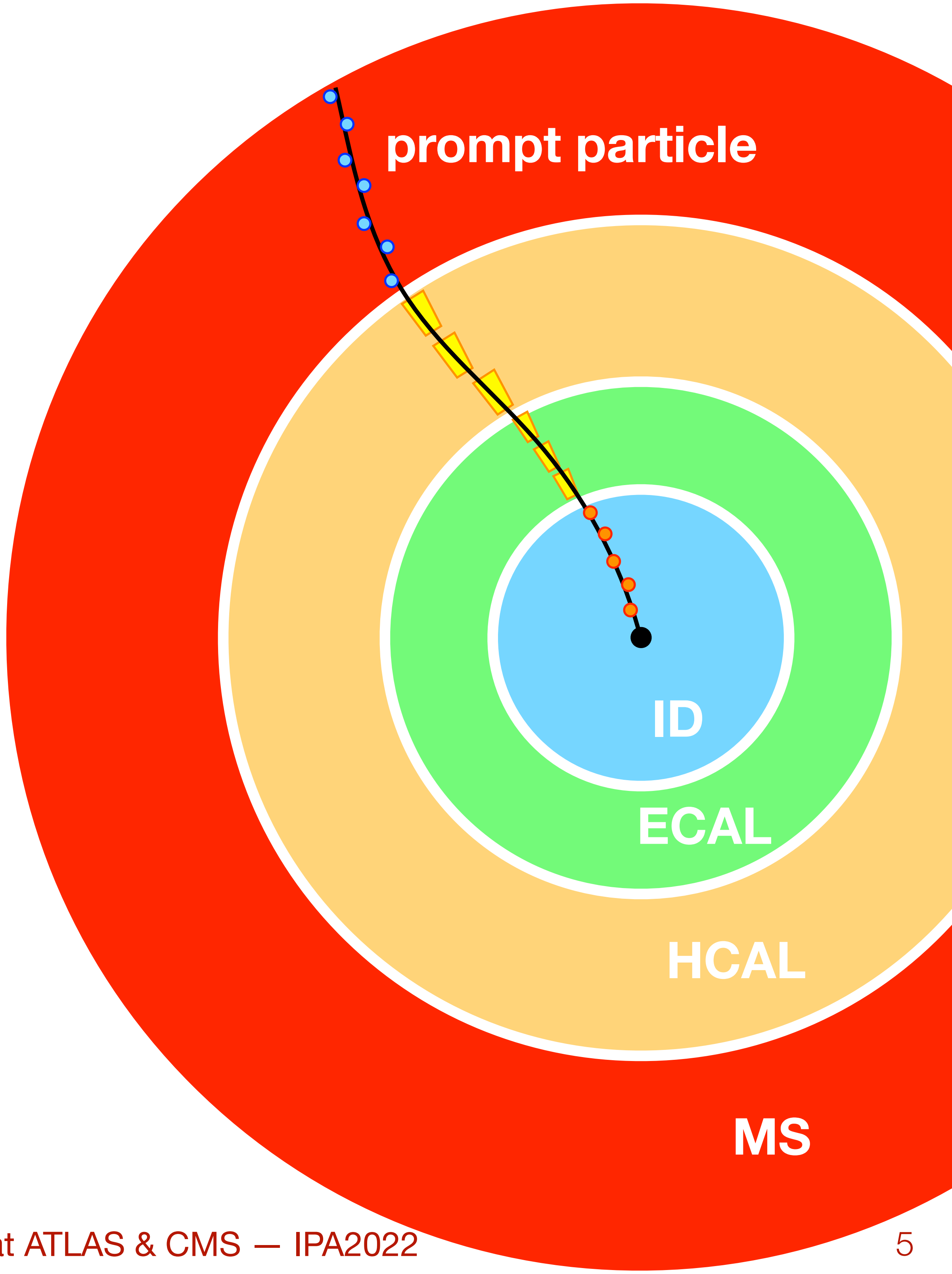






LLP signatures

- LLPs produce characteristic and "unusual" signals in ATLAS & CMS



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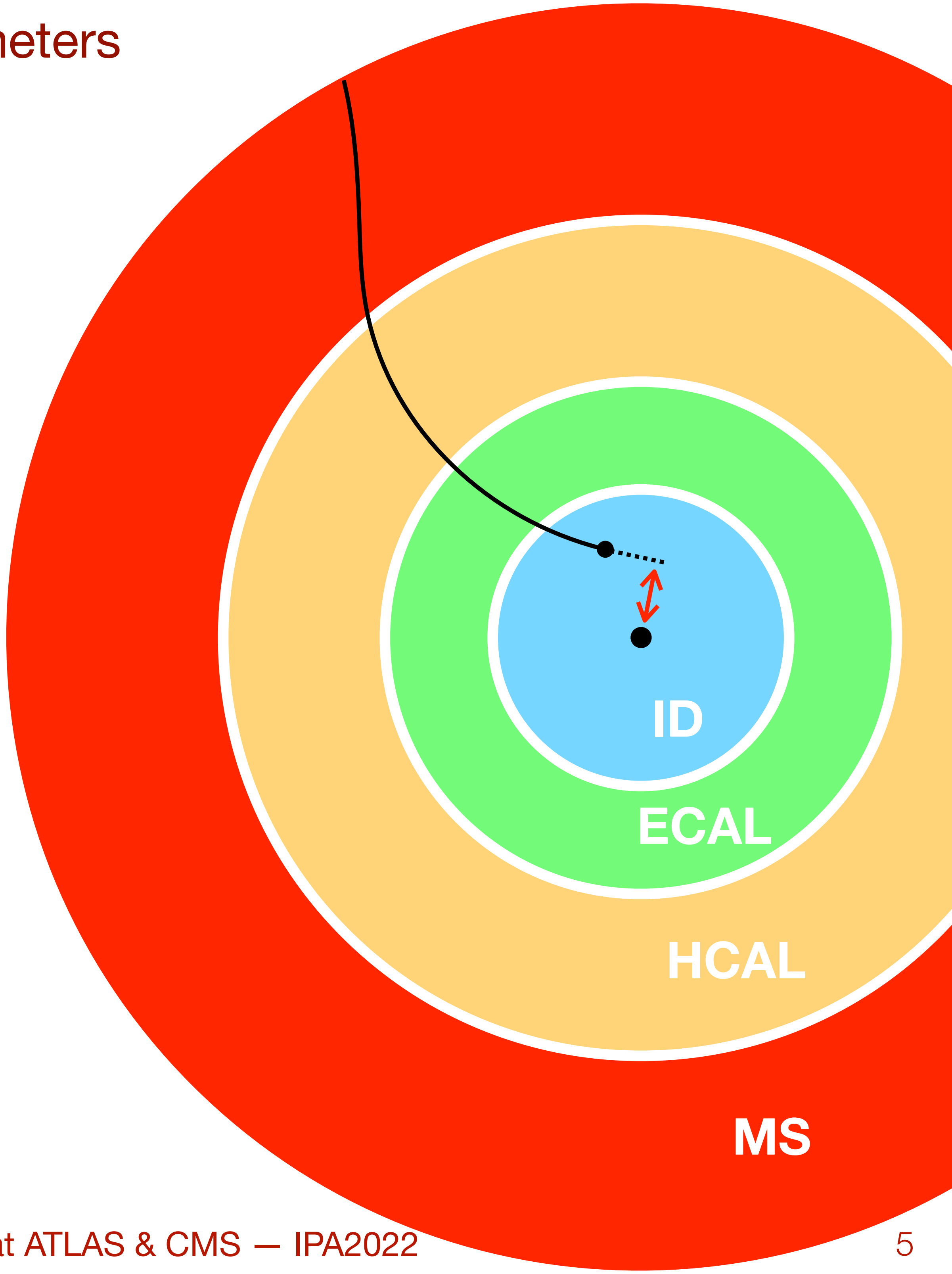

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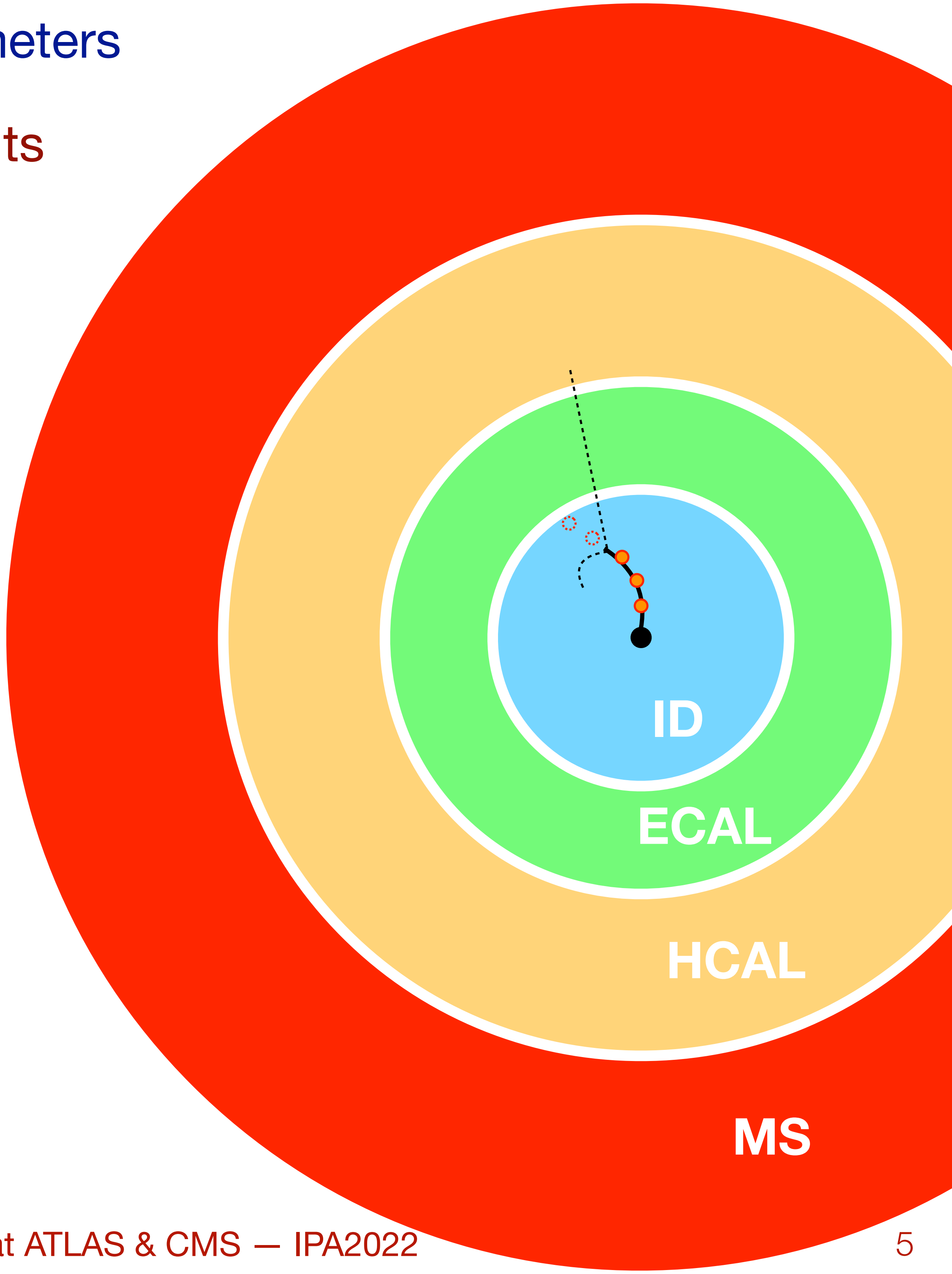

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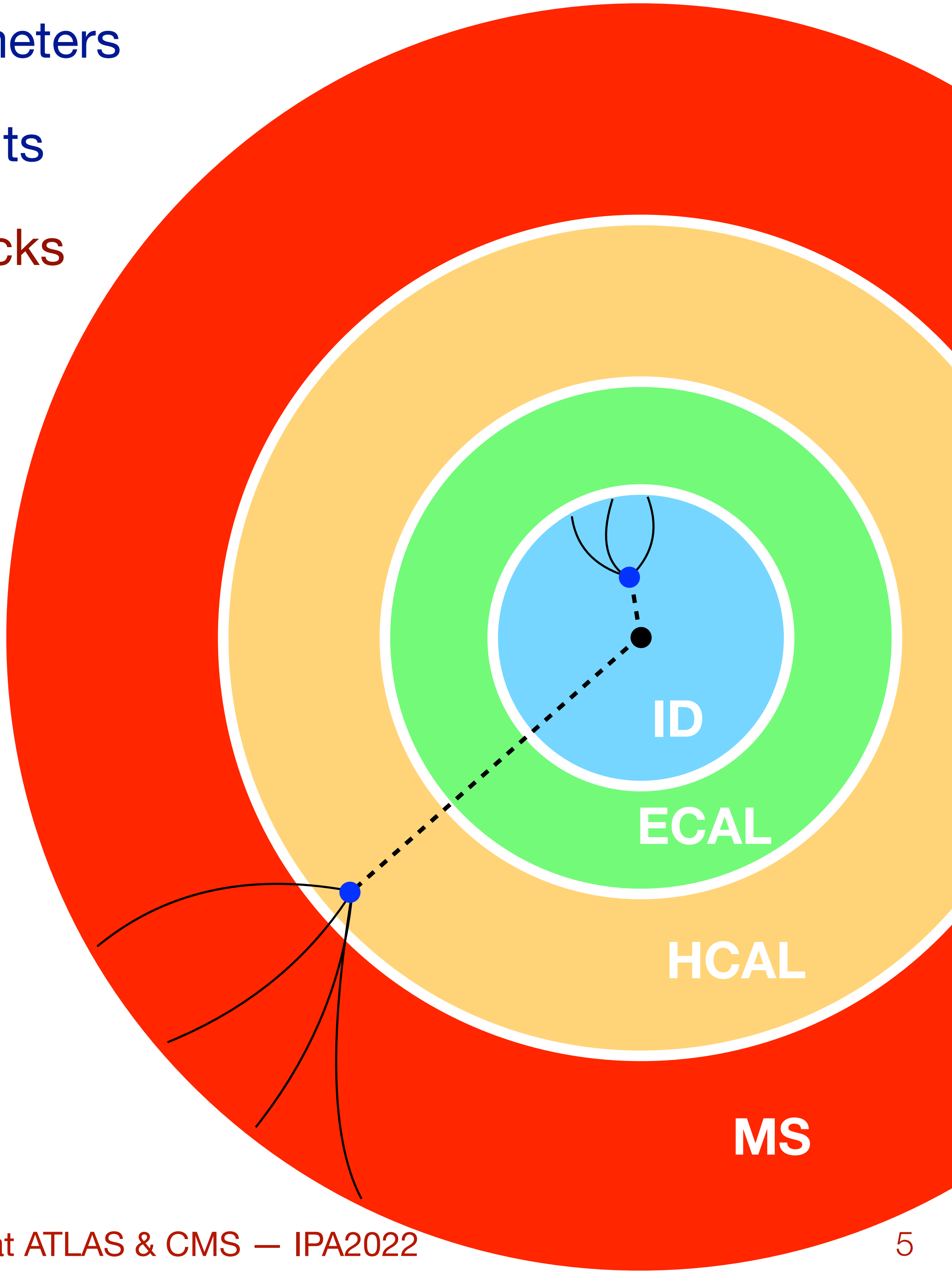

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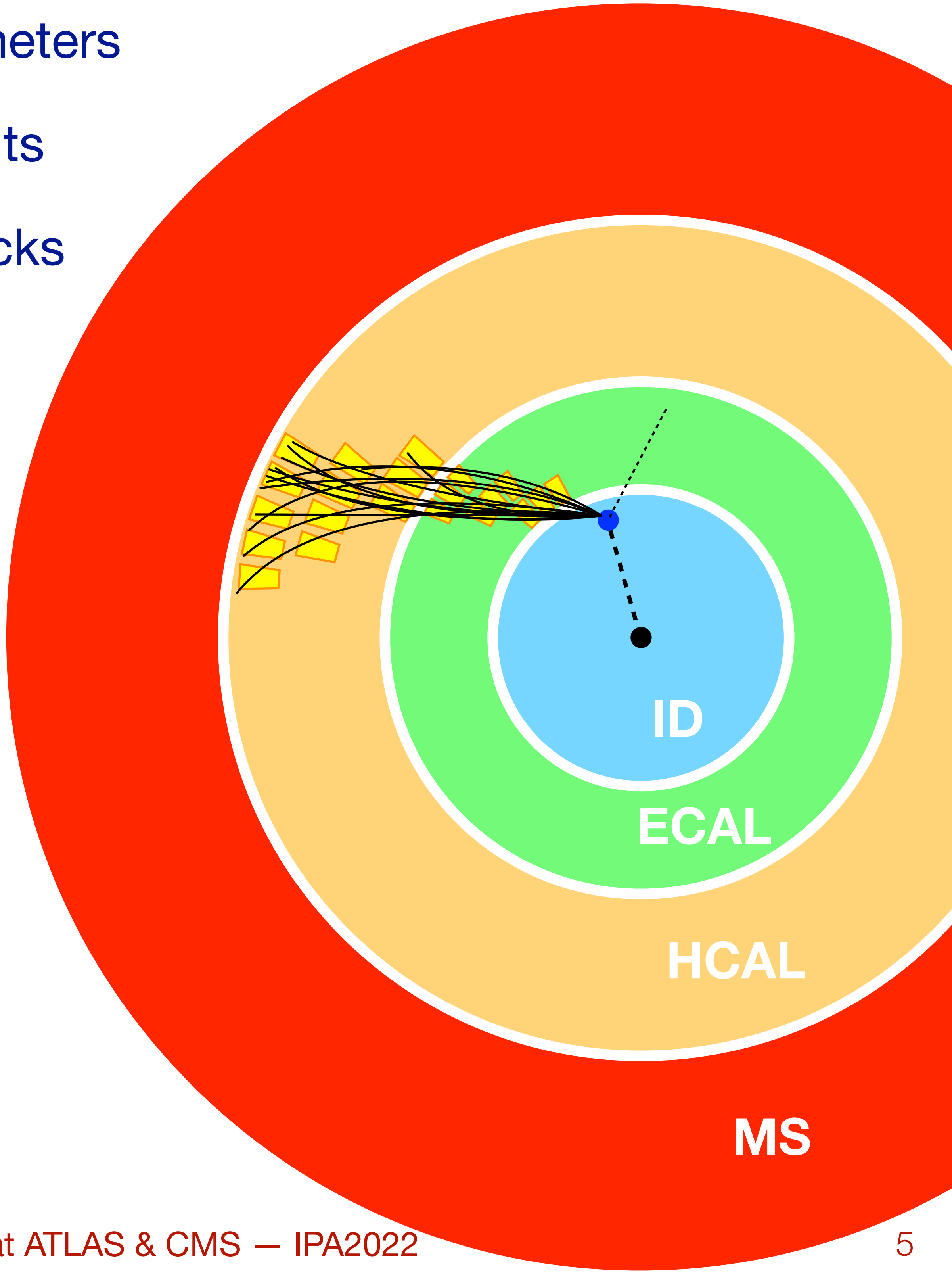
    - not pointing to the IP
    - delayed w.r.t. p-p collision



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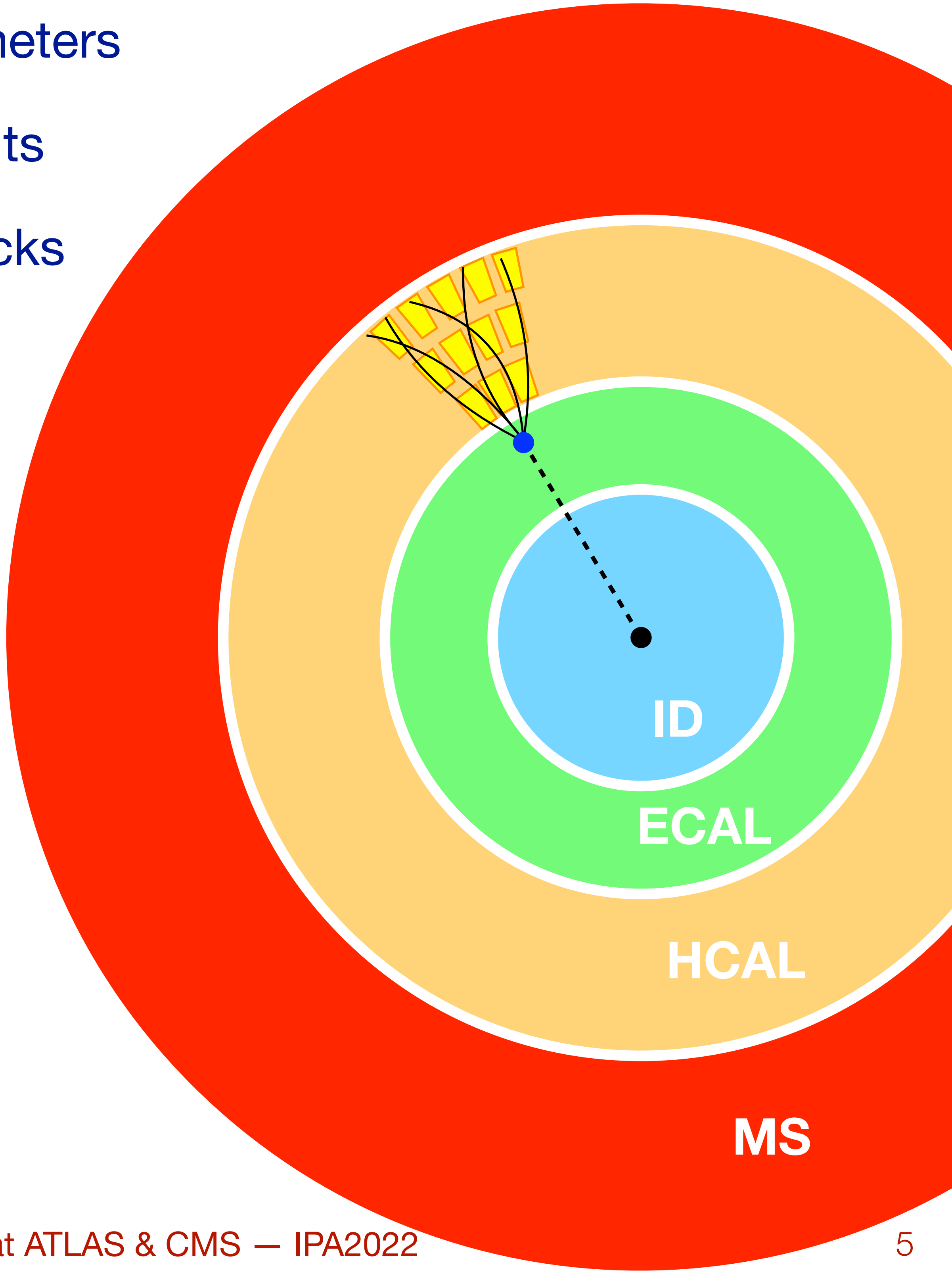

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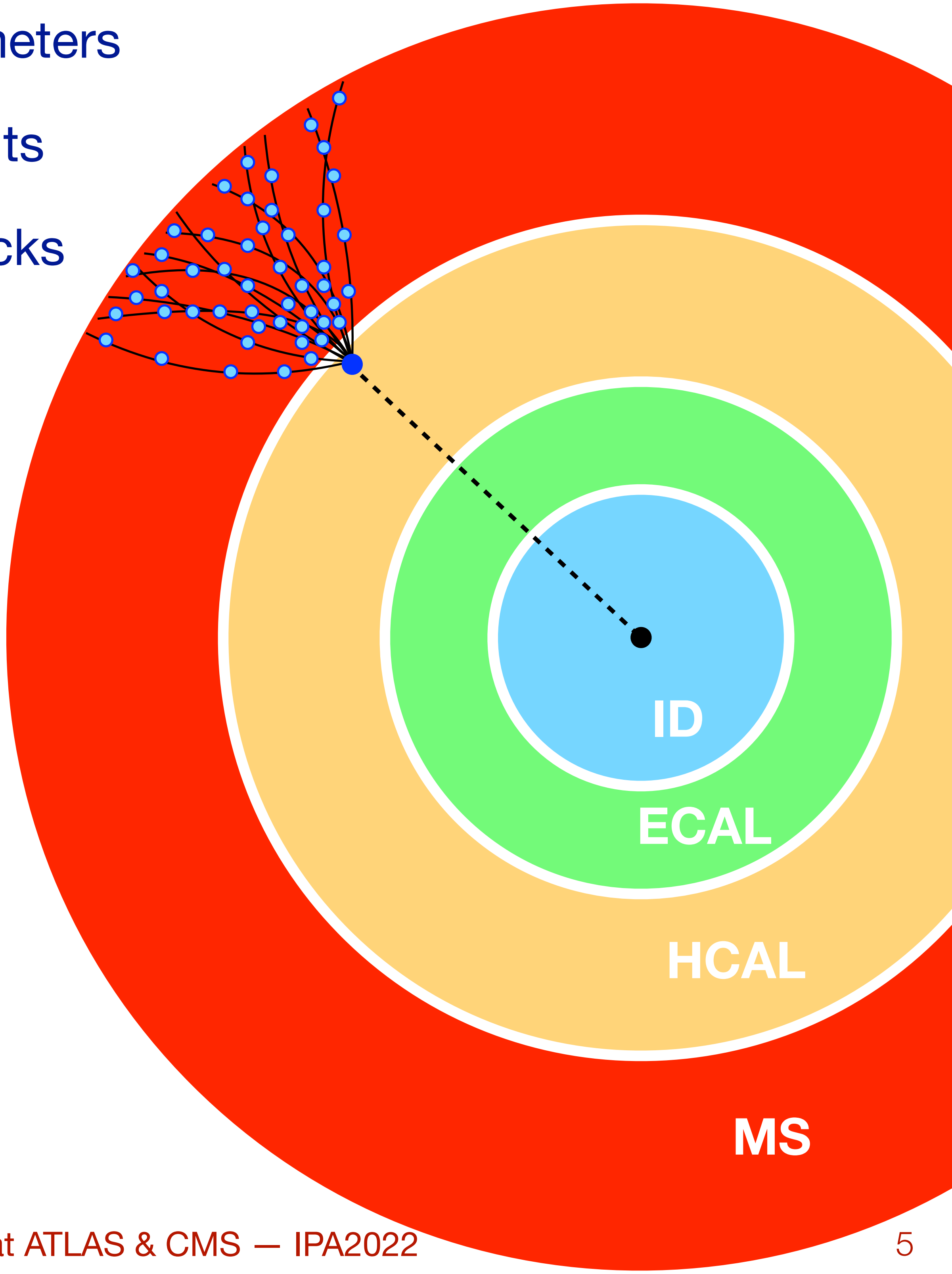

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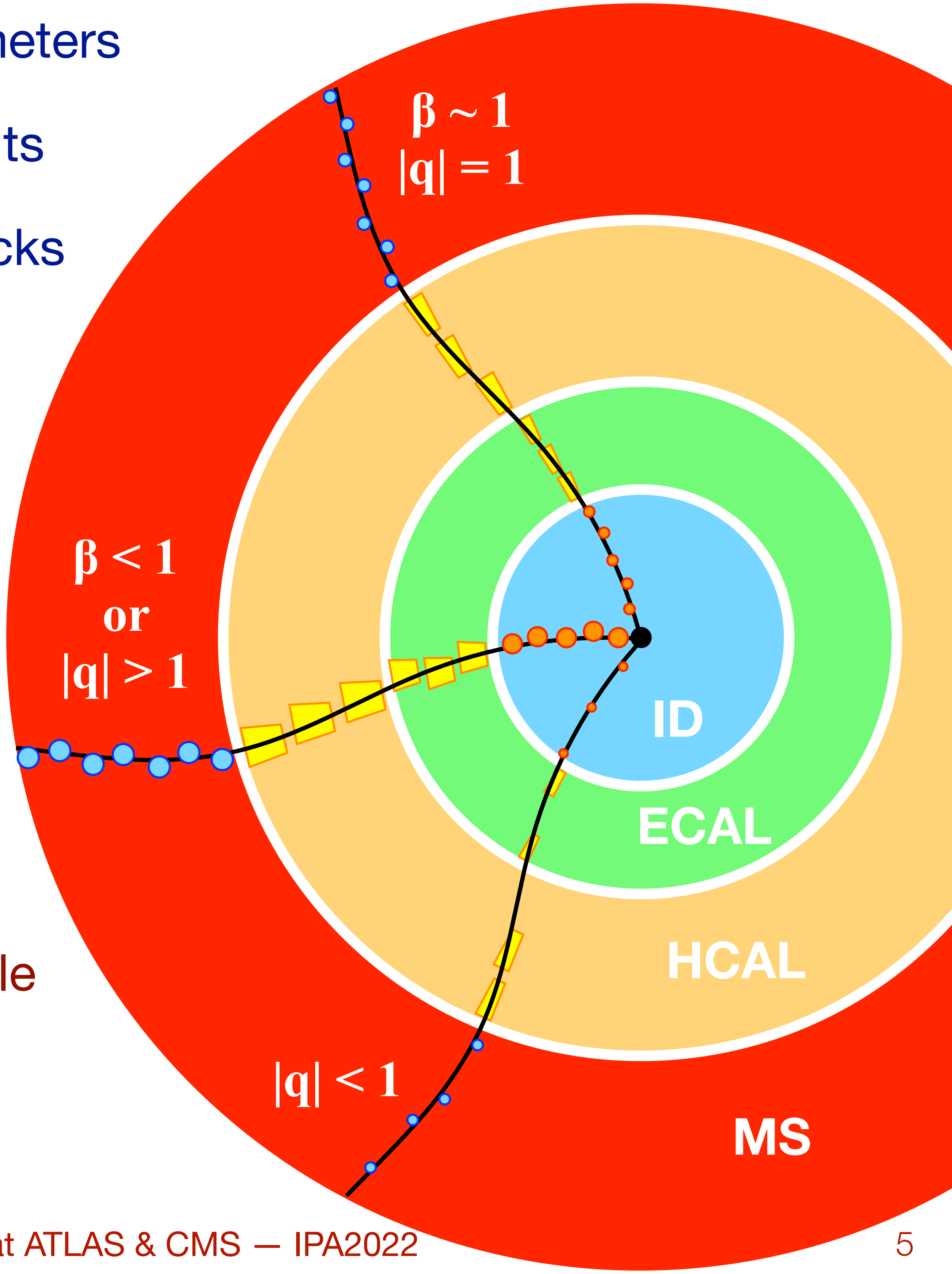
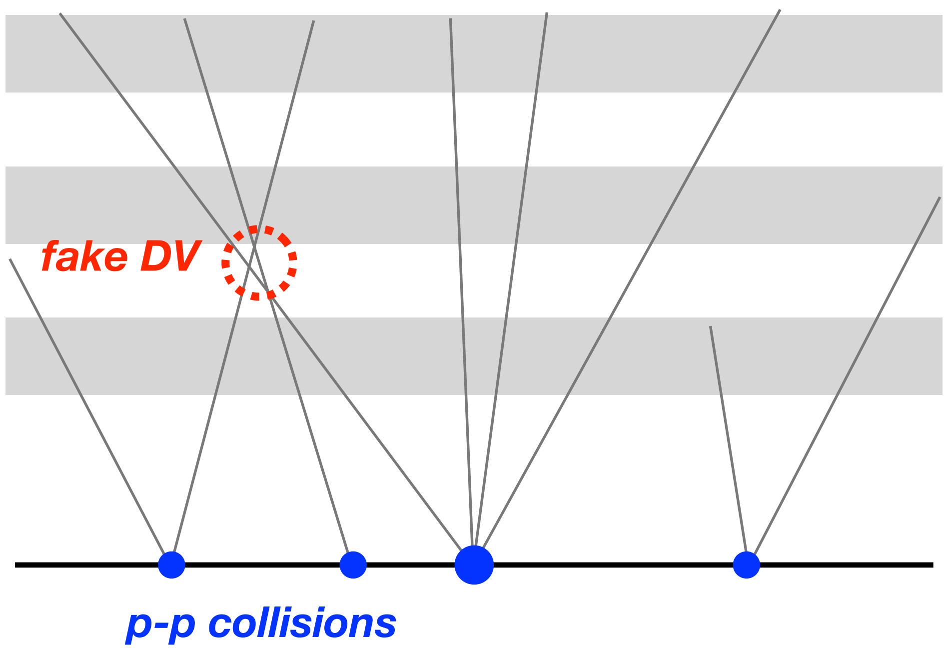
    - low ECAL/HCAL energy ratio
  - high-multiplicity shower in MS
  - unusual ionization levels
    - multiply/fractionally charged particle
    - slow, heavy particle



Typical backgrounds in LLP searches

- Common background sources emerge in many LLP searches
  - Random track crossings
    - Main background for many searches
    - Reduced by requirements on vertex quality and other vertex-related quantities
  - Interactions in the detector material
    - Veto vertices in the detector layers
  - Cosmic rays
    - Generate displaced tracks or anomalous energy deposits
    - Veto back-to-back muons and use detector timing
  - Beam-induced backgrounds (BIB)
    - Anomalous early deposits in the calorimeter barrel
    - Use shape and time of deposits to veto



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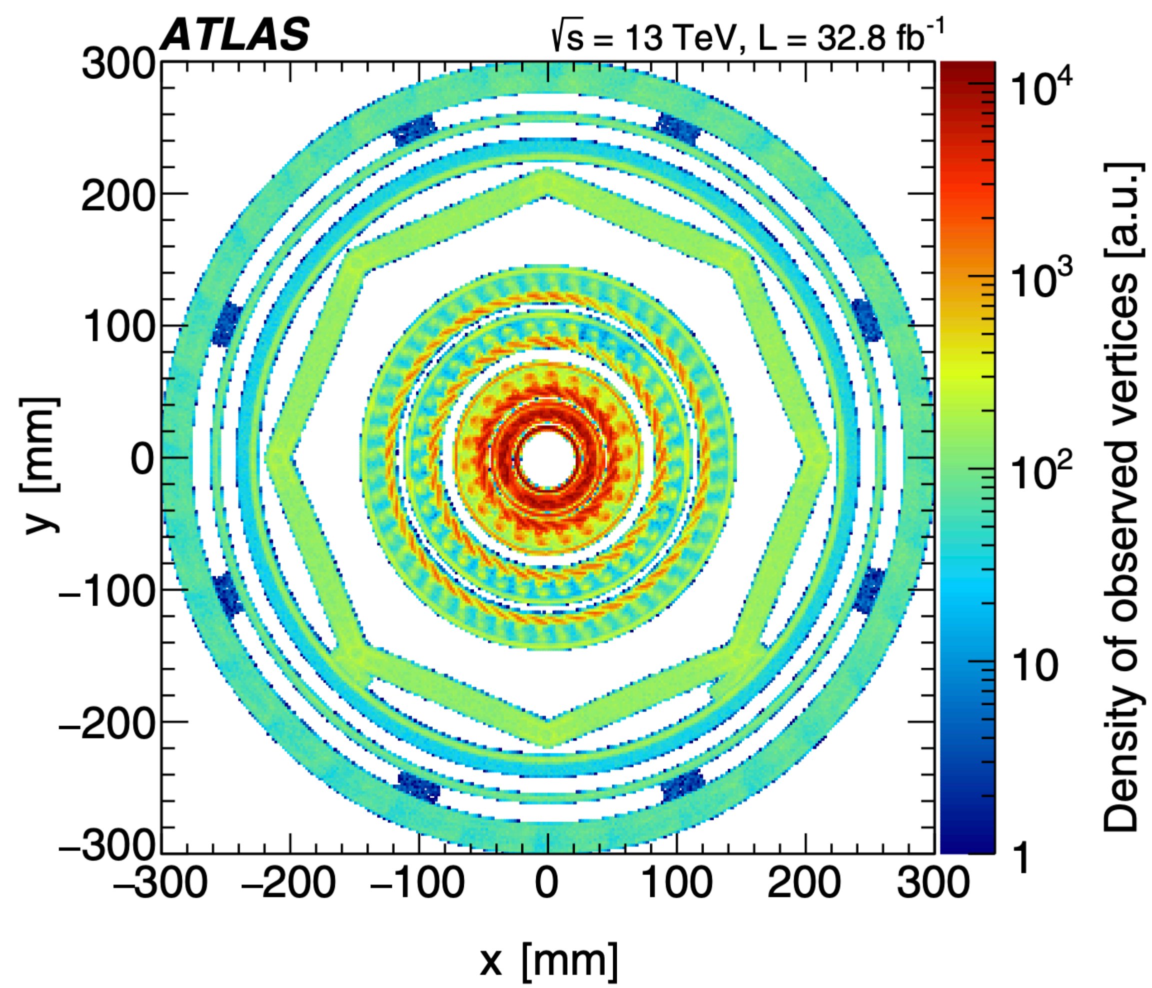

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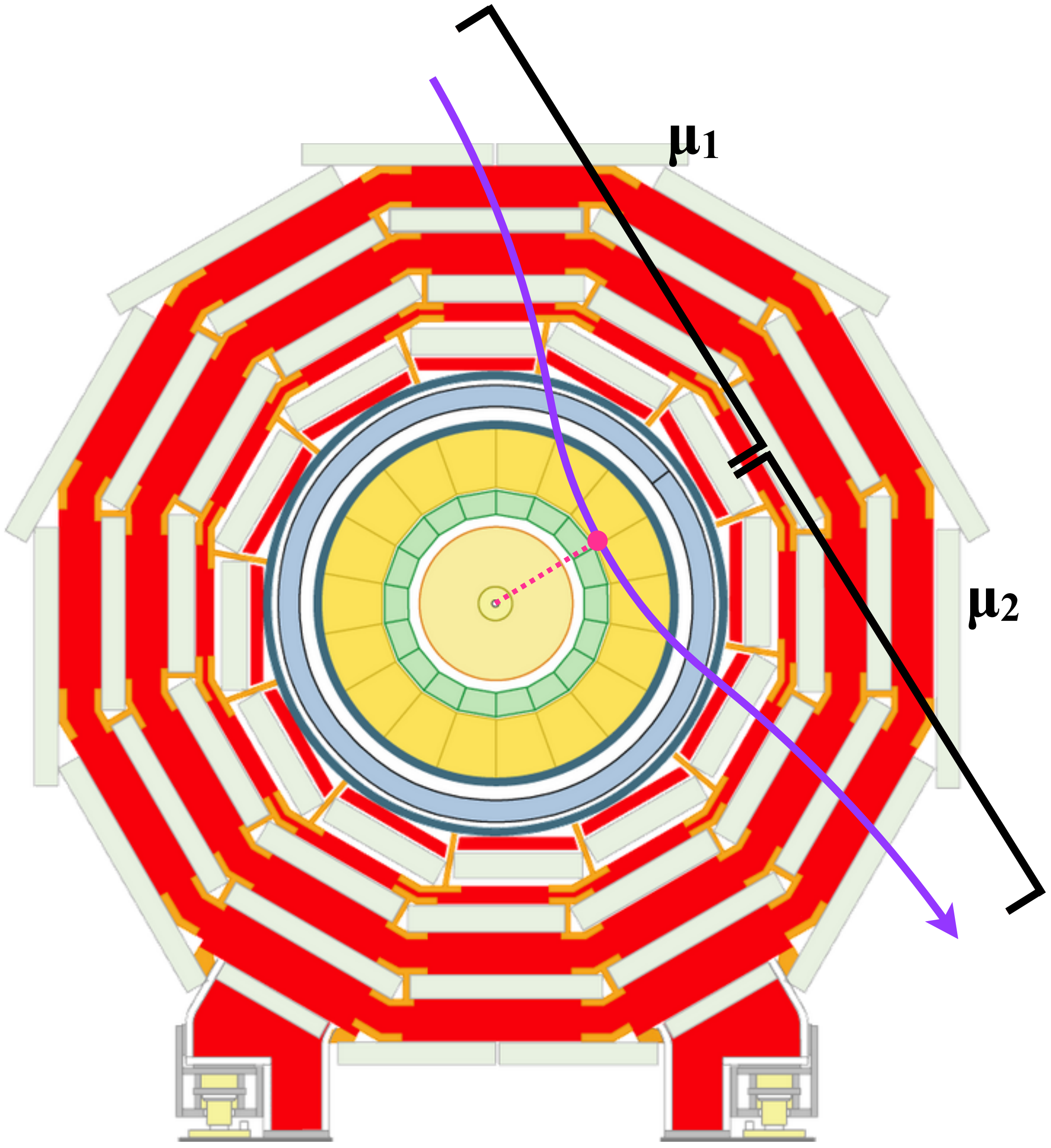

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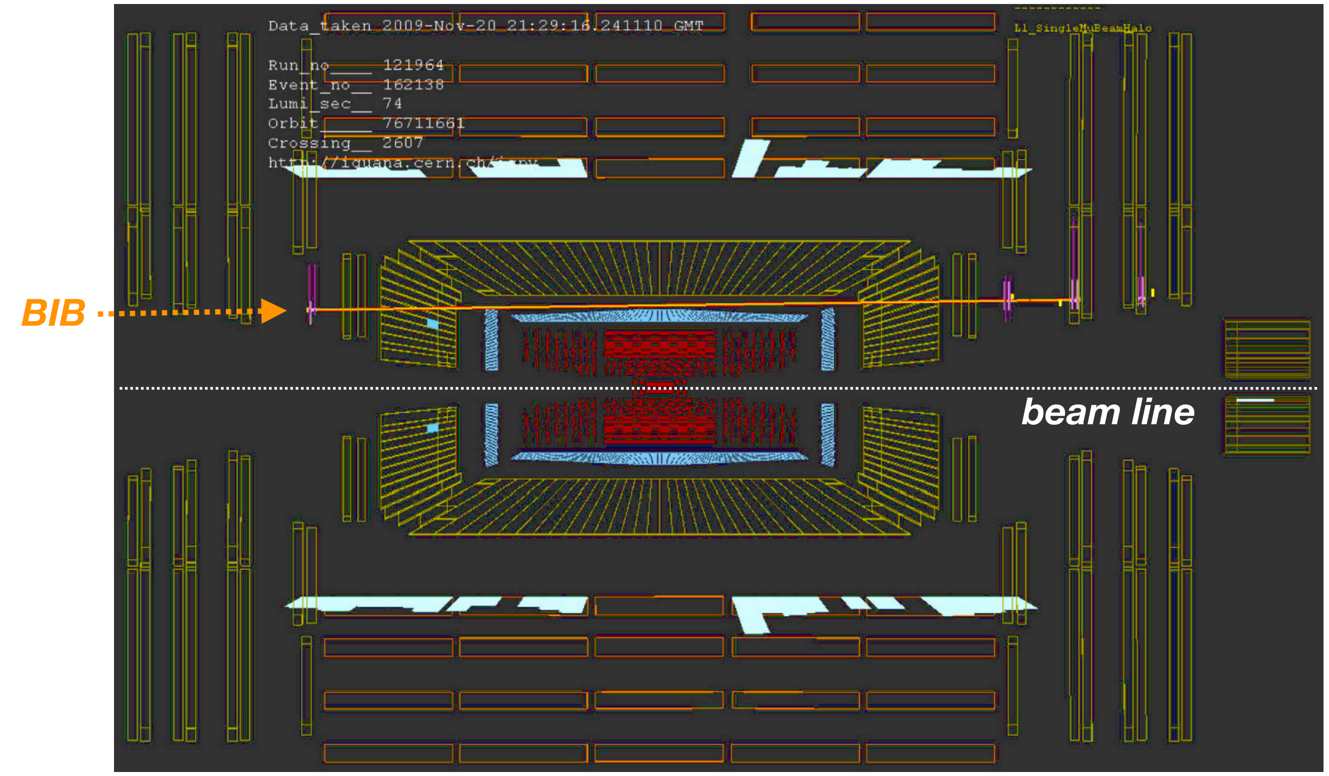


Latest LLP searches (by final states)

	Final state		ATLAS	CMS
Hadrons	Displaced jets and vertices	in beam pipe		Phys. Rev. D 104, 052011 (2021)
		in ID	ATLAS-CONF-2022-054	Phys. Rev. D 104, 012015 (2021)
		in ECAL or HCAL	JHEP 06 (2022) 005	Phys. Lett. B 797 (2019) 134876
		in ID and MS	Phys. Rev. D 101, 052013 (2020)	
		in MS	arXiv:2203.00587 [hep-ex]	Phys. Rev. Lett. 127, 261804 (2021)
		plus Z	JHEP 11 (2021) 229	JHEP 03 (2022) 160
			Phys. Rev. Lett. 122, 151801 (2019)	
		plus muon	Phys. Rev. D 102 (2020) 032006	
	Emerging jets			JHEP 02 (2019) 179
	Displaced taus			arXiv:2207.02254 [hep-ex]
Photons	Displaced/delayed photons		ATLAS-CONF-2022-017	Phys. Rev. D 100, 112003 (2019)
			ATLAS-CONF-2022-051	
Leptons	Displaced dileptons	within ID, no vertex	Phys. Rev. Lett. 127 (2021) 051802	Eur. Phys. J. C (2022) 82:153
		within ID, vertex	Phys. Lett. B 801 (2020) 135114	
		within ID, high-rate		JHEP 04 (2022) 062
		within MS	arXiv:2206.12181 [hep-ex]	arXiv:2205.08582 [hep-ex]
	HNL with displaced leptons		arXiv:2204.11988 [hep-ex]	JHEP 07 (2022) 081
Direct detection	Stopped particles		JHEP 07 (2021) 173	JHEP 05 (2018) 127
	Highly ionizing particles	HSCP	Phys. Rev. D 99, 092007 (2019)	Phys. Rev. D 94, 112004 (2016)
		multi-charged	ATLAS-CONF-2022-034	
		in Pixels (low cτ)	arXiv:2205.06013 [hep-ex]	
		HEC & monopoles	Phys. Rev. Lett. 124, 031802 (2020)	
	Fractionally charged particles			EXO-19-006 (PAS not yet available)
	Disappearing tracks	charginos pairs	Eur. Phys. J. C 82 (2022) 606	Phys. Lett. B 806 (2020) 135502
		gluino to charginos		Eur. Phys. J. C 80 (2020) 3
	SIMPs			Eur. Phys. J. C (2022) 82:213

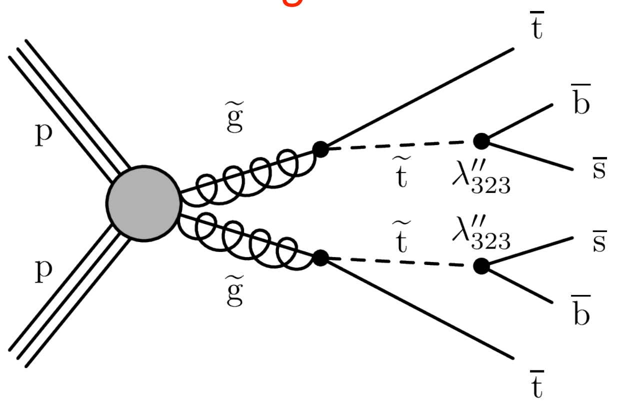
Searches with hadrons

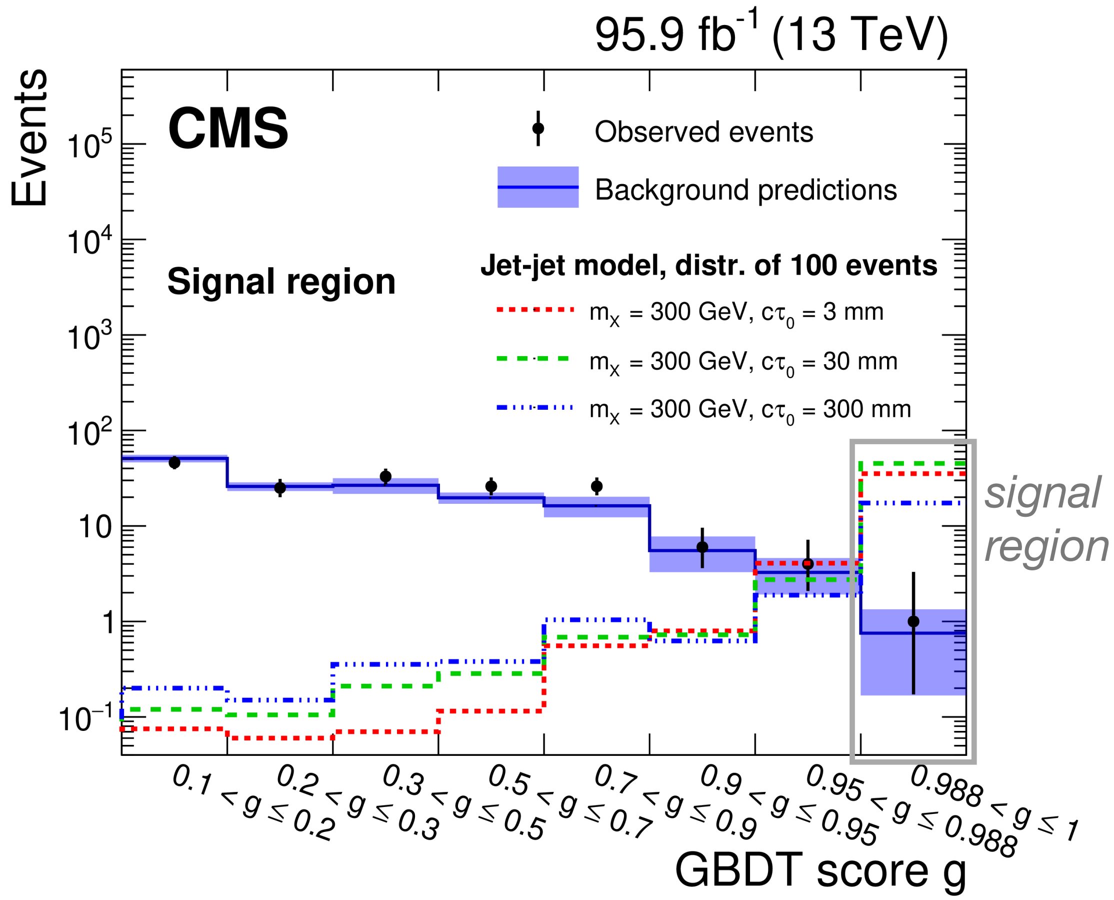
Displaced jets

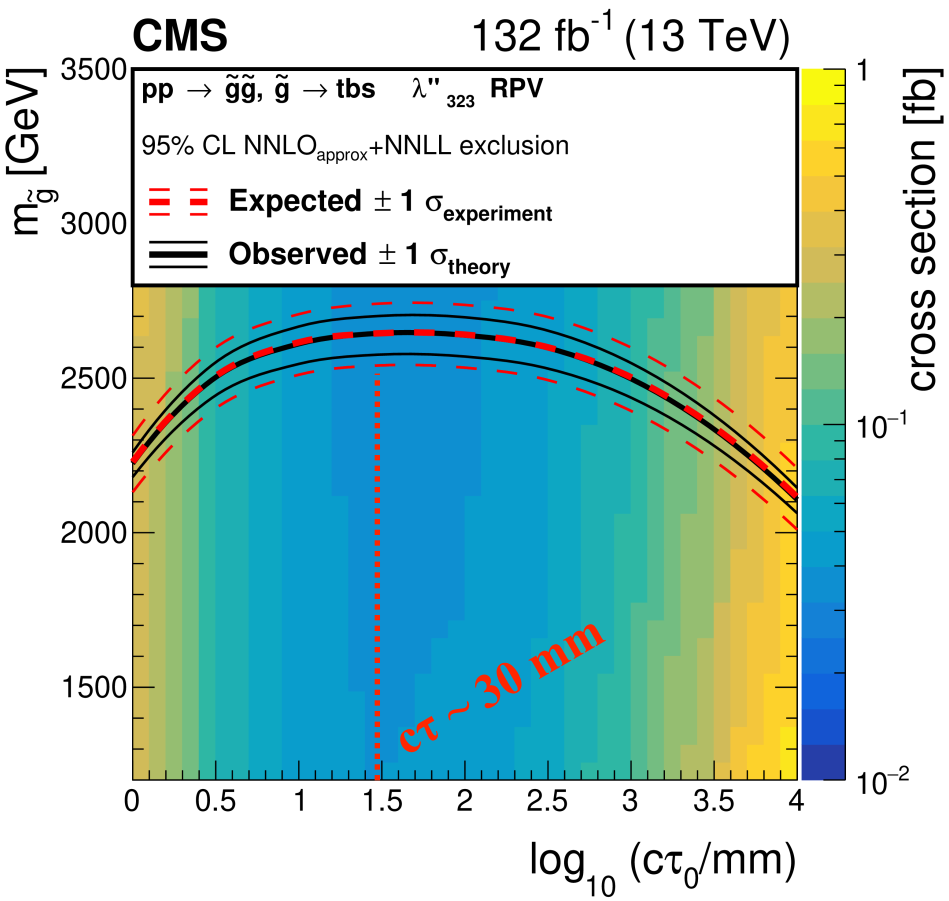
Phys. Rev. D 104, 012015 (2021)

- General search for **multi-jet** + **DVs** within the **ID**
  - ≥ 2 jets (trigger and offline), ≥ 1 DV associated to at least 1 jet
  - Main backgrounds: nuclear interactions, combinatorics, long-lived SM hadrons
    - measured in control regions in data
  - Final selection relies on a multi-variate analysis
  - No excess observed → limits on benchmark models

RPV SUSY: gluino → tbs



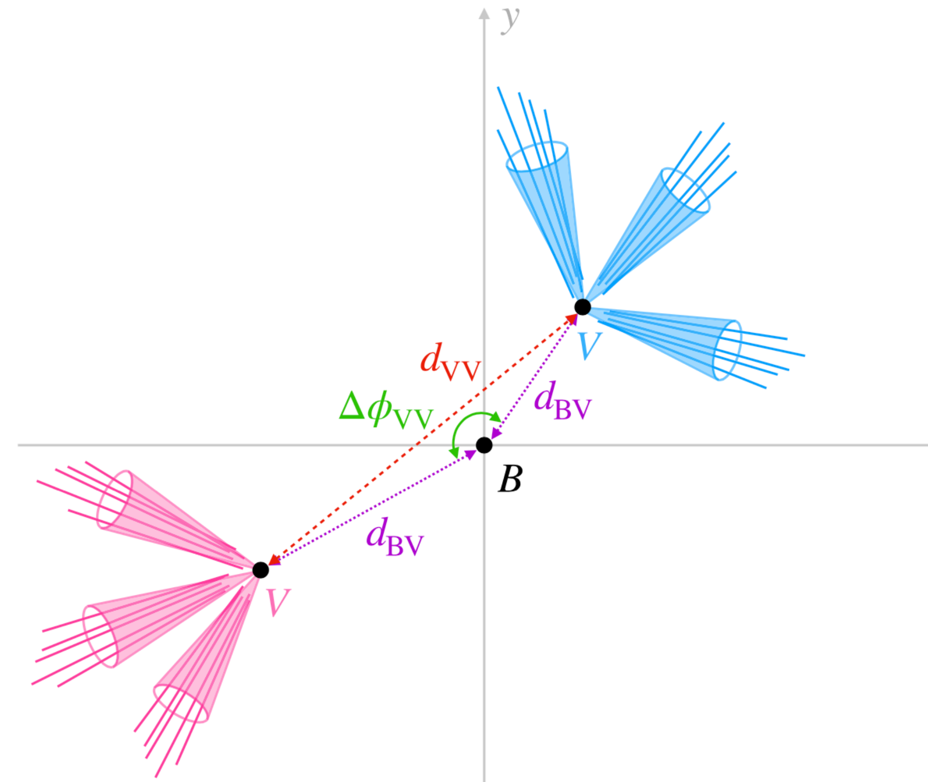


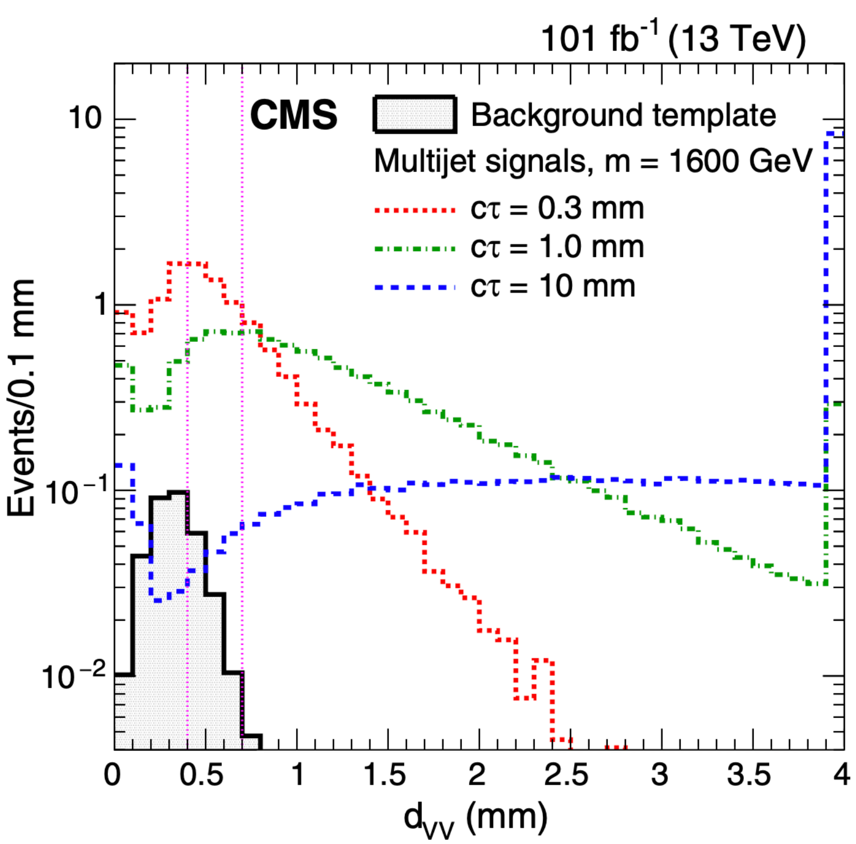


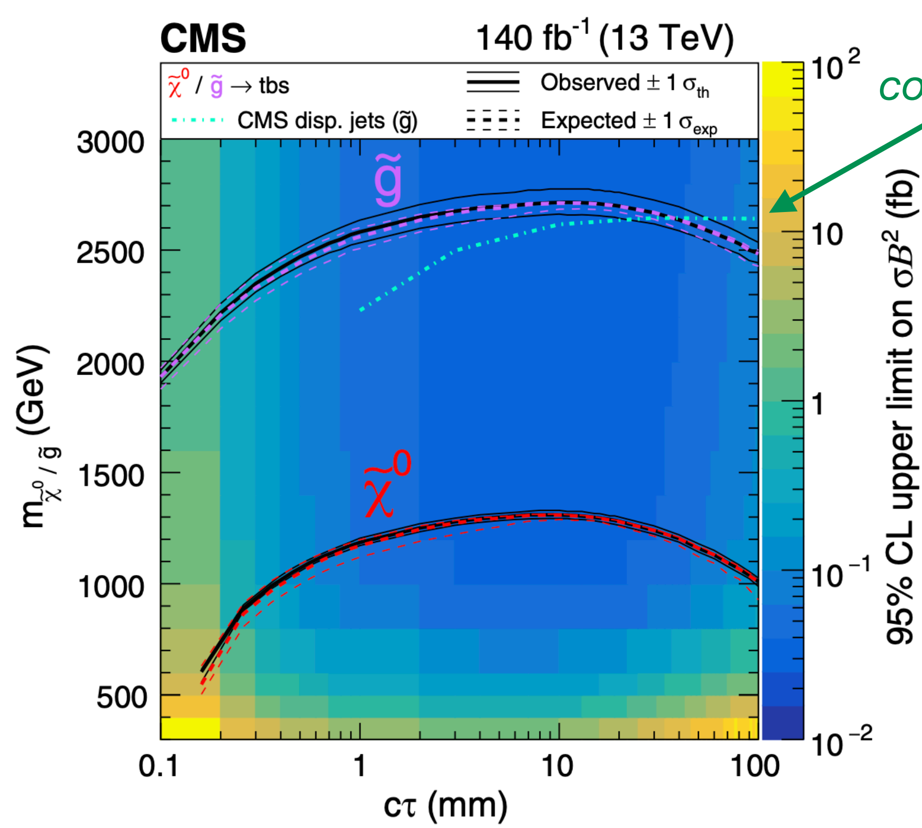
Pushing to lower $c\tau$

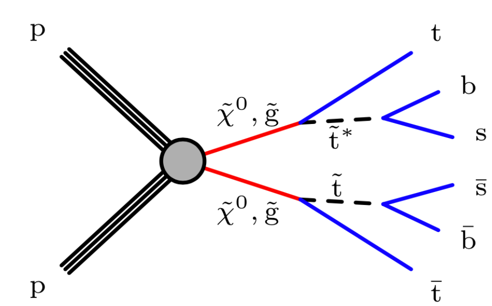
Phys. Rev. D 104, 052011 (2021)

- Search for **multi-jet** + **DVs** within the **beam pipe**
  - ≥ 4 jets, trigger on $H_T = \Sigma\, p_T\,(\mathrm{jet})$
  - ≥ 2 vertices with displacements < 2 cm
    - mostly SM backgrounds: b-jets, prompt vertices with a bad track
  - Distance d_{VV} between 2 DVs sensitive to several RPV SUSY scenarios
    - 0 events observed in signal region





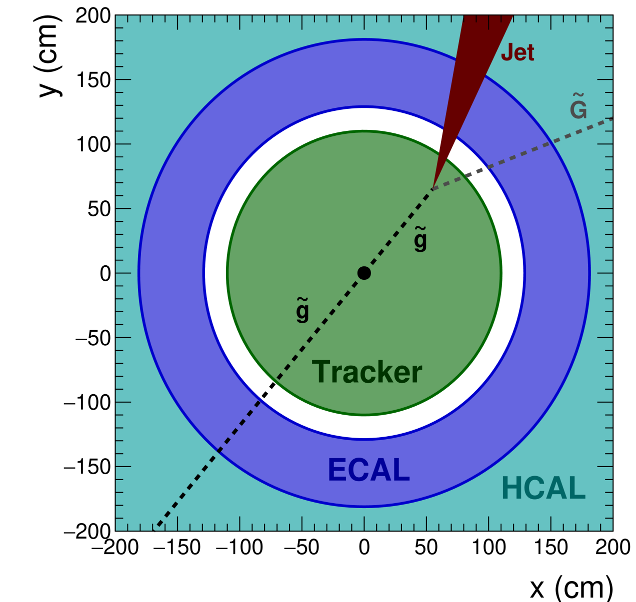


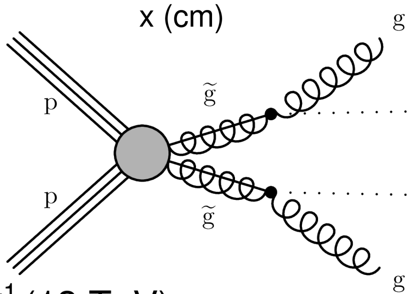


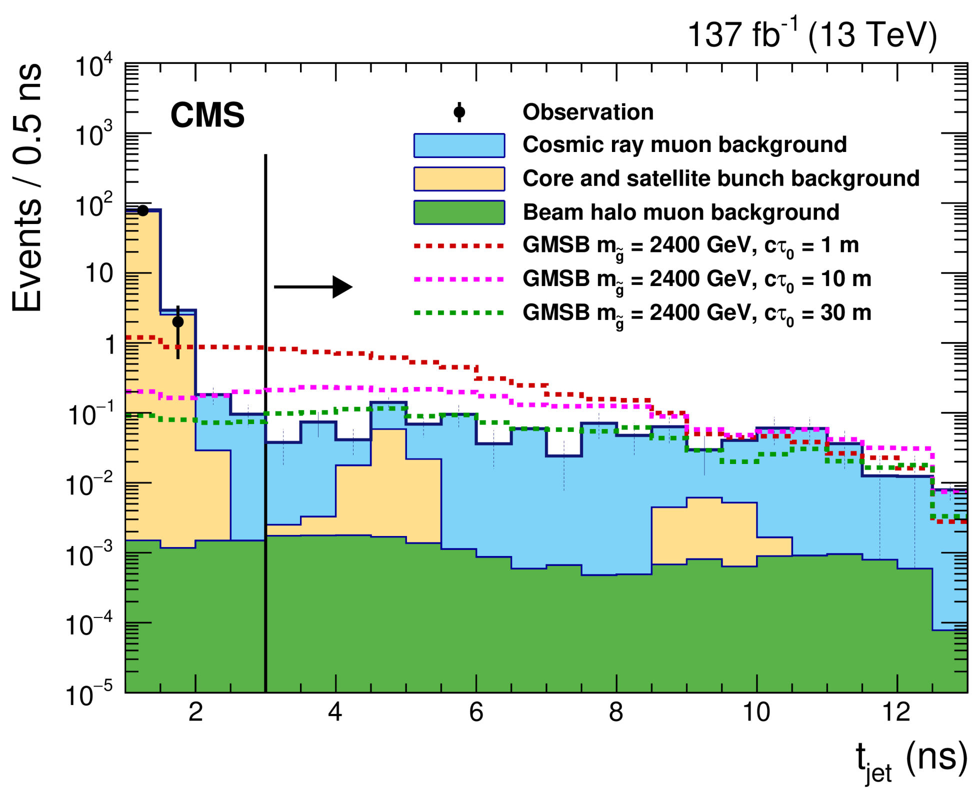
Pushing to larger cτ: jets in ECAL

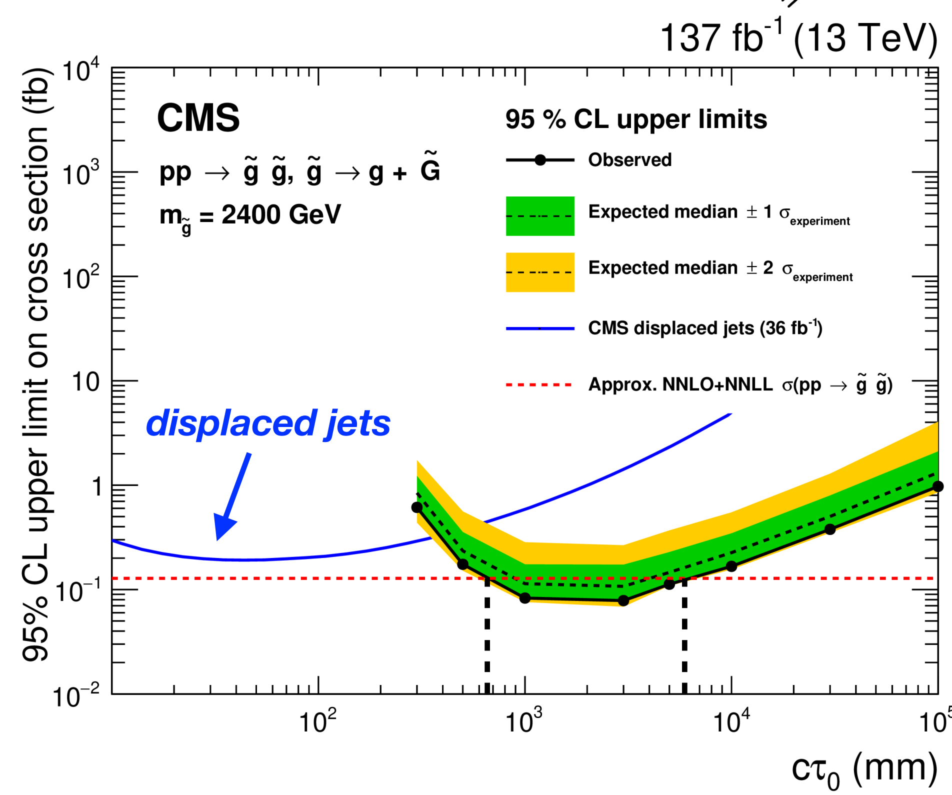
Phys. Lett. B 797 (2019) 134876

- Search for **heavy LLPs** decaying to jets in **ECAL**
  - TeV-scale particles that cross the ID (~1 m) before decaying hadronically
    - low β, indirect path → delayed jet, Δt ~ ns
  - CMS ECAL time resolution ~200 ps (E_T > 50 GeV)
  - Timing cut reduces the backgrounds to few events
  - No observed events → limits on GMSB model





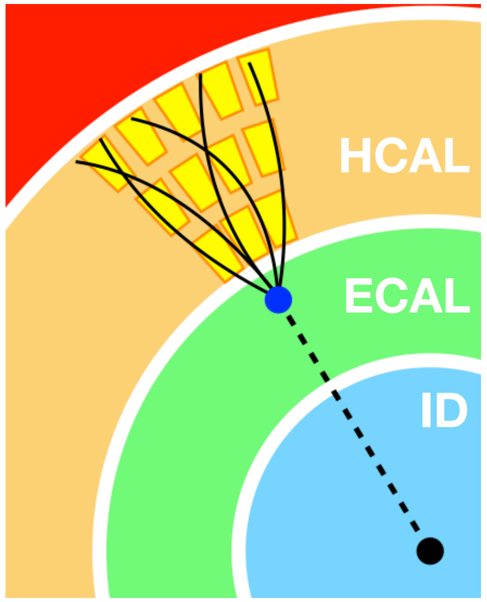


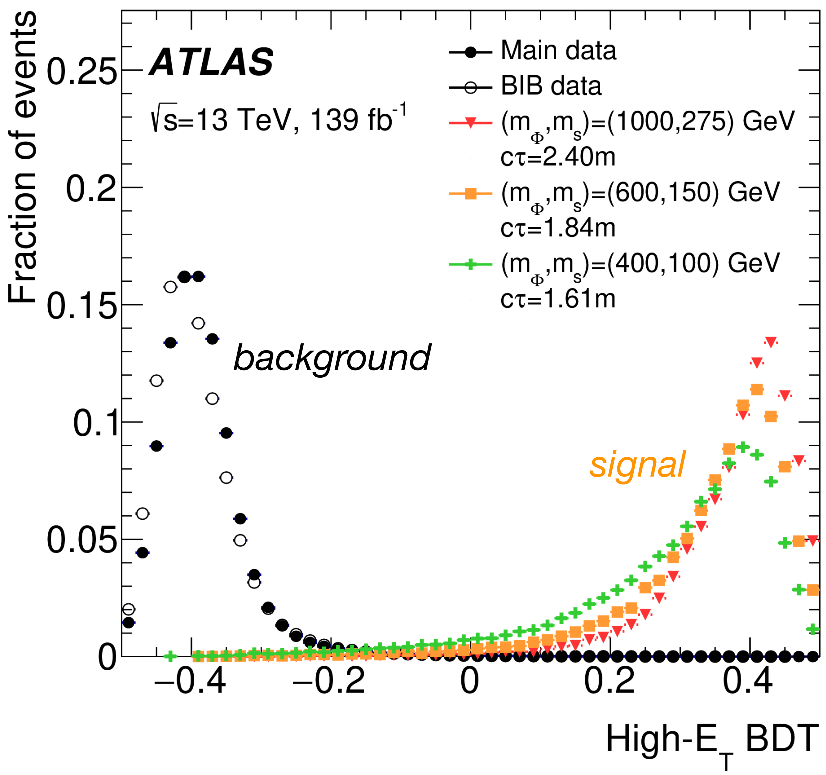


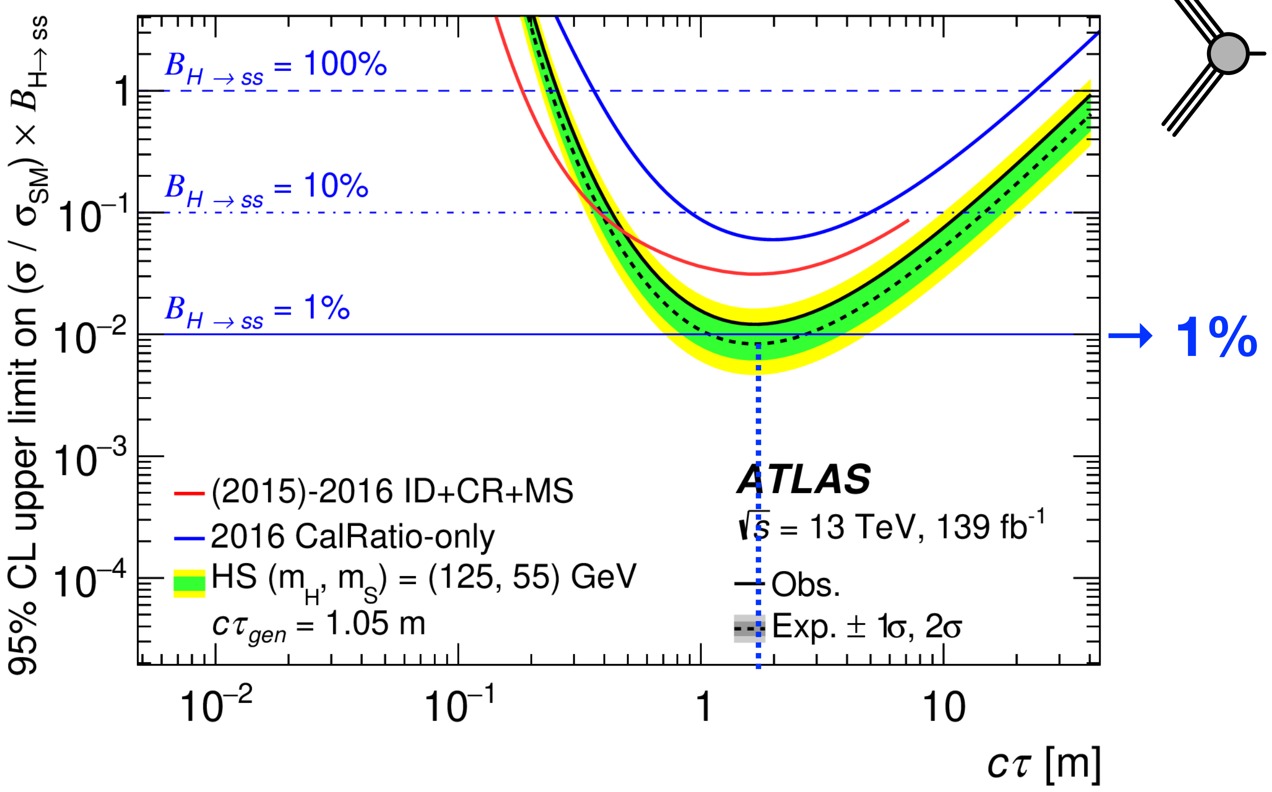
Pushing to larger cτ: jets in HCAL

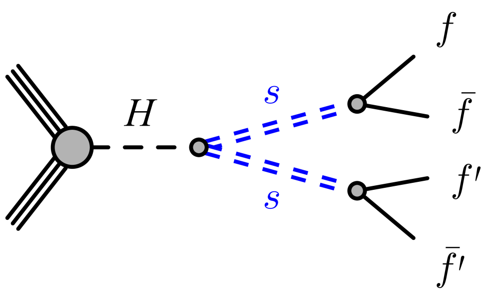
JHEP 06 (2022) 005

- LLPs decaying hadronically in **HCAL**
  - Dedicated *CalRatio* triggers, based on low ECAL/HCAL energy ratio
  - Main backgrounds: multi-jets, BIB, cosmics
  - MVA-based selection:
    - per-jet NN tagger + per-event BDT
  - No significant excesses, limits on SM-like & BSM H → SS decays







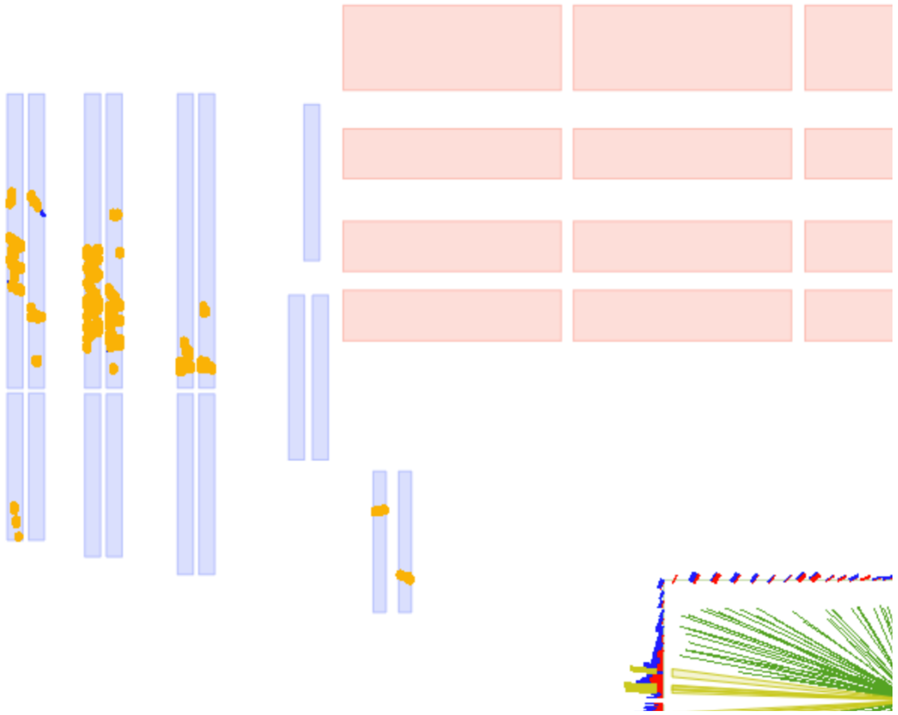


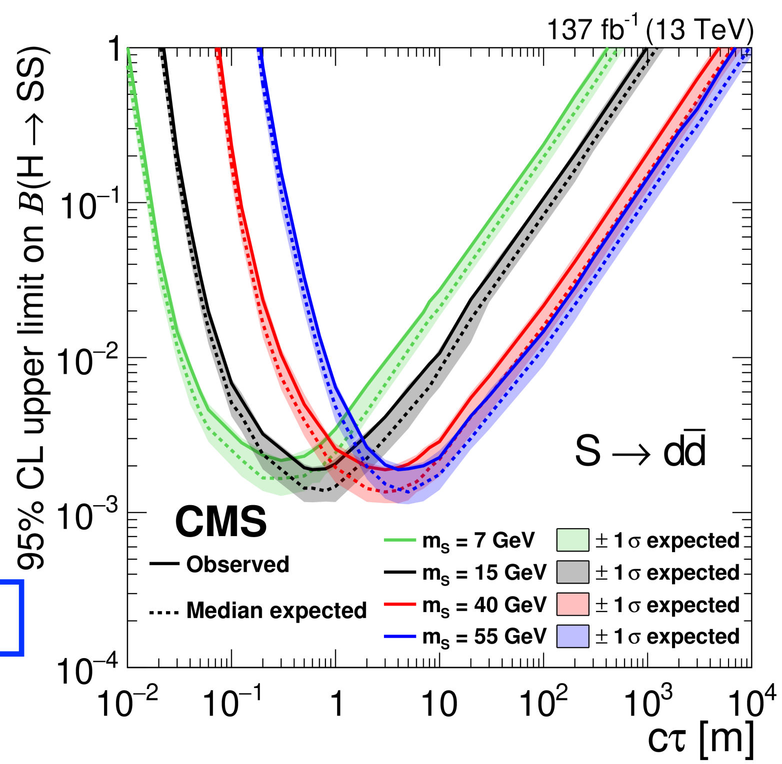
Pushing to larger cτ: jets in MS

arXiv:2203.00587 [hep-ex]

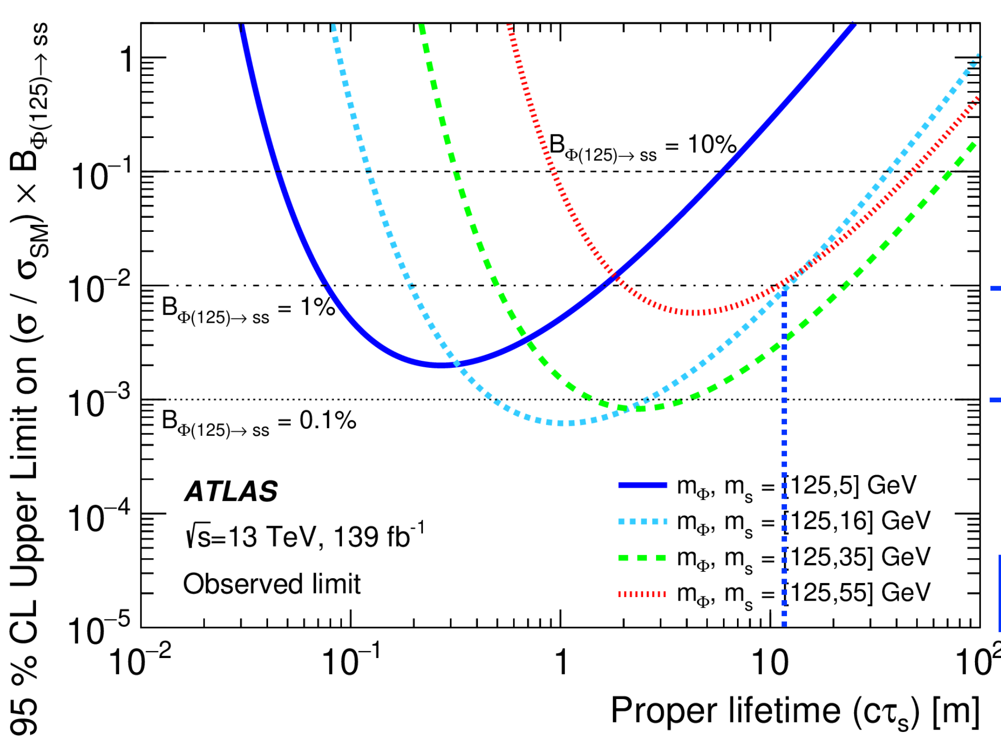
Phys. Rev. Lett. 127, 261804 (2021)

- Two different strategies for LLP **hadronic decays** in the **MS**
  - **ATLAS:** DVs fitted from MS tracklets
    - dedicated trigger
    - no matching activity in the ID and CALs
  - **CMS:** MS hit clustering
    - triggering on MET
    - restricted to MS endcaps (CSC)
  - Comparable sensitivity on SM H → SS scenario





B(S → dd) = 1



→ 1%

→ 0.1%

Yukawa-like B(S → ff)

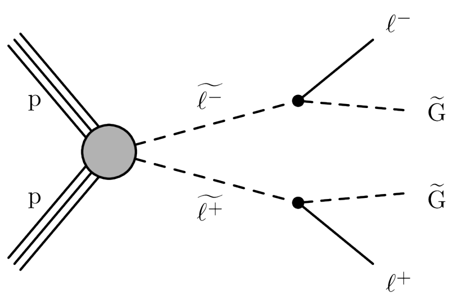
Searches with leptons

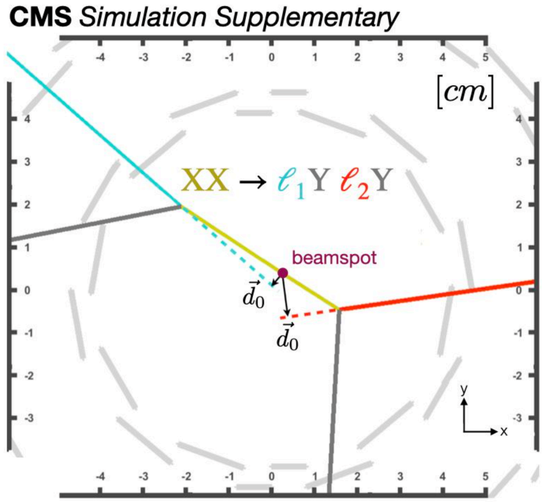
Displaced leptons

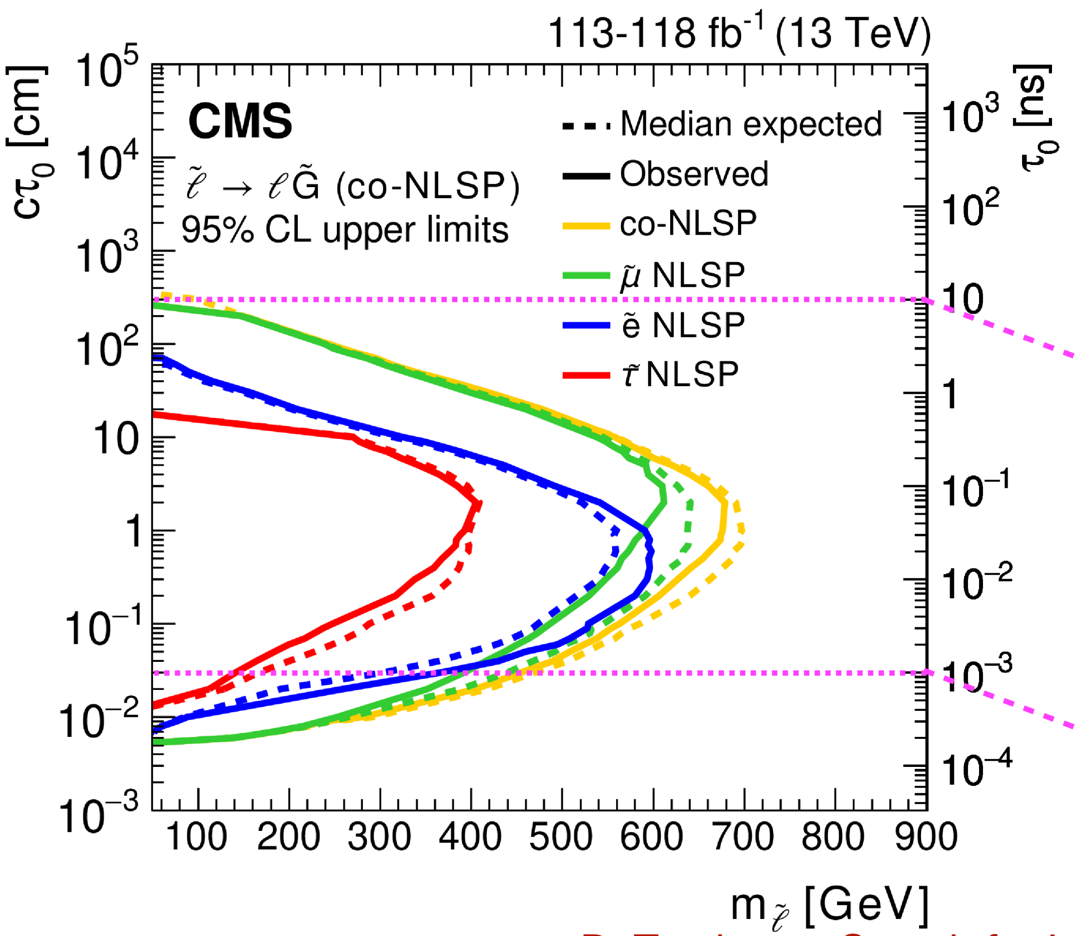
Phys. Rev. Lett. 127 (2021) 051802

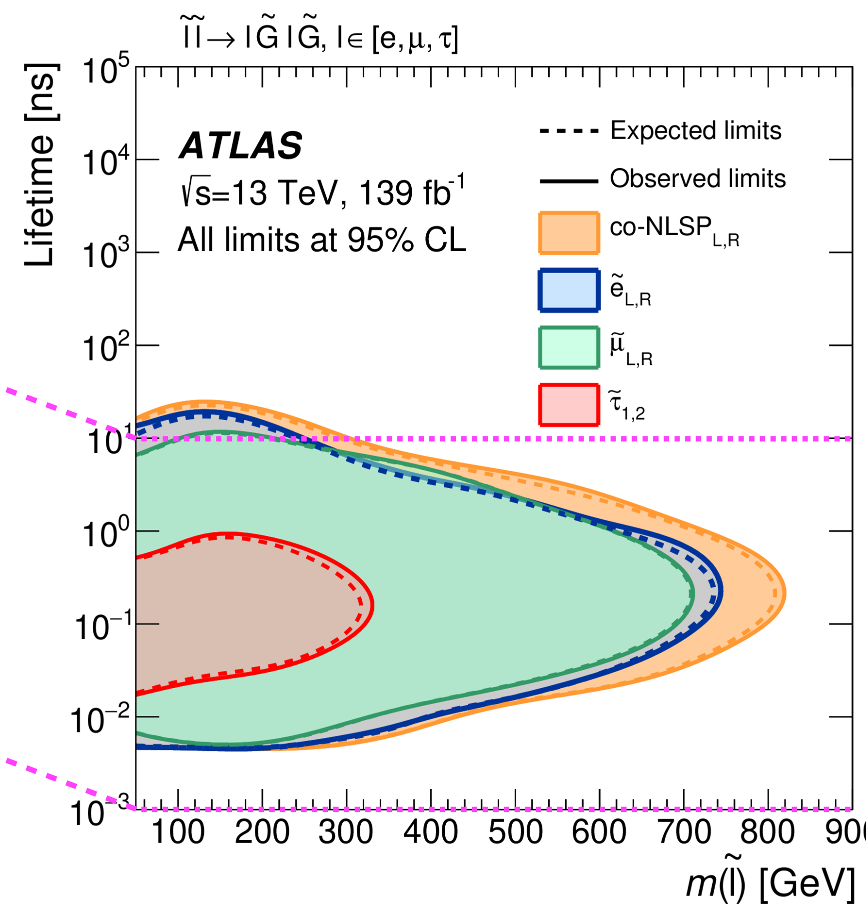
Eur. Phys. J. C (2022) 82:153

- Generic search for **displaced** ee, $e\mu$, $\mu\mu$ pairs within the **Pixel** and with **no vertex** requirements
  - Sensitive to a broad suite of models
    - slepton (e, μ, τ) pair production in GMSB
    - stop pair production in RPV
    - $H \to SS \to 4e$ / $2e2\mu$ / 4μ





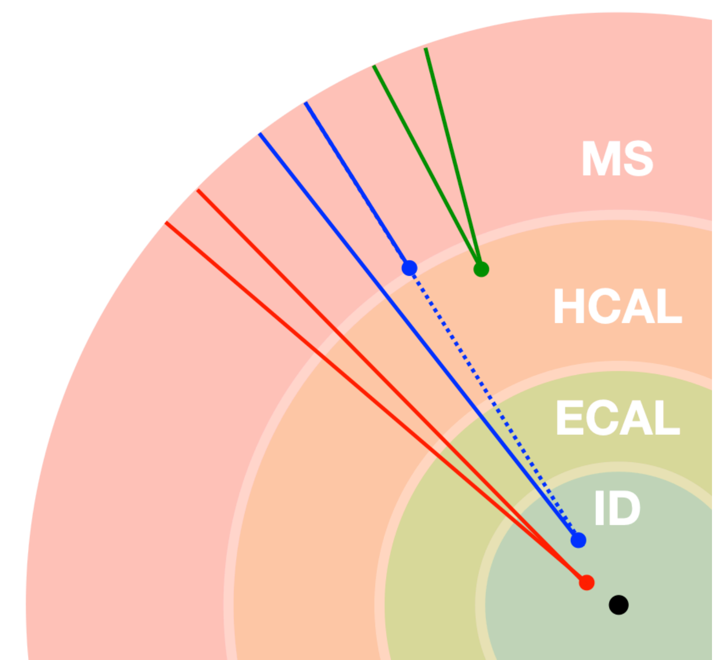


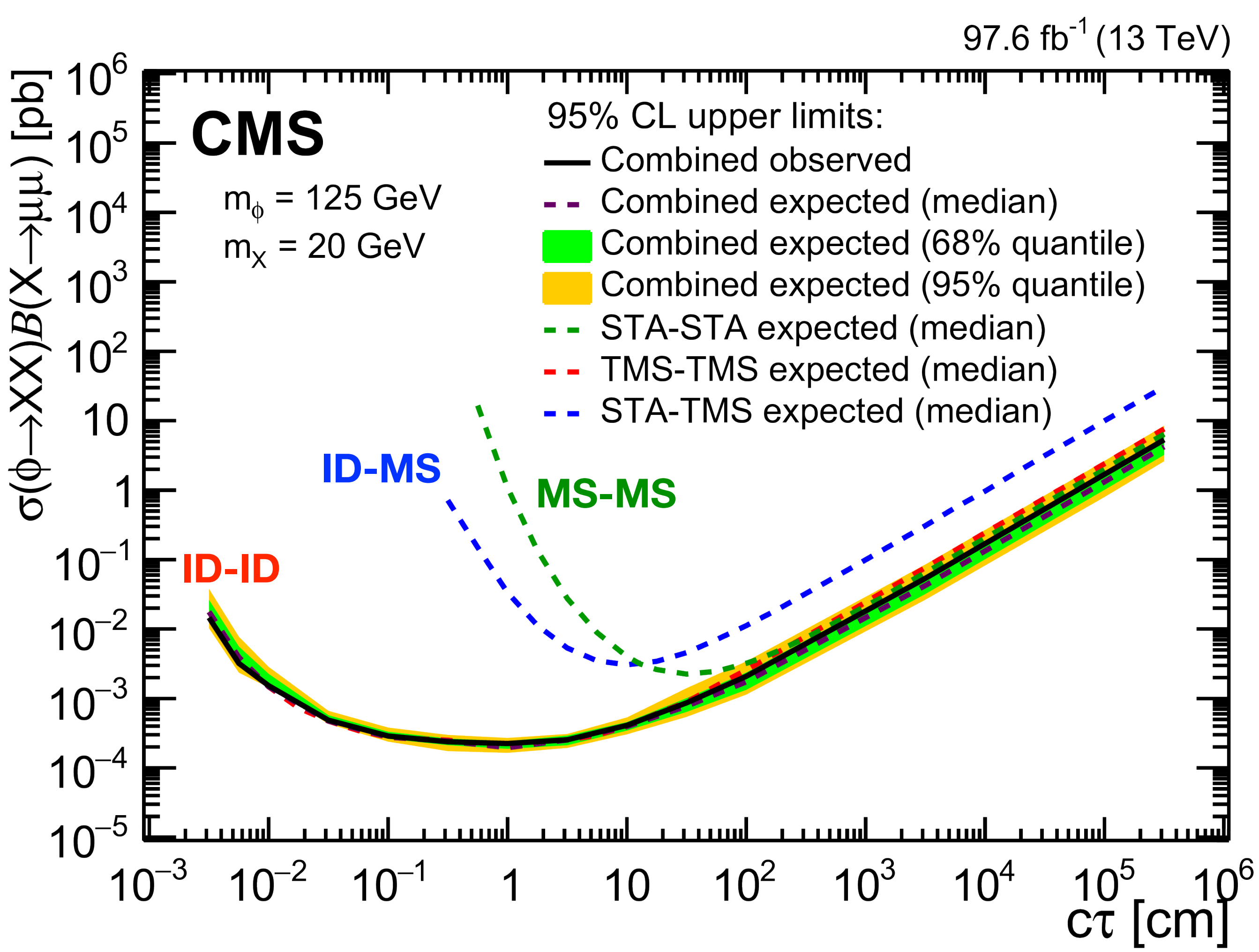


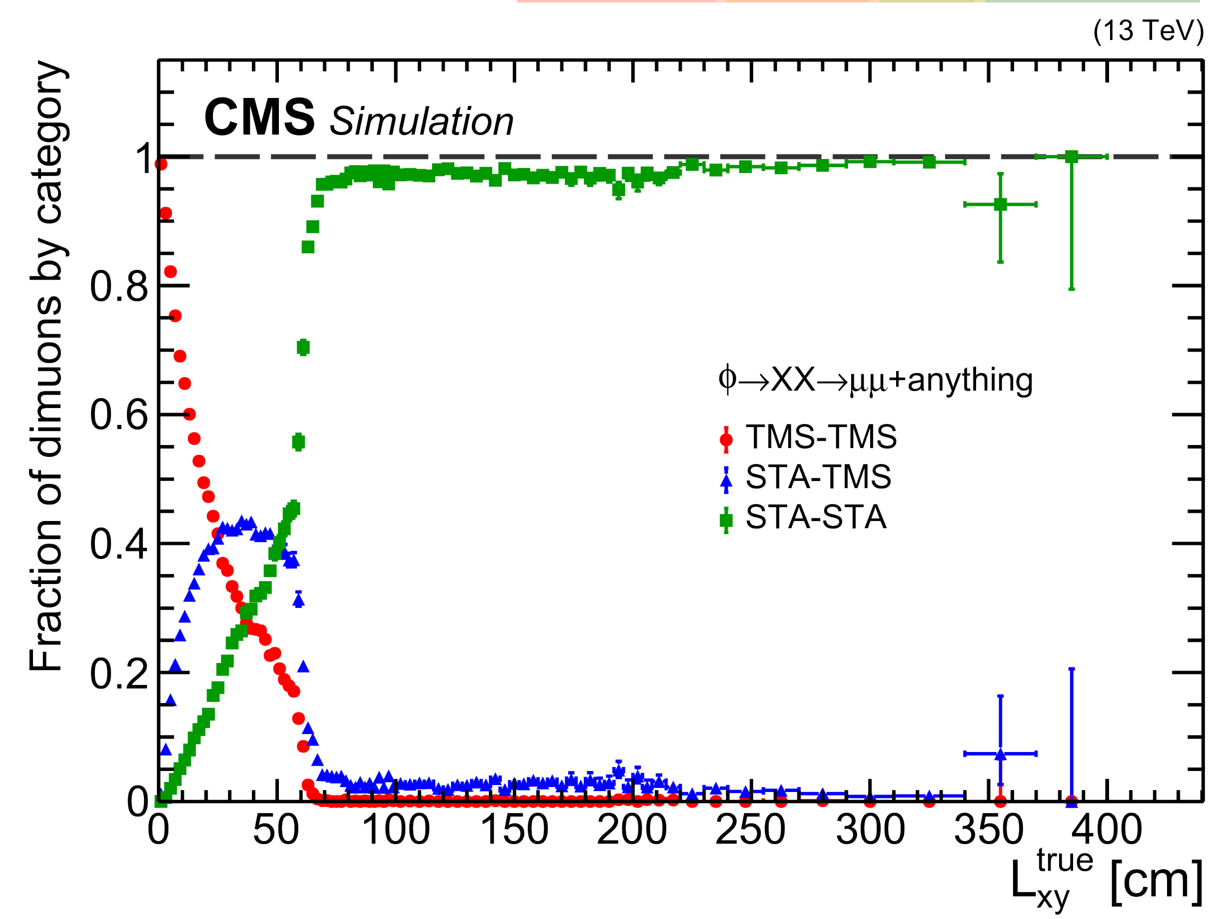
Large cτ: muons in ID + MS

arXiv:2205.08582 [hep-ex]

- Search for **di-muon vertices** in the **ID** and **MS**
  - Three μμ categories: **ID-ID**, **ID-MS**, **MS-MS**
  - Complementarity, cτ ~ 100 μm–1 km
  - Limits on BSM $H \to SS \to 2\mu + X$







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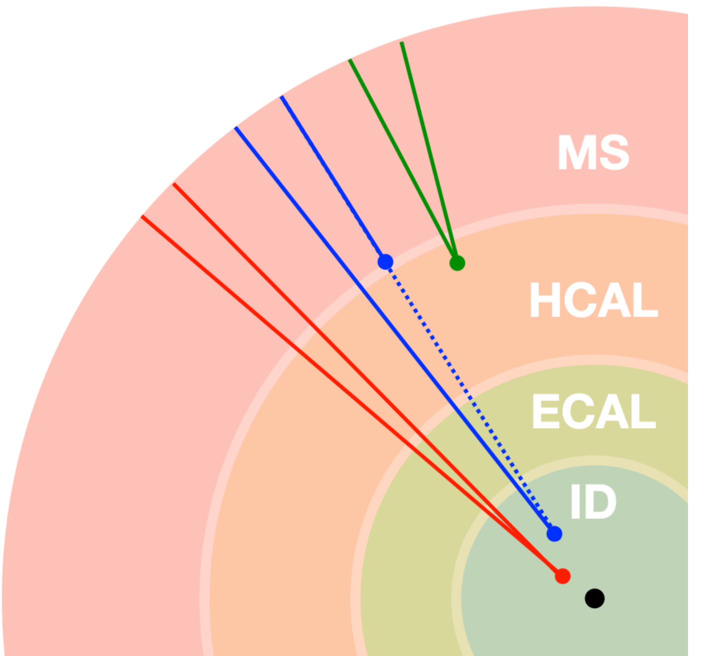
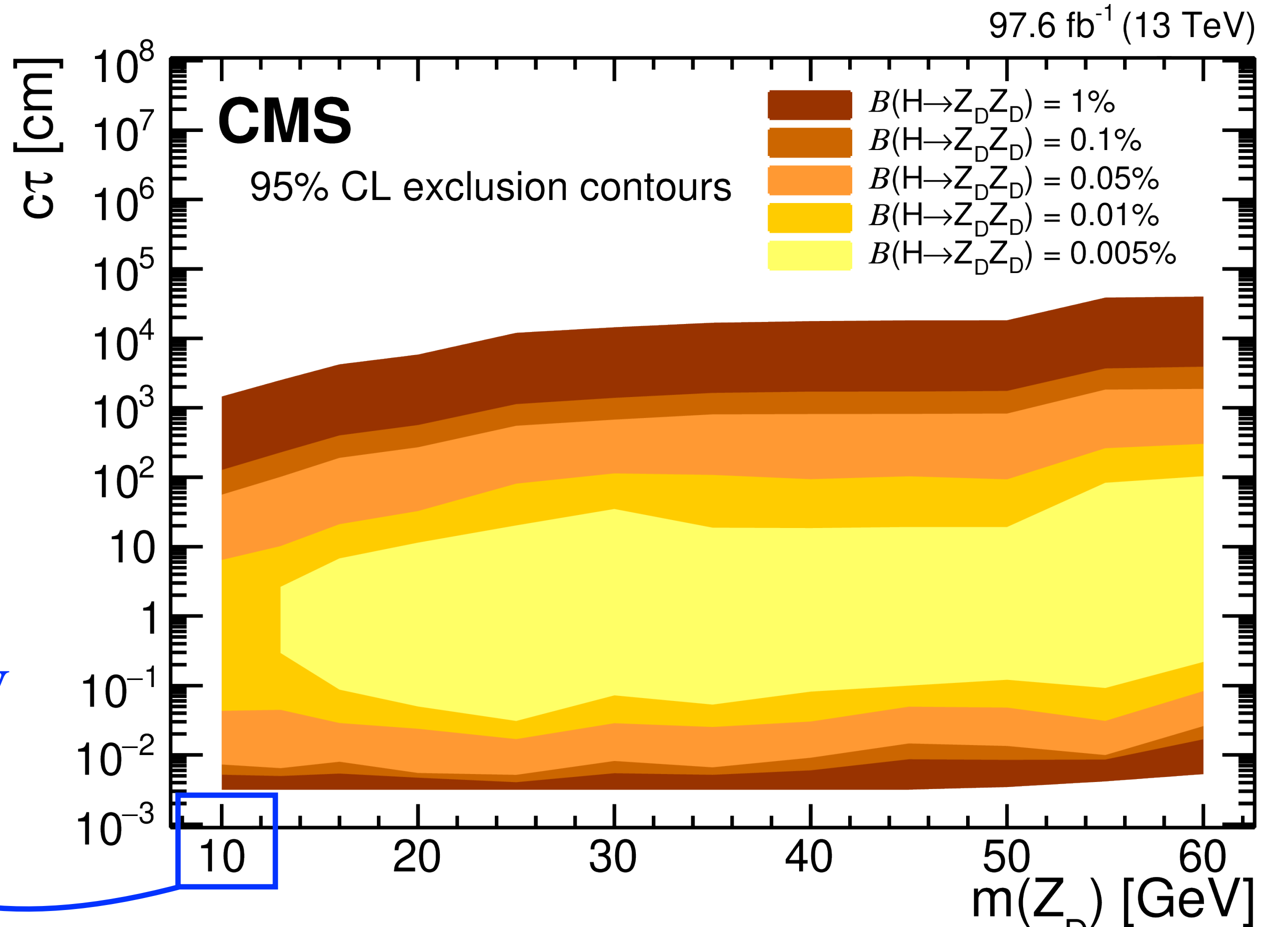
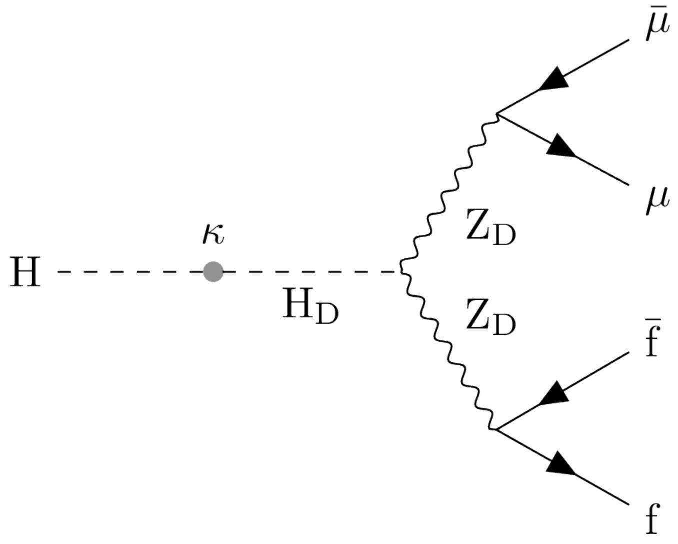
  - Limits on BSM $H \rightarrow SS \rightarrow 2\mu + X$
  - Limits on a Hidden Abelian Higgs Model (HADM) with dark photons: $H \rightarrow Z_D Z_D \rightarrow 2\mu + X$





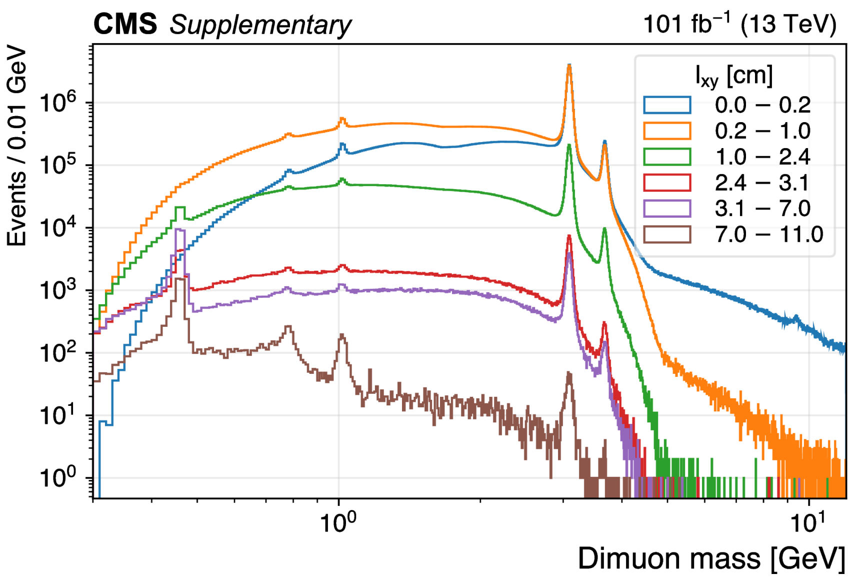
$m(Z_D) > 10$ GeV (from trigger)

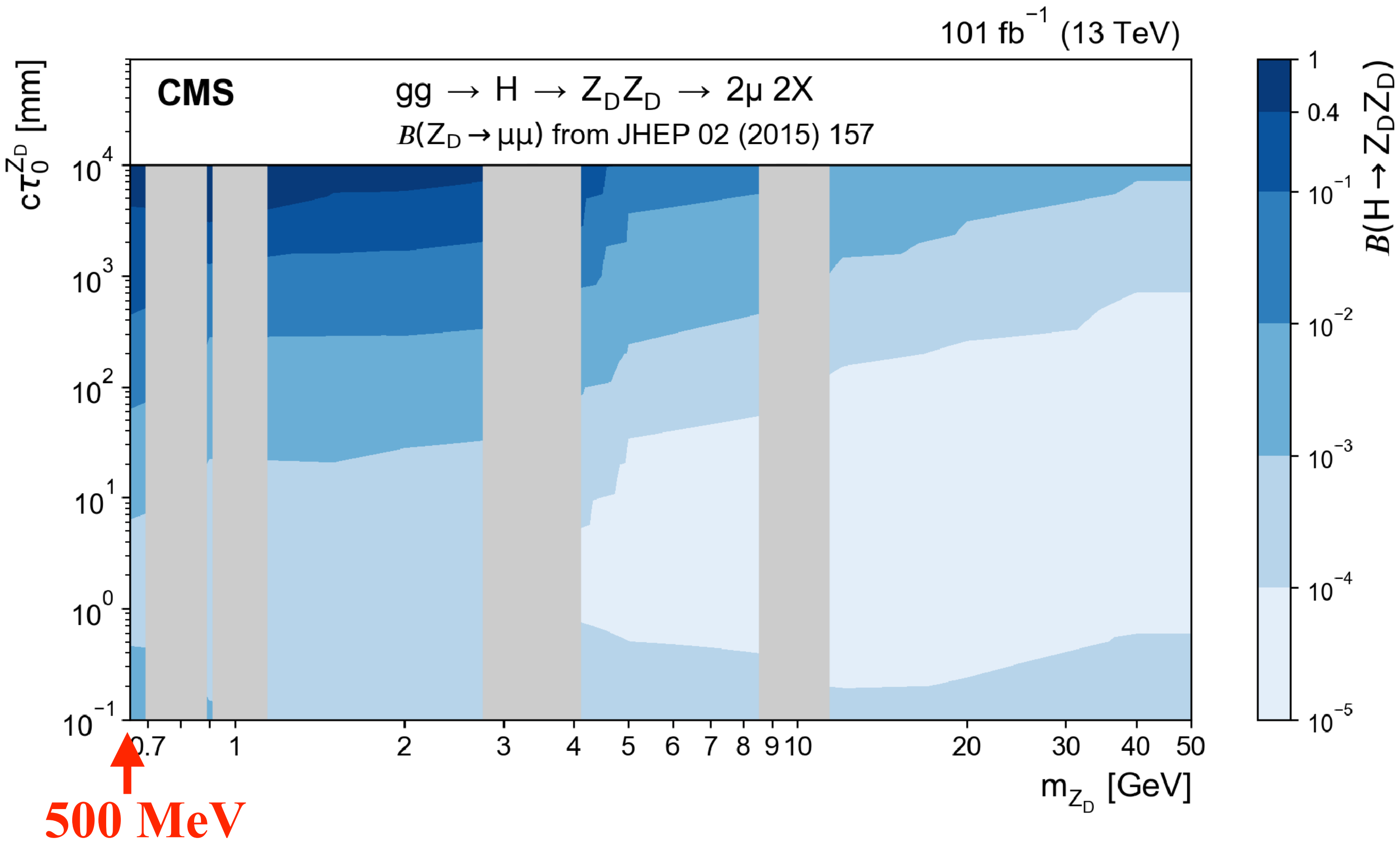


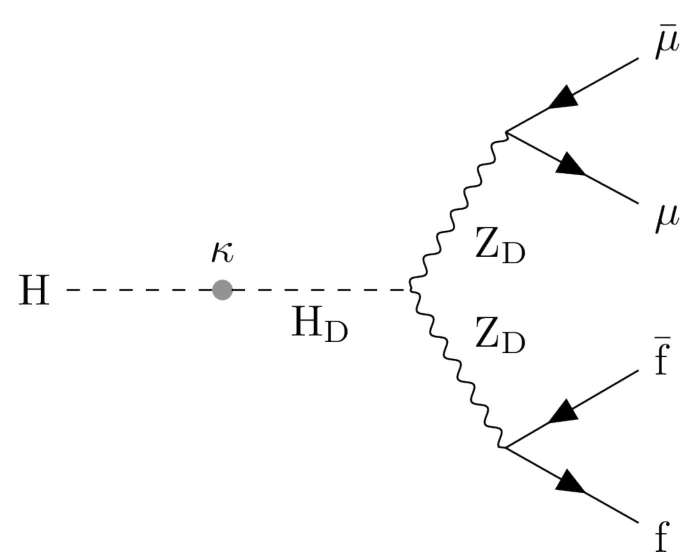
Low mass: high-rate muon triggers

JHEP 04 (2022) 062

- Low mass **di-muon vertices** within **Pixel** detector
  - *Scouting*: very-high-rate triggers with limited event content stored, to ensure affordable data throughput
    - di-muon masses > 300 MeV
    - limited information for analysis
  - Limits on HADM dark photon model: $H \to Z_D Z_D$







Very low mass: collimated particles

- Dark photons decaying to **collimated** **ee, μμ, qq** pairs in **HCAL** or **MS**
  - dark-photon jets (DPJs)
    - ee/qq in HCAL, CalRatio triggers
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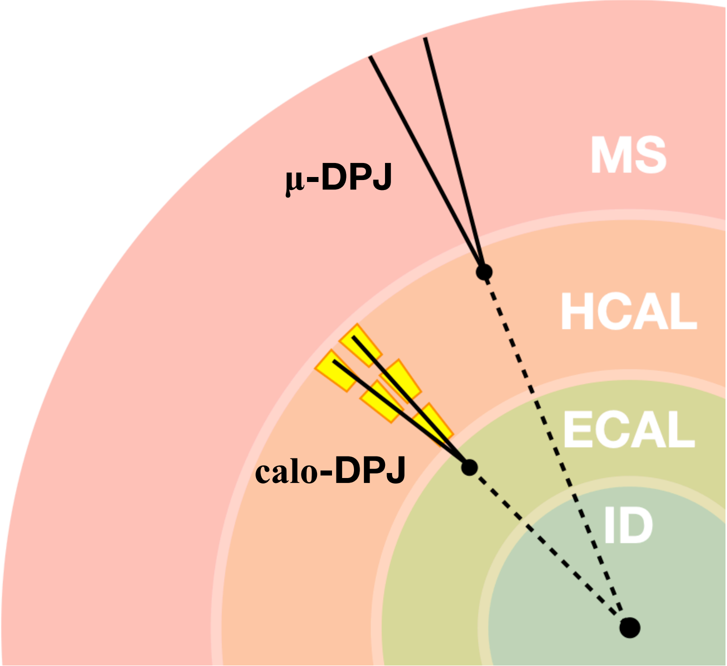
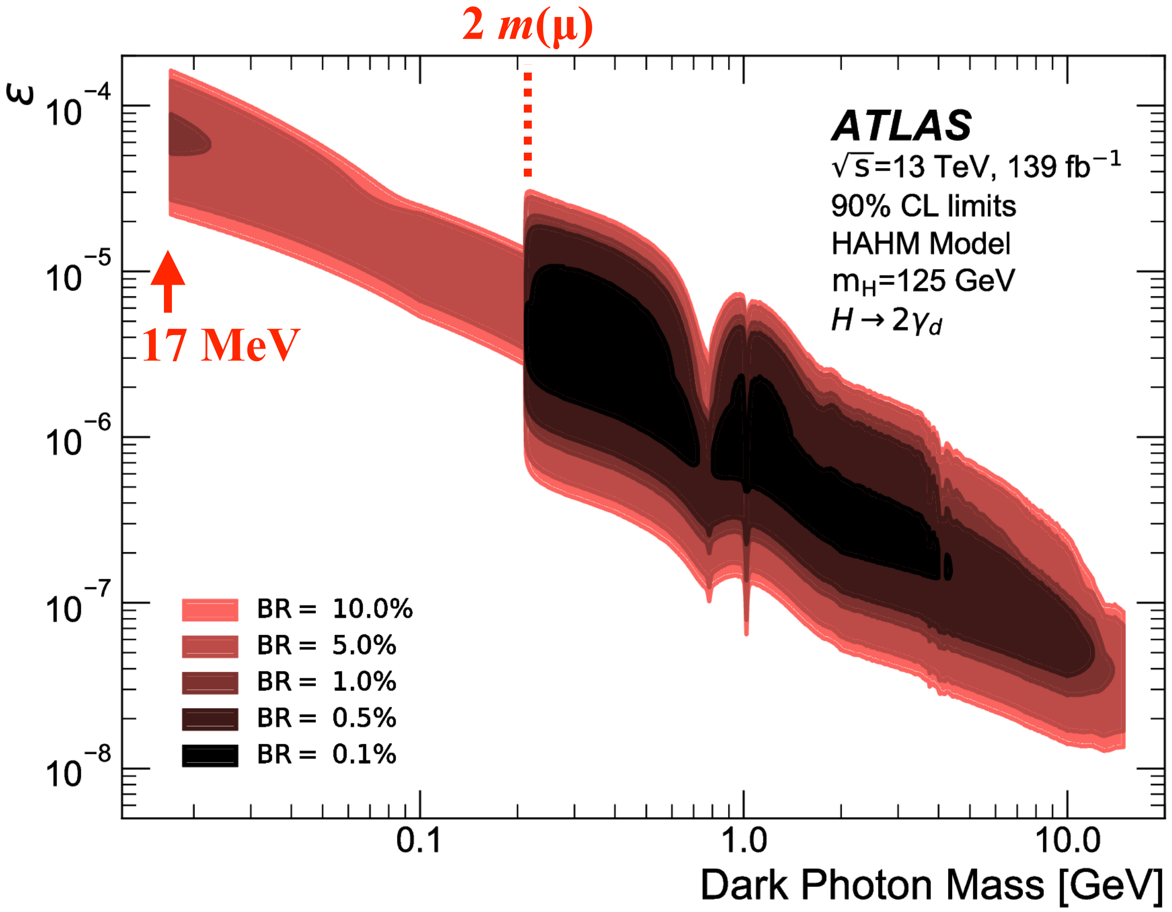
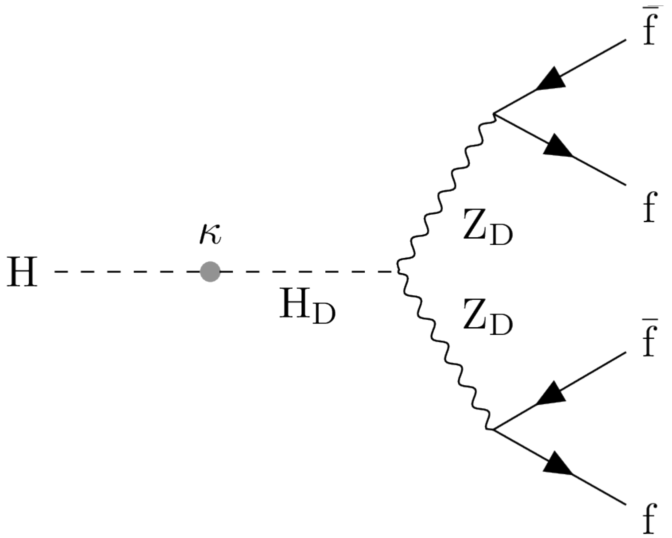
    - MVA taggers to reject background (BIB, cosmics, multi-jets)
  - Limits on HADM model for dark photon mass > 17 MeV





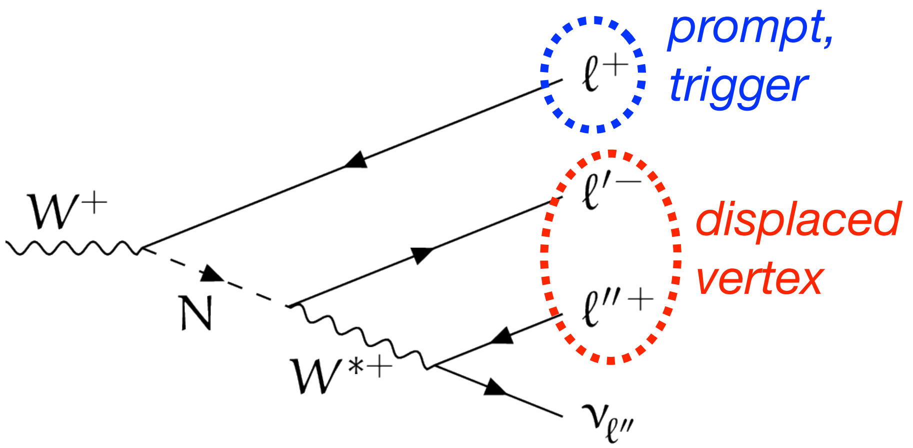


Long-lived HNL in leptonic channels

arXiv:2204.11988 [hep-ex]

JHEP 07 (2022) 081

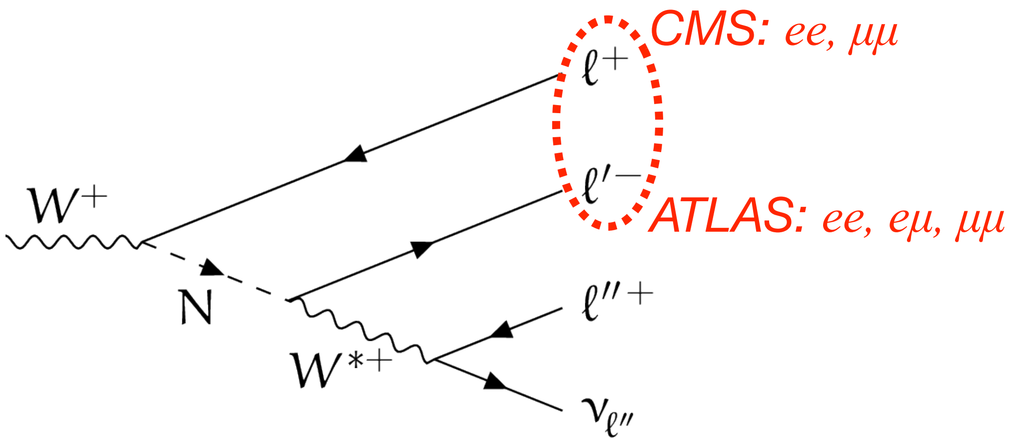
- Search for a **heavy neutrino** N in **Type-I seesaw** model
  - Decay $W \to \ell N \to \ell + \ell' \ell'' \nu$
  - For $m_N \lesssim 20$ GeV, long-lived N ($\tau_N \sim m_N^{-5}$)
    - ℓ'–ℓ'' form a DV, reconstructed within the ID
    - displaced ee, eμ, μμ with opposite charge
  - Dominant backgrounds after selection:
    - **ATLAS:** fake DVs from random track crossings
    - **CMS:** SM hadron decays (especially b hadrons)

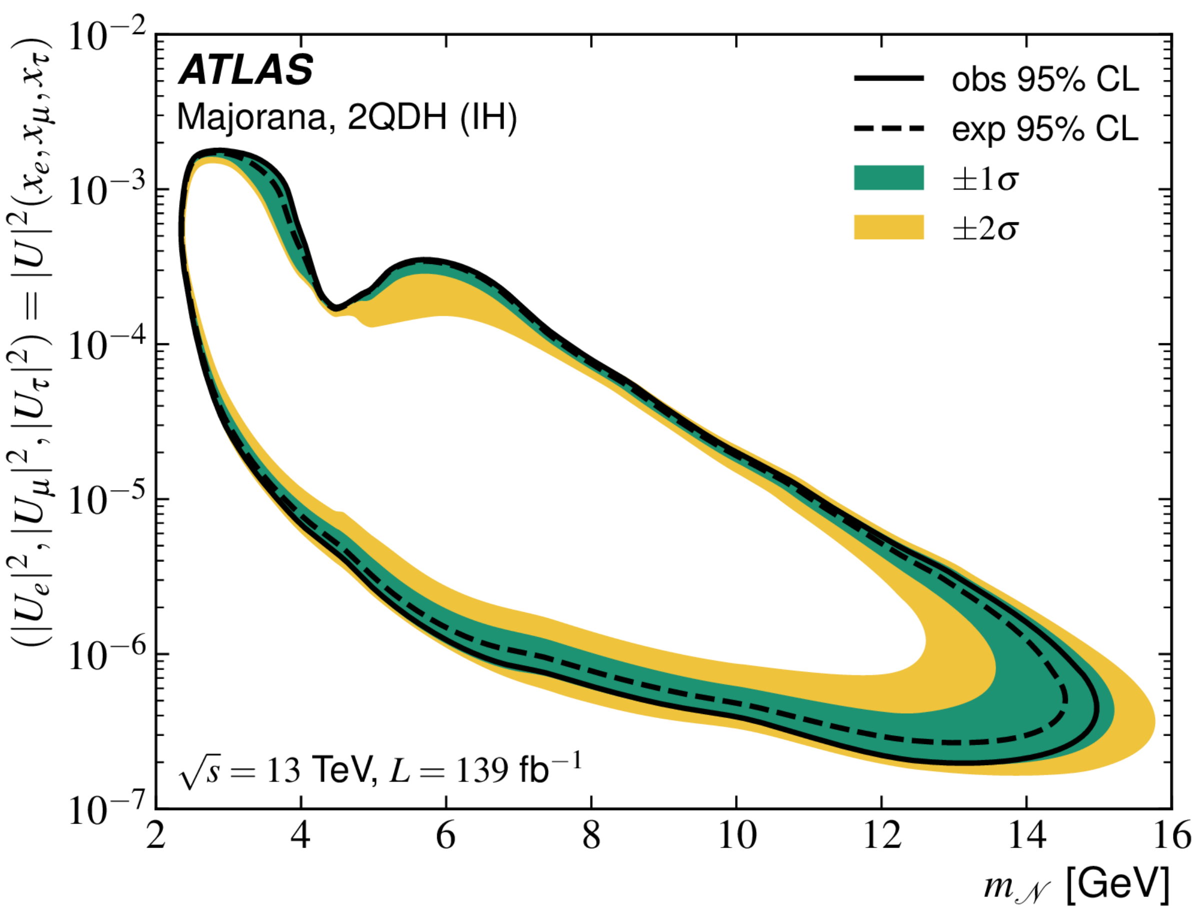


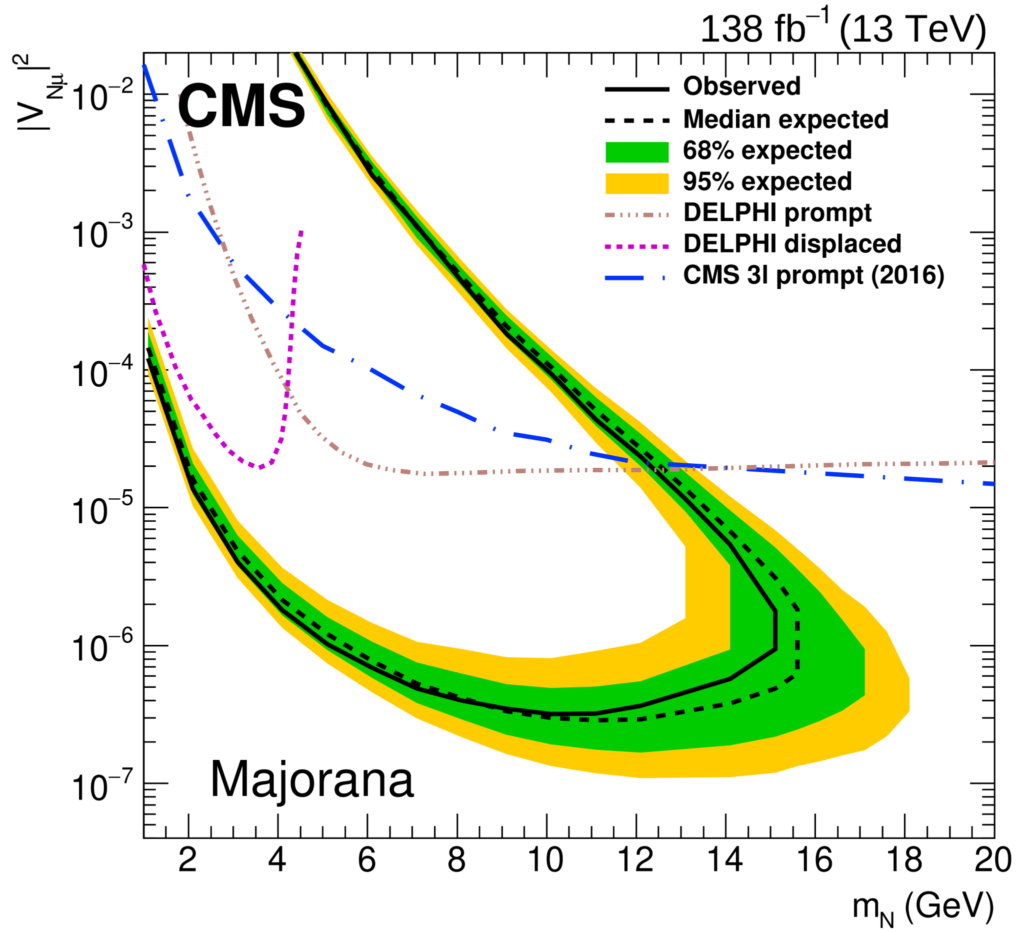
Long-lived HNL in leptonic channels

arXiv:2204.11988 [hep-ex]
JHEP 07 (2022) 081

- Limits on ν_ℓ–N mixing angles $|U_\ell|^2$ for Majorana or Dirac N
  - **CMS:** single-flavor couplings (e–N, μ–N), no lepton flavor mixing → $\ell\ell'$ = ee, μμ
  - **ATLAS:** more realistic model (2QDH) with lepton flavor mixing → $\ell\ell'$ = ee, eμ, μμ





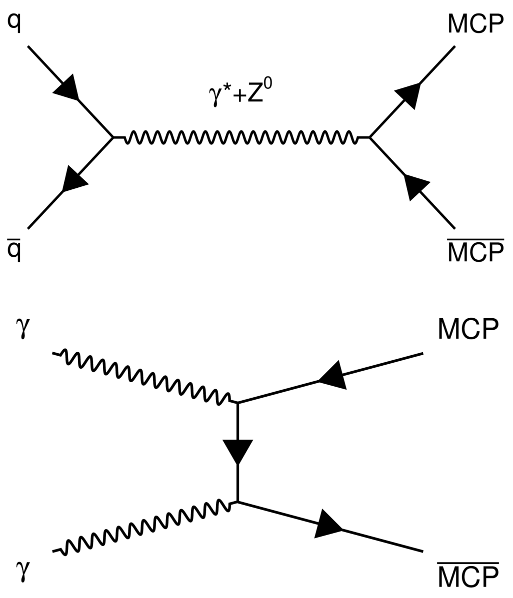


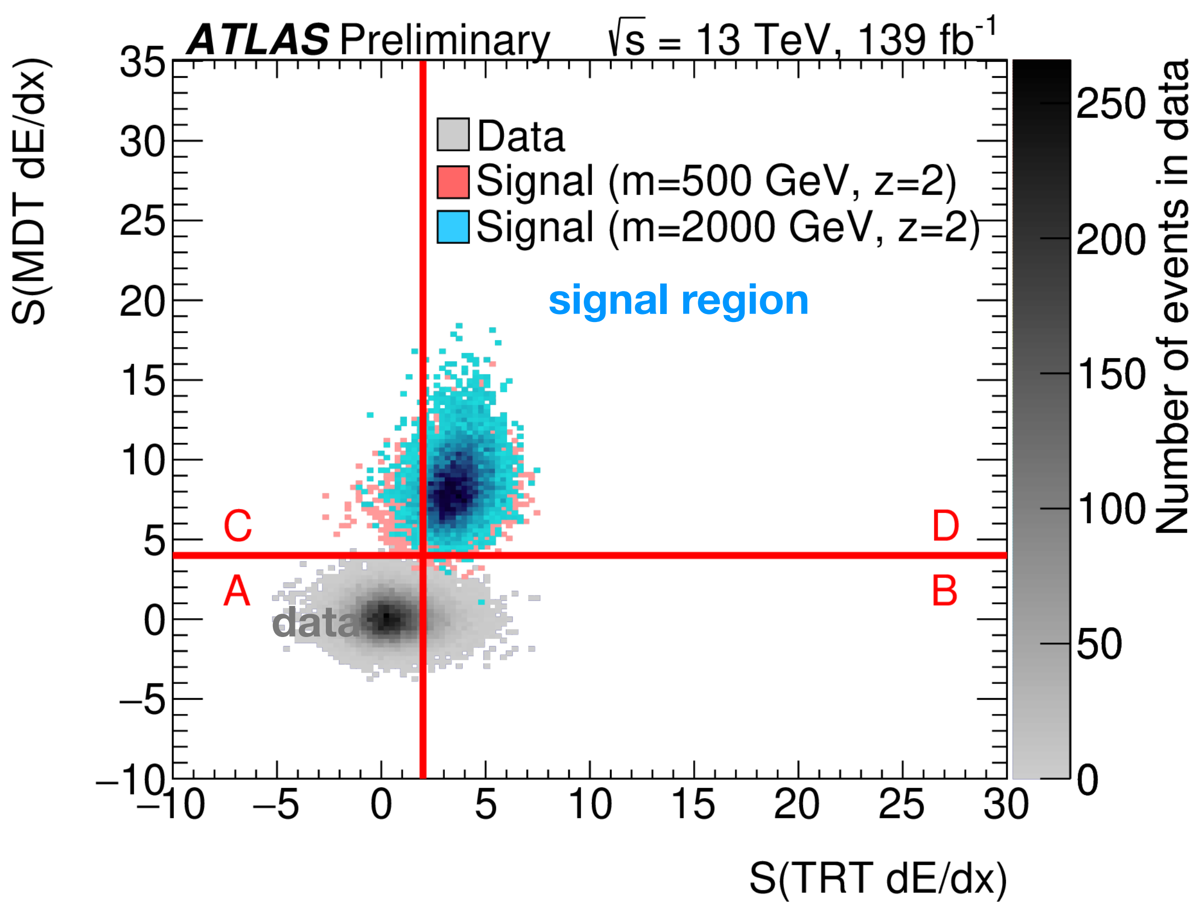
Direct detection searches

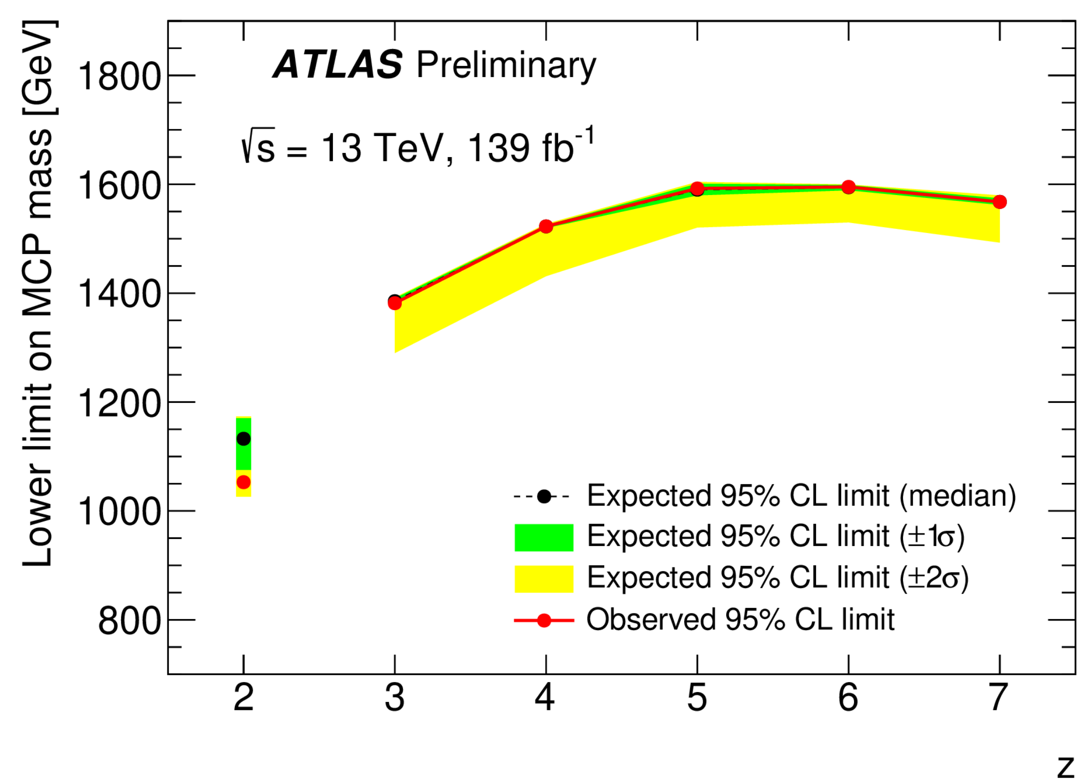
Multiply charged particles (MCPs)

ATLAS-CONF-2022-034

- Search for heavy **multi-charged particles** in **ID** and **MS**
  - Electric charge 2–7e
  - Reconstructed as muons in ID and MS
  - dE/dx significance from three sub-detectors
    - Pixel, TRT, MDT
  - No excess → limits on MCP mass *vs* charge



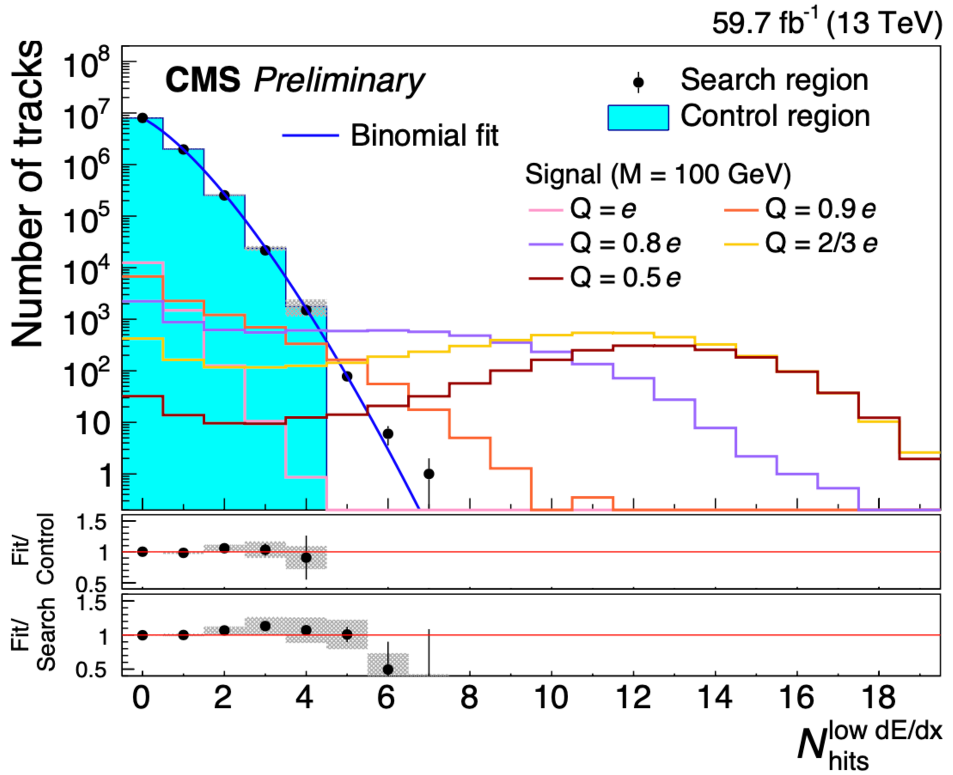


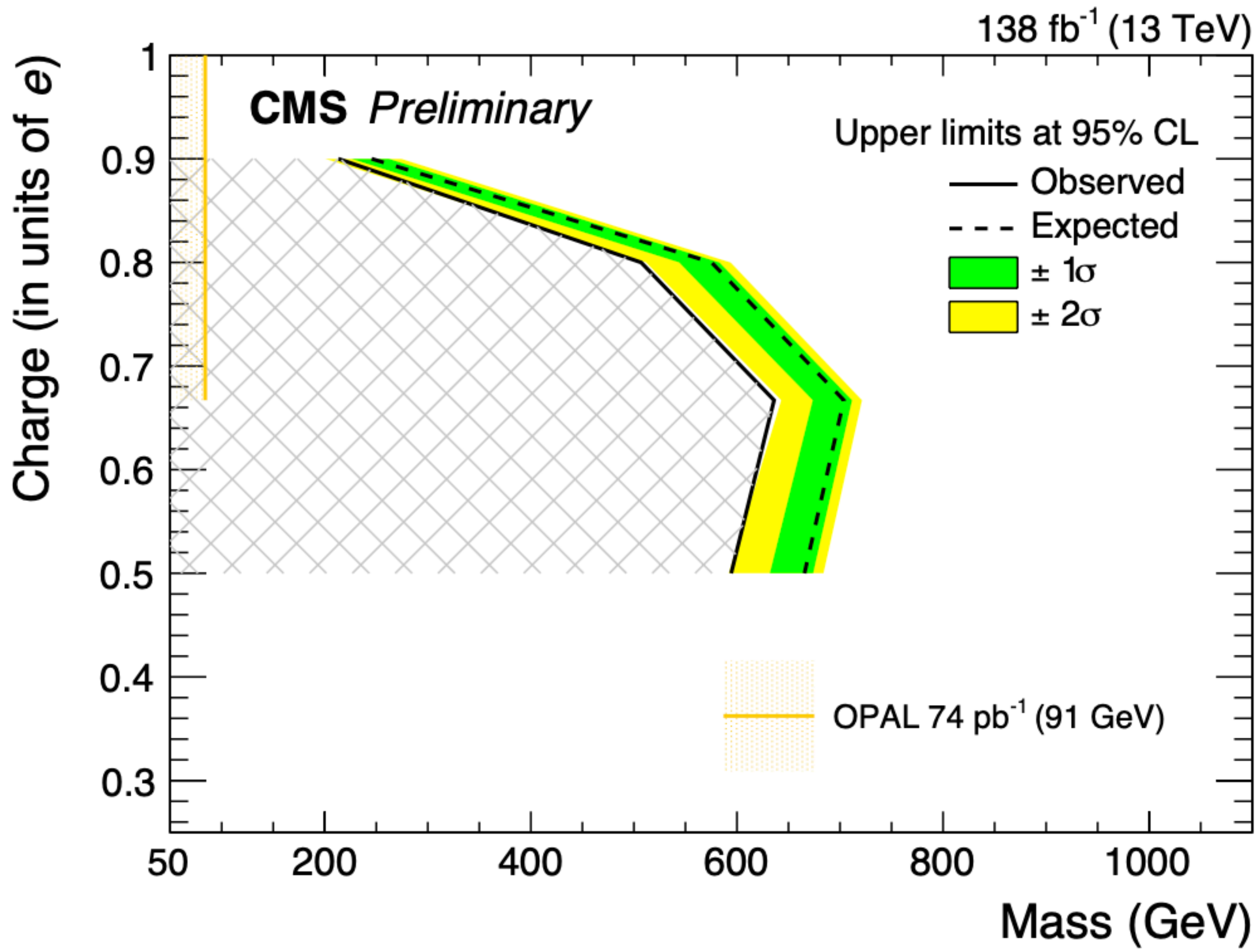


Fractionally charged particles (FCPs)

EXO-19-006

- Search for particles with **charge < 1e** in **ID** and **MS**
  - FCPs reconstructed as high-p_T muons
  - Large number of ID hits with low dE/dx
  - Data compatible with background → limits on FCP mass *vs* charge





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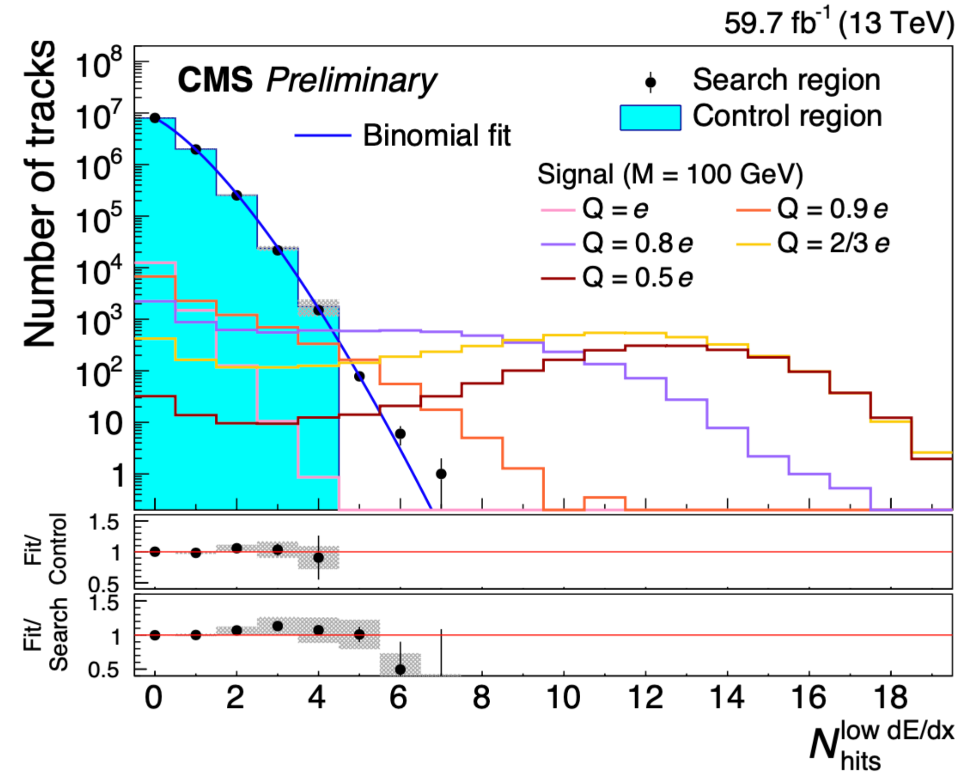
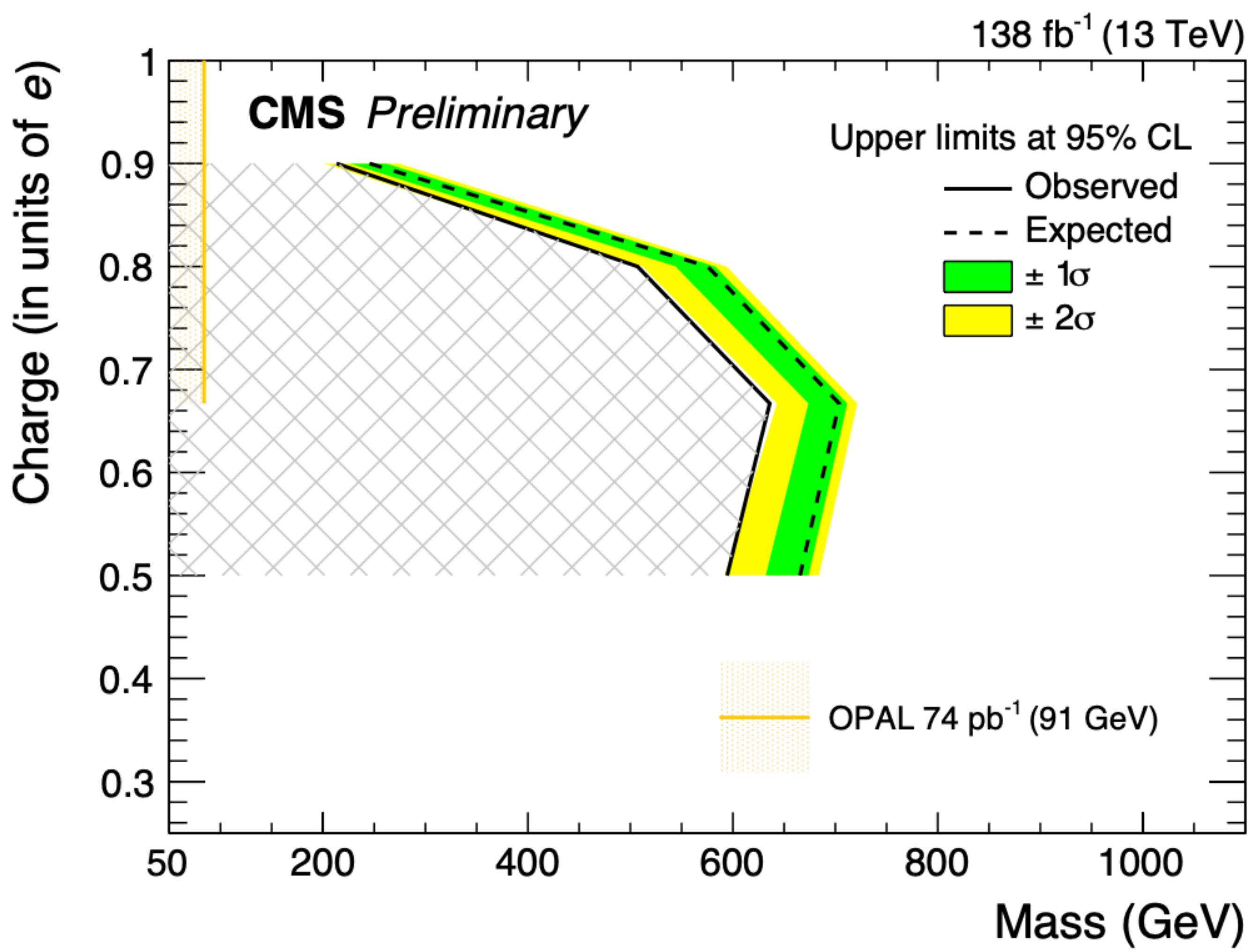




Run-1 results from CMS for 2/3e and 1/3e FCPs not shown

Results with Run-1 [*] uncovered an issue with the FCP simulation in the muon chambers, **now corrected for Run-2**

- No impact on Sig *vs* Bkg method (from tracker)
- Affects selection efficiency in trigger/offline reconstruction for charges of 1/3e

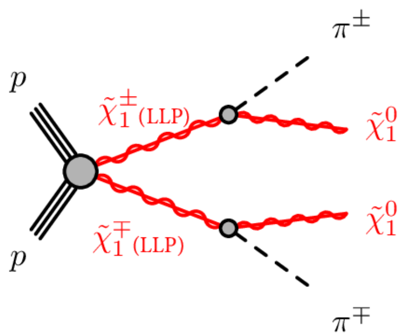
→ **Errata for Run-1 analysis are coming**
→ **Run-2 PAS will be held until errata is submitted**

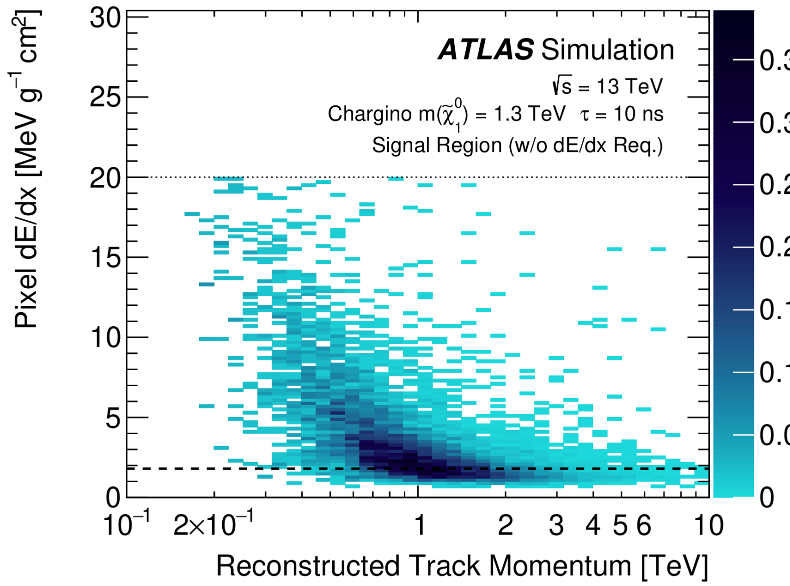
[*] PHYSICAL REVIEW D 87, 092008 and JHEP07 (2013) 122

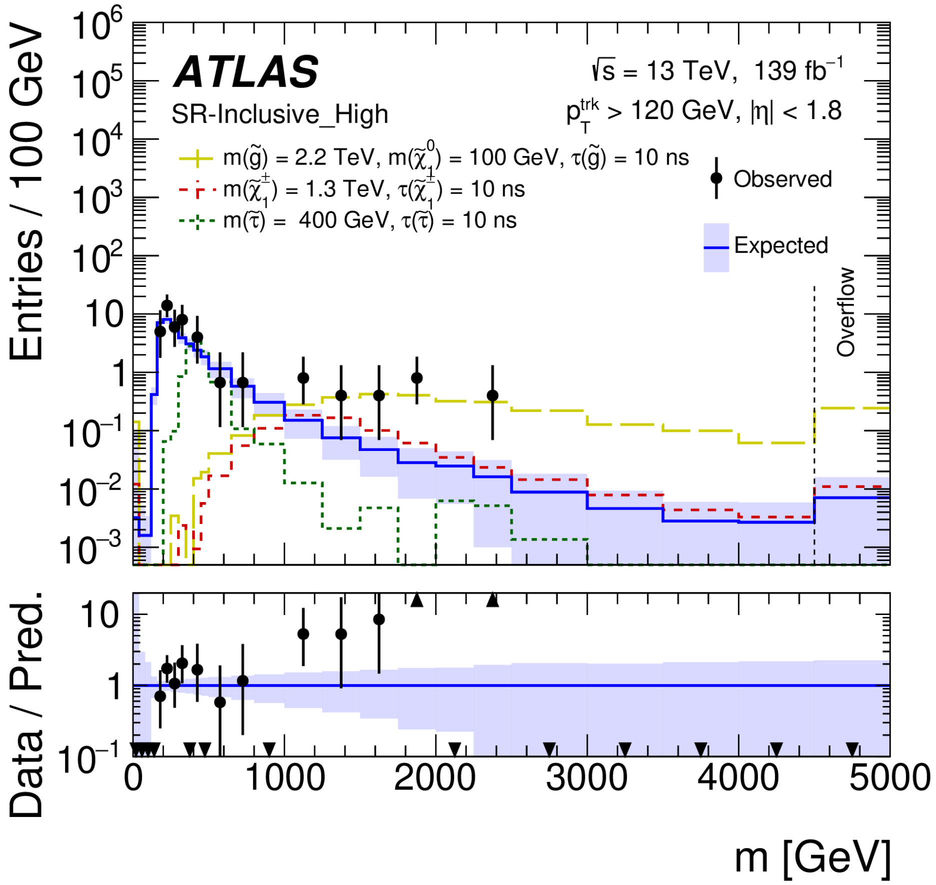
Highly ionizing particles

arXiv:2205.06013 [hep-ex]

- Search for **heavy charged LLPs** in the **ID**
  - Large dE/dx measured in Pixel layers
  - dE/dx ~ βγ = p/m → mass estimate
  - Compare dE/dx measurements with a data-driven background template
    - signal: chargino pair production







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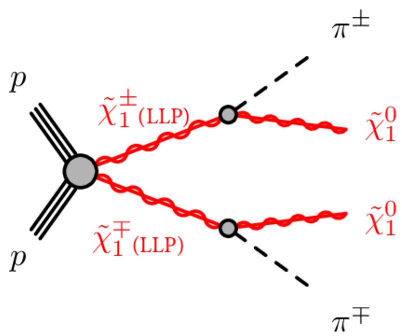
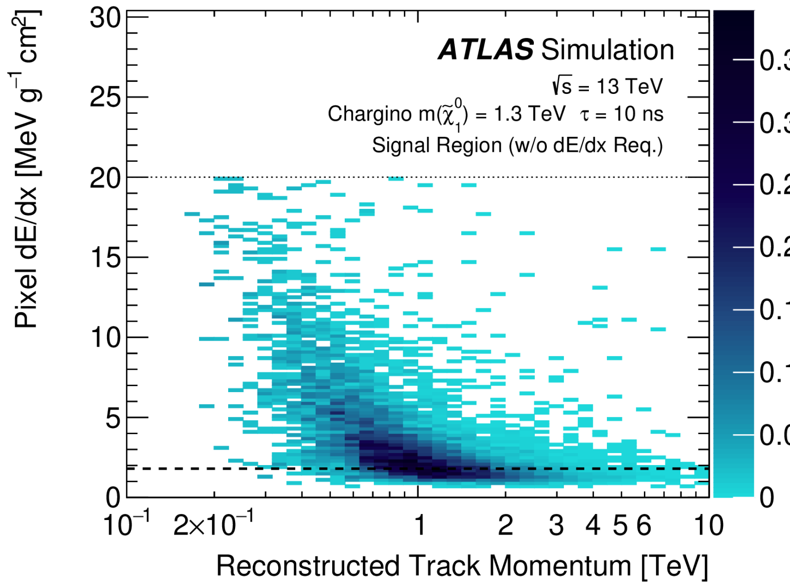
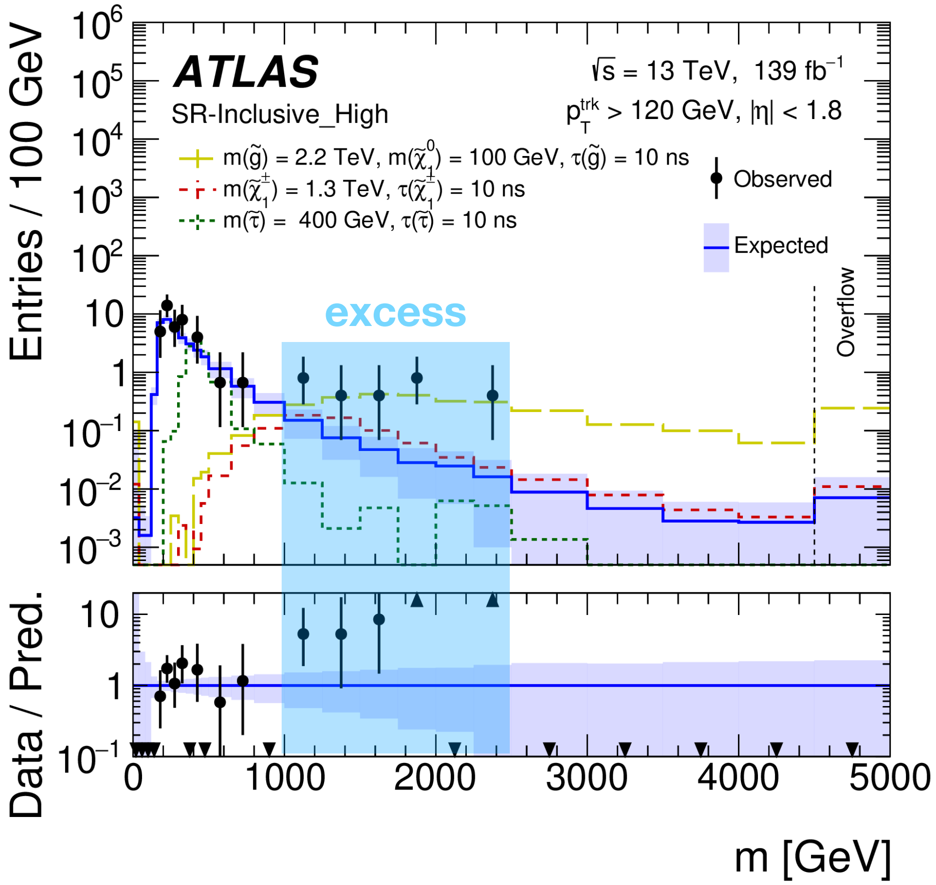


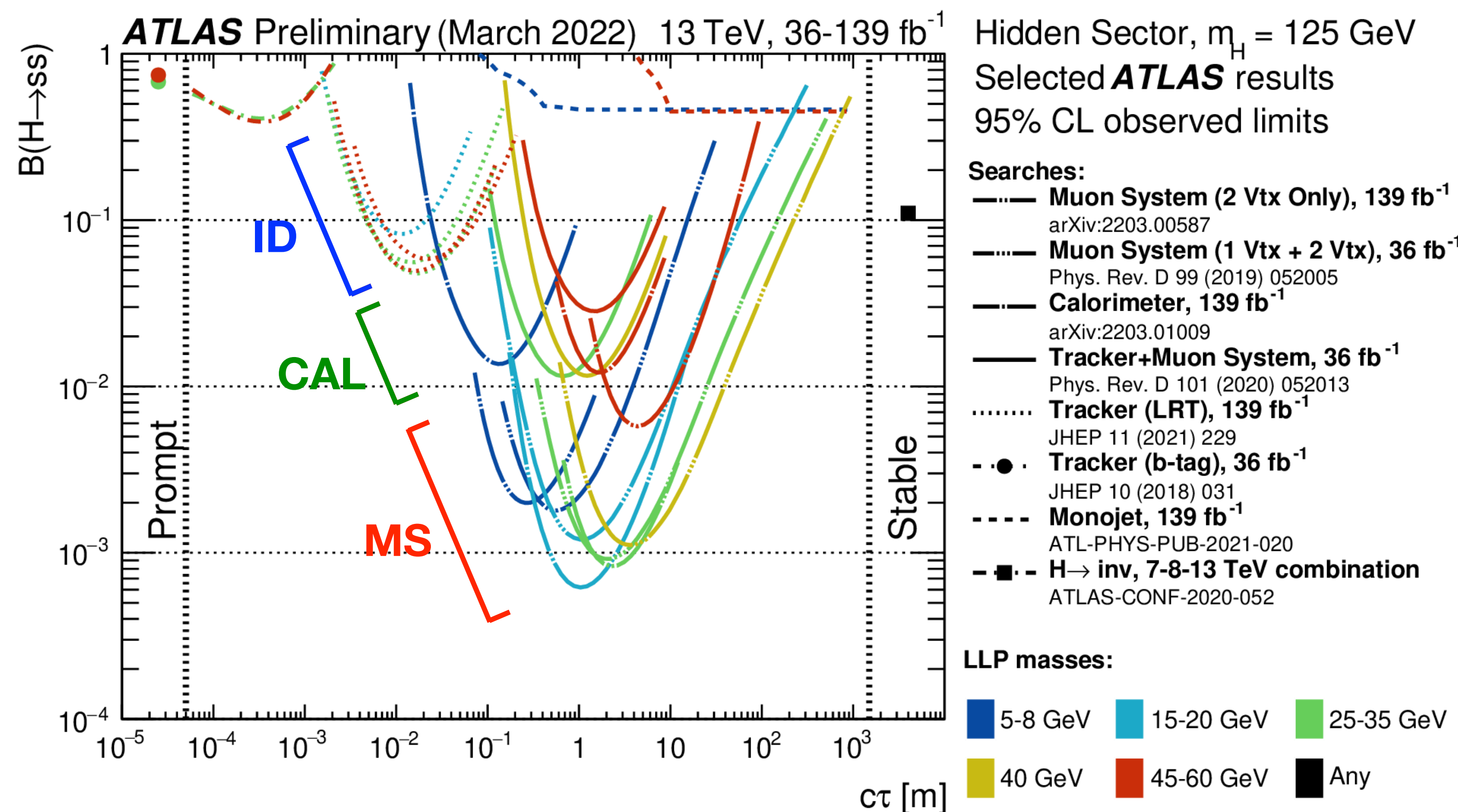




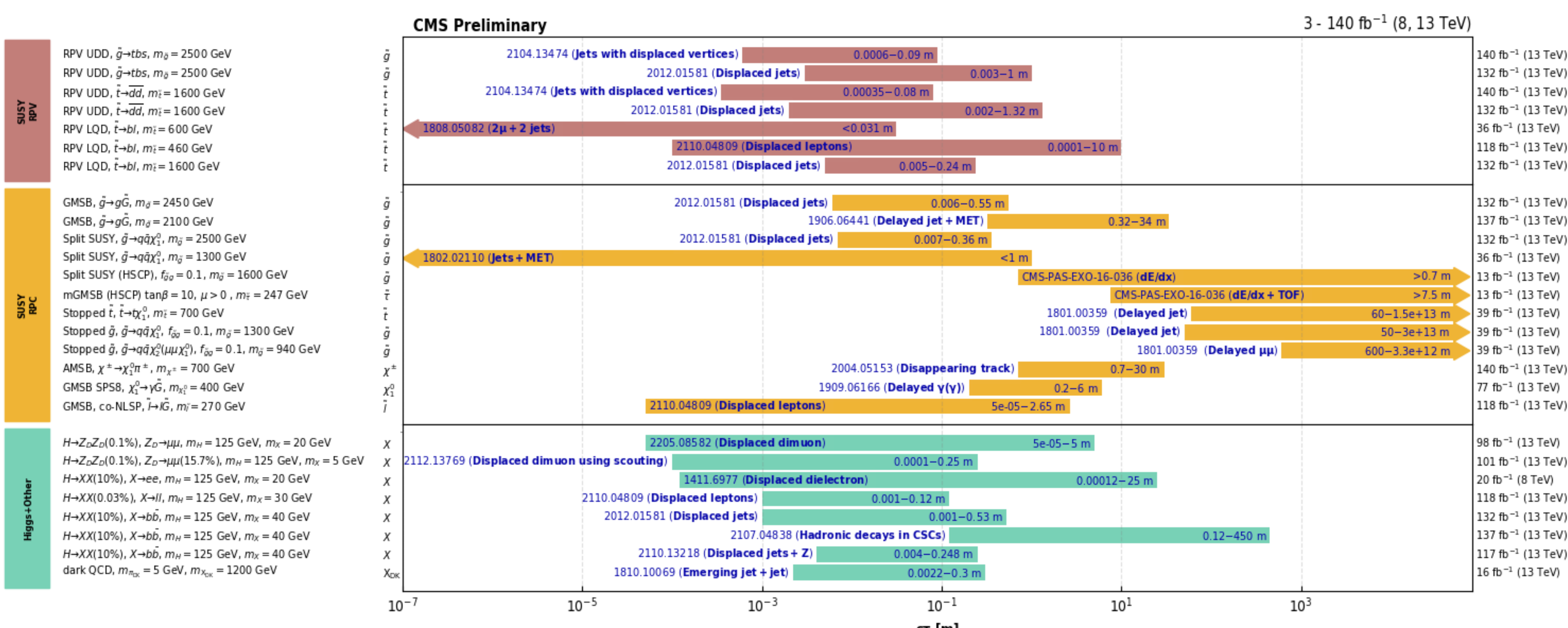
- Excess in the high-dE/dx region
  - 3.6σ local (3.3σ global) significance
  - $\beta \sim 0.5$ from dE/dx, but $\beta \sim 1$ from time-of-flight
    - incompatible with this signal!
    - also, no excess in other related analyses (e.g. multi-charged particles)

Summary plots

ATL-PHYS-PUB-2022-007



Overview of CMS long-lived particle searches



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

SummaryPlotsEXO13TeV

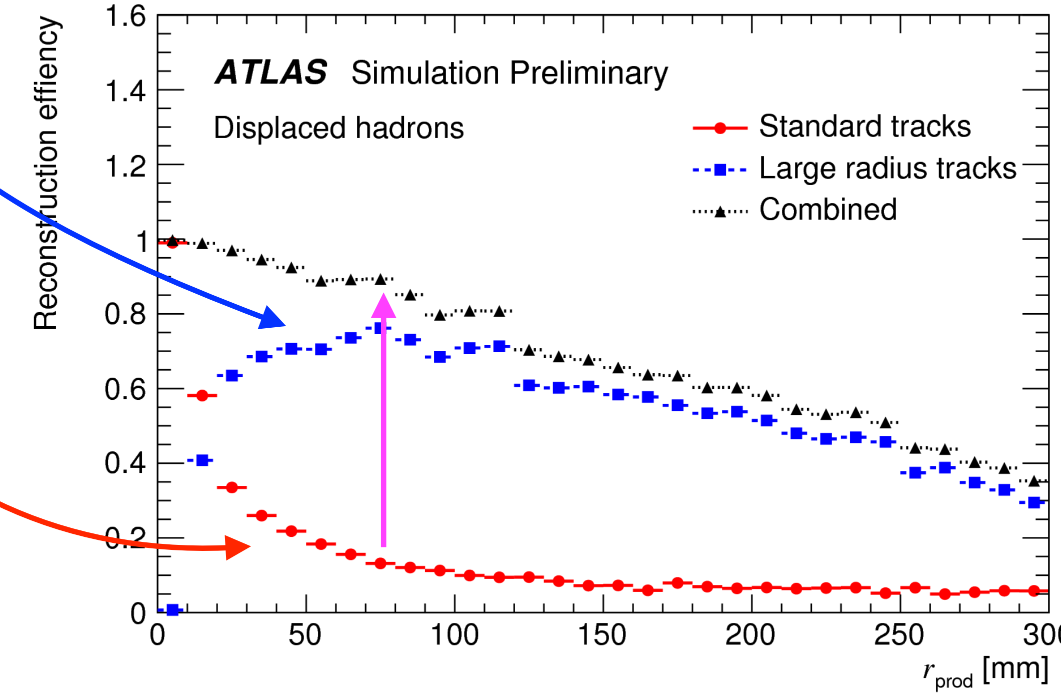
Conclusions and outlook

- In the last few years, ATLAS and CMS produced an impressive suite of LLP searches
  - Continuous effort to use the full potential of each sub-detector
  - Complementarity of different sub-detectors and techniques
- Still room for improvement and gaps to cover
  - New triggers for displaced signals
  - New dedicated reconstruction and analysis tools (e.g. based on ML)
  - Re-interpretation of prompt analyses for small displacements (e.g. see ATLAS-CONF-2018-003)
  - Extension to poorly covered channels (e.g. displaced taus)

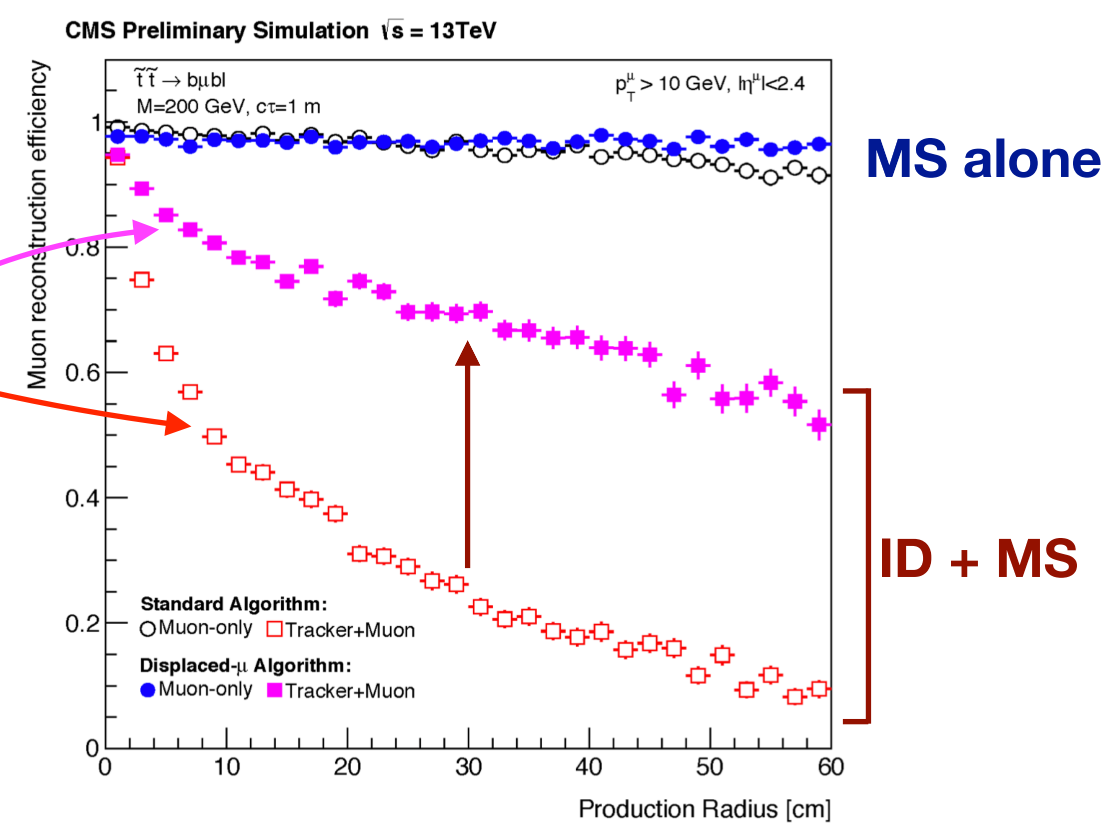
Backup

Tracking for displaced particles

- The ATLAS standard tracking is optimized for prompt particles
  - A dedicated *large-radius tracking* is run at a later stage on ~1% of the recorded data, using left-over hits from the *standard tracking*
    - in Run-3 LRT is incorporated with the standard tracking



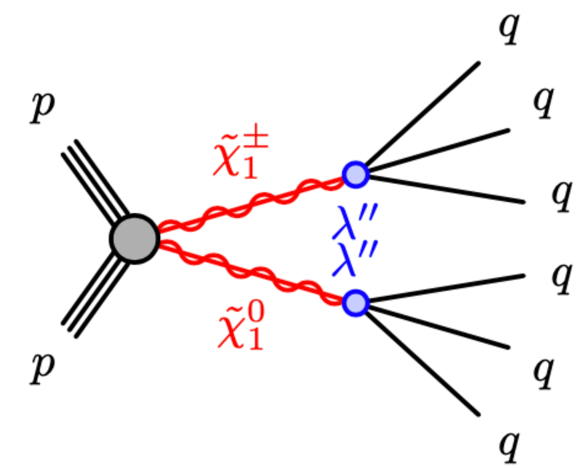
- In CMS, this approach is included in the *standard tracking*
- CMS also developed dedicated *displaced-muon algorithms*, using the MS alone or ID + MS



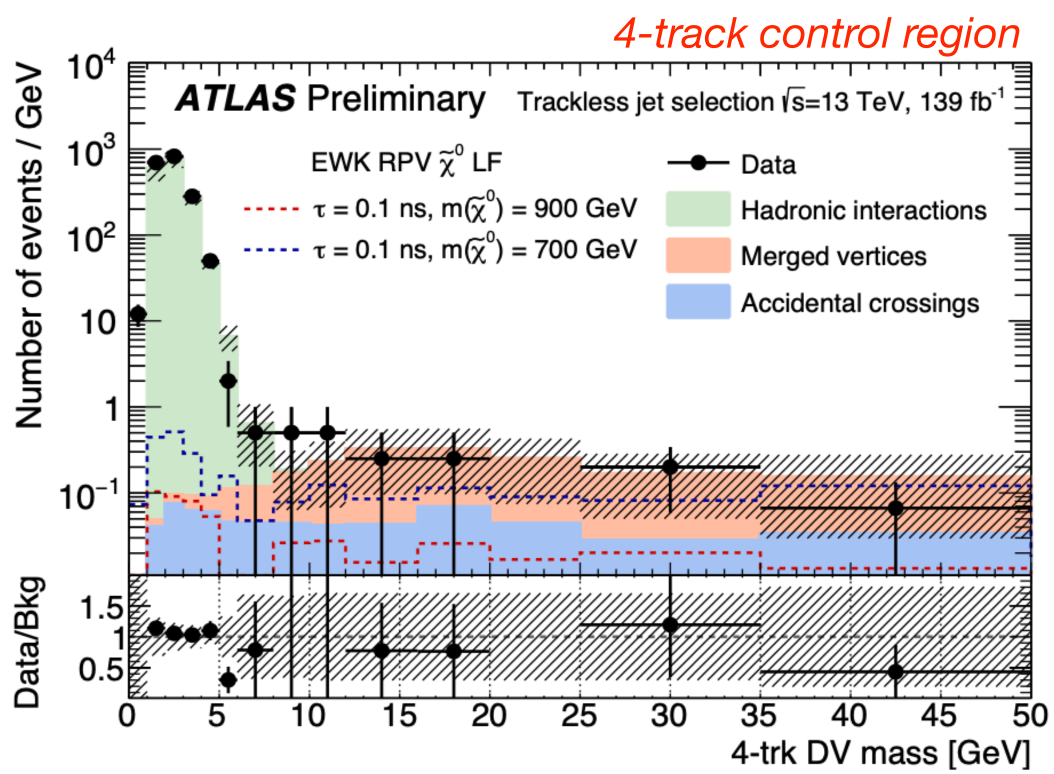
Displaced jets

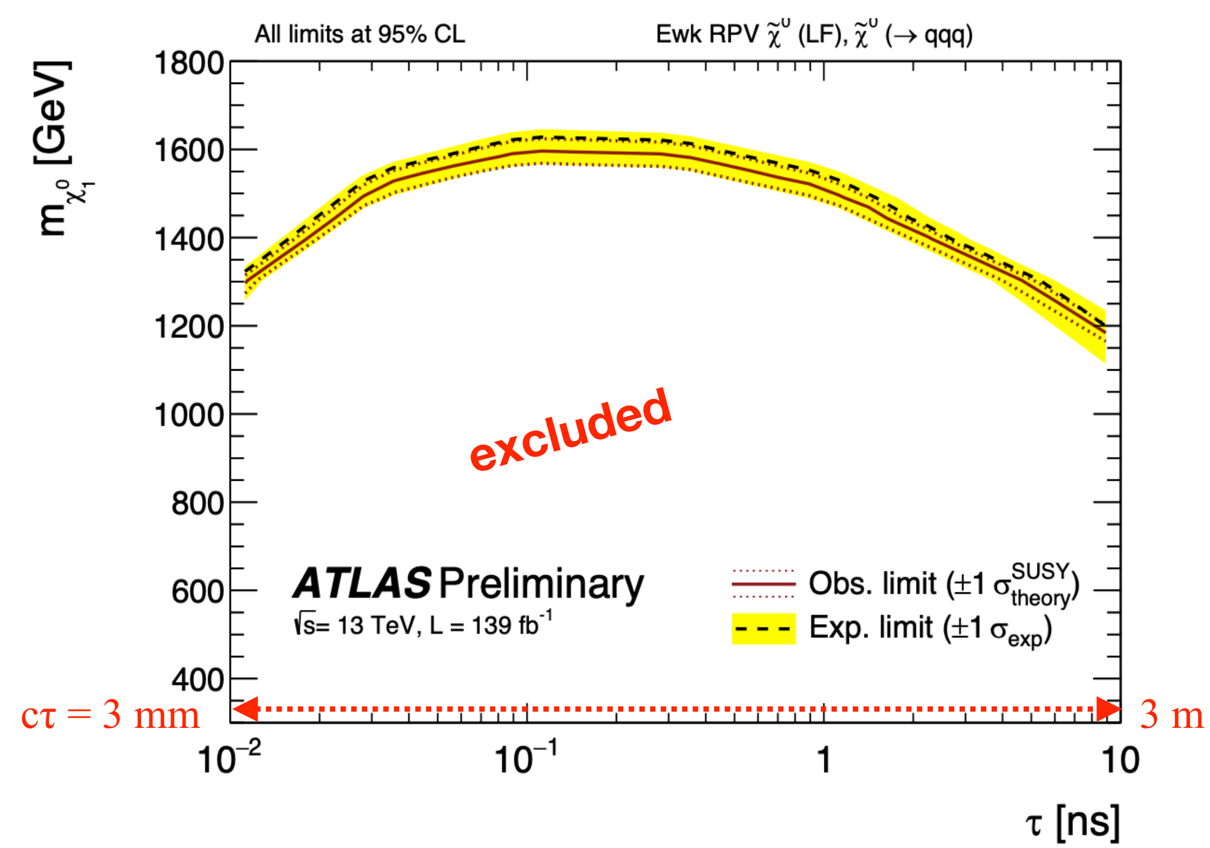
ATLAS-CONF-2022-054

- General search for **multi-jet** + **DVs** within the **ID**
  - ≥ 4–7 jets in trigger and offline
  - ≥ 1 DV (no jet-DV matching)
  - Main background from nuclear interactions, low-mass resonances, combinatorics
    - measured in data from DV-jet correlations
  - No excess observed → limits on RPV SUSY benchmark models



electroweak RPV model





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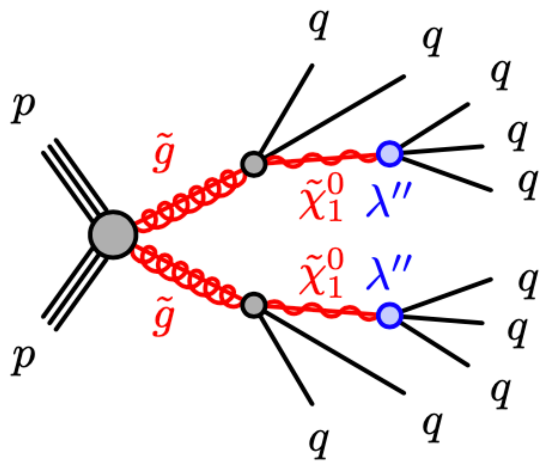
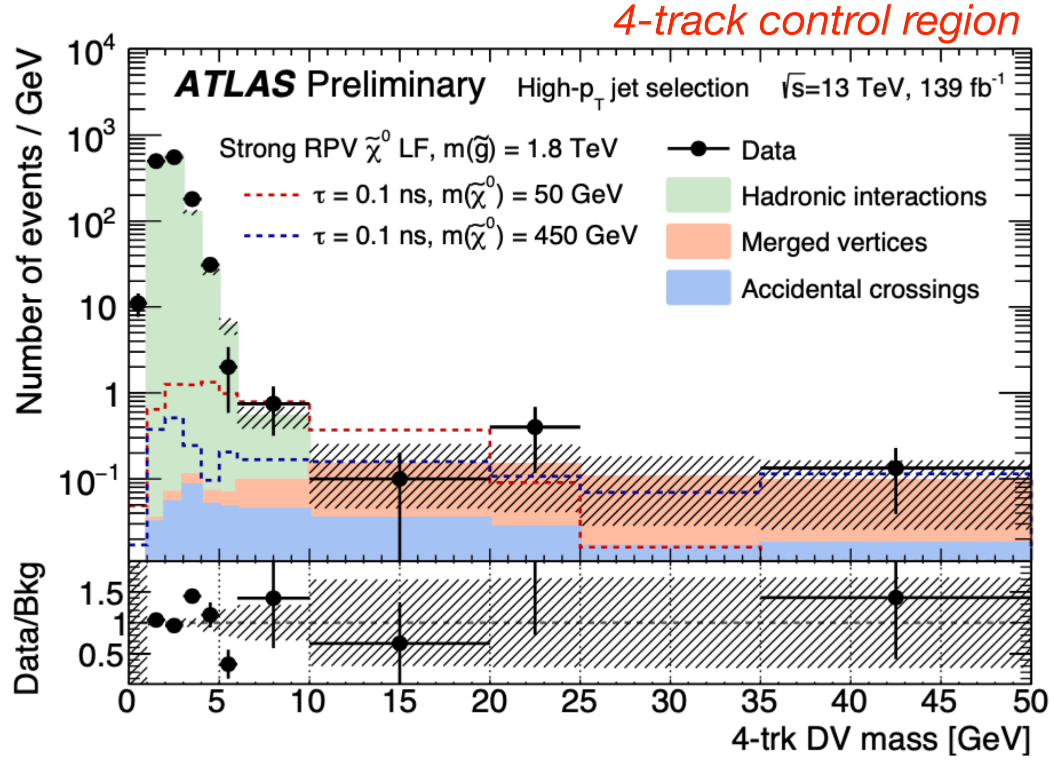
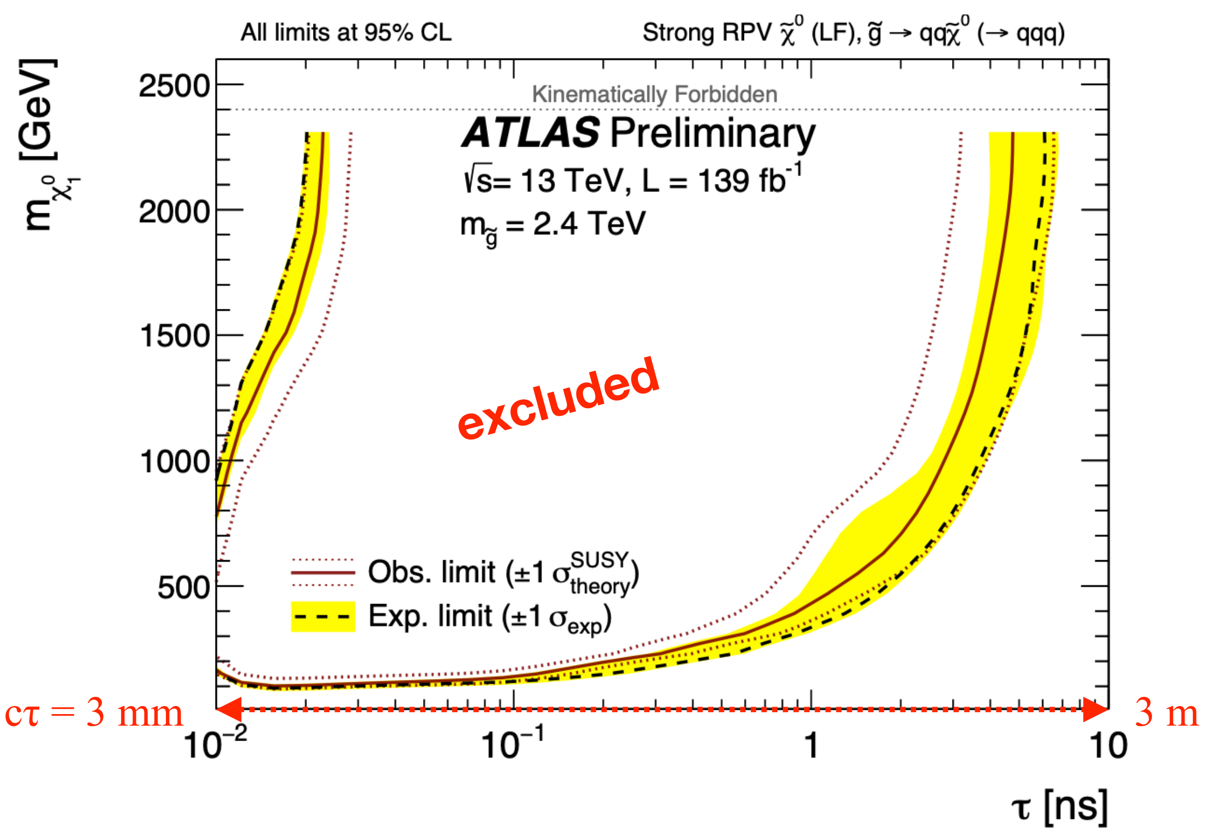


strong RPV model

4-track control region

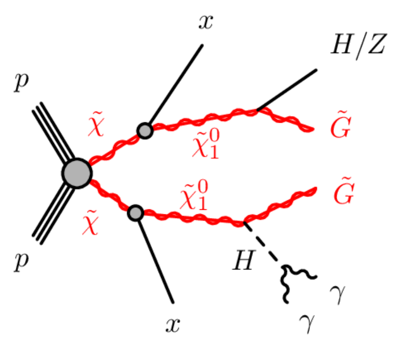


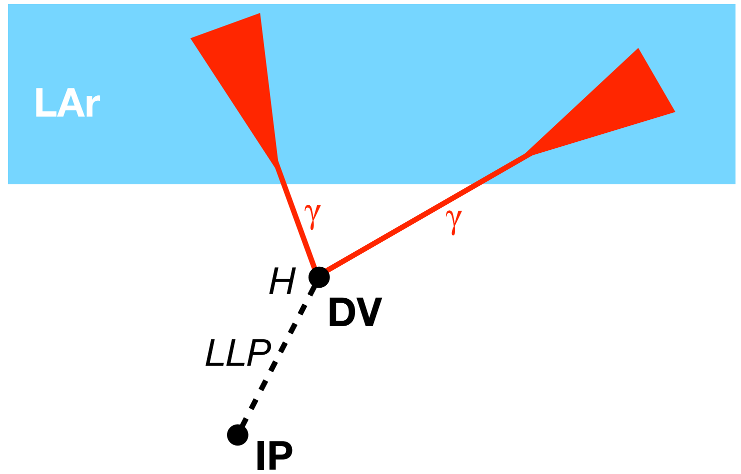


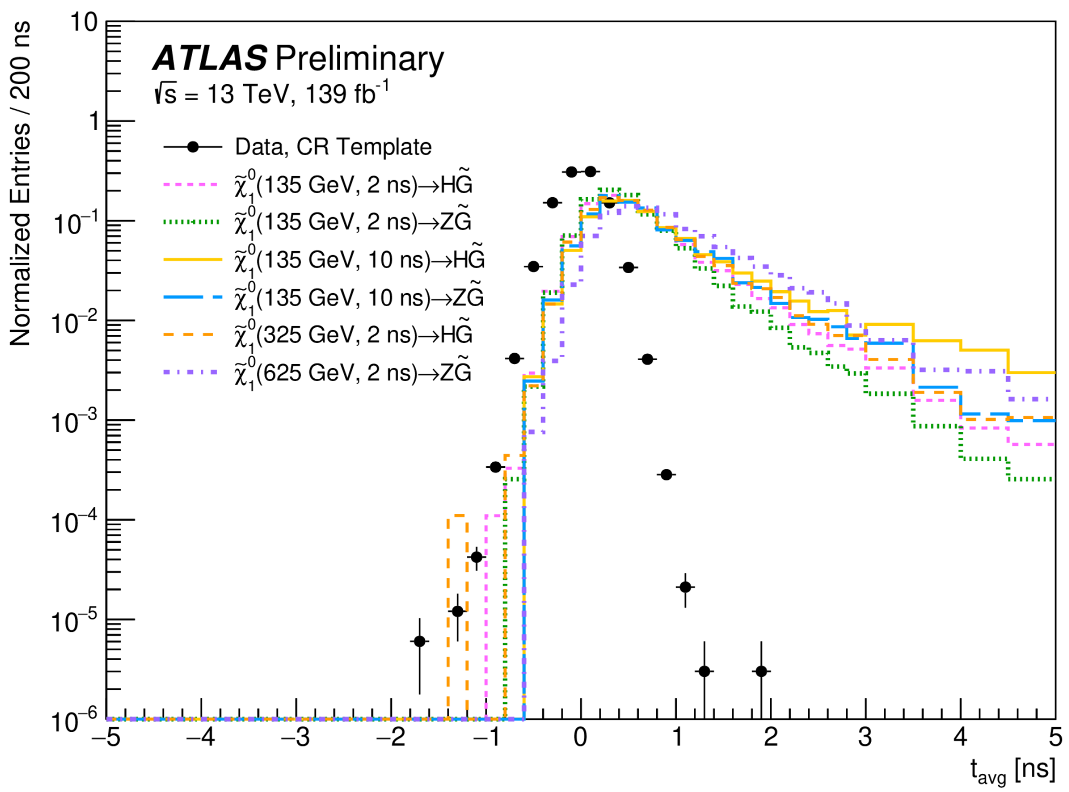
Displaced photons

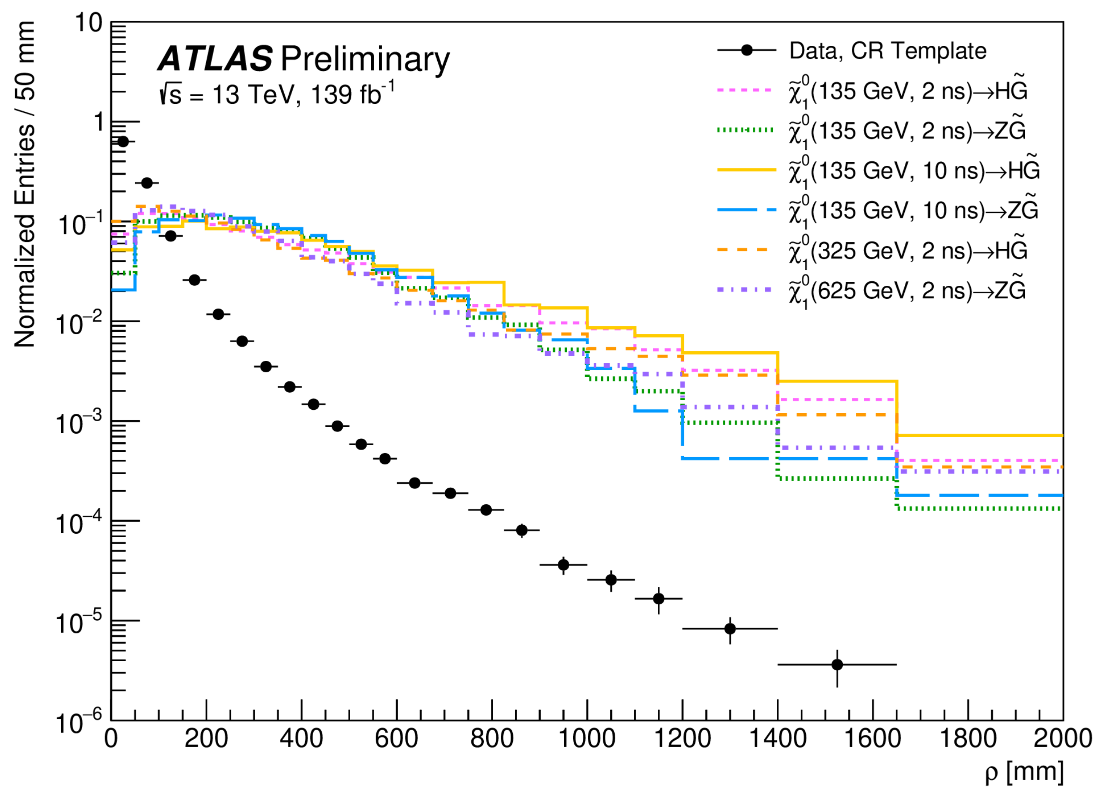
ATLAS-CONF-2022-051

- **Displaced** and **delayed** $H \to \gamma\gamma$ or $Z \to ee$ in **ECAL**
  - H/Z produced in decays of heavy, slow LLPs
  - Di-photon triggers for both $\gamma\gamma$ and ee
  - ECAL time resolution ~ 100 ps and segmentation
    - use photon time and di-photon 2D vertex









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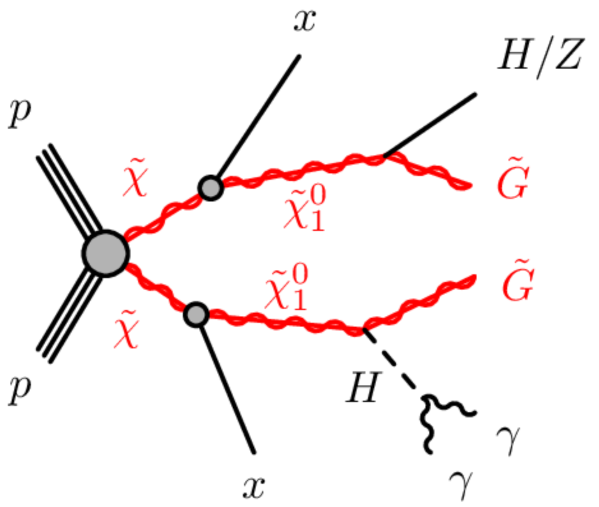

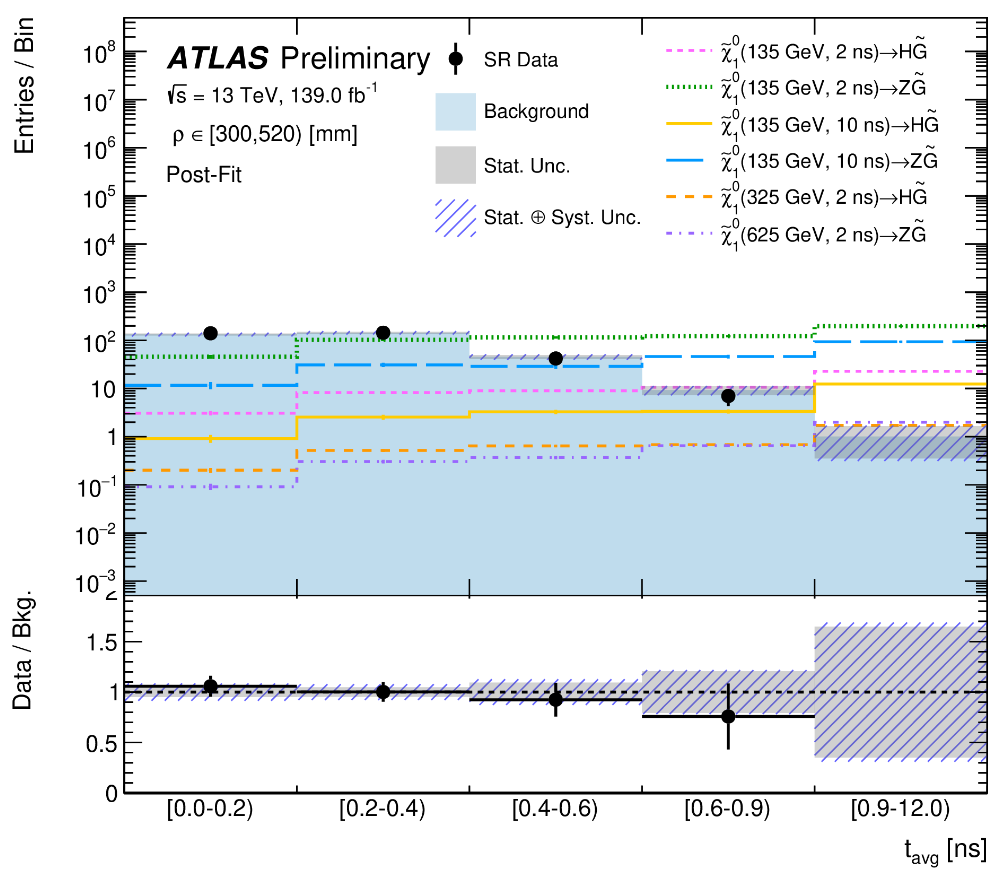

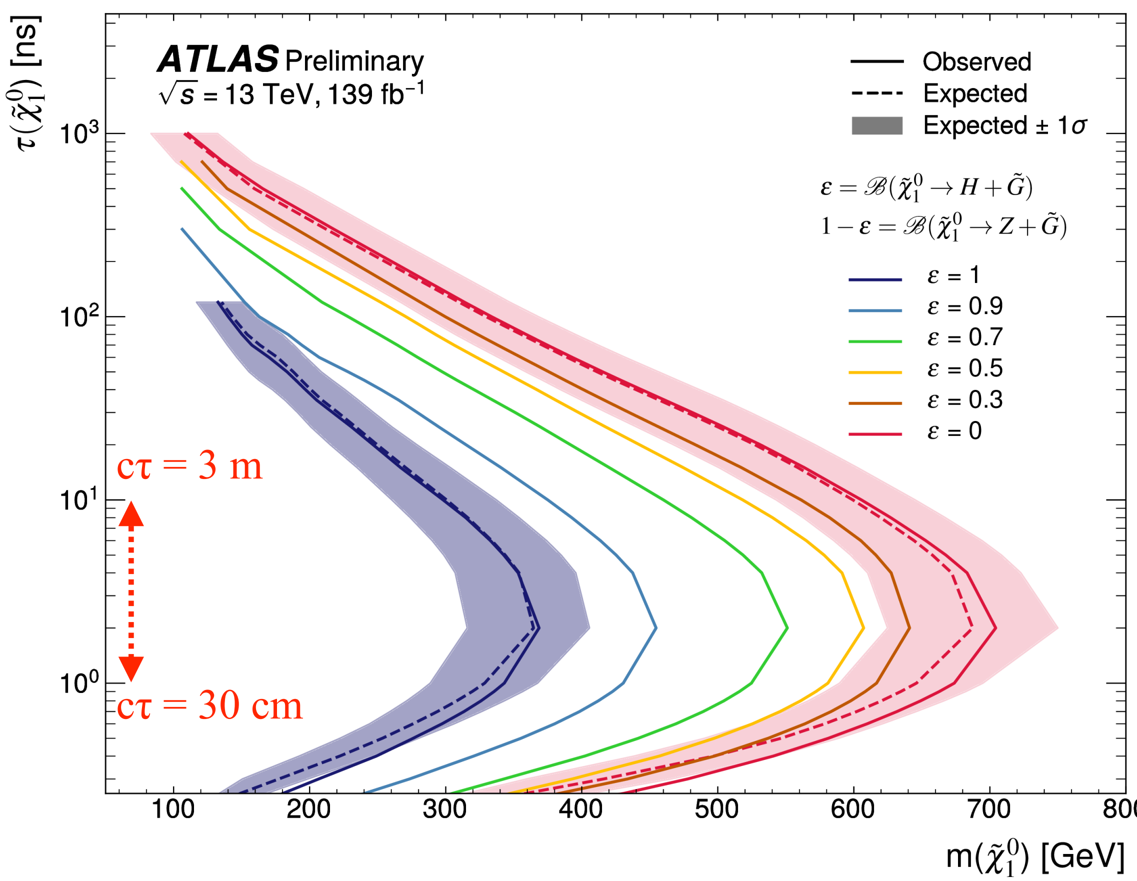

3 m

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    - di-muon masses > 300 MeV
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  - Limits on HADM dark photon model: $H \to Z_D Z_D$
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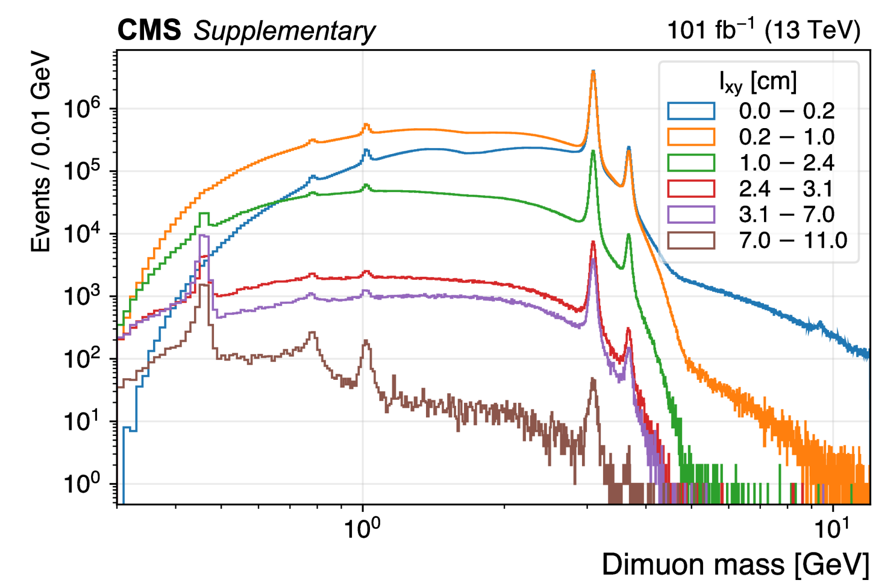

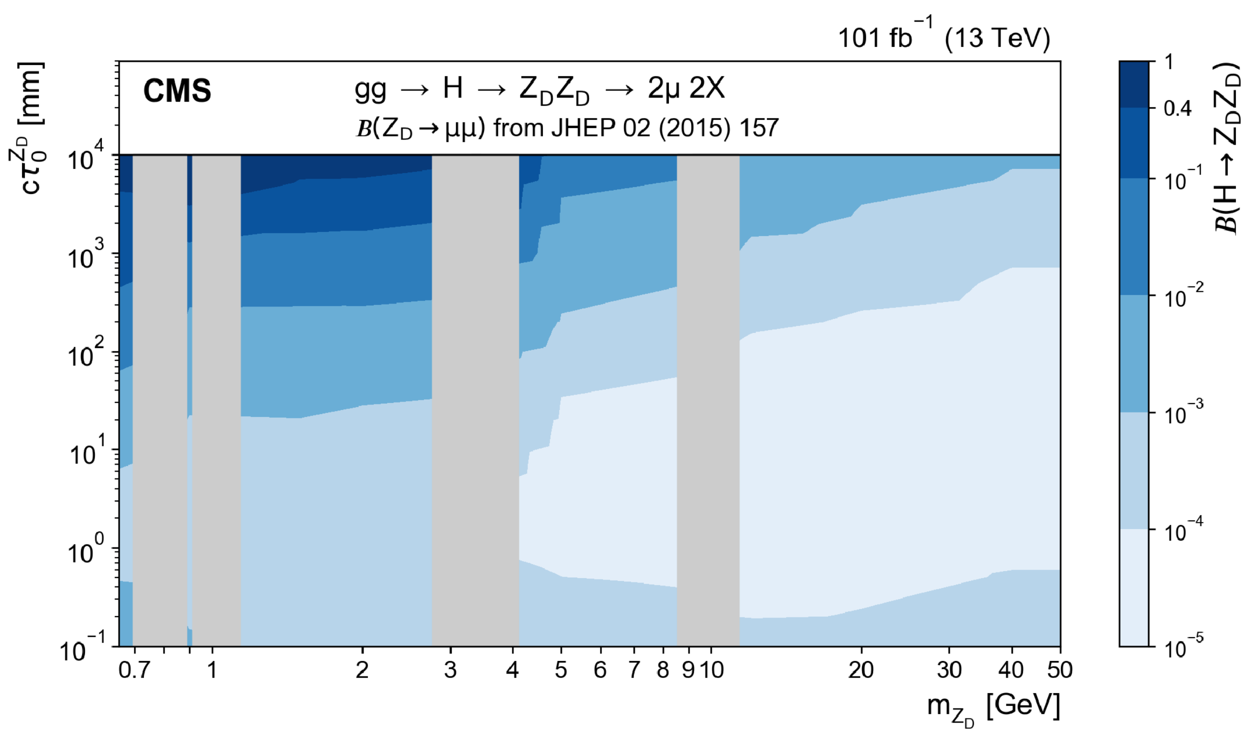

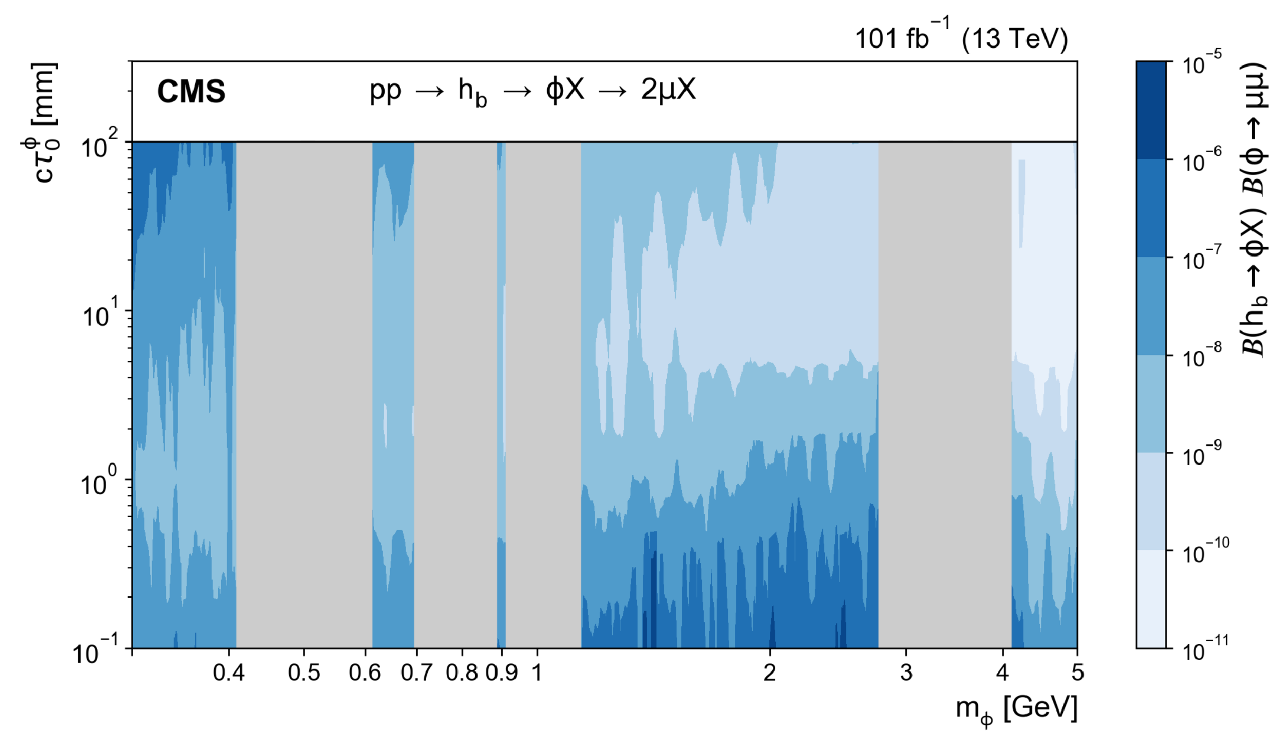

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arXiv:2206.12181 [hep-ex]

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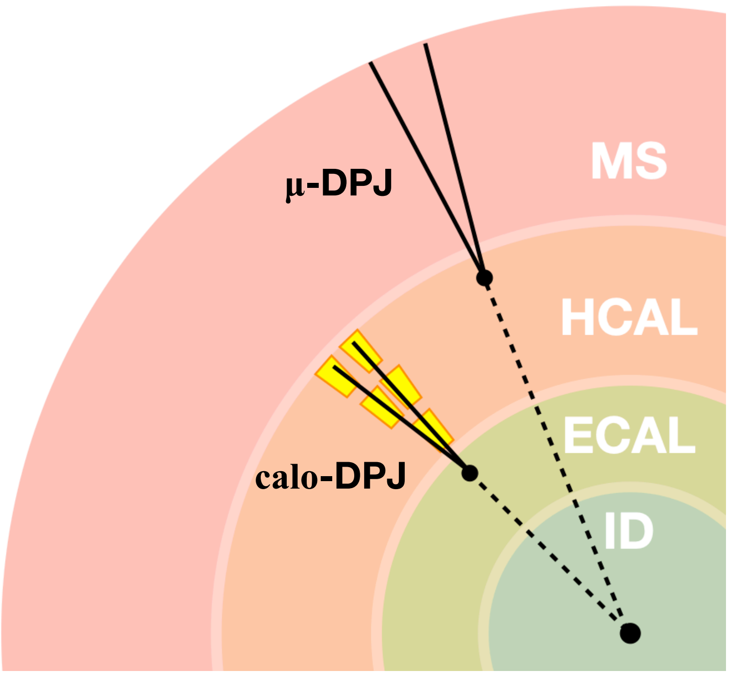

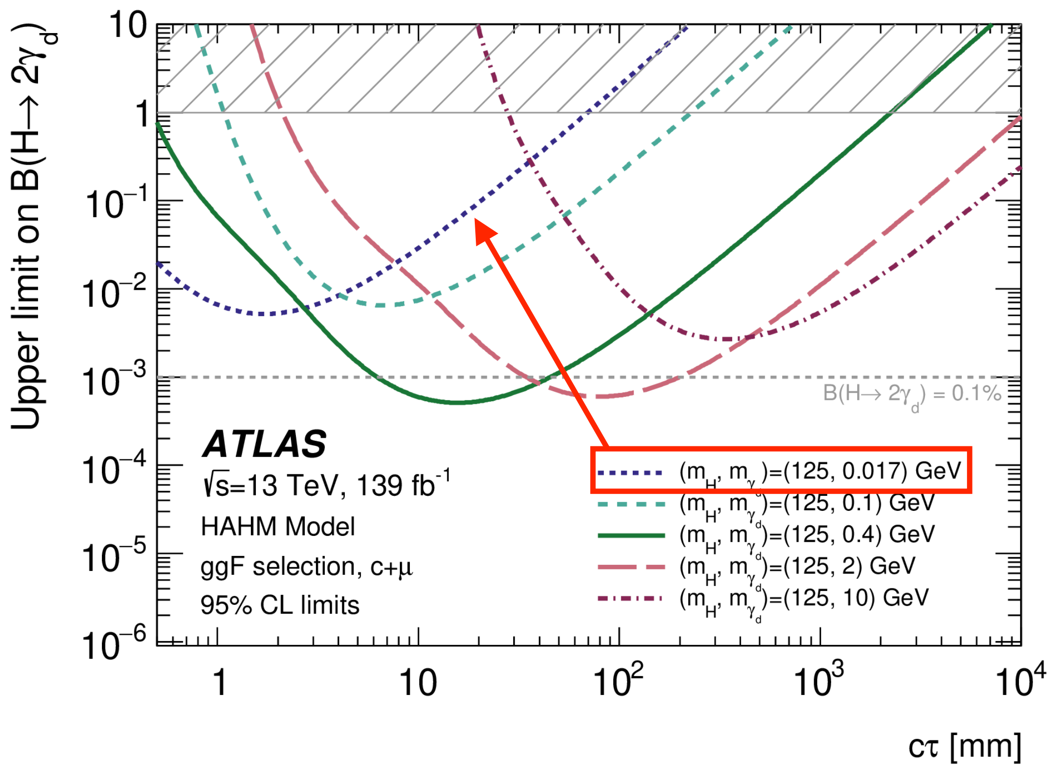

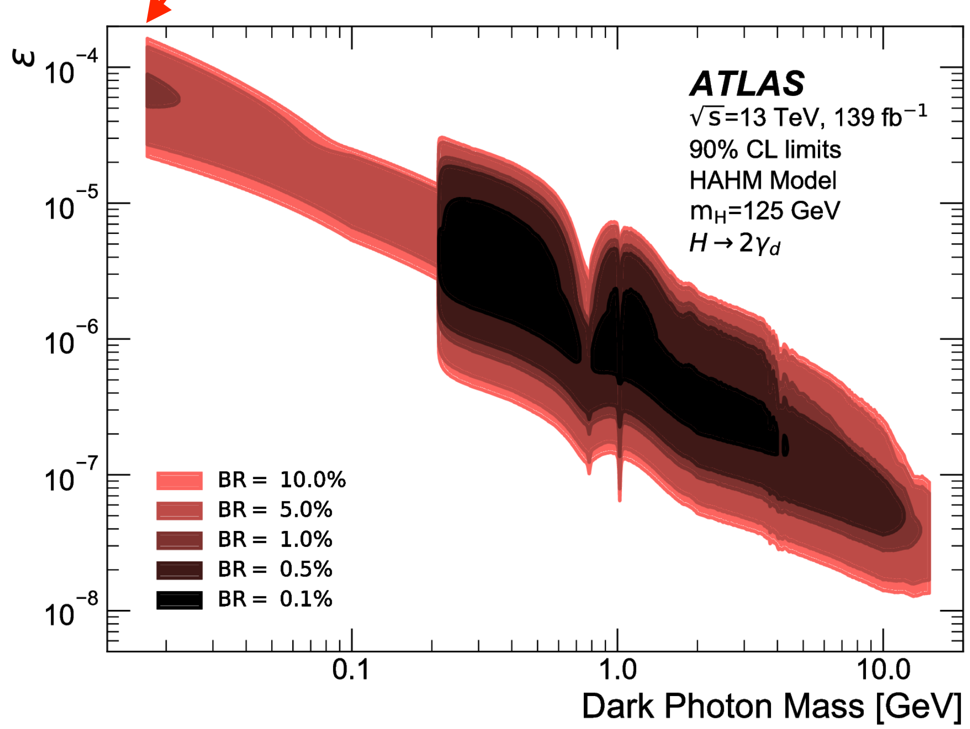

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