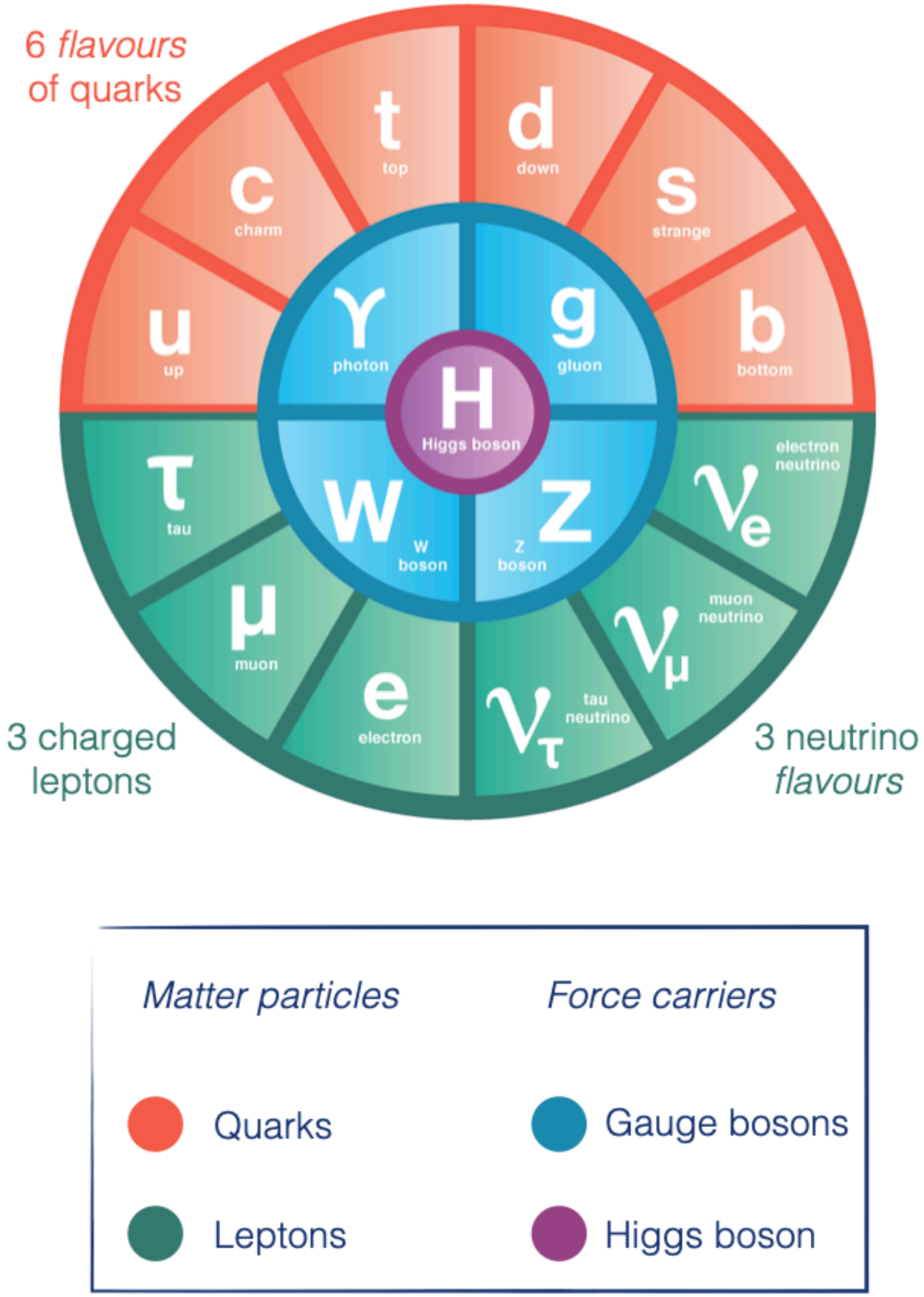
Exotic Decays of Higgs Bosons to Long-Lived Particles in ATLAS and CMS

Dominique Trischuk, on behalf of the collaborations
21st Workshop of the LHC Higgs Working Group
December 5, 2024

ATLAS EXPERIMENT · LHC Higgs Working Group · Brandeis University · CMS

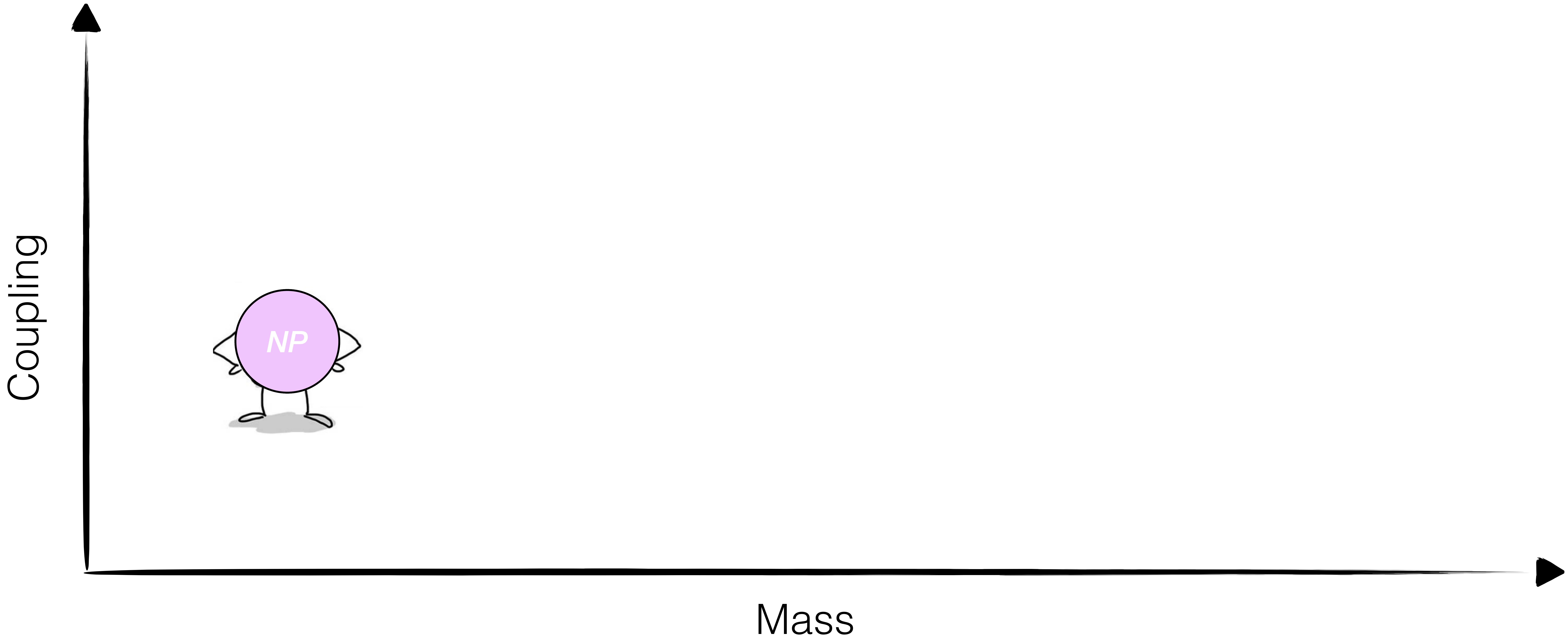
Testing the Standard Model



How to explore interconnection between particles and cosmology?

1. Understanding fundamental parameters
2. **Searching for new particles and forces!**

Where Are The New Particles?



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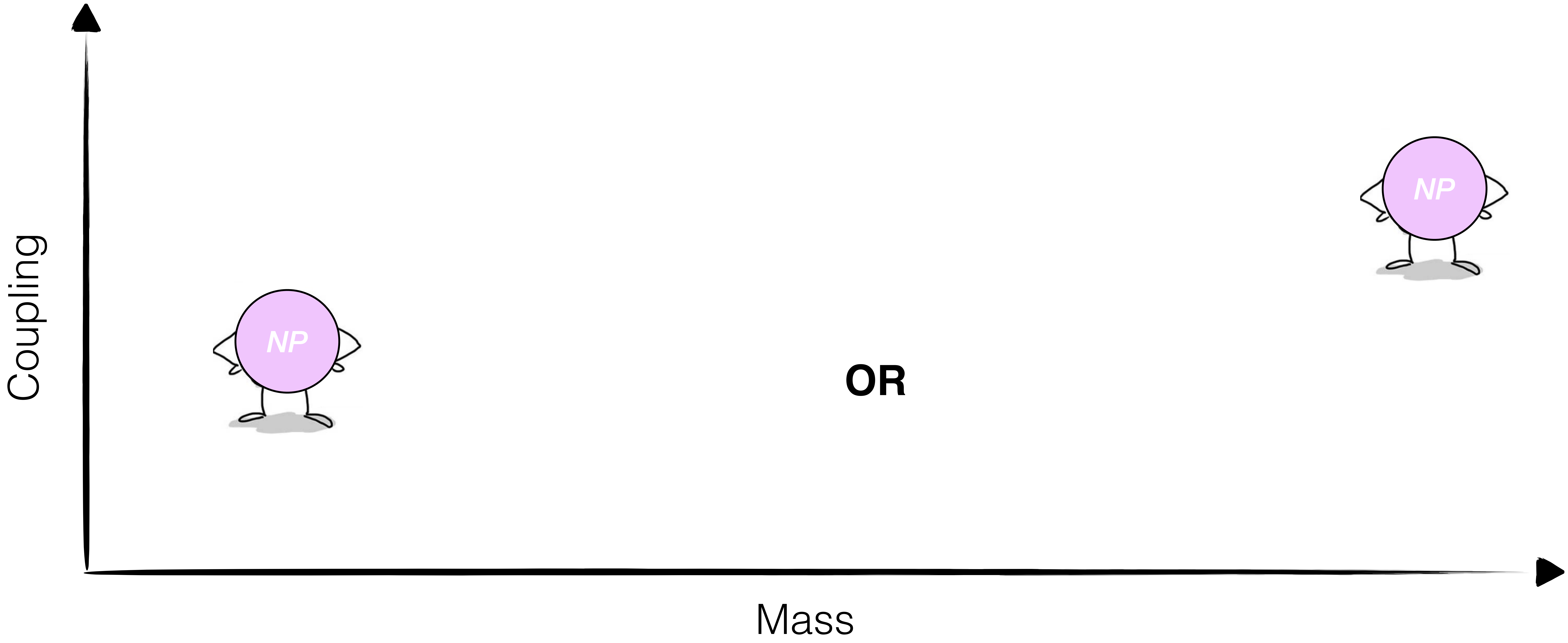

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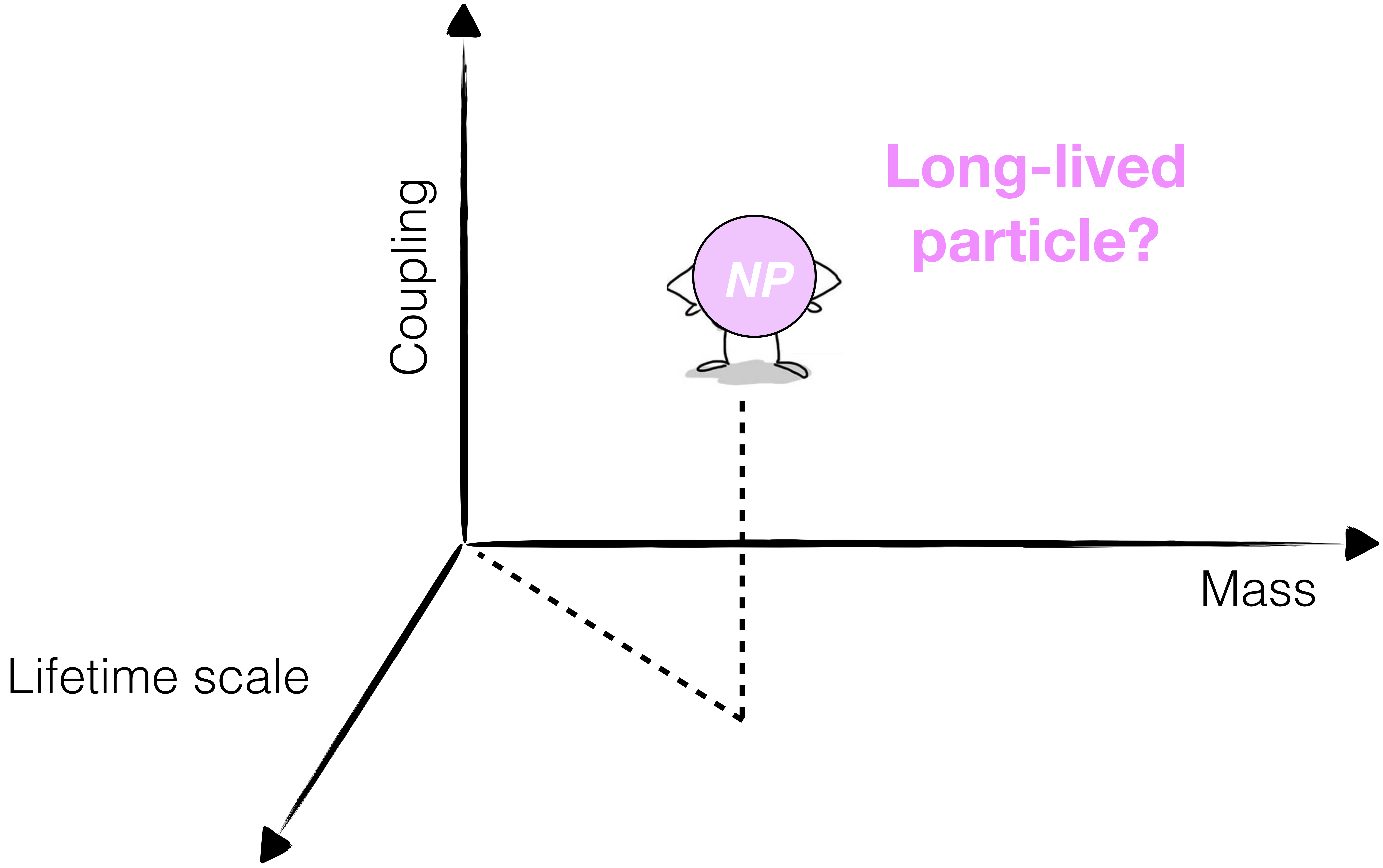


Long-Lived Particles

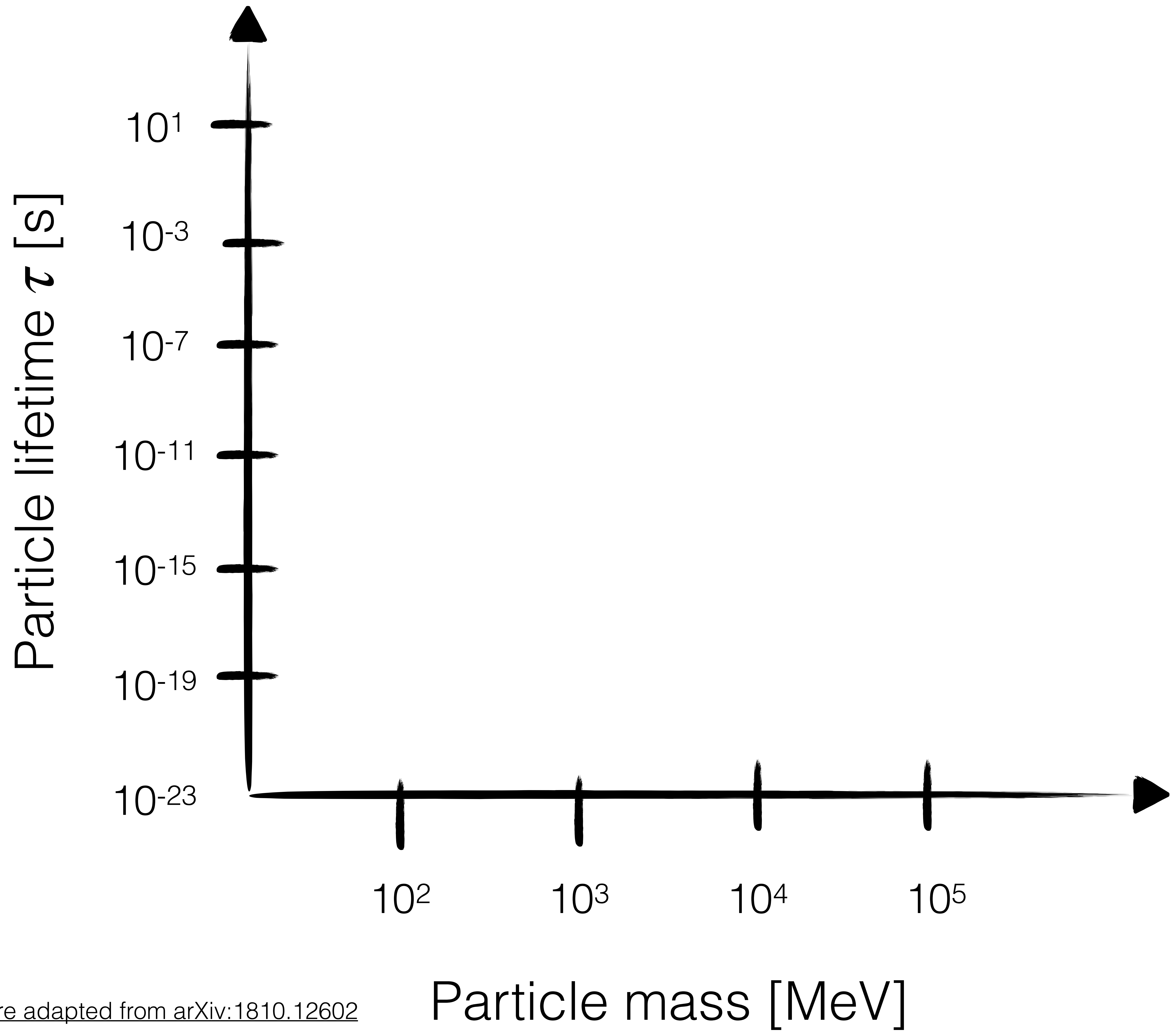


Figure adapted from arXiv:1810.12602

- Variety of mechanisms control a particle's lifetime including,
  - size of its interaction strength
  - mass of particle mediating its decay
  - approximate symmetries

Long-Lived Particles

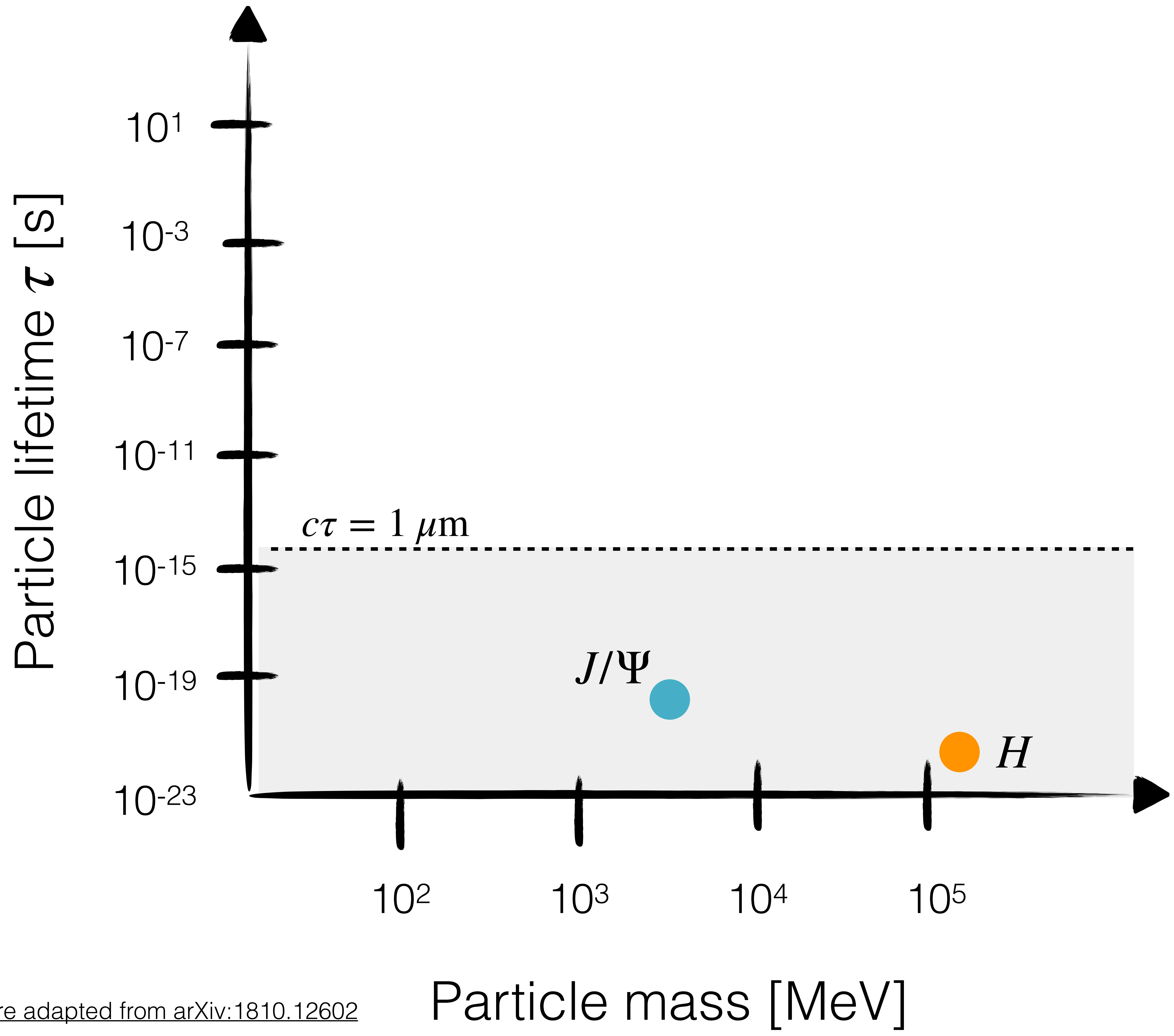
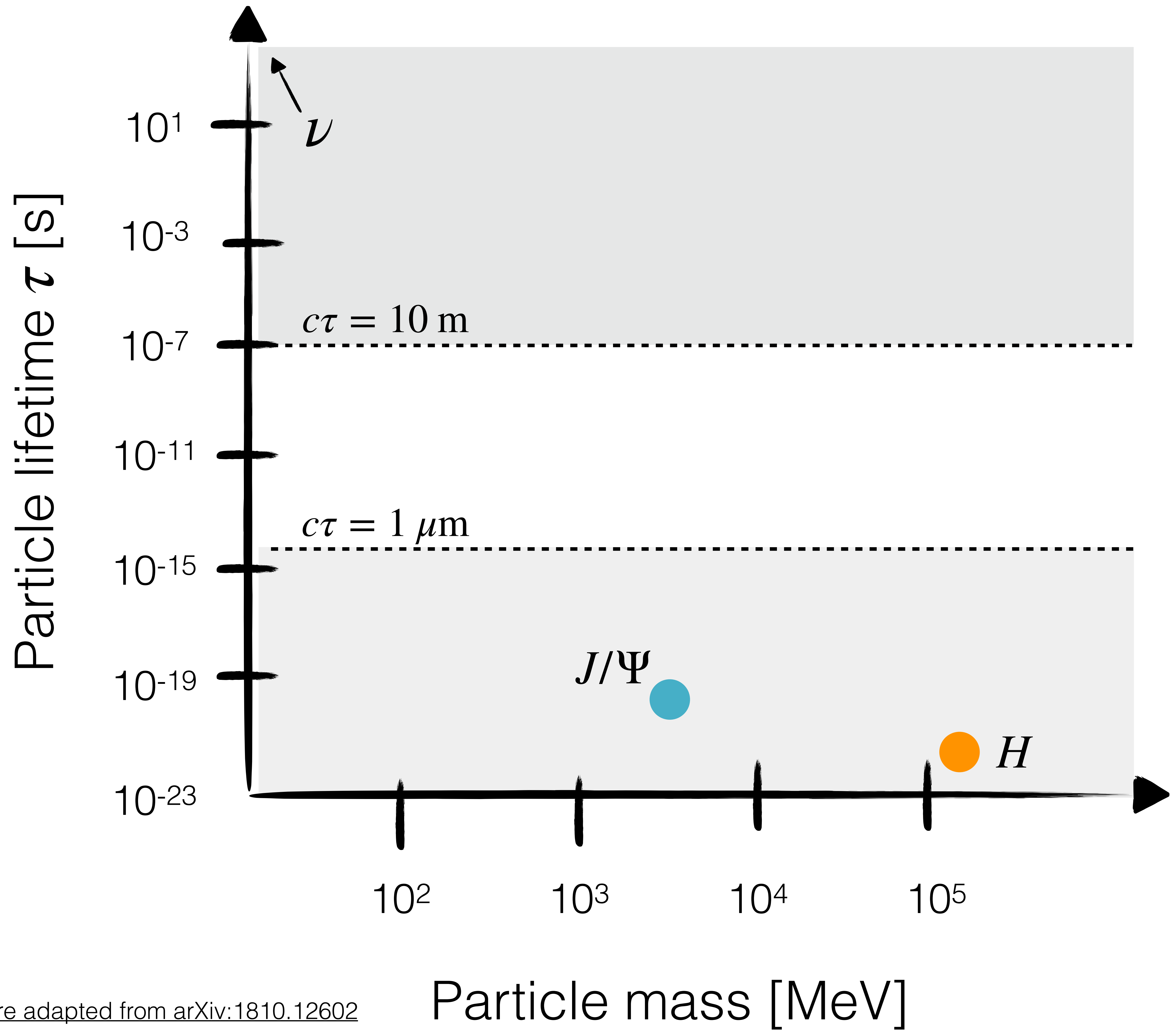


Figure adapted from arXiv:1810.12602

Detector prompt

bulk of the high-energy collider searches

Long-Lived Particles

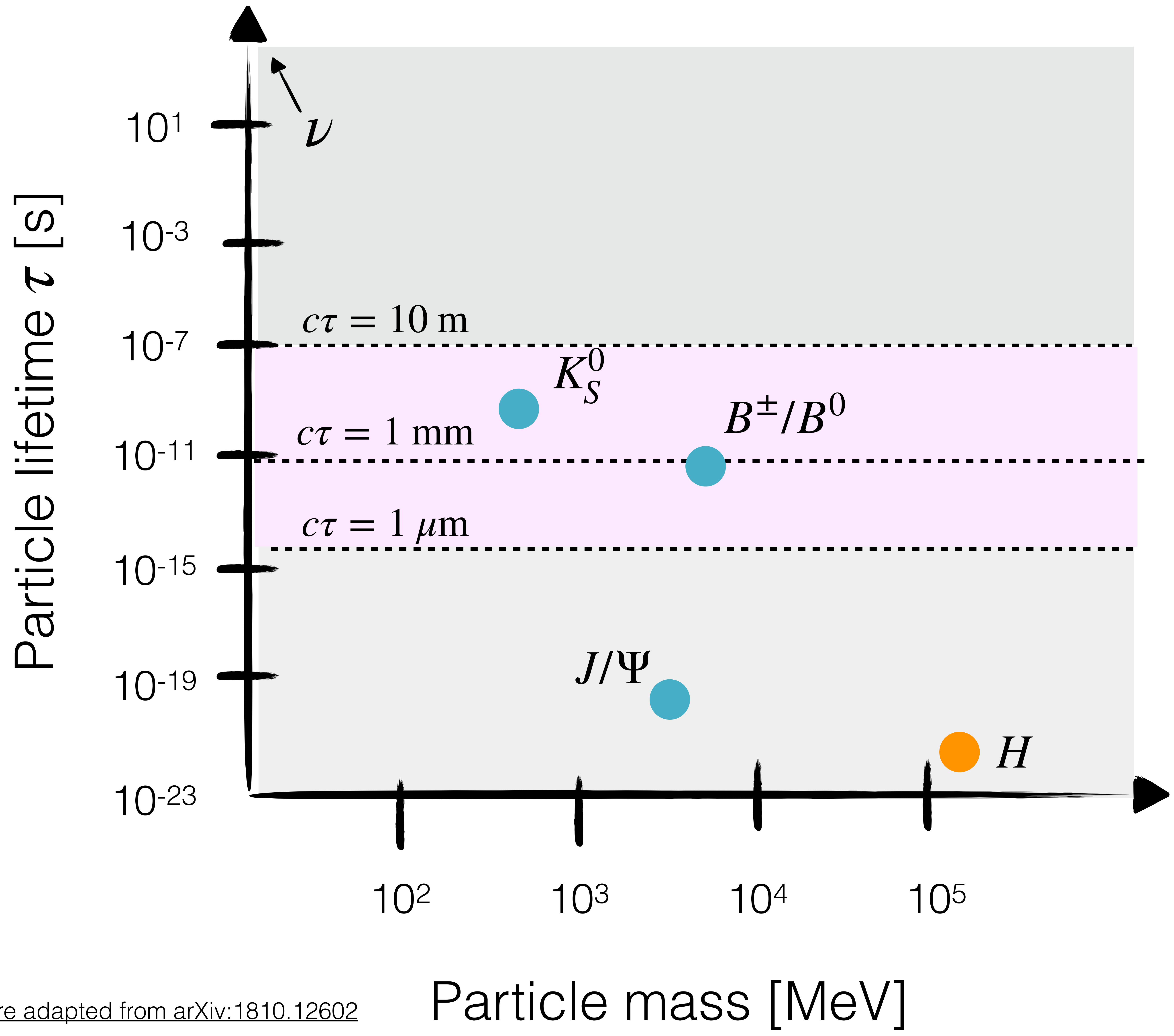


Detector stable → missing energy searches etc.

Detector prompt → bulk of the high-energy collider searches

Figure adapted from arXiv:1810.12602

Long-Lived Particles



Detector stable → missing energy searches etc.

Long-lived particles (LLPs)

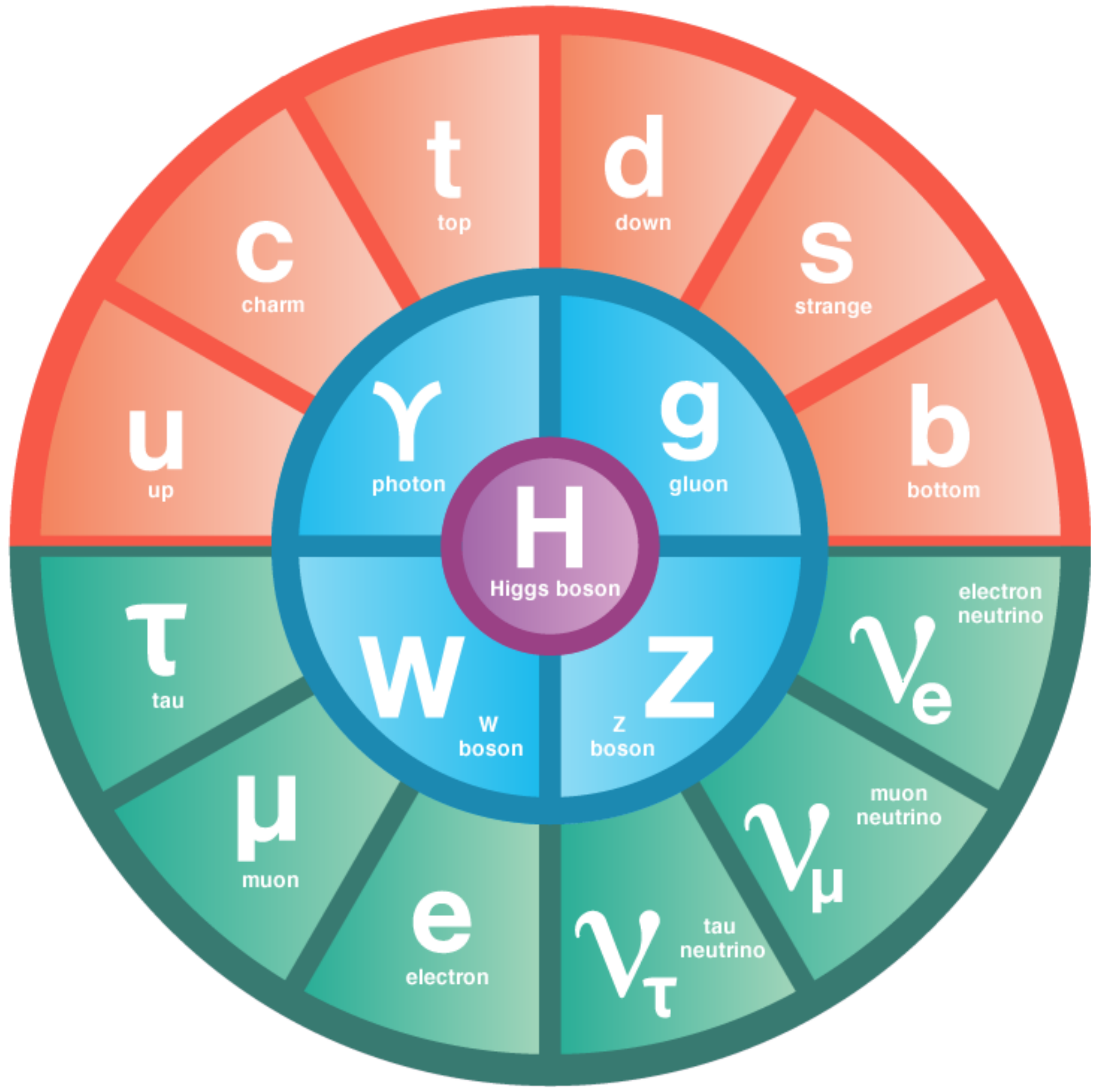
Detector prompt → bulk of the high-energy collider searches

Figure adapted from arXiv:1810.12602

Connection to the Dark Sector?

Visible sector

ordinary
matter
~ 5%



Mediator particle

"Scalar portal"

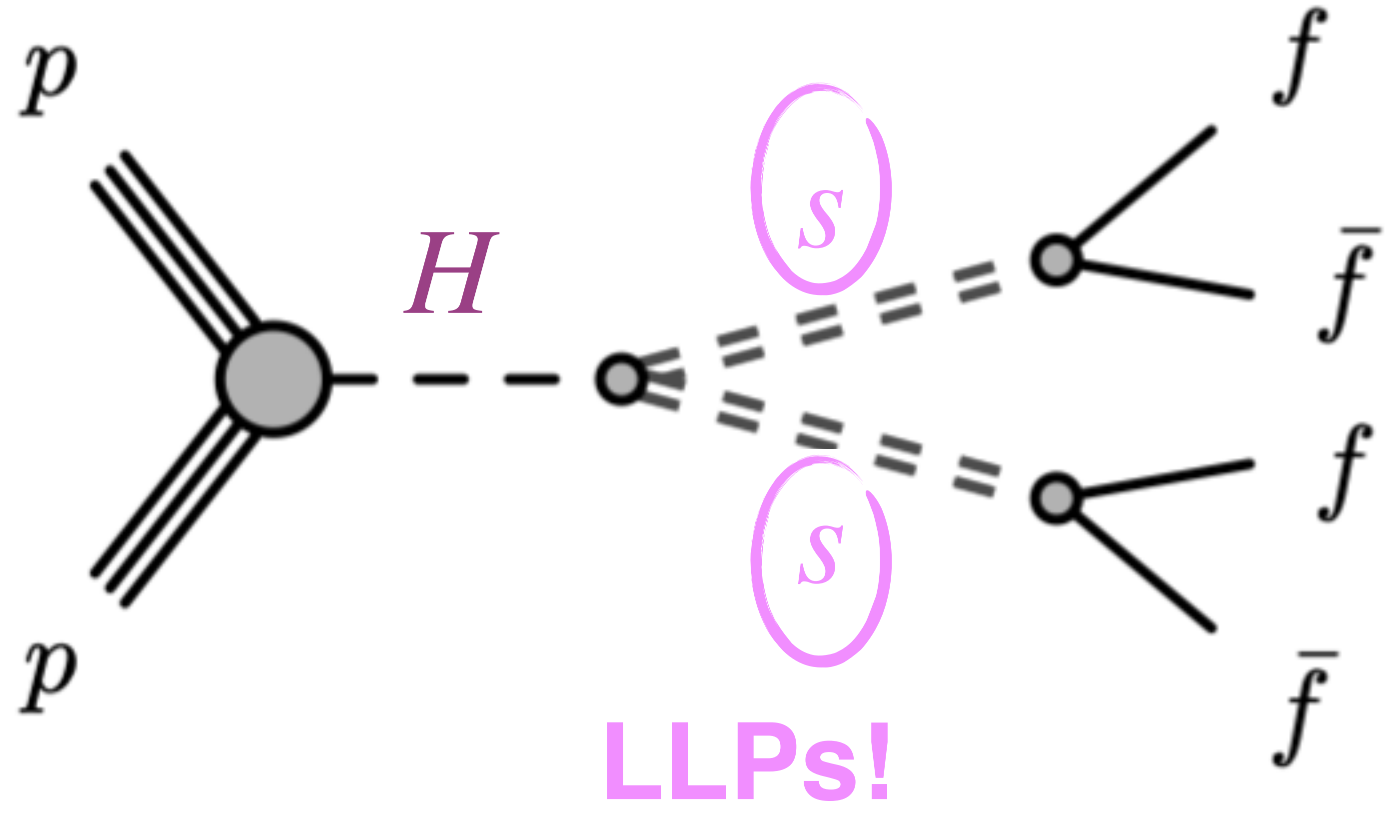
$h^\dagger h S^\dagger S$

Dark sector

dark
matter
~ 27%

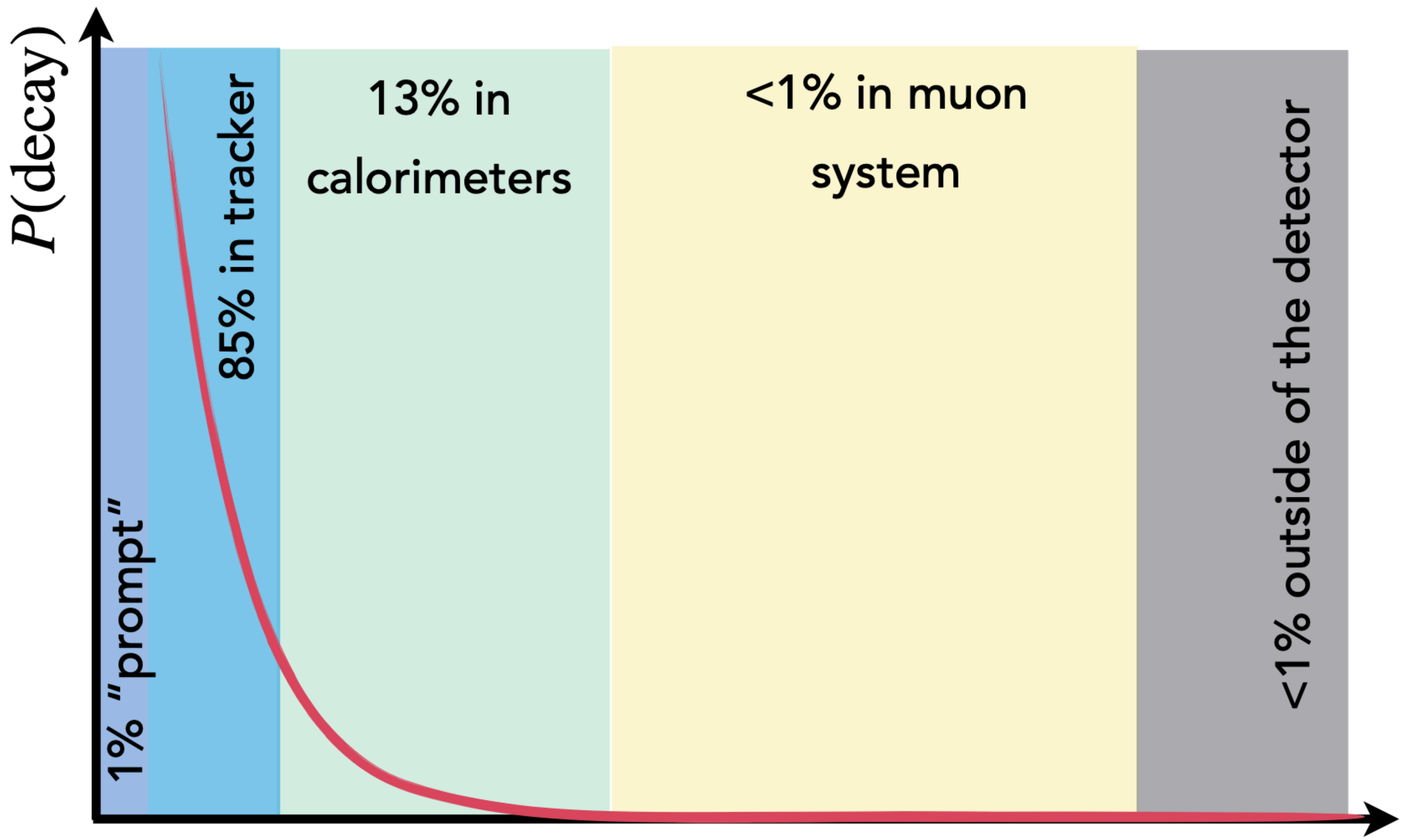
Connection to the **Higgs boson**?

- Scalar (s) becomes long-lived if coupling to the Standard Model particles are small



Where to Look for LLPs?

Search strategy depends on lifetime of the LLP:

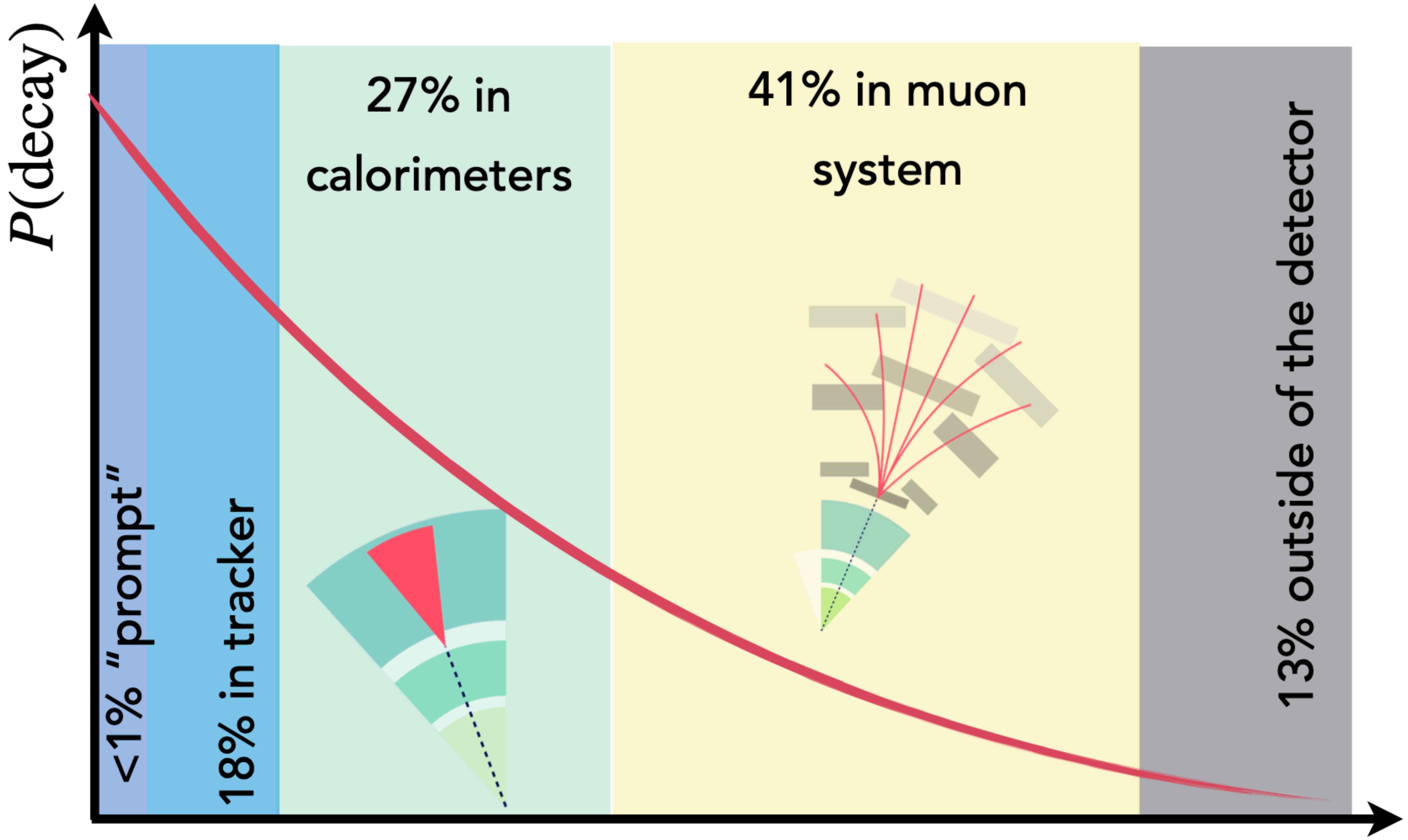


e.g. for $c\tau = 100\text{mm}, \beta\gamma \sim 5$

image credit: J. Burzynski

Where to Look for LLPs?

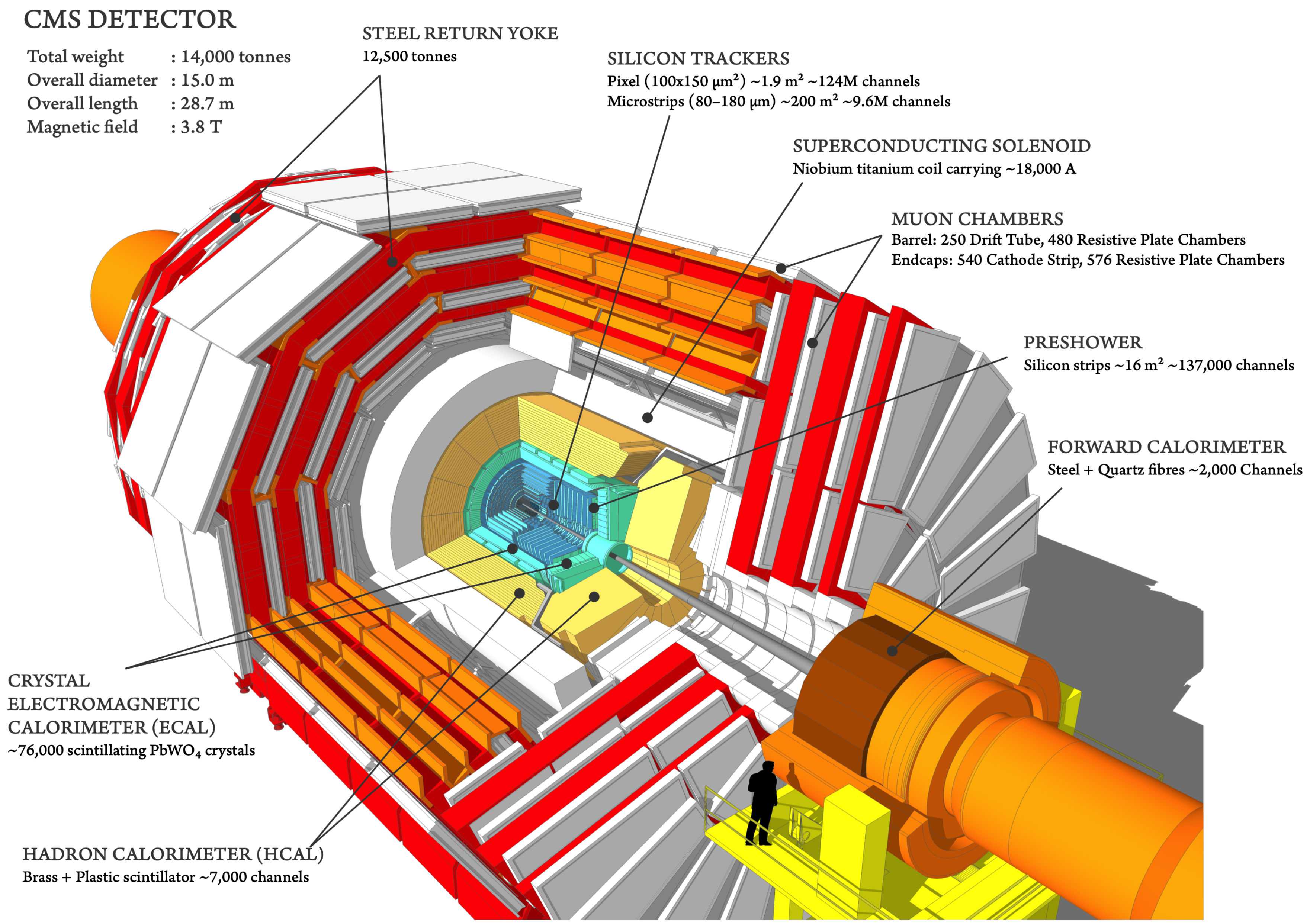
Search strategy depends on lifetime of the LLP:



e.g. for $c\tau = 1\text{m}, \beta\gamma \sim 5$

image credit: J. Burzynski

LLP Searches in ATLAS and CMS



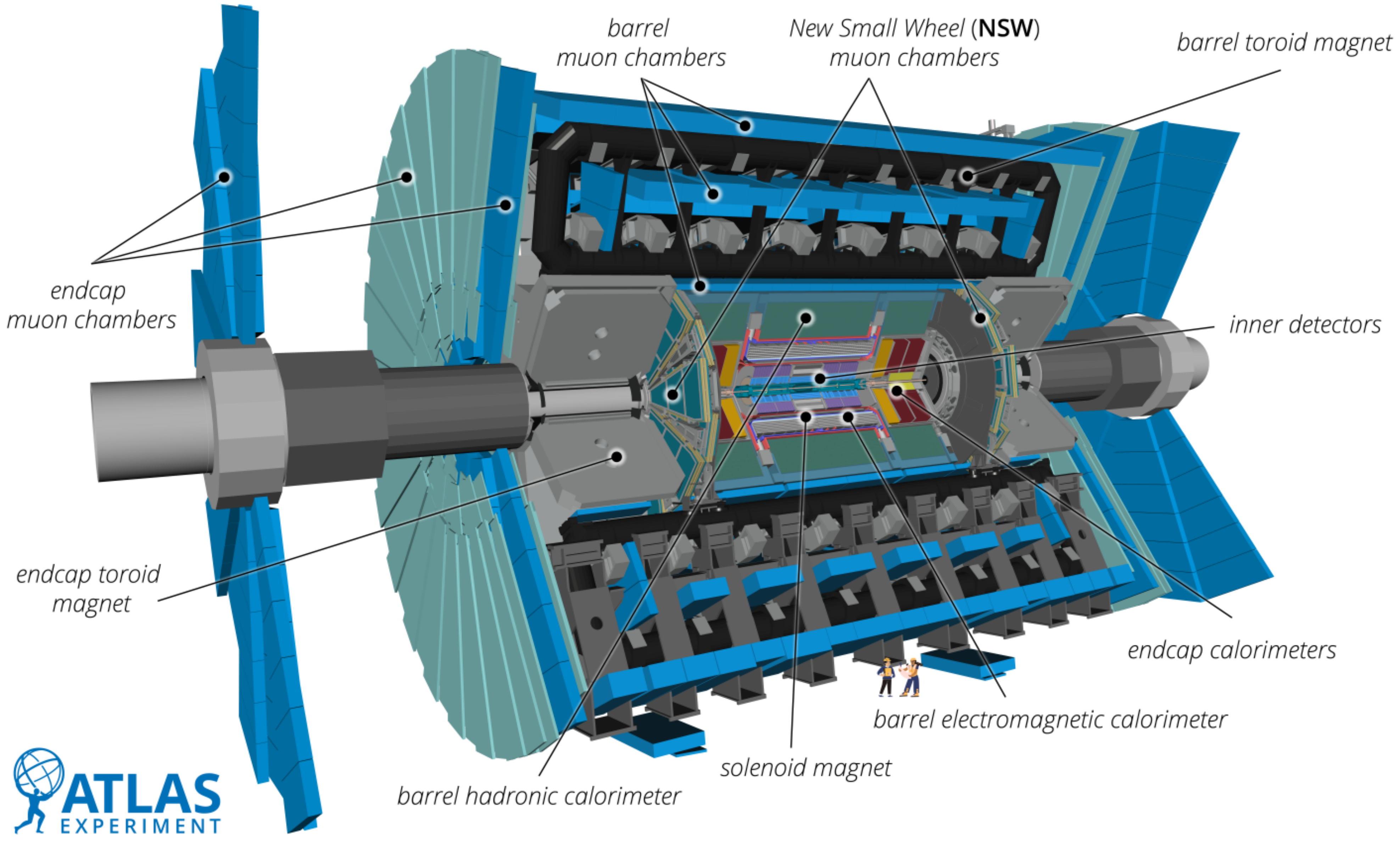
focus on latest results

CMS:

- **Tracker**, 34.7 fb^{-1} (13.6 TeV), arXiv:2409.10806
- **Muon system**, 138 fb^{-1} (13 TeV), Phys.Rev.D 110 (2024) 3 032007

ATLAS:

- **Tracker**, 37.5-140 fb^{-1} (13.6 TeV), Phys.Rev.Lett 133 161803 (2024)
- **Calorimeter**, 140 fb^{-1} (13 TeV), JHEP 11 (2024) 036

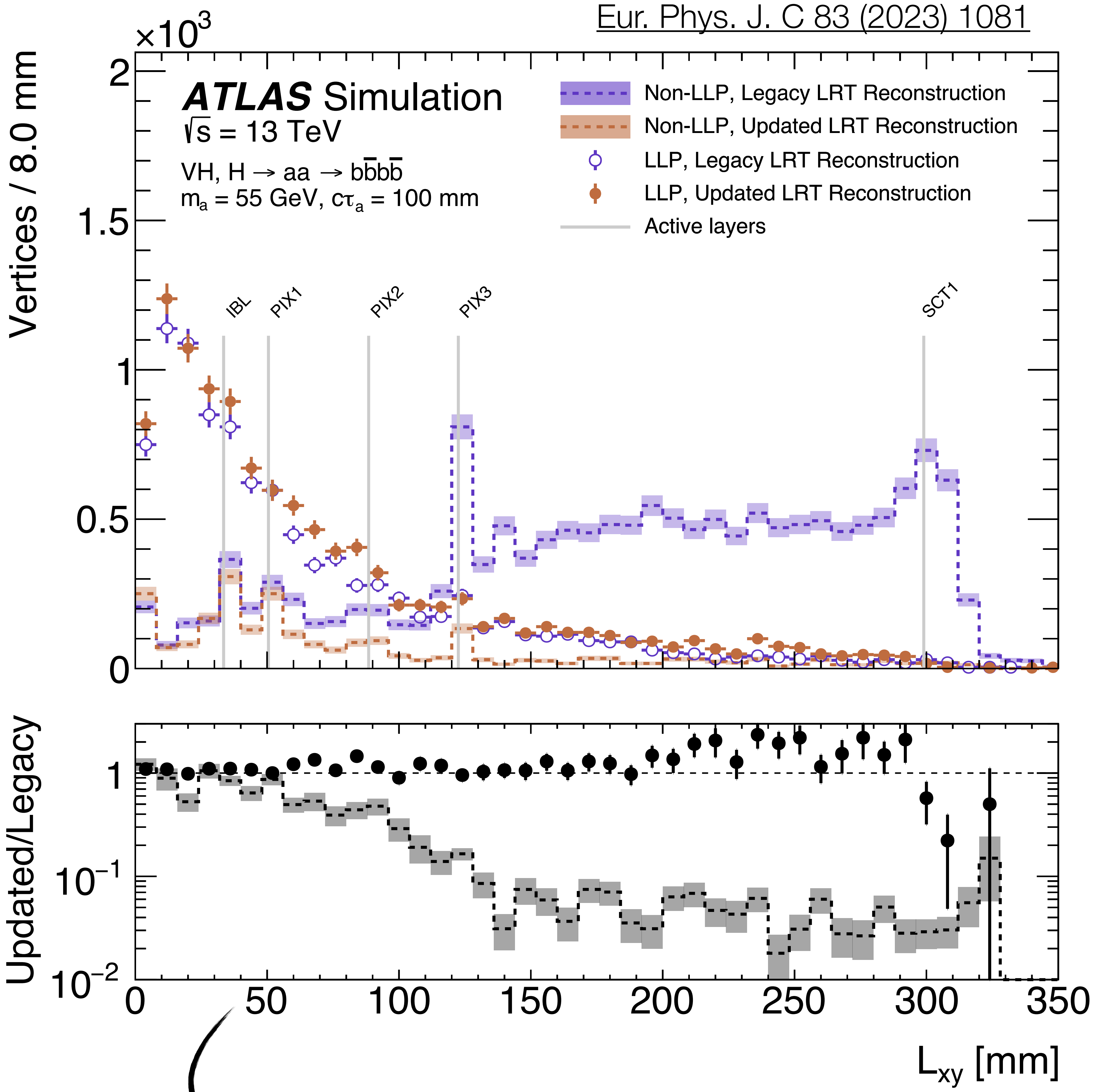


Tracker Search in ATLAS EXPERIMENT

Phys.Rev.Lett 133 161803 (2024)

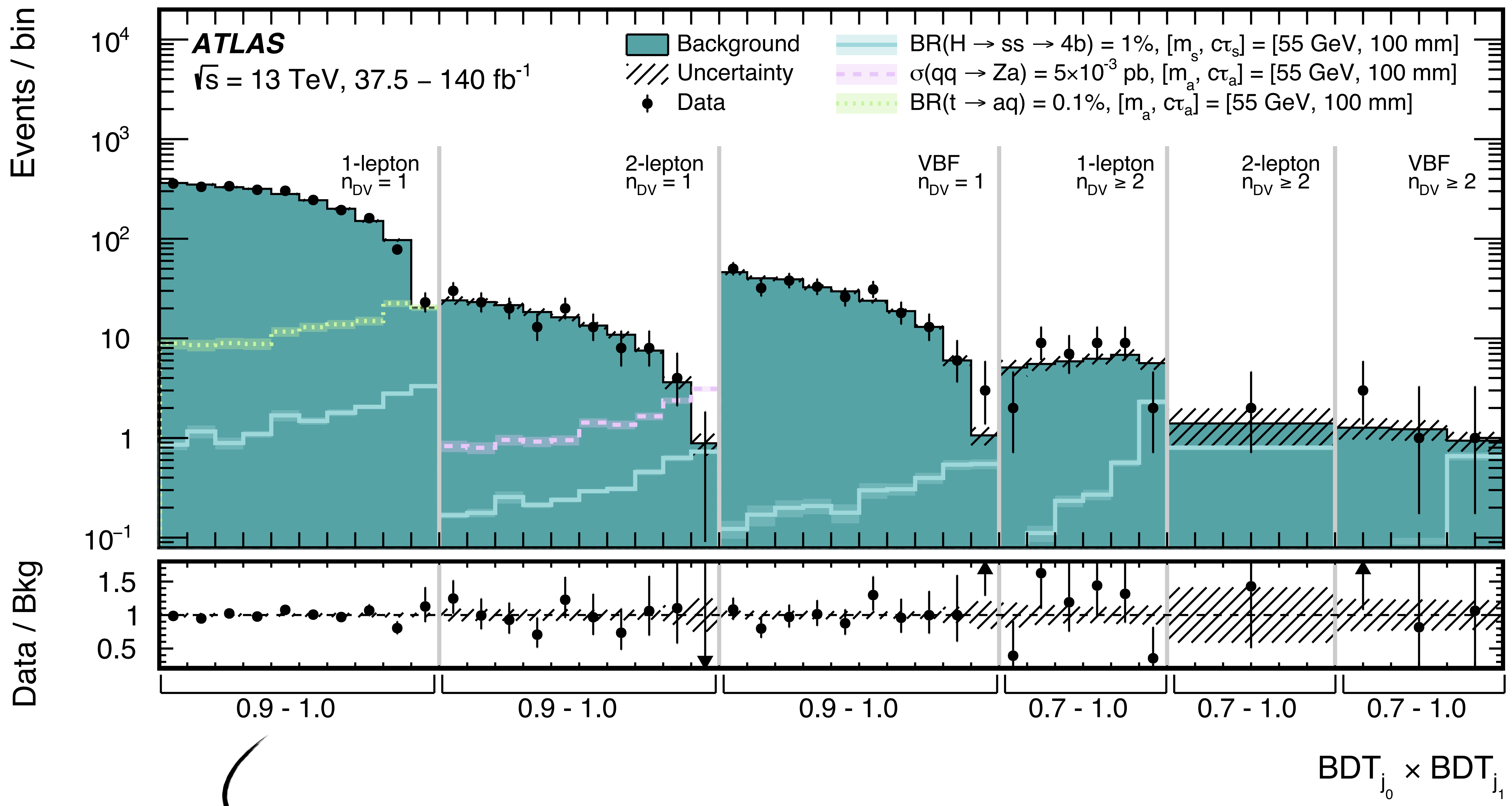
Recent ATLAS results significantly improved sensitivity to low lifetimes:

Eur. Phys. J. C 83 (2023) 1081



Sensitivity driven by improvements in displaced track reconstruction

Phys. Rev. Lett. 133 (2024) 161803



Search targeted *ZH, WH* and VBF Higgs production modes used a BDT to identify displaced jets

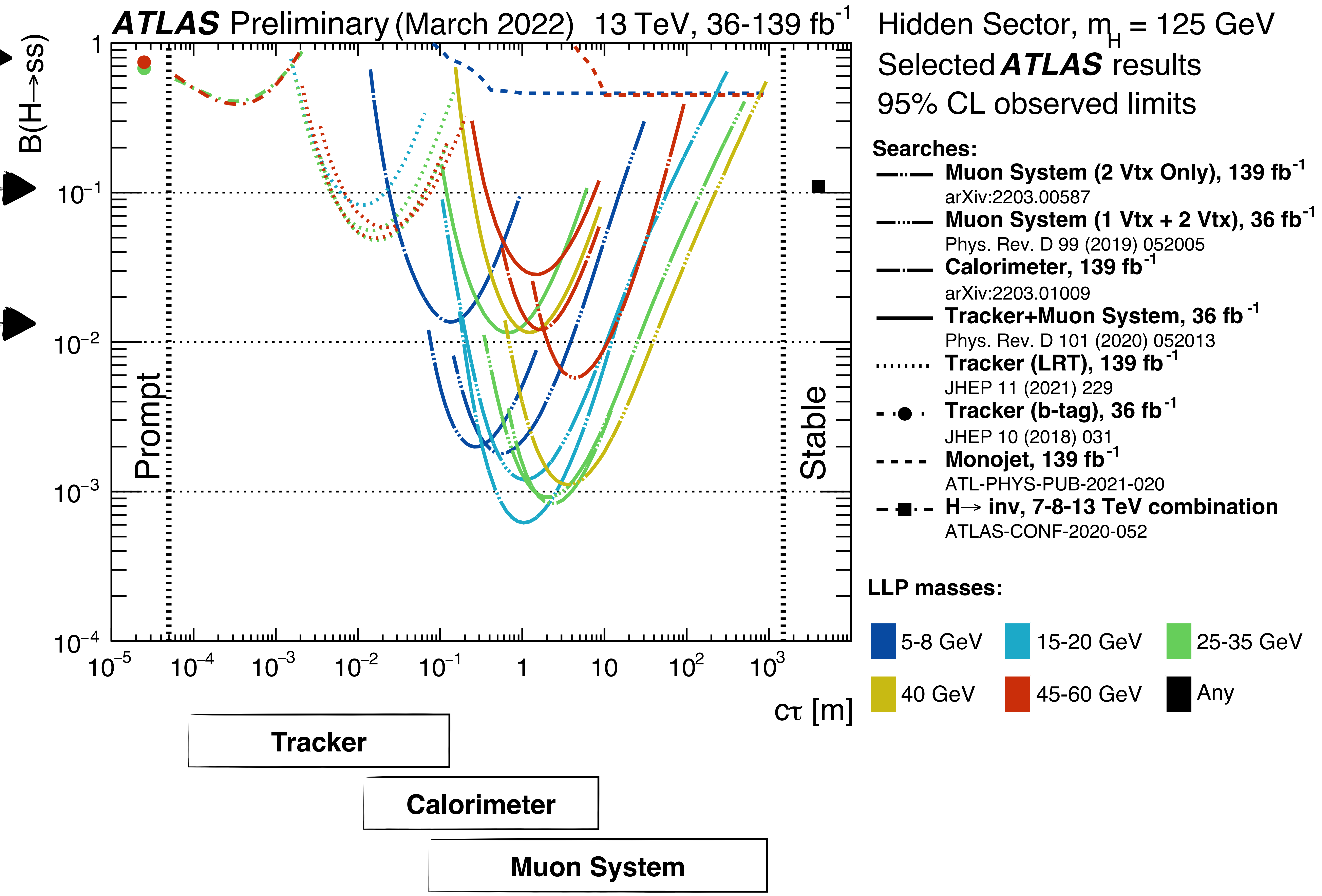
Tracker Search in ATLAS EXPERIMENT

ATL-PHYS-PUB-2024-003

Prompt searches

Higgs measurements

1%



ATLAS landscape for Higgs to LLP searches **prior to latest tracker search**

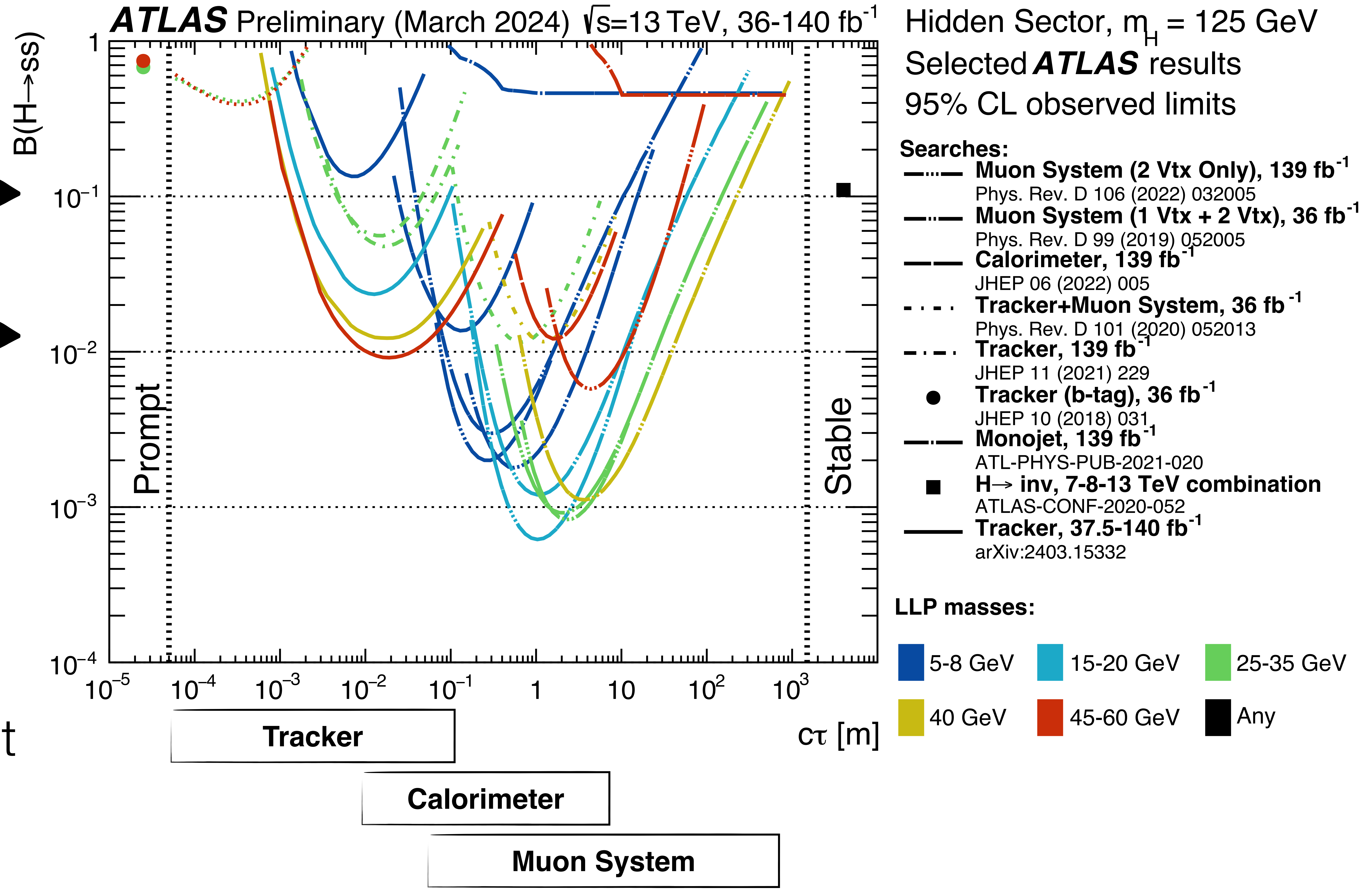
Tracker Search in ATLAS EXPERIMENT

ATL-PHYS-PUB-2024-003

Prompt searches

Higgs measurements

1%

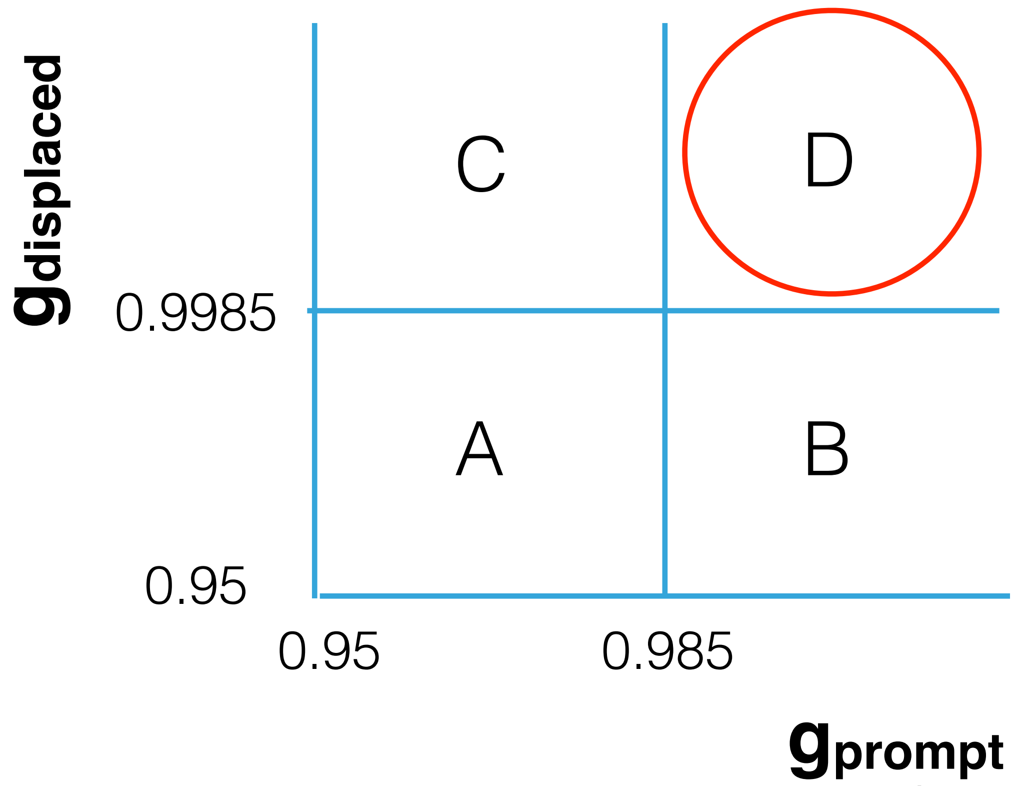


Factor x10 - 20 improvement on previous existing limits **using same dataset!**

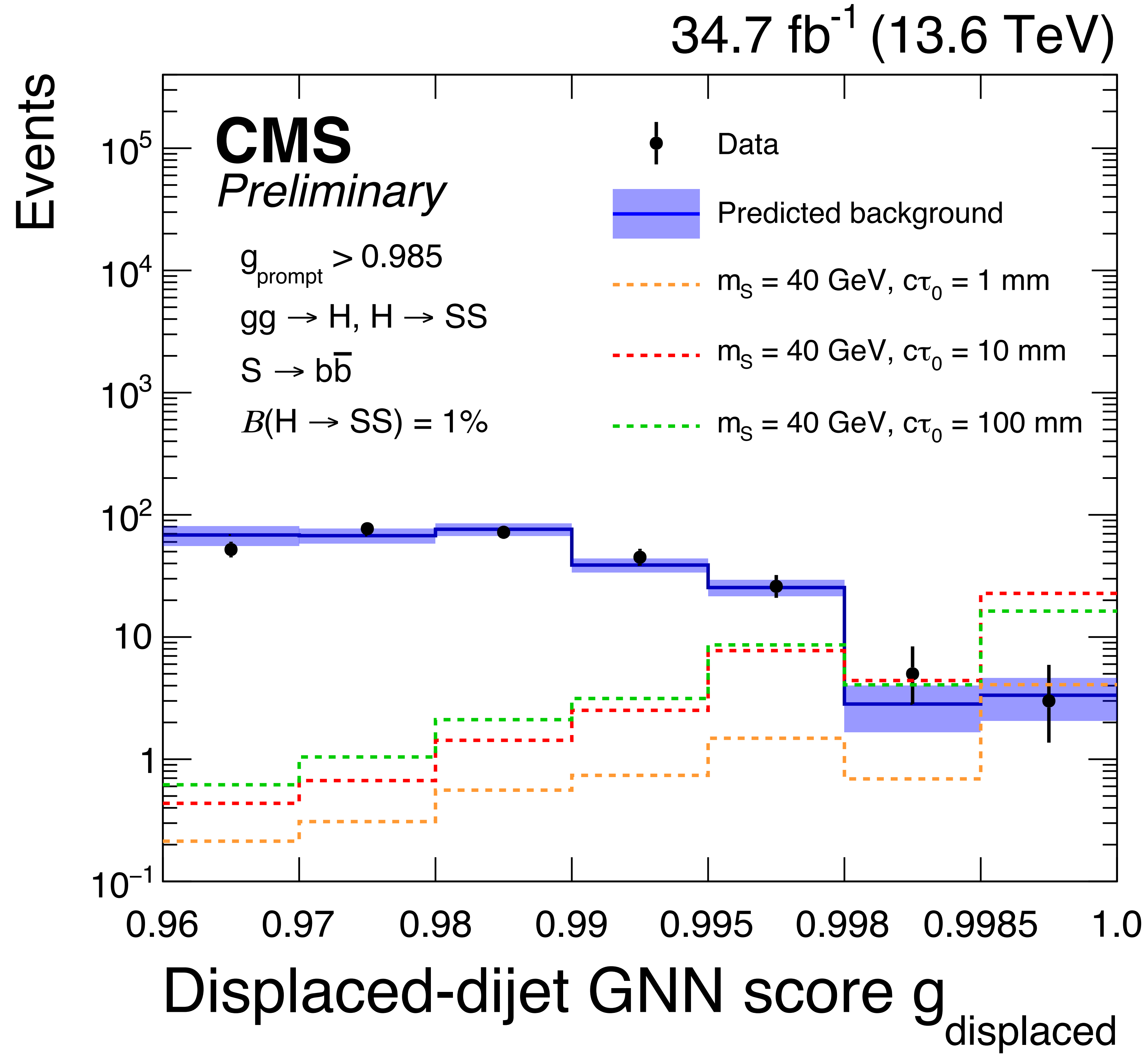
Tracker Search in CMS

CMS-PAS-EXO-23-013

- Targets ggF Higgs production with a partial run 3 result (34.7 fb^{-1})
- Uses **two displaced jet triggers** with requirements on large transverse momentum jets plus the presence of ‘prompt and ‘displaced’ tracks
- Uses two **Graph Neural Networks** (GNN) taggers trained to:
  - identify jets with **lots of displaced activity** ($g_{displaced}$)
  - identify jets with a **lack of prompt activity** (g_{prompt})
- Background estimate performed using ABCD method with outputs from the GNN taggers as discriminating variables



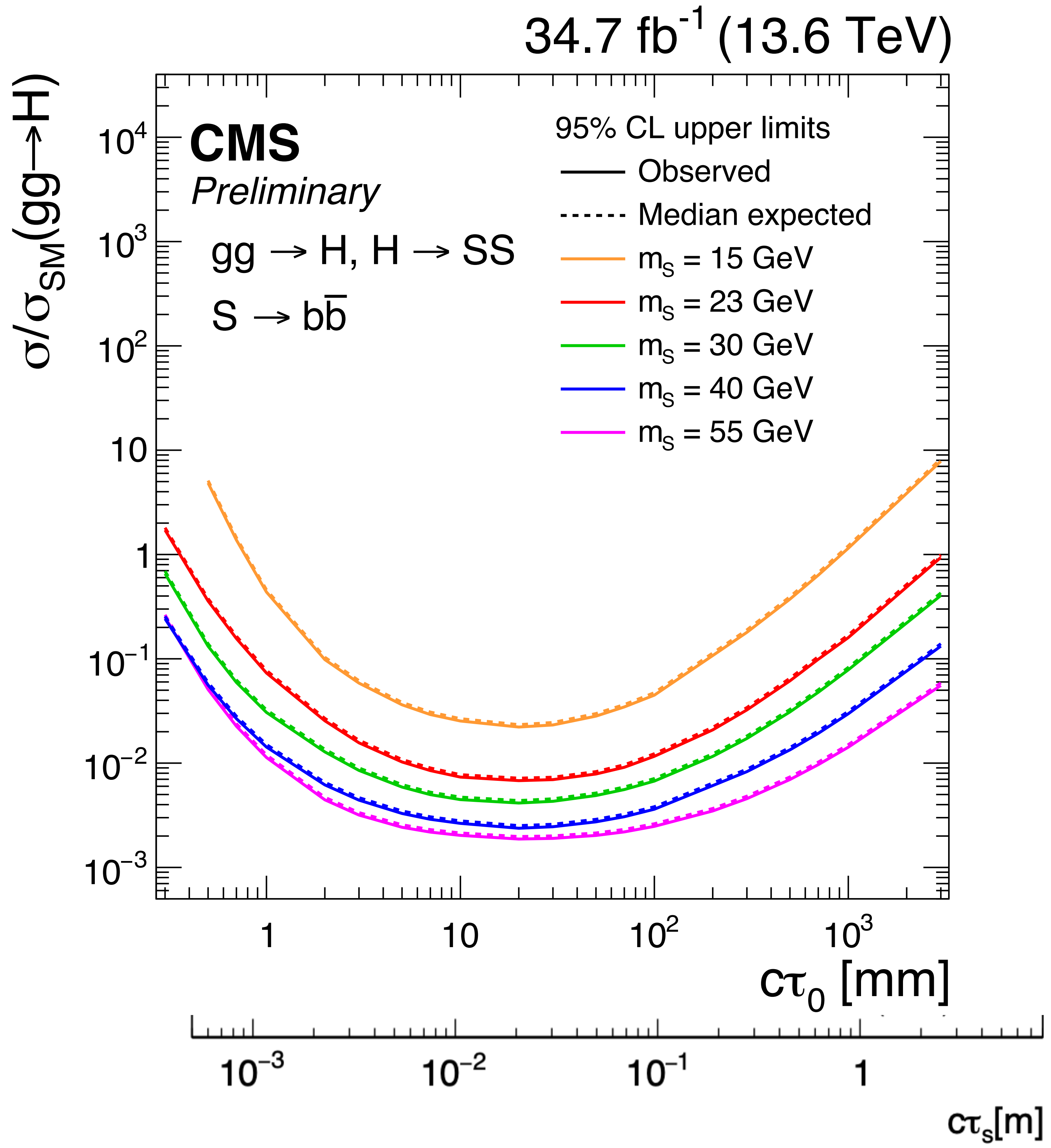
$N_D = N_B N_C / N_A$



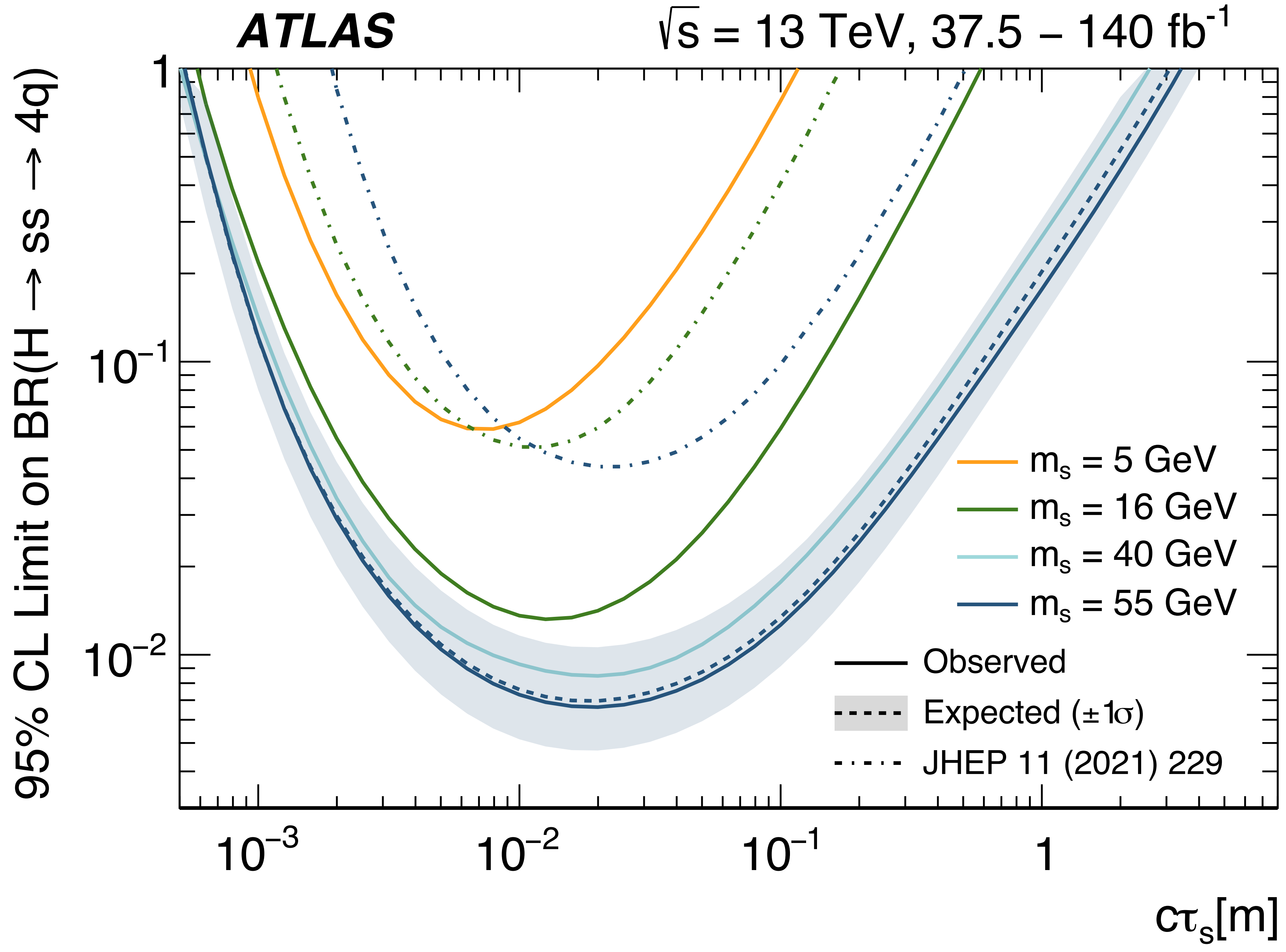
Comparison of Tracker Searches

- CMS has very competitive results, outperforming ATLAS for m_S > 16 GeV (with ~1/4 of the data!)
- ATLAS result is more sensitive at low masses (ie. m_S = 5-16 GeV)

CMS (CMS-PAS-EXO-23-013)



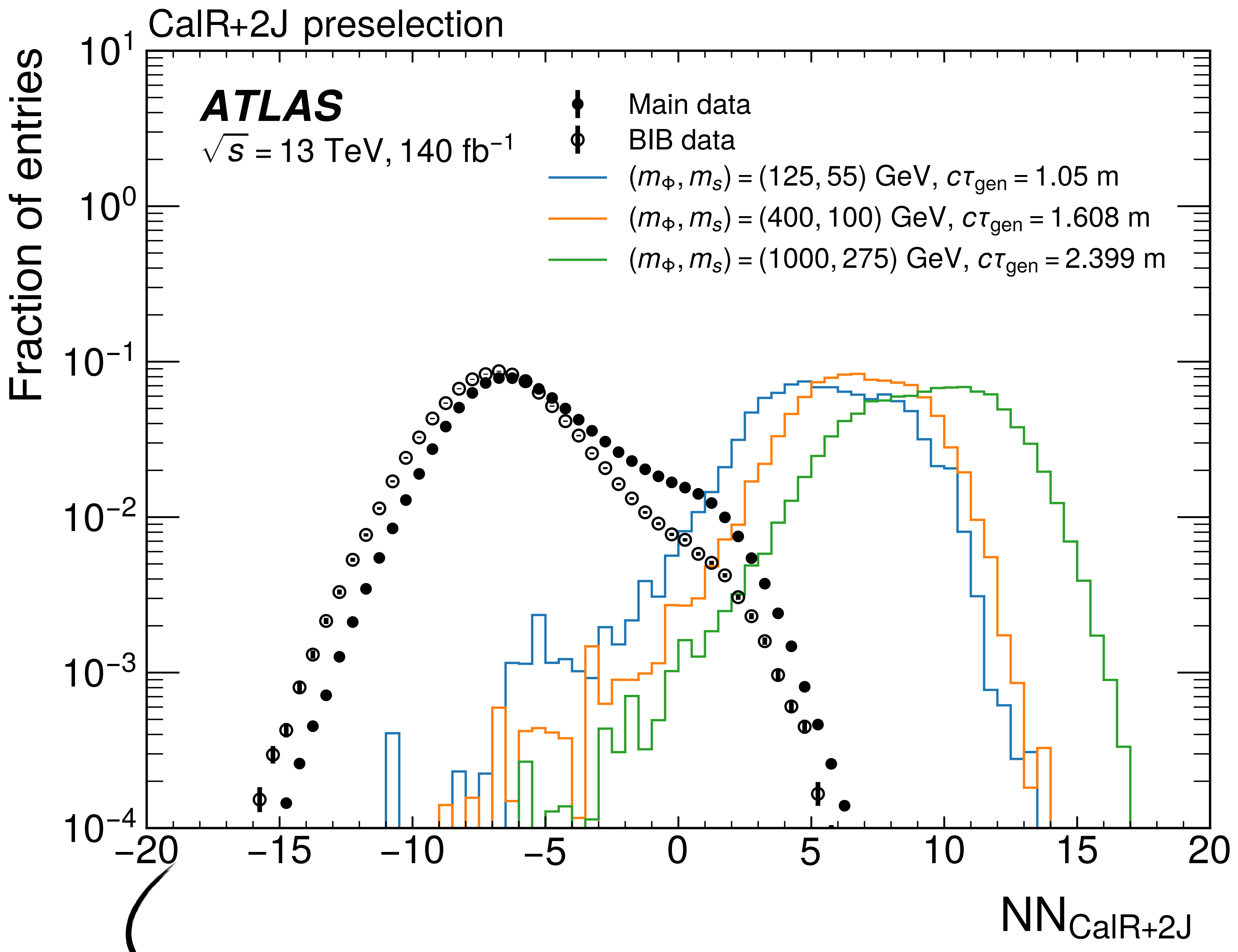
ATLAS (EXOT-2021-32)

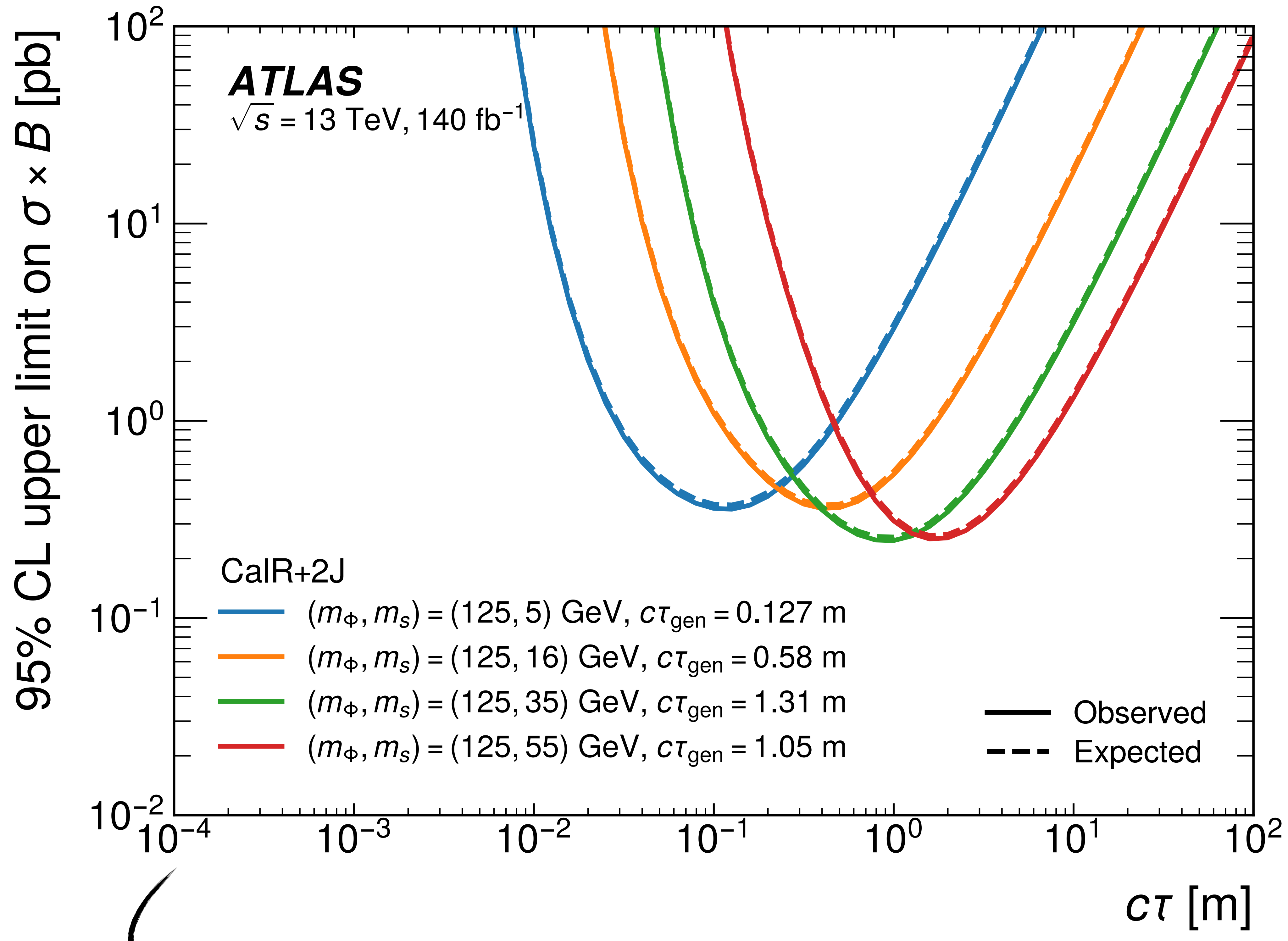


Calorimeter Search in ATLAS EXPERIMENT

JHEP 11 (2024) 036

For longer lifetimes, latest ATLAS **search in calorimeter** targets *VH* and ggF with at least one LLP decay after the tracker:





Main backgrounds of QCD/V+jets and beam induced background (BIB) are discriminated against using neural network

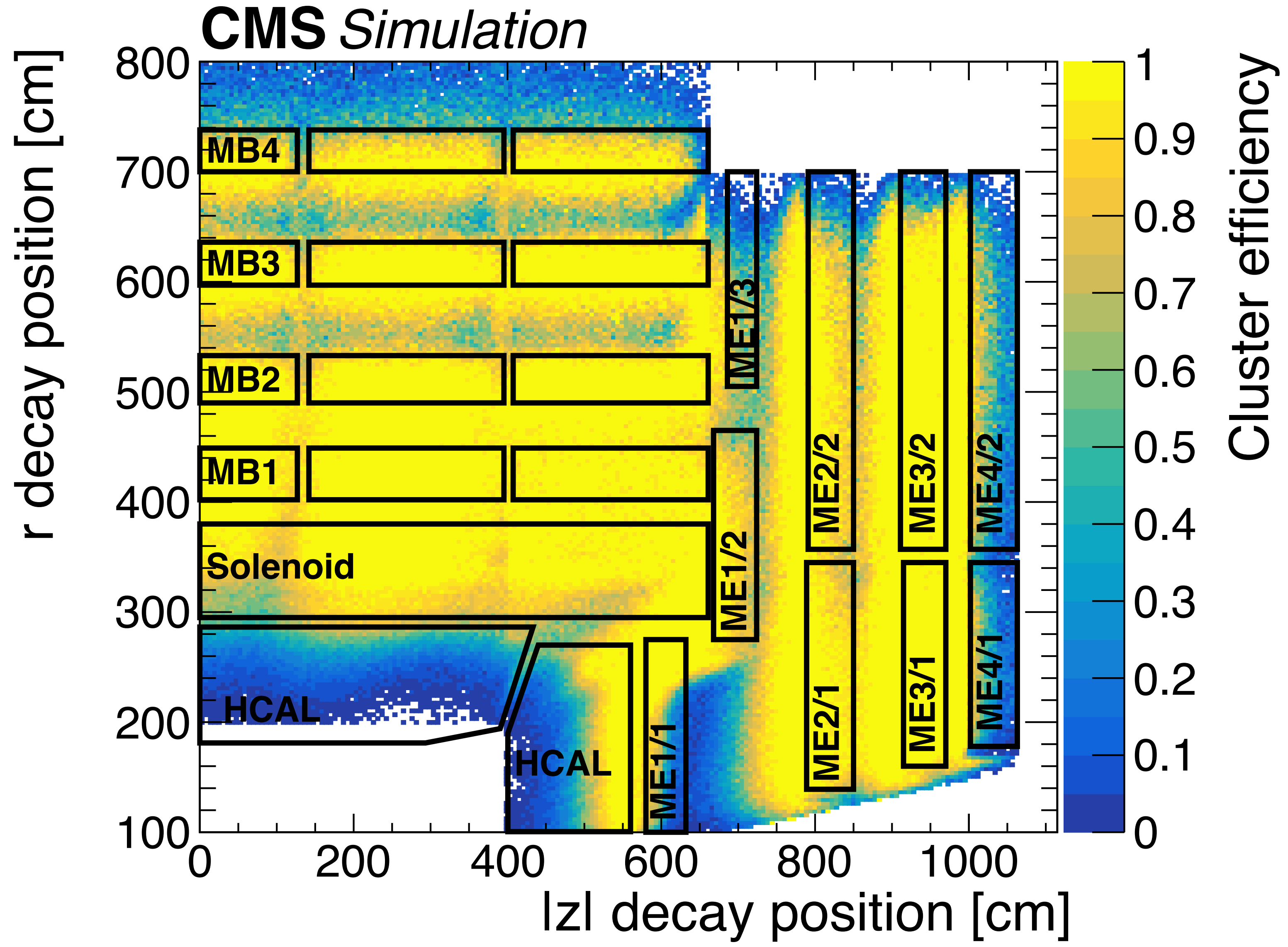
Improved sensitivity at shorter lifetimes w.r.t. 2 displaced jet search

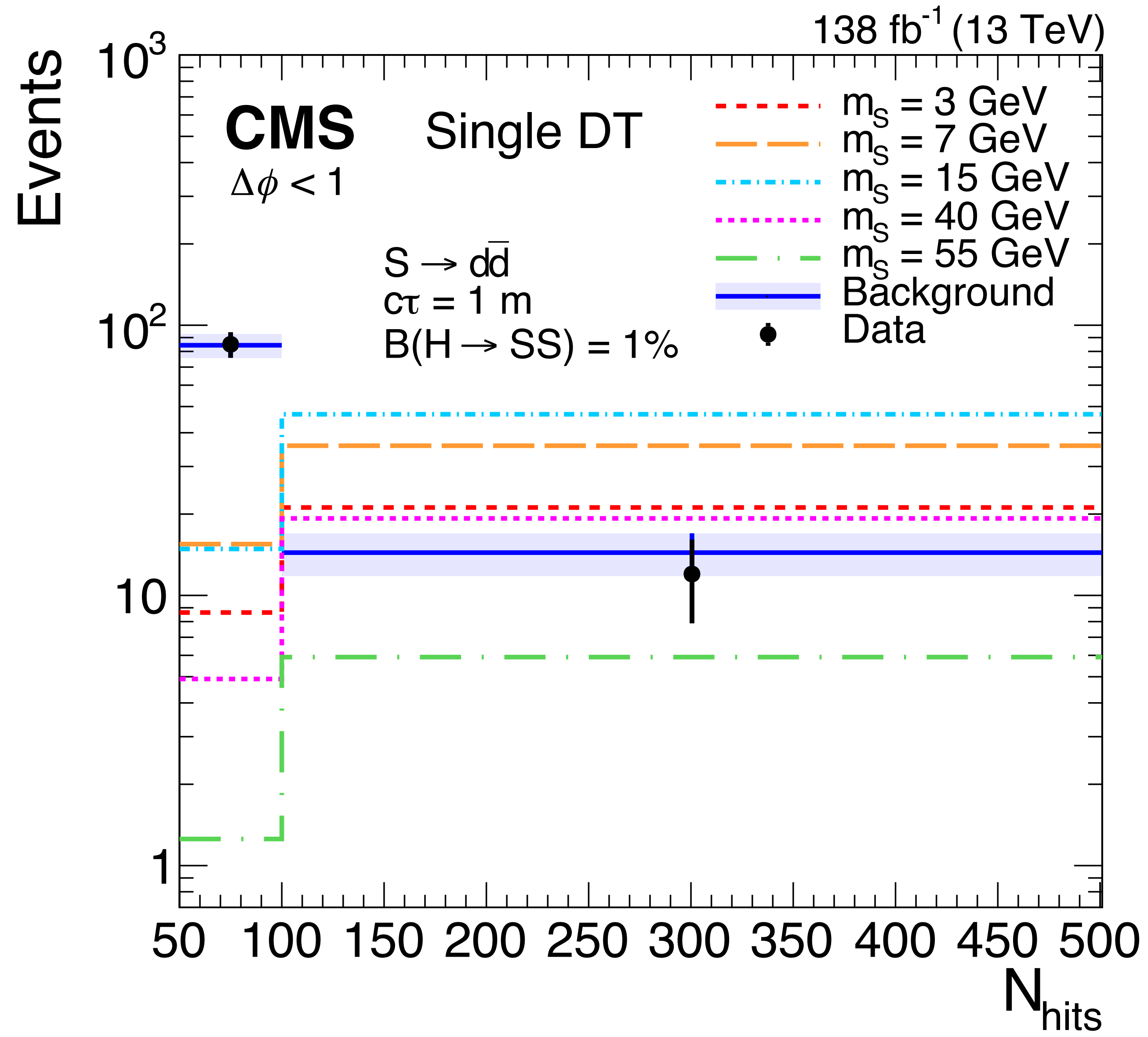
Muon System Search in CMS

[Phys. Rev. D 110, 032007](#)

For even longer lifetimes, **muon system** becomes dominant

- Targets ggF, VH and ttH Higgs production
- Search for LLP decays, which produce large clusters of hits in the following muon station
  - Uses the **muon system as a sampling calorimeter!**
- Trigger on events with **high missing transverse momentum** ($p_{T\,miss}$) and suppress backgrounds by exploiting **angular difference** between cluster and $p_{T\,miss}$



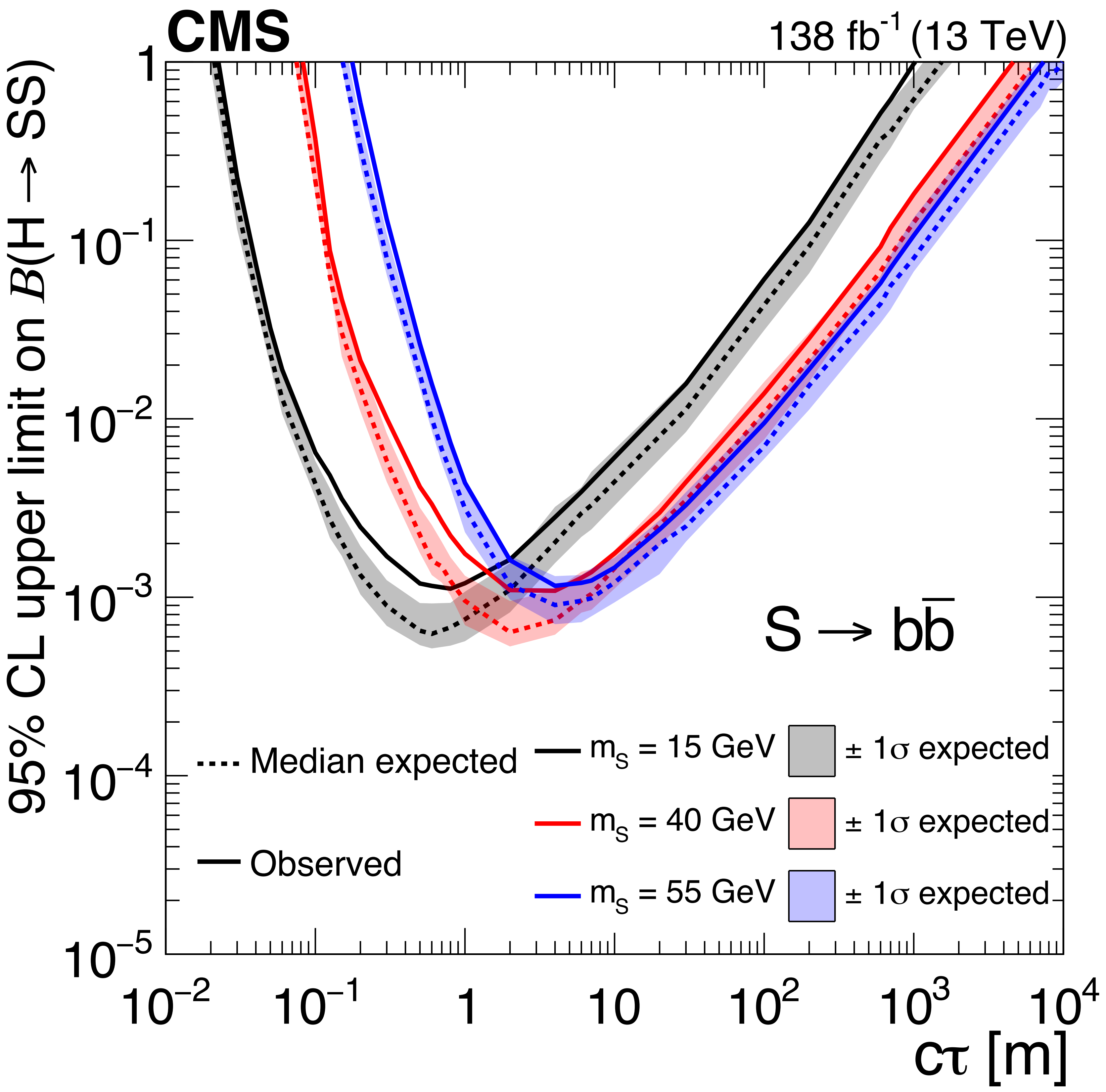


Comparison of CMS Searches

Complimentary lifetime coverage between tracker and muon system searches

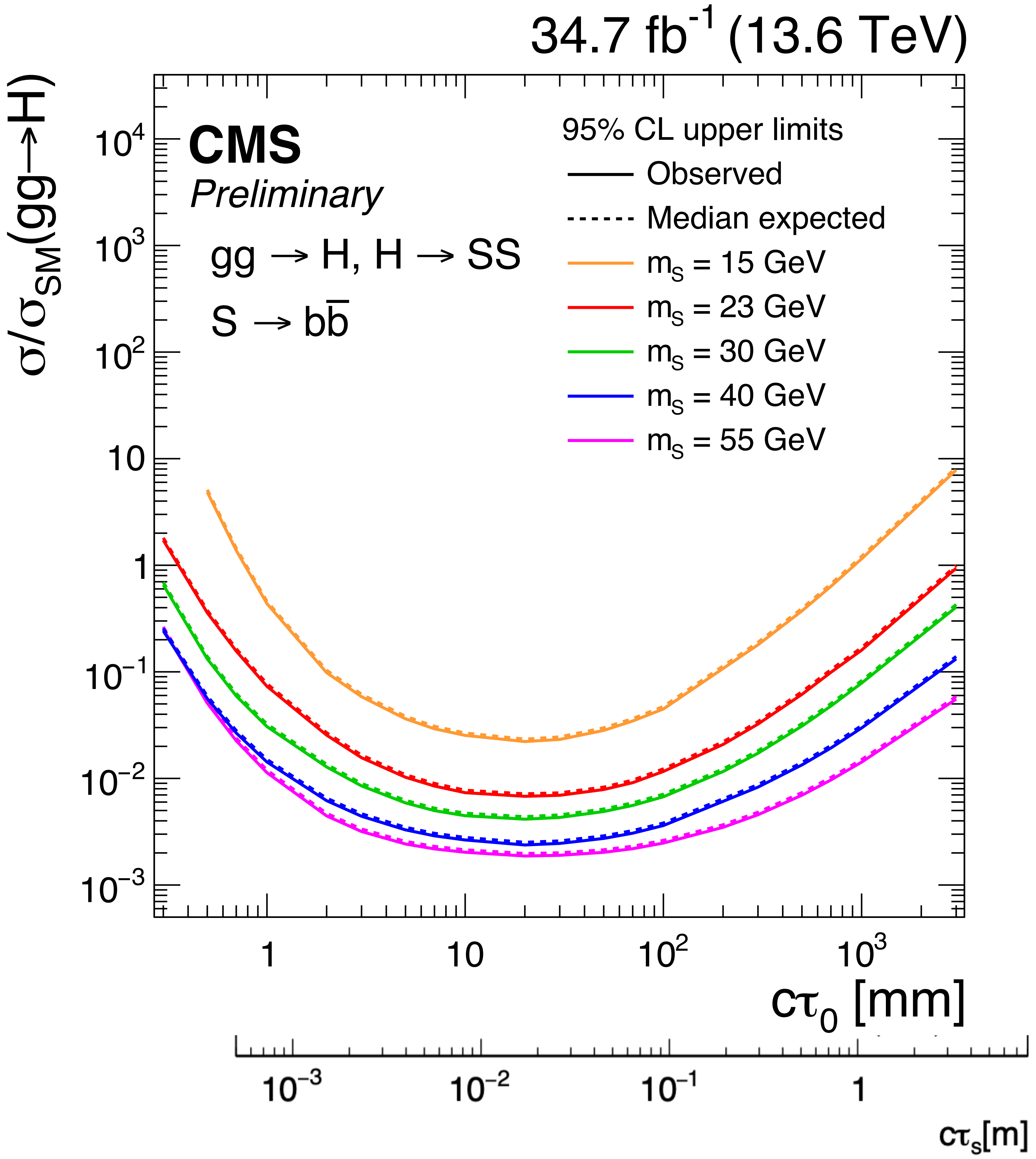
Muon System

(Phys. Rev. D 110, 032007)



Tracker

(CMS-PAS-EXO-23-013)

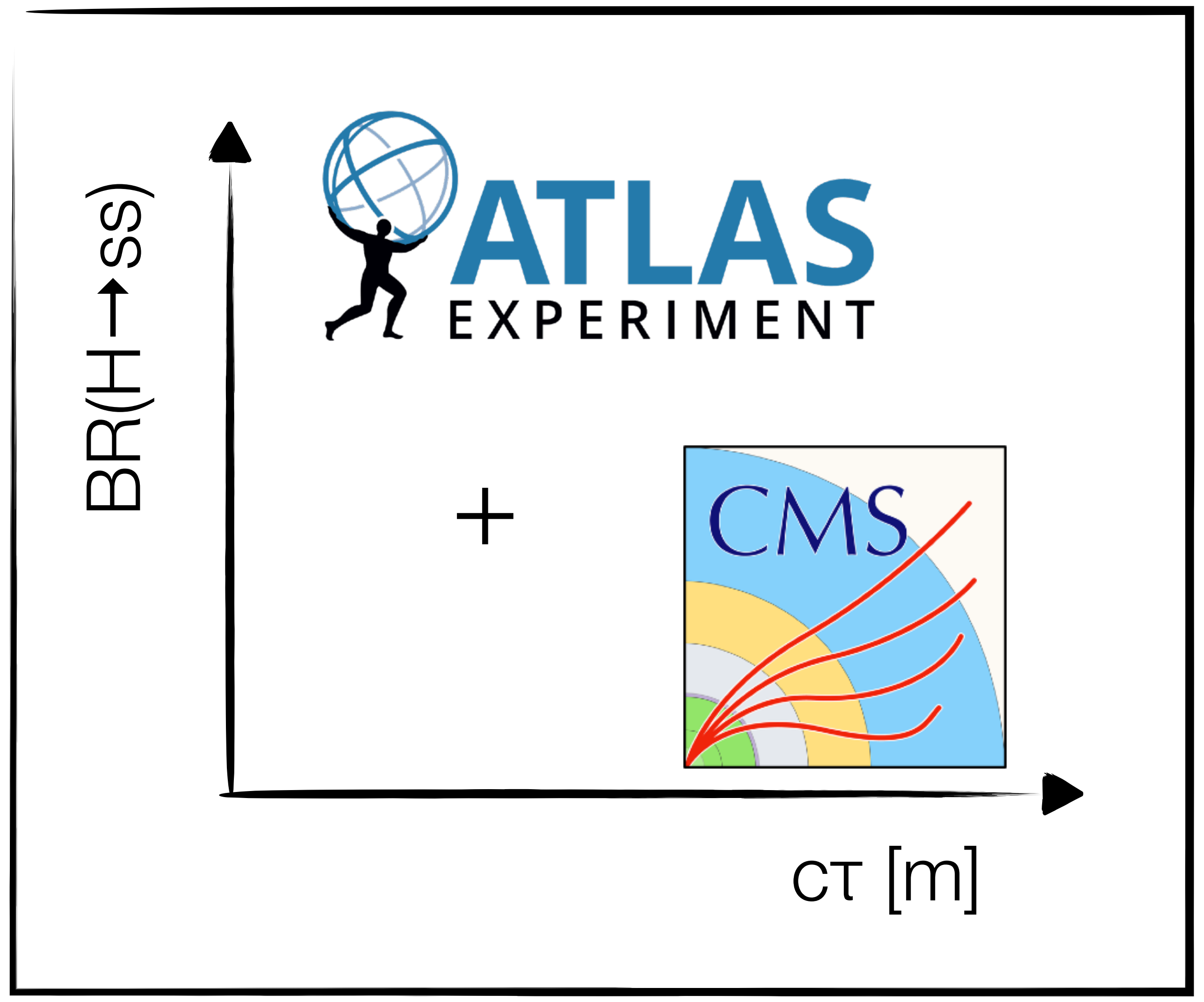


Conclusions

- Presented a summary of *recent searches* for long-lived particles which couple to the Higgs in ATLAS and CMS

- Developments of **new triggers**, **innovative analysis methods** and powerful **machine learning discriminants** are helping pushing sensitivity at the LHC

- Exciting times ahead with the quickly growing Run 3 dataset!

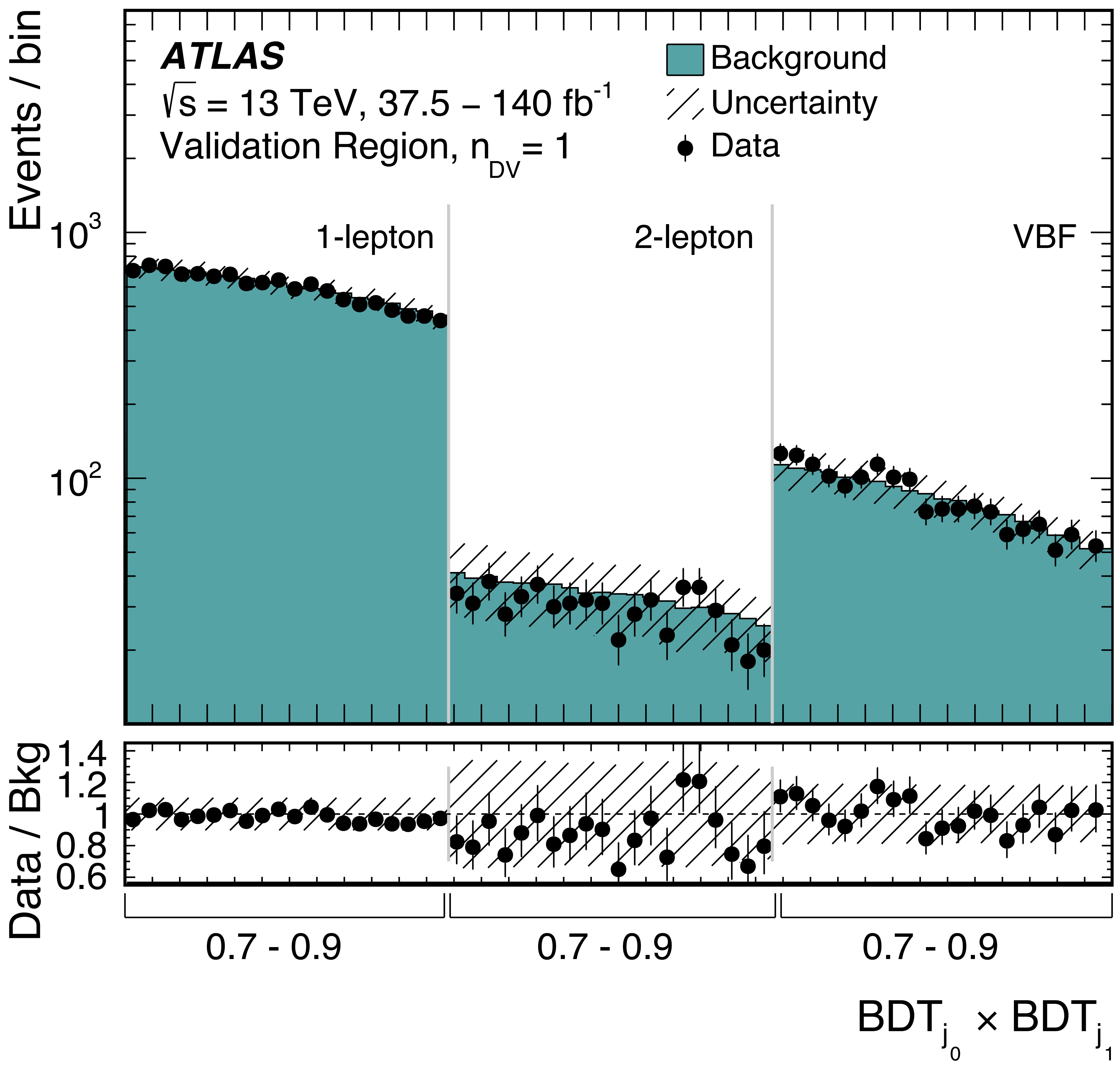


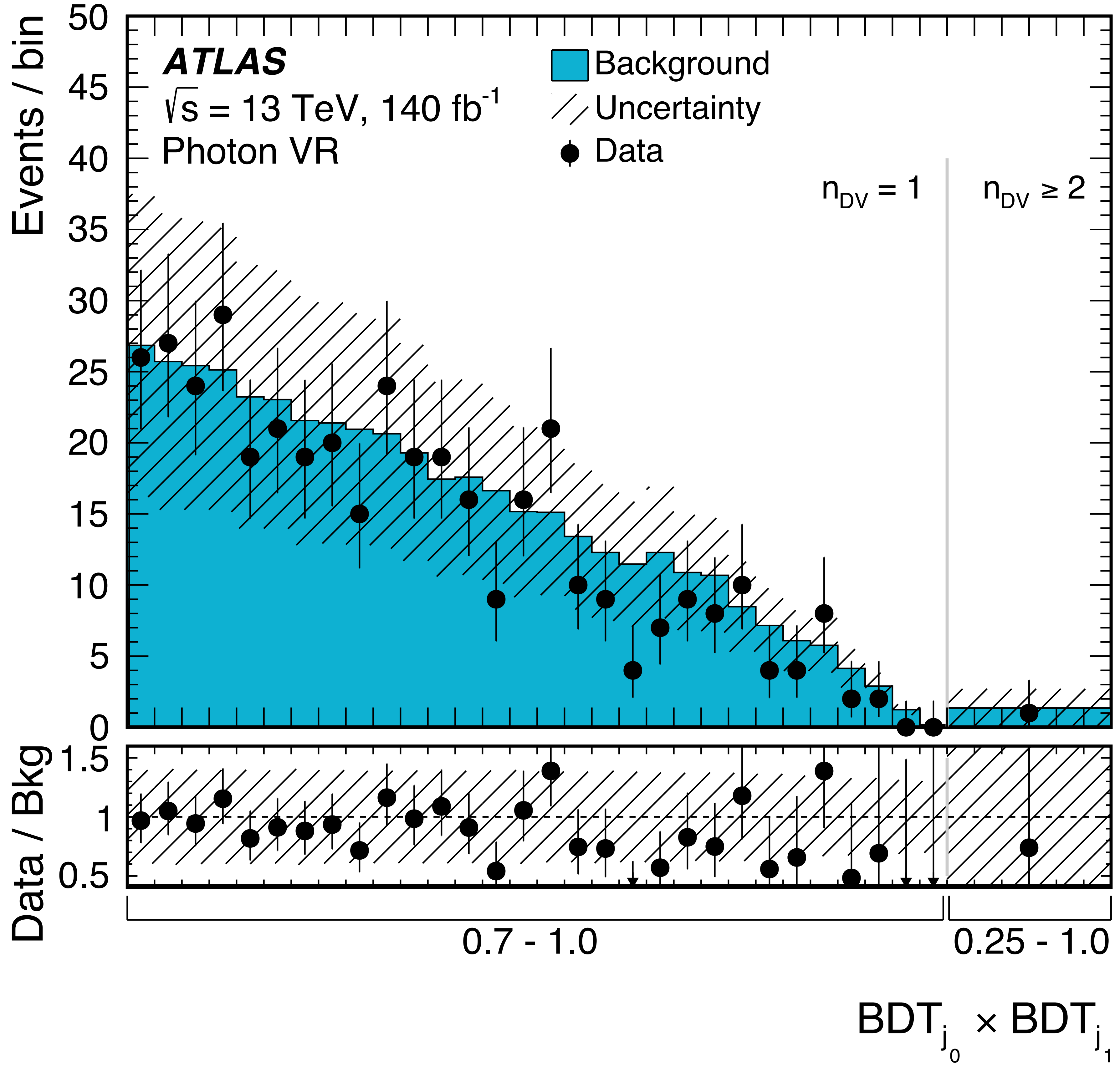
Stay tuned for LLP summary plots !

Backups

Tracker Search in ATLAS EXPERIMENT

Background estimate validated in CRs with intermediate event-level discriminant values and dedicated photon+jets region:





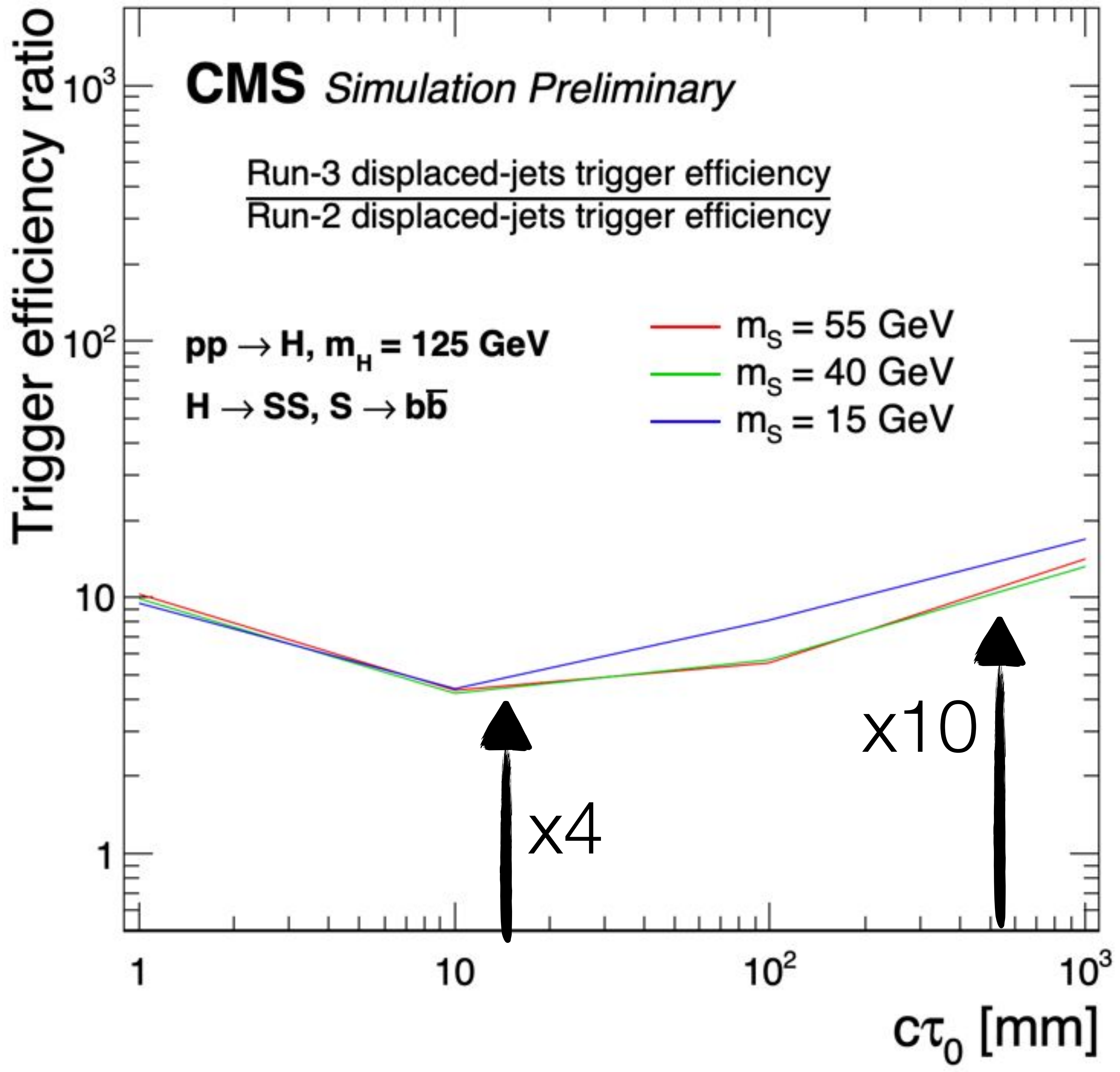
Tracker Search in CMS

CMS DP -2023/043

- Search relies on two displaced jet triggers seeded by scalar sum p_T of all jets with $p_T > 40$ GeV (H_T):
  - L1 seed requires $H_T > 430$ GeV; At HLT, jet has at most one prompt track
  - L1 requires $H_T > 240$ GeV and the presence of a pT > 6 GeV muon. At HLT, jet has at most 1 prompt and at least 1 displaced track

- Run 3 trigger efficiencies are higher than the Run 2 trigger efficiencies by a factor of 4 to 11 for m_S between 10 and 60 GeV and cτ between 1 and 1000 mm

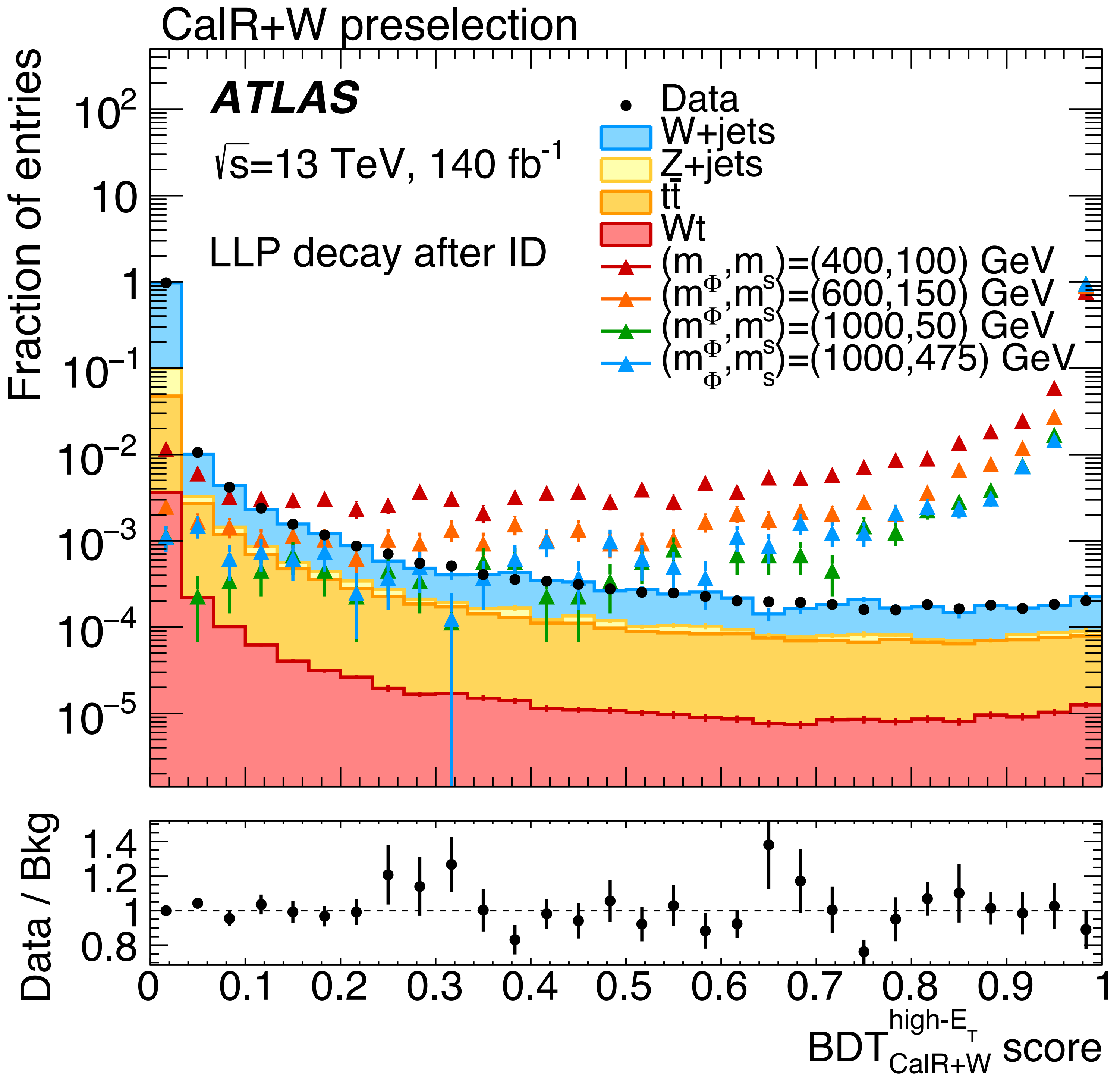
- The trigger rate is ~26 Hz at instantaneous luminosity of 2×10^{34} cm^{-2} s^{-1}

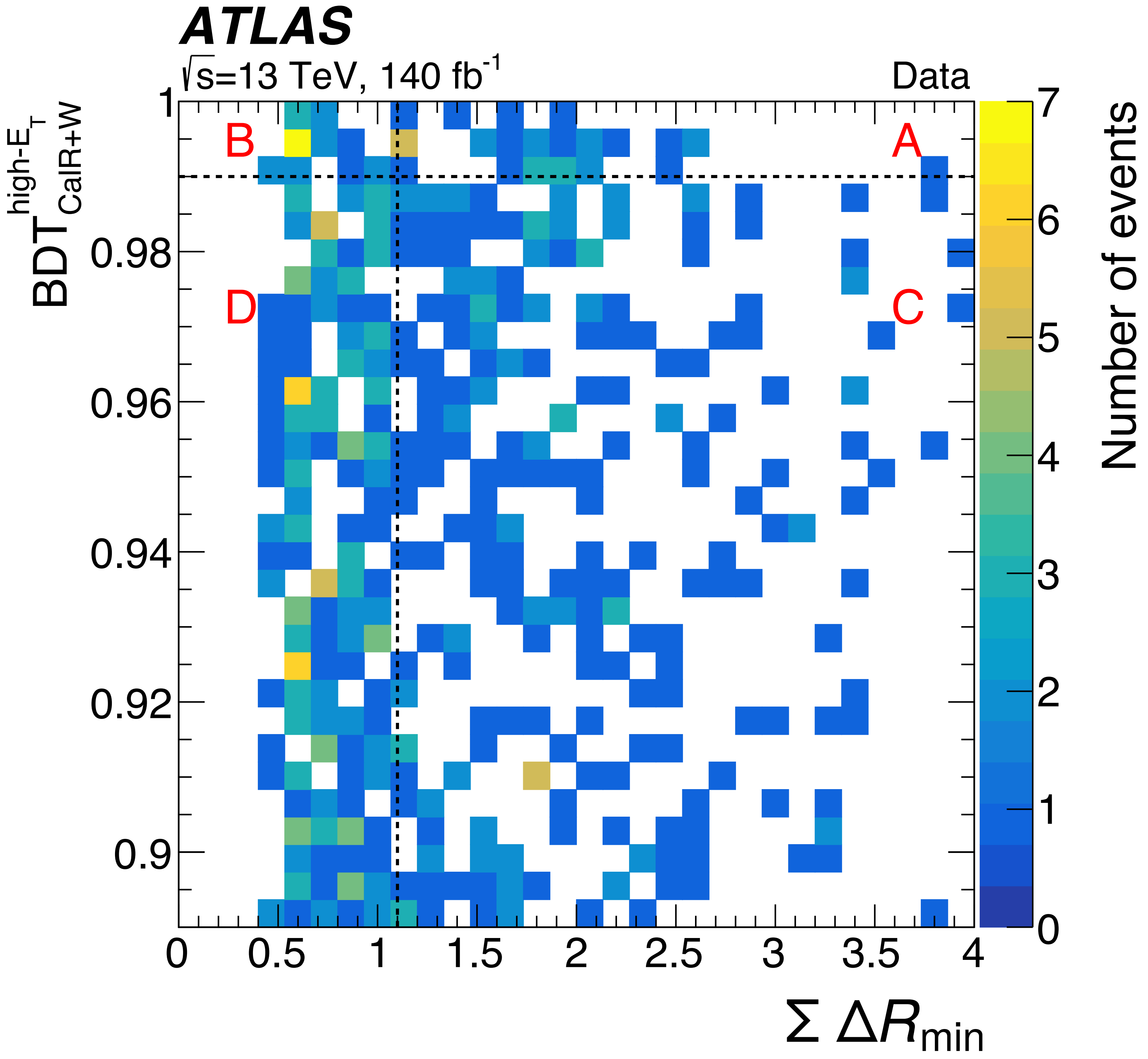


Calorimeter Search in ATLAS EXPERIMENT

JHEP 11 (2024) 036

- Additional displaced jet + lepton channel uses lepton triggers and a BDT to separate signal and background
- ABCD method used to estimate backgrounds

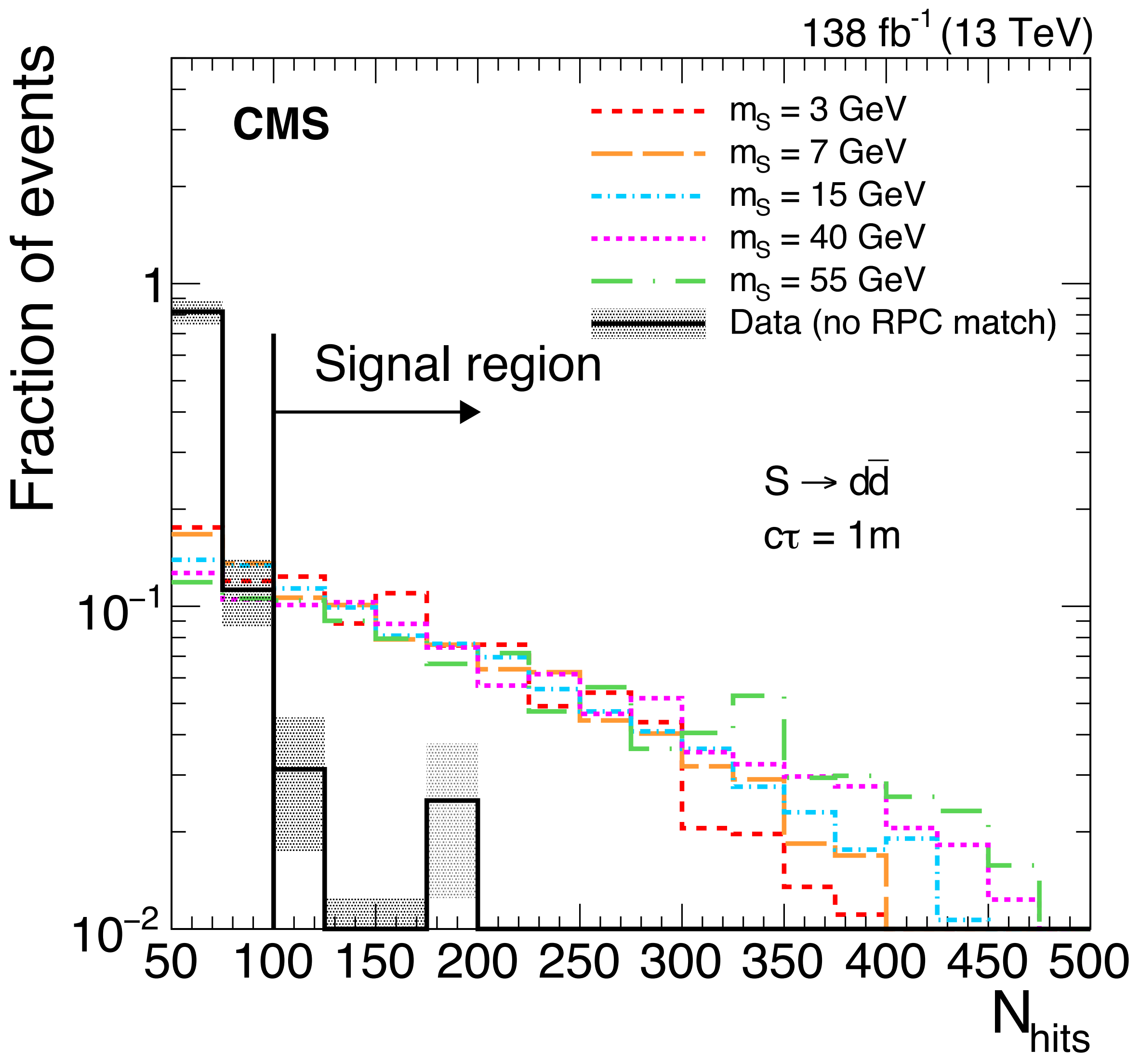


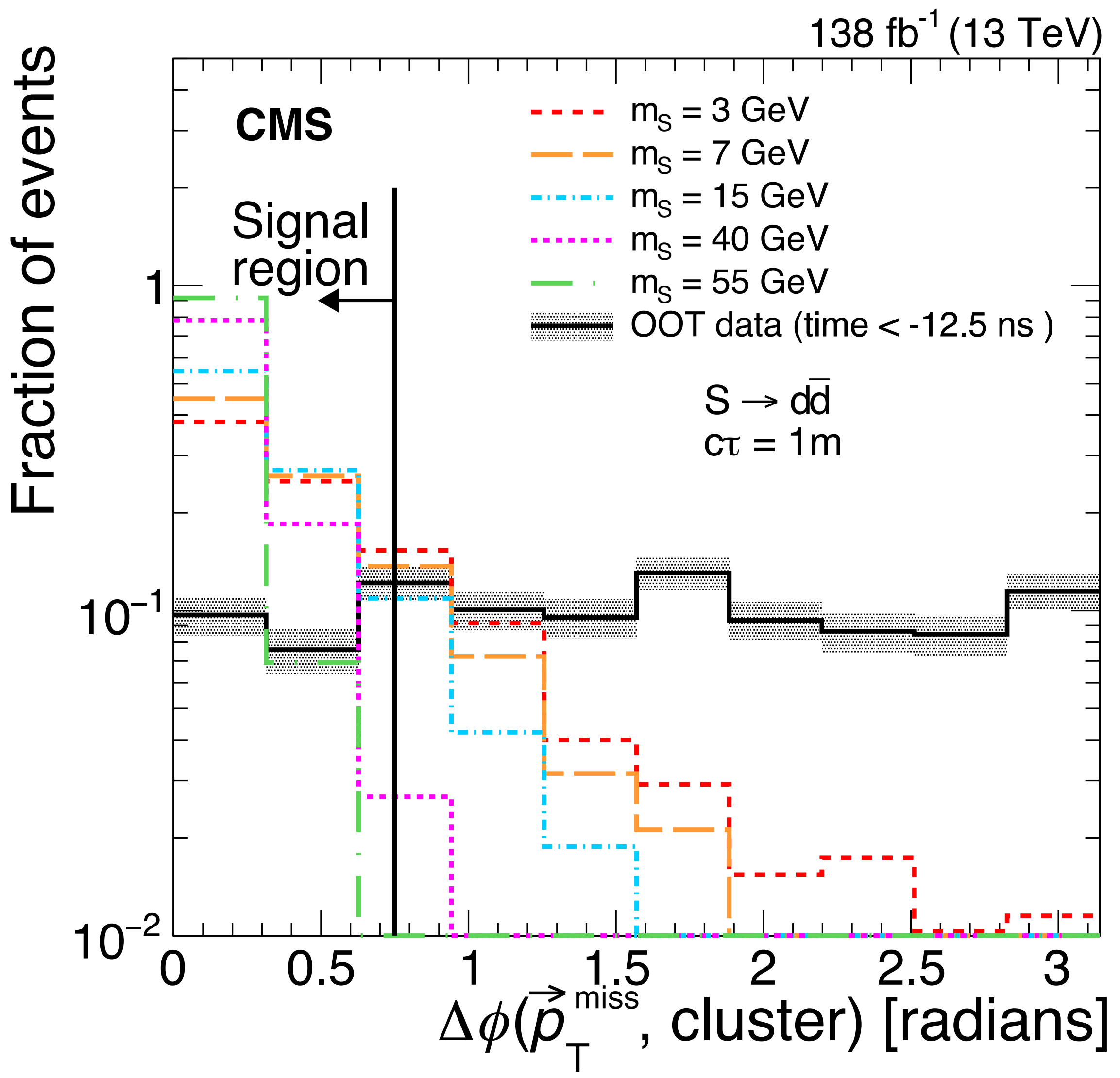


LLP Decays in Muon System

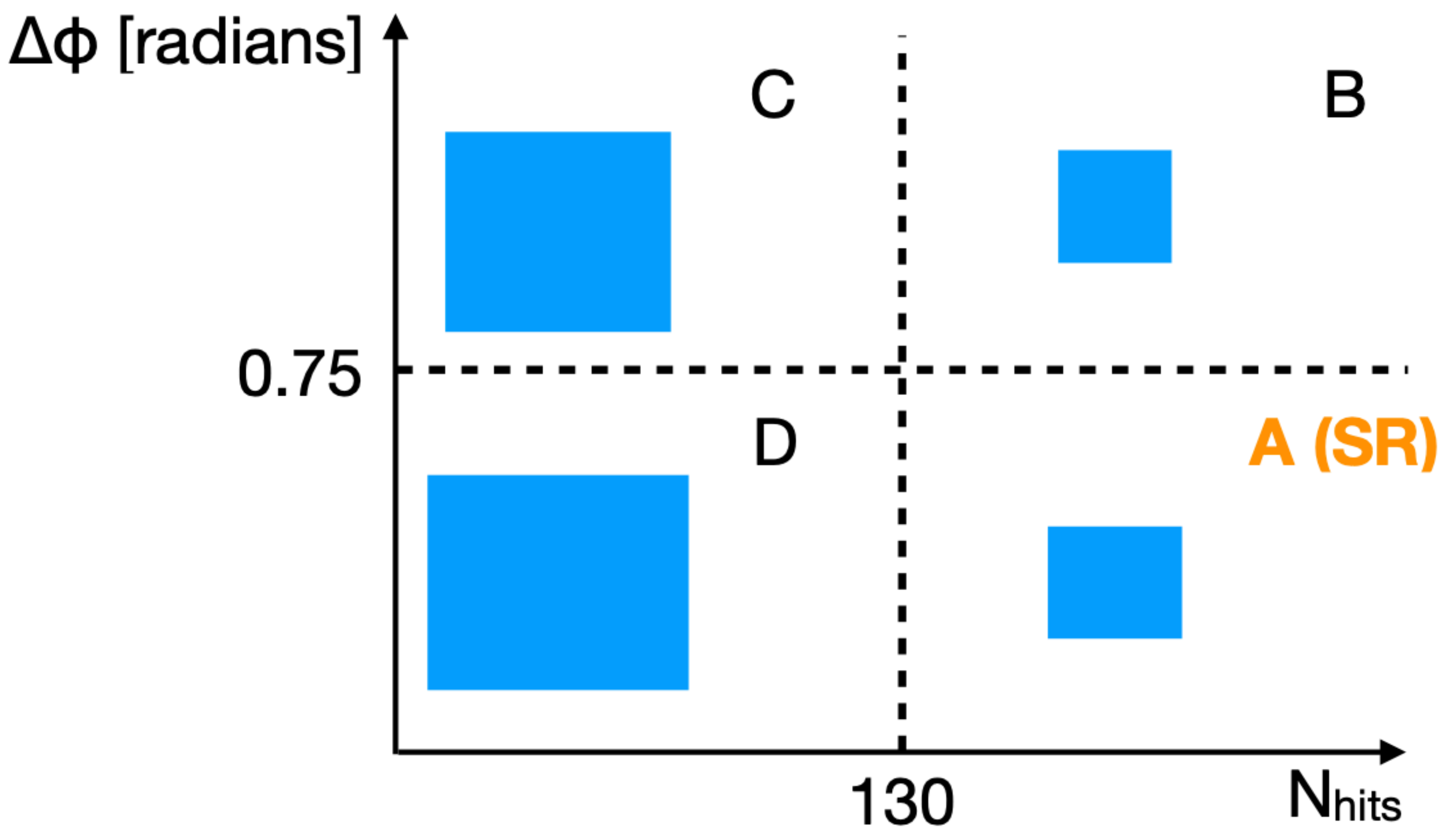
Phys. Rev. D 110, 032007

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





- **Main discriminating variables:**
  - Number of hits in the cluster (N_{hits})
  - Angular difference between $p_{T\ miss}$ and the cluster $\Delta\phi$ ($p_{T\ miss}$, cluster)



- ABCD method used to estimate backgrounds