Unconventional signatures in ATLAS

Challenges, detector considerations and HL-LHC prospects

Flavia de Almeida Dias

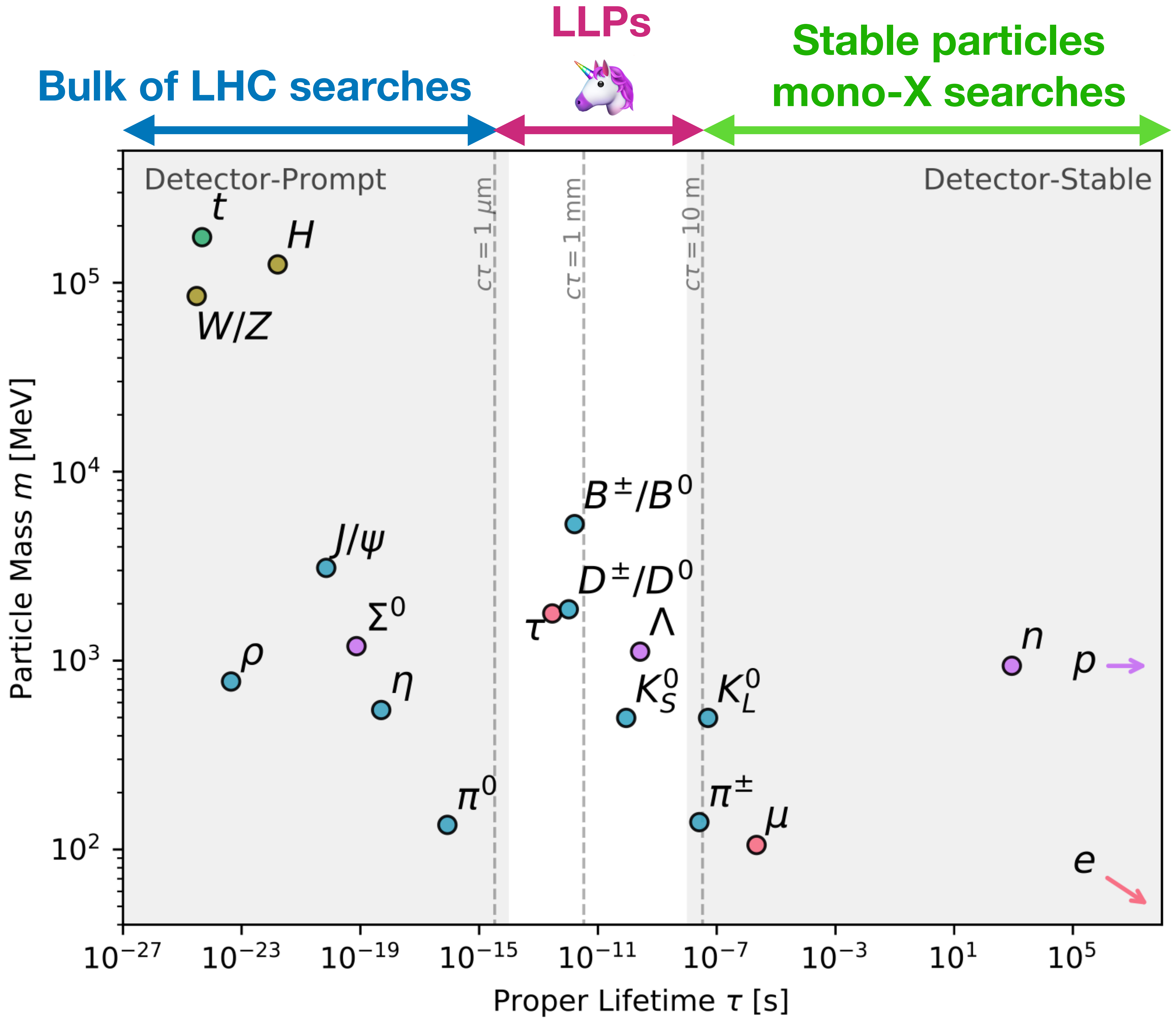
Bethe Forum - Long-Lived Particles

13 November 2023

University of Amsterdam
Institute of Physics

Searching the “lifetime" dimension

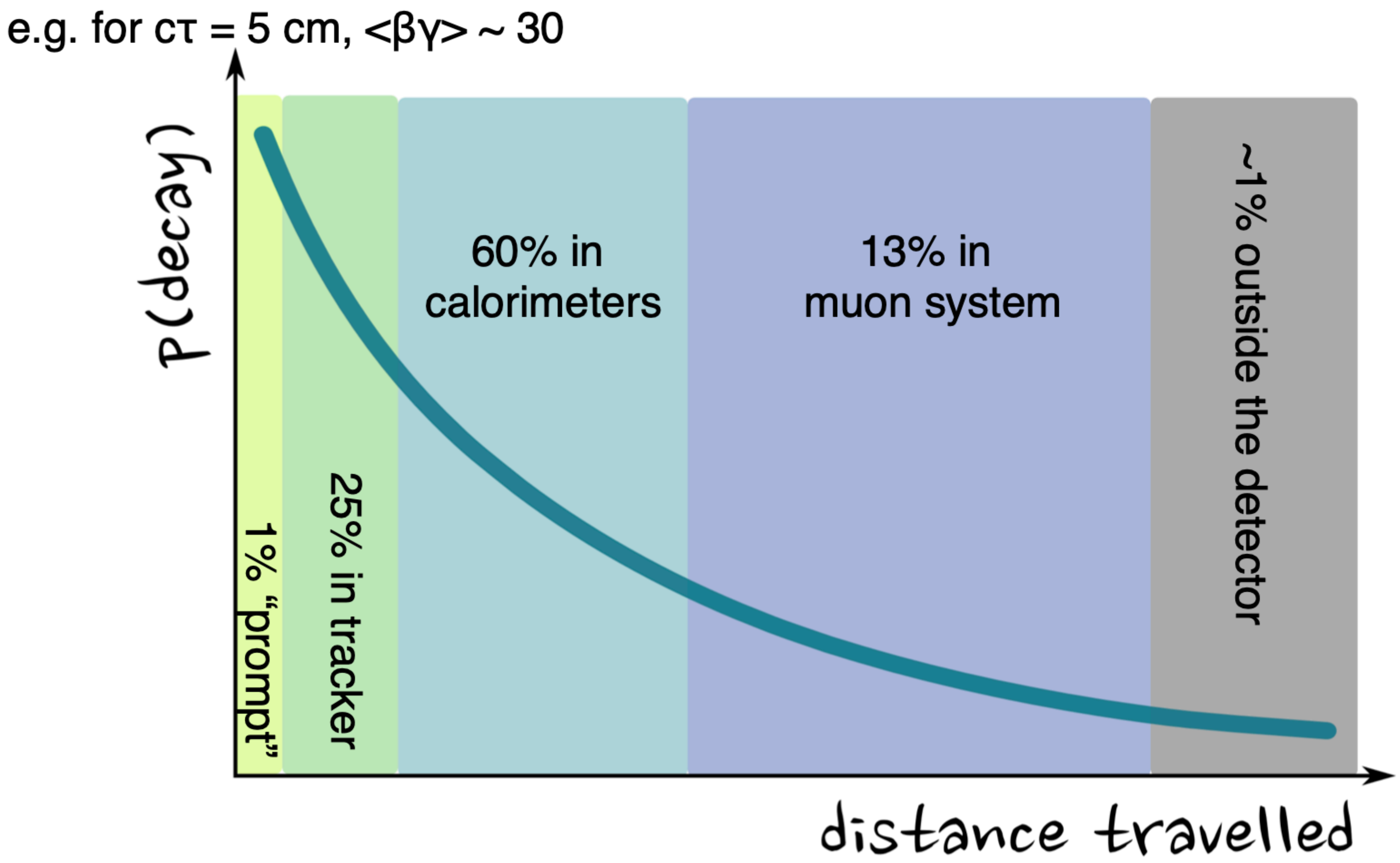
- Long-lived particles (LLPs): promising direction to expand searches @ LHC
  - ➡ Without dedicated searches, we could be missing new physics!
  - ➡ Impressive progress in recent years, but plenty of room for creativity!
  - ➡ Theoretically well motivated!
    - Ask the theorists in this room :)



From arXiv:1810.12602

Why do we need so many searches?

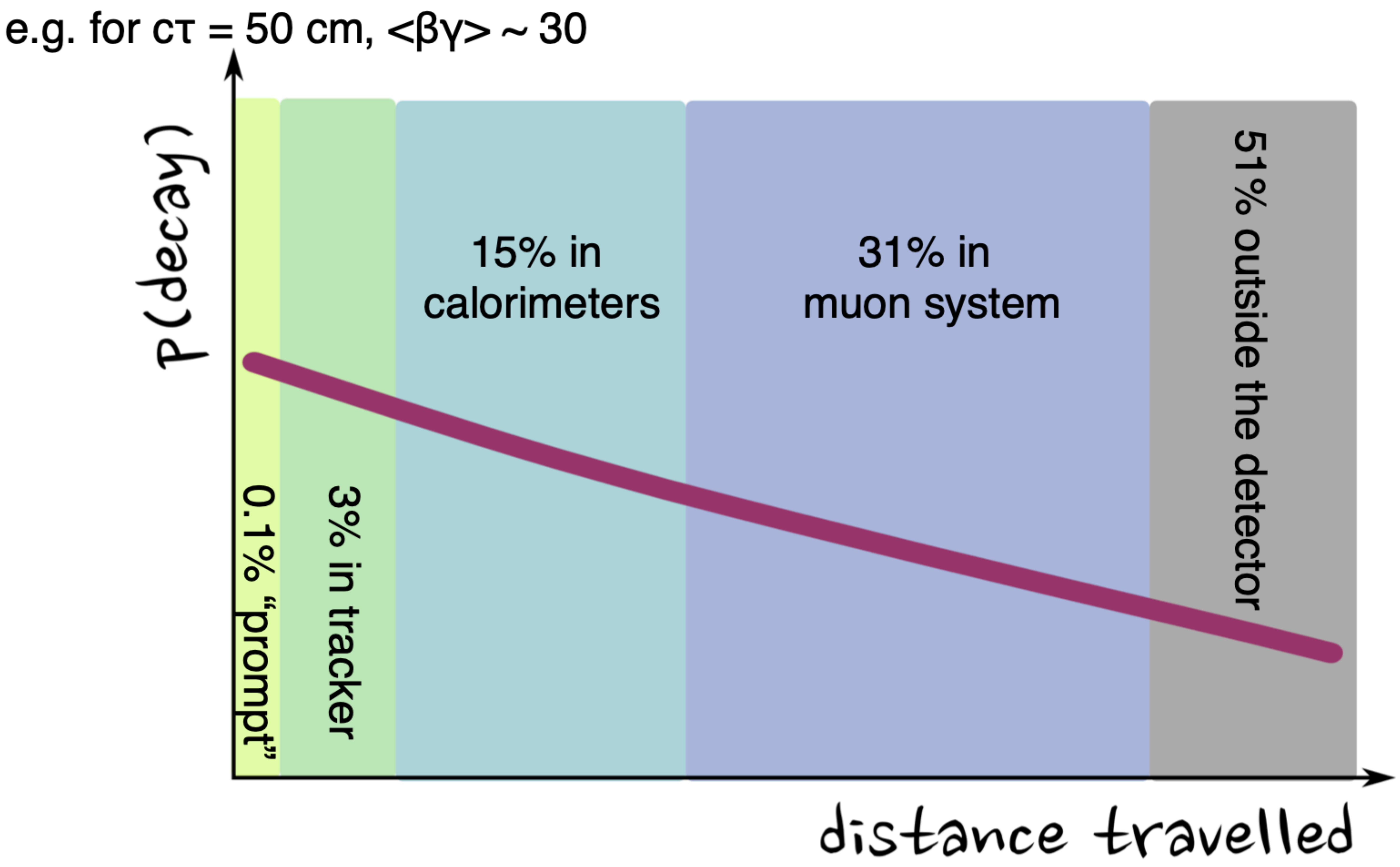
- Even particles with a short proper lifetime can decay with a large lab-frame distance:



From H. Russell

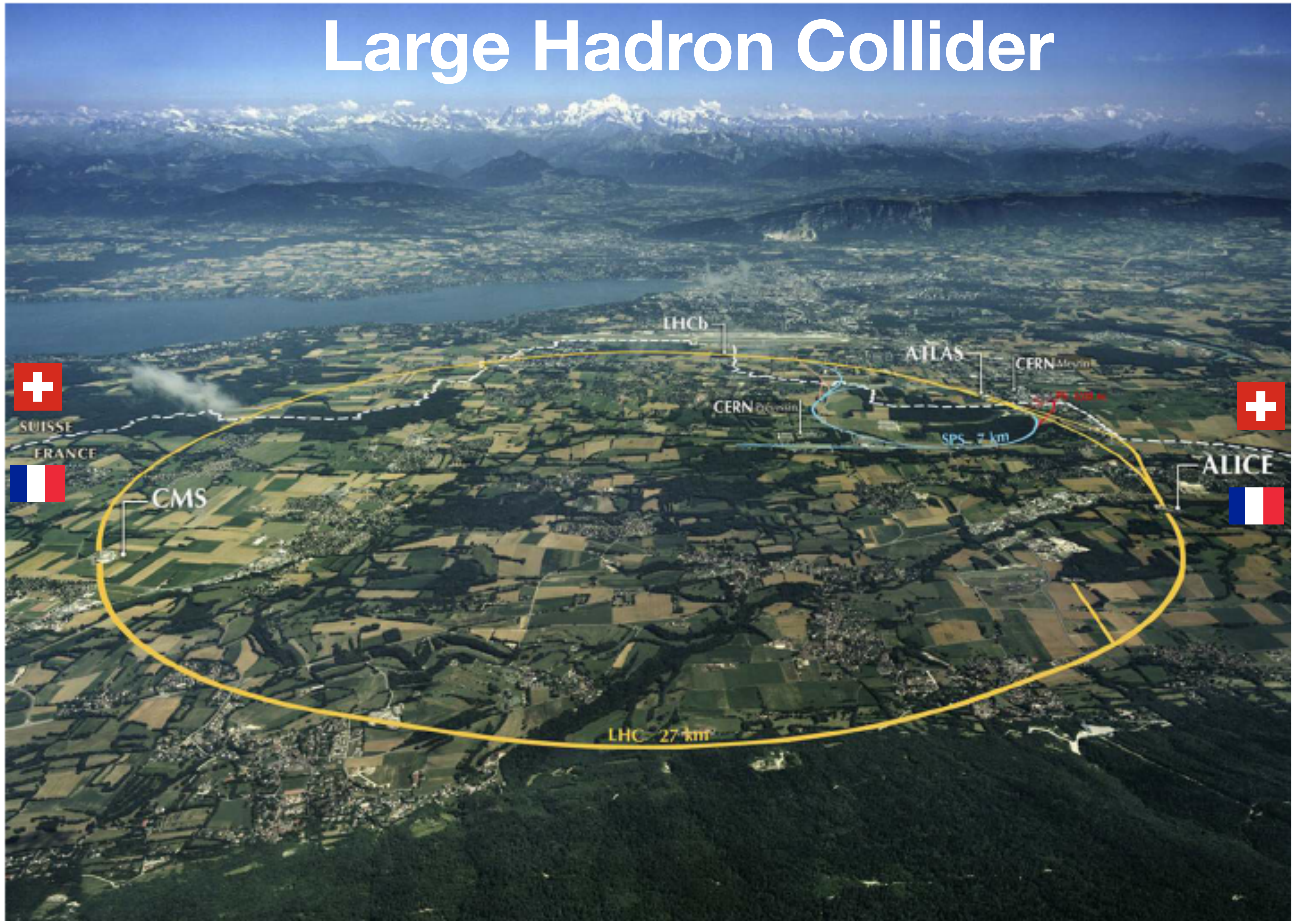
Why do we need so many searches?

- But if we want to consider particles with a longer lifetime, need a dramatically different search strategy!

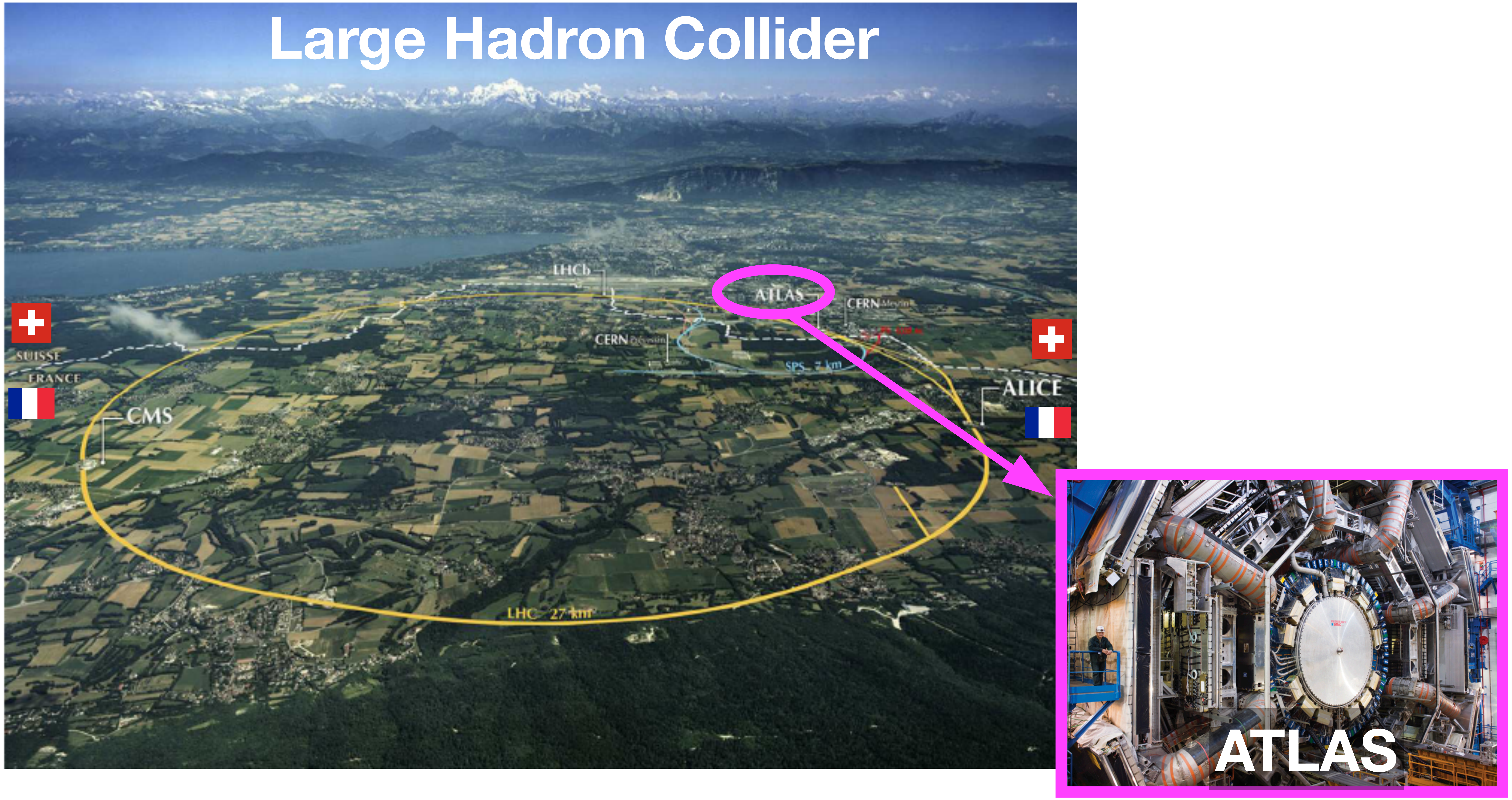


From H. Russell

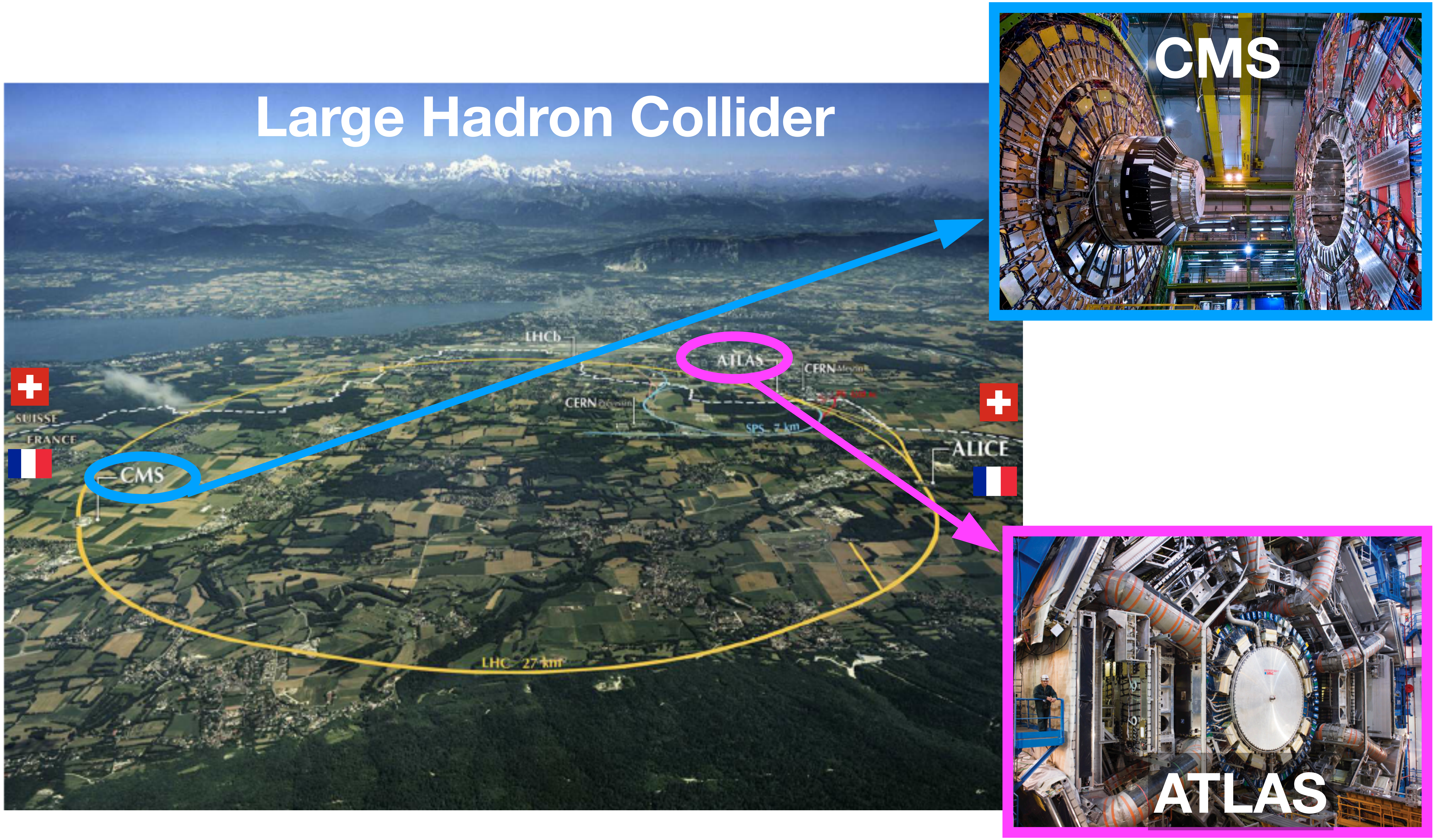
LLPs at LHC



Credit (all images): cds.cern.ch



Credit (all images): cds.cern.ch



Credit (all images): cds.cern.ch

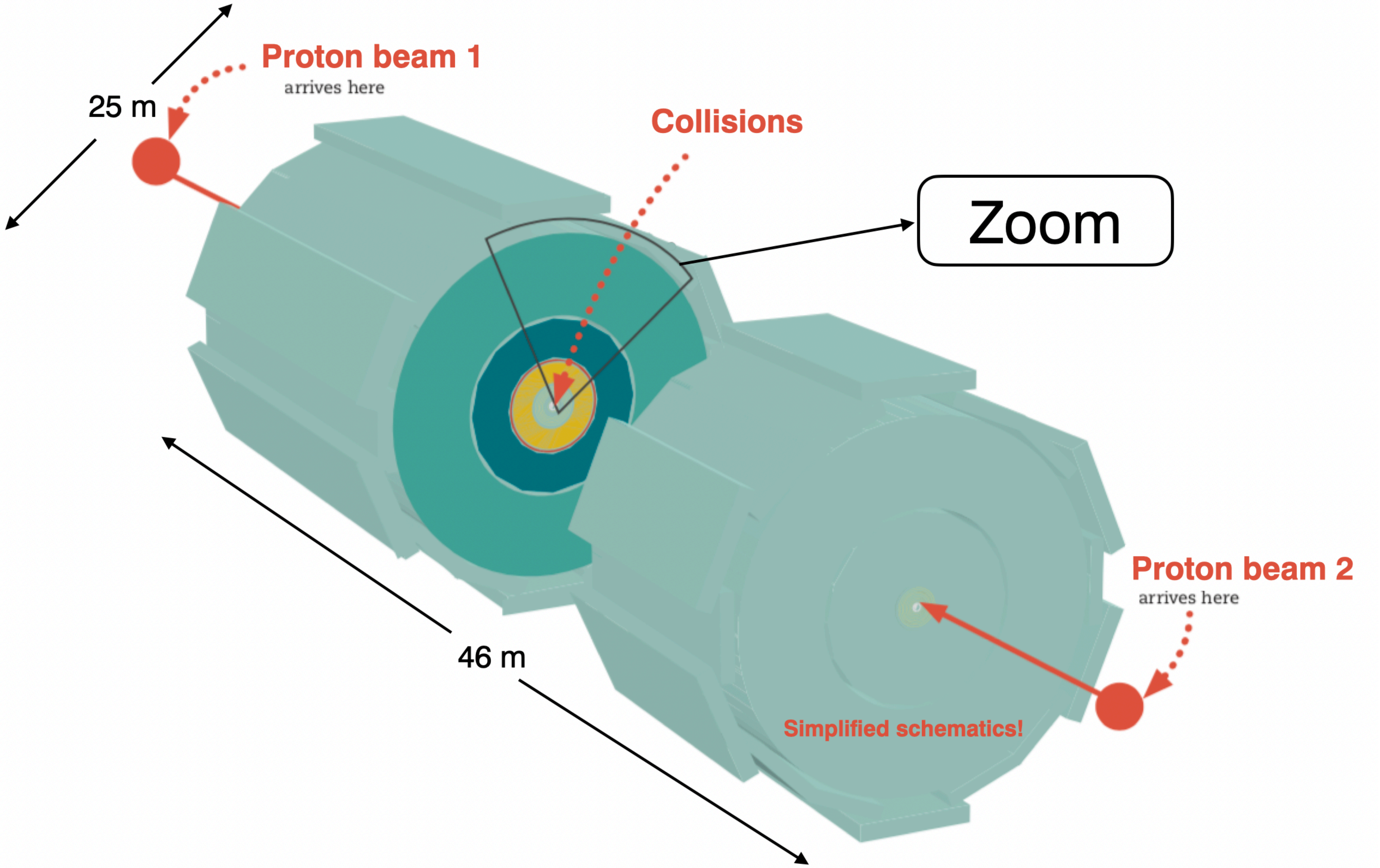
Credit (all images): cds.cern.ch

Credit (all images): cds.cern.ch

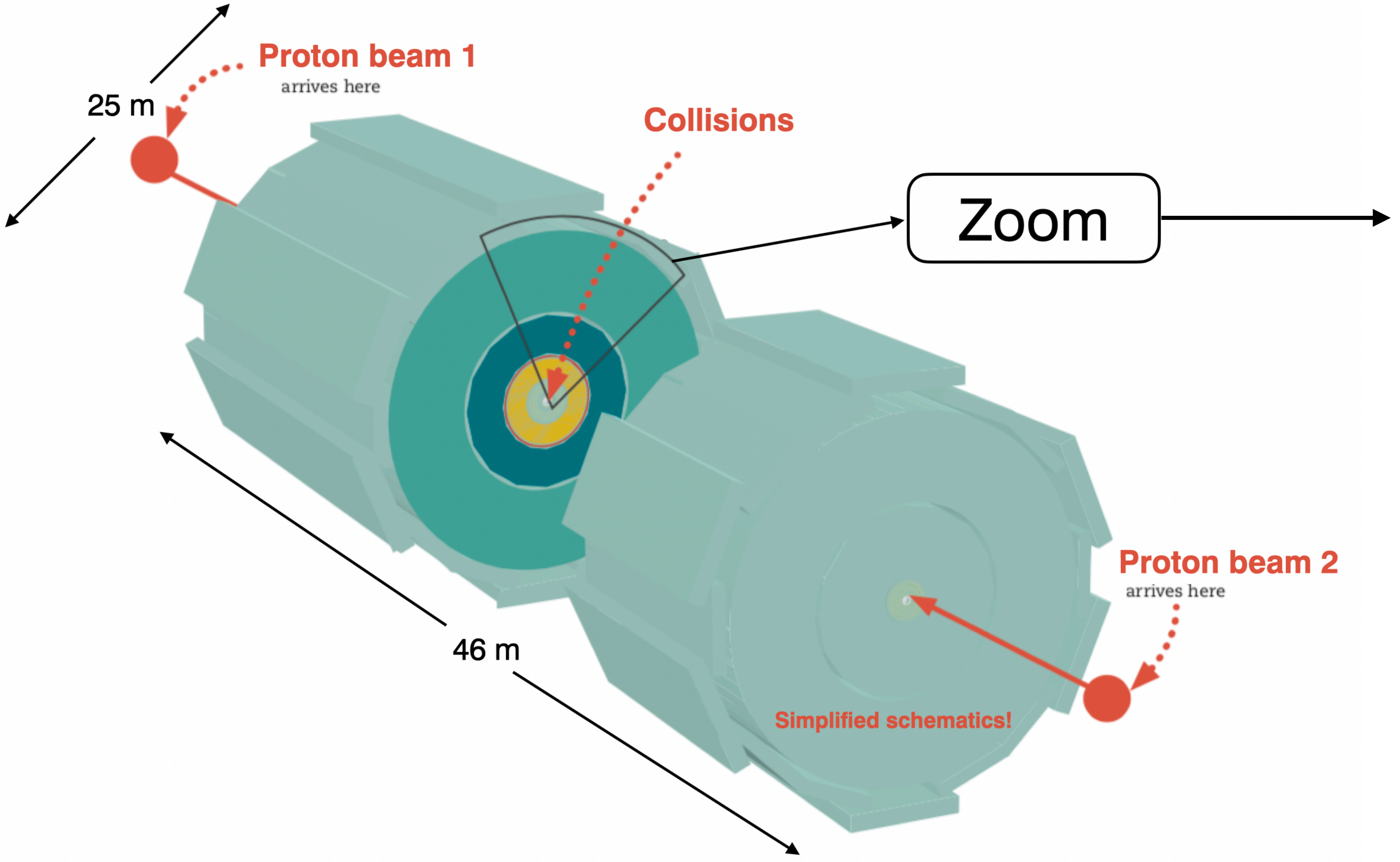
Nikhef UvA

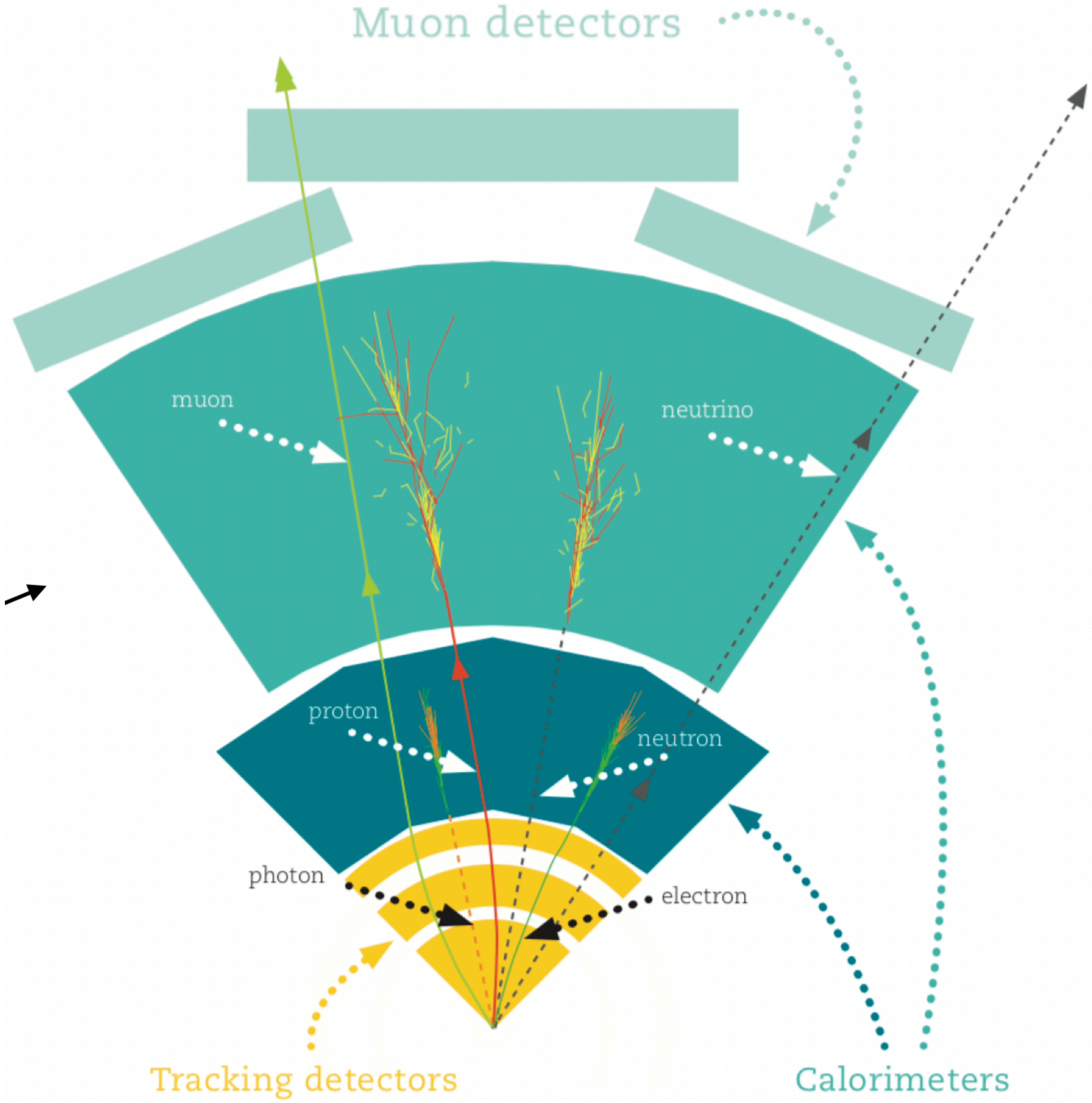
Credit (all images): cds.cern.ch

General-Purpose Particle Detectors



General-Purpose Particle Detectors





Unconventional Signatures - ATLAS & CMS-Style

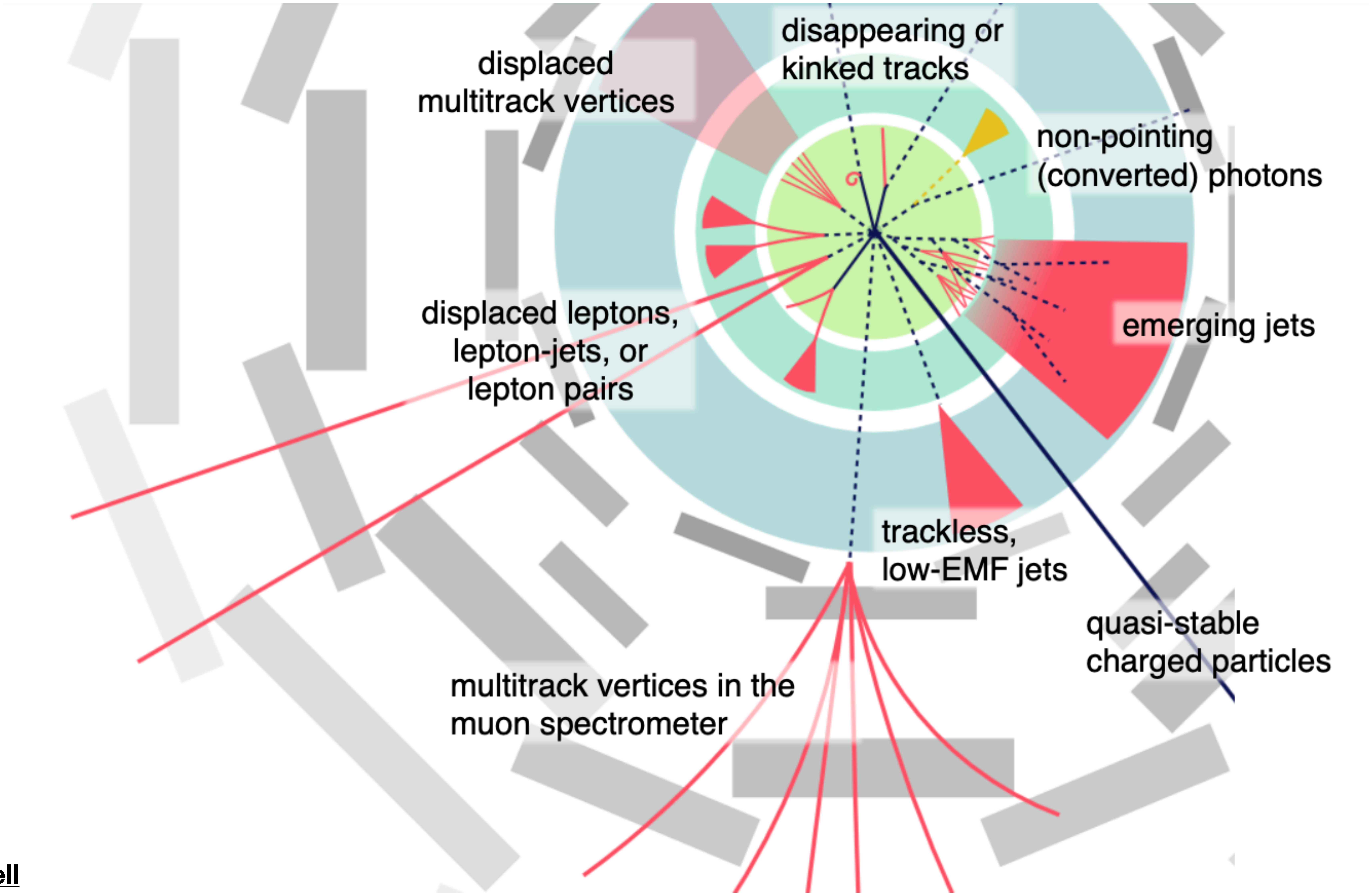


Figure from H. Russell

Unconventional Signatures - ATLAS & CMS-Style

ATLAS & CMS were not designed for LLP searches: custom reconstruction and techniques needed for these unusual signatures!

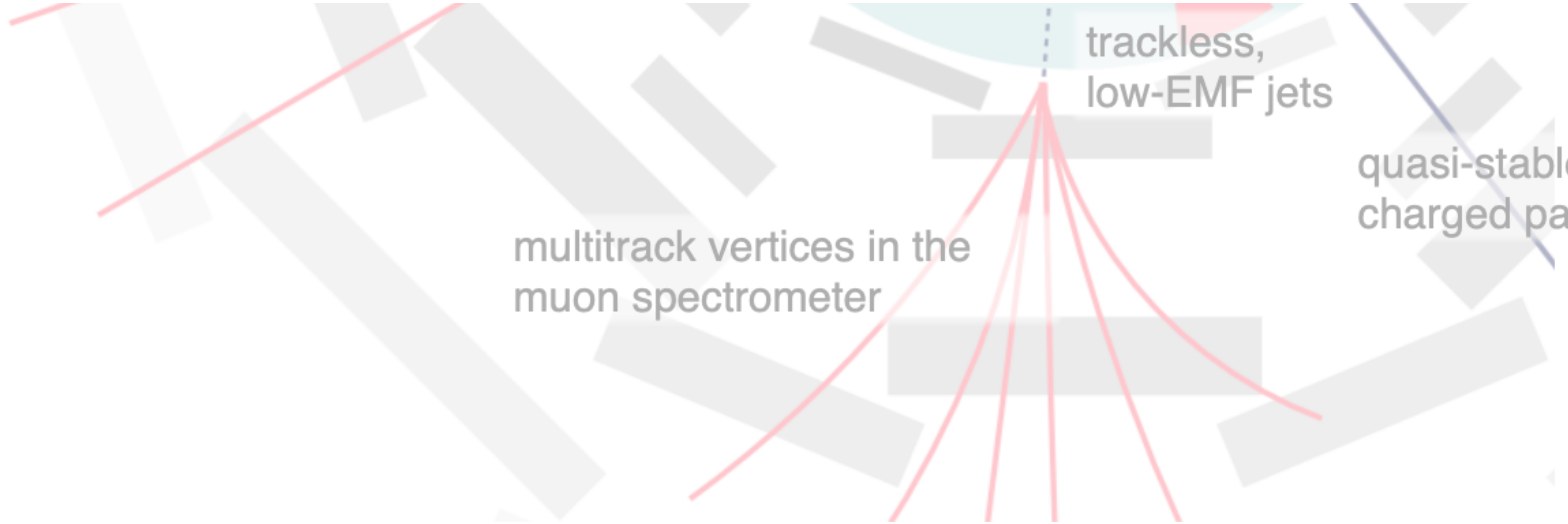
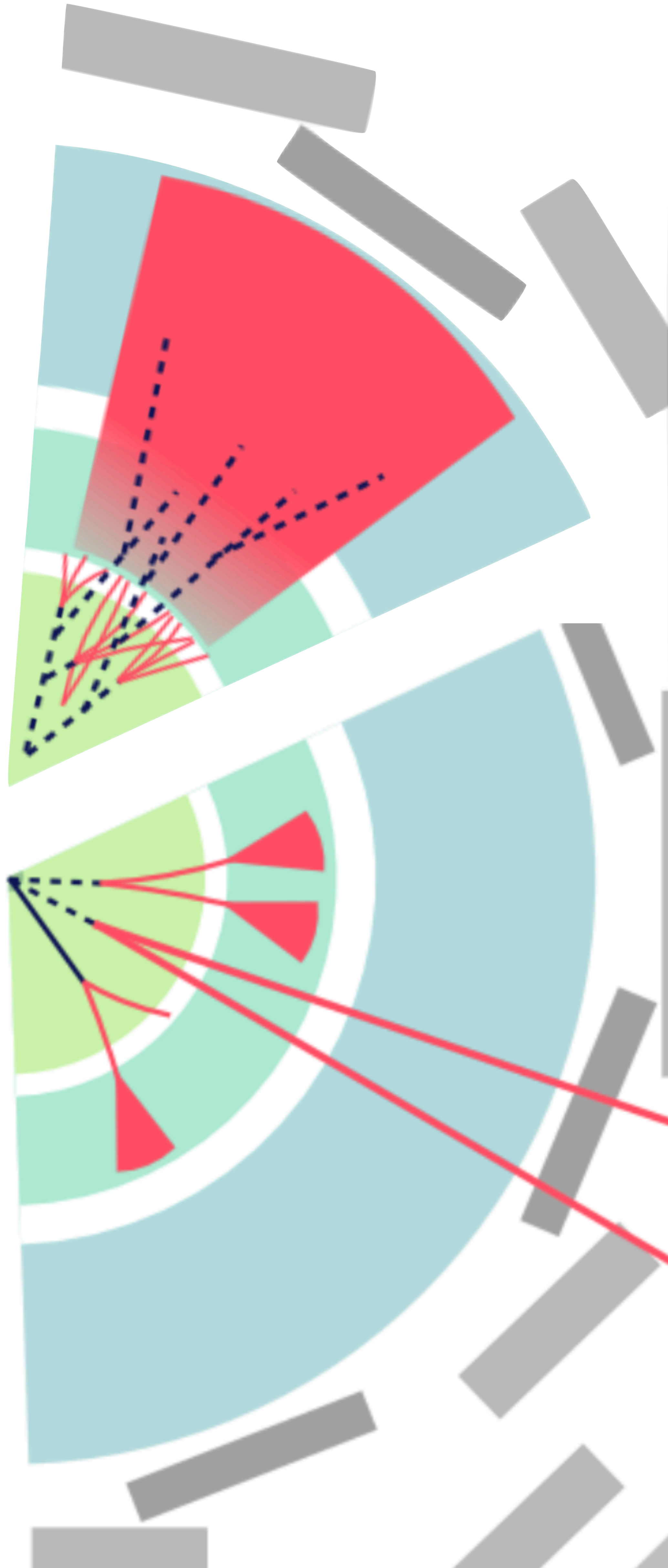


Figure from H. Russell

Nikhef UvA

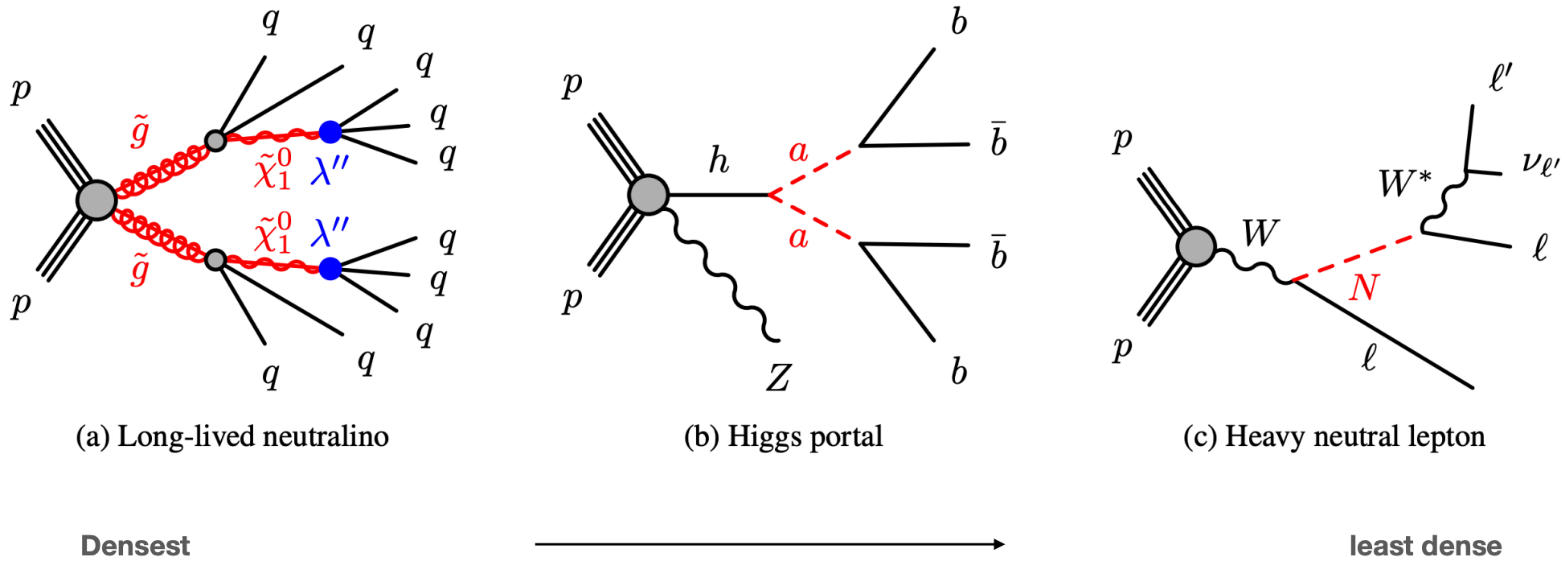
Decays in the Inner Tracker



Displaced Decays in the Inner Tracker

- Particles leave *some* hits in the inner tracking layers
  - ➡ One or multiple secondary vertices
- Challenges:
  - ➡ Dedicated triggers for such topologies
  - ➡ Dedicated reconstruction algorithms for tracks and vertices

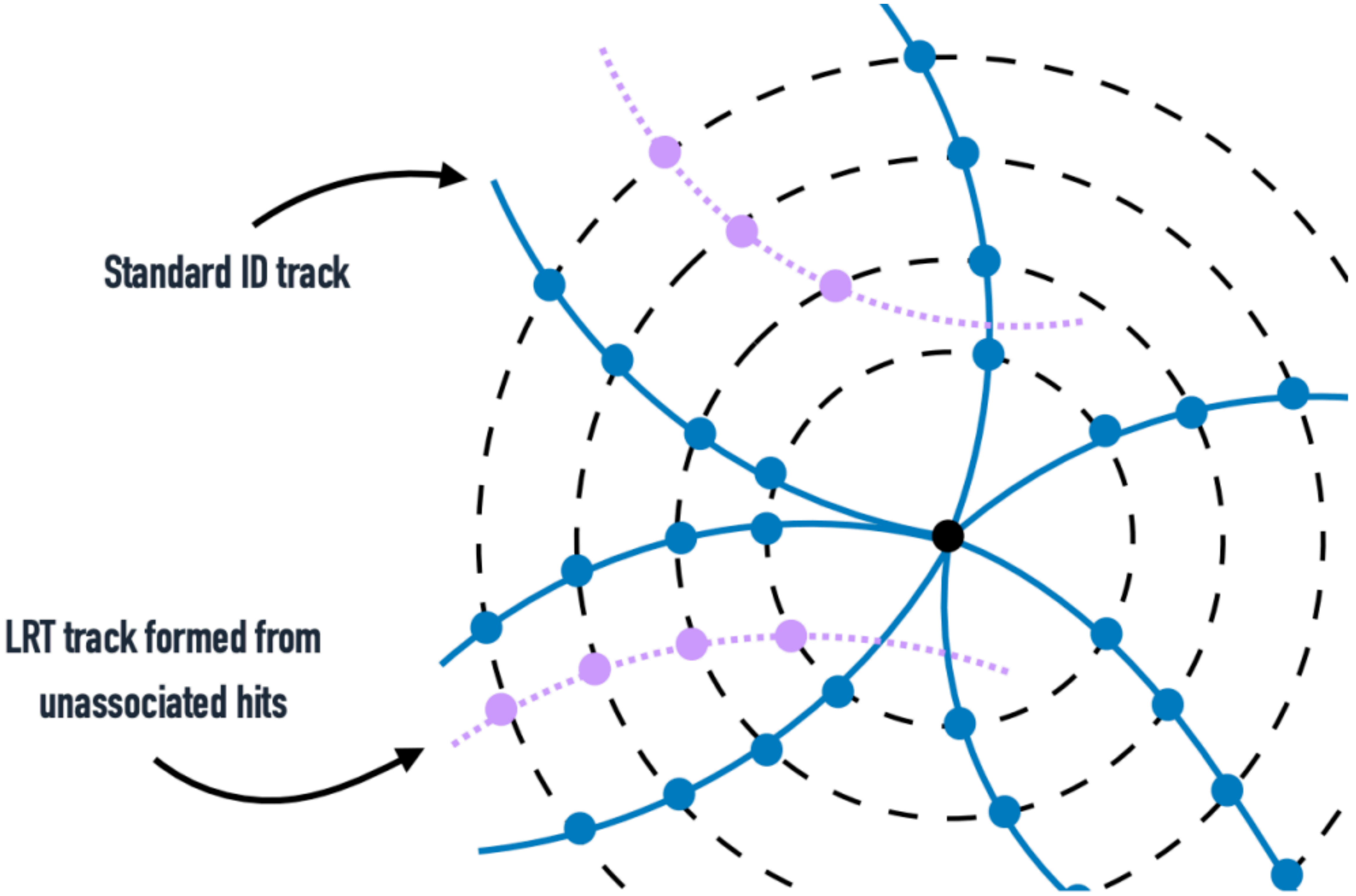
Different reconstruction challenges for ATLAS vs CMS



ATLAS Large-Radius Tracking

- Algorithm for LLPs in ATLAS
  - ➡ Large Radius Tracking (LRT): additional iteration on ID track hits, executed after standard track reconstruction
    - Runs exclusively on leftovers hits
    - Extend the sensitivity to a larger particle lifetime range

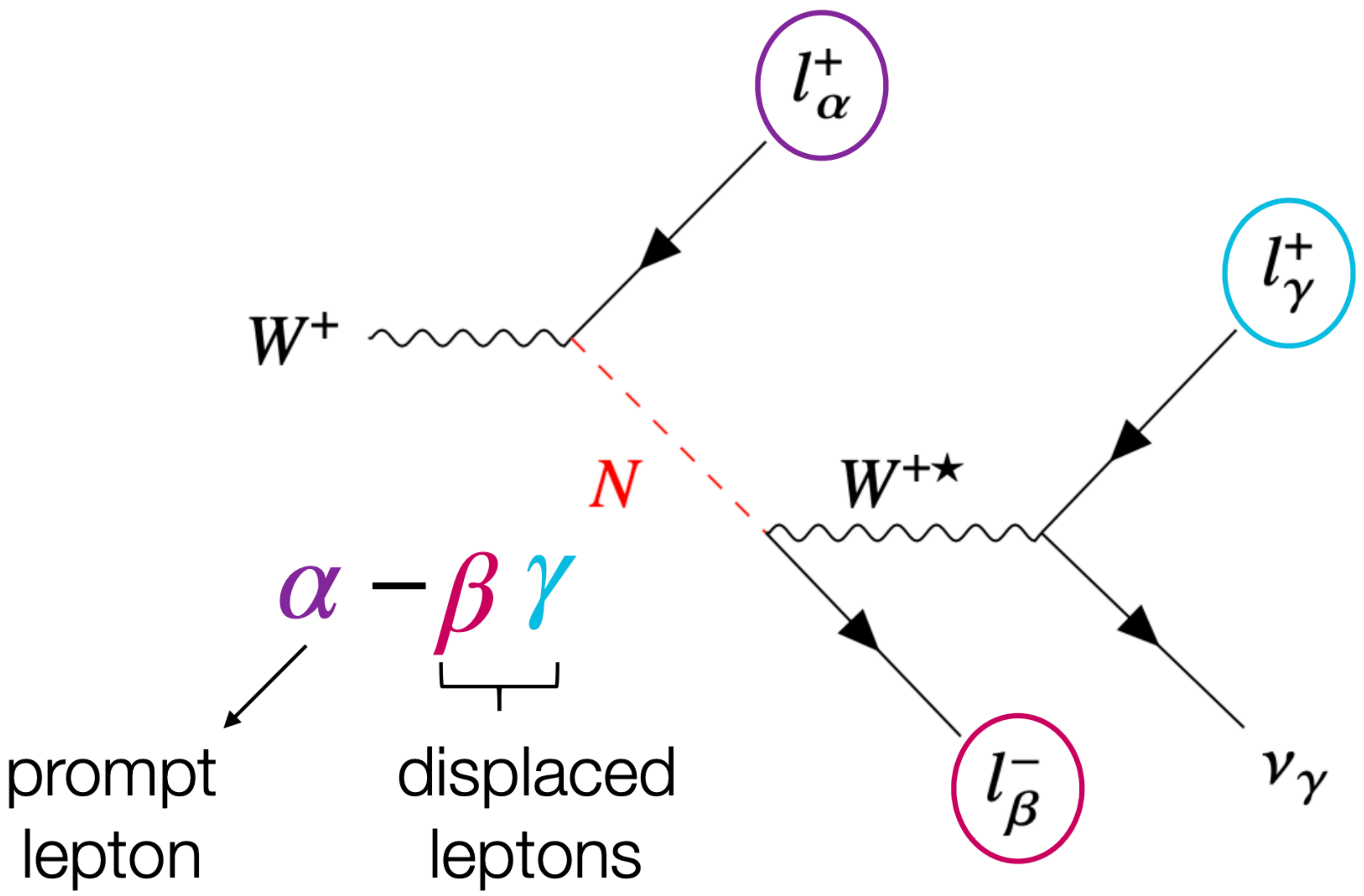
Selection Criteria	Primary	LRT
max. $\|d_0\|$ [mm]	5	300
max. $\|z_0\|$ [mm]	200	500
min. p_T [GeV]	0.5	1



From Hamza Hanif

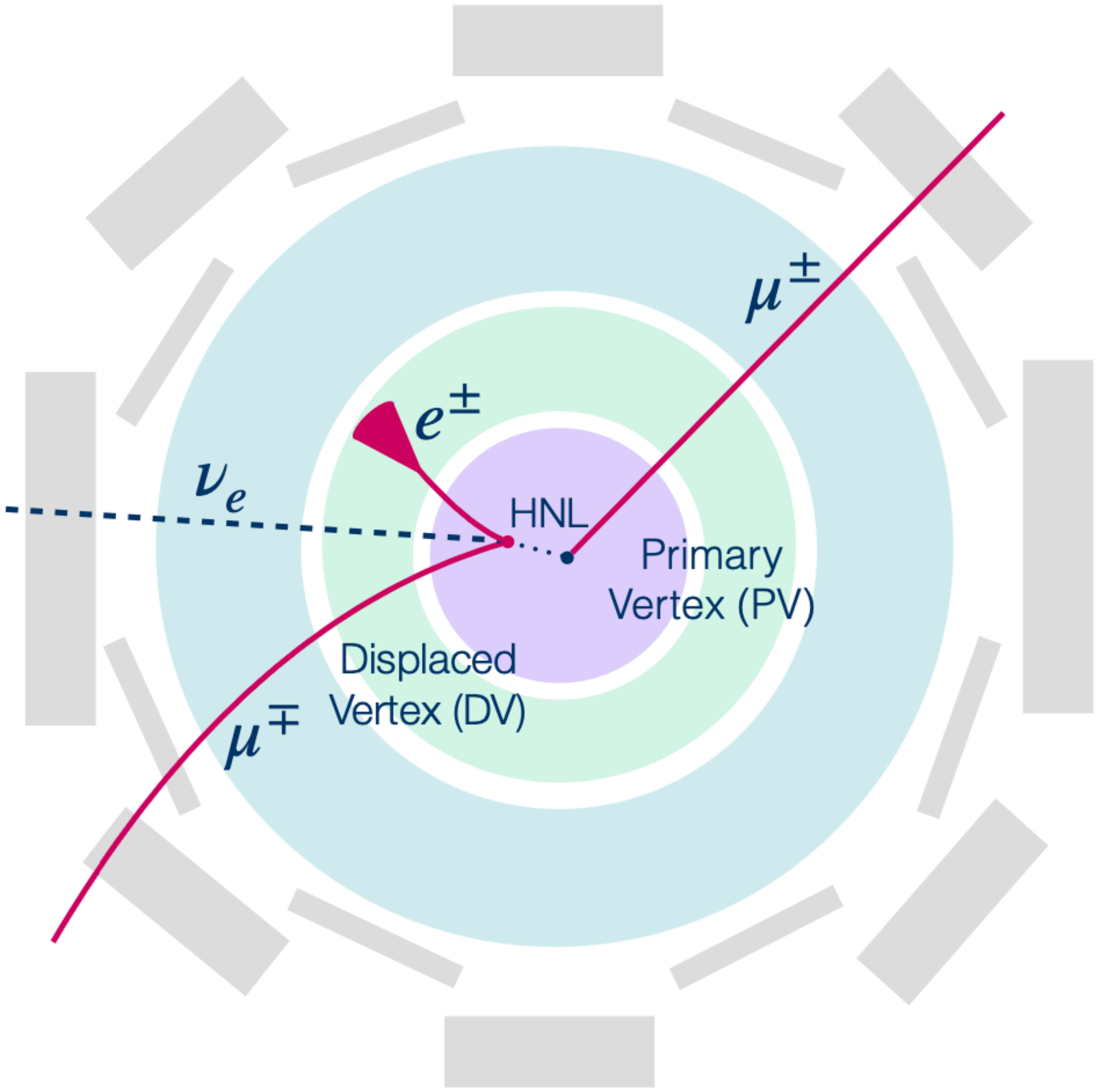
Search for Displaced Heavy Neutral Leptons

- Experimental dHNL signature:
  - ➡ Prompt lepton (trigger)
  - ➡ Displaced vertex with two opposite charge leptons



6 signal regions:
μ-μμ, μ-μe, μ-ee, e-ee, e-eμ, e-μμ

Figure from D. Trischuk

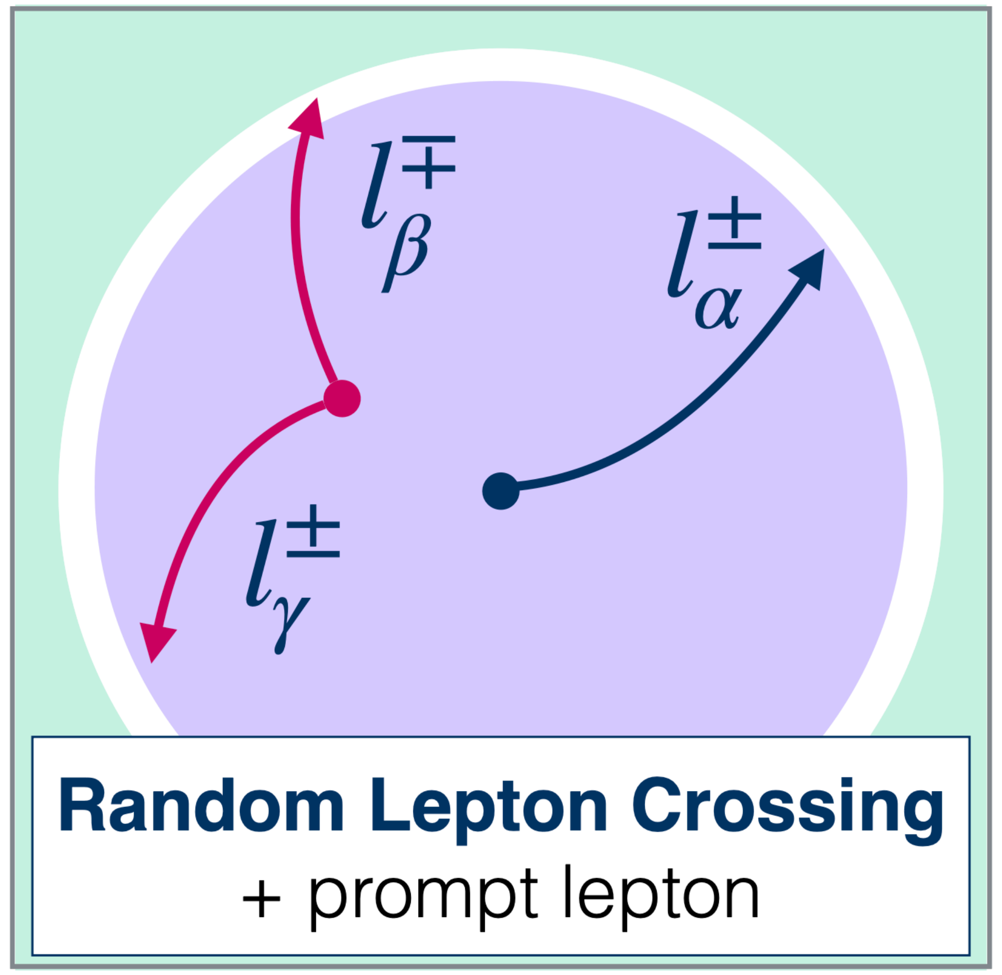


Phys. Rev. Lett. 131 (2023) 061803

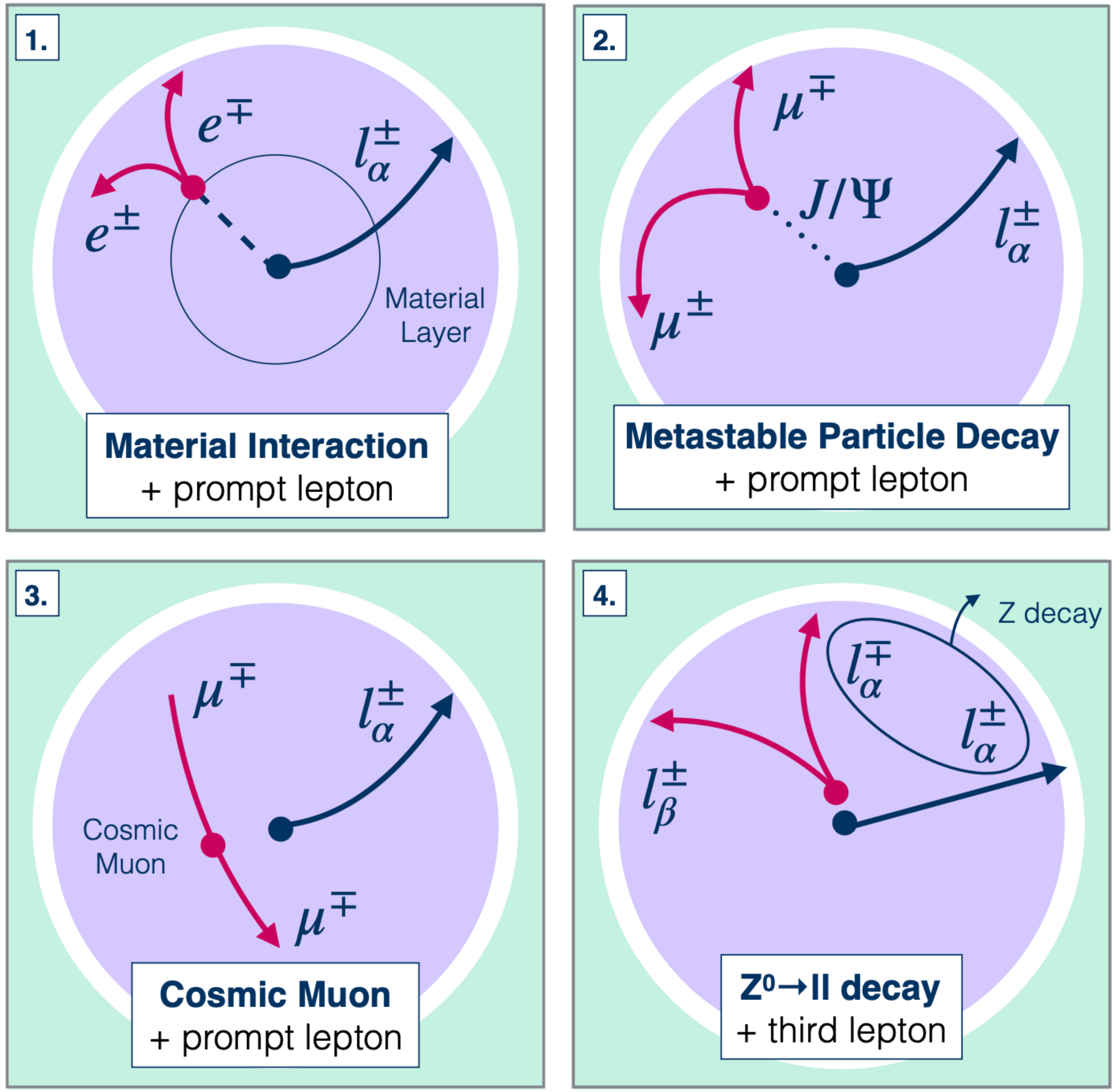
ATLAS EXPERIMENT Nikhef UvA

dHNLs: Backgrounds

Dominant background



Non-random backgrounds

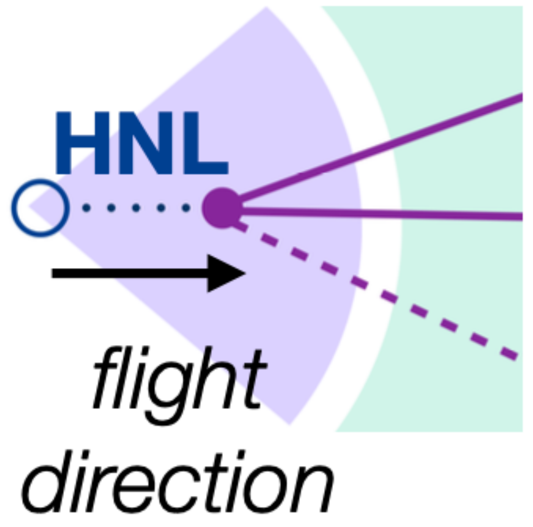


- Data-driven object shuffling method is used to estimate the background from random lepton crossings
- Dedicated selections to remove non-random backgrounds
  - ➡ e.g. invariant mass of the displaced vertex to reject heavy-flavour decays

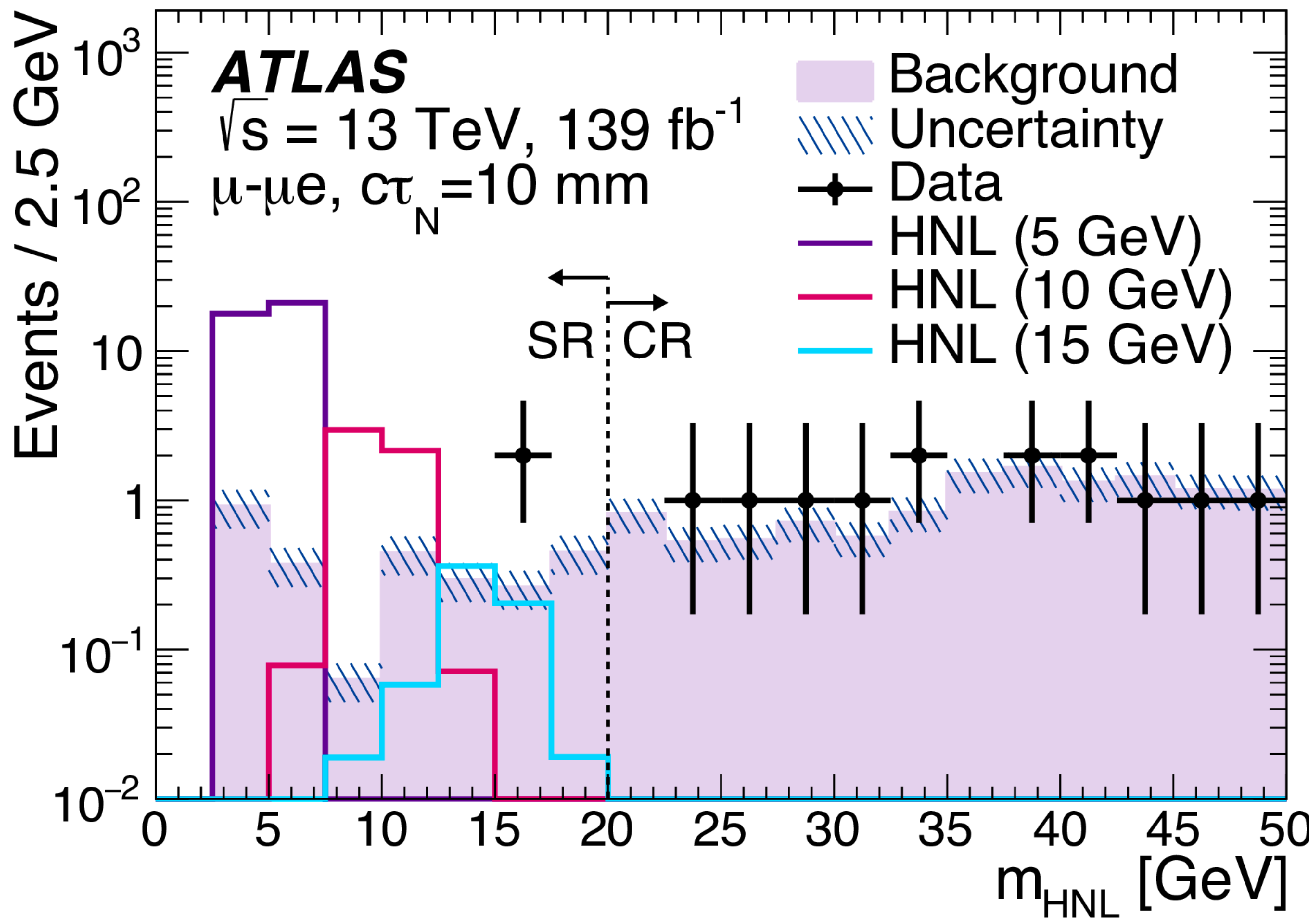
Figures from D. Trischuk

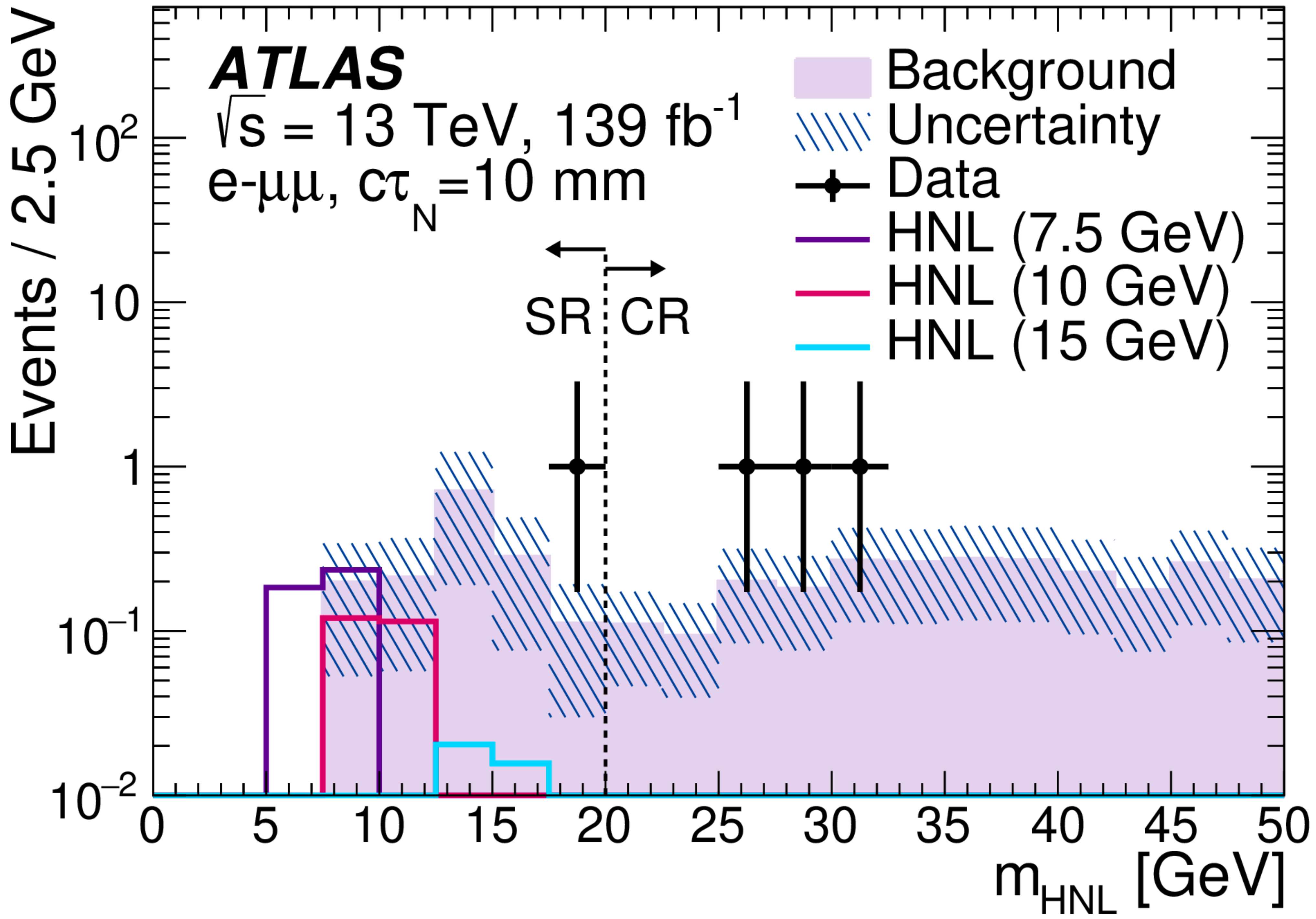
ATLAS Results: dHNL

- Energy-momentum conservation is used to reconstruct the HNL mass: $m_{HNL}^2 = (P_{l\beta} + P_{l\gamma} + P_{\nu\gamma})^2$



Phys. Rev. Lett. 131 (2023) 061803

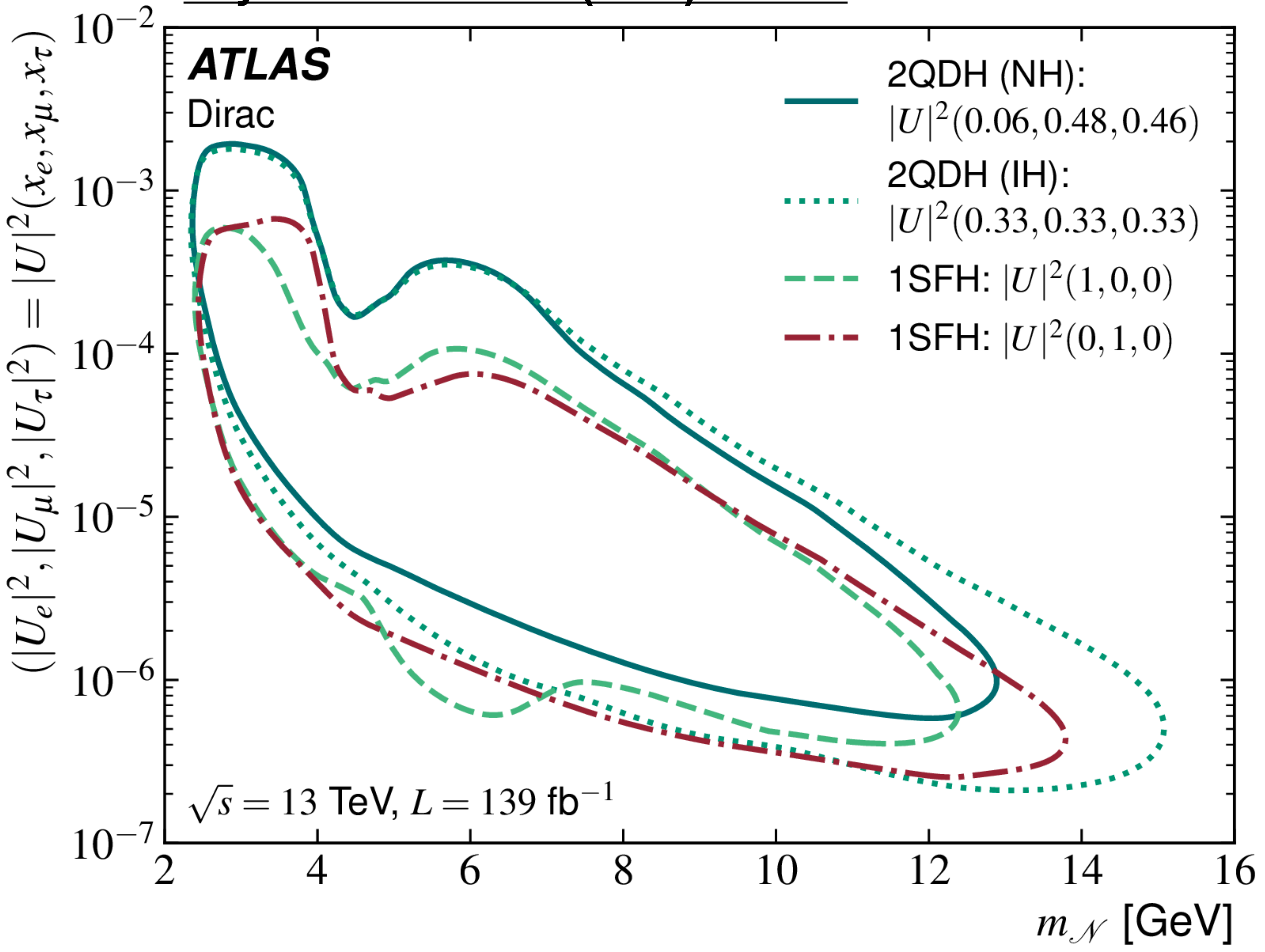




ATLAS Results: dHNL

- No excess observed ☹️

Phys. Rev. Lett. 131 (2023) 061803



Mixing: Electron-only

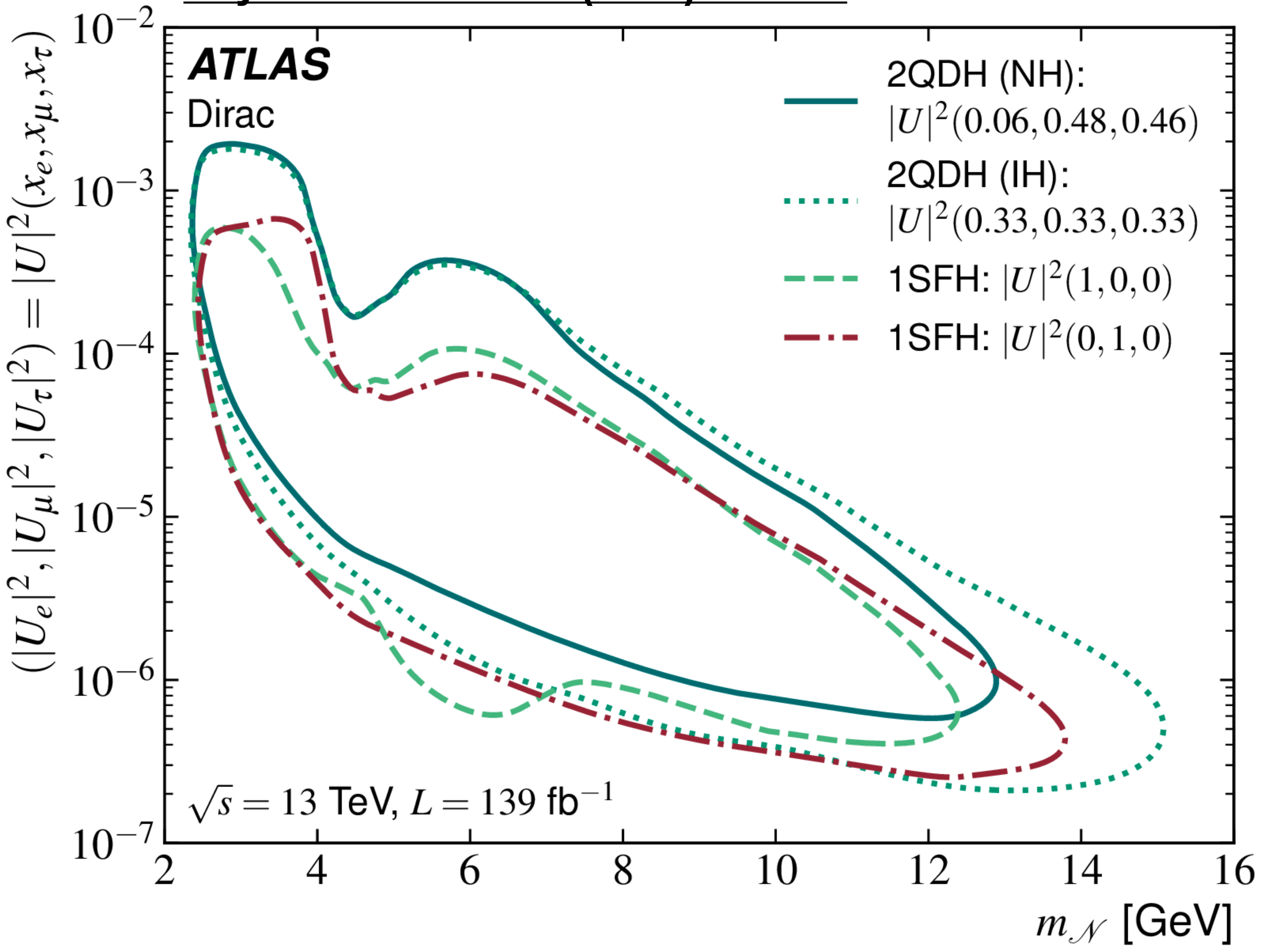
Multi-flavour

Muon-only

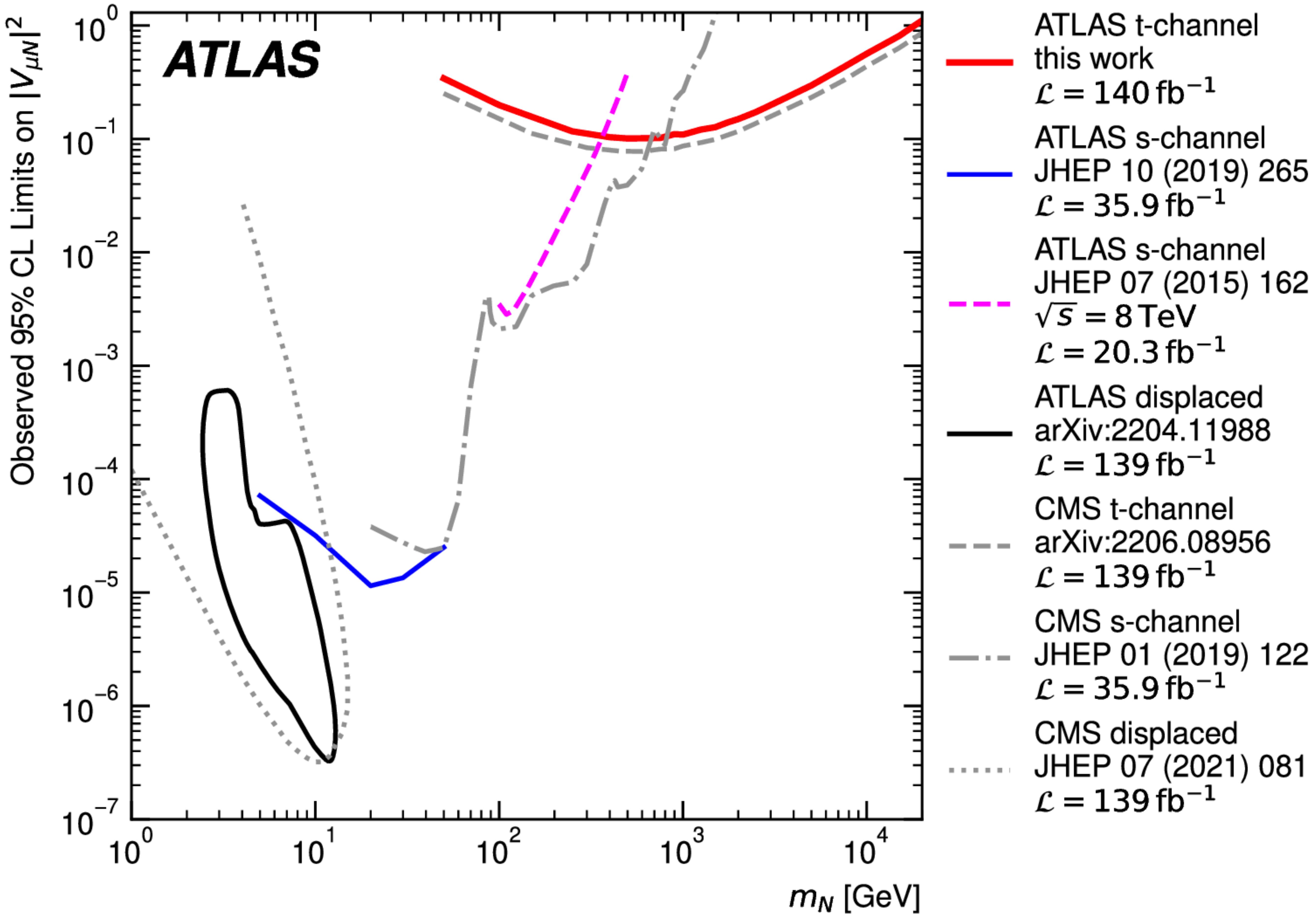
ATLAS Results: dHNL

- No excess observed ☹️

Phys. Rev. Lett. 131 (2023) 061803



arXiv:2305.14931

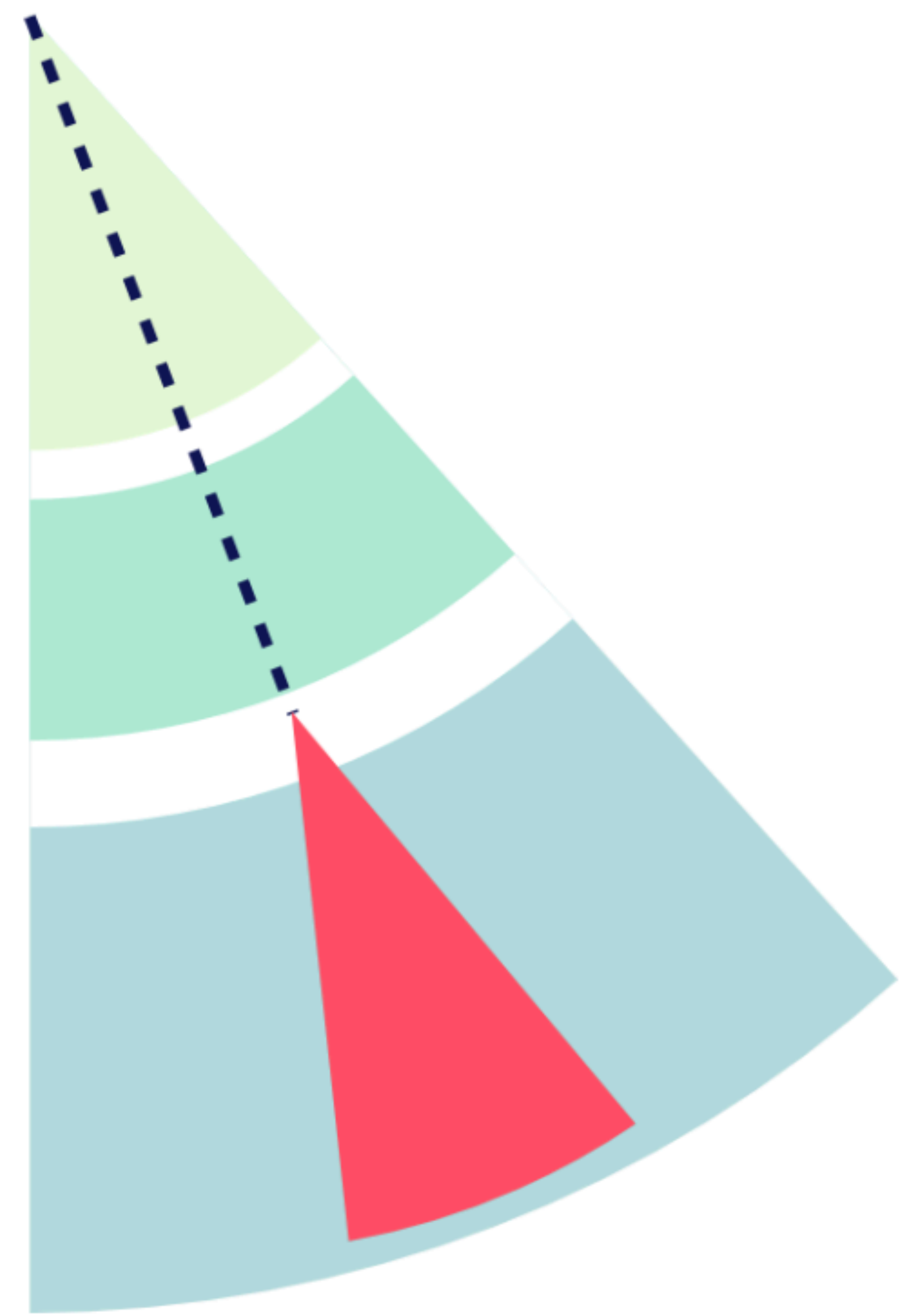


Mixing: Electron-only

Multi-flavour

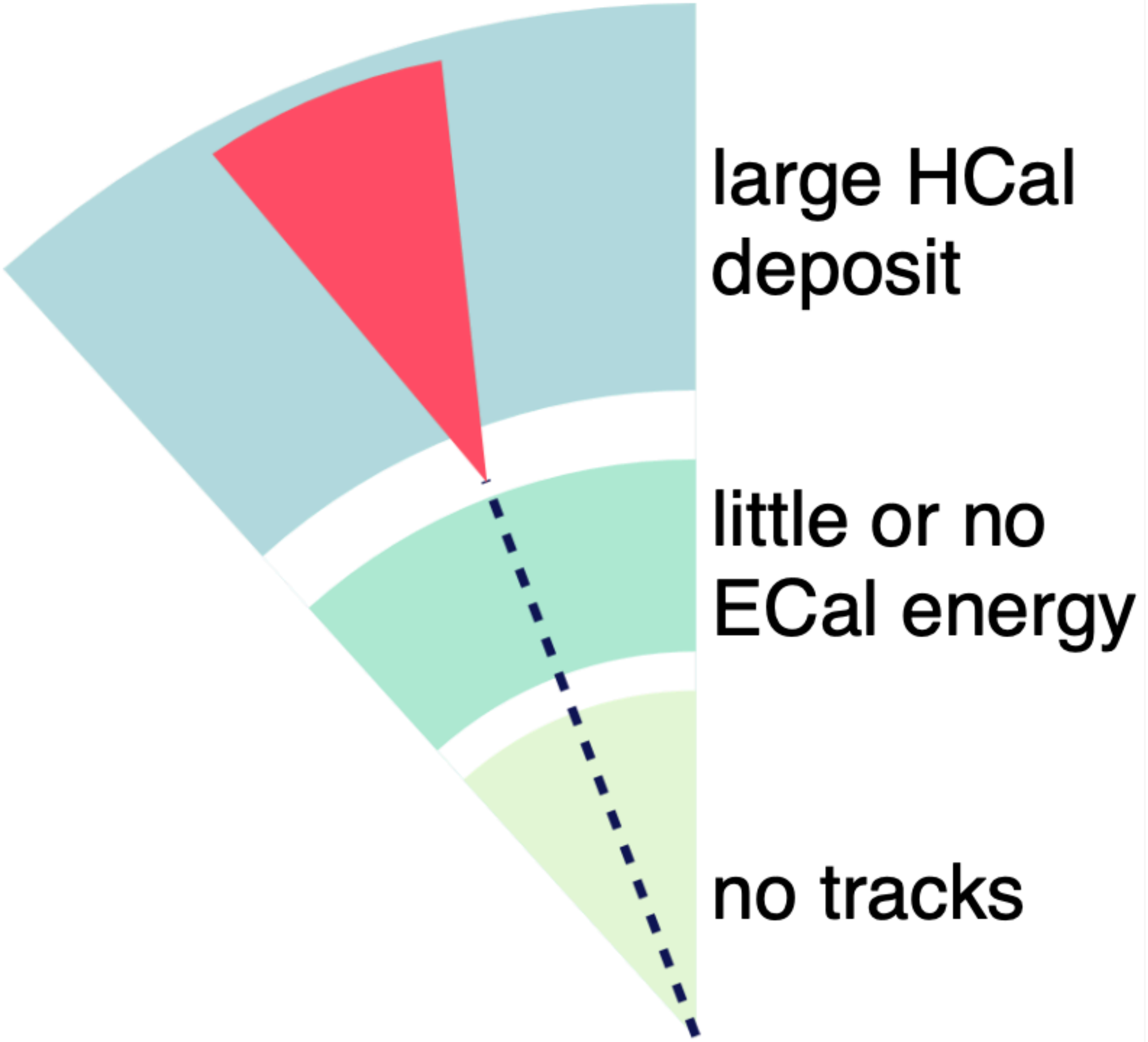
Muon-only

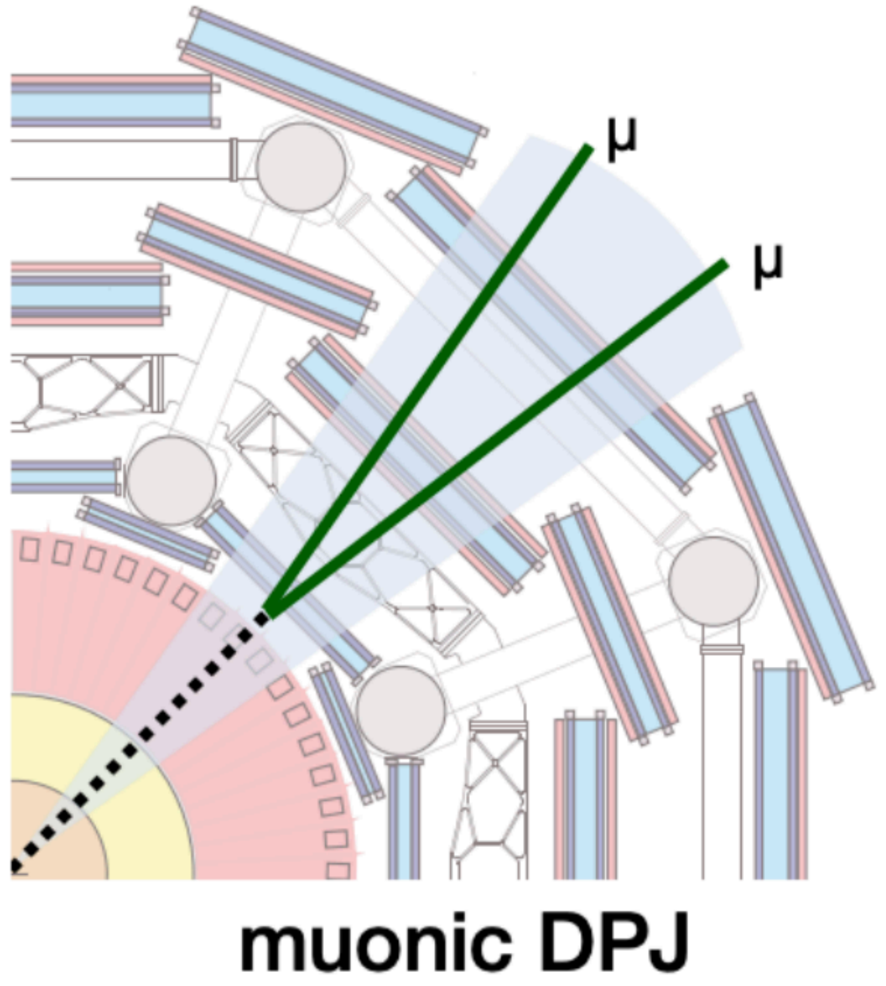
Decays in the Calorimeters

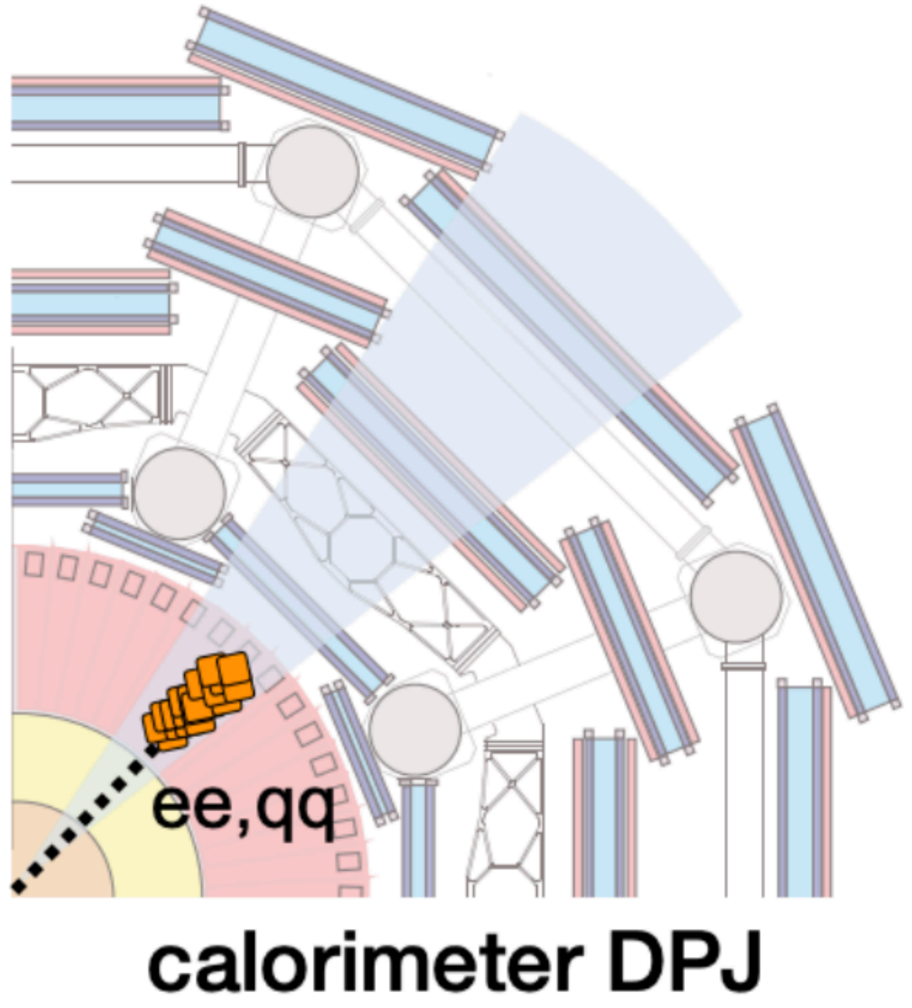


Decays in the Calorimeters

- No tracking information, info from calorimeters (and muon system)
  - ➡ Signatures: trackless jets, collimated lepton-jets
  - ➡ Can also look at non-pointing/non-prompt photons
  - ➡ Special triggers needed
  - ➡ Dedicated jet reconstruction needed

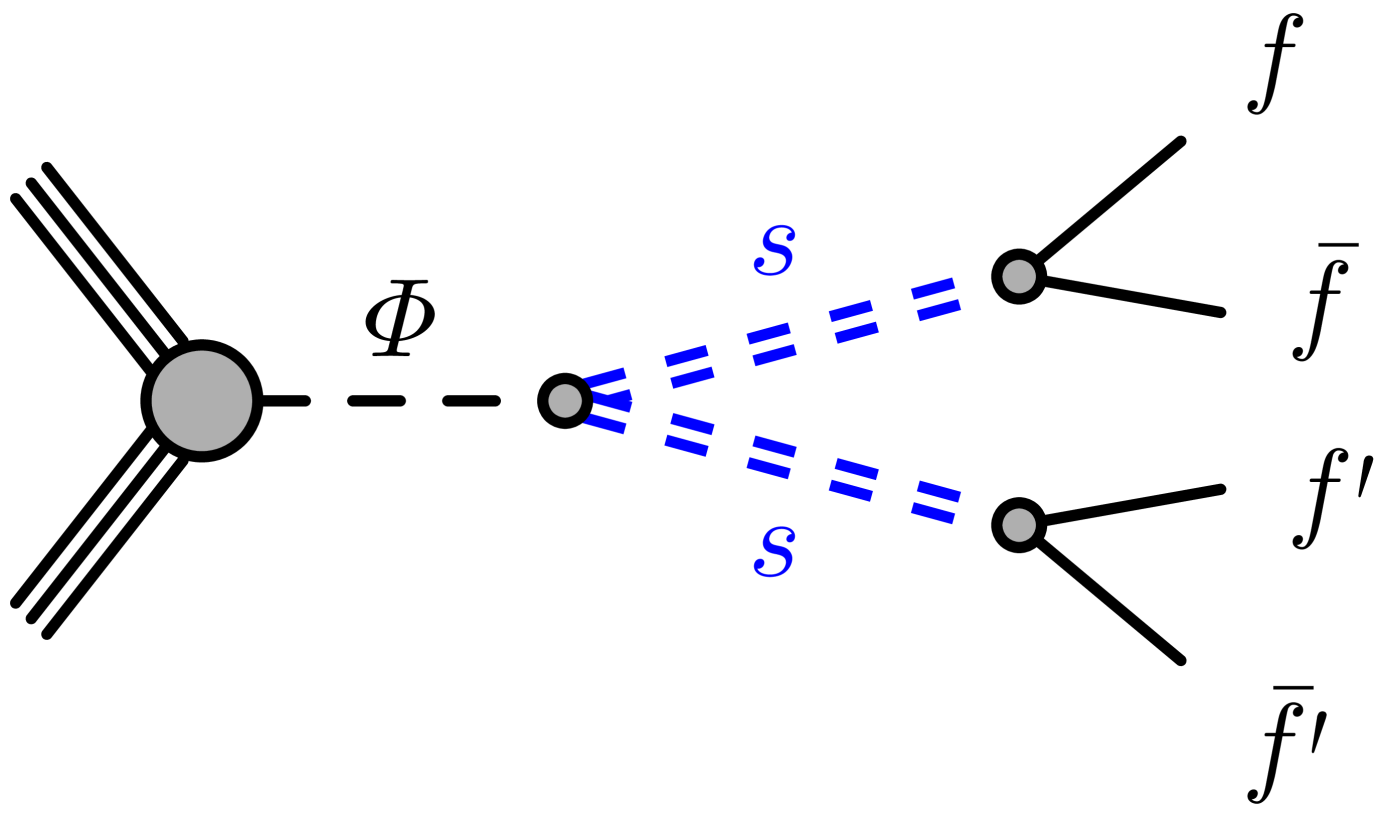




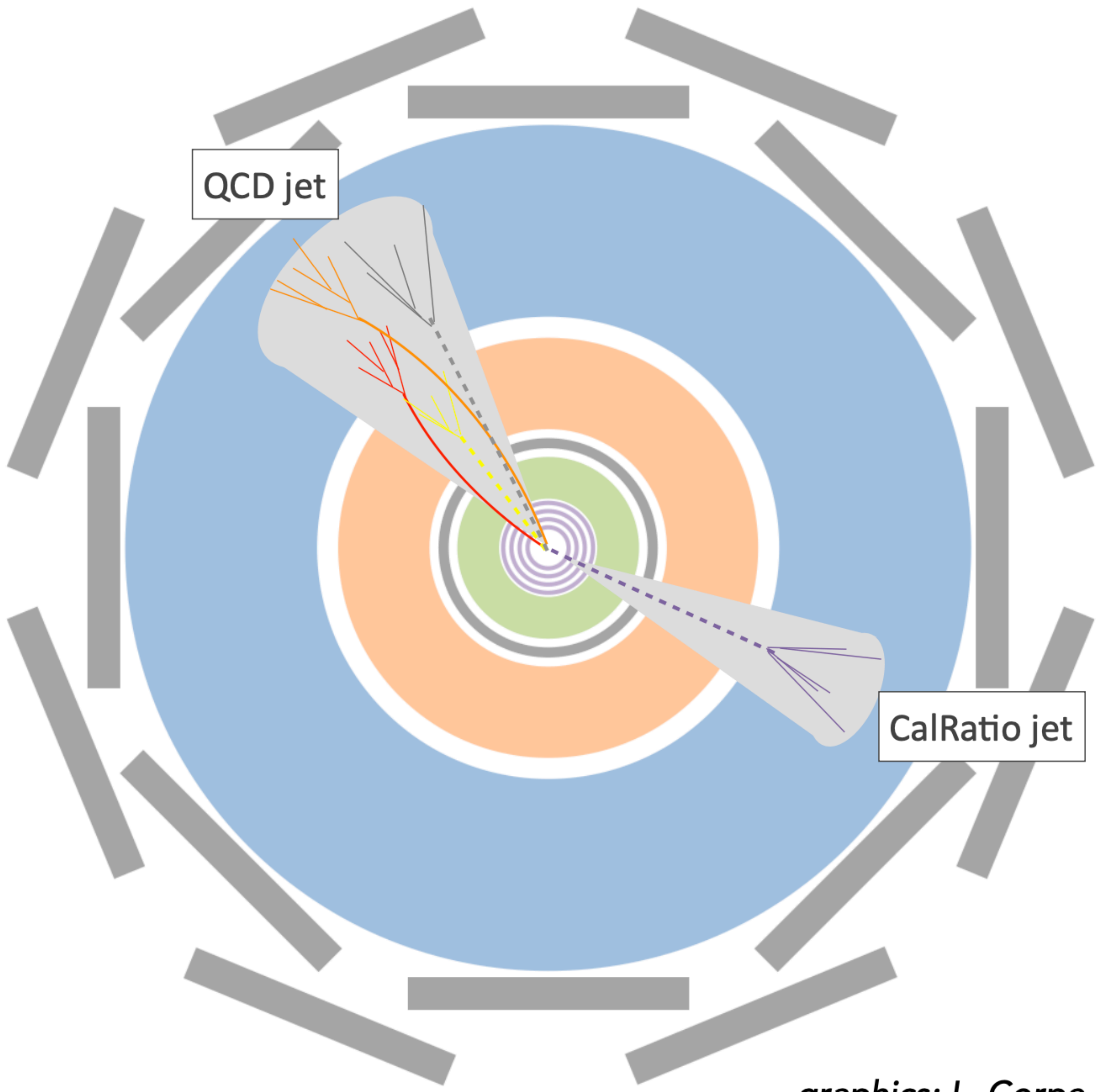


Searches for Neutral LLPs into Displaced Jets

JHEP 06 (2022) 005



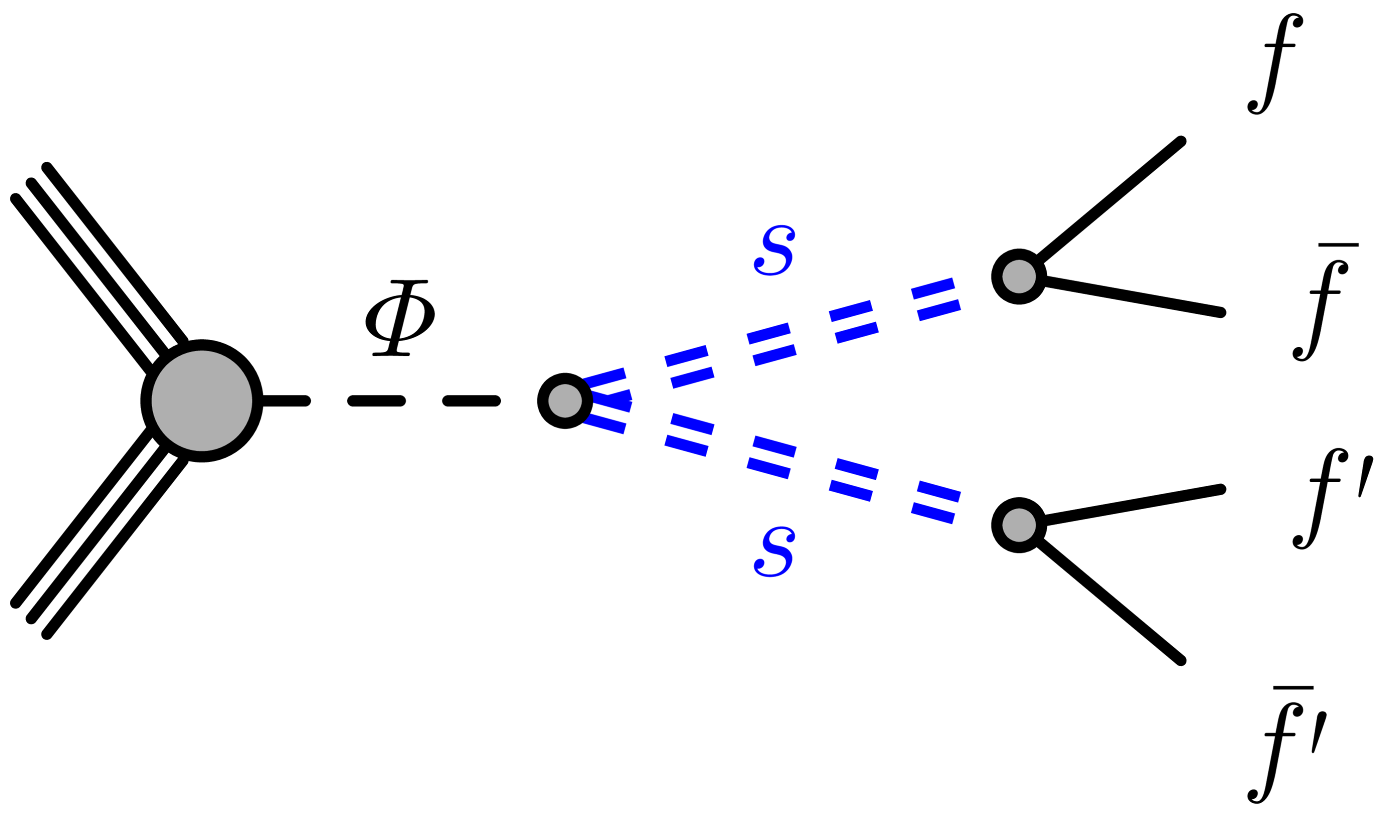
- Decay Higgs (like) to exotic scalars s
  - ➡ Differences to a regular SM jet:
    - Narrow
    - Trackless
    - Low fraction of energy in the ECAL; Calorimeter Ratio (CalRatio): E_{HCAL}/E_{ECAL}



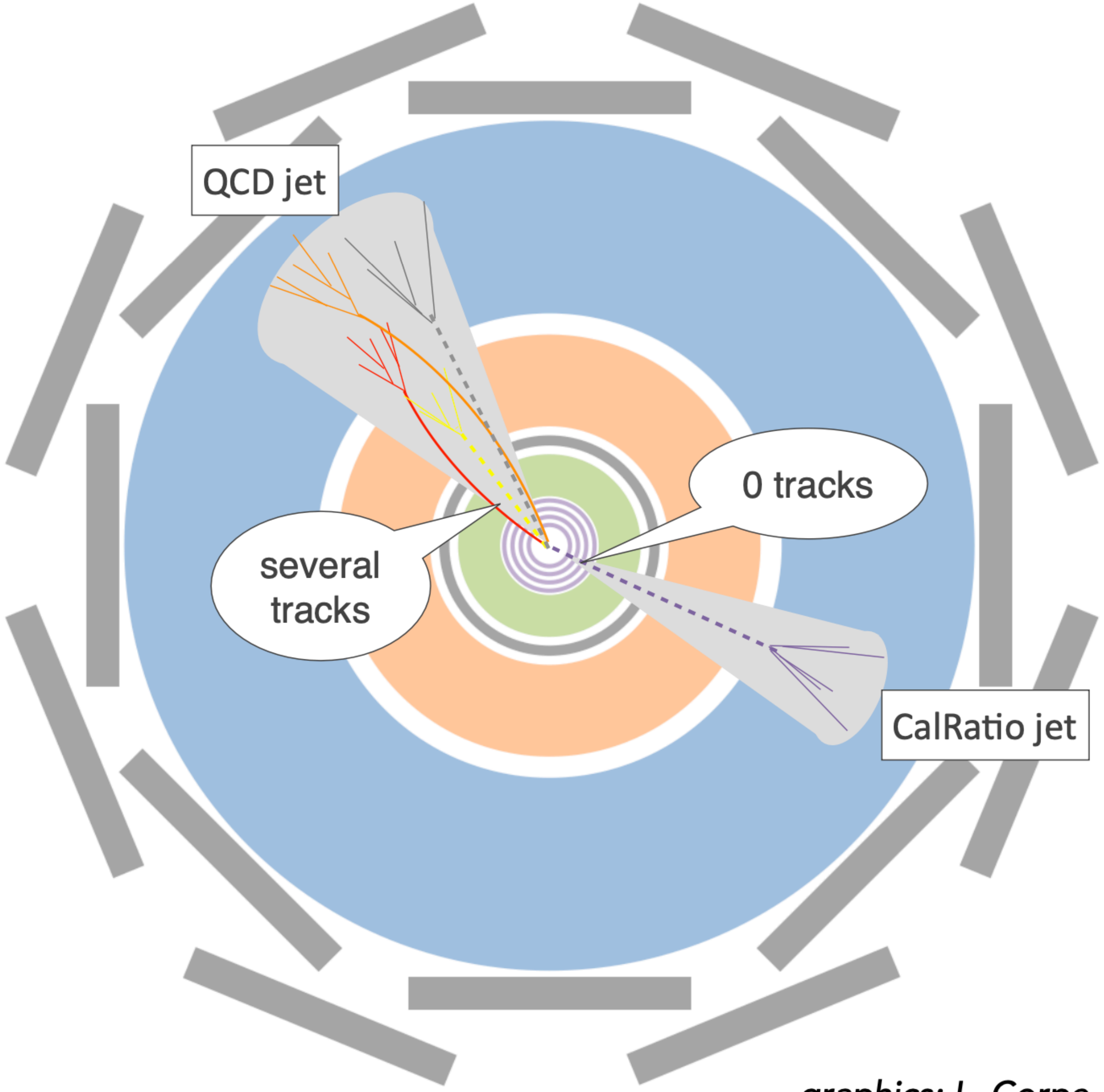
graphics: L. Corpe

Searches for Neutral LLPs into Displaced Jets

JHEP 06 (2022) 005



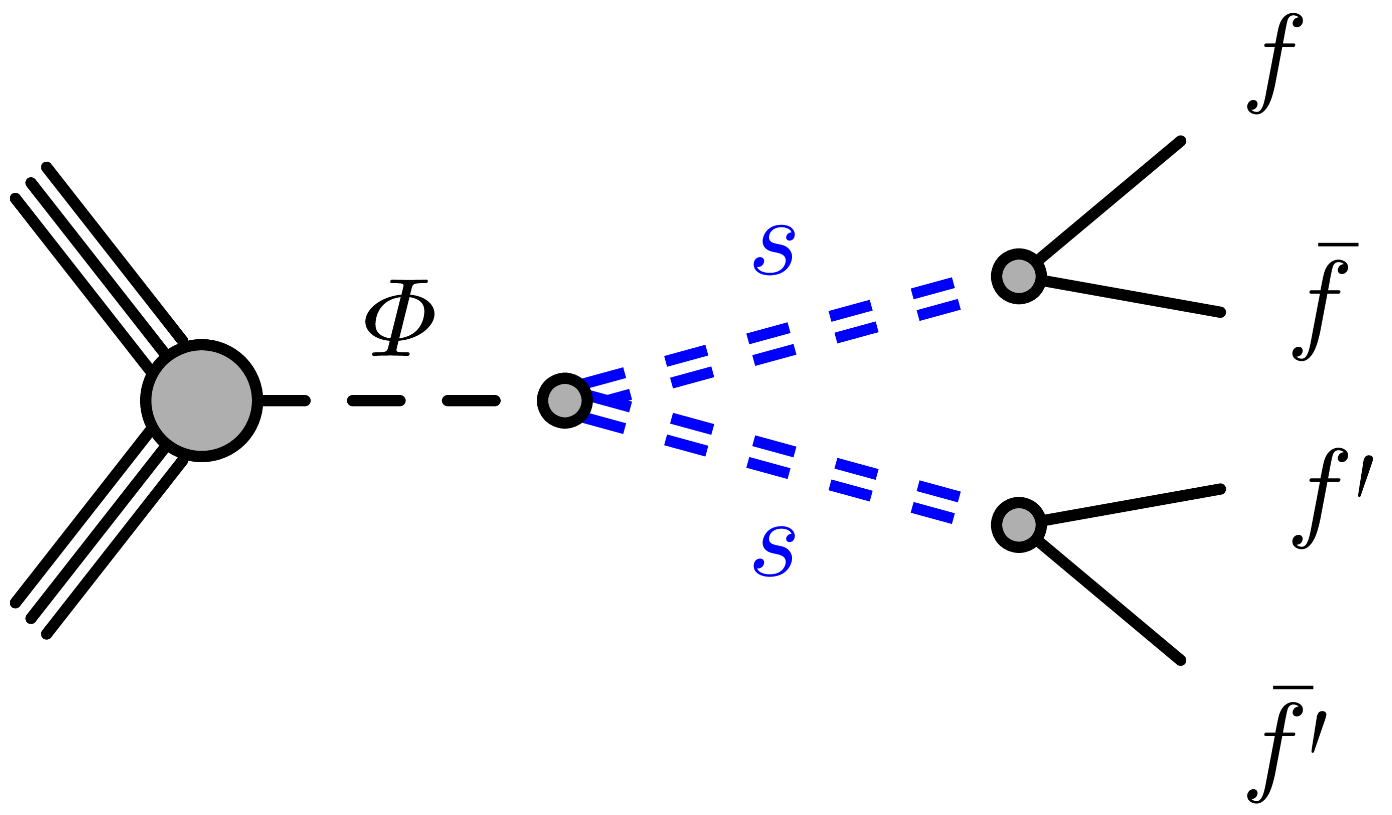
- Decay Higgs (like) to exotic scalars s
  - ➡ Differences to a regular SM jet:
    - Narrow
    - Trackless
    - Low fraction of energy in the ECAL; Calorimeter Ratio (CalRatio): E_{HCAL}/E_{ECAL}

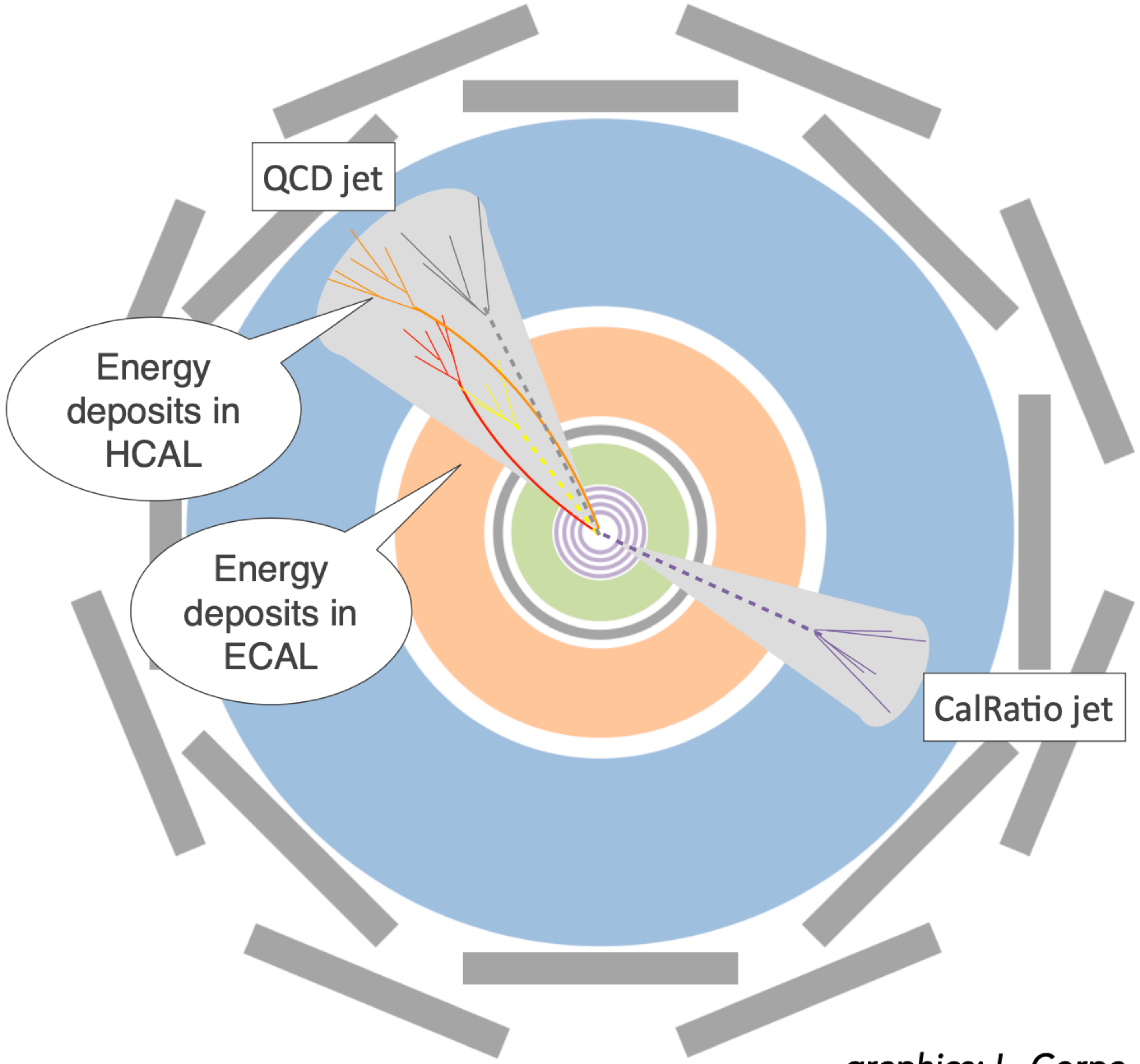


graphics: L. Corpe

Searches for Neutral LLPs into Displaced Jets

JHEP 06 (2022) 005



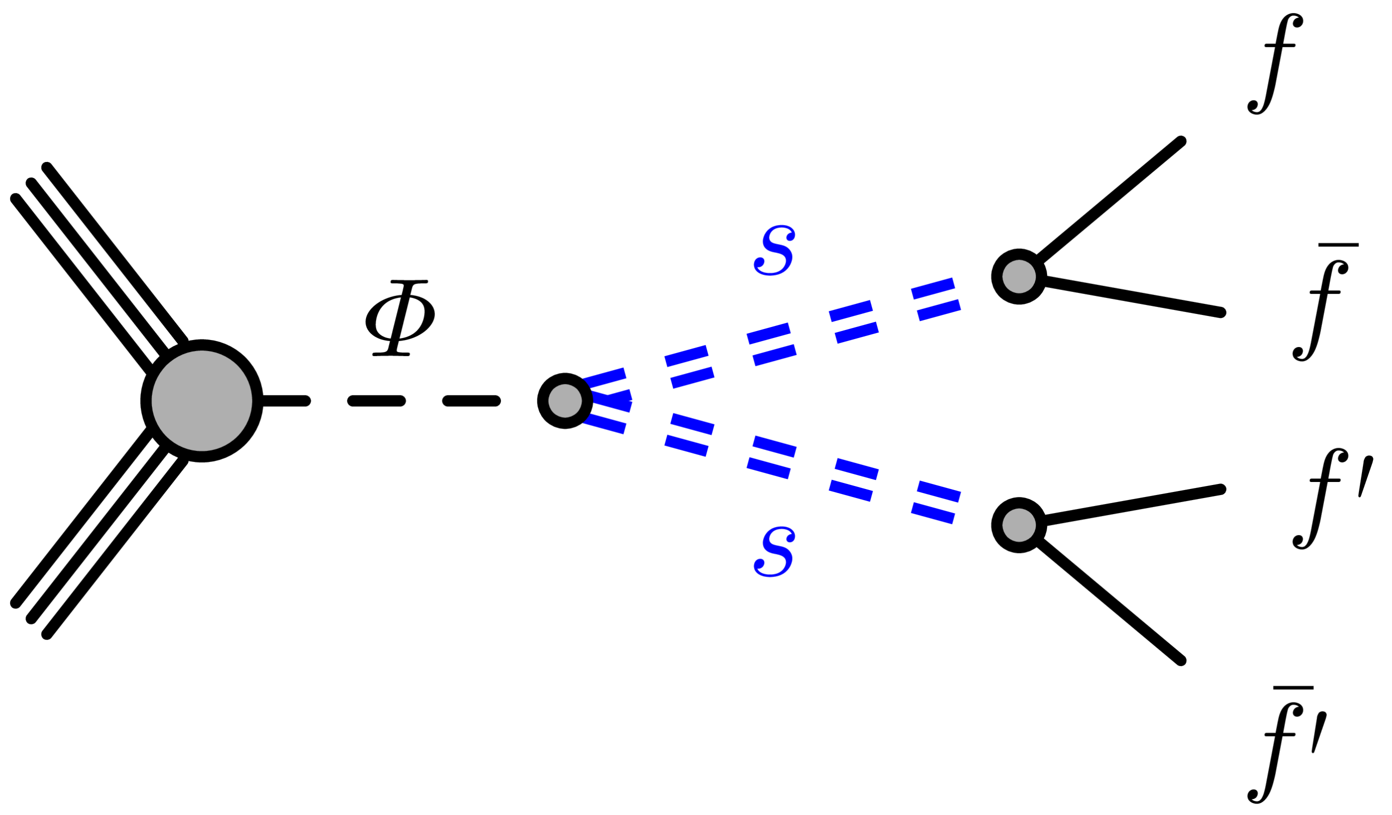


graphics: L. Corpe

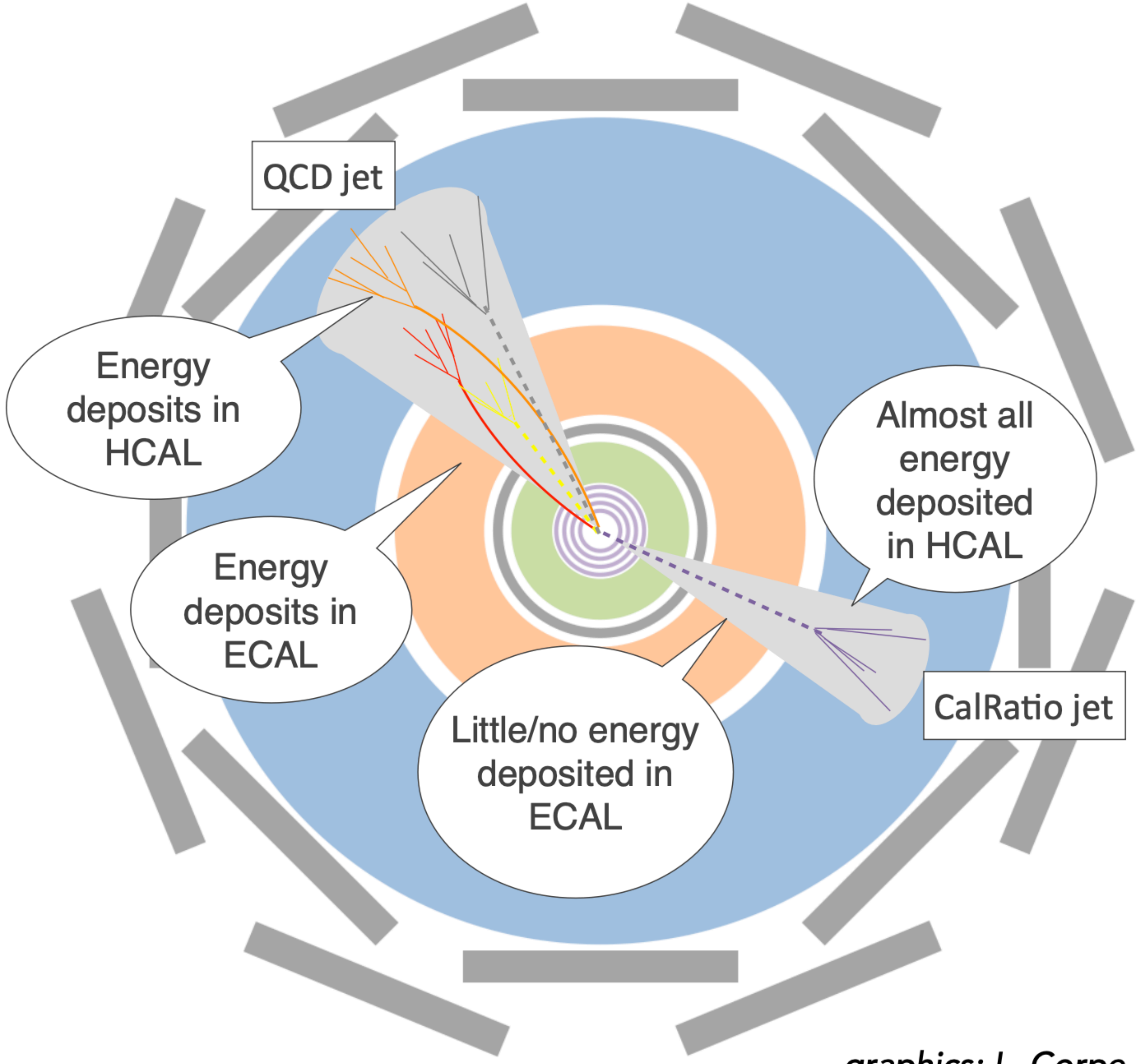
- Decay Higgs (like) to exotic scalars s
  - ➡ Differences to a regular SM jet:
    - Narrow
    - Trackless
    - Low fraction of energy in the ECAL; Calorimeter Ratio (CalRatio): E_{HCAL}/E_{ECAL}

Searches for Neutral LLPs into Displaced Jets

JHEP 06 (2022) 005



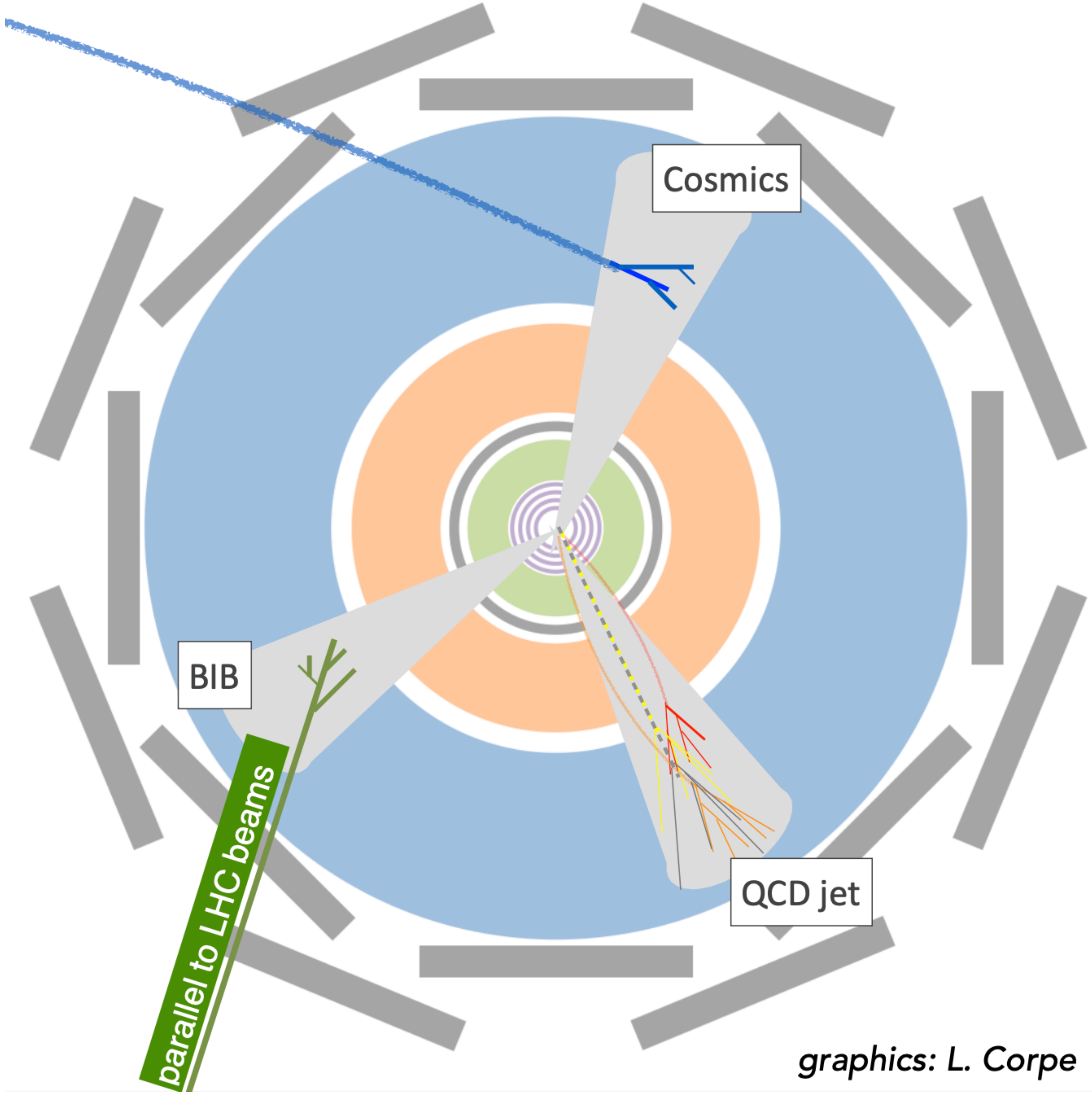
- Decay Higgs (like) to exotic scalars *s*
  - ➡ Differences to a regular SM jet:
    - Narrow
    - Trackless
    - Low fraction of energy in the ECAL; Calorimeter Ratio (CalRatio): E_{HCAL}/E_{ECAL}



graphics: L. Corpe

CalRatio: Backgrounds

- Main sources of background:
  - ➡ QCD jets
  - ➡ Beam-induced background (BIB)
  - ➡ Cosmic rays

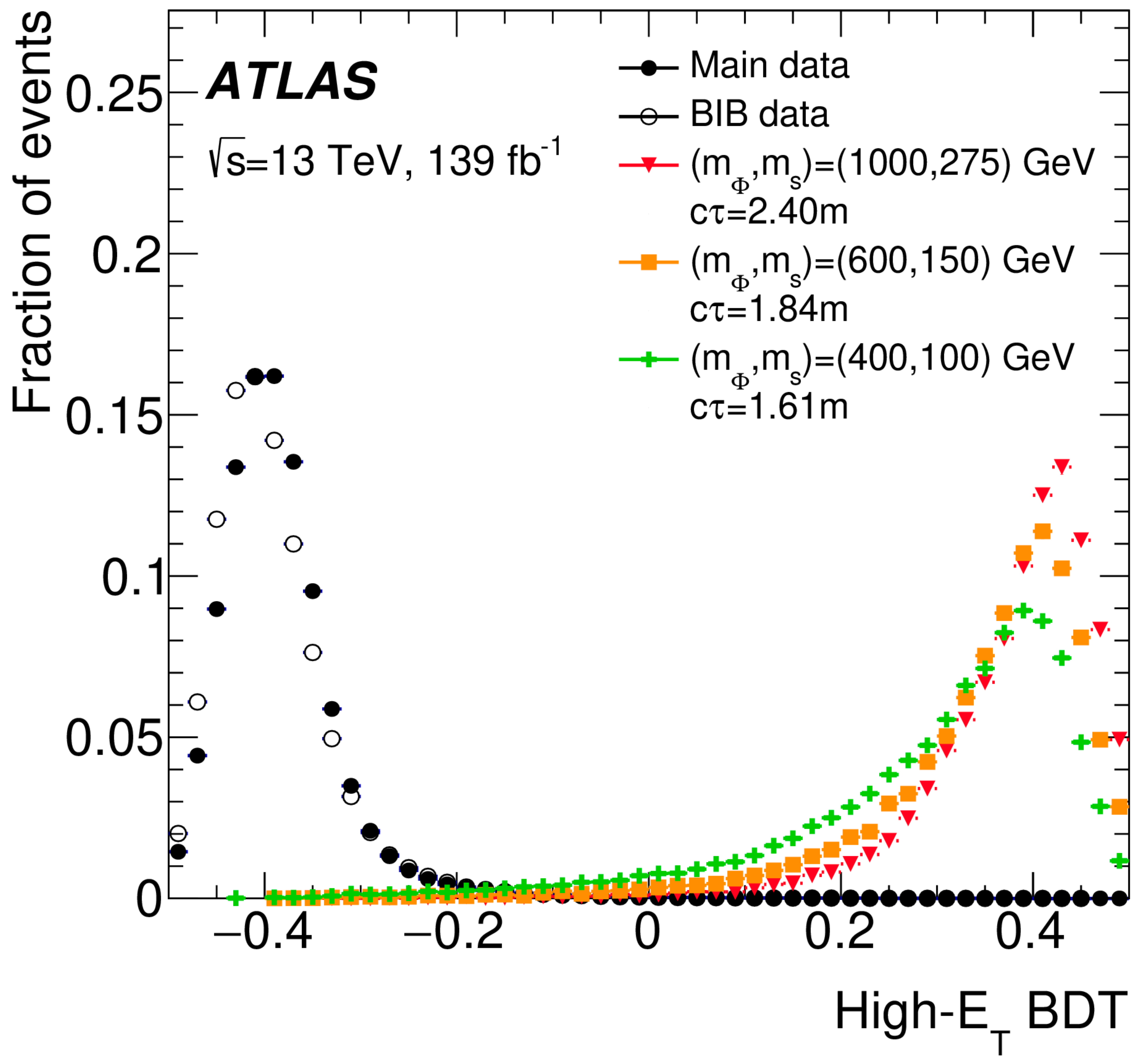


graphics: L. Corpe

CalRatio: Backgrounds

- Main sources of background:
  - ➡ QCD jets
  - ➡ Beam-induced background (BIB)
  - ➡ Cosmic rays
- Machine learning to help s/b ratio
  - ➡ Jet level NN for signal vs BIB/QCD
    - Low-level inputs: tracks, jet constituents, muon segments
  - ➡ Event level BDT selections
  - ➡ Data-driven ABCD allowing signal contamination

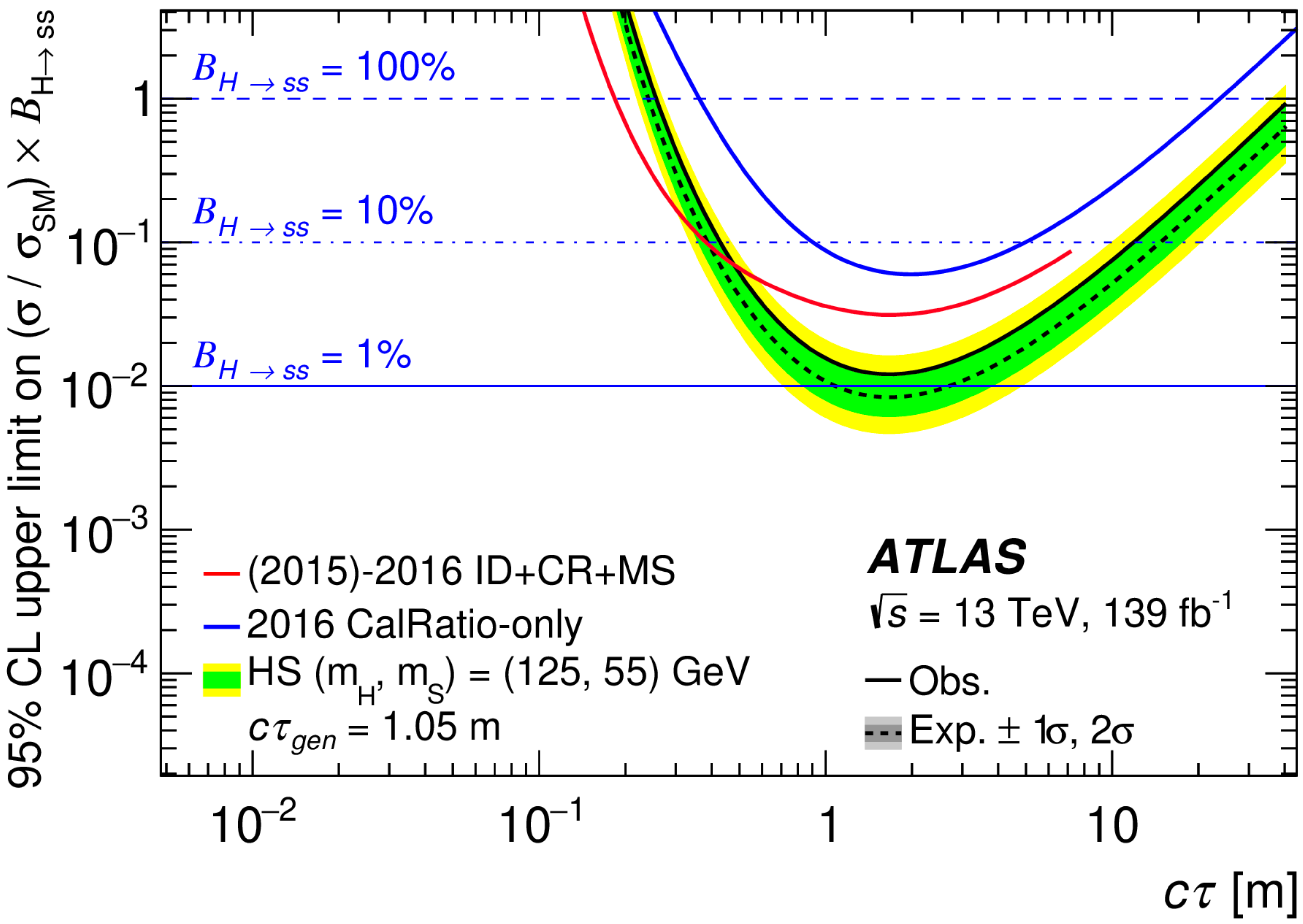
JHEP 06 (2022) 005



ATLAS Results: CalRatio

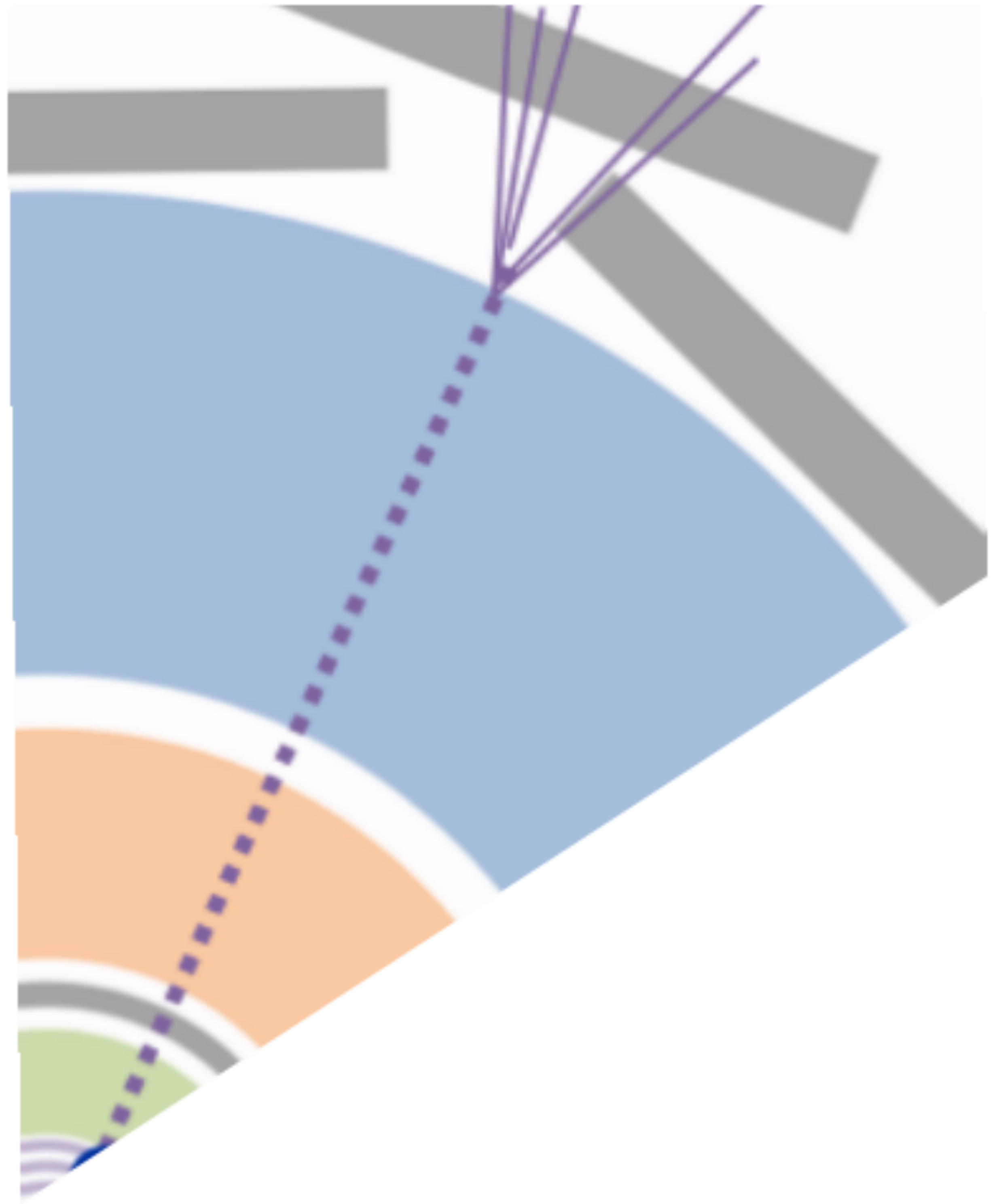
- No excess observed
  - ➡ Strong results for high mediator mass searches!
  - ➡ Here, only results with m_H=125 GeV
    - Other models and mass combinations in the paper

JHEP 06 (2022) 005



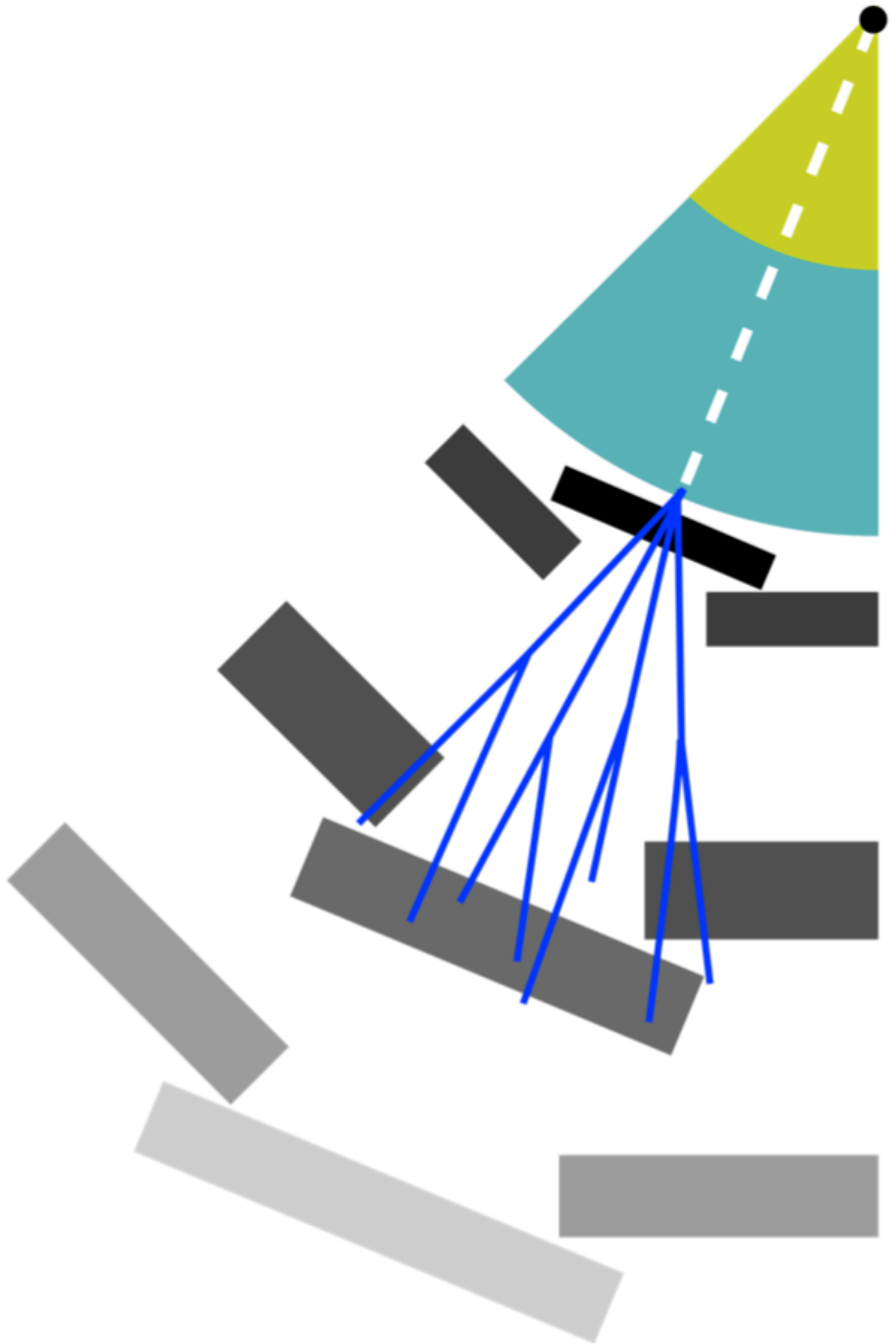
Nikhef

Decays in the Muon System



Decays in the Muon System

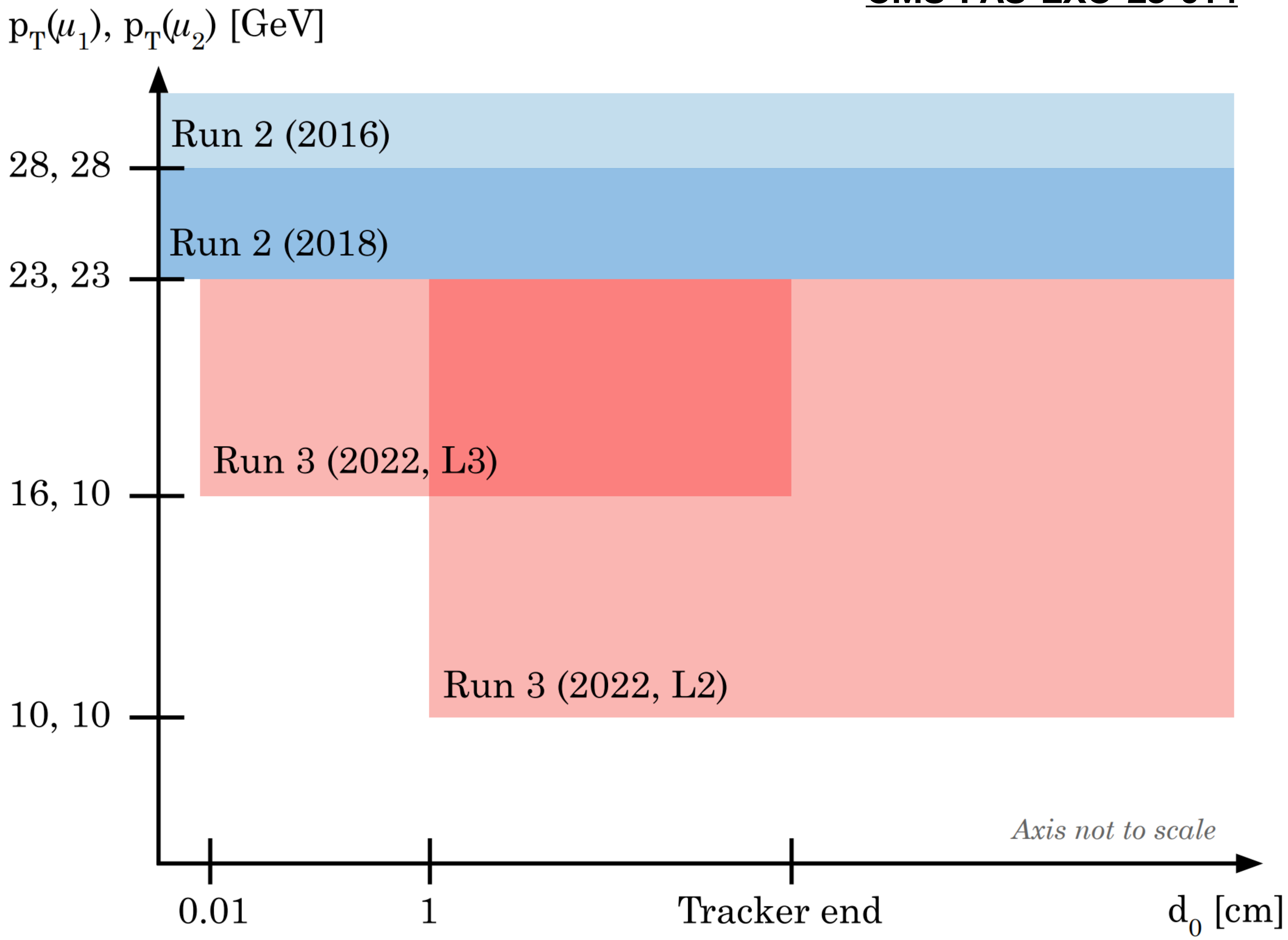
- Tracking in the muon spectrometer (MS): hadronic track-finding in individual chambers
  - ➡ Multitrack vertices without inner detector tracks or calorimeter jets
  - ➡ Dedicated triggers (large bunches of MS activity)
  - ➡ Dedicated vertexing algorithms



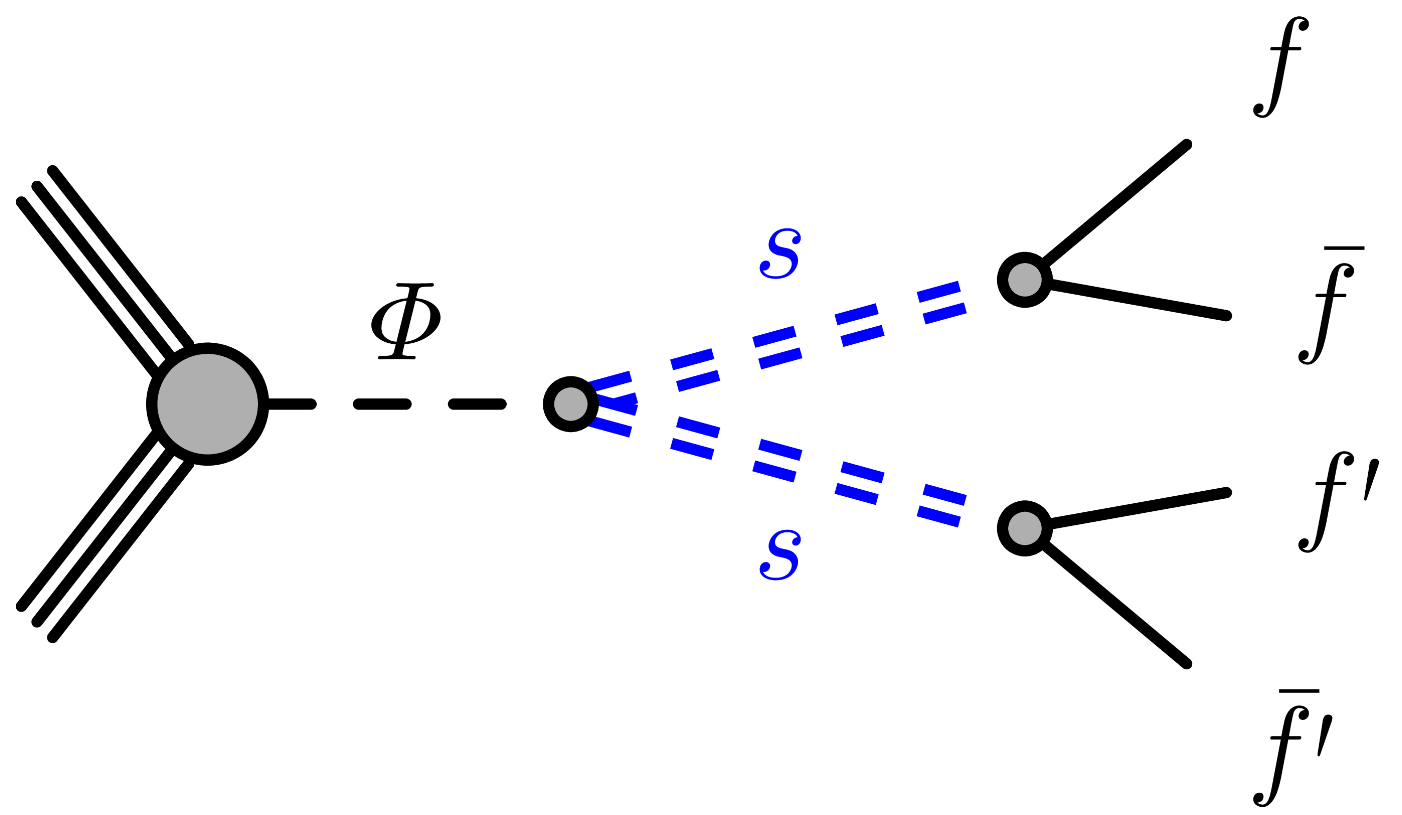
Decays in the Muon System

- CMS: Muon detectors used as a sampling calorimeter to identify particle showers from LLP decays
  - ➡ New CMS search for displaced muons already using Run-3 data and new triggers can be found at: CMS-PAS-EXO-23-014

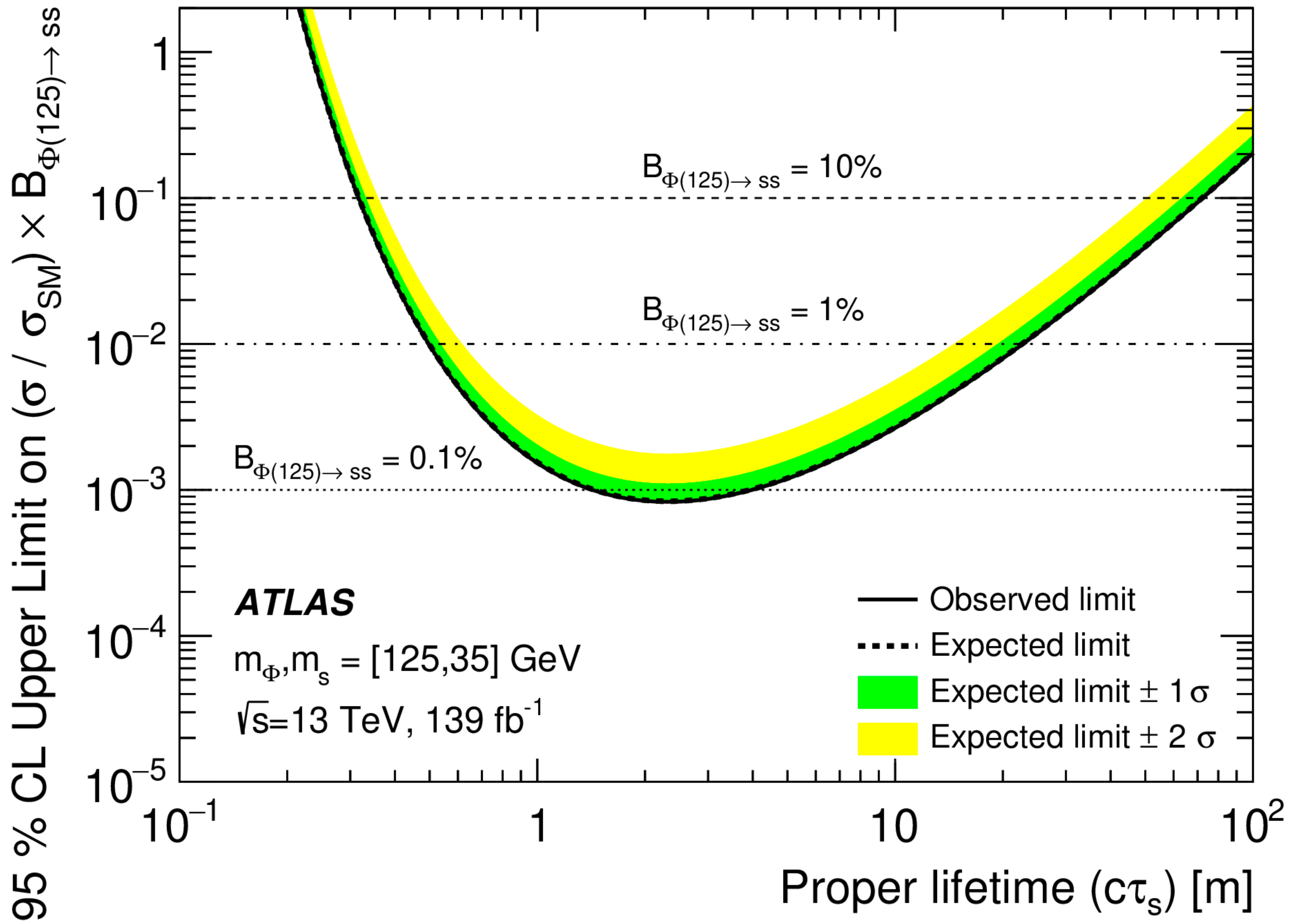
CMS-PAS-EXO-23-014



ATLAS: Search for Displaced Vertices in the MS



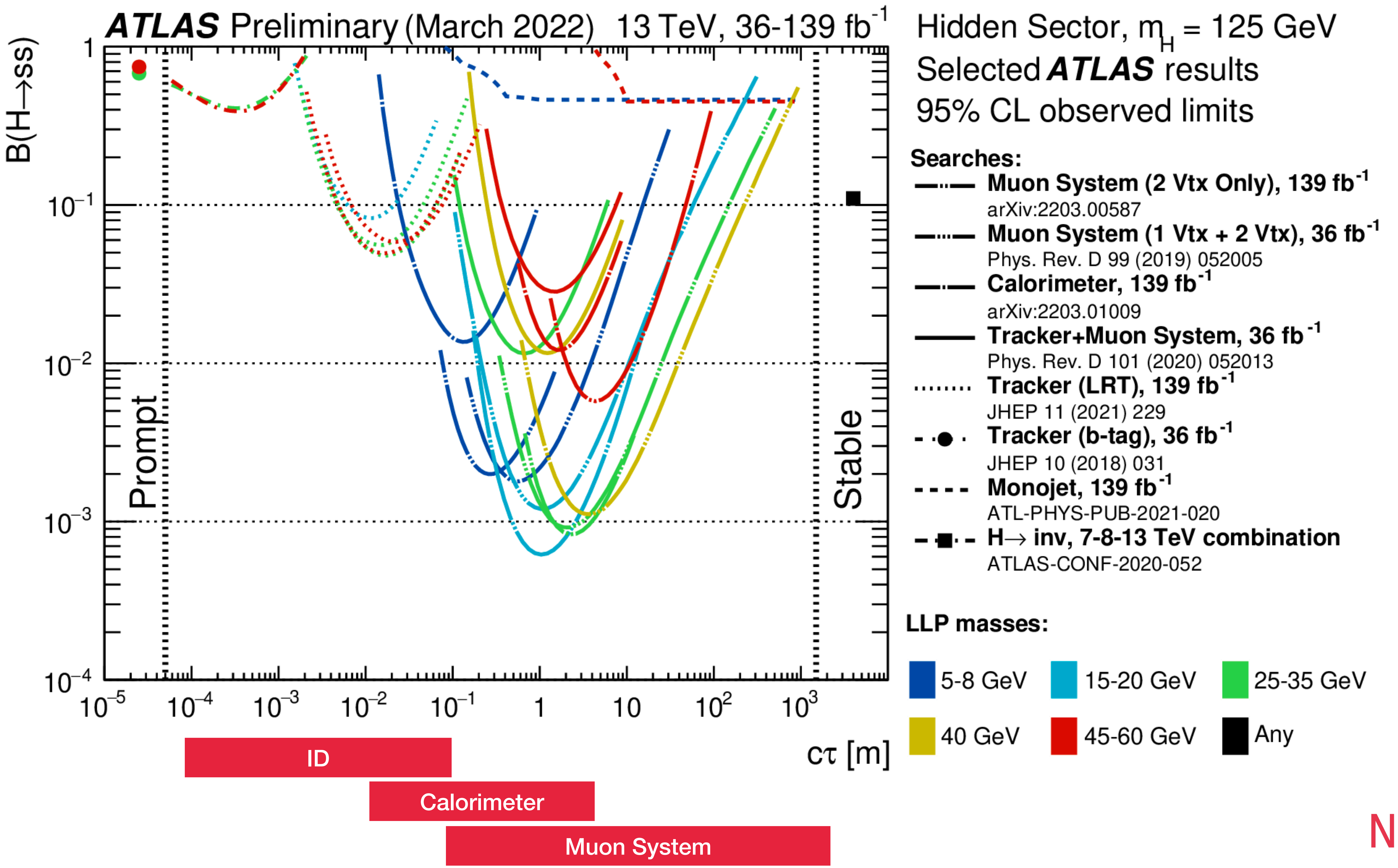
Phys. Rev. D 106, (2022) 032005



- Pairs of displaced vertices (DVs) in MS
  - ➡ From LLPs decaying into hadronic jets
  - ➡ Main background: QCD punch-through
  - ➡ Very low expected events: 0.32 ± 0.05 (statistical errors), zero observed

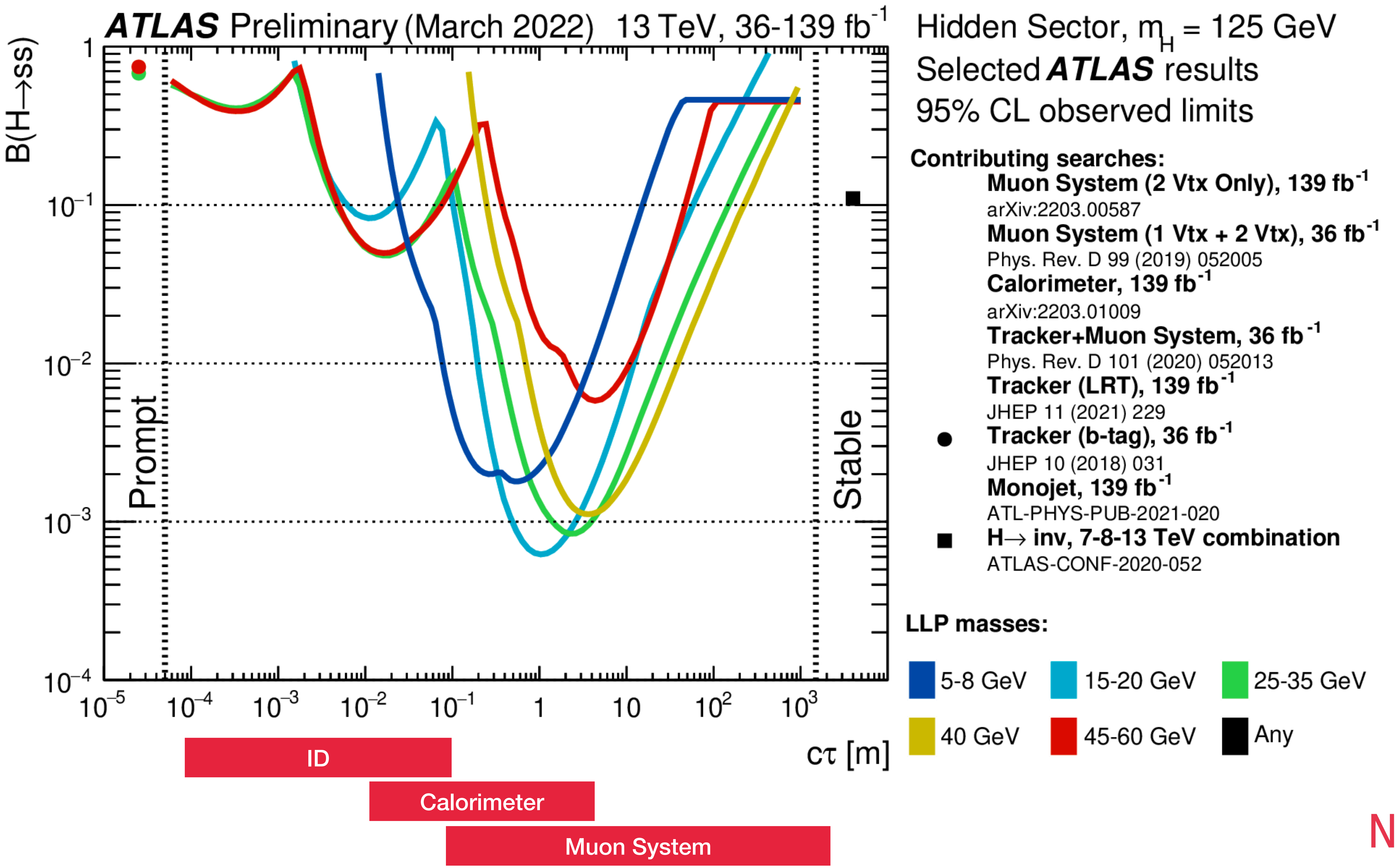
ATLAS Hidden Sector Summary

ATLAS-PHYS-PUB-2022-007

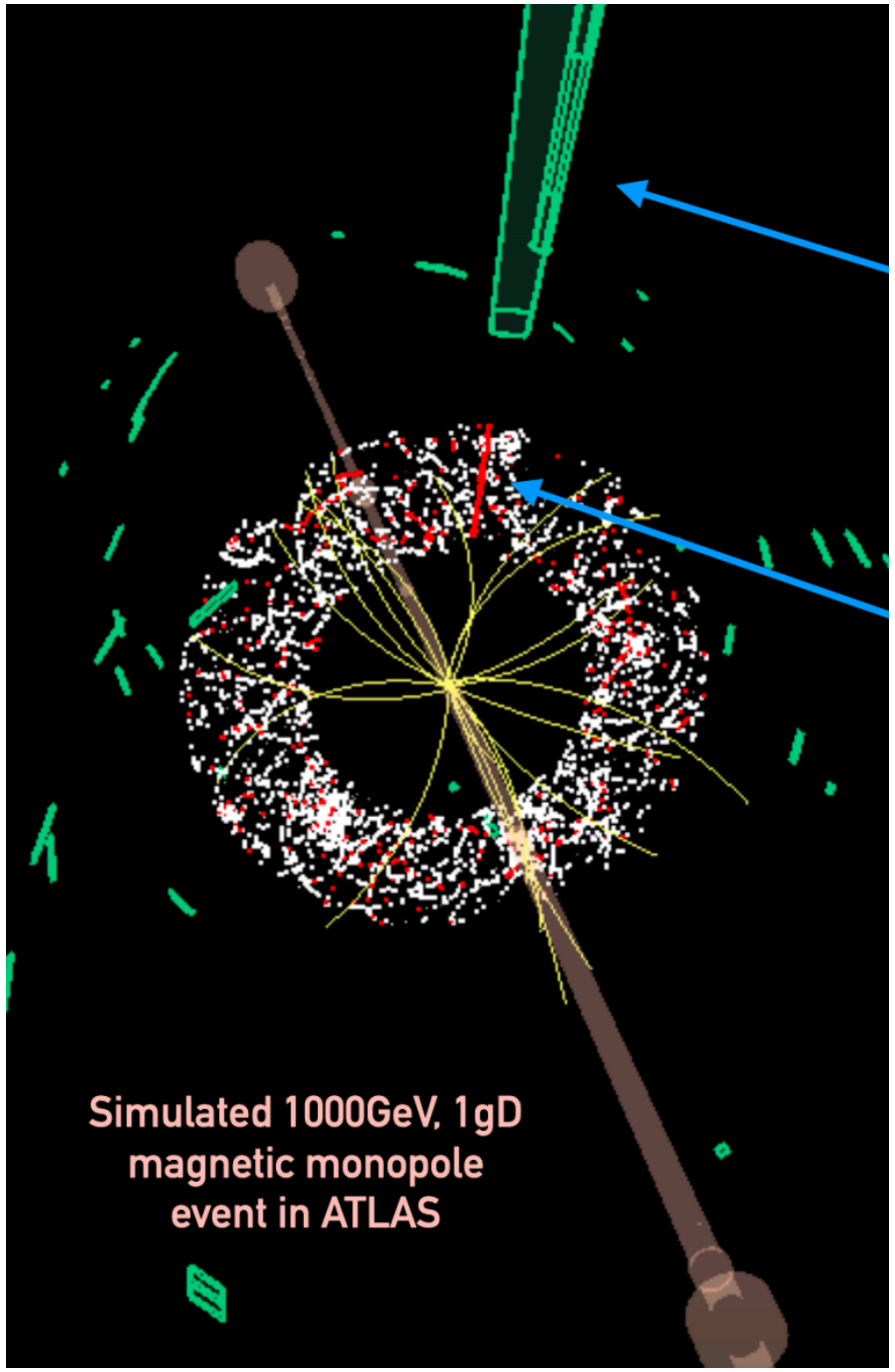


ATLAS Hidden Sector Summary

ATLAS-PHYS-PUB-2022-007



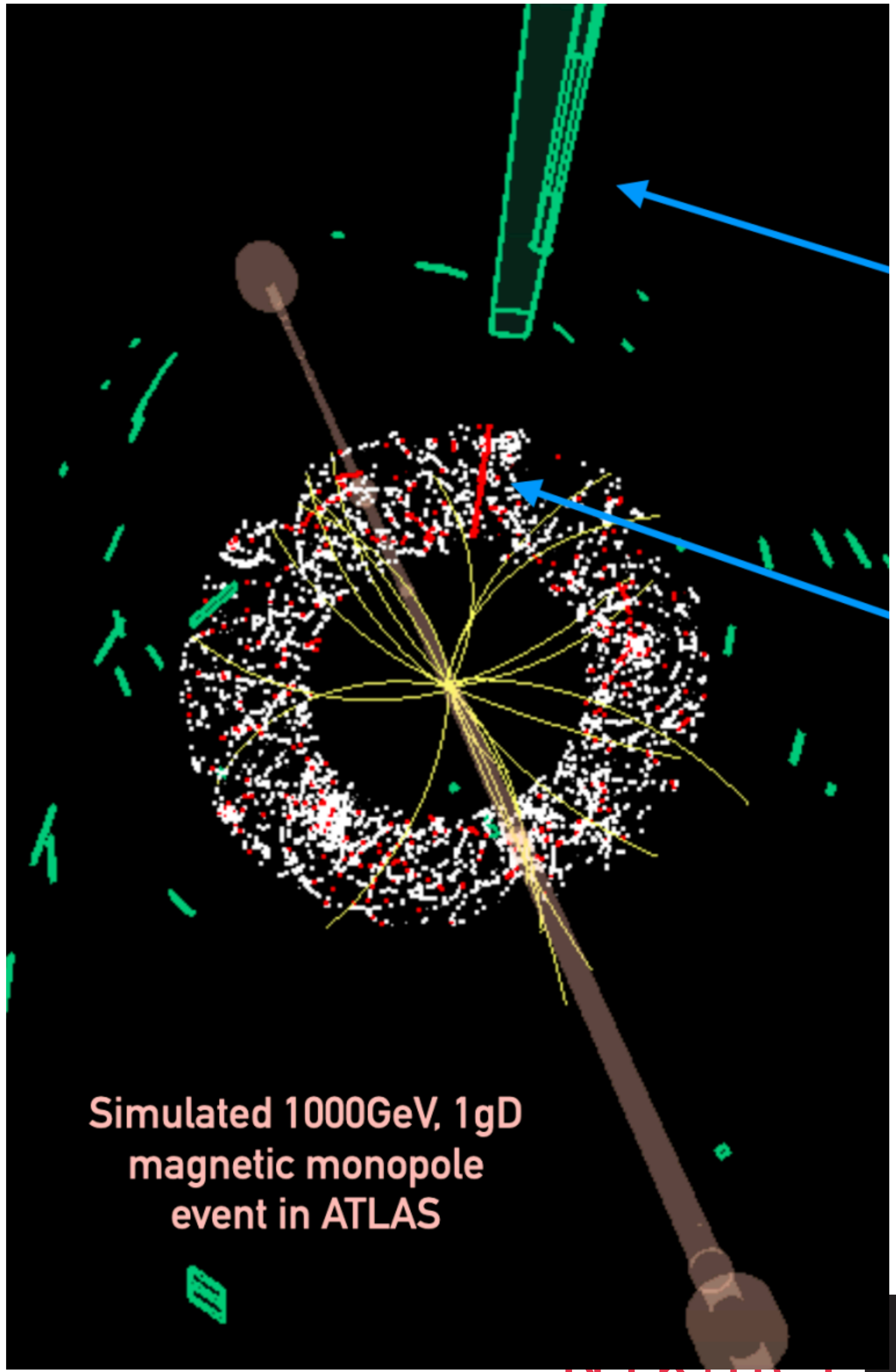
(Meta) Stable Charged Particles



Highly Ionising Particles / Magnetic Monopoles

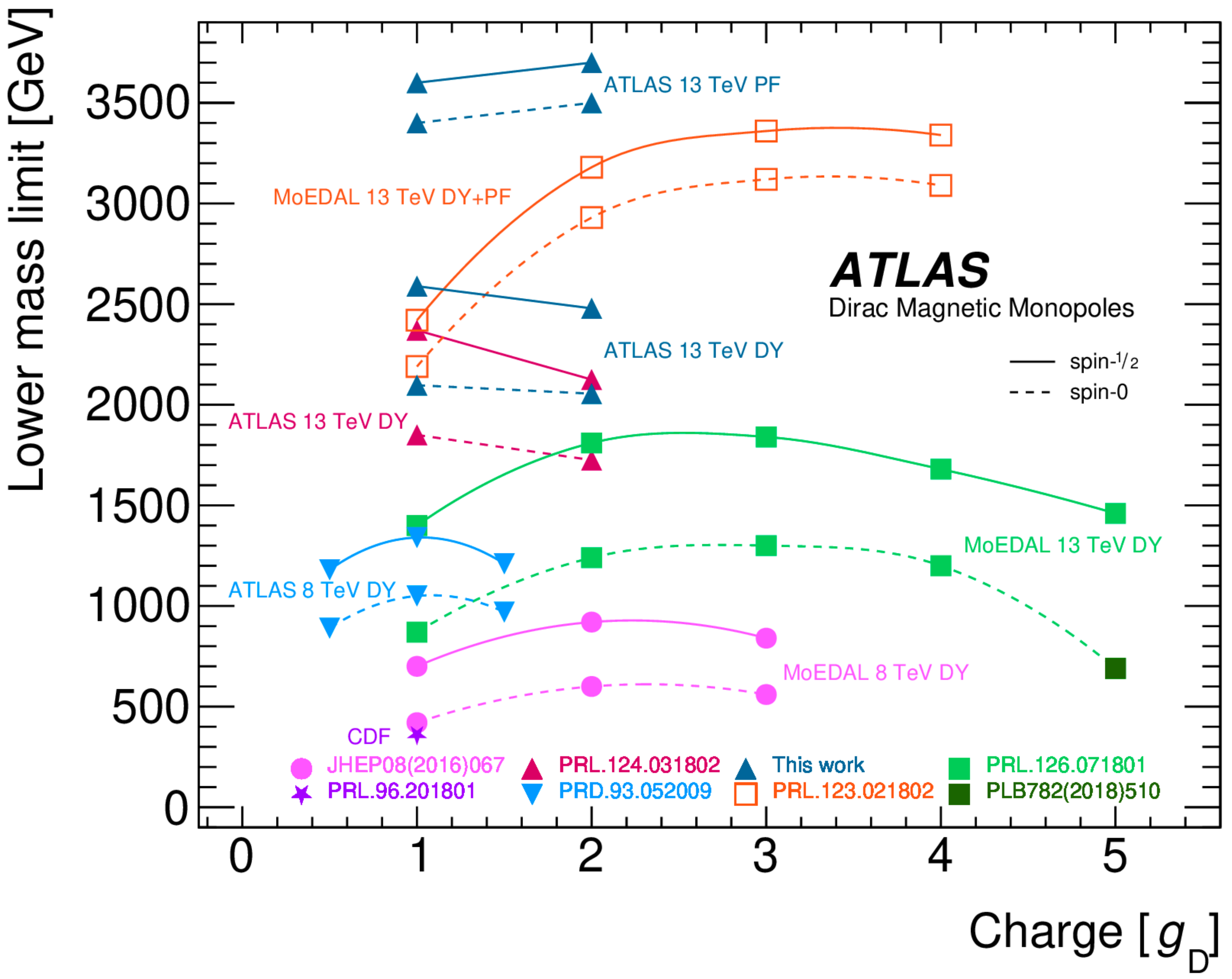
- Dirac magnetic monopoles or High Electric Charge Objects (Q-balls, micro black hole remnants)
  - ➡ Striking experimental signature: ~5000x more ionisation loss in detector than MIP
    - TRT High Threshold hits (delta rays) - used for dedicated trigger
    - Concentrated ECAL high energy deposition, no HCAL deposit
  - ➡ Data-driven ABCD method, 0 events observed, background expected 0.15 ± 0.04

$q_m = N g_D ec$, $g_D = 68.5$ $20 < |z| < 100$



Highly Ionising Particles / Magnetic Monopoles

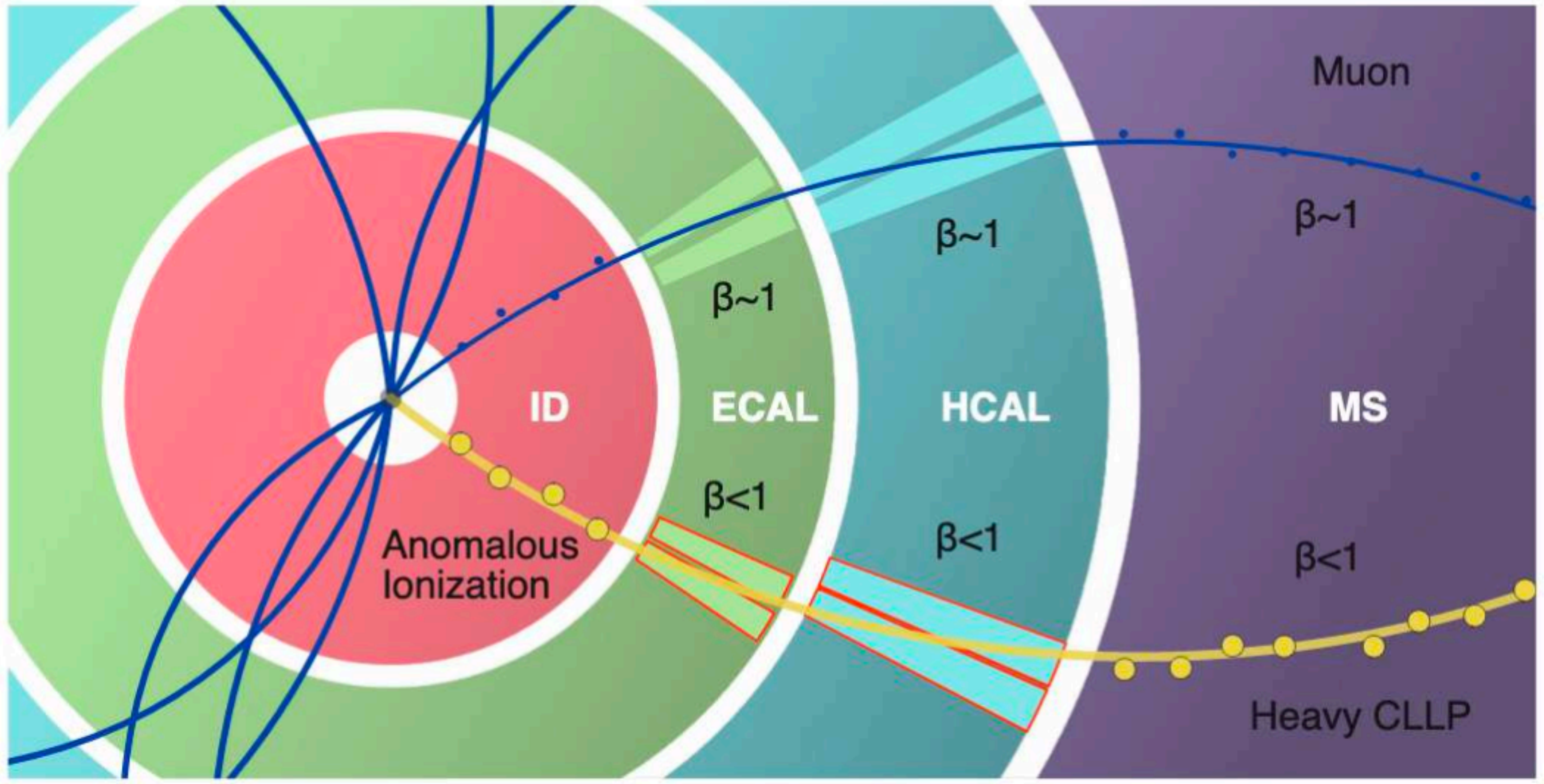
- Dirac magnetic monopoles or High Electric Charge Objects (Q-balls, micro black hole remnants)
  - ➡ Striking experimental signature: ~5000x more ionisation loss in detector than MIP
    - TRT High Threshold hits (delta rays) - used for dedicated trigger
    - Concentrated ECAL high energy deposition, no HCAL deposit
  - ➡ Data-driven ABCD method, 0 events observed, background expected 0.15 ± 0.04



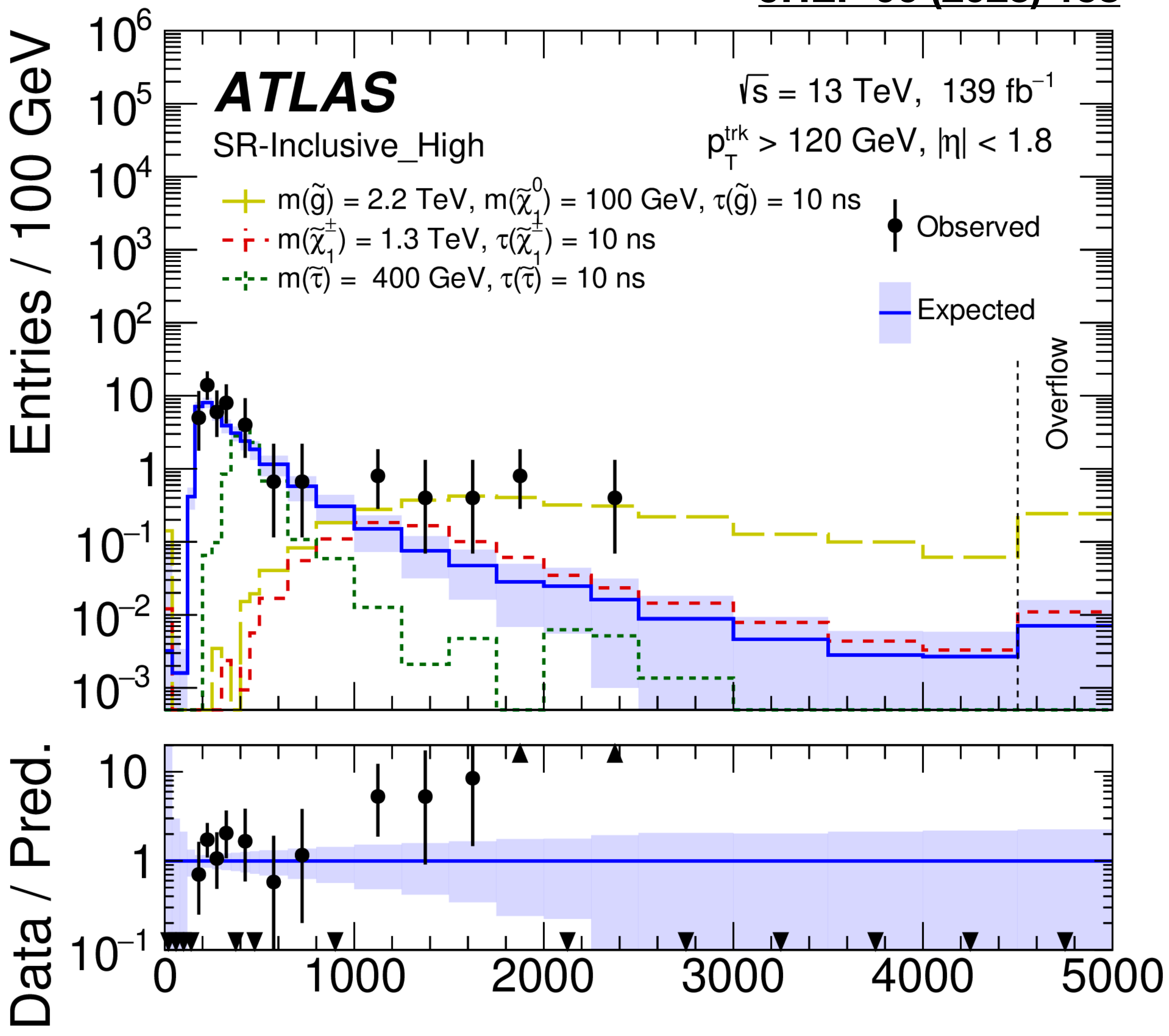
$q_m = N g_D ec$, $g_D = 68.5$ $20 < |z| < 100$

dE/dx (for charge 1)

- Massive, charged, LLPs
  - ➡ Slowly moving, high ionisation loss (dE/dx)
  - ➡ Trajectories in ID, dE/dx in Pixel (using Bethe-Bloch relation)



JHEP 06 (2023) 158

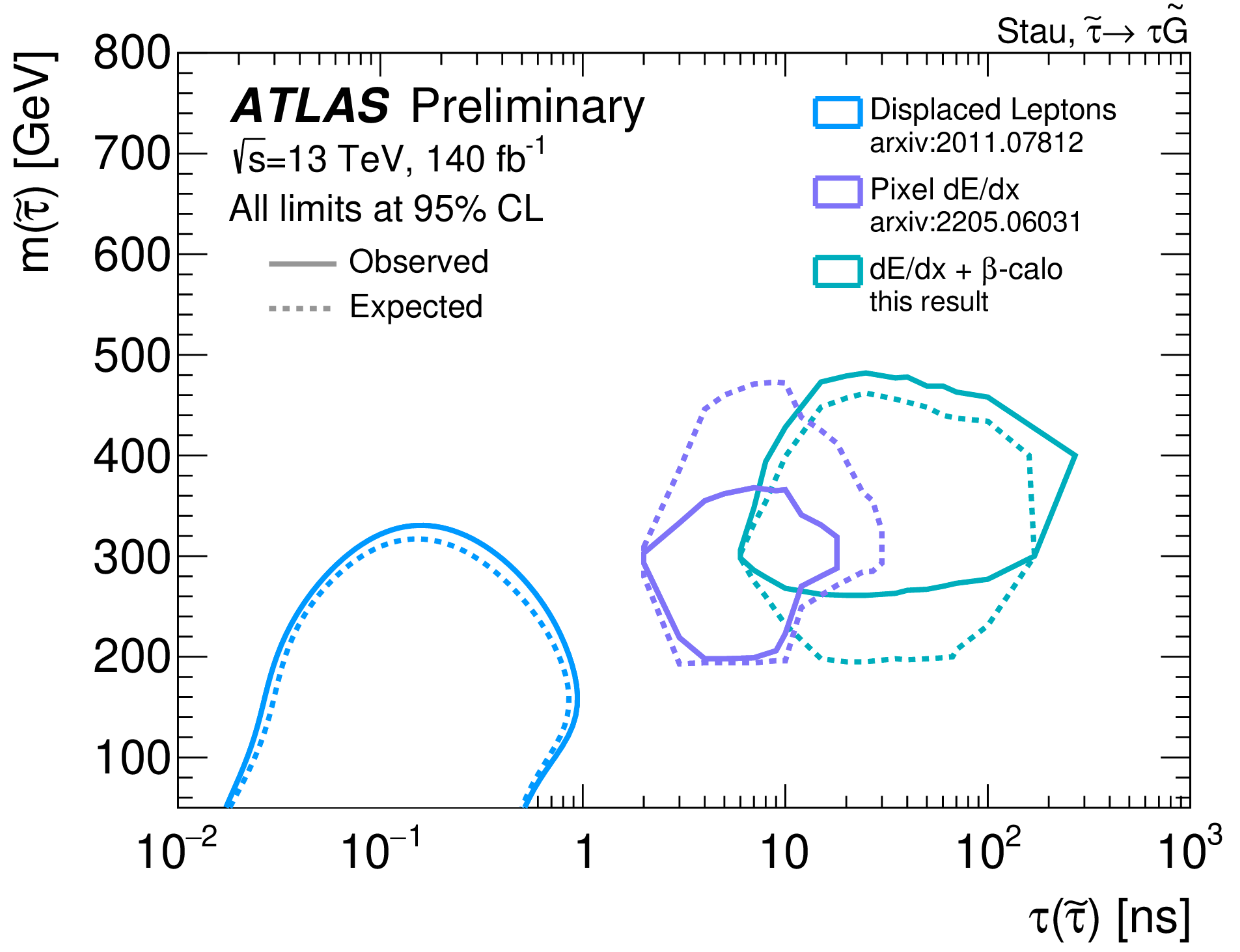


>3.3 σ excess m=~1.4 TeV

dE/dx (for charge 1)

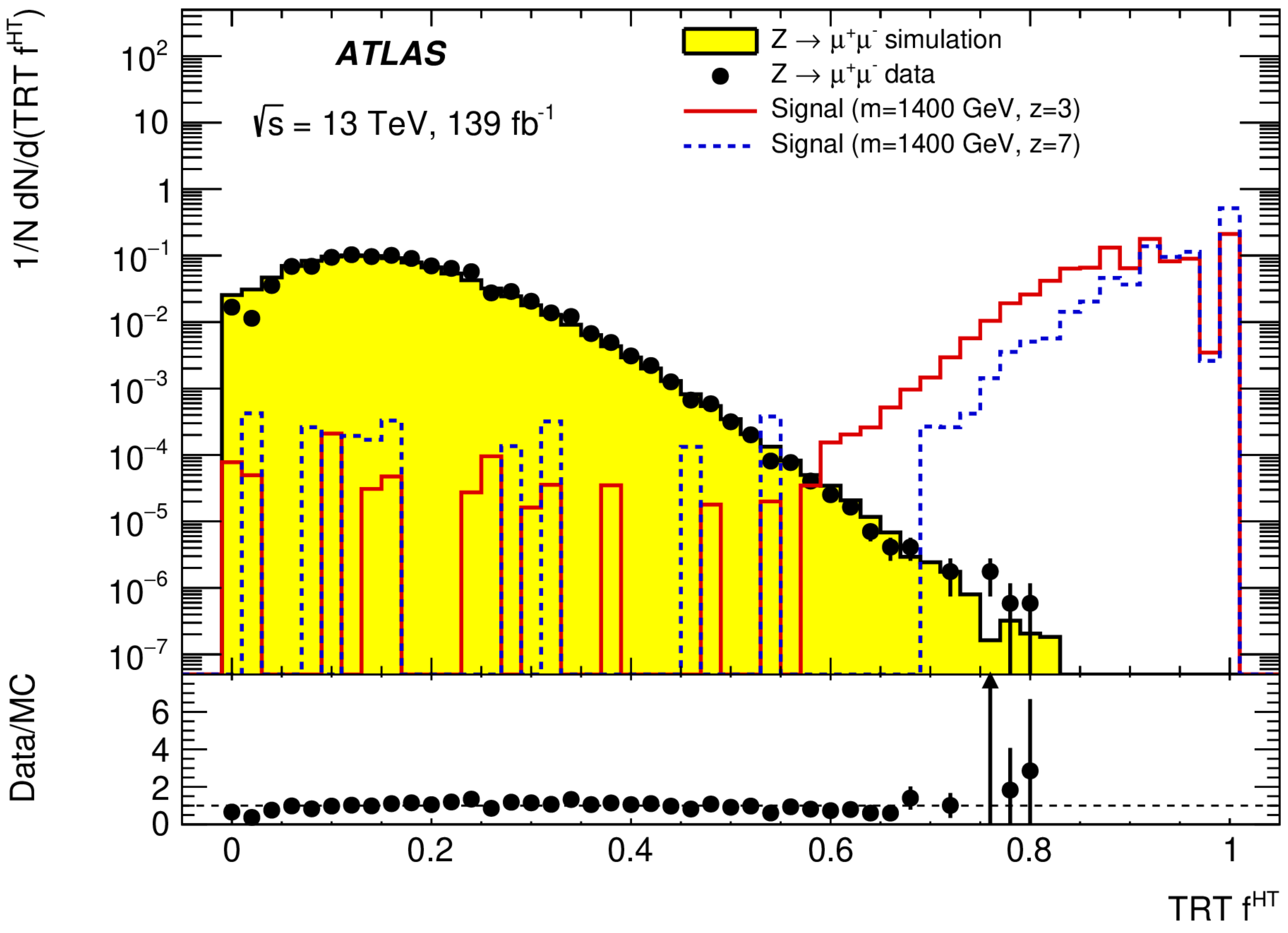
ATLAS-CONF-2023-044

- Massive, charged, LLPs
  - ➡ Slowly moving, high ionisation loss (dE/dx)
  - ➡ Trajectories in ID, dE/dx in Pixel (using Bethe-Bloch relation)
  - ➡ **Additional analysis also uses time of flight (ToF) in the calorimeter**
    - ➡ Excess not confirmed but also slightly different sensitivity



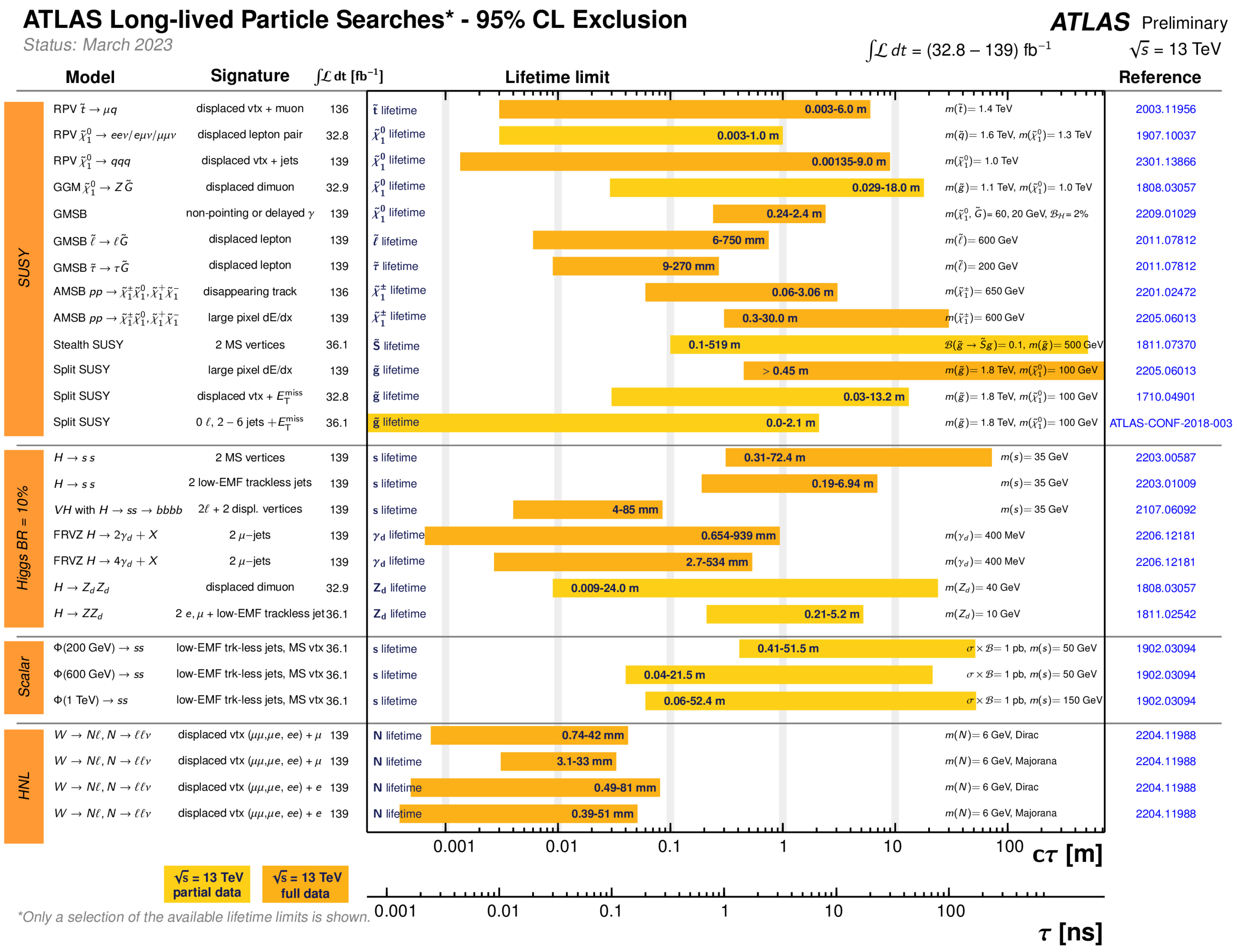
Multi-Charged Particles

- Heavy long-lived multi-charged particles: |q| ≤ ze, 2 ≤ z ≤ 7
  - ➡ Traverses entire detector without decays
  - ➡ High-pT muon-like signatures: high dE/dx values in: ID Pixel, TRT, MS
  - ➡ Also uses late-muon triggers (in addition to prompt muons and MET)



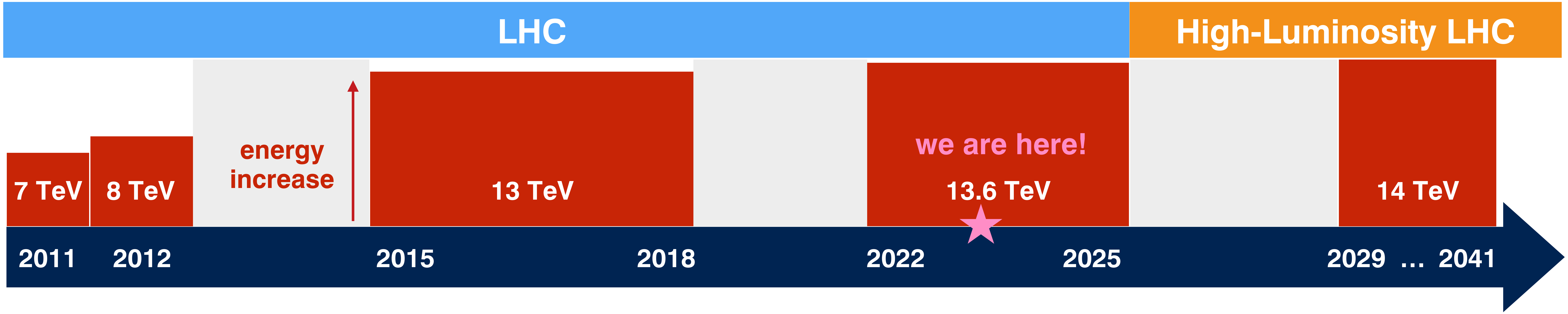
Search category	$N_{\text{data}}^{\text{A observed}}$	$N_{\text{data}}^{\text{B observed}}$	$N_{\text{data}}^{\text{C observed}}$	$N_{\text{data}}^{\text{D expected}}$	$N_{\text{data}}^{\text{D observed}}$
$z = 2$	41 674	5024	13	1.6 ± 0.4 (stat.) ± 0.5 (syst.)	4
$z > 2$	192 036 934	15 004	441	0.034 ± 0.002 (stat.) ± 0.004 (syst.)	0

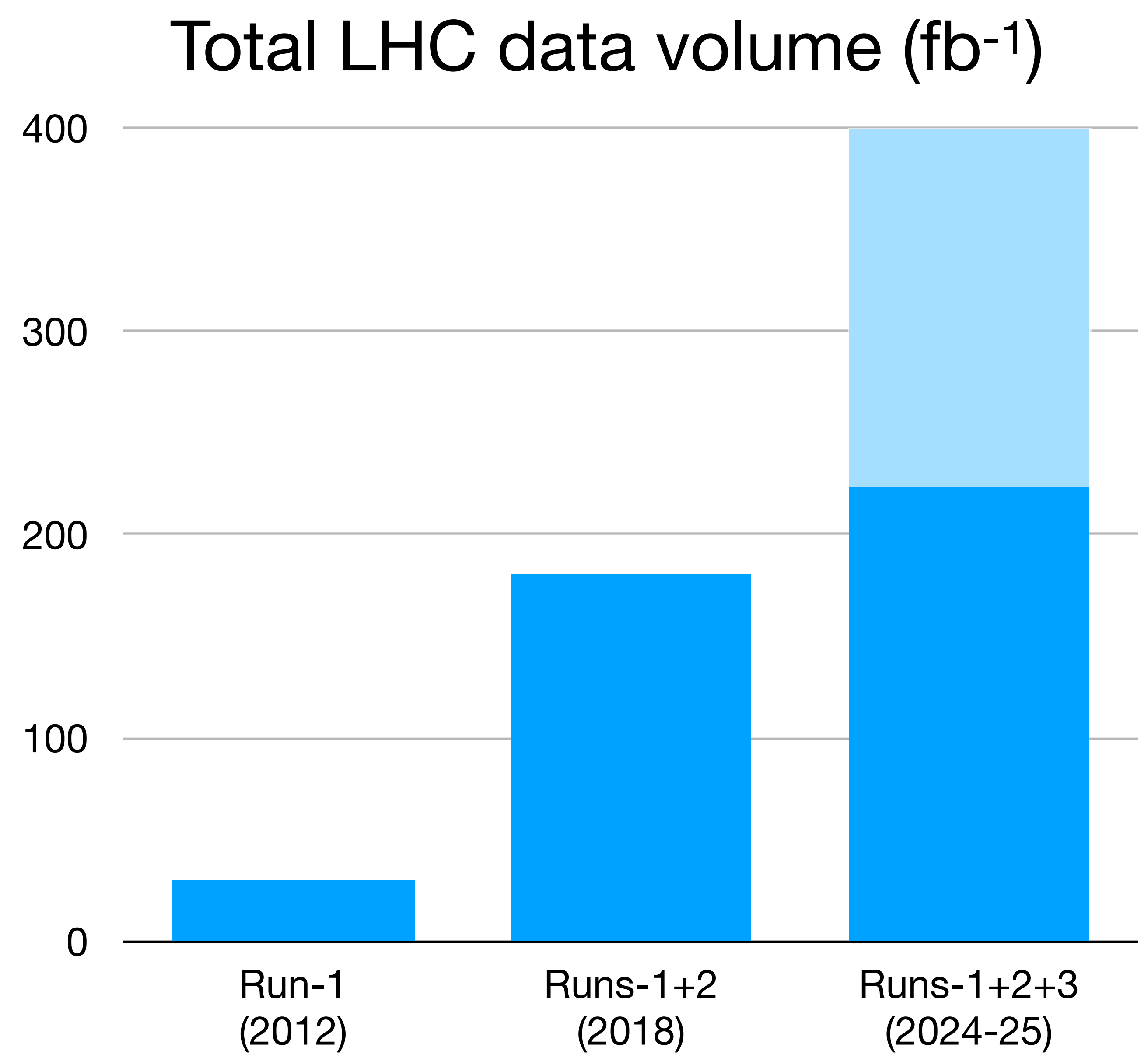
Long-Lived Particles at ATLAS - Summary

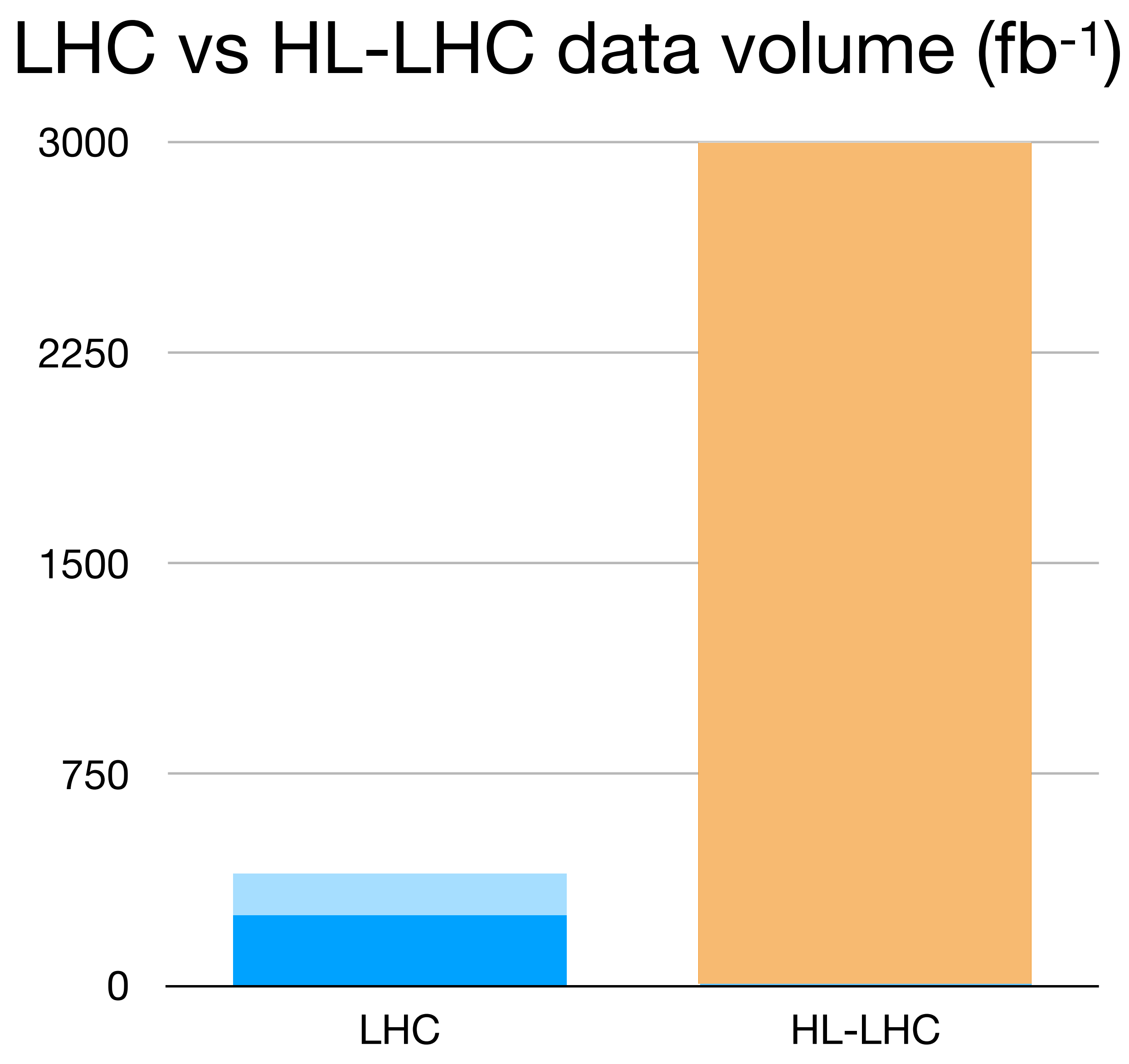


LLPs at LHC: Future Prospects

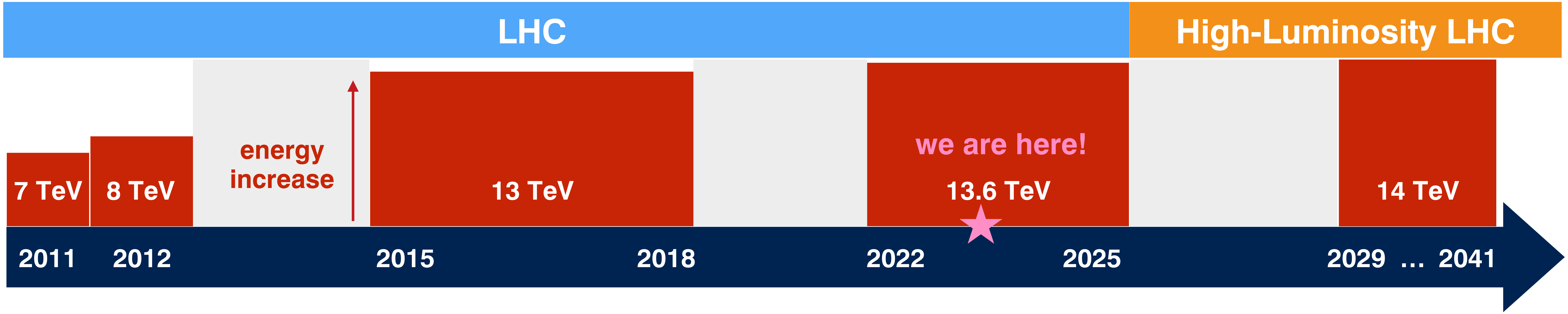
More data = Sharper images

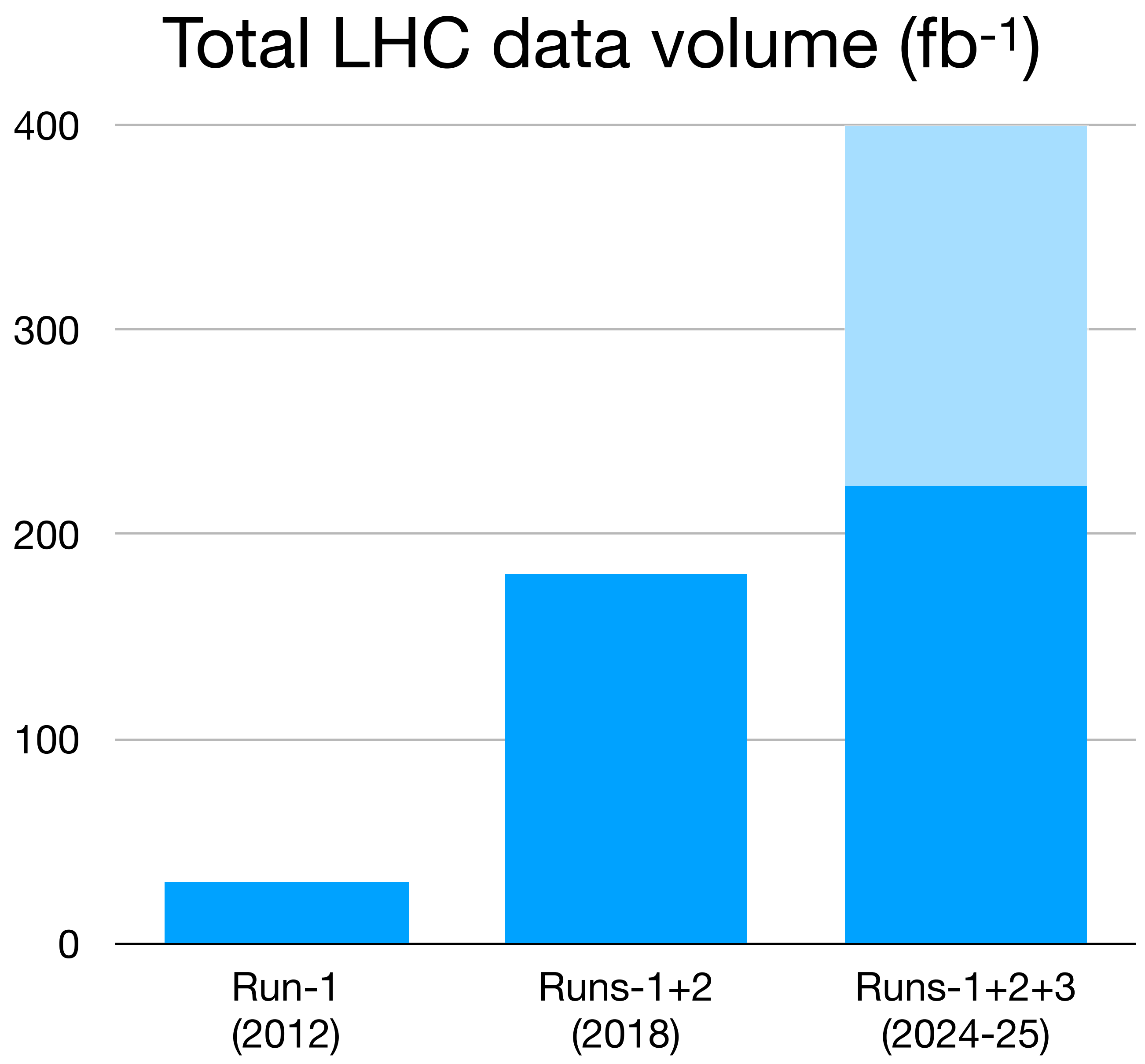


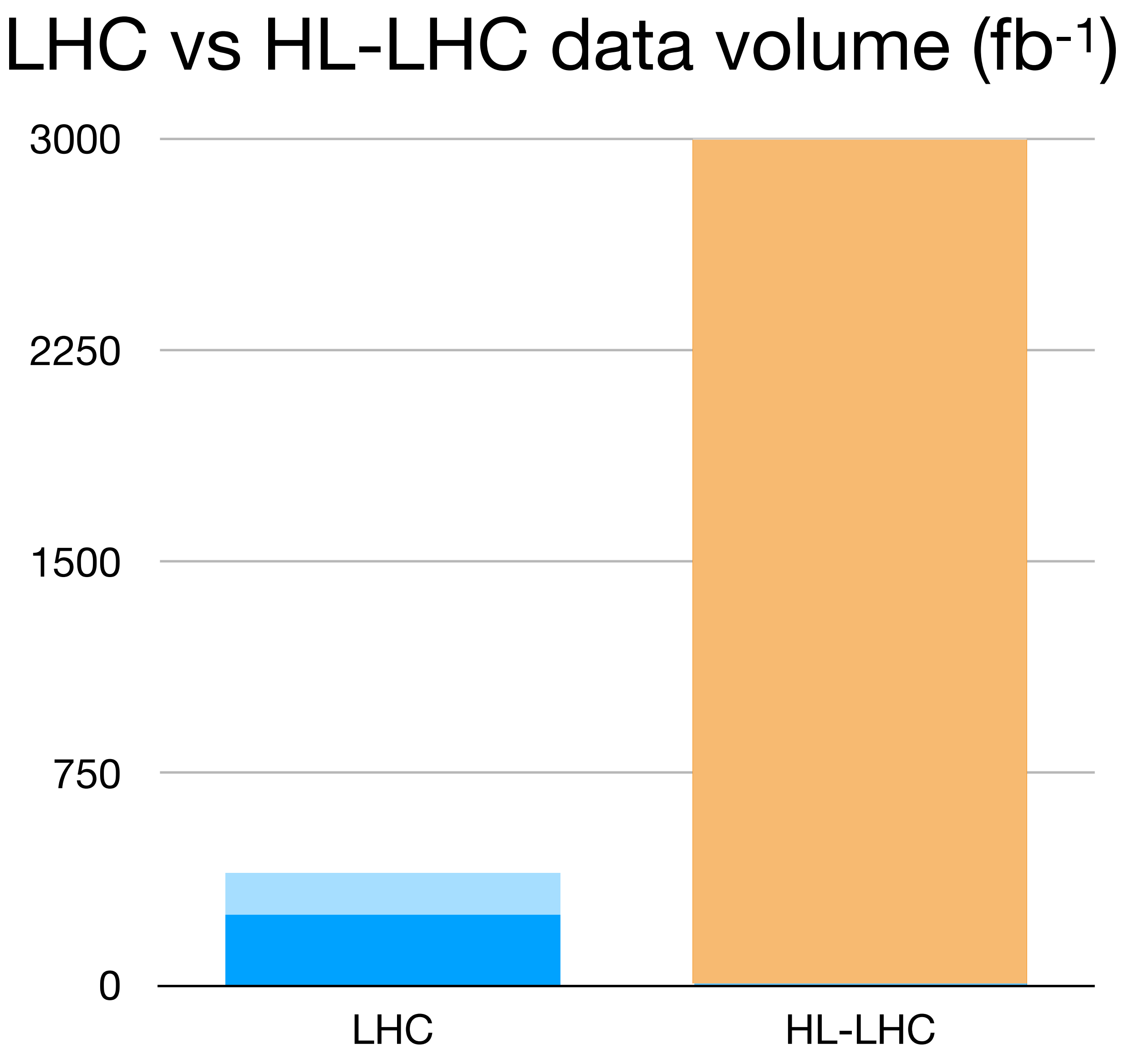




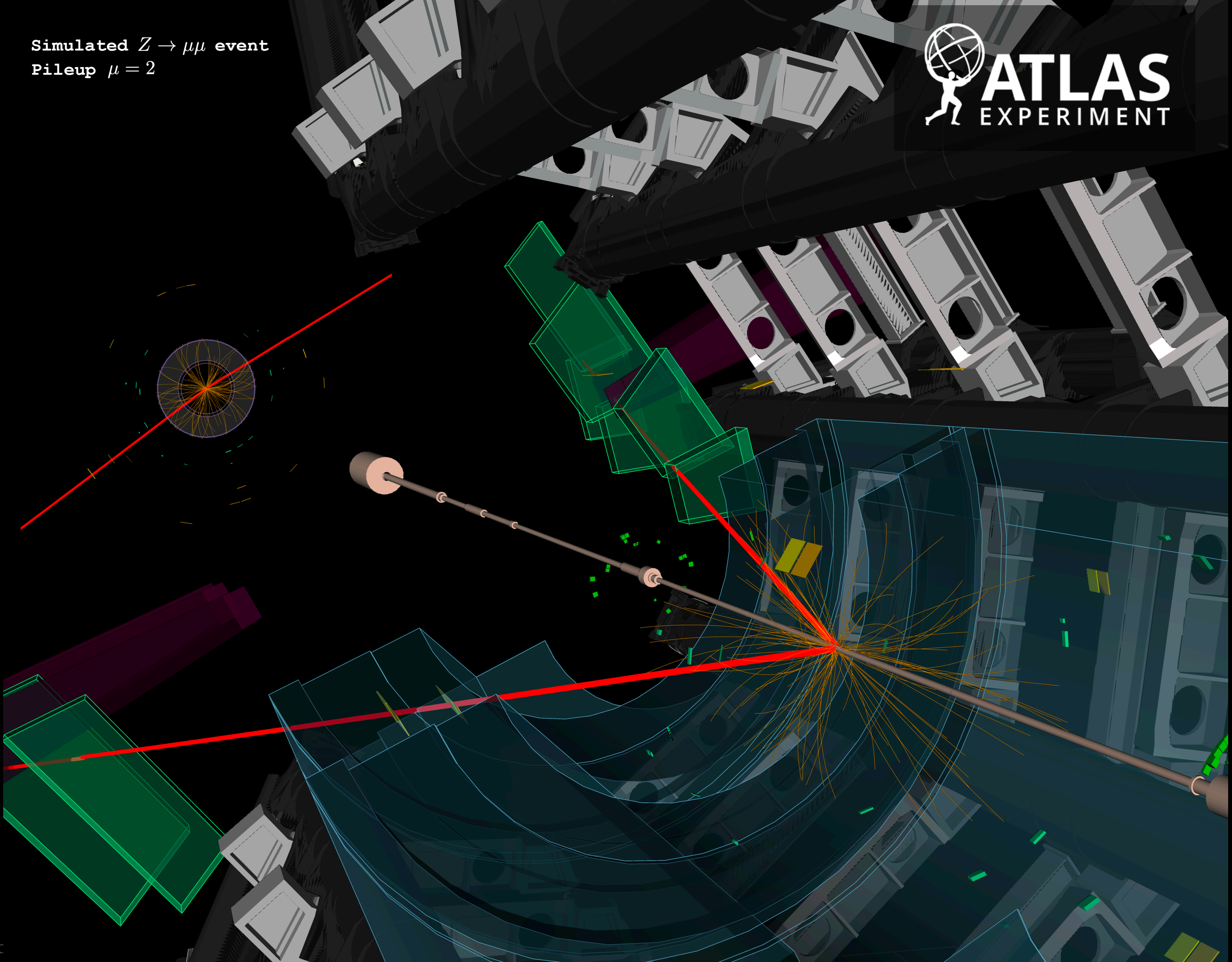
More data = Sharper images

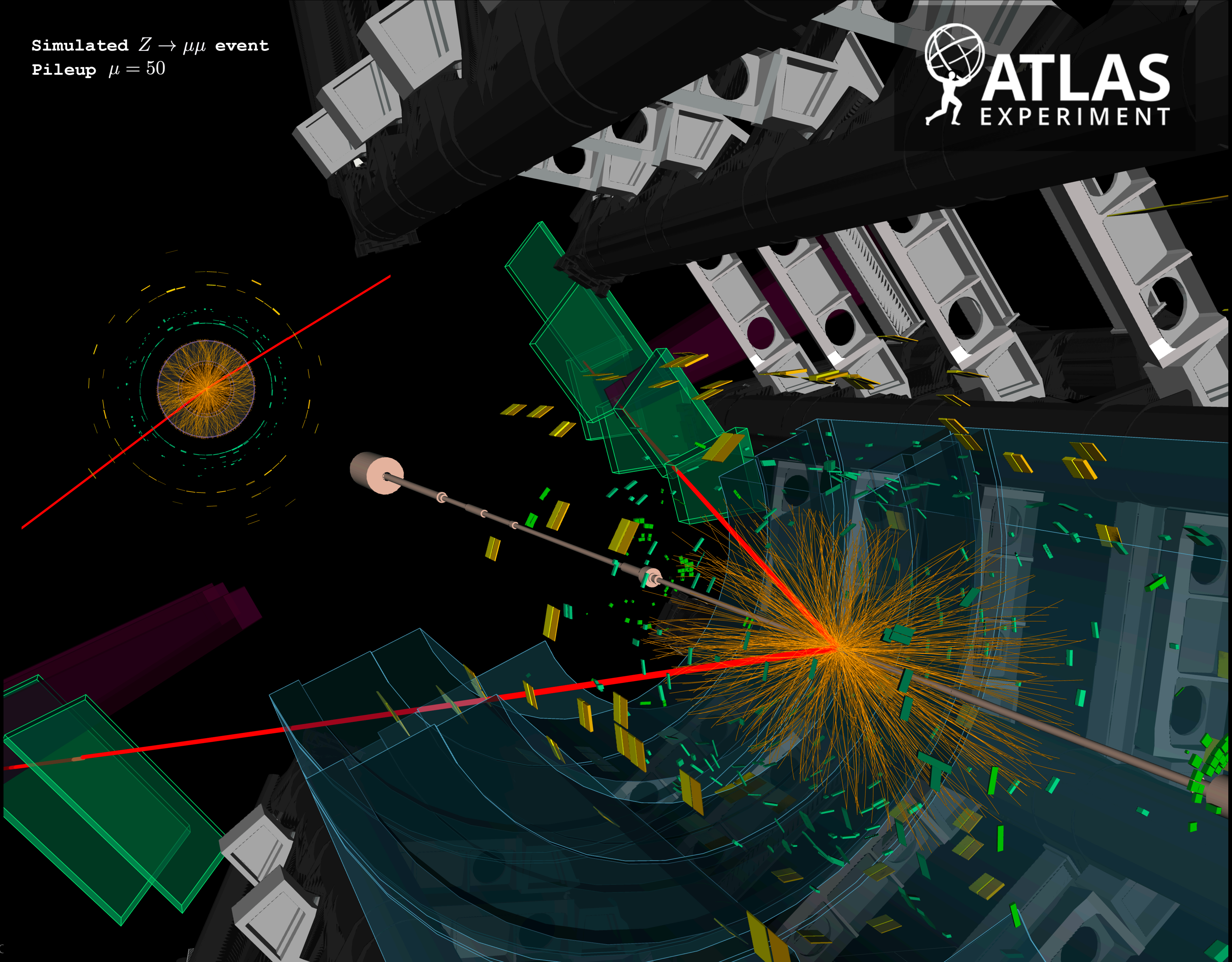


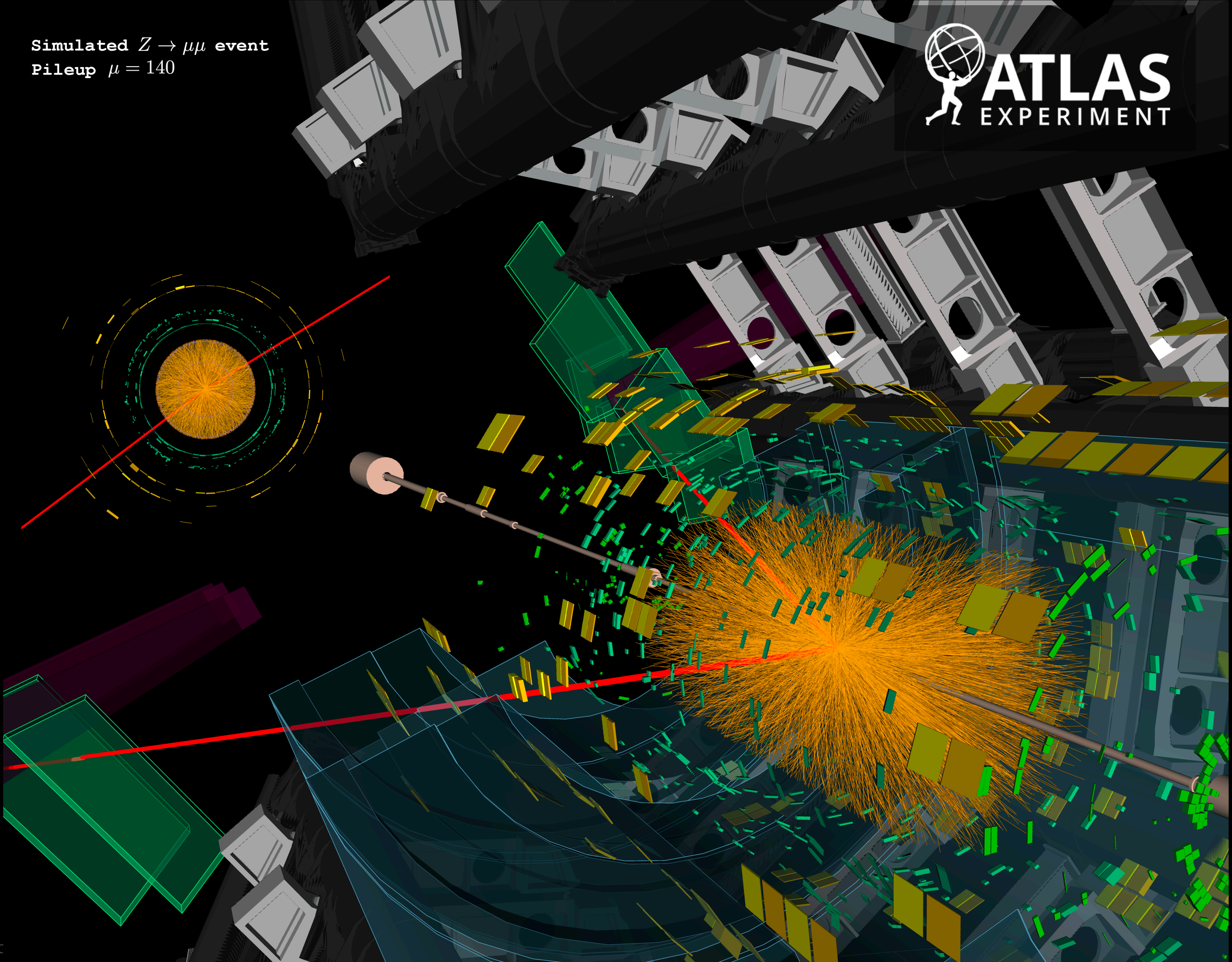




But only if we can keep/ improve performance in much harsher conditions!

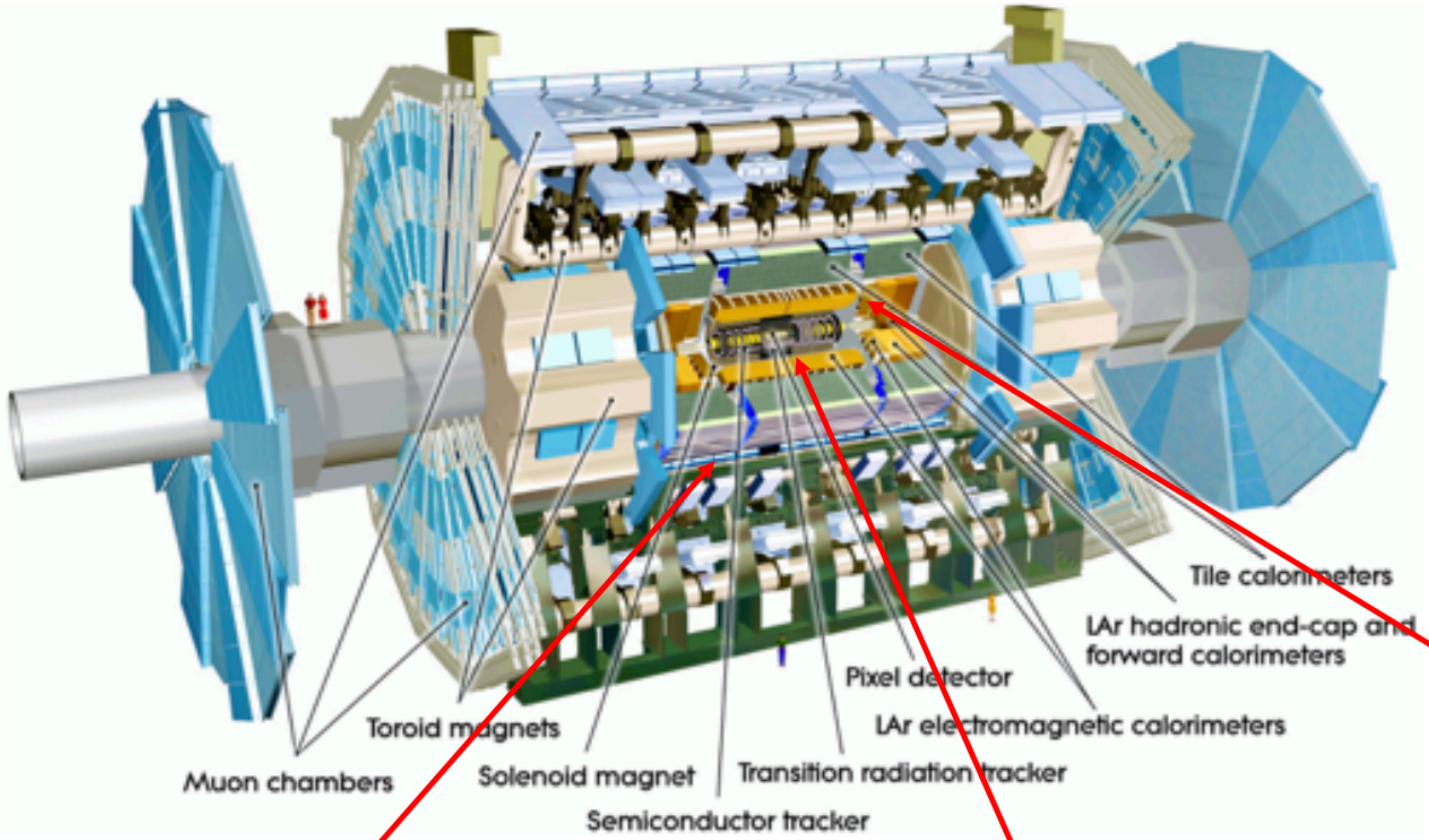

Simulated $Z \to \mu\mu$ event
Pileup $\mu = 2$
ATLAS
EXPERIMENT


Simulated $Z \to \mu\mu$ event
Pileup $\mu = 50$
ATLAS
EXPERIMENT


Simulated $Z \to \mu\mu$ event
Pileup $\mu = 140$
ATLAS
EXPERIMENT

ATLAS Phase-2 Upgrade for HL-LHC

From G. Unal



Upgraded Trigger and Data Acquisition system

Level-0 Trigger at 1 MHz

Improved High-Level Trigger (150 kHz full-scan tracking)

Electronics Upgrades

LAr Calorimeter

Tile Calorimeter

Muon system

High Granularity Timing Detector (HGTD)

Forward region ($2.4 < |\eta| < 4.0$)

Low-Gain Avalanche Detectors (LGAD) with 30 ps track resolution

New Muon Chambers

Inner barrel region with new RPC and sMDT detectors

New Inner Tracking Detector (ITk)

All silicon, up to $|\eta| = 4$

Additional small upgrades

Luminosity detectors (1% precision goal)

HL-ZDC

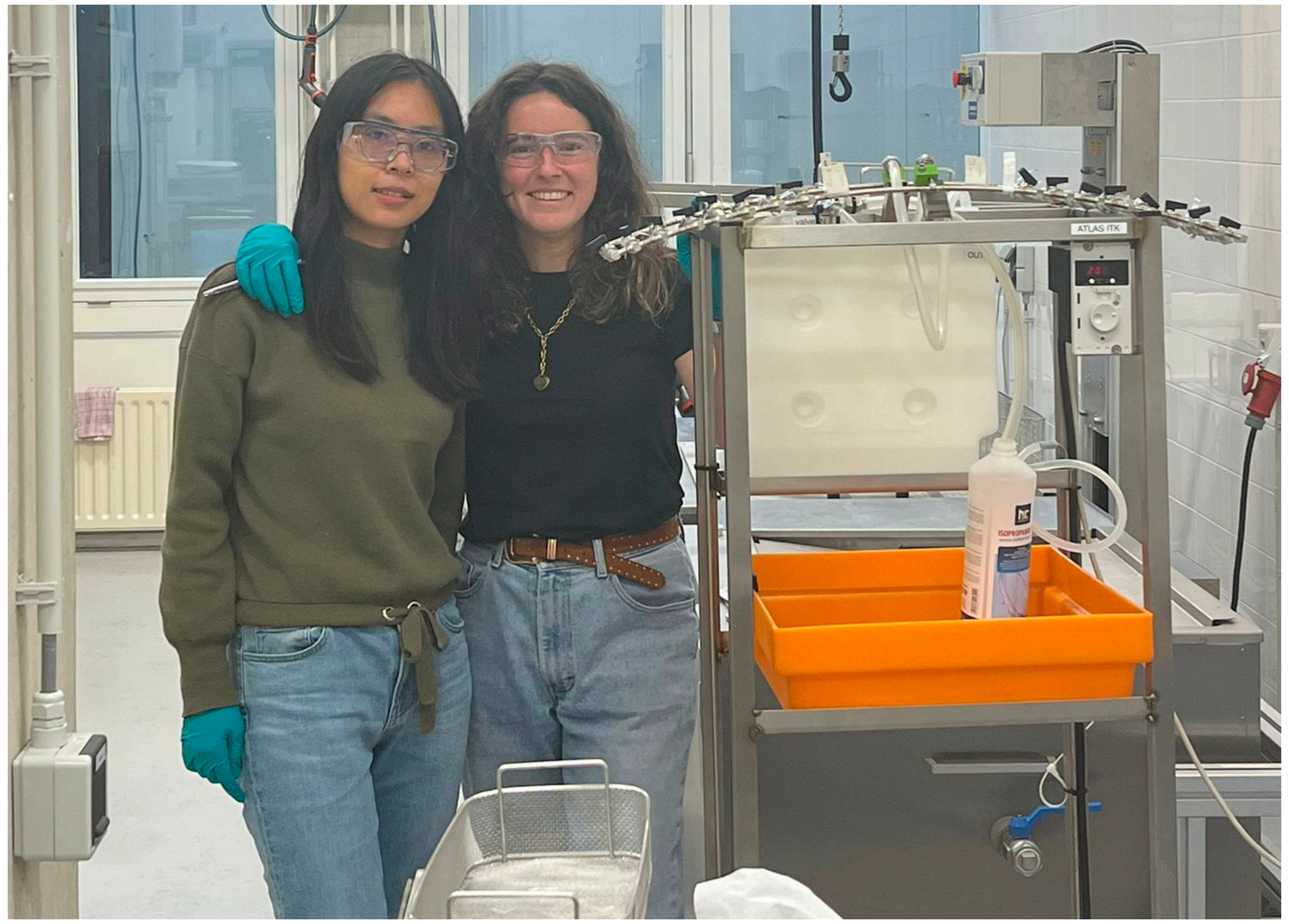
ATLAS EXPERIMENT

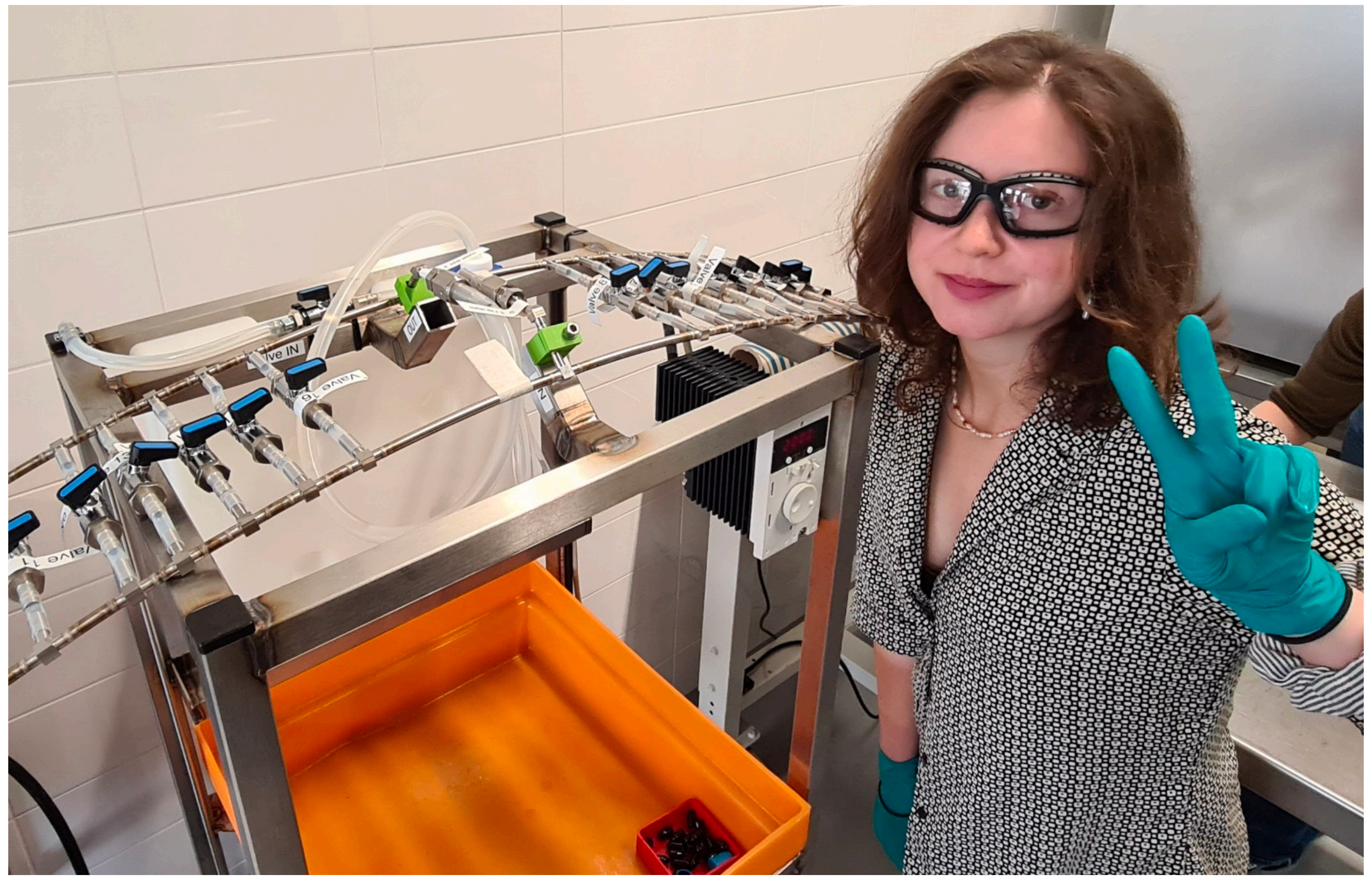
Detailed scope described in 7 TDRs approved by the CERN Research Board in 2017, 2018, 2020

hef

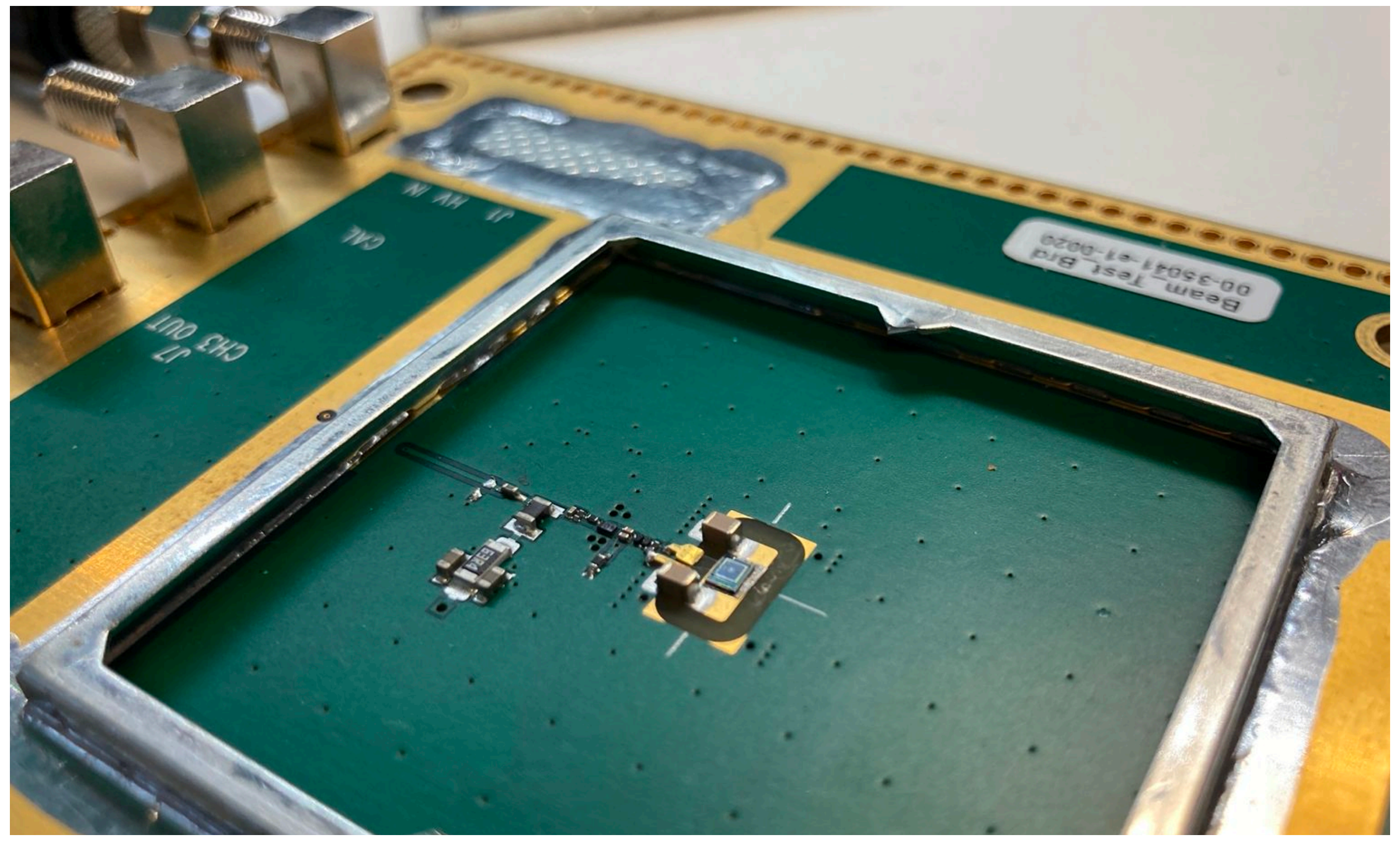
ITk and HGTD at Nikhef

ITk endcap mechanical structure

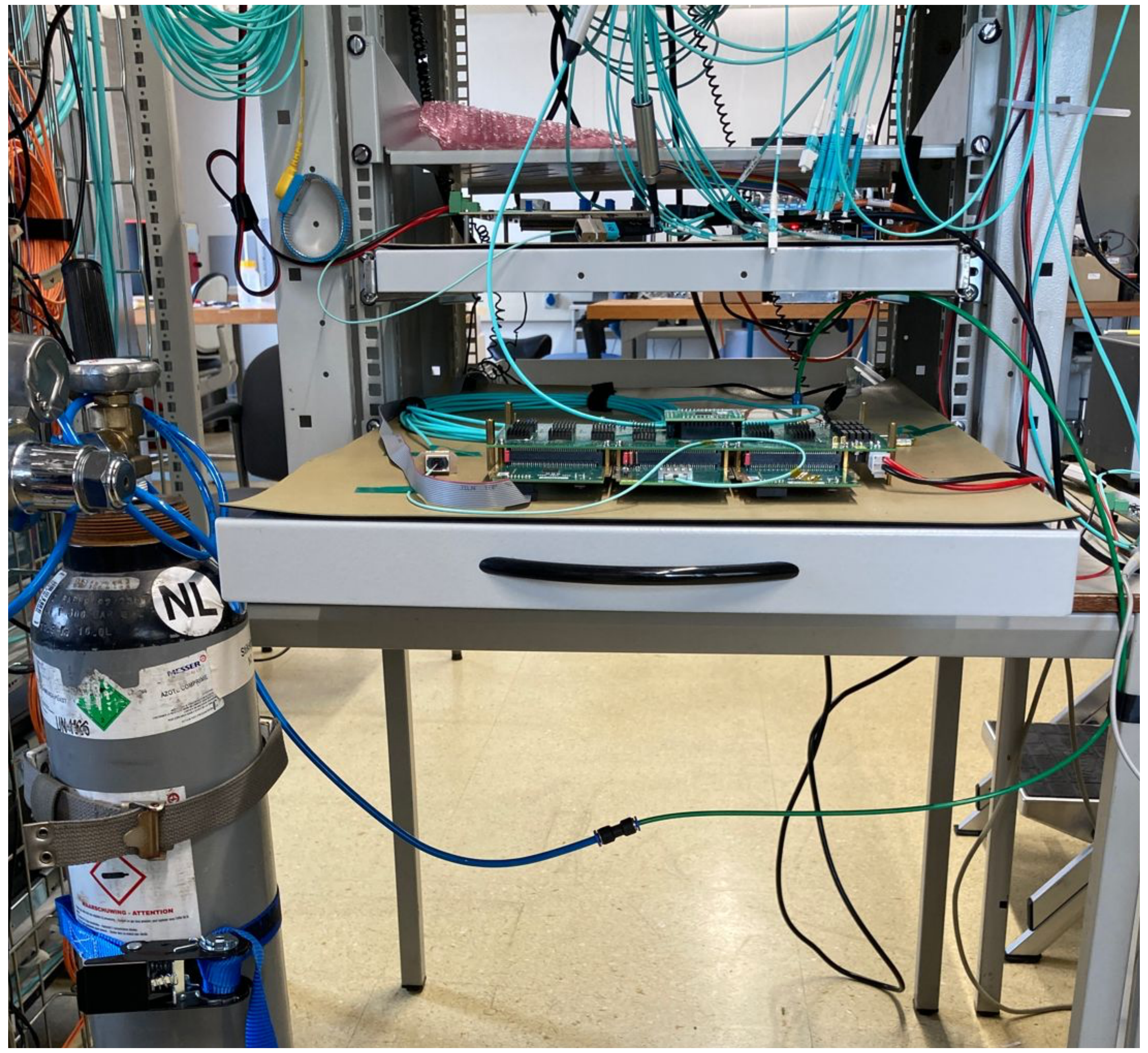




ITk flushing setup



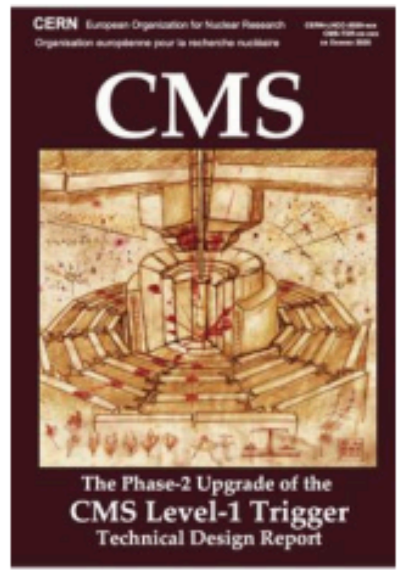
LGAD sensor on a test carrier board

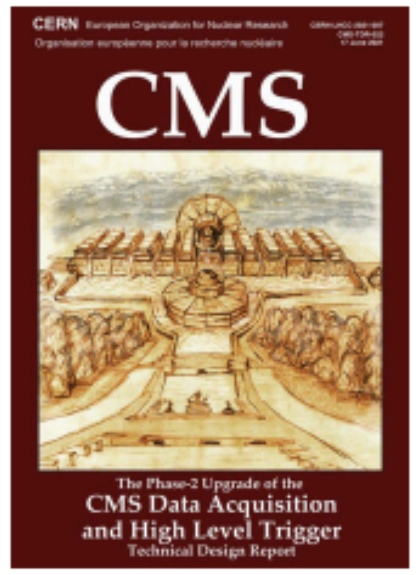


FELIX+HGTD readout

CMS Phase-2 Upgrade for HL-LHC

From A. Rizzi





L1-Trigger HLT/DAQ

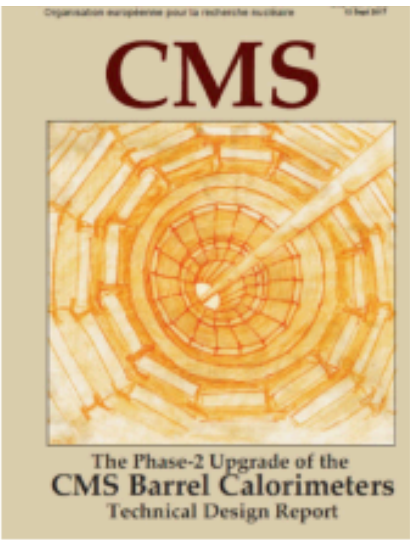
https://cds.cern.ch/record/2714892
https://cds.cern.ch/record/2759072

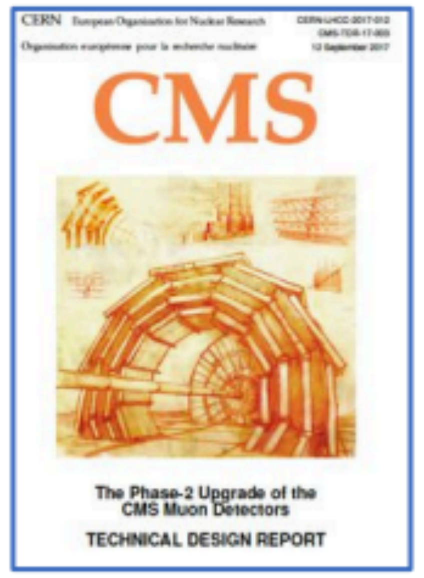
- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting

Barrel Calorimeters

https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

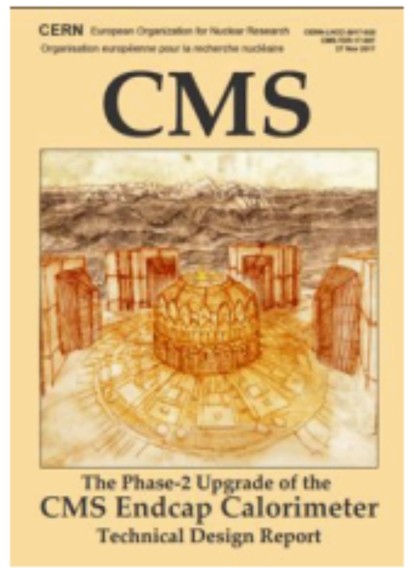




Muon systems

https://cds.cern.ch/record/2283189

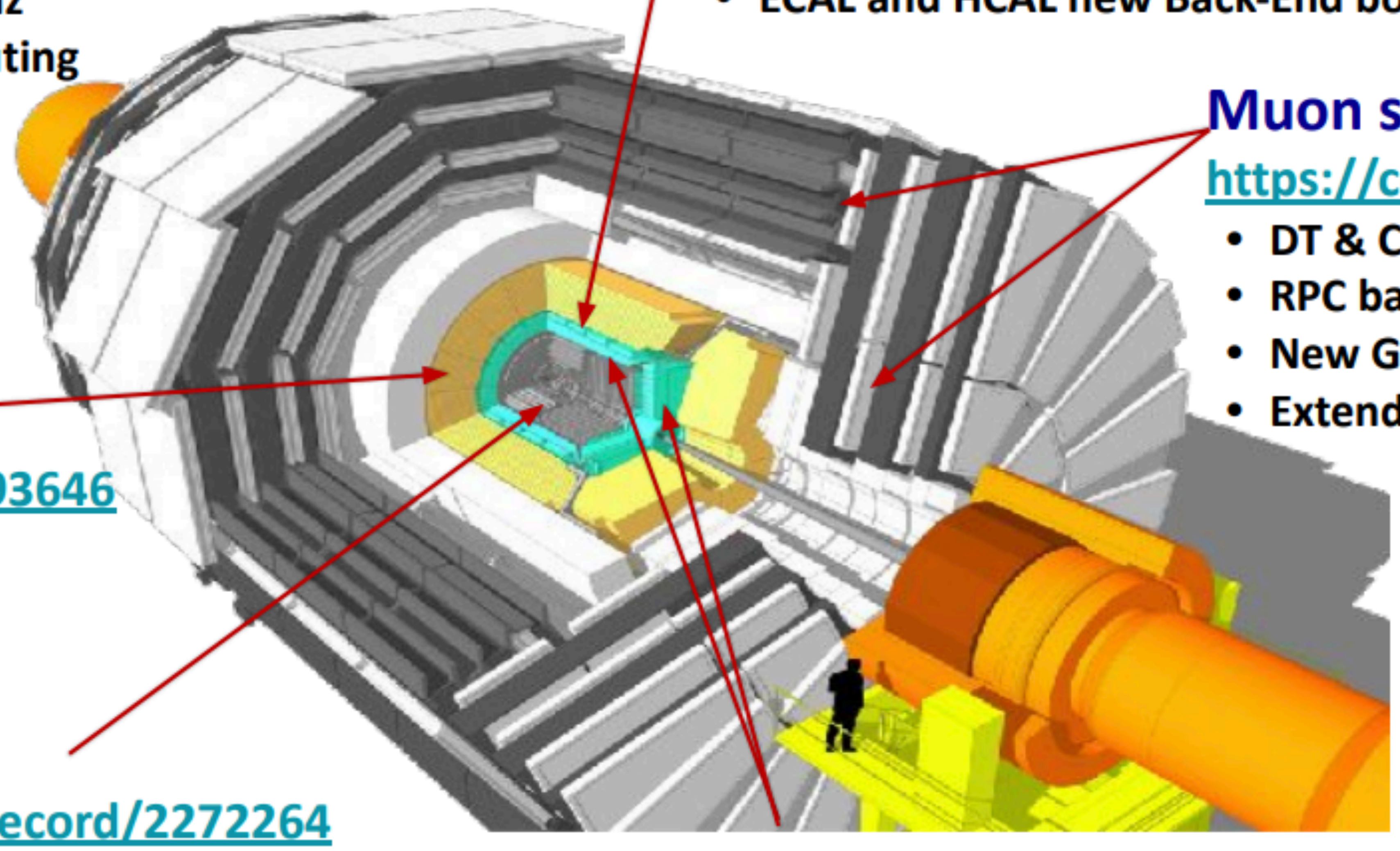
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



Calorimeter Endcap

https://cds.cern.ch/record/2293646

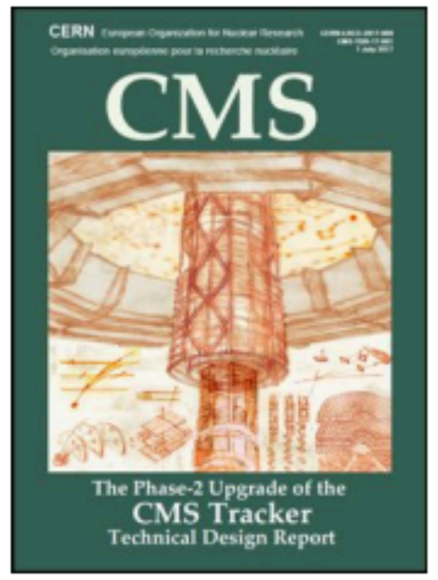
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS



Beam Radiation Instr. and Luminosity

http://cds.cern.ch/record/2759074

- Bunch-by-bunch luminosity measurement: 1% offline, 2% online



Tracker https://cds.cern.ch/record/2272264

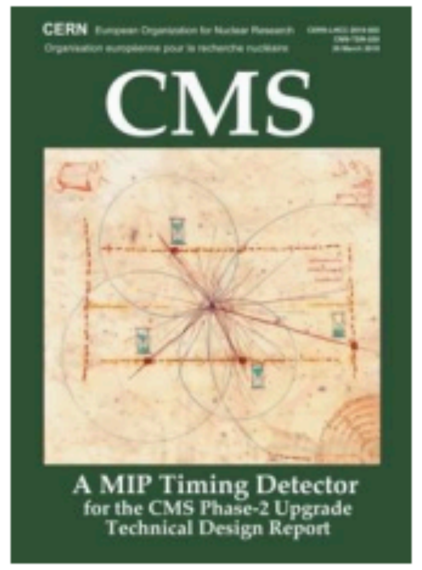
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

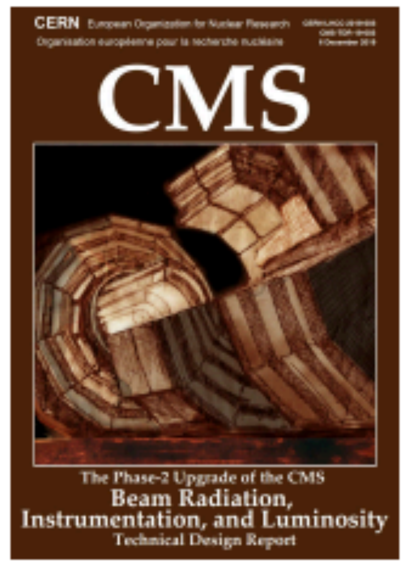
MIP Timing Detector

https://cds.cern.ch/record/2667167

Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes



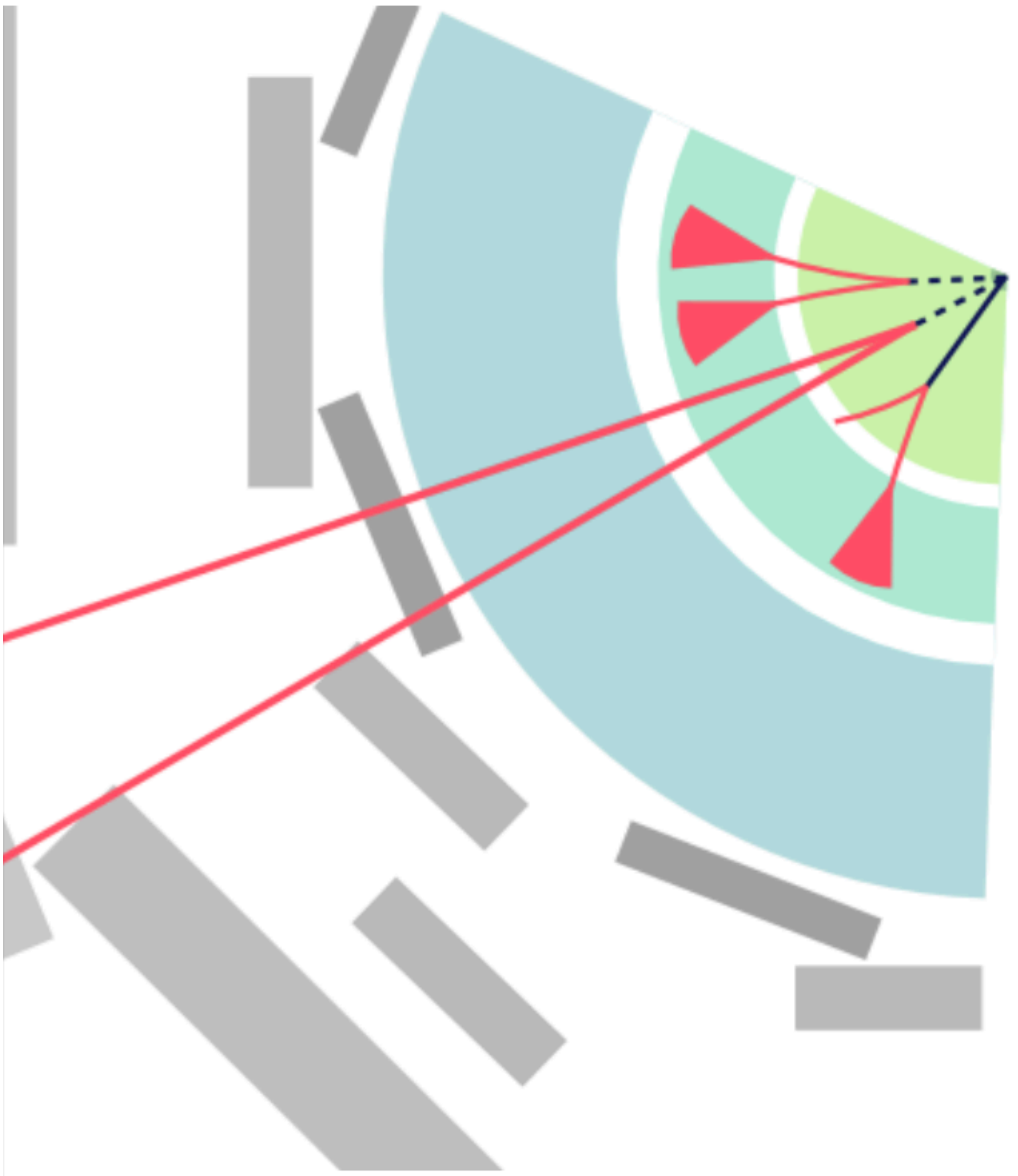


HL-LHC Upgrades and LLPs

TRACKING

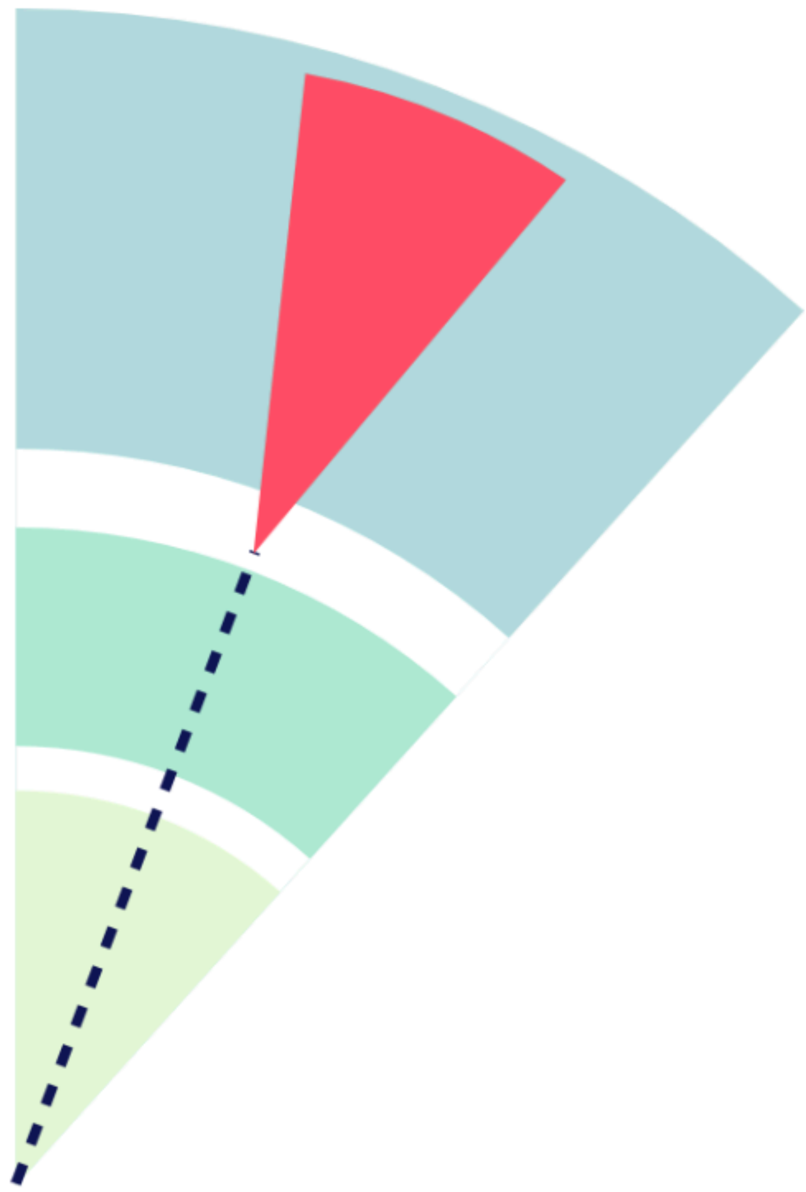
CMS: Allow for tracking information in L1 Trigger

ATLAS: All-silicon ITk (>3x current amount of silicon)
Extended coverage |η| < 4



CMS: Offline improvement in transverse impact parameter resolution

ATLAS: Improvements in reconstruction of displaced and disappearing tracks



CALORIMETRY

CMS: Allow for better timing resolution in ECAL

CMS: New high-granularity silicon calorimeters in endcap (3D imaging and timing)

CMS: Allow pointing of photons (already possible in ATLAS)

ATLAS: Readout upgrades, better granularity in triggers

ATLAS: Improving pointing by using HCAL information

J. Phys. G: Nucl. Part. Phys. 47 090501 (2020)

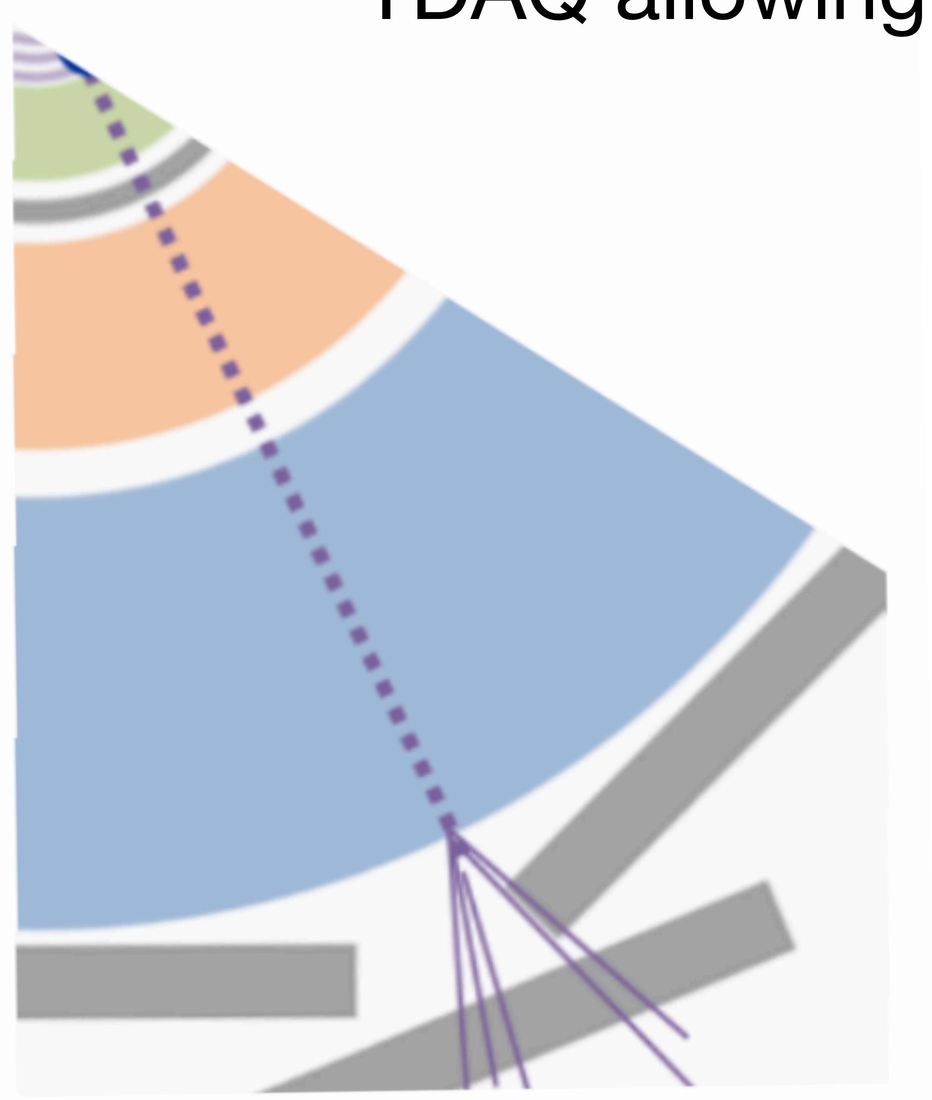
HL-LHC Upgrades and LLPs

MUONS

CMS: Increase coverage, better muon info at trigger level

CMS: Possibility to get Time of Flight in RPC stations

ATLAS: New Small Wheel already at Run-3; Upgrade on TDAQ allowing better algorithms (also at trigger)



TIMING & TRIGGER

CMS: Single layer timing detector in barrel and endcap (improve background rejection)

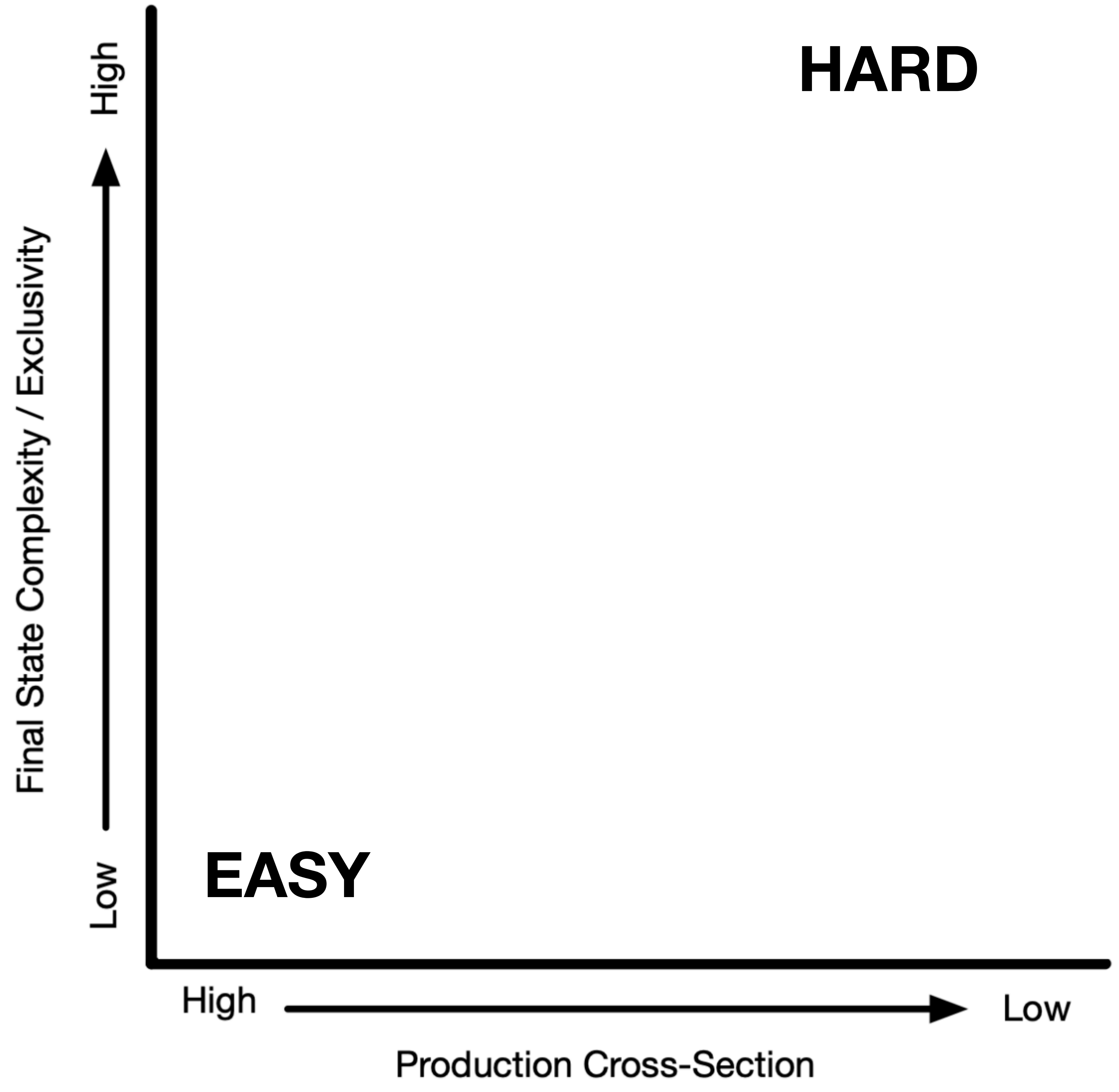
ATLAS: High-Granularity Timing Detector multiple layers in endcap (track-to-vertex association, identification improvements)

CMS: New L1 Global trigger, Correlator trigger, scouting/ parking for LLPs

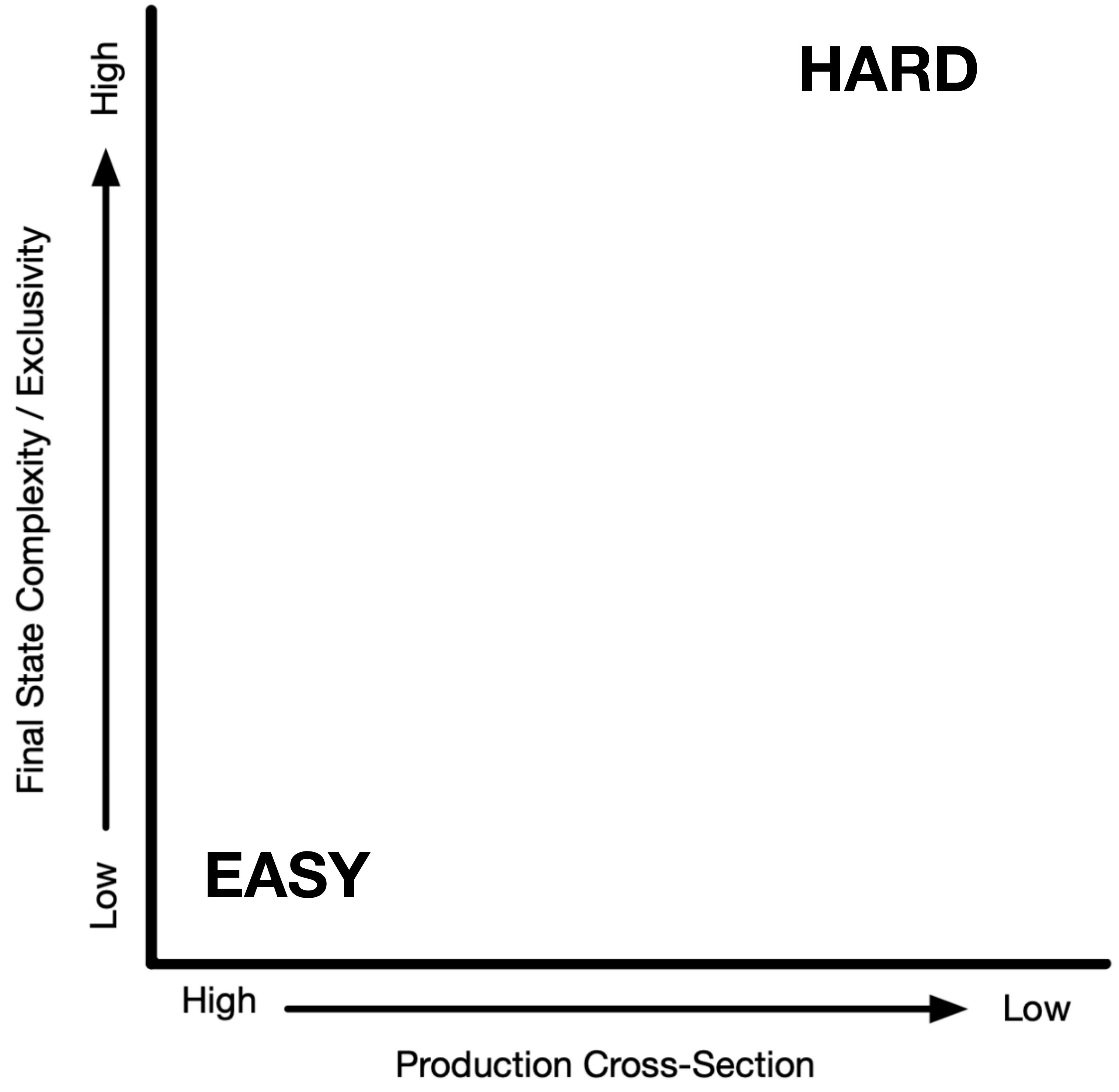
ATLAS: Improvement based on hardware triggers and ML in object identification

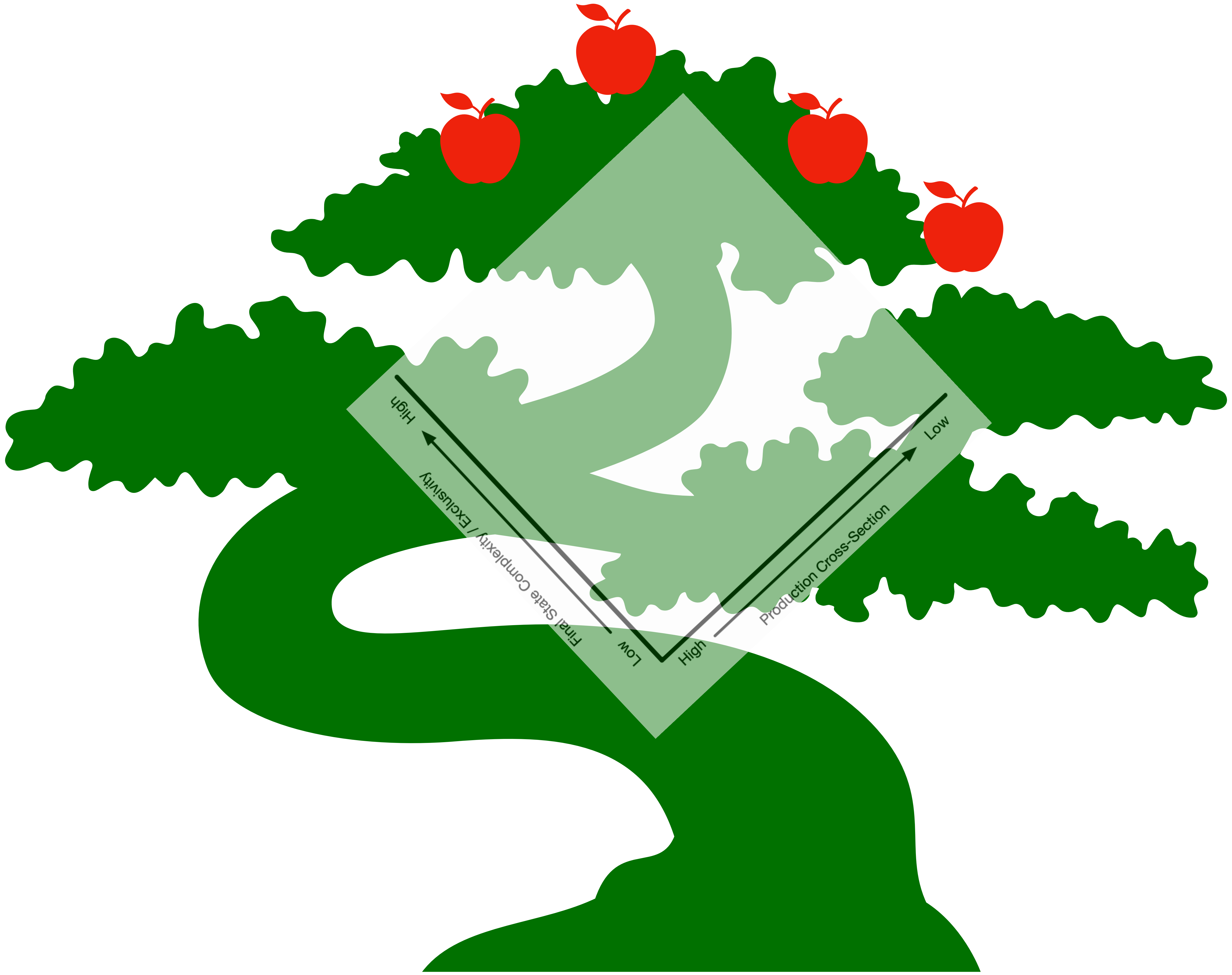
J. Phys. G: Nucl. Part. Phys. 47 090501 (2020)

BSM Searches

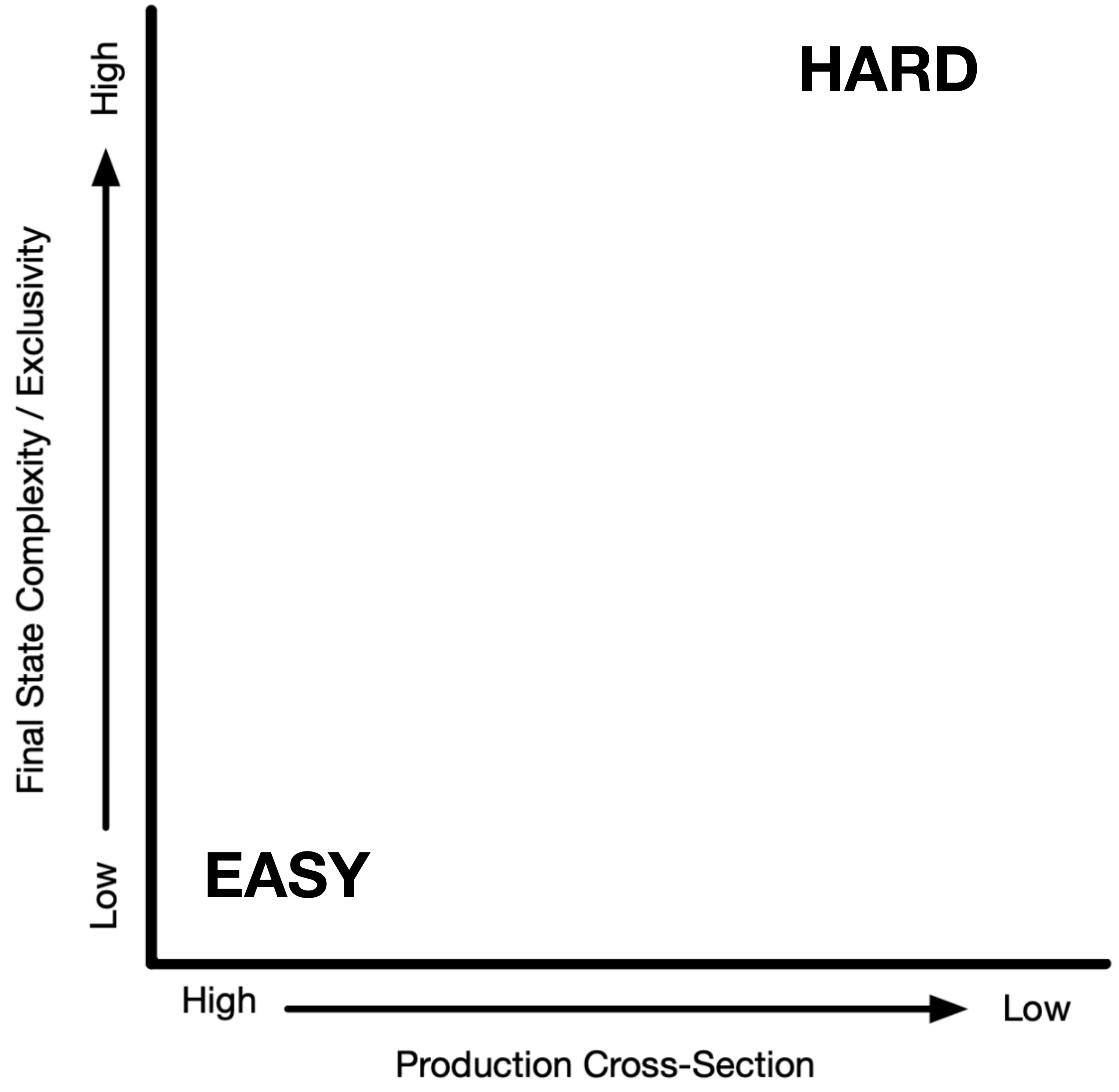


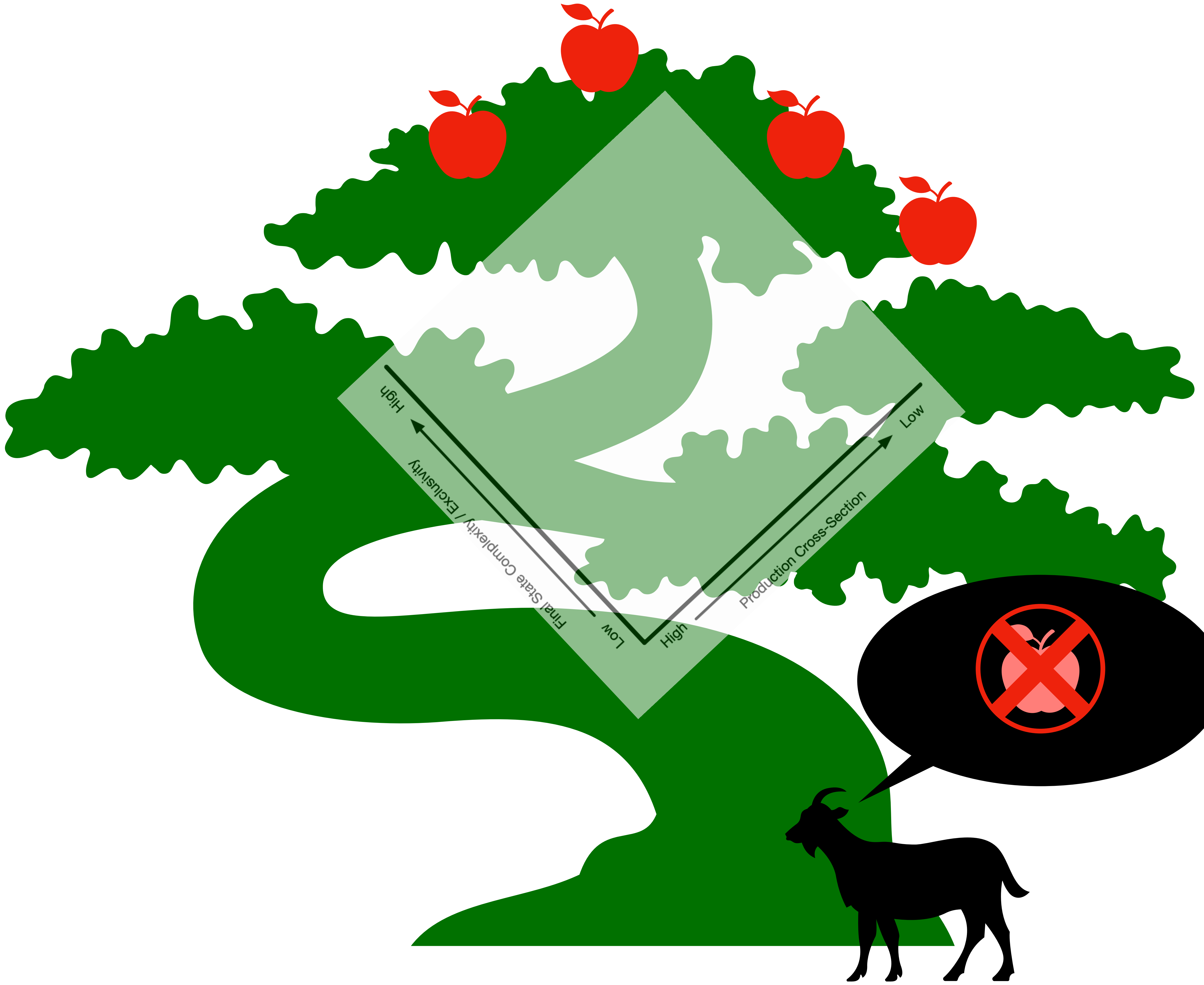
BSM Searches





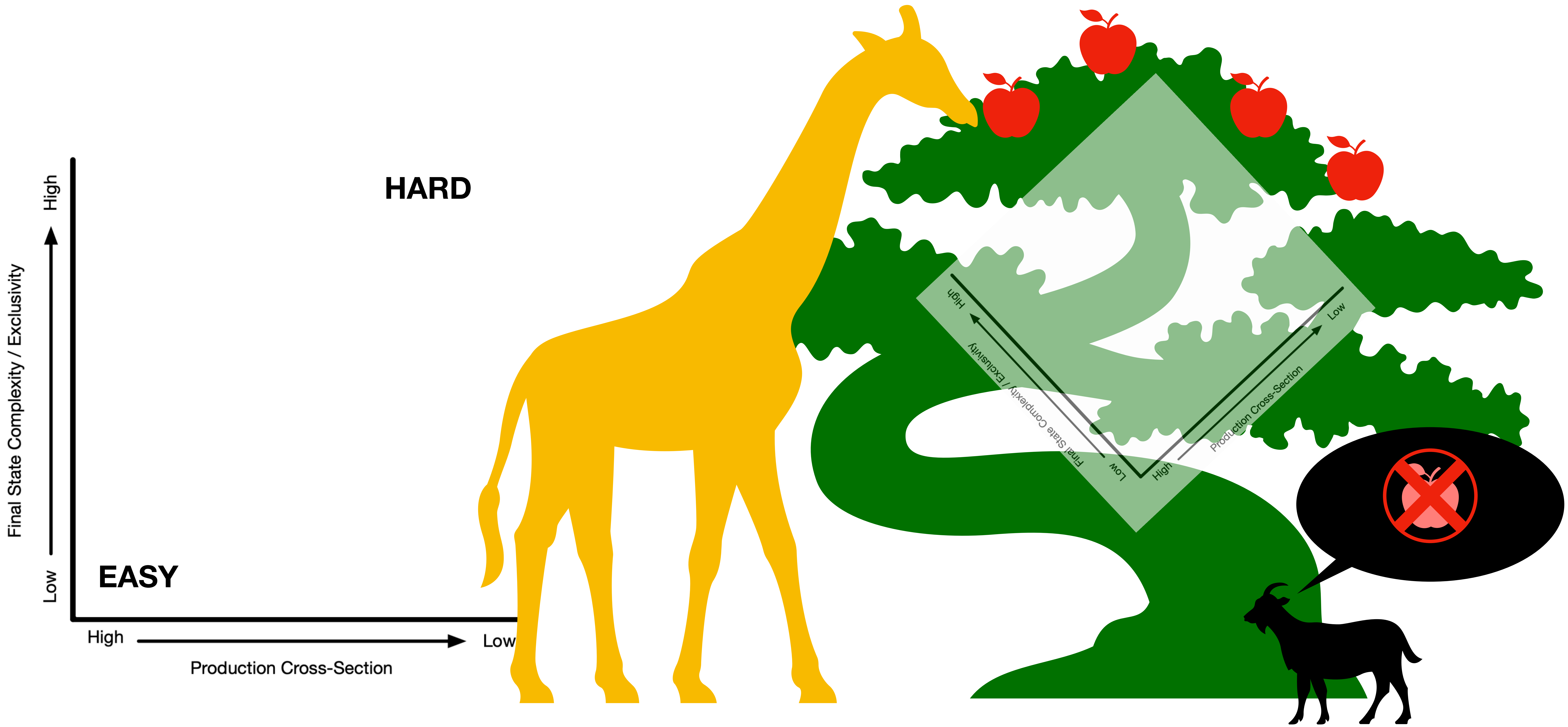
BSM Searches





BSM Searches

Analogy adapted from Dr. Dan Hayden from MSU



Disclaimer: biology not scientifically sound!

Leaving no stone unturned

Leaving no stone unturned

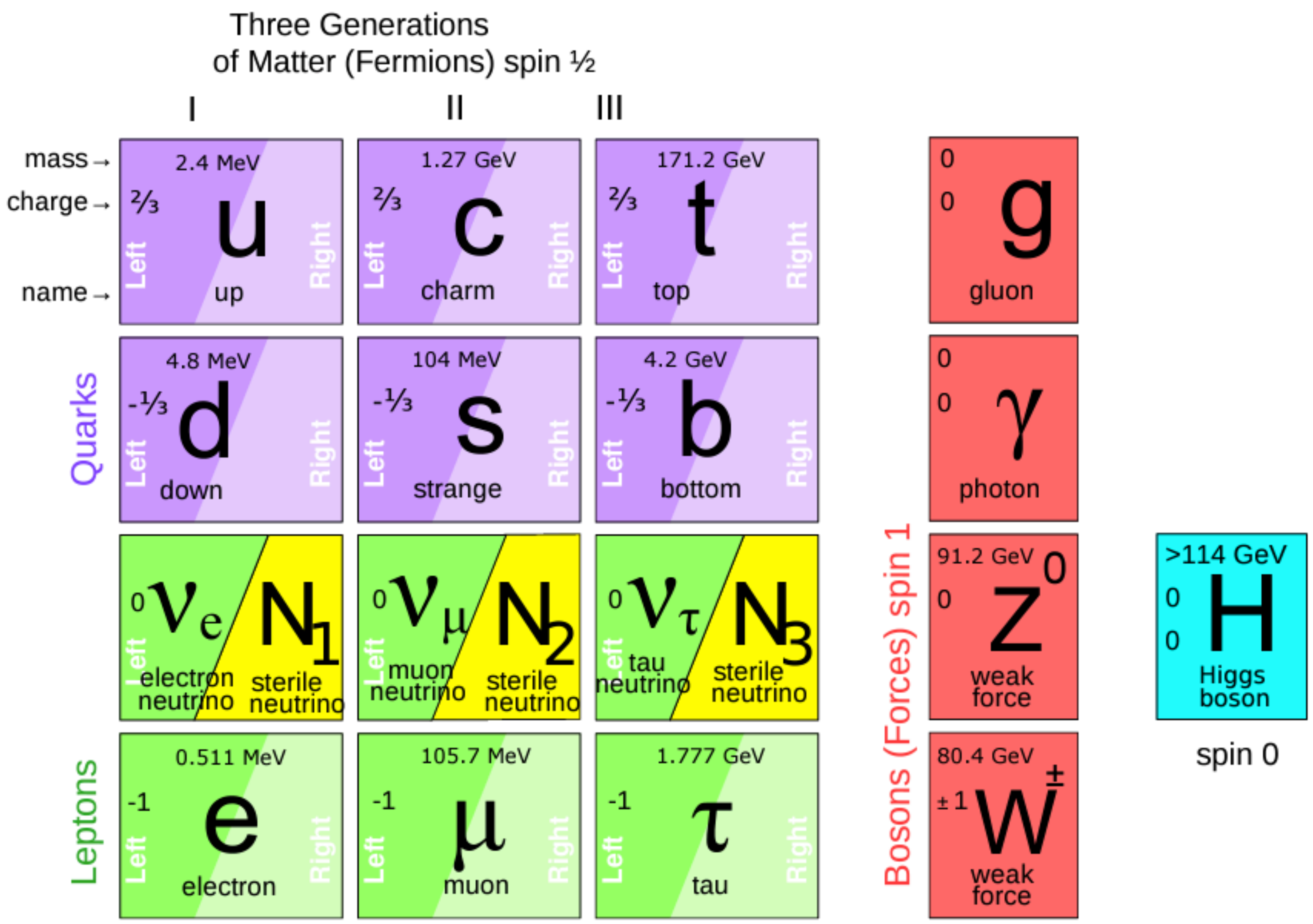
Summary and Outlook

- Long-lived particles expand the scope of searches at the LHC
- Many innovative searches ongoing in ATLAS and CMS, but also at LHCb, FASER, SND@LHC, NA 62, MoEDAL, MilliQan …
- Crucial to plan ahead: look towards experiment upgrades and new dedicated detectors such as the Forward Physics Facility, CODEX-b, MATHUSLA…
- Stay tuned for many new exciting things ahead!

Image by brgfx on Freepik

Backup

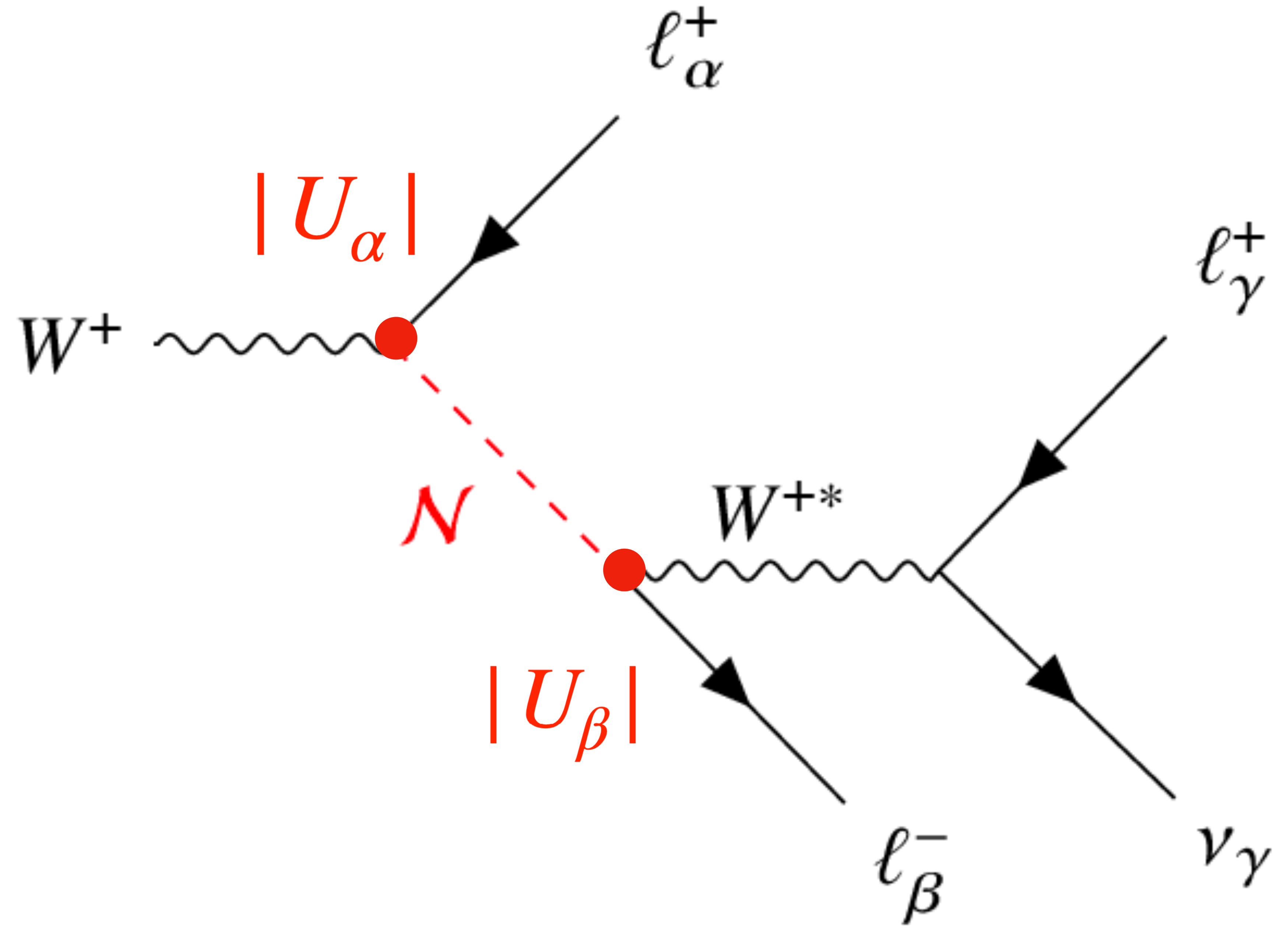
Search for Displaced Heavy Neutral Leptons



- SM extension with 3 HNLs
  - ➡ Introduce right-handed states known as heavy neutral leptons
  - ➡ Type-I seesaw mechanism explains light neutrino masses

Figure from arXiv:1301.5516

Experimentally Relevant Observables



$|U_\alpha|^2$ ⇒ mixing angle between SM ν and HNL

m_N ⇒ HNL mass

α, β, γ ⇒ lepton flavour index

- HNLs experience "weak-like" interactions controlled by dimensionless mixing angles ($|U_\alpha|^2$)
- m_N dictates kinematics of decay products
- HNL lifetime: $\tau_N \propto \dfrac{1}{m_N^5 |U_\alpha|^2}$

Can be LLPs! 🦄

- HNL can be Majorana- or Dirac-like particles
  - ➡ Dirac ⇒ Lepton Number is conserved (LNC)
  - ➡ Majorana ⇒ Lepton Number is violated (LNV)

ATLAS EXPERIMENT Nikhef UvA

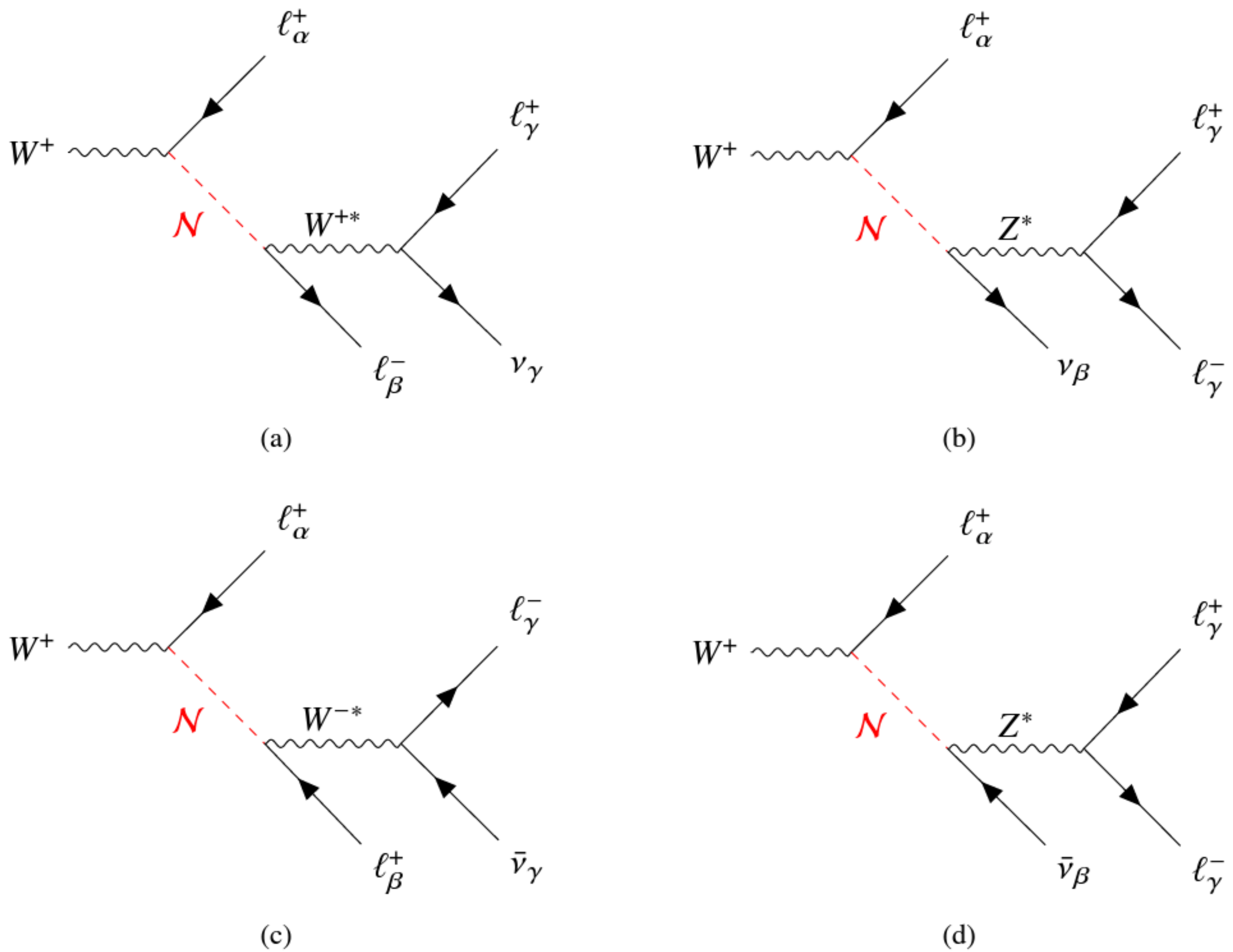
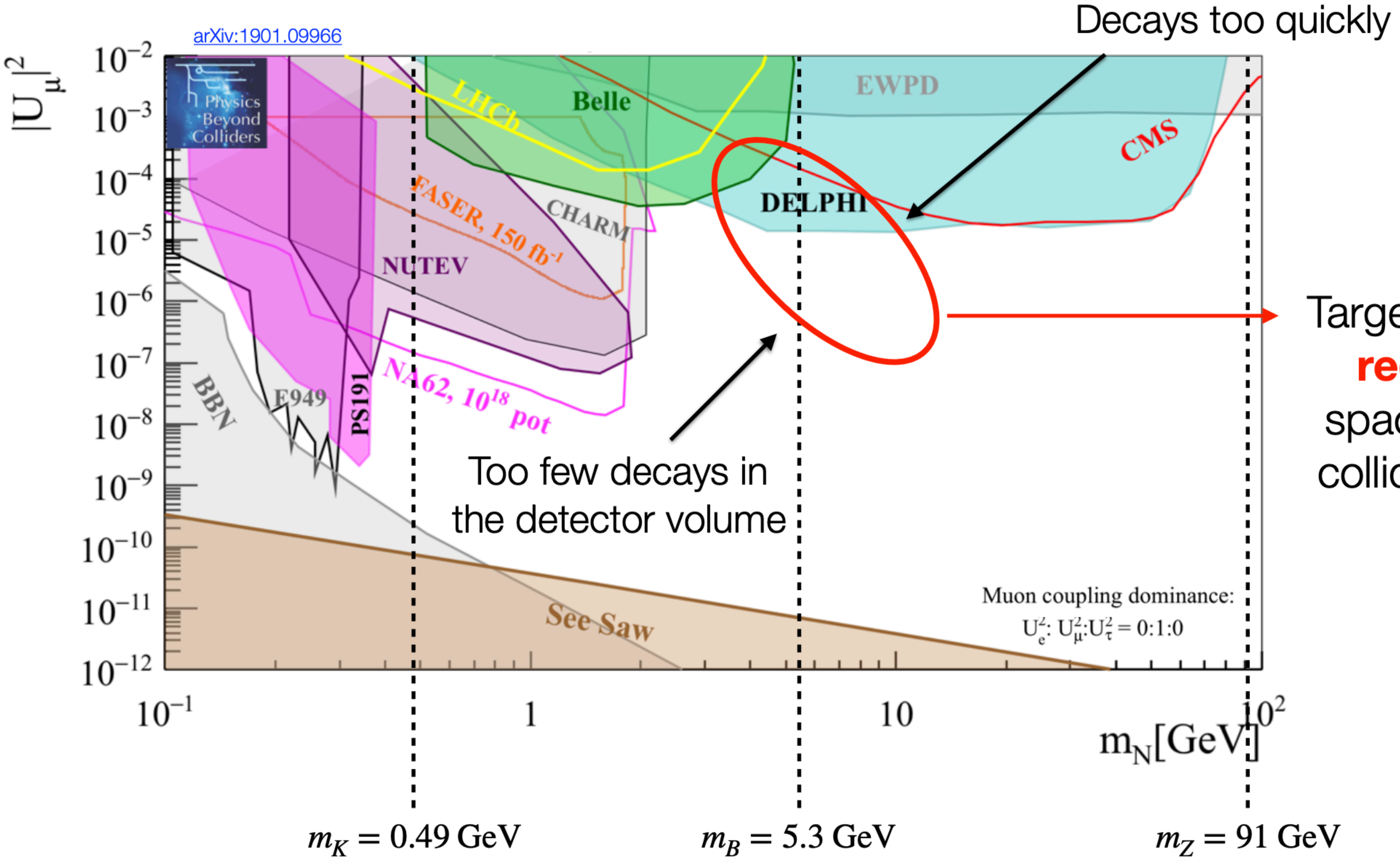


Figure 3: Feynman diagrams for the HNL production and decay modes targeted in this analysis. The flavors of the leptons in the diagrams, labeled by α, β, and γ, are either muons or electrons. If the charged leptons in the HNL decay have the same flavor, then both the diagrams with the virtual W (a,c) and virtual Z (b,d) contribute to the process. Lepton number conserving (a,b) and lepton number violating (c,d) processes are shown. Equivalent processes are also valid for an initial state W^- boson.

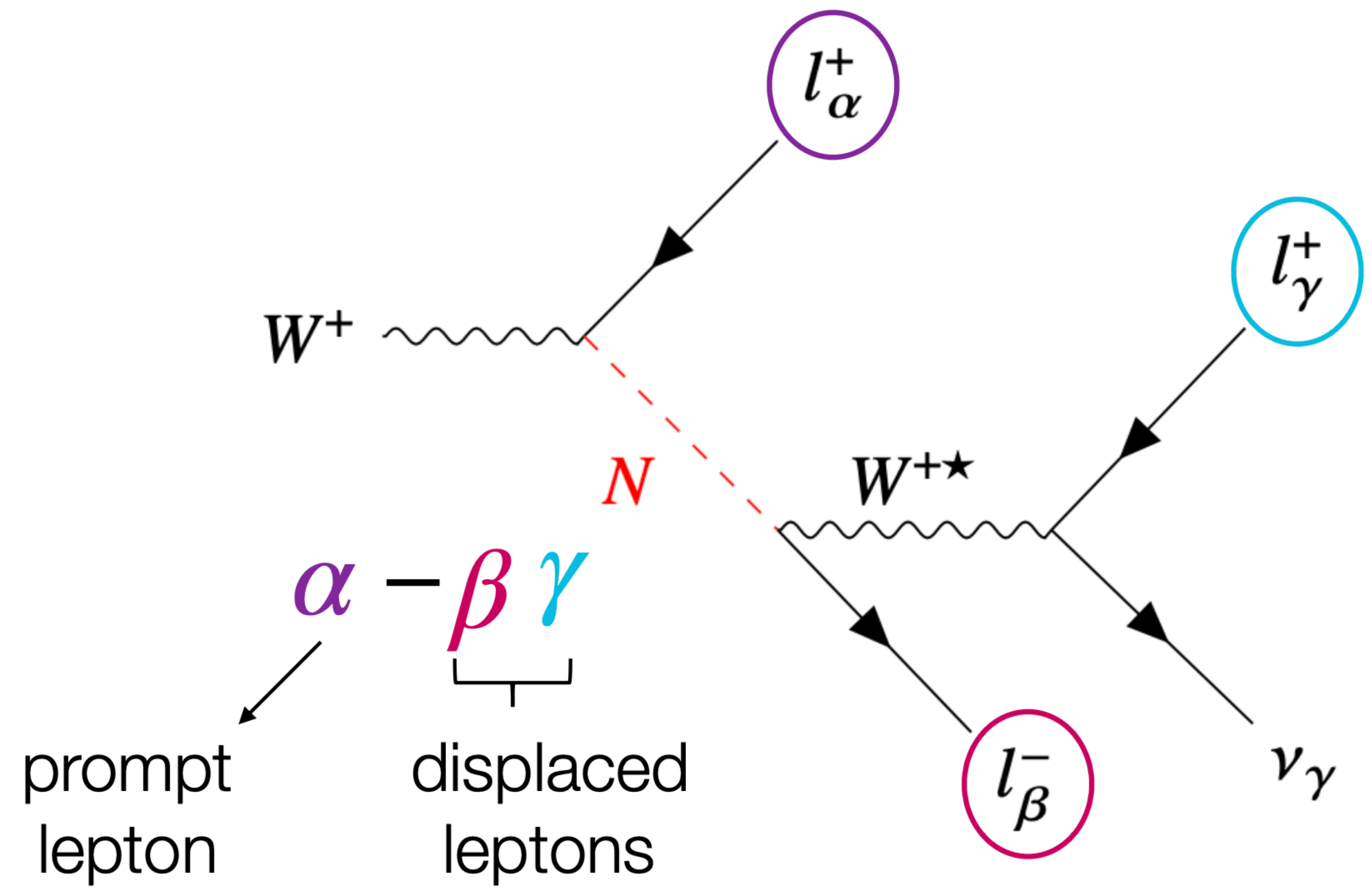
Experimental Picture



Target the **long-lived region** of phase space accessible at collider experiments!

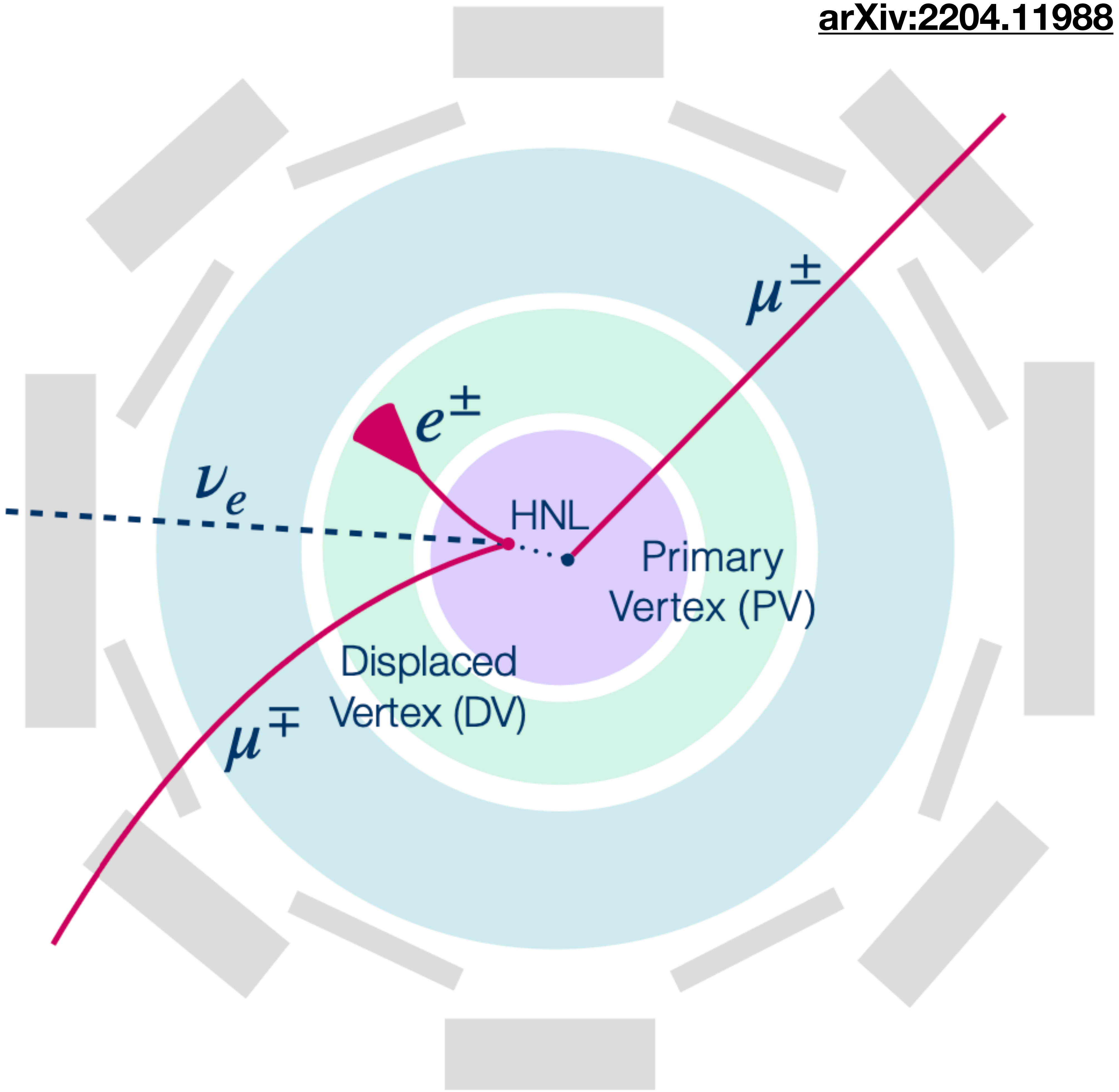
Displaced Heavy Neutral Leptons

- Experimental dHNL signature:
  - ➡ Prompt lepton (trigger)
  - ➡ Displaced vertex with two opposite charge leptons



6 signal regions:
μ-μμ, μ-μe, μ-ee, e-ee, e-eμ, e-μμ

Figure from D. Trischuk
arXiv:2204.11988

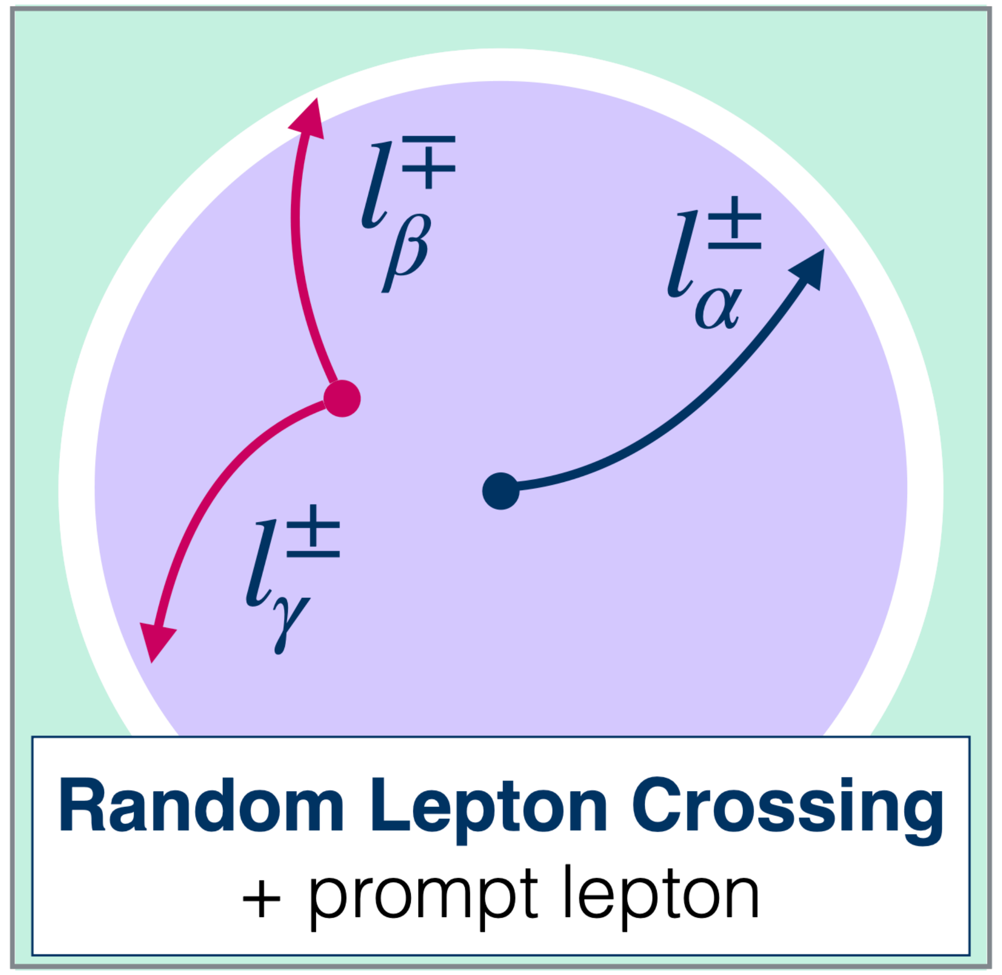


ATLAS EXPERIMENT

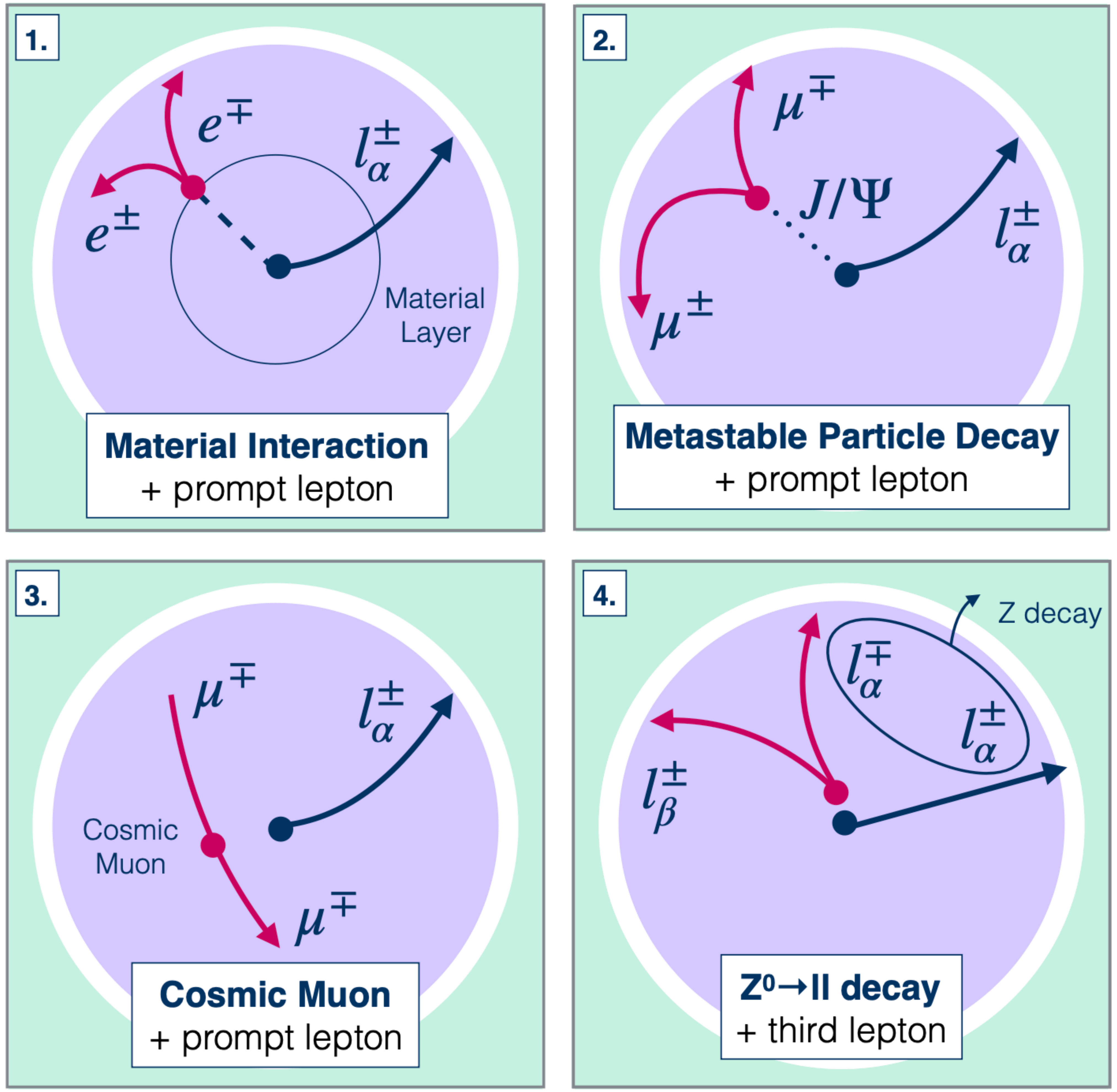
Nikhef UvA

dHNLs: Backgrounds

Dominant background



Non-random backgrounds

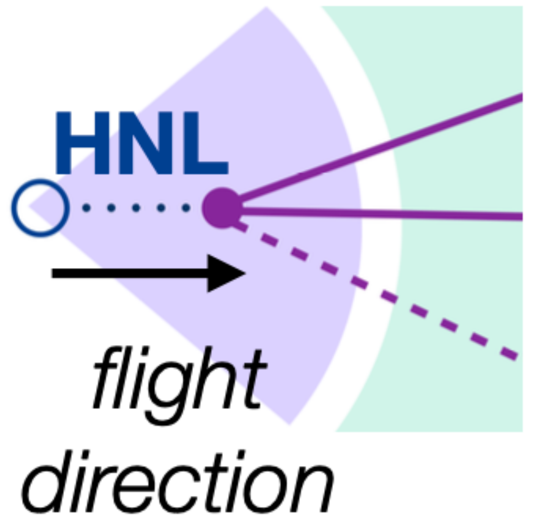


- Data-driven object shuffling method is used to estimate the background from random lepton crossings
- Dedicated selections to remove non-random backgrounds
  - ➡ e.g. invariant mass of the displaced vertex to reject heavy-flavour decays

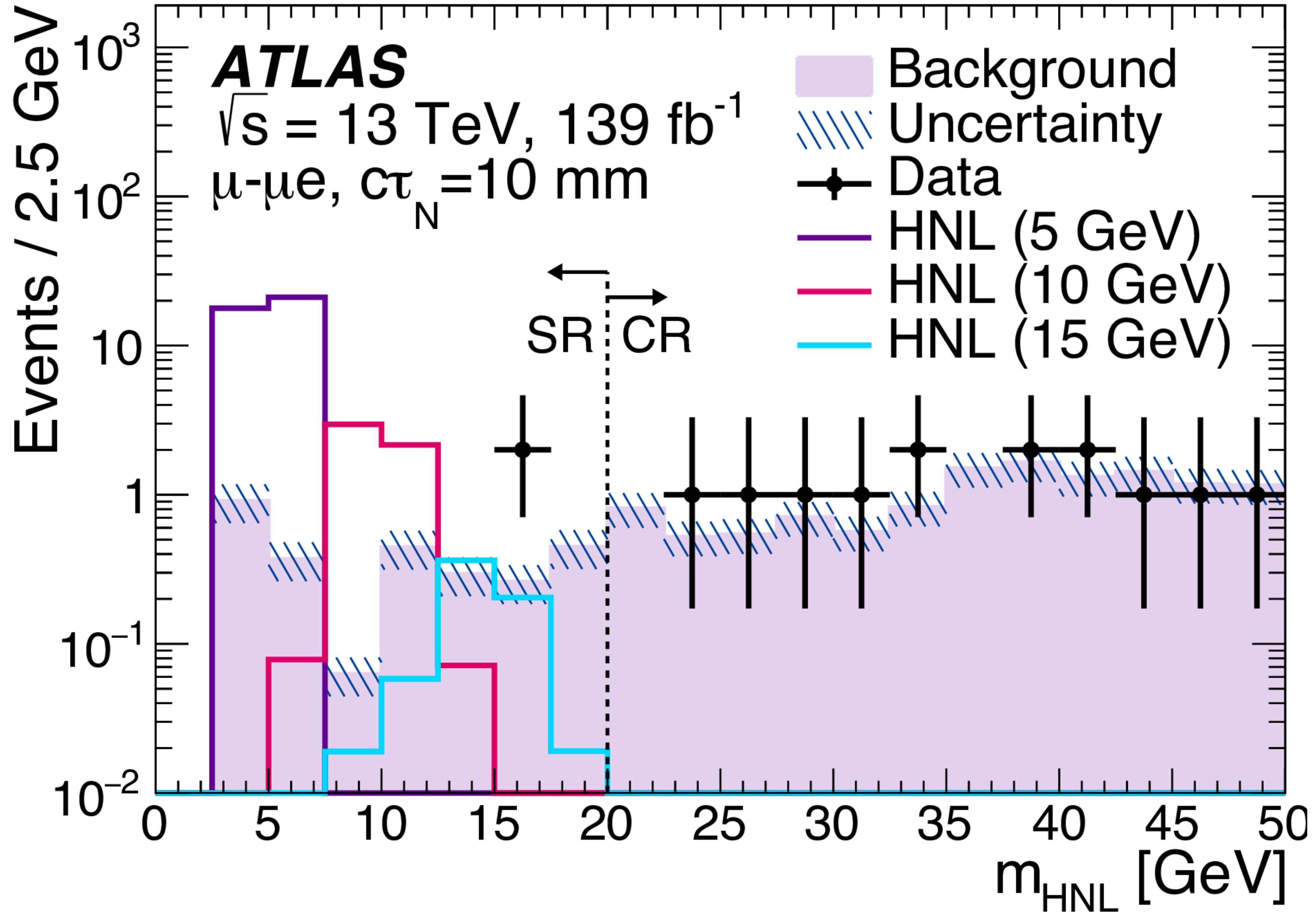
Figures from D. Trischuk

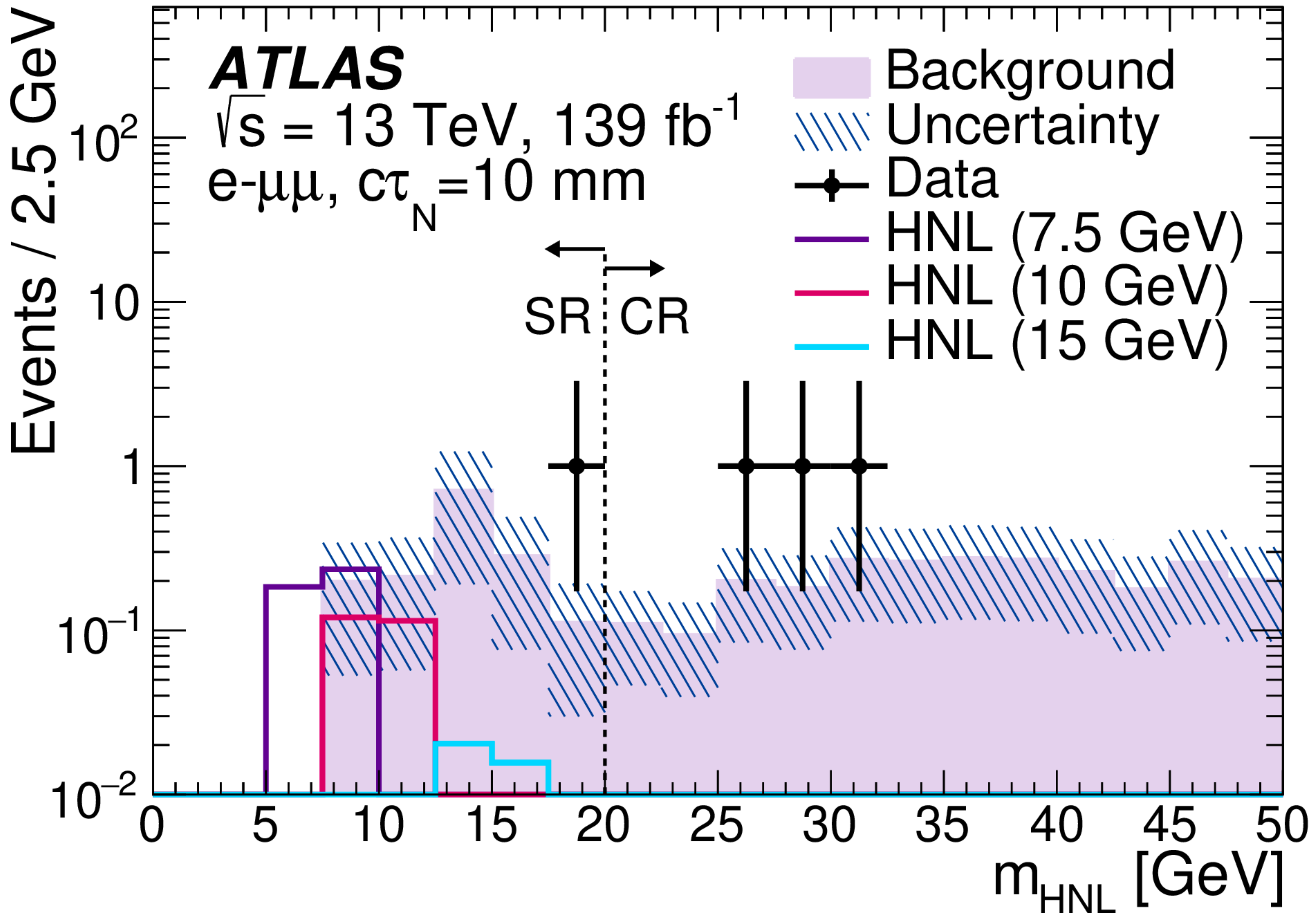
ATLAS Results: dHNL

- Energy-momentum conservation is used to reconstruct the HNL mass: $m_{HNL}^2 = (P_{l\beta} + P_{l\gamma} + P_{\nu\gamma})^2$



arXiv:2204.11988

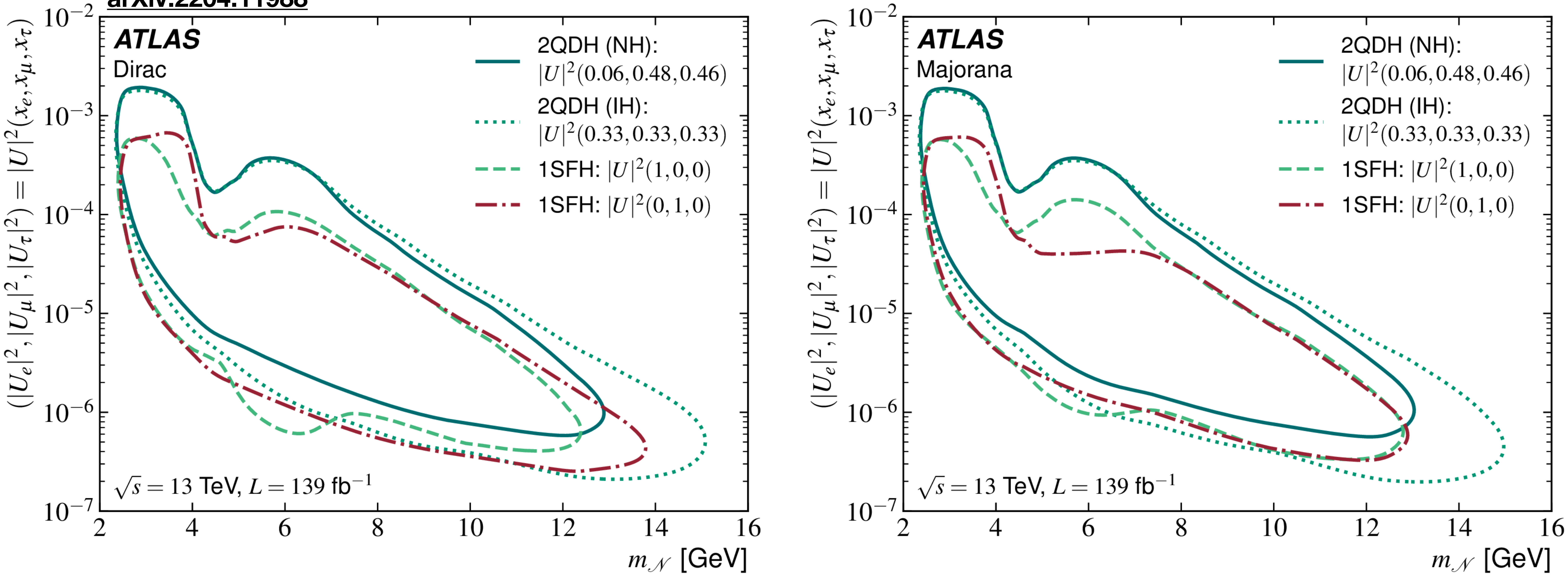




ATLAS Results: dHNL

- No excess observed ☹️

arXiv:2204.11988



Mixing:

Multi-flavour

Electron-only

Muon-only

Observed limits in the 2QDH scenario with inverted (IH) and normal (NH) mass hierarchy, and in 1SFH scenarios where the HNL mixes with only ν_μ or ν_e

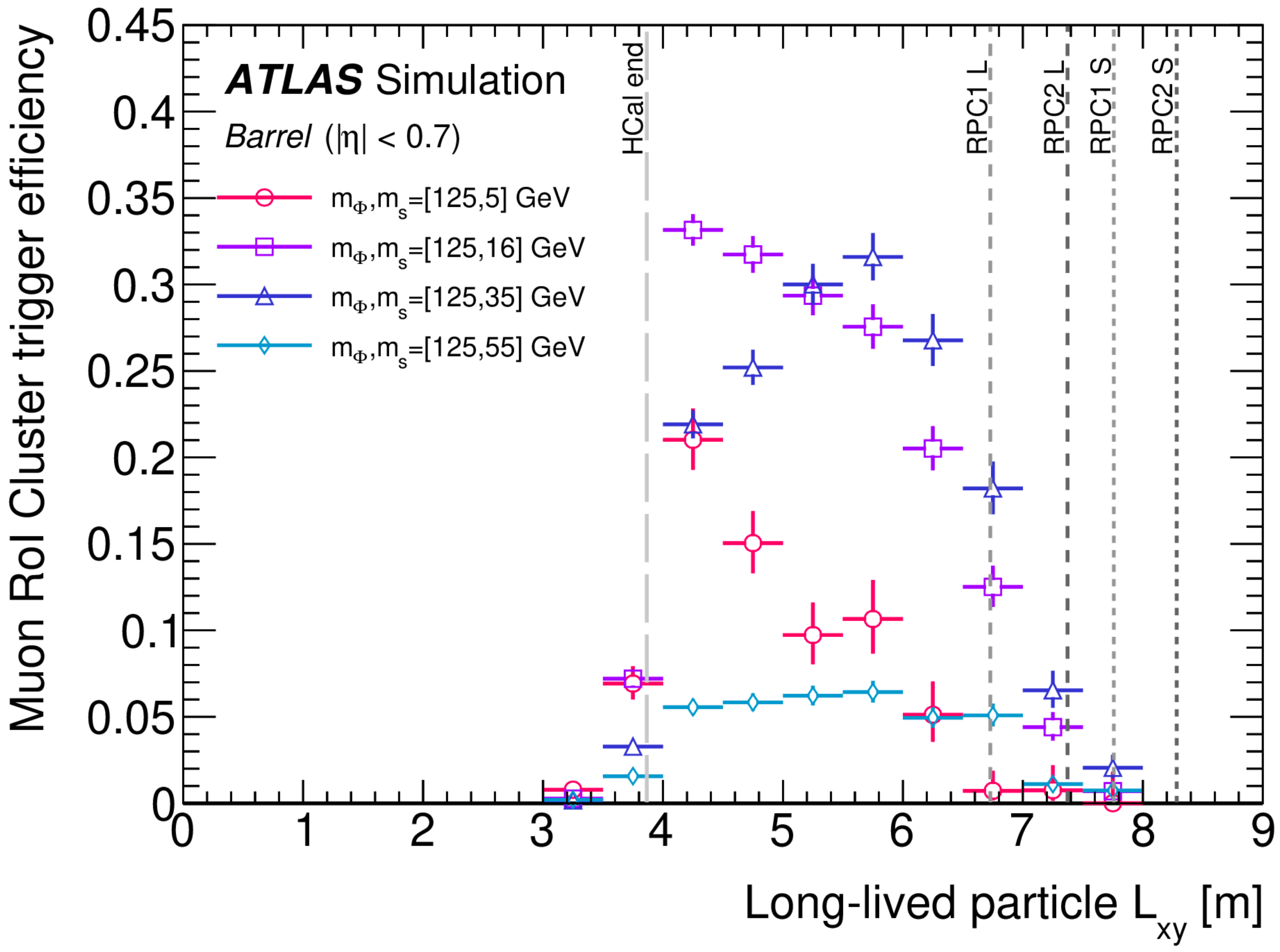
ATLAS Results: Cal Ratio

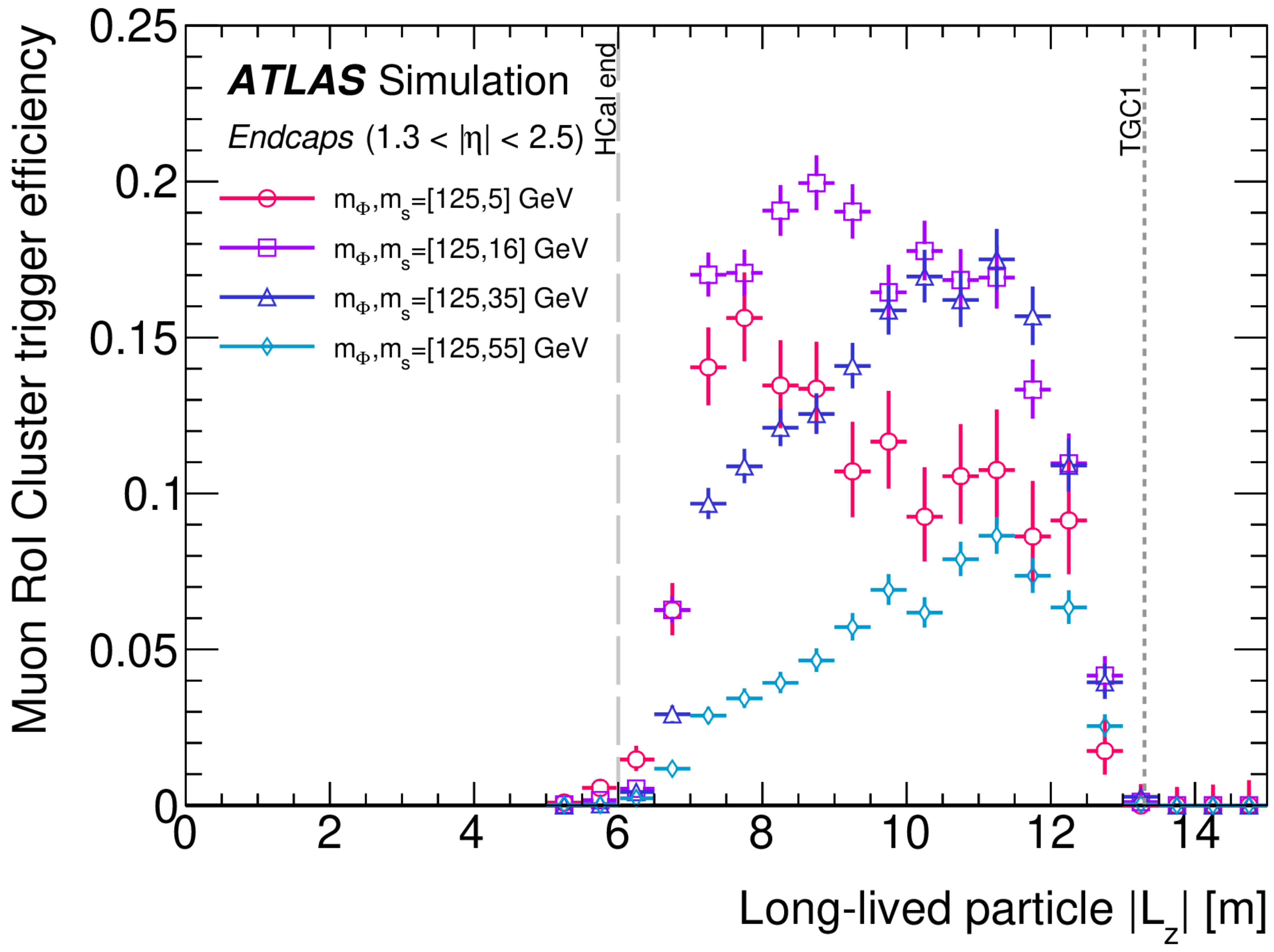
High-E_T selection	A	B	C	D
Observed data	22	7	233	131
a priori				
Estimated background	12.4 ± 4.7	7 ± 2.6	233 ± 15	131 ± 11
a posteriori (background-only fit)				
Fitted background	18.8 ± 3.5	10.2 ± 3.2	236 ± 15	128 ± 11
a posteriori (signal-plus-background fit)				
Fitted background	10.0 ± 6.0	5.7 ± 2.4	230 ± 15	131 ± 11
Fitted signal $((m_\Phi, m_s) = (600, 150)GeV))$	12.2 ± 8.7	1.4 ± 1.0	3.4 ± 2.5	< 1

Low-E_T selection	A	B	C	D
Observed data	23	3	220	61
a priori				
Estimated background	10.8 ± 6.6	3 ± 1.7	220 ± 15	61 ± 7.8
a posteriori (background-only fit)				
Fitted background	20.6 ± 4.0	5.4 ± 2.3	222 ± 15	59 ± 7.7
a posteriori (signal-plus-background fit)				
Fitted background	8.4 ± 7.7	2.4 ± 1.5	217 ± 15	61 ± 7.8
Fitted signal $((m_\Phi, m_s) = (125, 55)GeV))$	14.6 ± 9.9	< 1	3.2 ± 2.2	< 1

ATLAS 2MSVtx: Trigger Efficiencies

Phys. Rev. D 106, (2022) 032005





ATLAS 2MSVtx: Signal Efficiencies

Phys. Rev. D 106, (2022) 032005