Nikhef

Long-lived particle searches at the LHC and FPF

Flavia de Almeida Dias

Theory Meets Experiment 2023

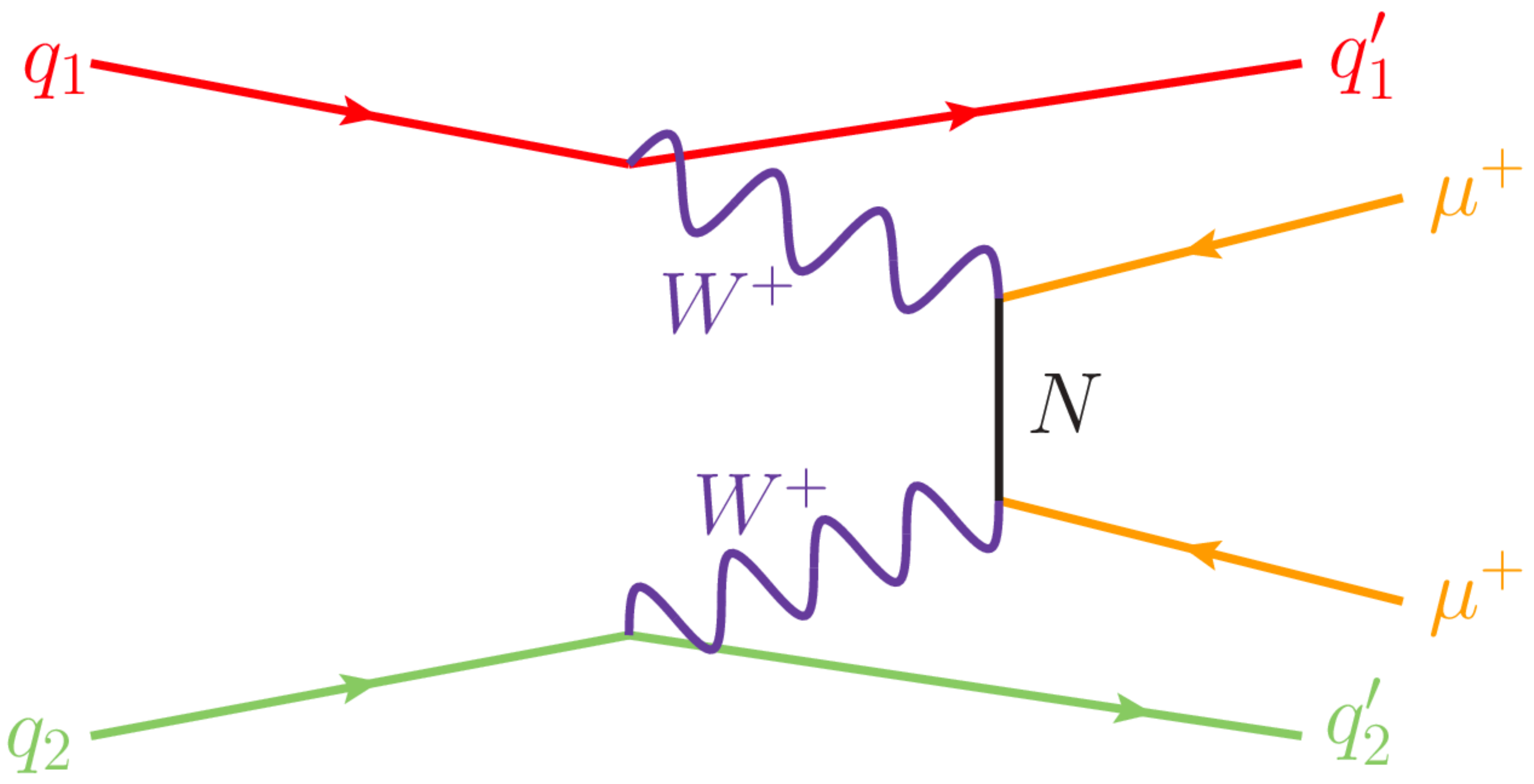
09 June 2023

University of Amsterdam
Institute of Physics

Interlude

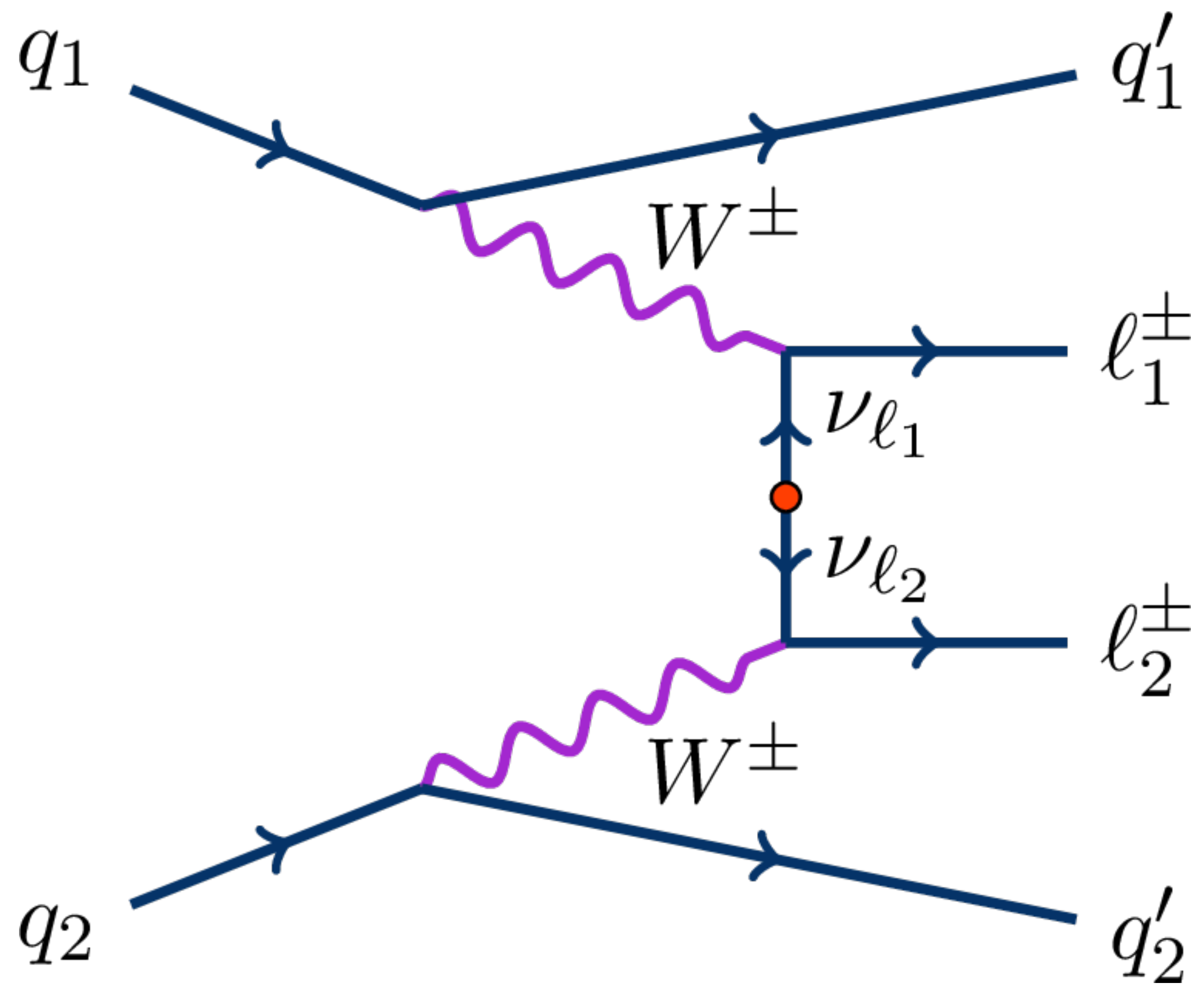
Neutrinoless Double Beta Decay at LHC

Same-sign μ±μ± production in W±W± scattering mediated by a Majorana neutrino N in proton-proton collisions



arXiv:2305.14931

Example Feynman diagram of processes mediated by the Weinberg operator at the LHC



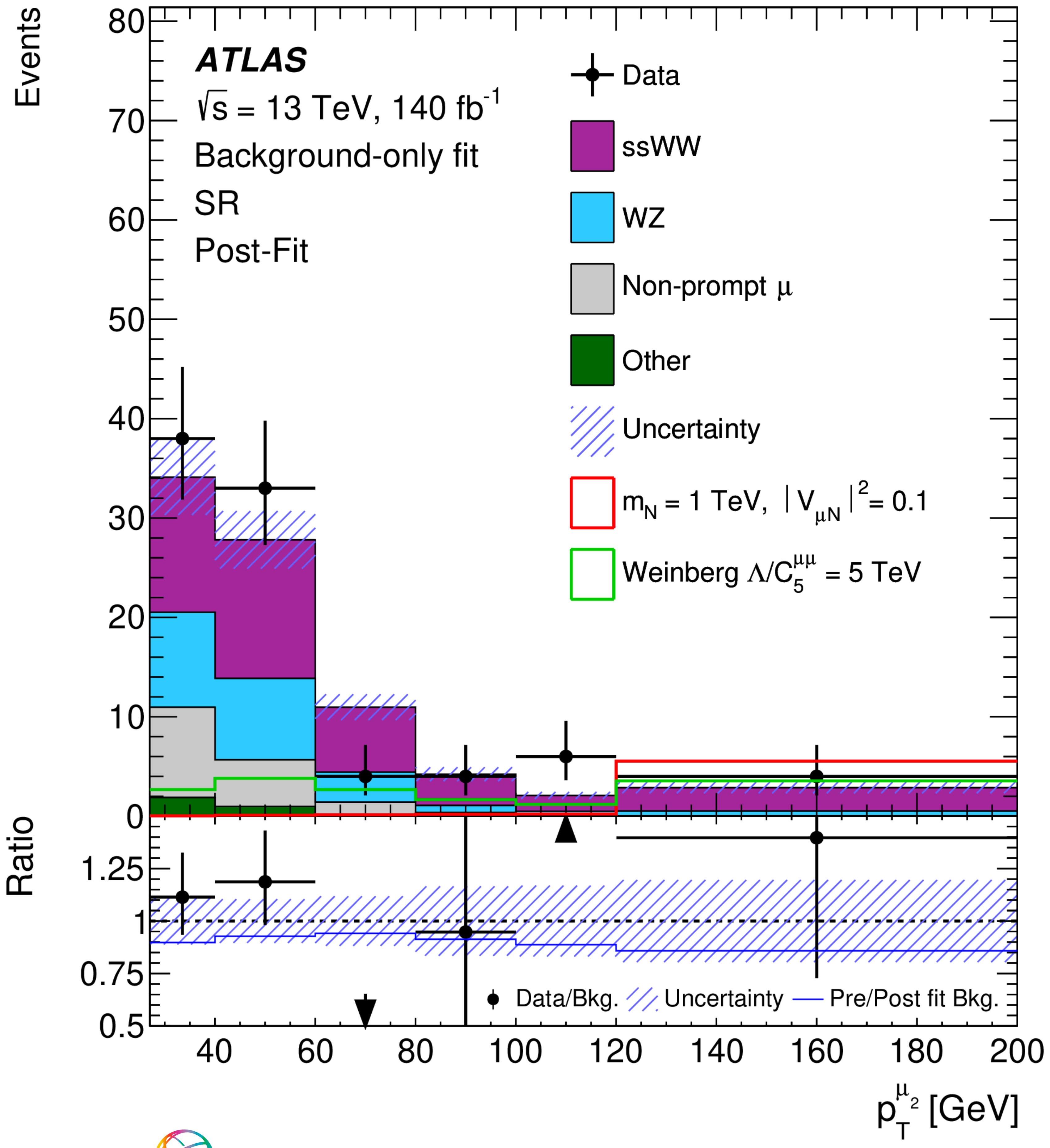
arXiv:2206.08956

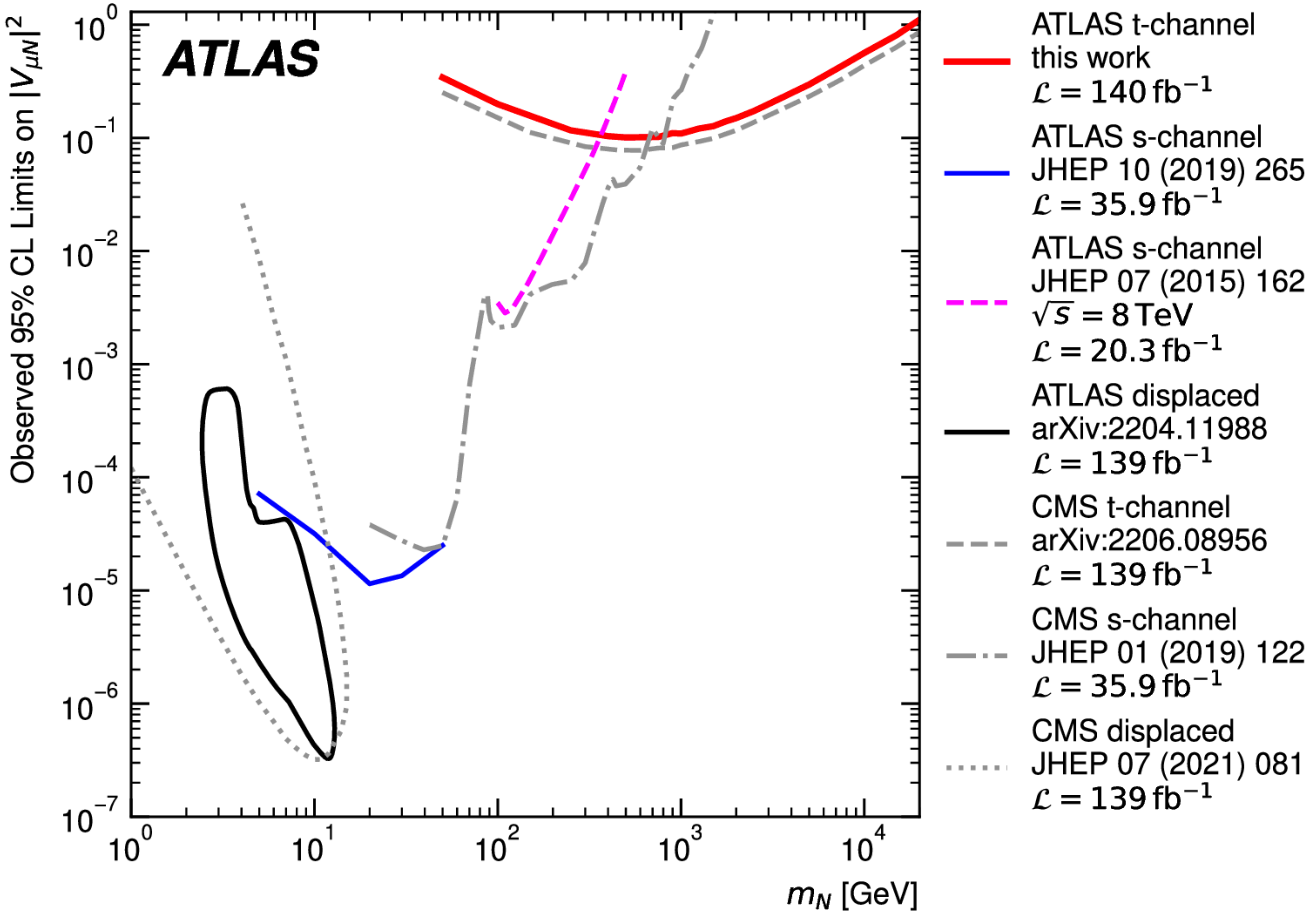
Neutrinoless Double Beta Decay at LHC

arXiv:2305.14931

Mengqing Wu

Nicolo de Groot



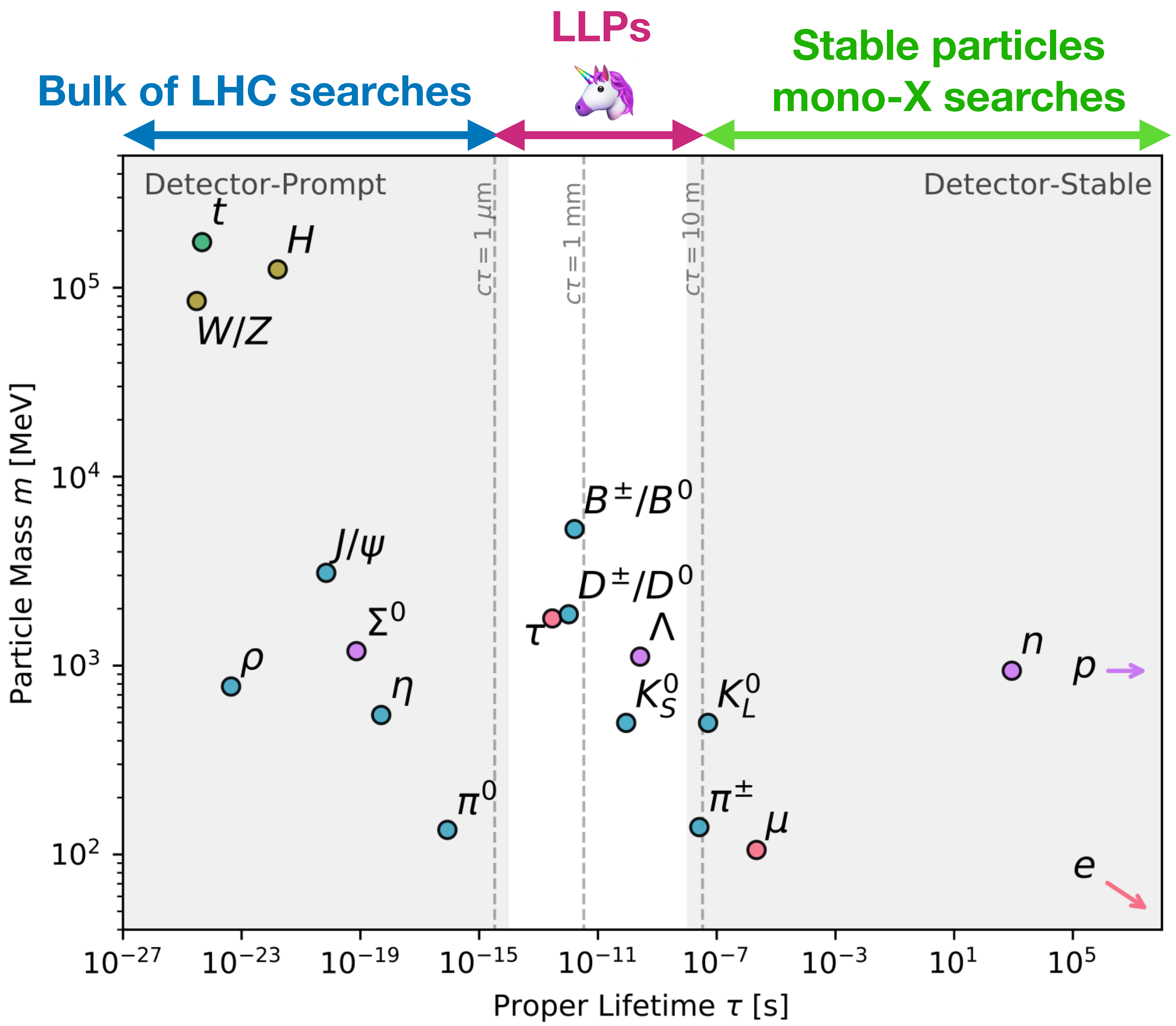


Long-Lived Particles:

Experimentalist perspective

Searching the "lifetime" dimension

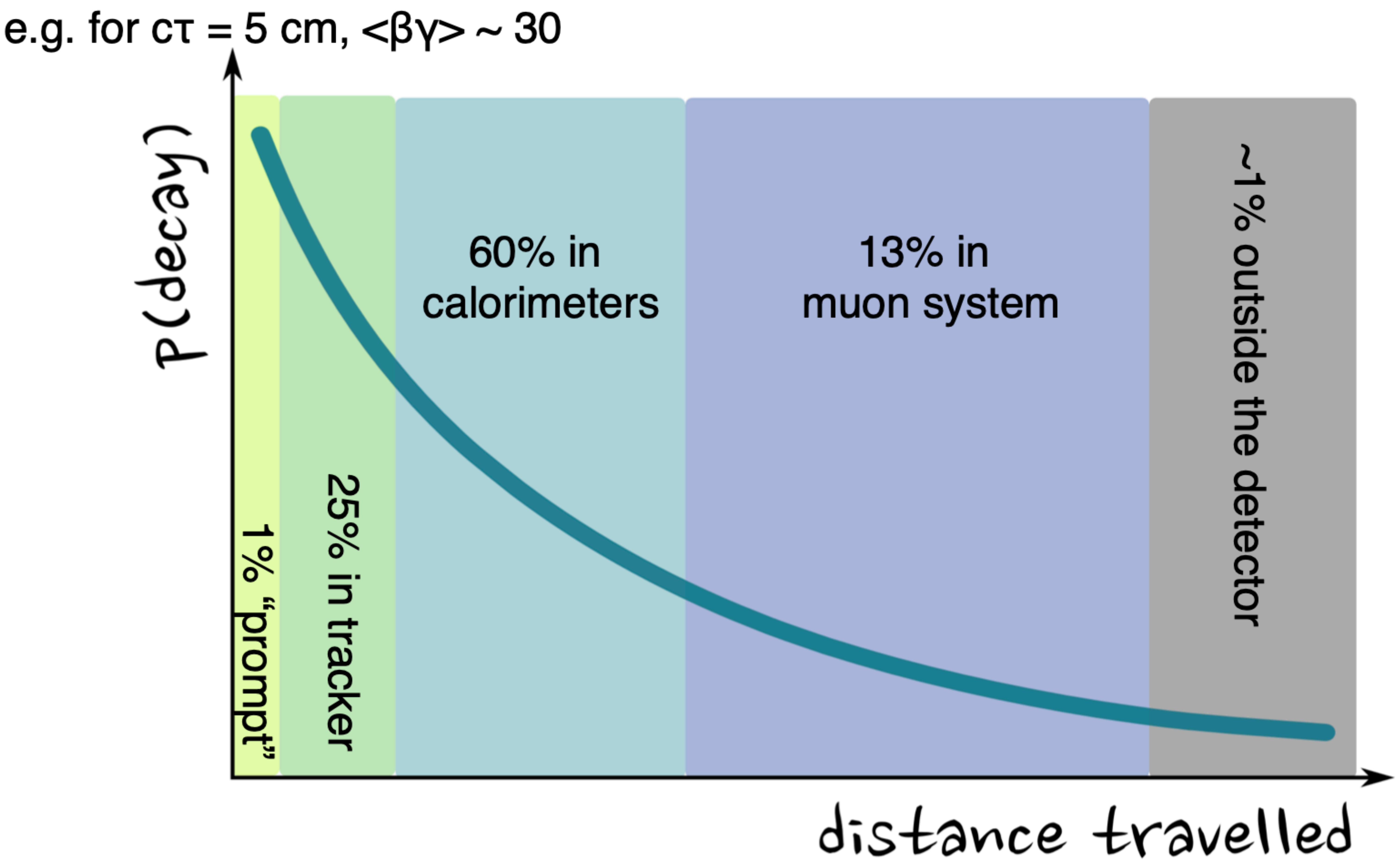
- Long-lived particles (LLPs): promising direction to expand searches @ LHC
  - ➡ Without dedicated searches, we could be missing new physics!
  - ➡ Impressive progress in recent years, but plenty of room for creativity!
  - ➡ Theoretically well motivated!
    - Ask the theorists in this room :)



From arXiv:1810.12602

Why do we need so many searches?

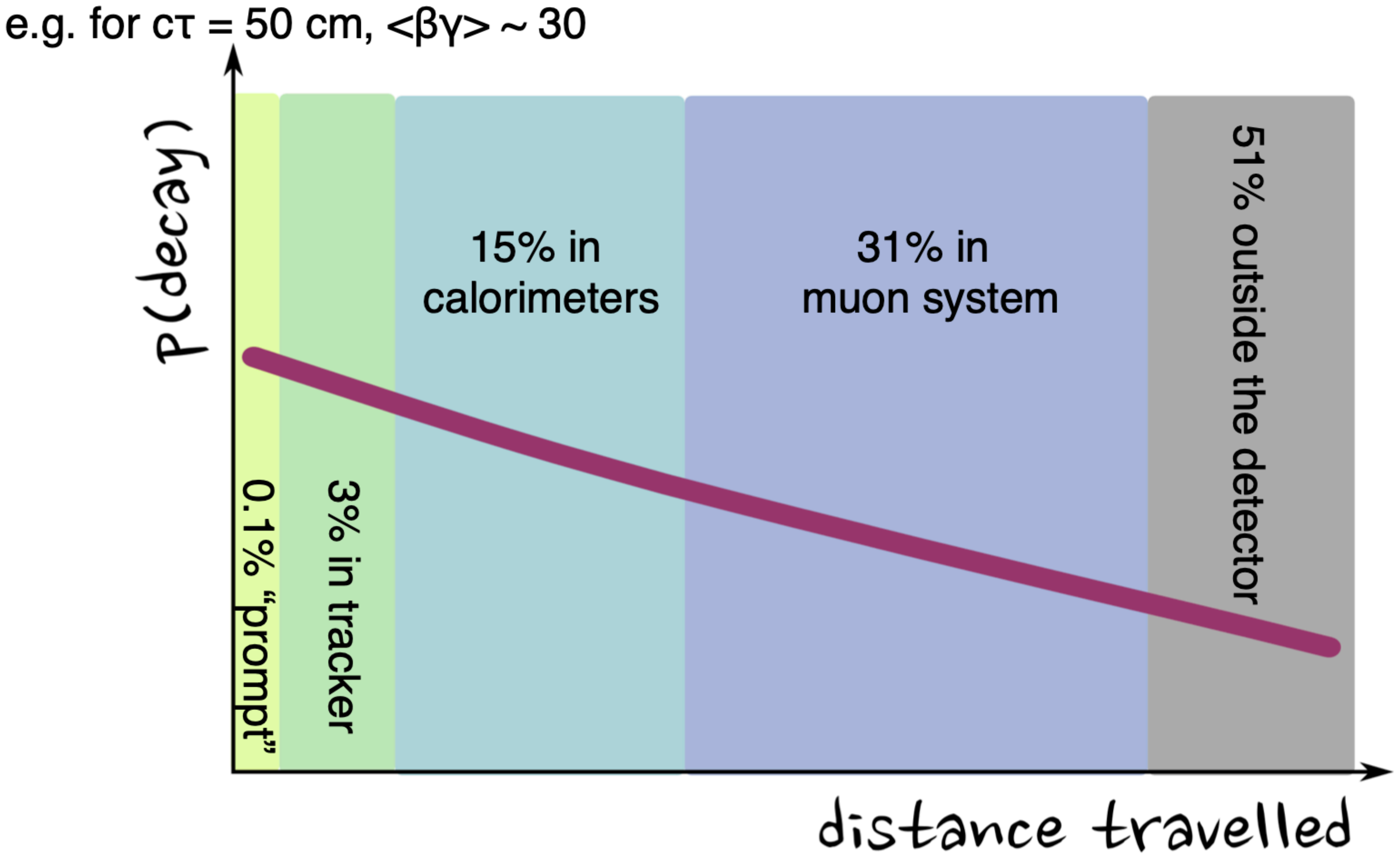
- Even particles with a short proper lifetime can decay with a large lab-frame distance:



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

Unconventional Signatures - ATLAS & CMS-Style

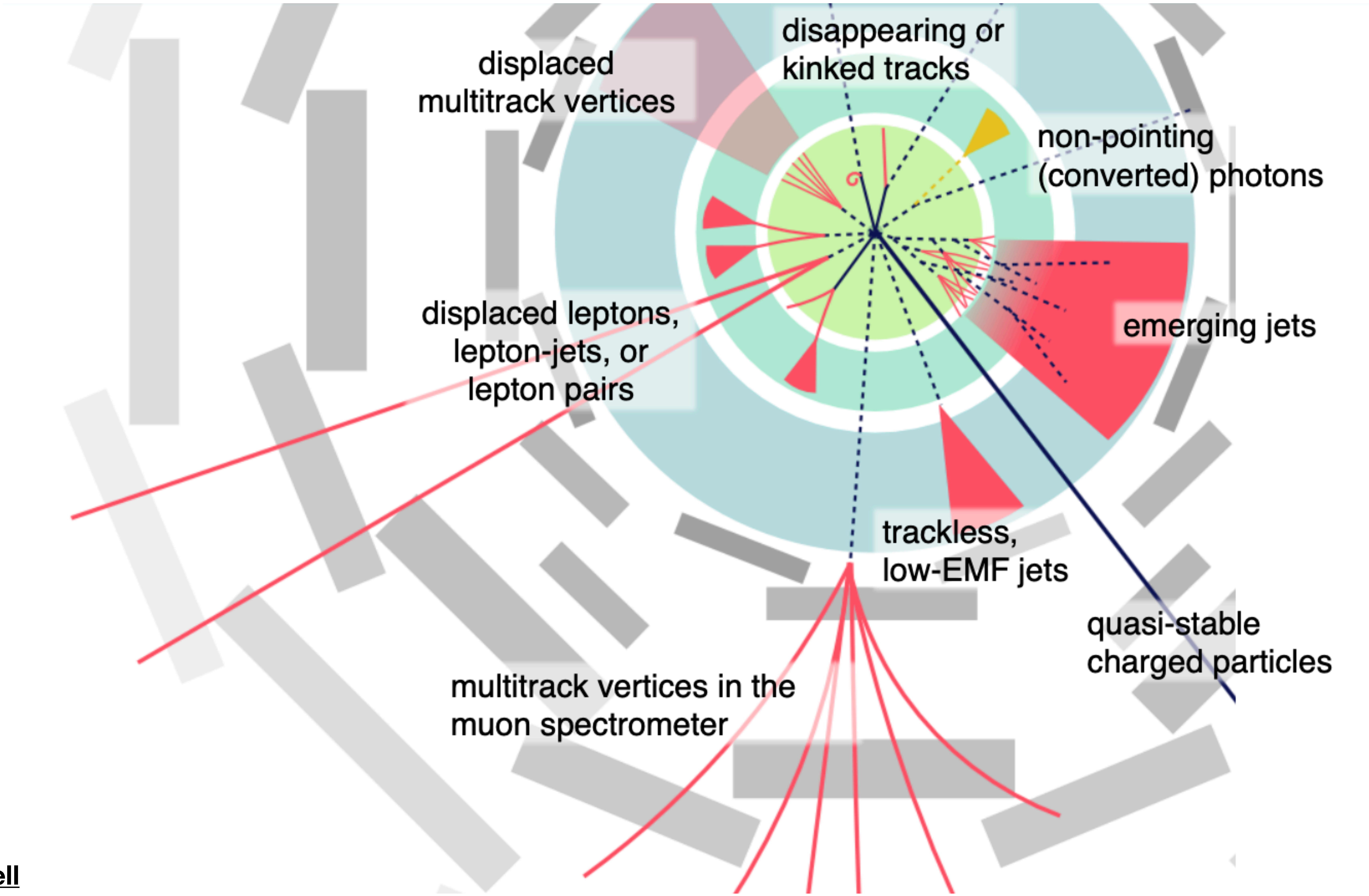


Figure from H. Russell

ATLAS Search for Displaced Heavy Neutral Leptons

arXiv:2204.11988, accepted by PRL

Search for Displaced Heavy Neutral Leptons

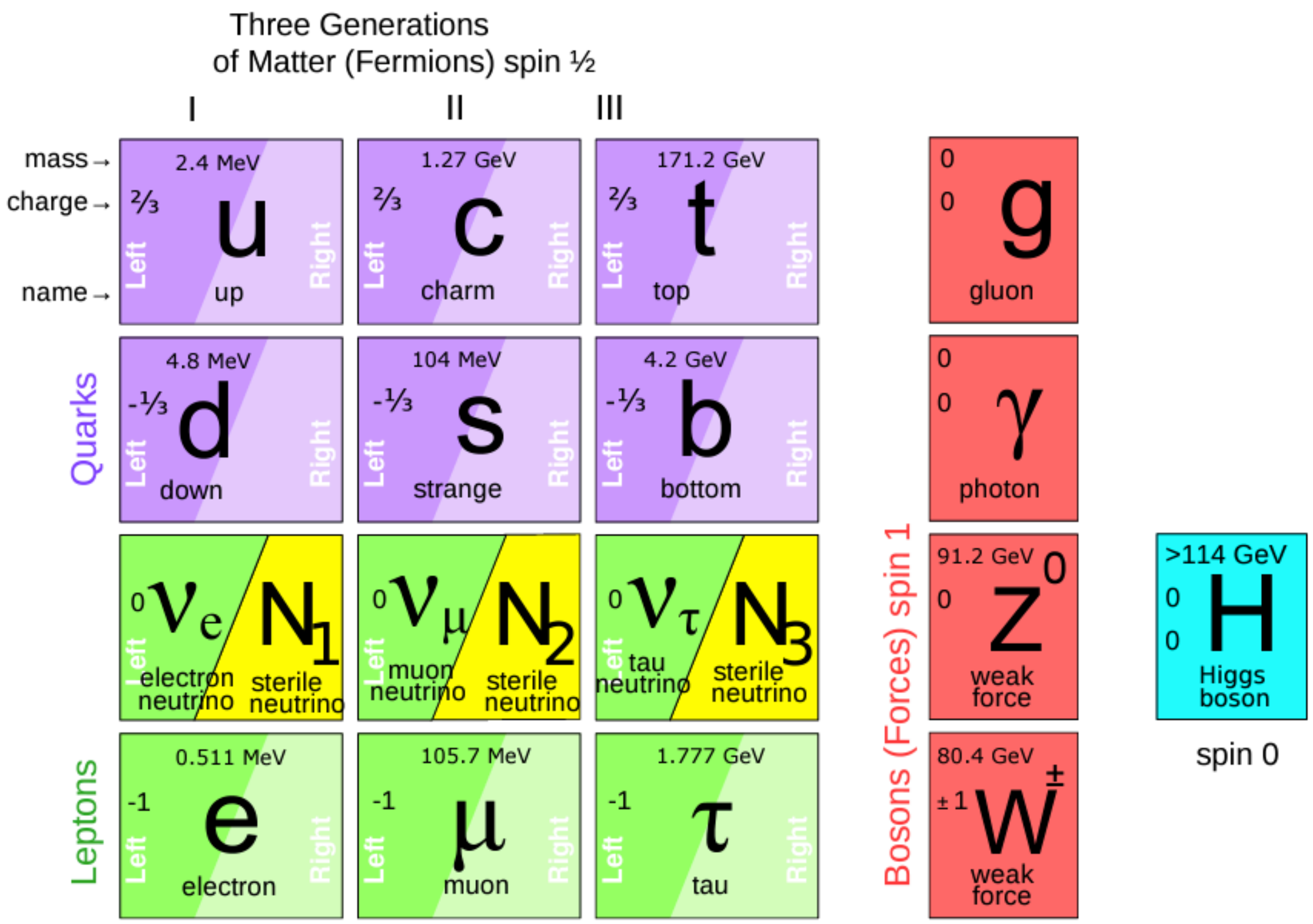
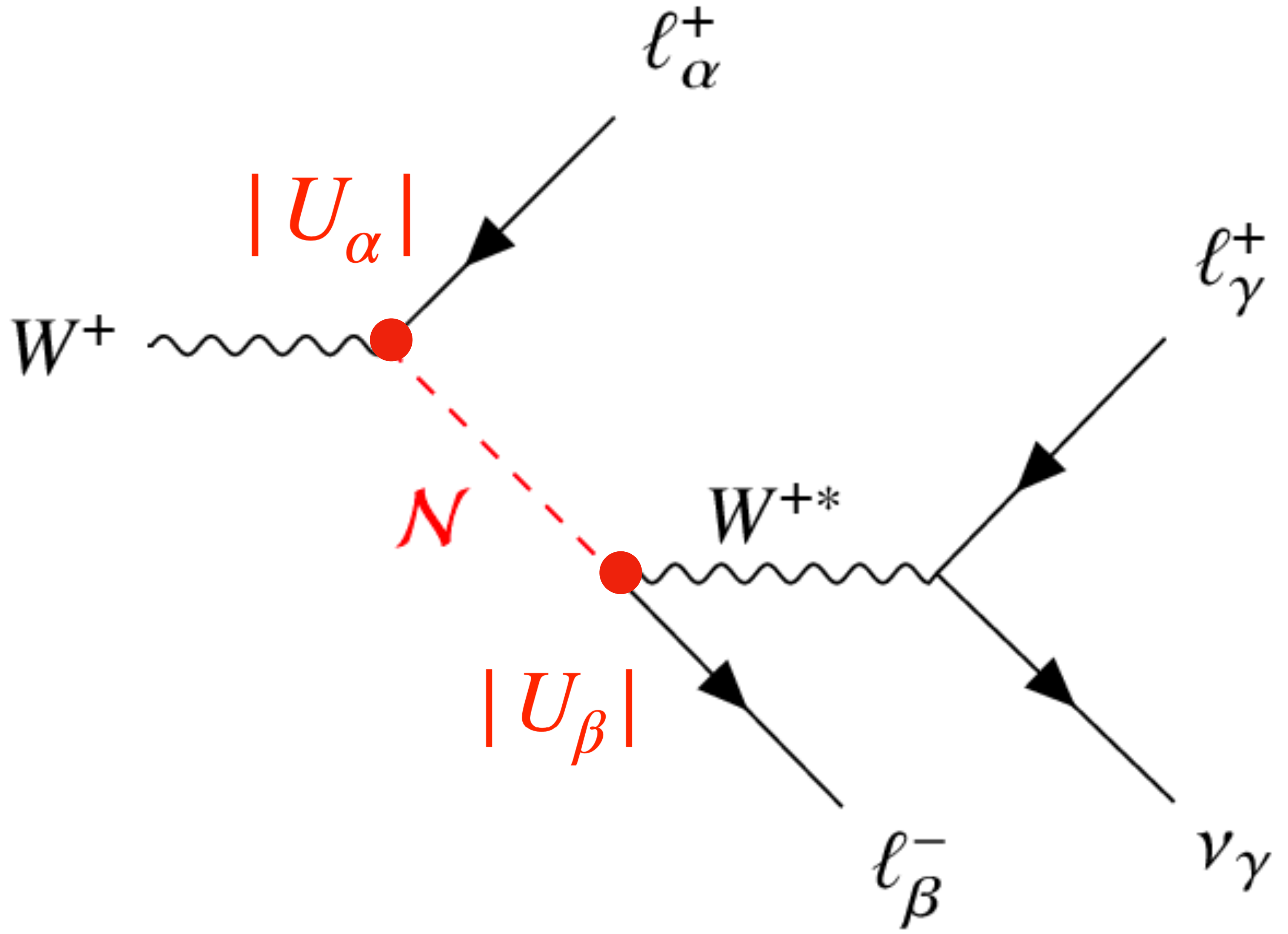


Figure from arXiv:1301.5516

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

Experimentally Relevant Observables



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

m_N $\Rightarrow$ **HNL mass**

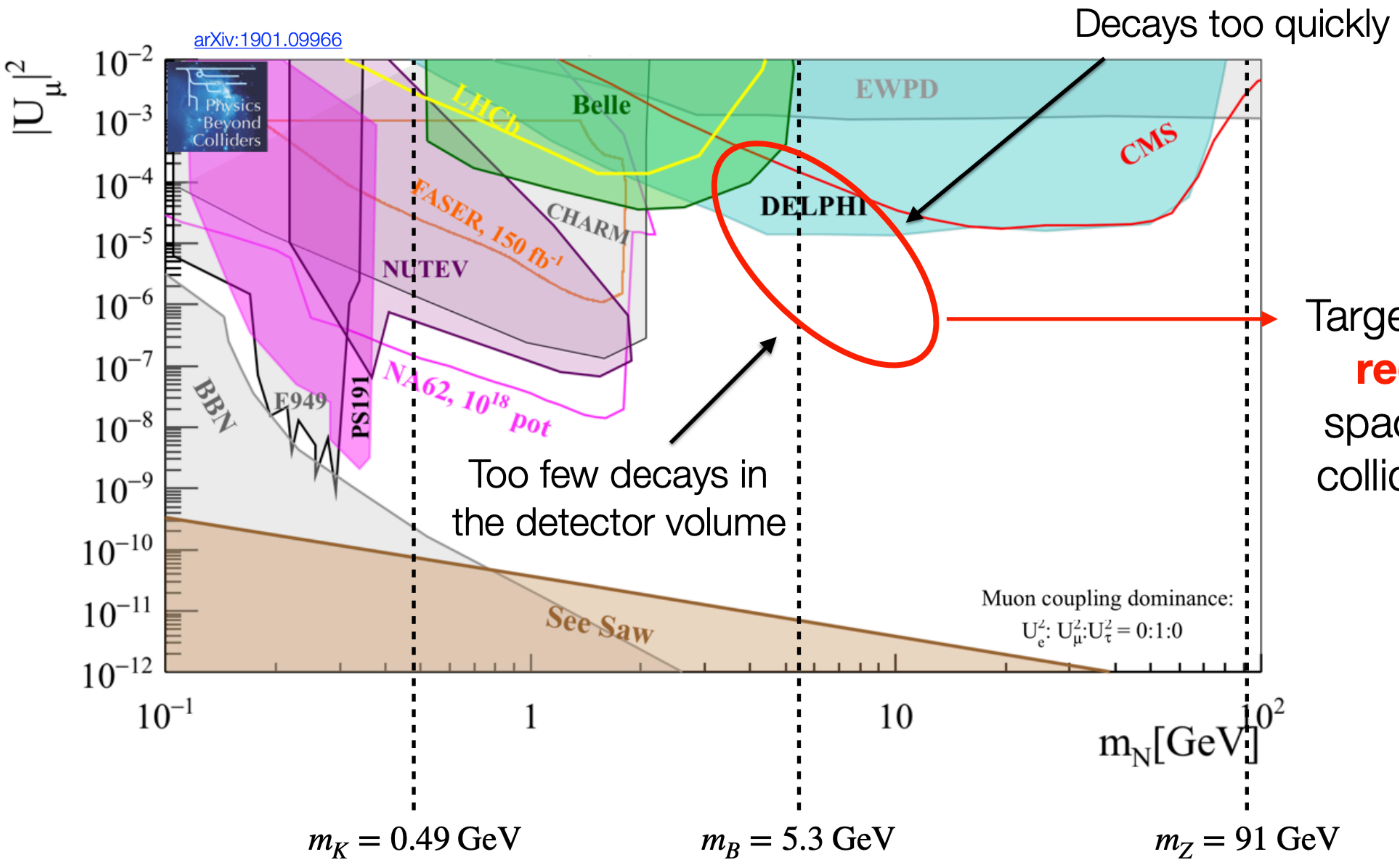
α, β, γ $\Rightarrow$ **lepton flavour index**

- 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 $\Rightarrow$ Lepton Number is conserved (LNC)
  - ➡ Majorana $\Rightarrow$ Lepton Number is violated (LNV)

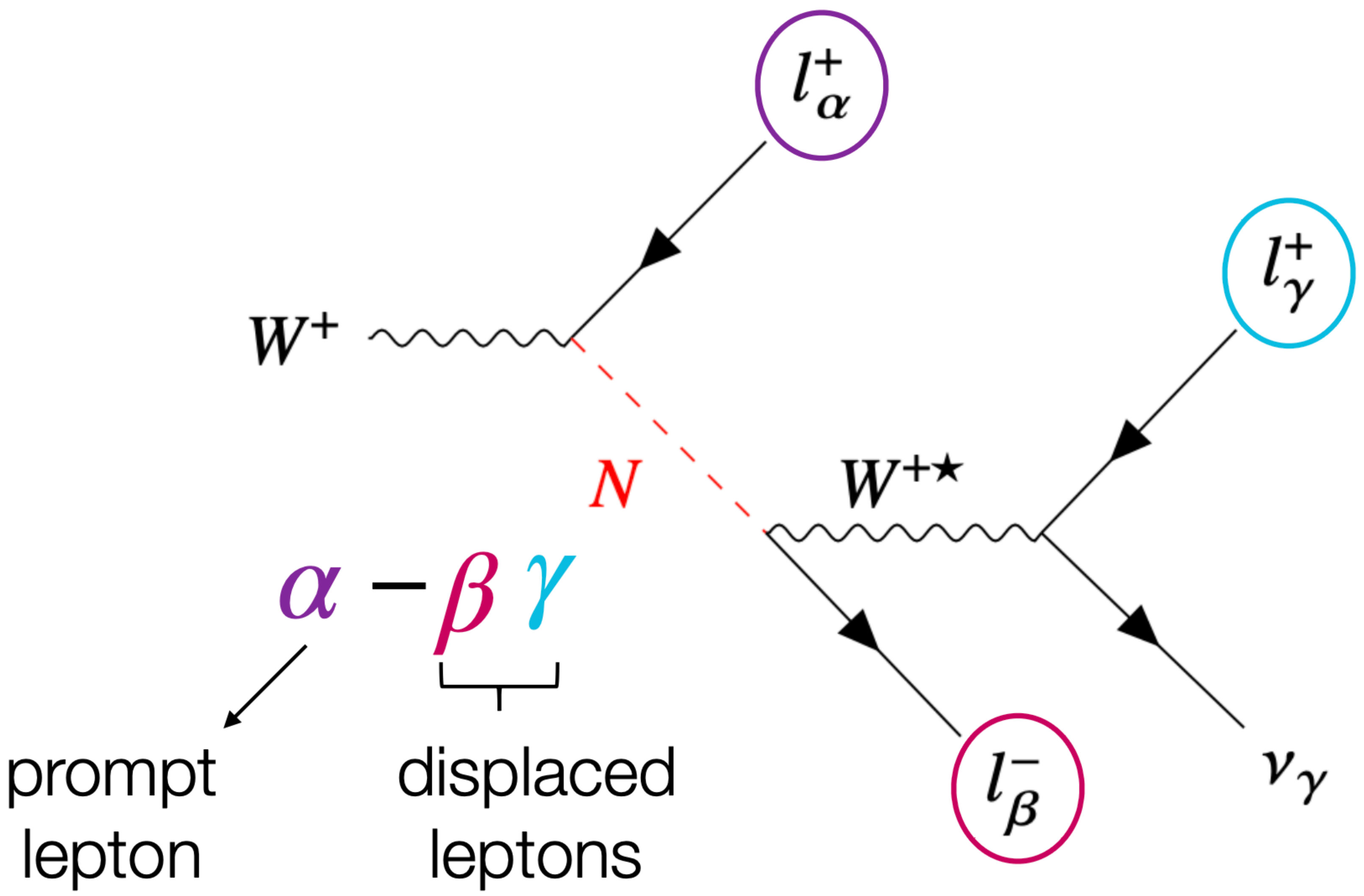
Experimental Picture



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

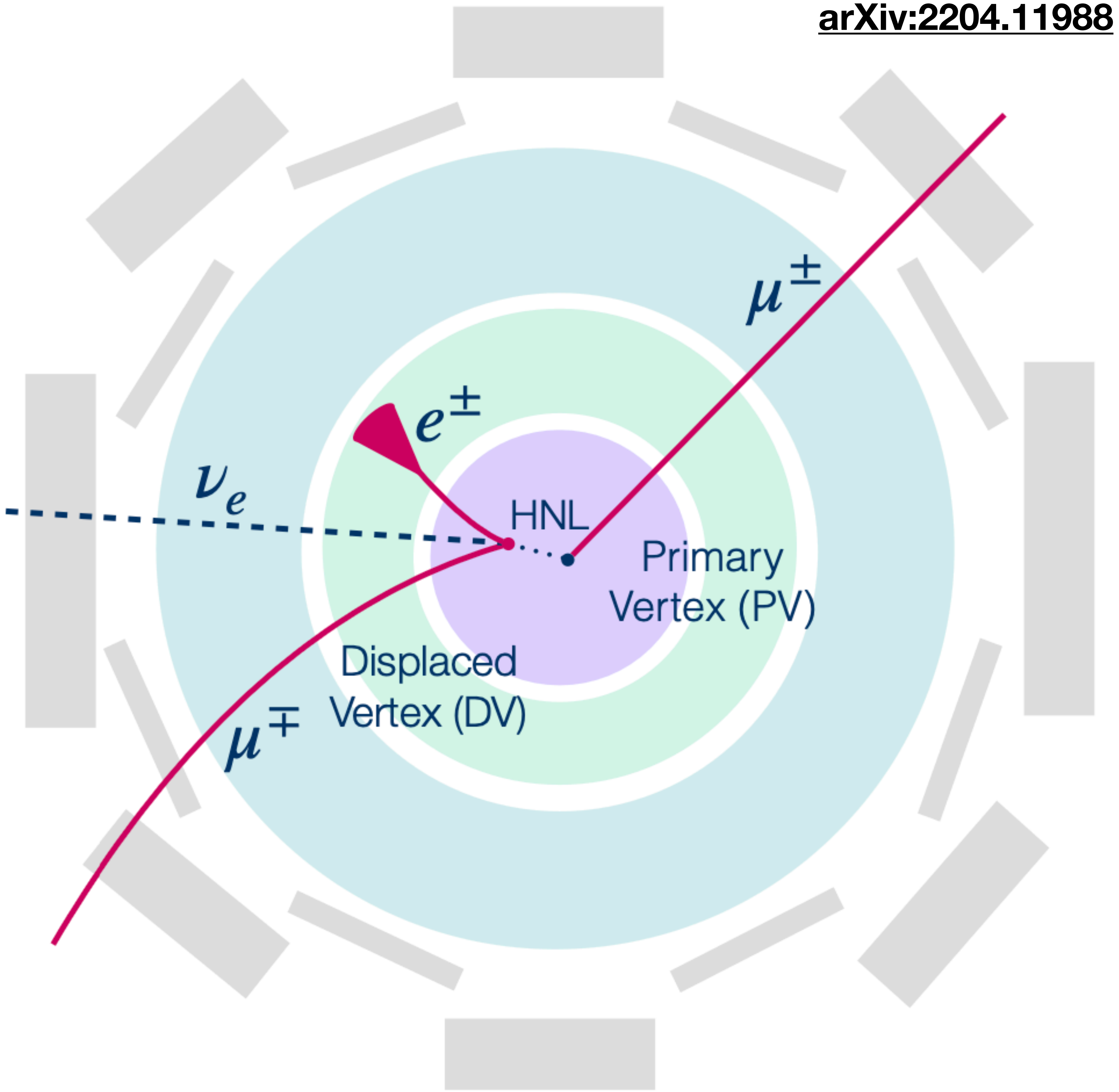
Displaced Heavy Neutral Leptons

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



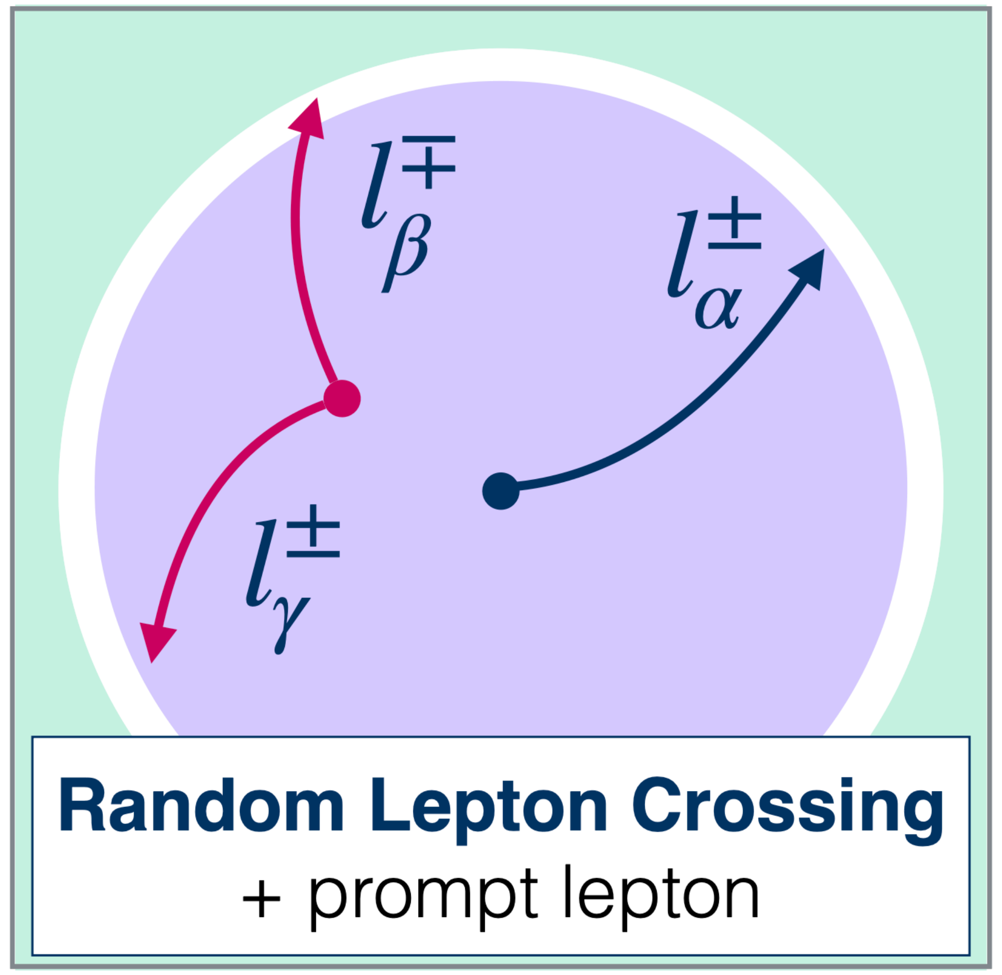
6 signal regions:
μ-μμ, μ-μe, μ-ee, e-ee, e-eμ, e-μμ

Figure from D. Trischuk
arXiv:2204.11988

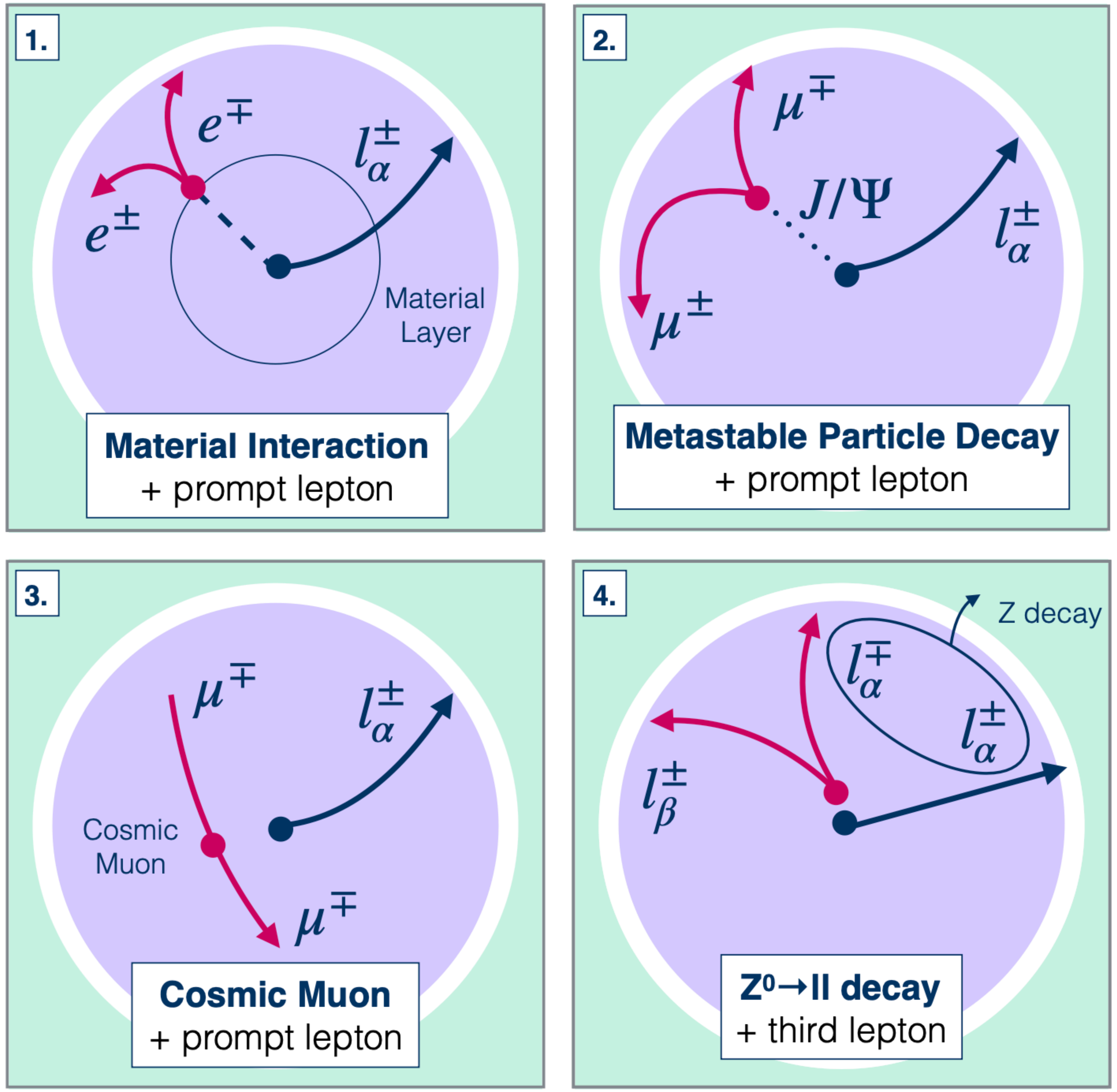


dHNLs: Backgrounds

Dominant background



Non-random backgrounds

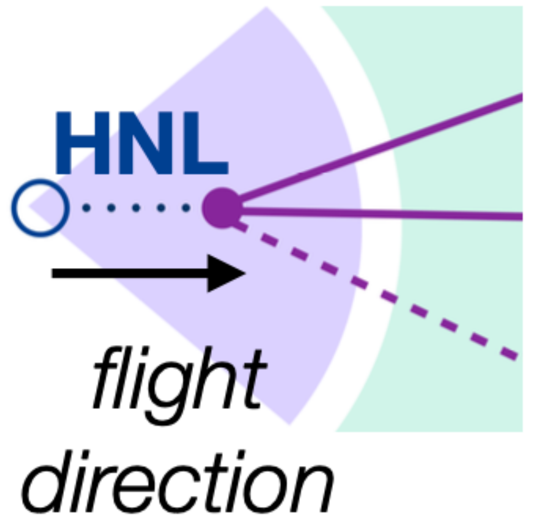


- Data-driven object shuffling method is used to estimate the background from random lepton crossings
- Dedicated selections to remove non-random backgrounds
  - ➡ e.g. invariant mass of the displaced vertex to reject heavy-flavour decays

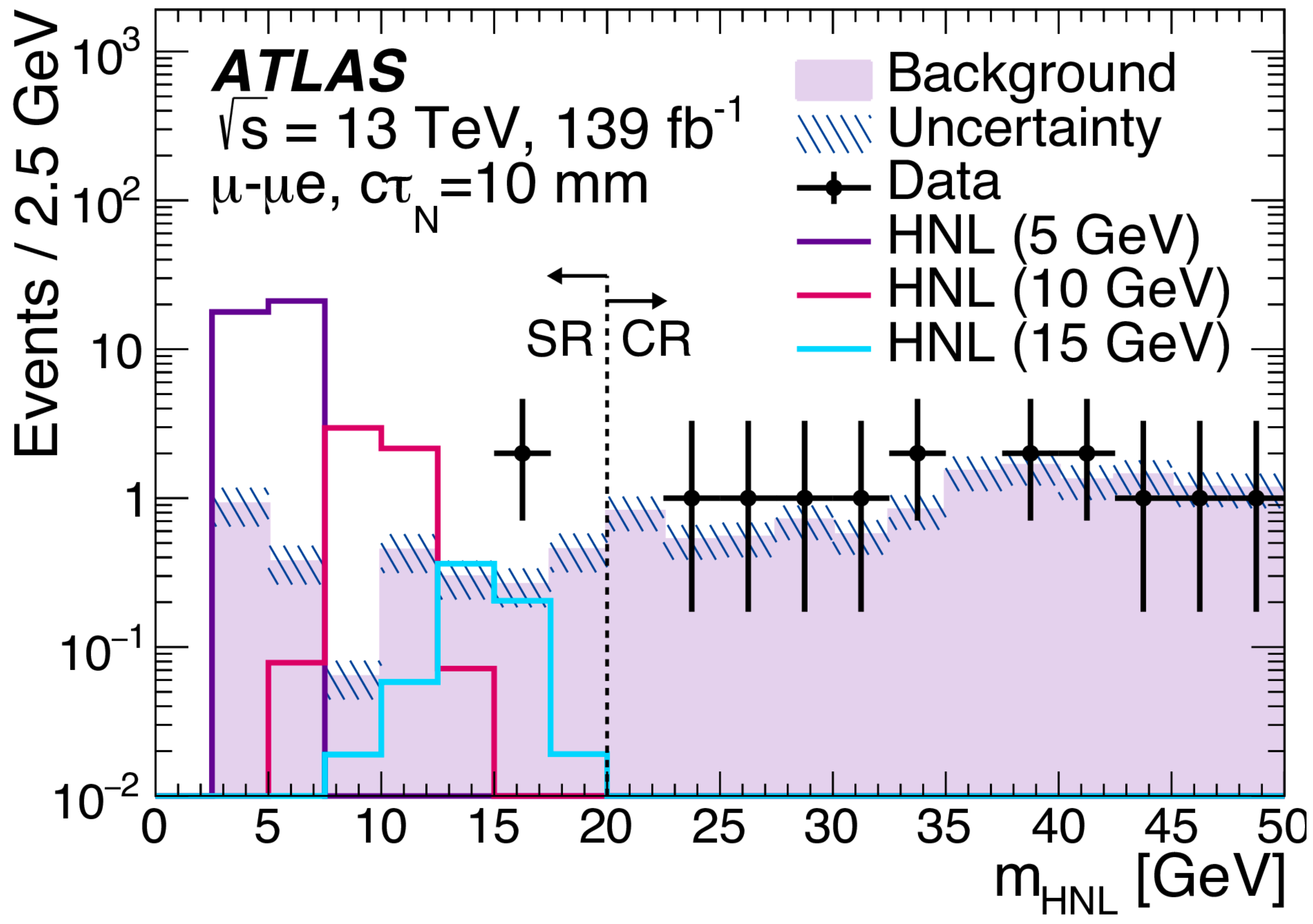
Figures from D. Trischuk

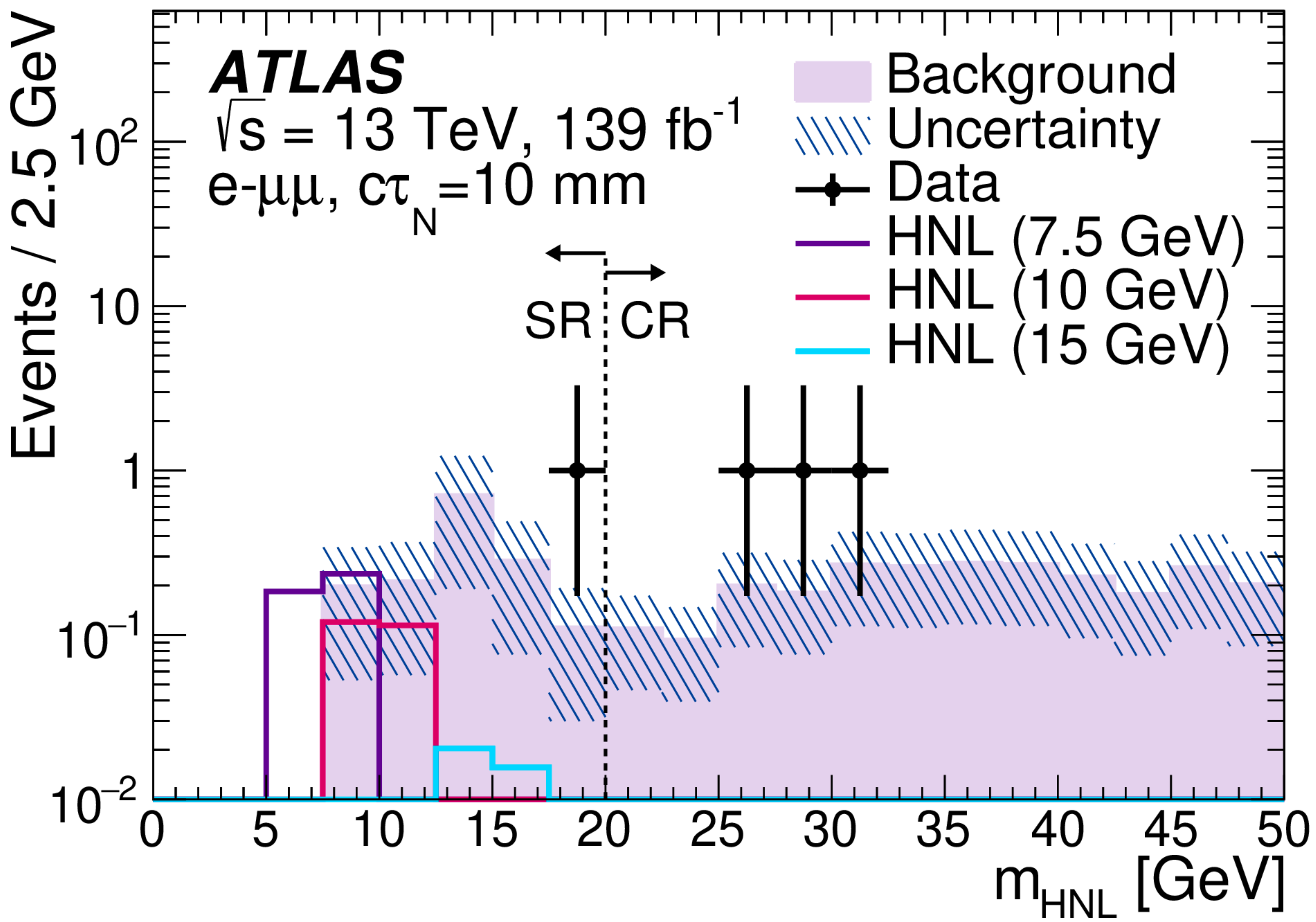
ATLAS Results: dHNL

- 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

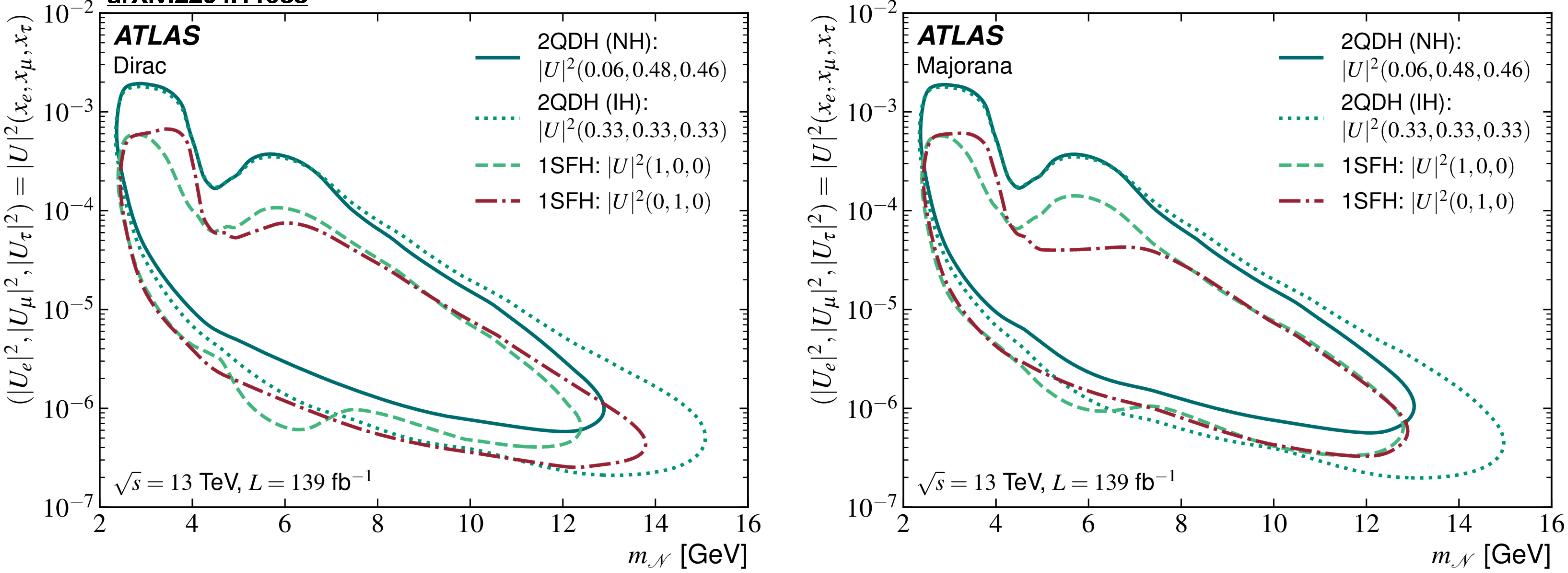




ATLAS Results: dHNL

- No excess observed ☹️

arXiv:2204.11988



Mixing:

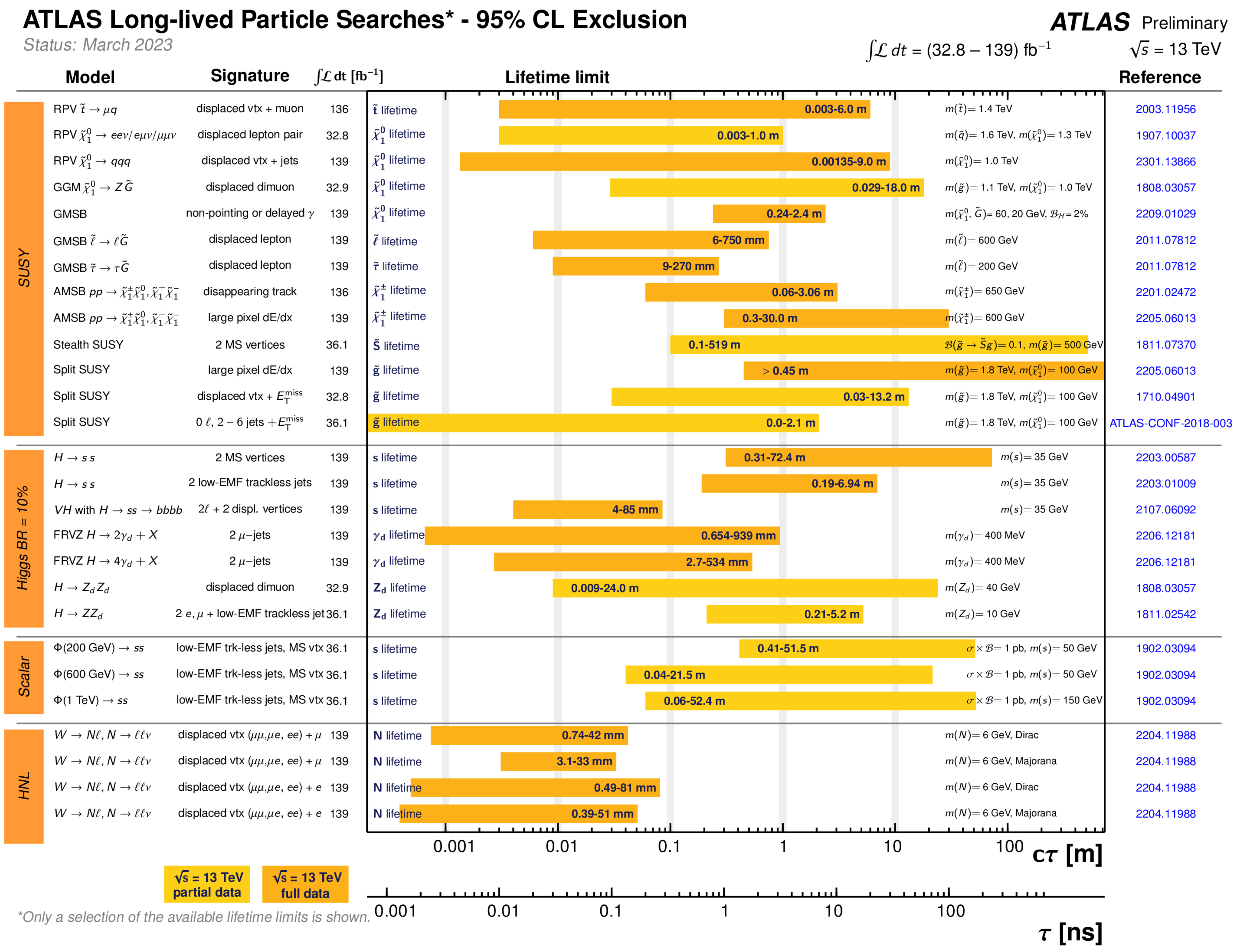
Multi-flavour

Electron-only

Muon-only

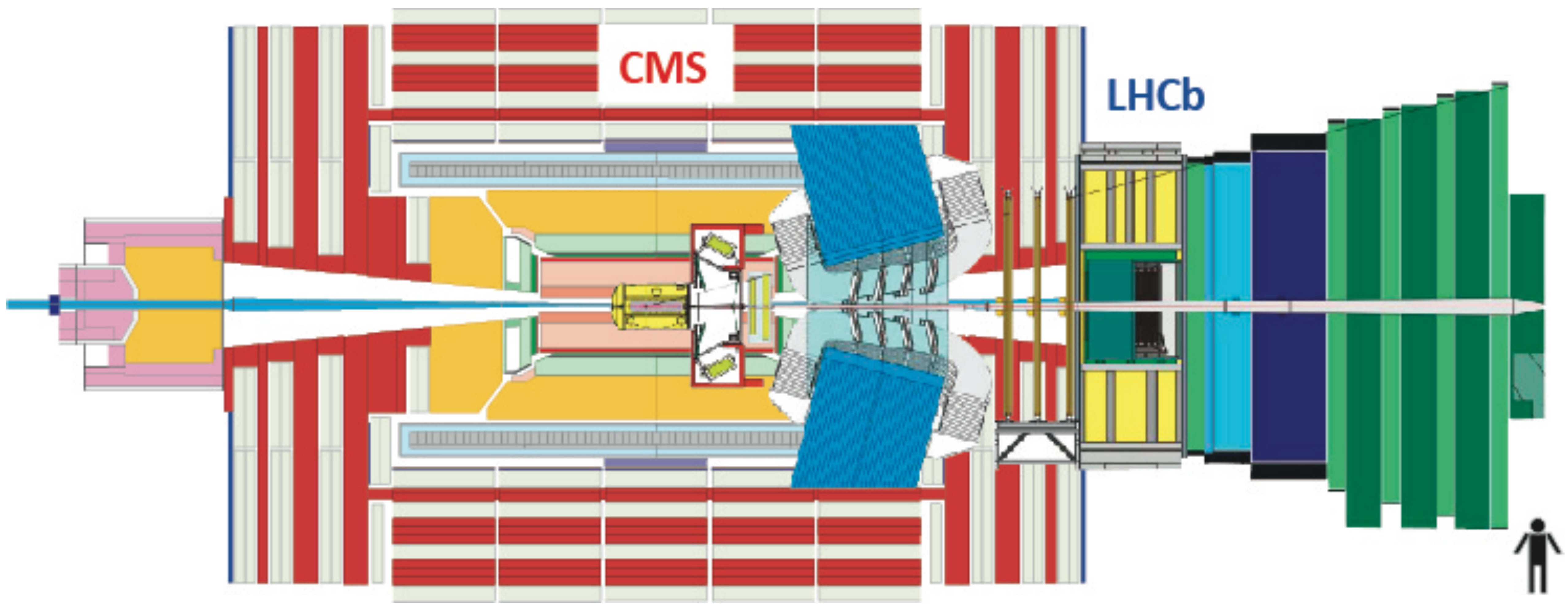
Observed limits in the 2QDH scenario with inverted (IH) and normal (NH) mass hierarchy, and in 1SFH scenarios where the HNL mixes with only ν_μ or ν_e

Long-Lived Particles at ATLAS - Summary



LLPs at LHCb

- Unique phase space region ($2 < \eta < 5$) complementary to ATLAS & CMS: low lifetime, low masses
  - ➡ Excellent track momentum resolution: 0.4% at 5 GeV to 0.6% at 100 GeV
  - ➡ Impact Parameter resolution 20 μm for high-p_T tracks, lifetime resolution of 0.2 ps



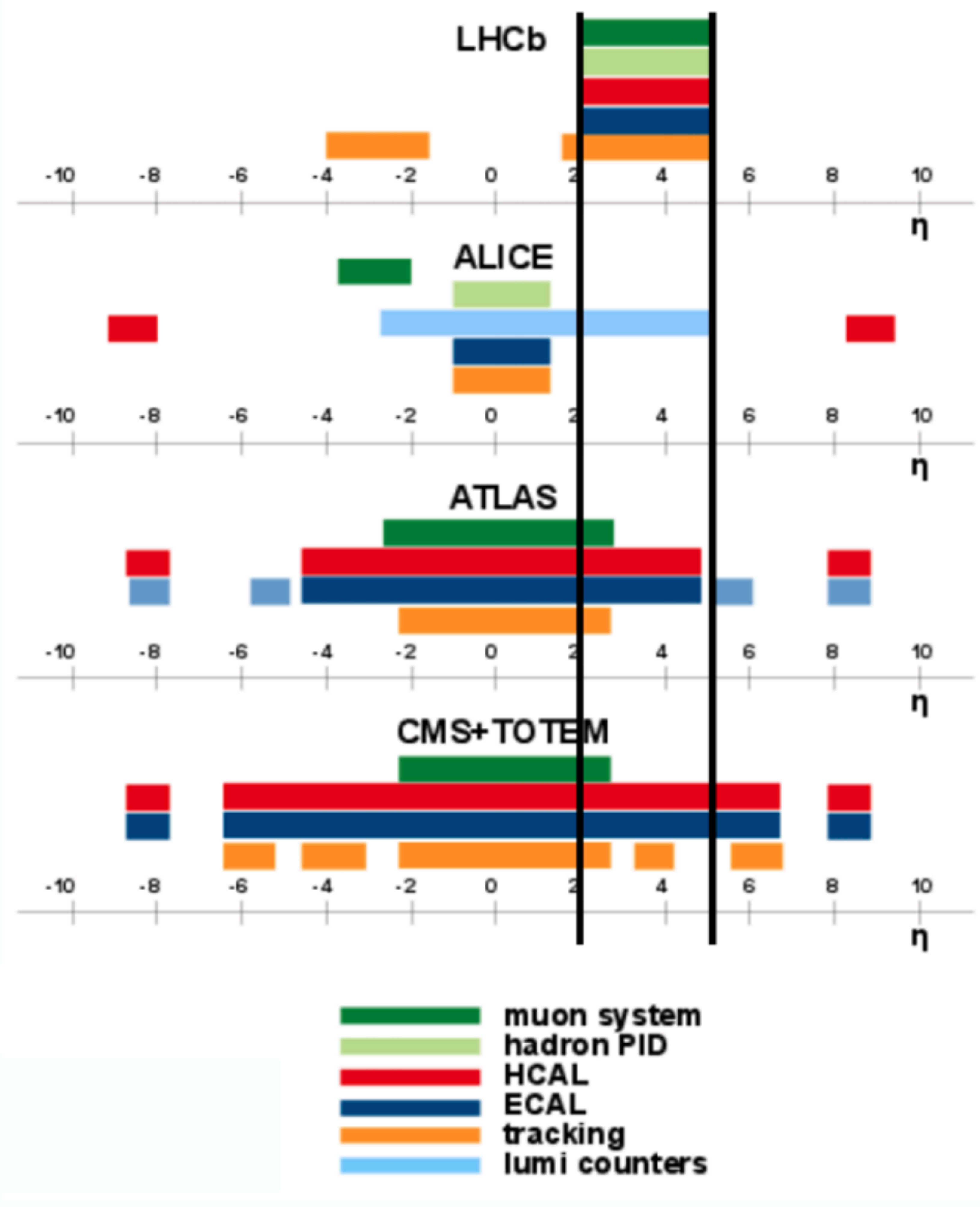


Image from D. Zuliani

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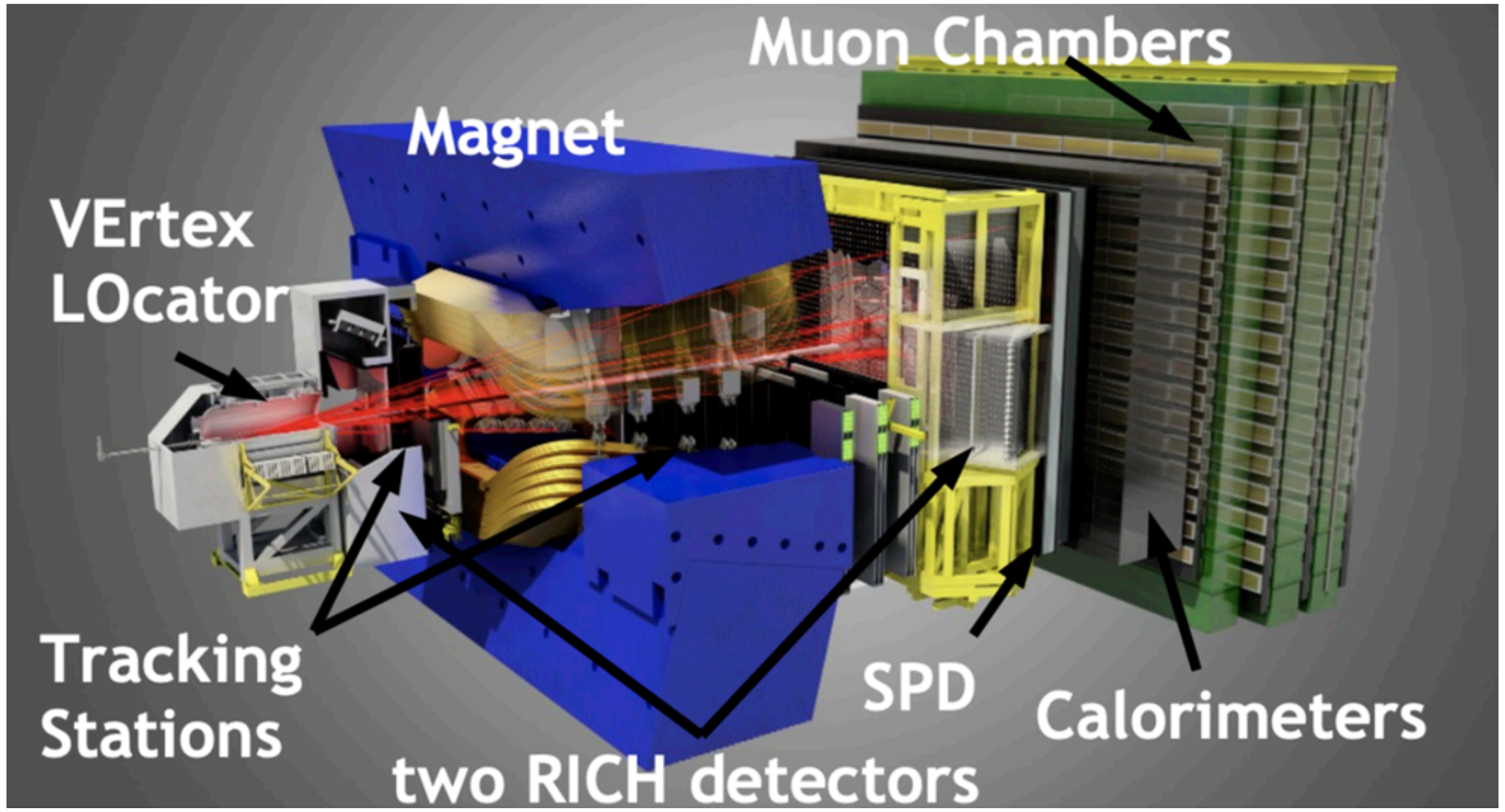
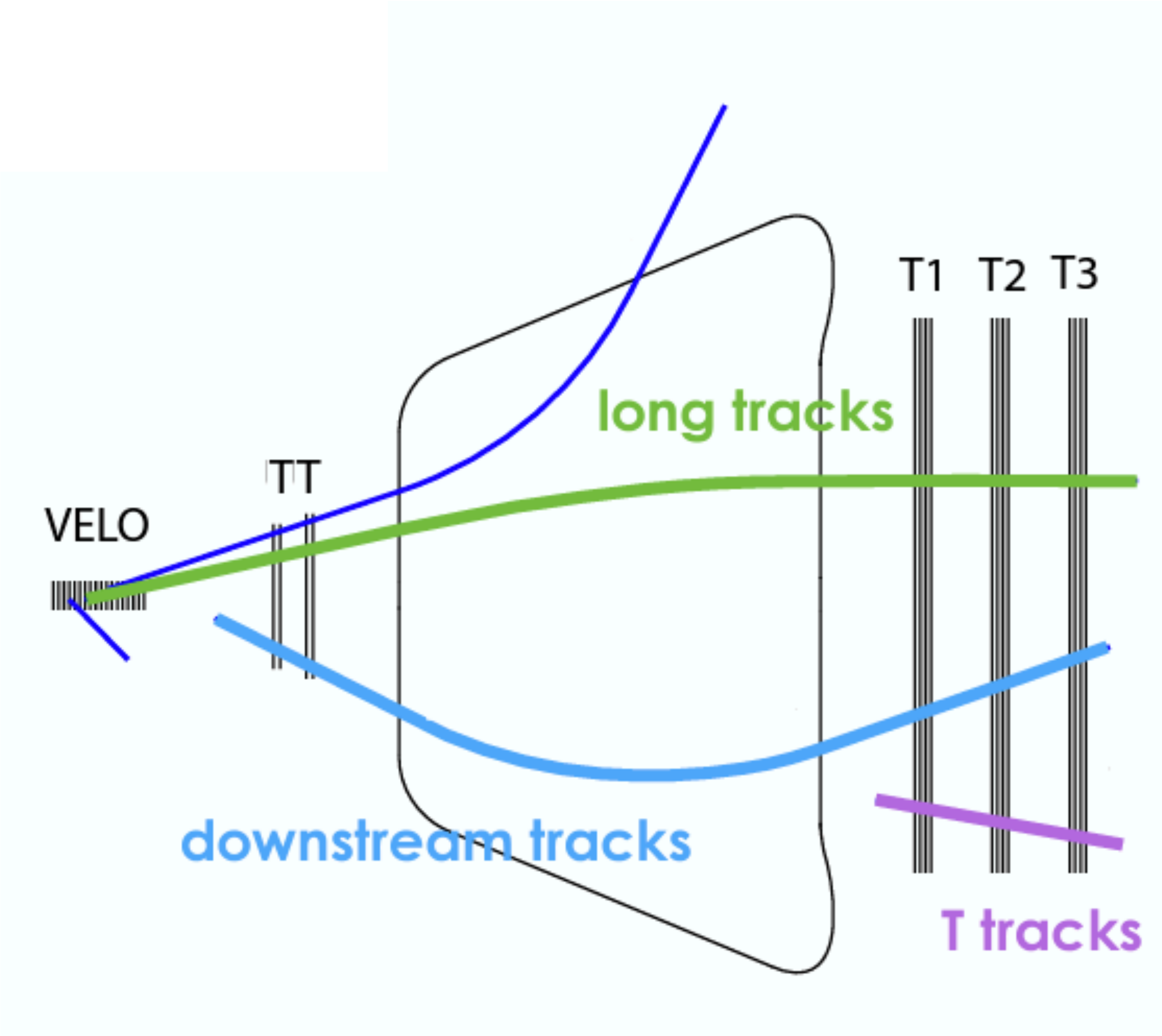




LHCb-FIGURE-2022-011

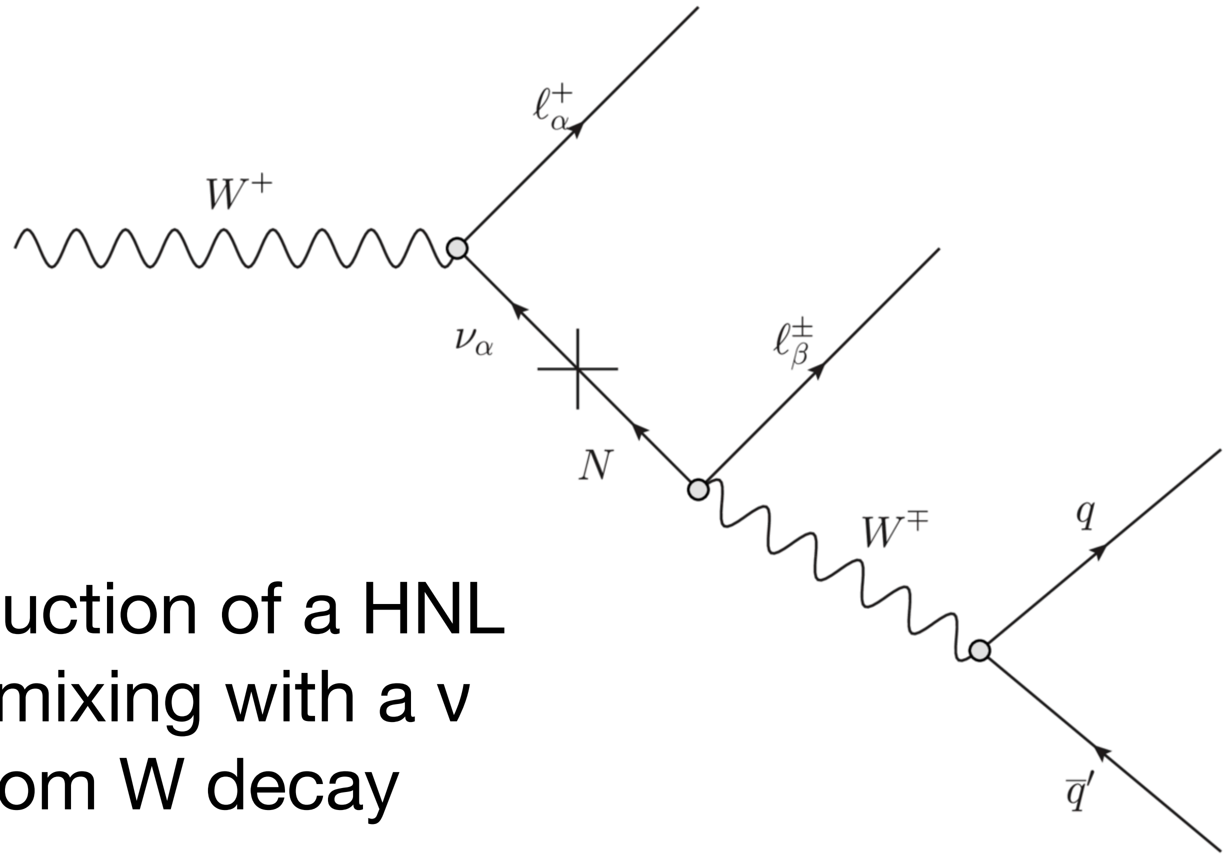
HNLs at LHCb - $W^+ \to \mu^+\mu^\pm j(j)$

Elena Dall'Occo
(Now at TU Dortmund)

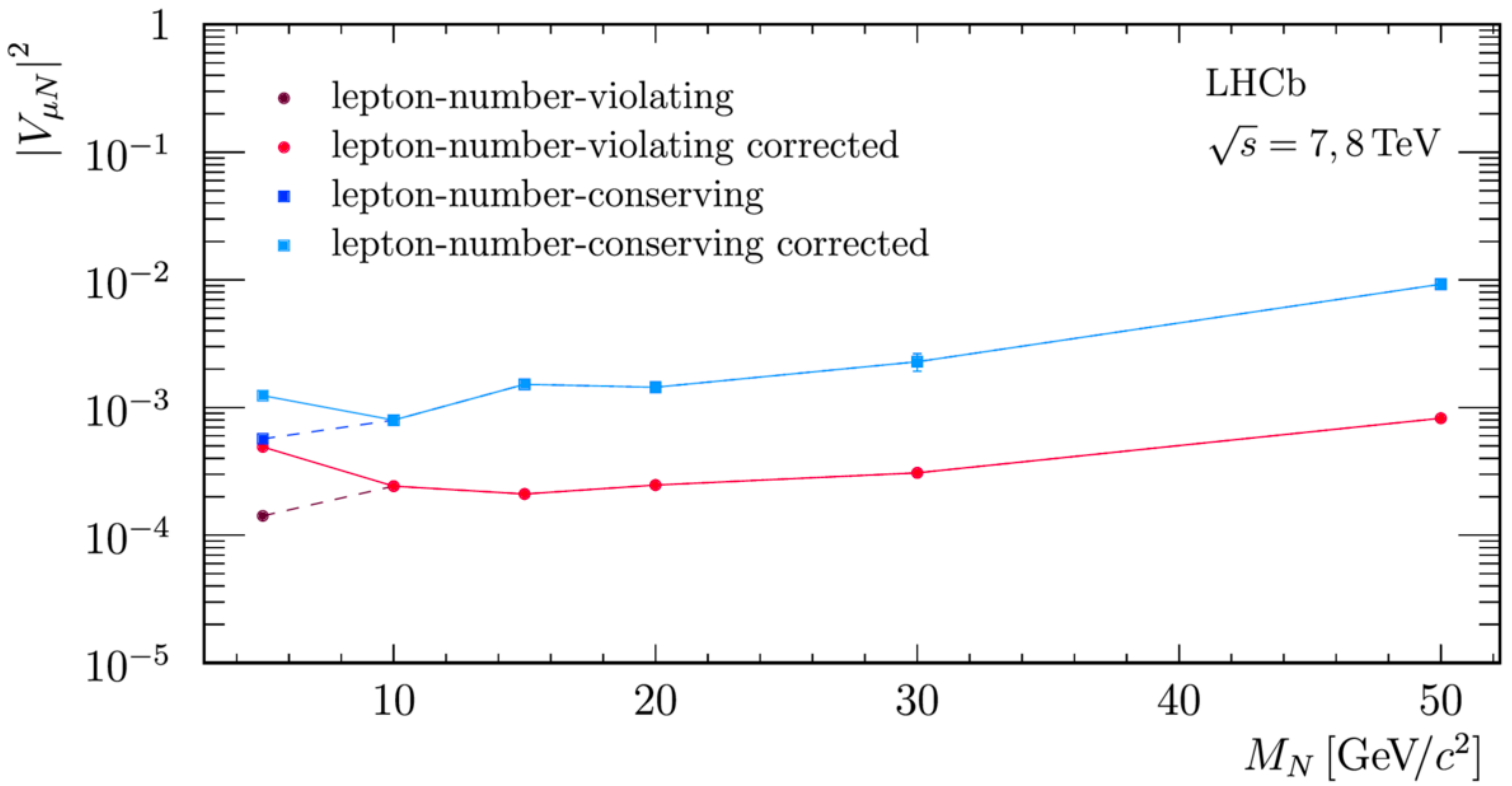
Valeriia Lukashenko
(now PhD in B→μeπ)

Wouter Hulsbergen

- Prompt HNL decays
  - ➡ Consider same- and opposite-sign muons (LNC and LNV)
  - ➡ 1 or 2 jets in the final state
  - ➡ Requirements on muon interaction points and BDT classifier to suppress background

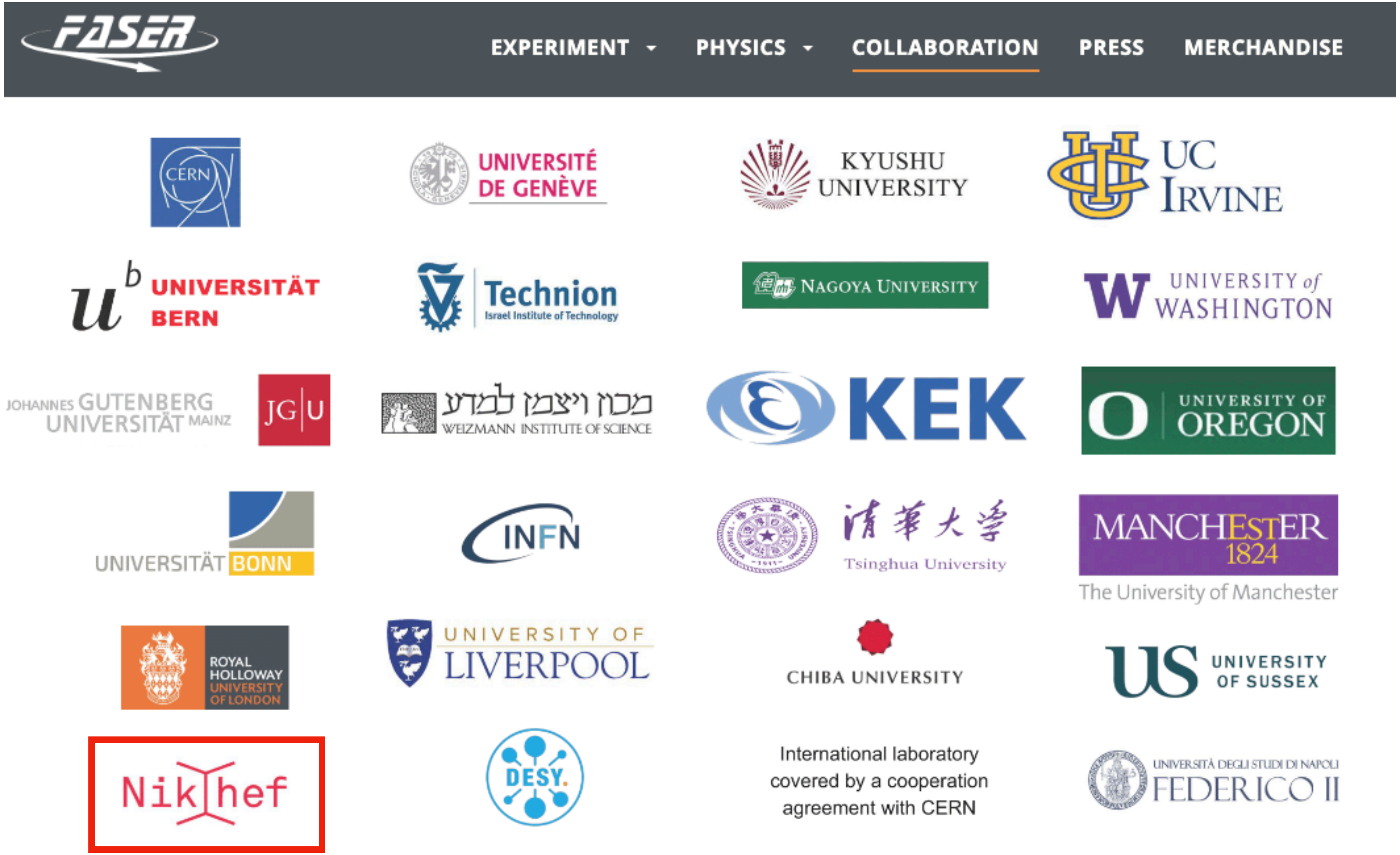


Production of a HNL via mixing with a ν from W decay



EUR. PHYS. J. C81, (2021) 248 **More Public results from LHCb**

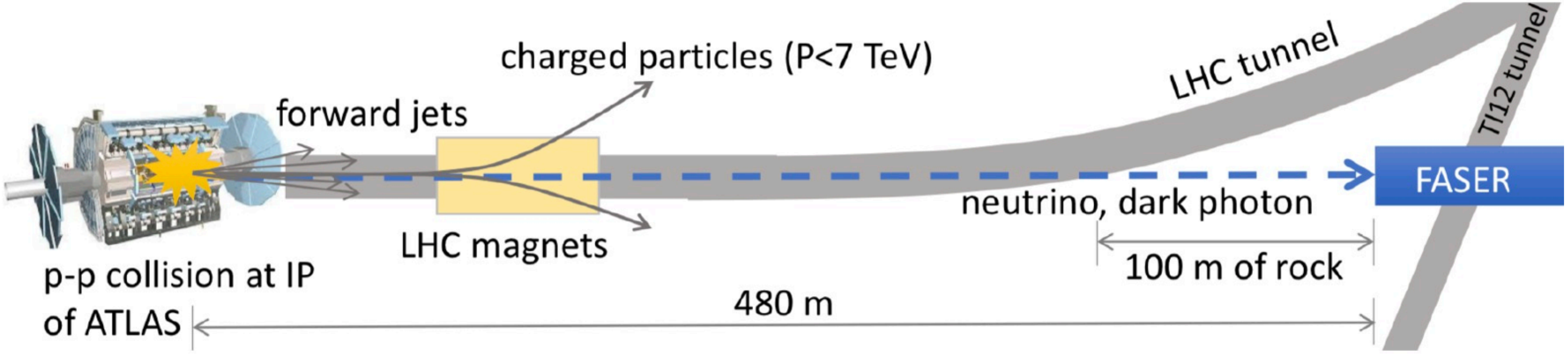
FASER: ForwArd Search ExpeRiment at the LHC



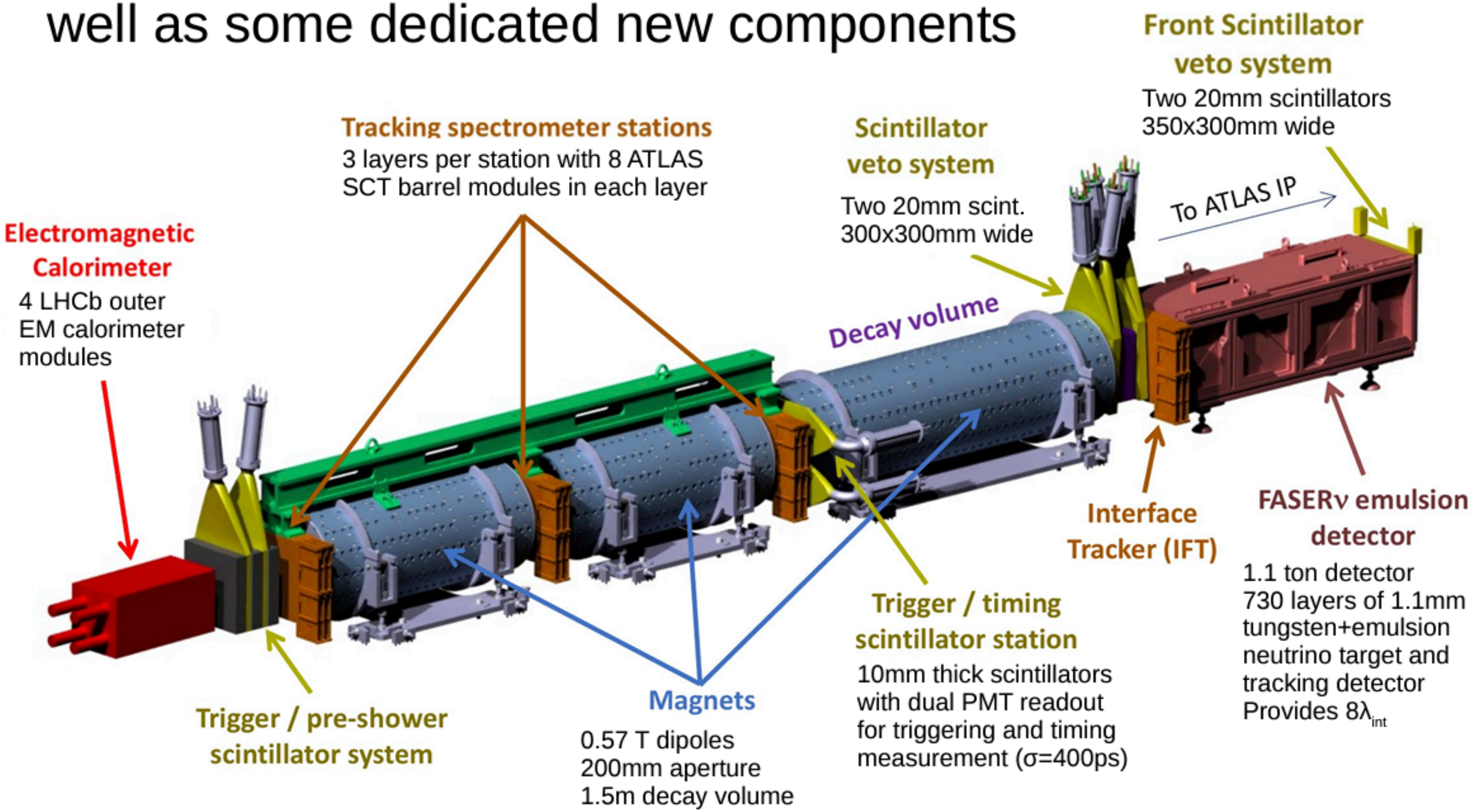
Lydia Brenner

FASER: ForwArd Search ExpeRiment at the LHC

- New, small experiment at the LHC: Constructed and installed in 2019-2021
- Targets light and weakly coupled particles
  - ➡ Exploits large LHC collision rate and highly-collimated forward production of light particles, for instance in pion decays (1% of pions with E > 10 GeV produced at $\eta > 9.2$)
  - ➡ Designed to detect both new long-lived BSM particles (e.g. dark photons, ALPs) as well as neutrinos
- Located 480m from ATLAS interaction point
  - ➡ LHC magnets as well 100m of rock shields most backgrounds



Experiment built from existing spare parts as well as some dedicated new components



10 cm radius

Angular acceptance
$\theta \lesssim 1$ mrad

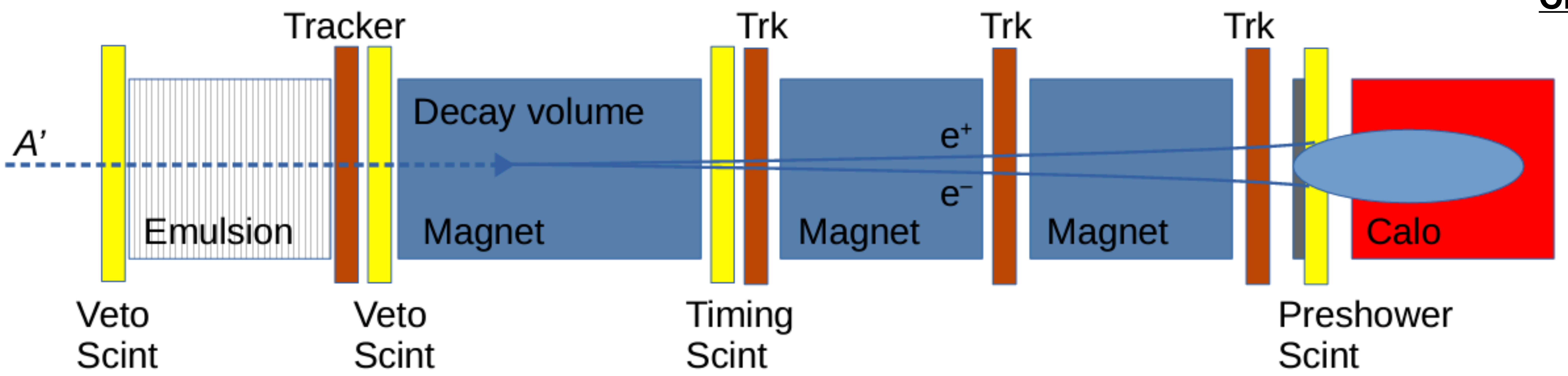
7m long

1.5 m decay volume

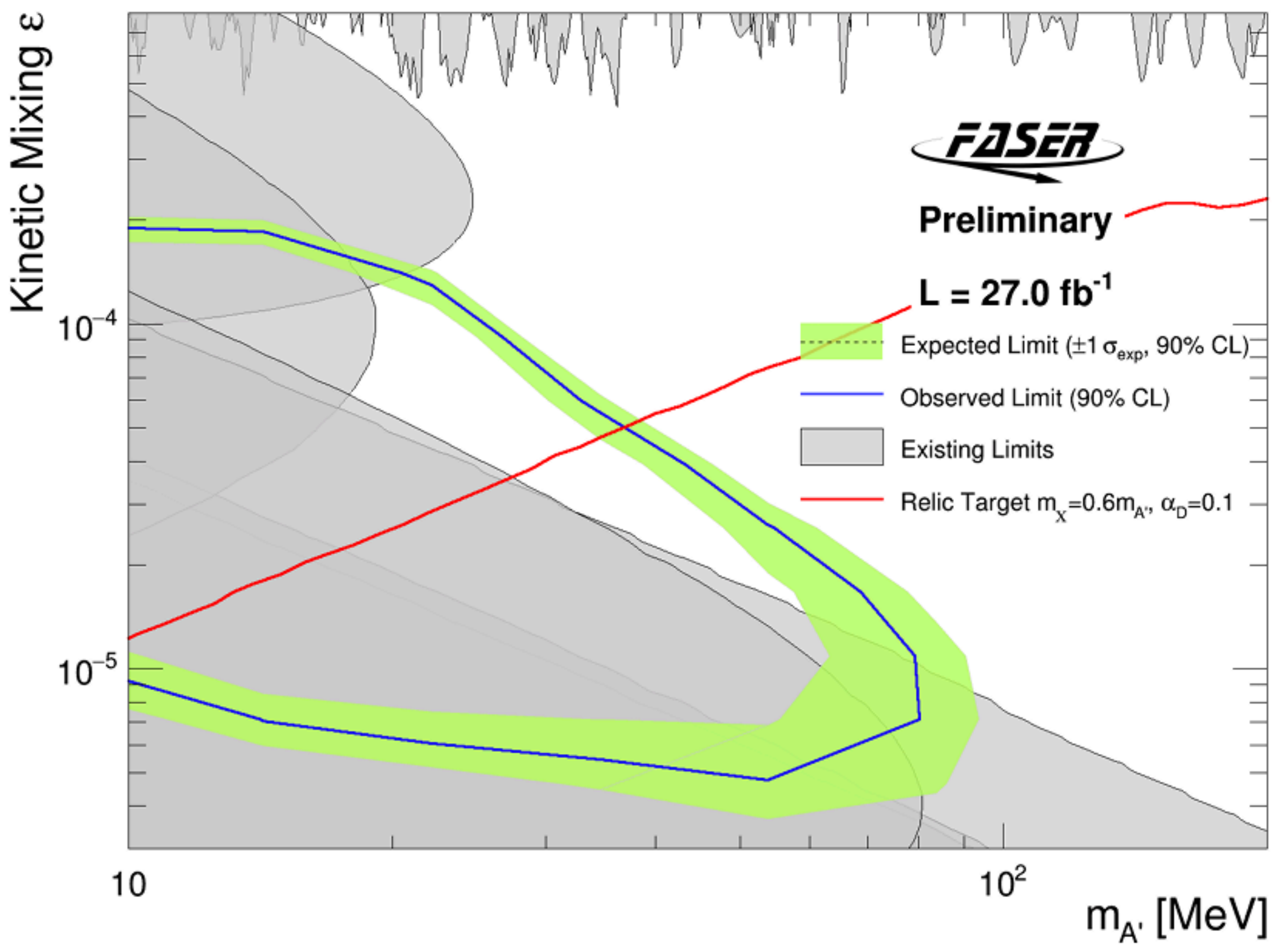
arXiv:2207.11427 **From B. Petersen**

FASER - Dark Photons

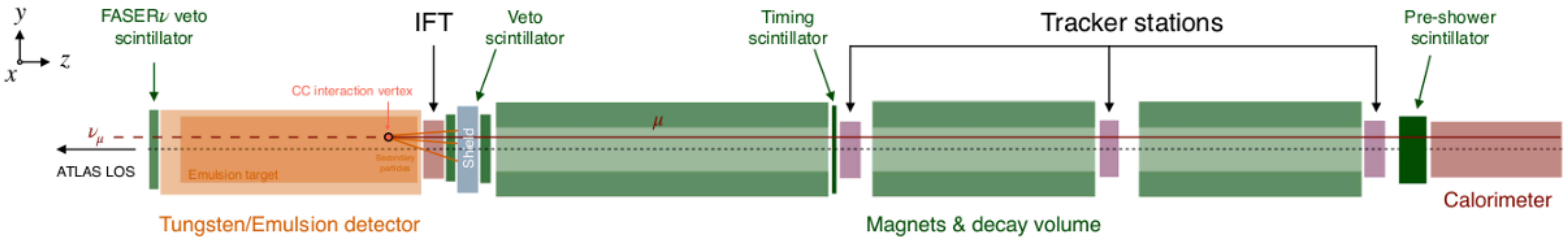
CERN-FASER-CONF-2023-01



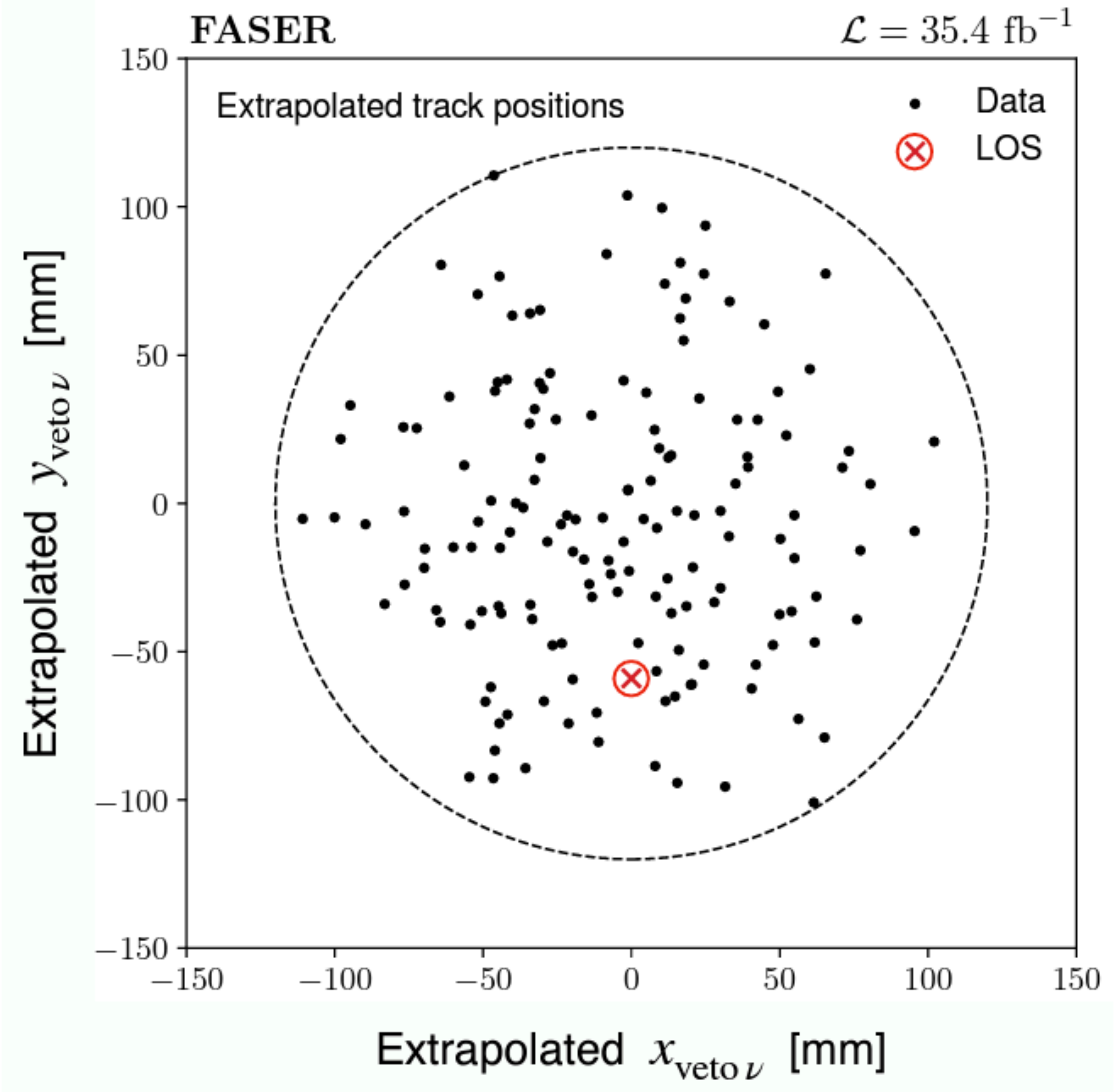
- Select e^+e^- pairs emerging in decay volume
  - ➡ Simple, robust selection criteria optimized for discovery
  - ➡ Events in collision crossing, during good physics data period
  - ➡ No signal in any of five scintillators



FASER-ν



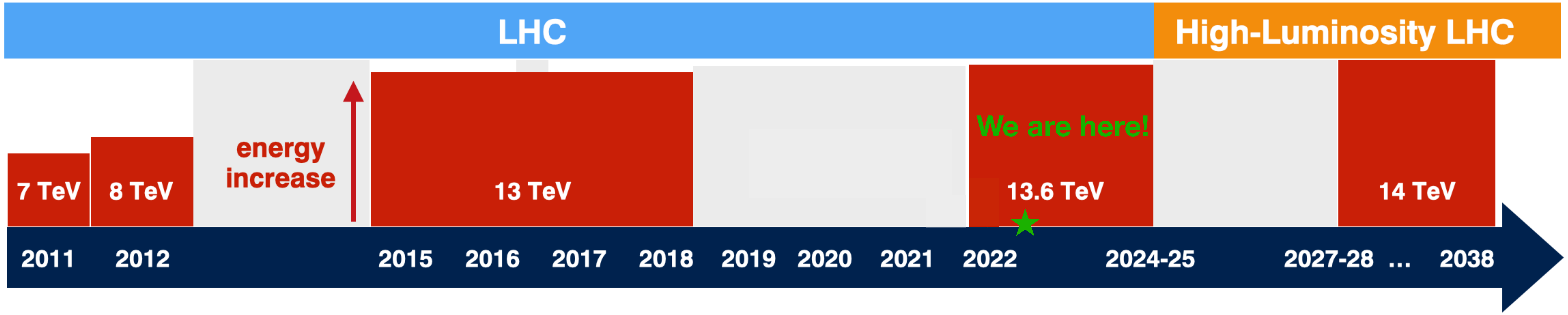
- First observation of collider neutrinos: 153^{+12}_{-13} events (16σ)
  - ➡ Used active electronic components of FASER
  - ➡ Track propagating through the entire length of FASER consistent with a muon neutrino charged-current interaction

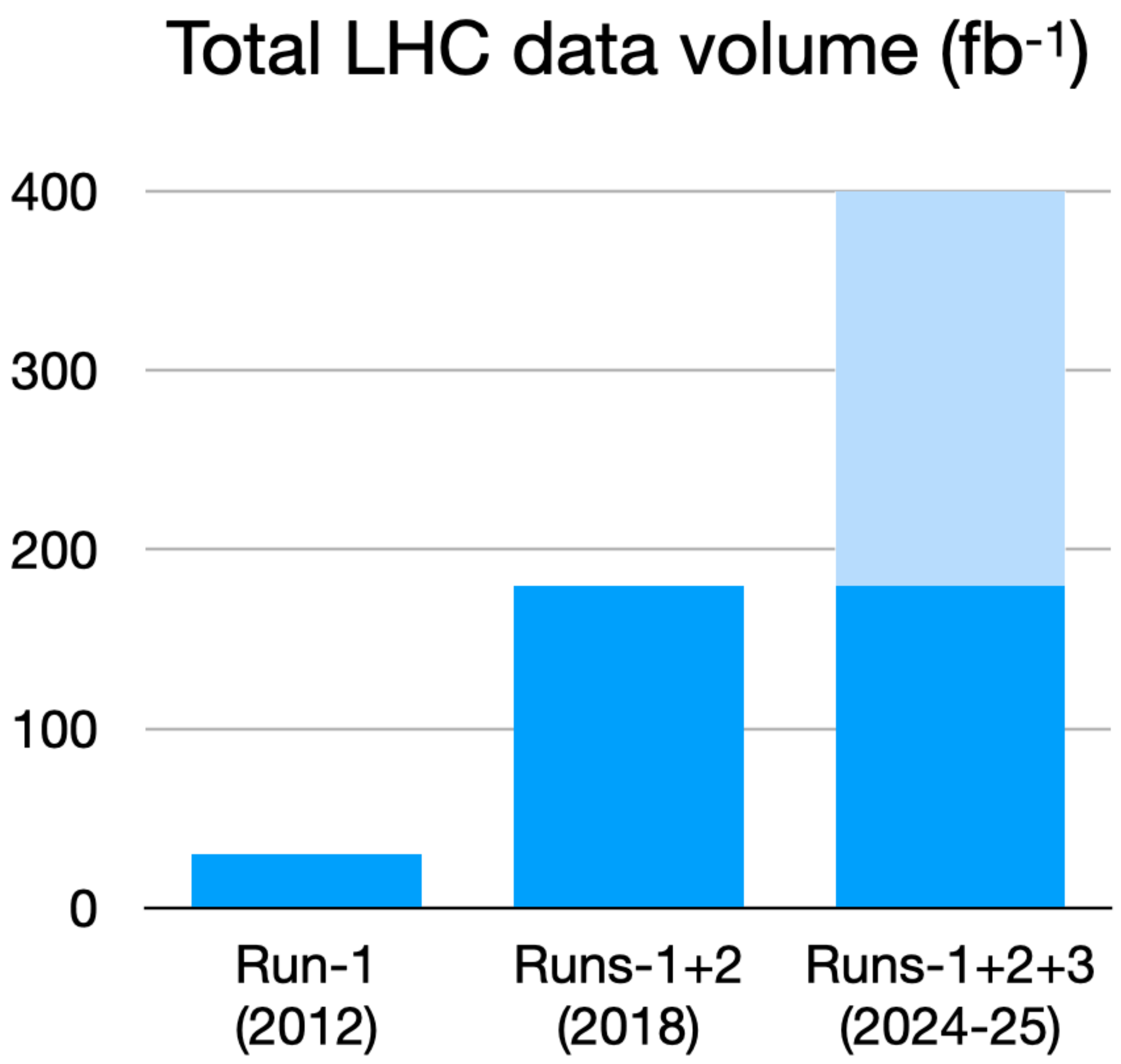


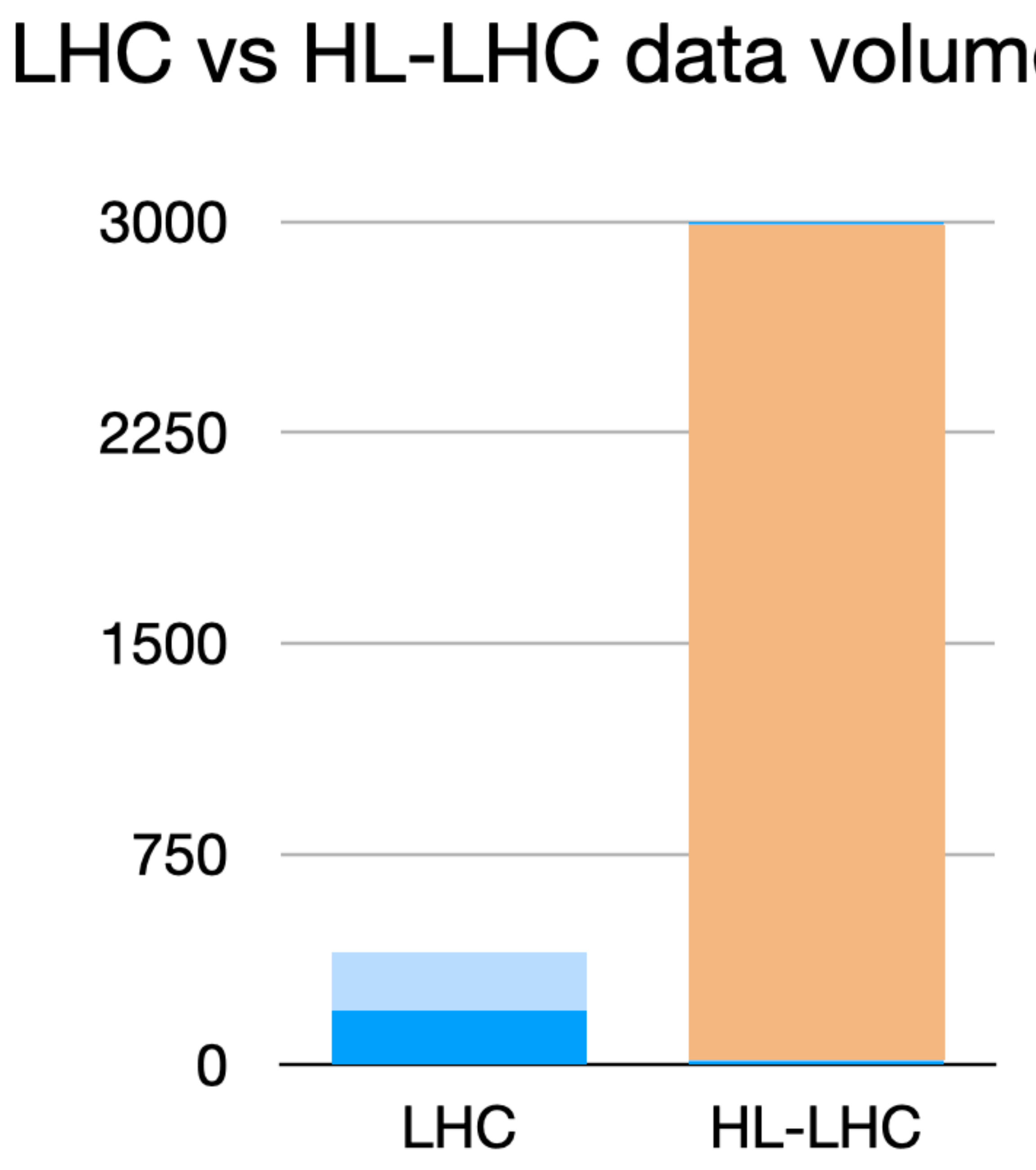
arXiv:2303.14185

LLPs at LHC: Future Prospects

More data = Sharper images

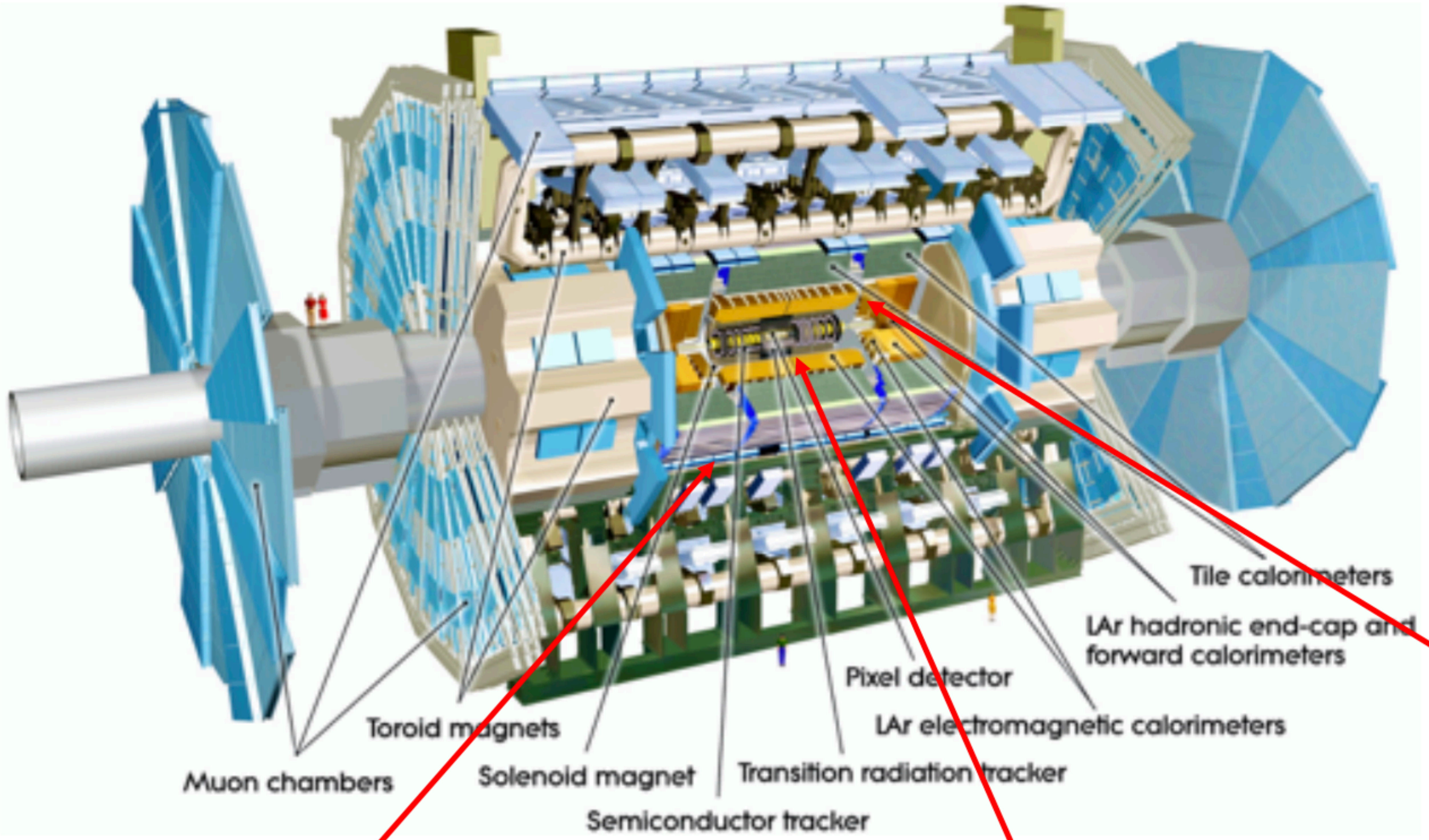






ATLAS Phase-2 Upgrade for HL-LHC

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

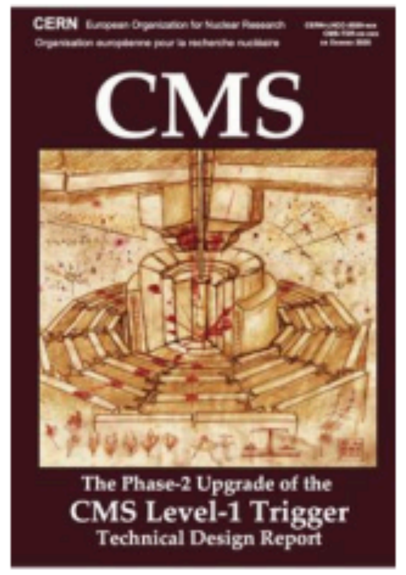
Luminosity detectors (1% precision goal)

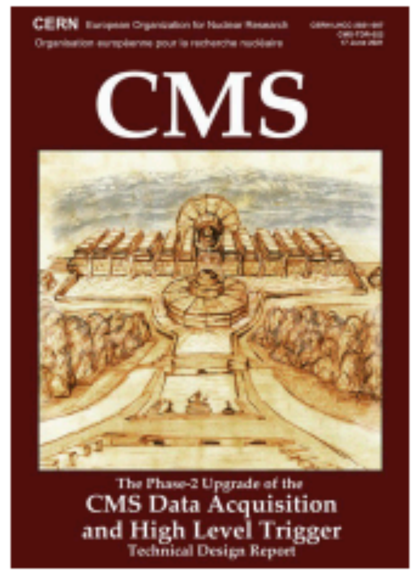
HL-ZDC

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

CMS Phase-2 Upgrade for HL-LHC

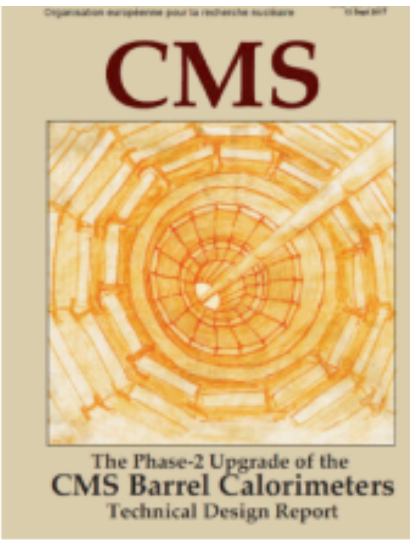
From A. Rizzi



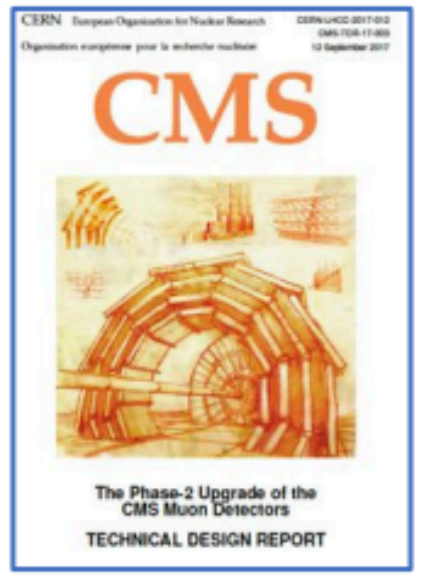


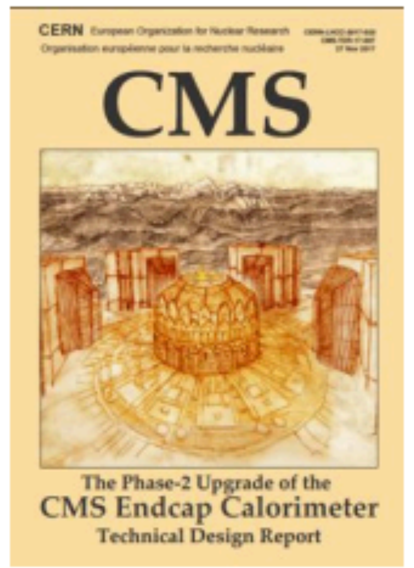
L1-Trigger HLT/DAQ
https://cds.cern.ch/record/2714892
https://cds.cern.ch/record/2759072
- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting

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

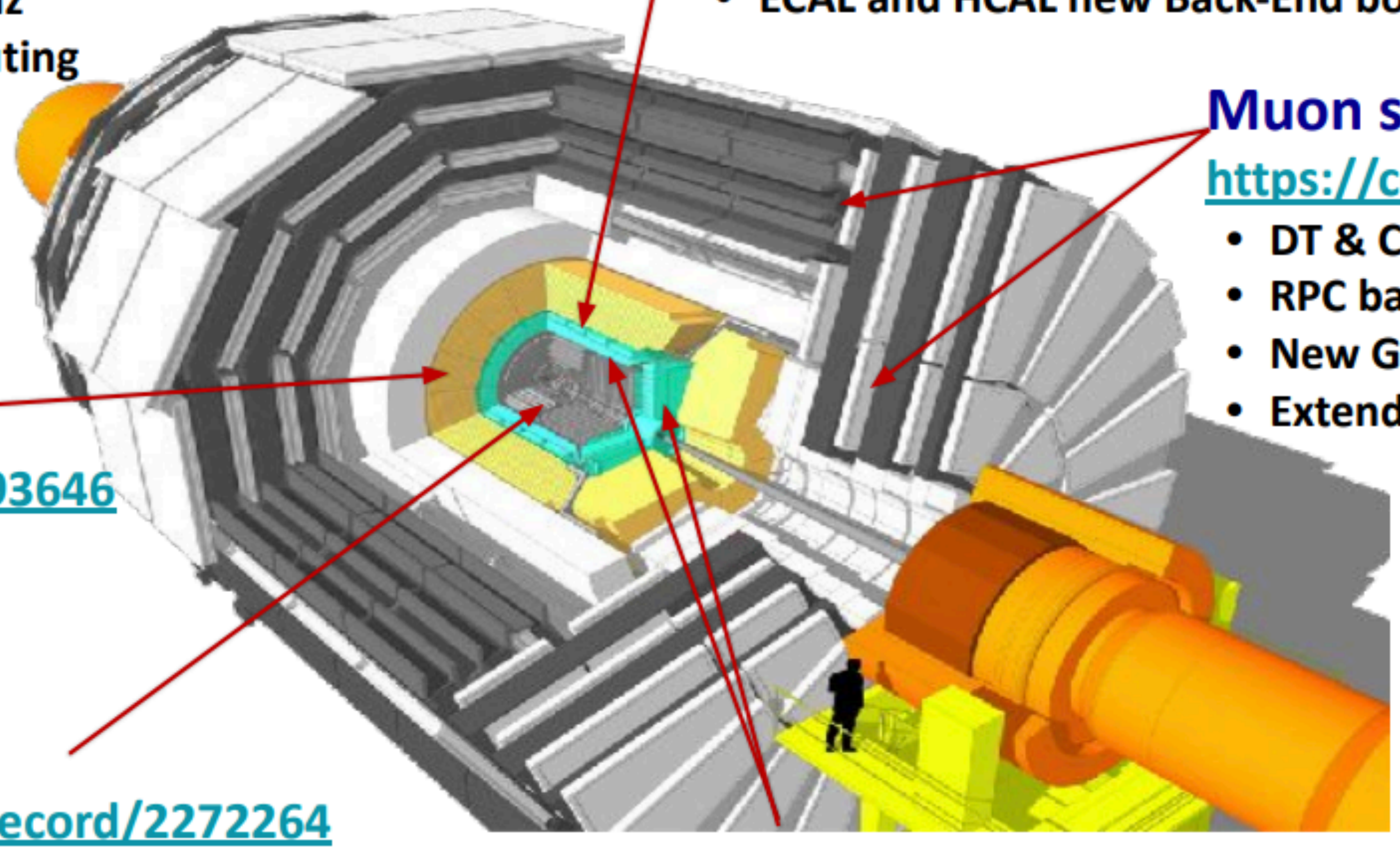


Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \approx 3$

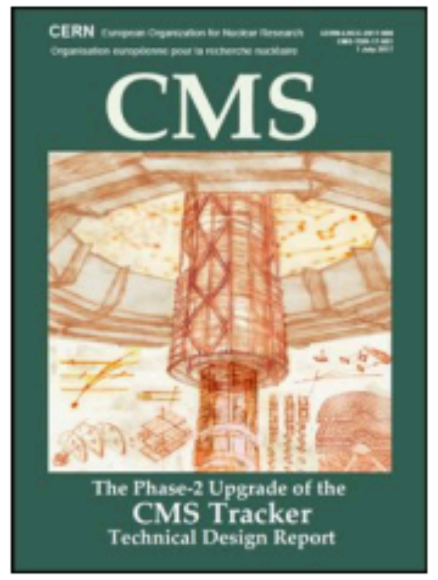




Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

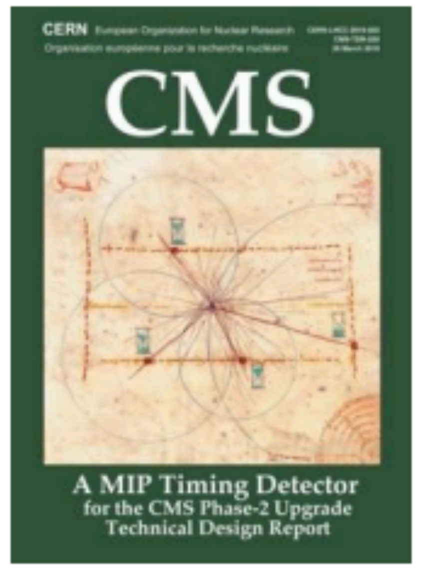


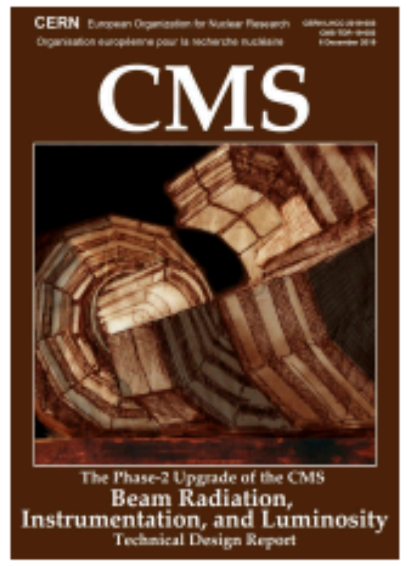
Beam Radiation Instr. and Luminosity
http://cds.cern.ch/record/2759074
- Bunch-by-bunch luminosity measurement: 1% offline, 2% online



Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \approx 3.8$

MIP Timing Detector
https://cds.cern.ch/record/2667167
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes





LHCb Phase-2 Upgrade for HL-LHC

From F. Blanc

← 9 fb^{-1} → ← Goal: 50 fb^{-1} → ← Goal: 300 fb^{-1} →

Upgrade I — Consolidation — Upgrade II

Run 1	LS1	Run 2	LS2		Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6
2011 2012	2013 2014	2015 2016 2017 2018	2019 2020 2021	2022	2023 2024 2025	2026 2027 2028	2029 2030 2031 2032	2033 2034	2035 2036 2037 2039	2040	2041 2042

- $\mathscr{L}_{\text{peak}} = 1.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, $\mathscr{L}_{\text{int}} \simeq 300 \text{fb}^{-1}$ (Run 5+6) , Pile-up ~ 40
- Starting R&D phase of new technologies

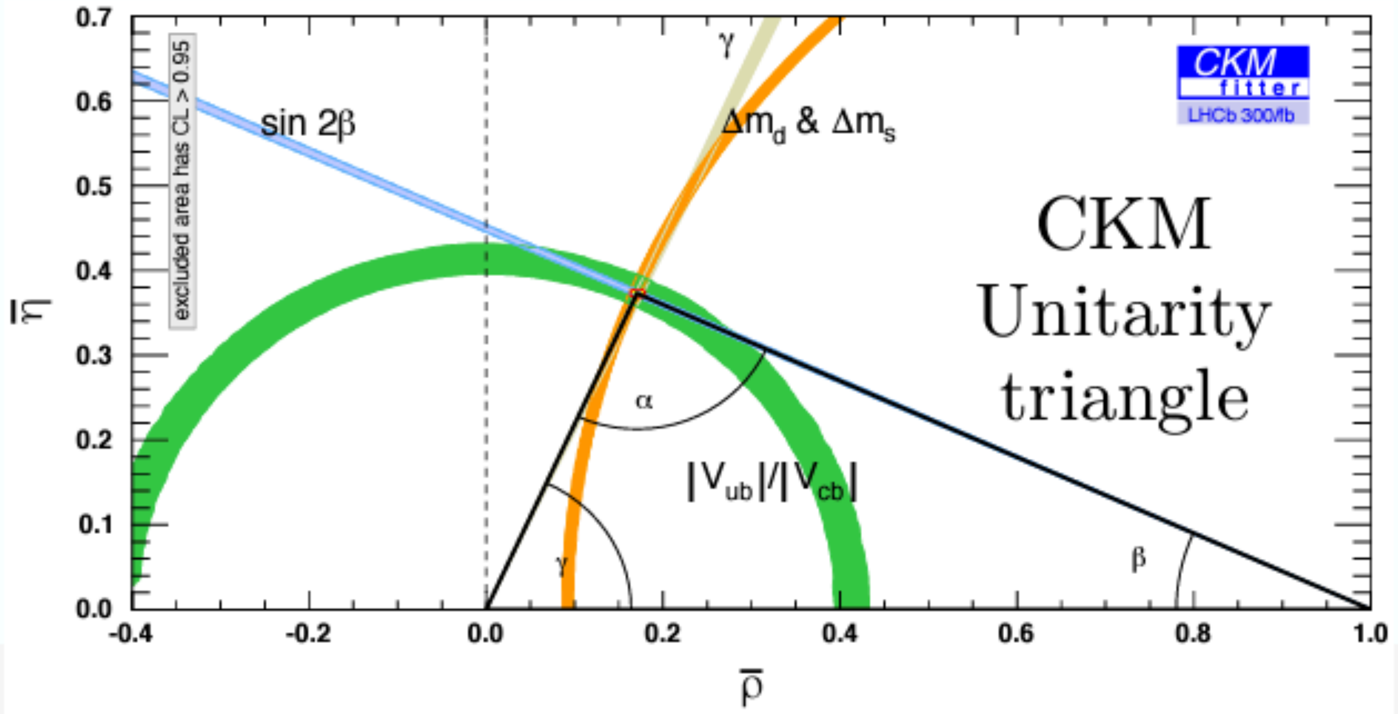
bridge to future accelerators

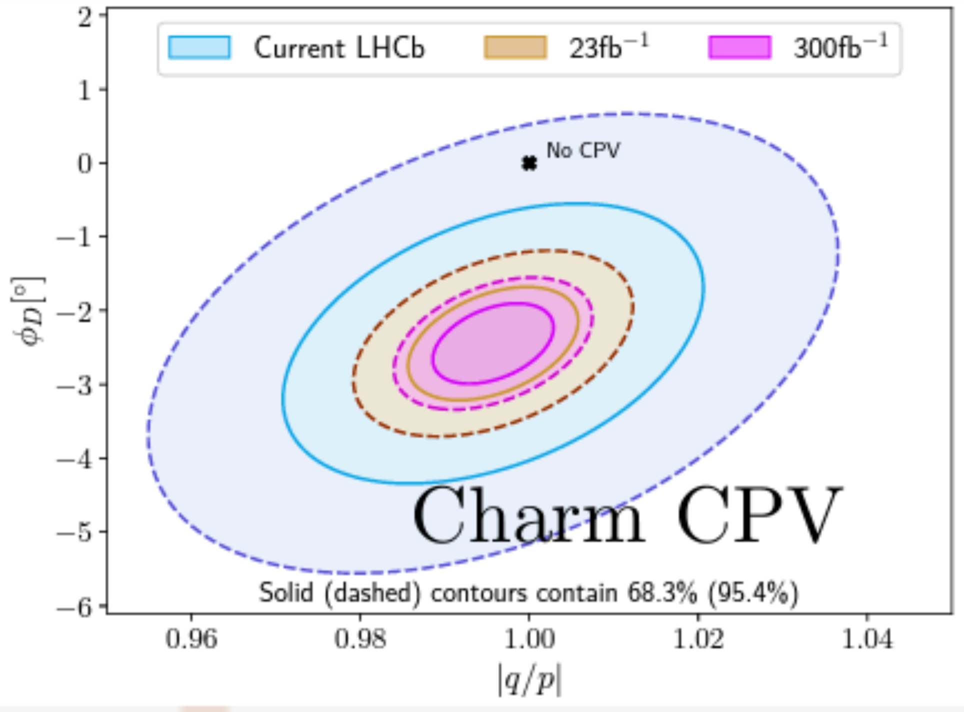
- precision timing for tracking and PID
- extreme radiation hardness
- low-cost monolithic pixels
- cryogenic cooling (for SiPMs)

→ **LHCb welcomes new collaborators!**

LHCC-2021-012

- Unprecedented sensitivity expected for flavour physics and beyond

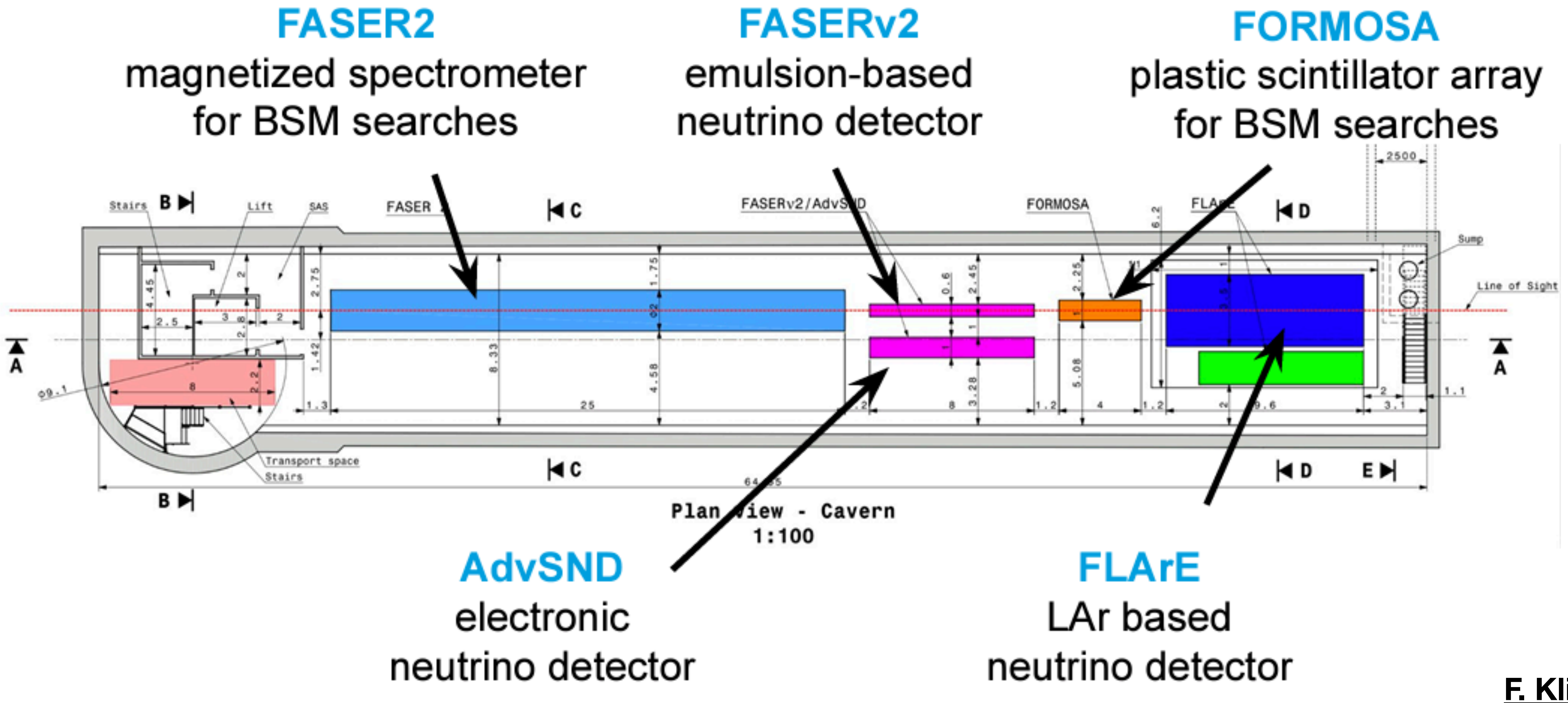




Future Facilities FPF: The Forward Physics Facility

FPF: Experiments

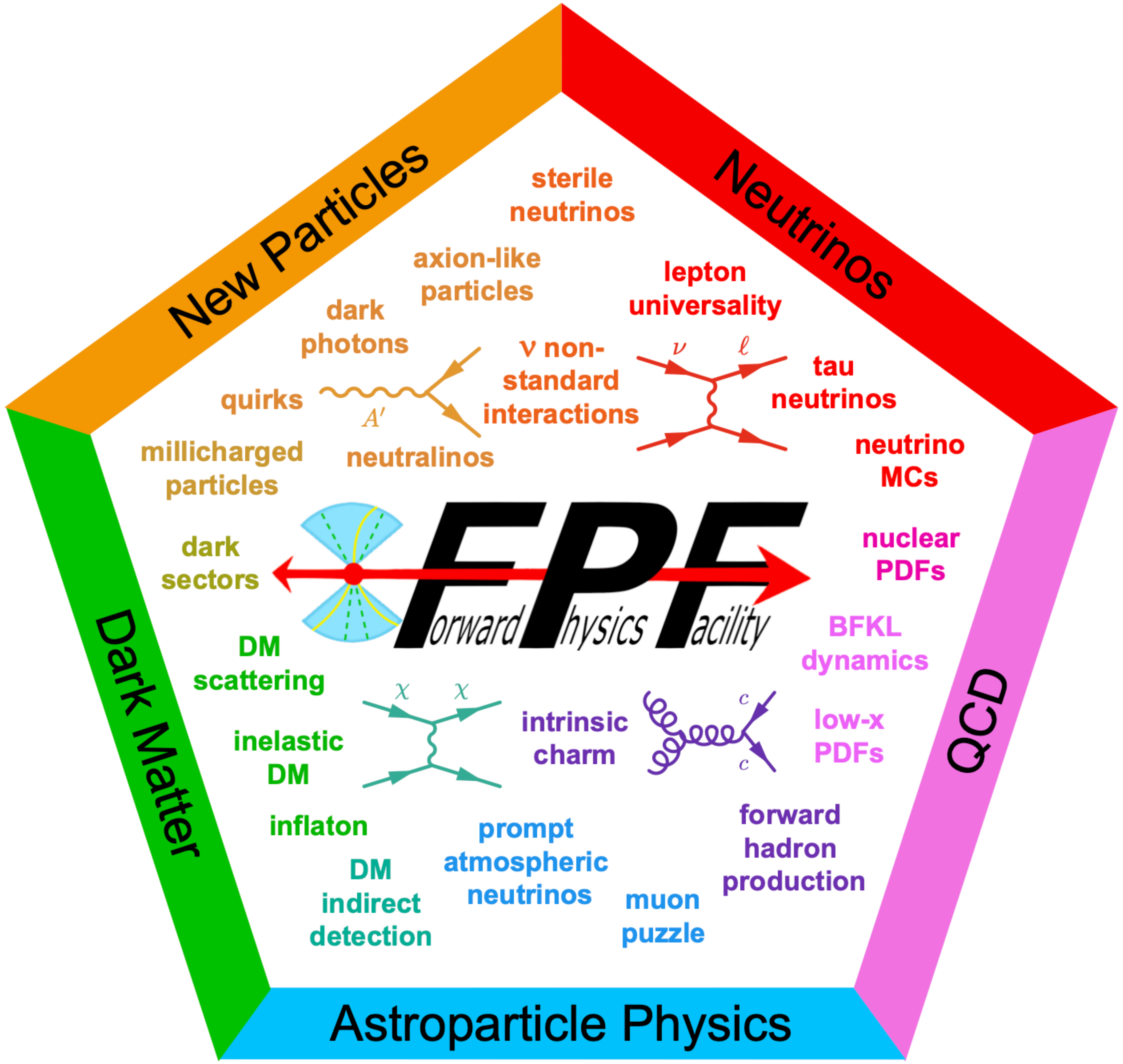
- The FPF would house a suite of experiments that will greatly enhance the LHC's physics potential for **BSM physics searches, neutrino physics** and **QCD**.



F. Kling

FPF: Physics Reach Summary

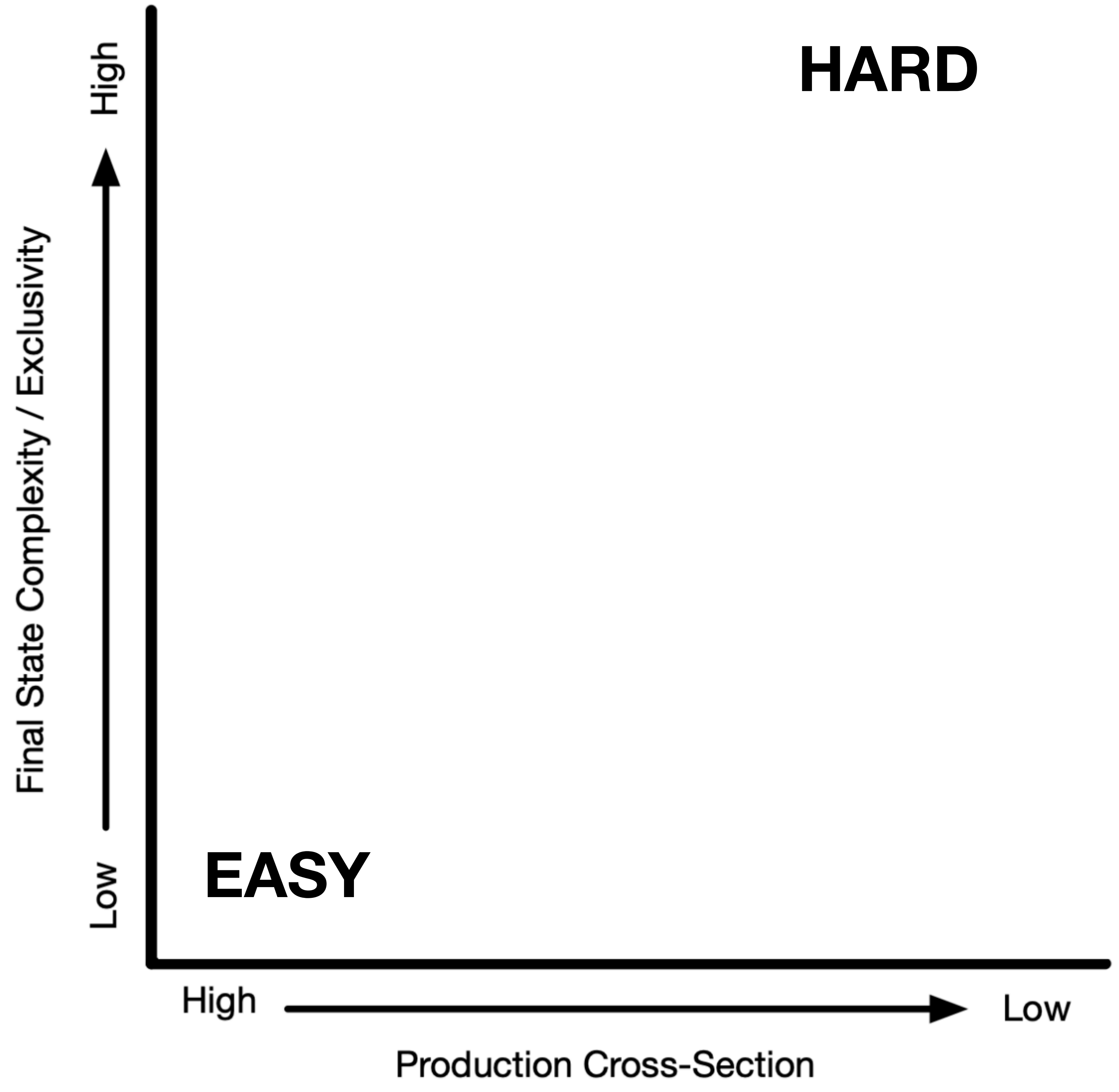
- Significant extension of LHC physics
  - ➡ BSM searches:
    - ➡ Very forward light BSM particles
    - ➡ Decaying dark sector LLPs
    - ➡ Milli-charged particles, dark matter scattering…
  - ➡ Neutrino physics:
    - ➡ Tau neutrino studies (current world sample <20)
    - ➡ EFT contraints on neutrino interactions
  - ➡ QCD, hadron structure, astroparticle physics:
    - ➡ Neutrino cross section measurements
    - ➡ Neutrino DIS to constrain proton and nuclear structure
    - ➡ Kay input to neutrino and cosmic rays experiments



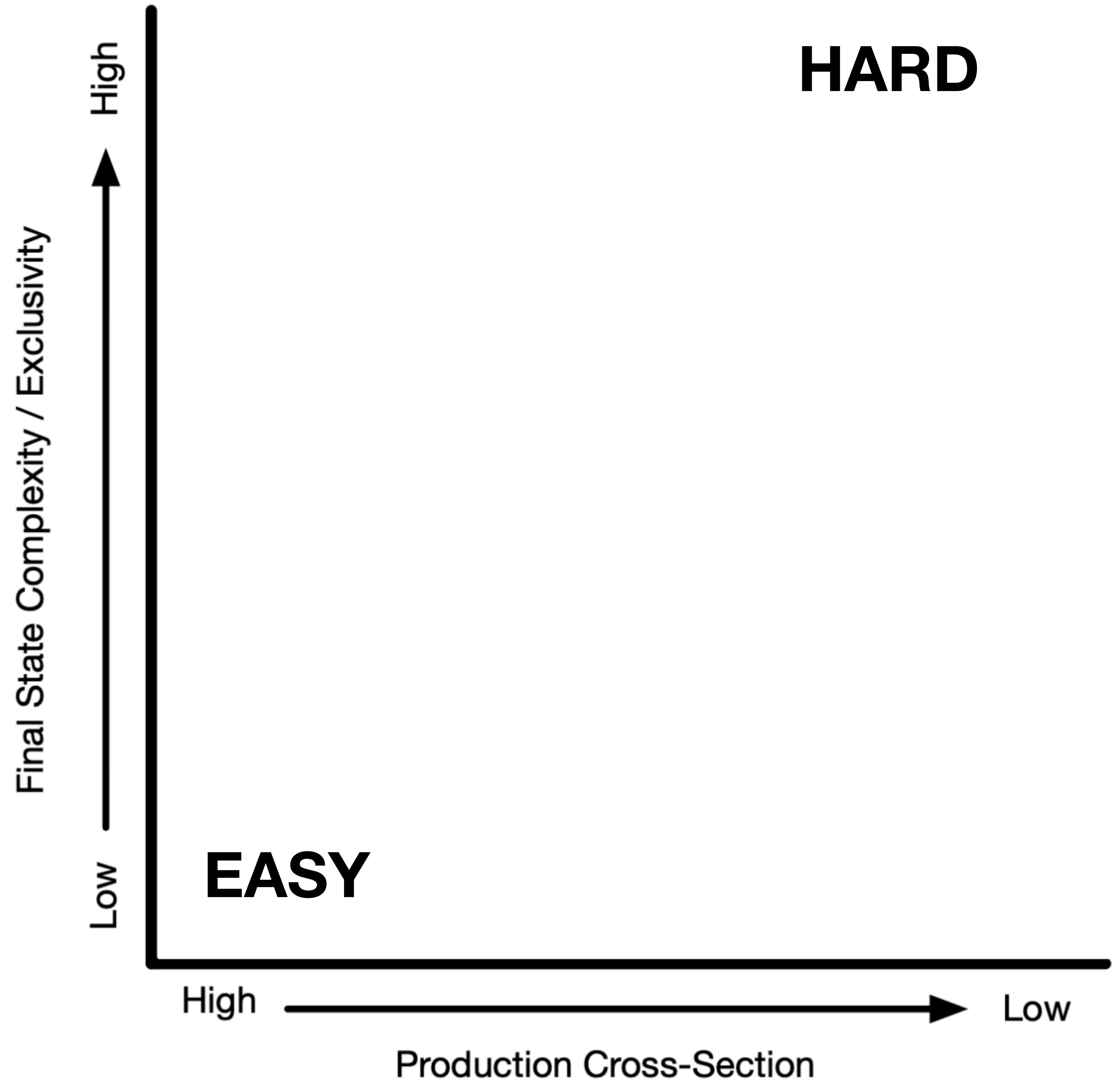
arXiv:2203.05090

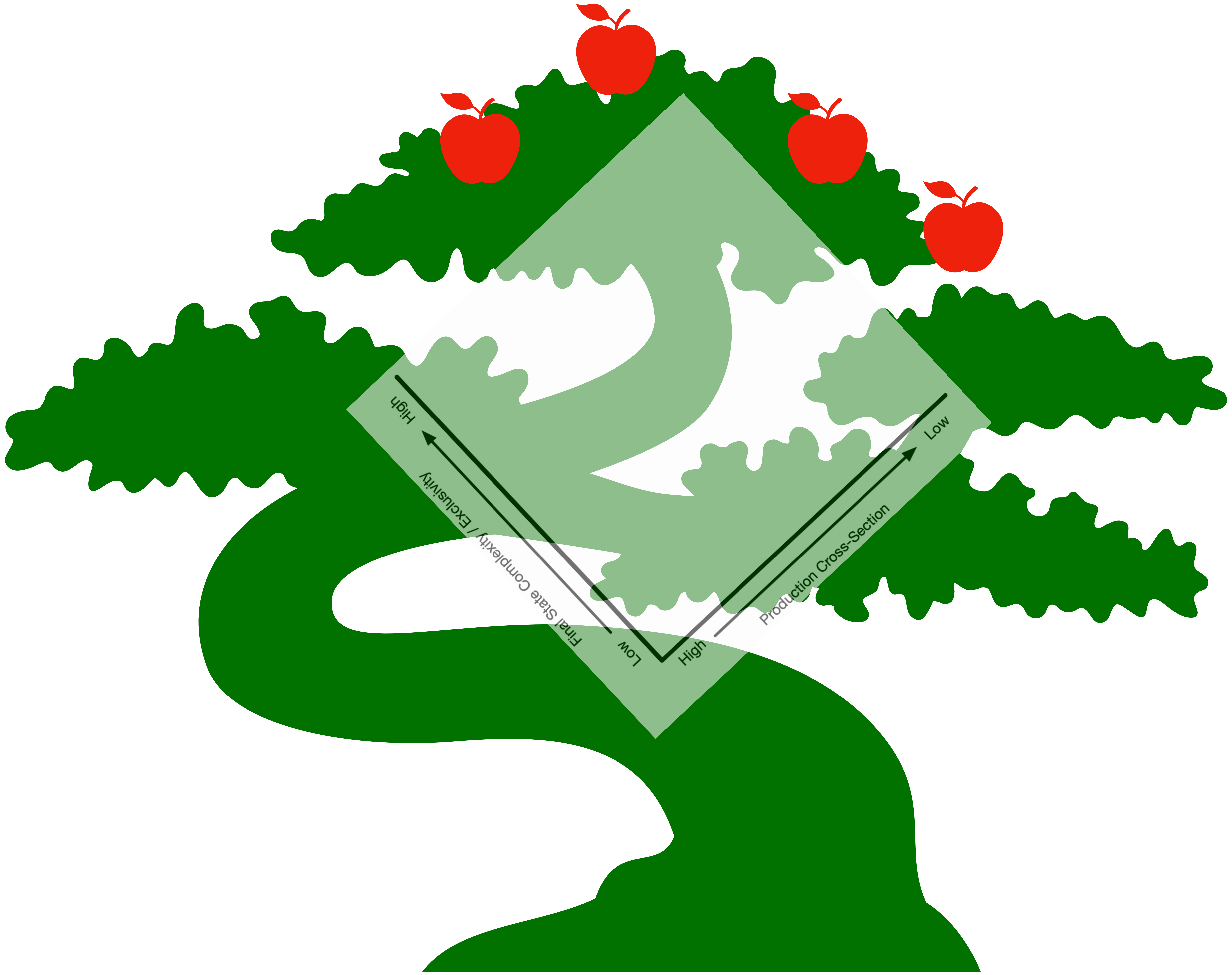
J. Rojo, L. Brenner

BSM Searches



BSM Searches





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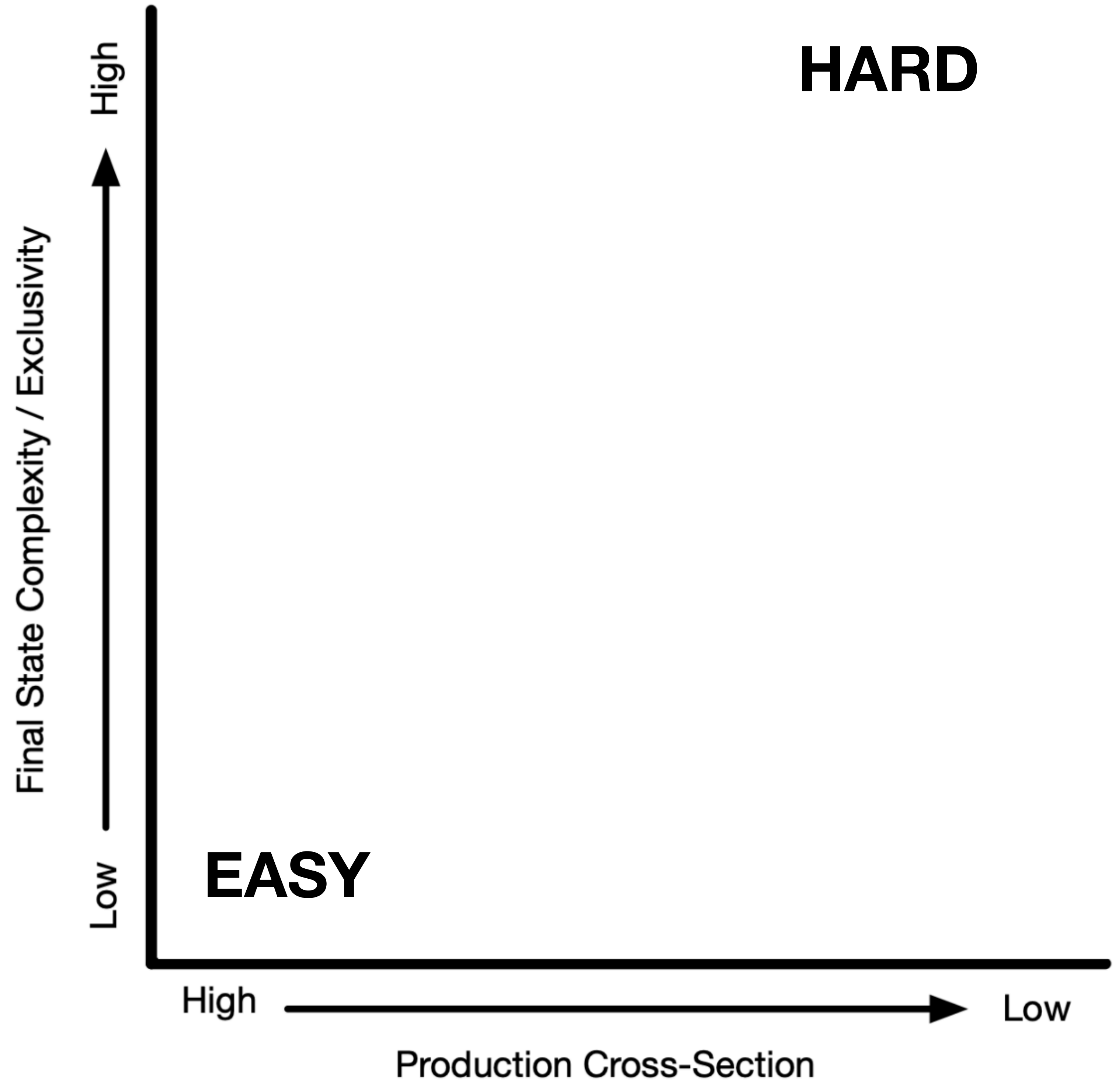
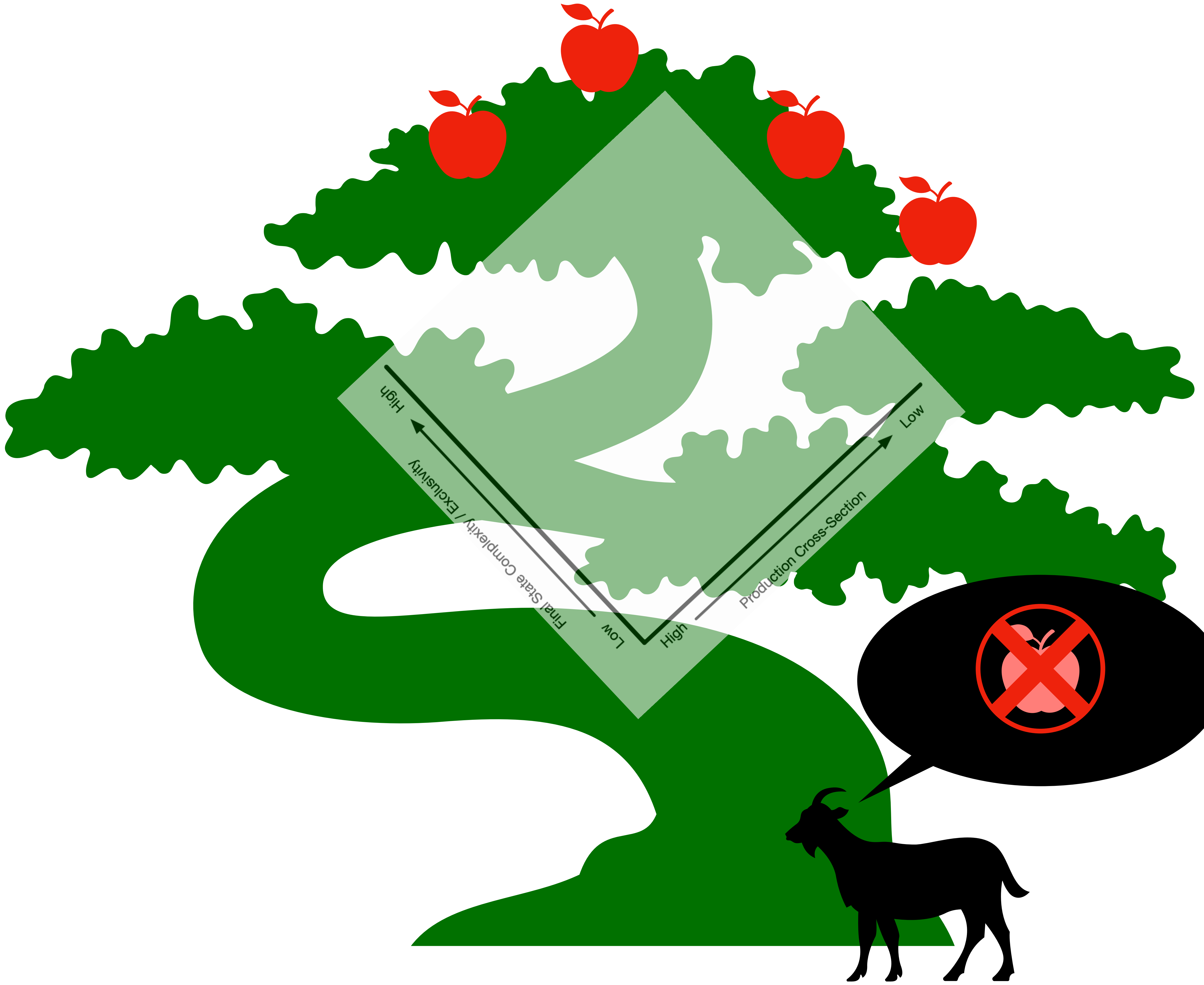
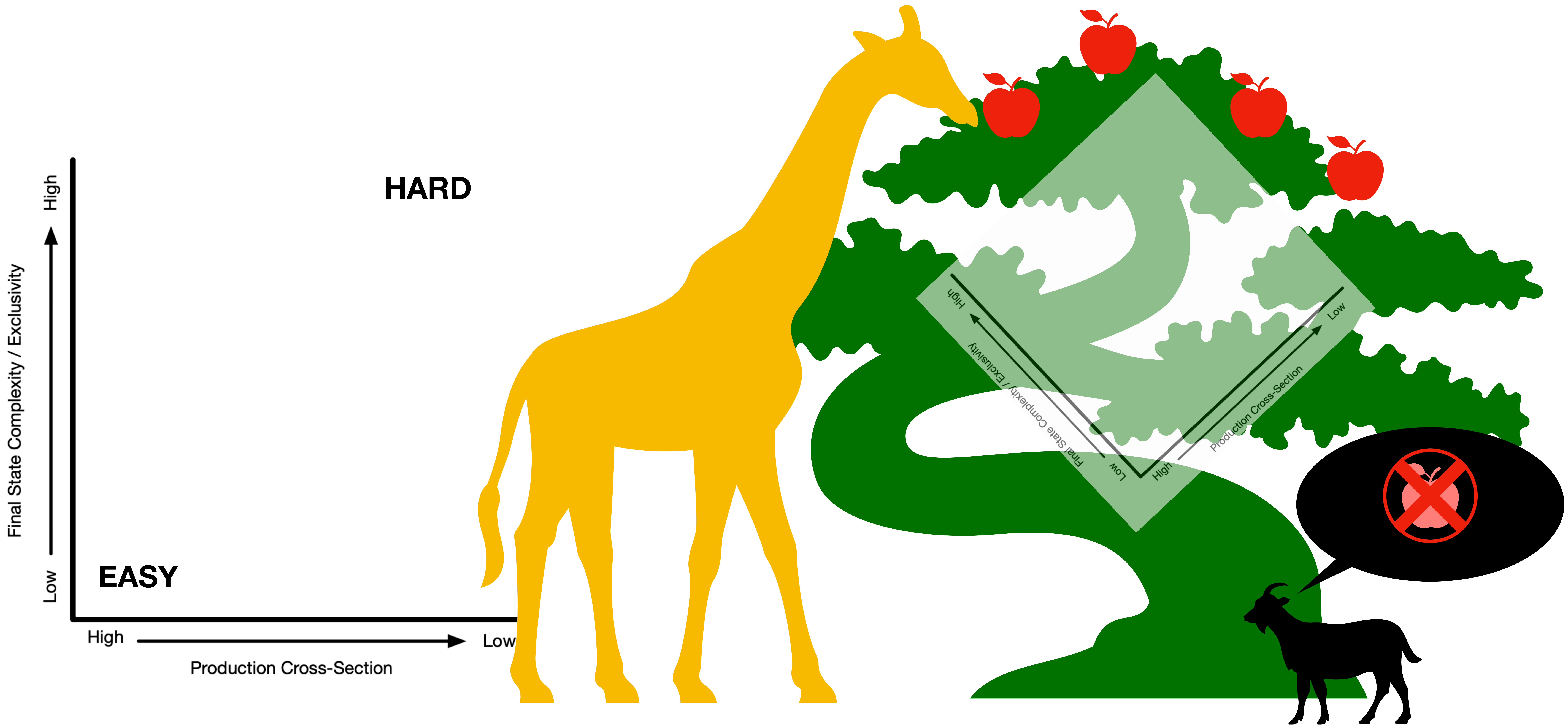




BSM Searches

Analogy adapted from Dr. Dan Hayden from MSU



Disclaimer: biology not scientifically sound!

Summary and Outlook

- Long-lived particles expand the scope of searches at the LHC
- Many innovative searches ongoing in ATLAS, CMS, LHCb, FASER (but also SND@LHC, NA 62)
- Crucial to plan ahead: look towards experiment upgrades and the Forward Physics Facility
- Stay tuned for many new exciting things ahead!
  - ➡ 13th LLP Community Workshop: 19-23 June, CERN

Image by brgfx on Freepik