Searches for Long-Lived Particles at the LHC

Biased selection of most recent results only!

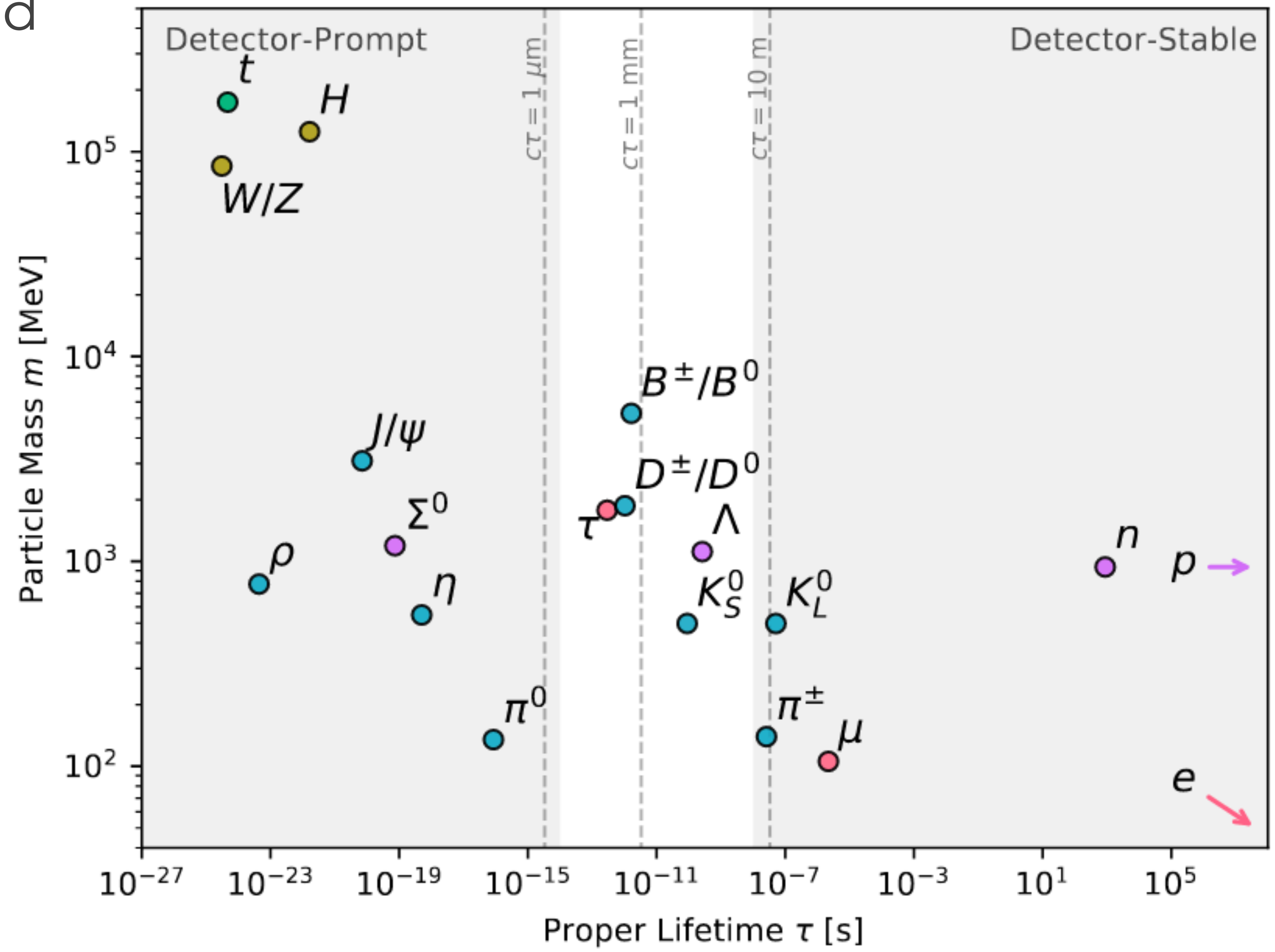
Matthias Danninger
Dark Interactions workshop 2022

Searching the "lifetime" dimension

LLPs are one promising direction to expand searches @ LHC

- Impressive progress in recent years!
  —> Still plenty of room for creativity

- Theoretically well motivated!
  - (nearly) mass-degenerate spectra
  - small couplings
  - highly virtual intermediate states



Images from arxiv1810.12602

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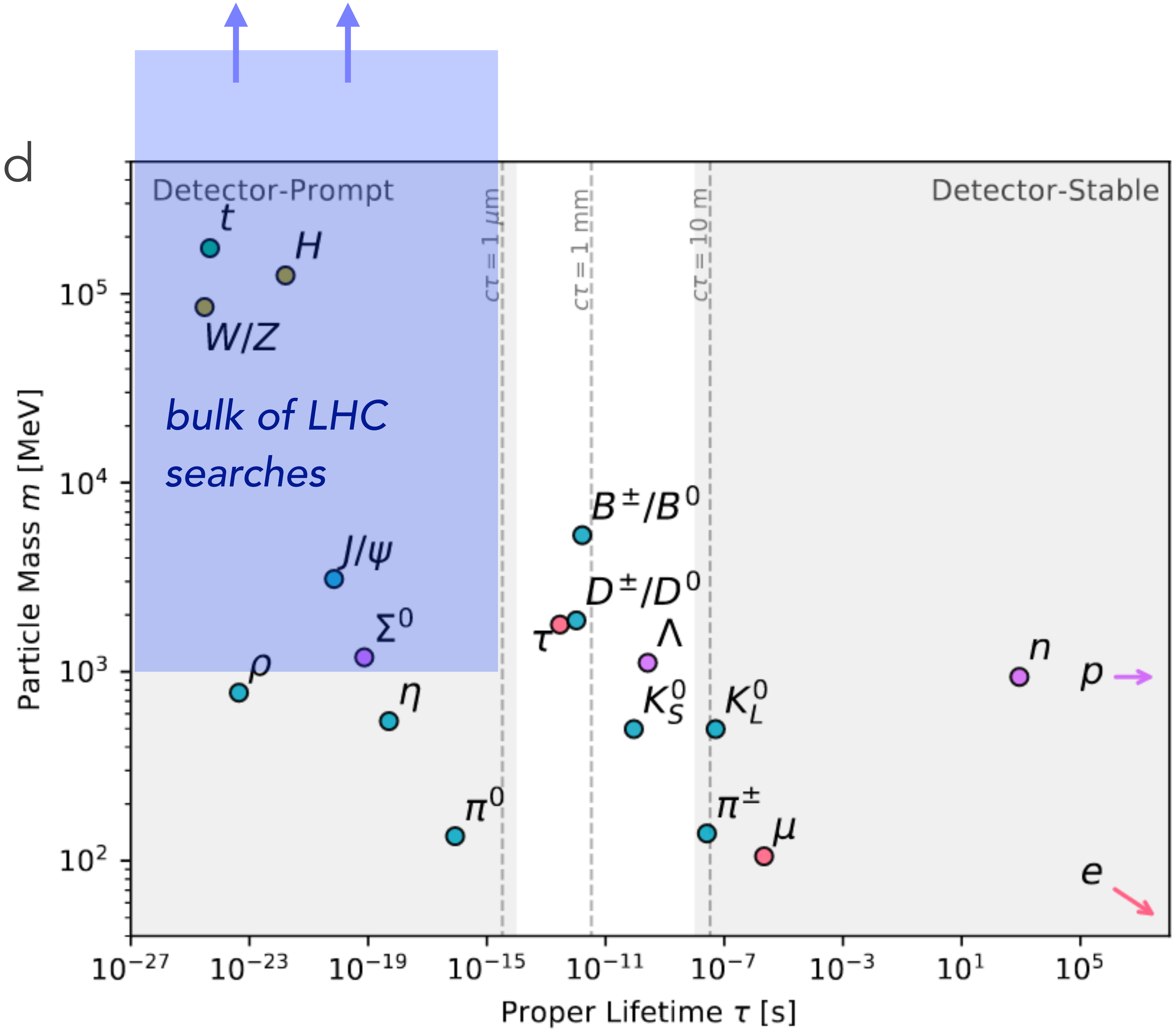

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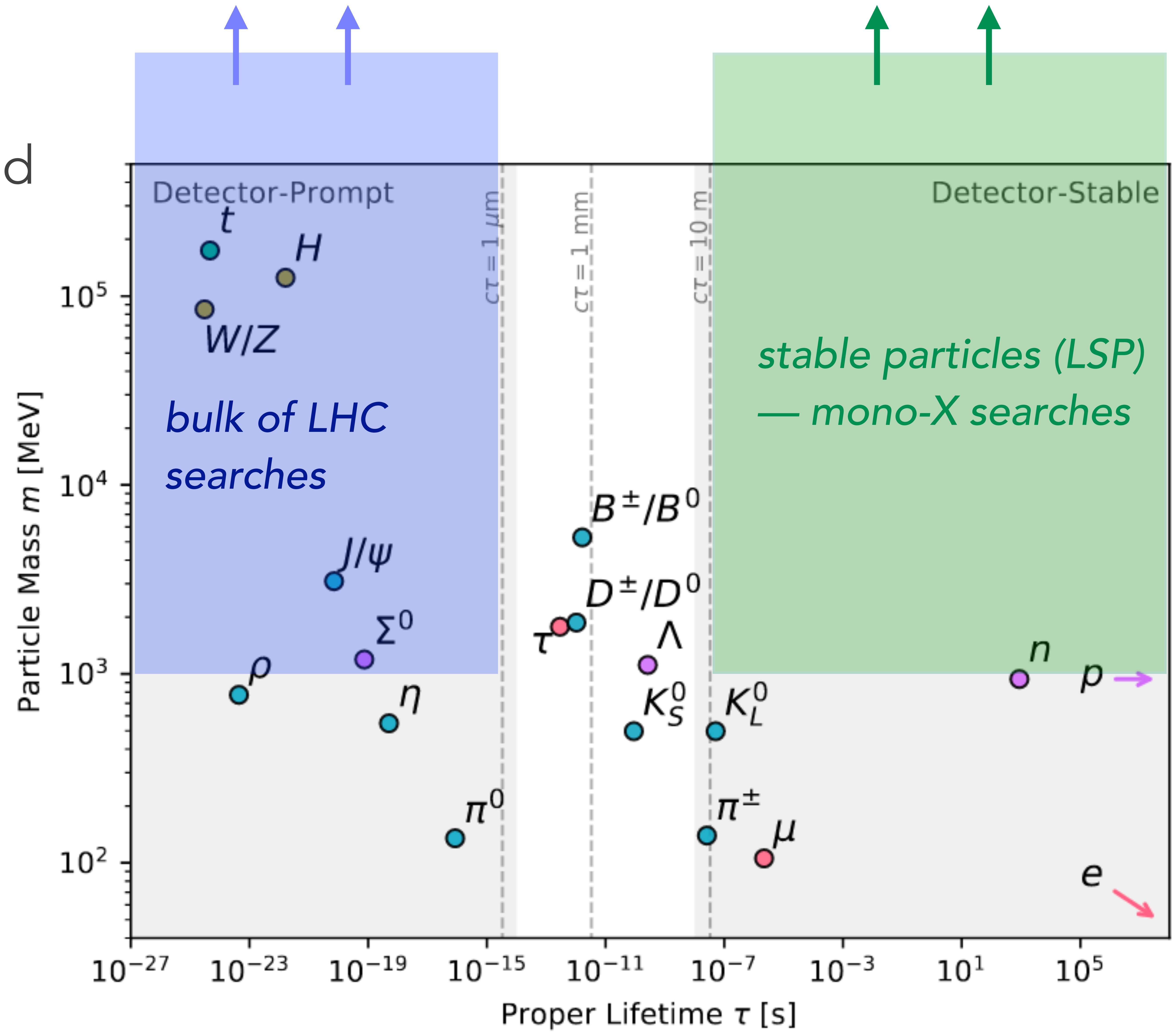

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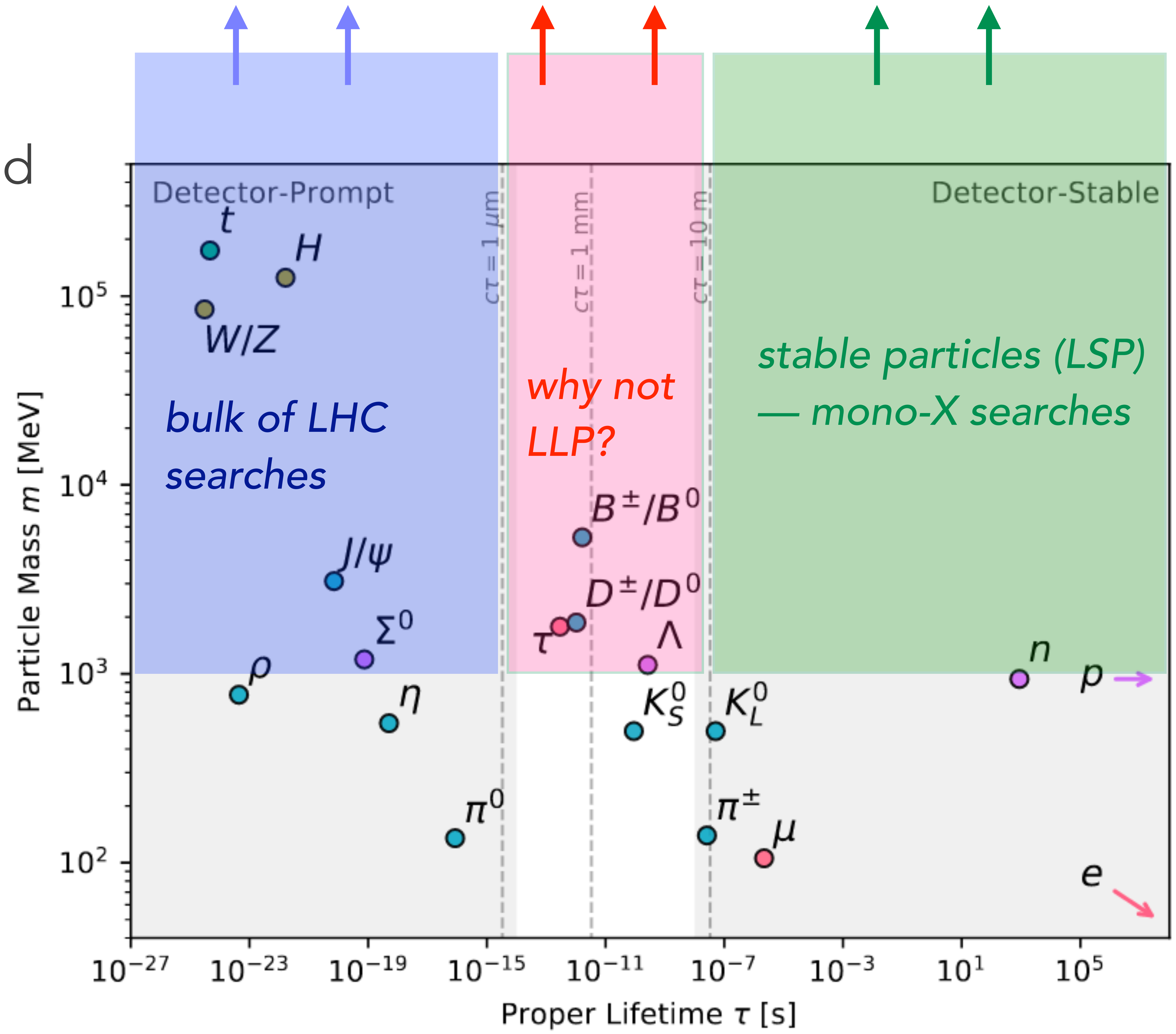

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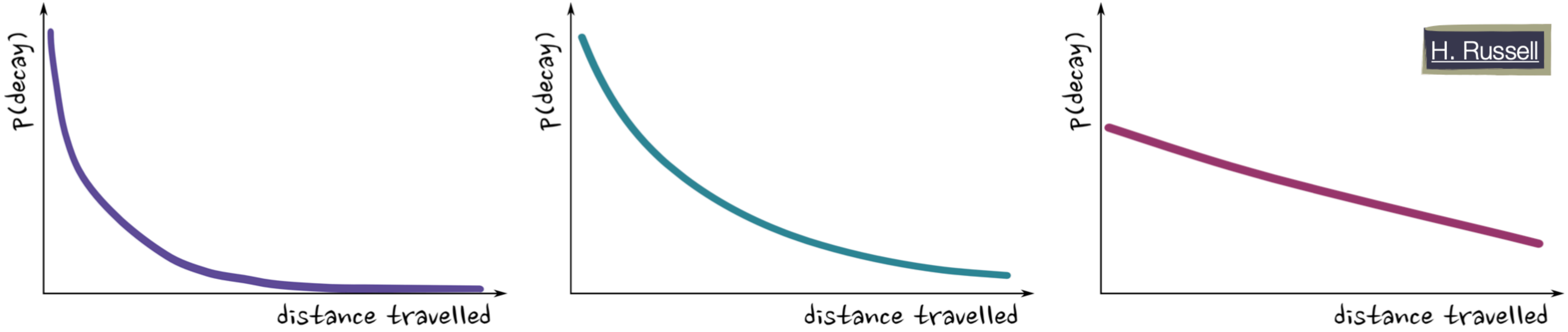
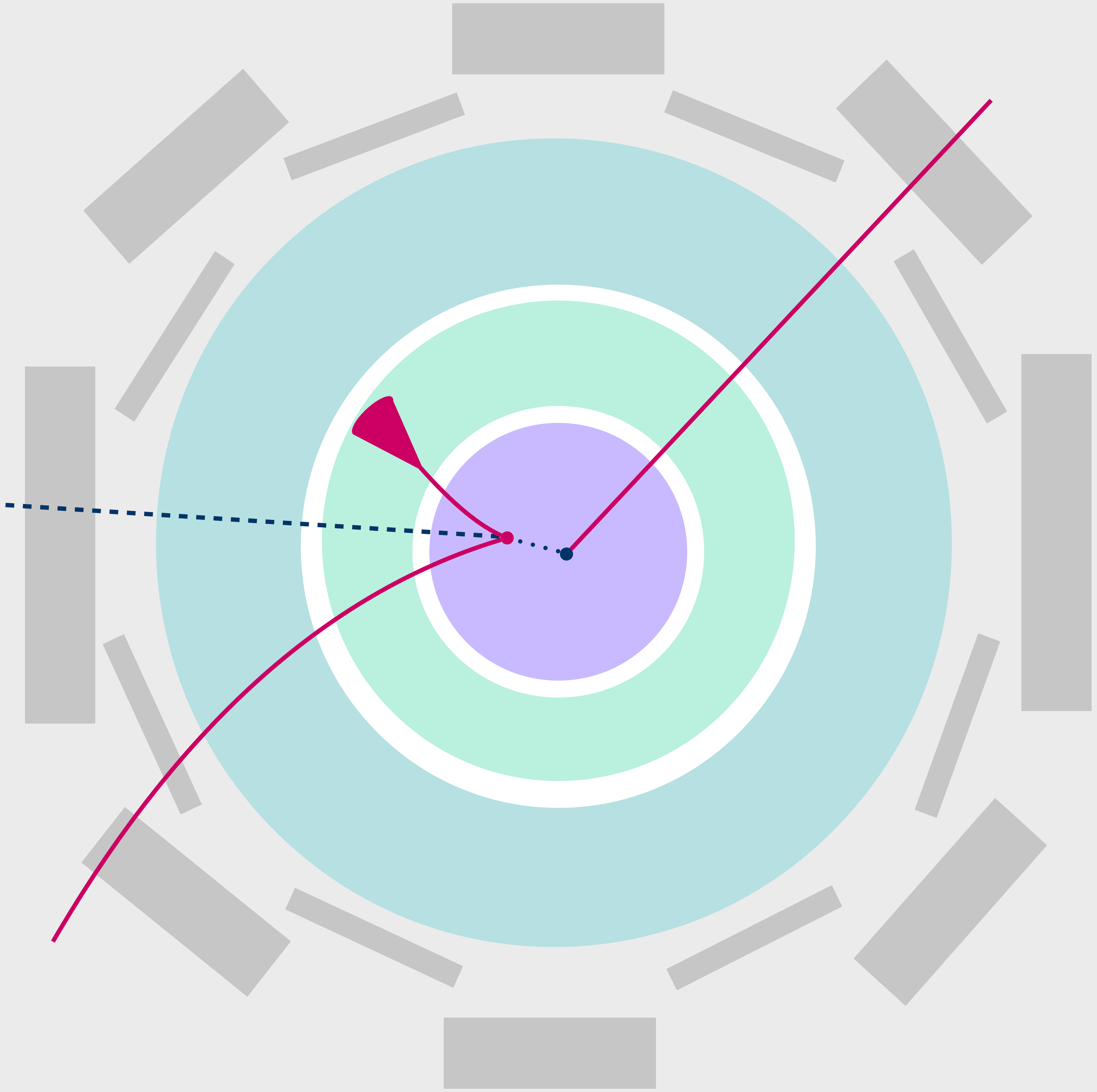
Searching the “lifetime” dimension

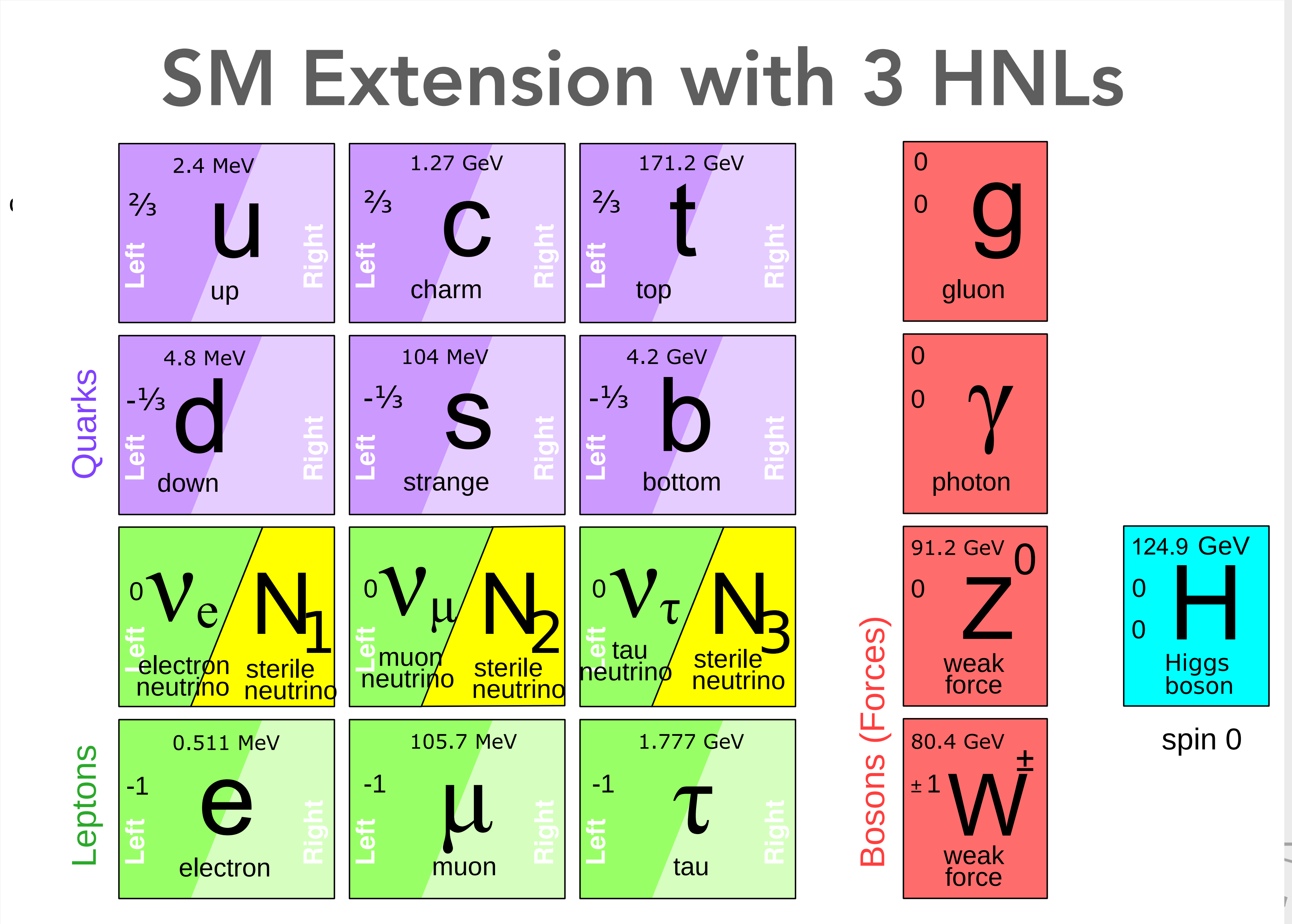
Experimentally: We are looking for particles that decay at a measurable distance from their production point (the pp interaction point at LHC experiments)



Long-lived sterile neutrinos

(Heavy Neutral Leptons, HNLs)





SM Extension with 3 HNLs

Quarks	2.4 MeV ⅔ u up Left Right	1.27 GeV ⅔ c charm Left Right	171.2 GeV ⅔ t top Left Right	0 0 g gluon	
	4.8 MeV -⅓ d down Left Right	104 MeV -⅓ s strange Left Right	4.2 GeV -⅓ b bottom Left Right	0 0 γ photon	
	0 ν_e / N_1 electron neutrino sterile neutrino Left	0 ν_μ / N_2 muon neutrino sterile neutrino Left	0 ν_τ / N_3 tau neutrino sterile neutrino Left	91.2 GeV 0 0 Z^0 weak force	124.9 GeV 0 0 H Higgs boson
Leptons	0.511 MeV -1 e electron Left Right	105.7 MeV -1 μ muon Left Right	1.777 GeV -1 τ tau Left Right	80.4 GeV ±1 $W^\pm$ weak force	spin 0

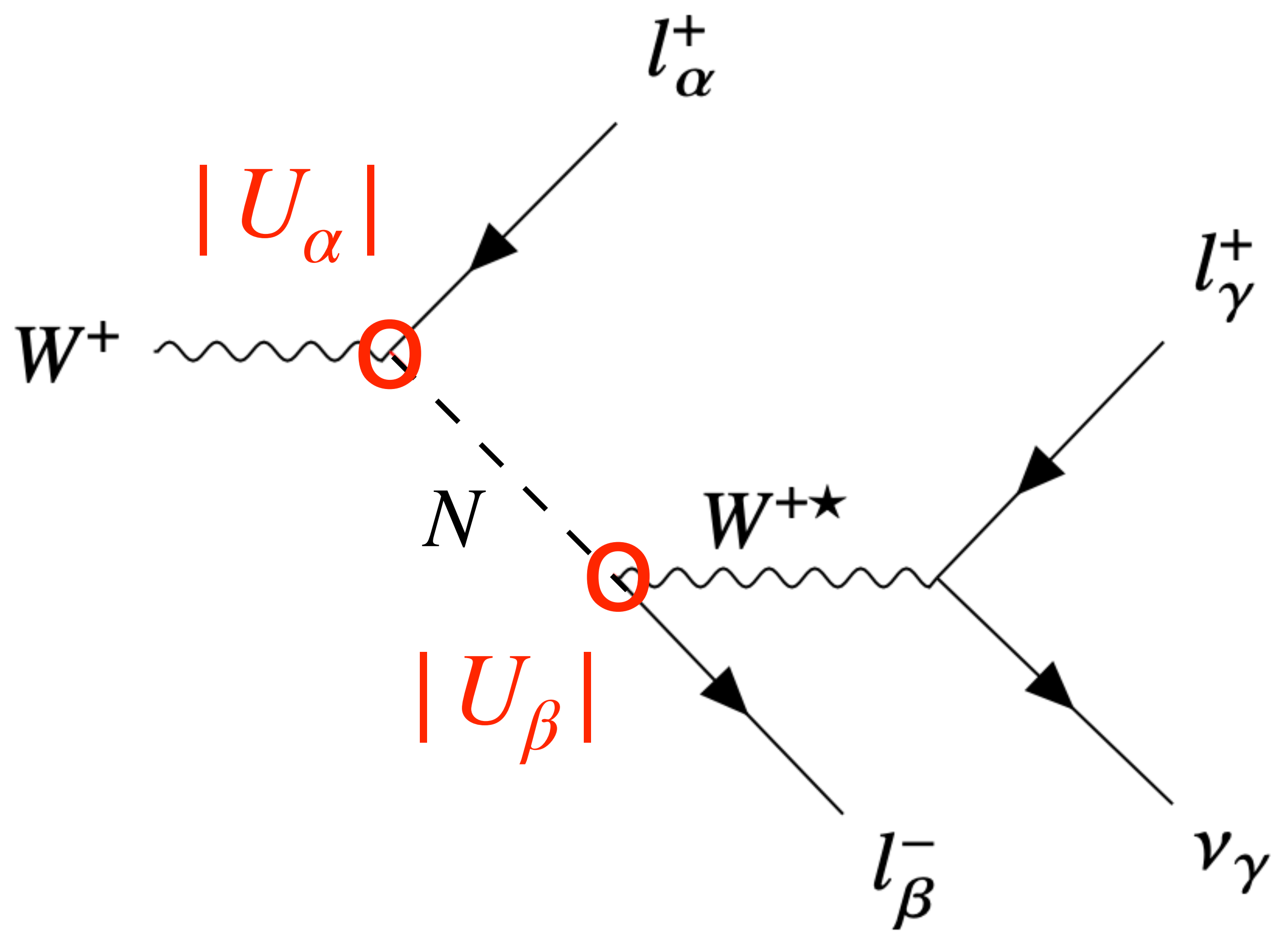
Bosons (Forces)

arxiv:1301.5516

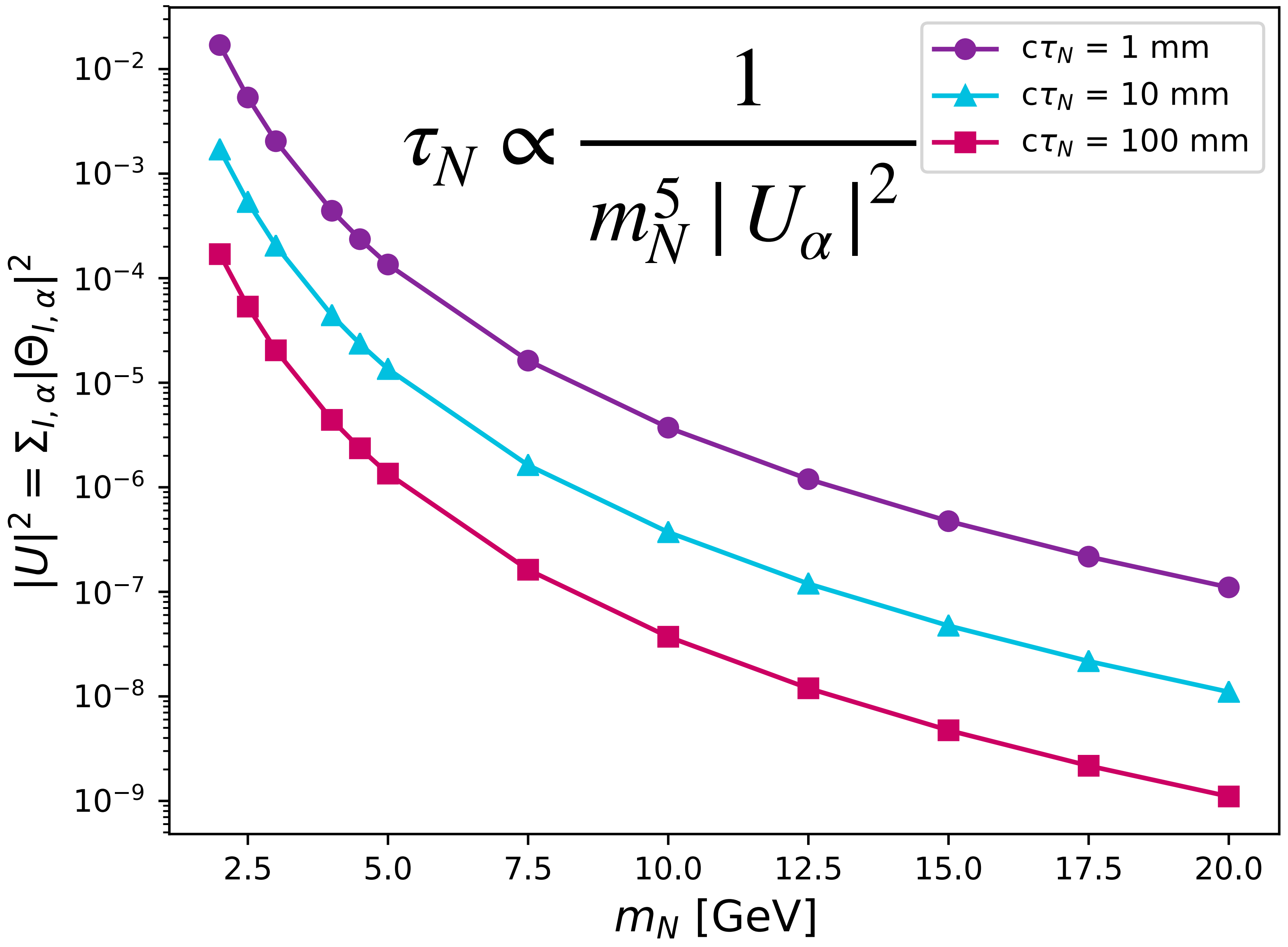
CMS: EXO-20-009

ATLAS: EXOT-2019-29

Long-lived sterile neutrinos (Heavy Neutral Leptons, HNLs)



- HNLs experience "weak-like" interactions controlled by dimensionless mixing angles ($|U_\alpha|^2$)
- m_N dictates kinematics of decay products
- HNL can be Majorana- or Dirac-like particle
  - Dirac —> Lepton Number is conserved **(LNC)**
  - Majorana —> Lepton Number is violated **(LNV)**



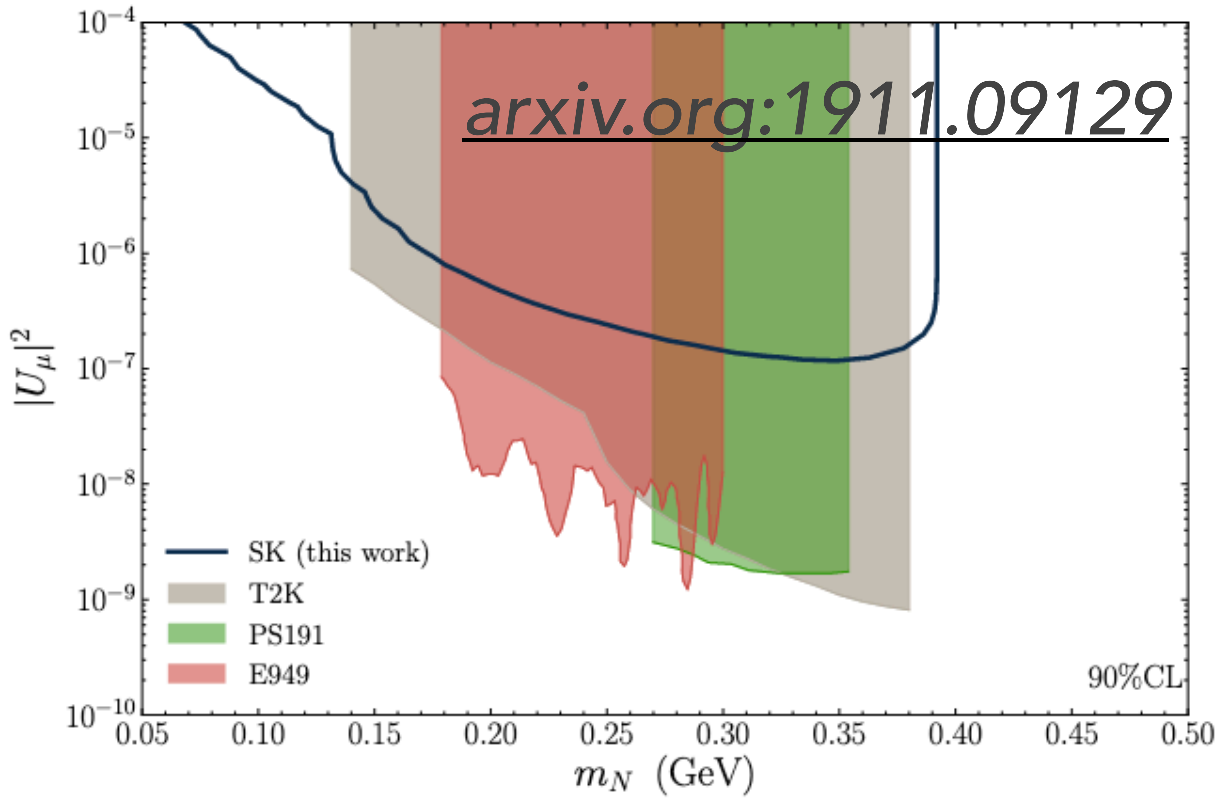
$$\tau_N \propto \frac{1}{m_N^5 |U_\alpha|^2}$$

Crucial HNL model parameters:

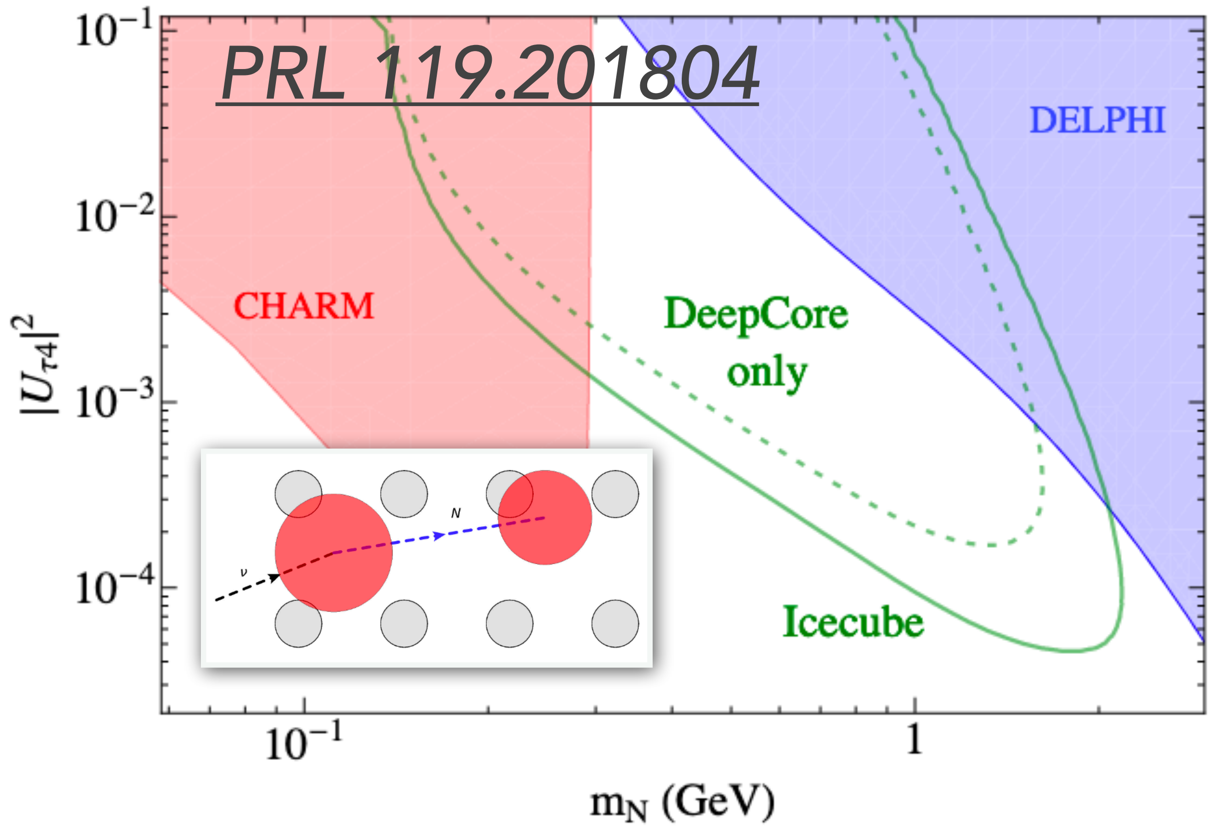
$\lvert U_\alpha \rvert^2$	Mixing angle between SM neutrino and HNL
m_N	HNL mass

Long-lived sterile neutrinos (Heavy Neutral Leptons, HNLs)

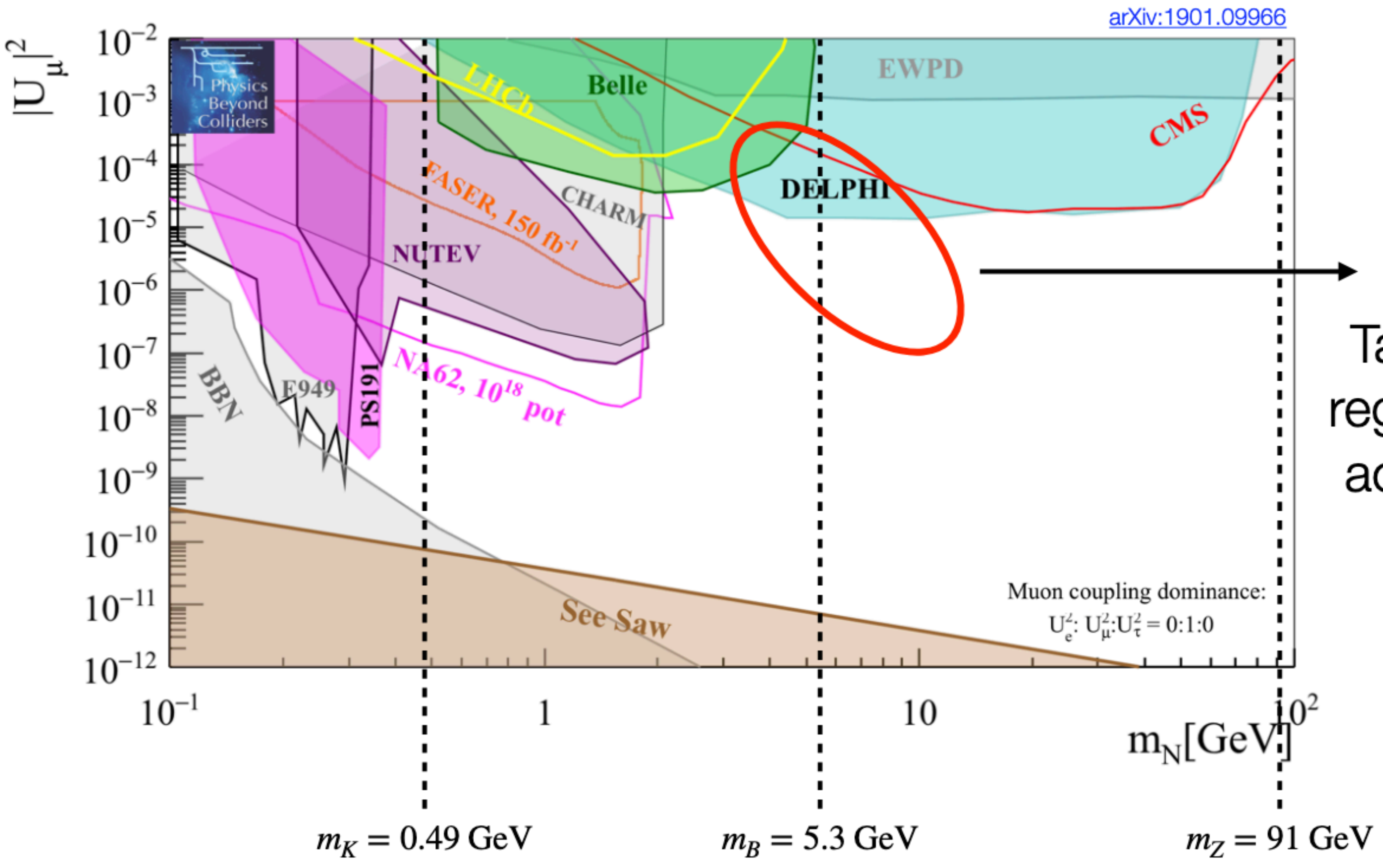
- Complementarity of searches is enormous for HNLs



arxiv.org:1911.09129



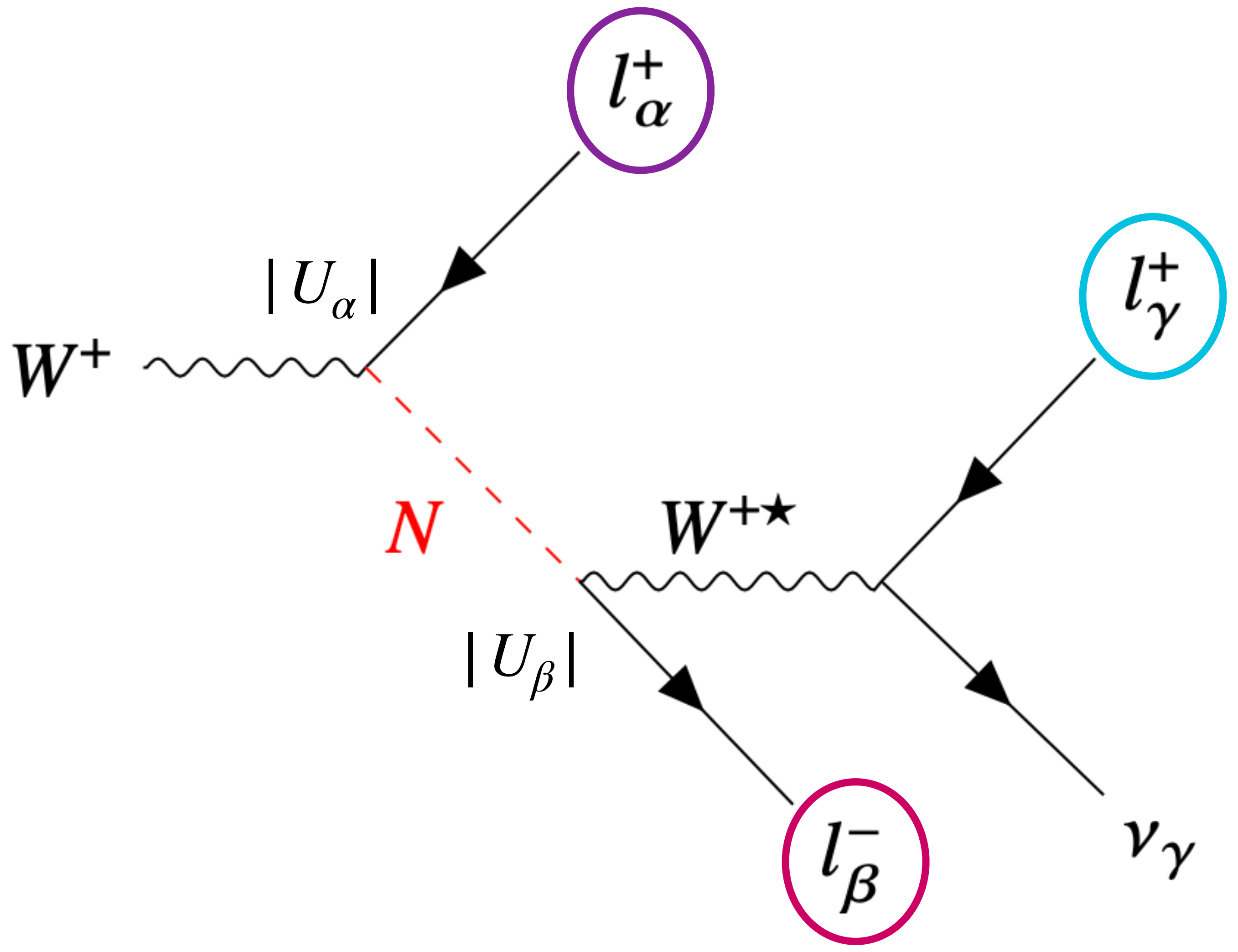
PRL 119.201804



arXiv:1901.09966

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

HNLs: Experimental signature



$$\underset{\swarrow\ \text{prompt}}{\alpha} - \underbrace{\beta\,\gamma}_{\text{displaced}}$$

<u>Experimental HNL Signature:</u>

- Prompt lepton
- DV with 2 leptons that have opposite **charge**

graphics: D. Trischuk

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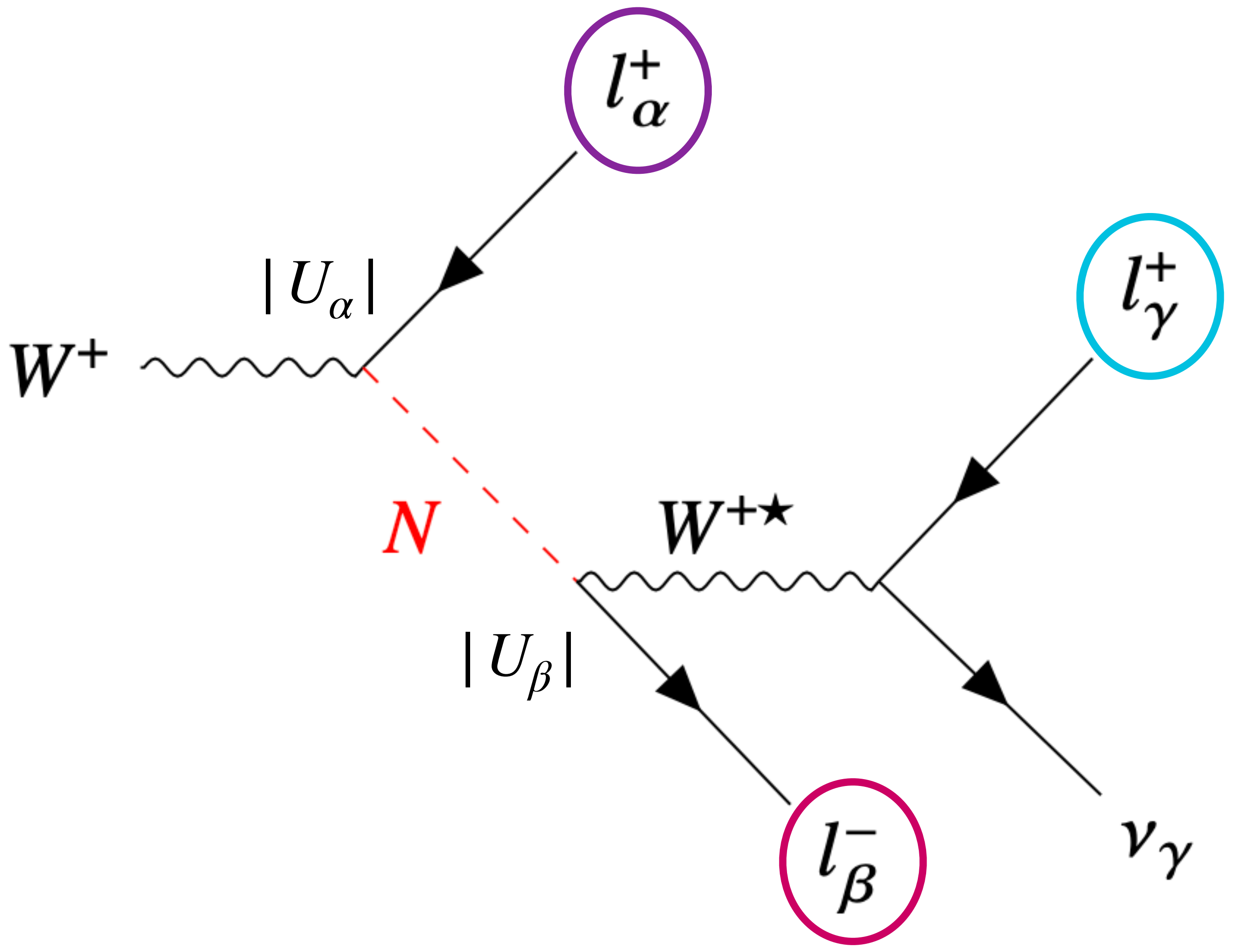

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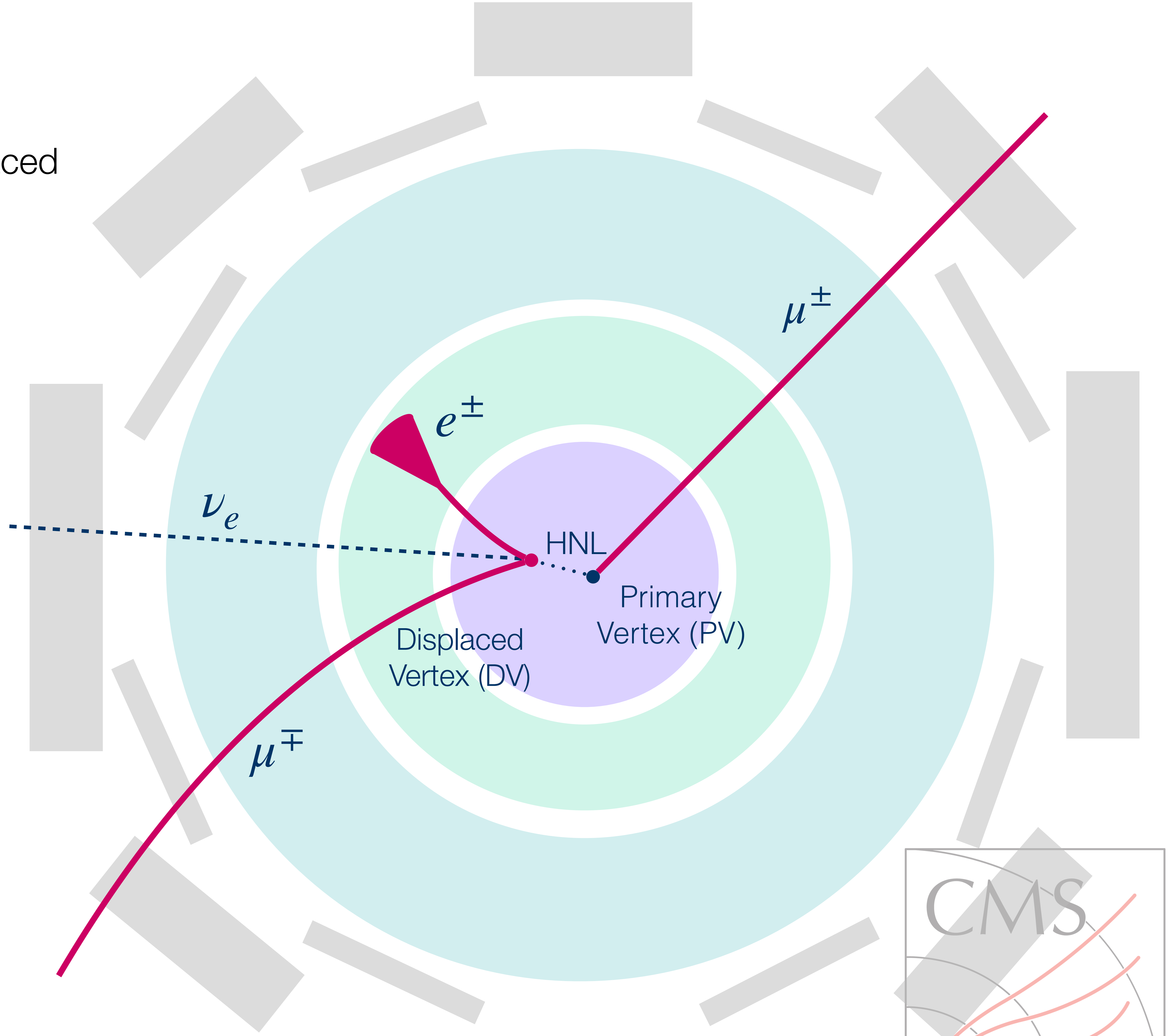

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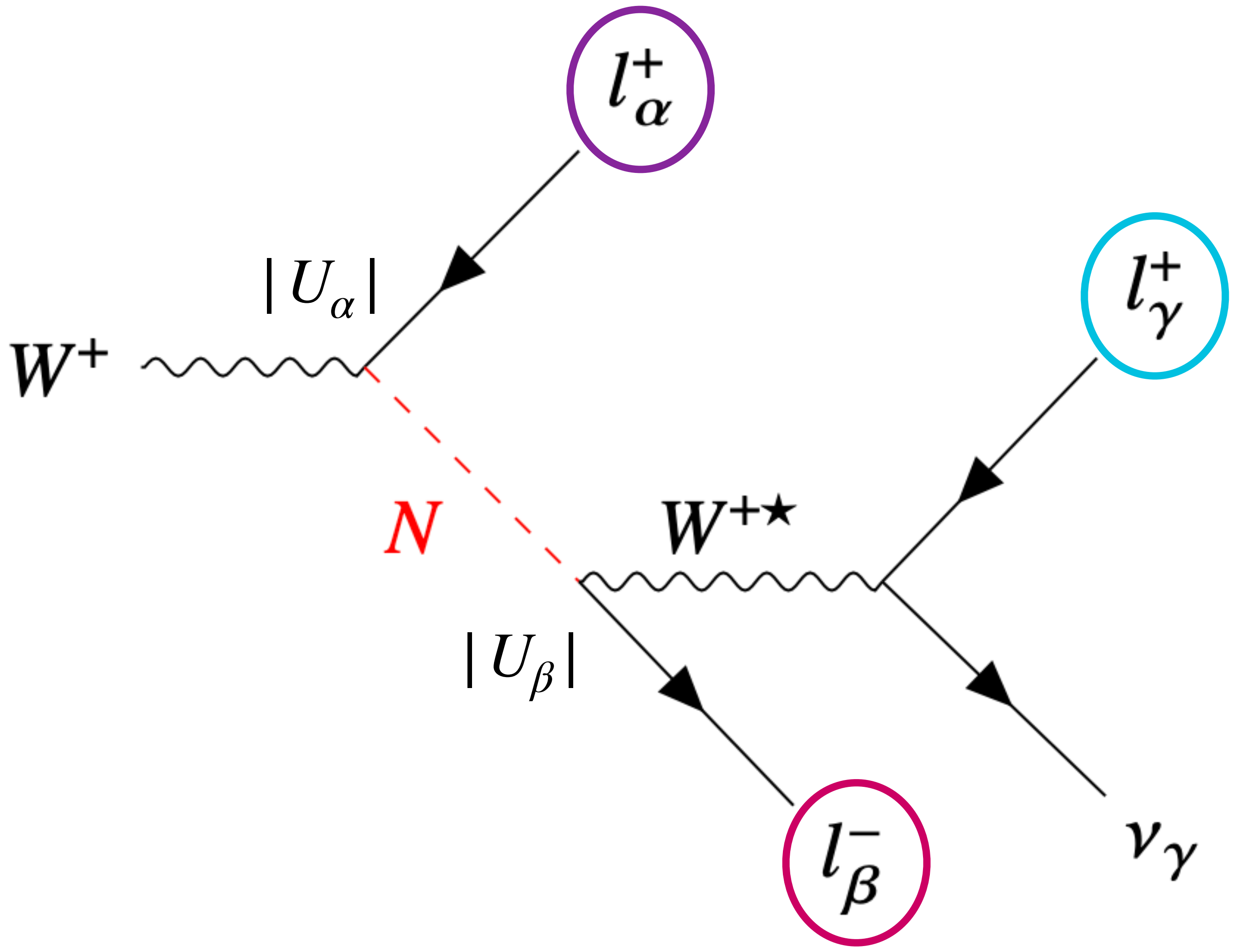

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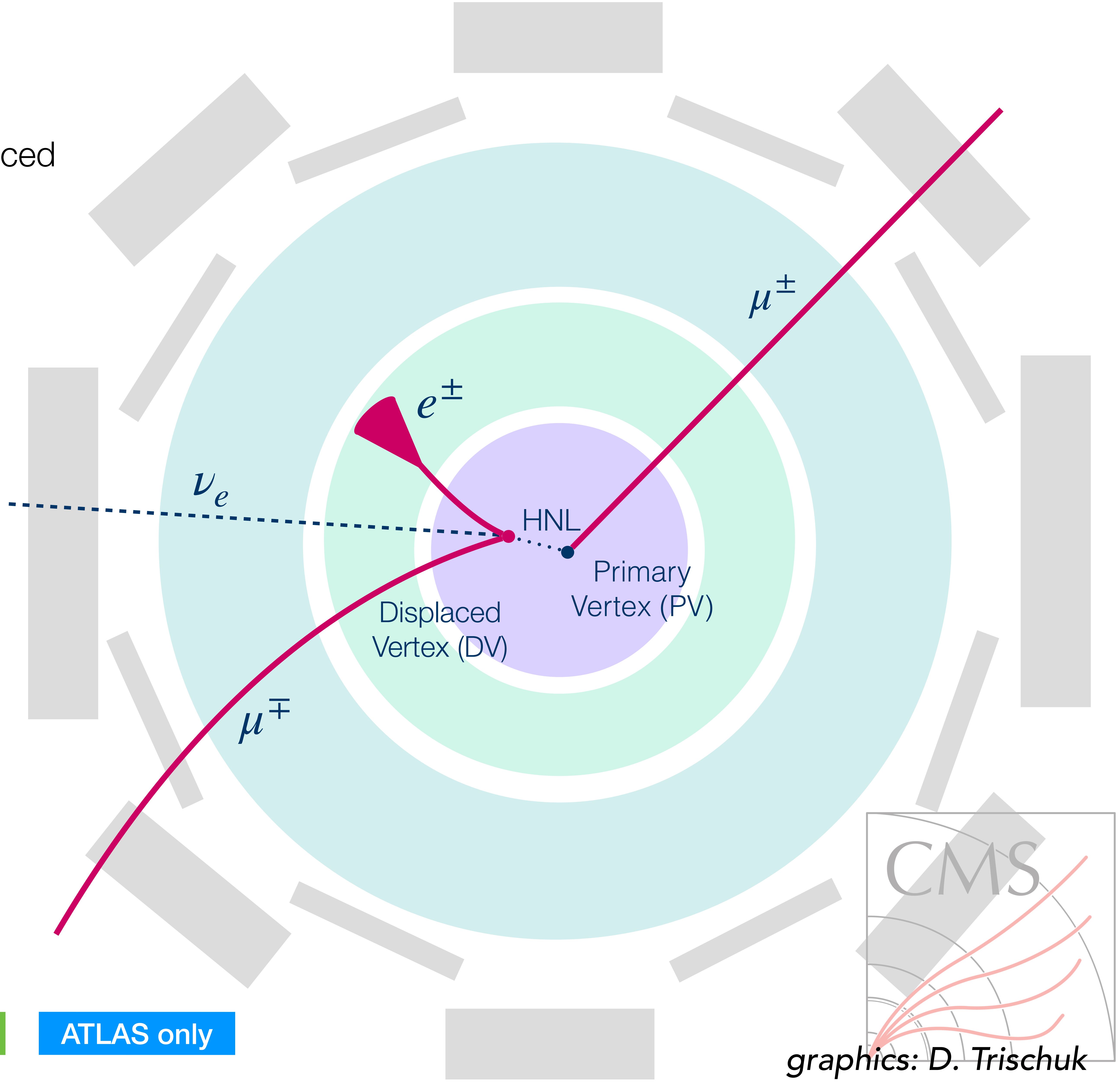
Six signal regions (SR):

μ-μμ, μ-μe, μ-ee, e-ee, e-eμ, e-μμ

ATLAS + CMS

ATLAS only



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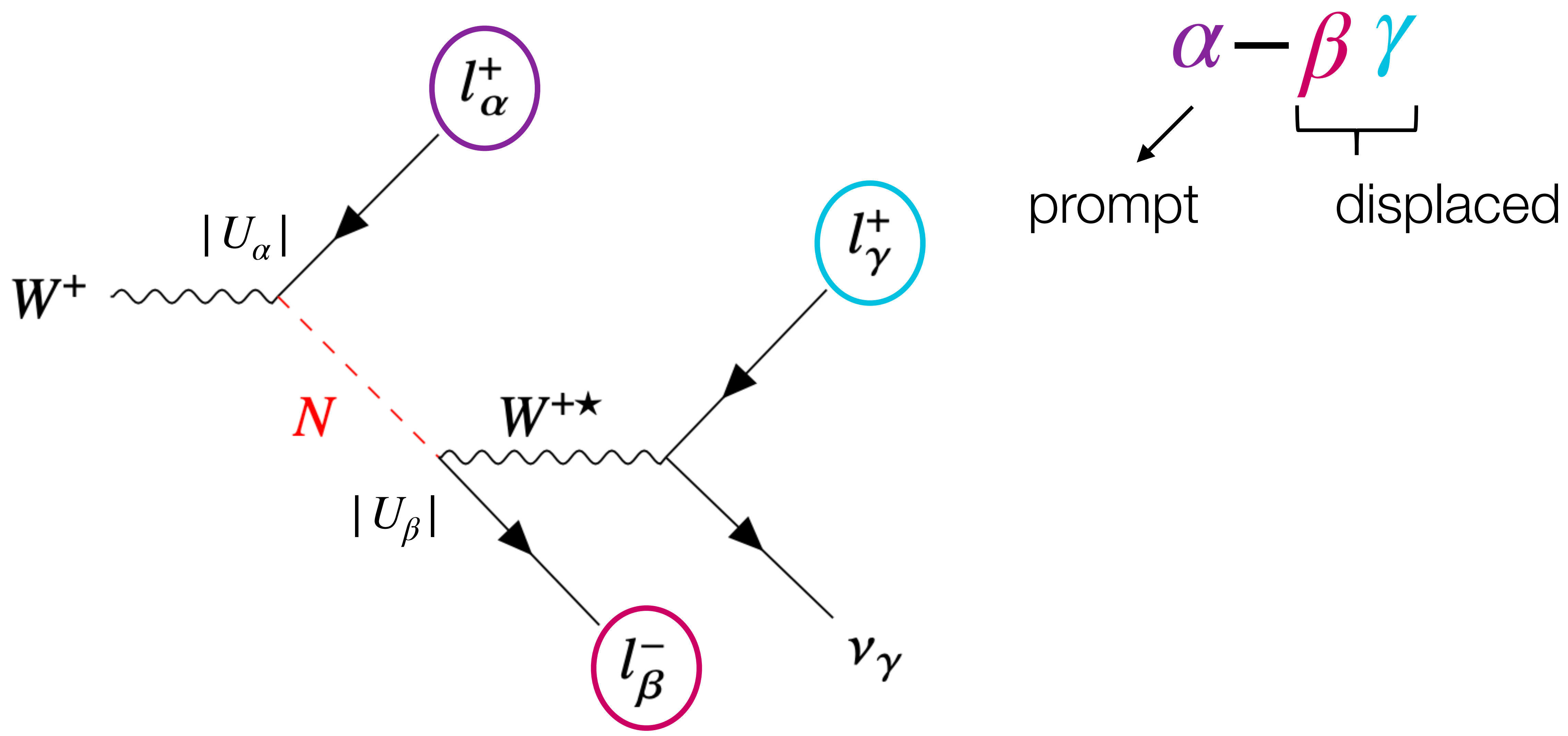
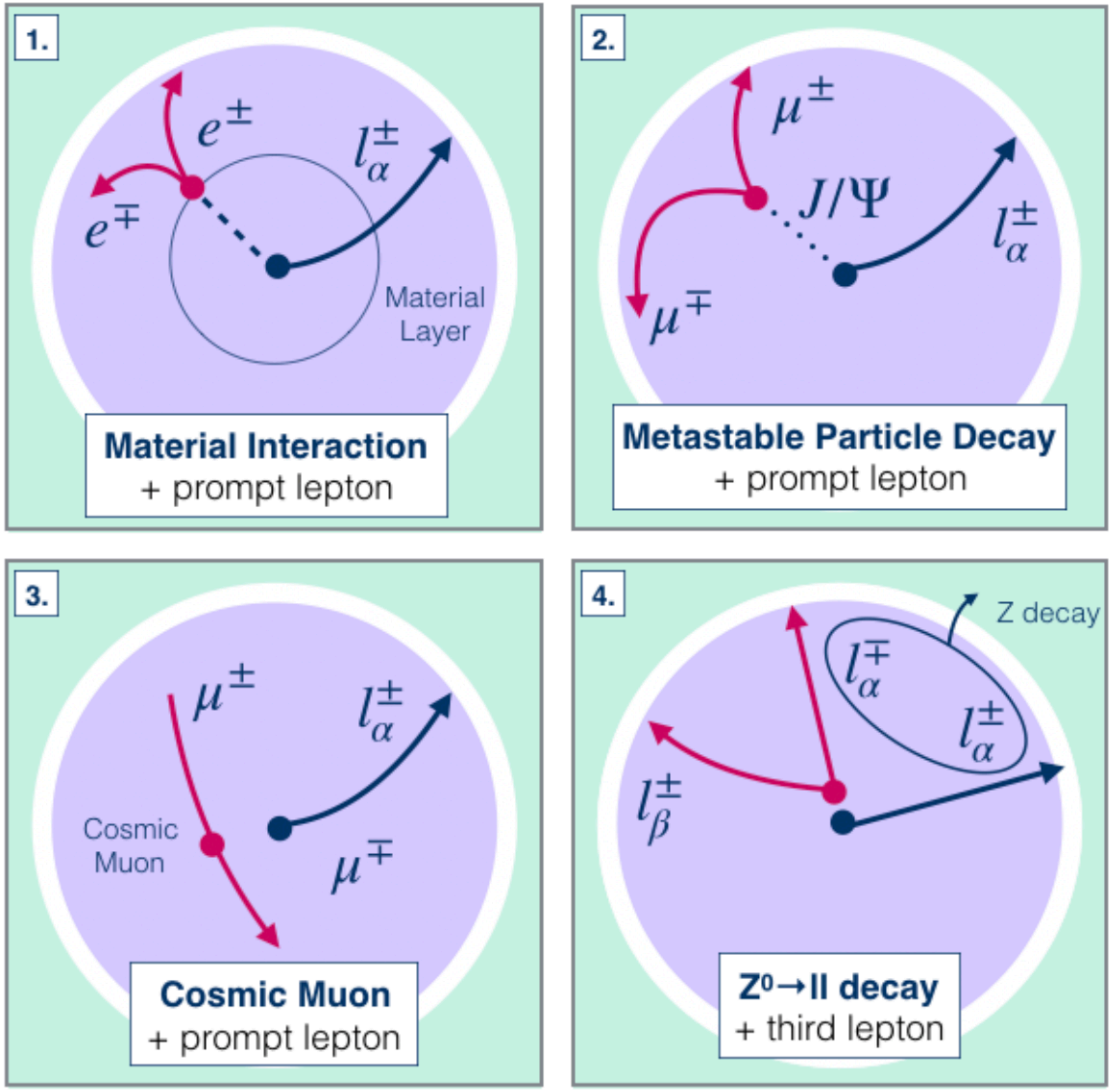


Dominant background sources:

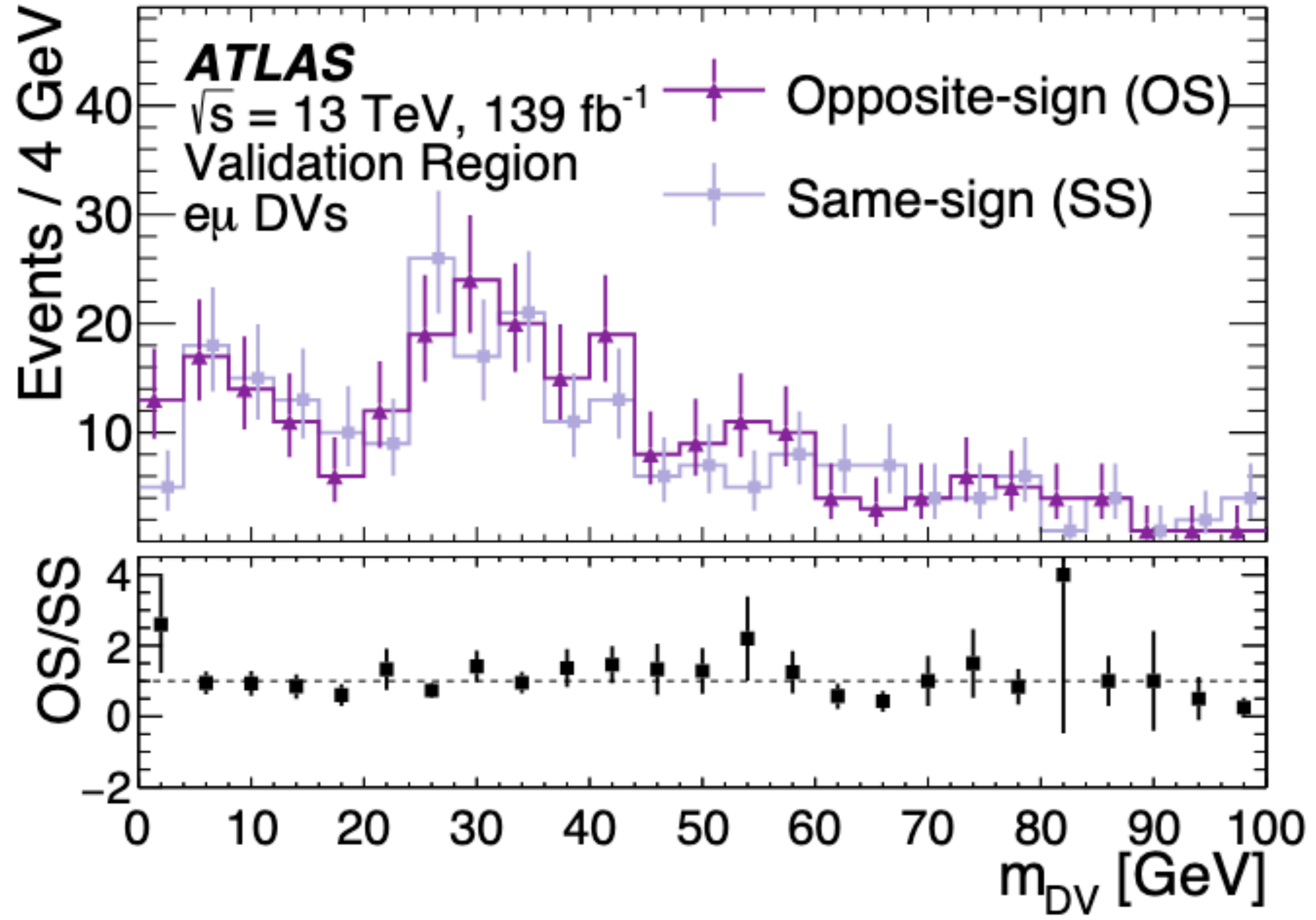
(1) Material interactions
(2) Metastable particle decays (J/ψ, B-hadrons,..)
(3) Cosmic muons
(4) Z decays paired with third lepton
(5) Random track crossing

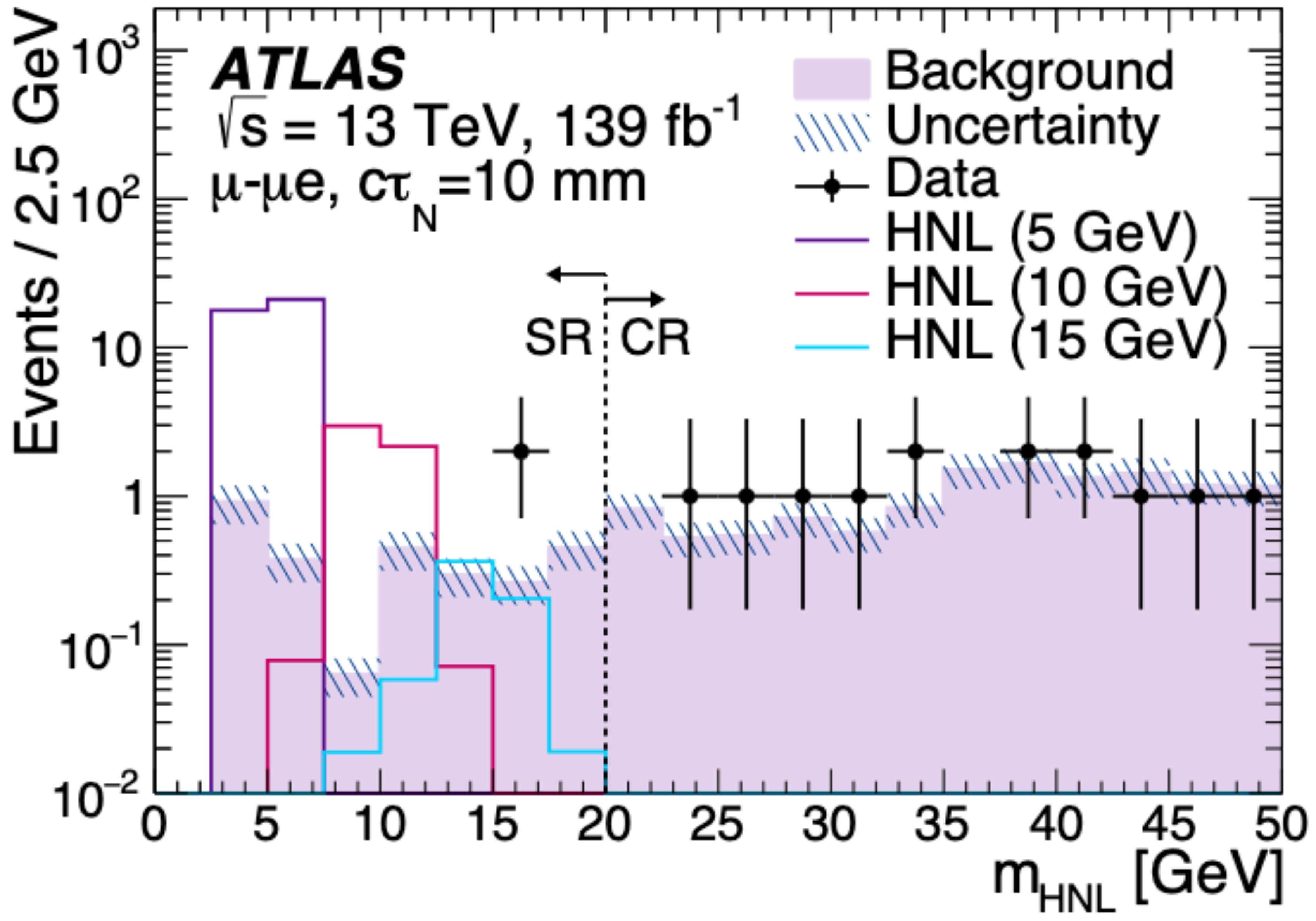


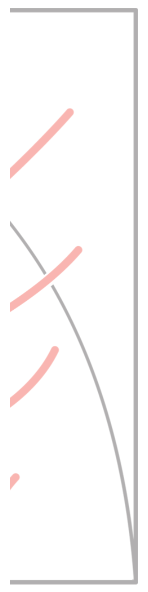
graphics: D. Trischuk

HNLs: ATLAS analysis details

- After cuts, background is dominated by random track crossings
- Validation region (prompt-lepton veto) is used for data driven background estimate in SR using toys
- **Energy-momentum conservation** is used to reconstruct the HNL mass $m_{\text{HNL}}^2 = (P_{l_\beta} + P_{l_\gamma} + P_{\nu_\gamma})^2$
- Simultaneous fit of SR & CR —> No excess observed







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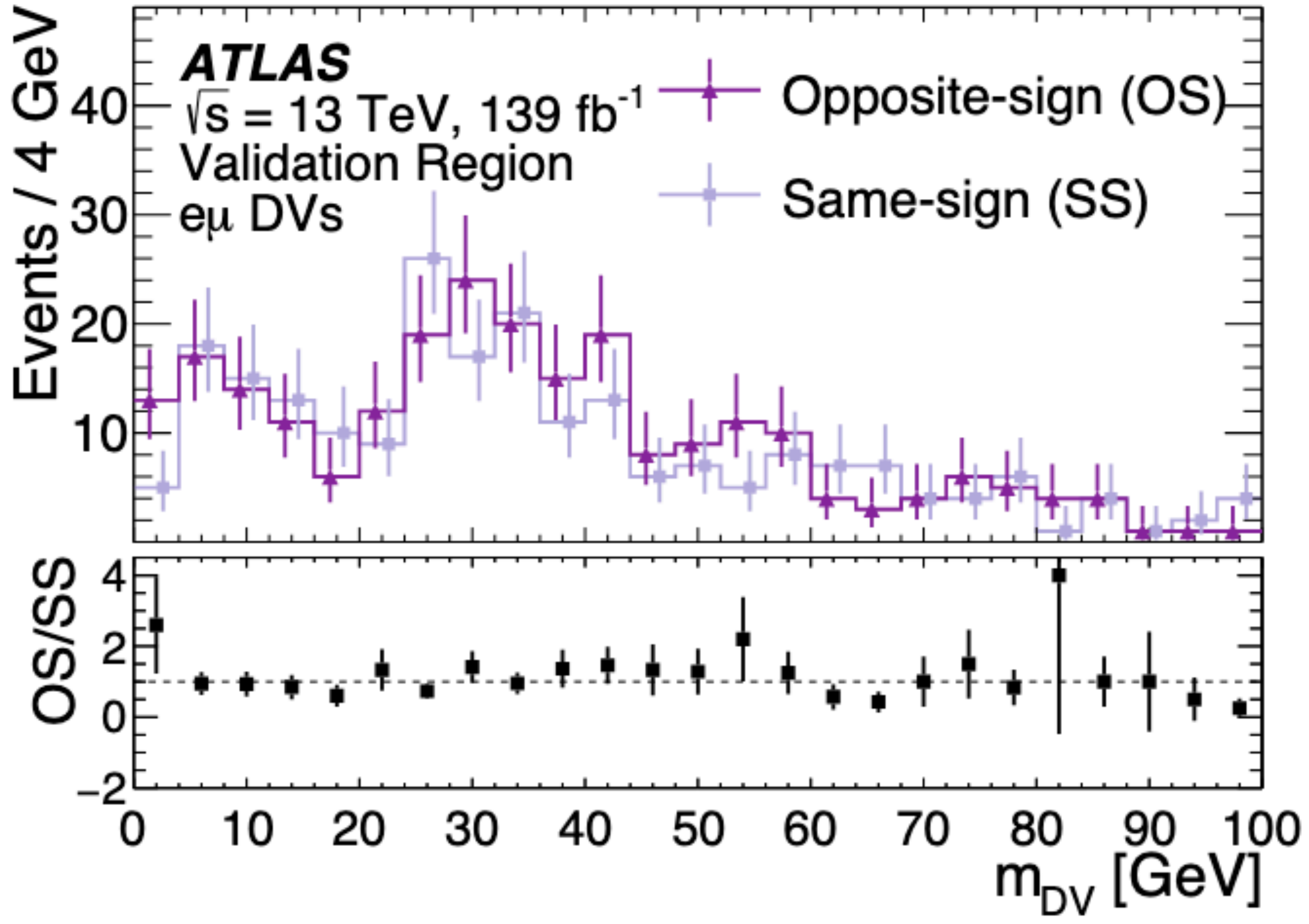
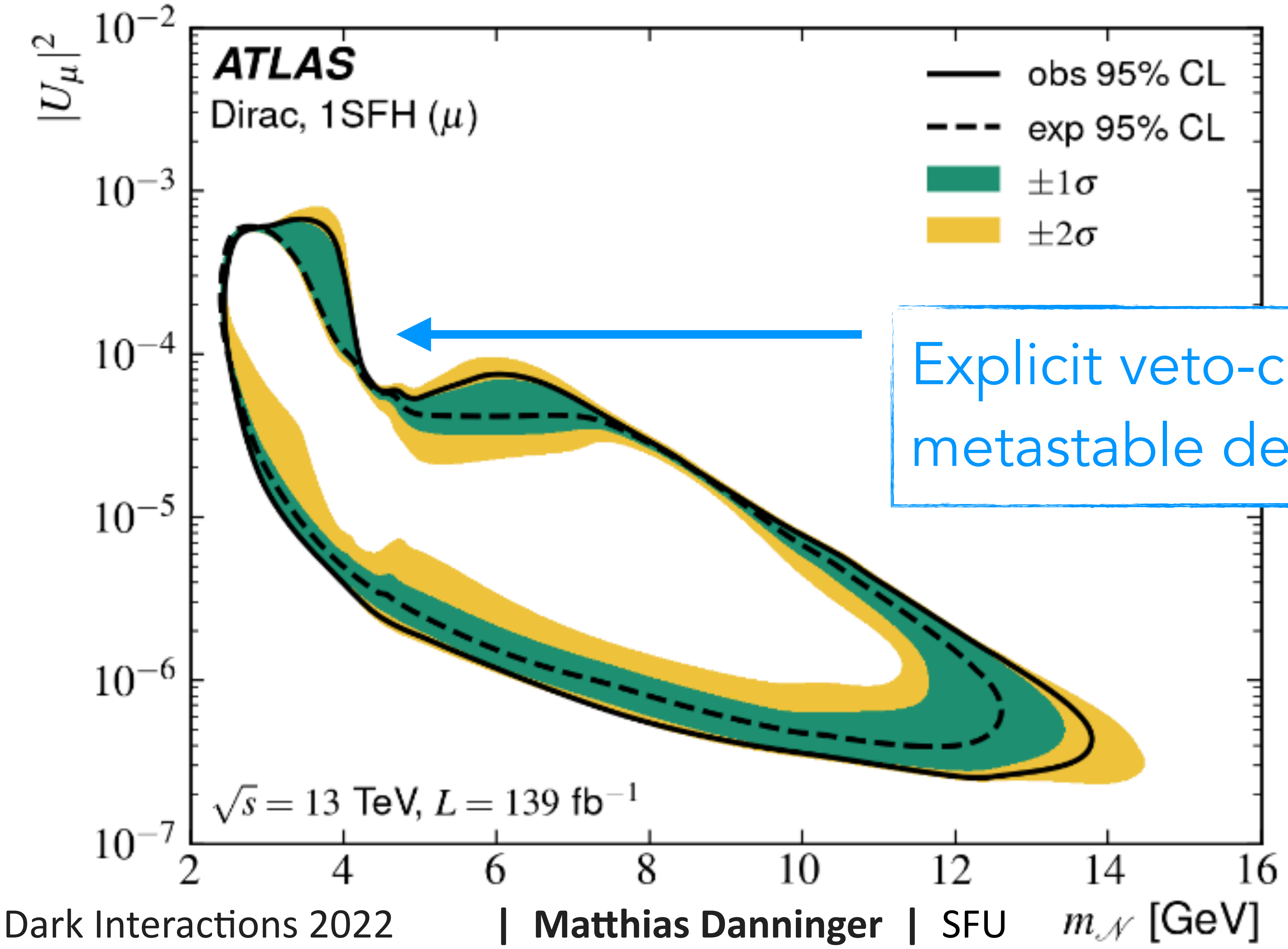
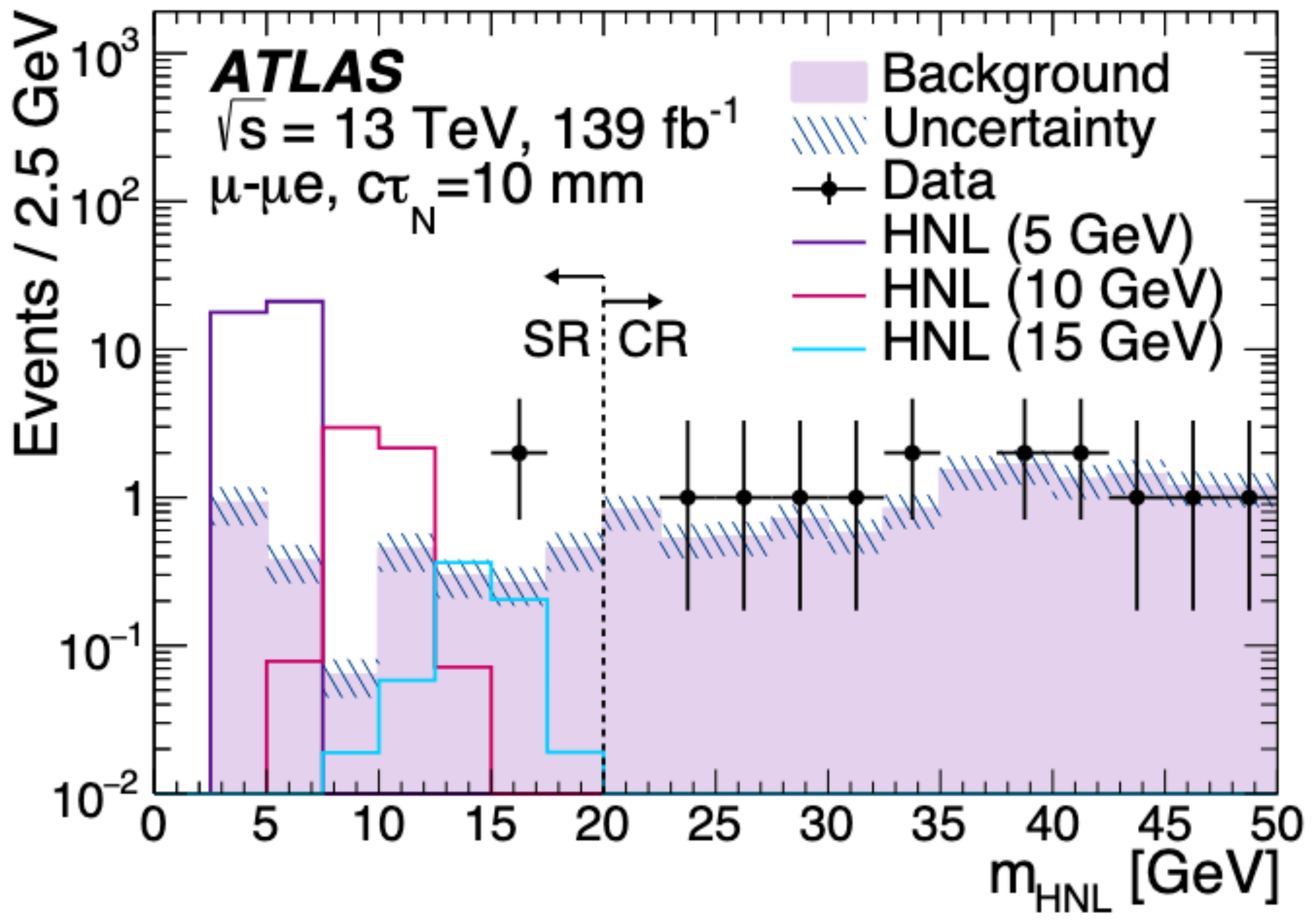


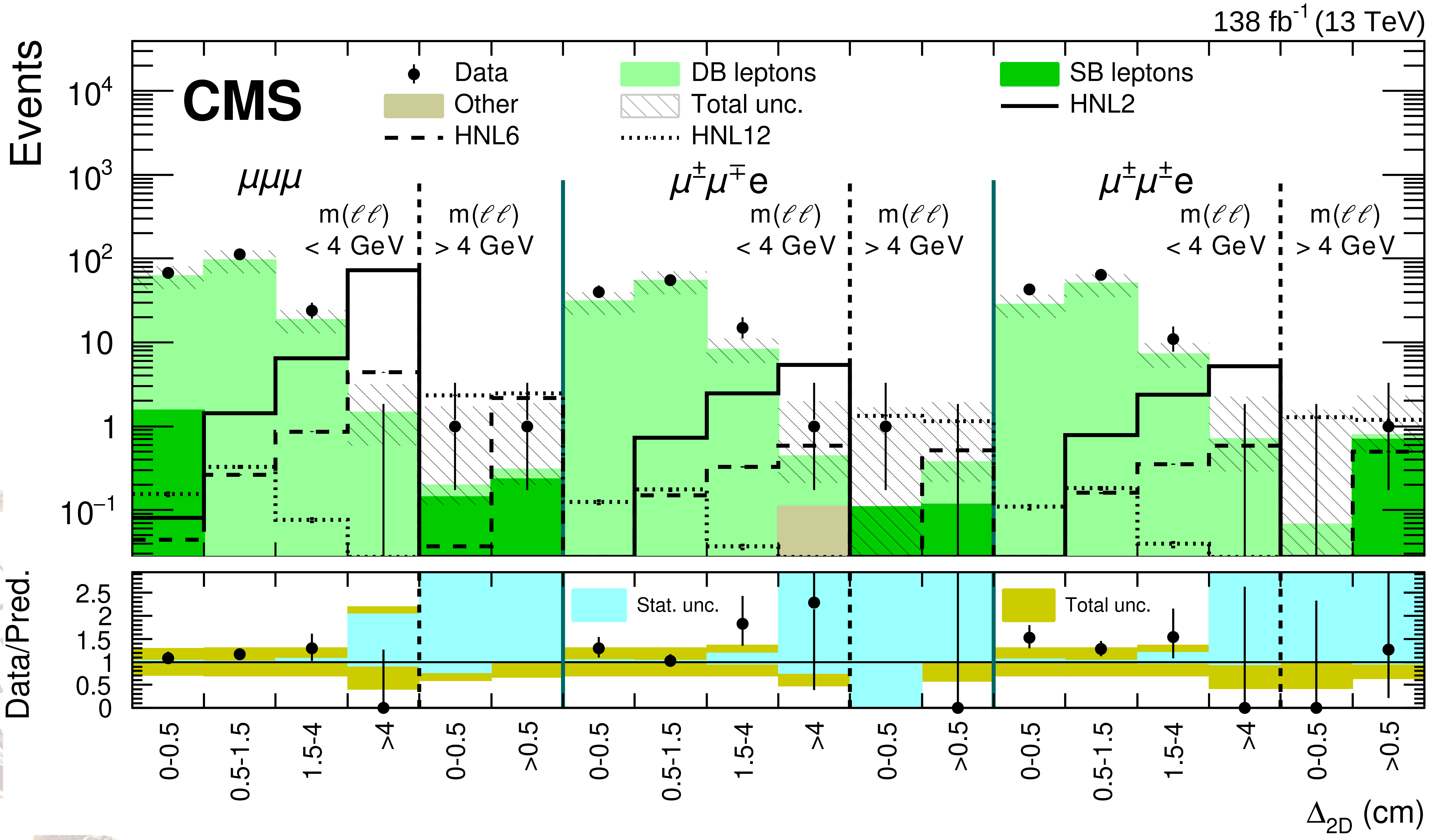


Explicit veto-cut on metastable decays



HNLs: CMS analysis details

- In each three-lepton final state events are categorized by:
  - Dilepton invariant mass of displaced lepton pair, $m_{(ll)}$
  - Explicit veto on b-jets
  - Transverse displacement of displaced lepton pair, Δ_{2D}
- SM background derived using data control samples
- No excess observed



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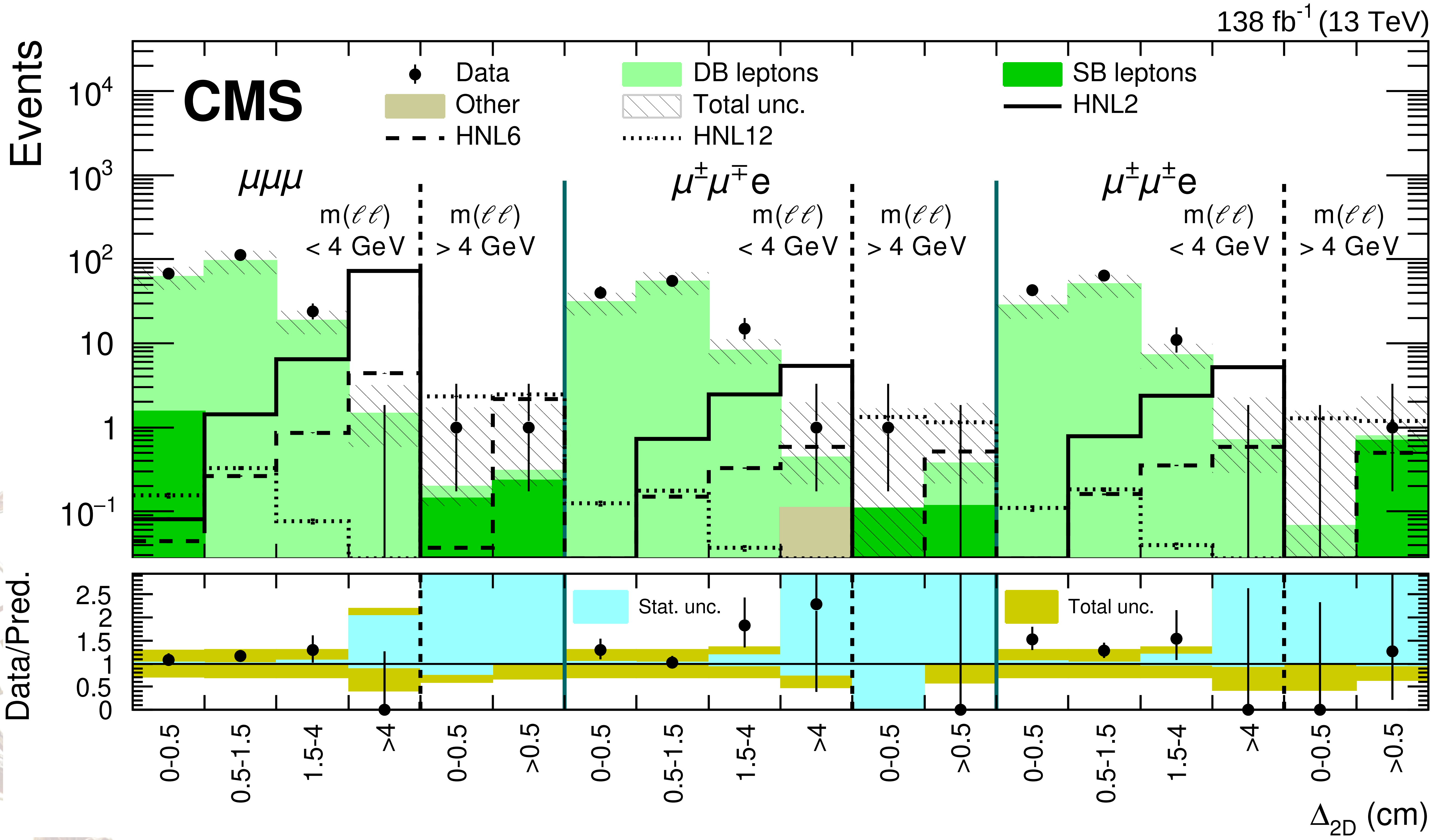

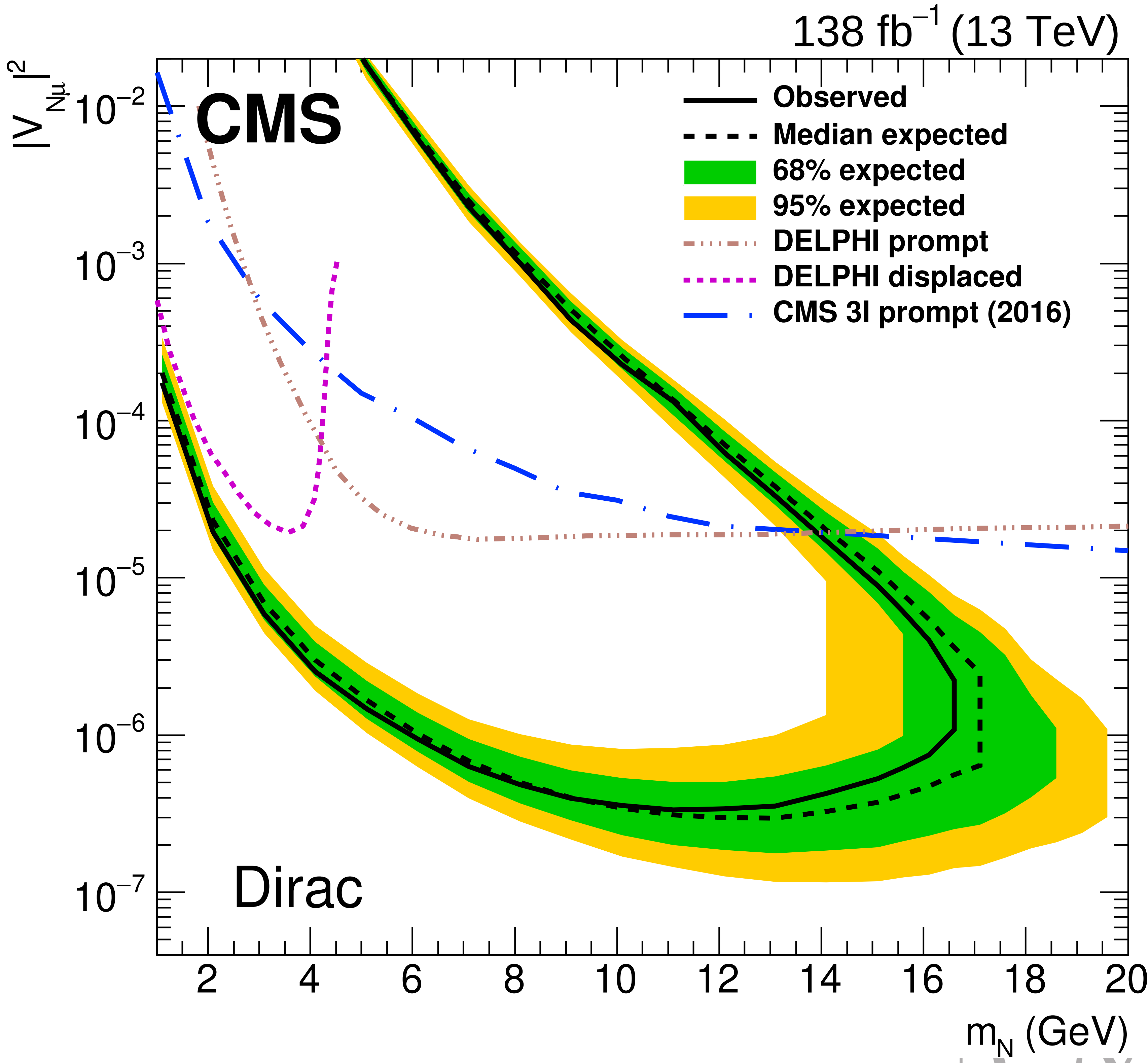

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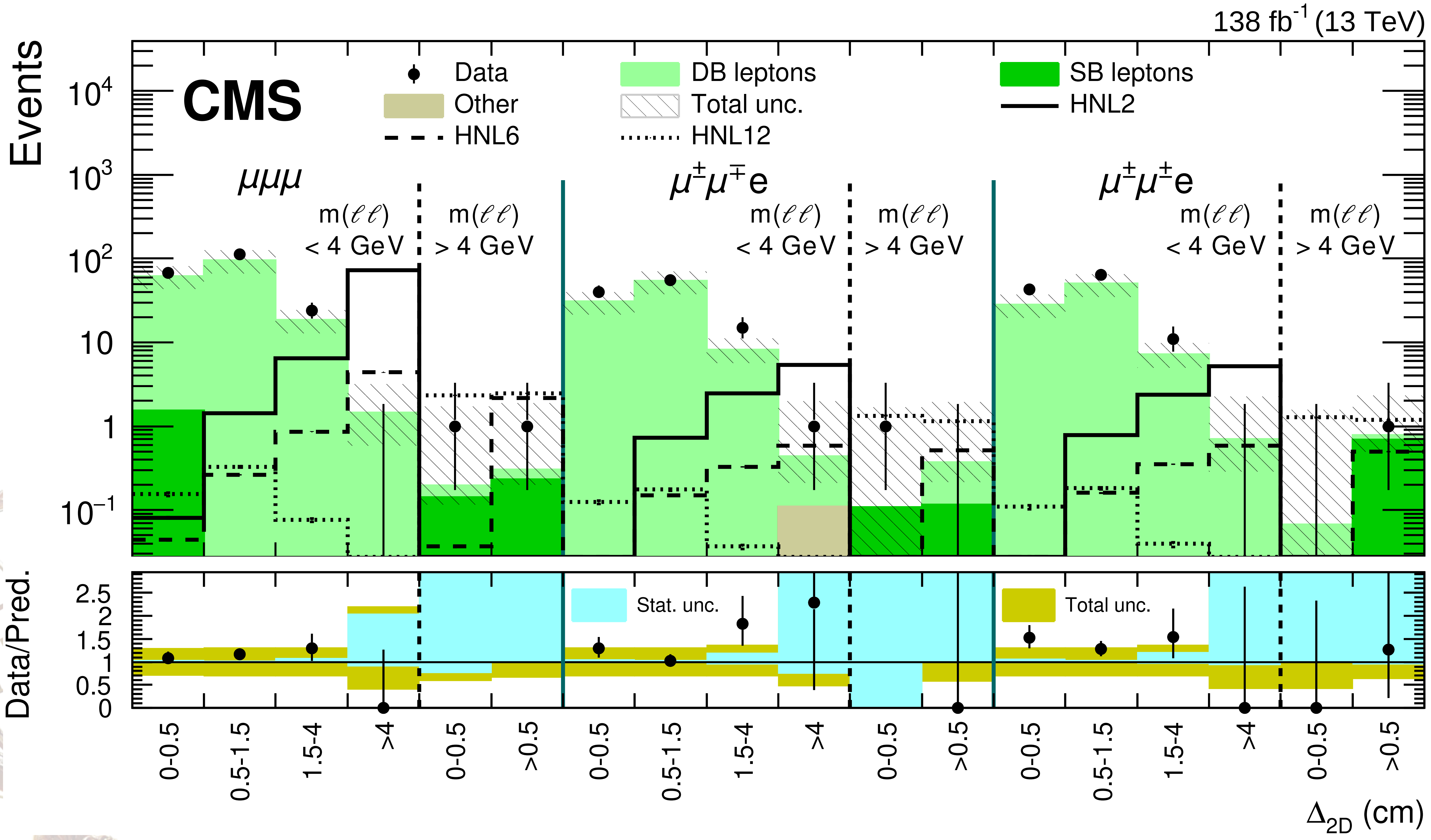
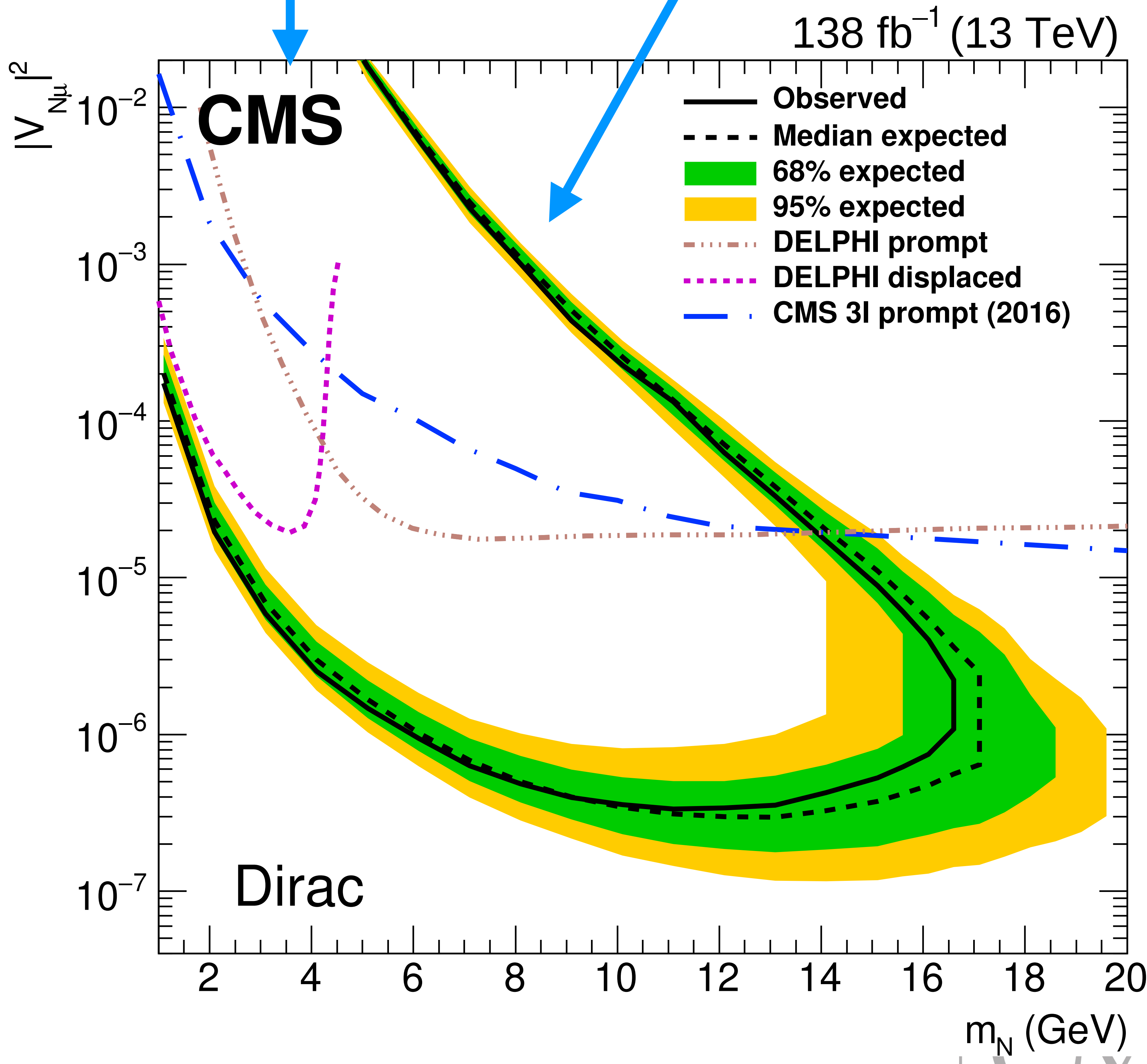


ATLAS vs. CMS:

- No low mass cut-off!
- Prompt to displaced continuous result!



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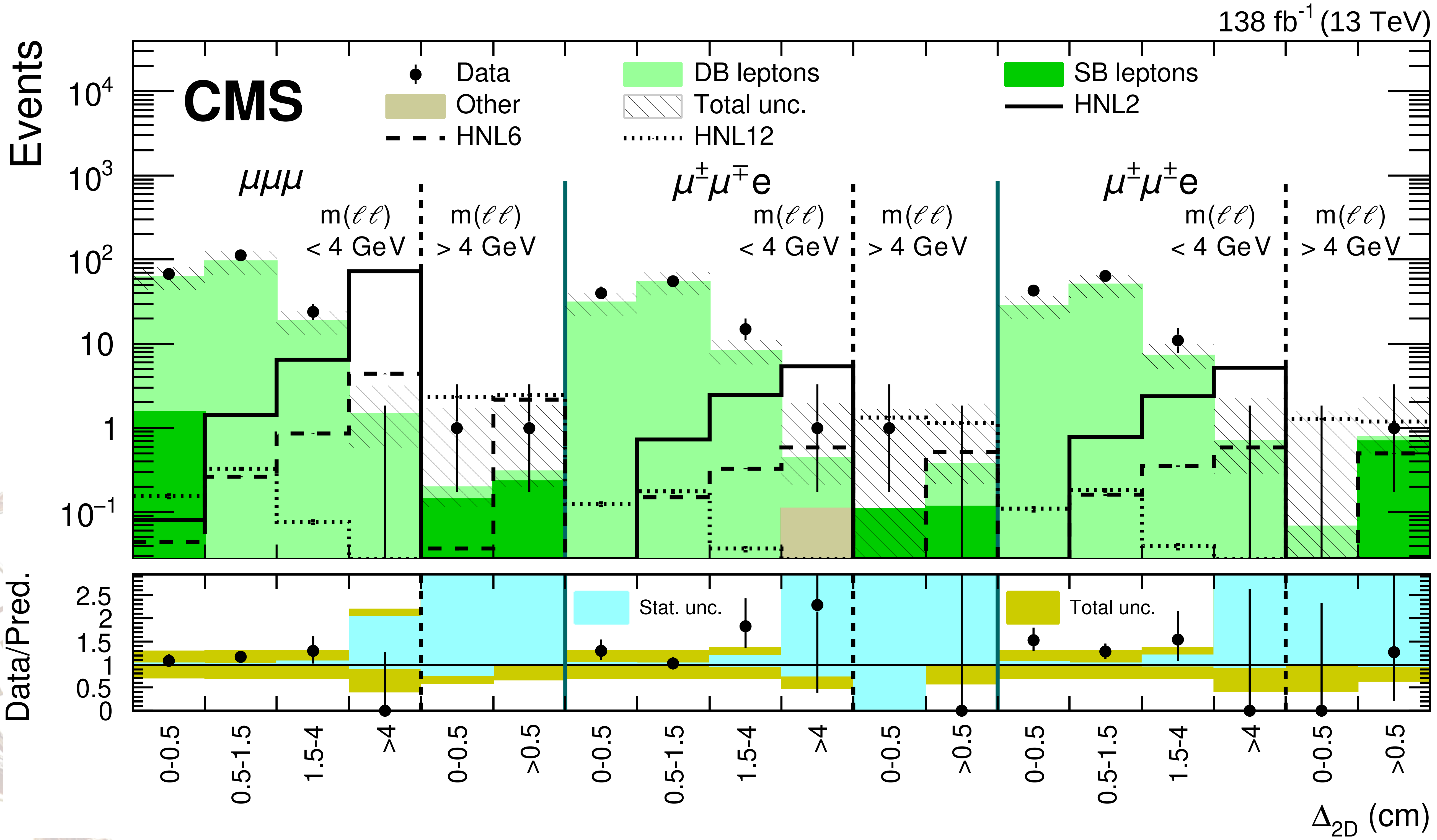

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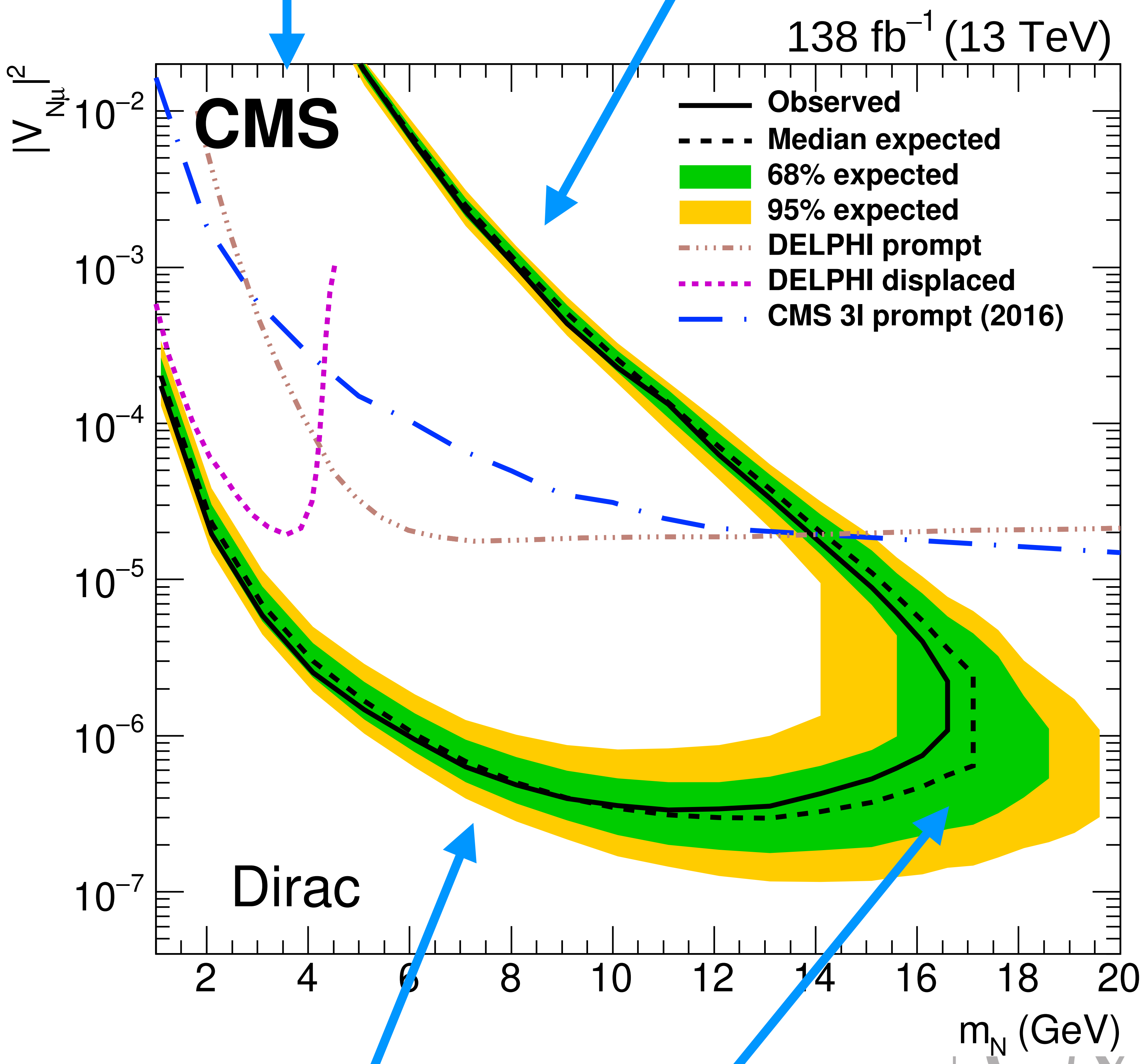


ATLAS vs. CMS:

- comparable mass - coupling reach

Results for HNL models

Mixing scenario benchmarks:

- Simple model: One HNL with single-flavour mixing (1SFH)

  Muon-only mixing ($|U_\mu|^2$) More data! ATLAS & CMS

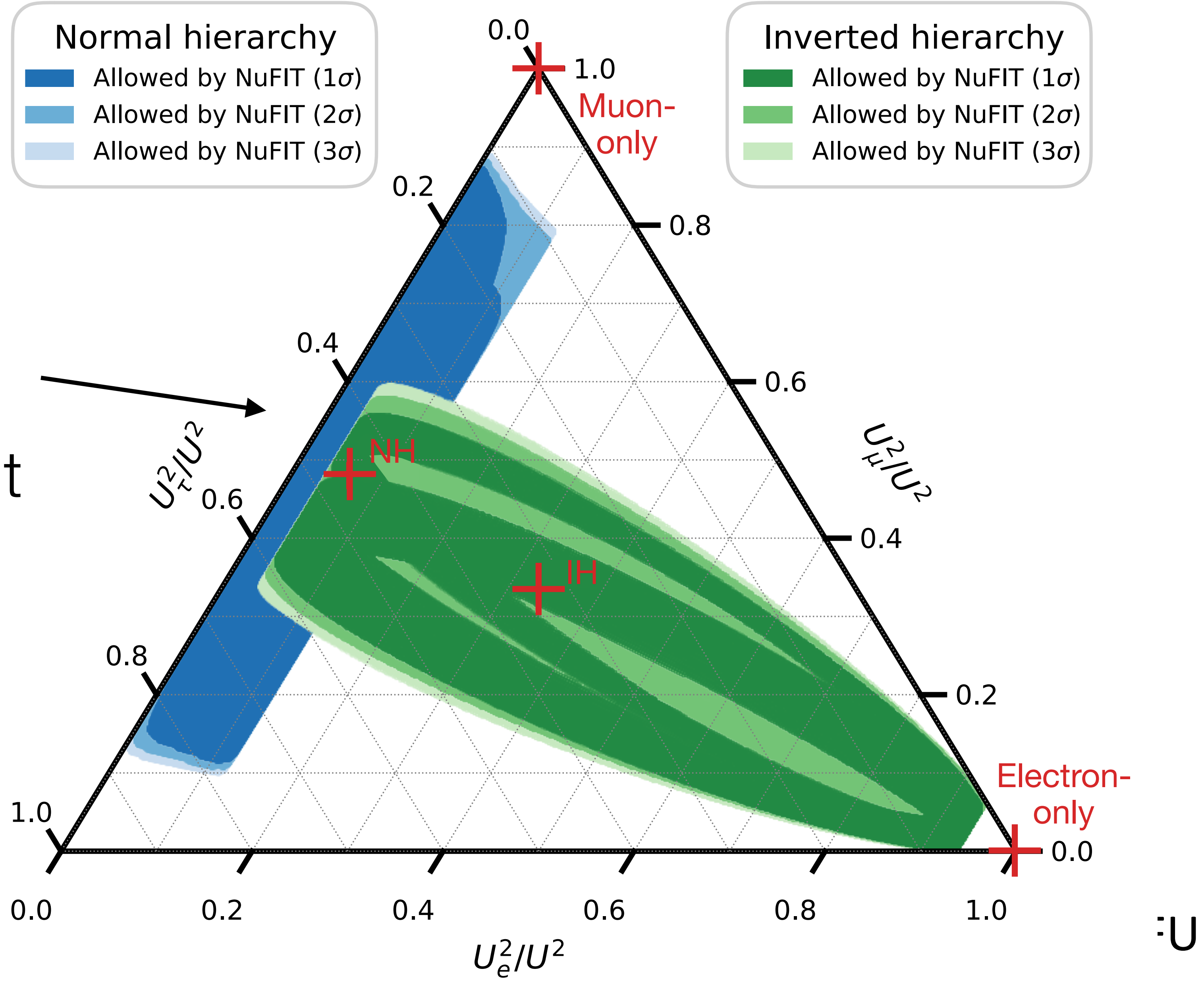
  Electron-only mixing ($|U_e|^2$) New! ATLAS & CMS

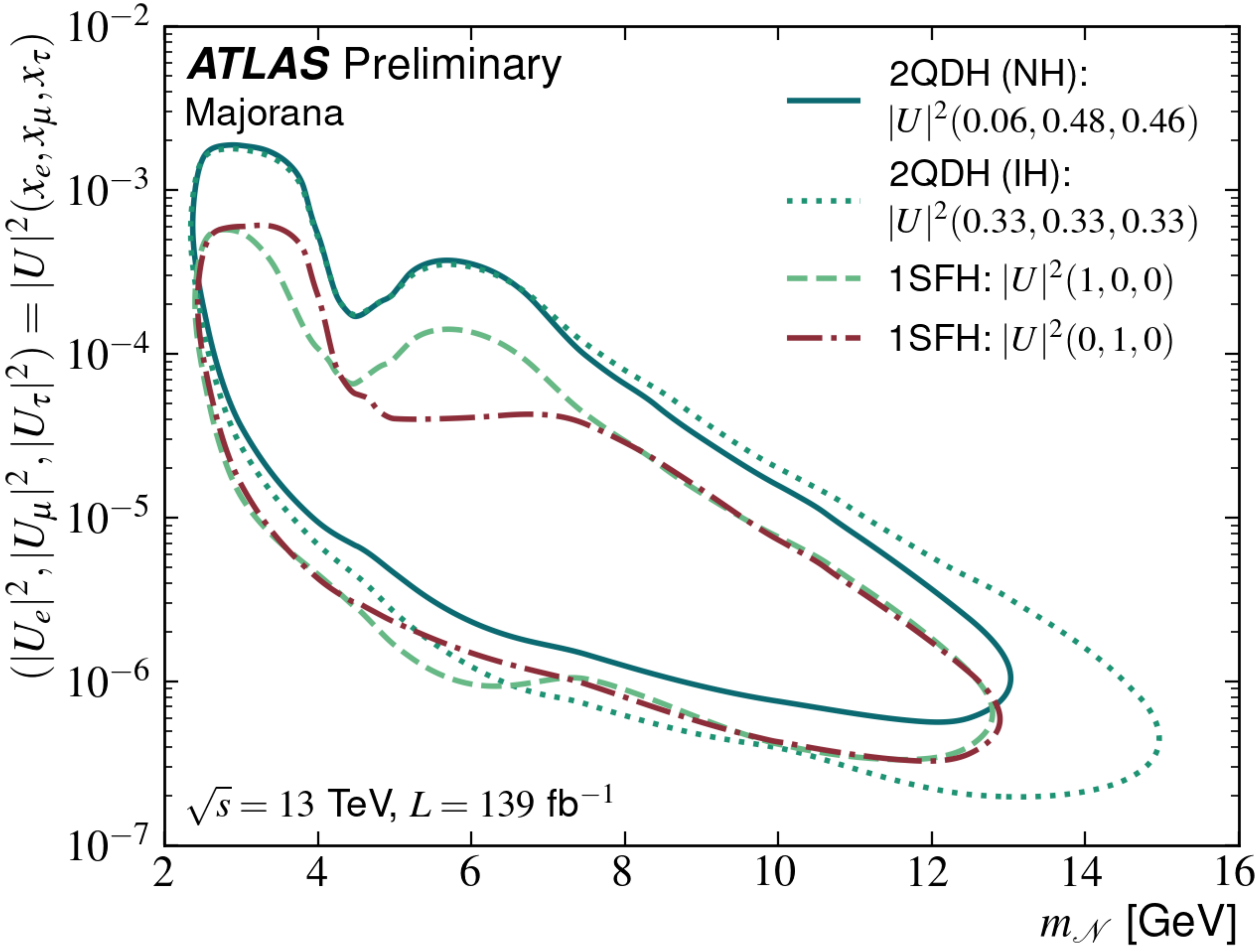
- Realistic scenario: Two quasi-degenerate HNLs with m₁~m₂ (2QDH)

  Inverted hierarchy (IH) mixing ($|U|^2$) New! ATLAS only

  Normal hierarchy (NH) mixing ($|U|^2$) New! ATLAS only

"Realistic" multi-flavour mixing models consistent





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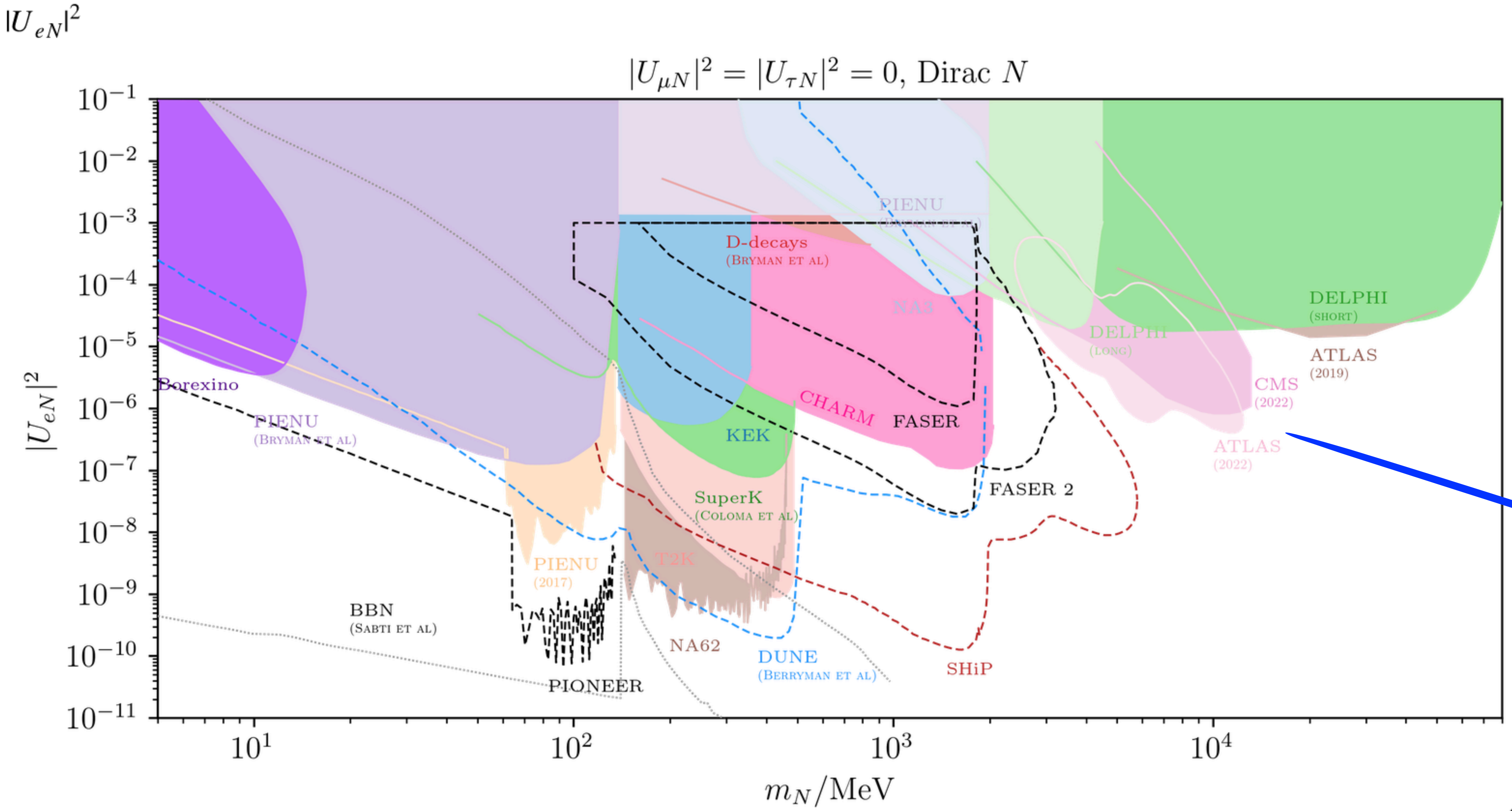

https://github.com/mhostert/Heavy-Neutrino-Limits

Interesting complementarity also to $0\nu\beta\beta$ experiments

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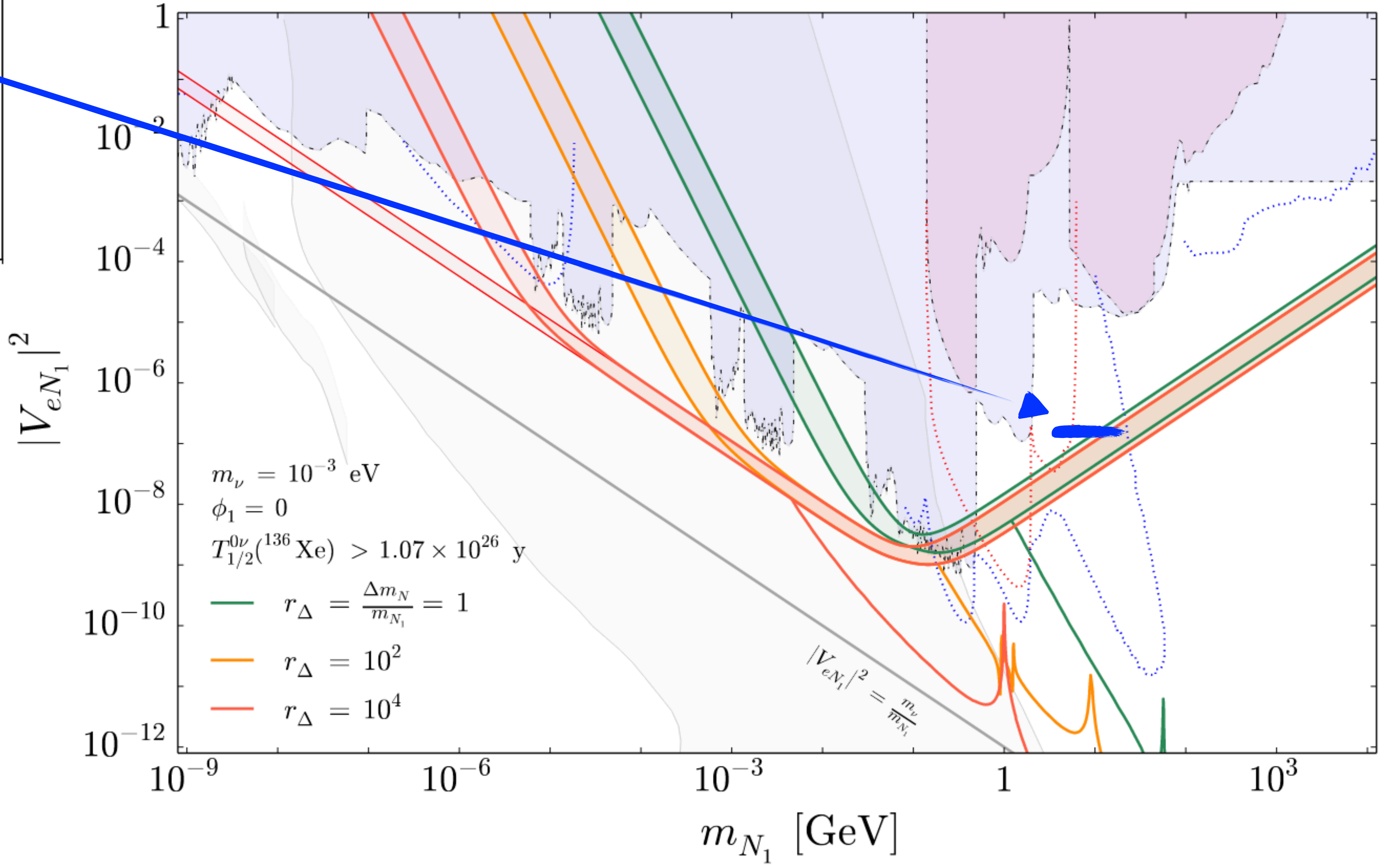
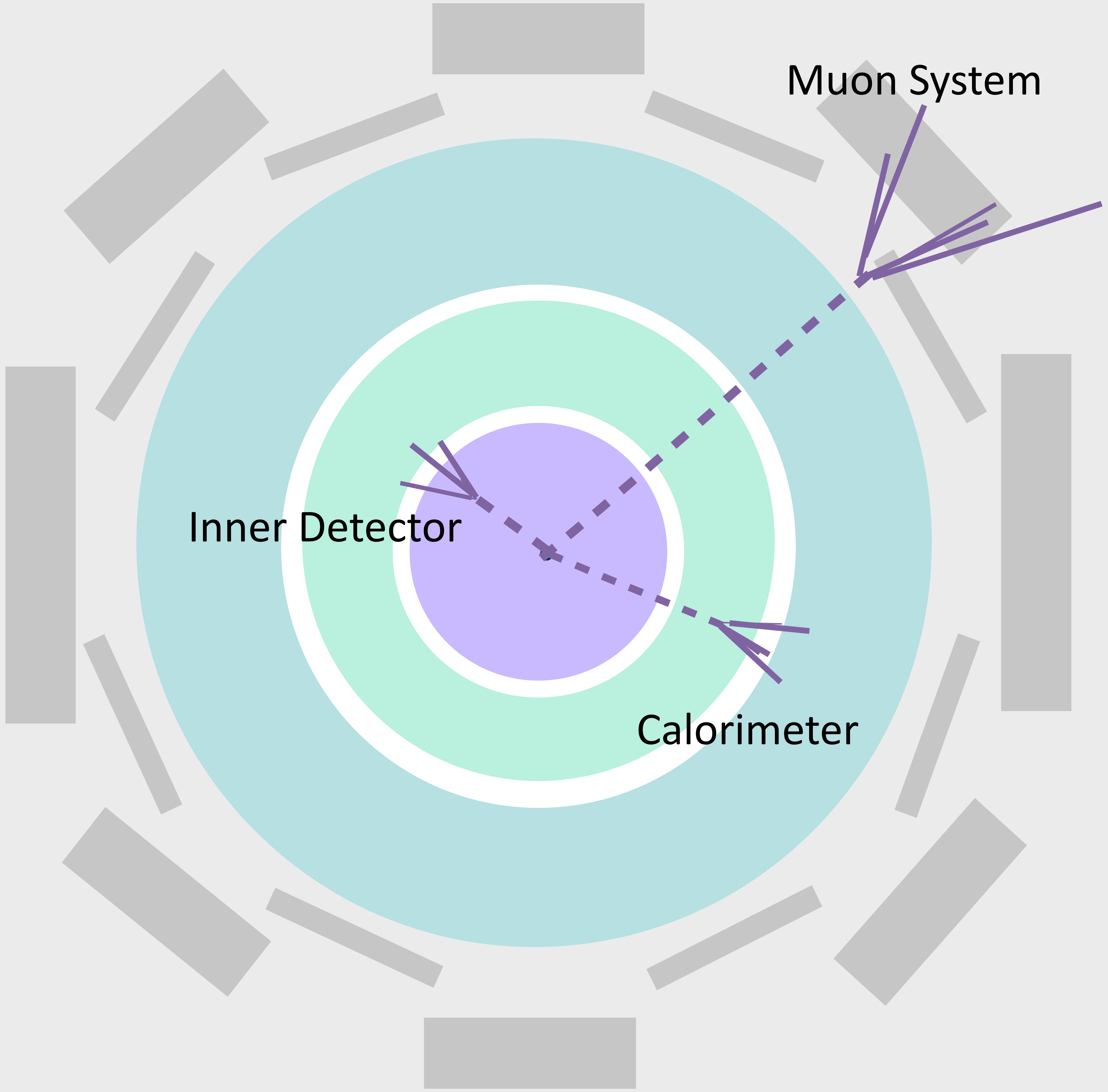
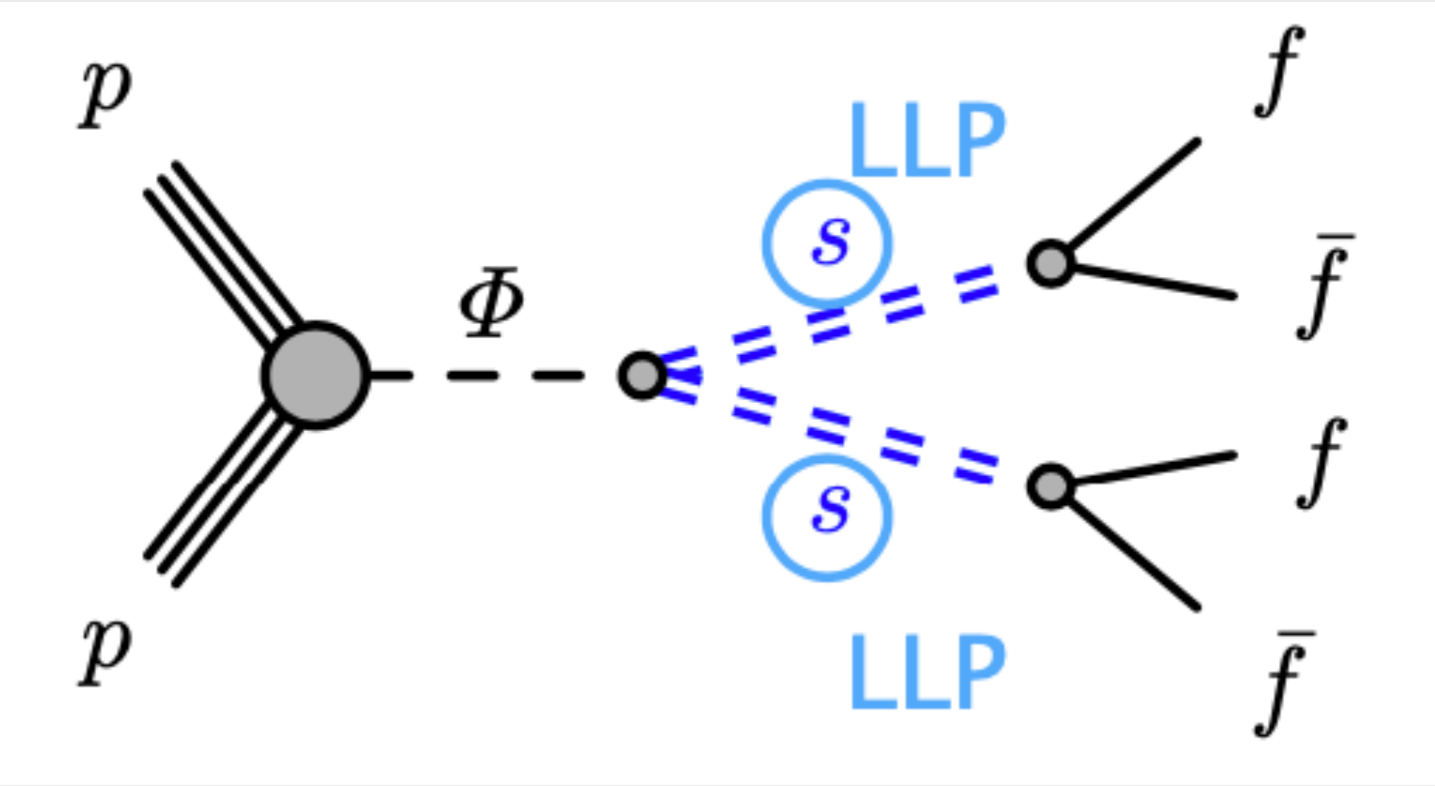


Hidden Sector Searches



Exotic Higgs decays
Decays of Higgs-like scalars



CMS: EXO-18-003, EXO-21-006, SummaryPlotsEXO13TeV

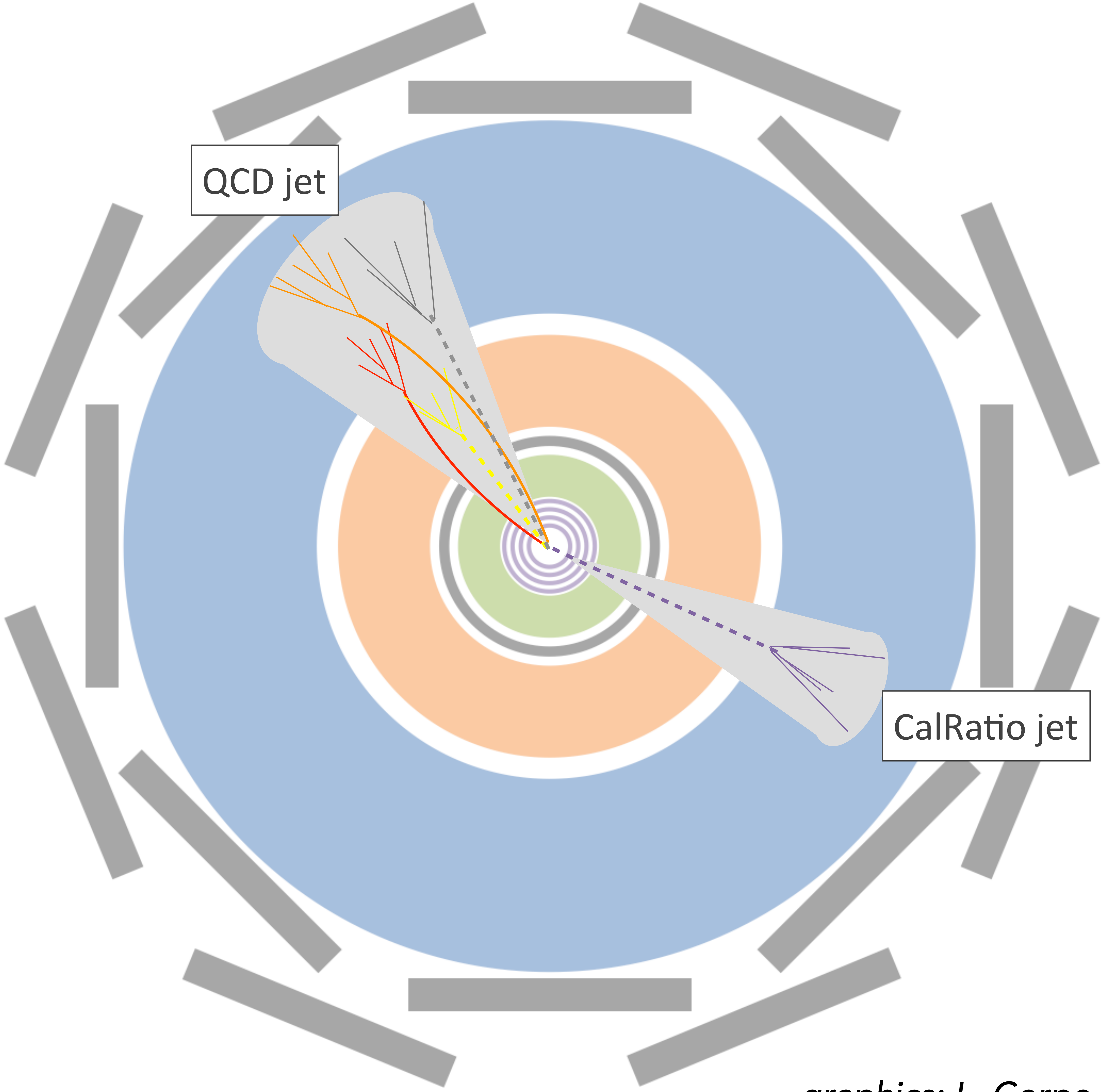
ATLAS: EXOT-2019-24, EXOT-2019-23 , EXOT-2018-57, ATL-PHYS-PUB-2022-007

Calorimeter-Ratio (CalRatio) Search

Search focuses on LLP decays in HCAL

- Differences to a regular SM jet:
  - **Narrow**
  - **Trackless**
  - **Low fraction of energy in the ECAL:** Define Calorimeter Ratio (CalRatio): E_{HCAL}/E_{ECAL}

- Signal: **CalRatio Jets**
  - Require 2 jets (pT > 40 GeV)
  - Pick **events with trackless jets:**
    - large $\sum\Delta R_{min}$ (jet, track)



graphics: L. Corpe

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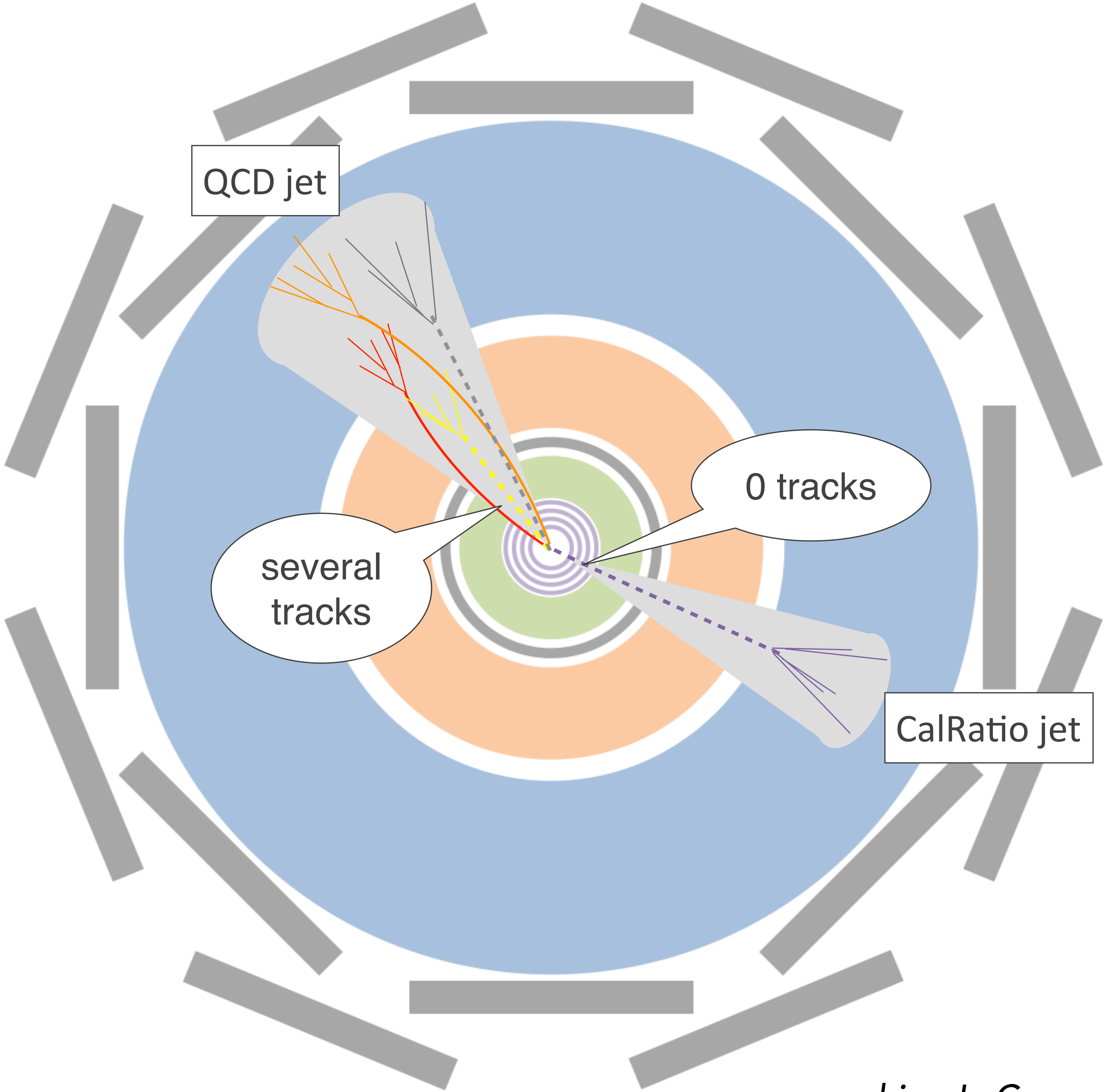

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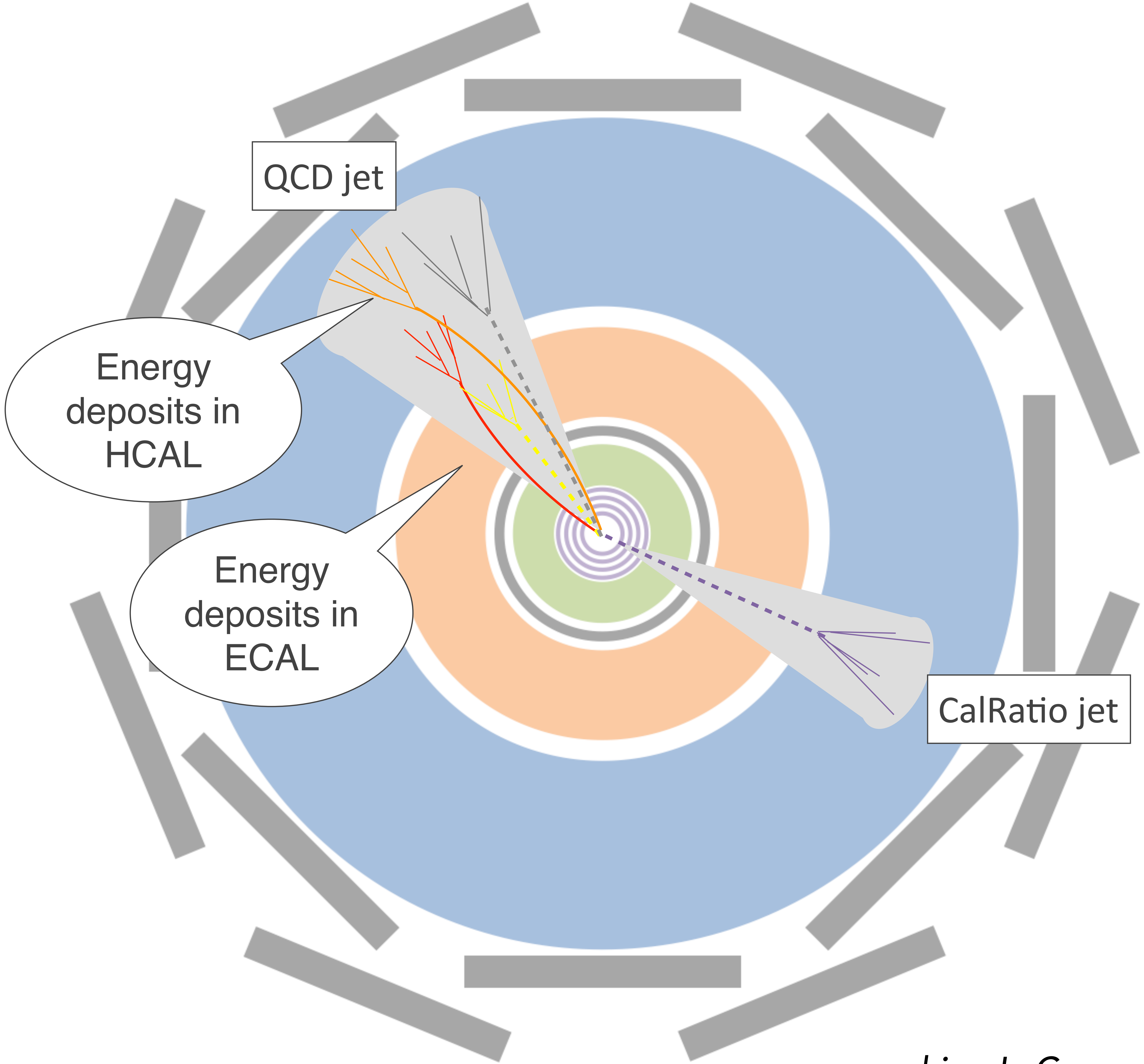

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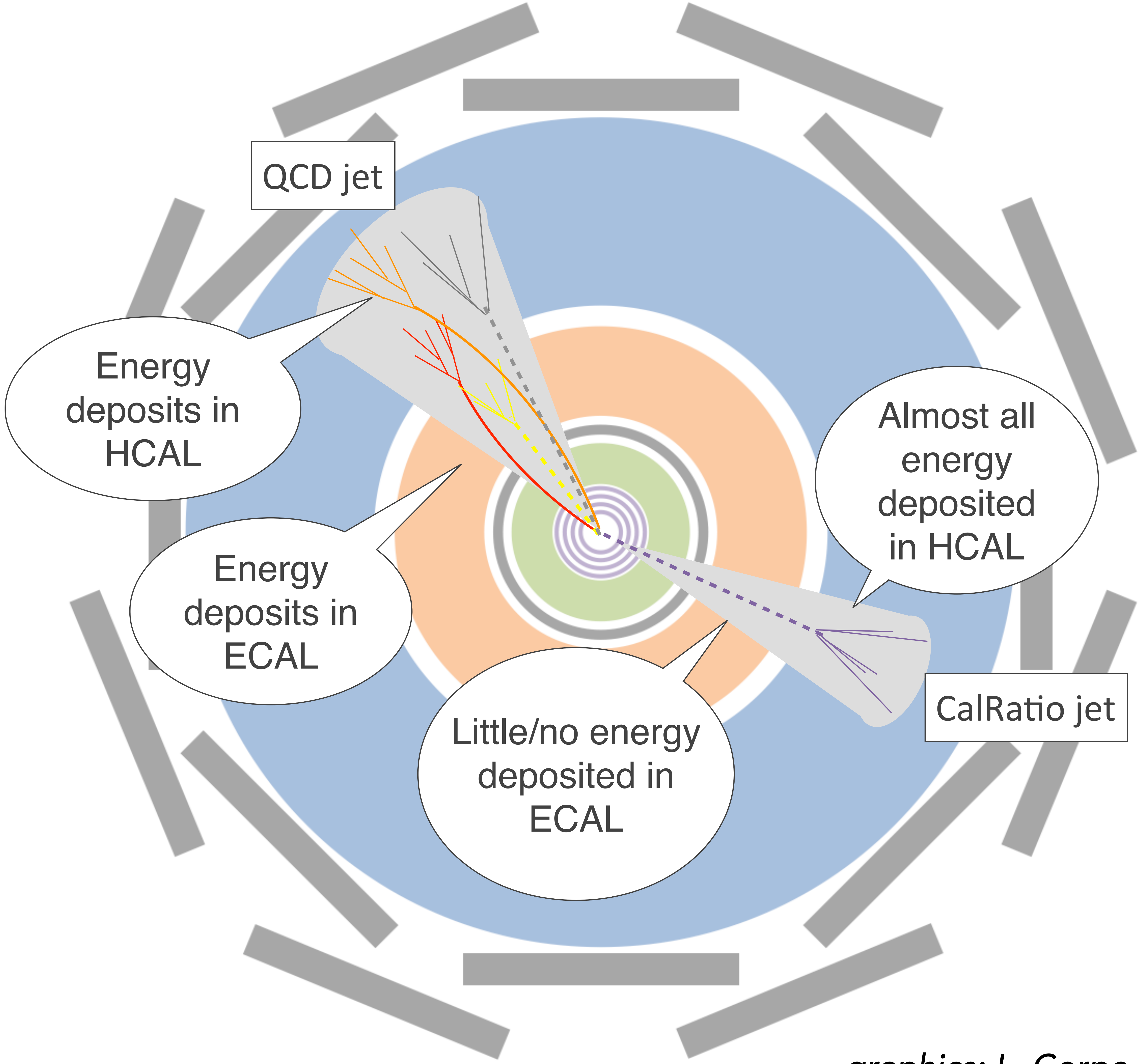
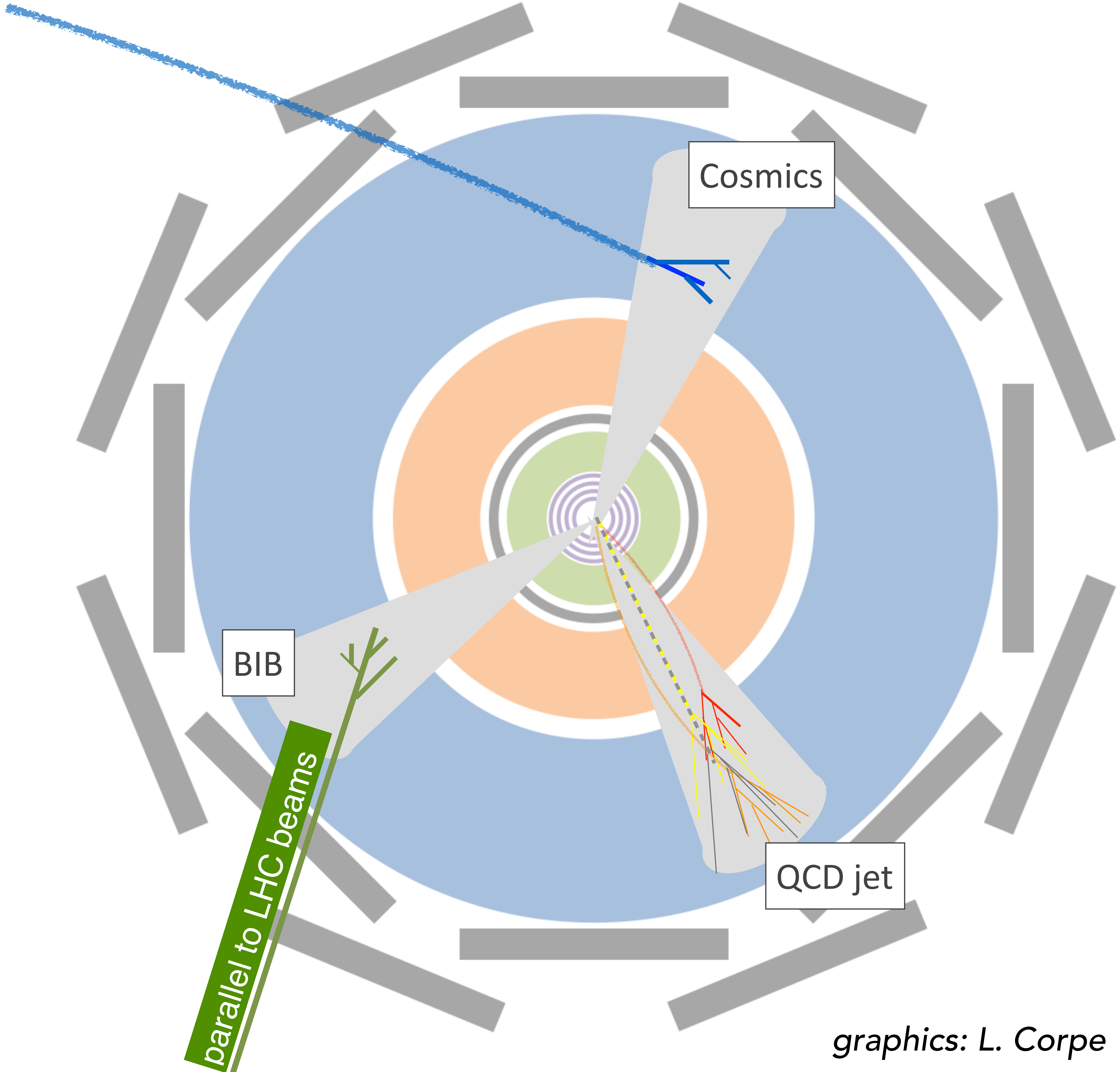


graphics: L. Corpe

Calorimeter-Ratio (Cal-Ratio) Search

Main sources of background:

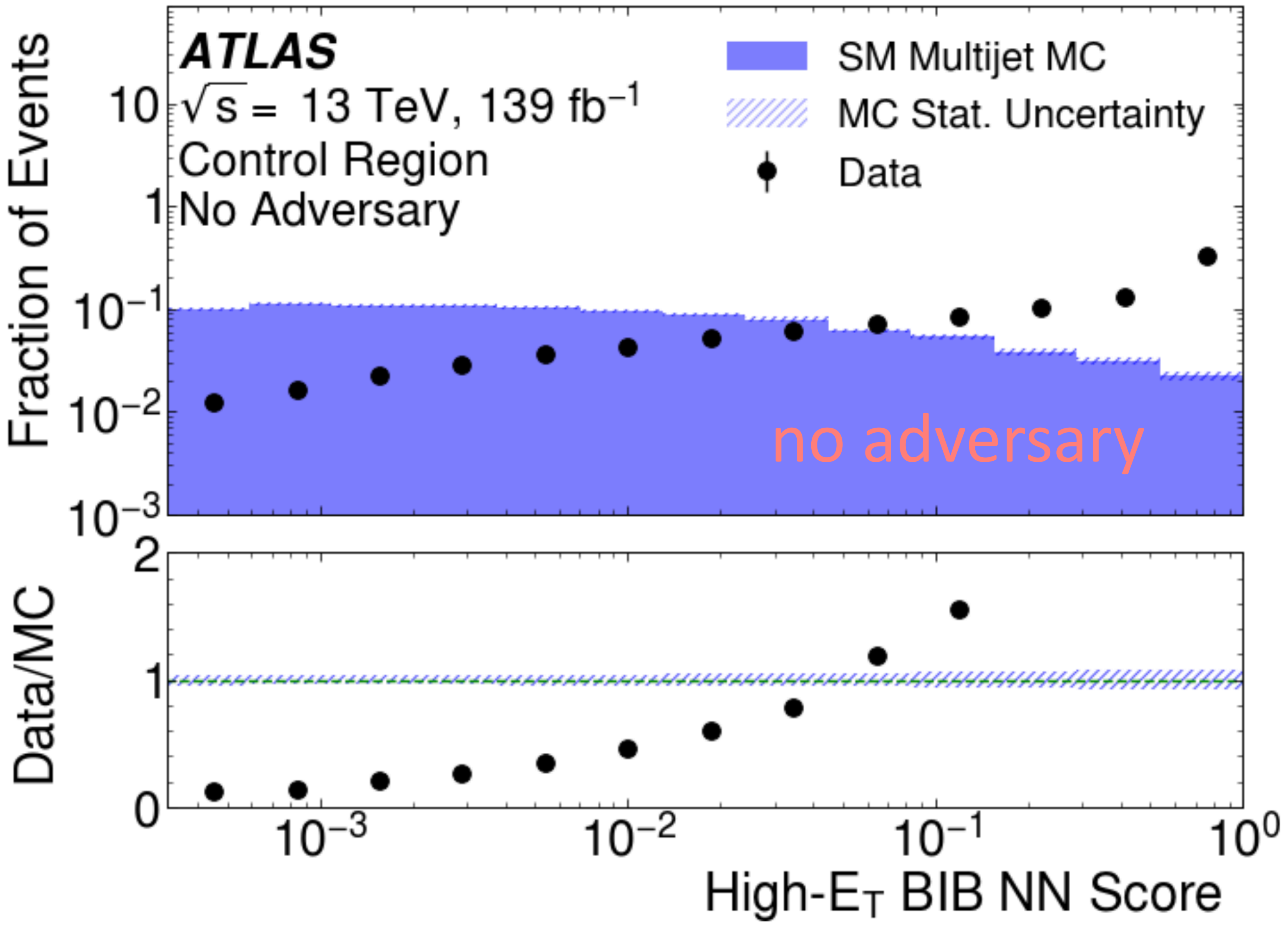
- QCD jets
- Beam-induced background (BIB)
- Cosmic Rays
- Can all look like narrow, trackless jets with high CalRatio!



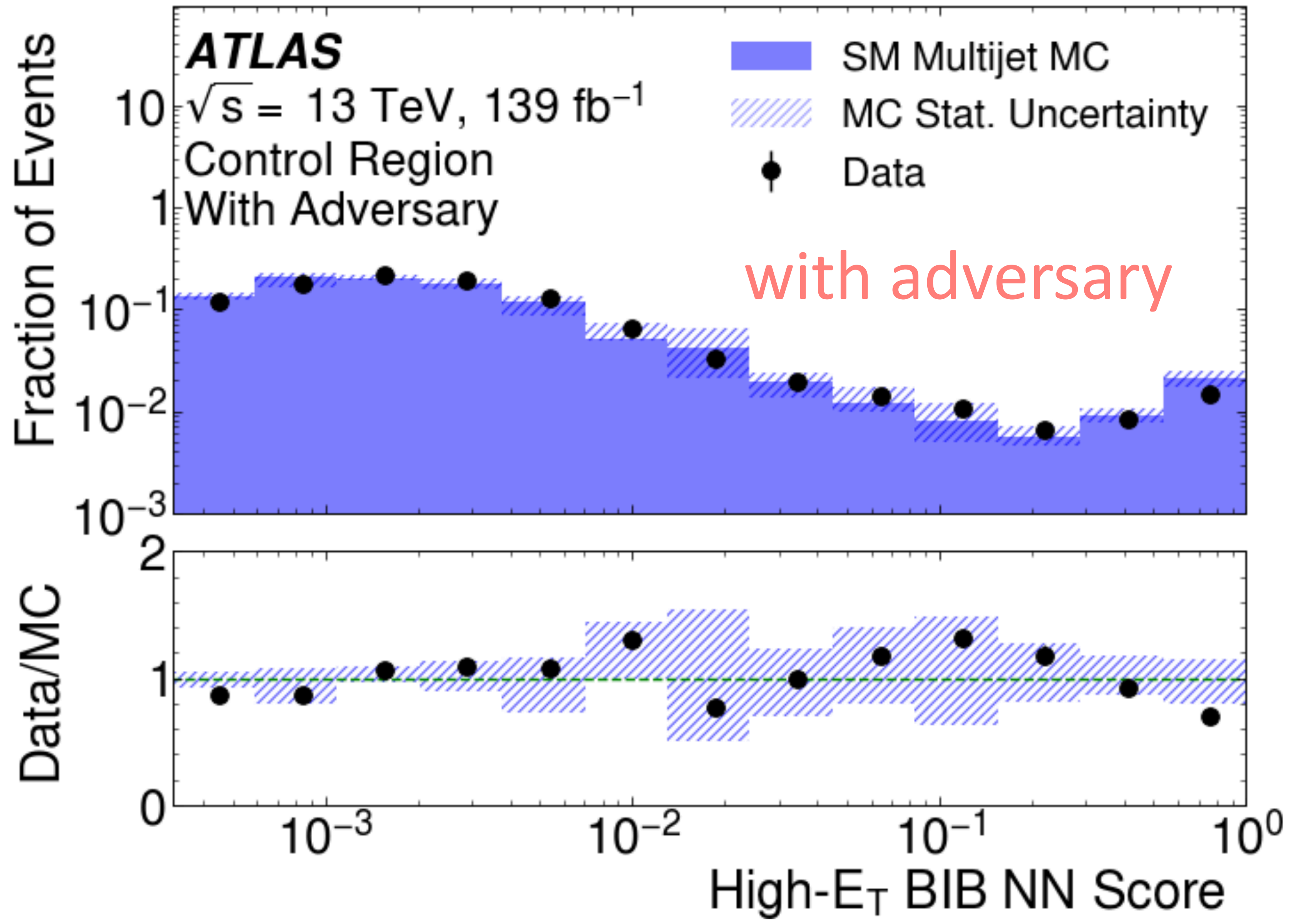
graphics: L. Corpe

CalRatio analysis details

- **Jet-level NN** is trained to separate signal from BIB and QCD background (CNN fed into LSTM)
    - Analysis split into 2 channels: low- and high-mass models
    - Variables with low level input: 10 track var., 10 jet constituents var., 6 muon segment var., and 3 jet var.
    - Adversarial Network is added to mitigate potential mis-modelling differences in simulation (e.g. cluster timing)



no adversary



with adversary

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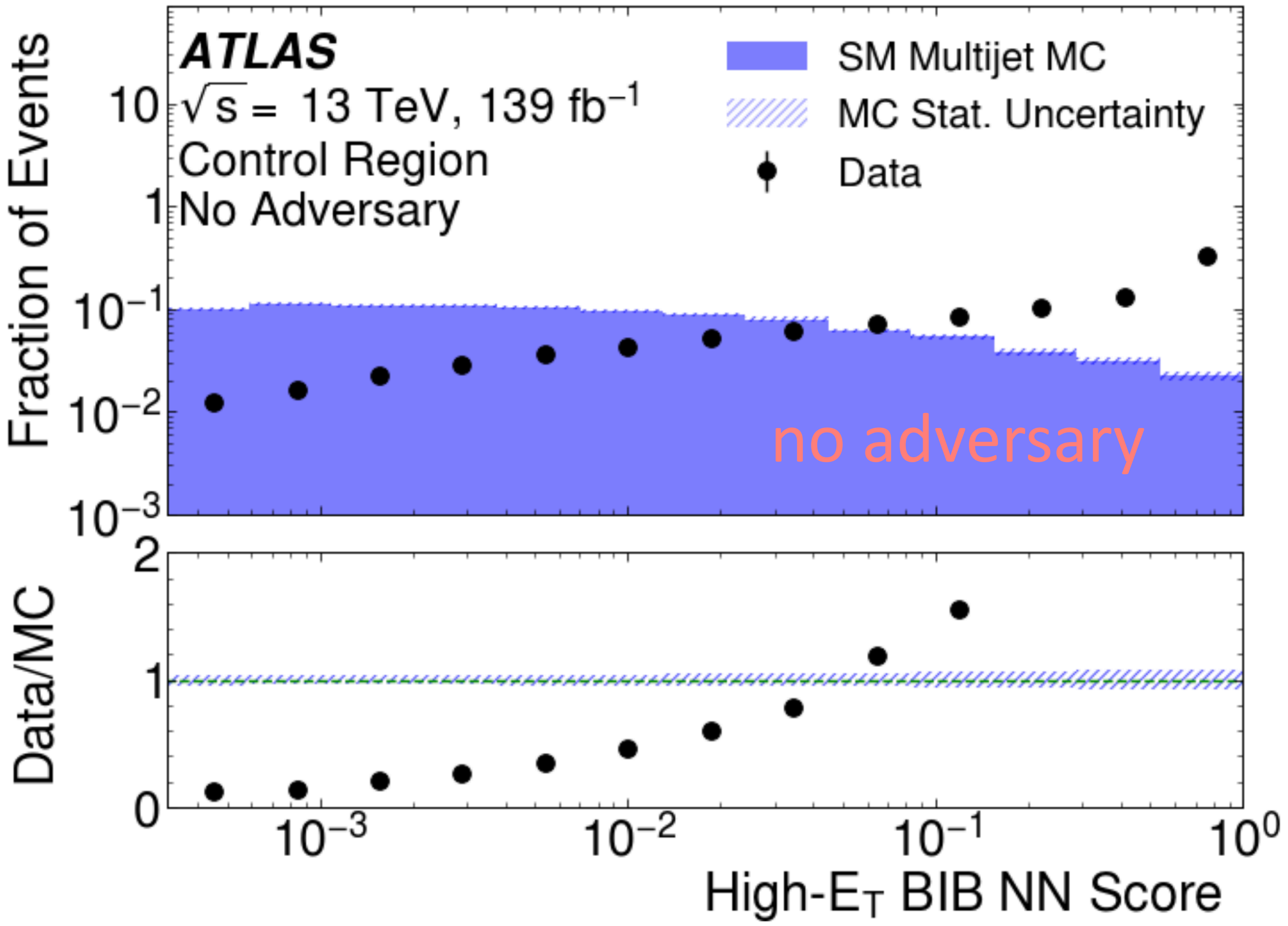
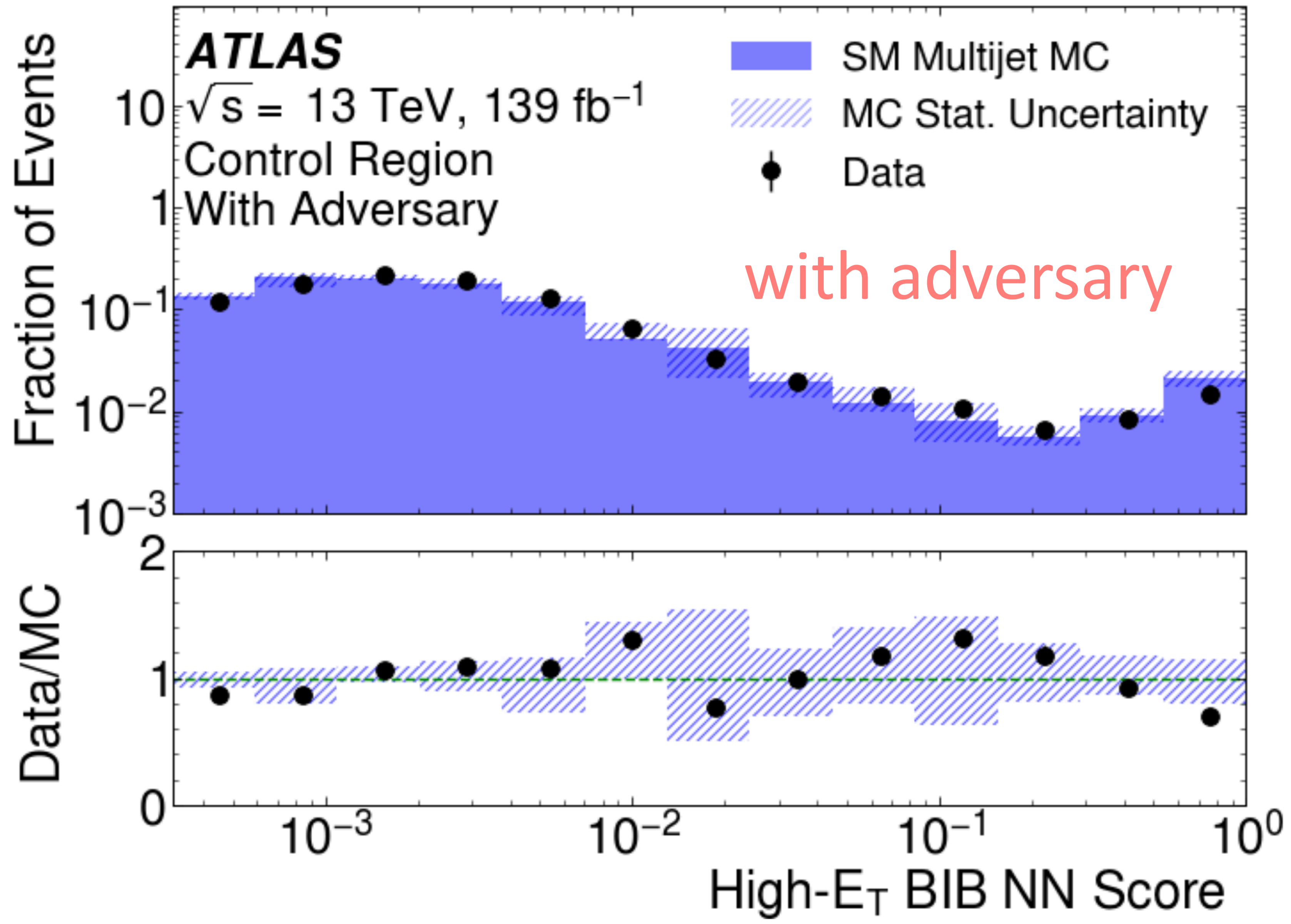
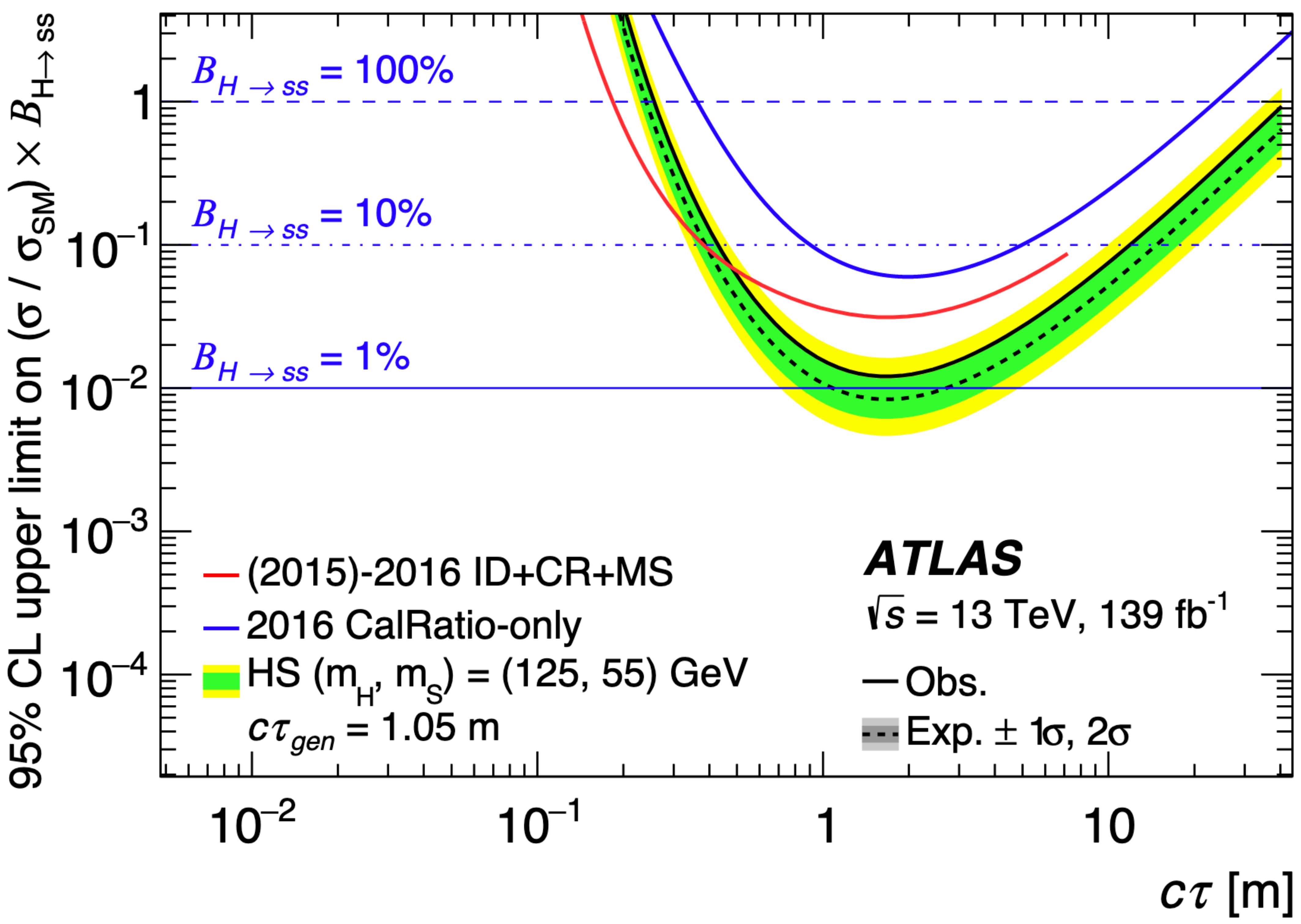
- Additional **event level BDT selections**
- **A data-driven background** estimation and signal hypothesis test is performed using a modified ABCD method(allowing signal contamination)

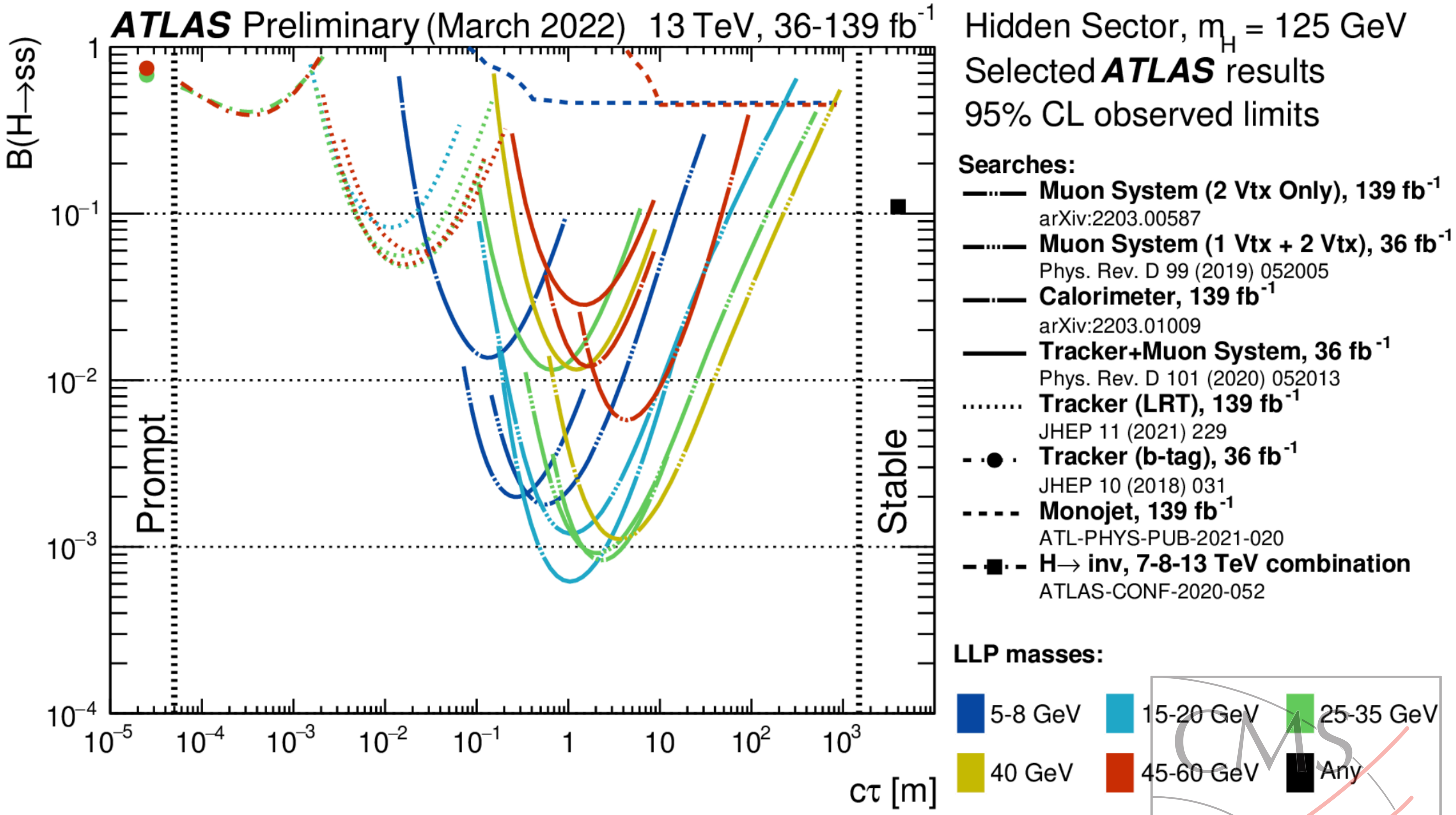




CalRatio results in context with other ATLAS results

- No excess observed
- Strong results for high mediator mass searches!
- Here, only results with m_H=125 GeV





CalRatio results in context with other ATLAS results

- No excess observed
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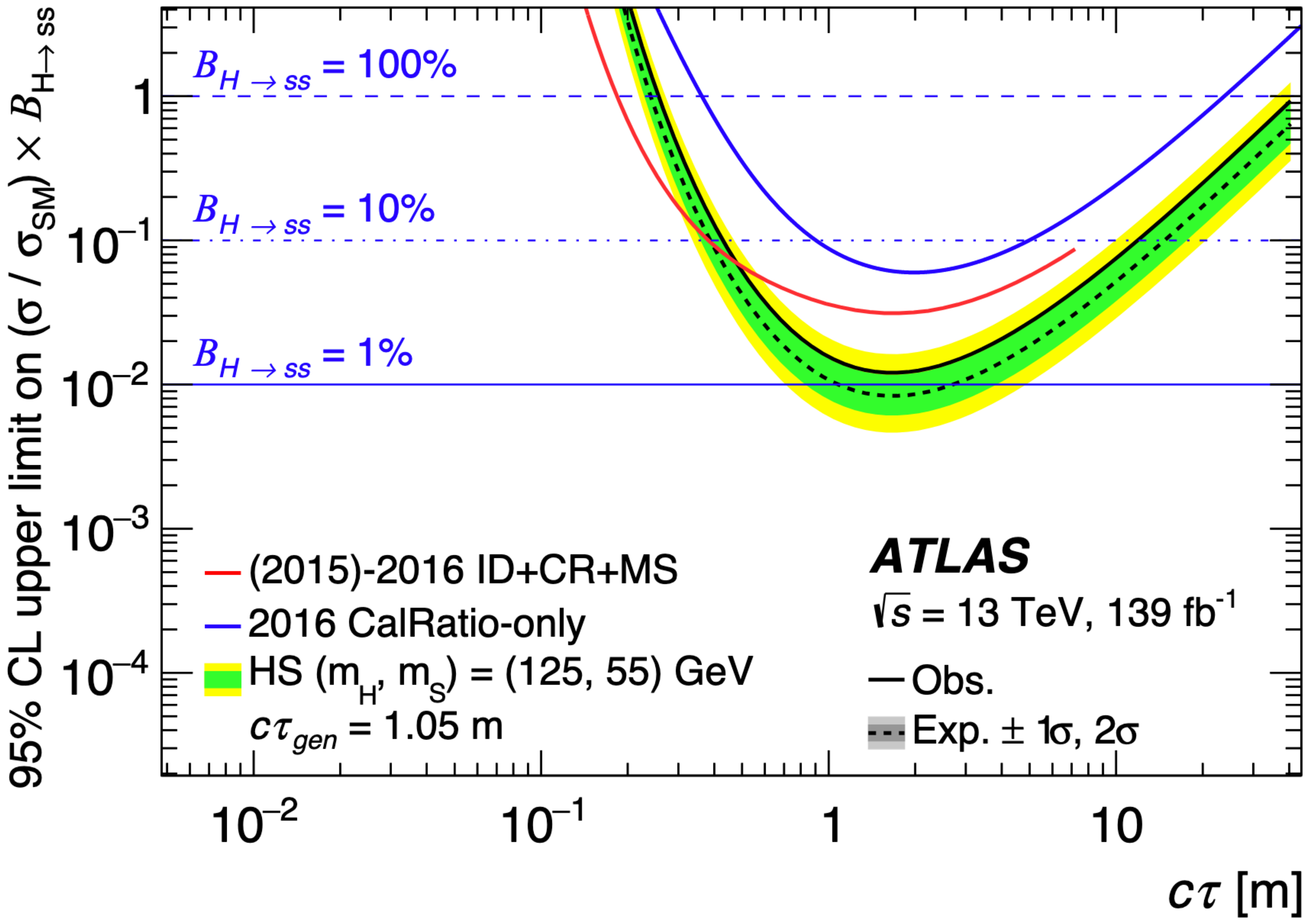

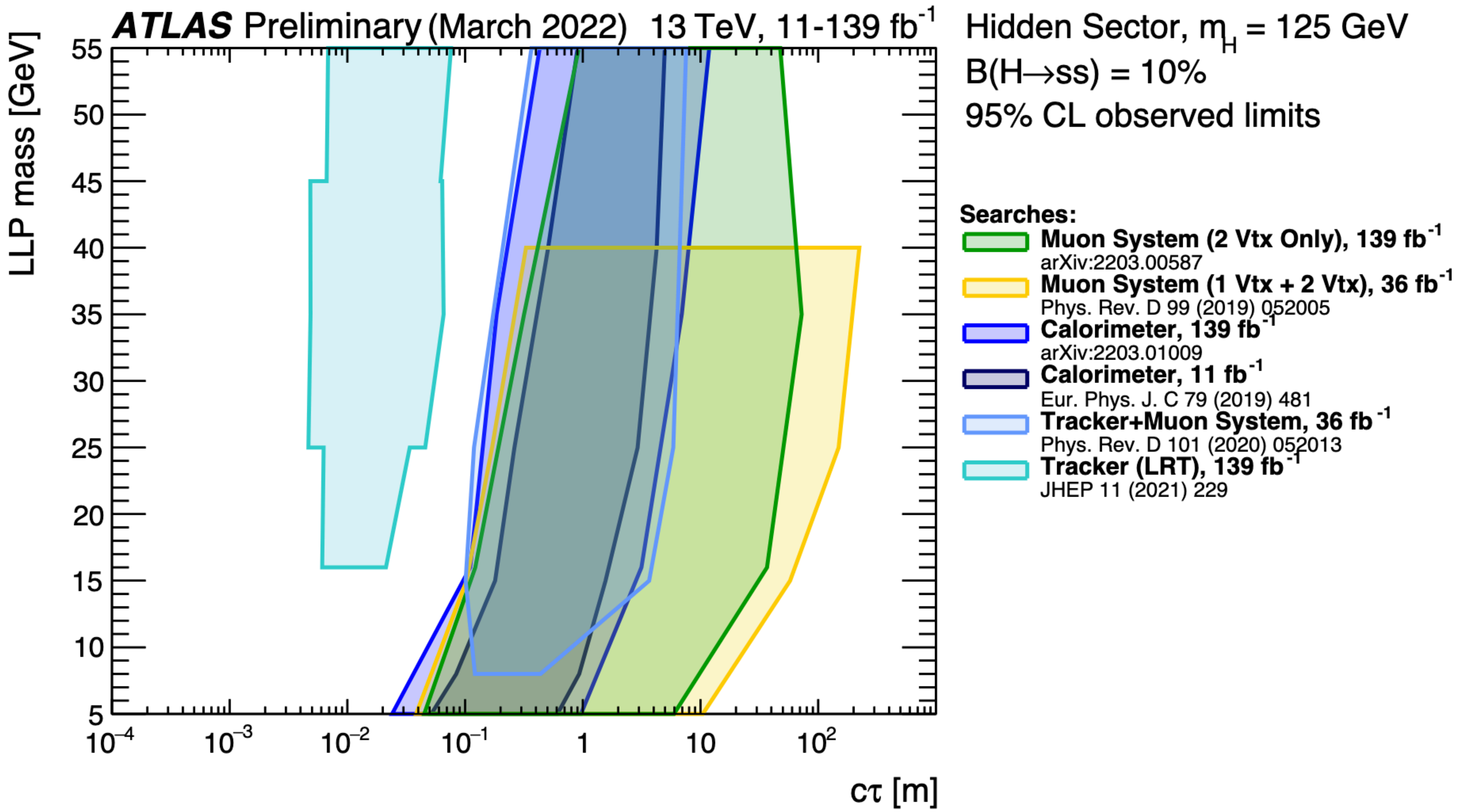

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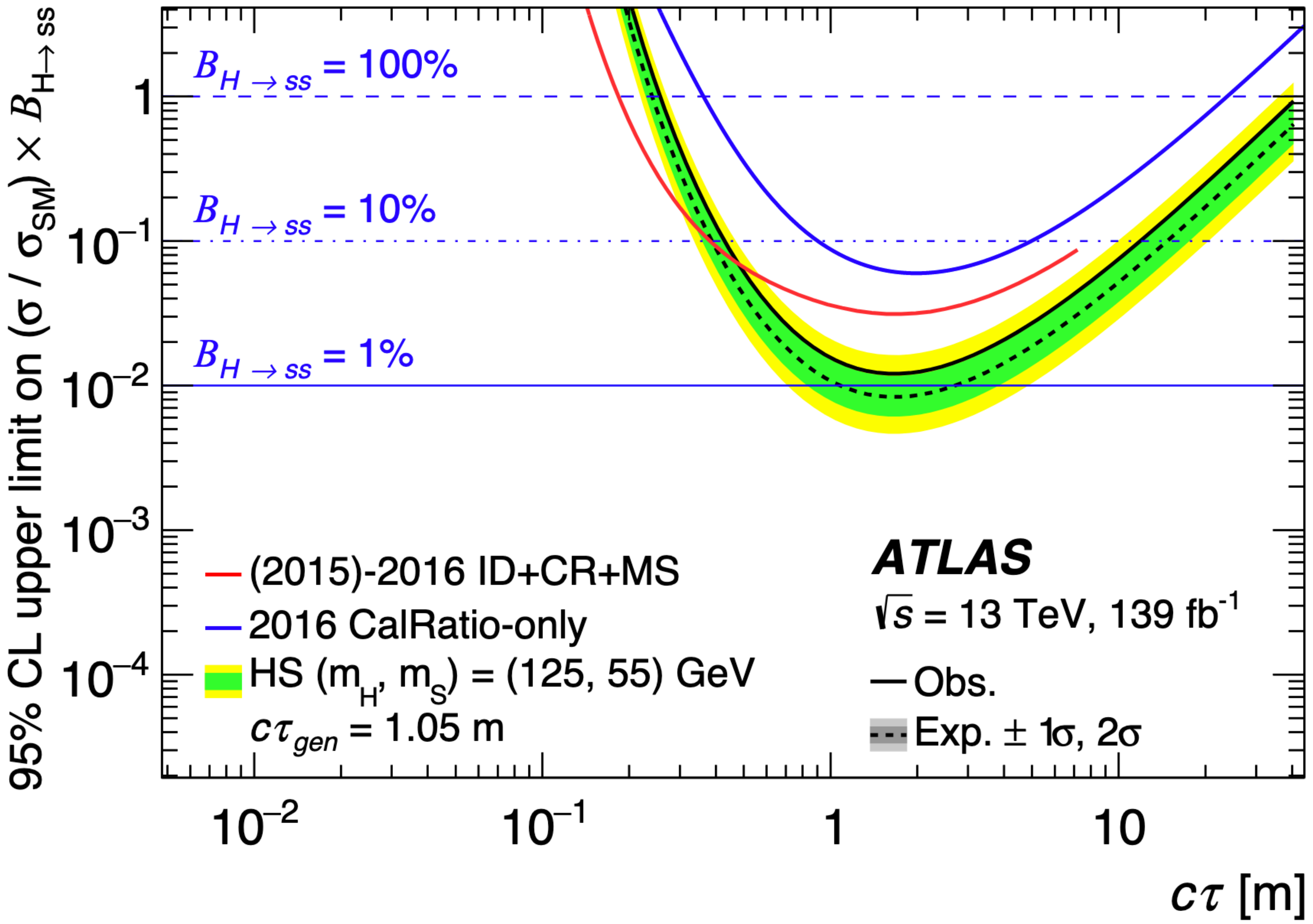

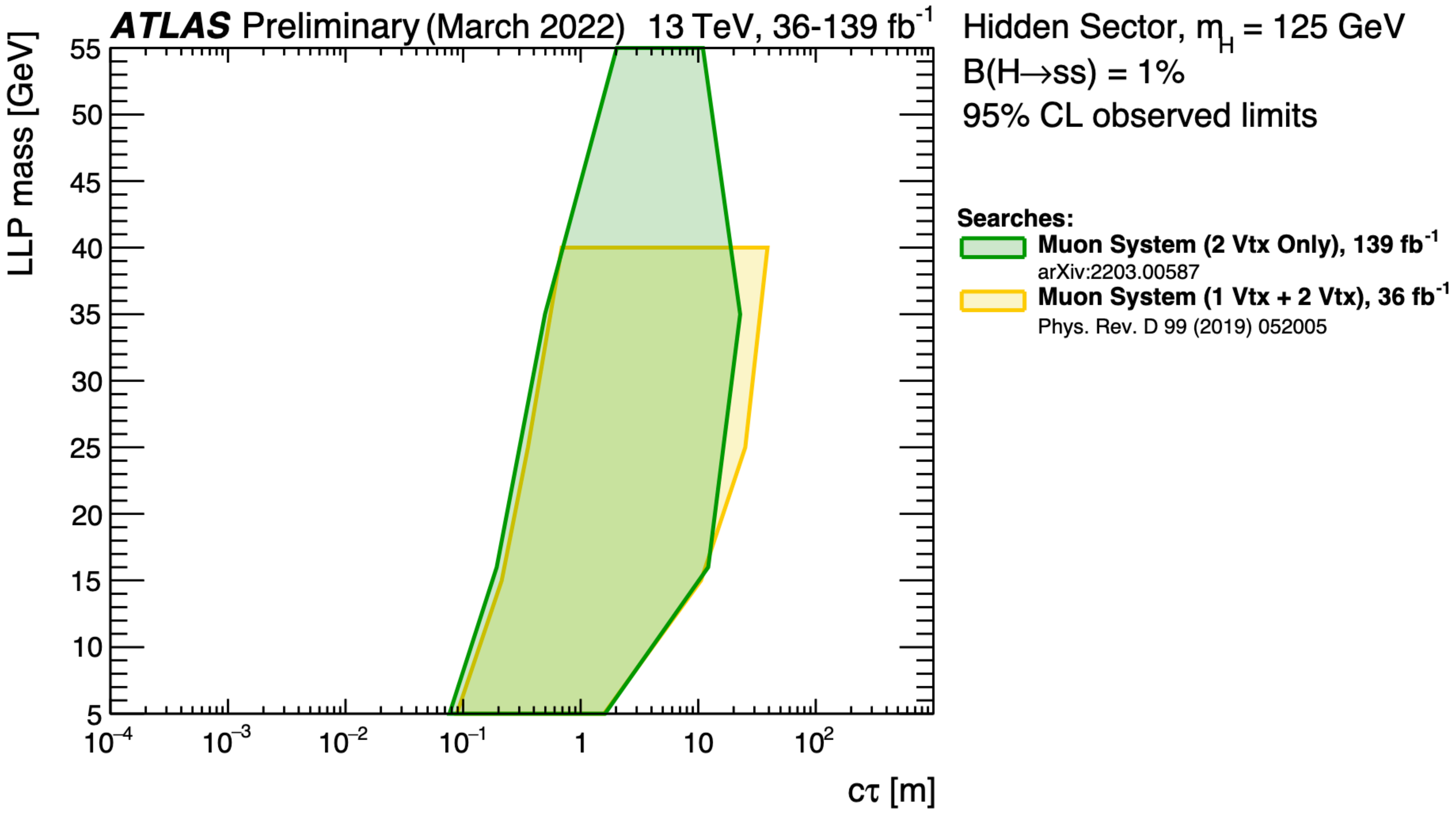

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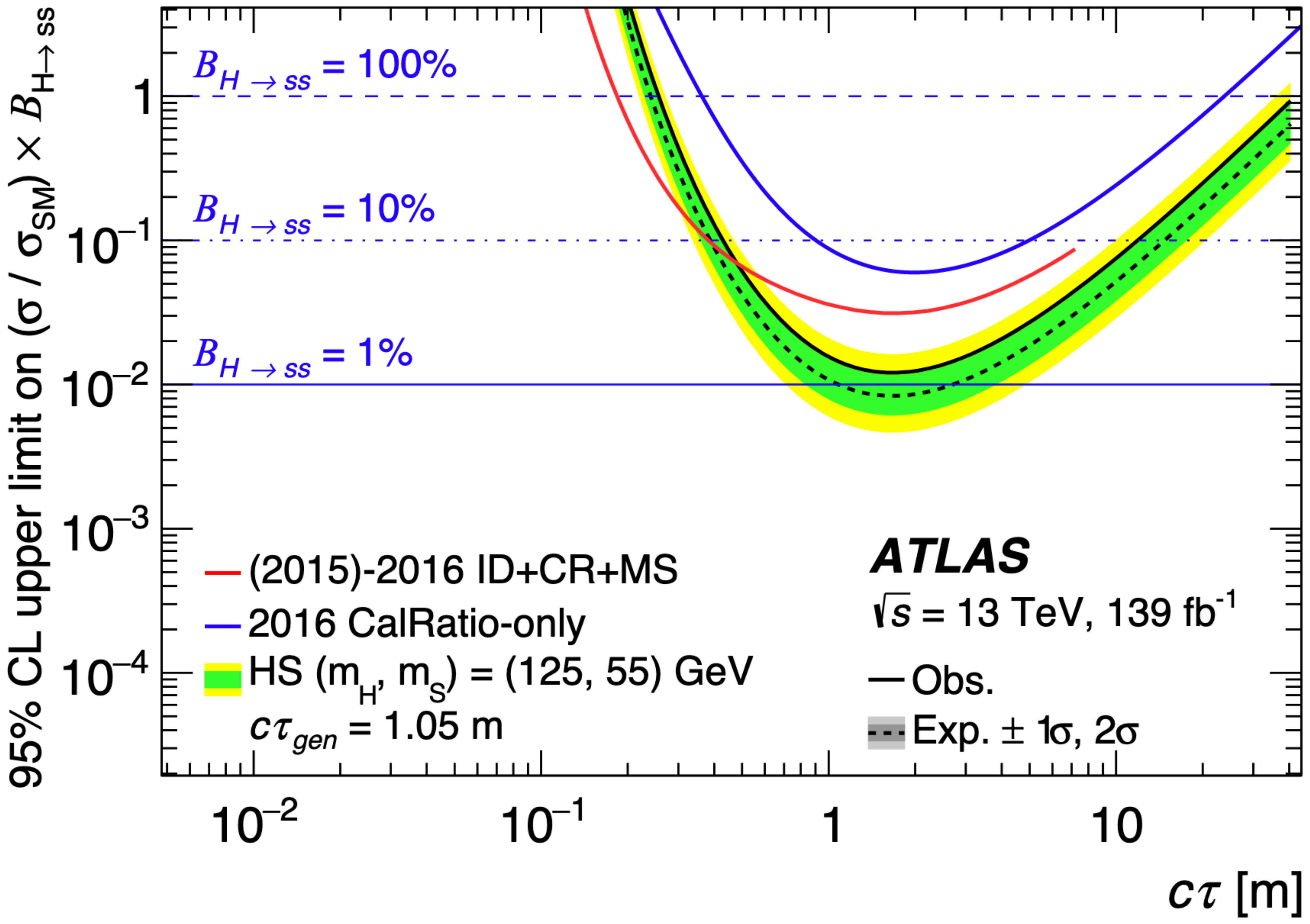
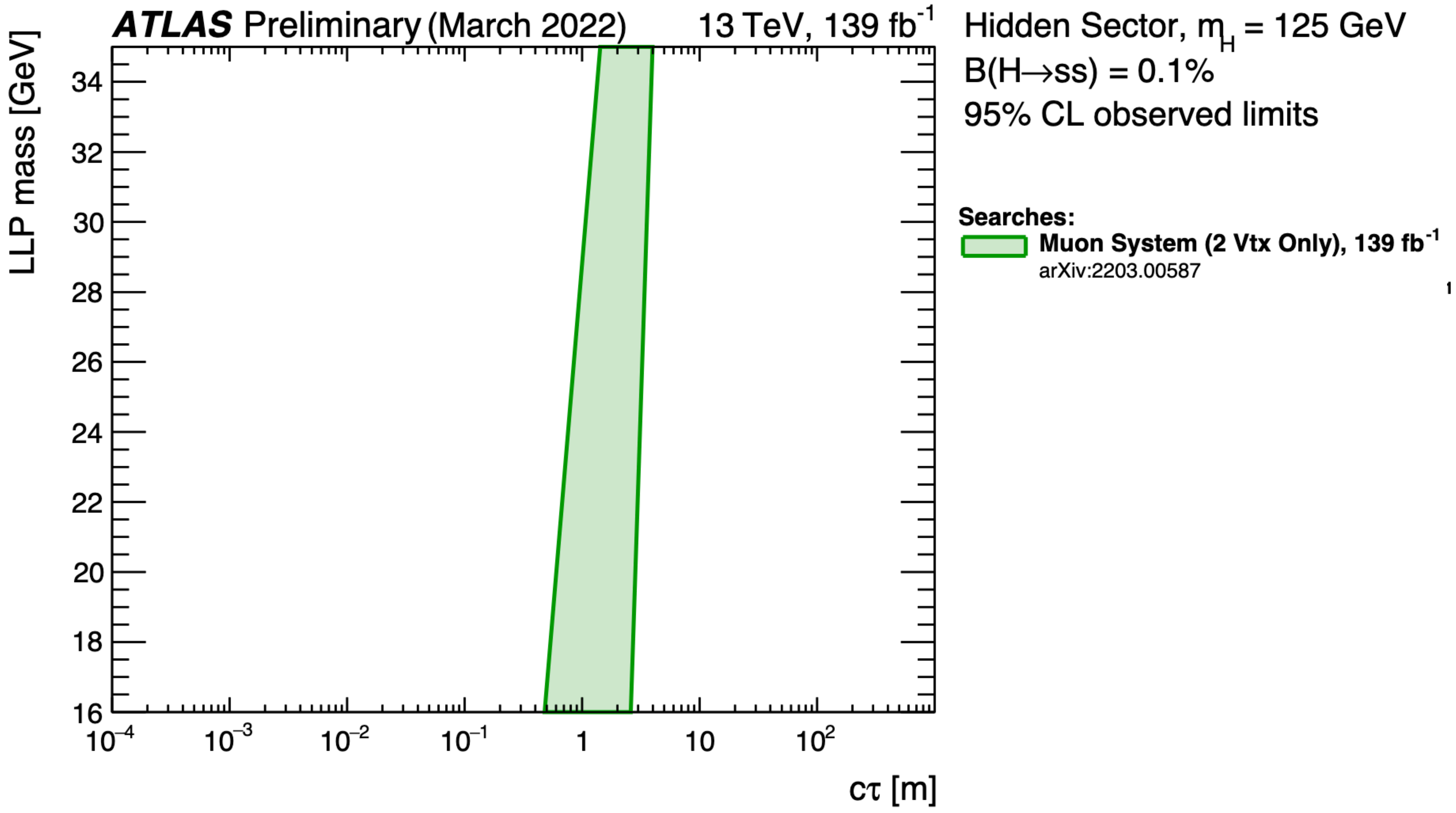
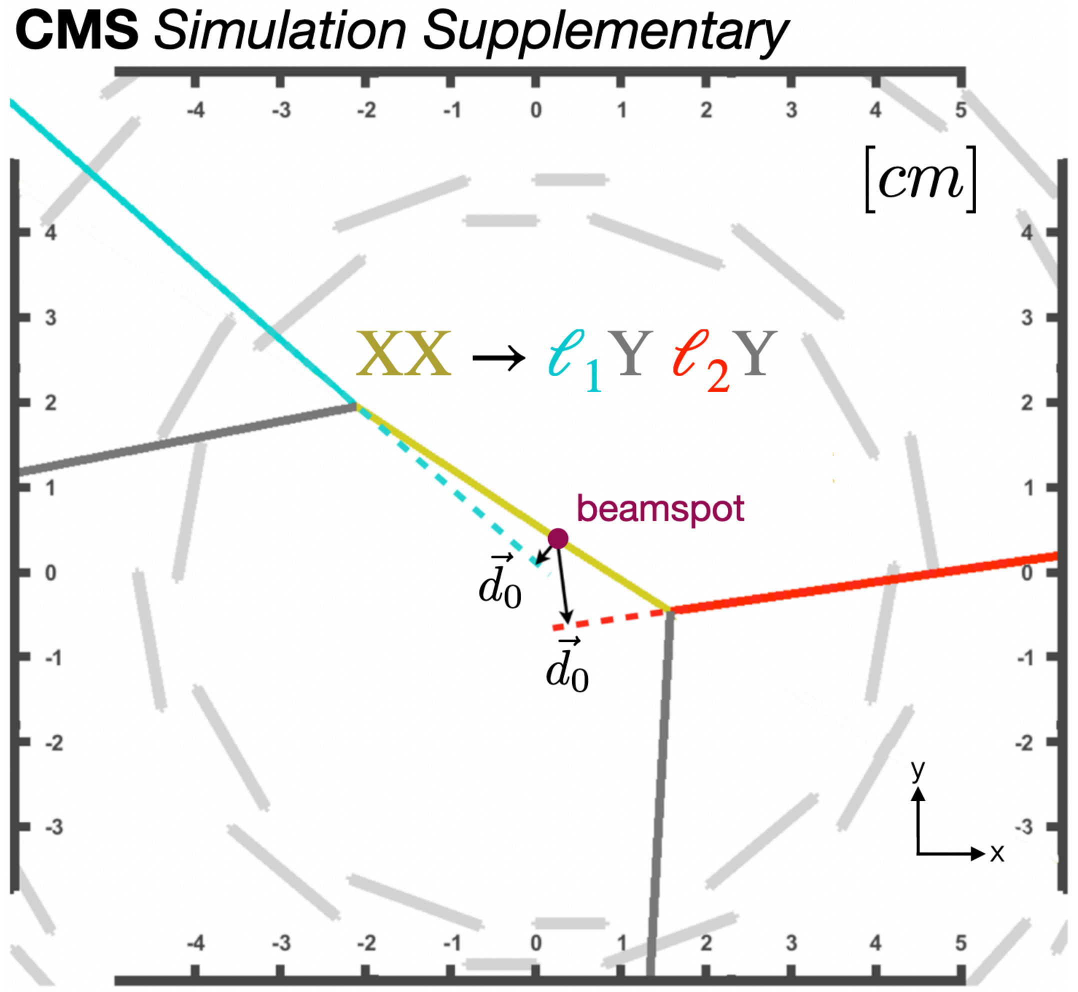




Recent CMS results on Hidden Sector Searches

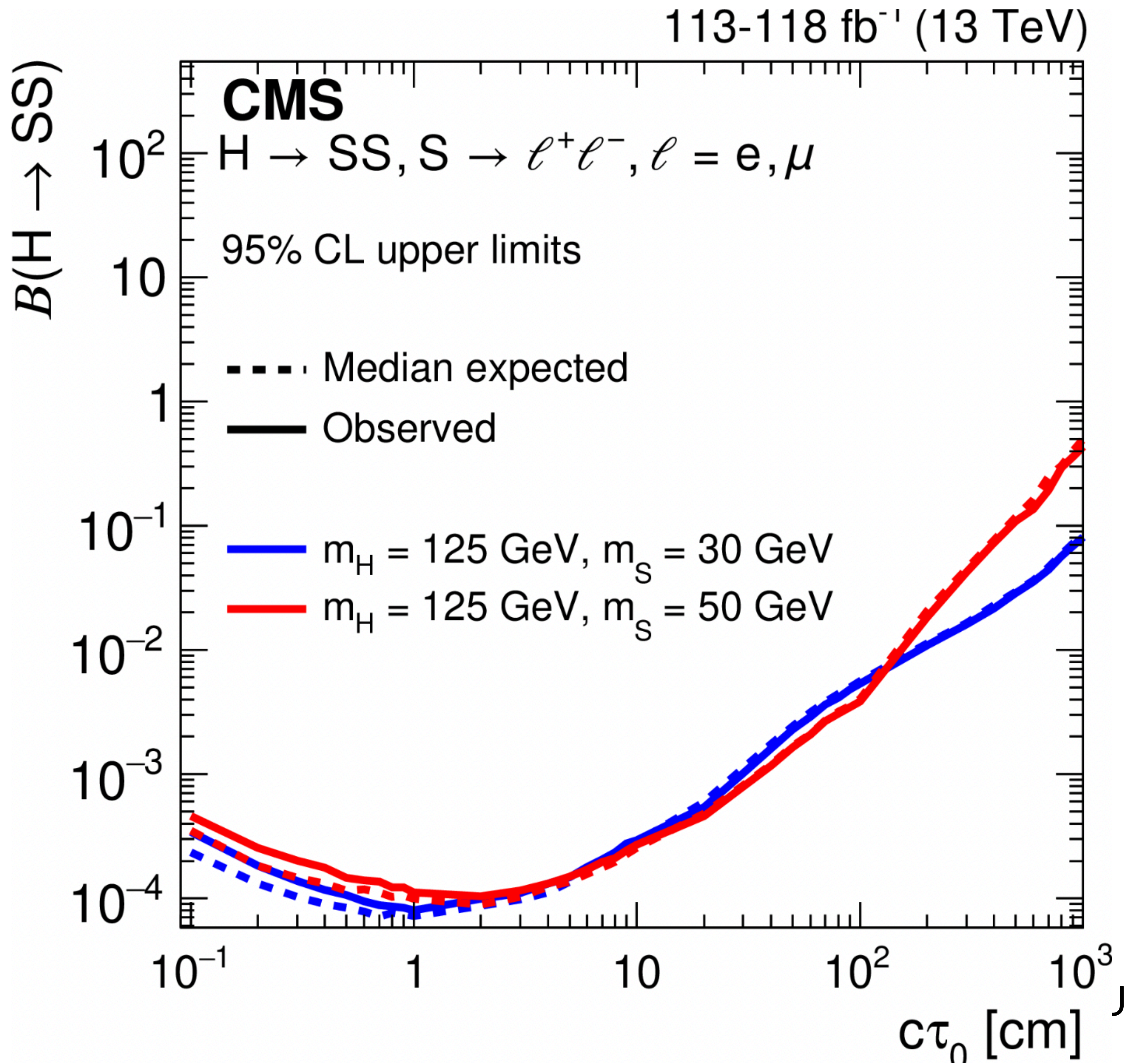


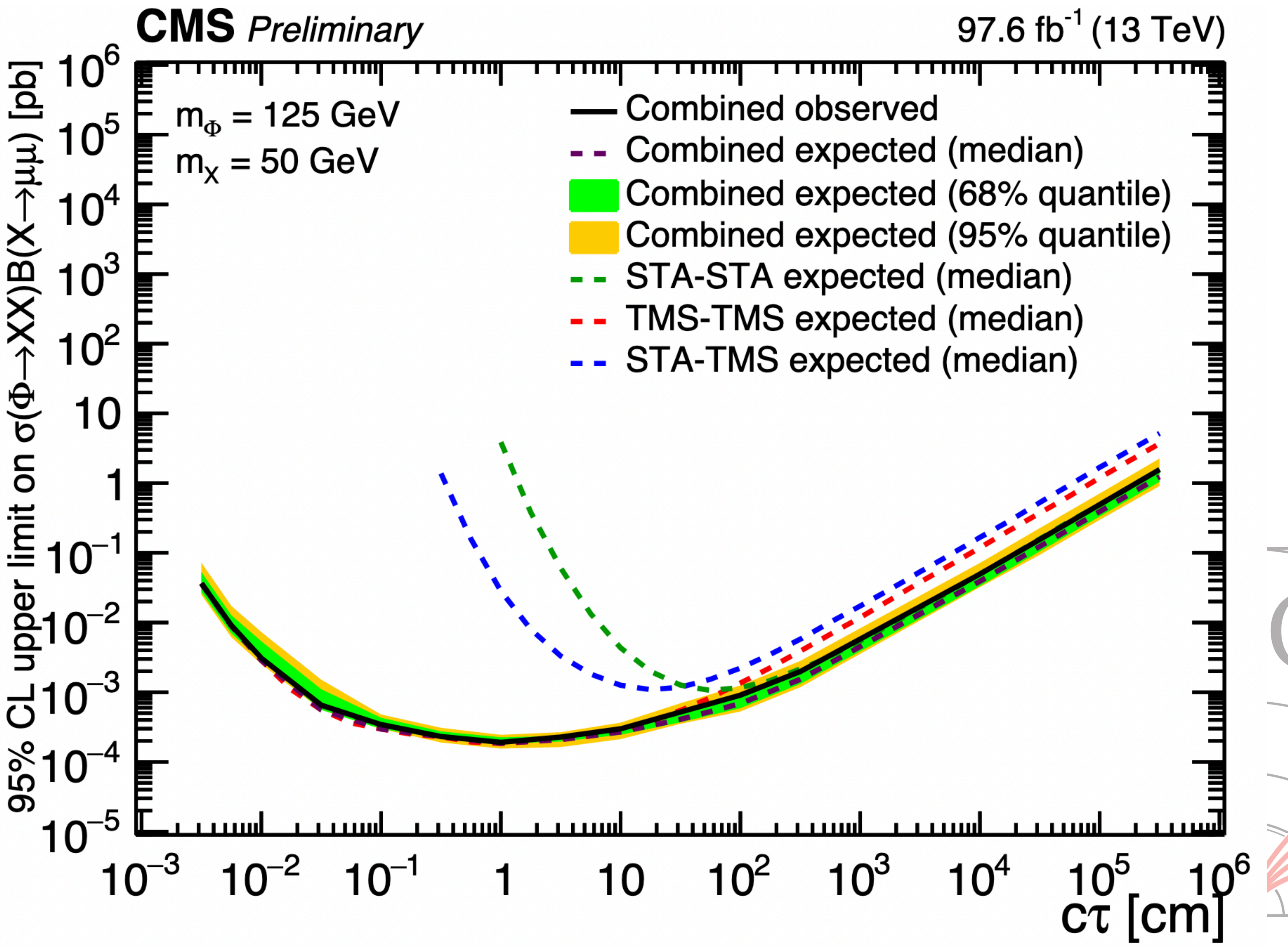
1) **Inclusive search for displaced leptons (EXO-18-003)**

- Focus on being model-independent (exclusively uses transverse impact parameter)
- Results interpreted for SUSY models and **Hidden Sector** (shown below) models

2) **LLPs decaying to pair of OS muons (EXO-21-006)**

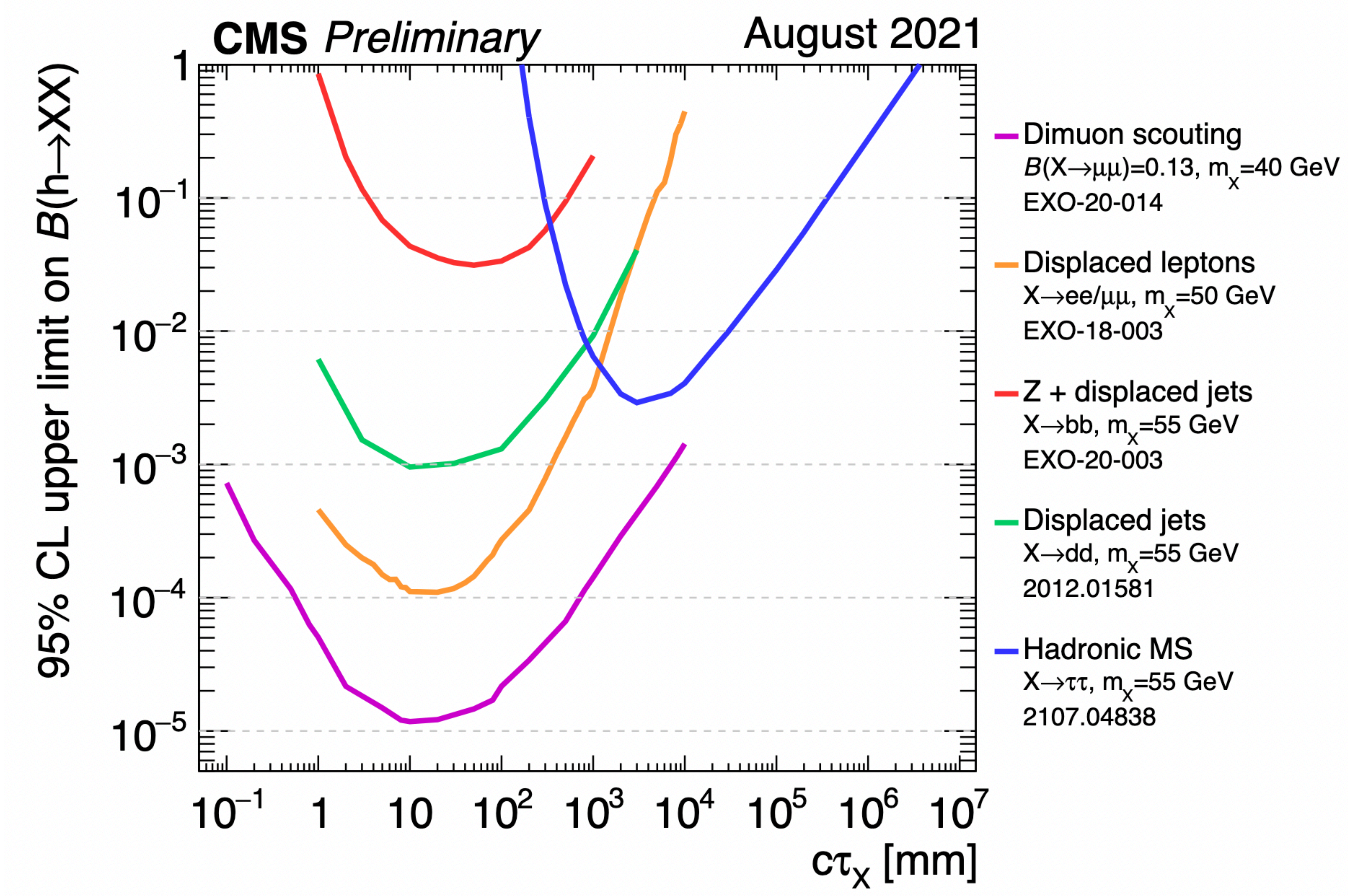
- Distances of decays ranging from several hundred μm to several meters —> *impressive range*



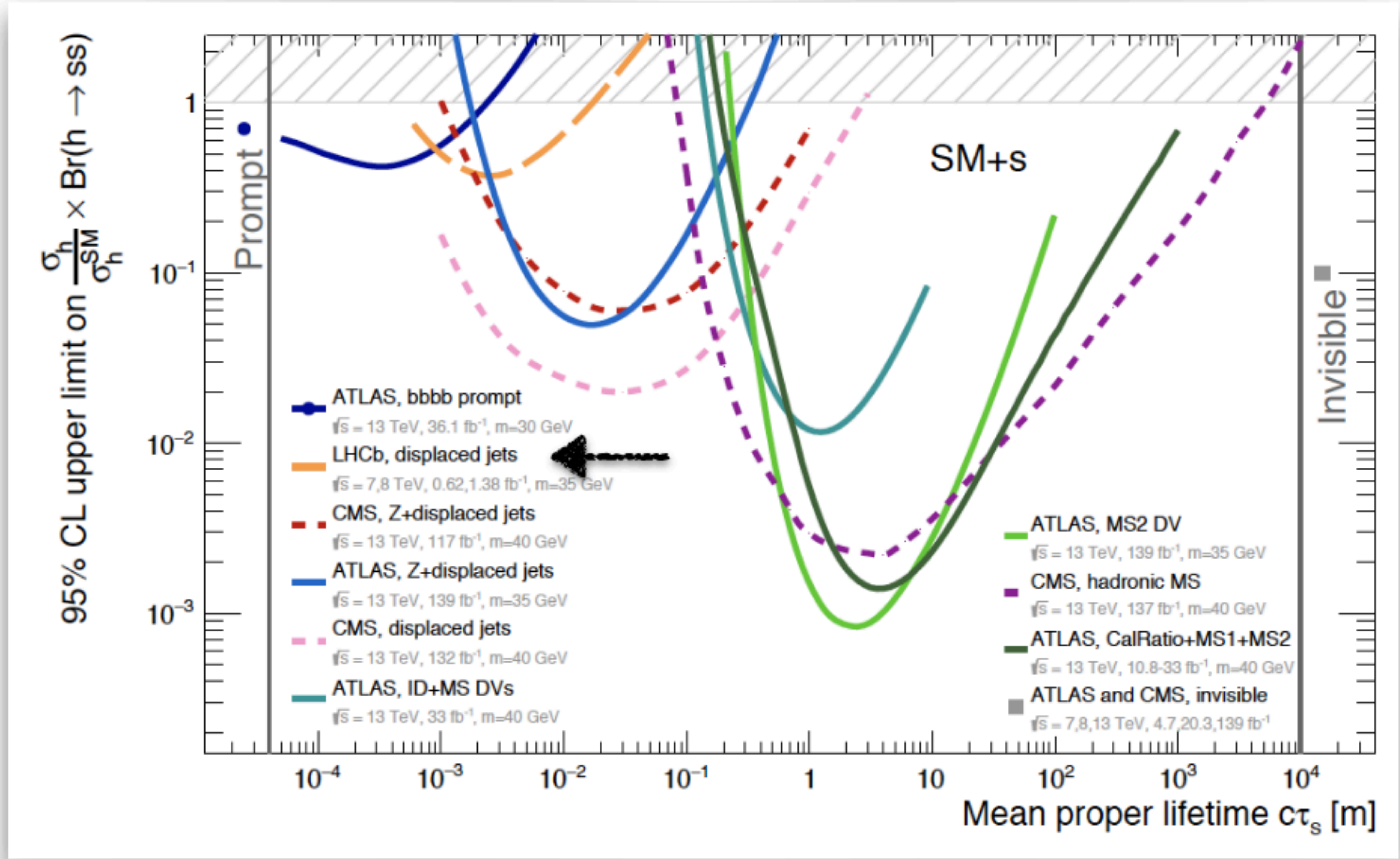


Recent CMS results on Hidden Sector Searches

Note for direct comparison to ATLAS: CMS results not corrected for decay branching fractions



Hidden Sector comparison

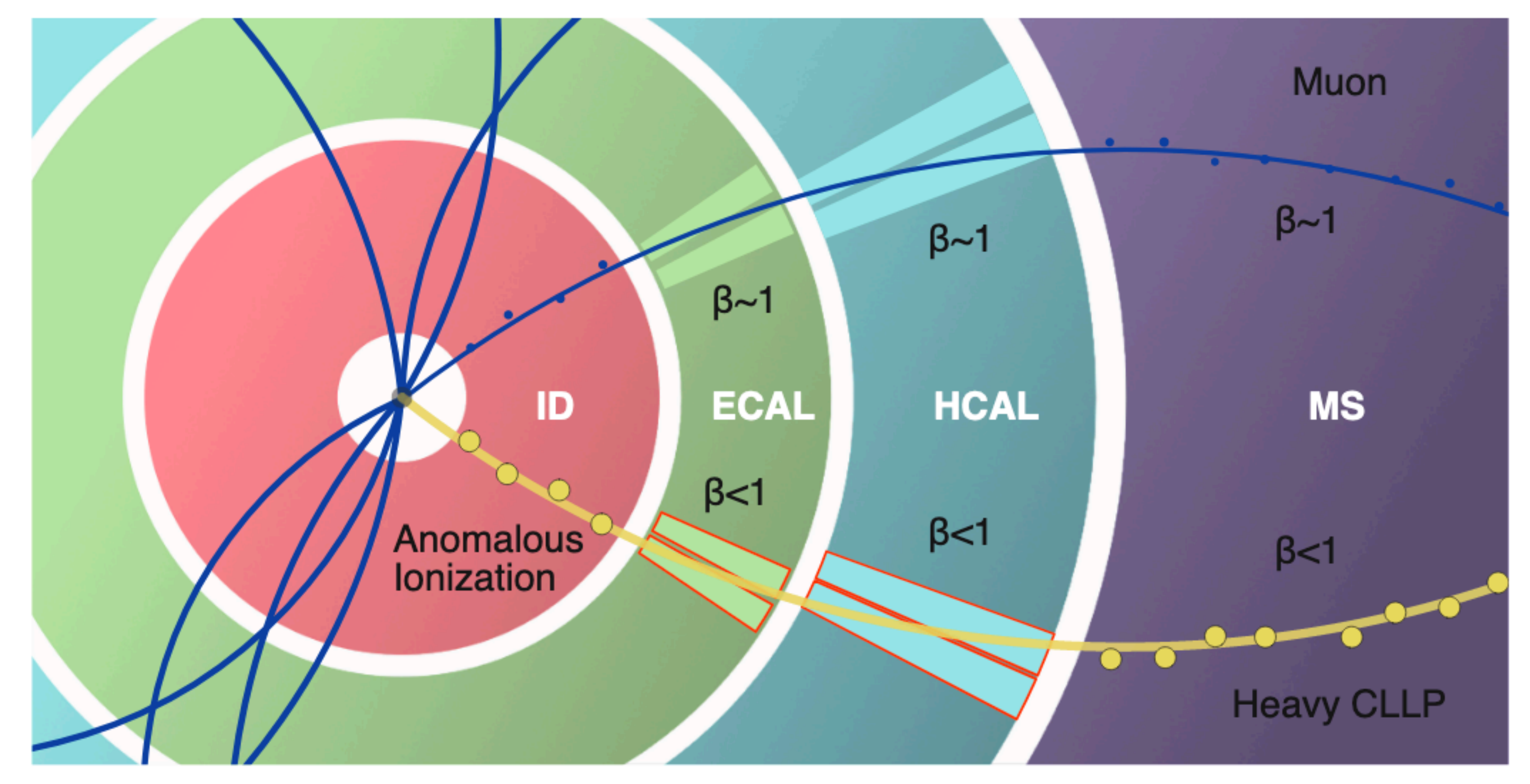


Cepeda, SG, Martinez-Outschoorn, Shelton, 2111.12751

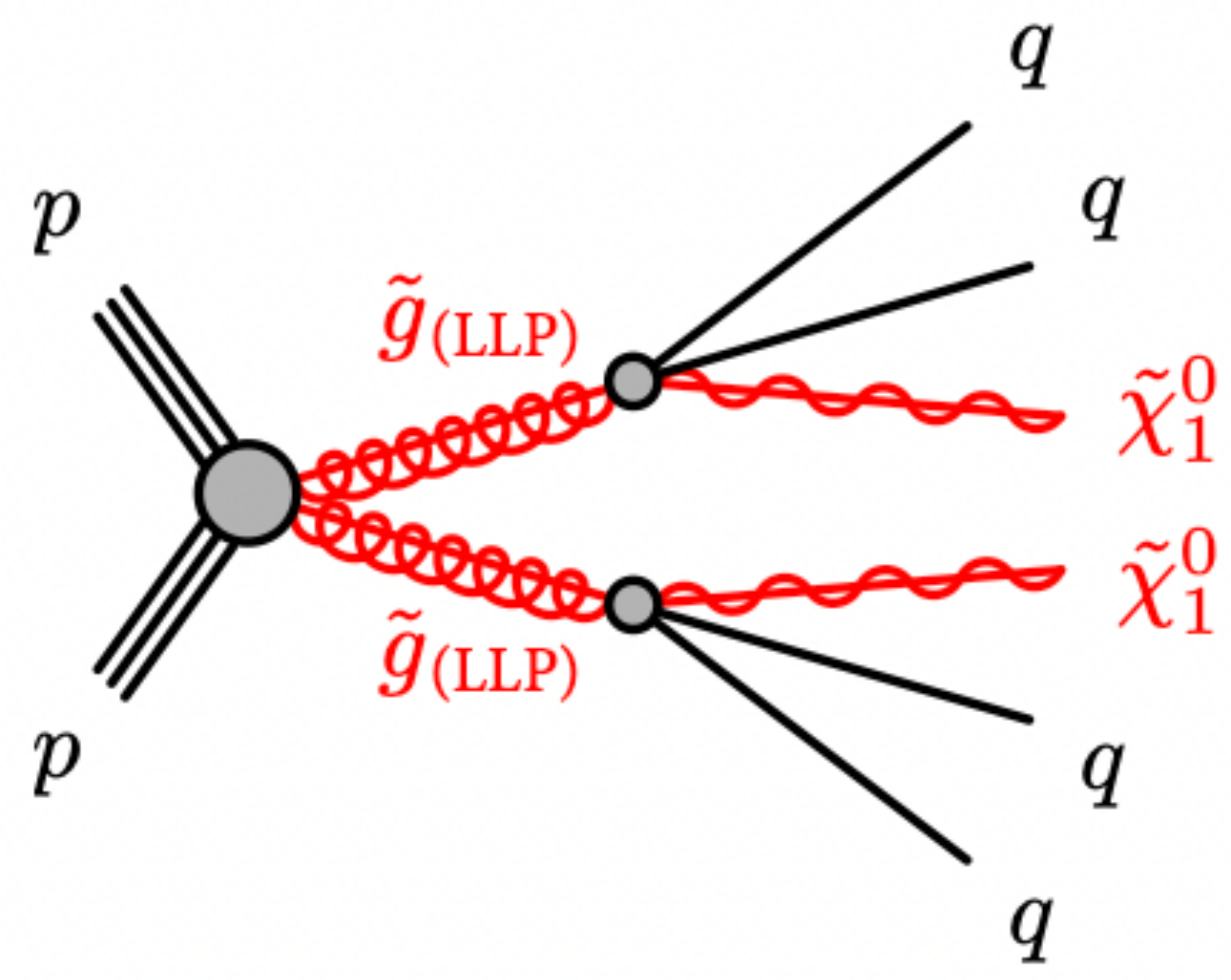
Direct Search

If LLP carries SM charge, we can look for its interactions with the detector directly

Here: dE/dx within the ATLAS Pixels



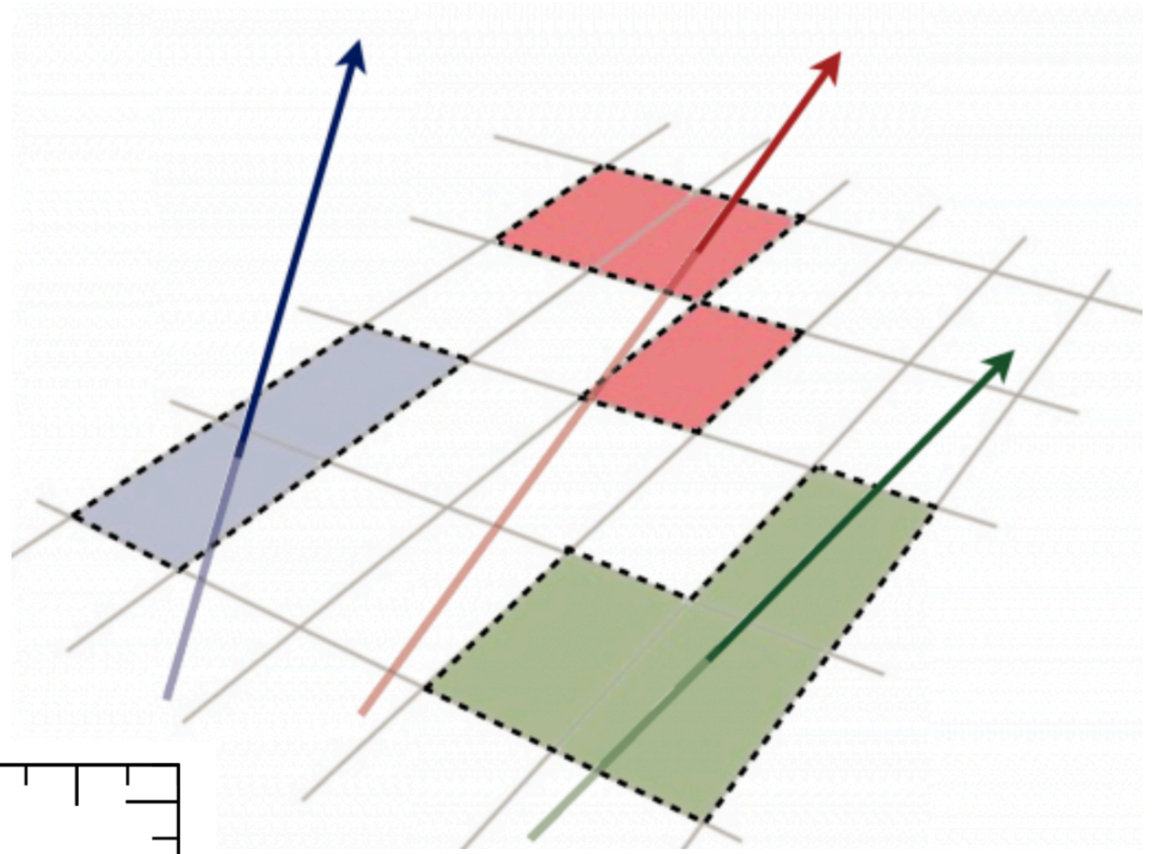
ATLAS: SUSY-2018-42



dE/dx analysis details

Analysis strategy

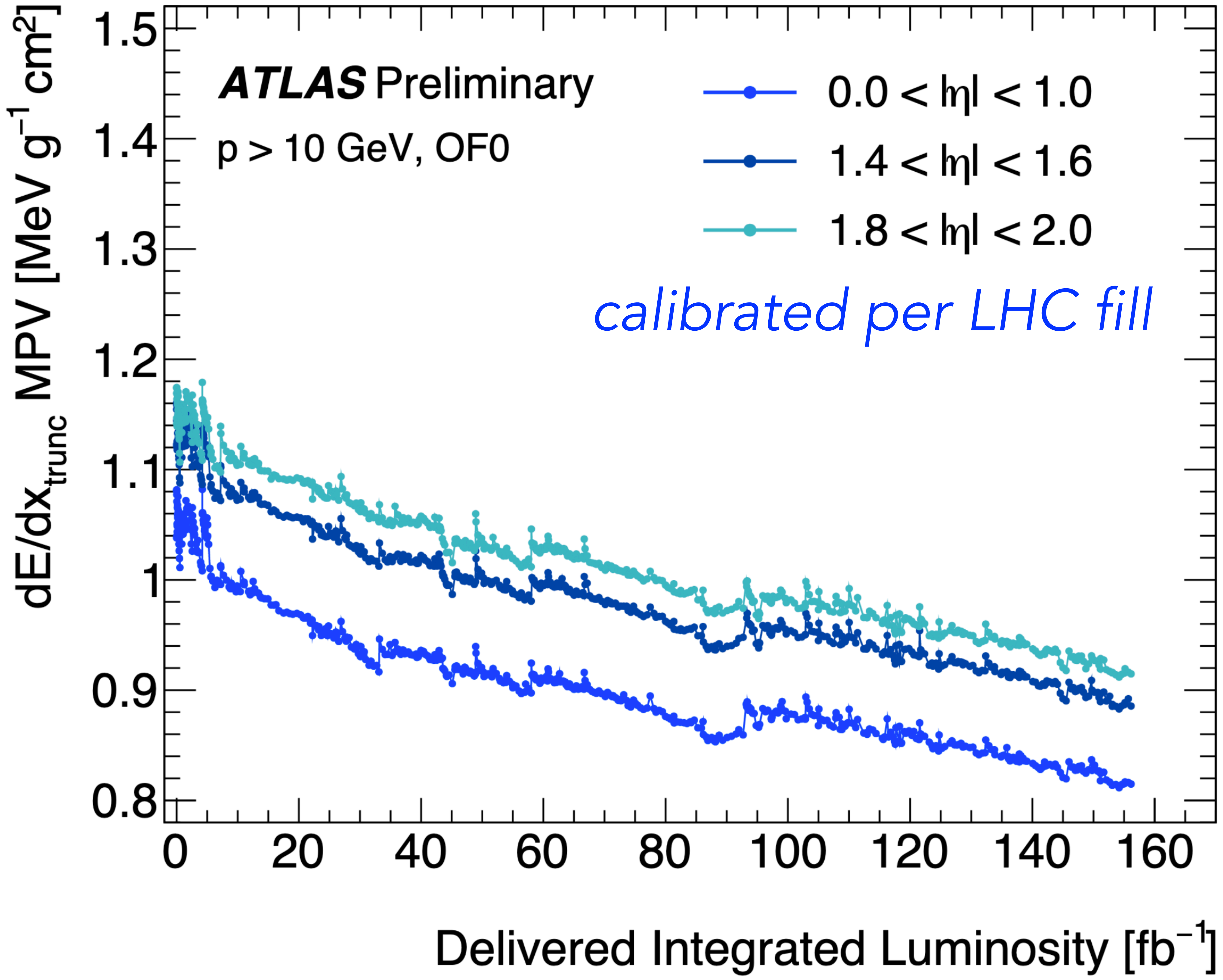
- Events are selected using MET Trigger
- Selecting isolated tracks with high p_T, and large specific ionization (|η|<1.8).
- *Reconstruct the mass of these tracks*



- dE/dx of a track is an average of all clusters on a track
- dE/dx depends on detector conditions

- Parameterize Bethe-Bloch relation to extract mapping of βγ to the **dE/dx**
- Mapping is used to extract βγ of individual tracks in analysis

$$m_{\mathrm{d}E/\mathrm{d}x} \equiv \frac{p_{\mathrm{reco}}}{\beta\gamma(\langle \mathrm{d}E/\mathrm{d}x\rangle_{\mathrm{corr}})}$$



calibrated per LHC fill

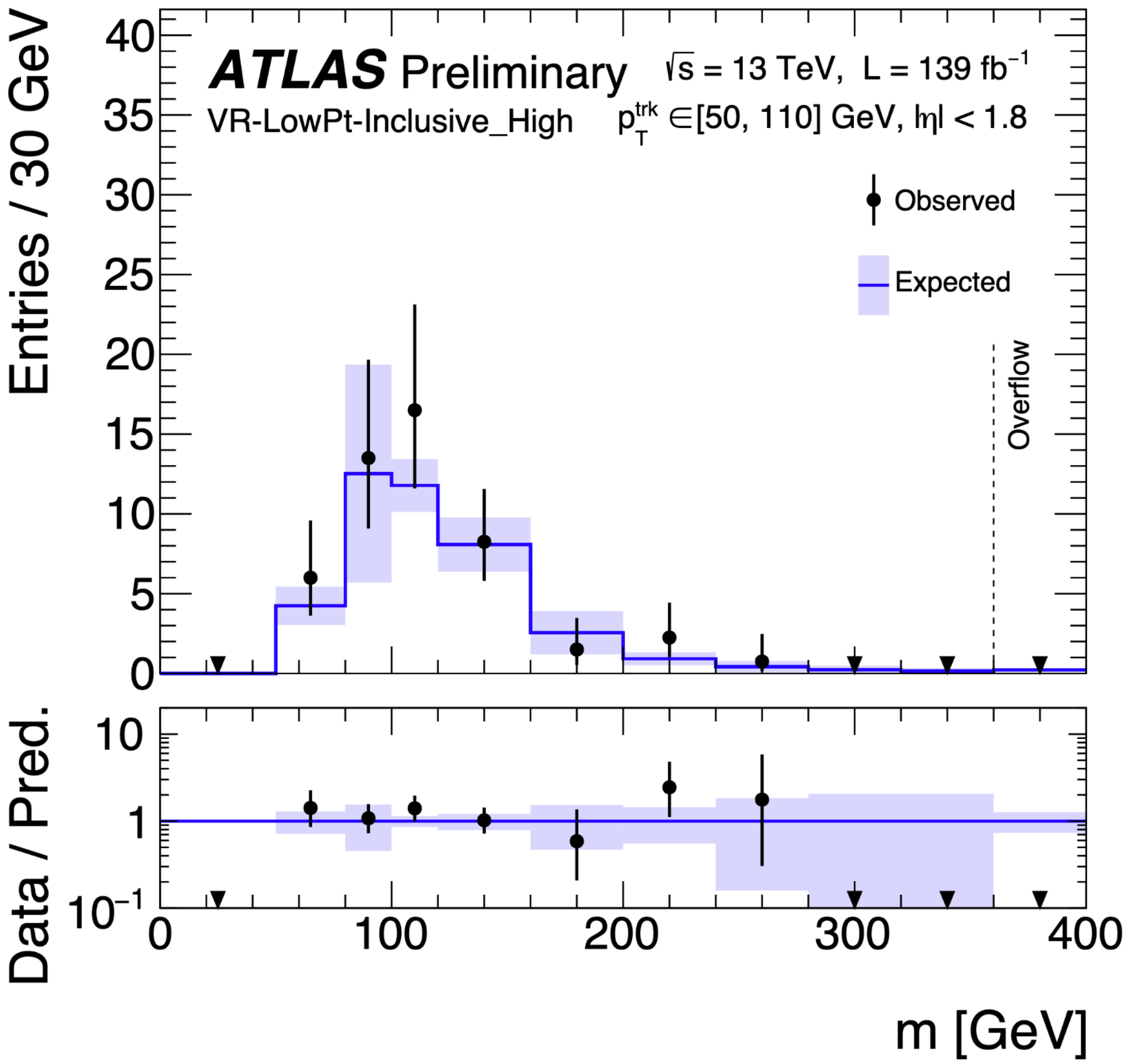
- Adjacent fired pixels are combined into clusters
- Cluster size depends on incident angle

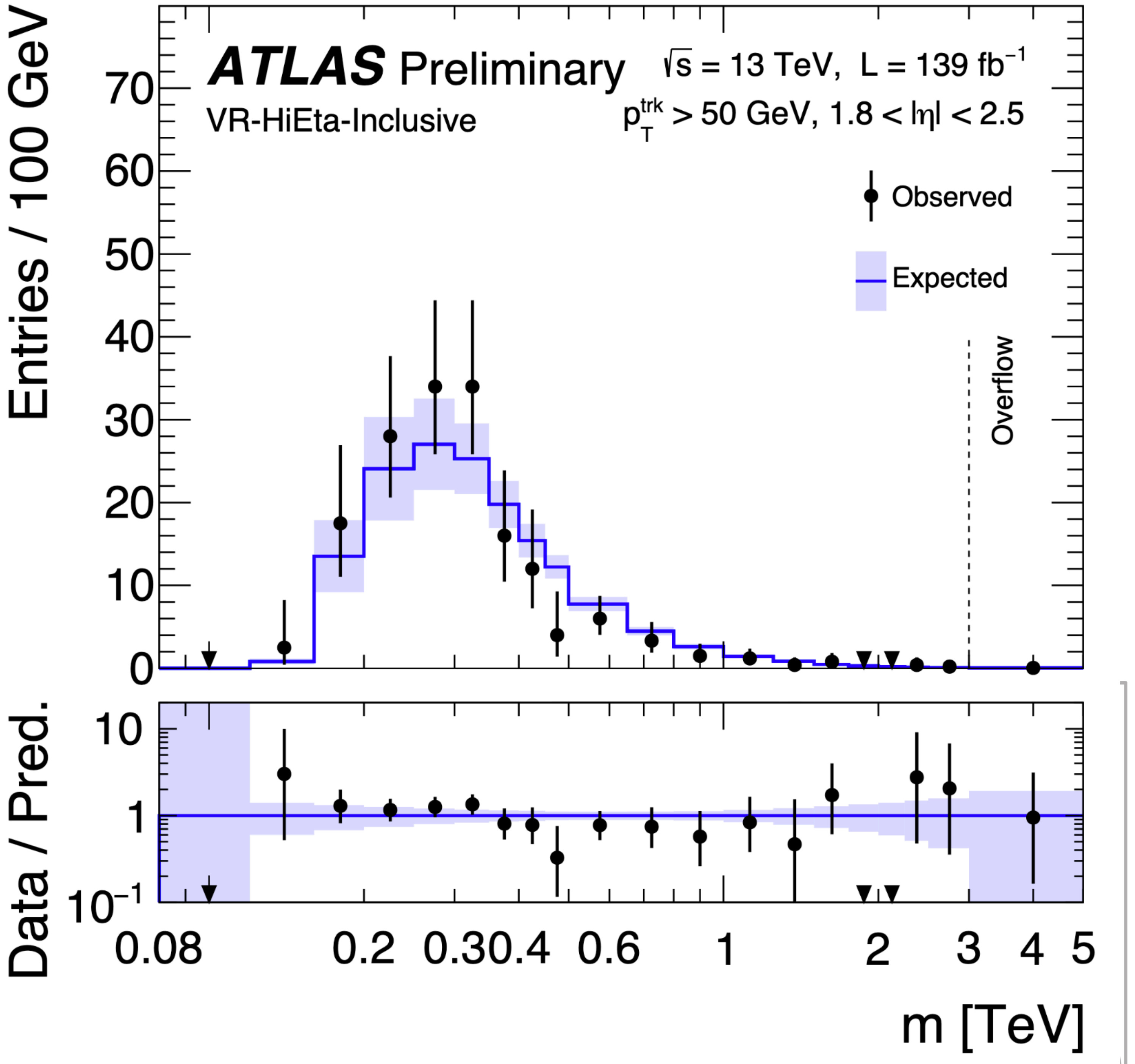
dE/dx analysis details

Analysis strategy

- Events are selected using MET Trigger
- Selecting isolated tracks with high p_T, and large specific ionization (|η|<1.8).
- Reconstruct the mass of these tracks
- *Generate data-driven background distributions using toys from track-mass templates*

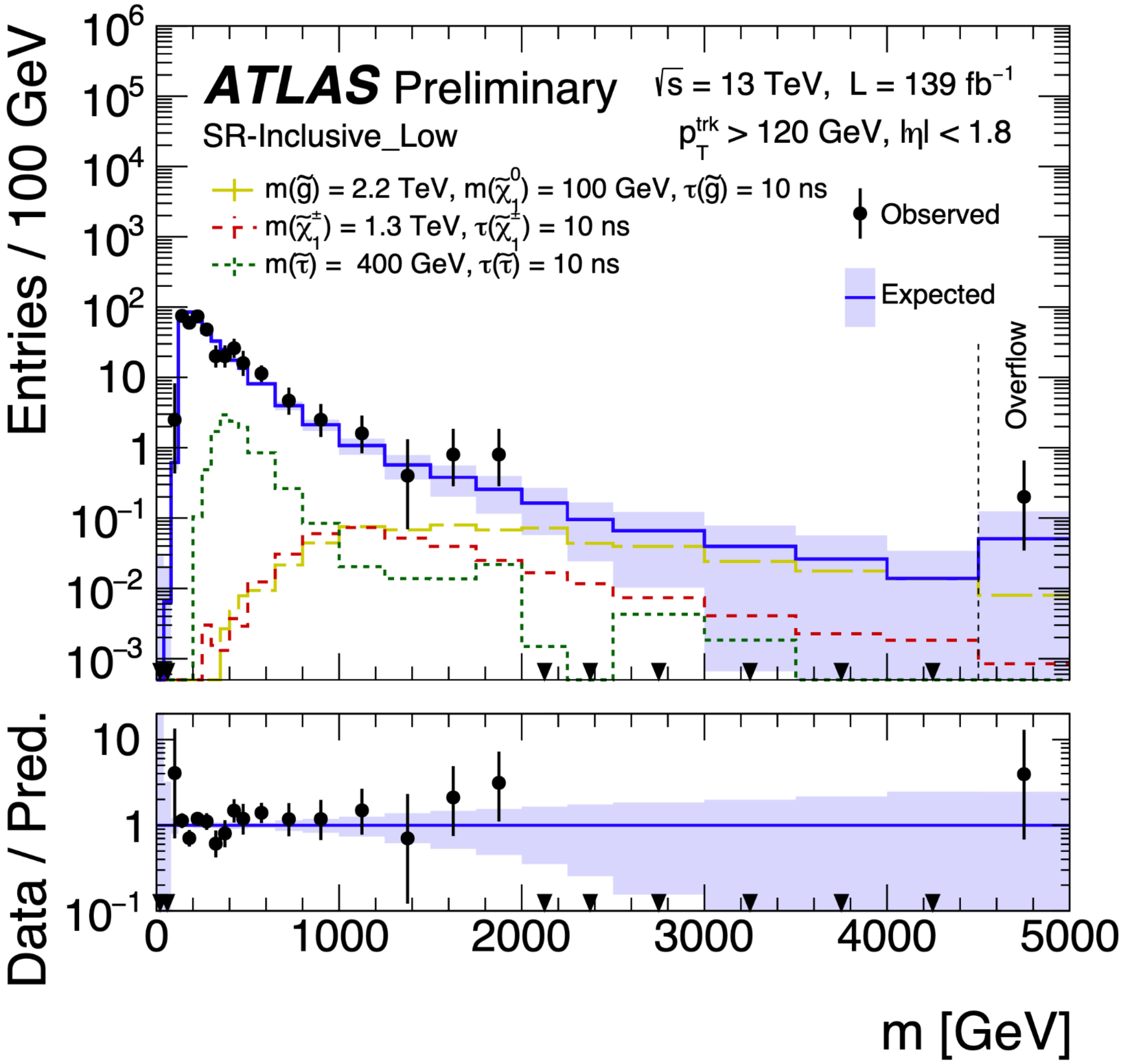
- Derive shape and normalization in CRs defined by inverted selections
- Validation regions show good normalization and shape agreement



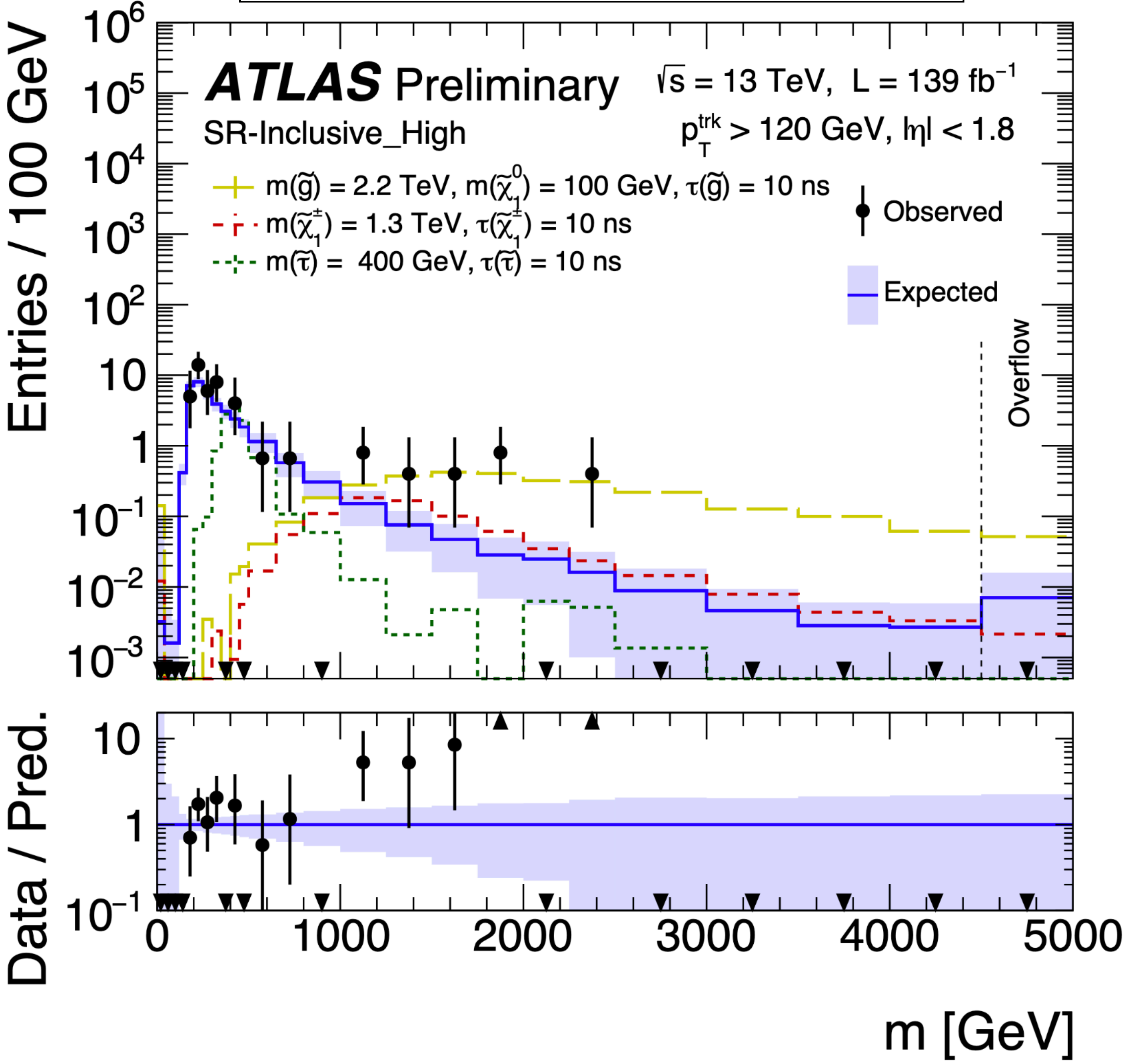


dE/dx Results — Discovery Regions

$\mathrm{d}E/\mathrm{d}x \in [1.8, 2.4]\ \mathrm{MeV\,g^{-1}cm^2}$



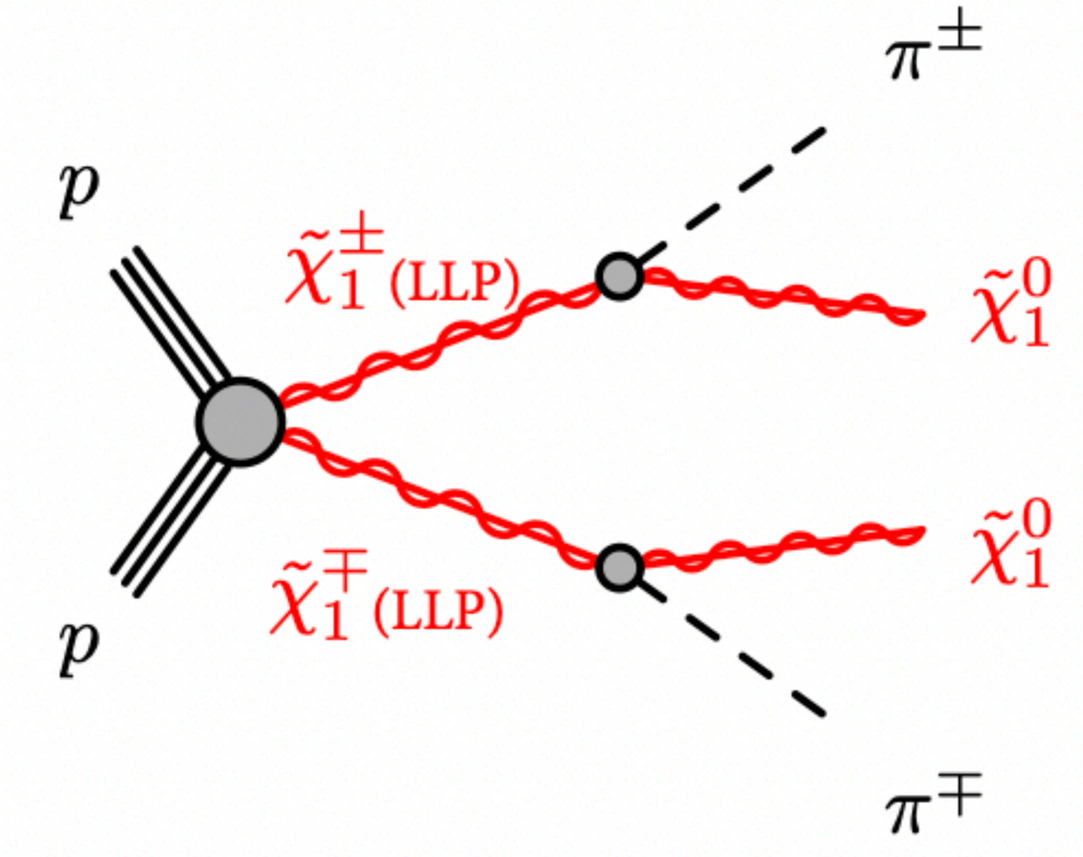
$\mathrm{d}E/\mathrm{d}x > 2.4\ \mathrm{MeV\,g^{-1}cm^2}$

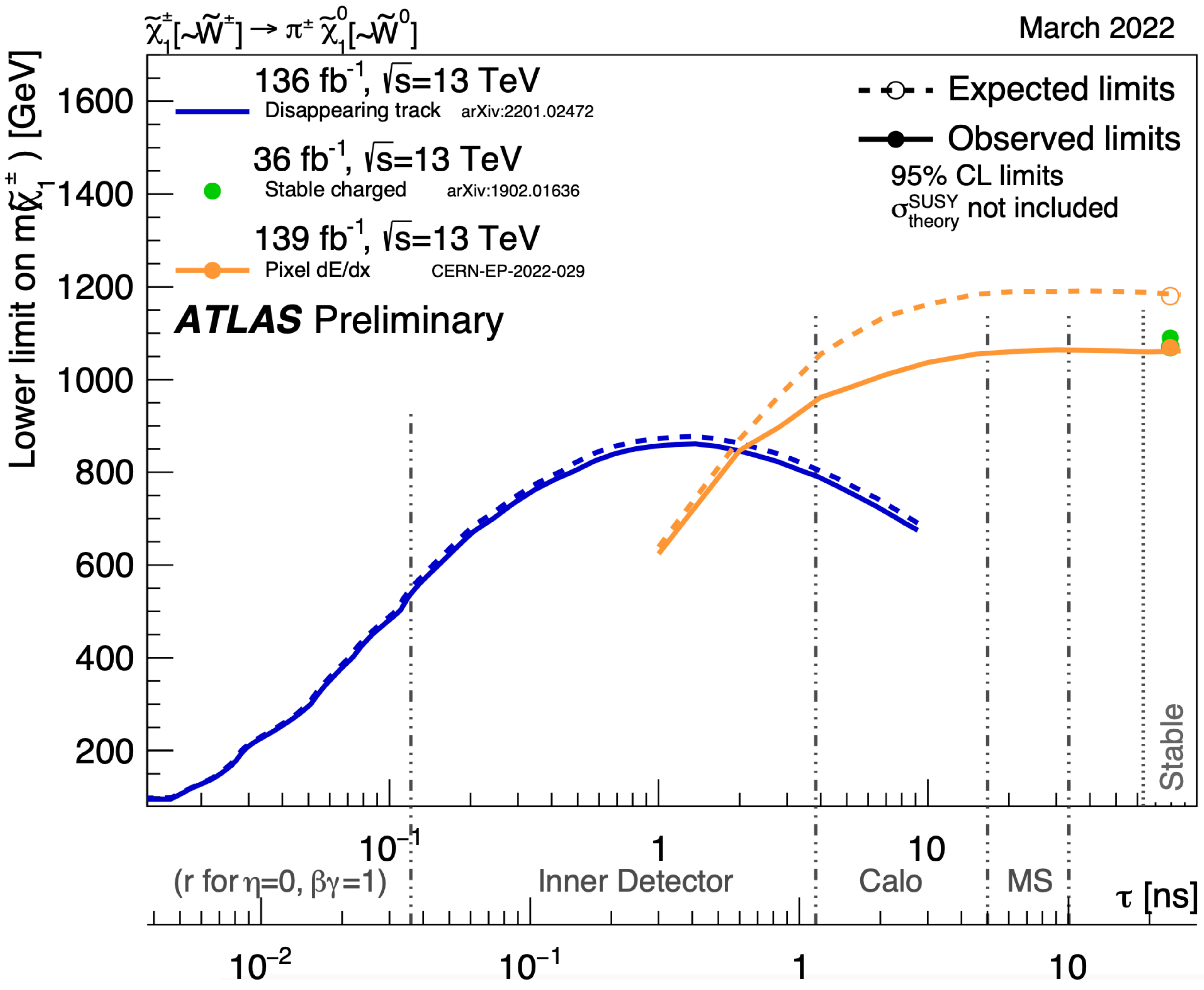


<u>Observations:</u>

- Overall good agreement between observed events and expected background
- An **excess of events** is observed in the “Inclusive-High” SR at masses exceeded 1 TeV
  - Local significance of 3.6σ, **global significance 3.3σ**
- **Caution:** ToF study of excess events with calorimeter and muon system show a β~1

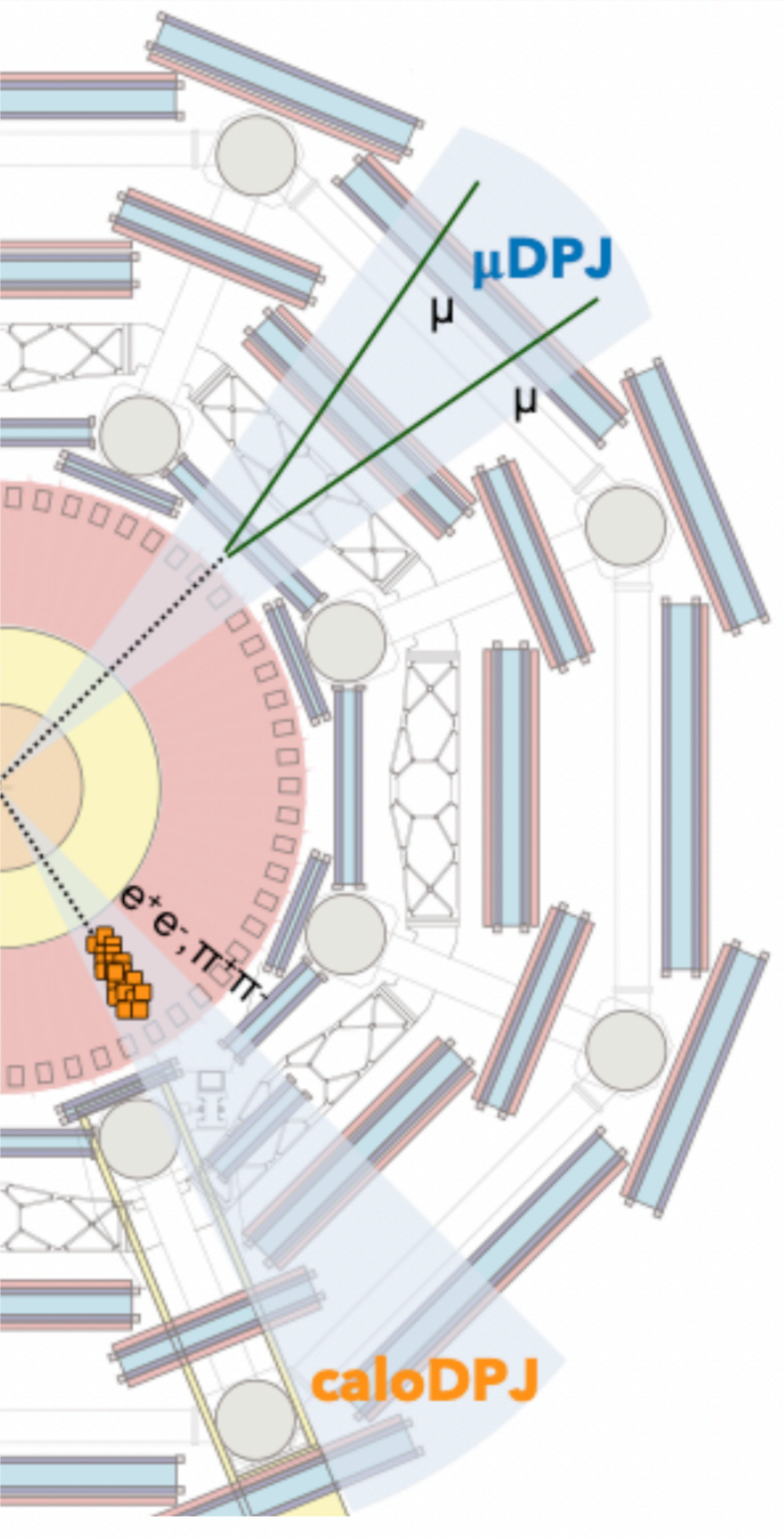
dE/dx Results — Limits





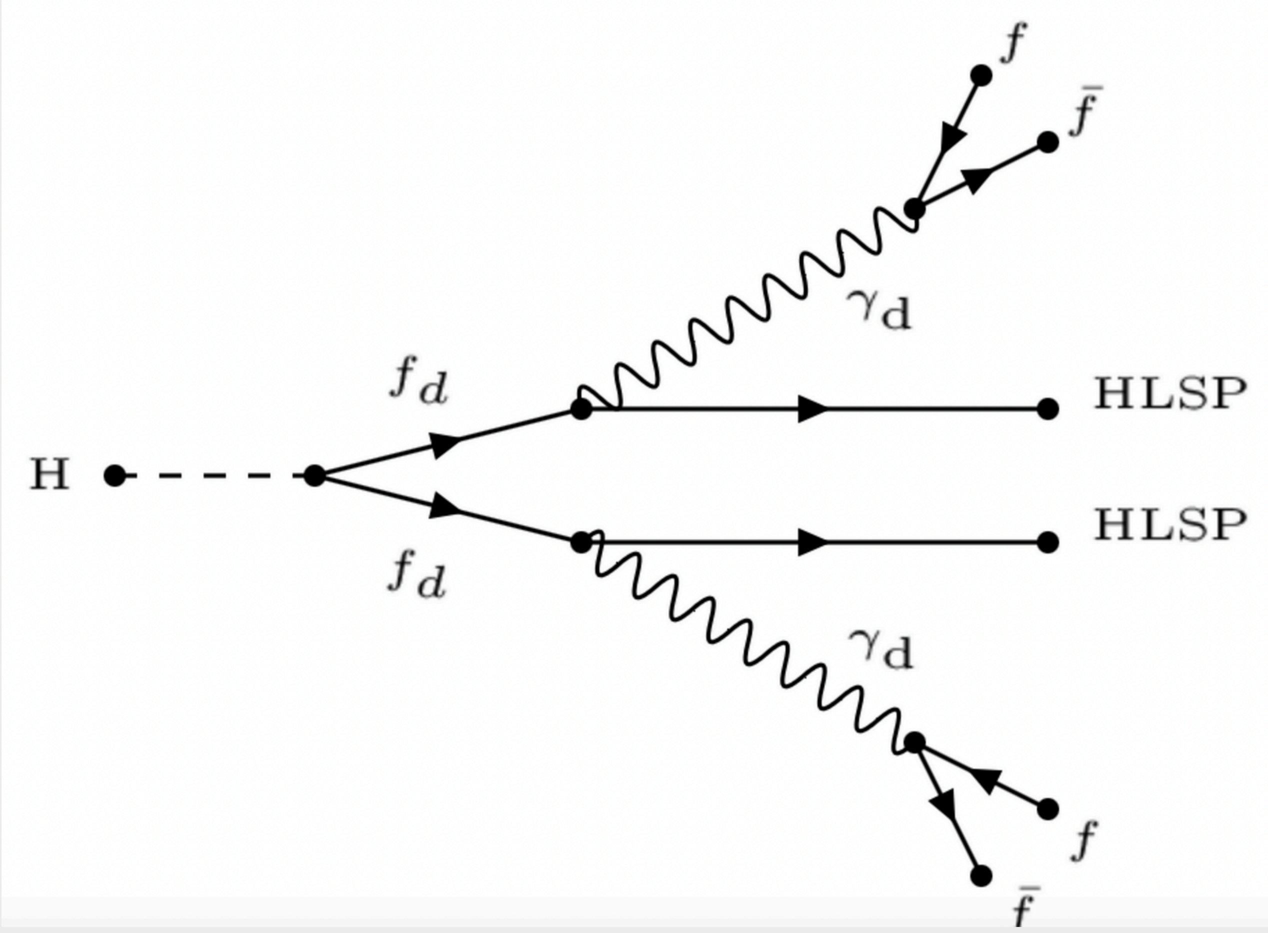
Observations:

- Due to the observed excess of events, the observed limits are lower than expected limits

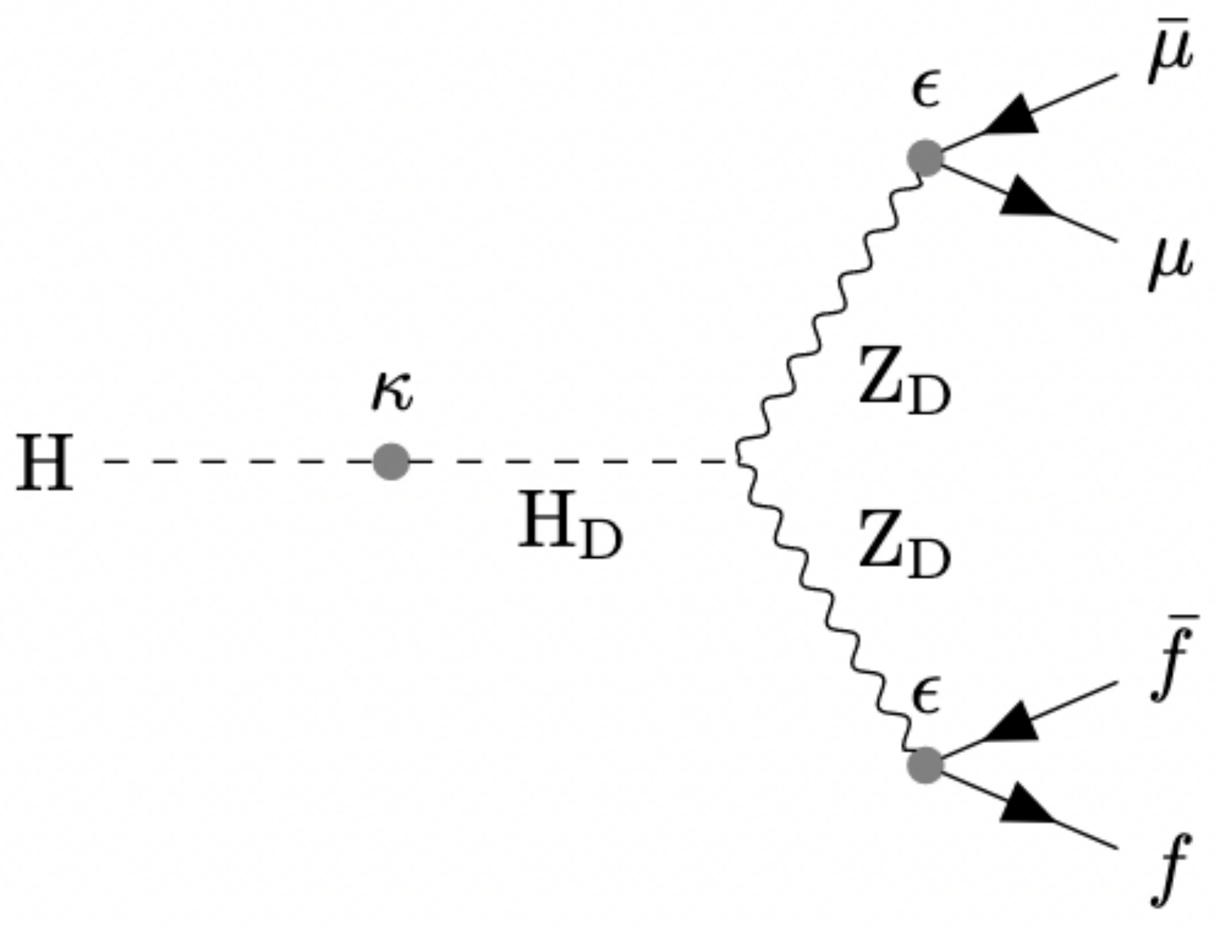


Dark photon searches at a glance

Falkowsky, Ruderman, Volansky, Zupan [FRVZ] model



Hidden Abelian Higgs model [HAHM] model



CMS: EXO-21-006, EXO-20-014

ATLAS: ATLAS-CONF-2022-001

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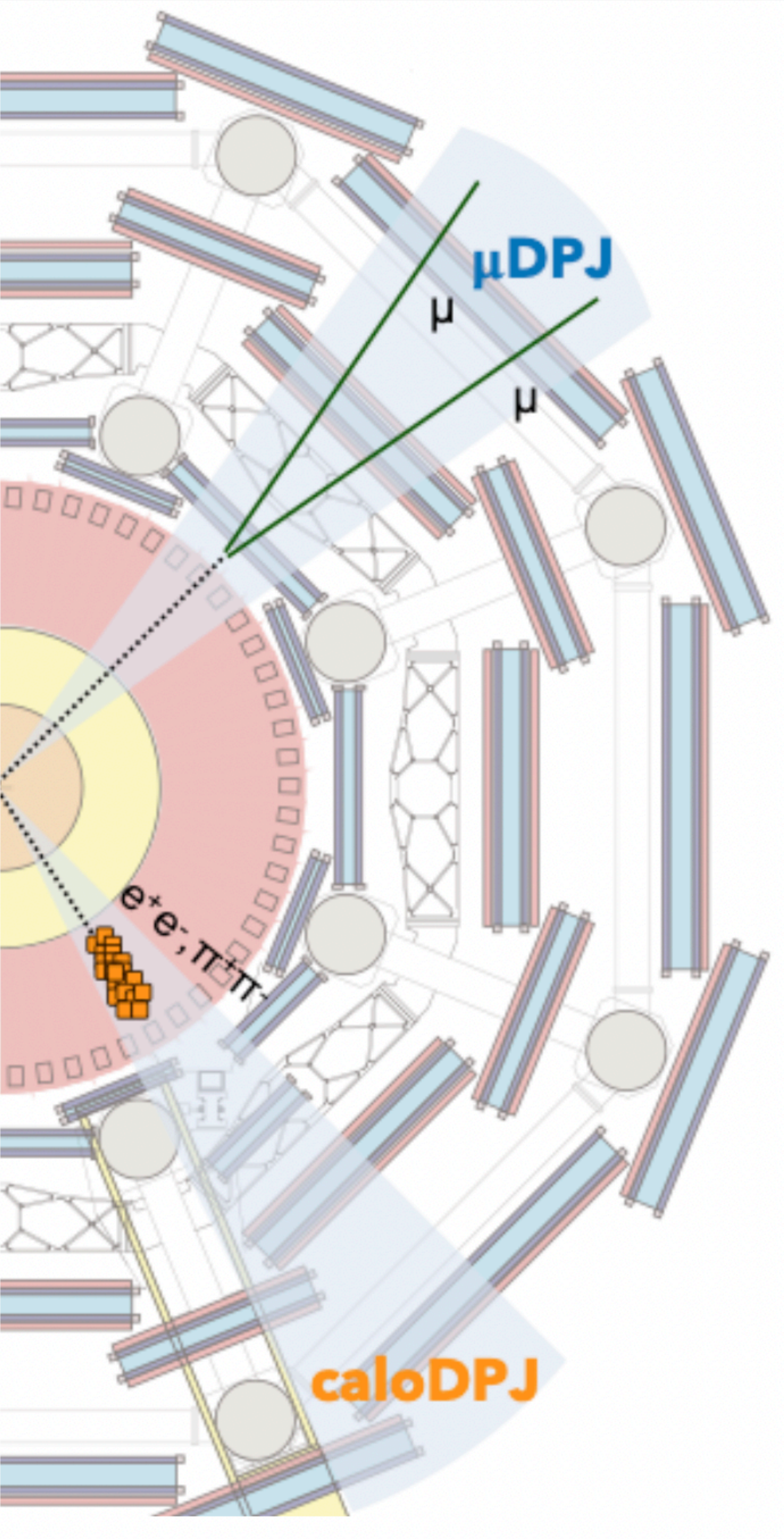

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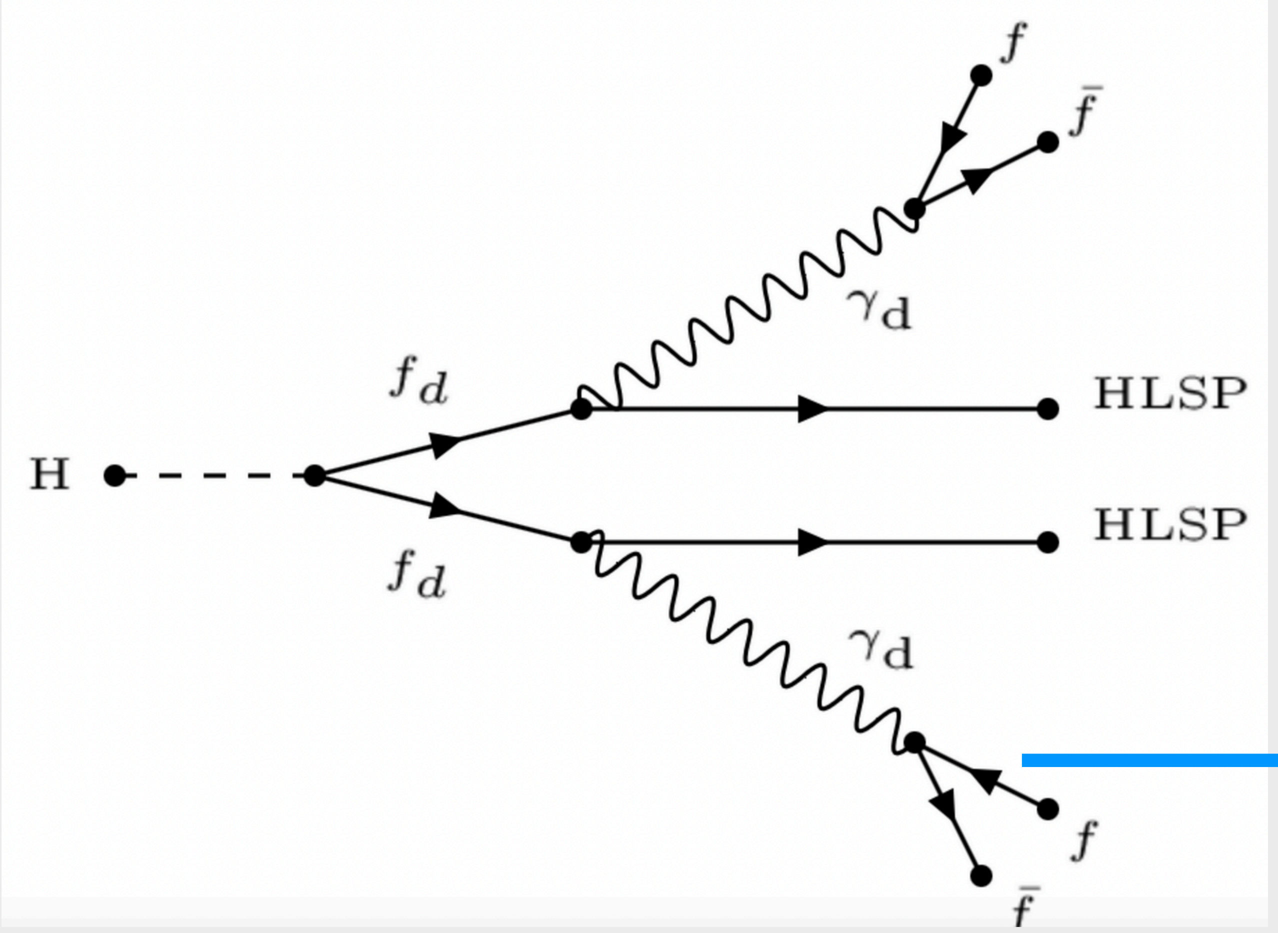

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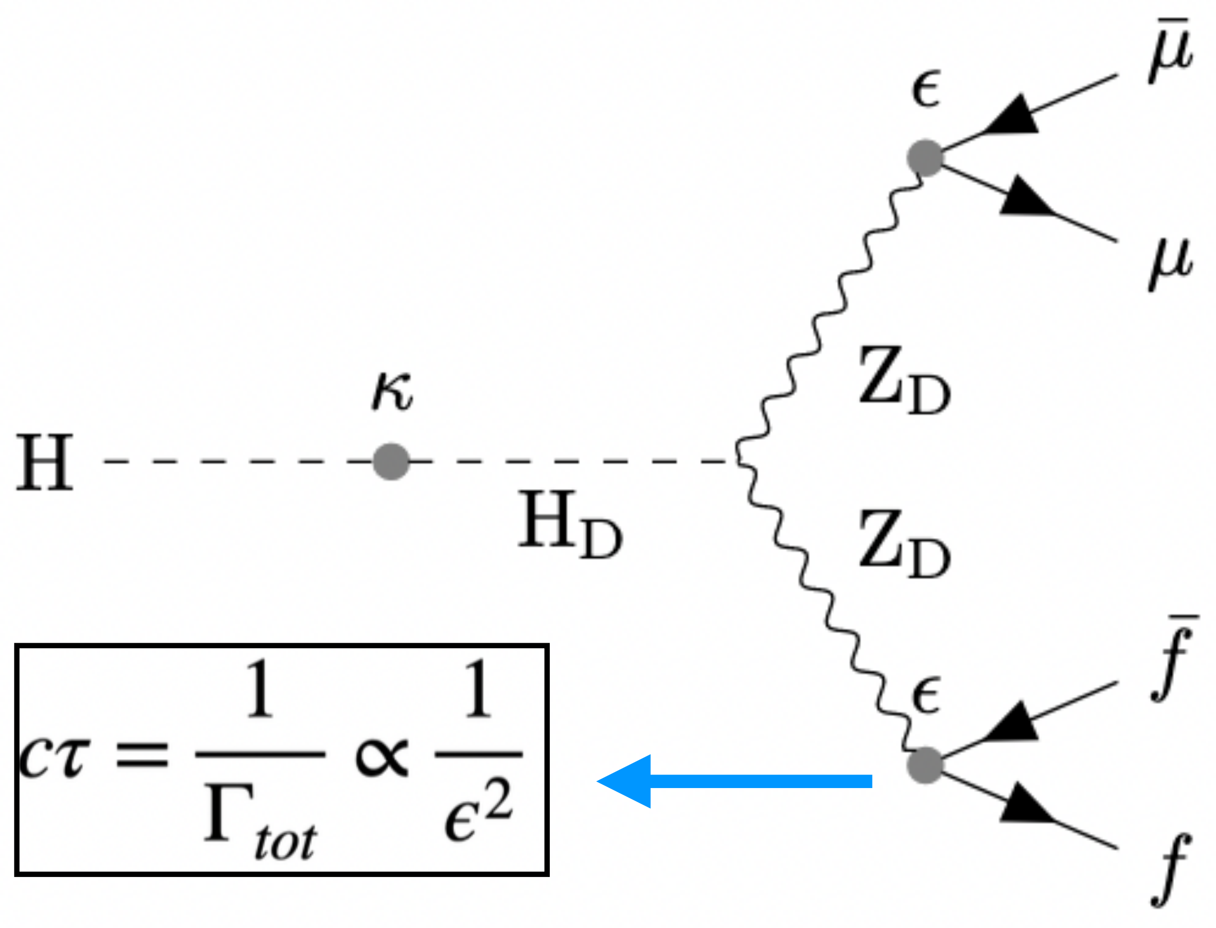


$$\boxed{c\tau = \frac{1}{\Gamma_{tot}} \propto \frac{1}{\epsilon^2}}$$

small couplings → displaced decays

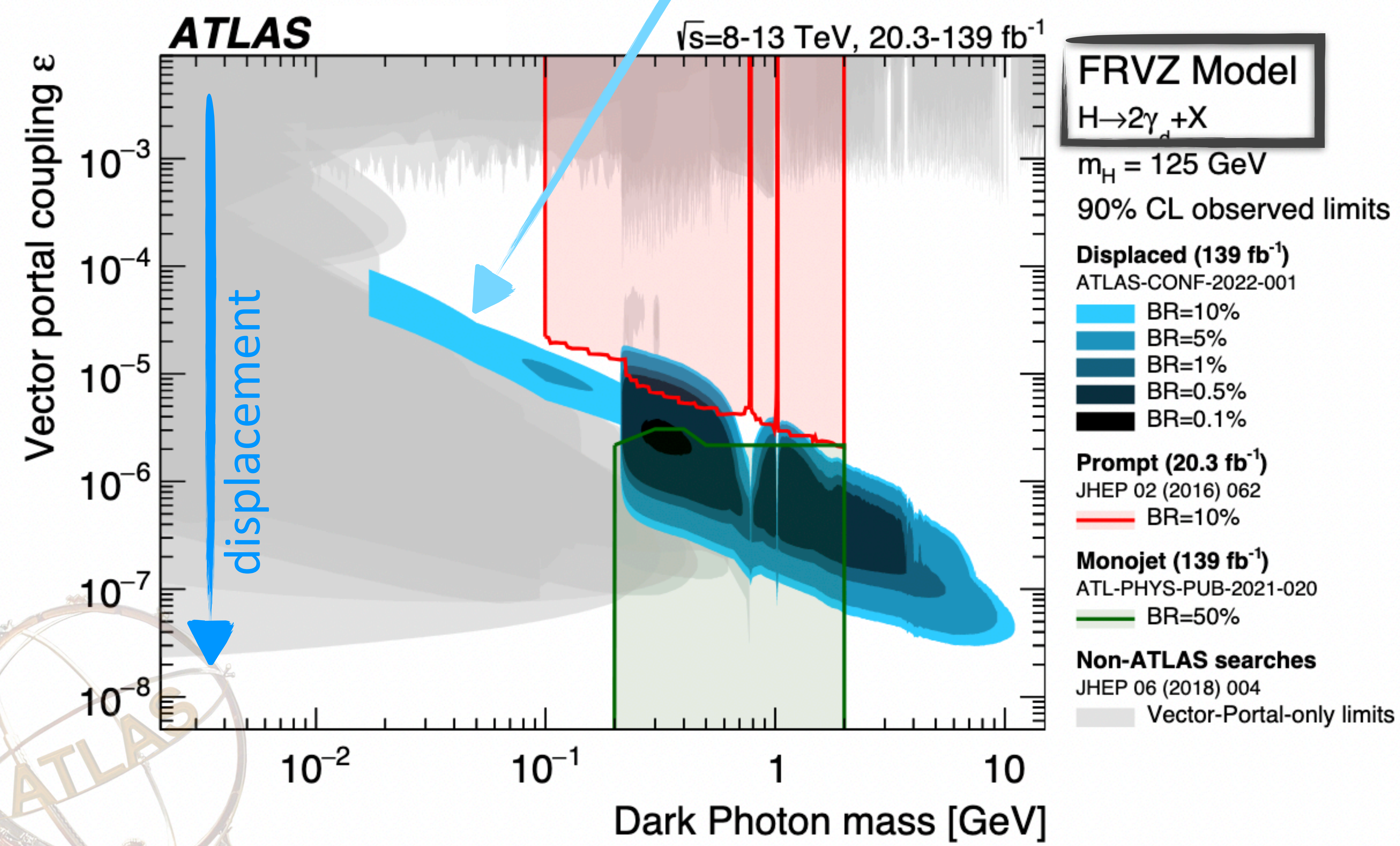
CMS: EXO-21-006, EXO-20-014

ATLAS: ATLAS-CONF-2022-001

Dark photon searches at a glance

ATLAS:

- First time exclusion in the *fully electron channel*
- Significant analysis improvements (CNN taggers) and WH topology allowed for exclusion of hadronic decays



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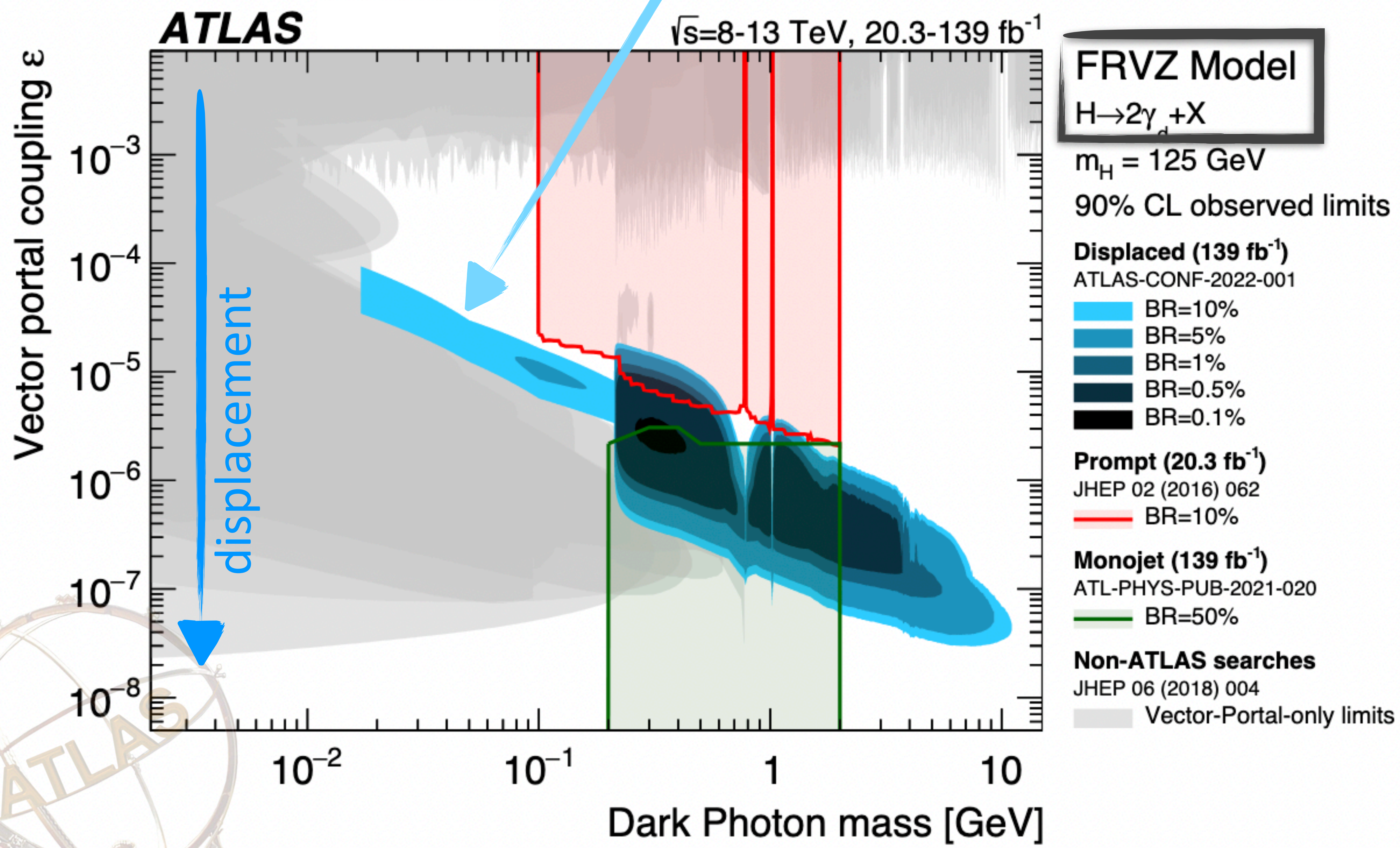

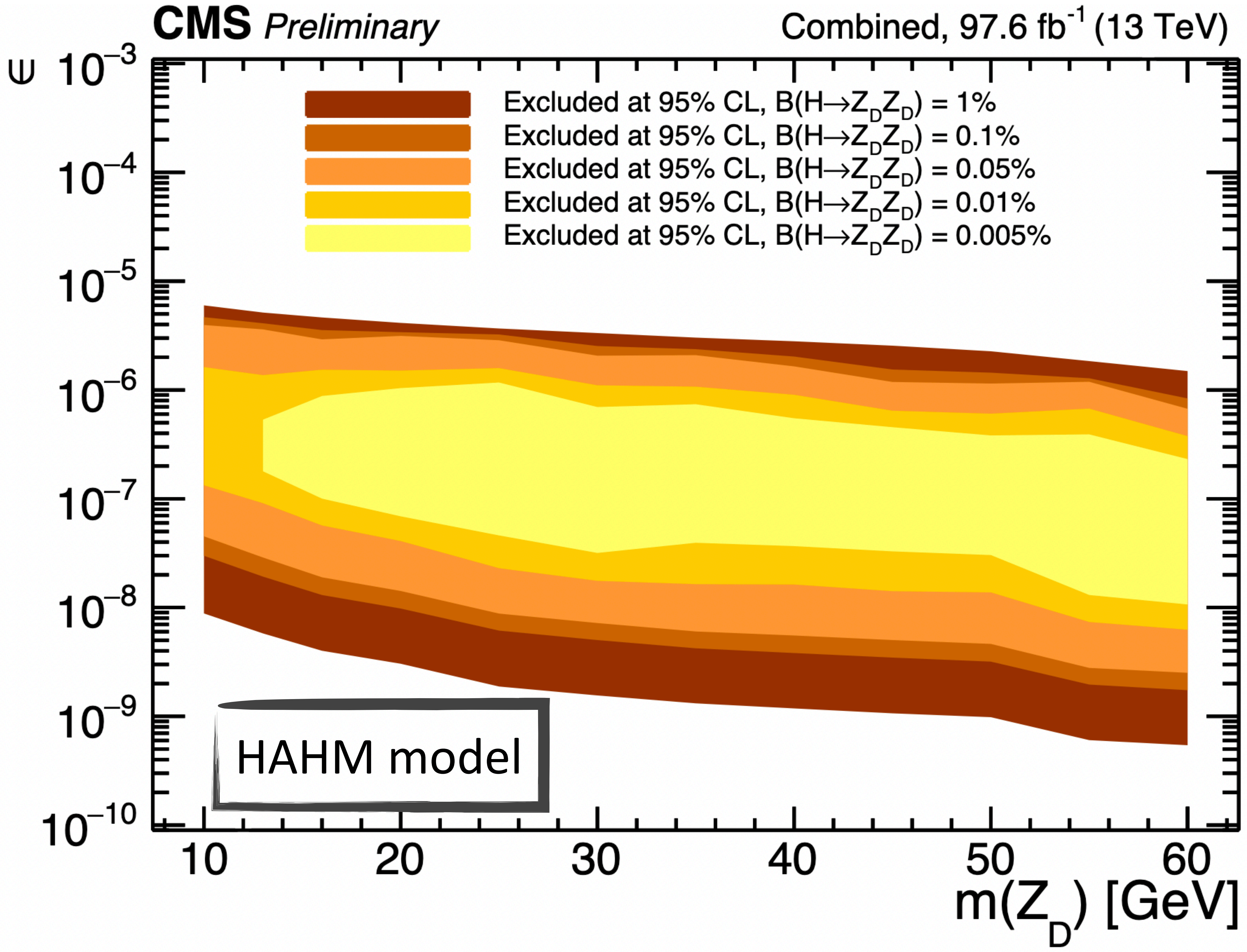

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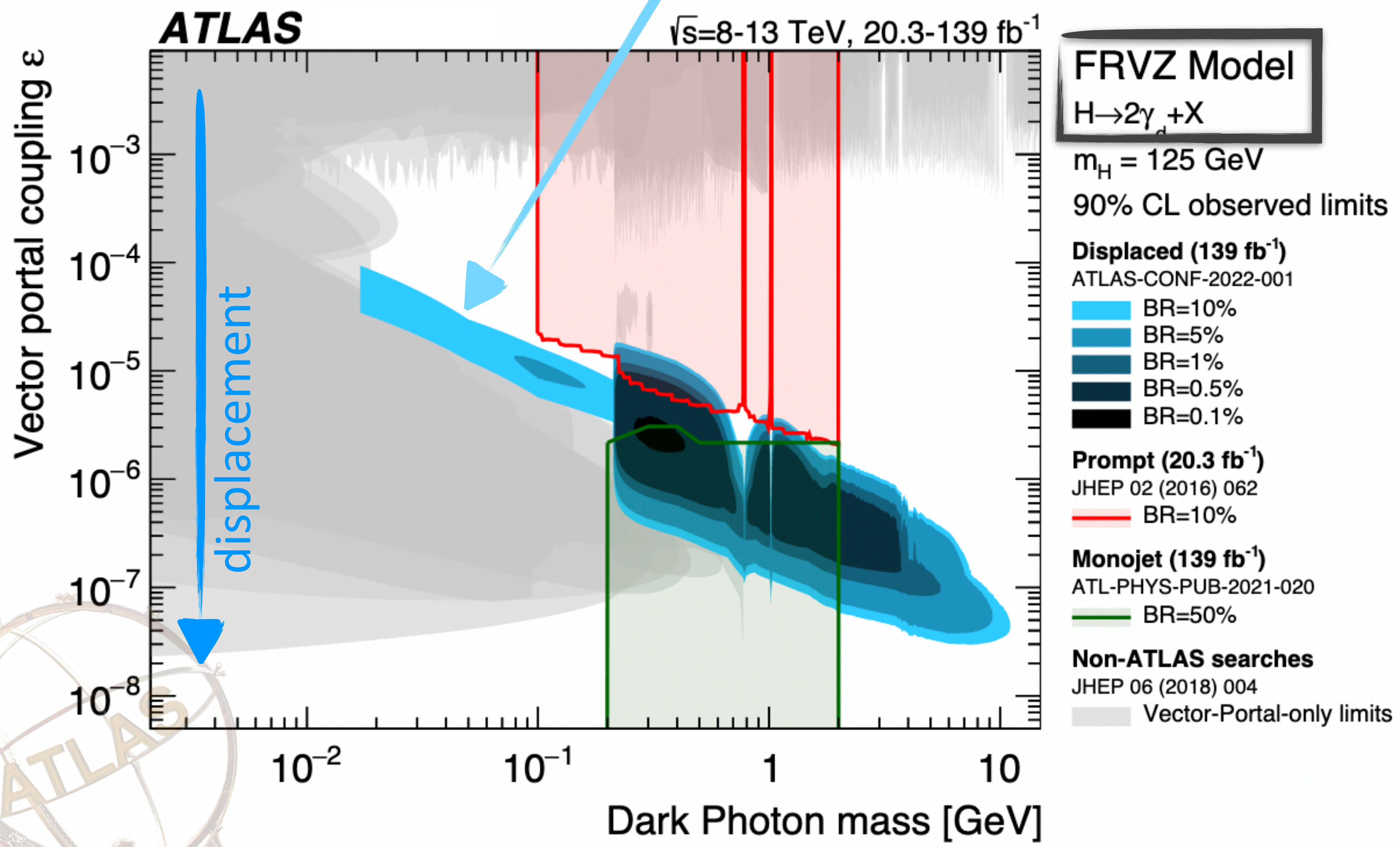
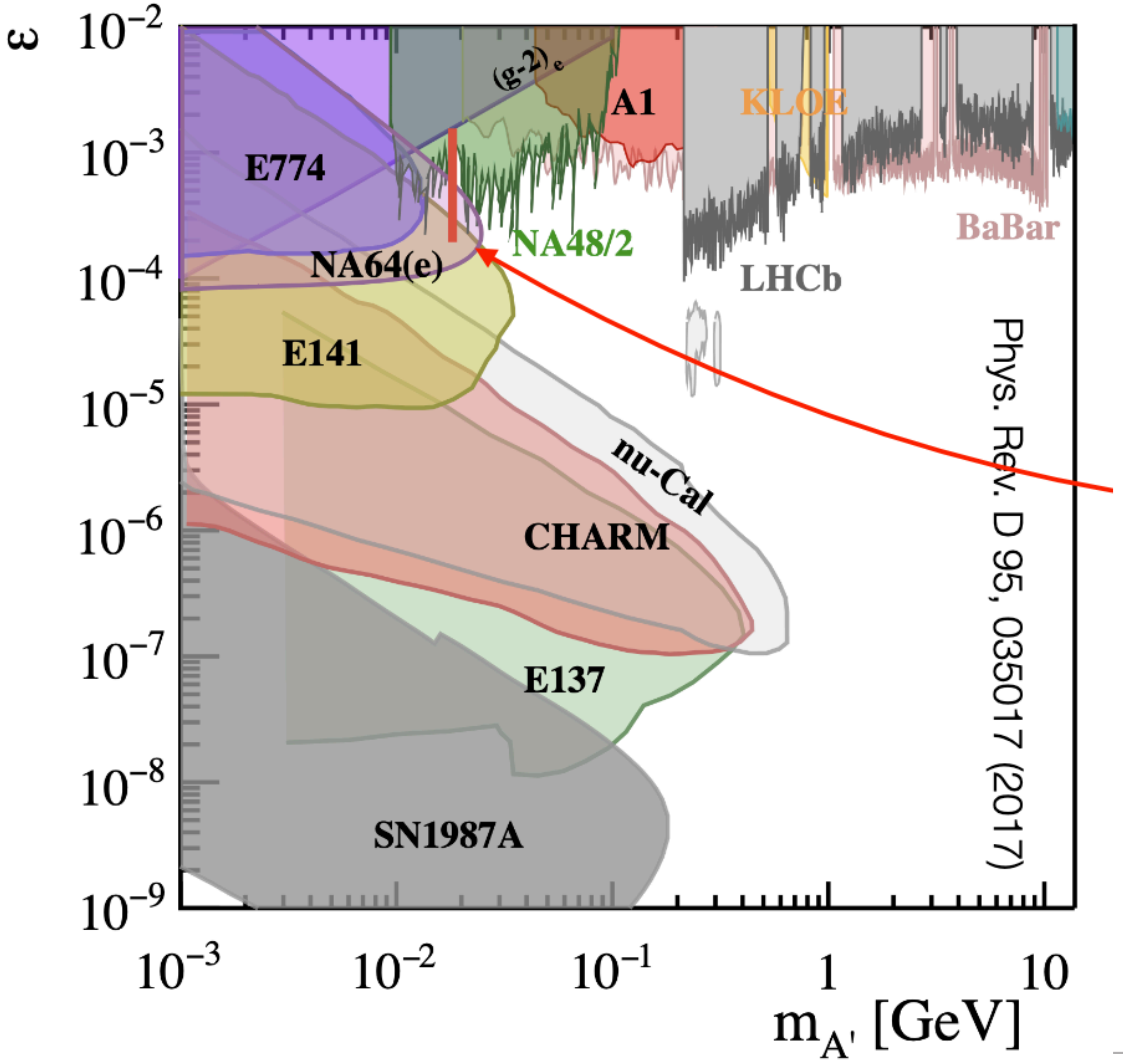
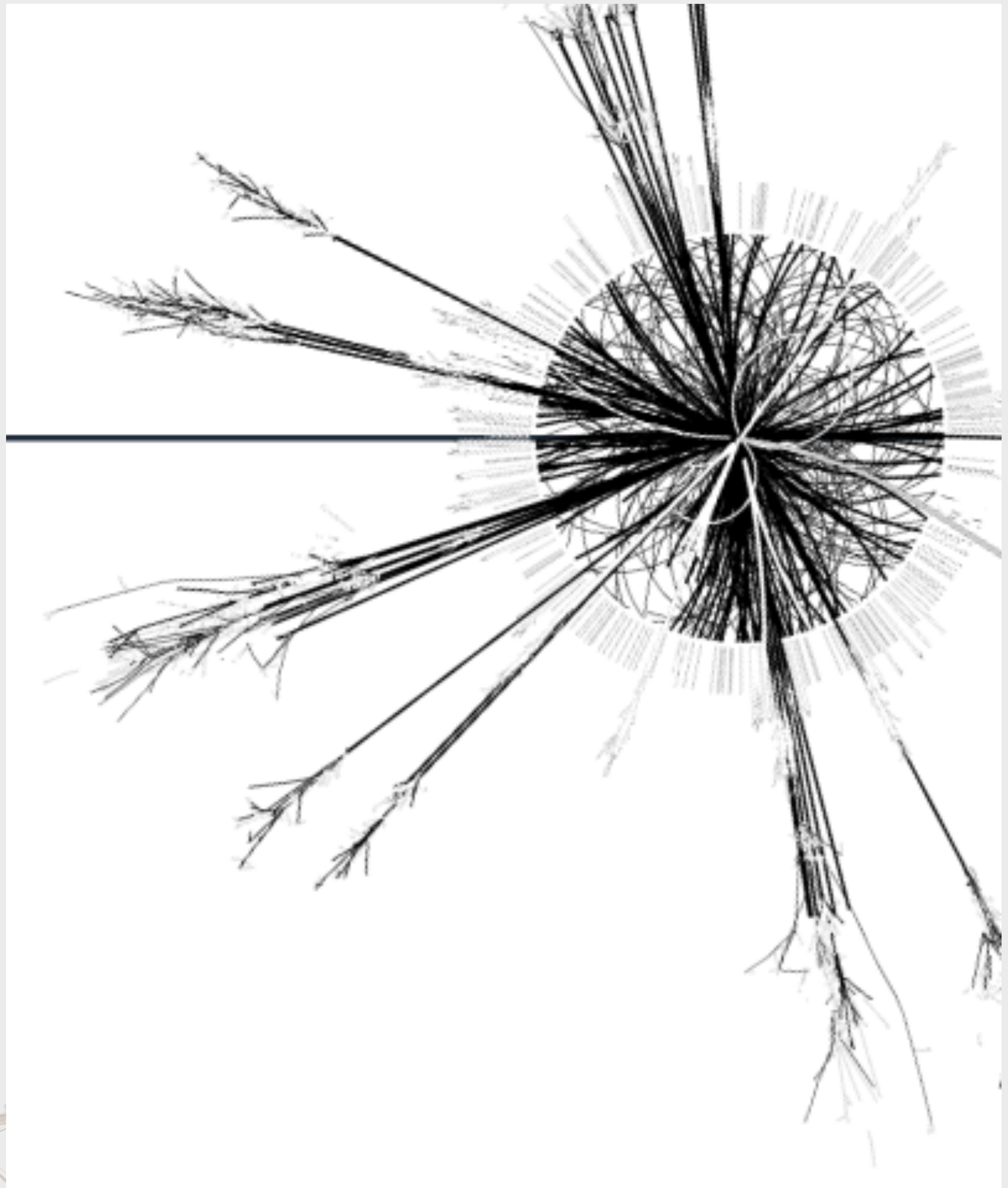




Anomalies show up here!

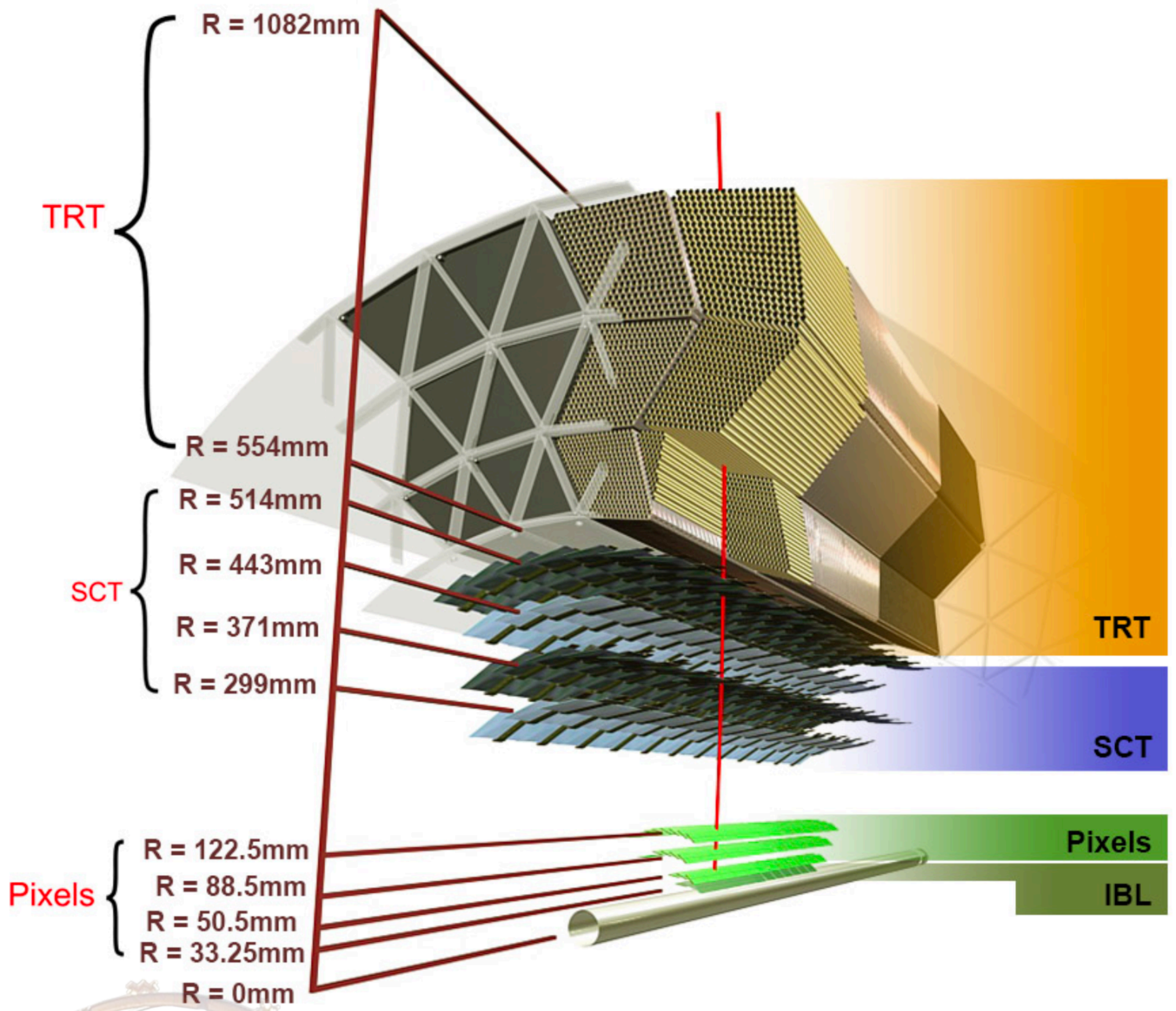
- Complementarity to probe X17 excess and g-2 results
- Tricky but maybe possible



New potential for Run 3 —> Improved triggers, reconstruction techniques and tools

Why LLP searches use non-standard reconstructions?

If you want to reconstruct a charged particle with Impact Parameters **(d_0,z_0)** outside the **prompt phase-space** —> **you need special reconstruction**



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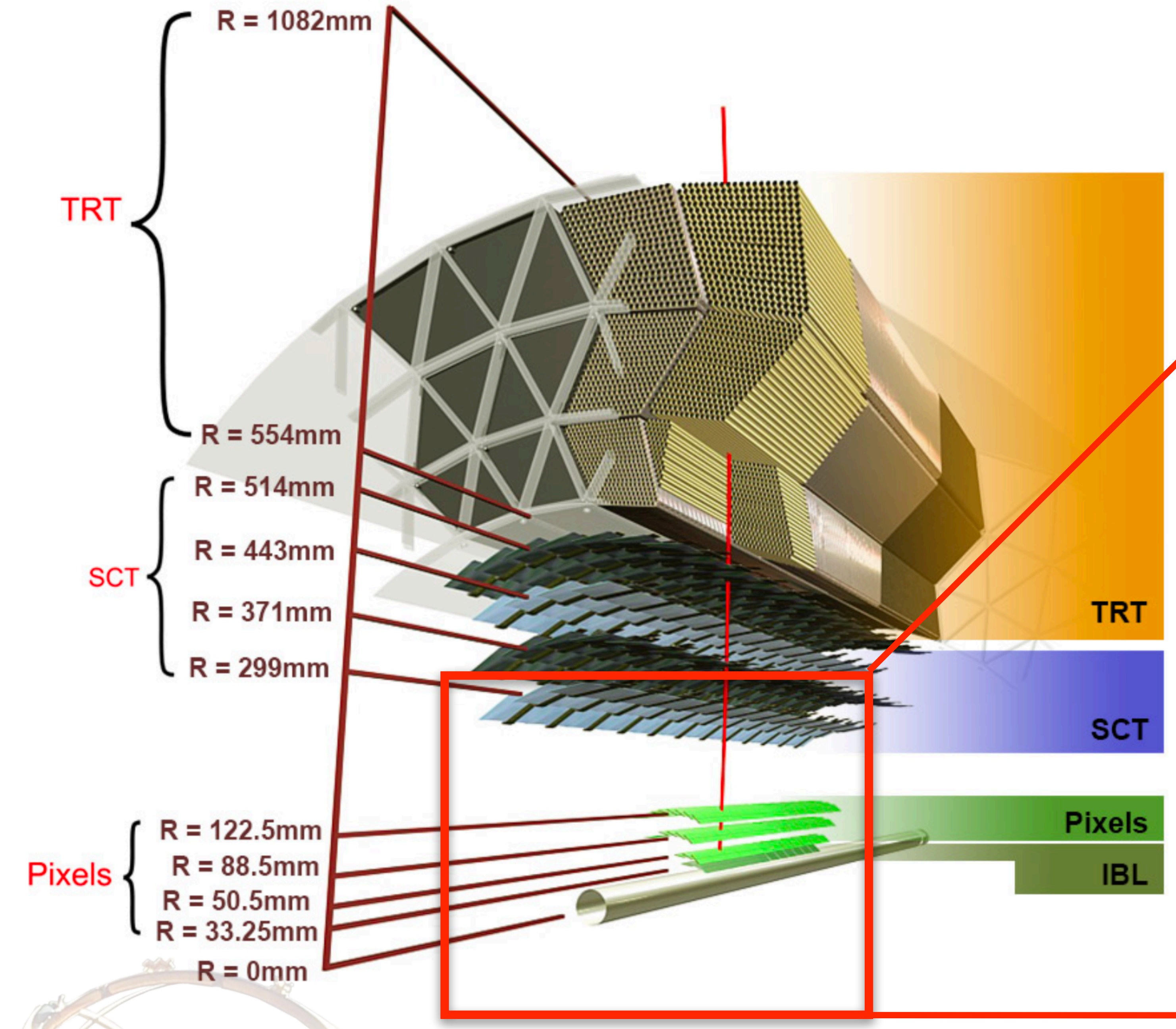

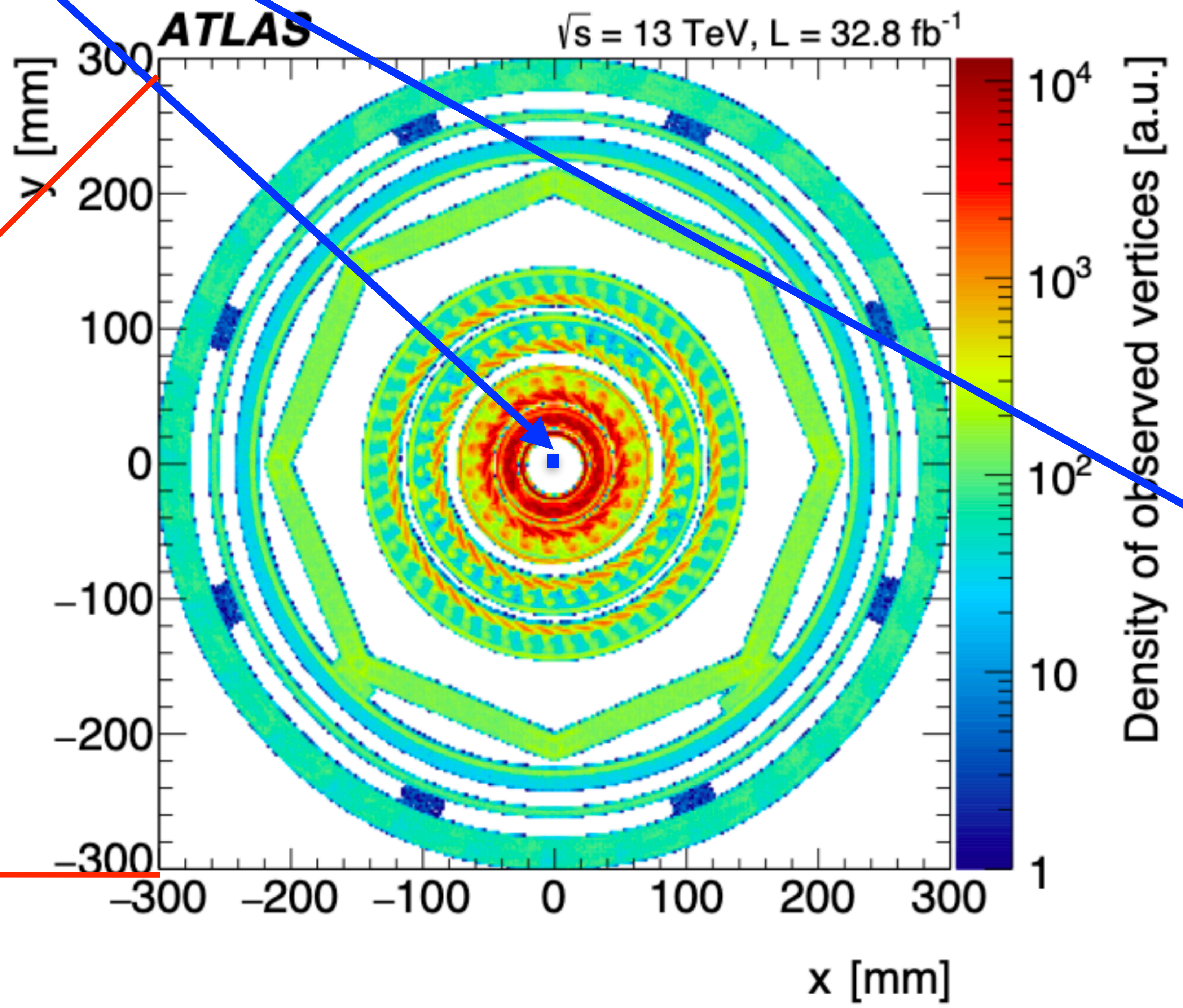

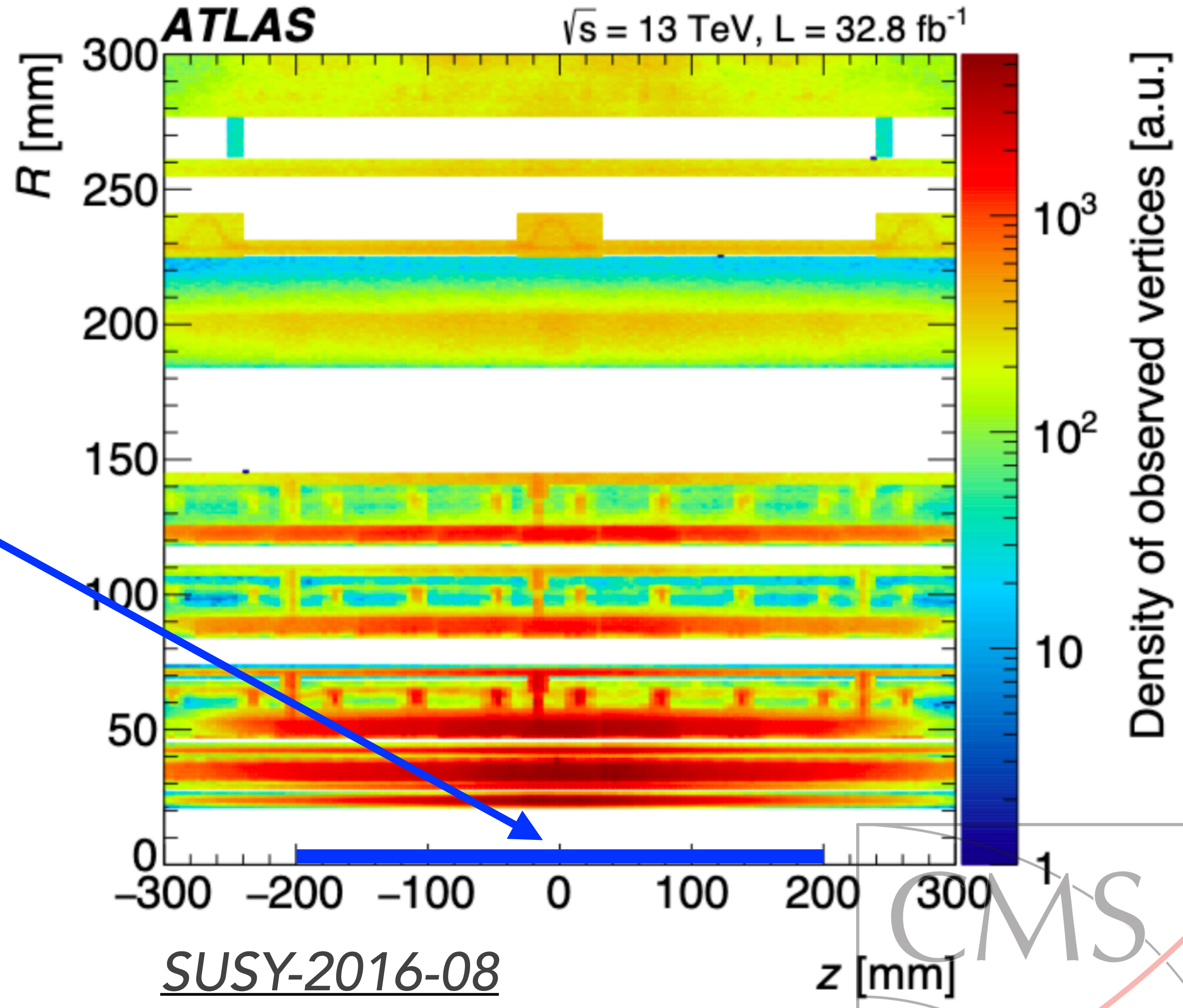

SUSY-2016-08

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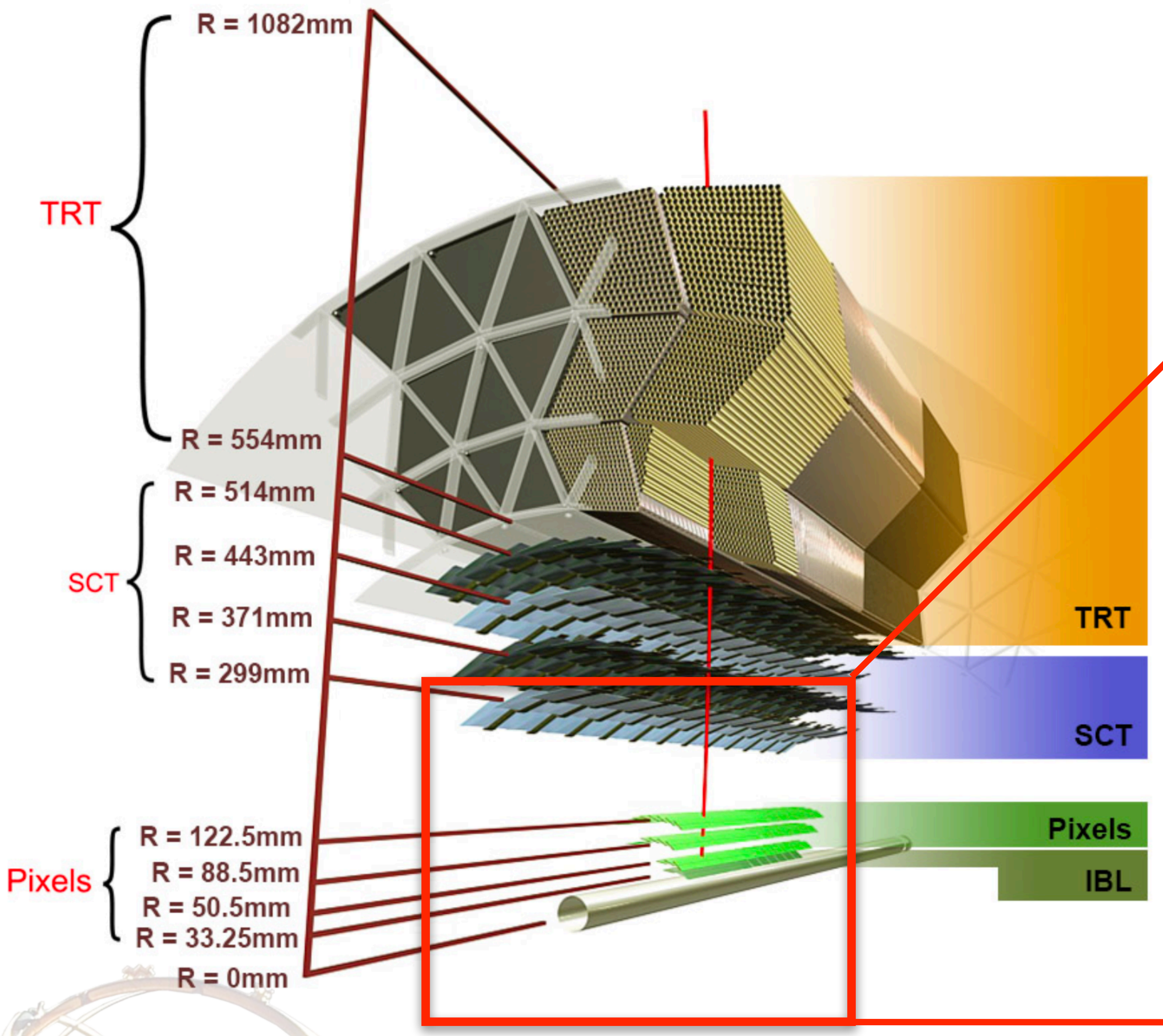
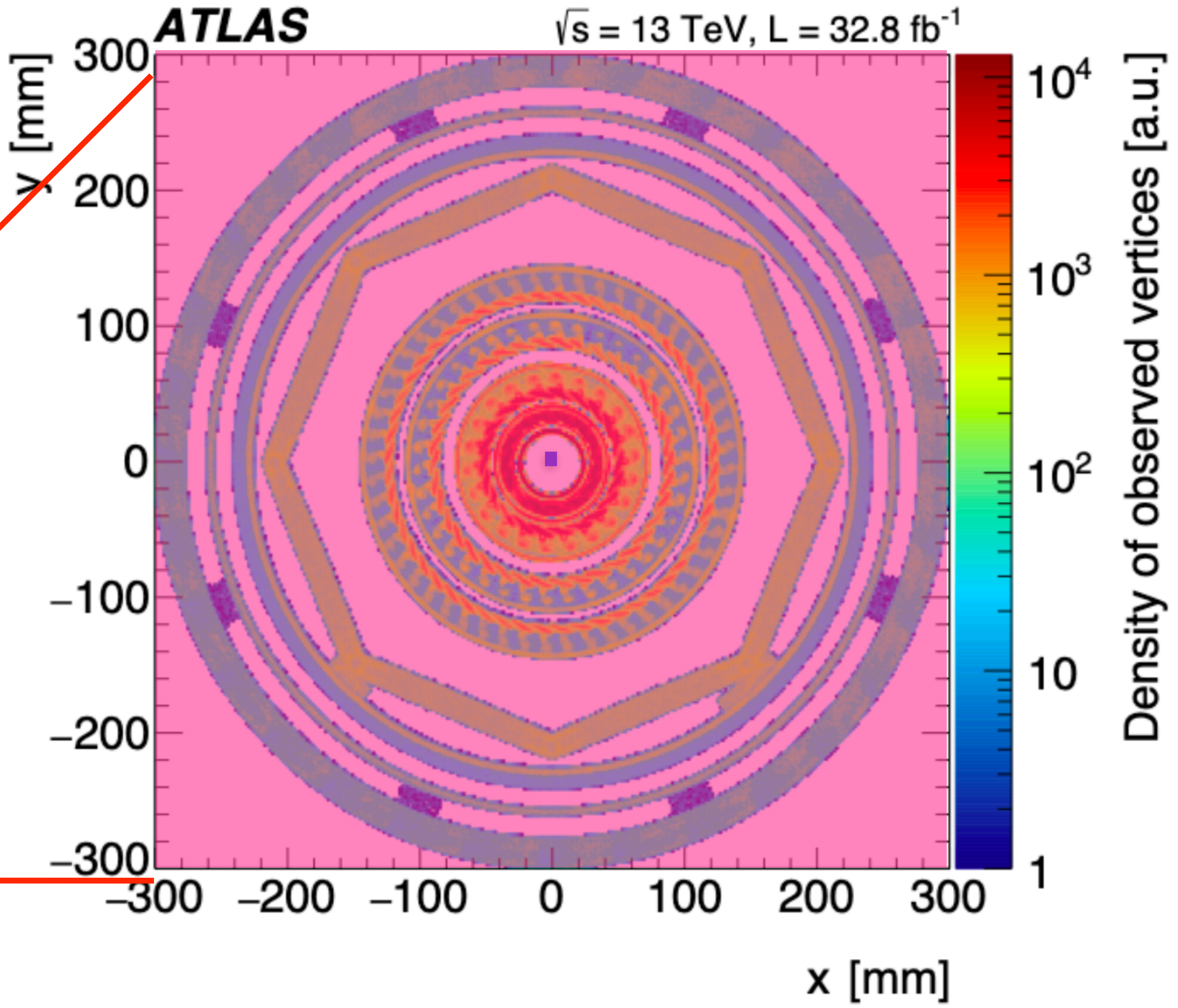
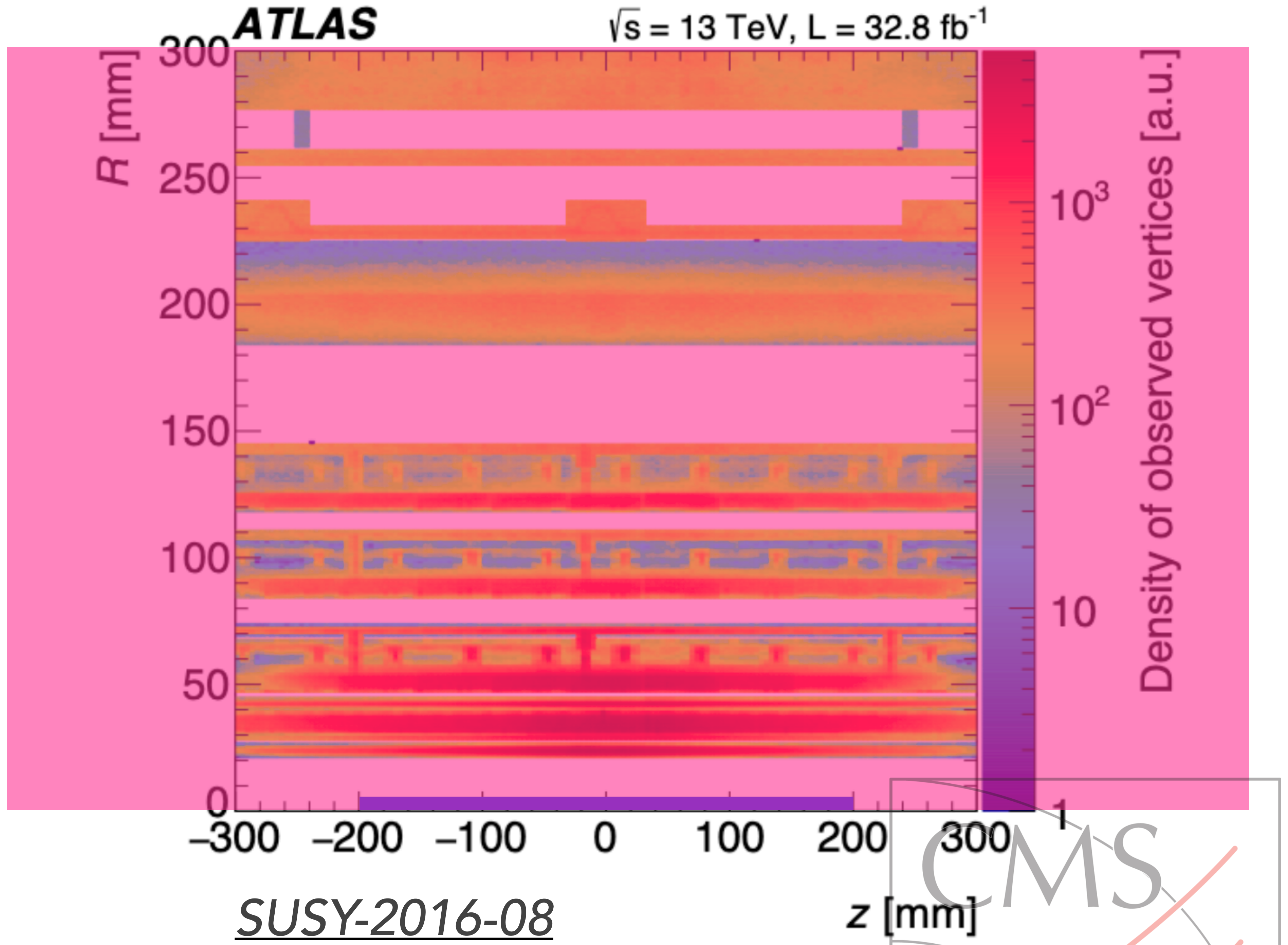


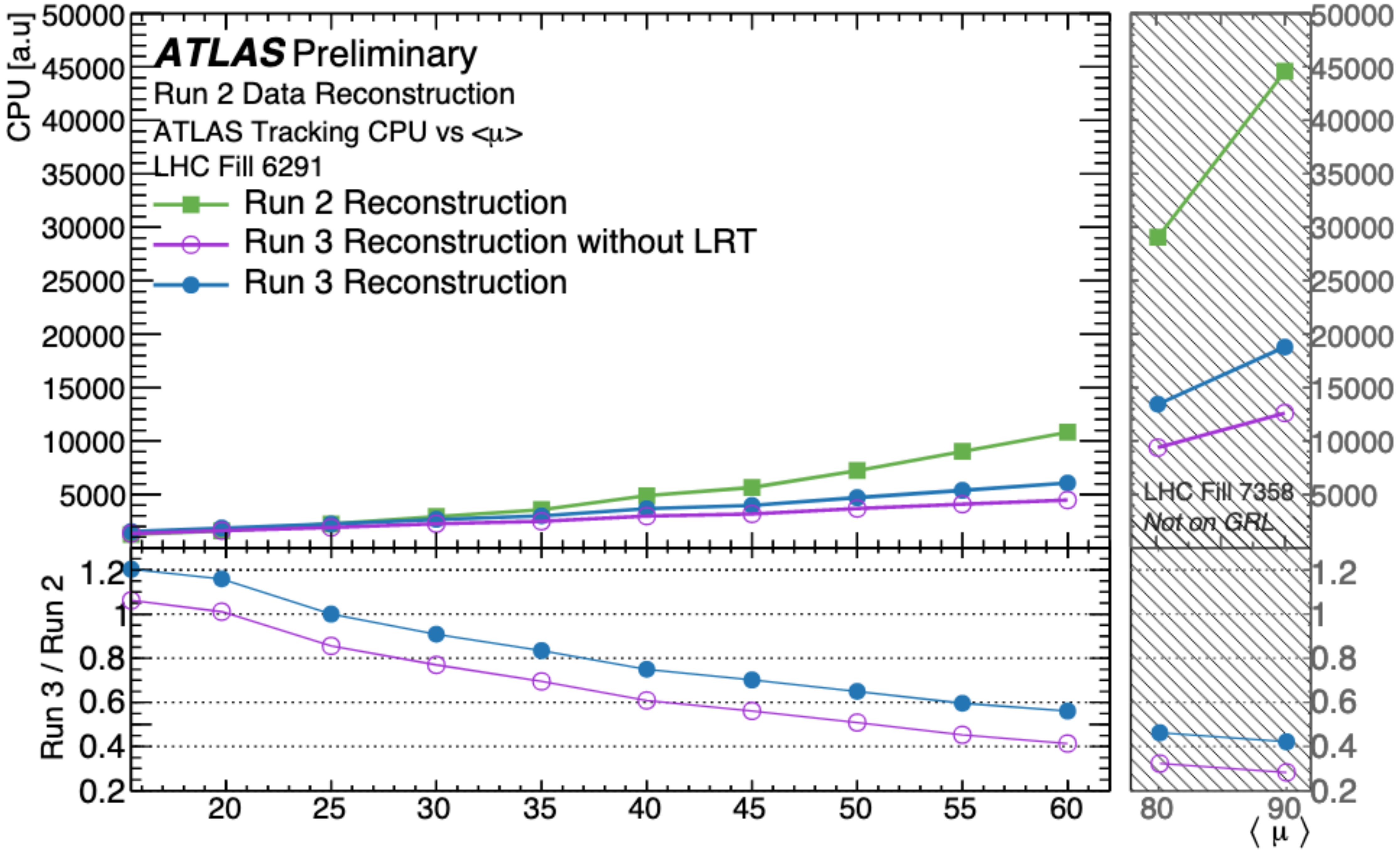


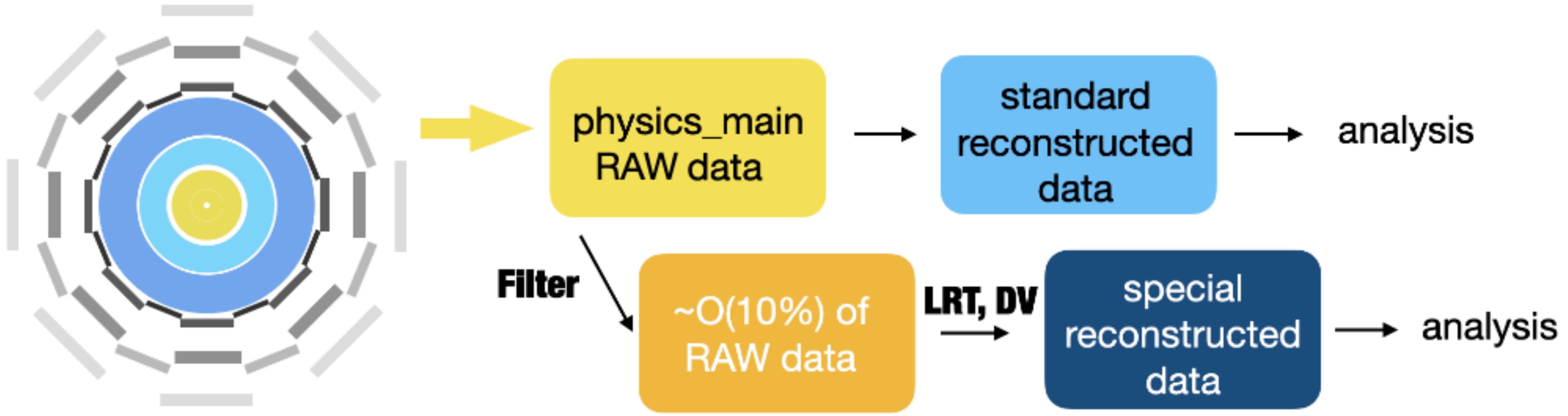


SUSY-2016-08

Long-lived special reconstructions

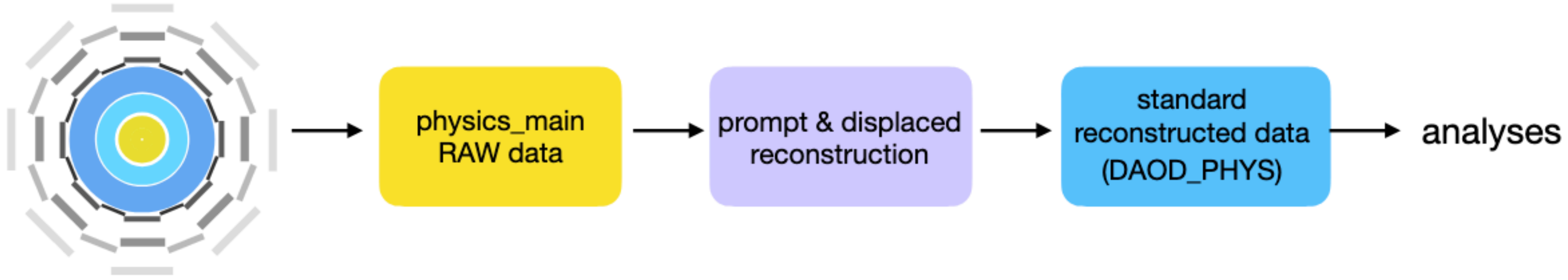
- Large-Radius tracking in ATLAS for Run 3 newly designed
- Huge computational and physics gain!
- New opportunities and flexibility!





physics_main RAW data → standard reconstructed data → analysis

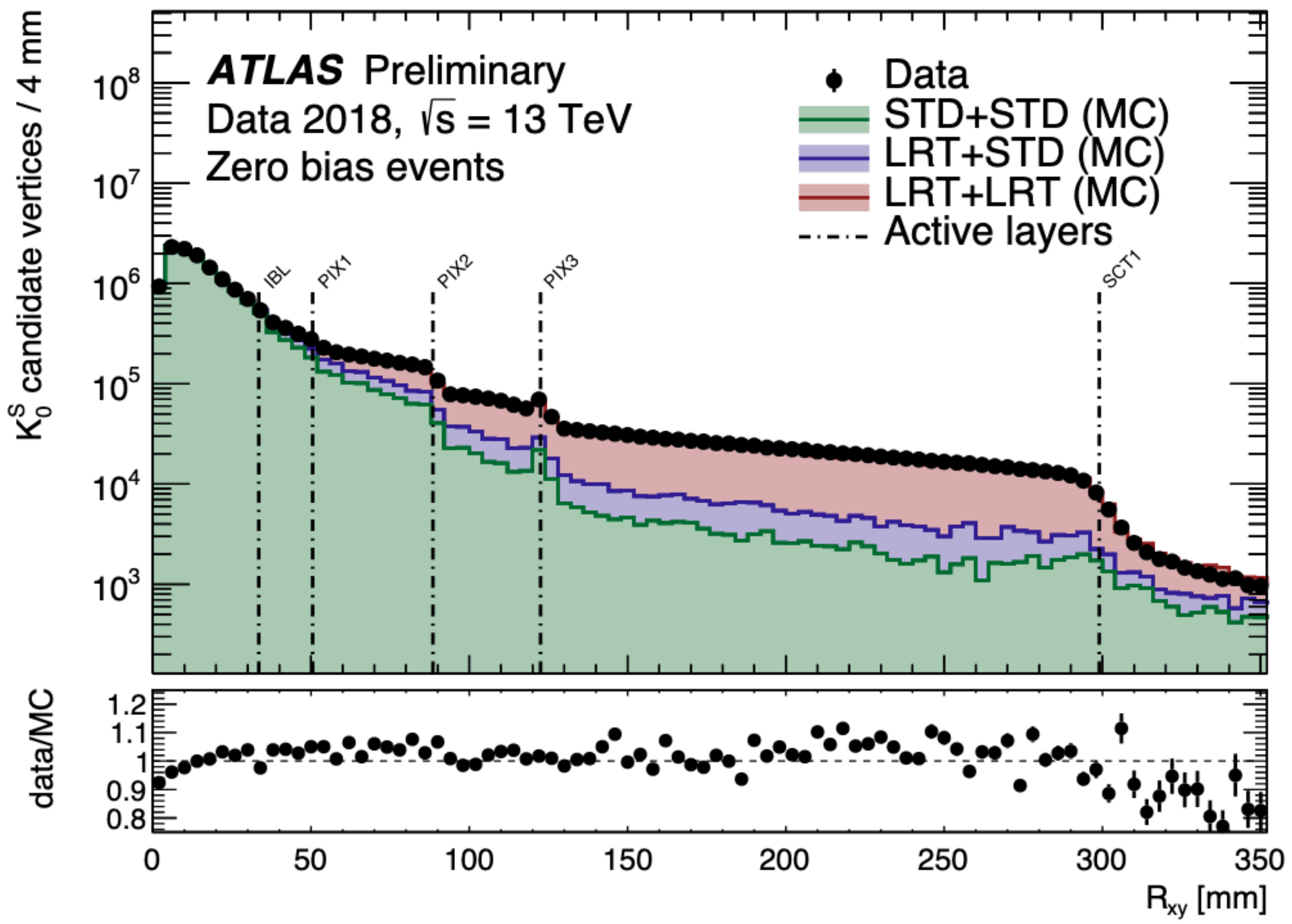
Filter → ~O(10%) of RAW data → LRT, DV → special reconstructed data → analysis

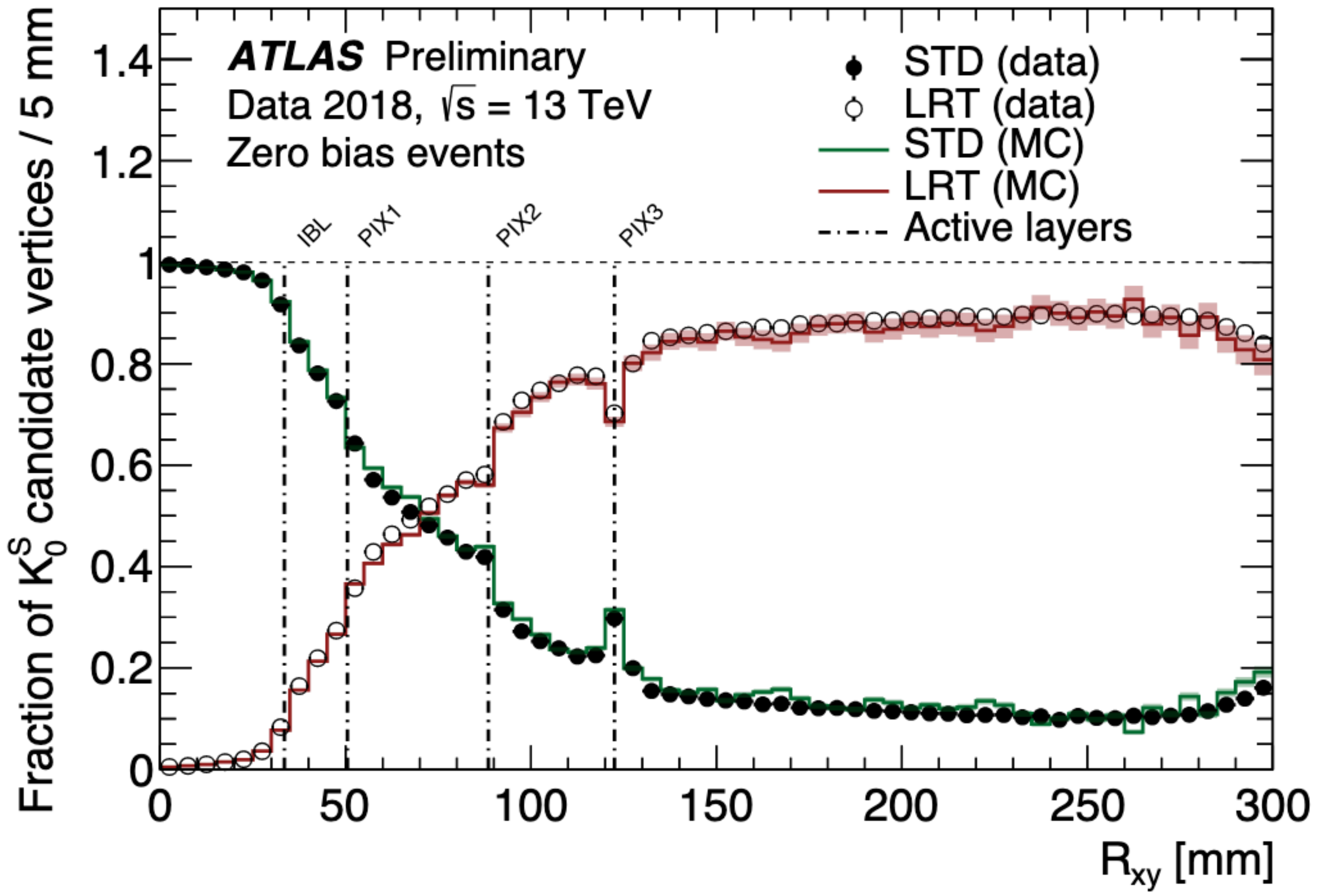


→ physics_main RAW data → prompt & displaced reconstruction → standard reconstructed data (DAOD_PHYS) → analyses

Long-lived special reconstructions

- Many analyses using LRT make use of additional secondary vertex reconstruction algorithms
- Comparisons performed between "zero-bias" data and simulated samples of inelastic scattering events
- To probe LRT efficiency in data, need a "standard candle"
  - K_0^S **decays are an ideal candidate:** $c\tau = 27\ \mathrm{mm}$





Long-lived special reconstructions

IDTR-2021-003

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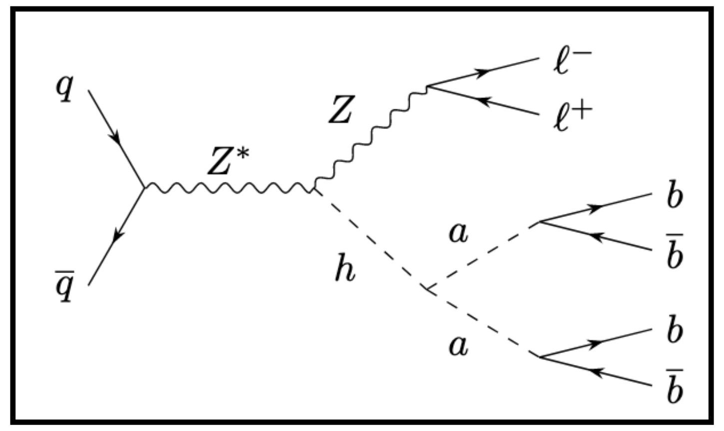

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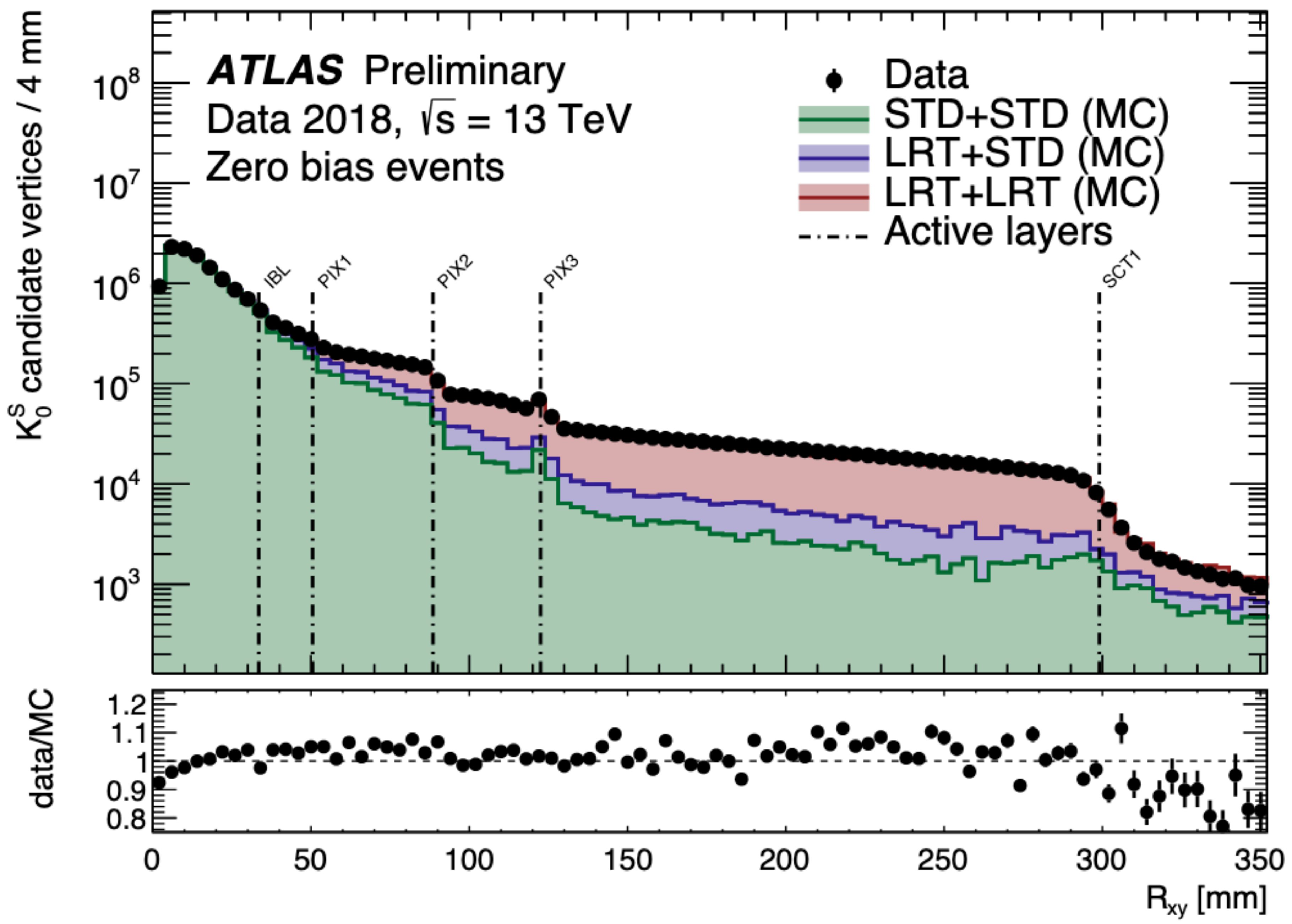
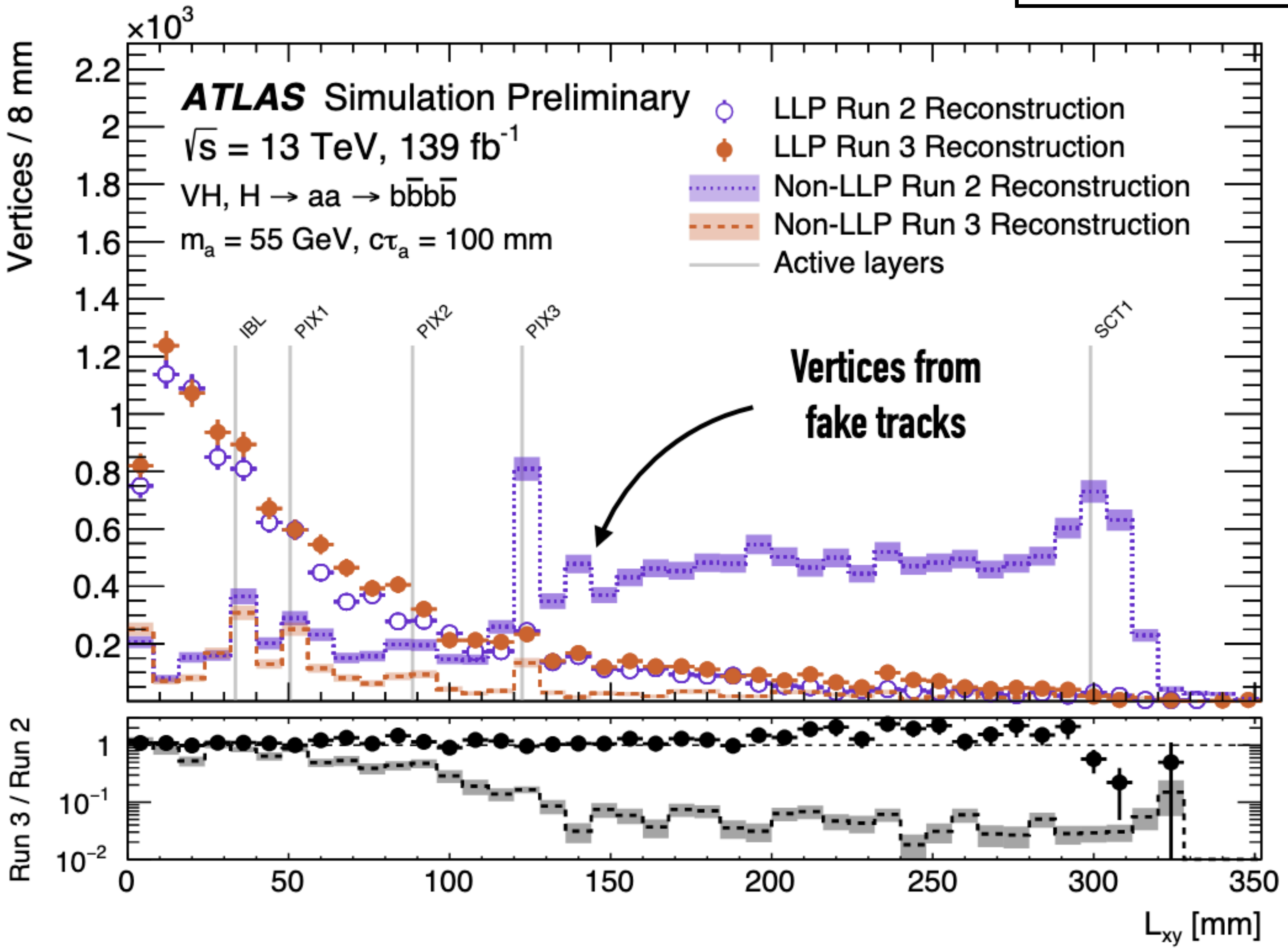




Conclusions

- ATLAS and CMS results of full Run 2 data achieve impressive constraints on LLP candidates
- We learn to use detectors "full potential" for unconventional searches & more for Run 3!
  - New LLP triggers (in particular also with displaced tracking)
  - New reconstruction techniques
  - Improved work-flow - ATLAS LLP tracking and lepton reconstruction NOW integrated in the main data processing chain —> CMS has this already for some years

Run 3 is exciting for LLP searches at the LHC

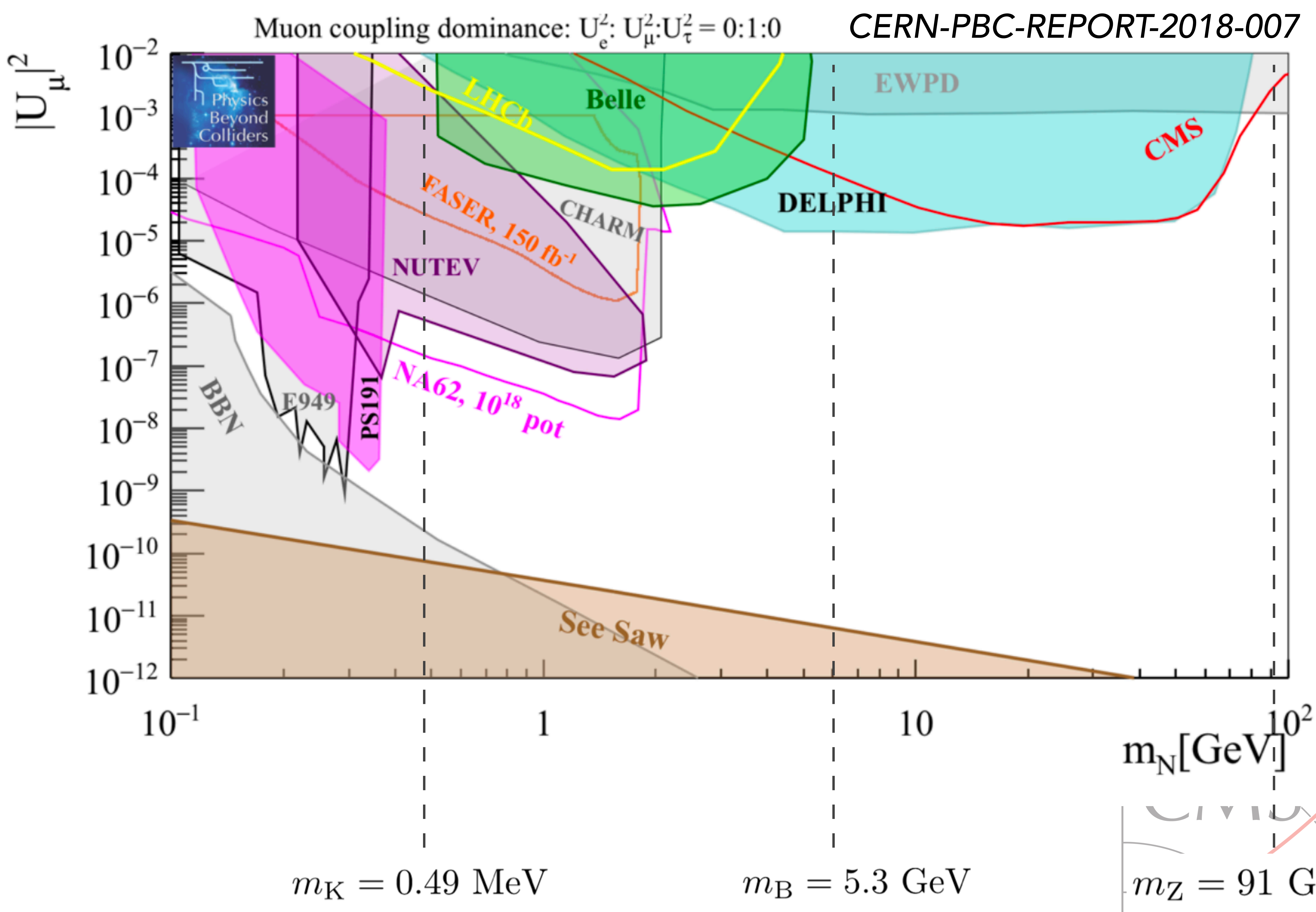
— New opportunities for discoveries —

Backup

HNL Experimental plane — colliders & fixed target

probing heavy neutral leptons (HNLs) at various experiments

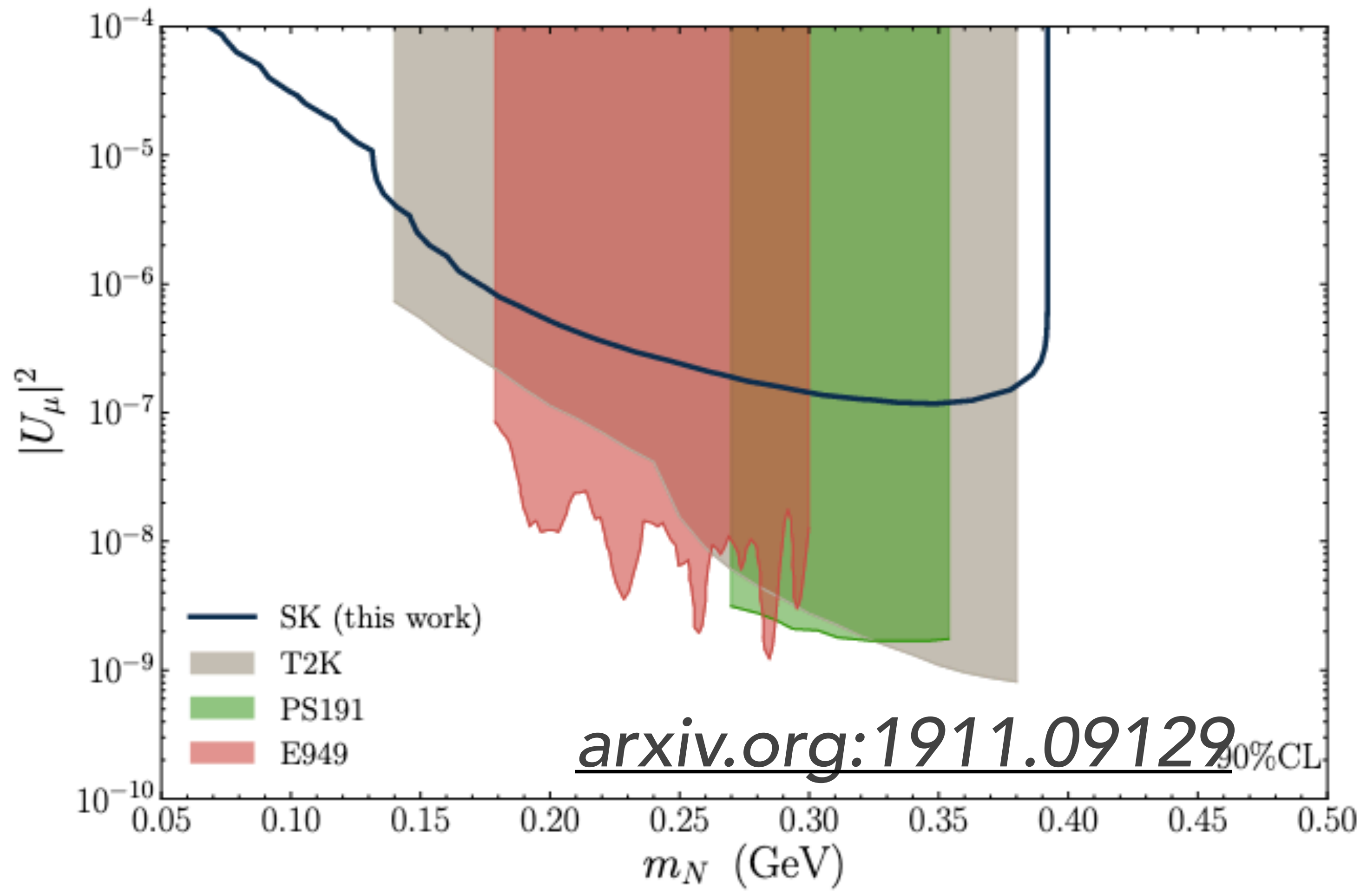
- below Kaon mass can use decays $K^\pm \to \ell^\pm N,\ K^\pm \to \mu\mu\pi$ (e.g. NA62)
- below B or D meson masses $B^\pm, D_s^\pm, \tau^\pm \to \ell^\pm N,\ D^0 \to \ell^\pm\pi^\mp N$ (e.g. Belle, LHCb)
- below W, Z boson masses results from LEP ($Z \to N\nu$), actively explored also at ATLAS, CMS
- above W, Z boson masses decay to onshell bosons $W^\pm \to \ell^\pm N,\ N \to \ell^\pm W^\mp, \nu Z, \nu H$



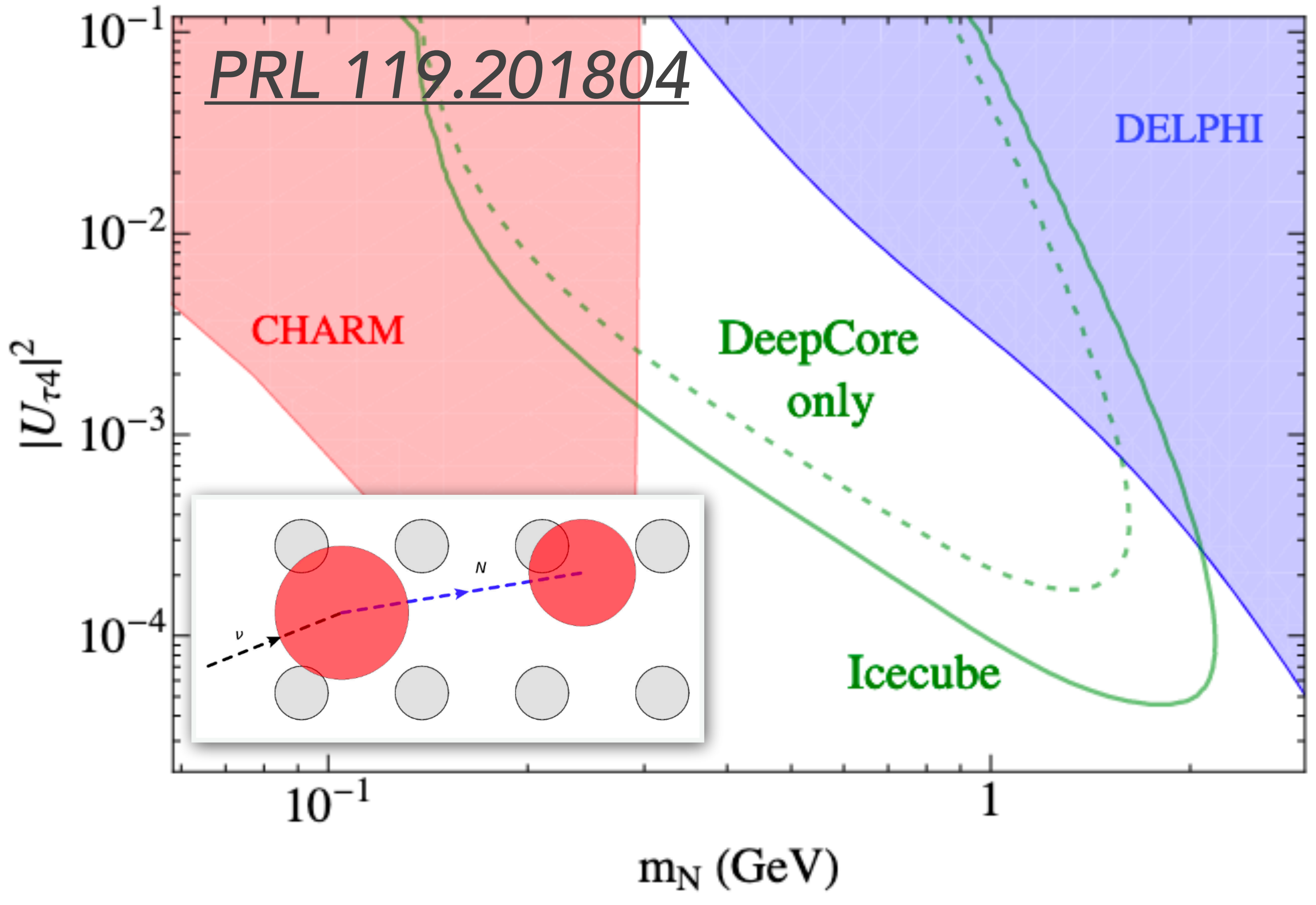
CERN-PBC-REPORT-2018-007

Global constraints on Sterile Neutrinos

- Complementarity of searches is enormous for HNLs

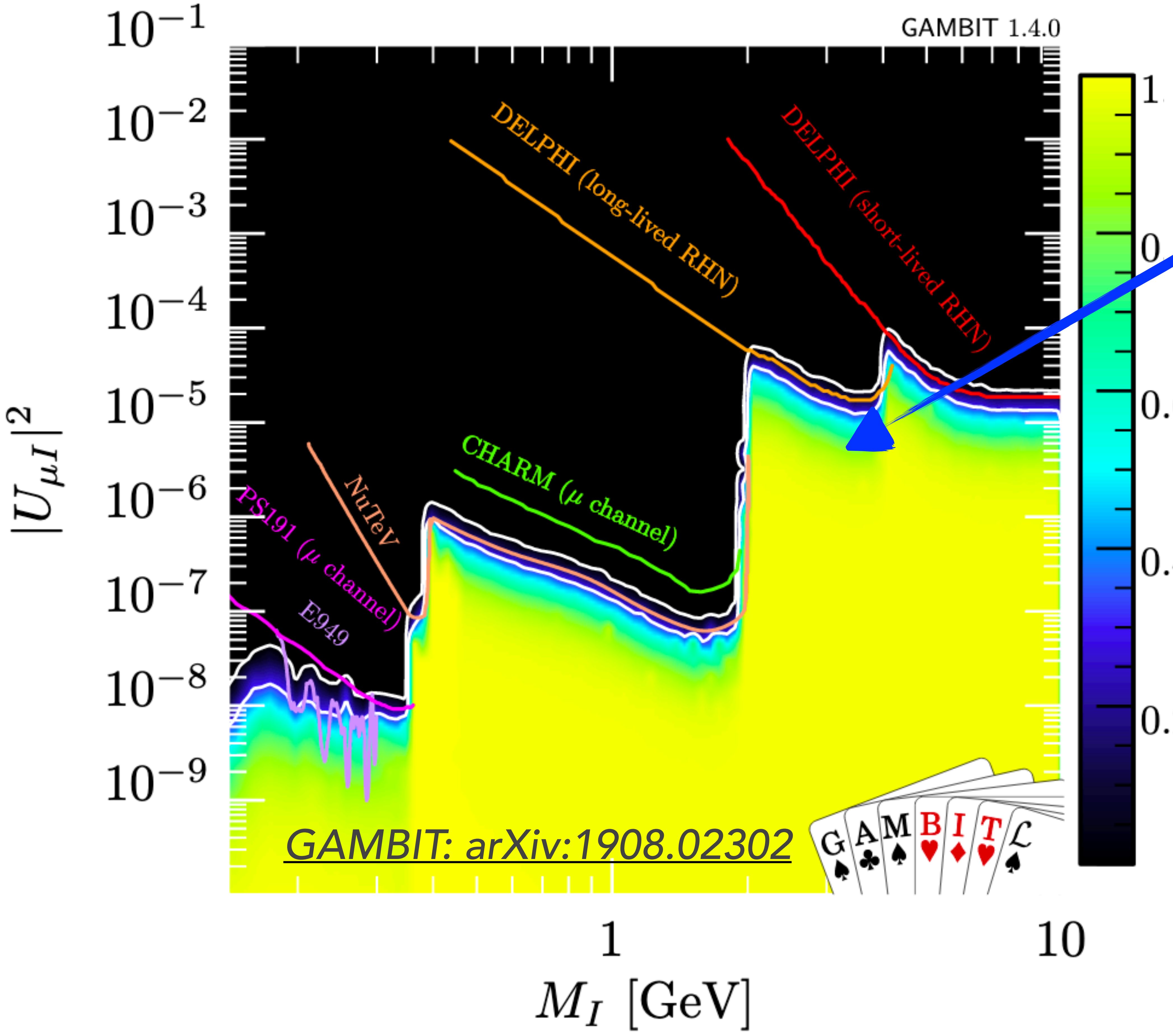


arxiv.org:1911.09129



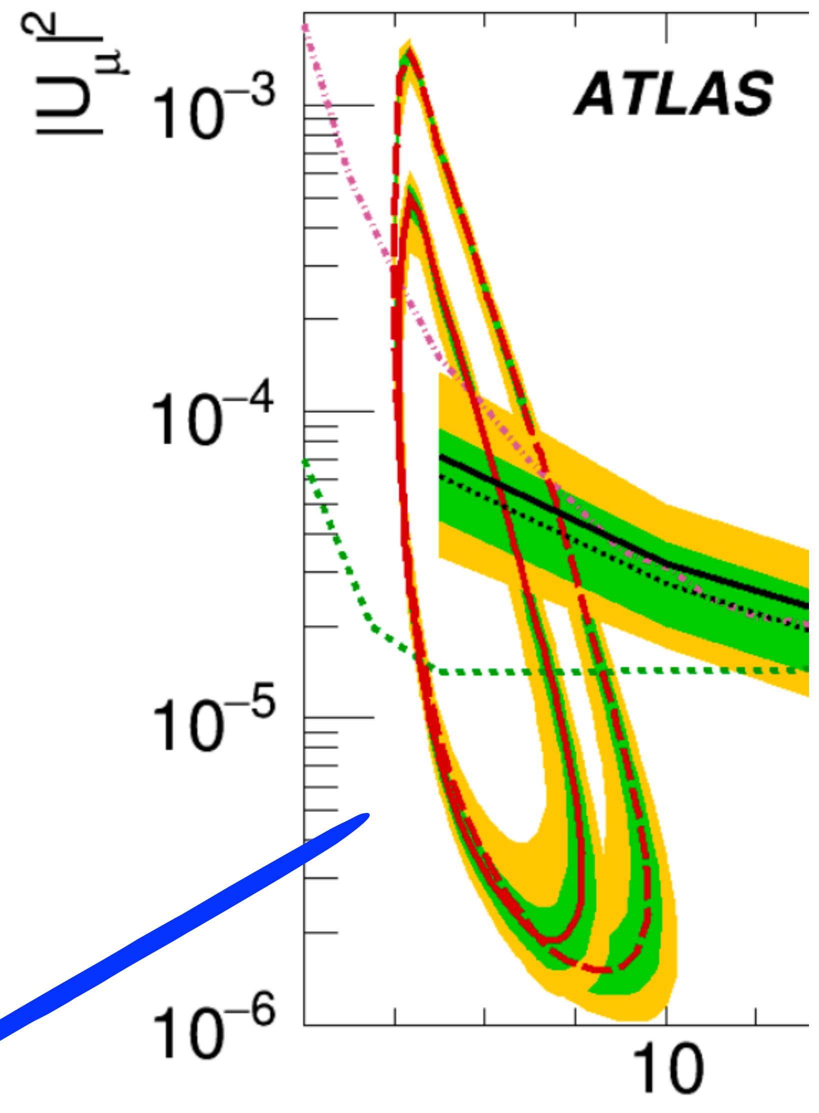
PRL 119.201804

EWPO, 0νββ, cLFV, CKM unitarity, BBN, direct searches, ν-osc.

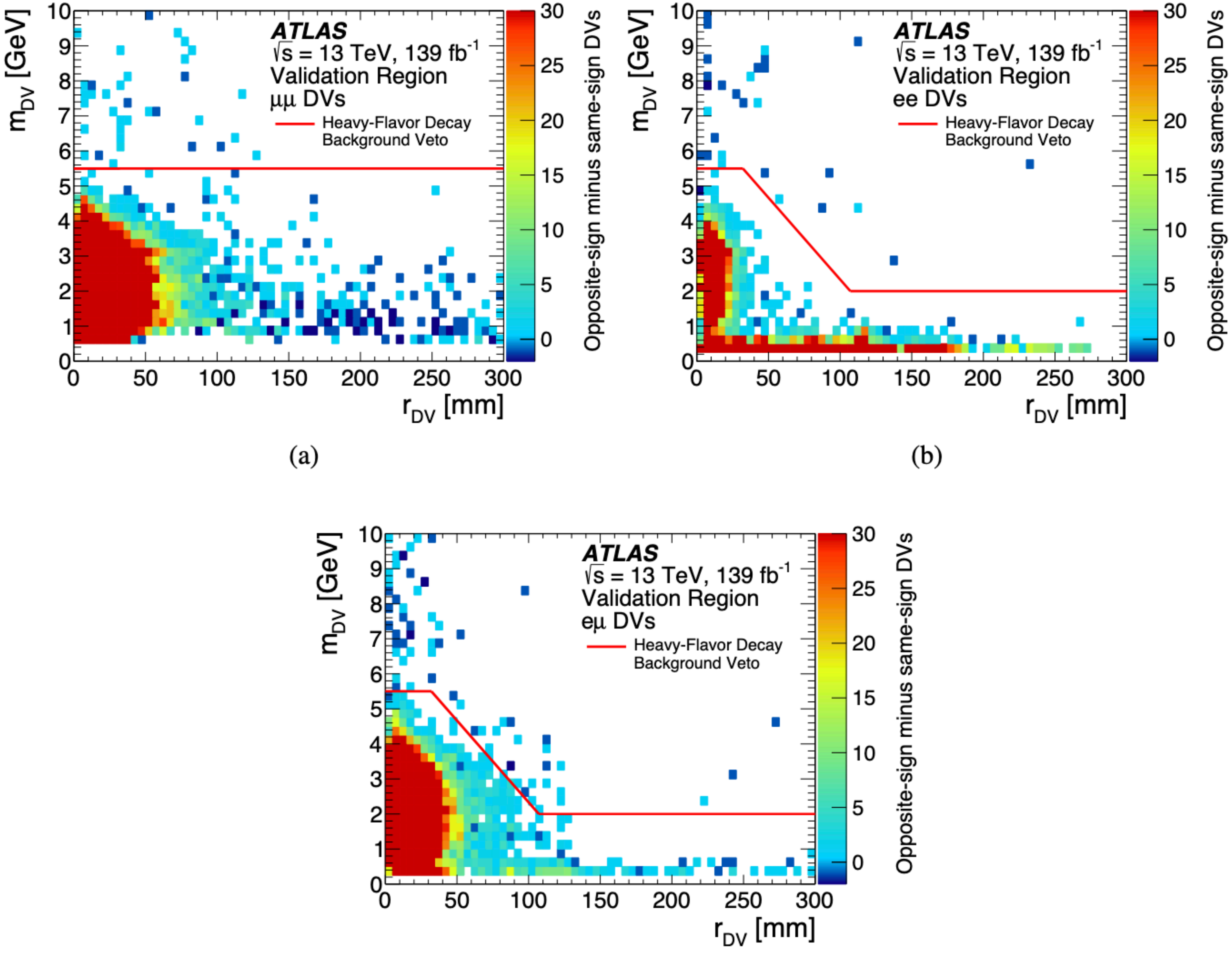


GAMBIT: arXiv:1908.02302

JHEP 10 (2019) 265



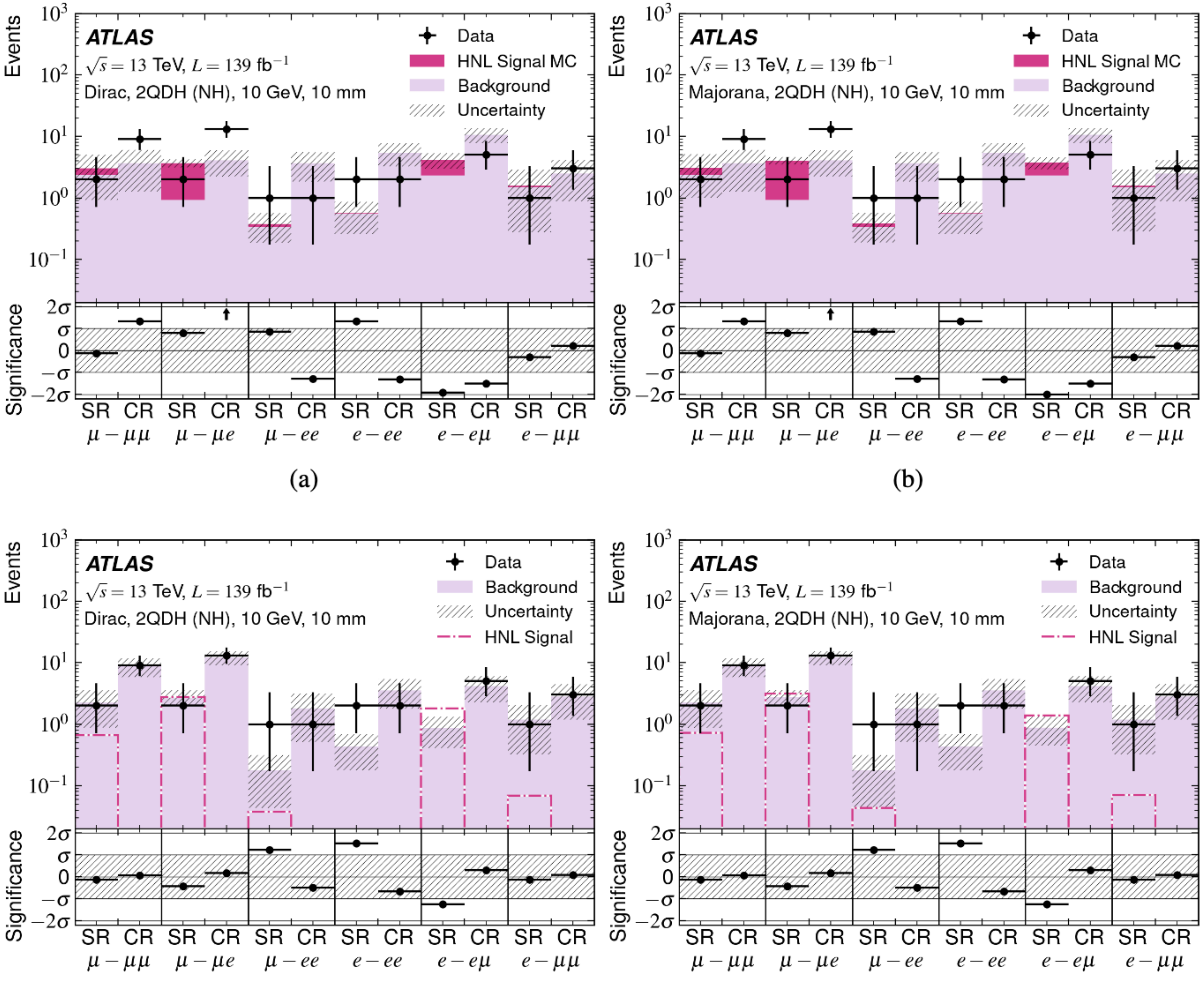
dHNL details



(a)

(b)

dHNL details



(a) (b)

(c) (d)

CalRatio — dNN details

Track Variables

- p_T
- η
- ϕ
- vertex_nParticles
- d_0
- z_0
- chiSquared
- SCTHits
- SCTHoles
- SCTShared

Topocluster variables

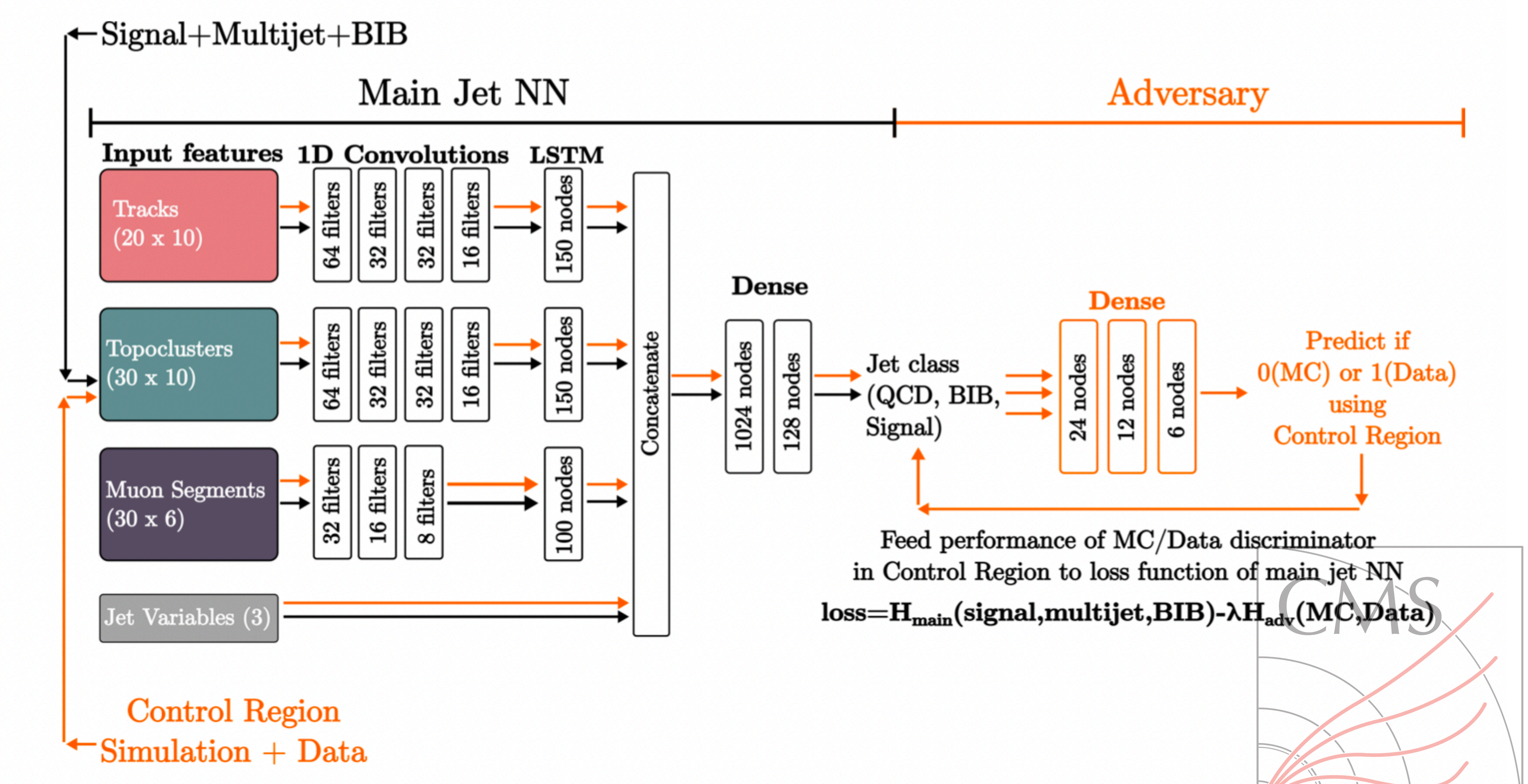
- p_T
- η
- ϕ
- l1hcal
- l2hcal
- l3hcal
- l4hcal
- l1ecal
- l2ecal
- l3ecal
- l4ecal
- time

Muon Segment variables

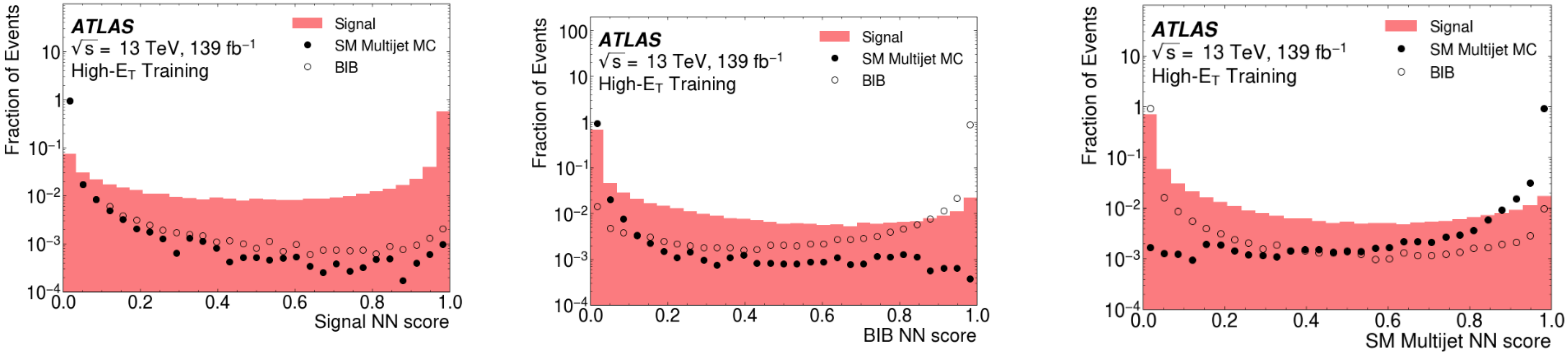
- η position
- ϕ position
- η direction
- ϕ direction
- chiSquared
- t0

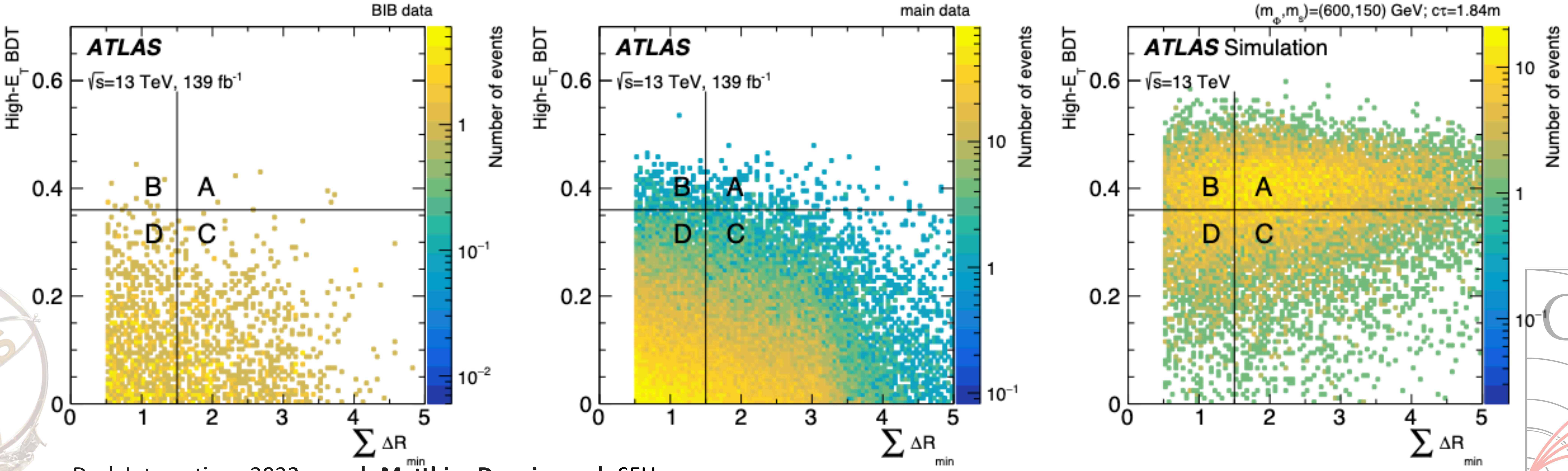
Jet variables

- p_T
- η
- ϕ



CalRatio — dNN details





dE/dx analysis details

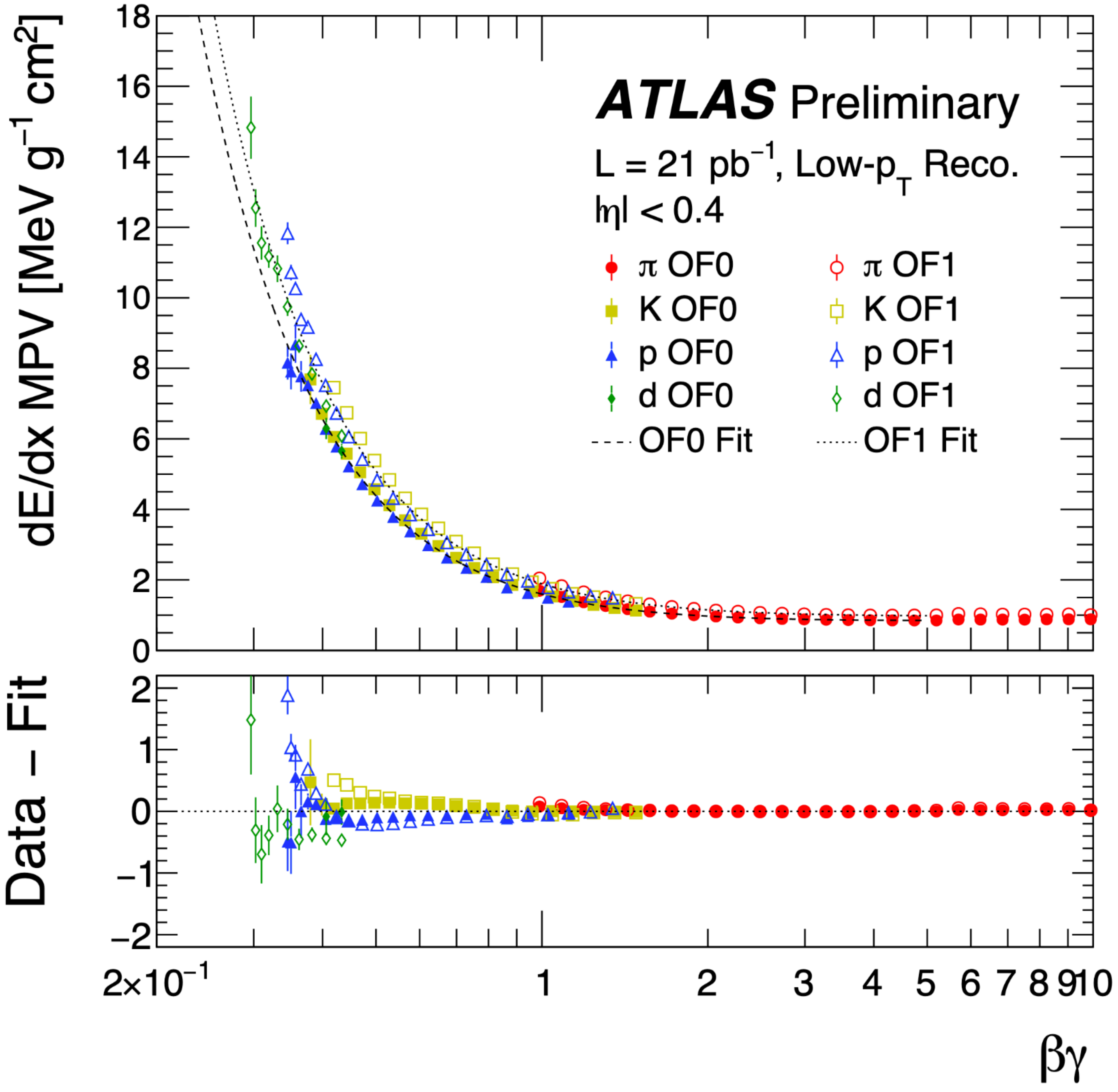
Analysis strategy

- Events are selected using MET Trigger
- Selecting isolated tracks with high p_T, and large specific ionization (|η|<1.8).
- *Reconstruct the mass of these tracks*

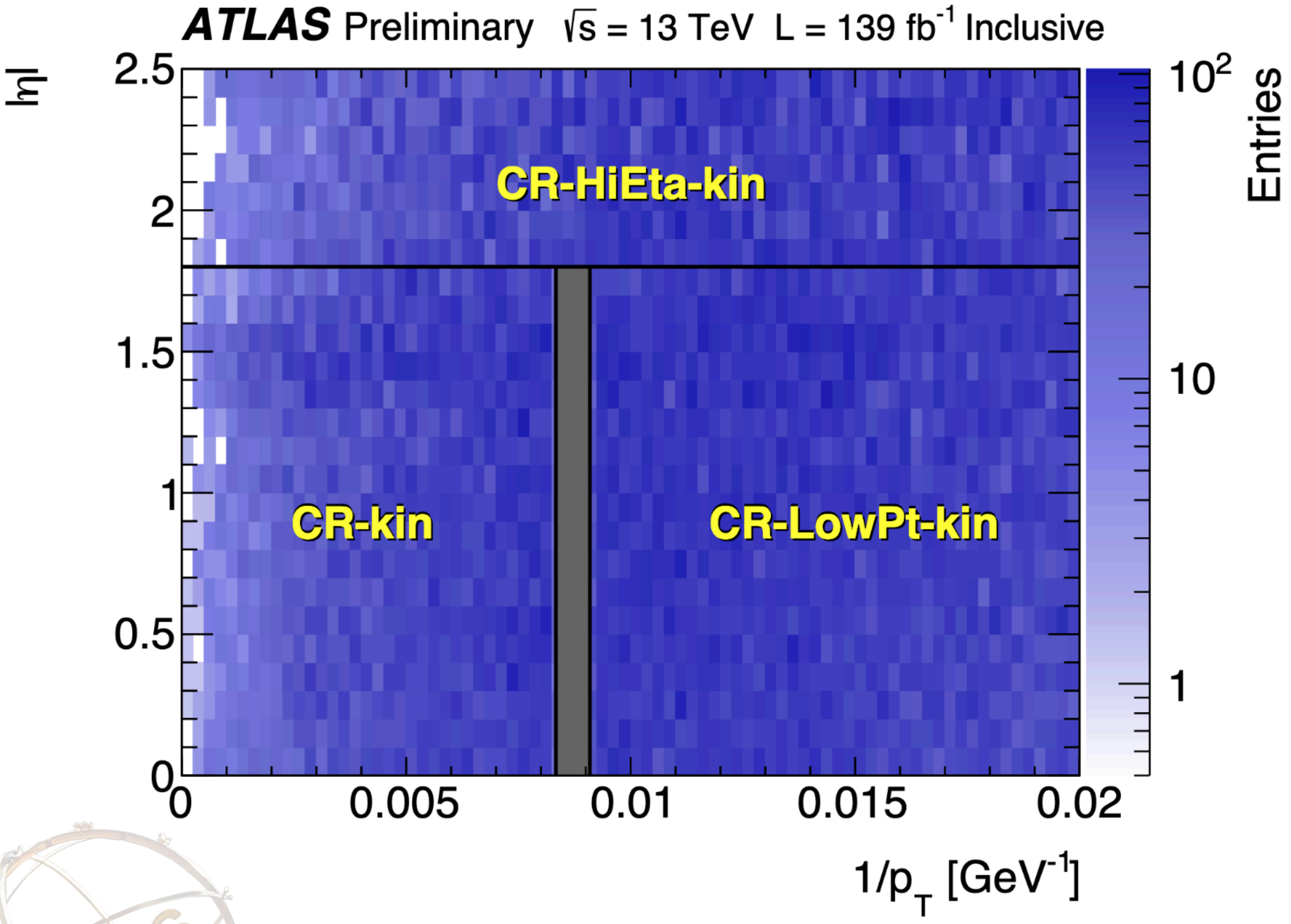
$$\mathrm{MPV}_{dE/\mathrm{dx}}(\beta\gamma) = \frac{1+(\beta\gamma)^2}{(\beta\gamma)^2}\left(c_0 + c_1\log_{10}(\beta\gamma) + c_2\left[\log_{10}(\beta\gamma)\right]^2\right)$$

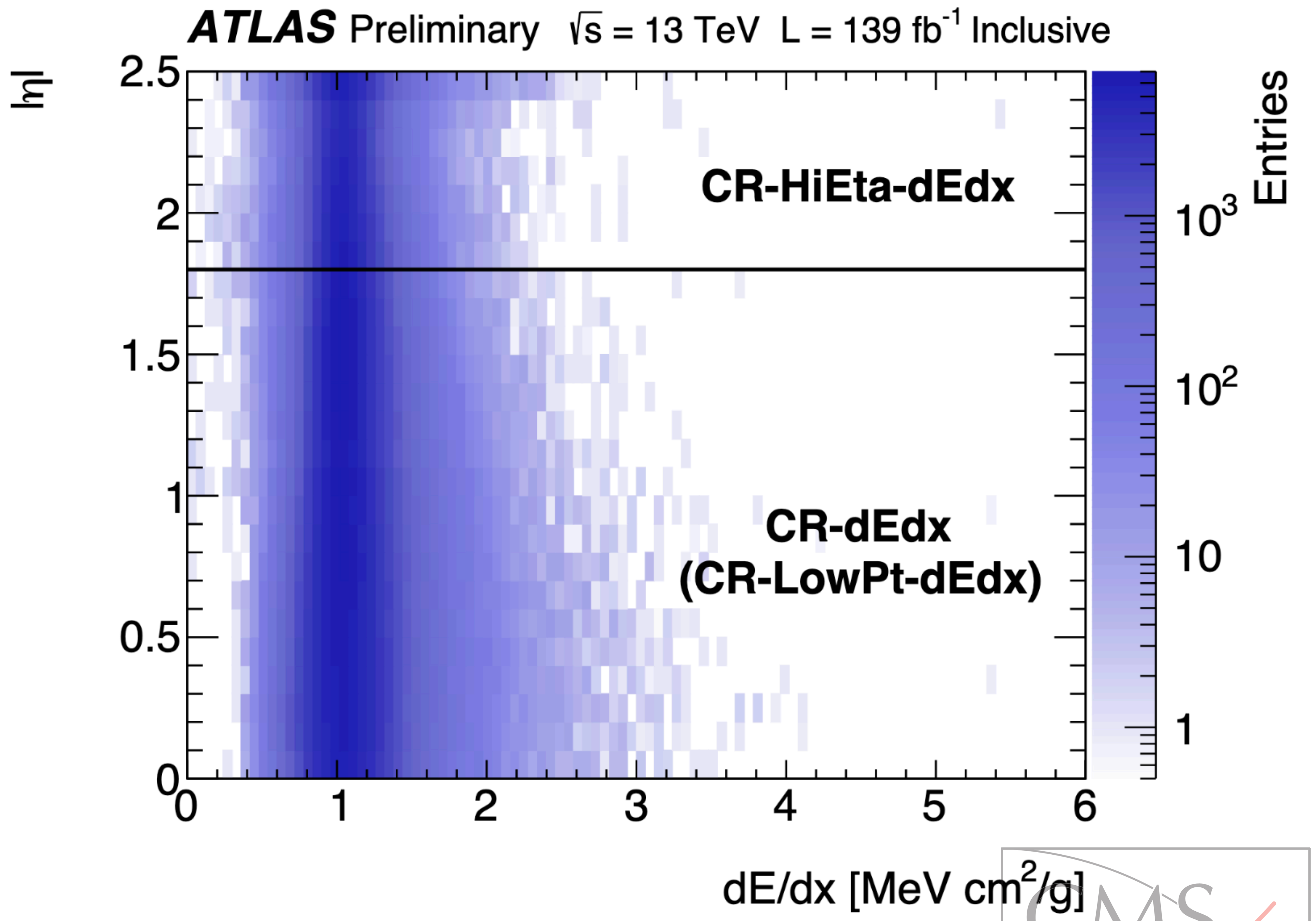
- Parameterize Bethe-Bloch relation (Low-pileup runs) to extract a mapping of βγ to the dE/dx measurements
- Mapping is used to extract βγ of individual tracks in analysis

$$m_{\mathrm{d}E/\mathrm{dx}} \equiv \frac{p_{\mathrm{reco}}}{\beta\gamma(\langle \mathrm{d}E/\mathrm{dx}\rangle_{\mathrm{corr}})}$$

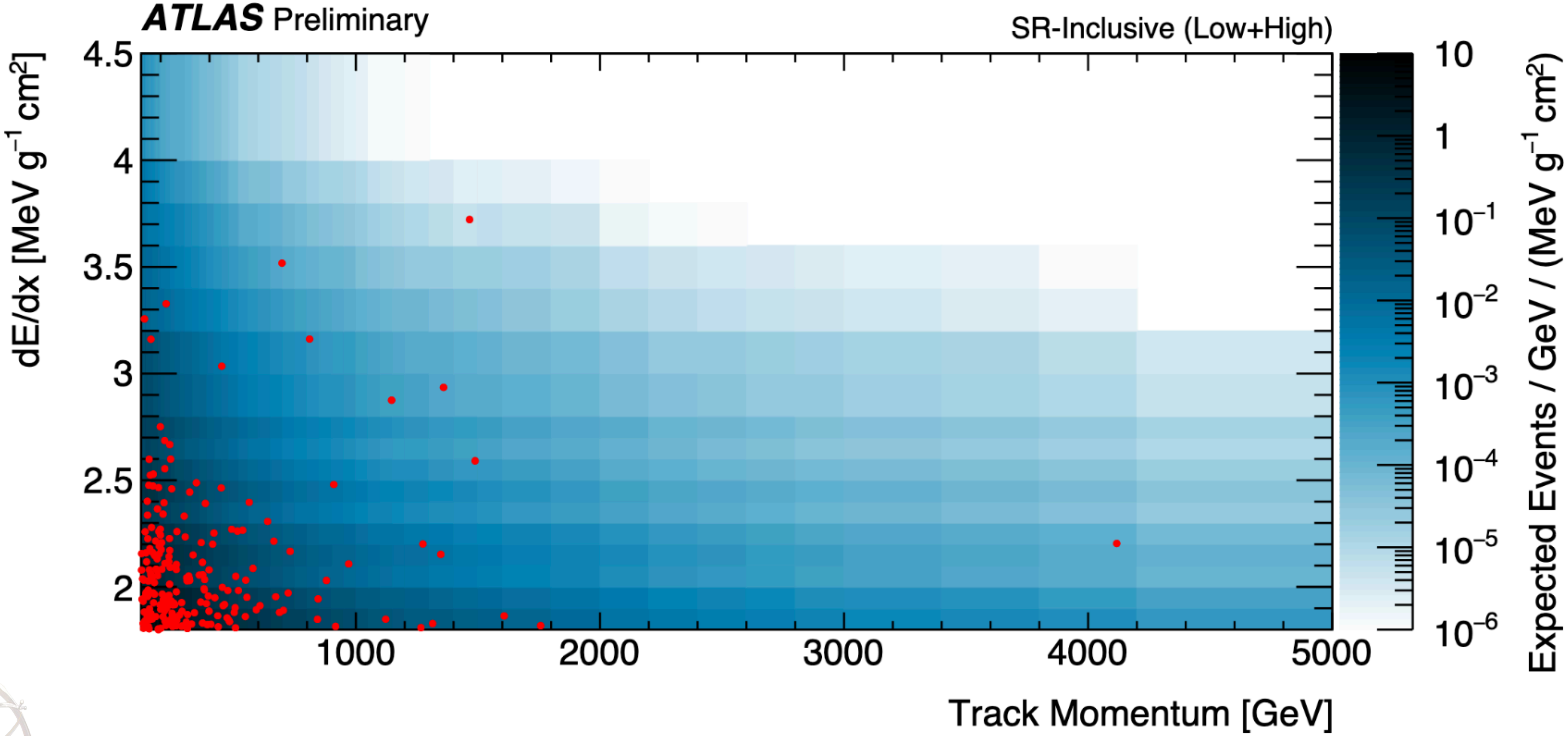


dE/dx additional details

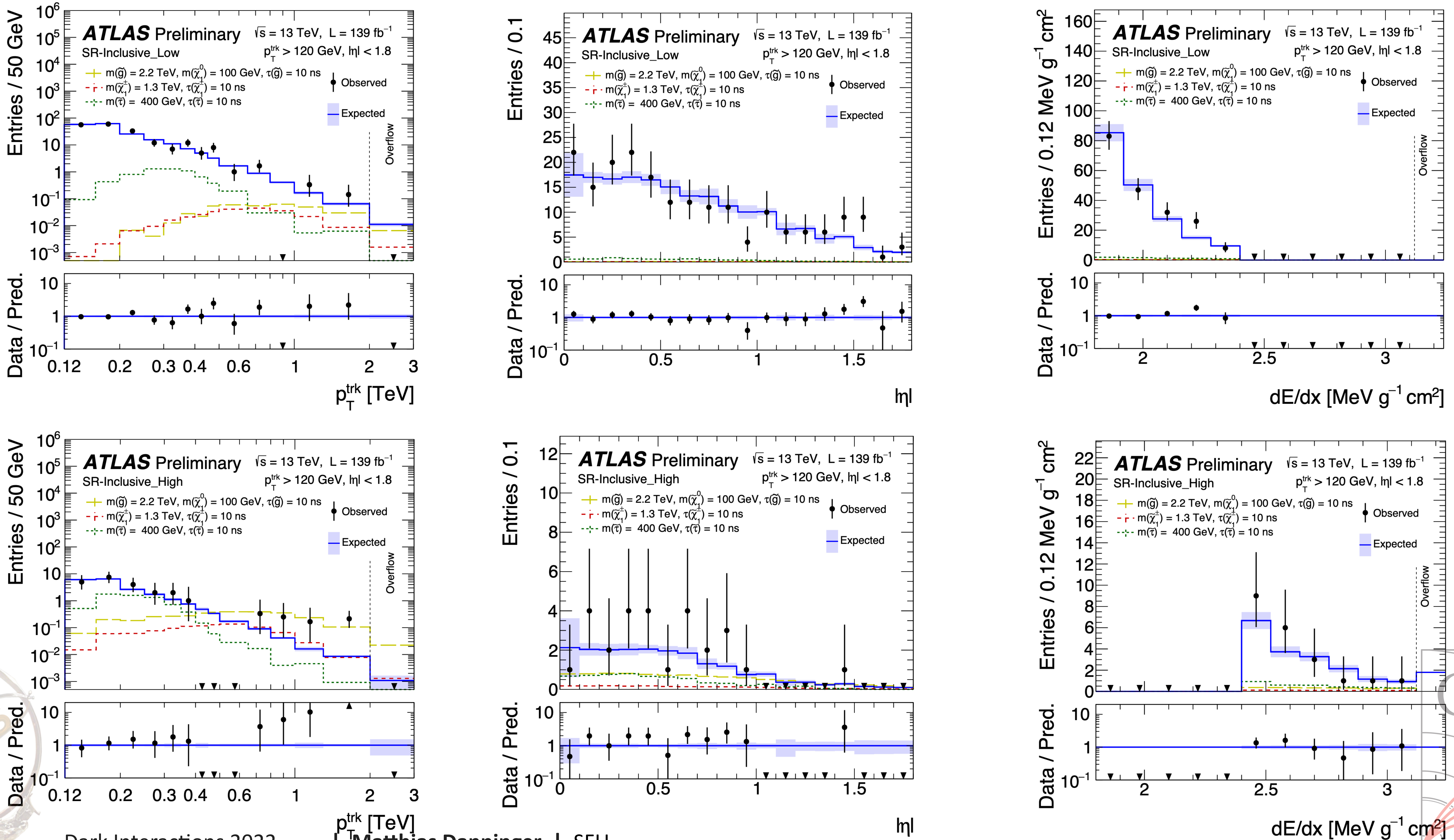




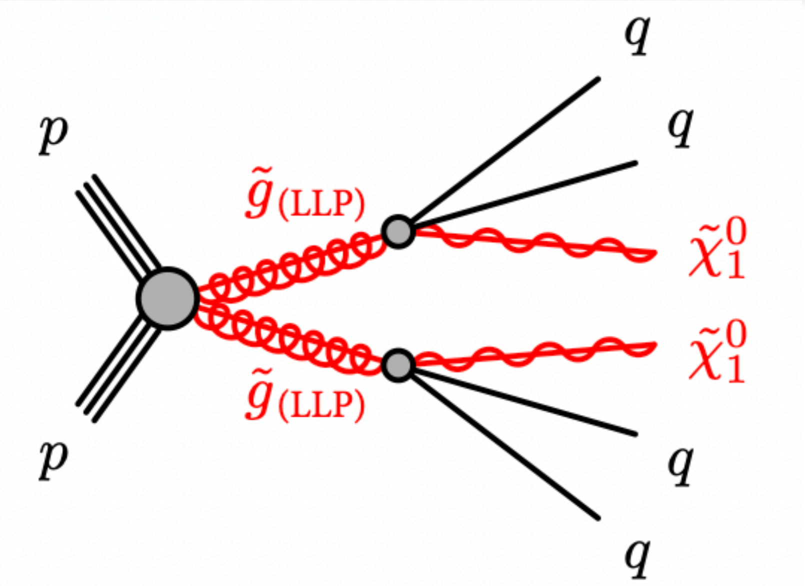
dE/dx additional details

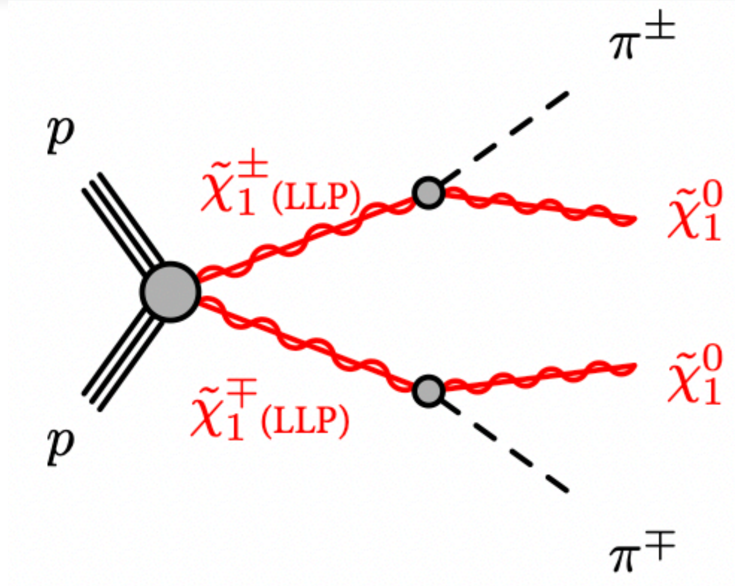


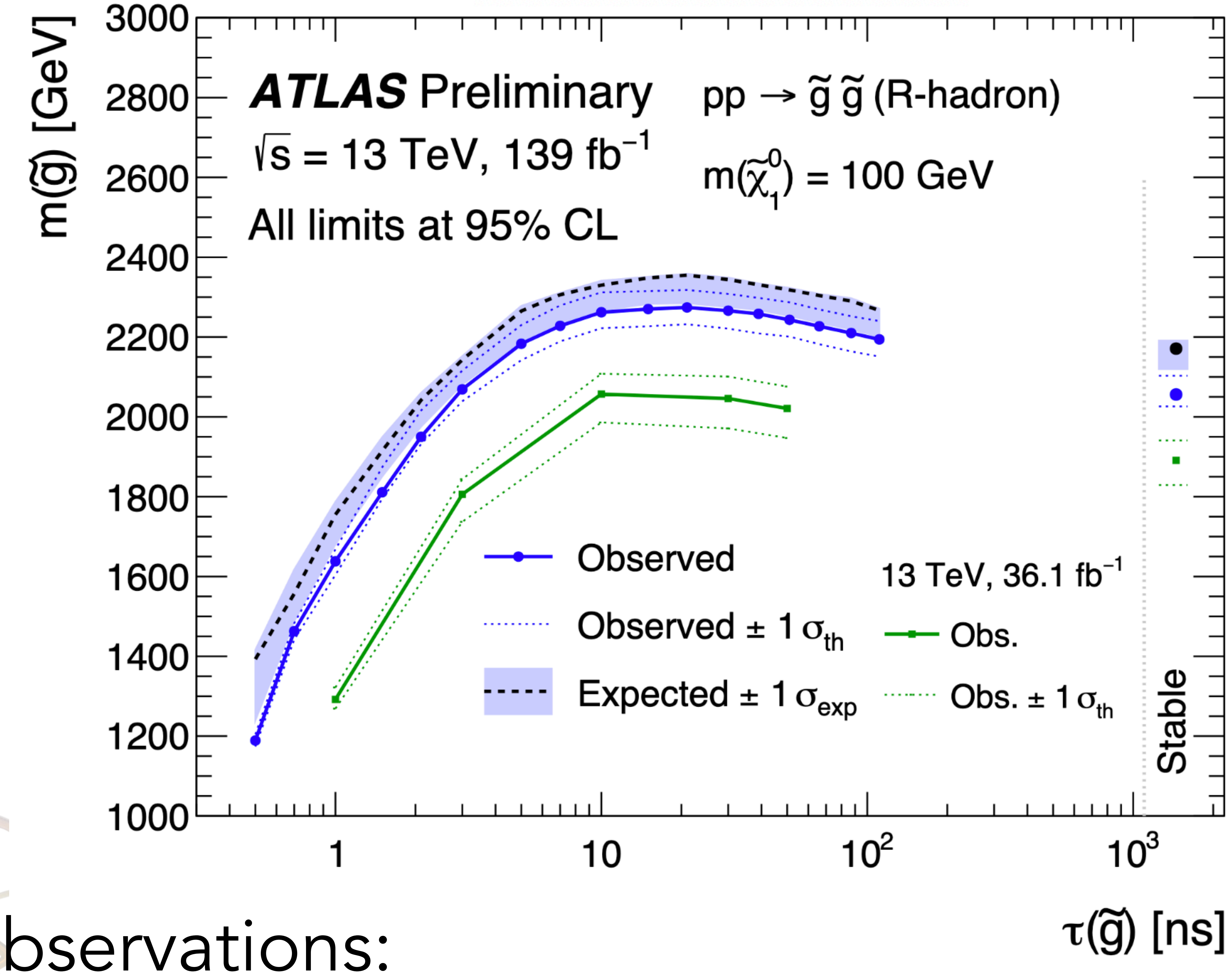
dE/dx additional details

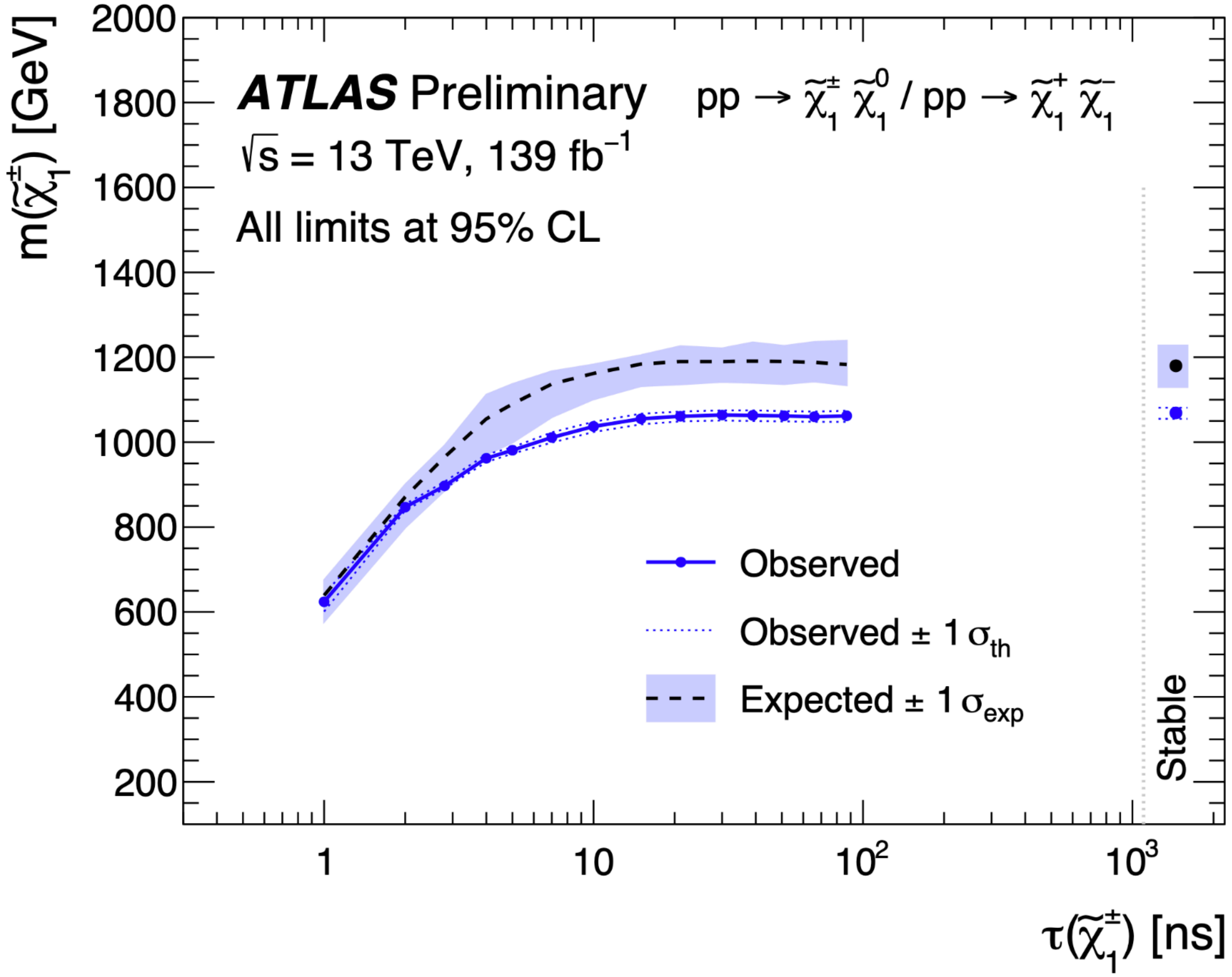


dE/dx Results — Limits





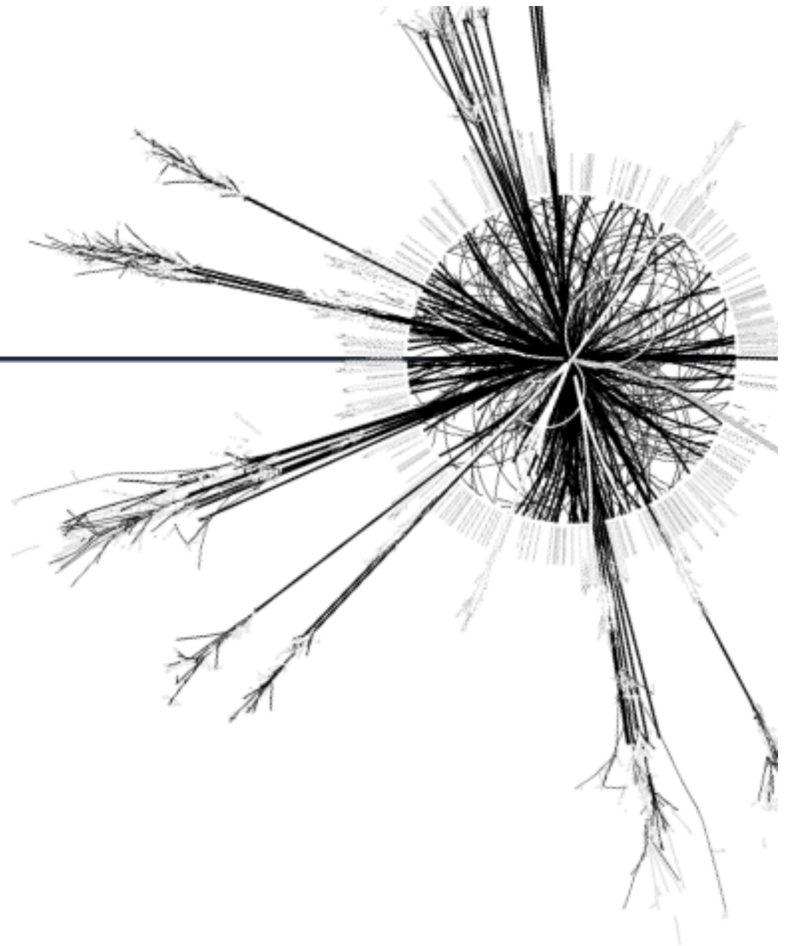




Observations:

- Due to the observed excess of events, the observed limits are lower than expected limits

LLP Reconstruction Efficiency

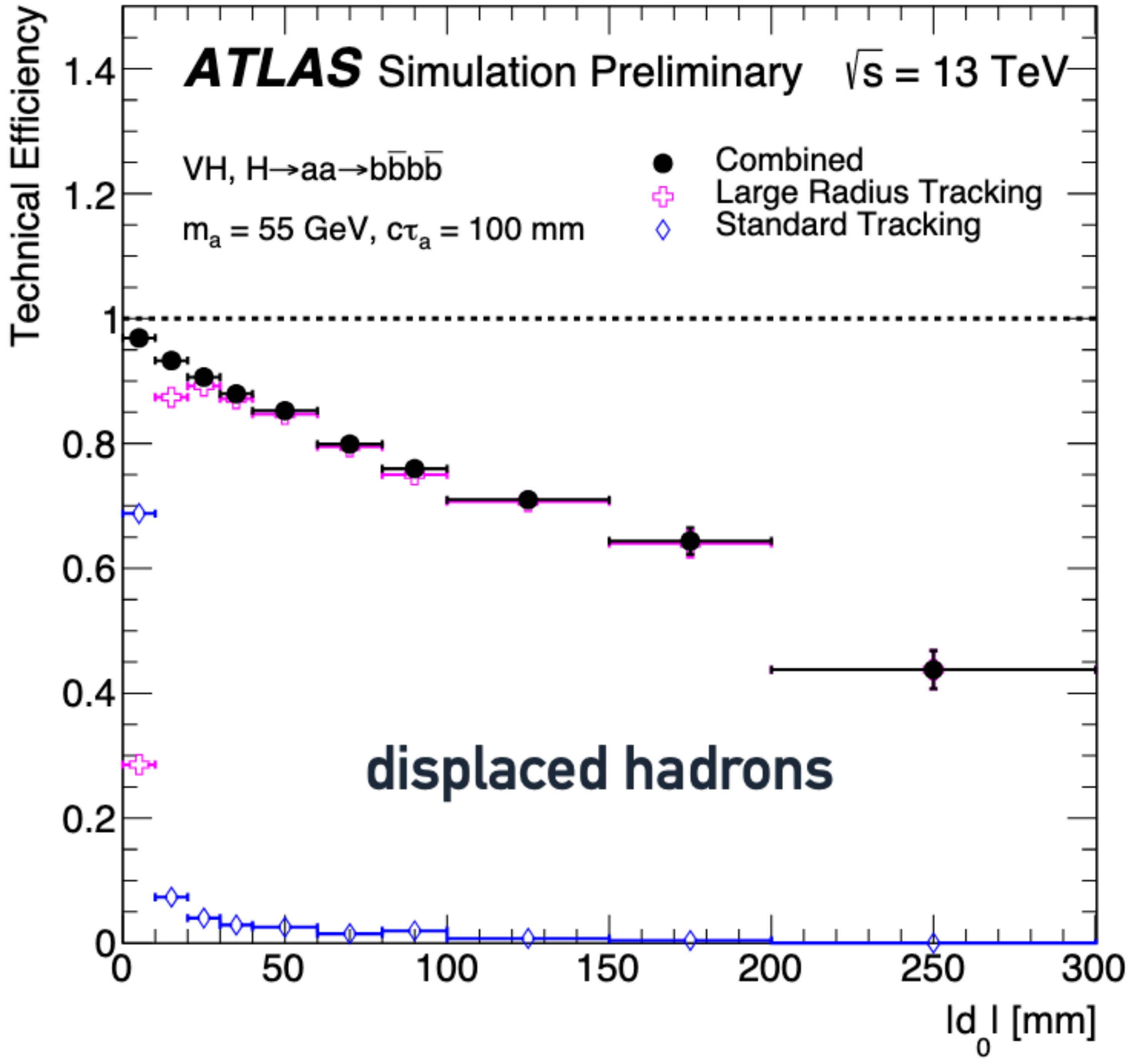


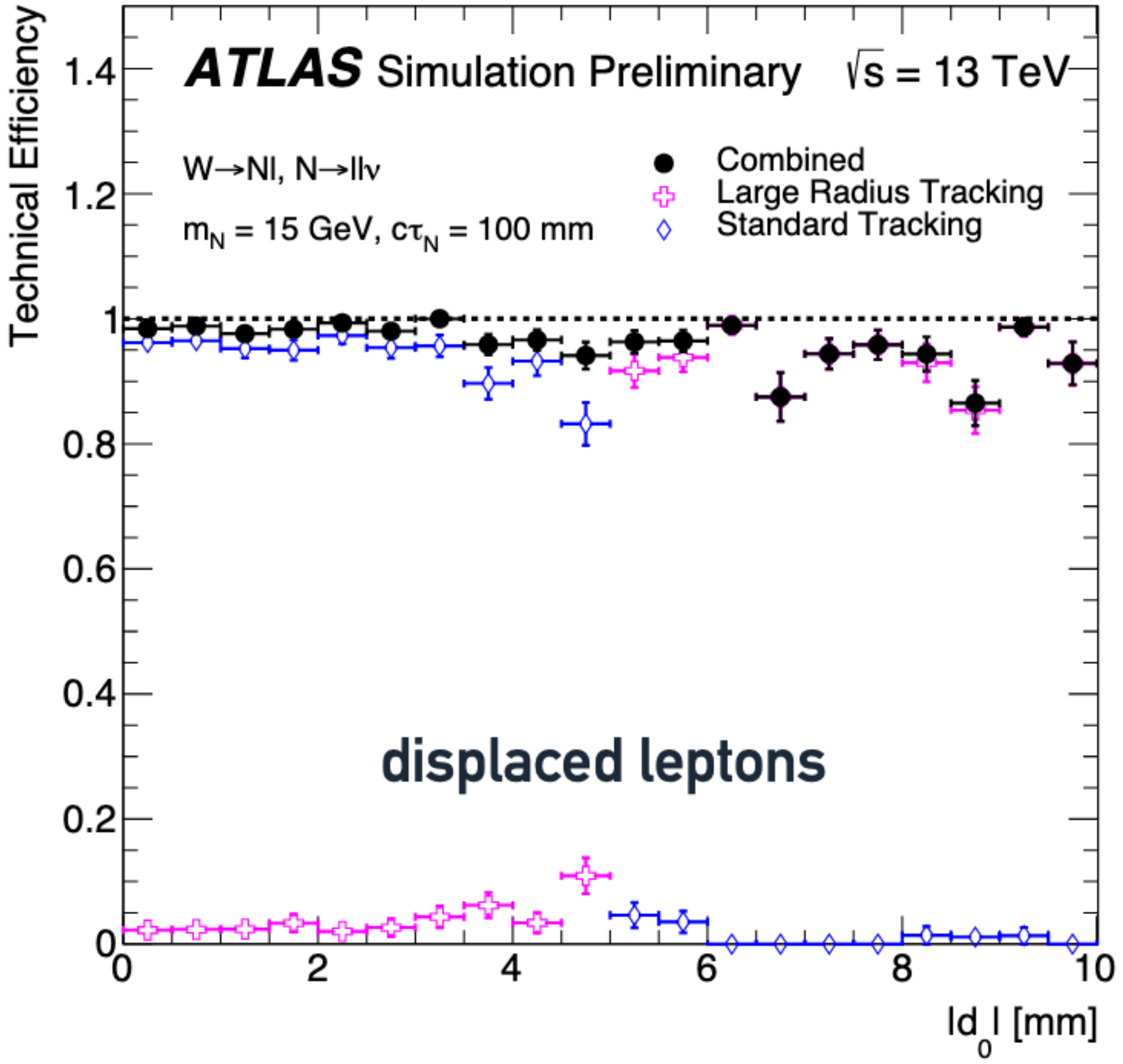
LRT recovers significant loss of standard tracking efficiency for truth particle $|d_0| > 5\ \mathrm{mm}$

- Technical efficiency: fraction of “reconstructible” truth particles matched to an LRT track
  - Quantifies performance on truth particles that could in principle be reconstructed by LRT

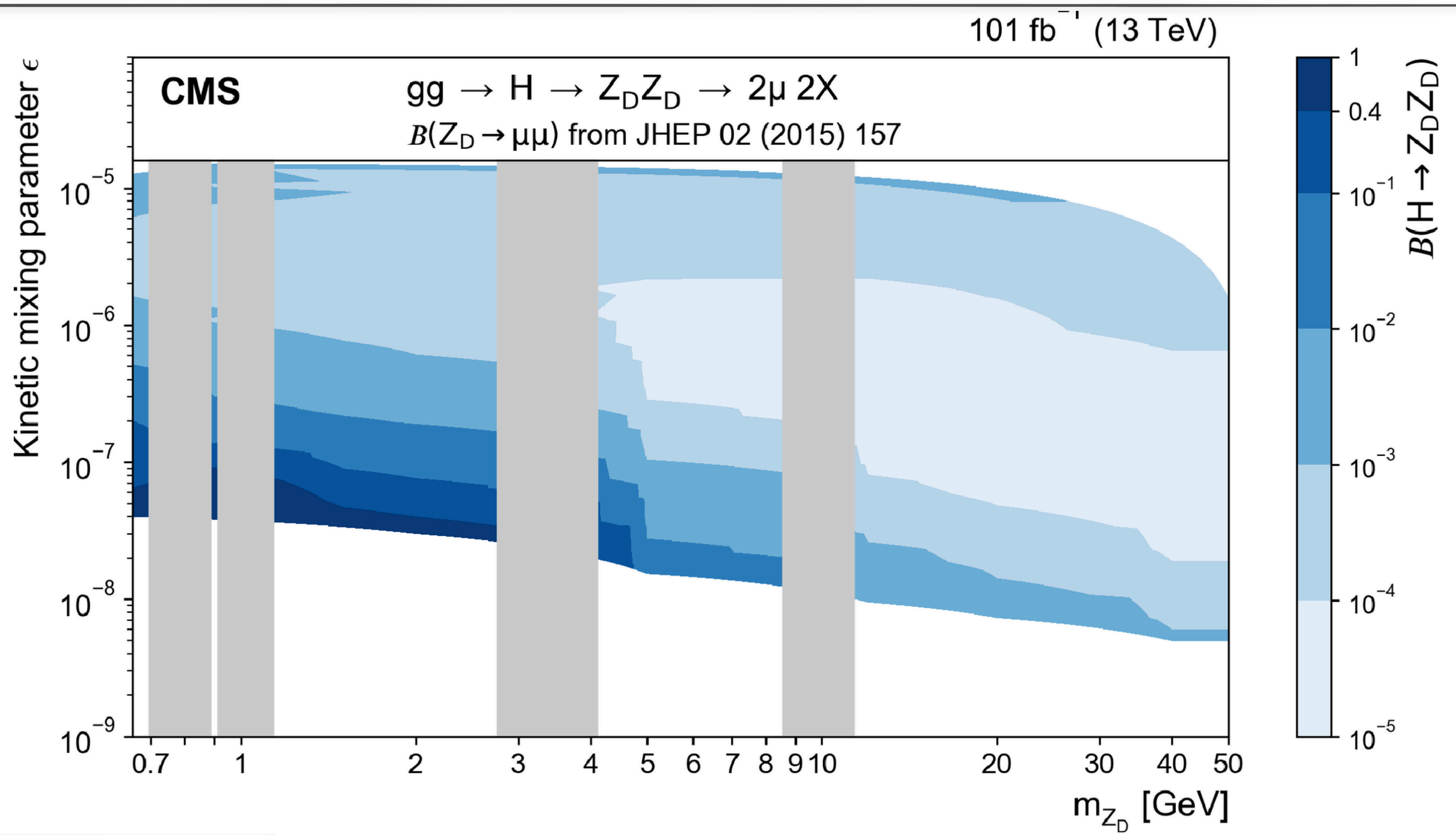
“Reconstructible” truth particle selections

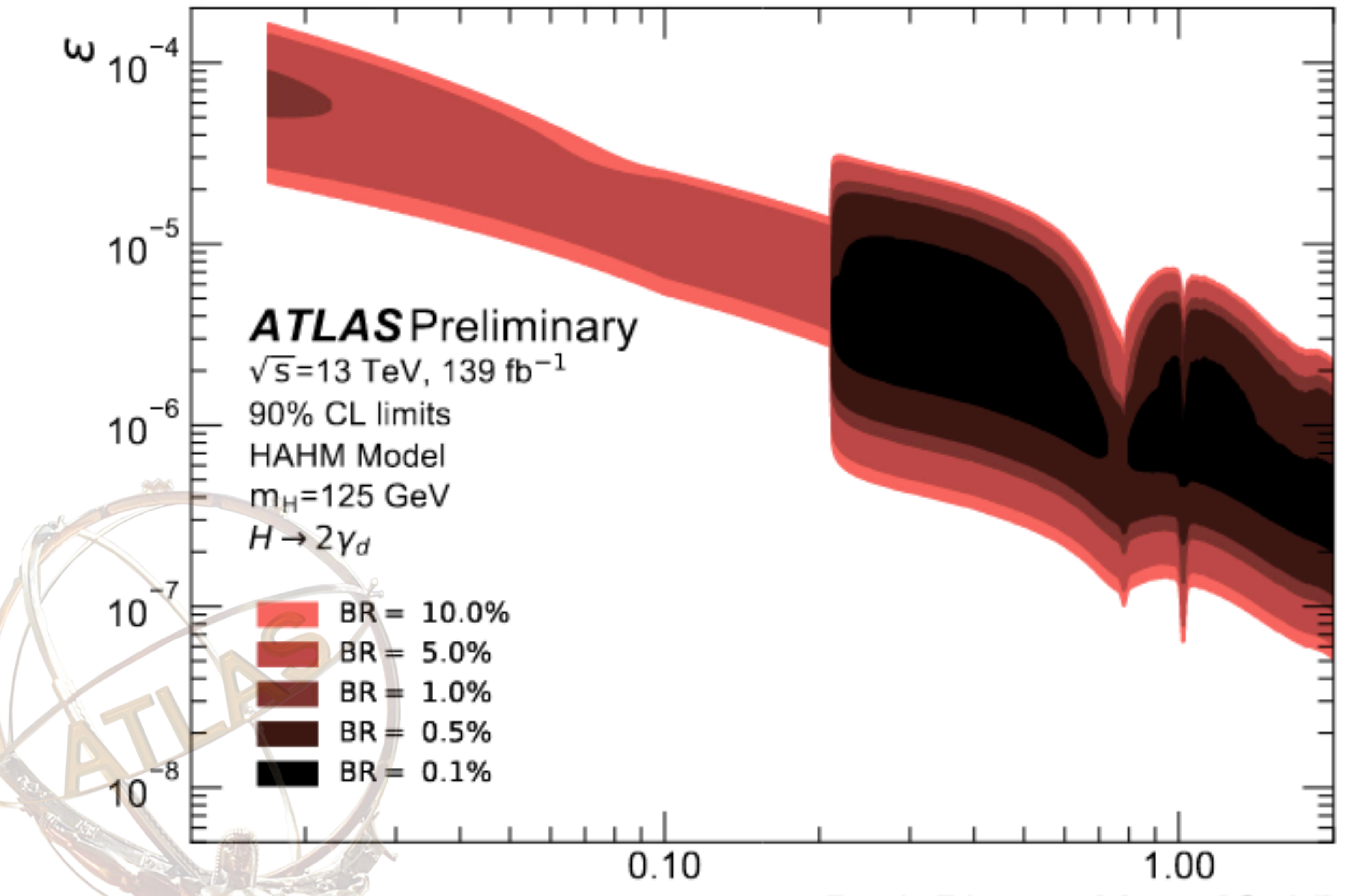
- From LLP decay
- Charge = ± 1
- $r_{\mathrm{prod}} < 440\ \mathrm{mm}$
- $p_{\mathrm{T}} > 1\ \mathrm{GeV},\ |\eta| < 2.5$
- $N_{\mathrm{Si}}^{\mathrm{hits}} \geq 8$





Hidden Sector comparison





Hidden Sector comparison