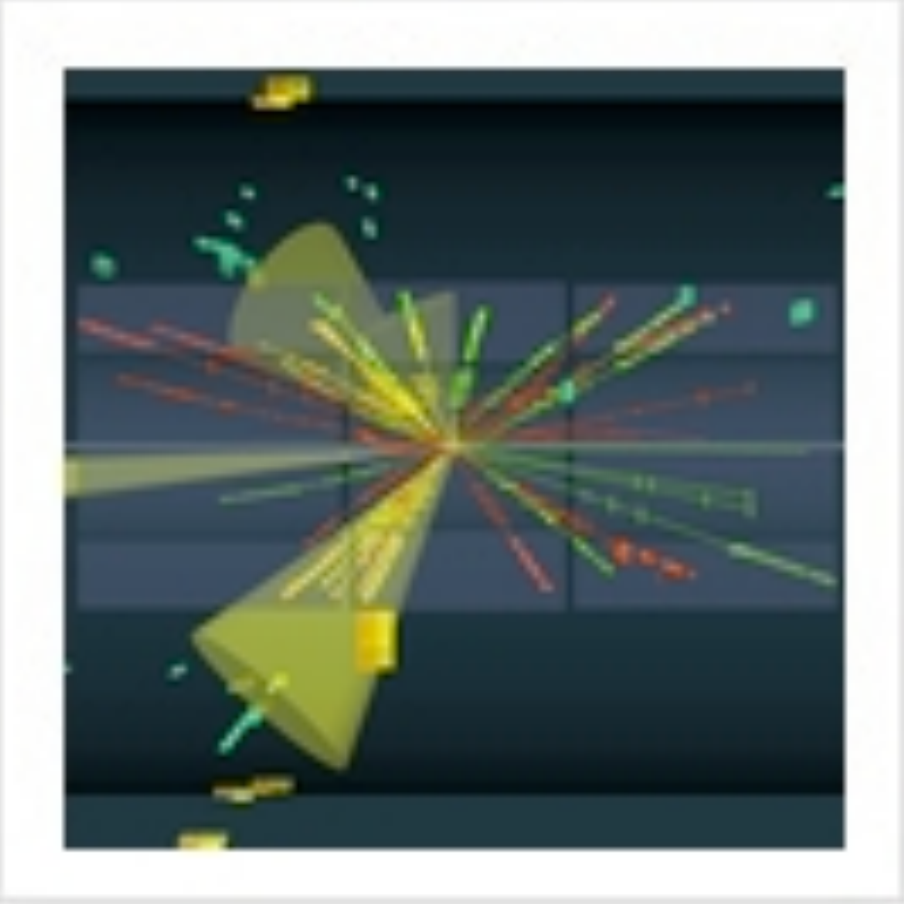
CENTRO DE CIENCIAS DE BENASQUE PEDRO PASCUAL

TAE 2022
International Workshop on High Energy Physics

Sep 04 -- Sep 17 2022



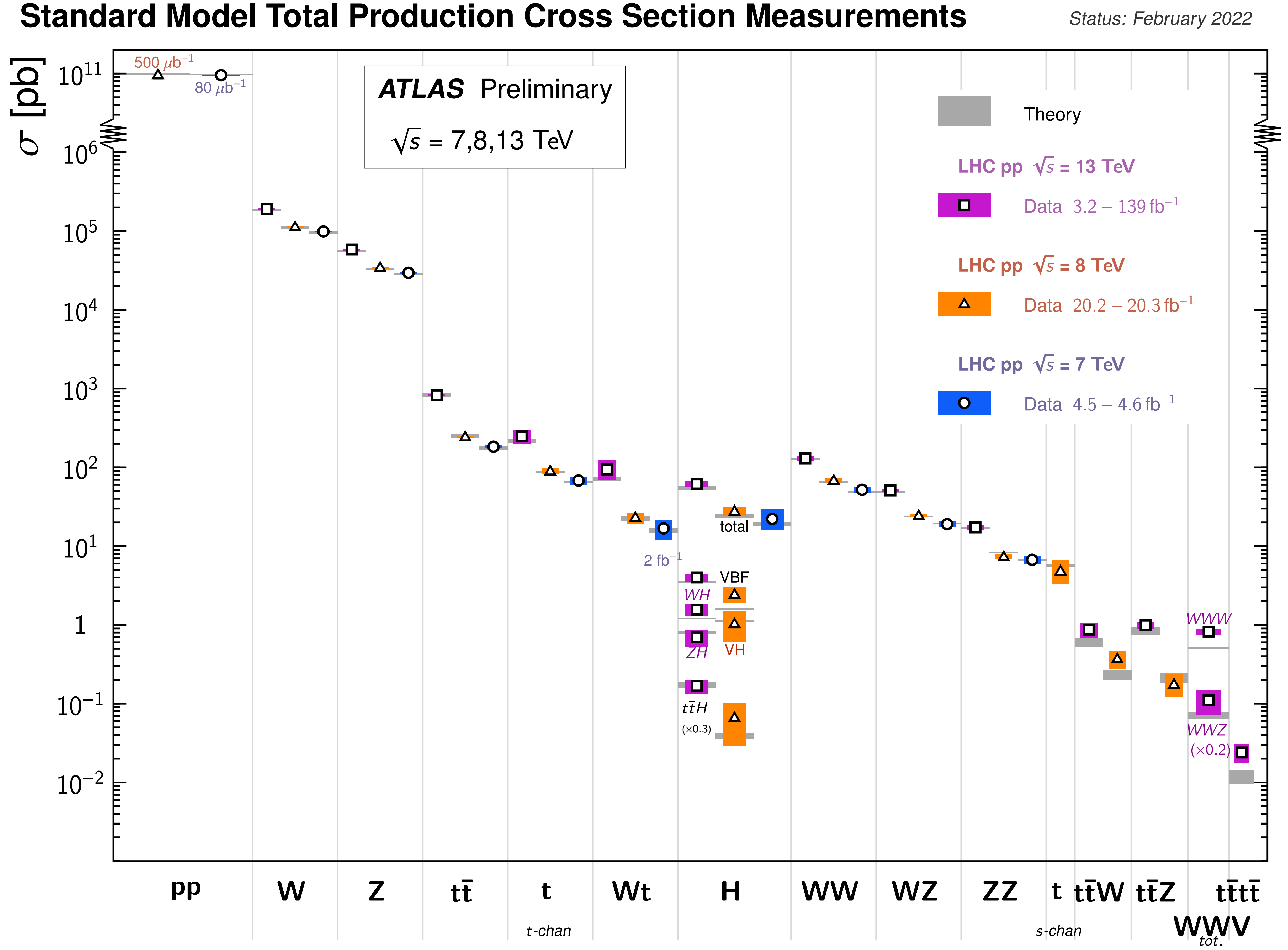
Long-lived particles (@ LHC)

Emma Torró
IFIC - Valencia

IFIC Institut de Física Corpuscular | CSIC Consejo Superior de Investigaciones Científicas | Vniversitat de València | ATLAS VLC Instituto de Física Corpuscular - Valencia | Generalitat Valenciana Conselleria d'Educació, Cultura i Esport | Gen-T

Searching for new physics

- Standard Model (SM): very successful theory
- Precise predictions, verified by experiment with impressive agreement with theory across orders of magnitude



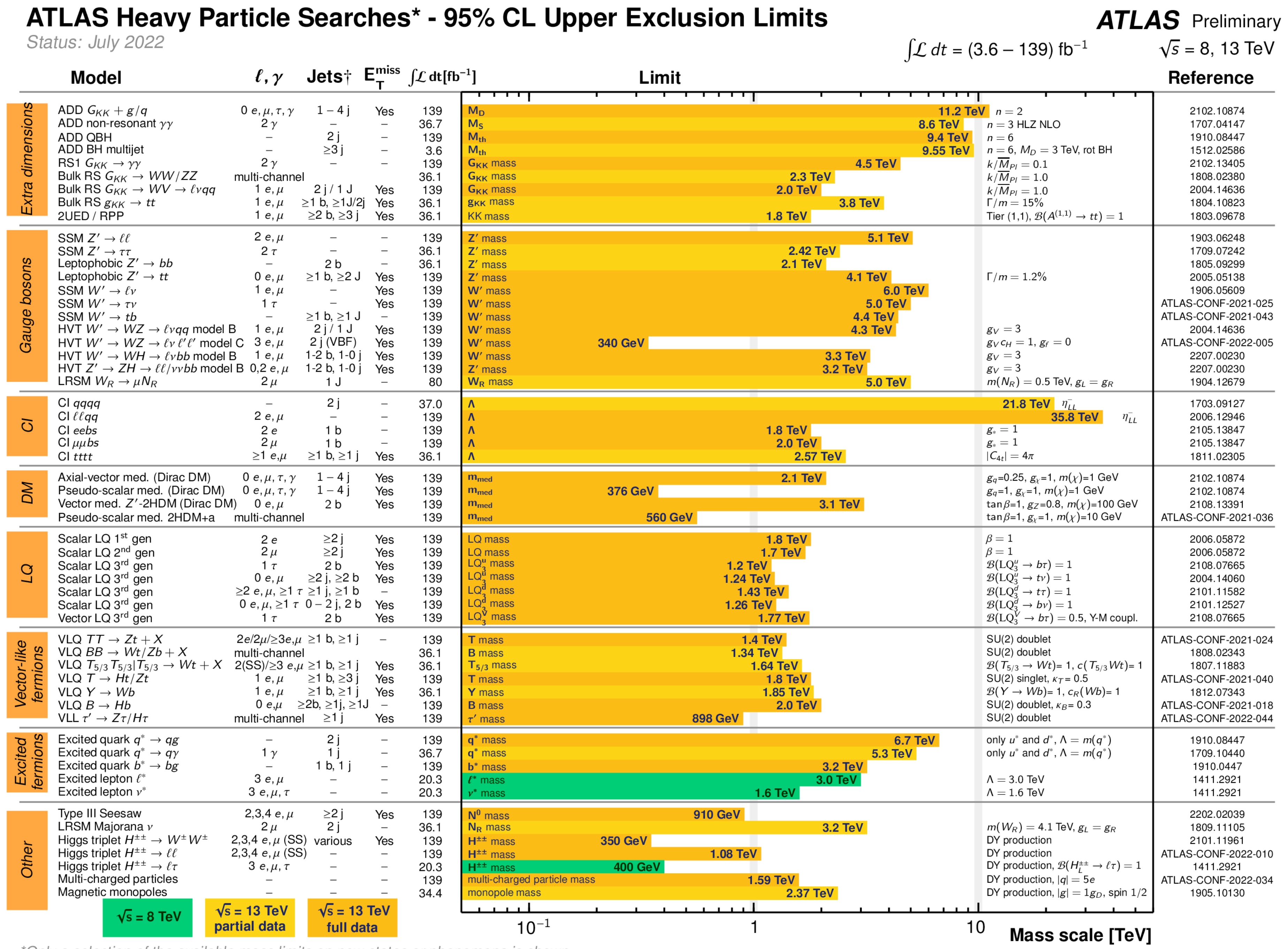
2012!!
The SM puzzle is complete but……

Searching for new physics

- Standard Model (SM): very successful theory
- Precise predictions, verified by experiment with impressive agreement with theory across orders of magnitude

- But we believe this picture is **not yet final**: observational and theoretical issues need resolution
- Searches for **beyond-Standard-Model physics** a core element of LHC programme

To date, **O(100) ATLAS, CMS, LHCb papers** on BSM searches with full Run 2 dataset!



*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

Still, no evidence of new physics…

But still many open questions

Why are we not finding new physics??

- Several possible reasons:
  - It is above the scale accessible by the LHC?? …..

    Not much we can do at the moment….

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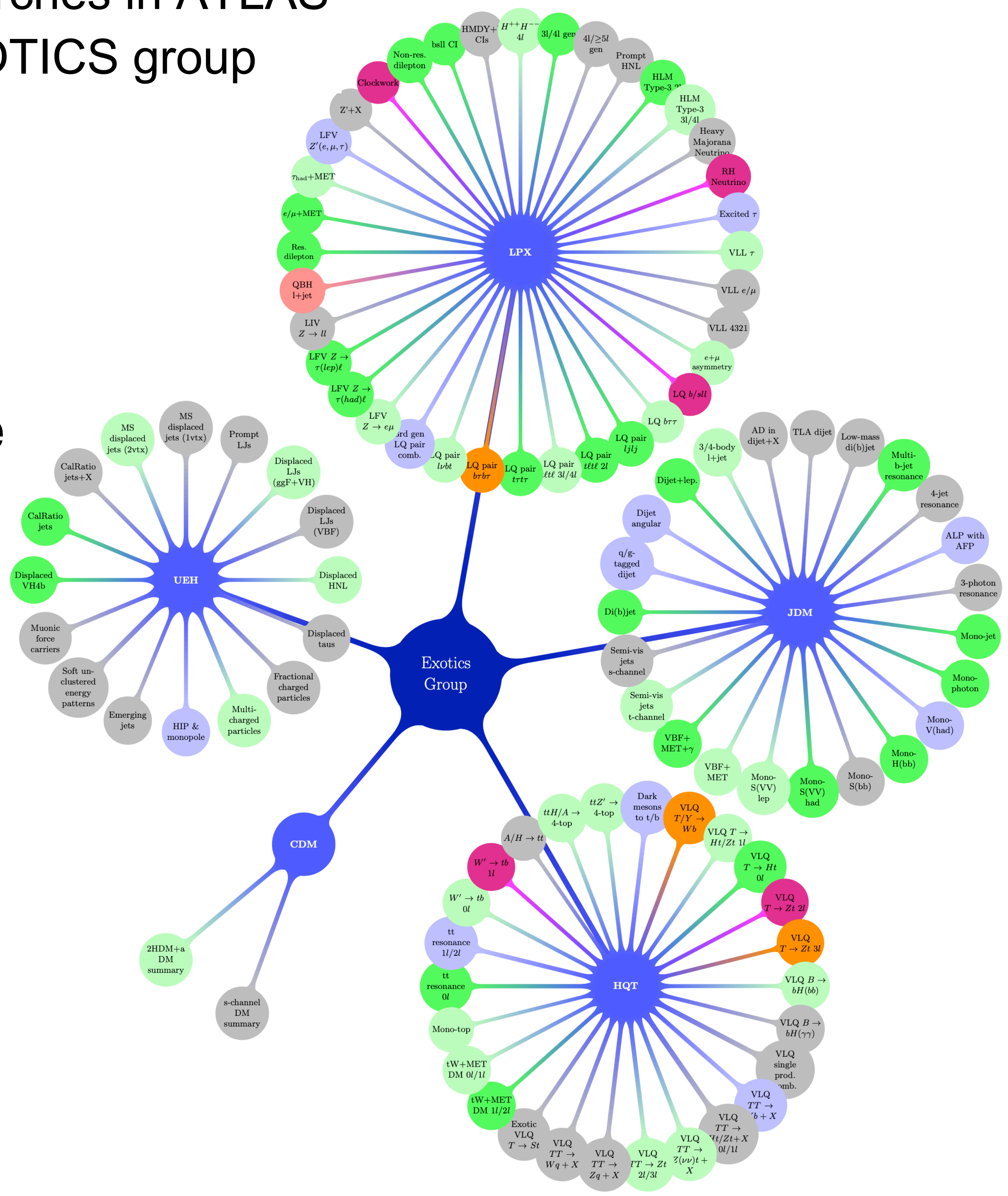
  - It isn't where we have been looking. What if it is just **very hard to see**?

Searches in ATLAS EXOTICS group



- Strategy: organize searches according to final states.
  - Start with the simple models, then if nothing new observed, we explore the more complex, well-motivated ones
    - Soft new particles
    - Low cross sections
    - Huge / difficult backgrounds
    - Long-lived particles with unconventional signatures

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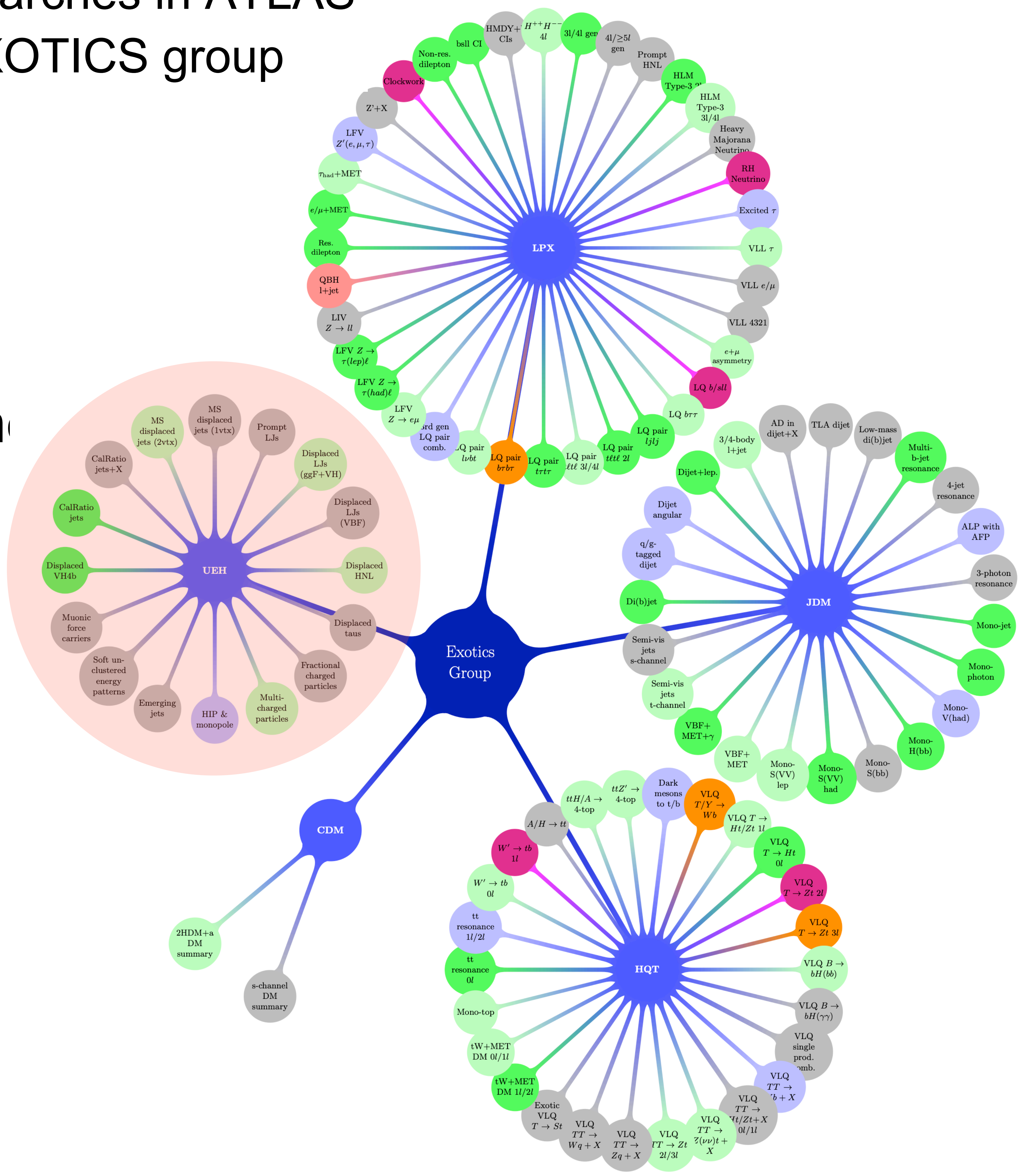

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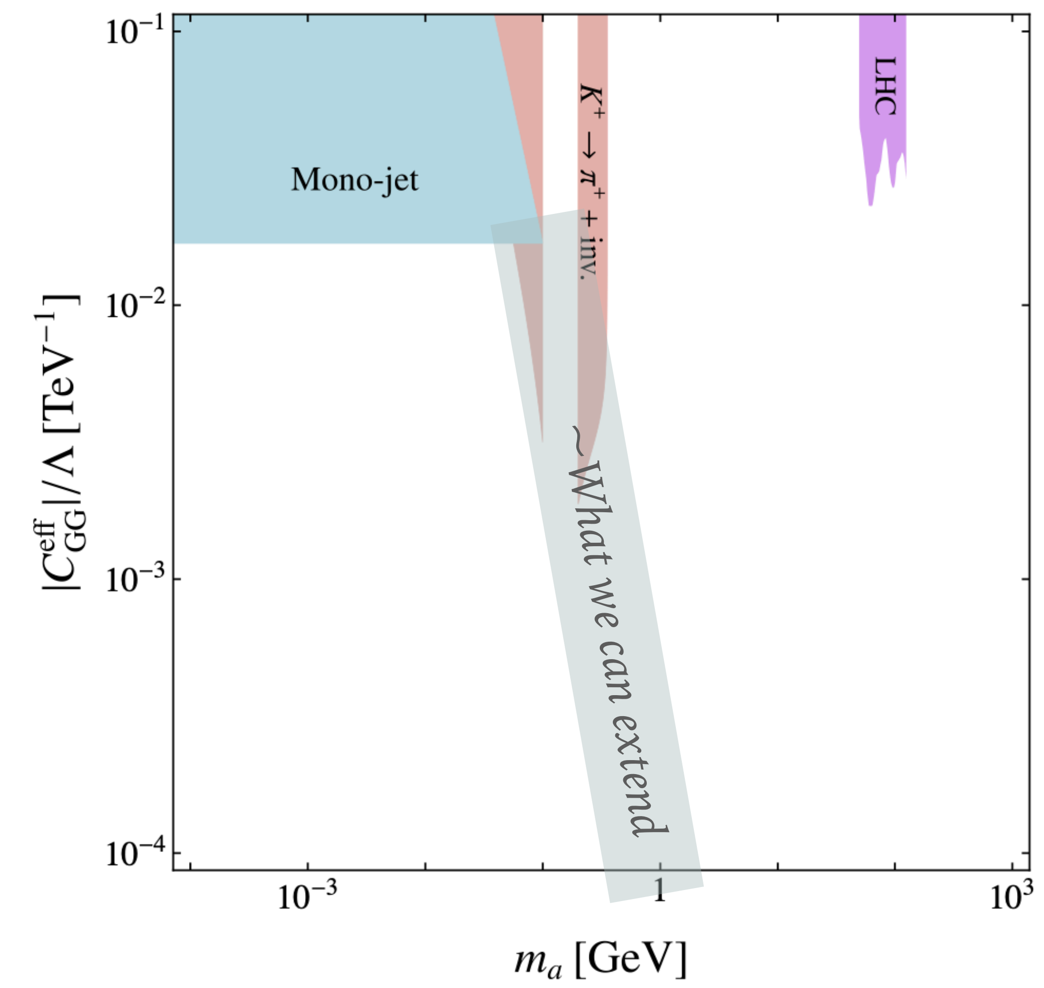
    - **Long-lived particles with unconventional signatures**

Long lifetimes can come from…

Example in BSM

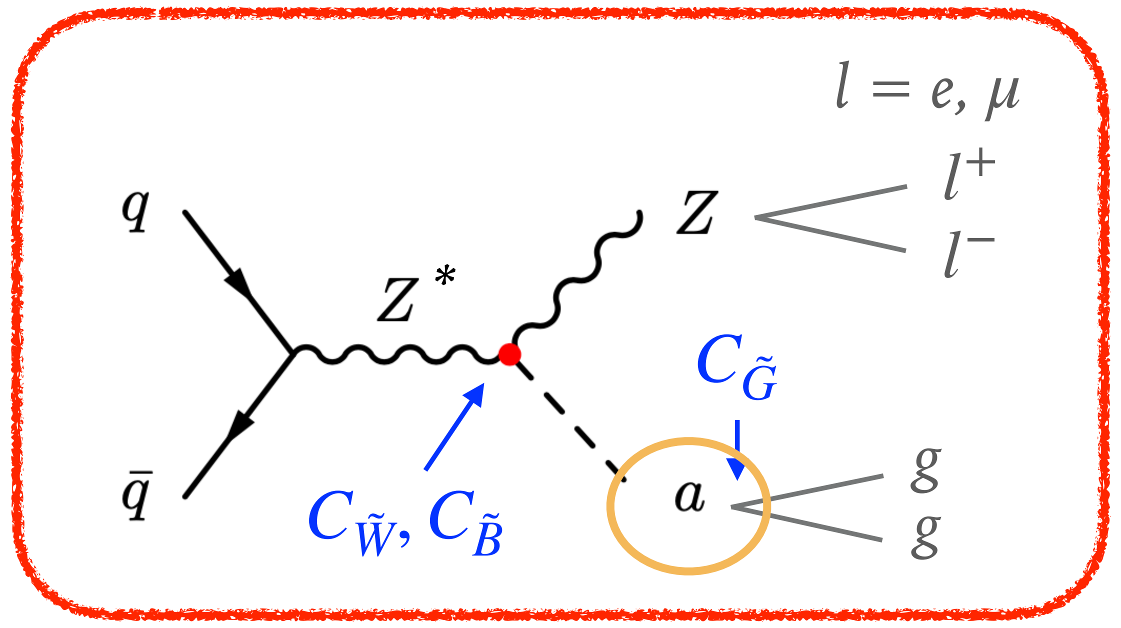
- Small couplings — Some parameter space in ALPs
- Decays via heavy particles — heavy neutrinos
- Limited phase space — compressed scenarios (almost degenerate masses)

ALPs



Limits on the ALP-gluon couplings vs. ALP mass from collider and accelerator searches

Axion-like particles



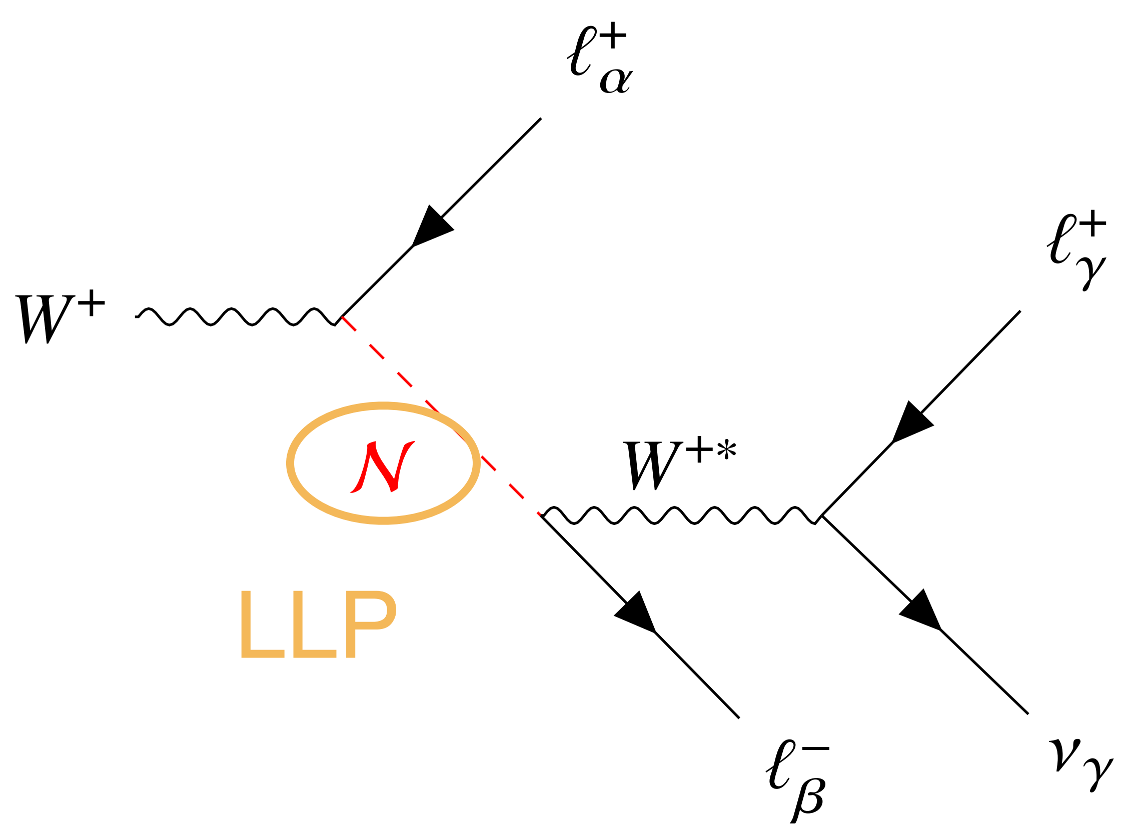
LLP

Width of ALP decay to gluons:

$$\Gamma_{ag} = 2C_{\tilde{G}}^2 Ma^3/(f_a^2\pi)$$

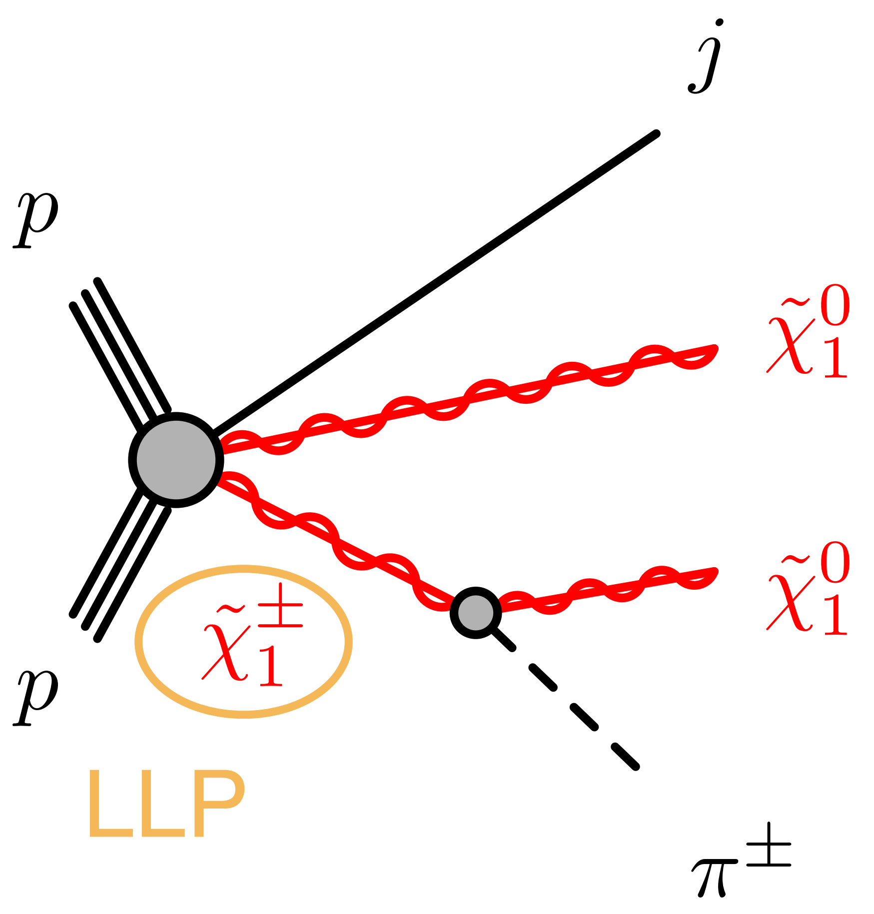
HNL

Heavy neutral lepton



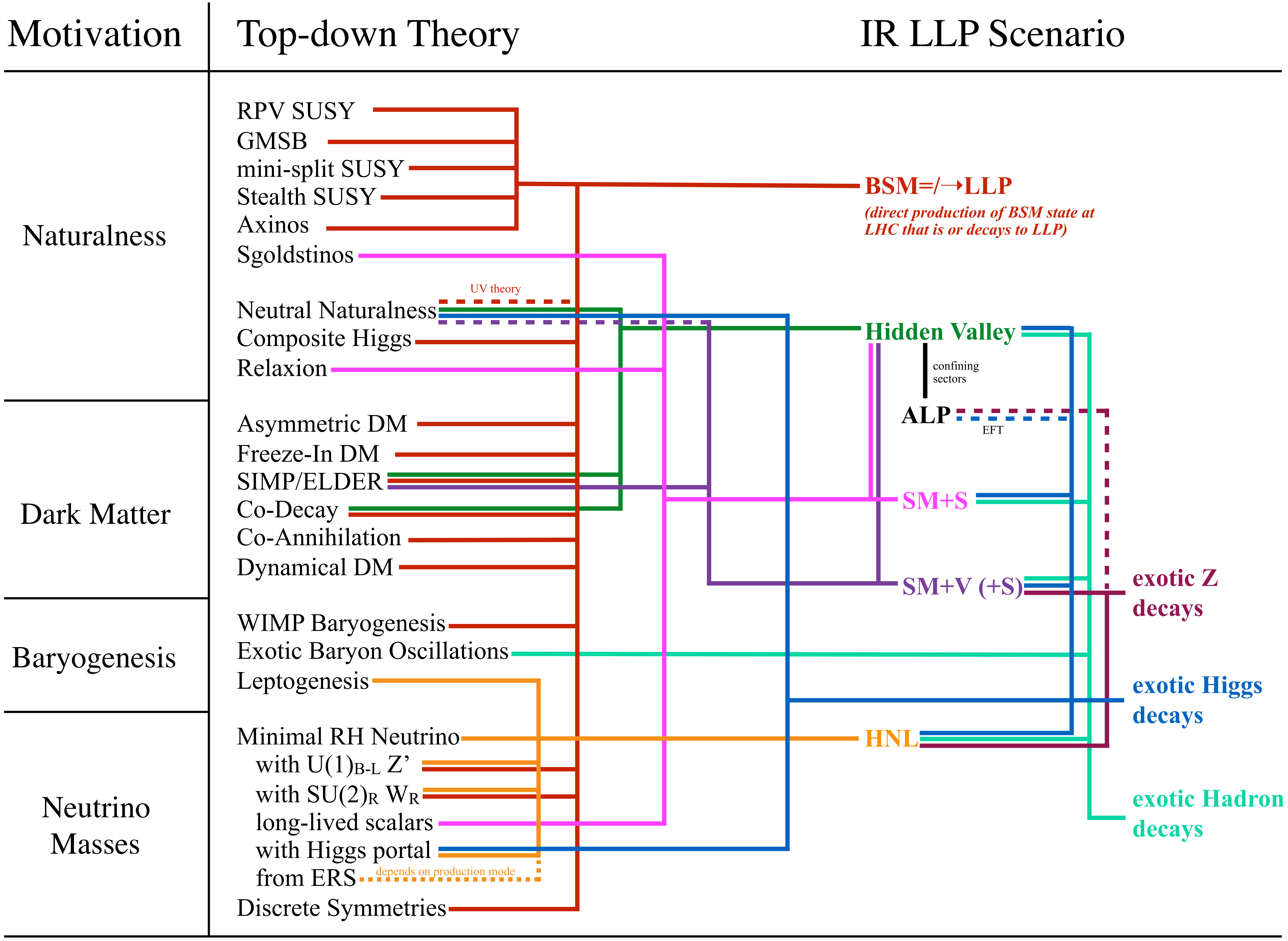
SUSY

AMSB, $m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_1^0}$



Long lifetimes can come from…

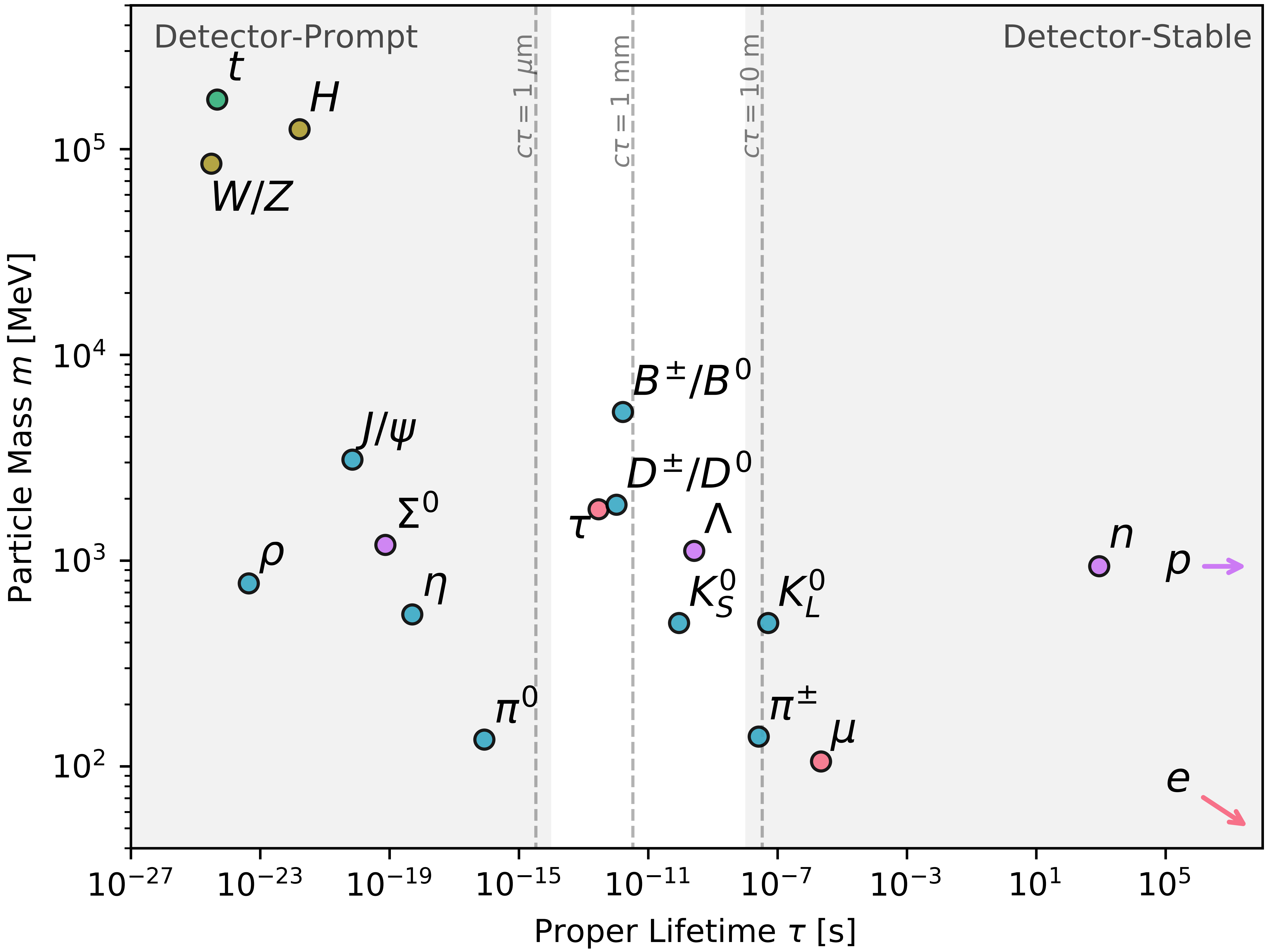
- Many different signal models predict LLP



Curtin et al, 1806.07396

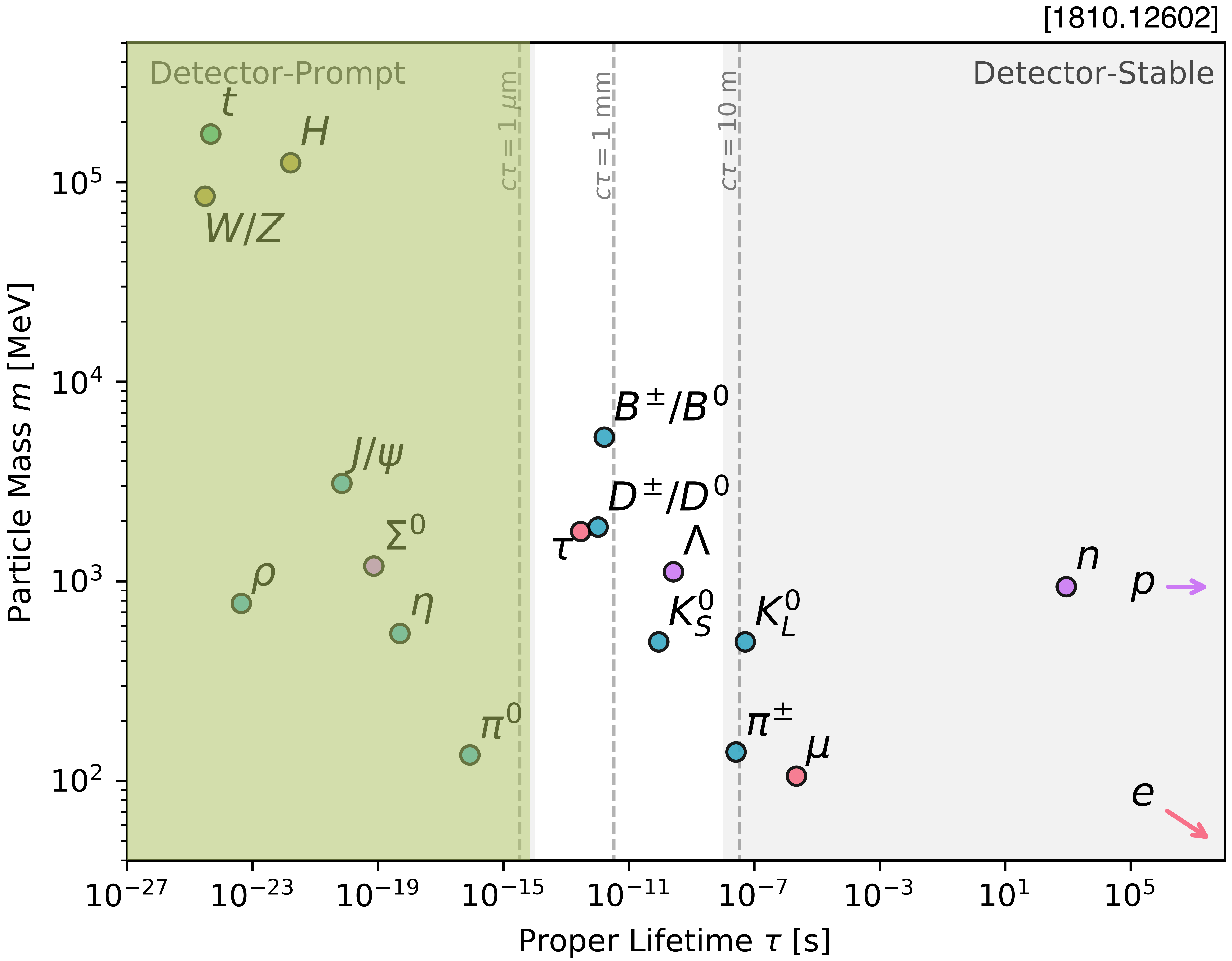
Searching for new physics. Where should we look?

[1810.12602]



Searching for new physics. Where should we look?

Prompt BSM being actively probed



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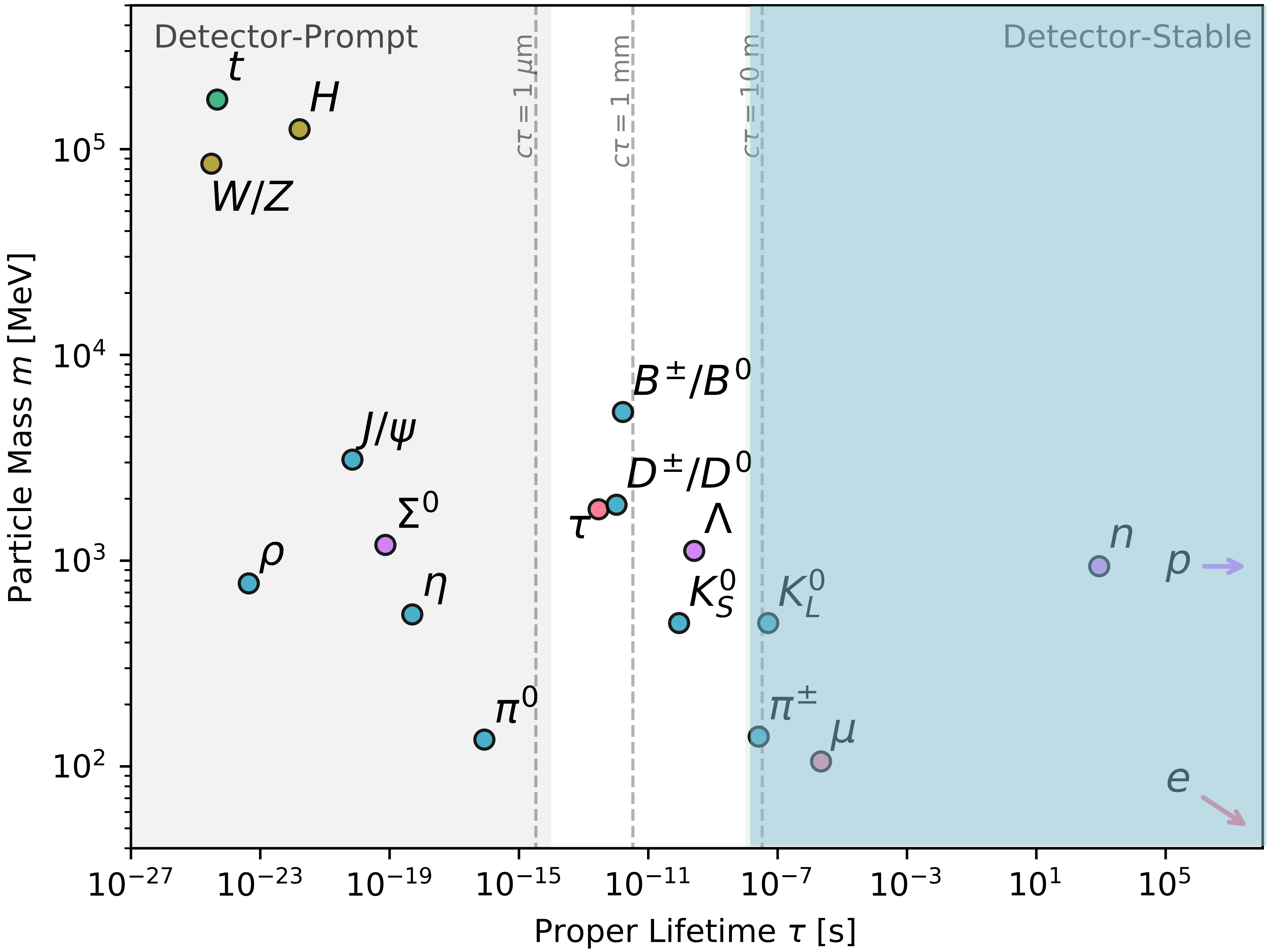


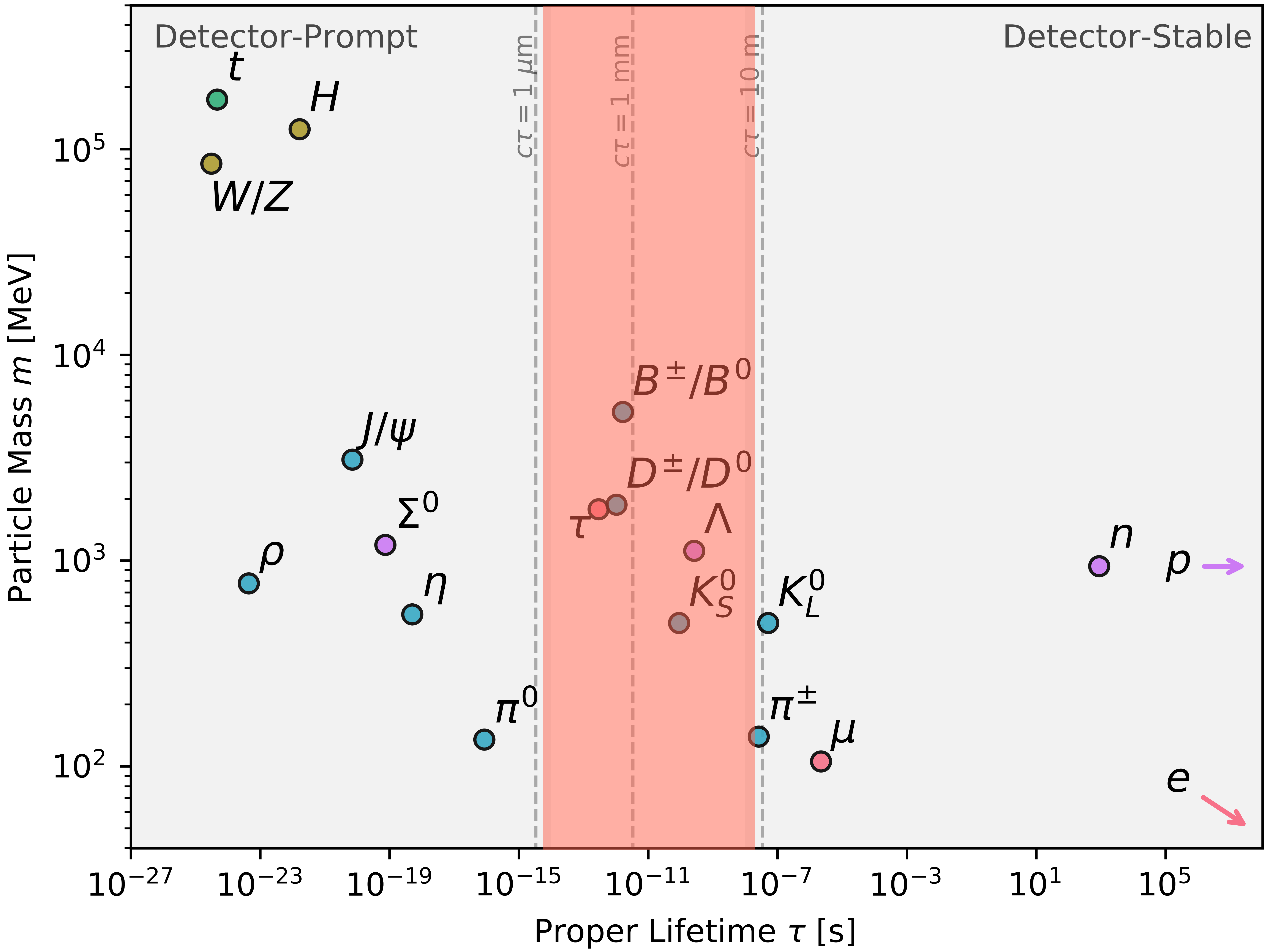
Very long-lived BSM being probed as missing transverse energy (unmeasured particles) or charged particles

Searching for new physics. Where should we look?

If BSM particles live here, they can evade most of our searches!!!

Dedicated searches needed!!

[1810.12602]

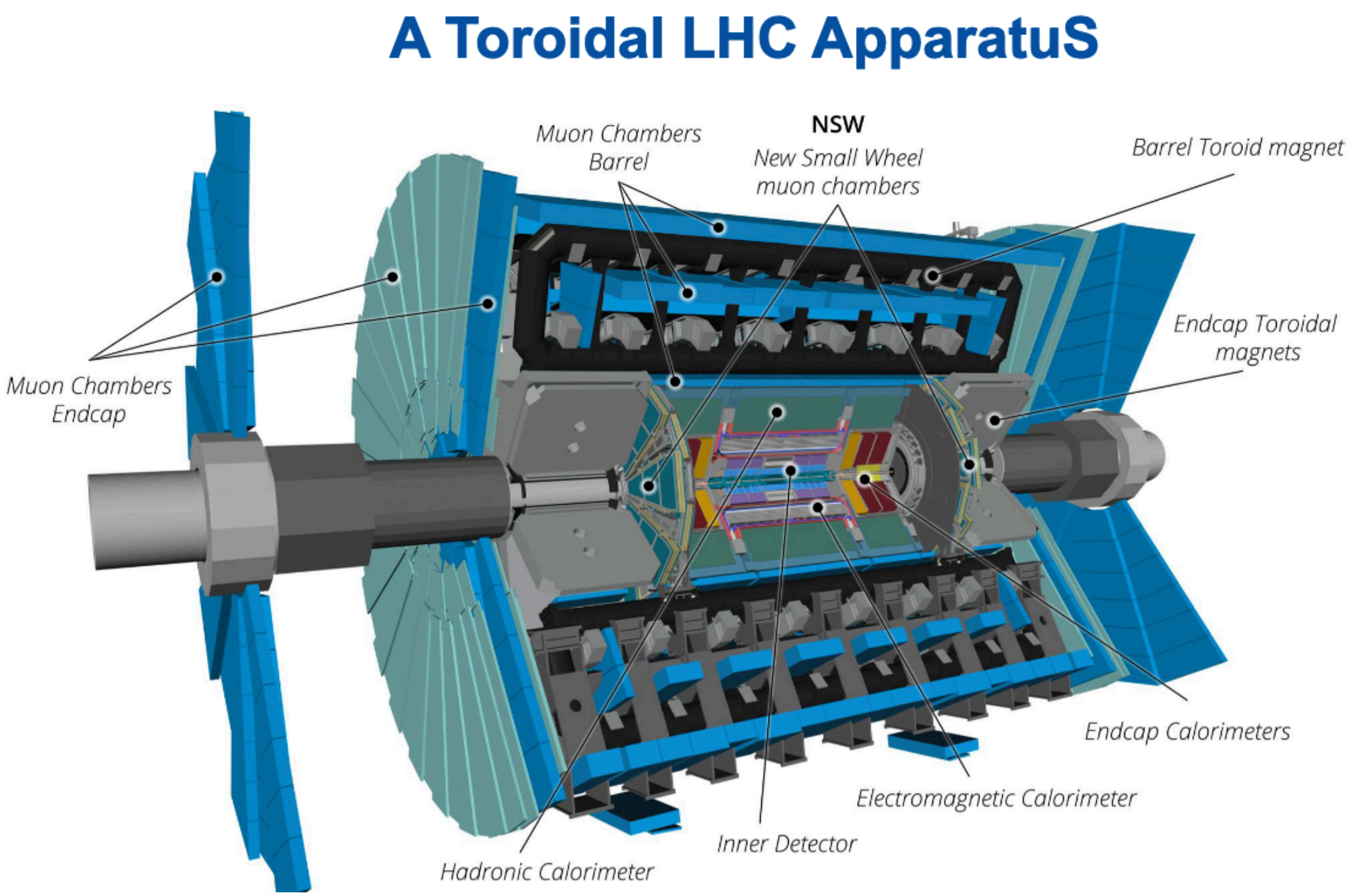


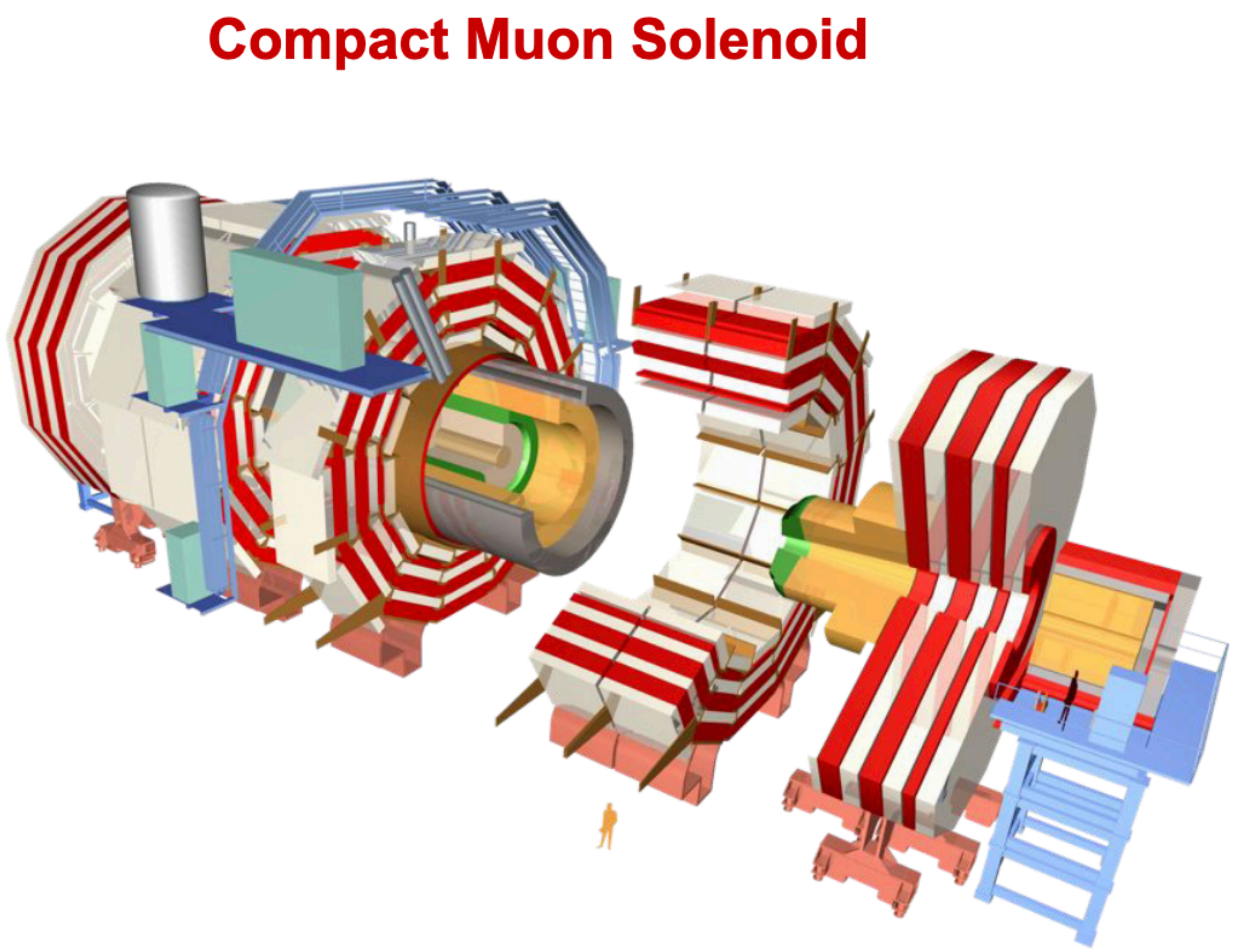
How can we look for LLPs in collider experiments?

That depends on:

LLP lifetime where is it more probable to find a LLP decay?

Imagine the ATLAS/CMS/LHCb detector structure….





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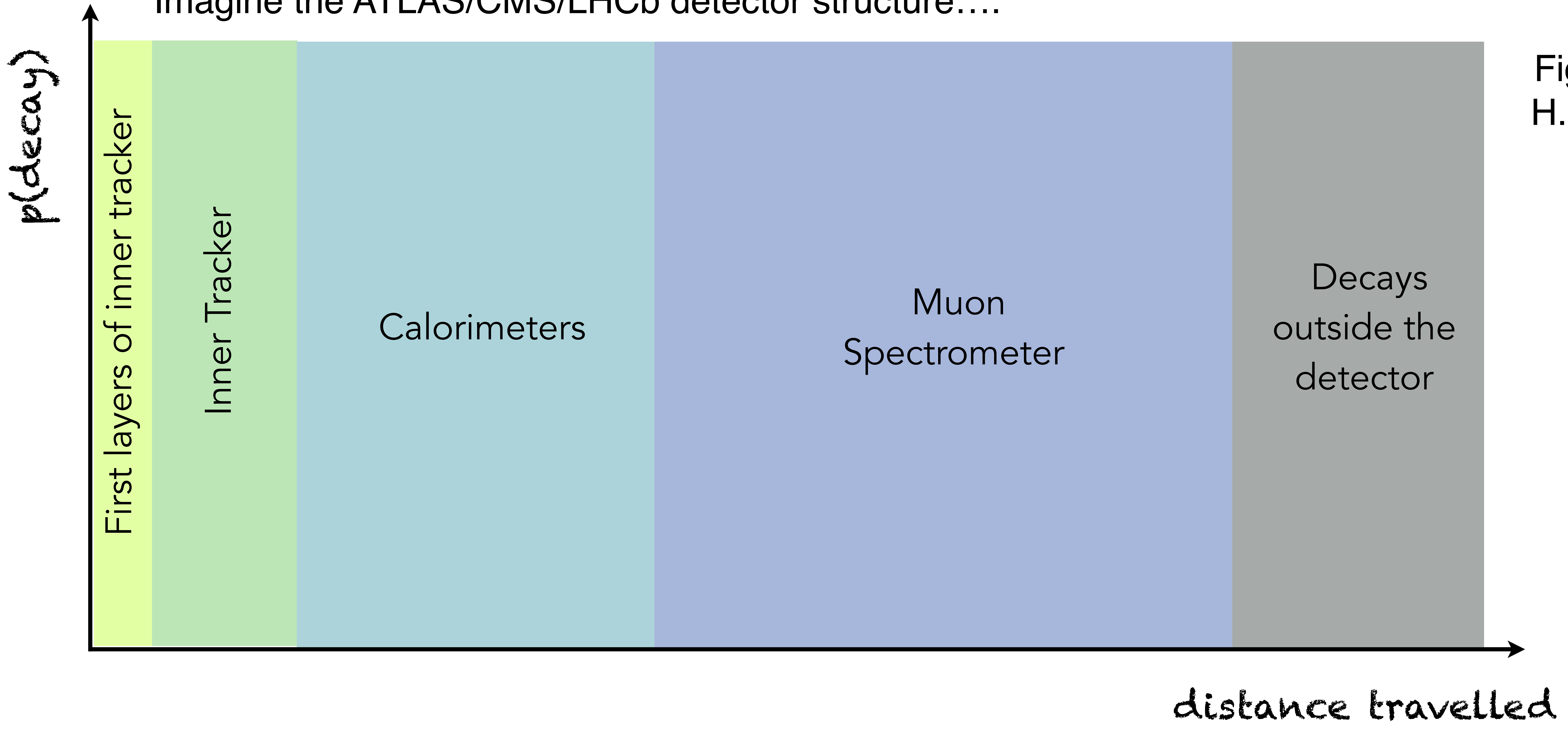

Figures by H. Russell

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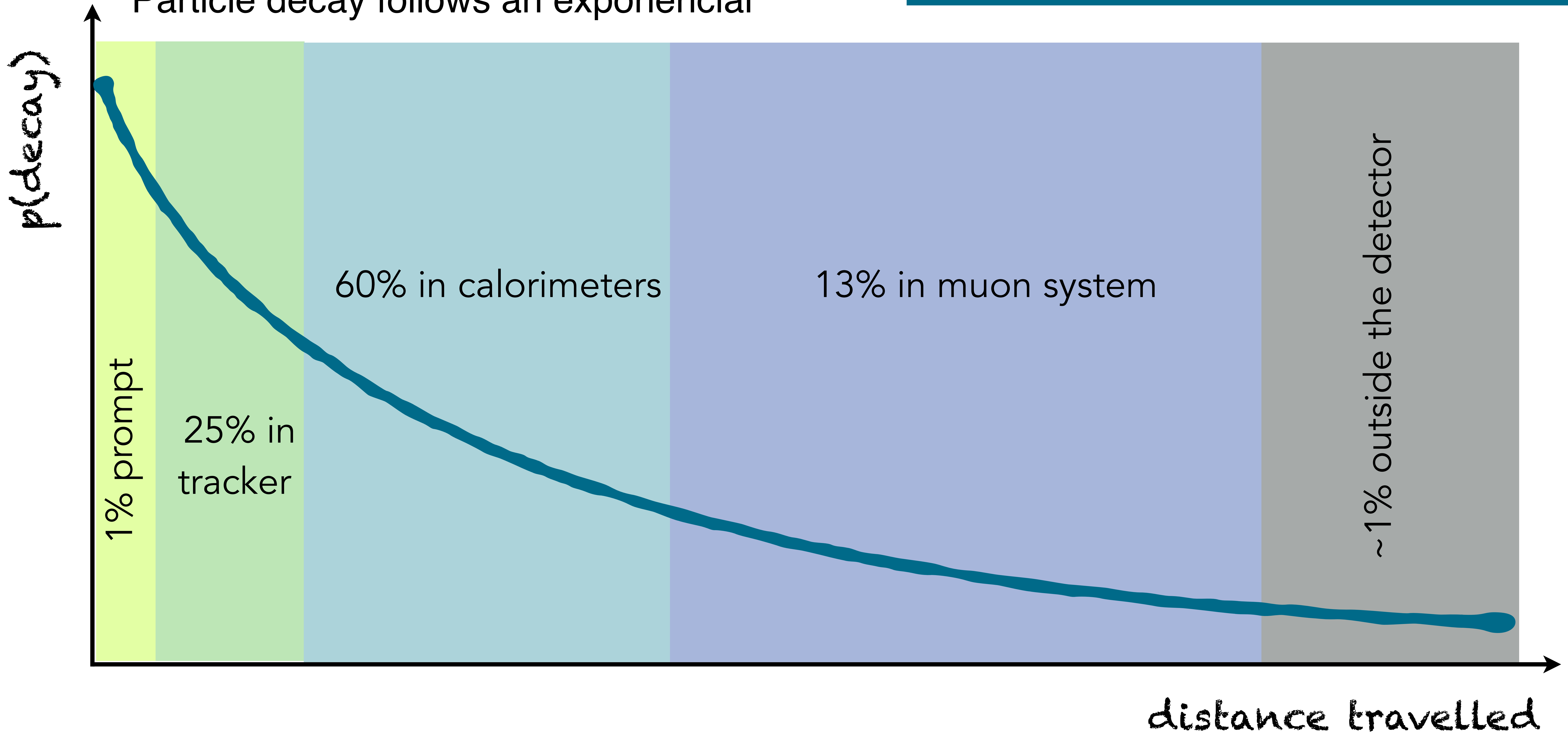
Example light particle with relatively short lifetime:
E.g. for $c\tau$ = 5 cm, $<\beta\gamma>$ ~ 30
Decays happen mainly in the Inner Detector and calo

Particle decay follows an exponencial



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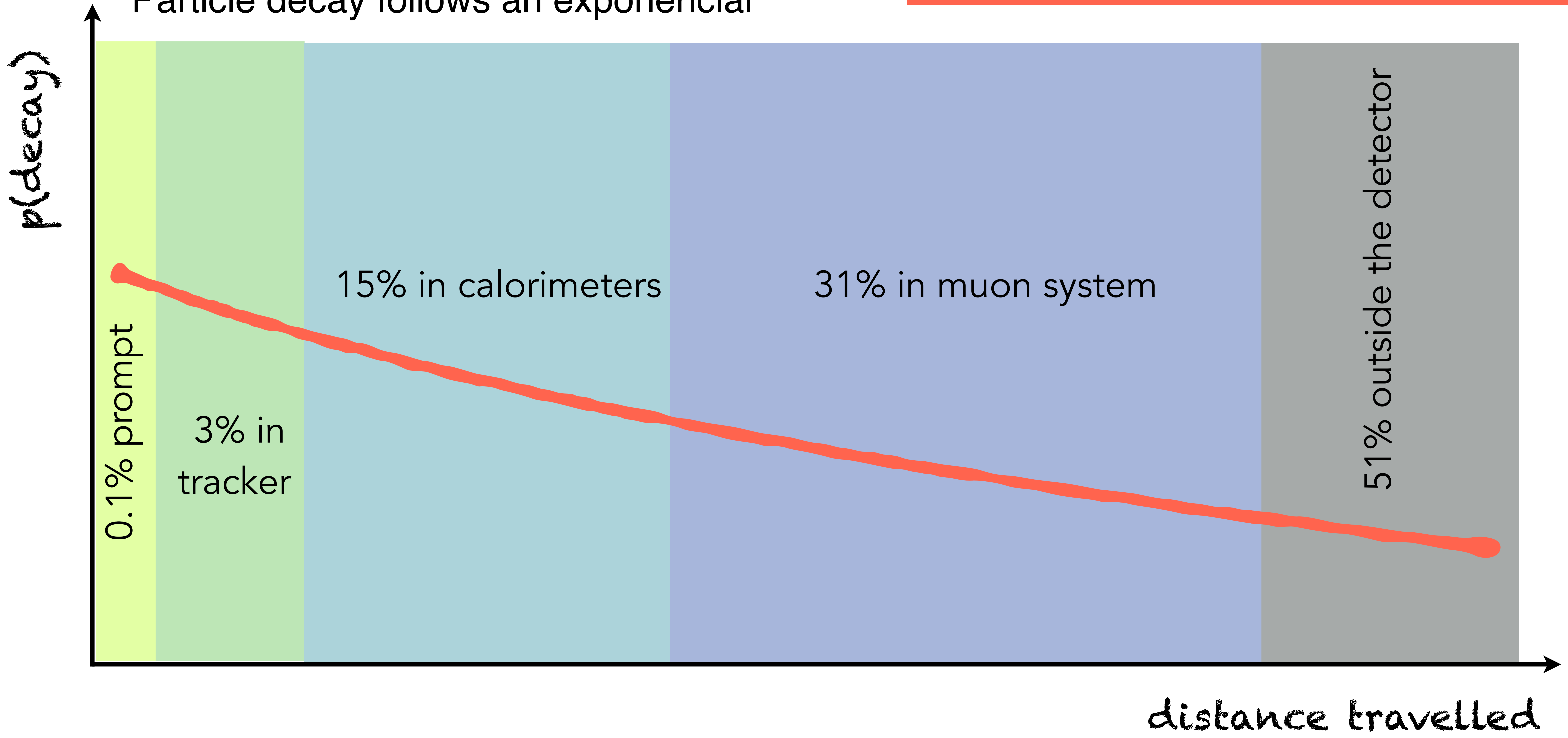

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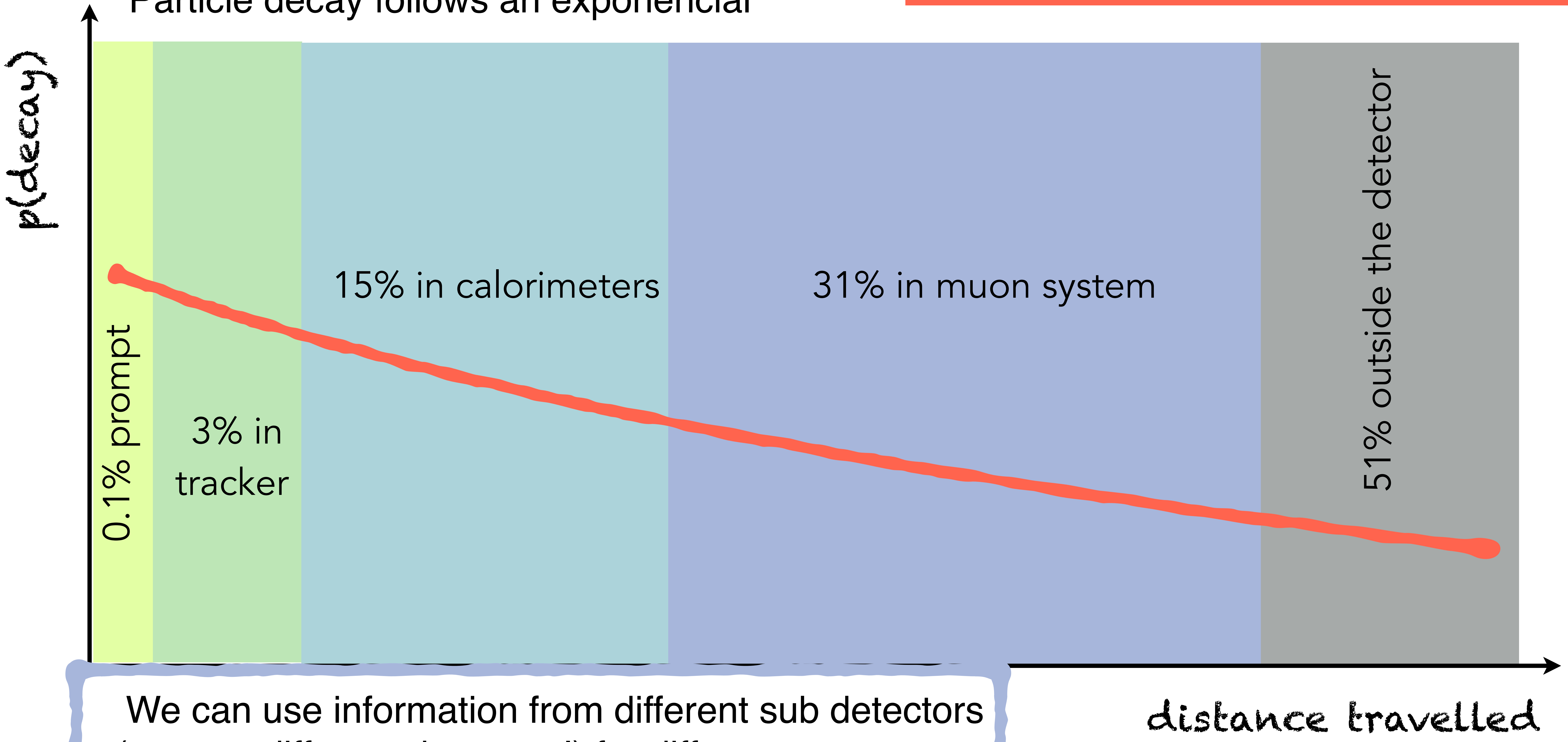


Figures by H. Russell

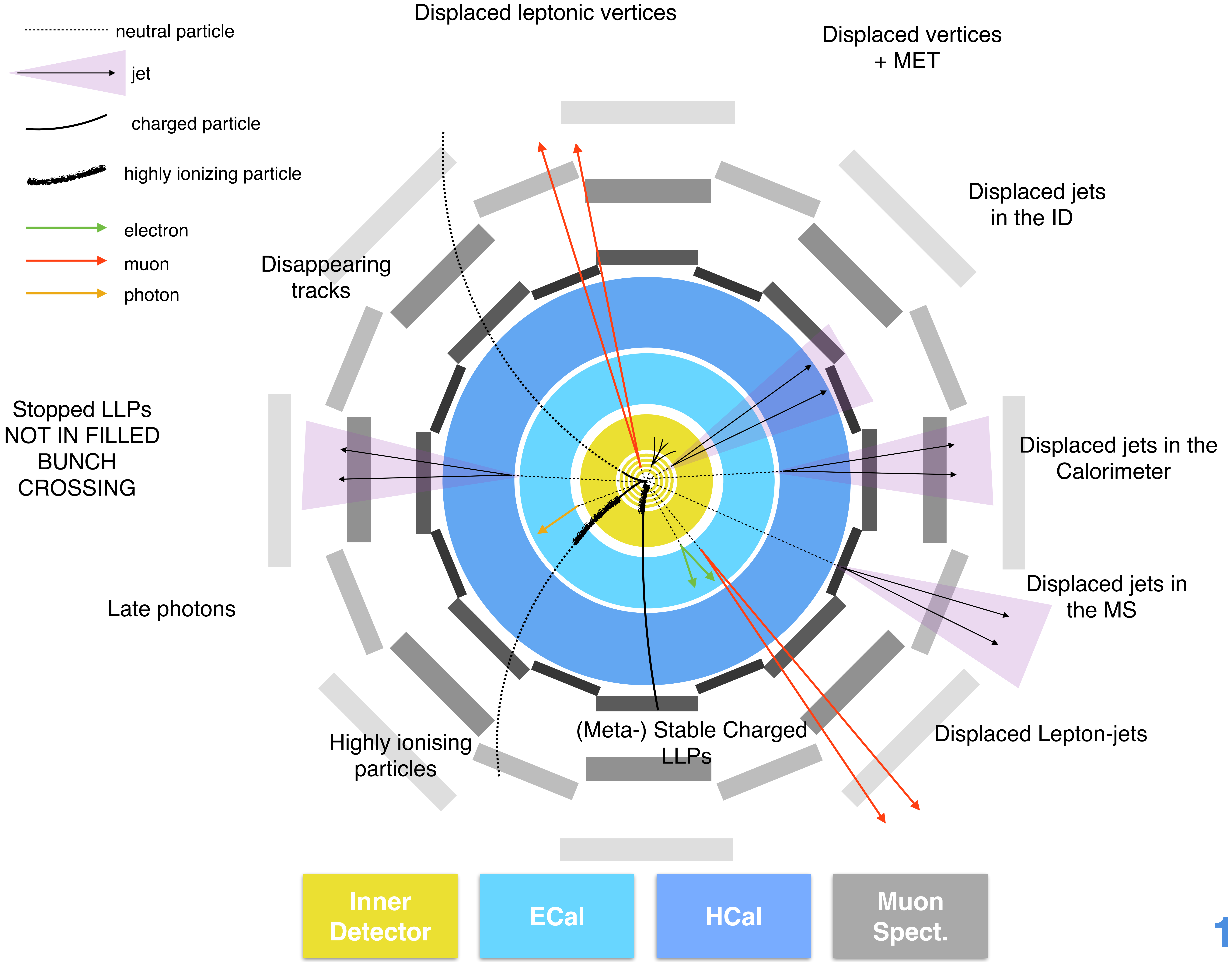
We can use information from different sub detectors (or even different detectors!) for different targets

How can we look for LLPs in collider experiments?

That depends on:

LLP lifetime **LLP nature**

- Is it charged?
  - Does it leave a standard track?
  - Is it highly ionising?
- Is it neutral?
  - which decay mode (hadronic, leptonic, photons, invisible)?



How can we look for LLPs in collider experiments?

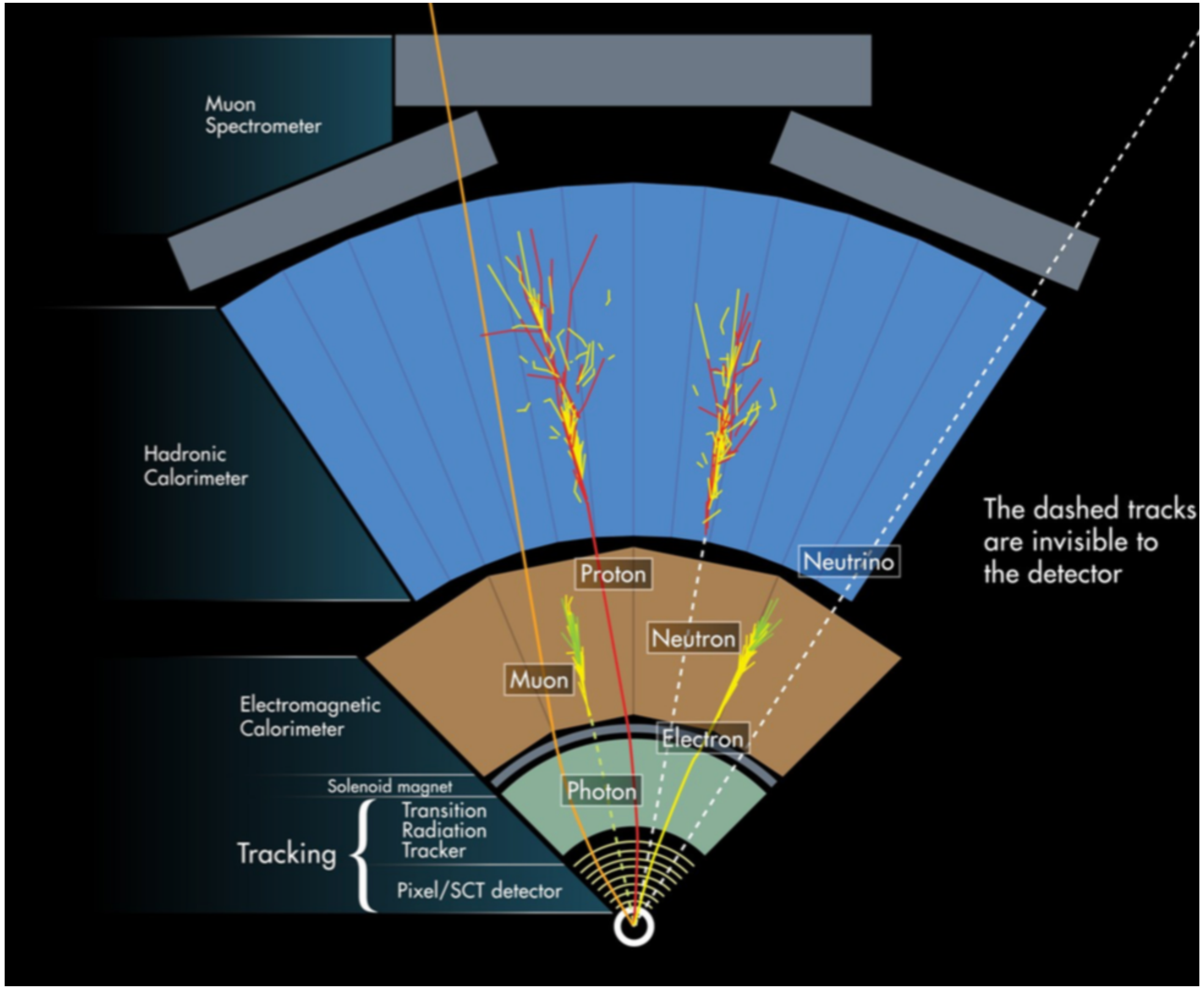
That depends on:

LLP lifetime | LLP nature | object identification

- ATLAS and CMS were designed to identify (prompt) SM particles

- Standard object ID algorithms assume prompt particles generated at the Interaction Point
  - don't have good efficiency for LLP reconstruction

- Then, can we look for LLPs in ATLAS and CMS?



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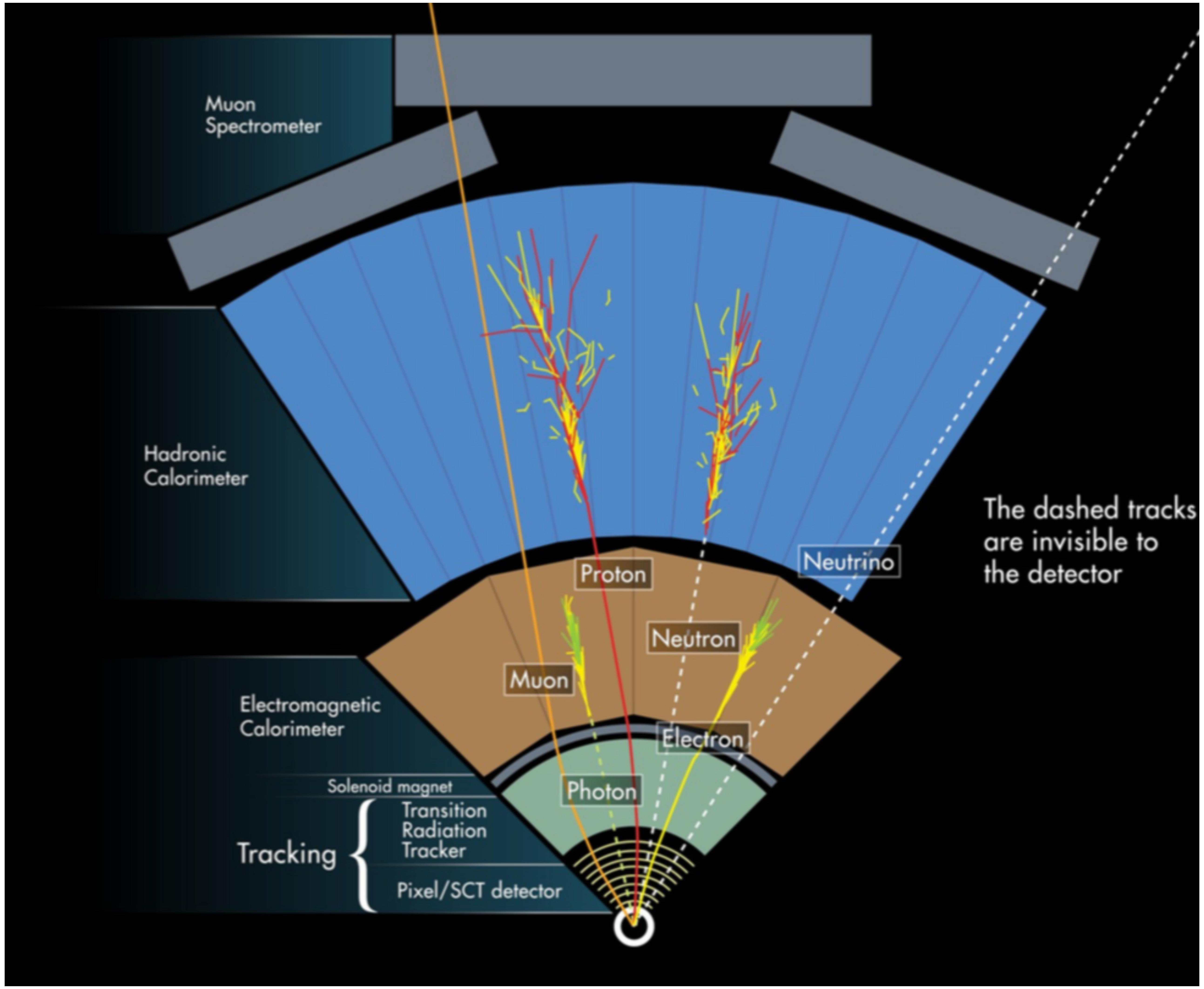

YES! But algorithms have to be adapted or invented!
Also moving to ML techniques for displaced objects identification

How can we look for LLPs in collider experiments?

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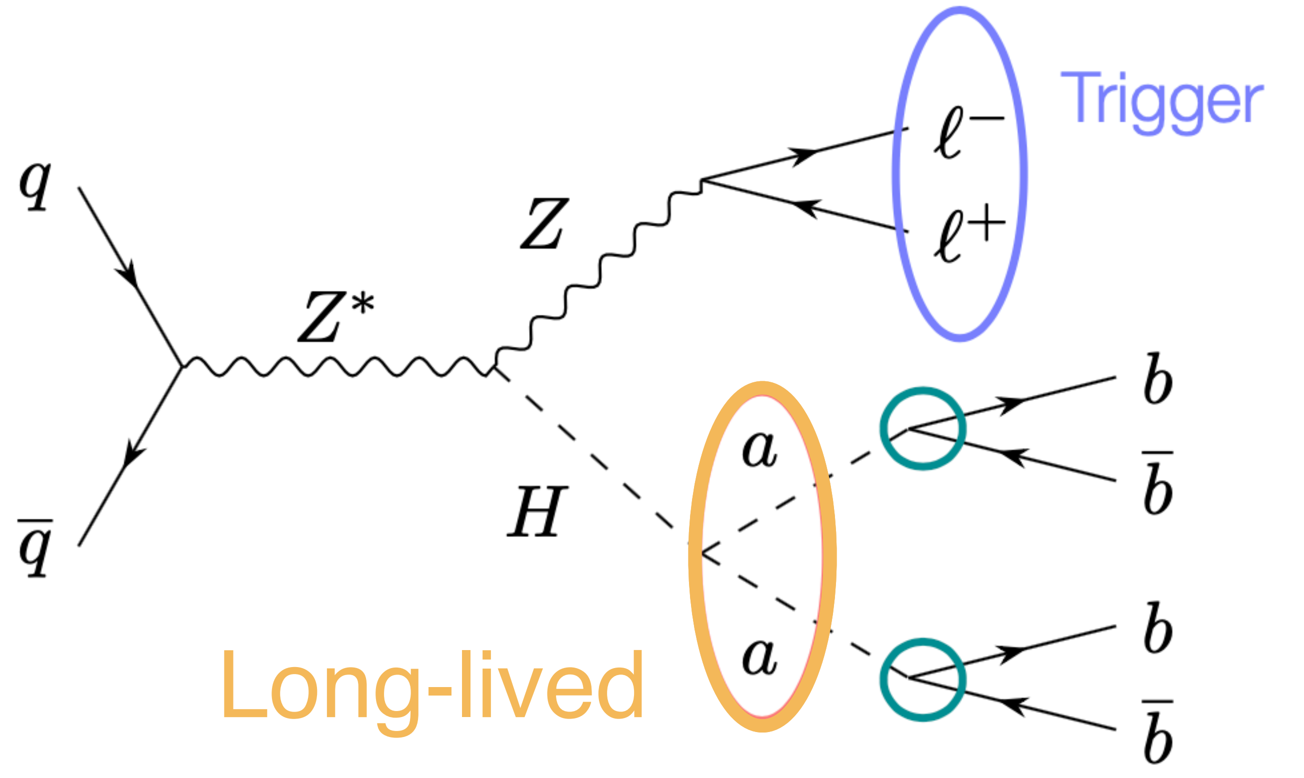
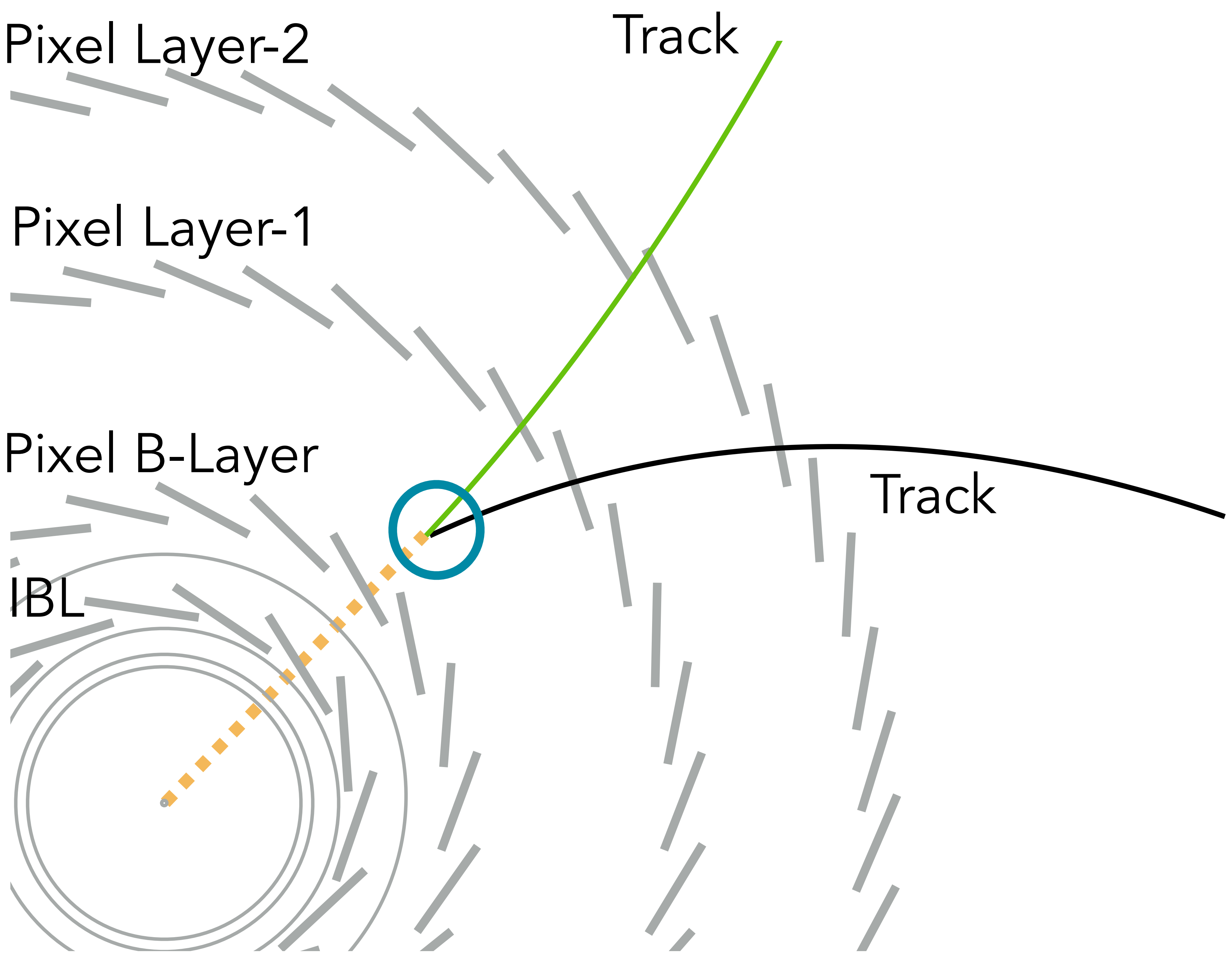
LLP lifetime | LLP nature | object identification

Example:
Large Radius Tracks (LRT)



- Standard tracking in ATLAS (similar in CMS) optimized for particles that point back to the interaction point with displacements of a few mm
  - tight requirements in number of silicon hits and impact parameter
  - would reject tracks from displaced decays



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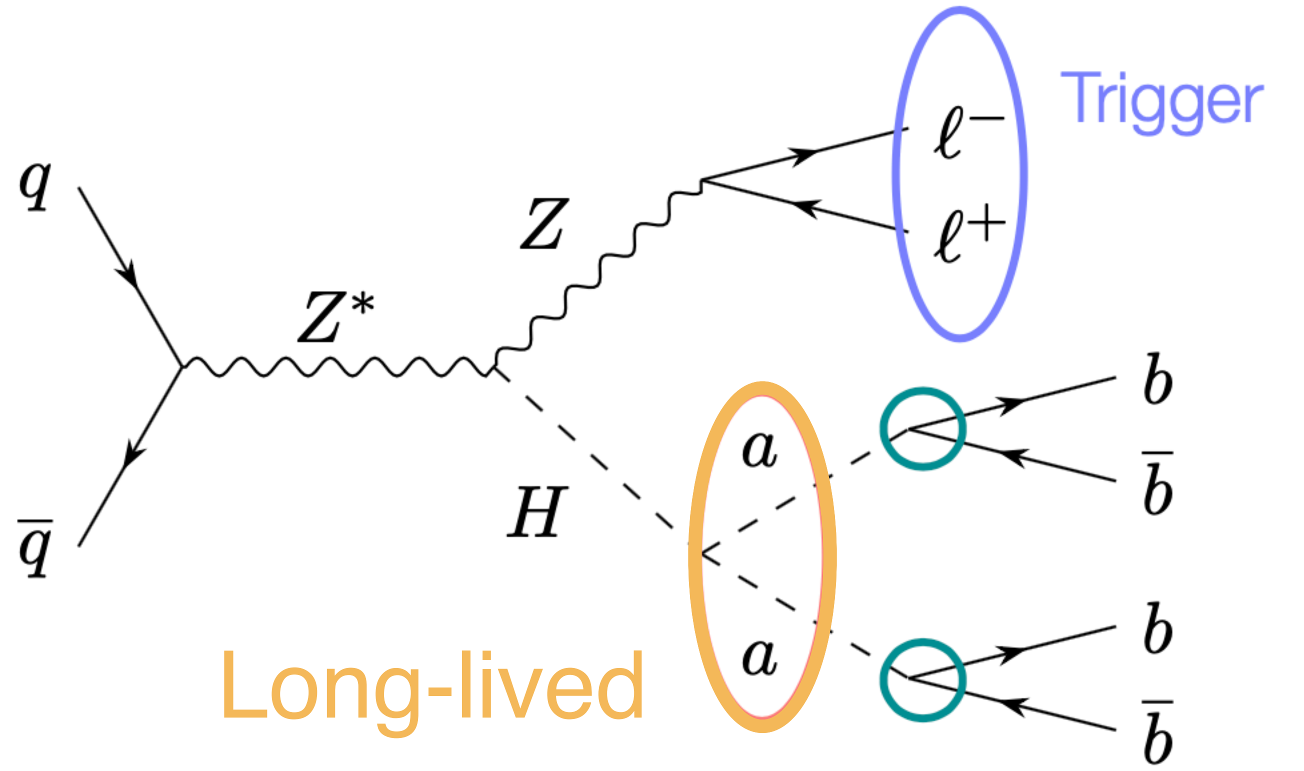

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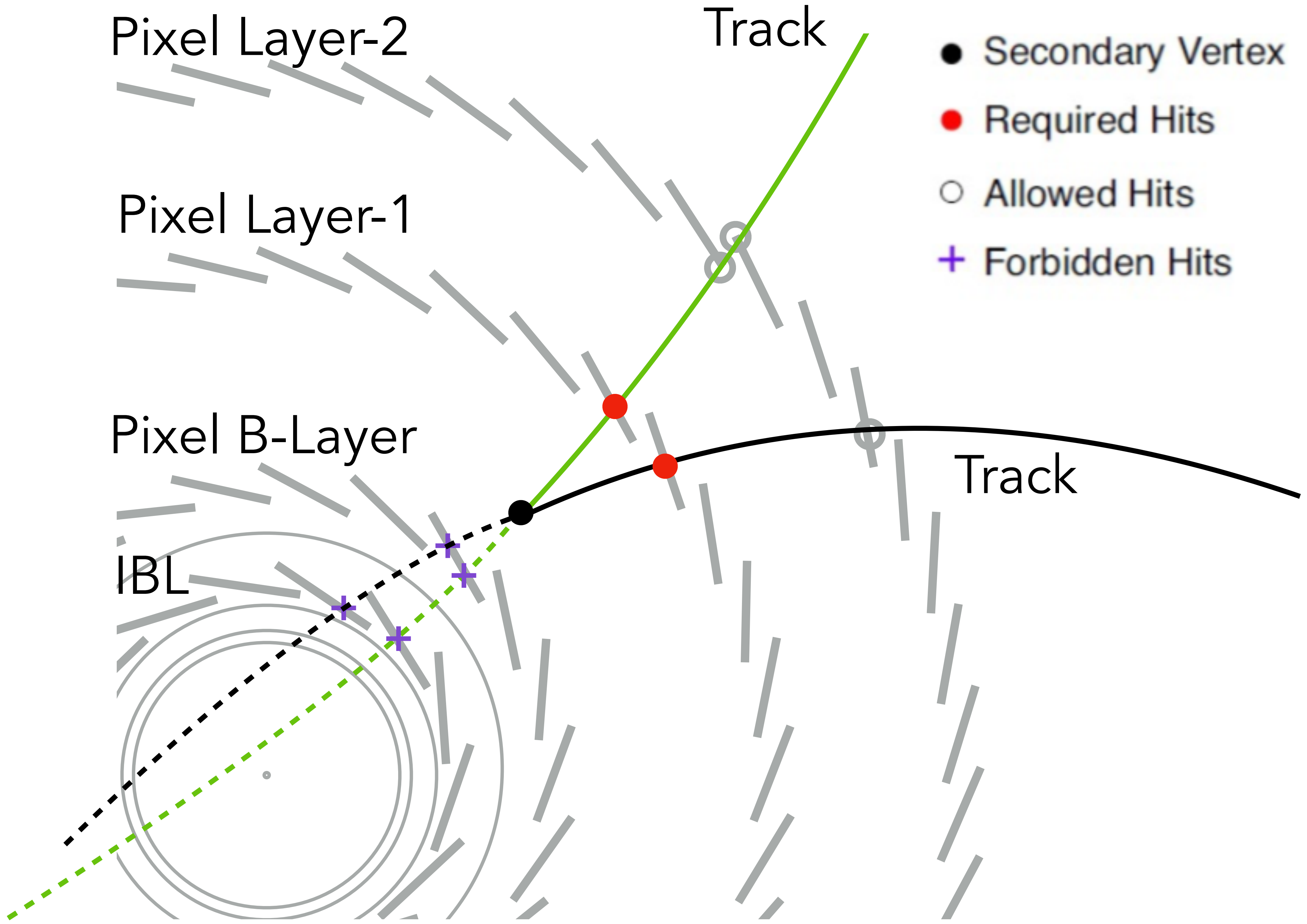

- Large radius tracking (LRT)
  - Relax requirements in number of silicon hits and impact parameter
  - Re-run only with hits not associated with existing tracks to form Displaced Vertices (DV)
- targets charged particles with displacements up to 300 mm improving acceptance for long-lived particles

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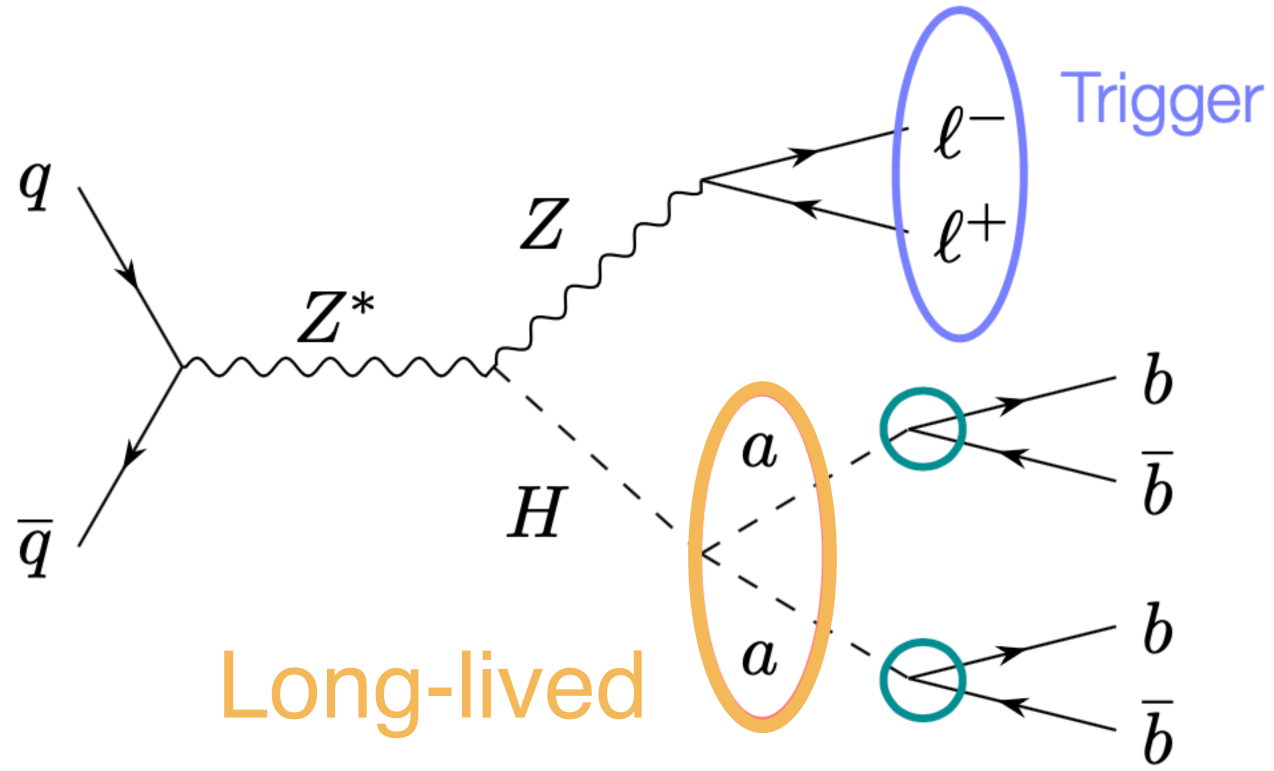

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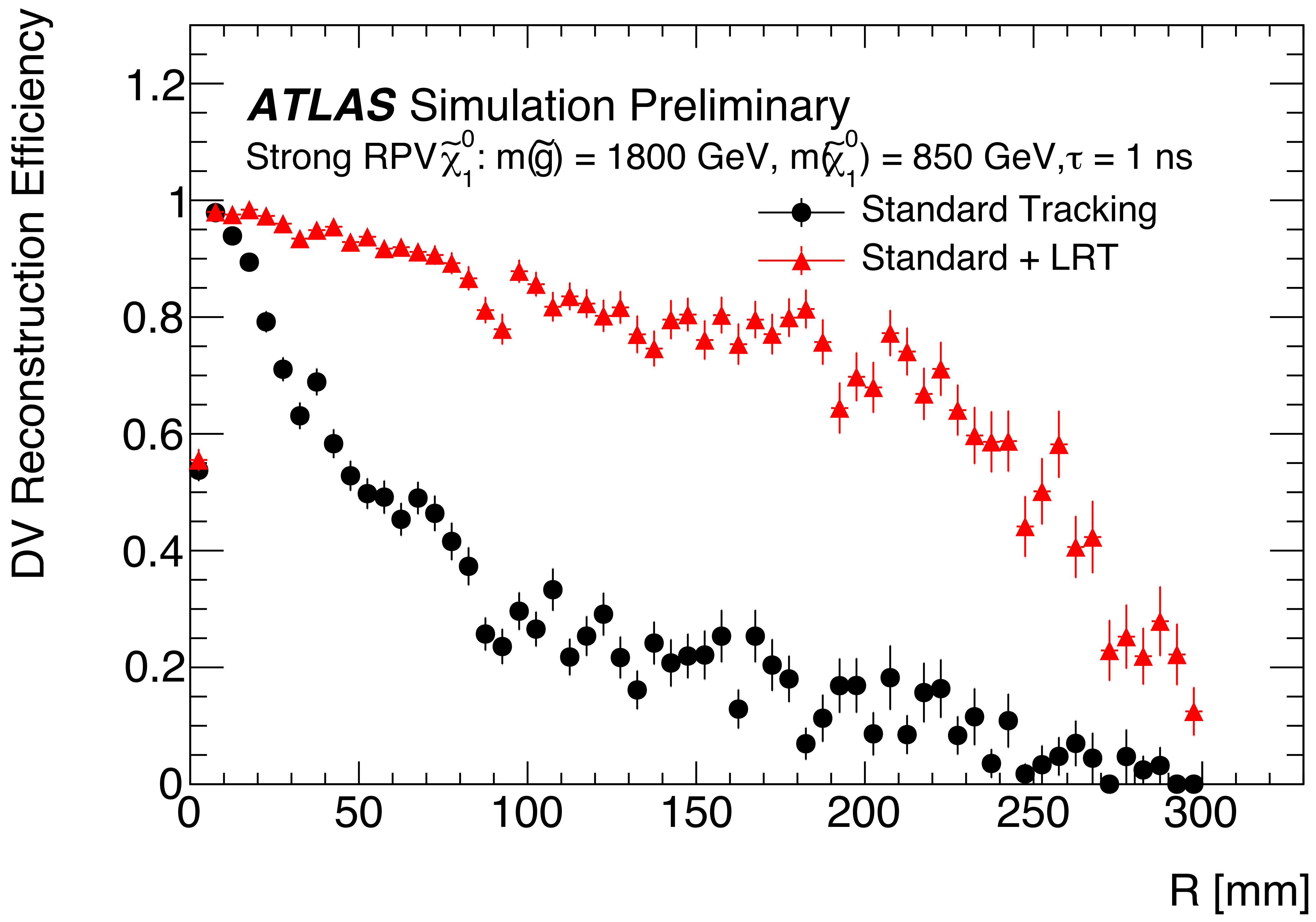


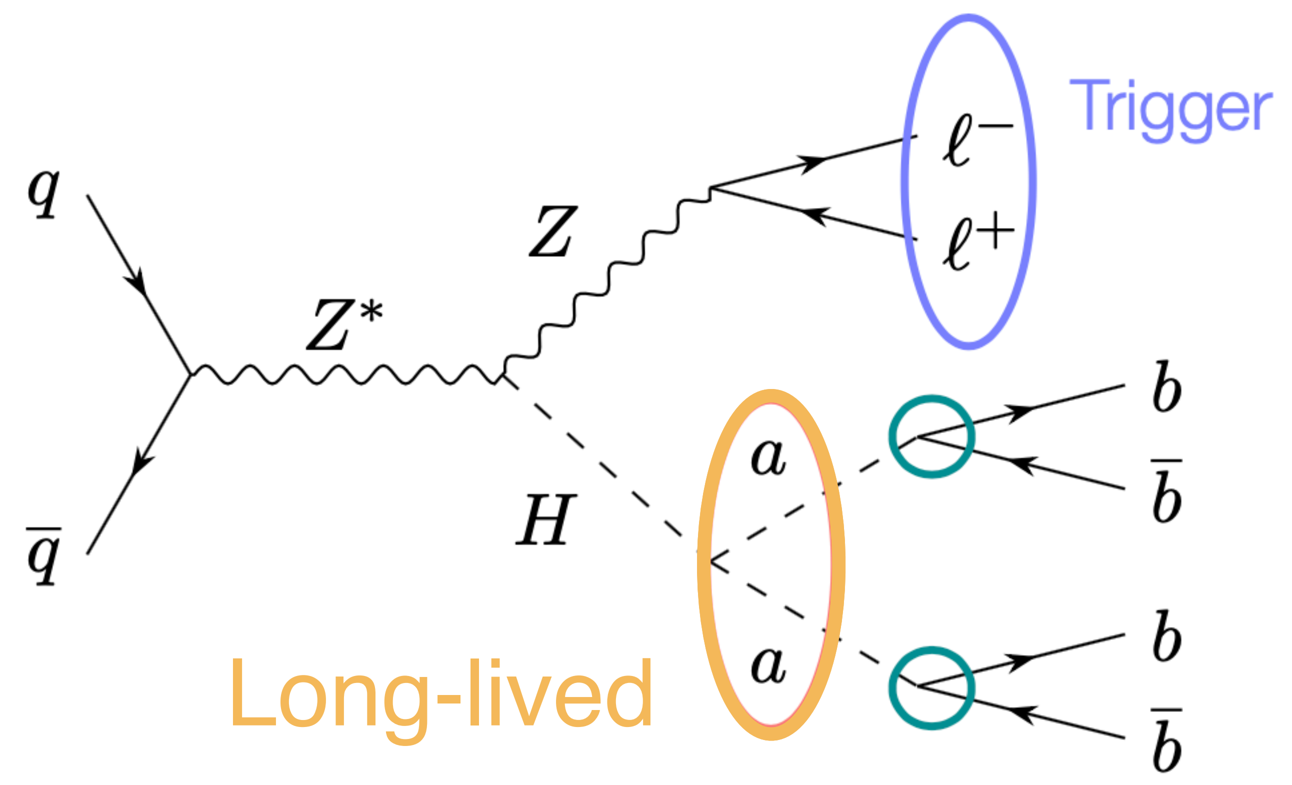
How can we look for LLPs in collider experiments?

That depends on:

LLP lifetime | LLP nature | object identification | trigger

- Trigger: combination of hardware + software that must decide very quickly whether to save an event or lose it forever
- Depending on the model:
    - Rely on additional SM-like activity

      (e, mu, jet, MET triggers)



Standard lepton triggers

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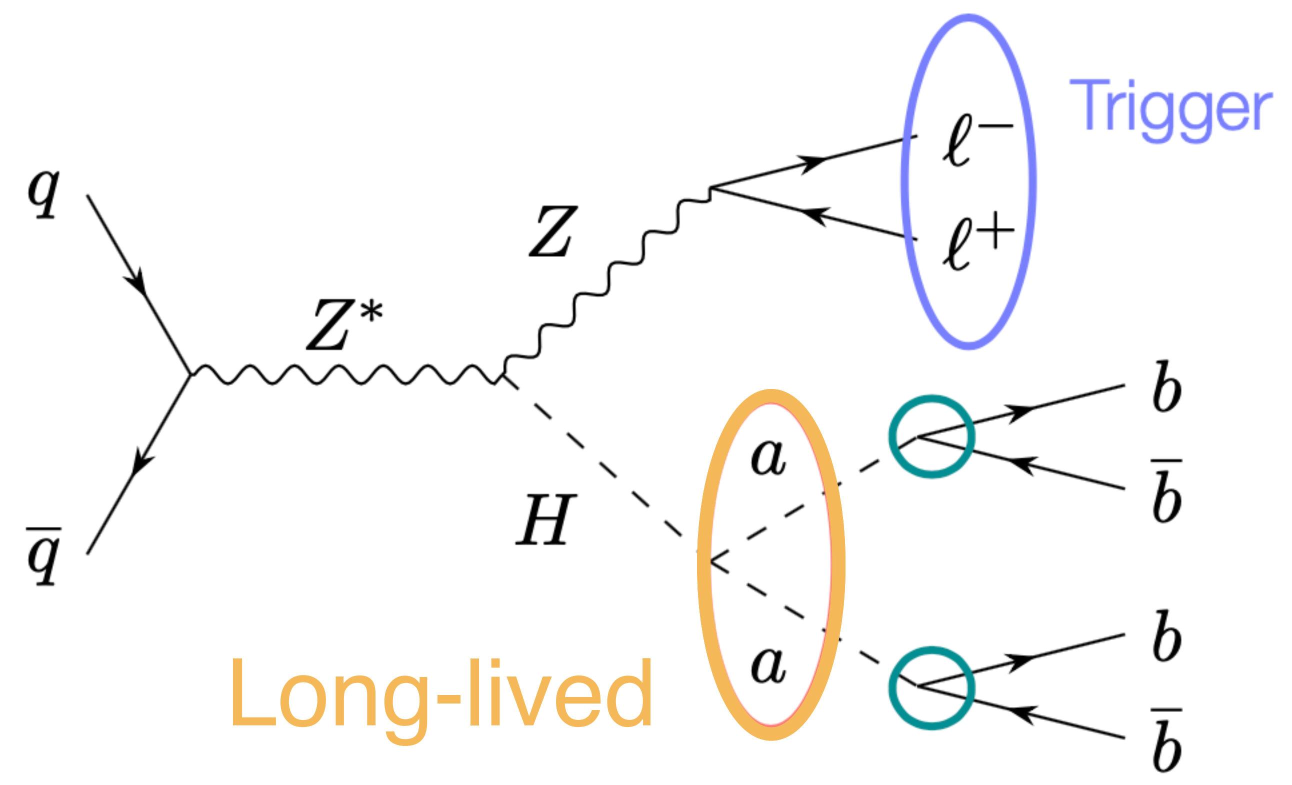

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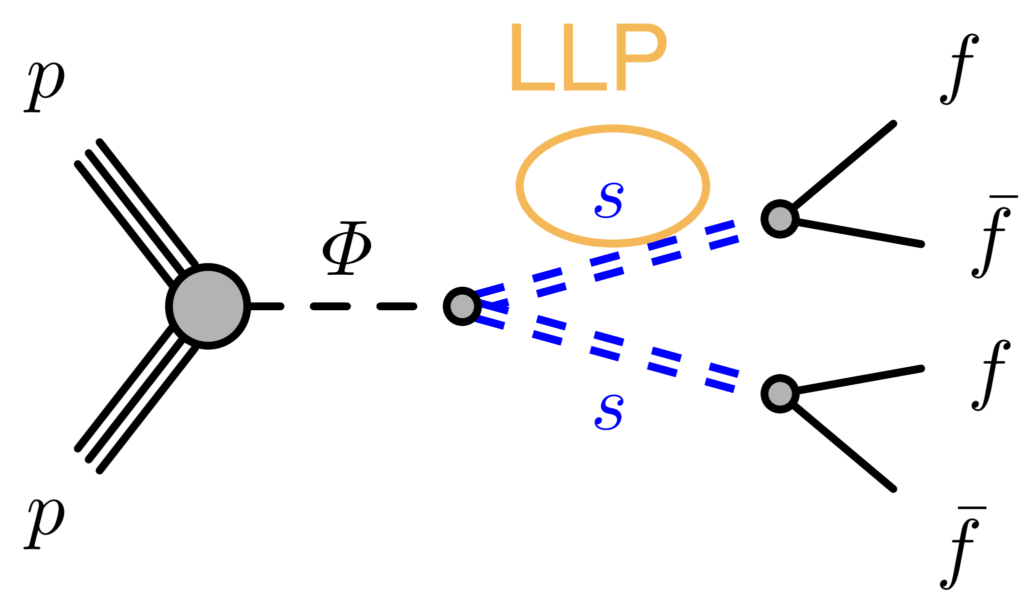

But what if there's no prompt

activity in the event??

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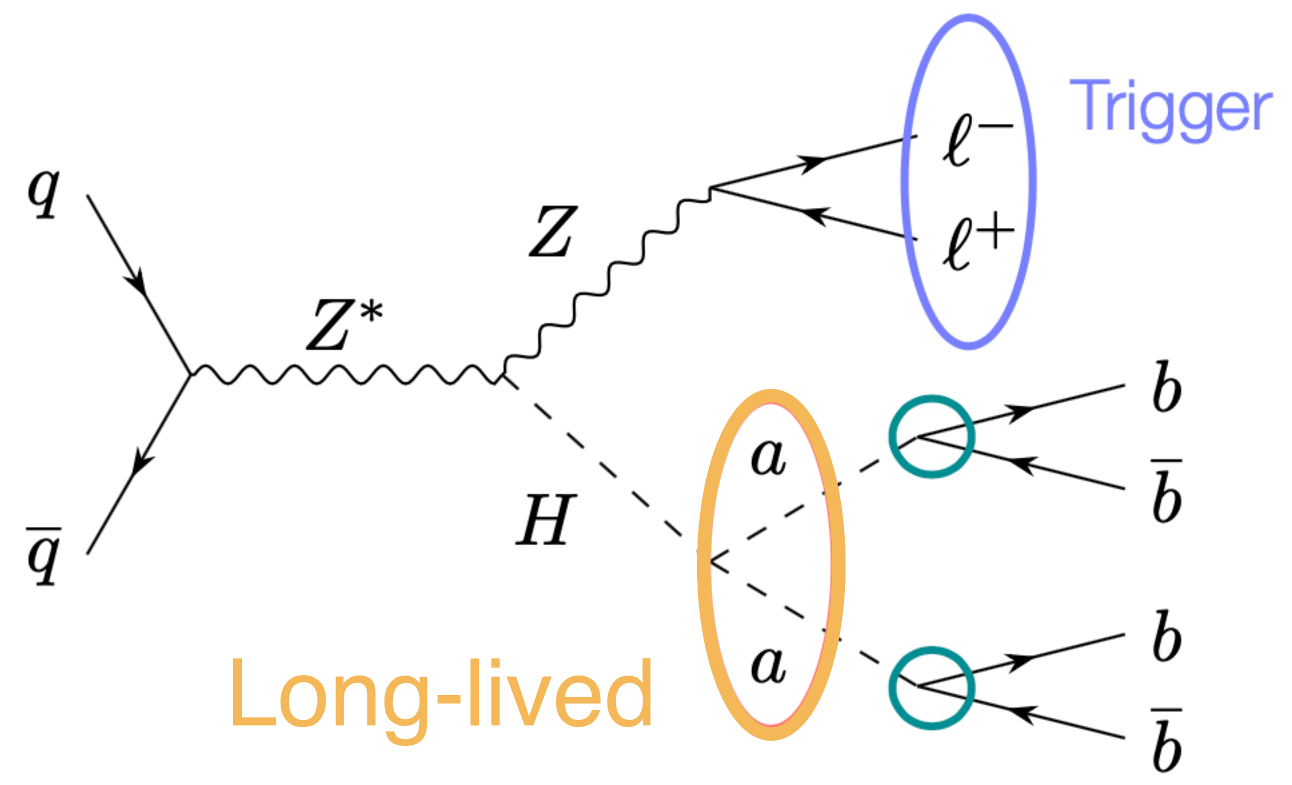
  - Develop dedicated triggers exploiting specific features



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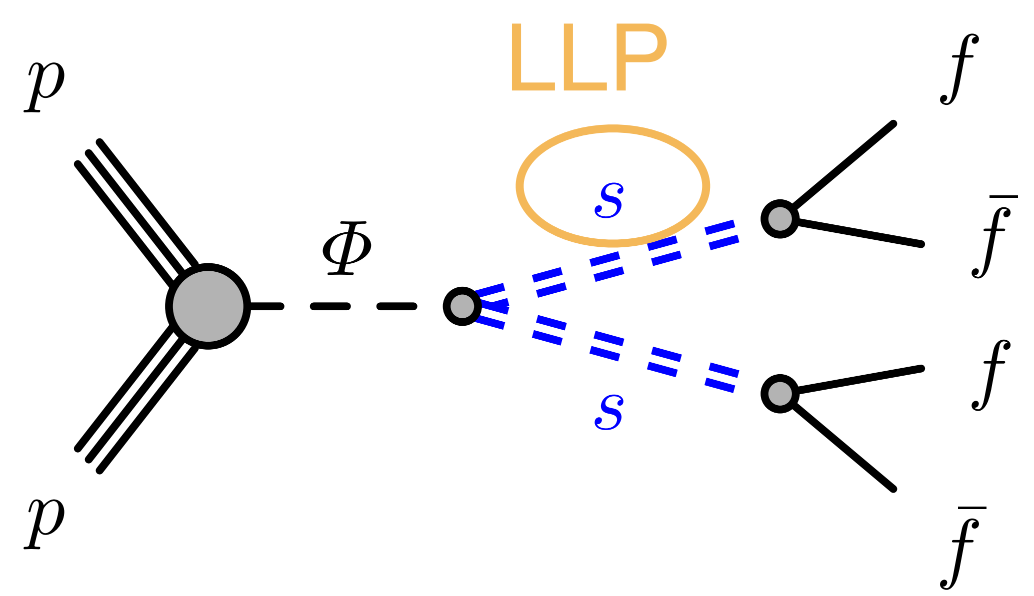

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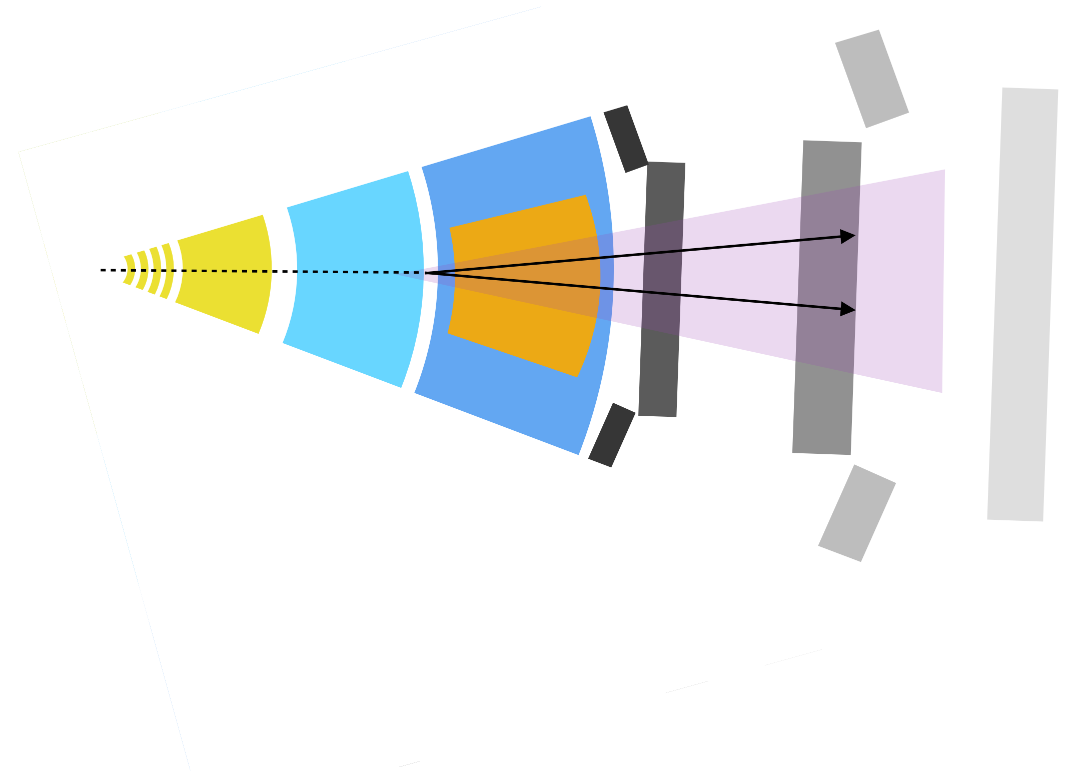

Dedicated trigger requires a jet with no ID tracks and most energy in the HCal

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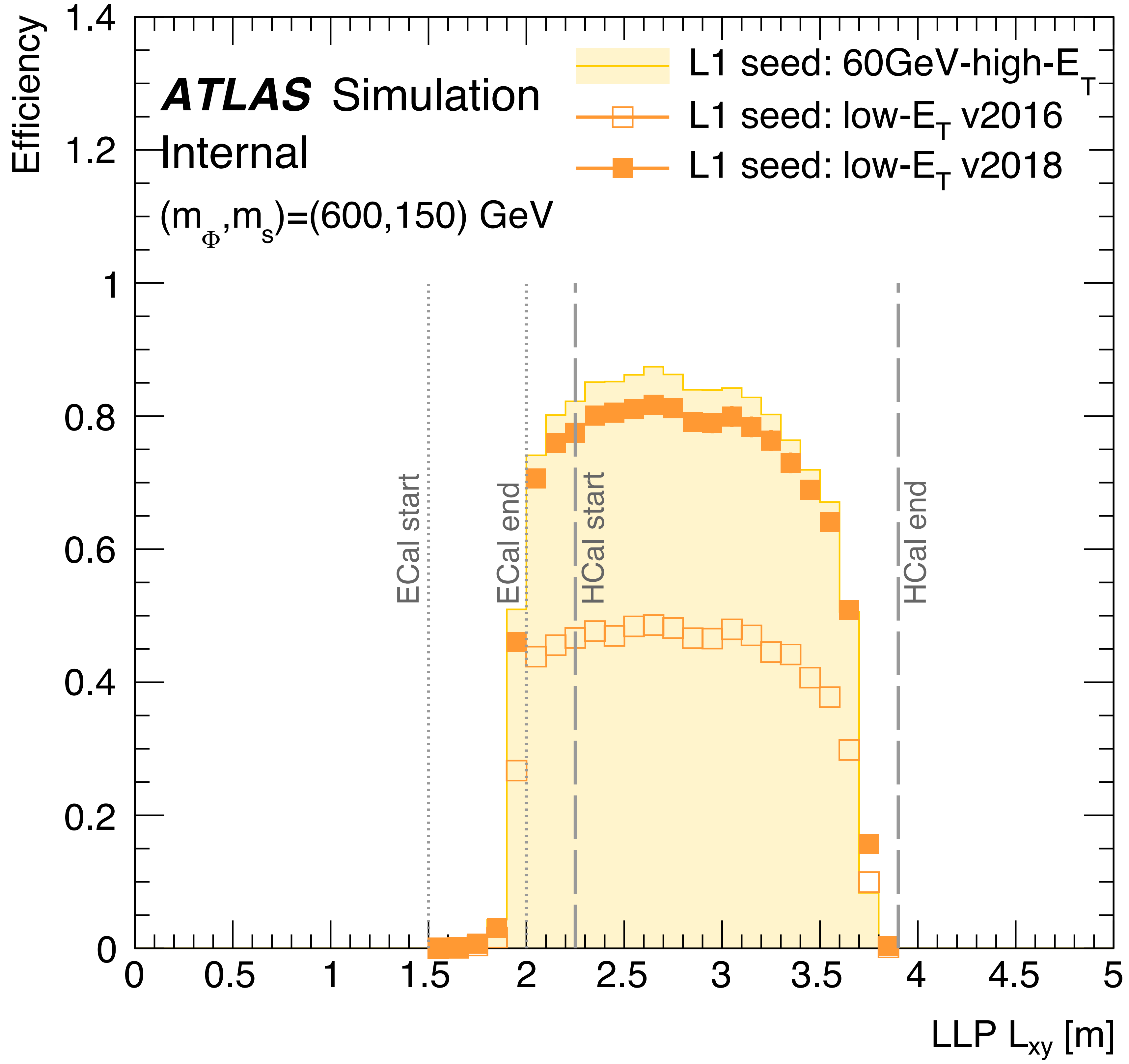

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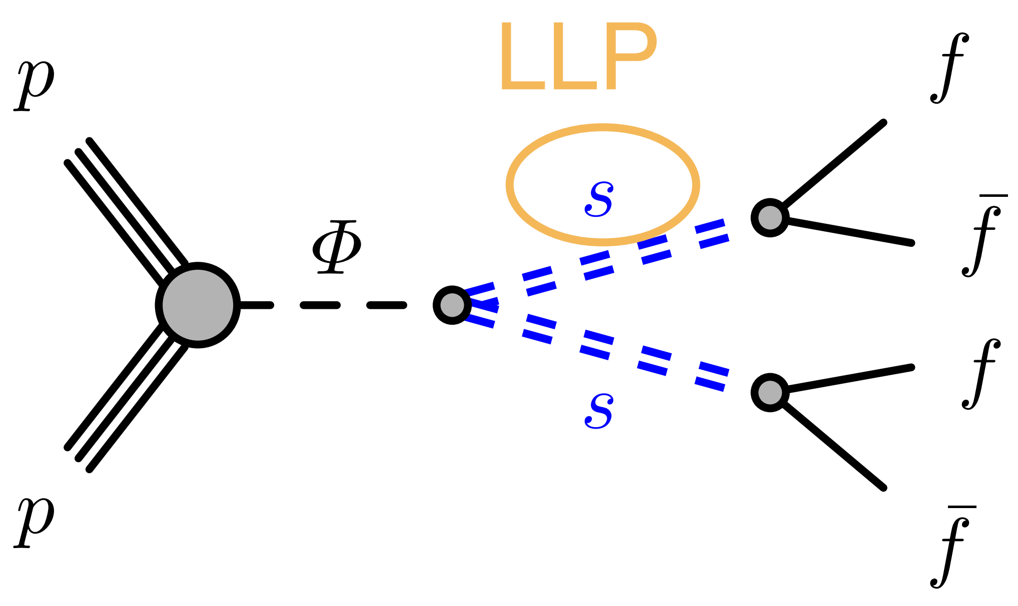

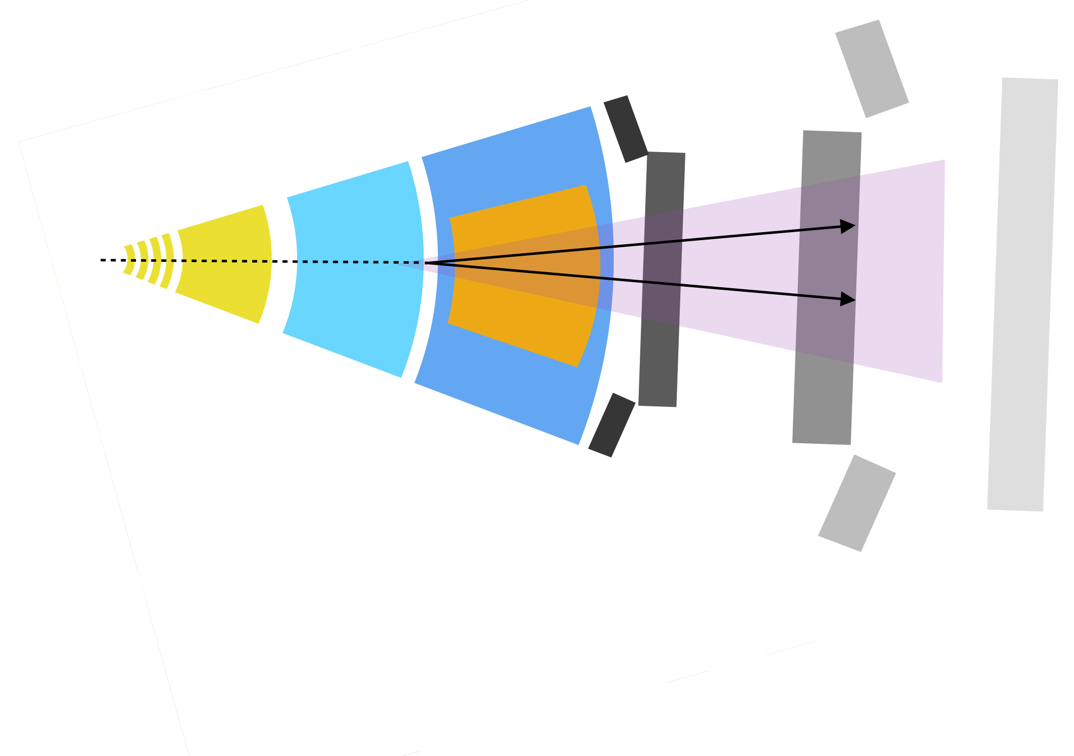

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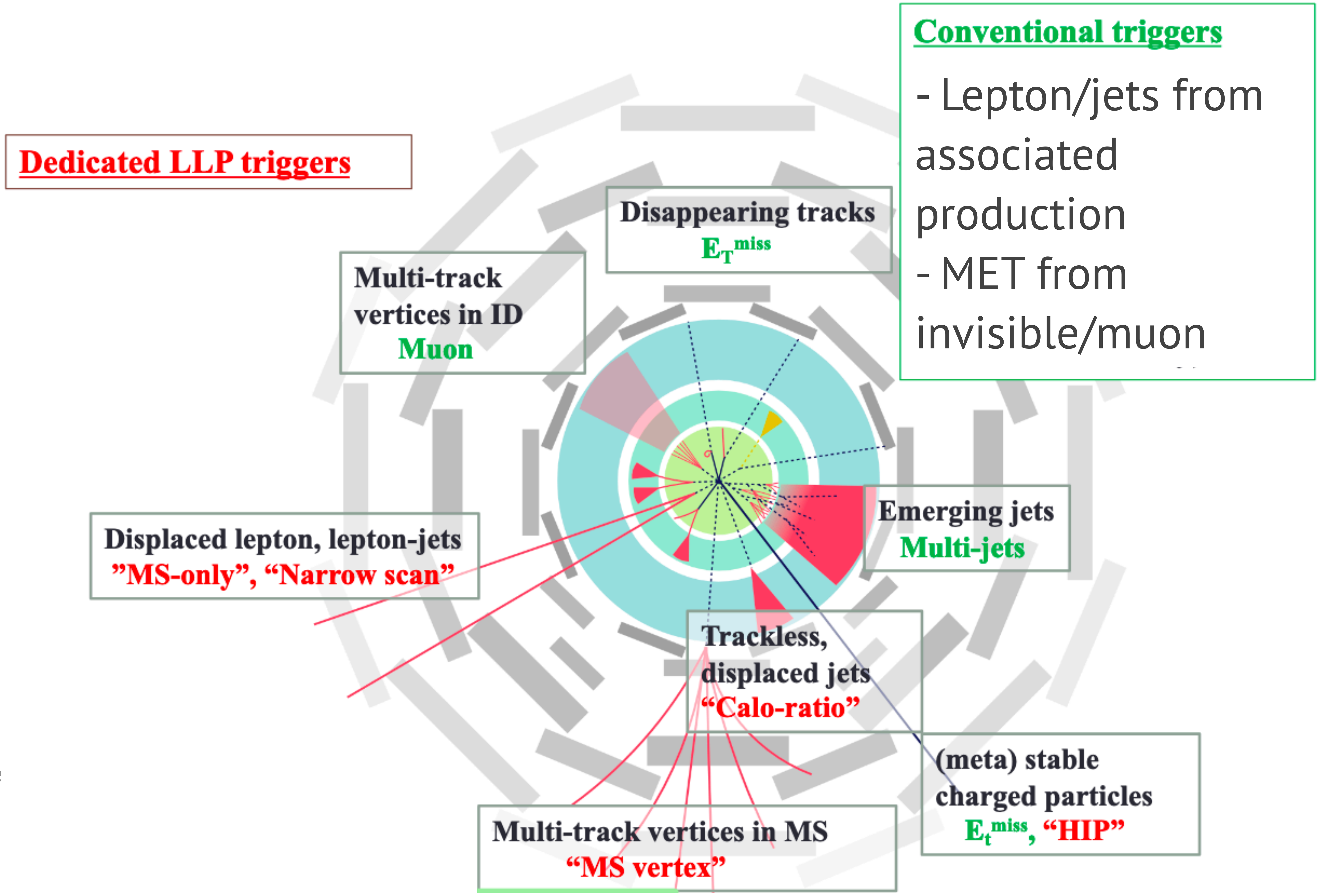


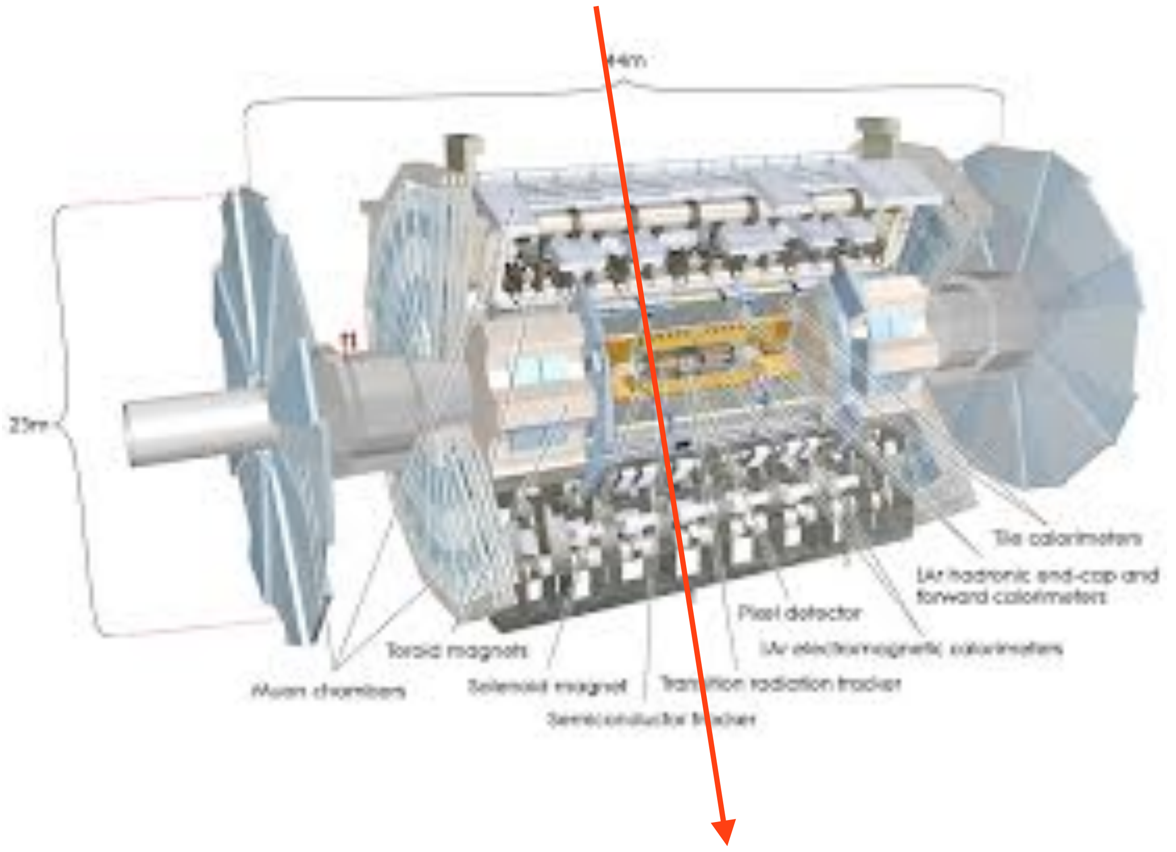
How can we look for LLPs in collider experiments?

That depends on:

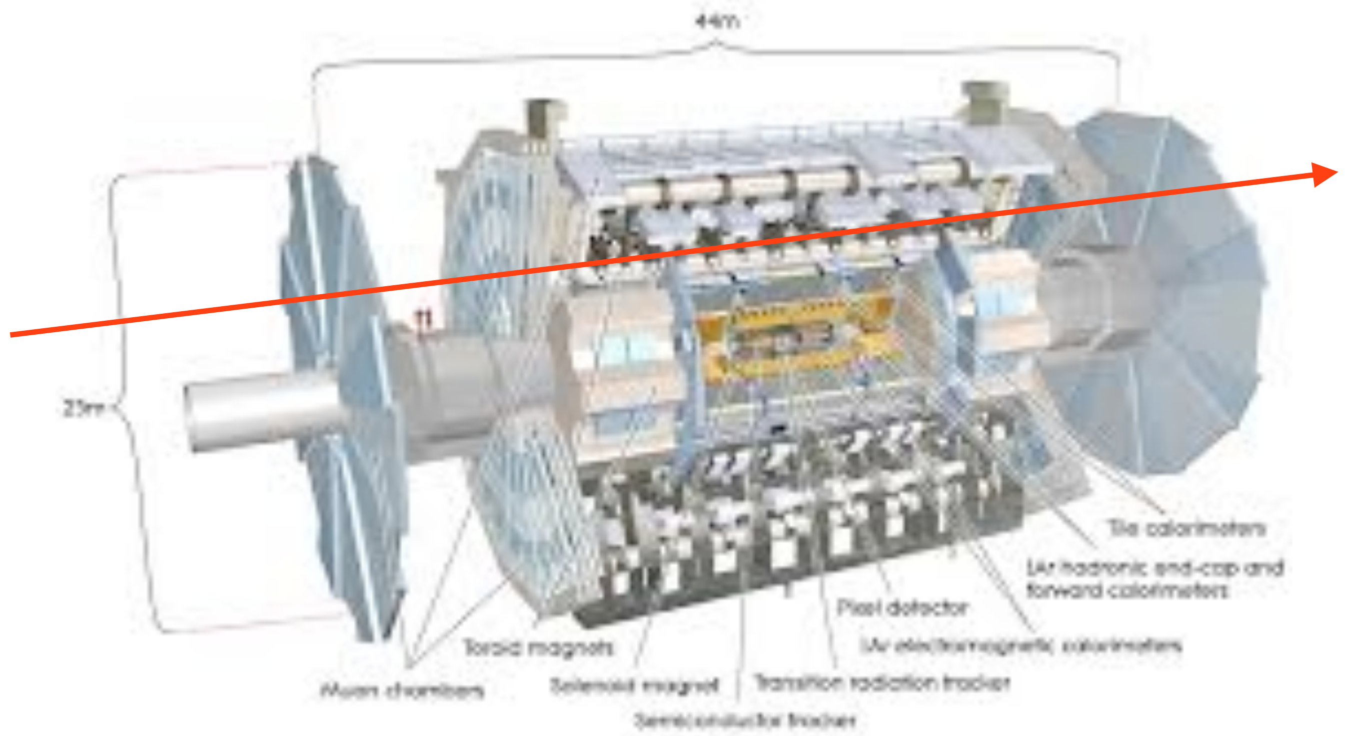
LLP lifetime | LLP nature | object identification | trigger | background rejection

- Small or unusual backgrounds play a key role:

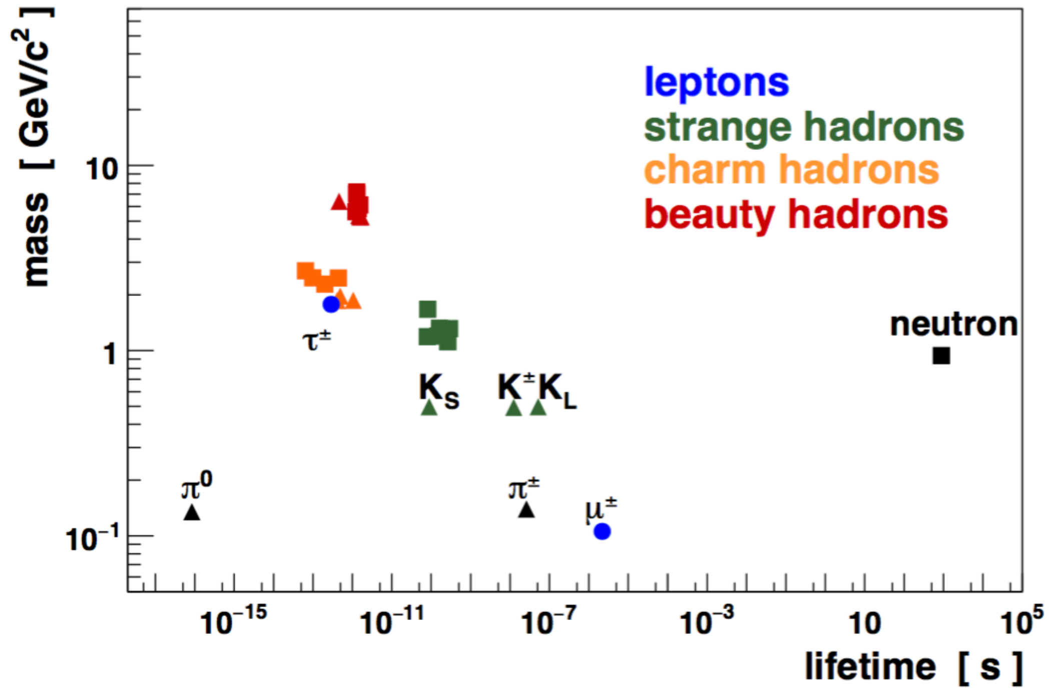
cosmic muons



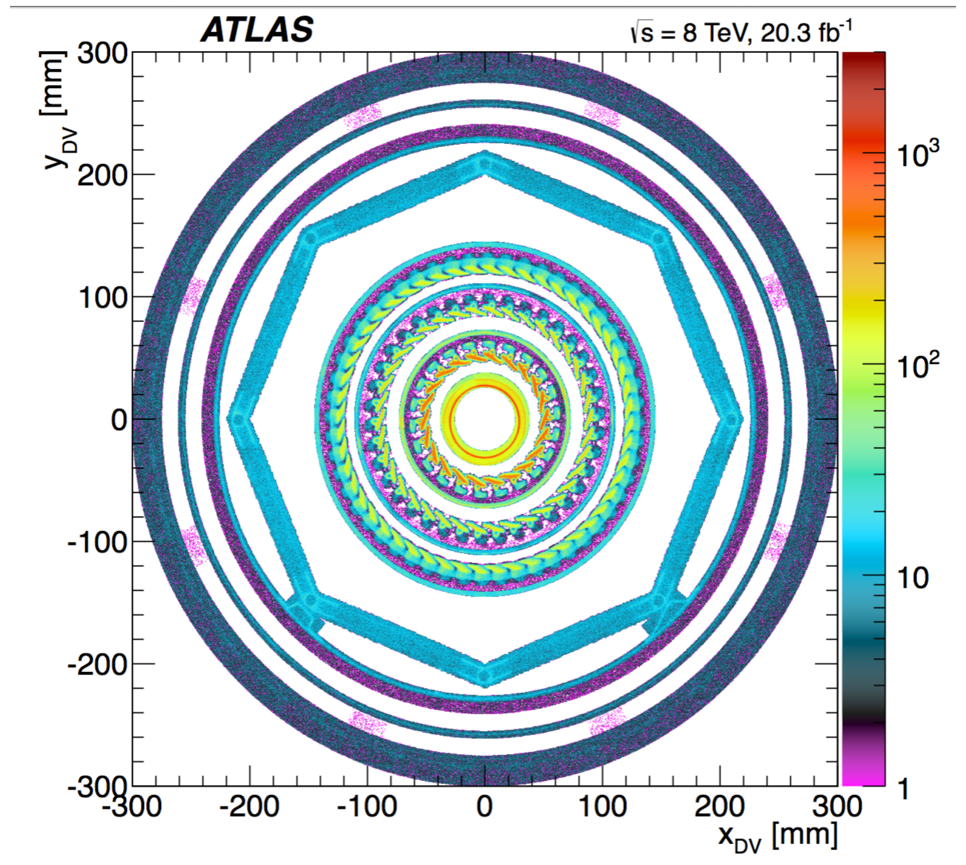
beam halo muons



SM particles with relatively long lifetime



material interactions



- For most of them, no good simulations
  - All searches rely on data-driven methods

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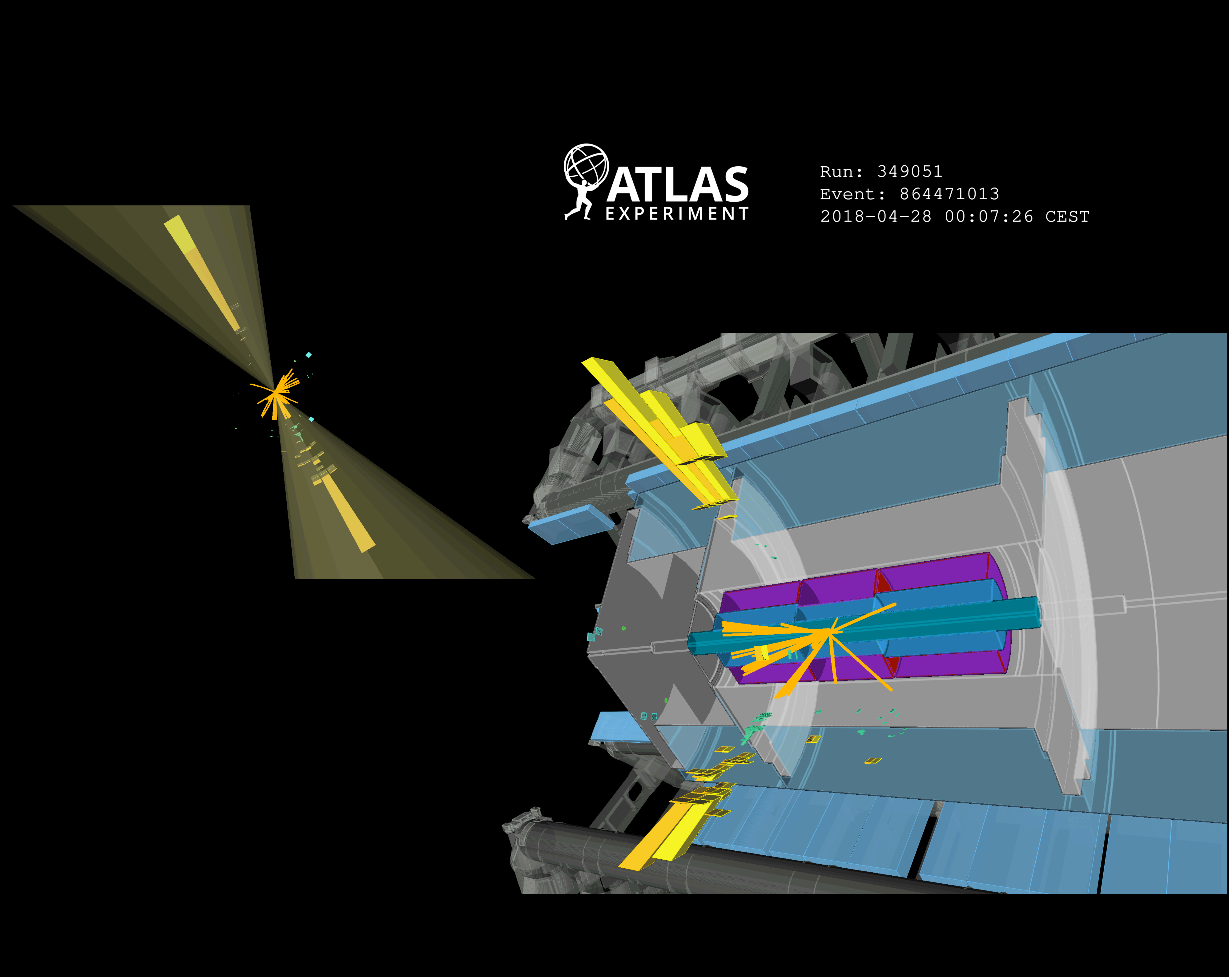
Systematics!!!

- Algorithms developed specifically for each analysis. Can't use ATLAS/CMS common recommendations for object reconstruction nor trigger

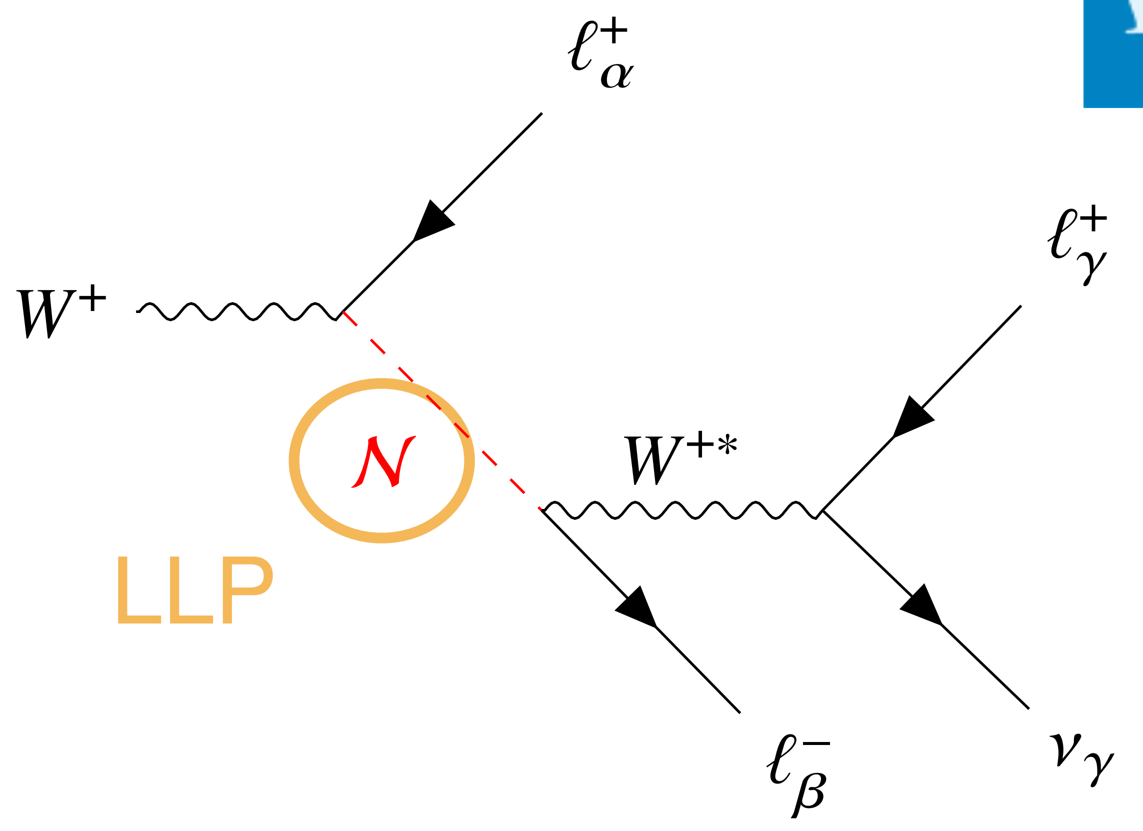


Examples of some unconvention al searches in LHCb, CMS, ATLAS

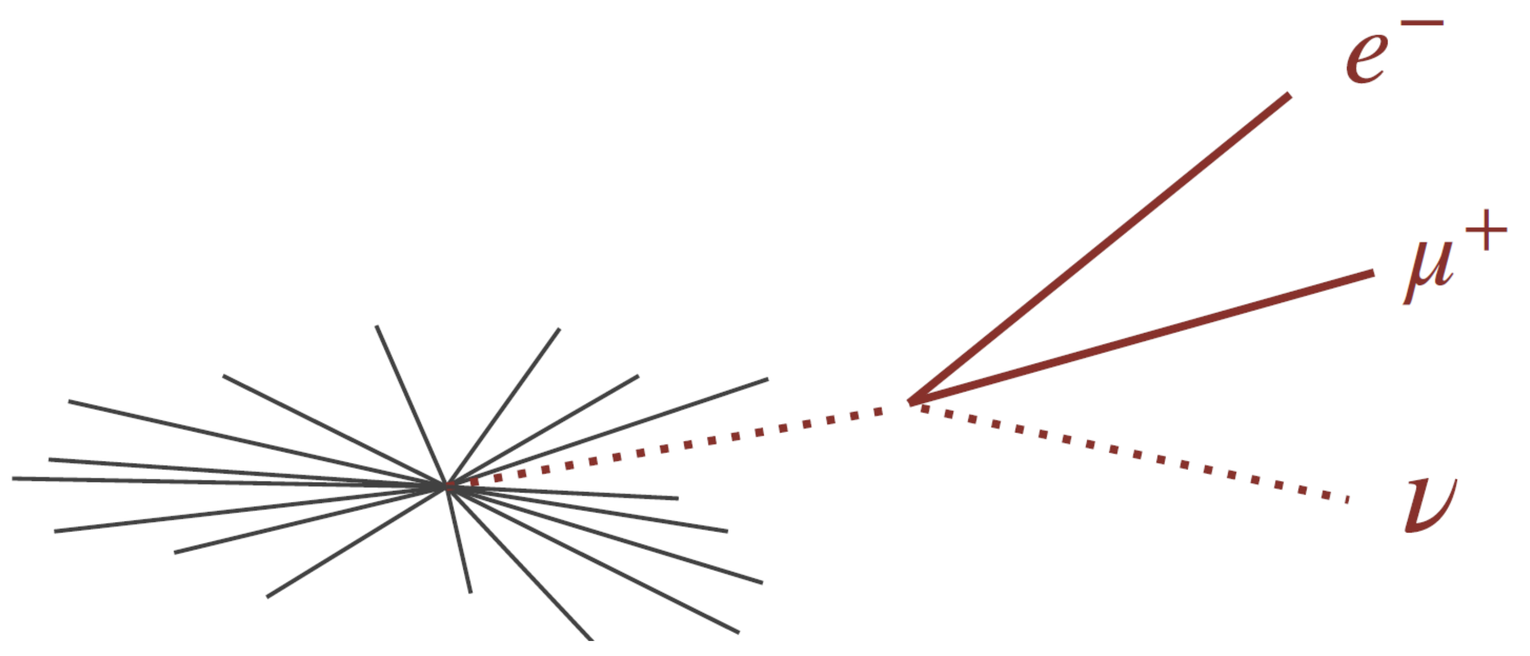
LLP decays in the ID - unconventional tracking

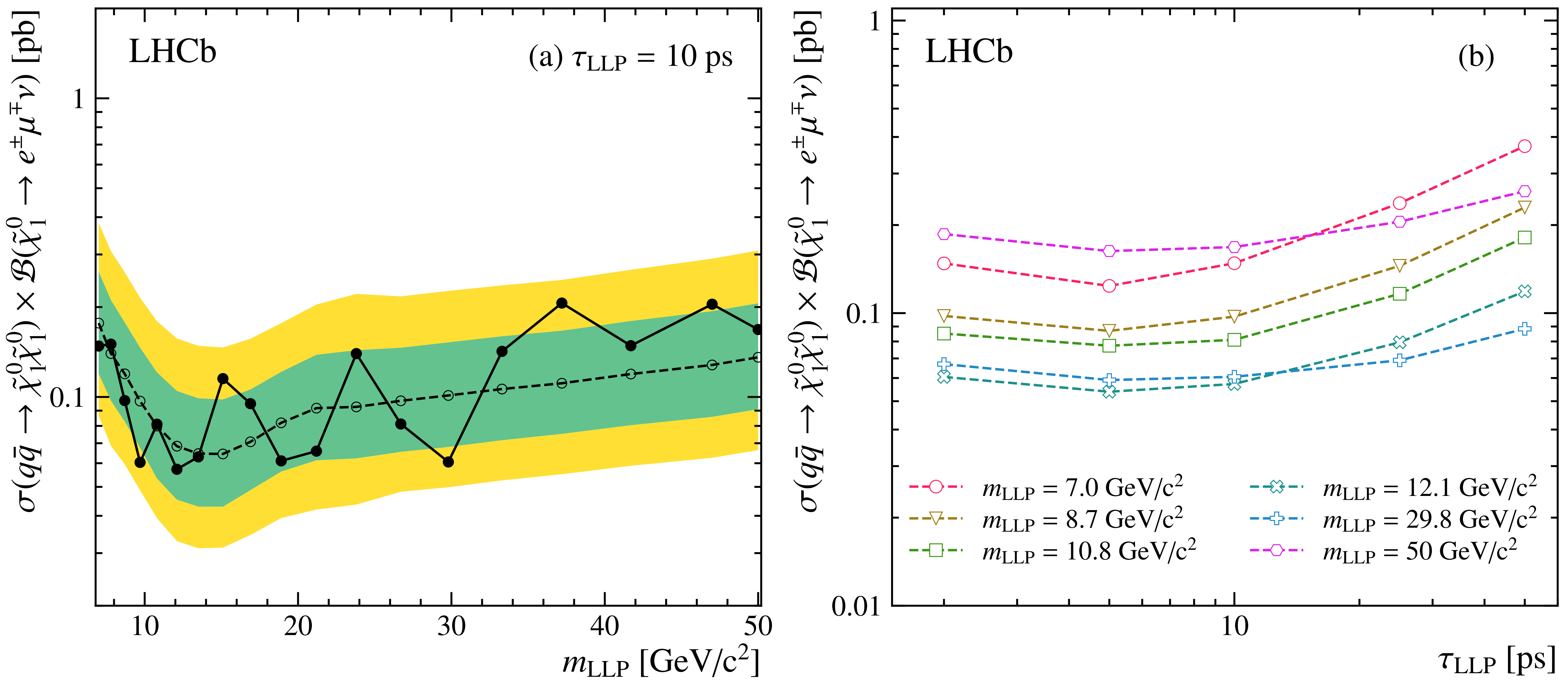
Single displaced vertex

Eur. Phys. J. C81 (2021) 261



- Search for single LLP decaying to e±μ∓ν,
  - Example, LLP can be neutralino (RPV) or HNL
- Search for displaced vertices with opposite sign e and μ
  - lifetimes between 2 and 50 ps
  - masses between 7 and 50 GeV
- Probes forward region (not covered by ATLAS and CMS)



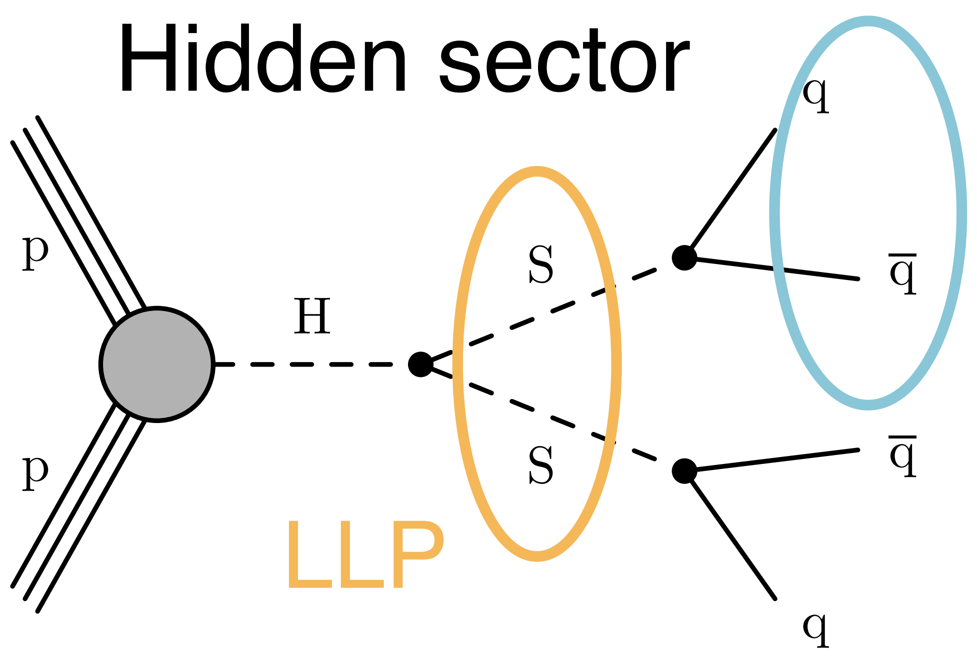


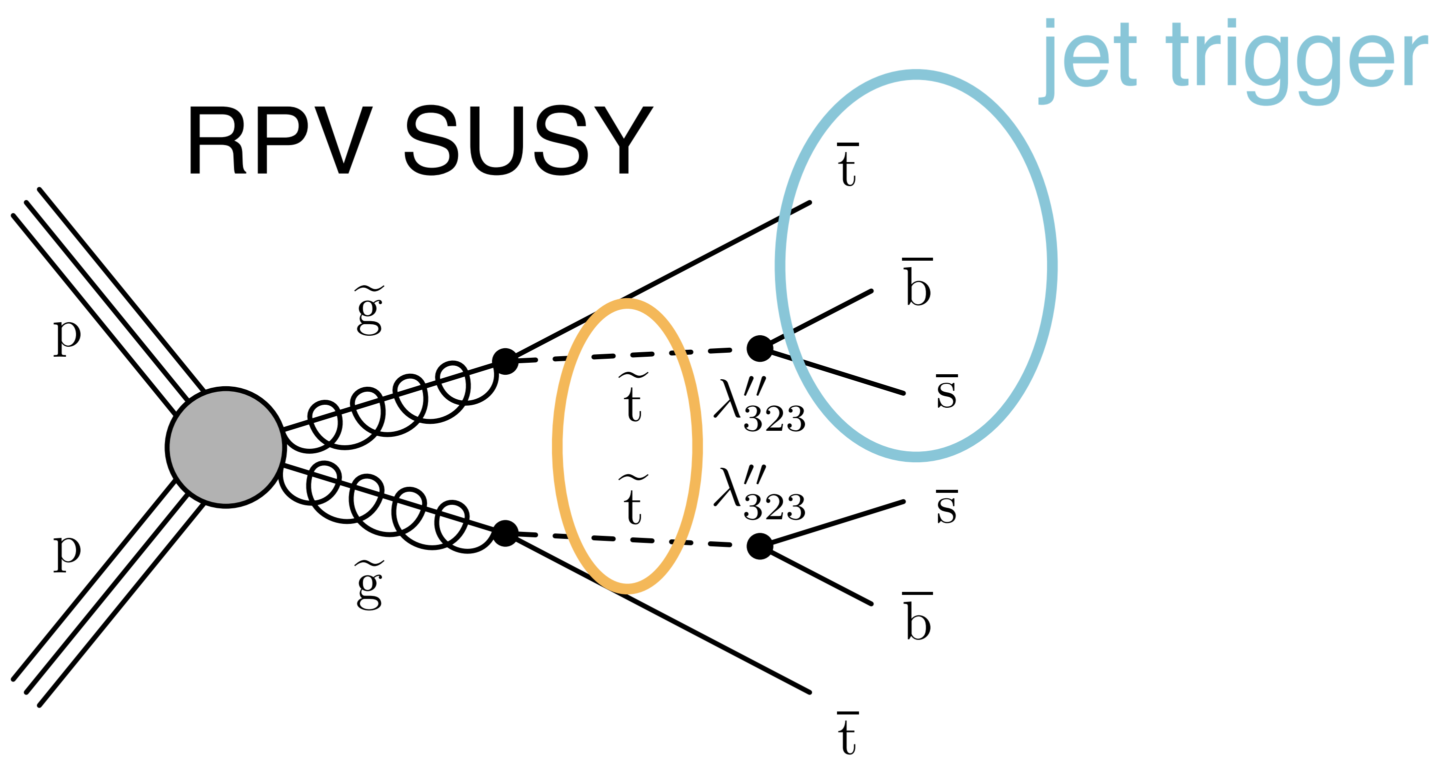
- Exclusion of lifetimes ~10 ps ($c\tau$ ~ 0.1 mm)

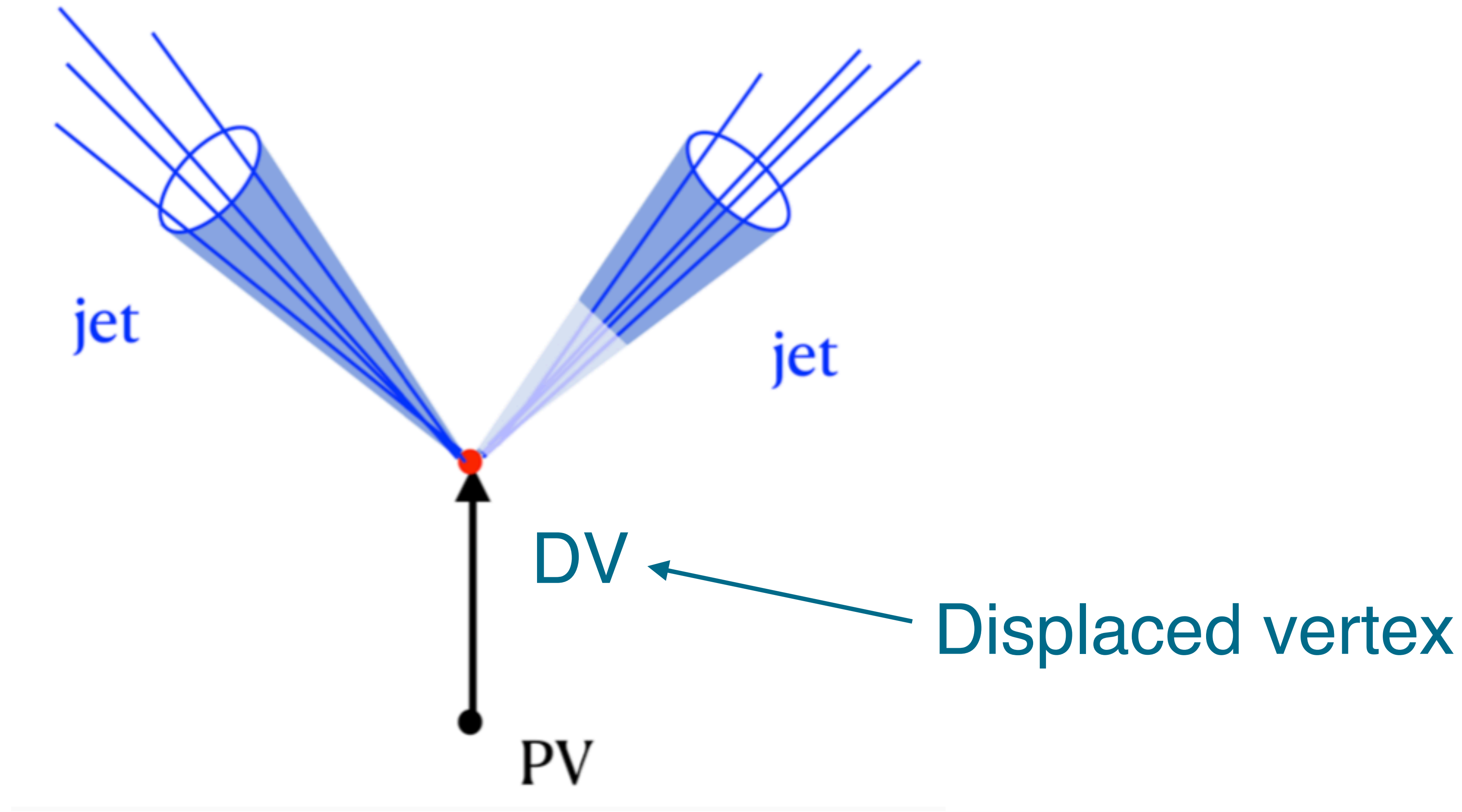
LLP decays in the ID - unconventional tracking

Pairs of displaced vertices

CMS-PAS-EXO-19-021



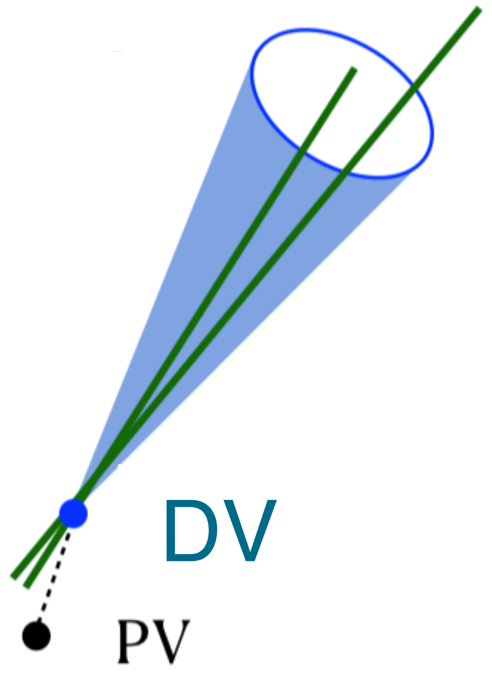




- Dedicated di-jet trigger
- Select dijet events and look for displaced vertex (DV) within them
- Select events with at least 1 DV
- MVA selection to discriminate signal from huge QCD background
- Minor backgrounds from heavy flavour decays and random track crossing

CMS high-level trigger

select displaced tracks online and tag displaced-jets with the HLT system by counting the number of prompt/displaced tracks associated with the jets



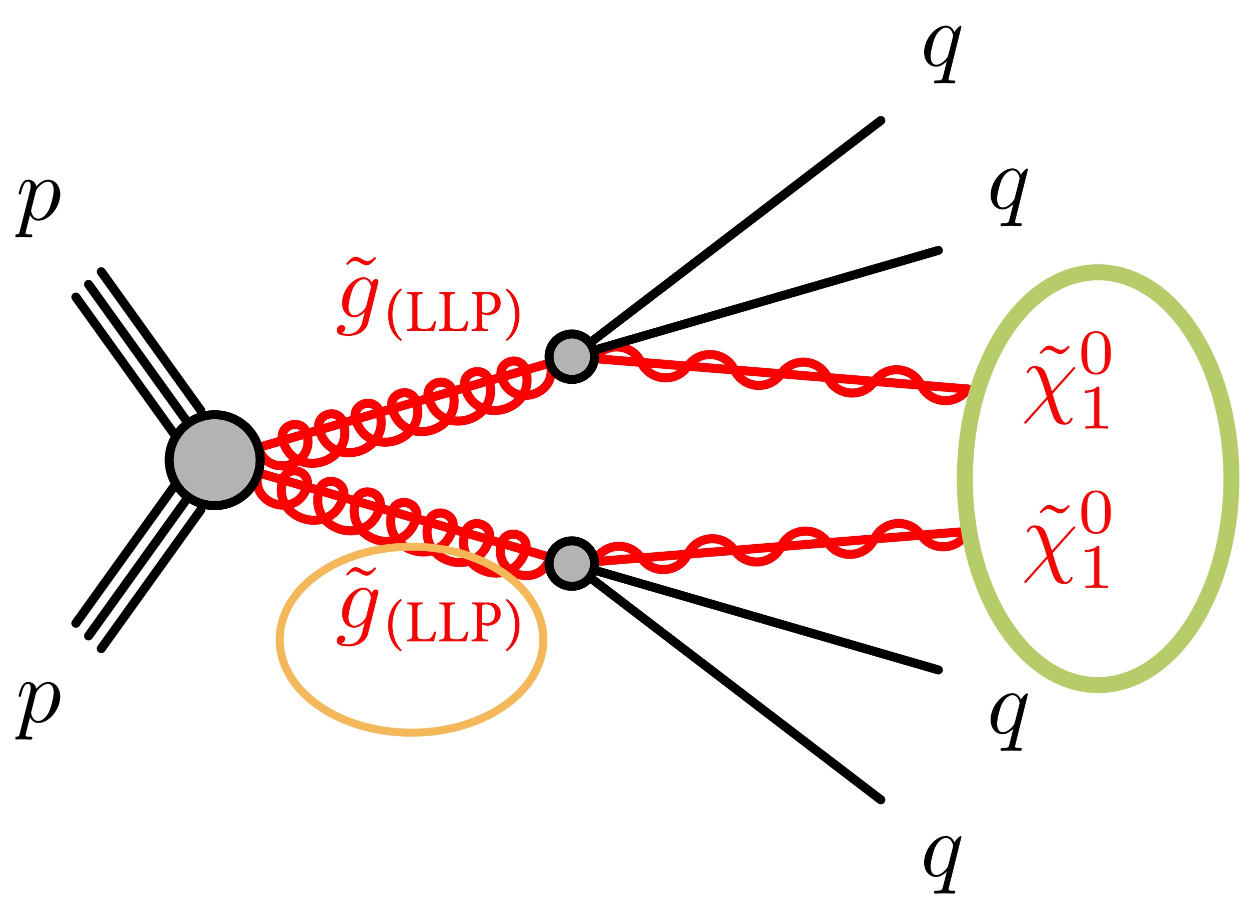
- Exclusion of $c\tau$ between 10 and 100 mm

Charged LLPs

Large dE/dx

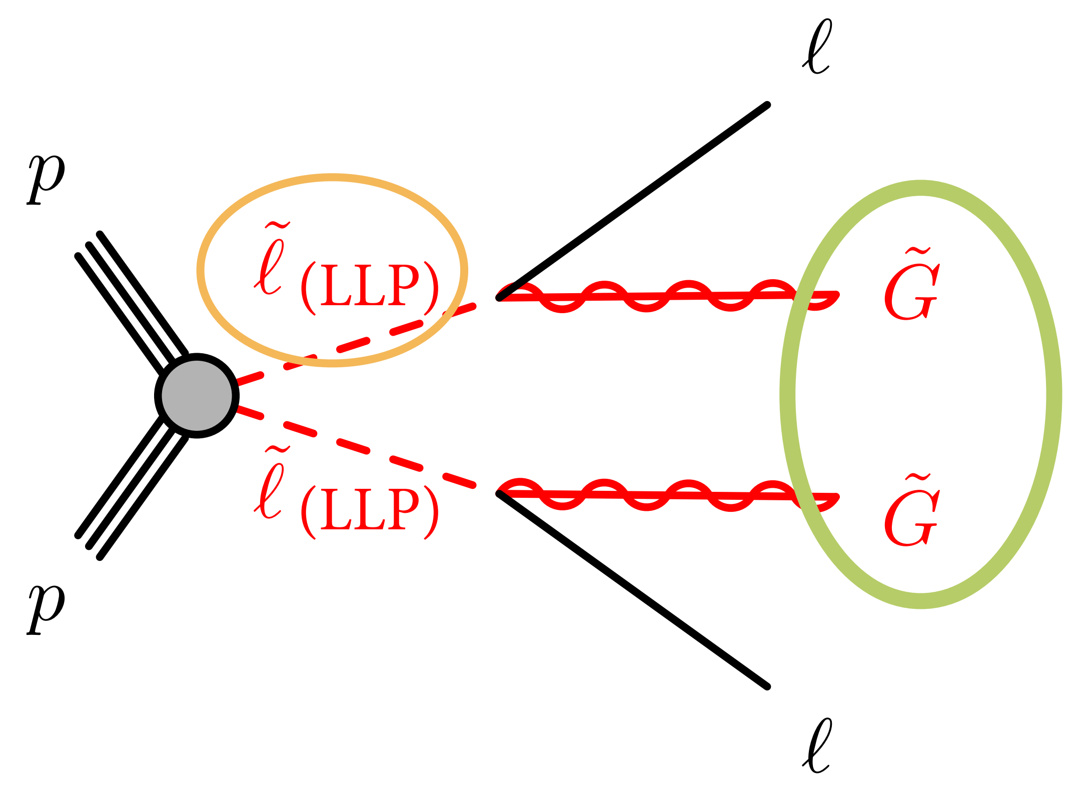
[2205.06013](2205.06013)

- Pair production of several different long-lived sparticles of charge $|q|$ = 1
  - isolated tracks with high transverse momenta (pT) and anomalously large specific ionisation losses (dE/dx)
  - particles are expected to move significantly slower than the speed of light
  - Use MET triggers
  - Fully data-driven background estimation!



High pT track with large dE/dx

LSP = MET



Charged LLPs
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[2205.06013](https://arxiv.org/abs/2205.06013)

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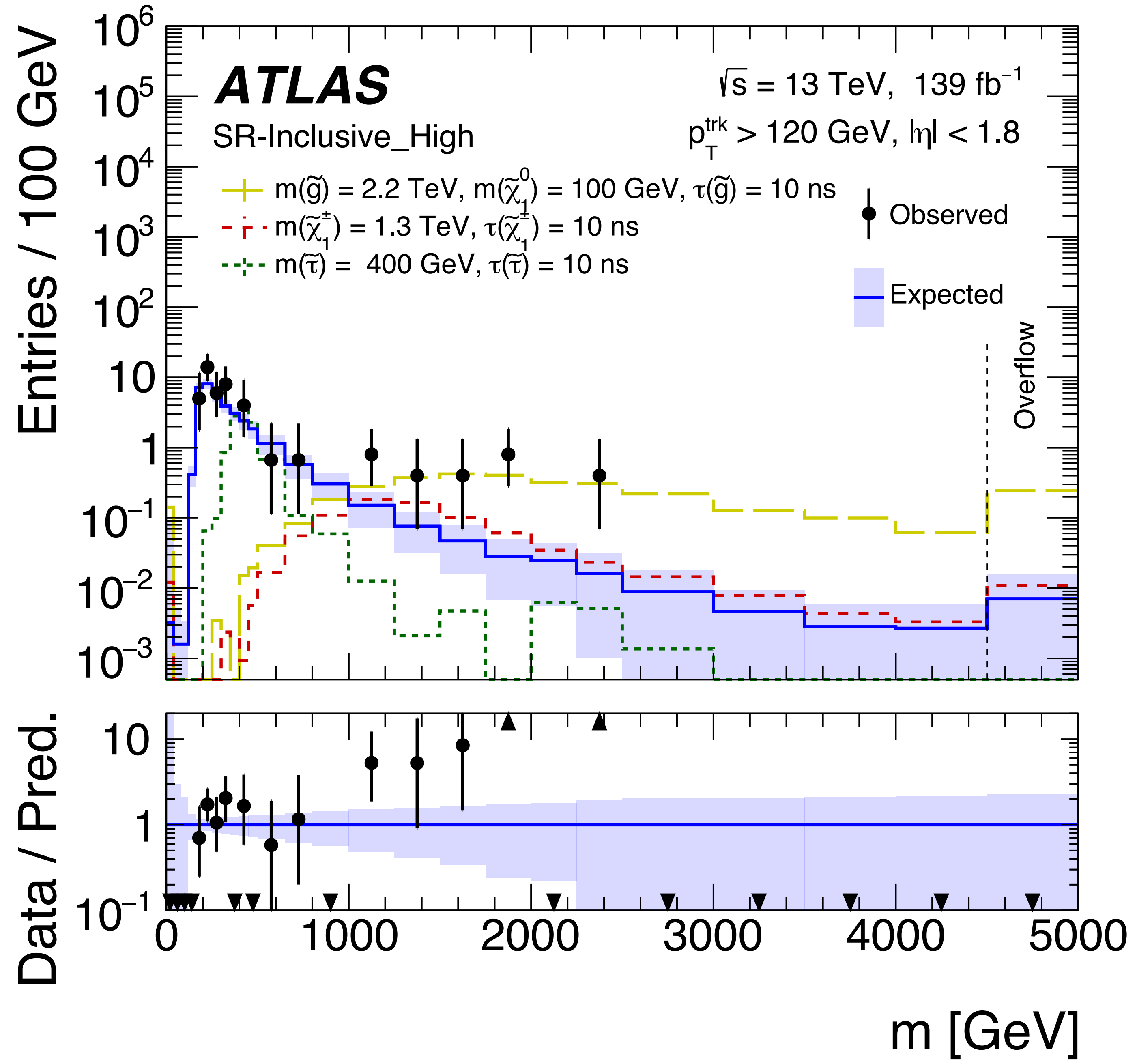

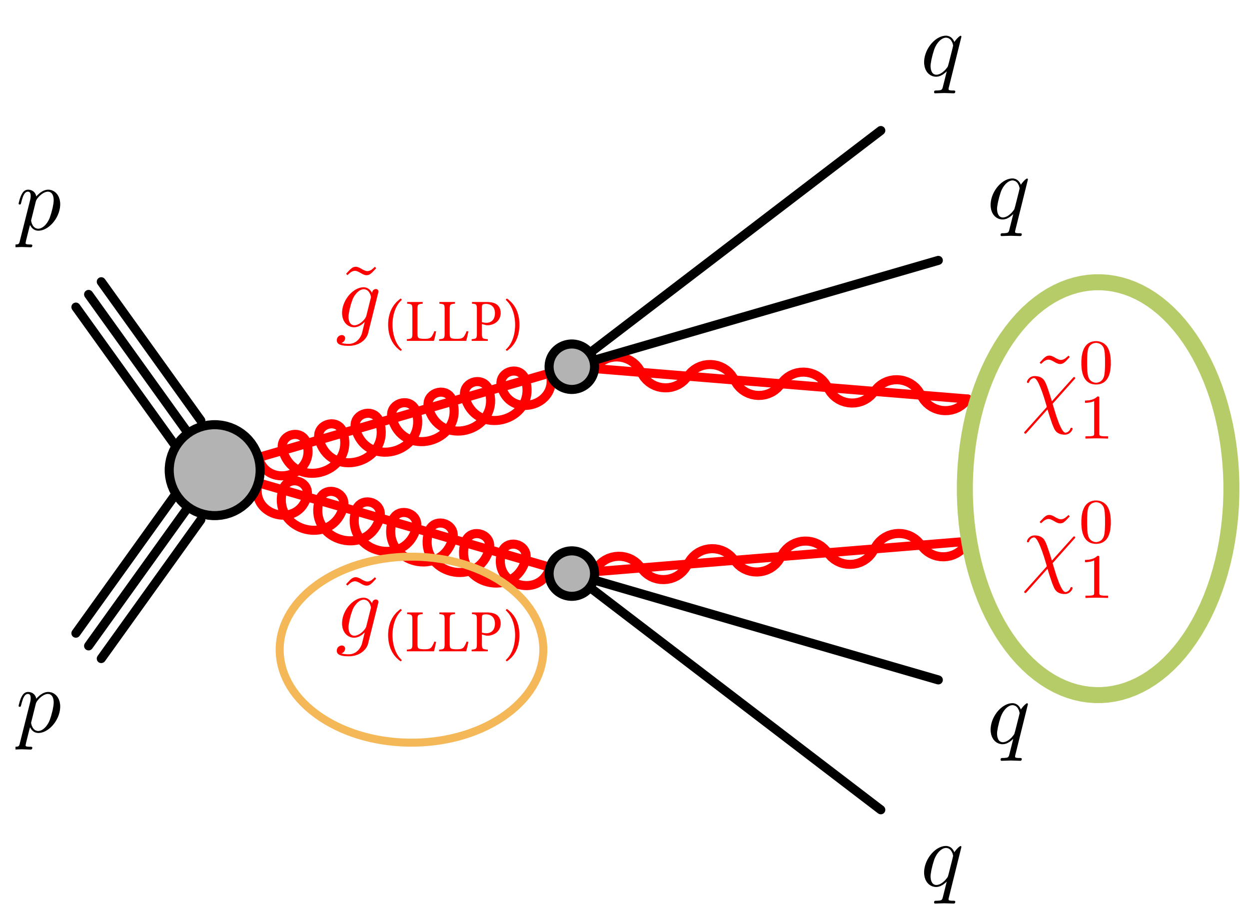

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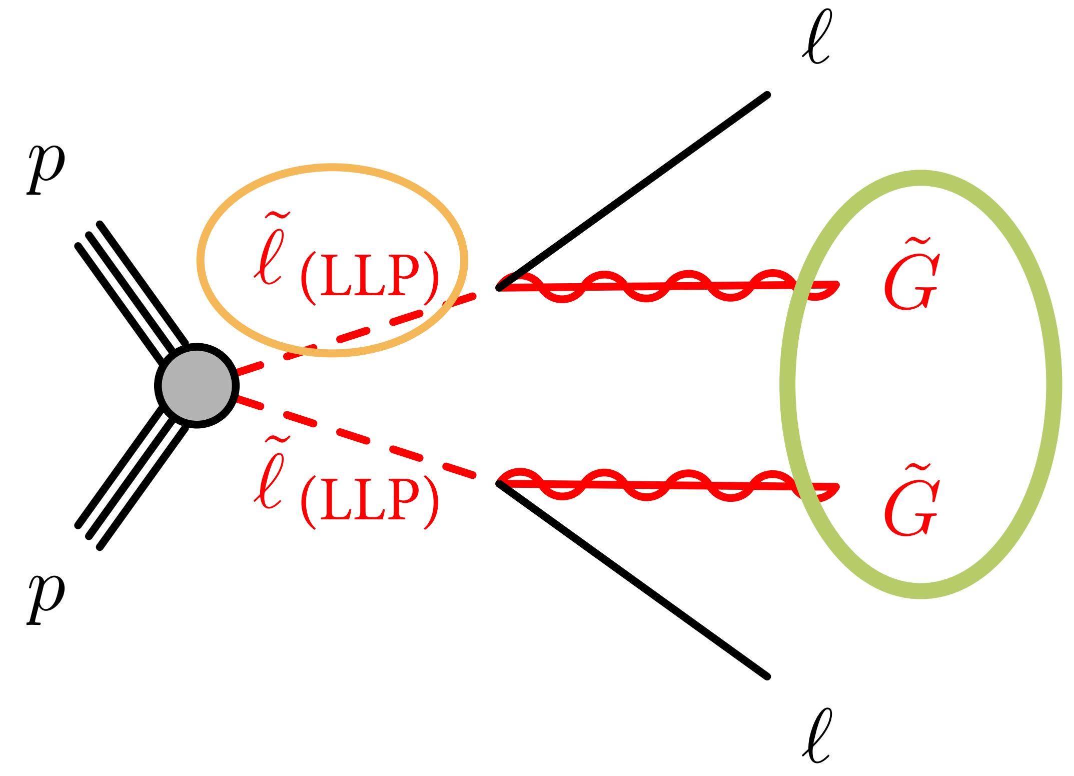

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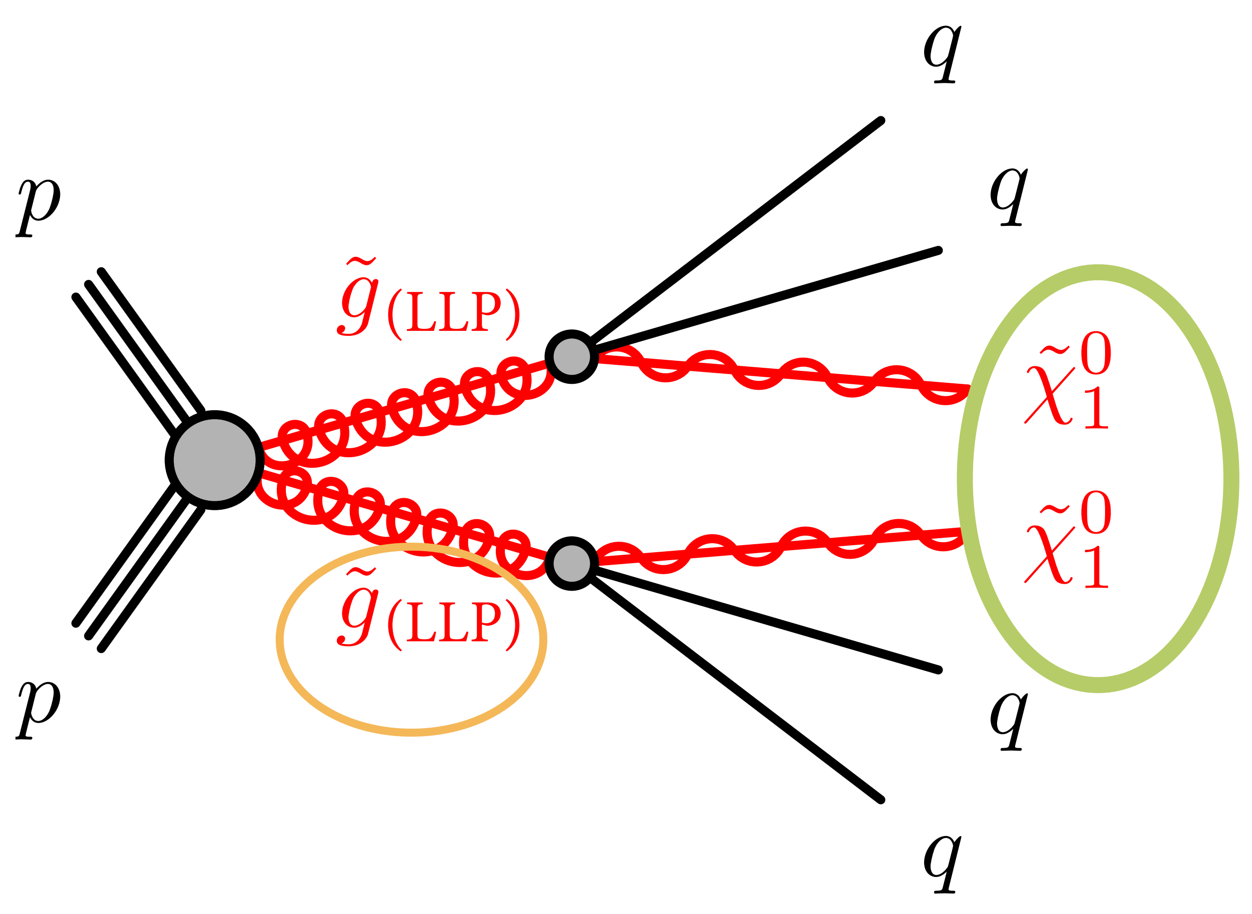
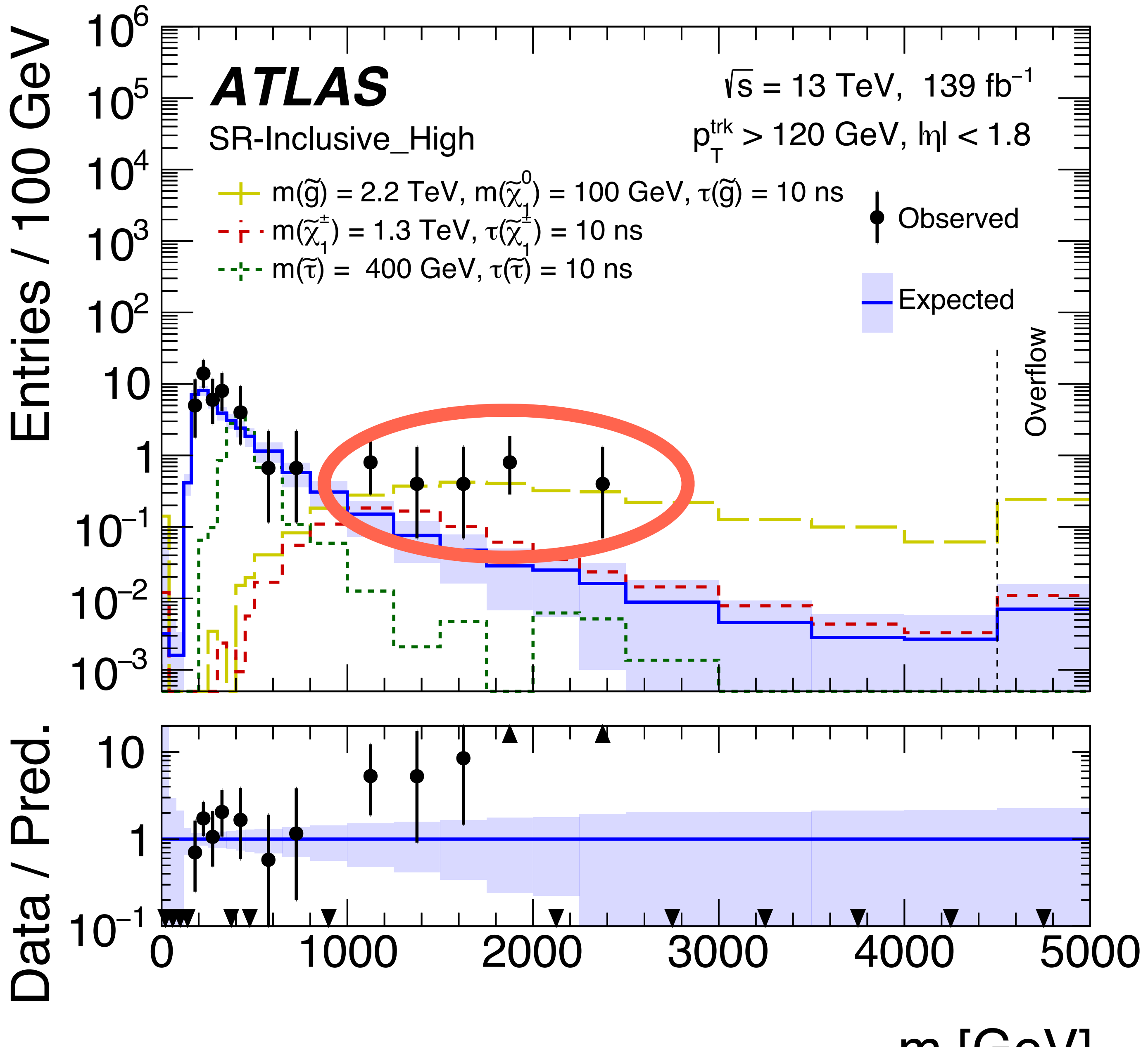


Target mass [GeV]	Mass window [GeV]	Exp.	Obs.	p_0	Z_{local}	$S^{95}_{\text{exp.}}$	$S^{95}_{\text{obs.}}$
		·egion bin					
		SR-Inclusive_High					
		·ifetime					
200	[120, 225]	5.6 ± 0.7	7	2.65×10^{-1}	0.6	$6.3^{+2.5}_{-1.7}$	7.8
300	[200, 350]	9.2 ± 0.8	14	7.11×10^{-2}	1.5	$7.6^{+3.0}_{-2.1}$	12.5
400	[300, 500]	5.8 ± 0.4	6	4.39×10^{-1}	0.1	$6.1^{+2.5}_{-1.8}$	6.5
450	[350, 600]	5.1 ± 0.4	3	5.00×10^{-1}	0.0	$6.0^{+2.2}_{-1.6}$	4.6
500	[400, 700]	4.3 ± 0.4	4	5.00×10^{-1}	0.0	$5.4^{+2.2}_{-1.3}$	5.2
550	[400, 800]	4.8 ± 0.4	4	5.00×10^{-1}	0.0	$5.8^{+2.5}_{-1.8}$	5.4
600	[450, 900]	3.91 ± 0.31	2	5.00×10^{-1}	0.0	$5.5^{+2.2}_{-1.6}$	4.0
650	[500, 1000]	3.22 ± 0.31	2	5.00×10^{-1}	0.0	$5.2^{+1.9}_{-1.6}$	4.4
700	[550, 1100]	2.64 ± 0.31	2	5.00×10^{-1}	0.0	$4.7^{+1.9}_{-1.0}$	4.3
800	[600, 1200]	2.22 ± 0.24	3	2.86×10^{-1}	0.6	$4.5^{+1.8}_{-1.0}$	5.5
900	[650, 1400]	2.0 ± 0.3	4	9.74×10^{-2}	1.3	$4.3^{+1.6}_{-0.9}$	6.8
1000	[700, 1850]	1.9 ± 0.5	4	9.01×10^{-2}	1.3	$4.1^{+1.9}_{-0.7}$	7.0
1200	[800, 2400]	1.5 ± 0.7	6	9.10×10^{-3}	2.4	$4.0^{+1.6}_{-0.8}$	10.0
1400	[900, 2900]	1.1 ± 0.7	7	2.08×10^{-3}	2.9	$4.0^{+1.4}_{-0.7}$	11.5
1600	[1000, 3450]	0.9 ± 0.5	7	6.03×10^{-4}	3.2	$3.6^{+1.5}_{-0.5}$	11.8
1800	[1100, 4000]	0.8 ± 0.6	7	8.87×10^{-4}	3.1	$3.5^{+1.1}_{-0.2}$	11.9
2000	[1200, 4600]	0.6 ± 0.5	5	4.92×10^{-3}	2.6	$3.1^{+1.1}_{-0.1}$	9.4



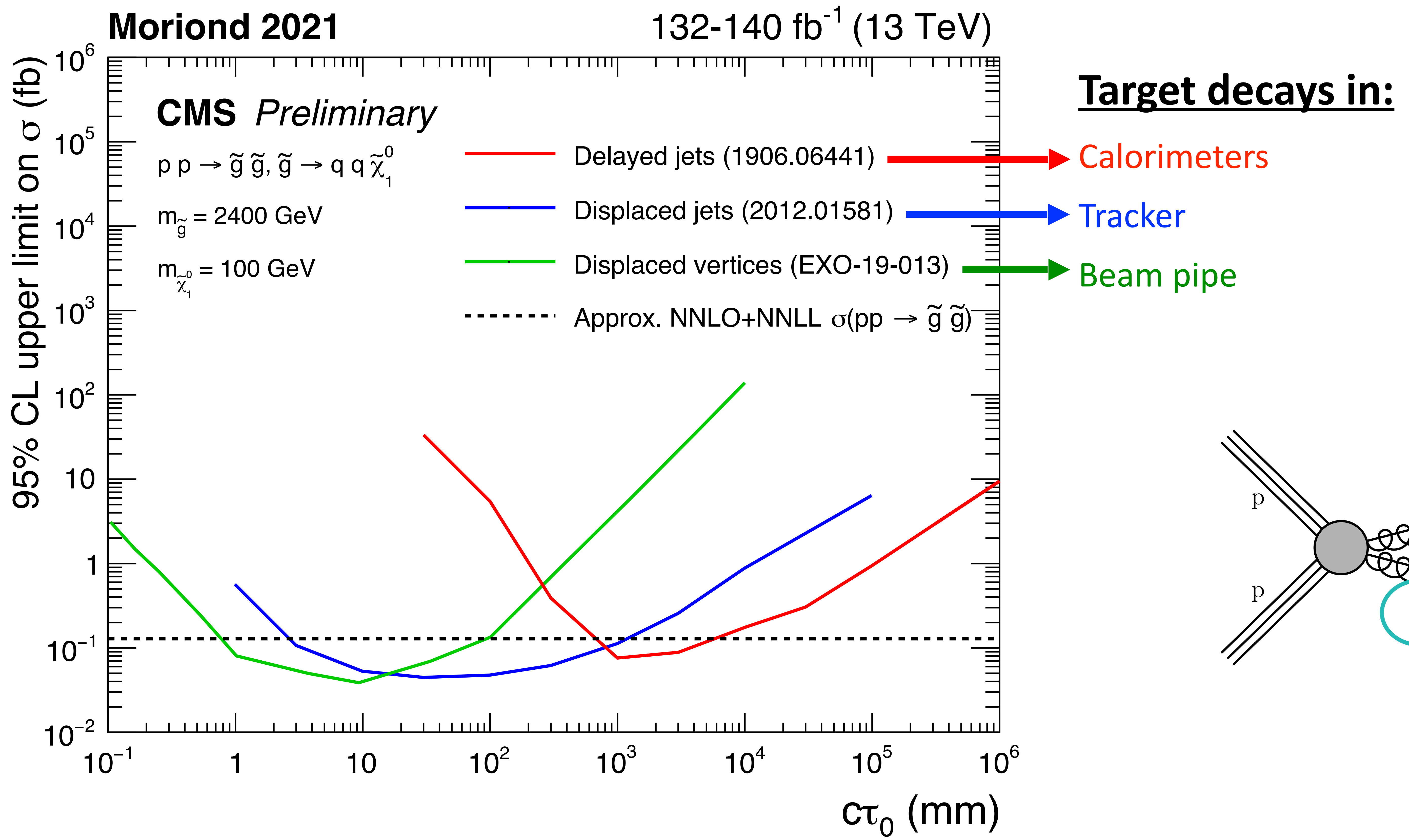
3.6 σ excess!!

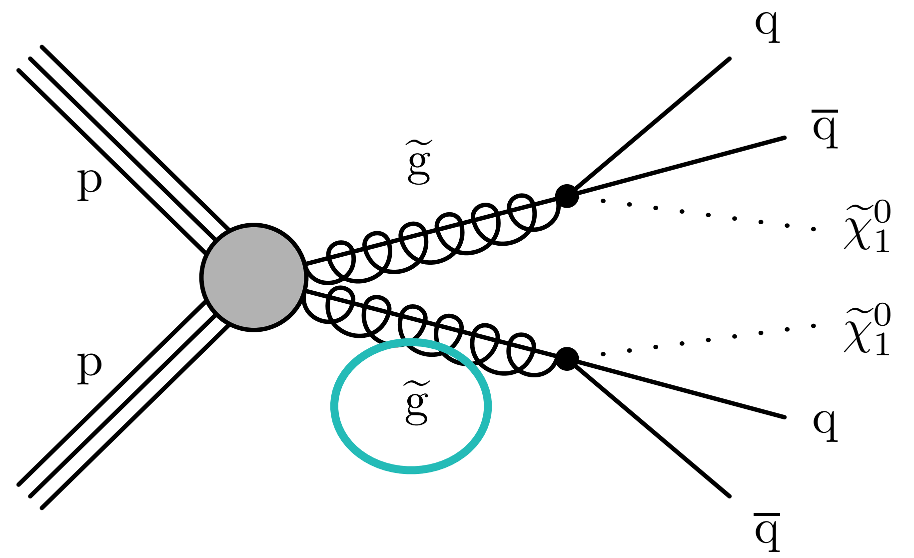
Is this New Physics???
Maybe, though… from the TOF of these events indicate that none of the candidate tracks are from charged particles moving significantly slower than the speed of light ☹

CMS doing a similar analysis
Analysis will be repeated in Run 3!

Complementary searches

- Searches for signatures in different subdetectors can be complementary





We can expand the lifetime coverage by using multiple search strategies

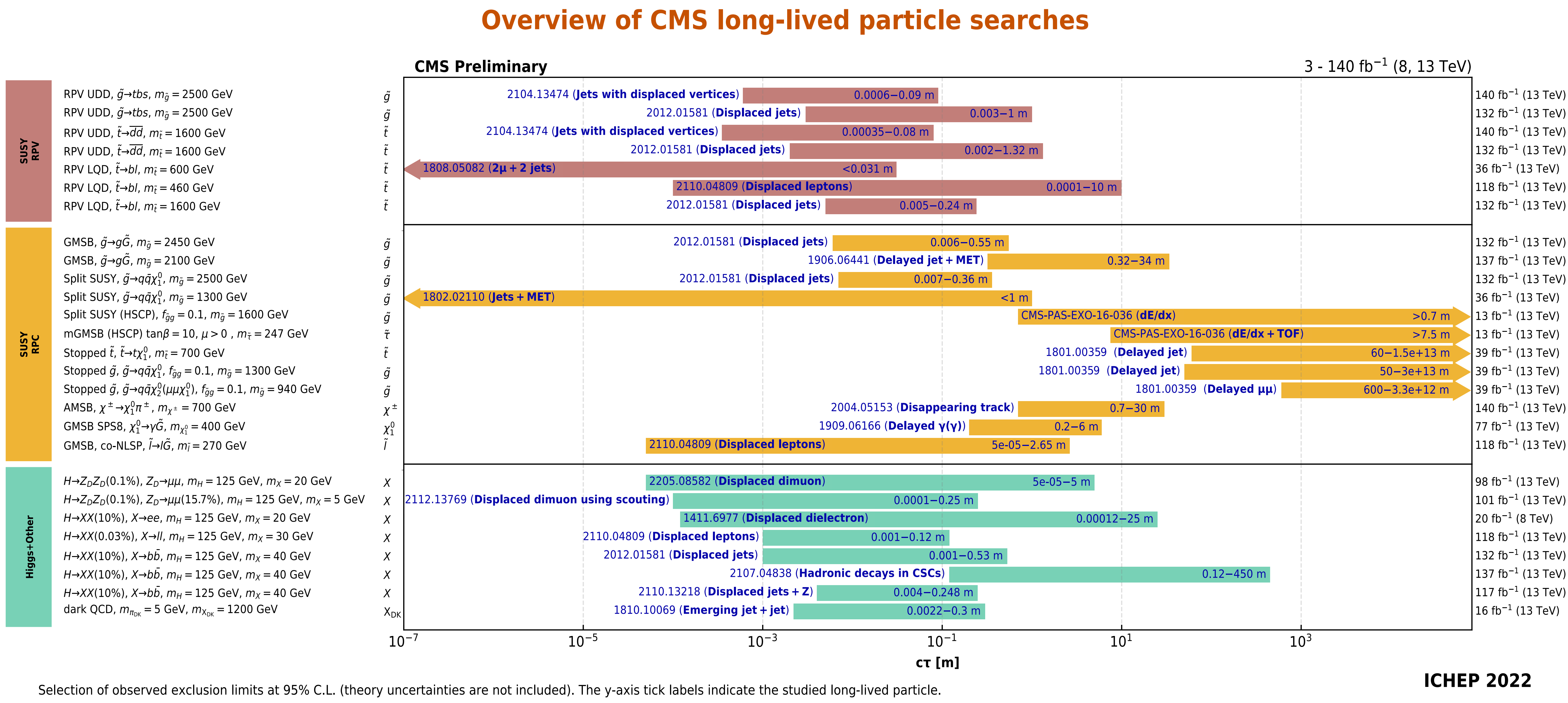
Complementary searches

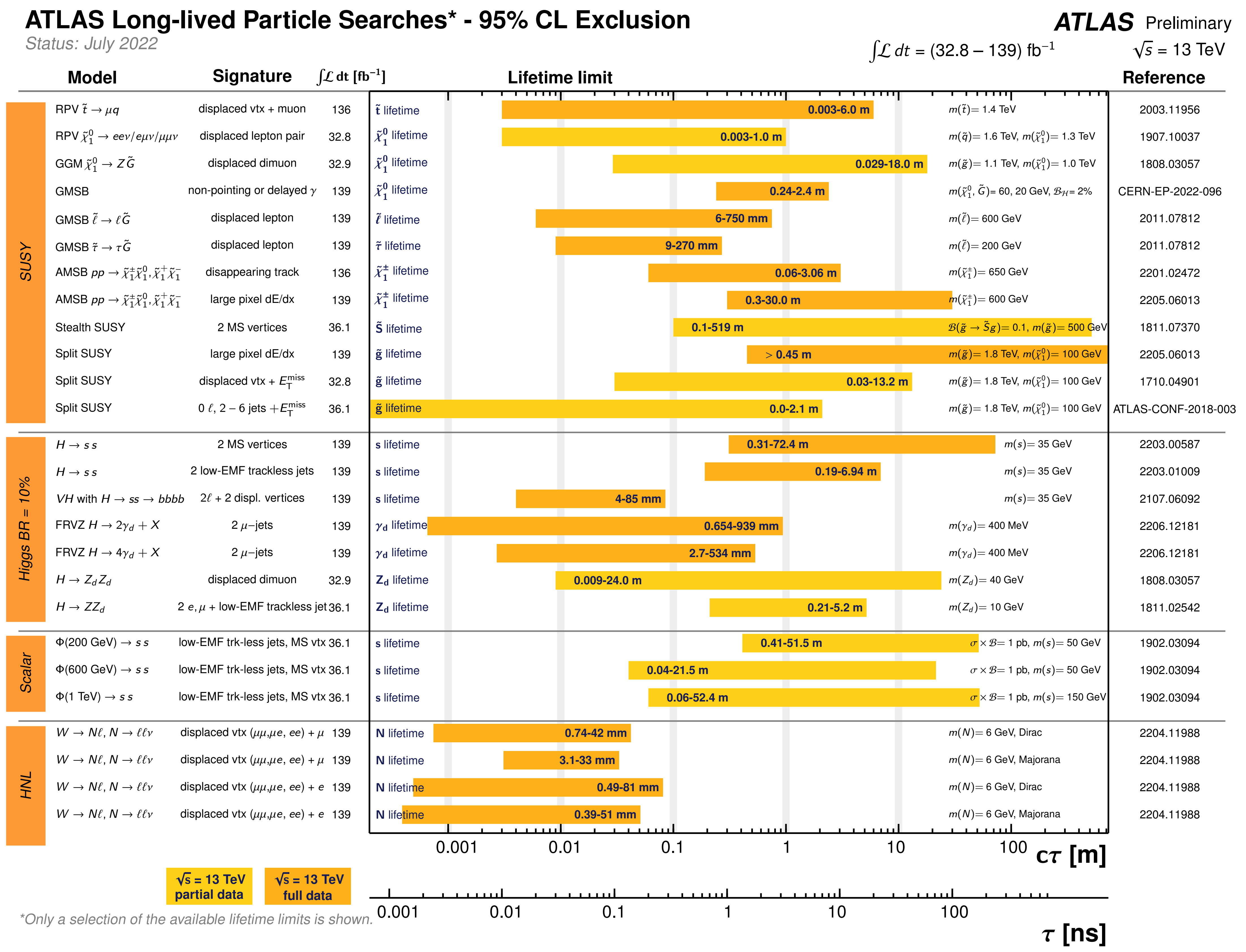
- Searches for signatures in different subdetectors can be complementary

Hard to compare between experiments
Not using the same benchmark models
Being discussed in the LHC LLP WG

- Among all LLP searches in ATLAS, CMS, and LHCb we've tested $c\tau$ from 10^{-5} to 10^{2} m!!

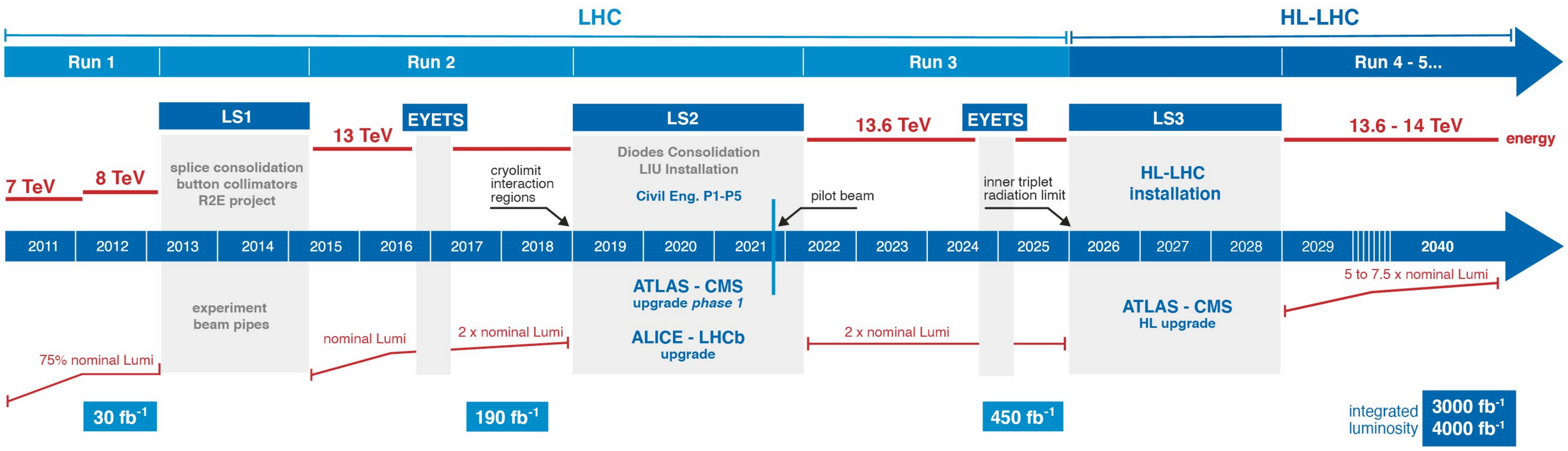
- Find a few more examples in backup





Looking at the future: Run 3 and HL-LHC

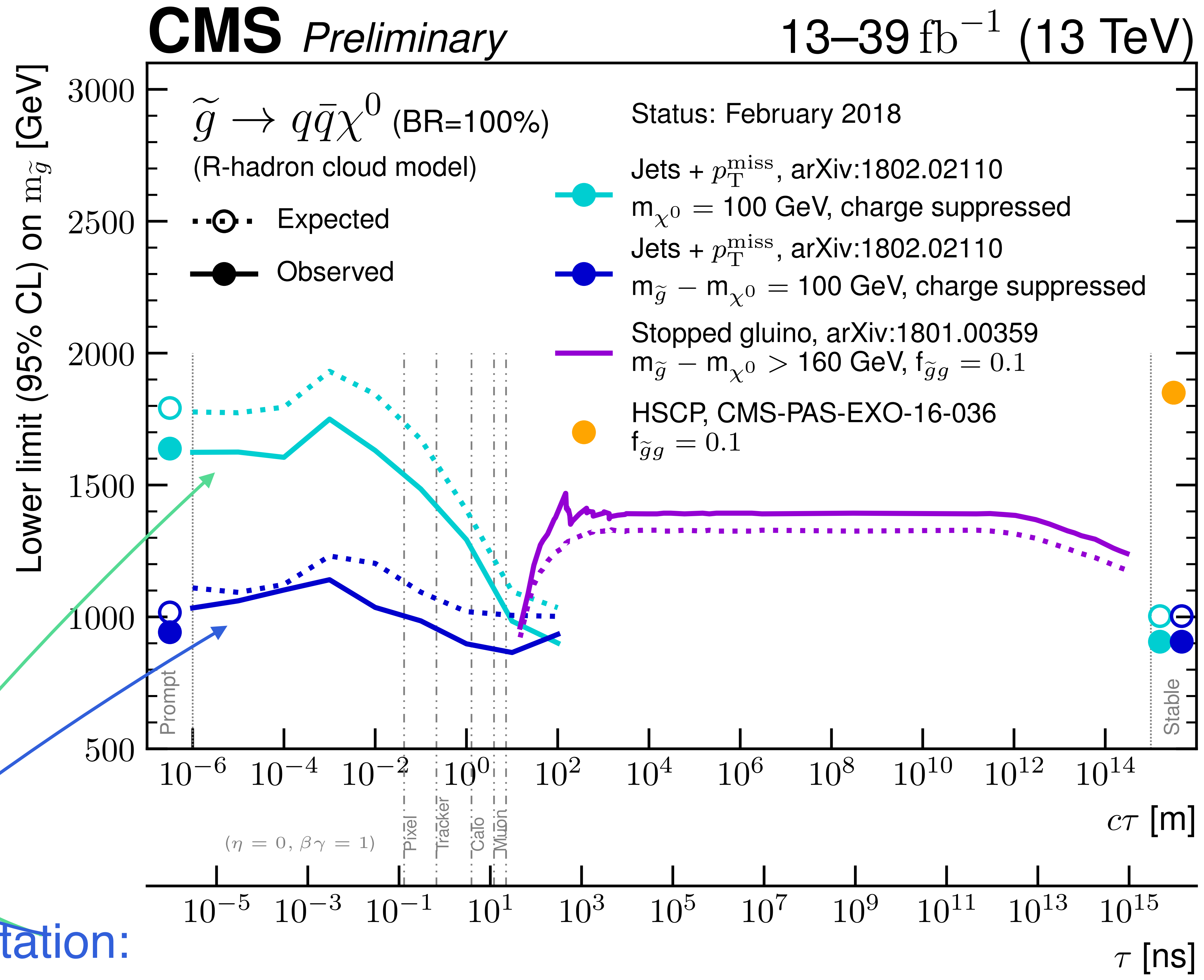
- Run 1 (2009-2013) and Run 2 (2015-2018) delivered 200/fb for the two general purpose experiments, ATLAS and CMS (only 5% of the total integrated luminosity to be collected)
- Run 3 (2022-2025) started with an energy of 13.6 TeV!
- High Luminosity LHC (HL-LHC) will start with Run 4 in 2029:
  - Expected integrated luminosity: 3000/fb, observation of Higgs boson self-coupling as physics driver



- How can we make the best use of the future data?
- Lots of plans and ideas…

Reinterpretation

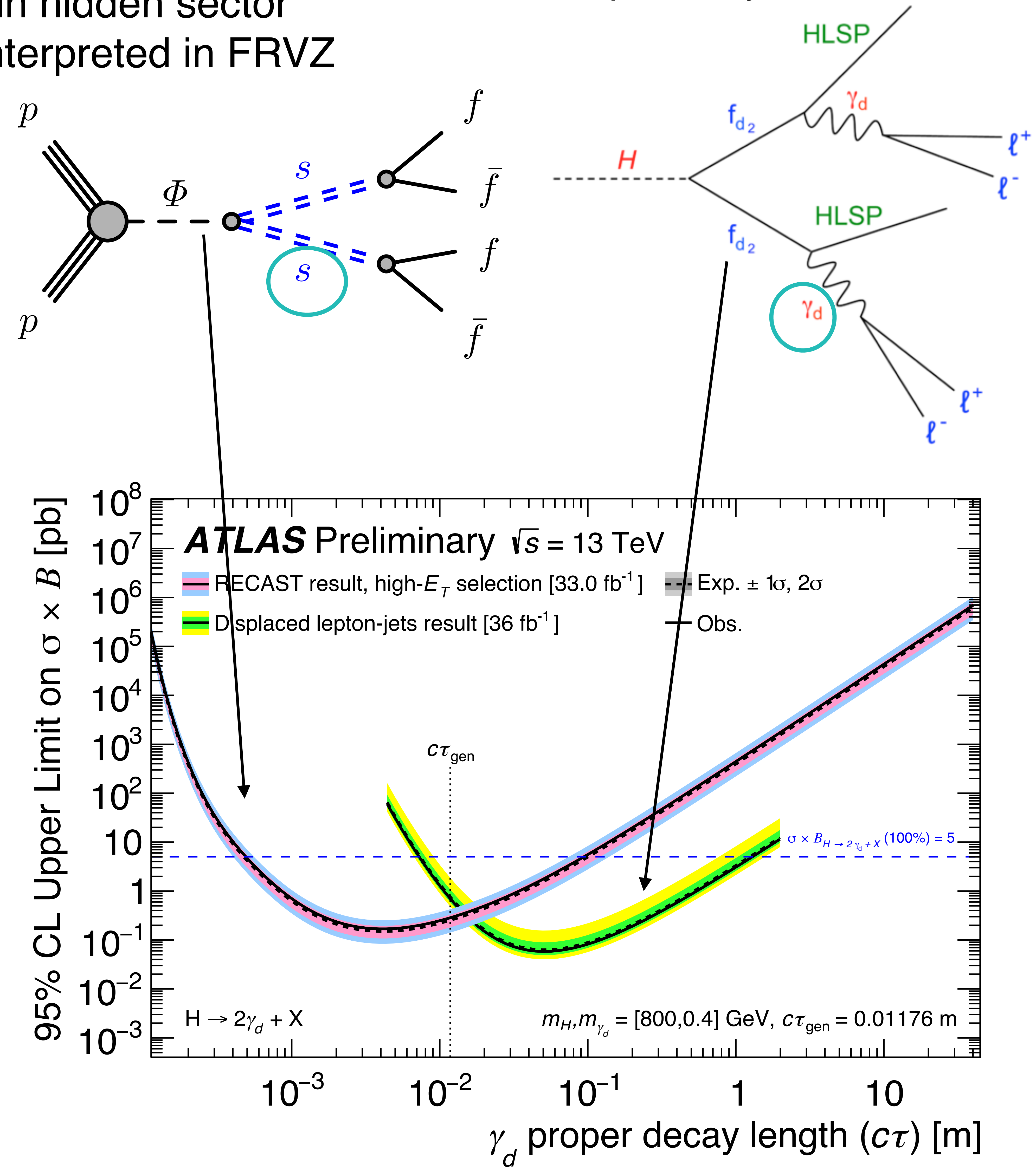
- Understanding backgrounds is a big part of the analysis
- Every search is defined based on a benchmark theory model but other models can lead to very similar signatures.
- Better understanding of general coverage of existing analyses



Re-interpretation:
[SUS-16-038]

Search for pairs of displaced jets in hidden sector
Reinterpreted in FRVZ

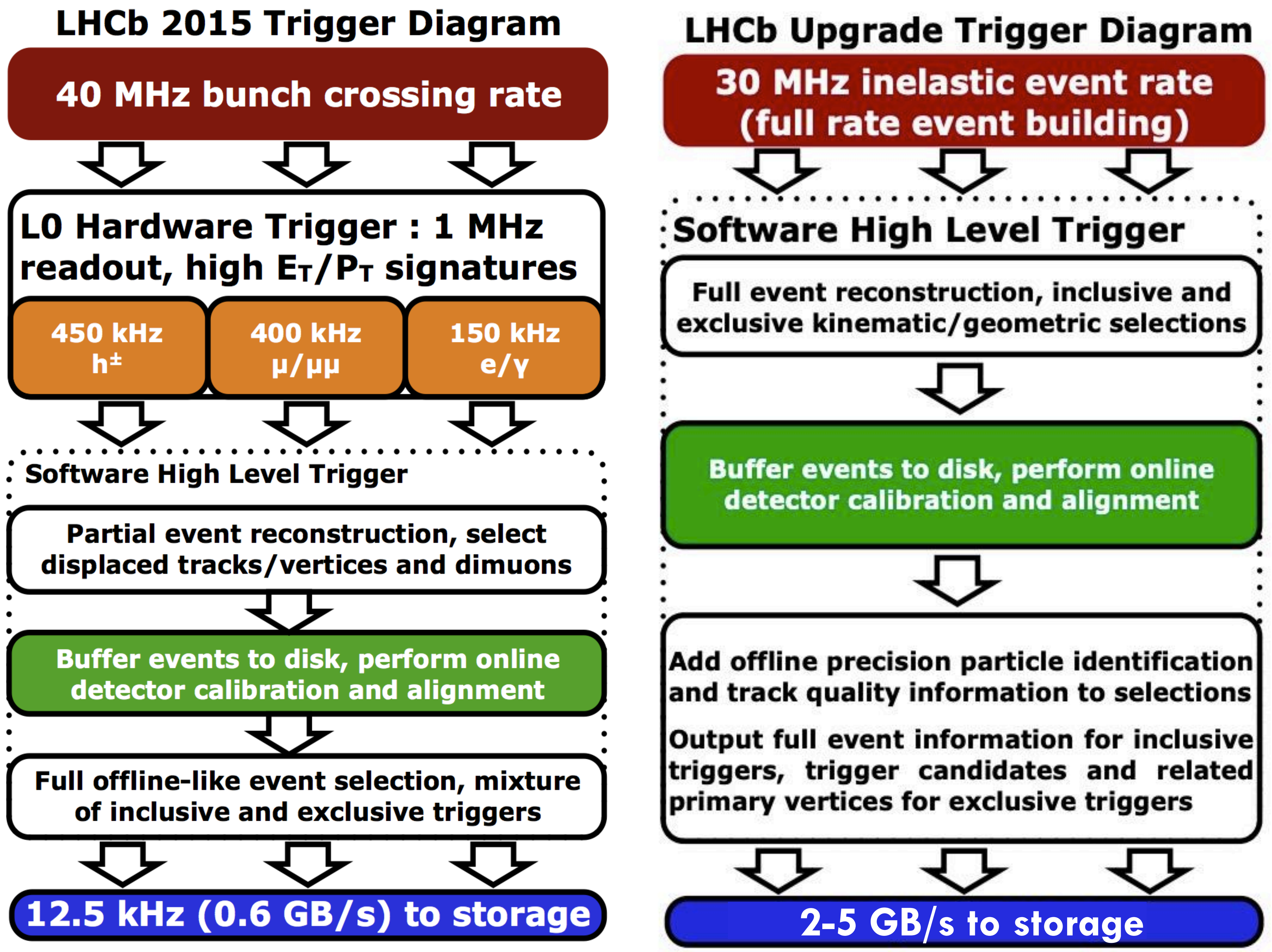
Dark matter FRVZ model
Original search for displaced dark photon jets



New triggers for Run 3

- Trigger is the first filter in data taking
- If we don't trigger on new processes we can't discover them!
- Run 3 is an opportunity to add ideas for new triggers
  - Study topologies or phase spaces that have not been ever looked at!
- The limit bandwidth is limited… How do we do that?

- LHCb: radical idea
- get rid of the L0 trigger in Run 3!!!
  - gain a factor 2 in hadronic channels
  - GPU-based HLT



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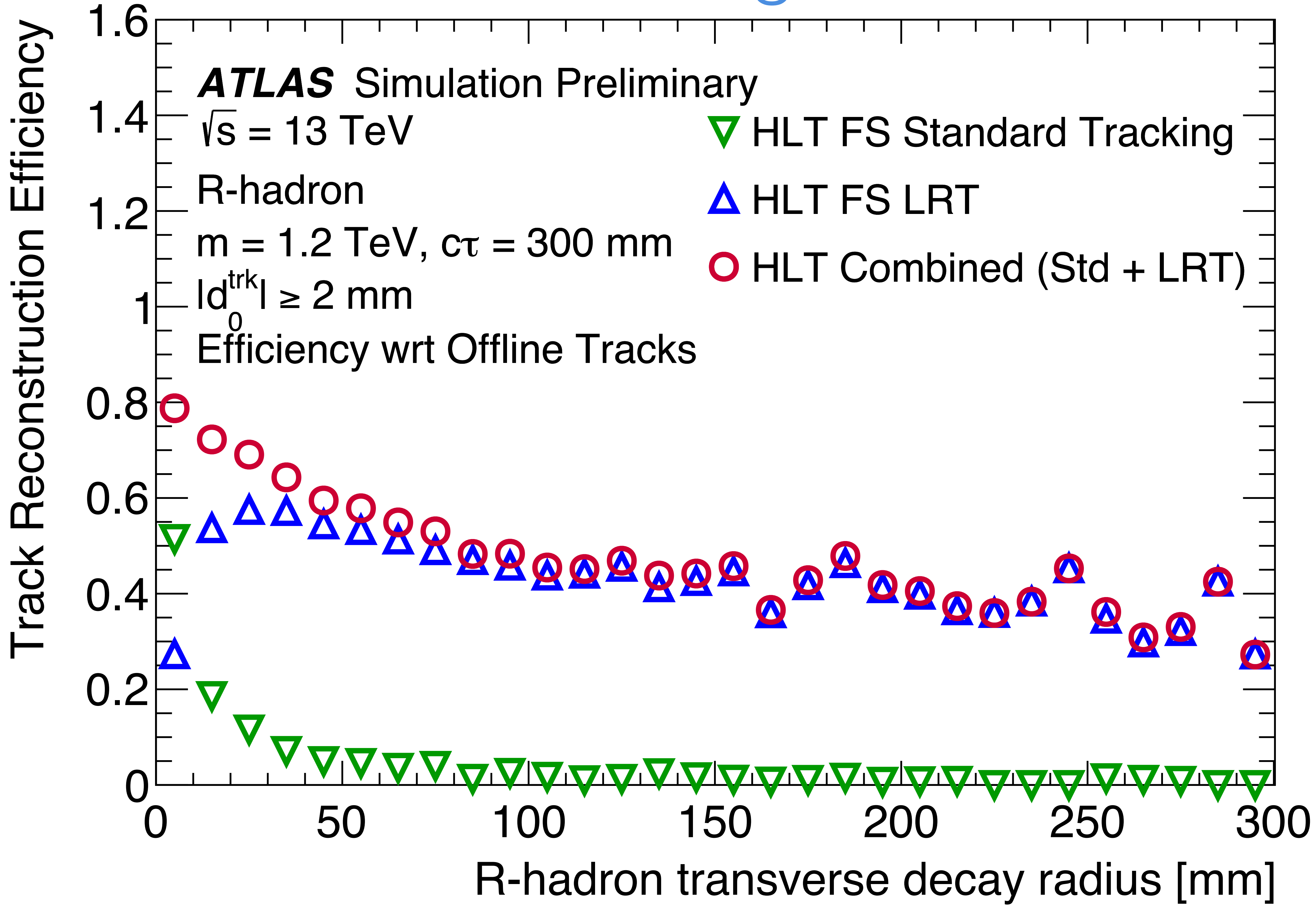
- In ATLAS and CMS: created and improving dedicated triggers for Run 3

- Great example: running ATLAS LRT at trigger level

HLTTrackingPublicResults

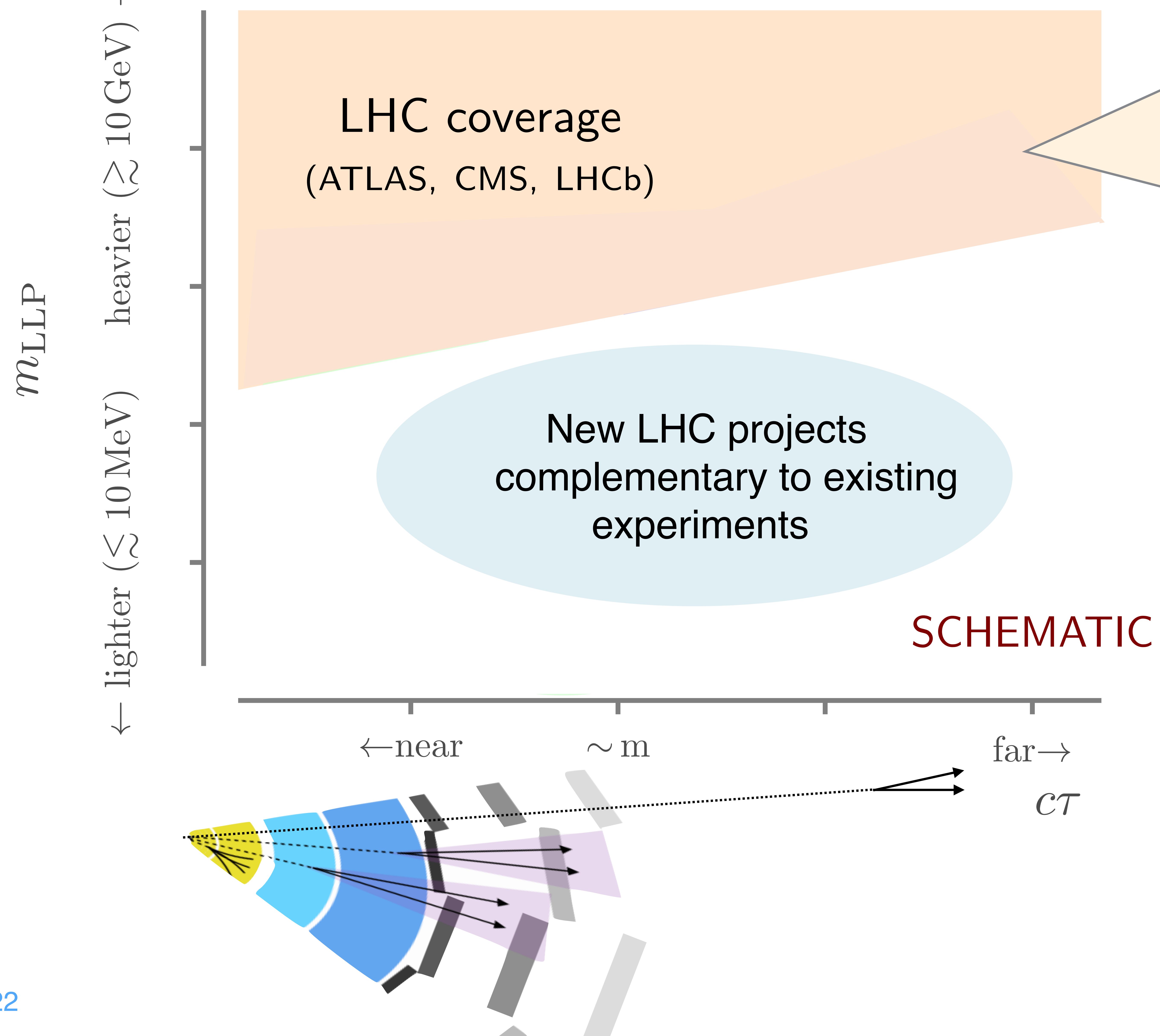


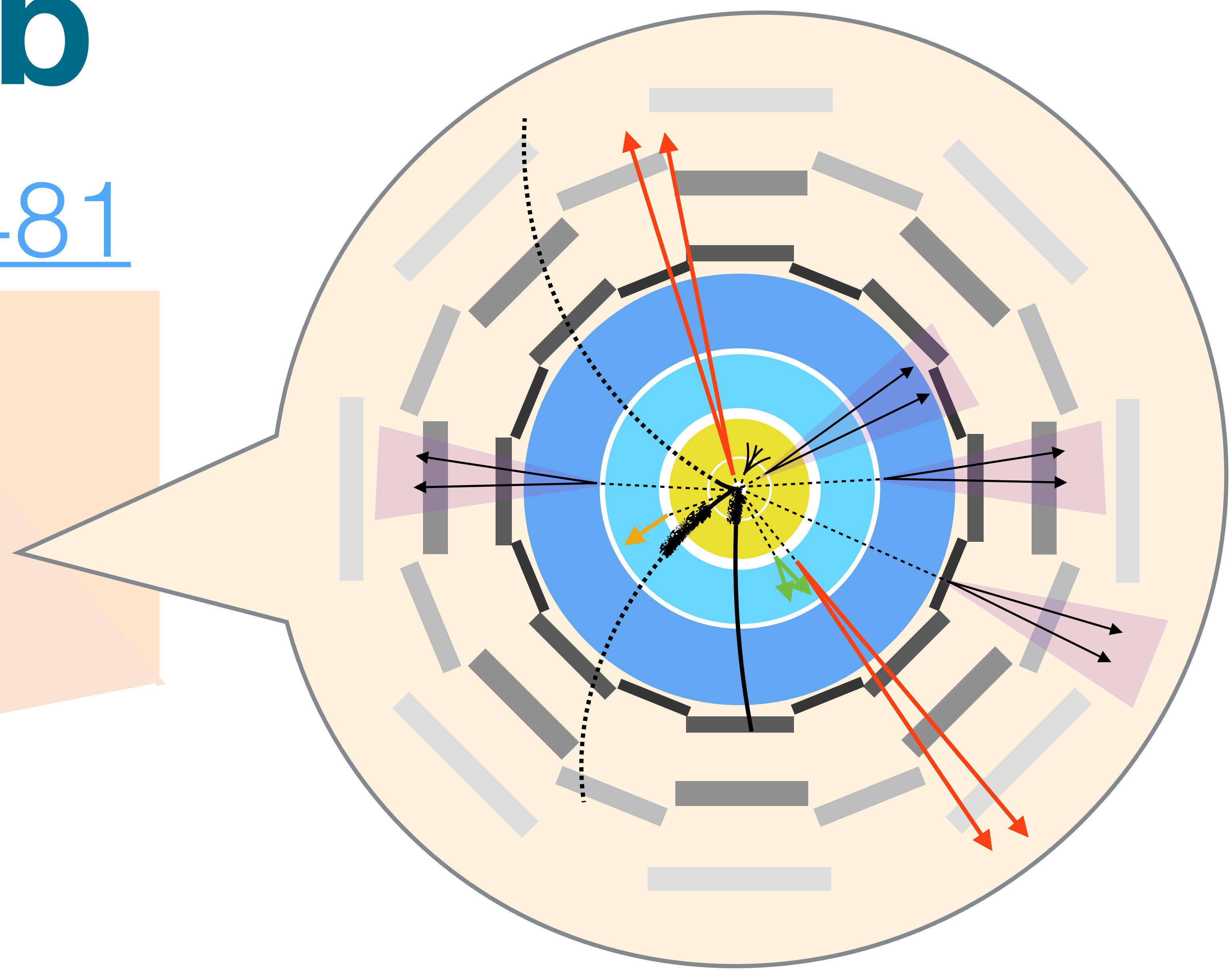
Searches beyond ATLAS, CMS, LHCb

- Many of the theories involving Long-lived particles give no specifications on lifetimes

- Need dedicated experiments far away from the IP!

[1911.00481](1911.00481)





- Trigger constraints
- lots of SM background
- limited by size

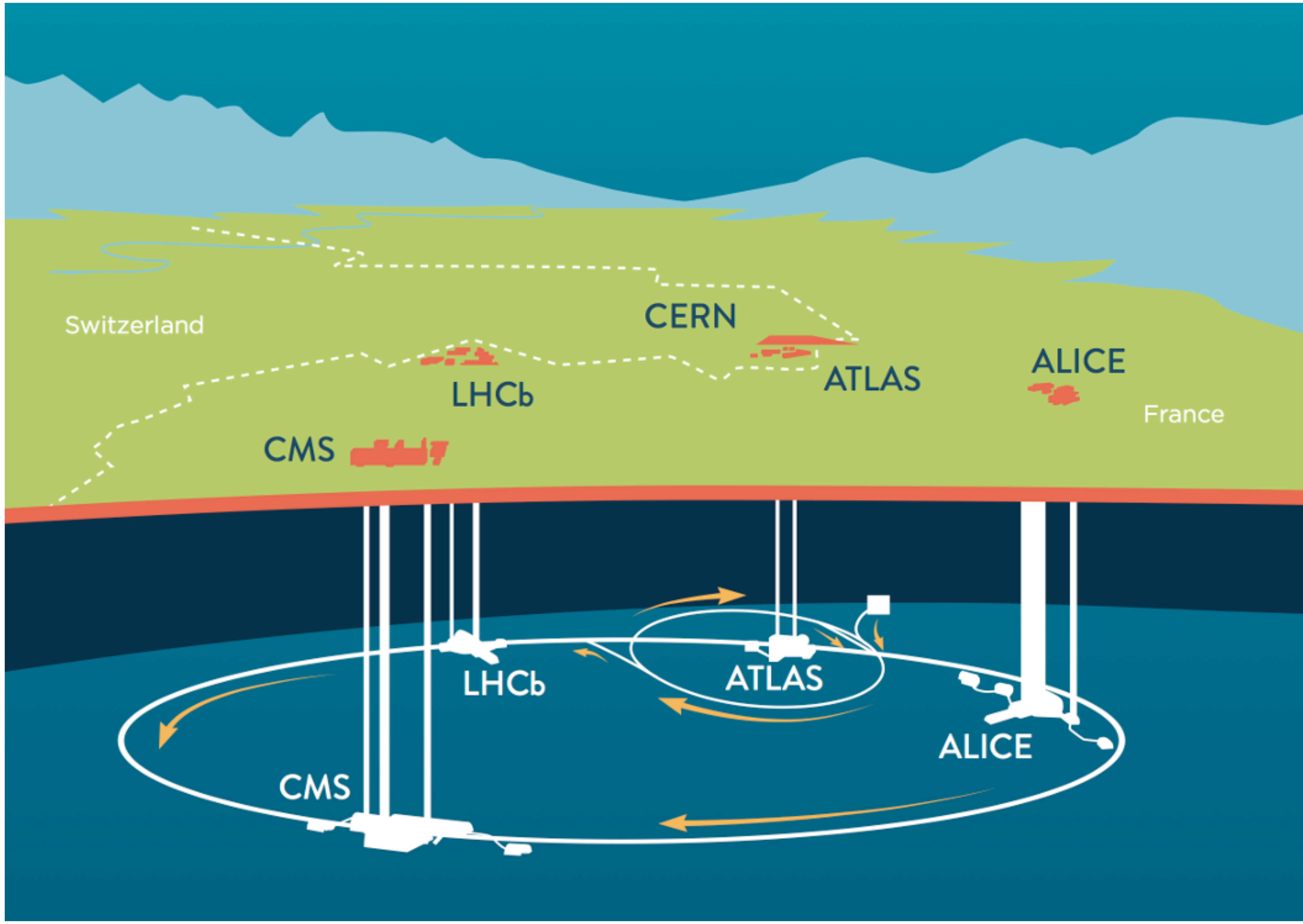
Overview of proposed LLP detectors at the LHC

- Huge range of lifetimes from ~50m to 10^8 m covered by different detector volume and distance form IP

- Range of models, couplings and masses covered by different angle wrt beam axis

- Many possible decay modes!

- Need variety of detectors = complementary



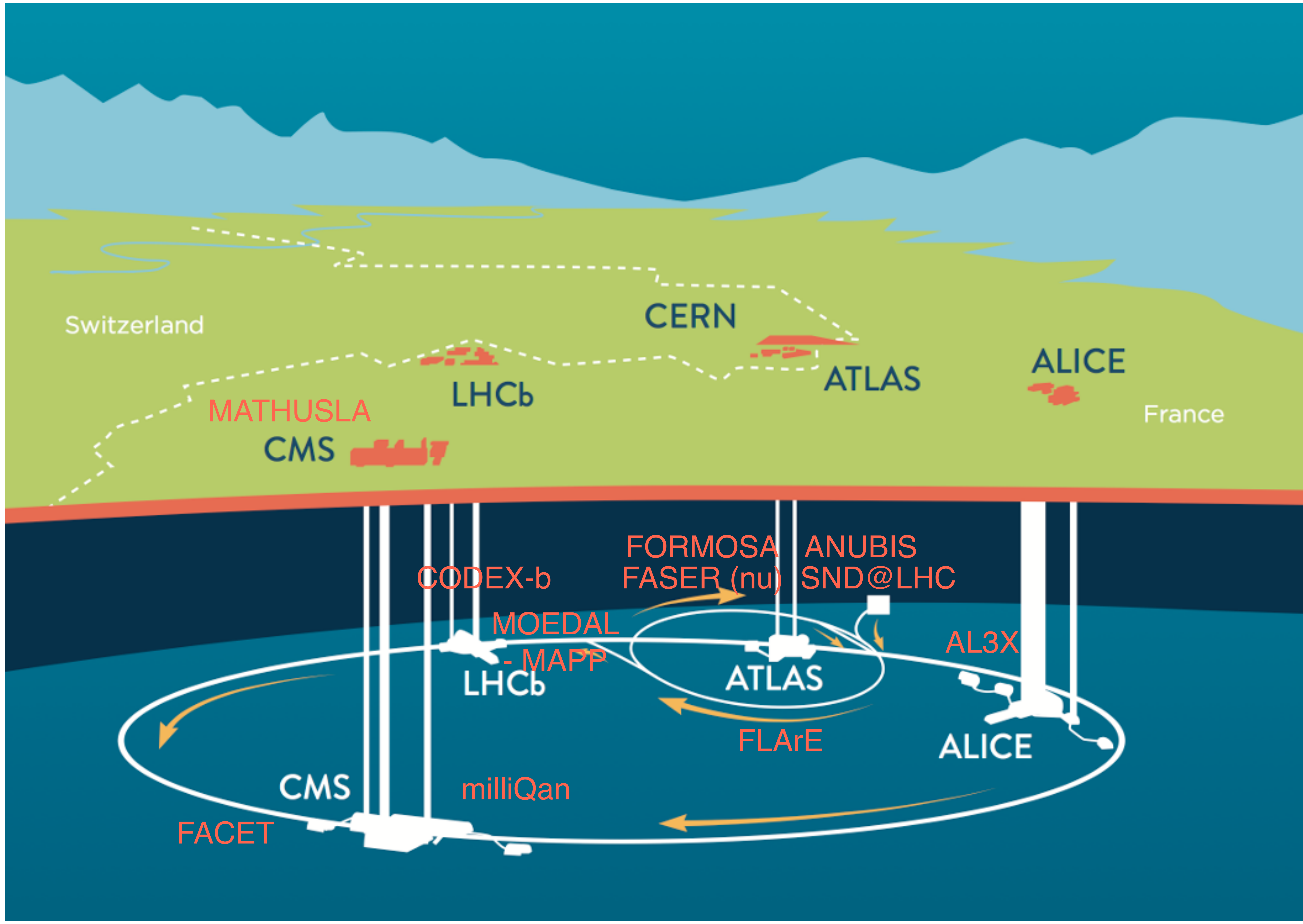
Overview of proposed LLP detectors at the LHC

- Huge range of lifetimes from ~10m to 10^8 m covered by different detector volume and distance form IP

- Range of models, couplings and masses covered by different angle wrt beam axis

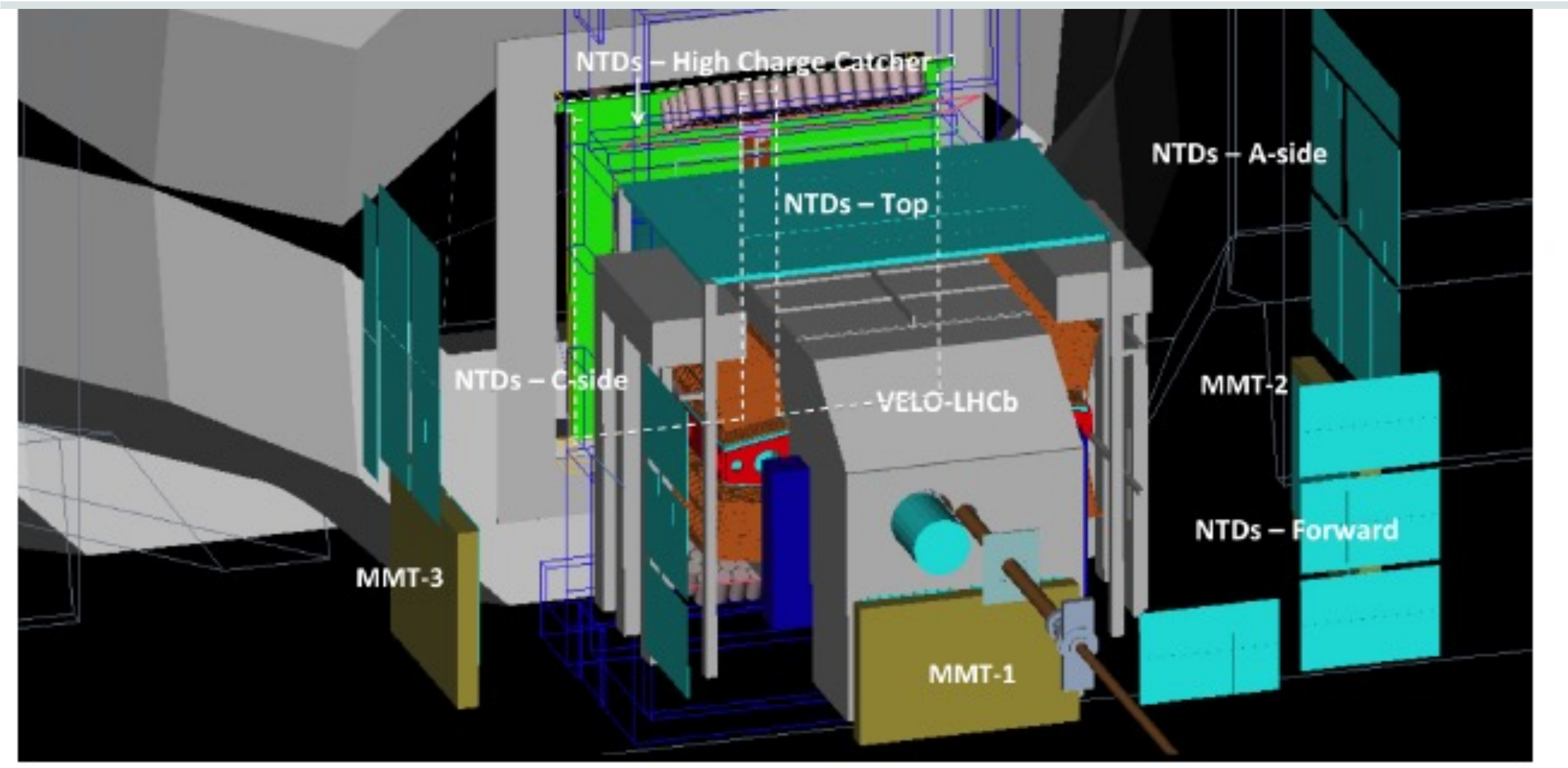
- Many possible decay modes!

- Need variety of detectors = complementary



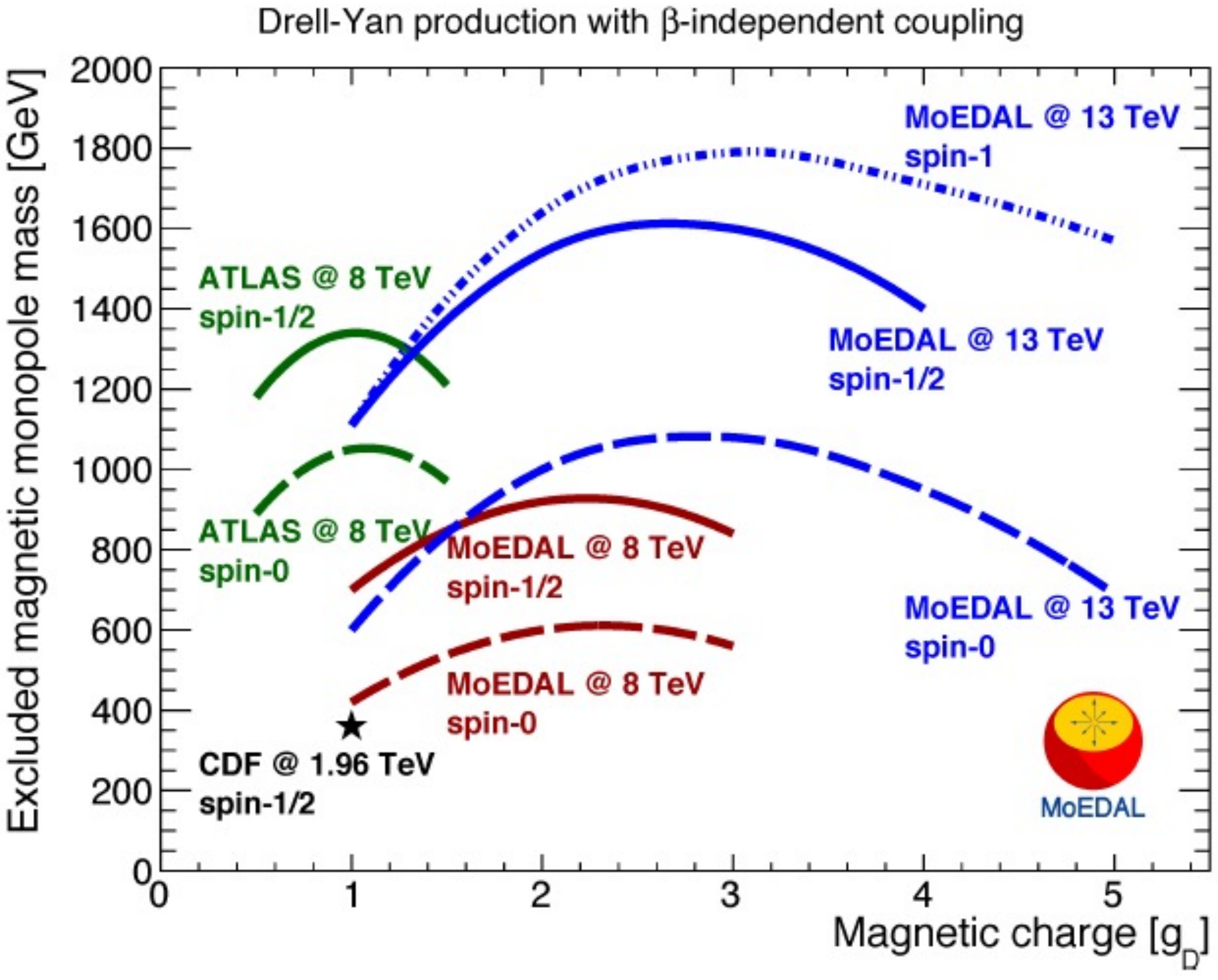
MoEDAL

MoEDAL



- Located at LHCb cavern, approved in 2010
- Target: highly ionizing particles, magnetic monopoles, massive pseudo-stable charged particles (sleptons, R-hadrons) , …

- Two technologies used:
  - Magnetic Monopole traps
    - bind a magnetically charged particles with an energy of 0.5 - 2.5 MeV and capture it inside the atomic lattice
  - Nuclear Track Detectors: when a HIP passes through the NTD, it creates an invisible damage along its track



- Moedal's results for monopoles leading mass limits

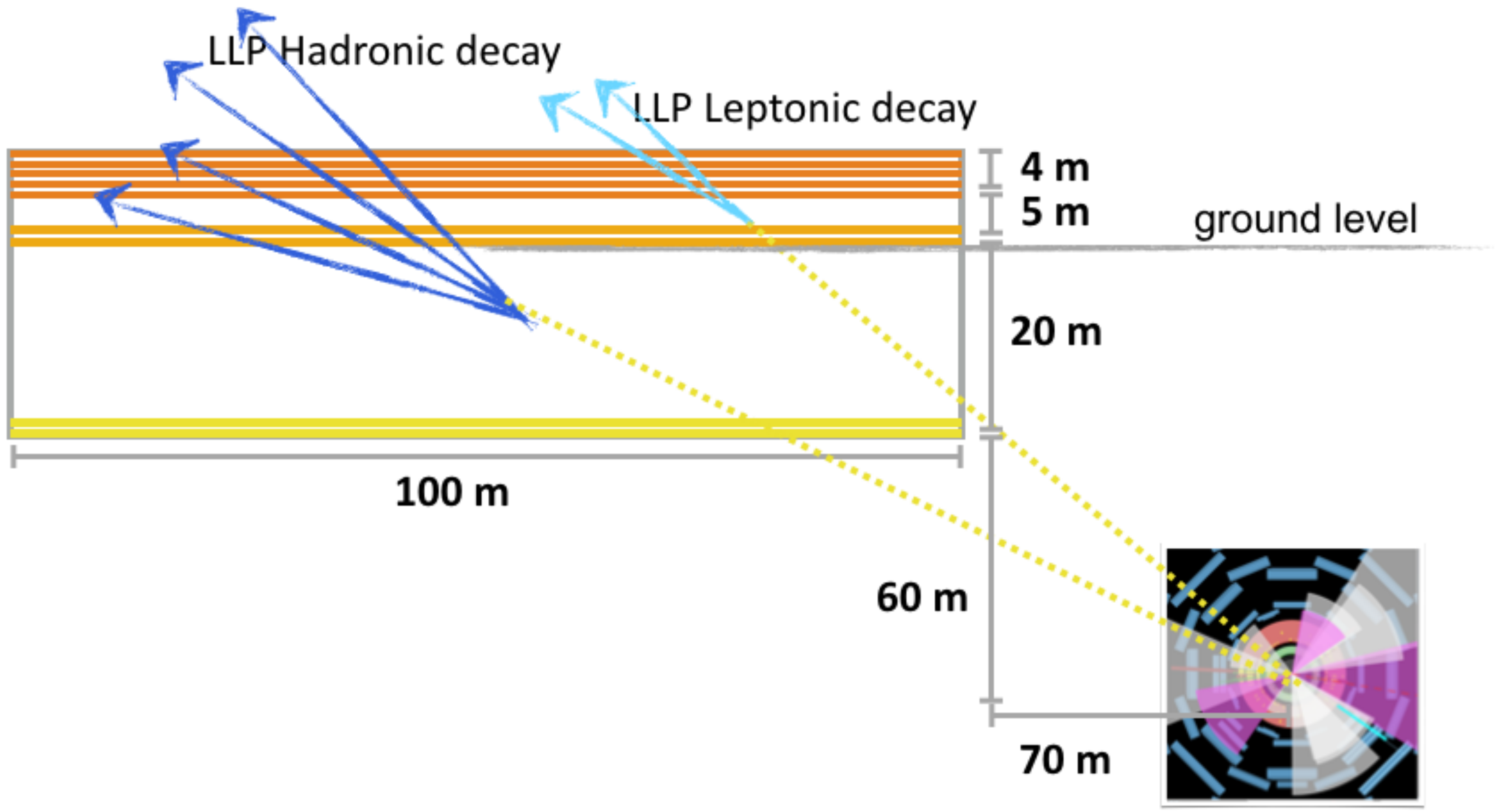
PhysRevLett.123.021802

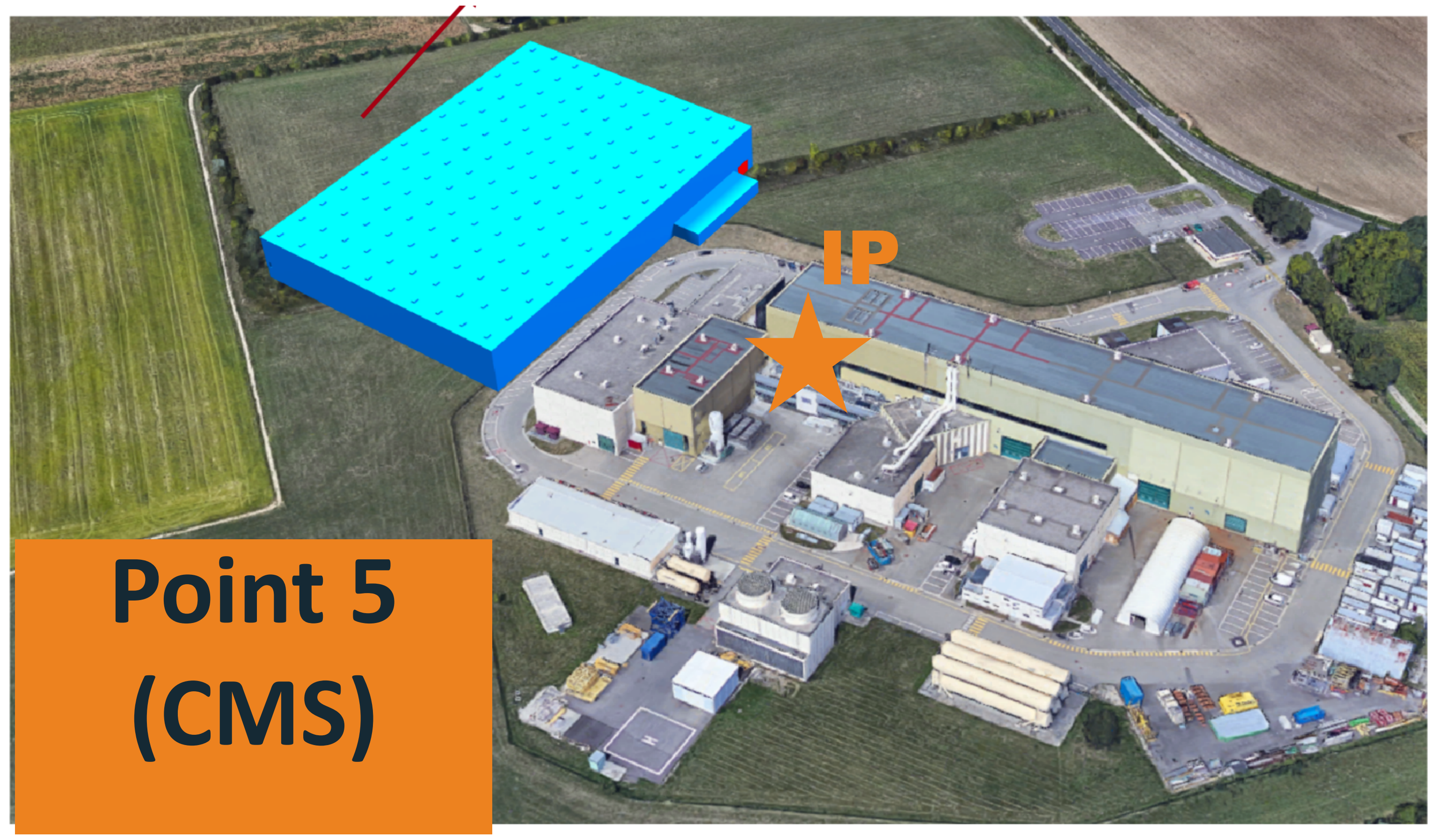
MATHUSLA

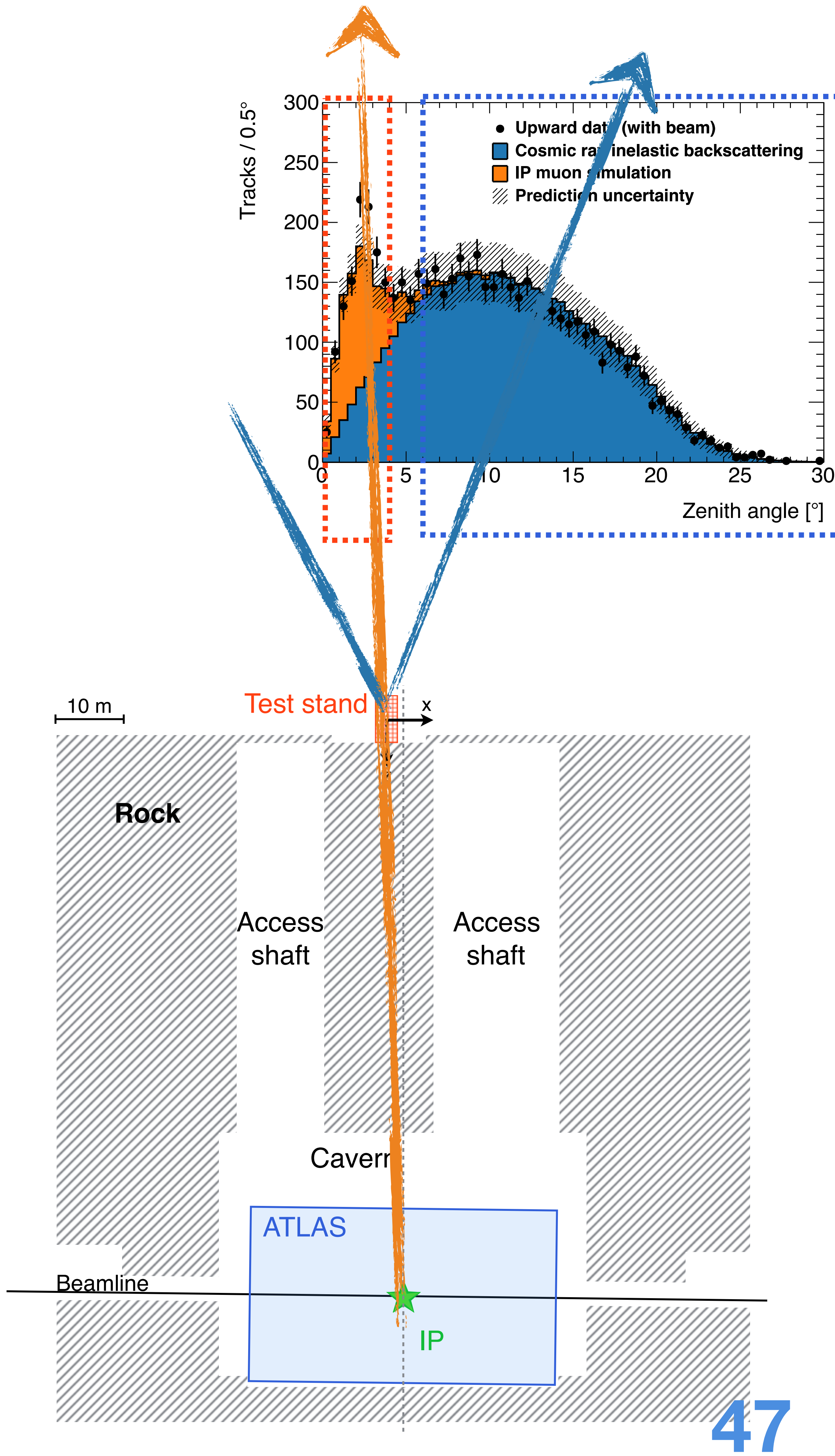
MAsive Timing Hodoscope for Ultra Stable neutraL pArticles

LoI: 1811.00927
Test stand: 2005.02018
Updated LoI: 2009.01693
Snowmass: 2203.08126

- Sensitive to LLPs with lifetime up to 10^8 m
- Placed on the surface above CMS during HL-LHC: rock shielding
  - Aiming for zero background analysis
- Large air decay volume with several scintillator layers for tracking
- Test stand with 2018 confirmed background hypothesis and gives confidence in projected physics reach

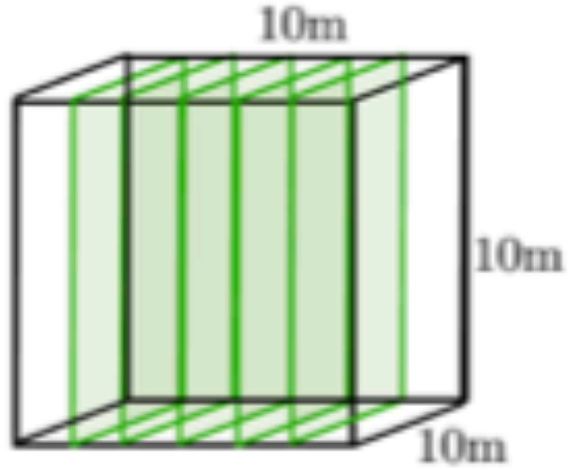






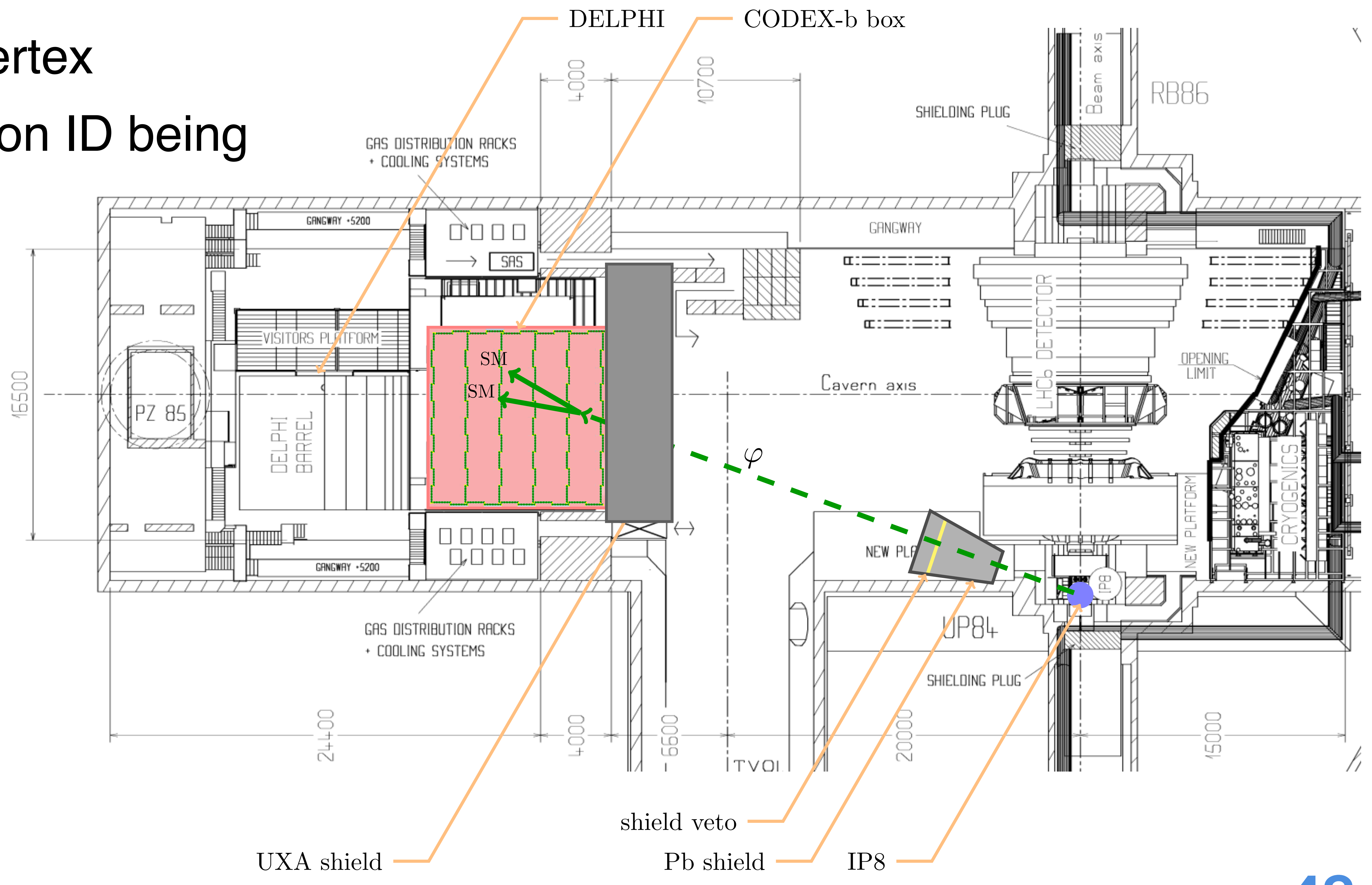
Compact Detector for Exotics at LHC-b

- Target: light, weakly interacting LLPs at HL-LHC
- Use LHCb trigger CPUs space in LHCb cavern / DELPHI location



- 10x10x10 m³ box
- 6 layers of RPCs for tracking to reconstruct LLP decay vertex
  - Addition of calorimetry or other material layers for photon ID being considered
- Shield veto agains collision backgrounds

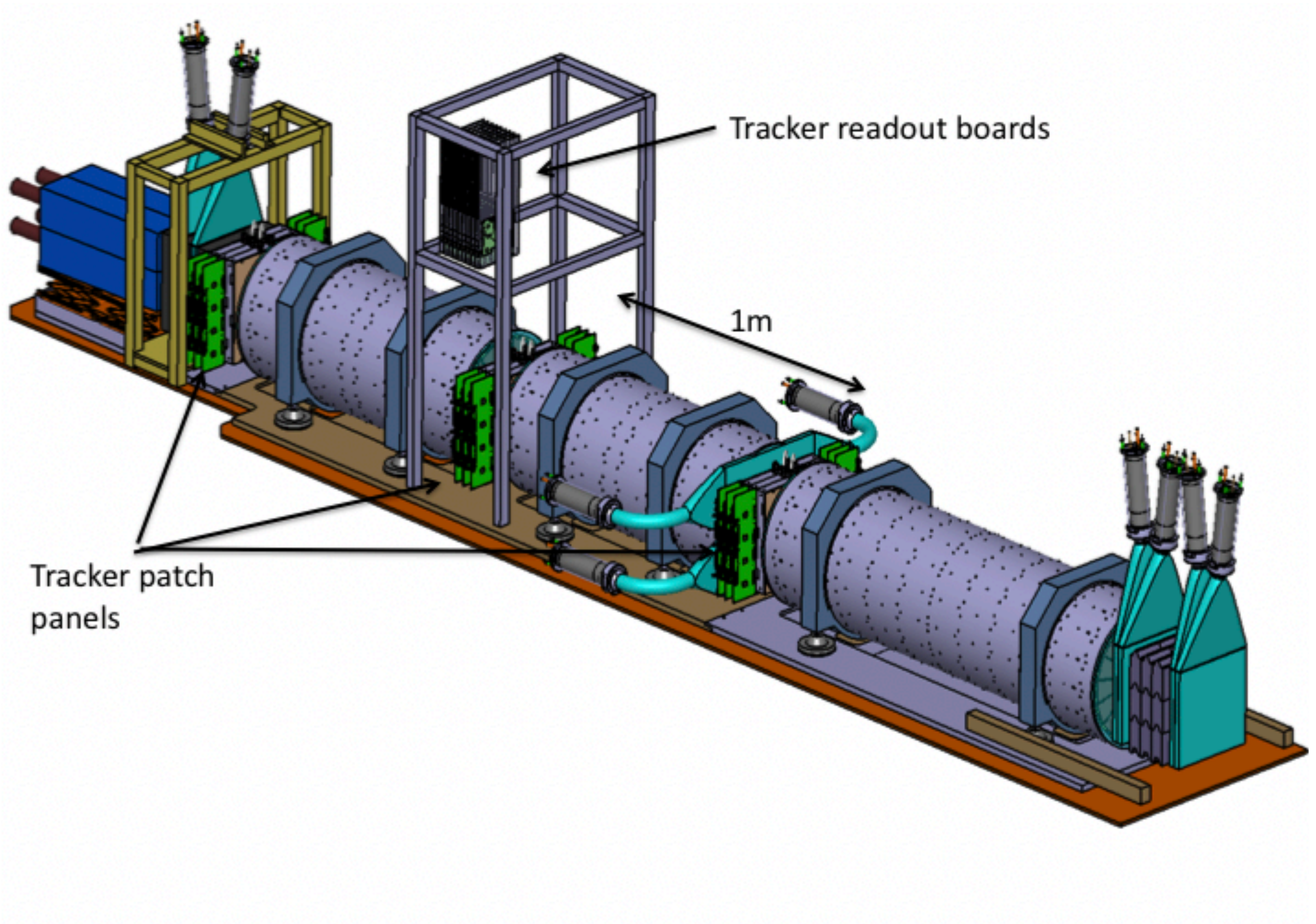
- Codex-beta:
  - demonstrator, 2x2x2 m³
  - data-taking in Run 3
  - Integrated with LHCb
  - will check backgrounds and technology
  - Full detector for Run 5

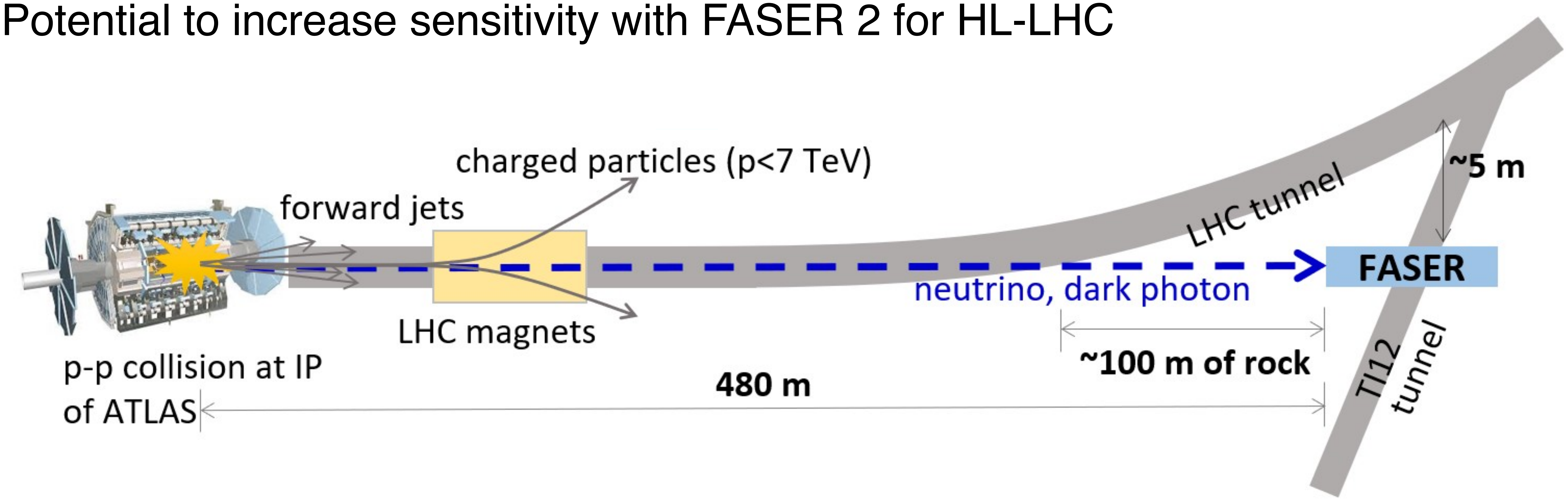


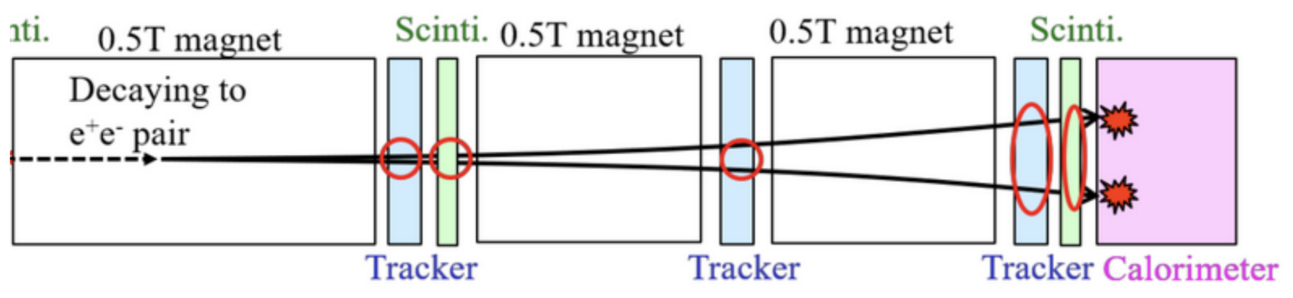
FASER

ForwArd Search ExpeRiment at the LHC

- Target: light, weakly interacting LLPs:
  - very rarely produced
  - along the beamline at low pT ~2% of pions produced within FASER angular acceptance
- Fast! LoI (2018), approved (2019), Installation (2020)
- Expected to start data-taking for Run3 (2022)
- Potential to increase sensitivity with FASER 2 for HL-LHC



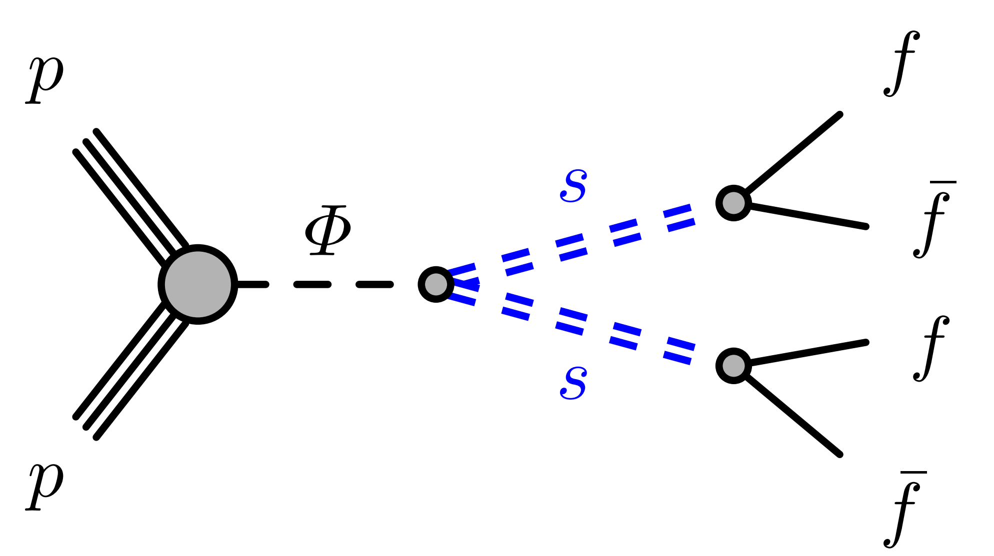


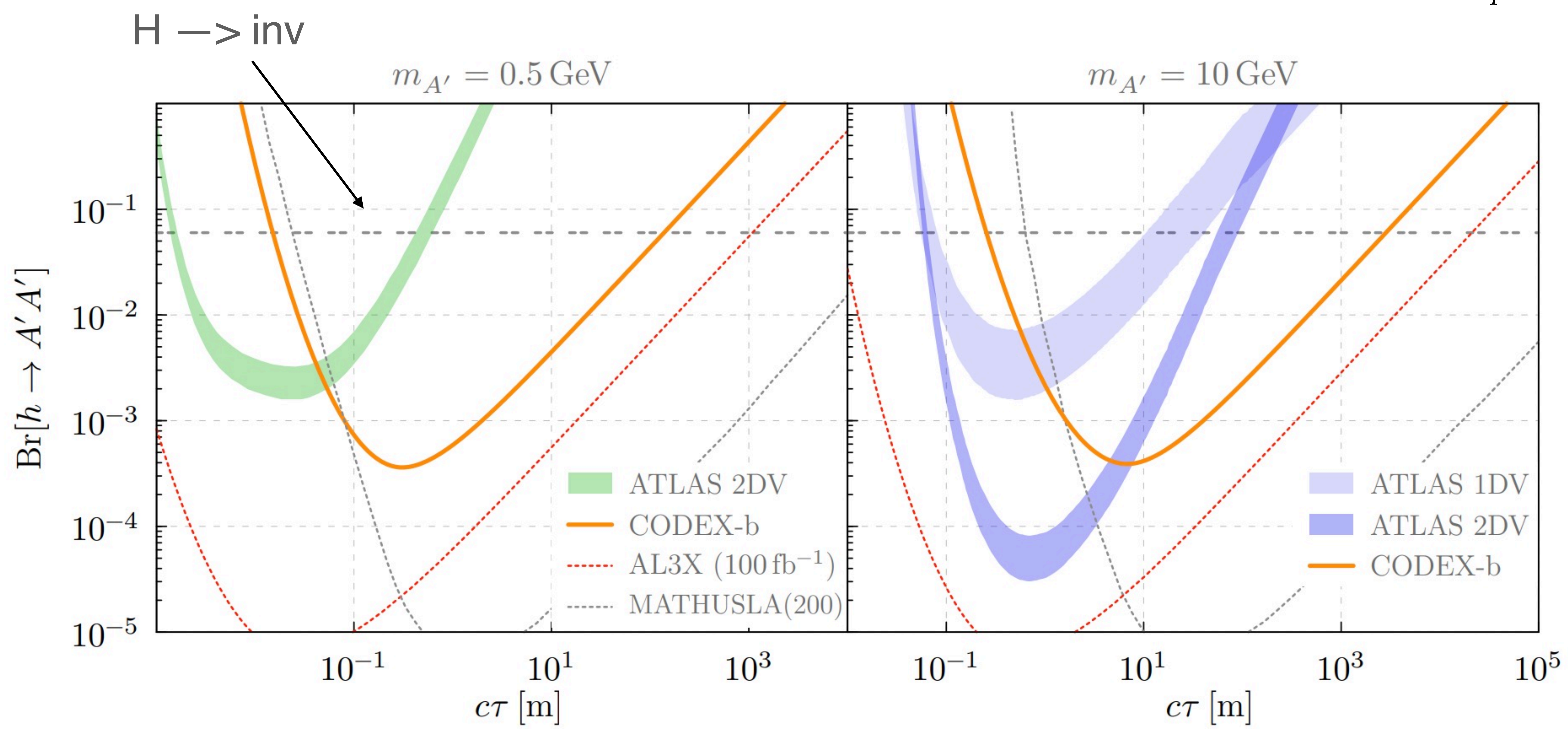


pp → A′(→ e+e-) + X, with E(A′)~TeV

1708.09389

Sensitivity — neutral LLPs, scalar mediators





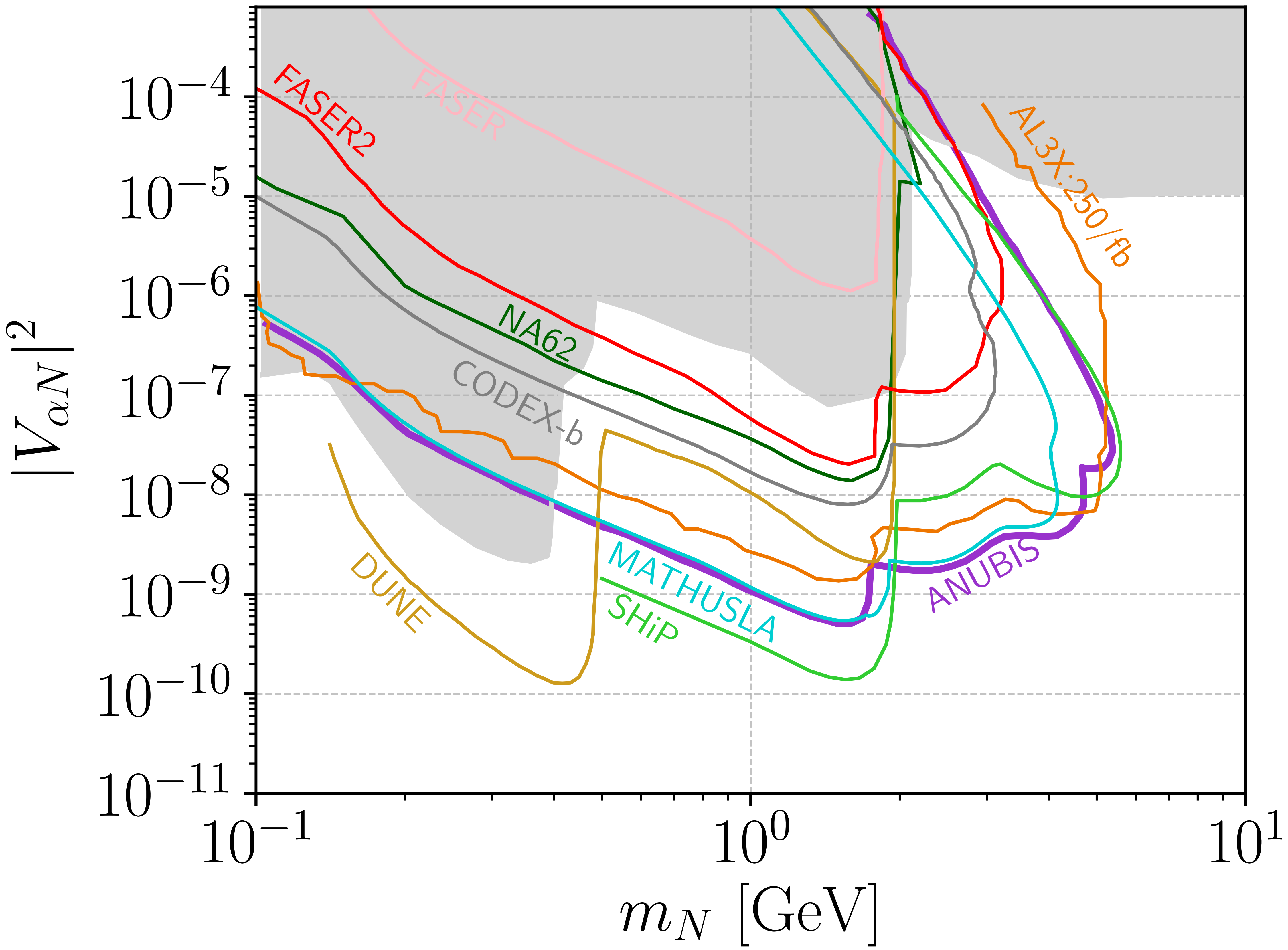
CODEX-b EoI: 1911.00481

- Mathusla: Good sensitivity for mass > 5 GeV and lifetime >> 100 m, even at low masses
- Codex-b 300/fb, complementary to MATHUSLA at shorter lifetimes

Sensitivity — neutral LLPs, HNLs

$\alpha = e, \mu$

$V_{\alpha N_j} \propto \sqrt{m_\nu / m_N}$



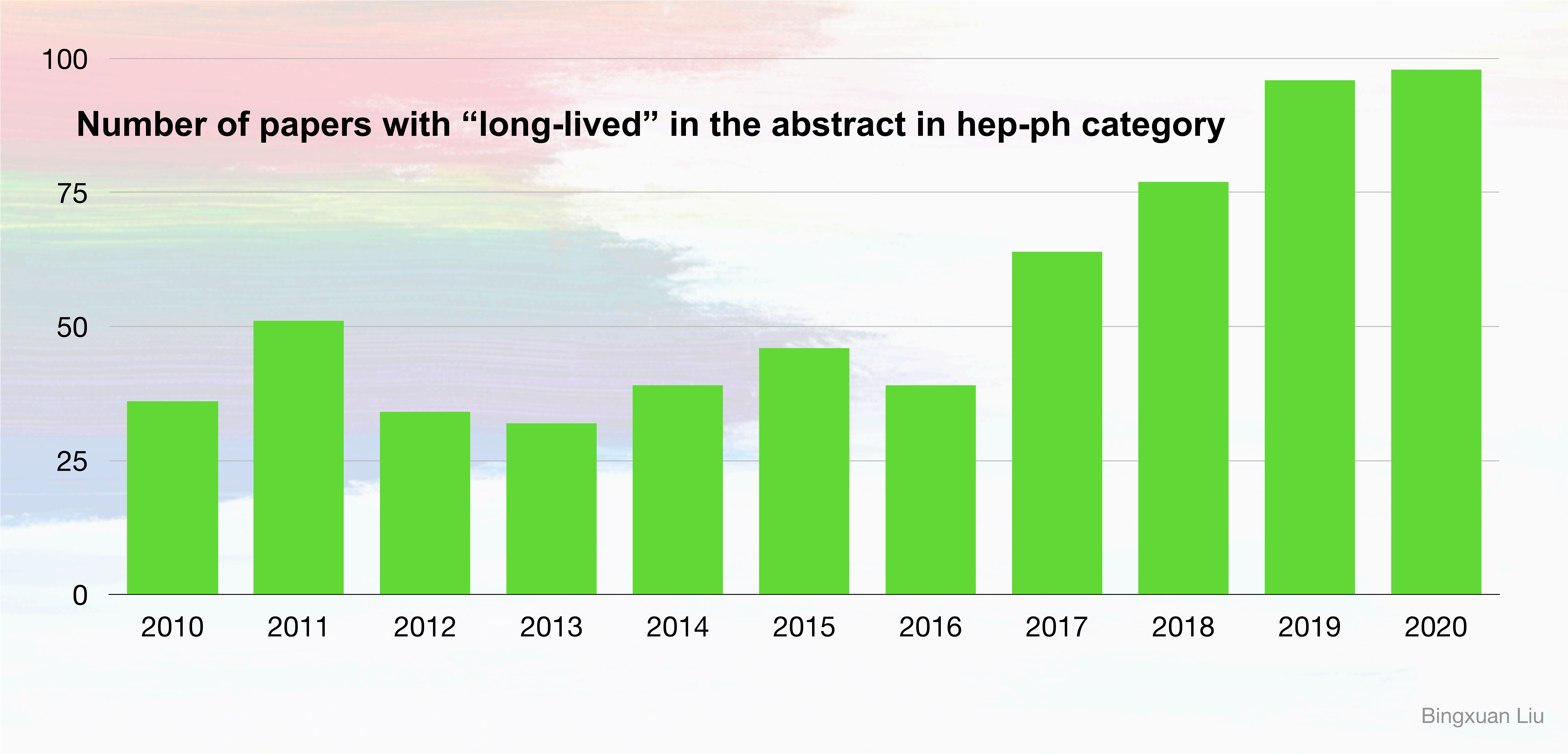
2001.04750

CODEX-b 300/fb
MATHUSLA 3/ab
ANUBIS shaft only 3/ab
FASER 3/ab
SHiP 2 × 10^{20} protons on target

- SHiP covers most of the space
- MATHUSLA, ANUBIS, AL3X better at masses > 1 GeV
- Complementarity between forward and transverse detectors!

Conclusions

- LLPs might be the key for finding BSM physics
- LLPs are gaining interest!



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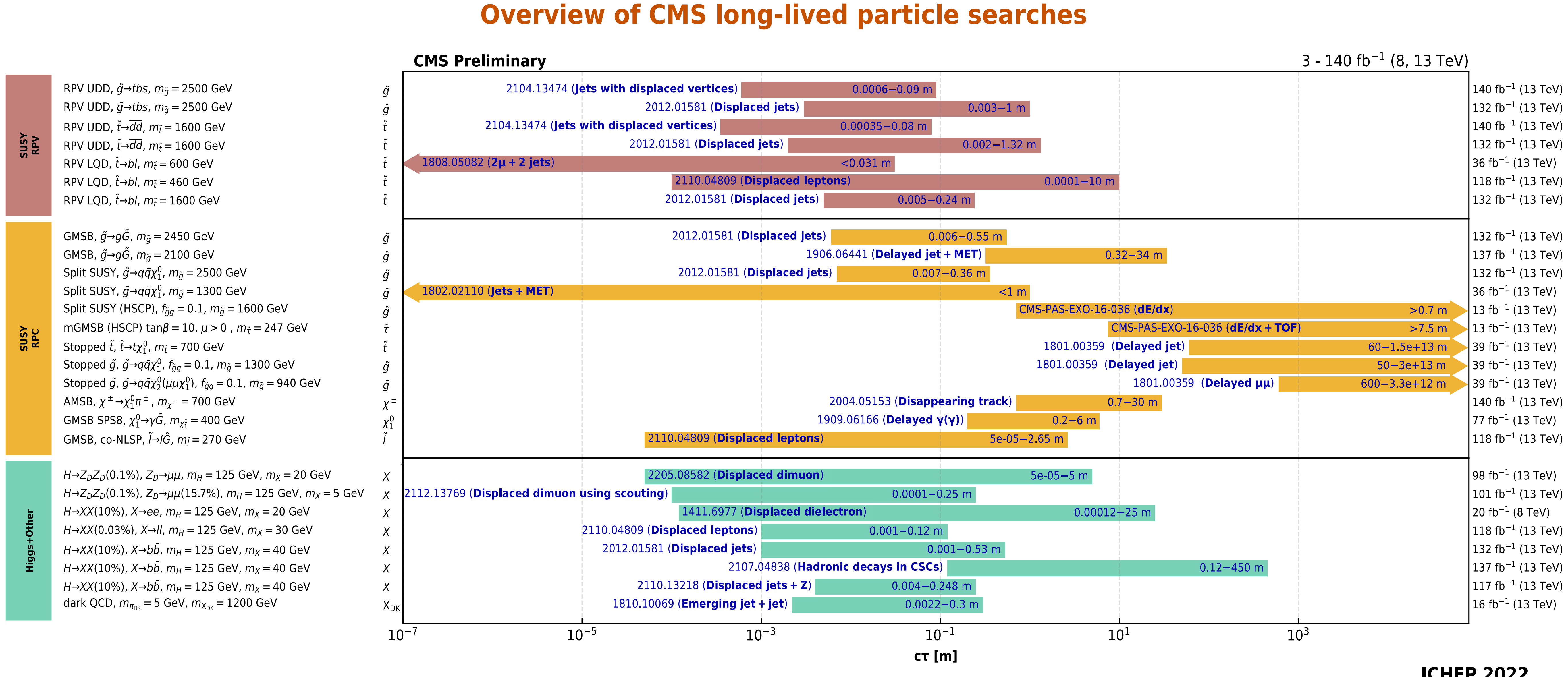
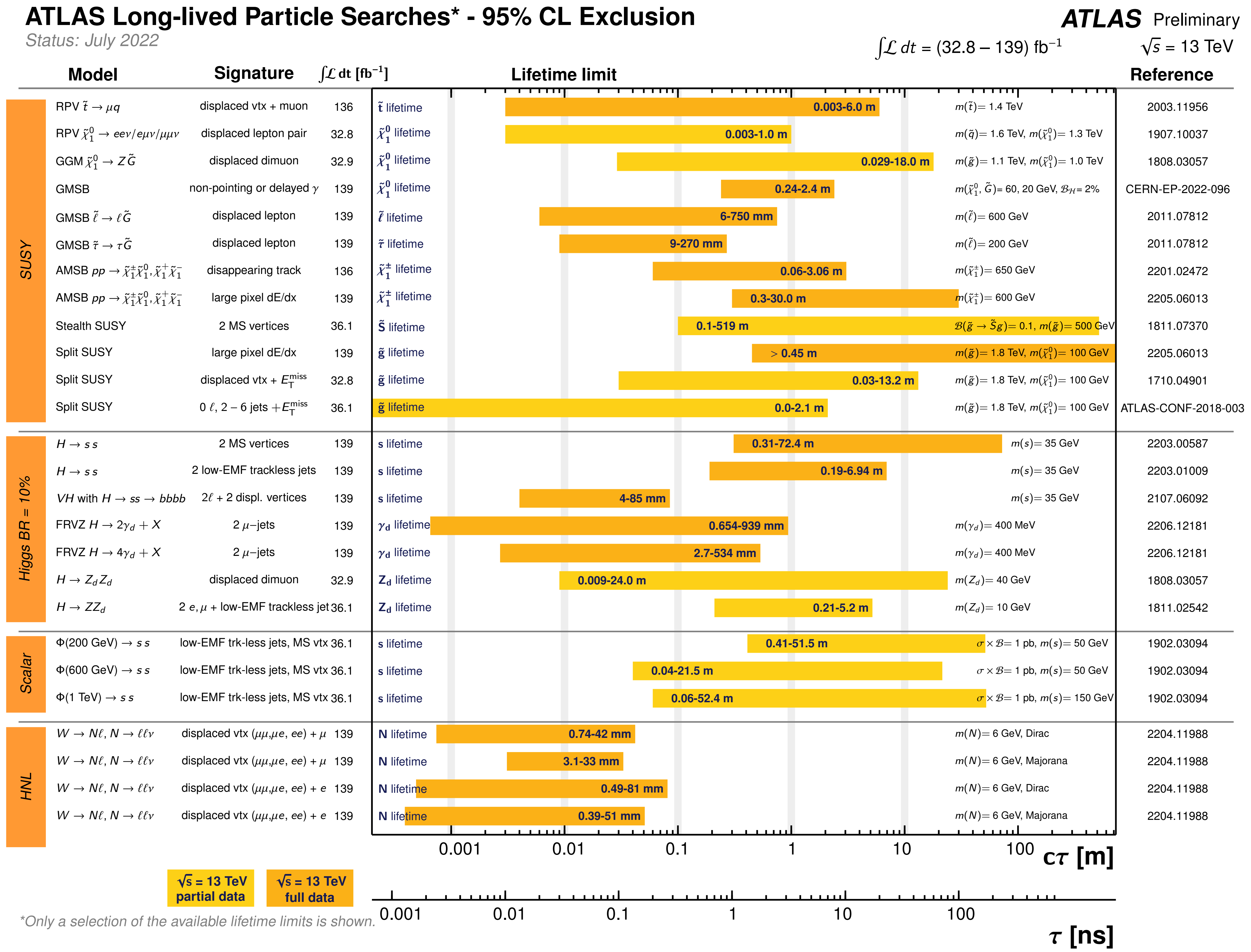
- Great effort at the LHC experiments to search for LLPs…



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



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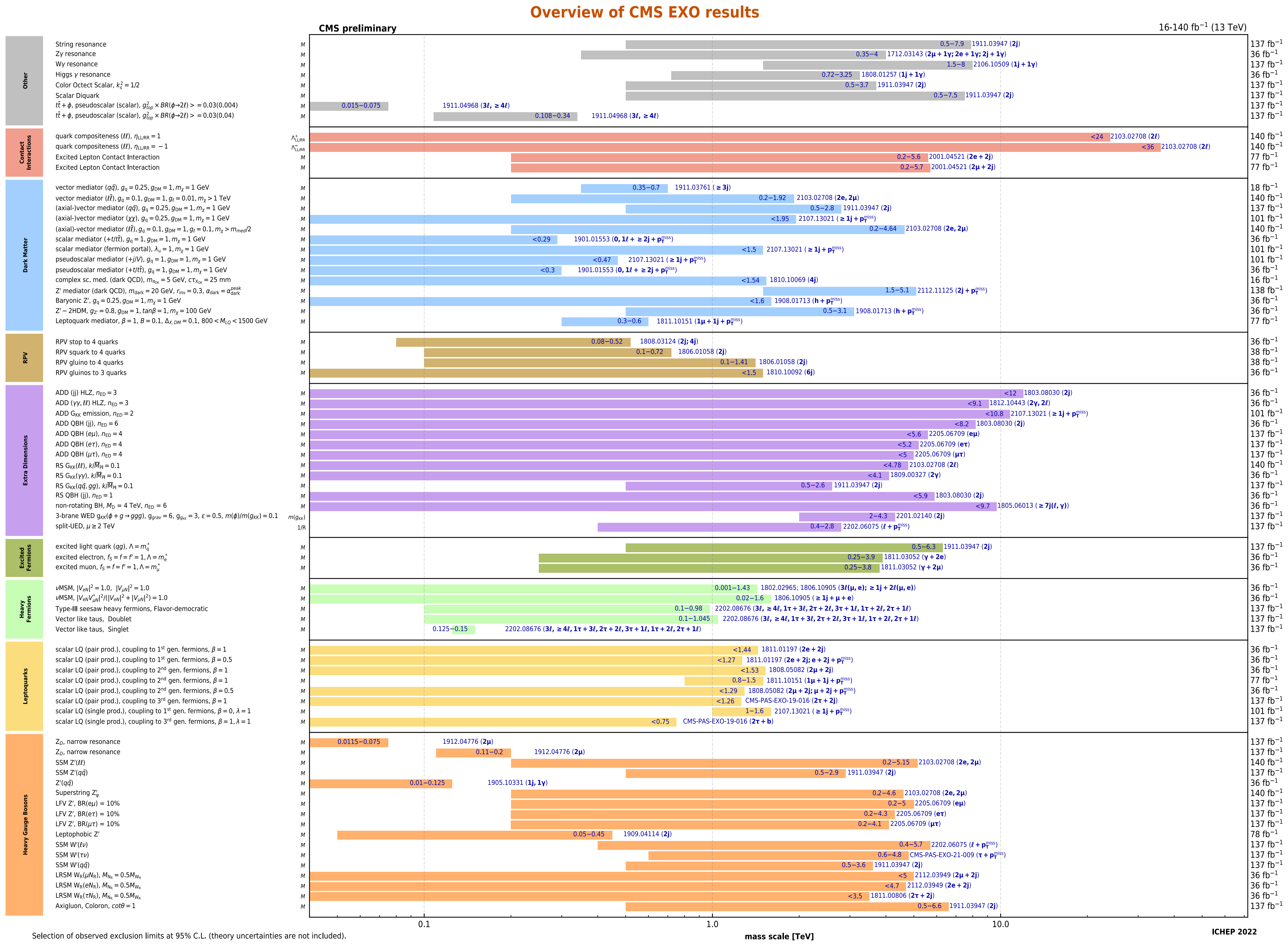
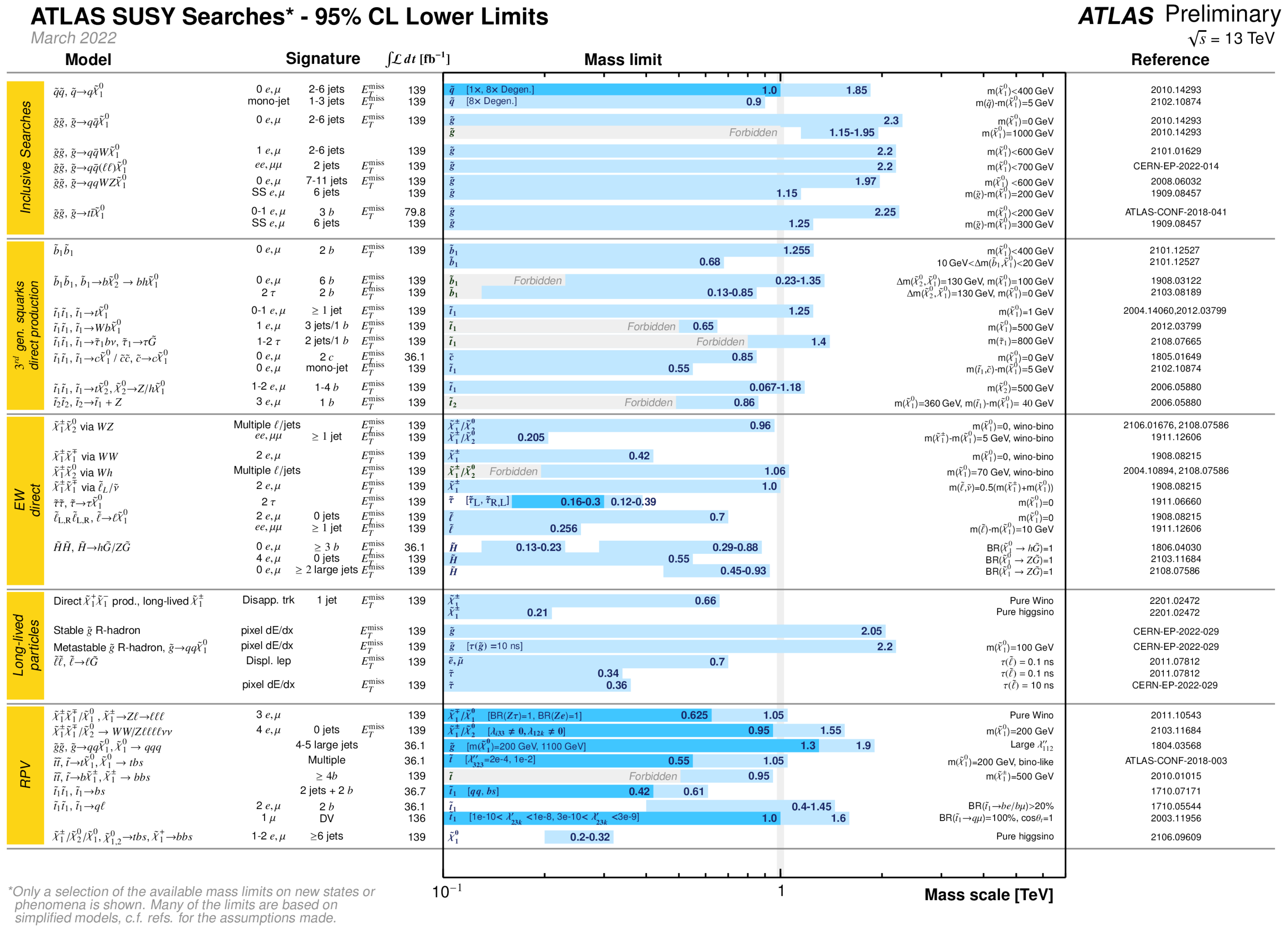
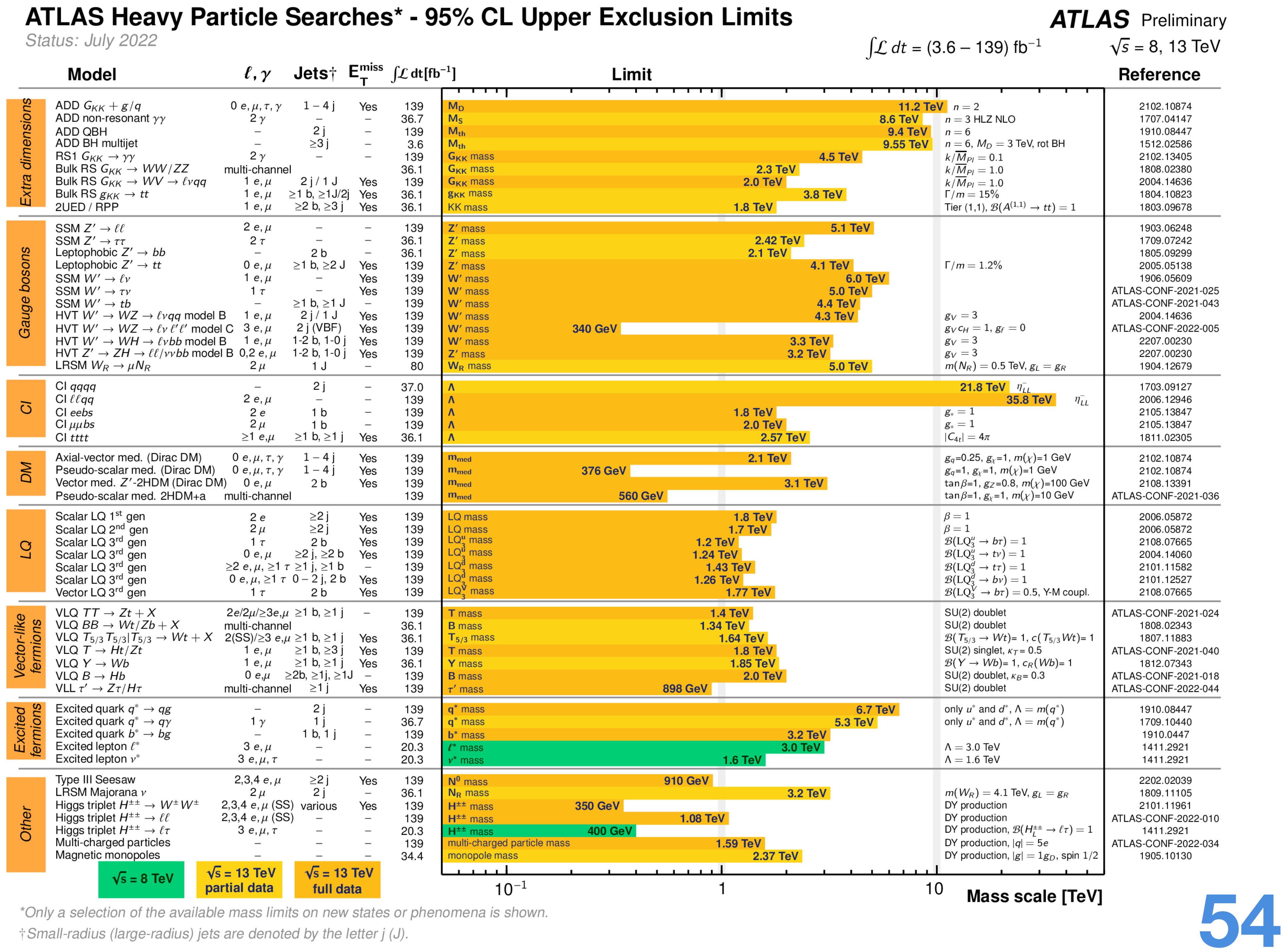
- Great effort at the LHC experiments to search for LLPs… BUT! still not even close to the effort in prompt searches







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- Run 3 and HL-LHC offer a great opportunity to innovate and plan for new unconventional searches yet to be explored
  - Development of new tools and strategies to improve identification of LLPs, pushing the detector beyond its original design capabilities

Conclusions

Most are young collaborations, happy to welcome new people

- LLPs might be the key for finding BSM physics
- LLPs are gaining interest!
- Great effort at the LHC experiments to search for LLPs… BUT! still not close to the effort in prompt searches

- Run 3 and HL-LHC offer a great opportunity to innovate and plan for new unconventional searches yet to be explored
  - Development of new tools and strategies to improve identification of LLPs, pushing the detector beyond its original design capabilities
- **The LLP community is growing**

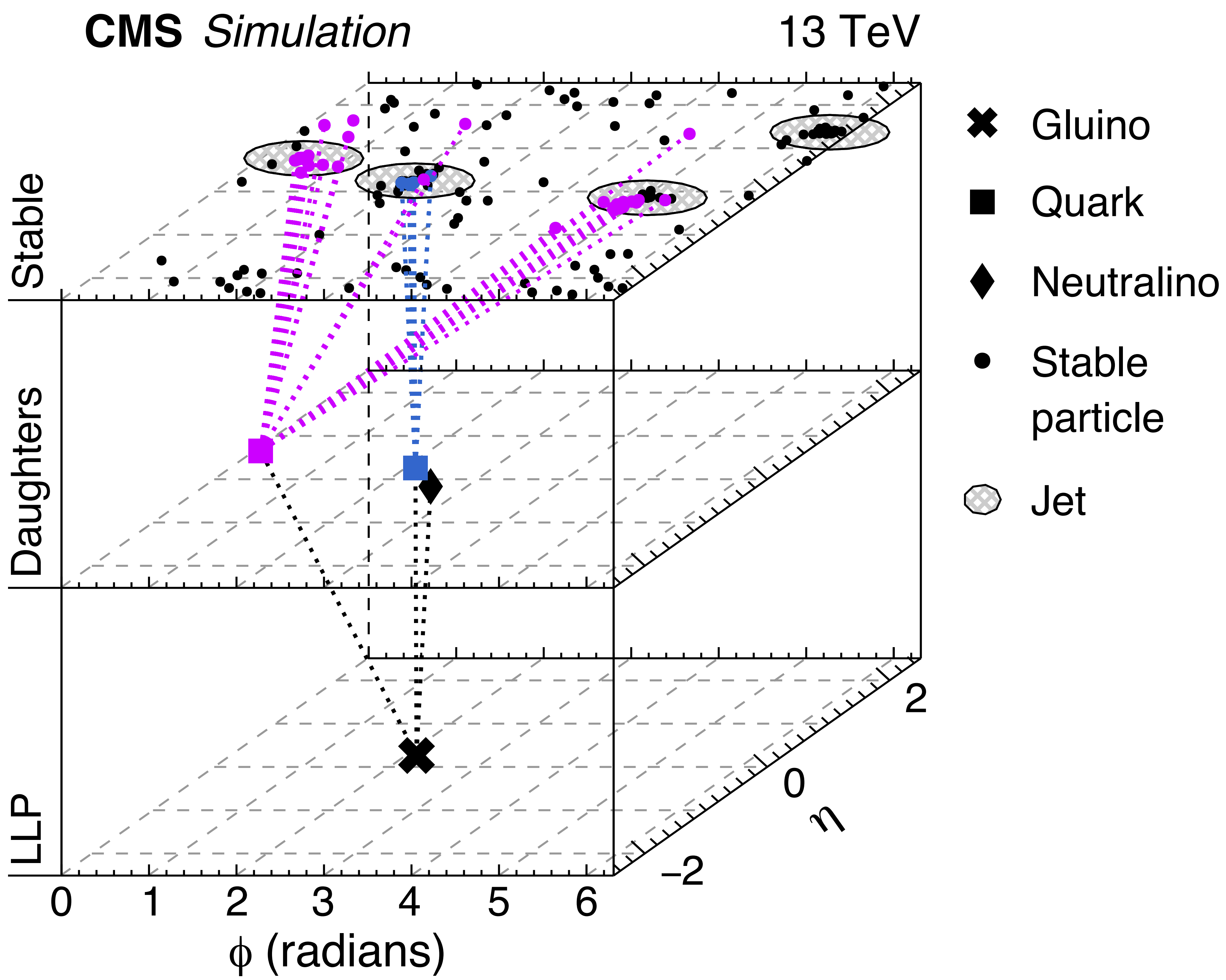
LHC LLP WG

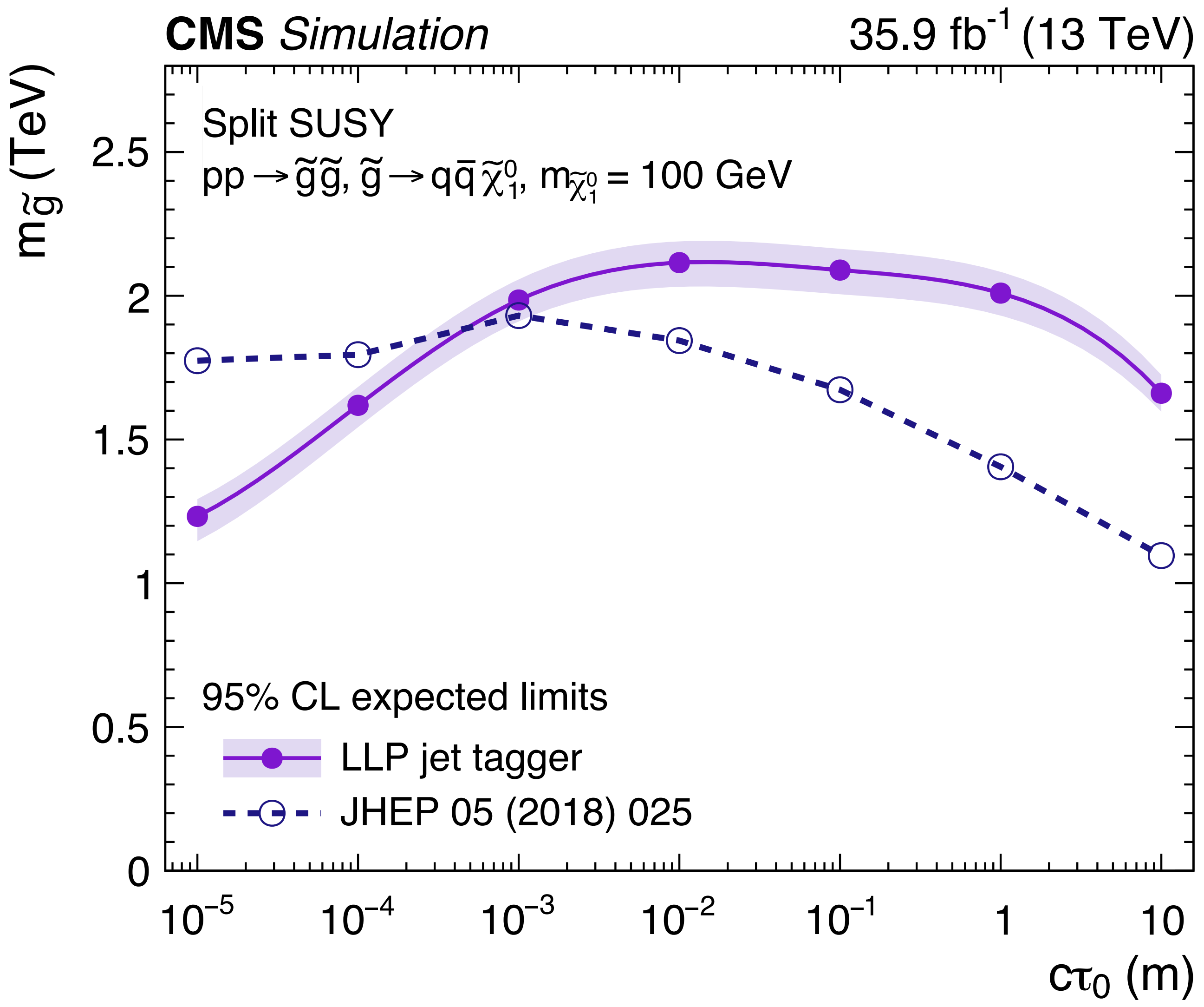
Backup

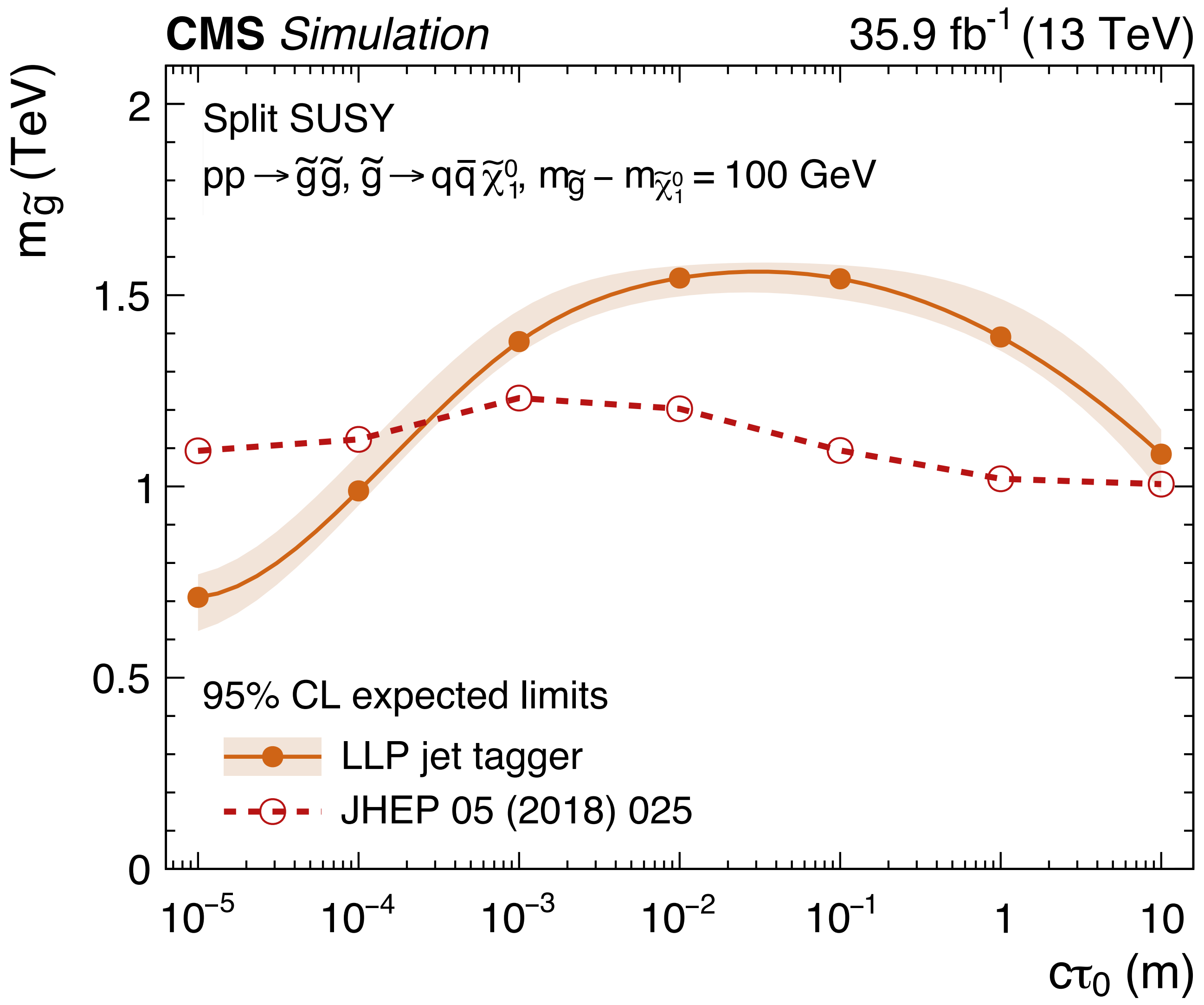
Improving object identification: Machine learning

CERN-EP-2019-281

- Identification of displaced objects is very challenging
- The use of machine learning techniques for the identification of LLPs is getting extended:
- CMS: deep neural network to identify displaced jets
  - for charged and neutral LLPs decaying hadronically
  - with and w/o DV
- using information from all jet constituents







Using the LLP jet tagger, limits are improved in a very noticeable way!

LLP decays in the ID - unconventional tracking

- Search for a low-mass dimuon resonance
- The X bosons can either decay promptly or displaced: lifetime O(1) ps
- The searches for displaced $X \rightarrow \mu^+\mu^-$ decays consider **masses up to 3 GeV**.
- dataset: run 2: 5.1 fb-1

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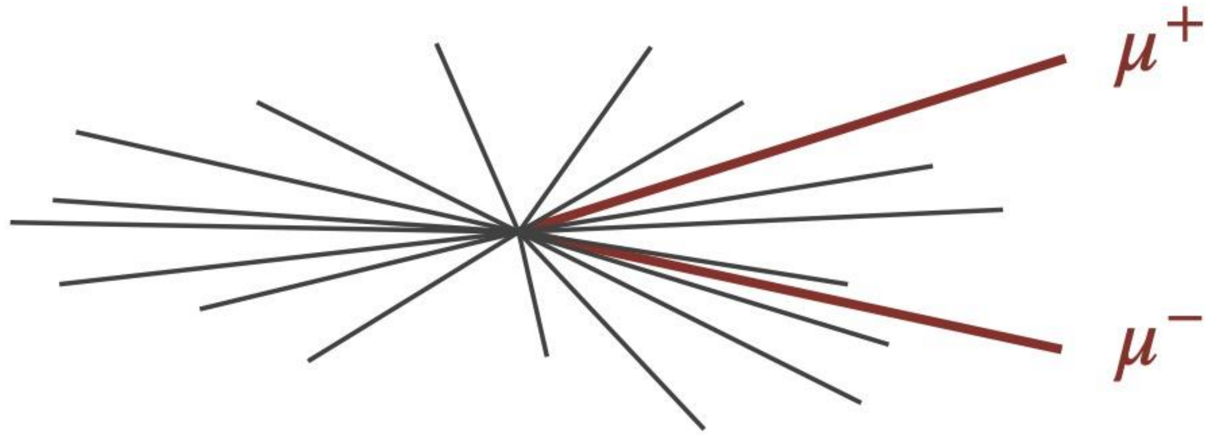
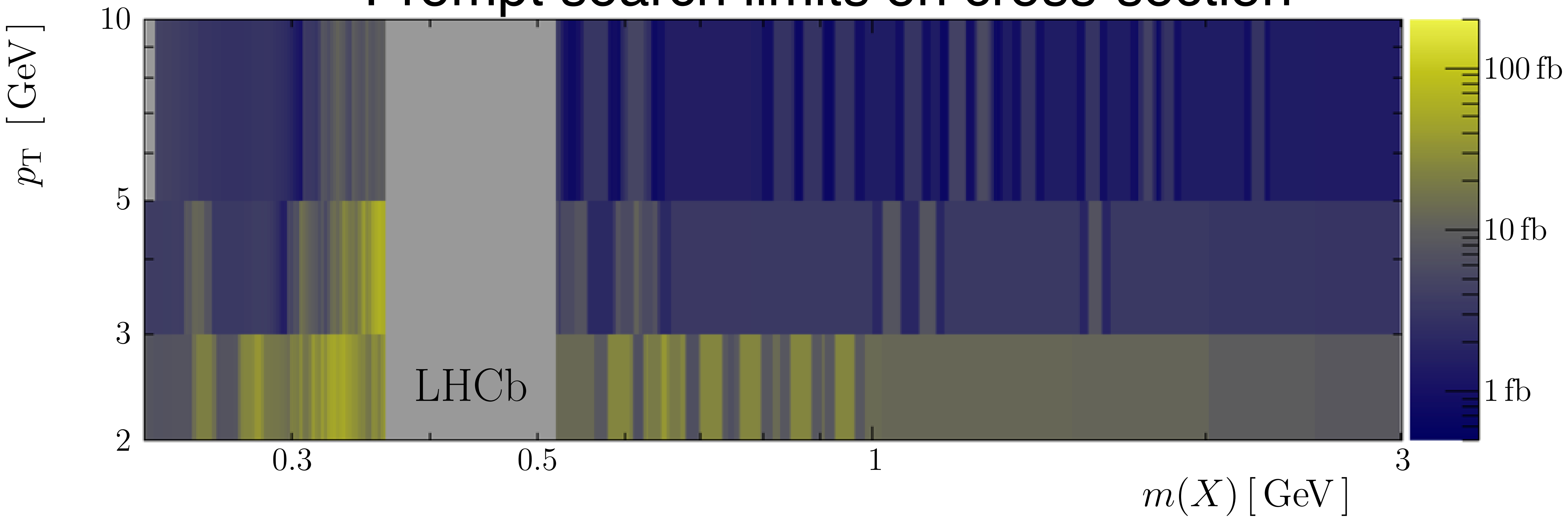
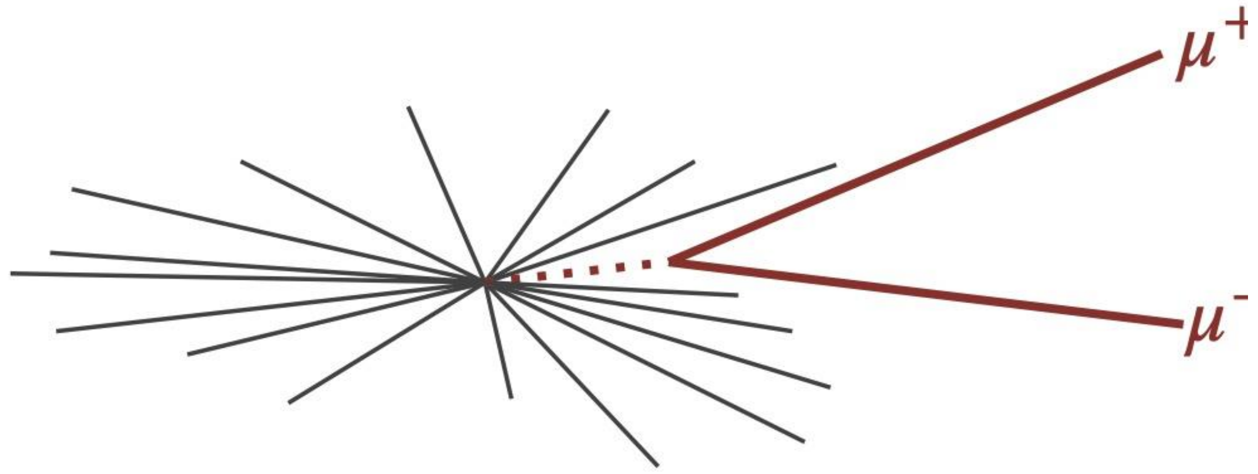
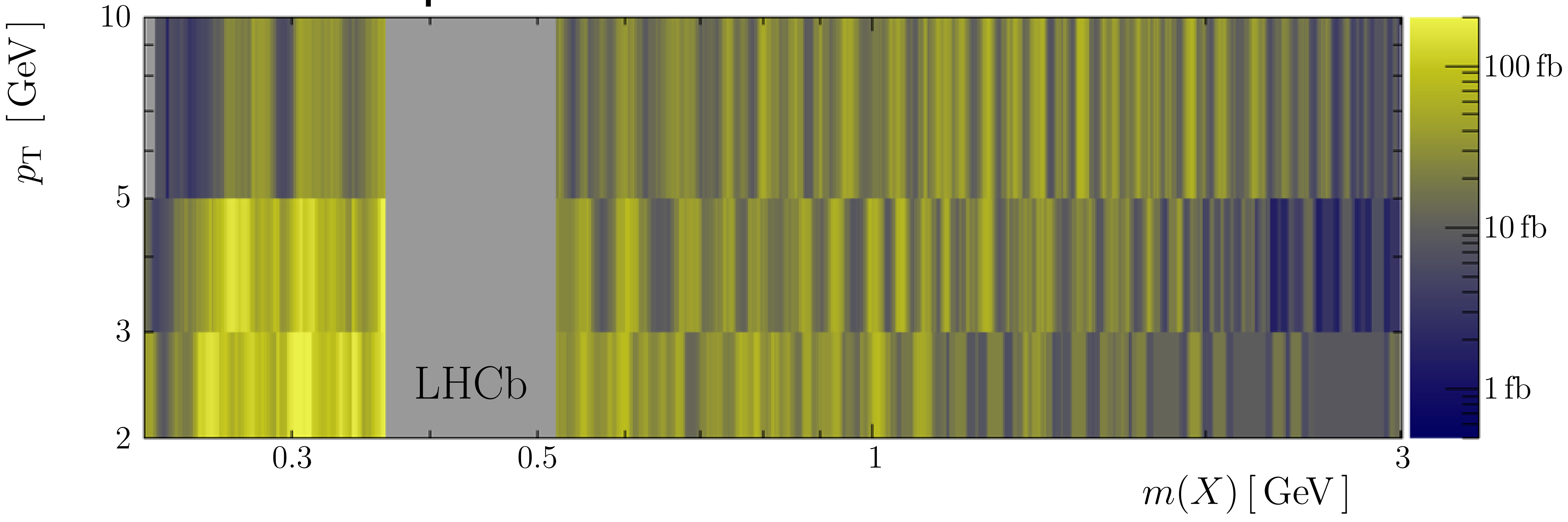


Prompt search limits on cross-section





Displaced search limits on cross-section



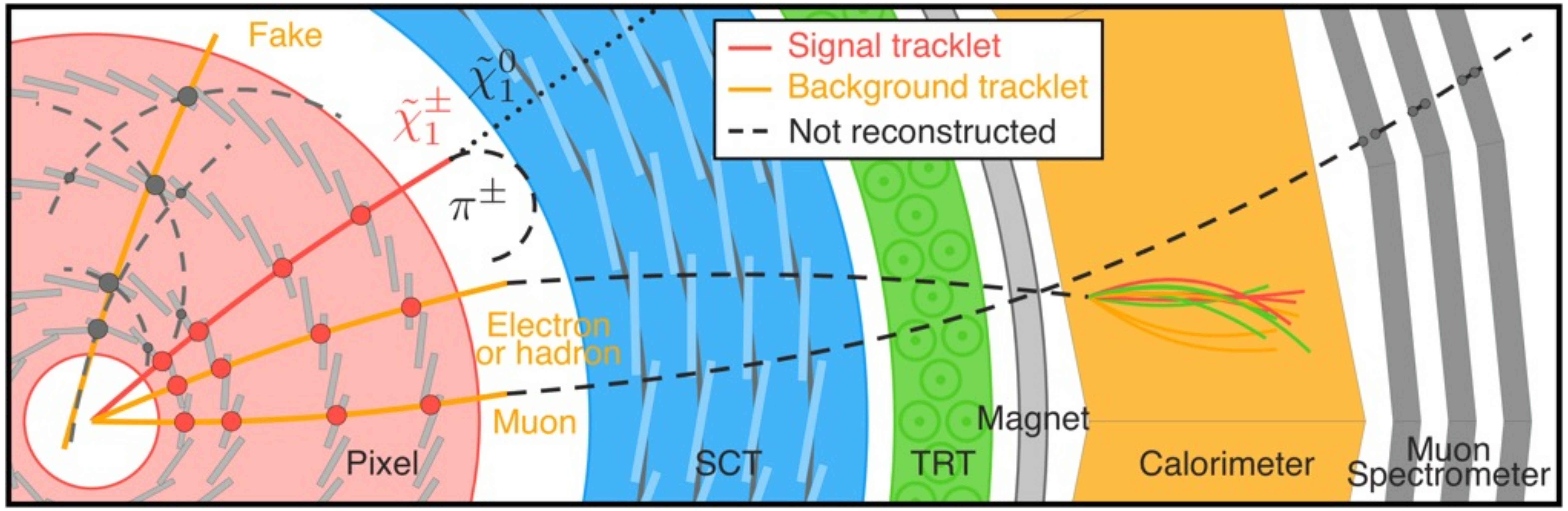
- Exclusion both in the prompt and displaced cases for masses below 3 GeV!

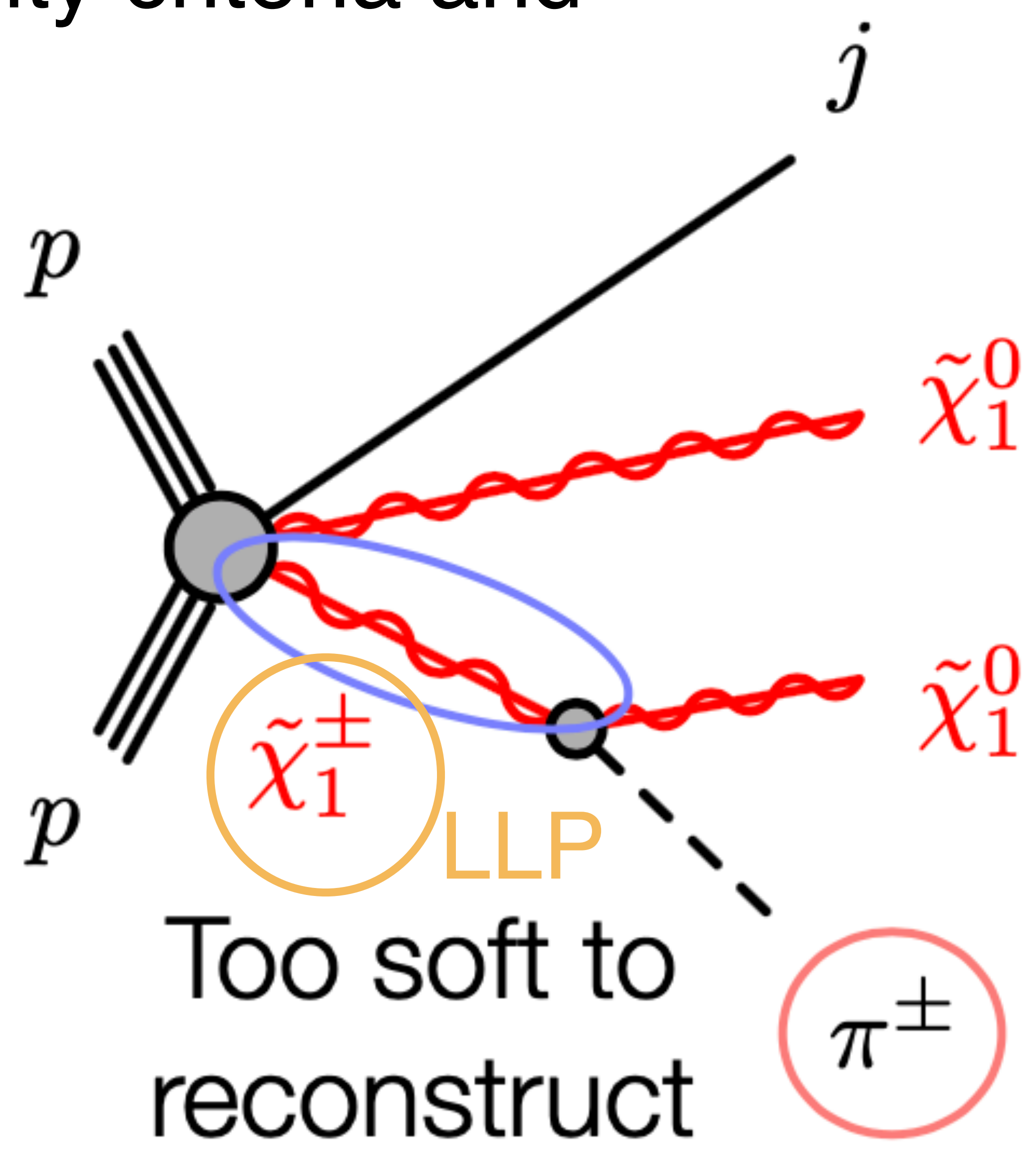
LLP decays in the ID - unconventional tracking

Disappearing tracks

ATLAS-CONF-2021-015

- Unconventional tracking can be used to search for multiple types of displaced objects
- Example: SUSY scenario with very small mass gap between neutrino and chargino:
    - Chargino becomes long-lived
    - Pion is too soft to be reconstructed
- MET trigger
    - High threshold, not optimal!
- Disappearing track: lacks hits in the outermost silicon layers and no calorimeter activity
- Significant improvement over previous results due to additional track quality criteria and increase in integrated luminosity



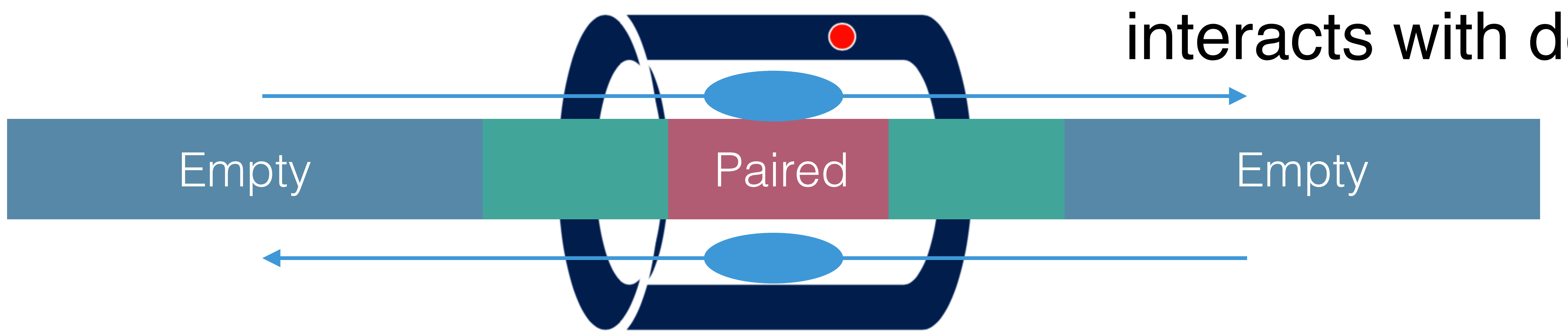


LLP decays in the calorimeters

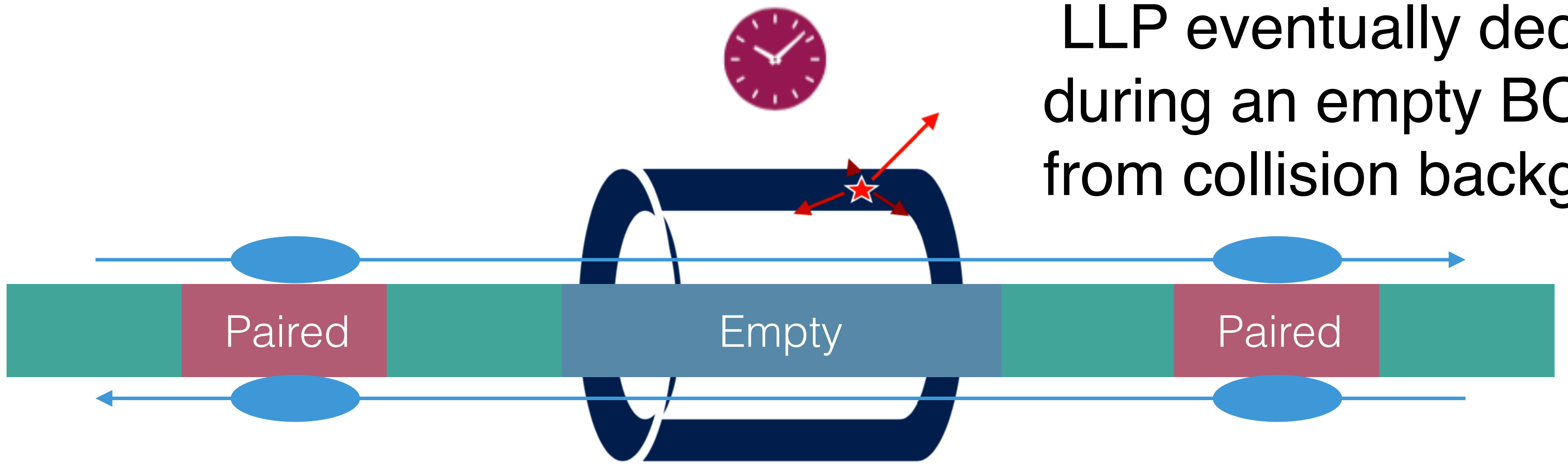
Stopped particles

CERN-EP-2021-041

- Search for late decays to hadronic jets from LLPs
- Benchmark: gluino R-hadrons with very high squark masses inducing large gluino lifetime
- Dedicated jet+MET trigger, recorded in empty bunch crossings (BC) to reduce background
- All backgrounds are non-collision in out-of-time BCs: cosmic-ray muons, beam-induced, cavern background
- Require special reconstruction configuration

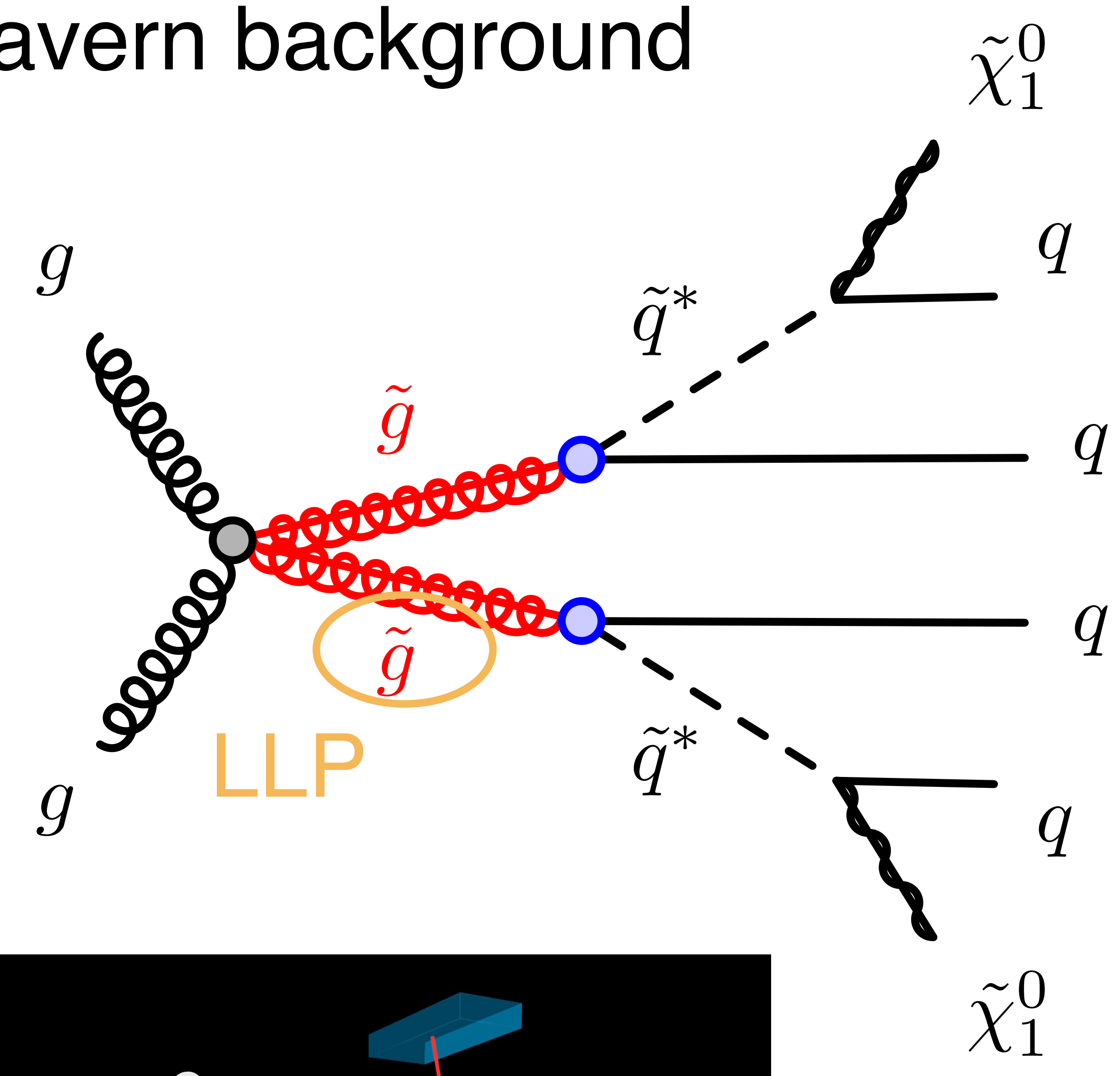


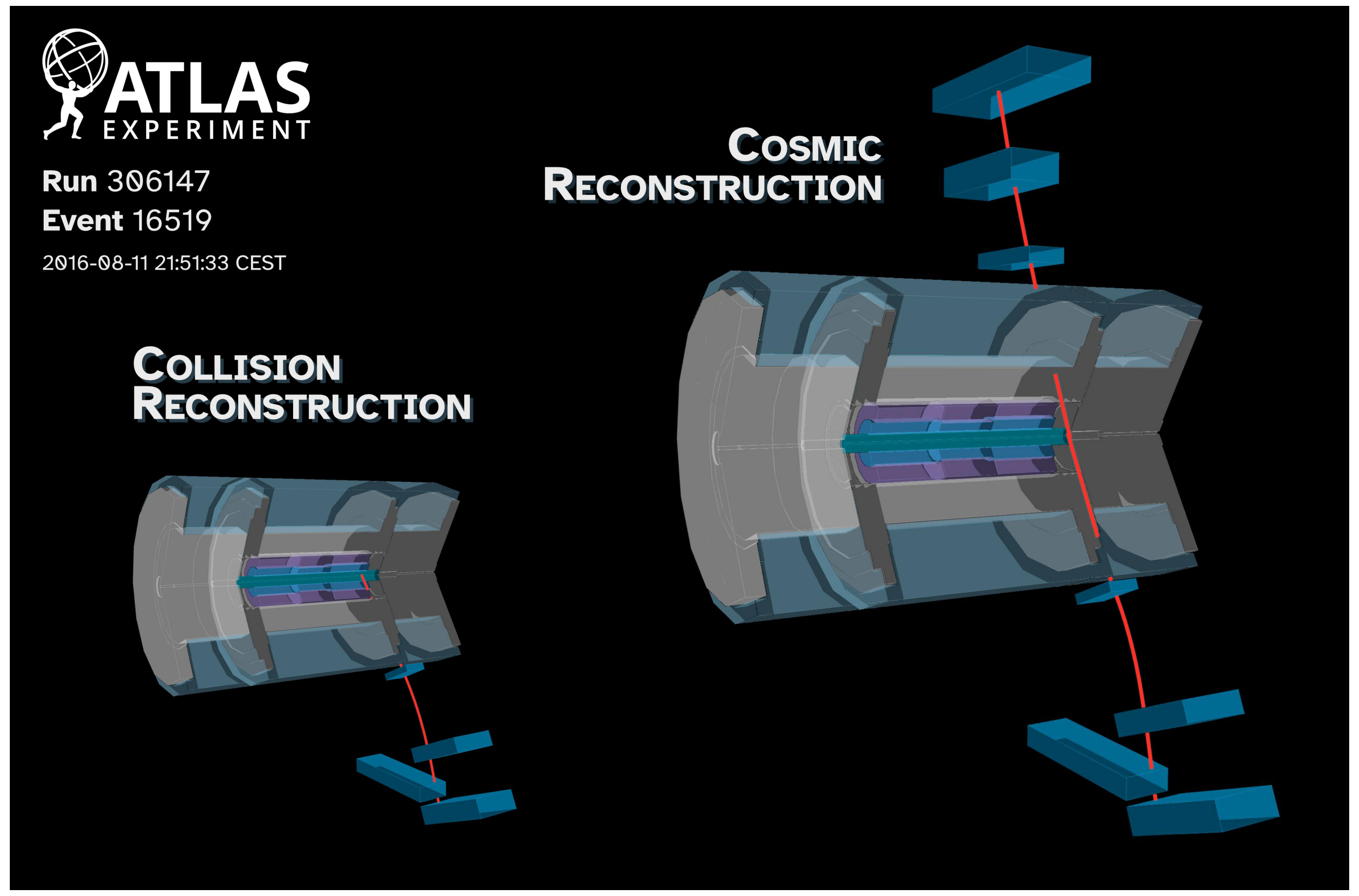
LLP produced in a paired BC interacts with detector and stops



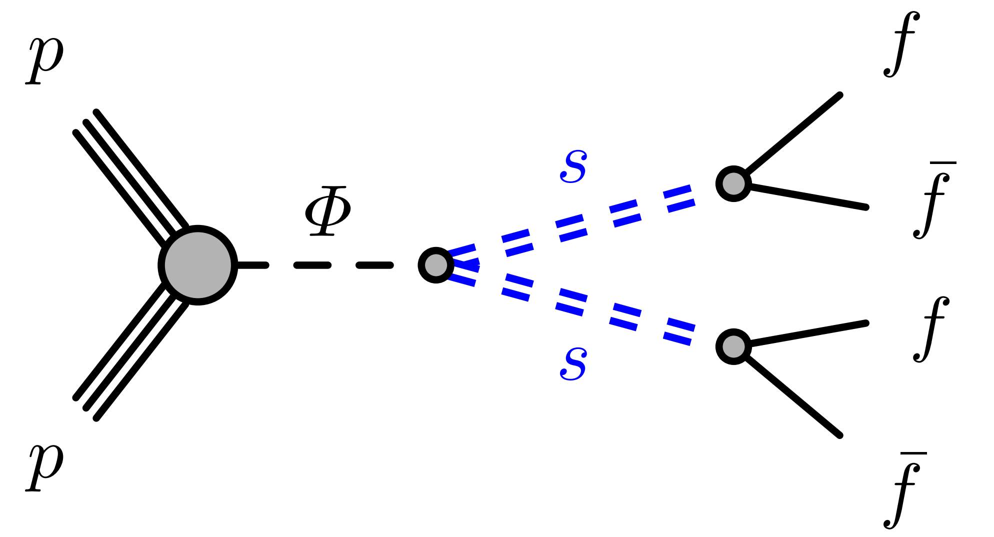
LLP eventually decays during an empty BC: free from collision background

Fig. inspired by C. Sebastiani





Sensitivity — neutral LLPs @ LHC
Scalar mediators



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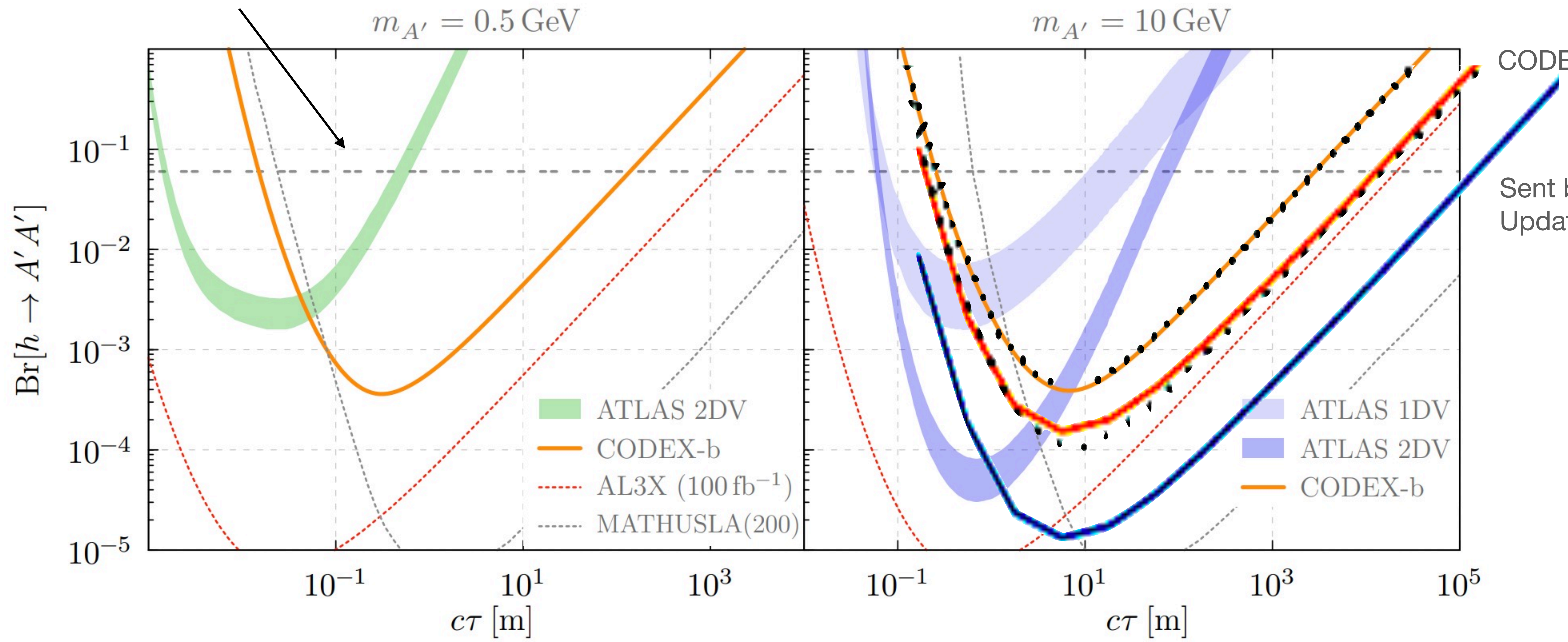


CODEX-b EoI: 1911.00481

Sent by Oleg Brandt
Updated from 1909.13022

- Mathusla: Good sensitivity for mass > 5 GeV and lifetime >> 100 m, even at low masses
- Codex-b 300/fb, complementary to MATHUSLA at shorter lifetimes

Anubis Cavern + shaft, 3/ab, 50 events
Anubis Cavern + shaft, 3/ab, 4 events
Codex-b 10m x 10m x 10m, 300/fb
Codex-b 20m x 10m x 10m, 1/ab

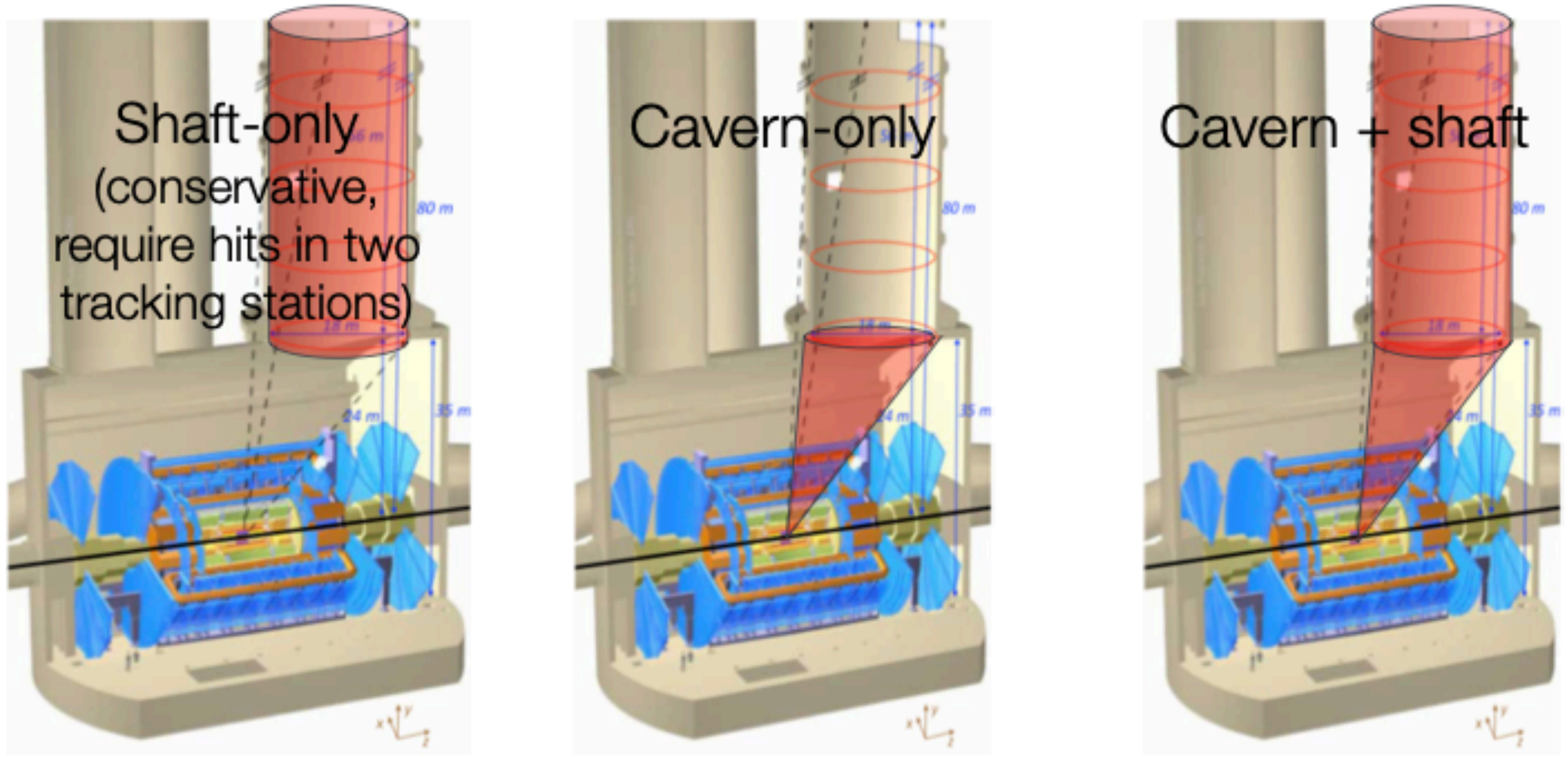
Background as in ATLAS MS vertex search
Similar reach as Codex 1/at

ANUBIS

An Underground Belayed In-Shaft

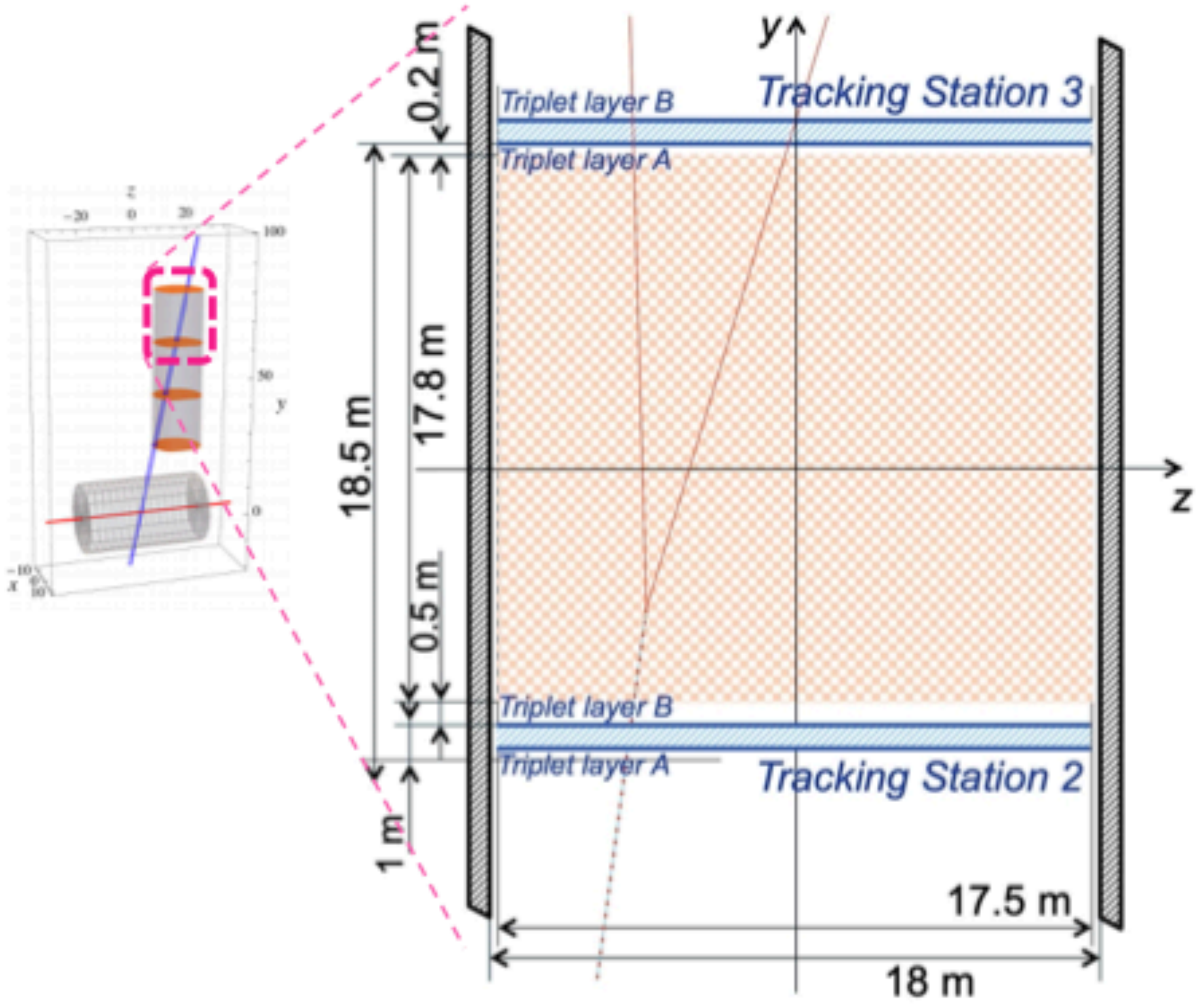
Proposal: 1909.13022

- Instrumenting ATLAS access shaft (56m) for HL-LHC
  - 3 possible configurations using the shaft and/or part of the cavern



- Plan: installing a demonstrator for Run 3

- 4 RPC layers for tracking
- Use timing to reject cosmic rays
- Can be combined with ATLAS information as veto and background estimator

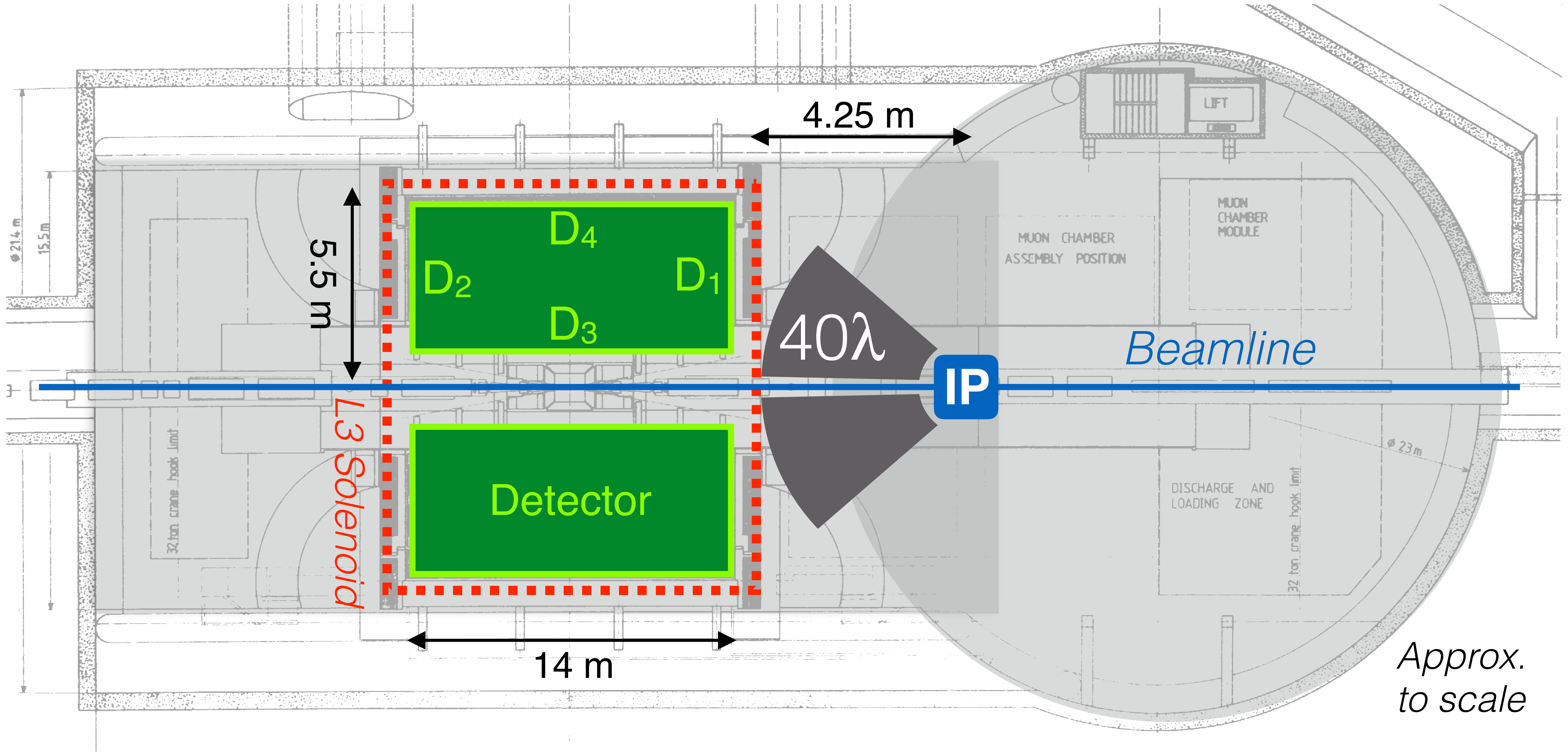


Al3X

A Laboratory for Long-Lived eXotics

Proposal: [PRD.99.015023]

- Use ALICE's cavern and magnet for LLP searches
- Implies that ALICE is removed!
- Requires upgrading IP2 to run at the nominal LHC luminosity
- The IP has to be moved so that the LLP has enough space to decay (would require adjusting magnets)
- Use existing magnets for momentum measurements
- Add absorber, aiming at zero background
- Quite unlikely to be built, but a good example on how to use existing caverns for LLP detectors

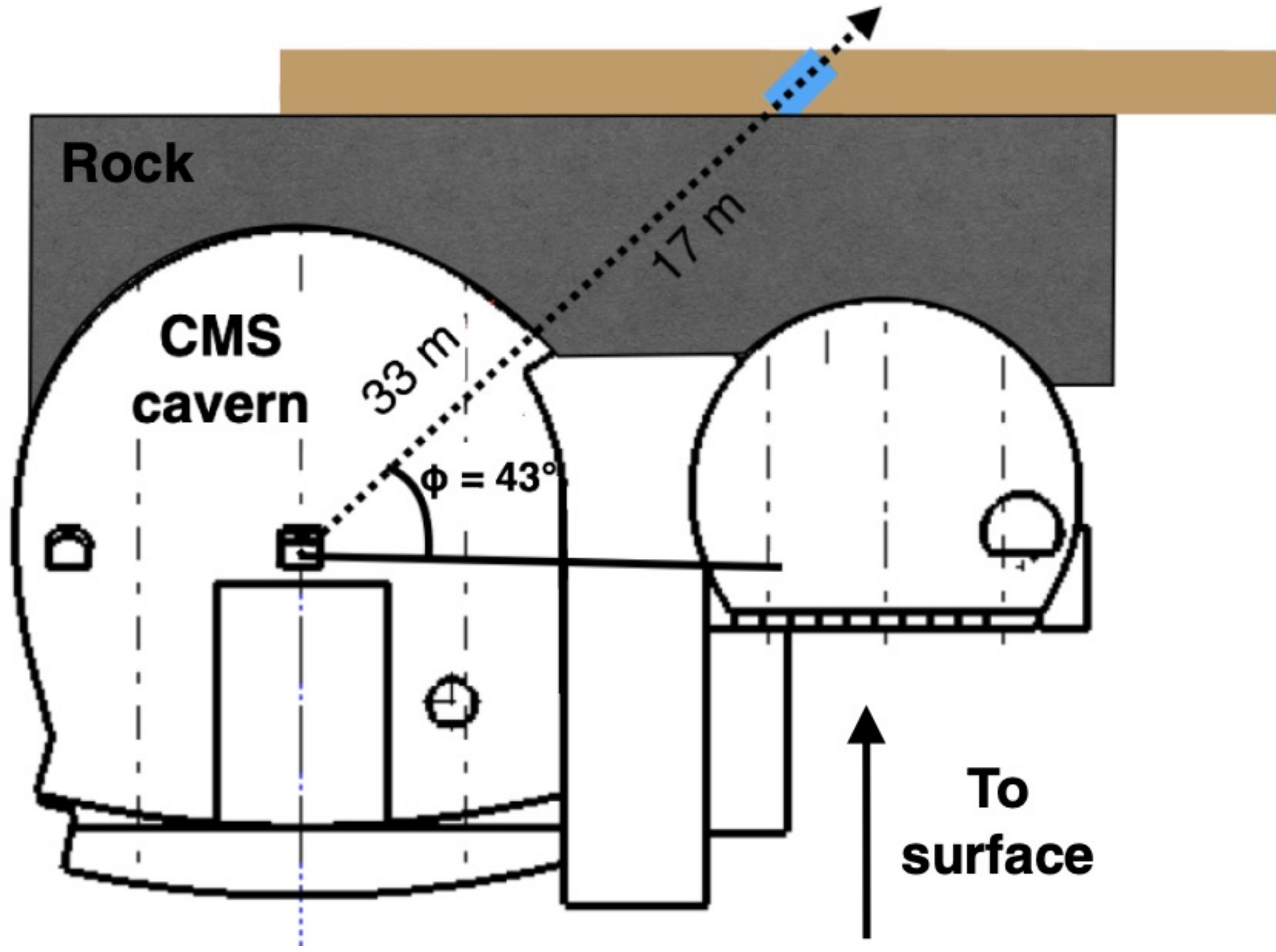


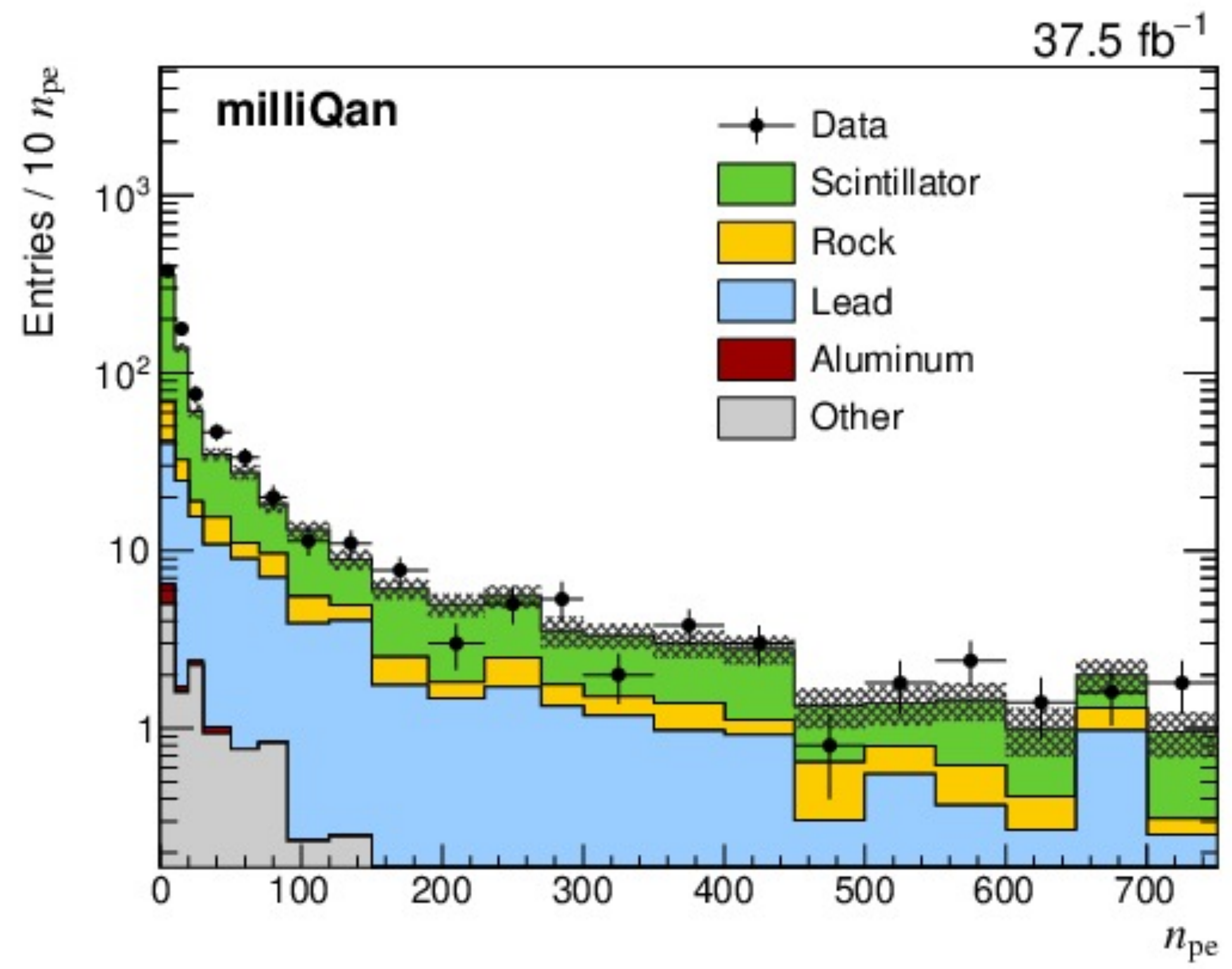
[2104.07151v1](https://arxiv.org/abs/2104.07151v1)
[1607.04669](https://arxiv.org/abs/1607.04669)

THE MILLIQAN EXPERIMENT

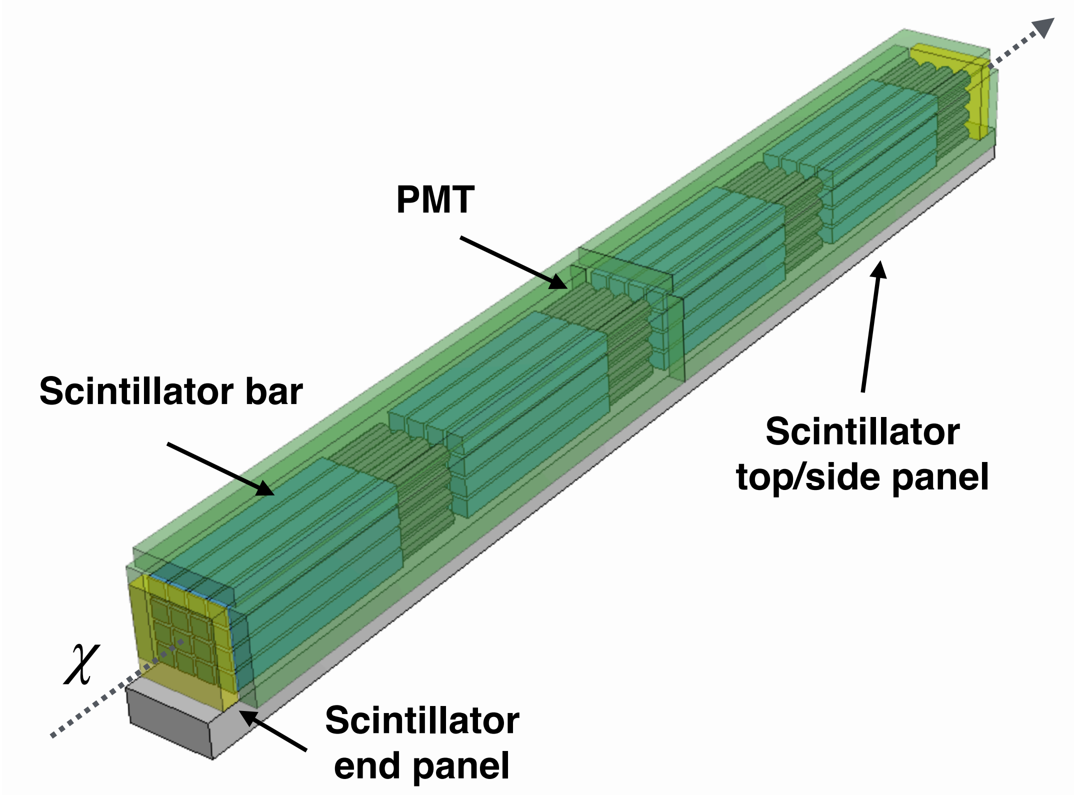
- Target Millicharged particles in dark QED with mass O(GeV)
- 70m underground (shielded from cosmics) and 33m from CMS IP (17m of rock, shiel from LHC)
- Scintillator bars + PMTs allow small ionisation signal from mCPs to be detected

- Prototype took data in 2018 (~1% of full detector), confirmed background expectatior

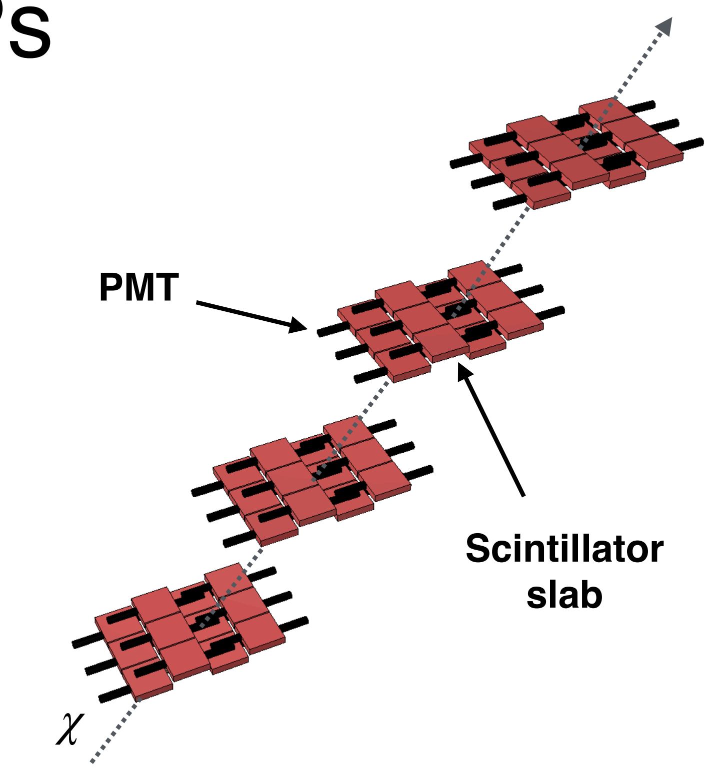




- Two detectors for Run 3
  - Bar detector (upgrade from milliQan demonstrator)
    - 0.2 m x 0.2 m x 3 m plastic scintillators bars
    - Background estimation validated with demonstrator



- Slab detector
  - 40 cm x 60 cm x 5 cm scintillator slabs
  - Helps with background rejection
  - Increased reach for heavier mCPs

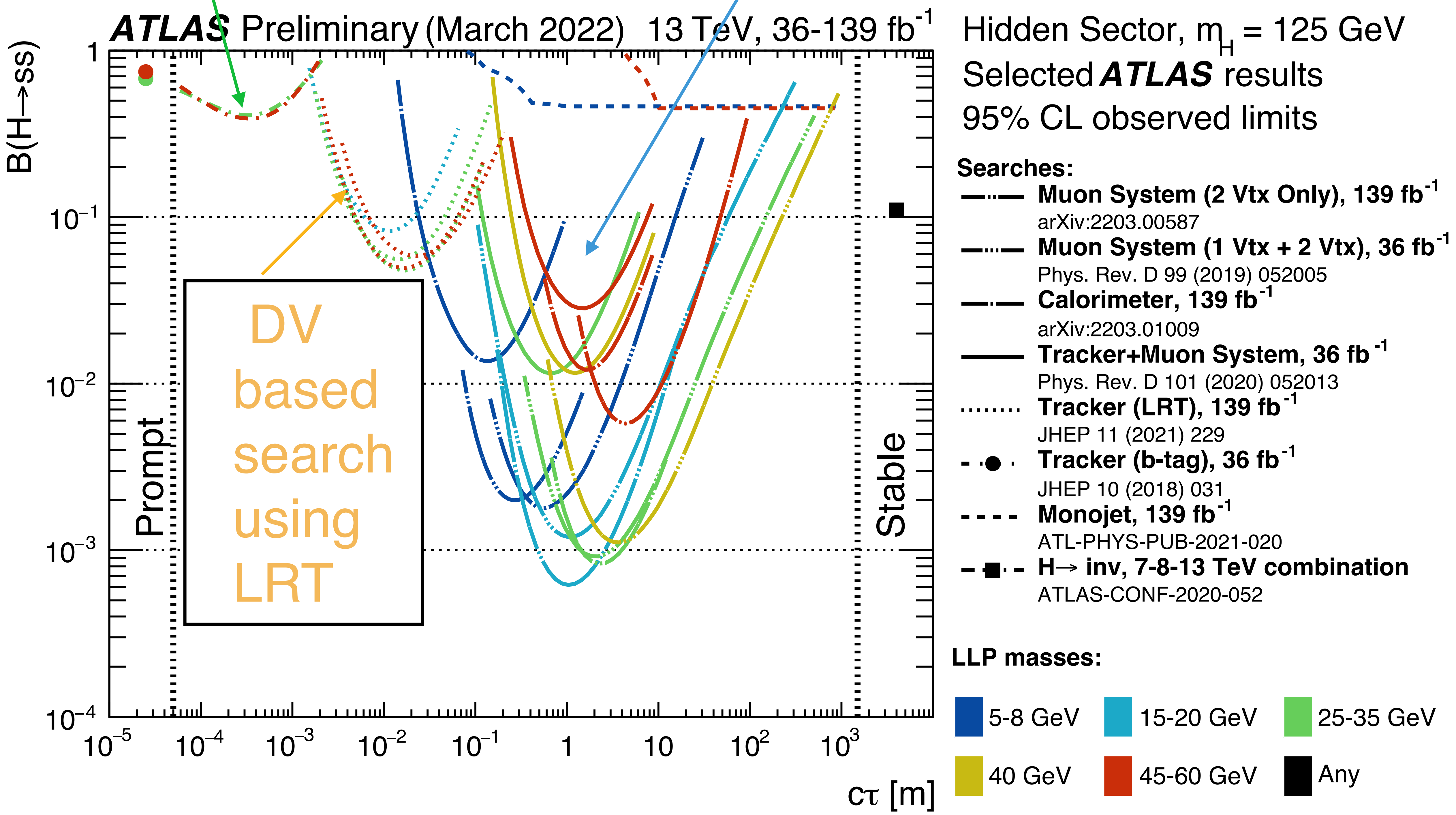


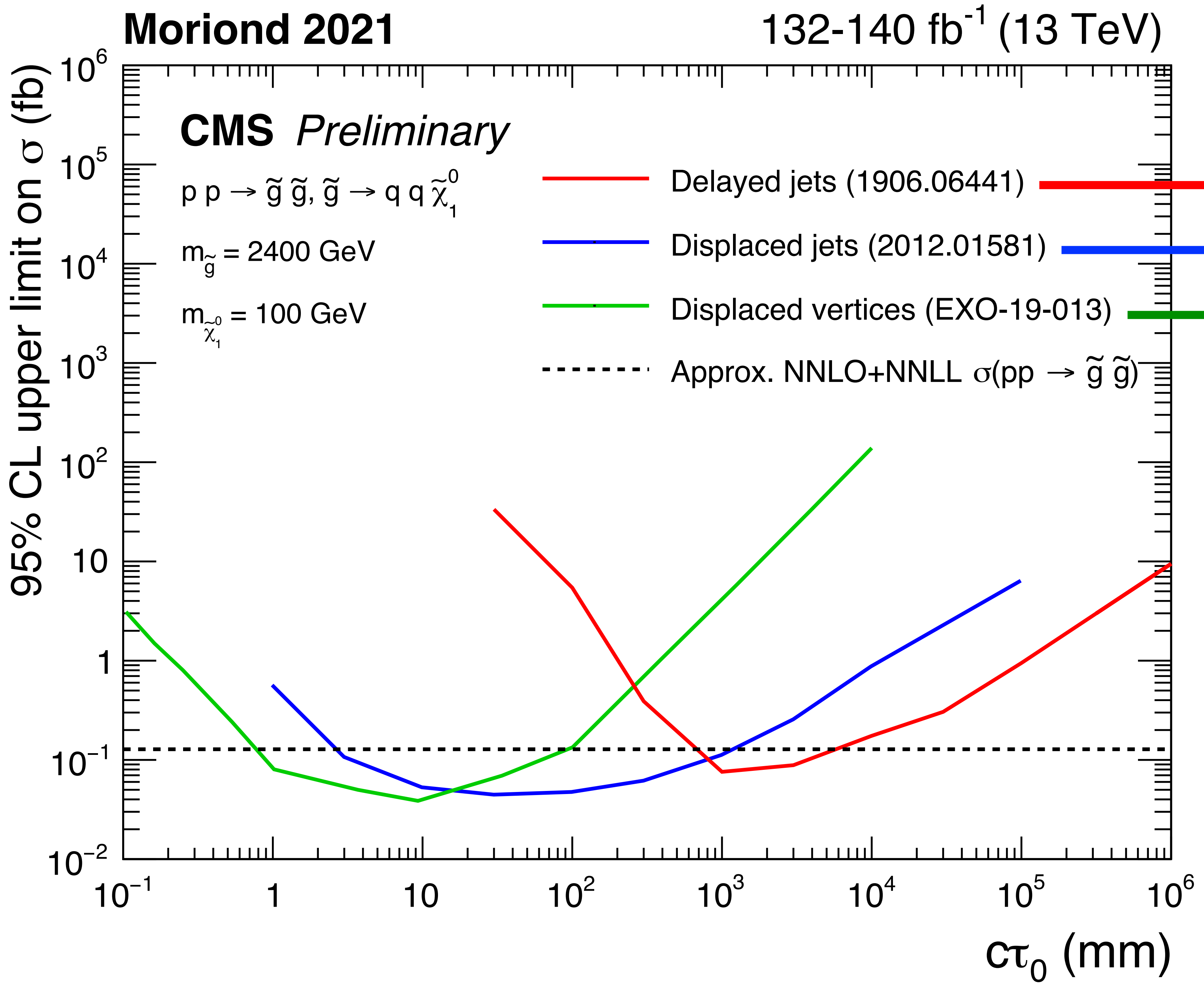
Complementary searches

- Searches for signatures in different subdetectors can be complementary

Prompt search reinterpretation

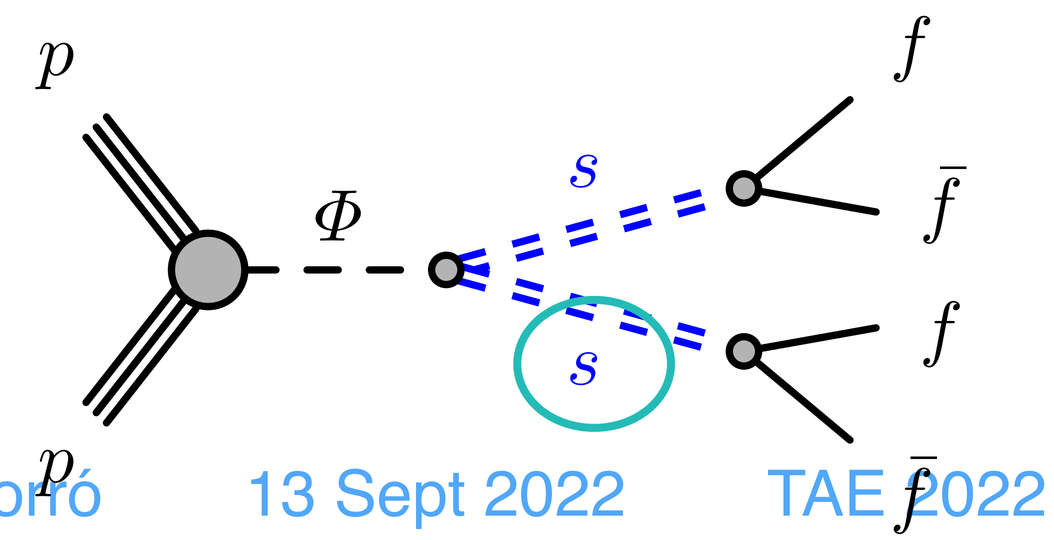
Calo/MS displaced objects searches





Target decays in:

- Calorimeters
- Tracker
- Beam pipe



We can expand the lifetime coverage by using multiple search strategies