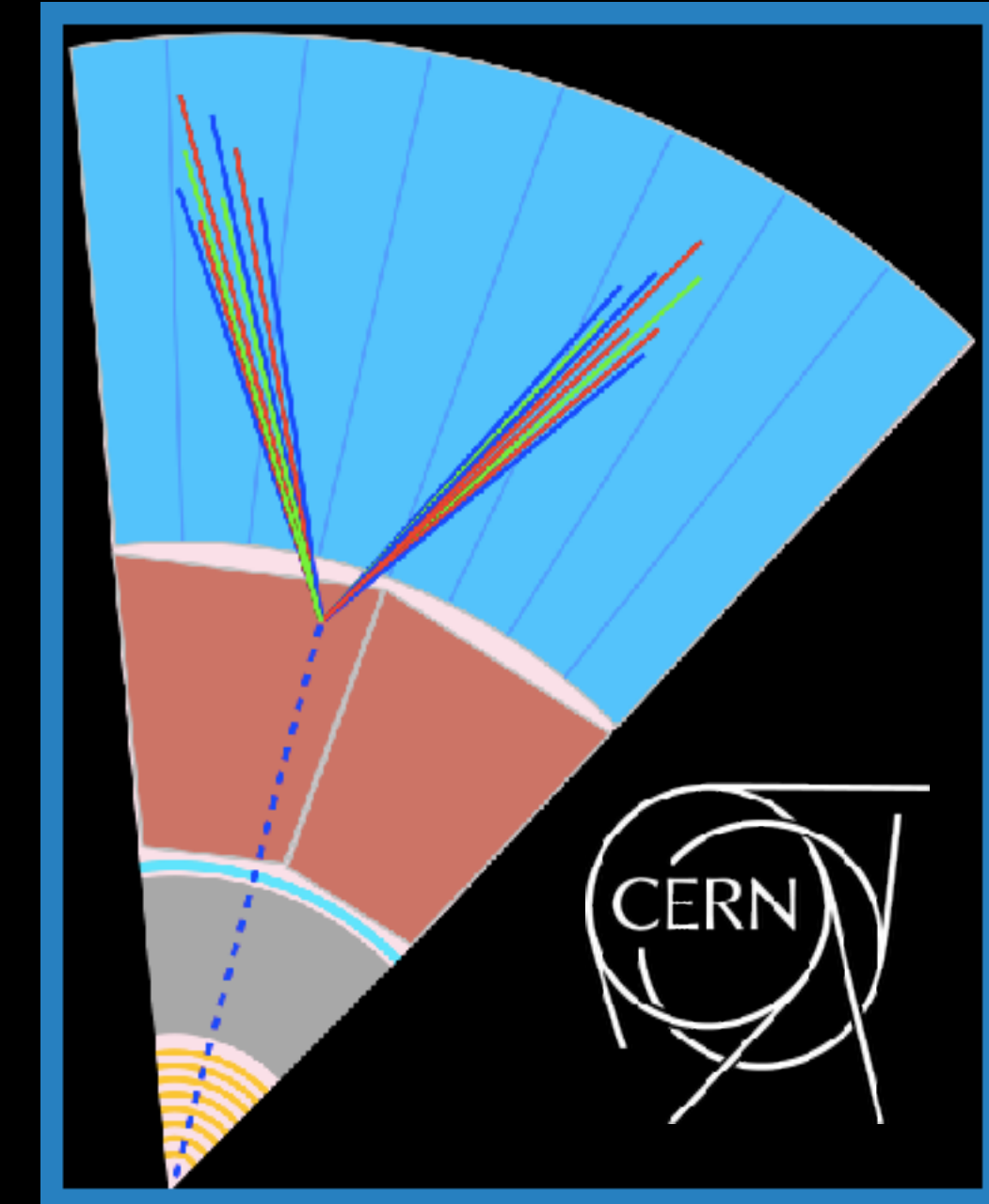
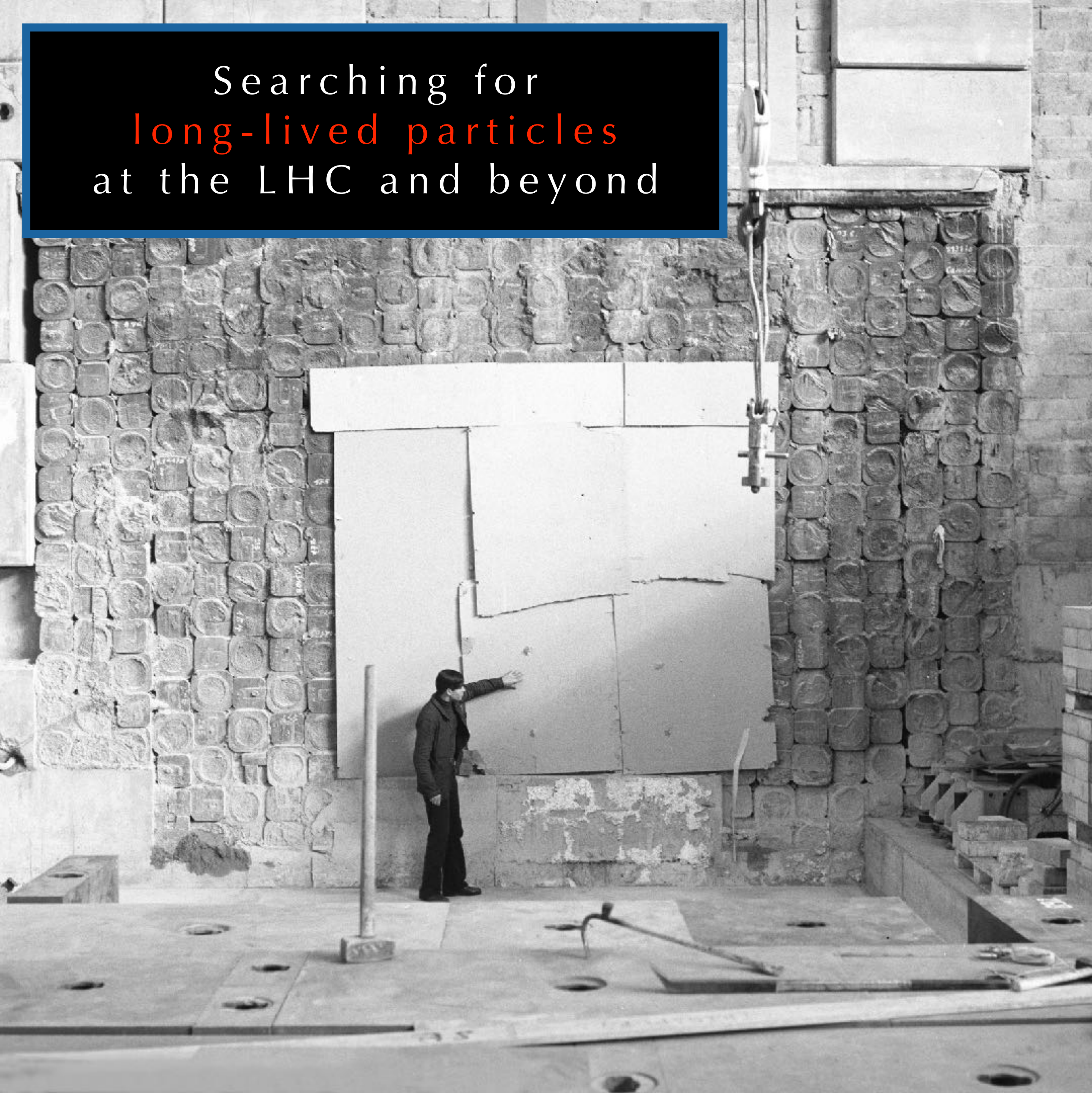


Searching for
long-lived particles
at the LHC and beyond



Seventh workshop of the
LHC **Long-Lived Particle** Community
indico.cern.ch/e/LHC_LL_P_May_2020

25-27 May 2020

Virtually everywhere

James Beacham
[Duke University]

Burning questions and answers in 2020

Electroweak symmetry breaking

- Does the Higgs boson exist?
- Is m_h natural or fine-tuned?
- If natural, what new physics/symmetry governs this?
- Does it regularize divergent $V_L V_L$ cross-section at high $m_{V_L V_L}$? Or new dynamics?
- Elementary or composite Higgs?
- Is it alone or does the Higgs have siblings and cousins?
- Origin of couplings to fermions?
- Coupling to dark matter?
- Connection to hidden sectors?
- Does it violate CP?
- Cosmological EW phase transition?

Dark matter

- What is it? WIMP, sterile neutrino, axion, NLSP, other hidden sector particle?
- Only one type?
- Only gravitational or other interactions?
- Are we wrong about gravity? An emergent phenomenon?

Two epochs of Universe's accelerated expansion

- Primordial: Is inflationary model correct? Which (scalar) field? Role of quantum gravity?
- Today: Dark energy (why is Λ so small?) or gravity modification?

Quarks and leptons

- Why three families?
- Why these masses and mixings?
- CP violation in the lepton sector
- Matter/anti-matter asymmetry
- Baryon and charged lepton number violation

Physics toward the Planck scale

- How does gravity play with the other forces?
- Are there more than three dimensions of space?
- Do all forces unify at high energy?
- Are there other forces?

Neutrinos

- Why do neutrinos have masses? And what are these masses?
- What's the role of h125?
- Majorana or Dirac?
- CP violation
- Are there more (sterile) neutrinos?

Inspired by I. Shipsey

Burning questions and answers in 2020

Electroweak symmetry breaking

- Does the Higgs boson exist?
- Is m_h natural or fine-tuned?
- If natural, what new physics/symmetry governs this?
- Does it regularize divergent $V_L V_L$ cross-section at high m_{V_L} ? Or new dynamics?
- Elementary or composite?
- Is it alone or does it have cousins?
- Origin of couplings to fermions?
- Coupling to dark matter?
- Connection to hidden sectors?
- Does it violate CP?
- Cosmological EW phase transition?

Dark matter

- What is it? WIMP, sterile neutrino, NLSP, other hidden sector?
- Only one type?
- Only gravitational or also interacts?
- Are we wrong about gravity? An emergent phenomenon?

Two epochs of Universe's accelerated expansion

- Primordial: Is inflationary model correct? Which (scalar) field? Role of quantum gravity?
- Today: Dark energy (why is Λ so small?) or gravity modification?

Quarks and leptons

- Why three families?
- Why these masses and mixings?
- CP violation in the lepton sector
- Matter/anti-matter asymmetry
- Baryon and charged lepton number violation

But the LHC has been taking data since 2010!

What could we be missing?

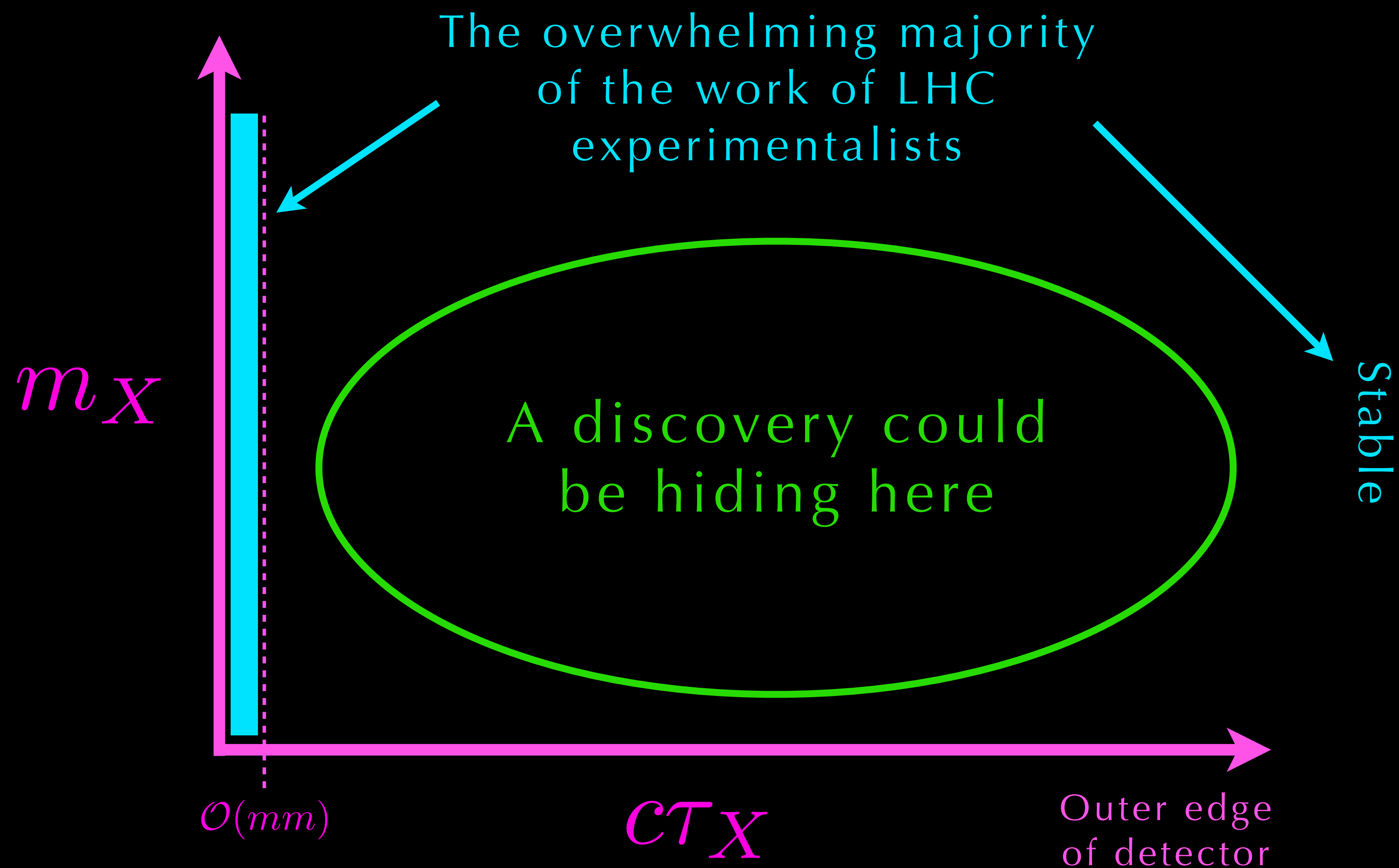
Planck scale
play with the other
in three dimensions
at high energy?
physics?

neutrino masses? And what are

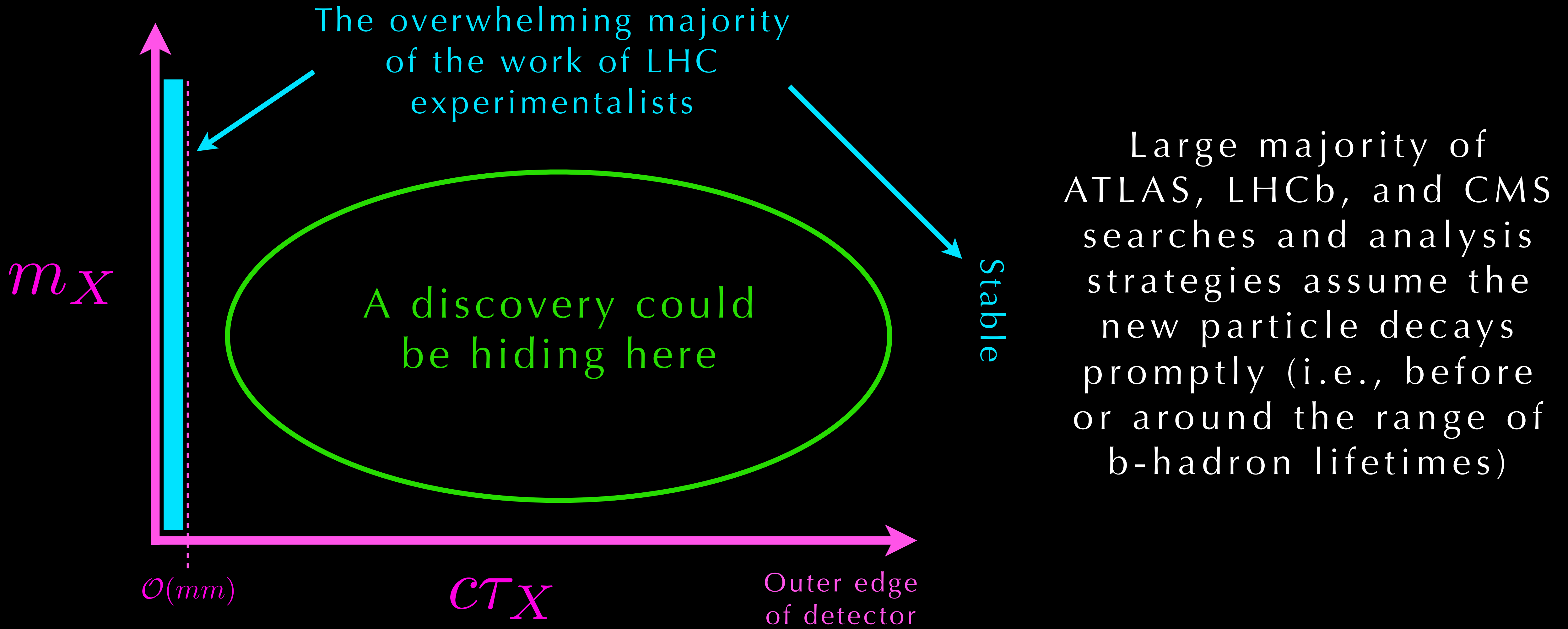
- these masses?
- What's the role of h_{125} ?
- Majorana or Dirac?
- CP violation
- Are there more (sterile) neutrinos?

Inspired by I. Shipsey

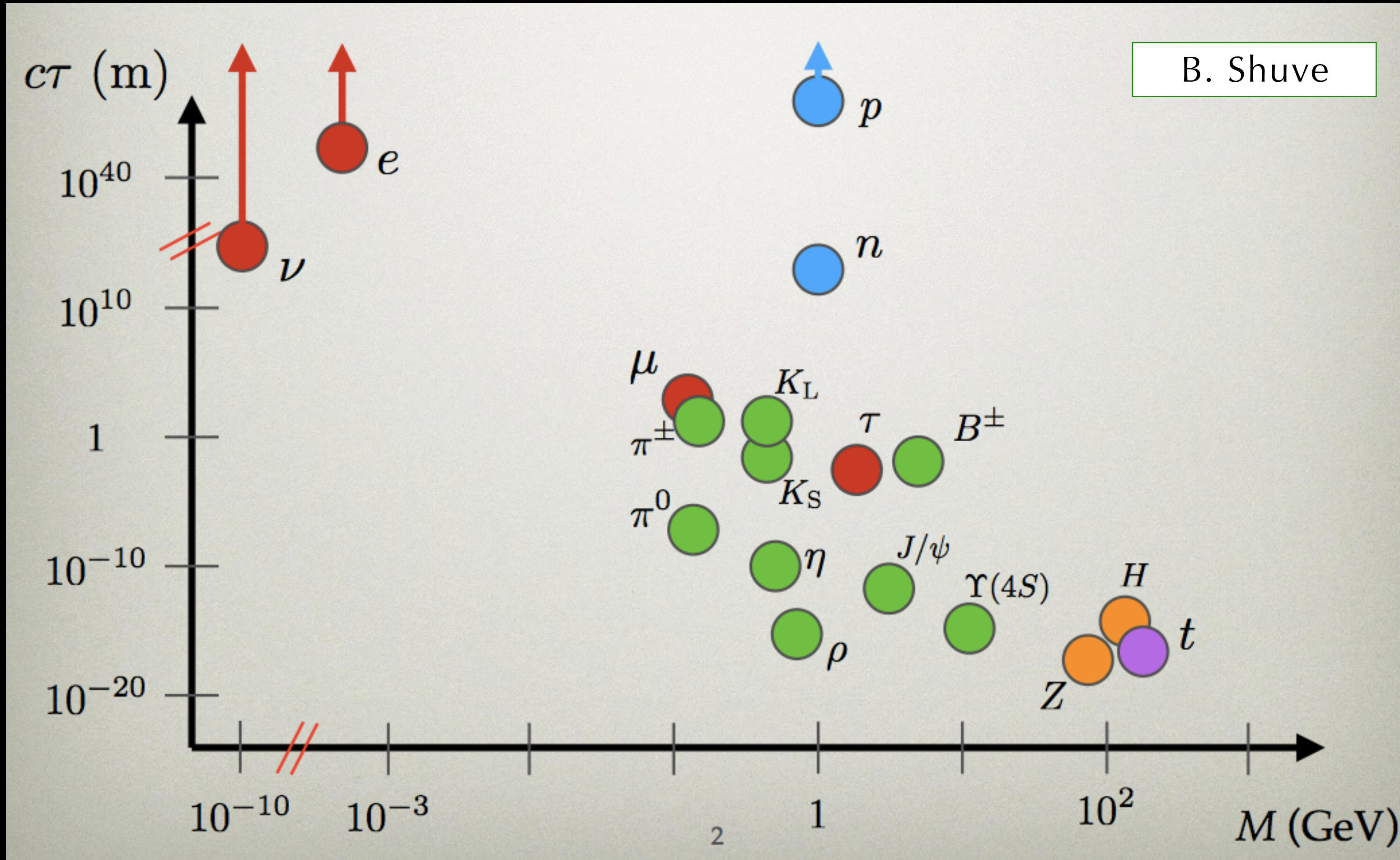
The lifetime frontier at the LHC



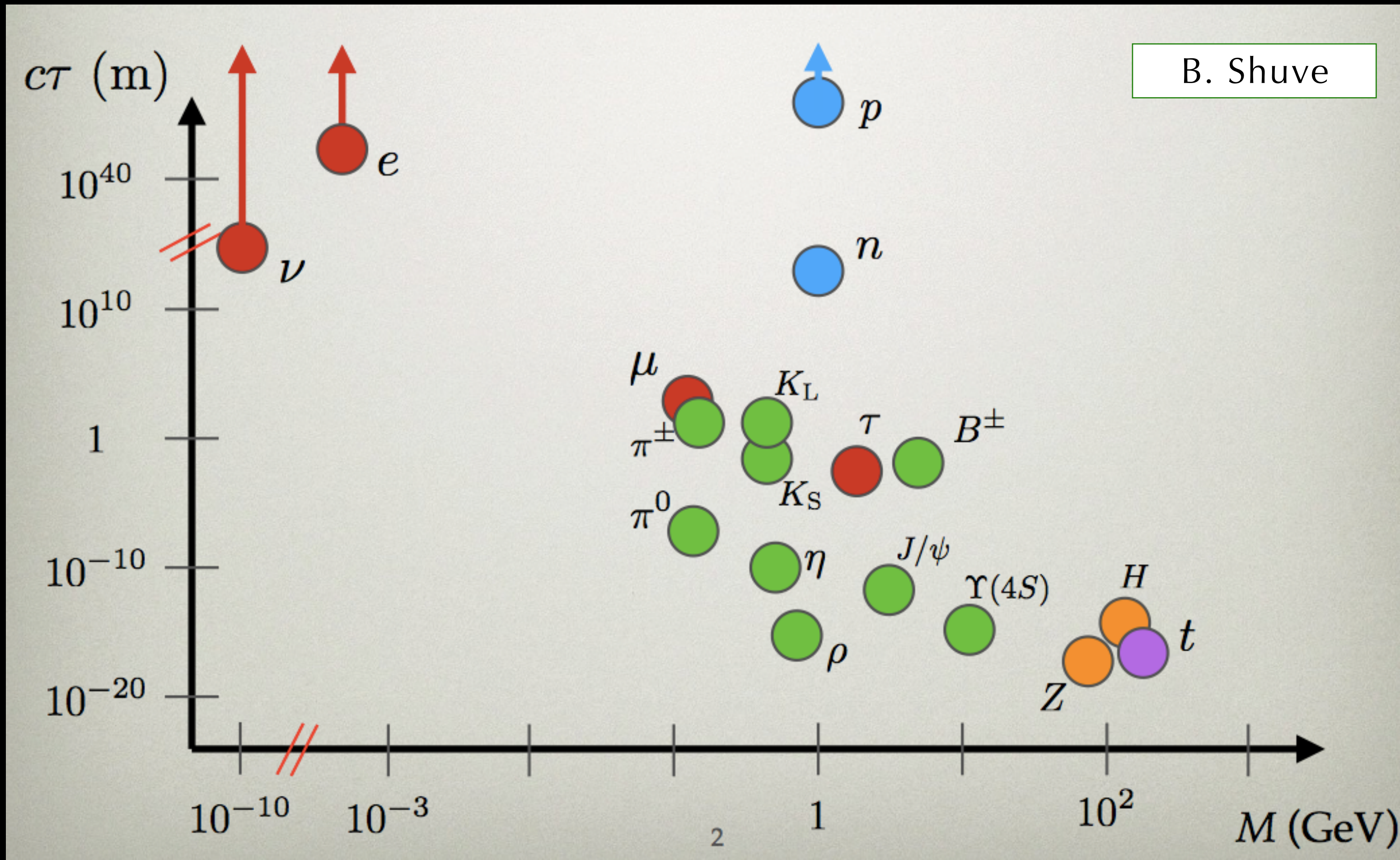
The lifetime frontier at the LHC



Long-lived particles (LLPs) in the Standard Model



Long-lived particles (LLPs) in the Standard Model

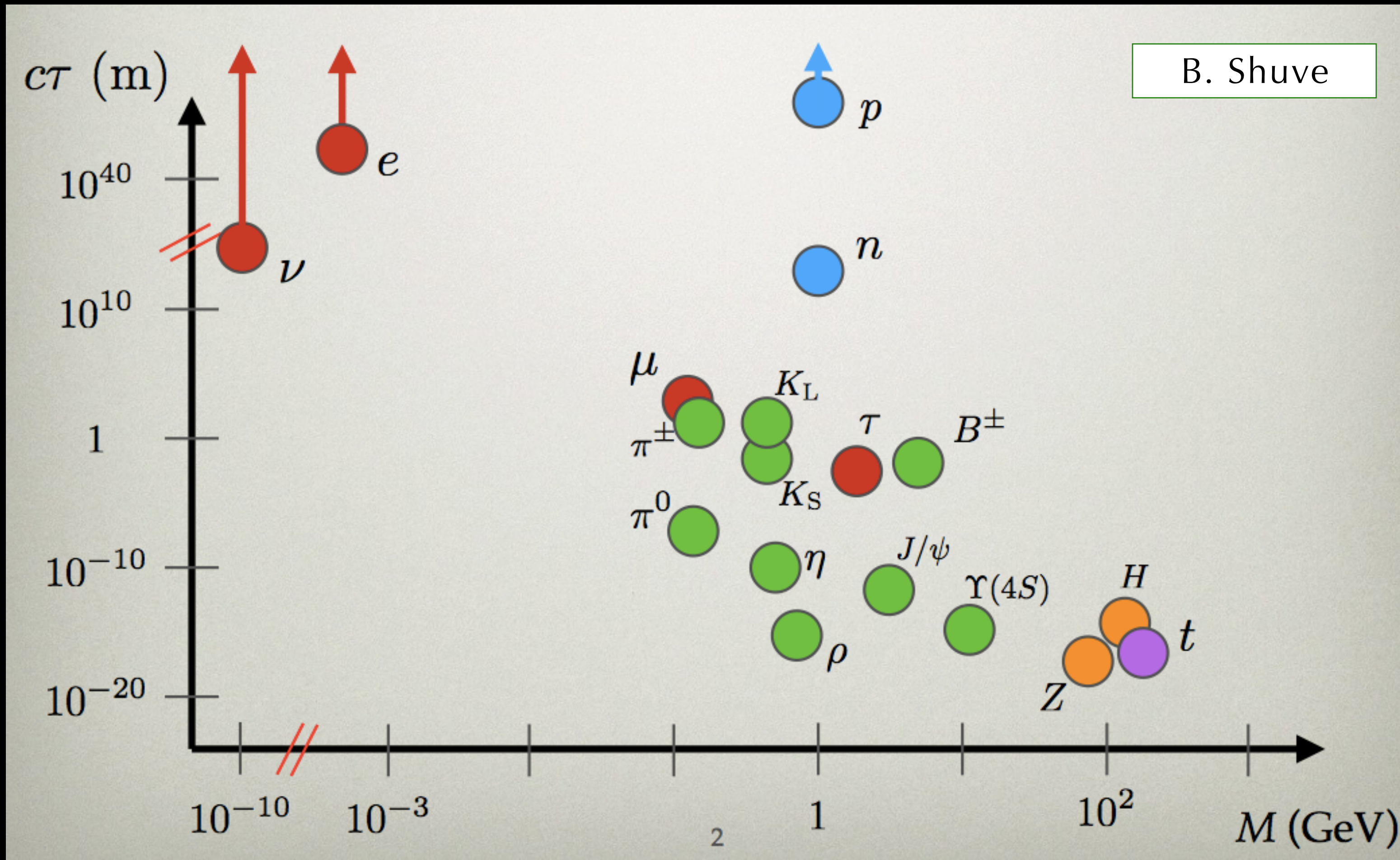


Particle lifetimes in the SM span a very wide range, and typically arise when approximate symmetries make the particle stable (small mass splittings, tiny couplings, etc.)

Small symmetry-breaking parameters can suppress the decay rate

Same principles apply to BSM particles; see [Nathaniel Craig's talk](#) in a bit for more details and theoretical perspective

Long-lived particles (LLPs) in the Standard Model



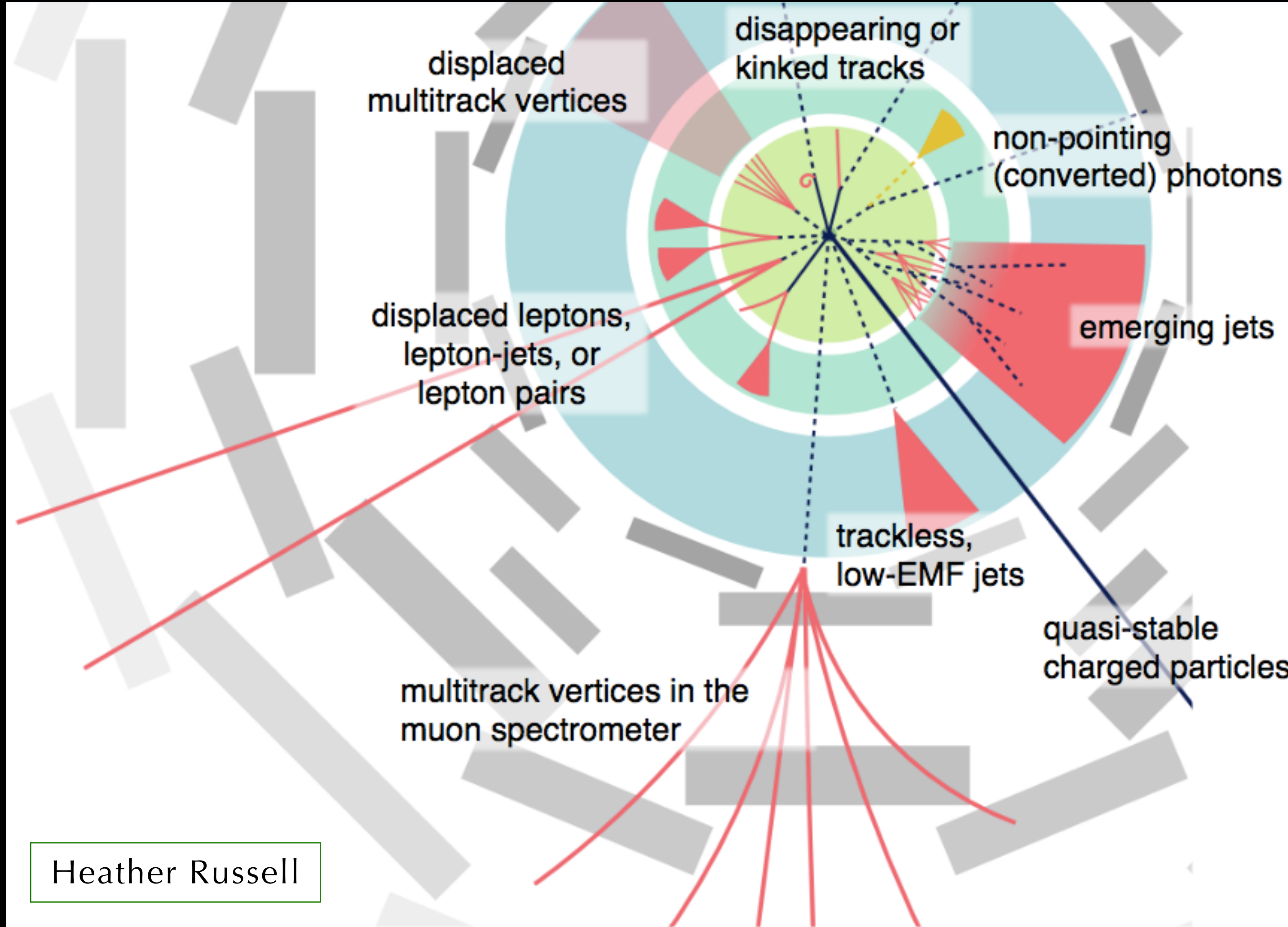
Particle lifetimes in the SM span a very wide range, and typically arise when approximate symmetries make the particle stable (small mass splittings, tiny couplings, etc.)

Small symmetry-breaking parameters can suppress the decay rate

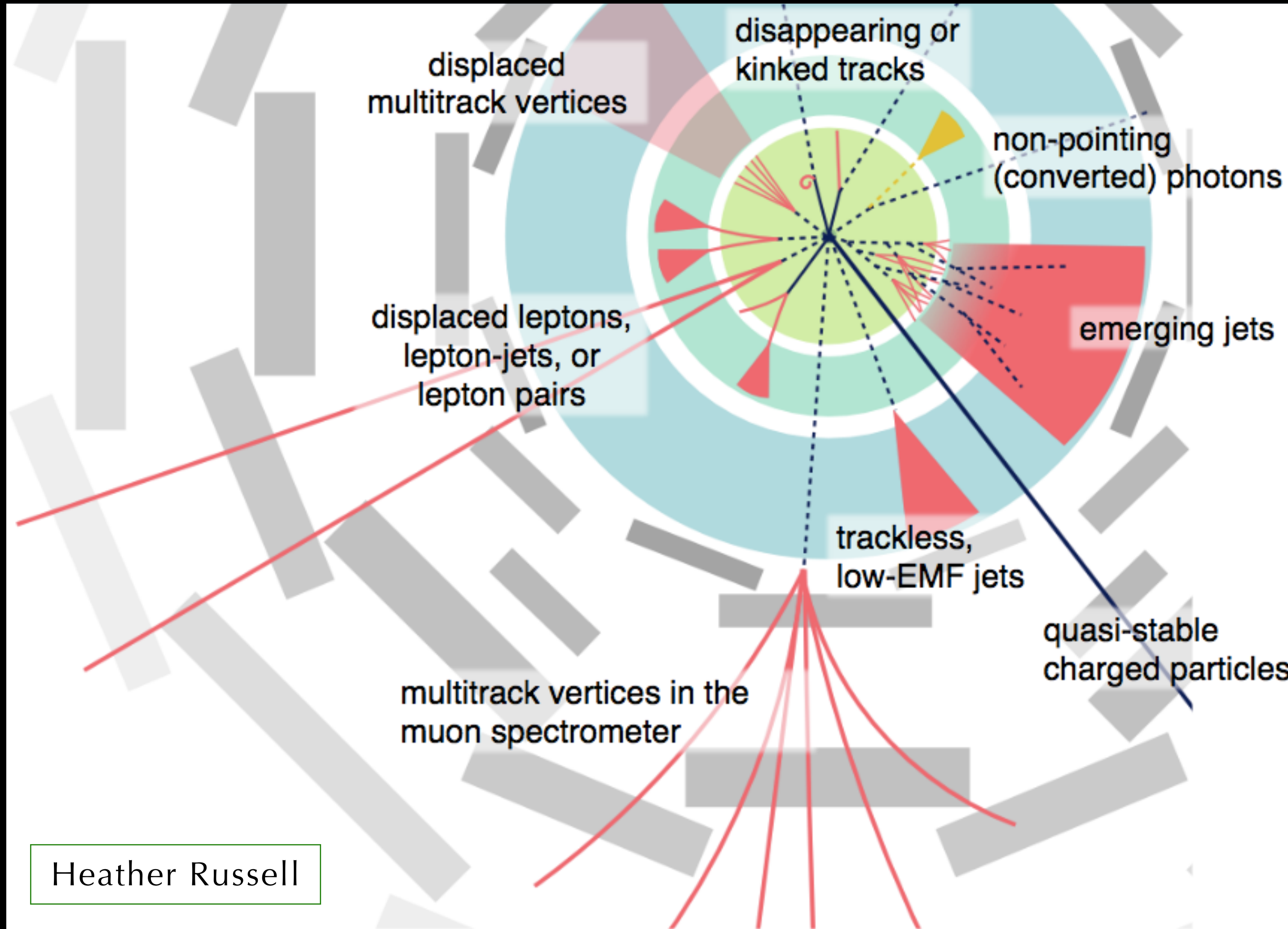
Same principles apply to BSM particles; see [Nathaniel Craig's talk](#) in a bit for more details and theoretical perspective

Experimentally, this obliges us to perform dedicated, signature-based searches for **long-lived** BSM particles

Long-lived particles from the main interaction points of the LHC

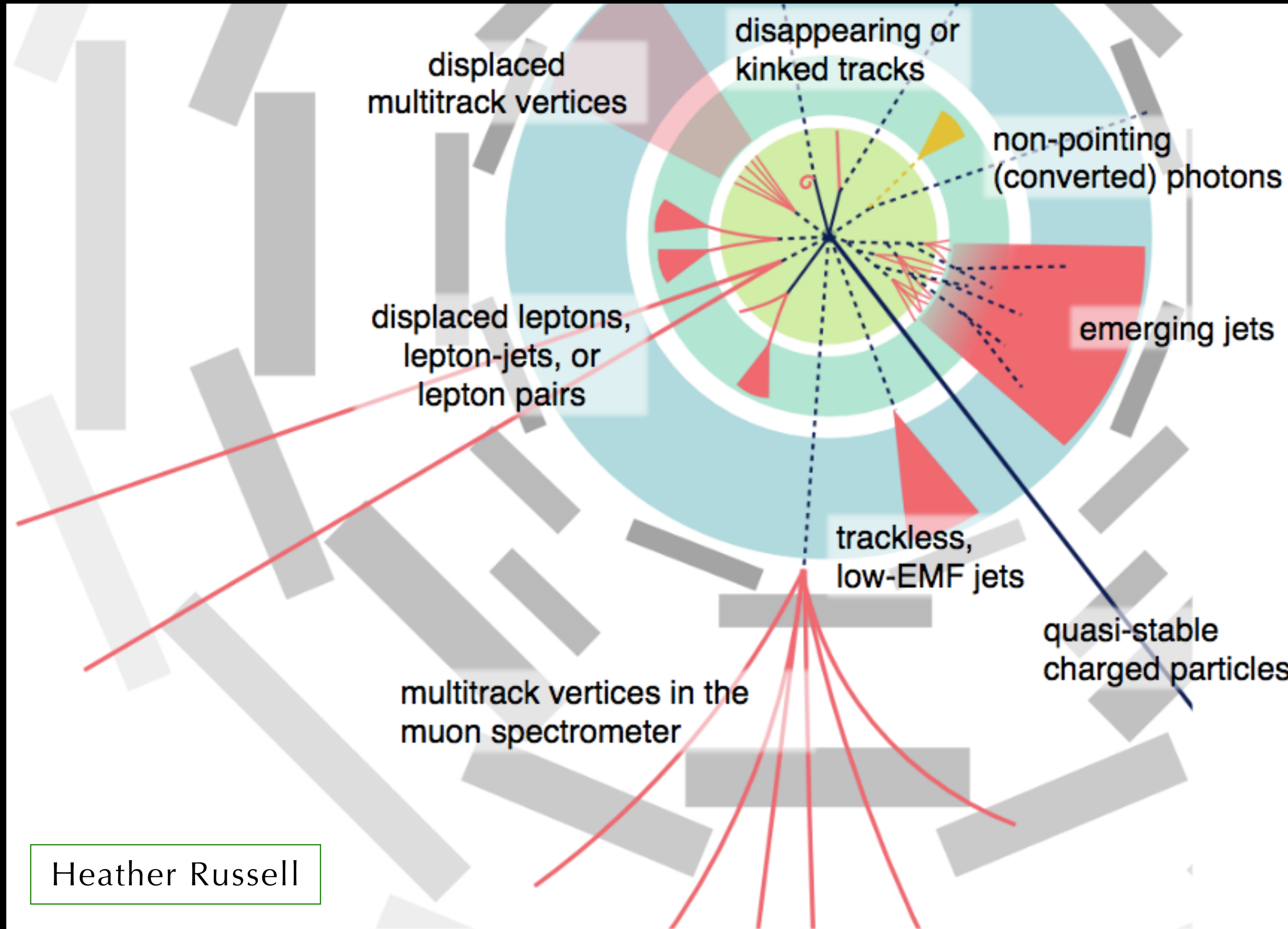


Long-lived particles from the main interaction points of the LHC



At the LHC, **LLP** = BSM particle with a non-negligible lifetime that gives up most of its energy or decays to SM somewhere in the detector acceptance of LHCb, CMS, ATLAS, MilliQan, MoEDAL, FASER, CODEX-b, MATHUSLA, AL3X, ANUBIS, etc.

Long-lived particles from the main interaction points of the LHC



We've been doing these searches since day one of the LHC (and at LEP, & Tevatron), but until ~2016, they were always considered fringe, and they still make up less than 10% of our "exotic" searches

Public results with the central LHC detectors

CMS Exotica LLP

CMS SUSY RPV

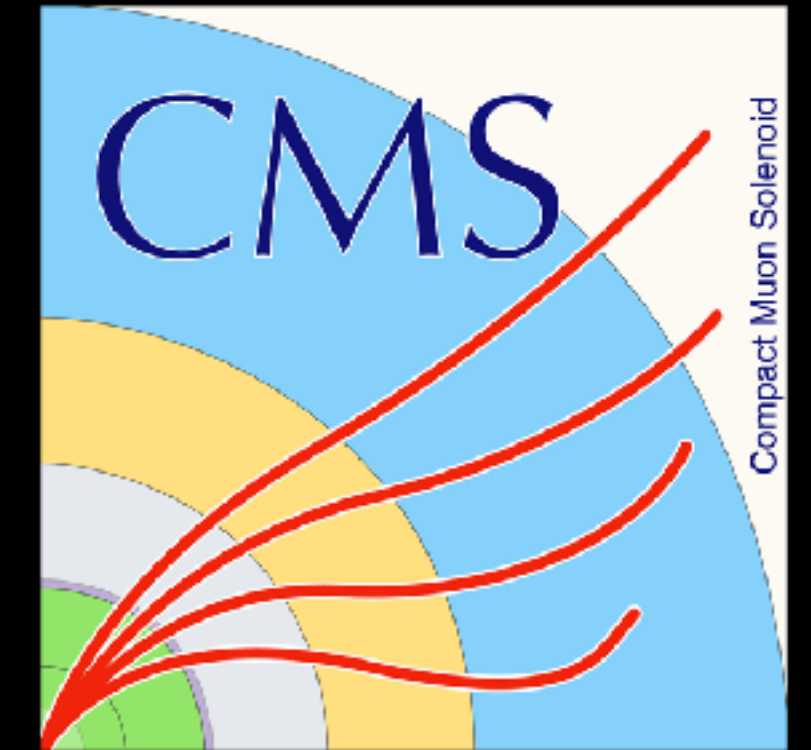
LHCb Public Results

ATLAS Exotics

ATLAS SUSY

At the LHC, **LLP** = BSM particle with a non-negligible lifetime that gives up most of its energy or decays to SM somewhere in the detector acceptance of LHCb, CMS, ATLAS, MilliQan, MoEDAL, FASER, CODEX-b, MATHUSLA, AL3X, ANUBIS, etc.

LHC Long-Lived Particle Community



...in collaboration with the theory/pheno community and MoEDAL, MilliQan, MATHUSLA, FASER, CODEX-b, AL3X, etc.

Formed in 2016 to address one question:
How do we best ensure that we don't miss BSM **LLP** signatures for the remainder of the LHC program?

Workshops —
two per year

LHC **LLP** white paper:
March 2019 — [arXiv:1903.04497](https://arxiv.org/abs/1903.04497)
To appear in J. Phys. G

Join the CERN egroup: lhc-llp

cern.ch/longlivedparticles

The LHC **LLP** Community white paper

[arXiv:1903.04497](https://arxiv.org/abs/1903.04497) (to appear in J. Phys. G)

Searching for Long-Lived Particles beyond the Standard Model at the Large Hadron Collider #3

Juliette Alimena (Ohio State U.), James Beacham (Duke U.), Martino Borsato (Heidelberg U.), Yangyang Cheng (Cornell U., LNS), Xabier Cid Vidal (Santiago de Compostela U.) et al. (Mar 11, 2019)

e-Print: [1903.04497](https://arxiv.org/abs/1903.04497) [hep-ex]

 pdf  links  cite

 83 citations

On the arXiv
11 March 2019

257 pages
(301 w/references)

201 authors /
contributors / endorsers

2 document editors

21 chapter editors

616 references

83 citations to date

A comprehensive document — a combination review paper, set of recommendations, accounting of open discovery possibilities, record of accumulated knowledge, and speculation for the future — that (paired with the MATHUSLA physics case document [arXiv:1806.07396](https://arxiv.org/abs/1806.07396) / [Rept.Prog.Phys. 82 \(2019\) no.11, 116201](https://doi.org/10.1088/1742-6596/82/11/116201)) serves as a definitive guide to LLP searches at the LHC

The LHC LLP Community white paper

[arXiv:1903.04497](https://arxiv.org/abs/1903.04497) (to appear in J. Phys. G)

Searching for Long-Lived Particles beyond the Standard Model at the Large Hadron Collider #3

Juliette Alimena (Ohio State U.), James Beacham (Duke U.), Martino Borsato (Heidelberg U.), Yangyang Cheng (Cornell U., LNS), Xabier Cid Vidal (Santiago de Compostela U.) et al. (Mar 11, 2019)

e-Print: [1903.04497](https://arxiv.org/abs/1903.04497) [hep-ex]

 pdf  links  cite

Community initially focused on the LHC, but the world of LLPs is larger

A comprehensive document, review paper, set of recommendations of open discovery potential, accumulated knowledge, and speculation for the future — that (paired with the MATHUSLA physics case document [arXiv:1806.07396](https://arxiv.org/abs/1806.07396) / [Rept. Prog. Phys. 82 \(2019\) no.11, 116201](https://doi.org/10.1088/1742-6596/82/11/116201)) serves as a definitive guide to LLP searches at the LHC

On the arXiv
11 March 2019

257 pages
(301 w/references)

201 authors /
contributors / endorsers

2 document editors

21 chapter editors

616 references

83 citations to date

Long-lived particles beyond the LHC

Our ability, as a field, to discover BSM **LLPs**, is not defined only by the interaction points of the LHC

- Many other experimental projects search for, are potentially sensitive to, or could be designed to be sensitive to **LLPs**
- If it's a BSM particle you can produce in an experiment that has a $c\tau$ in the cm to km range before it decays and its decay products hit your detector, then it's a **long-lived particle**
- This leads to obvious and clear connections among multiple projects around the globe, complementary to those at the LHC

Long-lived particles beyond the LHC

Our ability, as a field, to discover BSM LLPs, is not defined only by the interaction points of the LHC

- Many other experimental projects search for, are potentially sensitive to, or could be designed to be sensitive to LLPs
- If it's a BSM particle you can produce in an experiment that has a $c\tau$ in the cm to km range before it decays and its decay products hit your detector, then it's a long-lived particle
- This leads to obvious and clear connections among multiple projects around the globe, complementary to those at the LHC



- For example, it's crucial that future projects like the FCC, CEPC, CLIC/ILC, adopt accelerator and detector designs that maintain sensitivity to LLPs from the beginning

Long-lived particles beyond the LHC

Our ability, as a field, to discover BSM LLPs, is not defined only by the interaction points of the LHC

- Many other experimental projects search for, are potentially sensitive to, or could be designed to be sensitive to LLPs
- If it's a BSM particle you can produce in an experiment that has a $c\tau$ in the cm to km range before it decays and its decay products hit your detector, then it's a long-lived particle
- This leads to obvious and clear connections among multiple projects around the globe, complementary to those at the LHC



- For example, it's crucial that future projects like the FCC, CEPC, CLIC/ILC, adopt accelerator and detector designs that maintain sensitivity to LLPs from the beginning

- Thus, the LHC LLP Community workshops have become a regular platform to discuss, compare, and collaborate on LLP searches around the world (and beyond) and ideas to maintain discovery potential now and in the future

Long-lived particles beyond the LHC

Our ability, as a field, to discover BSM LLPs, is not defined only by the interaction points of the LHC

- Many other experimental projects search for, are potentially sensitive to, or could be designed to be sensitive to LLPs
- If it's a BSM particle you can produce in an experiment that has a $c\tau$ in the cm to km range before it decays and its decay products hit your detector, then it's a long-lived particle
- This leads to obvious a globe, complementary

The message is clear: multiple projects around the

Don't overlook the lifetime frontier

For example, it's crucial that future projects like the FCC, EPC, CLIC/ILC, adopt accelerator and detector designs that maintain sensitivity to LLPs from the beginning



- Thus, the LHC LLP Community workshops have become a regular platform to discuss, compare, and collaborate on LLP searches around the world (and beyond) and ideas to maintain discovery potential now and in the future

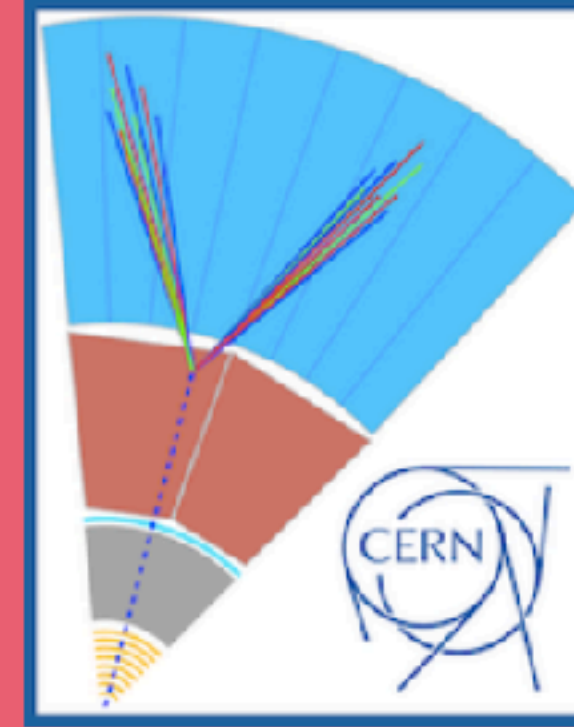
LHC LLP Community: Emphasis on “community”

Community is open to all

- By being here and participating, you're already a member; welcome!

Workshop is informal and collaboration-centered

- Discussion is of the highest priority



Searching for long-lived particles at the LHC: Seventh workshop of the LHC LLP Community

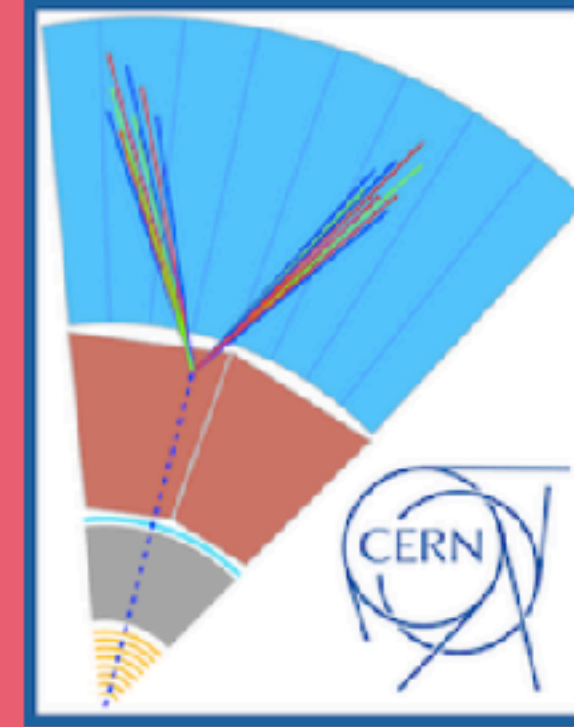
LHC LLP Community: Emphasis on “community”

Community is open to all

- By being here and participating, you're already a member; welcome!

Workshop is informal and collaboration-centered

- Discussion is of the highest priority



Searching for long-lived particles at the LHC: Seventh workshop of the LHC LLP Community

Community is collaboration – Collaboration is respect

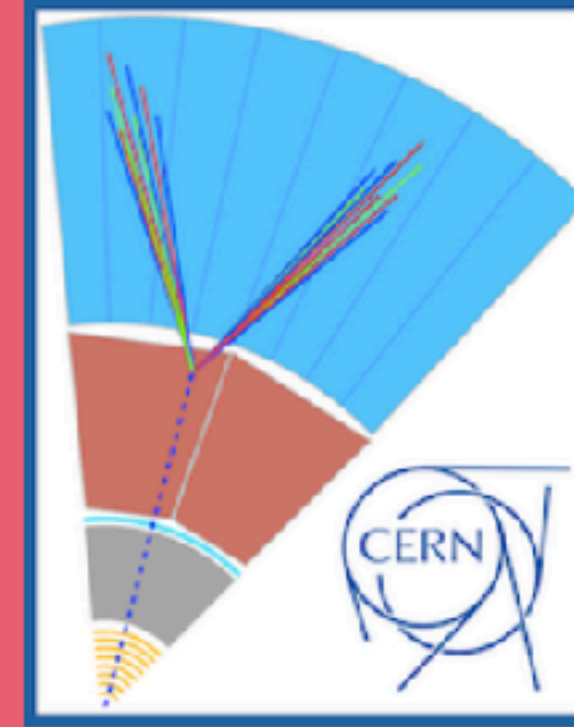
LHC LLP Community: Emphasis on “community”

Community is open to all

- By being here and participating, you’re already a member; welcome!

Workshop is informal and collaboration-centered

- Discussion is of the highest priority



Searching for long-lived particles at the LHC: Seventh workshop of the LHC LLP Community

Community is collaboration – Collaboration is respect

To all community members:

- Yes, ask a question and make a suggestion!

To all session chairs:

- Give ample space in discussion periods for those who haven’t had a chance to talk!

We’re radically inclusive and radically anti-harrassment

- The CERN Code of Conduct is a great place to start

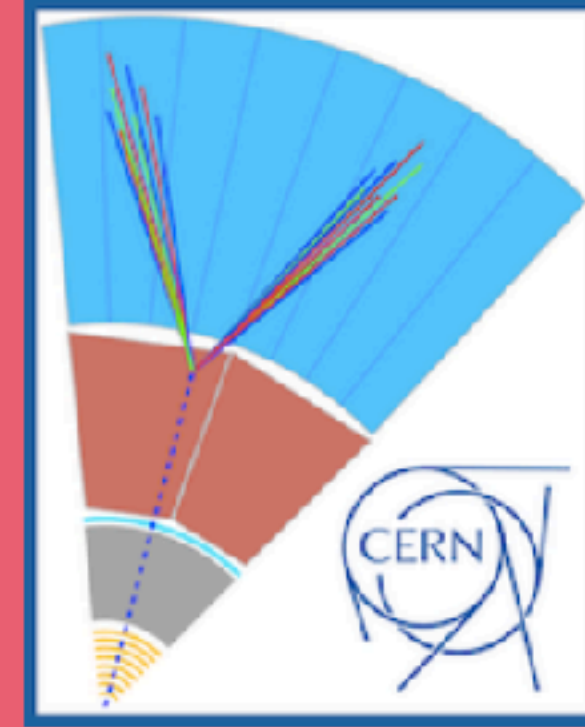
LHC LLP Community: Emphasis on “community”

Community is open to all

- By being here and participating, you’re already a member; welcome!

Workshop is informal and collaboration-centered

- Discussion is of the highest priority



Searching for long-lived particles at the LHC: Seventh workshop of the LHC LLP Community

Community is collaboration – Collaboration is respect

To all community members:

- Yes, ask a question and make a suggestion!

To all session chairs:

- Give ample space in discussion periods for those who haven’t had a chance to talk!

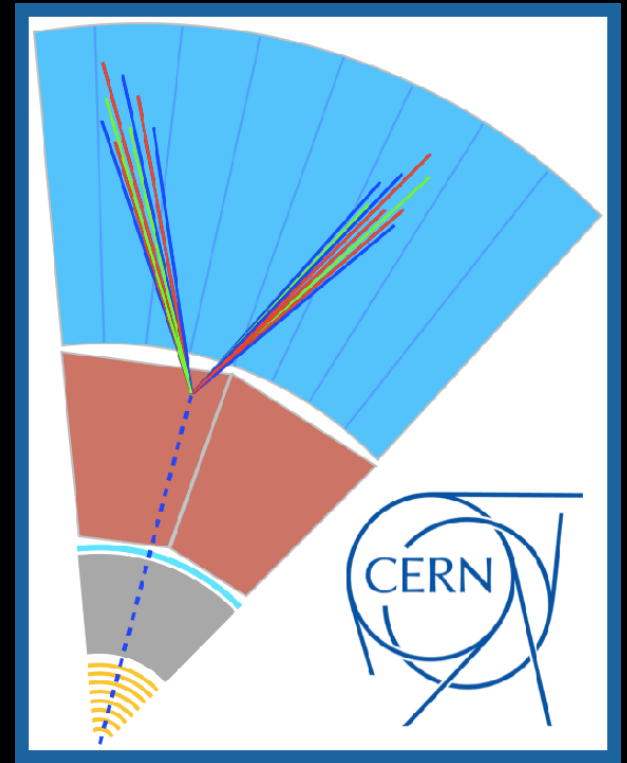
We’re radically inclusive and radically anti-harrassment

- The CERN Code of Conduct is a great place to start

We’re here to find new physics

- Both science and society suffer when ideas and thoughts aren’t heard because someone feels threatened, unwelcome, or marginalized
- This applies whether virtually or in person
- Harrassment is antithetical to the intention of this workshop
- We endeavor to create a positive and welcoming space!

#LHCLLP7 is our first fully virtual workshop



Adapting to the circumstances

- Format of fully plenary talks and discussions rather than featuring working breakout parallel sessions as usual
- Start at 13h and aim to end at ~19h Geneva time each day

Monday, 25 May

- 13:00 — Session 1 — Intro, dedicated detectors at the LHC, and new theory developments
- 15:45 — Session 2 — Theoretical overview, PBC & FIPs, HL-LHC, new theory/pheno ideas

Tuesday, 26 May

- 13:00 — Session 3 — More dedicated **LLP** detectors at the LHC and other **LLPs** at CERN
- 16:25 — Session 4 — New results from ATLAS and CMS, dark shower / dark QCD phenomenology

Wednesday, 27 May

- 13:00 — Session 5 — Triggering ideas for ATLAS and CMS and a new result from CMS
- 15:05 — Session 6 — Triggers for Run 3 for ATLAS, CMS, and LHCb: Why can't we trigger for X?
- 16:40 — Session 7 — LHC **LLP** Working Group kick-off

Speaking of which...

LHC LLP Working Group

LHC LLP Community has thrived as an LPCC activity since 2016

- Newly-formed formal “LHC LLP WG” within the LPCC (similar to others like ML, Top, DM, etc.) recently proposed to build on the experience of the LLP LHC Community and, preserving its main scientific objectives, it serves as a formal bridge with the relevant physics groups of the approved LHC experiments, to streamline the official endorsement of the WG's recommendations to the experiments
- Generally LLP WG meetings are going to be open and accessible to the whole community
- Discussion topics will be specifically related to needs formulated for the LHC program (but may need wider input)
- This WG is expected to produce formal conclusions and, if useful, documents on these relevant topics
- The outcome will be endorsed by the LHC management structures, ie as with other LHC WG groups that exist already

LHC LLP Working Group

You can help define the activities of the LHC LLP WG!

- Thus, our LHC LLP Community workshop will feature the first meeting of the LLP WG on Wednesday at 16:40 [Indico]
- The meeting is focused on the presentation of the foreseen activities of the WG, and on the collection of inputs and feedback from the community. We welcome explicit contributions during this meeting, and invite colleagues to begin now expressing their views through this collaborative document
- We have a few ideas already, but any comments added to the document will help trigger the discussions and inform the WG conveners
- If you would like to be assigned few minutes for a short contribution to the agenda of the WG meeting, please send mail to the WG conveners at `lhcllpwg-admin` at cern.ch
- These contributions should not address specific physics models, etc. (i.e., “your last paper”), but general aspects of the WG activities, expected deliverables, and operation mode
- If you’re interested in the future activities of the WG, please sign up to the WG mailing list (separate from the LLP community list), here

Informal satellite brainstorming session for Snowmass 2021

The Snowmass 2021 process is underway

- Multiple frontier groups and topical groups within the Snowmass structure that are related to LLPs, and they have several meetings planned for the coming months that will feature LLPs prominently
- In the LHC LLP Community spirit of providing a platform for brainstorming and discussion, we'll be holding an informal satellite session of our workshop dedicated to possible Snowmass contributions on Friday, 29 May 2020, at 4 PM Geneva time

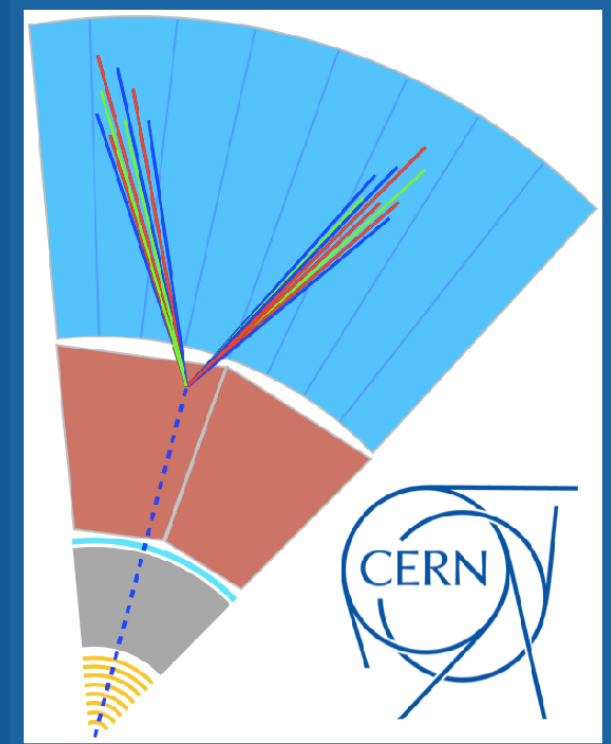
The logo for SnowMass2021, featuring the text "SnowMass2021" in a stylized, cursive font. "Snow" is in blue, "Mass" is in white, and "2021" is in white. The logo is set against a dark grey rectangular background.

indico.cern.ch/e/LHC_LLIP_May_2020_Satellite_Session

- Very informal, strictly a brainstorming / idea-tossing meeting of those who might be thinking about studies they'd like to contribute to Snowmass, to potentially connect people and facilitate collaboration in support of the Snowmass effort
- If you're already planning a contribution and would like to let everyone know, or if you simply have an idea for a contribution and are looking for collaborators, feel free to prepare a slide or two
- Otherwise, just bring ideas!



LHC Long-Lived Particle Community



Next workshop

*Searching for **long-lived particles**
at the LHC:
Eighth workshop of the
LHC **LLP** Community*

Tentative:

November 2020 at the
Tokyo Institute of Technology

https://indico.cern.ch/e/LHC_LLIP_Nov_2020

Join the CERN egroup: lhc-llp

FIPs 2020

Feebly-Interacting Particle workshop

Tentative: CERN — 2-4 September 2020

What are FIPs? Roughly: Any new physics with coupling $\lll 1$ and mass below the EW scale

Complementary to high-energy searches

Our LLP workshop was originally planned to be held at CERN right next to FIPs, this week

Still TBD whether FIPs happens in September at CERN, or virtually, or next year

See [Joerg Jaeckel's talk](#) in a few hours and stay tuned for updates

James Beacham [Duke]

FIPs 2020

Workshop on
Feebly-Interacting
Particles

RESCHEDULED:
2-4 September 2020
CERN

FIPS at colliders (including
ATLAS, CMS, LHCb)

extracted beams /
fixed-target experiments

neutrino experiments

direct and indirect
dark matter detectors

axion/ALP experiments

and beyond

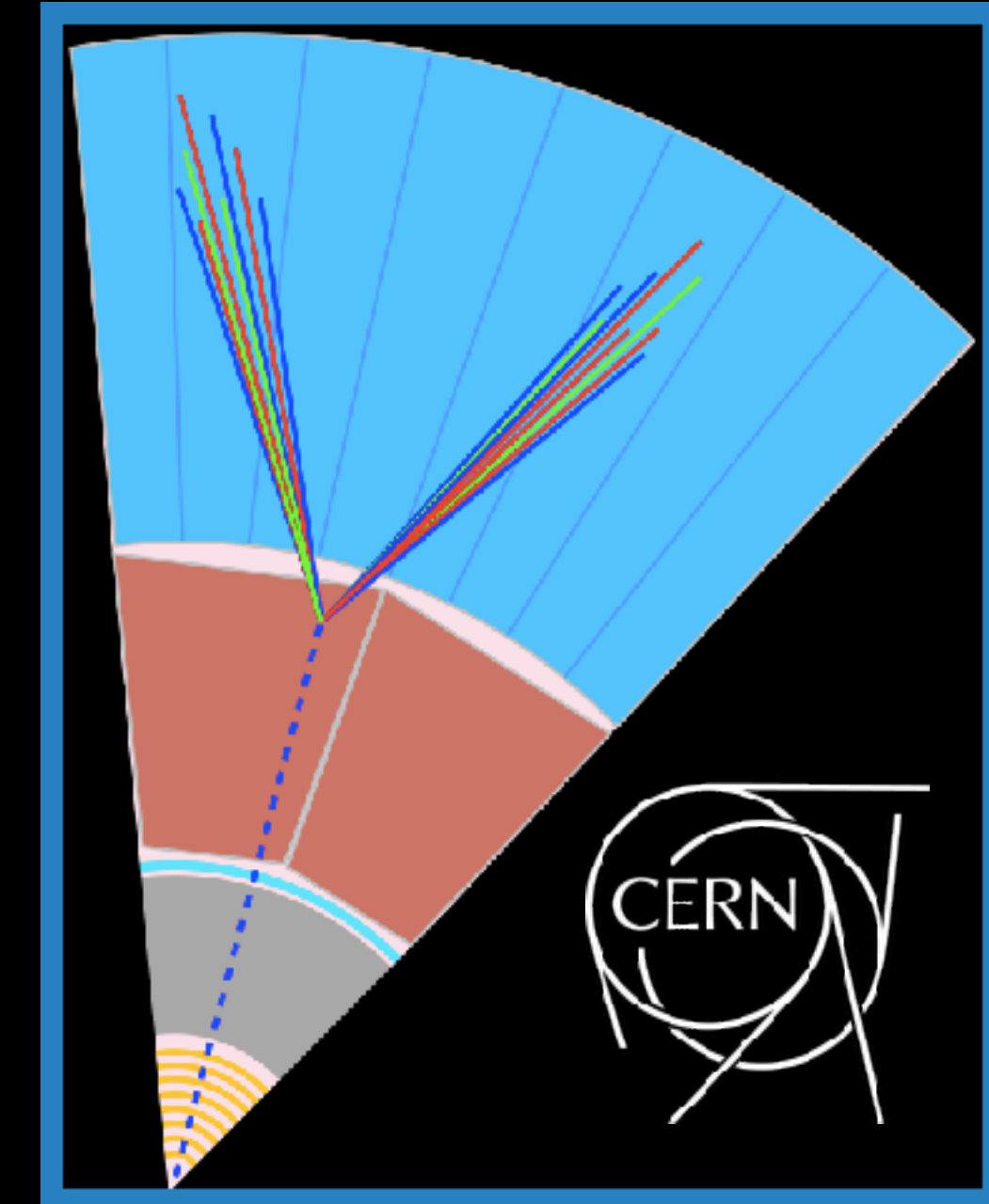
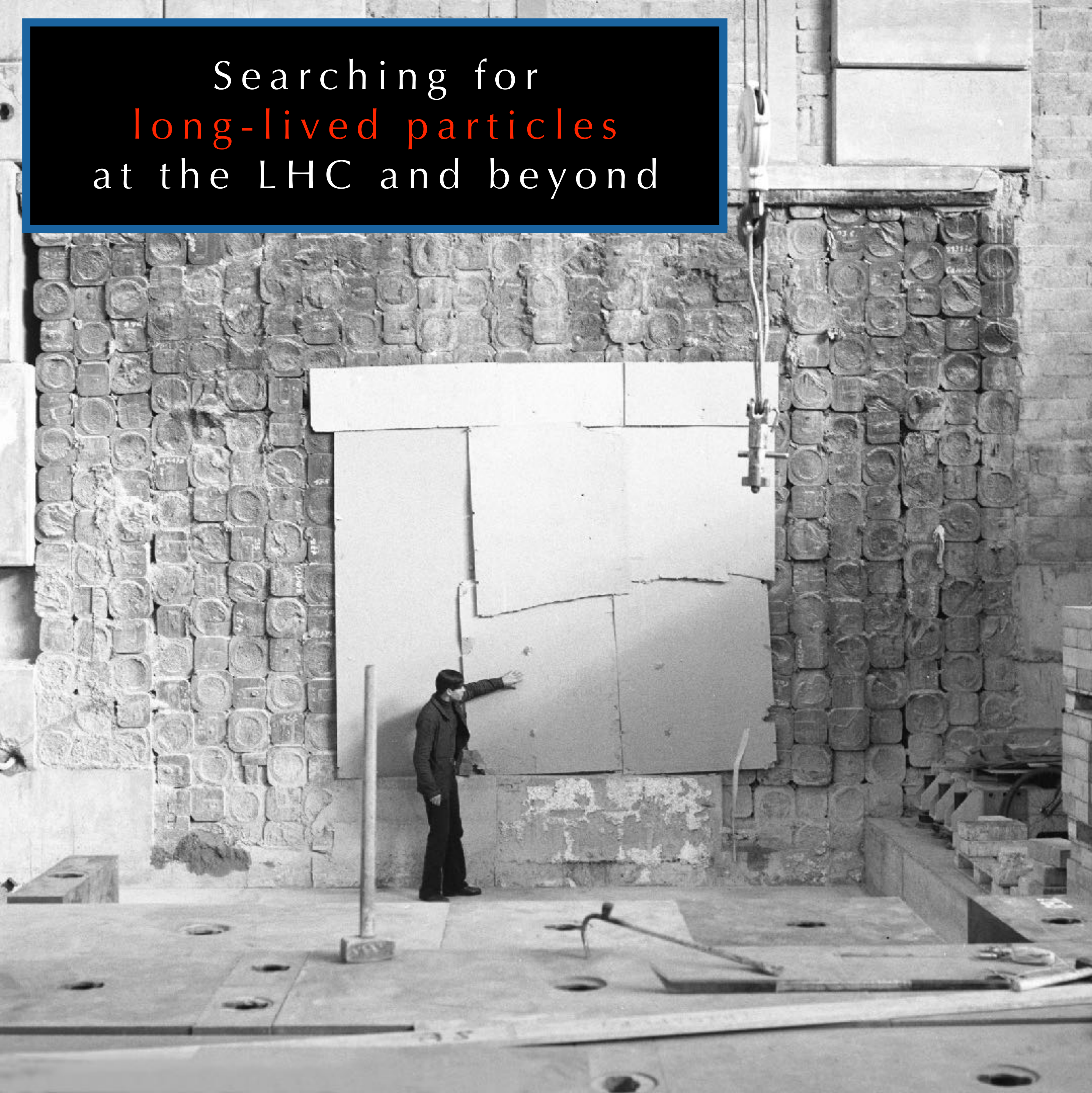
Organizers:

Martin Bauer
James Beacham
Albert De Roeck
Gian Francesco Giudice
Pilar Hernandez
Igor Irastorza
Joerg Jaeckel
Gordan Krnjaic
Gaia Lanfranchi
Jocelyn Monroe
Silvia Pascoli
Joshua Ruderman
Philip Schuster
Mikhail Shaposhnikov
Jessie Shelton

indico.cern.ch/e/FIPs_May_2020



Searching for
long-lived particles
at the LHC and beyond



Seventh workshop of the LHC
Long-Lived Particle Community

indico.cern.ch/e/LHC_LLPMay2020

25-27 May 2020

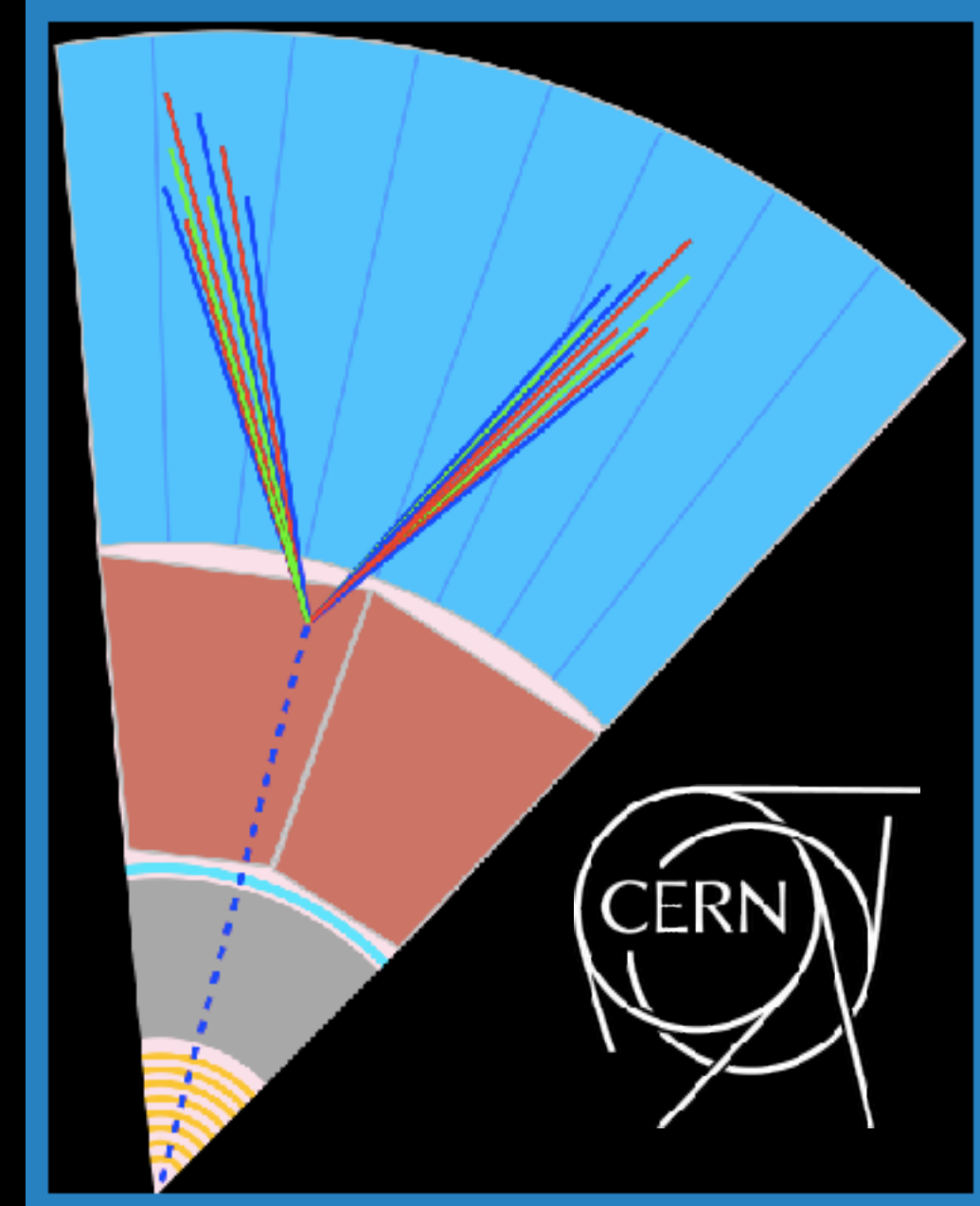
Virtually everywhere

Searching for
long-lived particles
at the LHC and beyond

Workshop goal:

Map the future of the
lifetime frontier.
You're doing it right now.

Welcome!



Seventh workshop of the LHC
Long-Lived Particle Community

indico.cern.ch/e/LHC_LLIP_May_2020

25-27 May 2020

Virtually everywhere