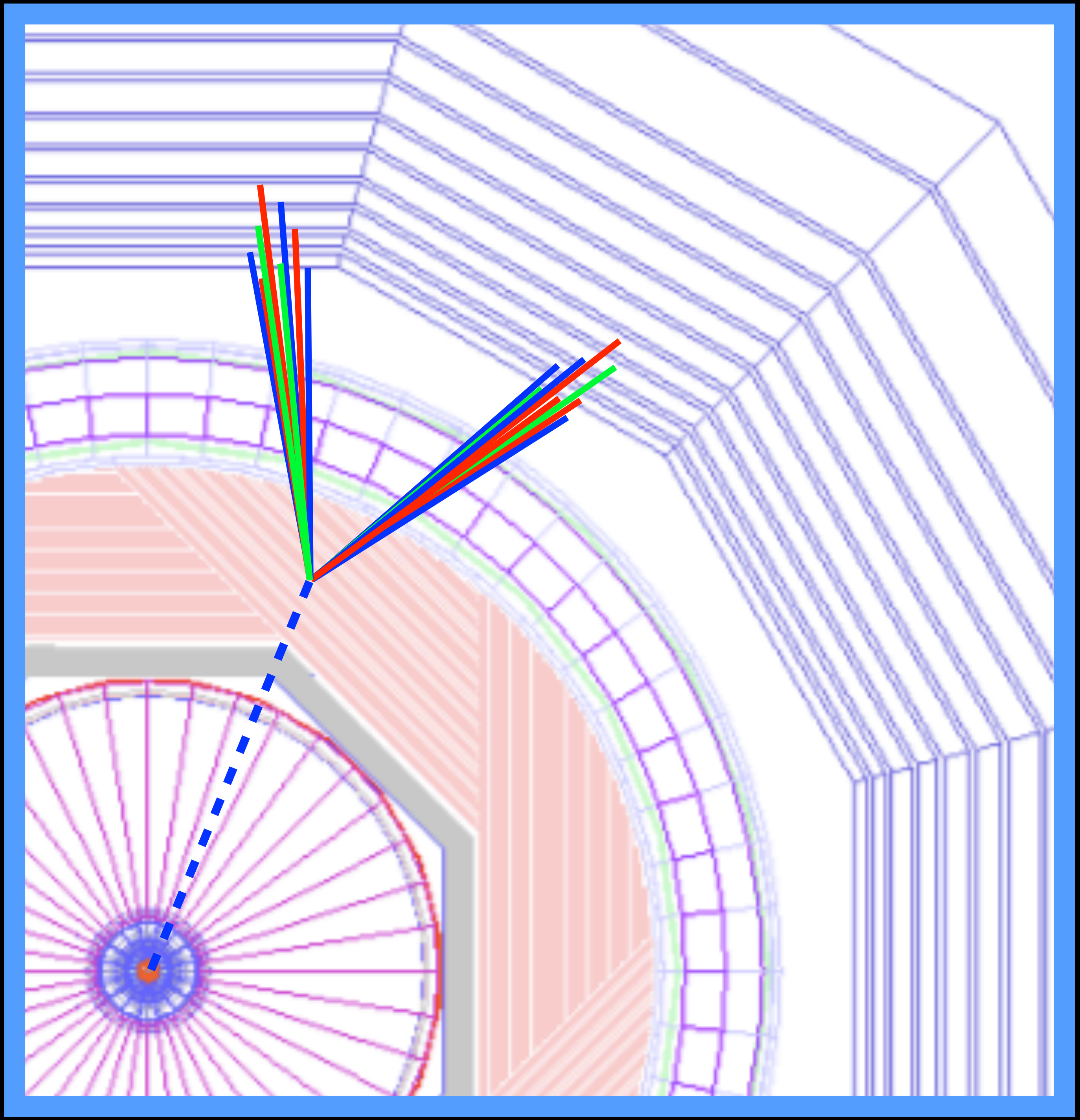


Searching for long-lived particles at future e+e- machines

Prospects and unknowns

James Beacham [Duke]

CEPC Workshop — IHEP — Beijing

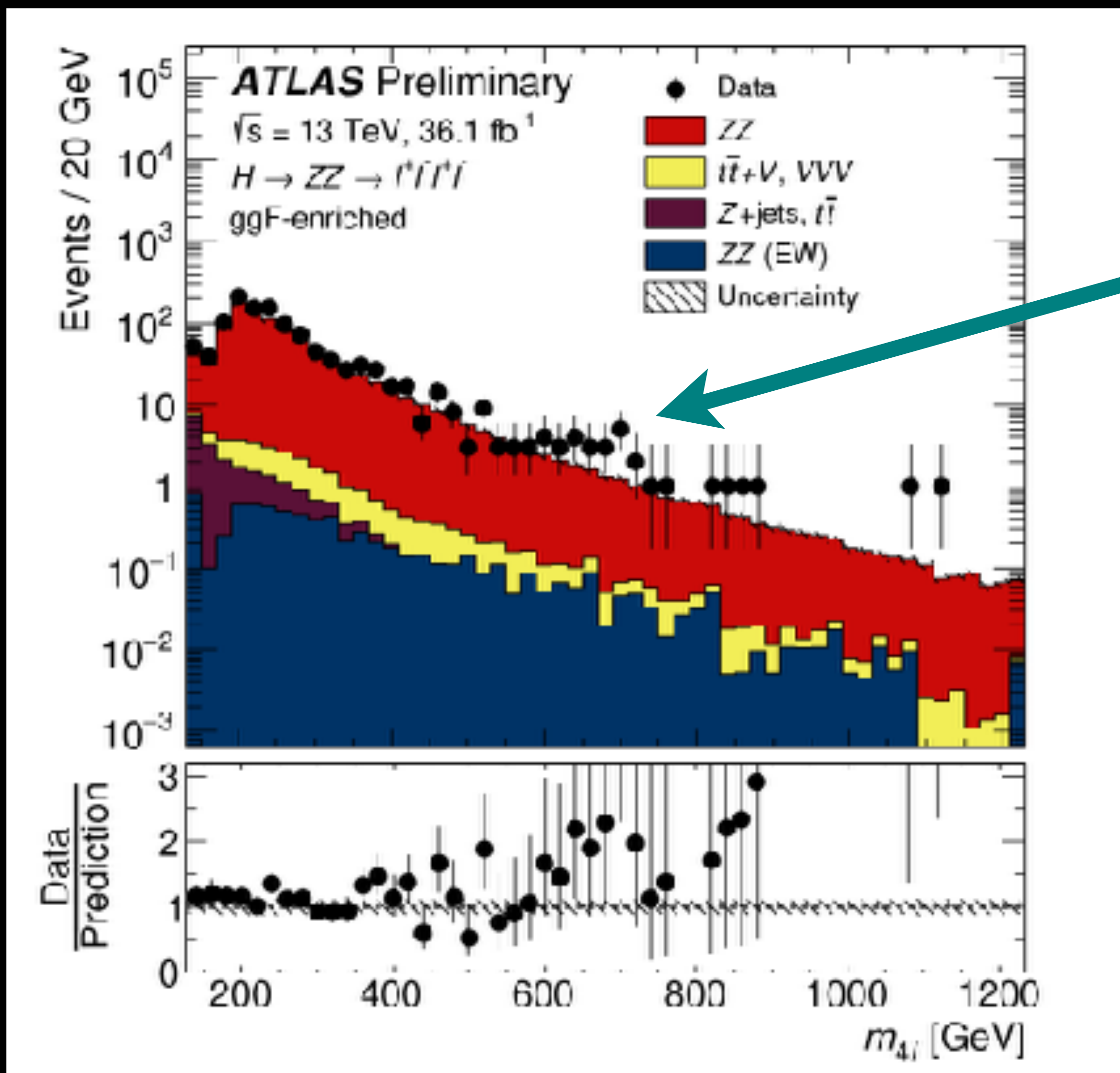
14 November 2018

or

what would *you* do with a million accessible Higgses and 10^{12} clean Z bosons?

New physics in 2018

Where to look next is not as straightforward as it was in the 90s and 2000s



?

We would certainly welcome some traditional theoretical guidance, but difficult to come by these days (WIMP miracle in tension, lack of plain vanilla SUSY, etc.)

But we're explorers & map-makers, not just SUSY/SSM Z′/QBH-hunters

Need to expand research programs to more general signature-driven searches motivated by generic features of collider phenomenology and look for deviations from expectations

This must be a component of a plan for future colliders, as well

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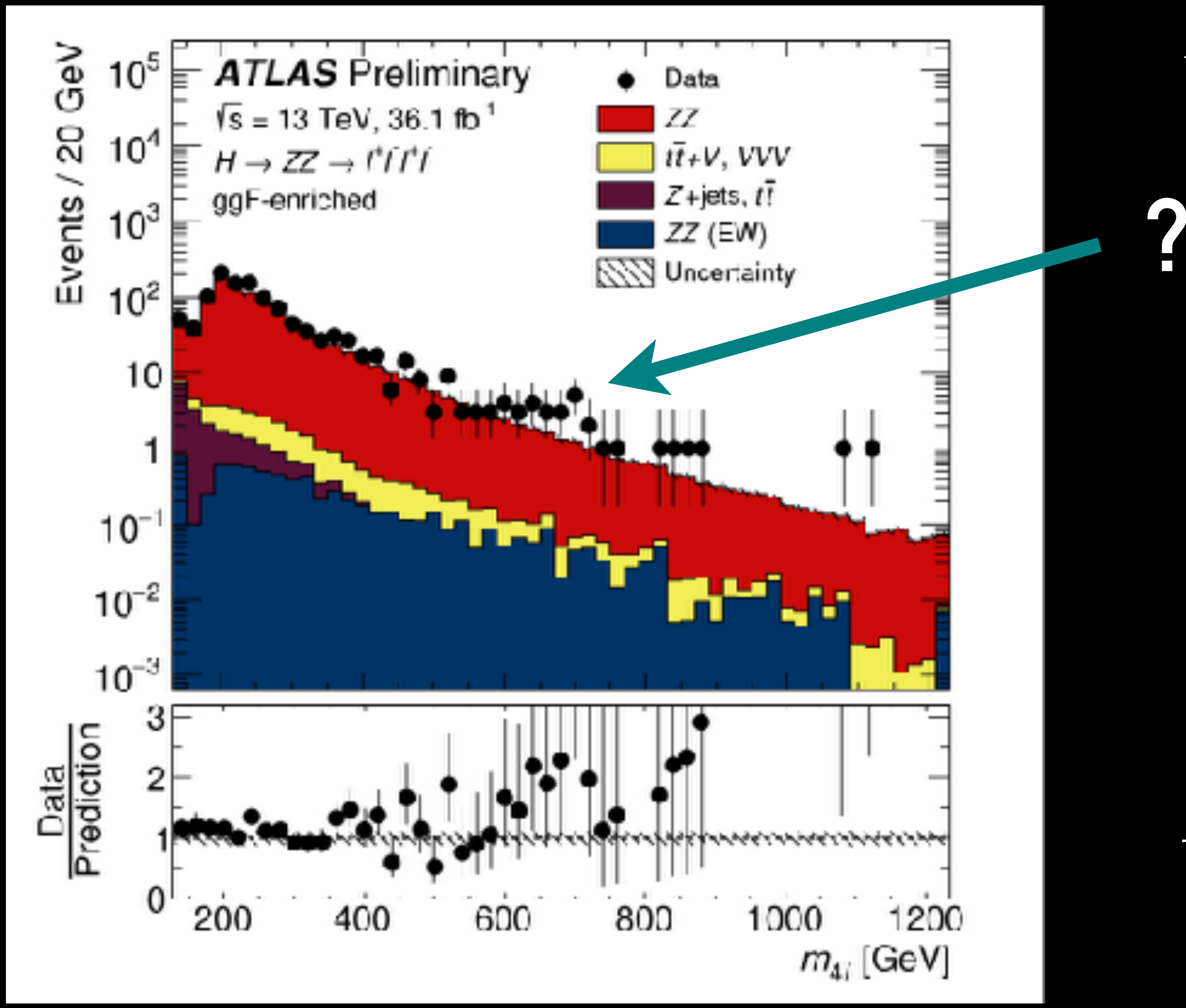

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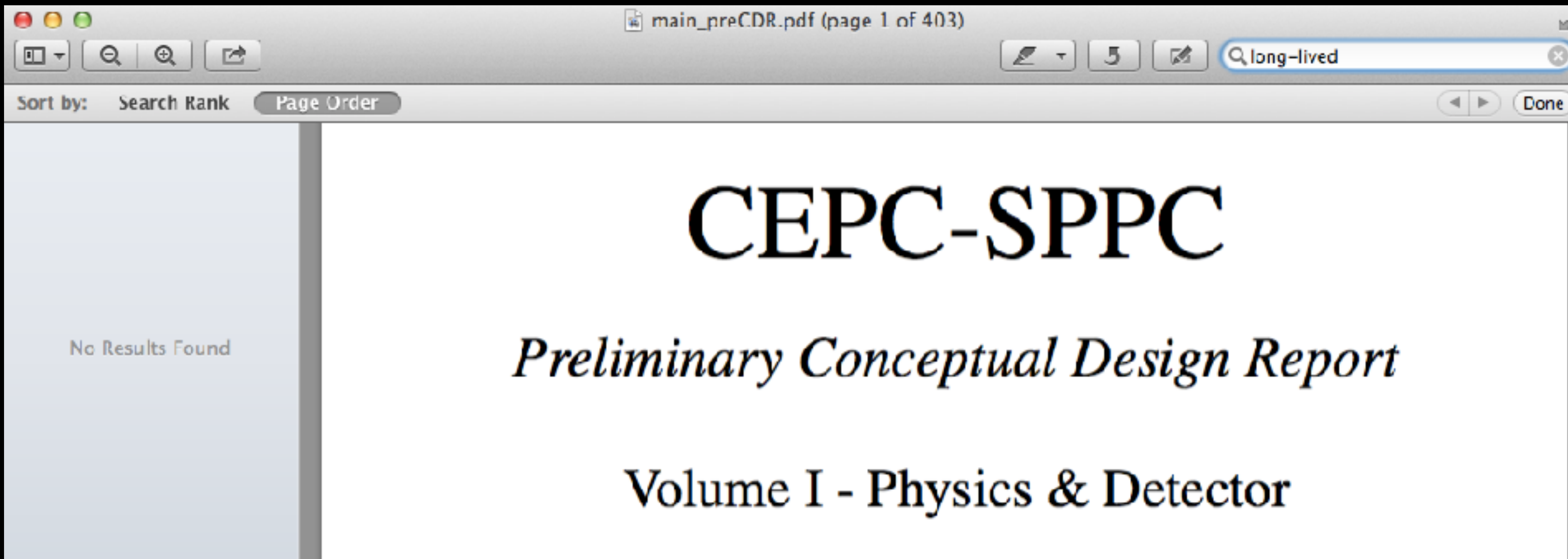
Planning for future colliders needs to incorporate the known *and* the less-well-known. How do we go beyond what we're good at?

What are we overlooking?

What are we overlooking?

One year ago



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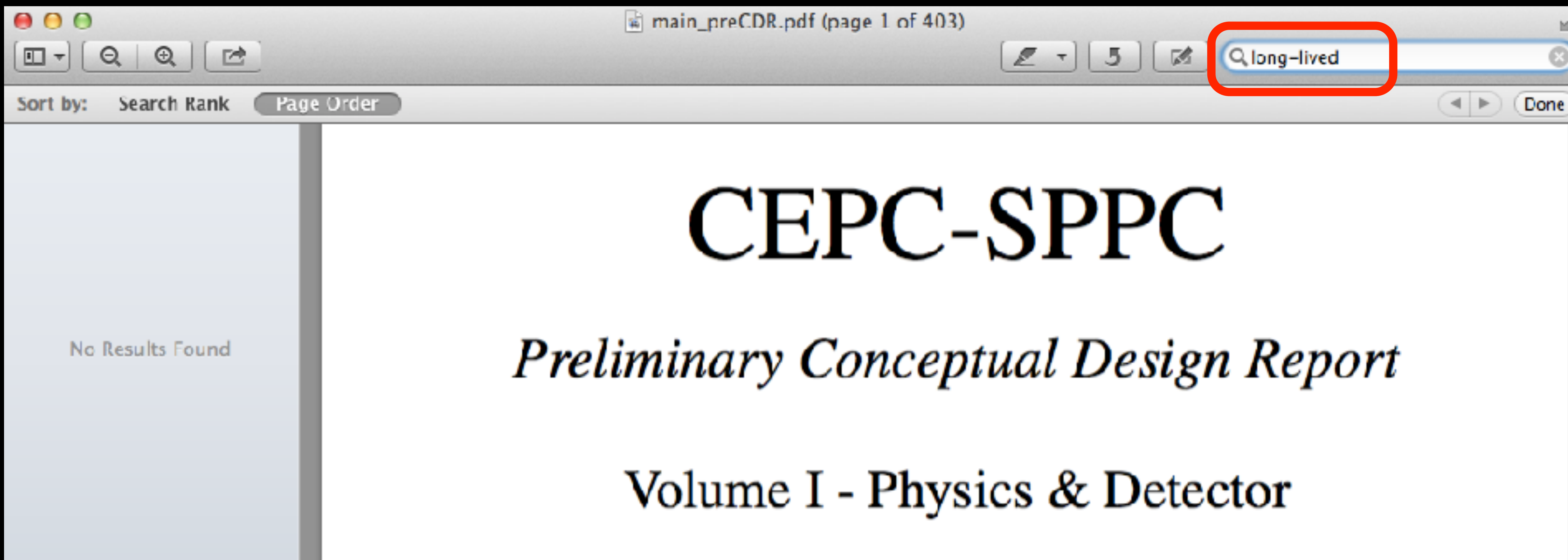

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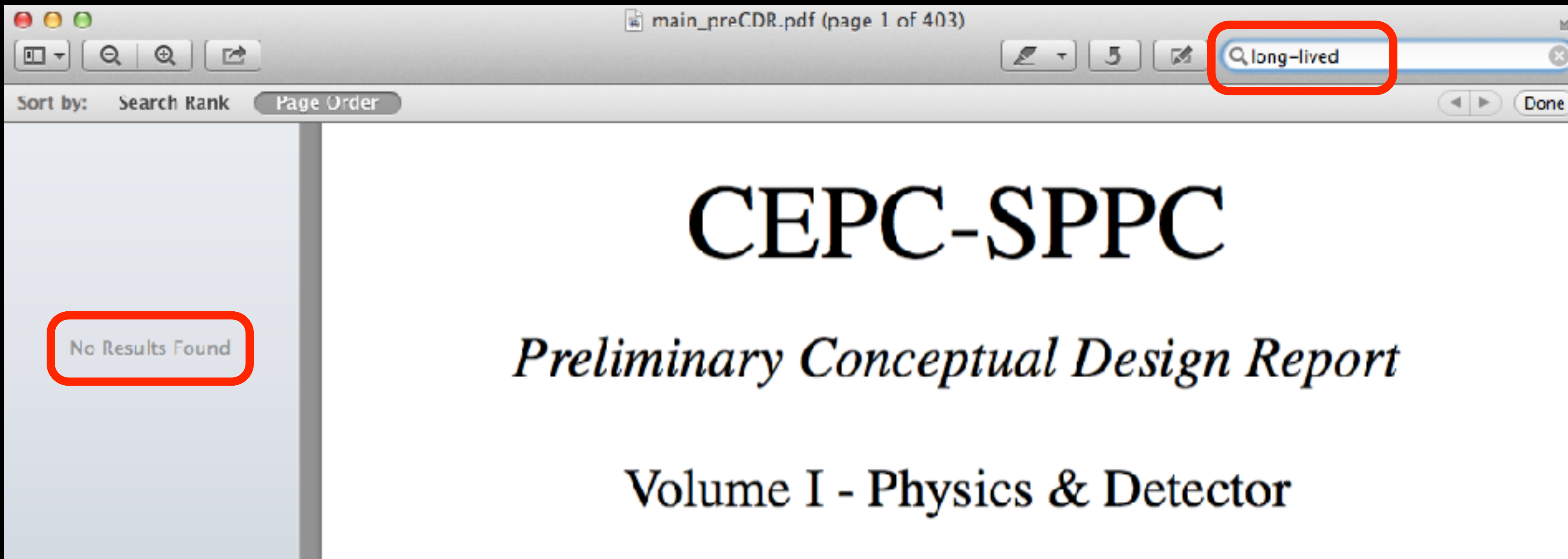

What are we overlooking?

Now, page 57, "Neutrino Connection"

DISPLACED SECONDARY VERTICES

The mechanism of neutrino mass generation can also give rise to truly exotic signatures in the form of long-lived particles whose decays produce displaced secondary vertices. Such displaced vertices are often poorly constrained at the LHC due to trigger and background limitations, whereas CEPC can provide significant sensitivity.

Single displaced vertex in Type I Seesaw: For masses below the W bosons's mass, m_W, the lifetime of N_i scales as $\tau_{N_i} \propto |\sum_a |\theta_{ai}|^2|^{-2} G_F^{-2} M_i^{-5}$ and their decays give rise to a visibly displaced secondary vertex in a large part of the allowed parameter space. Displaced vertex signatures have been studied in detail for the case of the Type I Seesaw, and the CEPC specific results from Refs. [261, 313] are shown in Figure 2.33 by the purple line. It is worth noting that with a longer Z-pole run the sensitivity for $M_i < m_Z$ can be significantly increased, see Figure 2.34. The sensitivity of a standard detector could be increased with additional detectors of the MATHUSLA [323, 324] or FASER [325] type.

Long lived neutral scalars: Due to mixing with the Higgs boson, the electrically neutral scalars in gauged $U(1)_{B-L}$ [326] or the neutral scalar from $SU(2)_R$ [327] can decay via the SM Yukawa couplings into the SM fermions. For masses in the GeV range, the resulting proper lifetimes can easily be $\mathcal{O}(1\text{ cm})$, such that their decays give rise to displaced secondary vertices.

Multiple displaced vertices: Pair production of N in exotic Higgs boson decays may lead to two displaced vertices, each containing a lepton and two jets at parton level, as pointed out in the context of LRSM [283, 284] and models with $B-L$ symmetry [299, 300]. Rare exotic decays of the SM-like Higgs boson to a pair of triplets with subsequent decay to 4 Ns leads to up to four displaced vertices with rather soft final states, for which the CEPC is likely to be much better suited than the LHC.

Similarly, the associated production of the scalar triplet at $e^+e^- \to Z^* \to Z\Delta_R^0$ leads to two displaced vertices when $\Delta_R^0 \to NN$, while Z decay gives additional prompt leptons/jets or missing energy.

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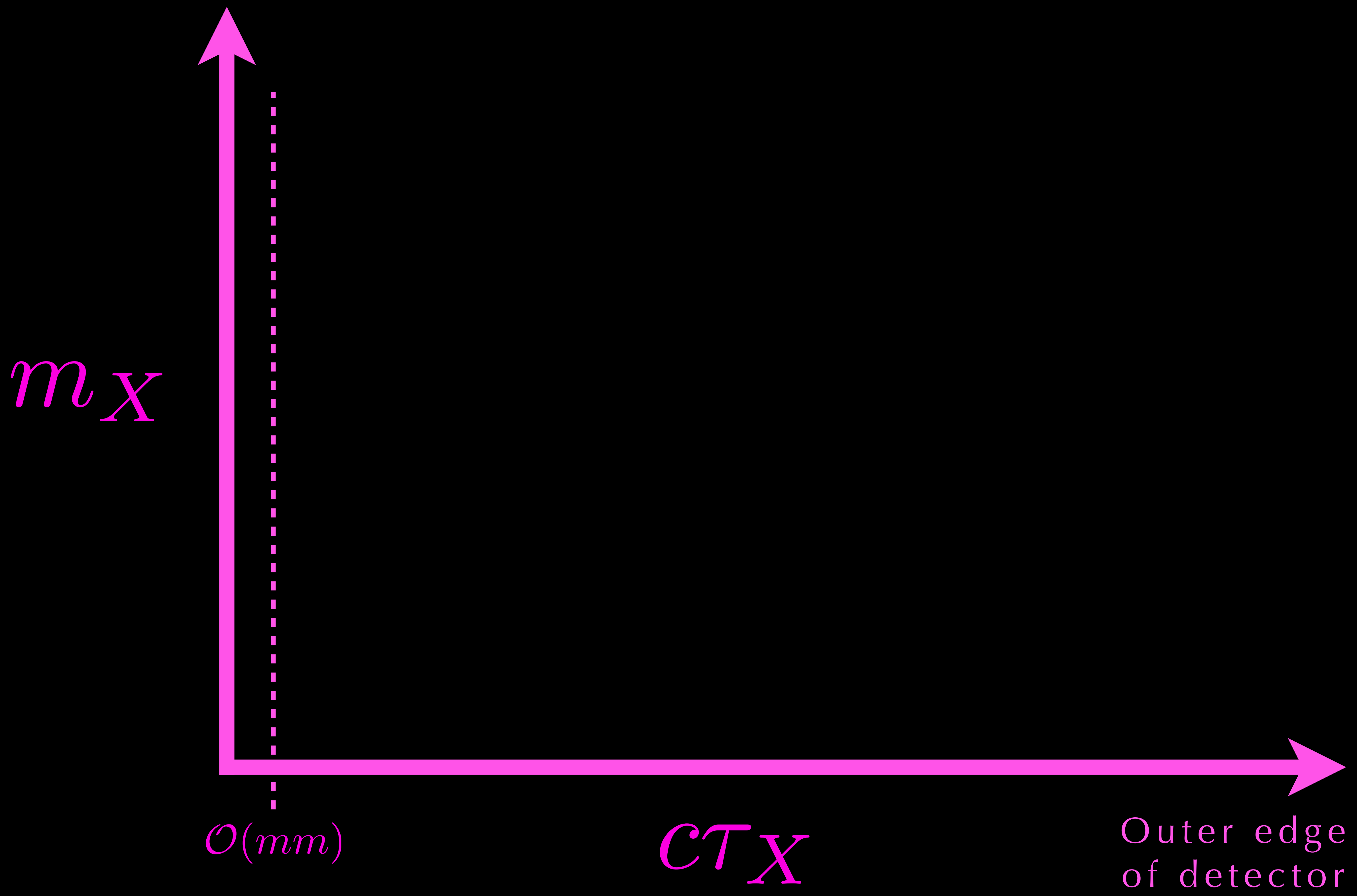
Excellent that some discussion of LLP signatures of heavy neutral leptons made it into the CDR! Now time to do the all the other studies.

New physics X at colliders



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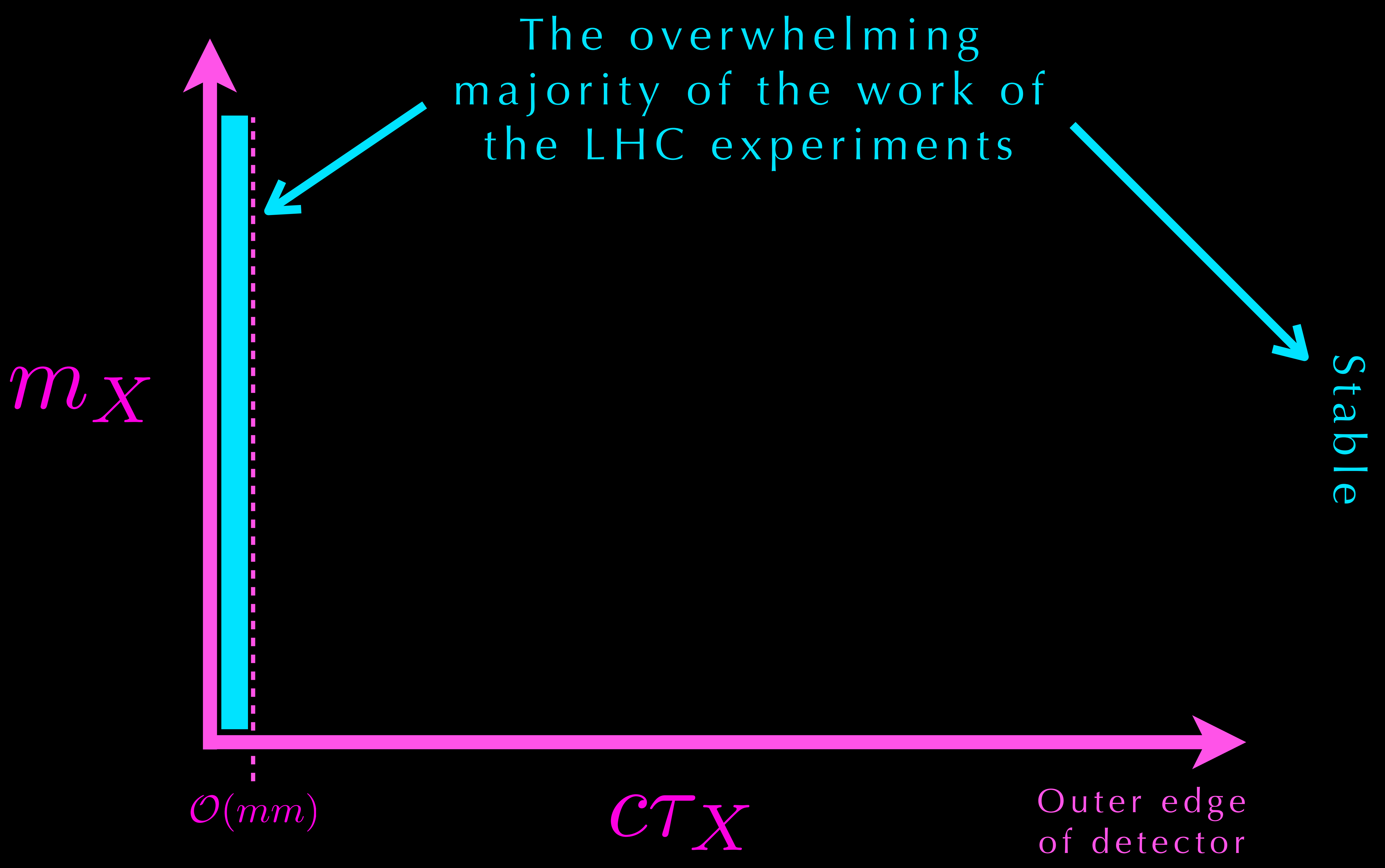

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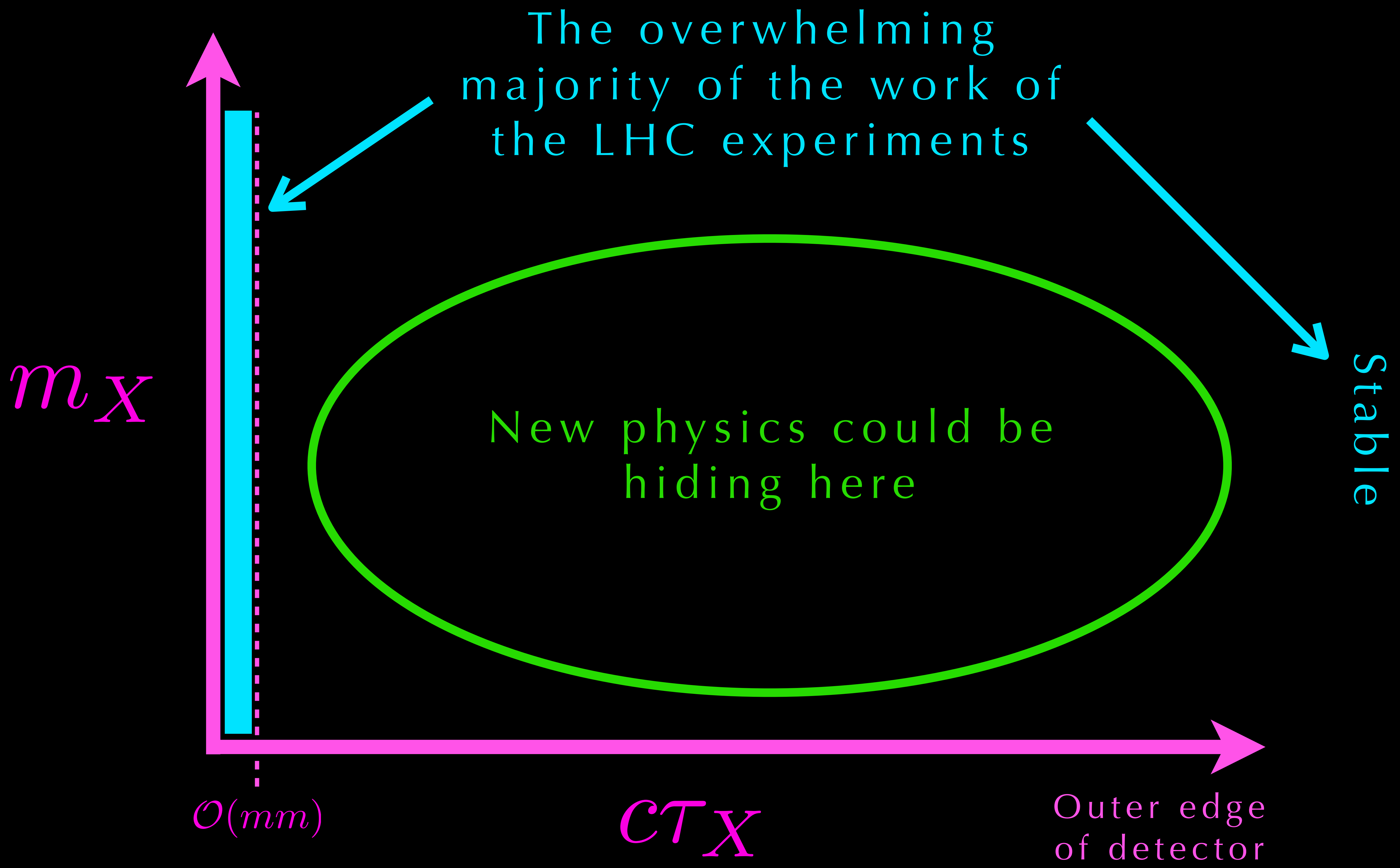
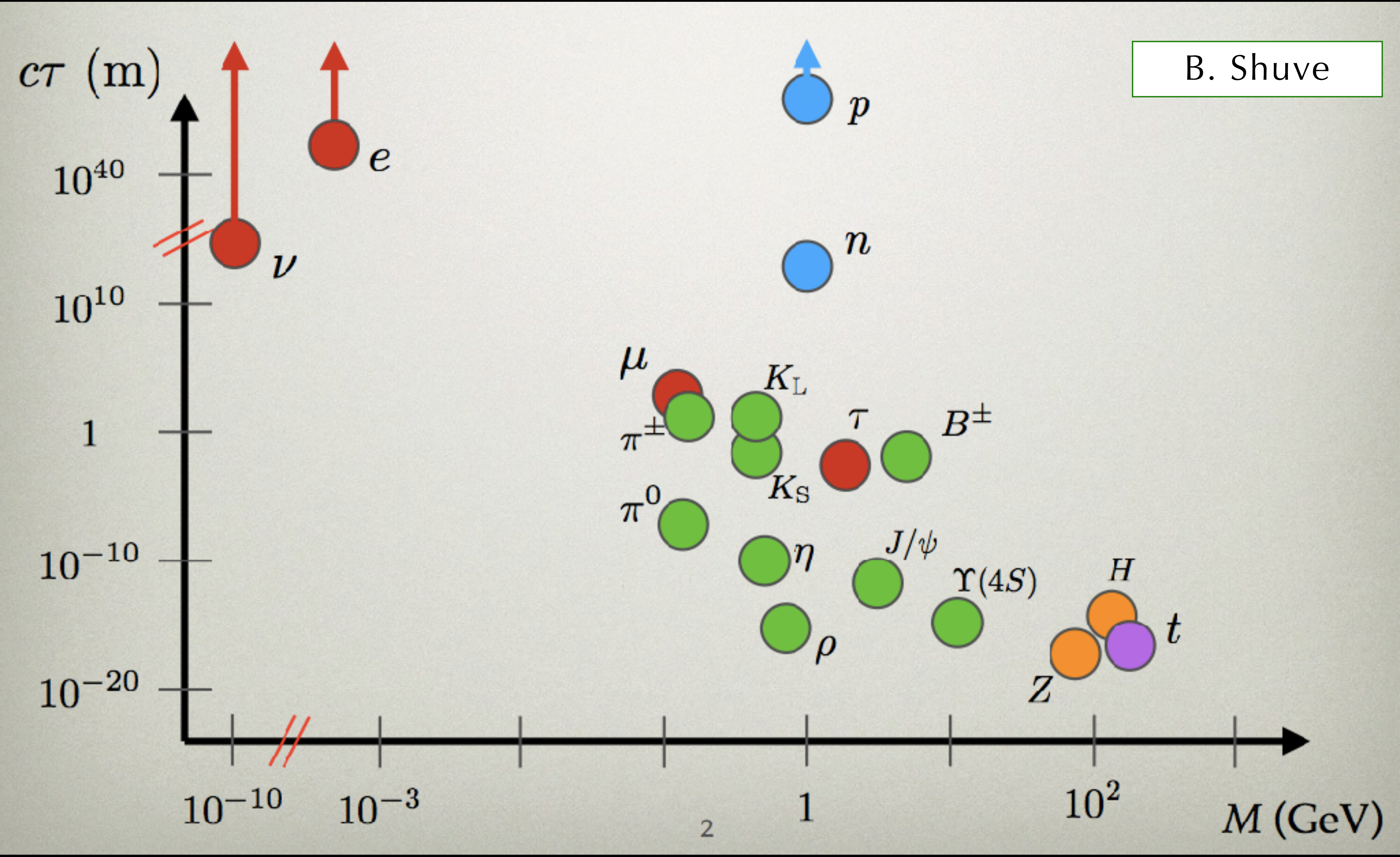


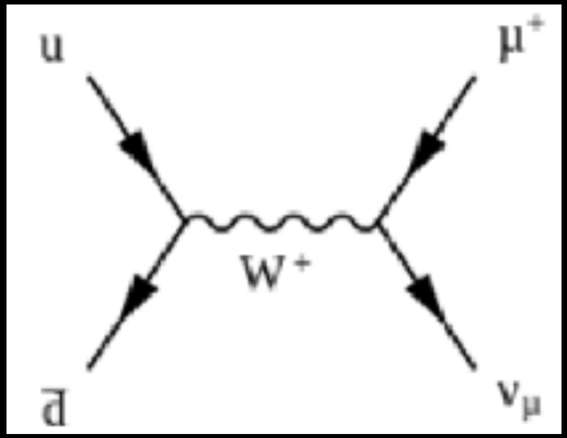
The lifetime frontier



LLPs — SM and beyond-the-SM

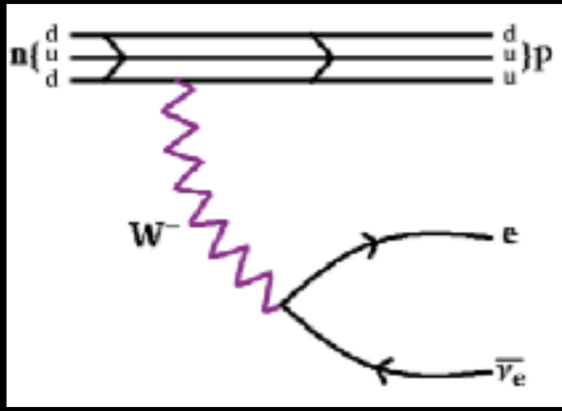
Long lifetimes typically arise in the SM when *approximate symmetries* make the particle stable

Small symmetry-breaking parameters can suppress the decay rate



Charged pion

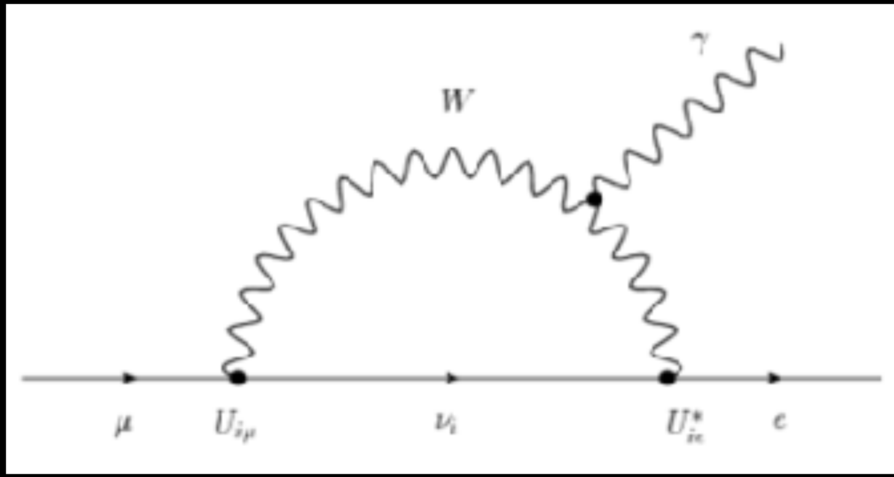
Decay highly off-shell



Neutron

Isospin: p and n nearly mass degenerate

Decay highly off-shell



FCNC

Lepton flavor violated only by extremely small neutrino Yukawas

$BR(\mu \to e\gamma) \sim 10^{-54}$

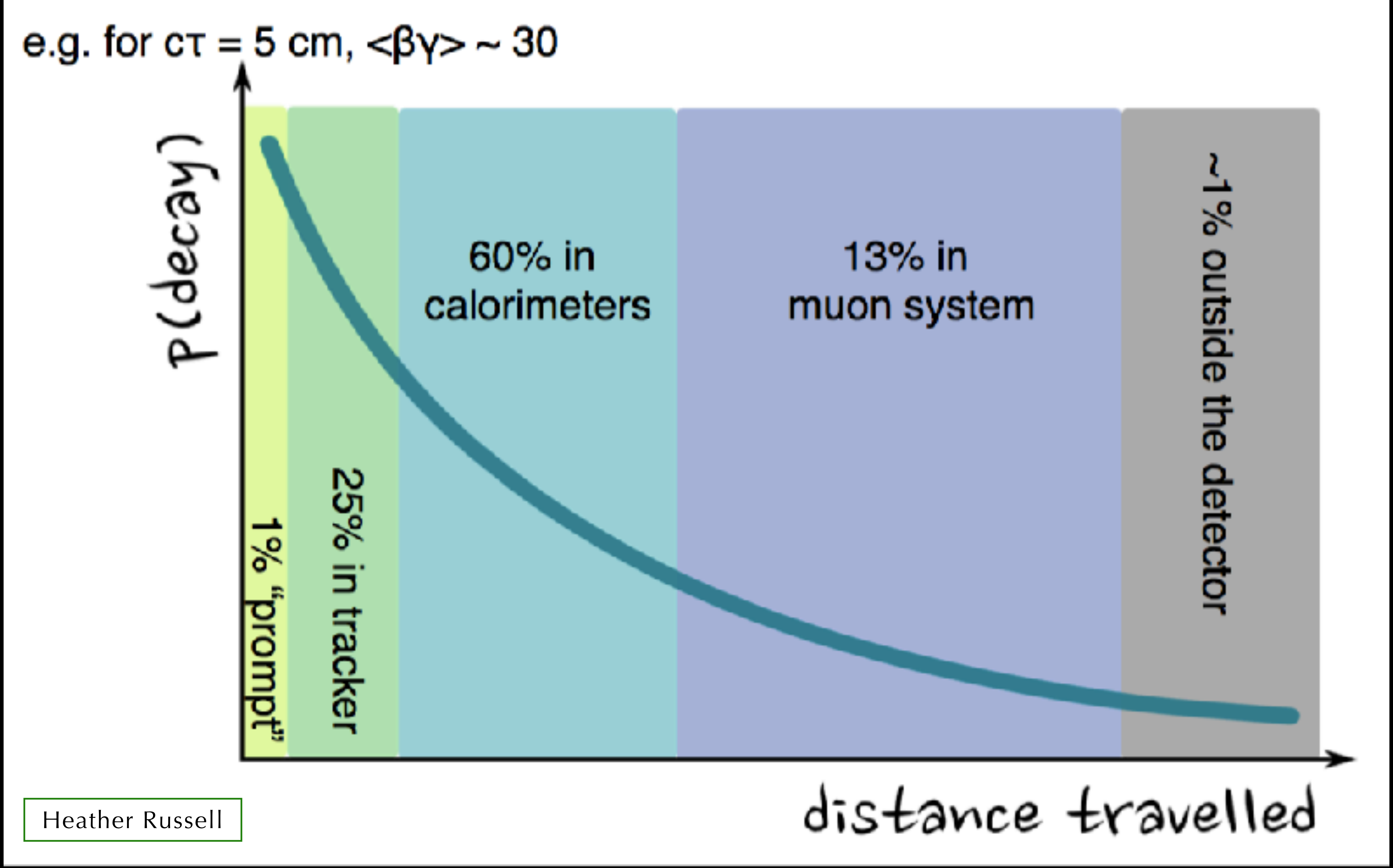
Same principles apply to BSM LLPs, which can generically appear

- Lifetime is best treated as a free parameter

Talks by Strassler, Knapen, Shuve, Ramsey-Mulsof, others

Long-Lived Particles at the LHC

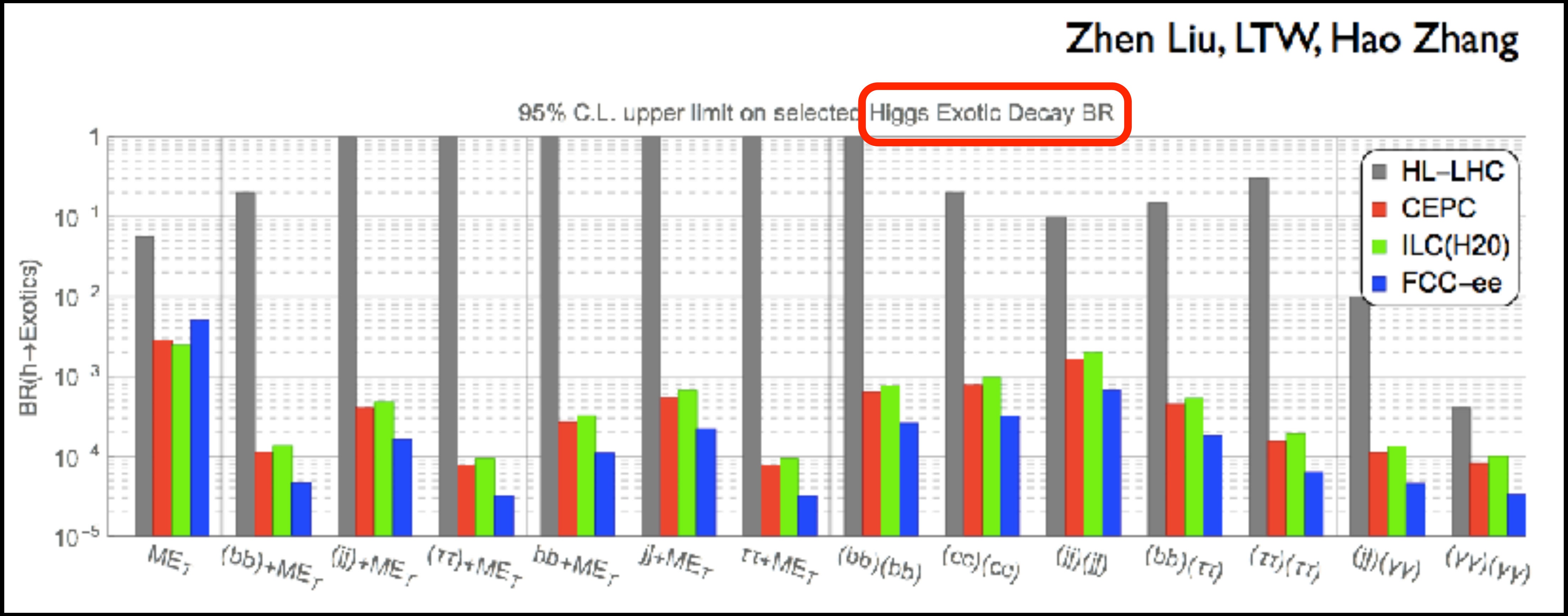
The observed lifetime of a particle is sampled from an exponential whose shape is set by its proper lifetime ctau

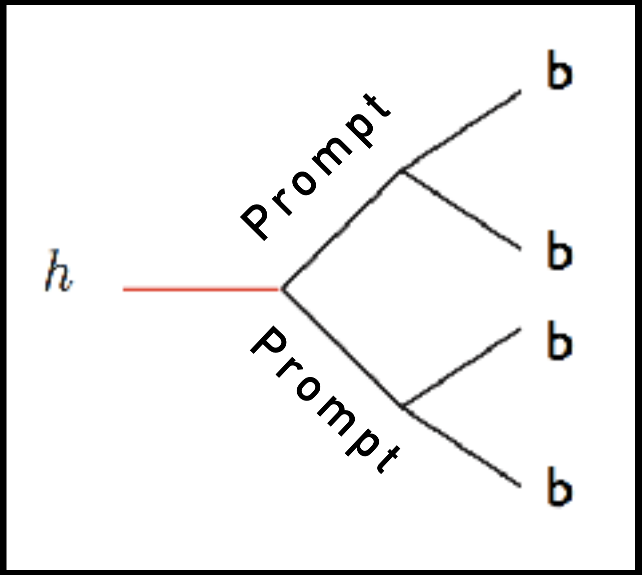


As a result, we use multiple search strategies targeting all subdetectors of ATLAS, CMS, and LHCb — and beyond the detectors

Overlooking new physics at future lepton colliders

More concretely, what are we missing at a nice, clean, lepton-collider Higgs/Z factory? E.g.,





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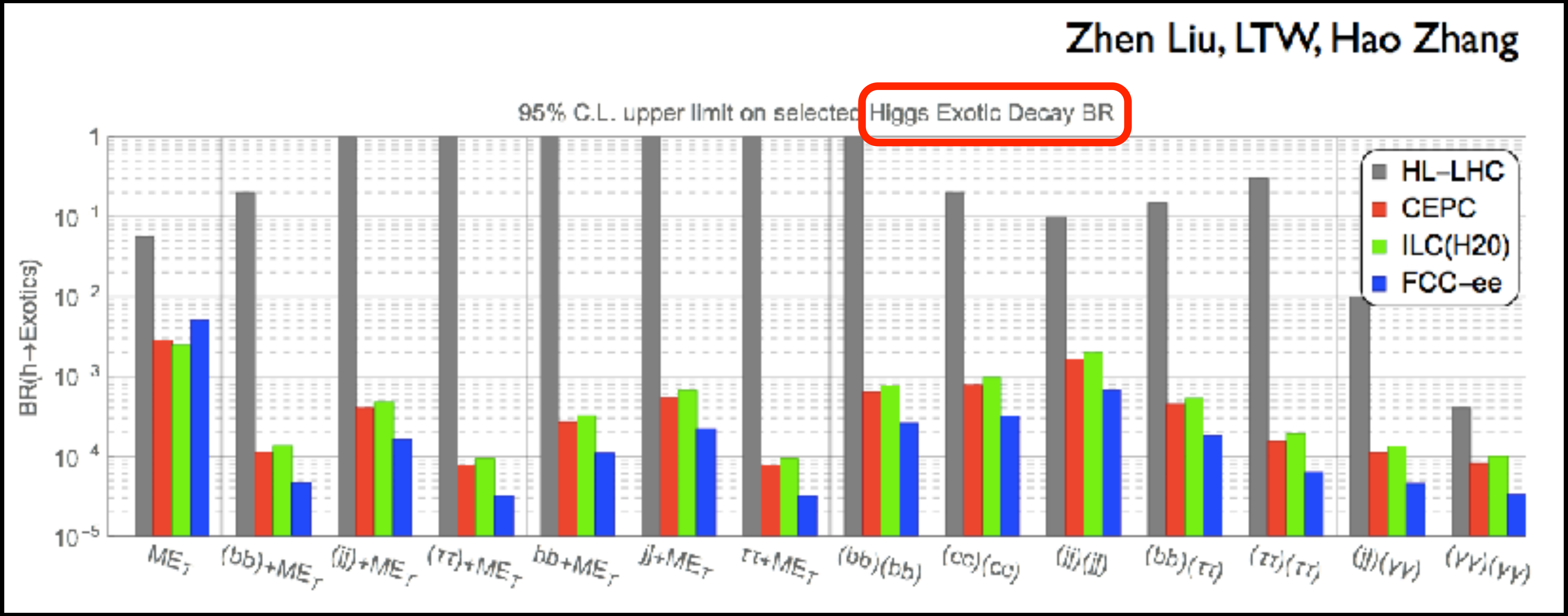
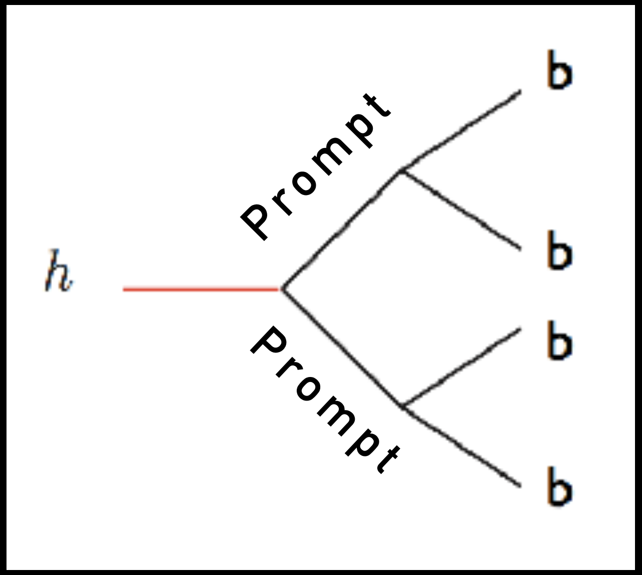
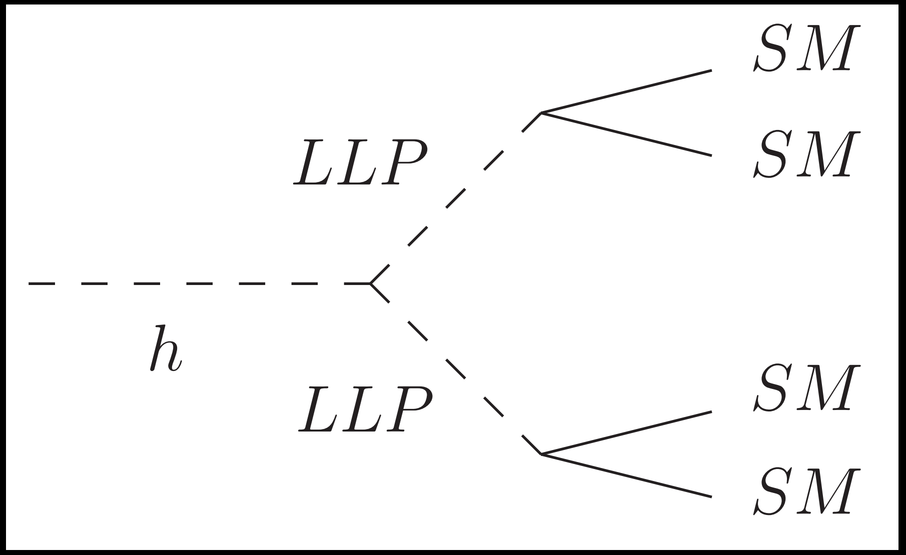




The intermediate particle can generically be long-lived —> completely different signatures



LLP searches in general at future machines

Most of the thought for future LLP searches (for all the classes of models we consider) has gone into future circular *hadron* colliders

- FCC-hh plans for higher $\sqrt{s}$ and higher luminosity
  - For direct production and detection of LLPs, hadron colliders win over lepton colliders, often by orders of magnitude
- Even HL-LHC will produce 100x more Higgses than CEPC…
- …BUT the e+e- environment is so much cleaner that we can focus on the places where dedicated-energy e+e- machines would win

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Hadron collider

Higher $\sqrt{s}$ —> higher mass new physics

Larger production rates for strongly produced new particles

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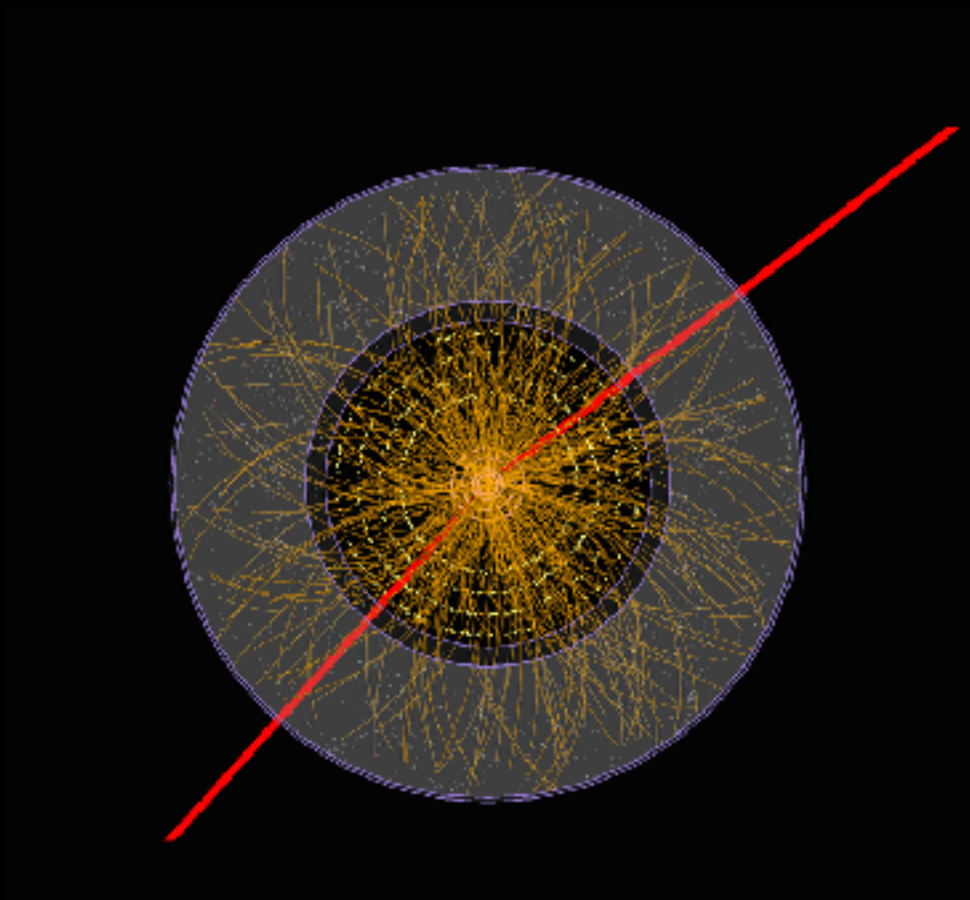
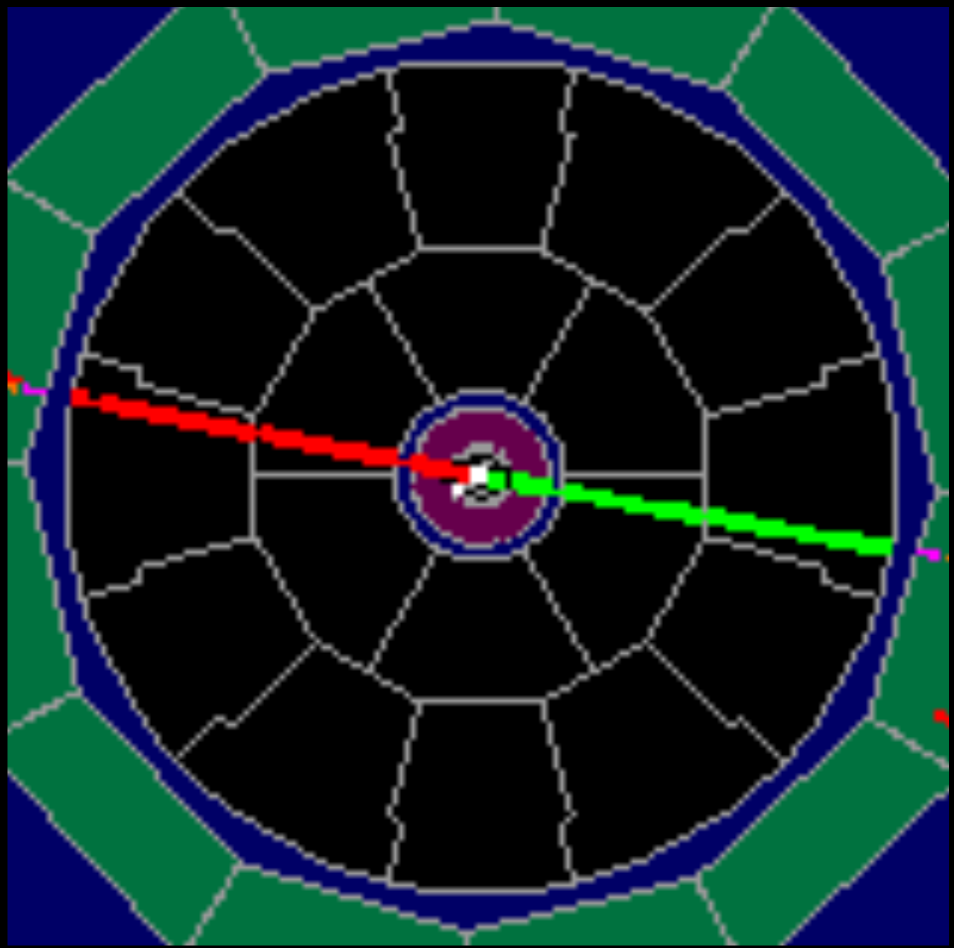
Hadron collider	e+e- collider
Higher √s —> higher mass new physics	Clean, clean, clean, clean collision environment!
Larger production rates for strongly produced new particles	A large number of Higgses and Zs that are clean and accessible

LLP searches at future e+e- machines like CEPC

Lepton collisions are beautifully clean!



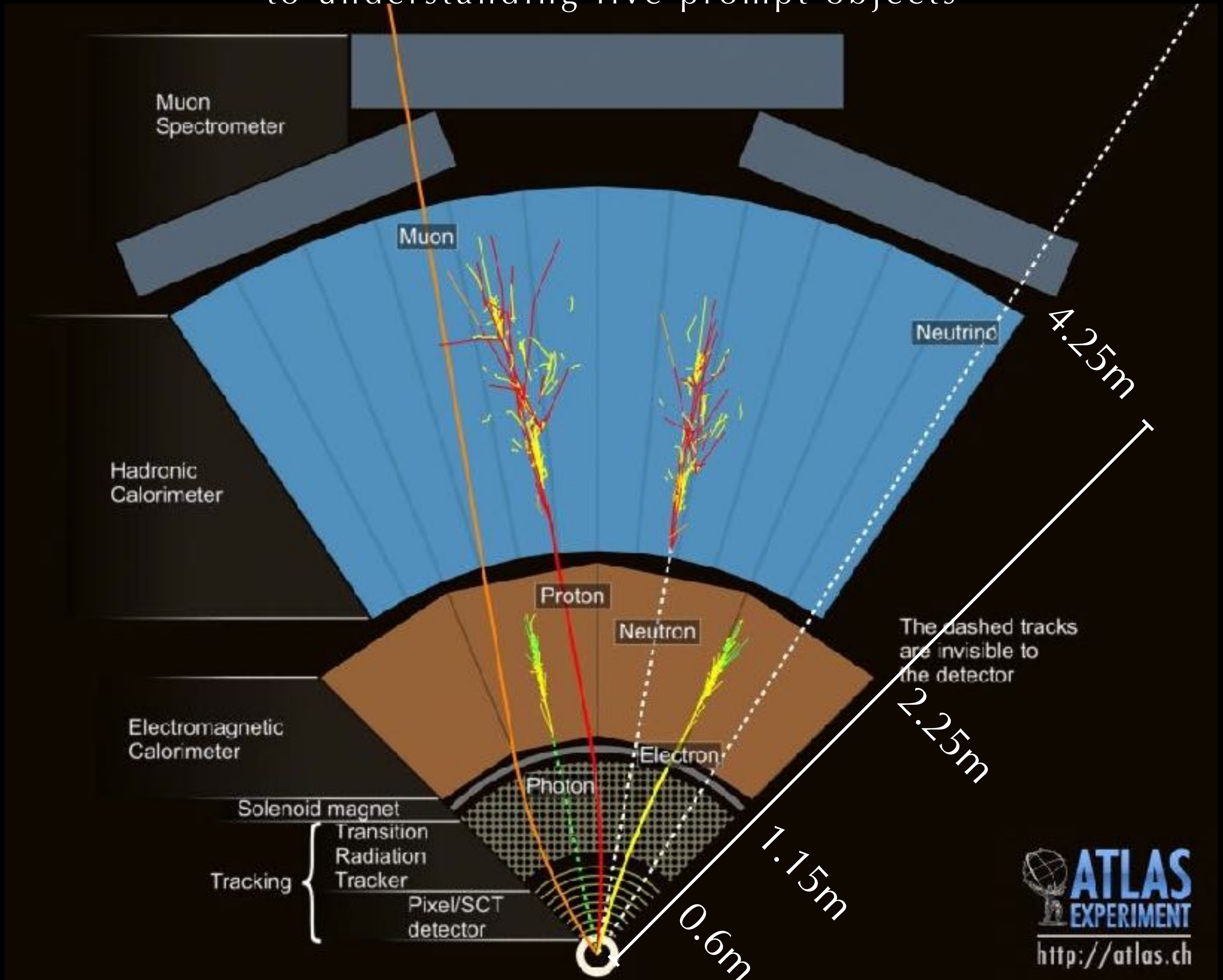
Z —> μμ at ATLAS



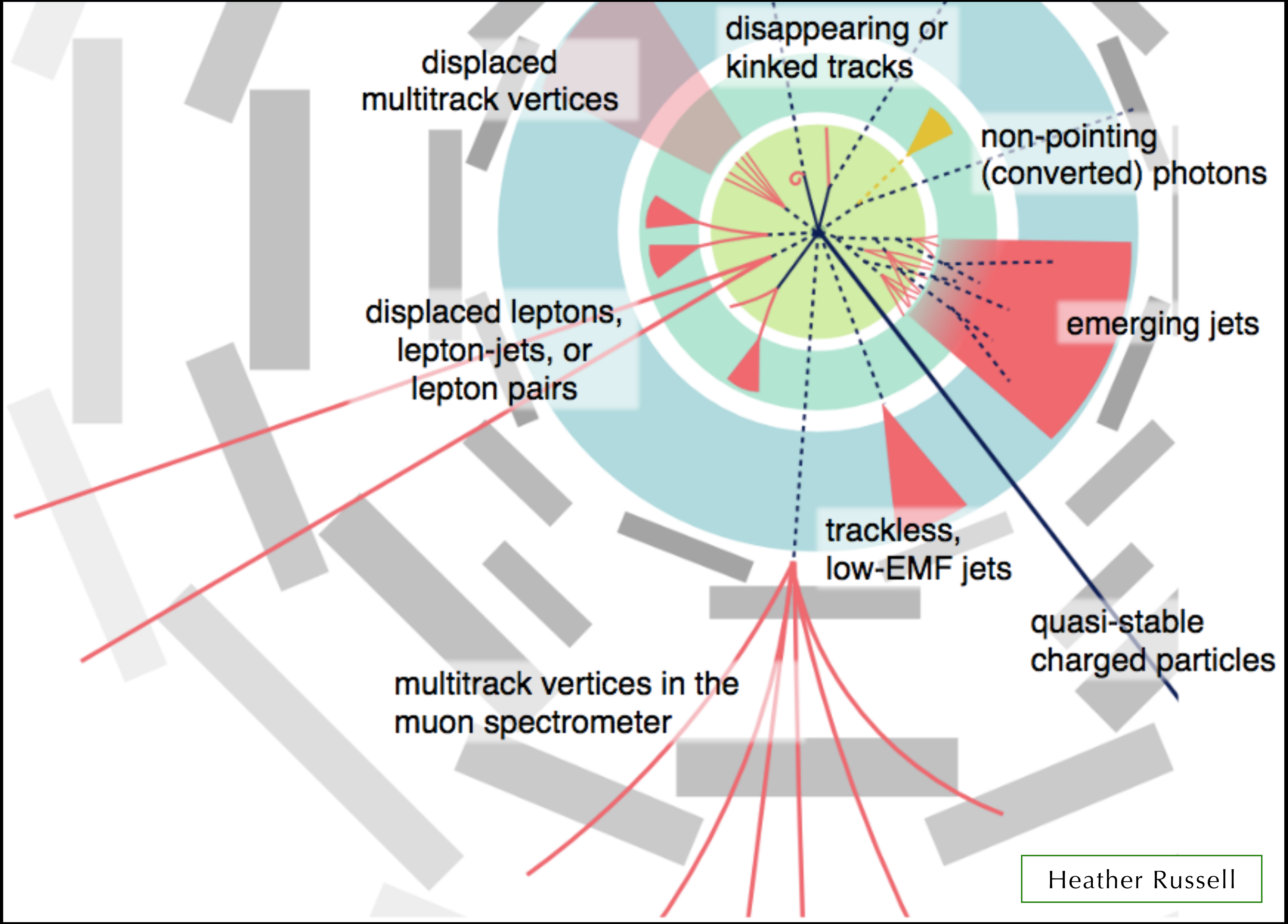
Z —> μμ at ALEPH

- Pileup not an issue — triggering straightforward
- Have full four-vector of initial state e+e- —> precision secondary vertexing
- Reconstruction of secondary vertices much closer to interaction point possible —> can push to lower lifetimes not so feasible at LHC: ~10 μm?
- Important: These searches are hard at the LHC, irrespective of pileup: Why?

95% of our analysis effort at the LHC is dedicated to understanding five prompt objects

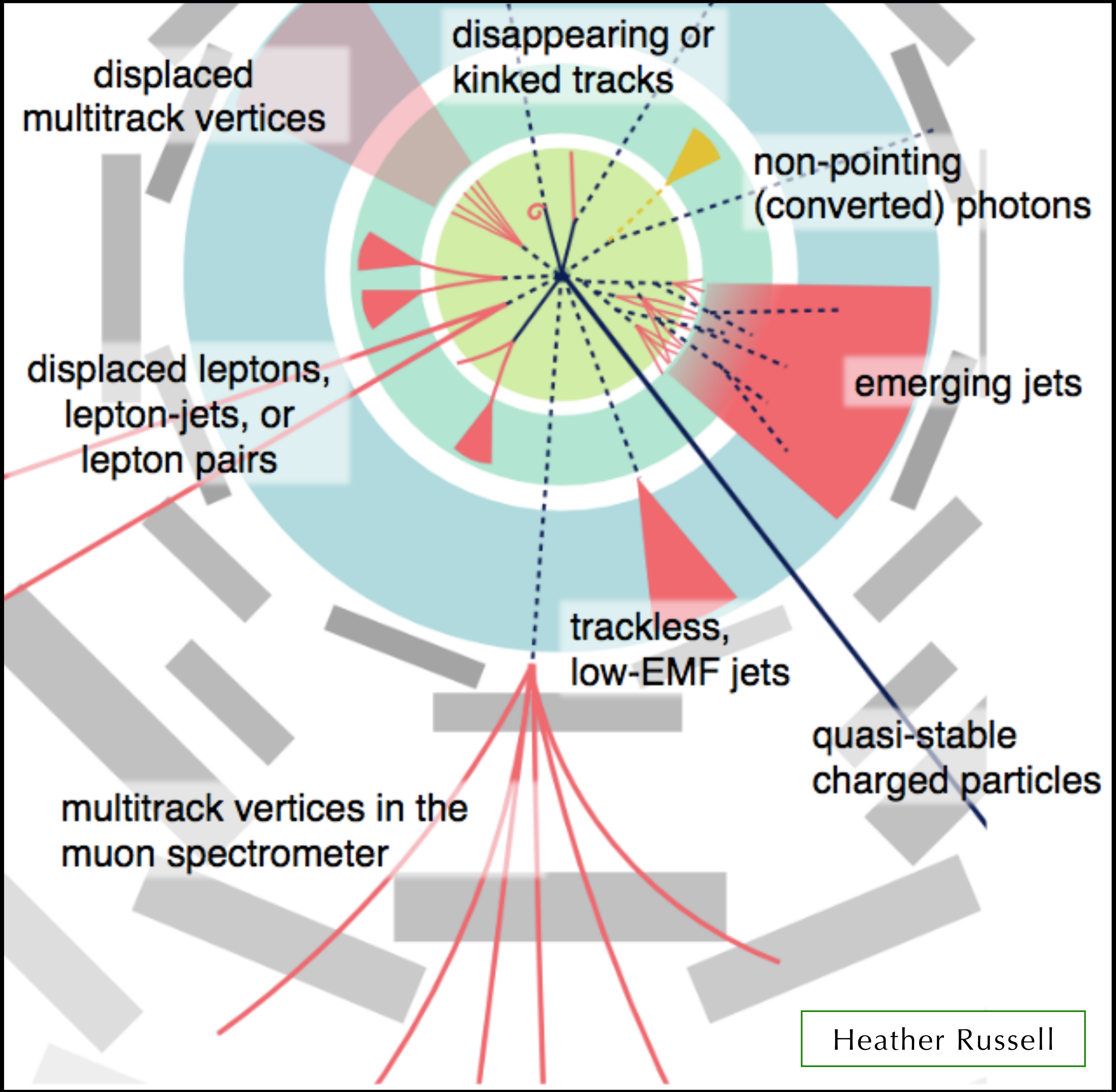


LLP searches involve wild detector objects



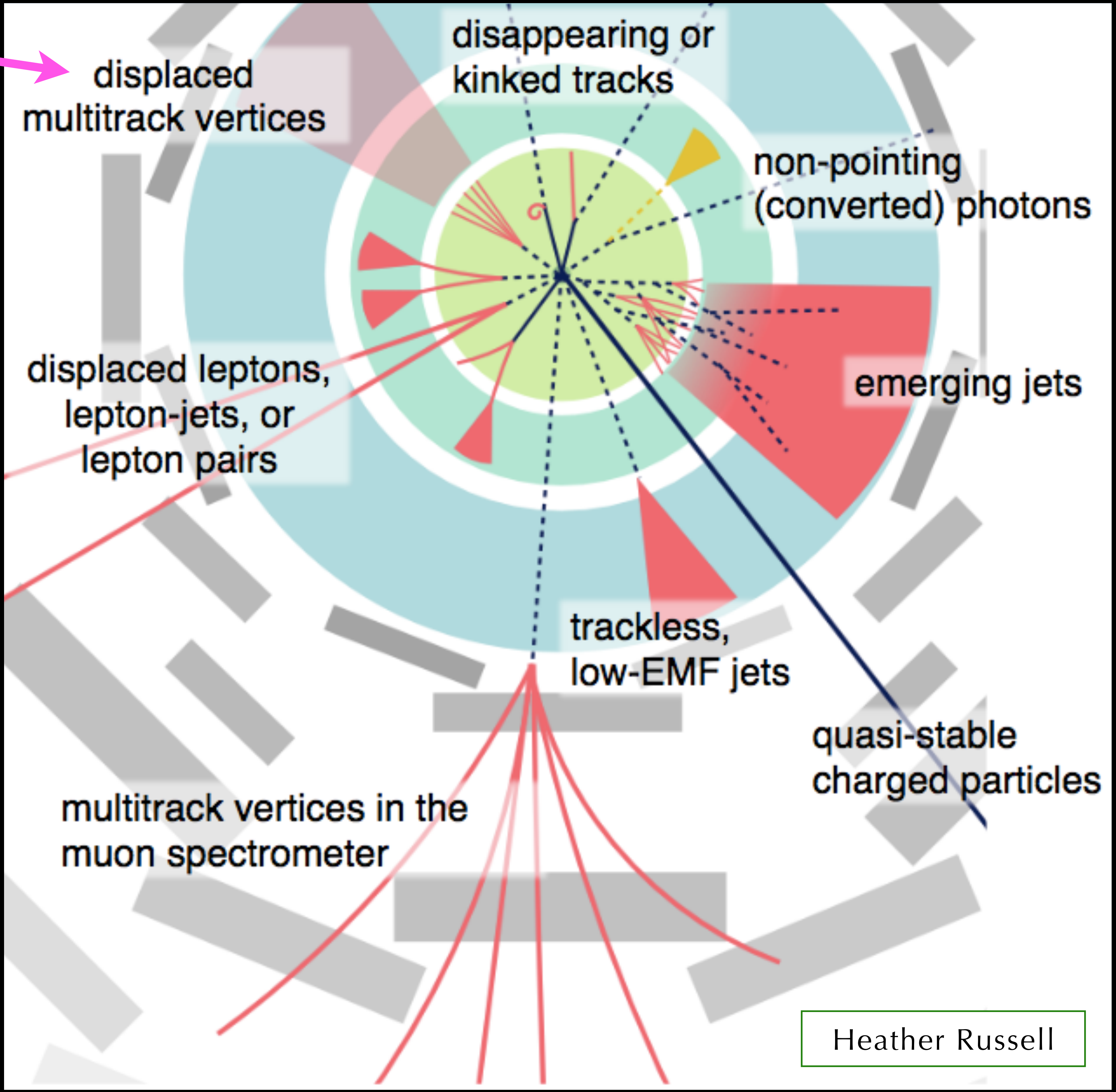
LLP searches involve wild detector objects

In which of these cases could an excellent detector at an e+e- machine have better (or complementary) sensitivity?



LLP searches involve wild detector objects

Cleaner inner detector environment with no pileup jets for small ctau —> e+e- could win!



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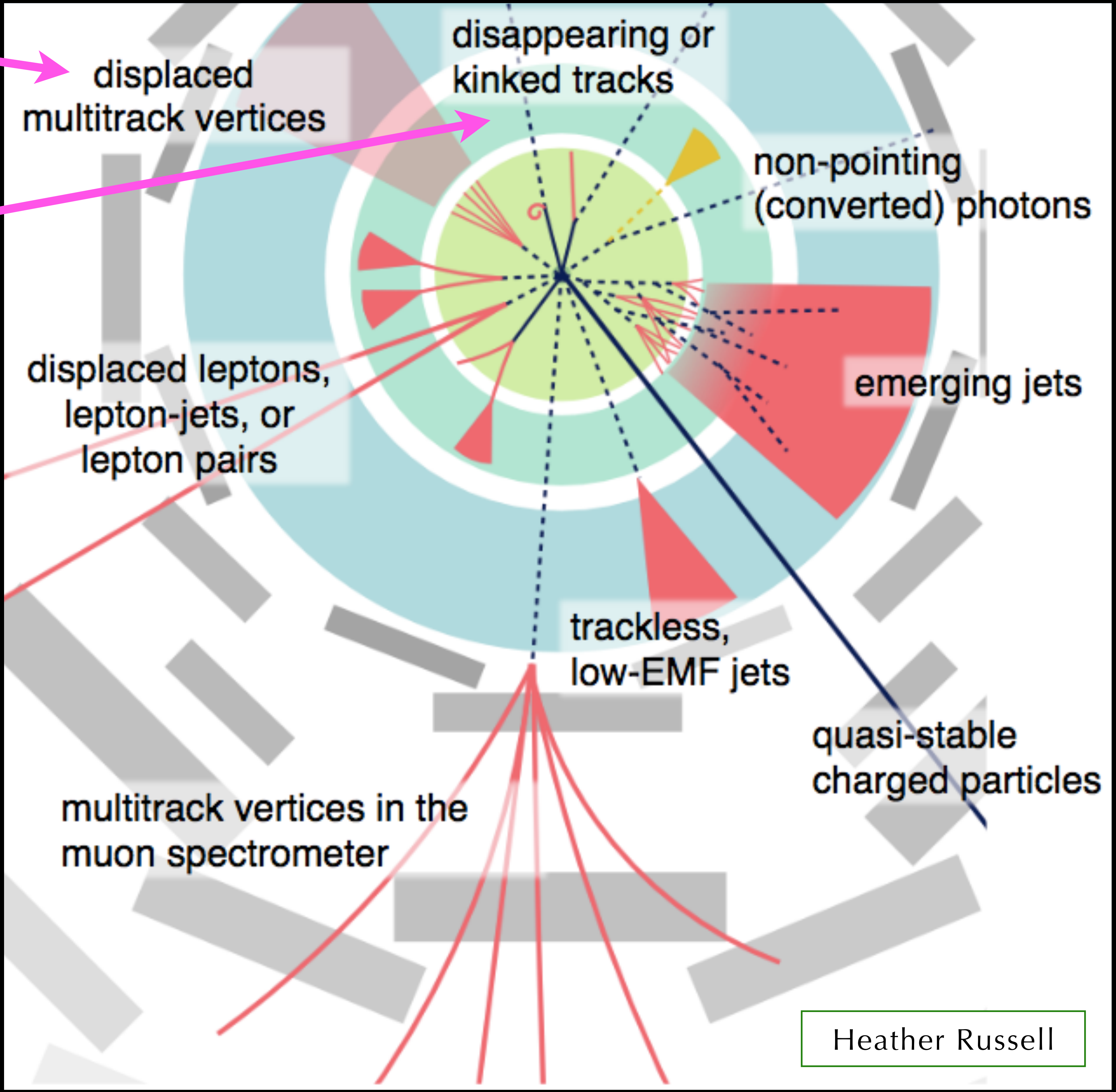
Cleaner inner detector environment with no pileup jets for very low-pT tracklets —> e+e- could win!



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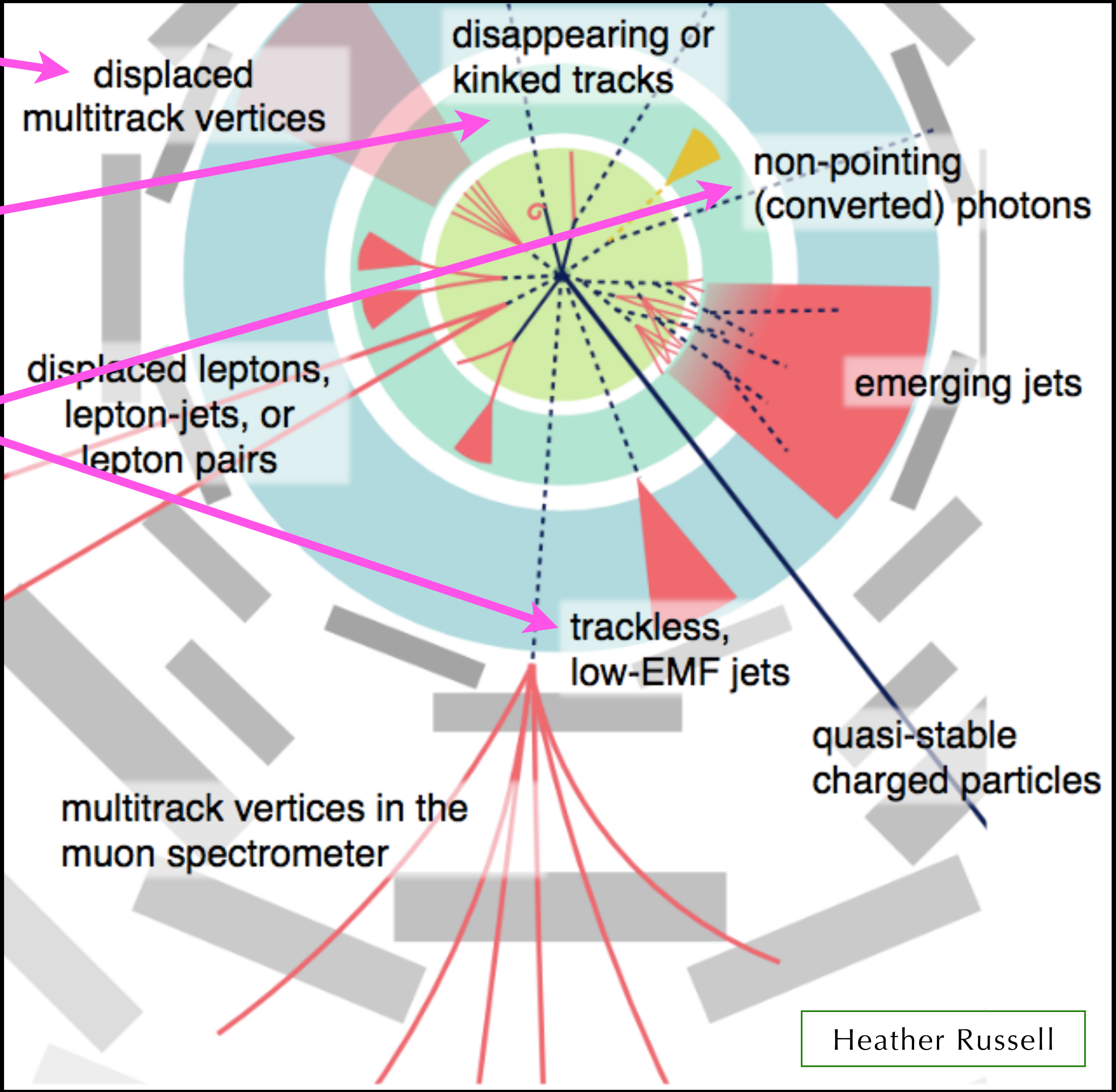

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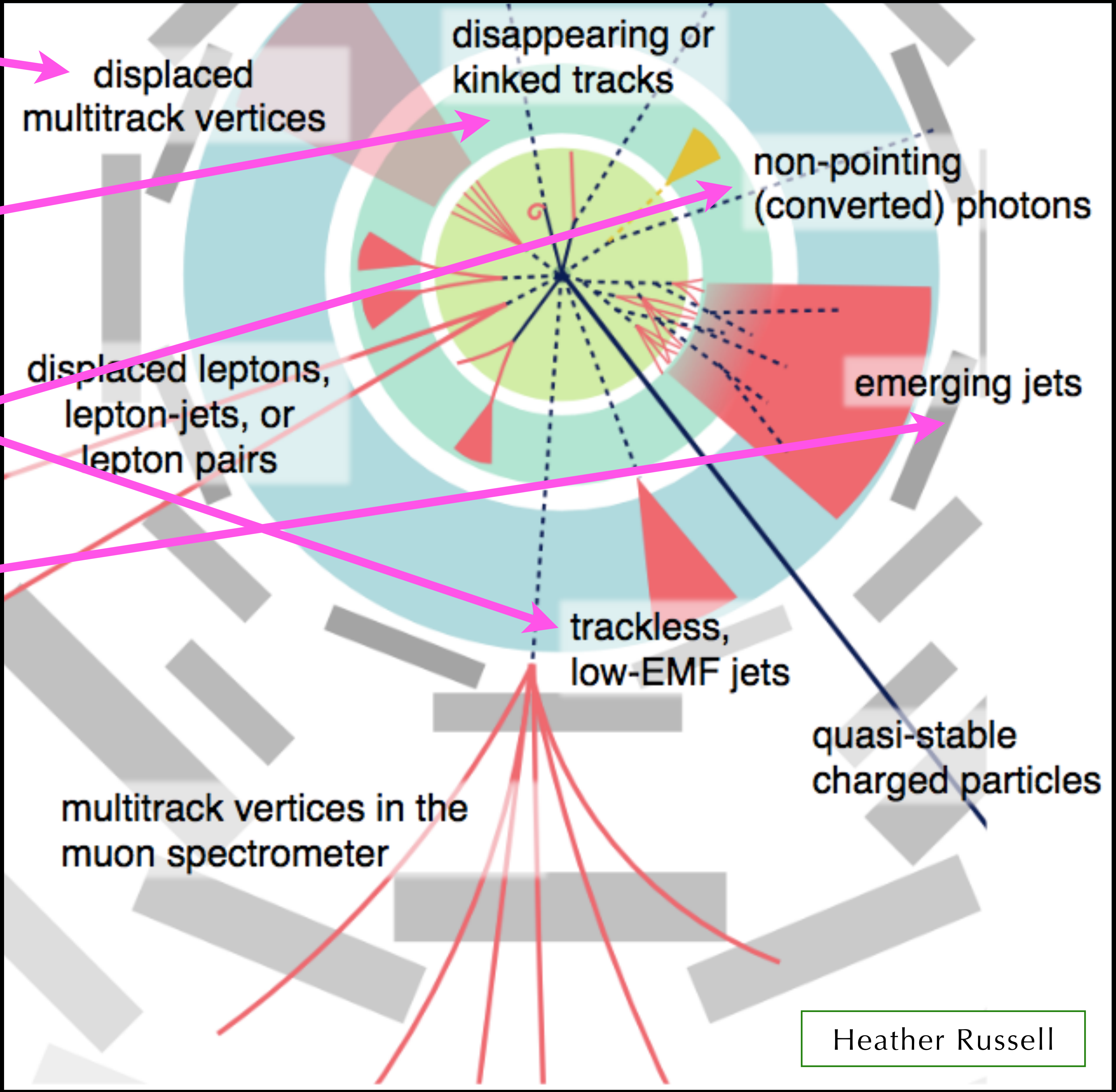

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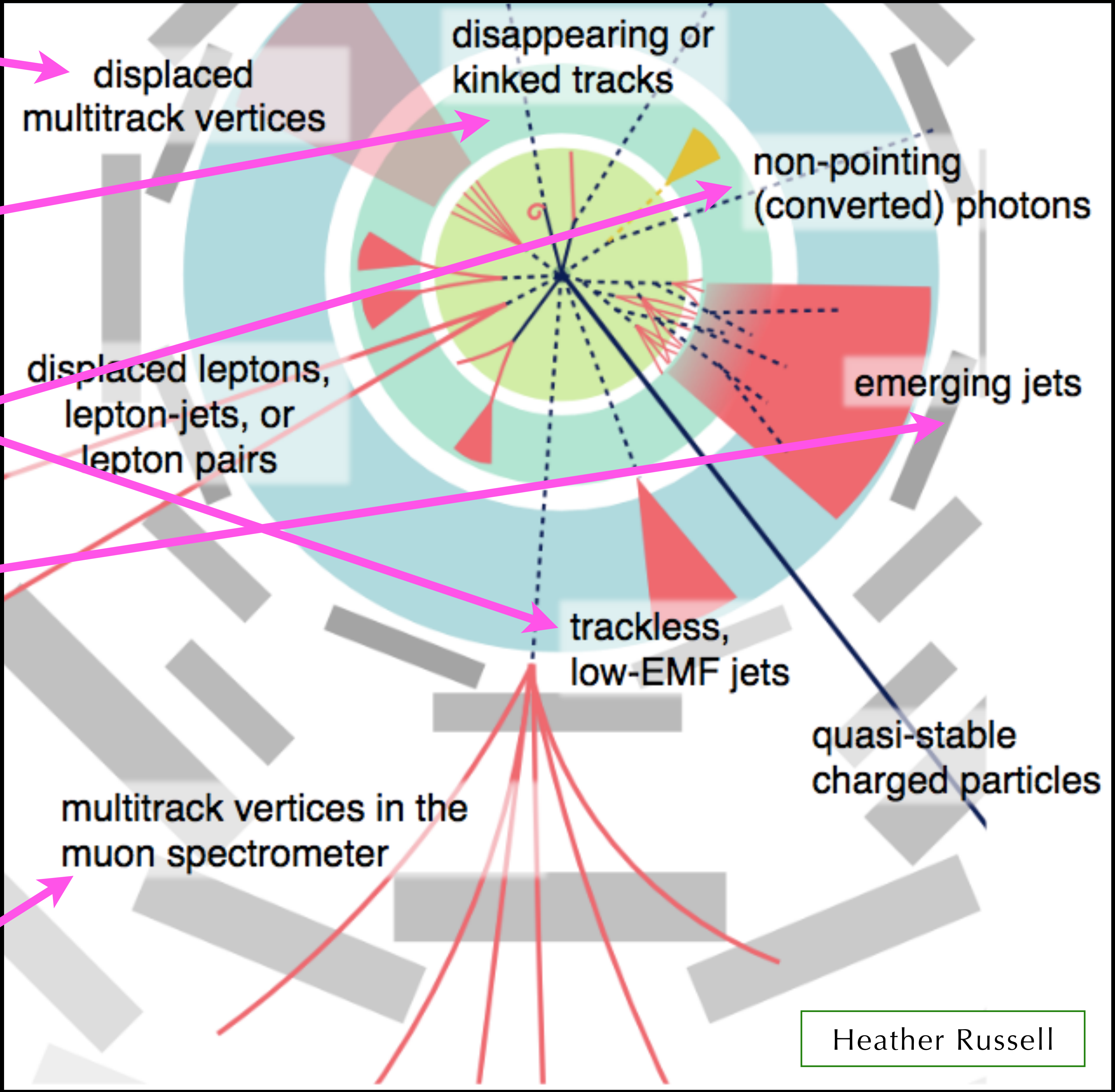

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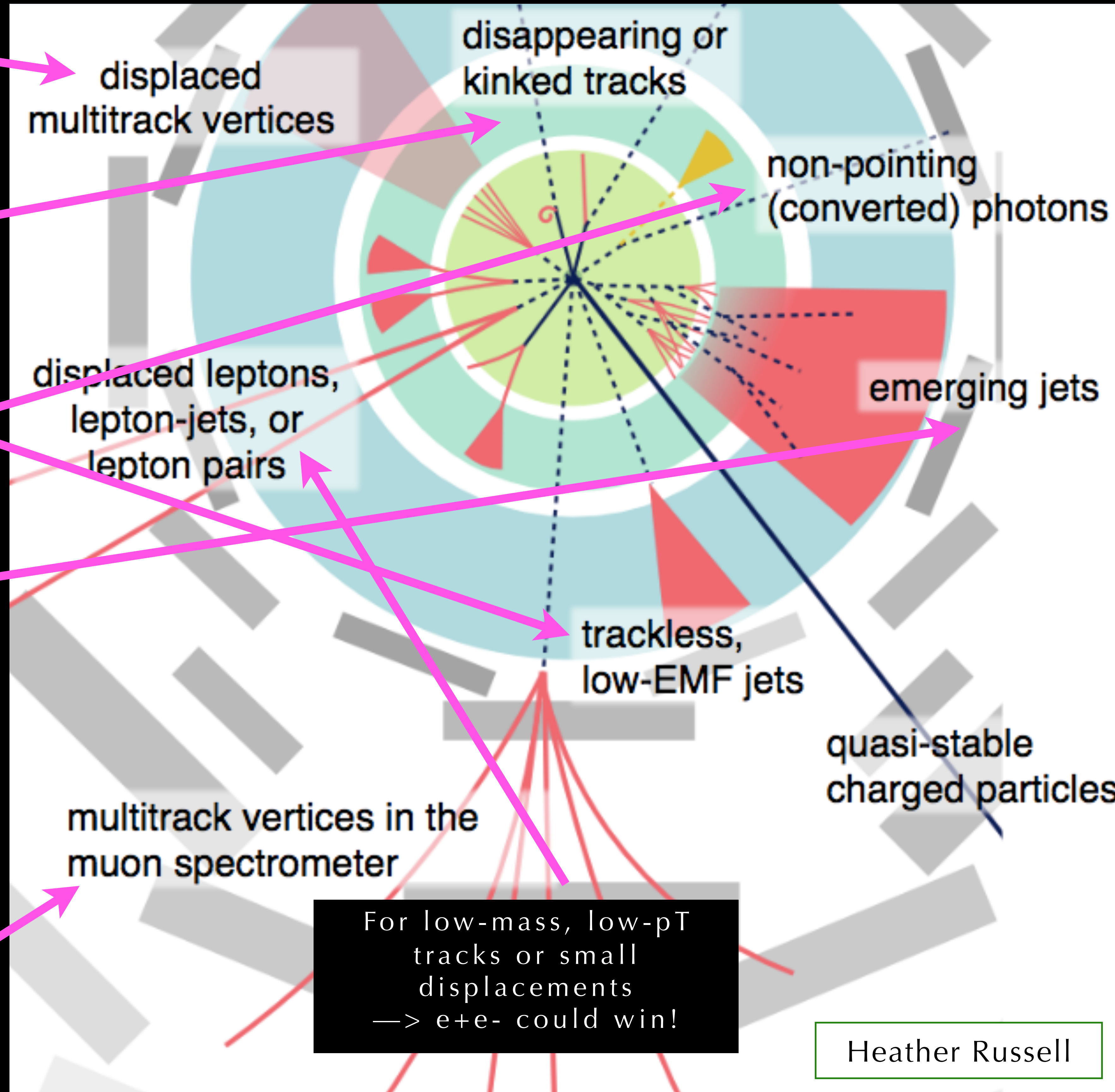


LLPs: LHC vs. future machines

Long-lived particle searches are signature-driven, requiring significant customization of analysis techniques

The LHC LLP community is small but much more motivated, active, and organized than at past machines — we have a golden opportunity to learn from current experience and plan for these signatures in advance for CEPC!

First searches at the LHC were mostly tailored to be background-free

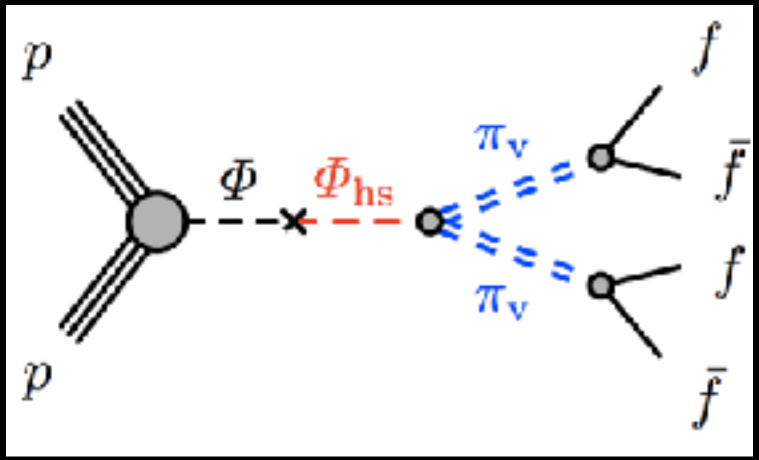
- Dominant backgrounds, though, can be from atypical sources (cosmics, beam halo, cavern, etc.)
- Great results but ended up being somewhat limited in scope (high p_T thresholds on objects and tracks, more stringent requirements on displaced vertices, etc.) which led to not-so-comprehensive coverage in LLP mass and ctau

Subsequent rounds of searches relax some requirements at the cost of higher backgrounds — example: Higgs to LLPs

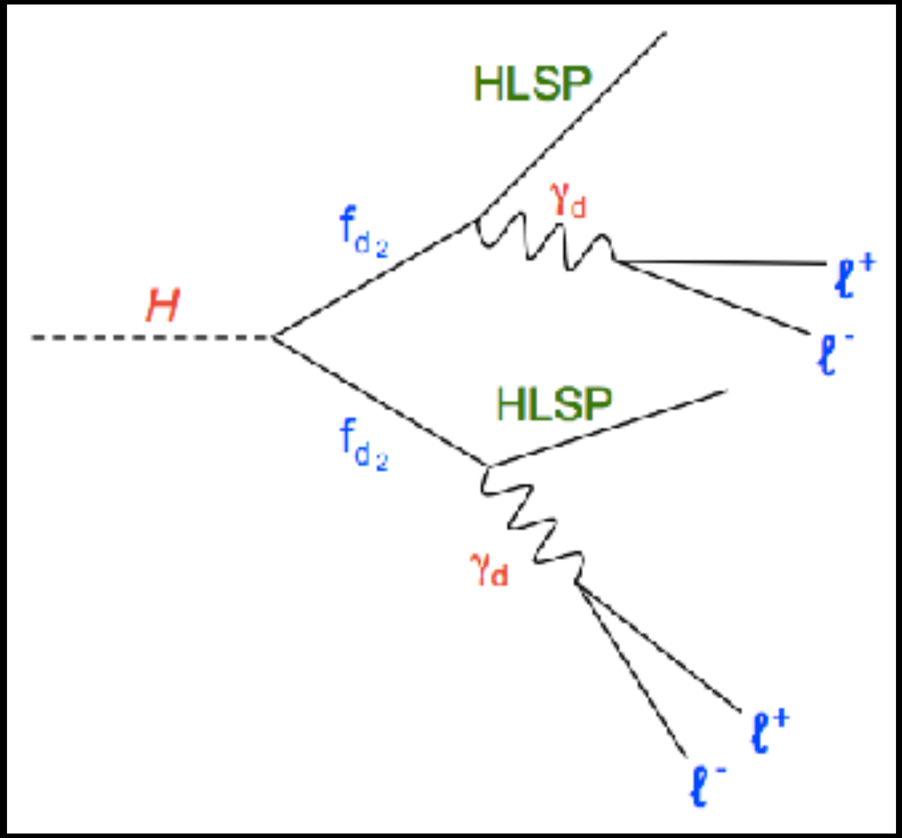
h125 —> LLPs

Higgs portal to hidden sector

- Small width of h125 —> easy to get BSM physics
- A wide range of LLP signatures can arise



Higgs mixing with hidden sector scalar

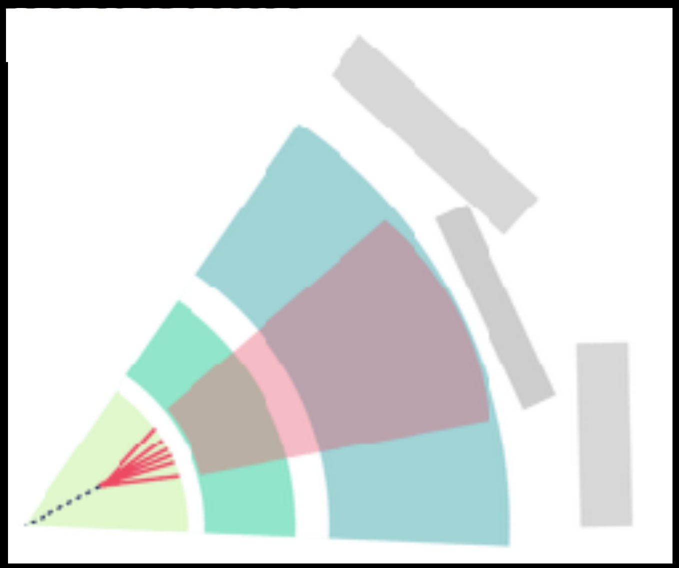


Higgs decaying to dark sector fermions which decay to long-lived dark photons and lepton-jets

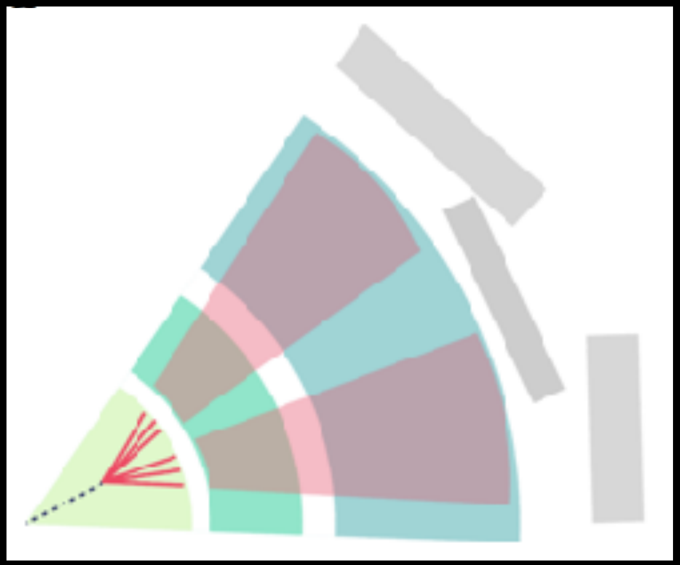
- At LHC can use Higgs VBF and associated production modes for triggering on additional prompt objects —> trivial for a ZH run at CEPC

Displaced hadronic jets

Lifetime a free parameter of BSM, so the LLP can decay anywhere in the detector volume



Inner detector…



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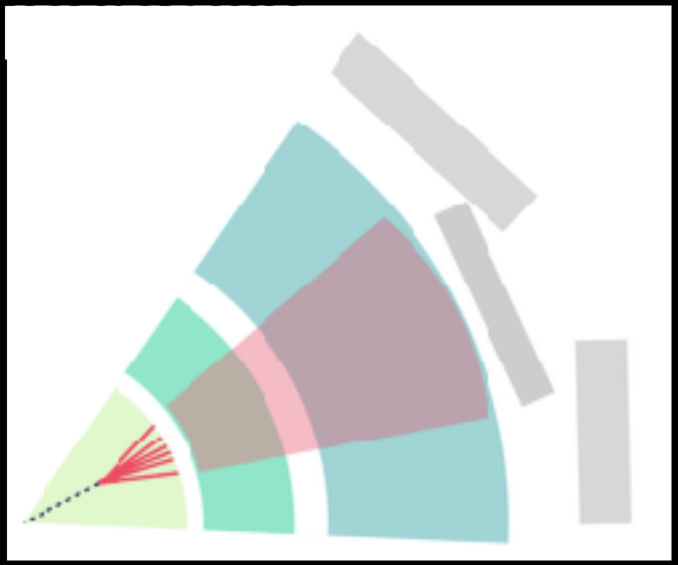
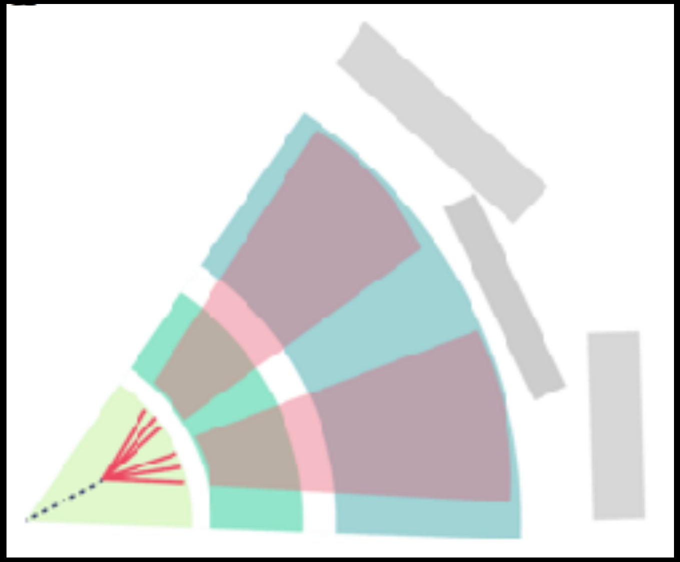


ATLAS approach — single multi-track vertex

Inner detector…

CMS and LHCb — displaced vertices with jet pairs downstream



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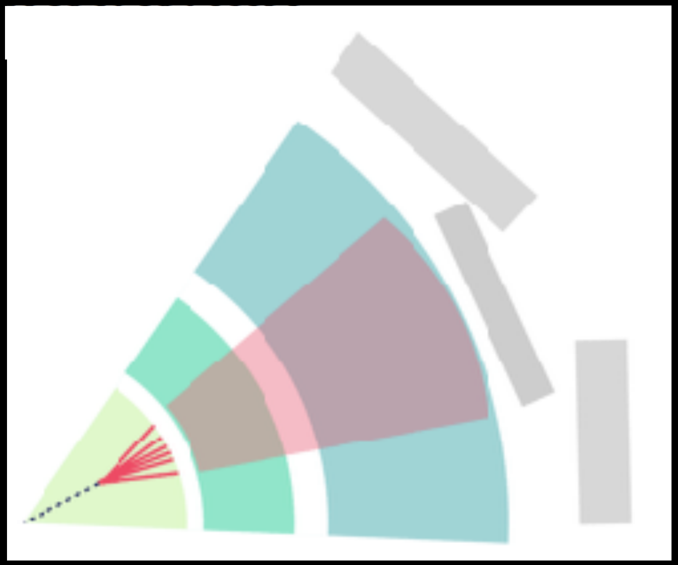

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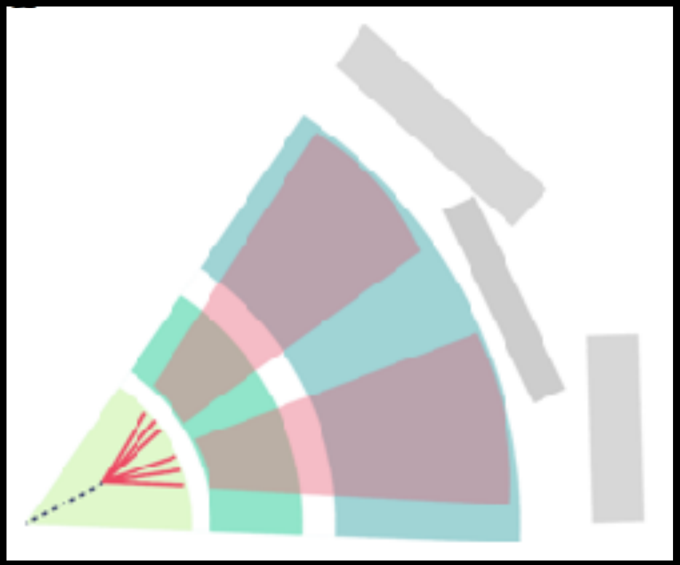

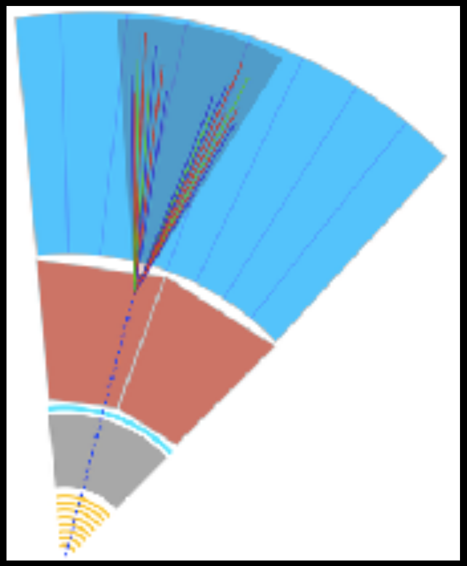

…or just before the hadronic calorimeter…

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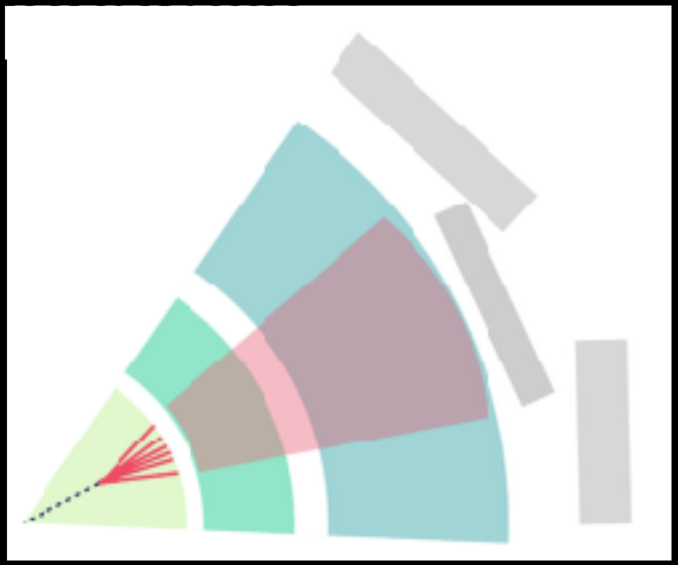

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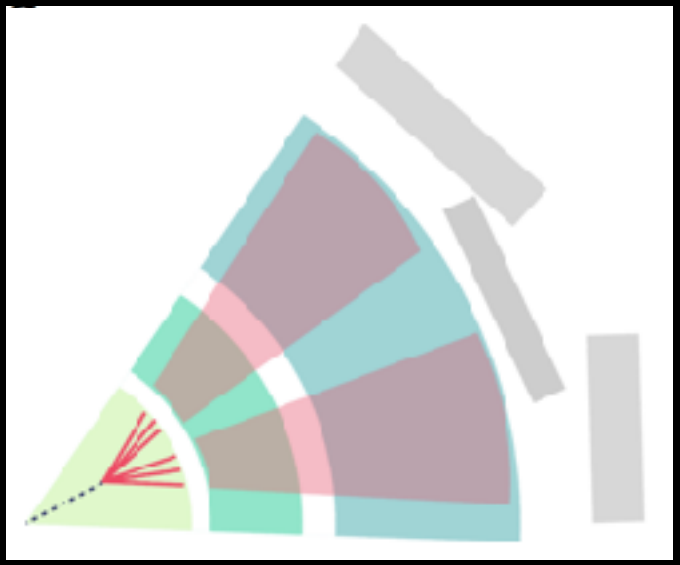
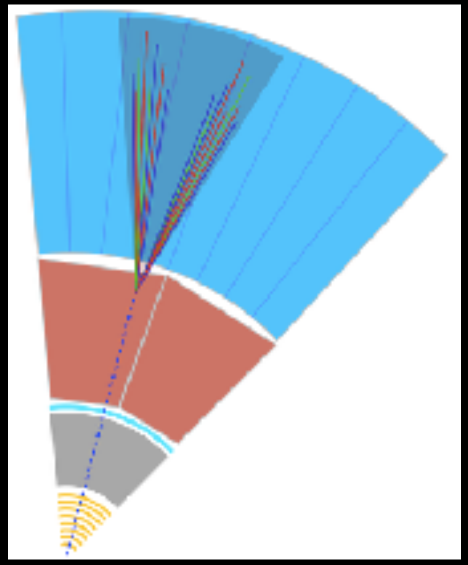
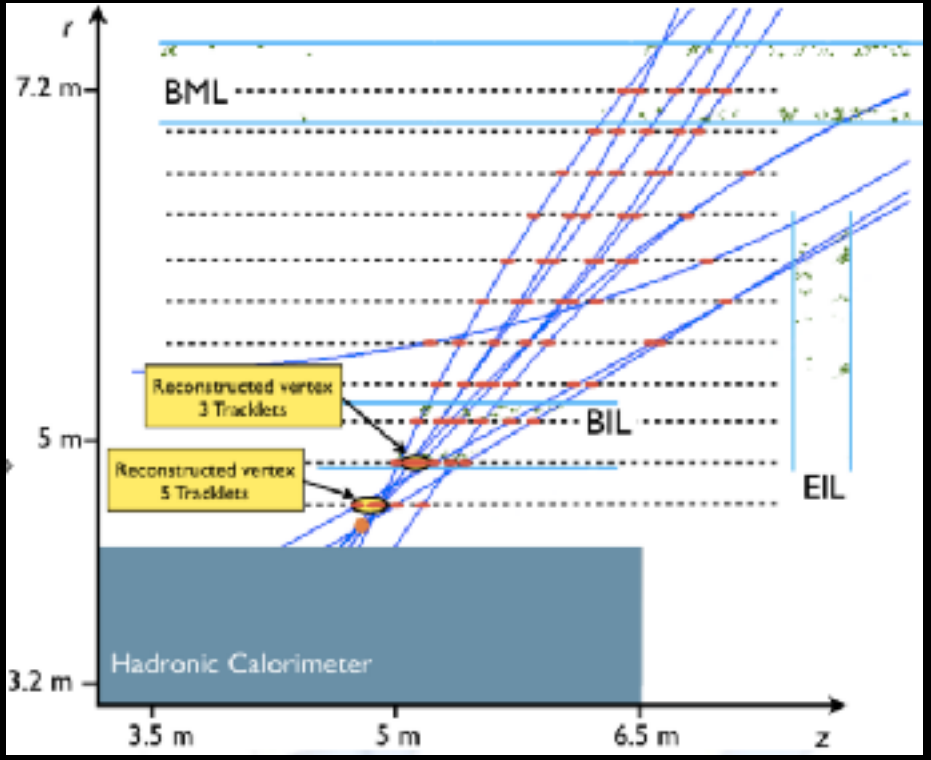




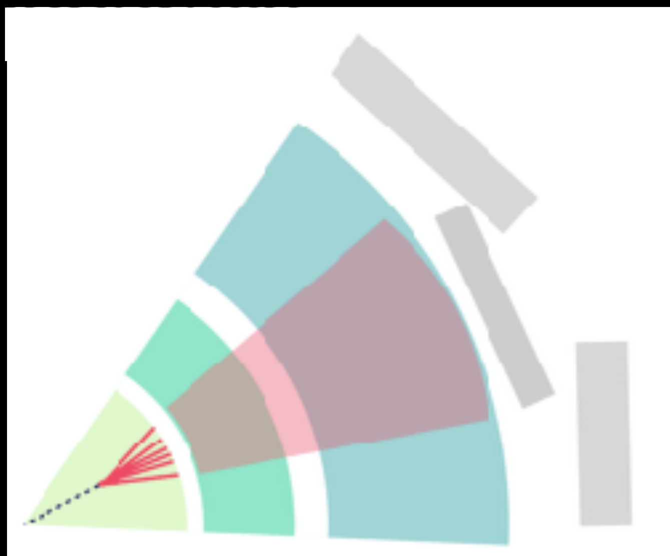
...or just before the hadronic calorimeter...

...or only in the MS



Displaced hadronic jets

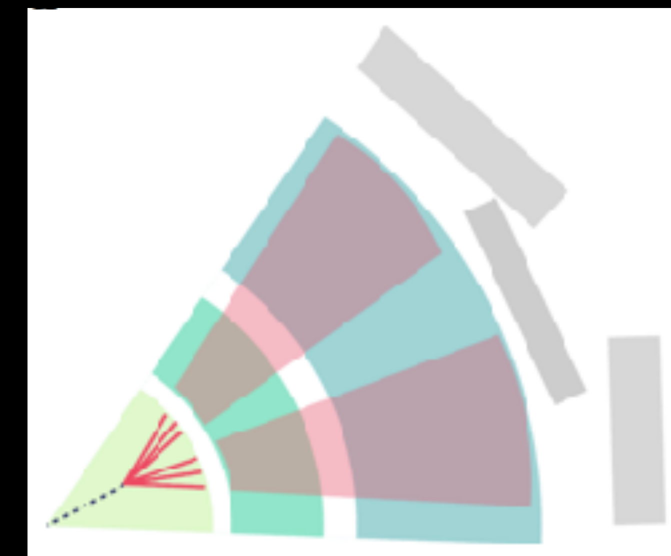
Lifetime a free parameter of BSM, so the LLP can decay anywhere in the detector volume

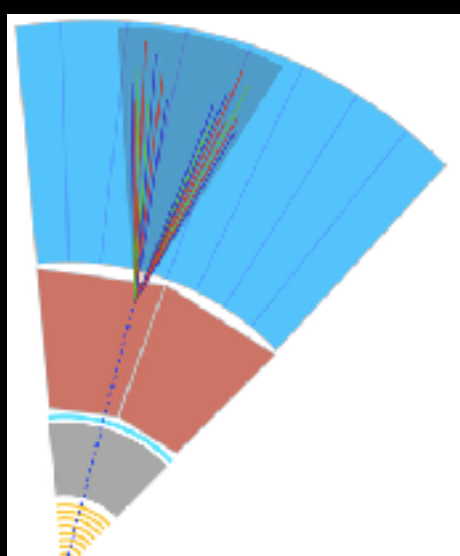


ATLAS approach — single multi-track vertex

Inner detector...

CMS and LHCb — displaced vertices with jet pairs downstream





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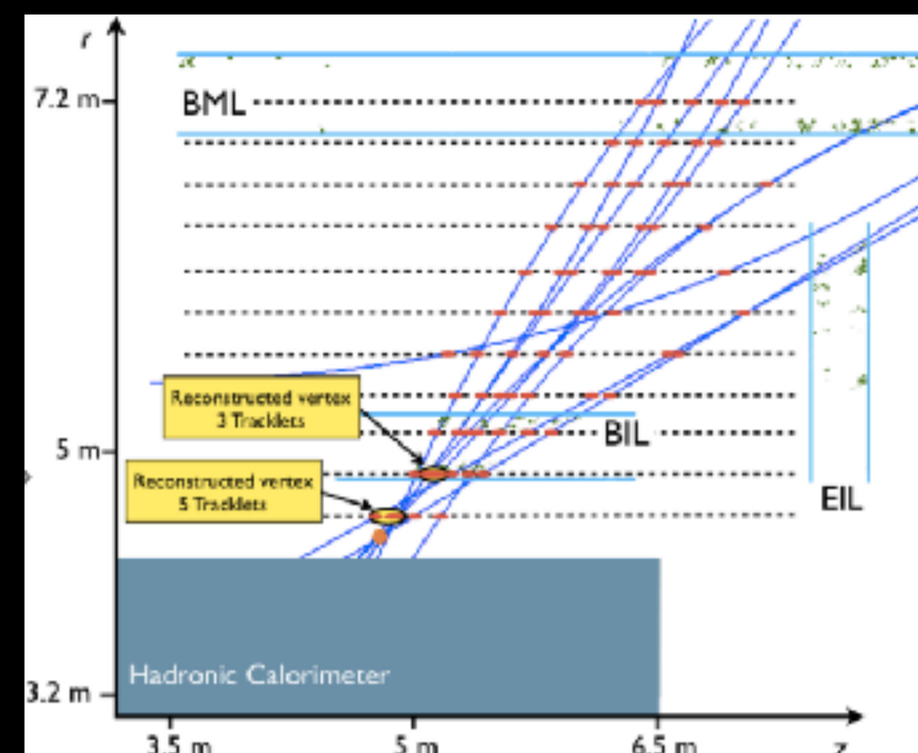
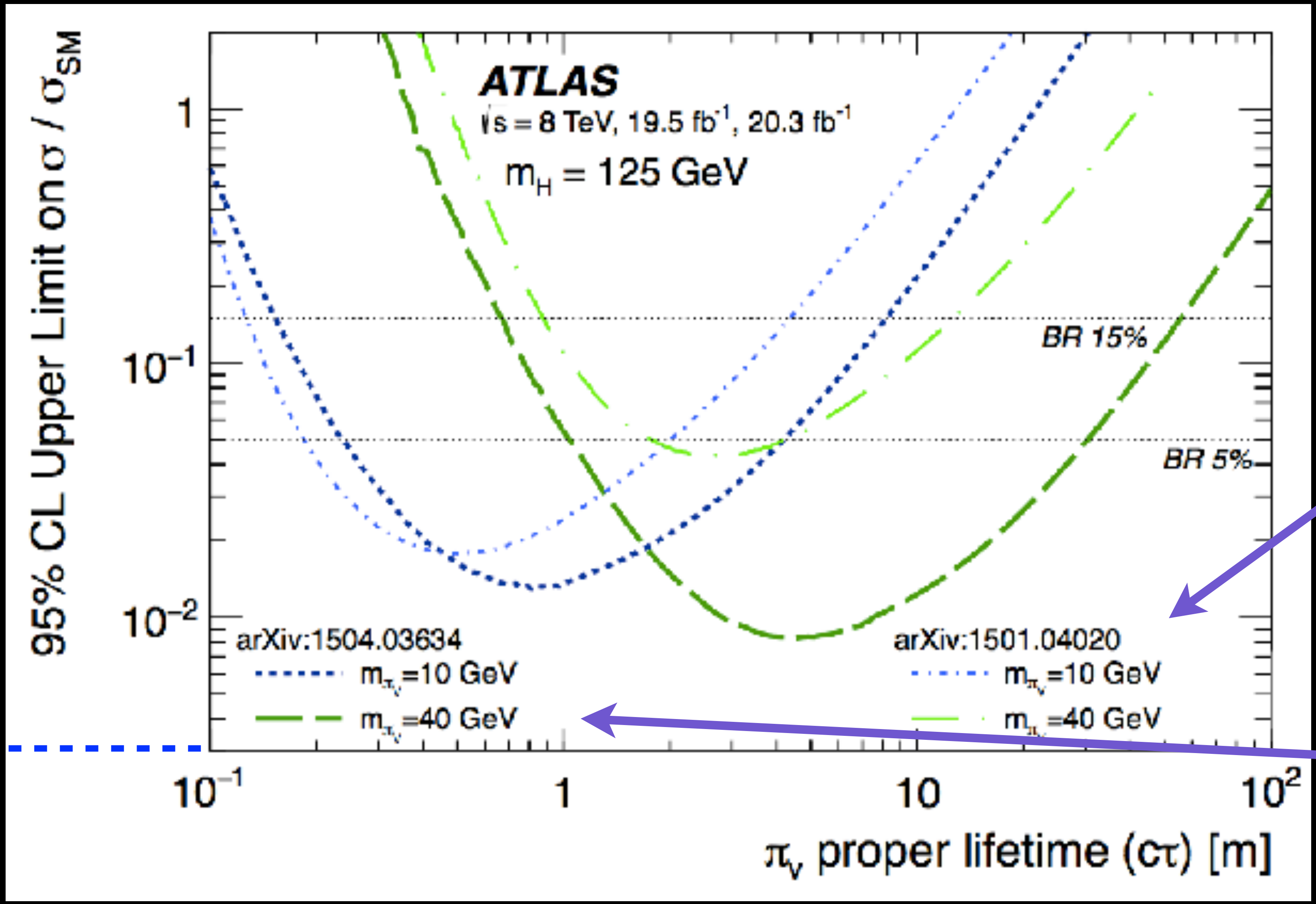


Each of these requires a different triggering and analysis strategy, and when you do all the work you can stitch the results together for h125 —> LLPs —> jets...

h125 —> displaced hadronic jets



Just-before-HCal search

ID/MS search

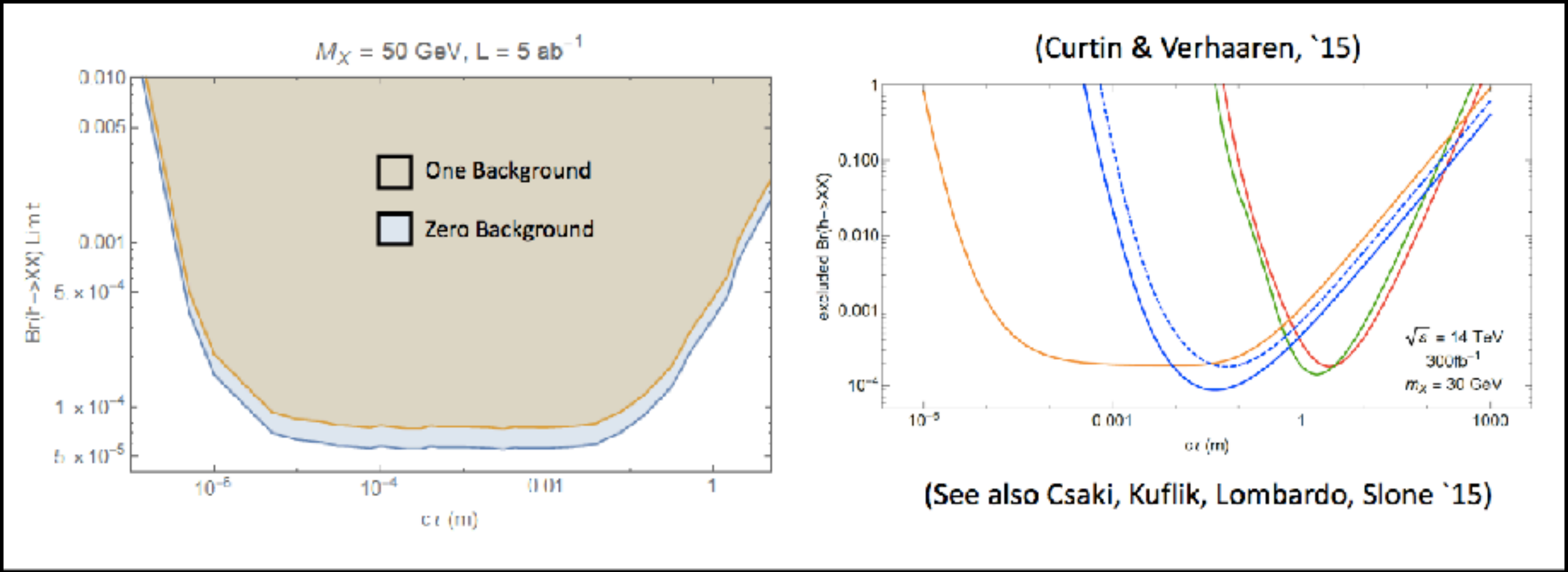
If the CEPC detectors can reconstruct displaced vertices at ~10μm, this is a complete game-changer for h125 —> LLPs —> SM

Prompt jet searches cover some of the range for small lifetimes, but pileup still dominates (and sensitivity still unknown)

h125 —> displaced hadronic jets at CEPC

Progress exists! Beautiful talk by Seth Koren yesterday showing first estimates for this vital benchmark scenario for CEPC

Koren, Craig, et al., CEPC	LHC projections



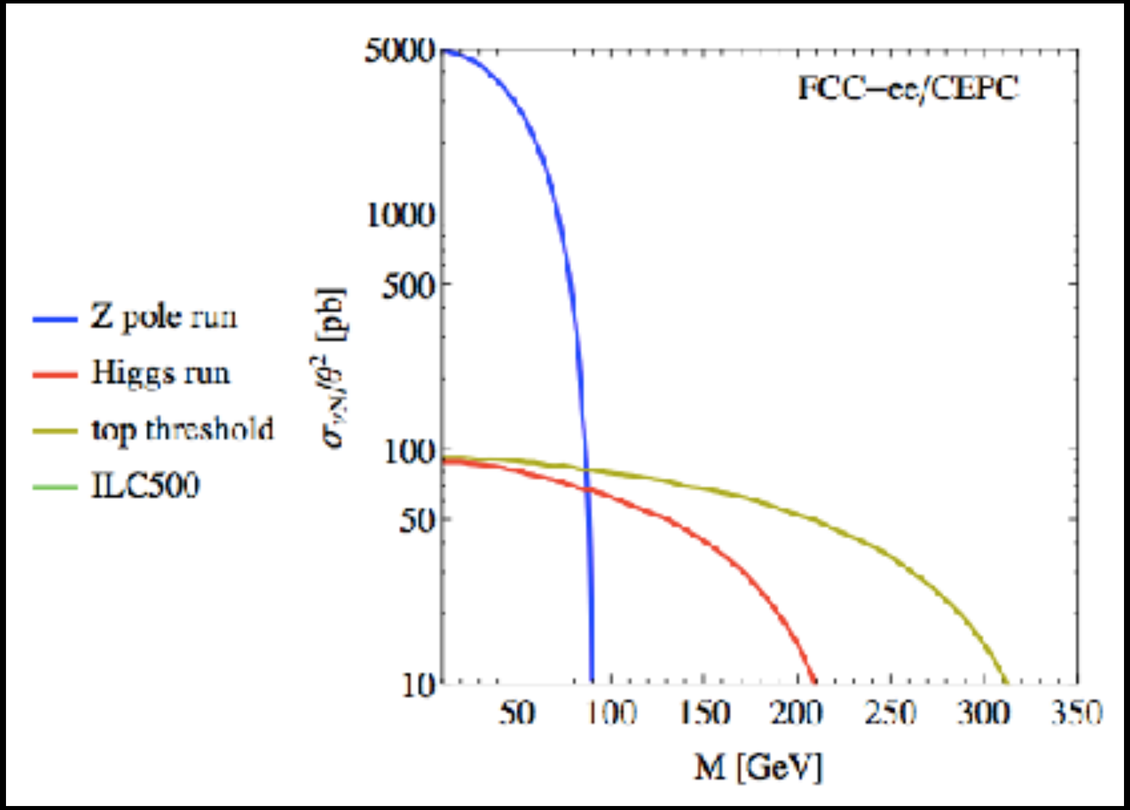
One opportunity for contribution: The ability of DELPHES to do displaced jet-finding could be improved

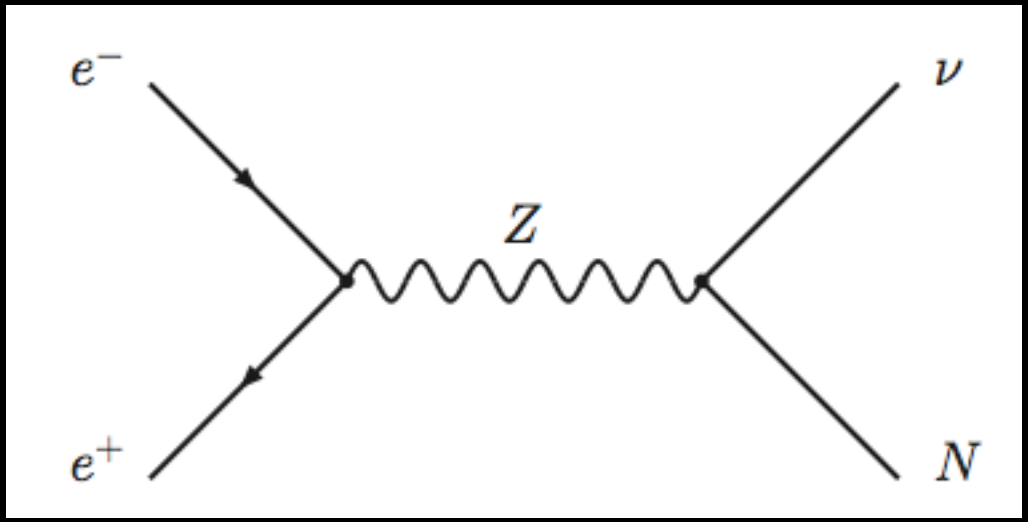
- With enough interest by the community, could encourage the DELPHES experts to move such capabilities higher on their to-do list

Very small displacements at a future e+e- machine

Study by Antusch, Cazzato, and Fischer [JHEP 1612 (2016) 007]

- Long-lived heavy (sterile) neutrinos with displaced vertices
- Uses ILC SiD as benchmark detector

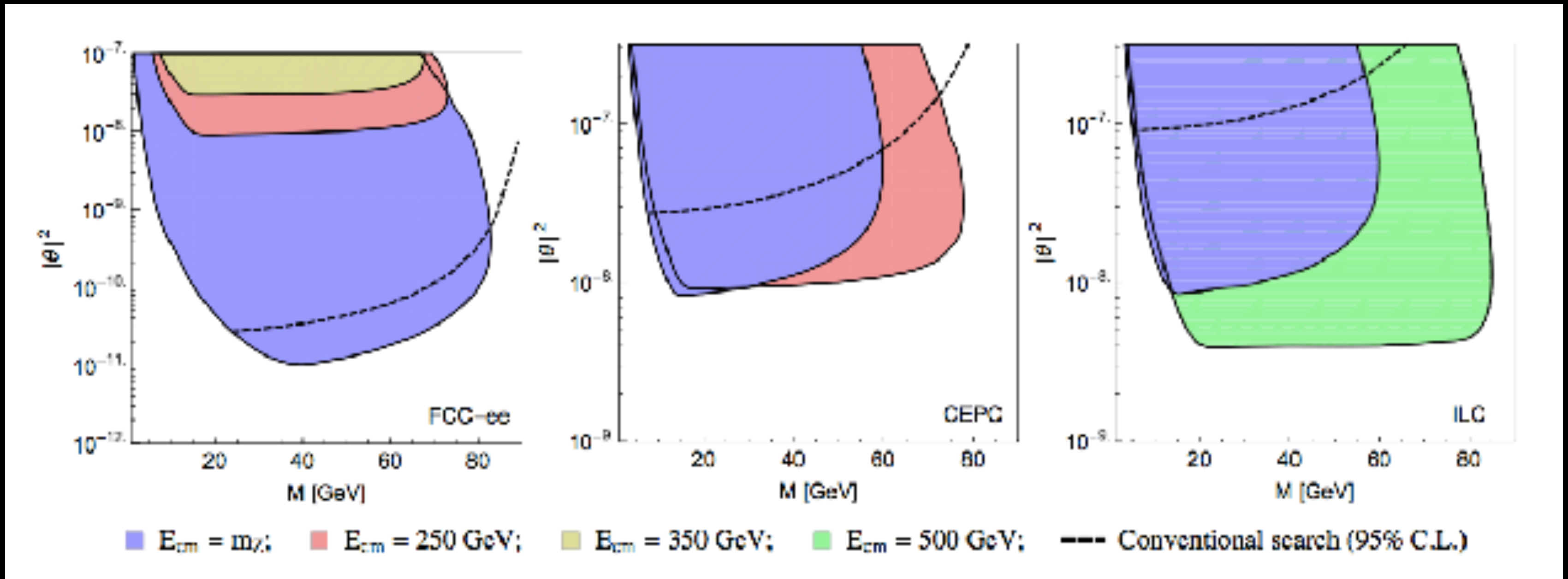




See also JHEP 09 (2018) 124

CEPC+SiD-type detector has excellent coverage at higher N masses at a Higgs-threshold run

They conclude that vertex displacements ~10 μm are possible! How does this relate to the detector proposals in the current version of the CDR?



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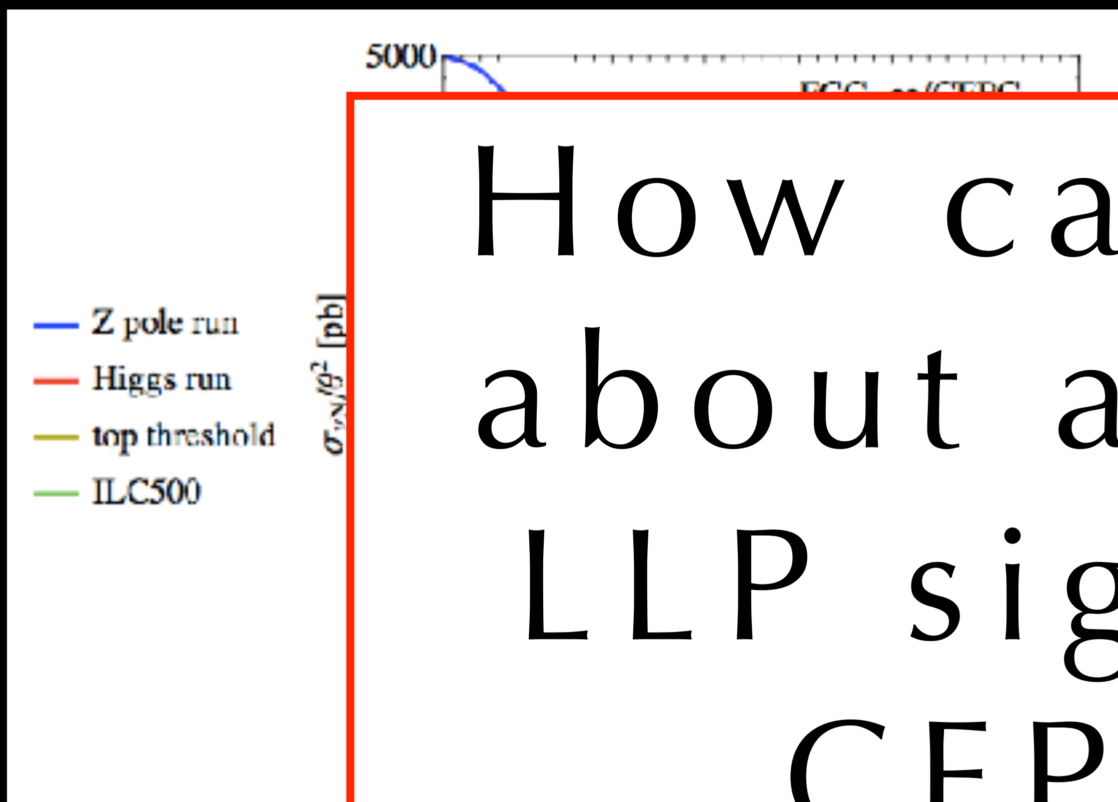

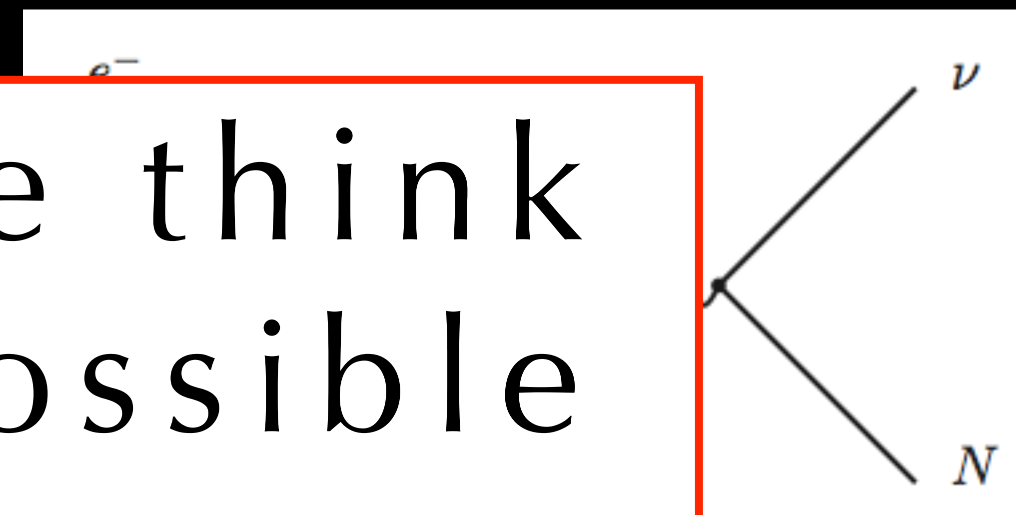

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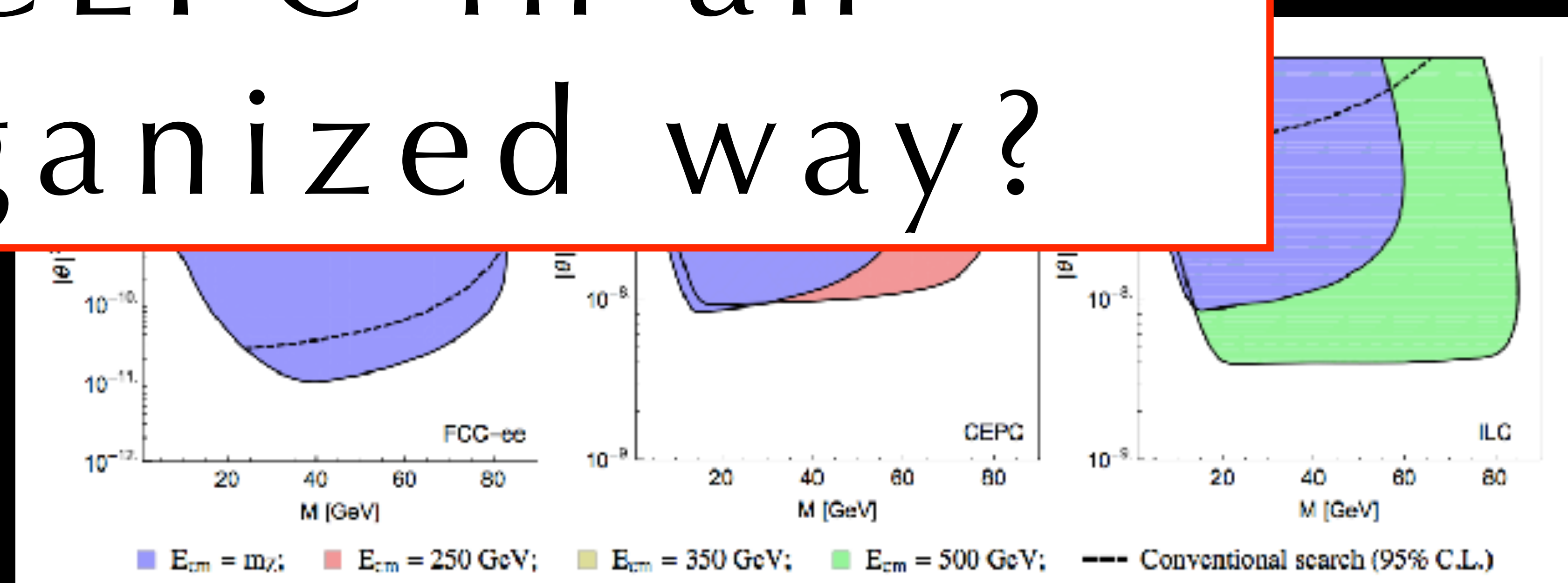
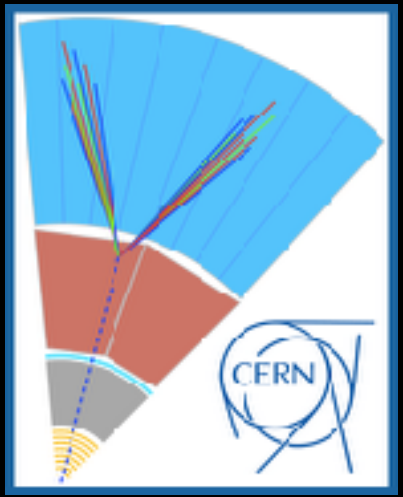
How can we think about all possible LLP signatures at CEPC in an organized way?

CEPC+SiD-ty
excellent cove
masses at a Hi

They conclude that vertex displacements ~10 μm are possible! How does this relate to the detector proposals in the current version of the CDR?



LHC Long-Lived Particle Community



We've recently been organizing our thinking around LLP signatures at the LHC

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

Recent workshops —>

CERN: indico.cern.ch/e/LHC_LLP_May_2018

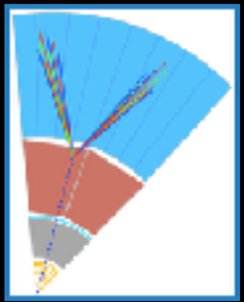
Nikhef: indico.cern.ch/e/LHC_LLP_October_2018

Overall goal is to address one question:

How do we best ensure that we don't miss BSM LLP signatures for the remainder of the LHC program?

Community white paper (to appear on 11 December 2018) focused on detector signatures that can arise from generic LLP decays with review of existing searches, recommendations, uncovered signatures, and a simplified model proposal

LHC LLP Community initiative



Same structure and simplified model framework (and community spirit) could serve as a means to study such classes of models and signatures at CEPC/FCC-ee

Find the places where CEPC / FCC-ee win over hadron colliders

- Generally hadrophobic LLPs?
- Dark QCD signatures like emerging jets and SUEP (soft, unclustered energy patterns); could ability to see high multiplicity of displaced vertices with a small number of low-pT tracks give advantages here?
- Very light, very soft, singly-produced LLPs?
- Tiny disappearing tracklets? (~10μm scale tracking will serve this, too)
- h125 —> long-lived dark Zs / dark photons —> electrons? (muons easy; electrons harder at hadron machines)
- Metastable charged particles?
- Extremely rare Z and BSM Z decays?

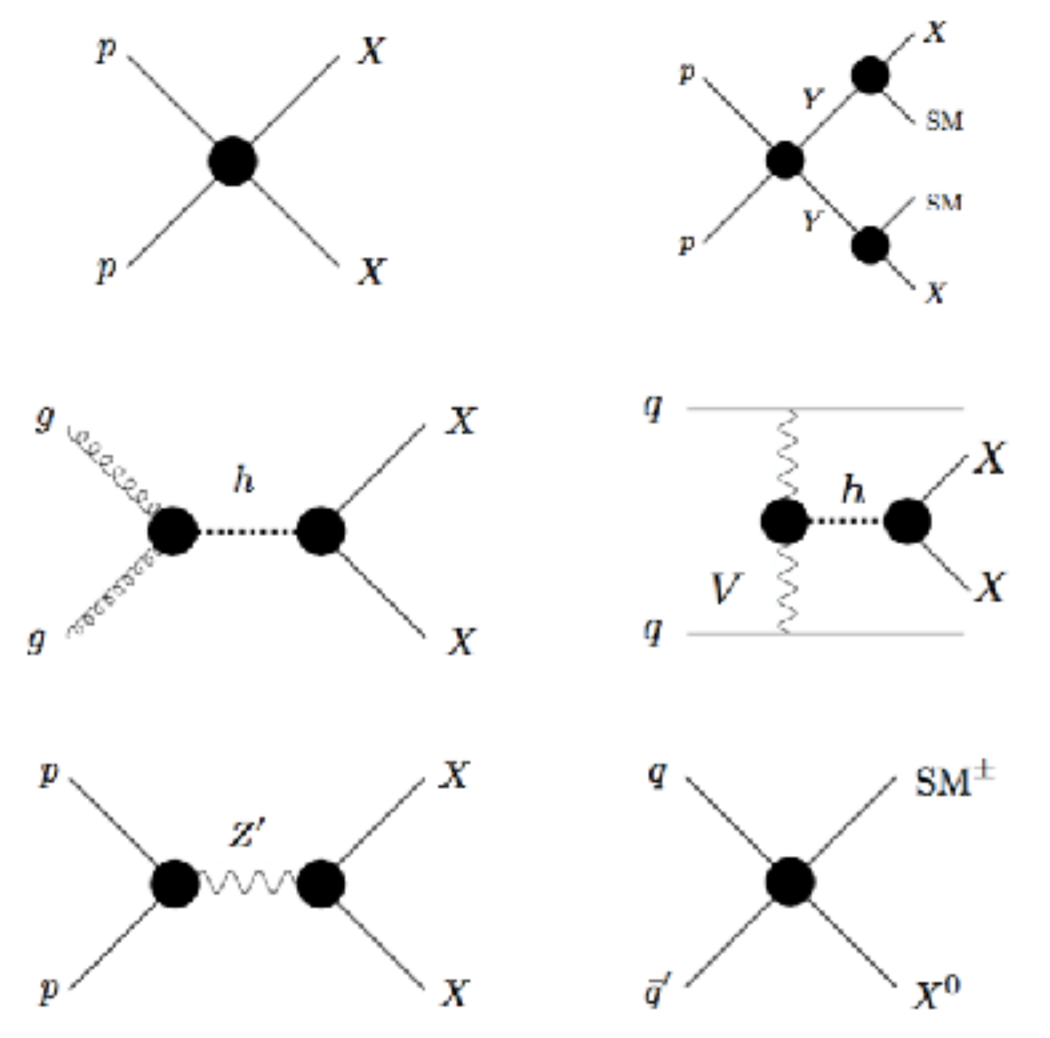
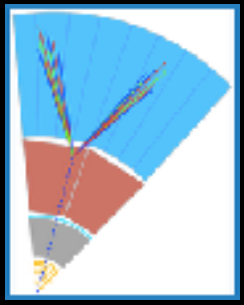


Figure 2.1: Schematic illustrations of LLP production modes in our simplified model framework. From top to bottom and left to right: direct pair production (DPP); heavy parent (HP); Higgs modes (HIG), including gluon fusion and VBF production (not shown here is VH production); heavy resonance (RES); charged current (CC).

LHC LLP Community initiative



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- Generall
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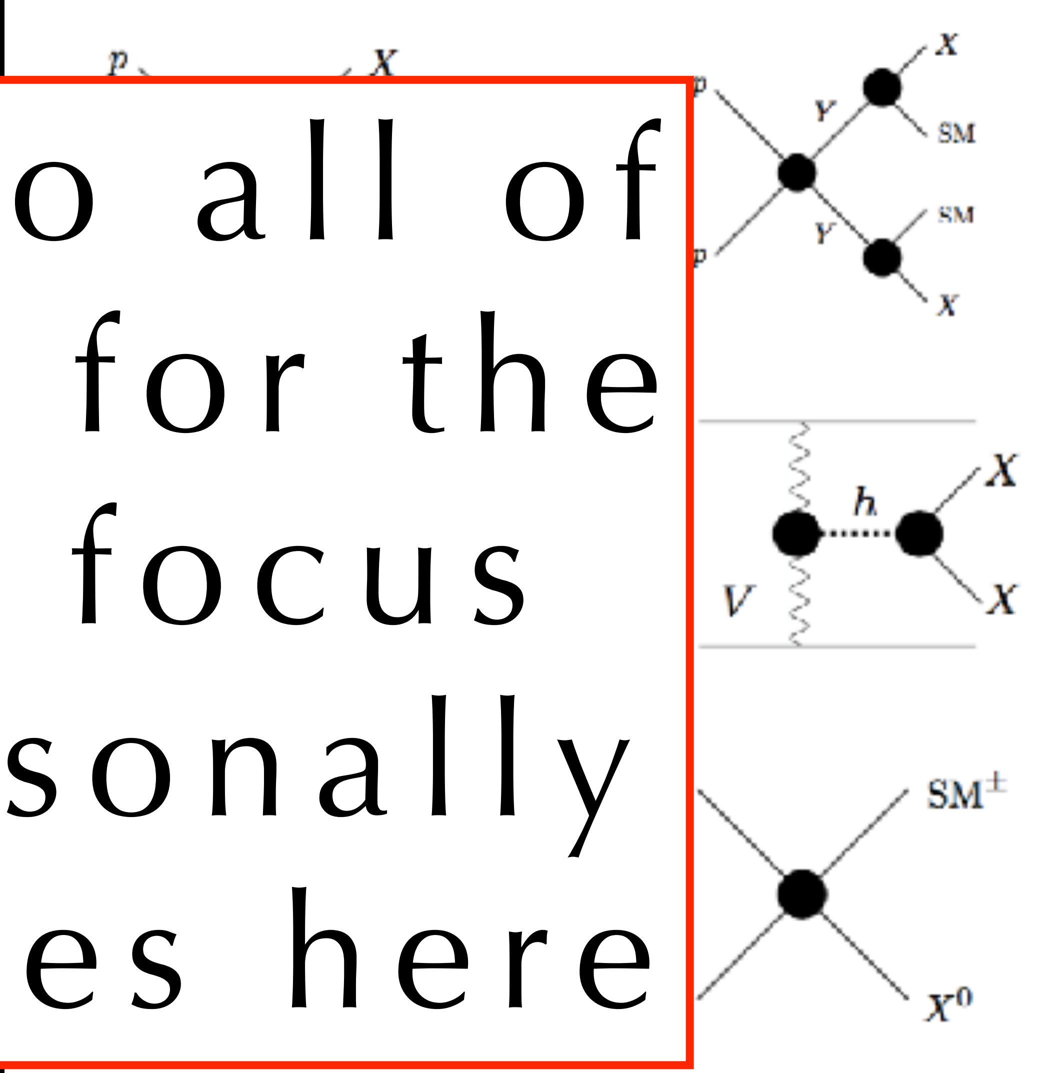
- Very ligh
- Tiny disa scale tra
- h125 —> photons —> electrons? (muons easy; electrons harder at hadron machines)
- Metastable charged particles?
- Extremely rare Z and BSM Z decays?

You should do all of these studies for the CEPC, but I focus on a few personally intriguing ones here



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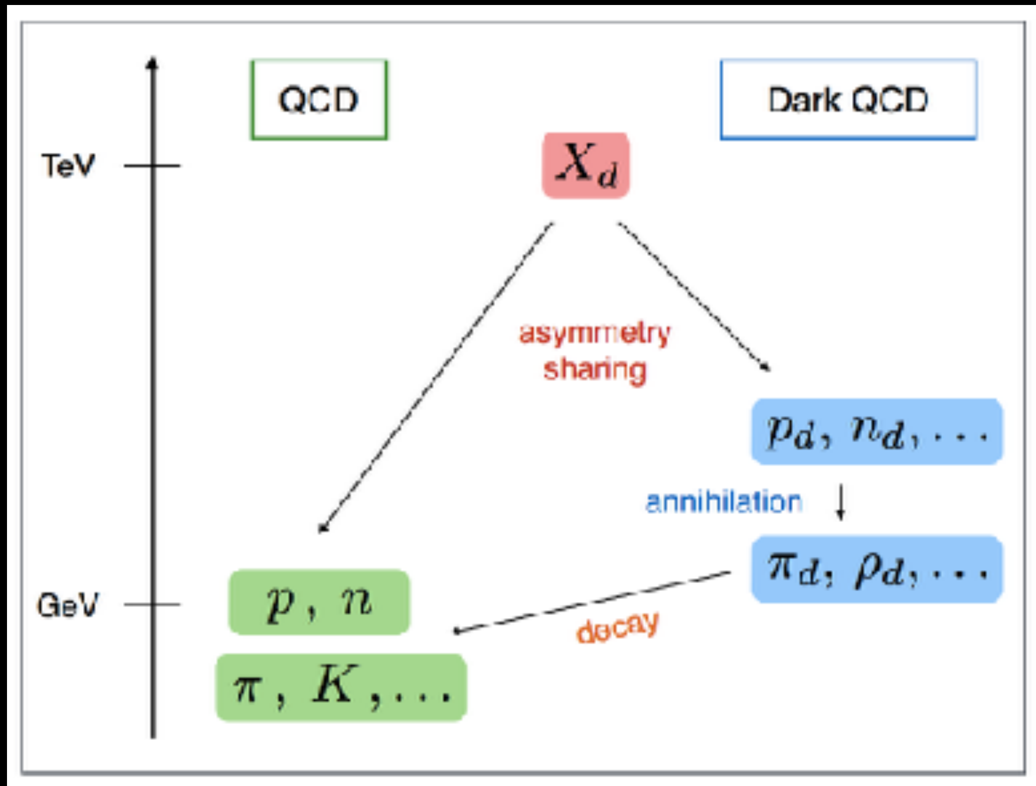
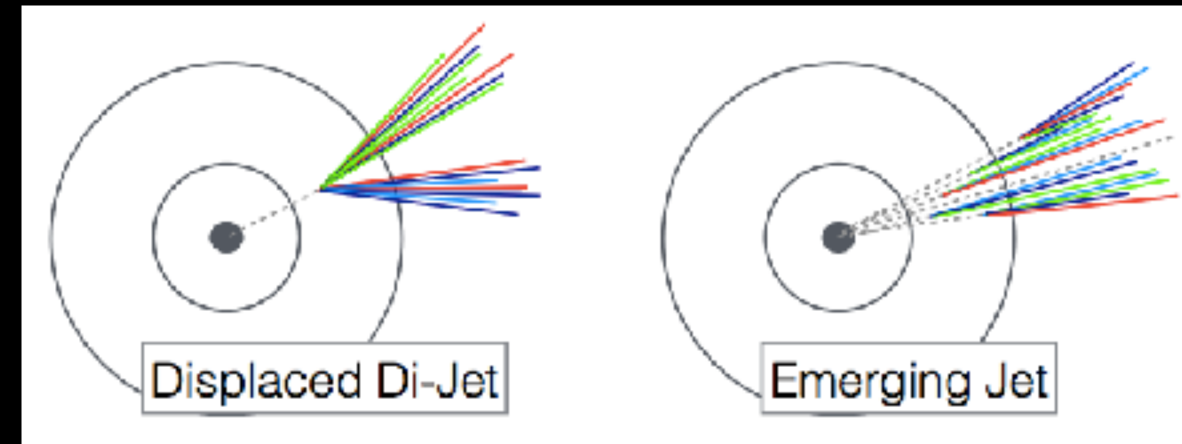
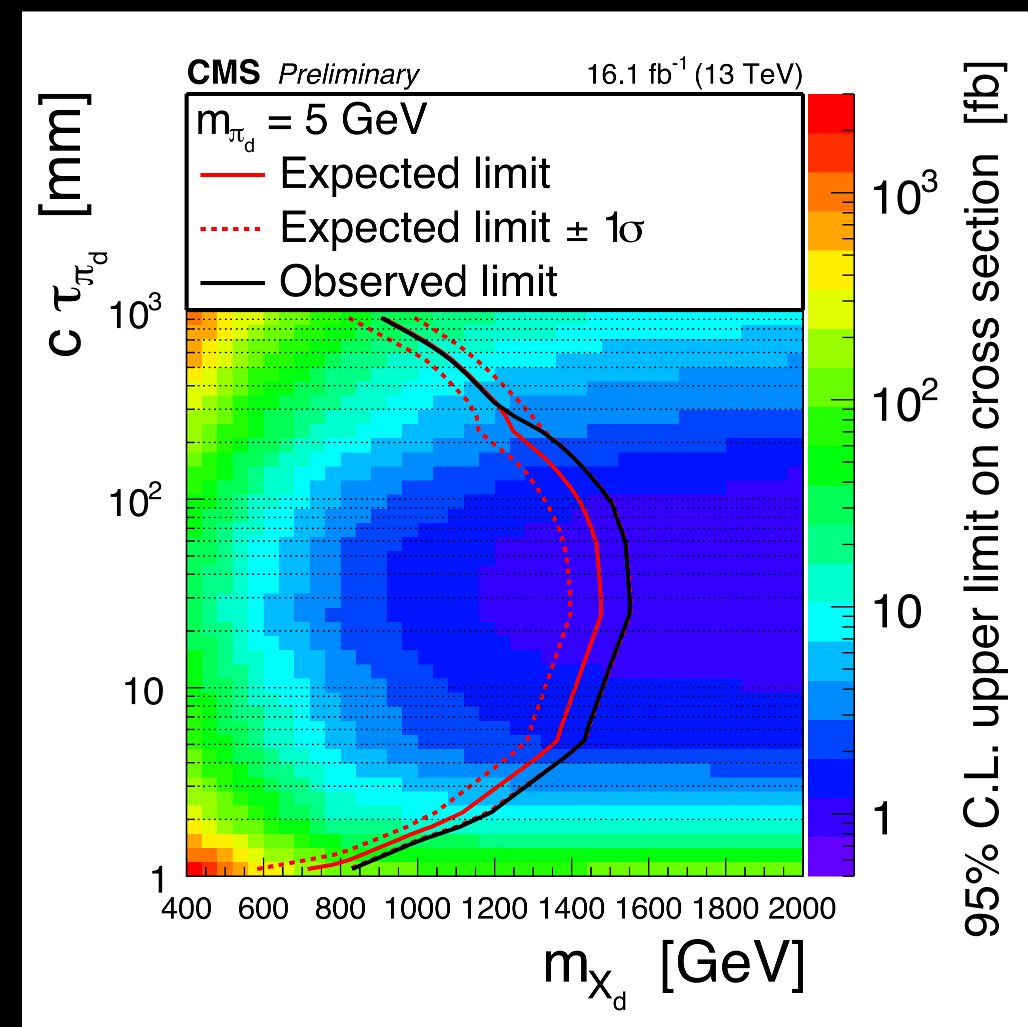


JHEP (2015) 2015: 59

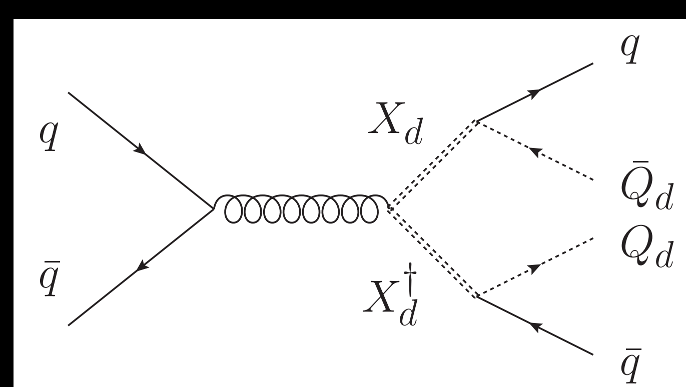


Dark quarks hadronize first in the hidden sector and, e.g., dark pions then decay to the visible sector via multiple displaced vertices of varying displacements within the same jet object



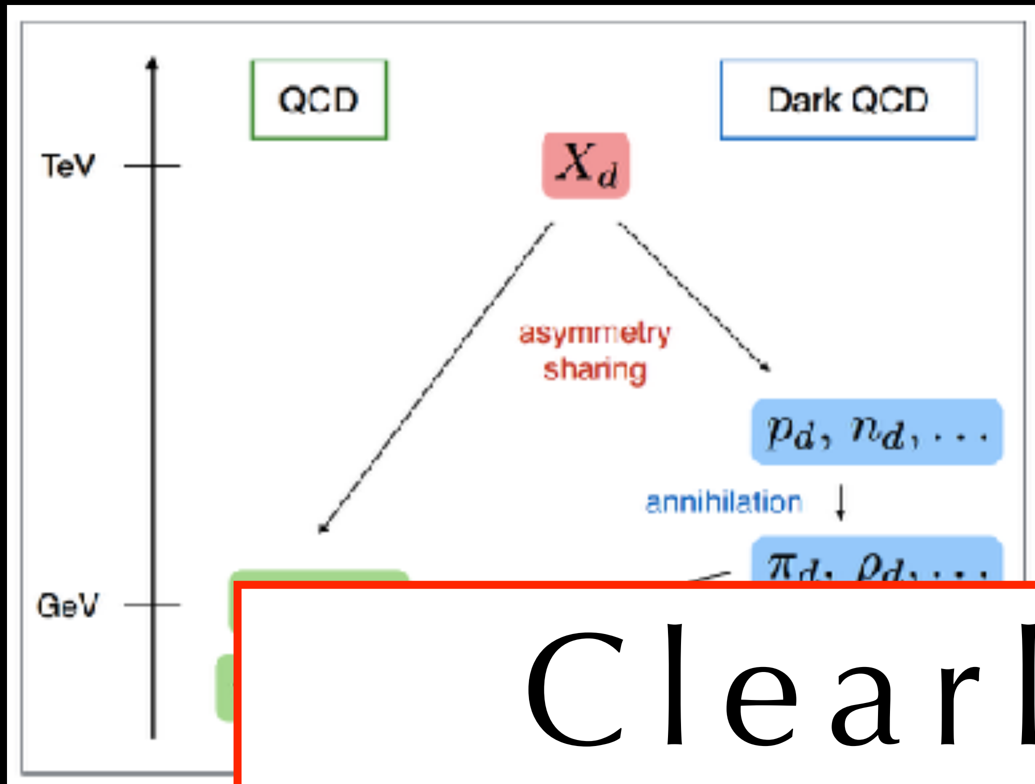
CMS-PAS-EXO-18-001

Thus, this is **neither prompt jets nor a pair of displaced jets** pointing to the same displaced vertex, but to **emerging jets**.



First results for this dark-QCD model at the LHC — ATLAS search in progress

Dark QCD / hidden valley models: Emerging jets



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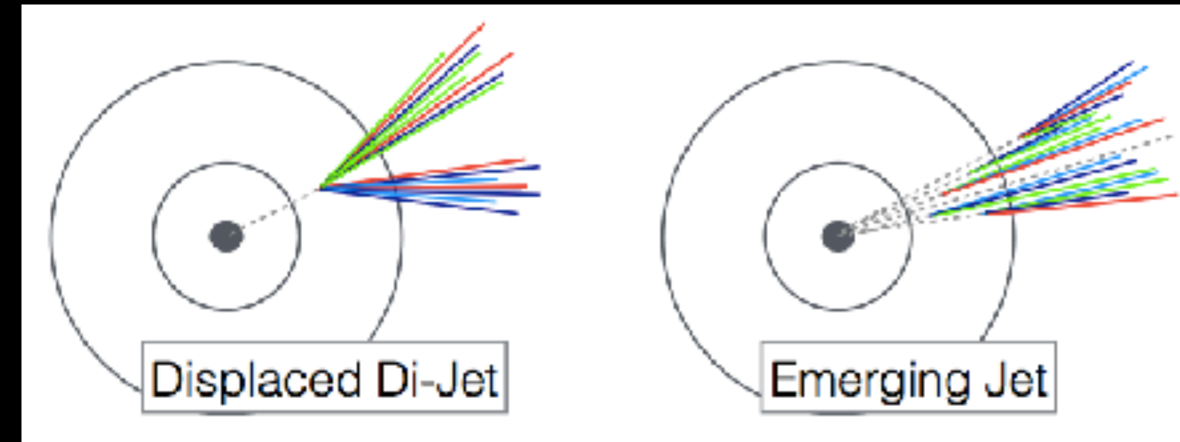
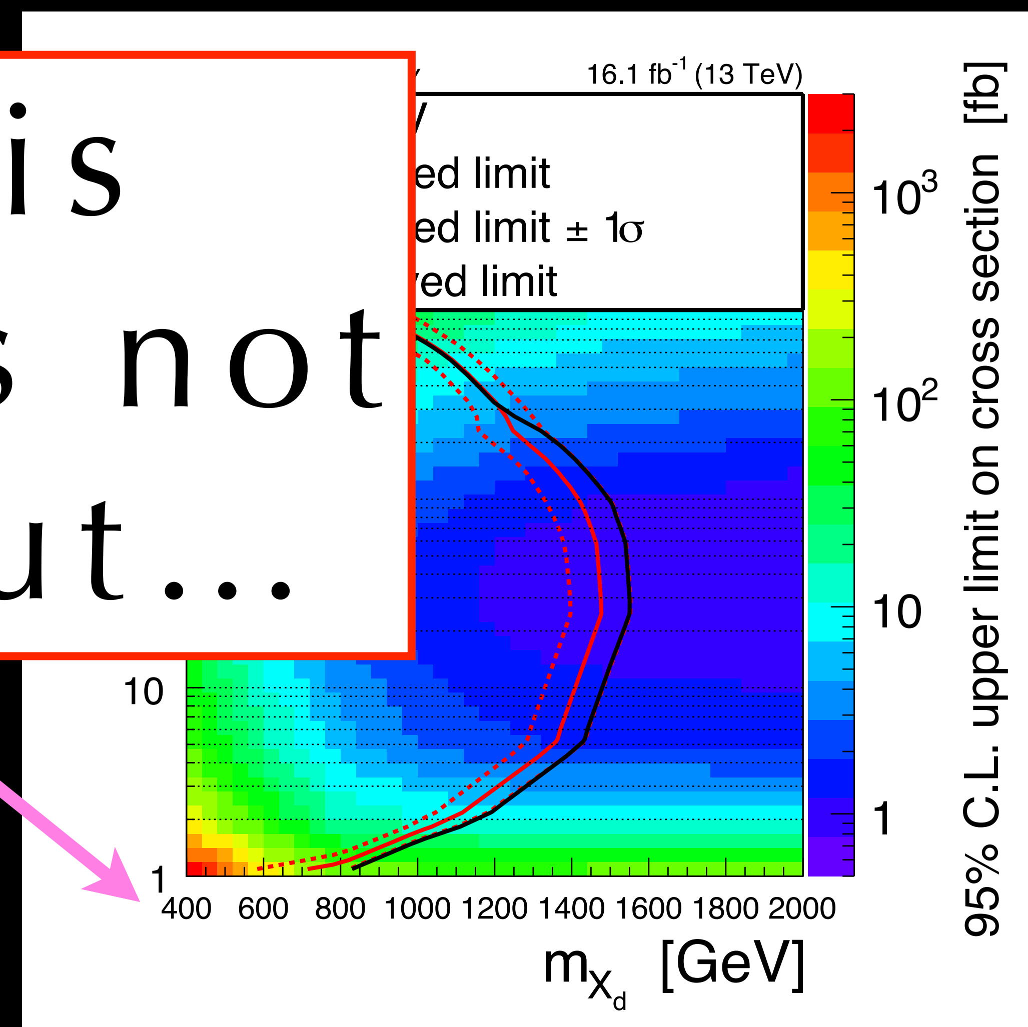
…(2015) 2015: 59



Clearly this benchmark is not for CEPC, but…



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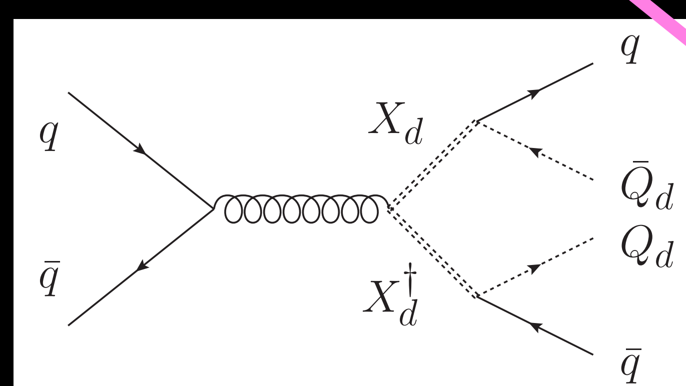

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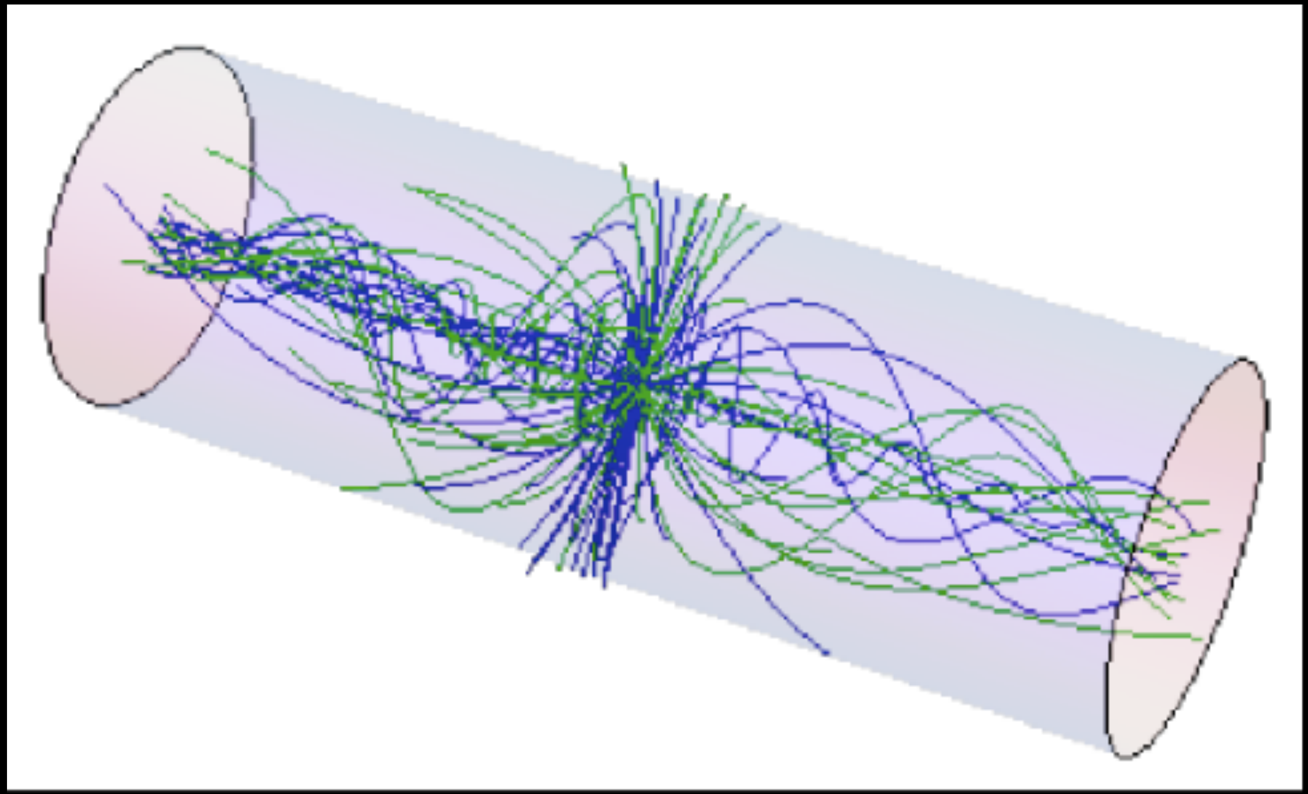
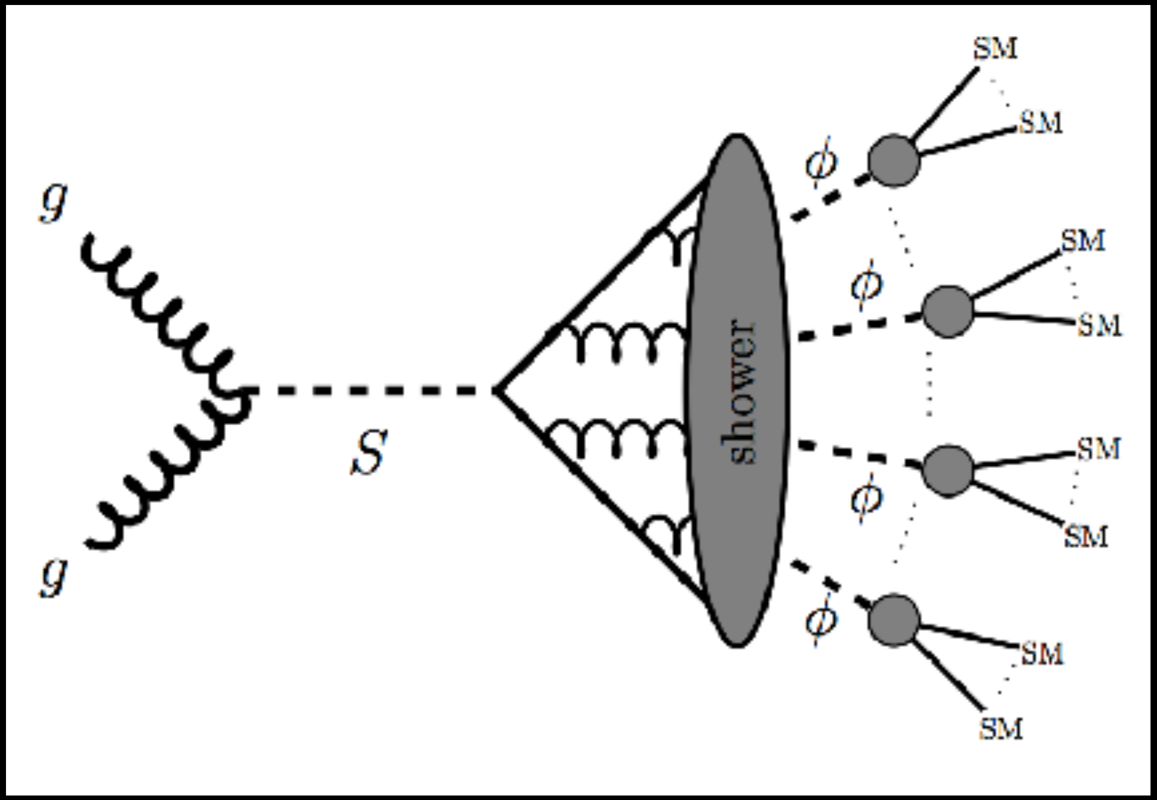
Soft unclustered energy patterns — SUEPs

What about the other end of the dark QCD spectrum?

- Very strongly coupled hidden sector yielding a soft radiation pattern in the detector
  - Soft, unclustered energy patterns, or SUEPs: JHEP (2017) 2017: 76



Cylinder is edge of ECal, with ~100 very soft electrons and muons swarming around



Hidden valley scenario with confining dynamics — here a strongly coupled regime with a high-mass mediator decaying eventually to a large multiplicity of low-energy SM states

Could a high multiplicity soft muon trigger be useful here?

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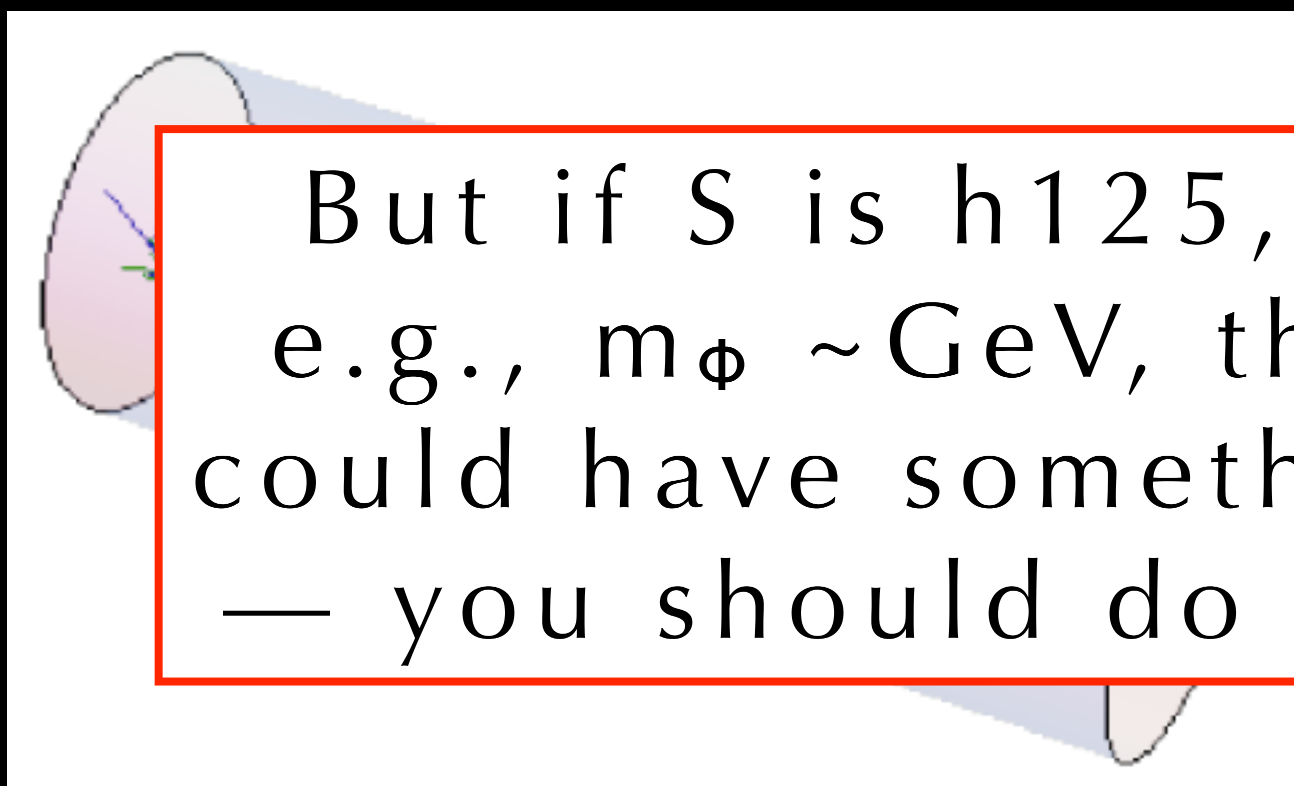
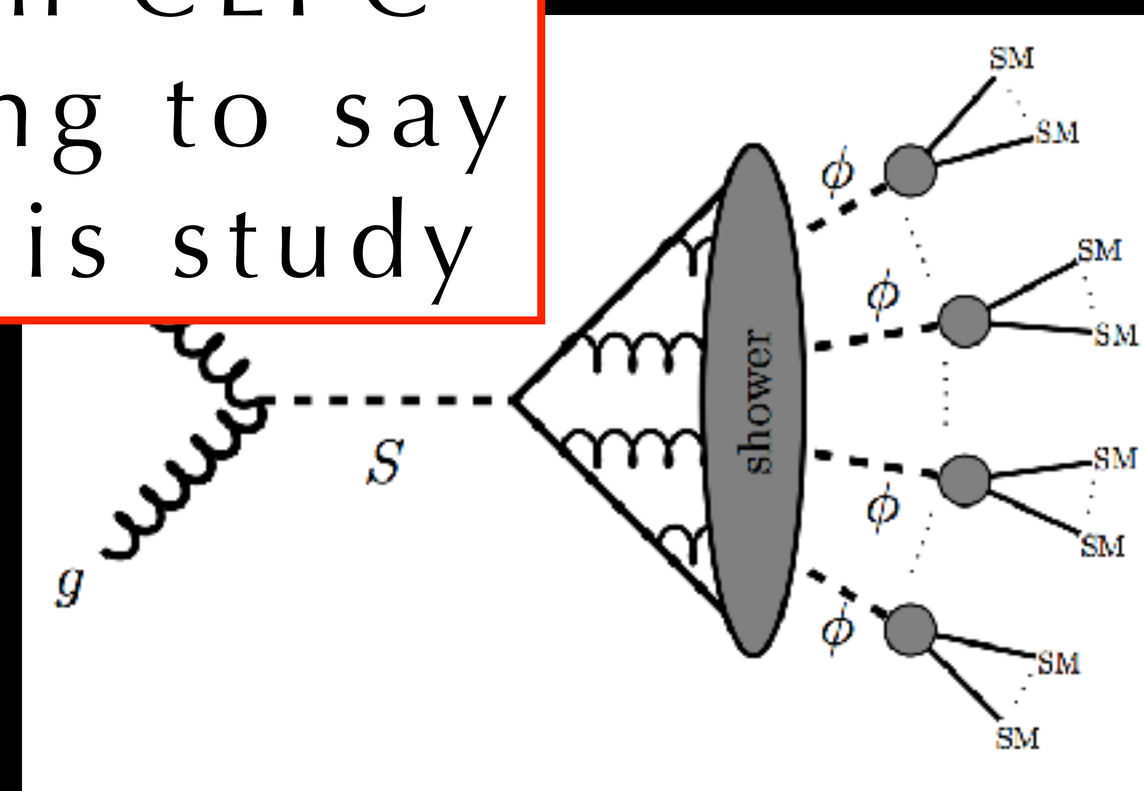


But if S is h125, and for, e.g., m_ϕ ~GeV, then CEPC could have something to say — you should do this study

… of ECal, with … lectrons and … ng around



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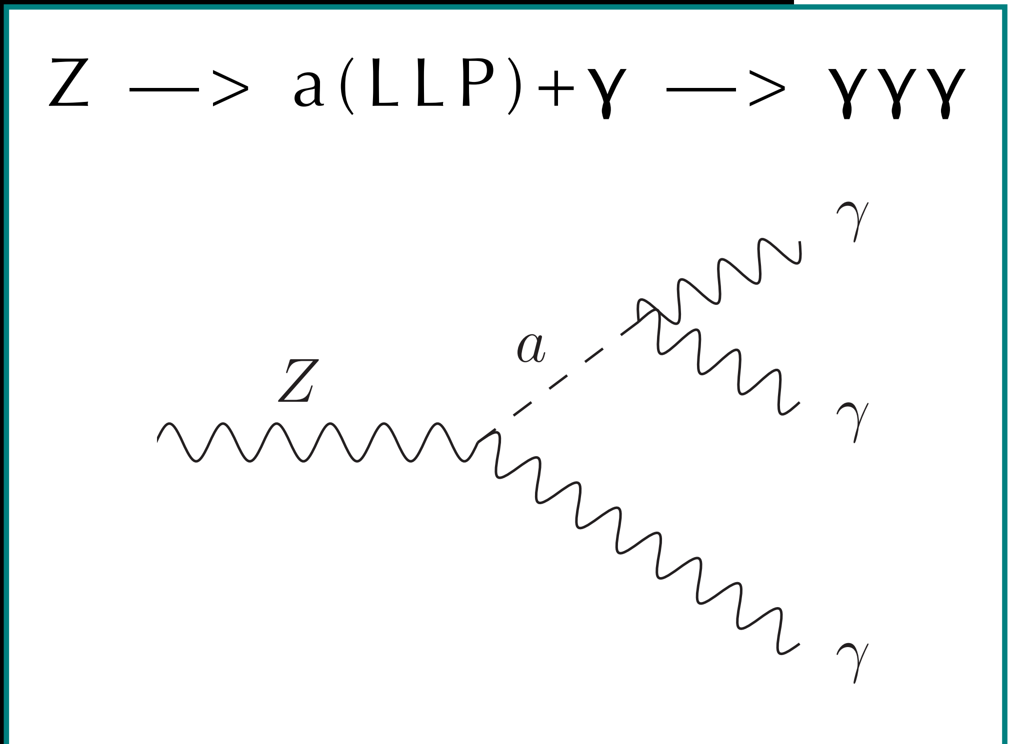


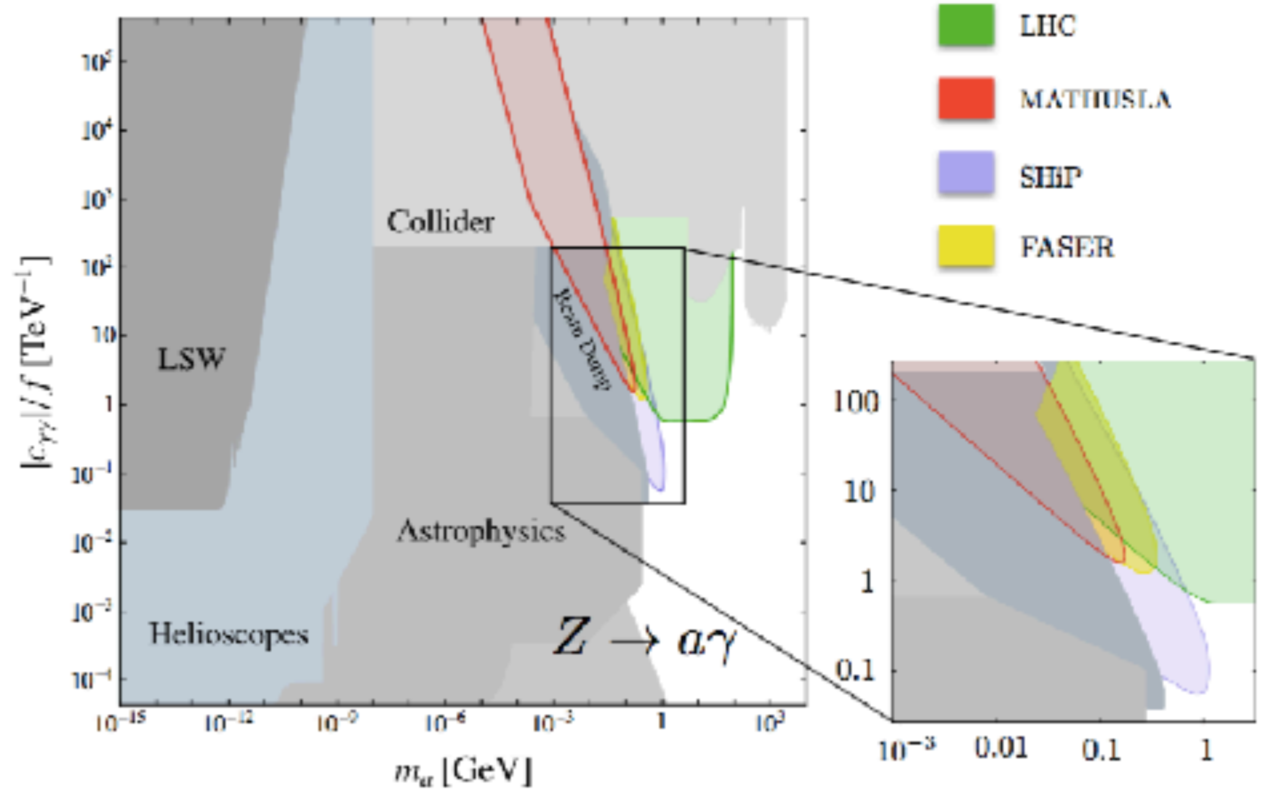


Fig. 70: Projected reach in searches for $Z \to a\gamma \to 3\gamma$ decays with ATLAS/CMS (green) and MATHUSLA (red, assuming the $200m \times 200m \times 20m$ benchmark geometry of Fig. 1) with $\sqrt{s} = 14$ TeV center-of-mass energy and 3000 fb^{-1} integrated luminosity. The area projected to be probed by the future experiments SHiP [219] and FASER [645] are shown in blue and yellow, respectively.

MATHUSLA physics case: arXiv:1806.07396

SM Z decaying to LLP + X

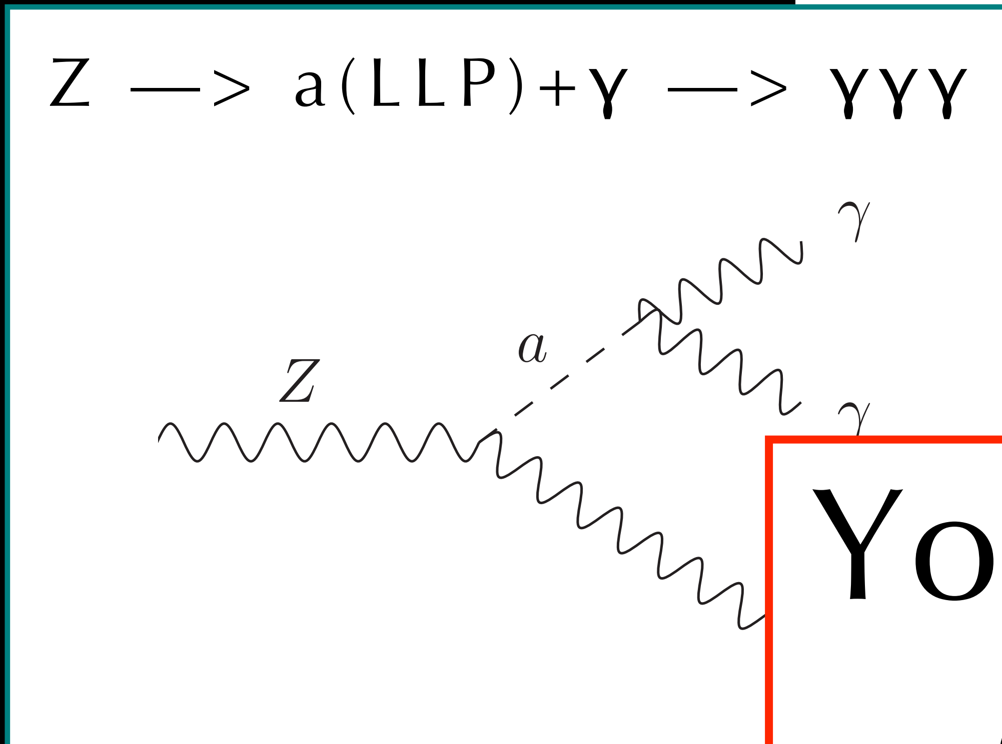
- Axion-like particle (ALP) + photon, ALP an LLP
  - For ALP decaying to photons, signature would be one prompt photon pointing to IP and two displaced, possibly non-pointing photons OR one non-pointing photon-jet
  - Q: What are the photon-pointing capabilities of the CEPC detector designs?

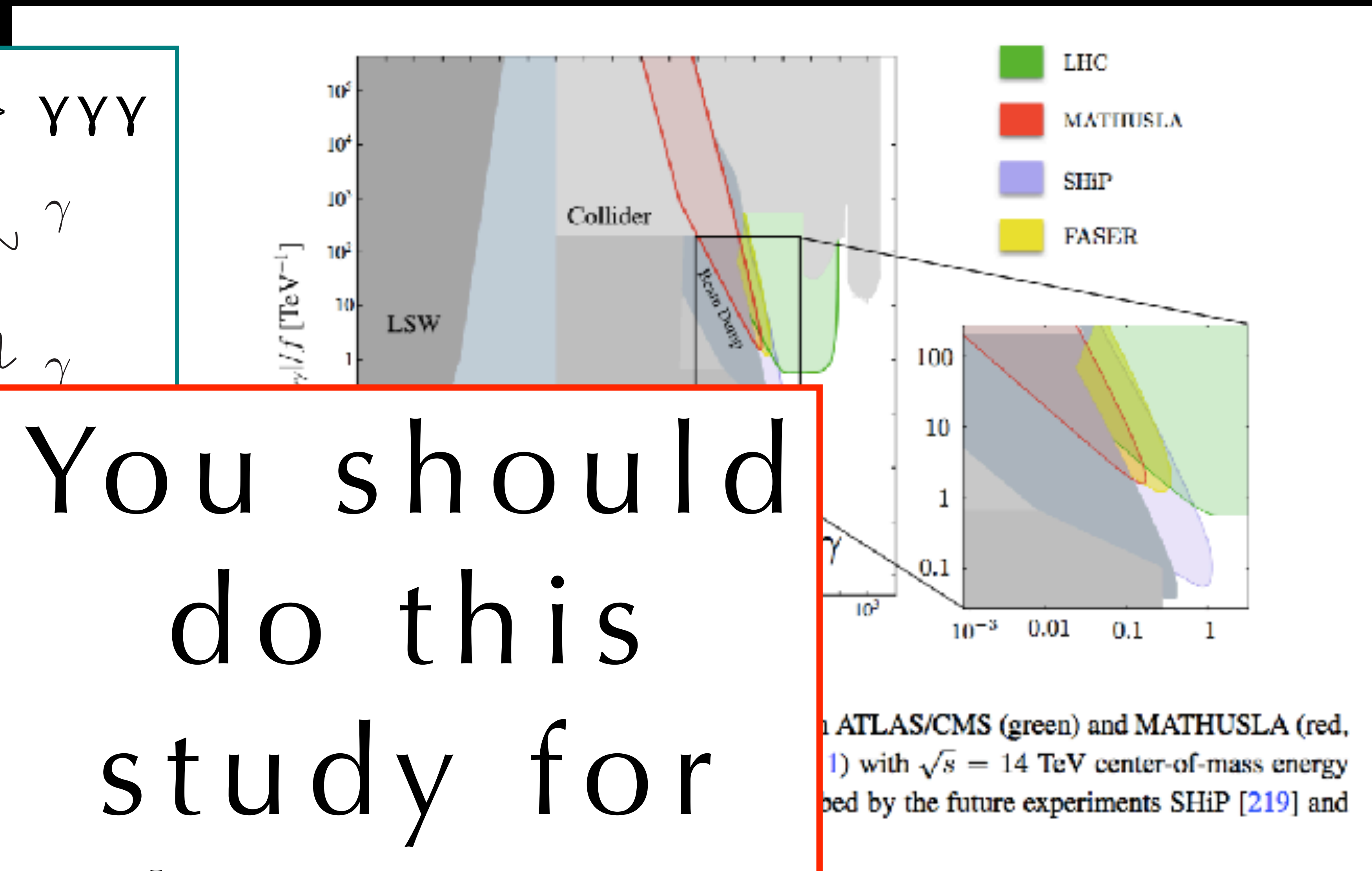
With 10^{12} Z bosons at CEPC / FCCee and an appropriate inner tracker, these could be LLP signatures where high-energy e+e- machines win

- Small lifetime regime + clean environment = potential discovery

Very rare processes: Z —> LLP+X

Z —> a(LLP)+γ —> γγγ





You should do this study for the CEPC

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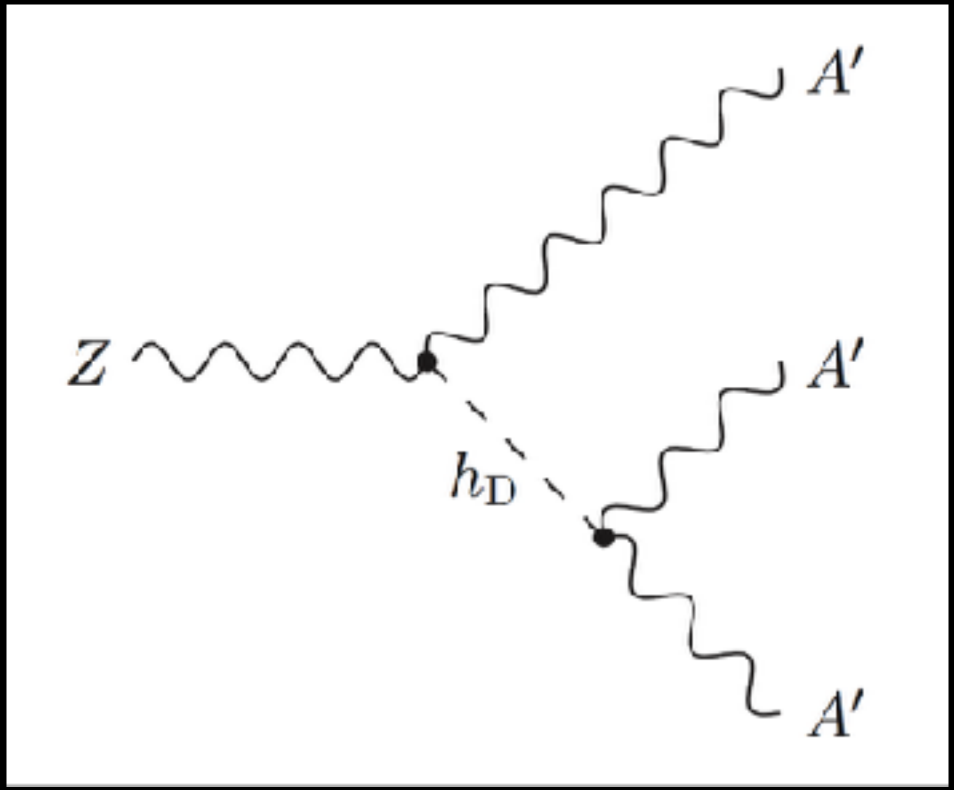

Studied in arXiv:1710.07635 for the LHC

SM Z decaying to LLP + X

- Dark Higgs with lifetime from ~mm to 100s of meters
  - A′/dark photon can decay promptly to leptons
  - Signature could be one prompt lepton-jet and two displaced LJs —> this would be distinctive and, for smaller lifetimes, more difficult at the LHC

Very rare processes: Z —> LLP+X

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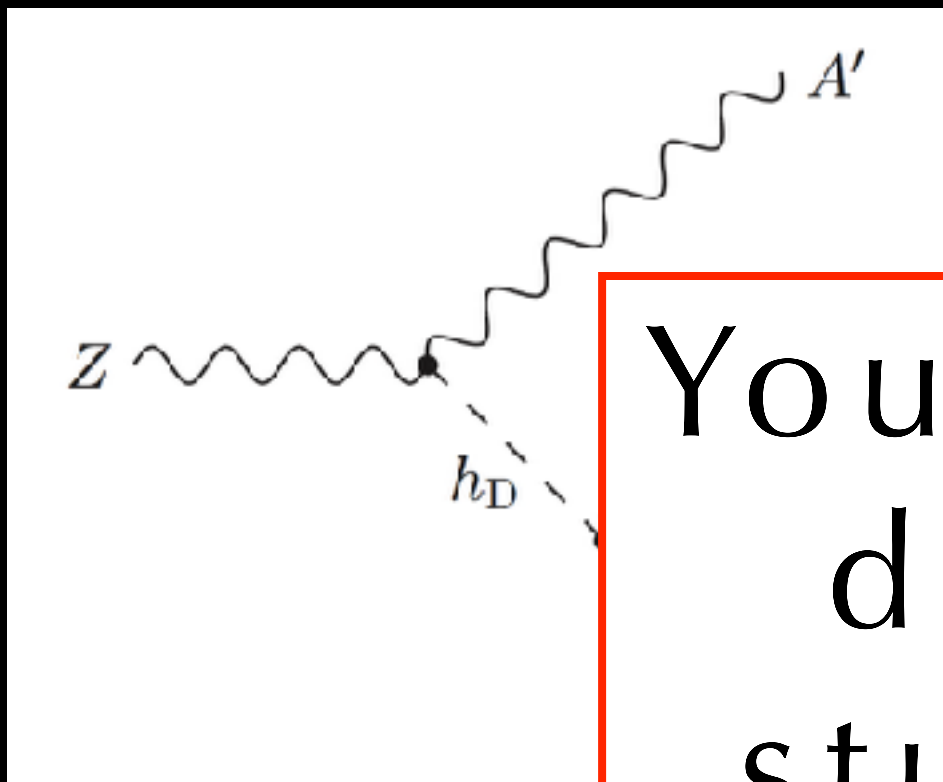

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Xiv:1710.07635
he LHC

SM Z decaying to L

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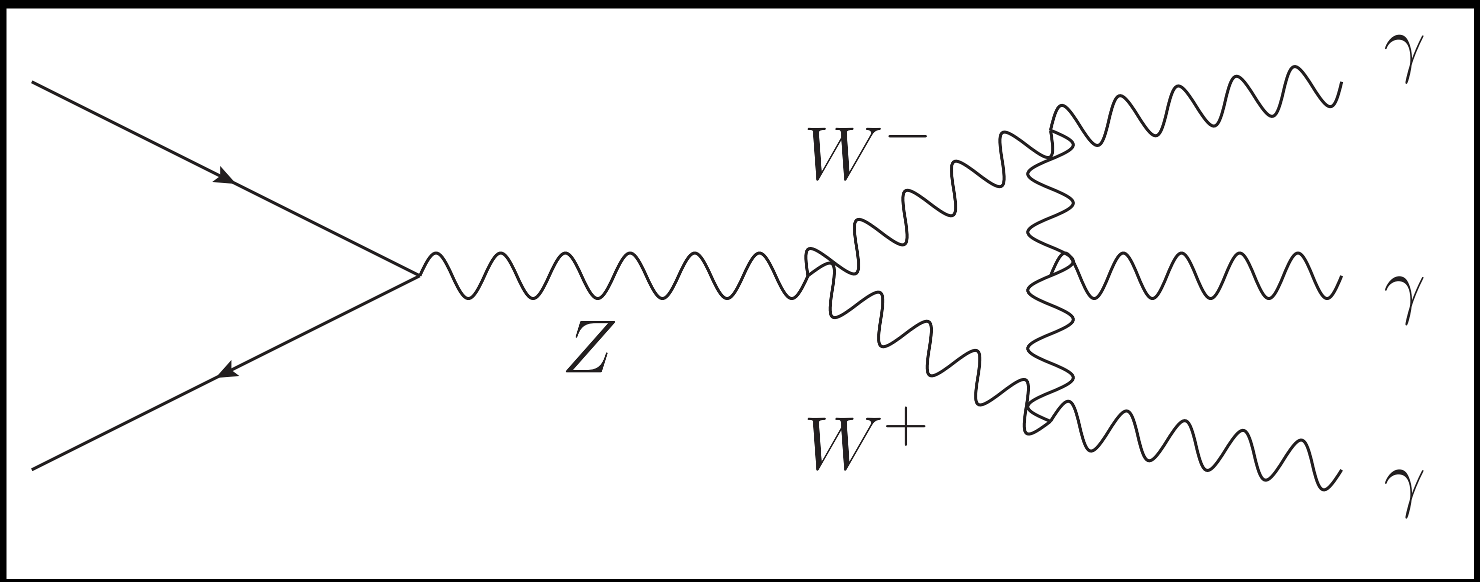
Bonus, related non-LLP idea — very rare processes within reach

SM Z —> γγγ

Predicted BR: 5e-10



ATLAS result at 8 TeV:
World's best limit

EPJC 76(4), 1-26 (2016)

Obs. (exp.) 95% CL upper limit on BR(Z—>3γ)

- 2.2 (2.0)e-6
  (almost 5 times better than LEP)

With 10^{12} Z bosons at CEPC could see SM process — and there are a few new-physics ideas (like monopoles) that could enhance this rate — L3 search

Conclusions — LLP searches at CEPC

The lifetime frontier is a key component of the future of collider physics, including at CEPC

- CEPC is a lepton-collider Higgs *and Z* factory with 5/ab
- This is likely excellent for classes of models that give rise to softer LLPs with very-short lifetimes where pileup at hadron colliders is problematic
- Fully take advantage of clean e+e- collisions
- A few benchmark scenarios mentioned here:
  - h125 —> very short lifetime LLPs —> hadronic jets — Seth's on it!
    - This *must* be a key component of the research program
  - Rare Z processes yielding LLP ALPs, dark Higgses or dark photons leading to displaced leptonic / photonic
    final states
    - Opportunity for someone in the audience to do these studies

In general, though, more studies needed, for many classes of models that yield rich signatures

- Some ILC studies for LLPs have been done over the years, and can learn much from them

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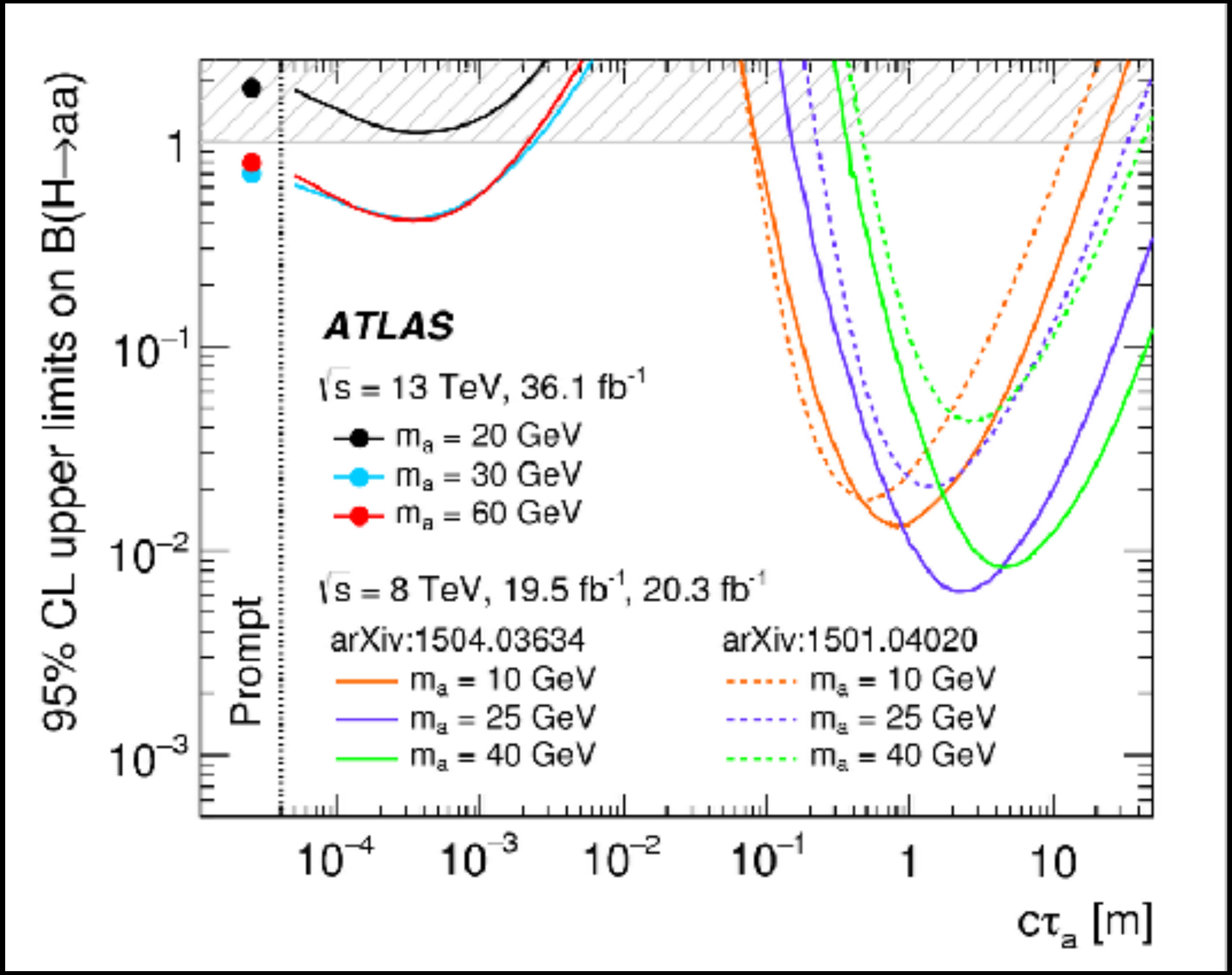
Take-home suggestions:

- Suggestion #1: Do the previously-mentioned studies on rare Z processes with displaced signatures, plus all the others

Conclusions — LLP searches at CEPC

Suggestion #2: To all those studying BSM physics at CEPC / FCCee, when generating MC, also generate a couple of points where your BSM particle has a small-but-non-negligible ctau and make a separate plot to see where your expected sensitivity dies off as a function of lifetime, too

Recent ATLAS example: Very short-lived LLPs decaying to jets



- Search for W/Z/h125 —> *aa* —> 4b for a promptly decaying *a*, where an additional limit was set on a scenario with an *a* with a non-zero lifetime [arXiv:1806.07355]
- Essentially required generating some additional simulated samples and calculating a limit, an excellent gain for just a little extra work
- One more plot to make when doing CEPC BSM projections!

Conclusions — LLP searches at CEPC

Suggestion #3: A dedicated study group on LLPs at future e+e- machines at our spring LHC LLP Community workshop at CERN

What would *I* do with a million accessible Higgses and 10^{12} clean Z bosons?

Conclusions — LLP searches at CEPC

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What would *I* do with a million accessible Higgses and 10^{12} clean Z bosons?

Search for very rare and very wild long-lived particle signatures that are buried at hadronic machines!

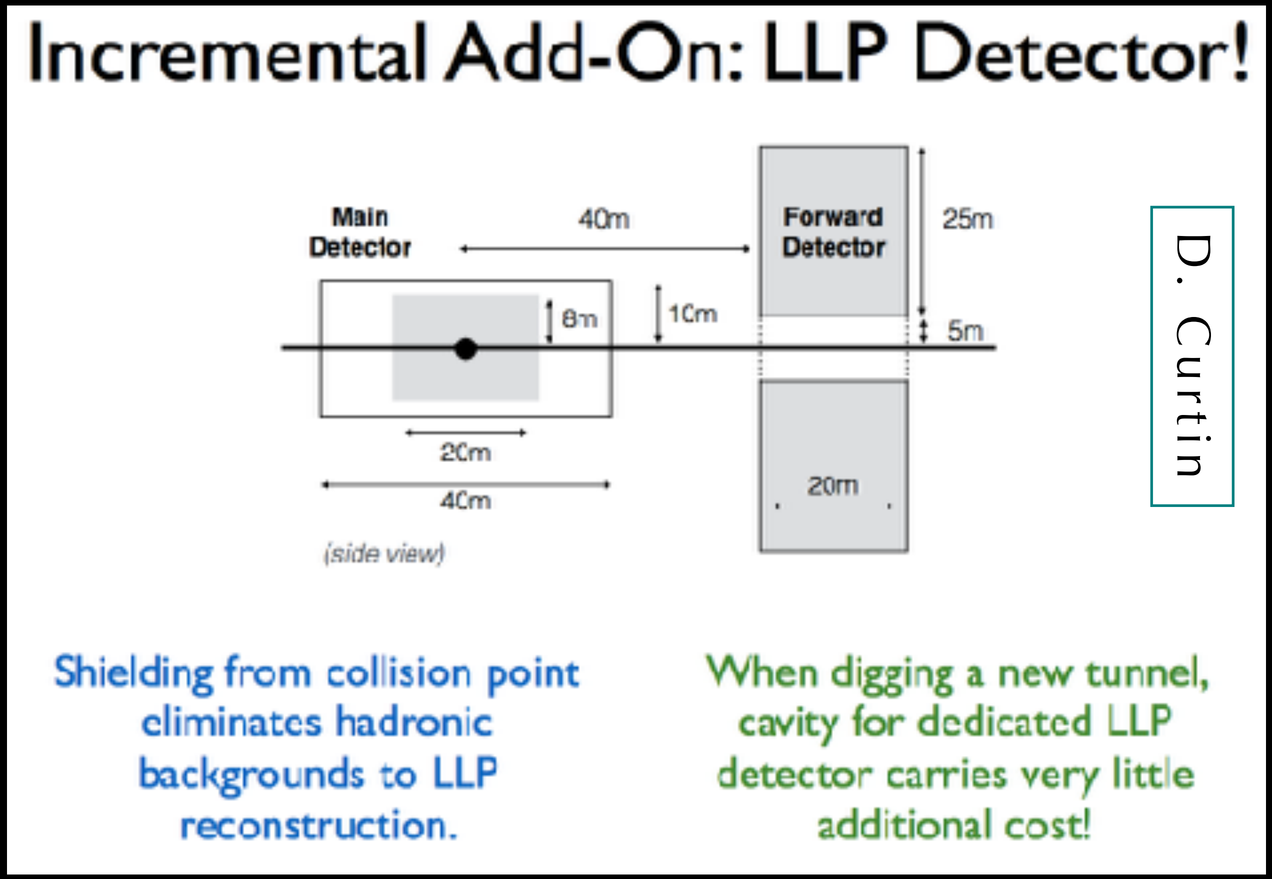
END

Reserve slides

Planning now for dedicated LLP (sub)detectors at CEPC

What detector capabilities have been studied for LLP searches at future e+e- machines like CEPC?

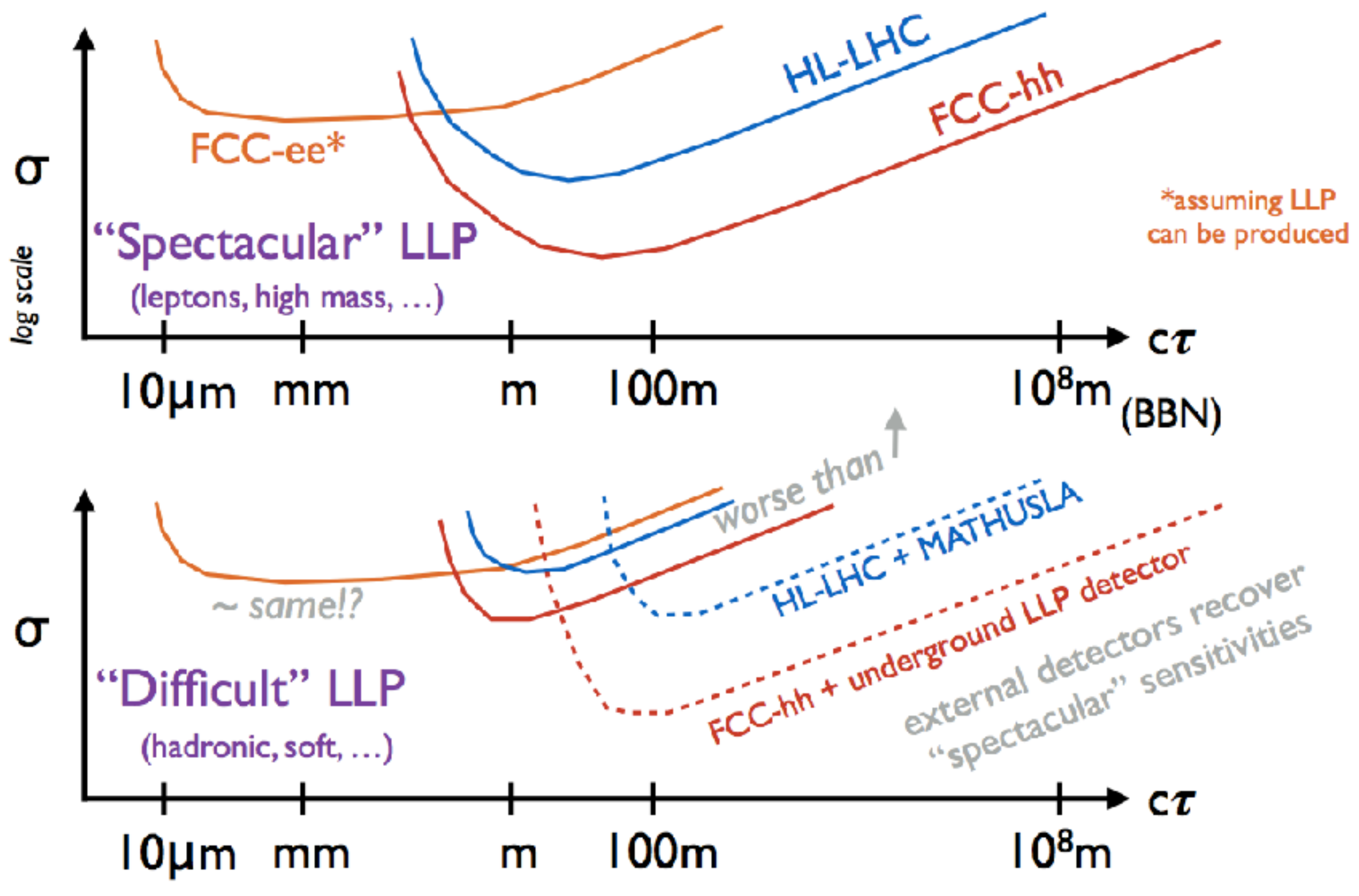
- Fast timing layers like those being discussed for ATLAS and CMS —> C. Tully timing layer for CEPC study
  - How could this aid searches for LLPs?
- Suggestions of dedicated detectors, e.g., a 1km decay tunnel lined with tracking, or a dedicated LLP detector underground



Several exciting dedicated LLP experiments either underway or planned at the LHC (MilliQan, MoEDAL, SHiP, FASER, CODEXb, MATHUSLA)

CEPC can incorporate these concepts from the beginning!

★Cartoon★ of relative LLP sensitivities



D. Curtin