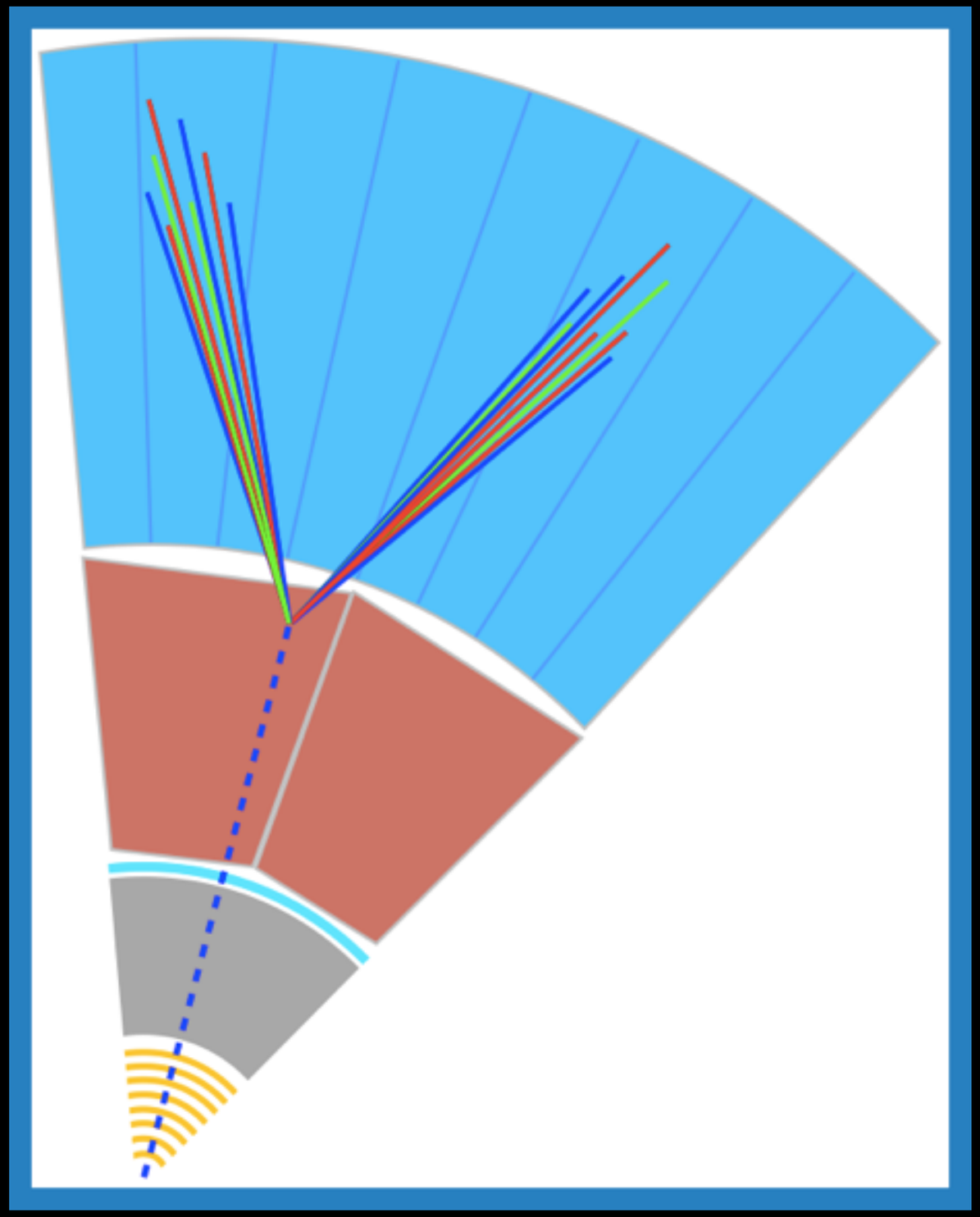
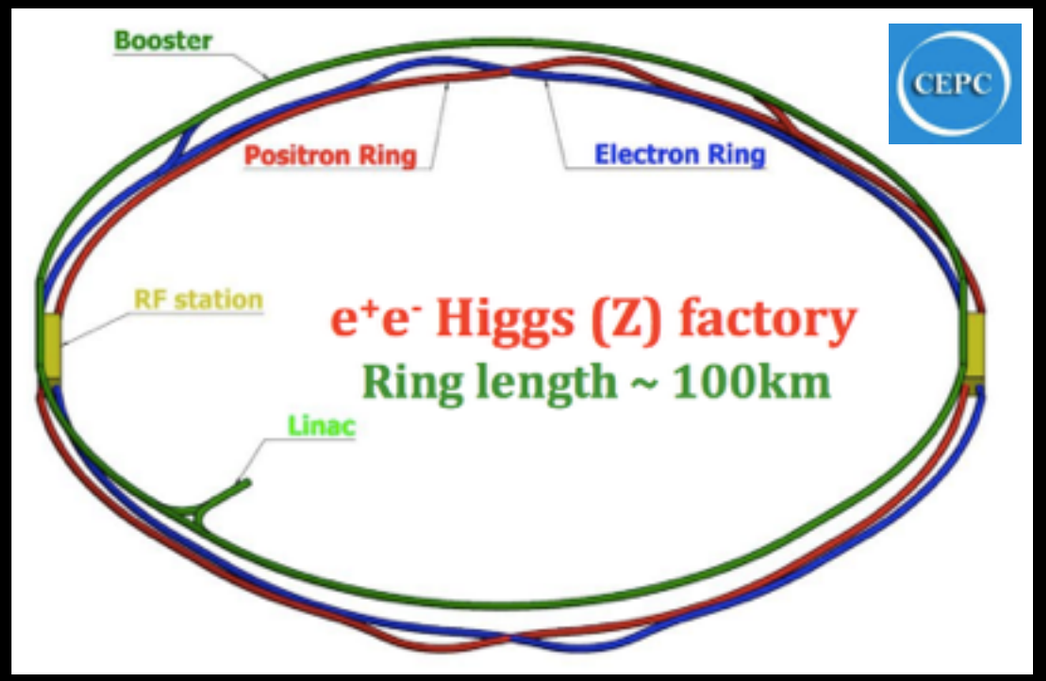


Searches for long-lived particles at the CEPC

Prospects and unknowns



Open questions before 4 July 2012

EWSB
- ❑ Does the Higgs boson exist?

Quarks and leptons:
- ❑ why 3 families ?
- ❑ masses and mixing
- ❑ *CP* violation in the lepton sector
- ❑ matter and antimatter asymmetry
- ❑ baryon and charged lepton number violation

Physics at the highest E-scales:
- ❑ how is gravity connected with the other forces ?
- ❑ do forces unify at high energy ?

Dark matter:
- ❑ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- ❑ one type or more ?
- ❑ only gravitational or other interactions ?

Neutrinos:
- ❑ ν masses and and their origin
- ❑ what is the role of $H(125)$?
- ❑ Majorana or Dirac ?
- ❑ *CP* violation
- ❑ additional species → sterile ν ?

The two epochs of Universe's accelerated expansion:
- ❑ primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- ❑ today: dark energy (why is Λ so small?) or gravity modification ?

SEARCH2016 Oxford -- Meade/Papucci/Shipsey/Sundrum

I. Shipsey

Open questions after 4 July 2012

Higgs boson and EWSB
- ❑ m_H natural or fine-tuned ?
- → if natural: what new physics/symmetry?
- ❑ does it regularize the divergent V_LV_L cross-section at high $M(V_LV_L)$? Or is there a new dynamics ?
- ❑ elementary or composite Higgs ?
- ❑ is it alone or are there other Higgs bosons ?
- ❑ origin of couplings to fermions
- ❑ coupling to dark matter ?
- ❑ does it violate CP ?
- ❑ cosmological EW phase transition

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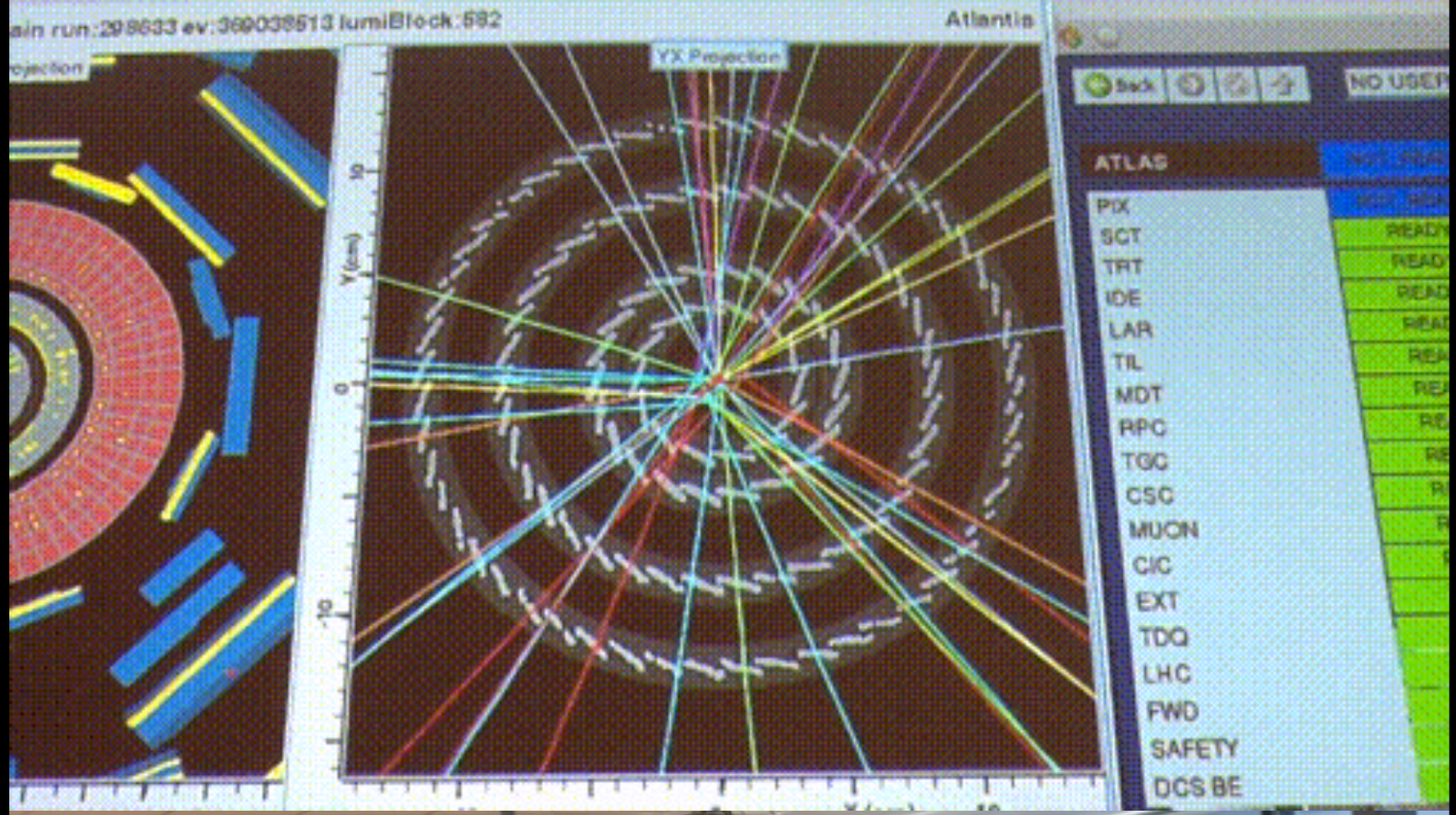
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SAFETY
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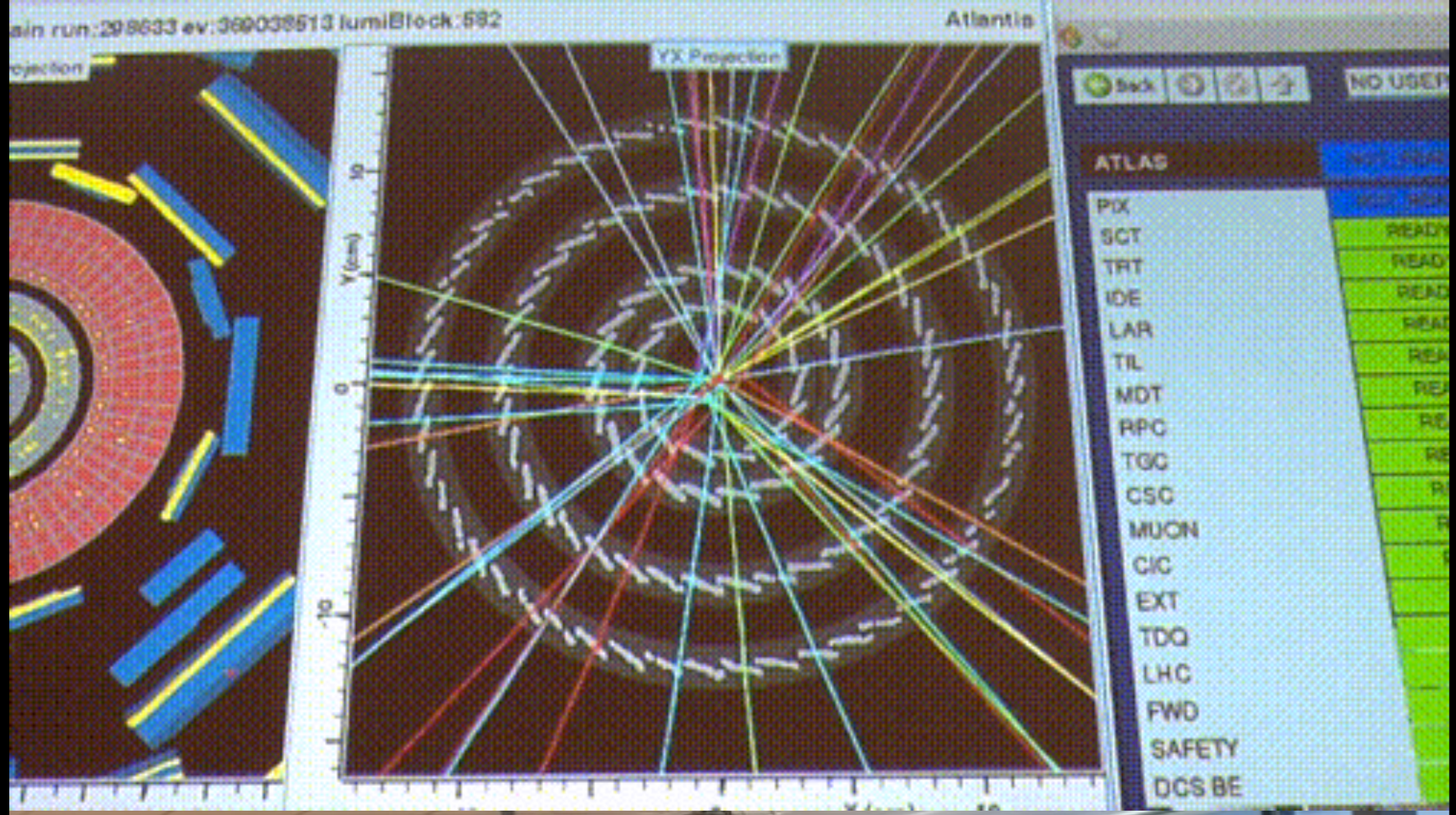
June 2015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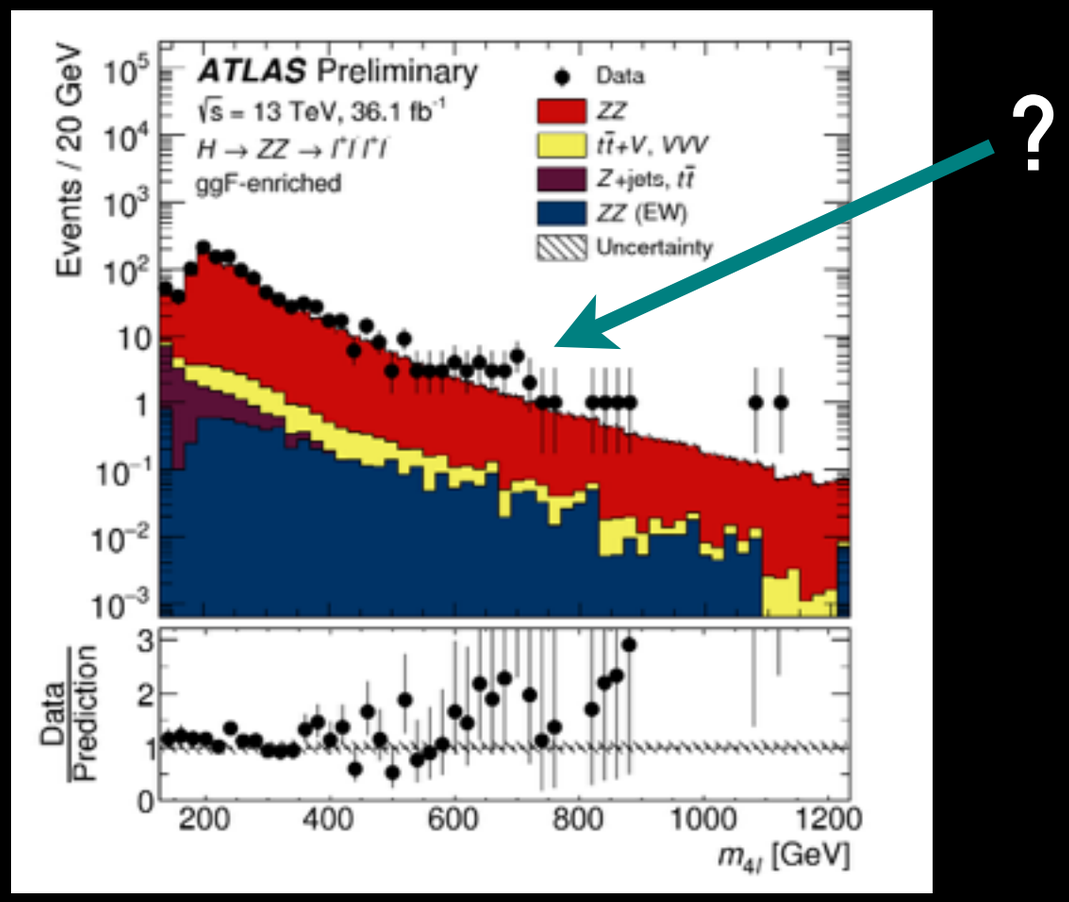
June 2015

New physics in 2017

Our first extensive look at 13 TeV at the LHC yields impressive agreement with Standard Model expectations and no huge, immediate resonances or excesses



?

There are no more guarantees and no ace-in-the-hole motivations

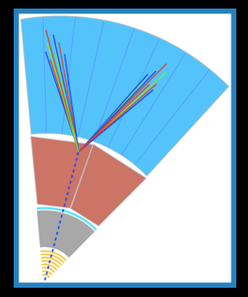
We must shift from theory-driven search strategies to signature-driven ones

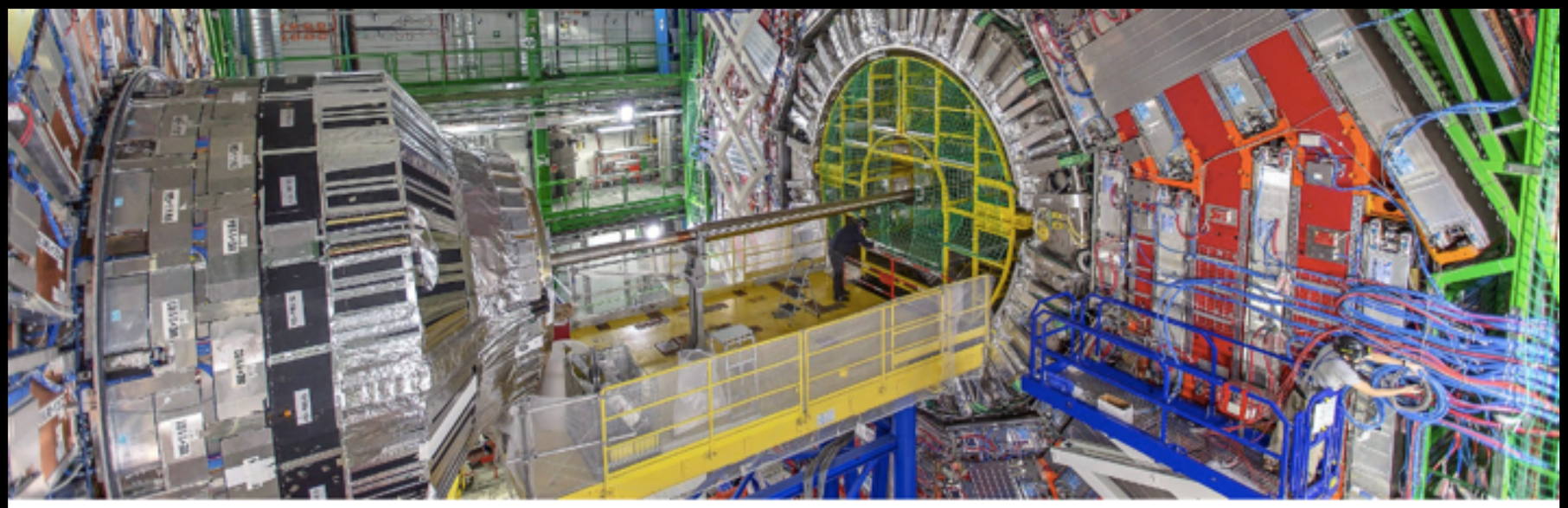
We're eager to see what 120/fb at the LHC and 3/ab at the HL-LHC uncover

Our job is to map out parameter and signature space, with a more comprehensive look at all possible signatures, precision measurements, and general deviations from expectation

This message is more challenging to impart to the public...

The paradigm is shifting — though slowly





CERN hosts thousands of scientists, representing 22 member countries, all working to understand how the universe was created. CMS is one of seven detectors on site. Leslye Davis/The New York Times

Yearning for New Physics at CERN, in a Post-Higgs Way

Physicists monitoring the Large Hadron Collider are seeking clues to a theory that will answer deeper questions about the cosmos. But the silence from the frontier has been ominous.

By DENNIS OVERBYE JUNE 19, 2017

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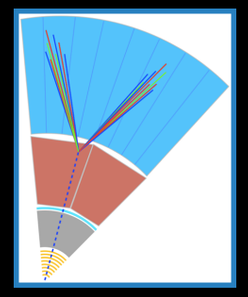

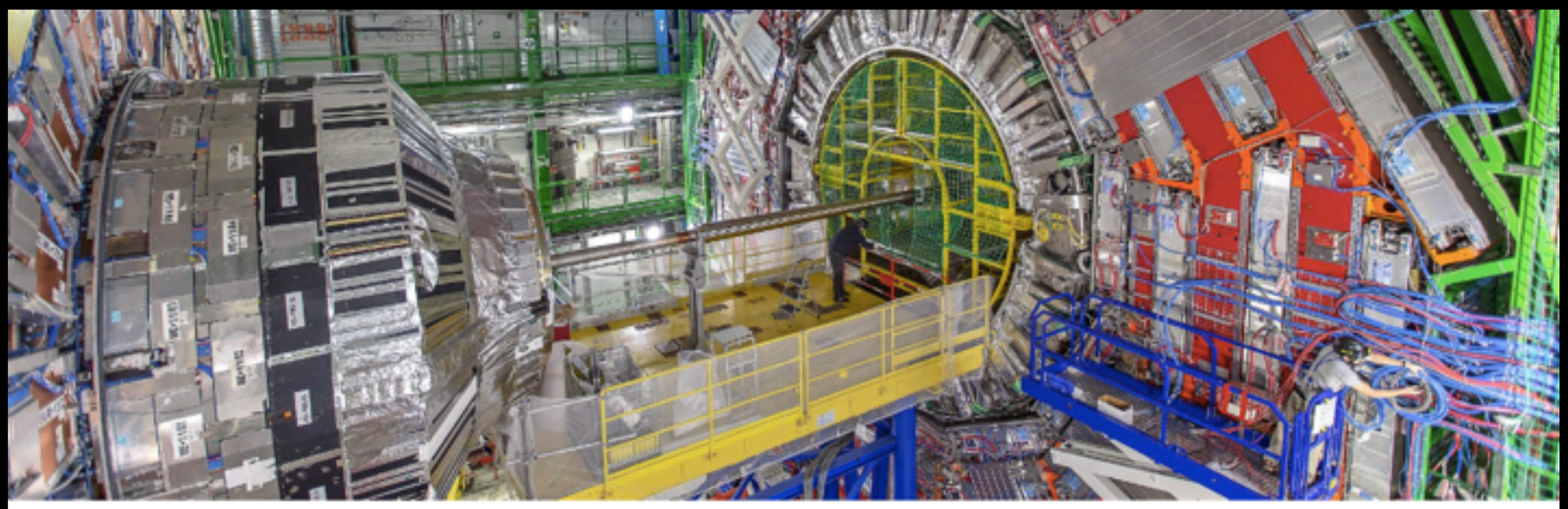

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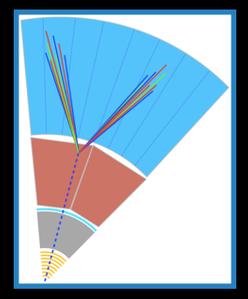

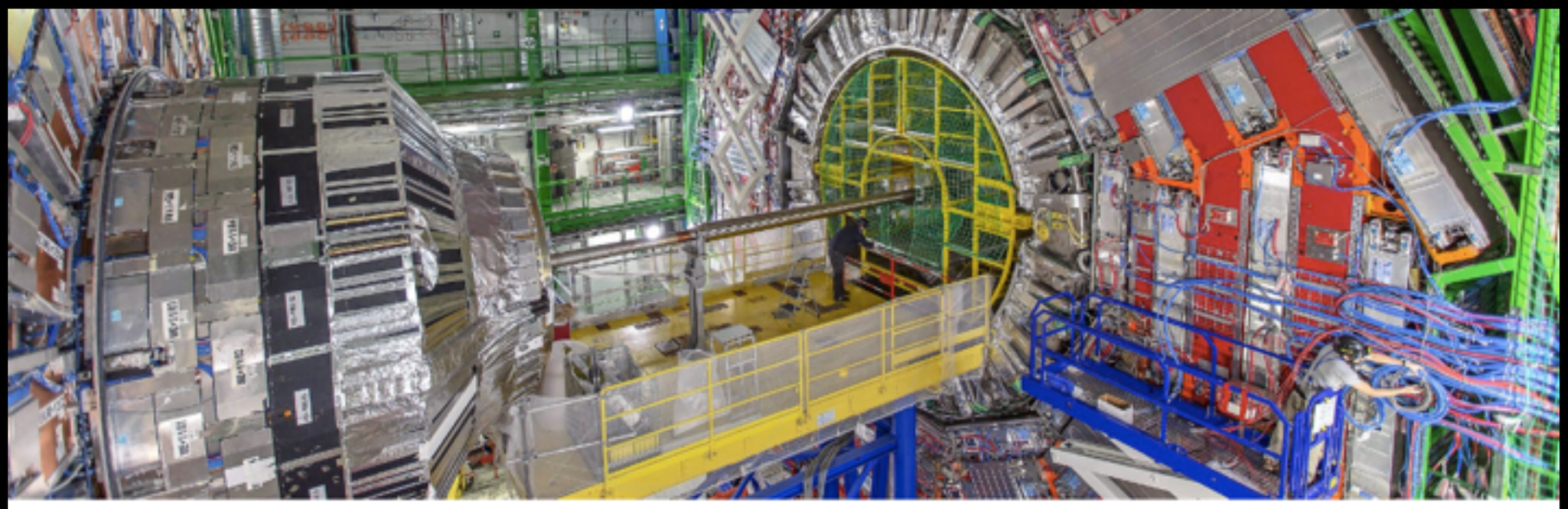

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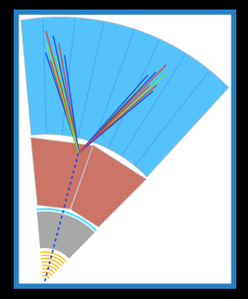

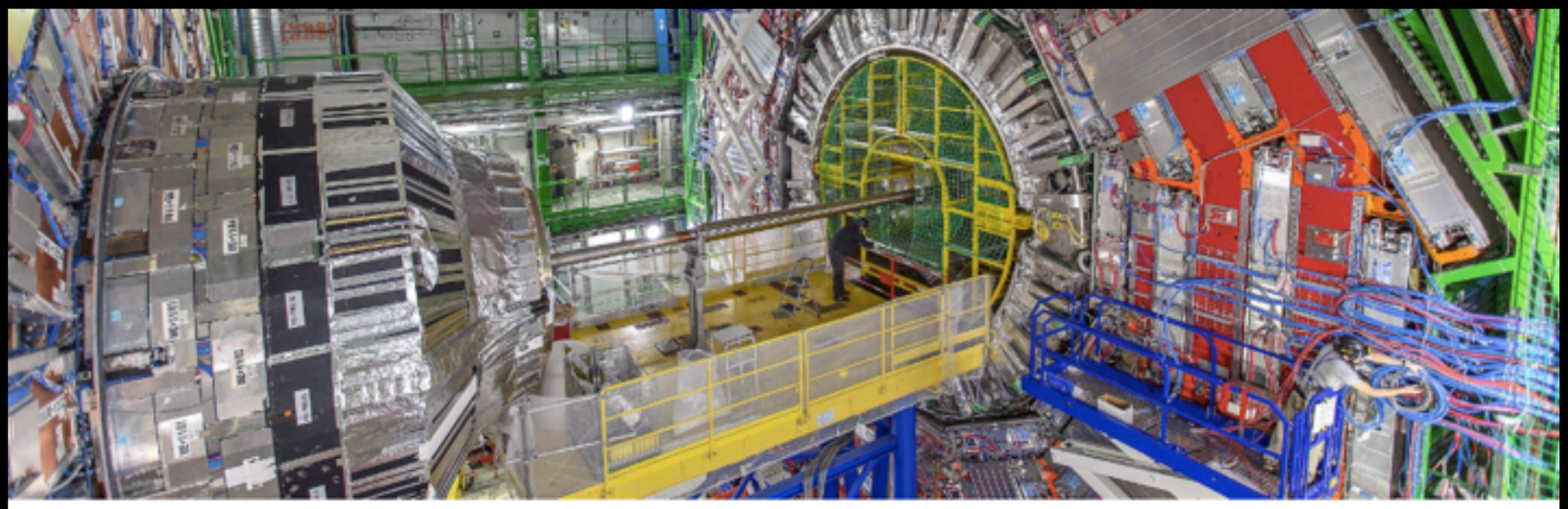

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Dennis Overbye Actions

In response to the message from James Beacham, 21/06/2017

To: James Beacham

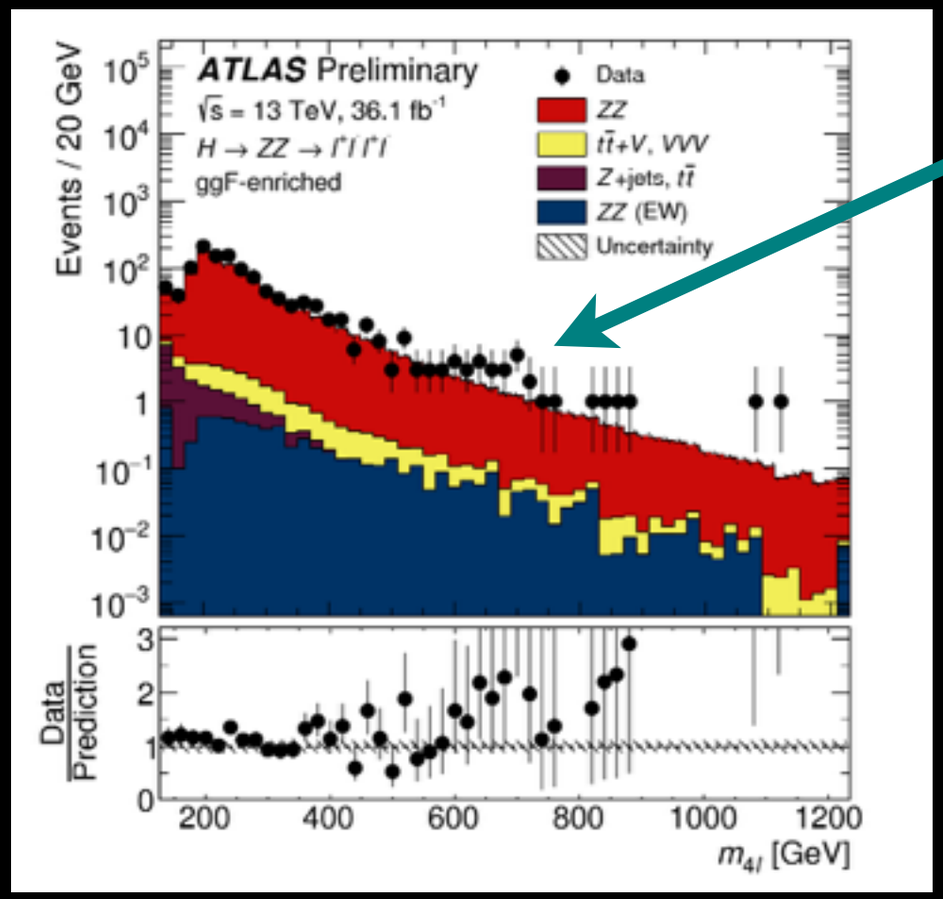
Inbox 22 June 2017 02:33

Well said
Lots of good ideas there but I have to get off my airplane now
Dennis

Sent from my iPhone

New physics in 2017

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



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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 particle physics and look for deviations from expectations — we're explorers & map-makers, not SUSY-hunters

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

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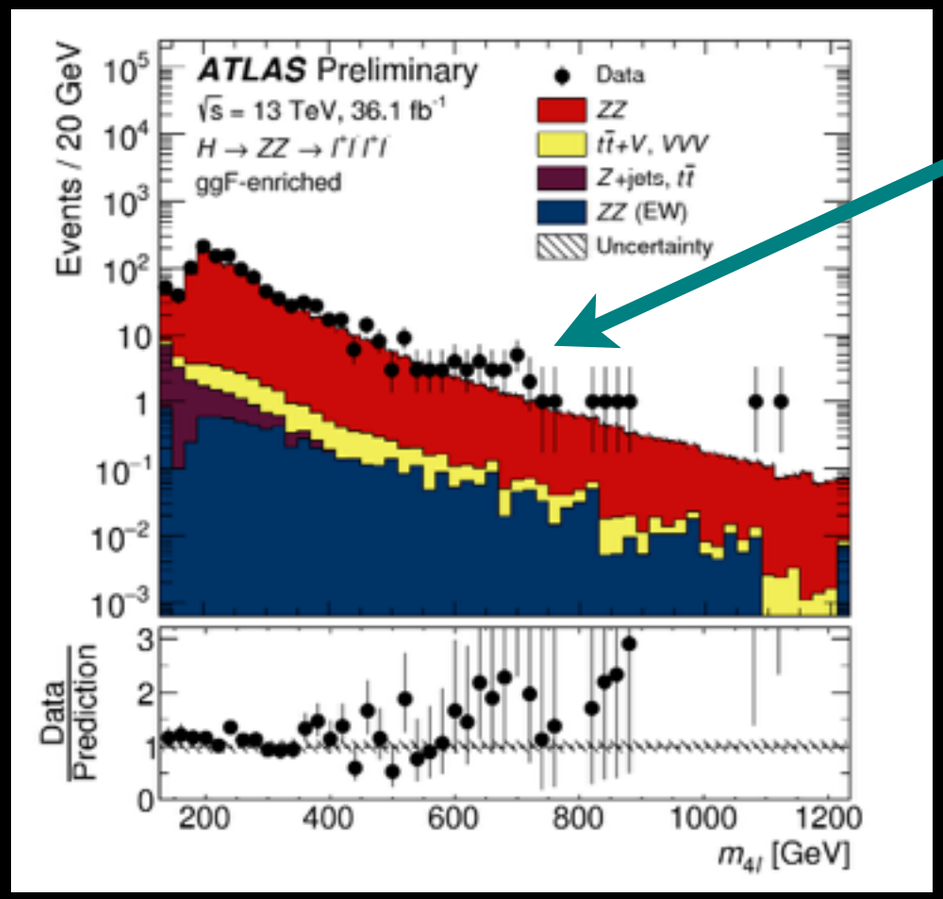

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Planning for future colliders needs to incorporate the known *and* the less-well-known. How do we go beyond what we're good at?

What are we overlooking?

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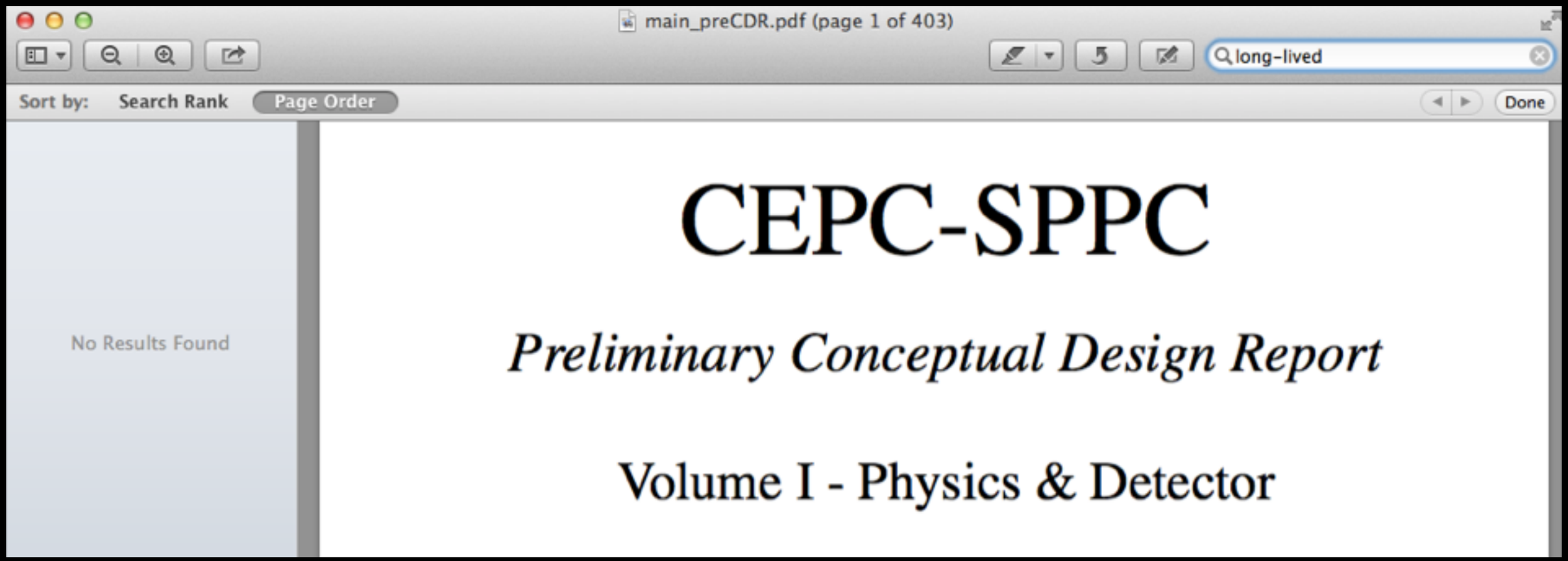

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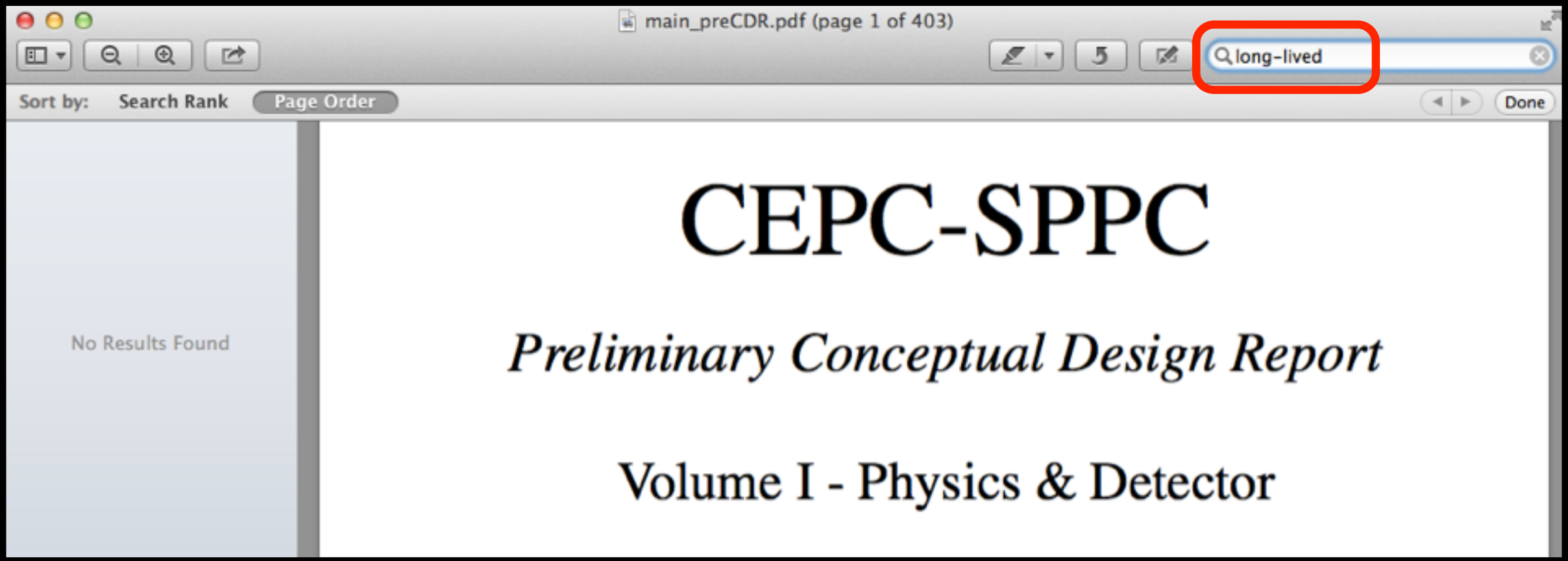

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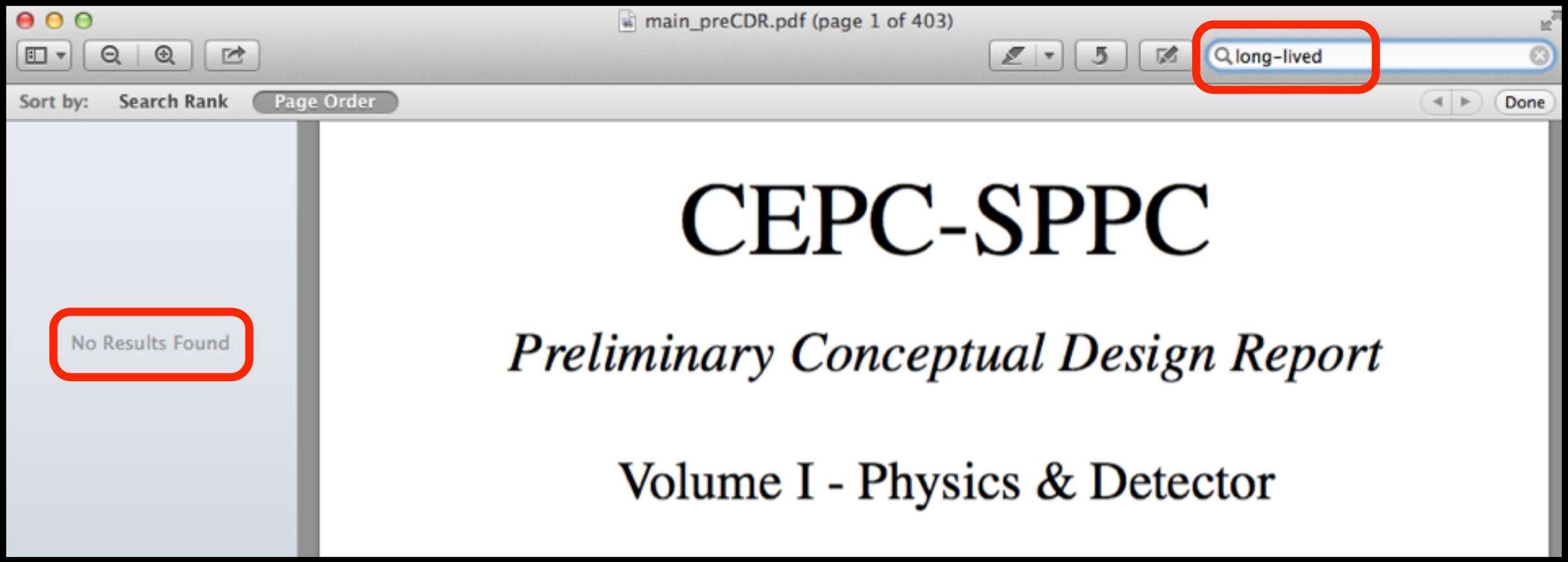

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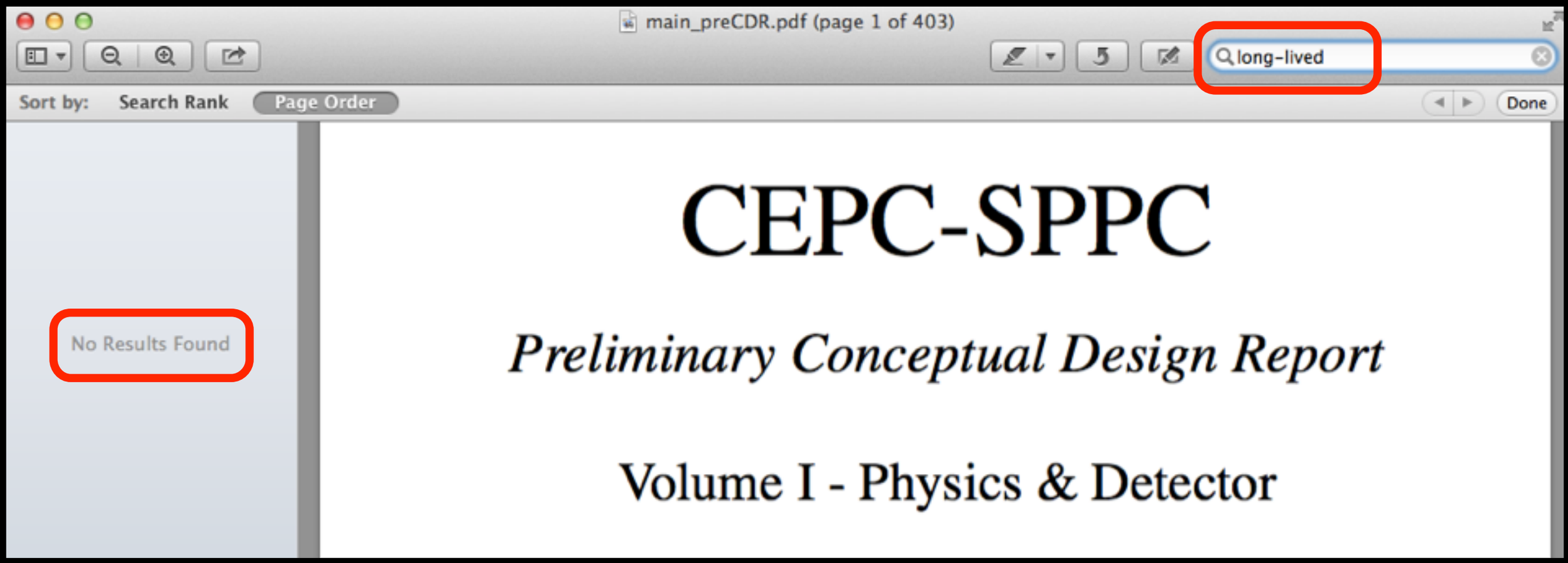
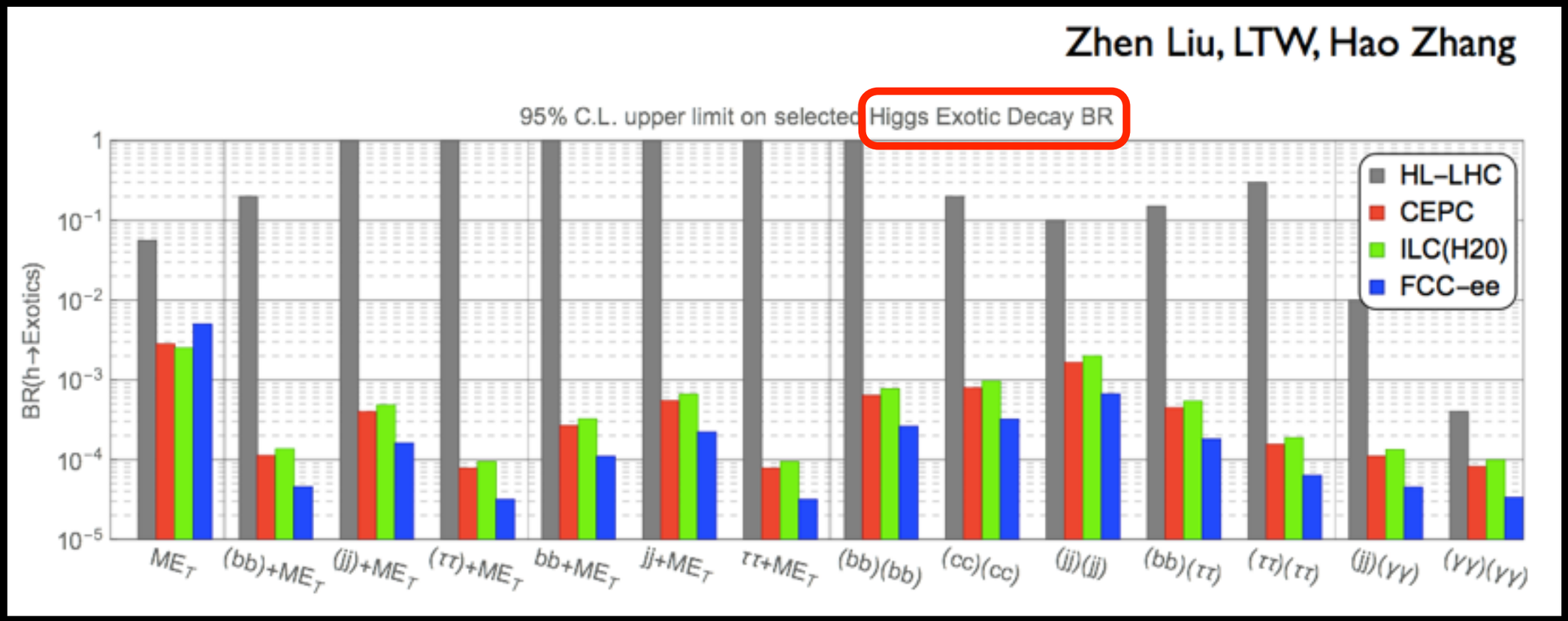
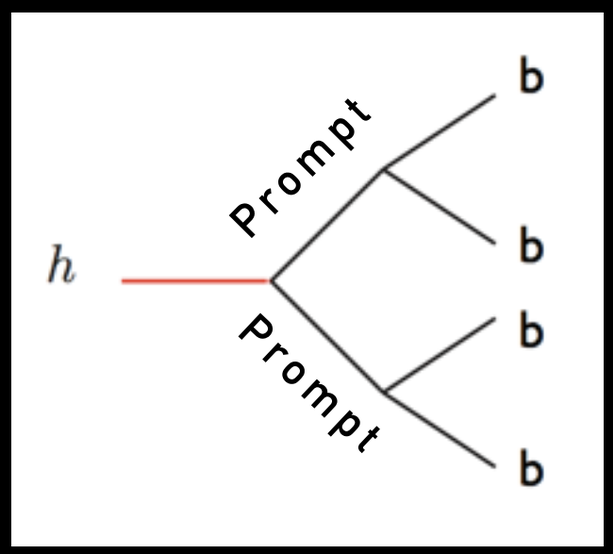


An excellent disappearing track search does exist,
but this is just the tip of the iceberg!

Overlooking new physics at future lepton colliders

More concretely, what are we missing at a nice, clean, lepton-collider Higgs factory?





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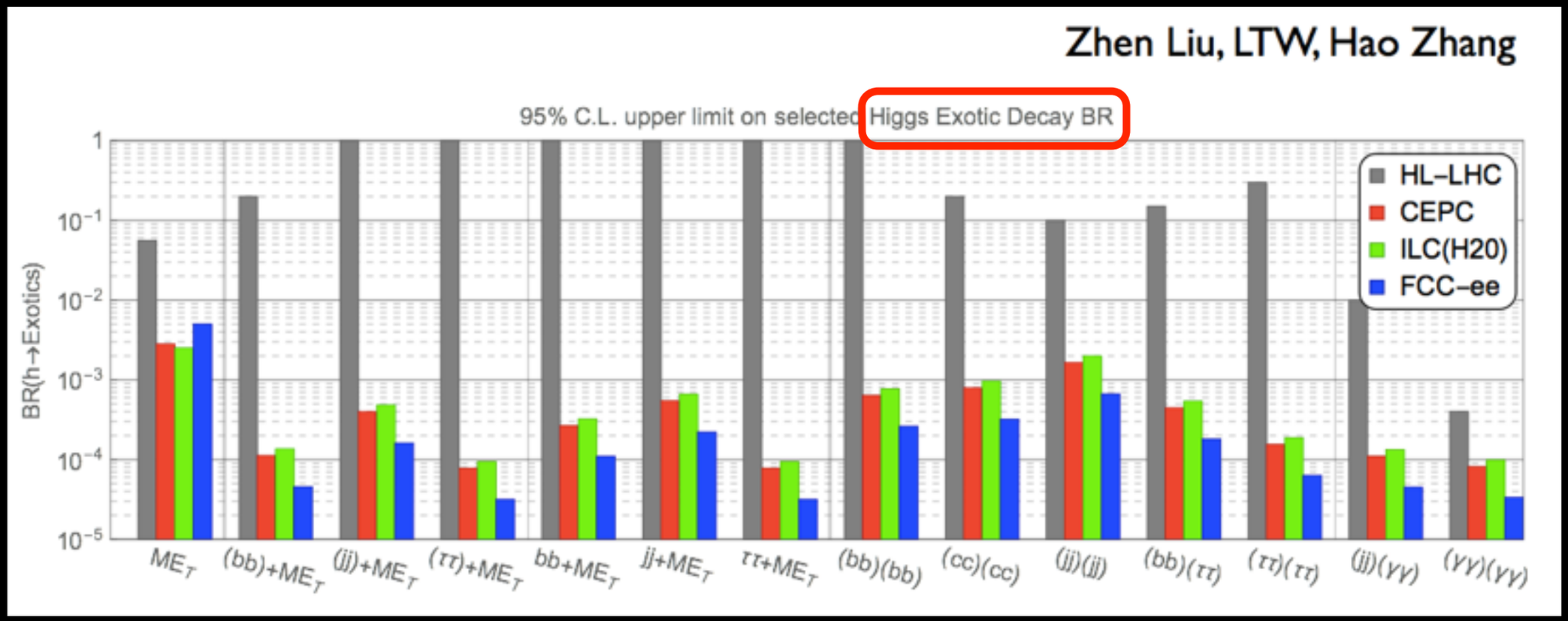
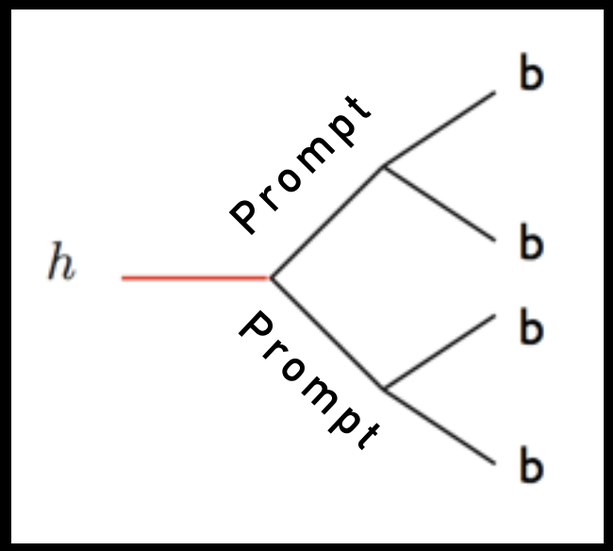
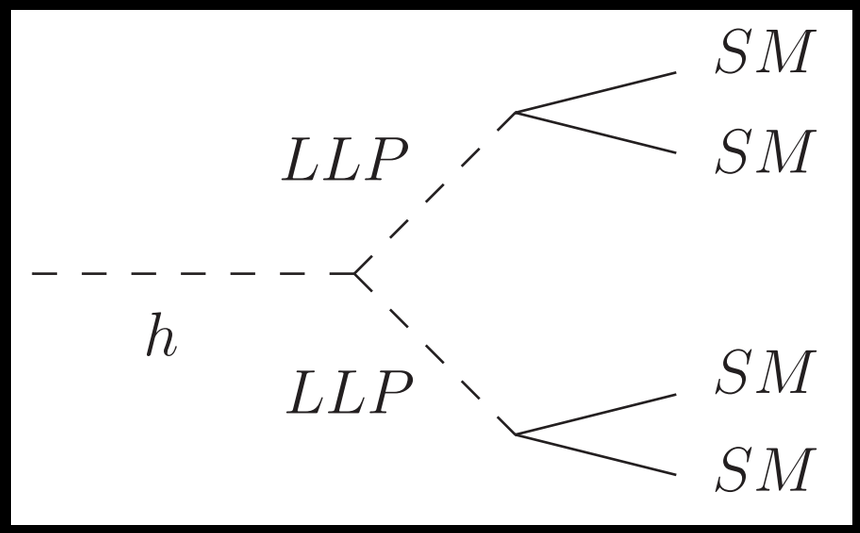
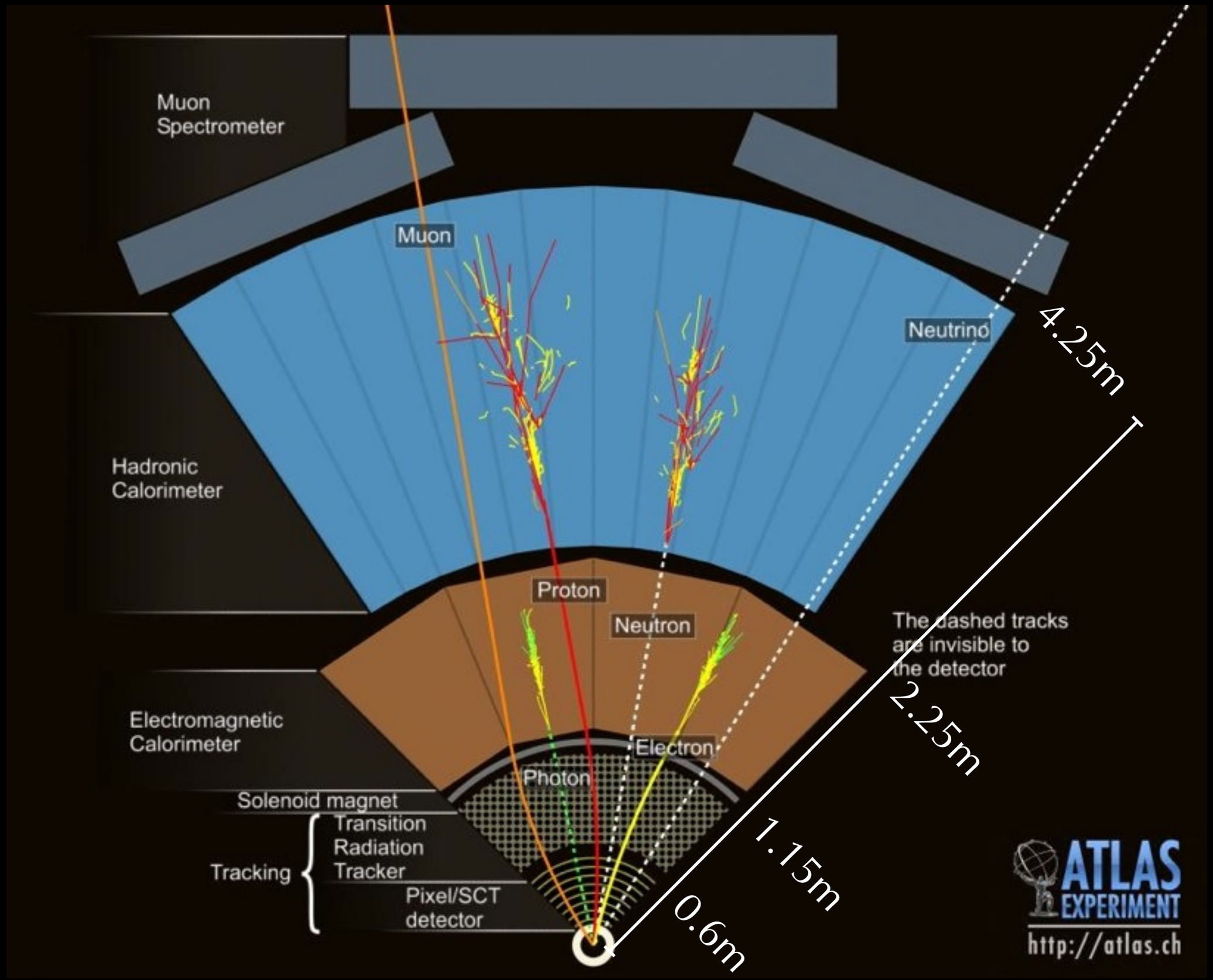




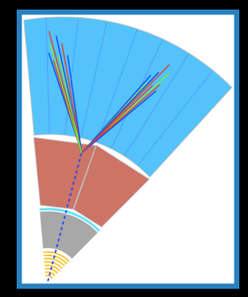
The intermediate particle can generically be long-lived —> completely different signatures

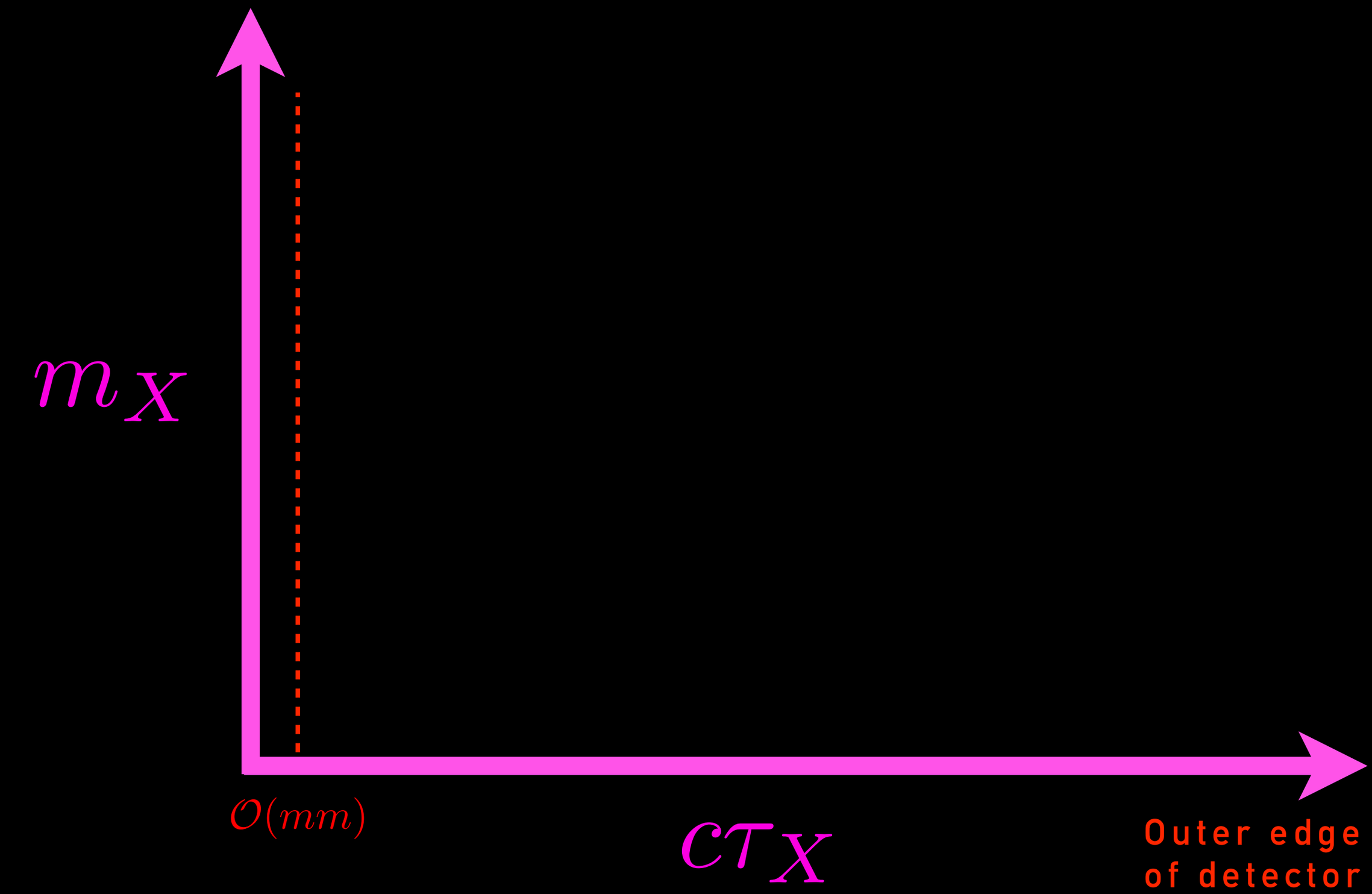


95% of our analysis effort is dedicated to understanding five prompt objects



New physics X at colliders





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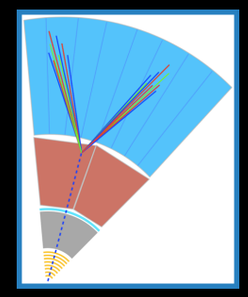


The overwhelming majority of the work of experimentalists

Stable

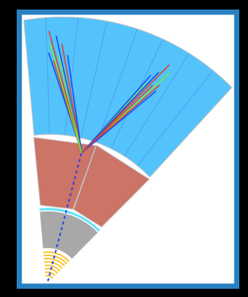
m_X

$\mathcal{O}(mm)$

$c\tau_X$

Outer edge of detector

New physics X at colliders



The overwhelming majority of the work of experimentalists

A relatively few intrepid explorers doing inventive things with long-lived particle signatures

Stable

m_X

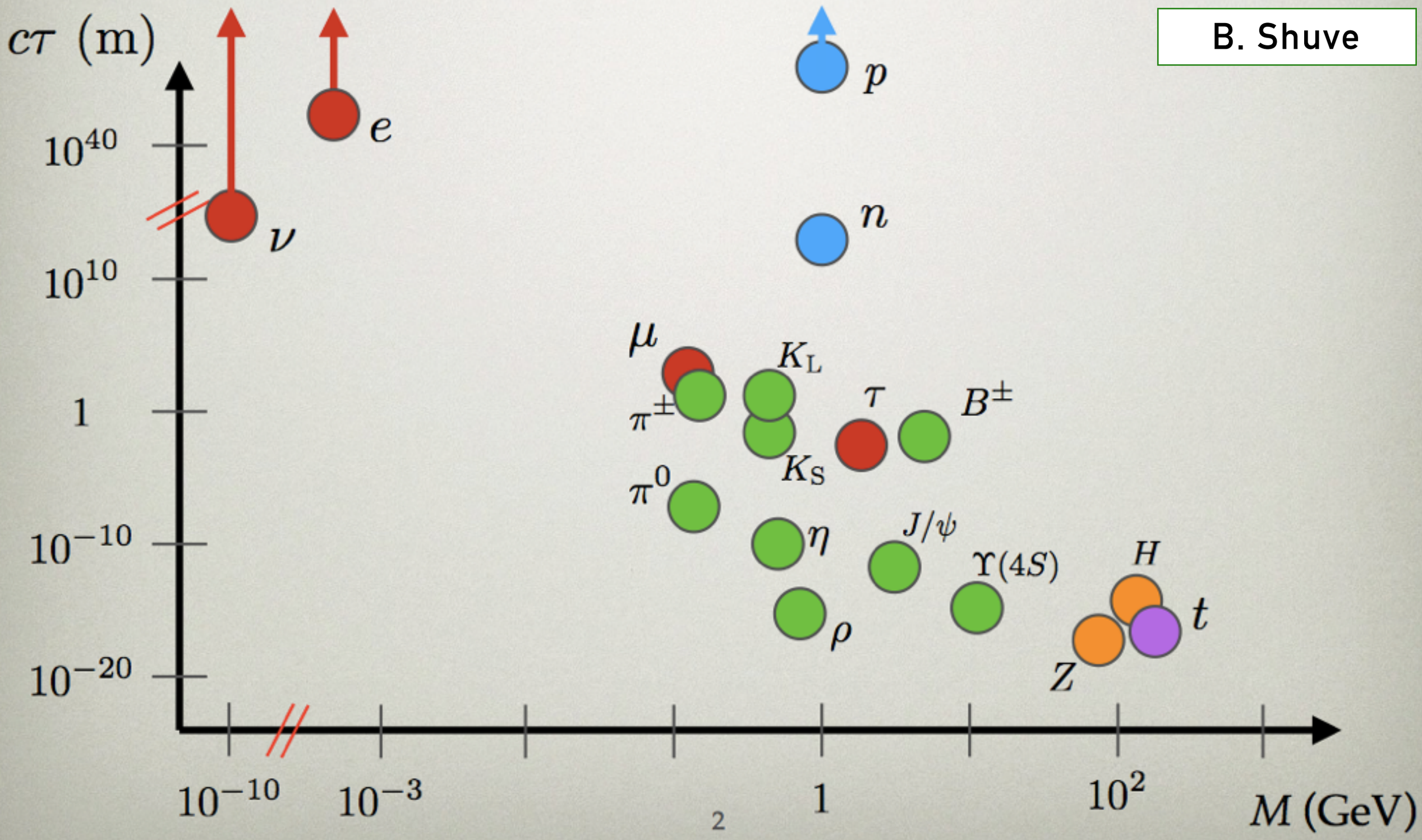
$\mathcal{O}(mm)$

$c\tau_X$

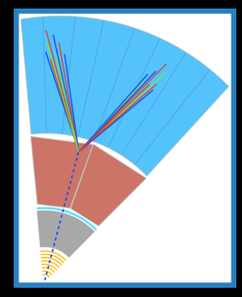
Outer edge of detector

The lifetime frontier

B. Shuve

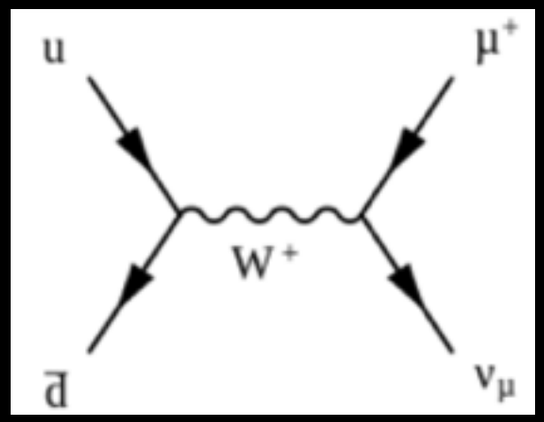


LLPs — SM and BSM



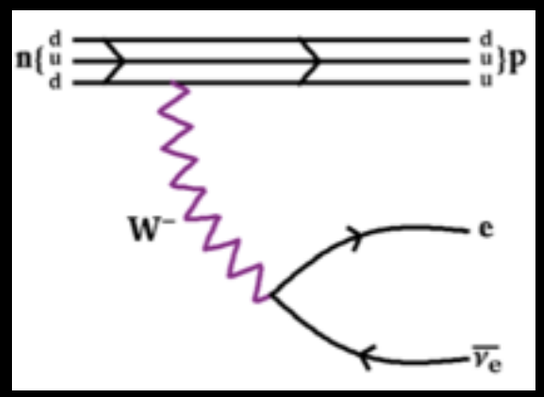
Long lifetimes typically arise in the SM when approximate symmetries make the particle stable

Small symmetry-breaking parameters can suppress the decay rate



Charged pion

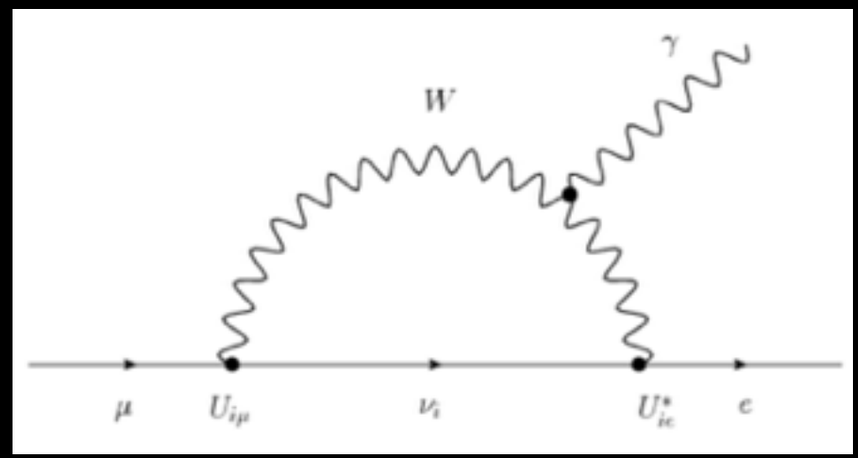
Decay highly off-shell



Neutron

Isospin: p and n nearly degenerate

Decay highly off-shell



FCNC

Lepton flavor violated only by extremely small neutrino Yukawas

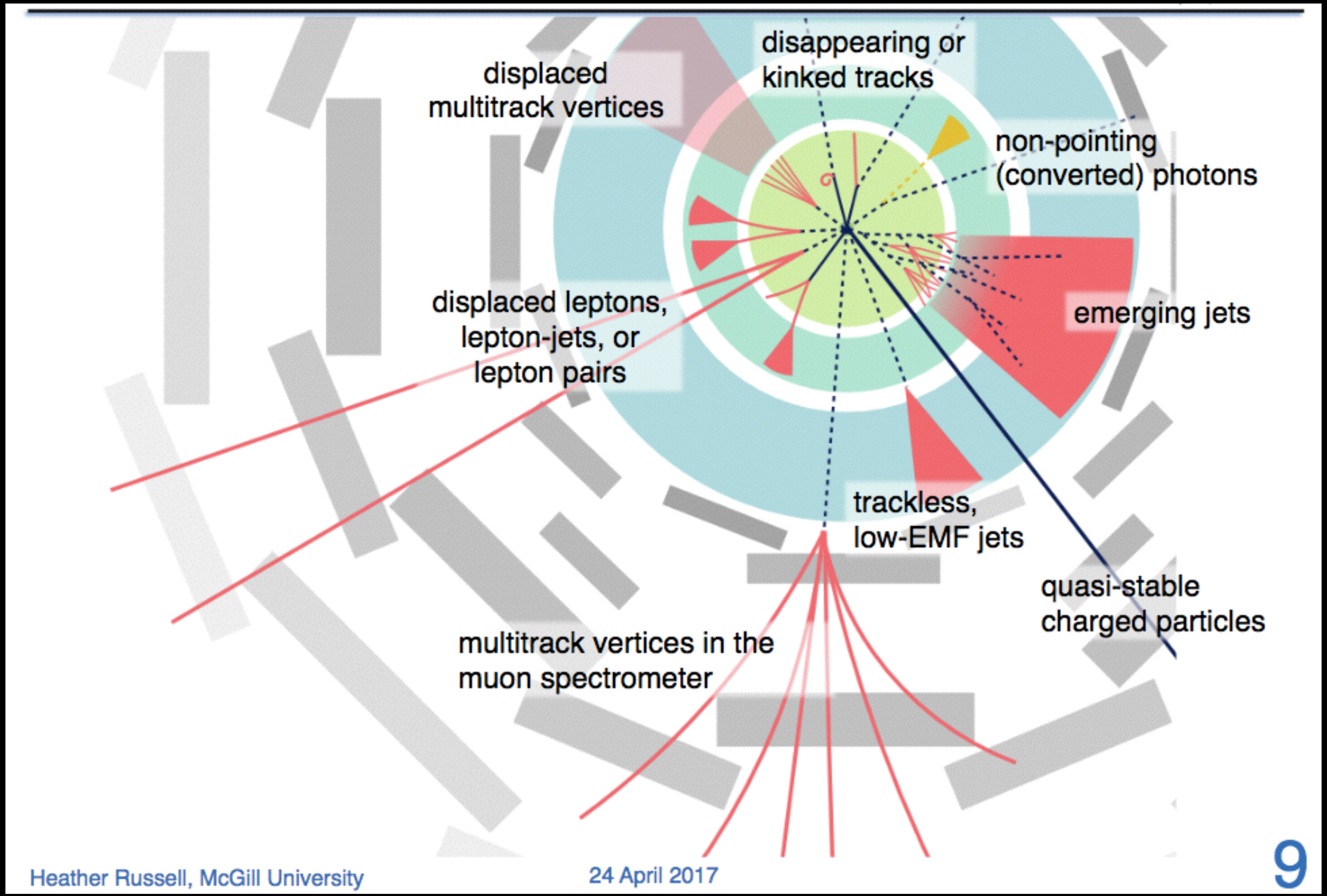
$BR(\mu \to e\gamma) \sim 10^{-54}$

Same principles apply to BSM LLPs, which can generically appear

- Lifetime is usually best treated as a free parameter

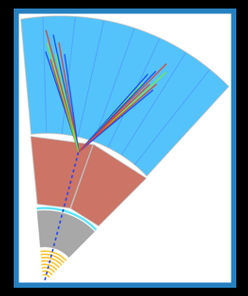
Talks by Strassler, Knapen, Shuve, Ramsey-Mulsof, others

Challenges of LLP searches in general



Heather Russell, McGill University 24 April 2017 9

LLPs at the LHC



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

First searches were mostly tailored to be background-free

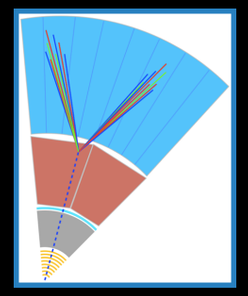
- Dominant backgrounds, though, can be from atypical sources (cosmics, beam halo, cavern, etc.)

- Great results but ended up being somewhat limited in scope (high pT 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

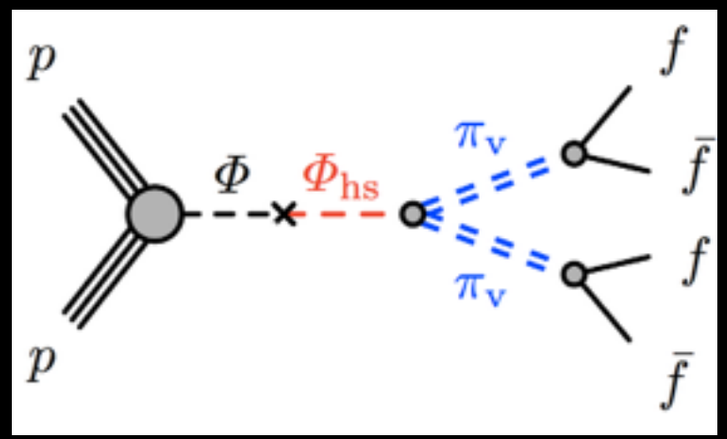
- Our relevant example here: h125 —> LLPs —> jets

h125 —> LLPs

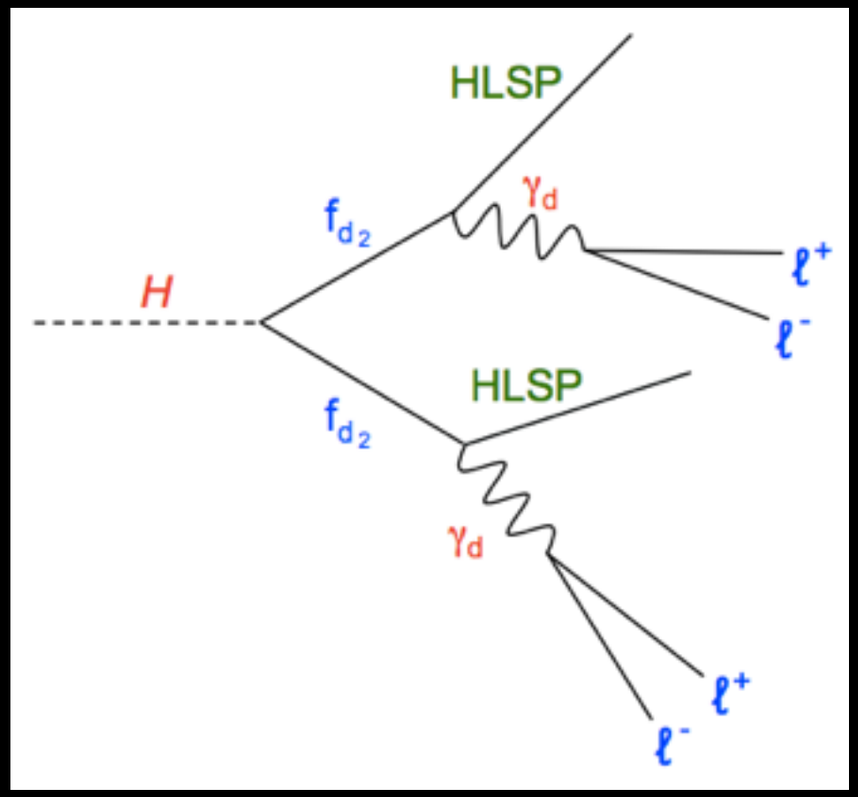


Higgs portal to hidden sector

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



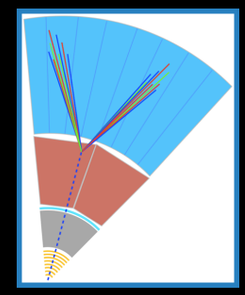
Higgs mixing with hidden sector scalar



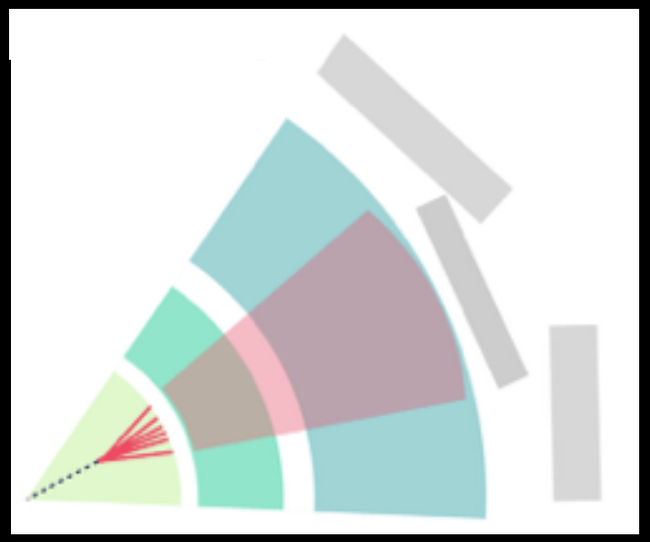
Higgs decaying to dark sector fermions which decay to long-lived dark photons and lepton-jets

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

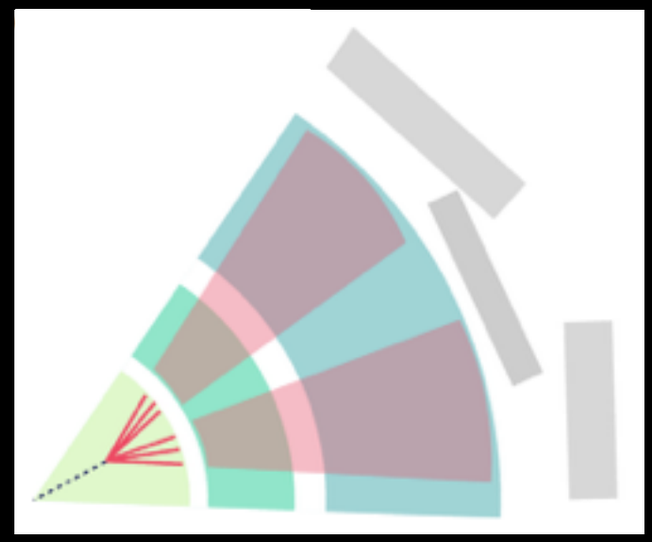
Displaced hadronic jets



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



Inner detector...



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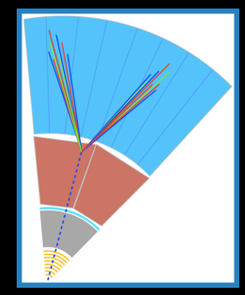

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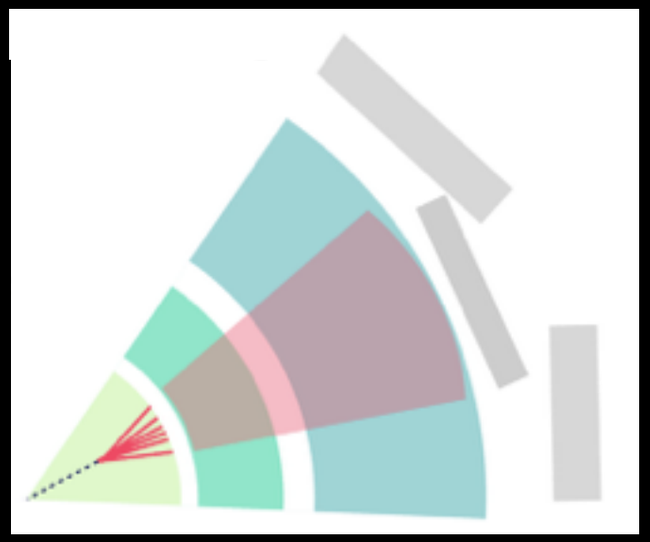
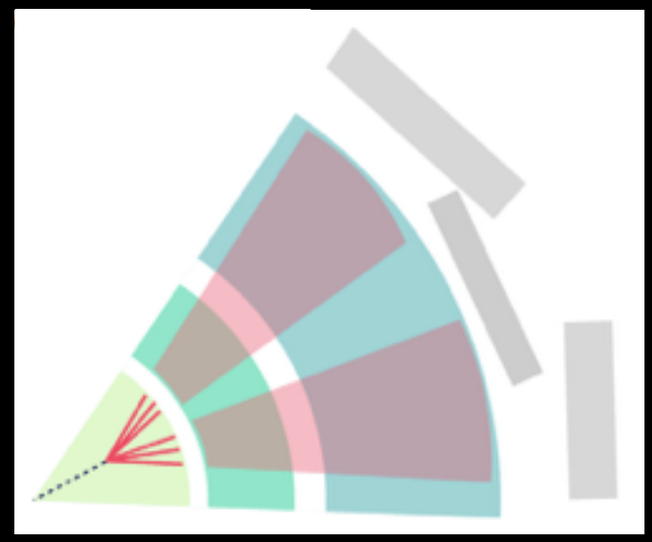


ATLAS approach —
single multi-track vertex

Inner detector...

CMS and LHCb —
displaced vertices with
jet pairs downstream



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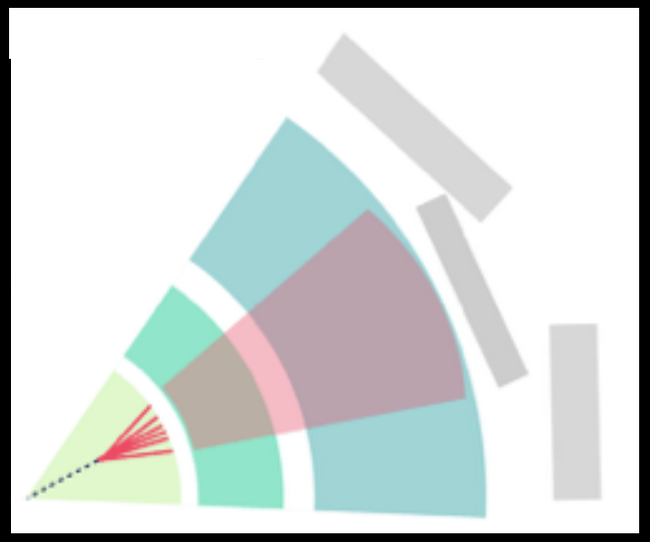

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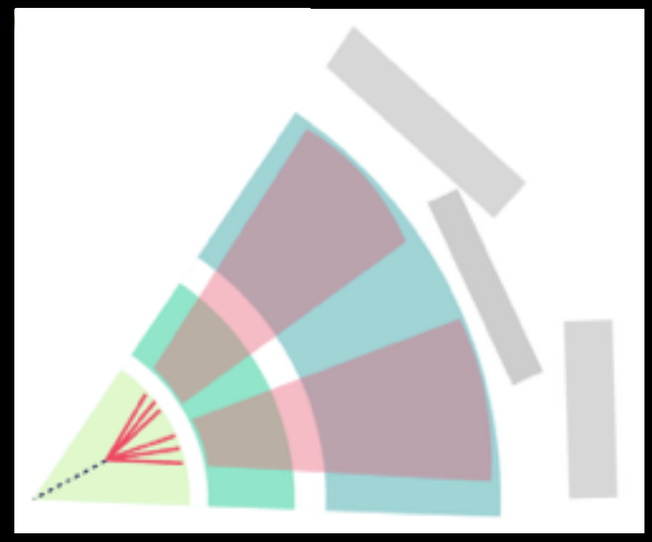

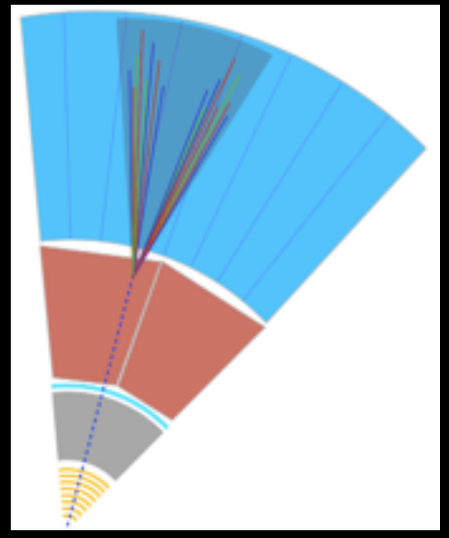

...or just before the hadronic calorimeter...

Displaced hadronic jets

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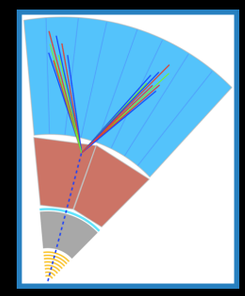

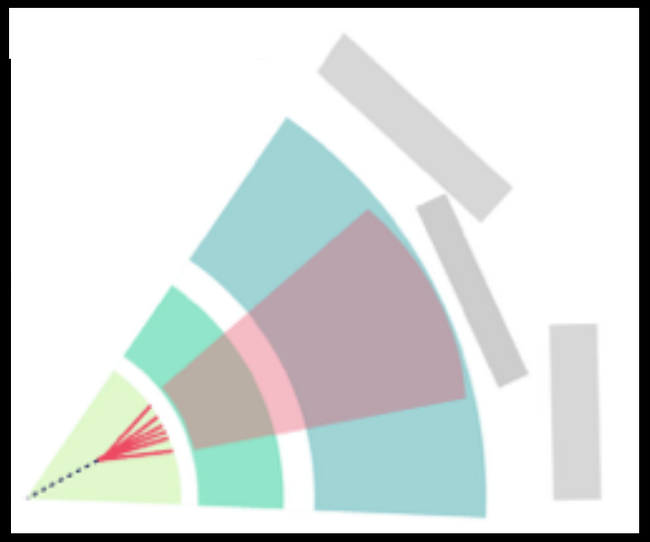

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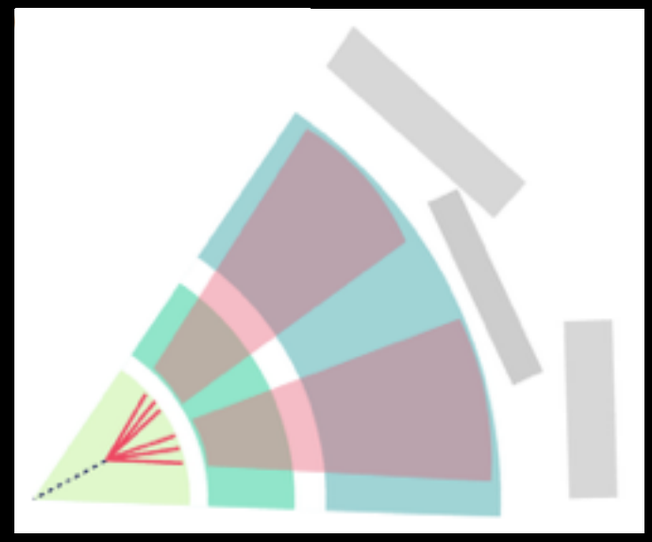
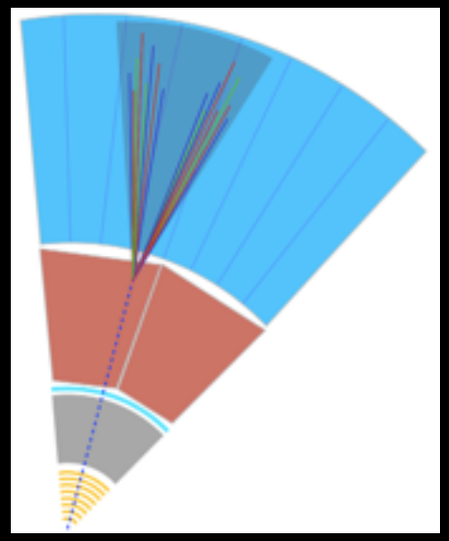
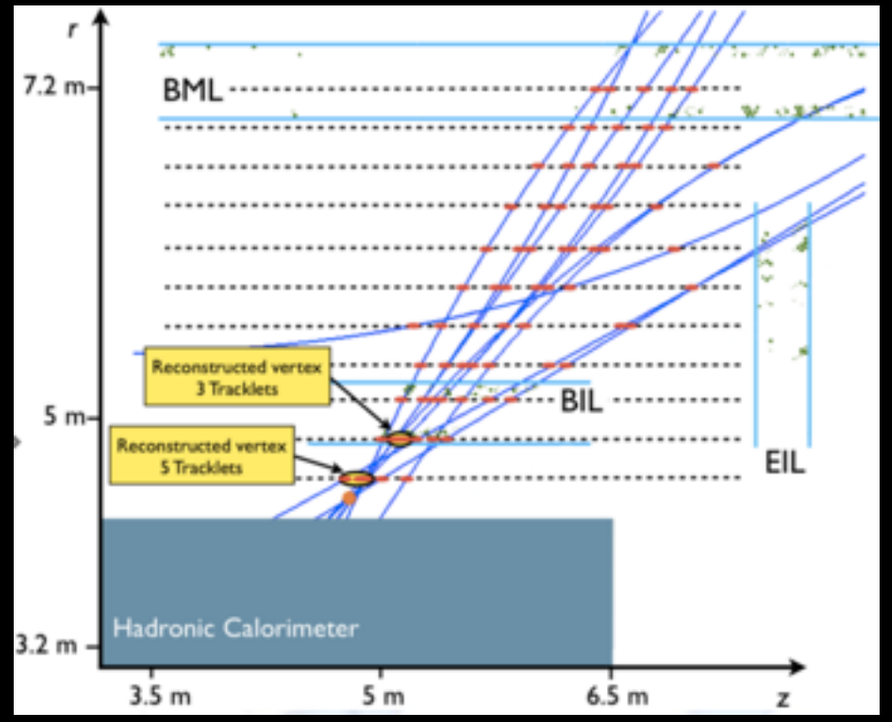




...or just before the hadronic calorimeter...

...or only in the MS



Displaced hadronic jets

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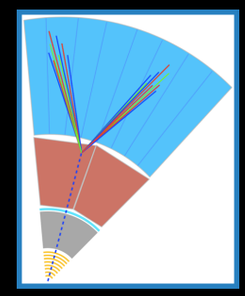

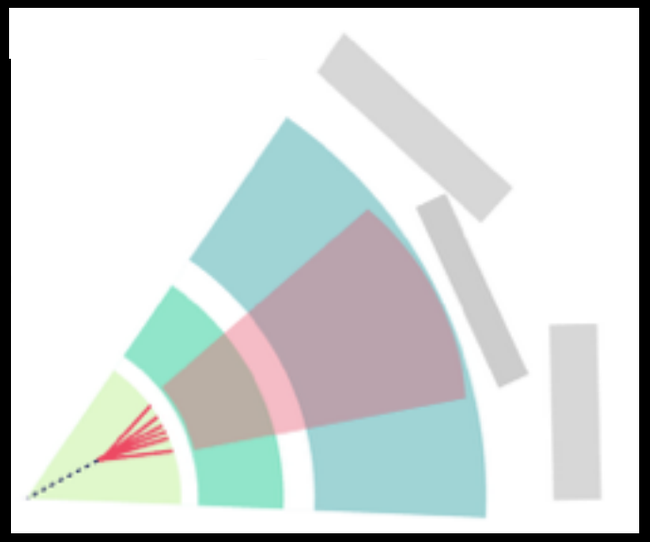

ATLAS approach — single multi-track vertex

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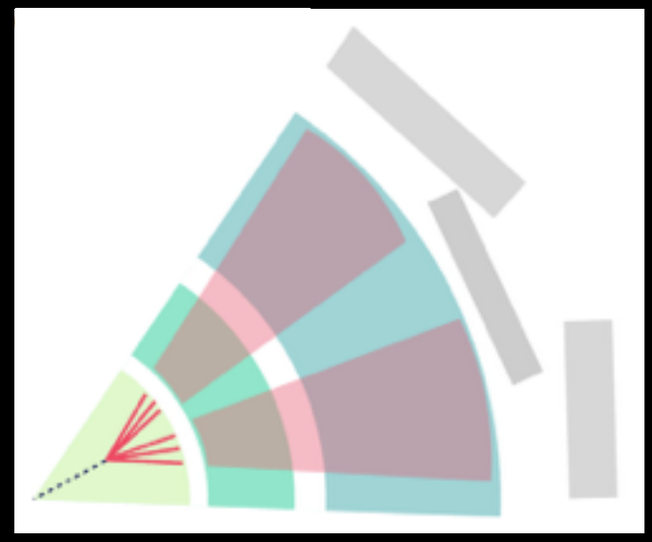
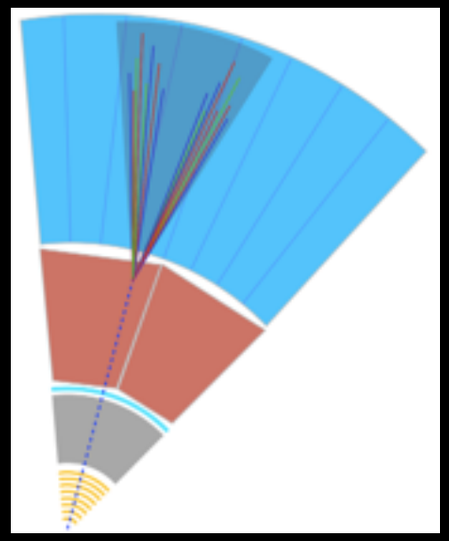
CMS and LHCb — displaced vertices with jet pairs downstream





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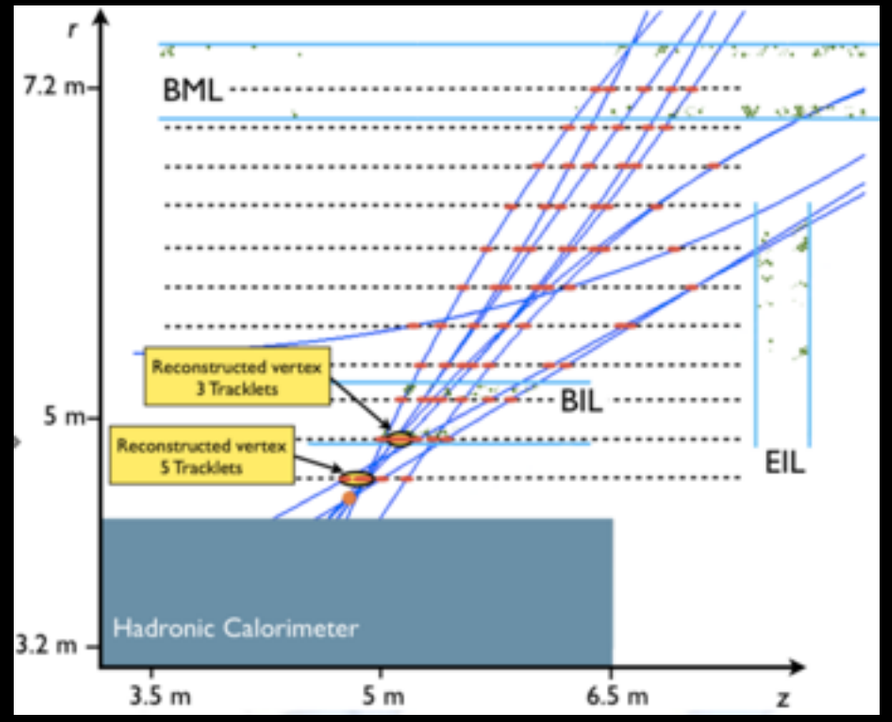
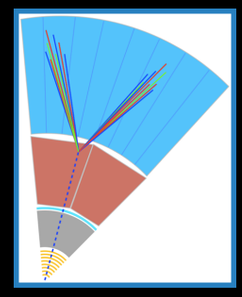
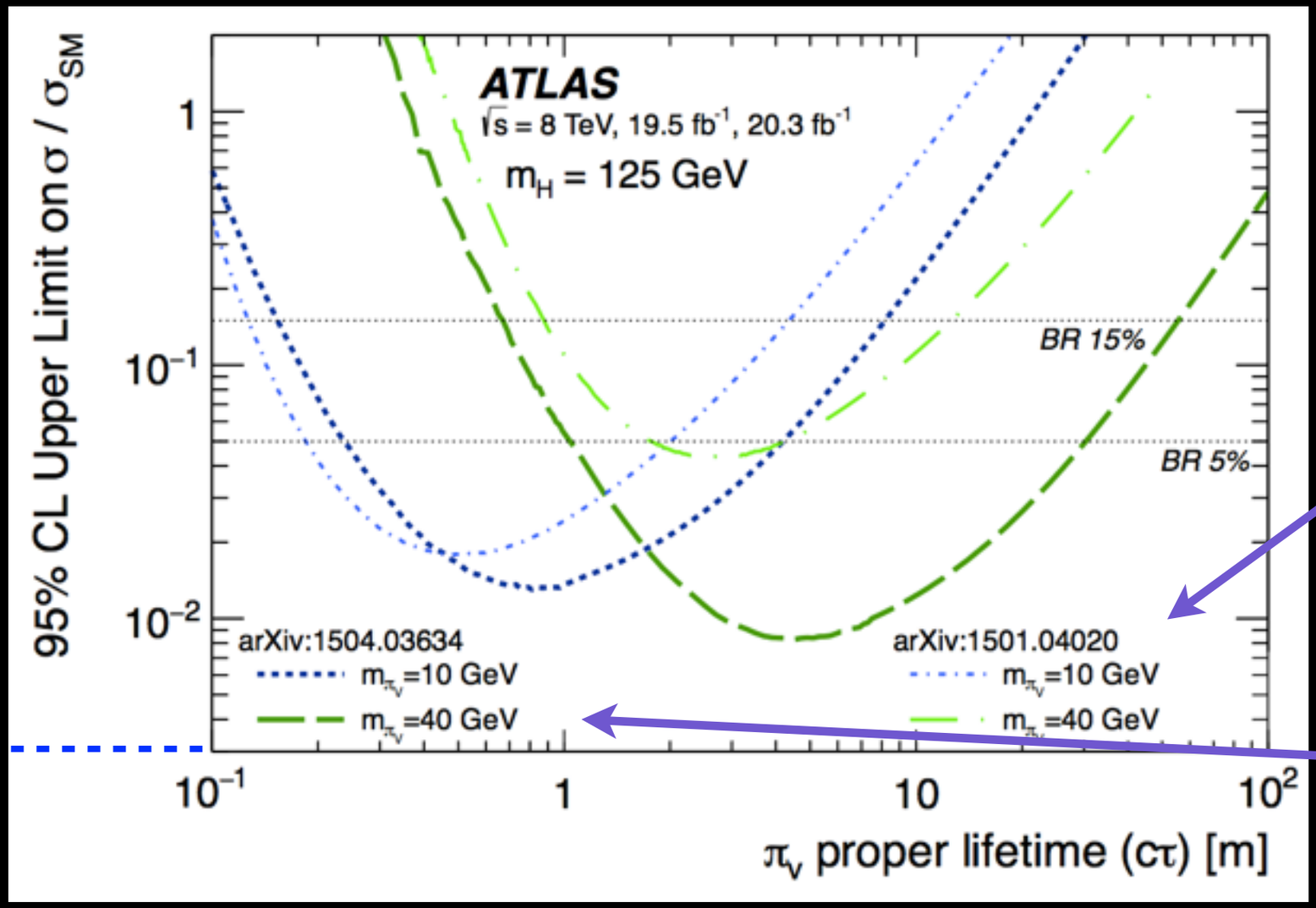


Each of these requires a different triggering and analysis strategy, and when you do all the painful work you can stitch the results together for h125 —> LLPs —> jets...

h125 —> displaced hadronic jets





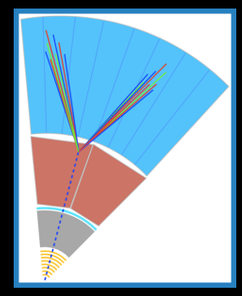
Just-before-HCal search

ID/MS search

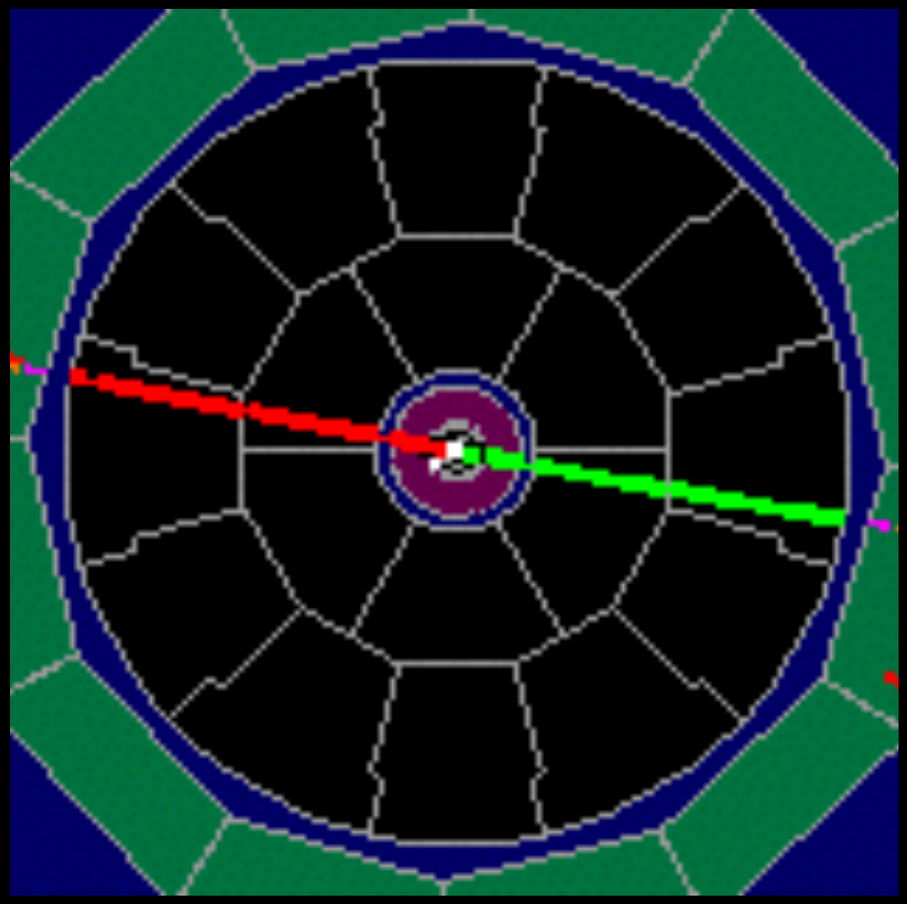
If the CEPC detector can reconstruct displaced vertices at ~10μm, this is a complete game-changer for h125 —> LLPs —> SM

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

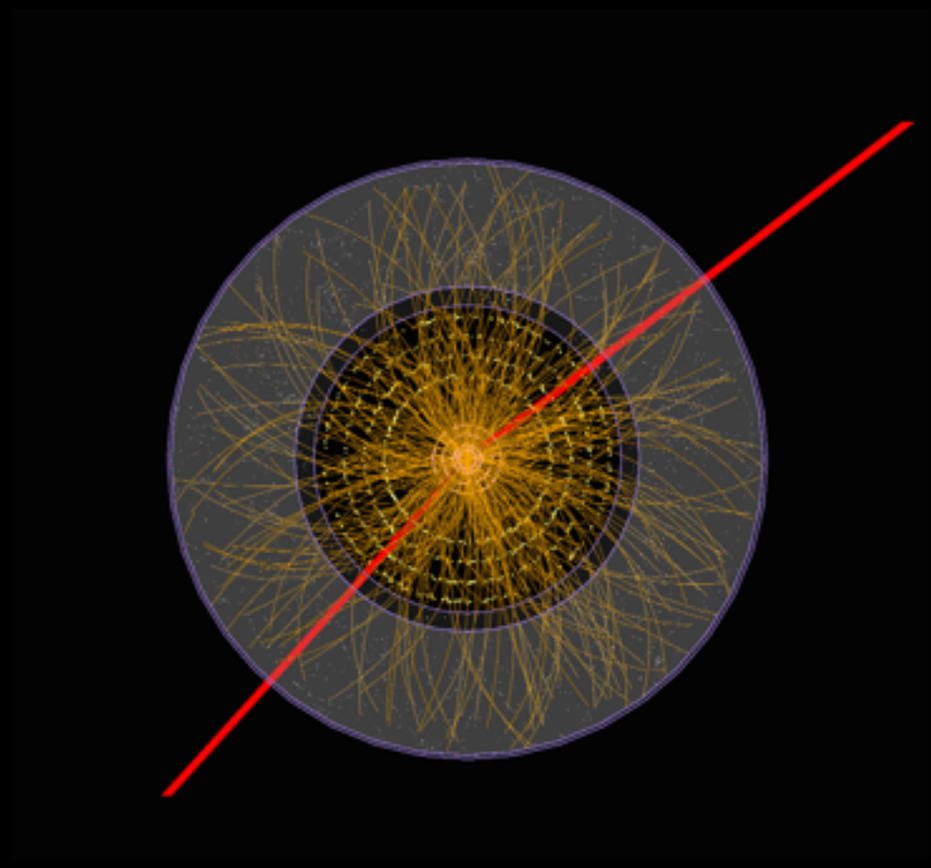
LLP searches at future e+e- machines like CEPC



Lepton collisions are beautifully clean!



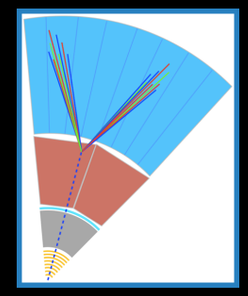
Z —> μμ at ALEPH



Z —> μμ at ATLAS

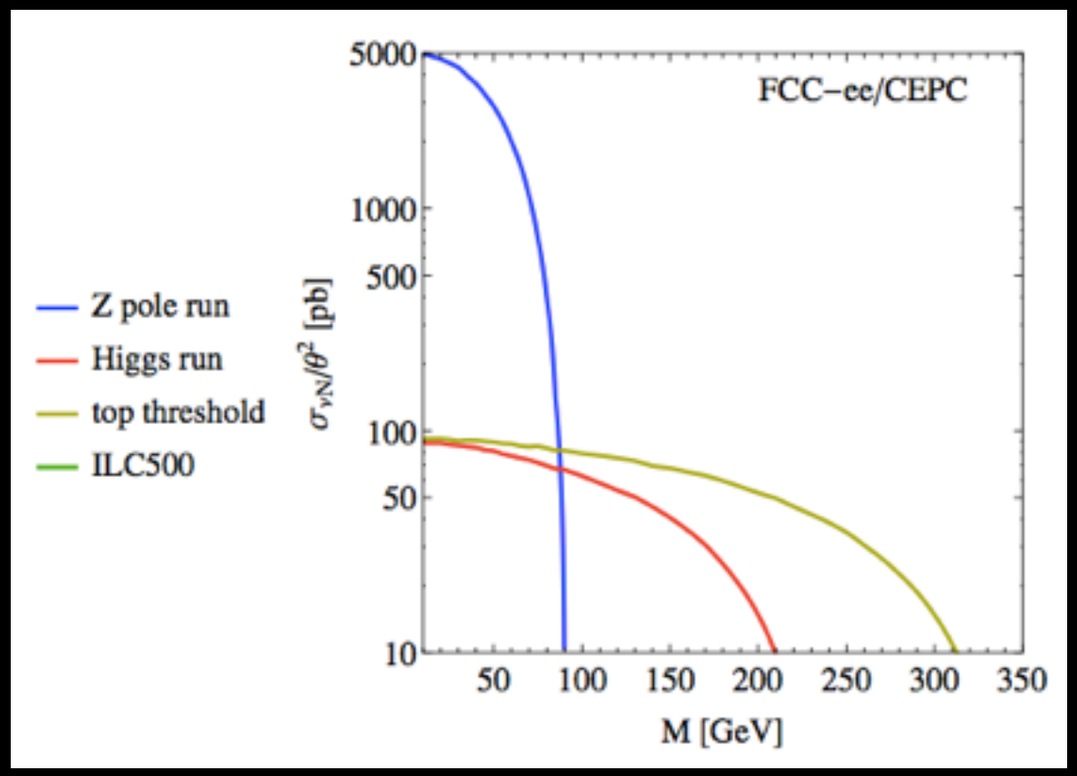
- Pileup not an issue — triggering straightforward
- Have full four-vector of initial state e+e- —> precision secondary vertexing
- Reconstruction of secondary vertices much closer to interaction point possible —> can push to lower lifetimes: ~10 μm?

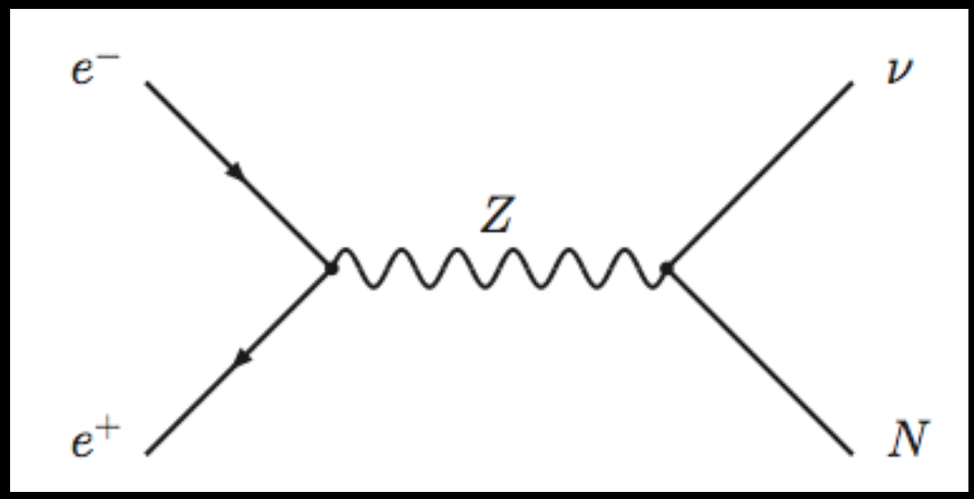
Very small displacements at a future e+e- machine



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

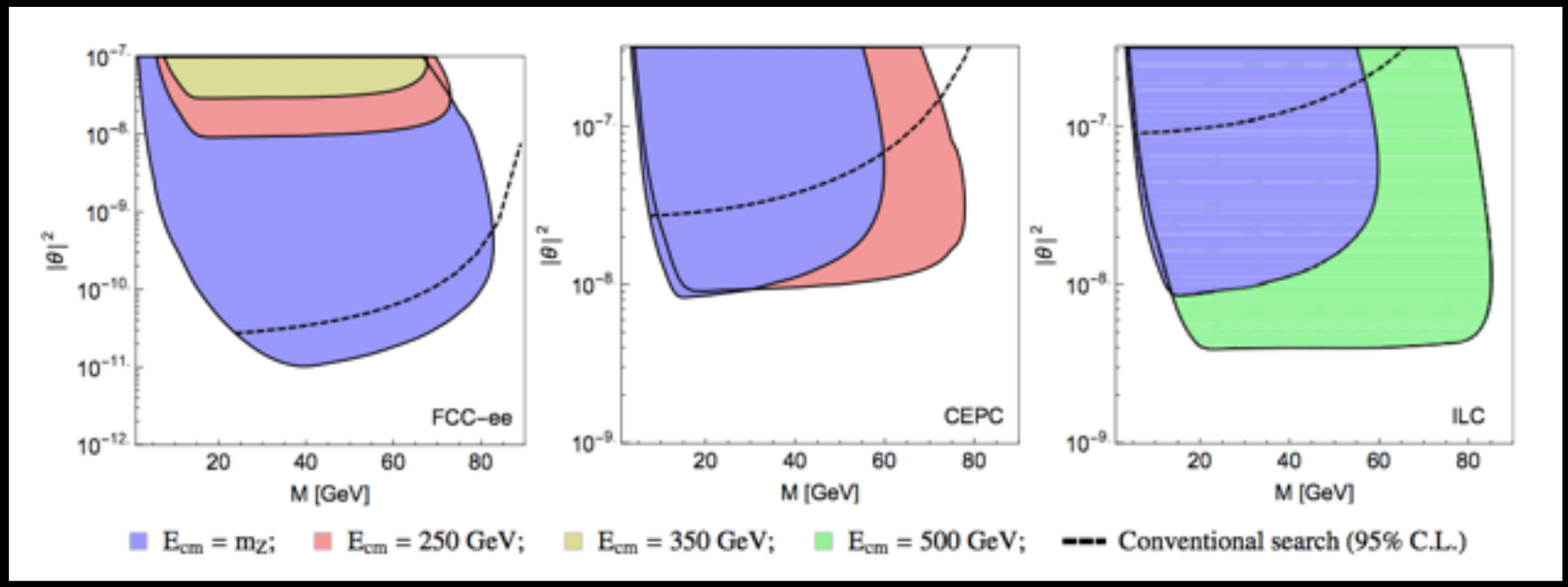
- Long-lived heavy (sterile) neutrinos with displaced vertices
- Uses ILC SiD as benchmark detector



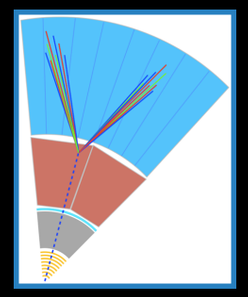


CEPC+SiD-type detector has excellent coverage at higher N masses at a Higgs-threshold run

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



LLP searches in general at future machines

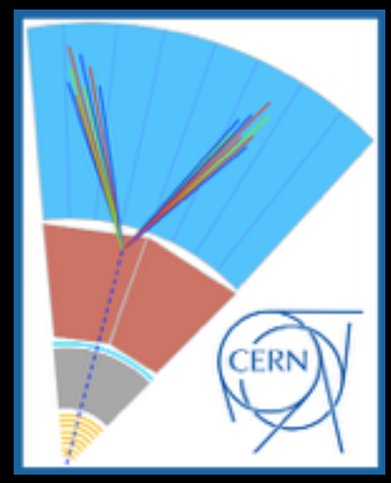


Most of the thought for future LLP searches (for all the classes of models we consider) has gone into future circular hadron colliders

- FCC-hh plans for higher √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 the biggest place where LLP discoveries could be hiding in 5/ab at the CEPC is in that <5% of the Higgs BR where h —> very-short-lifetime LLPs
- Pileup always challenging at hadron machines, and for low-mass BSM LLPs with very small lifetimes a lepton collider wins
- Some studies and thoughts already, but the main message:

LLPs at CEPC need more study!

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, etc., enthusiasts

Recent workshops —>

https://indico.cern.ch/e/LHC_LLP_April_2017

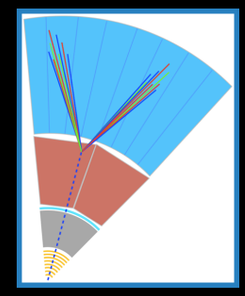
https://indico.cern.ch/e/LHC_LLP_October_2017

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?

Currently producing a community white paper (to appear end of 2017 or beginning of 2018) always focused on detector signatures that can arise from generic LLP decays with 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

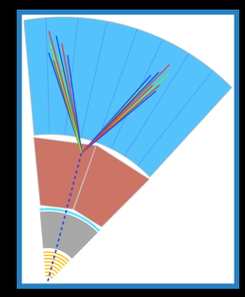
Production \ Decay	$\gamma\gamma$(+inv.)	γ + inv.	jj(+inv.)	$jj\ell$	$\ell^+\ell^-$(+inv.)	$\ell^+_\alpha\ell^-_{\beta\neq\alpha}$(+inv.)
DPP: sneutrino pair		SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q} \to jX$ or gluino pair $\tilde{g} \to jjX$		SUSY	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell} \to \ell X$ or chargino pair, $\tilde{\chi} \to WX$		SUSY	SUSY	SUSY	SUSY	SUSY
HIG: $h \to XX$ or $\to XX$ + inv.	Higgs, DM*		Higgs, DM*		Higgs, DM*	
HIG: $h \to X$ + inv.	DM*		DM*		DM*	
ZP: $Z(Z') \to XX$ or $\to XX$ + inv.	Z', DM*		Z', DM*		Z', DM*	
ZP: $Z(Z') \to X$ + inv.	DM		DM		DM	
CC: $W(W') \to \ell X$			RHν*	RHν	RHν*	RHν*

Table 2.1: **Simplified model channels for neutral LLPs.** The LLP is indicated by X.

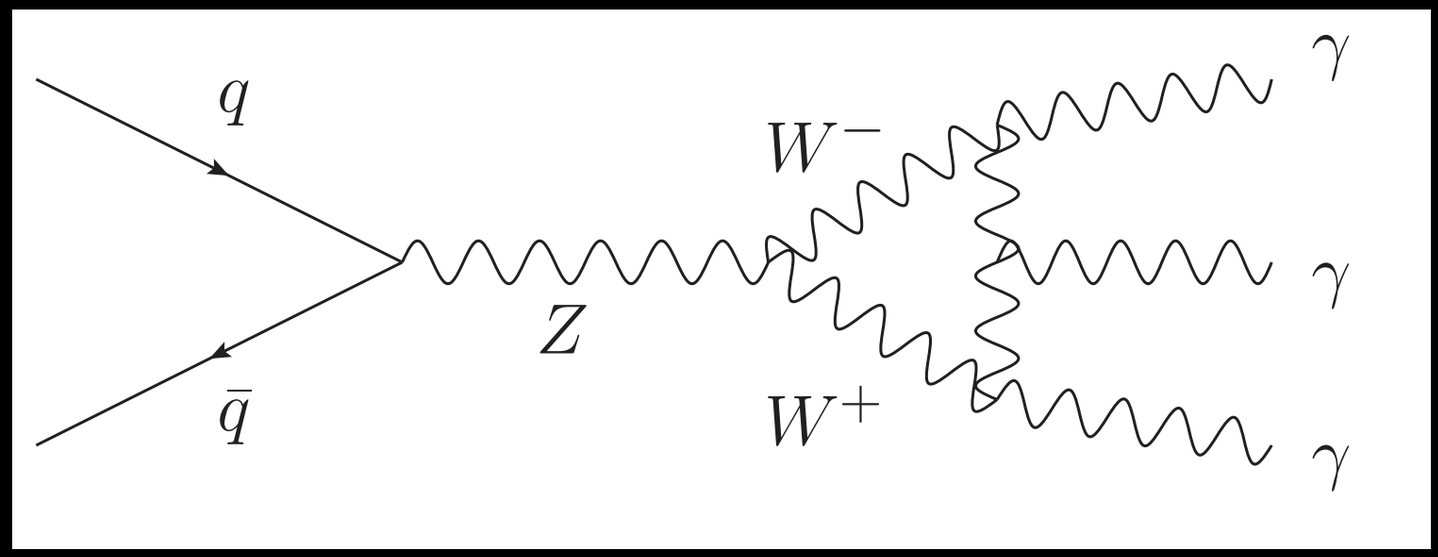
Find the places where CEPC / FCC-ee win over hadron colliders

- Hadrophobic LLPs?
- What are the production cross sections for dark QCD signatures like emerging jets and SUEP (soft, unclustered energy patterns)?
- Very light, very soft 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?

Other ideas — very rare processes within reach: Z —> 3LLP



Z —> $\gamma^{(d)}\gamma^{(d)}\gamma^{(d)}$



ATLAS result at 8 TeV: World's best limit on SM Z to three photons

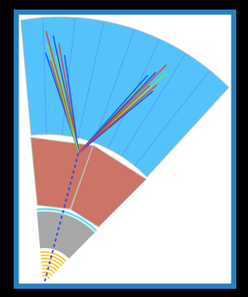
arXiv:1509.05051

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

- 2.2 (2.0)e-6
  (almost 5 times better than LEP)
- SM prediction: 5e-10

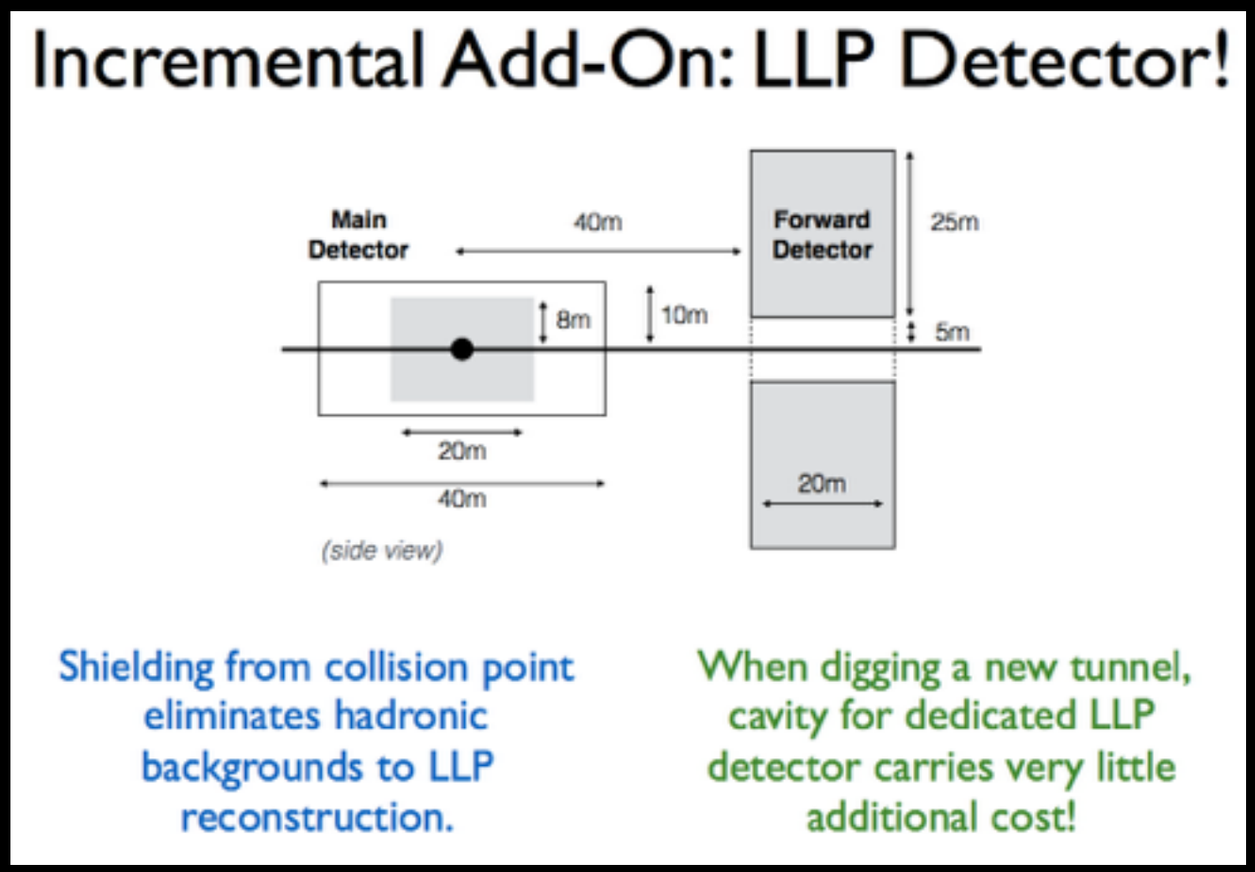
With 10^{12} Z bosons at CEPC could see SM process and hope to probe photon / long-lived dark photon mixing

More general open questions about LLP searches



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

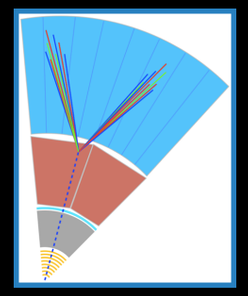


D. Curtin

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

CEPC should incorporate these concepts from the beginning!

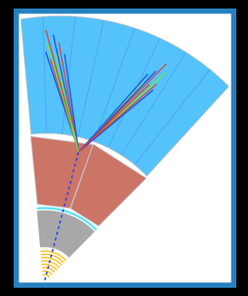
LLP searches at CEPC



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

- Preliminary thoughts from an LHC LLP-hunter:
  - CEPC is a lepton-collider Higgs factory with 5/ab
  - This is likely excellent for classes of models that give rise to LLPs with very-short lifetimes where pileup at hadron colliders is problematic
  - Benchmark scenario here:
    - h125 —> very short lifetime LLPs —> hadronic jets
      - This *must* be a key component of the research program
- Fully take advantage of clean (no pileup) collisions
- More studies needed, for h125 —> LLPs and the other classes of models that yield rich signatures
- Some ILC studies for LLPs have been done over the years, and can learn much from them
- Potential for a study group offshoot from the LHC LLP Community initiative: Stay tuned!

LLP searches at CEPC



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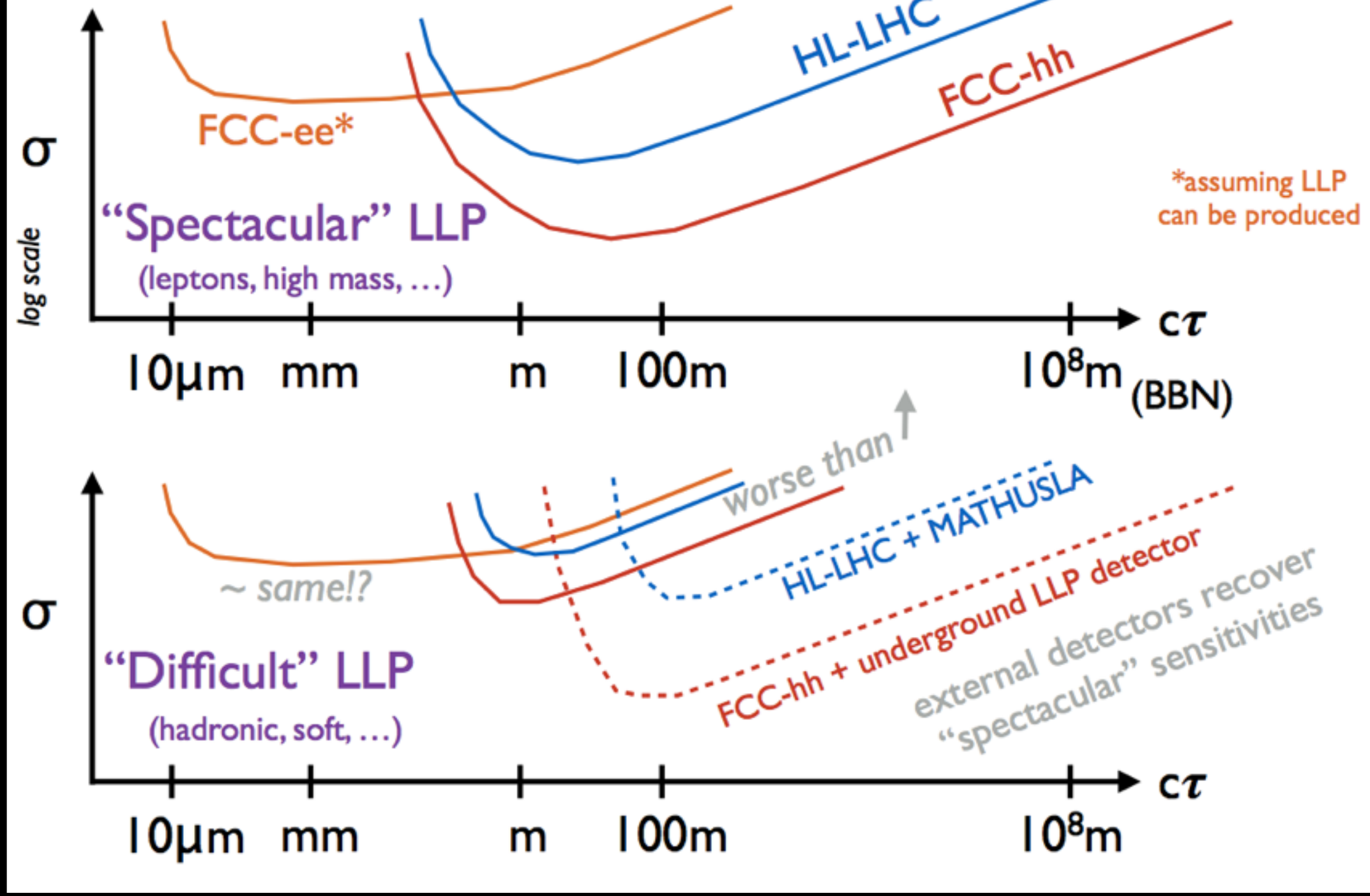
END

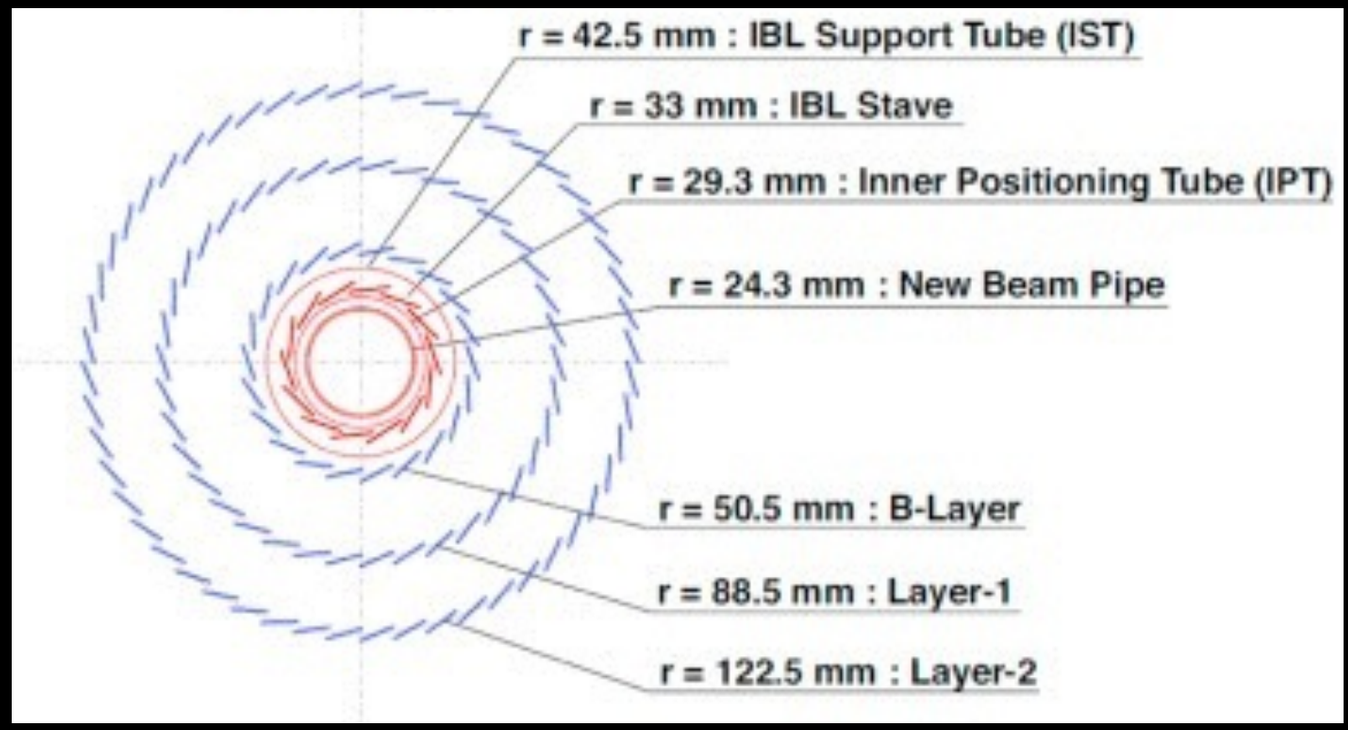
Reserve slides

★Cartoon★ of relative LLP sensitivities



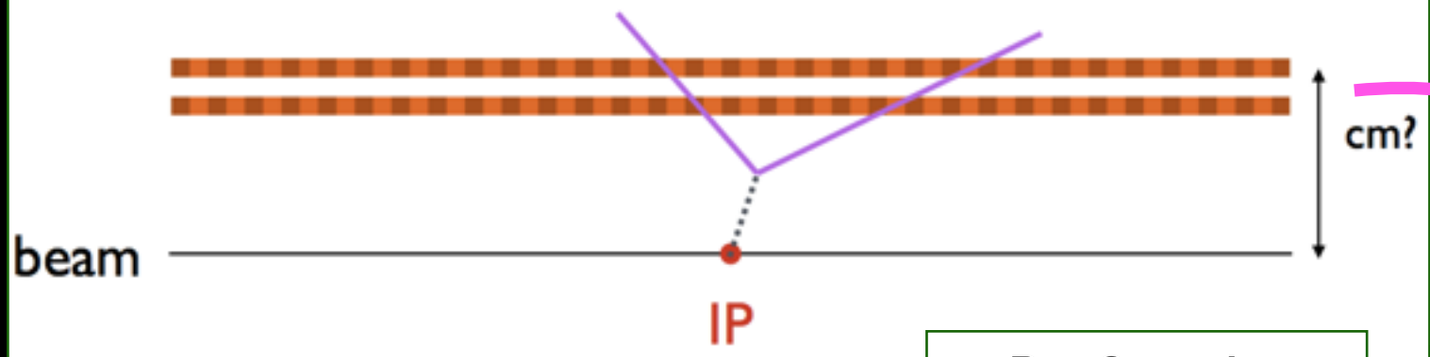
D. Curtin

Possible detector upgrades



Possible detector upgrades

What about triggering on very short decay lengths in tracker?



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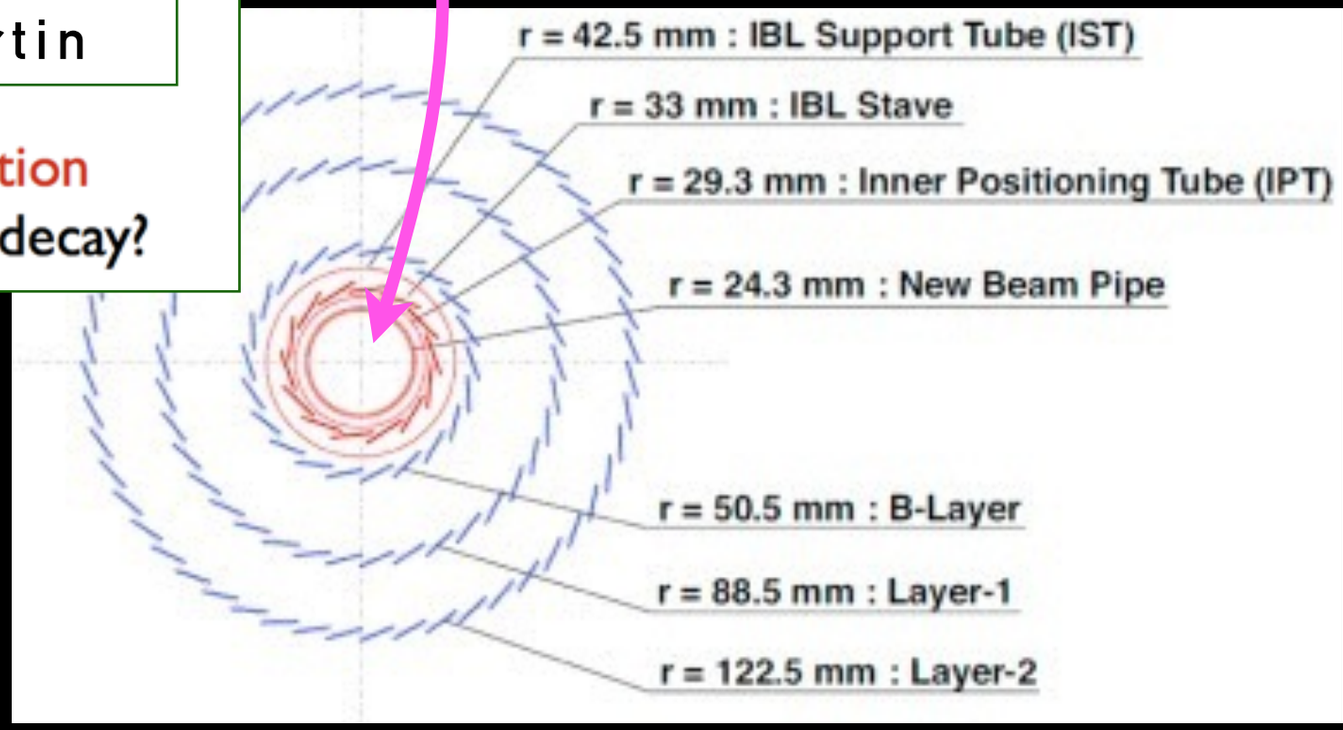
Some sort of tracklet-based DV reconstruction in the double-layer to trigger on possible LLP decay?



Possible detector upgrades

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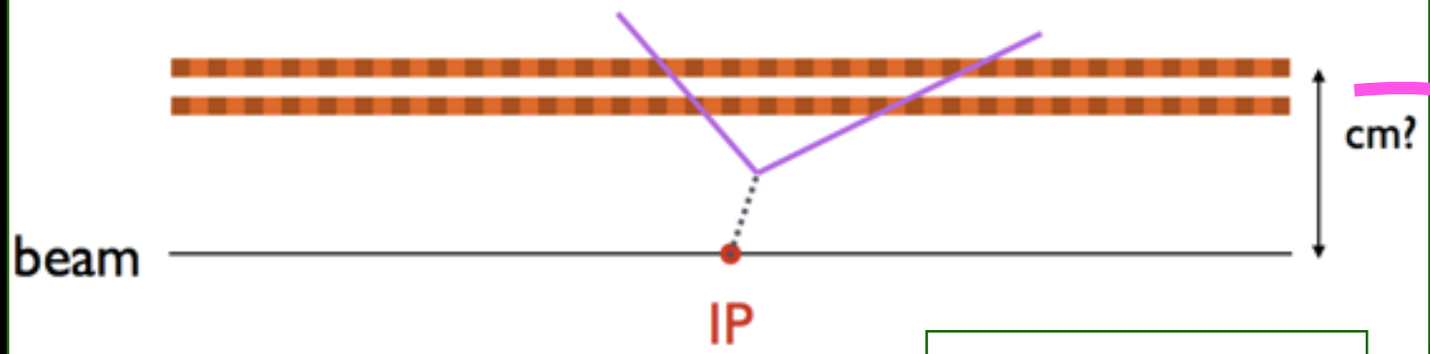
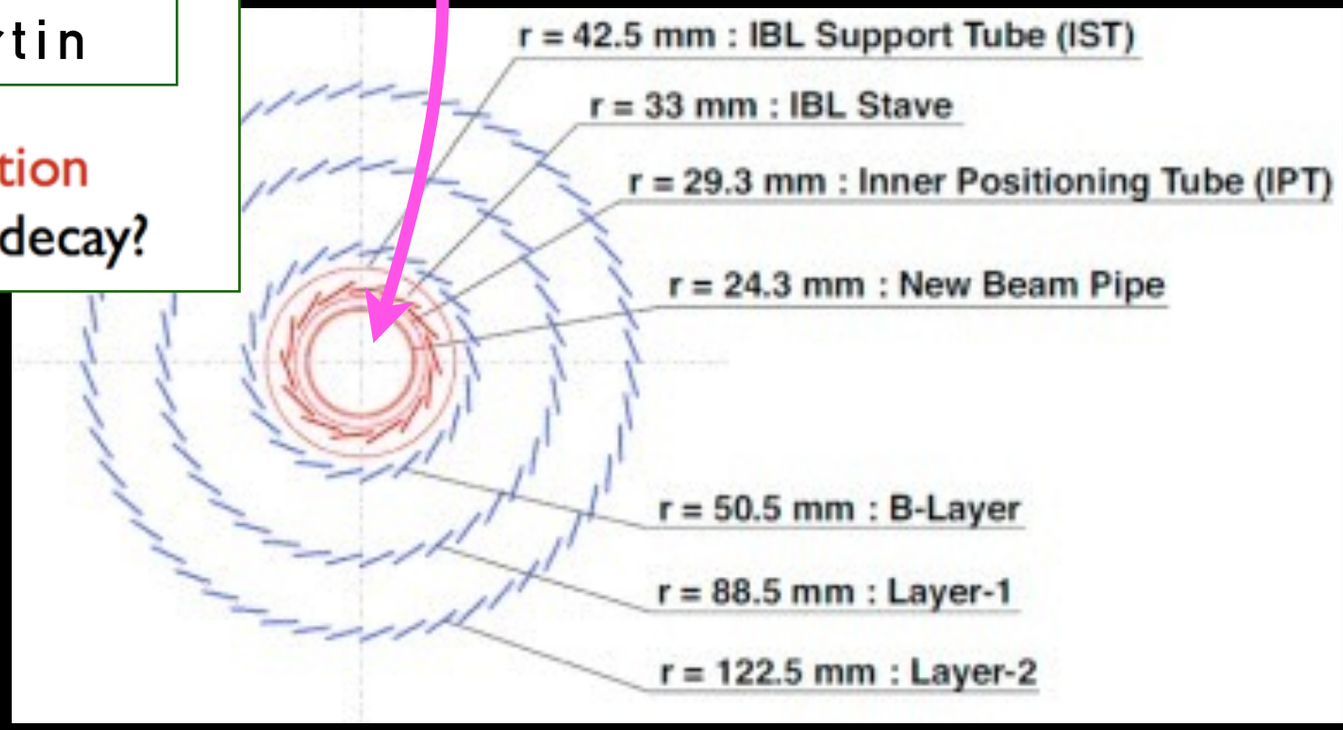


D. Curtin

Some sort of tracklet-based DV reconstruction in the double-layer to trigger on possible LLP decay?

Blue sky idea for ATLAS:

Simple high-resolution double-tracking layer inside the IBL



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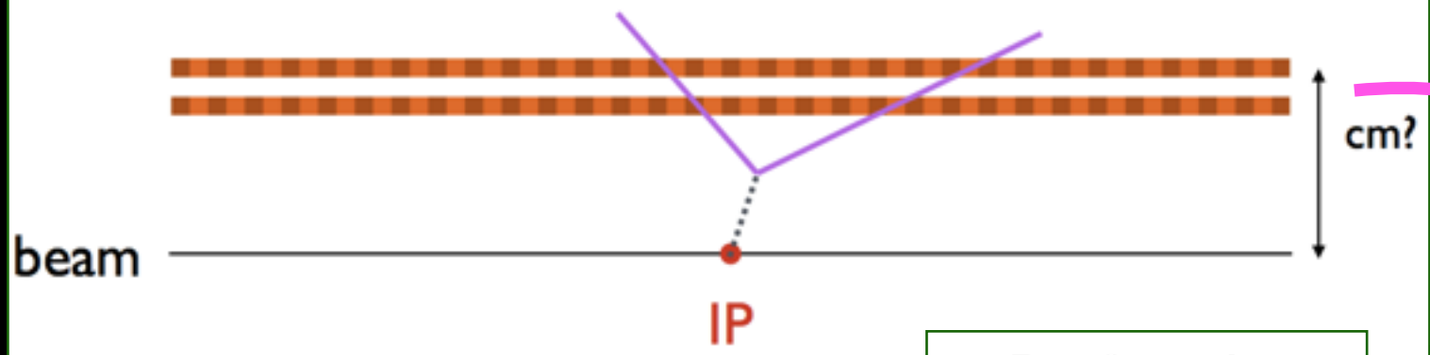

D. Curtin

Some sort of tracklet-based DV reconstruction in the double-layer to trigger on possible LLP decay?

- This would likely significantly improve our sensitivity to h125 decays to shorter-lifetime LLPs! But by how much?

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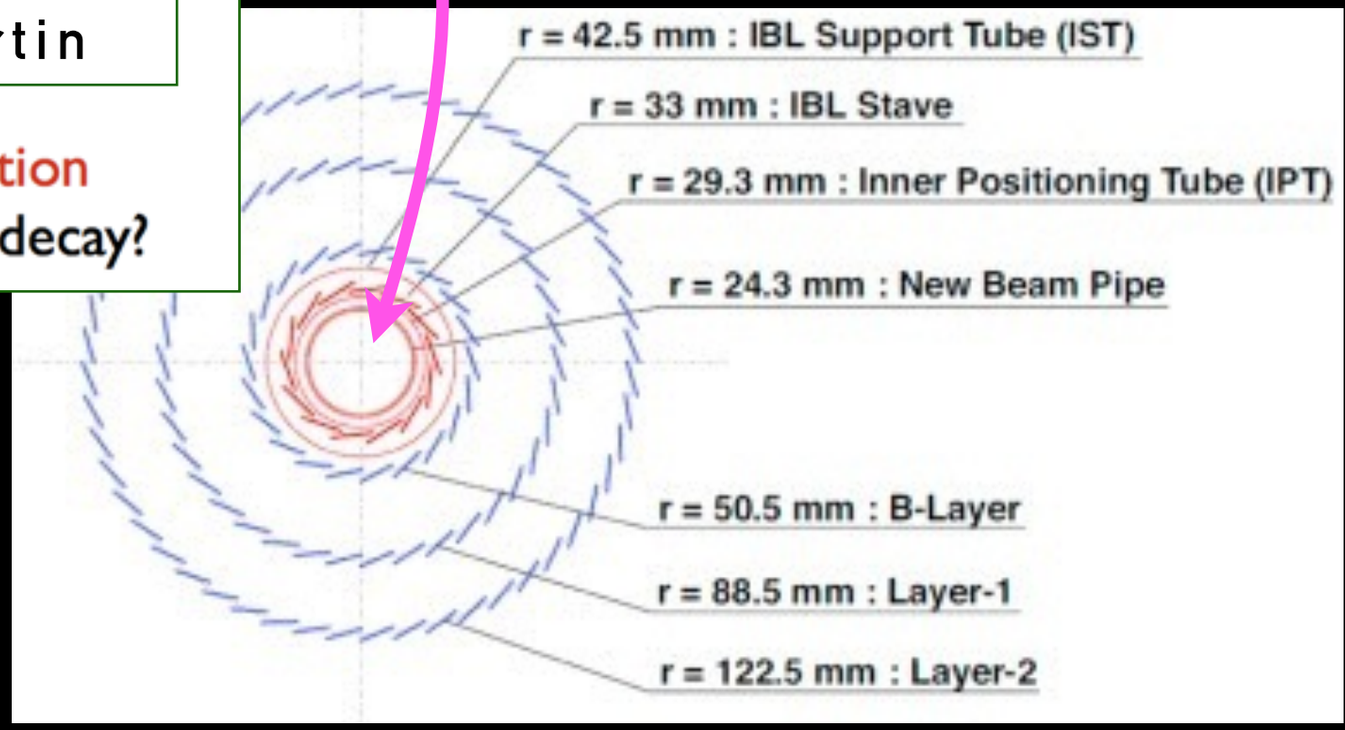

Possible detector upgrades

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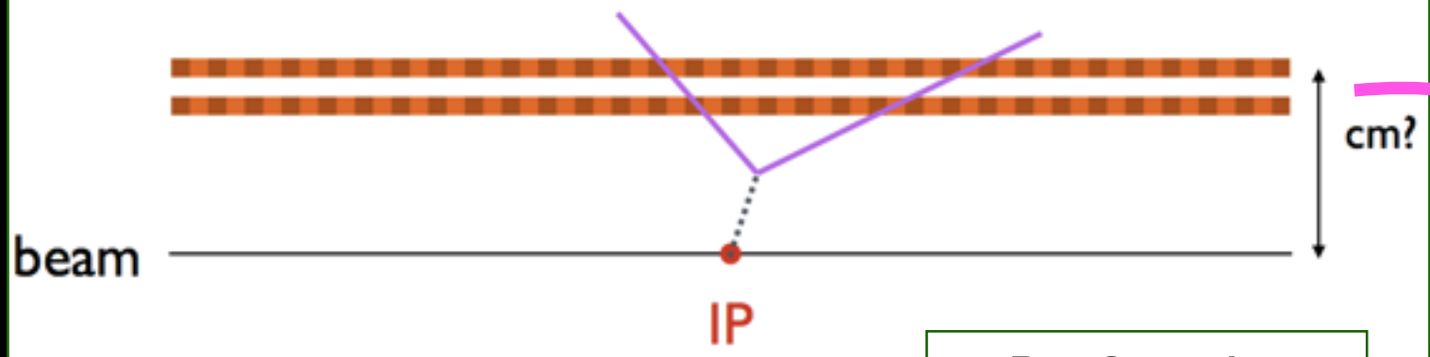

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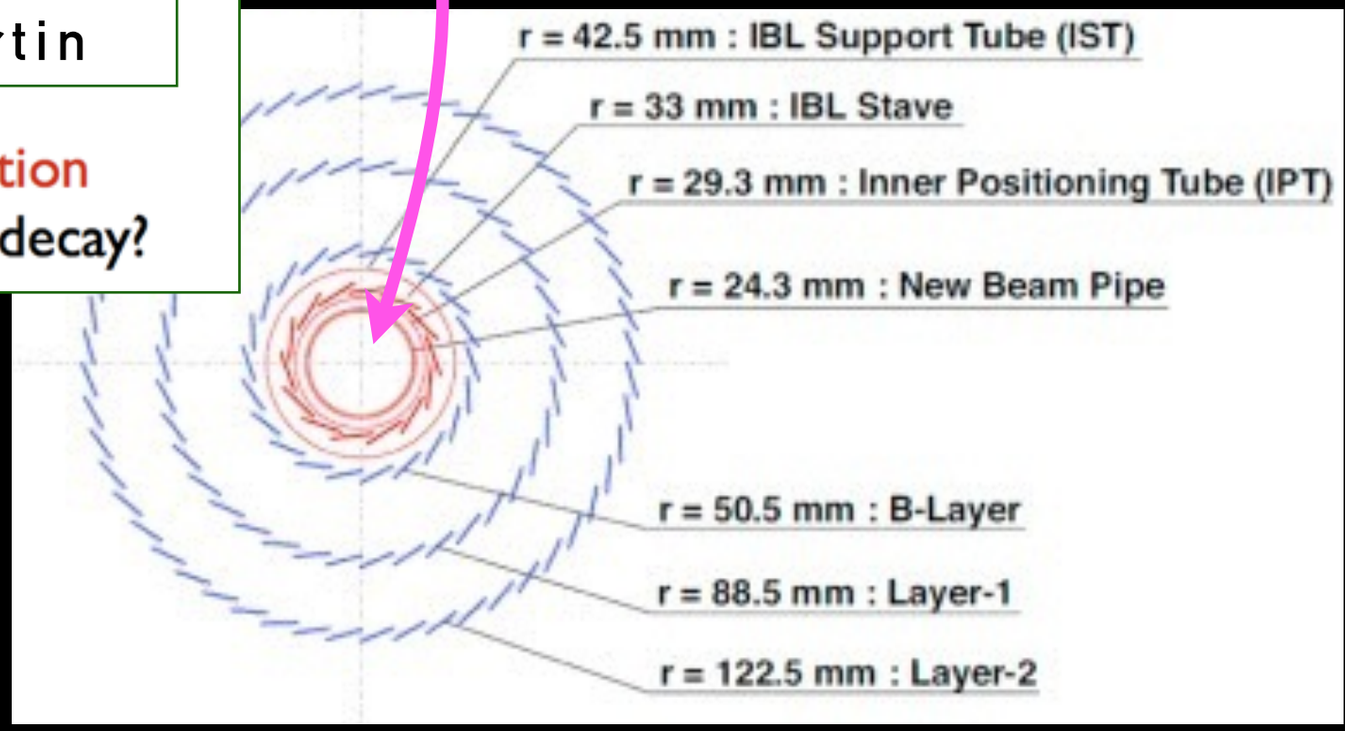
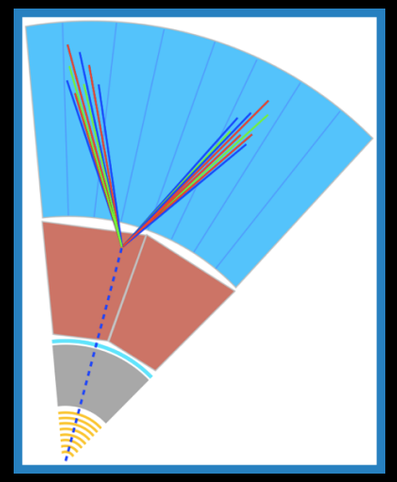


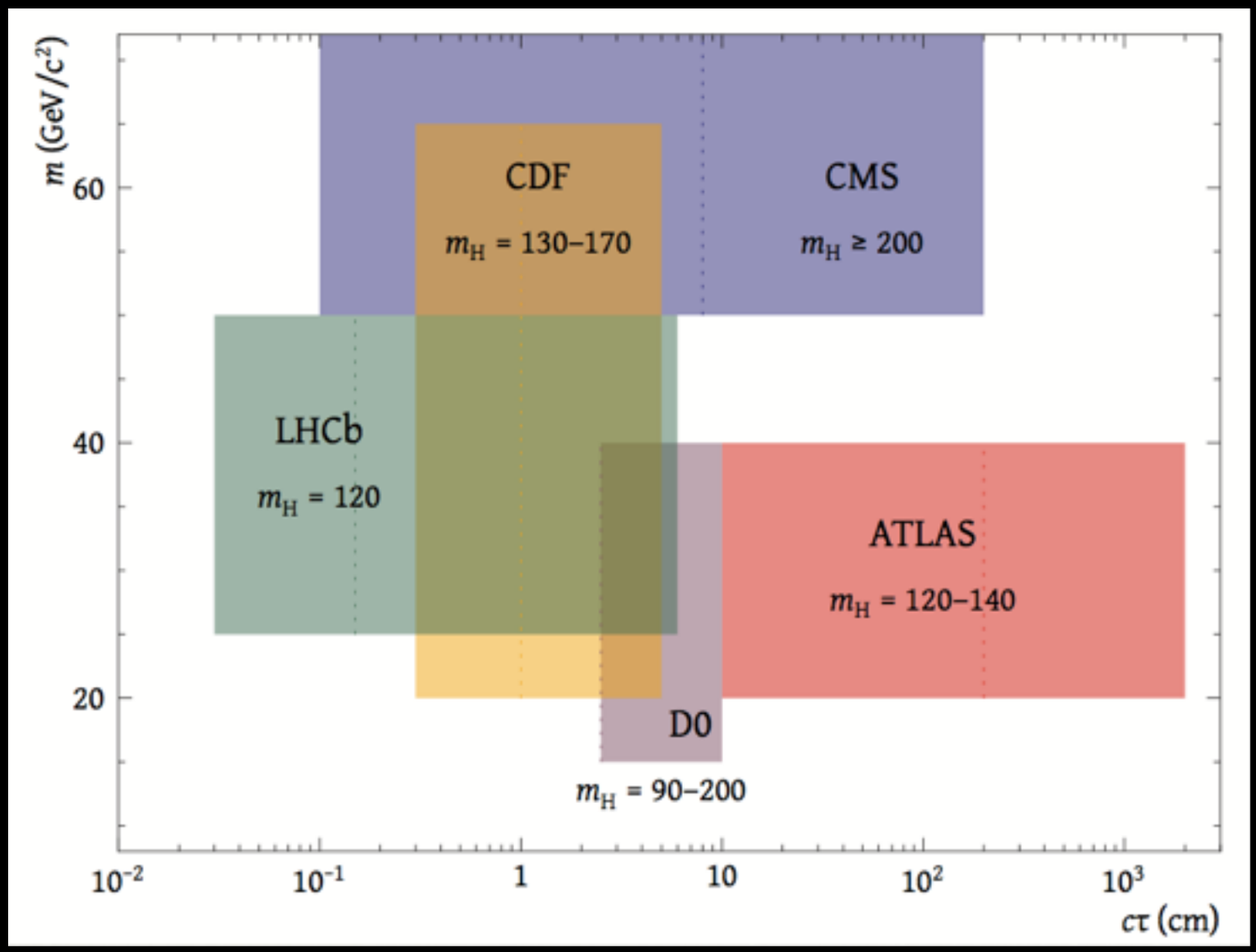
- This would likely significantly improve our sensitivity to h125 decays to shorter-lifetime LLPs! But by how much?

- Pileup at hadron colliders would likely make it useless!
- Would probably be incinerated by the beam!
- What about a purposely temporary next-to-beam tracking layer that would only survive a certain integrated luminosity and die?

BSM example: Hidden sector portals



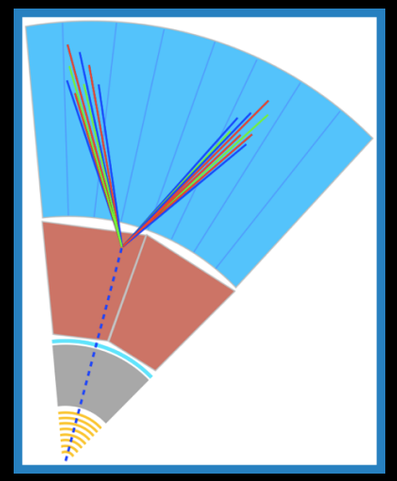
Higgs portal is also good for comparison among experiments



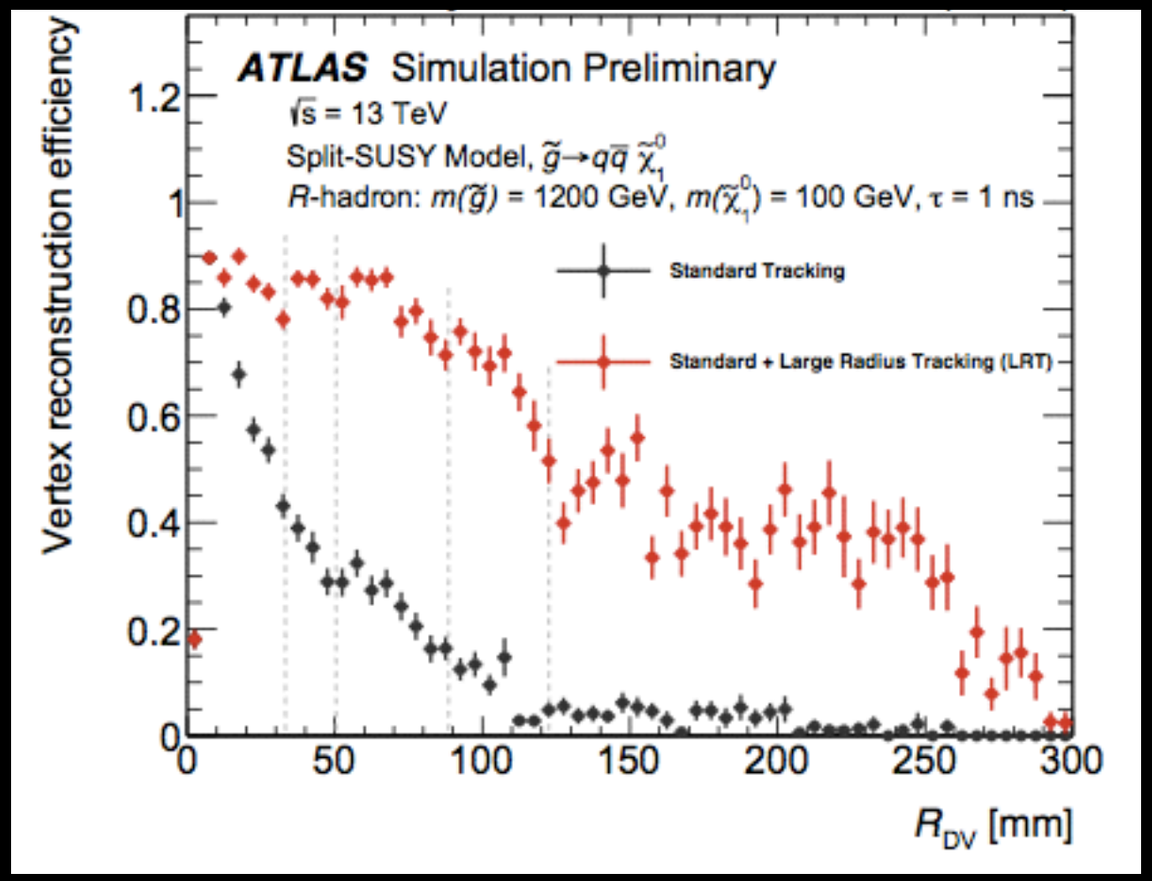
Pieter David thesis, LHCb, 2016

Displaced hadronic jets

The LLP can decay to jets in the inner tracker

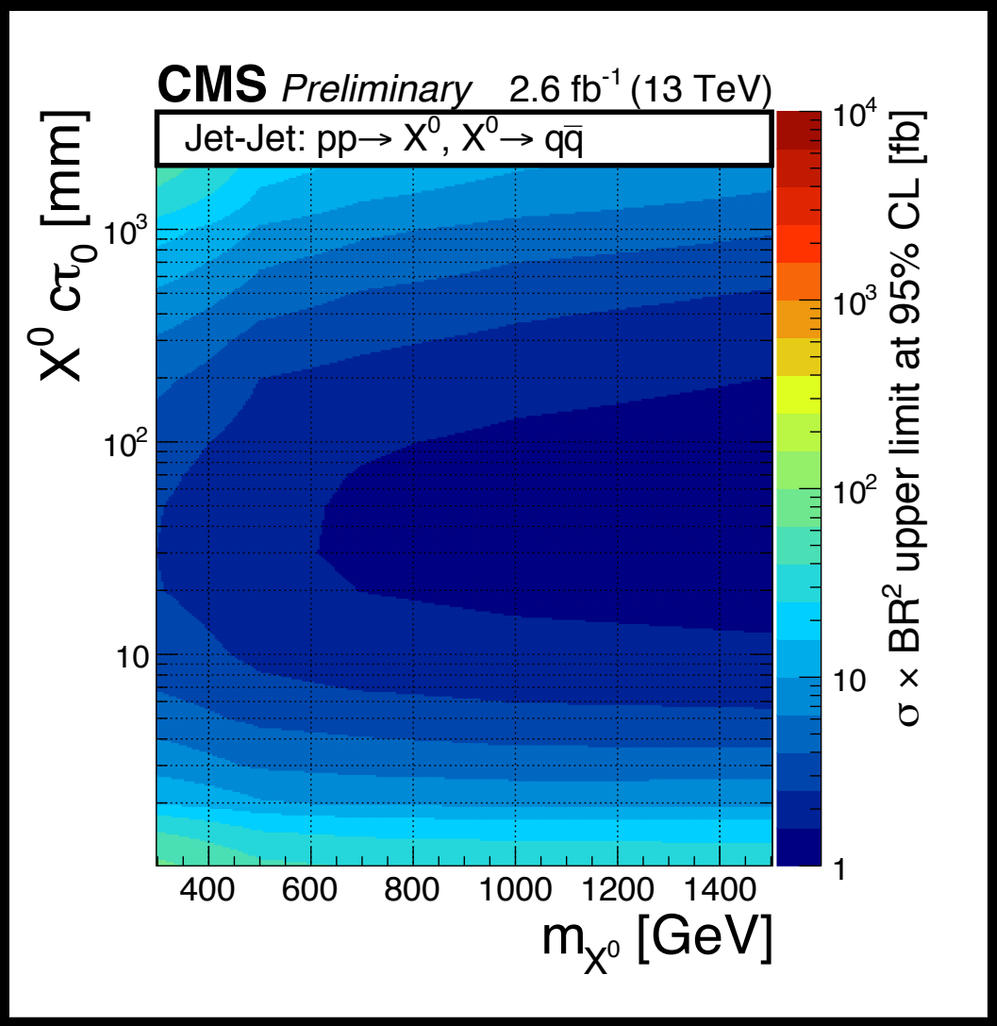


Phys. Rev. D 92, 072004 (2015)



Trigger on MET

CMS-PAS-EXO-16-003

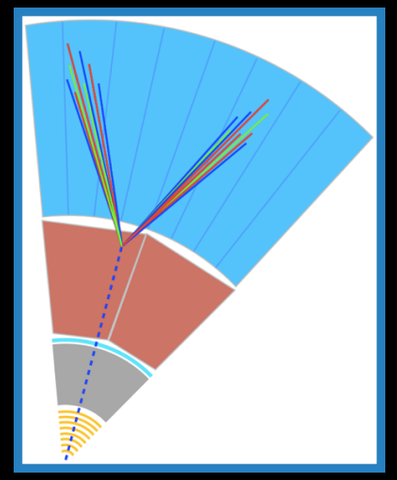


Specialized HT trigger with track veto

What we could do better

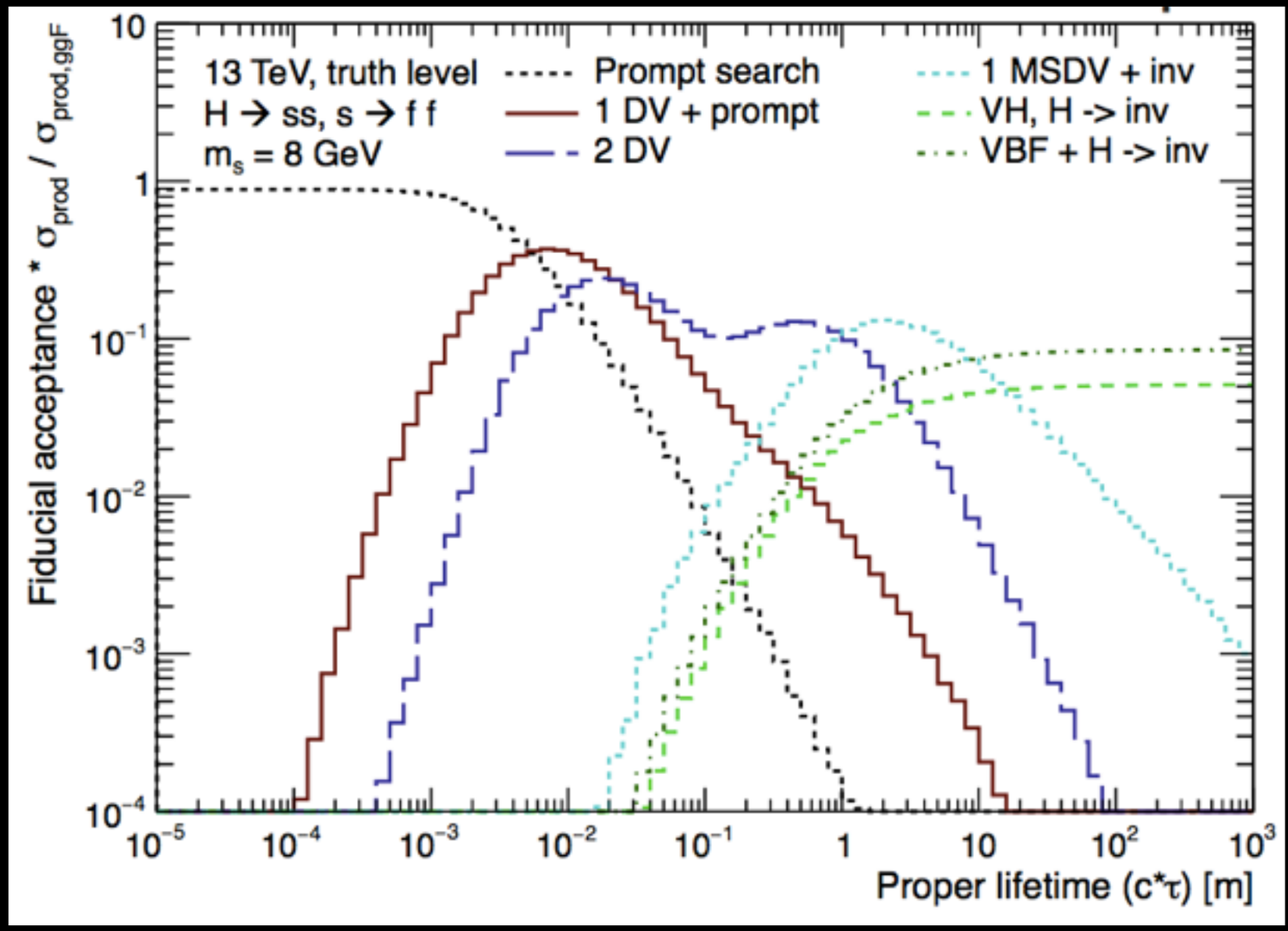
Where do our prompt and displaced searches overlap?

- Truth study by H. Russell for h125 decaying to fermions via a pair of 8 GeV LLPs at the 13 TeV LHC

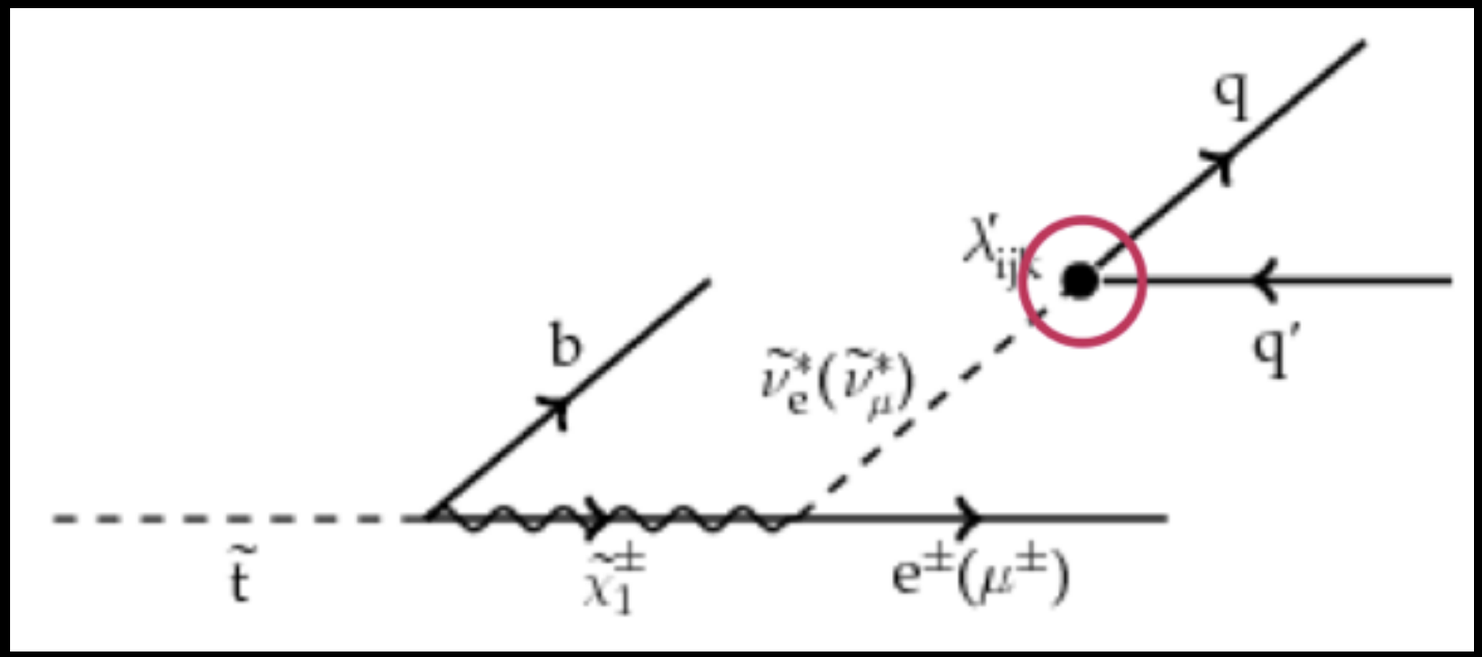


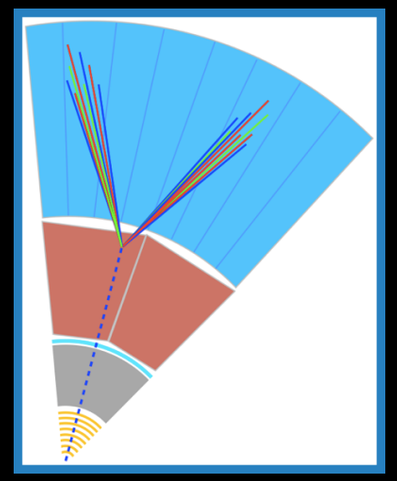
Probably our smaller-lifetime coverage isn't this good, but need to know the answer

Also need comprehensive studies of existing b-triggers for small-to-intermediate lifetime signatures, because...



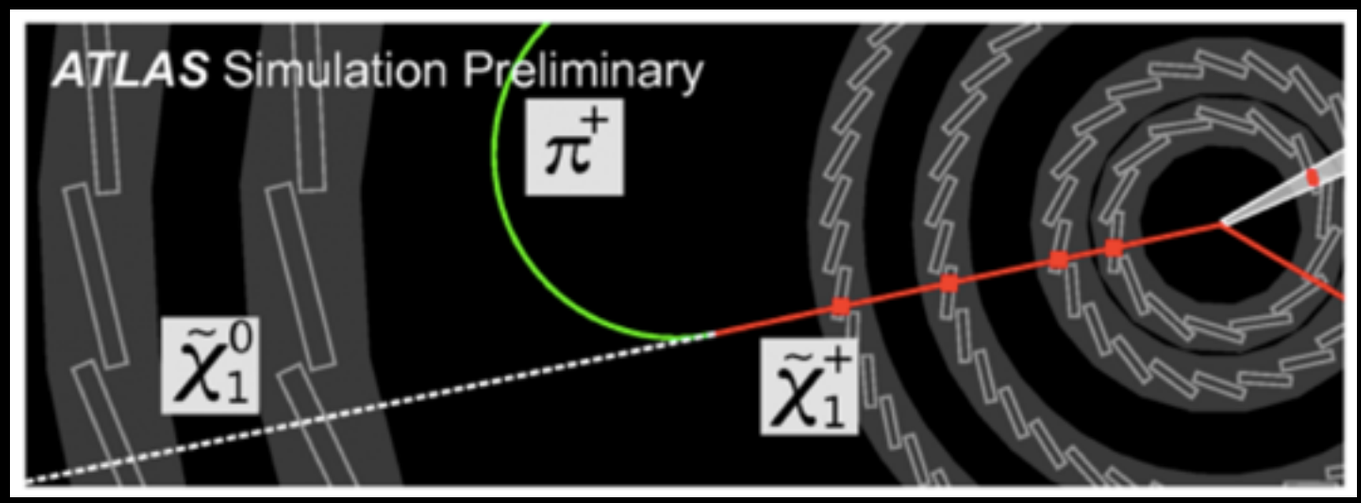
BSM example: RPV SUSY



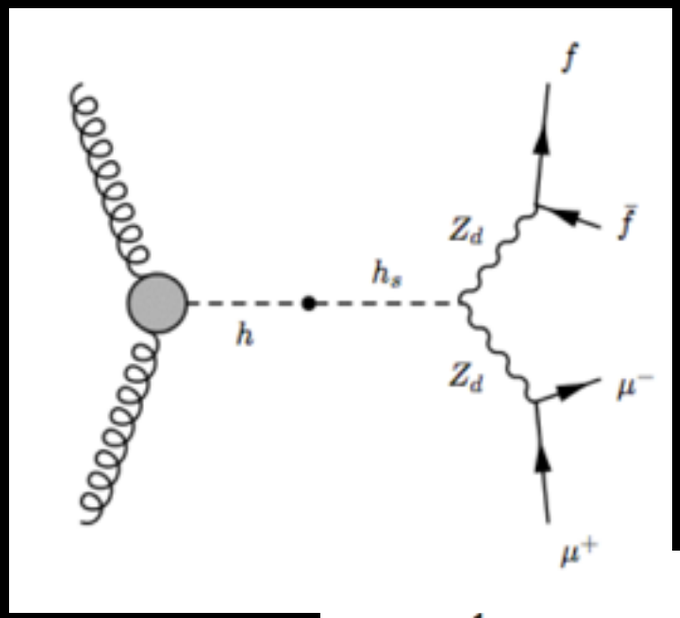


$|\lambda| < 10^{-8}$

Electroweak symmetry gives degeneracy of NLSP and LSP masses if little mixing between Higgsino / gauginos

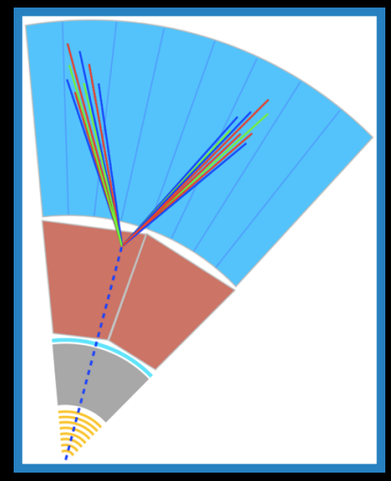


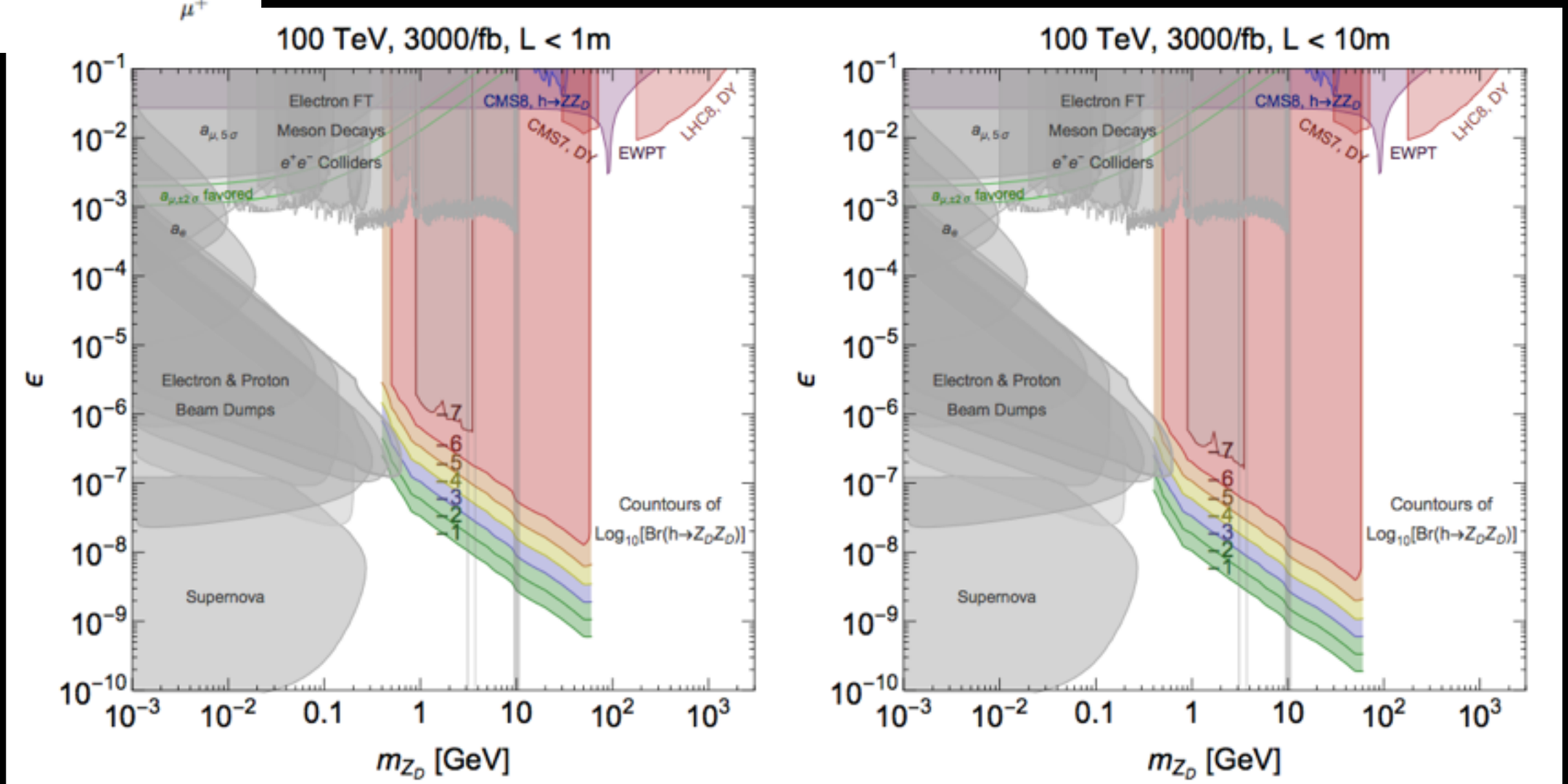
Displaced leptons at FCC-hh



Higgs mixing with dark Higgs and subsequent decay to long-lived Z_{dark} pairs

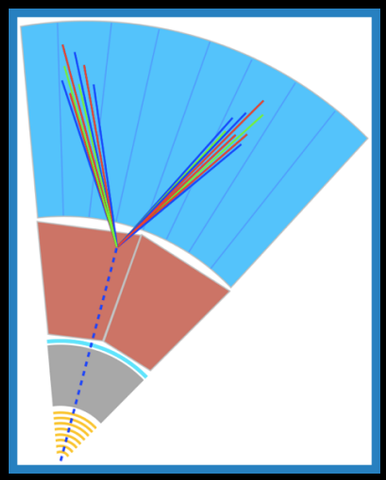
What would this look like for CEPC/FCC-ee?



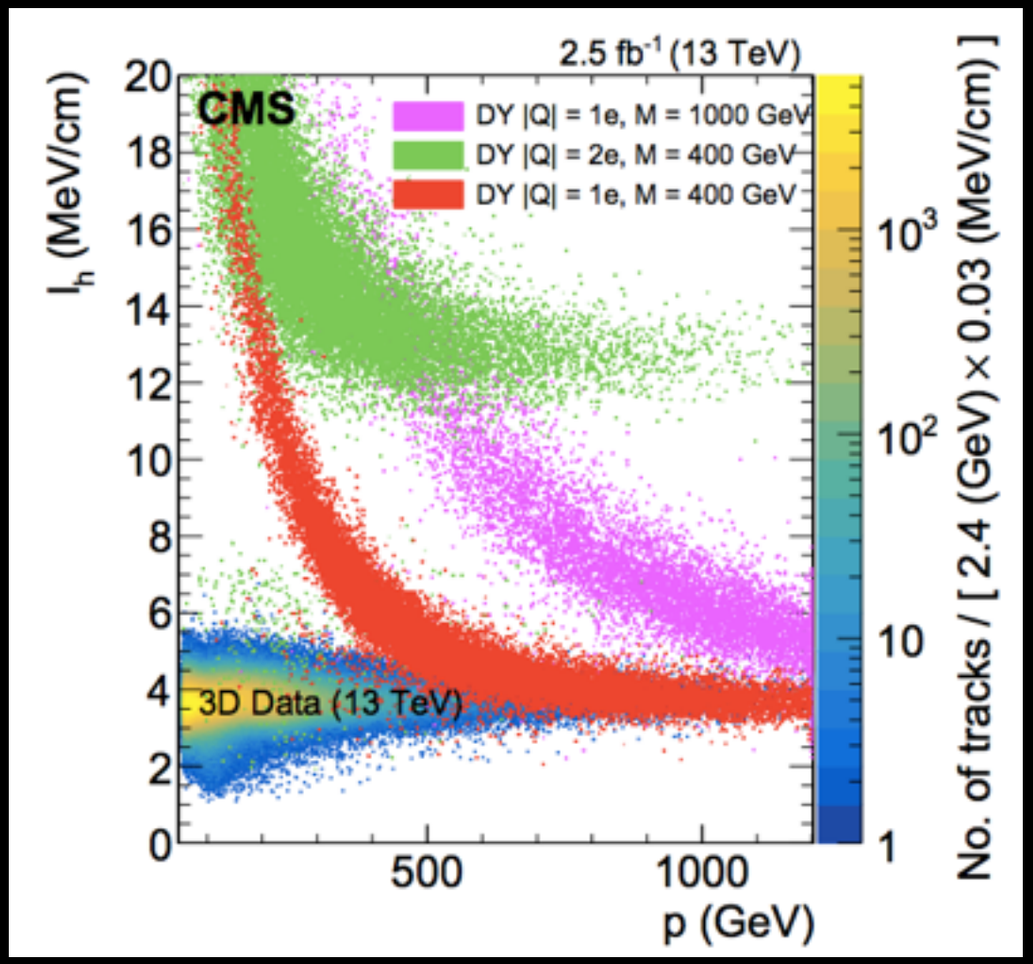


arXiv:1412.0018

What we do: Charged LLPs

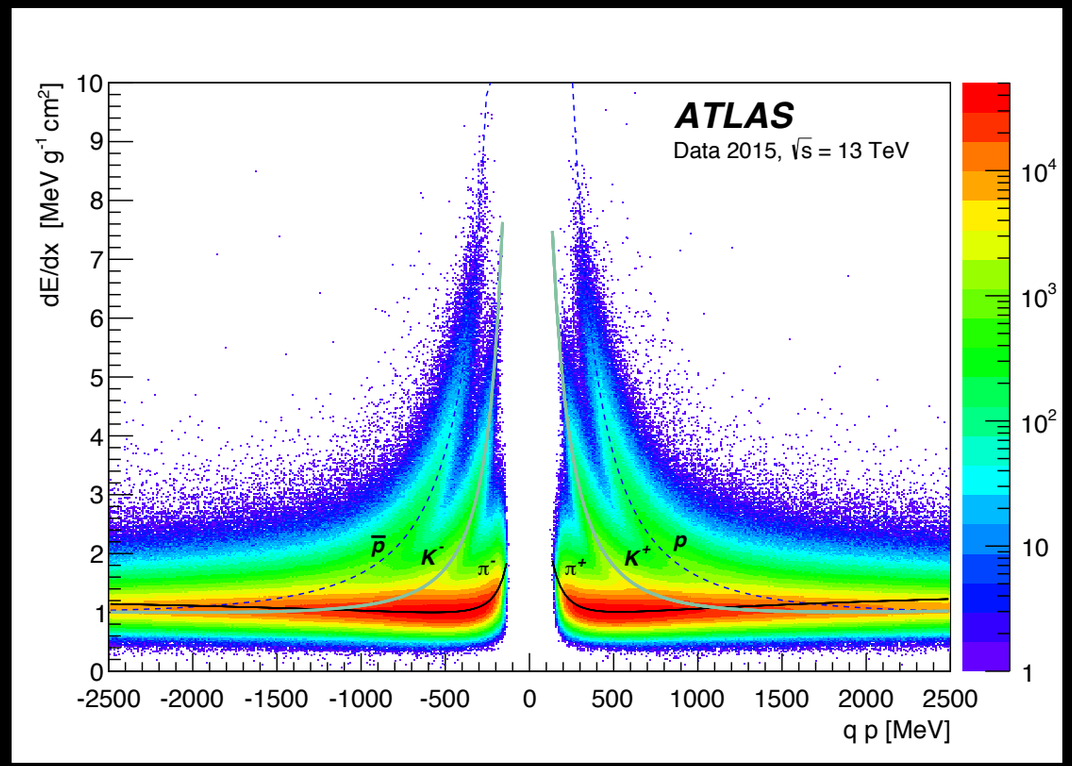


Phys. Rev. D 94, 112004 (2016)

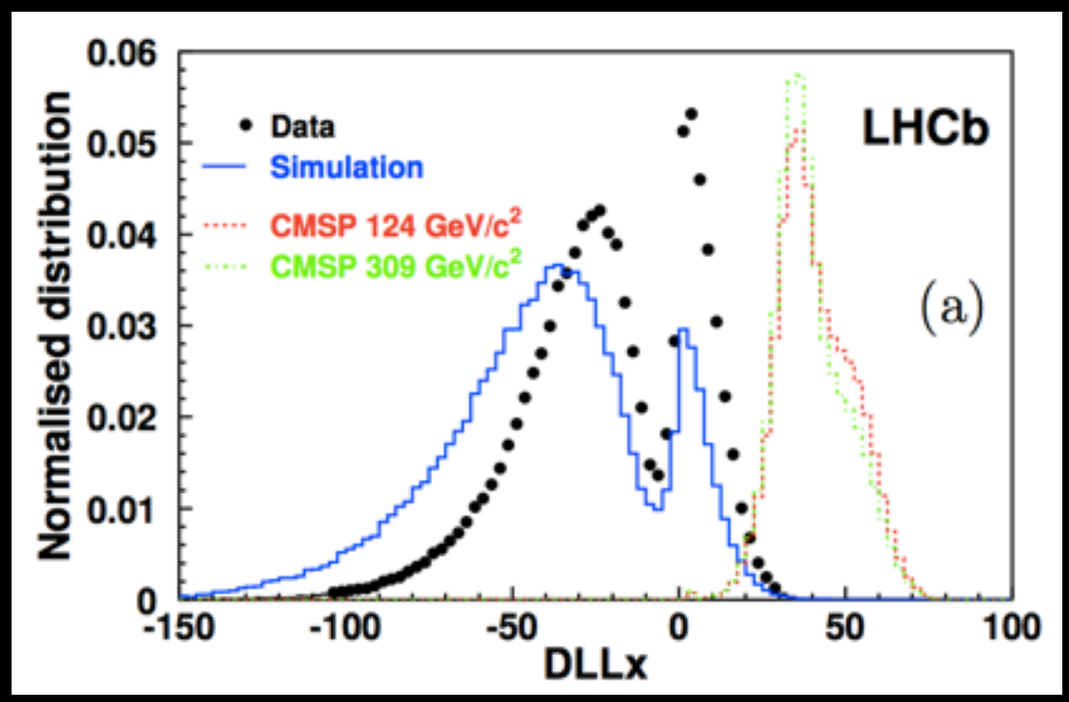


Estimator of dE/dx in pixels and silicon tracker

Phys. Rev. D 93, 112015 (2016)

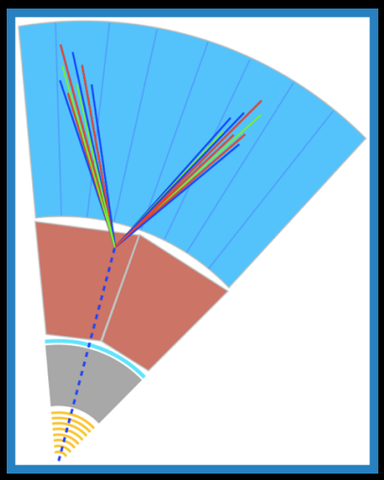


Eur.Phys.J. C75 (2015) no.12, 595

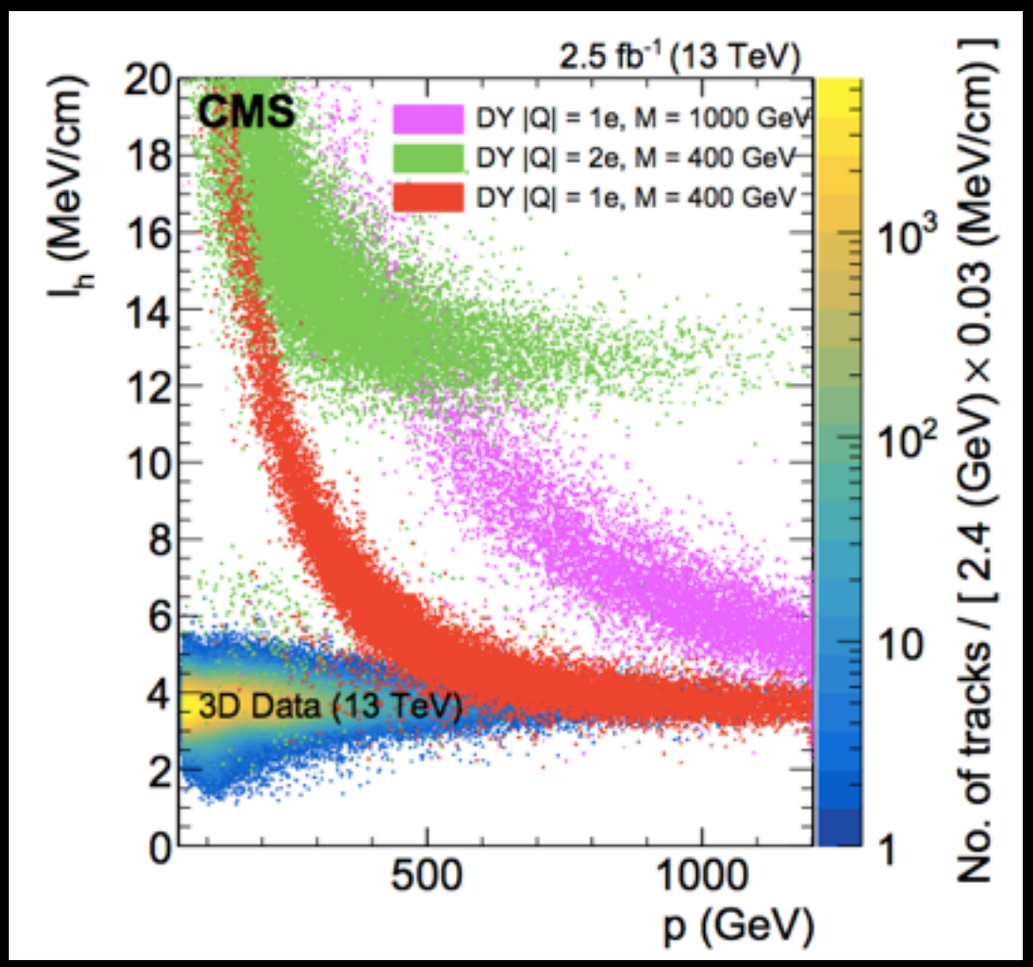


Measure of lack of Cherenkov radiation

What we do: Charged LLPs



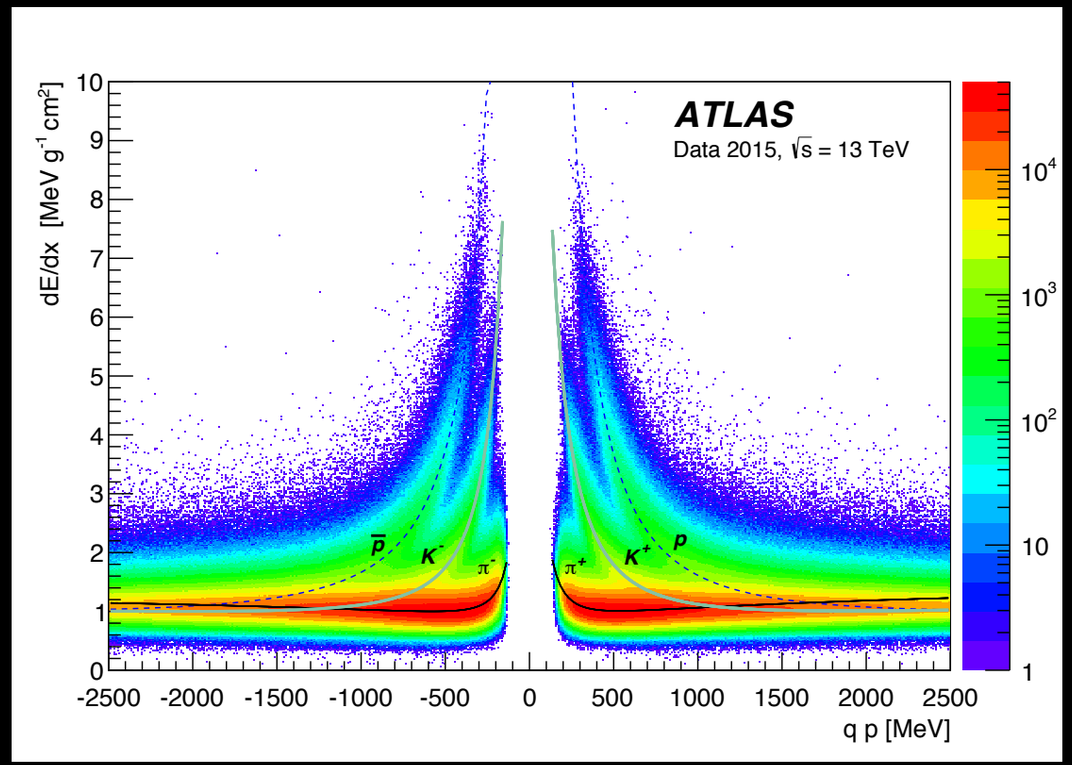
Phys. Rev. D 94, 112004 (2016)



Estimator of dE/dx in pixels and silicon tracker

How to get to lower masses?

Phys. Rev. D 93, 112015 (2016)



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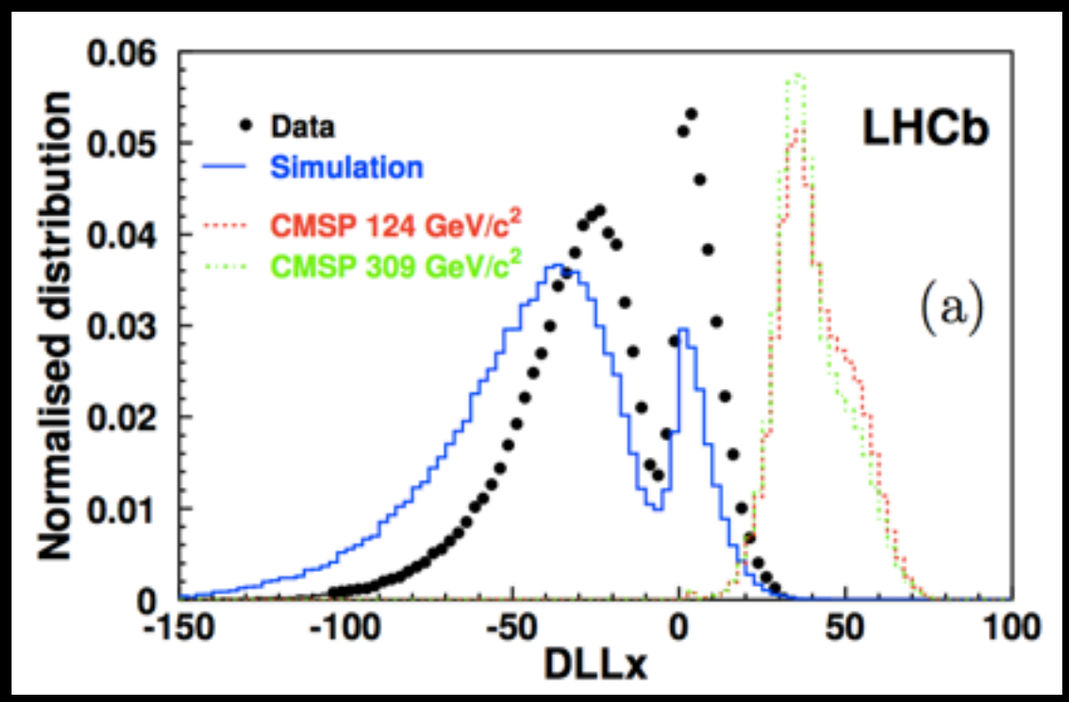
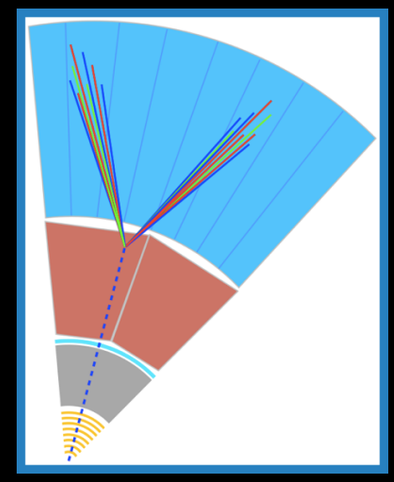
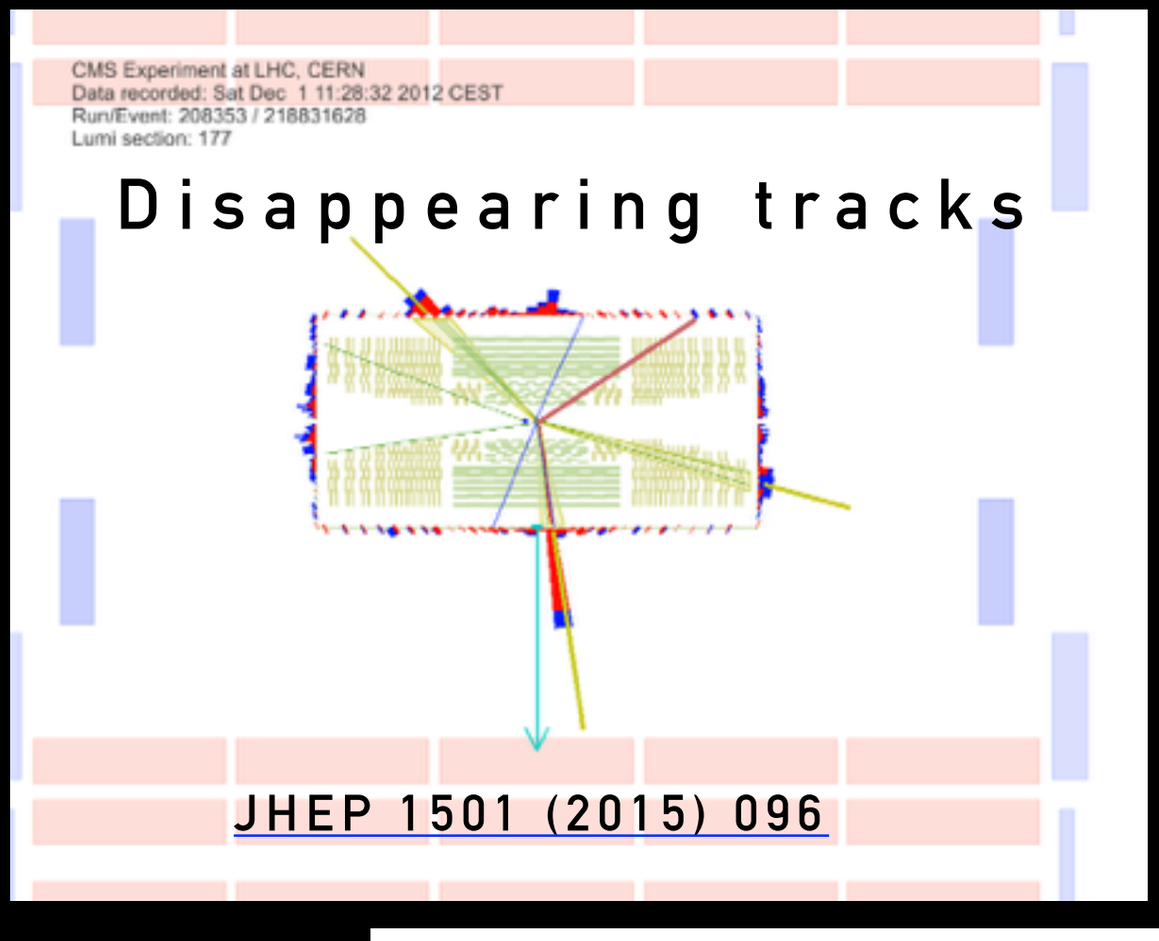


Measure of lack of Cherenkov radiation

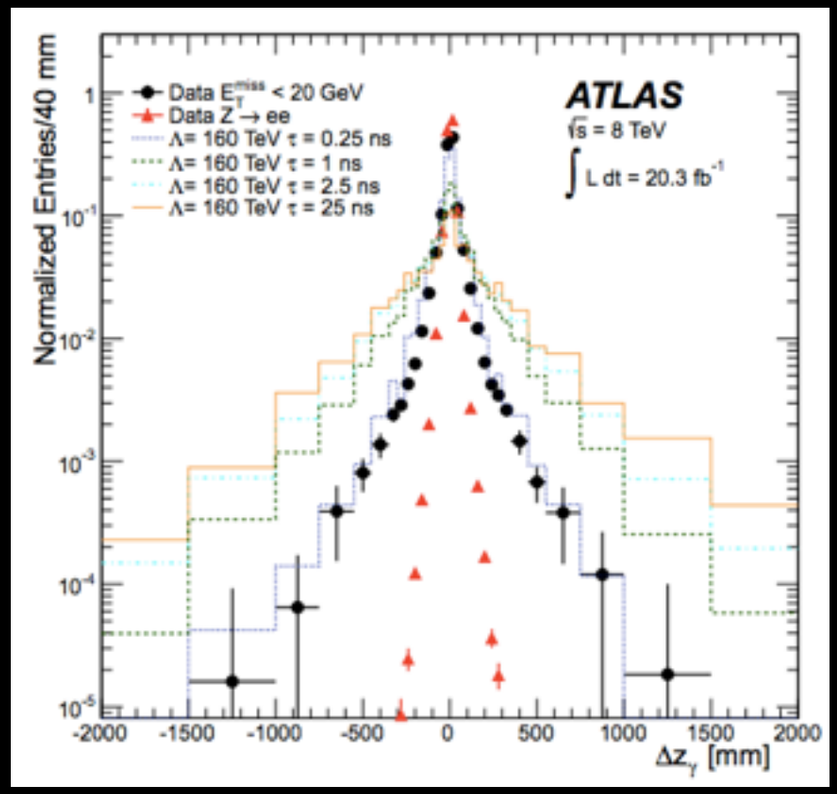
Other great searches not covered here





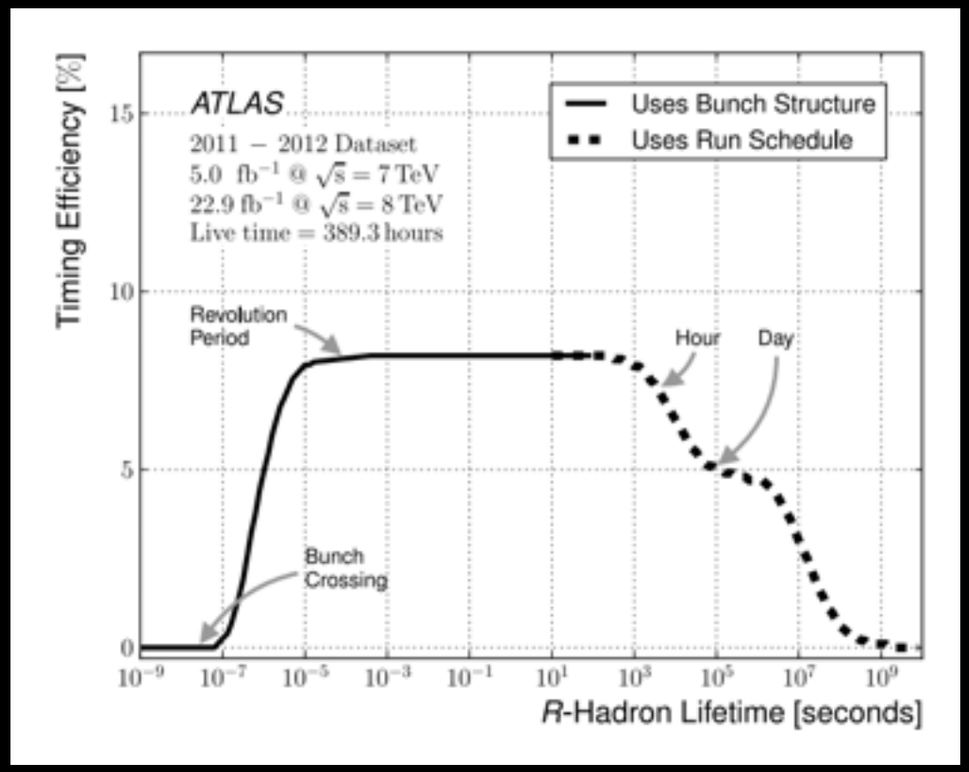
Disappearing tracks

JHEP 1501 (2015) 096



Non-pointing photons

Phys. Rev. D 90, 112005 (2014)

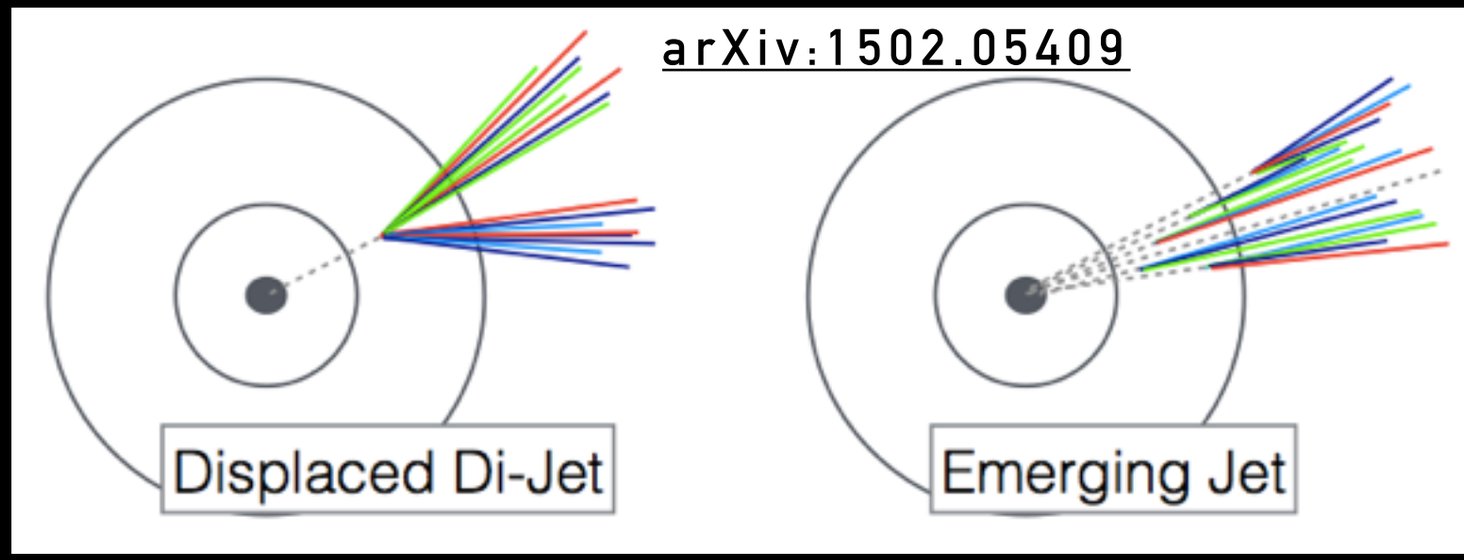


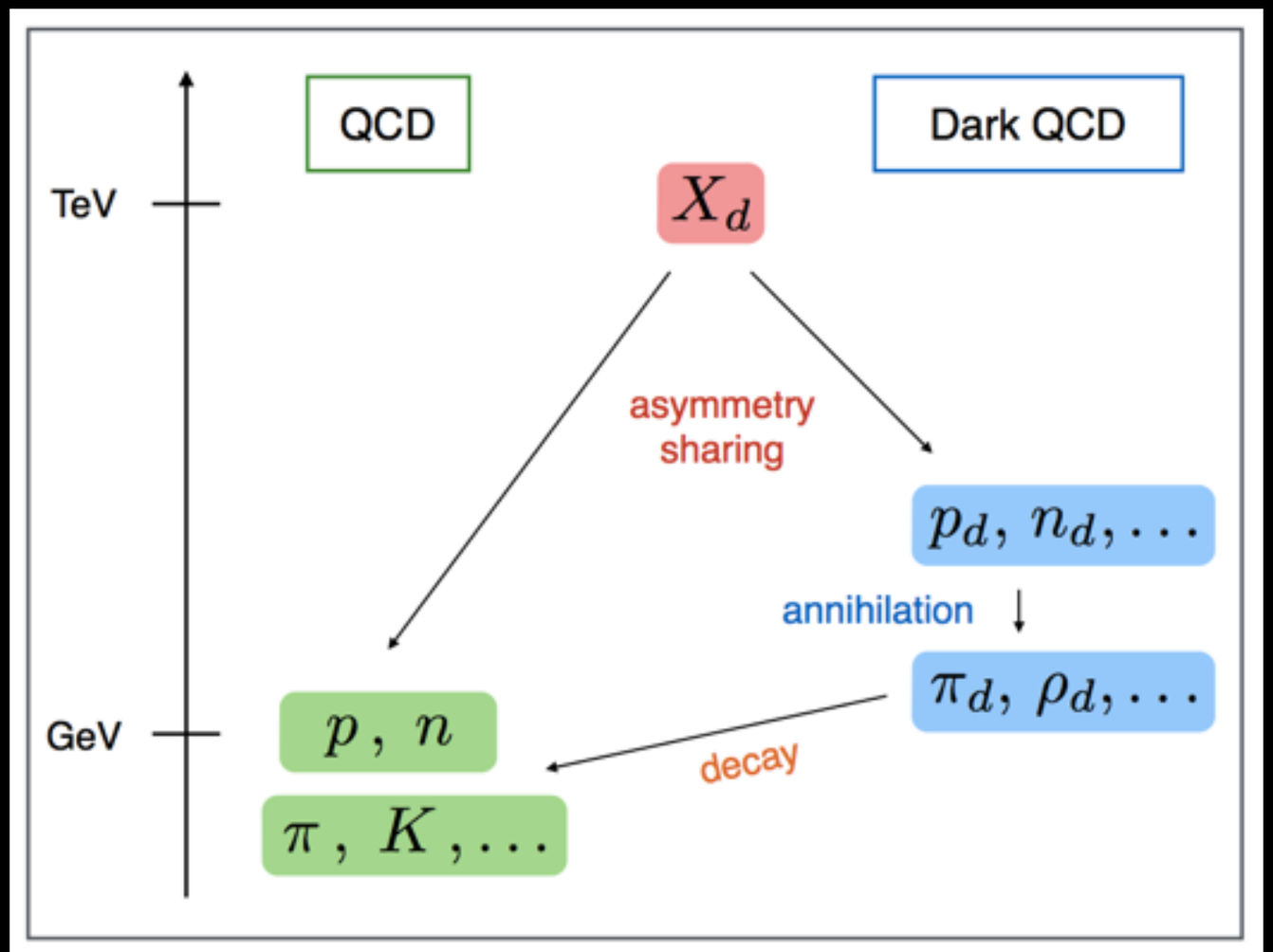
Stable/stopped particles

Phys. Rev. D 88, 112003 (2013)

Frontiers/uncovered realms: Emerging jets

Why should beyond-the-Standard Model physics be simple, like a U(1) symmetry? What about dark QCD?

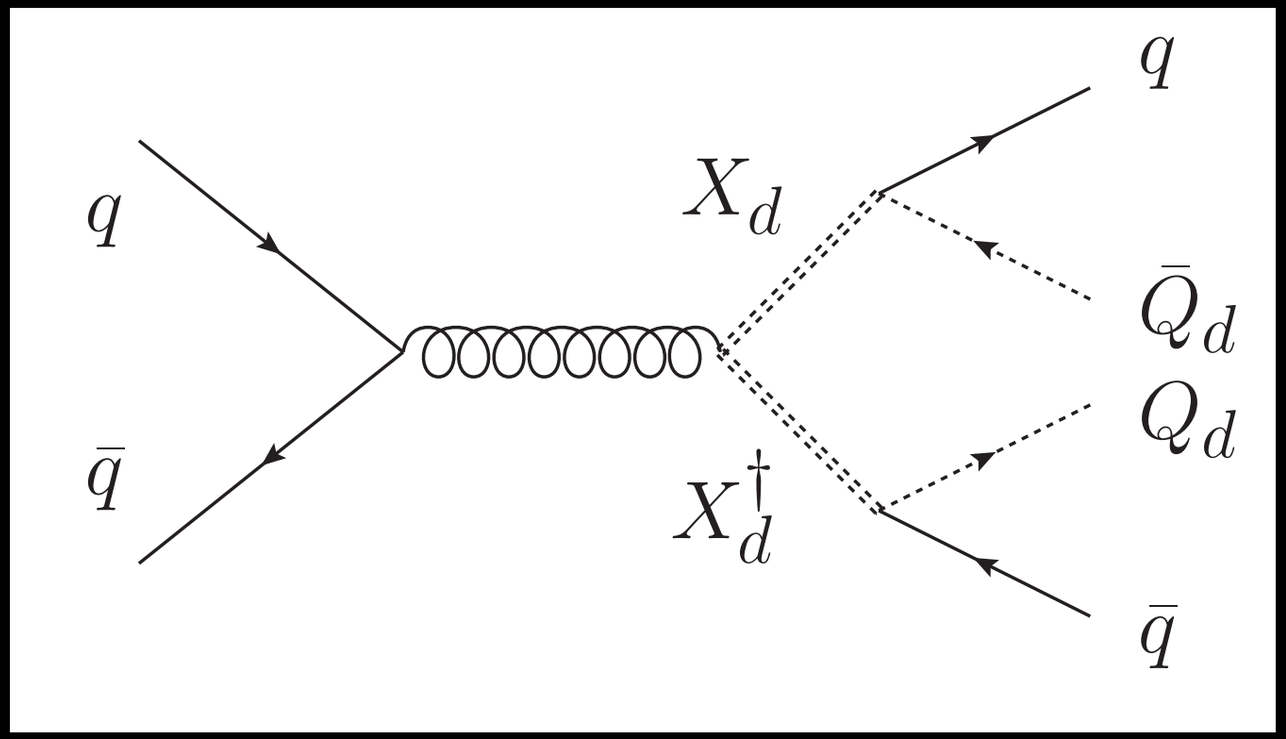


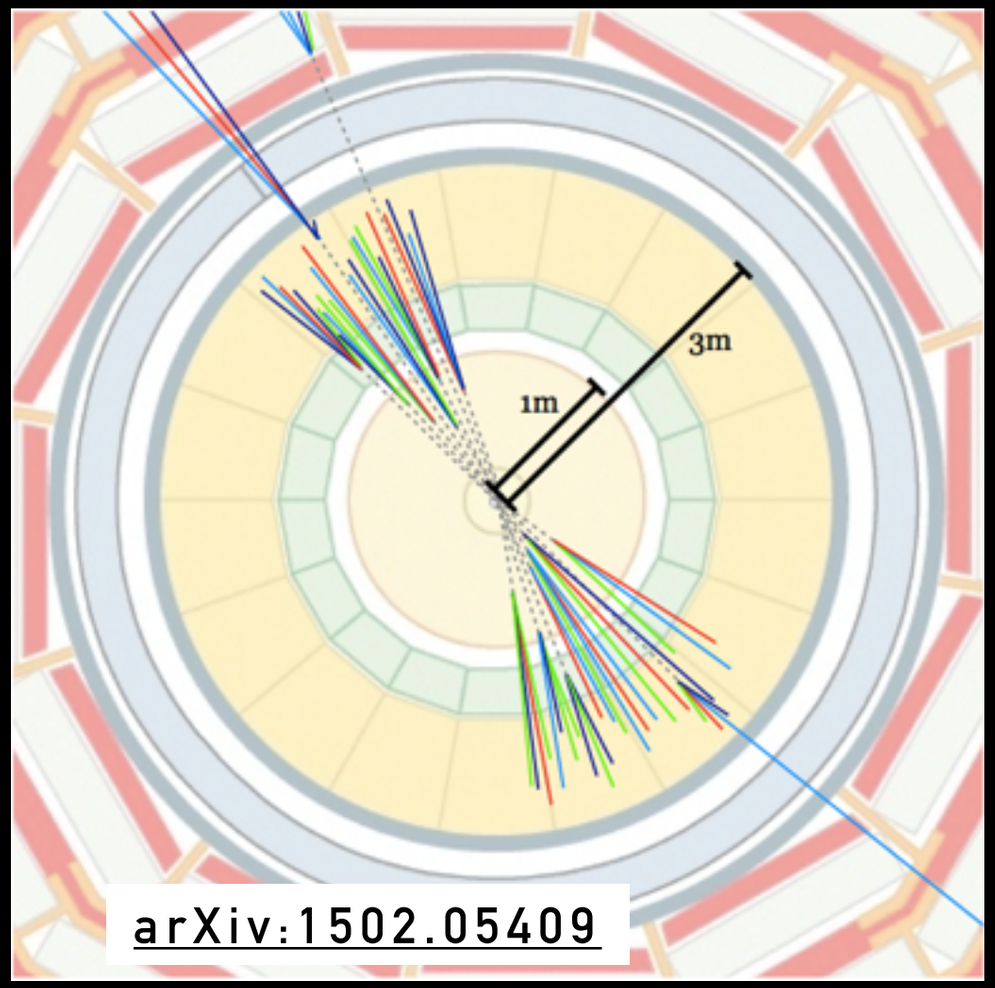


A novel LHC signature where dark or hidden sector quarks decay to the visible sector via multiple displaced vertices of varying displacements within the same jet object. Pair-produced dark quarks then give rise to neither prompt jets nor a pair of displaced jets pointing to the same displaced vertex, but to emerging jets.

Frontiers/uncovered realms: Emerging jets

Dark QCD-like sectors





Dark QCD —> dark quarks —> dark pions w/variable lifetimes —> jets w/multiple displaced vertices / tracks in a single jet or event

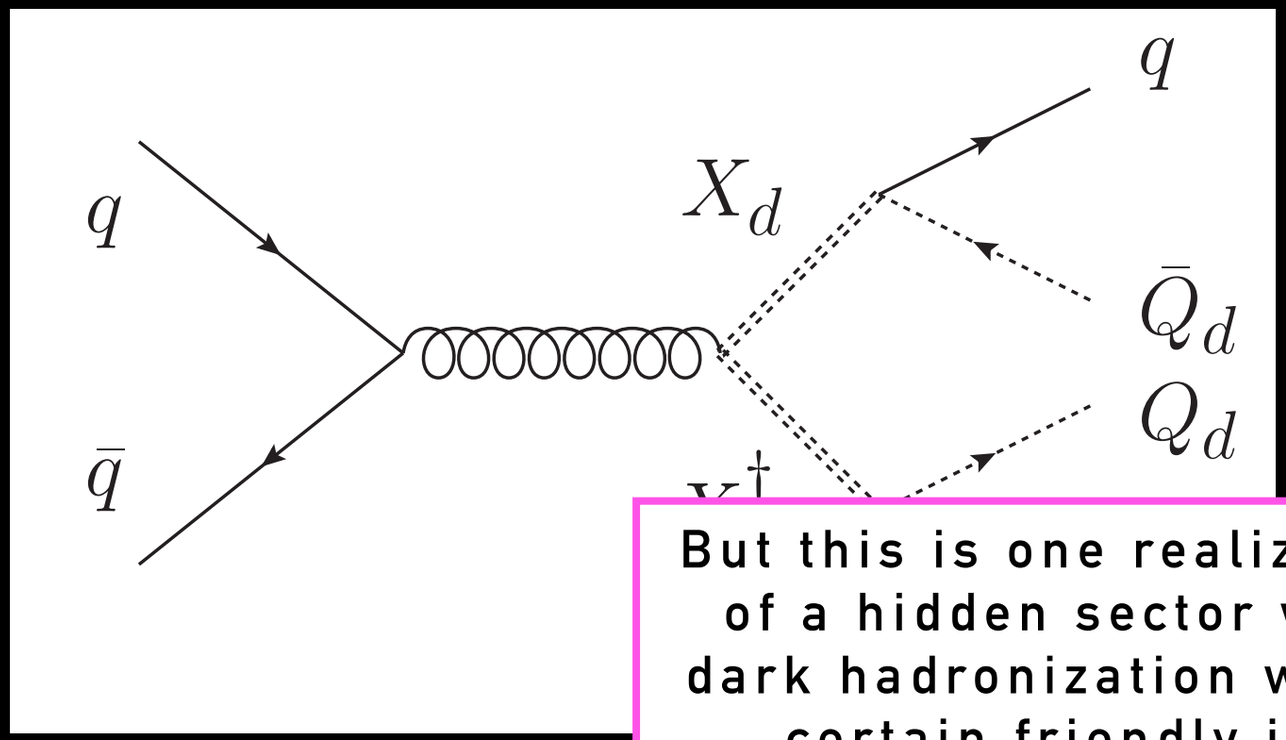
Analysis strategy could target 4-jet signal: 2 QCD jets + 2 dark-QCD / emerging jets

Need non-standard tracking for large-d0 tracks + secondary vertex finding routines

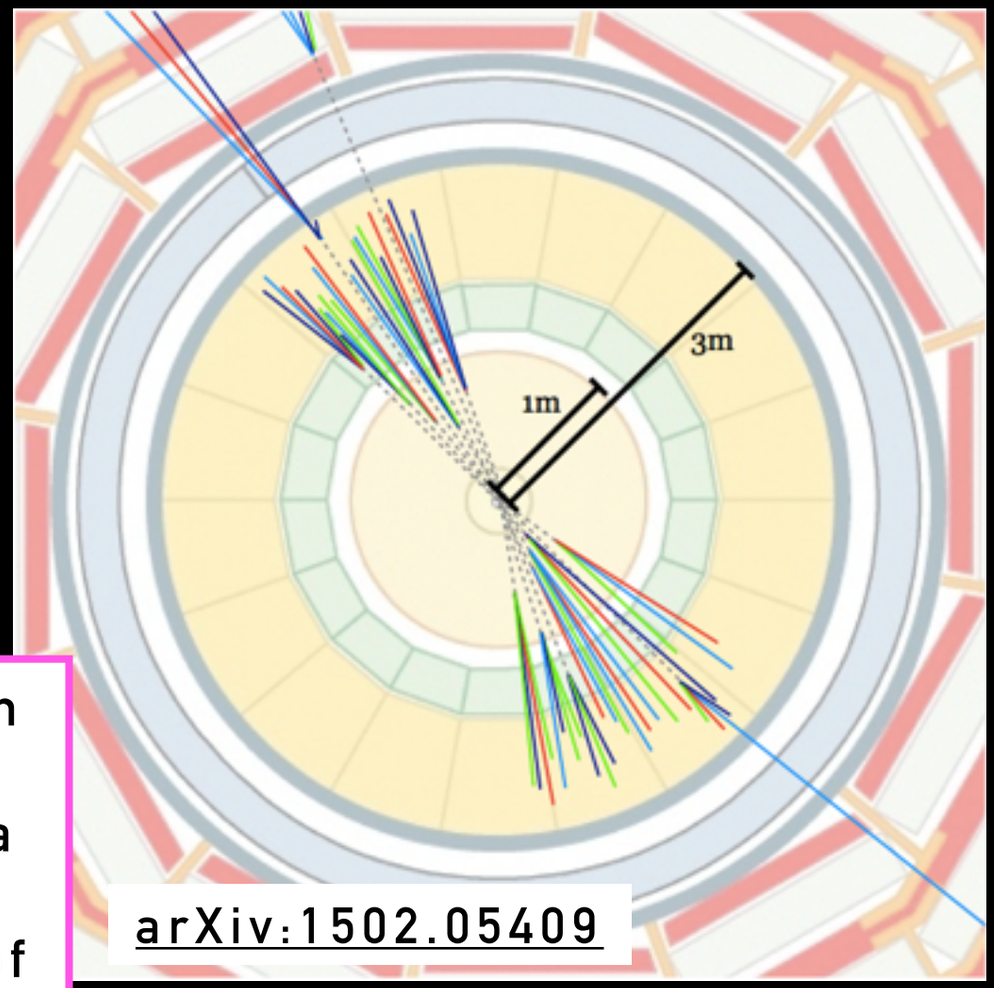
Searches underway in ATLAS and CMS; hopefully public results soon-ish!

Frontiers/uncovered realms: Emerging jets

Dark QCD-like sectors



But this is one realization of a hidden sector with dark hadronization with a certain friendly jet multiplicity and choices of mediator, dark vector meson, dark pion masses, dark confinement scale. How to design a comprehensive approach?



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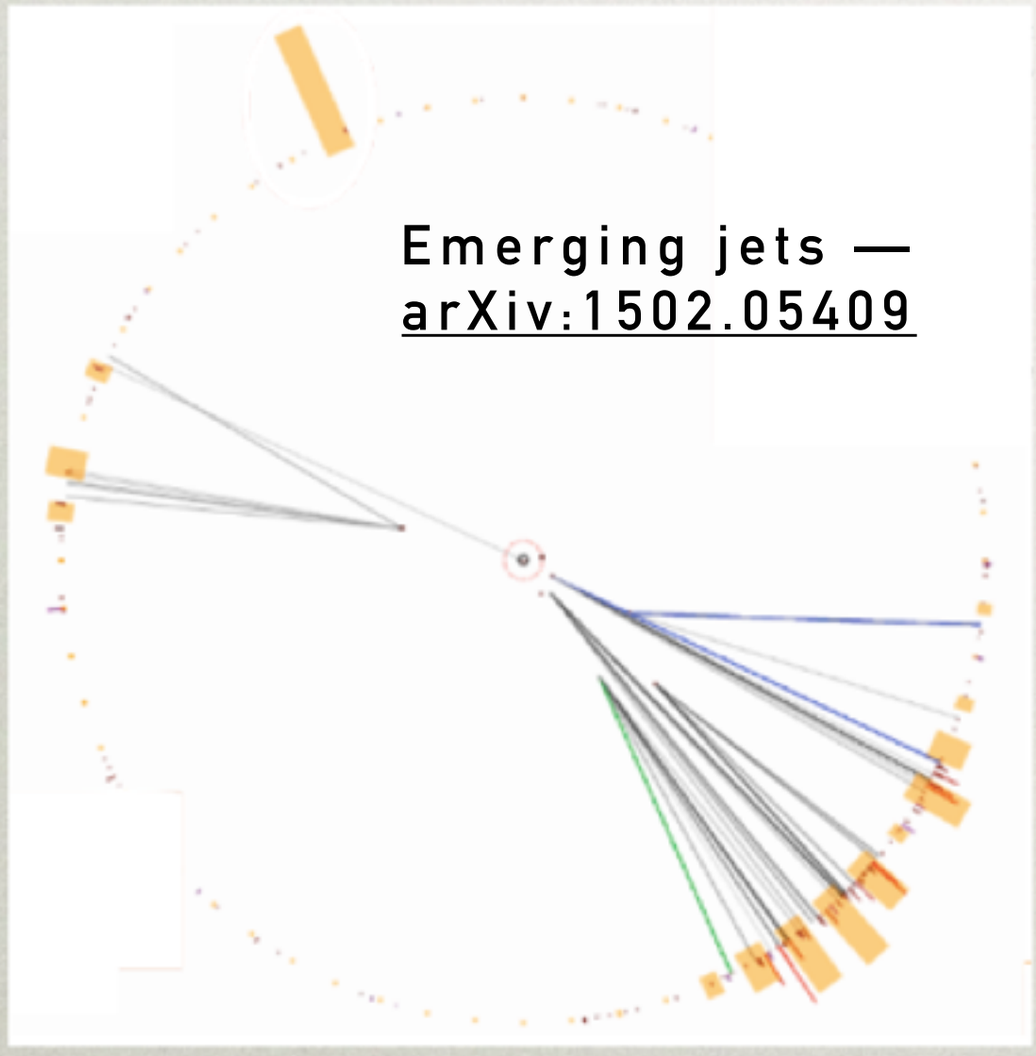
Frontiers/uncovered realms

Dark QCD-like sectors

- Emerging jets vs. SUEP (soft, unclustered energy patterns)
- How to interpolate between these two?
- Dark showers WG in LHC LLP Community — laying groundwork now

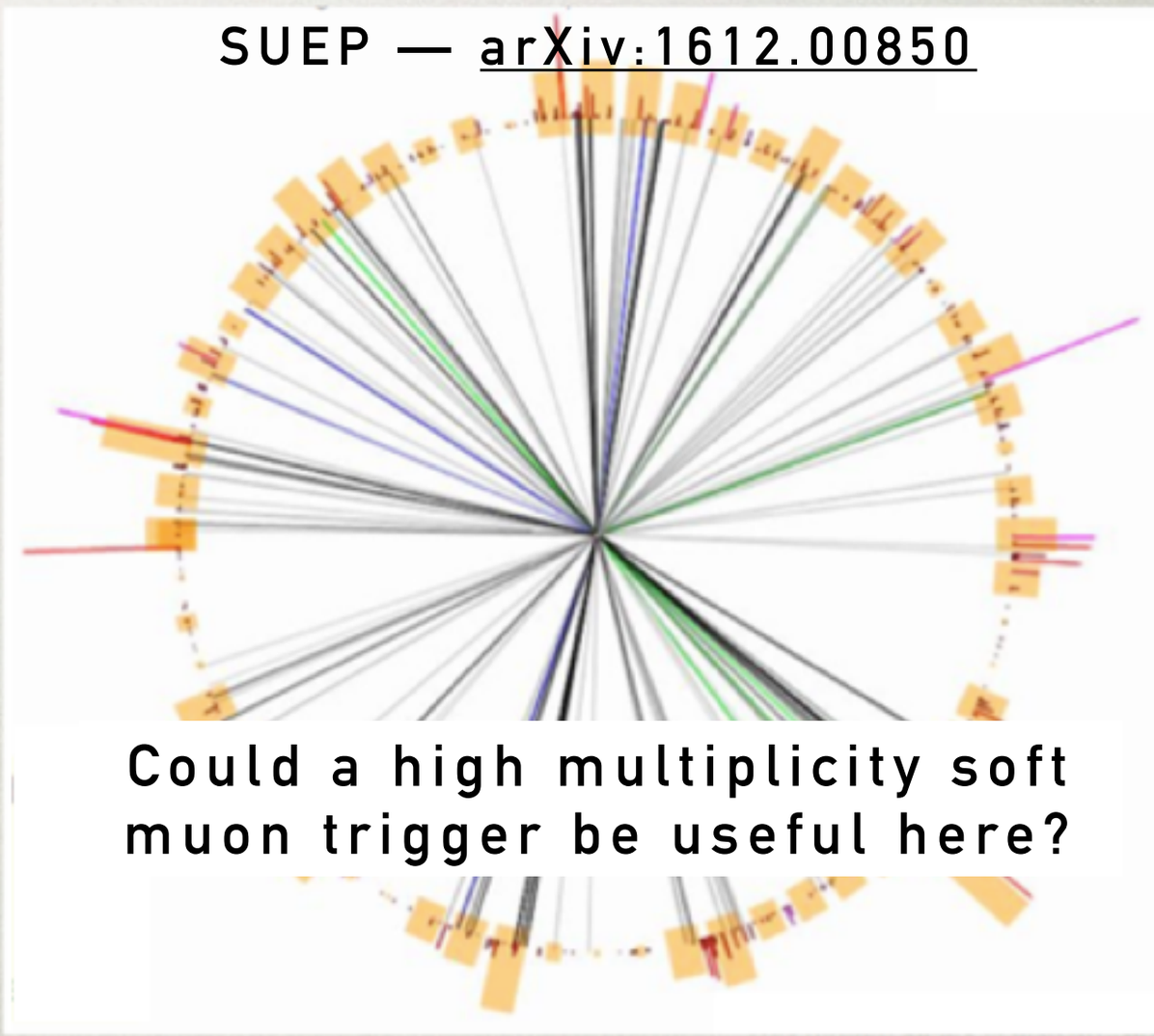
Schwaller, Stolarski, Weiler 2015

Emerging jets — arXiv:1502.05409



Knapen *et al.*, 2016

SUEP — arXiv:1612.00850



Could a high multiplicity soft muon trigger be useful here?

Images by M. Strassler