THEORY & PHENO OF LONG-LIVED PARTICLES

Brian Shuve

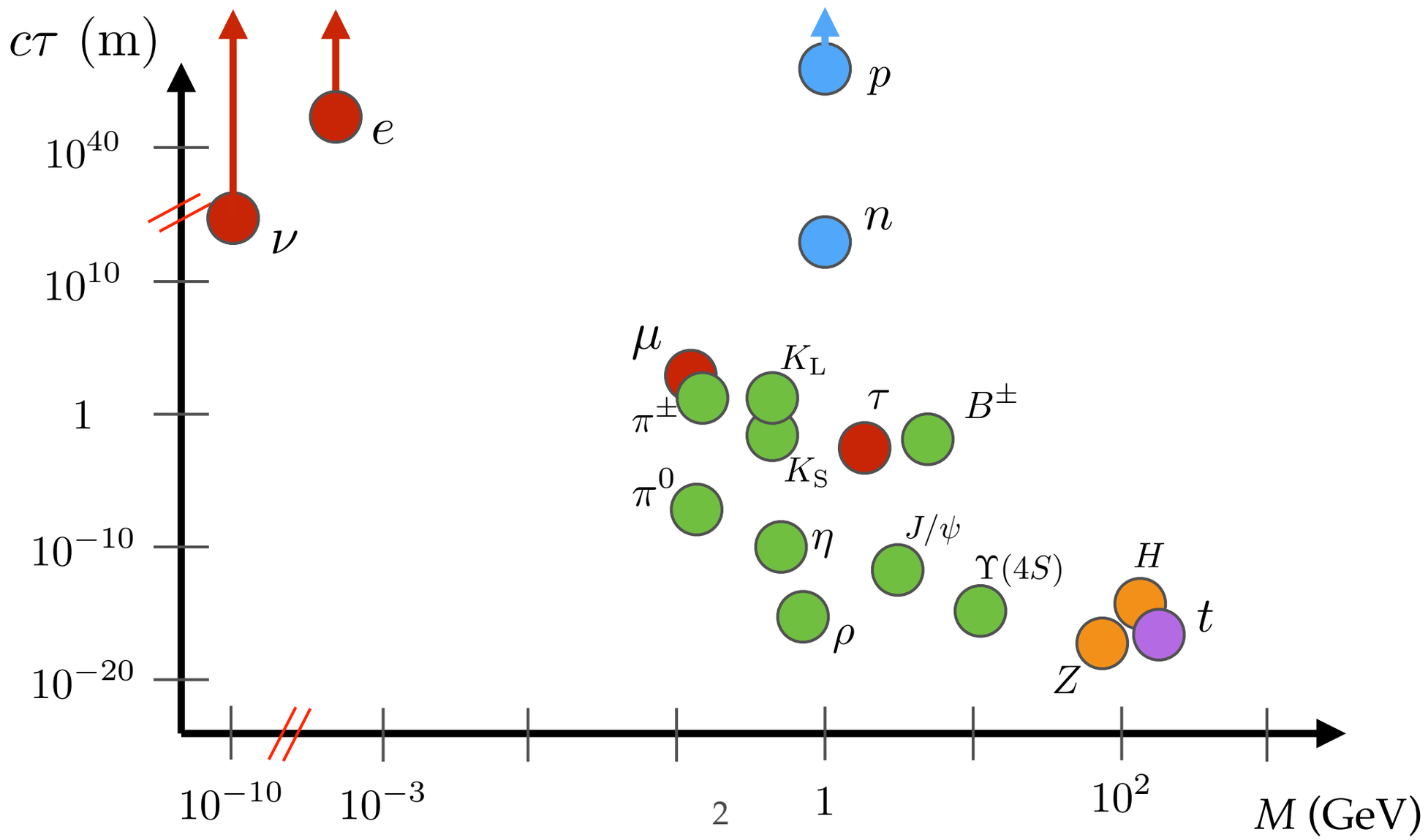
New Particles & Paradigms

HARVEY MUDD COLLEGE

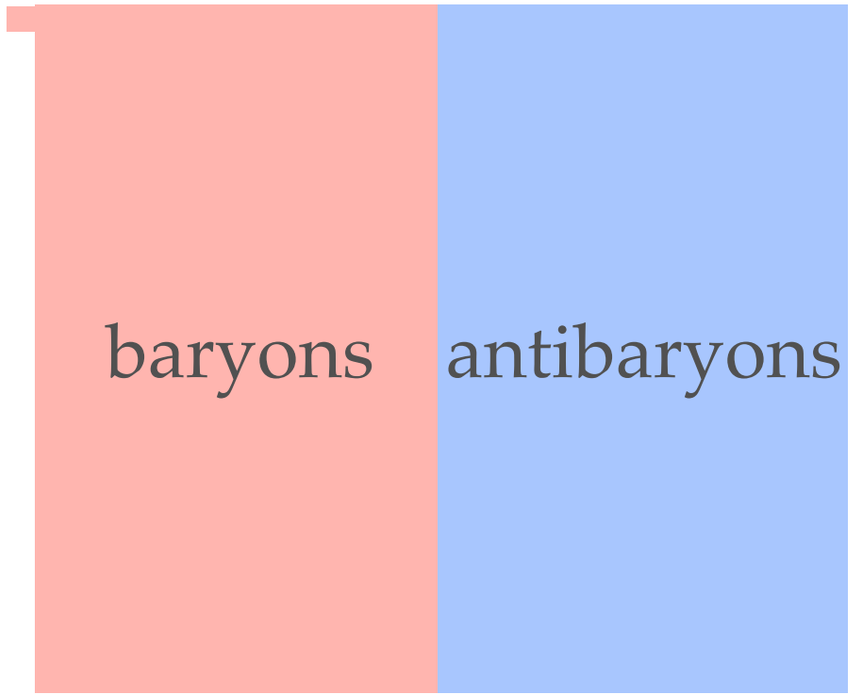
UCR

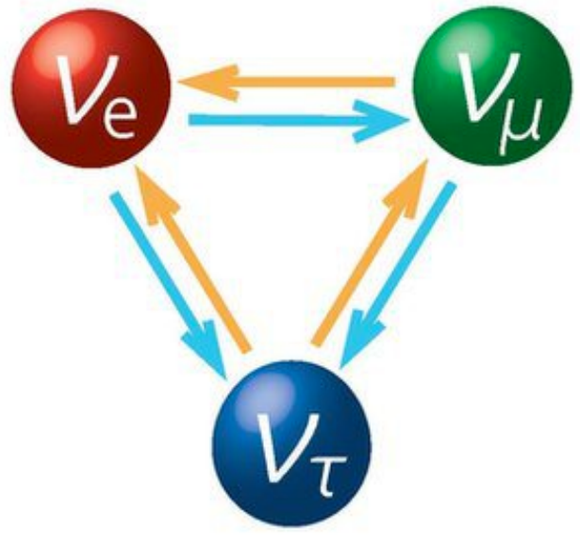
WHY LONG-LIVED PARTICLES?

- LLP = “long lived particle”
- Travels a macroscopic distance before decaying $(\gtrsim 0.01\ \mathrm{mm})$



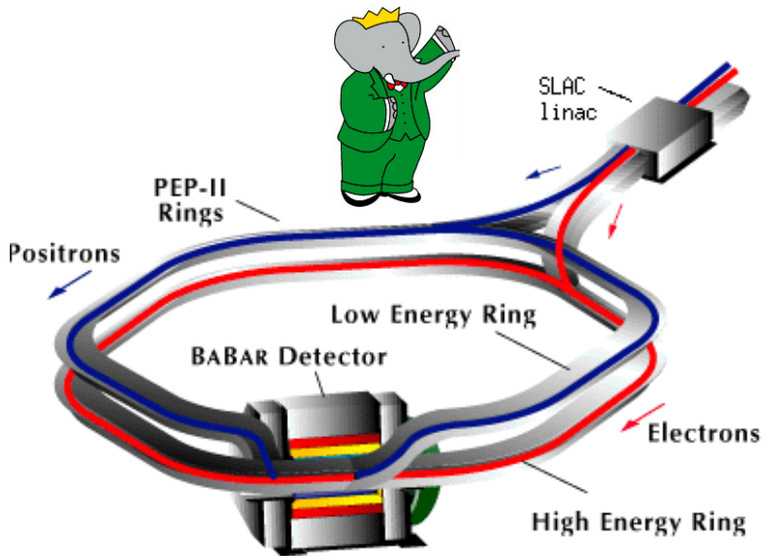
WHY LONG-LIVED PARTICLES?



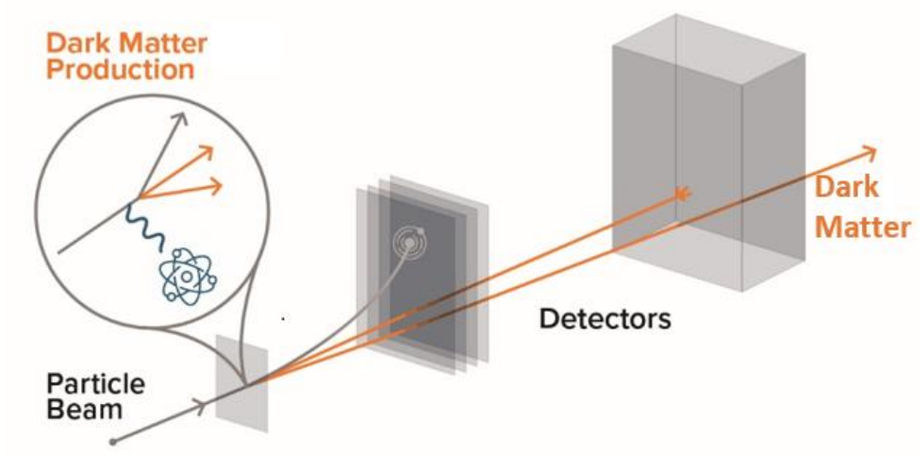


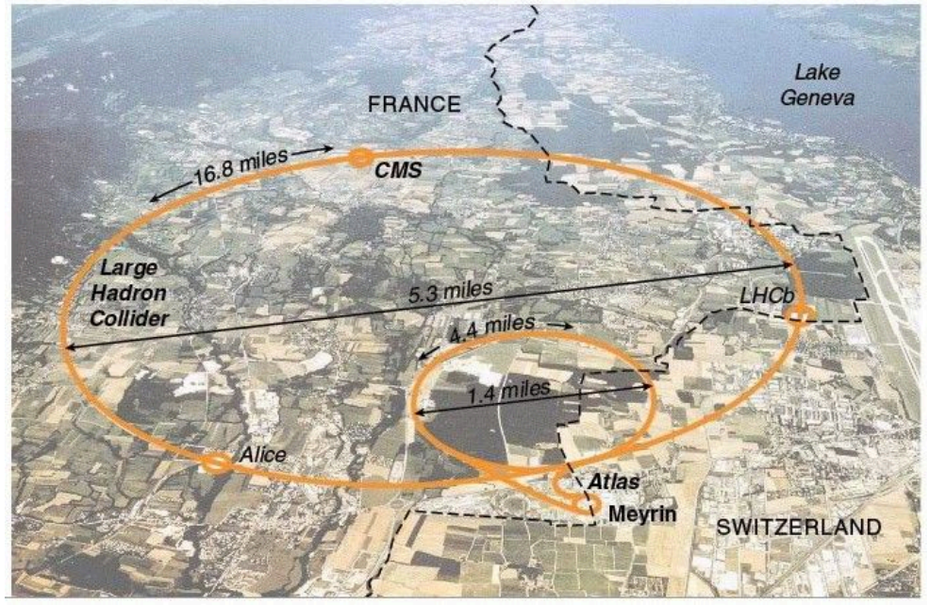
- Hidden sectors with small couplings, sub-weak masses can resolve each of these open questions

WHERE CAN WE LOOK?



mass/energy





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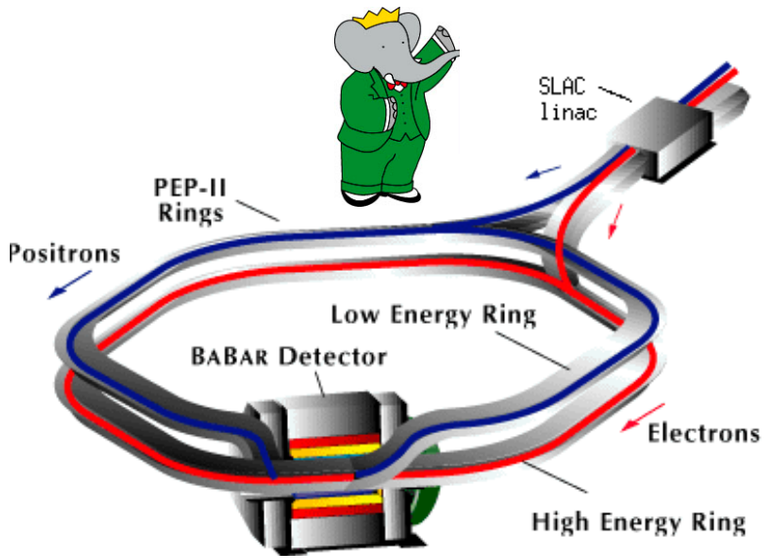

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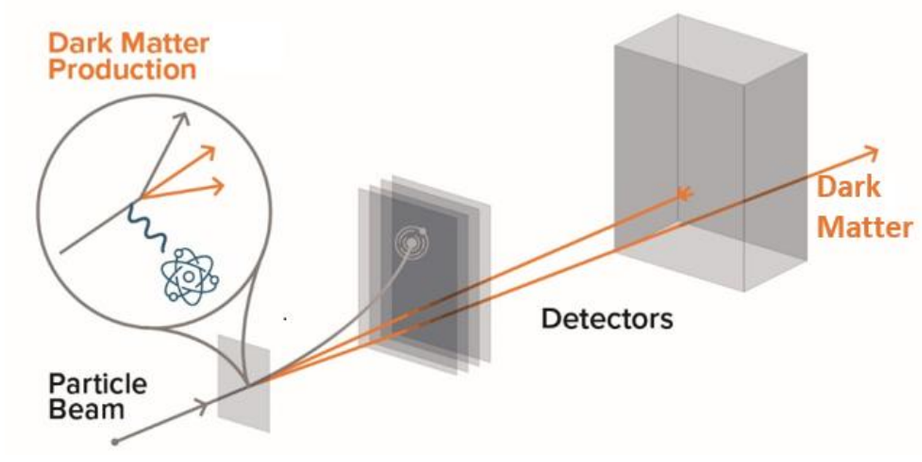

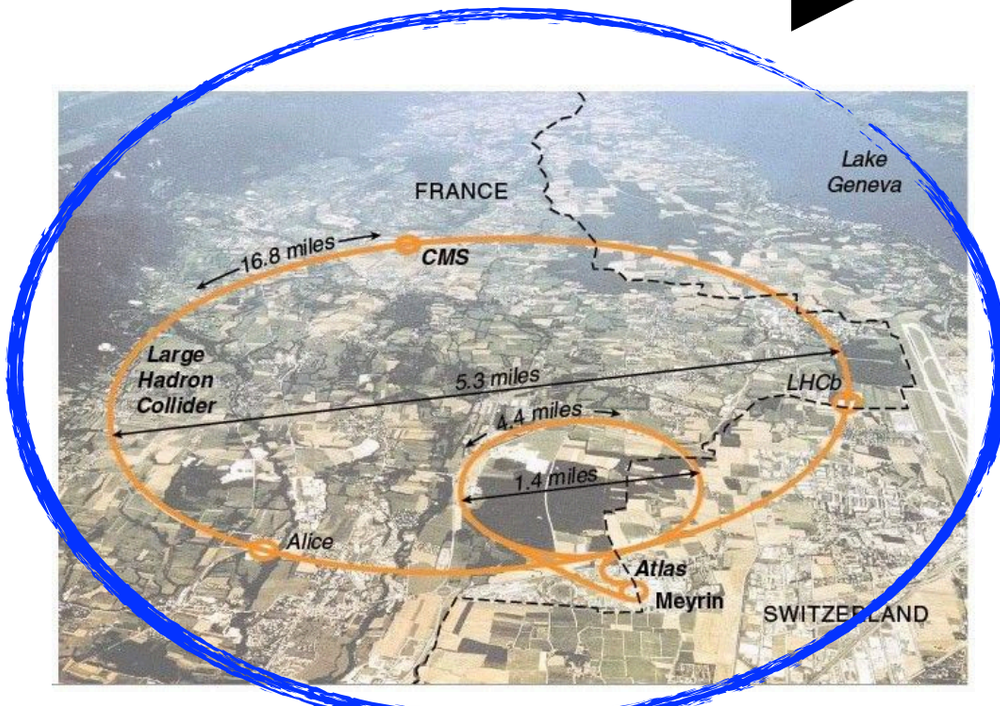

WHEN DOES LHC WIN?

"Heavy" LLPs:

$$M \gtrsim 100 \text{ GeV}$$

- Includes strong/electroweak production of LLPs (SUSY, etc)

- Generally lots of energy in detector

- Challenging to do, but relatively robust program exists

See Laura and Yangyang's talks!

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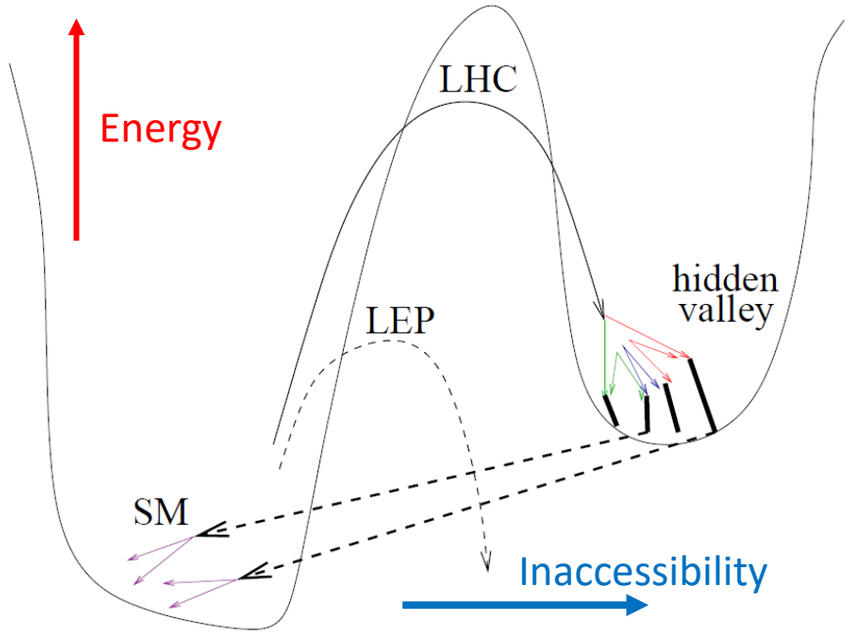
Hidden Valley:

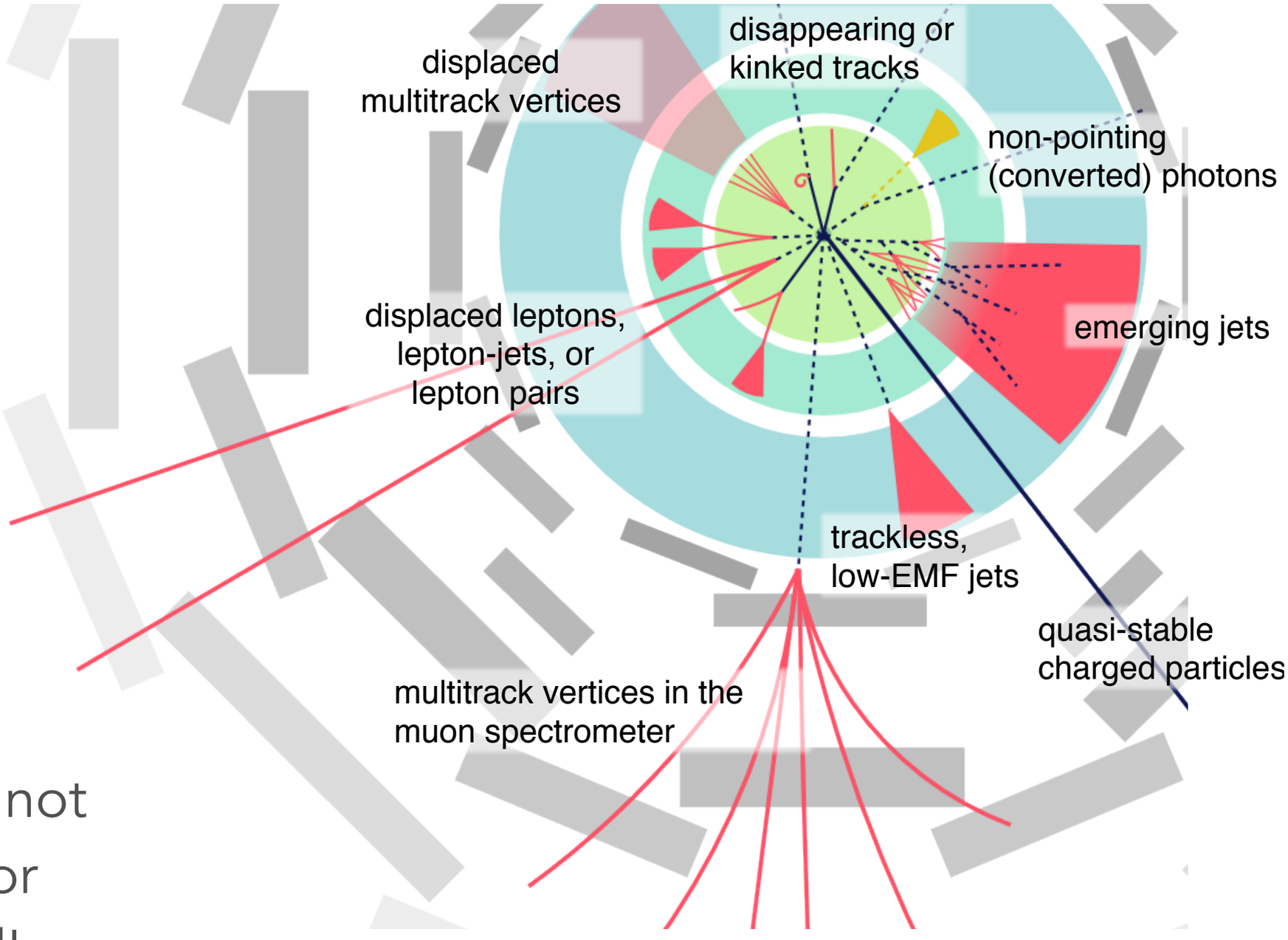
$$M \ll 100 \text{ GeV}$$



- Low-mass LLPs coupled by mediator only accessible at LHC
- Major challenge!

Strassler, Zurek 2006; Han *et al.*, 2008; …

LLPS AT LHC

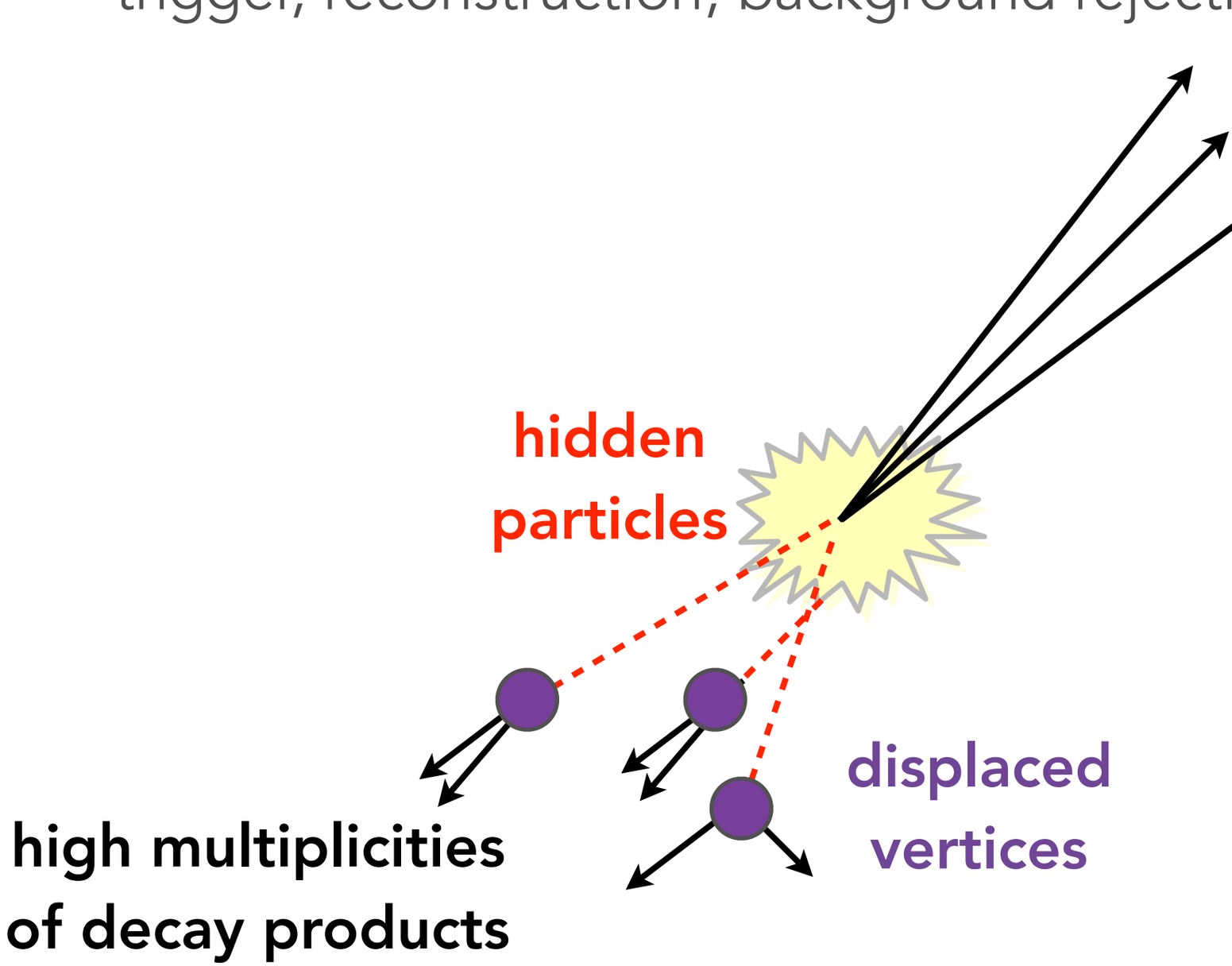


- Events might not be recorded or reconstructed!

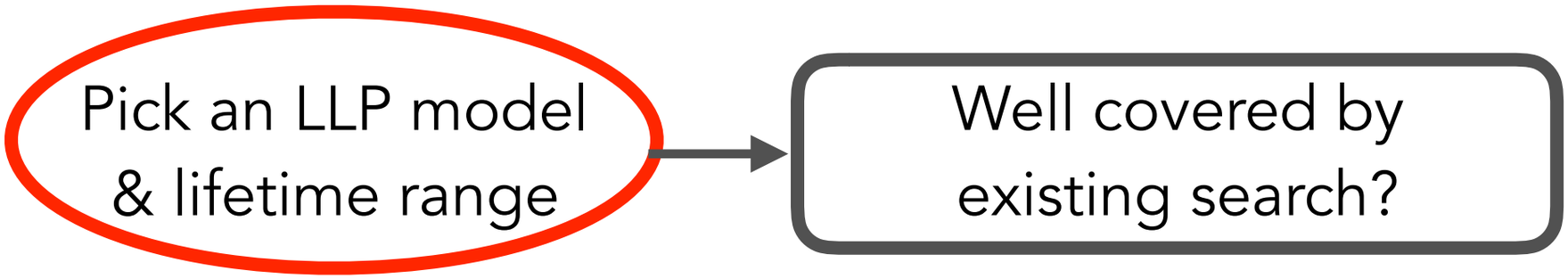
H. Russell, LHC LLP Community workshop, 2017

NEW LLP STRATEGIES

- Many hidden sector models have additional features that aid with trigger, reconstruction, background rejection



NEW LLP STRATEGIES



NEW LLP STRATEGIES

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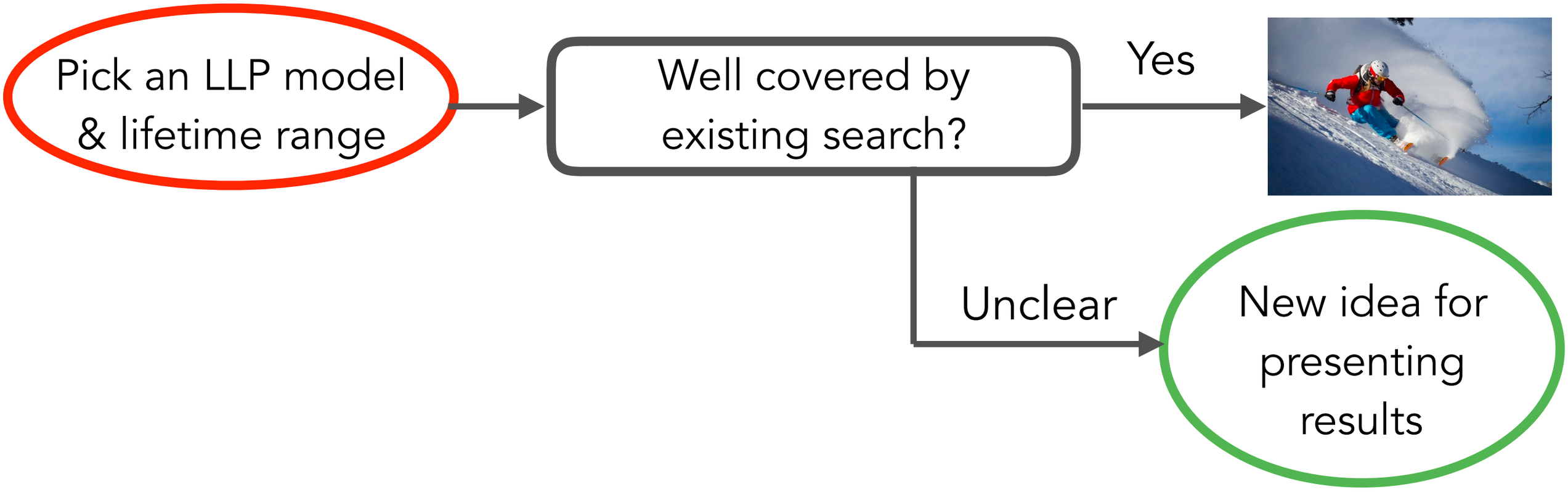

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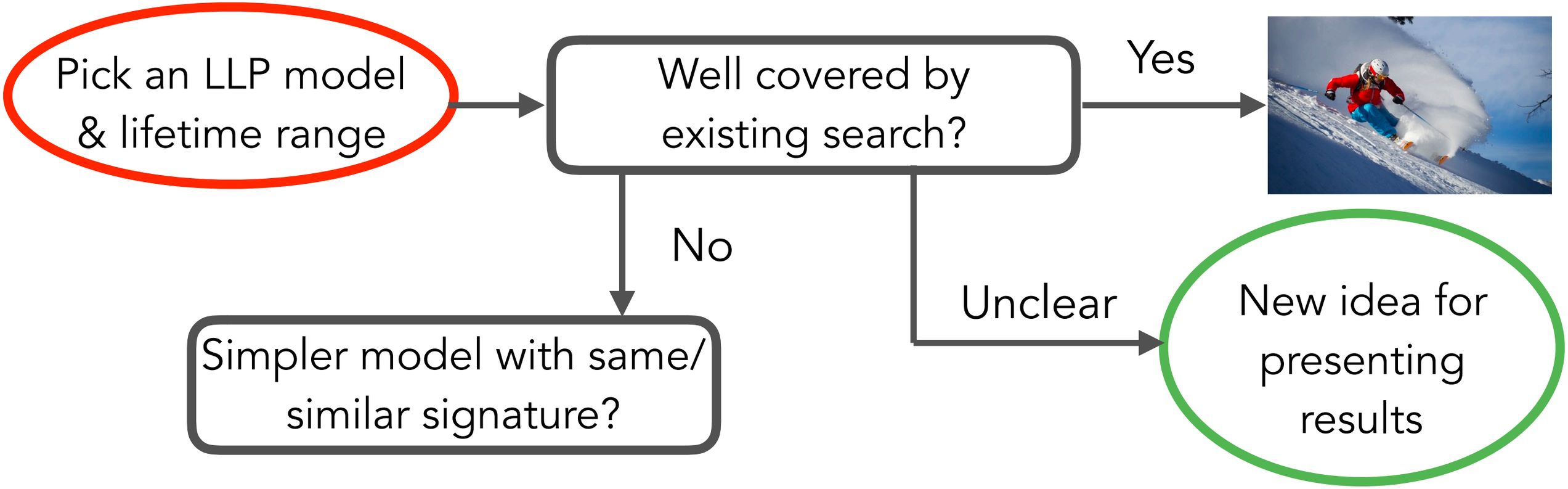

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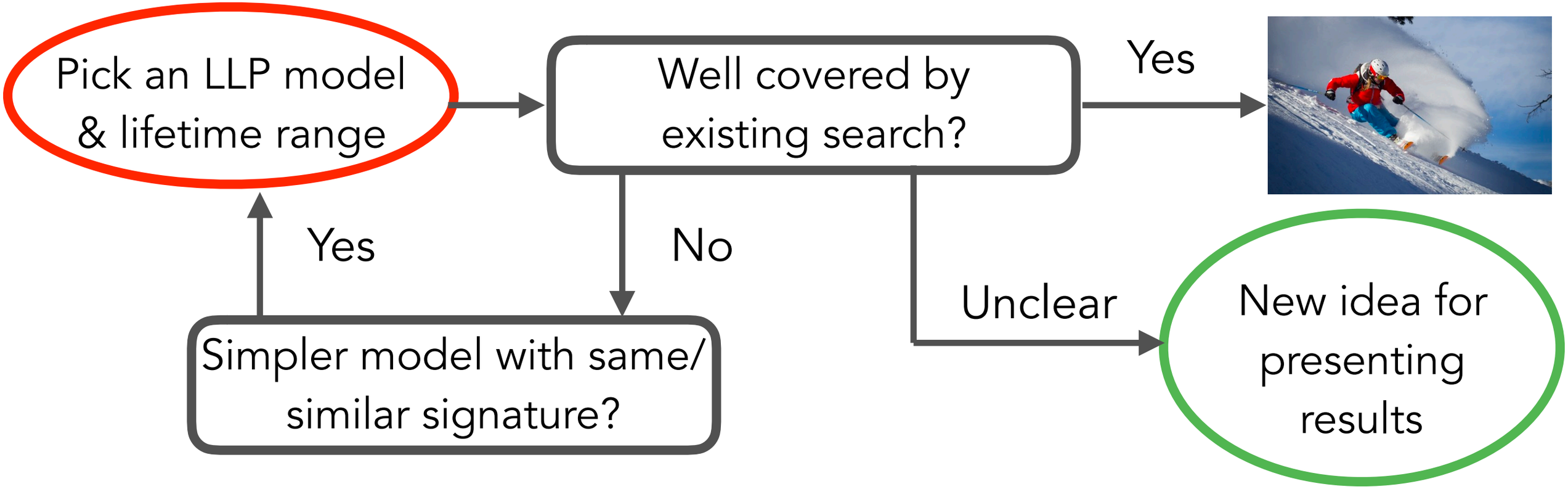

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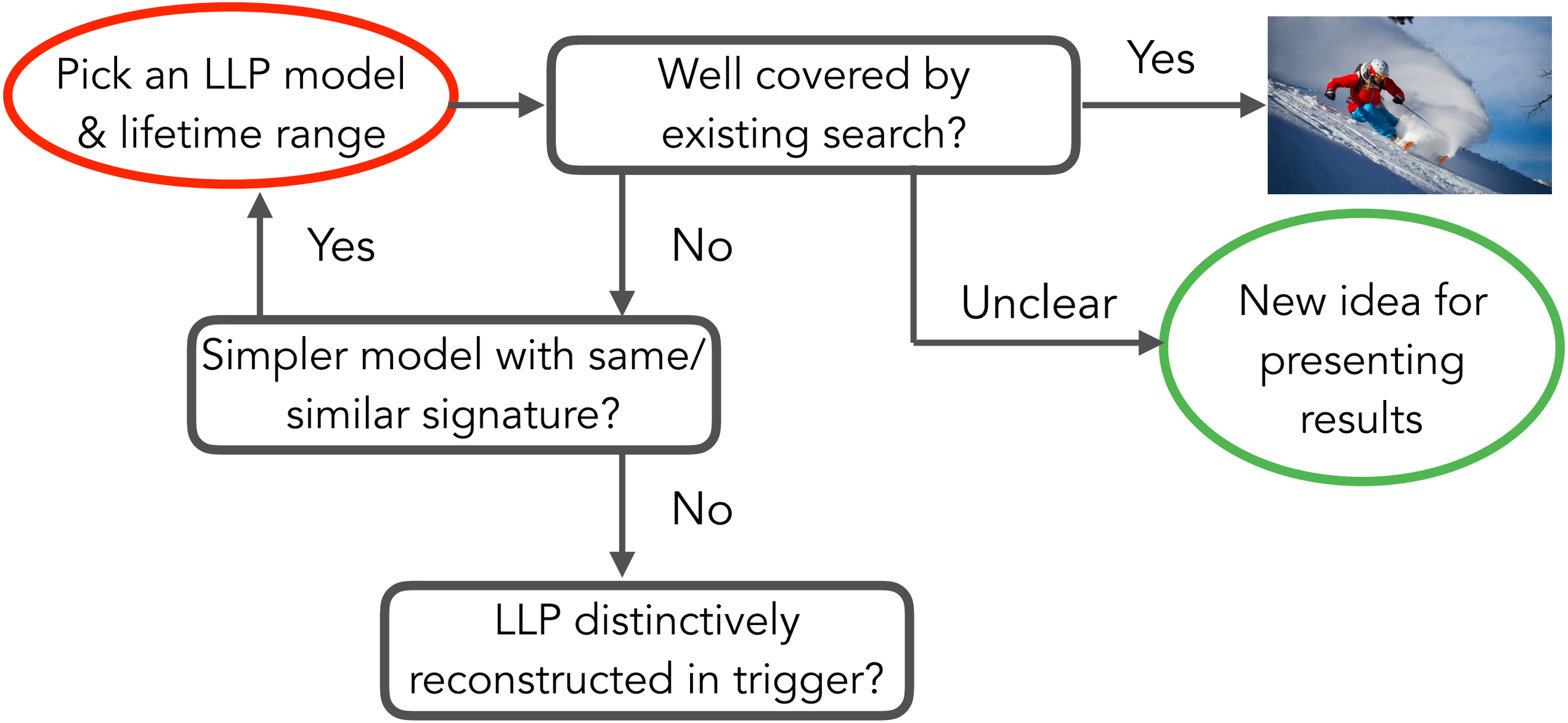

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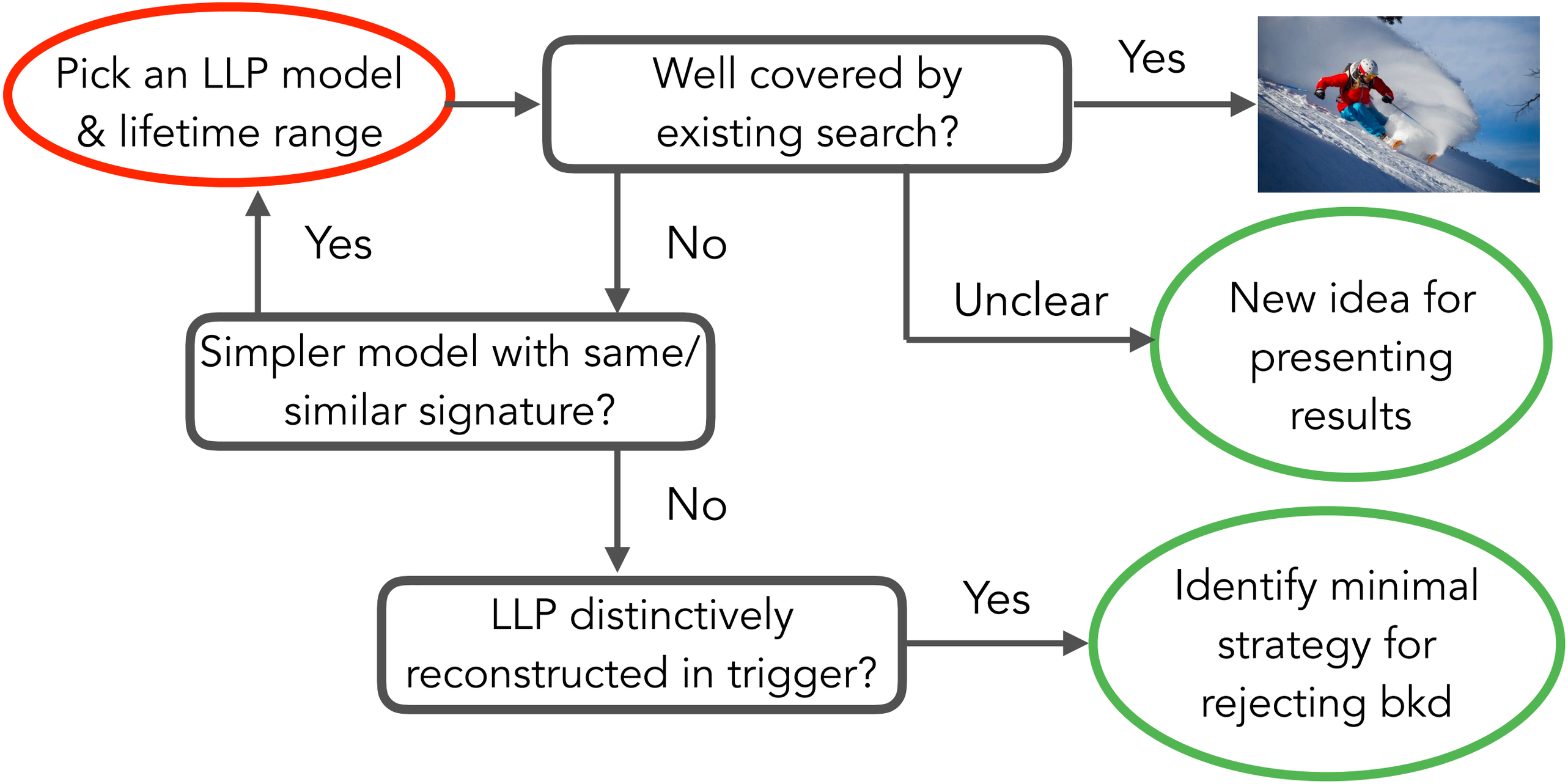

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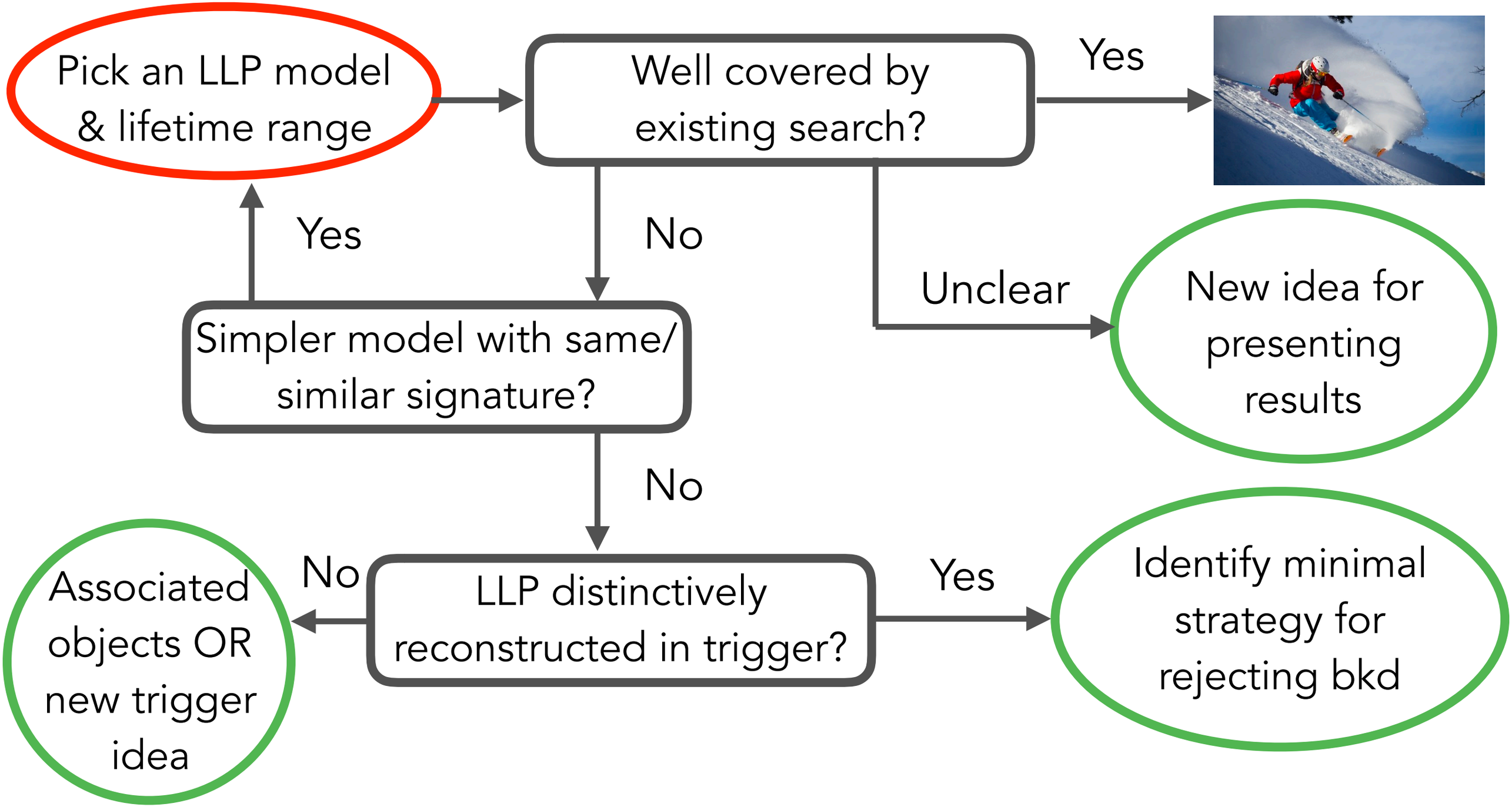


NEW LLP STRATEGIES

Pick an LLP model & lifetime range

Well covered by existing search?

Yes

No

Unclear

New idea for presenting results

Yes

Simpler model with same/ similar signature?

No

No

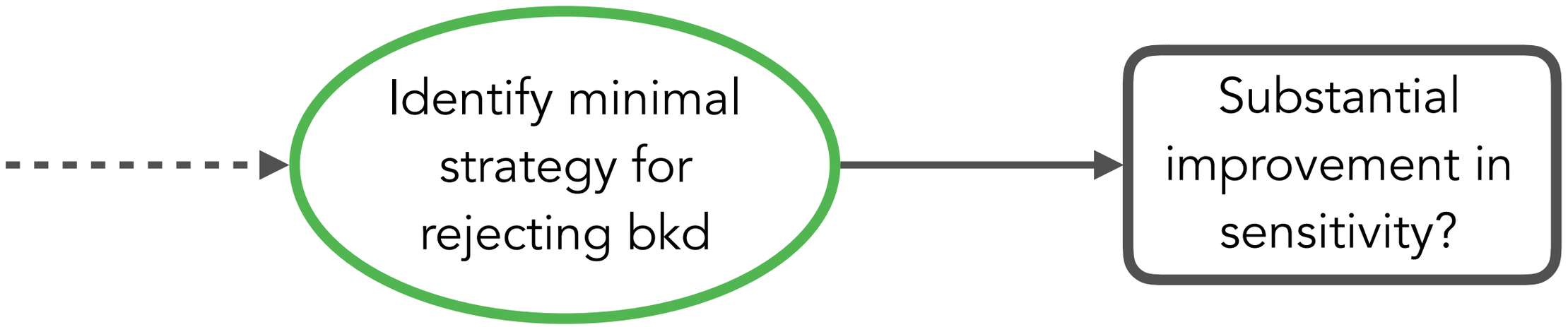
LLP distinctively reconstructed in trigger?

Yes

Associated objects OR new trigger idea

Identify minimal strategy for rejecting bkd

NEW LLP STRATEGIES



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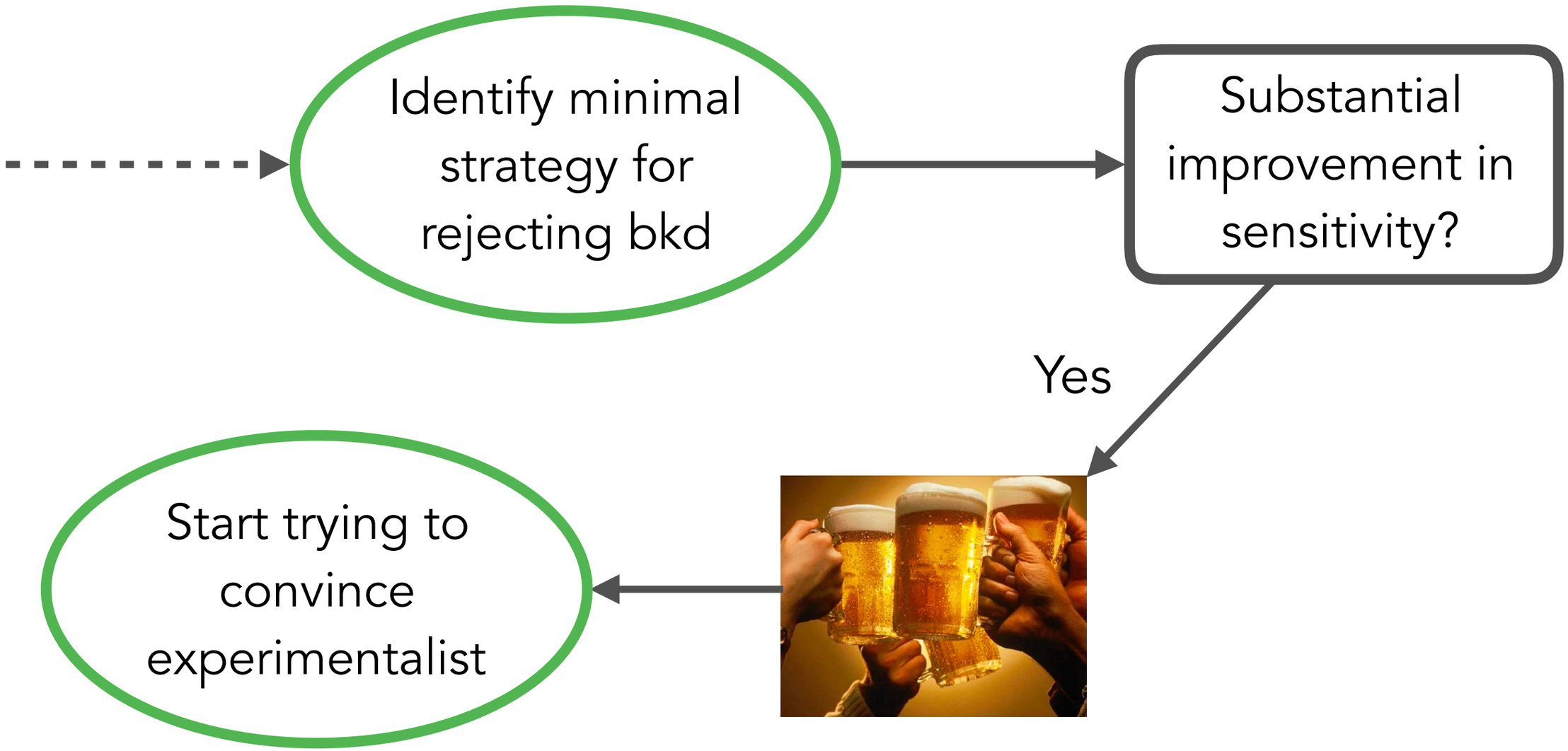

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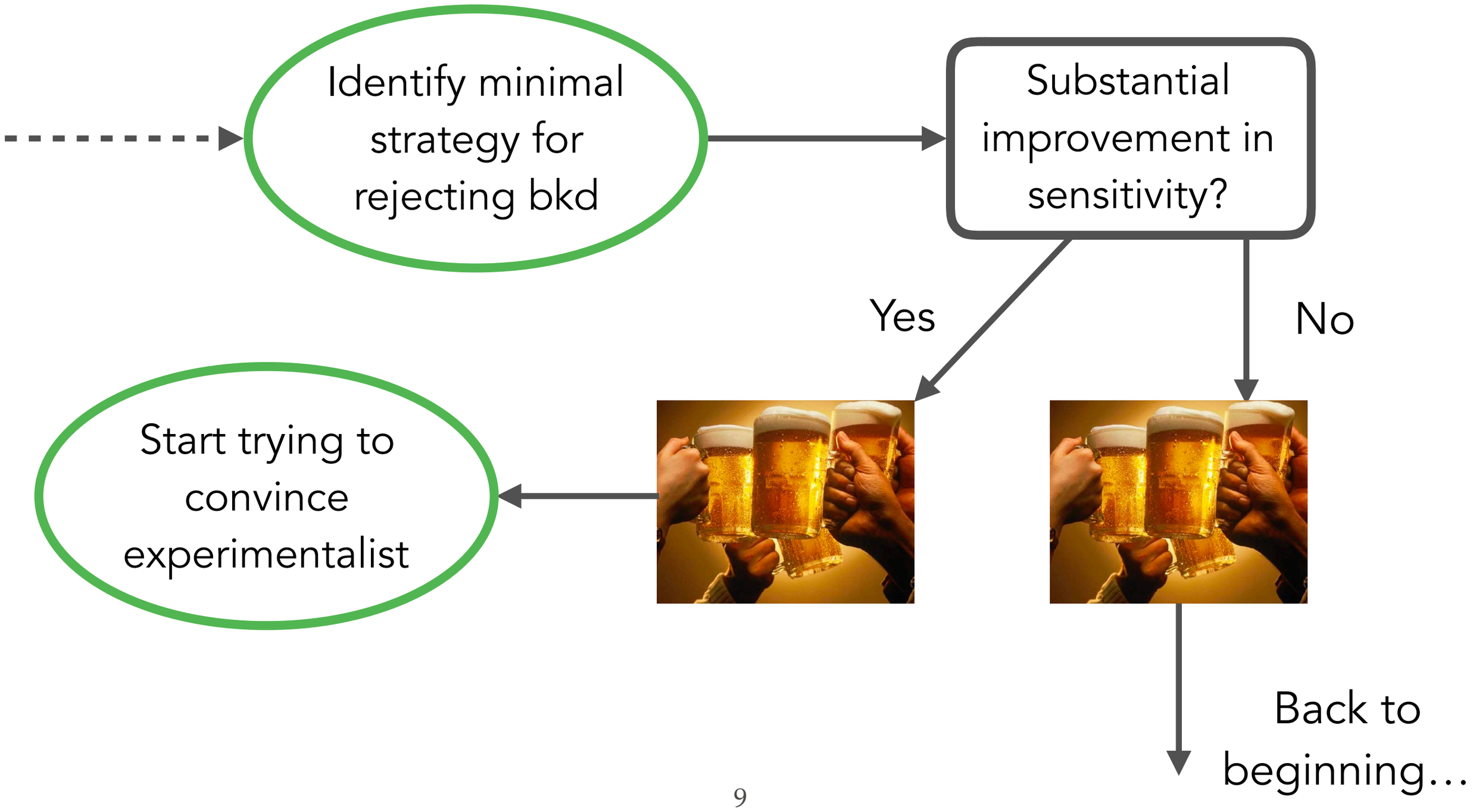
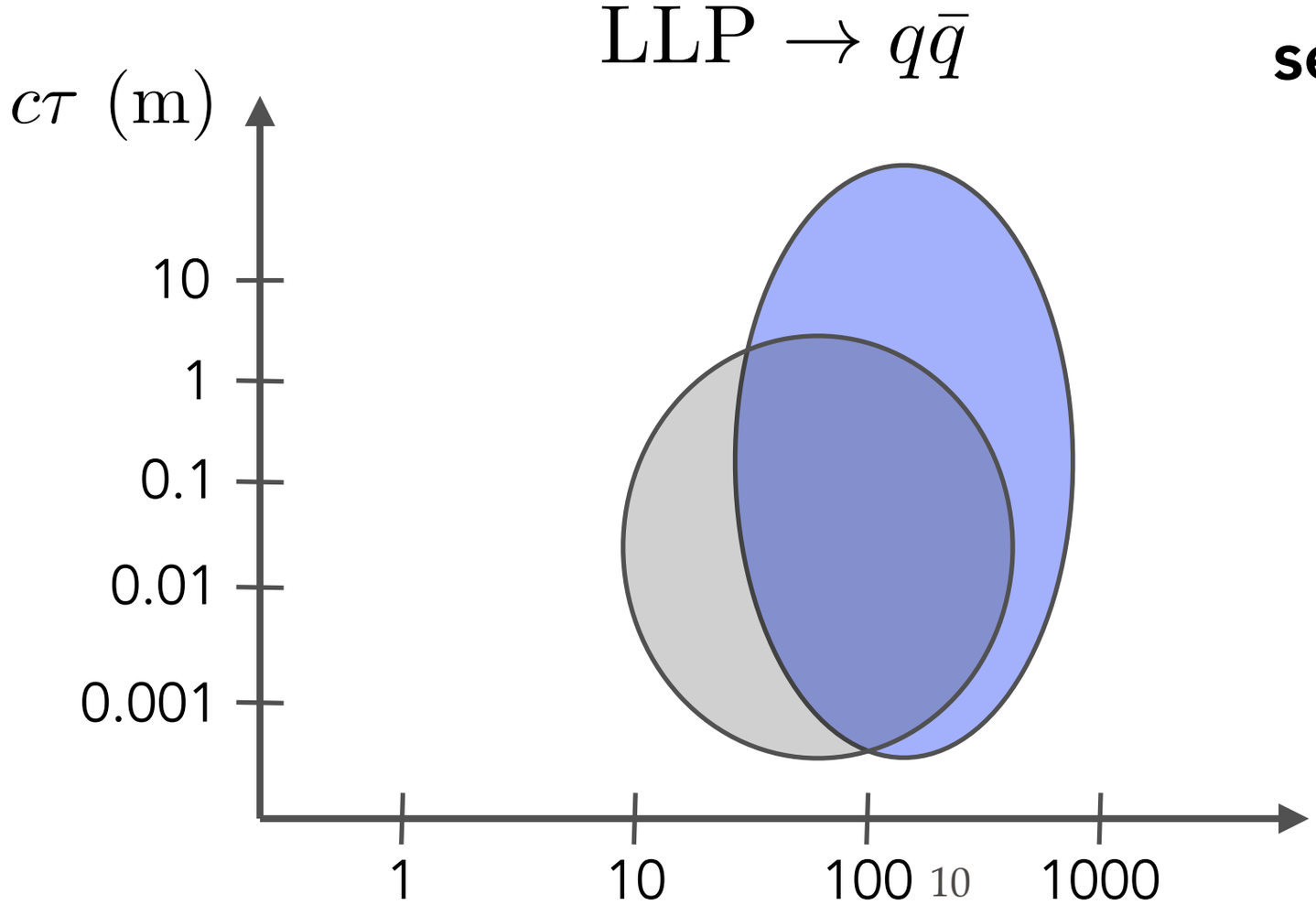


J. Alimena *et al.* (incl BS),1903.04497; see also, *e.g.*, Curtin *et al.*, 2013; Csaki *et al.*, 2015; Curtin, Verhaaren 2015

LLP STRATEGIES: GOAL

- Find most efficient way to cover the best motivated parameter space
- Identify gaps that can be filled with new search strategies or detector upgrades



search for 1 hadronic vertex in tracker

$h(125) \to \mathrm{LLP} + \mathrm{LLP}$

$\tilde{g} \to q + \mathrm{LLP}$

$Z'(500) \to \mathrm{LLP} + \mathrm{LLP}$

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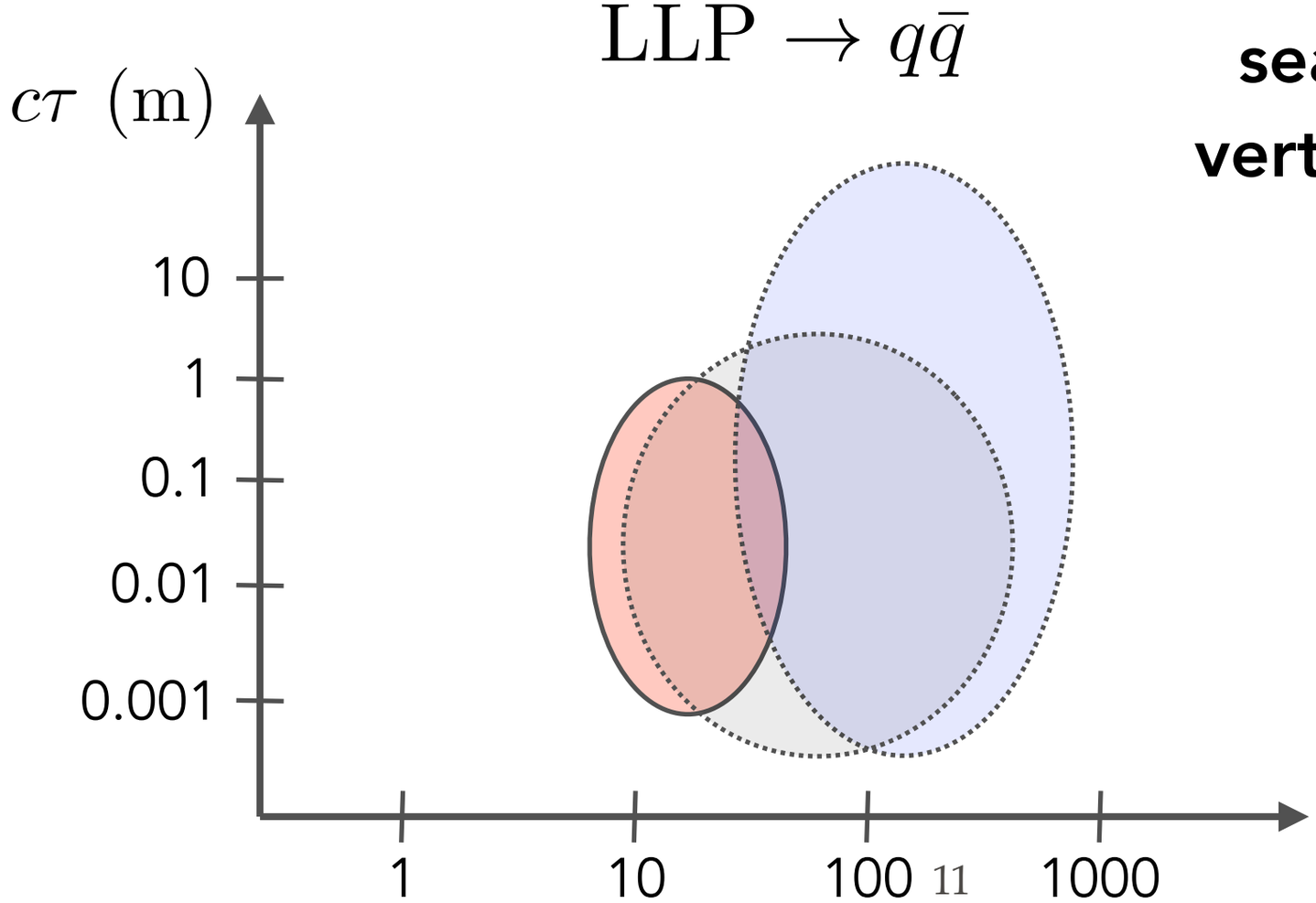

search for 1 hadronic vertex + prompt lepton

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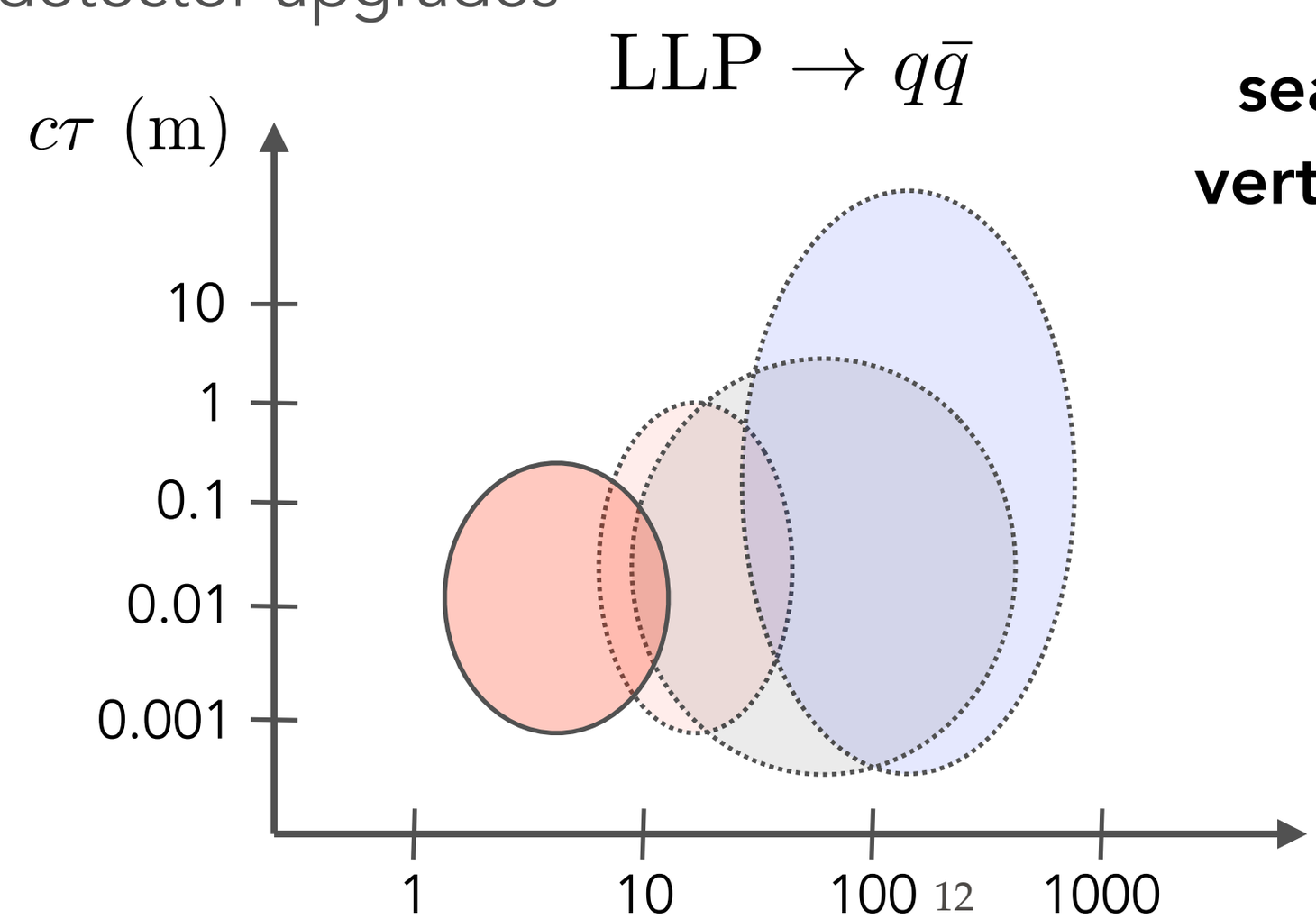

search for 2 hadronic vertex + prompt lepton

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$\tilde{g} \to q + \mathrm{LLP}$

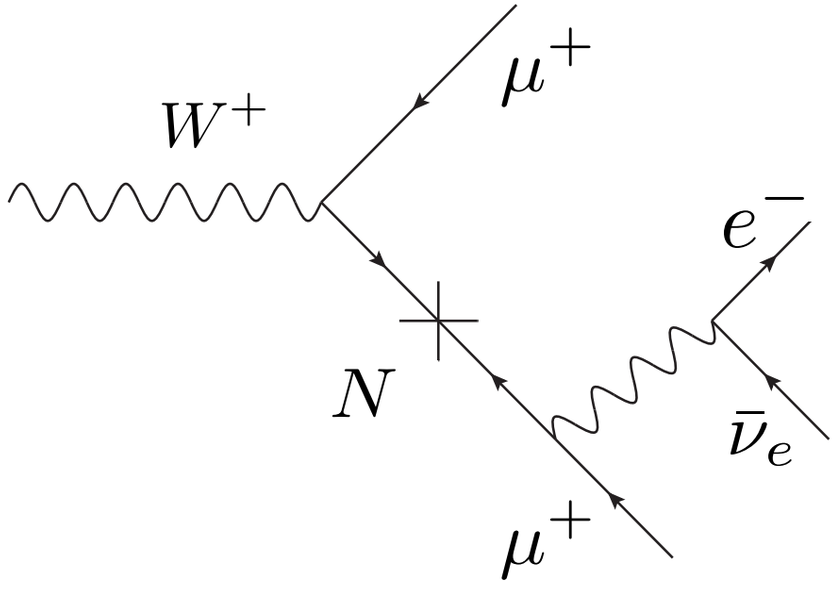
$Z'(500) \to \mathrm{LLP} + \mathrm{LLP}$

Izaguirre, BS, 1504.02470; see also Helo, Hirsch, Kovalenko, 1312.2900; Cottin, Helo, Hirsch, 1801.02734…

UNCHARTED EXAMPLES

- Some simple signatures not currently covered:

Sterile Neutrino:



Other production modes: Atre *et al.*, 2009; Basso *et al.*, 2009; Fileviez Perez *et al.*, 2009; Batell, Pospelov, BS, 2016; Gago *et al.*, 2015; Accomando *et al.*, 2016

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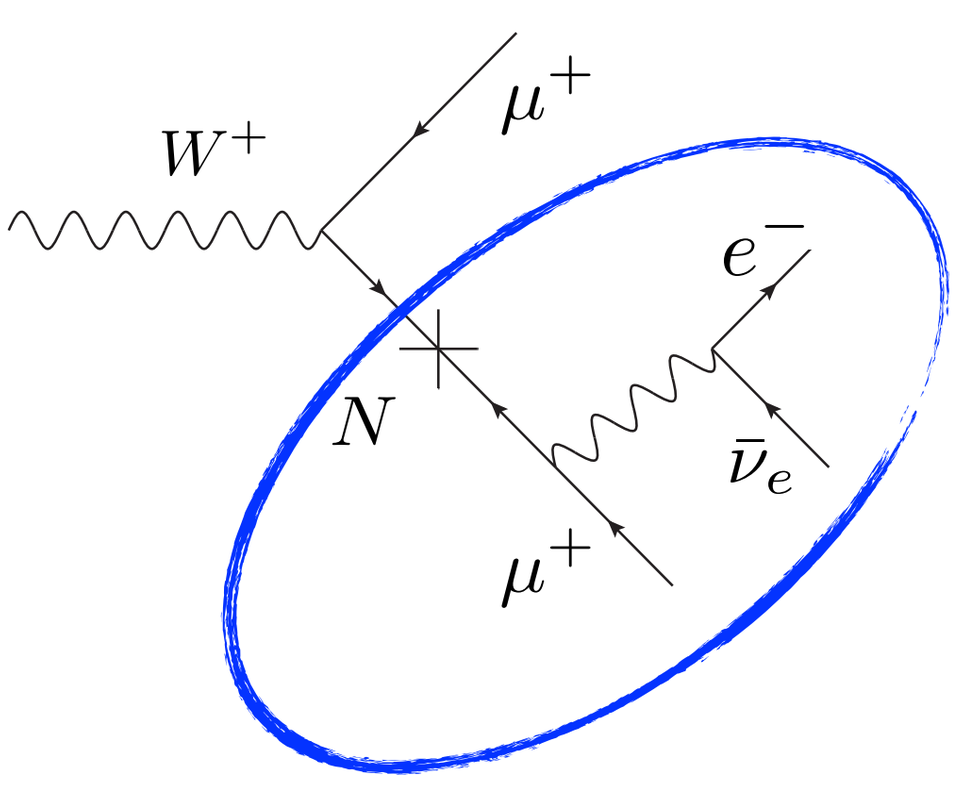

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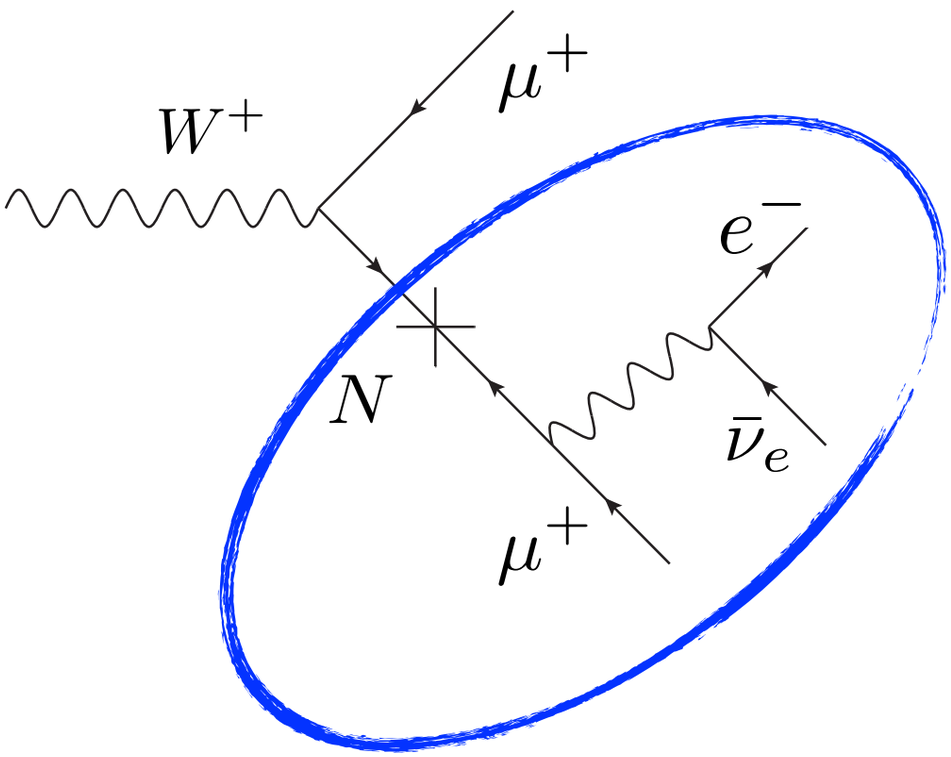
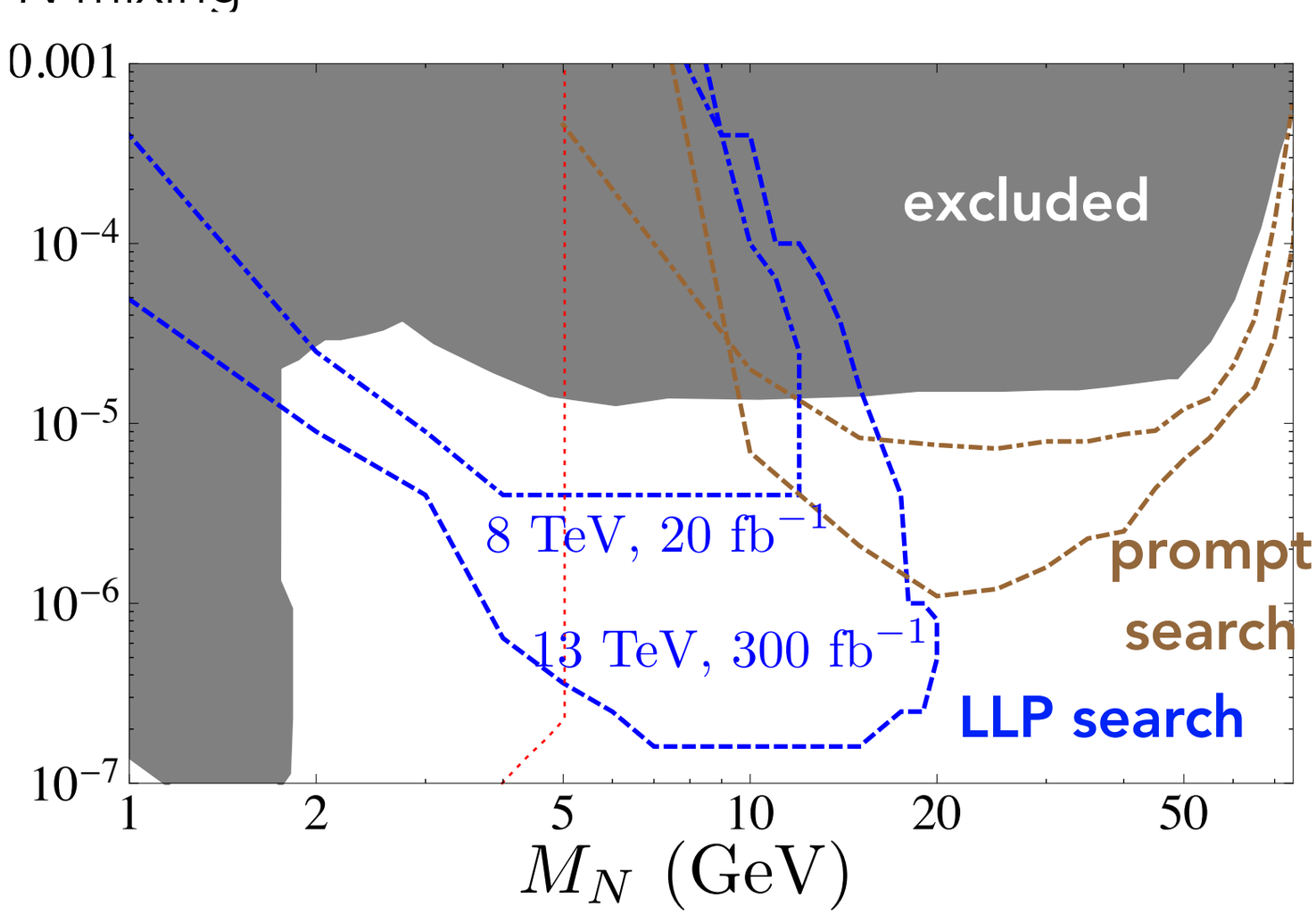


LLP



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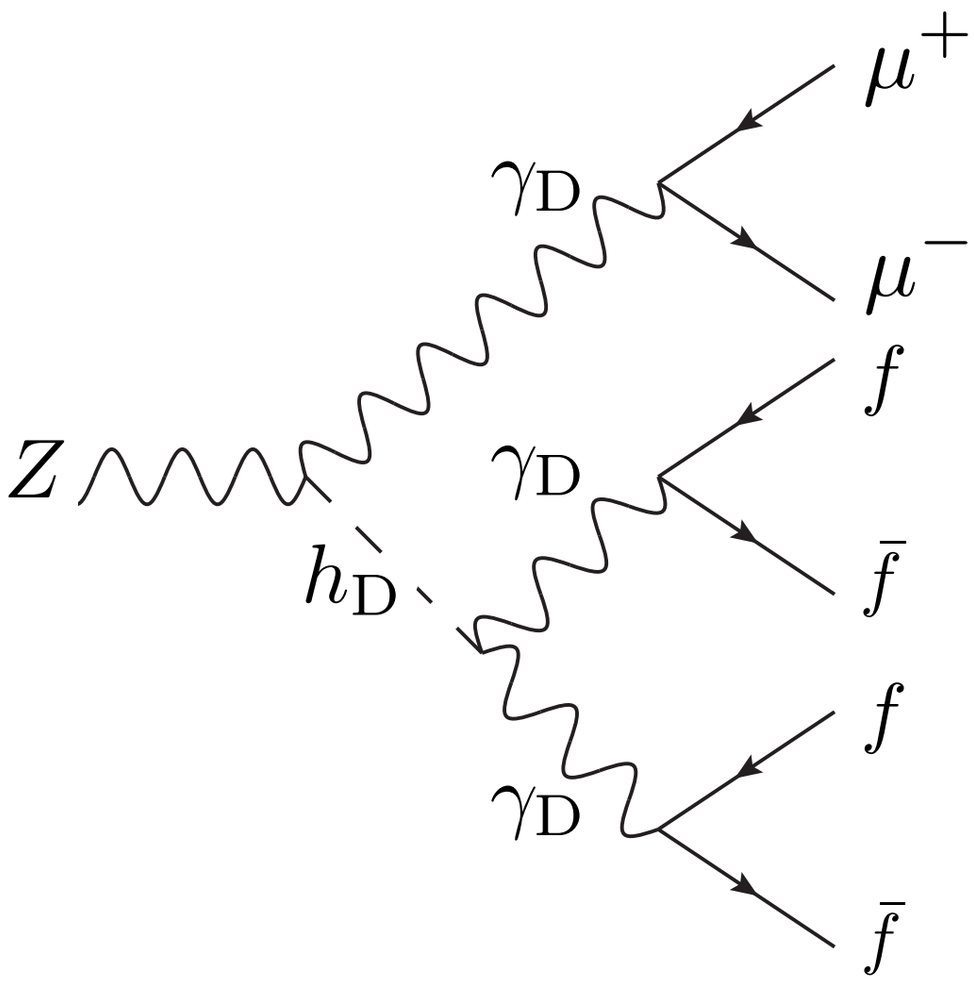
UNCHARTED EXAMPLES

Dark Higgs+Dark Photon:

- Z can decay up to 6 leptons!



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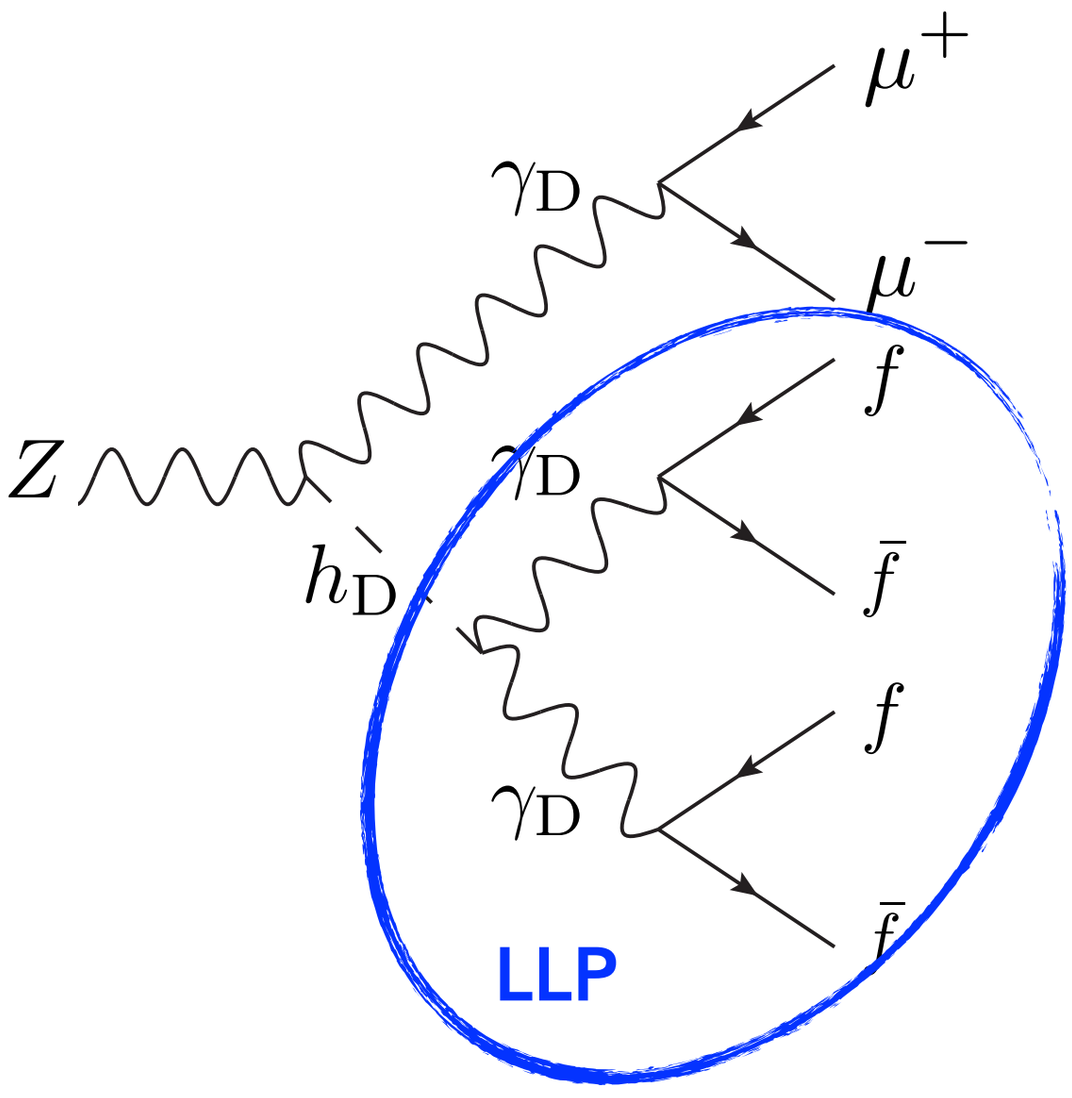

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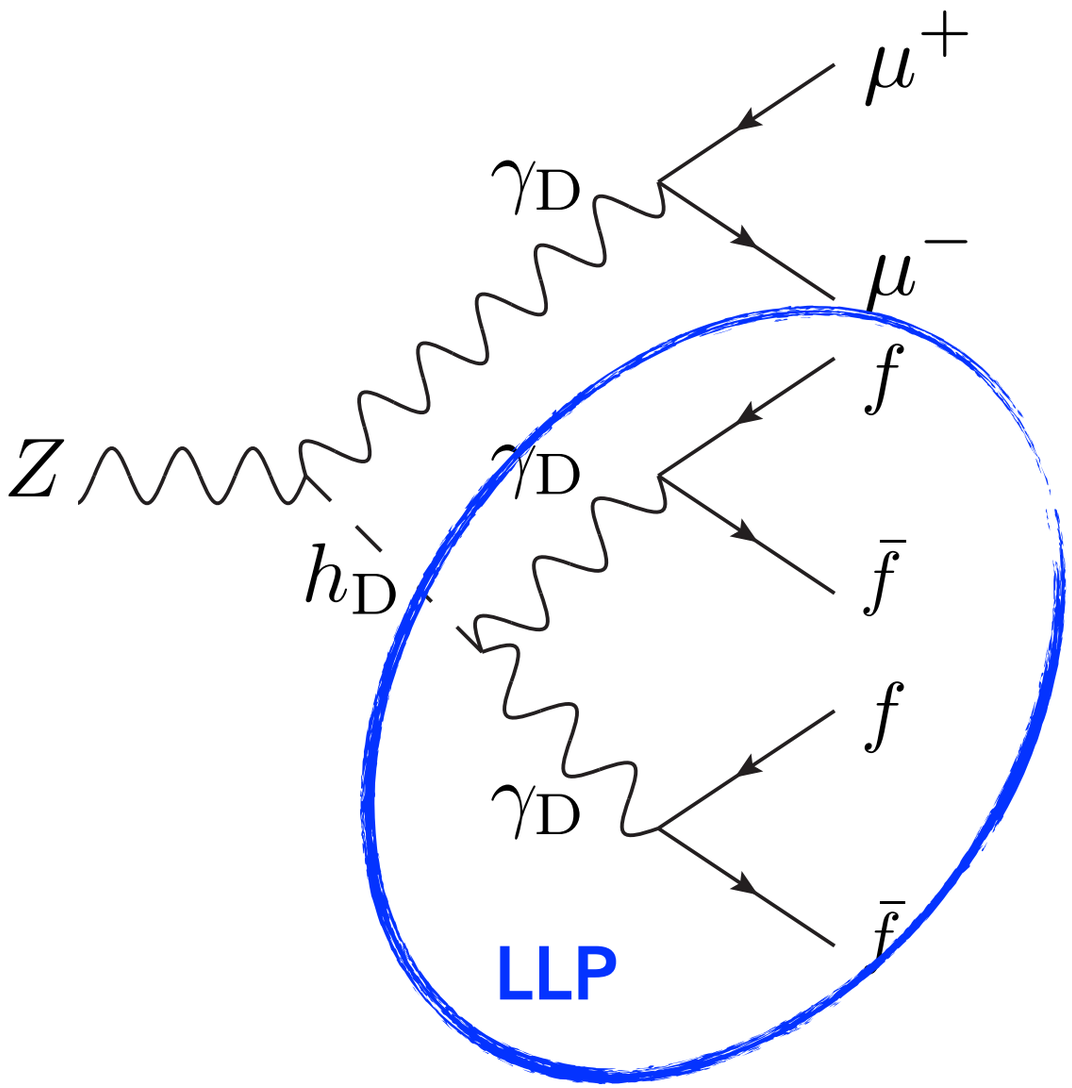
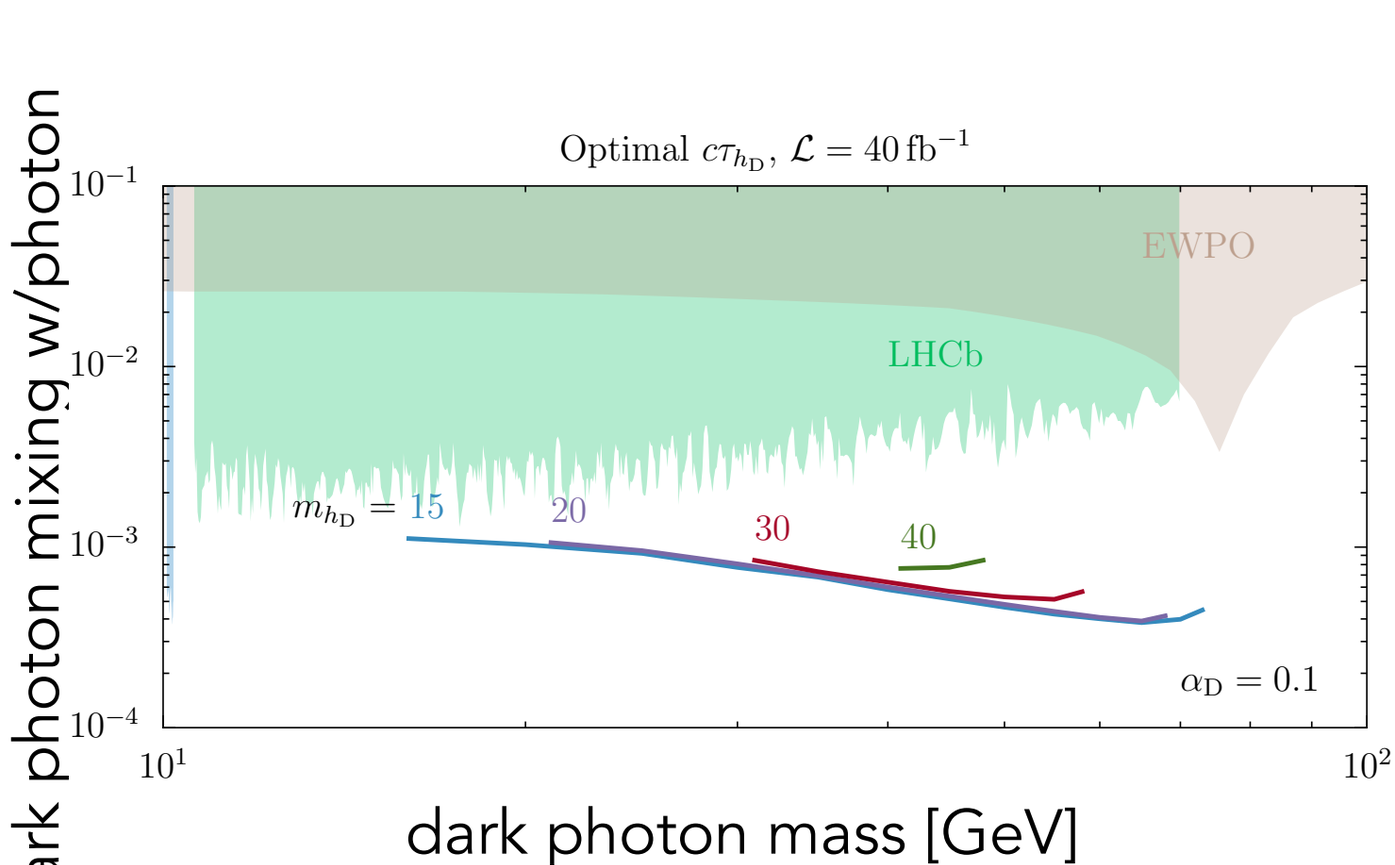


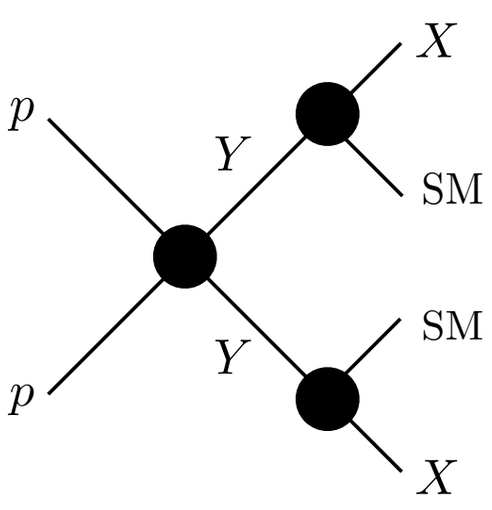


LHC LLP COMMUNITY

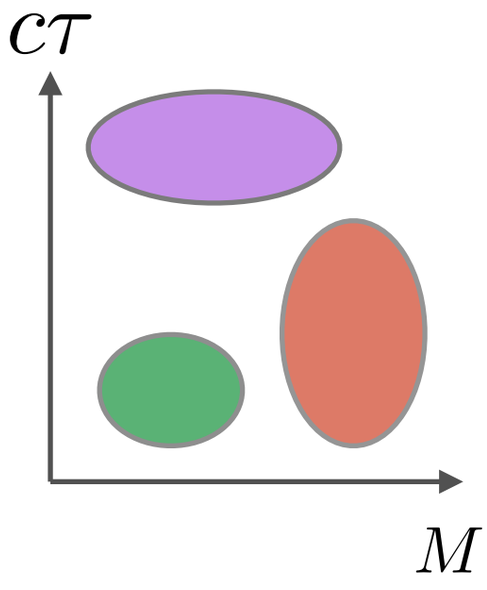
J. Alimena *et al.*, arXiv:1903.04497, submitted to J Phys G

Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider

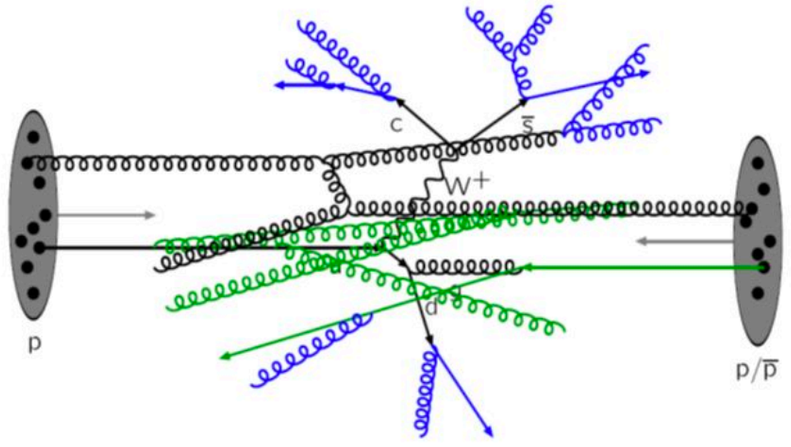
Document editors: James Beacham, Brian Shuve



organize production + decay modes



develop & synthesize current coverage, gaps, & proposals



model library & simulation frameworks

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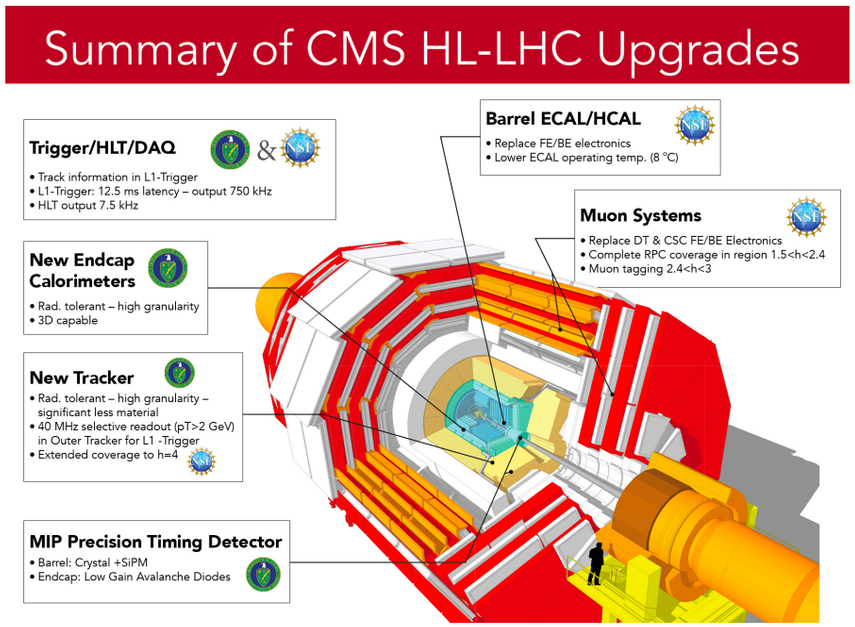
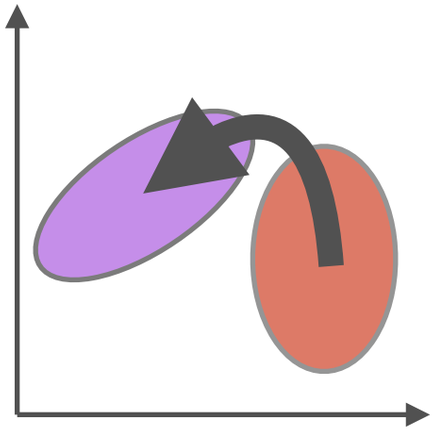
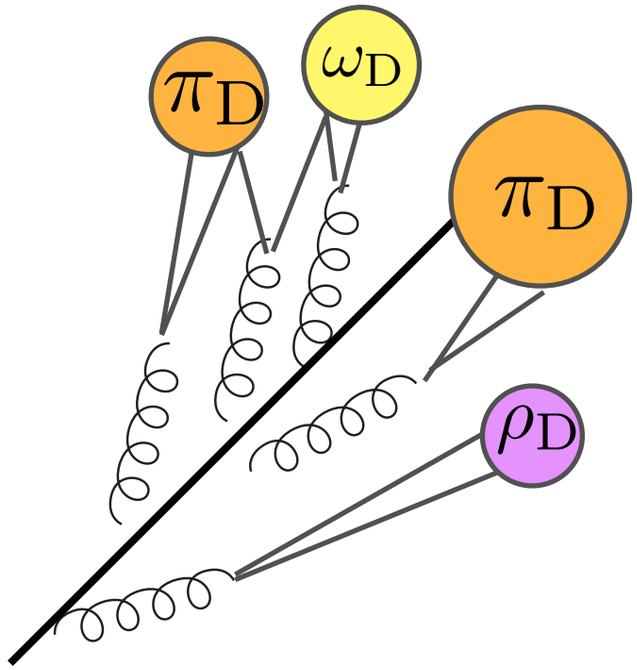


LLP potential & studies with upgraded detectors



reinterpretations of search results

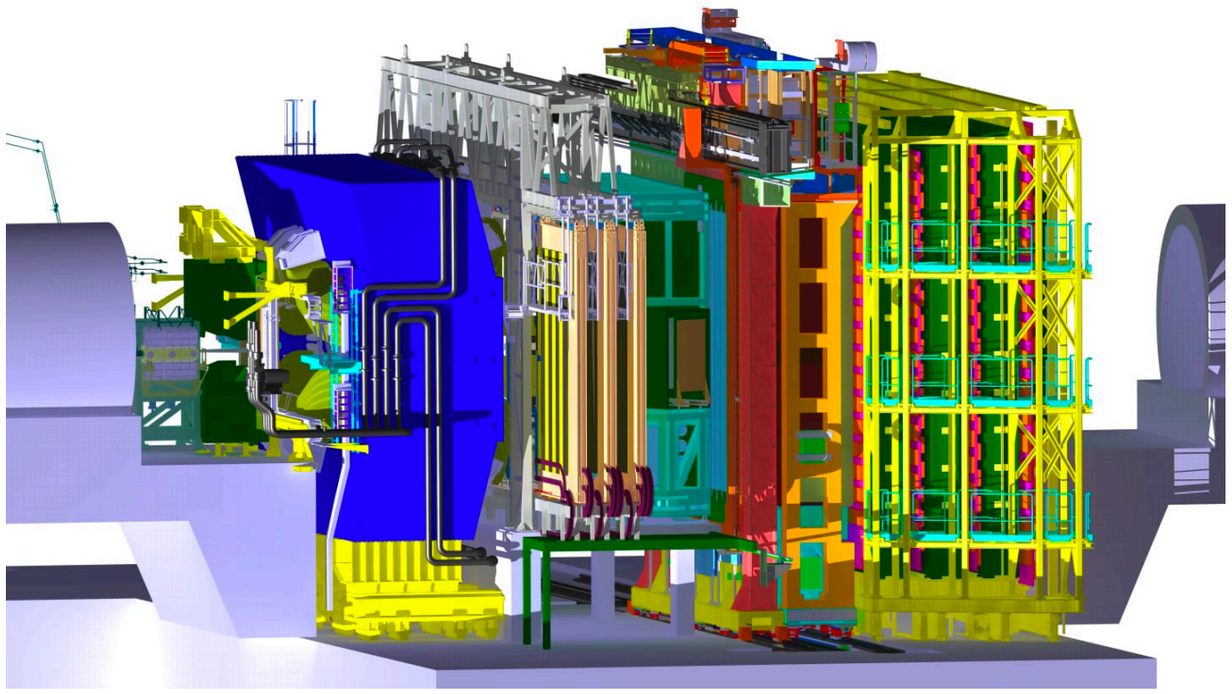


high multiplicities of LLPs, dark showers

WHAT'S NEXT AT LHC?

- LHCb trigger upgrade will allow fully online reconstruction in LHC Run 3 (starting 2021)
- LHCb prospects generally under-explored

see P. Ilten *et* al., 2016; A. Pierce *et al.*, 2017; S. Antusch *et al.*, 2017; BS, Peskin, 2016



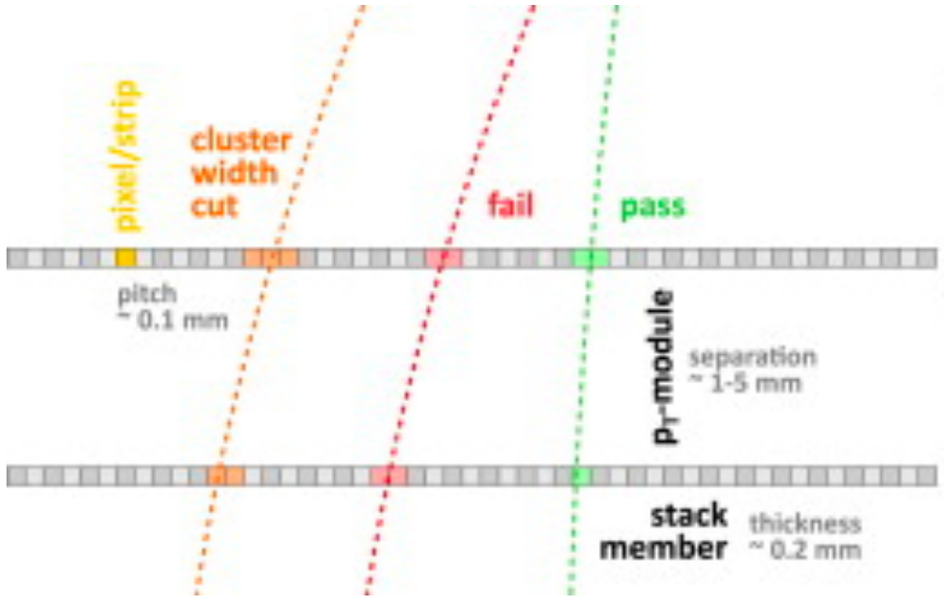
Examples of new ideas:

- Search for "true muonium" in displaced e^+e^-

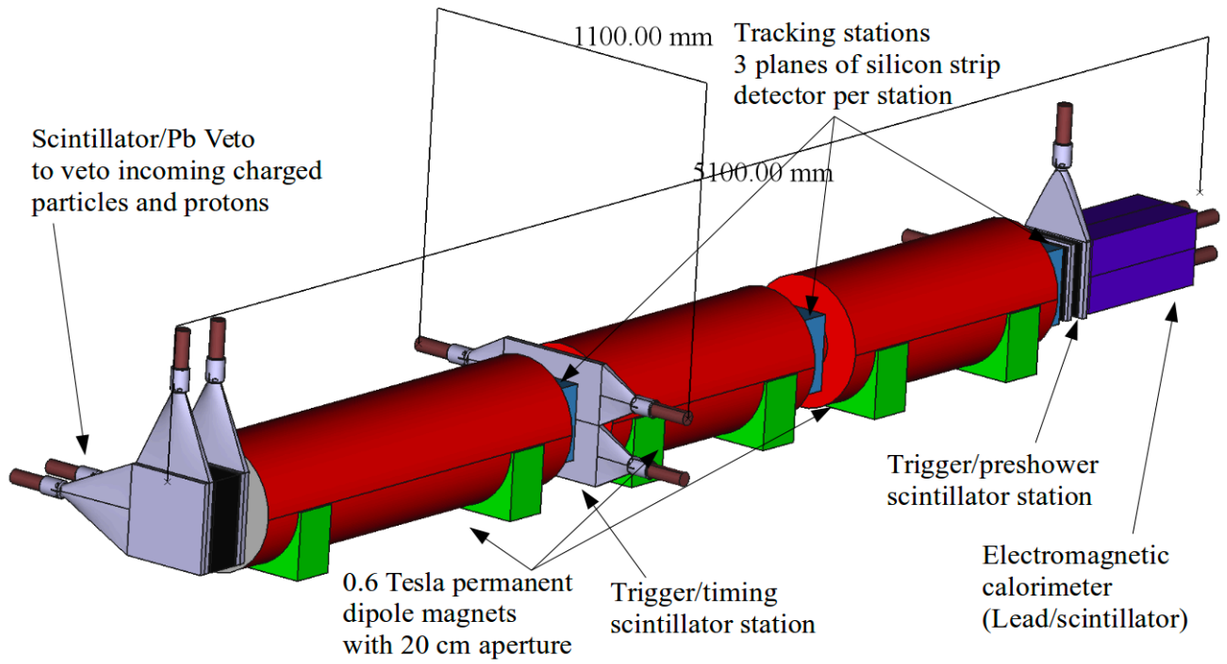
  Cid Vidal, Ilten, Plews, BS, Soreq, in progress
- Search for displaced hadronic LLPs in exclusive decays

  Cid Vidal, Pospelov, BS, Tsai, Zurita, in progress

WHAT'S NEXT AT LHC?

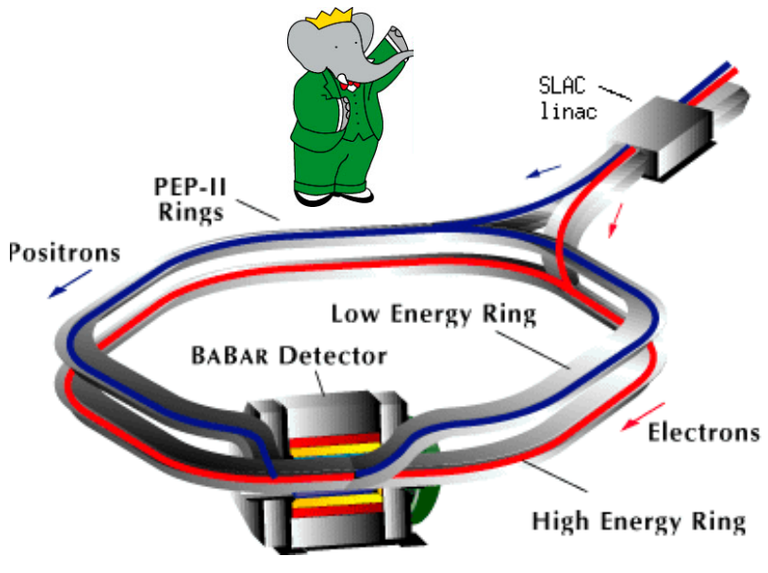


detector upgrades
(see Zhen's talk!)



new LHC detectors (see
Gaia's & Iftah's talk!)

LOWER ENERGY PROBES



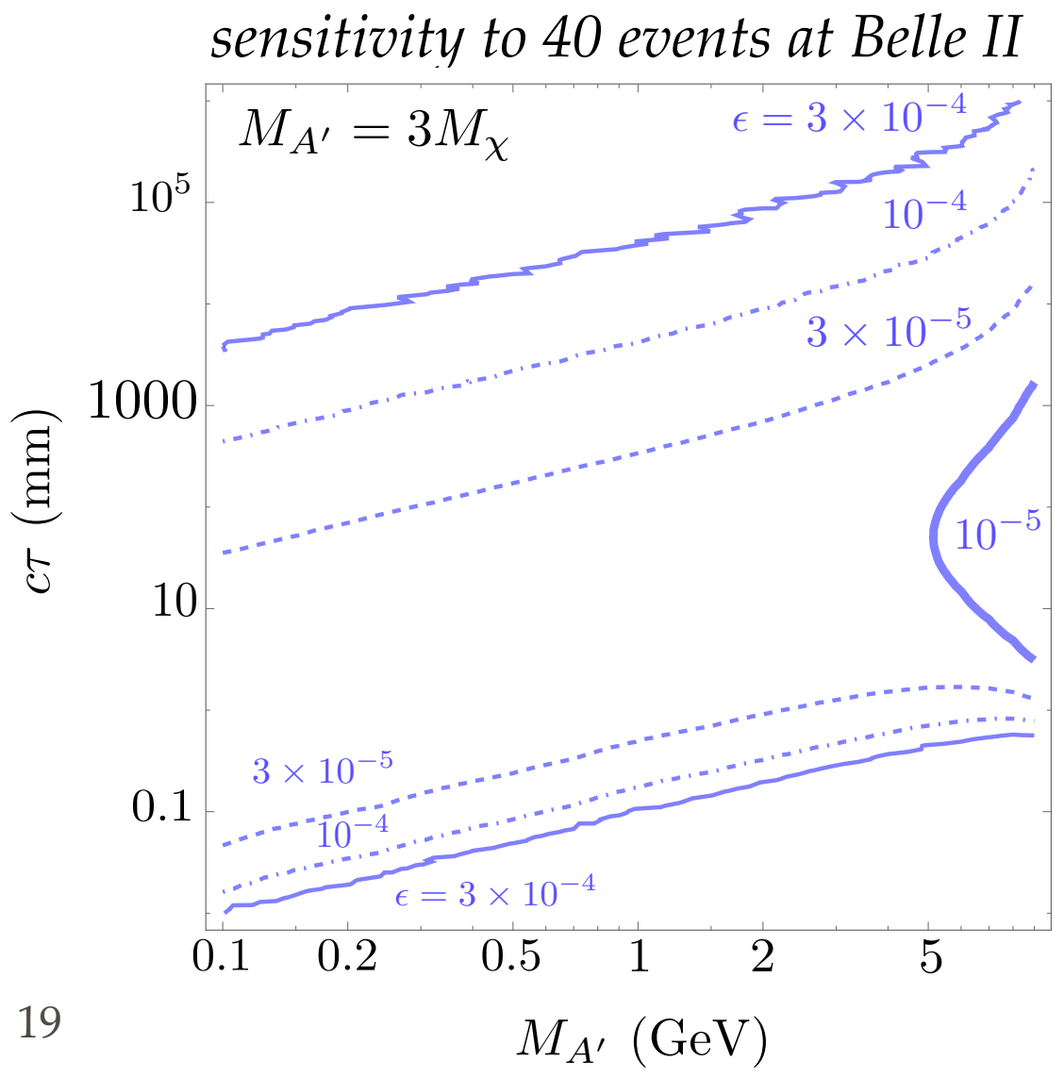
- B factories are lower energy but high intensity: best current sensitivity to many hidden sectors!

(see Gerald's talk!)

- There currently aren't many LLP searches

- Simple model:

$$e^+e^- \to \gamma A', A' \to XX$$



NEW PARTICLES & PARADIGMS

- Expanding interest in LLPs from hidden sectors and other theoretical motivations

- Exquisite understanding of detectors allows for ultra low backgrounds for LLP searches

- Growing excitement means more resources and person-power for LLP searches

- Upgrades to LHC detectors leading to new ideas for LLP reconstruction

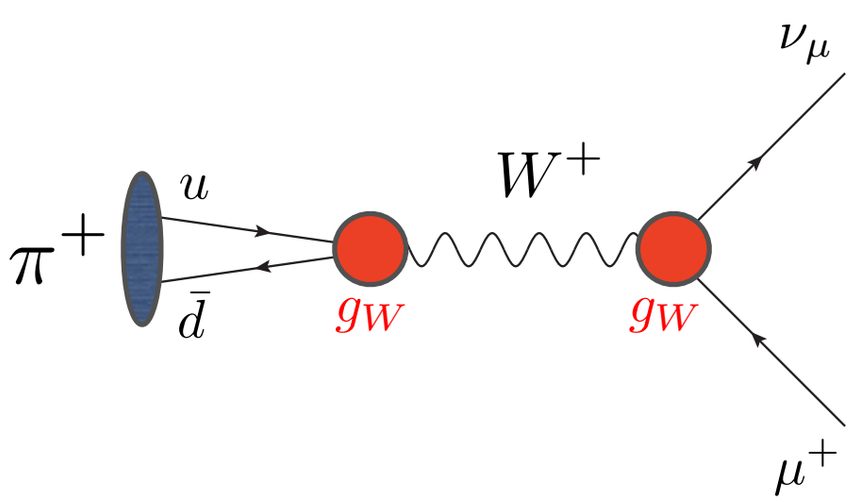
- Plethora of new low-energy experiments probing very light, very rare production of LLPs

BACKUP SLIDES

WHY LONG-LIVED PARTICLES?

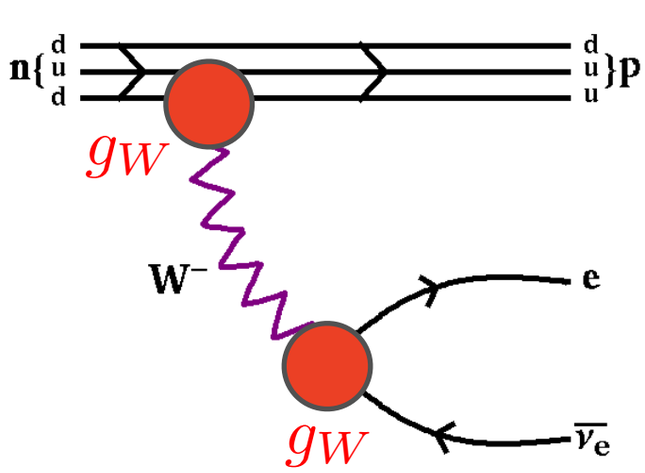
- What could make $\Gamma \ll M$?

Symmetries/off-shell decays:



$$\Gamma_{\pi^+} \sim g_W^4 \left(\frac{M_{\pi^+}^2 M_\mu^2}{M_W^4} \right) M_{\pi^+}$$

Small phase space:



$$\Gamma_n \sim g_W^4 \left(\frac{\Delta M}{M_W} \right)^4 \Delta M$$

WHY LONG-LIVED PARTICLES?

- Example: thermal DM below the weak scale (~GeV)
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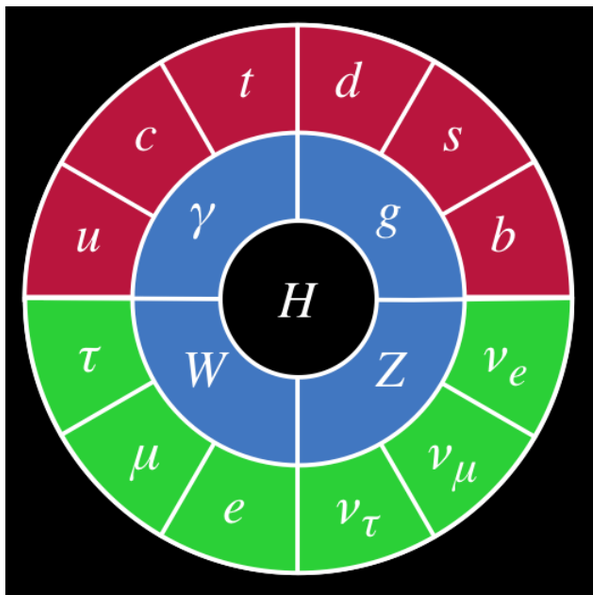
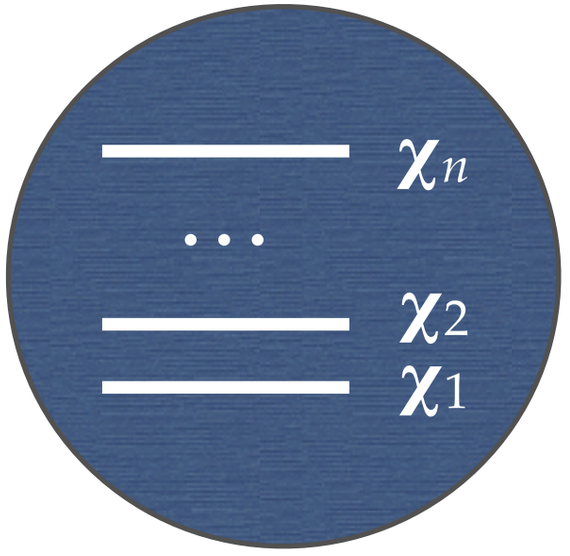
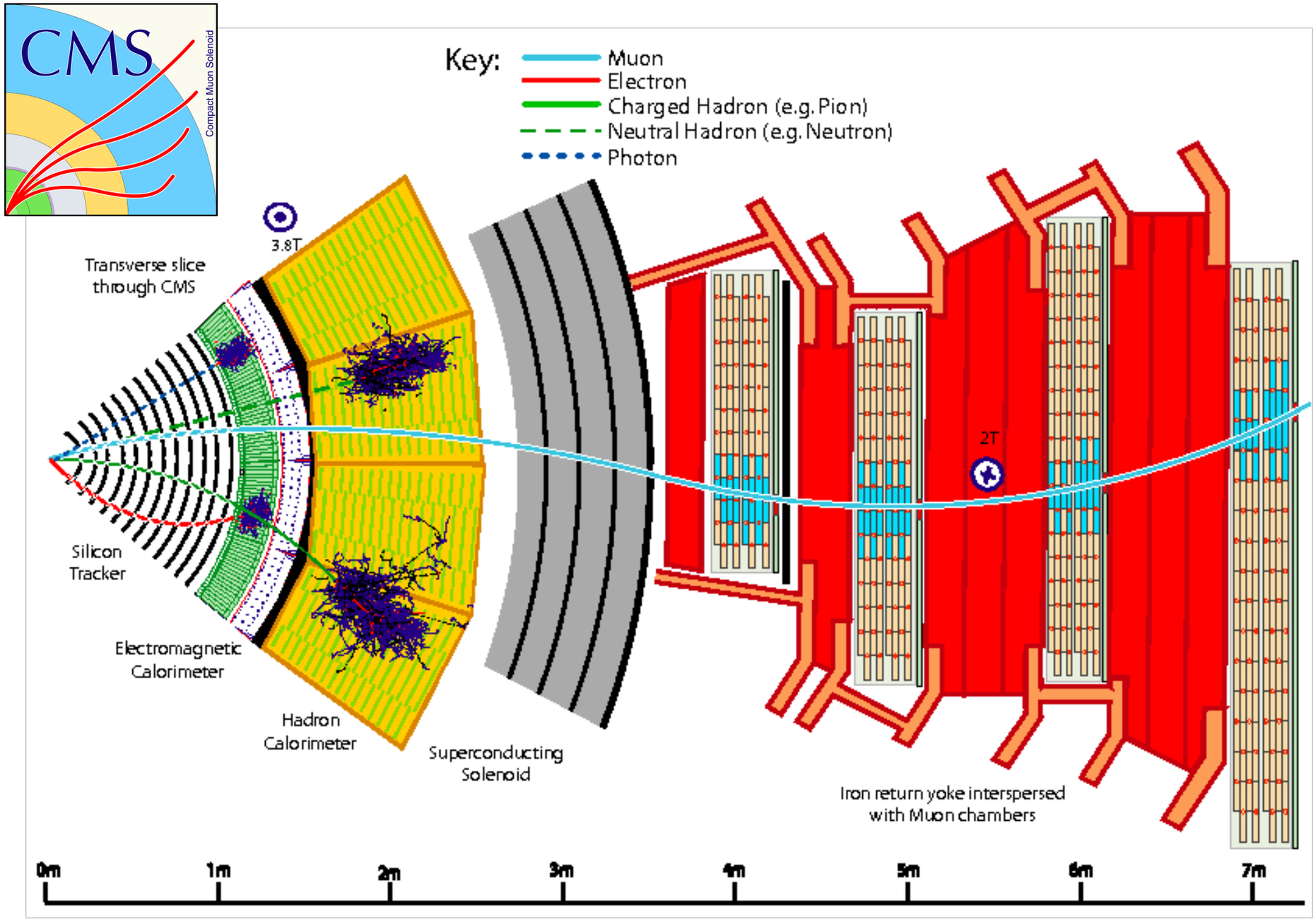


a'

$$\frac{\alpha_{a\chi}\alpha_{a\mathrm{SM}}}{M_\chi^2} \sim \frac{10^{-9}}{\mathrm{GeV}^2}$$

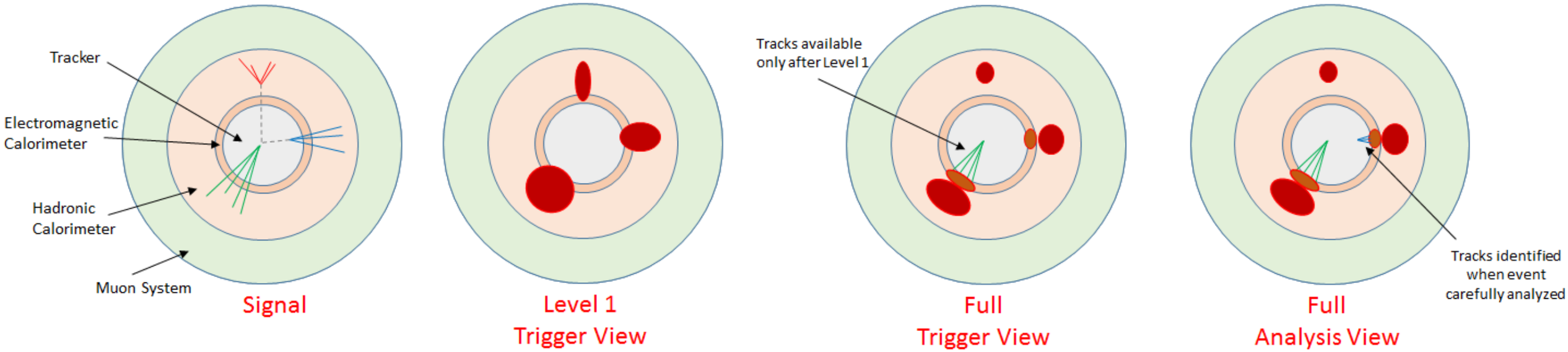


LLPS AT LHC


CMS
Compact Muon Solenoid
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
Transverse slice through CMS
3.8T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0m
1m
2m
3m
4m
5m
6m
7m

LLPS AT LHC

- But are events even recorded/reconstructed?

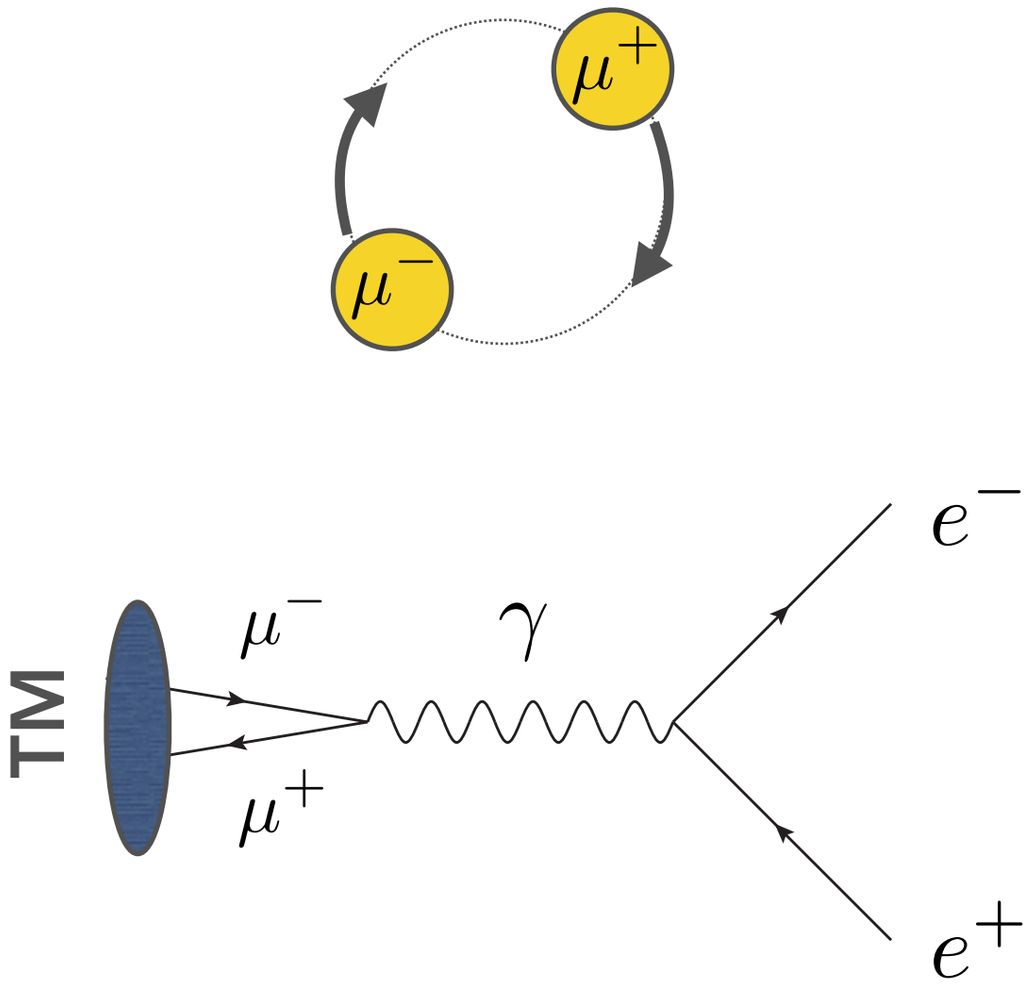


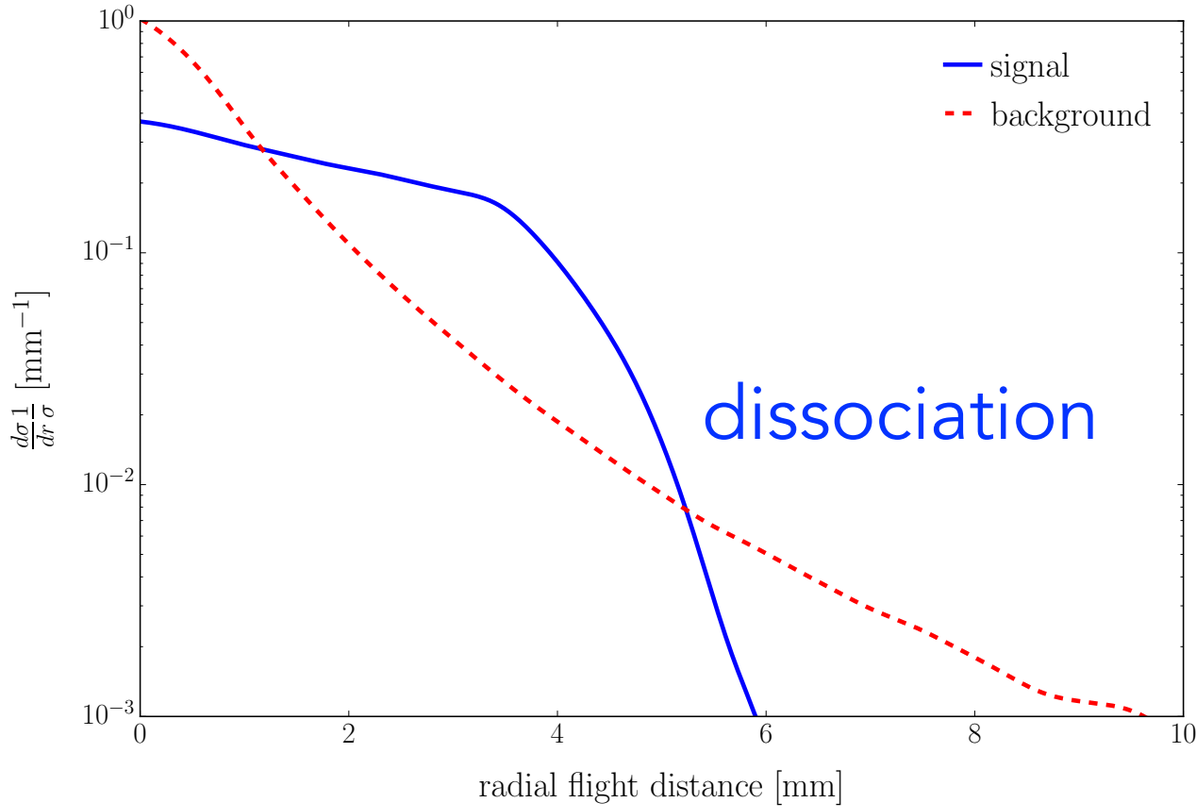
Matt Strassler, 2014

Cid Vidal, Ilten, Plews, BS, Soreq, in progress

WHAT'S NEXT AT LHC?

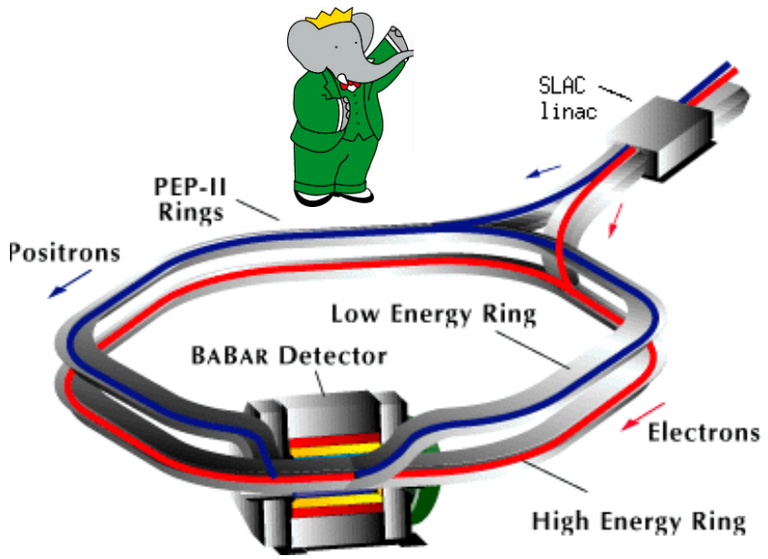
- True muonium





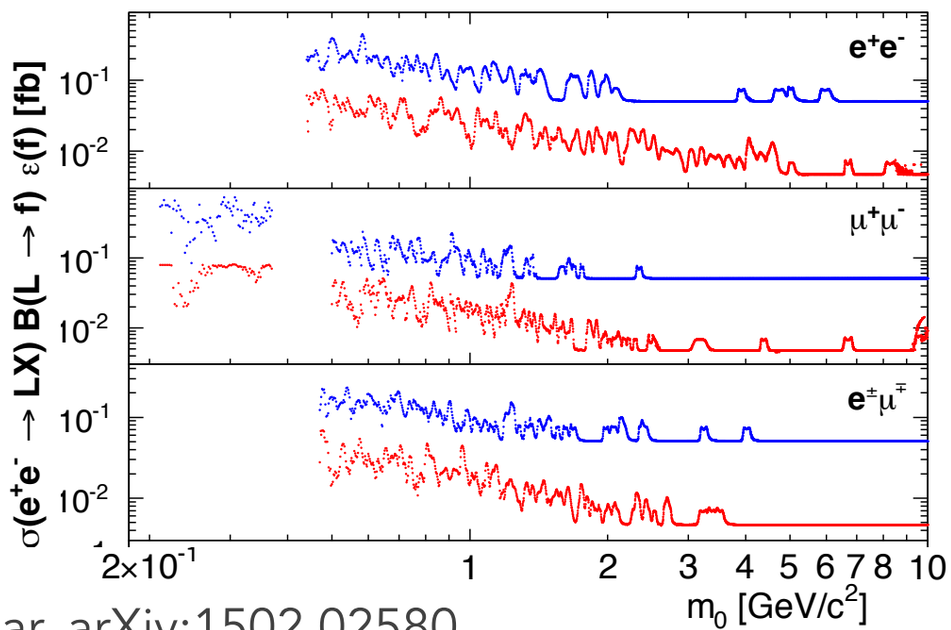
- Trigger, background under control
- Discovery possible with 15/fb!

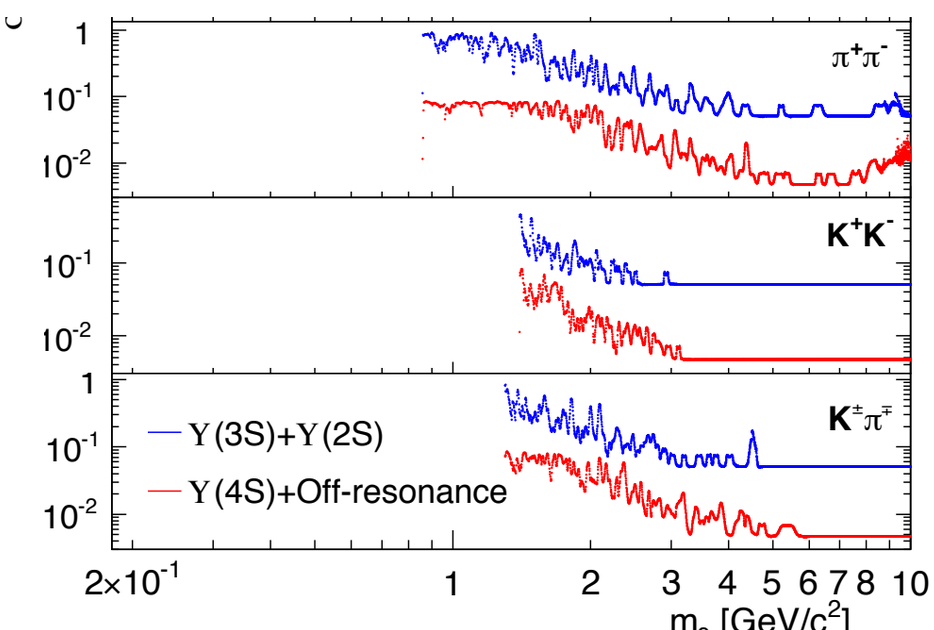
LOWER ENERGY PROBES



- BaBar and Belle II are e+e- colliders
- Lower energy but high intensity: best current sensitivity to many hidden sectors! (see Gerald's talk!)

- There currently aren't many LLP searches





BaBar, arXiv:1502.02580

LOWER ENERGY PROBES

- Backgrounds can be mitigated with 2 DVs or > 2 tracks
- Potentially extremely good sei
- Simple model:

$$e^+e^- \to \gamma A', A' \to XX$$

- Require both LLPs to decay within 0.5 cm < L_{xy} < 30 cm
- Sensitivity to particular production & decay modes ongoing

sensitivity to 40 events at Belle II