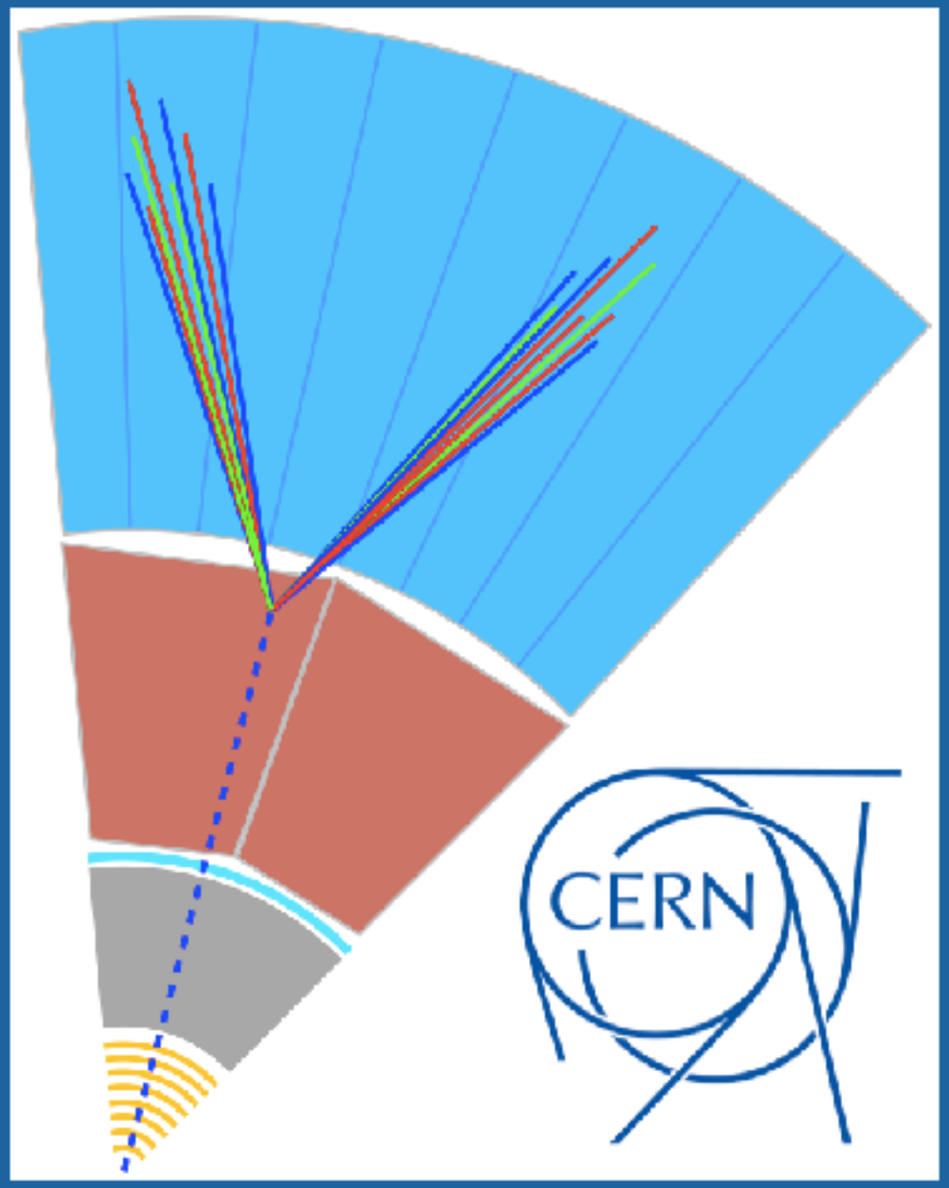


The LHC Long-Lived Particle Community

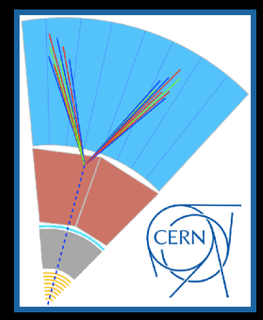
Physics Beyond Colliders workshop

14 June 2018

James Beacham [ATLAS/Ohio State]
Brian Shuve [Harvey Mudd]

on behalf of the group

New physics X at the LHC



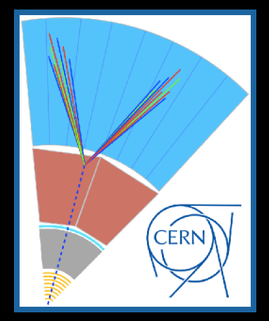
m_X

$\mathcal{O}(mm)$

$c\tau_X$

Outer edge of detector

New physics X at the LHC



The overwhelming majority of the work of the LHC experiments

m_X

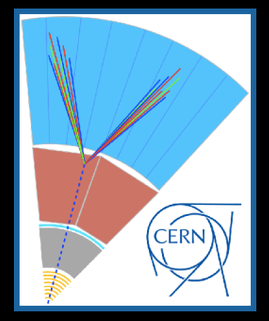
Stable

$\mathcal{O}(mm)$

$c\tau_X$

Outer edge of detector

New physics X at the LHC



The overwhelming majority of the work of the LHC experiments

Stable

m_X

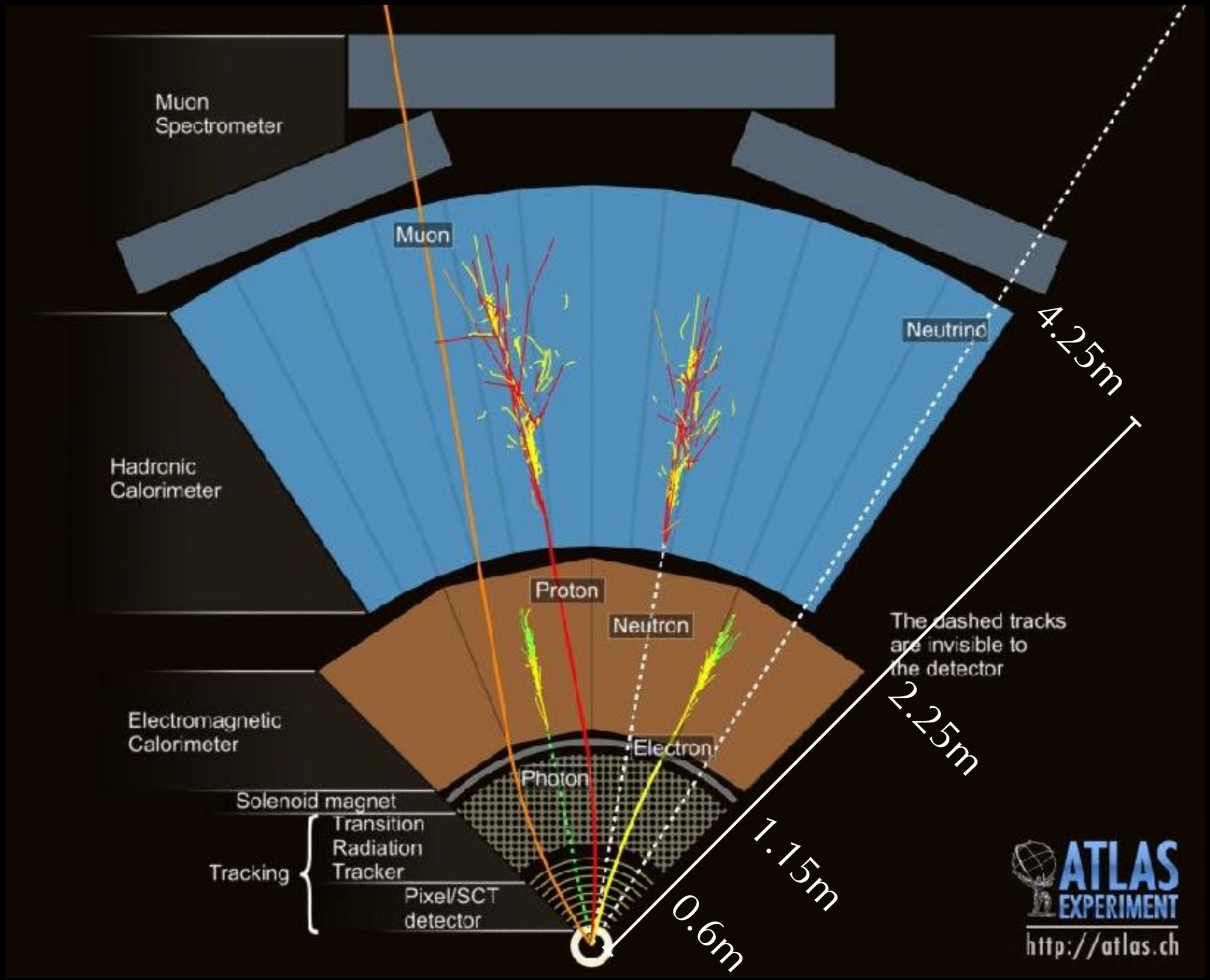
New physics could be hiding here

$\mathcal{O}(mm)$

$c\tau_X$

Outer edge of detector

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



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

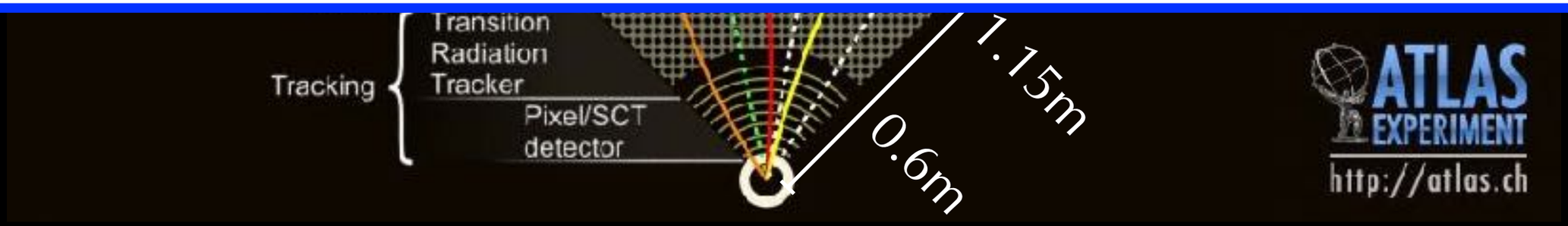
What we want:

- To reduce to negligible to chance that we'll miss new physics at the LHC

What we have:

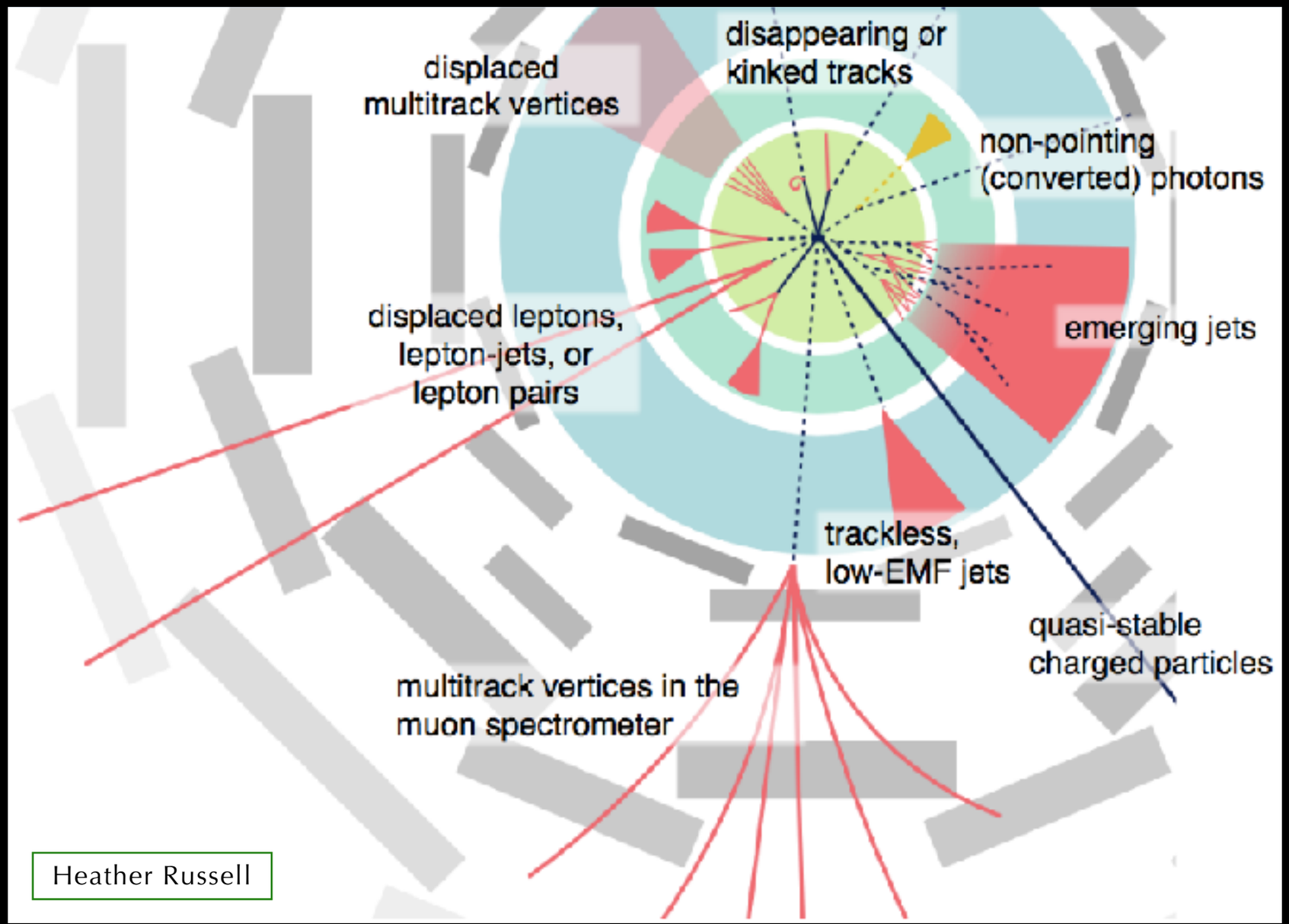
- The most sophisticated general-purpose detectors ever built at the highest *pp* √s ever used

Shift from model-first / signature-second to signature-first / model-second mindset



The LHC LLP Community

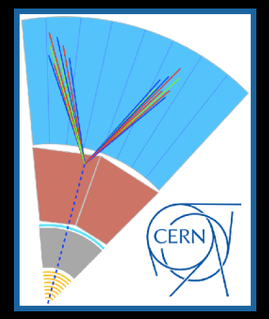
We map LLP signature space



What exactly do we mean by long-lived particle in the LHC context?

For our purposes, LLP = BSM particle with a non-negligible lifetime that dies (gives up all its energy or decays to SM) somewhere in the detector acceptance of LHCb, CMS, ATLAS, MilliQan, MoEDAL, FASER, Codex-b, MATHUSLA, etc.

The LHC LLP Community Initiative



Long-lived particle searches at ATLAS, CMS, LHCb are difficult

- Challenging triggering strategies
- Non-standard objects and reconstruction methods
- Baffling backgrounds irrelevant to standard searches for prompt or stable objects
- Difficult also means fun, but there's a danger we'll miss a possible discovery because of the atypical nature of these signatures

One question:

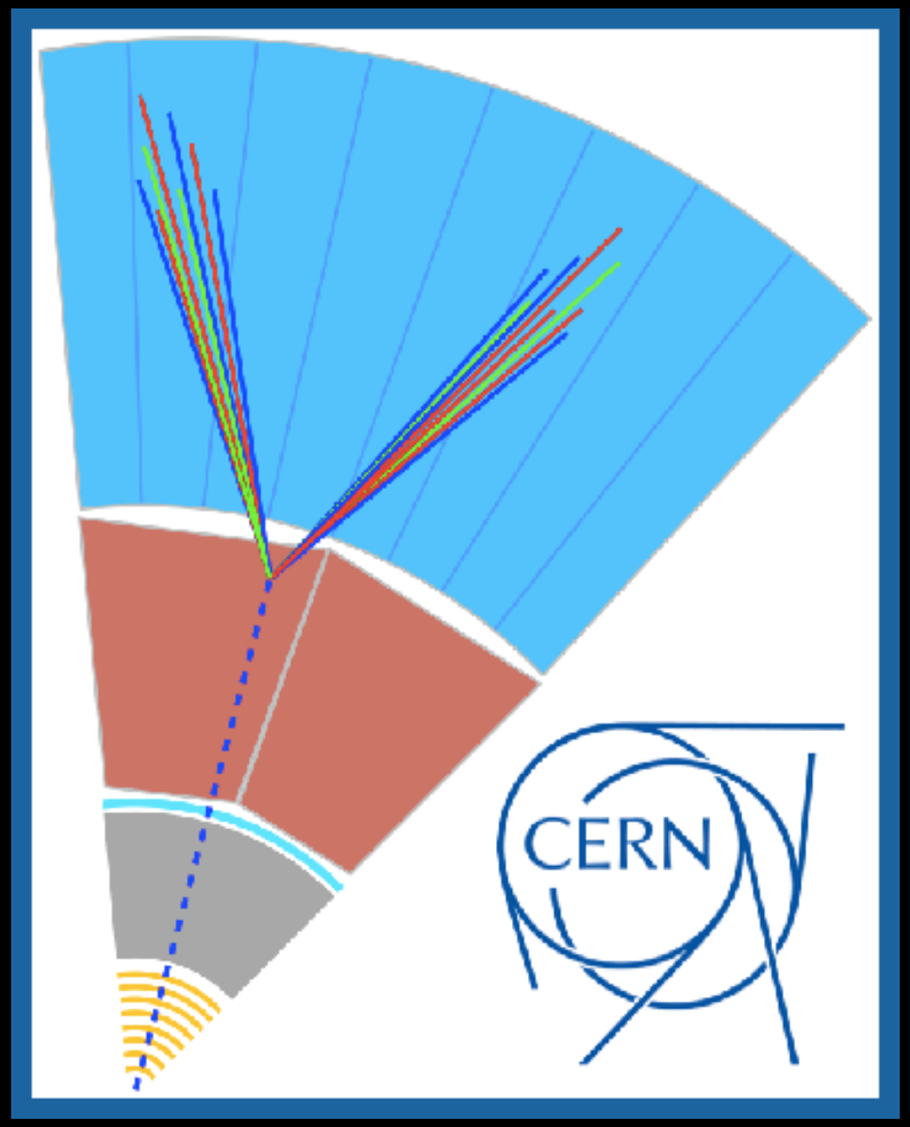
How do we best ensure that we don't miss BSM LLP signatures for the remainder of the LHC program and beyond?

Answer: Construct a *space* for the inter-experiment/theory community to discuss and collect the *results*

Space: Working-workshops

Results: White papers and website

LHC Long-Lived Particle Community



...building on the work of a few prior workshops

...in collaboration with the theory/pheno community and MoEDAL, milliQan, MATHUSLA, FASER, Codex-b, etc.

Workshops — two per year
Most recent last month:
LHC_LLP_May_2018

LHC LLP white paper in progress now
(likely public July)

Join the CERN egroup: lhc-llp

Website coming soon: cern.ch/longlivedparticles

LLP SEARCHES AT LHC

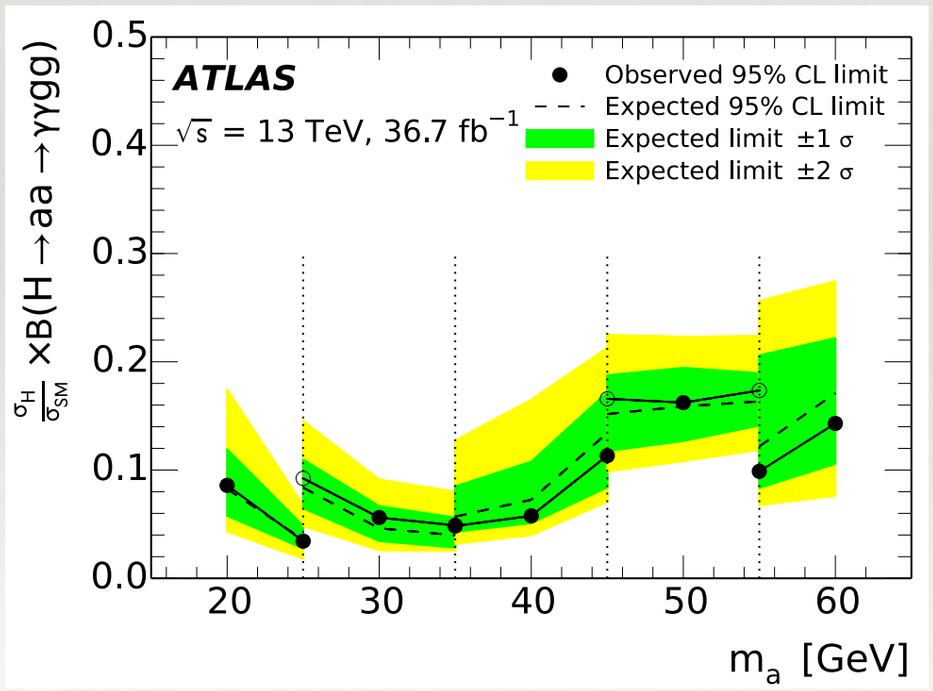
- **Opportunities:**
  - High CM energy & luminosity excellent for high-mass signals and hidden valleys
  - Huge, multi-purpose detectors can reconstruct displaced final states in a variety of ways
- **Challenges:**
  - Need to pass triggers, can't always reconstruct displaced object in trigger (esp. hard for hadronic decays)
  - Need dedicated searches for different decay modes, lifetimes to fight QCD, heavy flavour, and fake backgrounds

How can we be sure we aren't missing anything?

LLP SIMPLIFIED MODELS

- LHC-LLP group aims to address this question in assessing current searches, gaps in coverage, and potential for trigger+upgrades

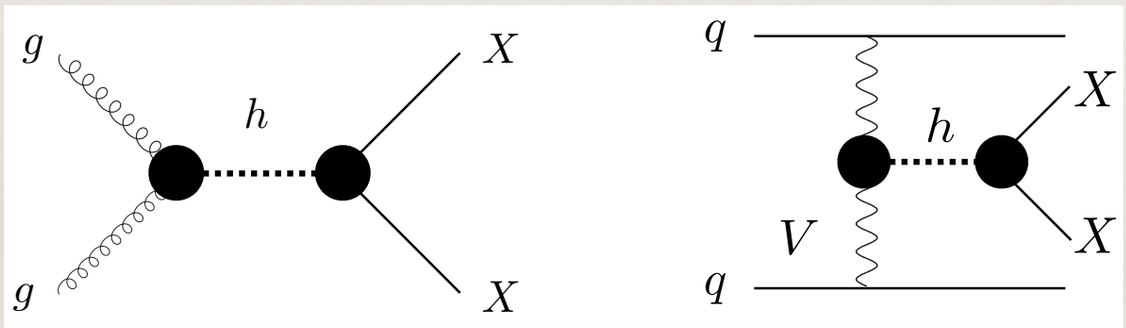
- Our approach is **signature driven**

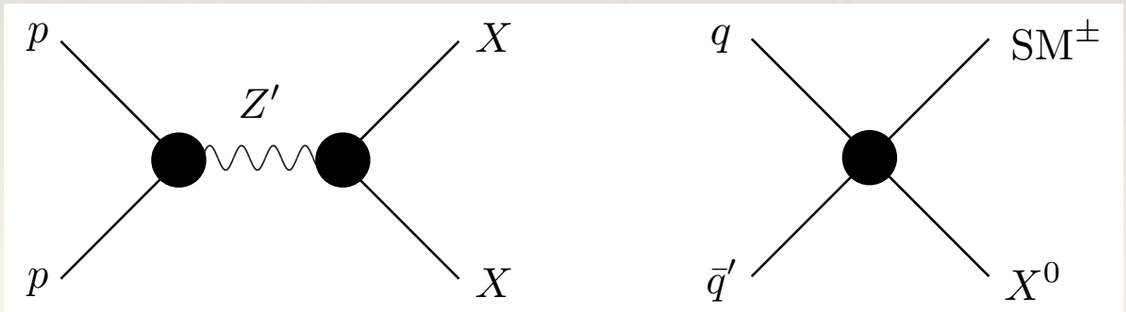


- Simplified models: production mode + decay mode + lifetime, set limit on *production cross section*

- We assessed a **minimal** set of production & decay modes to cover most motivated signatures

LLP SIMPLIFIED MODELS





Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha \ell^-_{\beta\neq\alpha}(+\text{inv.})$
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 $\to XX + \text{inv.}$	Higgs, DM*	†	Higgs, DM*	RHν	Higgs, DM* RHν*	RHν*
HIG: $h \to X + \text{inv.}$	DM*, RHν	†	DM*	RHν	DM*	†
RES: $Z(Z') \to XX$ or $\to XX + \text{inv.}$	Z', DM*	†	Z', DM*	RHν	Z', DM*	†
RES: $Z(Z') \to X + \text{inv.}$	DM	†	DM	RHν	DM	†
CC: $W(W') \to \ell X$	†	†	RHν*	RHν	RHν*	RHν*

LLP SIMPLIFIED MODELS

LHC LLP Community signature-driven simplified models approach and the PBC benchmarks are obliquely related, for clear reasons

- LHC LLP group takes advantage of the wonderfully general purpose detectors
- Signature-driven approach works for the LHC because each experiment is *pp* and with roughly comparable size/extent
- For PBC, in order to compare different production facilities and experimental setups, it is easier to consider a concrete model with correlated production rates, lifetimes, and kinematics
- While these approaches are distinct and complementary, the LHC-LLP signature-driven models can be mapped into PBC ones
  - Minimal dark photon = *Z'* model with leptonic decays (usually)
  - Minimal scalar model = Higgs model with hadronic decays
  - Etc.

LLP SIMPLIFIED MODELS

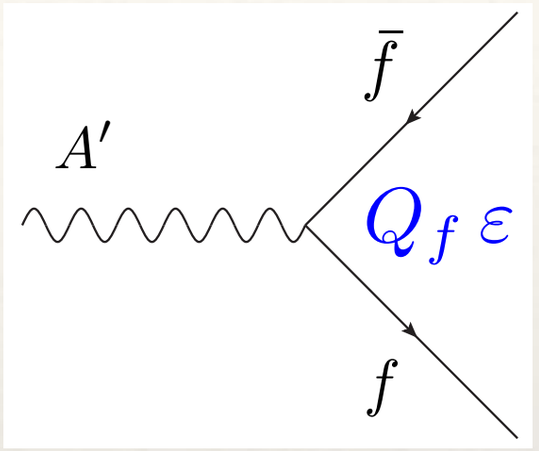
Additional complication / opportunity

- As a result of the intrinsic difficulties of searching for low-mass LLPs, *ATLAS and CMS don't have a large number of public results or projections in these ranges*
- We emphasize this in our white paper as a known unknown and an opportunity for the future!
- We're more than happy to encourage analyzers in the collaborations to perform these studies centrally with full simulation and backgrounds, with an eye toward any PBC document time scales
- Presented in the following are some examples of the known existing projections for some of the PBC benchmark models

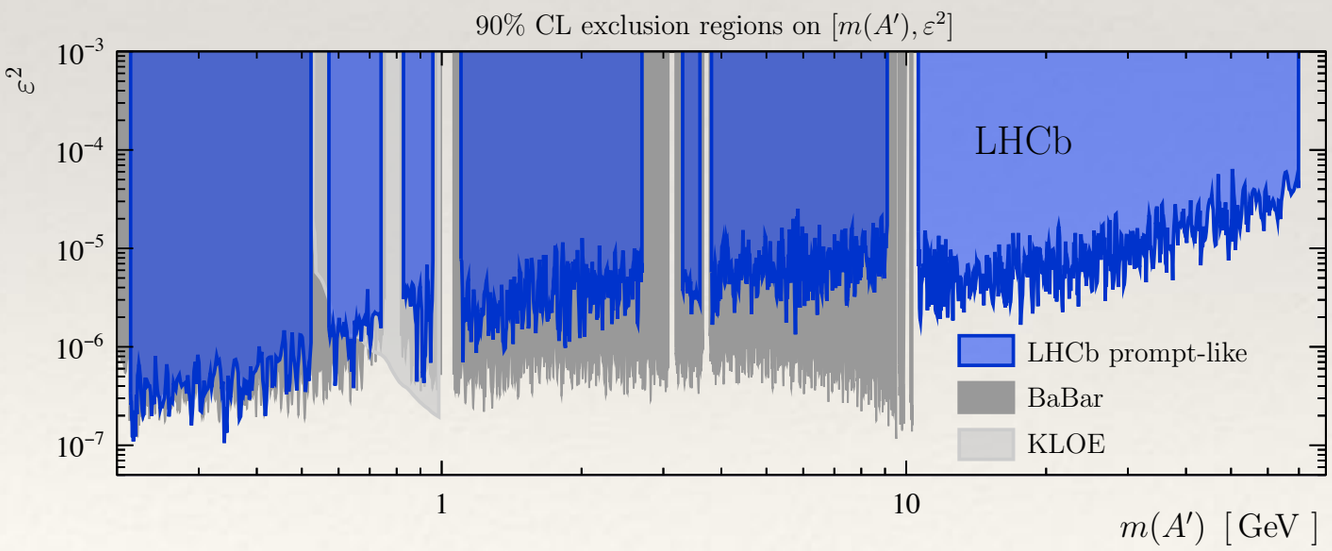
VECTOR PORTAL

BC1: Minimal Model

- Best sensitivity currently from LHCb at low mass



PROMPT



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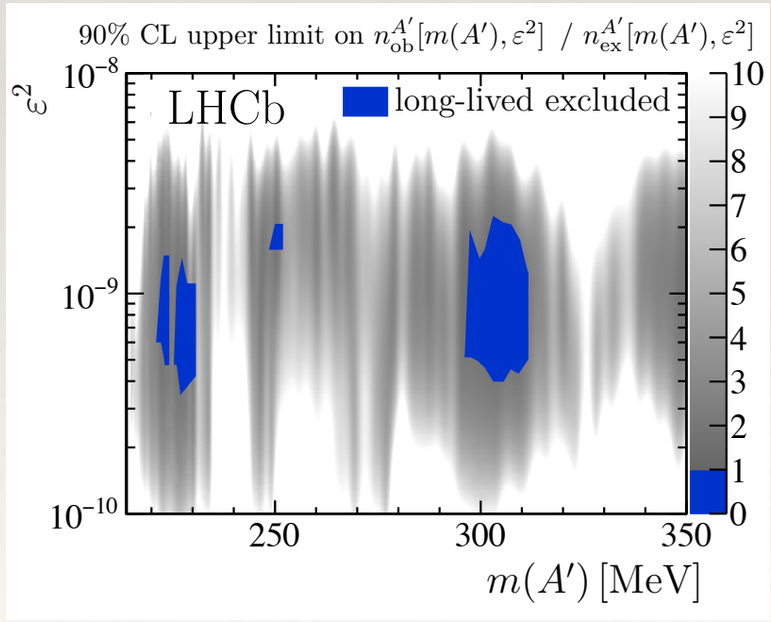
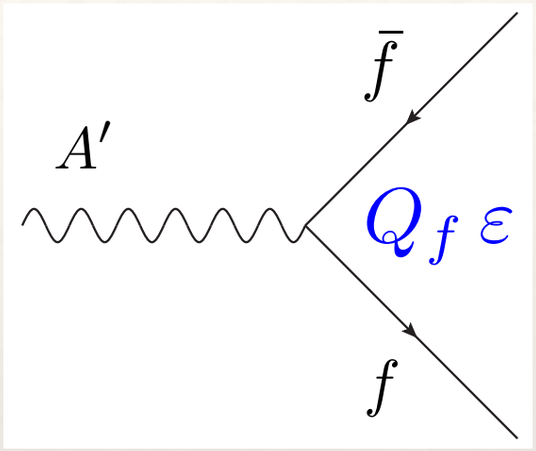


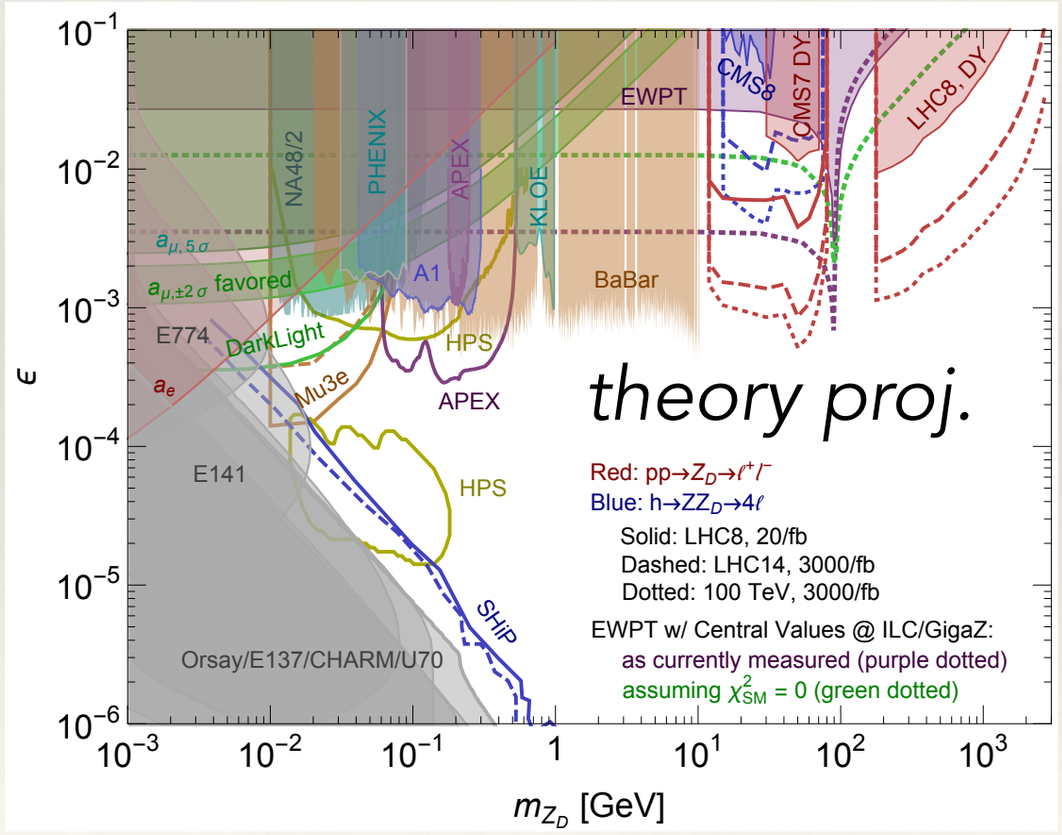
LHCb, arXiv:1710.02867

VECTOR PORTAL

BC1: Minimal Model

- Drell-Yan and Higgs probes can constrain low masses with ATLAS/CMS





Curtin *et al.*, arXiv:1412.0018

- DY at low mass not updated since CMS 7 TeV!

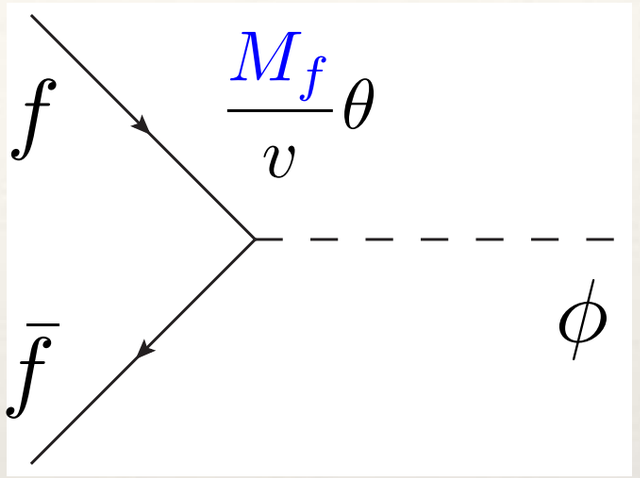
Hoenig, Samach, Tucker-Smith, arXiv:1408.1075

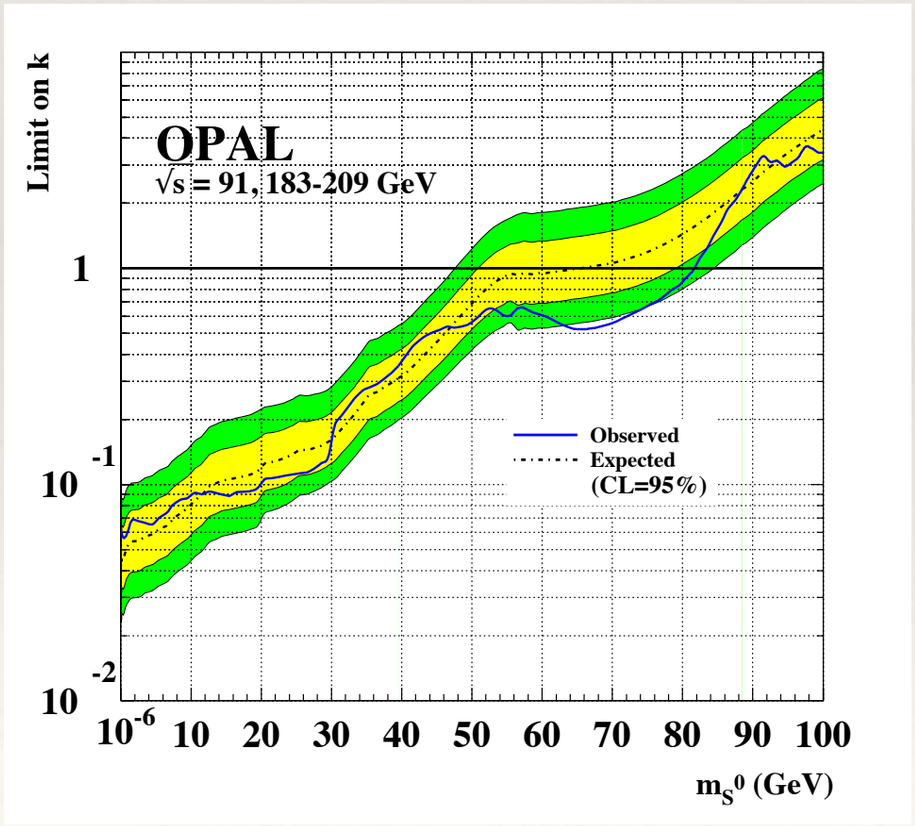
SCALAR PORTAL

BC4: Minimal Model

- At high mass (>100 GeV), can just do Higgs searches at different mass

- Strongest limit at low mass still comes from OPAL





OPAL, hep-ex/0206022

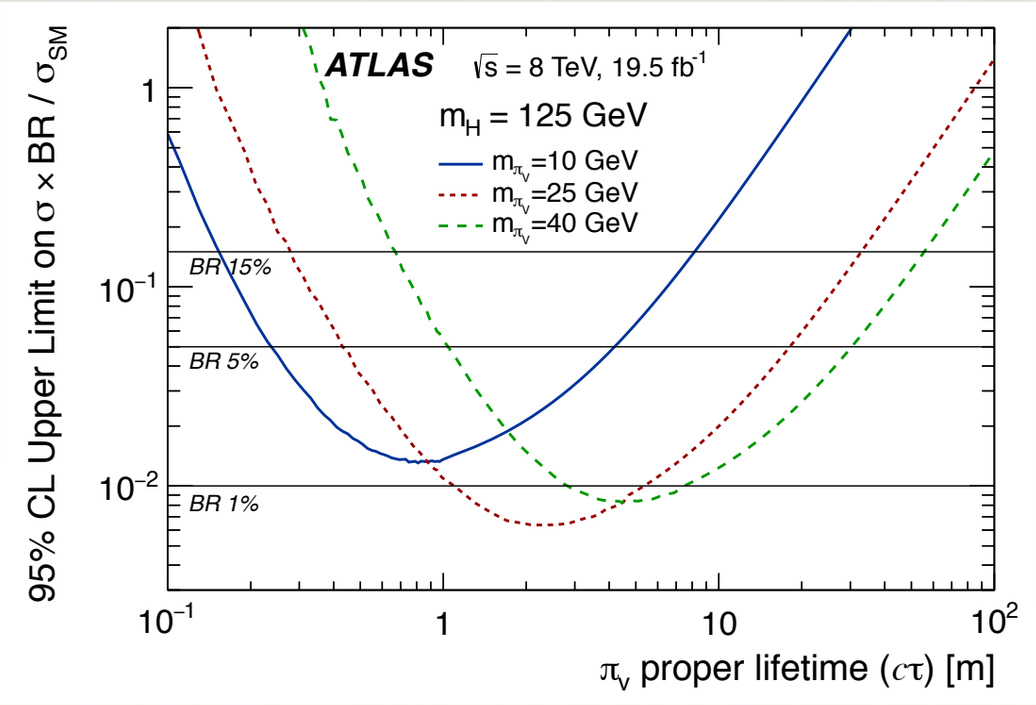
- Hard to trigger on mostly hadronic final state in ATLAS/CMS!

SCALAR PORTAL

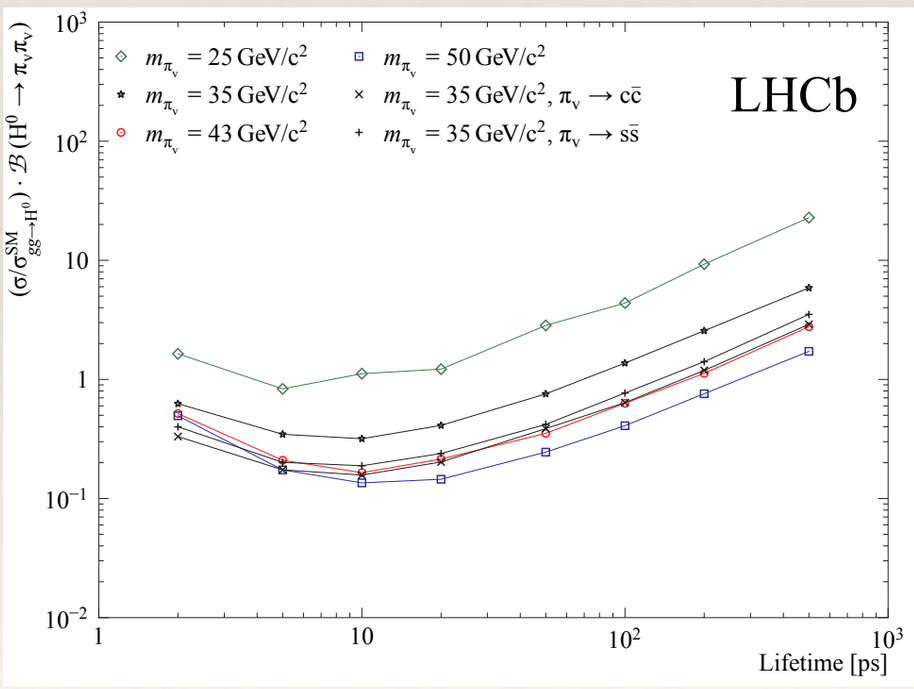
BC5: Pair production

- Several searches for Higgs to pair of resonances
- Displaced: at long lifetime, can use dedicated MS/calorimeter triggers; shorter lifetime hadronic decays still a big gap! (use associated object triggers, …)

ATLAS, arXiv:1504.03634

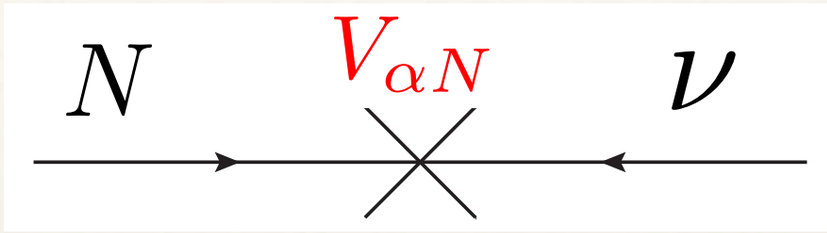


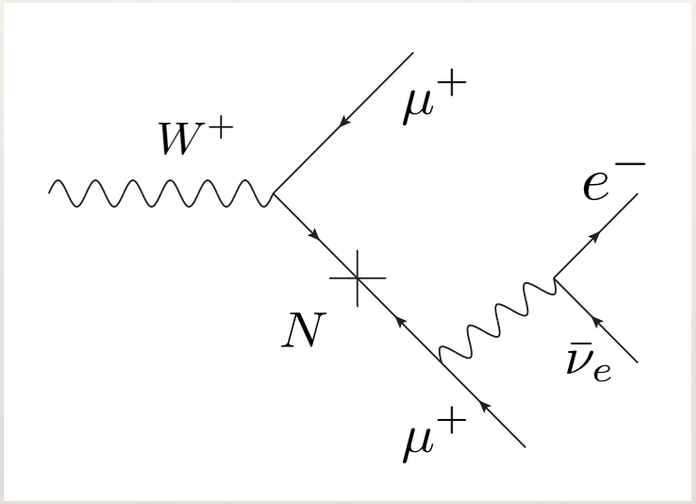
LHCb, arXiv:1705.07332



NEUTRINO PORTAL

BC6-7: Minimal Model

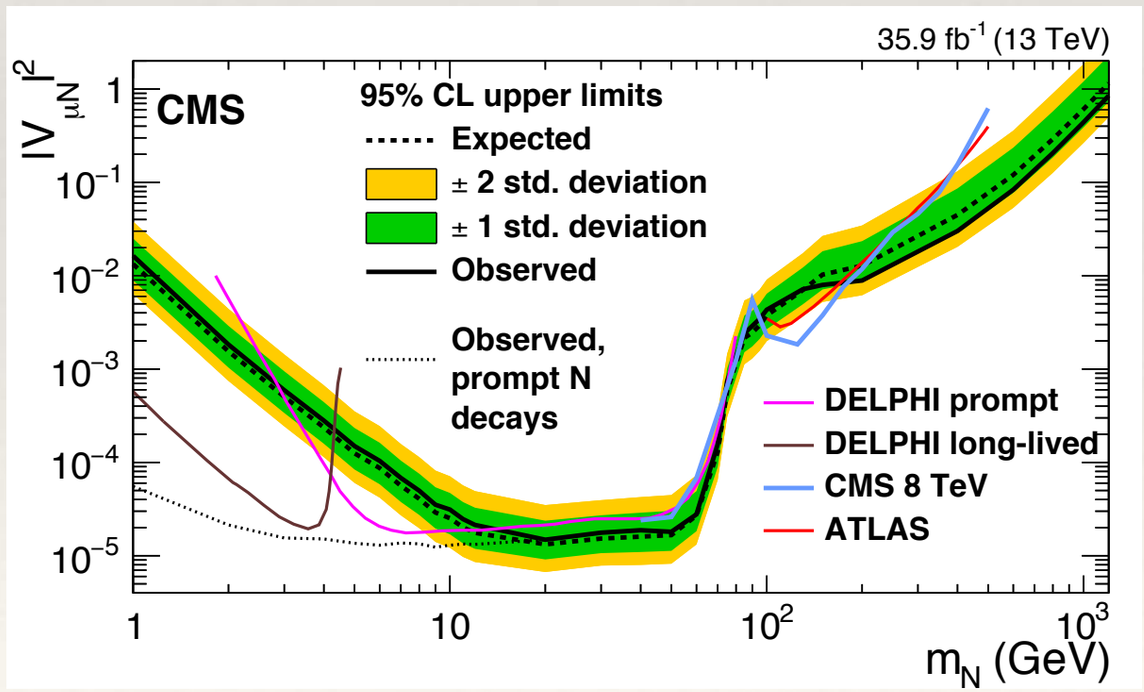




- At ATLAS/CMS, dominant production is from W decay, need to trigger on associated lepton

- Dedicated searches are *just* starting to beat LEP; more on the way for displaced/low-mass *N*

e.g., Helo, Hirsch, Kovalenko, arXiv:1312.2900
Izaguirre, Shuve, arXiv:1504.02740



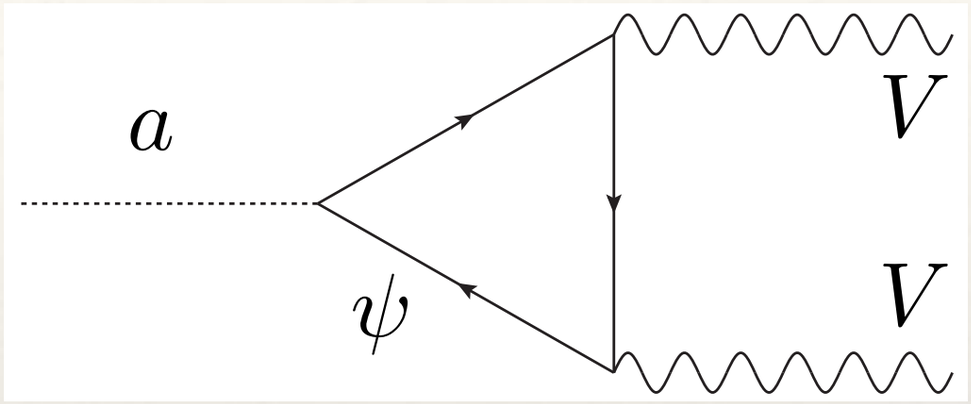
CMS, arXiv:1802.02965

AXION PORTAL

- Can have production like:

$$pp \to (\gamma/Z/W)^* \to (\gamma/Z/W)a$$

$$\gamma\gamma \to a \quad (\text{heavy ions})$$



- Low mass resonance (2-photon, hadronic, leptonic) in association with a gauge bosons

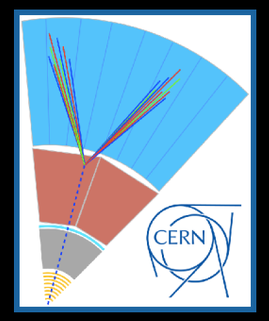
- Lots of theory work recently, but few LHC searches so far

e.g., Mimasu, Sanz, arXiv:1409.4792; Knapen *et al.*, arXiv:1607.06083; Jaeckel, Spannowsky, arXiv:1509.00476; Brivio *et* al., arXiv:1701.05379; Bauer, Neubert, Thamm, arXiv:1708.00443; Craig, Hook, Kasko, arXiv:1805.06538;

- Mono-X + resonance searches could be relevant for this

CMS, arXiv:1705.10532; ATLAS, arXiv:1801.08769

LHC LLP & PBC — Conclusion

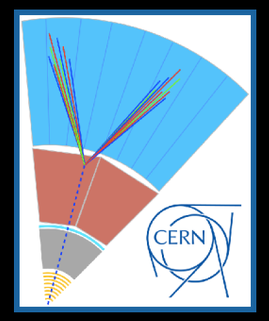


LHC LLP and PBC have complementary approaches to determining sensitivity to new particles with non-negligible ctaus from the perspective of the general purpose and dedicated detectors situated near the LHC interaction points

- LHC LLP simplified model approach is signature-first / model-second, but fairly clear mapping from ours into PBC benchmark choices
- Exclusions / coverage for high- and medium-mass/energy regimes can often be taken directly from the collaboration results and/or copious theory / pheno papers that collect and summarize
- Several known opportunities exist for ATLAS, CMS, and LHCb to do central, comprehensive studies for low-mass regimes for LLPs

END

LHC LLP & PBC — Conclusion



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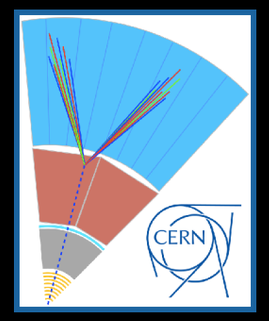
Additionally, there are several LLP-related signatures that people have expressed interest in studying for HL(HE)-LHC in ATLAS, CMS, LHCb

- LHC LLP Community can encourage analyzers to not overlook those signatures where the PBC-related projects have increased sensitivity, i.e., in lower-mass, softer regimes

END

LHC LLP & PBC — Conclusion



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- LHC LLP Community can encourage analyzers to not overlook those signatures where the PBC-related projects have increased sensitivity, i.e., in lower-mass, softer regimes

More than happy to spread the word and help facilitate this to whatever extent possible on the time scale of the PBC document

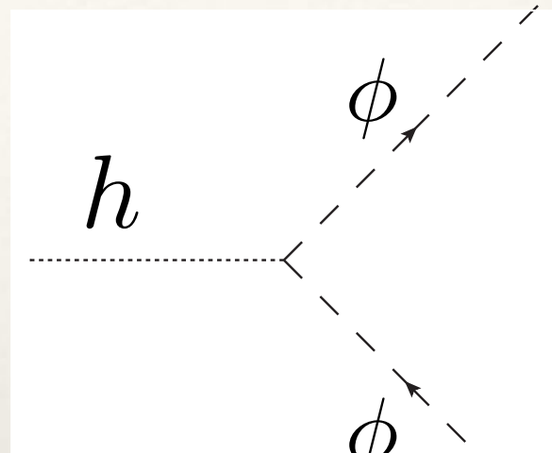
END

Reserve slides

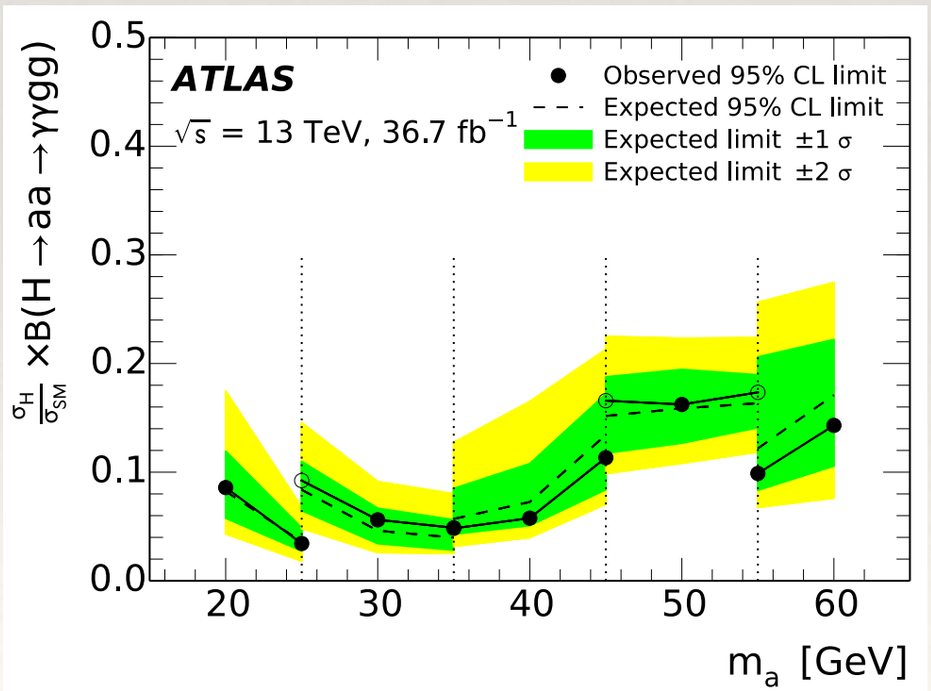
SCALAR PORTAL

BC5: Pair production

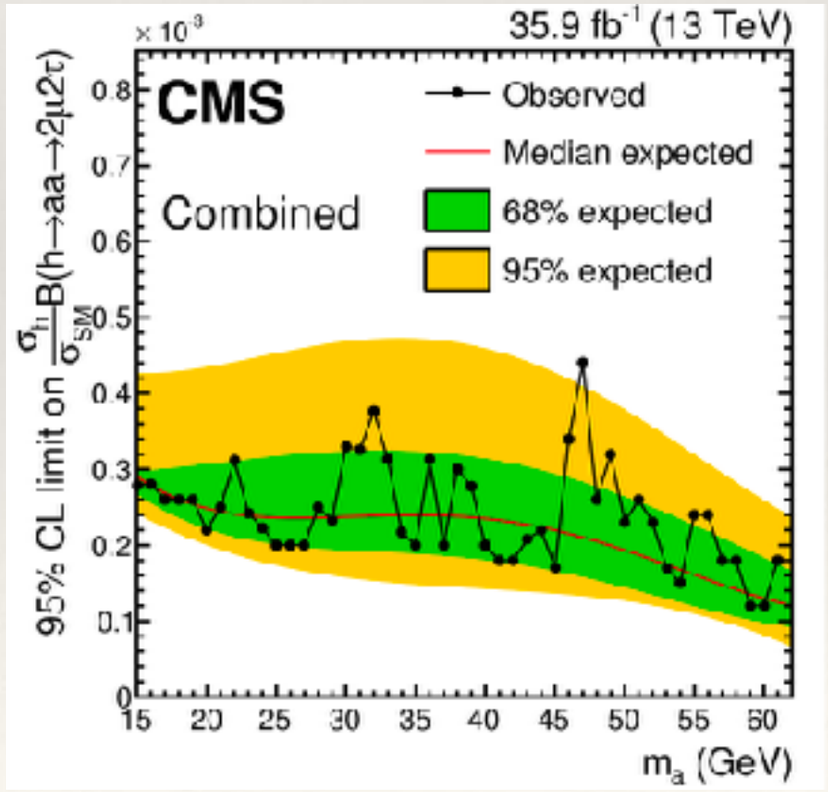
- Several searches for Higgs to pair of resonances
- Prompt: searches for decays to leptons, jets, photons
- Sensitivity limited by trigger, leptonic BR



ATLAS, arXiv:1803.11145



CMS, arXiv:1805.04865

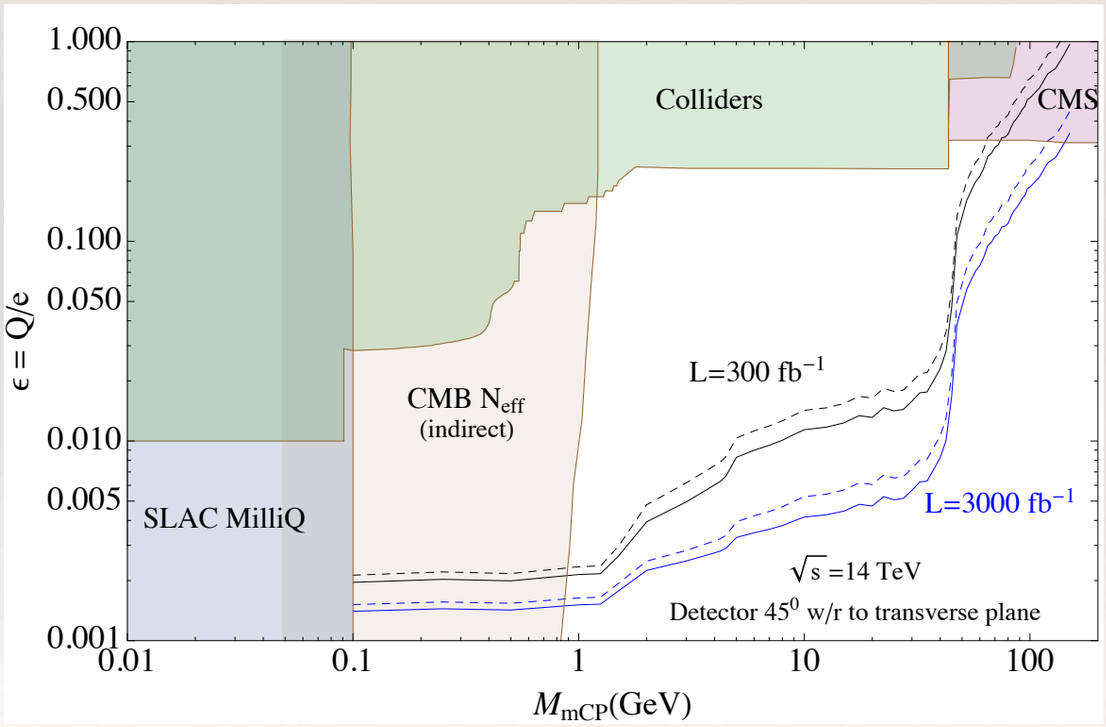


VECTOR PORTAL

BC3: Millicharges

- Can search for low-ionization tracks

CMS, arXiv:1210.2311



- Dedicated detector can do much better!

  e.g., milliQan

  Haas *et al.*, arXiv:1410.6816

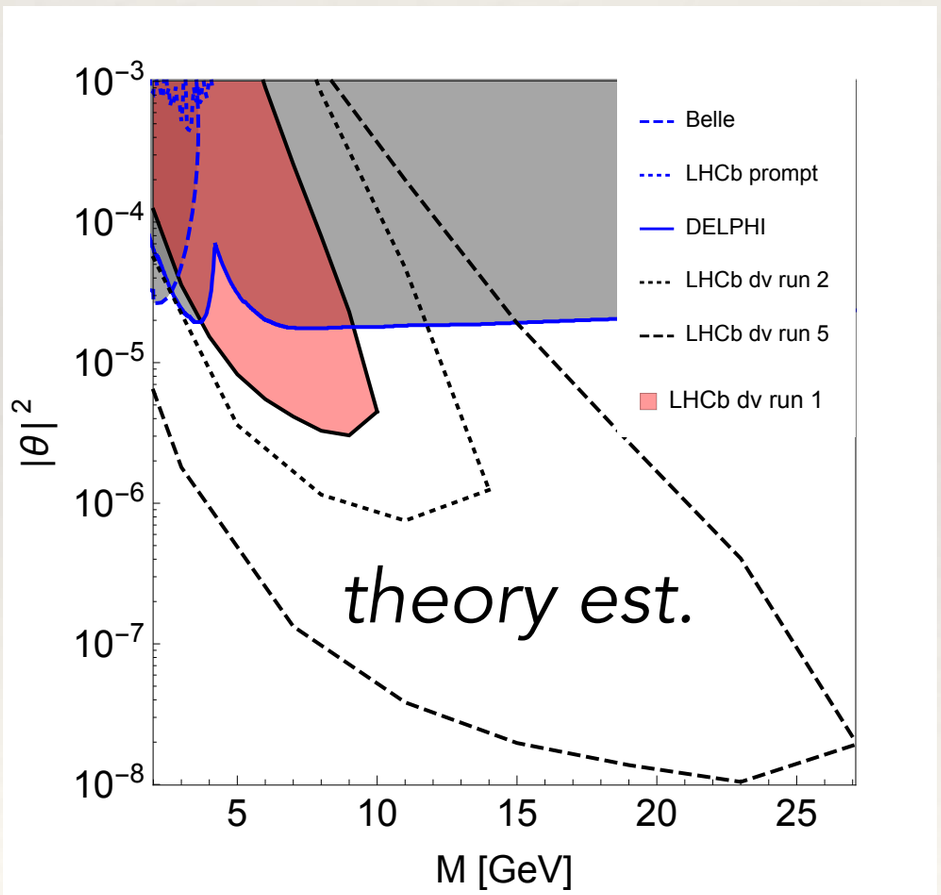
NEUTRINO PORTAL

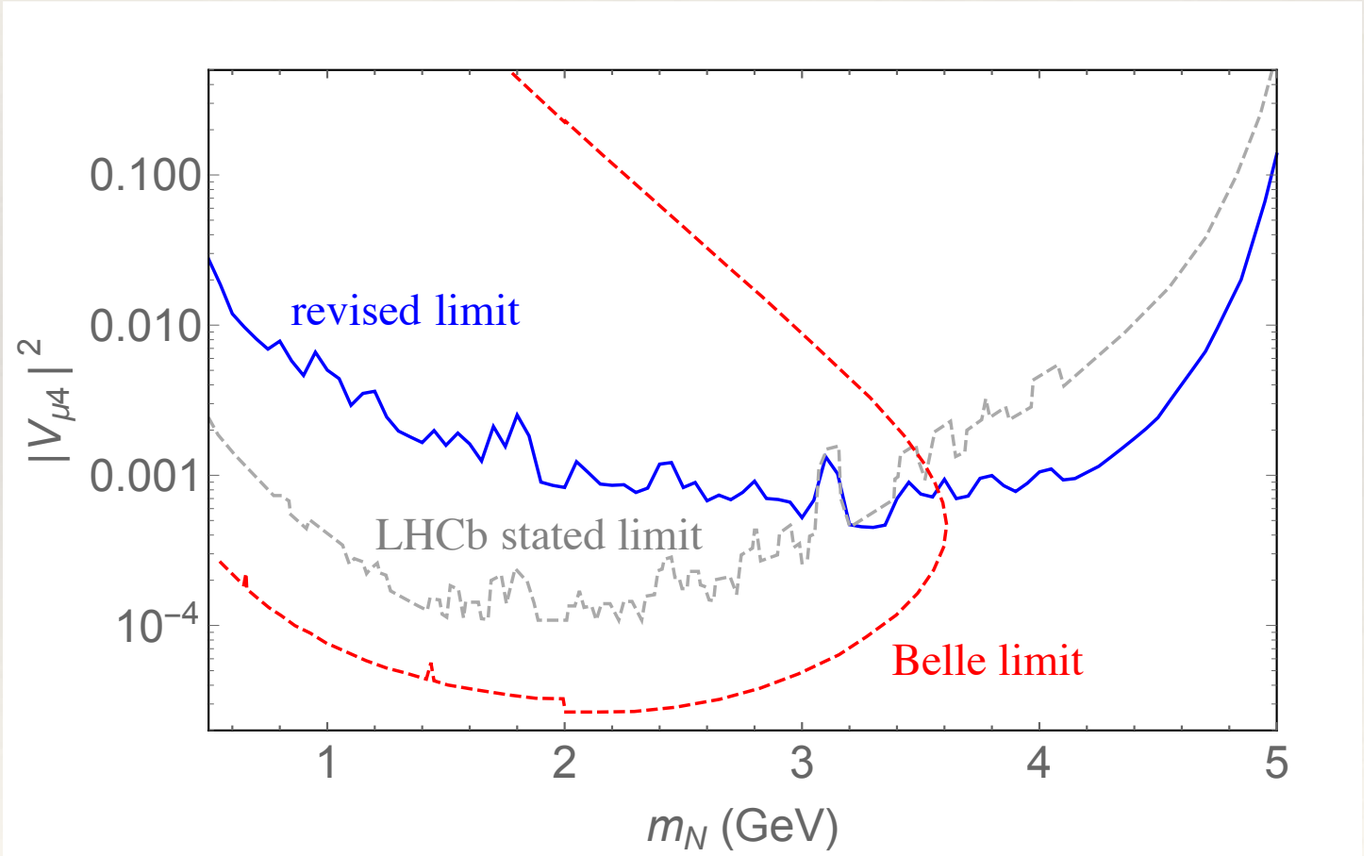
BC6-7: Minimal Model

- At LHCb, can use W decay or meson decay production
- More inclusive analysis could help with sensitivity to meson decays

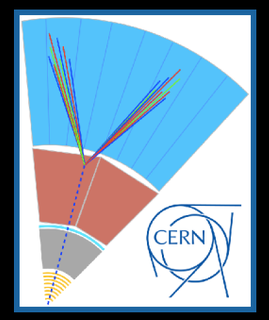
Antusch, Cazzato, Fischer, arXiv:1504.03634

LHCb: arXiv:1401.5361
Shuve, Peskin, arXiv:1607.04258





White paper: Simplified Models chapter



Signature first, model second

- General classes of motivations that can give rise to LLPs are many
  - Dark photons
  - Hidden valleys
  - R-parity violating supersymmetry
  - Dark QCD-like sectors
  - Heavy neutral leptons
  - Etc.

Instead of probing the parameter space of your favorite model, think about the more generic kinds of ways an LLP could be produced at the LHC interaction points and then how it could appear in the detector

- Much clearer way of comparing searches and noting whether and to what extent certain signatures have been covered
- Creates a useful grammar of LLP signatures/searches across experiment