Searches at the LHC including FASER

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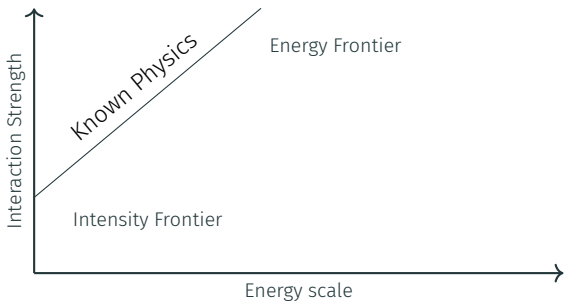
Outline

1. Introduction to dark sectors
2. Long lived particles at the LHC
3. Dark photons at LHCb
4. FASER
5. Conclusion/Outlook (inc. future projects)

The landscape

- So far at the LHC we have only seen (what looks like) the SM Higgs (and some tantalising anomalies)
- The existence of something like dark matter seems all but confirmed, but WIMPs have eluded us so far.
- The next energy scale could be at the Planck scale



→ Maybe the answers lie at lower energies $\lesssim \mathcal{O}(10\,\text{GeV})$, hidden by feeble interactions?

Searching for dark sectors

While the dark sector may be very rich, there are a finite number of portal terms which can link it to the SM:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{portal}} + \mathcal{L}_{\mathrm{DS}}$$

The CERN Physics Beyond Collider BSM working group defined several benchmark models for each portal to compare current and future experiments: [CERN-PBC-REPORT-2018-007]

- BC1-3: **Vector portal** (visible, invisible, milli-charged particles)
- BC4-5: **Scalar portal** (dark Higgs, +quartic coupling)
- BC6-8: **Neutrino/fermion portal** (e, μ, τ)
- BC9-11: **Axion-like particle portal** (photons, fermions, gluons)

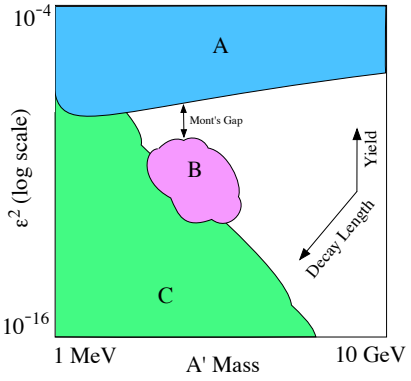
Dark photons

Kinetic mixing with SM photon with suppression factor ϵ:

$$\epsilon e A'_\mu J^\mu_{\mathrm{EM}}$$

- Production identical to γ^* → QCD, light meson decays, Drell-Yan
- Decay to visible particles if decay to dark matter not dominant/allowed ($m(A') < 2m(\chi)$)
- Mostly forward for light dark photons: LHCb and FASER ideally placed
- Well motivated as carrier of a new force and candidate for a mediator of dark matter

Dark photon landscape [arXiv:1608.08632]



- A: Bump hunts (visible or invisible)
- B(C): Displaced verteces with short(long) decay lengths

- Active and growing community studying long lived particles at the LHC
  - Recent whitepaper: [arXiv:1903.04497], to appear in J. Phys. G
  - Regular workshops
  - Bringing together experimentalists and theorists across (current and future) experiments

http://cern.ch/longlivedparticles

Dark sector signatures at ATLAS and CMS

- Dark sectors can result in a variety of signatures
- Many are free of SM background, but may require some creativity to reconstruct
- Focus on signatures reduces model-dependence
- Can benefit from upgrades:
  - CMS timing layer [CERN-LHCC-2017-027]
  - ATLAS ITk [ATLAS-TDR-030]

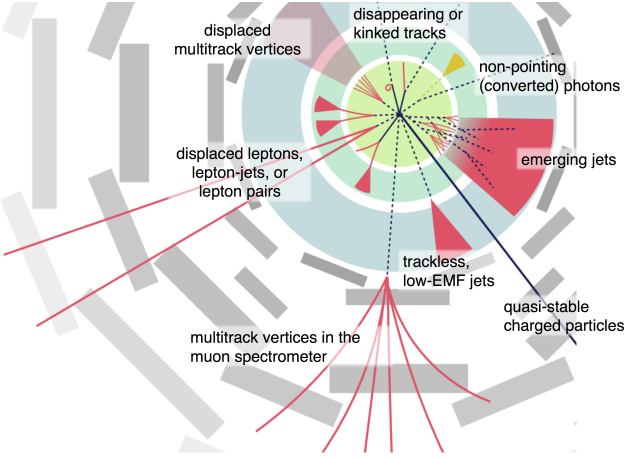
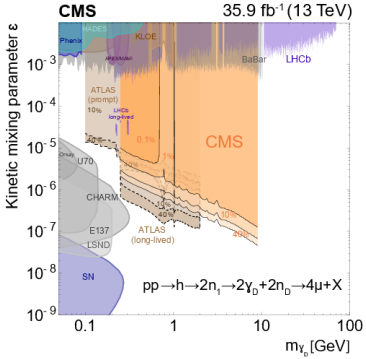


Fig: Heather Russel, 2017

Selected LHC results

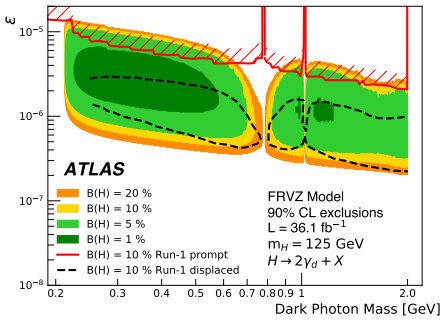
Pair produced dark photons

Prompt



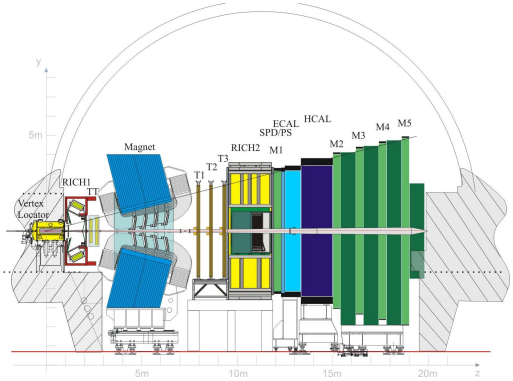
[PLB **796** (2019) 131-154]

Displaced



[arXiv:1909.01246]

And many more: ATLAS and CMS world-leading for higher-p_T LLP searches, see e.g. [arXiv:1903.04497]



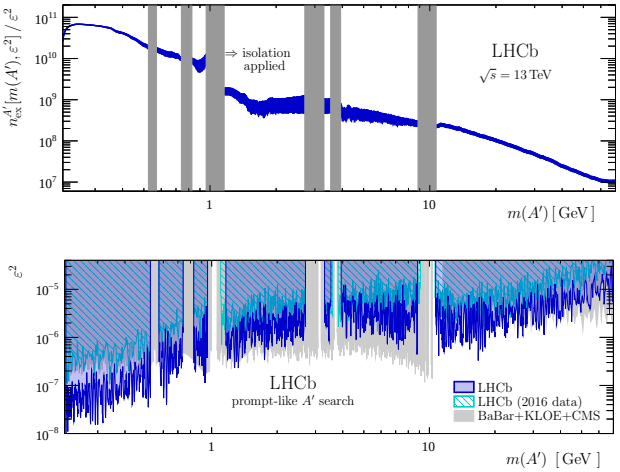
- Less luminosity, **but unique capabilities**
- Forward coverage favouring light particles:
  $2 < \eta < 5$
- Specialised detector:
  - Very good muon efficiency and momentum resolution
  - Very good primary and secondary vertex separation resolution
  - Good particle ID
  - Can trigger low-p_T muons: 1.5 GeV
- Velo upgrade and Real Time Analysis (RTA) will build on these strengths in run 3

- Update of [PRL **120** (2018) 061801], proposed in [PRL **116**, 251803 (2016)]
- Two searches: prompt + displaced ('long-lived')
- Using full run 2 sample: 5.5 fb^{-1}
- Fully data-driven using $\gamma^* \to \mu\mu$ as reference
- Assuming only visible decays, limits can be reinterpreted for combination of visible+invisible decays (or dark scalars) [JHEP **1806** (2018) 004]

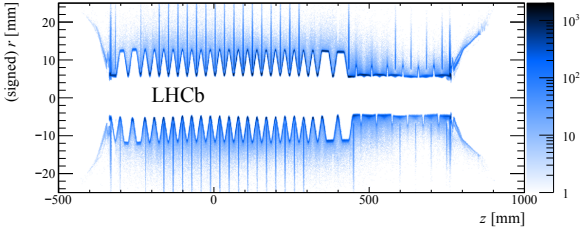
LHCb: Seach for $A' \to \mu\mu$ (prompt)

[arXiv:1910.06926]

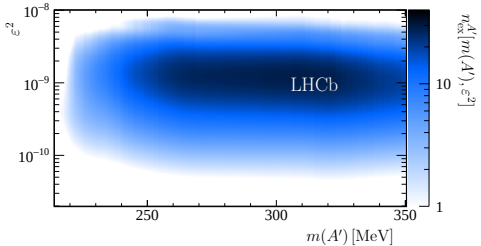
- A' indistinguishable from γ^* in production and decay: can exploit this to cancel efficiencies and systematics
- Scan mass range between dimuon threshold up to 70 GeV for A' signal, vetoing SM resonances
- Fit the $\min[\chi^2_{\rm IP}(\mu)]$-distribution to distinguish between prompt-$\mu\mu$ and background
- No excess found: set 90% CL limits

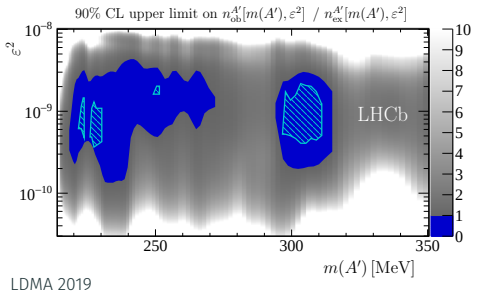


- Select dimuon pairs inconsistent with originating from any primary vertex
- Scan $m(A')$ and $\tau(A')[m(A'), \epsilon^2]$
- Background from photon conversion controlled using decay kinematics and a high-precision $3D$ material map of the VELO
- No excess found: set 90% CL limits

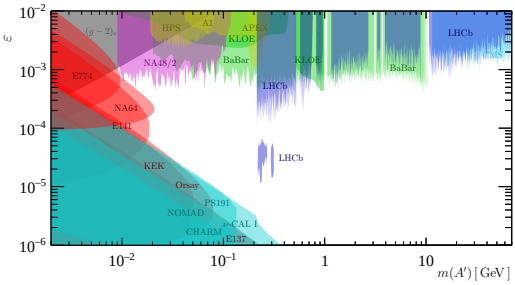


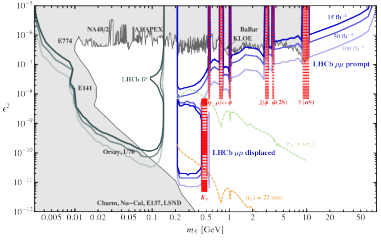
[JINST 13 (2018) no.06, P06008]

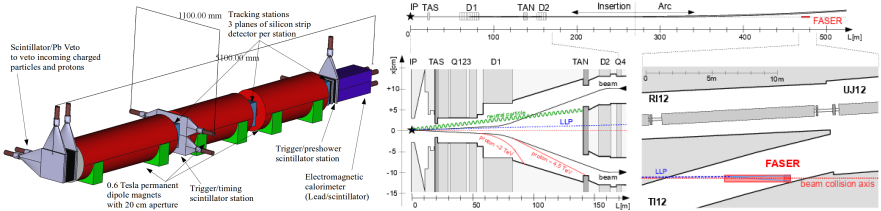




- Prompt search places most-stringent constraints on dark photons with $214 < m(A') < 740$ MeV and $10.6 < m(A') \lesssim 30$ GeV
- Long-lived search covers unique region between collider and beam-dump experiments inaccessible elsewhere
- +15 fb^{-1} expected in run 3 with upgraded detector and trigger will significantly extend the reach of the search
- Could be complemented by a search for $D^* \to D^0 A'(\to ee)$ [PRD **92**, 115017 (2015)] to reach lower masses



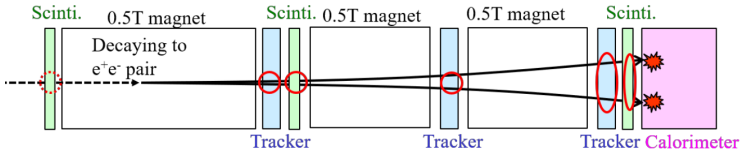




8th LHC experiment: funded and approved for run 3

- 480 m from ATLAS interaction point in TI12
- Charged particles are deflected by LHC magnets, neutral particles absorbed by rock
- Despite angular acceptance of 0.2 mrad, large yield of very boosted light mesons

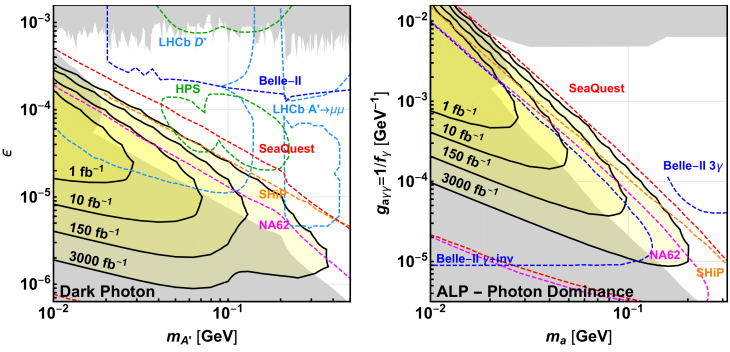
- Look for displaced vertex of two oppositely charged tracks: e.g. $A' \to ee$
- Extremely boosted signal leading to nearly collinear decay products



- Scintillator/Pb veto for charged particles and photons produced upstream of the detector
- Fine-grained trackers for vertexing
- ECAL can measure energy and reconstruct photons

FASER sensitivities: Dark Photon and ALP

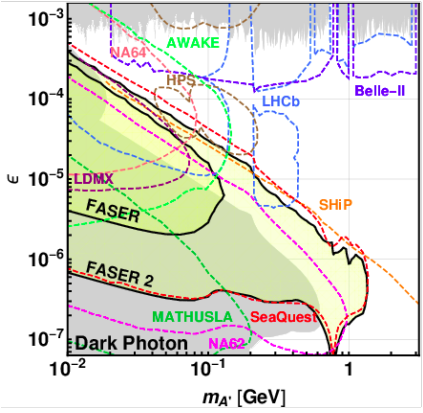
these and other models: [PRD 99, 095011]



- Run 3: 150 fb^{-1}
- Estimate zero background based on FLUKA, *in situ* measurements → 3 events for discovery
- Assume 100% detector/reconstruction efficiency

Proposed upgrade of FASER for the HL-LHC

	FASER	FASER2
decay volume length/metre	1.5	5
radius/metre	0.1	1
angular acceptance/mrad	0.2	2
$\int \mathcal{L} dt / \text{fb}^{-1}$	150	3000



There is also a proposed emulsion detector for neutrino physics upstream of FASER: FASERν [arXiv:1908.02310]

Future experiments

- MilliQan [arXiv:1607.04669] is designed to look for milli-charged particles (BC3) produced at the CMS interaction point, data taken with prototype in 2018
- SND@LHC [info soon] combines nuclear emulsions and active detectors to search for scattering of neutral particles, allowing study of neutrinos and light dark matter
- CODEX-b [arXiv:1911.00481], ANUBIS [arXiv:1909.13022], MATHUSLA [CERN-LHCC-2018-025] propose dedicated detectors for very long-lived particles near the LHC interaction points

Conclusion & Outlook

- Dark sector and long lived particles under active study at the LHC
- Reach complementary to beam dumps and non-accelerator searches
- Run 3 and HL-LHC will significantly push sensitivity of current searches—particularly for background-free searches
- New search ideas and new experiments for run 3 and beyond: a lot to look forward to!