# Long-lived searches, including MATHUSLA, FASER, CODEX-b

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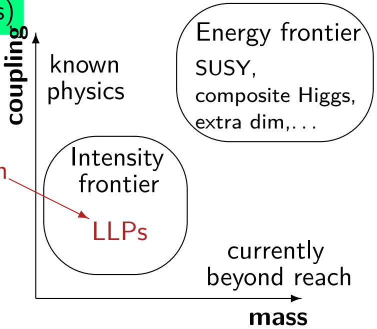
# (Light) Long-Lived Particles (LLPs)

light new particles,
weakly-coupled to the SM
that could avoid previous detection




1) Many theoretical frameworks:

dark photon, dark Higgs boson, axion-like particles (ALPs),
heavy neutral leptons (HNLs), (RPV) supersymmetry,
neutral naturalness, Hidden Valley scenarios, . . .

2) dark matter-SM mediators – correct thermal relic density, strongly interacting DM, asymmetric DM

3) baryogenesis, neutrino mass, hierarchy problem, . . .

4) Ongoing searches at the LHC + Many proposed experiments:
CODEX-b, FASER, MATHUSLA, MilliQan, NA62-dump, NA64, SeaQuest, SHiP,. . .
(Physics Beyond Colliders WG)

## Production and detection of LLPs

a) production modes

- exotic meson decays ($\pi$, $K$, $\eta$, $D$, $B$,...),
- invisible Higgs or $Z$ decays (both on- and off-shell)
- direct QCD production in $q\bar{q}$, $qg$ scatterings,
- decays of other new particles (e.g., SUSY)
- bremsstrahlung
- ...

b) detection – decays into the SM particles, displaced vertices

- decay modes: $\gamma\gamma$, leptonic modes $e^+e^-$, $\mu^+\mu^-$,
  various hadronic modes – higher multiplicity of tracks,
- decay in volume $L$ – distance to detector, $\Delta$ – detector size, $\bar{d} = \gamma\beta c\tau$

$$\mathcal{P}_{\rm dec} = \left(e^{-L/\bar{d}} - e^{-(L+\Delta)/\bar{d}}\right) \times \mathcal{A}_{\rm geom}$$

$$N_{\rm sig} \sim \begin{cases} \Delta/\bar{d} & \text{for } \bar{d} \gg L, \quad \text{very low coupling} \\ \exp\left(-L/\bar{d}\right) & \text{for } \bar{d} \ll L. \quad \text{exponential penalty} \end{cases}$$

"only" $1/\bar{d}$ suppression, but...
for too low couplings
inefficient production,

strong suppression,
LLPs decay before reaching detector,
for low enough $\bar{d}$ – ATLAS, CMS, LHCb,

sweet spot $\bar{d} = \gamma\beta c\tau \simeq L$

proposed experiments – "luminosity-independent" sensitivity

## Current status and challenges

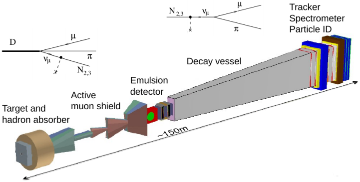
Current LHC searches (for more details see talks by Elena Dall'Occo and Viktor Kutzner):

- search for displaced vertices, disappearing tracks, stopped exotics (decays between $pp$ collisions),
- LHCb: displaced di-leptons, di-jets,...

Challenges:

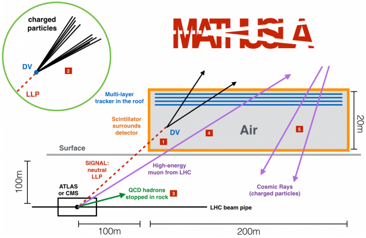
- light new particles are often produced in the forward direction – they avoid detection in high-$p_T$ searches,
- invisible Higgs decays – are the products stable or they decay further?
- compressed spectra or low-scale hidden sectors might leave too soft MET signatures in high-$p_T$ searches
- even for new particles discovered as MET: is it DM or a quasi-stable new particle? (large gap between LHC detector sizes and the BBN limits)

# Proposed experiments: CODEX-b, FASER, MATHUSLA, SHiP



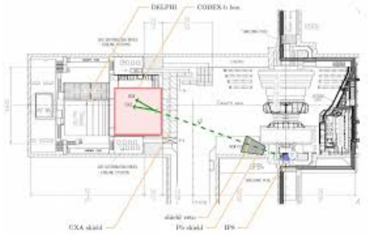

SHiP, Alekhin et al. (2015)

$\sim 1000\ \mathrm{m}^3$ , a few hundred million $



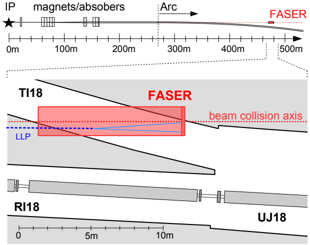

MATHUSLA, Chou, Curtin, Lubatti (2016)

$\sim 10^6\ \mathrm{m}^3$ , $\sim 50\mathrm{M}\$$



CODEX-b, Gligorov, Knapen, Papucci, Robinson (2016)

$\sim 1000\ \mathrm{m}^3$




FASER, Feng, Galon, Kling, Trojanowski (2016)

$\sim 1 - 10\ \mathrm{m}^3$

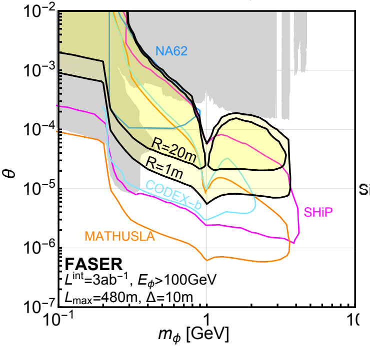
## Dark Higgs boson

- Dark Higgs boson: additional hidden real scalar field $\phi$,
- often adopted phenomenological parametrization:

$$\mathcal{L} \supset -m_\phi^2\, \phi^2 - \sin\theta \frac{m_f}{v}\, \phi \bar{f} f - \lambda v h \phi\phi$$

- Higgs-like couplings suppressed by $\theta^2$,
- production: $B$ and $K$ decays, $h \to \phi\phi$,
- decays: into the heaviest kinematically allowed states: $\mu^+\mu^-$, $\pi\pi$, $KK$, ...

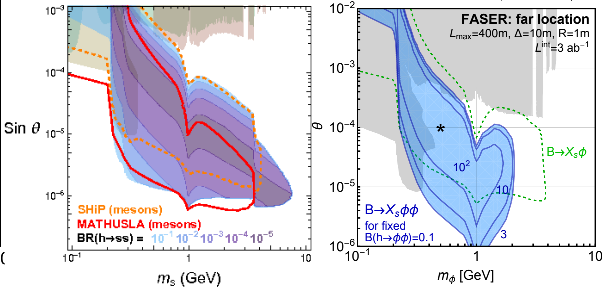
$B \to X_s \phi$




J.L. Feng *et al*, Phys.Rev. D97 (2018) no.5, 055034

Invisible Higgs decays

$h \to \phi\phi$ $\qquad$ $B \to X_s\, h^*(\to \phi\phi)$



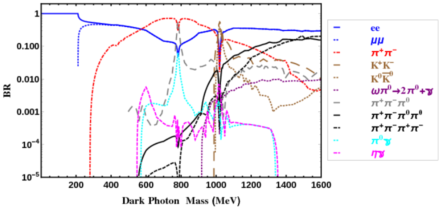

J. Evans, Phys.Rev. D97 (2018) no.5, 055046

# Dark photon

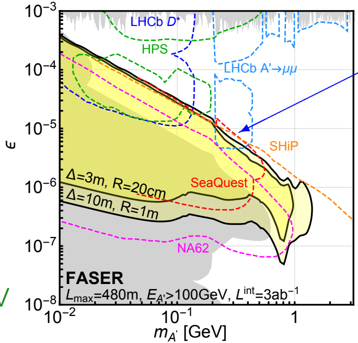
- (broken) dark $U(1)$ gauge group,
- kinetic mixing with the SM photon: $\epsilon\, F^{\mu\nu}\, F'_{\mu\nu}$,
- after field redefinition:

$$\mathcal{L} \supset -\frac{1}{4}\, F^{\mu\nu} F_{\mu\nu} - \frac{1}{4}\, F'^{\mu\nu} F'_{\mu\nu} + \frac{1}{2}\, m^2_{A'}\, A'_\mu A'^\mu + \sum \bar{f}(i\not{\partial} - \epsilon\, e q_f\, A')f$$

- production: $\pi^0$ and $\eta$ decays, bremsstrahlung,
  direct production in $q\bar{q}$ scatterings
- decays: dominantly into $e^+e^-$ and $\mu^+\mu^-$ up to $\sim 500$ MeV,
  then various hadronic decay modes




J. Alexander *et al.*, Dark Sectors 2016 Workshop: Community Report




exponential penalty

FASER, SHiP, SeaQuest comparable reaches

low $\epsilon$ region
SHiP reach: $\epsilon \sim 10^{-8}$ and $m_{A'} \sim 7$ GeV

E. Graverini, CERN-SHiP-NOTE-2016-004

## Axion-like particles (ALPs)

– similarly to the QCD axion, they can appear as pseudo-Nambu-Goldstone bosons in theories with broken global symmetries

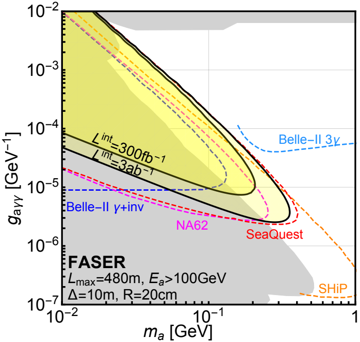
– suppressed dim-5 couplings to gauge bosons $(1/\Lambda) a V^{\mu\nu} \tilde{V}_{\mu\nu}$,

– dim-5 couplings to fermions also allowed $(\partial_\mu a/\Lambda)\bar{f}\gamma_\mu\gamma_5 f$,

– interesting pheno scenario – dominant $a\gamma\gamma$ coupling

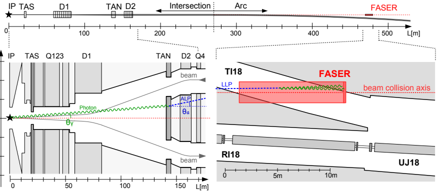
B. Döbrich *et al*, JHEP 1602 (2016) 018

ALP coupling to $\gamma\gamma$




### ALPs at FASER – LHC as a photon beam-dump

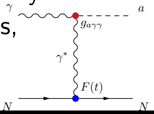
J.L. Feng, I. Galon, F. Kling, ST, hep-ph/1806.xxxx (tomorrow)




– high-energy $\gamma$s produced at the IP,

– $\gamma$s hit the neutral absorber TA(X)N $\sim 130$ m away from the IP,

– ALP production mainly in the Primakoff process,




– also exotic $\pi^0$ and $\eta$ decays,

– ALPs decay into 2 photons in FASER

## Conclusions

- Light long-lived particles – theoretically motivated, phenomenologically very appealing,
- possible low-hanging fruits that can be discovered with even very small detectors $\sim 1\ \mathrm{m}^3$ (FASER),
- larger detectors looking for LLPs in i.a. invisible Higgs decays can probe lifetime up to the BBN limit (MATHUSLA),
- new detectors can be easily incorporated into the existing LHC infrastructure and experimental programs (CODEX-b, FASER),
- the larger, the better sensitivity (SHiP),...
- ...but sometimes size (and luminosity) does NOT matter (exponential penalty, great dark photon reach of FASER),
- LLP studies – innovative ideas and new approaches (high-energy photon beam-dump at the LHC/FASER).

**You are highly welcome to join the efforts!**