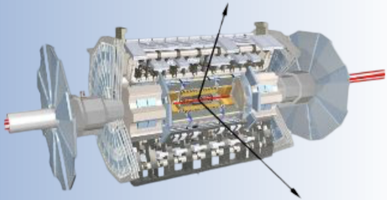
BSM Physics at the The **F**orw**A**rd **S**earch **E**xpe**R**iment

Eli Welch, on behalf of the FASER collaboration

LLWI, February, 2024

Recall LHC setup

- LHC is at the intensity frontier
- Heavy physics produced in pp collisions in the ATLAS detector



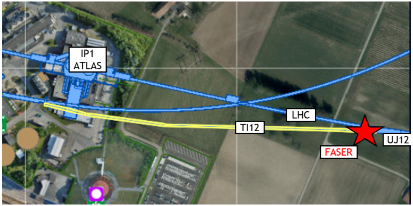
Run	$\sqrt{s}$ (TeV)	$\mathcal{L}$ expected (fb^{-1})
3	13.6	250
4	14.0	680

- Designed to search for physics with high p_t: SUSY, top, Higgs...
- Very successful
- However, abundant π, K, D mesons produced along the longitudinal direction

What is FASER?

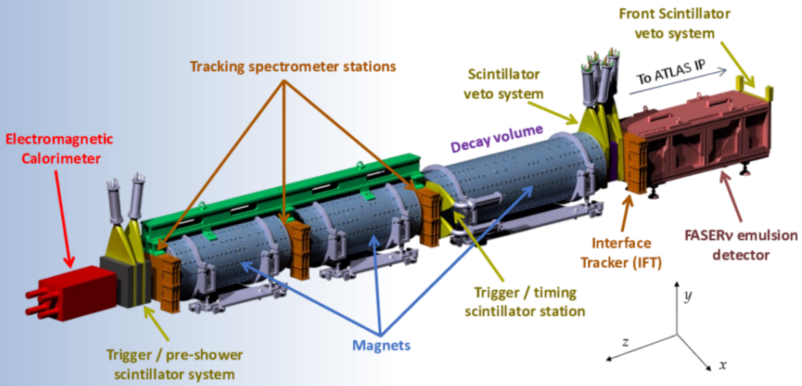
- In 2017, theorists at UC Irvine realized that the high-p_t focused setup of detectors at the LHC could be blind to the space of light and feebly coupled new physics accesible by the far-forward region of collisions
- In 2018 they proposed FASER and by 2021 the detector was installed and ready for data taking in Run 3
- Designed to search for long lived particles (LLPs) and study high energy neutrino interactions

- The detector is located $480m$ downstream of the ATLAS IP, and centered on the beam collision axis line of sight (LOS). $\sim 100m$ of rock shield the detector from collision background



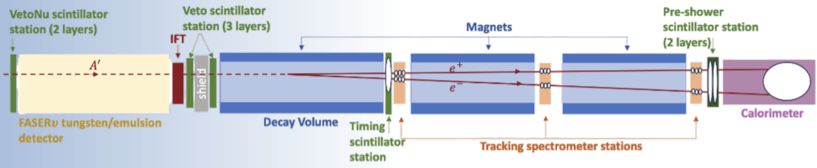
J. L. Feng, I. Galon, F. Kling, S. Trojanowski, *FASER: ForwArd Search ExpeRiment at the LHC*, Phys. Rev. D 97, 035001 (2018) arXiv:1901.04468

The FASER detector



- The active transverse area of the detector is defined by the circular magnet aperture with a radius of 10 cm
- $\eta > 9.2$

The FASER detector

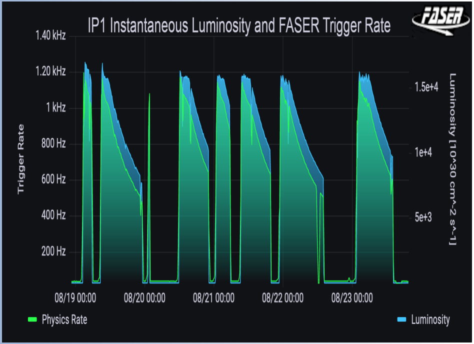


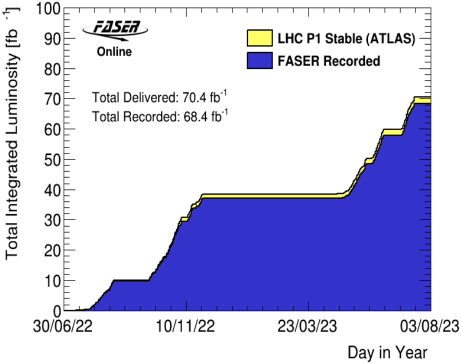
- LLP passes through veto scintillator stations
- Decays
  - Decay volume for charged final states
  - Decay volume + magnet separation regions for neutral final states
- Charged final states separated by magnets
- Tracking and timing scintillator stations
- Pre-shower to distinguish photons/neutrinos
- Calorimeter measures total EM energy deposit

FASER Collaboration, *The FASER Detector*, CERN-FASER-2022-001 (2022) arXiv:2207.11427

FASER performance

FASER has exhibited exceptional operational performance to date.





BSM Physics

- Lots of BSM physics discovery potential at FASER
- Focus on two models with completed analyses + five more “fully validated” models

Simulation setup for subsequent reach plots:

- Ran with FORESEE [1]
- Charged decays: Decay volume length = 1.5 m
- Neutral decays: Decay volume length =3.5 m. Requires the upgraded pre-shower module (to enable background free analysis for neutral final states, see later), starting from 2025.
- Distance to detector = 480 m
- Radius of detector = 0.1 m
- Assume 100% detector efficiency (sensitivity does not noticeably change for 50% efficiency)
- Assume 0 background (almost background free analysis already achieved)

Setup	E (TeV)	L (/fb)	Offset from LOS (cm) *
2025	13.6	90	2.8
Run 3 (total)	13.6	250	5.9 (avg.)
Run 4	14	680	7.1

* Detector alignment with LOS is slightly effected by beam crossing angle (different for different years). Reduces physics acceptance.

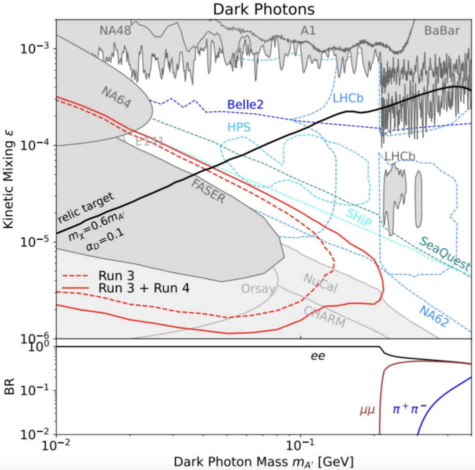
[1] F. Kling, S. Trojanowski *FORESEE: FORward Experiment SEnsitivity Estimator for the LHC and future hadron colliders*, Phys. Rev. D 104, 035012 (2021) arXiv:1901.04468

BSM Potential: Dark Photon

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon e q_f \bar{f} \not{A}' f$$

- Among the best-motivated non-gravitational DM interactions are with SM particles through renormalisable couplings.
- DM could be a component of a dark sector containing U(1) electromagnetic force mediated by a new gauge boson, A', yielding interactions of the form $F^{\mu\nu} F^D_{\mu\nu}$
- Production channels:
  1) Light meson decays $\pi^0 \to A'\gamma$, $\eta \to A'\gamma$
  2) Dark Bremsstrahlung
  3) Drell-Yan
  4) Mixing with ρ, ω, ϕ mesons

- Coupling to the SM is very weak
- $B(\pi^0 \to A'\gamma) \propto \epsilon^2$, $\bar{d}_{A'} \propto \frac{1}{\epsilon^2}$ small production, but decay length of $\mathcal{O}(100m)$ for models of interest



FASER Collaboration, *Search for Dark Photons with the FASER detector at the LHC FASER Collaboration*, Phys. Lett. B 848 138378 (2024) arXiv:2308.05587v2

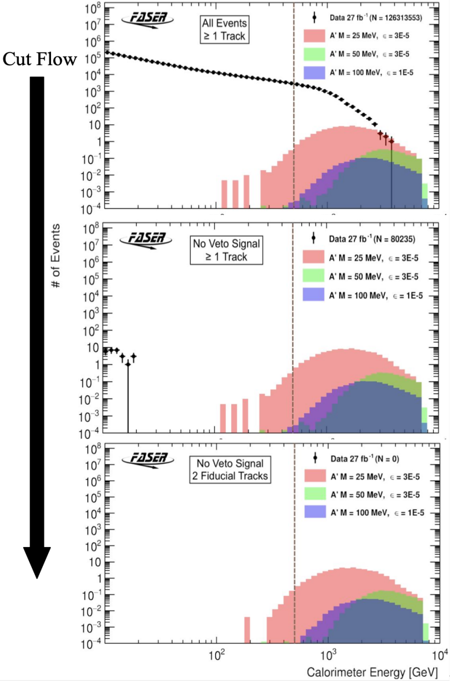
Backgrounds for A'

- All backgrounds considered for A' analysis with $27 fb^{-1}$ of data:
  - Veto inefficiency: negligible
  - Large-angle muons that miss the veto system: negligible
  - Non-collision events from the beam and cosmic rays: negligible
  - Events from neutrino interactions: $(1.5 \pm 2.0) \times 10^{-3}$
  - Events from neutral hadron interactions: $(8.4 \pm 11.9) \times 10^{-4}$
- Total background of $(2.3 \pm 2.3) \times 10^{-3}$ events from neutrino and neutral hadron interactions
- Similar backgrounds for B-L gauge boson analysis and other LLPs

FASER Collaboration, *Search for Dark Photons with the FASER detector at the LHC FASER Collaboration*, Phys. Lett. B 848 138378 (2024) arXiv:2308.05587v2

A' Event Selection

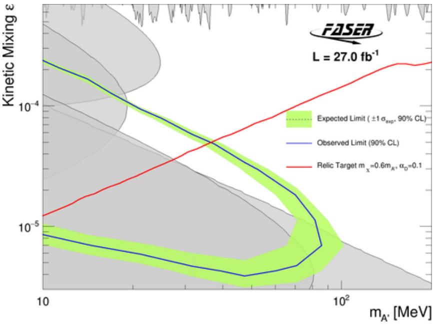
- **Signal region event requirement:**
  - event time is consistent with a colliding bunch at IP1;
  - no signal in any of the five veto scintillators;
    – required to be less than half that expected from a MIP
  - signal in the scintillators that are downstream of the decay volume;
    – required to be compatible with or larger than expected for two MIPs
  - two fiducial reconstructed tracks of good quality;
    – a good quality track has a track fit $\frac{\chi^2}{N_{d.o.f}} < 25$, at least 12 hits on track, and a momentum > 20 GeV
    – a fiducial track has an extrapolated position of < 9.5 cm radius at all scintillators and tracking stations
  - total calorimeter energy greater than 500 GeV;
- Typical signal efficiency for A' decaying in FASER of 50%
- Identical event selection used for B-L gauge boson



FASER Collaboration, *Search for Dark Photons with the FASER detector at the LHC FASER Collaboration*, Phys. Lett. B 848 138378 (2024) arXiv:2308.05587v2

BSM Completed Analyses: Dark Photon

- With 27.0 fb^{-1} of integrated luminosity in LHC Run 3, FASER observed 0 events in an almost background free analysis
- World-leading constraints on dark photons with couplings $\epsilon \sim 2 \times 10^{-5} - 1 \times 10^{-4}$ and mass $\sim 17MeV - 70MeV$
- The constrained parameter space includes a cosmologically favoured thermal relic target region

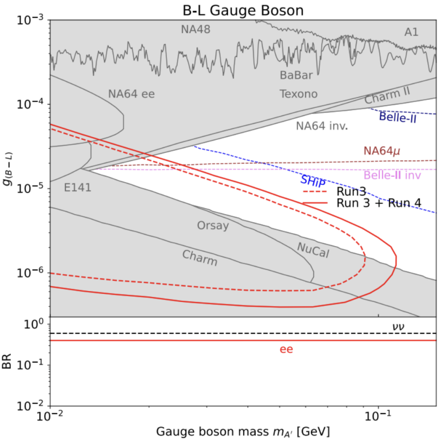


FASER Collaboration, *Search for Dark Photons with the FASER detector at the LHC FASER Collaboration*, Phys. Lett. B 848 138378 (2024) arXiv:2308.05587v2

BSM Potential: B-L Gauge Boson

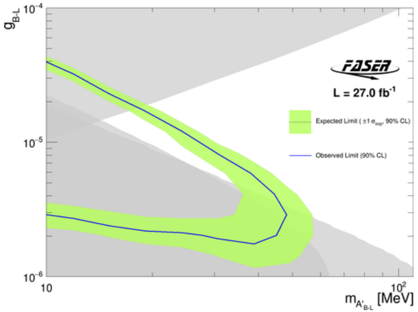
$$\mathcal{L} \supset \frac{1}{2} m^2_{A'_{B-L}} A'^2_{B-L} - g_{B-L} \sum_f Q^f_{B-L} A'^{\mu}_{B-L} \bar{f} \gamma_\mu f$$

- The accidental conservation of baryon number B and (total) lepton number L in the SM suggests that these conserved quantities, and linear combinations there of, may be linked not just to global, but to local gauge symmetries. A particularly well-motivated example is the gauge symmetry B-L
- B-L is free of quantum anomalies
- Can be made a local symmetry with the introduction of three sterile neutrinos
- Production channels:
  1) Light meson decays
  $\pi^0 \to A'_{B-L}\gamma \,, \eta \to A'_{B-L}\gamma$



BSM Completed Analyses: B-L Gauge Boson

- Decays to electrons , SM neutrinos, and possibly the sterile neutrinos required for the model
- Assuming $m_{\nu_{sterile}} > \frac{m_{B-L}}{2}$, $B(A'_{B-L} \to e^+e^-) \approx 40\%$ (25% if not). The analysis is the same as for A'
- In this model, the region probed by FASER is cosmologically favoured by both freeze-out and freeze-in mechanisms with $\nu_{sterile}$ as the dark matter



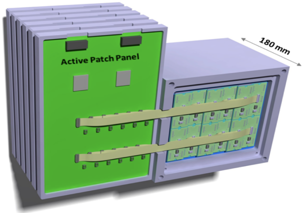
FASER Collaboration, *Search for Dark Photons with the FASER detector at the LHC FASER Collaboration*, Phys. Lett. B 848 138378 (2024) arXiv:2308.05587v2

Axion-Like Particles (ALPs)

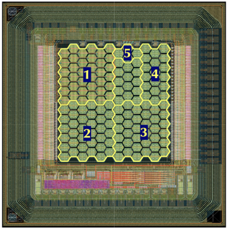
- Couple to the SM through dimension-5 operators
- ALPS are pseudoscalar SM singlets that can appear as pseudo-Nambu-Goldstone bosons in theories with broken global symmetries in analogy to the QCD axion
- Can yield dark matter with the correct relic density
- At FASER, nearly all neutral final states
- Event selection uses timing stations, preshower, and calorimeter
- Analysis currently underway for ALP-W, ALP-photon, ALP-g models with 60 fb^{-1} of run 3 data (2022+2023 data)
- Neutrinos interacting in the calorimeter are main source of background for ALPS
- Enhanced ALP physics reach at FASER with 2025 preshower upgrade

The FASER detector: Preshower Upgrade

- A high-precision preshower detector is being constructed to be installed in January 2025, allowing to distinguish the predicted axion-like particles signature of two high energy photons
- Designed to separate photons only 0.2mm apart
- Will utilize a monolithic detector ASIC based on an R&D that has been ongoing at the University of Geneva since 2015
- The new preshower consists of 6 planes of silicon pixels with a granularity of 100 μm interleaved with tungsten absorber planes



(Above) The 6 preshower planes and read-out. (Below) Prototype chip of the FASER WSi preshower.

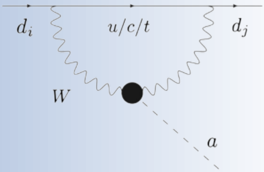


BSM Potential: ALP-W

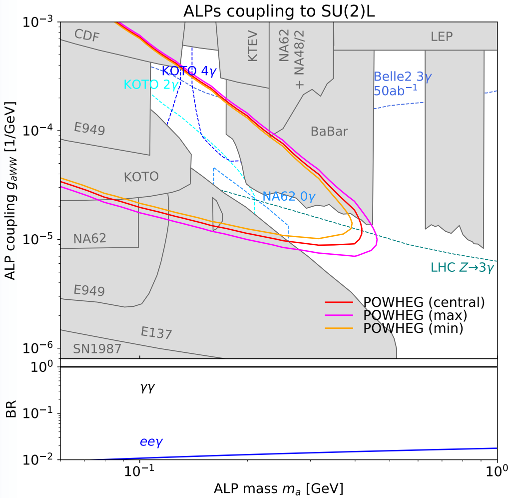
$$\mathcal{L} \supset -\frac{1}{2}m_a^2 a^2 - \frac{1}{4} g_{aWW} a W^{A\mu\nu} \widetilde{W}^A_{\mu\nu}$$

- After EWSB, the ALP acquires couplings to all the electroweak gauge bosons e.g. W-bosons
- The coupling to W-bosons allows for an abundant production at the LHC via loop induced decays
- Production channels:
  1) Flavor-changing neutral currents via W loop

$K^+ \to \pi^+ a$
$K_L \to \pi^0 a$
$b \to X_s a$



- Current analysis underway with $60\,fb^{-1}$ of LHC run 3 data
- Reach for 2025 + run 4:

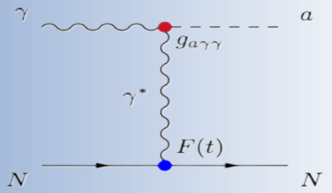


BSM Potential: ALP-photon

$$\mathcal{L} \supset -\frac{1}{2}m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

- Assume the case in which the ALPs only couple to photons at the high-energy scale Λ
- Production channels:

1) Photons produced in the forward direction create an effective beam dump experiment with the LHC IP1 neutral beam aborsber (TAN) where ALPs are produced through the Primakoff process:



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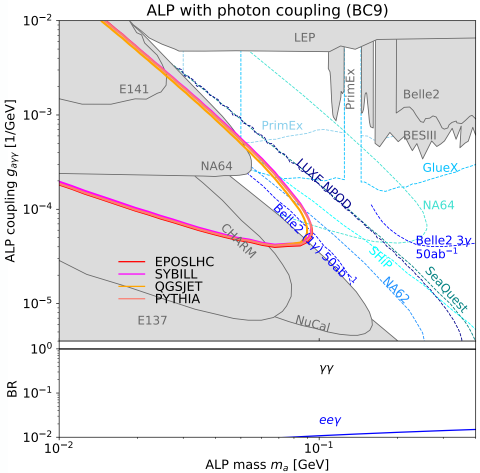


All BSM models considered so far at FASER

Roughly in order of validation/reach:

- Dark Photon
- U(1) B-L gauge boson
- ALP-W
- ALP-γ
- ALP-g
- U(1) B gauge boson
- Up-Philic
- FASER + LHC magnets as ALP-Light-Shining-through-Walls experiment [1]
- Protophobic gauge boson (ATOMKI anomaly)
- Inelastic darkmatter [2]
- Heavy neutral leptons
- Quirks [3]
- Model independent analysis

[1] F Kling, P Quilez, *ALP Searches at the LHC: FASER as a Light Shining through Walls Experiment.* Phys.Rev.D 106 (2022) 5, 055036. arXiv:2204.03599v2

[2] K. R. Dienes, J. L. Feng, M. Fieg, F. Huang, S. J. Lee, B. Thomas, *Extending the Discovery Potential for Inelastic-Dipole Dark Matter with FASER.* Phys. Rev. D 107, 115006 (2012). arXiv:2301.05252v2

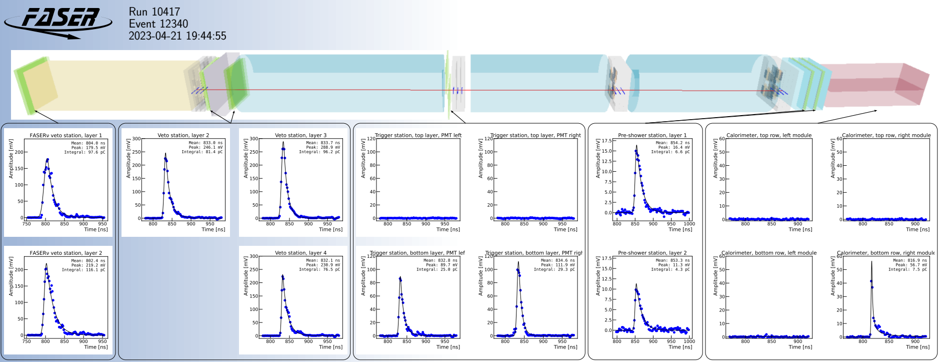
[3] Li, J., Pei, J., Ran, L.j. et al., *The quirk signal at FASER and FASER 2.* J. High Energ. Phys. 2021, 109 (2021). arXiv:2108.06748v2

FASER has sensitivity reach in many BSM models, and will be excluding new parameter space or discovering new particles in the coming weeks and months.

The addition of the new pre-shower detector will greatly expand the physics search capability for neutral final states for 2025 and beyond. FASER has been approved for run 4!

Additional slides...

FASER event display with waveforms of modules



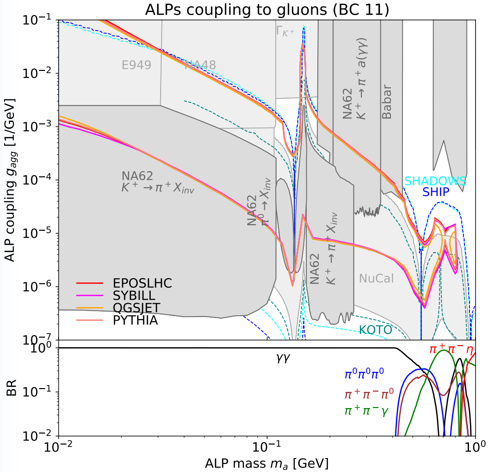
Event display of a muon traversing FASER recorded on 21 April 2023 with 6.8 TeV stable beams. The measured track momentum is 1.30 TeV. The waveforms are shown for signals in scintillator counters and calorimeter modules and are fitted using a Crystal Ball function. All PMT waveforms are consistent with a muon passing through the scintillators and one of the calorimeter modules. The event has been triggered by modules in the FASER veto station, veto station and trigger station with pulses above 25 mV, and by modules in the pre-shower station with pulses above above 3 mV. The ATLAS interaction point is 480 m to the left of the detector shown. The detected hits in the semiconductor tracker modules are shown with blue lines and the reconstructed track is shown with a red line. In the title of the waveform plots, left and right is defined facing the downstream direction.

BSM Potential: ALP-gluon

$$\mathcal{L} \supset -\frac{1}{2}m_a^2 a^2 - \frac{1}{8}g_s^2 g_{agg} a G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

- Assume the case in which ALPs only couple to gluons at the scale $\Lambda = 1\text{TeV}$
- If the ALP is sufficiently light, $m_a < 2\pi\Lambda_{QCD}$, its interactions can be described using chiral perturbation theory. In this case, the ALP mixes with the with π^0, η , η'
- Production channels:
  1) Mixing with π^0 , η , η'
  2) B decays

- Current analysis underway with $60\,fb^{-1}$ of LHC run 3 data
- Reach for 2025 + run 4:



FASER Collaboration, *FASER's physics reach for long-lived particles*, Phys. Rev. D 99, 095011 (2019) arXiv:1811.12522v3

BSM Potential: U(1)B

$$\mathcal{L} \supset \frac{1}{2} m_{A'_B}^2 A'^2_B - g_B \sum_f Q_B^f \bar{f} \gamma^\mu f A'_{B\mu}$$

- Hadrophilic vector boson mediator. Based on a gauged $U(1)_B$ baryon number symmetry
- Sizable couplings to quarks and (loop-)suppressed couplings to all leptons
- Production channels:
  1) Pseudo-scalar decays
     $\pi^0 \to A'_B \gamma$
     $\eta \to A'_B \gamma$
     $\eta' \to A'_B \gamma$

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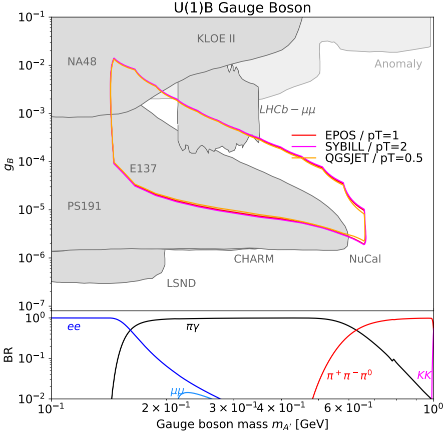


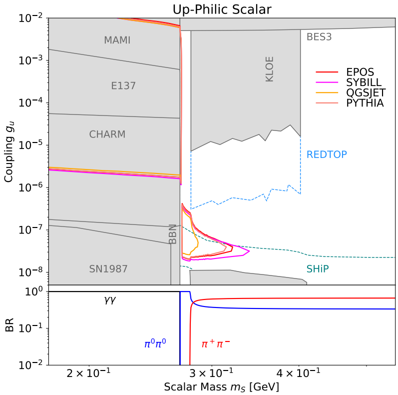
B. Batell, J. L. Feng, M. Fieg, A. Ismail, F. Kling, R. M. Abraham, and S.Trojanowski, *Hadrophilic dark sectors at the Forward Physics Facility*, Phys. Rev. D 105, 075001 (2022) arXiv:2111.10343v3

BSM Potential: Up-Phillic Scalar

$$\mathcal{L} \supset -\frac{1}{2}m_S^2 S^2 - g_u \bar{u} u S$$

- Light scalars coupled dominantly to the up quarks
- Coupling light scalars to only selected SM mass eigenstates avoids stringent constraints from flavor bounds, while simultaneously keeping the production rate high in pp collisions
- Production channels:
  1) Pseudo-scalar decays
     $\eta \to \pi^0 S$
     $\eta' \to \pi^0 S$
     $K^+ \to \pi^+ S$

- Current analysis underway with $60 fb^{-1}$ of LHC run 3 data
- Reach for 2025 + run 4 :



F. Kling, S. Trojanowski *FORESEE: FORward Experiment SEnsitivity Estimator for the LHC and future hadron colliders*, Phys. Rev. D 104, 035012 (2021) arXiv:1901.04468