Overview of BSM searches at Forward Physics Experiments.

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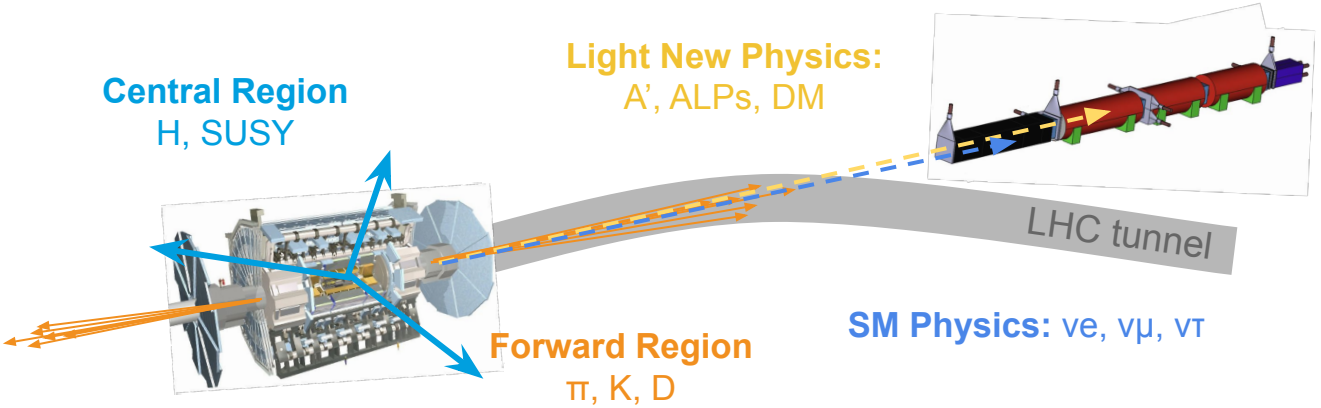
Light Dark World 2025, 16.09.2025

Idea and Motivation.



LHC was designed to search for (and study) heavy strongly coupled particles: existing experiments well suited for this, and performing well

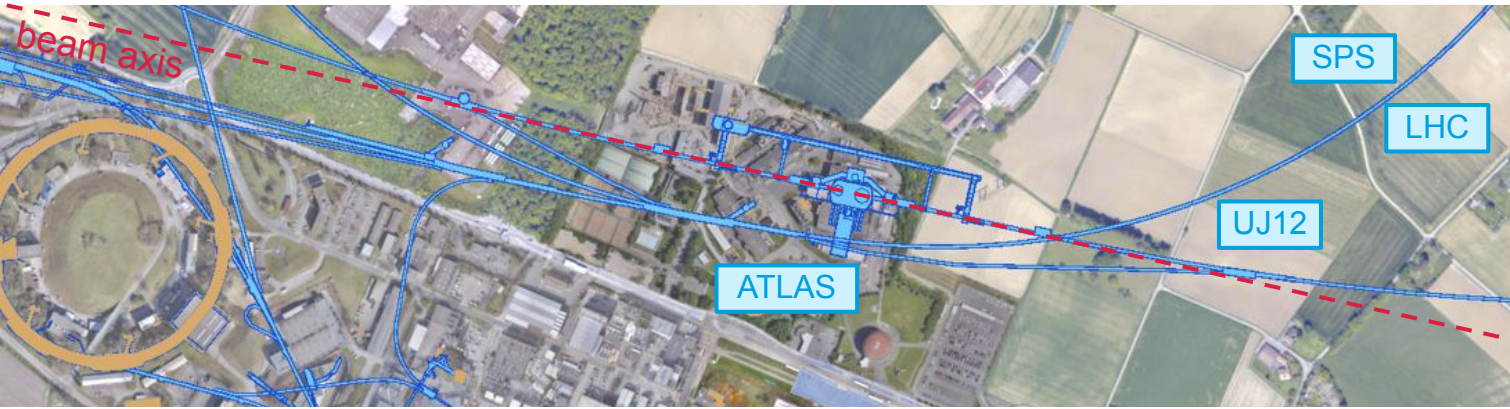
Huge number of light SM hadrons are produced in the forward direction: opportunity for weakly coupled, light new particles (dark sectors)

Weak coupling means very rarely produced, and long-lived: place detector along far away along beam axis

Experimental Program

Experimental Program.

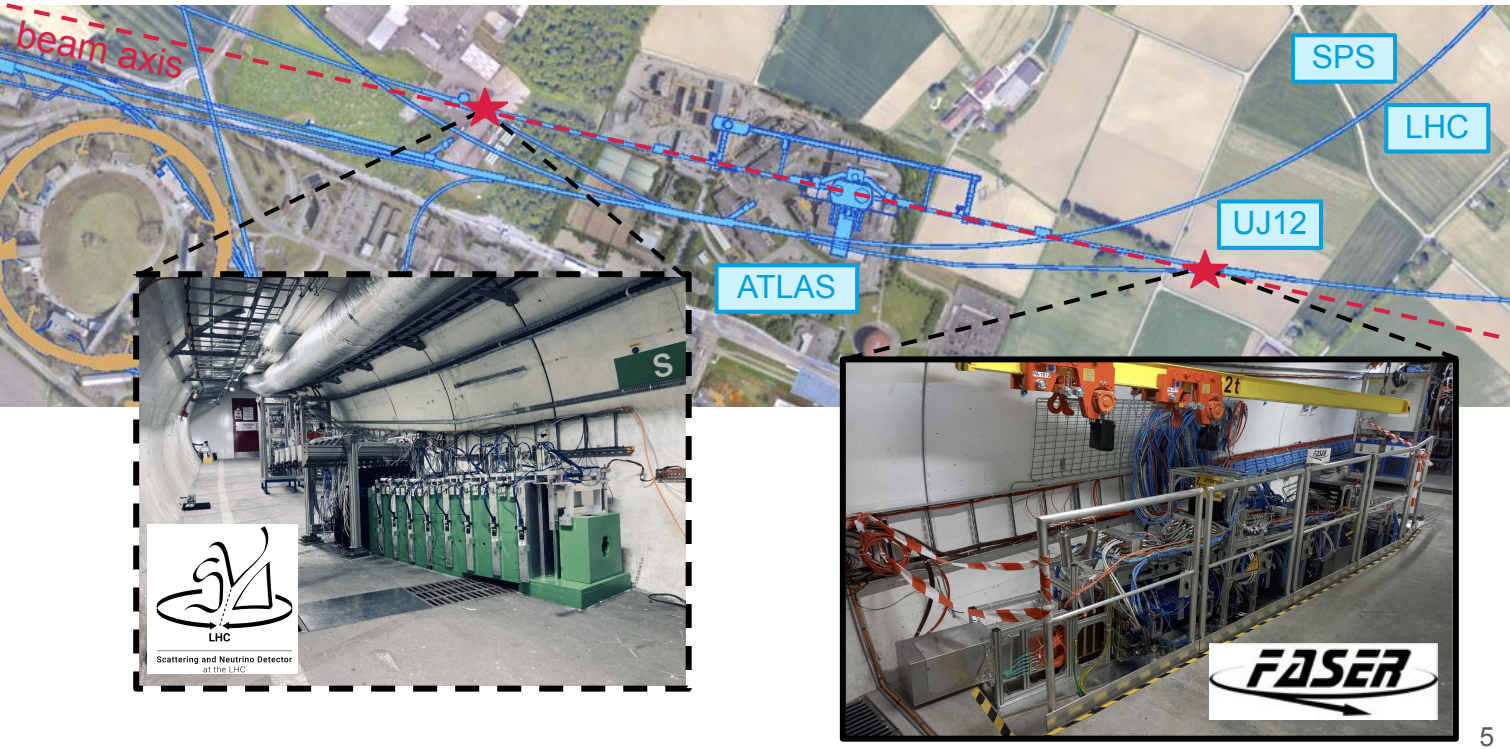
There is potential for forward physics experiments along beam axis.



Experimental Program.

There is potential for forward physics experiments along beam axis.

Two new experiments started operation in 2022 to exploit this potential:
SND@LHC and FASER.

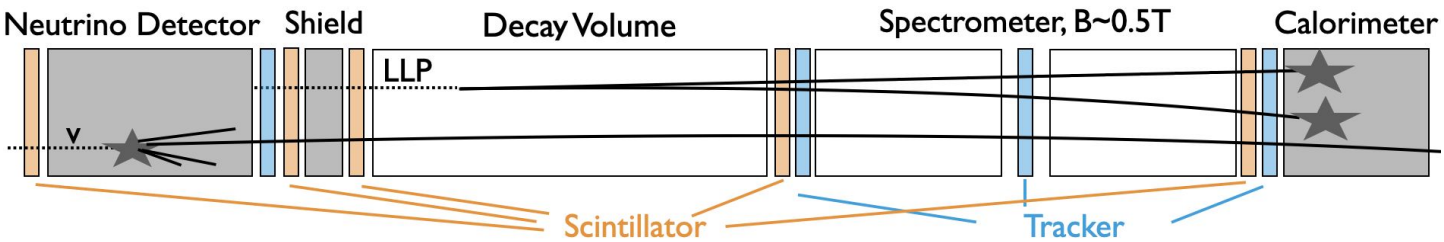


FASER Experiment.

(as imagined by a theorist)

Goal 1: Search for New Physics:

- decay of long-lived particles, e.g. A' → e e
- highly energetic particles emerge from empty decay volume
- need front veto, tracker, calorimeter



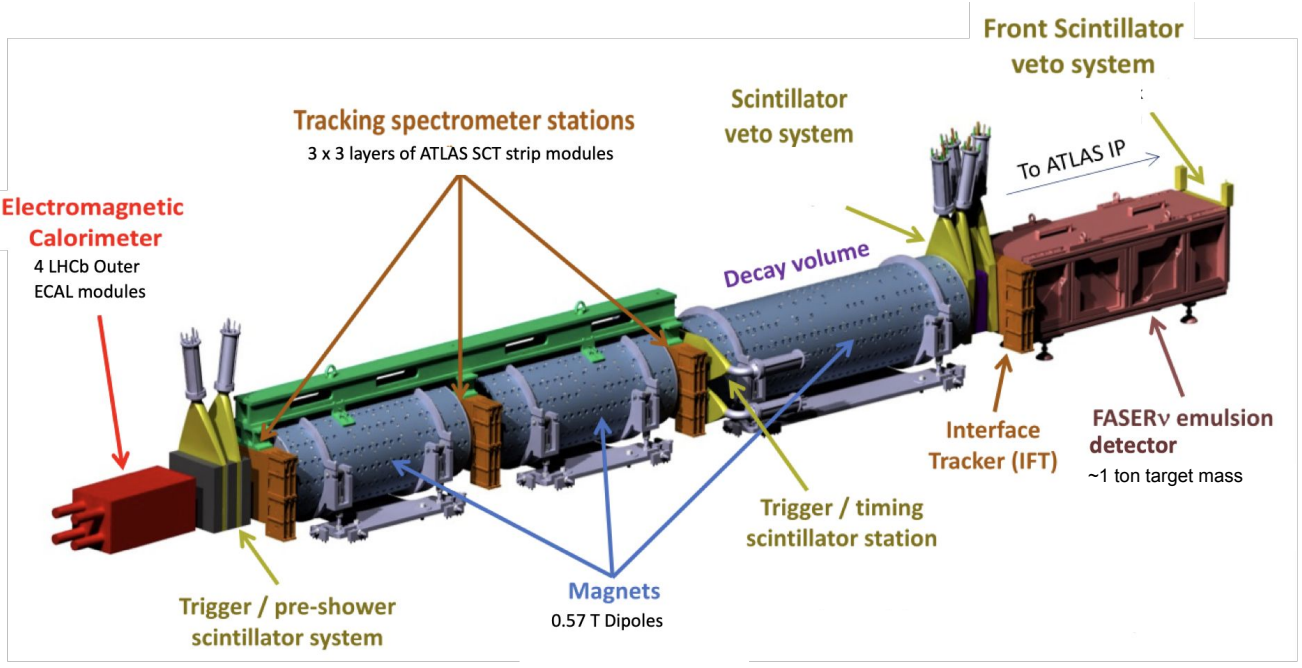
Goal 2: Neutrino Measurements

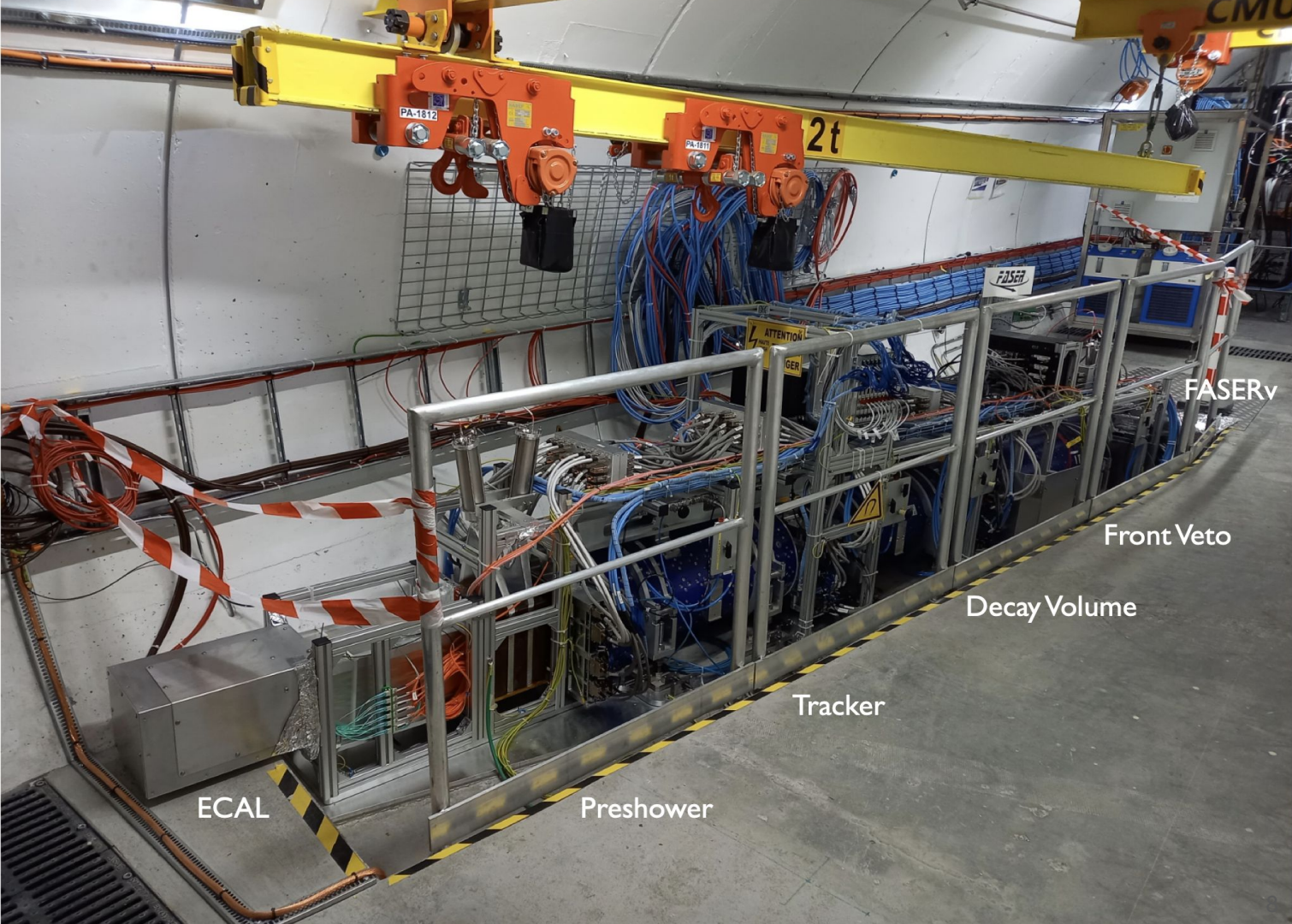
- interactions of collider neutrinos, e.g. ν N → μ + hadrons
- highly energetic particles emerge from dense material
- dedicated emulsion neutrino detector in front

FASER Experiment.

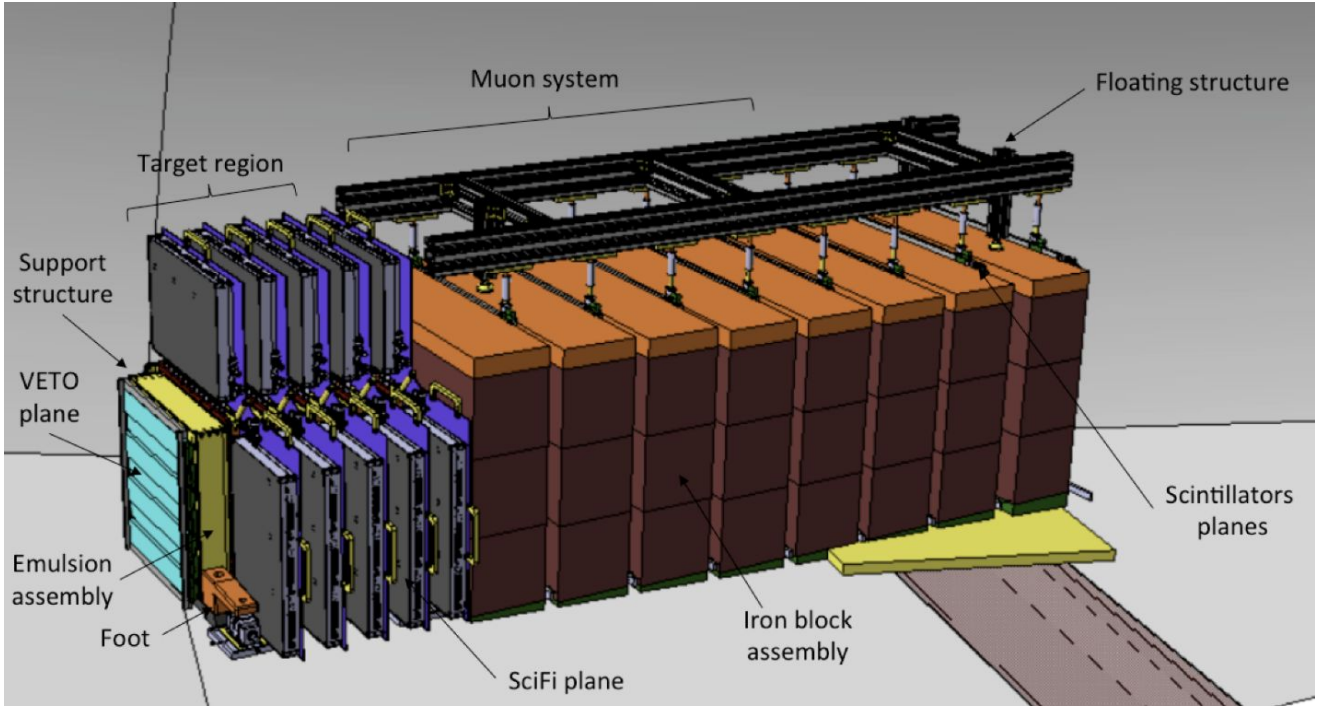
(as realized by the experimentalists)

[FASER, arXiv:2207.11427]




FASERv
Front Veto
Decay Volume
Tracker
Preshower
ECAL

SND@LHC.

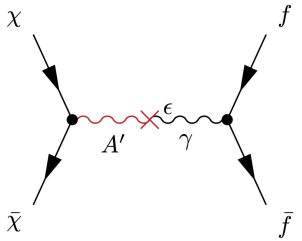

Muon system
Floating structure
Target region
Support structure
VETO plane
Scintillators planes
Emulsion assembly
Foot
Iron block assembly
SciFi plane

First Results on LLP Searches

Dark Photons: Theory.

The Dark Photon (A') Portal

- arise in many hidden sector models
- (massive) gauge boson of a U(1)D gauge group
- weakly coupled to SM via kinetic mixing with photon



$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu + \sum_f \epsilon e q_f \, \bar{f} \not{A}' f + g_D \, \bar{\chi} \not{A}' \chi$$

A' phenomenology at FASER

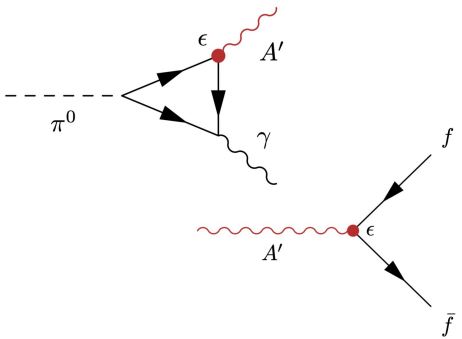
- MeV A' s produced mainly in meson decays

$$\mathrm{BR}(\pi^0 \to \gamma A') = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_\pi^2}\right)^3$$

- mA'<2mX: A' is long-lived

$$\bar{d} \approx 80\mathrm{m} \; B_e \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\mathrm{TeV}}\right] \left[\frac{100 \; \mathrm{MeV}}{m_{A'}}\right]^2$$

- for mA'<2mμ: A' only decays to e+e- pair

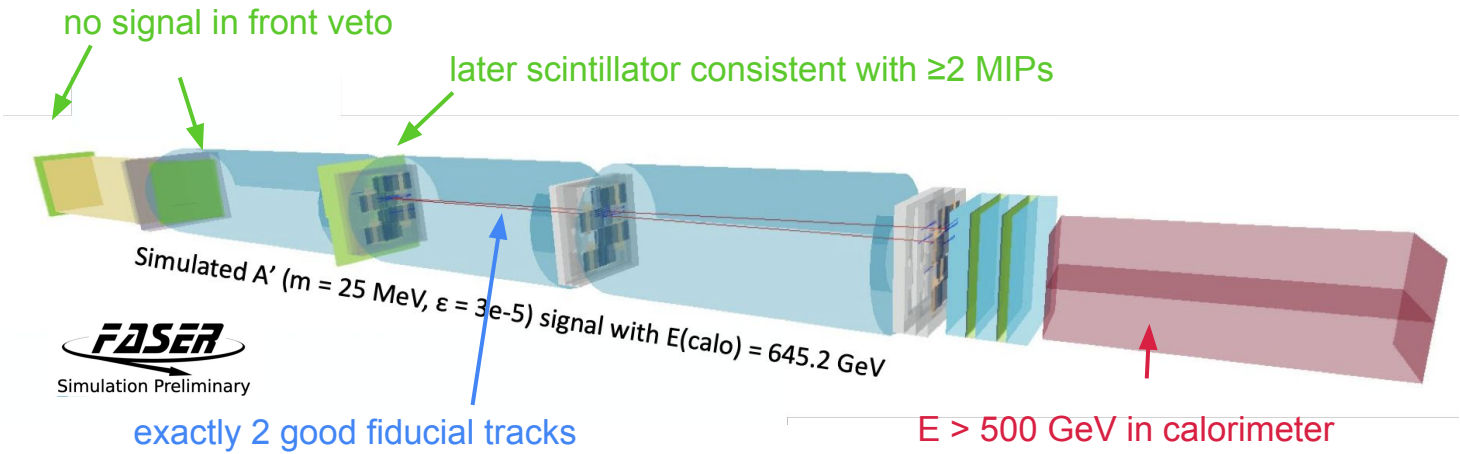


FASER's Dark Photon Search.

In 2023, FASER performed a first search targeting dark photons. [FASER, arXiv:2308.05587]

Simple and robust high energy e+e- selection, optimised for discovery

Expected background: $(2.0 \pm 2.7) \times 10^{-3}$ events (mainly neutrinos)



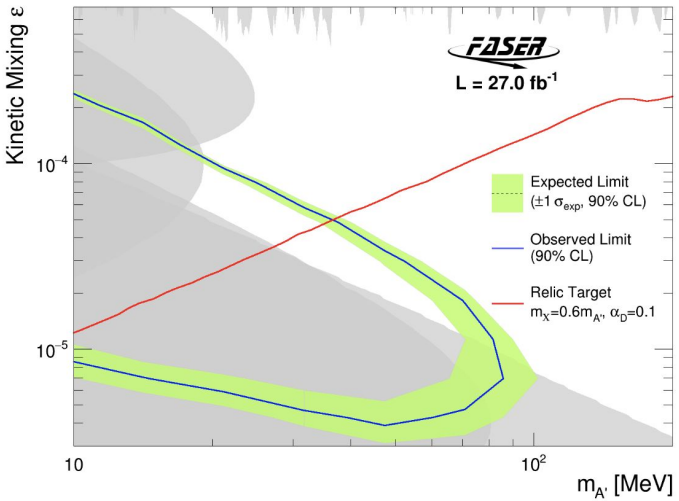
FASER's Dark Photon Search.

No events found in signal region.

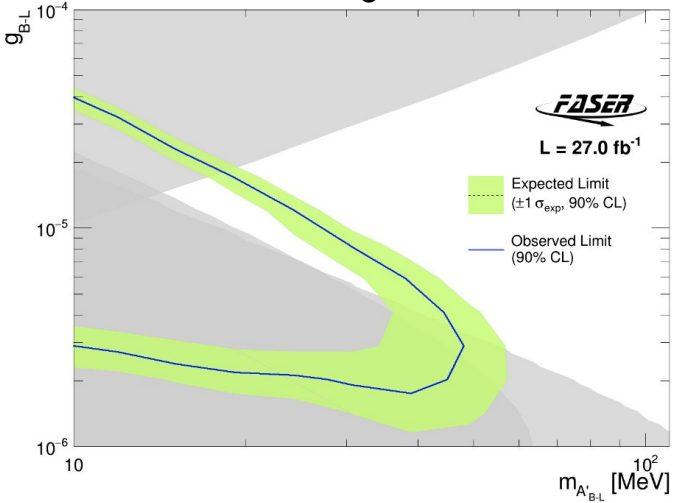
Based on this null results, FASER sets limits in previously unexplored parameter space

Probing region interesting from thermal relic target.

Dark Photon



B-L Gauge Boson



ALPs: Theory.

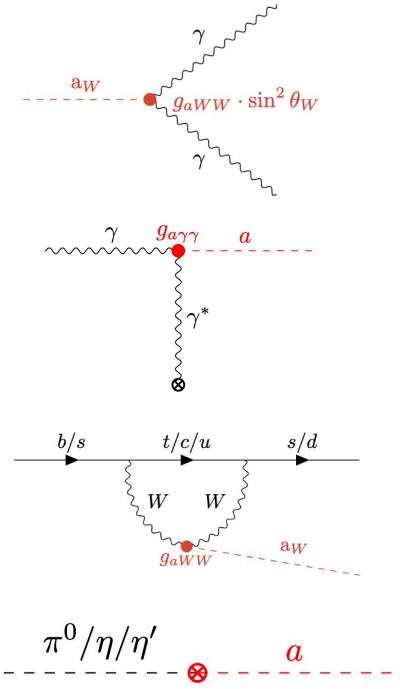
Axion Like Particles (ALPs):

- pseudo-Nambu-Goldstone bosons in theories with broken global symmetries
- could be motivated by strong CP-problem, remnants of GUTs or string theory

Effective Low-energy Lagrangian:

$$\mathcal{L}_{ALP} = -m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{1}{4} g_{aWW} W_{a,\mu\nu} \tilde{W}^{a,\mu\nu} - \frac{1}{4} g_{agg} G_{a,\mu\nu} \tilde{G}^{a,\mu\nu}$$

- in principle arbitrary couplings to all SM particles
- we consider
  * photophilic ALP: gaγγ ≠ 0
  * electroweak-philic ALP: gaγγ = sin²θW gaWW ≠ 0
  * gluon-philic ALP: gagg ≠ 0



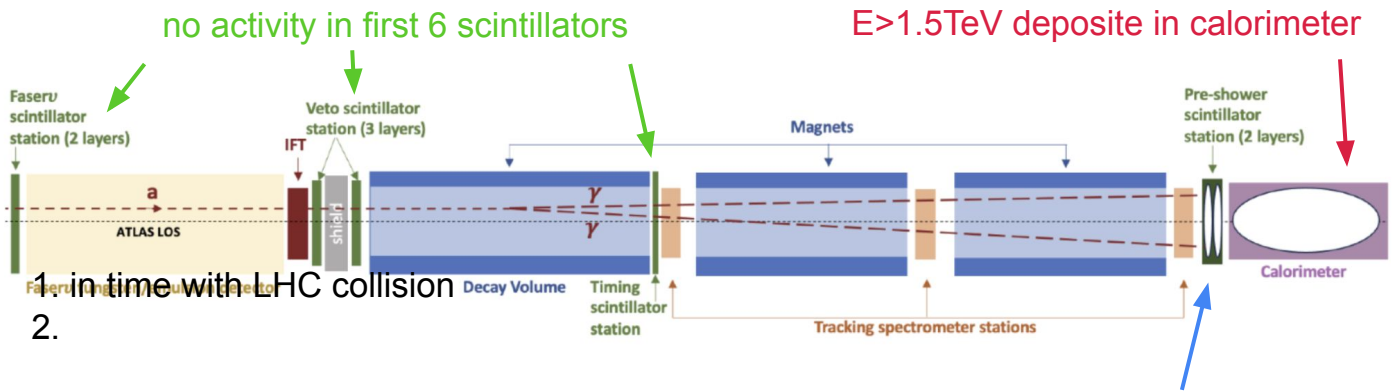
LHC Phenomenology:

- ALP decays to photon, can be long-lived for g<<1
- ALP produced via Primakoff process (photophilic), B > Xs a decays (electroweak-philic) and mixing with π0/η/η' (gluon-philic)

FASER's ALPs Search.

In 2024, FASER performed another search targeting ALPs. [FASER, 2410.10363]

Search for highly energetic photons emerging in decay volume.

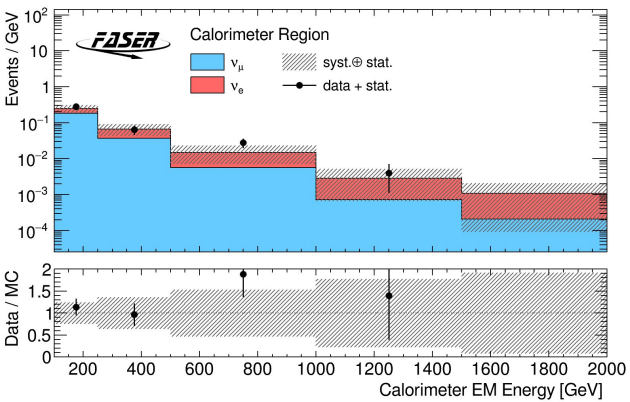


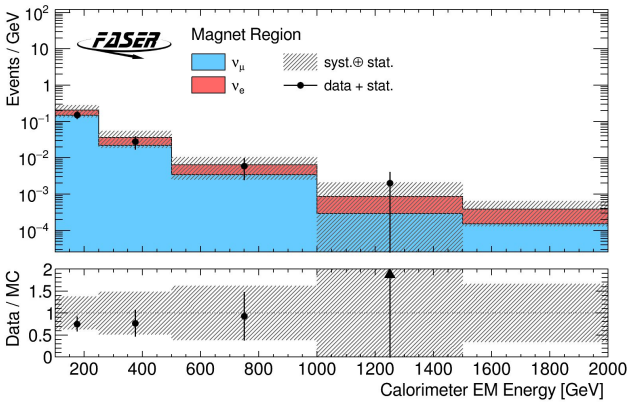
FASER's ALPs Search.

Backgrounds mainly due to neutrino interactions (in preshower),
all other source found negligible

Backgrounds estimated using MC and validated using control regions.

Expect 0.4 ± 0.4 events in signal region
(fixed before looking at control regions)



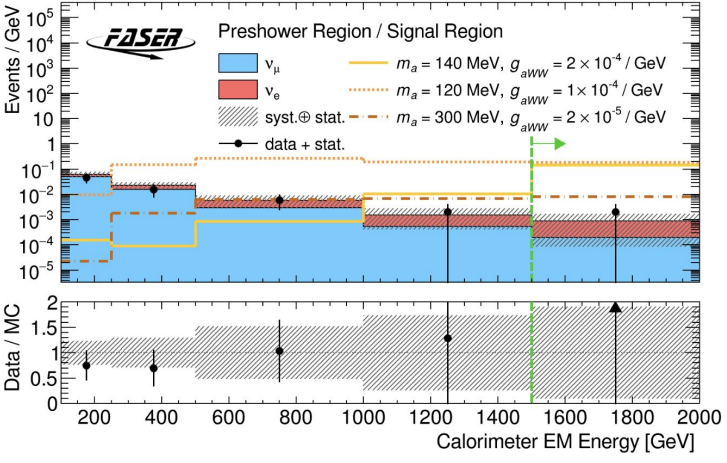


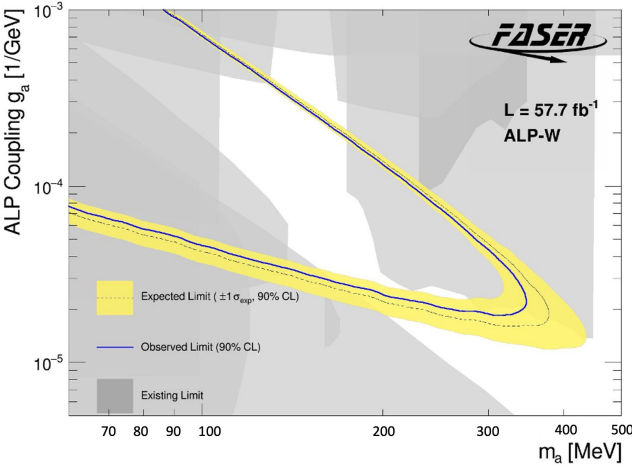
FASER's ALPs Search.

Expecting 0.4 ± 0.4 from neutrino interactions in pre-shower

Observed 1 event in 58/fb after unblinding

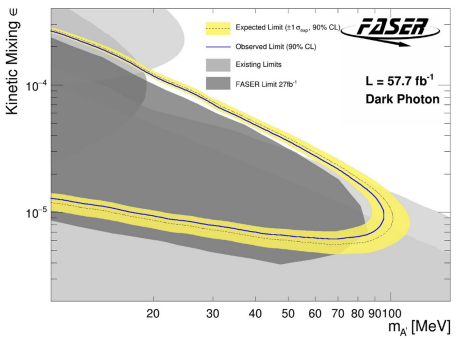
Constraints on previously allowed parameter space of ALPs models

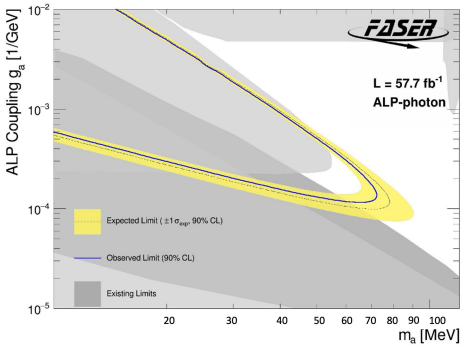


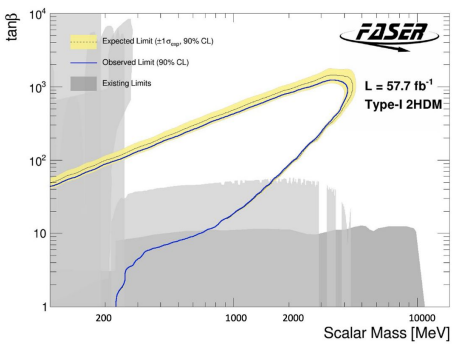


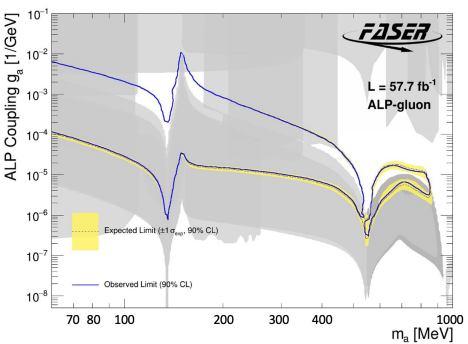
FASER's ALPs Search.

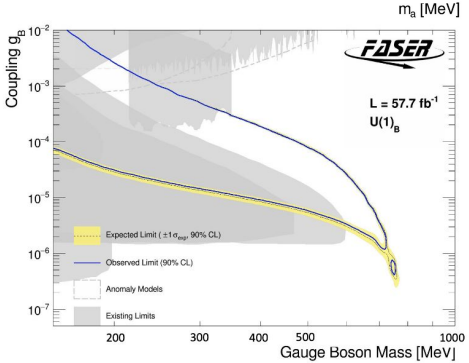
Recasted constraints for a variety of models, such as ALPs, 2HDM scalars, U(1)B gauge bosons, up-philic scalars. Many of those benchmarks were suggested by the community.

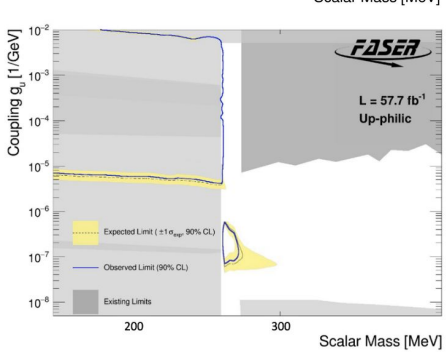












Recent Theory Efforts

Spin Correlations.

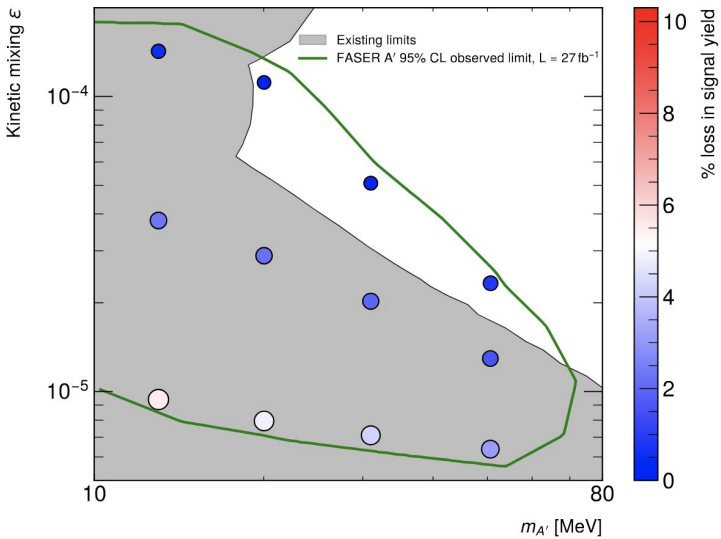
So far spin correlations have been ignored: A' production and decay were treated separately and dark photon is assumed to decay isotropically

Recent work investigates spin correlations [Feng, Toman, Welch 2508.18352]

Source of spin correlation: pion decay to longitudinally polarised dark photon is forbidden.

For FASER the effects from spin correlations remain negligible.

However, the spin correlations can be relevant in the parameter space covered by SHiP.



Bremsstrahlung.

Proton Bremsstrahlung is an important production mode of dark photons.

In the past mostly modelled via FWW approximation [Blumlein, Brunner: 1311.3870]
More recent description via quasi-real approximation with Dawson correction
[Foroughi-Abari, Ritz: 2108.05900] [Foroughi-Abari,Reimitz, Ritz: 2409.09123]

More recently, a form factor was obtained that could be applied to models with arbitrary coupling structures [FK, Reimitz, Ritz: 2509.09437]

Construct parameterization with correct normalization at t=0 and and correct asymptotic behaviours for F1 and F2 at large t.

Common fit to large sets of proton and neutron data.

$$F_i^p(t) = x_\omega F_{i,\omega}(t) + x_\phi F_{i,\phi}(t) + x_\rho F_{i,\rho}(t)$$
$$F_i^n(t) = x_\omega F_{i,\omega}(t) + x_\phi F_{i,\phi}(t) - x_\rho F_{i,\rho}(t)$$

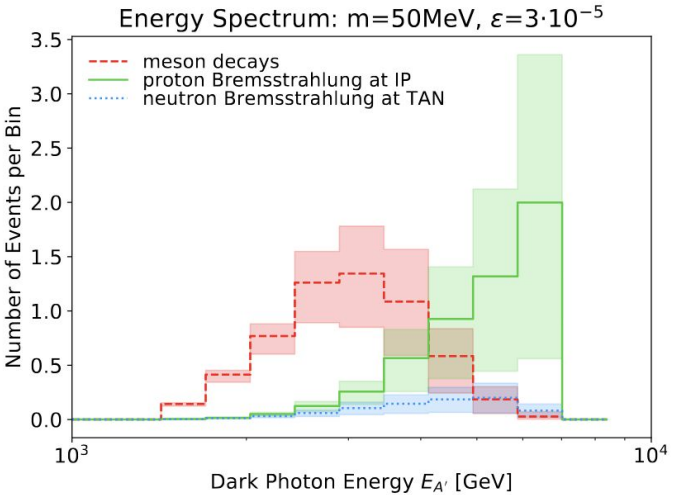
Model	x_u	x_d	x_s	x_ω	x_ρ	x_ϕ	x_p	x_n	x_ℓ	x_ν
Dark photon	+2/3	−1/3	−1/3	1	1	1	1	0	-1	0
$U(1)_{B-L}$	+1/3	+1/3	+1/3	2	0	-1	1	1	-1	-1
$U(1)_B$	+1/3	+1/3	+1/3	2	0	-1	1	1	0	0
Protophobic	−1/3	+2/3	+2/3	1	-1	-2	0	1	-1	0

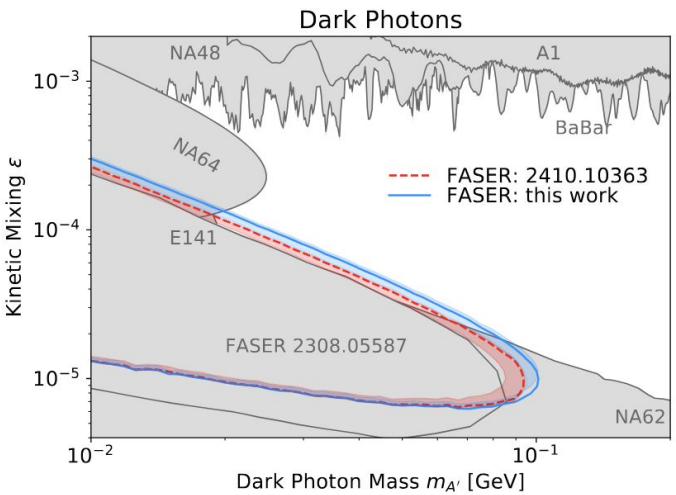
Bremsstrahlung.

Updated description of Bremsstrahlung and its uncertainties.

First estimate of A' production via neutron bremsstrahlung in absorbers.

Recast of FASER's ALP analysis found that the excluded region increased.

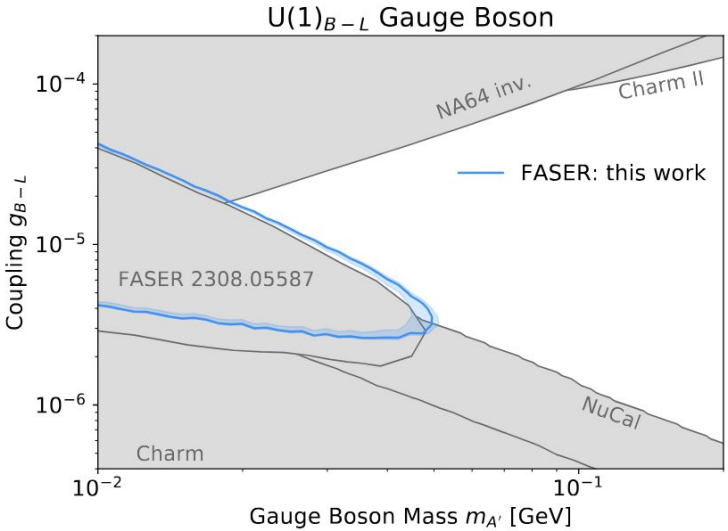


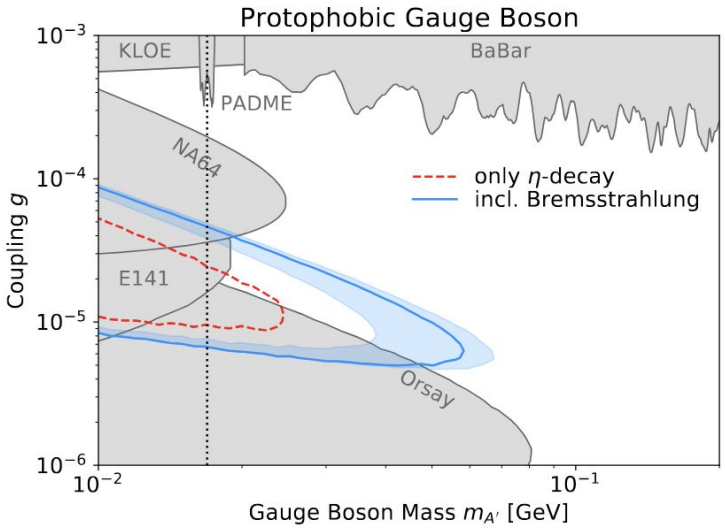


Bremsstrahlung.

Improved results also for B-L gauge boson.

First results for a protophobic gauge boson, as motivated by the ATOMKI anomaly.



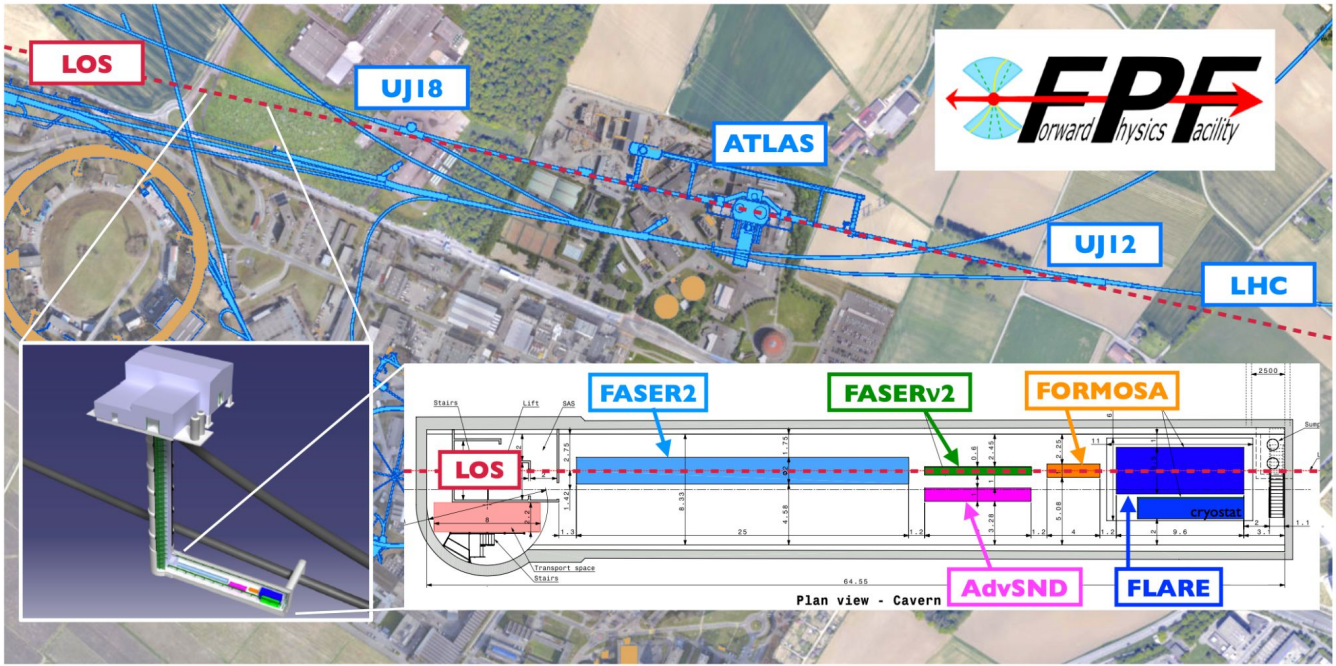


Further Plans and Ideas for Forward Physics Searches at the LHC

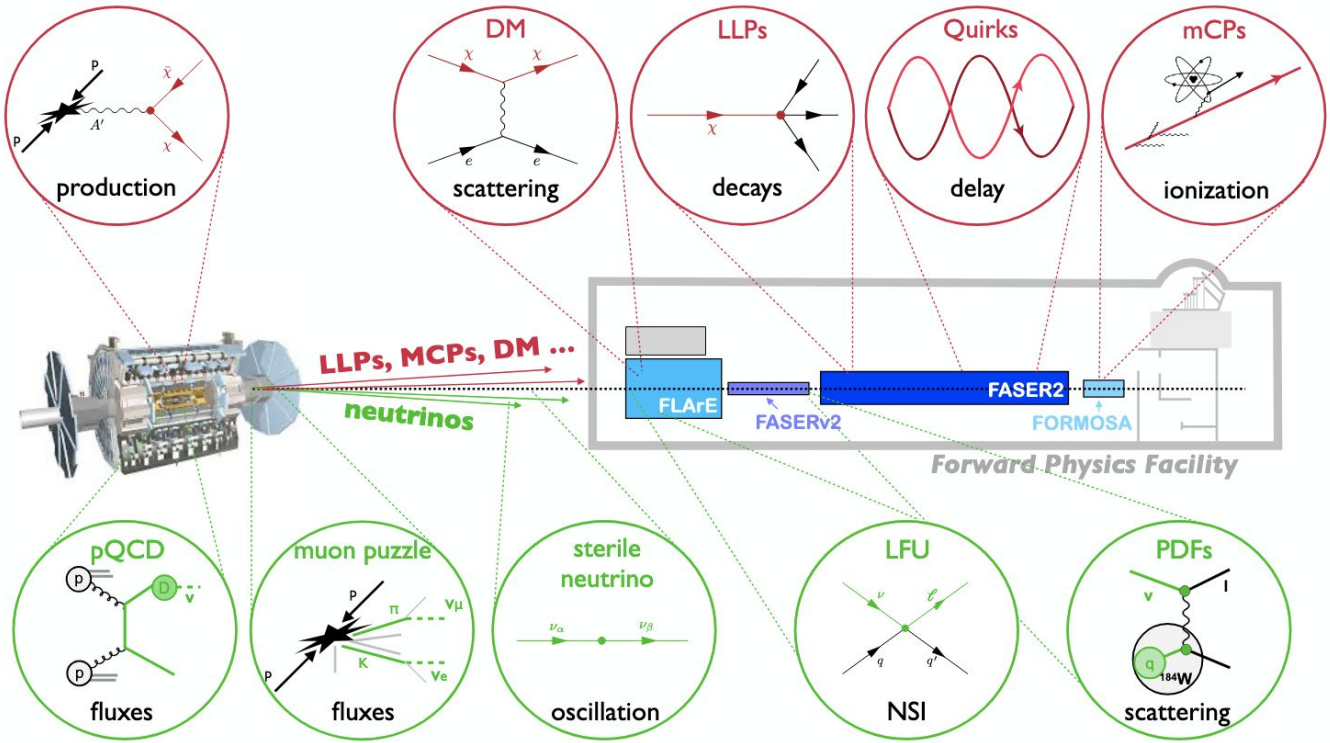
Forward Physics Facility.

Continuation of this program envisioned for HL-LHC era (2030s).

Proposal to create a dedicated **Forward Physics Facility (FPF)** for the HL-LHC: suite of experiments that will greatly enhance the LHC's physics potential for BSM physics searches, neutrino physics, QCD and astro-particle physics.



Physics Opportunities.

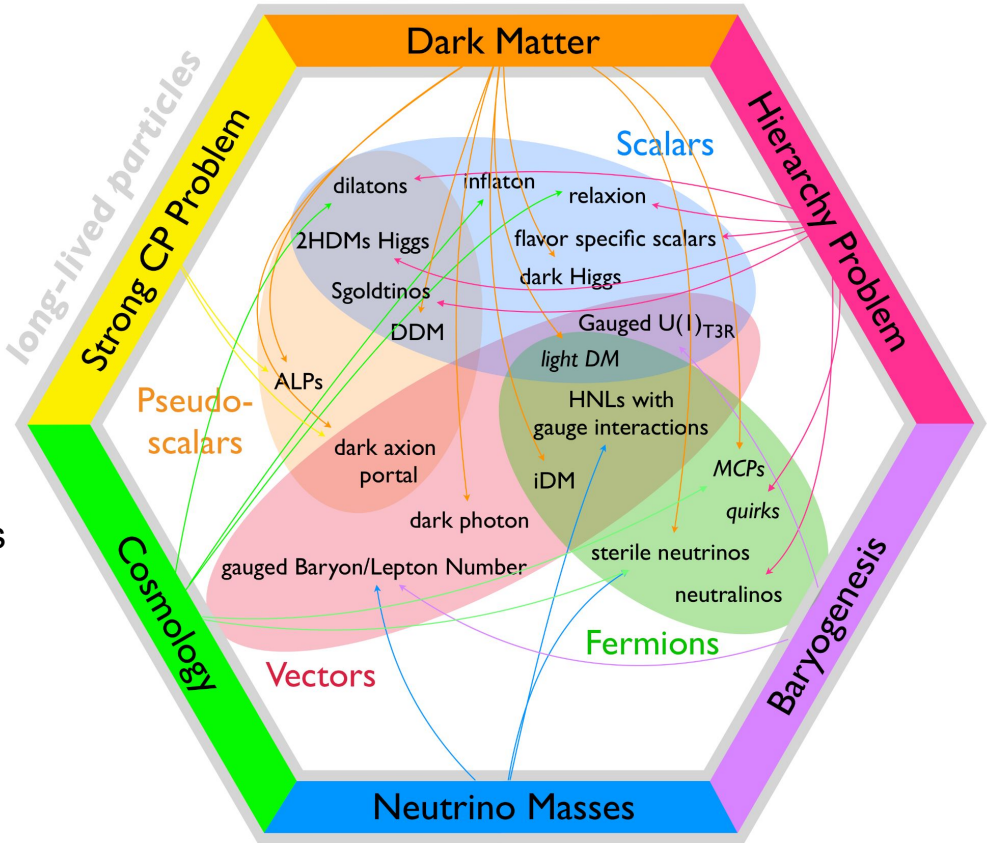


More Long-Lived Particles.

More analyses ongoing / planned.

Light new physics models can address many outstanding problems in particle physics

[Feng, FK, Reno, Rojo, Soldin et al. 2203.05090]

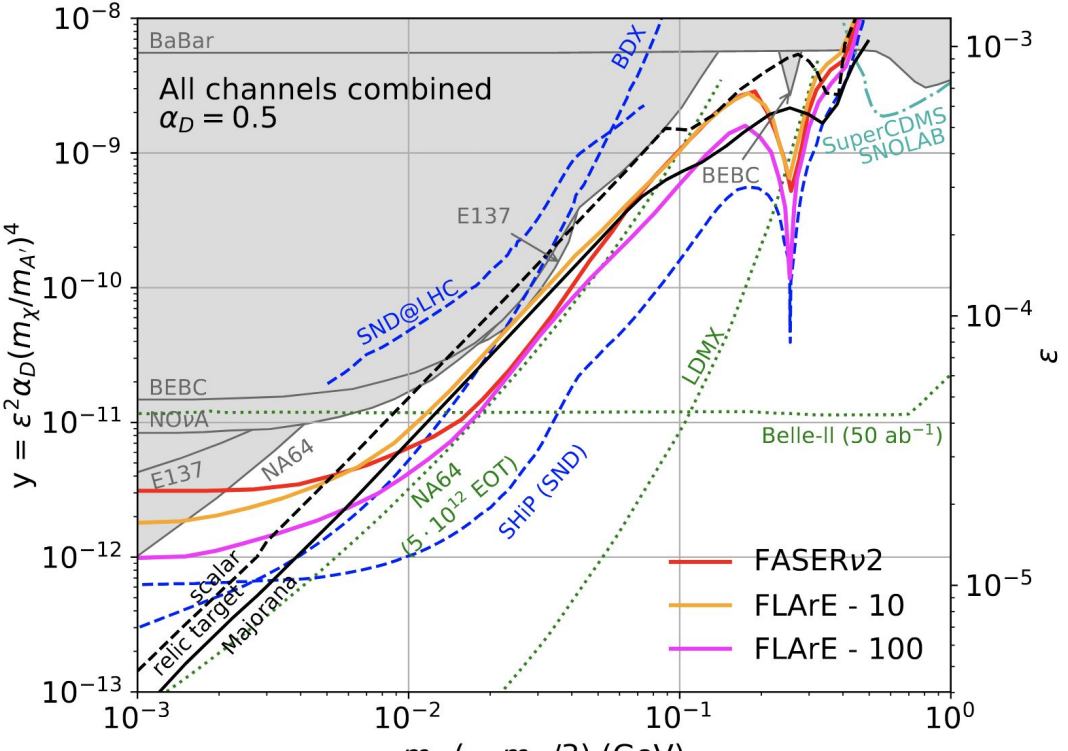


Dark Matter Scattering.

if mA' > 2mX : A' decays to DM

→ LHC produces energetic DM beam [**Batell**, **Feng**,**Trojanowksi**: 2101.10338]

DM scatters in **FLArE** and **FASERv2** neutrino detector: X e → X e.

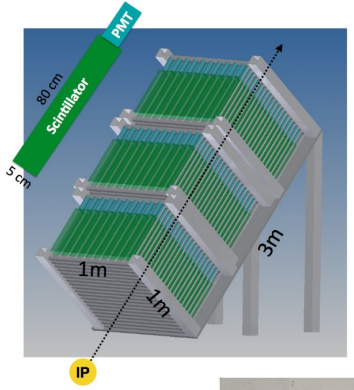


Millicharged Particles.

millicharge Q=εe → search for minimum ionizing particle with very small dE/dx

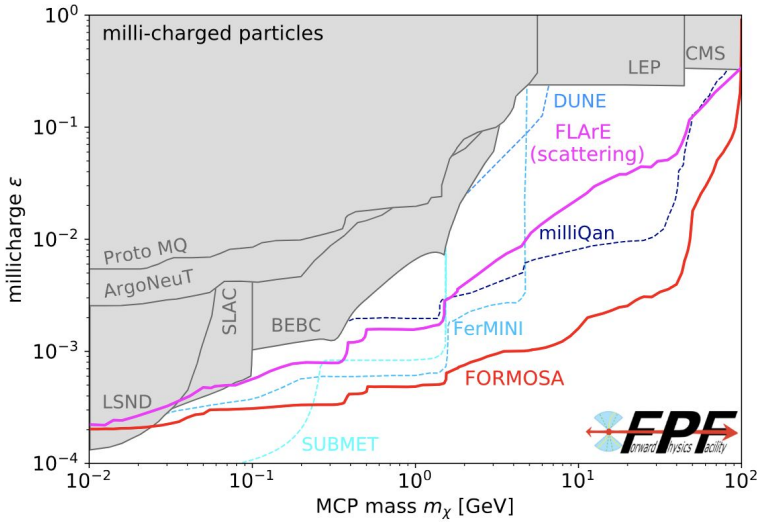
MilliQan was proposed as dedicated LHC experiment to search for MCPs near CMS

Flux is ~100 times larger in forward direction: **FORMOSA** [Abari, FK, Tsai, 2010.07941]



[MilliQan, 1607.04669]

Demonstrator installed last year.

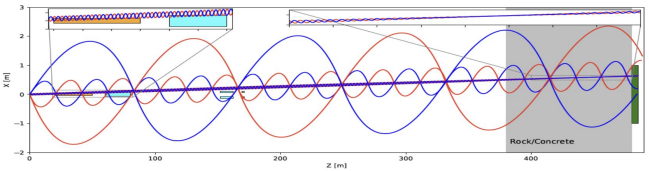


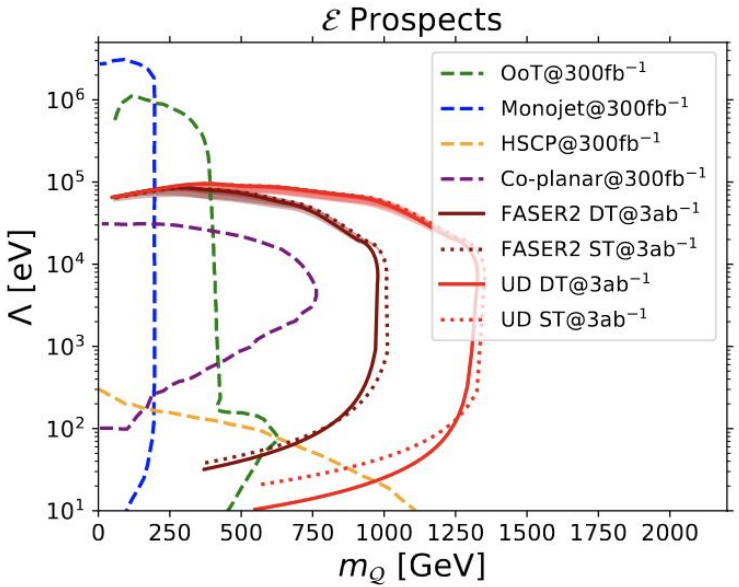
Quirks.

FASER and **FASER2** may also be able to probe quirks

- mass range of 100s GeV - TeV motivated by hierarchy problem, neutral naturalness
- quirk-anti-quirk system bound by hidden QCD, highly forward peaked
- signature: delayed/slow tracks

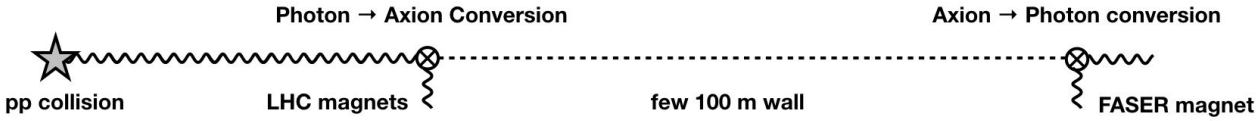
[**Feng**, Li, Liao, Ni, Pei; 2404.13814]





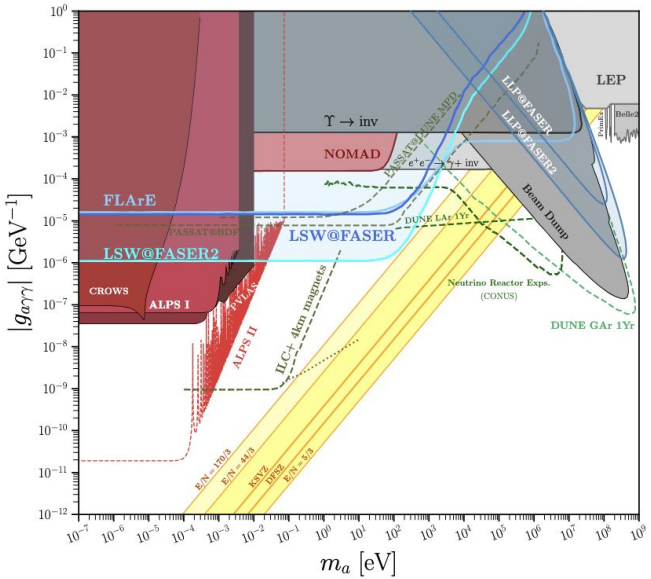
ALP Conversion.

Consider LHC and FASER as a light shining through a wall experiment [FK, Quilez, 2204.03599]



- appearance of single photon
- strongest purely laboratory bound at $m_a > 10$ meV

- of course much stronger astro bounds

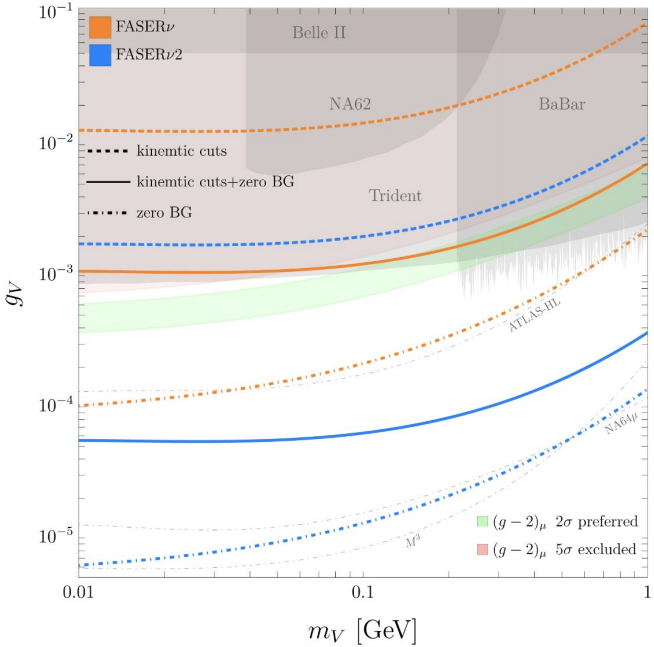


Muonic Forces.

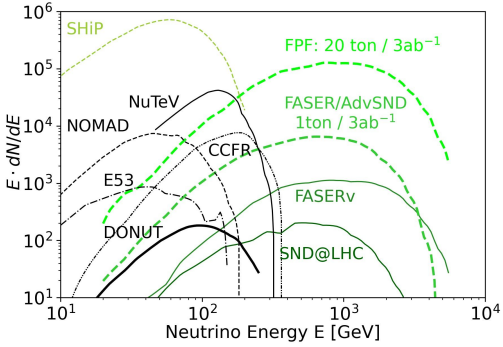
There is a large flux of TeV-energy muons going through FPF experiments: 0.1Hz/cm² or 10^{11}ab/m²

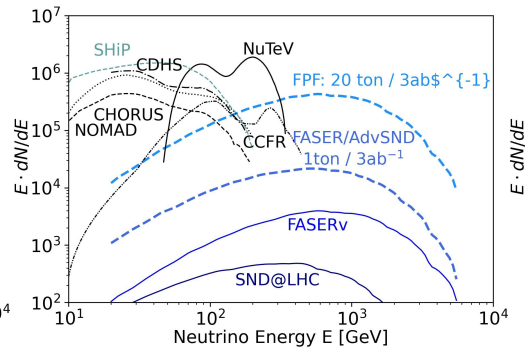
Search for missing-momentum signatures in muon scattering

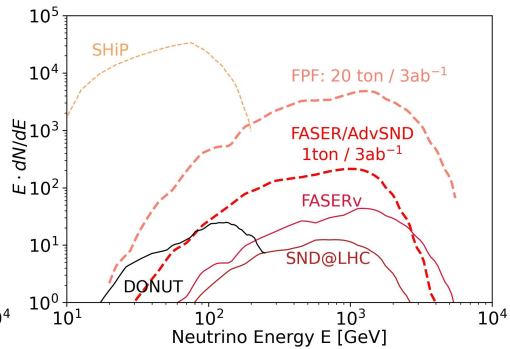
[Ariga, Balkin, Galon, Kajomovitz, **Soreq**, 2305.03102]



Collider Neutrino Physics.





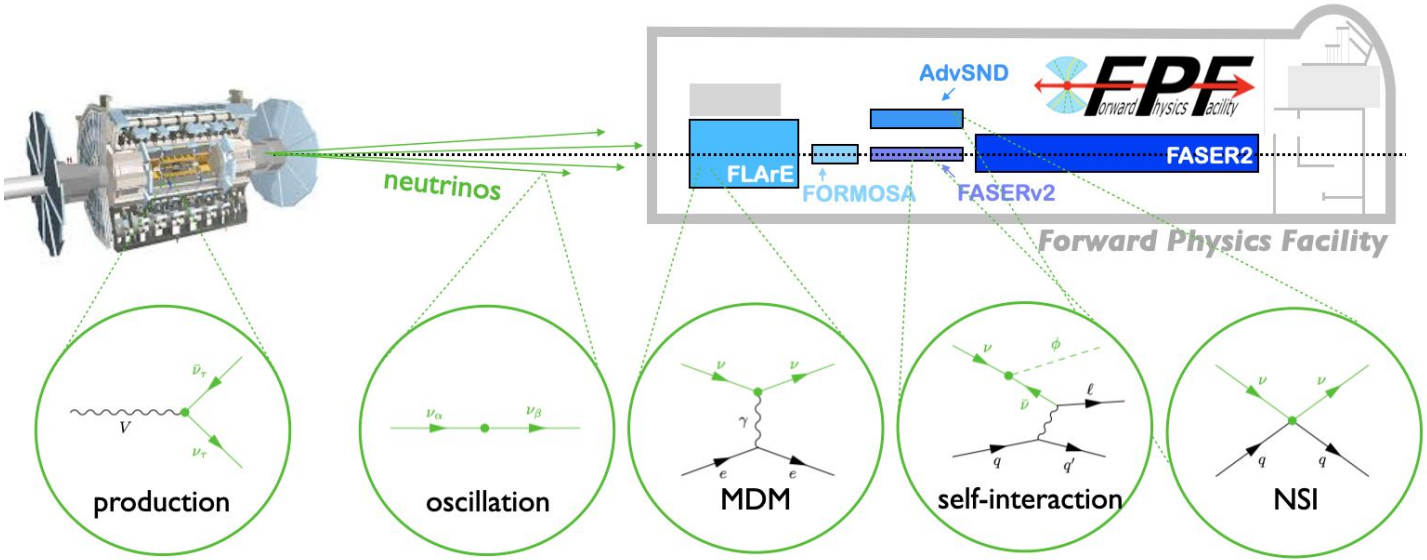


LHC neutrinos uniquely cover unexplored TeV energy range.

Thousands of neutrino interactions in current detectors.

Please talk to me in a coffee break if you are interested.

Collider Neutrinos: BSM Physics.



[FK, 2005.03594]

[FASER, 1908.02310]

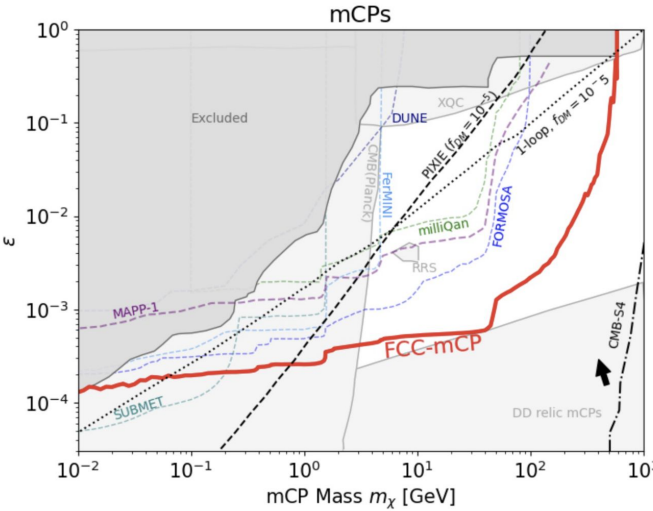
[Abraham, Abari, FK, Tsai, 2301.10254]

[Kelly, FK, Tuckler, Zhang, 2111.05868]

[Abraham, Ismail, FK, 2012.10500]

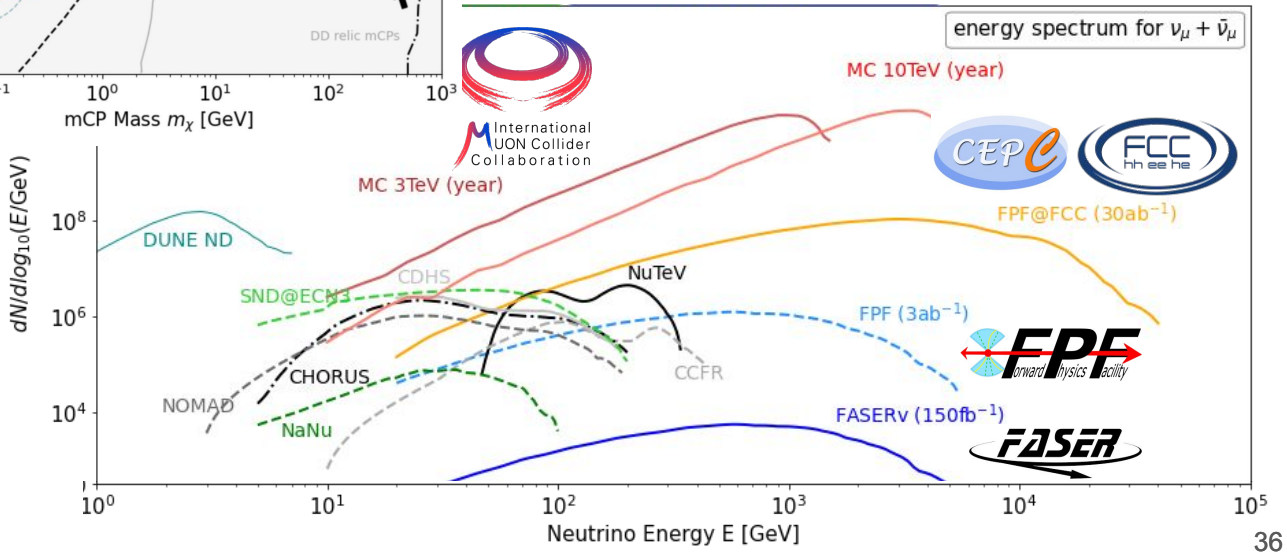
Outlook: Far Future

Forward Physics beyond LHC.



The same ideas also apply to future colliders!

[FPF, 2203.05090] [Abraham, Adhikary, Feng, Fieg, FK, Rojo, Trojanowski, 2409.02163]] [MuCol Interim report, 2407.12450]



Summary

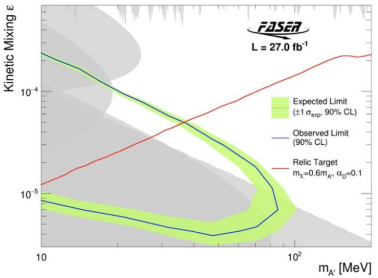
Summary.

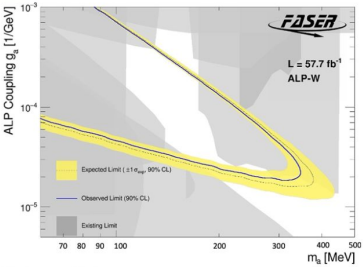
With FASER and SND, a novel forward physics program emerged to fully exploit the LHC.

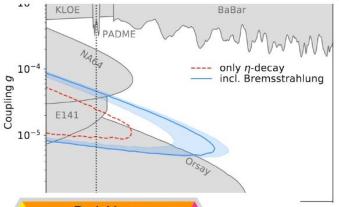
First searches for dark photon and ALPs were performed by FASER.

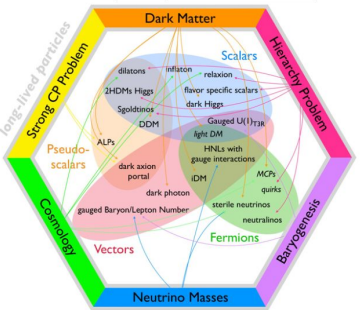
In addition, this program also observed LHC neutrinos for the first time.

Many more exciting results to come.









Program heavily benefited from good ideas in the community.

Let's come up with some new ideas!