Discovery Potential for ALPs at FASER and FASER 2

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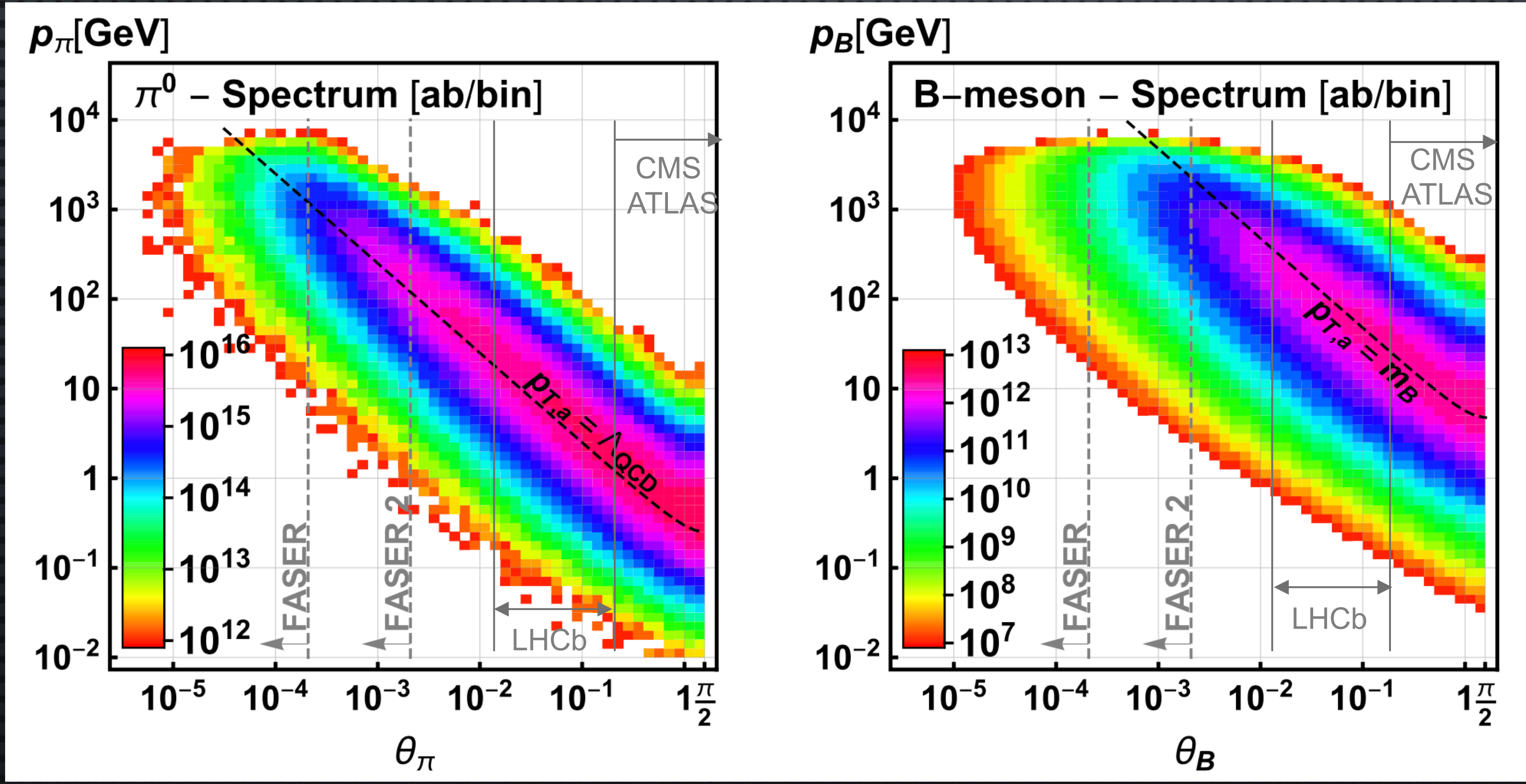
Content

The main purpose for the ForwArd Search ExpeRiment (FASER) is to searching for LLPs with mass around ~100 MeV and couplings ~10^{-4} and measuring the cross section of neutrinos ~TeV.

- Introduce the location and layout of FASER and FASER 2.
- Show the typical signal for ALPs and possible backgrounds.
- Newest measurement and result on ALPs at FASER with an integrated luminosity of $57.7\ fb^{-1}$. See Xin Chen's talk on 9th August for details.
- Estimated future potential at FASER and FASER 2 during LHC Run 3 and HL-LHC separately.

Forward Physics at the LHC

- On LHC, searches for new physics primarily focused on the relatively high p_T region (large angle to the beam line) at large experiments, e.g. CMS, ATLAS and LHCb.
- The inelastic cross section of p-p collision at the LHC is still considerable at extremely small angle to the beam line.
- FASER (ForwArd Search ExpeRiment) is designed to search for new physics (mainly for searching for LLPs and neutrino cross section measurement) in the very forward region (< 1 mrad).



Meson production rate in the (θ, p) plane, with $\mathcal{L} = 150\ fb^{-1}$

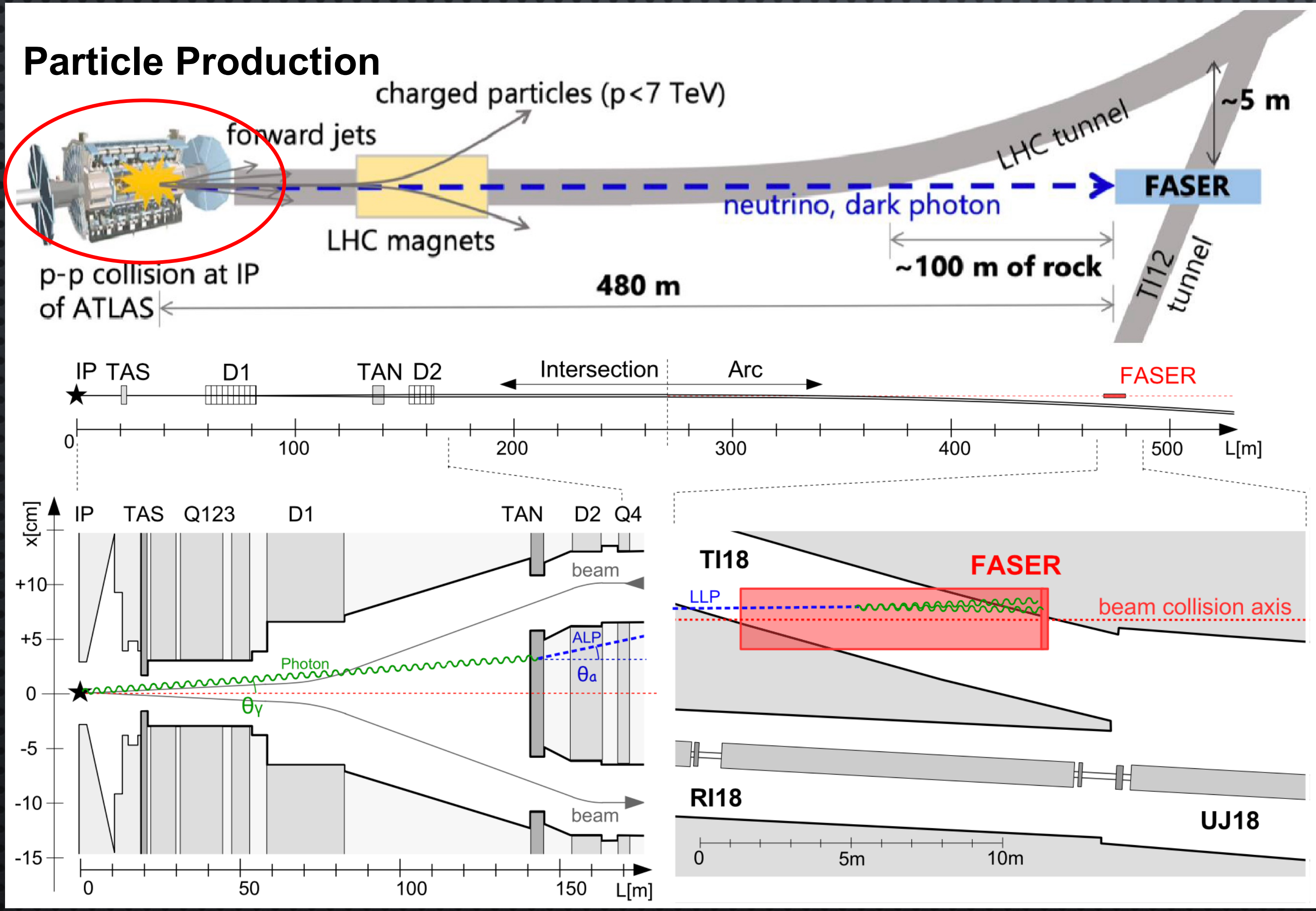
arXiv: 1811.12522

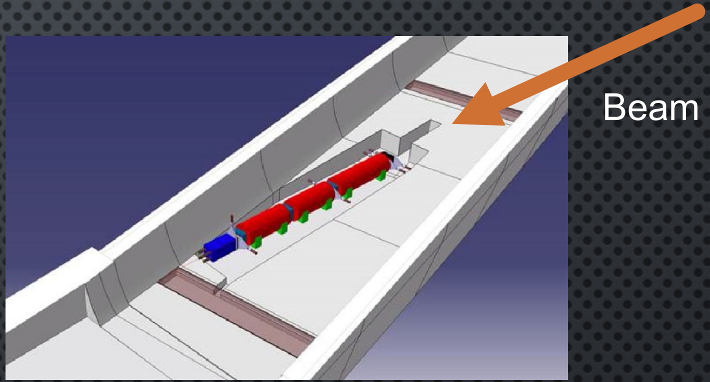
0.6% (10%) of π_0 with energy > 10 GeV (arXiv: 1811.12522) are produced within 0.2 mrad (2 mrad) of the beam collision axis, which is the angular acceptance for FASER and (FASER 2)

FASER Location

FASER is located ~500 m downstream from the ATLAS interacting point (IP).
Interested particles are produced at the IP and transferred 500 m to FASER.

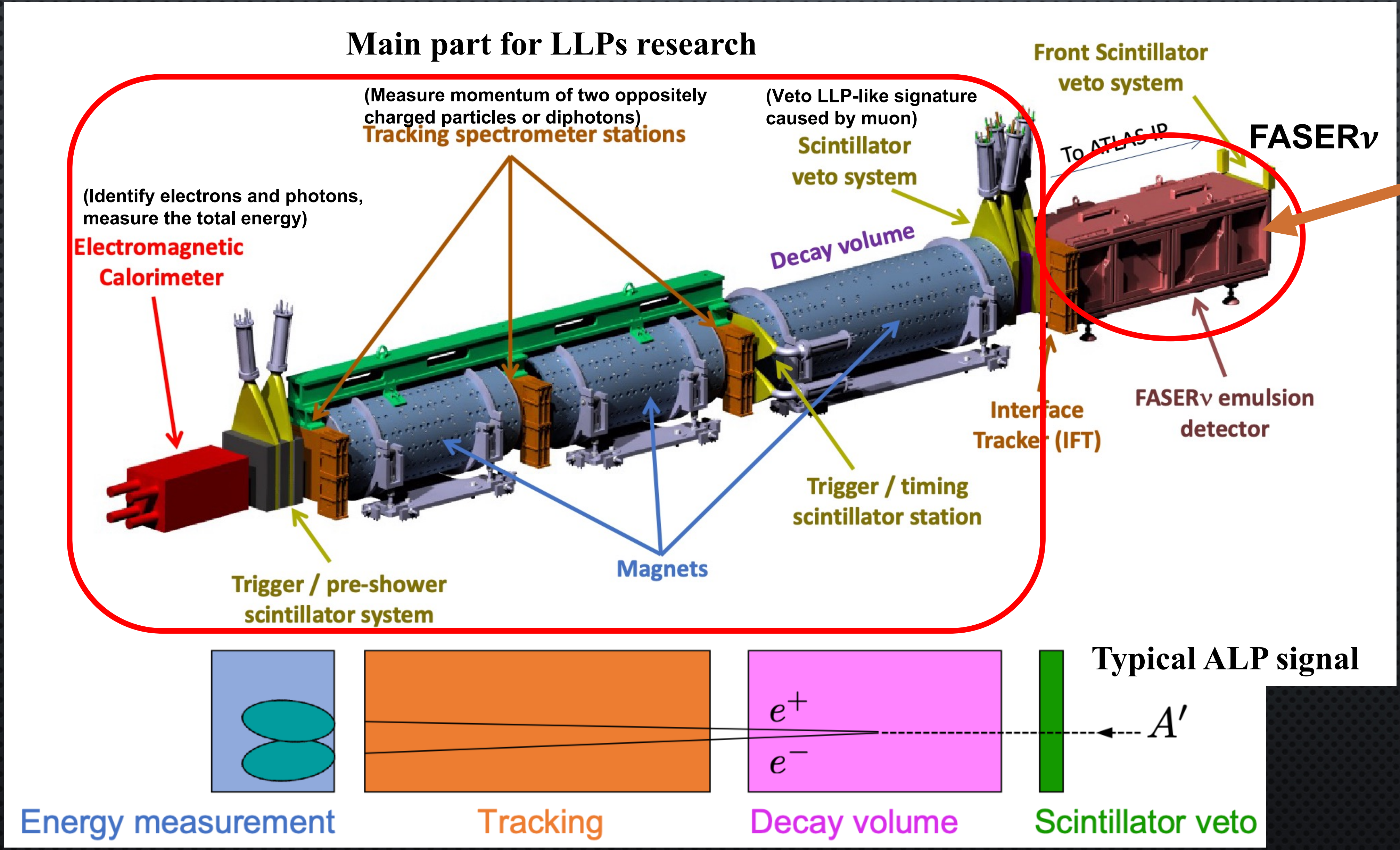
An on-axis cylindrical detector with the beam line across the center of it, which covers the region of angles $\theta < 0.2\ mrad$ from the beam line.





Beam Side

FASER Layout



Beam Side

Letter of Intent: arXiv: 1811.10243

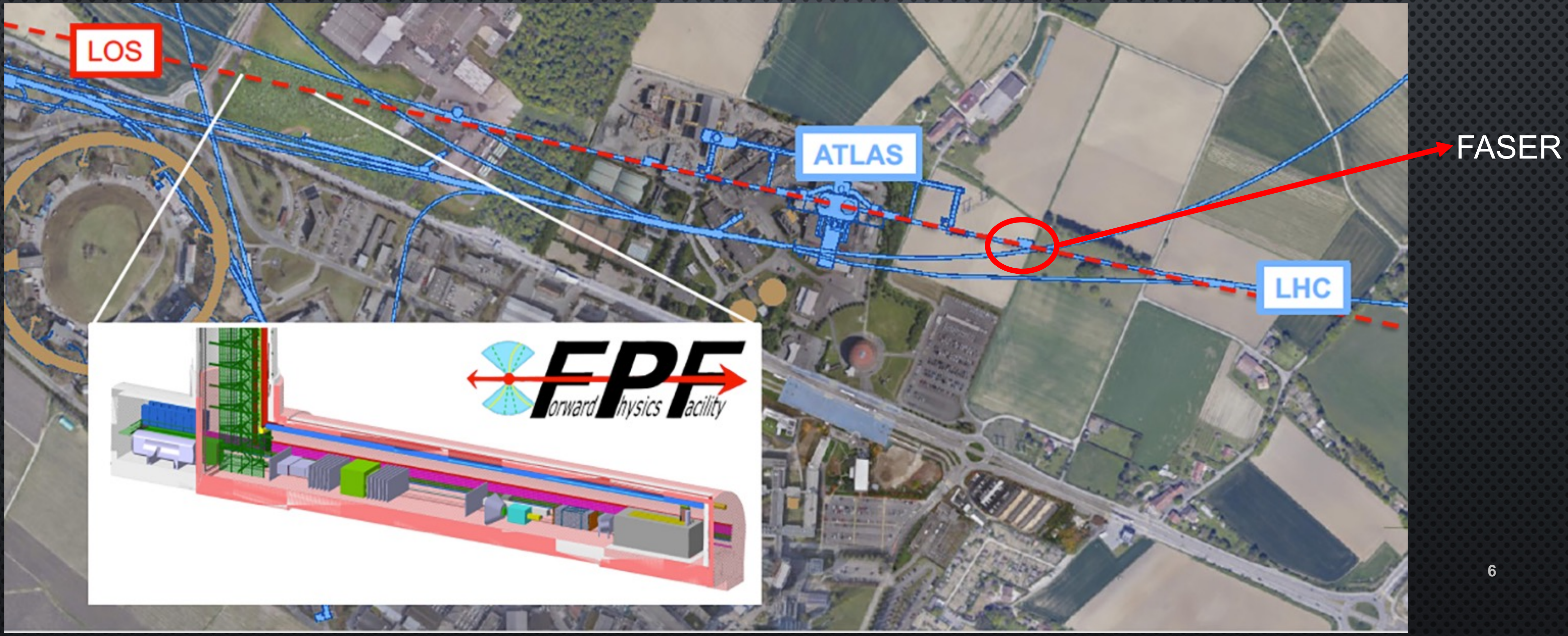
Technical Proposal: arXiv: 1812.09139

FASER as built: arXiv: 2207.11427

FASER 2 Location

- The FASER 2 experiment is in Forward Physics Facility (FPF) at CERN
- Facility is proposed to be built during Long Shutdown 3 from 2026-2028
- Experiment begin taking data during Run 4 (after 2029)
- The facility is ~600 m west of ATLAS, and shielded from IP by 200 m of rock
- The cavern is 75 m-long, 8.75 m-high, 12.5 m-wide

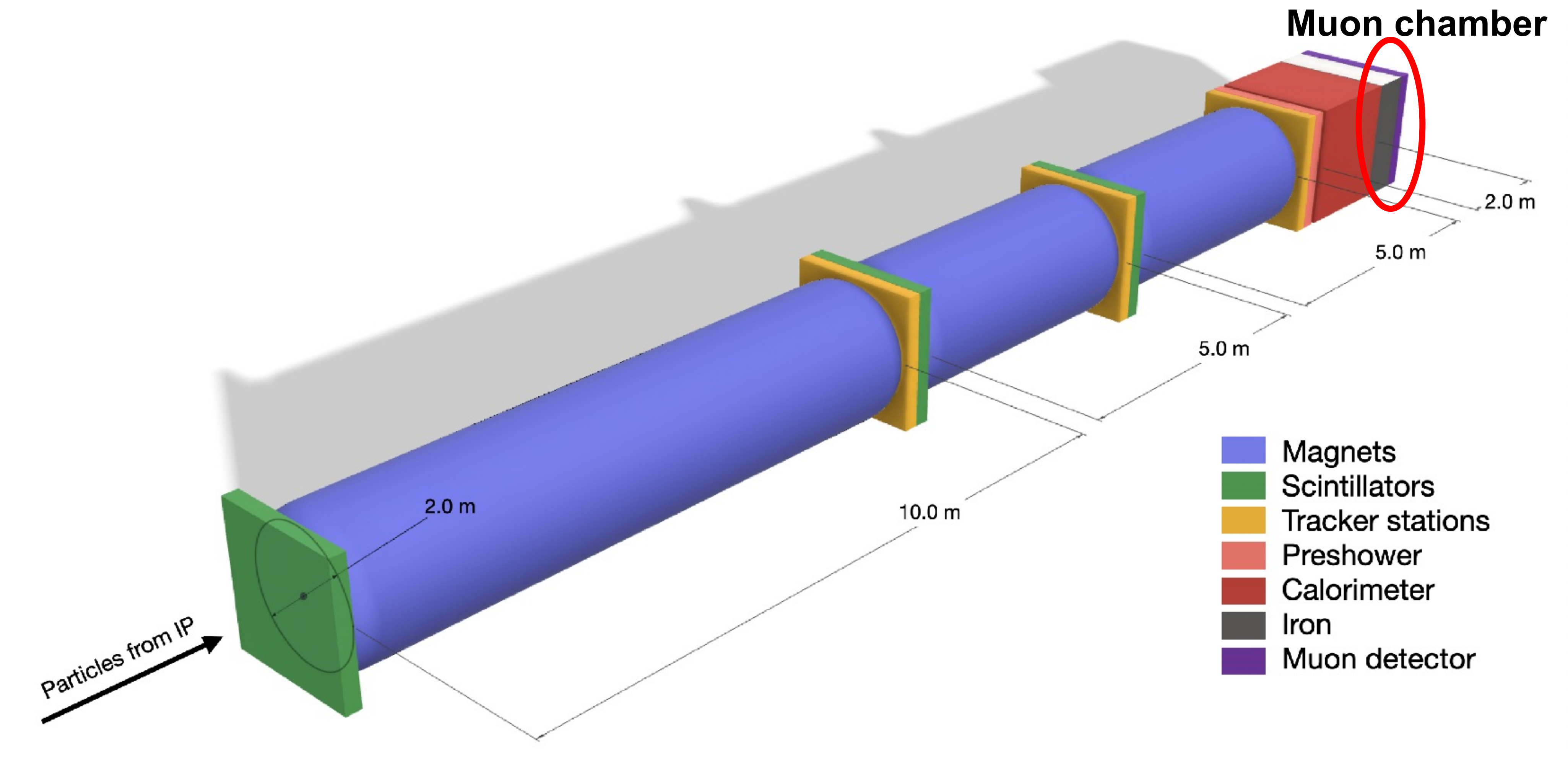
Long Whitepaper: arXiv:2203.05090
Updates: CERN-PBC-Notes-2024-004



FASER 2 Detector

- FASER 2 is a scaled up version of FASER detector.
- With ~100x larger transverse area and ~10x longer decay volume.
- An extra muon chamber in the end, which is used to identify muon events.

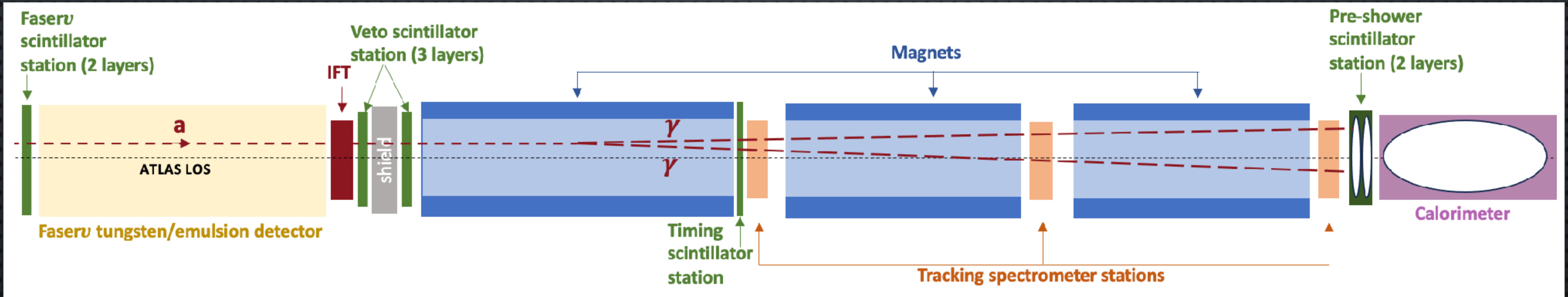
arXiv:2203.05090



Expected ALPs Signal

After production in IP (TAN), an ALP travels $L = 480\ (340)\ m$ to FASER and decay to a pair of opposite charged particles or diphoton in the 1.5 m long decay volume. Then measured momentum and energy in the tracking spectrometer and EM calorimeter.

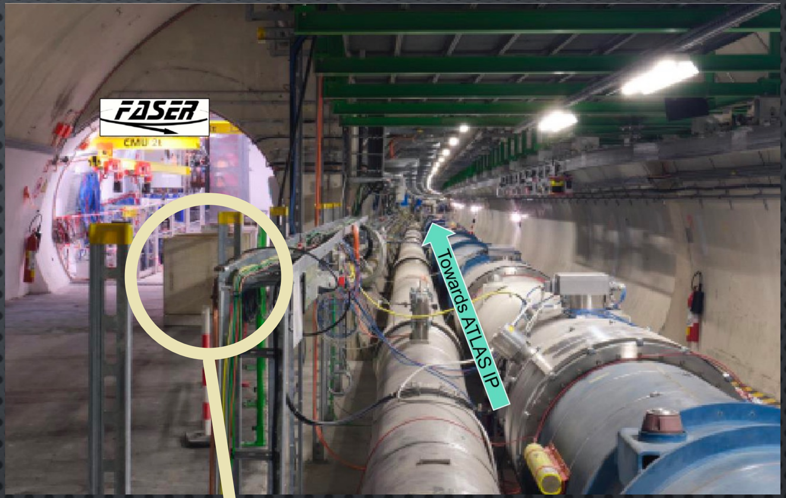
$$pp \rightarrow ALP + X, \quad ALP\ travels \sim O(100)\ m, \quad ALP \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \gamma\gamma, \ldots$$



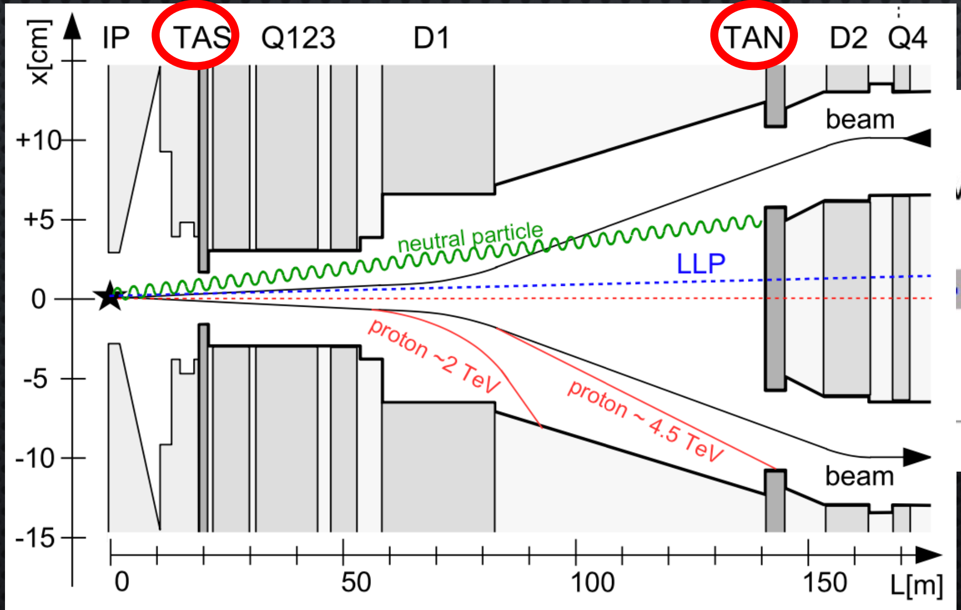
Background Shielding

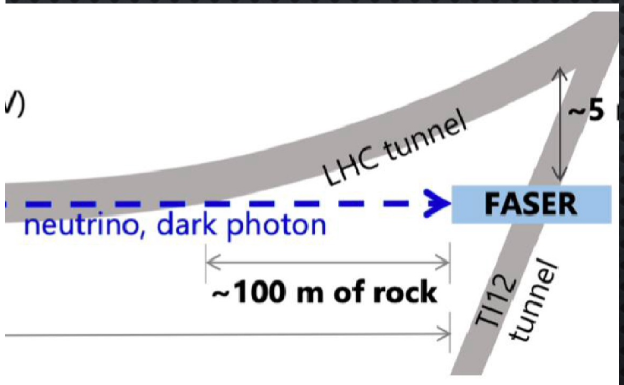
In the searching for rare events, background needs to be carefully considered. Fortunately, FASER is well shielded from high-energy particle fluxes, e.g.:

- LHC infrastructure: TAS and TAN absorber, D1 and D2 magnet dipole.
- 100 m of Rock: absorb a huge number of backgrounds
- Side concrete shielding: protect FASER away from the radiation induced by the beam line



Only muons and neutrinos from the IP can pass through the shielding and arrive FASER.





Muon Background

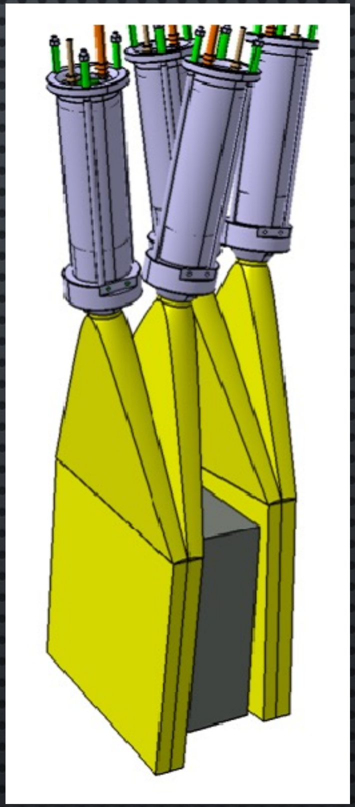
- High energy muon produces photons and showers due to bremsstrahlung in rock.
- The primary muon will pass through FASER together with the background caused by showers and photons.

- So background can be rejected by vetoing events with muon entering the scintillators.

- Each scintillator has an efficiency > 99.99%, making all the backgrounds listed in the table negligible.
- The lead layer between scintillators is used to convert single photon to EM shower and making the event vetoed by the scintillator.

Process	Expected Number of Events
μ	540M
$\mu + \gamma_{\text{brem}}$ $[\mu + (\gamma_{\text{brem}} \to e^+e^-)]$	41K [7.4K]
$\mu +$ EM shower	22K
$\mu +$ hadronic shower	21K

Radiative processes associated with muon's energy $\geq$ 100 GeV (with integrated luminosity 150 fb^{-1})



Two layer of scintillators with a layer of lead before the decay volume

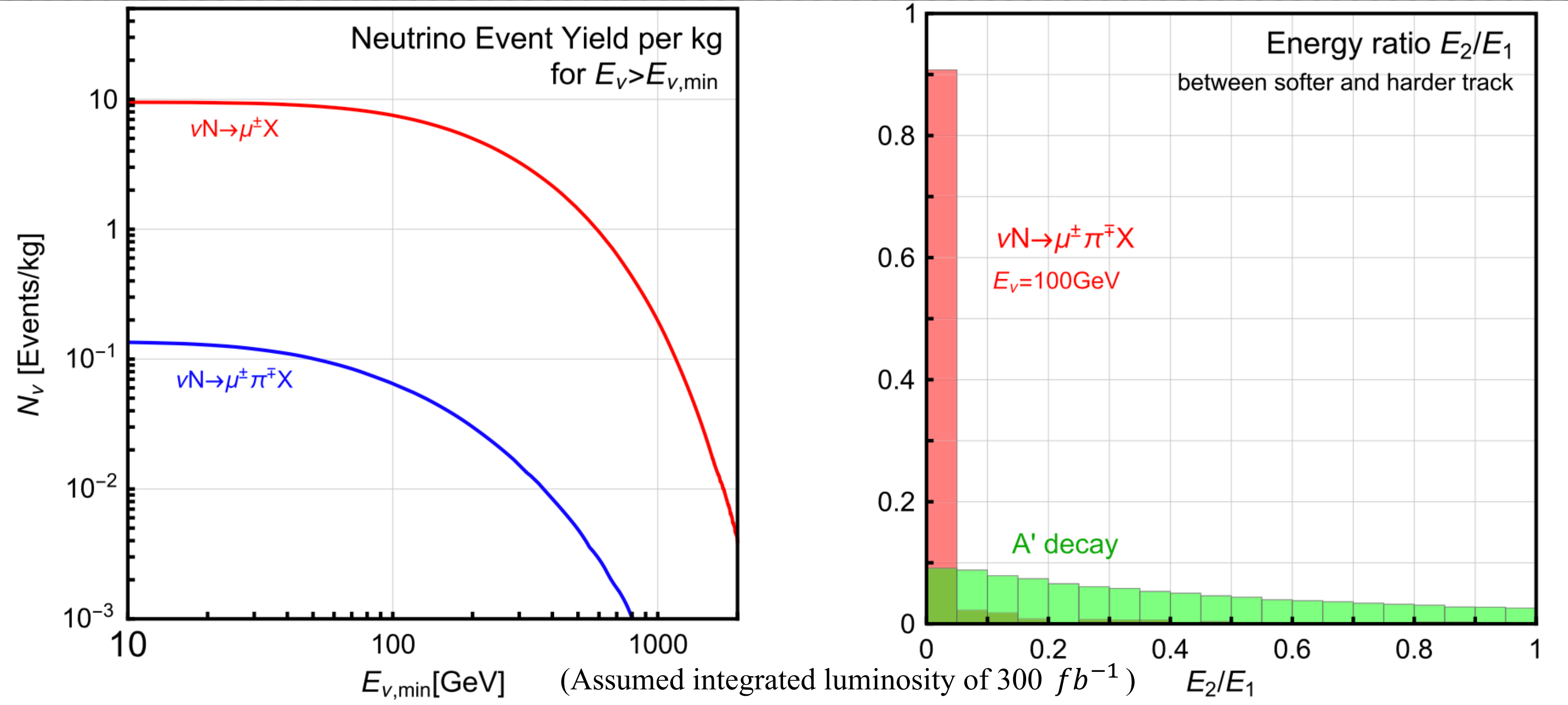
Neutrino Background

Neutrino can produce background through double simultaneous charged-current (CC) events or one single pion event. Both have two energetic charged track, which can be mistaken as signal:

CC events: $2\nu_l 2N \rightarrow 2lX$ single pion event: $\nu_\mu N \rightarrow \mu^-\pi^+X$

Number of events per kilogram of detector mass

Ratio of energies between two charged tracks



(Assumed integrated luminosity of 300 fb^{-1})

arXiv: 1708.09389

A numerical estimation is made for both events, both are possible to be discriminated from LLP signal:

- The possibility for double simultaneous CC events is negligible.
- In $\nu_\mu N \rightarrow \mu^-\pi^+X$ process, the π is much softer than μ (energy of π is small), while the energy of two charged track decaying from ALPs is similar. So requiring the ratio of energies to be $E_2/E_1 > 0.1$ can remove almost all of the background, while sacrificing little of the signal.

Searching for LLPs

Due to the similar properties, the constrain on parameter space to many LLPs can be extended by FASER and FASER 2. A lot of efforts were made for these models, the result is collected in arXiv: 1811.12522

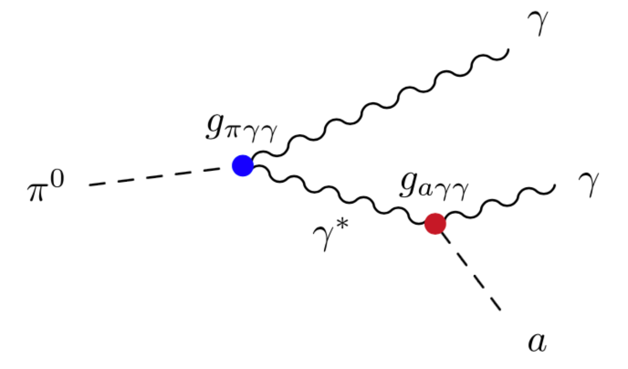
Ability to extend the current constrain on parameter space

Benchmark model	Label	Section	PBC	Refs.	FASER	FASER 2
Dark photons	V1	IV A	BC1	[7]	✓	✓
$B-L$ gauge bosons	V2	IV B	⋯	[30]	✓	✓
$L_i - L_j$ gauge bosons	V3	IV C	⋯	[30]	⋯	⋯
Dark Higgs bosons	S1	V A	BC4	[26,27]	⋯	✓
Dark Higgs bosons with hSS	S2	V B	BC5	[26]	⋯	✓
HNLs with e	F1	VI	BC6	[28,29]	⋯	✓
HNLs with μ	F2	VI	BC7	[28,29]	⋯	✓
HNLs with τ	F3	VI	BC8	[28,29]	✓	✓
ALPs with photon	A1	VII A	BC9	[32]	✓	✓
ALPs with fermion	A2	VII B	BC10	⋯	⋯	✓
ALPs with gluon	A3	VII C	BC11	⋯	✓	✓
Dark pseudoscalars	P1	VIII	⋯	[36]	⋯	✓

Production of ALPs

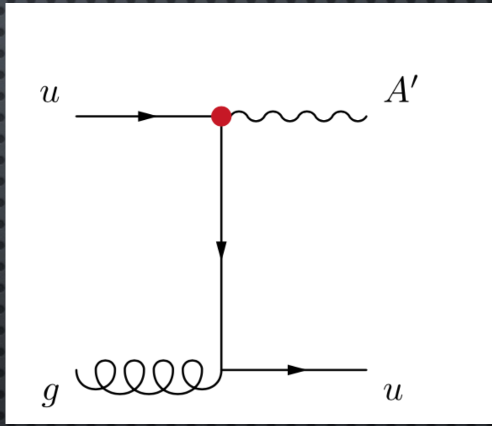
In the most general case, ALPs can have arbitrary couplings to photons, gluons, fermions and W bosons, with mass m_a being independent parameter. They can be produced at the LHC in several different processes as followed:

Rare decay of SM hadrons



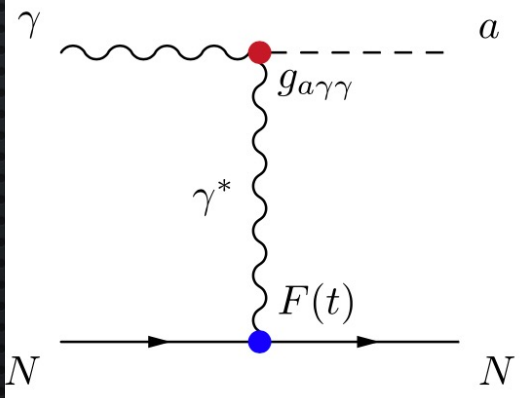
Dominant when ALPs couple to quarks. The leading production mechanism is typically the decay of lightest mesons that are kinematically allowed to decay to the ALPs.

Hard scattering of partons



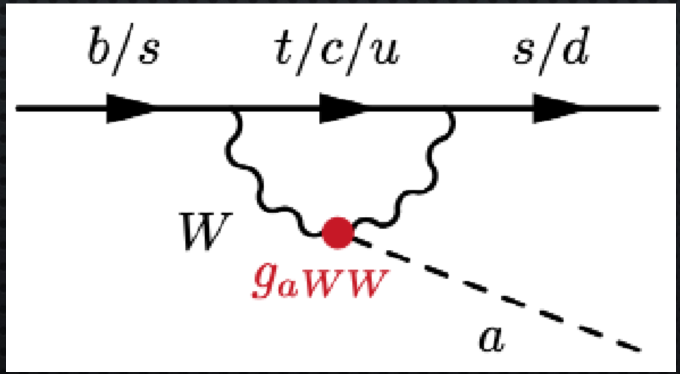
Dominant when ALPs couple to gluons. The production mode suffers from large uncertainties, so not take into account when presenting the FASER reach.

Beam dump production from SM particles hitting the TAN



The Primakoff process dominant in the case of ALPs coupling to two photons.

Decay from B meson

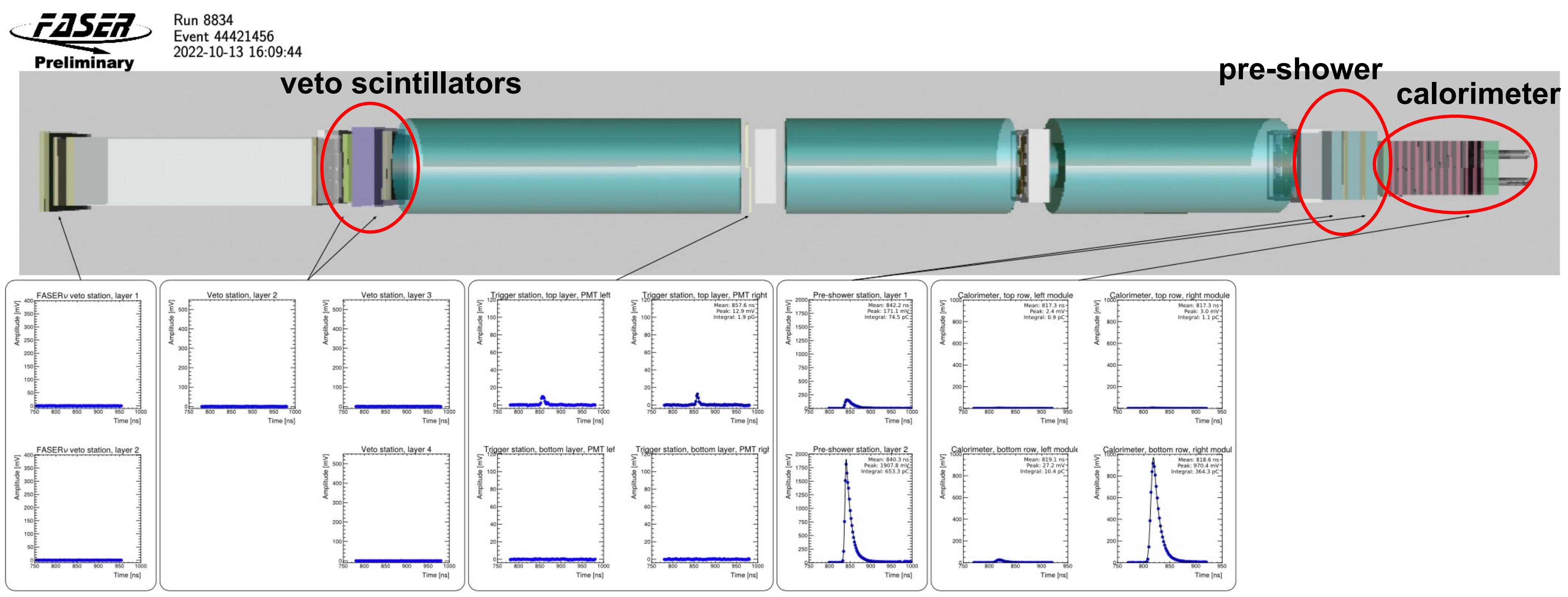


Dominant when ALPs couple to weak gauge boson. The leading production mechanism is typically the decay of B mesons.

Candidate Event for ALP

One candidate event for ALP was observed using 2022 and 2023 LHC p-p collision data at $\sqrt{s} = 13.6\ TeV$, corresponding to an integrated luminosity of $57.7\ fb^{-1}$ with the summarized event selection:

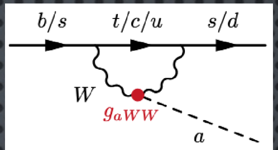
- No signal is observed in the veto scintillators, since ALPs are electrically neutral.
- The pre-shower charge deposits consistent with an EM shower arising from the decay diphoton.
- A large energy deposit in the calorimeter left by the high-energy photon pairs.



CERN-FASER-CONF-2024-001

Constrained Parameter Space

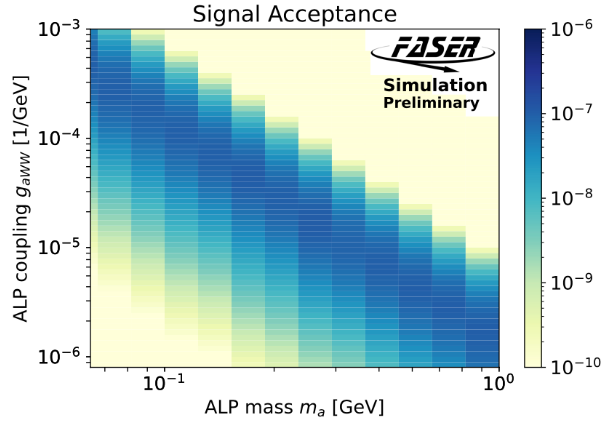
$$\mathcal{L} \supset -\frac{1}{2}m_a^2 a^2 - \frac{1}{4} g_{aWW}\, a W^{a,\mu\nu}\tilde{W}^a_{\mu\nu}$$



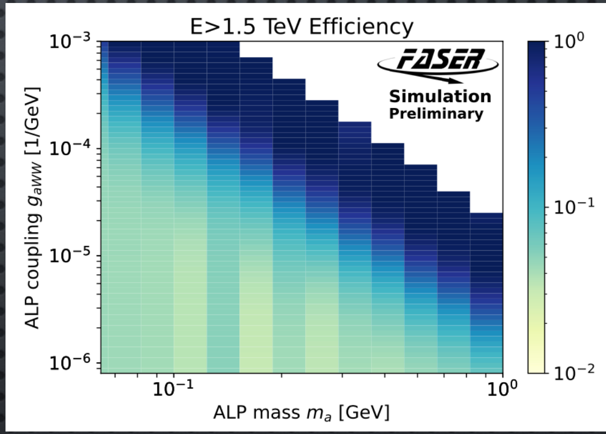
CERN-FASER-CONF-2024-001

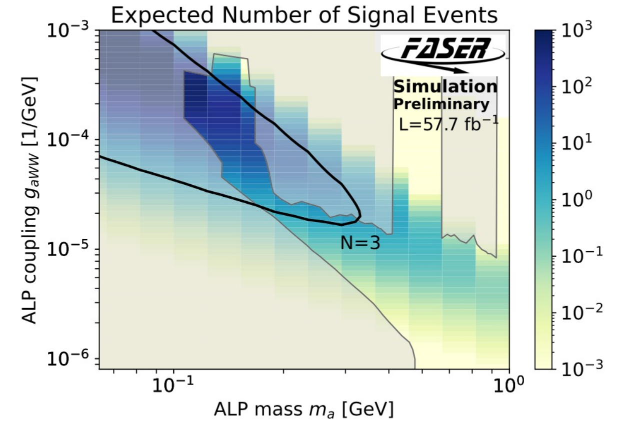
The measurement result has also been used to evaluate the constrain on parameter space for ALPs coupling with weak gauge boson and decaying mode to diphoton.

The acceptance for ALP events with the ALP decay inside FASER's decay volume



The efficiency of selecting ALP events with ALP energies above 1.5 TeV





Expected number of signal events

- The parameter space inside the contour of N=3 can be excluded since only one signal is observed.
- Shaded areas is previously excluded parameter space by other experiments.

See Xin Chen's talk on 9th August for detail

Other ALP Couplings

Parameters of FASER and FASER 2 used for simulation:

$$\textbf{FASER}: \Delta = 1.5 \text{ m}, \quad R = 10 \text{ cm}, \quad \mathcal{L} = 150 \text{ fb}^{-1}$$
$$\textbf{FASER2}: \Delta = 5 \text{ m}, \quad R = 1 \text{ m}, \quad \mathcal{L} = 3 \text{ ab}^{-1}.$$

Not only the coupling to W boson, the physics reach for other couplings models has also been estimated for FASER and FASER 2. The detector efficiency is assumed to be 100% for convenience.

arXiv: 1811.12522

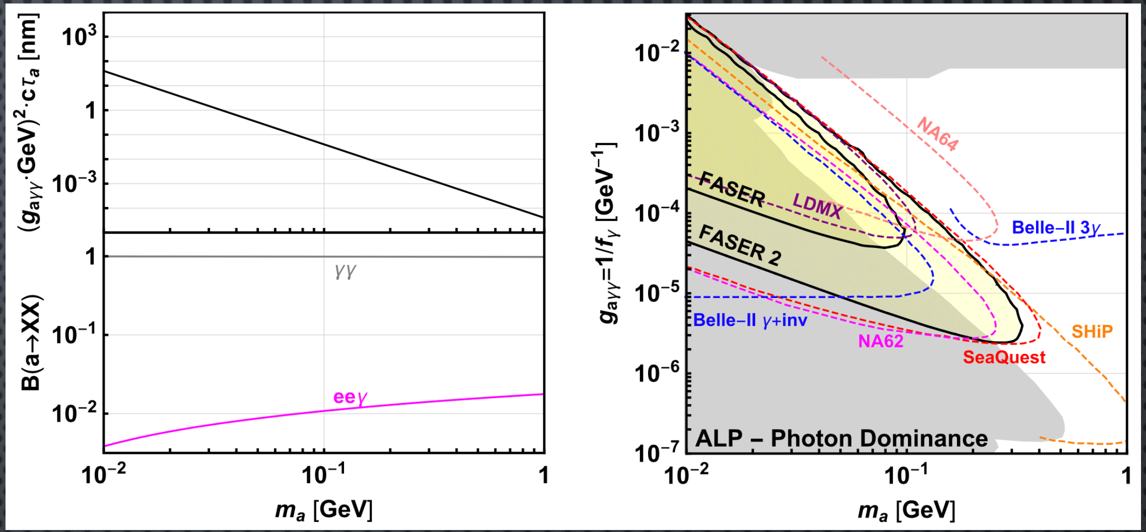
Couplings	Effective Lagrangian	Production Mode	Decay Mode
Photon Dominance	$\mathcal{L} \supset -\frac{1}{2}m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu}\tilde{F}_{\mu\nu}$	Primakoff Process with differential cross section: $\frac{d\sigma_{\text{Prim}}}{d\theta_{a\gamma}} = 2\pi\alpha Z^2 F^2(t) \frac{8\Gamma_a}{m_a^3} \frac{p_a^4 \sin^3\theta_{a\gamma}}{t^2} = \frac{1}{4} g_{a\gamma\gamma}^2 \alpha Z^2 F^2(t) \frac{p_a^4 \sin^3\theta_{a\gamma}}{t^2},$	Dominant: $\Gamma(a \to \gamma\gamma) = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$ Subdominant: $B(a \to \gamma e^+ e^-) \approx 1\%$
Fermion Dominance	$\mathcal{L} \supset -\frac{1}{2}m_a^2 a^2 - i g_{\text{aff}}\, a \sum_f \frac{m_f}{v} \bar{f}\gamma_5 f + [g_{asb}(g_{\text{aff}}) a \bar{s}_L b_R + \text{H.c.}],$	Flavor-changed heavy meson decay, with branch ratio : $B(B \to X_s a) \approx \left[3.1\left(1 - \frac{m_a^2}{m_B^2}\right) + 3.7\left(1 - \frac{m_a^2}{m_B^2}\right)^3\right] \times g_{\text{aff}}^2,$	Dominant, decay to quarks and leptons: $f = e, \mu, \tau, c, b$ $\Gamma(a \to ff) = N_c^f g_{\text{aff}}^2 \frac{m_a m_f^2}{8\pi v^2} \sqrt{1 - \frac{4m_f^2}{m_a^2}}$ Subdominant: $a \to \gamma\gamma$
Gluon Dominance	$\mathcal{L} \supset -\frac{1}{2}m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma}(g_{agg}) a F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{g_s^2}{8} g_{agg}\, a \text{Tr} G_{\mu\nu}\tilde{G}^{\mu\nu} - i\sum_q g_{aqq}(g_{agg}) \frac{m_q}{v} a \bar{f}\gamma_5 f + [g_{asb}(g_{agg}) a \bar{s}_L b_R + \text{H.c.}]$	Mix with the neutral pseudoscalar mesons, with cross section: $\sigma(a) = \lvert\theta_{a\pi}\rvert^2 \sigma(\pi) + \lvert\theta_{a\eta}\rvert^2 \sigma(\eta) + \lvert\theta_{a\eta'}\rvert^2 \sigma(\eta').$ Flavor-changed heavy meson decay, with branch ratio: $B(B \to X_s a) \approx \left[33\left(1 - \frac{m_a^2}{m_B^2}\right) + 40\left(1 - \frac{m_a^2}{m_B^2}\right)^3\right] \times \mathcal{UV} \times (g_{agg} \cdot \text{GeV})^2,$	Low mass, decay to photon pair: $\Gamma(a \to \gamma\gamma) = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$ High mass, hadronic decay: $a \to 3\pi$, $a \to \eta\pi\pi$ $a \to \rho\pi, f_0\pi, a_0\pi, KK^*$

Photon Dominance

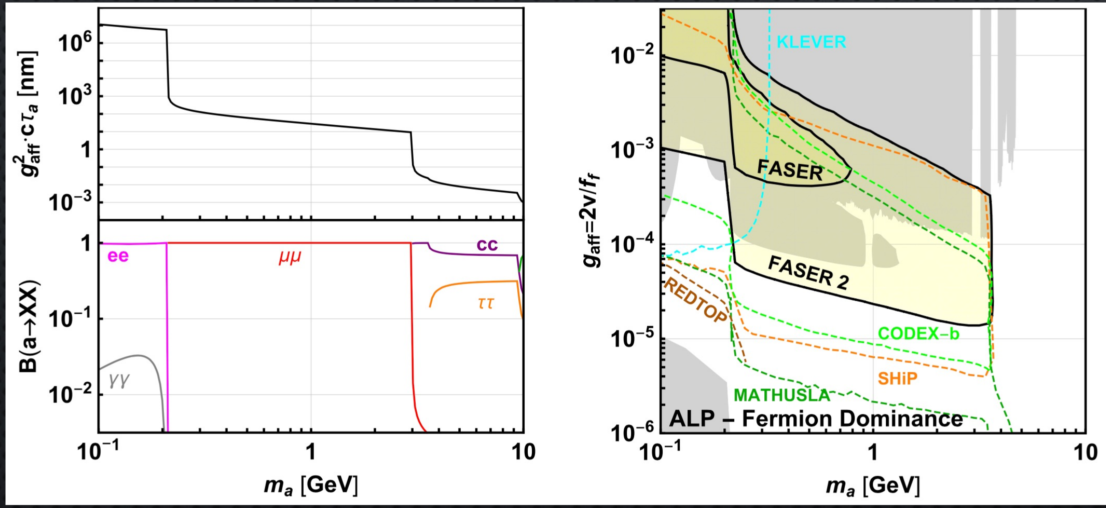
arXiv: 1811.12522

The decay length (top left panel)
Decay branching fraction (bottom left panel)
FASER's expected reach (right panel)

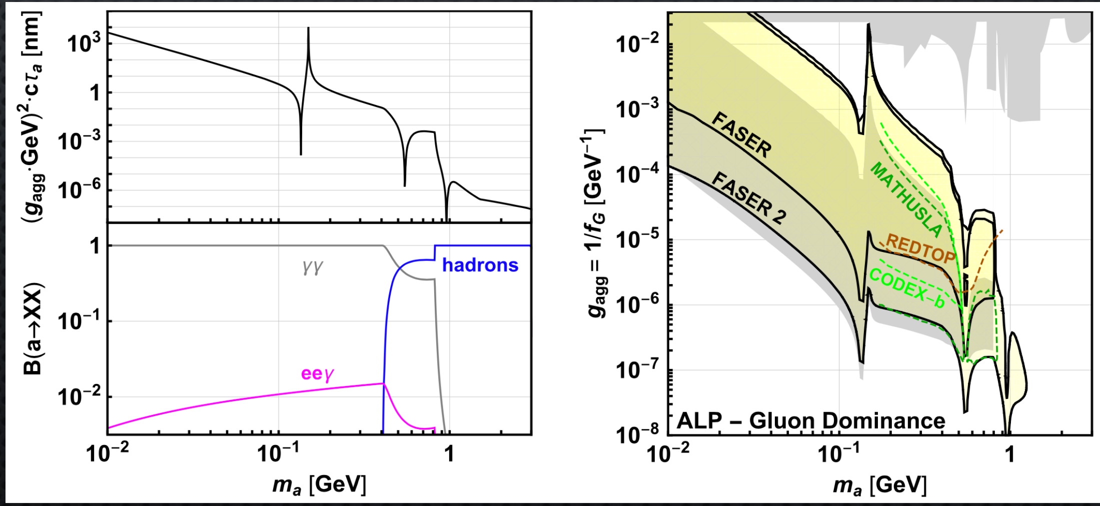
ALPs with dominantly photon couplings



ALPs with dominantly fermion couplings



ALPs with dominantly gluon couplings



Summary

- FASER is designed to search for LLPs including ALPs in the far-forward region on LHC.
- FASER 2 is a scaled up version of FASER, and is planned to collect data during LHC Run 4.
- Backgrounds are very low, making FASER sensitive to signals.
- FASER has already completed its first ALP search using 2022 and 2023 LHC p-p collision data at $\sqrt{s} = 13.6\ TeV$, corresponding to an integrated luminosity of $57.7\ fb^{-1}$. See Xin Chen's talk on 9th August and the paper CERN-FASER-CONF-2024-001.
- Both FASER and FASER 2 have discovery prospects for ALPs coupling to photons, fermions, gluons and weak gauge bosons in some unconstrained parameter space.

Backup Slides

FASER COLLABORATION

101 collaborators, 27 institutions, 11 countries

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LHC Schedule