New particle searches at FASER and future prospect on Forward Physics Facility at LHC

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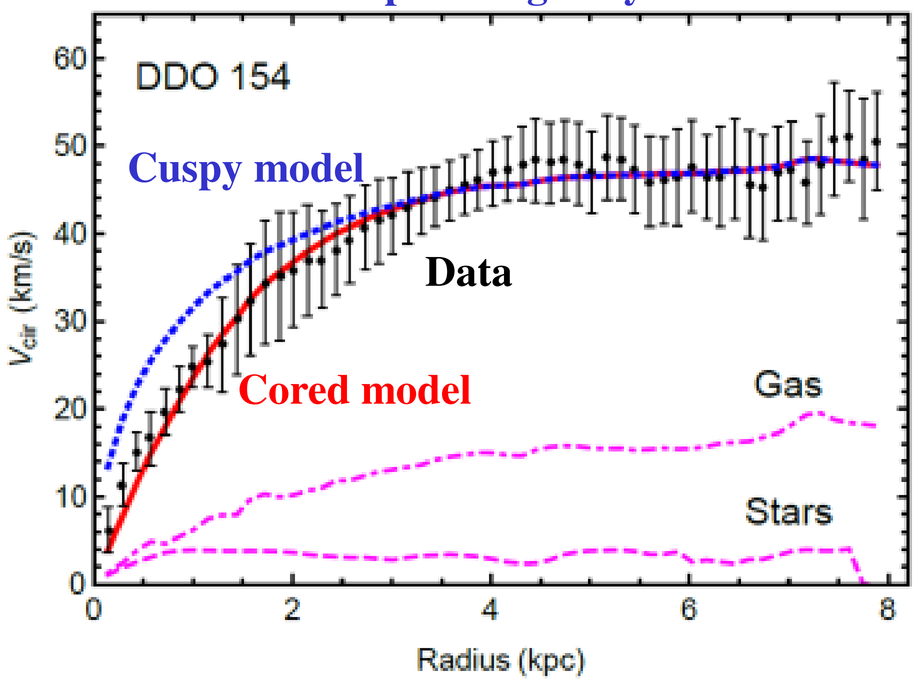
Physics motivation of FASER

Core-cusp problem

- Rotational speed of galaxies indicates that Dark Matter (DM) follows a cored (uniform) distribution in it.
- But, WIMPs(Weakly Interacting Massive Particles) DM creates cusp density at the center of the galaxy.
  - Called as core-cusp problem or small-scale problem
- Several models to realize the cored DM density are proposed without WIMPs DM.

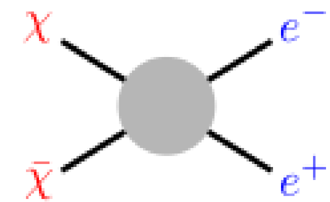
Here, WIMPless miracle is assumed as benchmark model.

Rotational speed of galaxy v.s. radius



WIMPless miracle (1)

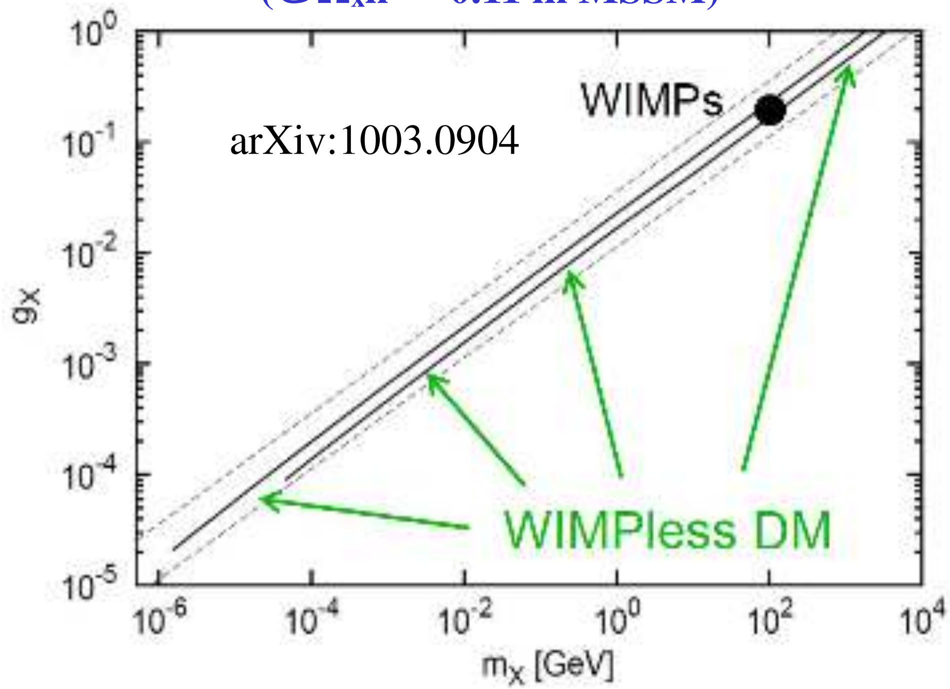
- Condition to satisfy the thermal relic density: $\Omega_X \propto \frac{m_X^2}{g_X^4}$ ($\Omega_X \sim 0.23$)



- WIMPs pick up only one parameter set: $(m_X, g_X) \sim (\mathrm{m}_{\mathrm{weak}}, g_{\mathrm{weak}}) \sim (100\ \mathrm{GeV}, 0.65)$
- But, any parameter sets satisfying the relation above can reproduce the thermal relic density.
- There are several physics models like GSMB in which m_X^2/g_X^4 has constant value naturally [PRL 101, 231301 (2008)].

WIMPless miracle

DM coupling v.s. DM mass
(@$\Omega_x h^2$ = 0.11 in MSSM)



WIMPless miracle (2)

- One of the way to realize WIMPless miracle is to introduce new mediator (A') for DM interactions.
- If the new mediator is mixed with SM particles, the effective coupling between DM and SM particles is determined by the mixing angle (ε).

Low mass DM ($m_X \ll \mathrm{m}_{\mathrm{weak}}$)

⇩

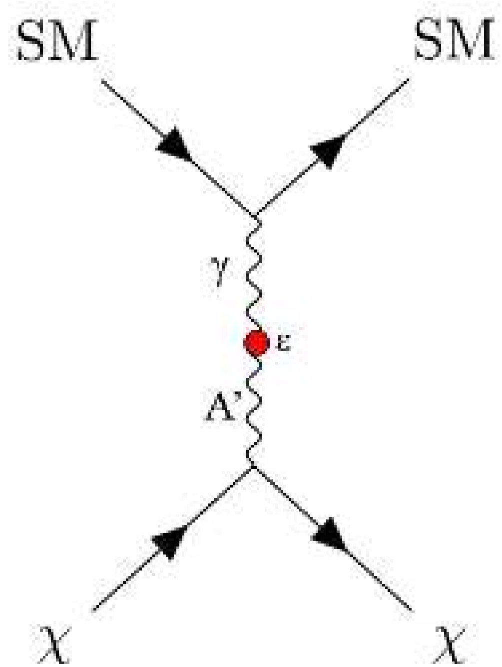
Small coupling with SM ($g_X \ll g_{\mathrm{weak}}$)

⇩

Small mixing angle between mediator and SM particles ($\varepsilon \ll 1$)

⇩

A' becomes a long lived particle with small coupling to SM particles (e.g., dark photon).



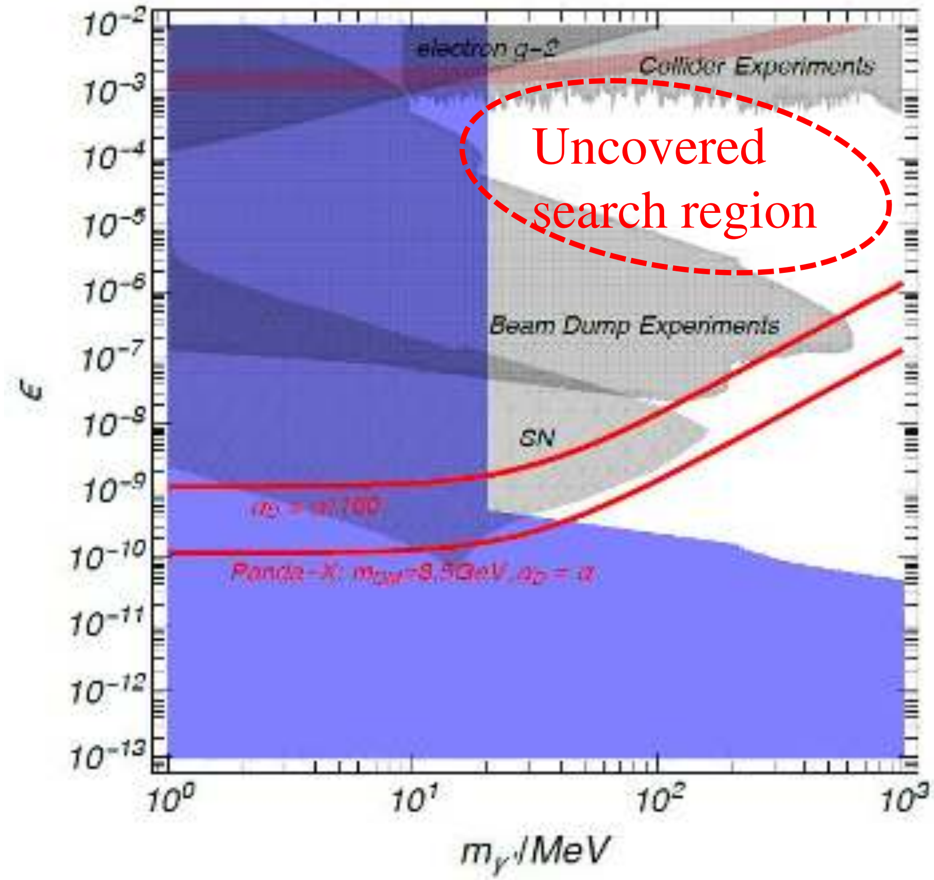
Current limit on dark photon

Limit on dark photon

- Collider experiments give the limits for the strong coupling region ($\varepsilon \sim 10^{-3}$)
  - No sensitivity to $\varepsilon < 10^{-3}$ due to detector acceptance
- Beam dump experiments constrain the small coupling region.

Search region is gap between the two excluded areas.

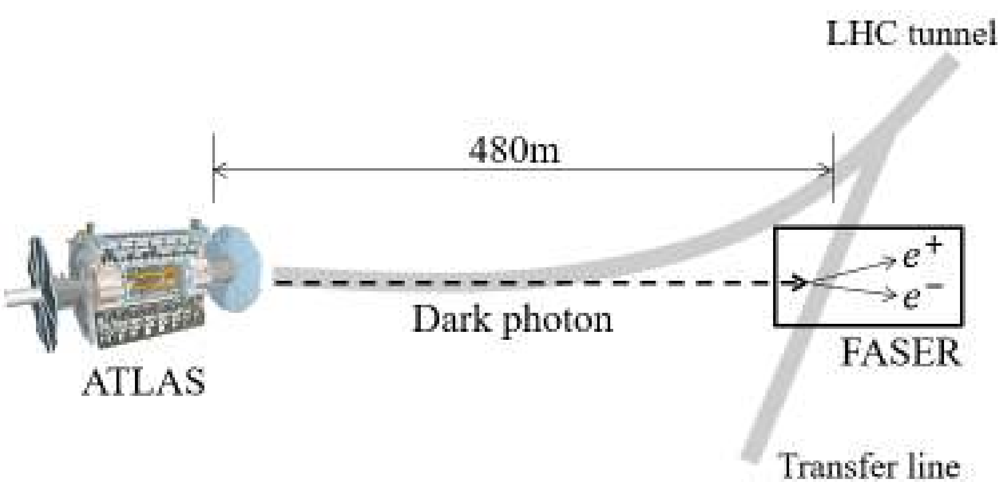
Limits on dark photon (arXiv:1805.06876)

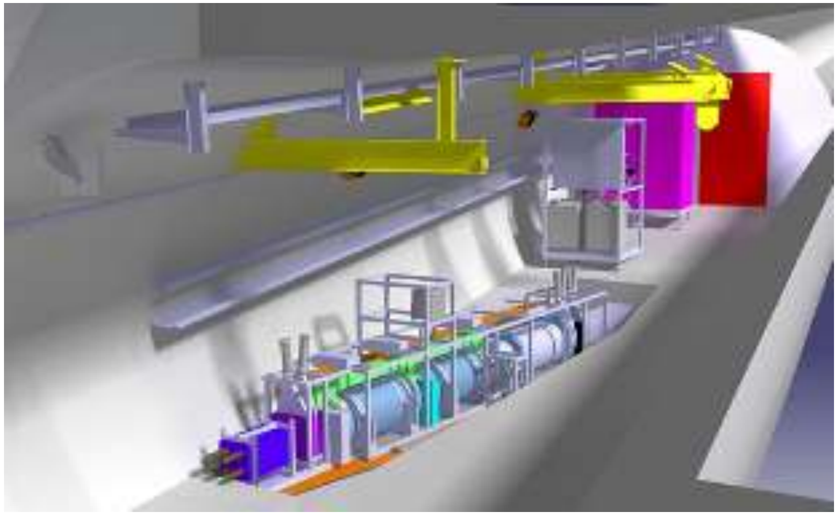


FASER

FASER overview

- FASER (ForwArd Search ExpeRiment at the LHC) is a new experiment to search for new long-lived particles and measure neutrino interactions at TeV region, which started physics data-taking in 2022.
- Benchmark search: dark photon decaying into e^-e^+pair (A' → e^-e^+)
  - Other searches: dark Higgs, Axion-like particle, sterile neutrino, etc..
- The detector is placed 480 m downstream of ATLAS interaction point.

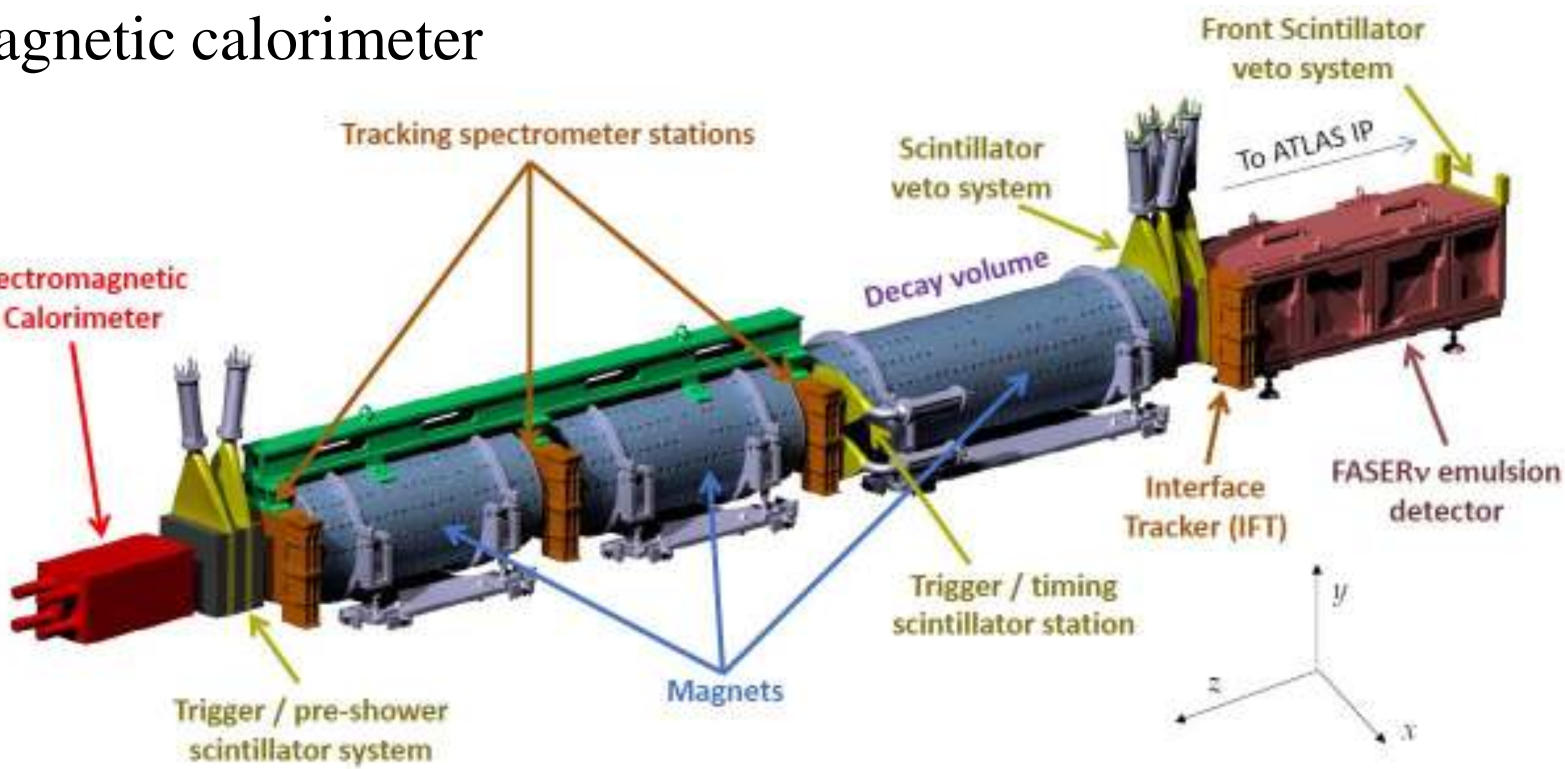




FASER detector

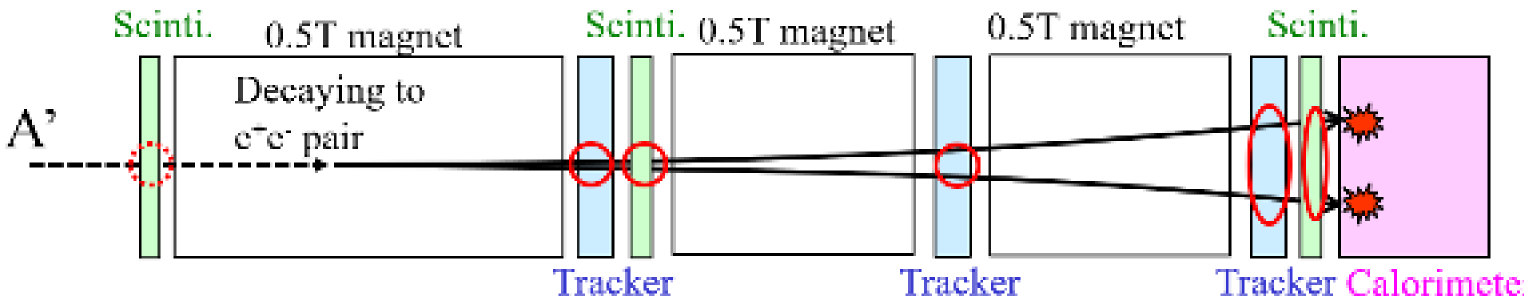
- Scintillator veto/trigger
- 1.5-m decay volume (0.57 T B-field)
- 2-m spectrometer (0.57 T B-field)
  - 3 tracking stations
- Electro-magnetic calorimeter

- Neutrino detector (FASERν)
  - Scintillator veto
  - Emulsion detector
  - 1 tracker station



Signal and background

Benchmark signal : Electron-positron tracks from dark photon



Background

- Most of backgrounds are absorbed by natural rock and LHC material.
- High energy muon with radiative γ and neutrino events are the main background.
  - Muons with EM/HD shower: 80k events
  - CC/NC neutrino interaction above 100 GeV: a few events

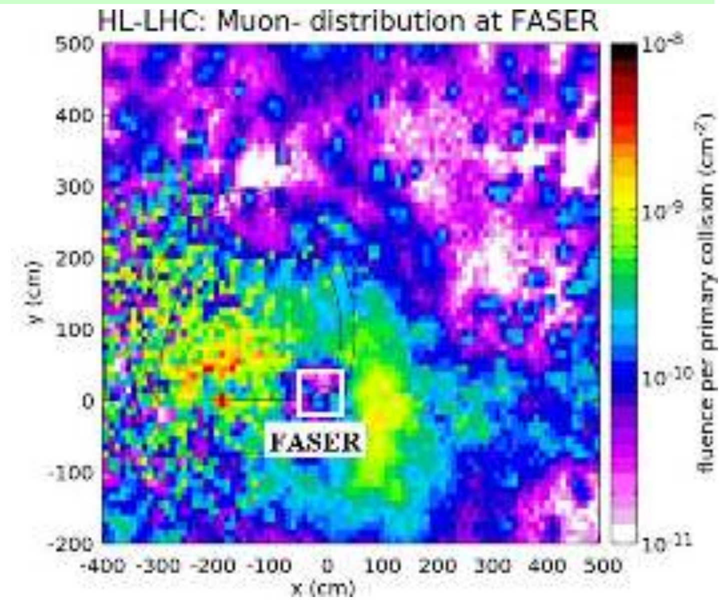
} $150\ fb^{-1}$ @Run3

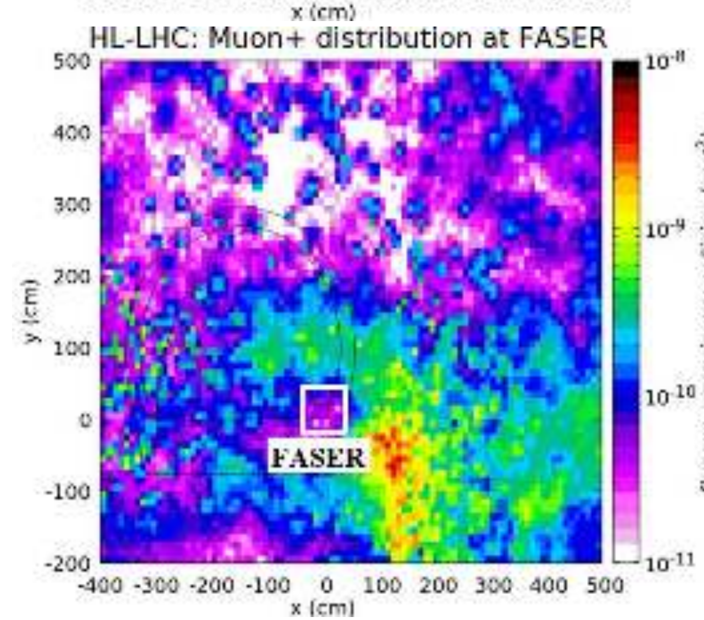
The backgrounds can be suppressed to negligible level with 2 scintillator layers with 99.99% veto efficiency

How FASER is miracle?

- High energy muons created at ATLAS IP is the largest background.
- These muons are bent to escape from FASER acceptance by LHC magnet.
  - μ^-/ μ^+ is bent to left/right direction with respect to FASER.

FASER site is the perfect place to escape from high energy muons by chance!





Expected rate of charged particles(FLUKA)

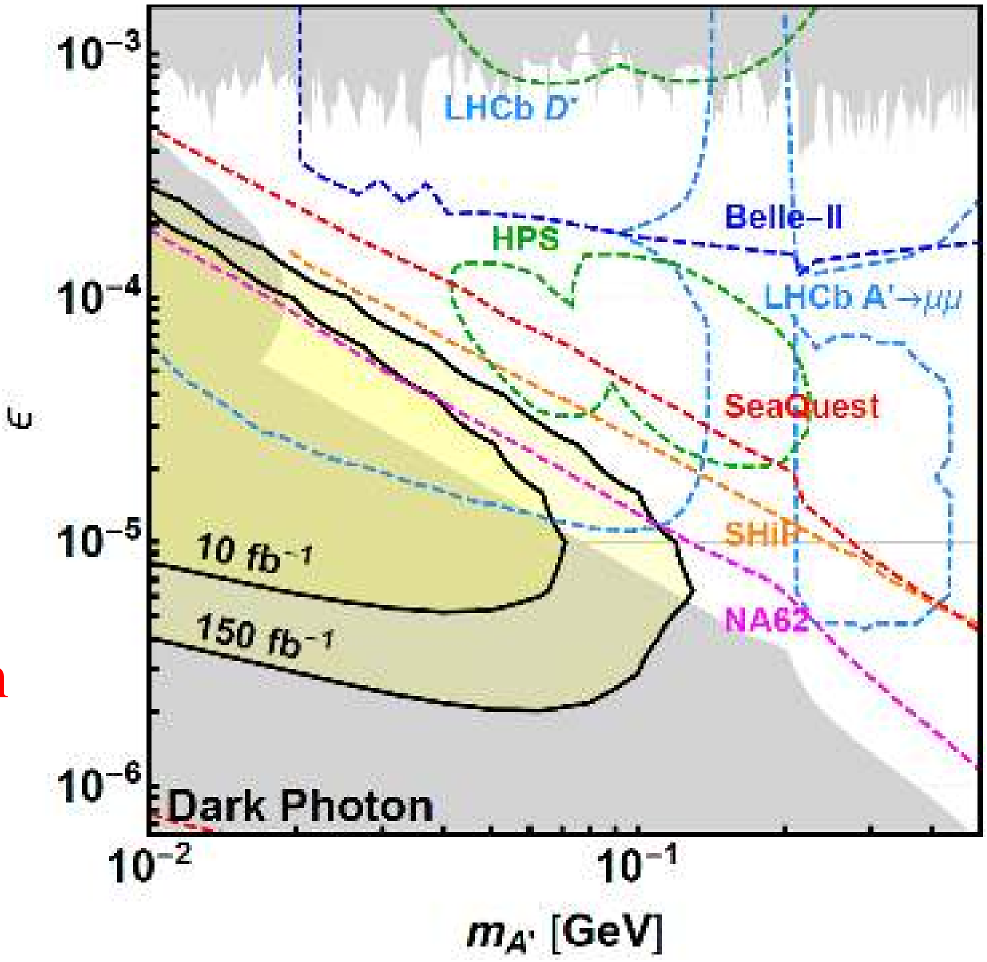
Energy threshold [GeV]	Charged particle flux [cm^{-2} s^{-1}]
10	0.40
100	0.20
1000	0.06

Sensitivity to dark photon

- FASER is sensitive to the coupling of 10^{-4}~10^{-5}.
- New parameter region can be explored only with 2022 data (38.5 fb^{-1}).
- LHCb and Belle II are sensitive to the strong coupling region.

→ Most of search region for $m_{A'}$ bellow 100 MeV can be explored in combination with FASER, LHCb and Belle II.

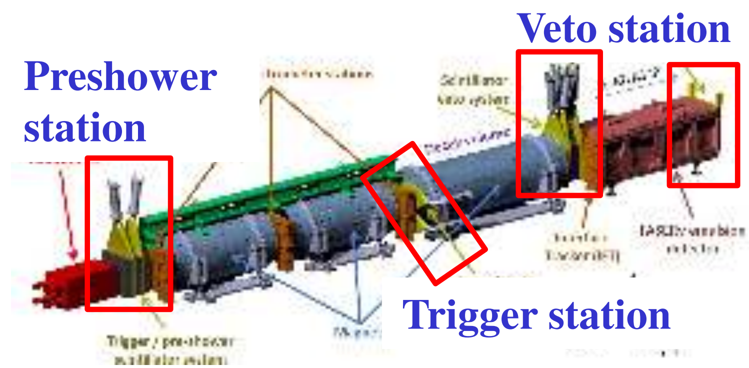
Expected sensitivity to dark photon

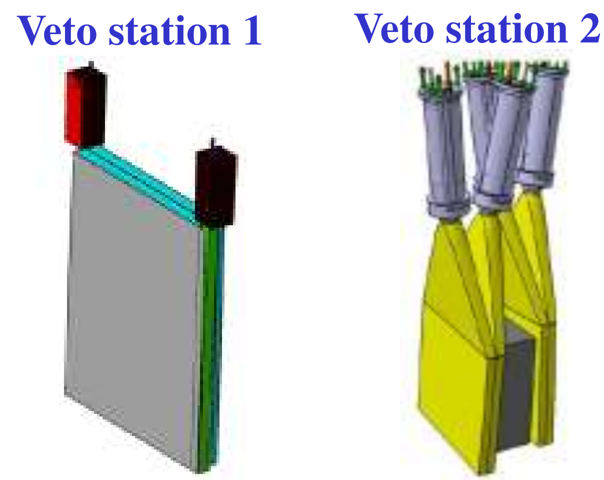


Development/installation of FASER detector

Scintillator (1)

Scintillator detector consists of 2 veto, Trigger and Preshower stations.





Veto station 1

- Placed upstream of FASERν
- A pair of two scintillator layers
- Reject charged particles coming from the upstream

Veto station 2

- Placed in front of the decay volume
- Two pairs of two scintillator layers and lead absorber in-between
- Reject charged particles and γ's converted in Pb absorber

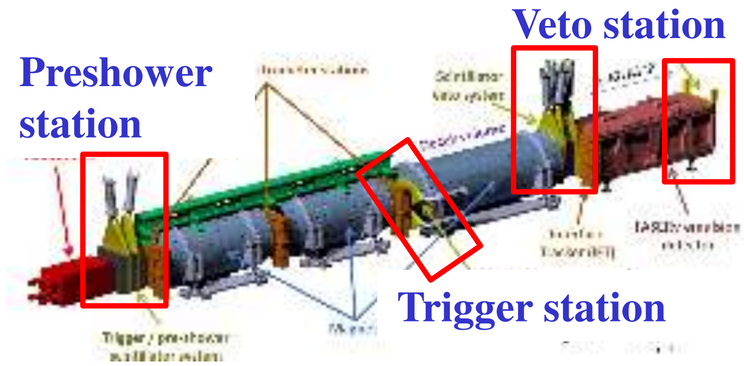
Scintillator (2)

Trigger station

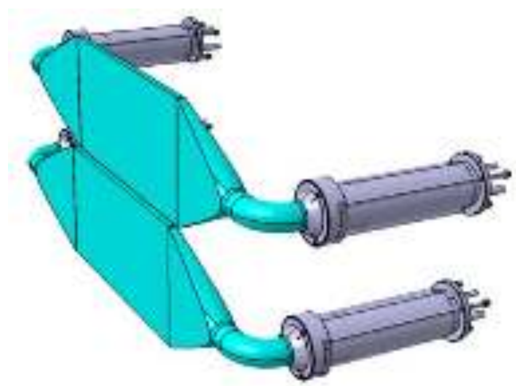
- Placed at the end of the decay volume
- Publish triggers to take charged particles created in FASER decay volume.

Preshower station

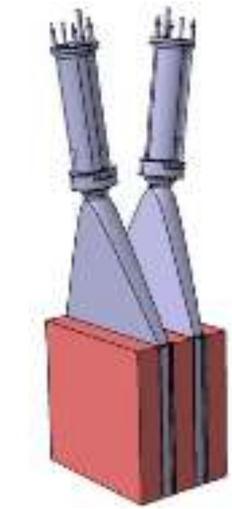
- Placed in front of EM calorimeter
- Two scintillator layers sandwiched by 3 tungsten layers
- Veto γ's created from deep inelastic scattering of high energy neutrinos.

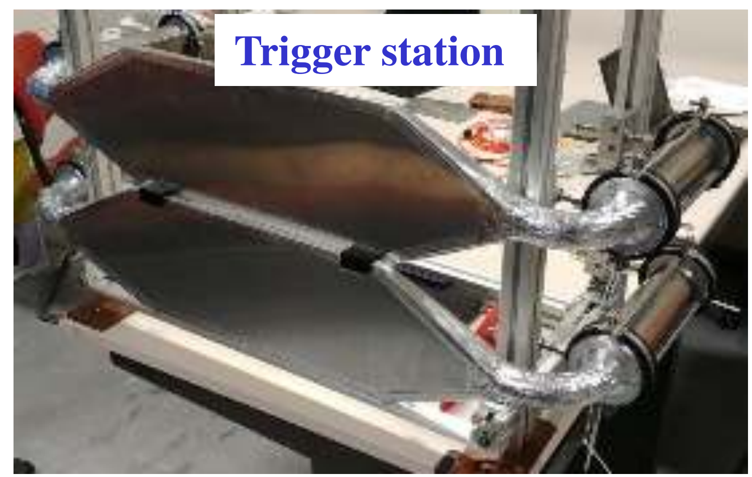


Trigger station



Preshower station



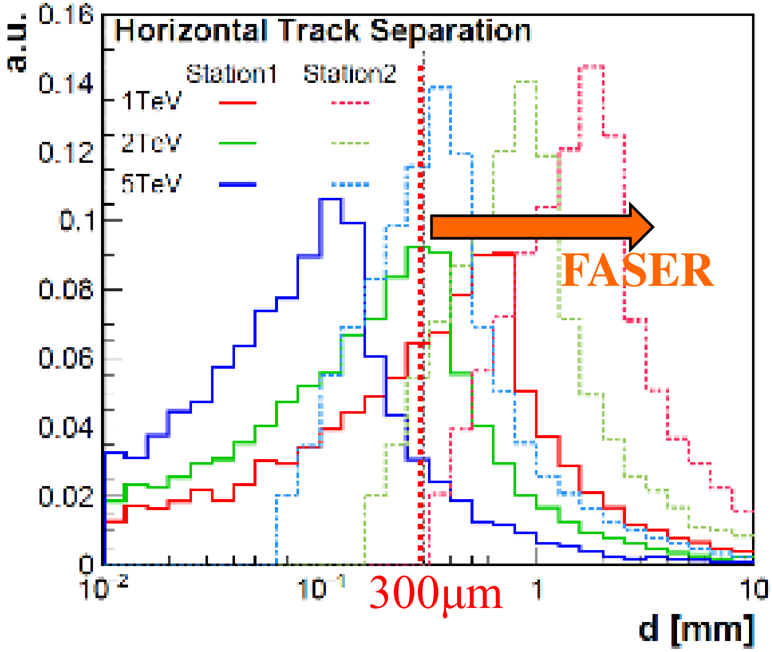


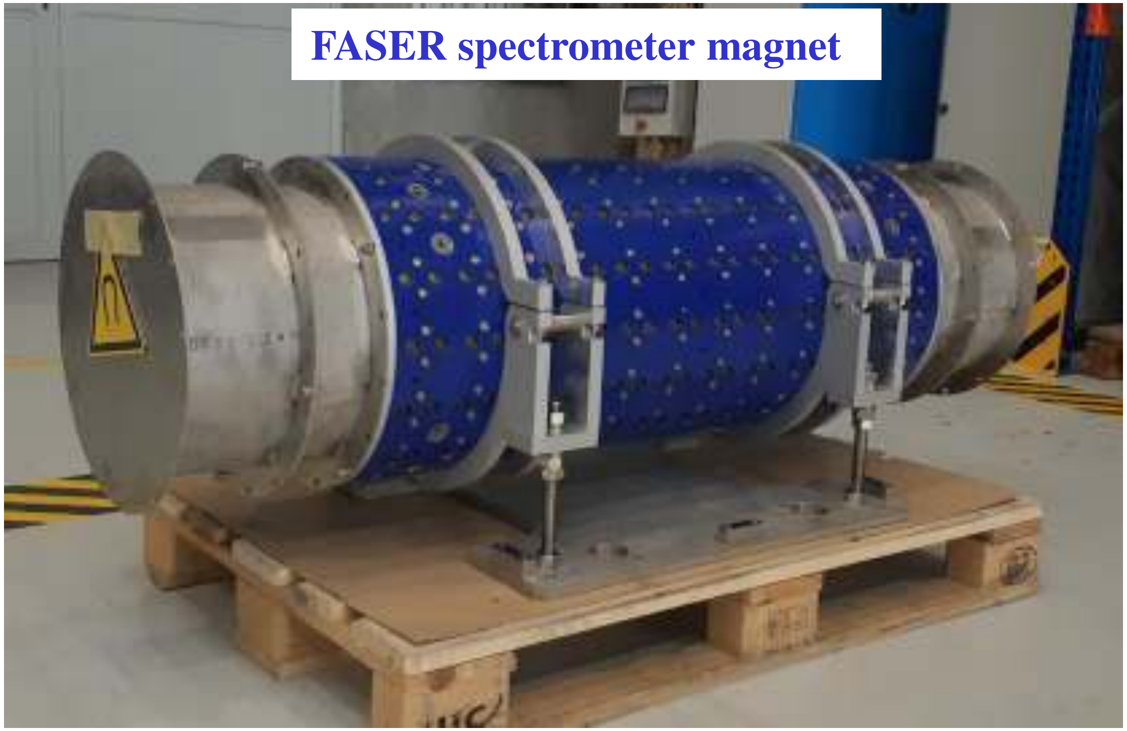
Dipole magnet

- 0.57 T permanent magnet is used to separate electron-positron tracks.
- The spectrometer is required to have capability to separate electron-positron tracks with 300 μm distance ($m_{A'} = 100$ MeV)

➡ Silicon strip detector is used for the tracker.

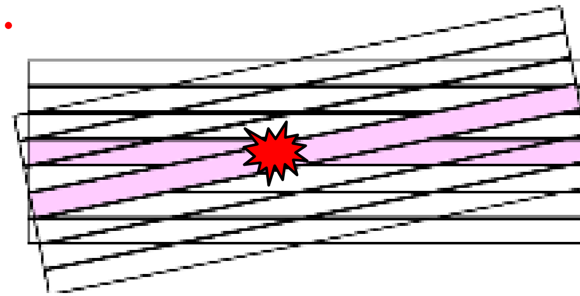
Distance btw e^-/e^+ from A' @FASER ($m_{A'} = 100$ MeV)





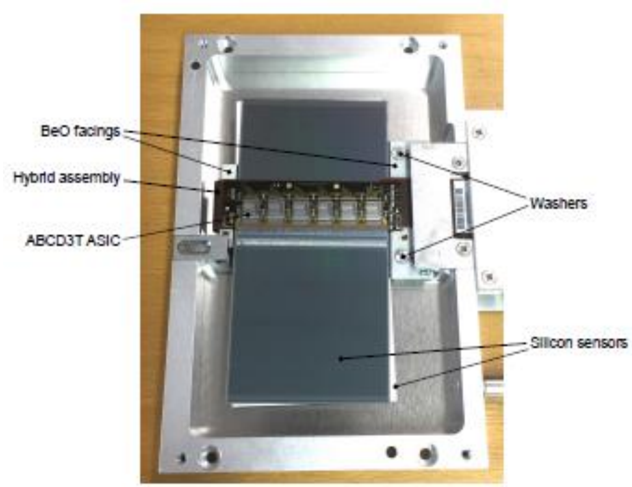
FASER tracker (1)

- 80 spares of ATLAS SCT barrel module are used.
  - Offered by ATLAS SCT group
- Strip pitch: 80 µm, strip length: 12.8 cm

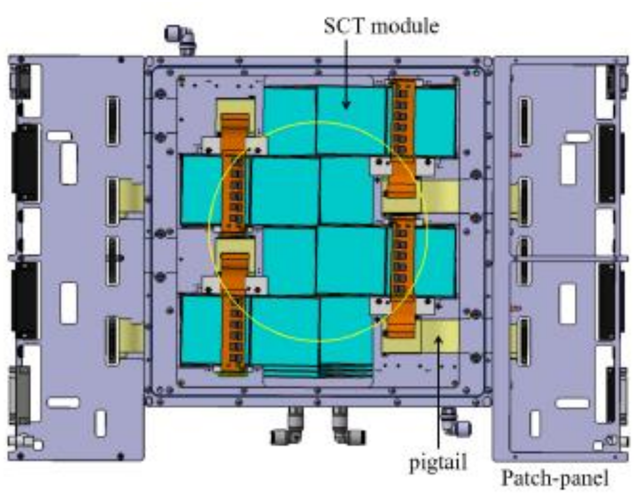


- The tracker consists of 9 SCT layers (3 stations)
  - 1 layer with 8 SCT modules, 1 station with 3 layers

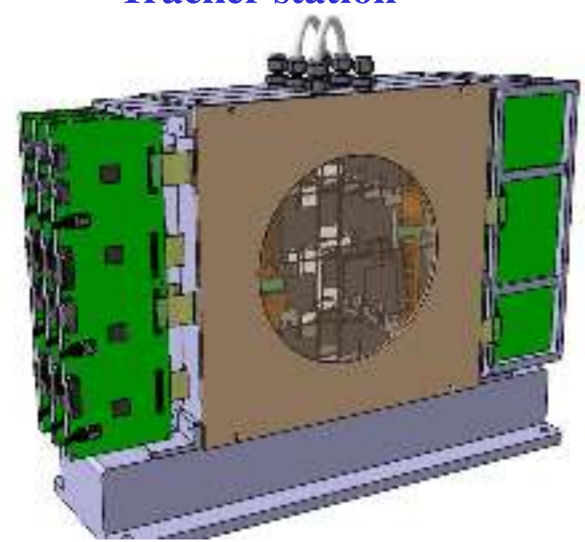
ATLAS SCT barrel module



Tracker layer

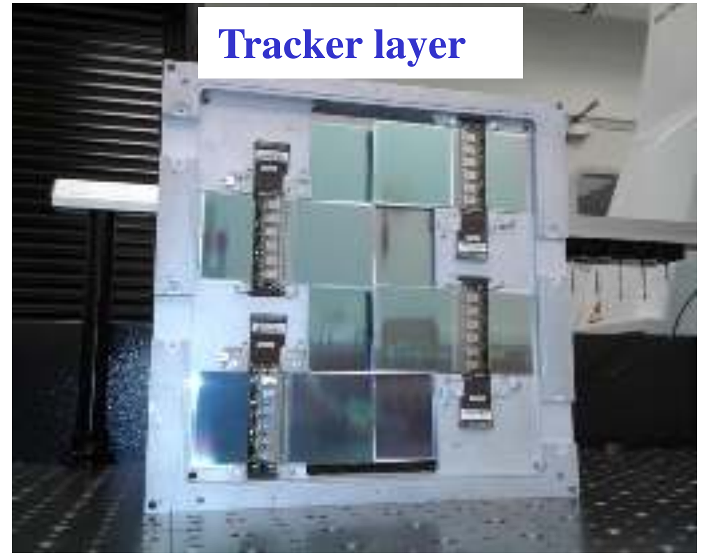


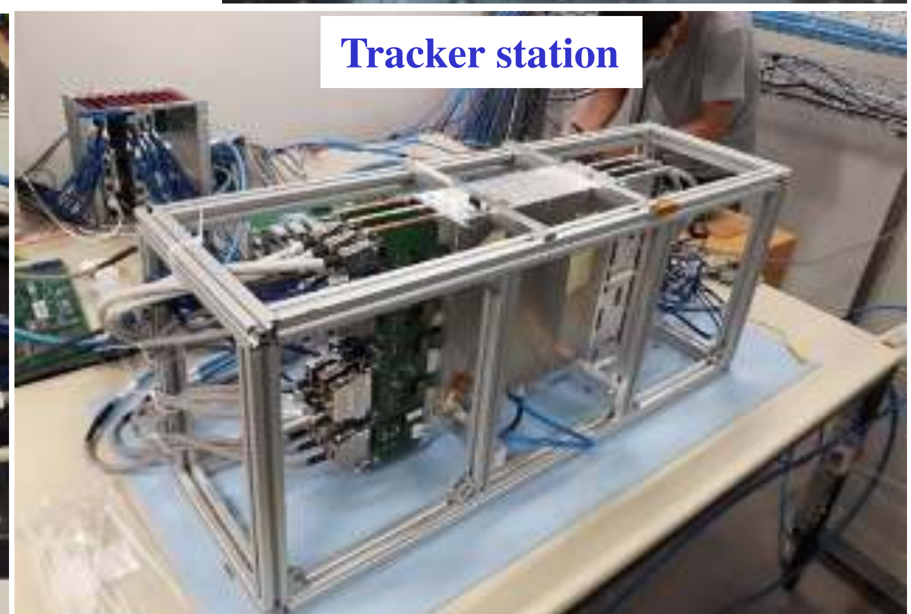
Tracker station



FASER tracker (2)

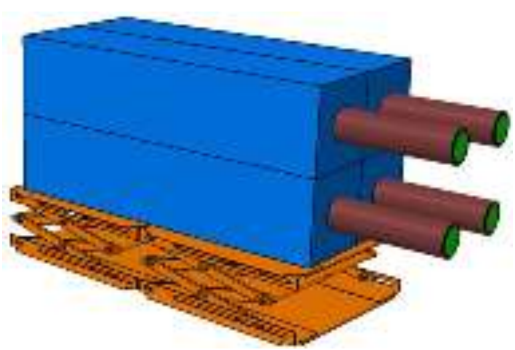
- The electrical tests were performed to select 80 modules with the best quality from the spares of ATLAS SCT.
- Production of the layer started in July 2020.
- All 9 layers were produced until November 2020 (3 stations).





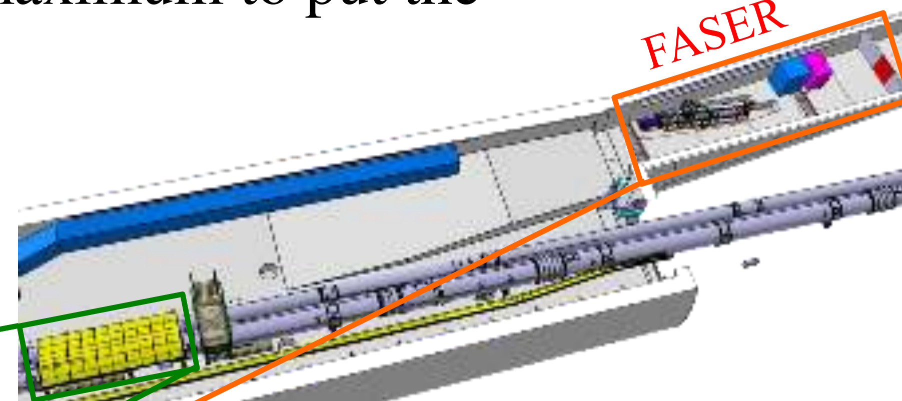
Electro-magnetic calorimeter

- 4 spares of LHCb EM calorimeter are used.
- Consists of 66 layers of 2 mm lead and 4 mm plastic scintillator (~25 radiation length)
- About 1% energy resolution for TeV energy deposit.
- The detector was assembled together with Preshower station.



Civil engineering

- The floor was dug by 50 cm at the maximum to put the detector on LOS (Line Of Site).
- The protection cover was placed on LHC magnet.
- The civil engineering was finished in the spring of 2020.



Installation activities

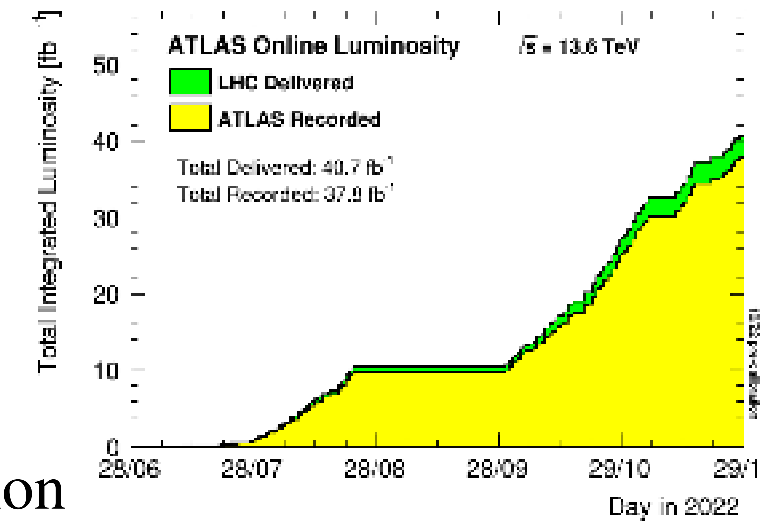
- Most of the FASER main detector was installed in spring 2020.
- The commissioning was performed until 2022 spring, taking data of comic rays and events from test pp collisions.
- Installation of FASERν was done in March 2022.
  - The emulsion films will be replaced 11 times every 30-50 fb^{-1}.

2022 data-taking

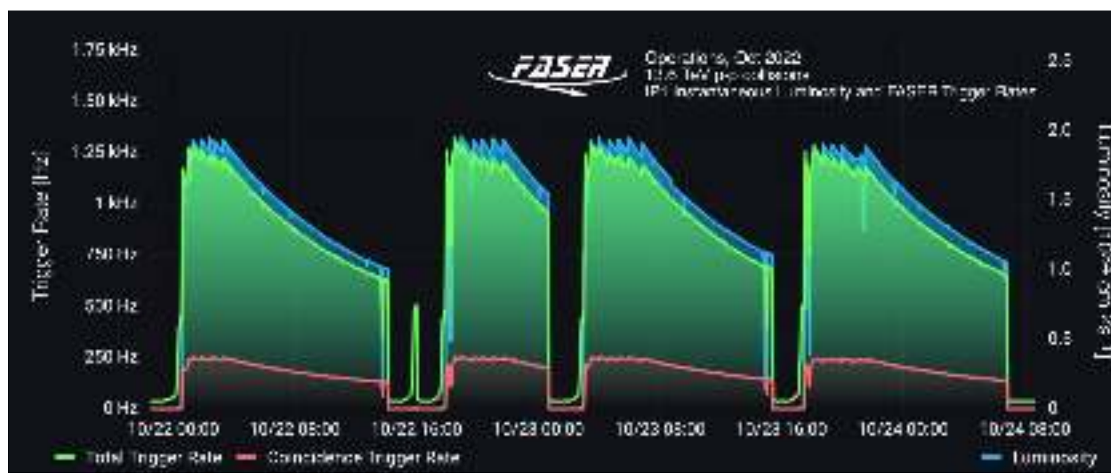
Physics data-taking

- LHC Run3 started with 13.6 pp colliding energy in 2022 summer.
- FASER took data since the beginning of LHC Run 3 and 38.5 fb^{-1} of physics data was collected in 2022.
- The maximum trigger rate was 1.25 kHz.
  - 2 times larger than the original expectation
  - Due to high environmental radiation
- Data could be taken without problem with high trigger rate.
  - physics deadtime <2%

Int. luminosity in 2022 @ATLAS-IP



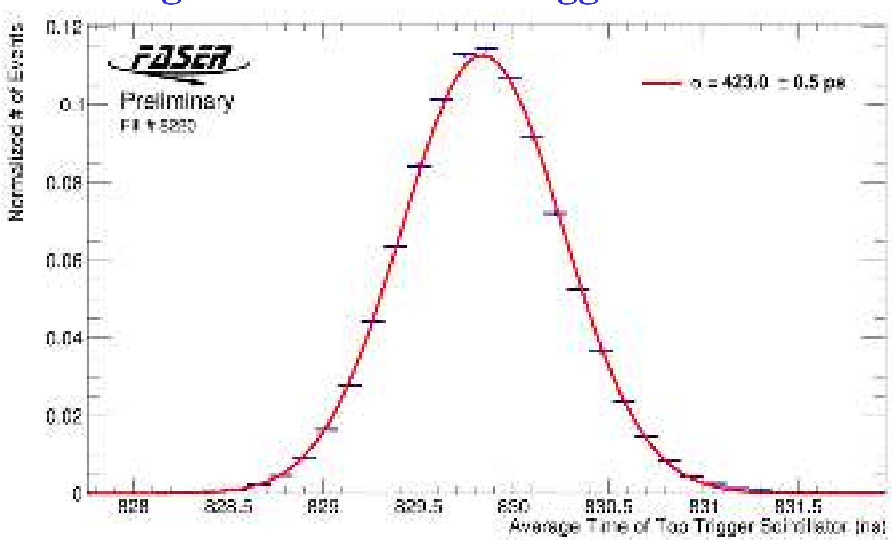
Trigger rate at FASER



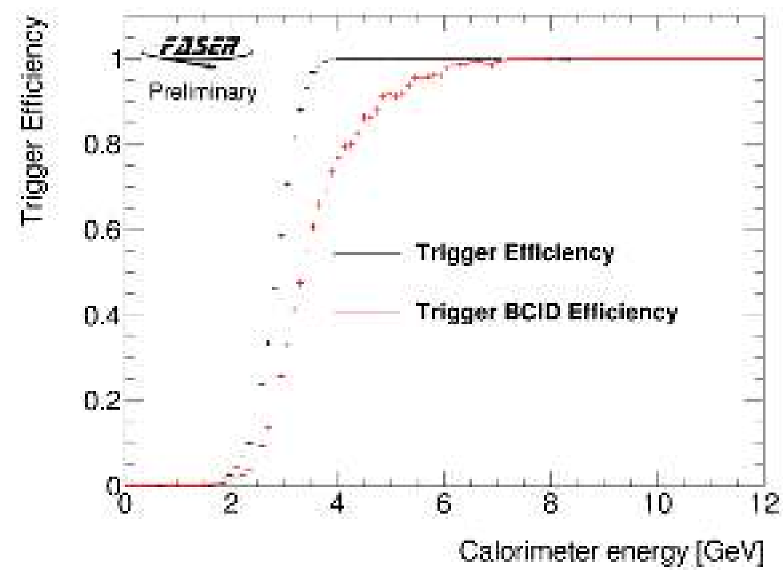
Trigger/veto performance

- The timing resolution of 423 ps was obtained with the timing counter.
- Trigger efficiency of preshower detector is 100% for electrons with the energy above ~8 GeV.
  - BCID efficiency is a fraction of events that match with correct BCID.
- The single veto layer achieved 99.9996% veto efficiency.

Timing distribution with trigger scintillator



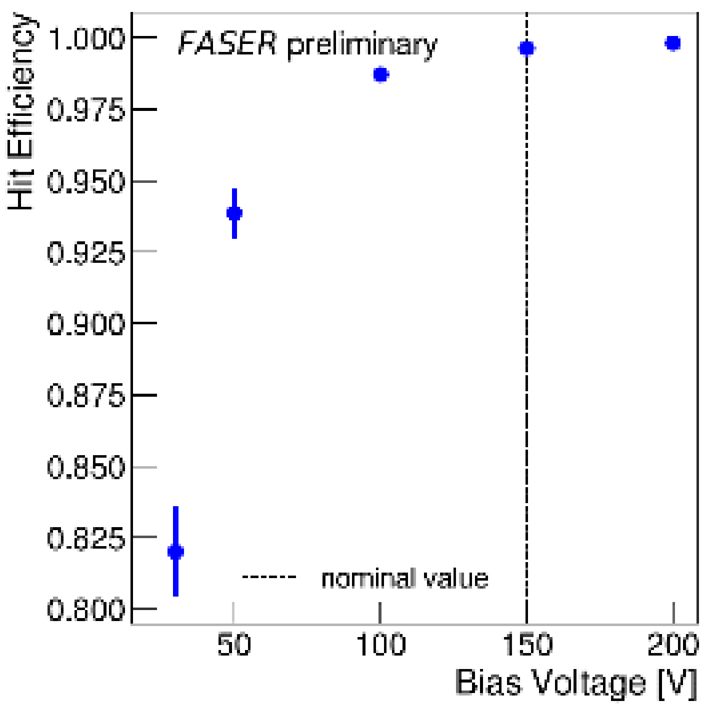
Trigger eff. v.s. EM energy @preshower detector



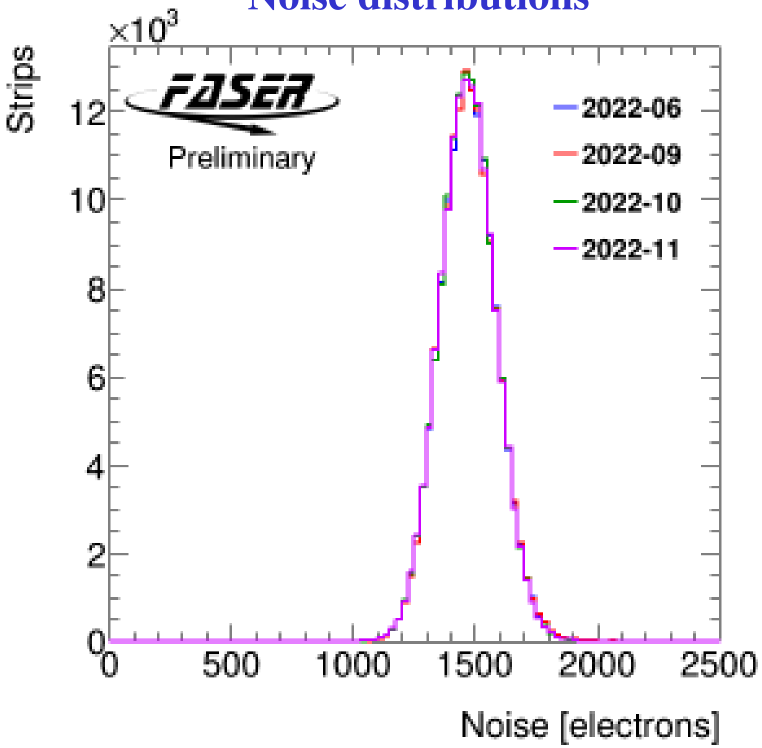
Tracker performance

- The hit efficiency of the tracker is 99.64% with the nominal operation voltage for the silicon strip sensors (150 V).
- The noise level is about 1500 electrons, that is comparable with the value of ATLAS SCT.

Hit efficiency v.s. Bias voltage



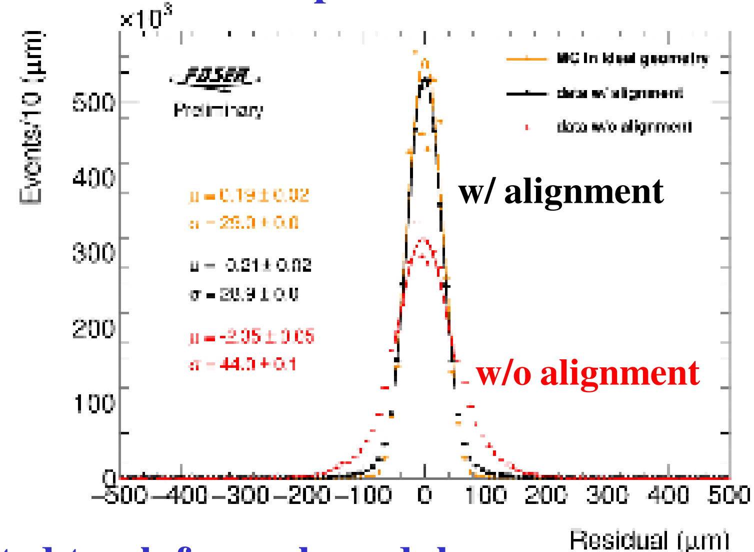
Noise distributions



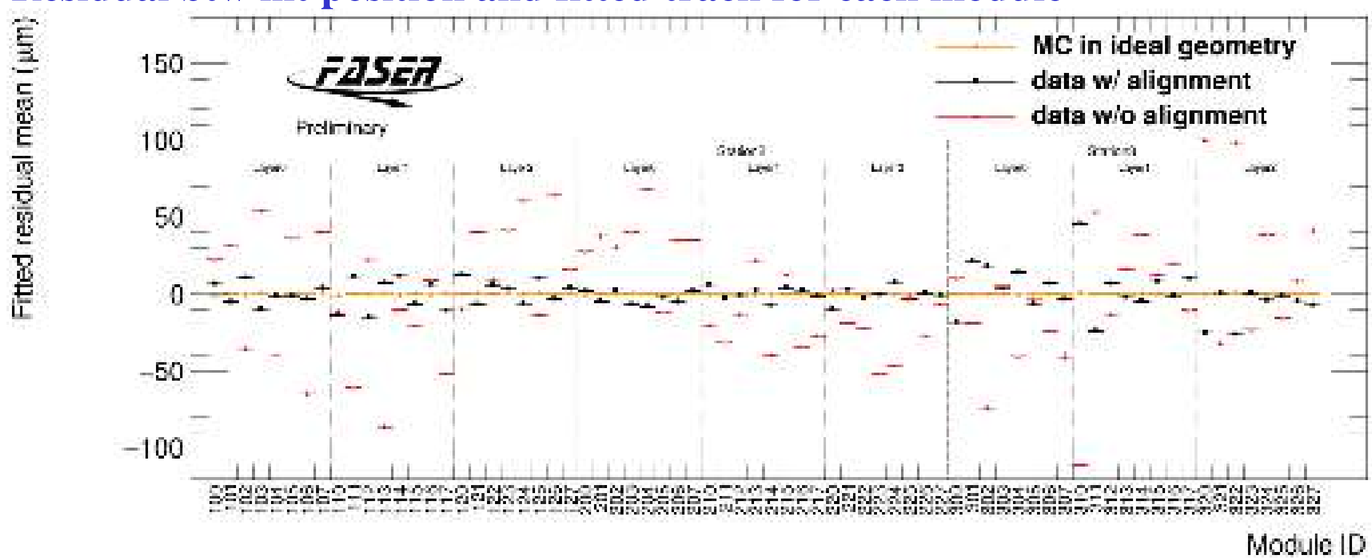
Tracker alignment

- The hit residuals are improved from 44.0 um to 28.9 um by offline alignment.

Residual btw hit position and fitted track

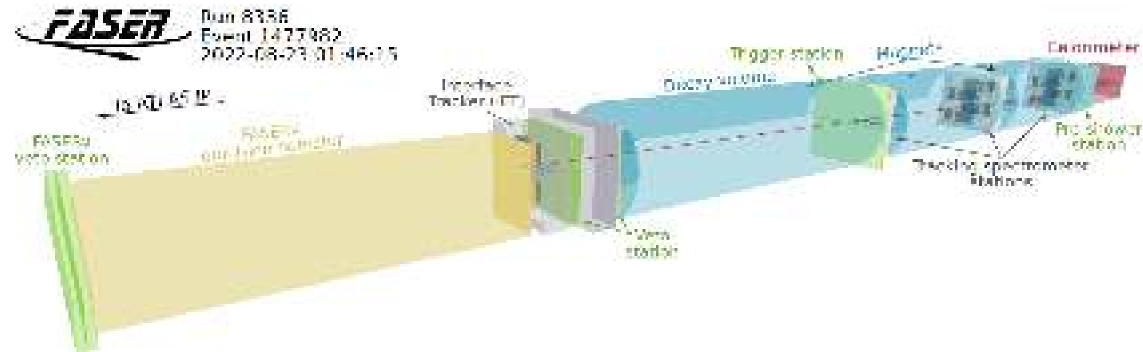


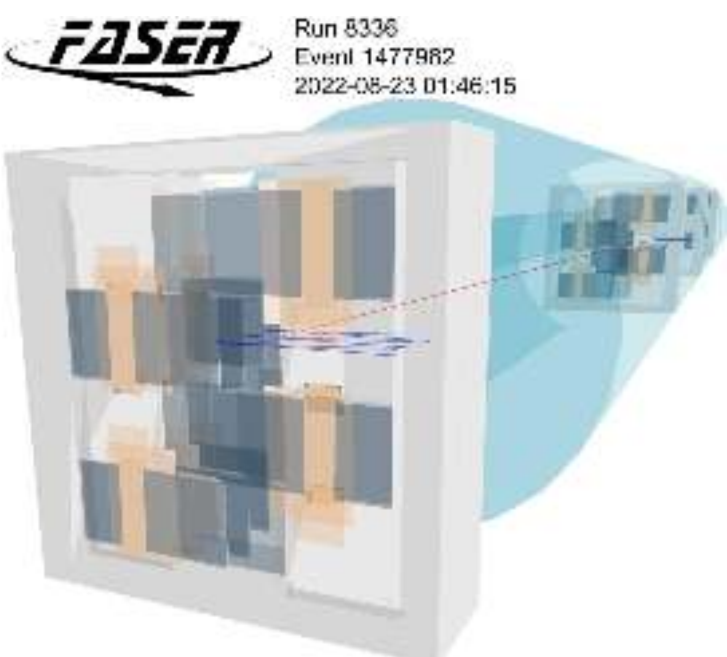
Residual btw hit position and fitted track for each module

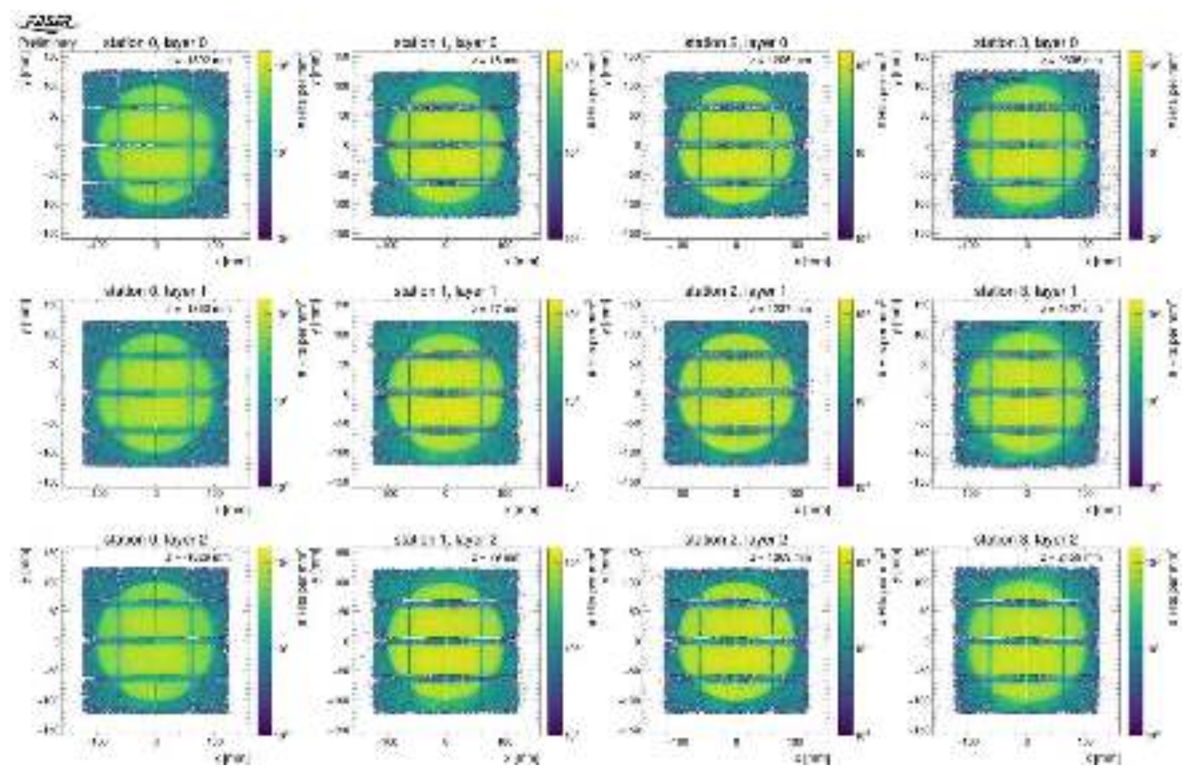


Event display and hit distributions

- Each events can be checked with the display.
- Uniform hit distribution was obtained in the sensitive region of the tracker layers.



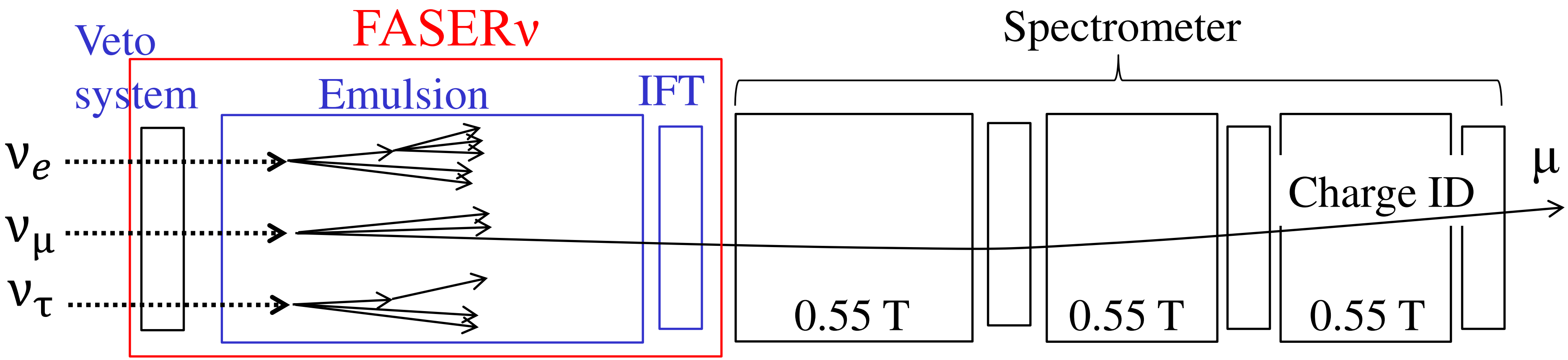




Neutrino measurement at FASER

FASERν complex

- Veto scintillator system at the most front part of FASERν rejects charged particles coming from the upstream.
- The emulsion detector with 700 layers of an emulsion film and 1.1 mm tungsten plate (220 X_0)
  - The emulsion films will be replaced every 30-50 fb^{-1}.
- Silicon strip tracker (IFT: InterFace Tracker) for the interface of tracking with FASER spectrometer behind it.
  - Charge identification of muons is possible.



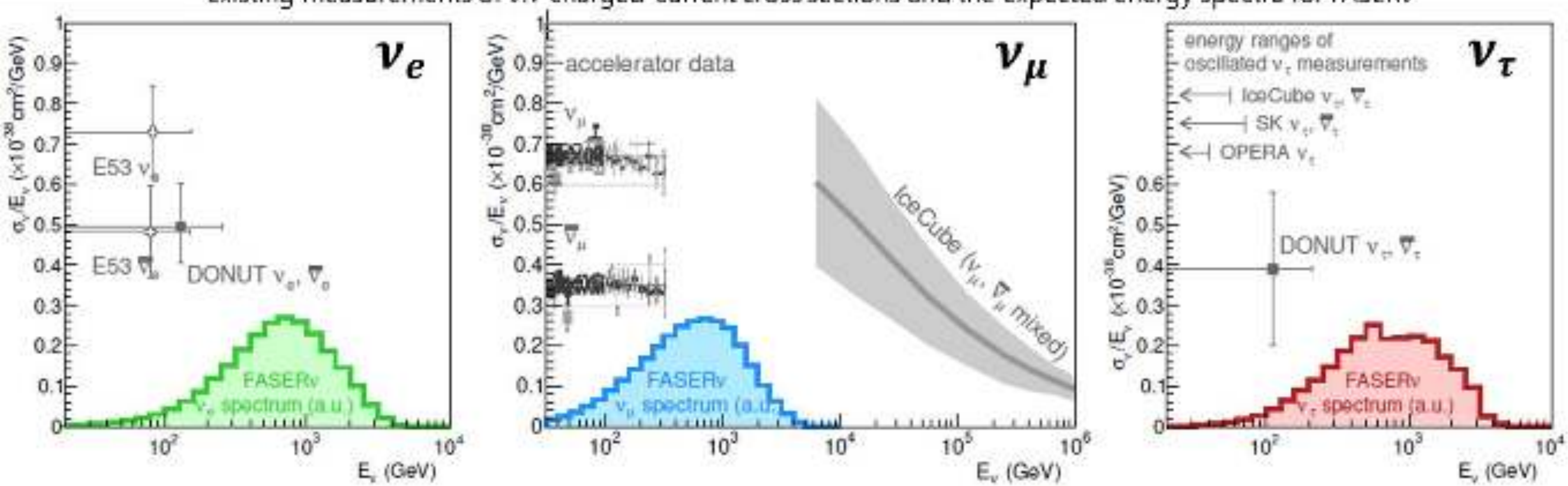
Neutrino measurement (1)

- FASERν will measure neutrino cross-sections at TeV region which is uncovered by existing experiments.
- All neutrino flavors in Charged Current (CC) interactions can be identified including τ-neutrino, thanks to excellent position resolution of the emulsion detector.

Expected # of CC interaction with 150 fb^{-1} @FASERν [PRD 104, 113008 (2021)]

Generators		FASERν		
Light hadrons	Heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	901	4783	14.7
DPMJET	DPMJET	3457	7088	97
EPOSLHC	PYTHIA8 (Hard)	1513	5905	34.2
QGSJET	PYTHIA8 (Soft)	970	5351	16.1
Combination (all)		1710^{+1746}_{-809}	5782^{+1306}_{-998}	$40.5^{+56.6}_{-25.8}$
Combination (w/o DPMJET)		1128^{+385}_{-257}	5346^{+558}_{-565}	$21.6^{+12.5}_{-6.9}$

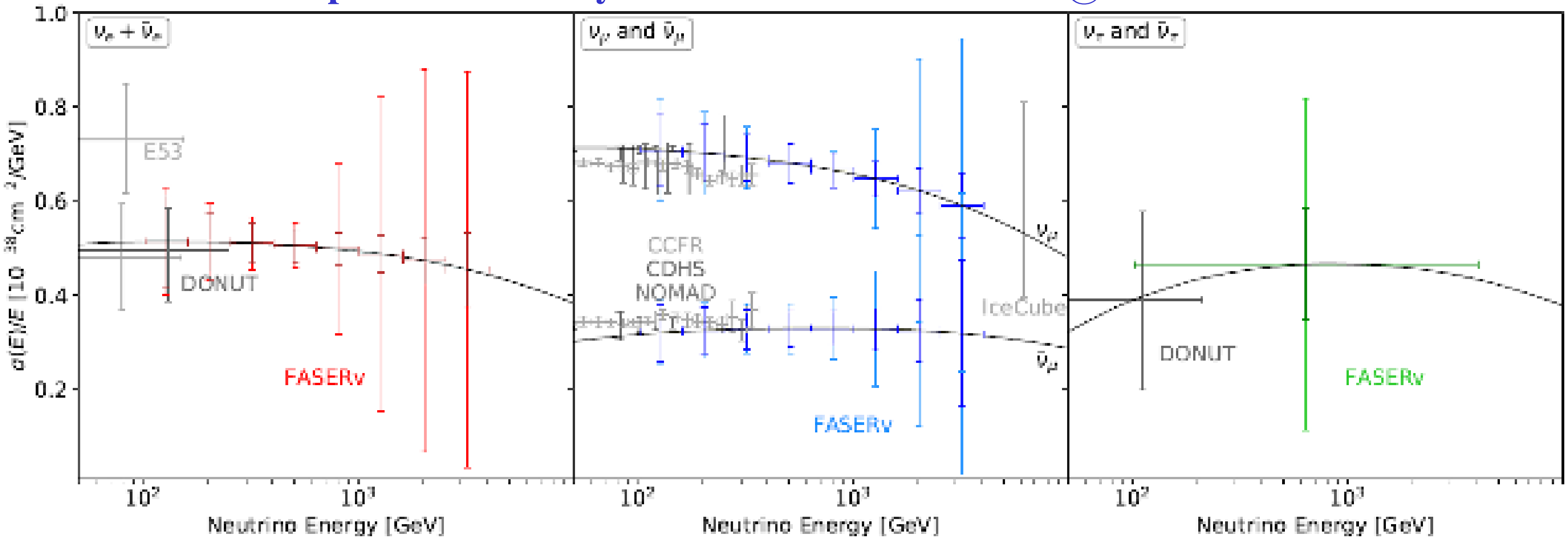
Existing measurements of νN charged-current cross sections and the expected energy spectra for FASERν



Neutrino measurement (2)

- FASERν measure CC cross-section at TeV region, and its consistency with Standard Model (SM) will be studied.
- The anomaly of the third generation coupling will be explored.
  - 3.2σ deviation from SM is reported in the quark-sector [here].
- The charge measurement in cooperation with spectrometer behind FASERν enables to separate $\nu_\mu/\bar{\nu}_\mu$.

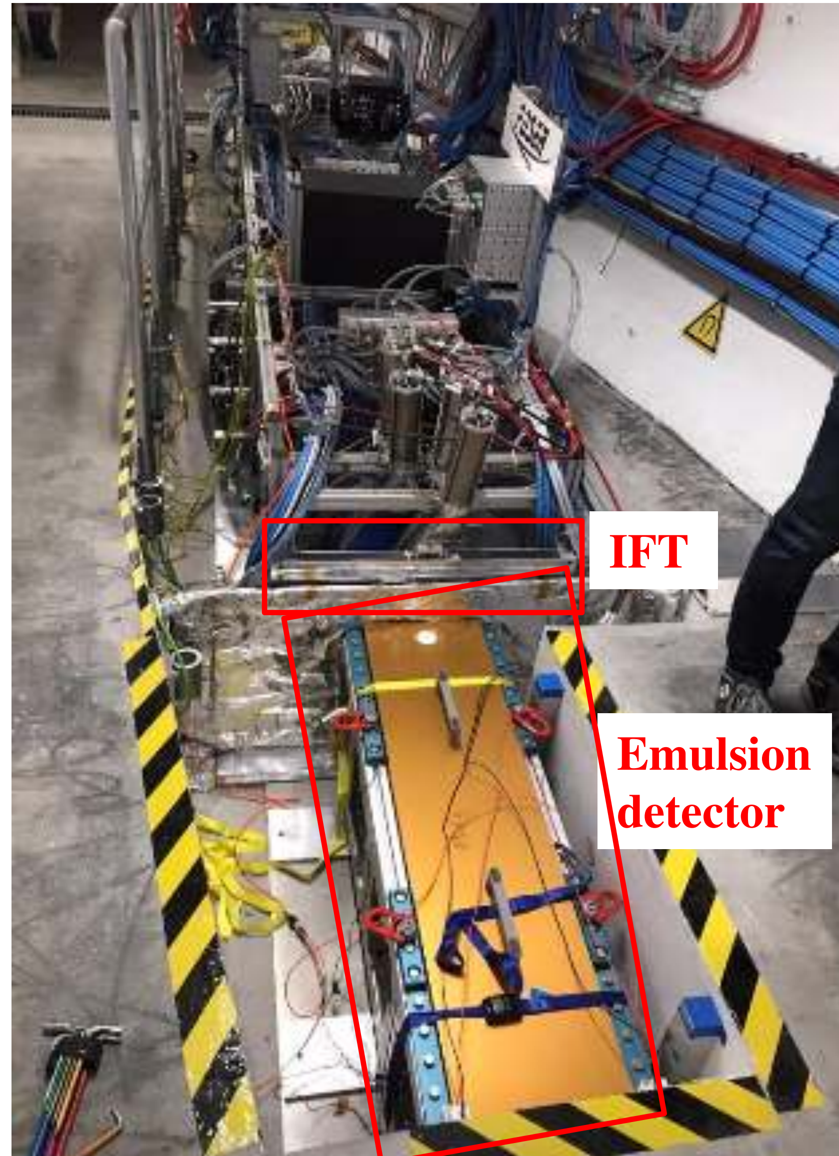
Expected sensitivity to neutrino cross-sections @FASERν



FASERν installation

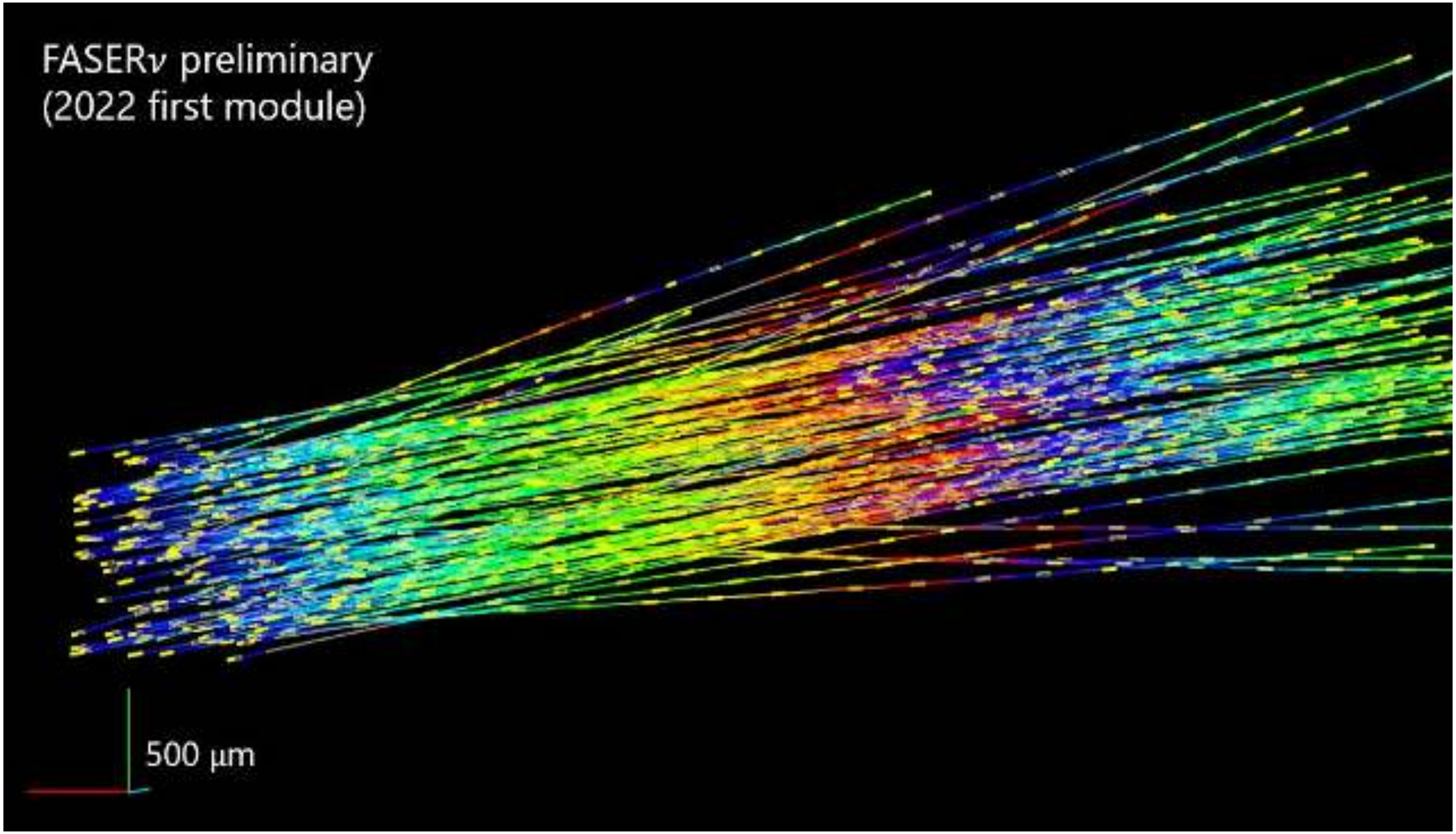
- IFT was installed in November 2021.
- The first emulsion box was installed in March 2022.
  - The films were replaced 2 times in 2022.

Film production facility



Tracks in emulsion detector

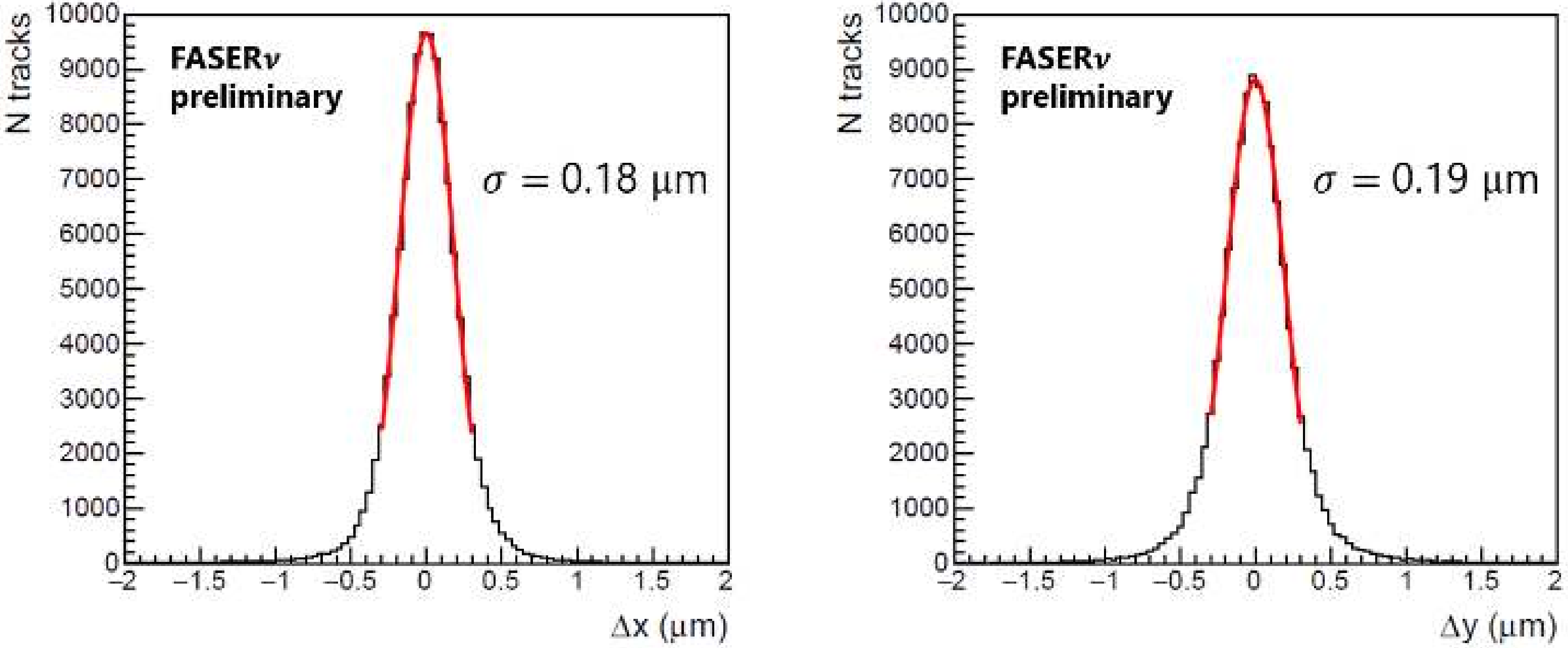
- Reconstructed tracks in the emulsion detector with 0.5 fb^{-1}.
- The track density is 2.3×10^4 cm^{-2} per fb^{-1}.



Performance of emulsion detector

- The position resolution better than 0.2 um was obtained in the emulsion detector.

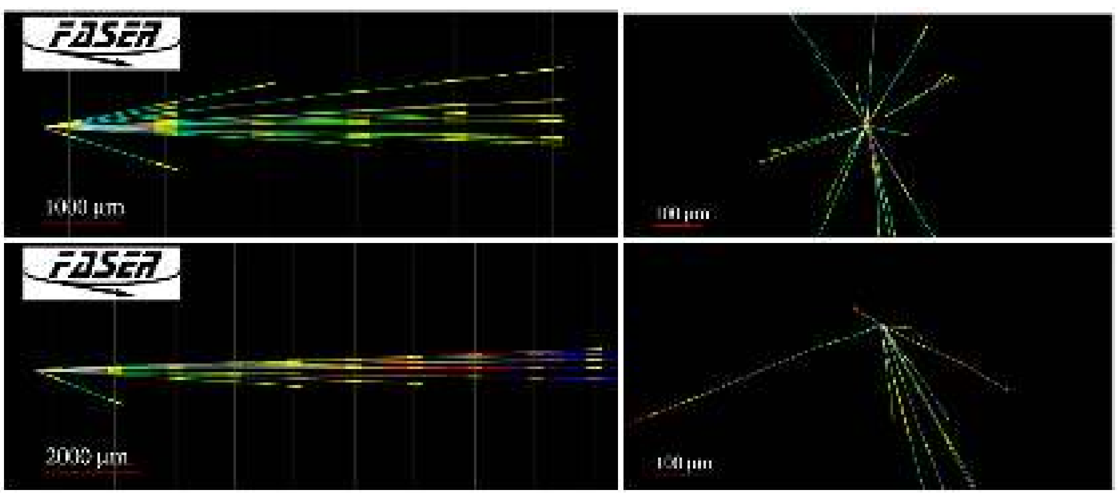
Residuals between hit position and reconstructed tracks @Emulsion detector



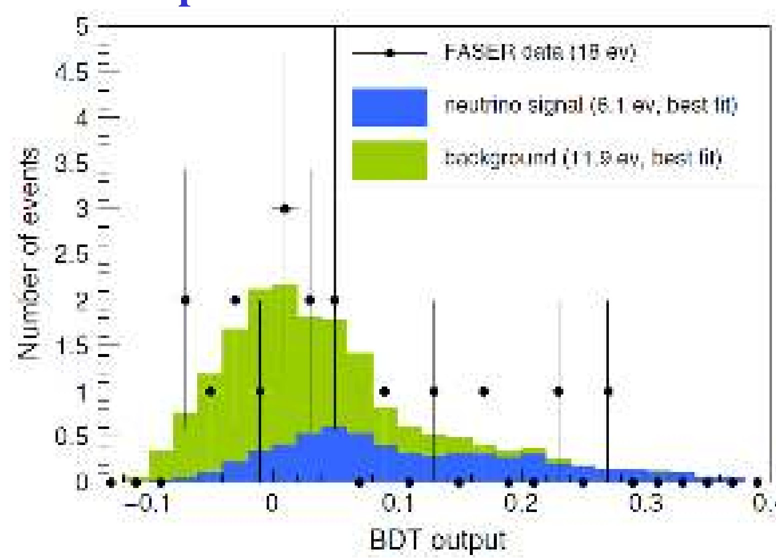
Neutrino detection at 2018 pilot-run

- Neutrino detection was performed with a 30 kg emulsion detector at TI18, collecting 12.5 fb^{-1} of data in 2018.
- 18 candidates of the neutral vertex were detected, that are the first candidates of the neutrino interactions at a collider.
- 2.7σ excess of neutrino-like signal above muon-induced background is measured and the results were published in [PRD 104, L091101 (2021)].

Neutrino event candidates



BDT outputs of observed neutral vertices

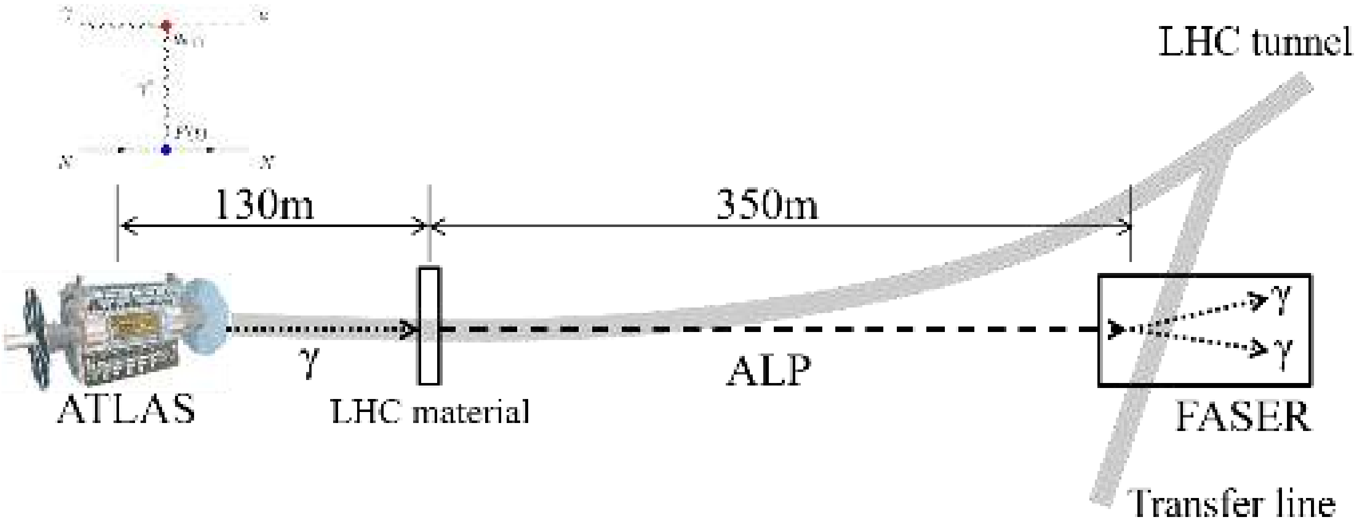


Preshower detector upgrade

Pixel detector to search for ALP

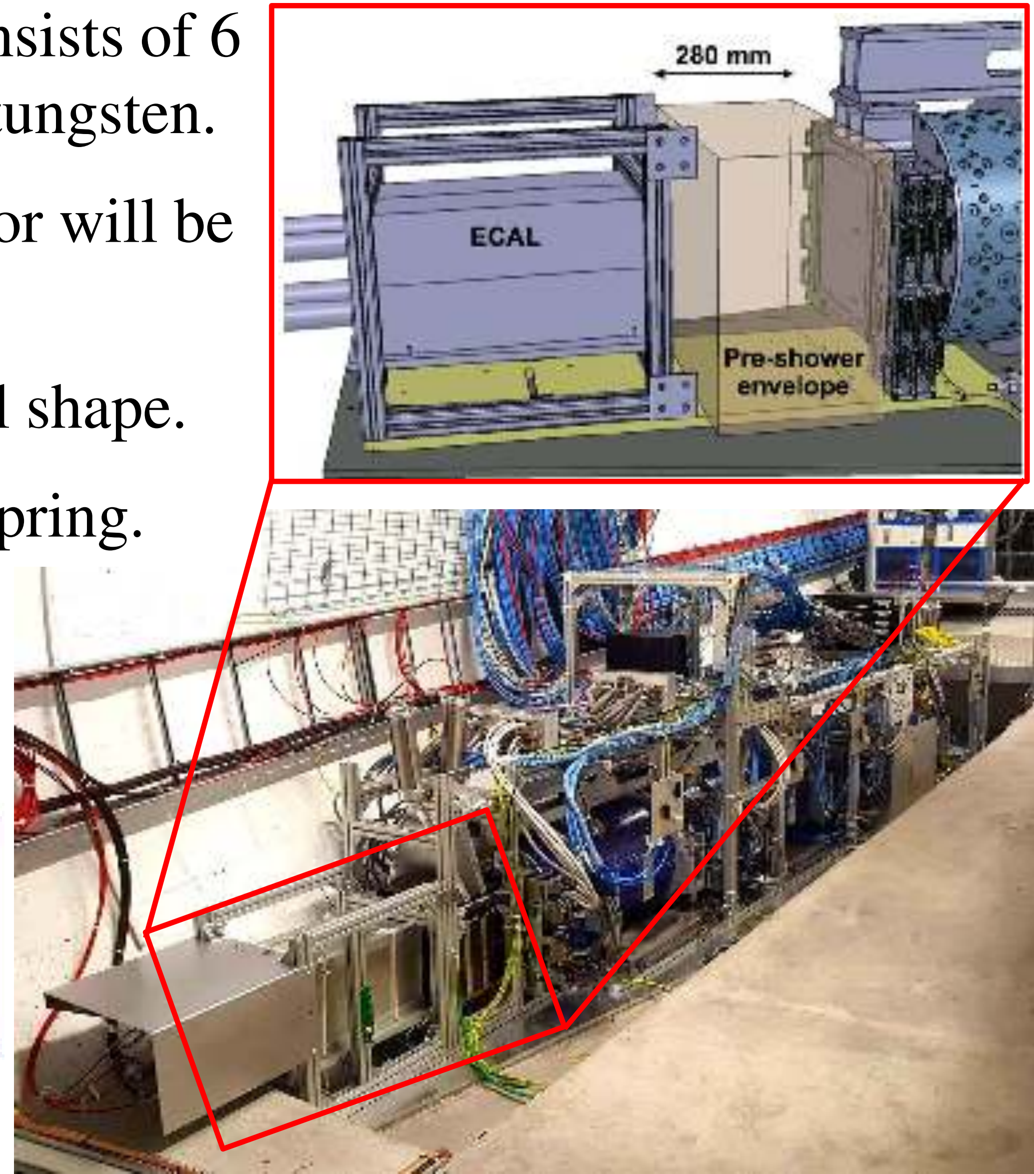
- ALP (Axion Like Particle) can be created with Primakoff interaction between γ and LHC material 130 m downstream from ATLAS IP.
  - ALP is a pseudo scaler in SM singlet and couples to SM particles via dimension-5 interaction.
- Detection of 2 γ's is important to identify ALP.
- FASER ECAL is separated into only 4 parts and there is no segmentation in the current Preshower detector in front of it.

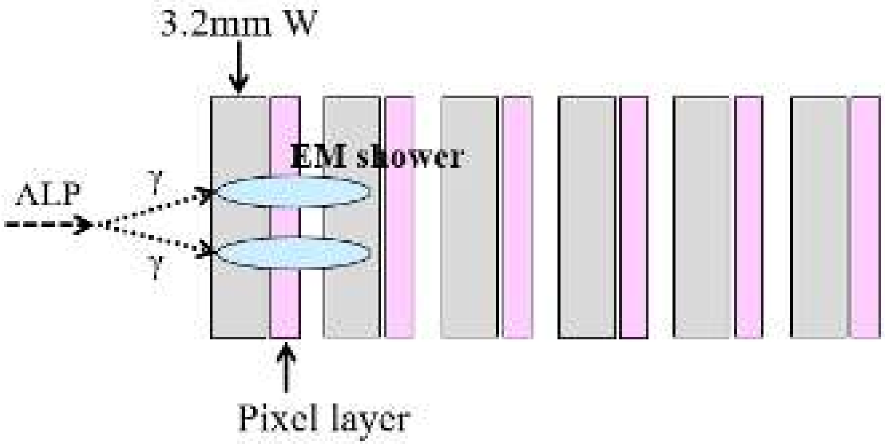
New Preshower detector with fine granularity



Preshower detector upgrade

- The new preshower detector consists of 6 layers of the pixel detector and tungsten.
- SiGe-BiCMOS monolithic sensor will be used for the pixel detector.
- Pixel size is 65 um of hexagonal shape.
- Installation is planned in 2025 spring.

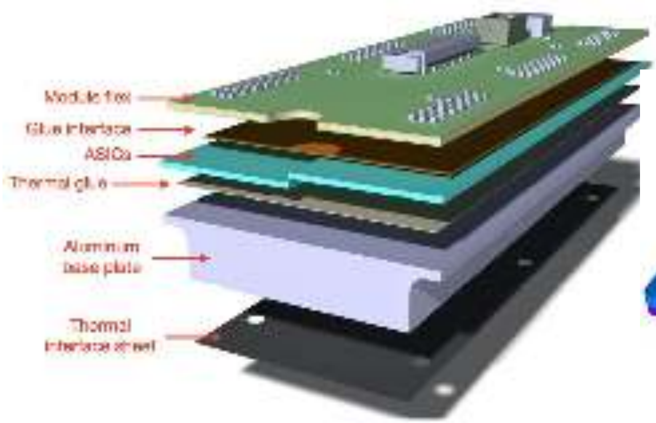




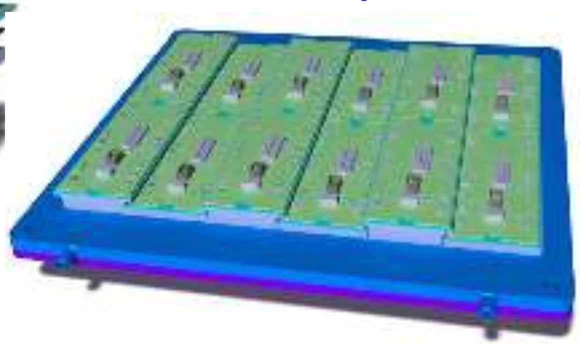
Design of new preshower detector

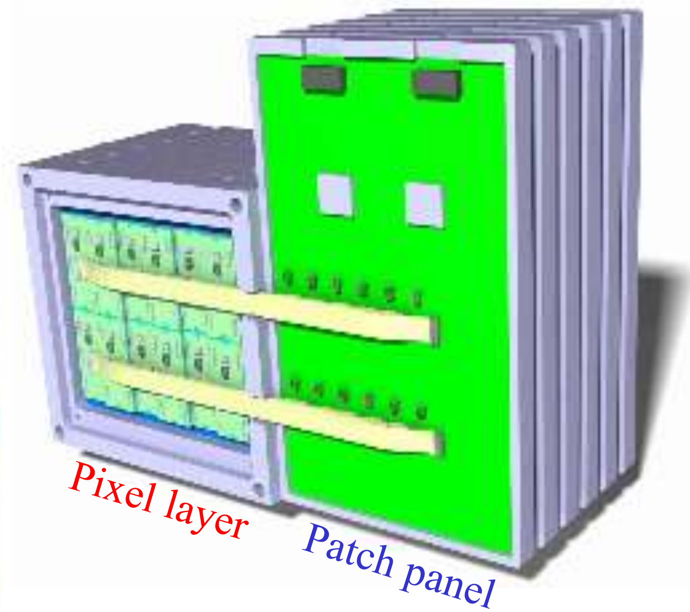
- 6 SiGe-BiCMOS sensors per module (Module size : 6.7 x 3.1 cm^2)
  - The sensors and module flex are connected with wire bonding.
- 12 modules are used for one layer.
- The cooling plate is made with aluminum alloy (AlSi10Mg) for the water cooling of 15 degree.
  - The cooling pipe is embedded with 3D printing
  - Power consumption: ~150 mW/cm^2

SiGe-BiCMOS pixel module



Pixel layer

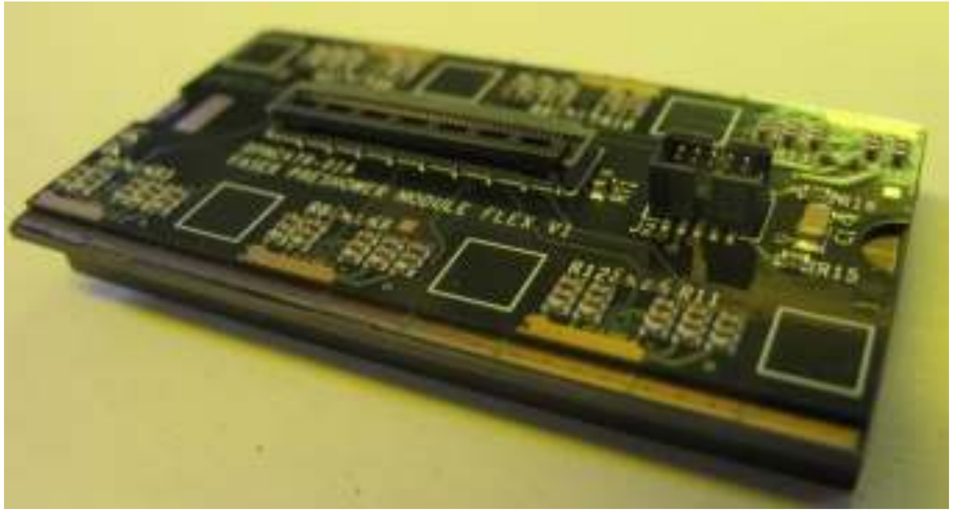


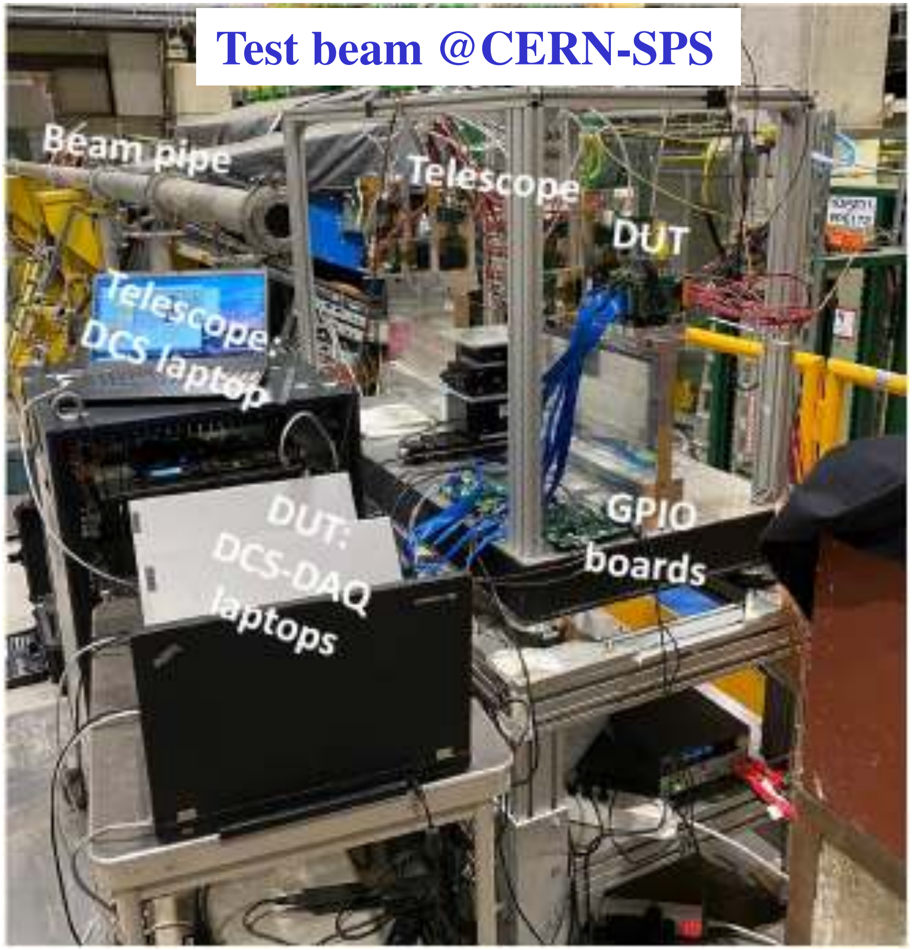


Development of new preshower detector

- The prototype module was produced during 2022.
  - All the components (sensors, module flex, power flex) are functional.
- The beam test was performed at CERN SPS.
- The production of the final sensor will start in spring 2023.

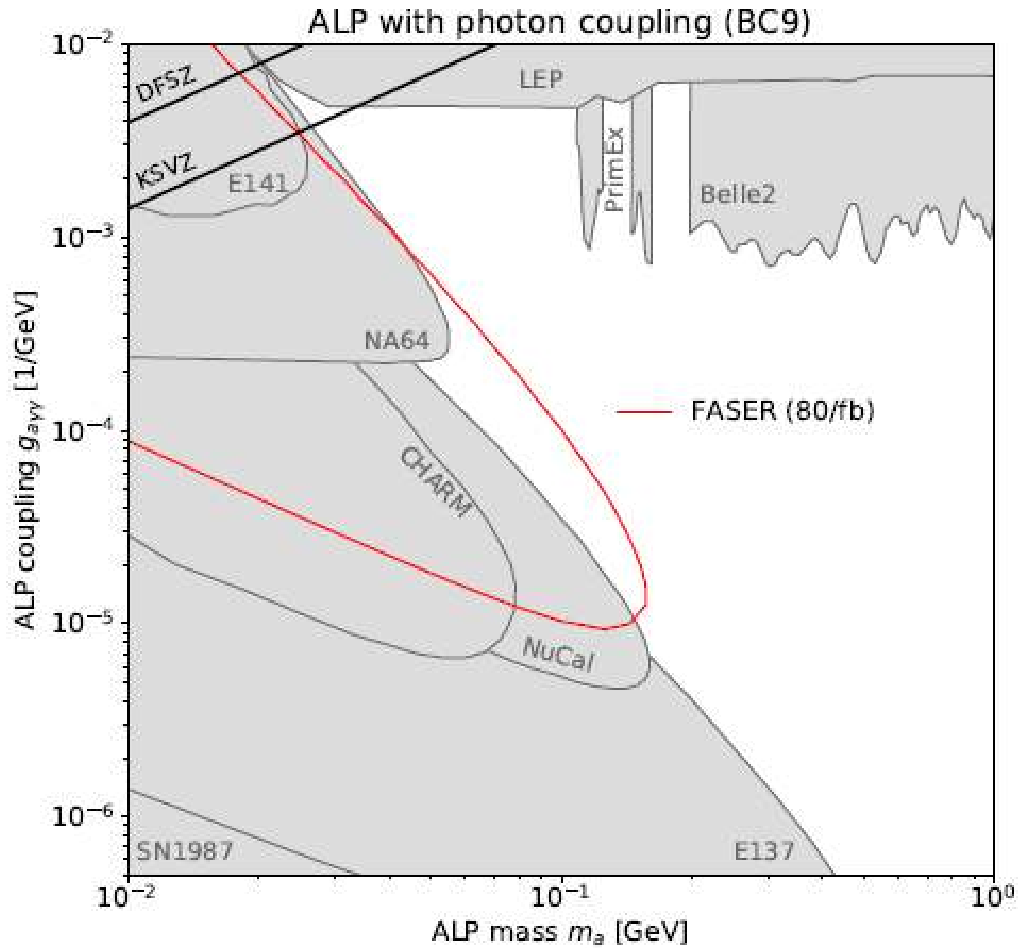
Prototype module





Sensitivity to ALPs

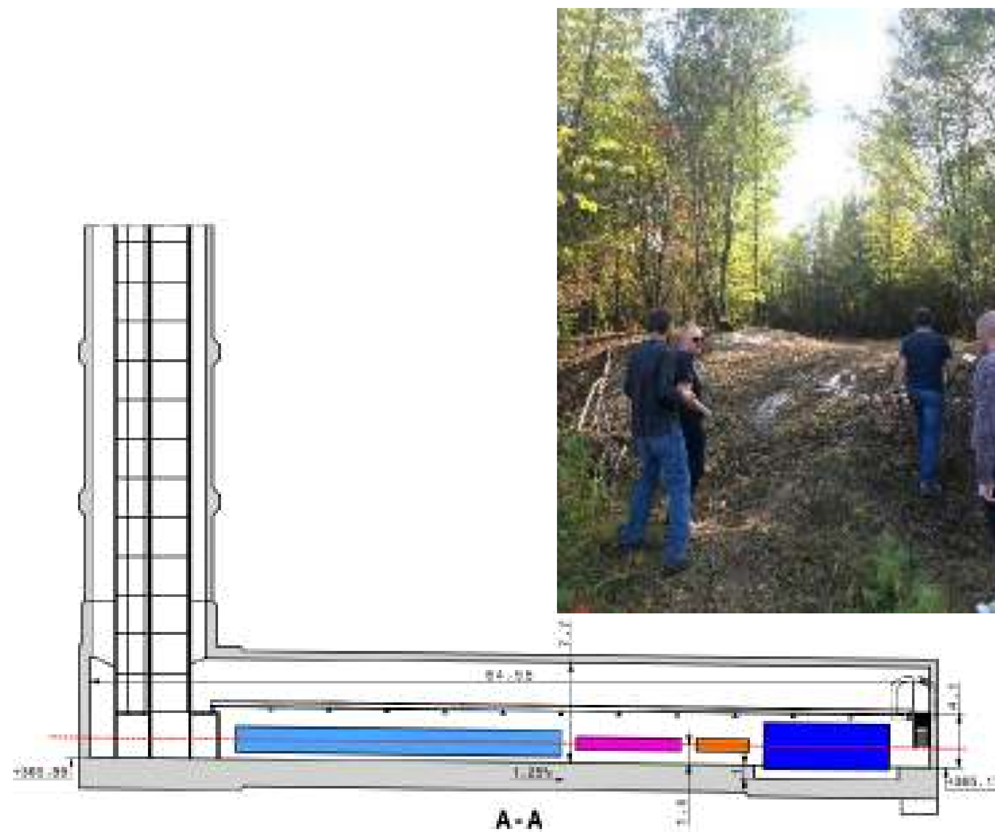
New search region can be explored only with 2025 data with new preshower detector.



Forward Physics Facility at HL-LHC

Forward Physics Facility (FPF)

- FPF is a proposal to construct a new facility to enable a suite of new experiments that target BSM dark sector search, neutrino physics and QCD physics.
- The facility will be constructed at ~600 m from the ATLAS IP.
- Size: 64 m (L), 4 m (R)
- Total cost: ~40 MCHF



Proposed experiments at FPF

5 experiments are proposed to utilize FPF.

FASER2

- Light dark-sector particles
- Scaled up version of FASER (1 m radius v.s. 0.1 m)

FASERν2

- Mostly neutrino physics
- O(20 tn) emulsion/tungsten detector (FASERν × 20)

FLArE

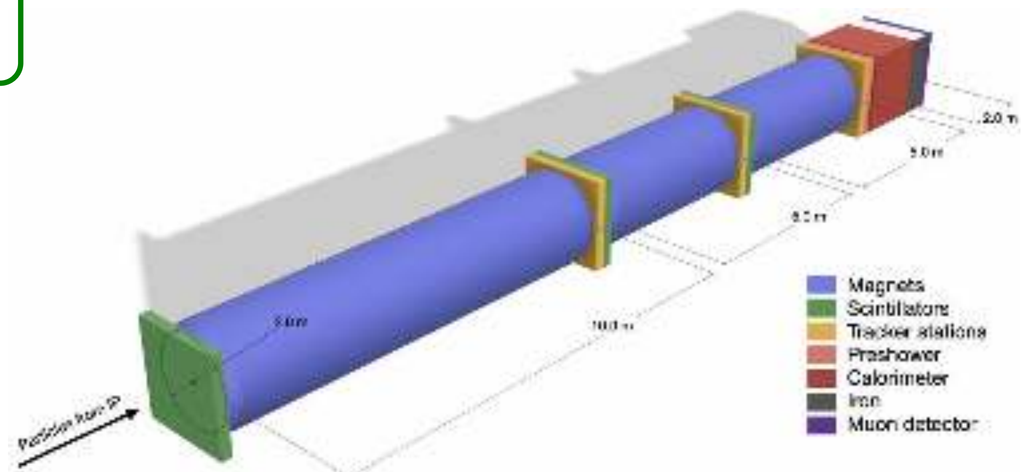
- DM scattering, neutrino physics
- O(10 tn) LAr TPC detector

AdvSND

- Neutrino physics slightly off-axis

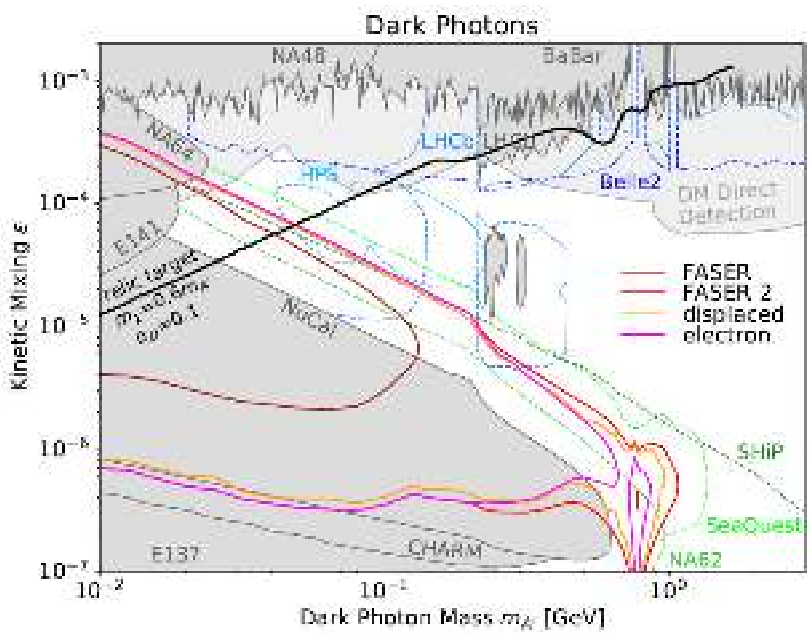
FORMOSA

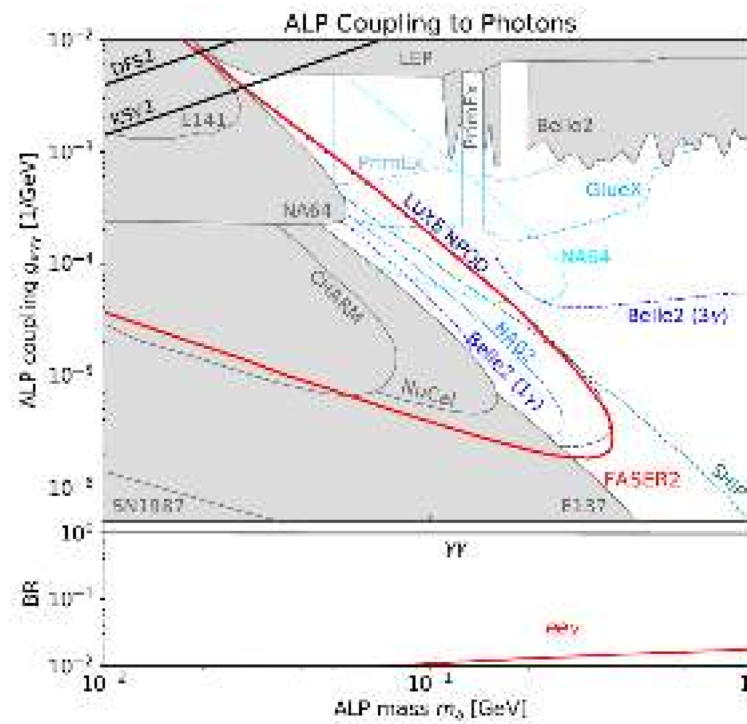
- Milicharged particle
- Scintillator based, similar to current miliQan experiment



Sensitivity to new physics @FPF

- FASER2 extends sensitivity to dark photon mass by one order of magnitude with respect to FASER.
  - Almost all parameter region bellow 0.5 GeV can be explored with other experiments.
- Sensitivity to ALP is also improved significantly.

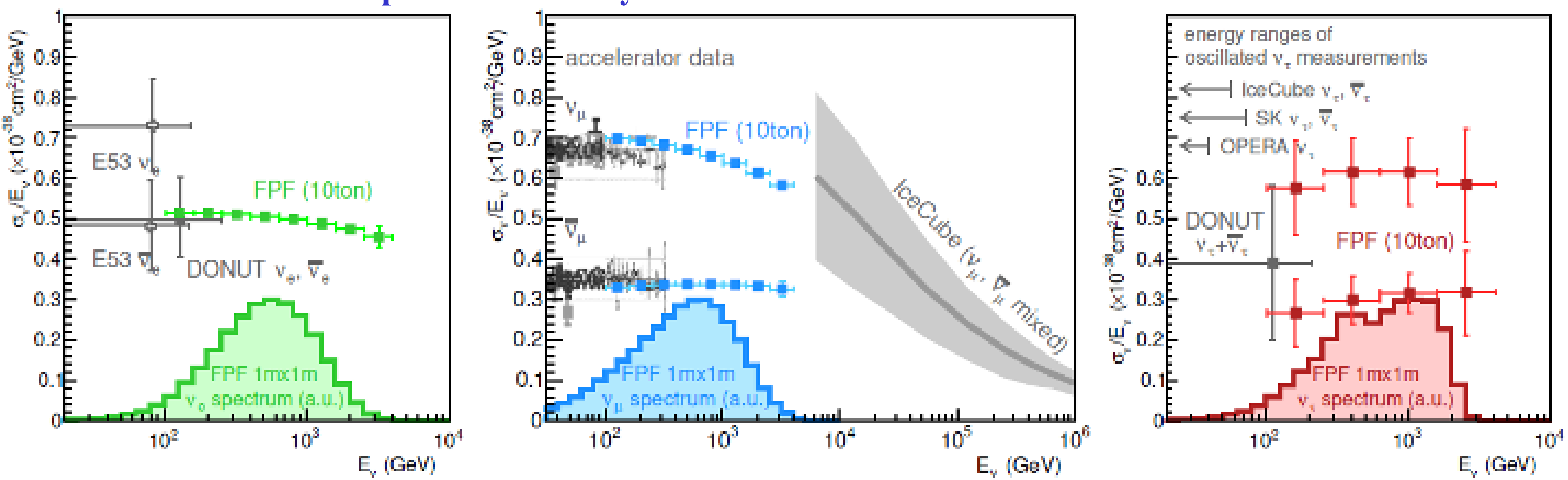




Sensitivity to neutrinos @FPF

- The charged current interactions of all neutrino flavors can be measured with high precision (O(1-10%)) at FASERν2.
- FASERν2 can identify ν_τ and $\bar{\nu}_\tau$ separately.
  - FASERν will measure the total cross-section of ν_τ and $\bar{\nu}_\tau$ for the first time.
- The neutral current interactions will be also measured.

Expected sensitivity to neutrino interactions at FASERν2



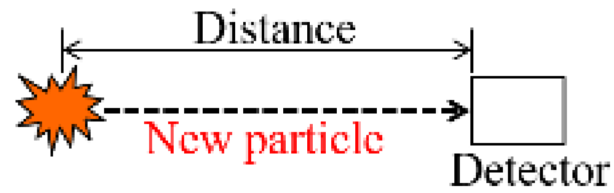
Summary & Conclusions

- FASER is a new experiment to search for new long-lived particles and measure interactions of high energy neutrinos, that are generated at pp collisions in the LHC.
  - [Tracker paper], [TDAQ paper], [FASER detector paper]
- The detector construction was successfully until the beginning of LHC Run 3 and the physics data-taking started in 2022 summer.
- The new parameter space of several new particles like dark photon will be explored by using 2022 data.
- New Preshower detector with SiGe-BiCMOS pixel detector is being developed for the ALP search, aiming the installation in 2025 spring.
- FPF is a proposal to construct a new facility to enable a suite of new experiments using the forward pp interactions.
  - FASER2 and FASERν2 will be performed at FPF.

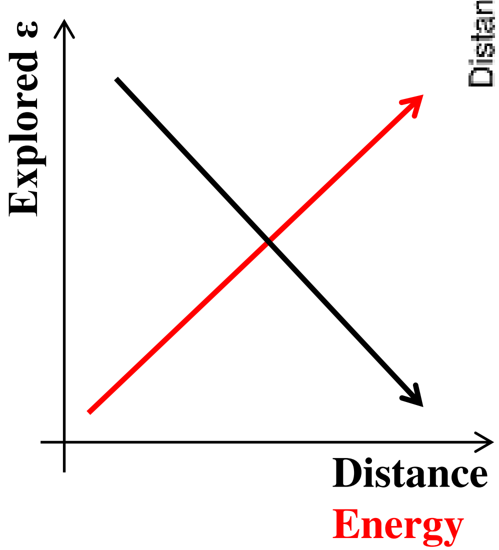
Backup

Sensitivity to small coupling region

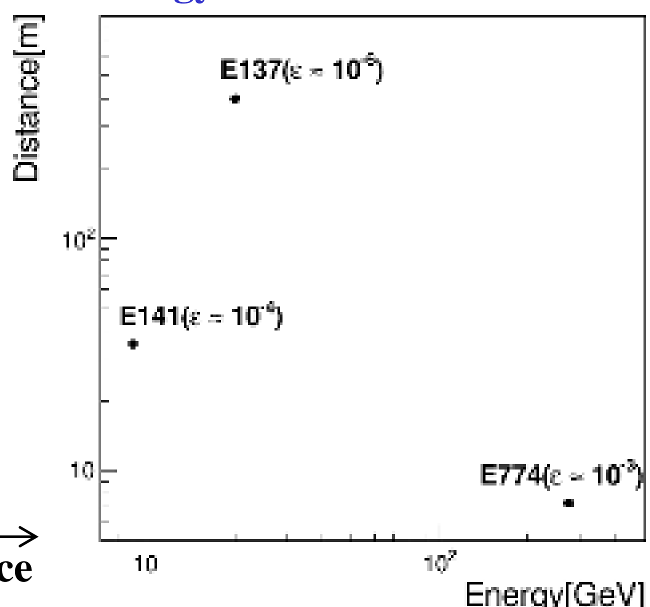
- Beam dump experiments provide limits on small coupling region (SLAC E137, SLAC E141, FLAB E774) [arXiv:0906.0580].

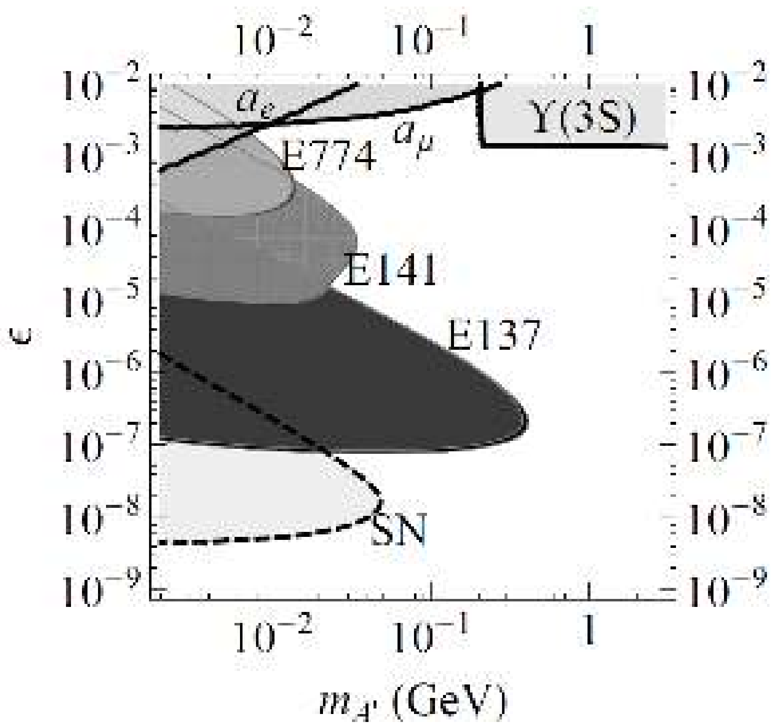


- The beam energy and distance between production point and detector determines sensitive region of the new particles.



Energy v.s. distance to detector



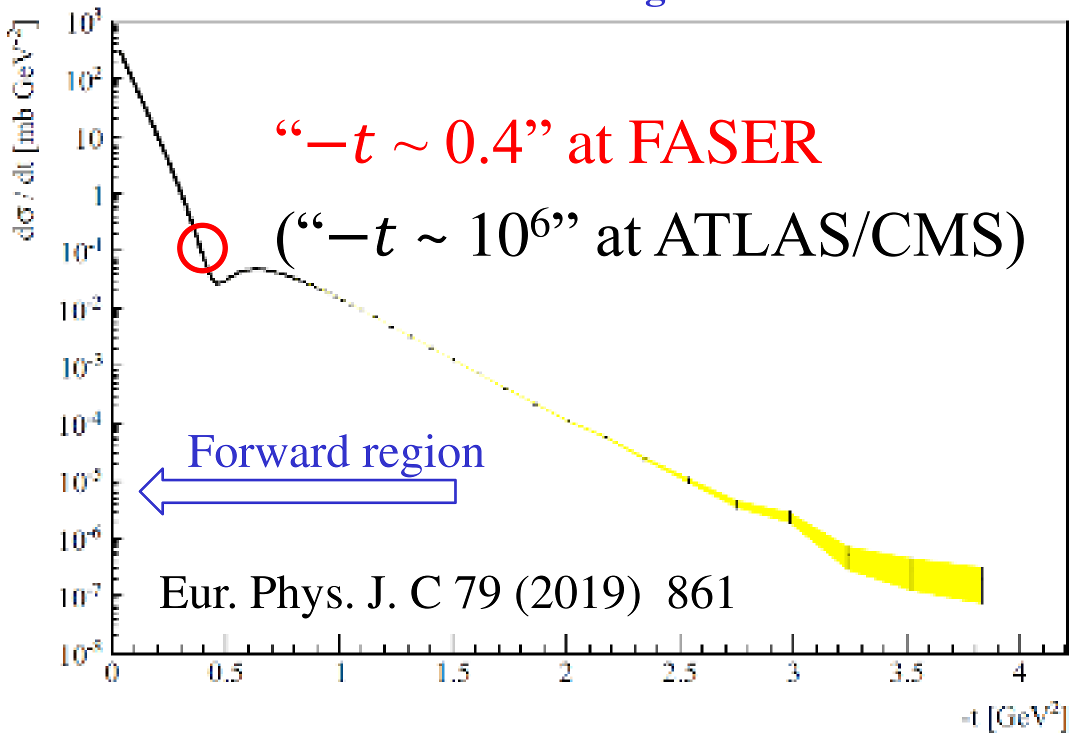


Benefit to use forward events

The cross-section of the inelastic scattering increases exponentially at the forward region (Bjorken scaling).

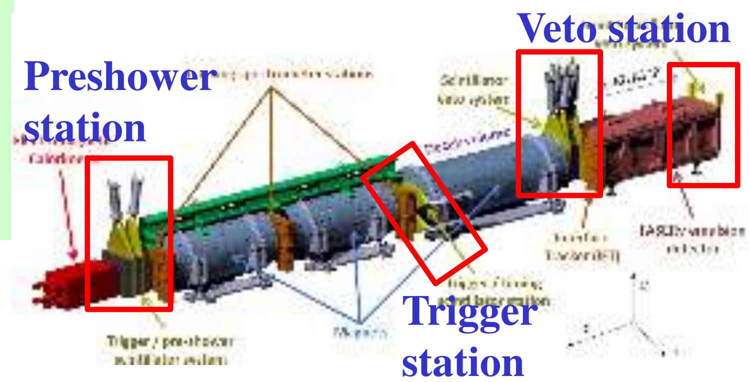
FASER placed at the forward region has high sensitivity to new particles even though the detector is compact.

Cross-section of inelastic scattering with 13 TeV at LHC



$$-t = p^2\,\theta^{*2}$$

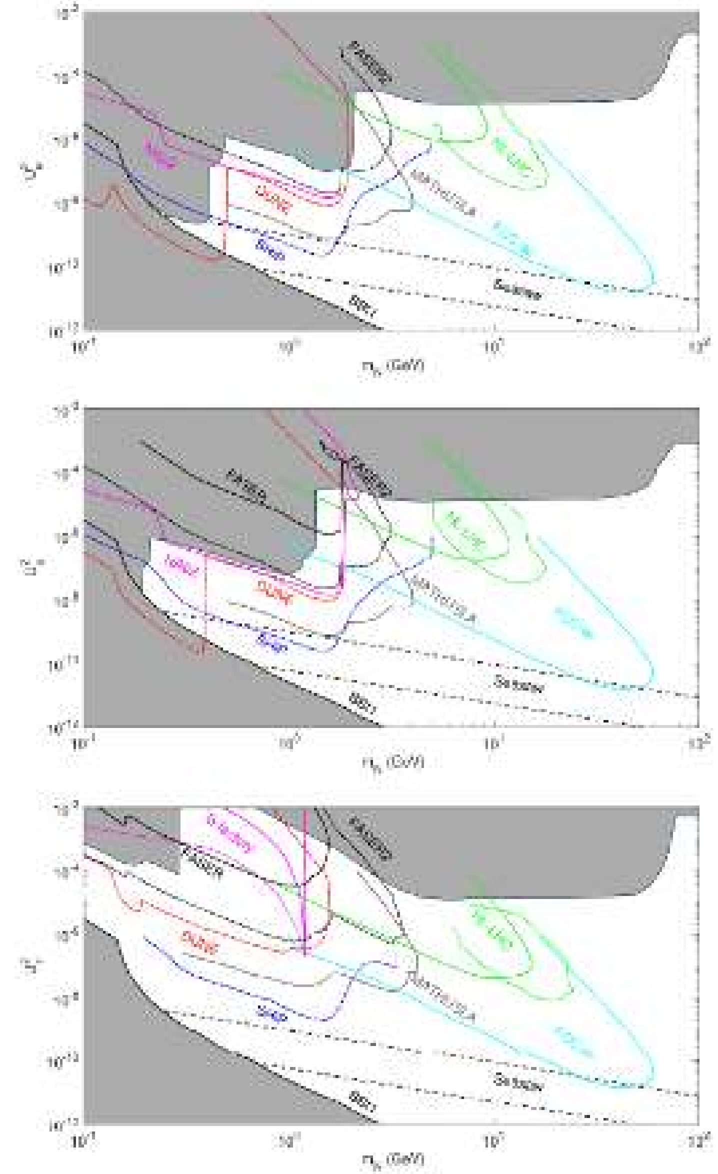
Scintillator performance



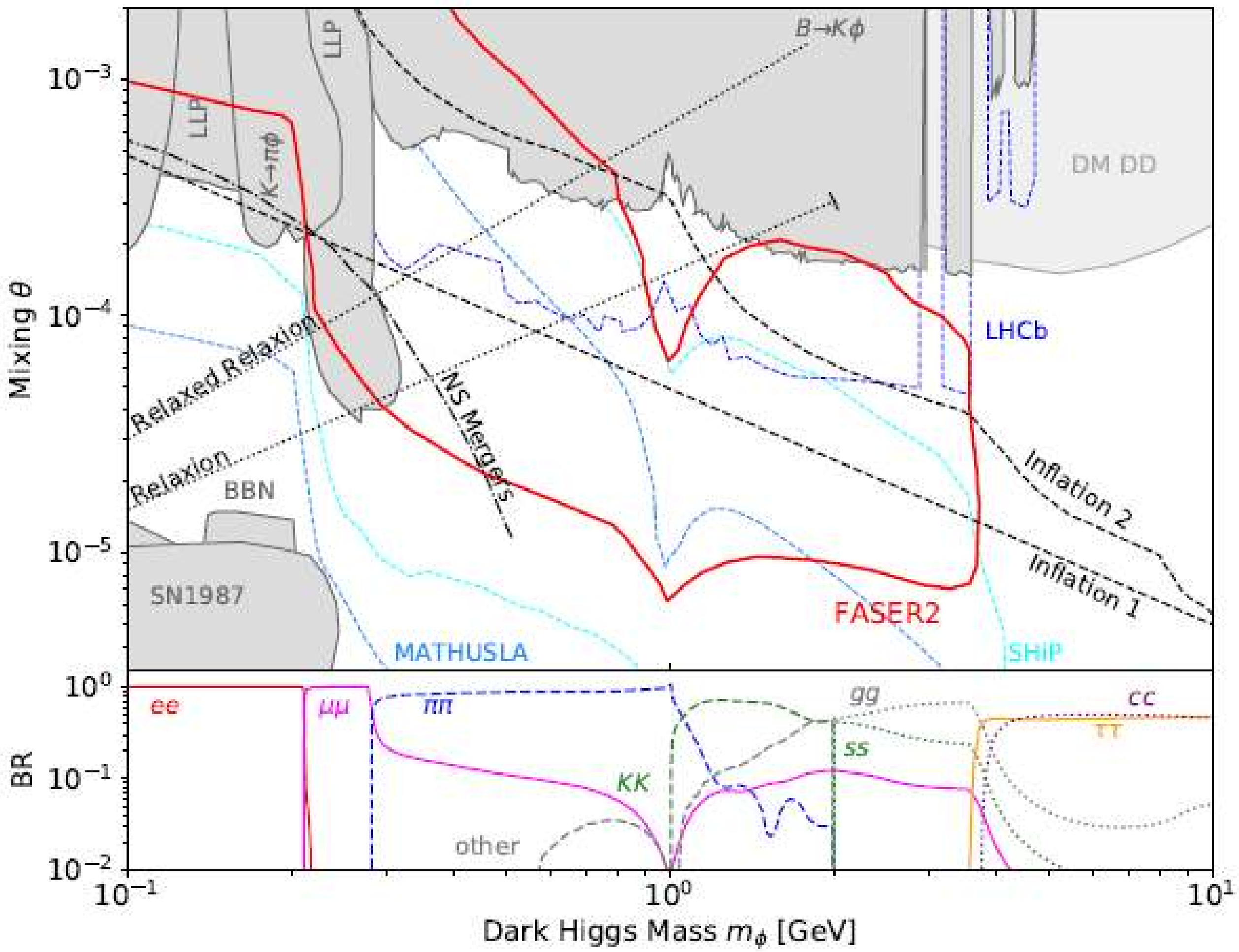
Veto efficiency of >99.99% is achieved.

Station	Module	Gain ($\times 10^6$)	MIP signal: Efficiency	MIP signal: Most probable signal
Veto station 1	1	4.85 ± 0.07	$> 99.99\%$	205 p.e.
	2	4.10 ± 0.17	$> 99.95\%$	200 p.e.
Veto station 2	1	2.69 ± 0.02	$> 99.985\%$	285 p.e.
	2	3.30 ± 0.04	$> 99.995\%$	380 p.e.
	3	4.19 ± 0.07	$> 99.996\%$	360 p.e.
	4	4.27 ± 0.08	$> 99.991\%$	305 p.e.
Timing station	1, PMT 1	1.44 ± 0.03	$> 99.7\%$	85 p.e.
	1, PMT 2	1.74 ± 0.03	$> 99.8\%$	135 p.e.
	2, PMT 1	2.20 ± 0.04	$> 99.8\%$	135 p.e.
	2, PMT 2	2.48 ± 0.05	$> 99.8\%$	115 p.e.
Preshower	1	3.96 ± 0.04	$> 99.96\%$	330 p.e.
	2	4.73 ± 0.05	$> 99.97\%$	370 p.e.

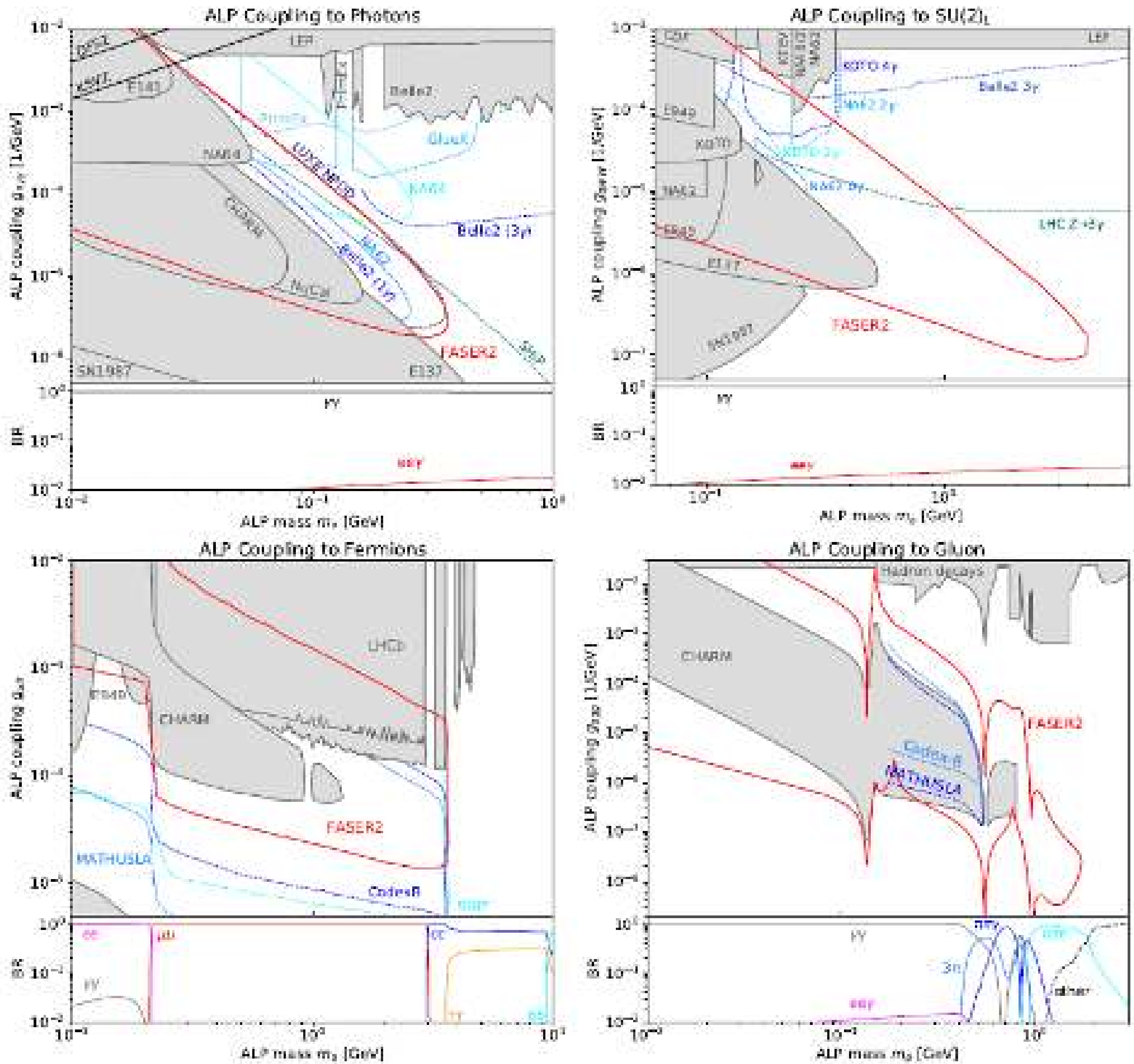
Sensitivity to sterile neutrino @FPF



Sensitivity to dark Higgs @FPF



Sensitivity to ALP @FPF



FASER collaboration

FASER collaboration consists of 9 countries, 22 institutes and 75 members, that is getting bigger.

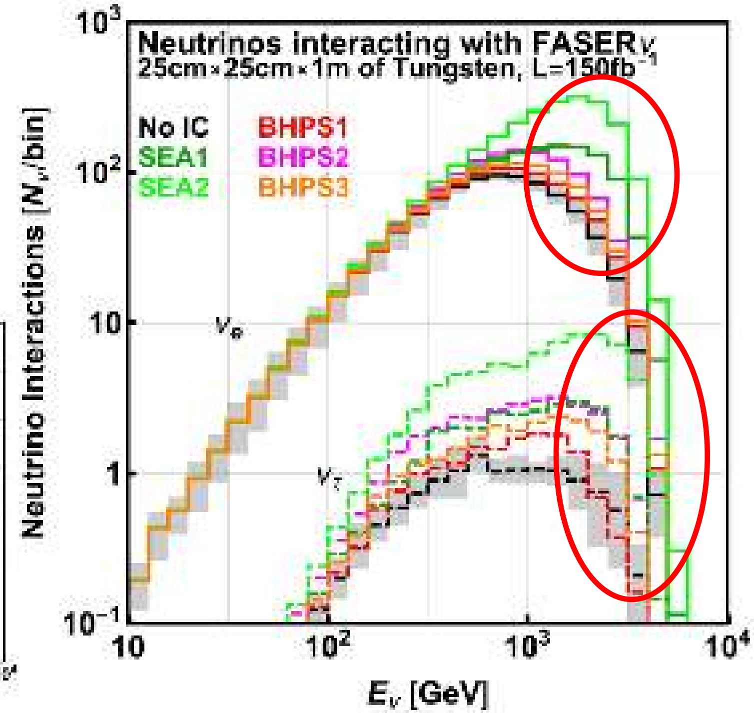
CERN
UNIVERSITÉ DE GENÈVE
KYUSHU UNIVERSITY
UC IRVINE
u^b UNIVERSITÄT BERN
Technion Israel Institute of Technology
NAGOYA UNIVERSITY
UNIVERSITY of WASHINGTON
JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U
מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE
KEK
UNIVERSITY OF OREGON
UNIVERSITÄT BONN
INFN
清華大学 Tsinghua University
MANCHESTER 1824 The University of Manchester
ROYAL HOLLOWAY UNIVERSITY OF LONDON
UNIVERSITY OF LIVERPOOL
CHIBA UNIVERSITY
US UNIVERSITY OF SUSSEX
DESY.
JINR

FASERν

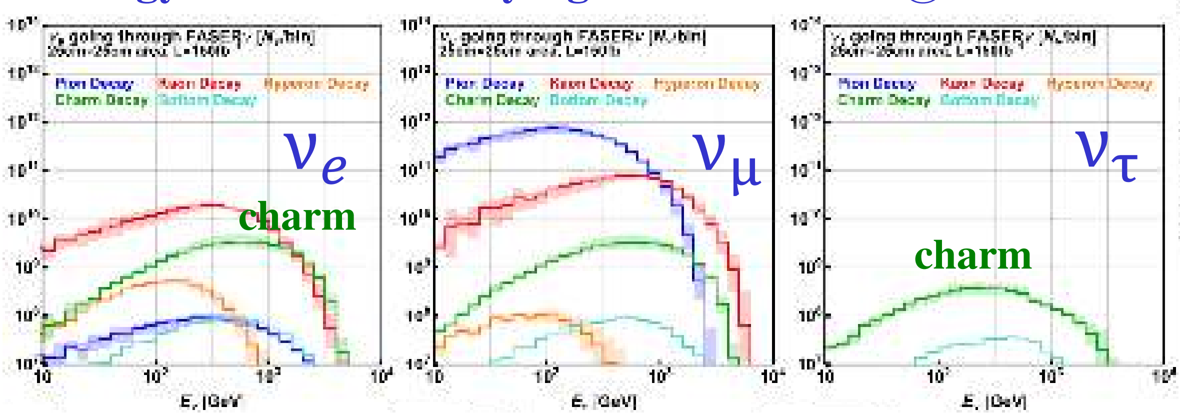
Charm quark density in proton (2)

- ν_e/ν_τ is created mainly from charm decays at high energy.
  - ν_μ is produced from kaon decays.
- FASERν can constrain charm parton distribution function in proton, measuring energy distributions of ν_e/ν_τ.

Expected energy distributions of ν_e/ν_τ @FASERν

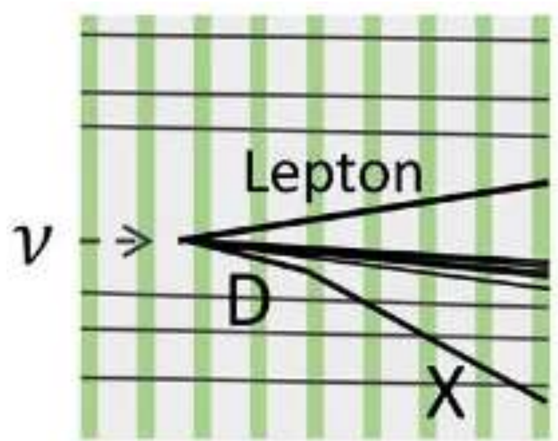


Energy of mesons decaying into neutrinos @FASERν

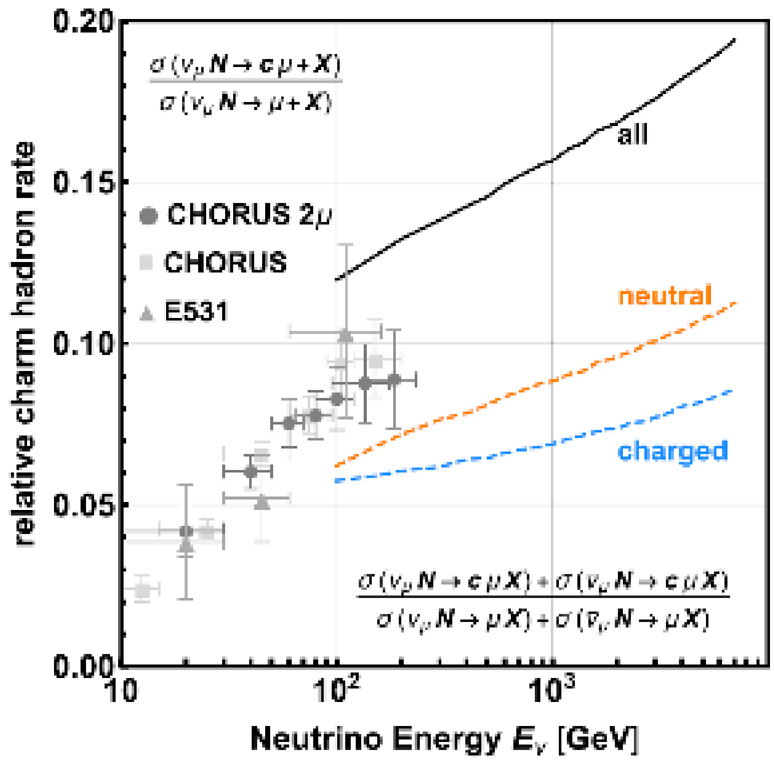


Cham-associated neutrino events

- FASERν can measure neutrino interactions associated with D-mesons in the final states.
- 10-20% of neutrino interaction at FASERν is accompanied with D-mesons.
- The emulsion detector can identify D-mesons, measuring tracks and their decay products.



Fraction of neutrino events associated with D-meson @FASERν



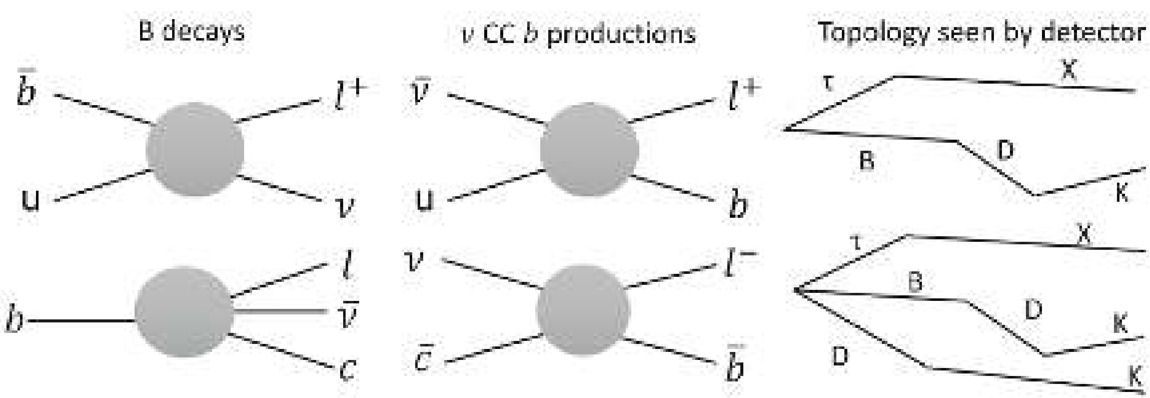
Beauty-associated neutrino events (1)

- Results in measurements in of B→D*ℓν, B→K*ℓℓ and B^+→K^+ℓℓ suggest lepton universality violation.

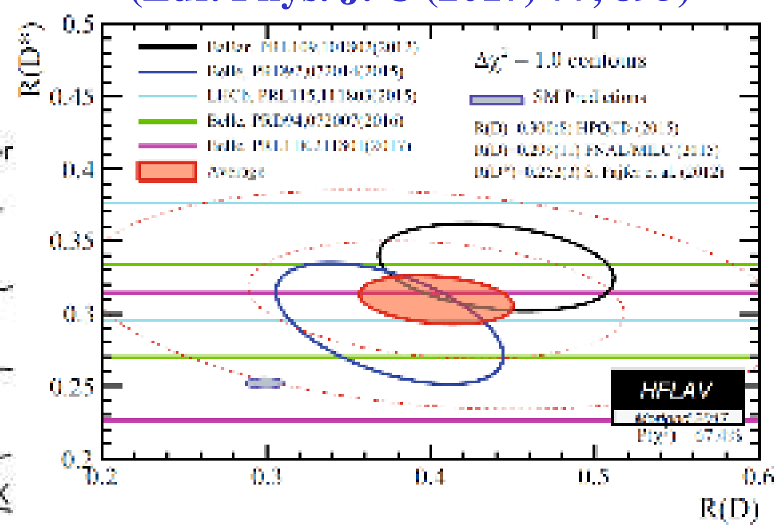
- The neutrino interactions in FASERν are the same as them, exchanging the internal/external lines in Feynman diagrams.

$$\mathcal{R}(D) = \frac{\mathcal{B}(B \to D\tau\nu_\tau)}{\mathcal{B}(B \to D\ell\nu_\ell)},$$

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu_\ell)}$$



R(D) v.s. R(D*)
(Eur. Phys. J. C (2017) 77, 895)



Beauty-associated neutrino events (2)

- Since cross-section of these processes are suppressed by a factor of $O(V_{ub}{}^2) \sim 10^{-5}$, beauty-associated neutrino events cannot be observed at FASERν in Run3 in SM.
  - Expected number of the events: O(0.1)
- But, the observation means discovery of new physics.
- In addition, lepton universality violation in the third generation can be investigated with sensitivity to ν_τ.

Sterile neutrino oscillation (1)

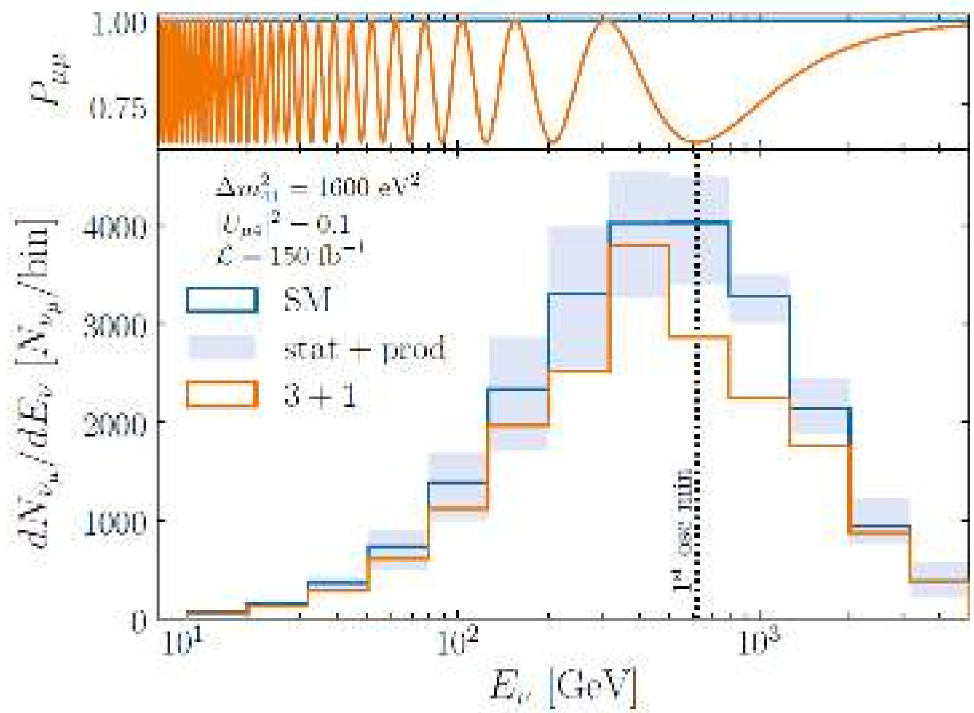
- SM excludes possibility of neutrino oscillation in FASER condition.
  - E_ν = 800 GeV, L = 480 m.

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)\sin^2\frac{\Delta m_{41}^2 L}{4E},$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{\alpha\beta}\sin^2\frac{\Delta m_{41}^2 L}{4E}.$$

- Observation of neutrino appearance/disappearance indicates existence of sterile neutrinos.

Neutrino energy distribution @FASERν



Sterile neutrino oscillation (2)

- Sensitivity to sterile neutrino oscillation was evaluated, assuming energy resolution of 45%.
- For ν_e, FASERν has sensitivity to 2.7σ discovery region with Gallium detector [arXiv:1006.3244].