FASER/FASERν at LHC

December 15th, 2020

Yosuke Takubo (KEK)

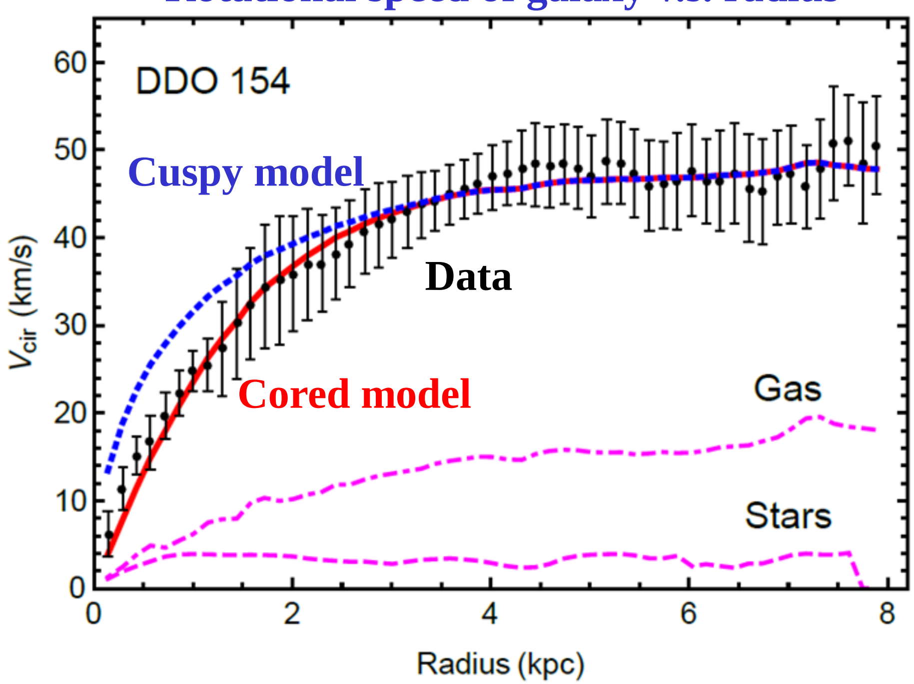
Physics motivation of FASER

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.

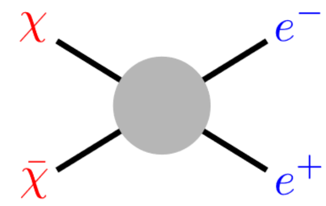
Here, WIMPless miracle is assumed as benchmark model.

Rotational speed of galaxy v.s. radius



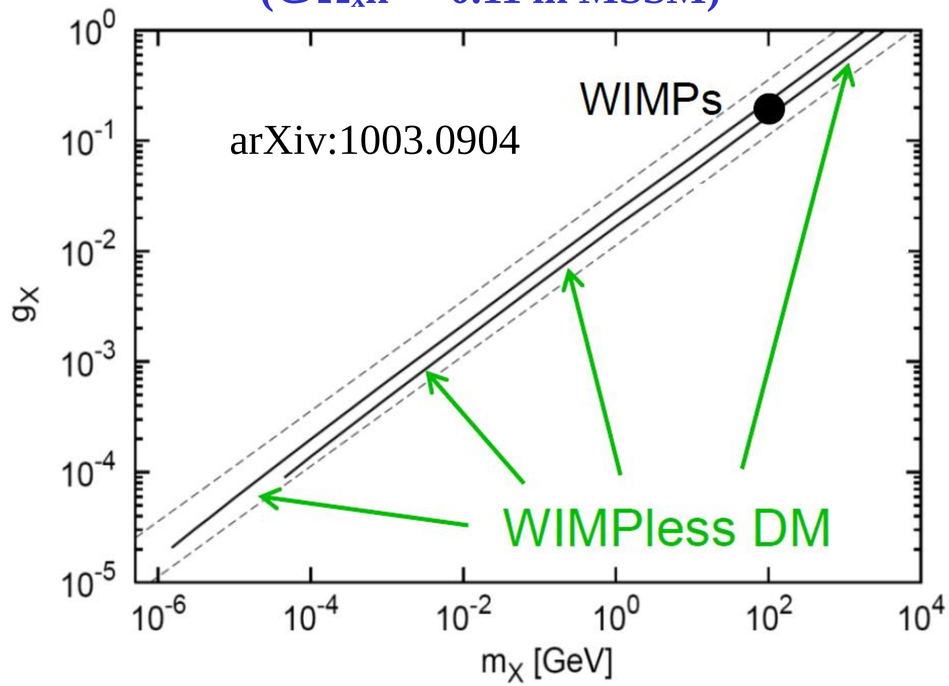
WIMPless miracle (1)

- 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:
  $(m_X, g_X) \sim (\mathrm{m_{weak}}, g_{\mathrm{weak}}) \sim (100\ \mathrm{GeV}, 0.65)$



- 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)).

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



WIMPless miracle

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

⇩

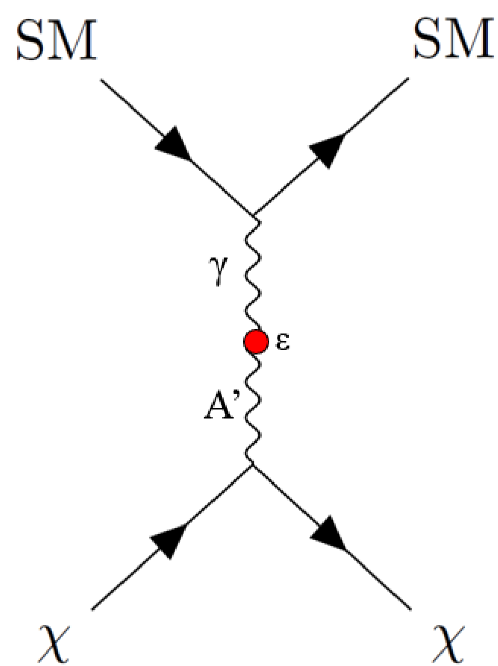
Small coupling with SM ($g_X \ll g_{\mathrm{weak}}$)

⇩

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).



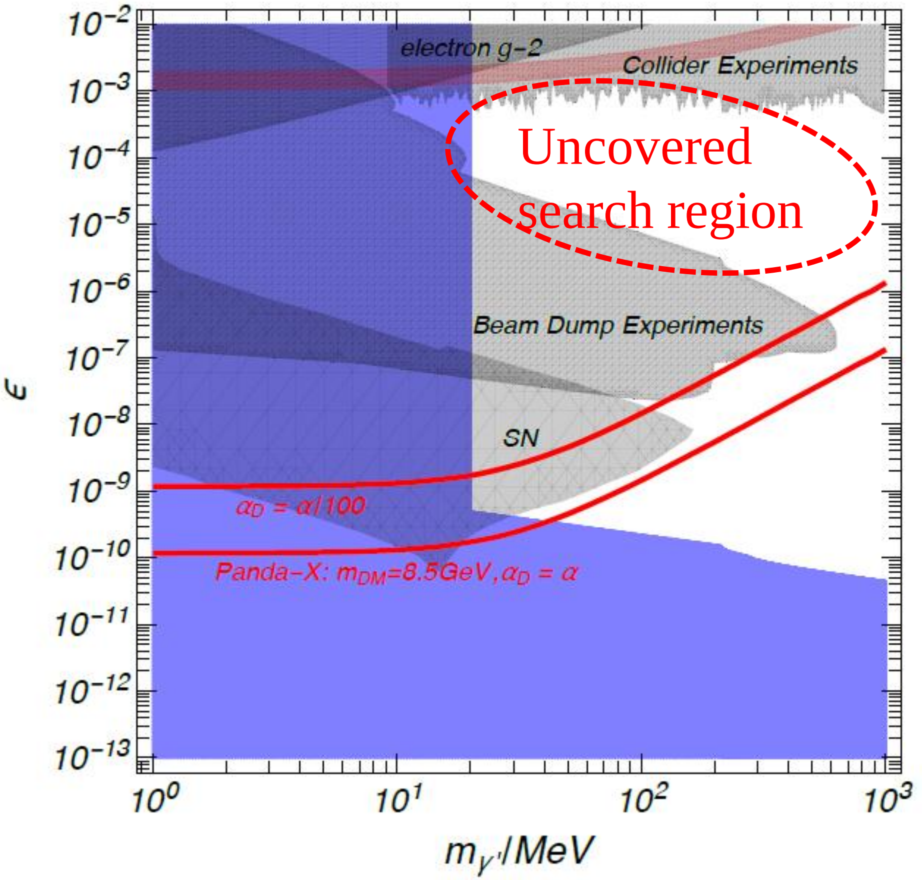
Current limit on dark photon

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.

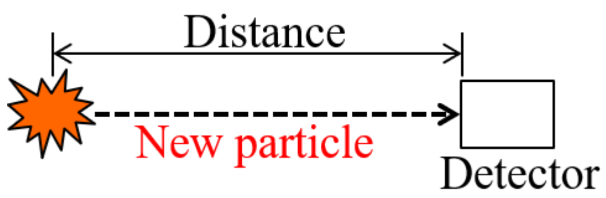
Search region is gap between the two excluded areas.

Limits on dark photon (arXiv:1805.06876)

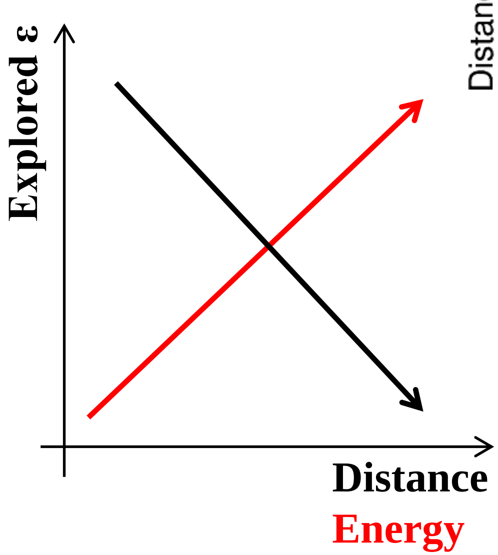


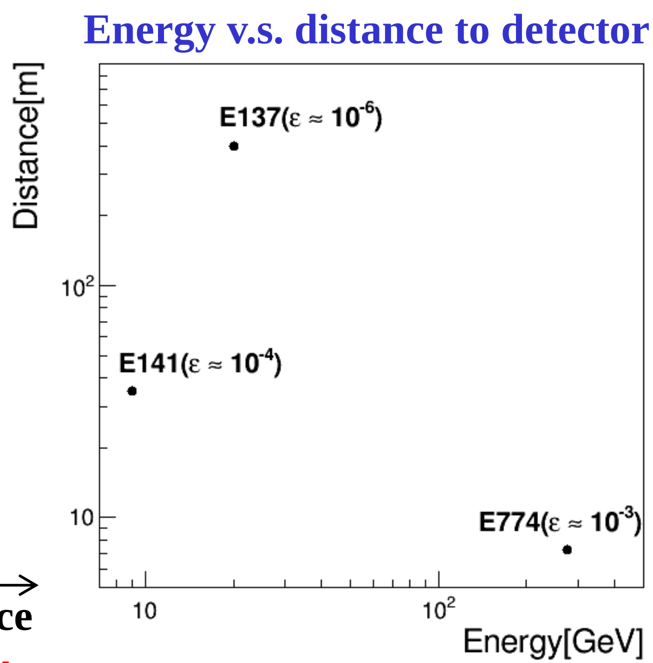
Sensitivity to small coupling region

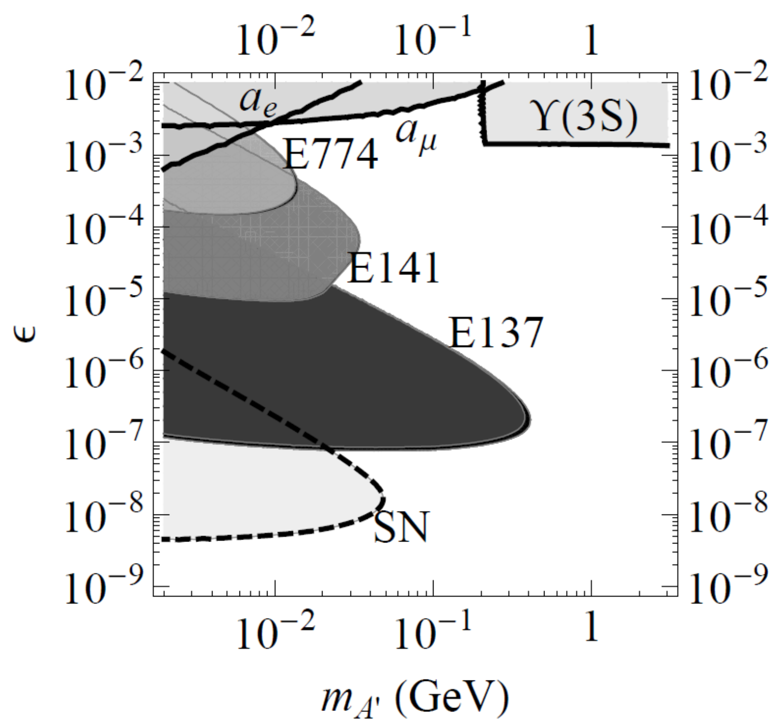
- Beam dump experiments provide limits on small coupling region (SLAC E137, SLAC E141, FLAB E774) [arXiv:0906.0580].



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



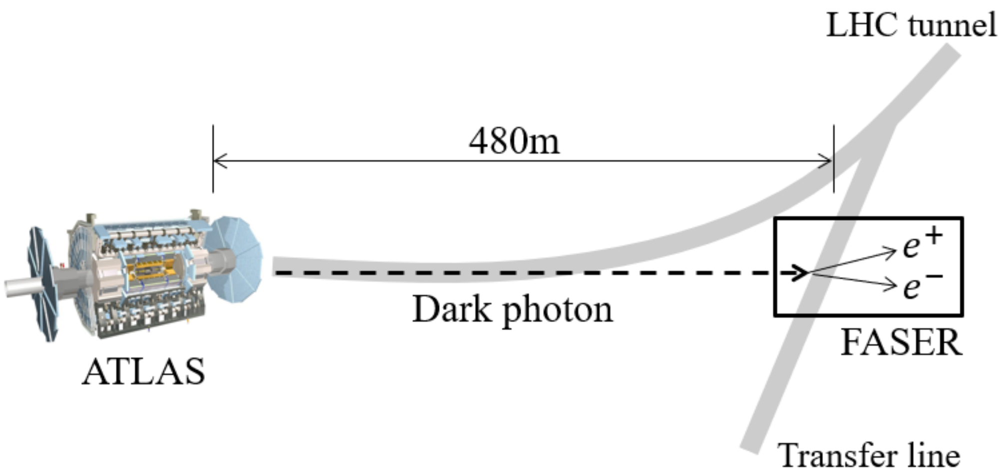


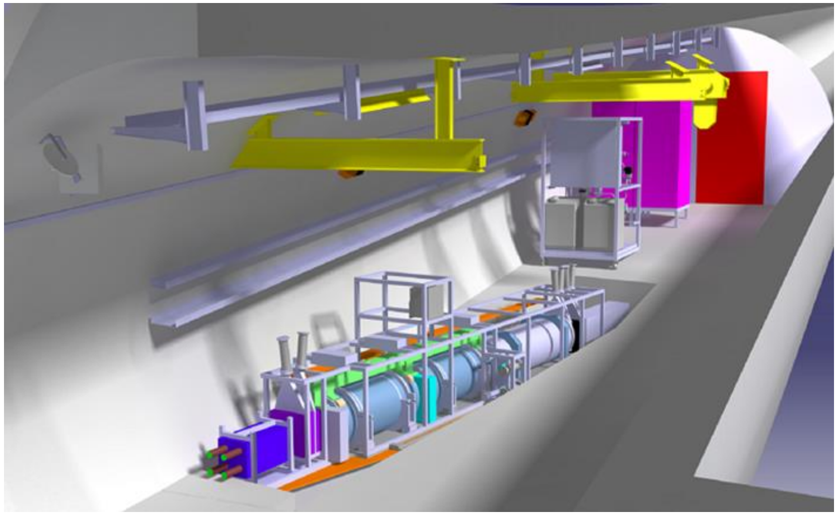


FASER

FASER overview

- FASER (ForwArd Search ExpeRiment at the LHC) is a new experiment to search for new long-lived particles, starting 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.
- The first experiment to search for new particles, utilizing large cross-section of pp interaction in the forward region at LHC.



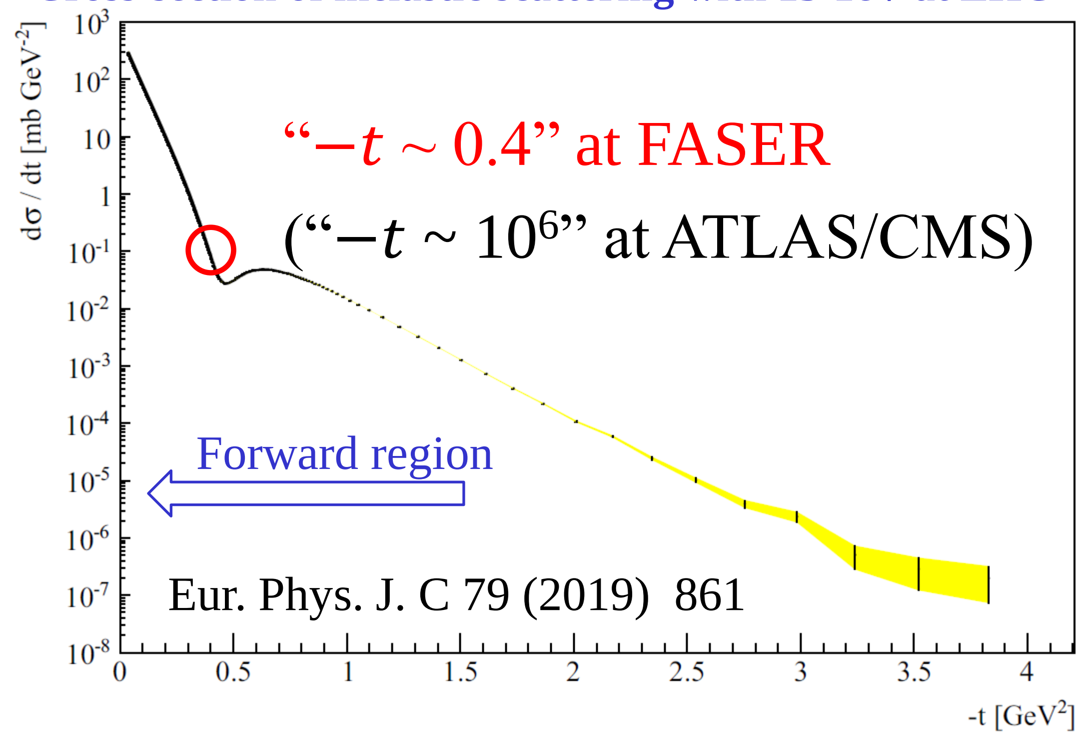


Benefit to use forward events

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.

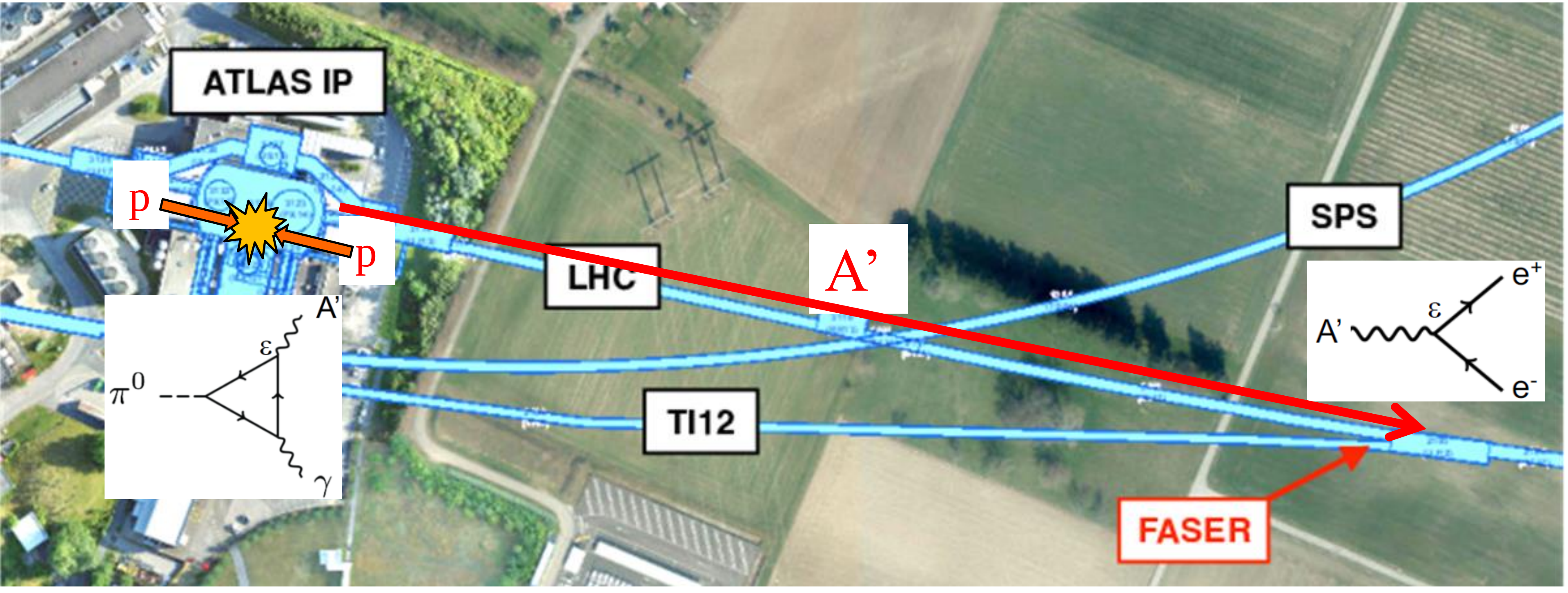
Cross-section of inelastic scattering with 13 TeV at LHC



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

Detection of long-lived particles (1)

- Let's consider to detect dark photons with ($m_{A'} = 100$ MeV, $\varepsilon = 10^{-5}$) at FASER
  - ε : mixing angle between A' and γ
- Large amount of π^0s are produced in pp collisions, and dark photons are generated from $\pi^0 \rightarrow A'\gamma$ process.



Detection of long-lived particles (2)

Calculate the signal yield in FASER acceptance:

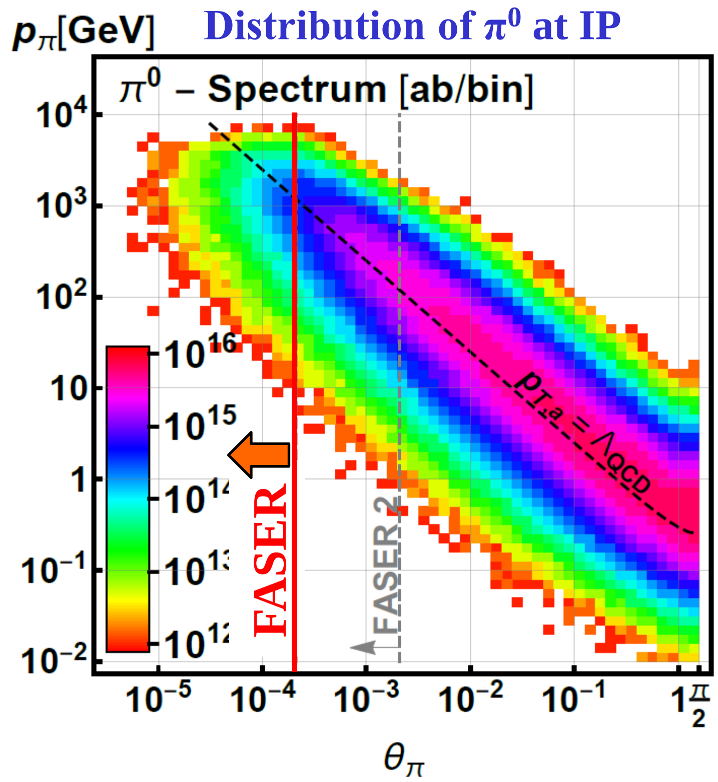
- Radius: 10 cm, length: 1.5 m

1. About 2.3×10^{17} π^0s will be produced with 150 fb^{-1} in LHC Run3.

2. 0.6% of π^0s are contained in the detector acceptance.

3. BR($\pi^0 \rightarrow A'\gamma$) : $\varepsilon^2 = 10^{-10}$

4. Detector acceptance for $A' \rightarrow e^- e^+$: ~10^{-3}



[2.3x10^{17}] x [0.6%] x [10^{-10}] x [10^{-3}]

~ 100 events can be detected at FASER!

FASER concepts

Low cost!

- Compact detector (radius: 10 cm, length: 5 m)
- The detectors developed for other experiments will be recycled as much as possible (tracker, calorimeter, DAQ system)
- Construction cost: <1 MCHF (~1 Oku yen)

Quick!

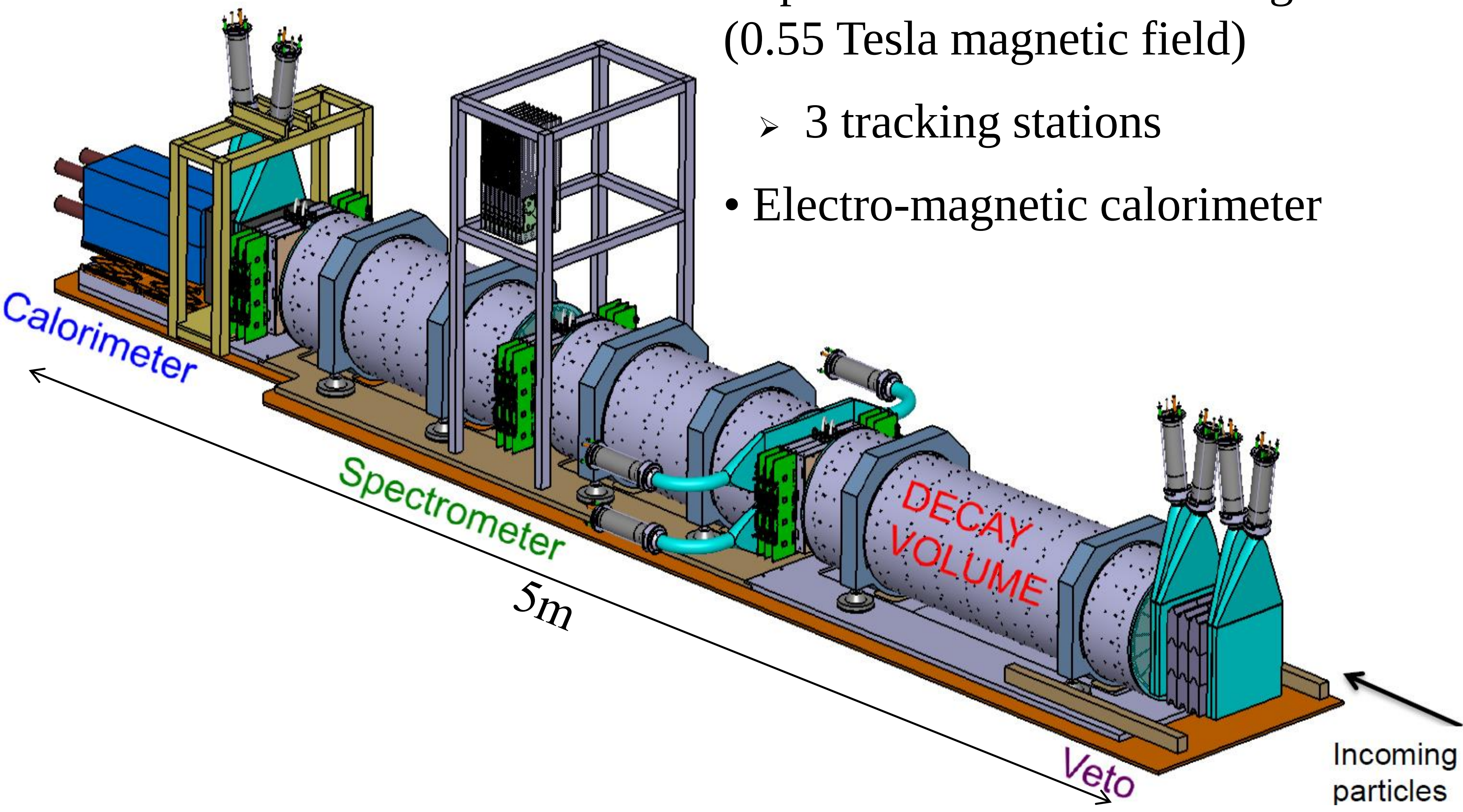
- Construct the detector in 2 years of LHC shutdown and start data-taking at the beginning of LHC Run3 (2022).
- It is big advantage to use detectors that are already used in other experiments and whose performance is already known.

Excellent physics sensitivity!

- FASER has sensitivity to large parameter space of new particles which is not explored yet.

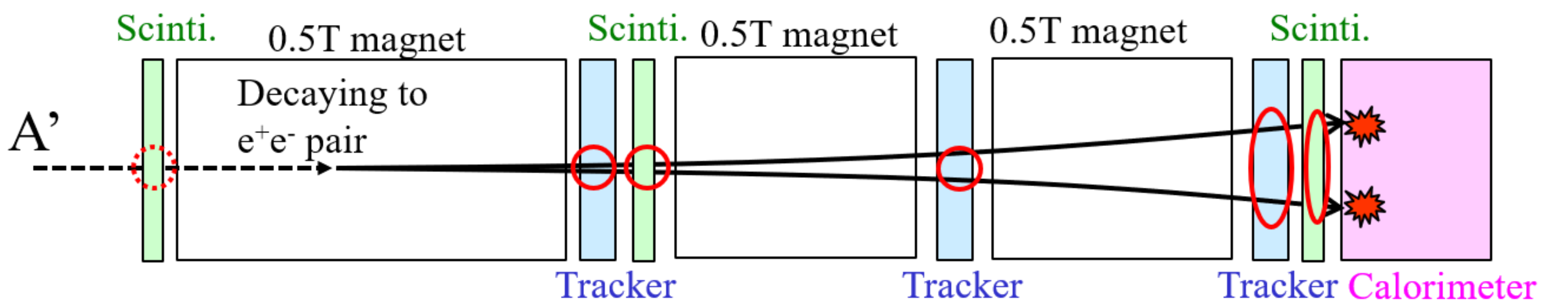
FASER detector

- Scintillator veto/trigger
- Decay volume with1.5 m length (0.55 Tesla magnetic field)
- Spectrometer with 2 m length (0.55 Tesla magnetic field)
  - 3 tracking stations
- Electro-magnetic calorimeter



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

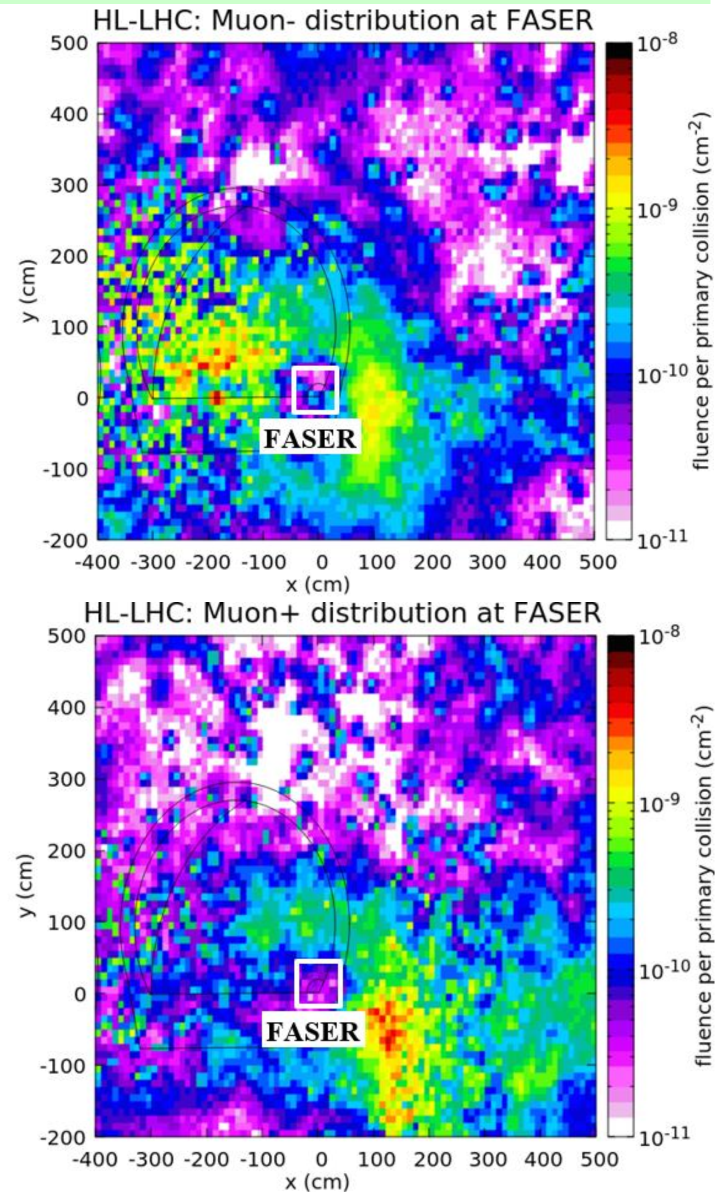
How FASER is miracle?

- 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

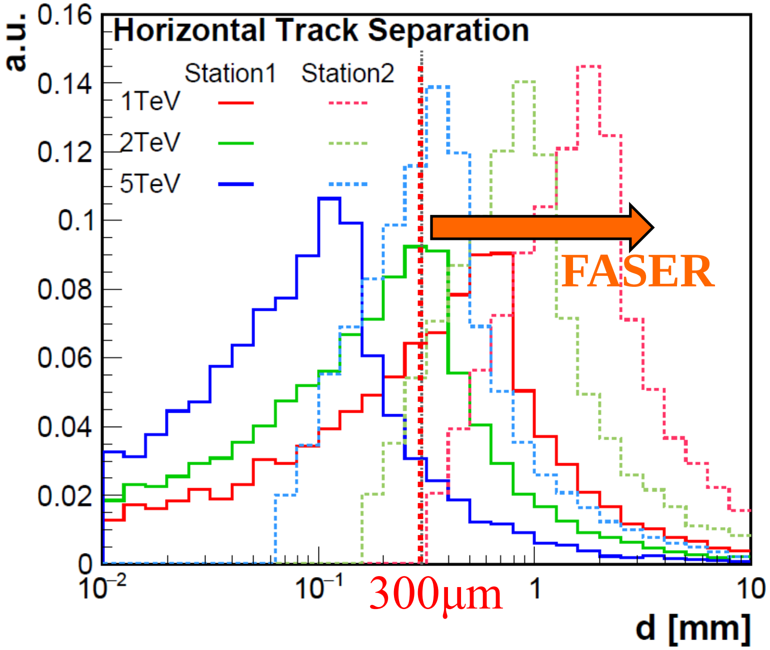


Requirement to spectrometer

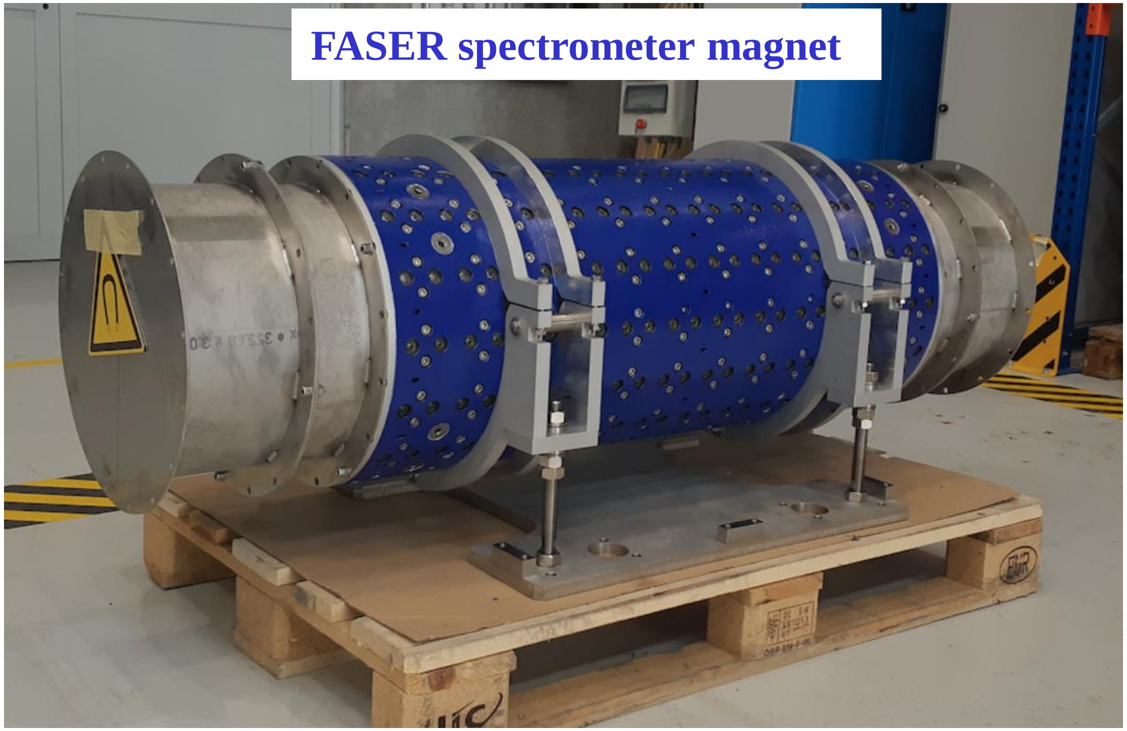
- 0.55 T permanent magnet is used to separate electron-positron tracks.
- The spectrometer is required to have capability to separate electron-positron tracks with 300 μm distance ($m_{A'}$ = 100 MeV)

➡ Silicon strip detector is used for the tracker.

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

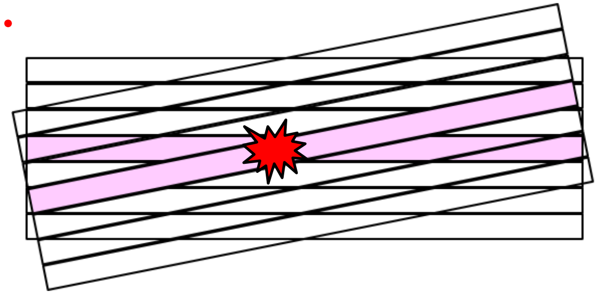


FASER spectrometer magnet



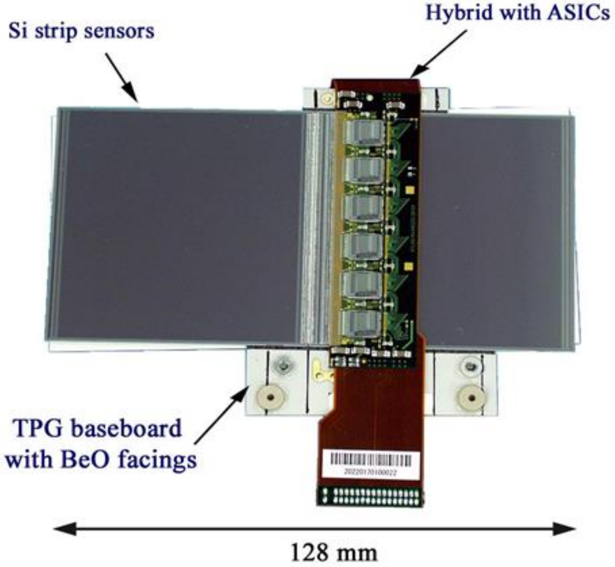
FASER tracker (Introduction)

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

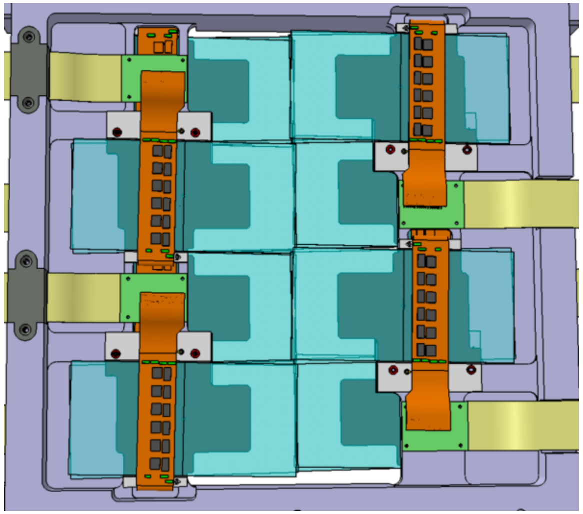


- The tracker consists of 9 SCT layers (3 station)
  - 1 layer with 8 SCT modules, 1 station with 3 layers

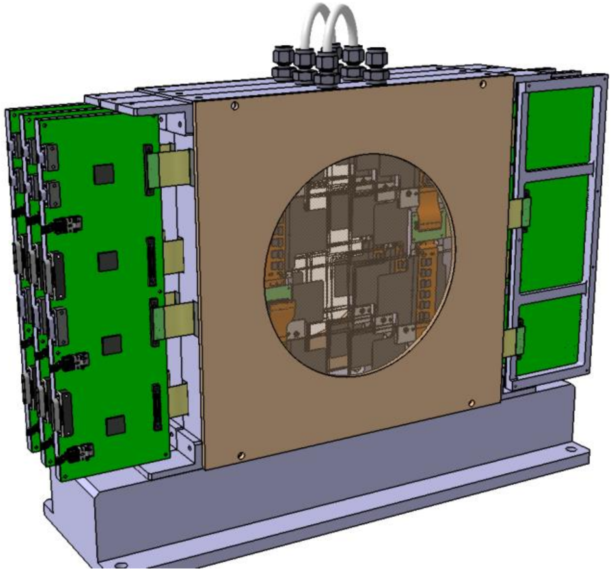
ATLAS SCT barrel module



Tracker layer

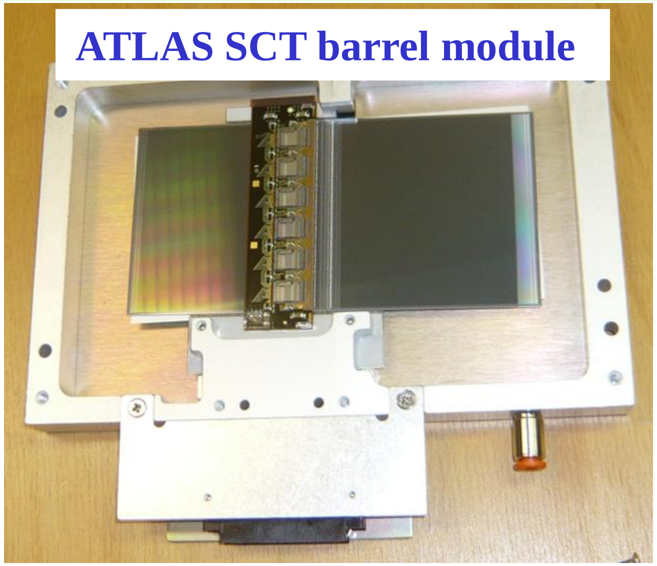


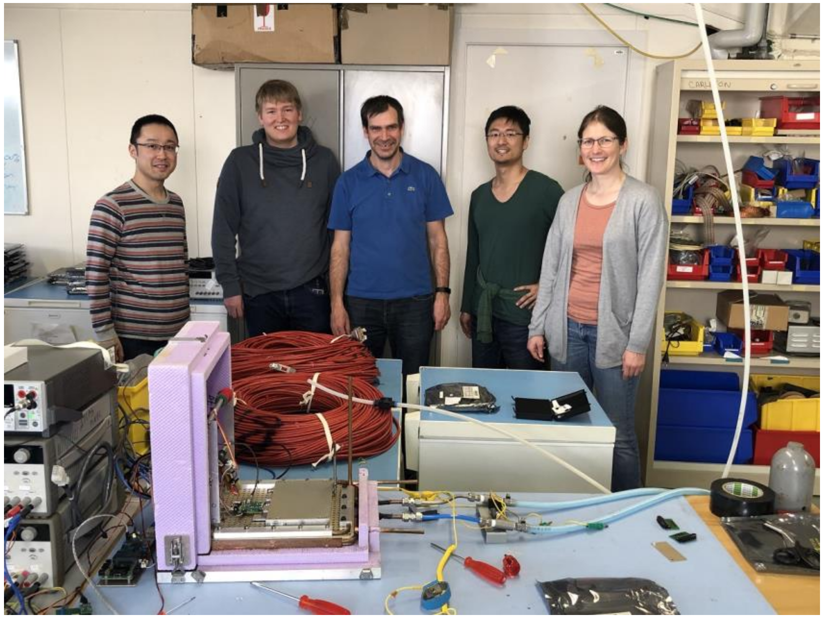
Tracker station



FASER tracker (module selection)

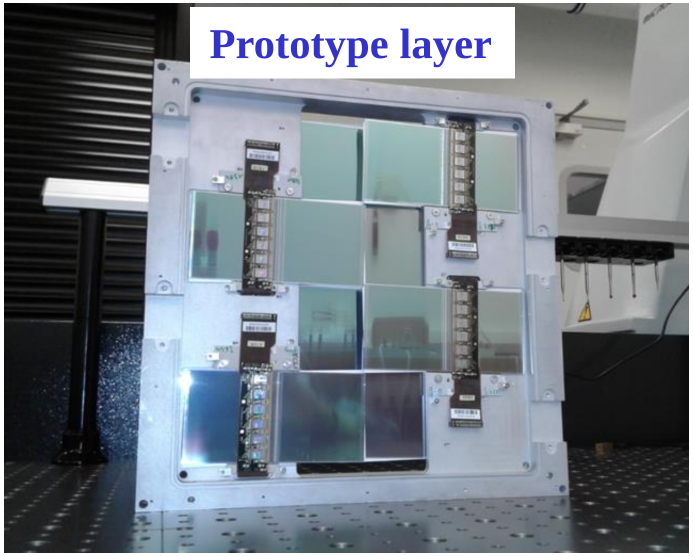
- There were ~200 spares of ATLAS SCT barrel module that spent 20 years since the production.
- 80 modules with the best quality needs to be selected for FASER tracker.
- The quality assurance test was performed with DAQ system developed at Cambridge university.
  - No degradation was observed in the module performance.
- The module selection was finished until the spring of 2019.

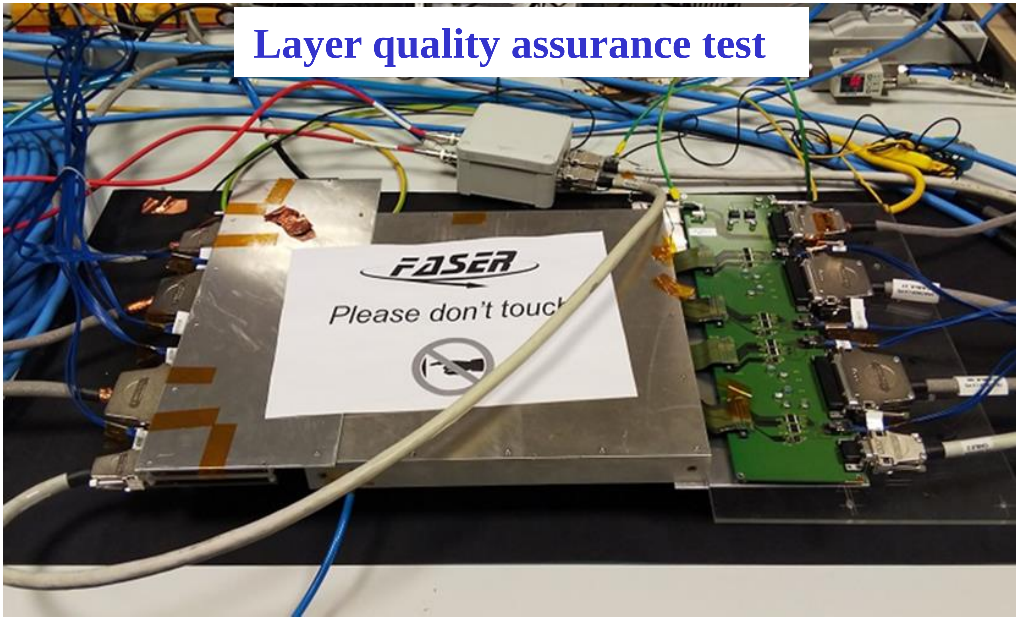


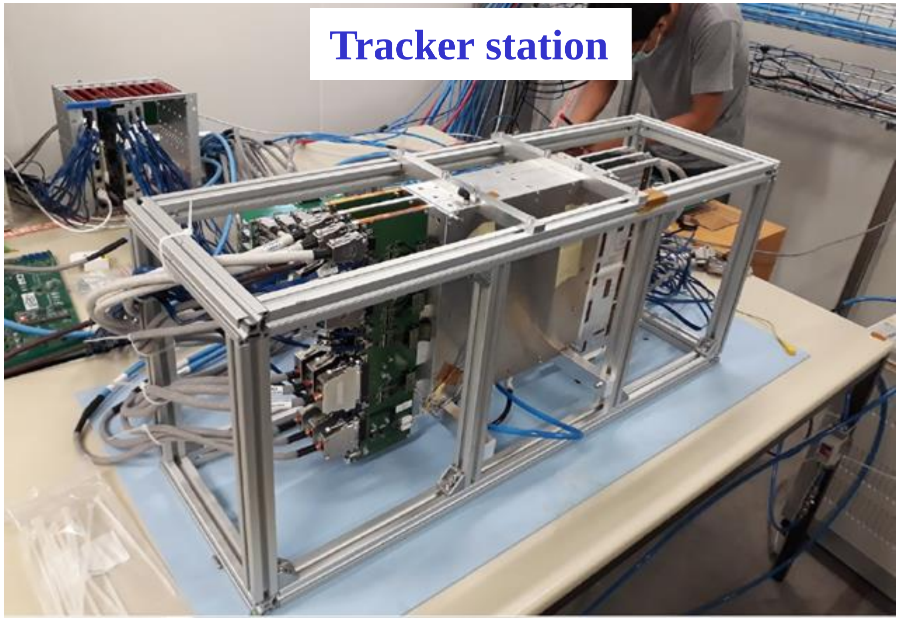


FASER tracker (layer construction)

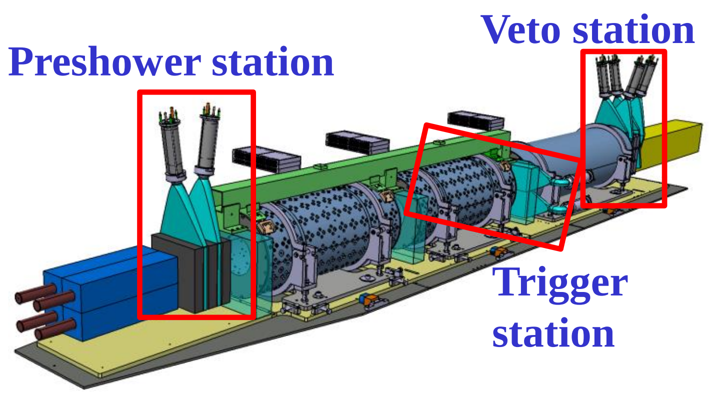
- The frame design was optimized, developing the prototype layer.
- The production of the layer started in July 2020.
- All 9 layers were produced until November 2020 (3 stations).







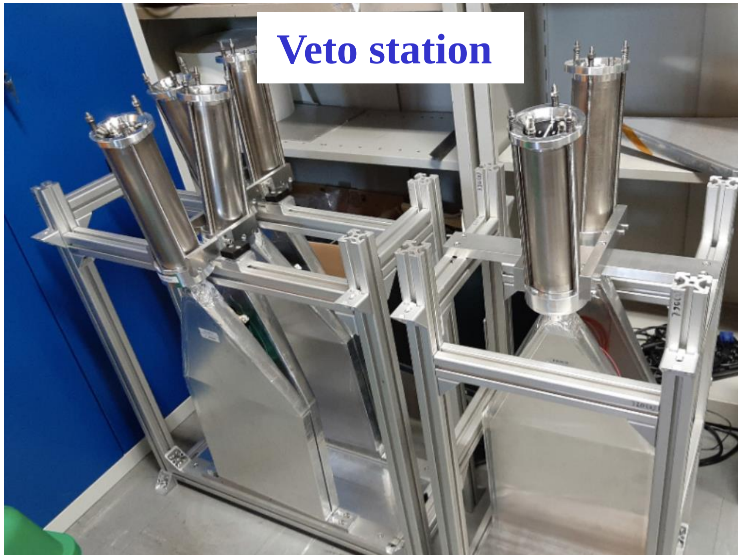
Scintillator



The scintillator detector consists of 3 stations.

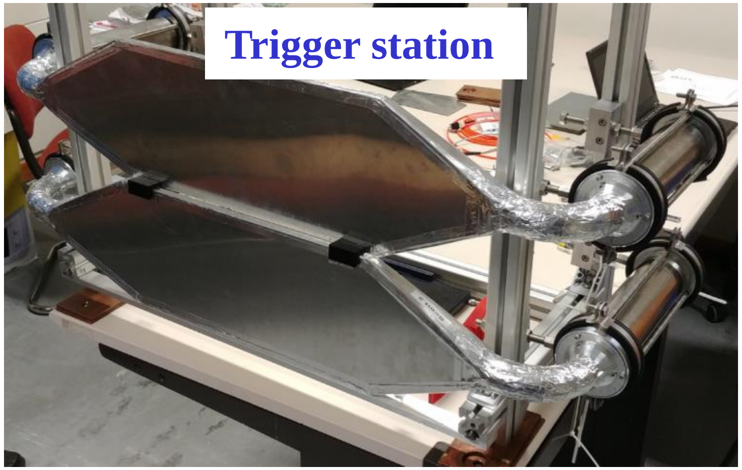
Veto station

Reject charge particles and γ's converted in Pb layer.



Trigger station

Publish triggers to take charged particles created in FASER decay volume.



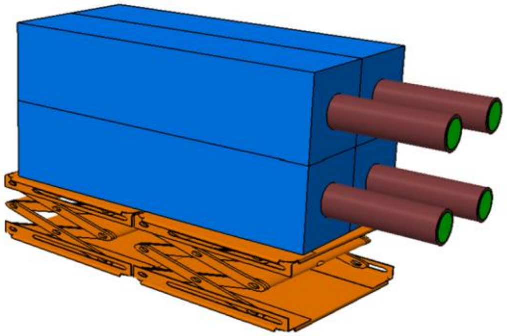
Preshower station

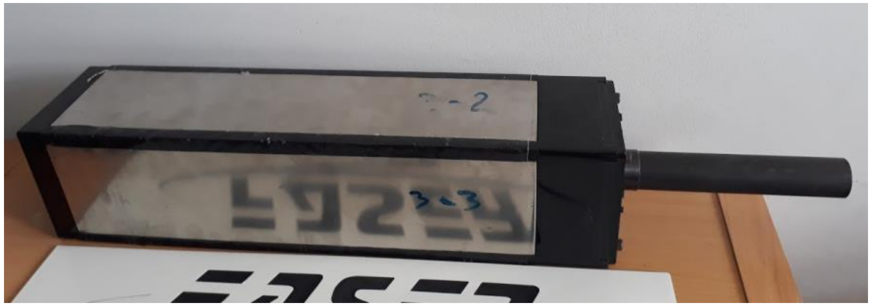
Creates γ shower in Pb layer to identify neutrino events in the calorimeter.

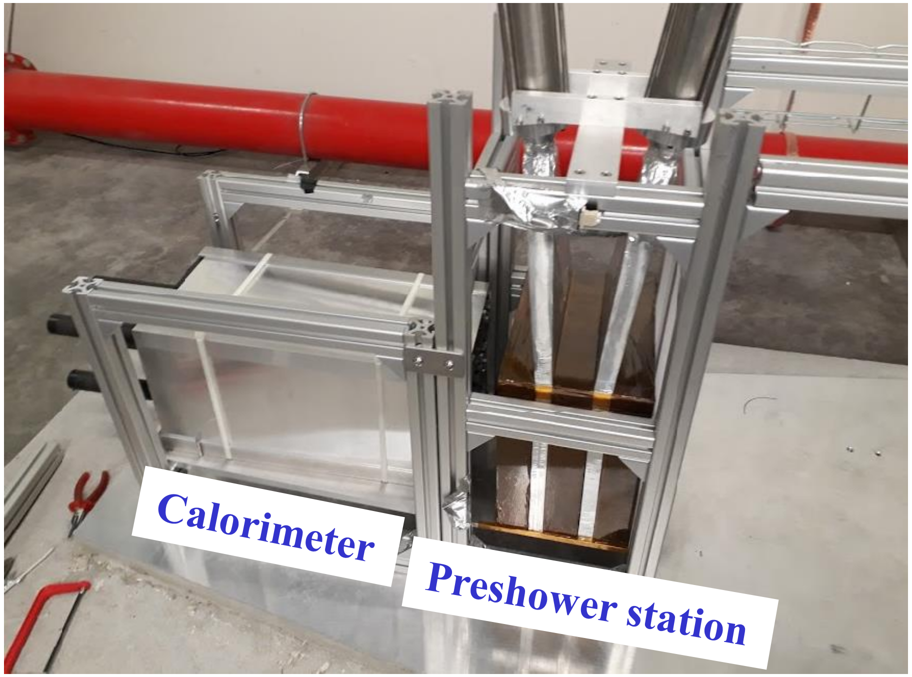
All scintillators were produced.

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.

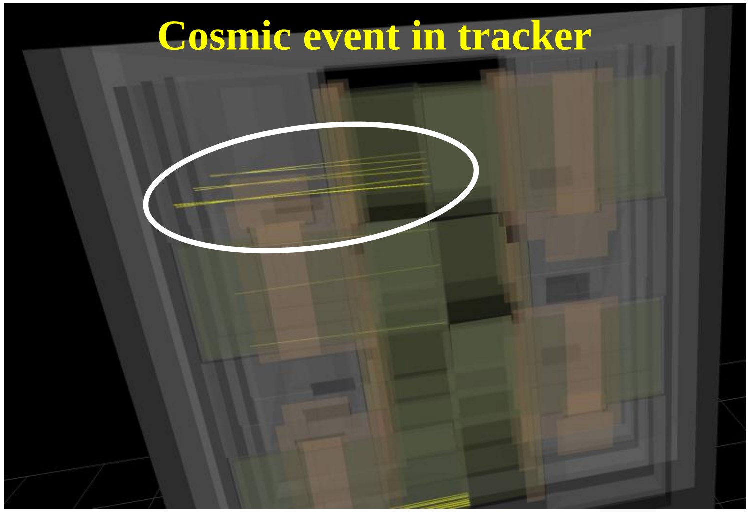


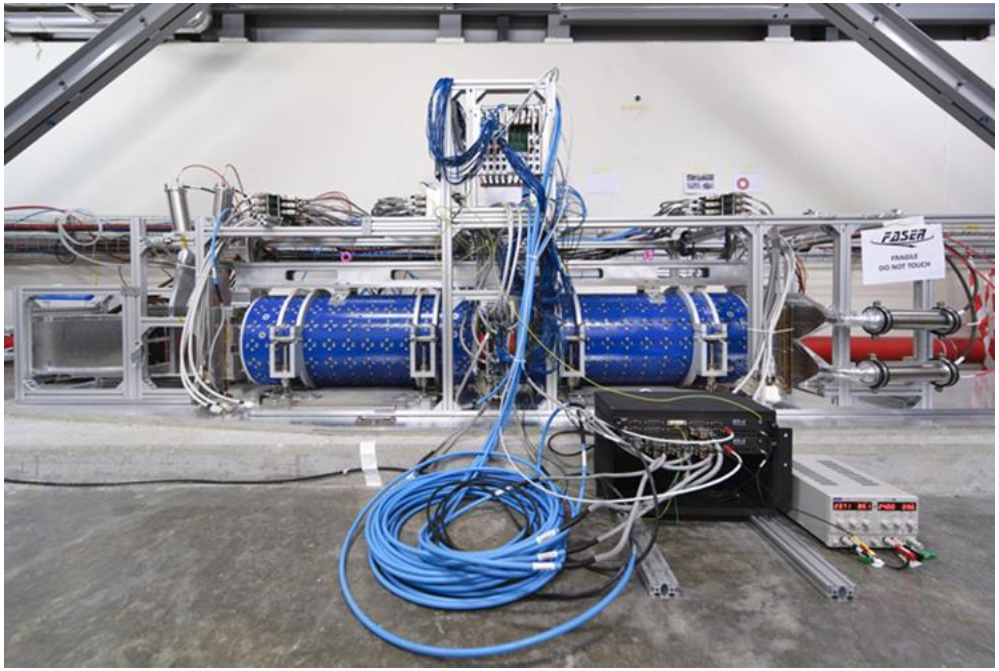


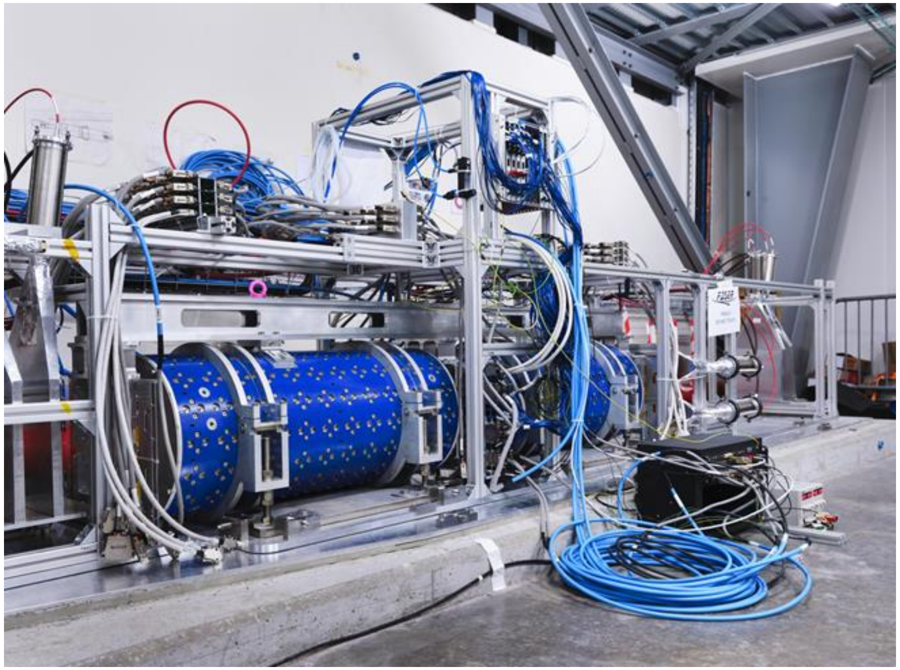


Commissioning on ground

- Before installing the detector, the commissioning was performed on ground.
- All detector elements were placed in the final configuration, and readout test was performed including cosmic data-taking.

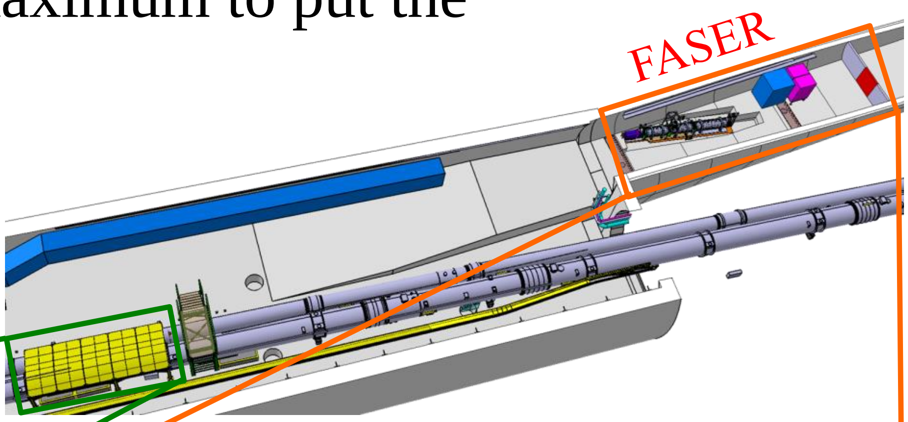






Civil engineering

- 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

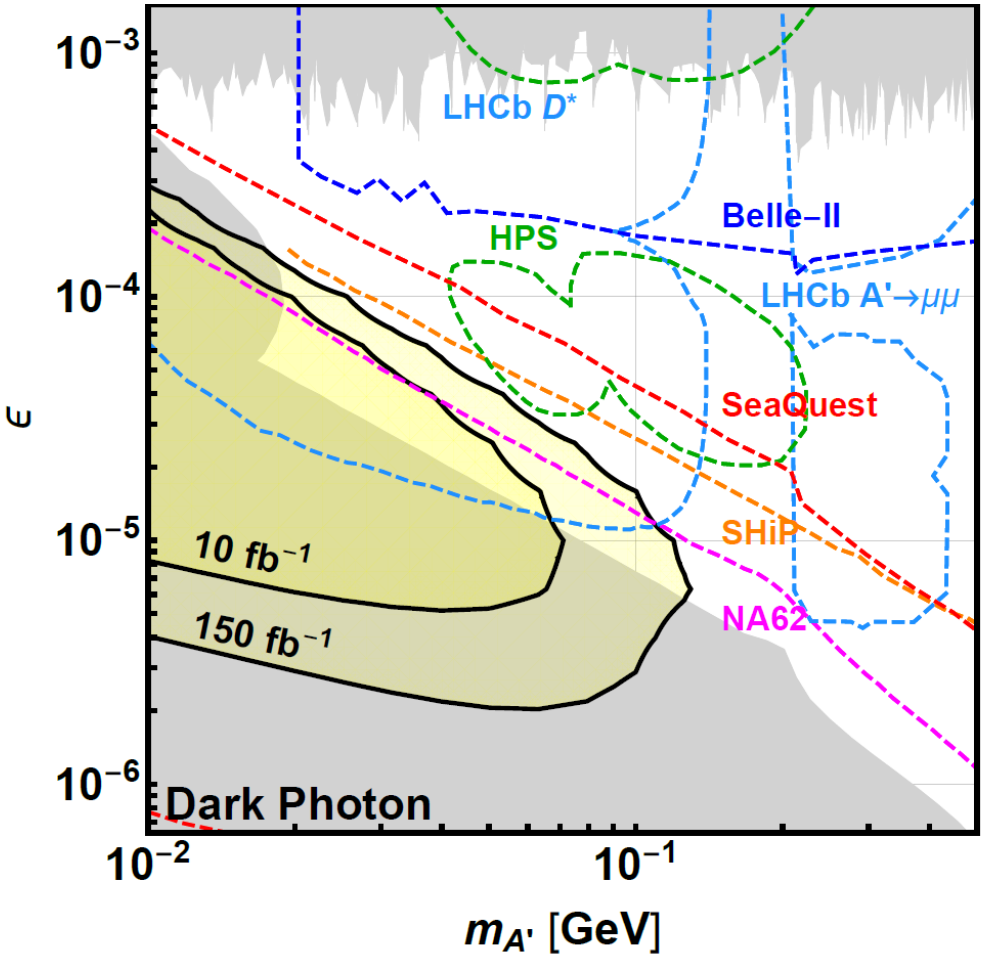
- Experimental components already installed: cooling unite, crates, cables, magnets and trigger scintillator station
- The alignment of the magnets was finished with 0.2 mm precision.
- The tracker will be installed in January 2021.

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 (~20 fb^{-1}).
- LHCb and Belle II are sensitive to the strong coupling region.

→ Most of search region for $m_{A'}$ bellow 1 GeV can be explored in combination with FASER, LHCb and Belle II.

Expected sensitivity to dark photon



Current status of new particle search

Several experiments are proposed to explore the same search region as FASER.

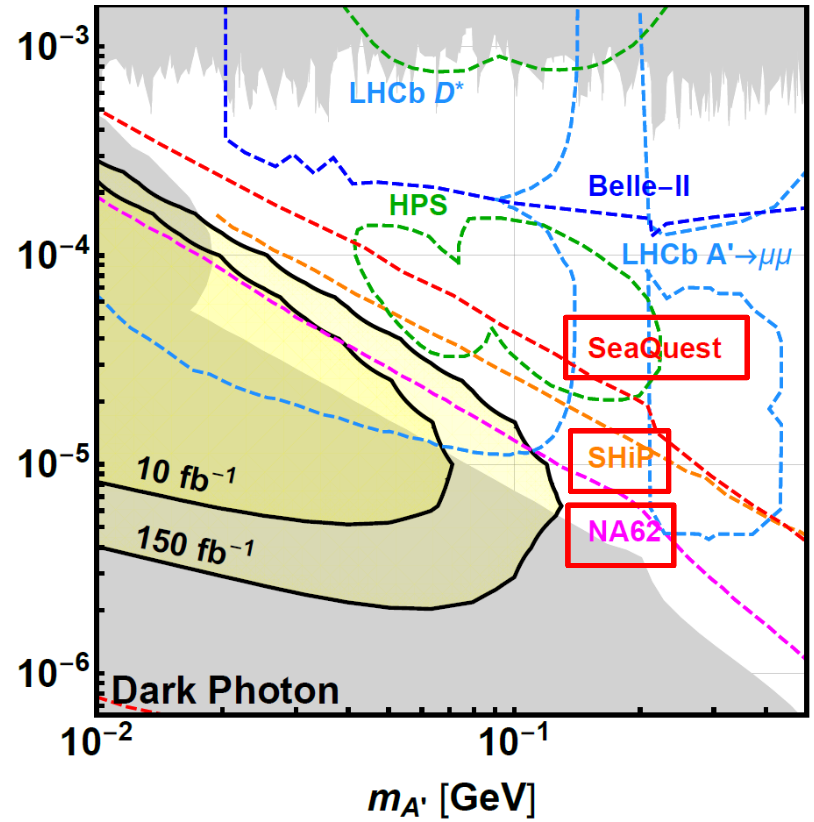
SHiP

- Beam dump experiment using proton beam at CERN-SPS
- Strong magnetic field and large beam dump are necessary.

NA62/SeaQuest

- On-going experiment for other physics target (Kaon/Nuclear experiment)
- Detector upgrade is necessary.

Expected sensitivity to dark photon



Any experiments are not approved and funded yet.

→ FASER is only secure experiment to take place.

FASER history and future plan

- LOI (Letter Of Intent) was submitted to LHC Committee (arXiv:1811.10243) in August 2018.
- TP (Technical Proposal) was submitted to LHC Committee (arXiv:1812:09139) in November 2018.
- The project was approved by CERN in March 2019.
- Cost for the detector construction and operation was offered by Simons foundation and Heising-Simons foundation.
- The detector installation at FASER site will finish in January 2021.
- The commissioning will be performed during 2021.
- The physics data-taking will start from the beginning of LHC Run3 (2022).

FASER collaboration

FASER collaboration consists of 8 countries, 18 institutes and 65 members, that is getting bigger.

CERN

UNIVERSITÉ DE GENÈVE

KYUSHU UNIVERSITY

UC IRVINE

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

清華大學 Tsinghua University

SLAC NATIONAL ACCELERATOR LABORATORY

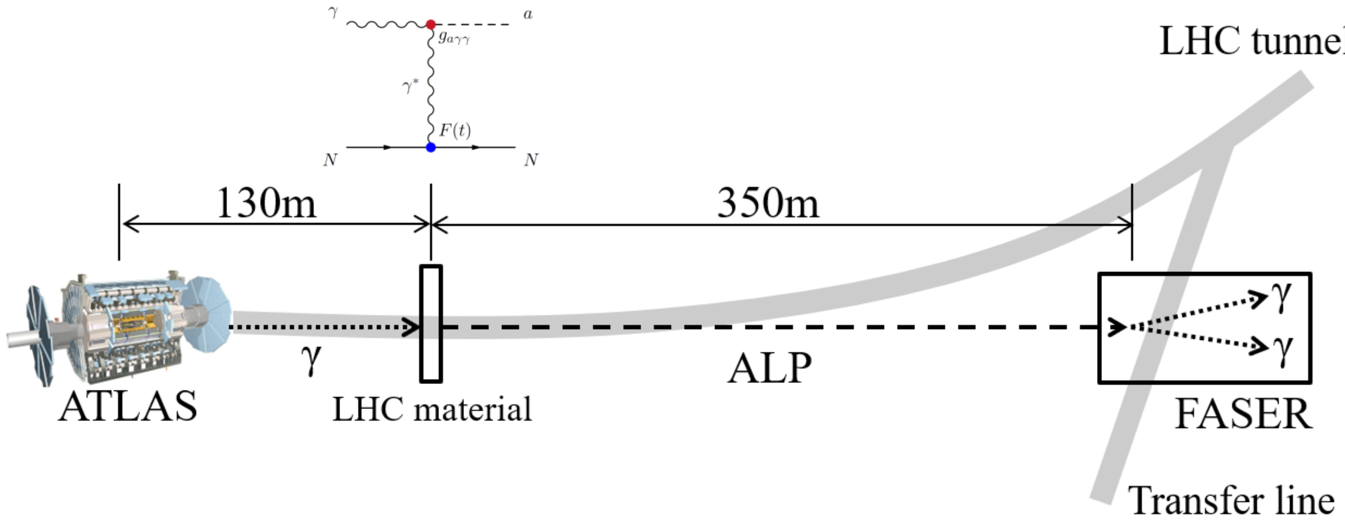
ROYAL HOLLOWAY UNIVERSITY OF LONDON

UNIVERSITY OF LIVERPOOL

FASER upgrade

Pixel detector to search for ALP (1)

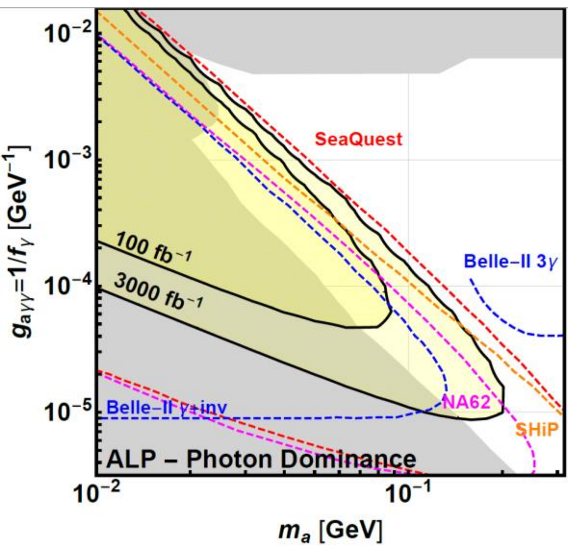
- Search for ALP(Axion Like Particle) is one of the important physics programs at FASER.
  - ALP is a pseudo scaler in SM singlet and couples to SM particles via dimension-5 interaction.
- ALP can be created with Primakoff interaction between γ and LHC material 130 m downstream from ATLAS IP.
- Aim to detector ALP decaying into 2 γ's in FASER detector.



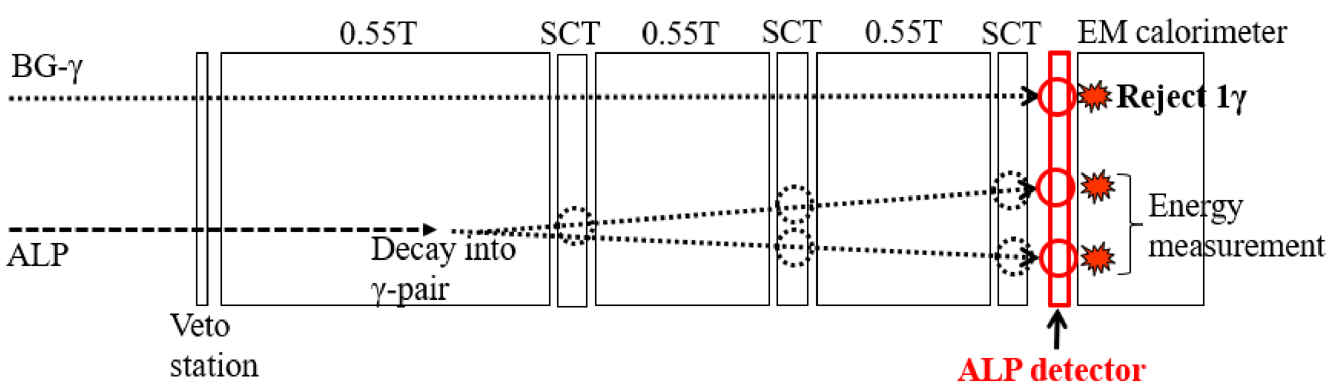
Pixel detector to search for ALP (2)

- It is crucial to identify 2 γ's close to each other for ALP detection.
- FASER calorimeter does not have capability of the 2-γ separation without segmentation.
- If the 2 γ's can be identified, FASER can explore ALP in Run 3.

Sensitivity to ALP with 2γ separation capability @FASER

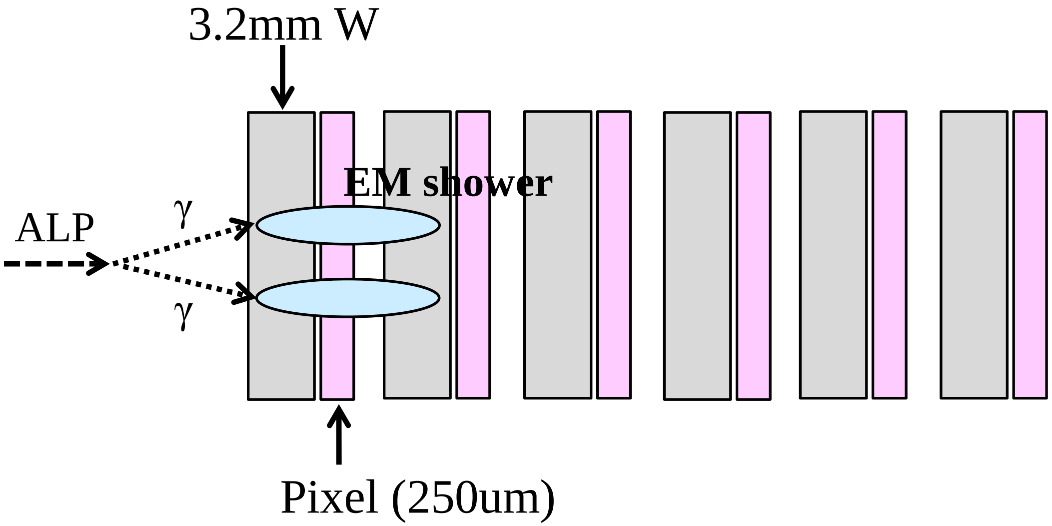


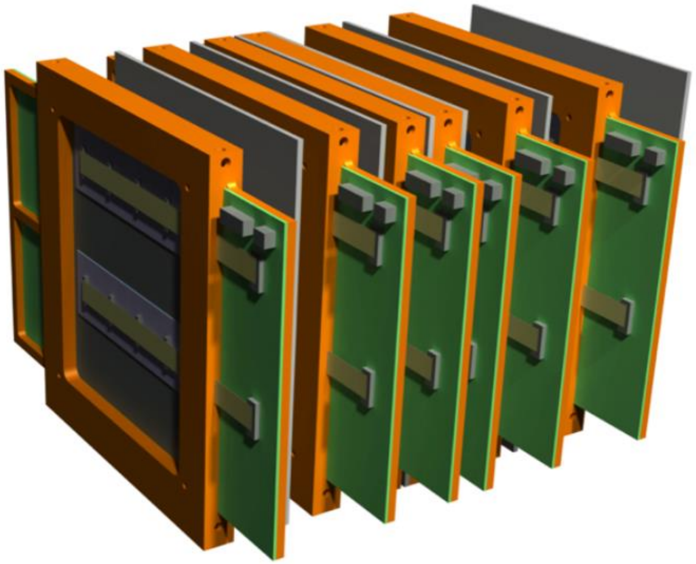
New preshower detector with pixel detector will be developed.



Pixel detector to search for ALP (3)

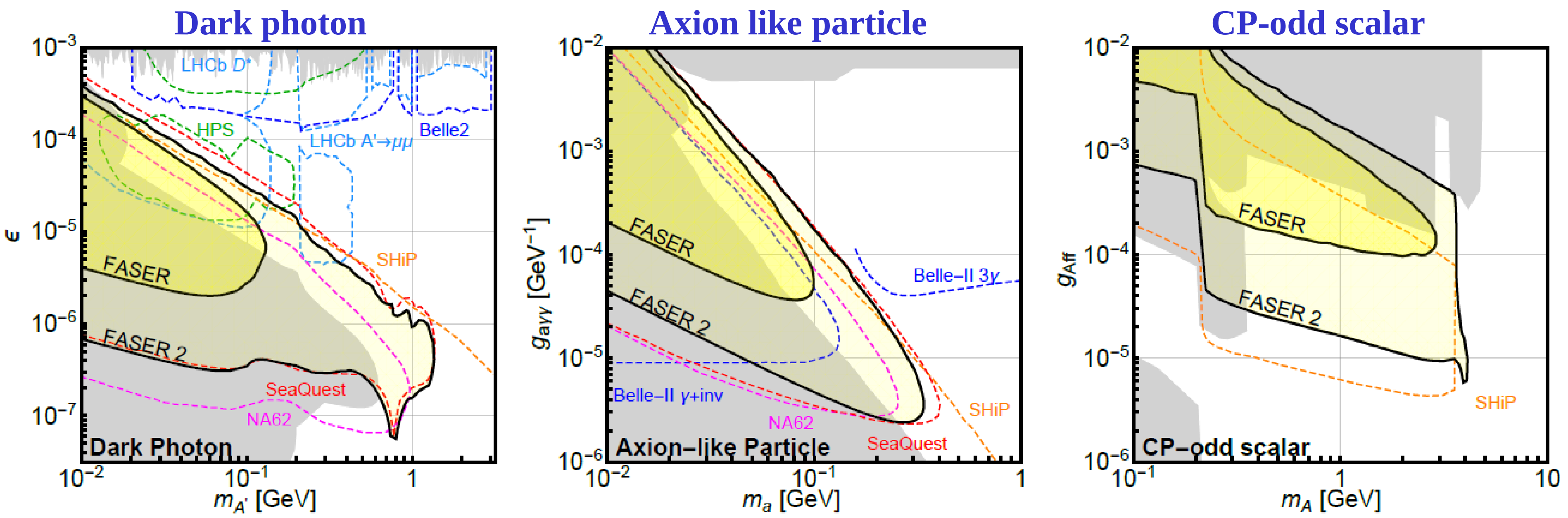
- The new preshower detector with BiCMOS monolithic pixel detector is under development (6 layers of "pixel + Tungsten").
  - 100 um pixel pitch, 50 ps time resolution
  - Cooperation with Geneva U., KEK, Kushu U. and Mainz U.
- The prototype sensor was produced in the autumn of 2020.
- Aim to install the detector before the last year of LHC (2024).





FASER2 @HL-LHC (1)

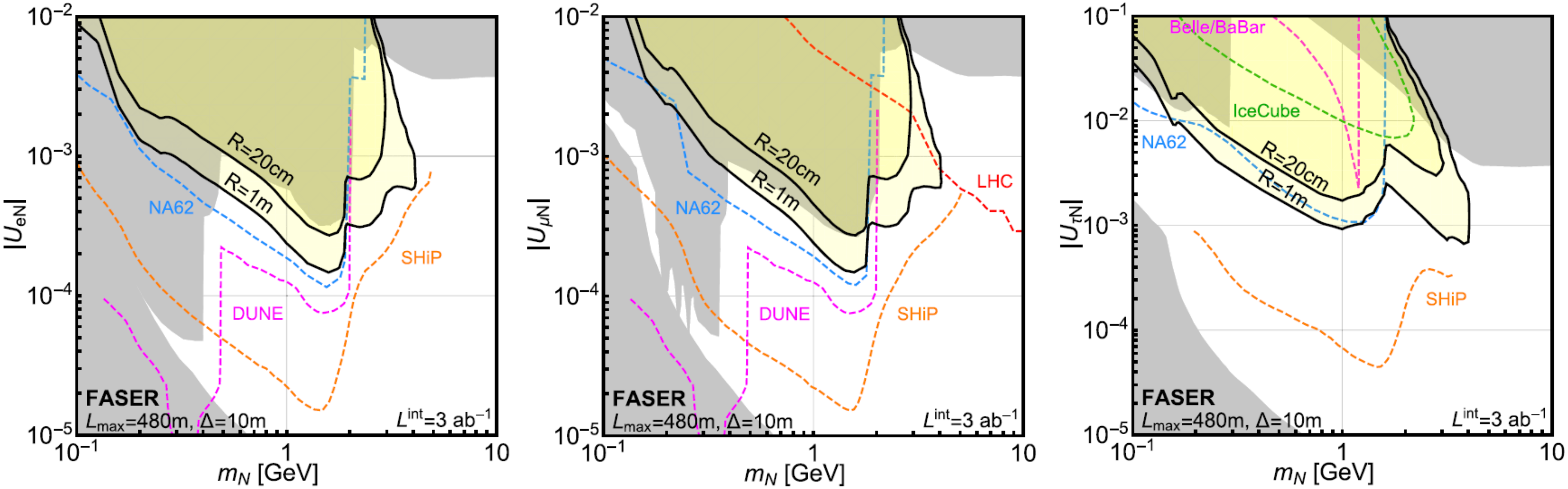
- FASER2 is upgrade project of FASER for HL(High Luminosity)-LHC.
- Aim to improve the physics sensitivity with larger detector acceptance.
  - Radius: 1 m (FASER: 10 cm)
  - Decay volume length: 5 m (FASER: 1.5 m)
- FASER2 can explore much larger parameter space for dark sector.



FASER2 @HL-LHC (2)

- FASER2 has better sensitivity also to HNLs (Heavy Neutral Leptons).
- The new preshower detector with pixel detector will improve identification capability of τ in the final states.

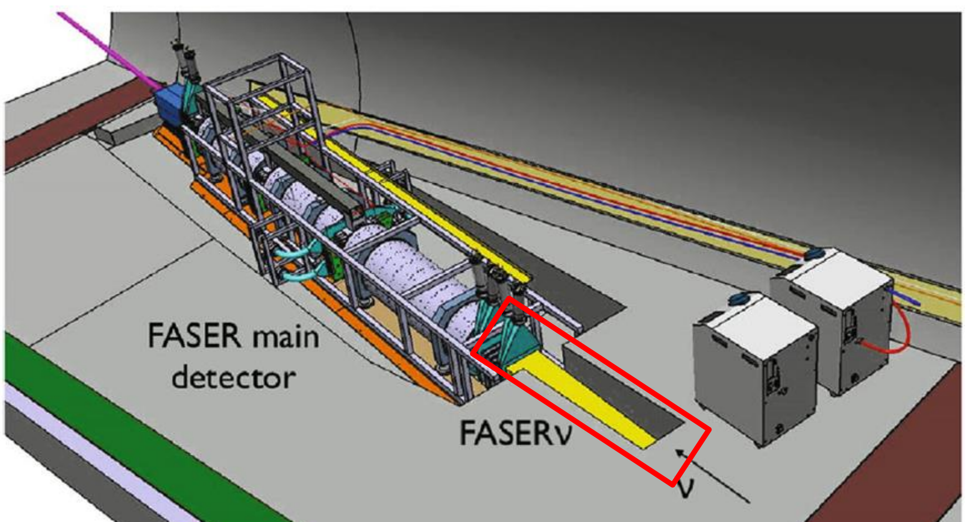
Expected sensitivity to HNL



Neutrino measurement at FASERν

FASERν

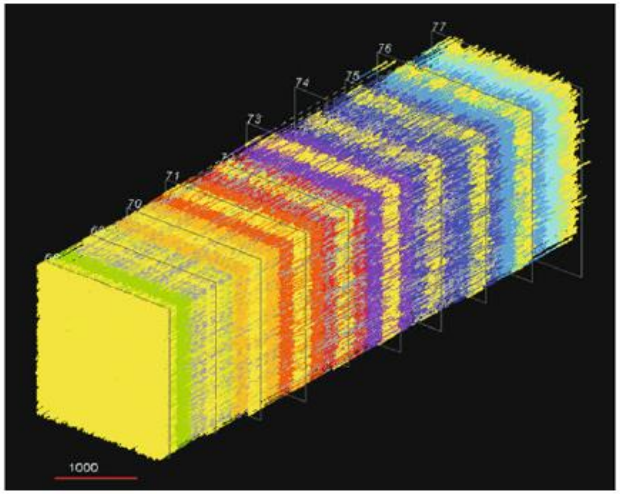
- FASERν is a project to measure cross-sections of neutrinos produced in pp collisions at ATLAS IP, starting from 2022.
- The first experiment to measure neutrinos created in beam collisions.
- 1,000 layers of emulsion films and 1mm tungsten plate in front of FASER (1.2 t, 285 X_0)
- The silicon strip tracker will be used for the interface between emulsion and FASER main tracker.

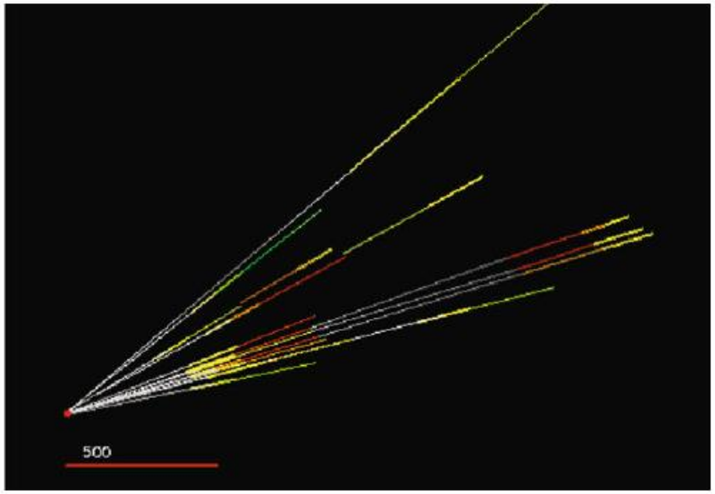


30 kg pilot emulsion detector

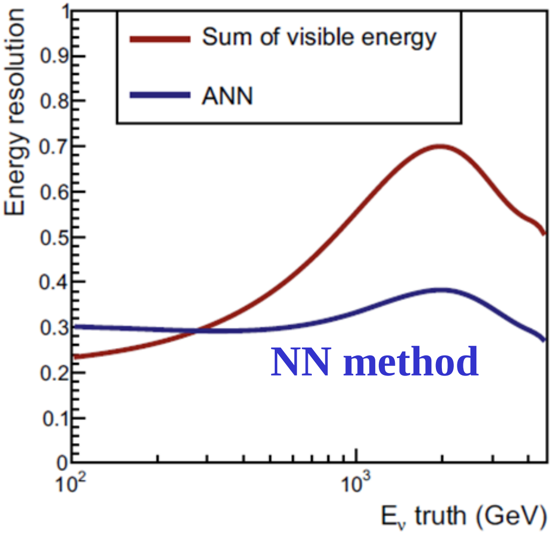
Neutrino detection with emulsion

- The emulsion detector accumulates all tracks for certain data-taking period, and the tracks are reconstructed by scanning the films afterwards.
- The position resolution of ~1 μm can be achieved but timing information is not available.
- About 30% of energy resolution can be realized in measurement with neural network method.





Expected energy resolution

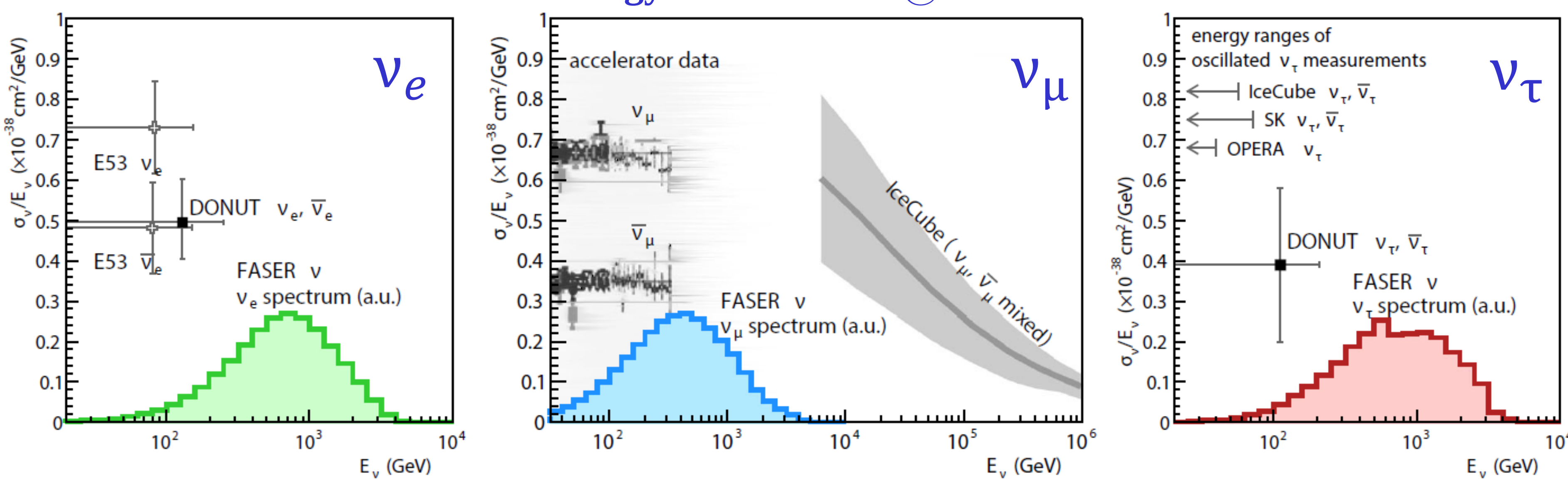


Neutrino cross-section measurement (1)

- FASERν will measure neutrino cross-sections at TeV region.
  - ➢ Uncovered region by existing experiments
- All neutrino flavors can be identified, thanks to excellent position resolution of the emulsion detector.

	CC events @150 fb^{-1}
$\nu_e + \bar{\nu}_e$	~1.3 x 10^3
$\nu_\mu + \bar{\nu}_\mu$	~2.0 x 10^4
$\nu_\tau + \bar{\nu}_\tau$	~20

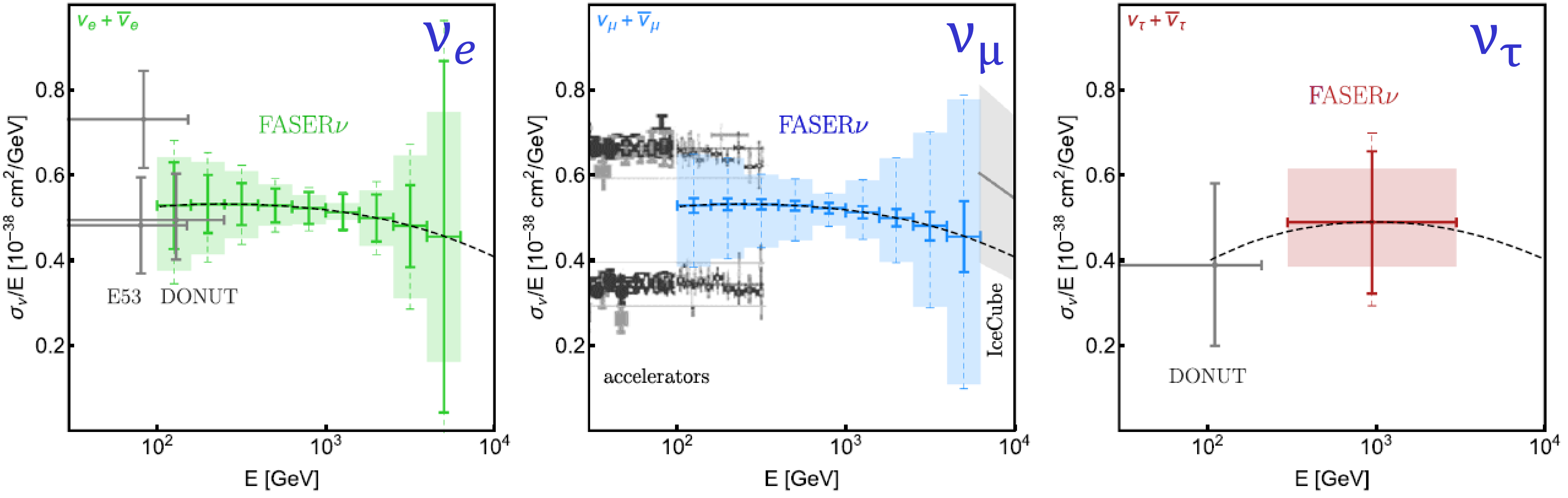
Neutrino energy distributions @FASERν



Neutrino cross-section measurement (2)

- FASERν can measure cross-sections with high precision for all neutrino flavors.
- Lepton flavor universality in neutrino sector can be investigated.
- For ν_μ, $\nu_\mu/\bar{\nu}_\mu$ can be separated with charge measurement in cooperation with FASER main tracker.

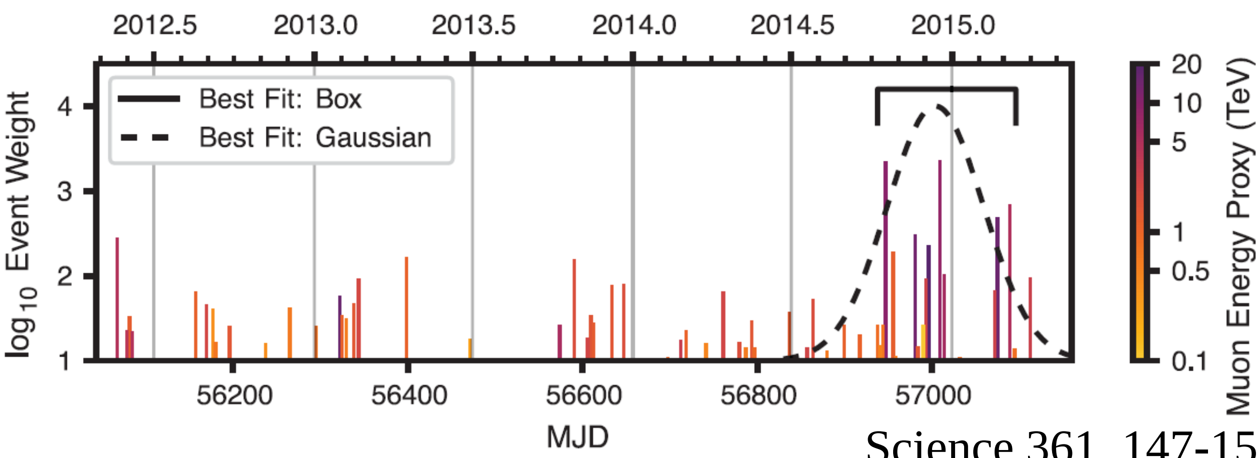
Expected sensitivity to neutrino cross-sections @FASERν



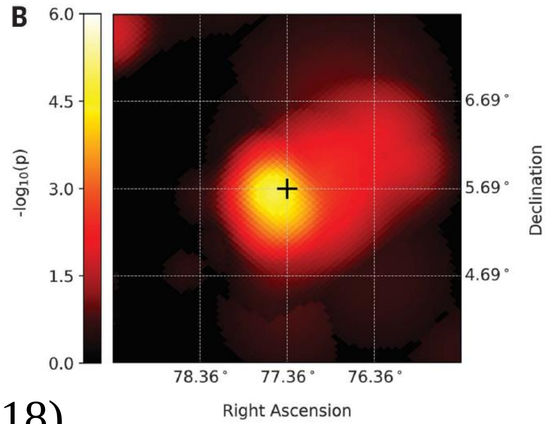
Charm quark density in proton (1)

- Large systematic error is assigned on production cross-section of heavy mesons in forward region in pp collisions.
  - It variates from 10% to 50%, depending on simulation model.
- Reducing the uncertainty is crucial for extragalactic neutrino searches at IceCube to evaluate the prompt atmospheric neutrino background.
  - Understanding charm parton distribution function is eager.

Weight and energy of individual events in direction of blazar TXS 0506+056 @IceCube



p-value of high energy neutrino events v.s. position of blazar TXS 0506+056("+" mark) @IceCube

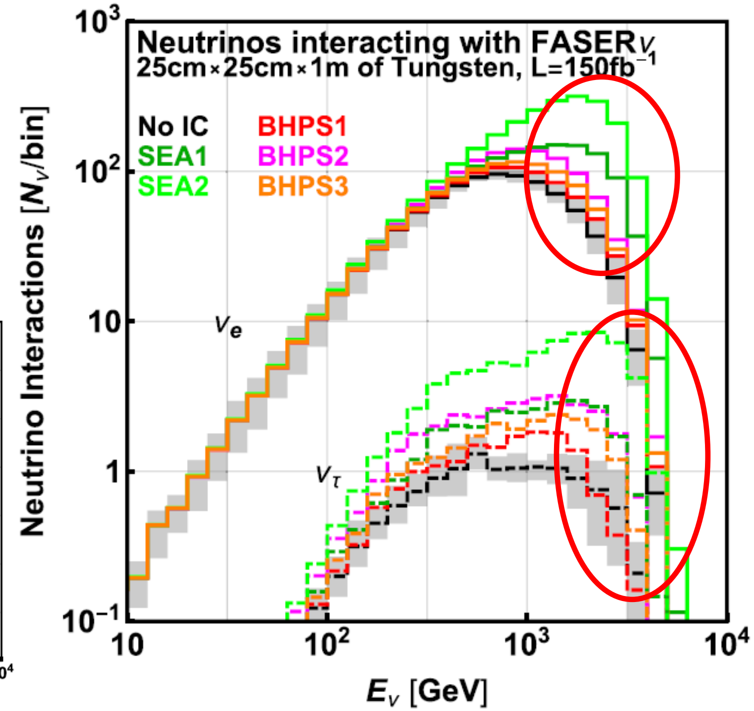


Science 361, 147-151 (2018)

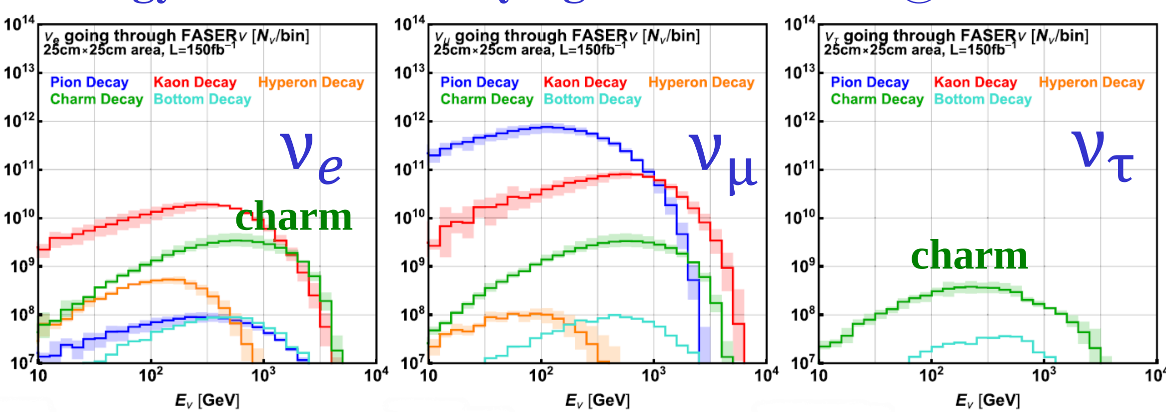
Charm quark density in proton (2)

- 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



Sterile neutrino oscillation (1)

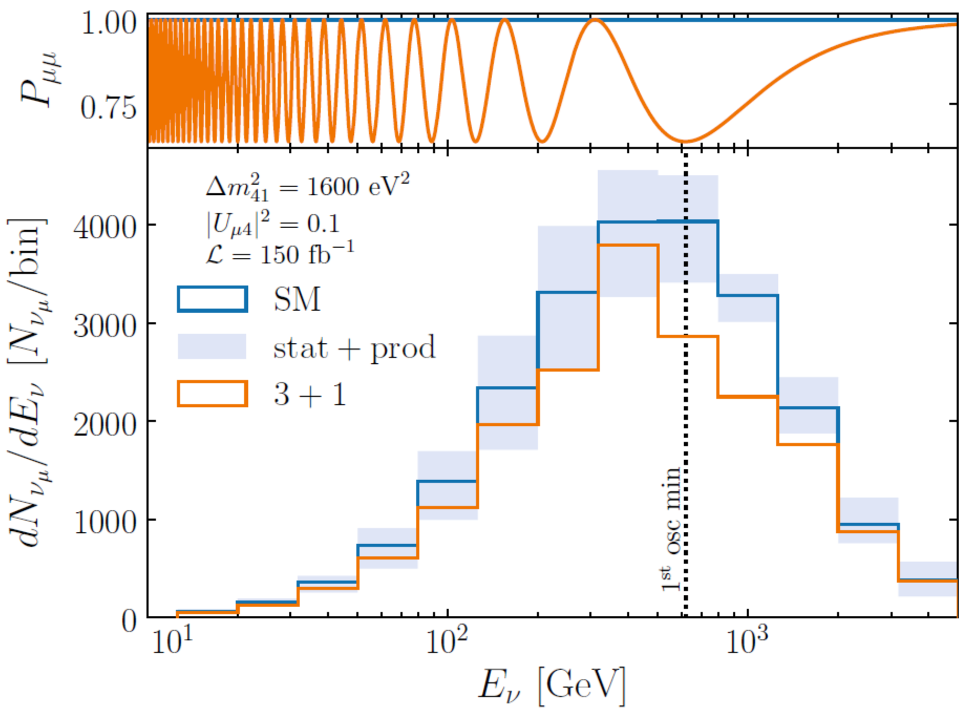
- SM excludes possibility of neutrino oscillation in FASER condition.
  - ➢ E_ν = 800 GeV, L = 480 m.

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

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

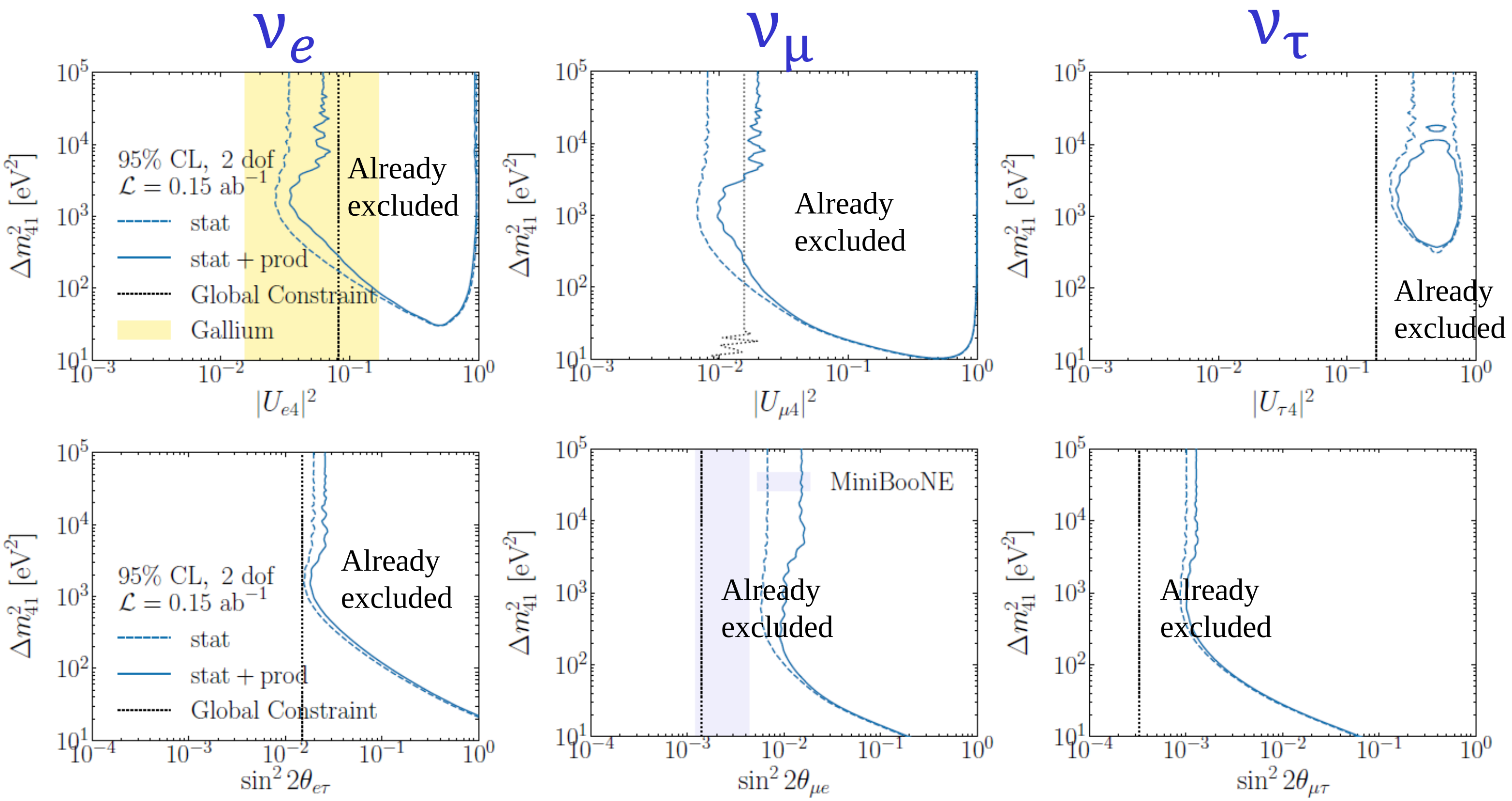
- Observation of neutrino appearance/disappearance indicates existence of sterile neutrinos.

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].



Forward Physics Facility

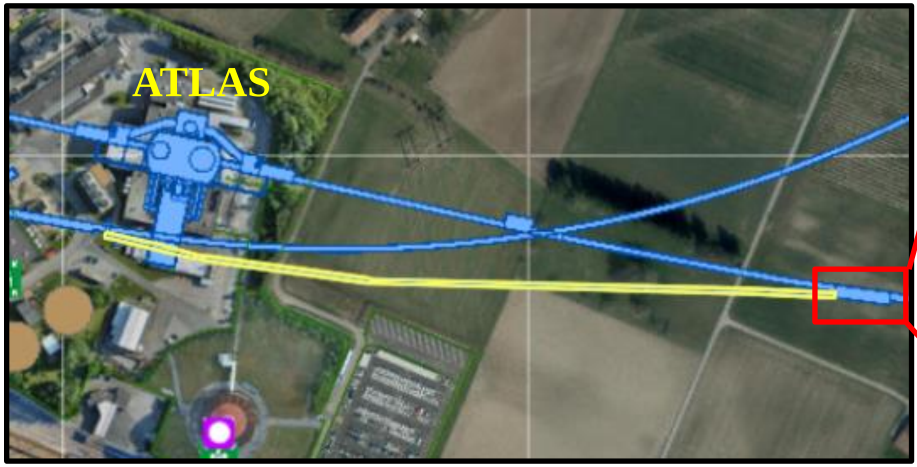
Forward Physics Facility project

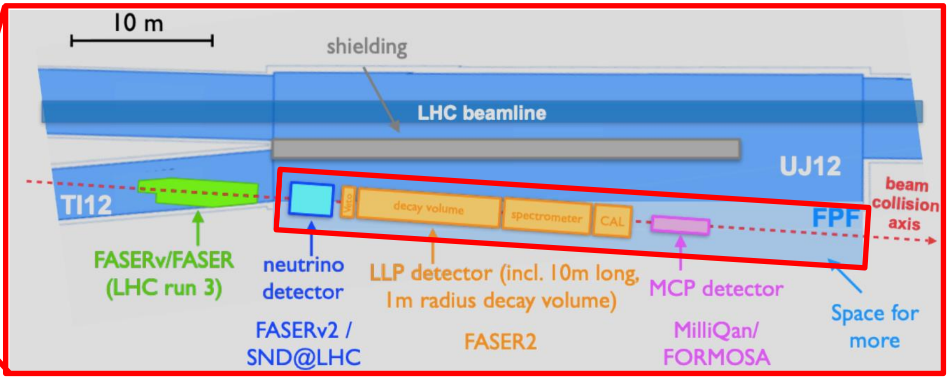
- The project to construct a new facility to explore several forward physics in pp collisions at HL-LHC.

Current candidates of experiment

- FASER2: Search for long-lived particles
- FASERν2/SMD: High energy neutrino measurement
- MilliQan/FORMOSA: Search for new millicharged particles.

- Discussion on the project was just started [here].





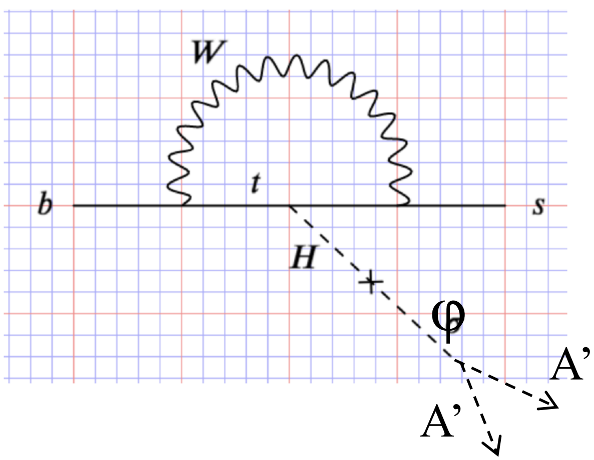
Summary & Conclusions

- FASER is a new experiment to search for new long-lived particles generated at pp collisions at the LHC (the detail is here).
- The detector construction is ongoing and the installation will finish in January 2021.
- The physics data-taking will start at LHC Run3 in 2022.
- The new parameter space can be explored only with data taken in the first year (20 fb^{-1}).
- Development of new preshower detector with pixel detector was started for ALP search, aiming the installation in 2024.
- Upgrade project for HL-LHC (FASER2) is also under discussion.
- FASERν will measure cross-sections of high energy neutrinos with ~1 TeV for all neutrino flavors.

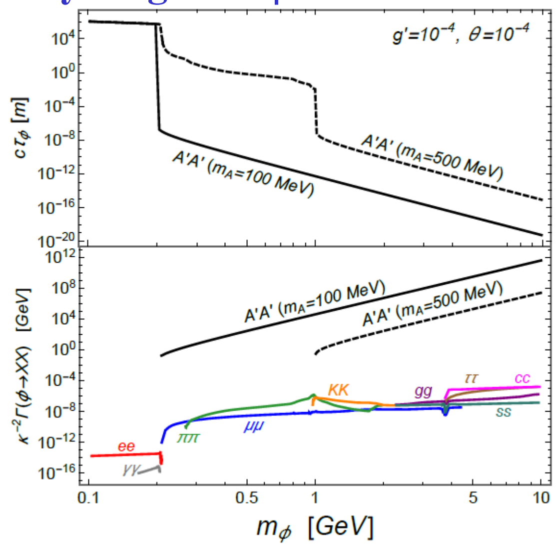
Backup

Search for dark photon in dark Higgs decays (1)

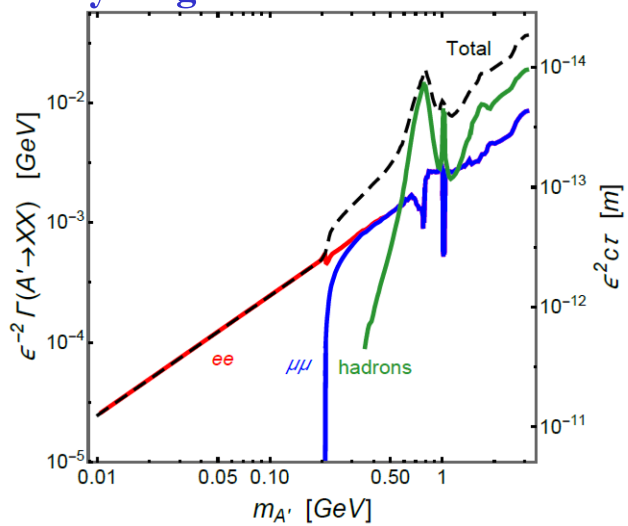
- Dark Higgs related with new U(1) symmetry (φ) obtains VEV via the symmetry breaking, and accordingly dark photon (A') gets mass.
- Φ can be produced from meson decays (especially B meson) via H-φ mixing and quickly decays into an A' pair if $m_\varphi >> m_{A'}$.
- A' decays into a lepton pair via mixing with γ.
- The signal appears together with direct production in meson decays.



Decay length of φ v.s. mass width



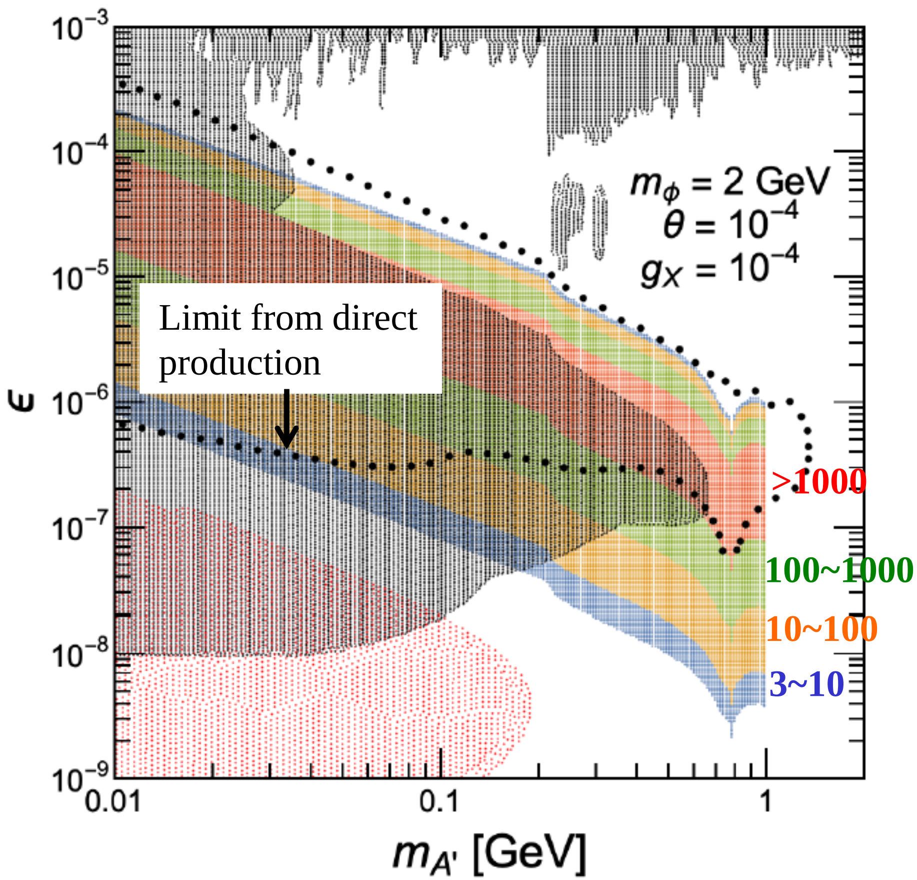
Decay length of A' v.s. mass width



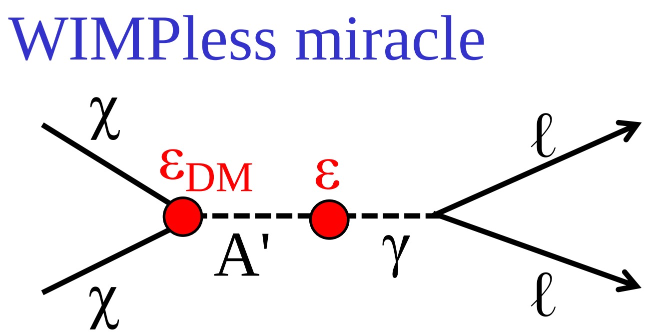
Search for dark photon in dark Higgs decays (2)

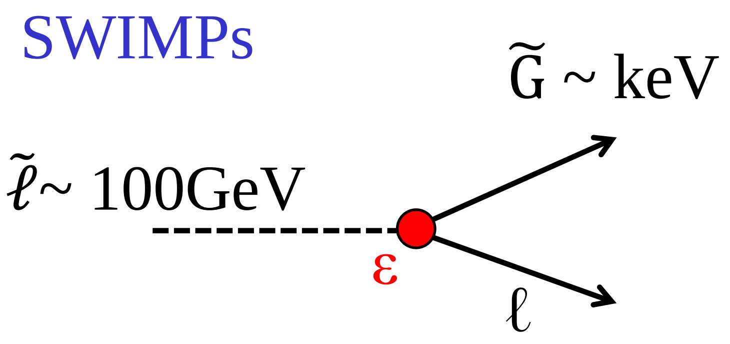
- Yield of 2A' from $\varphi \rightarrow A'A'$ decays in FASER was evaluated (m_φ = 2 GeV, $\theta_{\varphi\text{-}H} = 10^{-4}$, $g_{\varphi\text{-}A'} = 10^{-4}$)
- $\varphi \rightarrow A'A'$ events contribute to small coupling region at FASER2.
  - FASER may have the sensitivity, depending on the parameter set.
- Collaborative work with K. Asai (Tokyo), T. Araki (Ohu), H. Otono (Kyushu) (arXiv:2008.12765).

Expected # of A' events from φ decays @FASER2



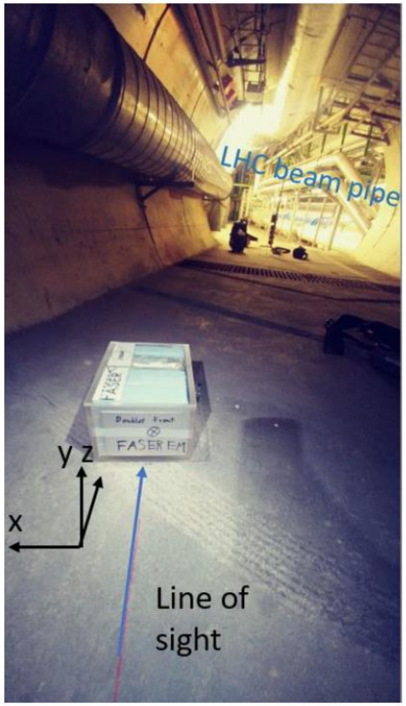
Dark matter & New light particles





	Mass	Coupling
WIMP miracle	O (100 GeV)	$\varepsilon \sim 1$
WIMPless miracle	MeV ~ GeV	$\varepsilon_{DM} \sim 1$, $\varepsilon << 1$
SIMPs	O (100 GeV)	$\varepsilon_{DM} > 1$, $\varepsilon << 1$
SWIMPs	O (100 GeV) decays into O (keV)	$\varepsilon << 1$

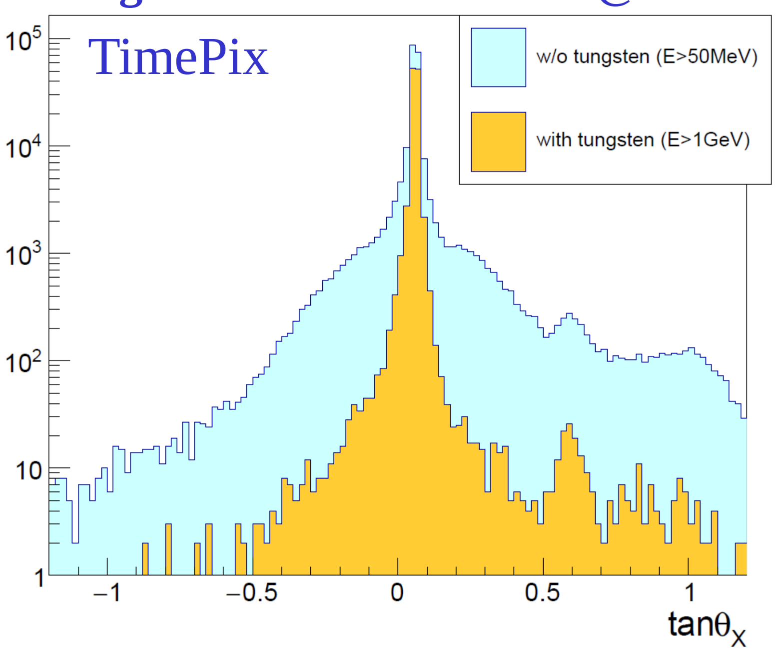
Beam background & Radiation



Beam background

- The emulsion detector and TimePix beam loss monitor were installed at TI12 in 2018 to measure particle flux.
- The results were consistent with FLUKA expectation.
- Detailed study is ongoing.

Angular dist. of beam BG @TI12

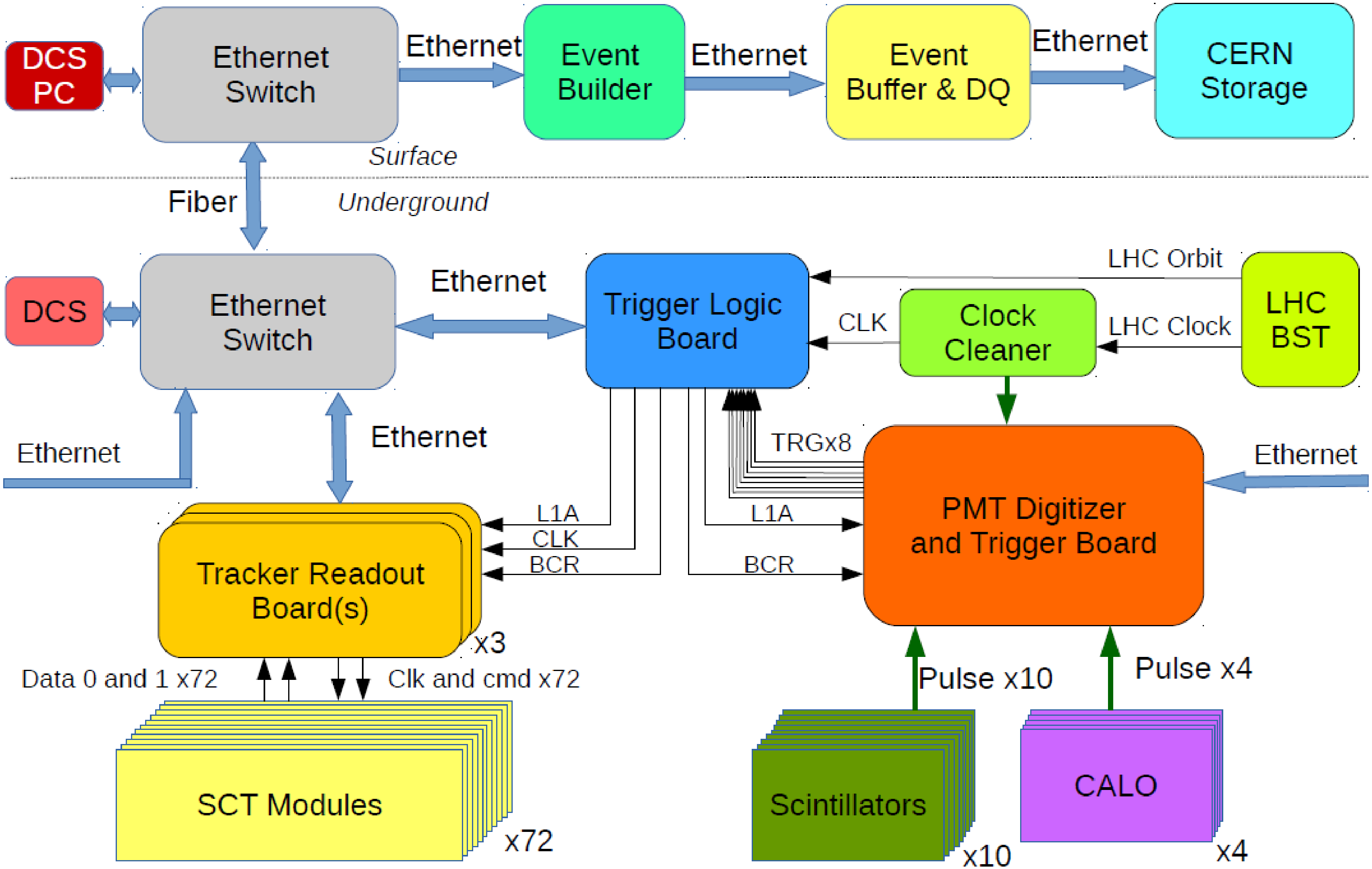


Radiation

- FLUKA expectation was confirmed by measurement with BatMon detector:
  - $<5 \times 10^{-3}$ Gy/year
  - $<5 \times 10^{7}$ 1 MeV n_{eq}/year
- FASER does not need radiation hard electronics.

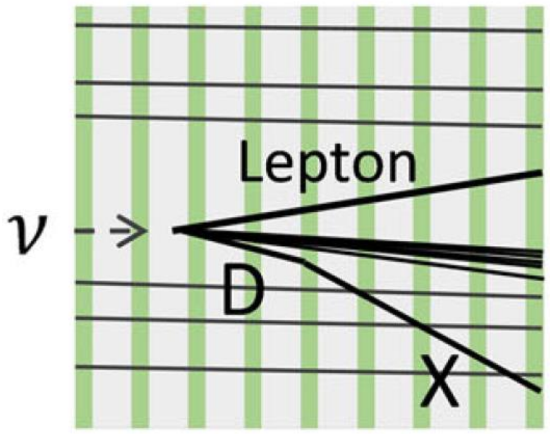
FASER Trigger/DAQ

TDAQ system dedicated for FASER will be newly developed.

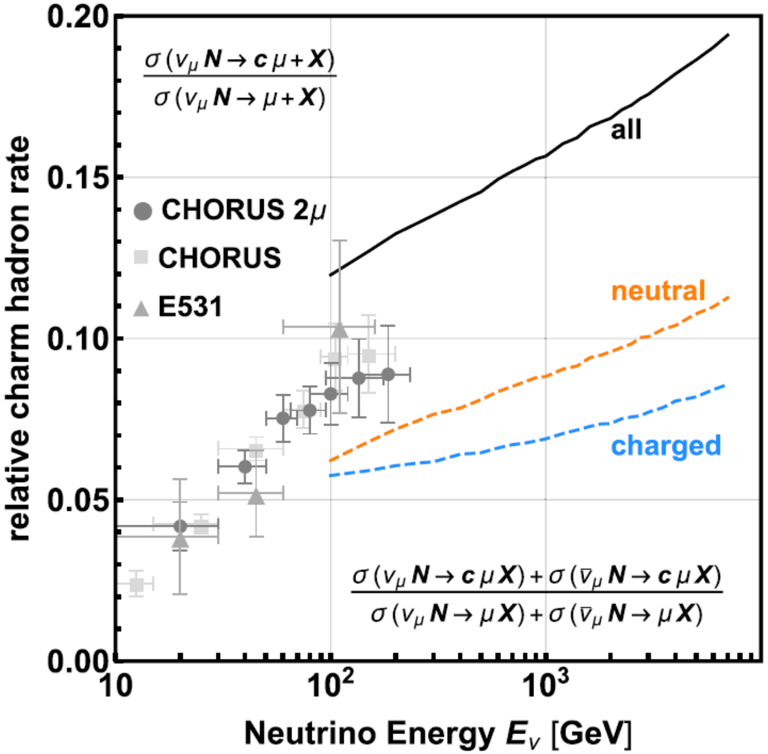


Cham-associated neutrino events

- 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



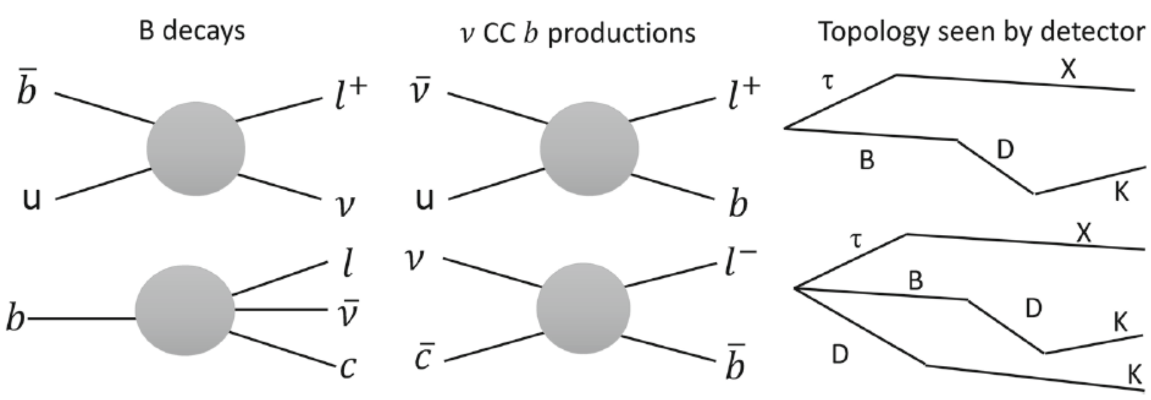
Beauty-associated neutrino events (1)

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

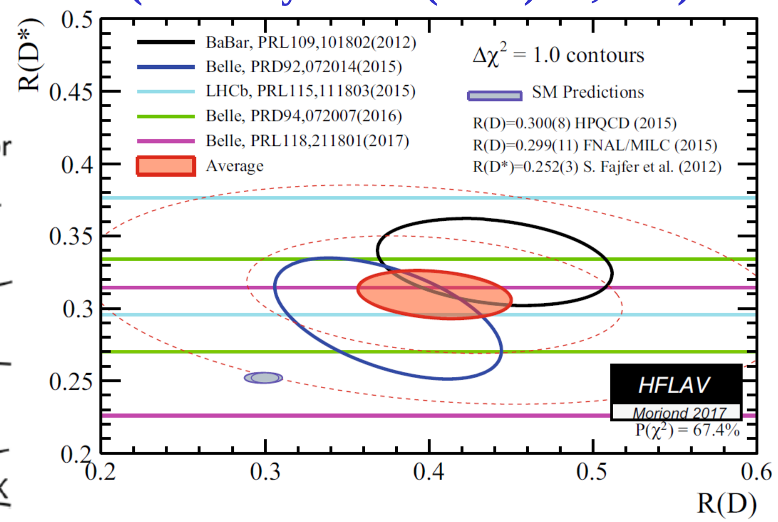
- The neutrino interactions in FASERν are the same as them, exchanging the internal/external lines in Feynman diagrams.

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

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



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.