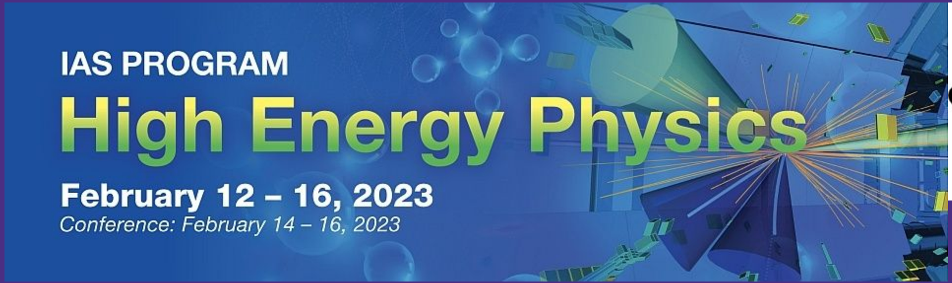


FASER

The FASER experiment at (HL-)LHC

Shih-Chieh Hsu, Ke Li
on behalf of FASER collaborations
02/13/2023

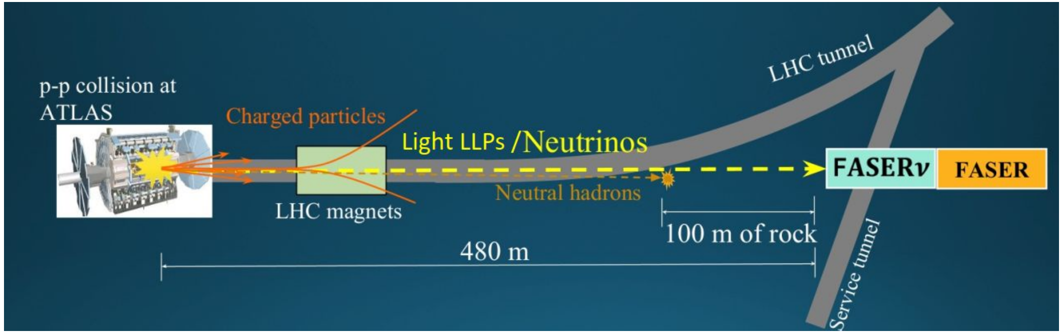
IAS on HEP 2023

UNIVERSITY *of* WASHINGTON

FASER is supported by:
Heising-Simons foundation and Simons Foundation.

ForwArd Search ExpeRiment

- **Faser is designed to search for long lived particle (LLP) and neutrino produced in pp collision in ATLAS IP:**
  - The LLP is produced in the decay of SM meson which predominantly produced very collimated with the beam direction
  - Even small detectors on (or close to) the LOS can have good sensitivity in these scenarios
    - e.g. 1% of pions with E > 10 GeV are produced in the forward 0.000001% of the solid angle ($\eta > 9.2$)
  - 480m from ATLAS IP in the forward regions
  - 100m rock to shield most of the background



arXiv:2207.11427

FASER detector

EM Calorimeter:

- 66 scintillator + lead planes
- ~25 X_0

Scintillator:

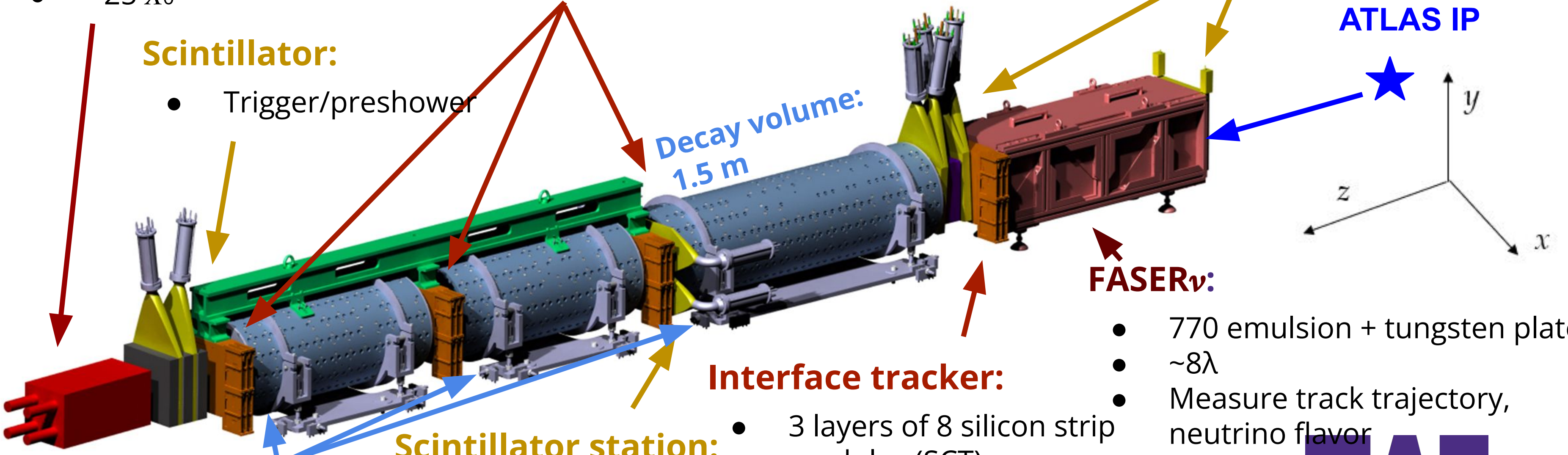
- Trigger/preshower

3 Tracker stations:

- Each has 3 layer of 8 silicon strip modules
- Measure track trajectory
- More details in NIMA166825(2022)

Scintillator

- Veto charged particles



FASERν:

- 770 emulsion + tungsten plate
- ~8λ
- Measure track trajectory, neutrino flavor

Interface tracker:

- 3 layers of 8 silicon strip modules (SCT)

Scintillator station:

- Trigger/timing
- More details in INST16,P12028 (2021)

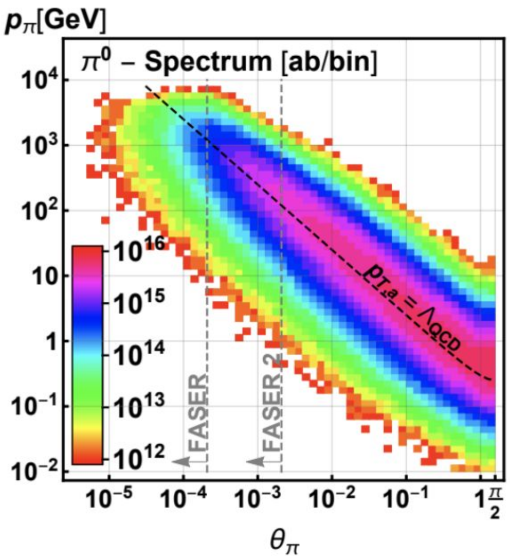
Magnets:

0.55 T

Long-lived particles

> Searches for new weakly interacting light particles, coupling to SM in forward region $pp \to \mathrm{LLP} + X, \quad \mathrm{LLP\ travels} \sim 480\ \mathrm{m}, \quad \mathrm{LLP} \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \gamma\gamma, \ldots,$
  - Produced in decays of light mesons (e.g. π^0, K)
  - Light SM particles abundantly present in pp collisions, primarily in large pseudorapidity
  - Dark photon, axion-like particle (ALP) ...

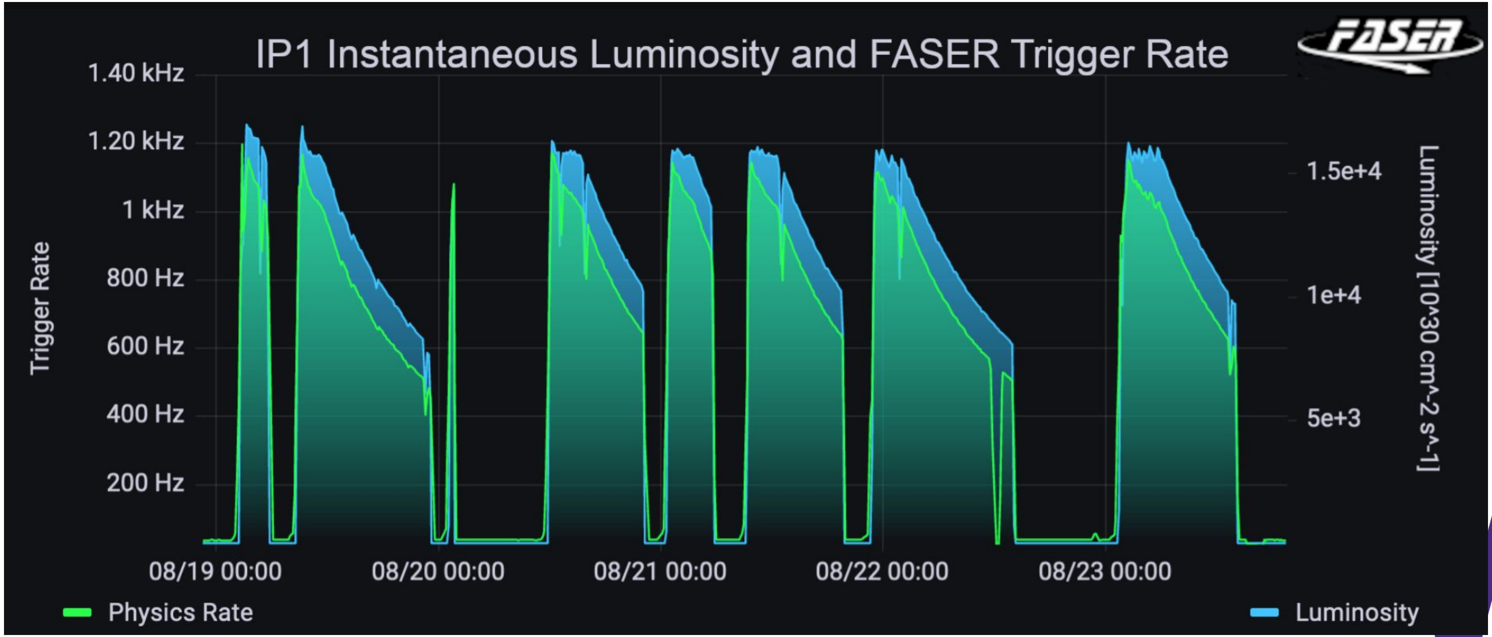
- By being on the LOS maximises the acceptance for potential signals
- In Run-3 of the LHC we expect O(10^{14}) π^0 to be produced in the FASER acceptance.



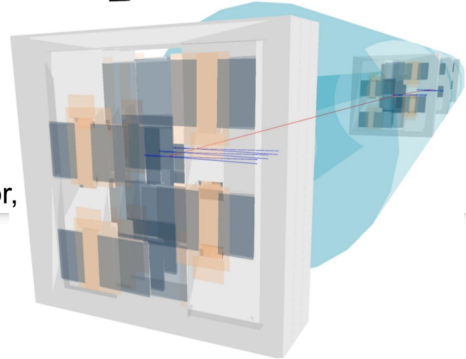
More details in PRD.99.095011 (2019)

FASER operations

- FASER successfully collected ~40/fb of 13.6 TeV collision data in 2022 running (July -Dec)
- Average trigger rate: ~700Hz
- Detector operations went very smoothly



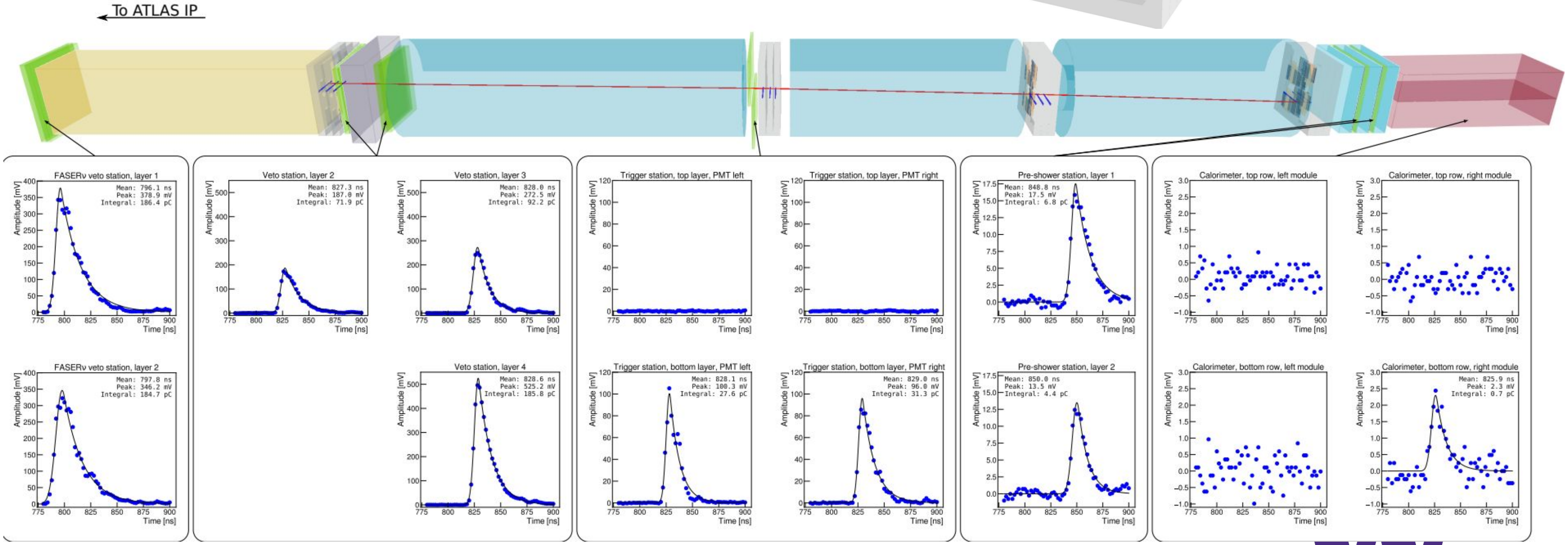
Run 8336
Event 1477982
2022-08-23 01:46:15



First collision data

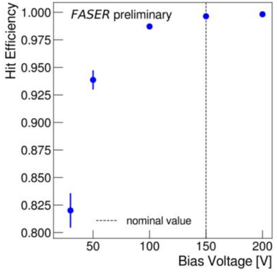
Event display of a muon traversing the full detector, all parts of the detector performing as expected.

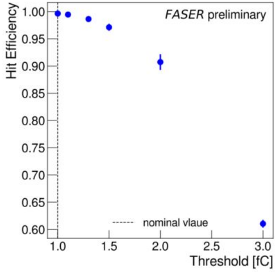
Run 8336
Event 1477982
2022-08-23 01:46:15

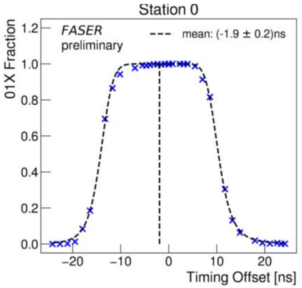


Detector performance - tracker

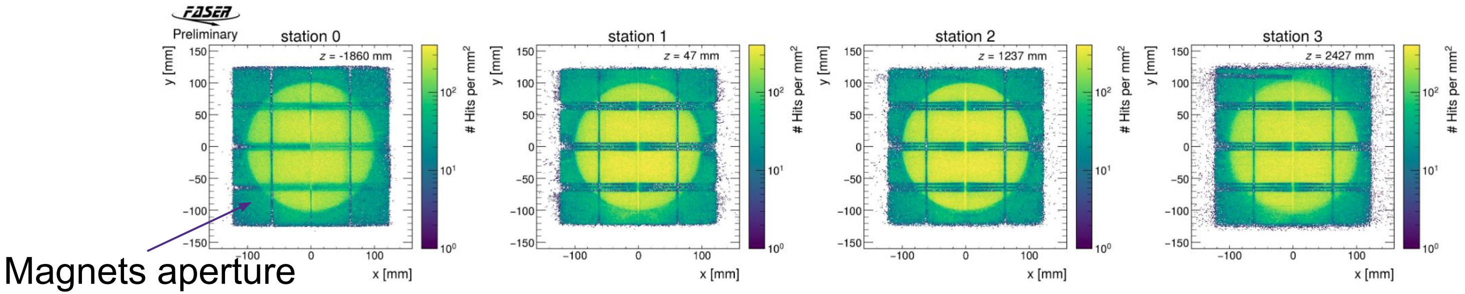
- Build of same silicon strip module (SCT) as ATLAS, module fine time tuned with 390 ps precision
- Hit efficiency of 99.64±0.10% at threshold of 1.0 fC and sensor bias 150V





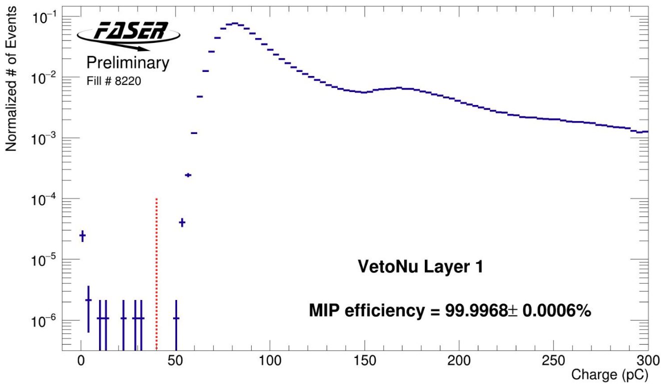


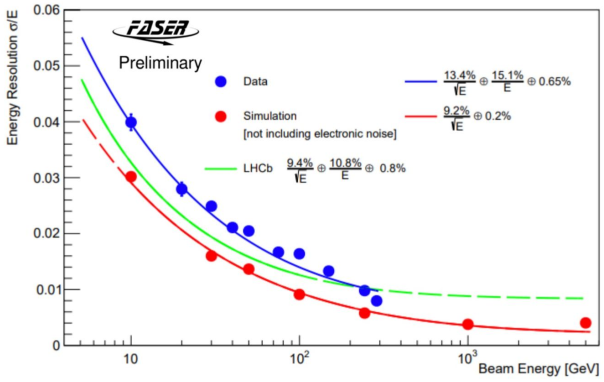
- Total number of dead/noisy strips < 0.5%
- Inefficiency from module edges are expected

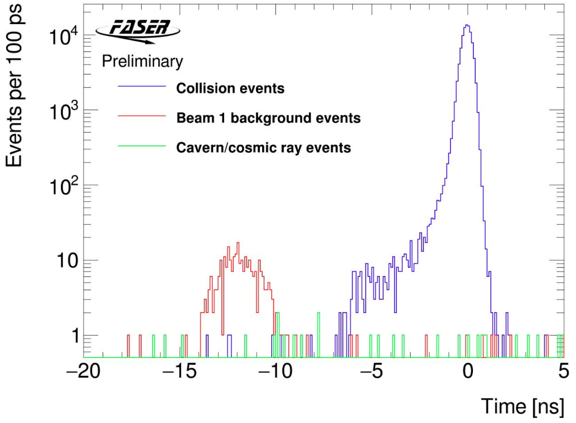


Detector performance - scintillator/calorimeter

- Veto scintillator efficiency from data:
  - >99.99% for each veto scintillator
  - Veto O(10^8) muons by combining 4 scintillators
- Calorimeter energy resolution measured with electrons in test beam
  - Resolution at O(1%) at high energy as expected
- Timing resolution ~250ps
  - Reject the beam-1 background efficiently

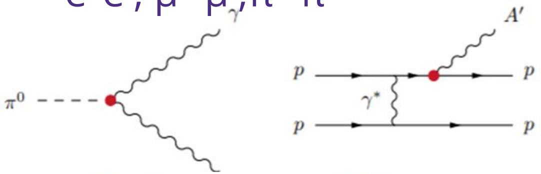


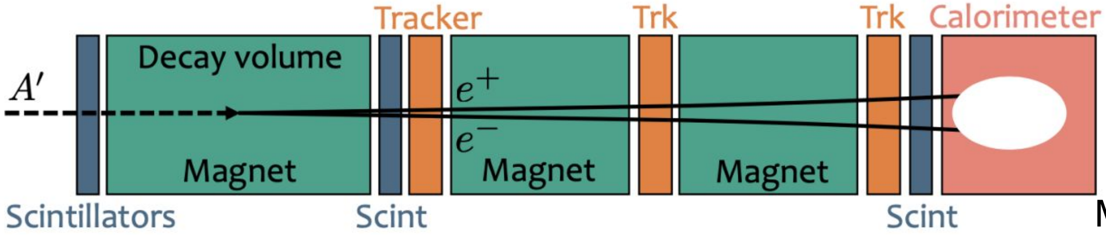


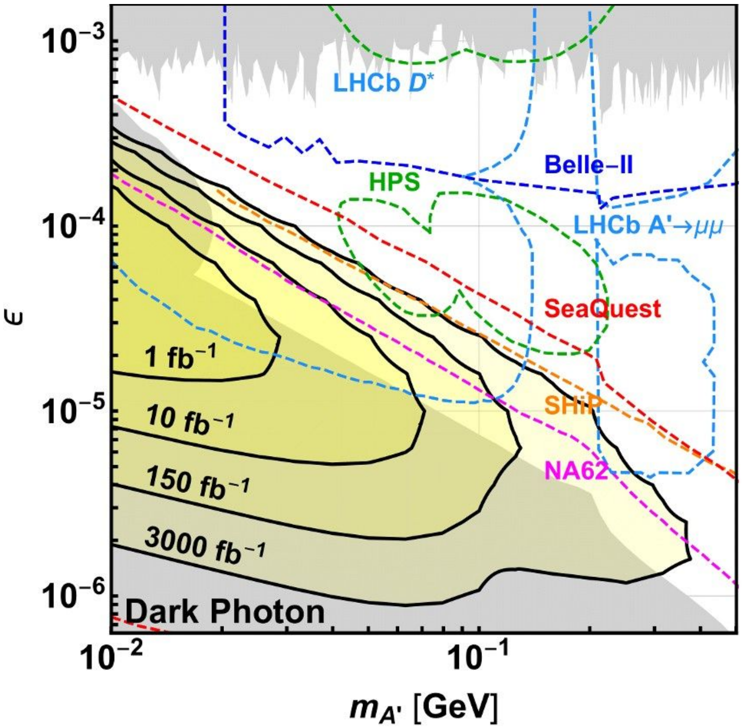


Dark photon

- Even with 1/fb of data FASER will have sensitivity to unconstrained parameter space
- Production:
  - mainly from decays of light mesons, π, η and dark bremsstrahlung.
- Decays:two charged particles
  - e^+e^-, $\mu^+ \mu^-$,$\pi^+ \pi^-$







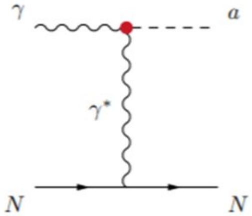
More details in PRD.99.095011 (2019)

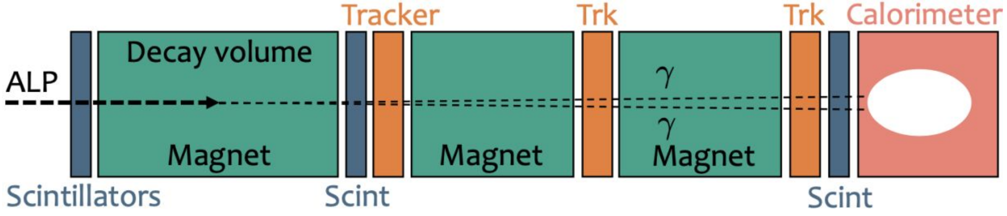
Axion-like particles (ALPs)

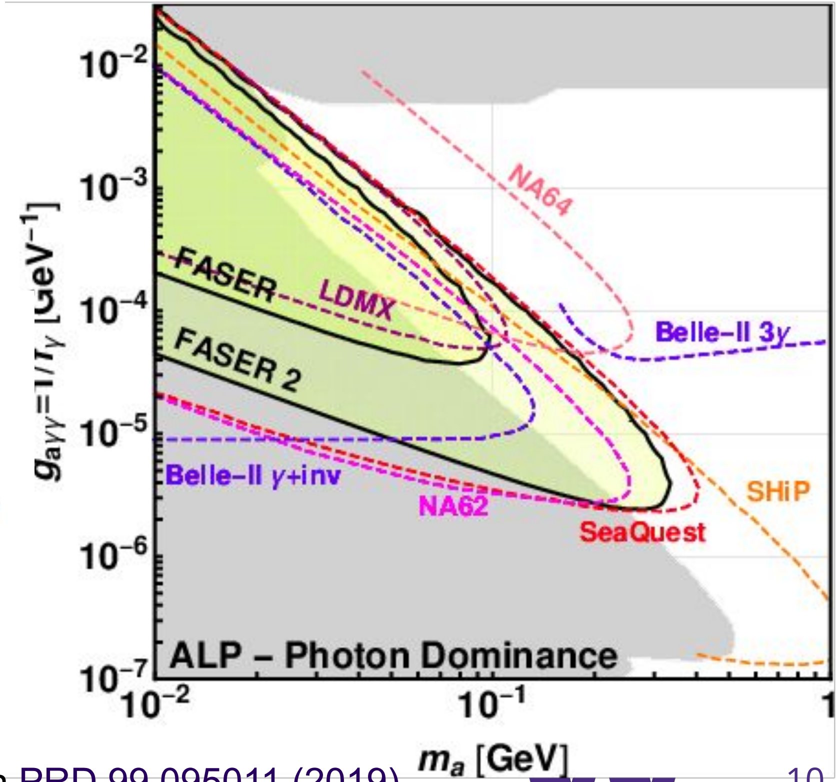
In the case of ALPs only couple to photons

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

- Mainly produced via Primakoff process ($\gamma N \to aN$) In forward region of pp collision
- $a \to \gamma\gamma$ or γe^+e^-



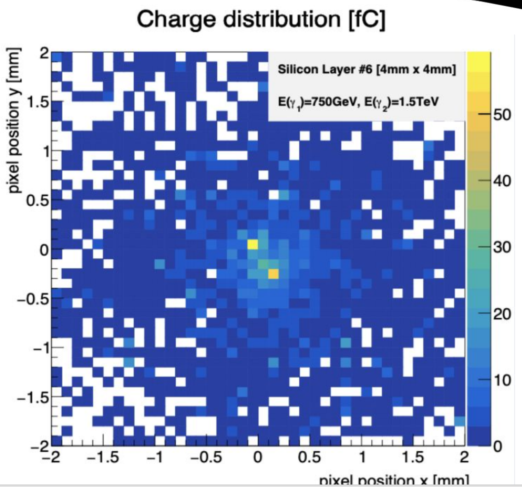


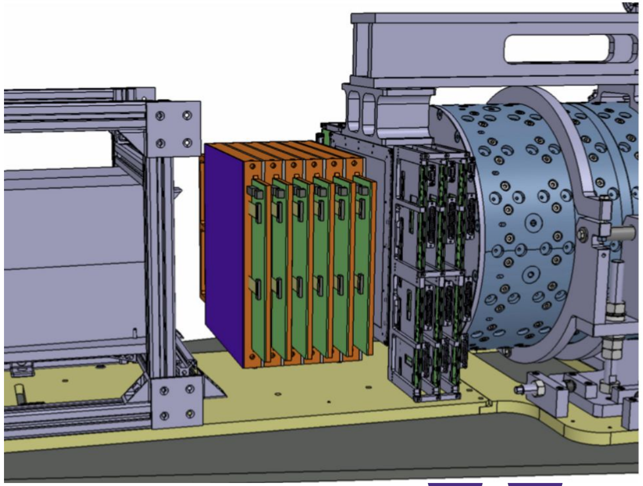


More details in PRD.99.095011 (2019)

Pre-shower upgrade

- Current pre-shower unable to separate closely spaced high energy photons(e.g. from ALP decay)
- Upgrade to enable detecting ALPs$\rightarrow \gamma\gamma$ searches
  - Able to reconstruct 2 high energy photons separately by ~200μm
- New pre-shower: high-resolution silicon pre-shower detector using monolithic pixel ASICs
  - hexagonal pixels of 65µm side
  - Planned to be ready for 2024 data taking



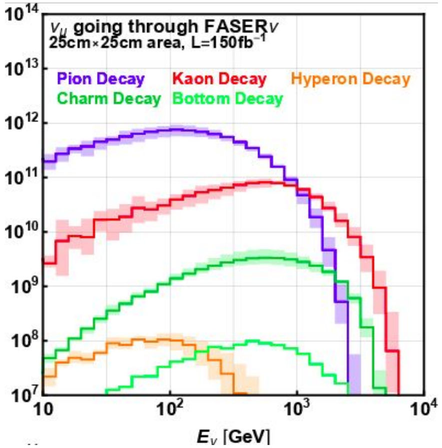


More details in CERN-LHCC-2022-006

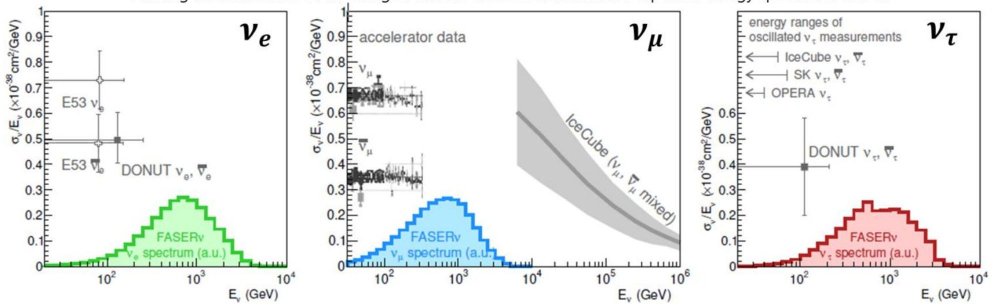
Neutrinos from LHC

- A huge number of neutrinos produced in the LHC collisions traverse the FASER location covering an unexplored neutrino energy regime
  - Originate from hadron decays, mainly pion, kaon and charm mesons
- FASERν is an emulsion/tungsten detector placed in front of the main FASER detector to detect all flavor of neutrino interactions

150/fb at 14 TeV	ν_e	ν_μ	ν_τ
Main source	Kaon decay	Pion decay	Charm decays
# traversing FASERν	$O(10^{11})$	$O(10^{12})$	$O(10^{9})$
# interacting with FASERν	~1300	~20000	~20



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



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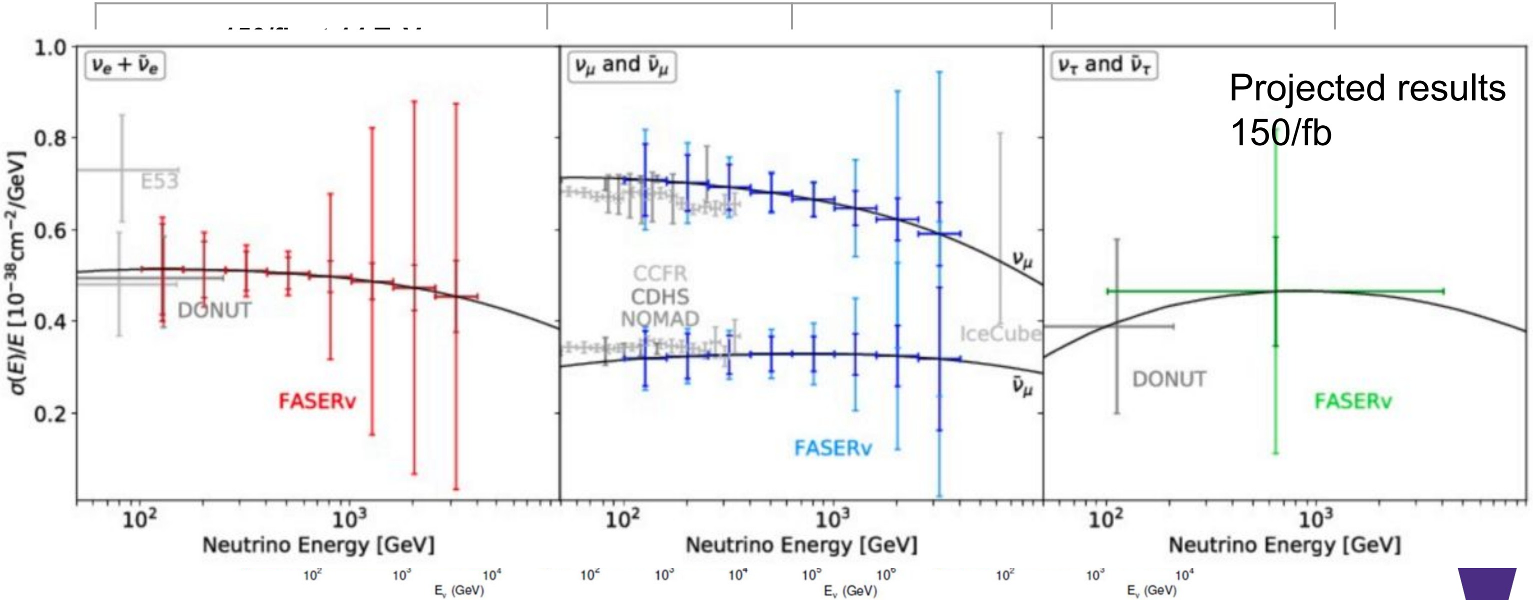
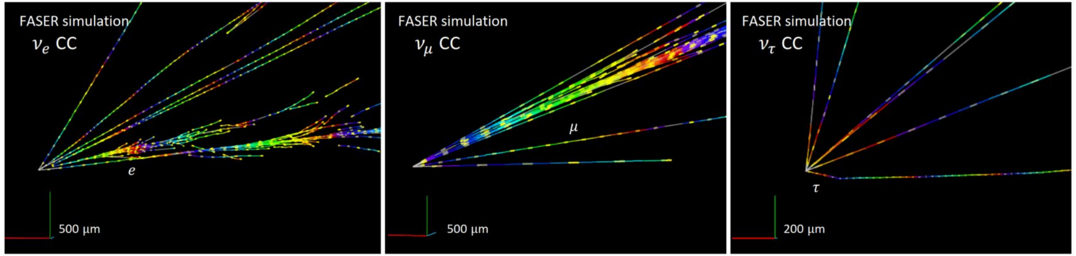
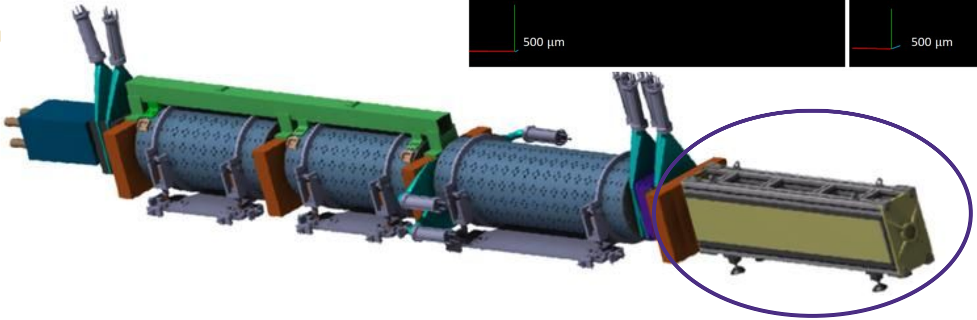
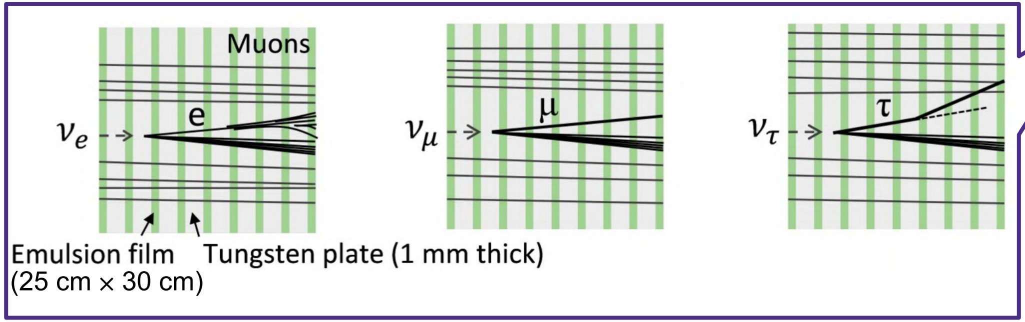


FASERν detector





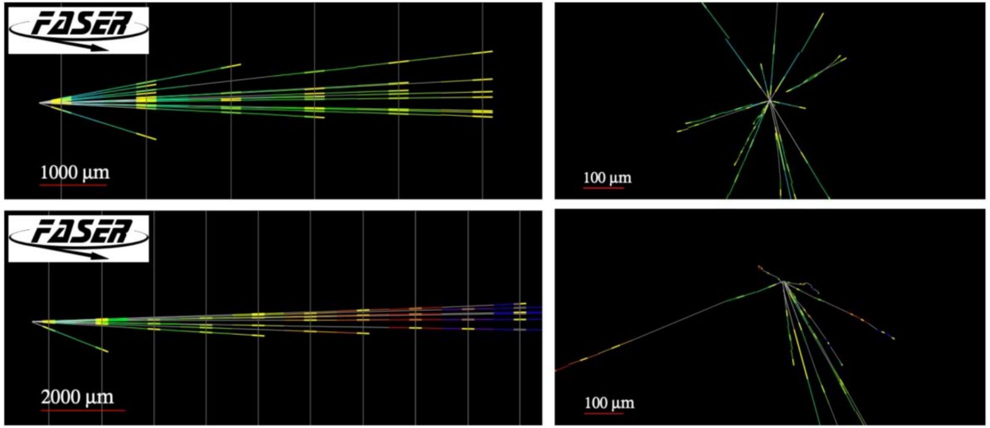


- 730 × 1.1mm thick tungsten plates, interleaved with emulsion films
- 1m long, 1.1 ton detector
- Capable to distinguish all flavours of neutrino
- Emulsion films has excellent position/angular resolution but no time information
- Need to be replaced every ~3 months

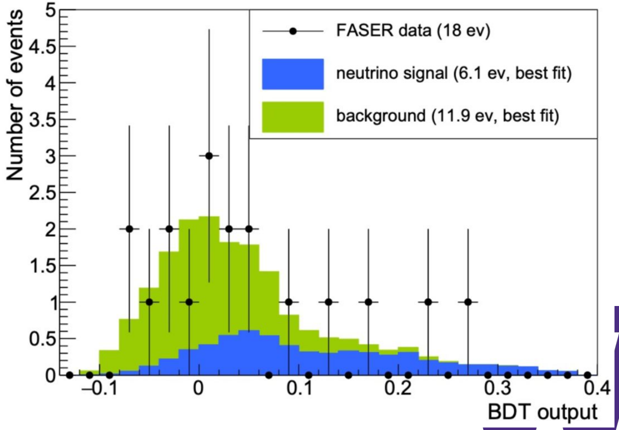
Neutrino reconstruction efficiency: >80% with a energy resolution ~30%

FASERν pilot run

- A small emulsion detector (10kg target mass) to validate simulation of background particle flux
- 12.2/fb data collected in ~1 month
- 18 neutral vertices detected
- Main background from muon induced neutral hadron
- Best fit on BDT score shows 6.1 neutrino candidates (3.3 expected) with a significance of 2.7σ



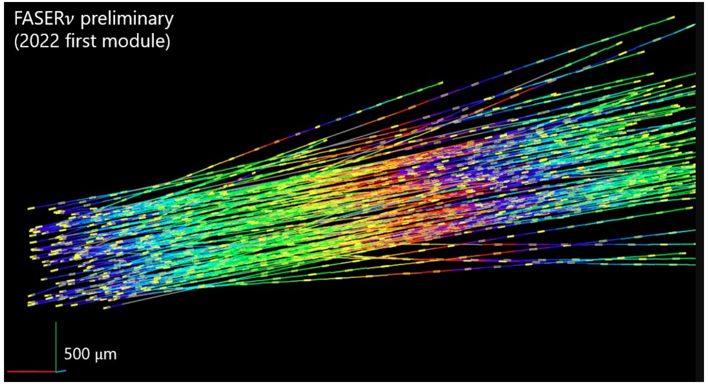
First candidate collider neutrino !

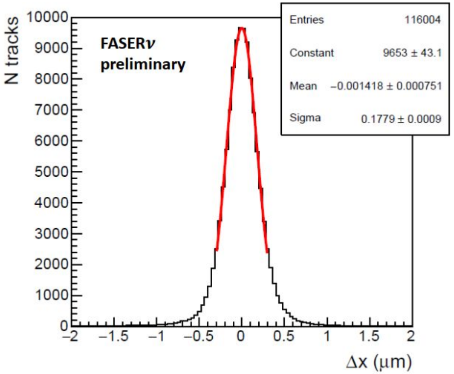


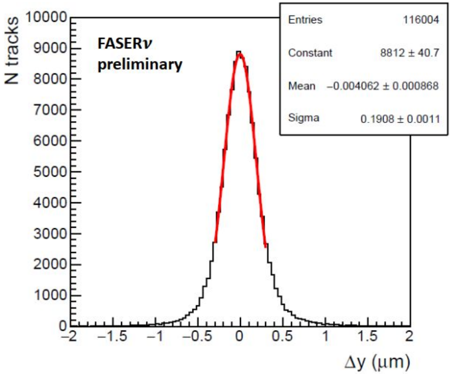
Detector performance - FASERν

- First emulsion detector collected 0.5/fb collision data for the first 4 weeks of Run3
  - Used for commissioning and validation of data acquisition and processing
- Measured track multiplicity 2.3×10^4 cm^2/fb^{-1} consist with FLUKA simulation and in-situ measurement in 2018
- Very good spatial resolution (0.2um)
- Collected >40/fb data !

		Integrated luminosity (/fb)	# neutrino interaction expected
2022 1st module	Mar 15 - Jul 26	0.5	~7
2022 2nd module	Jul 26 - Sep 13	10.6	~530
2022 3rd module	Sep 13 - Nov 29	~30	~1000

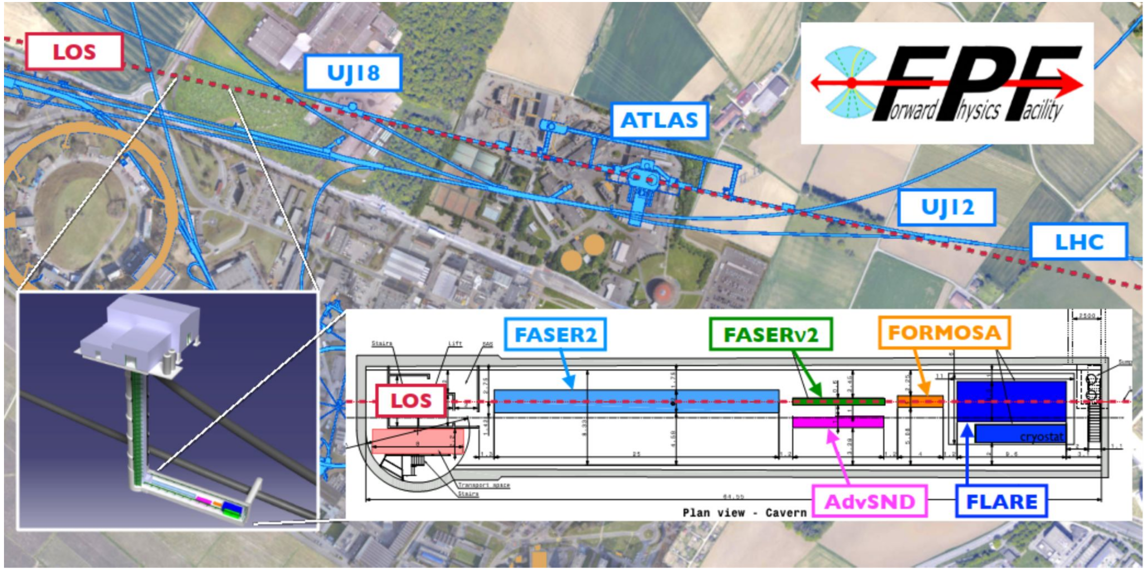




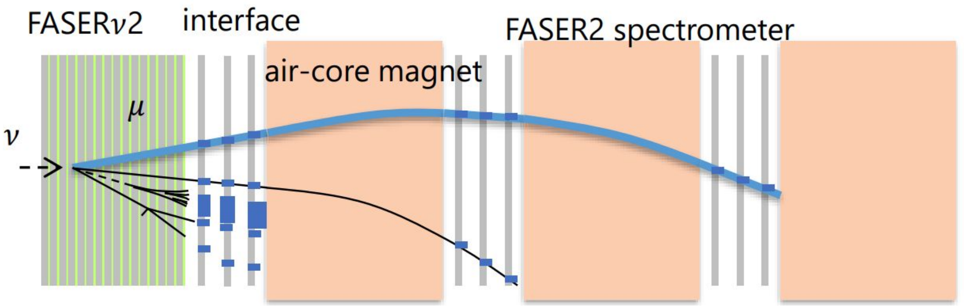


FPF and FASER2

- FASER2 for HL-LHC
  - Radius increased to 1m (FASER is 10cm)
  - Acceptance (π^0) increased to 10% (FASER is 0.6%)
- The FPF is proposal to create a new facility to house a suite of experiments on LOS
  - FASER2
  - FASERnu2
  - AdvSND
  - FLArE
  - FORMOSA



J. Phys. G: Nucl. Part. Phys. 50 030501



40cm×40cm×8m, 20 tons

O(10^5)ν_e ,O(10^6)ν_μ ,O(10^3)ν_τ expected in O(10tons) detector)

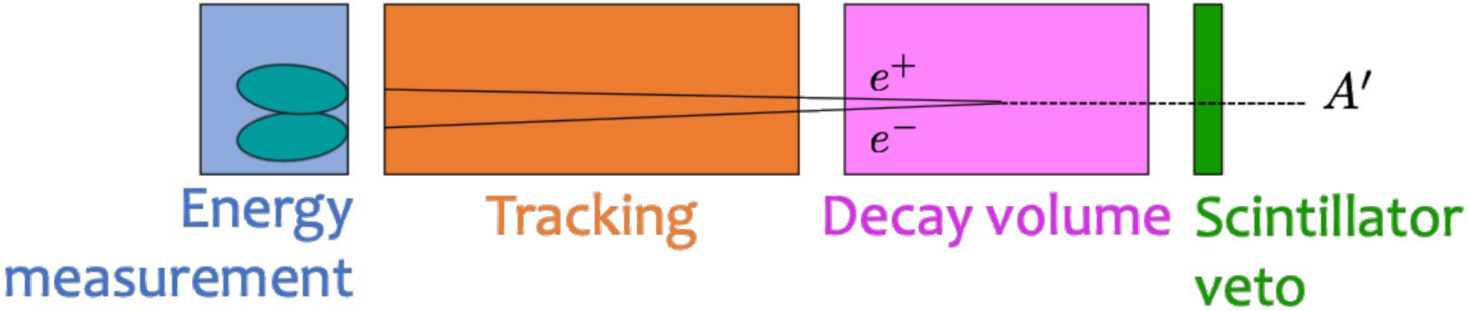
Summary and outlook

- FASER is well constructed and started to collect collision data at July 2022
  - Detector operated well in 2022 running, and collected >40/fb data
  - Will increase the sensitivity for light weakly interacting new particles at the LHC, complementing the other LHC experiments
  - Will make first collider neutrino measurements
- **Aiming to have first results in 1 month**
- Strong physics case emerging for large upgraded FASER2 detectors beyond Run 3, to be housed in the proposed Forward Physics Facility (FPF)

back-up

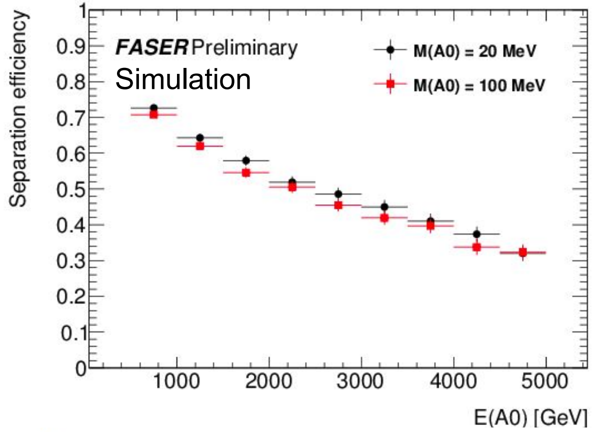
FASER detector

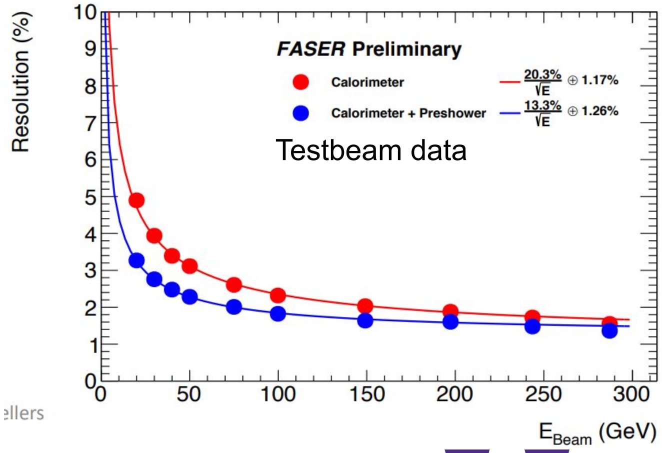
- A veto scintillator to veto charged particles
- A 1.5-meter magnetized decay volume
- A 2-meter magnetic spectrometer with three tracking stations
- An electromagnetic calorimeter
- Three scintillator stations for triggering, veto and precise timing



Key features for BSM search

- > Trigger rate O(700 Hz) - dominated by muons
- > Muon flux is 1 Hz/cm^2 for L=2×10^{34} cm^{-2}s^{-1}
  - – Confirmed by in situ measurements in 2018.
- > Tracking detector strip pitch 80 μm with 40 mrad stereo angle
  - – ~ 20 μm resolution in precision coordinate
  - – ~ 550 μm in the other coordinate
- > Good separation for two collimated tracks
- > EM shower energy resolution: ~1% for TeV deposits





ellers

Leptonphobic portal

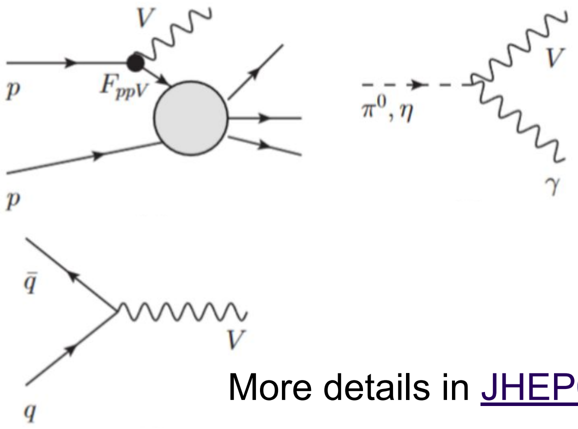
Scalar particle χ coupled to the SM via leptonphobic portal

$$\mathcal{L}_{\text{leptophob}} = -g_B V^\mu J^B_\mu + g_B V^\mu(\partial_\mu \chi^\dagger \chi + \chi^\dagger \partial_\mu \chi), \quad J^B_\mu = \frac{1}{3}\sum_q \bar{q}\gamma_\mu q$$

In p-p collision,

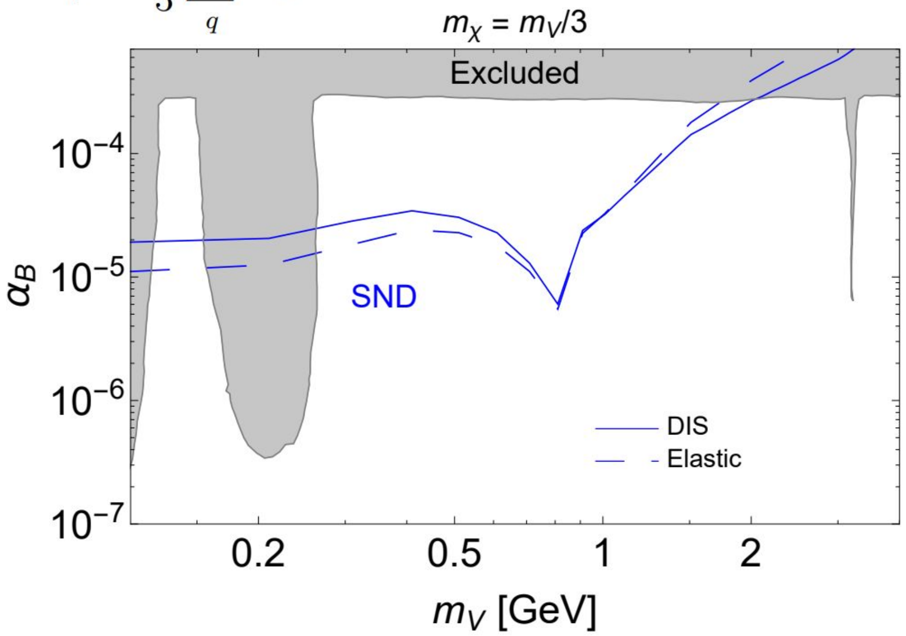
$$p+p \to V, V \to \chi\bar{\chi}$$

Vector mediator may be produced via:

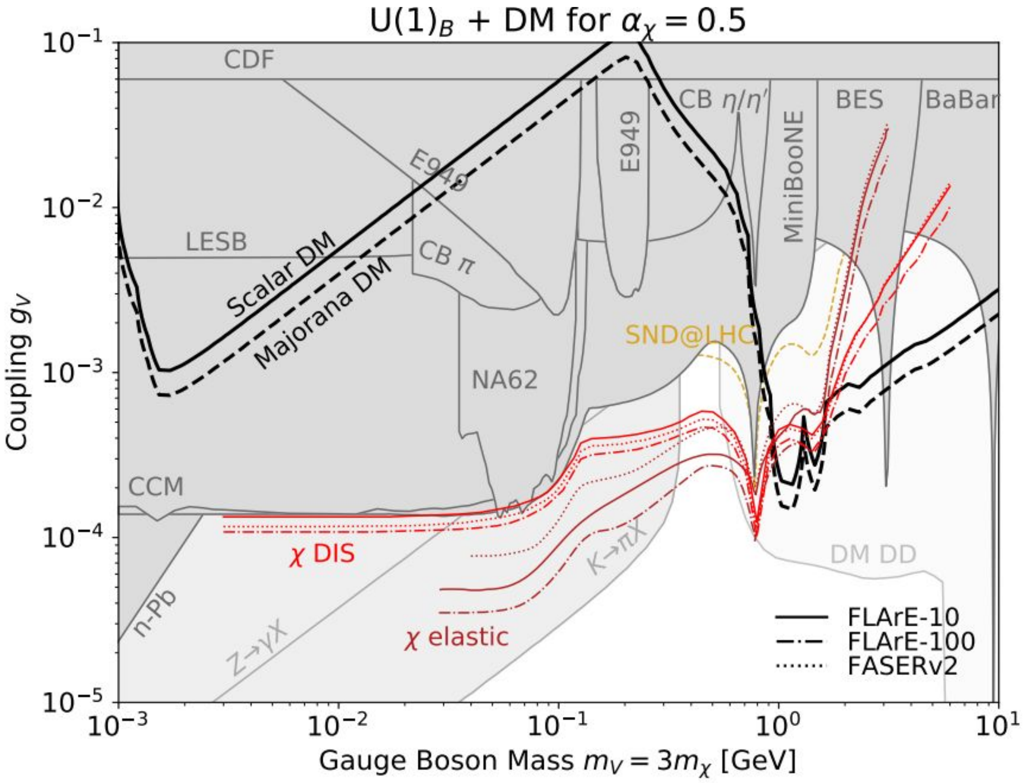


More details in JHEP03(2022)006

Grey region excluded by CDF, BES, E949 and BNL



Summary for different experiments



arXiv:2111.10343

Vector mediator: dark photon (A')

Vector portal with minimal SM extension

$$\mathcal{L}_{A'} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m^2_{A'}}{2}A'^{\mu}A'_{\mu} - \frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu},$$

- Assume $\mathrm{BF}(A' \to \chi\chi^\dagger) \sim 1$
- A' Is produced in:
  - Meson (η,π^0...) decay
  - Proton bremsstrahlung
- Zero SM background from simulation
- Compared to NA64
  - Complementary approach: direct search
  - Suppressed by ε^2

Grey/orange region excluded by MiniBooNe and NA64

$m_{A'} = 3\,m_\chi$ and $\alpha_D = 0.1$.