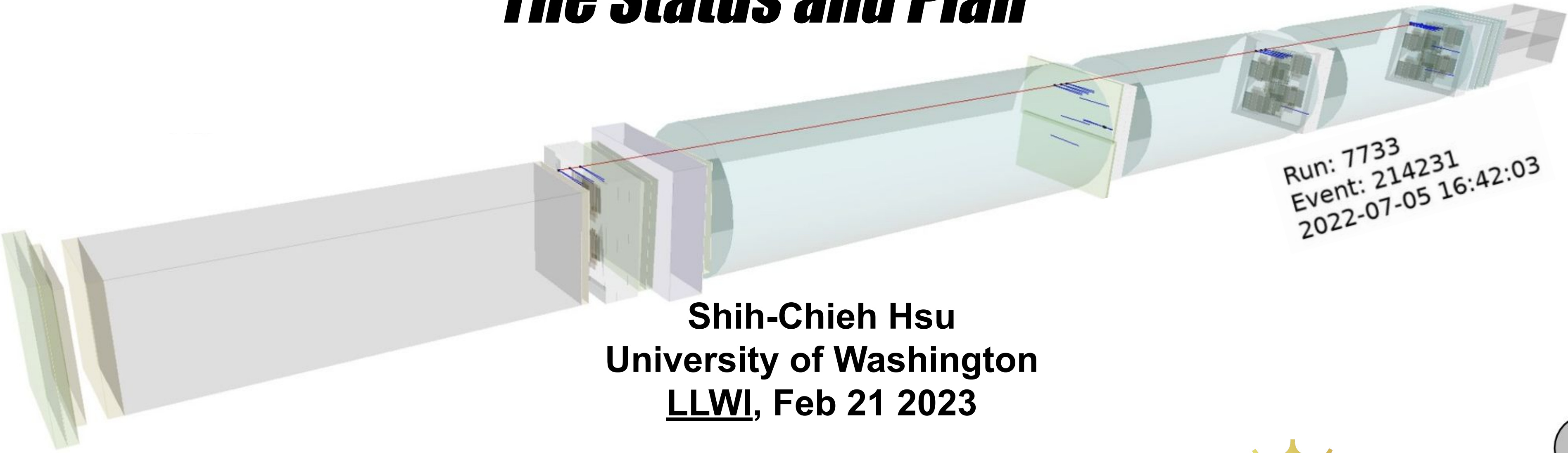
FASER

The Status and Plan



Shih-Chieh Hsu
University of Washington

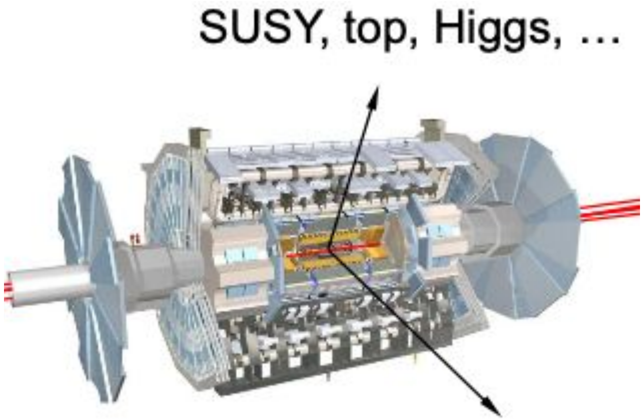
LLWI, Feb 21 2023

HEISING-SIMONS FOUNDATION SIMONS FOUNDATION Swiss National Science Foundation 科研費 KAKENHI erc NSF

Energy frontier at the LHC

The LHC collisions with the highest center-of-mass energy in the world.

- It was designed to search for heavy strongly produced new particles, and to study heavy Standard Model physics
- Existing experiments well suited for this, and performing extremely well



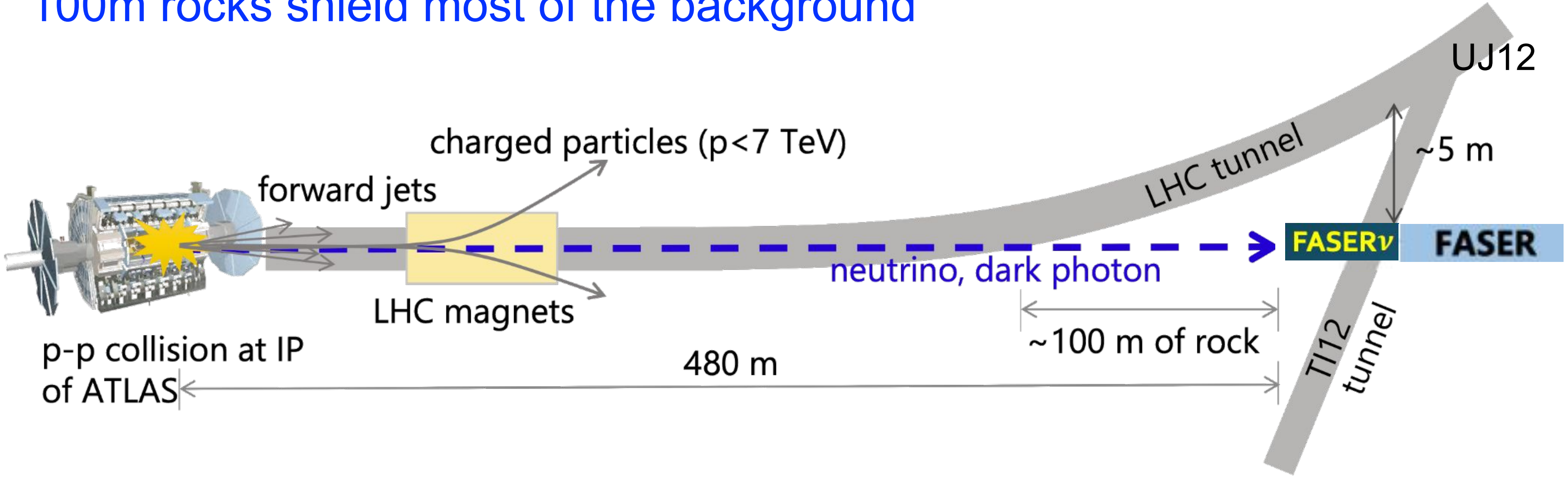
Intensity frontier at the LHC

The LHC collisions with high luminosity for study of intensity frontier physics

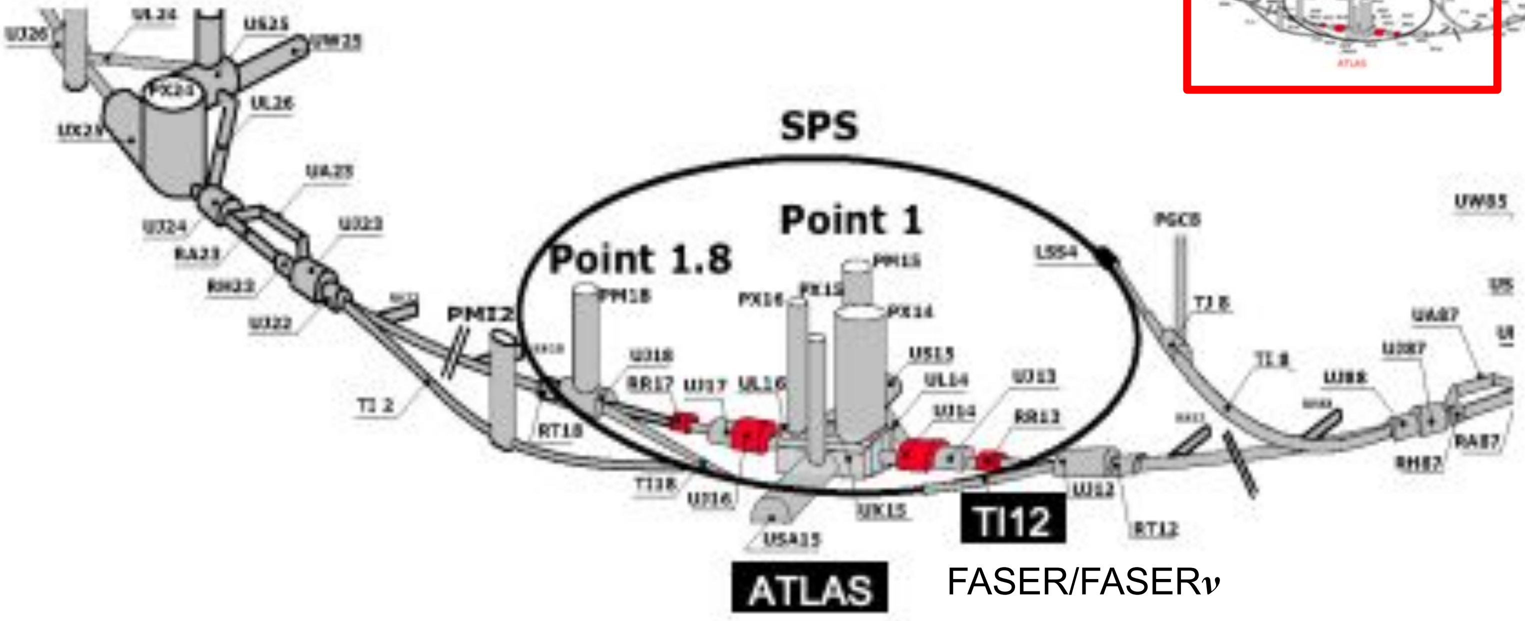
- The huge number of light SM hadrons that are produced in the LHC collisions opens the window for LHC to study this domain normally studied by the fixed target experiments.

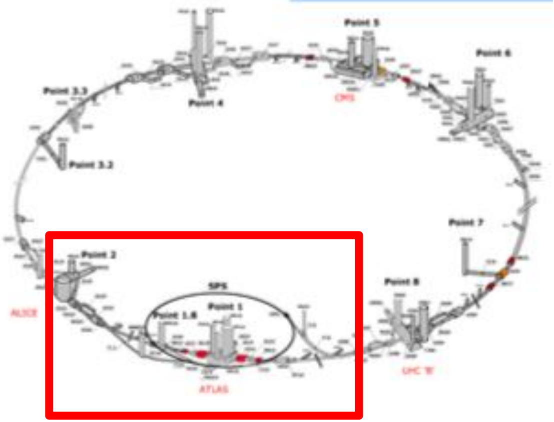
Forward **S**earch **E**xp**ER**iment at the LHC

- Many light particles at LHC produced in π, K, D meson decay
  - N~ 10^{16} pions/10^{12} neutrinos in LHC Run 3 (2022-2025)
  - E~ TeV, $\theta_{\text{beam axis}}$ ~ mrad
- Unique opportunities to search long-lived particles and measure energetic neutrino
  - 480m downstream from ATLAS, placed directly into the beam
  - 100m rocks shield most of the background



FASER Location: TI12 tunnel





FASER/FASERν

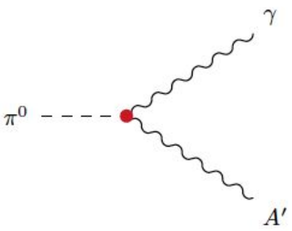
Dark Sector Search with FASER

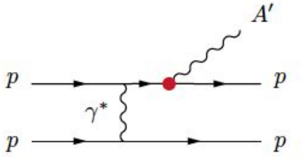
Dark Photon

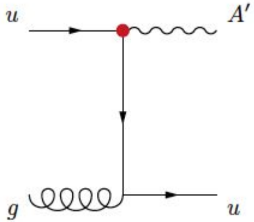
Spin 1, couples weakly to SM fermions

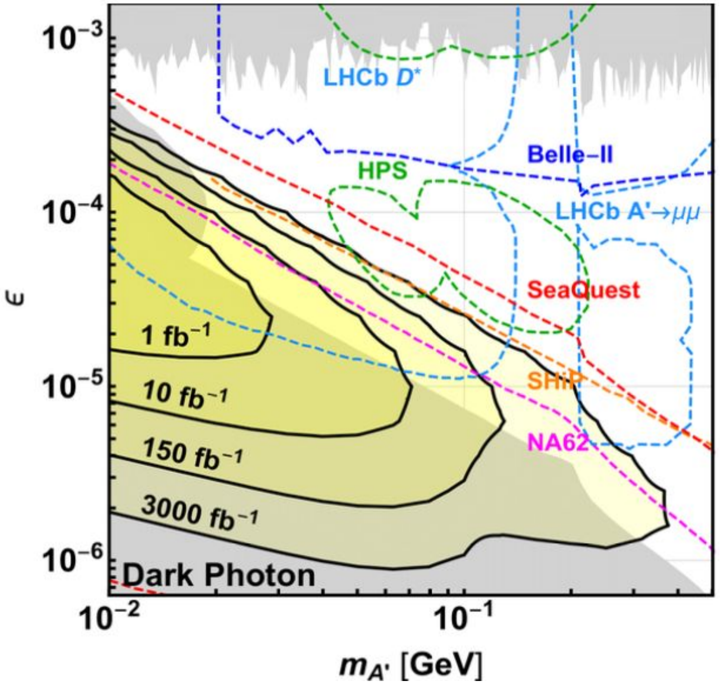
$$\mathcal{L} \supset -\frac{\varepsilon'}{2} F_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m'^2 X^2$$

Mainly from decays of light mesons, π, η, dark bremsstrahlung and hard scattering



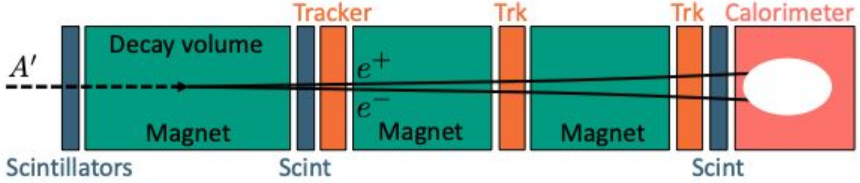






A’ → e+e-, μ+ μ-,π+ π-

480m

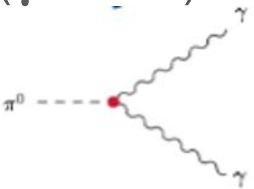


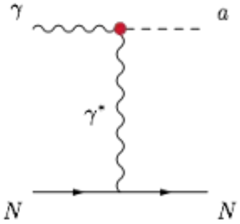
Axion-like Particles

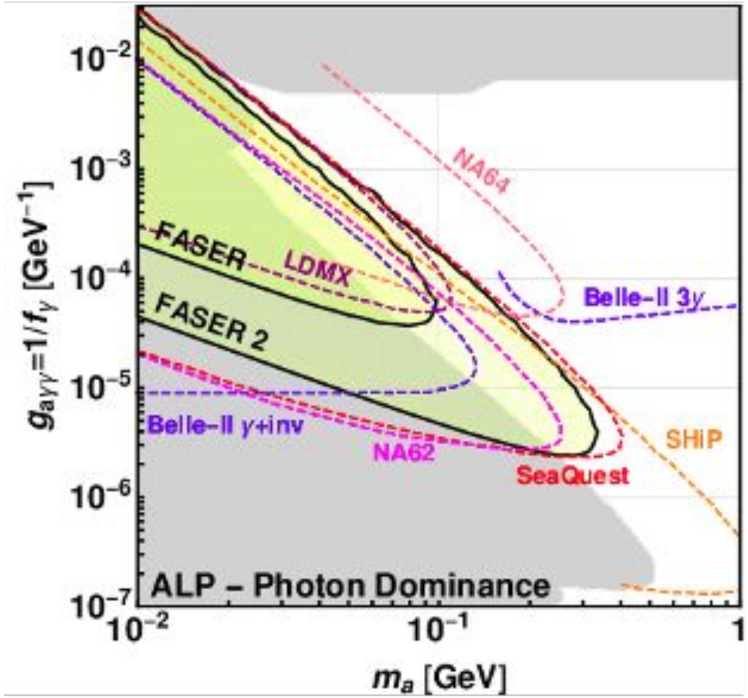
ALPs only couple to photons

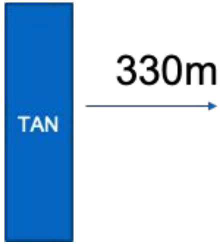
$$\mathcal{L} \supset -\frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu} \widetilde{F}_{\mu\nu} ,$$

Mainly produced via Primakoff process ($\gamma N \rightarrow aN$)

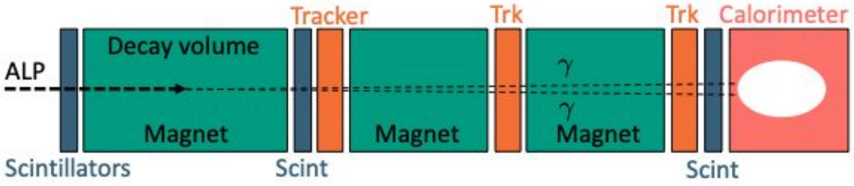








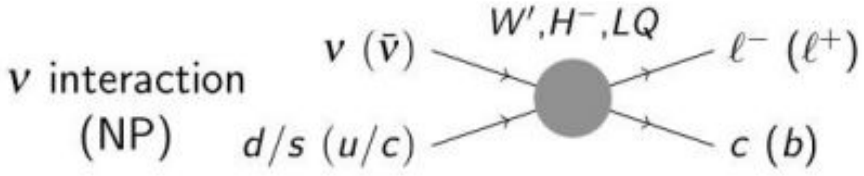
a→γγ or γe+e-

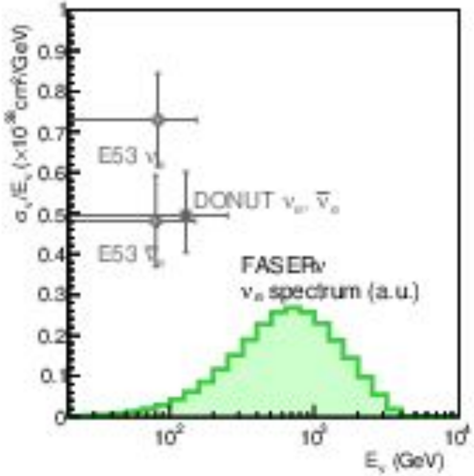


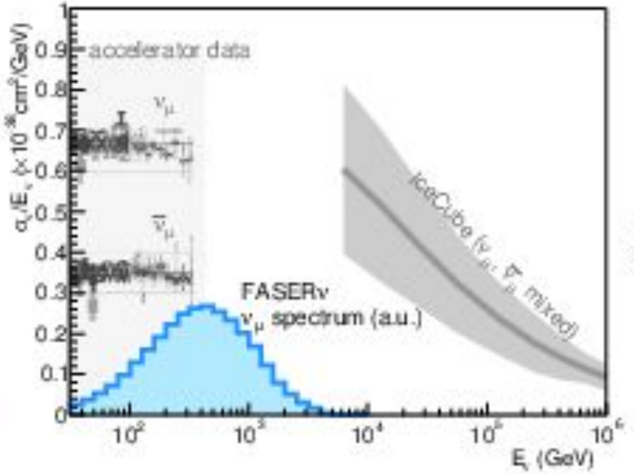
Neutrino Physics with FASERν

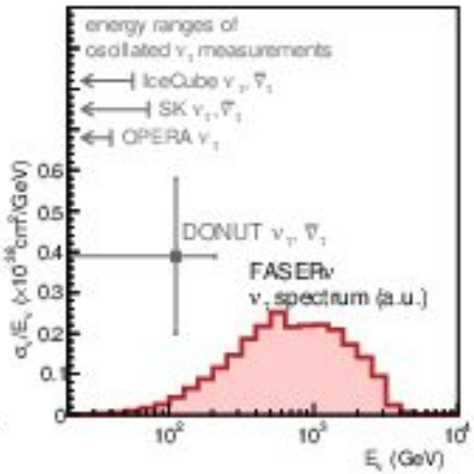
Exploring neutrinos at the TeV energy

Sensitive to new physics by measuring scattering cross sections and studying each flavor





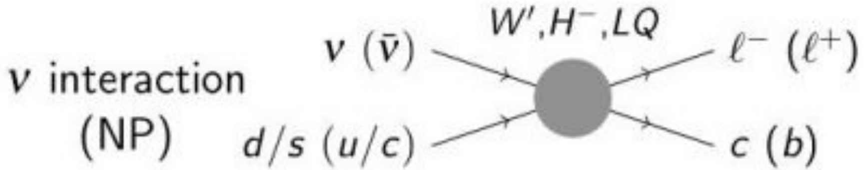


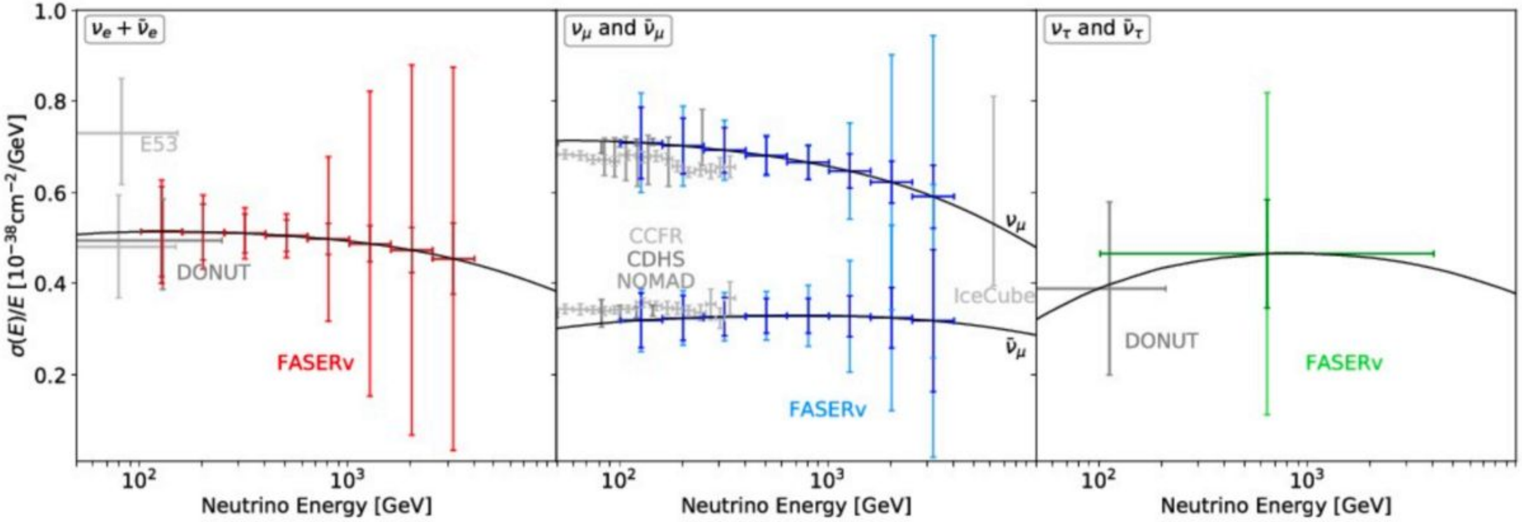


150/fb ~1300 interactions ~20000 interactions ~20 interactions

Exploring neutrinos at the TeV energy

Sensitive to new physics by measuring scattering cross sections and studying each flavor

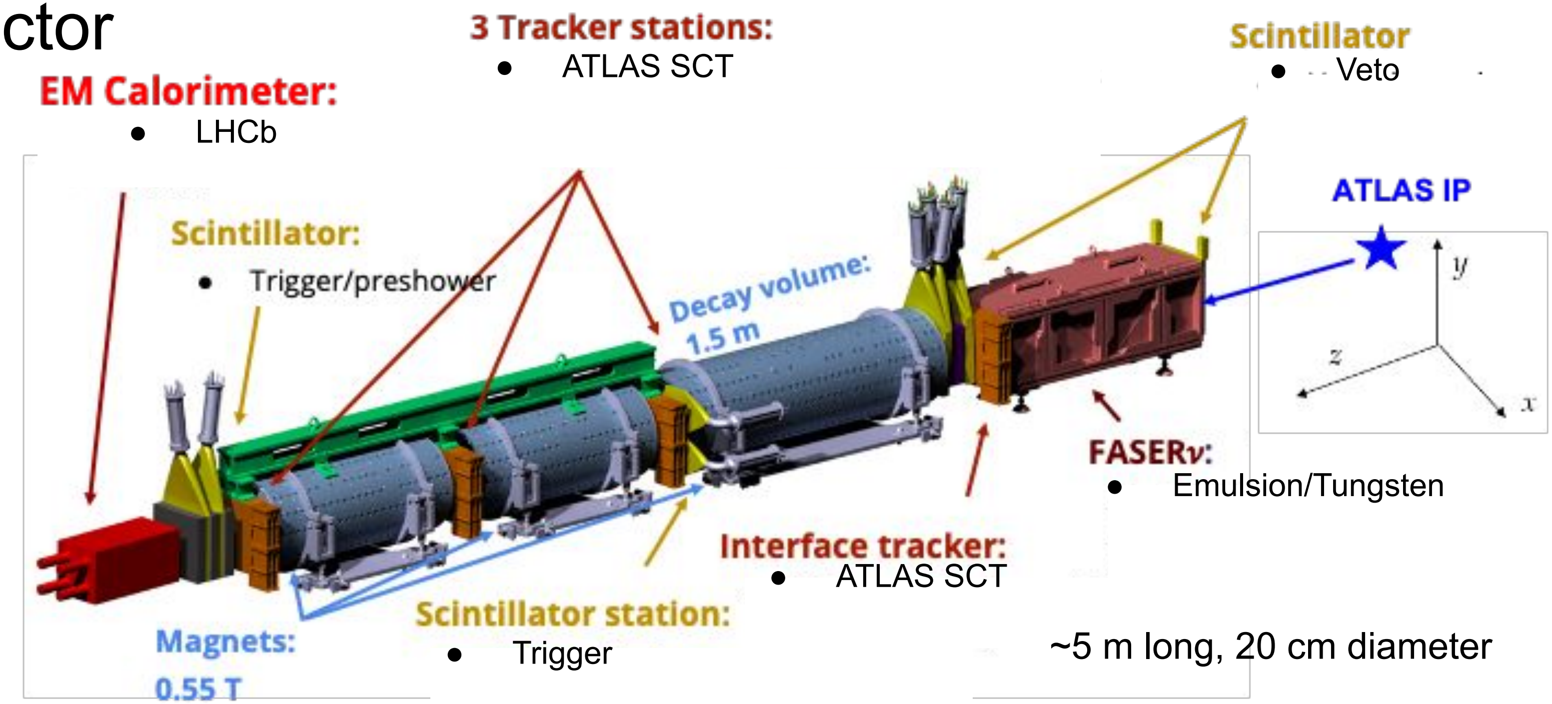




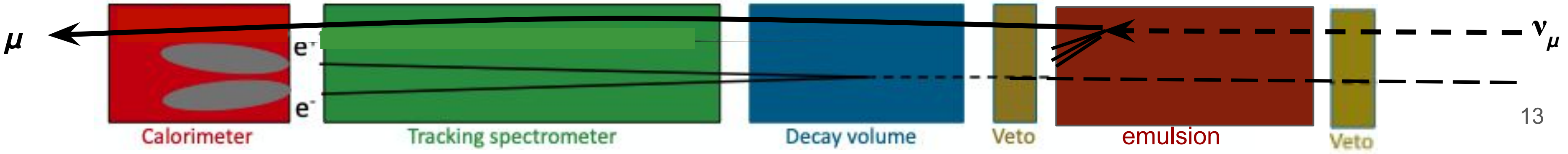
FASER/FASERν Detector

arxiv: 2207.11427

Detector



~5 m long, 20 cm diameter

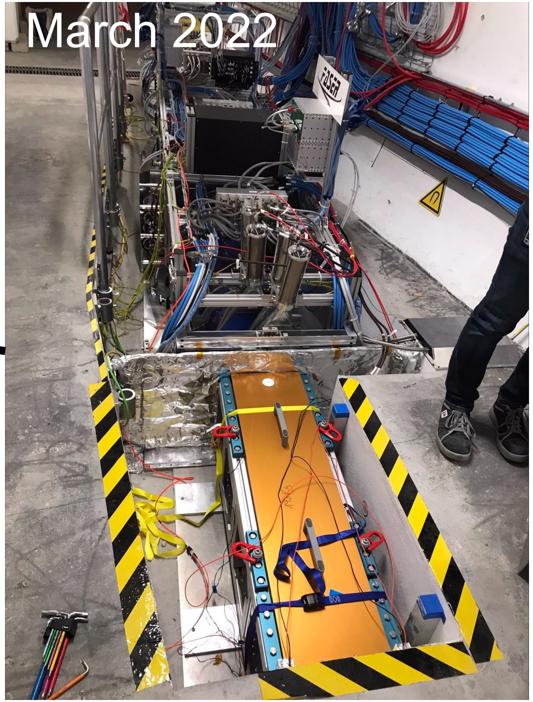


FASER in TI12

LOI arXiv:1811.10243
TDR arXiv:1812.09139

Complete Installation in TI12

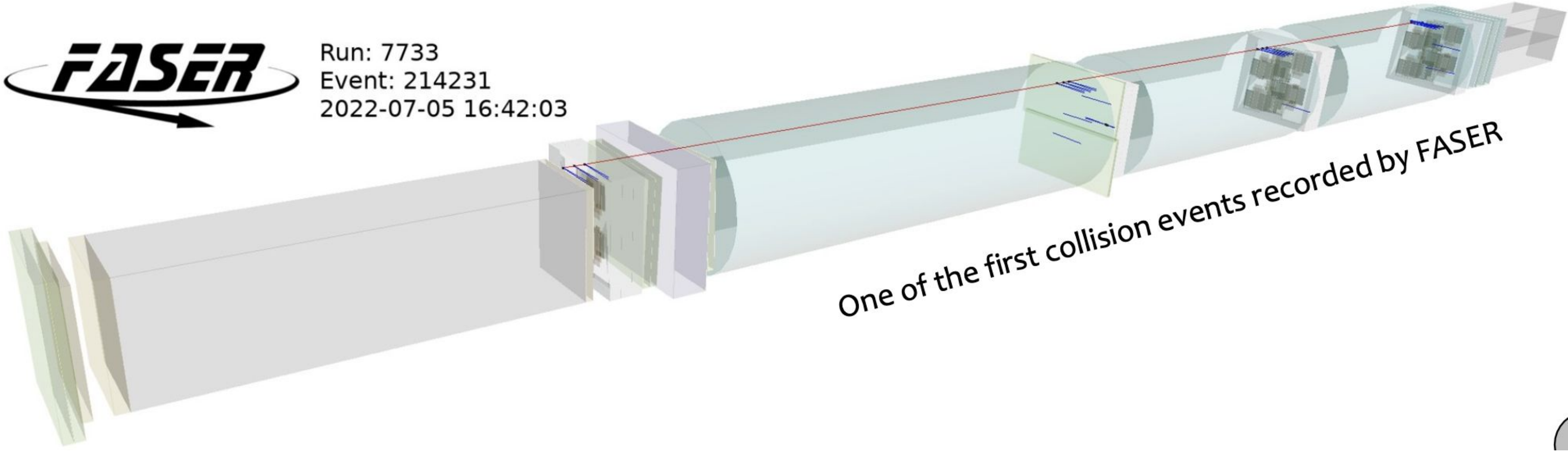
From
ATLAS



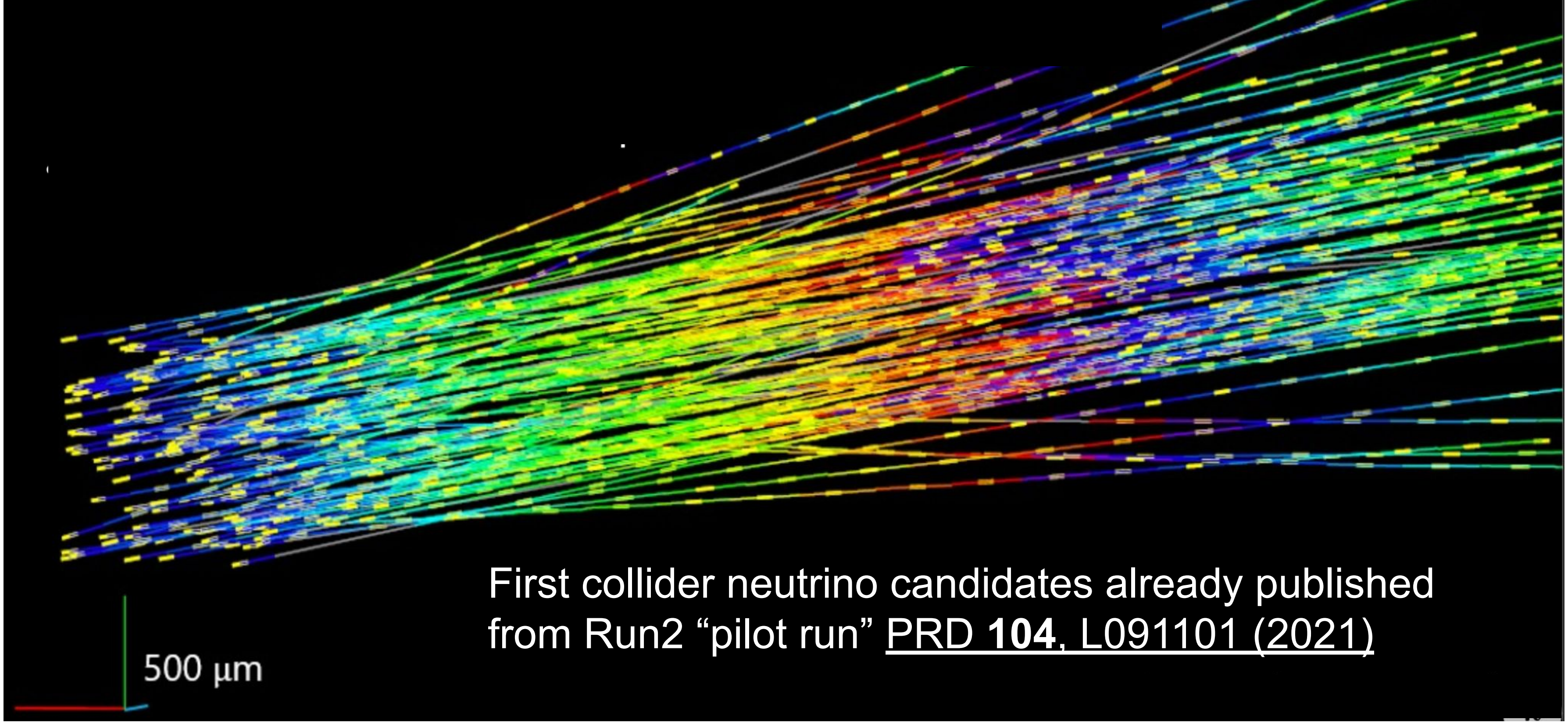
FASER spectrometer (magnets and tracker), trigger scintillators and calorimeter

Emulsion/Tungsten, IFT and veto scintillator

Run 3 Data Taking



First 2022 collisions as seen by FASERν

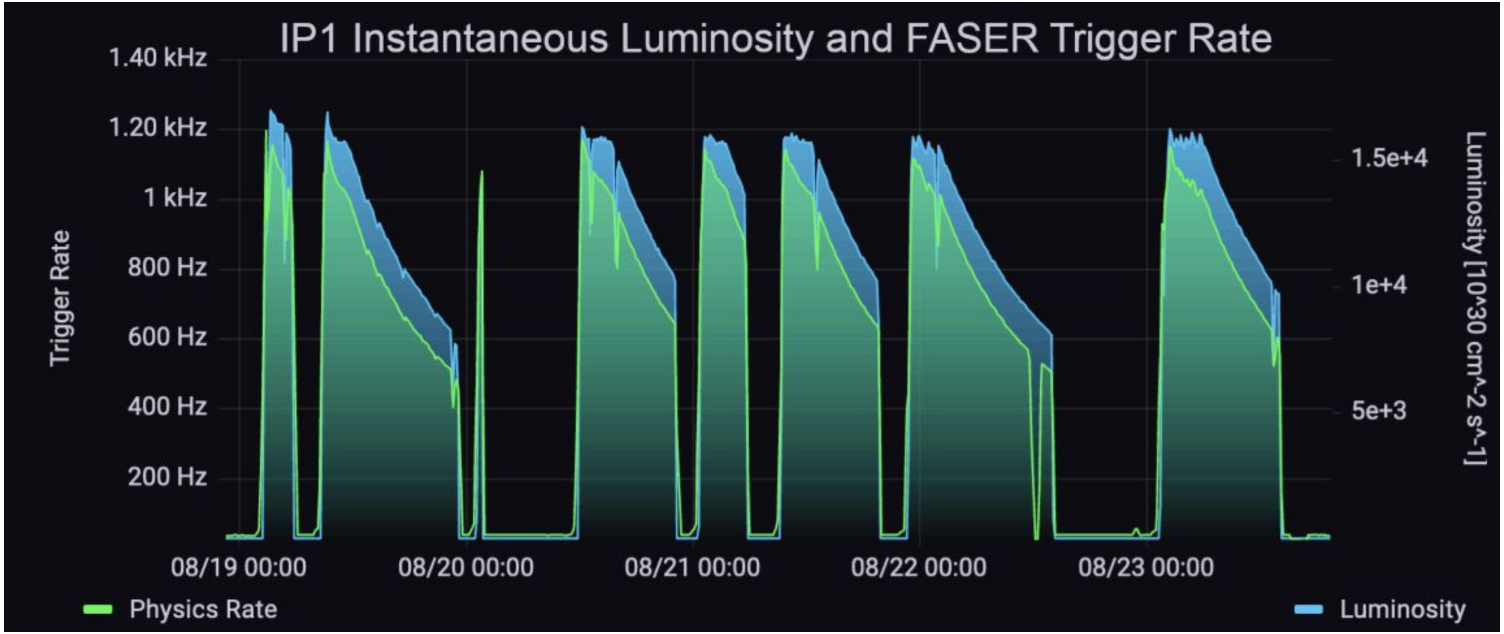


First collider neutrino candidates already published from Run2 “pilot run” PRD **104**, L091101 (2021)

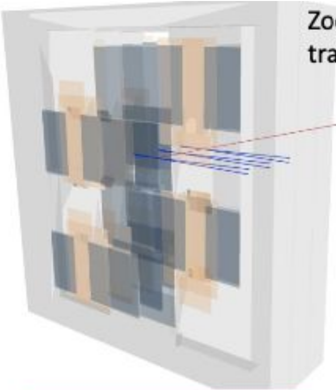
Operation and Detector Performance

Smooth operation since July 2022

- No major issues observed so far. Detector time in with the first collision data.
- > 35/fb data recorded (<2.5% of data lost due to operational issues).
- Maximum trigger rate is ~1.2 kHz (physics deadtime < 2%).



Collision Muon Event



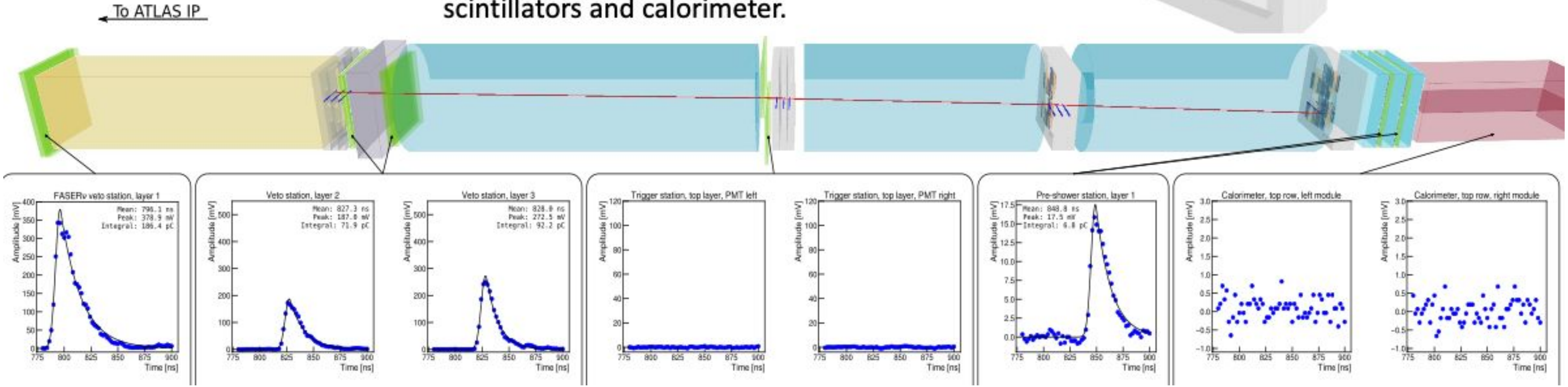
Zoom in of 1st tracking station

J. Boyd

FASER

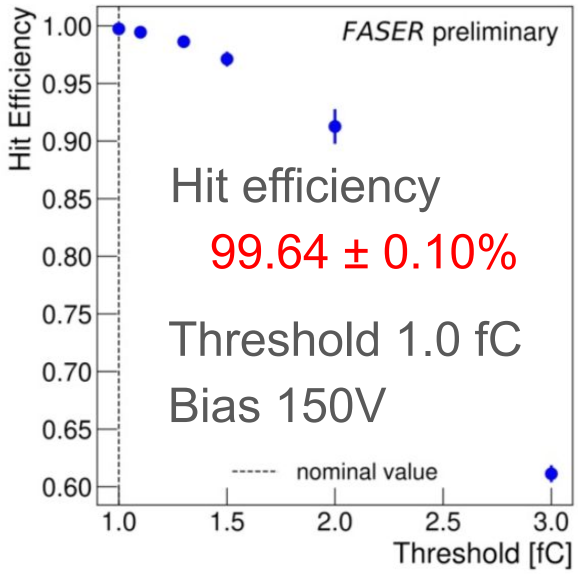
Run 8336
Event 1477982
2022-08-23 01:46:15

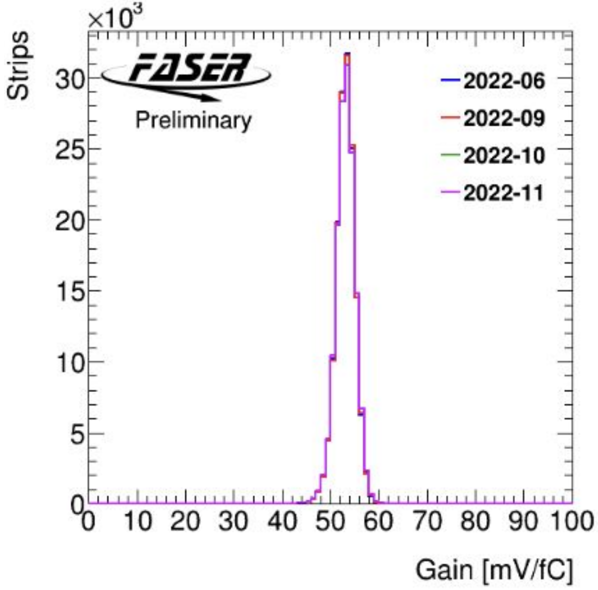
Collision event with a muon traversing FASER
Reconstructed momentum 22 GeV.
Signal consistent with MIP seen in all scintillators and calorimeter.

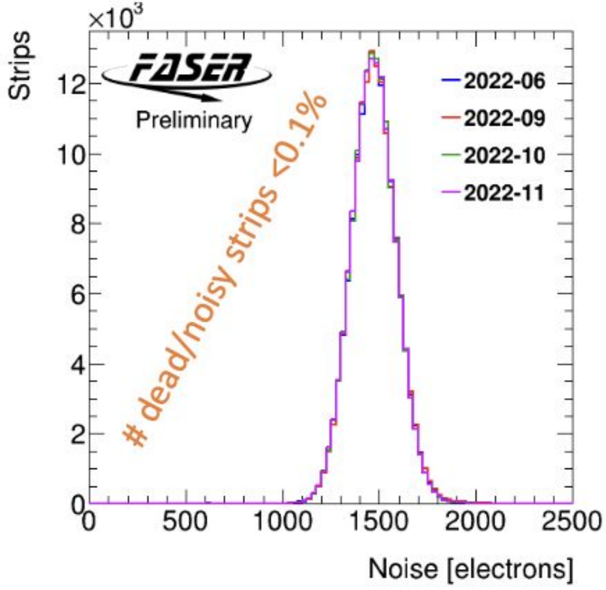


Tracker stable performance since 2022

- More than 99.5% strips are active
- Calibration periodically performed to achieve performance as good as the ATLAS SCT

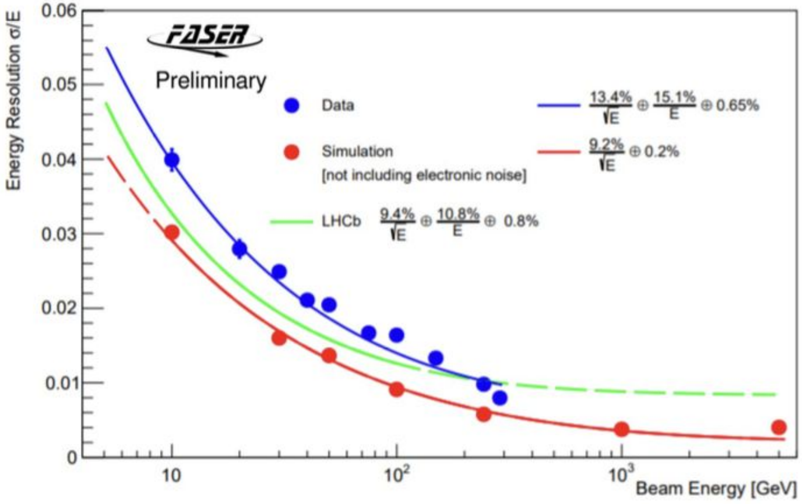


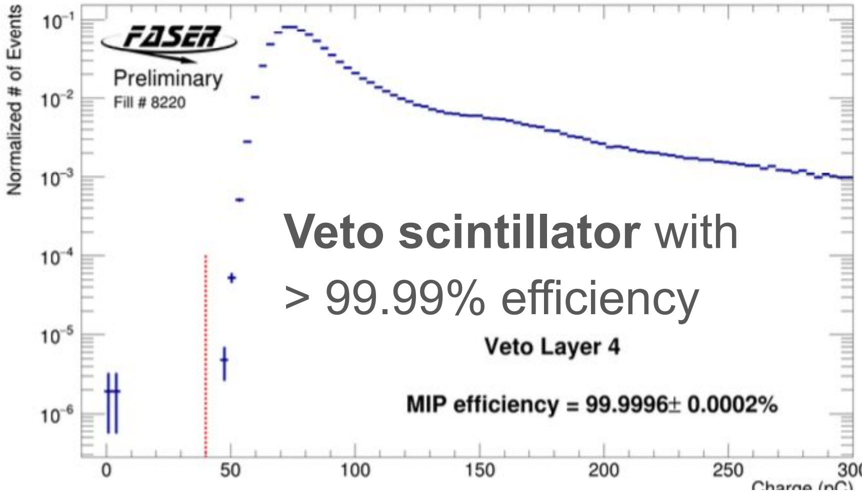




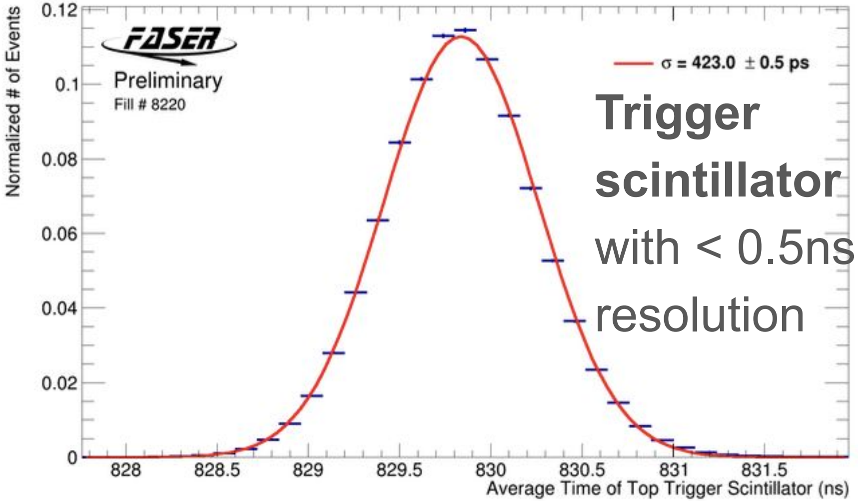
Calorimeter and Scintillator

Calorimeter
resolution confirmed ~1% for energetic electrons





Veto scintillator with > 99.99% efficiency

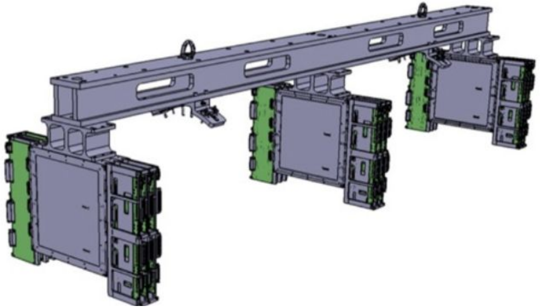


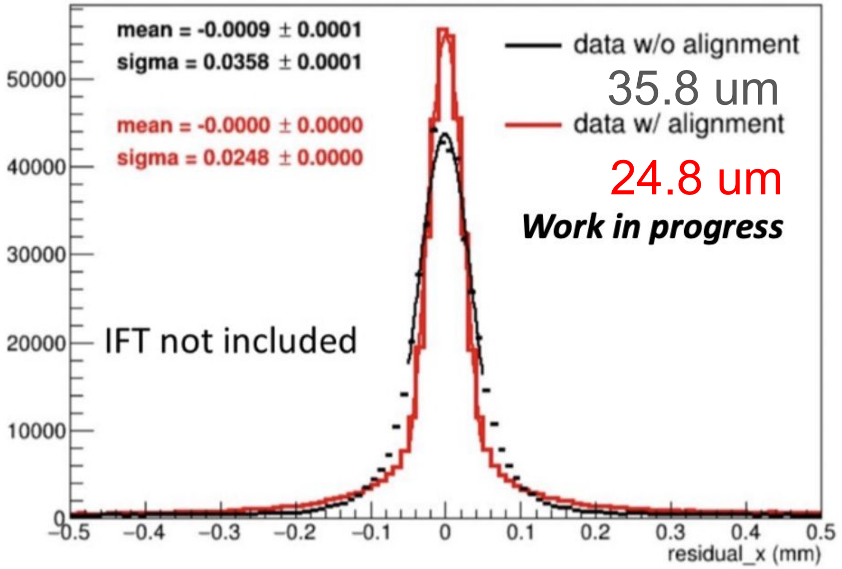
Trigger scintillator with < 0.5ns resolution

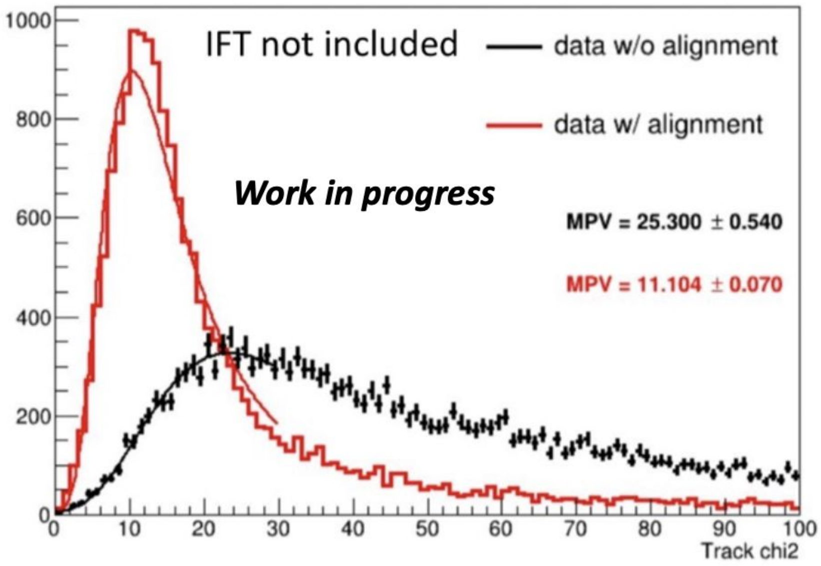
Track based alignment in progress

Significant improvement of hit residuals and track chi2

- Three tracker stations are connected to the backbone, mechanically decoupled from fourth tracker station (IFT)

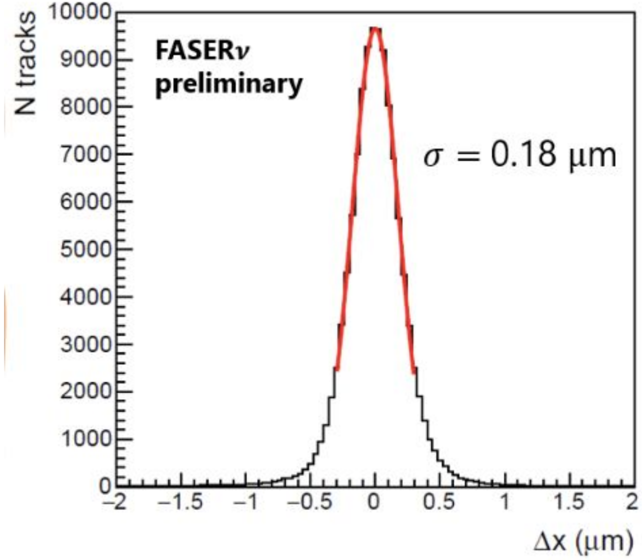


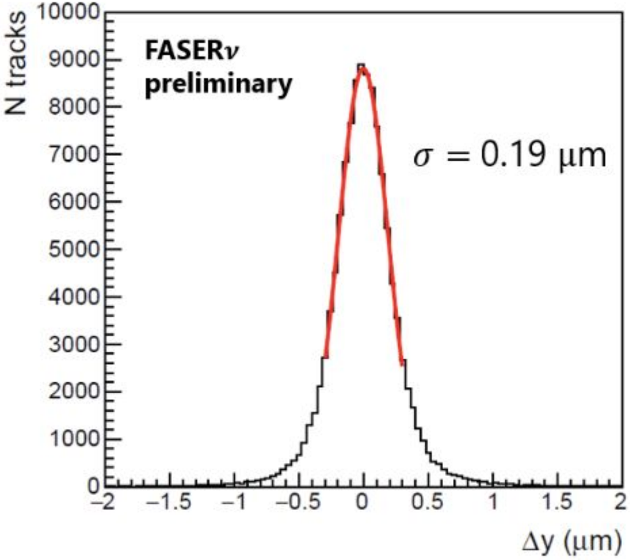




FASERnu performance in the first 2022 collisions

- 10/fb data (~500 neutrinos, films installed in July 26 and removed in Sep 2)
- Measured track multiplicity consistent with FLUKA simulations (1.2×10^4 tracks/cm^2/fb^{-1})
- Excellent track resolution measured in first data!

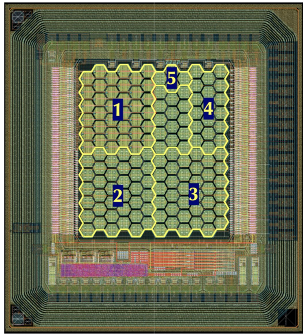




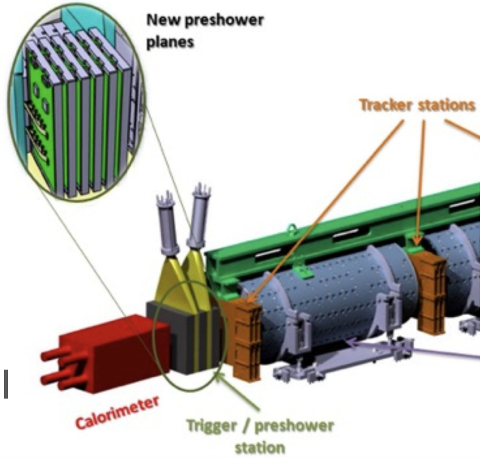
Run 3 and Beyond

Pre-shower upgrade for 2025 (3rd year of run 3)

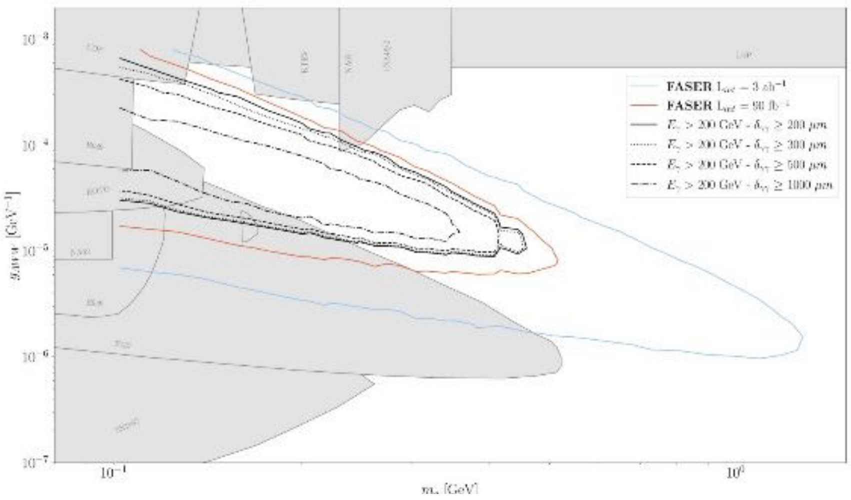
- Preshower scintillator will be replaced by hybrid pixel detector
- Installation by the end of 2023, and data-taking from 2024



100μm pitch hexagonal
130nm SiGe BiCMOS



- Upgrade to enable detecting ALPs$\rightarrow \gamma\gamma$ searches (2 photon separation by ~200μm)



- Approved by CERN research board in April 2022 [CERN-LHCC-2022-006]

Snowmass White paper
arXiv:2203.05090

5th FPF meeting
https://indico.cern.ch/event/1196506/

Forward Physics Facility toward HL-LHC

A new dedicated facility 617 m to west of ATLAS (IP1) for 5 experiments

Rich and broad physics programs:

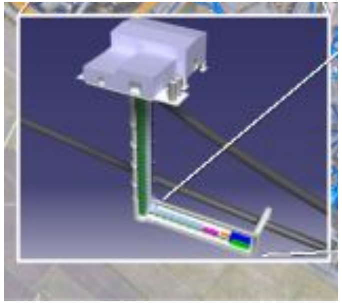
- Dark sector searches
- Neutrino physics
- QCD

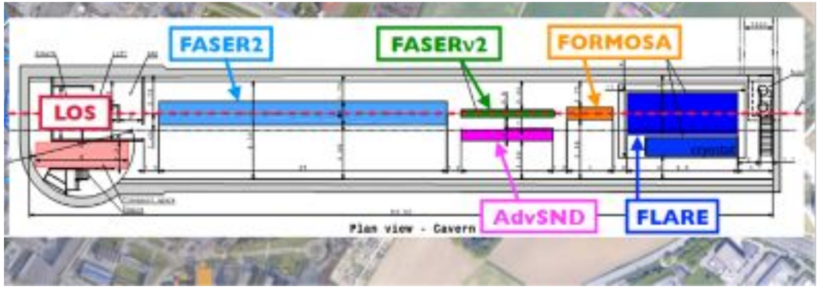
FASER 2

- 2m diameter (FASER x10)
- Sensitive to particles produced from heavy flavor decay

FASERν2

- $\mathcal{O}$(20tn) emulsion/tungsten detector (FASERν x20)





65m x 9.7m x 7.7m
88m high shaft

Summary

- FASER - a new forward experiment at the LHC in the unused tunnel, TI12
    - Give access to light weakly-coupled particles in MeV-GeV range
    - Probe TeV-energy neutrino in all flavors - First collider neutrino candidate is published!
- Smooth data taking in LHC Run 3 from 2022:
    - Great progress of operation and performance matching expectation
    - Simulation and data analysis on-going
- Upgrade toward enhancing **forward physics program**
    - Near term preshower upgrade for ALP search
    - Longer term Forward Physics Facility enabling broad physics programs
        - Tight timeline for construction
        - More discussions in Seattle Snowmass Community Summer Study July 17-26 2022

Snowmass 2021

Community Summer Study SNOWMASS 2022 July 17 - 26 Seattle

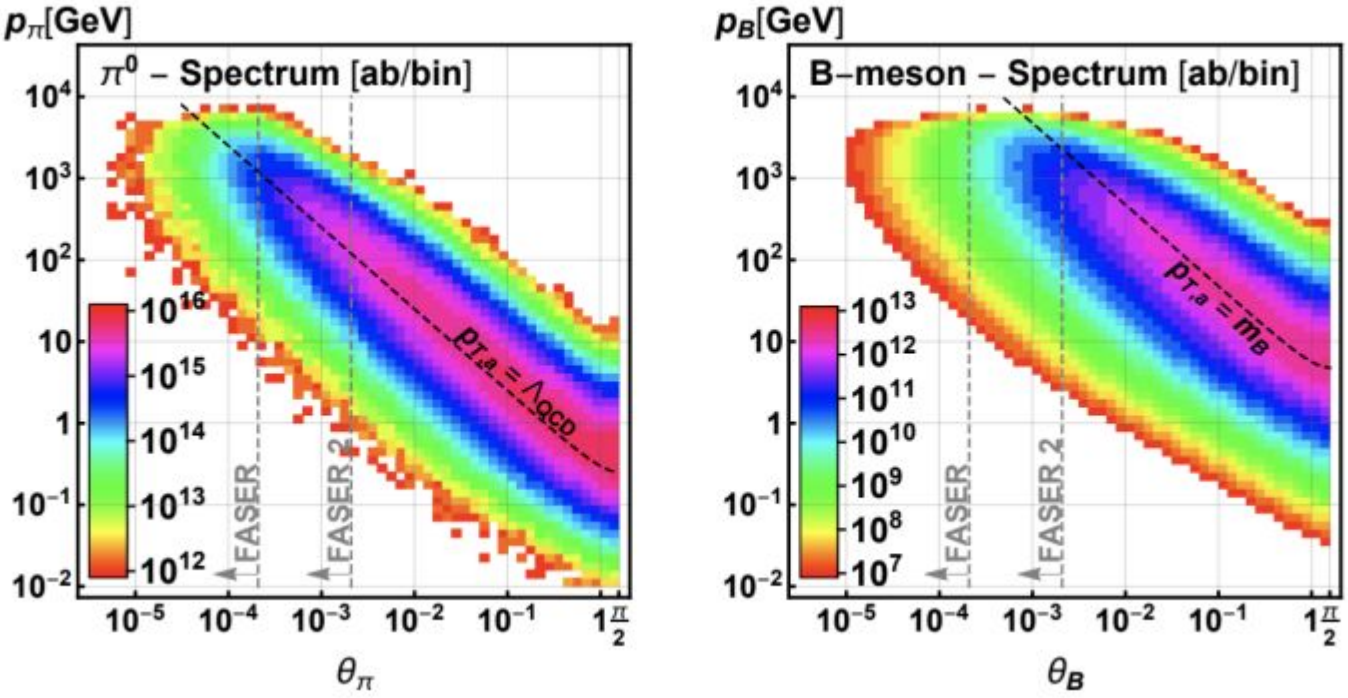
http://seattlesnowmass2021.net/

Thank you for your attention

85 members
22 institutions (**3** USA)
9 countries

CERN · Université de Genève · Kyushu University · UC Irvine · Universität Bern · Technion · Nagoya University · University of Washington · Johannes Gutenberg Universität Mainz · Weizmann Institute of Science · KEK · University of Oregon · Universität Bonn · INFN · Tsinghua University · Manchester 1824 The University of Manchester · Royal Holloway University of London · University of Liverpool · Chiba University · University of Sussex · DESY · JINR

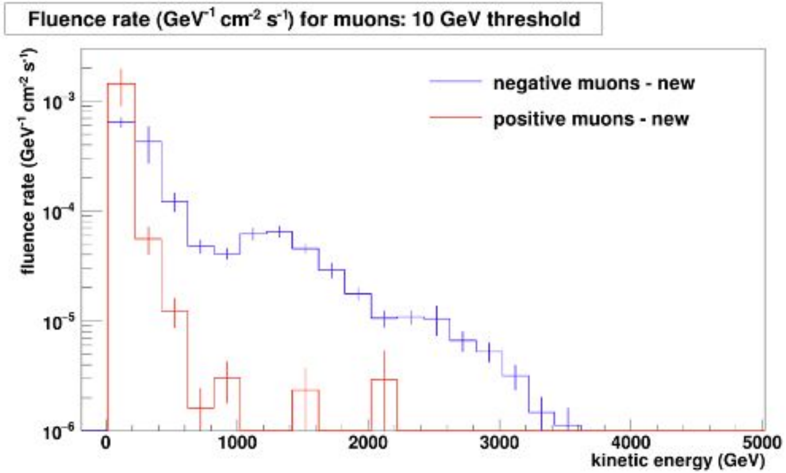
Backup



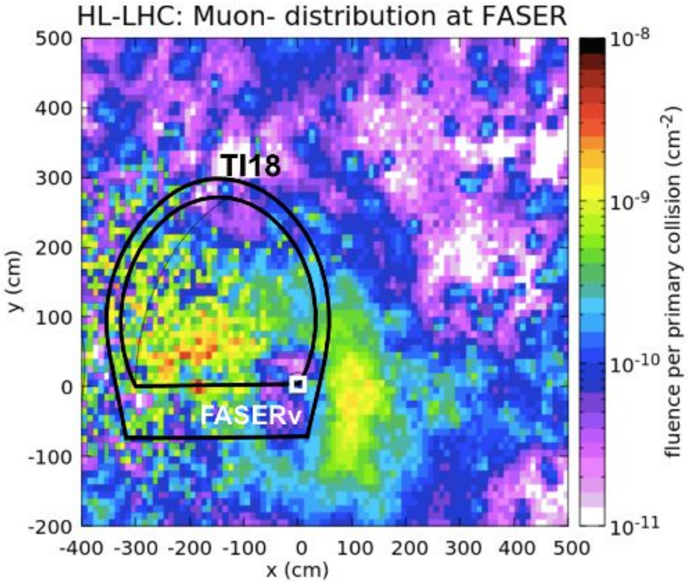
p_π[GeV]
π^0 – Spectrum [ab/bin]
$p_{T,a} = \Lambda_{QCD}$
FASER
FASER 2
θ_π
p_B[GeV]
B–meson – Spectrum [ab/bin]
$p_{T,a} = m_B$
FASER
FASER 2
θ_B

Beam Backgrounds

- FLUKA simulations and in situ measurements have been used to assess the backgrounds expected in FRASER
- FLUKA simulations studied particles entering FASER from:
  - – IP1 collisions, off-orbit protons hitting beam pipe aperture, beam-gas interactions
- Expect a flux of high energy muons (E>10 GeV) of 0.5 $cm^{-2}s^{-1}$ at FASER for $2x10^{34}cm^{-2}s^{-1}$ luminosity from IP1 collisions

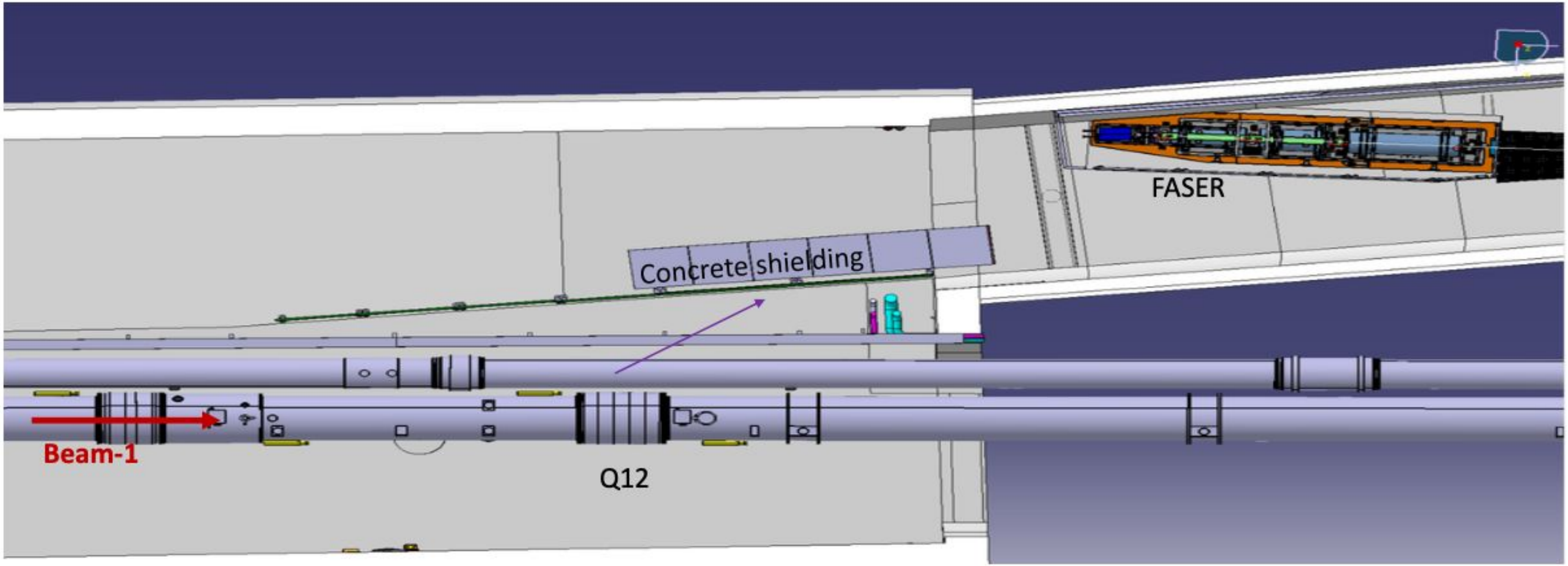


Large muon charge asymmetry at FASER due to LHC bending magnets

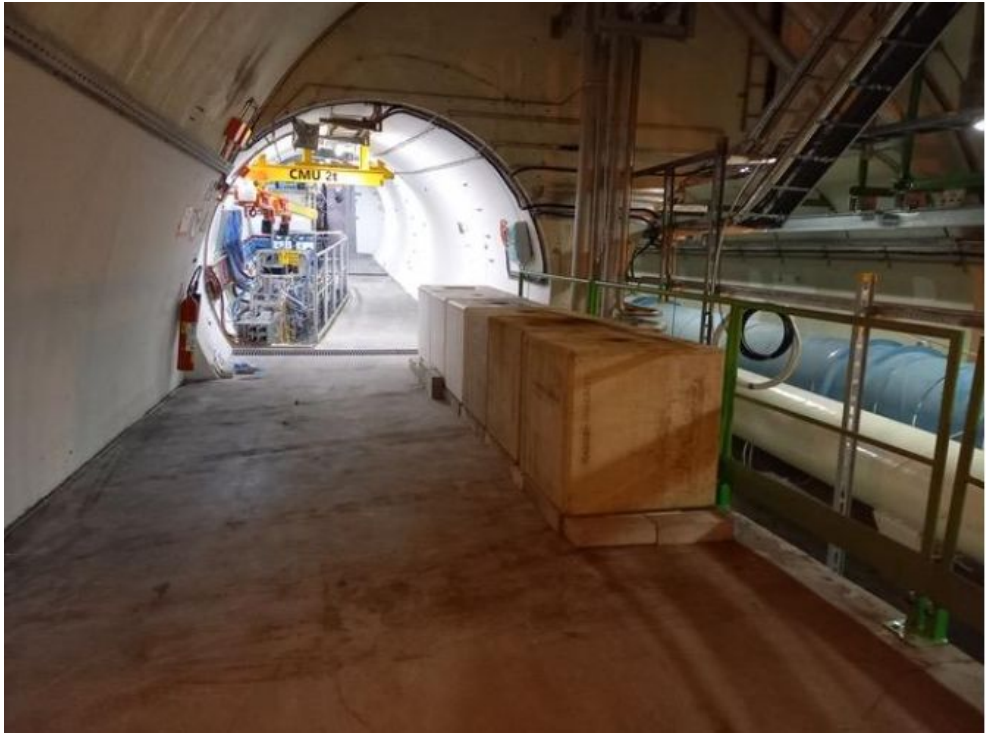


In Nov 2021 pilot run, beam-1 bunches pass the back of FASER with interactions in Q12 magnet was observed.

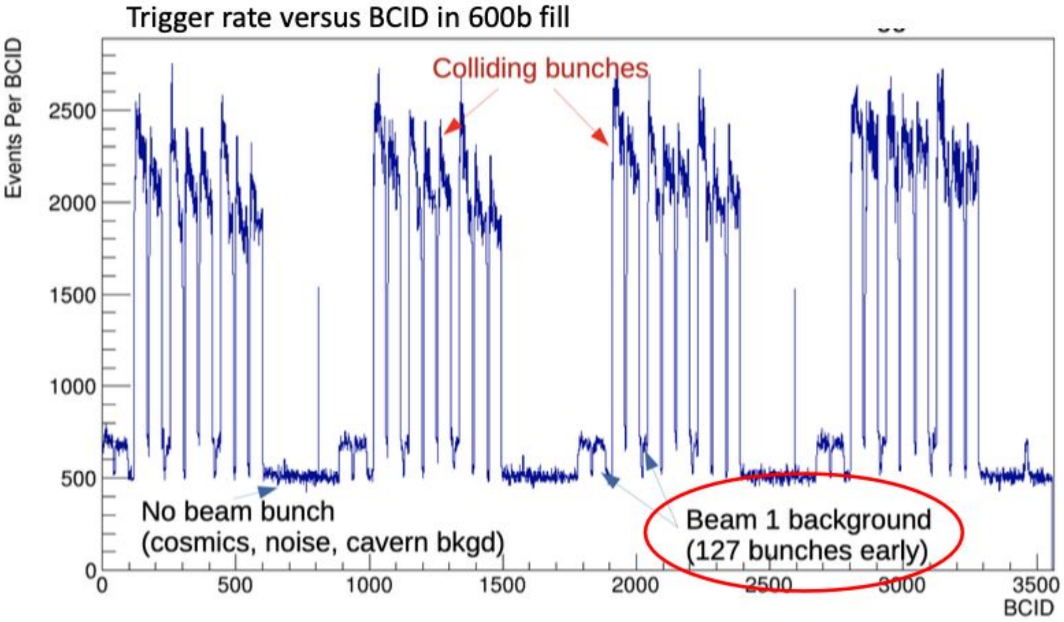
This background is ~3.2μs (127 BCs) too early compared to particles coming from IP1 to FASER



Beam-1 concrete shielding

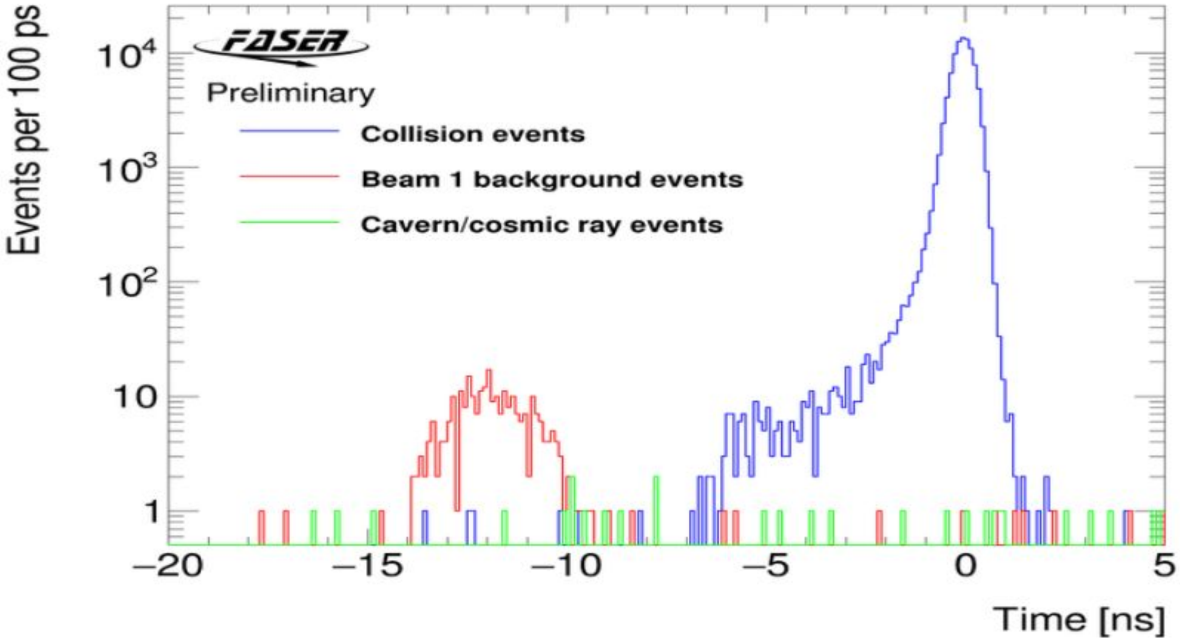


Beam-1 background observation



When LHC running with small number of bunches (600b in this plot), can identify specific BCs corresponding to beam-1 background and with no colliding bunch in IP1.

Beam-1 background removal using calorimeter timing



Calorimeter PMT

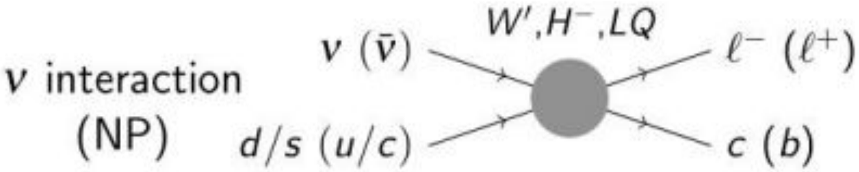
Excellent timing resolution for large energy signals (<300ps)

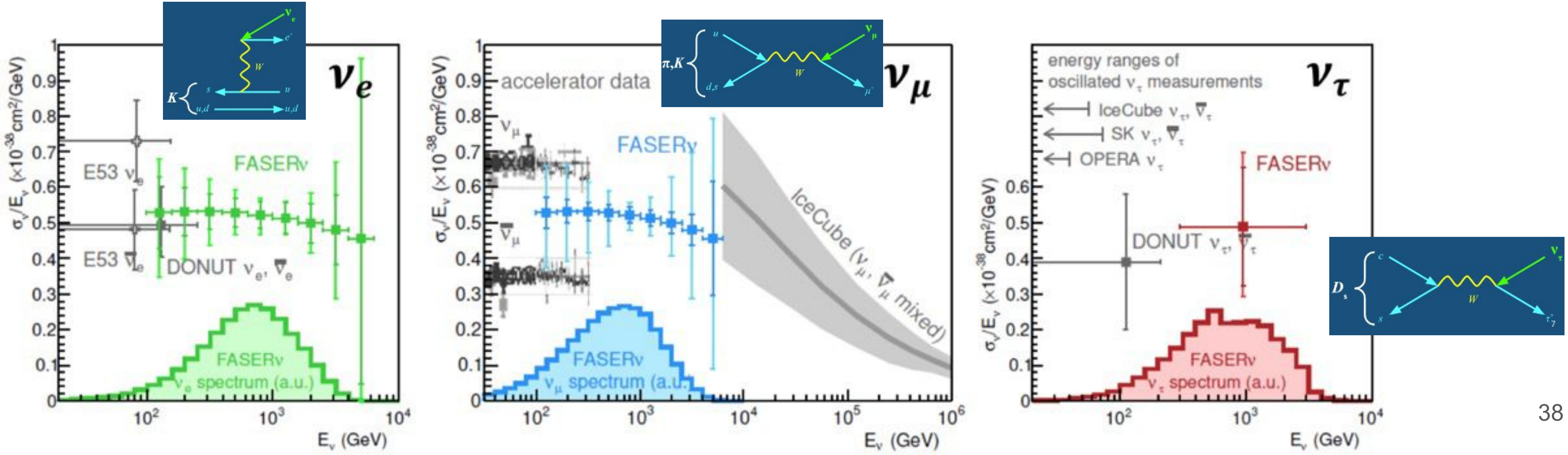
FASER neutrino sensitivity

150/fb @14TeV	ν_e	ν_μ	ν_τ
Main production source	kaon decay	pion decay	charm decay
# traversing FASERν 25cm x 30cm	$O(10^{11})$	$O(10^{12})$	$O(10^{9})$
# interacting in FASERν (1.1tn Tungsten)	~1300	~20000	~20

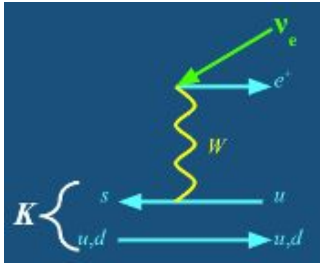
Exploring neutrinos at the TeV energy

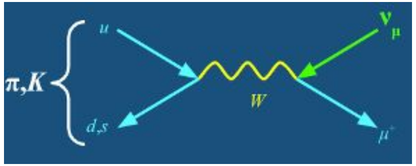
Sensitive to new physics by measuring scattering cross sections and studying each flavor

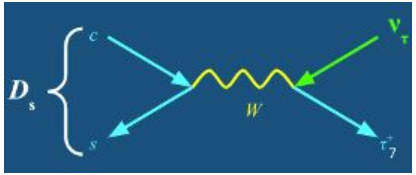


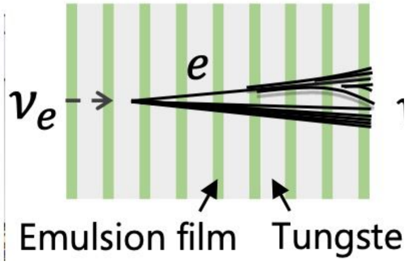


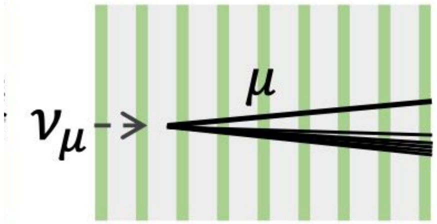
Neutrino Flavor Detection with Emulsion

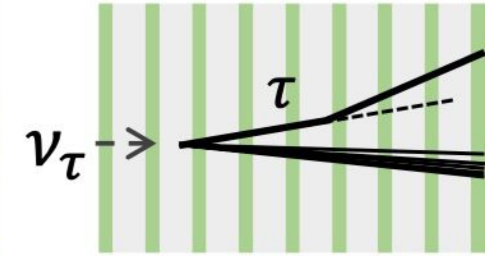




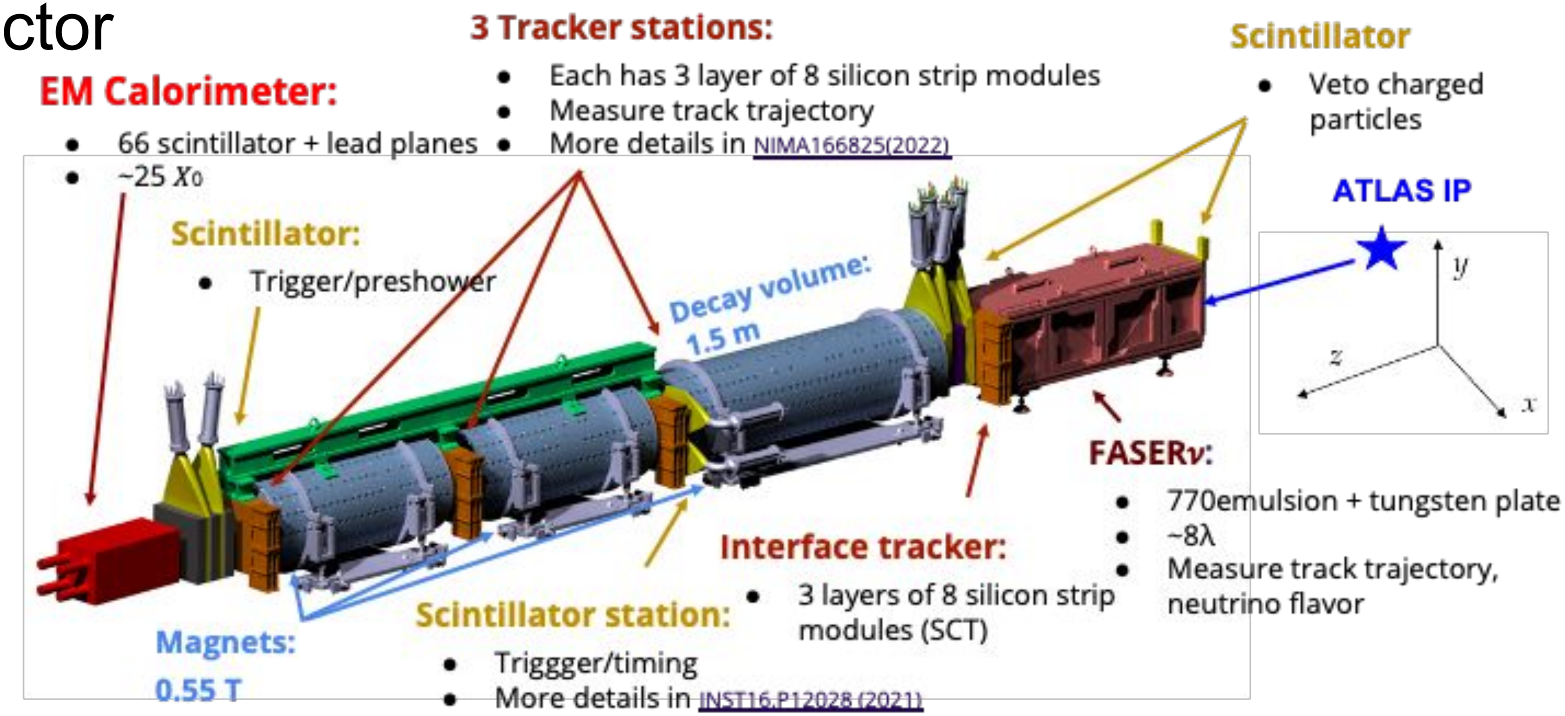




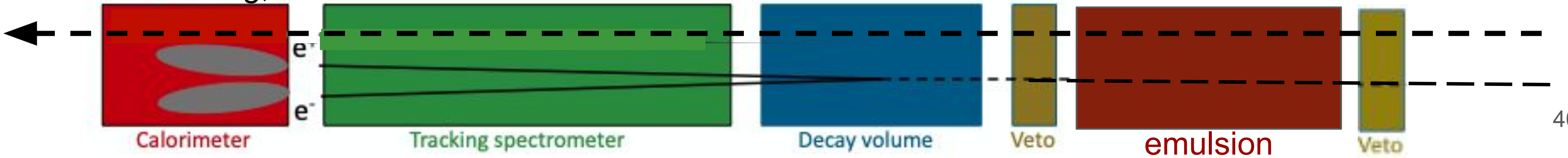




Detector

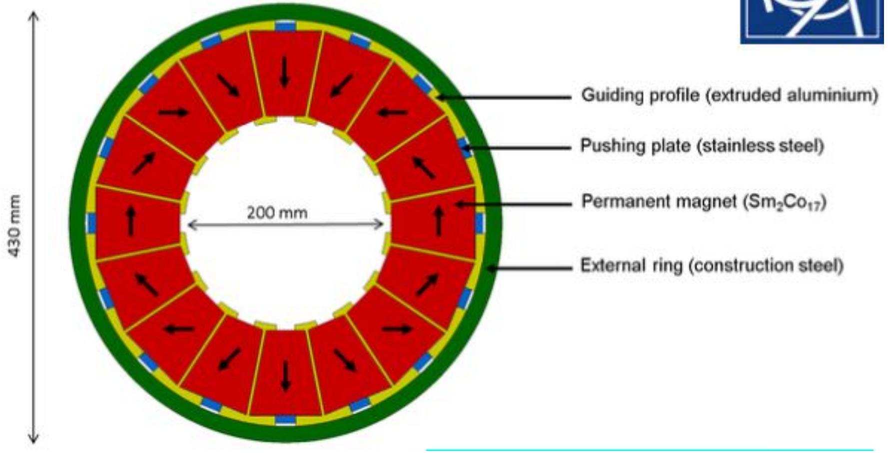


~5 m long, 20 cm diameter



Magnet

0.57T permanent dipole magnets based on the Halbach array design. Designed, constructed and measured by CERN group.

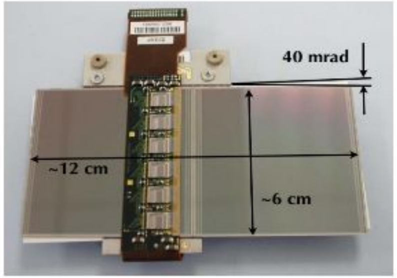


NIMA (2022) 166825

Silicon Tracker

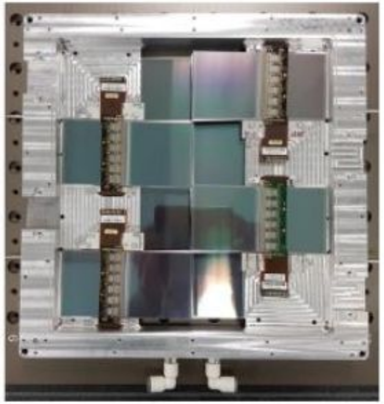
- Based on ATLAS SCT modules:
  8 modules x 3 layers x 4 stations = 96 modules
  - Resolution: 17 um x 580 um
  - Good separation for two collimated tracks

- 4 stations commissioned and installed
  - 99.9% strips are active
  - Expected noise/gain are confirmed
  - Thermal performance looks good
  - Interlock/safety are carefully verified



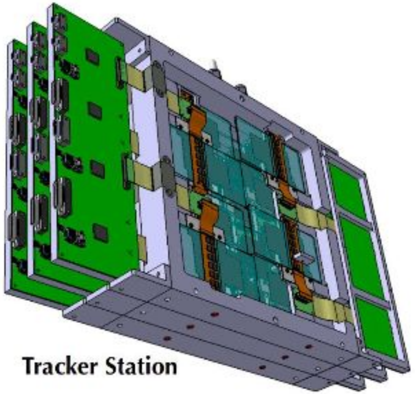
SCT module

80 um pitch, 768 strips/side
40 mrad stereo angle



Tracking layer

24 cm x 24 cm
sensitive area



Tracker Station

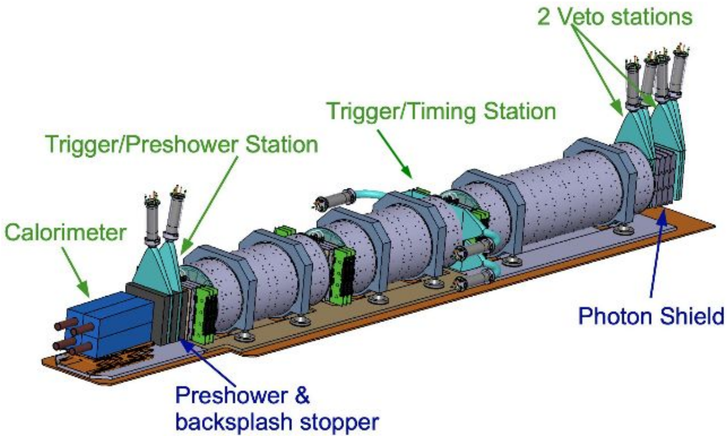
Scintillator

Scintillator function

- Vetoing incoming charged particles - Very high efficiency needed ($\mathcal{O}$(108) incoming muons in 150/fb)
- Triggering
- Timing measurement - ~0.5 ns resolution
- Simple pre-shower for calorimeter

Four scintillator stations are commissioned and installed

- > 99.9% efficiency, enough to trigger LLP decay inside the FASER detector
- Confirmed by in situ measurements in 2018.



Calorimeter

Calorimeter function

- EM energy of full event
- Electron/photon identification
- Triggering

Calorimeter is based on four LHCb ECAL module.
One module has:

- 12 cm x 12 cm x 75 cm (25 X_0, including PMT)
- 66 layers of (2mm lead and 4mm scintillator)
- Resolution ~1% for 1 TeV electron energy deposits

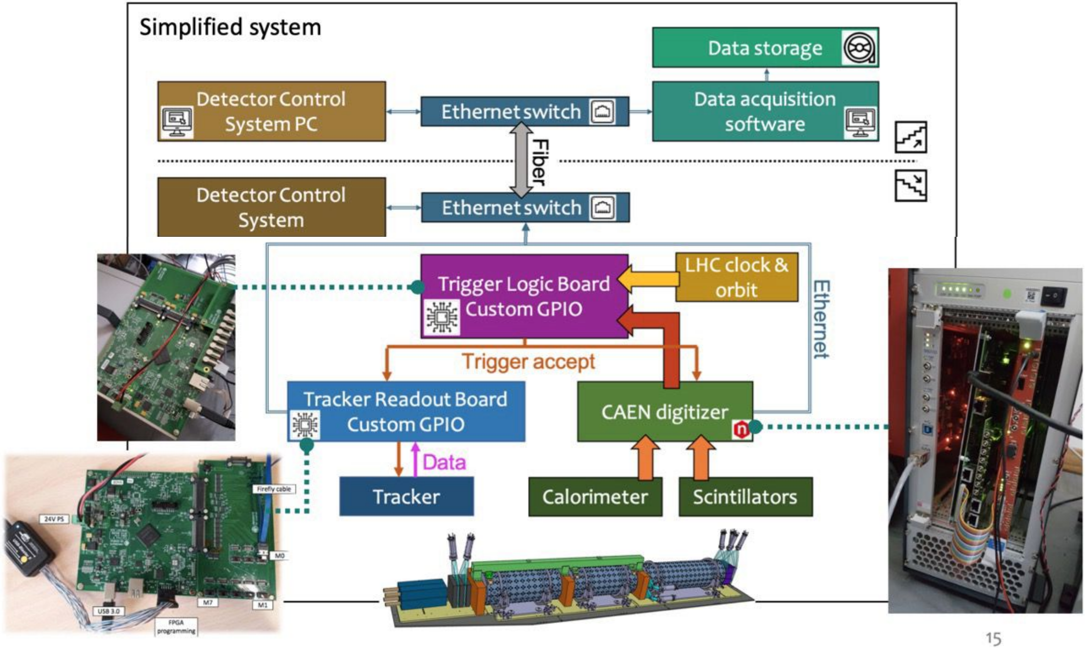
Trigger and Data acquisition

- Tracker: Custom General purpose I/O (GPIO) board

- Scintillator and Calorimeter: CAEN digitiser

- Trigger: Custom GPIO board
  - 1 KHz expected rate (dominant by muon flux, 1 Hz/cm^2 for L=2×10^{34} cm^{-2}s^{-1})
  - Event size (~25 KB)
  - Clock and bunch taken from LHC

- Ethernet switch -> Servers on surface

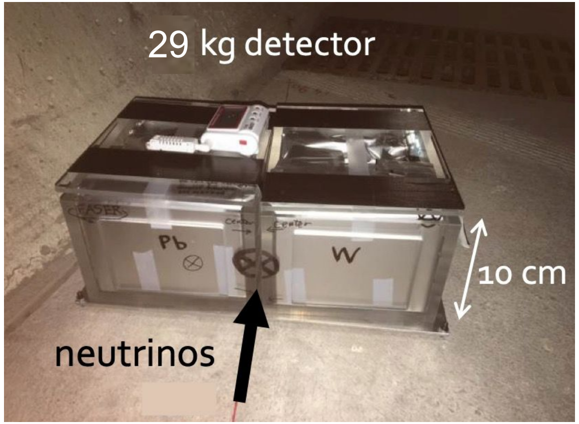


All components are installed and pass 1KHz test
Paper is published: [2021 JINST 16 P12028]

FASERν Emulsion/Tungsten

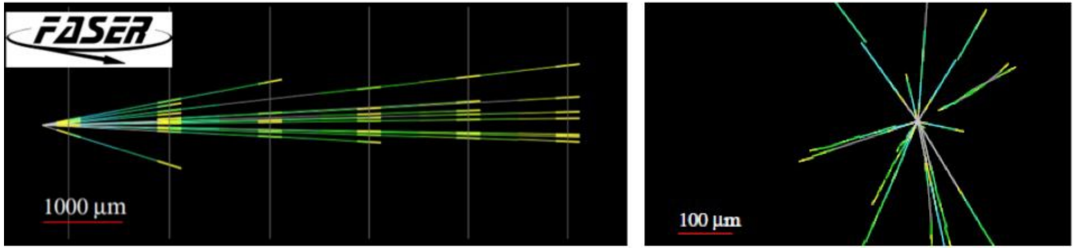
Charged particle ionization recorded and can be amplified and fixed by chemical development of film

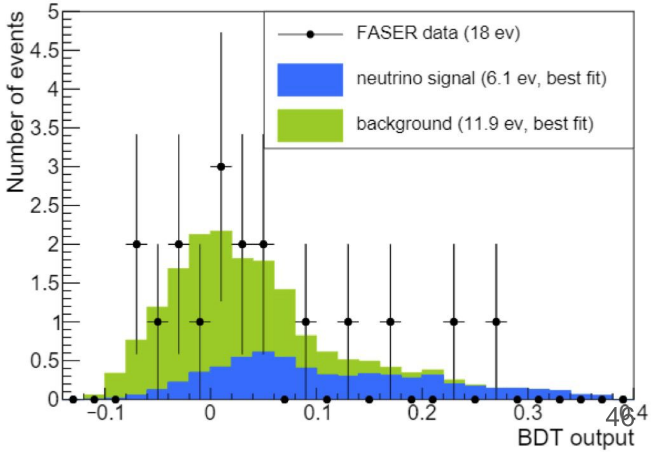
- 770 emulsions interleaved with 1-mm-thick tungsten plates (1.1 tonnes)
- Track position resolution ~50 nm
- Angular resolution ~0.35 mrad
- No Timing information



Pilot detector (29 kg) exposed in TI18 for 1 month in 2018

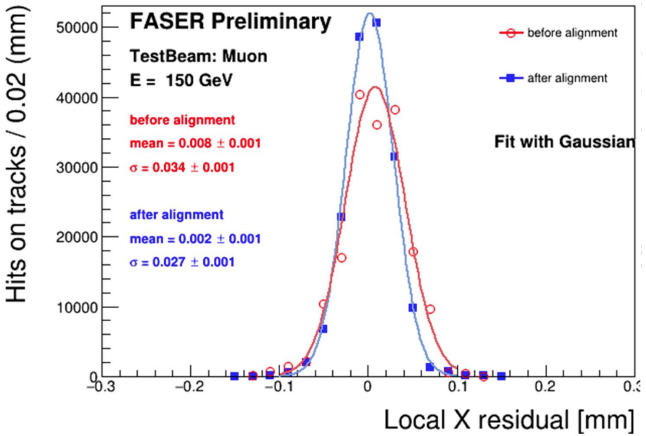
- Observed first collider ν candidates (2.7σ) with 12.2 fb^{-1} data!
- [Phys. ReV. D 104, L091101]



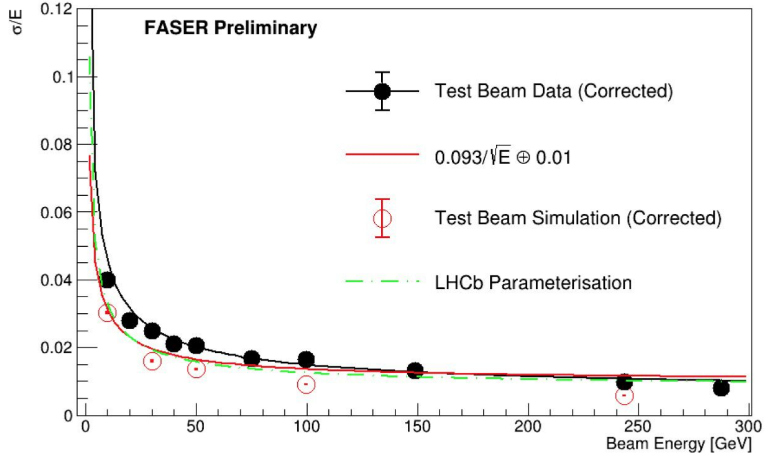


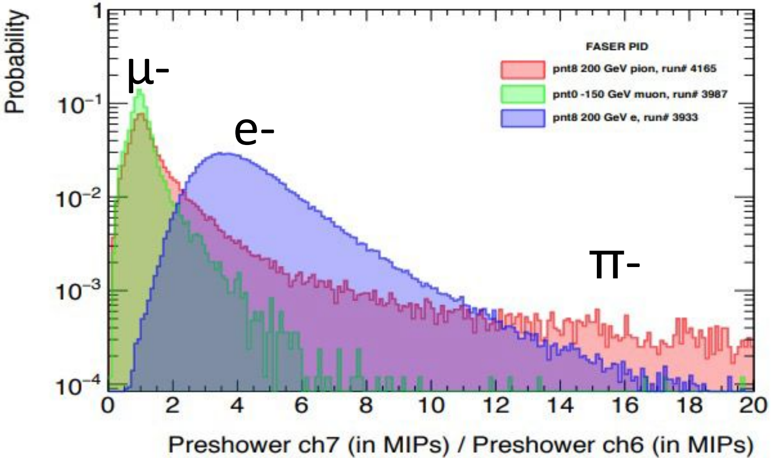
Test Beam Summer 2021

e (5-300 GeV)
μ (150 GeV)
π (200 GeV)

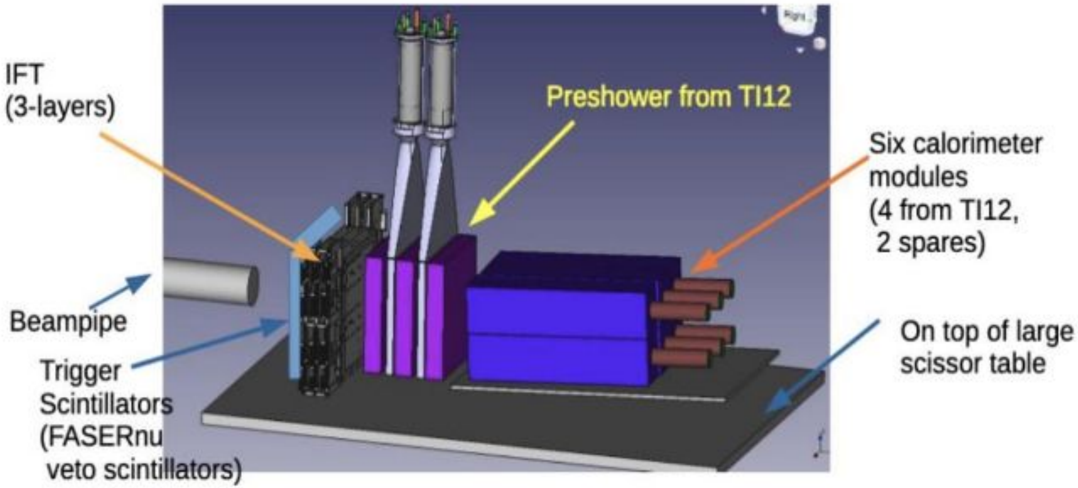


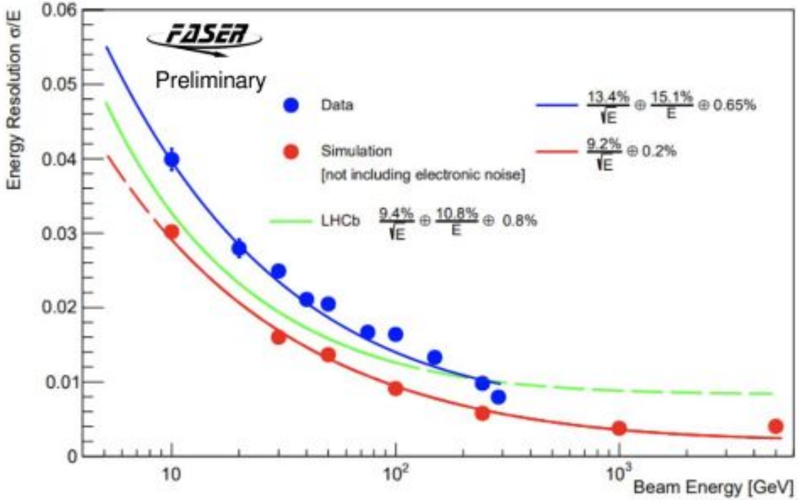
Reasonable energy resolution confirmed





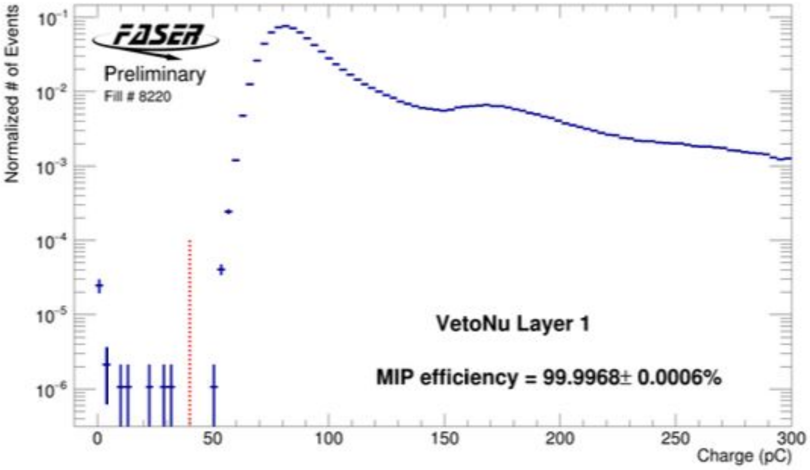
Calorimeter



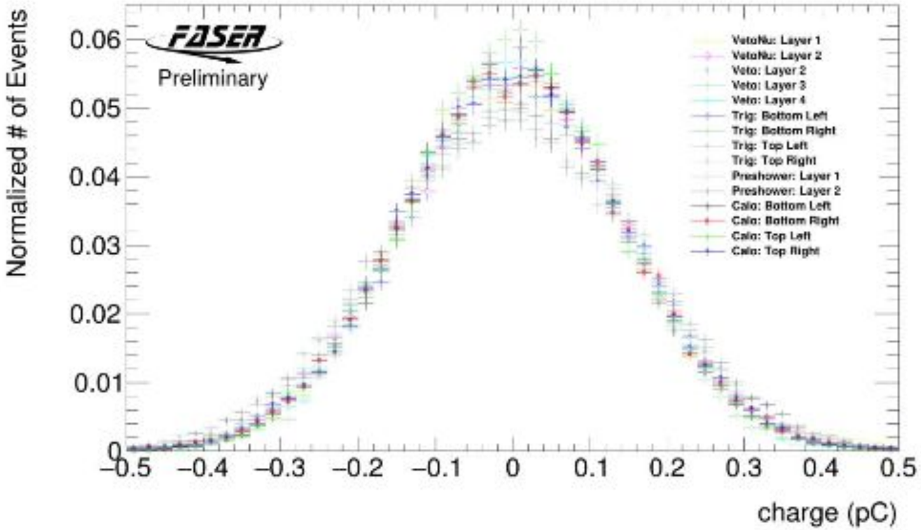


- Calorimeter energy resolution measured with SPS test beam in summer 2021
- Confirming $\mathcal{O}(1\%)$ resolution for high energy electrons.
- Testbeam also used to demonstrate calibration method using muon MIP peak to set energy scale at low energy, and LED calibration pulses to scale this to high energy as PMT gain changed.

Scintillator and Calorimeter

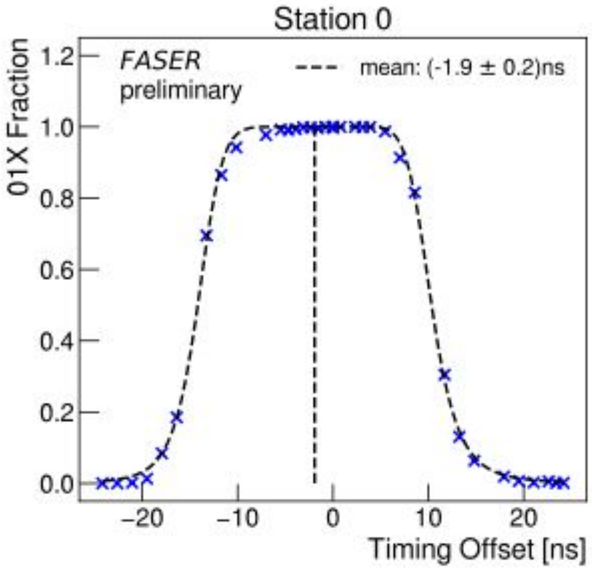


Veto efficiency measurement in data, for events with track that extrapolates into the scintillator. Each individual scintillator efficiency >99.99%.



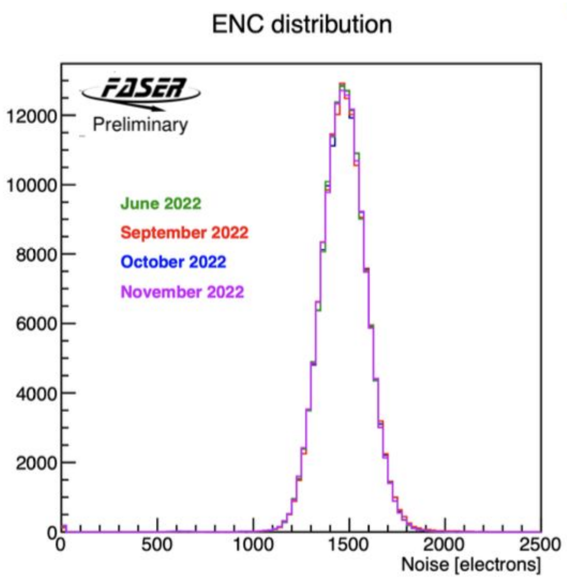
Scintillator noise measured in random triggered events, observed noise ~0.15pC and dominated by digitizer noise. Noise much less than MIP signal (~70pC)

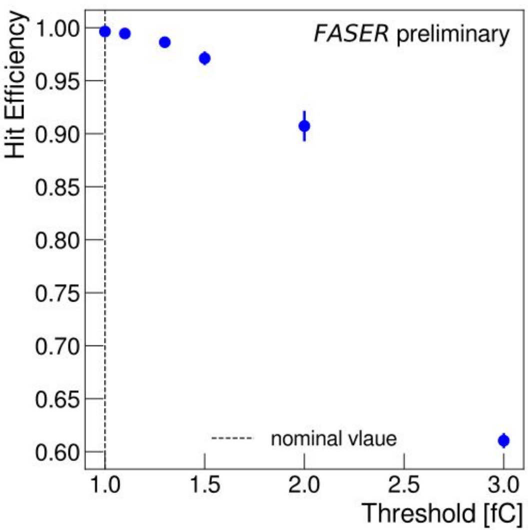
Tracker timing-in

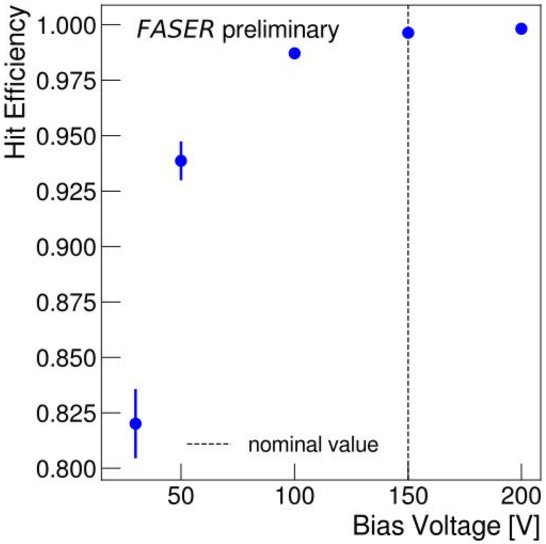


Used early collision data tracks to set fine timing delay in the readout of each SCT module, in order to optimize fraction of hits on track in middle of three 25ns time bins read out.

Tracker noise and hit efficiency





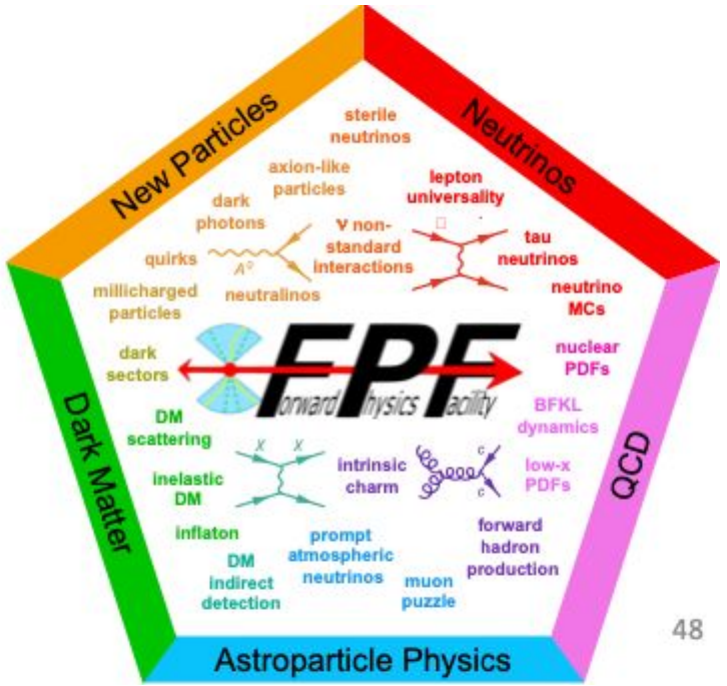


Number of dead/noisy strips constant and <0.1%.

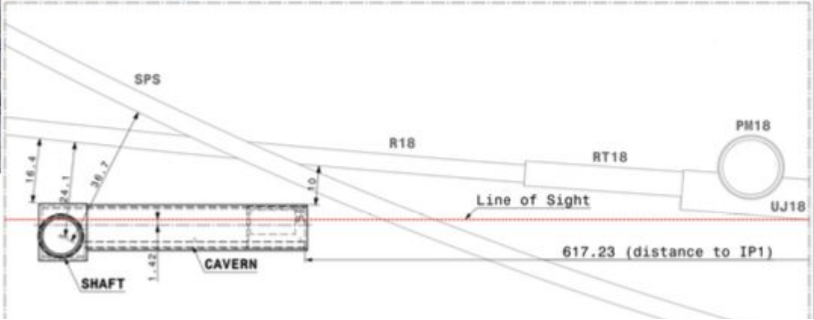
Observe as expected very high efficiency >99.6%.

Forward Physics Facility

- The Forward Physics Facility (FPF) is a proposal to create a new facility to enable a suite of new experiments to be situated on the LOS
- Three main physics motivations
  - Beyond Standard Model (BSM) “dark sector” searches
  - Neutrino physics
  - QCD physics



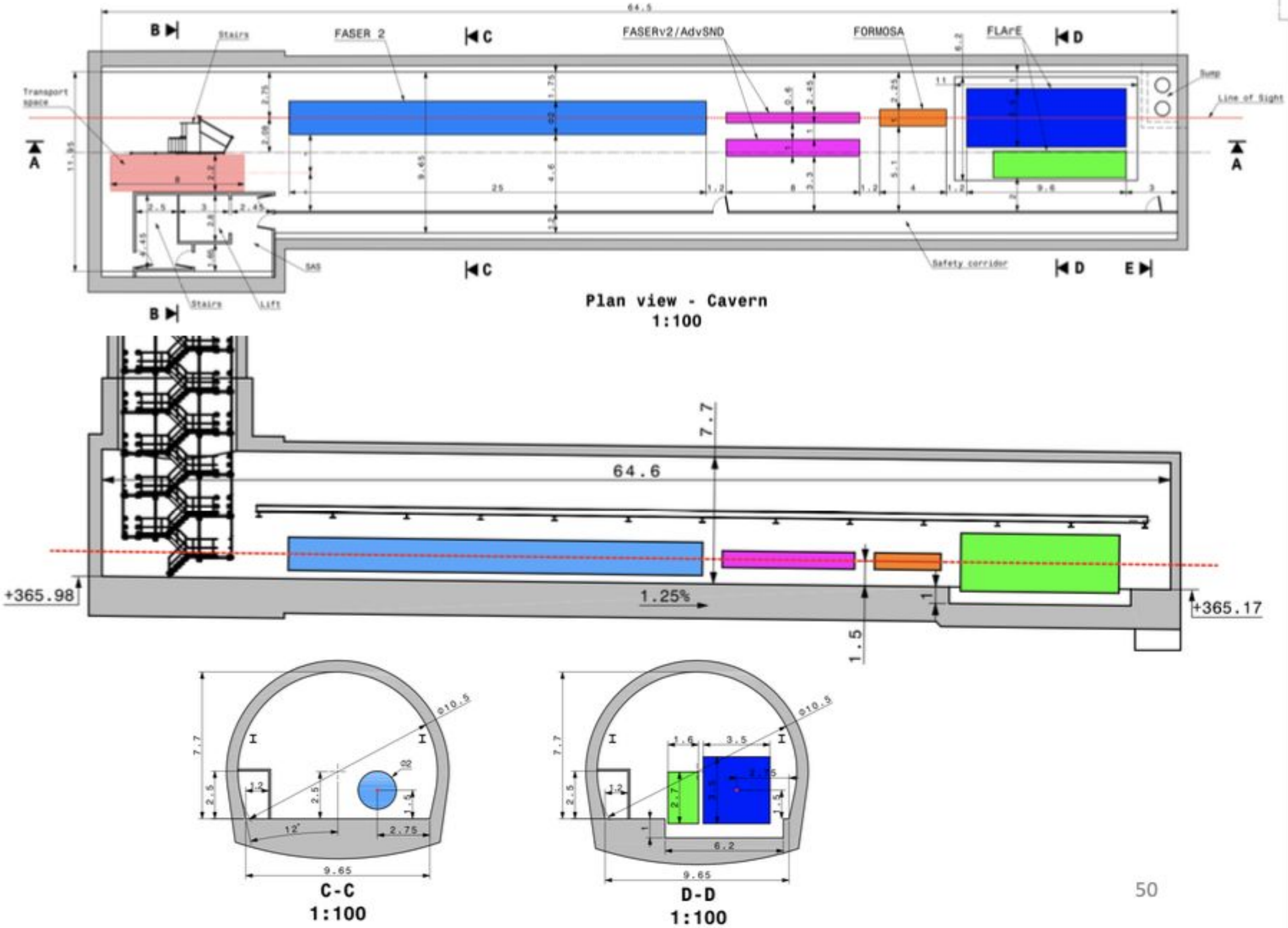
FPF Location

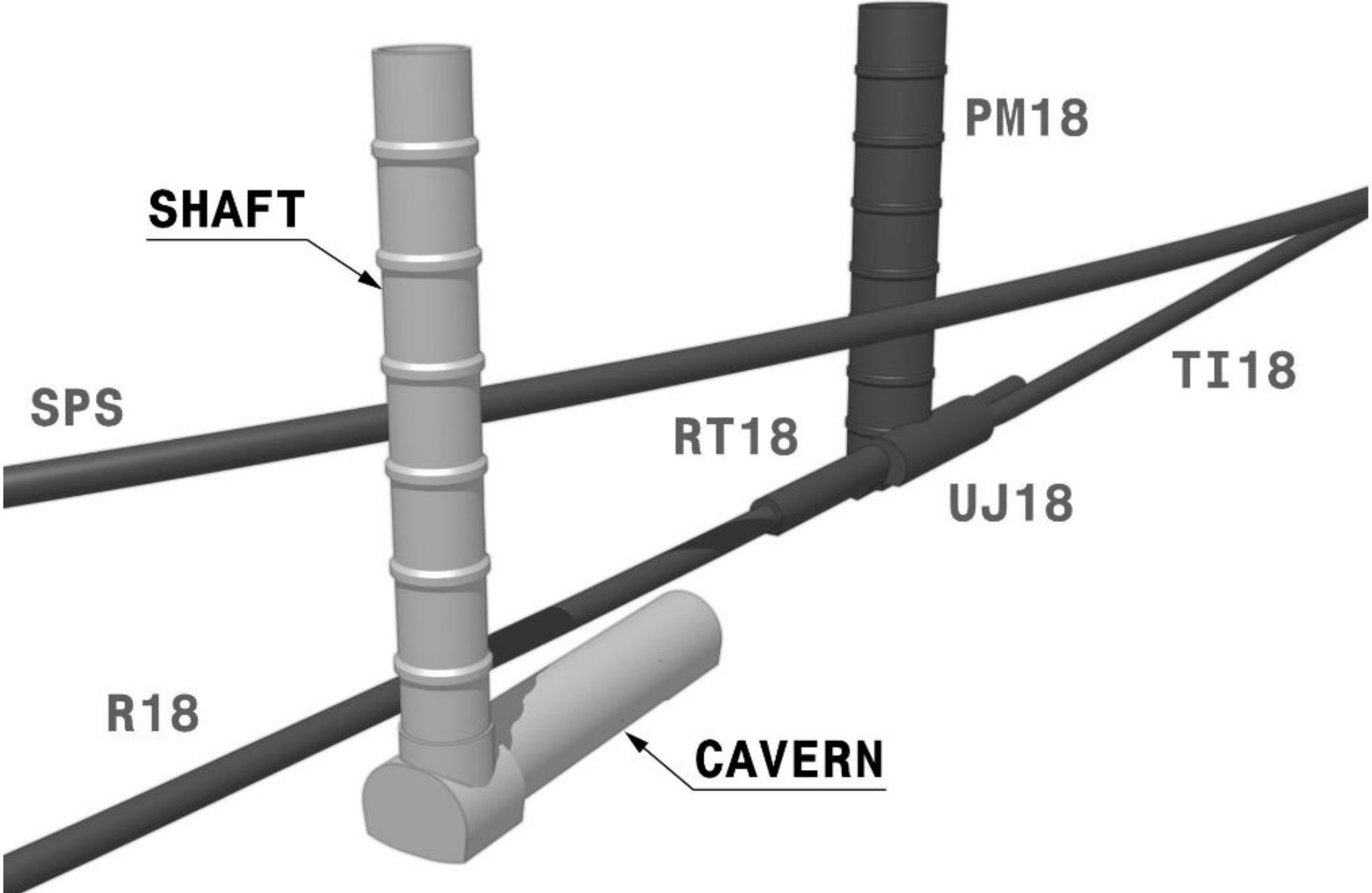


After several studies by CERN civil engineering team, looking at options around both the ATLAS and CMS interaction points have now converged on the dedicated new facility in the SM18 area as the baseline proposal. This is ~600m from the ATLAS IP (to the west), and is situated on CERN land.

FPF Facility:

65m long, 9.7m wide, 7.7m high cavern.
Connected to surface through 88m high shaft (9.1m diameter): 617m from IP1.




PM18
SHAFT
TI18
SPS
RT18
UJ18
R18
CAVERN

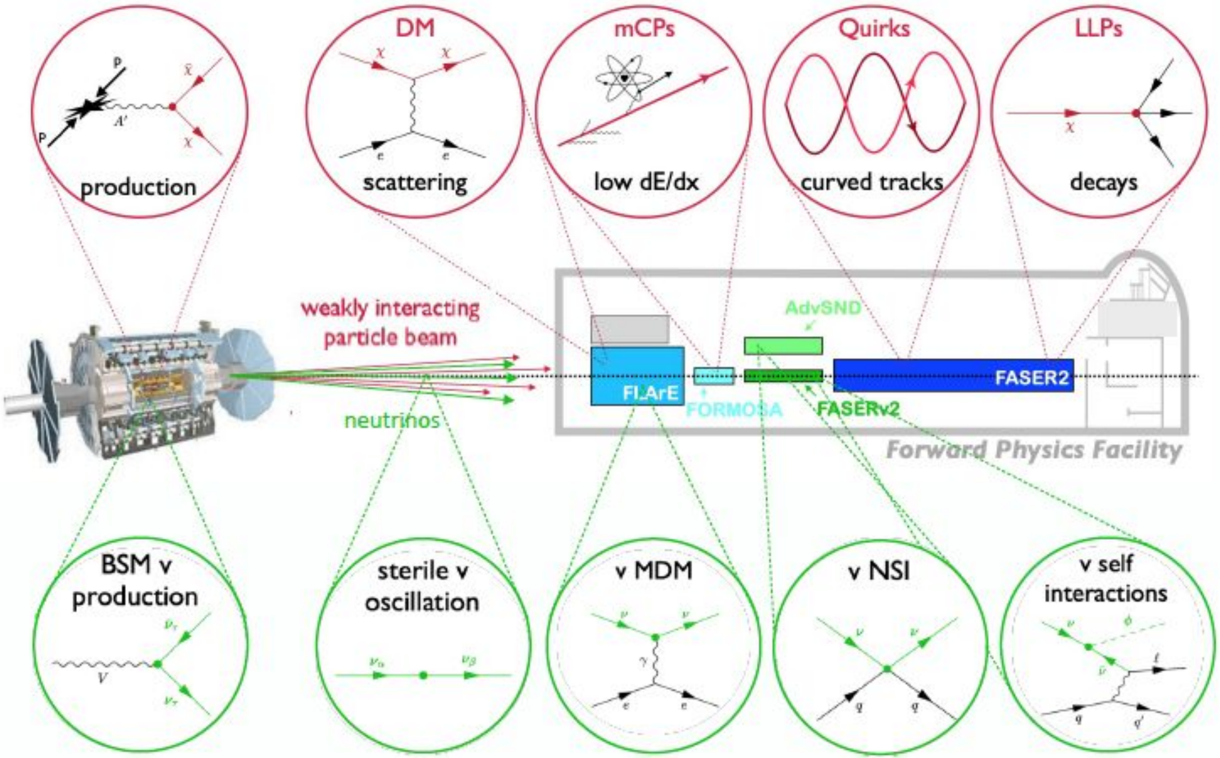
Physics Program of Forward Physics Facility

BSM particles can be detected in various ways

- Giving access to wide range of models

Neutrinos can be used to search for BSM effects

- Production
- Propagation
- Interaction



FPF experiments

At the moment there are 5 proposed experiments to be situated in the FPF. With different capabilities and covering different rapidity regions:

- FLArE
    - $\mathcal{O}$(10tn) LAr TPC detector
    - DM scattering
    - Neutrino physics ($\nu\mu/\nu e$, capability for $\nu\tau$ under study) • Full view of neutrino interaction event
- FASERv2
    - $\mathcal{O}$(20tn) emulsion/tungsten detector (FASERv x20)
    - Mostly for tau neutrino physics • Interfaced to FASER2 spectrometer for muon charge ID ($\nu\tau$/ $\nu\tau$ separation)
- AdvSND
    - Neutrino detector slightly off-axis
    - Provides complementary sensitivity for PDFs from covering different rapidity to FASERv2

- FASER 2
    - Detector for observing decays of light dark-sector particles
    - Similar to scaled up version of FASER (1m radius vs 0.1m)
    - Increases sensitivity to particles produced in heavy flavour decay

• Larger size requires change in detector and magnet technology: Superconducting magnet

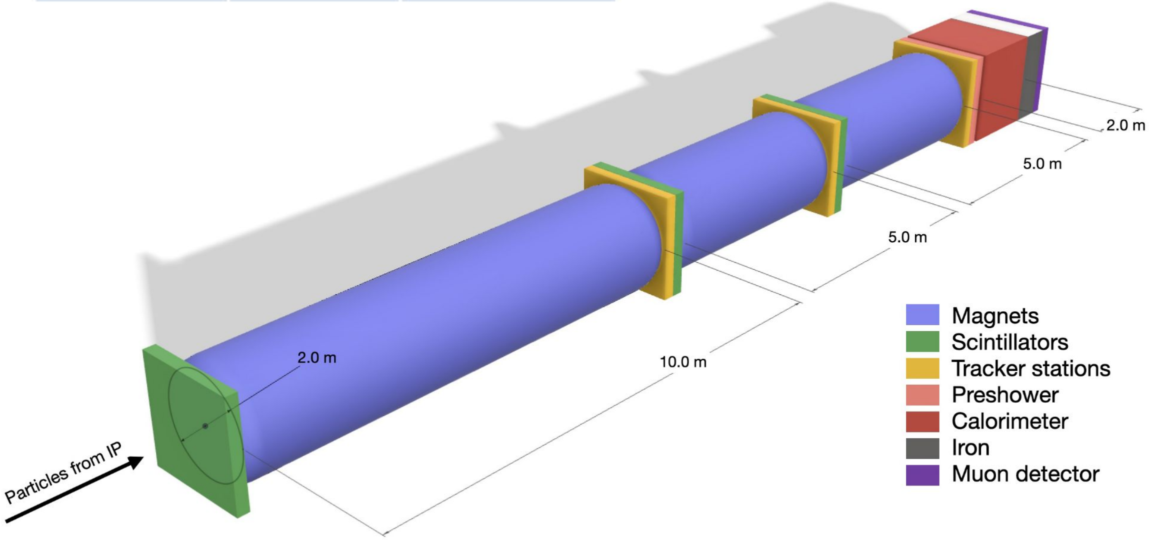
- FORMOSA
    - Milli Charged particle detector
    - Scintillator based, similar to current milliKan experiment

FASER 2

	FASER	FASER2
R [m]	0.1	1
DV [m}	1.5	10
TS [m]	2.6	10

scaled up version of FASER2 with ~100 x active area

- Veto: similar scintillator-based
- Magnets: Superconducting w/ B = 1 T
- Tracker: much larger using e.g. SiFI/SiPM
- Calo/Muon: enhanced PID & position resol.

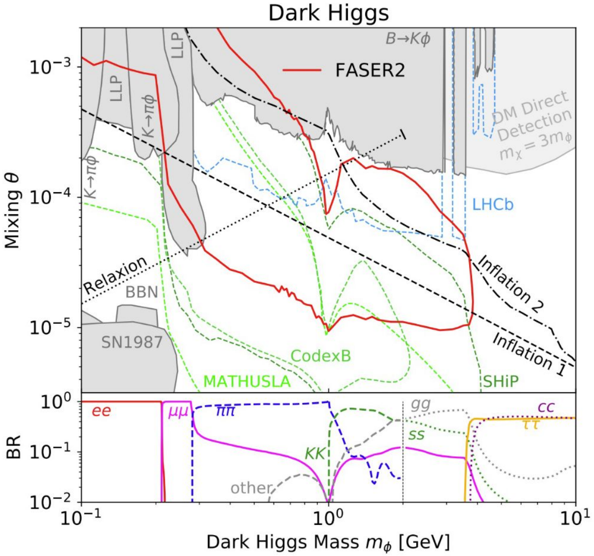


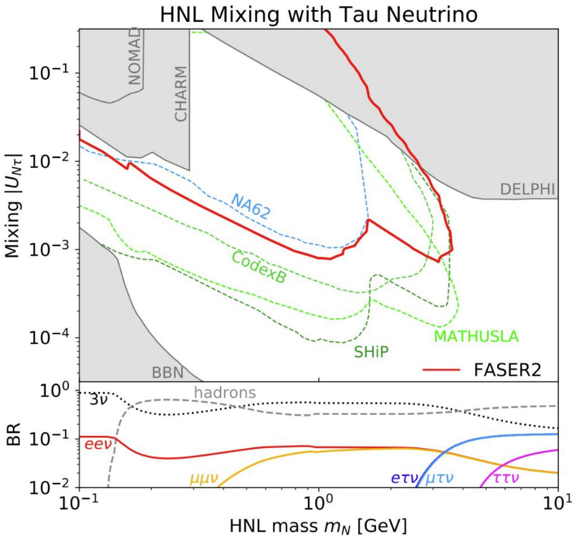
FASER 2 Physics

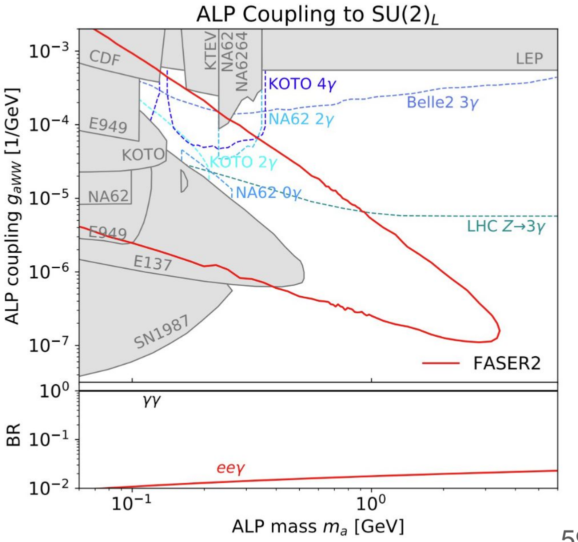
- Wide LLP program probing many models
- Dark vectors, (pseudo) scalars, ALPs,

HNLs, …
- Extended sensitivity to higher mass

	Run3 (2022-2025)	HL-LHC (2029-)
Benchmark Model	FASER	FASER 2
Dark Photons	√	√
$B-L$ Gauge Bosons	√	√
L_i-L_j Gauge Bosons	—	—
Dark Higgs Bosons	—	√
Dark Higgs Bosons with hSS	—	√
HNLs with e	—	√
HNLs with μ	—	√
HNLs with τ	√	√
ALPs with Photon	√	√
ALPs with Fermion	—	√
ALPs with Gluon	√	√
Dark Pseudoscalars	—	√

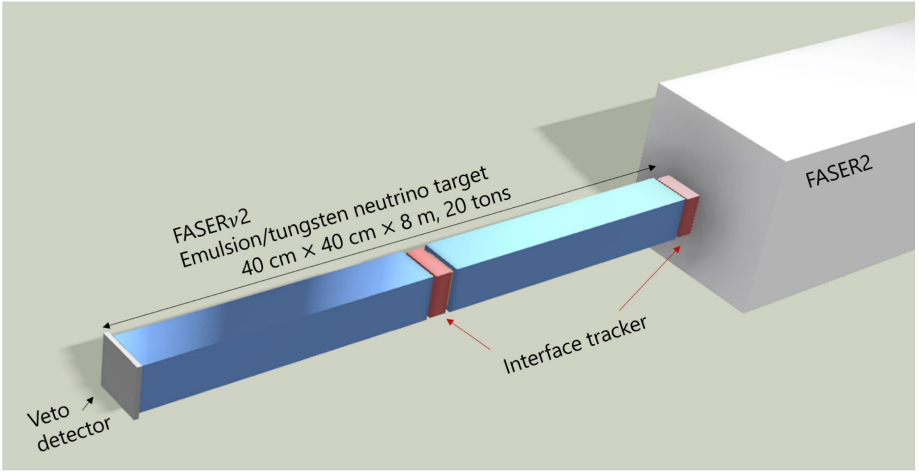


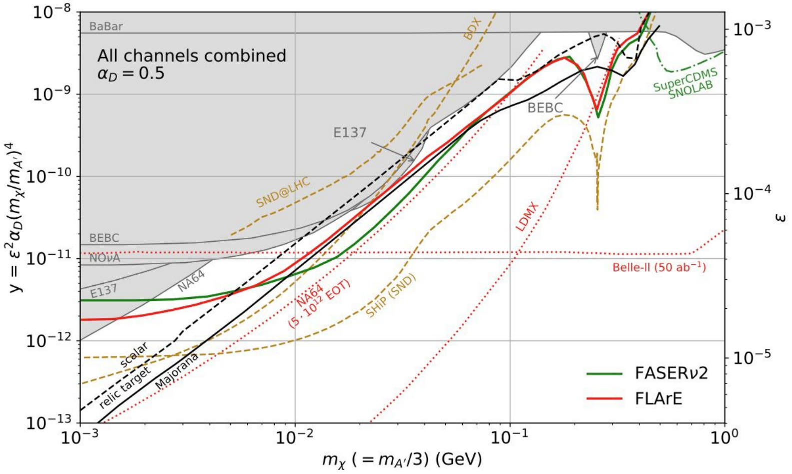




FASERv2

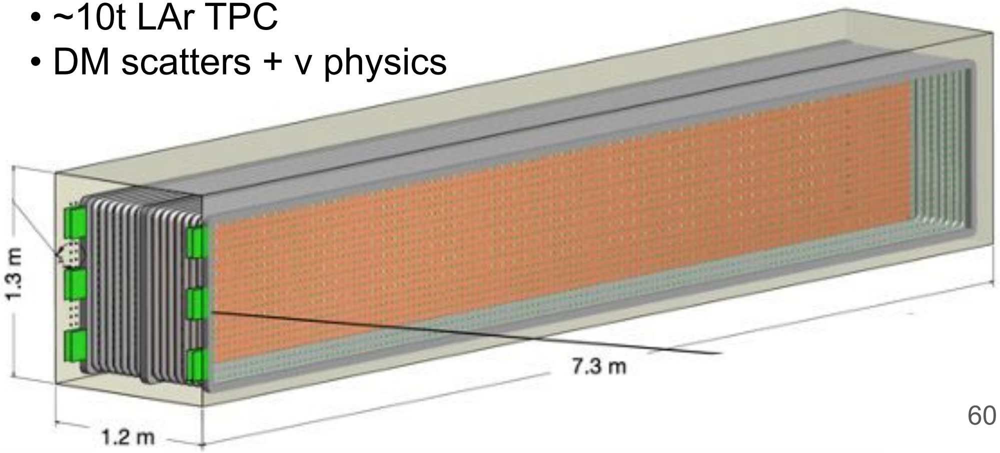
- ~20t emulsion + tungsten detector
- Focus on vτ





FLArE: Forward Liquid Argon Experiment

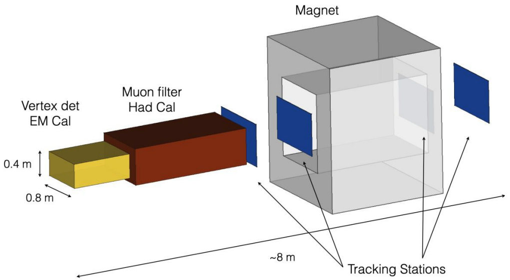
- ~10t LAr TPC
- DM scatters + v physics



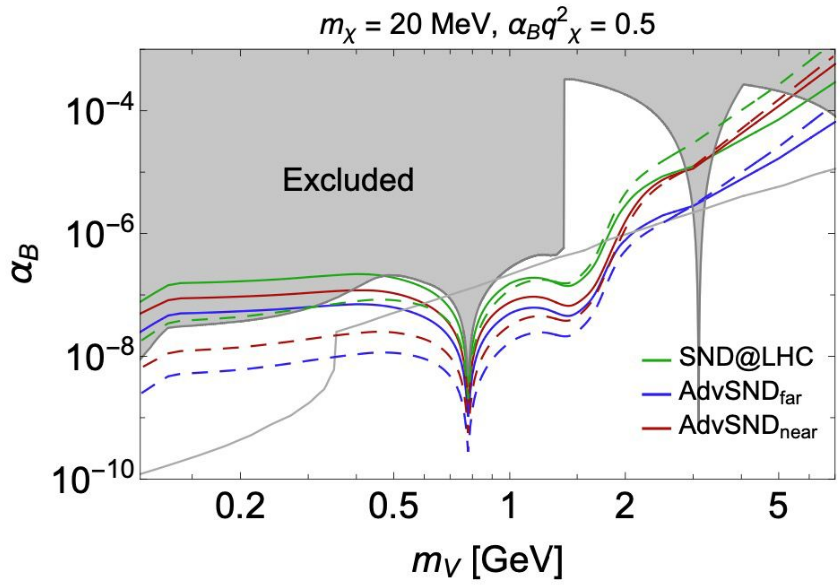
Other experiments

AdvSND

- Off-axis ν detector



- Forward charm prod. + low-x gluon PDF



FORMOSA: FORward MicrOcharge SeArch

- Scintillator/tungsten detector
- For milli-charged particles