30th Anniversary of the Rencontres du Vietnam

Aug 6 – 12

ICISE

WINDOWS ON THE UNIVERSE

2023

First results from FASER at LHC

Ke Li on behalf of FASER Collaboration

30th Anniversary of Rencontres du Vietnam

08/08/2023

FASER

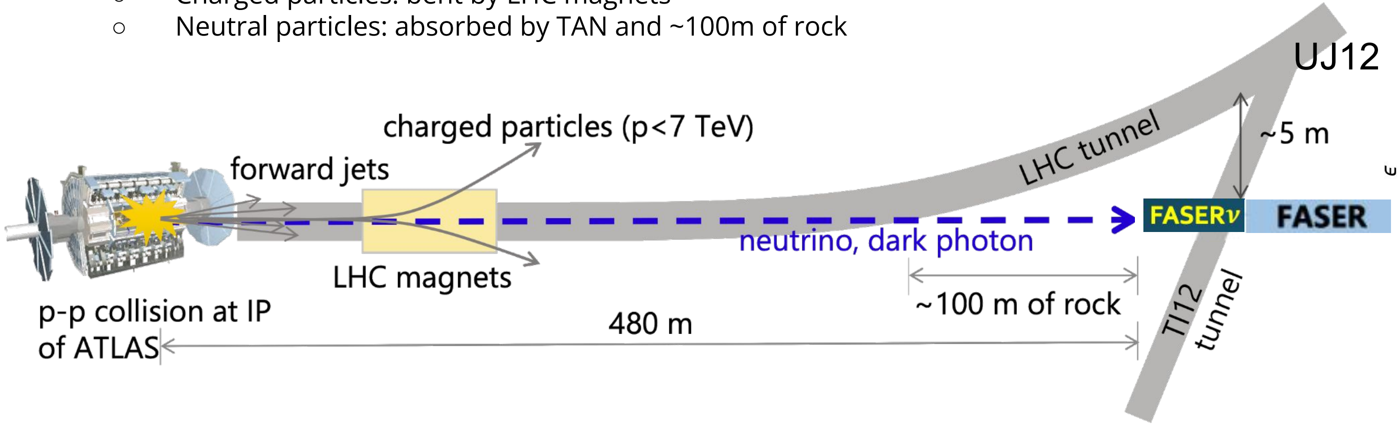
UNIVERSITY of WASHINGTON

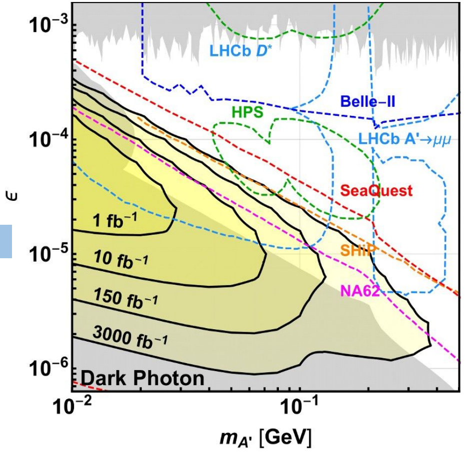
Overview

- Motivation of FASER experiment
  - Search for and study of long lived particles (LLPs) and neutrinos
  - More fully realize the discovery potential of the LHC
- Design, construction, commissioning, and data-taking
  - ~ 5 years from conception to physics results
- First physics results
  - Search for dark photon [CERN-FASER-CONF-2023-001]
  - First direct detection of collider neutrinos [PhysRevLett.131.031801(2023)]
- Beyond Run3
  - FASER2, FASERν2, and the Forward Physics Facility (FPF)

ForwArd Search ExpeRiment (FASER) at the LHC

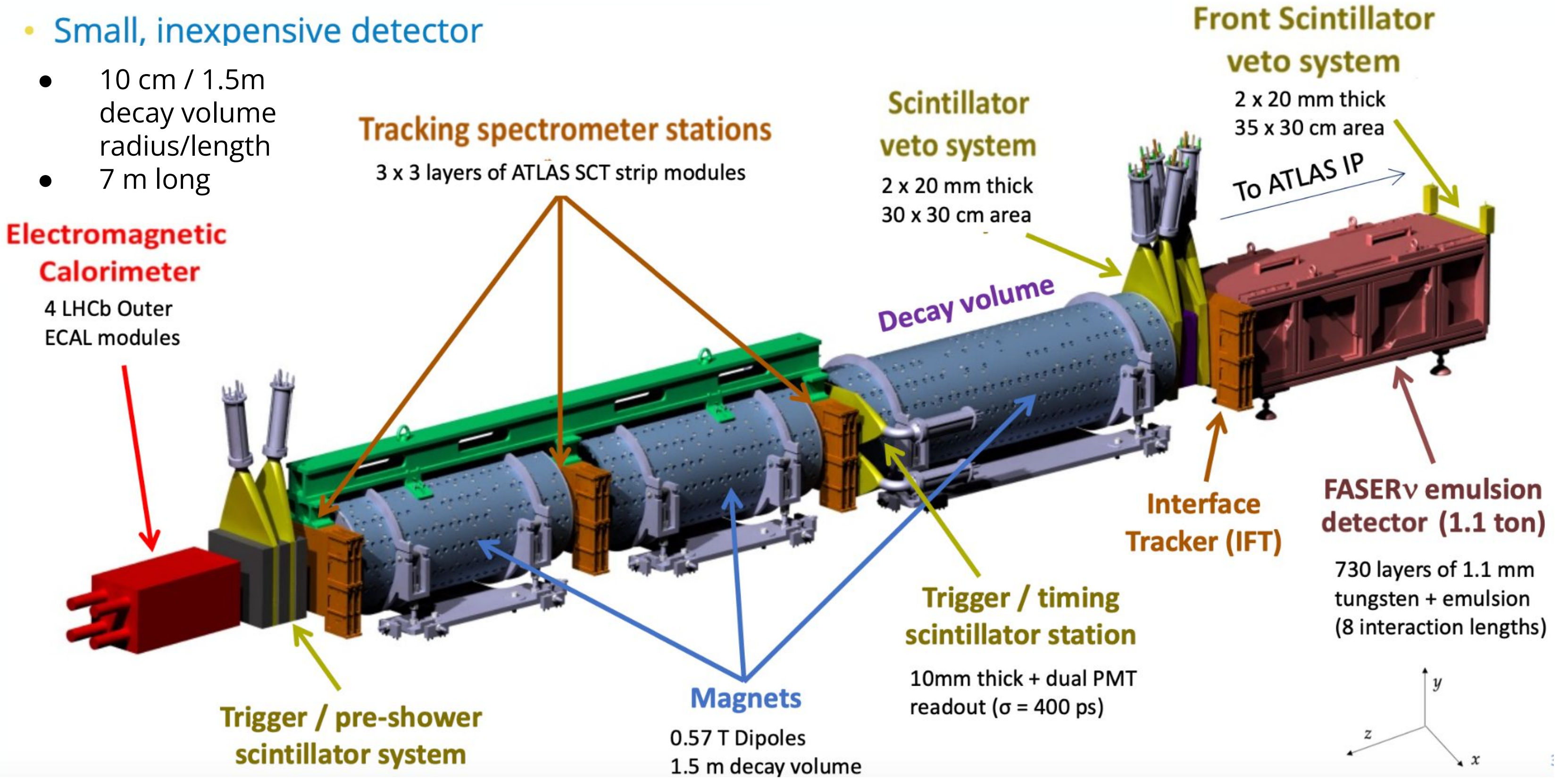
- FASER is designed to search for **LLPs** and **neutrinos** produced in pp collisions at the ATLAS IP
- Light LLPs are produced in the decay of SM mesons, which are predominantly produced very collimated in the beam direction
- Even small detectors on (or close to) the **LOS** can have good sensitivity in these scenarios
  - N~ 10^{16} pions/10^{12} neutrinos in LHC Run 3 (2022-2025)
  - E~ TeV, $\theta_{\text{beam axis}}$ ~ mrad
    - e.g. 1% of pions with E > 10 GeV are produced in the forward 0.000001% of the solid angle (η > 9.2)
  - Even with 1 fb^{-1} of data FASER will have sensitivity to unconstrained parameter space
- Unique opportunities to search for long-lived particles and measure very high energy neutrino interactions
- Almost **background free**
  - Charged particles: bent by LHC magnets
  - Neutral particles: absorbed by TAN and ~100m of rock





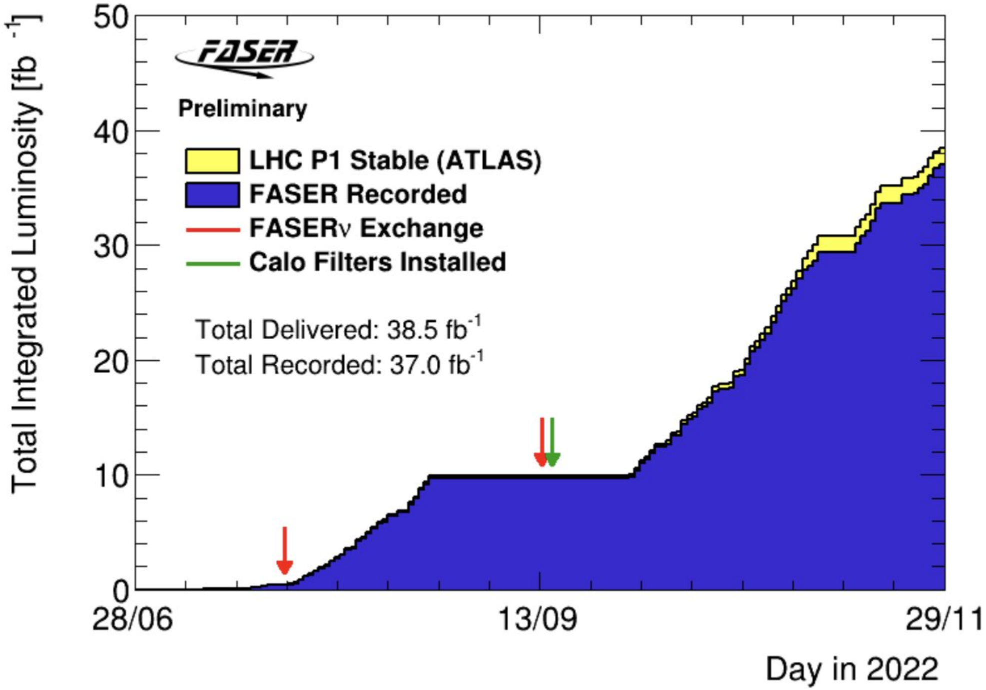
FASER detector

- Small, inexpensive detector
  - 10 cm / 1.5m decay volume radius/length
  - 7 m long



FASER operation

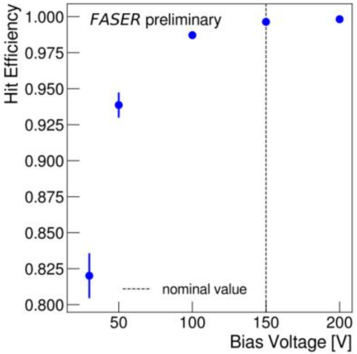
- Successfully constructed, installed and commissioned
- Smoothly operated throughout 2022
  - Continuous data taking
  - Largely automated
  - Up to 1.3 kHz
- Recorded 96.1% of delivered luminosity
  - DAQ dead-time of 1.3%
  - A couple of DAQ crashes
- Emulsion detector exchanged twice
  - Needed to manage the occupancy
  - First box only partially filled
- Calorimeter gain optimised for:
  - Low E (<300 GeV) before 2nd exchange
  - High E (up to 3 TeV) after the exchange
- Smoothly operating at 2023
  - Another ~30 fb^{-1} data



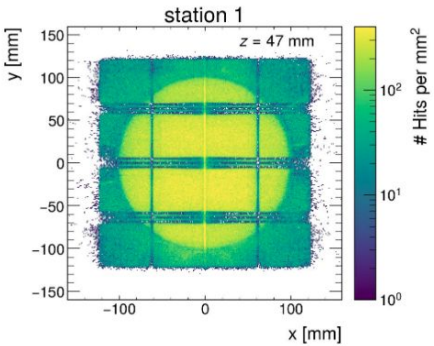
Analyses presented use 27.0 fb^{-1} or 35.4 fb^{-1}

Detector performance from data

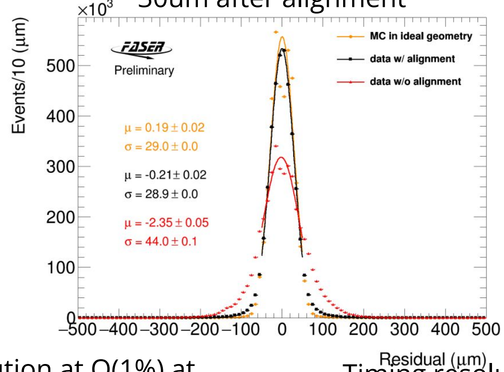
Hit efficiency of 99.64±0.10%



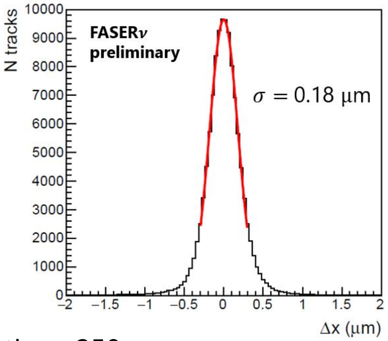
Total number of dead/noisy strips < 0.5%



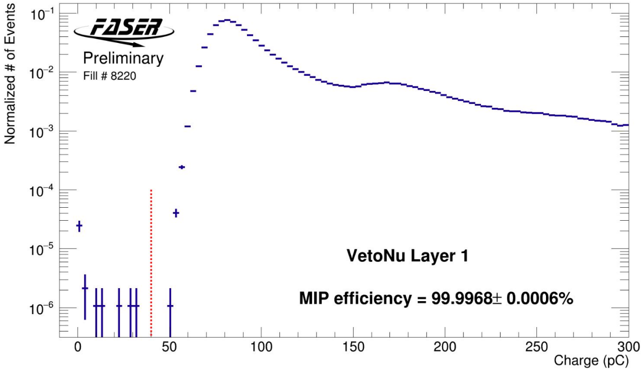
Unbiased residual resolution: ~30um after alignment



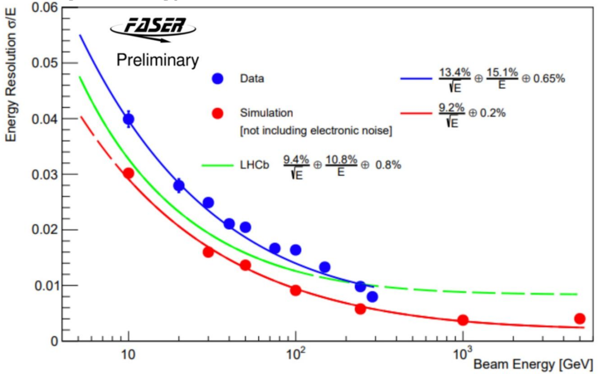
Spatial resolution for FASERν detector: ~-0.2um



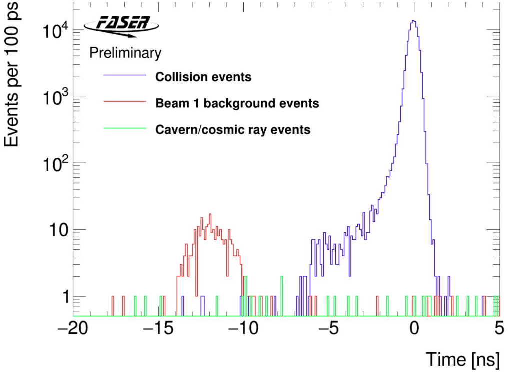
>99.99% veto eff. for each veto scintillator
Veto O(10^8) muons by 4 scintillators



Deposit energy resolution at O(1%) at high energy

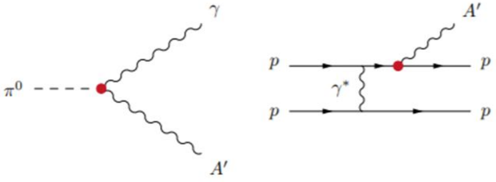


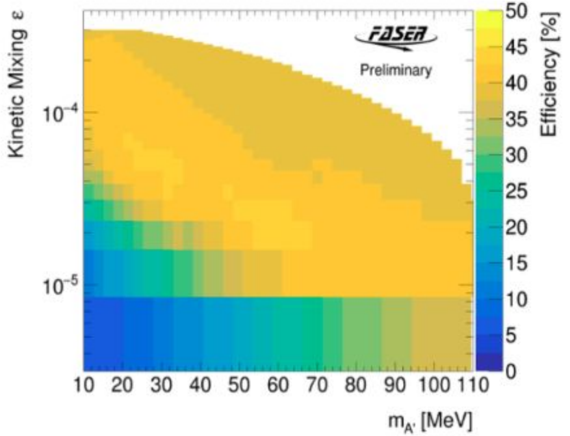
Timing resolution ~250ps
Reject the beam-1 background efficiently



Search for dark photon

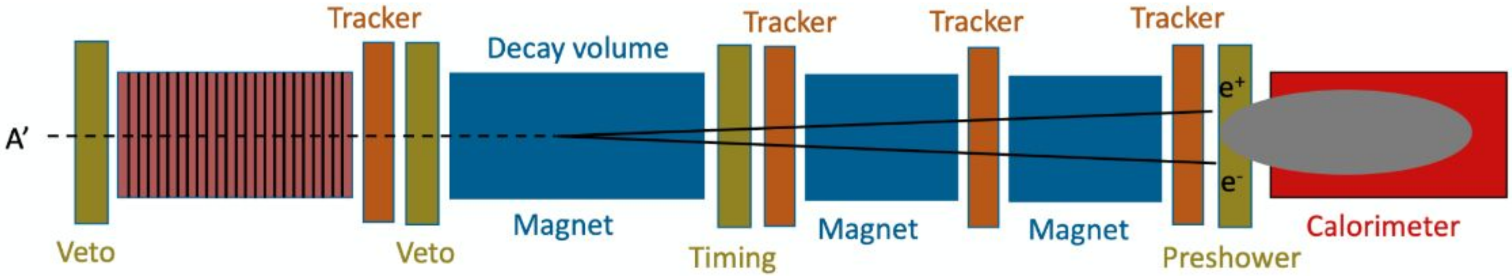
- Mainly produced from decay of light mesons (π^0 and η), and dark bremsstrahlung
- Simple and robust $A' \to e^+e^-$ selection, optimised for discovery
  - Blind events with no veto signal and E(calo) >100 GeV
  - Eff. of ~40% across region of sensitivity





1, good quality collision event

4, Timing and preshower consistent with ≥ 2 MIPs



2, No signal (<40pC) in any veto scintillator

3, Exactly 2 good tracks in fiducial volume:
- p > 20 GeV and r <95 mm (r of magnet: 100 mm)
- Extrapolated to r<95 mm at veto scintillators

5, Energy in calorimeter E > 500 GeV

Background estimation

- Main background is from neutrino interactions
  - Primarily coming from vicinity of timing detector
  - Estimated from GENIE simulation equivalent of 300 ab^{-1} data
    - Uncertainties from neutrino flux and mismodeling
  - Predicted events with E(calo) > 500 GeV:

$$\mathbf{N = (1.8 \pm 2.4) \times 10^{-3}}$$

- Neutral hadrons (K_s) from upstream muons interacting in rock in front of FASER
  - Heavily suppressed
    - High energy muon nearly always continues after interaction
    - Has to pass through 8 interactions length (FASERν)
    - Decay products have to leave E(calo) > 500 GeV
  - Data-driven estimation from lower energy events with 2 or 3 tracks and different veto conditions

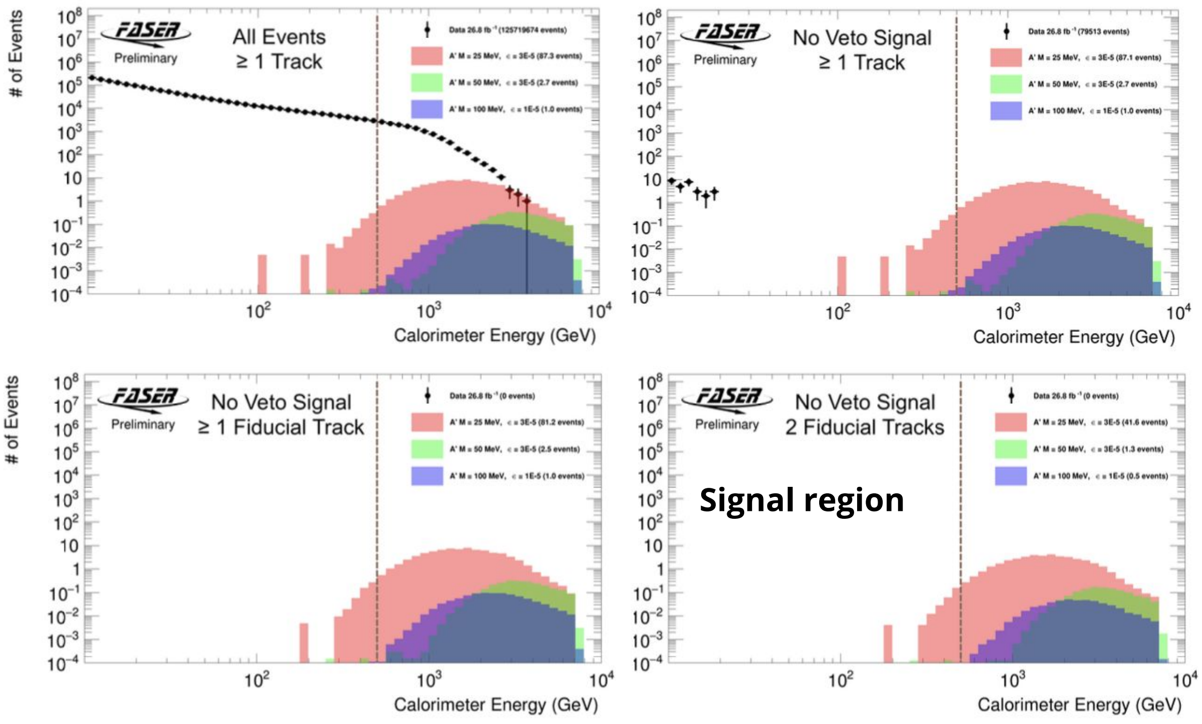
$$\mathbf{N = (2.2 \pm 3.1) \times 10^{-4}}$$

- Other background
  - Veto inefficiency
    - Measured layer-by-layer via muons with tracks pointing back to vetos
    - Layer efficiency > 99.999%
  - Non-collision backgrounds
    - Cosmics measured in runs with no beam
    - Near-by beam background measurement in non-colliding bunches
  - **Negligible**

- Total background prediction:

$$\mathbf{N = (2.02 \pm 2.4) \times 10^{-3}}$$

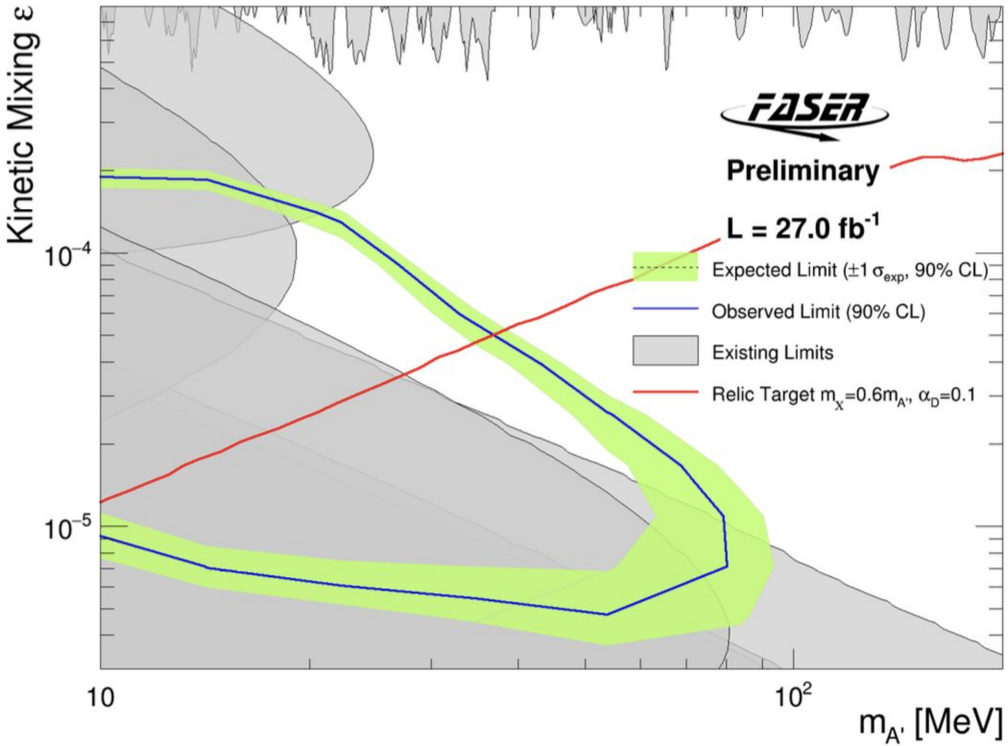
Observed yields



- **No events in unblinded signal region**
- Not even any with ≥ 1 fiducial track

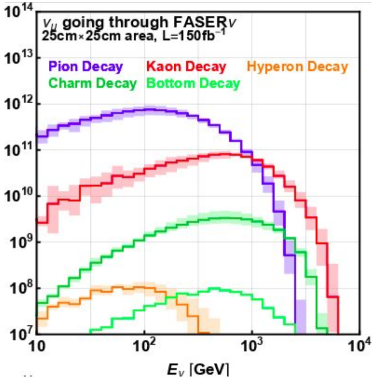
Observed limits

- No event in SR is observed
- **FASER sets limits in previously unexplored parameter space !**
  - Probes new territory in the interesting thermal-relic region
- **Updating the study with improvements from reconstruction**
  - A better track finding algorithm and detector alignment
  - Results will be released soon.



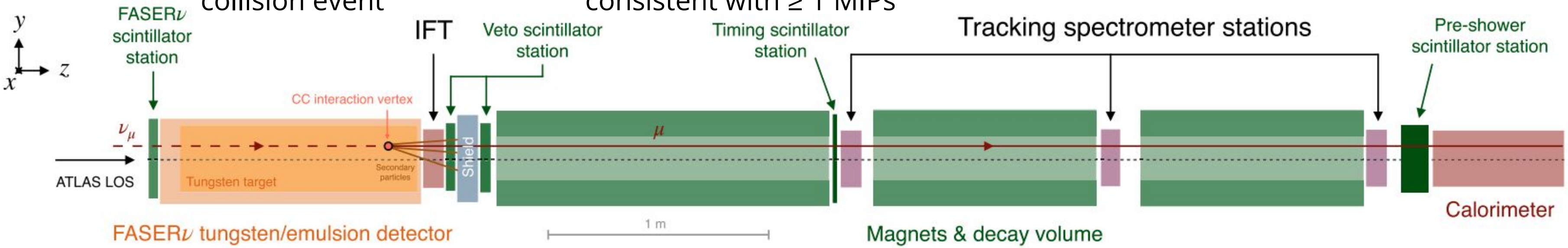
First direct observation of collider neutrinos

- 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
- Expected to record several 1000 of neutrino interactions in Run3
  - **~1000 ν_e, ~10000 ν_μ, ~50 ν_τ**
- For first study, we use silicon tracker to detect neutrino interaction at FASERν
  - Focusing on ν_μ CC interactions



1, good quality collision event

4, Timing and preshower consistent with ≥ 1 MIPs



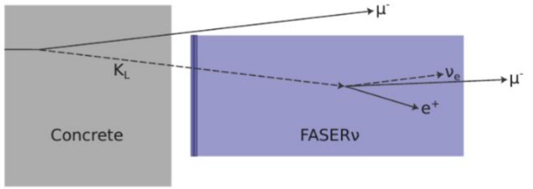
2, No signal (<40pC) in 2 front vetos, but signal (>40pC) in other 3 vetos

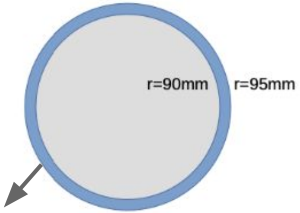
3, Exactly 1 good fiducial track
- p >100 GeV, θ<25 mrad, r<95mm
- Extrapolated to r<95 mm at veto scintillators

Background estimation

- Neutral hadrons from muon interaction in front of FASER
  - Simulate 2.1×10^{9} μ events based on the FLUKA energy spectrum
    - Expect ~300 neutral hadrons with E>100GeV reaching FASER
  - Propagate through the last 8m of rock

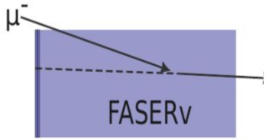
  N = (0.11 ± 0.06)

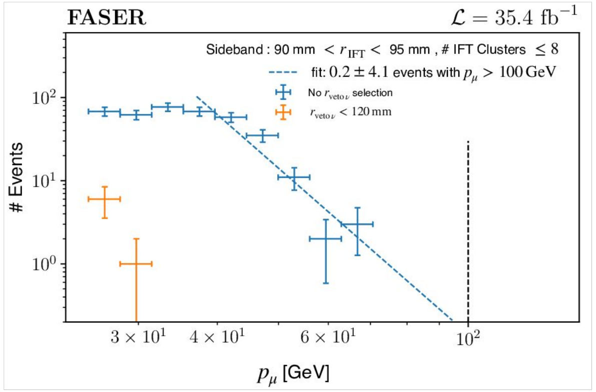




- Geometric background from muon scattering
  - Estimated from a geometric sideband
  - Uncertainty is estimated from varying selections

  N = (0.08 ± 1.83)





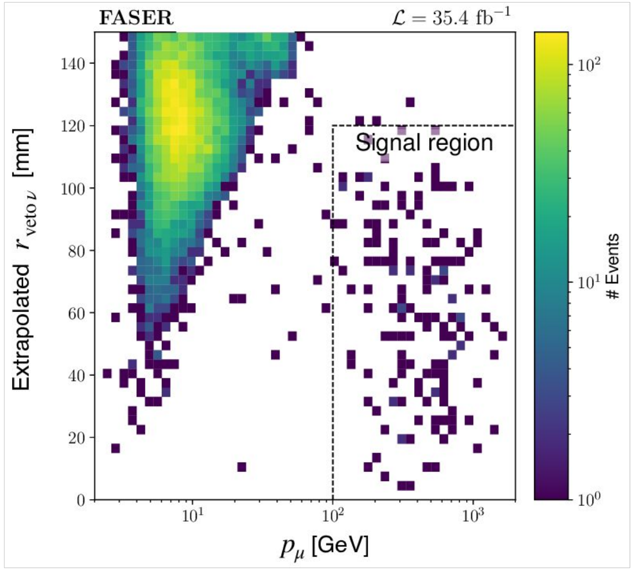
- Veto inefficiency
  - Estimate from fitting with 0/1/2 veto fired layers
  - **Negligible** due to high veto efficiency

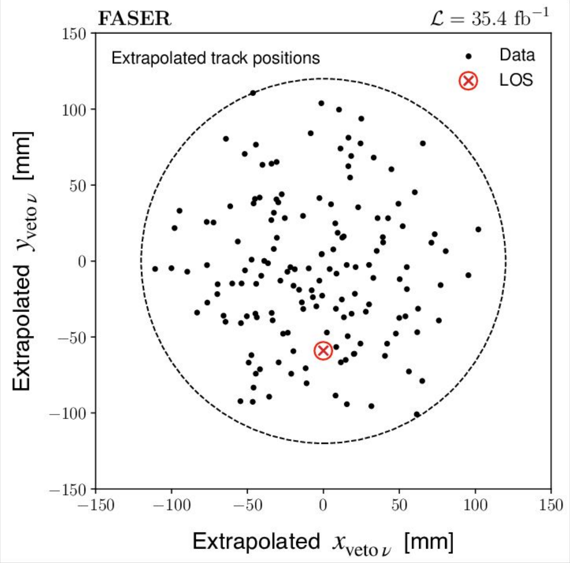
First direct observation of collider neutrinos

- Observed **153 events** with 0.2 background
  - Consistent with prediction: 151 ± 41
- Significance of **16σ**

$$n_\nu = 153^{+12}_{-13}(\text{stat})\,^{+2}_{-2}(\text{bkg}) = 153^{+12}_{-13}(\text{tot})$$

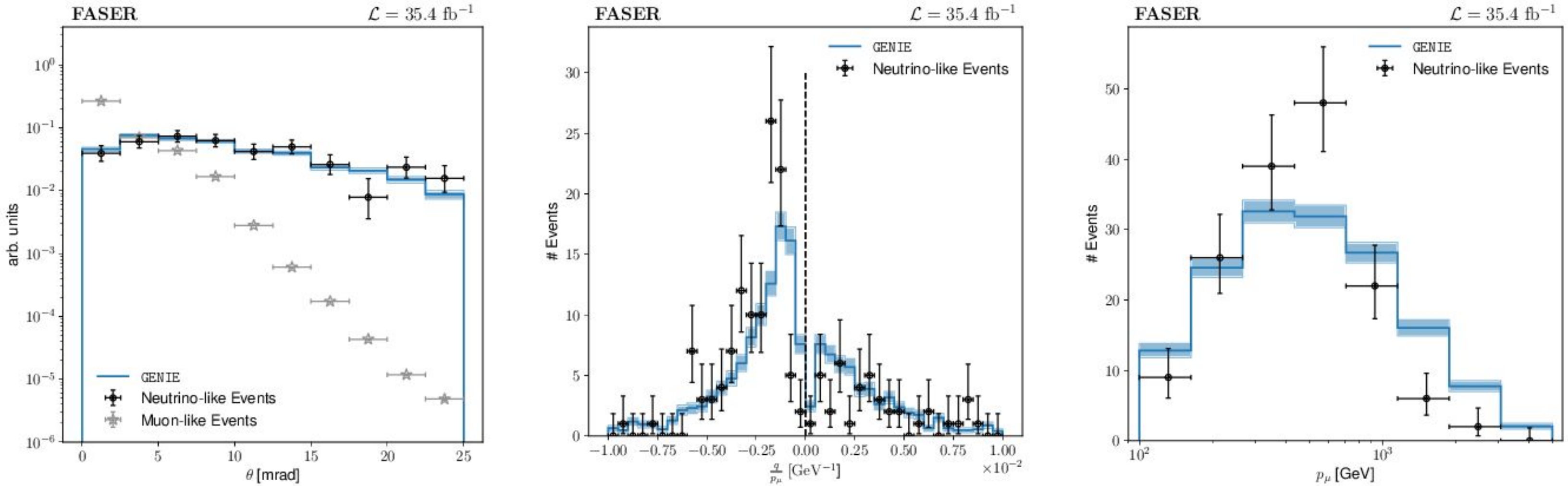
SND@LHC observed ~8 events with a significance of 6.8**σ**, more details in Cristovao's talk at Thursday





Neutrino characteristic

- Candidate neutrino events match expectation of signal
  - Most events have high momentum muon
  - More ν_μ than anti- ν_μ
- Opening a new window for neutrino study
- More studies are on-going
  - e.g. measurements using FASERν detector



Note: no acceptance corrections nor systematic uncertainties here

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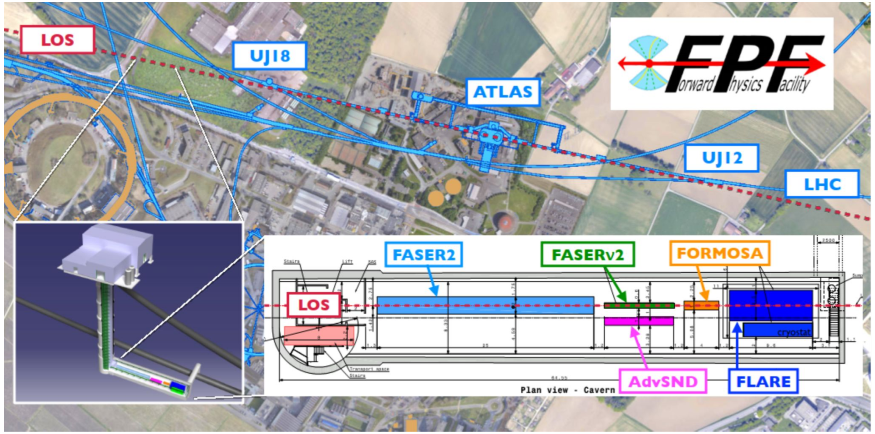
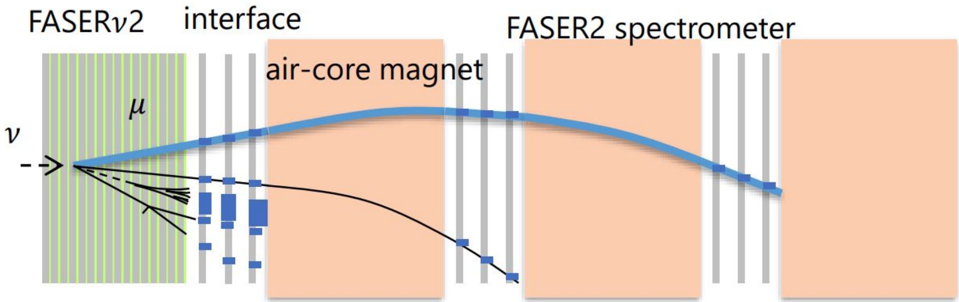
FASER2, FASERν2, and Forward Physics Facility (FPF)

- FASER2 for HL-LHC
  - Radius increased to 1m (FASER is 10cm)
  - Acceptance (π^0) increased to 10% (FASER is 0.6%)
  - Sensitivity improved by four orders of magnitude in many models
- FASERν2
  - 40cm×40cm×8m, 20 tons
  - O(10^5)ν_e ,O(10^6)ν_μ ,O(10^4)ν_τ expected in O(10) ton detector
- The FPF is proposal to create a new facility to house a suite of experiments on LOS
  - FASER2
  - FASERnu2
  - AdvSND
  - FLArE
  - FORMOSA
- More details in 6th FPF workshop





Summary and prospects

- FASER successfully constructed and took data of Run 3
  - Detector operated well and collected ~40 fb^{-1} of data in 2022 and ~30 fb^{-1} in 2023
- Excluded A’ in region of low mass and kinetic mixing
  - Probes new territory in the interesting thermal-relic region
- Observed ~153 ν_μ CC interactions
  - First direct detection of collider neutrinos!
  - Opens new window for high-energy ν studies
- More studies are in progress
  - e.g. ALPs, neutrino cross sections, new A’ search
  - New ideas are welcome
- Strong physics case emerging for large upgraded FASER2 and FASERν2 detectors beyond Run 3, to be housed in the proposed Forward Physics Facility (FPF)

Acknowledgement

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We also thank

- The LHC for excellent performance in 2022
- ATLAS for luminosity information
- ATLAS for use of ATHENA s/w framework
- ATLAS SCT for spare tracker modules
- LHCb for spare ECLA modules
- CERN FLUKA team for bkgrd simulations
- CERN PBC and technical infrastructure groups for excellent support during FASER's design, construction, installation