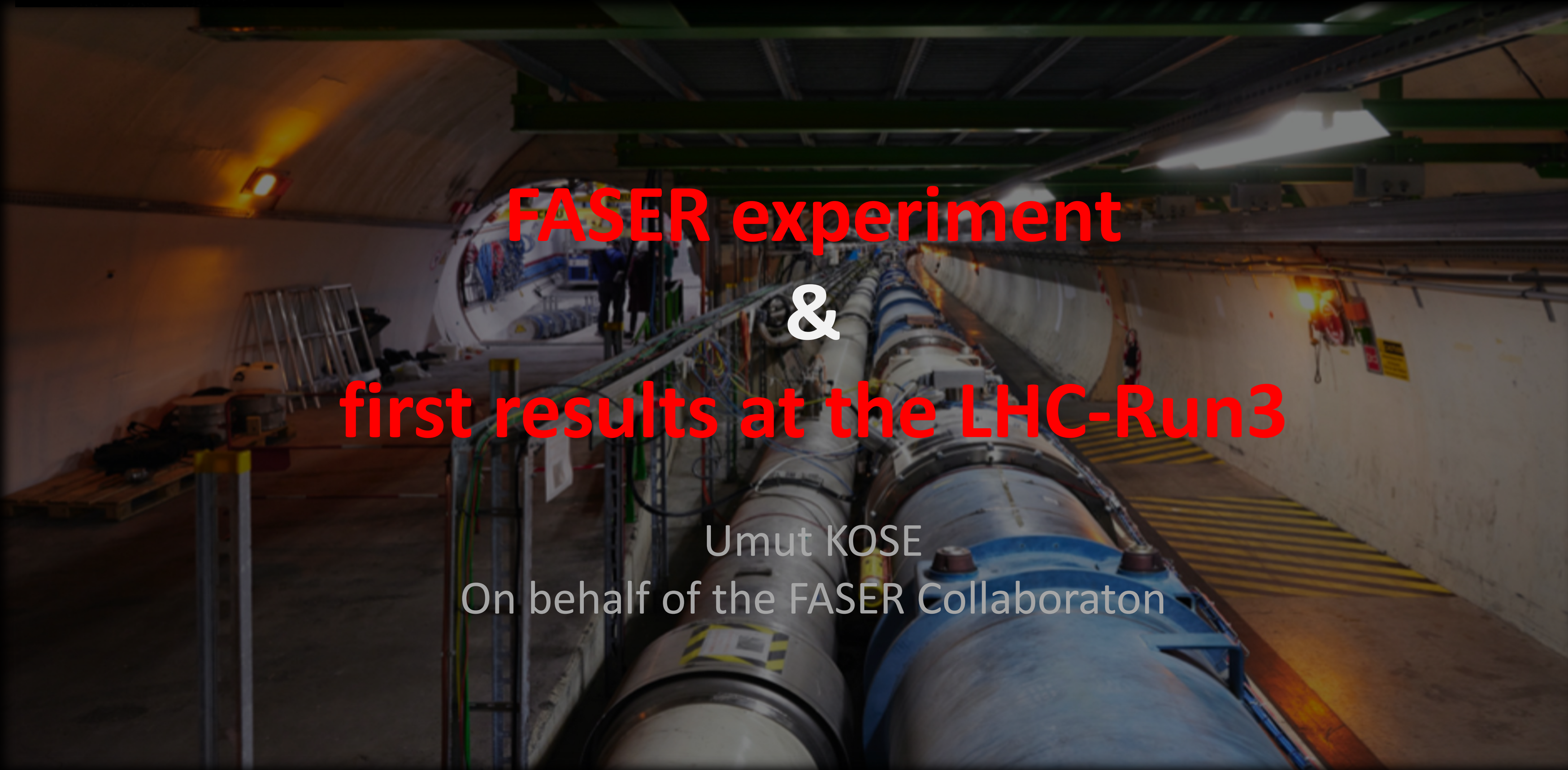


FASER experiment
&
first results at the LHC-Run3

Umut KOSE
On behalf of the FASER Collaboraton

The 17th International Workshop on Tau Lepton Physics
TAU2023, 04-08 December 2023

Overview

- Description of the experiment
  arXiv:2207.11427

- Dark Photon Search in FASER
  arXiv:2308.05587

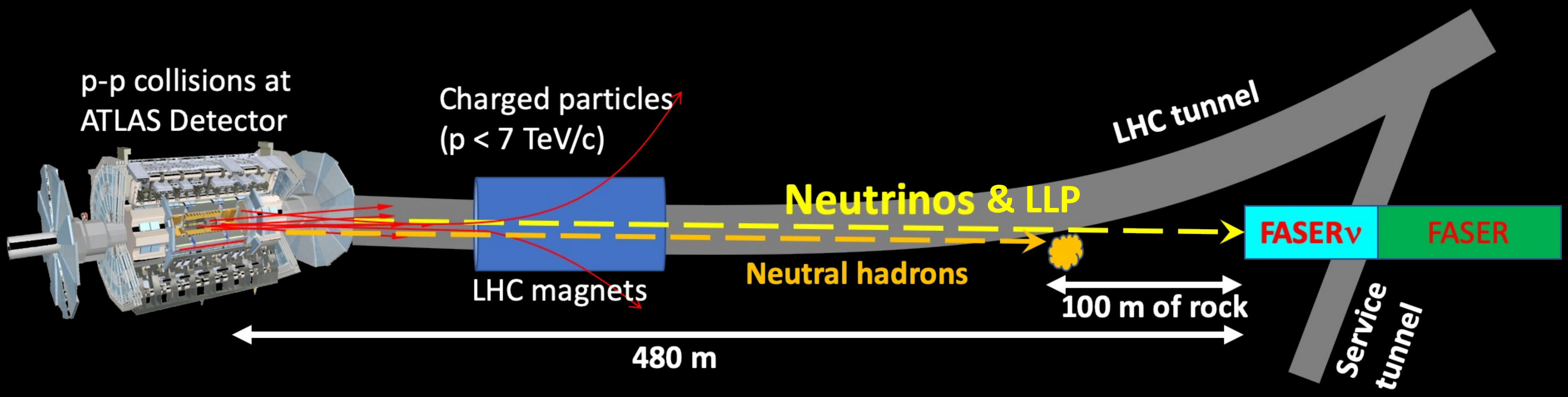
- Direct detection of LHC neutrinos with FASER electronic detector
  arXiv:2303.14185

- LHC neutrinos with FASERν emulsion detector
  CERN-FASER-CONF-2023-002

- Conclusions

ForwArd Search ExpeRiment (FASER) at the LHC

- FASER is a new forward LHC experiment :
  - Installed into the LHC complex
  - Designed to search for light and weakly interacting particles produced in p-p collisions at the ATLAS interaction point (IP)
    - Targets long-lived BSM particles (e.g. A’, ALPs) and neutrinos
    - Exploiting large LHC collision rate + forward-peaked production
  - Located at 480 m downstream of ATLAS IP
    - LHC magnets and 100 m of rock shield most background
  - First data taking in July 2022 at the start of Run3



LHC as a dark photon factory

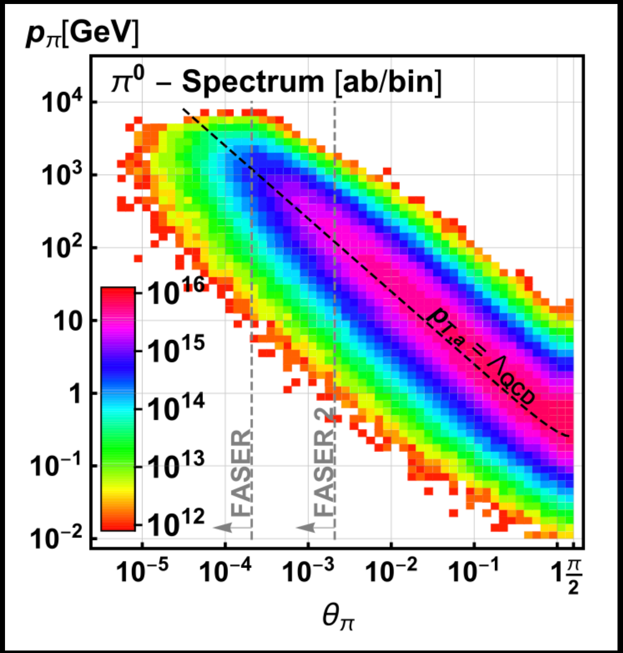
- At $\sqrt{s} = 13\ TeV$ energy, the total inelastic proton-proton scattering cross section is measured by ATLAS and CMS: $\sigma_{inel}(13TeV) \approx 75\ mb$, with most of it in the very forward direction.

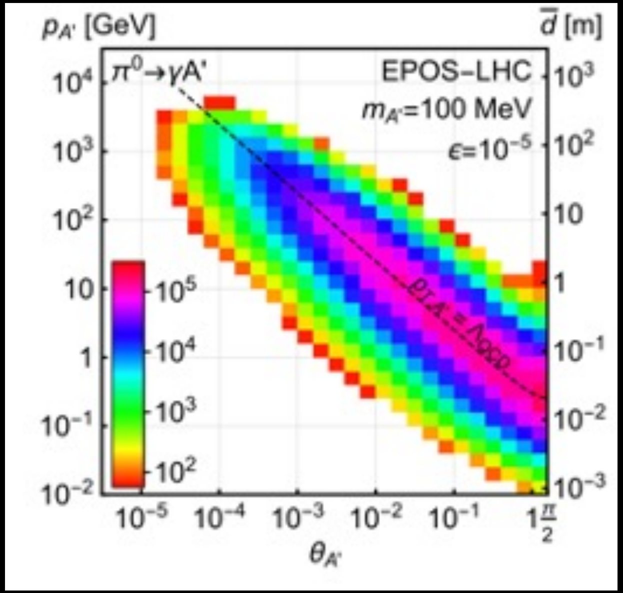
- Considering $150\ fb^{-1}$, we expect 1.1×10^{16} inelastic pp scattering events, implying extraordinary meson production rates of

  $N_{\pi^0} \approx 2.3\times10^{17}$, $N_{\eta} \approx 2.5\times10^{16}$, $N_{D} \approx 1.1\times10^{15}$
  and $N_{B} \approx 7.1\times10^{13}$

- FASER as forward detector placed on the beam collision axis downstream from IP, will be sensitive to new physics: such as dark photons produced in light meson decays.

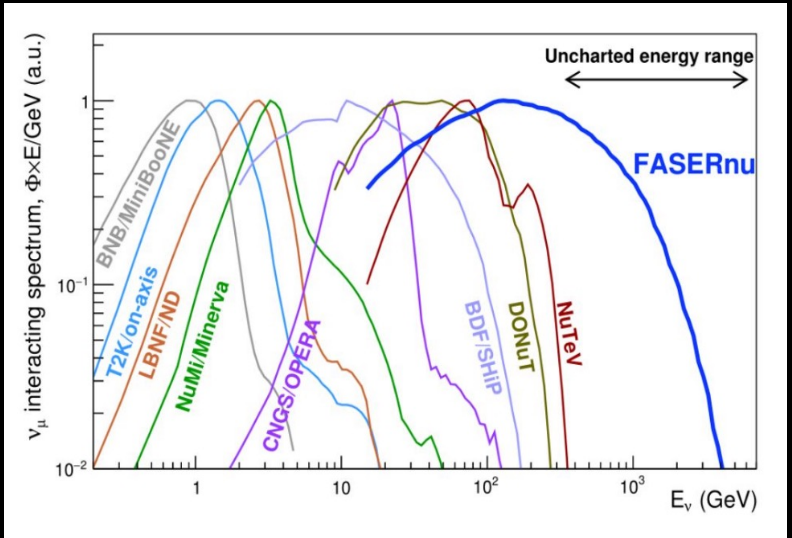
  arXiv:1708.09389
  https://doi.org/10.1103/PhysRevD.99.095011



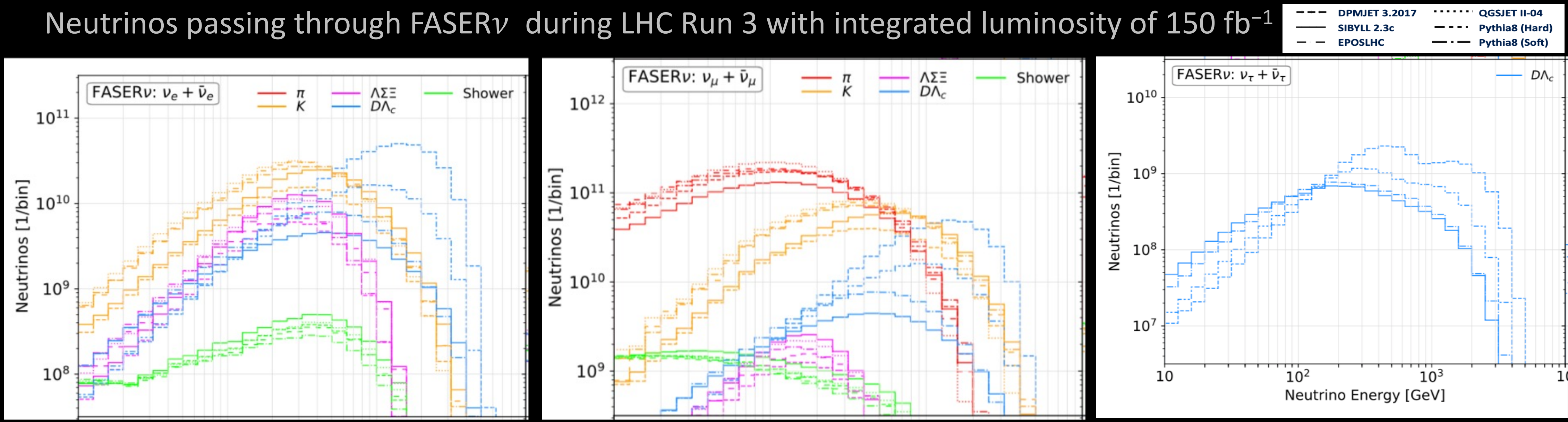


LHC as a source of neutrinos

- Huge flux of neutrinos at LHC produced at collision points in the far forward direction, from a variety of sources: pion, kaon, hyperon and charm decays.
  - Intense: ~10^{12} neutrino in LHC Run-3
  - Highly collimated, beam size $\approx O(10cm)$
  - ~TeV neutrinos/antineutrinos in all flavours



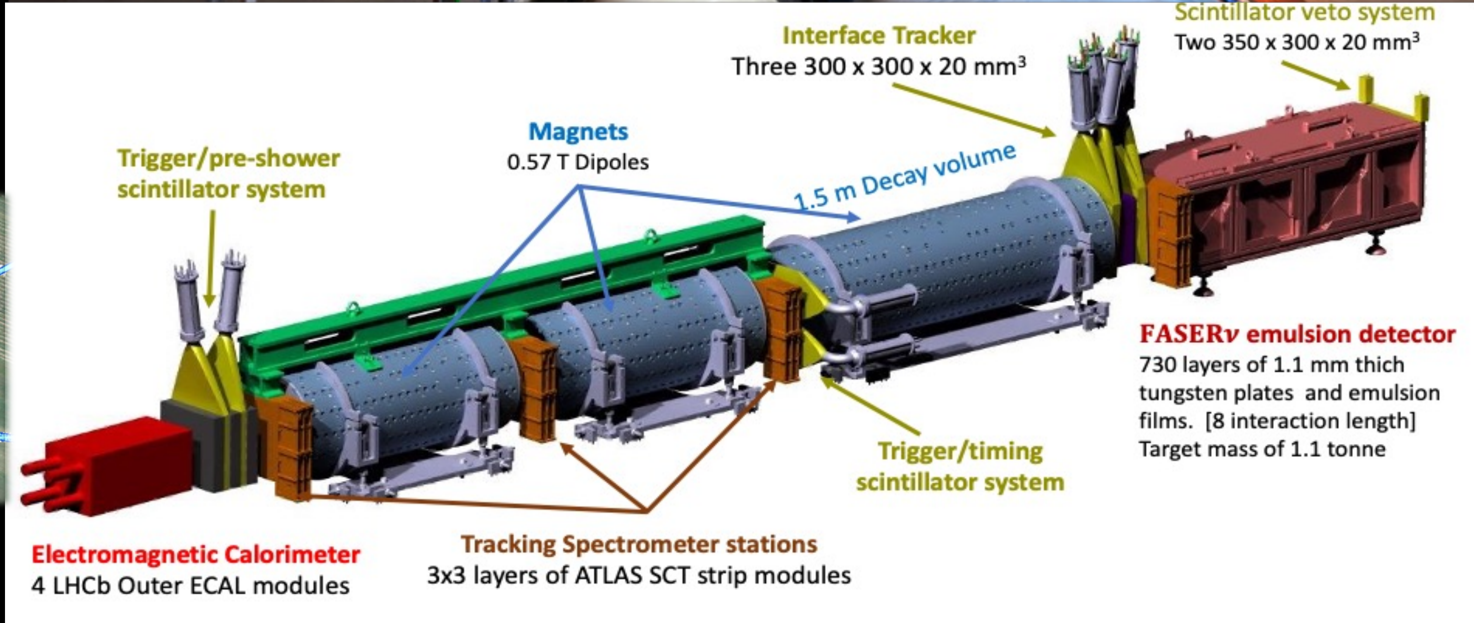
Neutrinos passing through FASERν during LHC Run 3 with integrated luminosity of 150 fb^{-1}

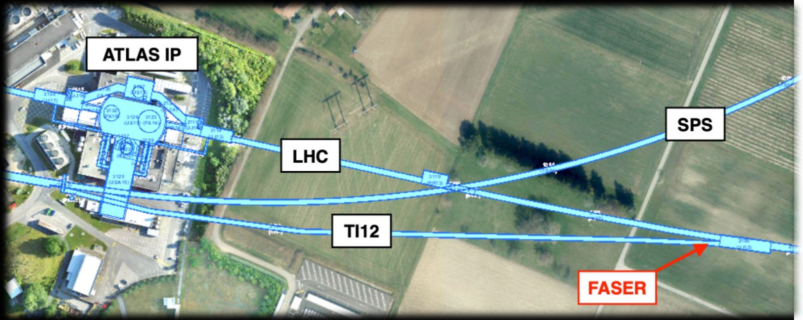


Phys. Rev. D **104**, 113008

FASER Detector

- Located at LHC service tunnel TI12
- Small and inexpensive detector
  - 10 cm radius of active volume, 7 m long
- Successfully installed and commissioned in 2021

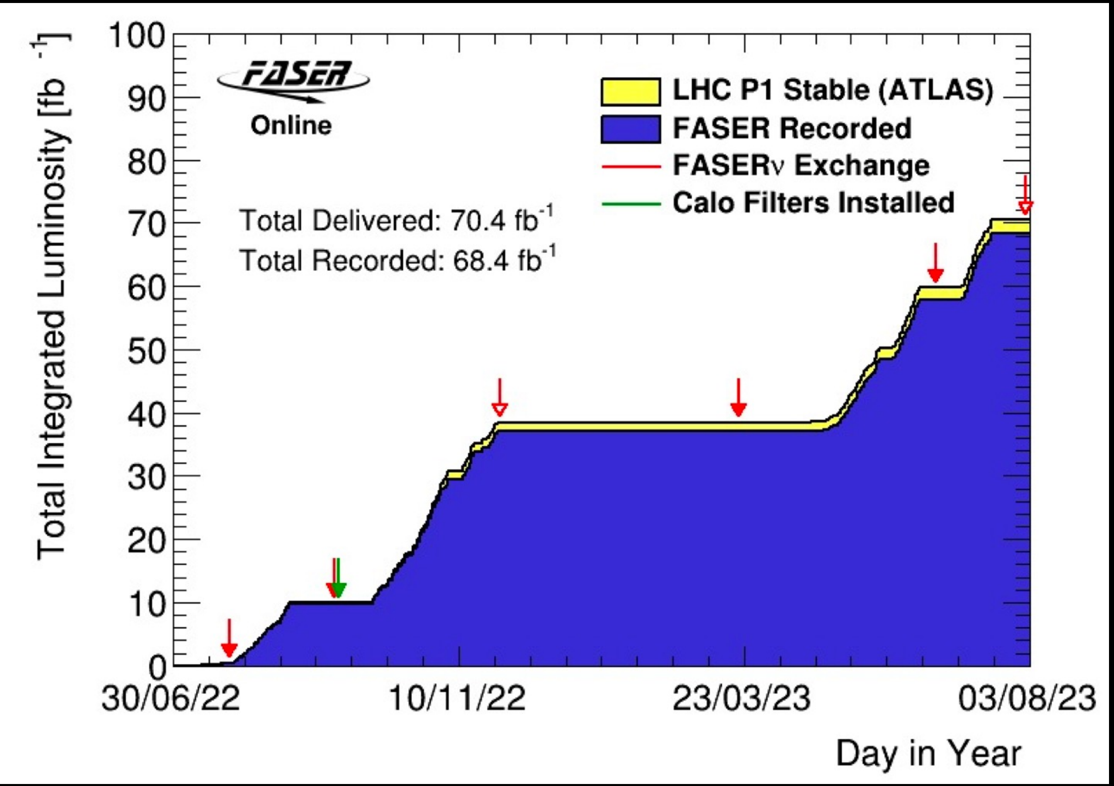




arXiv:2207.11427

FASER operation at Run3

- Successfully operated throughout 2022 and 2023
  - Continuous data taking
  - Largely automated
  - Up to 1.3 kHz
- Recorded ~97% of delivered luminosity
  - DAQ dead-time of 1.3%
  - A couple of DAQ crashes
- Emulsion detector exchange
  - Typically exchange during LHC Technical Stops
  - Needed to manage the occupancy ($\mathcal{O}(10^6)$ tracks/cm^2)
  - First box only partially filled

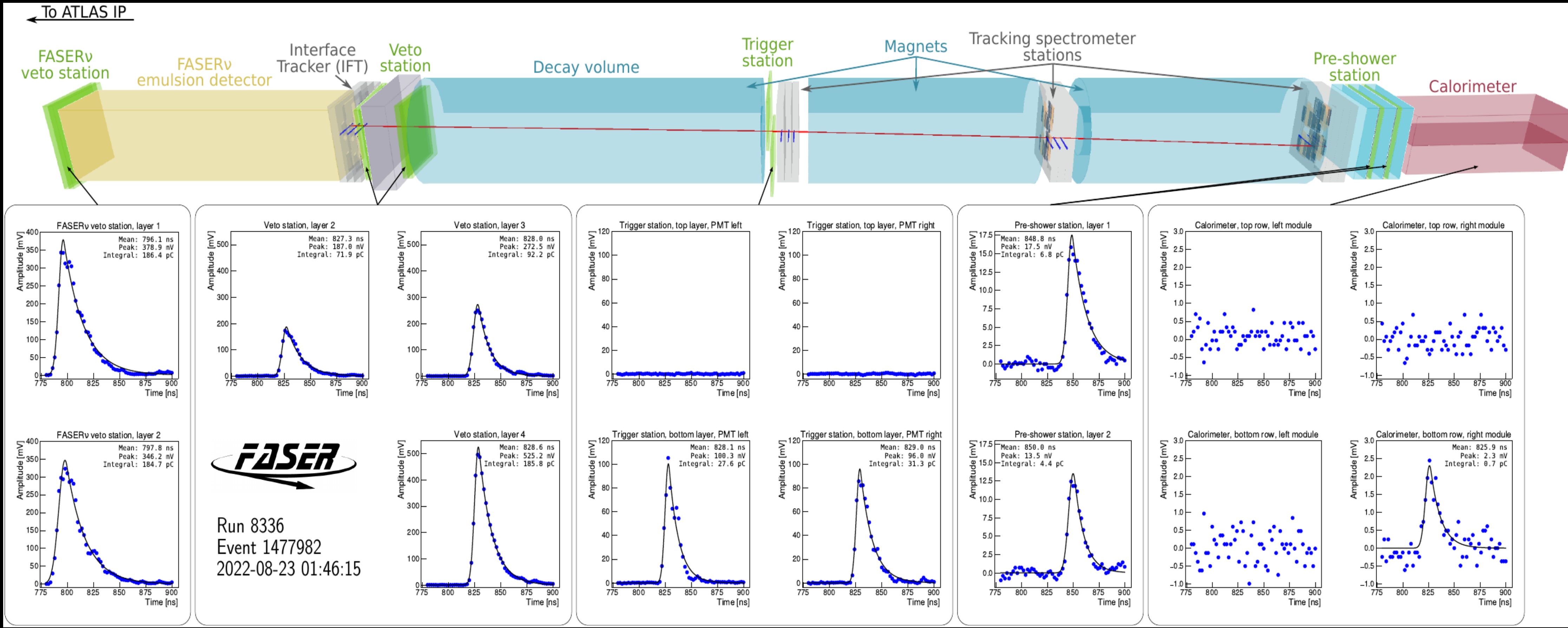


- Calorimeter gain optimised for:
  - Low E (<300 GeV) before 2nd exchange
  - High E (up to 3 TeV) after the exchange

Nearly 70 fb^{-1} of data recorded with data taking efficiency of 97%

FASER Detector operation

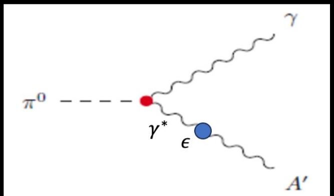
- All detector components performing excellently
- More than 500M single-muon events recorded



Muon passing through full detector: energy deposition on scintillator and calorimeter consistent with minimum ionizing particle

[1] Dark photon search in FASER

arXiv:2105.07077



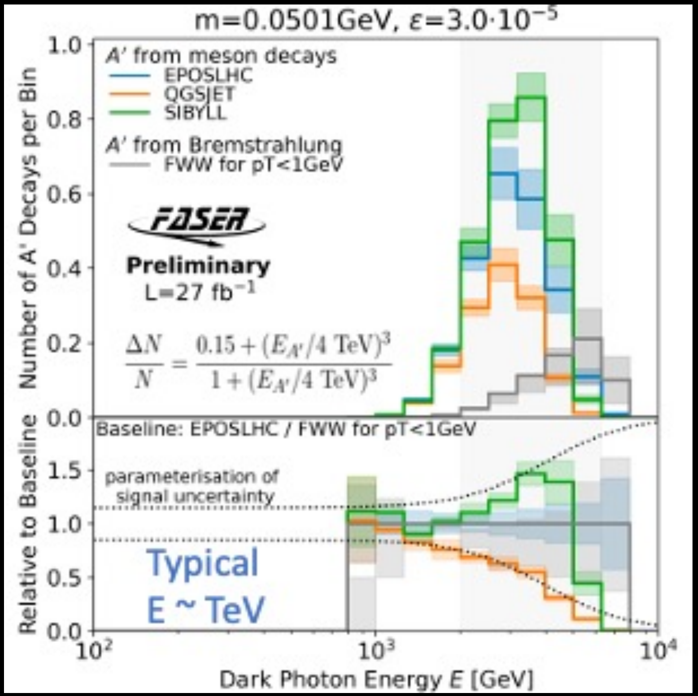
- **Dark photons:** hypothetical gauge boson couple to dark matter and other hidden sector particles, can mix to the ordinary photons of SM.
- Mainly produced at the LHC through $\pi^0 \to A'\gamma$, $\eta \to A'\gamma$ and dark bremsstrahlung $pp \to ppA'$.

$$B(\pi^0 \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \to \gamma\gamma)$$

- Characterized by its mass, $m_{A'}$, and coupling parameter, ϵ.
- Long decay length (for $E_{A'} \gg m_{A'} \gg m_e$)

$$L = c\beta\tau\gamma \approx (80m) \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{TeV}\right] \left[\frac{100\ MeV}{m_{A'}}\right]^2$$

- In the range of $2m_e < m_{A'} < 2m_\mu \simeq 211$ MeV, decays 100 % to $A' \to e^-e^+$
- For dark photons with TeV energies, FASER will be sensitive in parameter space with $m_{A'} \sim 100\ MeV$ and $\epsilon \sim 10^{-5}$.



The energy spectrum of dark photons in FASER produced with meson production modelled by different generators (EPOS-LHC, QGSJET II-04 and SIBYLL 2.3d).

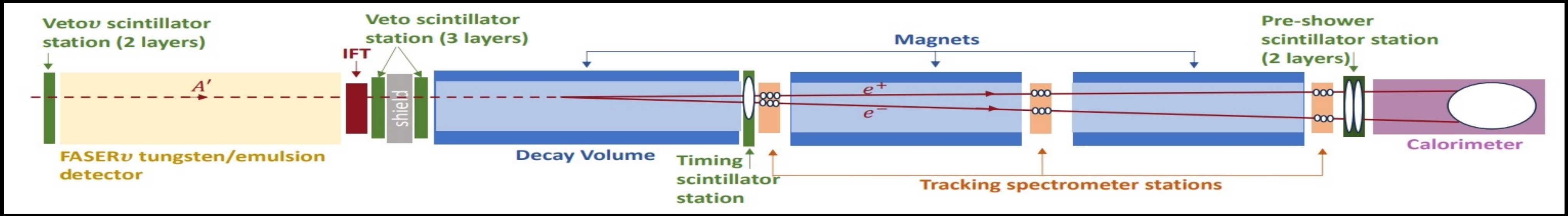
Dataset collected at $\sqrt{s} = 13.6\ TeV$ from September to November 2022 corresponding to integrated lumiosity of 27.0 fb^{-1} used to search for dark photon in FASER.

Dark photon selection in FASER

- Based on simple and robust $A' \rightarrow e^- e^+$ selection criteria and optimized for early discovery

No signal in any of the five veto scintillators

Timing and preshower consistent with ≥2 MIPs



Event time is consistent with a colliding bunch at ATLAS IP

Exactly two good tracks in fiducial volume (p > 20 GeV and r < 95 mm, extrapolating to r < 95 mm at vetos)

Total calorimeter energy E > 500 GeV

Background:

- Neutrino interactions at vicinity of timing detector
  - Estimated to be $(1.5 \pm 0.5(stat.) \pm 1.9(syst.)) \times 10^{-3}$ events (using 300 ab^{-1} neutrino MC sample)
- Neutral hadrons produced in muon interaction in the rock, interacting or decaying the decay volume
  - Estimated from lower energy events with 2/3 tracks and different veto conditions $(8.4 \pm 11.9) \times 10^{-4}$ events
- Total backround $(2.3 \pm 2.3) \times 10^{-3}$ events

Dark photon results

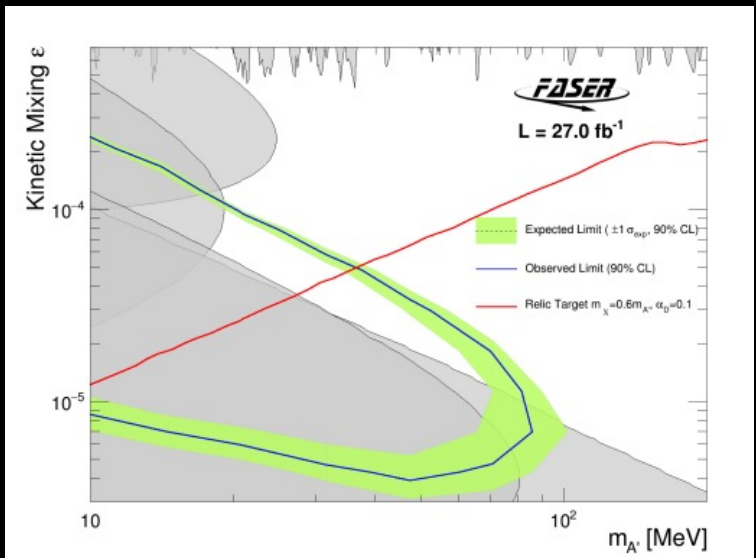
- No events seen in unblinded signal region
- With null-result, FASER sets limits on previously unexplored parameter space
- At the 90% confidence level, FASER excludes the region of

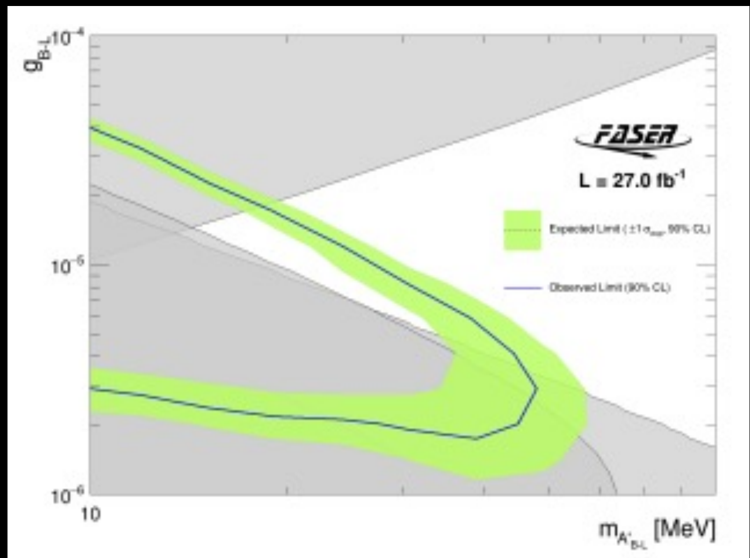
$\epsilon \sim 4\times10^{-6} - 2\times10^{-4}$ and $m_{A'} \sim 10\ MeV - 80\ MeV$

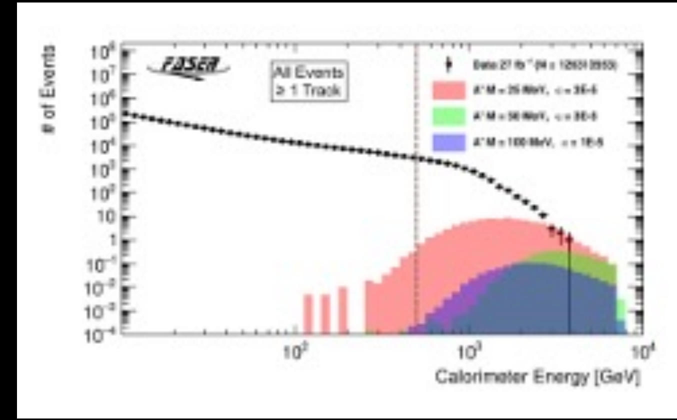
in the dark photon parameter space, as well as the region of

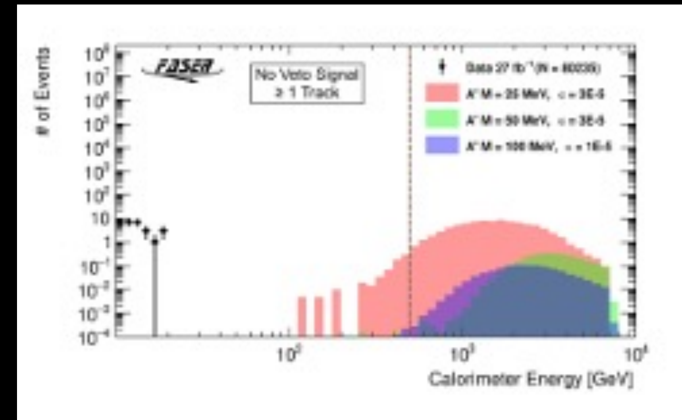
$g_{B-L} \sim 3\times10^{-6} - 4\times10^{-5}$ and $m_{A'_{B-L}} \sim 10\ MeV - 50\ MeV$

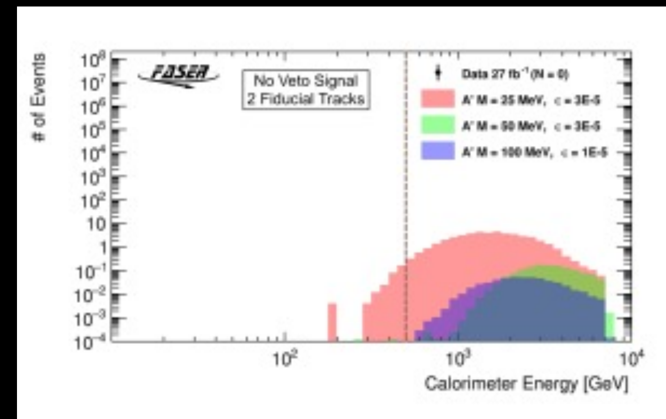
in the B – L gauge boson parameter space











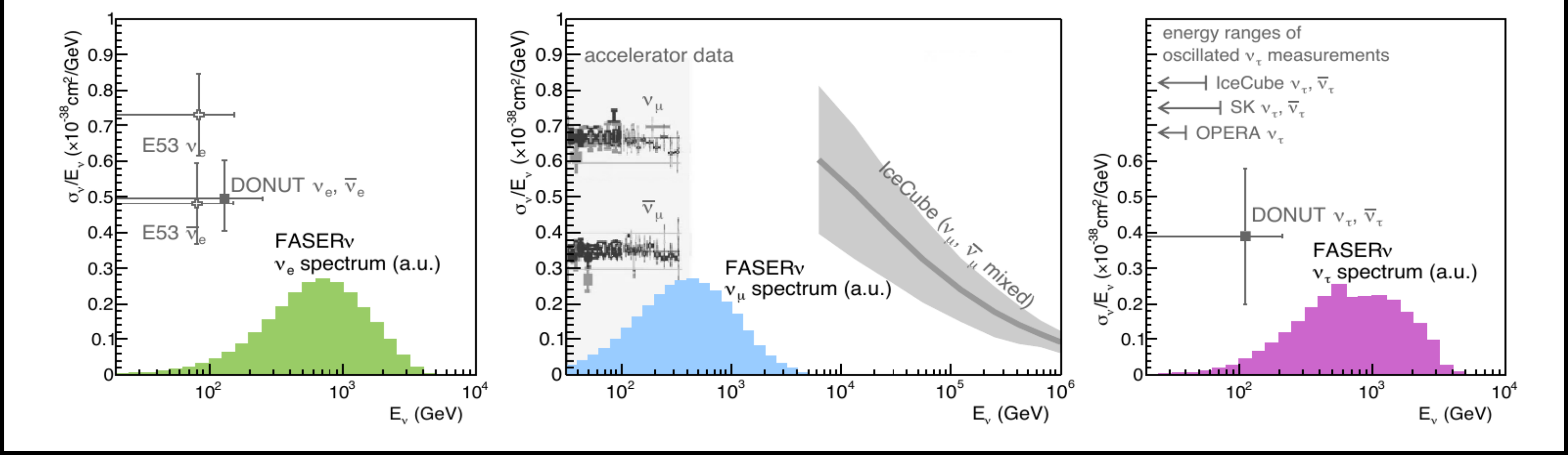
[2] LHC Neutrinos in FASER/FASERν

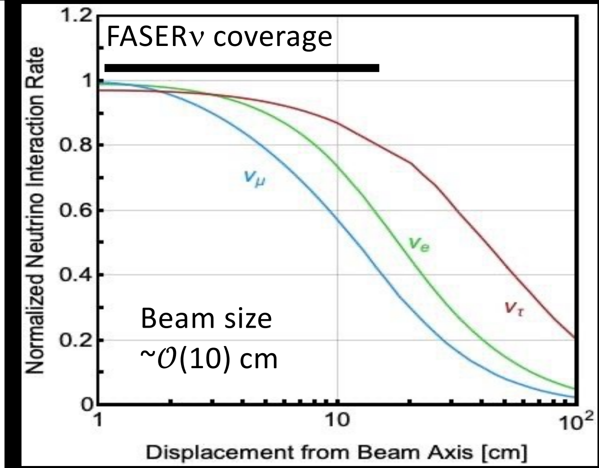
- Dedicated emulsion subdetector to study unexplored energy regime (TeV neutrinos)
- Neutrino flux for all flavours maximized on the collision axis line of sight
- Study production, propagation and interactions of high energy neutrinos
- Primary goal of FASERν is the cross-section measurements of different flavor at TeV energies.
  FASER Collaboration, Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310
- Probing neutrino related models of new physics

Expected number of νCC interaction events occurring in FASERν during LHC Run 3 with 250 fb^{-1} integrated luminosity based on Phys. Rev. D **104**, 113008

Generators		FASERν		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	1501	7971	24.5
DPMJET	DPMJET	5761	11813	161
EPOSLHC	Pythia8 (Hard)	2521	9841	57
QGSJET	Pythia8 (Soft)	1616	8918	26.8
Combination (all)		2850^{+2910}_{-1348}	9636^{+2176}_{-1663}	67.5^{+94}_{-43}
Combination (w/o DPMJET)		1880^{+641}_{-378}	8910^{+930}_{-938}	$36^{+20.8}_{-11.5}$

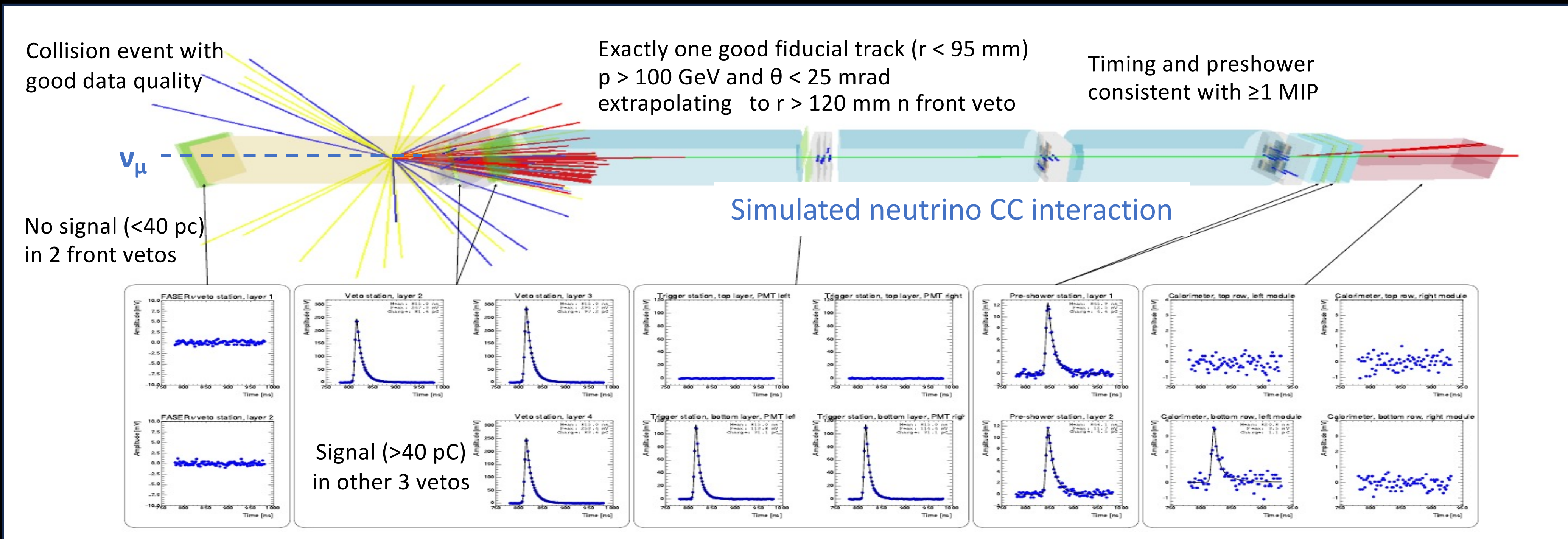
Directly observed $\nu_\tau CC$ interactions (event-by-event):
9 at DONUT and 10 at OPERA experiments





[2.1] First Direct Observation of Collider Neutrinos with FASER at the LHC

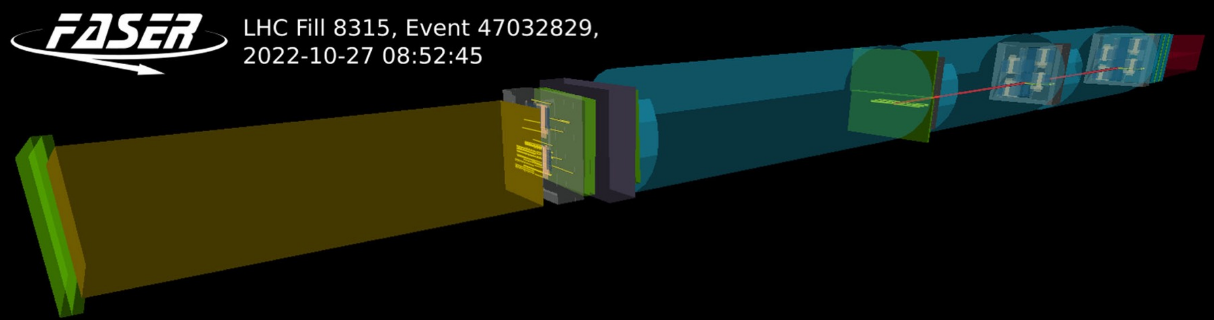
- Just using spectrometer and veto systems, $\nu_\mu\ CC$ and $\bar{\nu}_\mu\ CC$ interactions can be detected
- Dataset collected at $\sqrt{s} = 13.6\ TeV$ from July to November 2022 corresponding to integrated lumiosity of 35.4 fb^{-1} used for the first direct observation of neutrino interactions using the active electronic components of FASER detector.

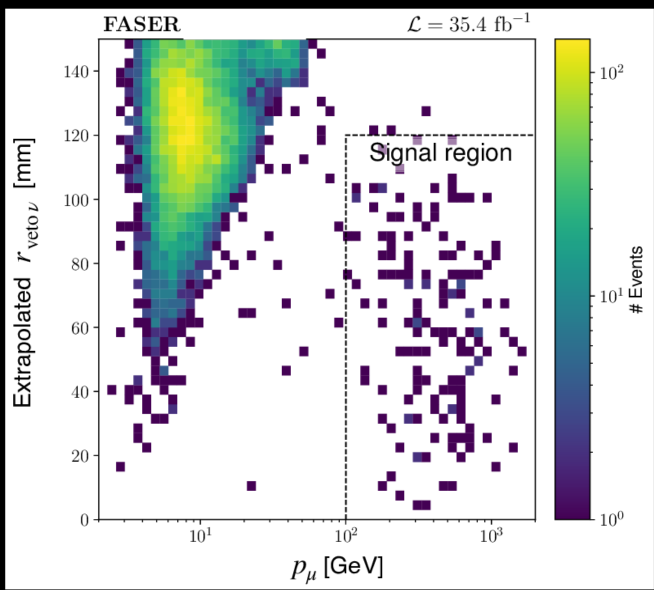


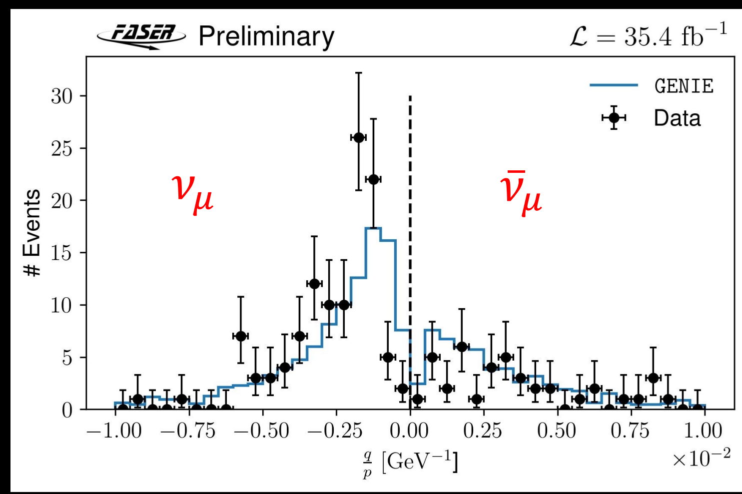
[Phys. Rev. Lett. 131, 031801 (2023)](#)

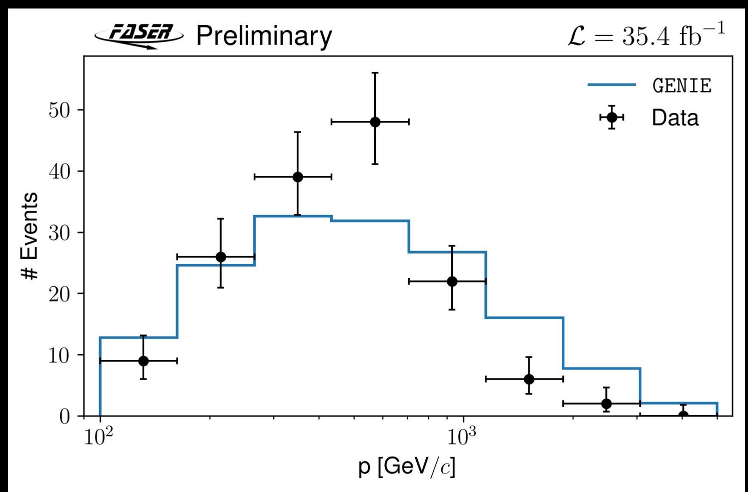
Neutrino Results

- Expecting 151 ± 41 neutrino events from $\nu_\mu\ CC$ (and $\bar{\nu}_\mu\ CC$) interactions using GENIE simulation
  - Uncertainty from difference between generators (DPMJET & SIBYLL).
- Background:
  - Neutral hadrons: 0.11 ± 0.06 events
  - Muon scattering: 0.08 ± 1.83 events
  - Veto inefficiency: negligible
- Unblinded results:
  - 153 events in the signal region
  - Signal significance of 16σ









[Phys. Rev. Lett. 131, 031801 (2023)]

[2.2] Neutrino Results from FASERν

CERN-FASER-CONF-2023-002

- Since March 2022, five FASERν emulsion modules are exchanged during LHC technical stop
  - FASERν emulsion detector is passive and records signals from all traversing charged particles
  - To keep the detector occupancy at an acceptable level for analysis, $\mathcal{O}(10^6)$ tracks/cm^2

- Analysed dataset was collected by exposing to 9.5 fb^{-1} pp collision data from July to November 2022 at $\sqrt{s} = 13.6\ TeV$.

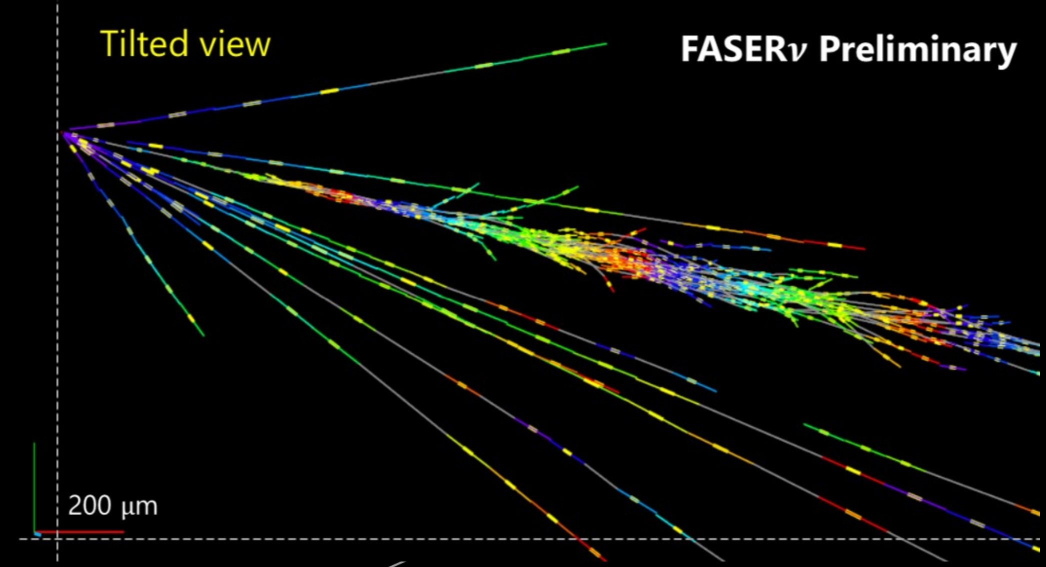
- 150 out of 730 emulson fims are analysed to search for LHC neutrino interaction vertices.
  - Corresponding to 68 kg of target mass
  - Selecting vertices with associated lepton candidate, e or μ, with E_{lep} > 200 GeV

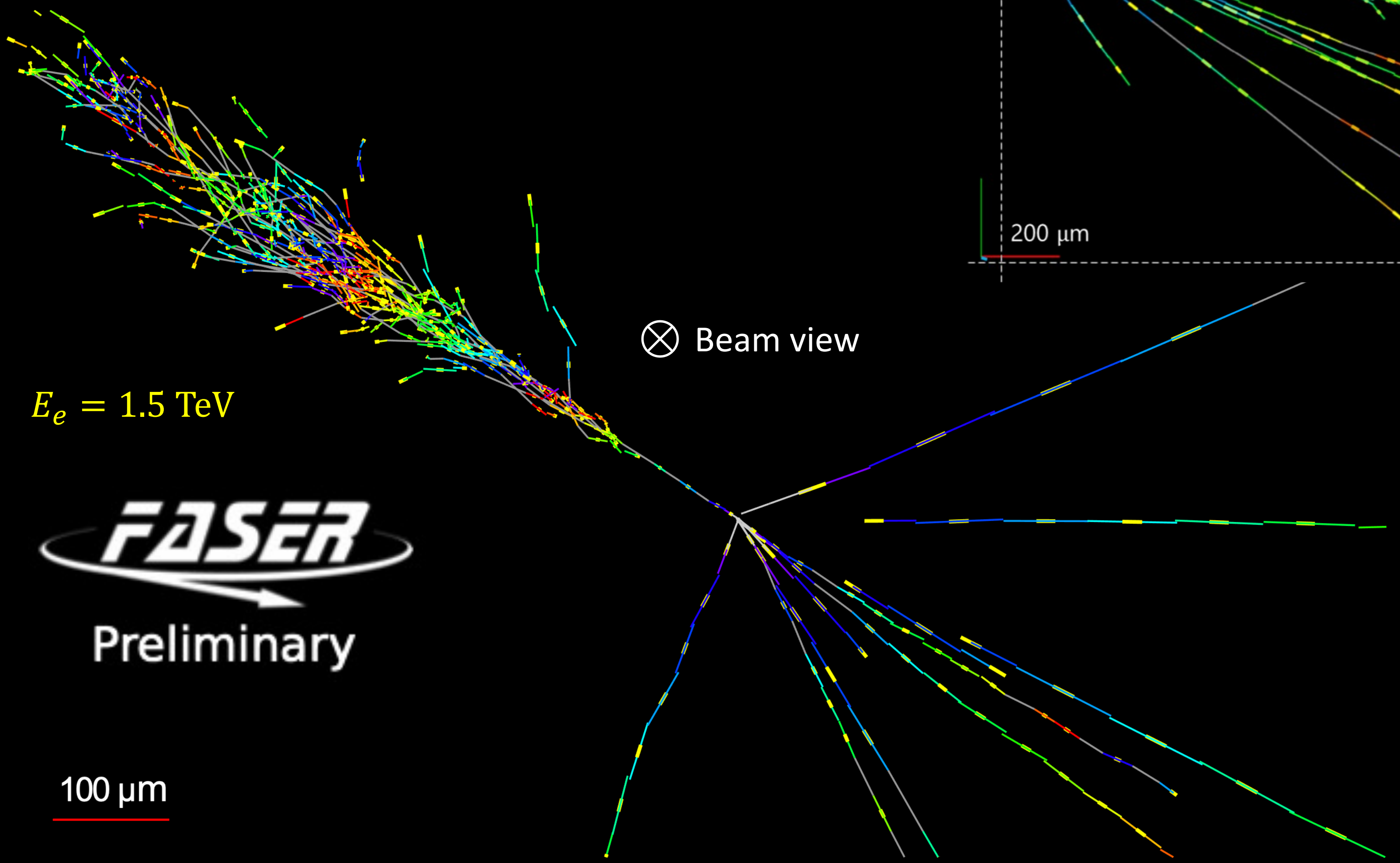
FASER Preliminary

	Expected background		Expected signal	**Observed**
	Hadron int.	ν NC int.		
ν_e CC	0.002 $\pm$0.002(stat)$\pm$0.002(syst)	-	$1.2\ ^{+4.0}_{-0.6}$	3
ν_μ CC	0.32 $\pm$0.15(stat)$\pm$0.16(syst)	0.19$\pm$0.15	$4.4\ ^{+4.2}_{-1.4}$	4

Three $\nu_e CC$ and four $\nu_\mu CC$ candidates are observed, probability to be explained by background 1.6×10^{-7} (5.1σ) and 5.2×10^{-3} (2.5σ) , respectively.

First direct observation of $\nu_e CC$ at the LHC





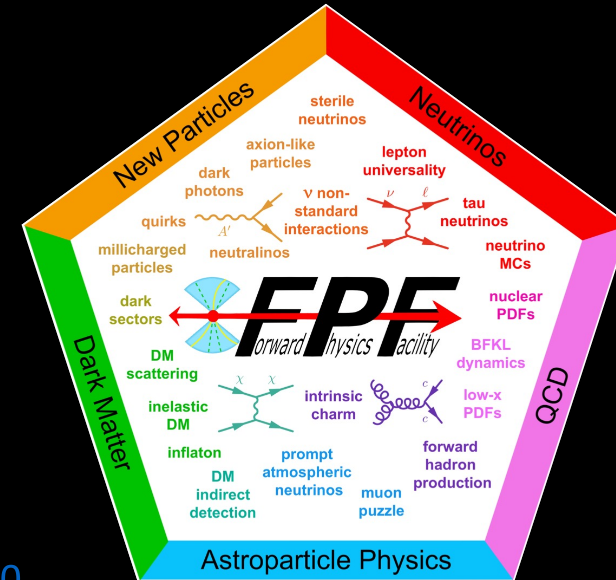
- Vertex with 11 tracks
  - 615 μm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max @ $7.8X_0$
  - θ_e = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest

FASER Preliminary

Forward Physics Facility (FPF)

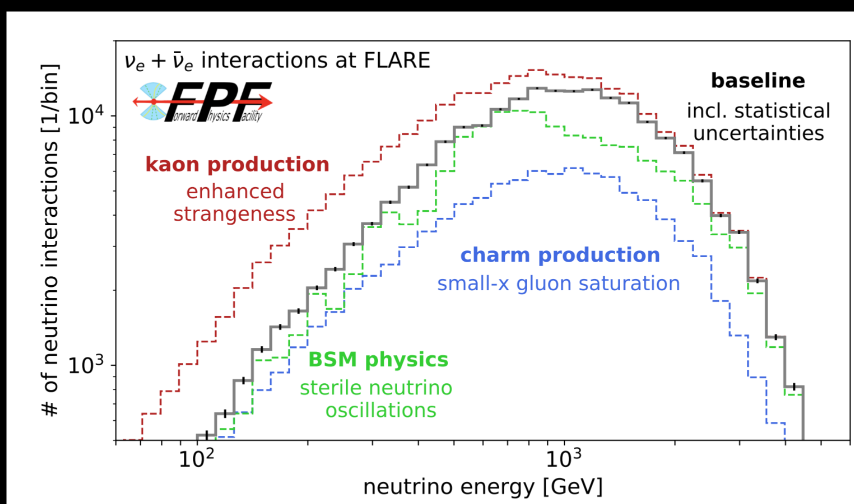
- FPF is proposed new facility to fully exploit the LHC's physics potential in the forward direction during the High-Luminosity LHC era
  - BSM physics searches, neutrino physics, QCD and astro-particle physics
- New underground cavern and shaft, 600 m away from the ATLAS IP, 65 m long and 8.5 m wide
- High statistics highest energy neutrinos/antineutrinos:
  - $\mathcal{O}$(10tonne) detectors with HL-LHC
  - $\mathcal{O}(10^5)$ ν_e, $\mathcal{O}(10^6)$ ν_μ and $\mathcal{O}(10^4)$ ν_τ interactions

  with energies from $\mathcal{O}(100)$ GeV to a few TeV

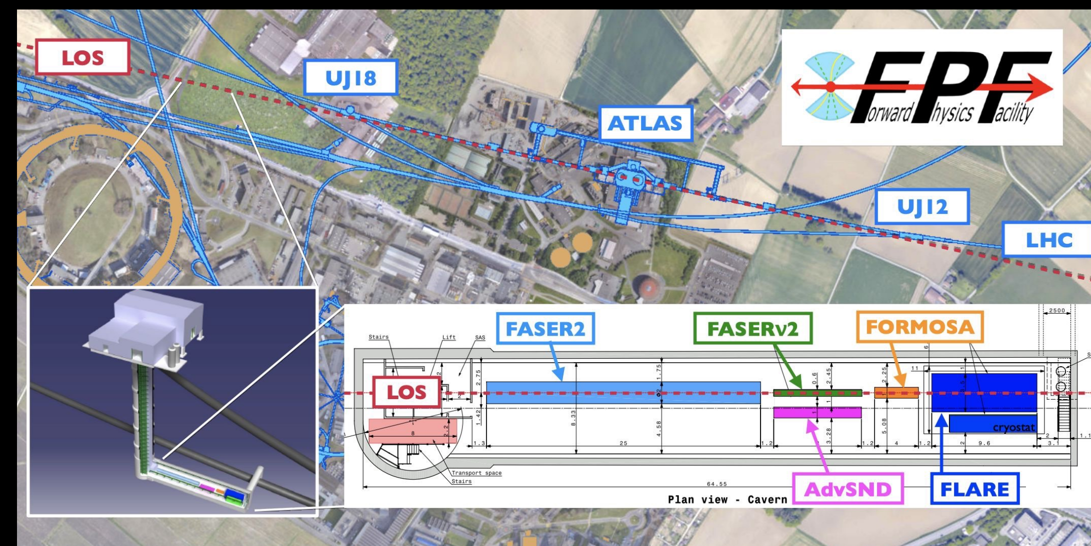


arXiv:2203.05090

Physics topics



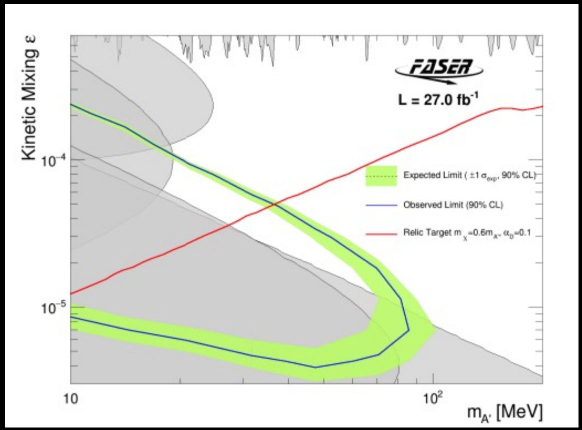
Scaled to the nominal HL-LHC luminosity of $5\times10^{34}\ cm^{-2}s^{-1}$

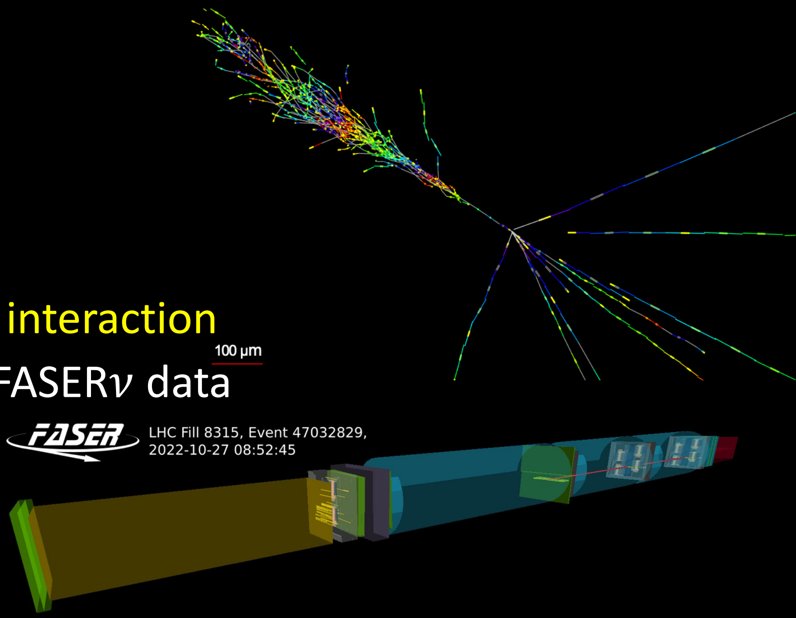


See talks from Jianming Bian, Yu-Dai Tsai

Conclusions

- FASER successfully took data in first year of Run 3 at the LHC
  - Running with fully functional detector and very good efficiency
- Excluded dark photon (A') in region of low mass and kinetic mixing
  - Probes new territory in interesting thermal-relic region
- Neutrino search in FASER/FASERν
  - Opens new window for high-energy neutrino study
  - First direct observation of collider neutrinos
    - ~153 $\nu_\mu CC$ interactions in spectrometer
  - More searches and neutrino measurements at FASERν
    - Observing for the first time the highest energy, 1.5 TeV, $\nu_e CC$ interaction
    - Three $\nu_e CC$ and four $\nu_\mu CC$ candidates observed in subset of FASERν data
- Looking forward to up to 10x more LHC run-3 data
- More results are coming, stay tuned!





Thank you!

FASER supported by

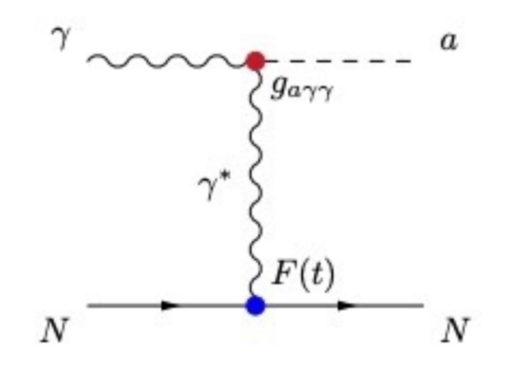
FASER Collaboration

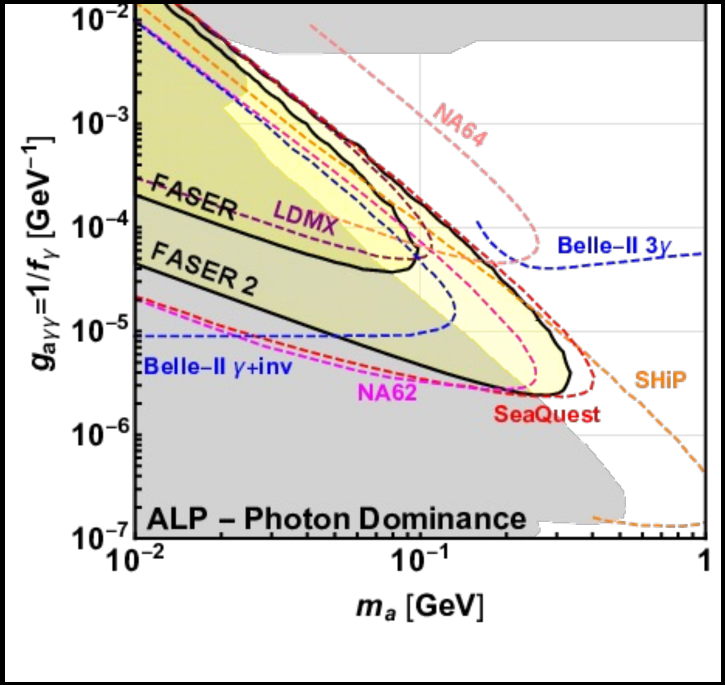
International laboratory covered by a cooperation agreement with CERN

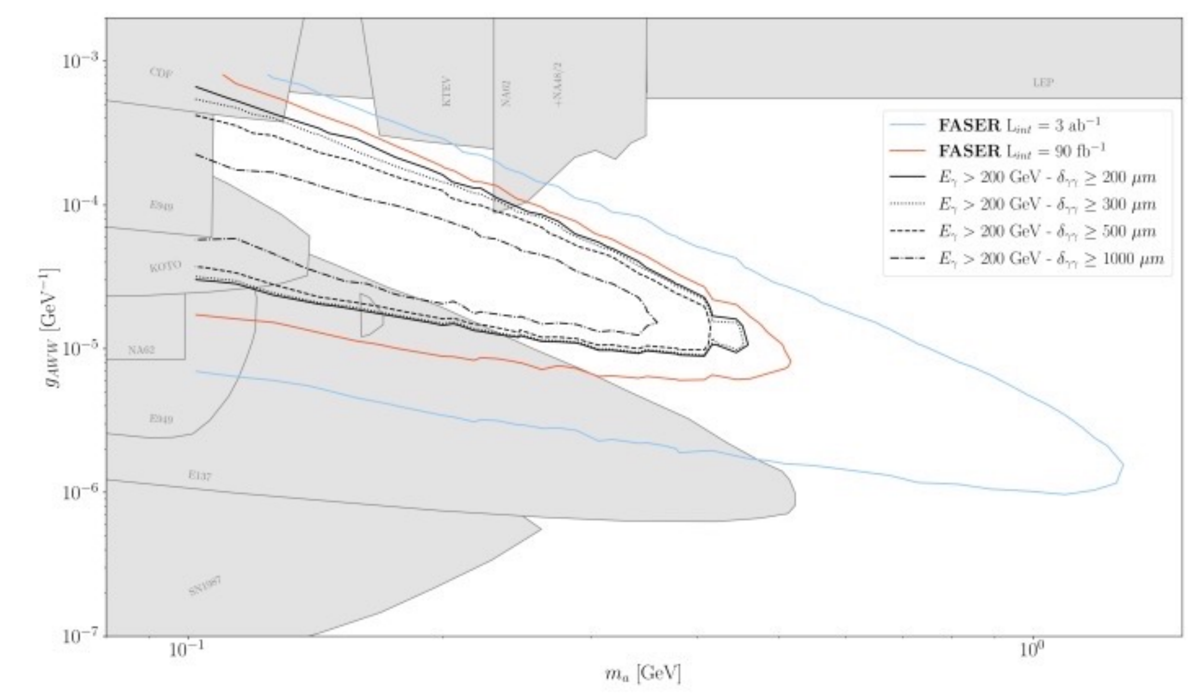
Backup

Axionlike particles at FASER: The LHC as a photon beam dump

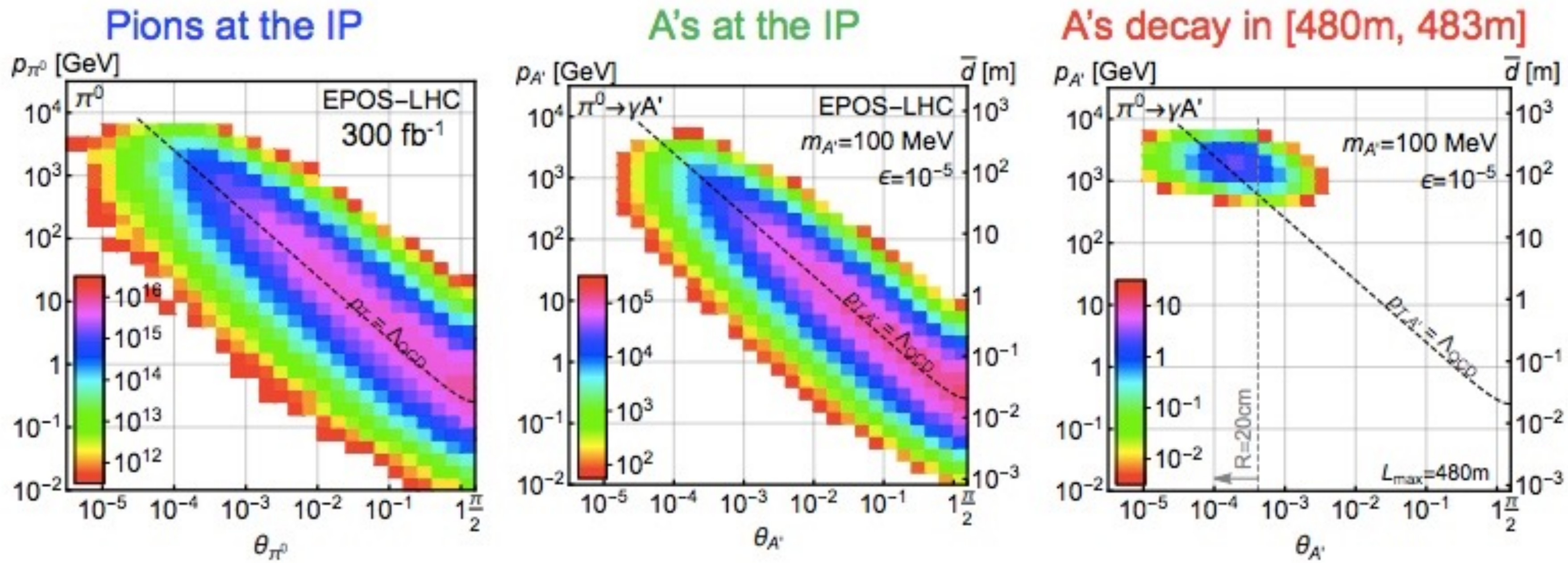
- ALPs with photon-like couplings can be produced by high energy photons in the forward direction interacting with LHC material (the TAN absorber) via the Primakoff process. **"LHC as a photon beam dump".** The ALP can then decay to 2 photons in FASER: [Phys. Rev. D98 no. 5, (2018) 055021]
- ALPs with W-like couplings can be produced in b hadron decays, and decay to 2 photons in FASER
  - FASER sensitivity nicely fits between existing collider and fixed target







Dark Photon production



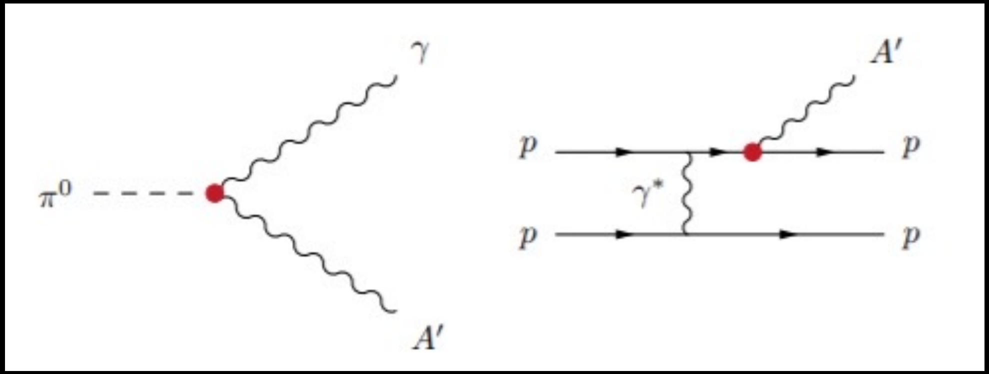
- Simulations greatly refined by LHC data
- Production is peaked at $p_T \sim \Lambda_{QCD} \sim 250$ MeV
- Enormous event rates: $N_\pi \sim 10^{15}$ per bin

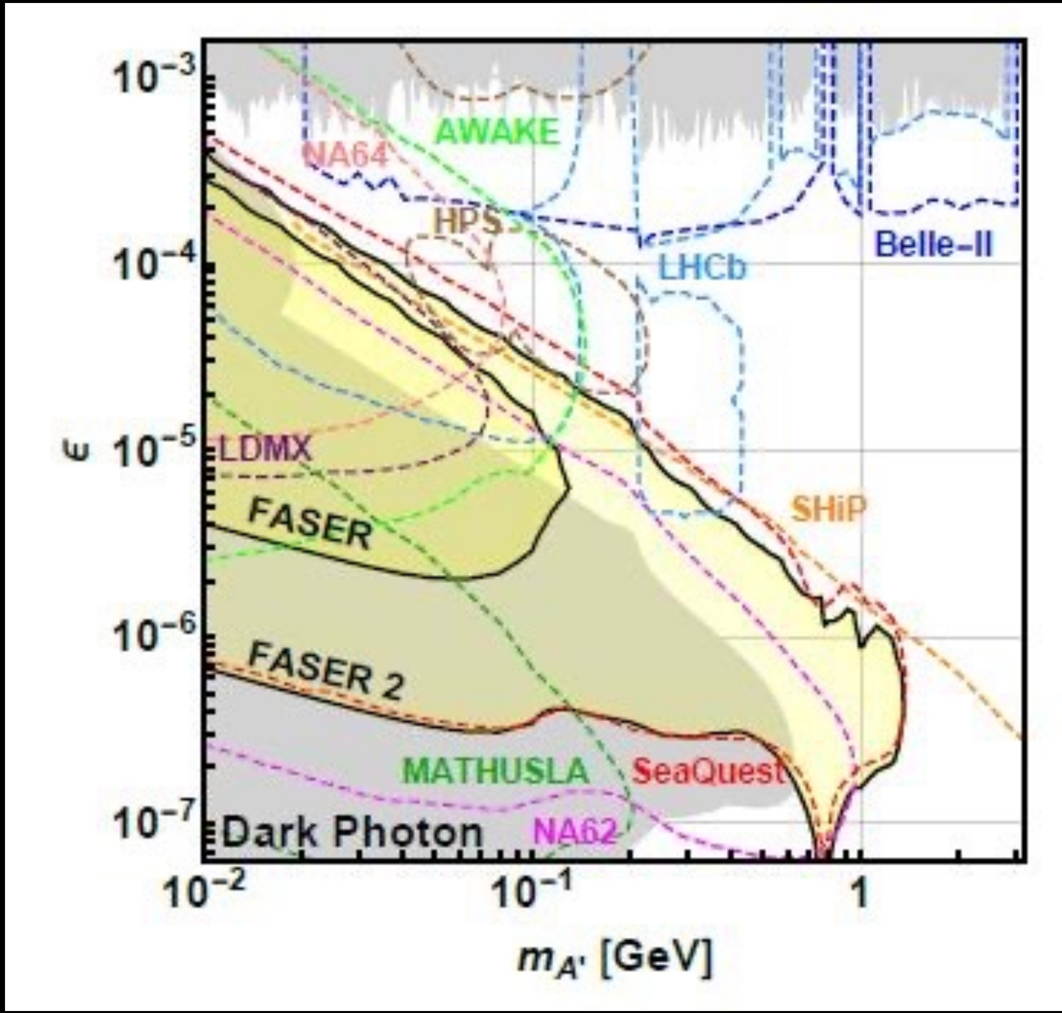
- Production is peaked at $p_T \sim \Lambda_{QCD} \sim 250$ MeV
- Rates highly suppressed by $\varepsilon^2 \sim 10^{-10}$
- But still $N_{A'} \sim 10^5$ per bin

- Only highly boosted ~TeV A's decay in FASER
- Rates again suppressed by decay requirement
- But still $N_{A'} \sim 100$ signal events, and almost all are within 20 cm of "on axis"

Expected sensitivity for dark photon

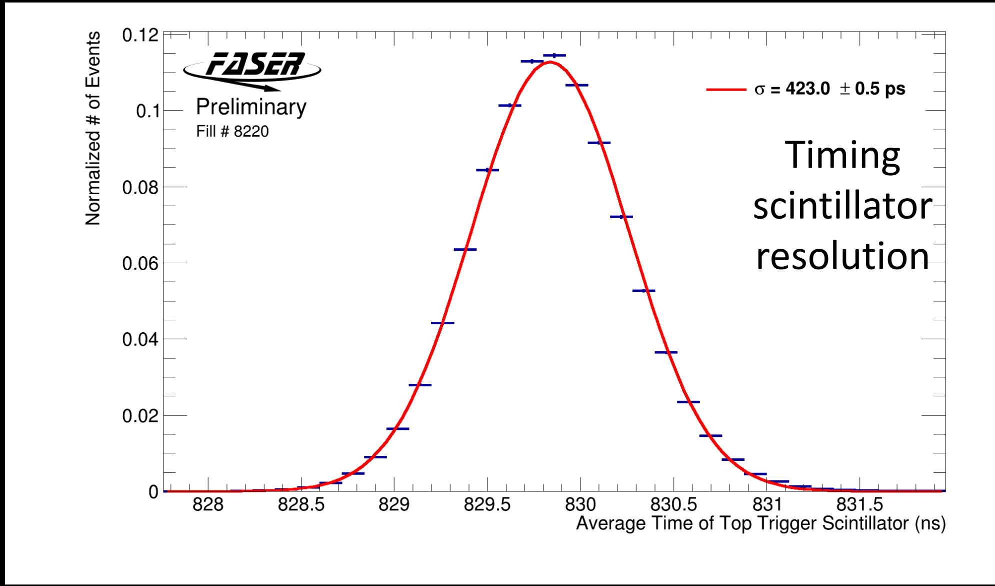
- FASER (150/fb) and FASER 2 (3/ab) benchmark sensitivities
- Production:
  - mainly through decays of light mesons,
    - $\pi^o, \eta \rightarrow \gamma A^o$
    - and through dark bremsstrahlung.
- Decays:
  - $e^+e^-,\ \mu^+\mu^-, \tau^+\tau^-$

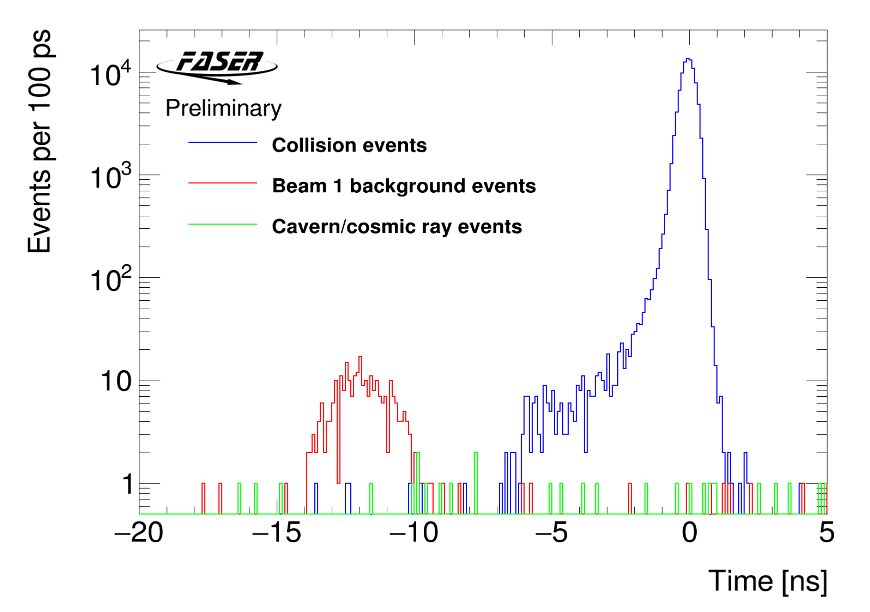


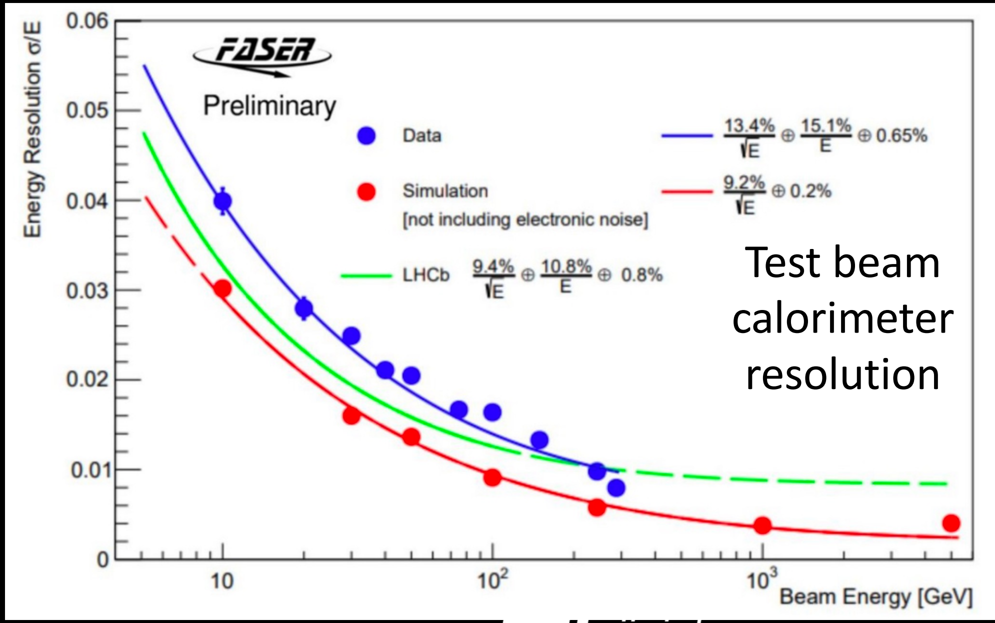


Detector Performance: Timing and Calo

- Calorimeter resolution measured in test beam
  - Better than 1% at high energy
- Precision timing of both scintillator and calorimeter
  - Not used in current analyses

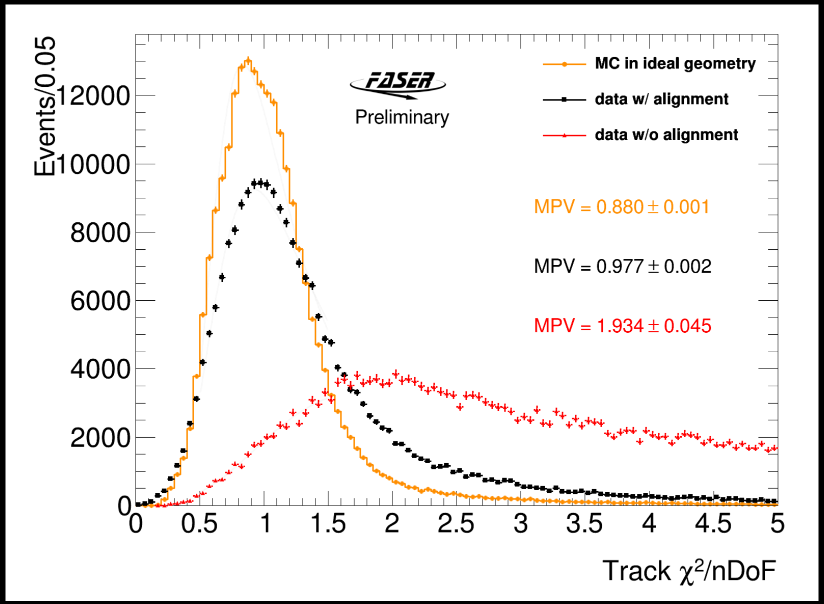


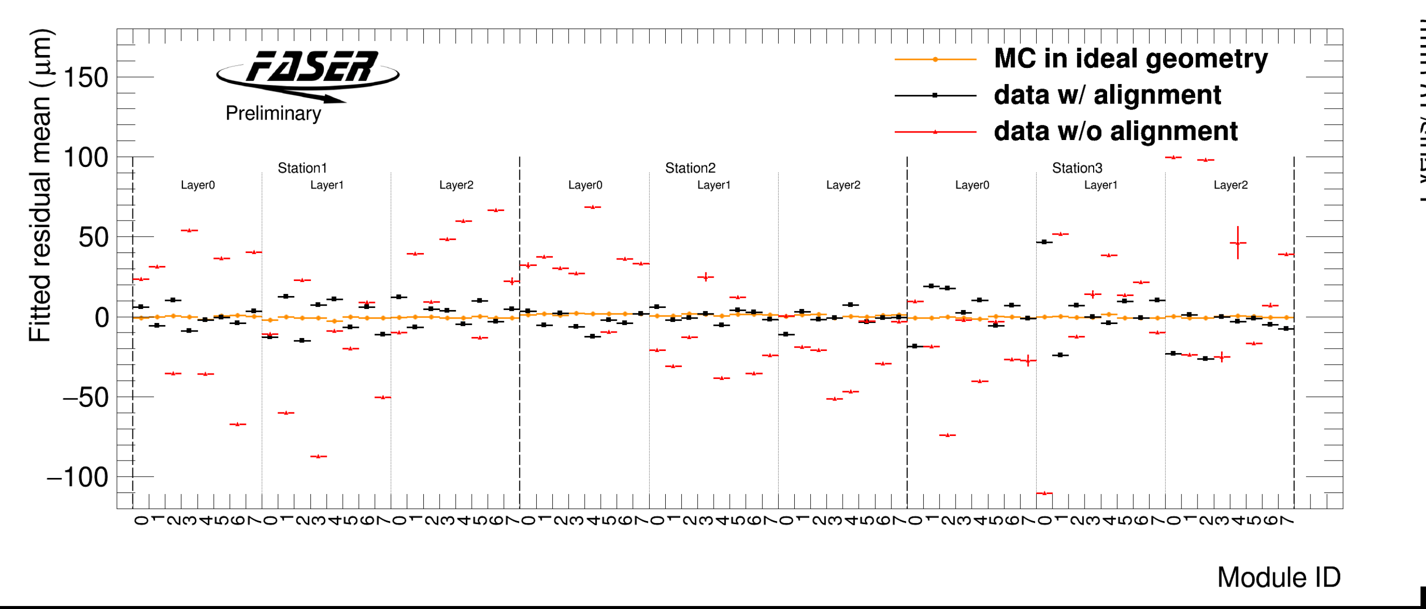


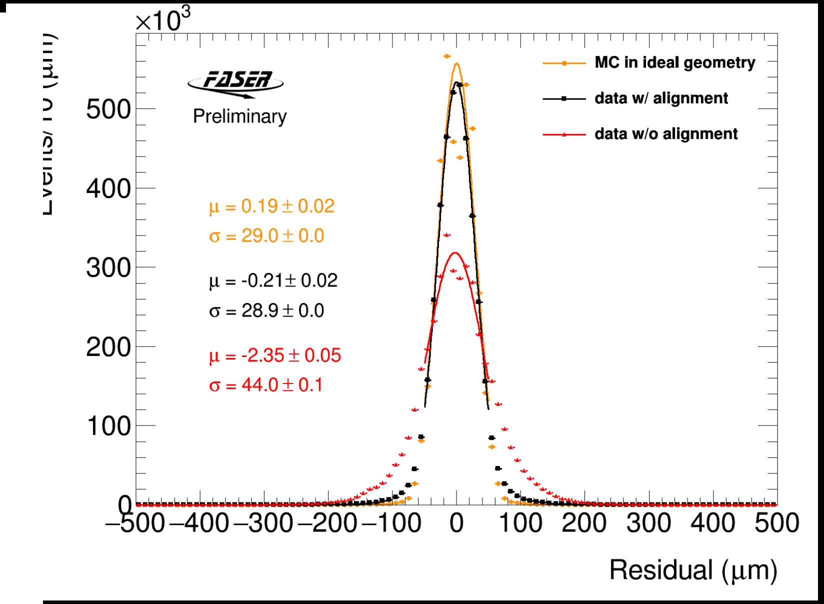


Detector Performance: Tracker Alignment

- Tracker aligned using iterative local χ^2 method
  - Validated using simulation with misalignment
- Currently only aligning two most sensitive parameters
  - Vertical shift and in-plane rotation
- Aligned residuals close to ideal geometry simulation







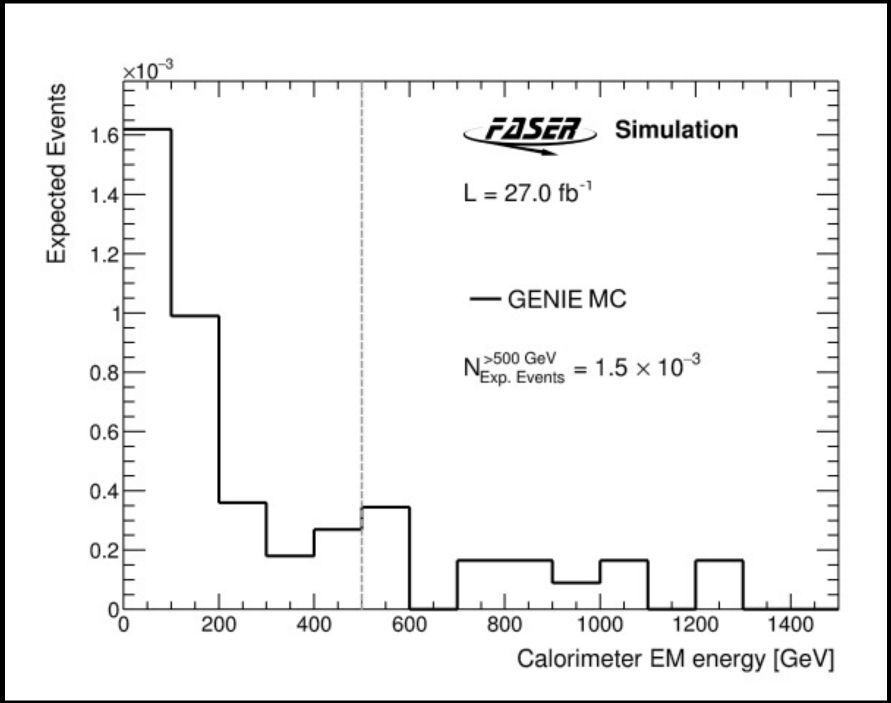
Dark Photon Backgrounds

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

$$(1.5 \pm 0.5(stat.) \pm 1.9(syst.)) \times 10^{-3}$$

- **Neutral hadrons (e.g. K_s) from upstream muons interacting in rock in front of FASER**
  - Heavily suppressed since:
    - Muon nearly always continues after interaction
    - Has to pass through 8 interaction length (FASERν)
    - Decay products have to leave E(calo) > 500 GeV
  - Estimated from lower energy events with 2 or 3 tracks and different veto conditions

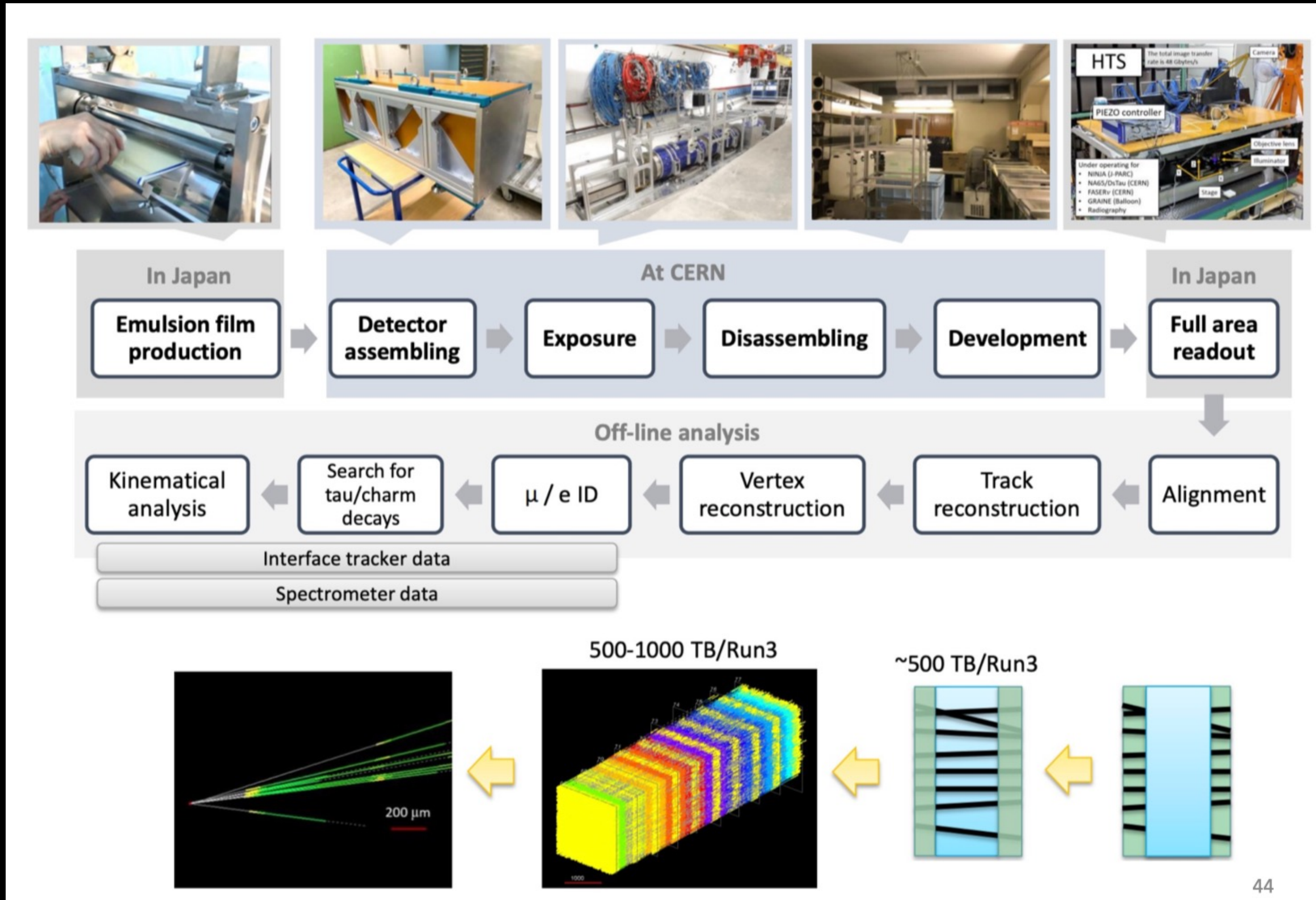
$$(8.4 \pm 11.9) \times 10^{-4}$$



Total background prediction

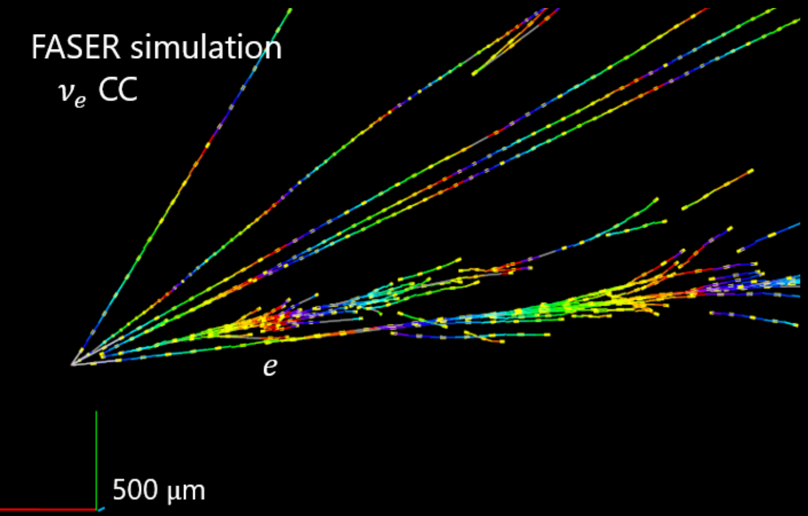
$$(2.3 \pm 2.3) \times 10^{-3}$$

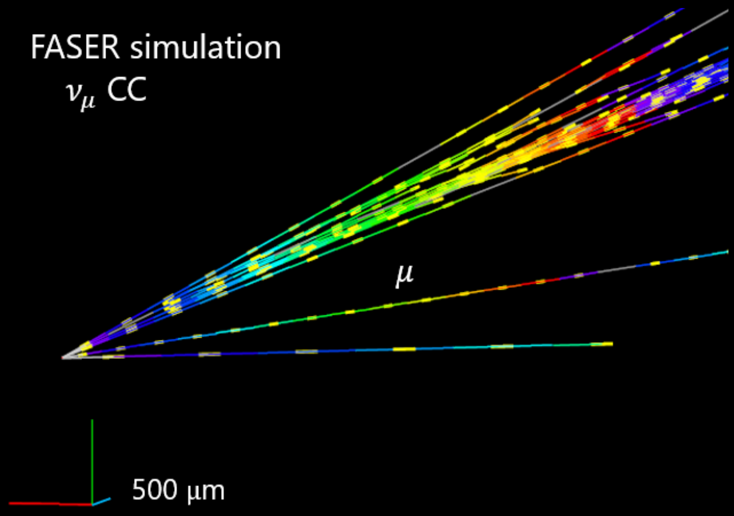
FASERν workflow: From emulsion production to physics analysis

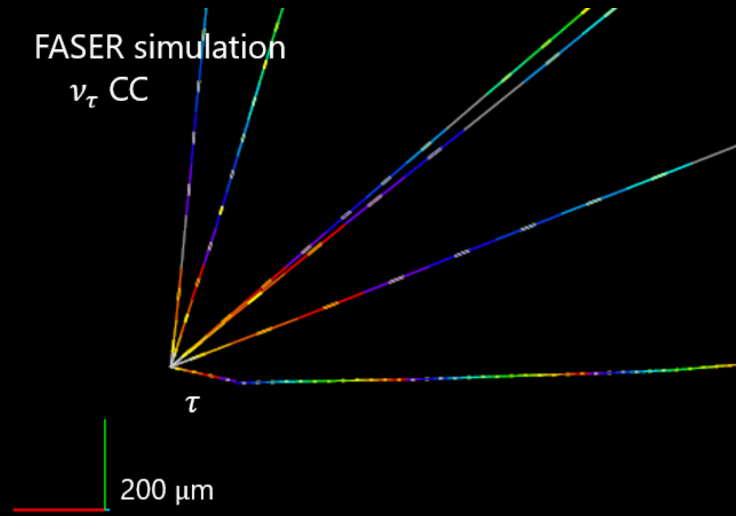


FASERν neutrino interaction classification

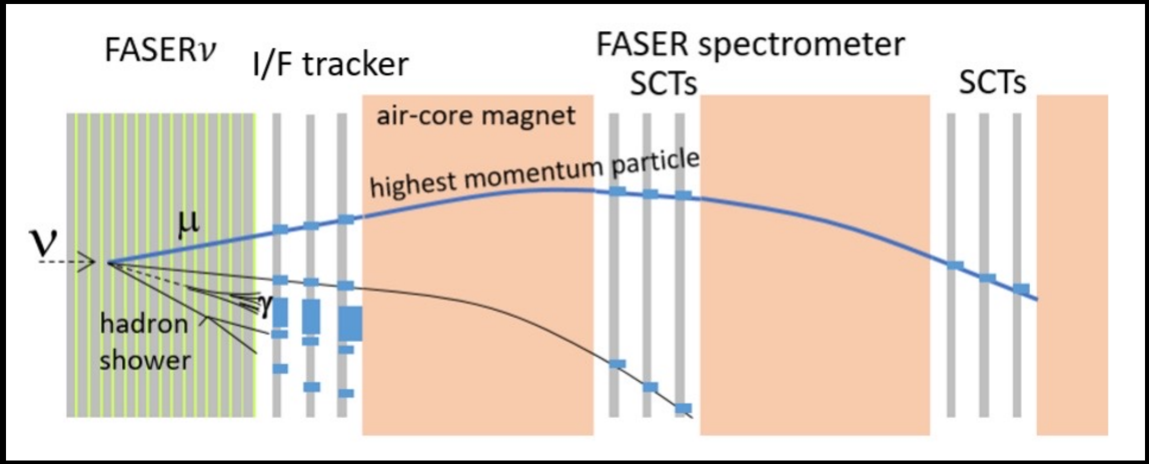
- **Event classification** by topology and kinematics
- **Neutrino energy measurement** with ANN by combining topological and kinematical variables. Energy resolution of $\Delta E/E \sim 30\%$
- **Muon identification** by their track length in the detector ($8\lambda_{int}$)
- **Muon charge identification** by use of FASER spectrometer: distinguishing ν_μ and $\bar{\nu}_\mu$



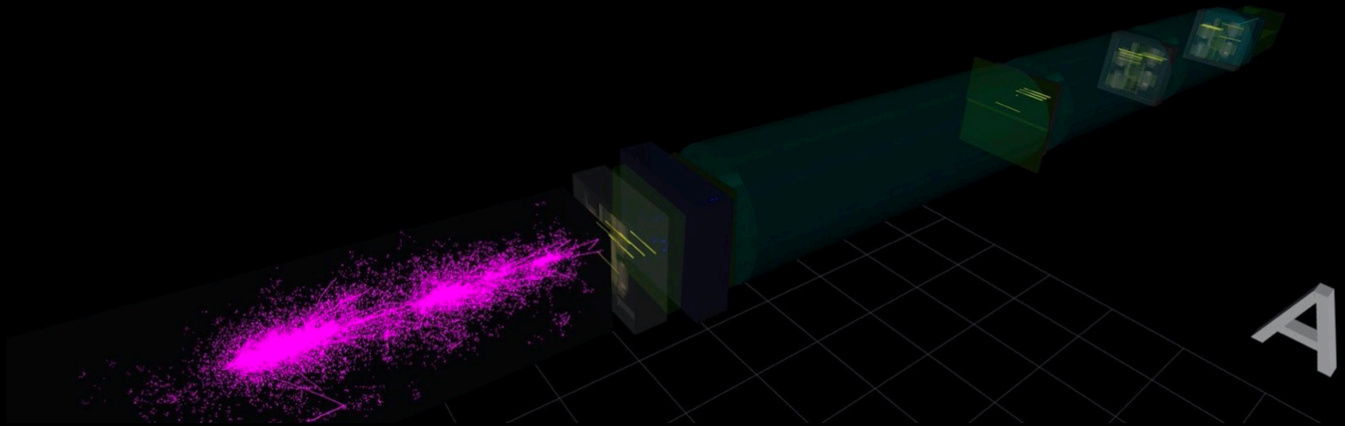




- Track matching between trackers and the emulsion detector
  - Enable charge identification and ν_μ, $\bar{\nu}_\mu$ classification and potentially ν_τ, $\bar{\nu}_\tau$

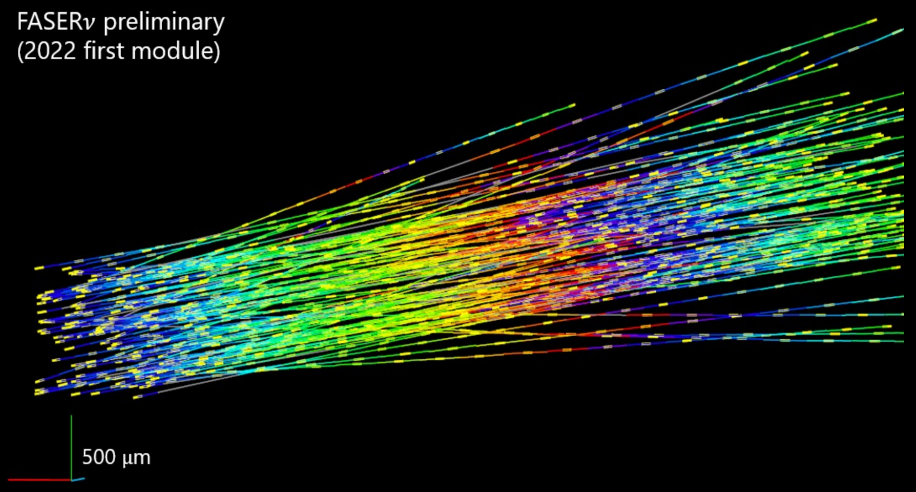


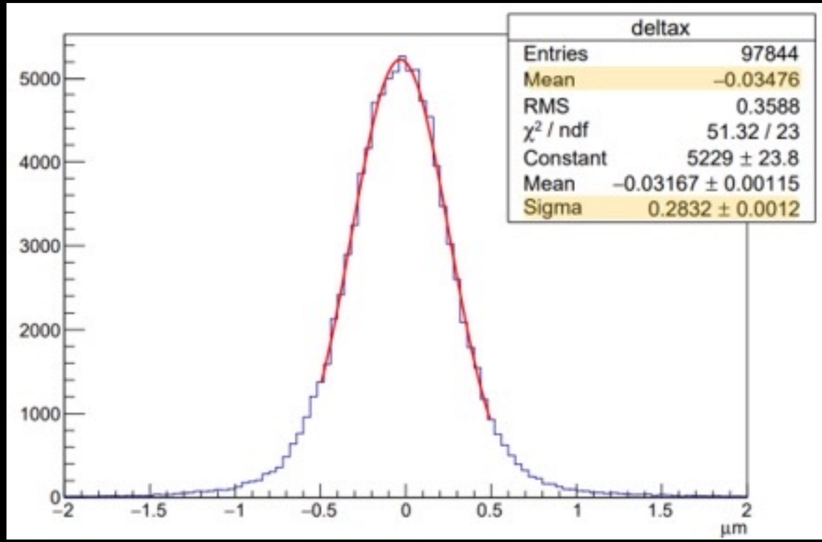
FASER MC simulation
Event display of neutrino interaction



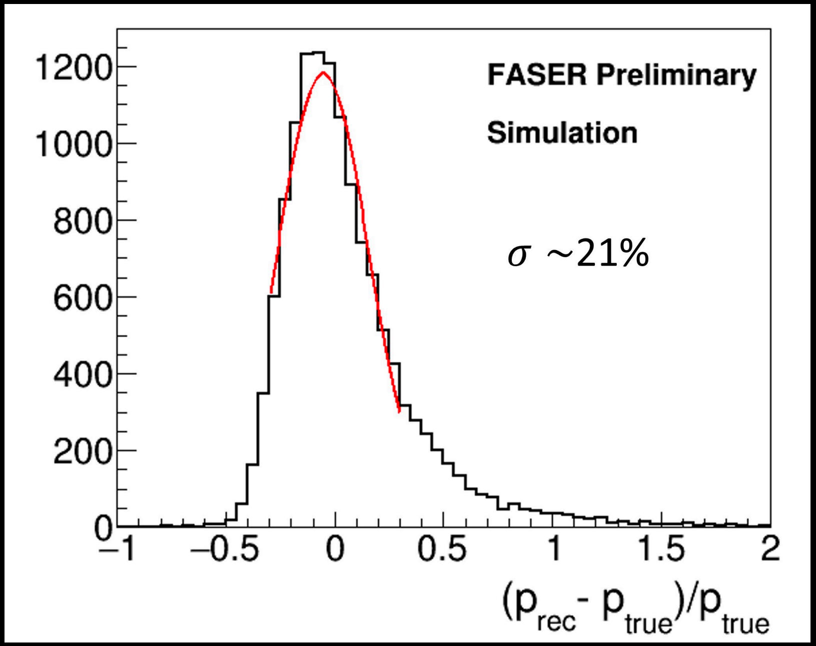
Detector Performance: Emulsion

- Excellent hit resolution (0.3 µm) after dedicated film alignment





- Muon momentum measured by multiple columb scattering
  - Resolution from simulation ~20% at p=200 GeV.
  - Validated by splitting long tracks in data.



Shower energy measurement in FASERν

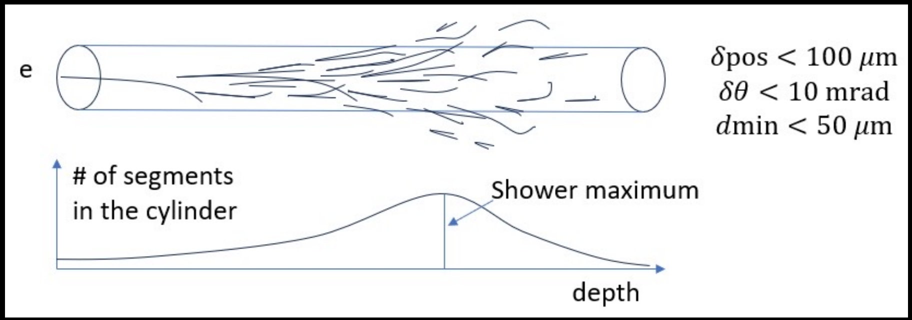
- Reconstruct EM shower in thin cone.
- Performed by counting number of segments within a cylinder along an electron candidate
  - shower maximum has the highest number of segments.

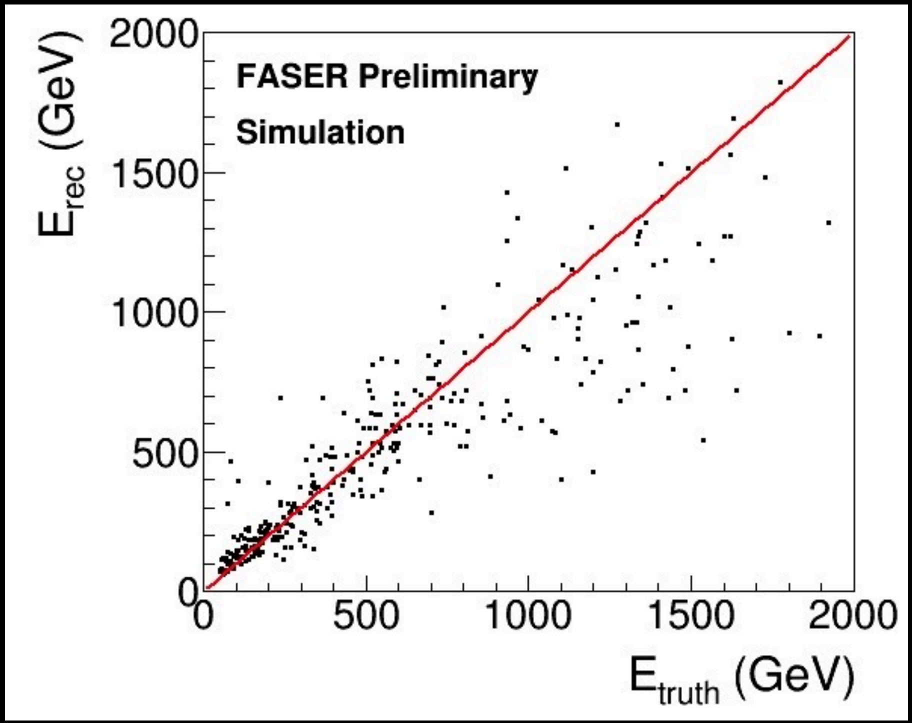
- Background segments are sizable
  - cylinder size limited to r = 100 µm, length = 8 cm
  - segment angle with respect to shower axis < 10 mrad
  - minimum distance to segment < 50 µm.

- Average background estimated by using random cylinders and subtracting from the shower before energy estimation.

- Resolution:
  from MC ~25% at p=200 GeV

- More work ongoing to improve the resolution of energy

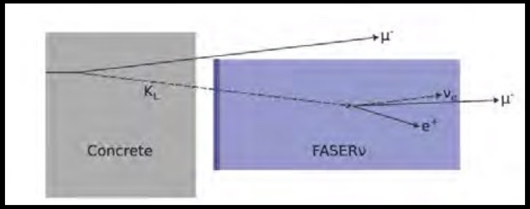


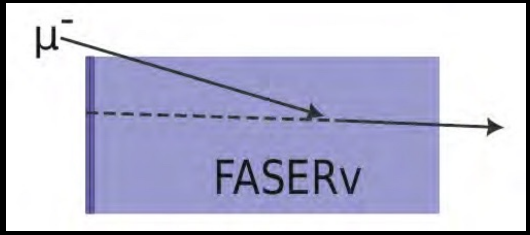


Backgrounds: Neutrino search in FASER

- Neutral hadrons estimated from simulation
  - Expect ~300 neutral hadrons with E>100 GeV reaching FASERn, most accompanied by μ, but conservatively assume missed
  - Estimate fraction of these passing event selection, most are absorbed in tungsten with no highmomentum track

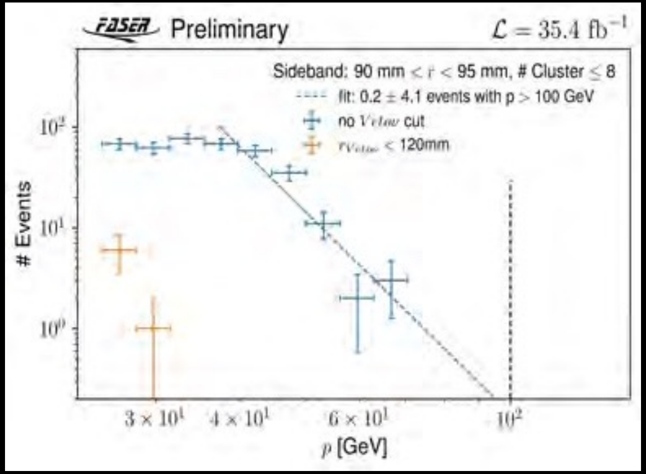
    0.11 ± 0.06 events





- Scattered muons estimated from data
  - Take events w/o front veto radius requirement and single track segment in first tracker station with 90 < r < 95 mm, fit to extrapolate to higher momentum
  - Scale by number of events with front veto cut, use MC to extrapolate to signal region

    0.08 ± 1.83 events

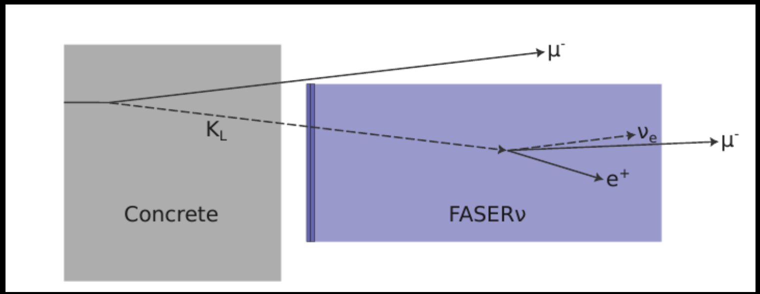


- Veto inefficiency estimated from final fit

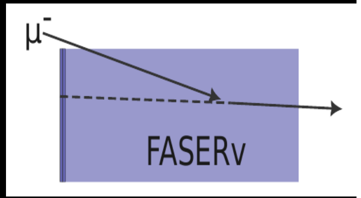
  negligible

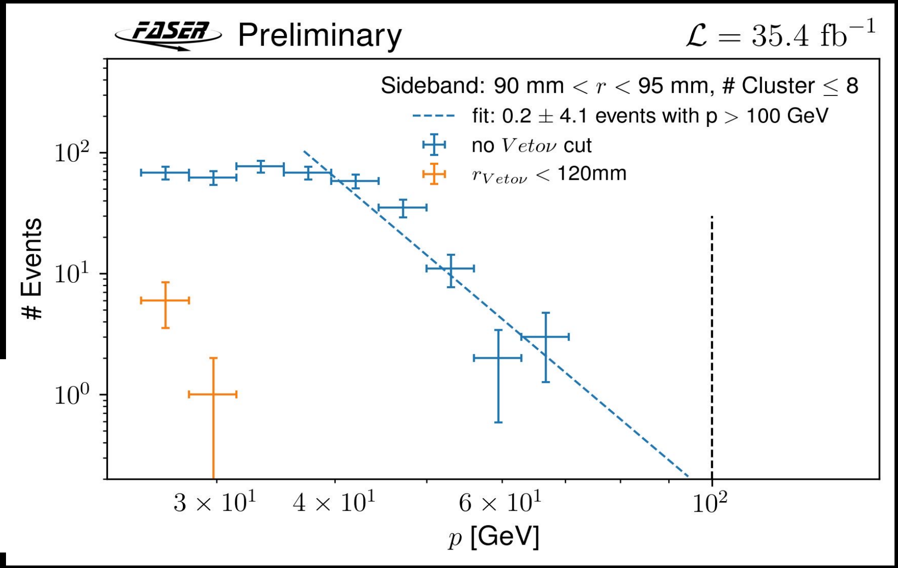
Neutrino Backgrounds for neutrino interaction search in FASER

- **Neutral hadrons estimated from 2-step simulation**
  - Expect ~300 neutral hadrons with E>100 GeV reaching FASERν
    - Most accompanied by μ but conservatively assume missed
  - Estimate fraction of these passing event selection
    - Most are absorbed in tungsten with no high-momentum track
  - Predict N = 0.11 ± 0.06 events

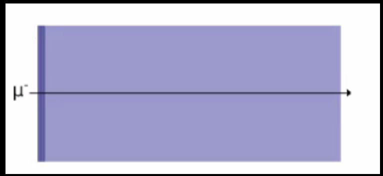


- **Scattered muons estimated from data SB**
  - Take events w/o front veto radius requirement and single track segment in first tracker station with 90 < r < 95 mm
    - Fit to extrapolate to higher momentum
  - Scale by # events with front veto cut
    - Use MC to extrapolate to signal region
  - Predict N = 0.08 ± 1.83 events
    - Uncertainty from varying selection

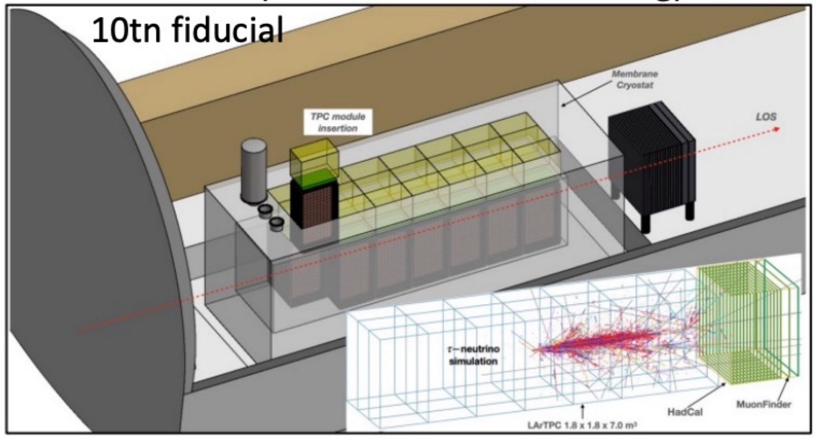




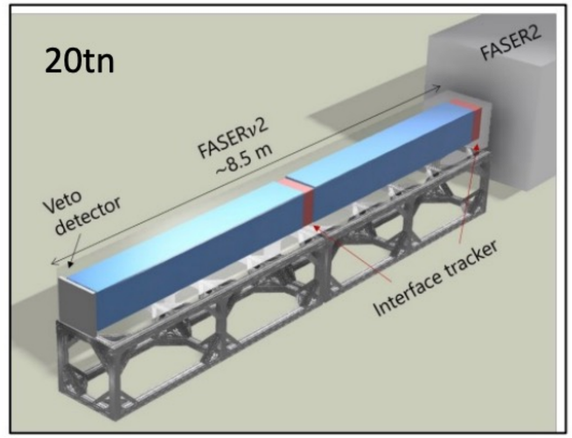
- **Veto inefficiency estimated from final fit**
  - Fit events with 0 (SR) and also 1 (1^{st} or 2^{nd}) or 2 front veto layers firing
  - Find negligible background due to very high veto efficiency



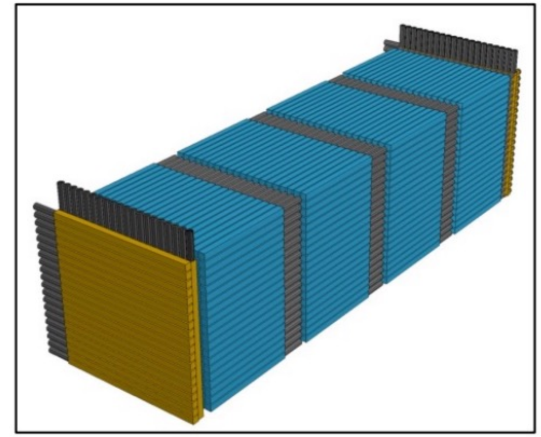
FLArE: LAr TPC (neutrinos + DM scattering)



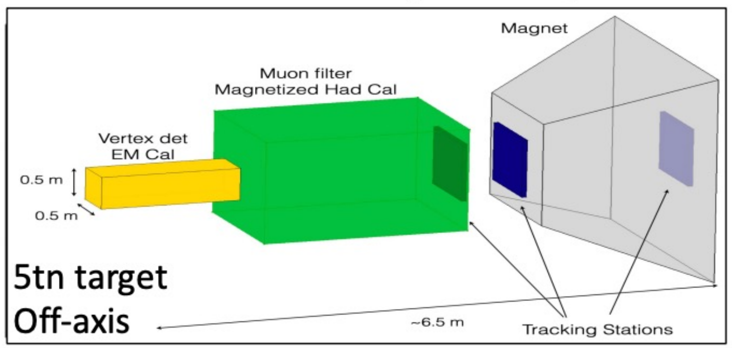
FASERv2: Emulsion (neutrinos)



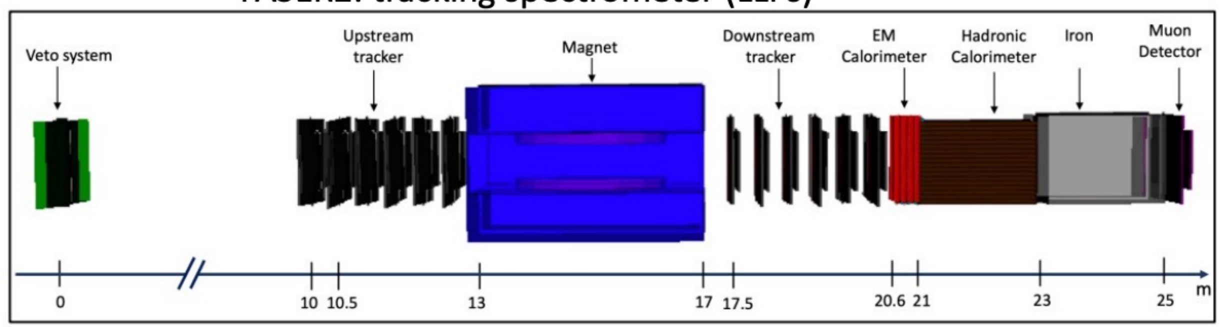
FORMOSA: Scintillators (milicharged



AdvSND: electronic (neutrinos)



FASER2: tracking spectrometer (LLPs)



Physics Studies: BSM