Search for collider neutrinos with FASER

WiV2023
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on behalf of FASER collaboration

Outline

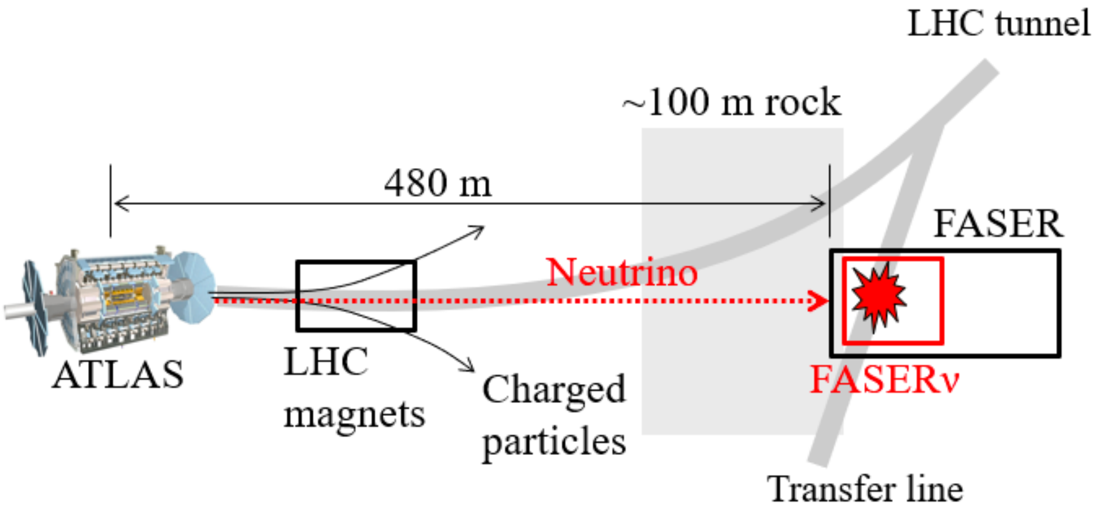
- FASER and FASERν detector
- FASERν pilot result
- First direct observation of collider neutrinos
- Summary

FASER collaboration

85 members from 22 institutions and 9 countries

FASER and FASERν

- FASER is a new detector to search for light, weakly coupled long-lived particles and measure cross-sections of neutrinos, that are produced in pp collisions at ATLAS Interaction Point (IP), starting in 2022 together with LHC Run-3.

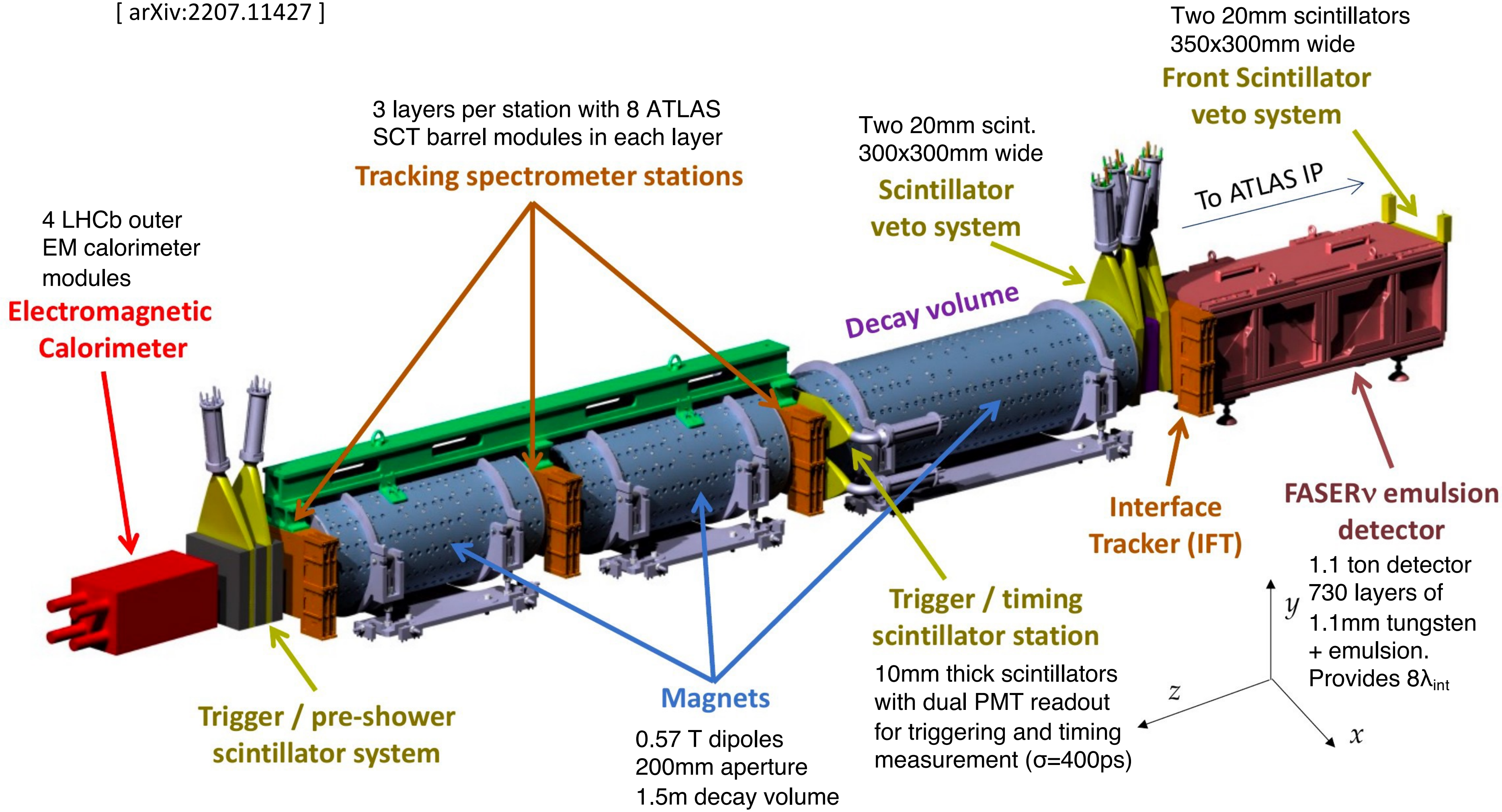


- FASERν is a detector (part of FASER) for neutrino measurements. Will make the first measurements of neutrinos from a collider and in unexplored energy regime.

FASER detector

Built from existing spare parts and some dedicated new components

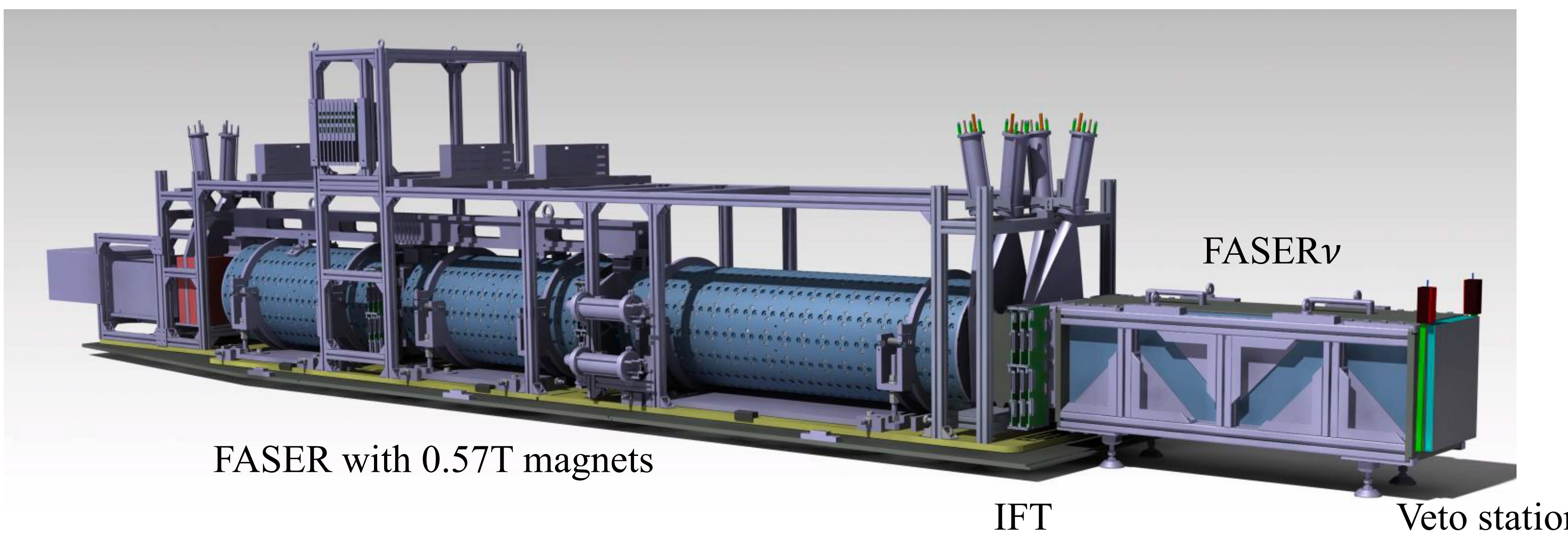
[arXiv:2207.11427]



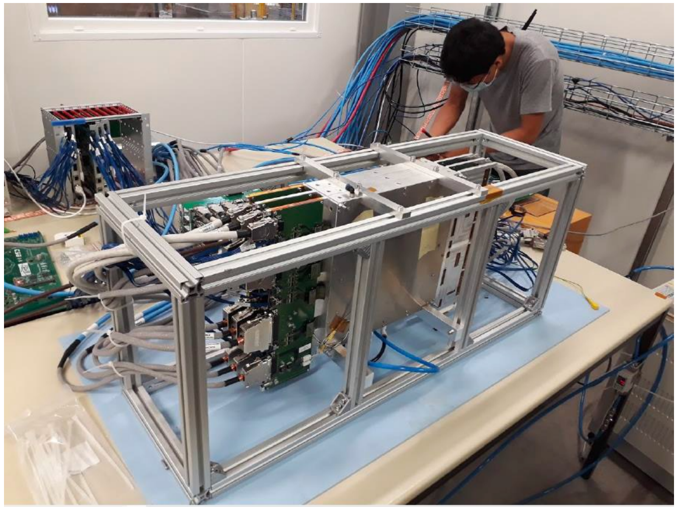
FASERν detector in front of FASER

- FASERν is a detector consisting of emulsion, tungsten, IFT and veto station
  - Composed of 730 1.1-mm-thick tungsten plates, interleaved with emulsion films
  - An area of 25×30 cm^2, 1.1 m long, 1.1 tons detector (220 $X0$)

- FASERν is placed in front of the FASER main detector



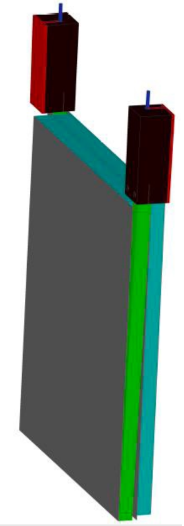
IFT and veto system



- **IFT** uses the same design as the tracker station in the FASER spectrometer. Important for track matching between FASER and FASERν

  – Silicon strip detector with ATLAS SCT barrel modules
  – Test beam data obtained with CERN SPS facility

PMT (H11934-300)

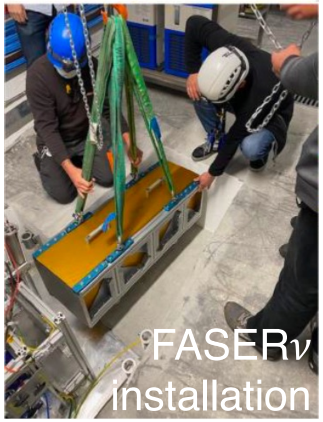


30×35 cm^2

- **Veto station** consists of two 2-cm scintillators and WLS (Wave Length Shifting) bars with two PMTs. Rejects upstream charged particles

  – The PMTs were tested
  – The scintillators have been tested with cosmic rays

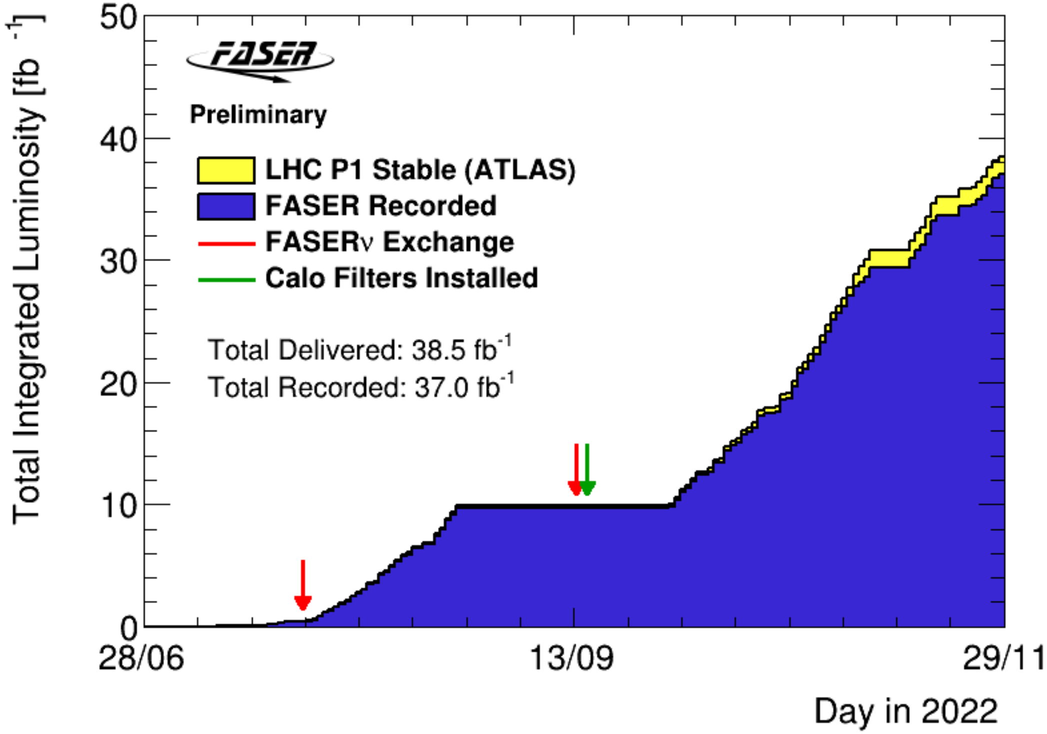
Preparation for Run-3



Full FASER installation

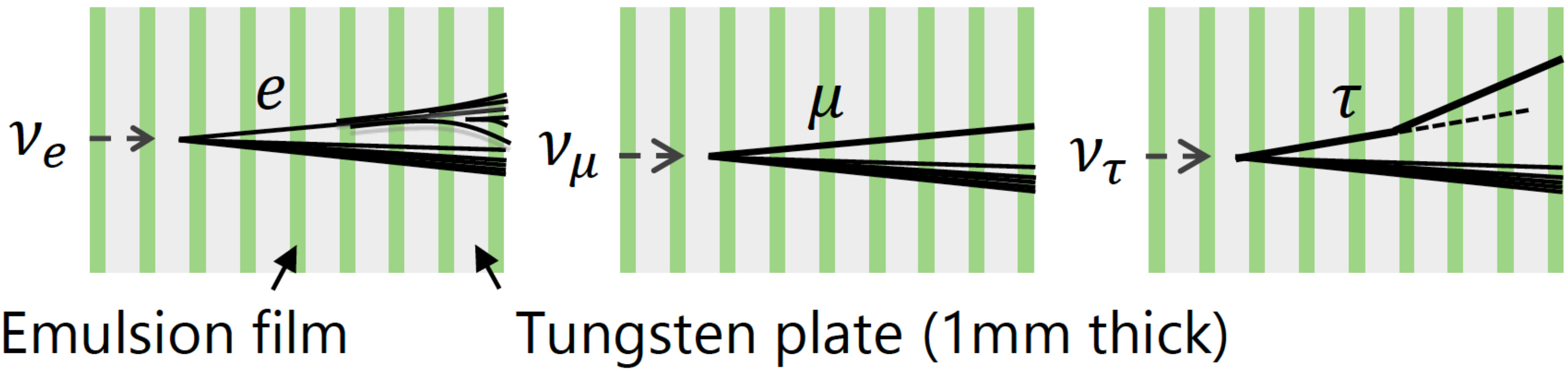
Installation fully completed in November 2021, ahead of Run 3

Luminosity



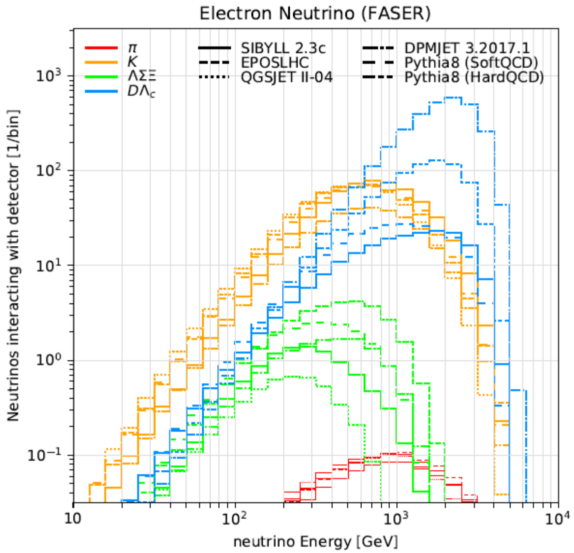
- Successfully operated during all of 2022
  Continuous and largely automatic data-taking at up to 1.3 kHz
- Recorded 96.1% of delivered luminosity
  DAQ dead time of 1.3%, rest lost to a couple of DAQ crashes
- Emulsion detector exchanged twice to manage background occupancy
  First box was only partially filled with emulsion

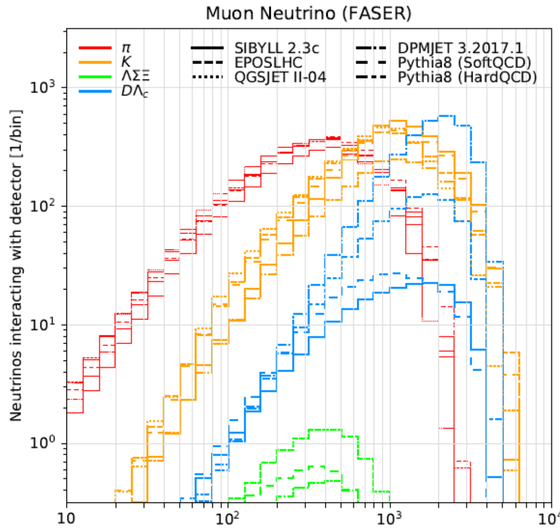
Neutrino detection in emulsions

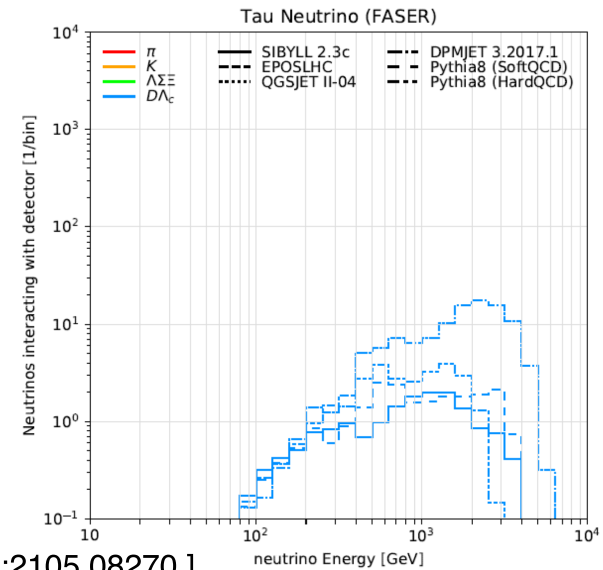


- All flavors of neutrino interactions can be detected and distinguished from each other
  - ✓ Muon identification by its track length in the detector (8 λ_{int})
  - ✓ Muon charge identification with tracking stations - distinguishing ν_μ and $\bar{\nu}_\mu$
  - ✓ Neutrino energy measurement with ANN by combining topological and kinematical variables

Expected Neutrino event rates at Run-3







[F. Kling, arXiv:2105.08270]

Expected number of CC interactions in FASERν during Run-3

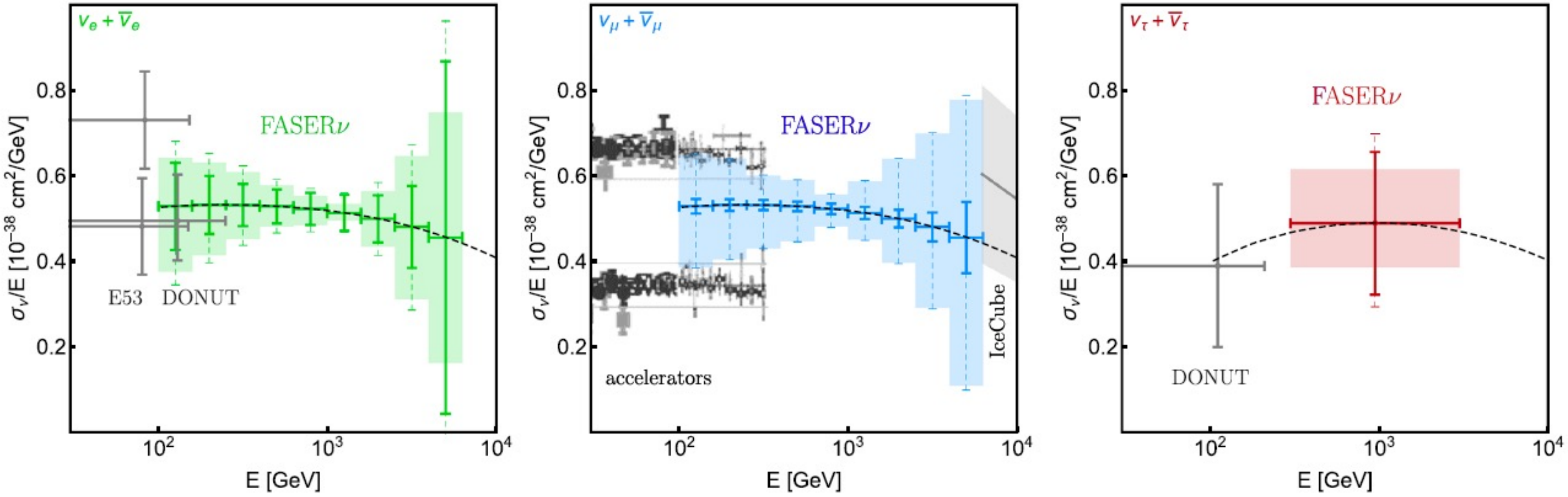
Generators		FASERν		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	1343	6072	21.2
DPMJET	DPMJET	4614	9198	131
EPOSLHC	Pythia8 (Hard)	2109	7763	48.9
QGSJET	Pythia8 (Soft)	1437	7162	24.5
Combination (all)		2376^{+2238}_{-1032}	7549^{+1649}_{-1476}	$56.4^{+74.5}_{-35.1}$
Combination (w/o DPMJET)		1630^{+479}_{-286}	7000^{+763}_{-926}	$31.5^{+17.3}_{-10.3}$

- A high-intensity beam of neutrinos will be produced in the far-forward direction at ATLAS

- FASERν's LOS maximizes fluxes of all neutrino flavors. Most abundant is ν_μ

Charged Current interactions

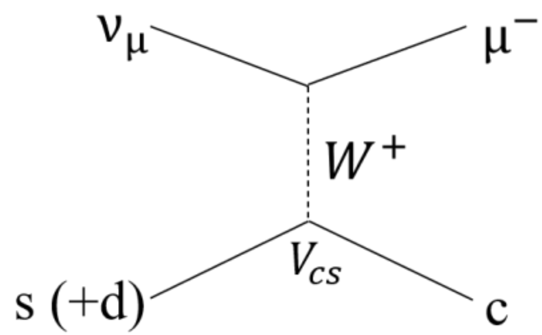
Expected sensitivity to neutrino cross-sections



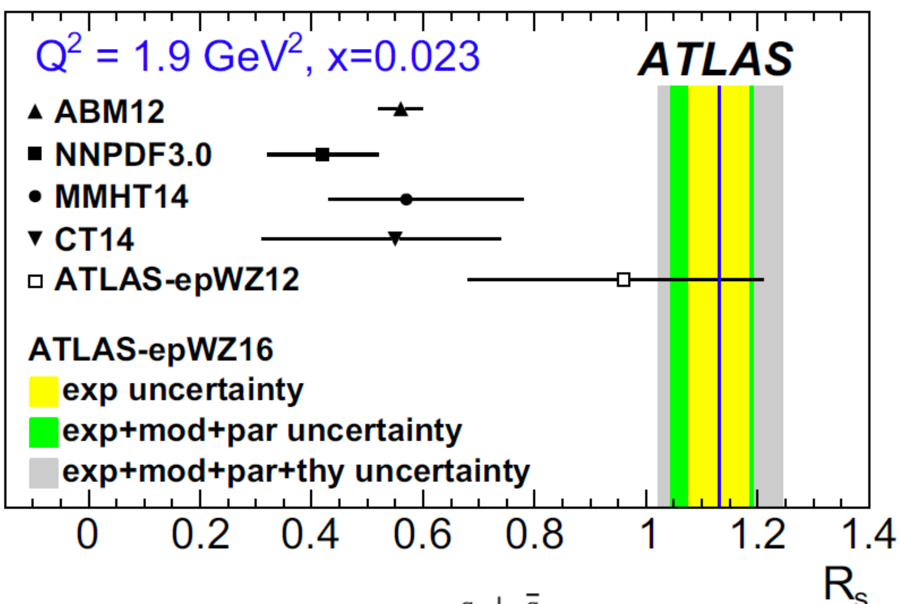
- FASERν will measure neutrino cross-sections at TeV scale which is uncovered by existing experiments
- Due to excellent position resolution of the emulsion detector, CC cross-sections will be measured for all neutrino flavors
- The charge measurement in FASER tracking stations behind FASERν to separate ν_μ and $\bar{\nu}_\mu$

Proton PDF

D meson production in CC ν_μ interaction is sensitive to strange PDF in a proton where tension exists between ATLAS and PDF predictions

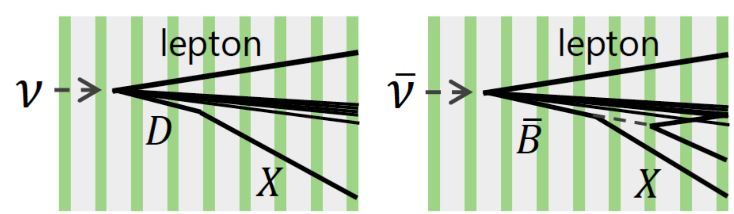


[Eur. Phys. J. C77 (2017) 367]

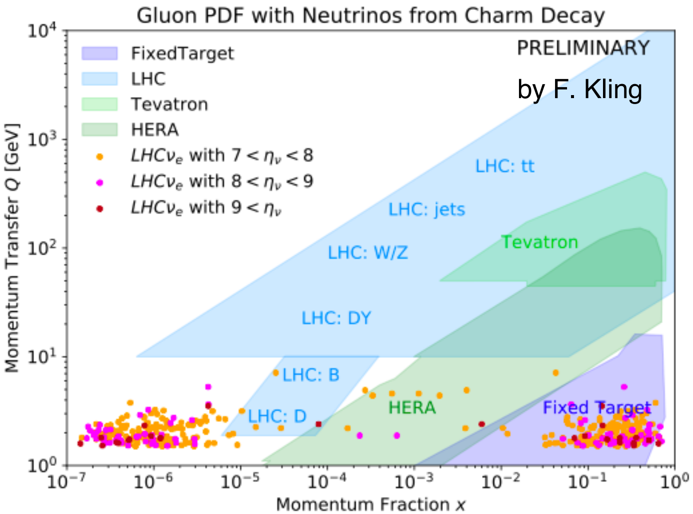


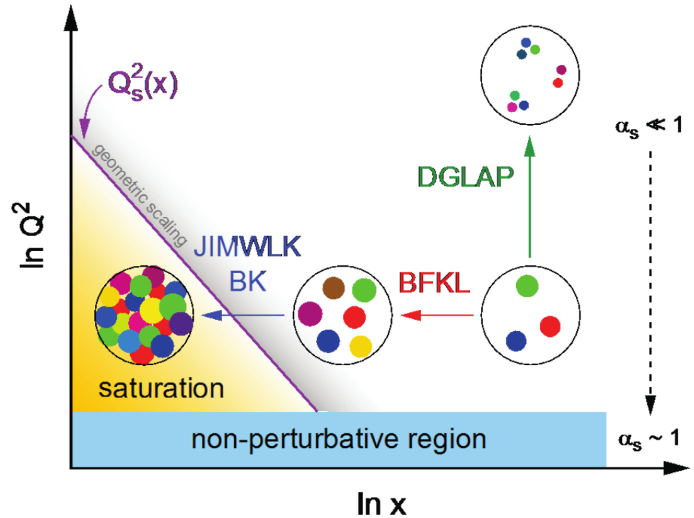
$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$

Neutrino CC interaction with beauty production? – Has never been detected:

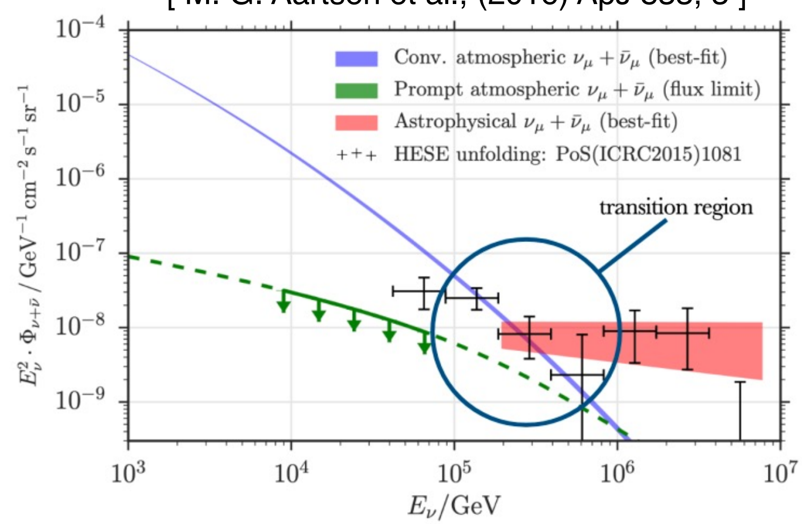


Forward physics





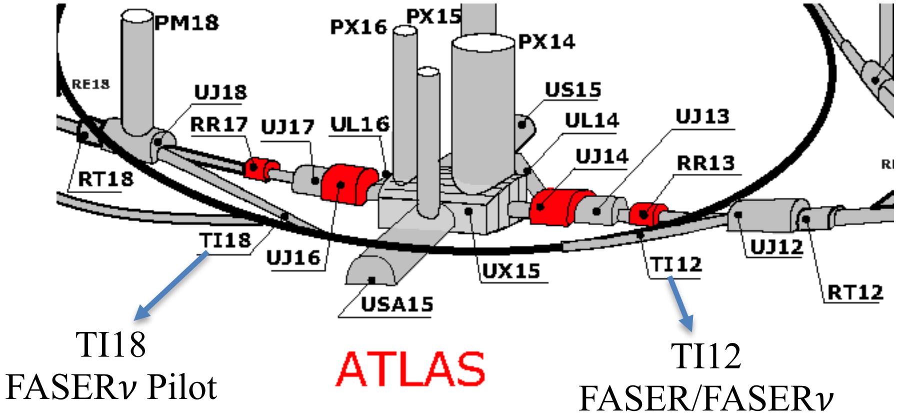
[M. G. Aartsen et al., (2016) ApJ 833, 3]



- Neutrino flux and its energy spectrum can allow to probe small-x PDF, effects of gluon saturation, and intrinsic charm

- Proton-proton collision at LHC corresponds to ~100 PeV proton interaction with fixed target. Cross-section of heavy mesons at LHC can provide constraint on the prompt atmospheric neutrino flux

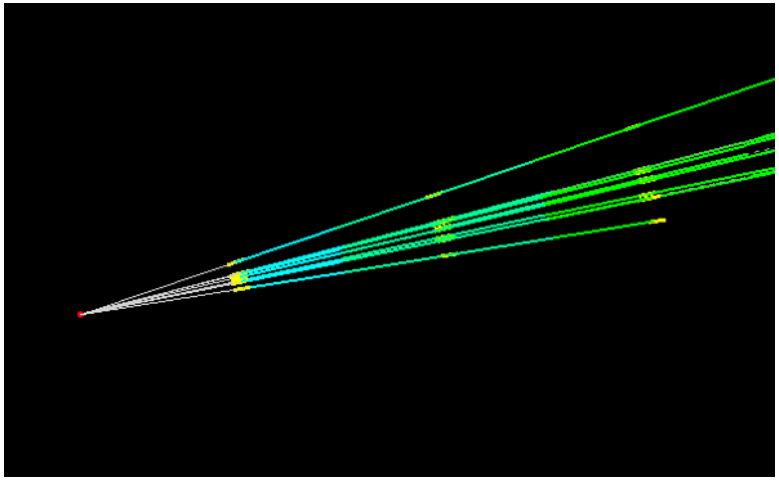
2018 FASERν pilot run



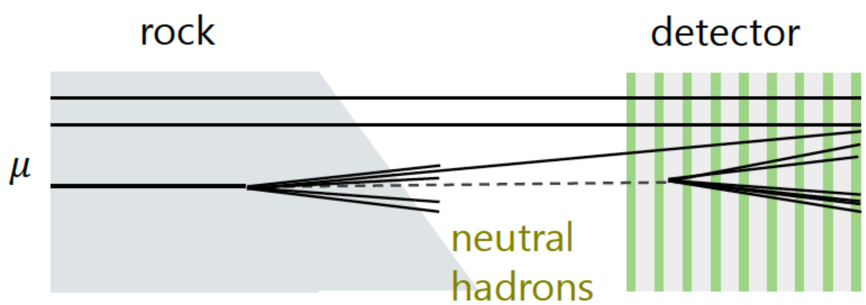
- The pilot runs were taken place for neutrino detection and flux measurement of charged particles at tunnels TI12 and TI18 in 2018

- TI18 is the tunnel at the same distance from ATLAS IP as TI12 but opposite side

- The neutrino detection was performed with a 30 kg emulsion detector installed at TI18, collecting 12.5 fb^{-1} of data



Pilot run background



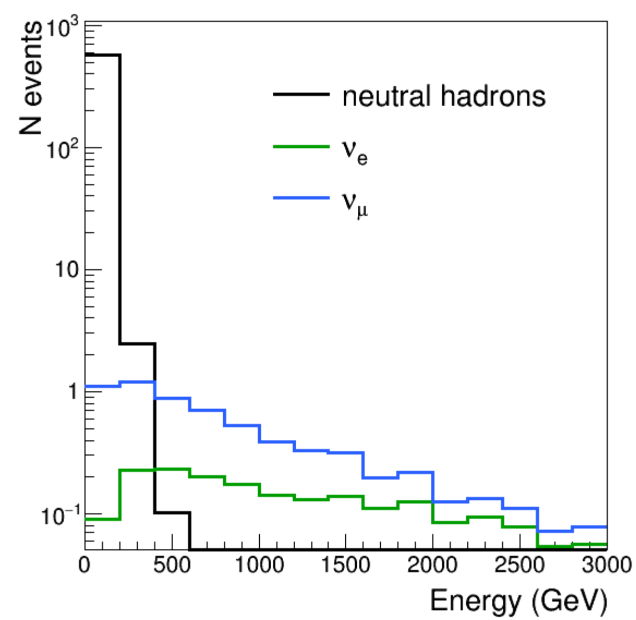
The production rates of neutral hadrons per incident muon
[arXiv:2105.06197]

	Negative Muons	Positive Muons
K_L	3.3×10^{-5}	9.4×10^{-6}
K_S	8.0×10^{-6}	2.3×10^{-6}
n	2.6×10^{-5}	7.7×10^{-6}
$\bar{n}$	1.1×10^{-5}	3.2×10^{-6}
Λ	3.5×10^{-6}	1.8×10^{-6}
$\bar{\Lambda}$	2.8×10^{-6}	8.7×10^{-7}

- Energy of upstream neutral hadrons are low $\longrightarrow$ can suppress them by vertex topology

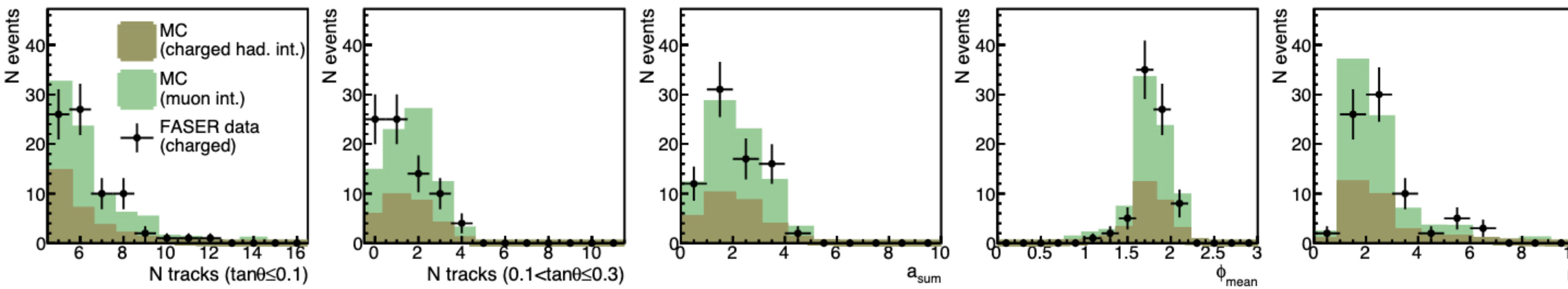
- The largest background are muons, which can be vetoed by emulsion vertices with a charged parent

- Muons produce neutral hadrons in upstream rock, which can mimic neutrino interaction vertices – use Geant4 to simulate

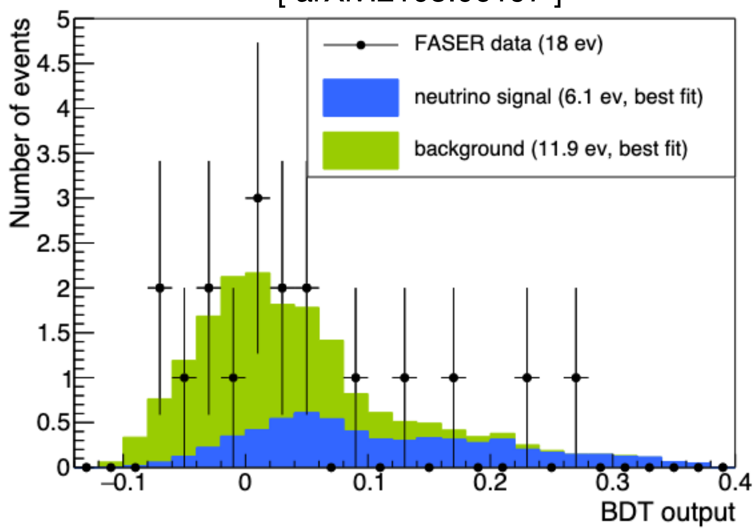


Pilot data analysis

To validate the MC modeling of the BDT input variables, charged vertices from muons and hadrons are checked



[arXiv:2105.06197]



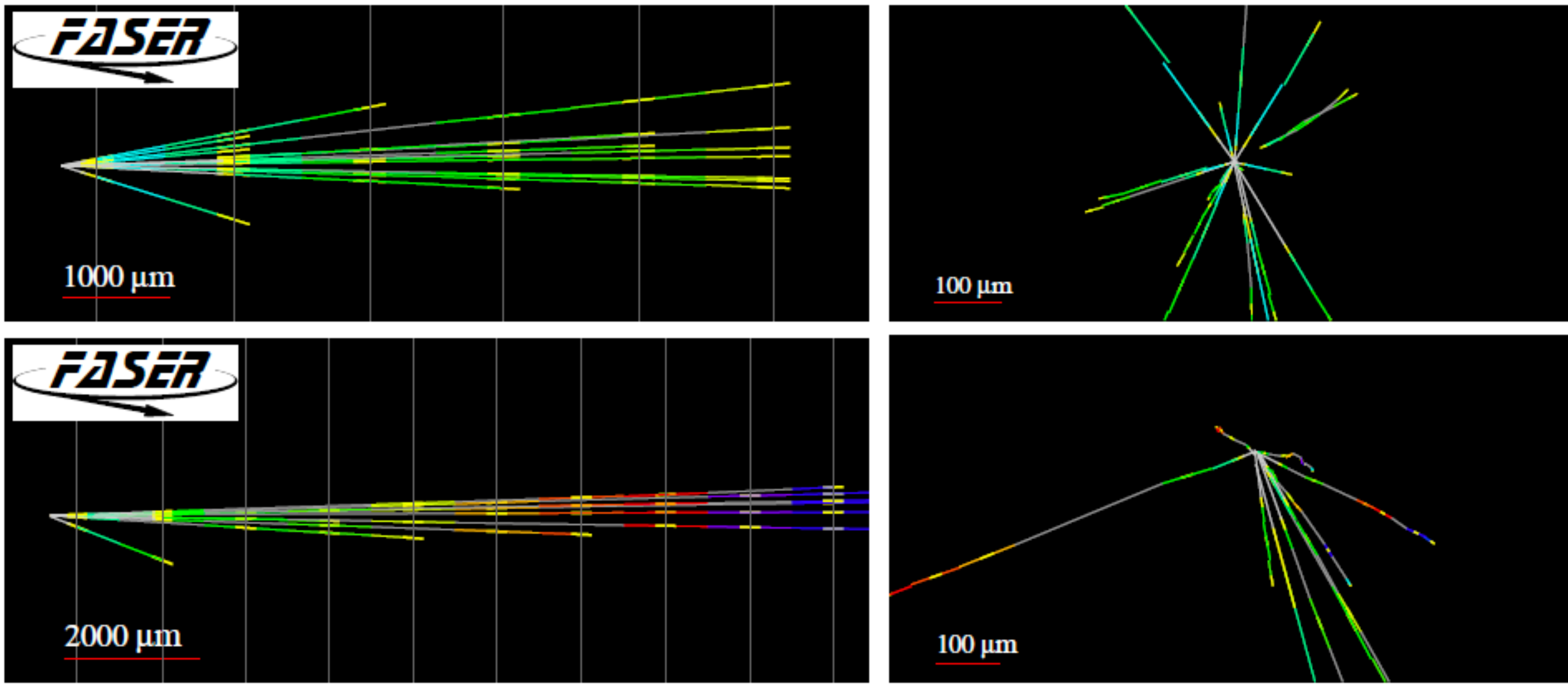
- Muon from the interactions of the true neutrino events can not be identified ($\lambda_{\rm int}$ too short compared to FASERν). Use BDT to discriminate signal and background with the 5 input variables

- Out of 18 neutral vertices, 6.1 signal events (2.7 σ) are obtained from the fit, while $3.3^{+1.7}_{-0.9}$ is expected. This result demonstrates **detection of neutrinos at the LHC**

Neutrino candidates in pilot data

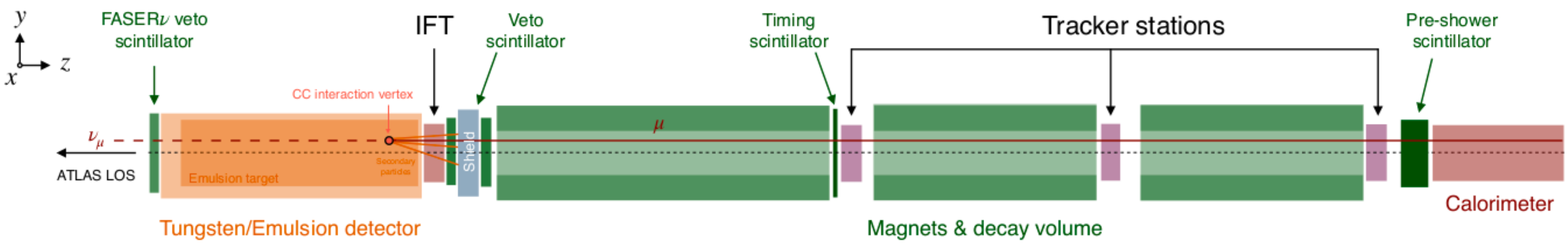
Longitudinal view

Transverse view



Neutrino electronic event selection

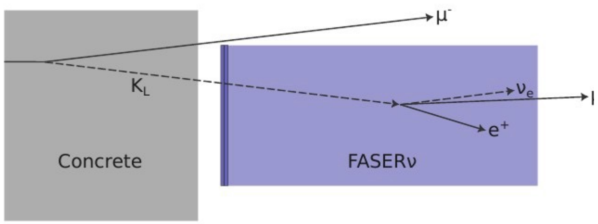
[arXiv:2303.14185]



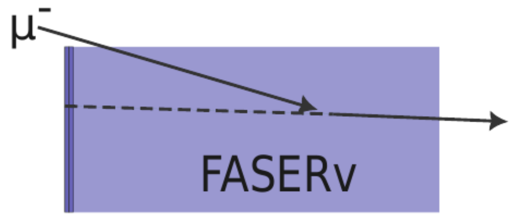
- Selection criteria:
  - ✓ Events in collision bunches, during good physics data periods (35.4 fb^{-1})
  - ✓ No signal in FASERν scintillators with more than 40 pC
  - ✓ Signal in the scintillators downstream of the lead wall and in the calorimeter should be consistent with a MIP (e.g., last two veto layers >40pC)
  - ✓ Exactly one good quality spectrometer track with p>100 GeV with at least 11 silicon hits (out of 18)
  - ✓ Track extrapolated to IFT r_{max}<95mm
  - ✓ Track extrapolated to FASERν scintillators $r_{veto\ \nu}$<120mm
  - ✓ Track polar angle less than 25 mrad
- Based on simulation expect 151±41 neutrino events, uncertainty given by difference between two event generators. Not separating neutrinos and anti-neutrinos. Currently not trying to make cross section measurement

Neutrino event background

Neutral hadrons



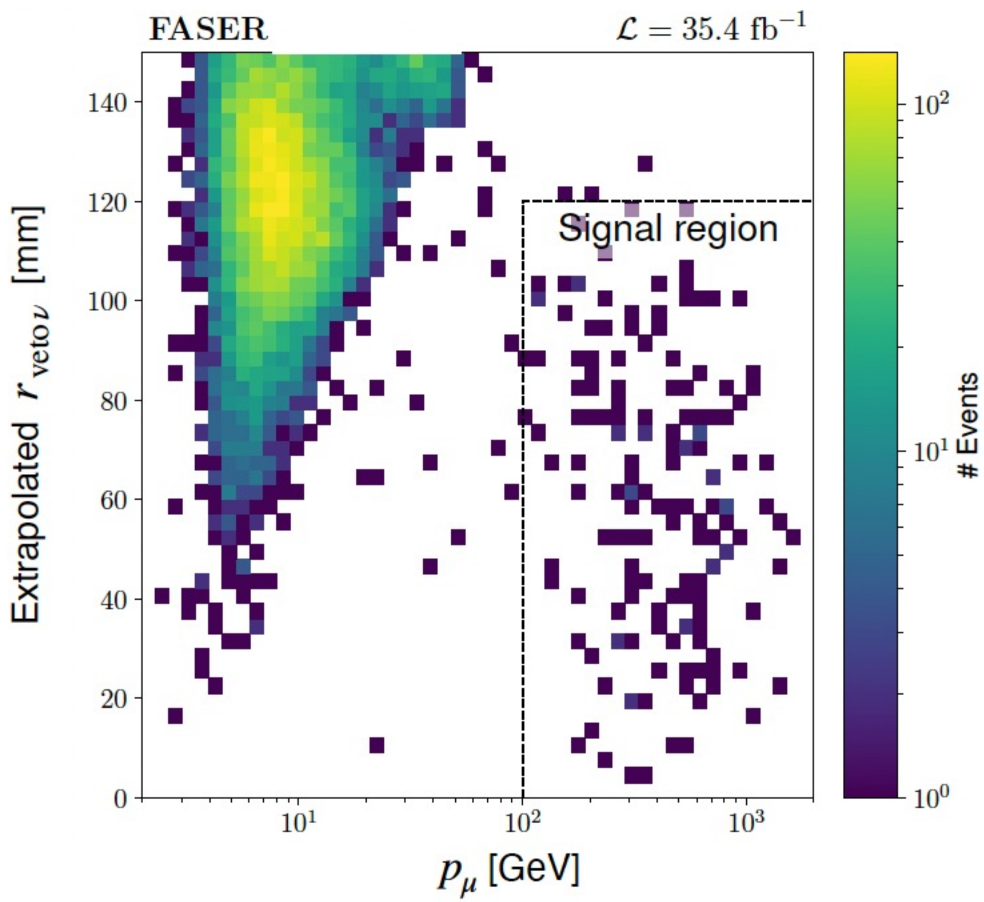
Geometric bkg



FASERν scint. ineff.

- Neutral hadrons estimated from MC simulation
  - Expect O(300) neutral hadrons with E>100 GeV from concrete to reach FASERν
  - Most will be accompanied by muon, but conservatively assume it is missed
  - Most neutral hadrons absorbed in tungsten without producing high-momentum track
  - In total expect just 0.11 ± 0.06 events
- Geometric bkg estimated from control region of events with single track extrapolation within 90 mm$<r_{max}<$95 mm. Expect 0.08 ± 1.83 events
- Veto inefficiency estimated from events with just one veto scintillator layer firing

Neutrino events observation

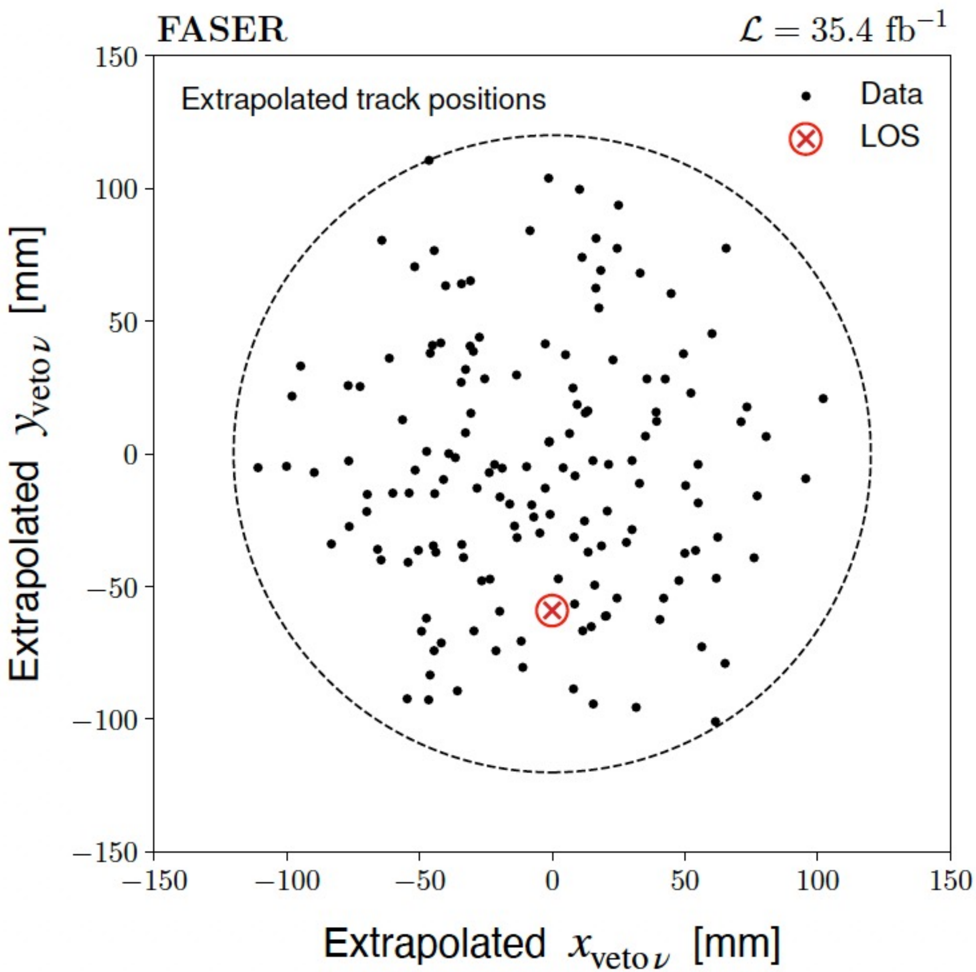


Use a binned extended maximum likelihood fit, and introduce nuisance parameters to constrain the estimated background events to their expectations using Gaussian priors. Fitted value:

$$n_\nu = 153^{+12}_{-13}(\mathrm{stat.})^{+2}_{-2}(\mathrm{bkg.})$$

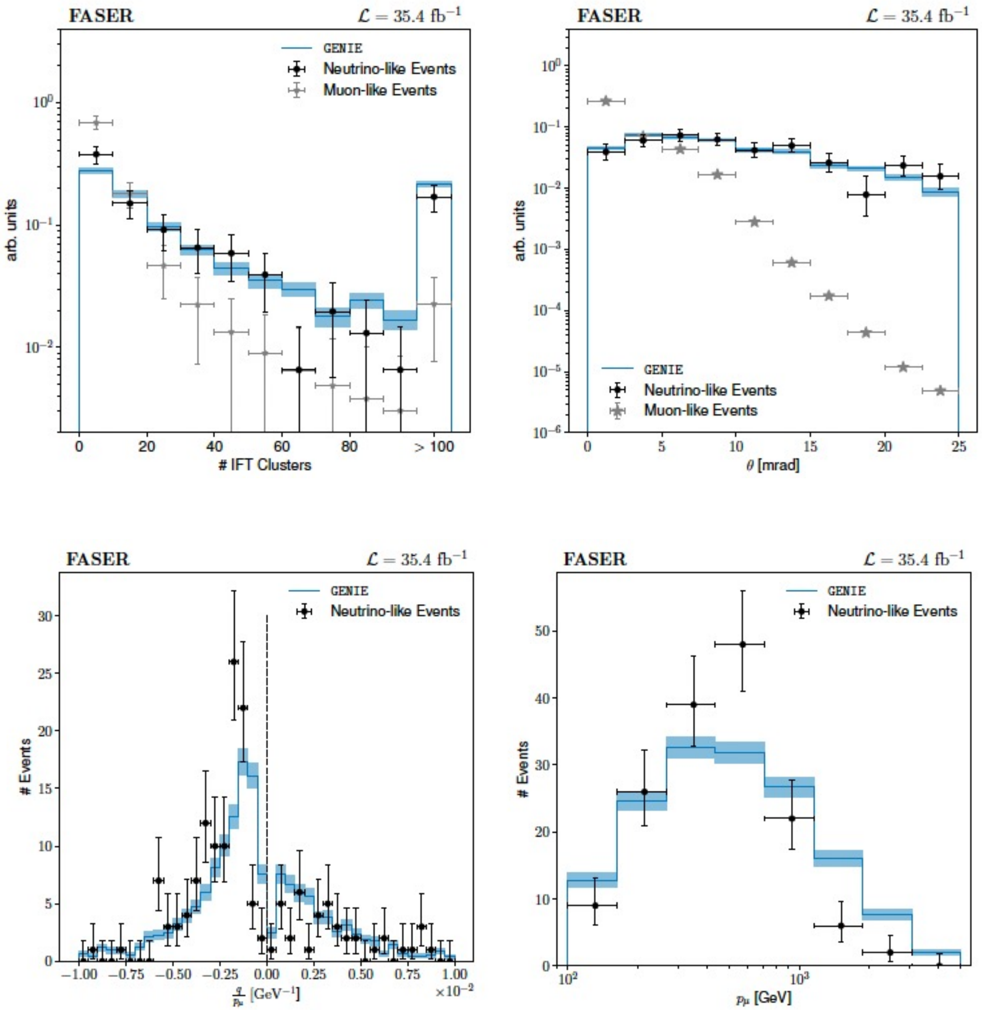
Use a discovery test statistic to determine the significance of the observed signal over the background-only hypothesis. A significance of 16σ is observed based on asymptotic formulas

Neutrino event distributions



As expected, that the identified neutrino candidates are distributed around the ATLAS LOS and do not cluster at a specific point of origin

Neutrino event distributions

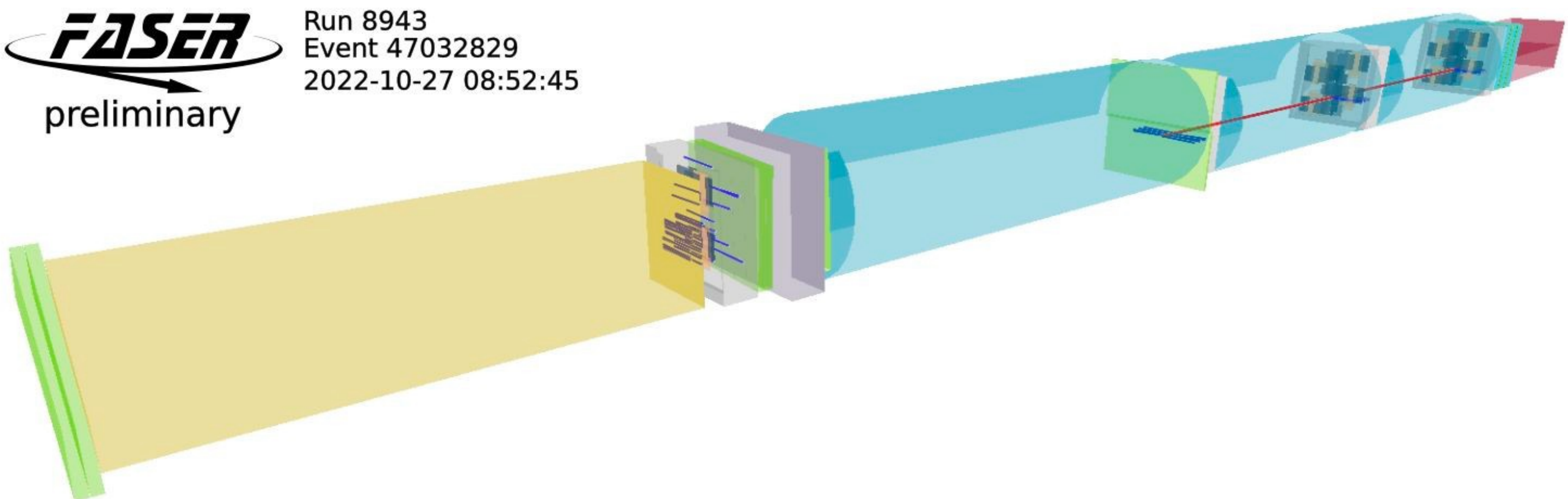


The CC neutrino interactions produce on average a larger number of particles than MIP interactions. The muon polar angle from neutrino interactions is also larger

40 (out of ~153) events with a positively-charged track Candidate from anti-neutrinos. Since ~80% of neutrino's momentum is transferred to muon, most of these observed neutrinos have momentum >200 GeV

Neutrino event display

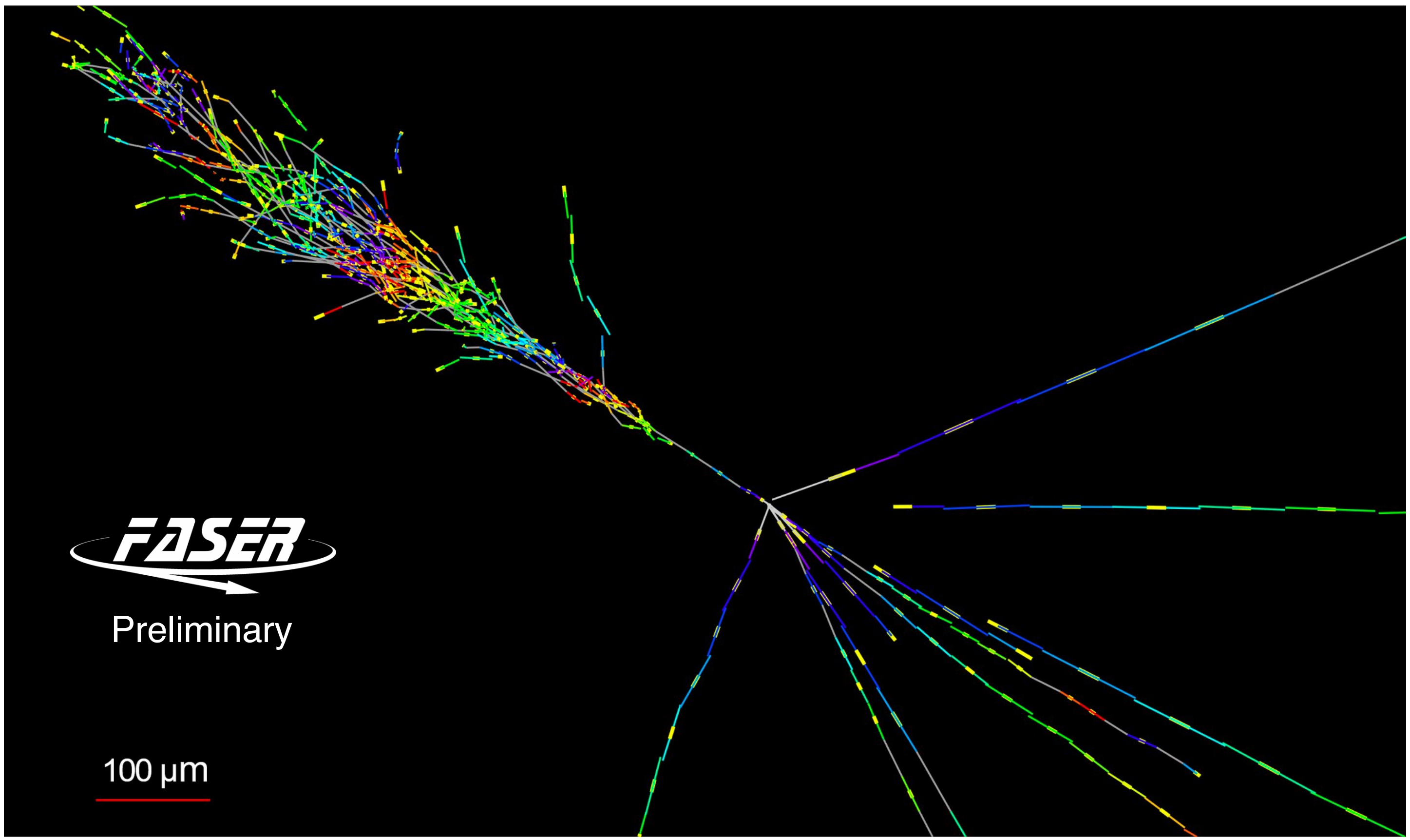
- Event display of a neutrino interaction candidate with secondary particles activity in the IFT



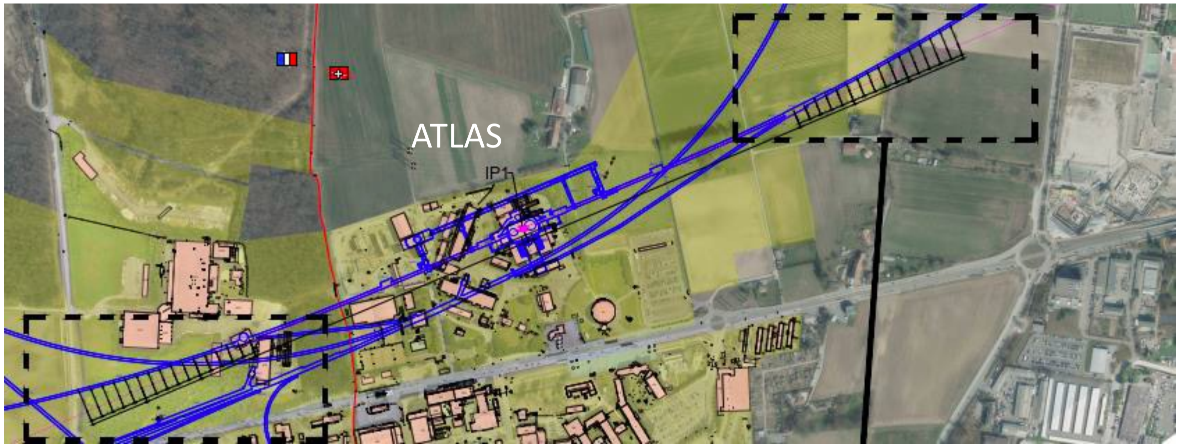
r_{VetoNu}[mm]	$r_{IFT}[mm]$	$r_{Tracker}[mm]$	θ [mrad]	p [GeV]	q	clusters IFT
57.2	55.8	54.6	2.5	843.8	-1	57

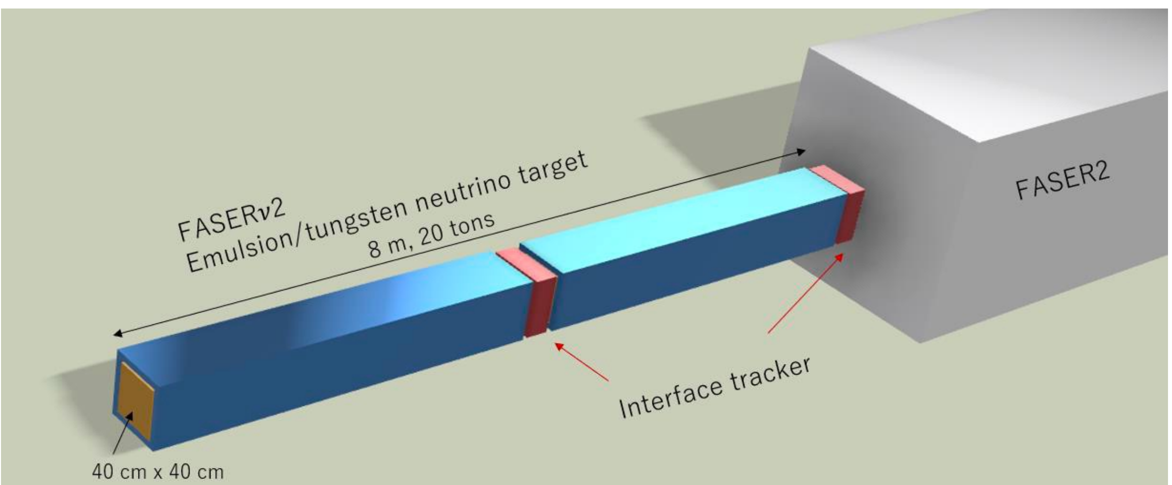
Neutrino event display in FASERν

- Analysis of emulsion detector still underway. The event display of a ν_e-like event: 11 tracks at the vertex, 175° between e-like track and others, θ_e=11 mrad w.r.t. beam



Detector upgrade





- The Forward Physics Facility (FPF) for the HL-LHC is a proposed facility that could house a suite of new forward experiments
  - – The background muon rate may be able to be reduced with a sweeper magnet (studies ongoing)
  - – Detector upgrade is being discussed
- FASER$\boldsymbol{\nu}$2, 10 times bigger target mass, can have 200-fold increase in neutrino event rate
  - – e.g., ~3000 ν_τ interactions are expected

Summary

- FASER successfully took data in first year of Run 3. Running at very good efficiency with fully functional detector
- First physics results are available in 2023
  - Observed ~150 neutrino CC interactions with the electronic components
    - ✓ First direct observation of collider neutrinos
    - ✓ Open new window for studying high energy neutrinos
  - Excluded dark photon in region of low mass, low kinetic mixing. Excluded new regions in the parameter space
- Expect up to 10 times more data coming in the next years with full Run 3, and expect more searches and neutrino measurements to come

Backup Slides

Pilot data event reconstruction

Selection cuts are applied on the tracks to enhance signal and suppress backgrounds

- Reconstructed tracks passing through at least 3 plates
- Vertex reconstruction for tracks with a minimum distance within 5 μm
- Converging patterns with 5 or more tracks were then identified as vertices
- Collimation cuts on vertices:
  - The number of tracks with $\tan\theta \leq 0.1$ with respect to the beam direction is required to be 5 or more
  - The number of tracks with $\tan\theta > 0.1$ with respect to the beam direction is required to be 4 or less

✓ Vertices are categorized as charged or neutral based on the presence or absence, respectively, of charged parent tracks

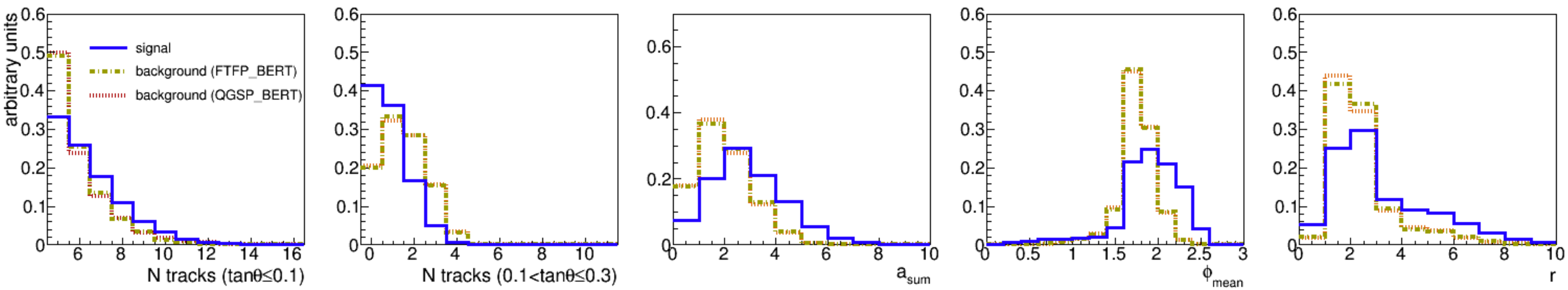
✓ In the signal, all neutrino flavors are combined

✓ 18 neutral vertices were selected

Selection efficiency cuts for signal and neutral hadron background (E > 10 GeV)

Signal		Background		
			FTFP_BERT	QGSP_BERT
ν_e	0.490	K_L	0.017	0.015
$\bar{\nu_e}$	0.343	K_S	0.037	0.031
ν_μ	0.377	n	0.011	0.012
$\bar{\nu_\mu}$	0.266	$\bar{n}$	0.013	0.013
ν_τ	0.454	Λ	0.020	0.021
$\bar{\nu_\tau}$	0.368	$\bar{\Lambda}$	0.018	0.018

Kinematic variables in pilot data

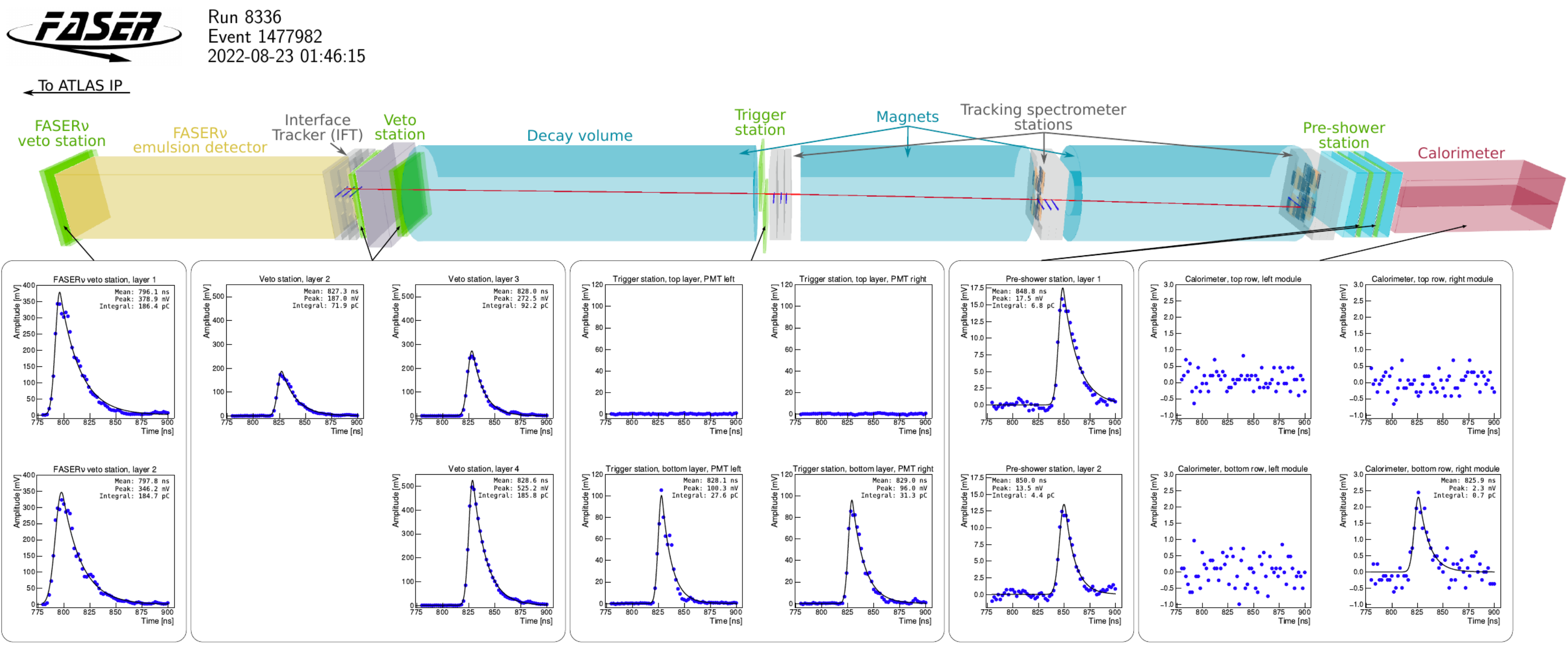


Five kinematic variables are used to separate signal and background

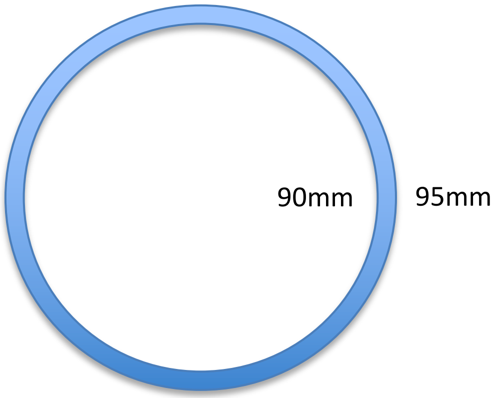
Variable	description
N_{trk} $(\tan\theta \le 0.1)$	The number of tracks with tanθ≤0.1 with respect to the beam direction
N_{trk} $(0.1 < \tan\theta \le 0.3)$	The number of tracks with 0.1<tanθ≤0.3 with respect to the beam direction
a_{sum}	The absolute value of vector sum of transverse angles calculated considering all the tracks as unit vectors in the plane transverse to the beam direction
ϕ_{mean}	For each track in the event, calculate the mean value of opening angles between the track and the others in the plane transverse to the beam direction, and then take the maximum value in the event
r	For each track in the event, calculate the ratio of the number of tracks with opening angle ≤90 degrees and >90 degrees in the plane transverse to the beam direction, and then take the maximum value in the event

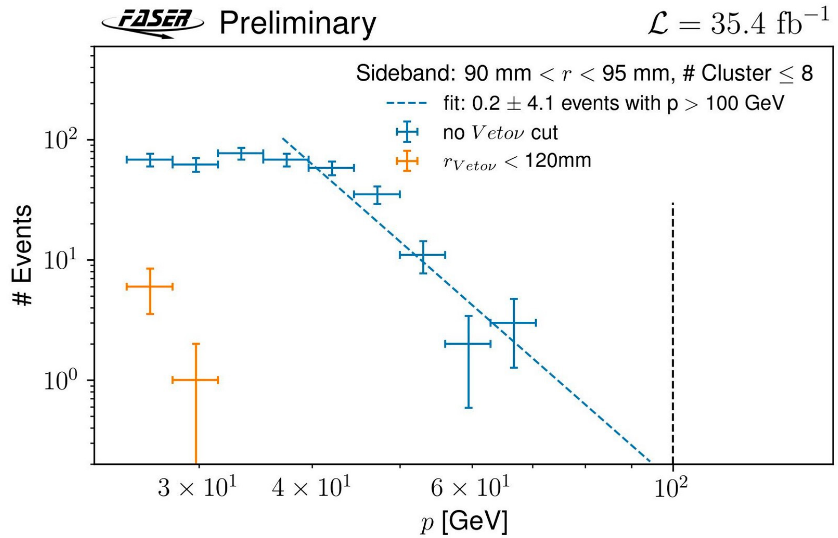
Muon event display in full FASER

- Event display of a muon traversing the full FASER detector



Geometric background





- Geometric background of muons by-passing veto measured in outer annulus at 50 GeV<p<100 GeV without radius requirement at FASERν scintillators
  - Also require tracker station hits consistent with 1 track. Negligible neutrino bkg
- Fit momentum to extrapolate to p>100 GeV
- Scale with rate of events inside $r_{\text{veto } \nu}$<120mm
  - 0 events, so use 5.9 events as upper limit
- Scale from annulus to full acceptance using large angle muon simulation

FASERν scintillator inefficiency

Category	Events	Expectation
Signal	153	$n_\nu + n_b \cdot p_1 \cdot p_2 + n_{\text{had}} + n_{\text{geo}} \cdot f_{\text{geo}}$
n_{10}	4	$n_b \cdot (1 - p_1) \cdot p_2$
n_{01}	6	$n_b \cdot p_1 \cdot (1 - p_2)$
n_2	64014695	$n_b \cdot (1 - p_1) \cdot (1 - p_2)$

n_{10}: Events for which the first layer of the FASERν scintillator produces a charge of >40 pC in the PMT, but no signal with sufficient charge is seen in the second layer
n_{01}: Analogous events for which more than 40pC in the PMT was observed in the second layer, but not in the first layer
n_2: Events for which both layers observe more than 40pC of charge

The determined inefficiencies of the two FASERν scintillators are

$$p_1 = (6^{+4}_{-3})\times 10^{-8}, p_2 = (9^{+4}_{-3})\times 10^{-8},$$

The backgrounds from cosmic rays and LHC beam background (with no collisions) are found to be negligible

Dark photon – introduction

- Dark photon *A'* can act as a portal between the hidden sector of the SM particles via a small mixing ε:

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon\, e \sum_f q_f A'_\mu \bar{f} \gamma^\mu f$$

- When *A'* mass is less than ~211 MeV, it decays dominantly into an electron and positron pair

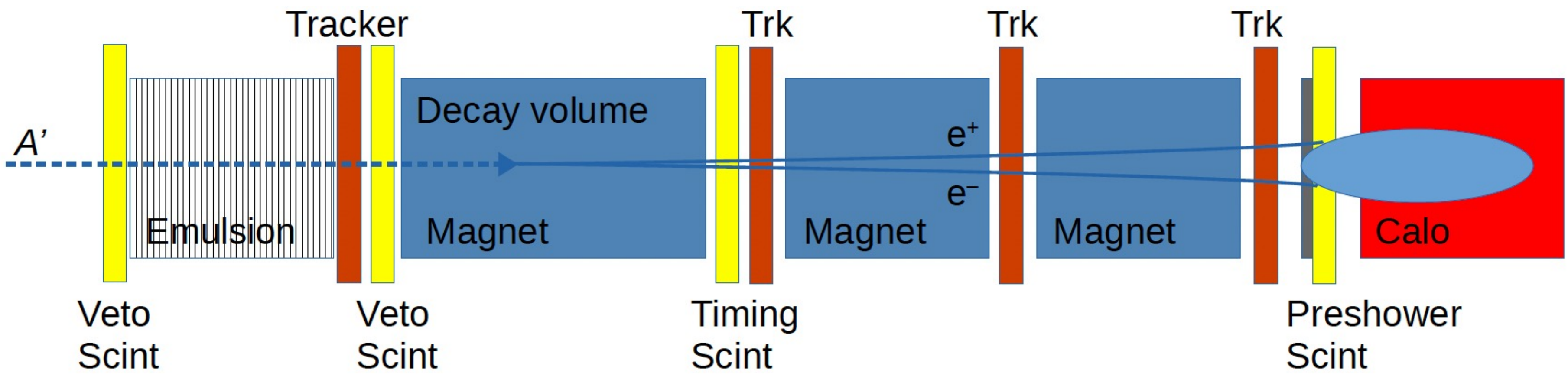
$$\Gamma_e \equiv \Gamma(A' \to e^+ e^-) = \frac{\epsilon^2 e^2 m_{A'}}{12\pi} \left[1 - \left(\frac{2m_e}{m_{A'}} \right)^2 \right]^{1/2} \left[1 + \frac{2m_e^2}{m_{A'}^2} \right]$$

- *A'* is mainly produced in the forward regions of the collider (via *A'* Bremsstrahlung or $\pi^0 \to A'\gamma$), so FASER is ideal for the dark photon search. Its decay length is

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

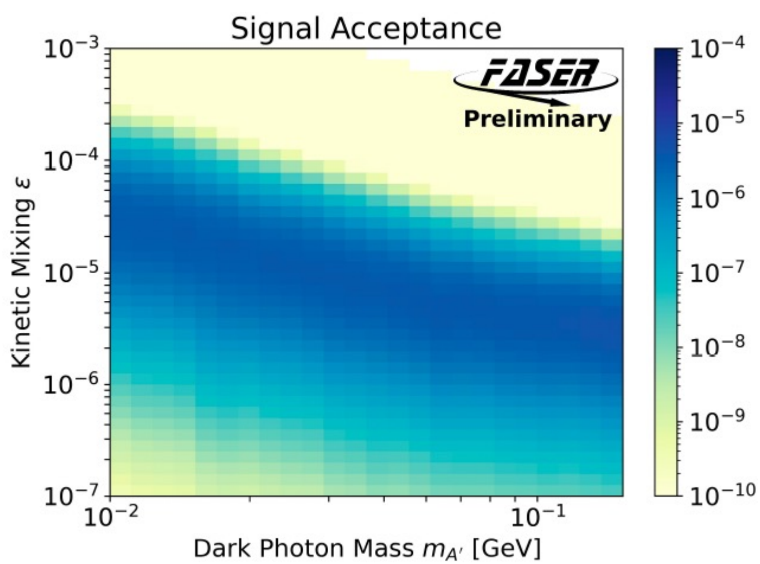
Dark photon event selection

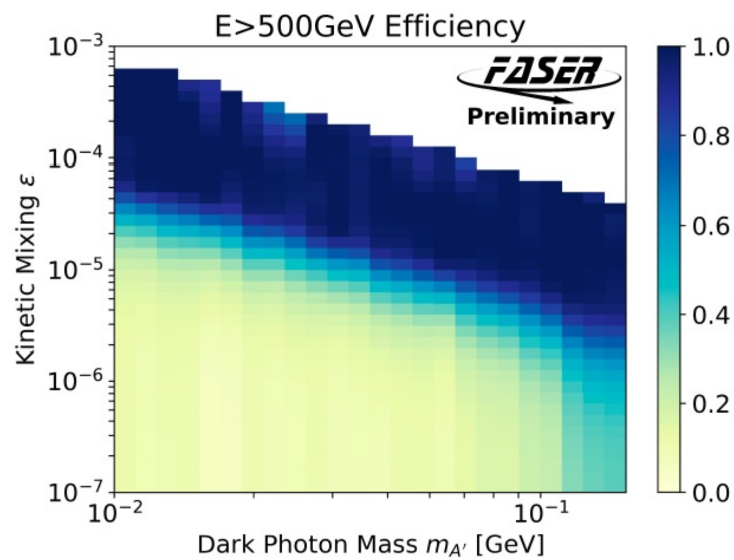
[CERN-FASER-CONF-2023-001]

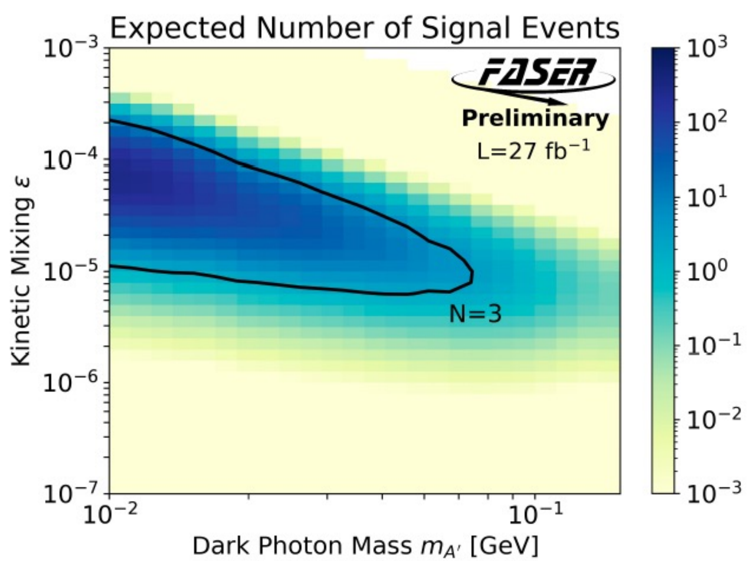


- Selection optimized for discovery:
  - Events in bunch collision, during good physics data period
  - No signal in any of five veto scintillators (<40 pC)
  - Timing and pre-shower scintillators consistent with ≥2 MIPs
  - Exactly two good quality tracks with p>20 GeV
  - Both tracks in fiducial tracking volume, r_{max}<95 mm
  - Both tracks extrapolate to $r_{veto\ \nu}$<95 mm in veto scintillators
  - Total calorimeter energy >500 GeV (A' should be highly boosted to travel to FASER)

Dark photon acceptance and efficiency



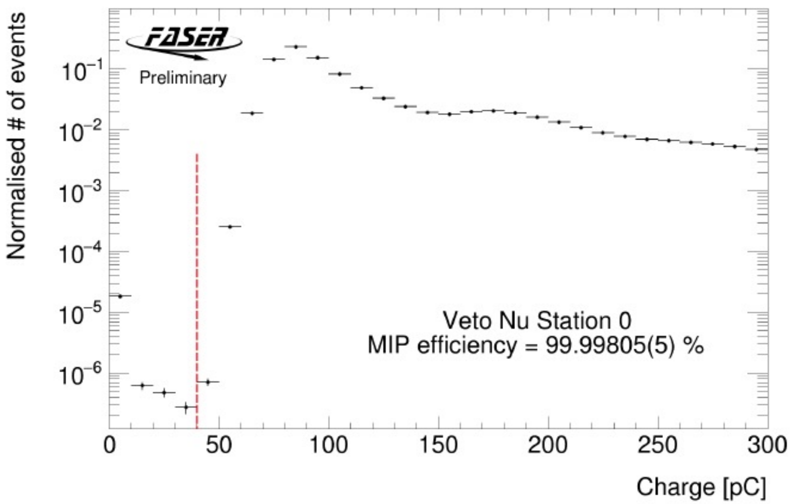


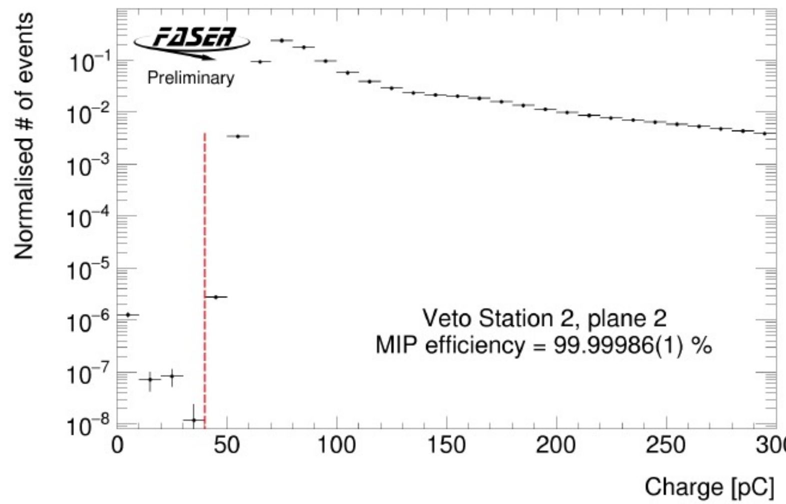


- FASER solid angle coverage is only ~10^{-8}.
- For a particular A' mass, if ε is too larger (small), A' will decay too fast (no decay) inside FASER
- For fixed ε, production cross section decrease with increasing A' mass

Veto efficiency

Charge distribution in the most downstream VetoNu scintillator (left) and the most upstream Veto scintillator (right)





- Require no signal in the five veto layers (2 FASER veto layers and 3 veto stations)
- Veto scintillator efficiencies measured by extrapolating tracks triggered in timing scintillator back to the five veto layers
- All inefficiencies below 2×10^{-5}. With five layers, even 10^8 muons going through veto produces negligible background even before any other selections applied

Background from neutral hadrons

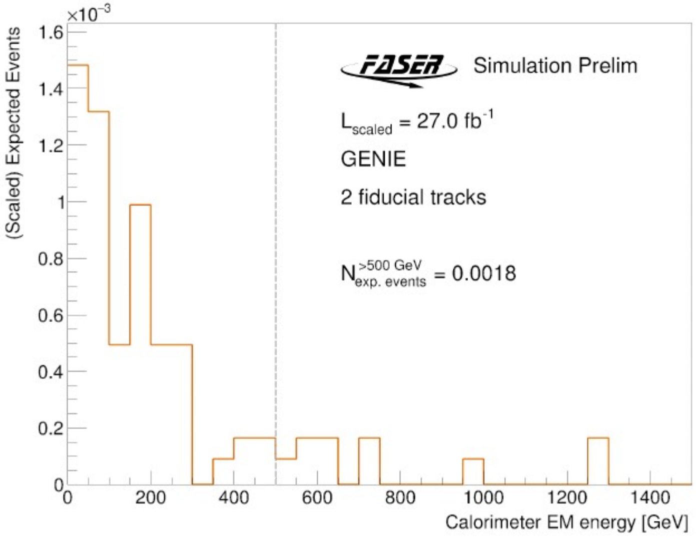
- Neutral hadrons are mainly produced in muon interactions in the rock in front of FASER. Heavily suppressed due to
  - Have to traverse the full FASERν detector
  - The parent muon has to miss the veto scintillators
  - Hadron decay products has to leave E>500 GeV in calorimeter
- They are estimated with the following steps
  - Derive a ratio of E>500 GeV to E<100 GeV events with three tracks (one of which is the parent muon)
  - Count events with two tracks (with no parent muon) with E<100 GeV. To allow for sufficient event counts, require no signal in FASERν scintillators, but no requirement in the veto scintillators
  - Scale the two-track event counts with the ratio
  - Photon conversion events are suppressed with E/p<0.5
- The estimated neutral hadron events is $(2.2 \pm 3.1)\times 10^{-4}$

Selection	Nevents E<100 GeV	Nevents E>500 GeV
3 tracks (VetoNu signal)	544.7	11.0
2 tracks (No VetoNu signal)	1	Predicted: 0.02

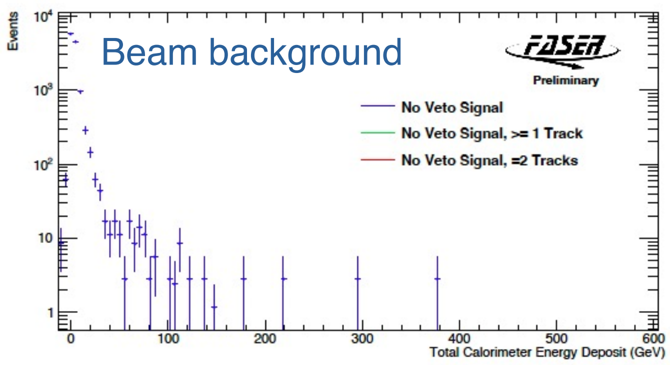
Neutrino and non-collision backgrounds

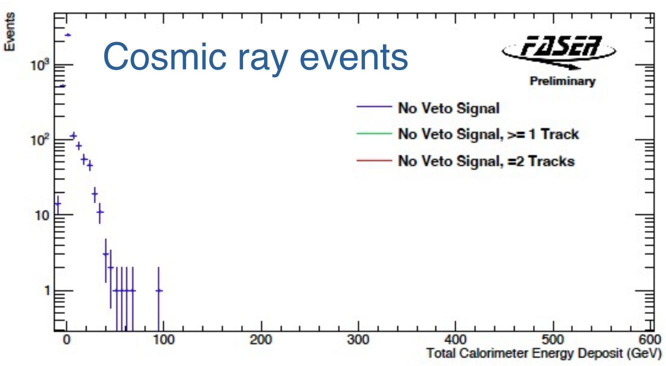
Neutrino background is the largest one in the analysis. Estimated from simulation

- Using GENIE generator (300 ab^{-1})
- With uncertainties for mismodelling and neutrino flux, expect 0.0018 ± 0.0024 (syst.) ± 0.0005 (stat.) events per 27 fb^{-1} of data
- Occurring in trigger/timing scintillators
- Background from neutrino induced hadrons upstream found to be negligible



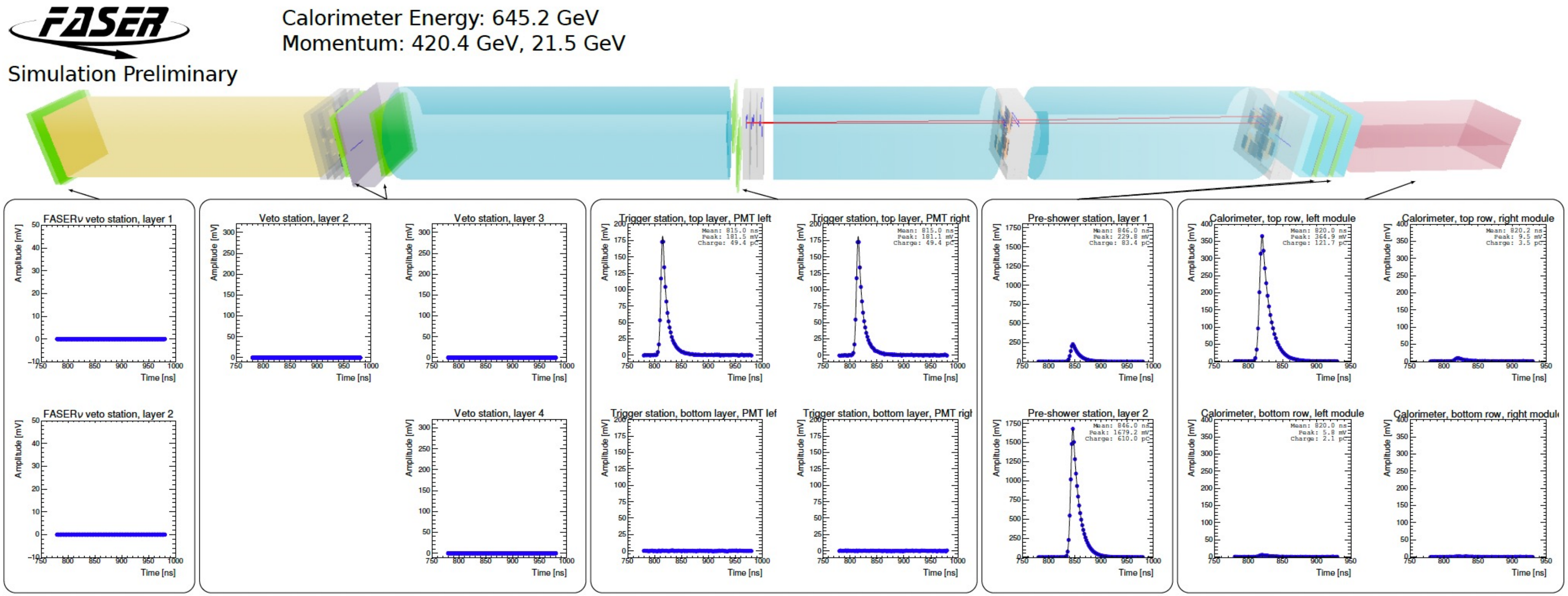
Non-collision background from cosmic and near-by beam debris is negligible. Studied in non-colliding bunches and runs without beam. No such events seen with E>500 GeV or a reconstructed track





Signal event display

- Example of a simulated Dark Photon decaying inside the detector decay volume

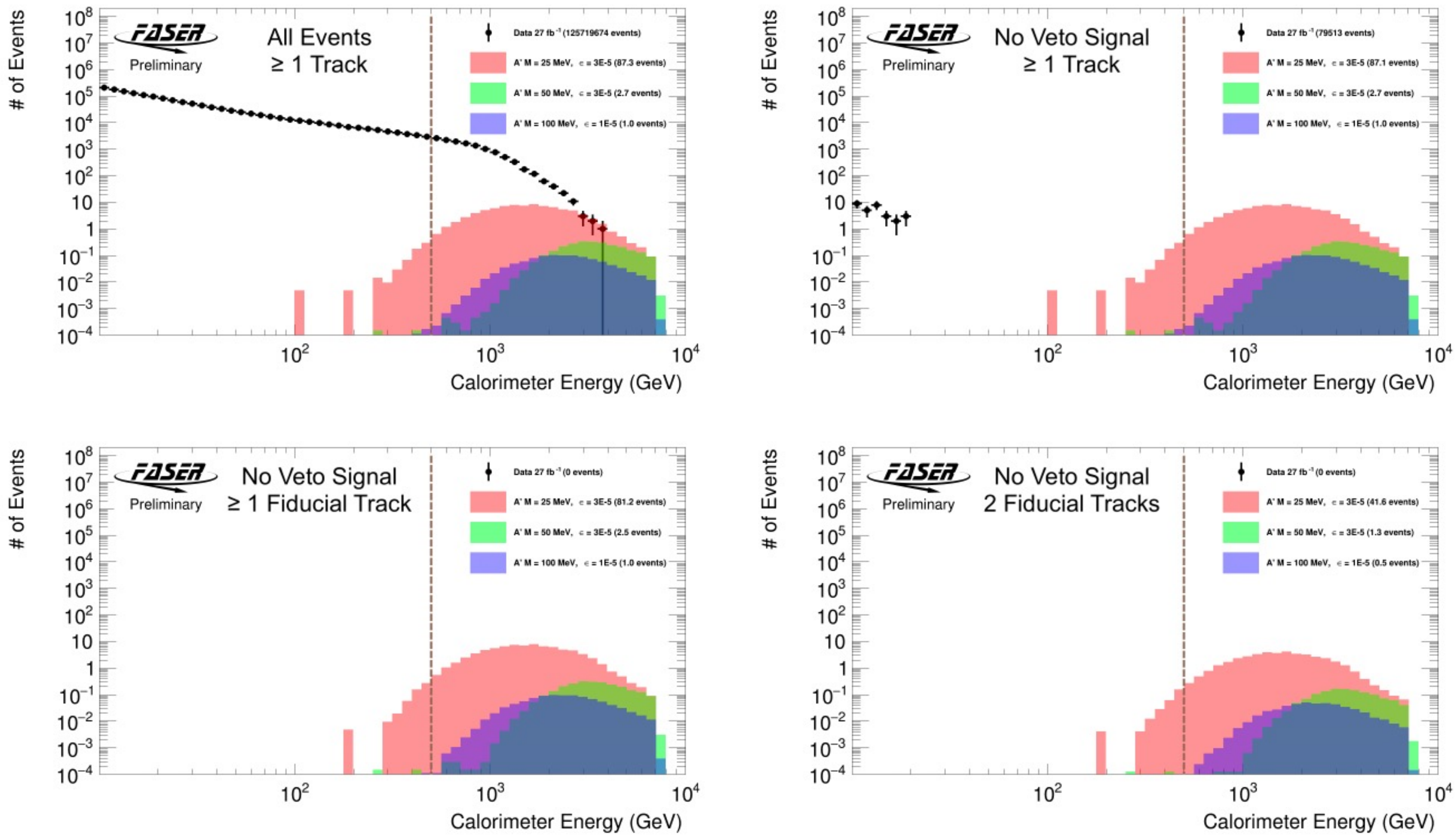


Event cut flow

- Data and example signal efficiencies for analysis selections
- Note pre-selection to have at least one reconstructed track (no quality cuts) in the event has been applied on data

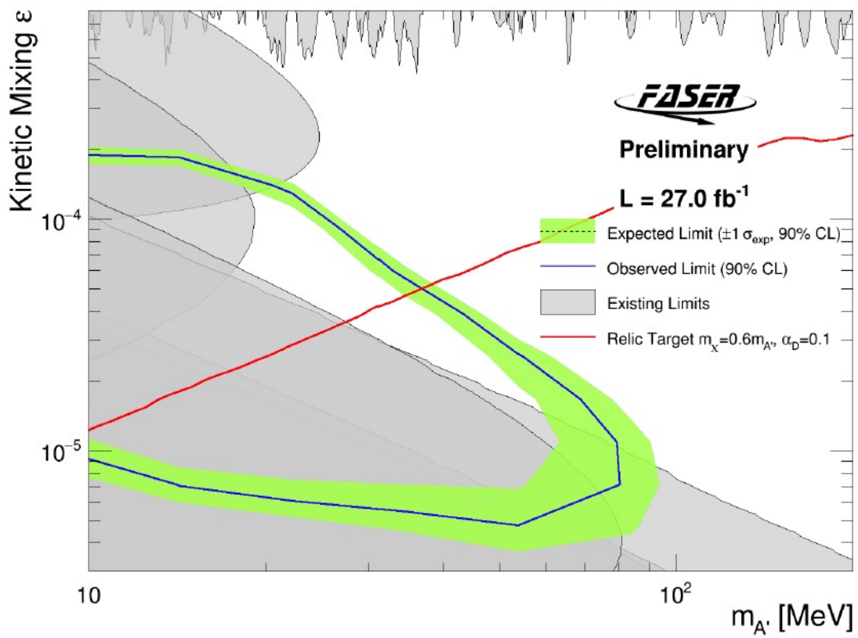
Cut	Data		Signal ($\varepsilon = 3 \times 10^{-5}$, $m_{A'} = 25.1\,\mathrm{MeV}$)	
	Events	Efficiency	Events	Efficiency
Good collision event	151750788	—	95.3	99.7%
No Veto Signal	1235830	0.814%	94.0	98.4%
Timing/Preshower Signal	313988	0.207%	93.0	97.3%
≥ 1 good track	21329	0.014%	85.2	89.2%
$= 2$ good tracks	0	0.000%	44.5	46.6%
Track radius < 95 mm	0	0.000%	40.4	42.3%
Calo energy > 500 GeV	0	0.000%	39.7	41.6%

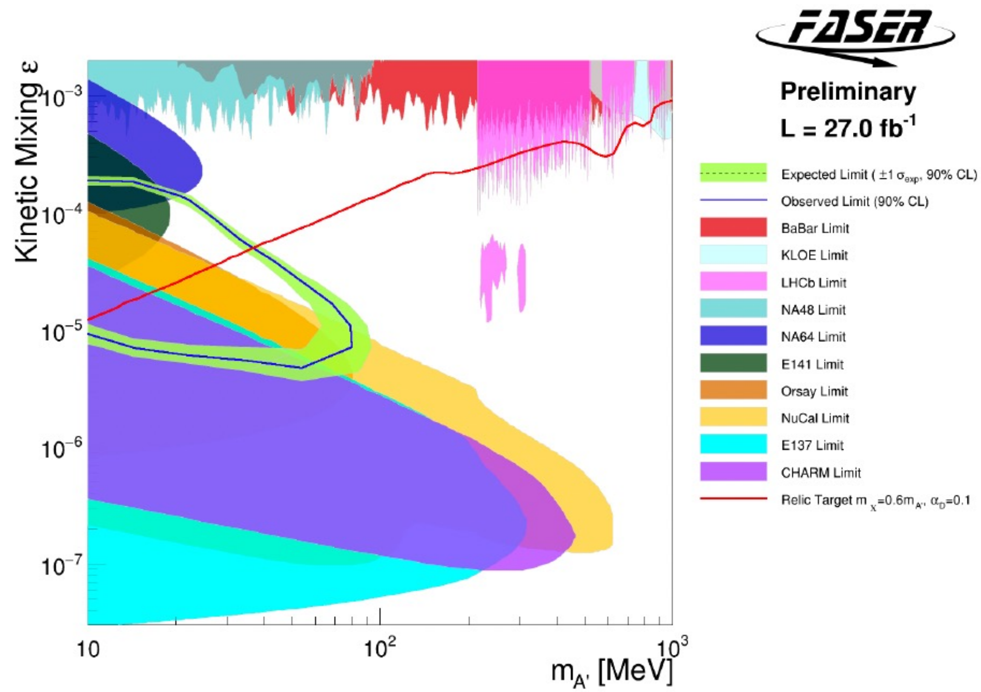
Data in signal region



- Total background expected: 0.0020 ± 0.0024
- No events seen in the signal region

Dark photon sensitivities



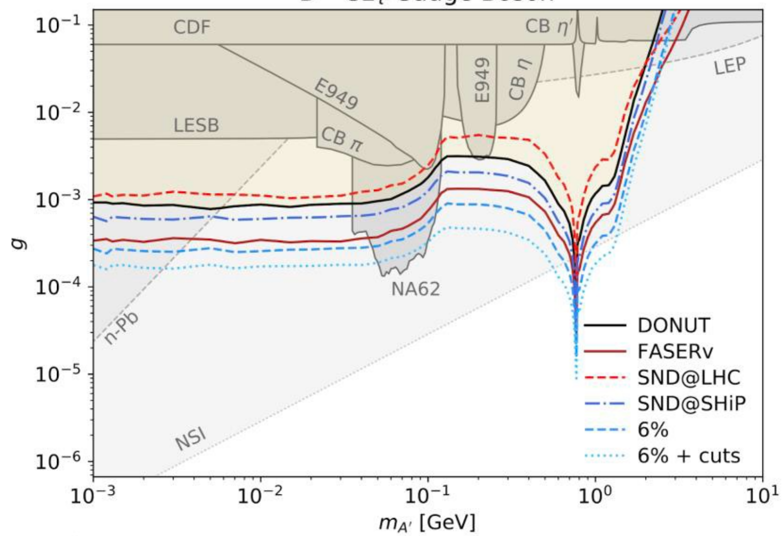


- FASER sets limits (profile likelihood approach) on previously unexplored parameter space
- Region below the relic target line would have an over-abundance of dark matter (excluded cosmologically), although the line is model-dependent: $m_\chi/m_{A'} = 0.6$ and coupling between A' and χ is $\alpha_D = 0.1$
- Very recent NA62 result overlaps with the FASER excluded region mainly below the relic target line (bot shown here)

FASERν2 for BSM physics

- The tau neutrino flux is small in SM. A new light weakly coupled gauge bosons decaying into tau neutrinos could significantly enhance the tau neutrino flux

[F. Kling, Phys. Rev. D 102 (2020) 015007]

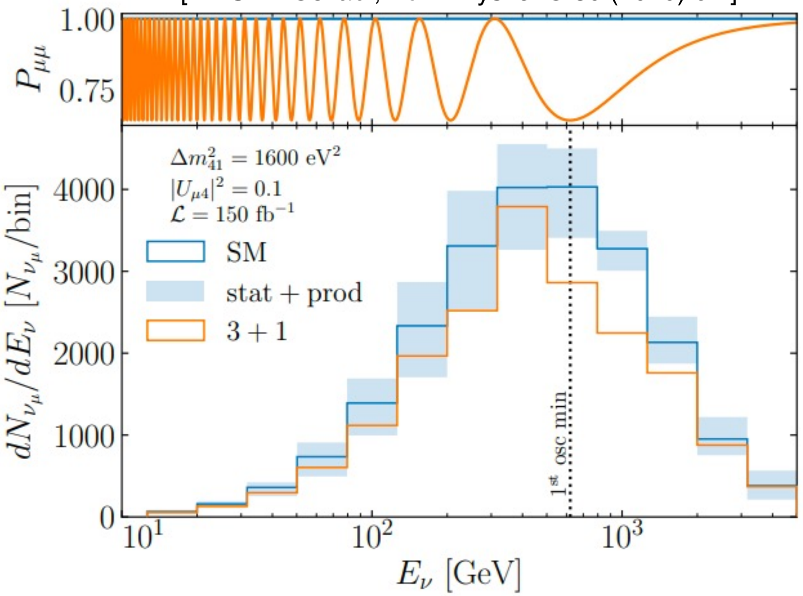


- SM neutrino oscillations are expected to be negligible at FASERν. However, sterile neutrinos with mass ~40 eV can cause oscillations. FASERν could act as a short-baseline neutrino experiment

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4|U_{\alpha4}|^2(1-|U_{\alpha4}|^2)\sin^2\frac{\Delta m_{41}^2 L}{4E} \,,$$

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

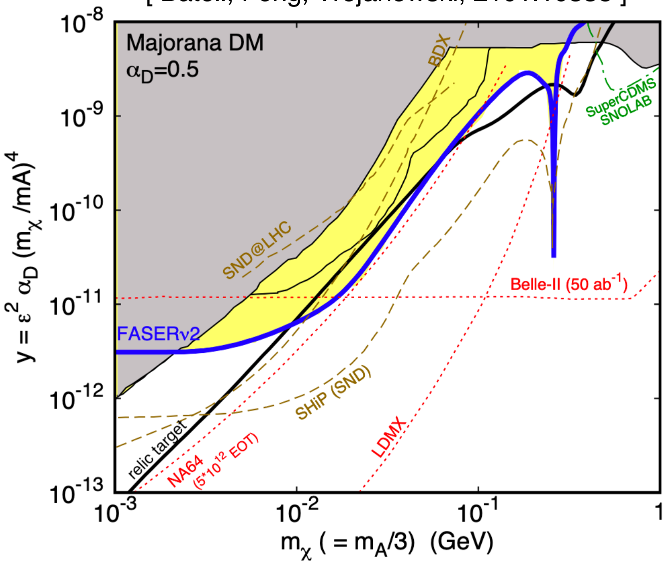
[FASER Collab., Eur. Phys. J. C 80 (2020) 61]



FASERν2 for BSM physics

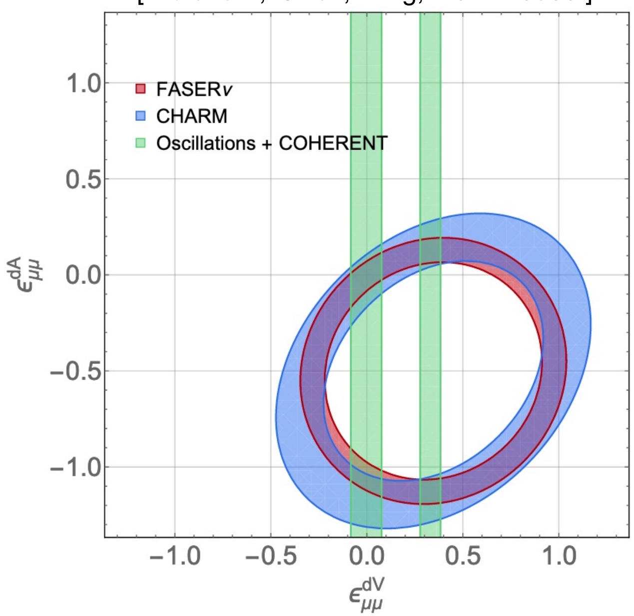
- If DM is light, the LHC can produce an energetic and collimated DM beam towards FASERν. FASERνcould therefore also search for DM scattering

[Batell, Feng, Trojanowski, 2101.10338]



- FASERνalso measures cross-section of Neutral Current (NC) neutrino interactions. Non-Standard Interaction (NSI) can be explored in conjunction with measurement of CC cross-section

[Abraham, Ismail, Kling, 2012.10500]



DIS cross-section of CC/NC interactions