First physics results from the FASER experiment

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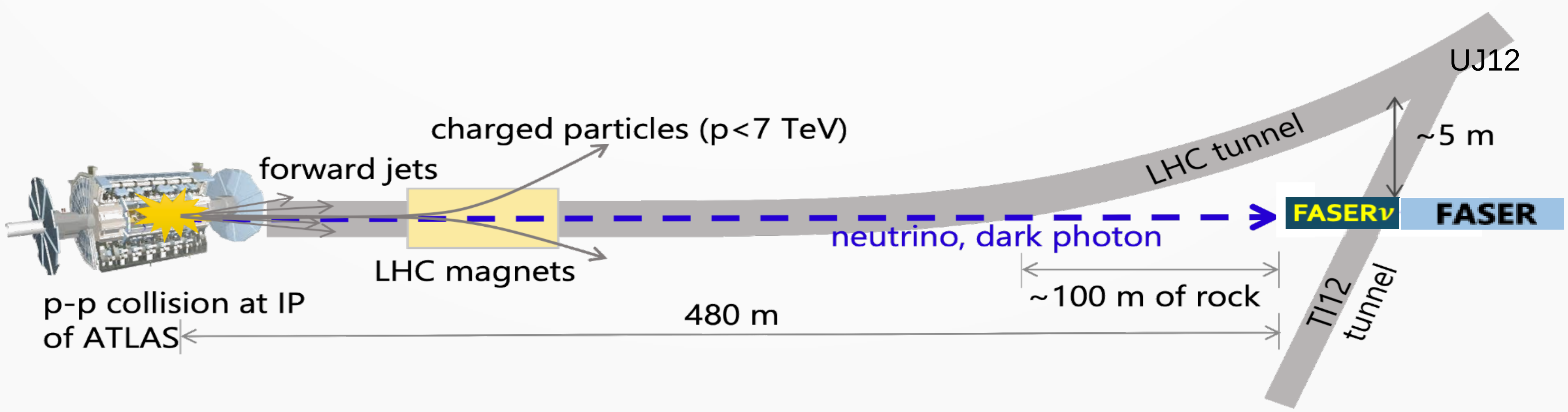
ForwArd Search ExpeRiment idea

FASER is designed to compliment the LHC programme:

- LHC Run 3 expected integrated luminosity >150 fb^{-1}
- $O(10^{16})$ inelastic p-p scattering events is expected
- **Long-lived particles (LLP) with TeV energies** potentially can be produced in ATLAS interaction point (IP)

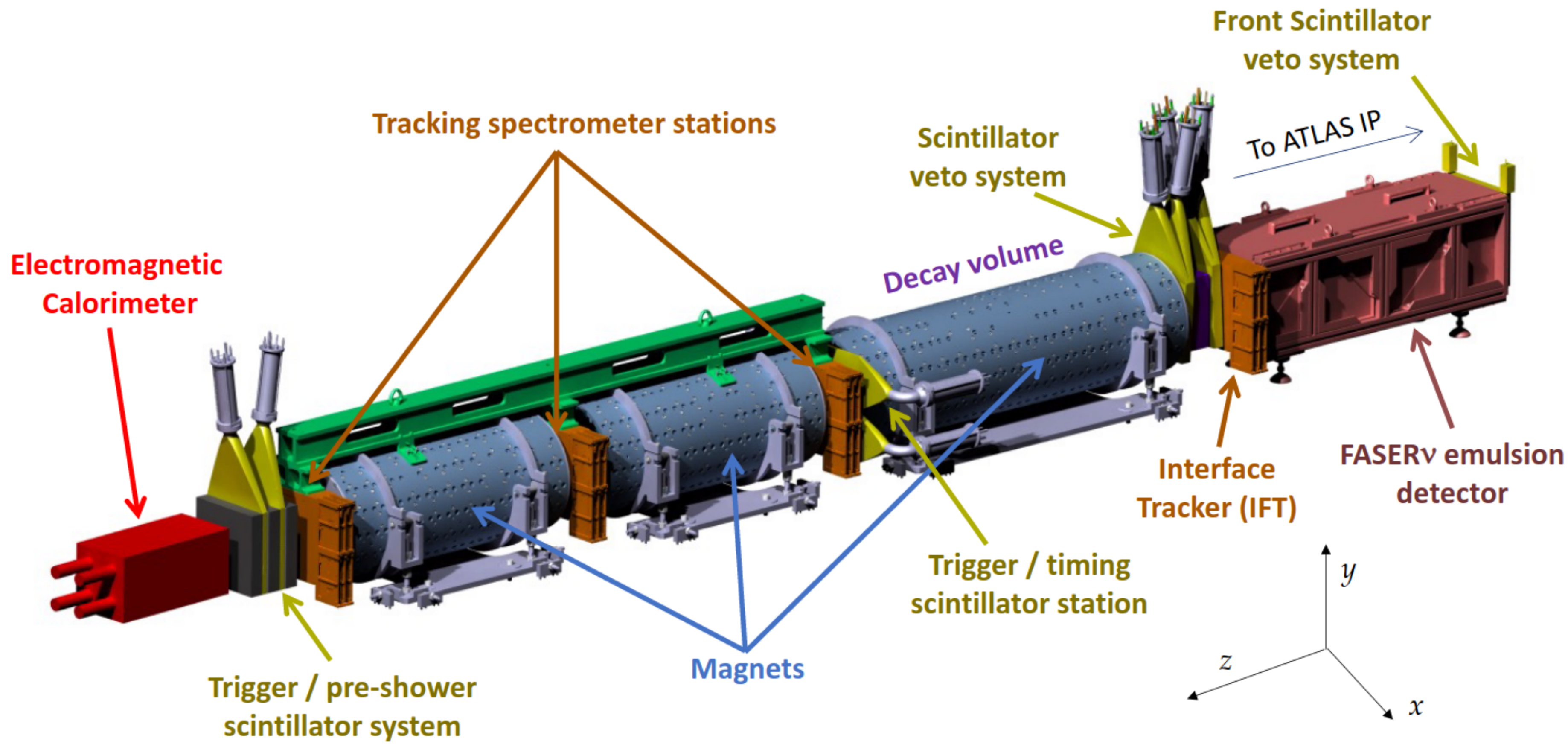
  $pp \to LLP + X$, $LLP \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \gamma\gamma, \ldots$
- Located in TI12 tunnel — unused one, the beam collision axis passes along the tunnel floor
- ~480 m away from the ATLAS IP
- In the SM, only muons and **neutrinos** can reach detector. **LLPs can decay in FASER**.



Detector

arXiv: 2207.11427

7 m long
1.5 m decay volume



Transverse size is limited by the tunnel and trench constraints, detector must be centred on the LOS to within ~10 cm to maximise number of LLP decays and neutrino interactions

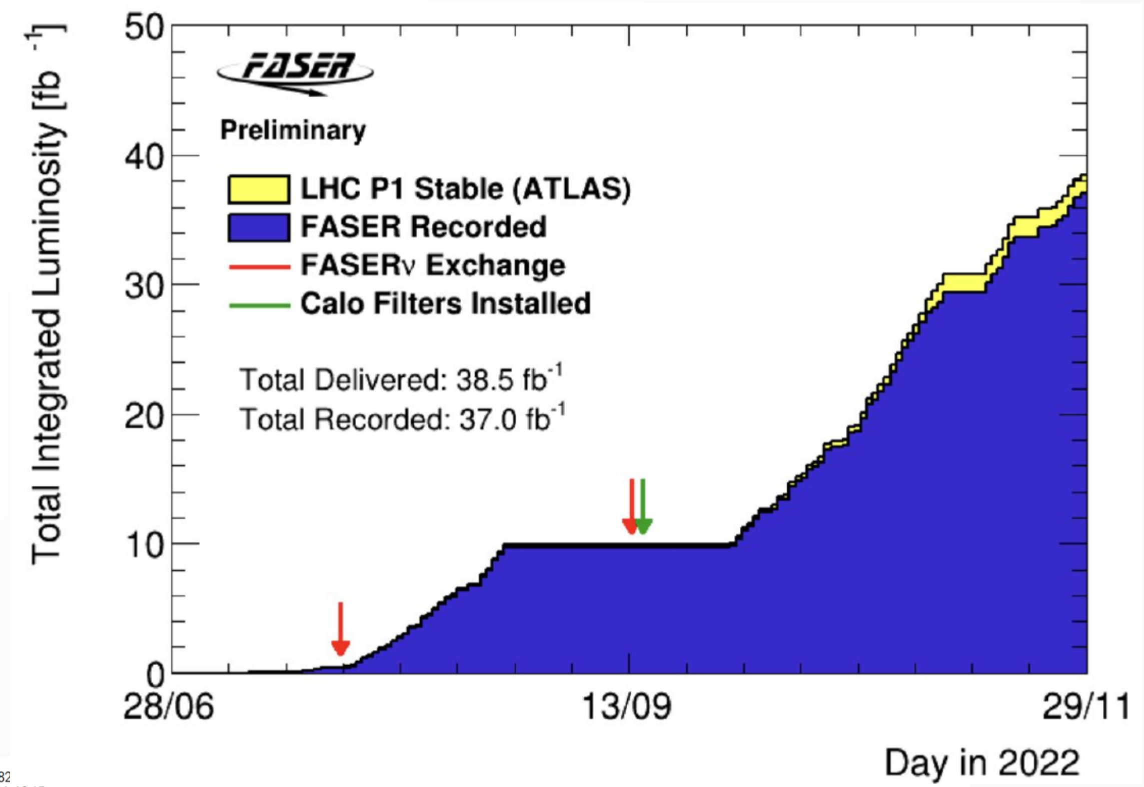
Signatures of the Dark Sector particles and neutrinos are quite different

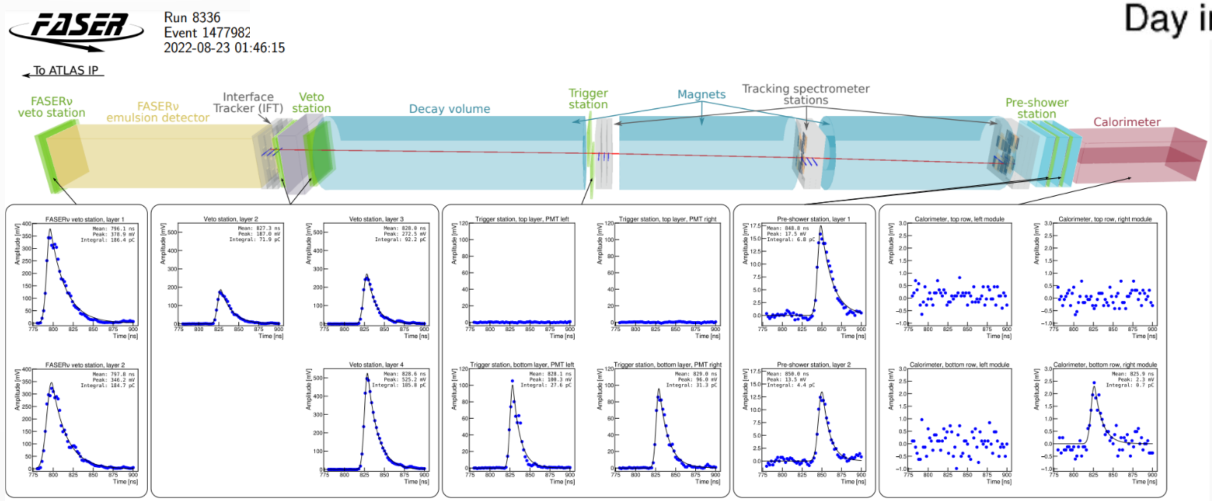
To fullfil physics program complex detector is needed which satisfy to strict requirements on positional resolution, precision of energy and momentum measurement, particles identification

Detector operation

- March 2021 — installed, cosmic data taking
- July 2022 — physics data taking started

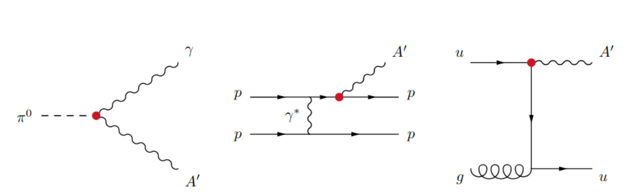
- **Smoothly operated in 2022**
  - Continuous data taking
  - Largely automated
  - Up to 1.3 kHz trigger rate
  - More than 350 x 10^6 single muon events recorded
- **Recorded 96.1% of delivered luminosity**
  - DAQ dead-time of 1.3%
  - A couple of DAQ crashes
- **Emulsion detector exchanged twice**
  - Needed to manage the occupancy
  - First box only partially filled
- **Calorimeter gain optimised**
  - Low E (< 300 GeV) before 2nd exchange
  - High E (up to 3 TeV) after the exchange
- **Smoothly operating in 2023**
  - Another ~30 fb^{-1} data





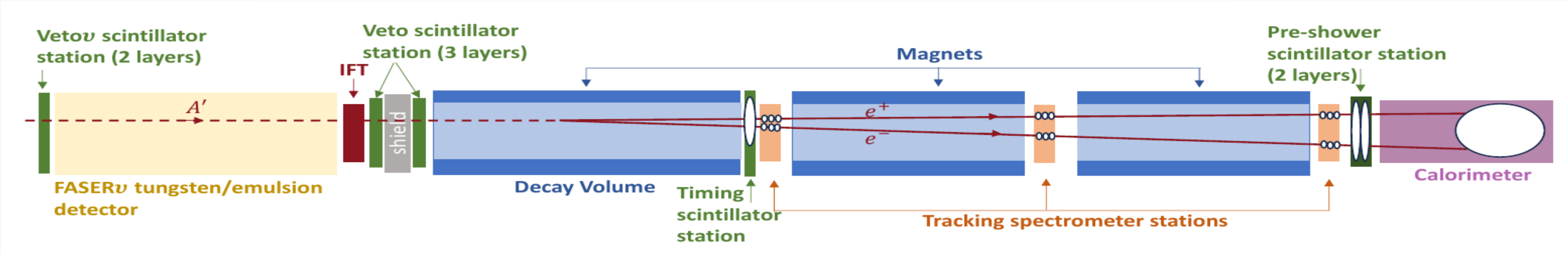
Search for dark photon

- Dark photon is a hypothetical particle belonging to Dark Sector (DS)
- Produced in light mesons decays, through dark bremsstrahlung etc.



- Huge number of light mesons with TeV energies are concentrated in the very forward direction in the FASER angular acceptance, $O(10^{15})$
- Significant discovery potential with >150 fb^{-1} expected in Run 3
  - Simple event selection optimised for discovery
  - Signal selection ~40% of region of sensitivity

1. good quality collision event



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

4. Timing and preshower consistent with ≥ 2 MIPs

5. Energy in calorimeter E > 500 GeV

Search for dark photon

Background sources estimated for 27 fb^{-1}

Neutrino interactions (dominant)

- Mainly coming from interactions in timing detector
- Estimated from GENIE simulation of 300 ab^{-1} data
- Uncertainties from neutrino flux and interactions modeling
- Predicted events with E_{calo} > 500 GeV

(1.5 ± 0.5 (stat.) ± 1.9 (syst.)) ×10^{-3}

Neutral hadrons

- From muons interacting in rock in front of FASER
- Heavily suppressed
  - by the need to pass through 8 interactions lengths
  - by the need for the parent muon to scatter to miss the veto scintillators
  - Decay products have to leave E_{calo} > 500 GeV
- Data-driven estimation

(0.84 ± 1.19) ×10^{-3}

Other negligible:

Veto inefficiency

- Measured layer-by-layer via muons with tracks pointing back to vetos
- Layer efficiency > 99.999%

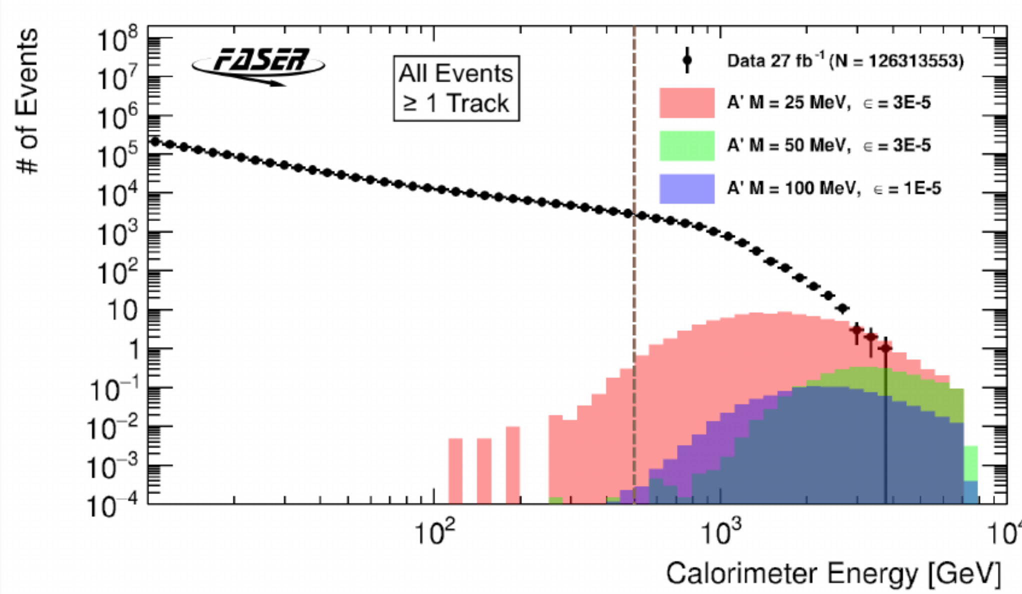
Large-Angle muons

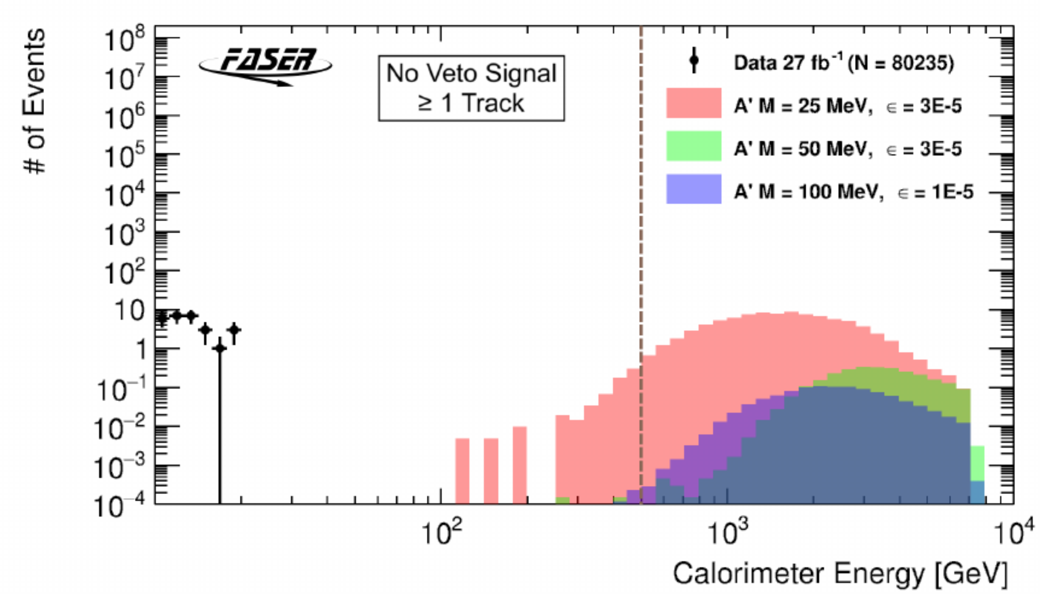
Non-collision events

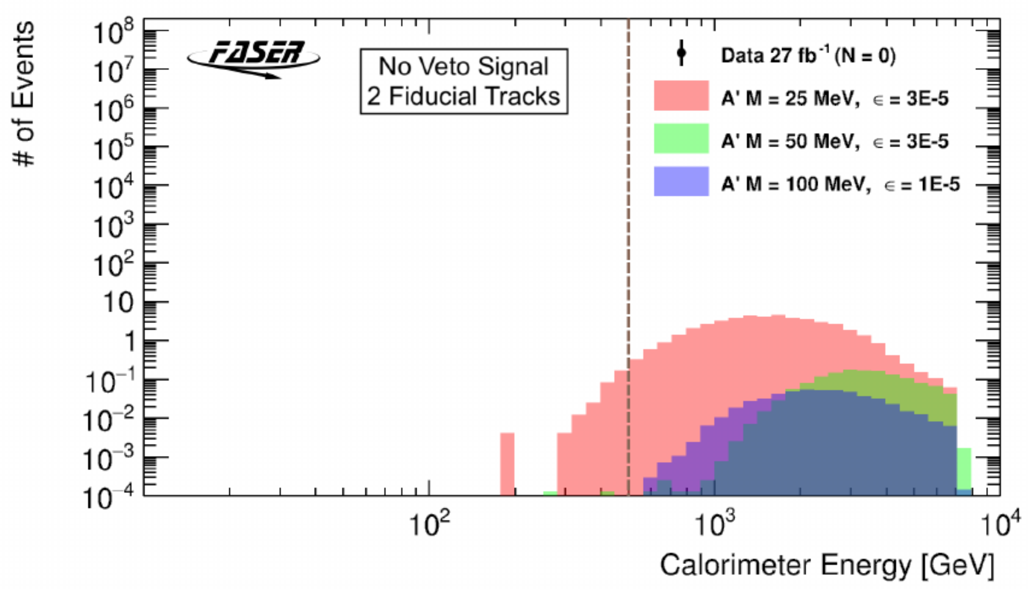
- Cosmics measured in runs with no beam
- Near-by beam background measurement in non-colliding bunches

Total background of (2.3 ± 2.3) ×10^{-3} events

Search for dark photon







Unblinded results

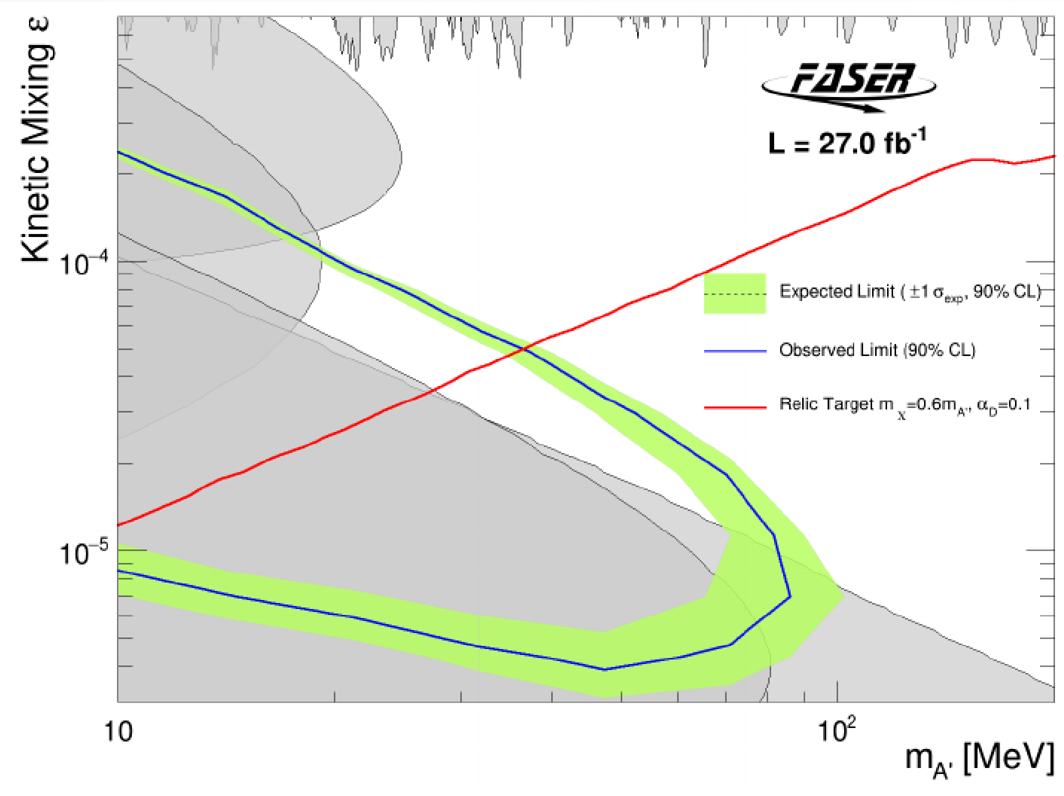
No events in signal region

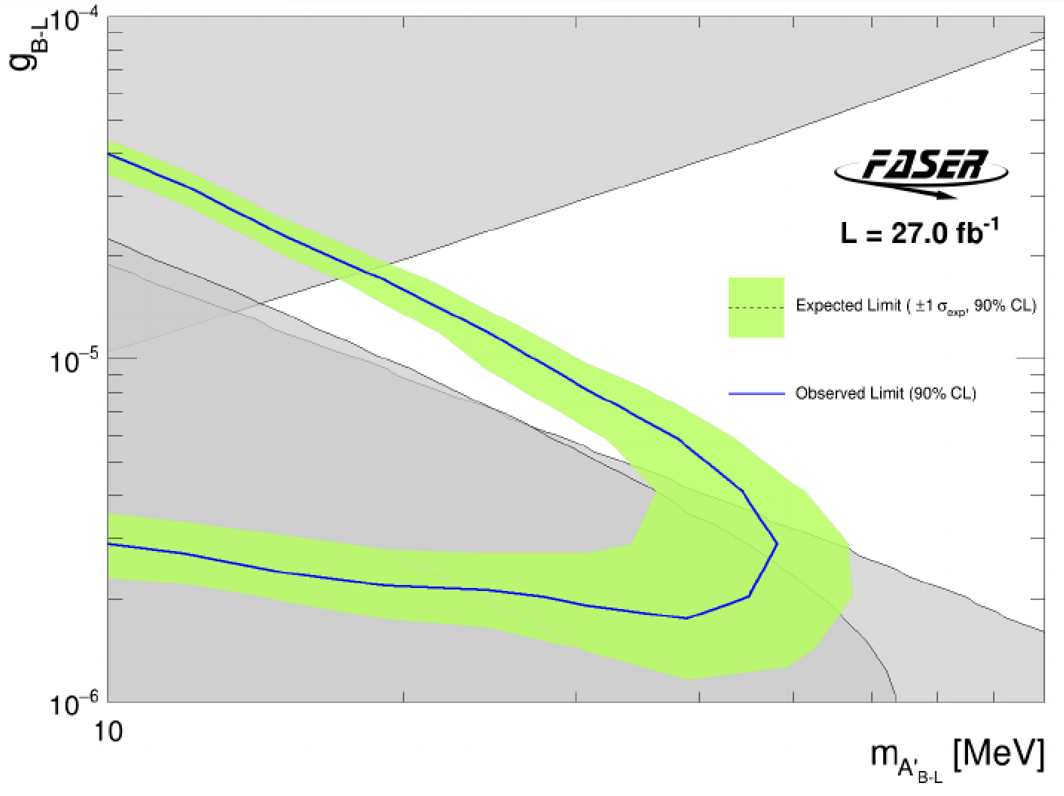
Search for dark photon

No event in unblinded SR

- **FASER sets limits in previously unexplored parameter space !**
- Probes new territory in the interesting thermal-relic region
- Results reinterpreted in terms of B-L model

arxiv:2308.05587[hep-ex]



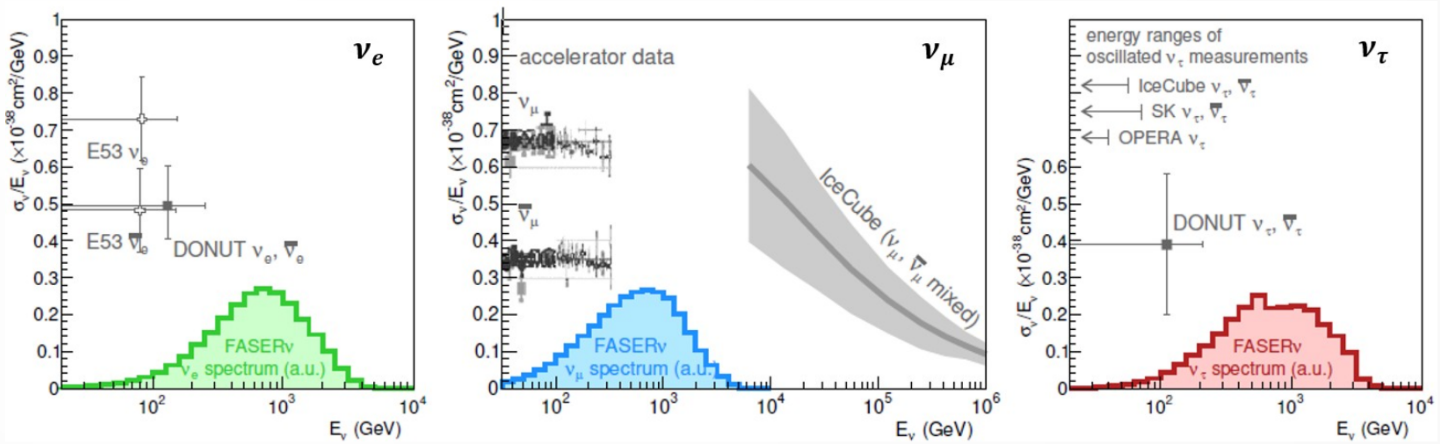


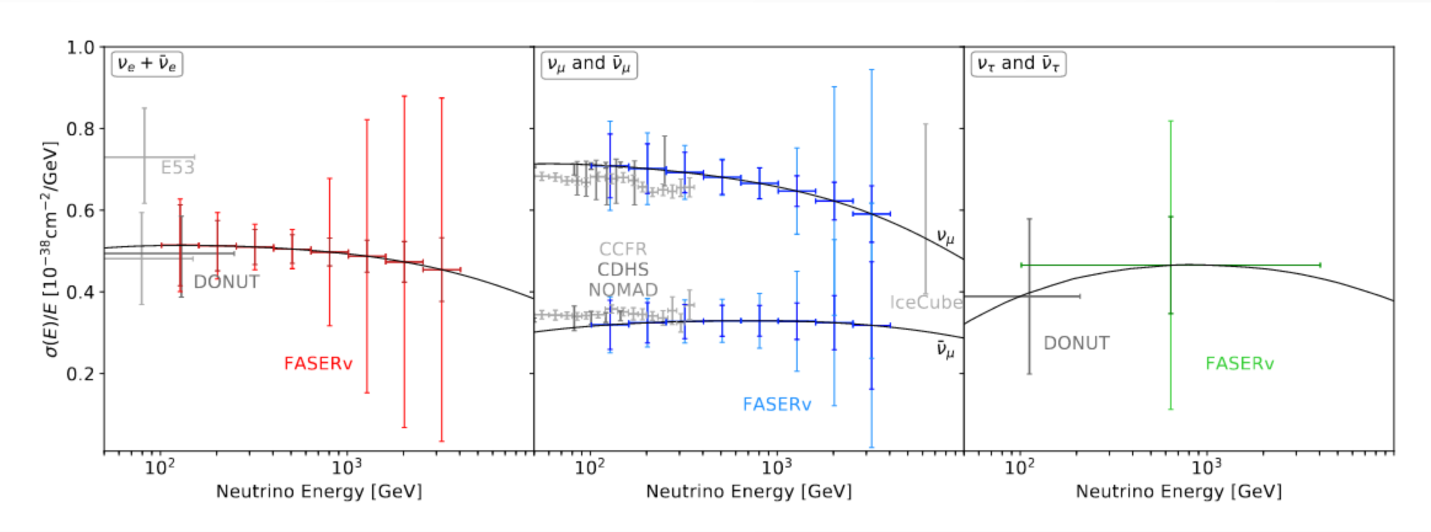
Neutrino physics

- Huge number of neutrinos from LHC collisions products decays are expected to pass through the FASER location in unexplored energy regime
- 1.1 tn emulsion/Tungsted detector, FASERν, is placed to register neutrinos of all flavours

  Expect to register in LHC Run 3
  $\sim$1000 ν_e, $\sim$10000 ν_μ , 50 ν_τ

- The goal is neutrino cross section measurement at high energies
-
- Neutrino energy resolution of ~30% is expected from the simulation



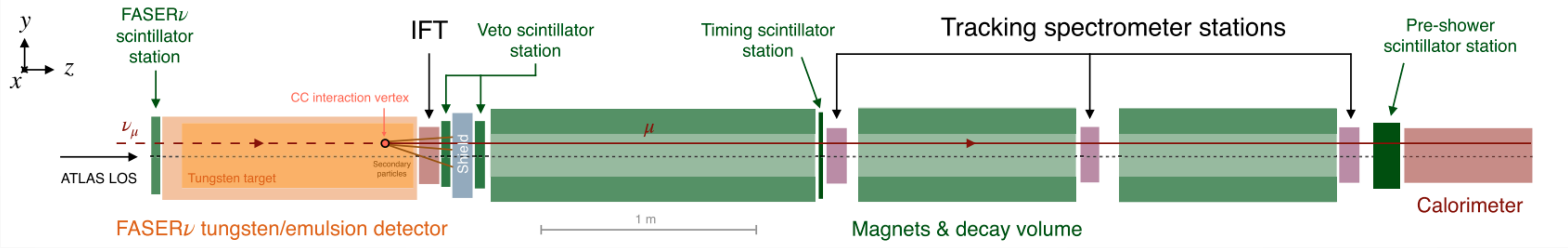


Expectation for 150 fb^{-1}

First direct observation of collider neutrinos

First study was focused on ν_μ CC interactions at FASERν with silicon tracker data usage done for 35.4 fb^{-1}

1. good quality collision event



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

4. Timing and preshower consistent with ≥ 1 MIPs

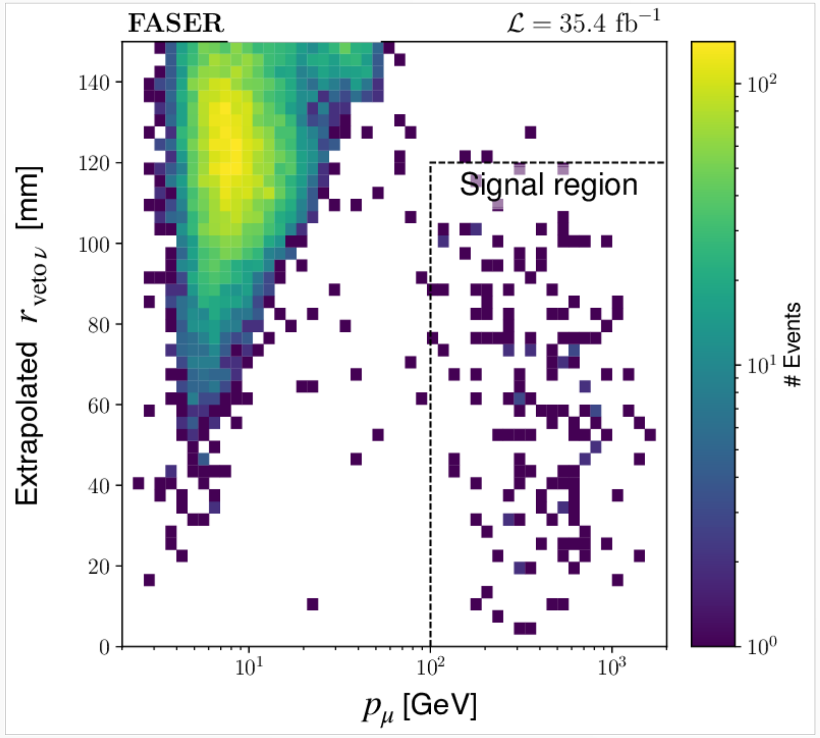
Background estimation

Neutral hadrons — **0.11±0.06** events
Muon scattering — **0.08±1.83** events
Veto inefficiency — negligible

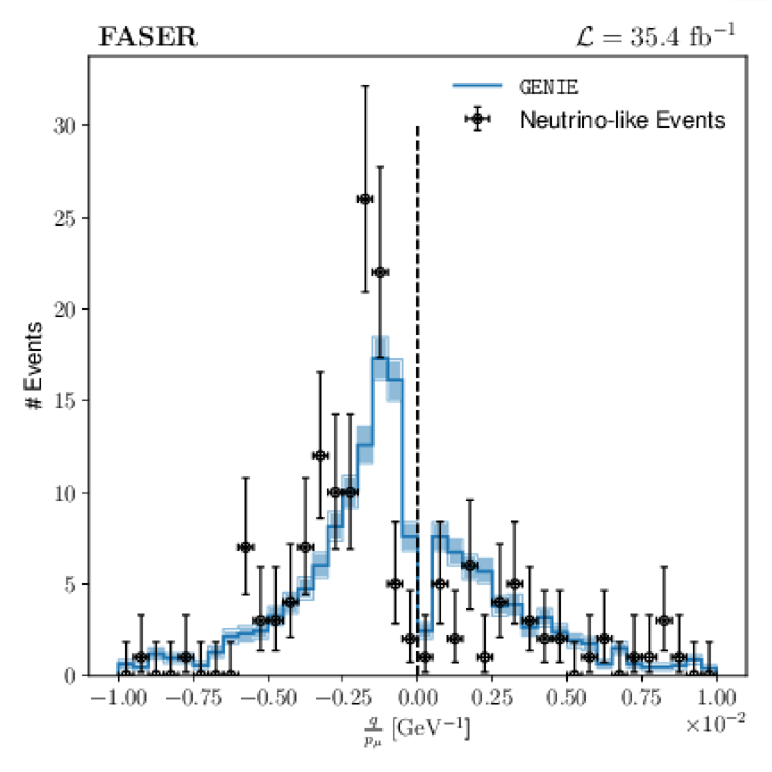
Expected signal

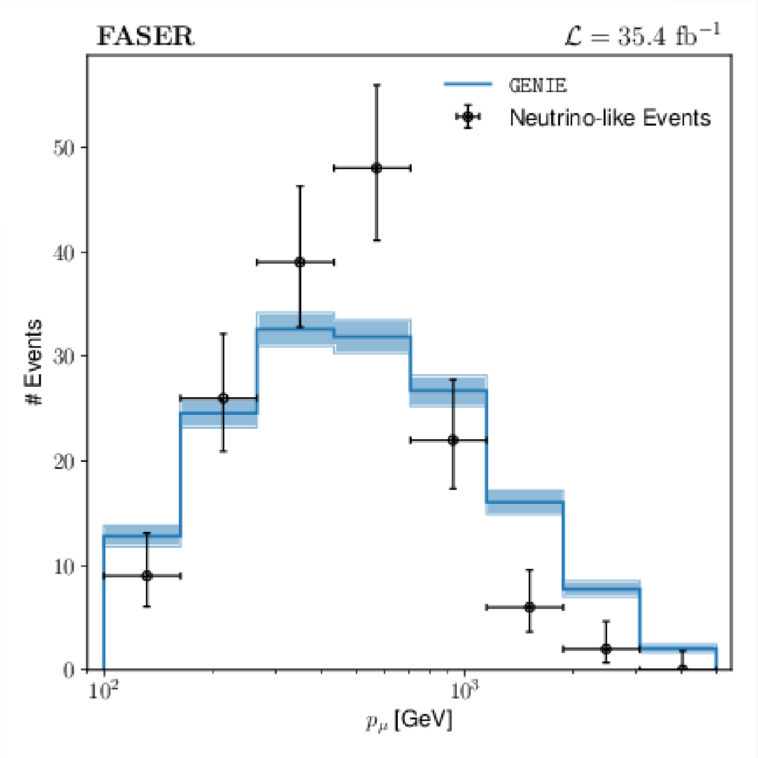
151±41 events
Uncertainty from DPMJET and SIBYLL

First direct observation of collider neutrinos



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



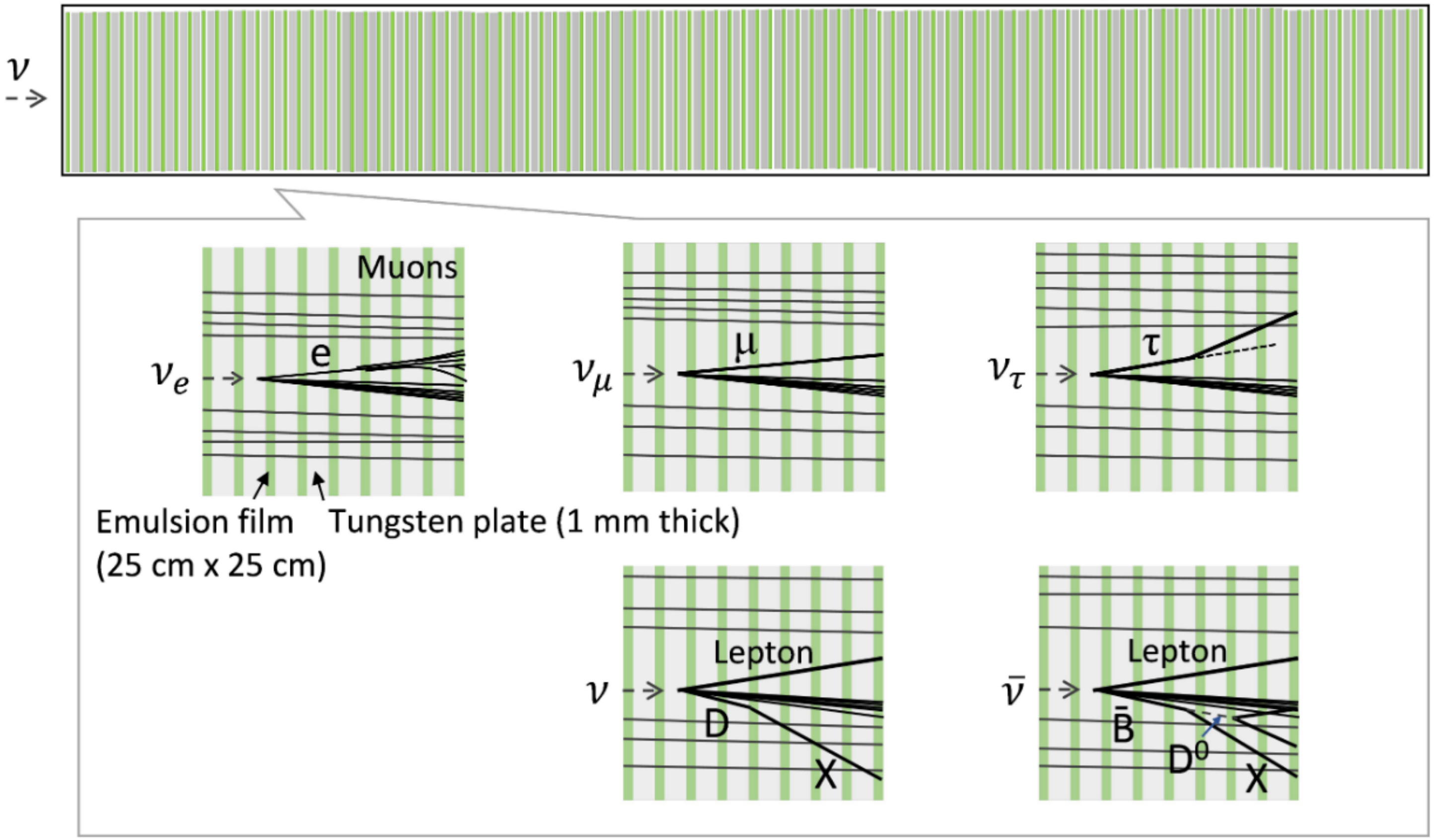


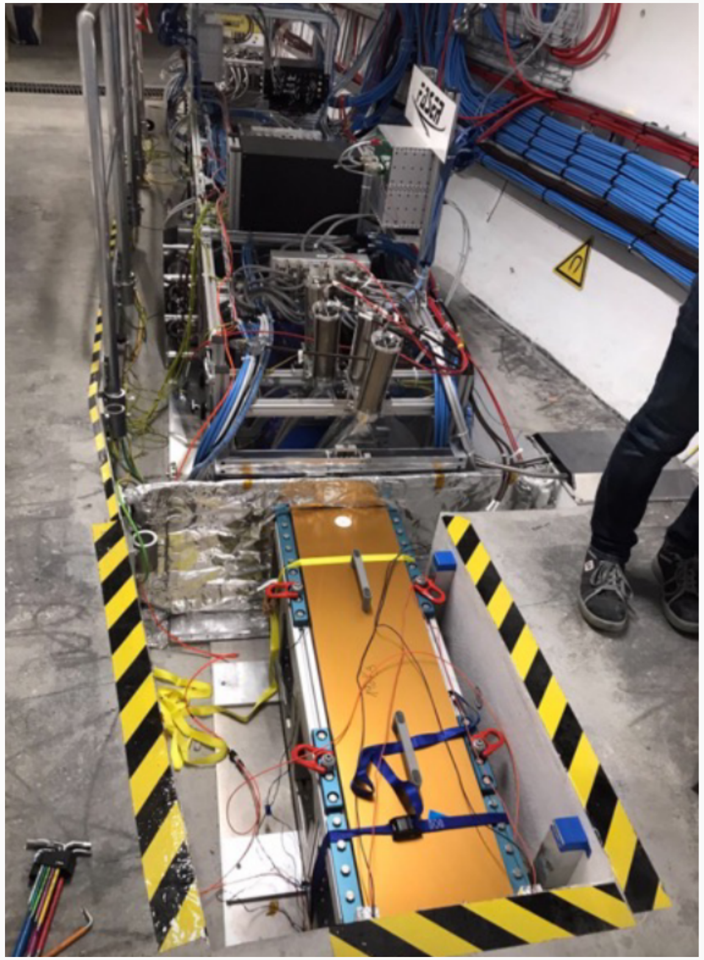
- Observed **153 events** with 0.2 background
- Consistent with prediction: 151 ± 41
- Significance of **16σ**

no systematic uncertainties included

FASERν

- 1m x 30 cm x 25 cm, 1.1 tn
- 730 of 1.1 mm thick tungsten plates interleaved with emulsion films
- Emulsion has excellent space/angular resolution
- Allow to distinguish all neutrino flavours





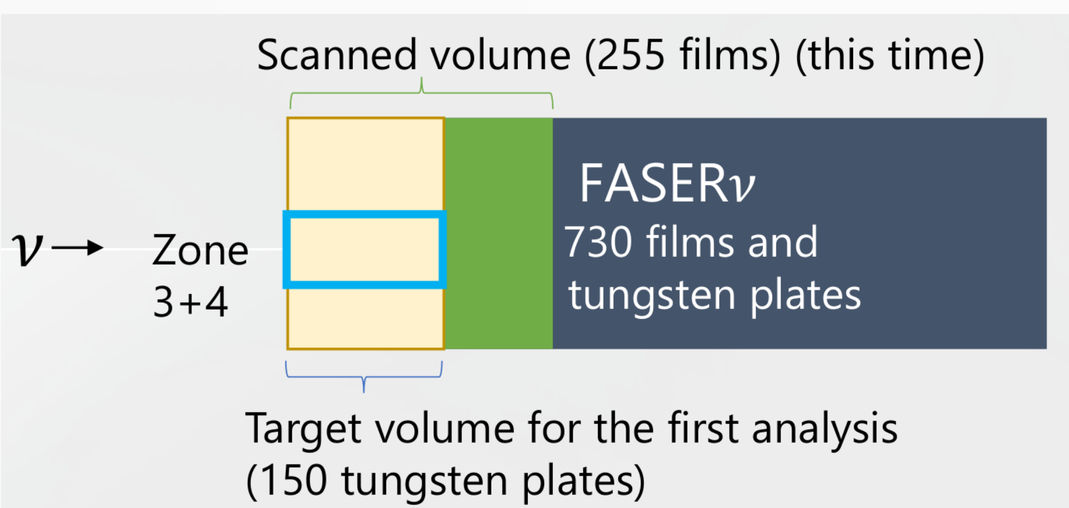
Detector has to be replaced each 30-50 fb^{-1}. Replaced during technical stops during LHC run to have managable track density.

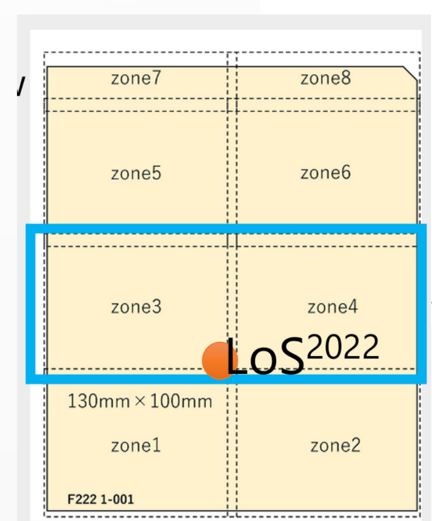
FASERν first data

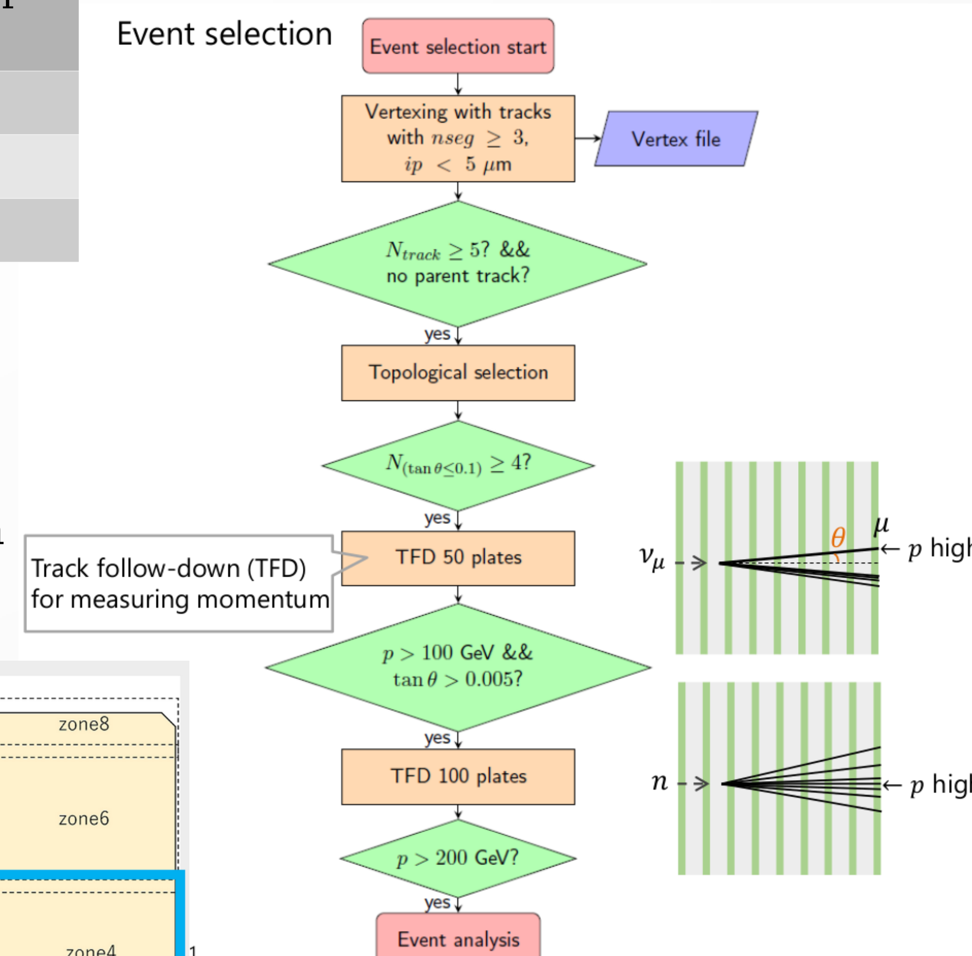
	Installed period	load	Integrated luminosity per module (fb^{-1})
2021 1st module	Mar 15 — Jul 26	• 30%	0.4705
2022 2nd module	**Jul 26 — Sep 13**	• **100%**	**9.523**
2022 3rd module	Sep 13 — Nov 29	• 100%	28.9082

Analysis strategy

- 250/730 films zones 3+4 of 2nd module
- 150 films for vertex reconstruction and 100 films for E/p estimation
- Select ν_e and ν_μ with p_{lep}>200 GeV/c

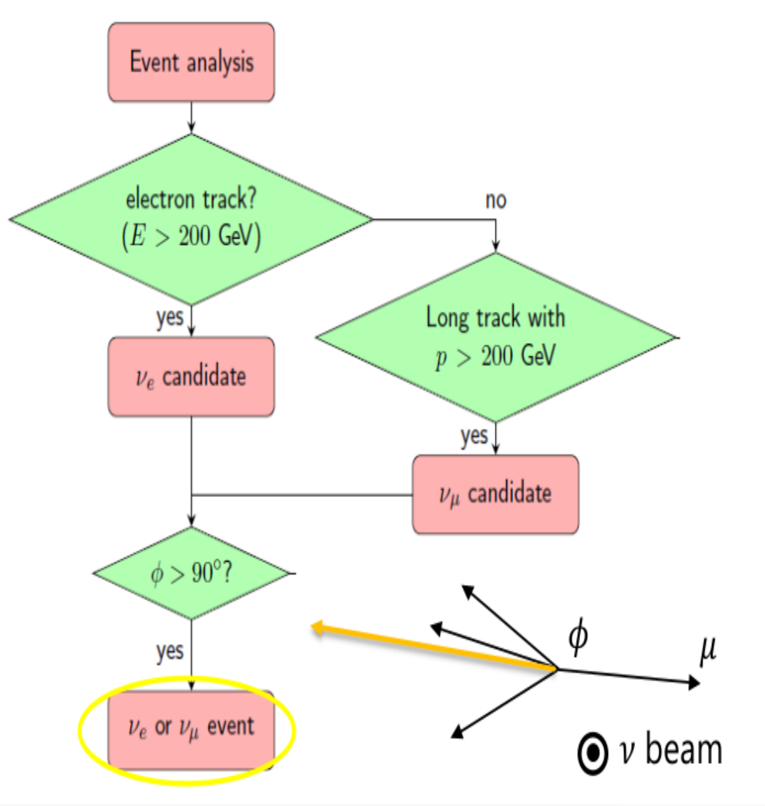






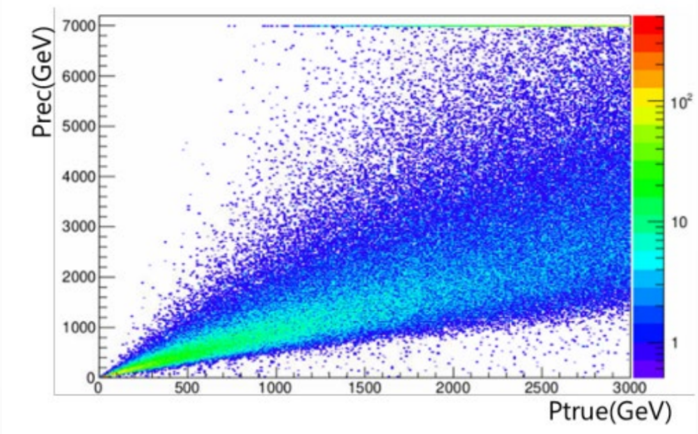
FASERν first data

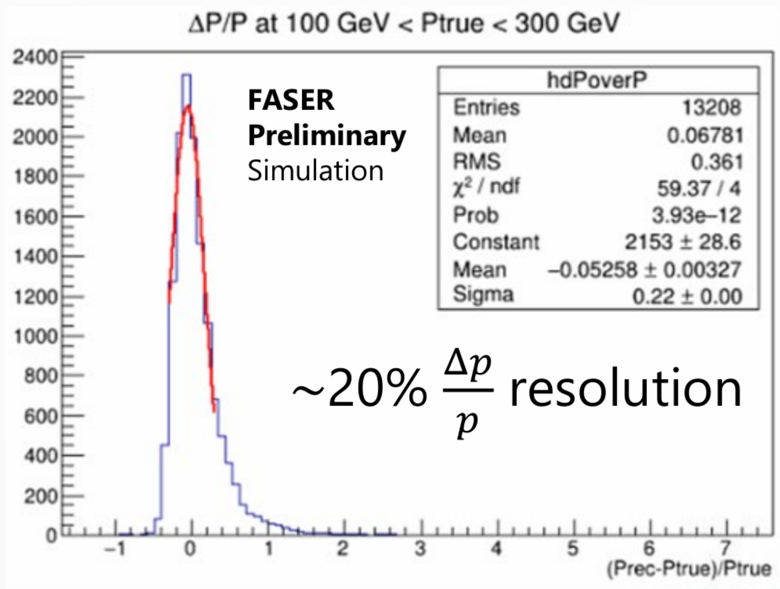
Event classification



Muon momentum

Reconstruction by
measurement of segments positions

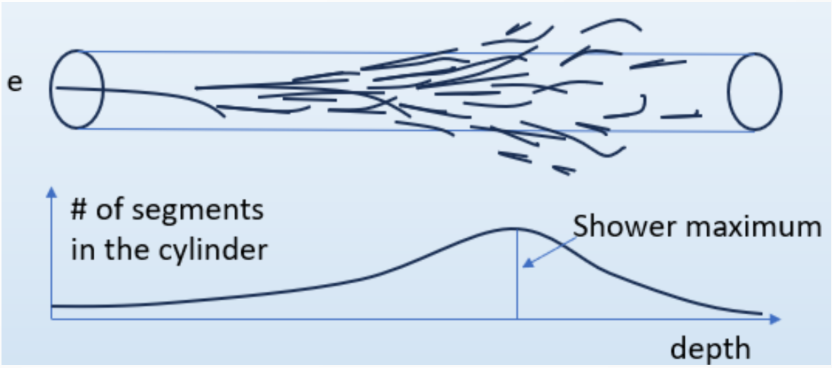


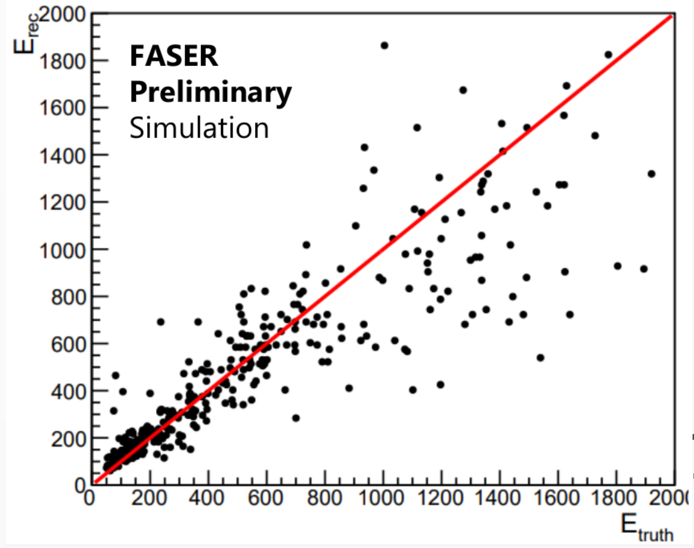


$\sim 20\% \; \frac{\Delta p}{p}$ resolution

Electron energy

Reconstruction by
number of segments around shower maximum Resolution ~25%





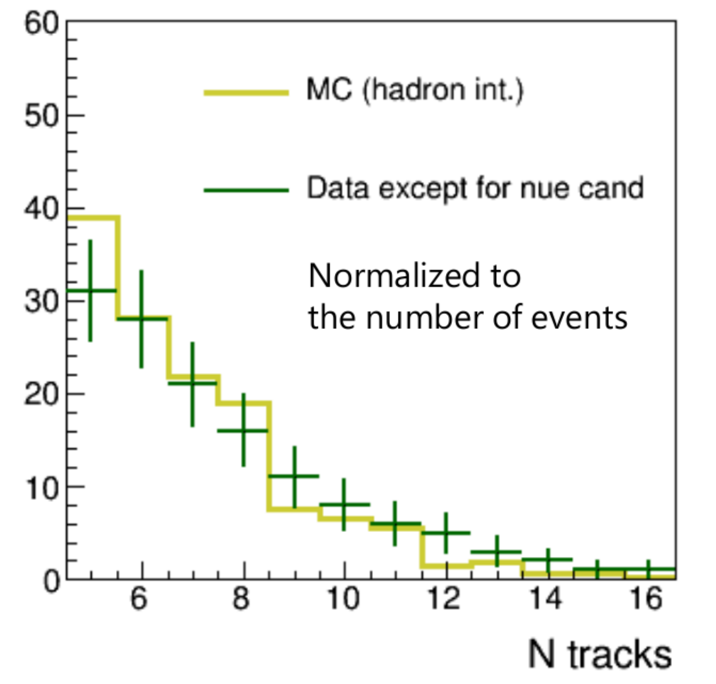
FASERν first data

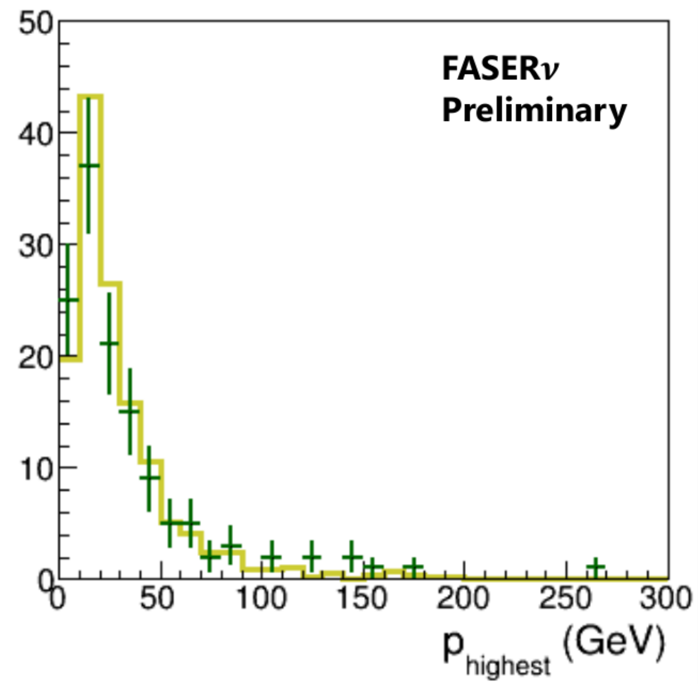
Located verteces sample is dominated by neutral hadron interactions (K_S, K_L, n, Λ) before the high-energy selection.

Expectation from simulation ⟷ **Data**

216 vertices

133 vertices (140 with 7 ν CC candidates)

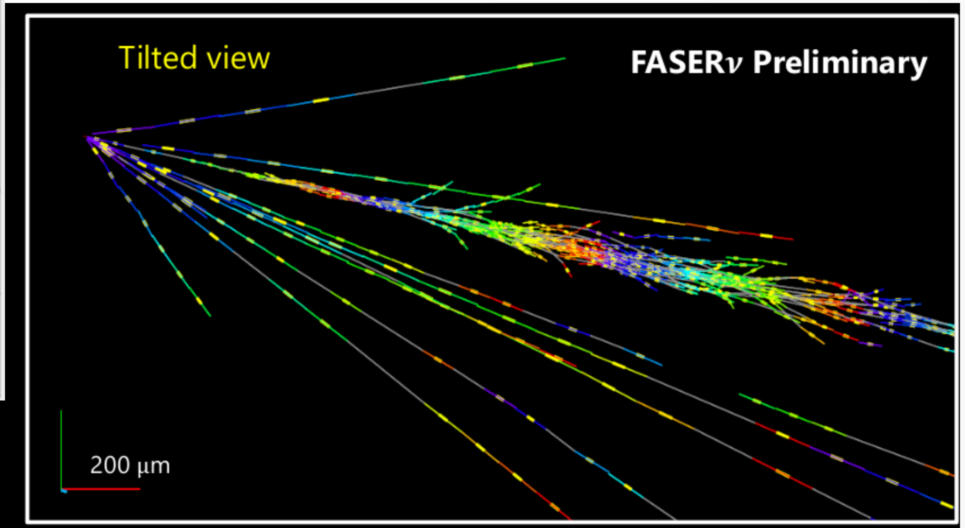


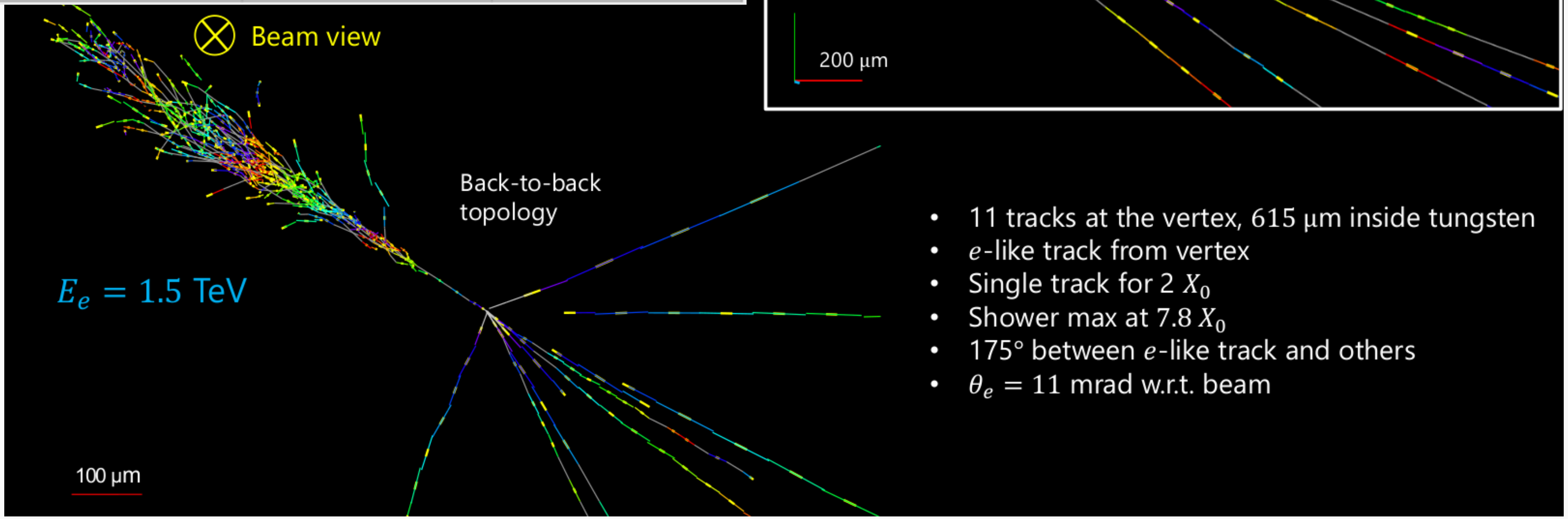


- The event rate in agreement with the expectation within 50% uncertainty.
- Agreement in the parameter distributions
- Validating the background simulation at low energy
- After selection the background estimates with MC samples of individual neutral hadrons (equivalent 20xdata)

FASERν first data

Preliminary	Expected background		Expected signal	Observed
	Hadron int.	ν NC int.		
ν_e CC	0.002±0.002	-	$1.2^{+4.0}_{-0.6}$	3
ν_μ CC	0.32±0.16	0.19±0.15	$4.4^{+4.2}_{-1.4}$	4





3 ν_e CC candidates

→ Probability to be explained by BG is 1.6 x 10^{-7}

→ 5σ exclusion of the background-only hypothesis

First direct observation of ν_e CC interactions at the LHC

Summary

- FASER is successfully taking data in LHC Run3
  - Detector operated well and collected ~37 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
  - More studies are in progress - ALPs, new A' search

arxiv:2308.05587[hep-ex]

- Observed ~153 ν_μ CC interactions at the LHC by electronic detectors
  - **First direct detection of collider neutrinos!**
  - Opens new window for high-energy ν studies

10.1103/PhysRevLett.131.031801

- New results on neutrinos from FASERν distinguishing ν_e CC and ν_μ CC interaction candidate
  - **First direct detection of ν_e CC at the LHC at the highest energy ever observed**
  - More measurements to come including high energy ν_τ, cross sections measurement

FASER and FASERν are supported by:

Thank you for attention!

CERN
UNIVERSITÉ DE GENÈVE
KYUSHU UNIVERSITY
UC IRVINE
UNIVERSITÄT BERN
Technion Israel Institute of Technology
NAGOYA UNIVERSITY
UNIVERSITY of WASHINGTON
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UNIVERSITY OF LIVERPOOL
CHIBA UNIVERSITY
US UNIVERSITY OF SUSSEX
DESY.
JINR

BACKUP SLIDES

References

1. Search for Dark Photons with the FASER detector at the LHC arXiv:2308.05587[hep-ex]
2. First Direct Observation of Collider Neutrinos with FASER at the LHC
   Physical Review Letters and arXiv:2303.14285v2[hep-ex]
3. The FASER Detector arXiv: 2207.11427
4. The FASER W-Si High Precision Preshower Technical Proposal CERN document server
5. The tracking detector of the FASER experiment NIMA 166825 (2022) and arXiv: 2112.01116
6. The trigger and data acquisition system of the FASER experiment
   Journal of Instrumentation and arXiv: 2110.15186
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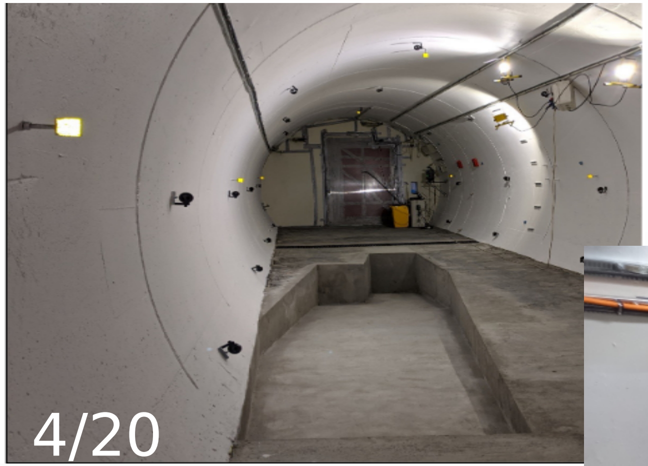
8. Technical Proposal of FASERν neutrino detector CERN document server and arXiv: 2001.03073
9. Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC
   European Physical Journal C and arXiv: 1908.02310
10. FASER's Physics Reach for Long-Lived Particles Physical Review D and arXiv: 1811.12522
11. Technical Proposal CERN document server and arXiv: 1812.09139
12. Letter of Intent CERN document server and arXiv: 1811.10243

Further FPF references: https://pbc.web.cern.ch/fpf-resources

Detector installation



The floor was lower ~ 45 cm at the front of detector to install detector along the beam collosion axis

FASER was installed into TI12 in March 2021 and started cosmic data taking

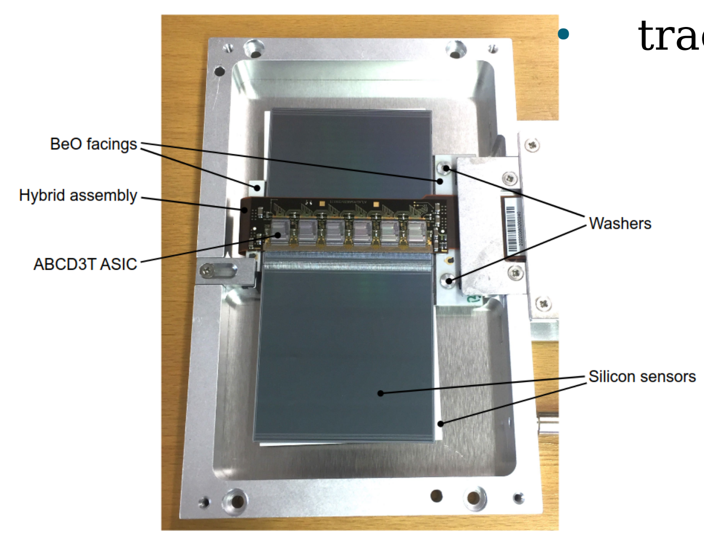
Physics data taking started in July 2022

37 fb^{-1} of the data has been collected in 2022

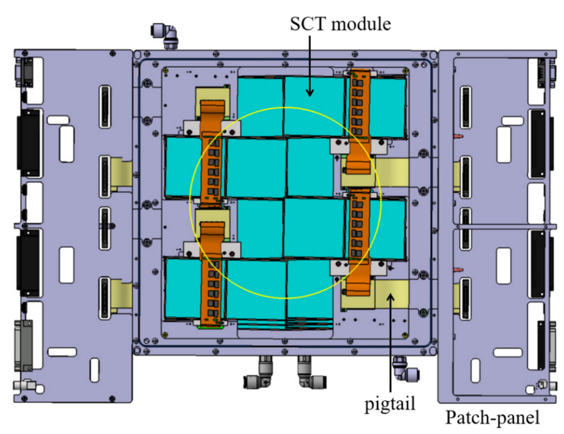
In 2023 another ~30 fb^{-1} of the data

Tracker spectrometer and IFT

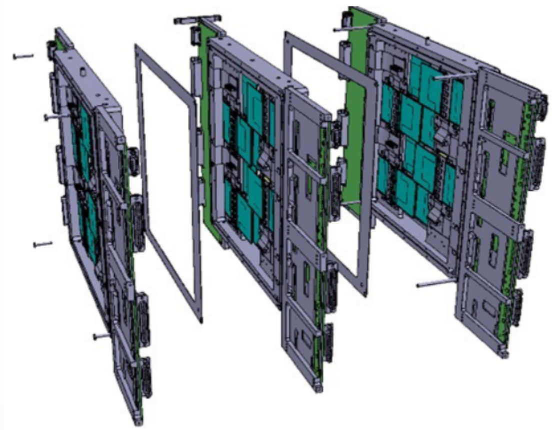
- tracking spectrometer (3 tracking stations) + IFT (1 tracking station) after FASERν



SCT Module



Tracker Plane



Tracker Station

NIMA 166825 (2022)

Component	Material	Number / station	X_0 (%) Central region	X_0 (%) Edge region
Silicon sensor	Si	6	1.8%	1.8%
Station Covers	CFRP	2	0.3%	0.3%
SCT module support	TPG	3	-	0.6%
C-C Hybrid	C (based)	3	-	2.2%
ABCD chips	Si	3	-	6.5%
Layer frame	Al	3	-	10.1%
Total / station	-	-	**2.1%**	**21.5%**

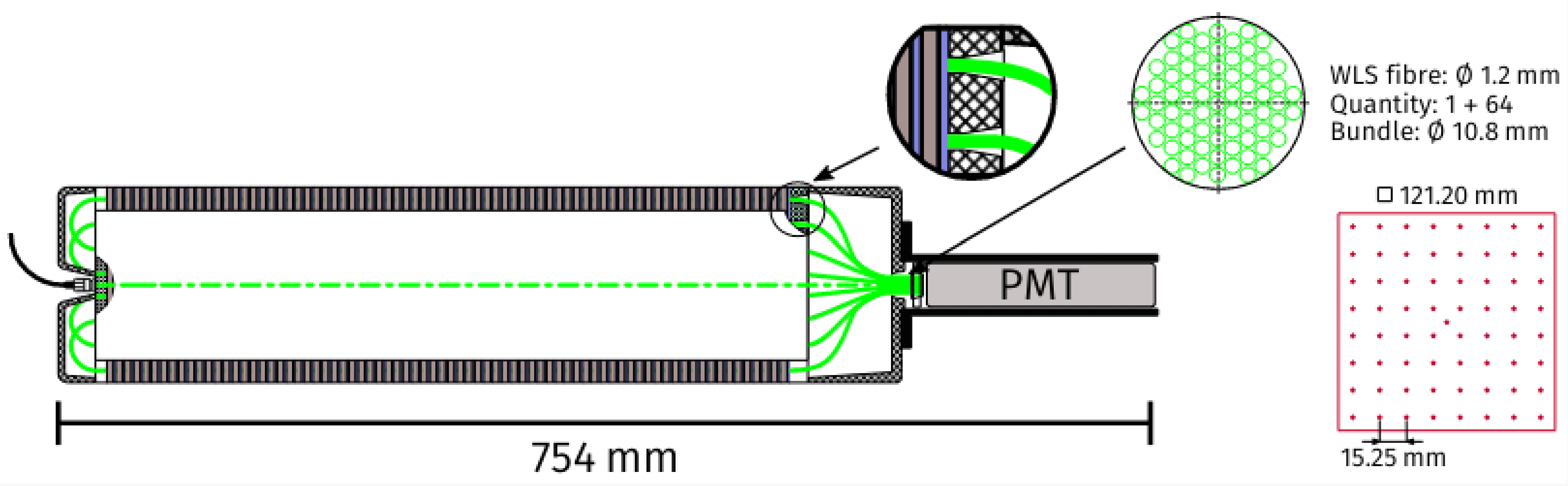
- The total number of dead channels was measured ~0.5%

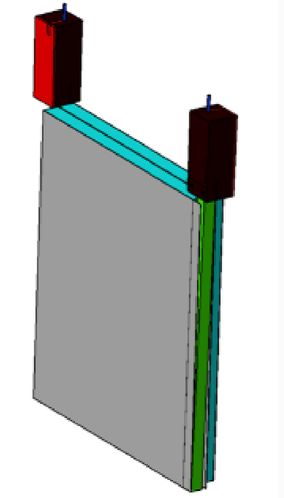
- Hit efficiency above 99.8% was confirmed in the 2021 test beam at the H2 beamline at the CERN-SPS

Calorimeter and scintillators

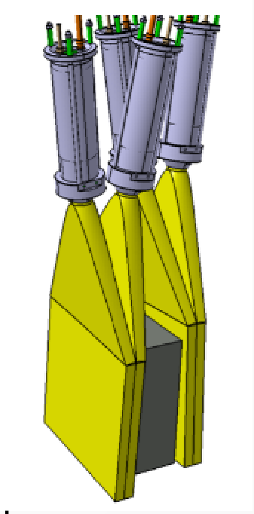
- 4 scintillator stations with multiple layers per each station
  - Data driven veto efficiency measurement. Each scintillator efficiency >99.99%
  - Efficiency of 4 scintillator combined veto O(10^8) muons expected in Run 3

- EM calorimeter made of spare LHCb modules
  - 66 layers of lead-scintillator plates read by 2x2 array of PMTs
  - Calorimeter readout optimised to measure multi-TeV deposits w/o saturation

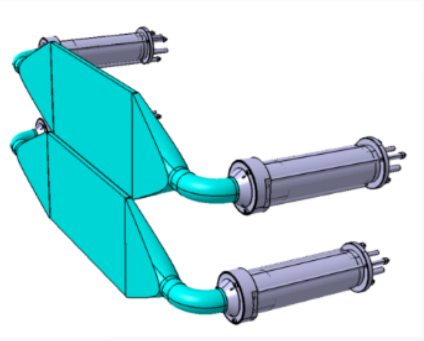




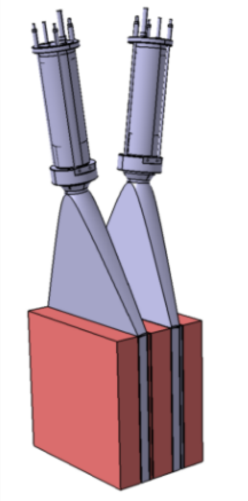
(a) FASERν veto



(b) Veto



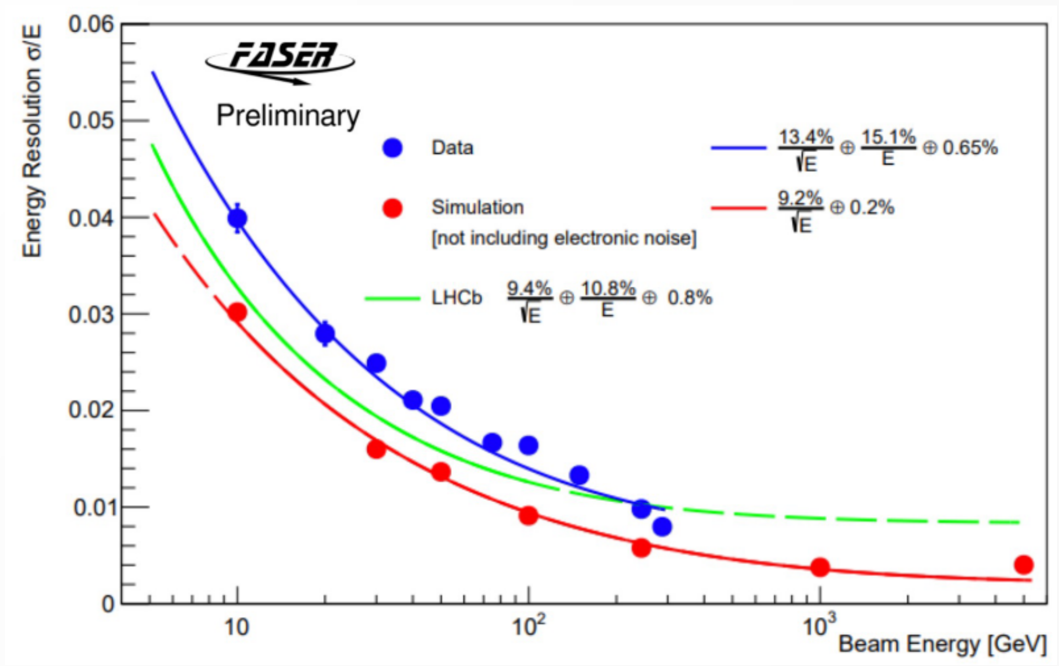
(c) Timing

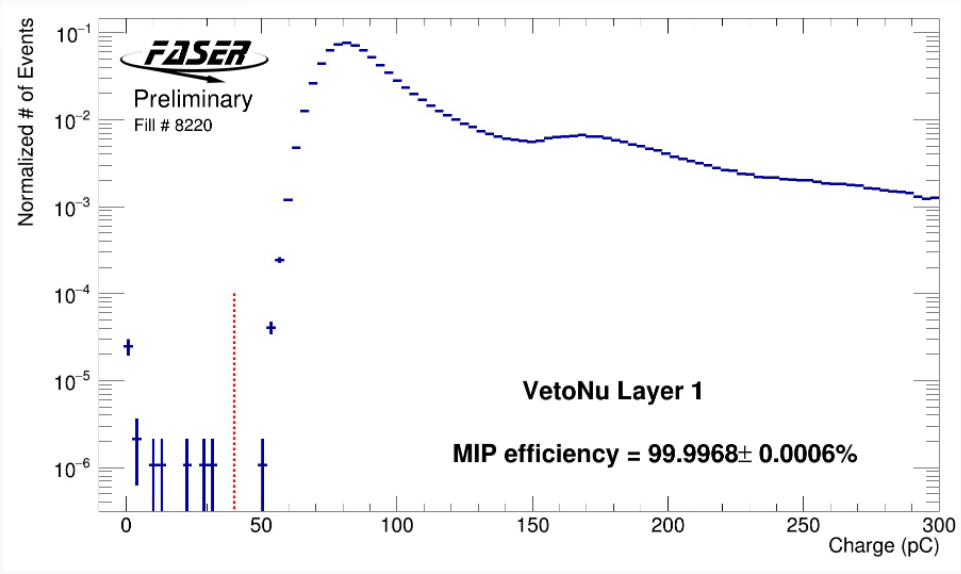


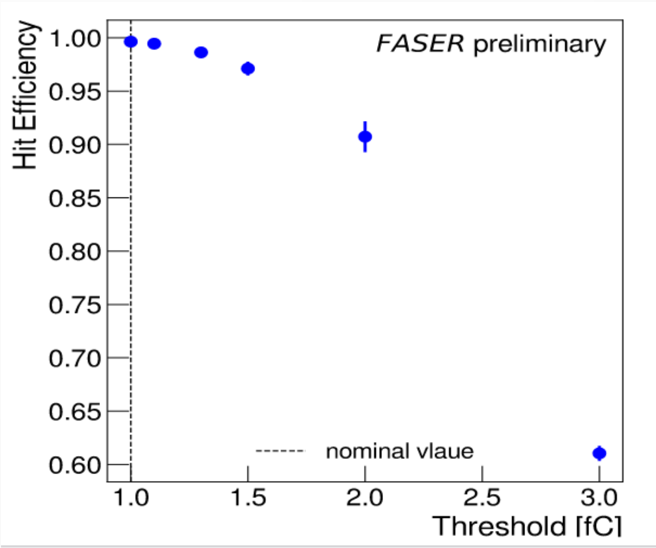
(d) Preshower

FASER detector performance

- Data driven veto efficiency measurement. Each scintillator efficiency >99.99%
- Efficiency of 4 scintillator combined veto O(10^8) muons expected in Run 3
- Calorimeter energy resolution measured with electrons in test beam – as expected resolution O(1%) at high energy.
- Tracker hit efficiency measured in data to be >99.6% as expected



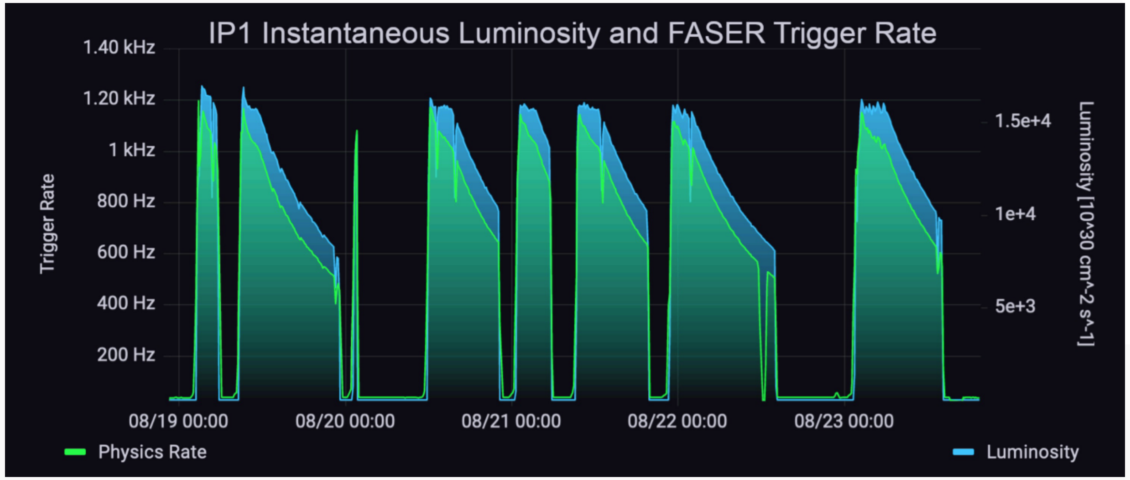


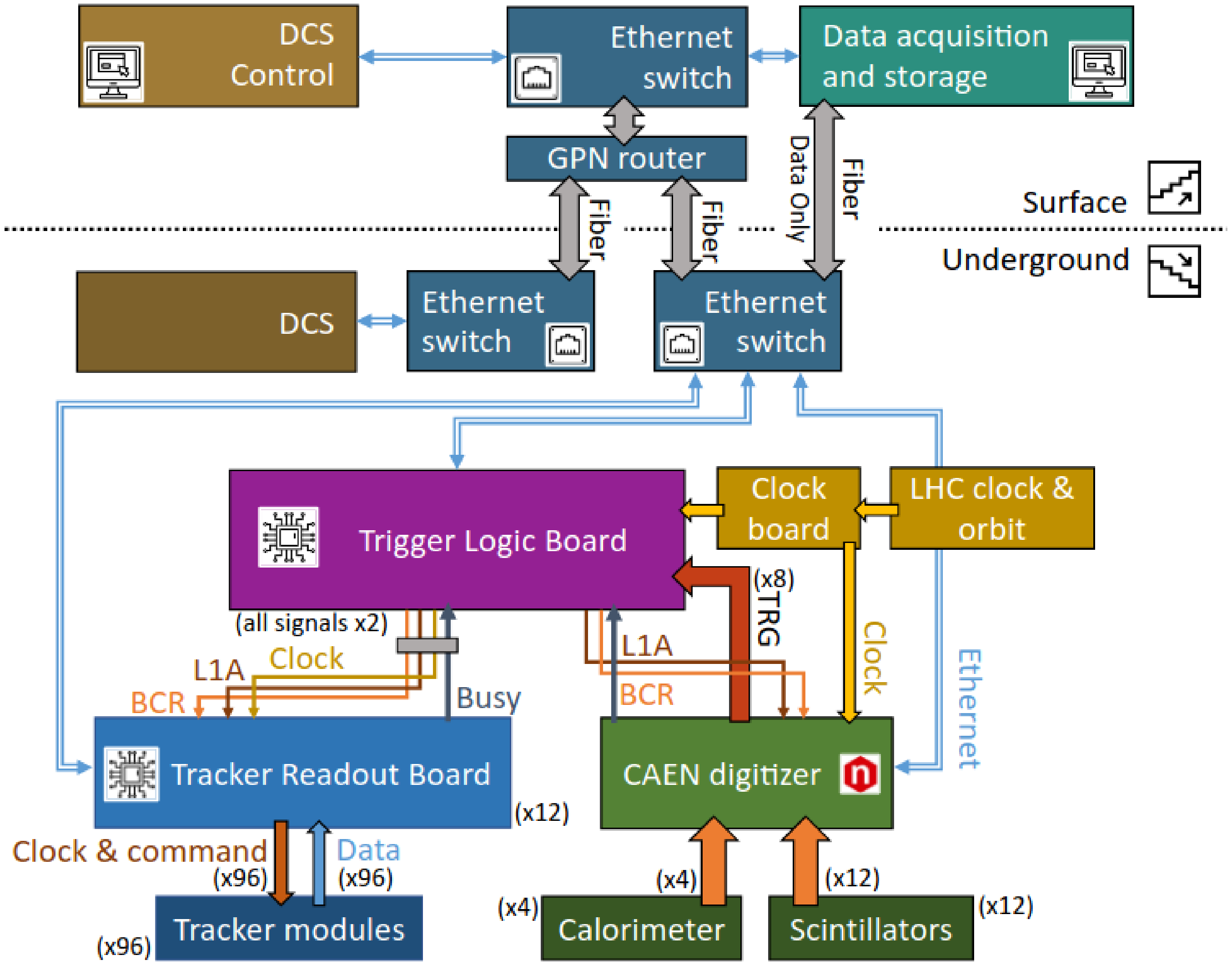


Trigger and DAQ

The maximum trigger rate is ~1.2kHz (nearly 2x the expectation)

- Trigger signal provided by PMTs from scintillators and calorimeter
- Trigger system run synchronously to the 40.8 MHz LHC clock
- DAQ: configuration and readout
- Monitoring: check data flow, detector conditions, data quality





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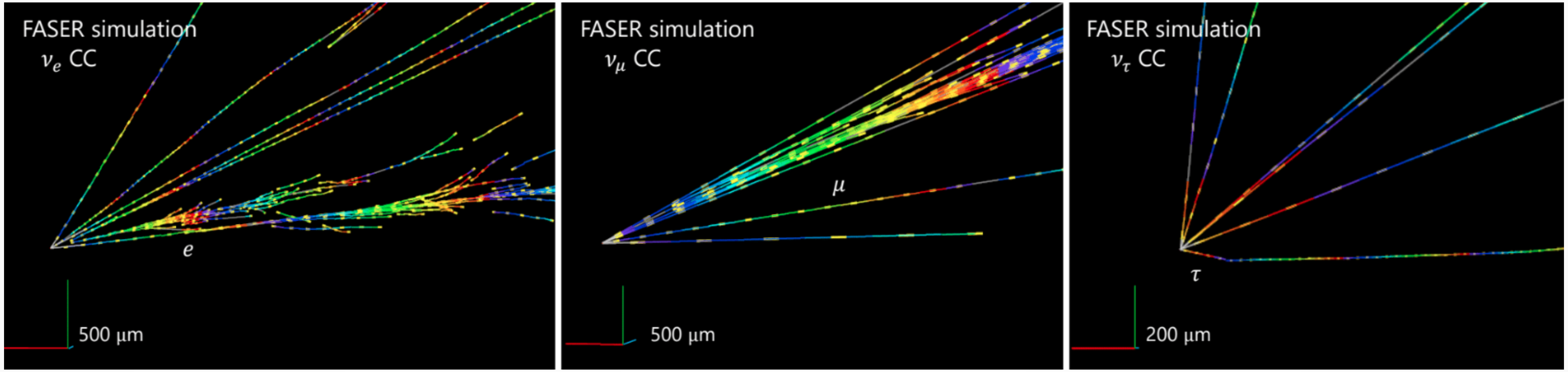
FASERν simulation



Yellow line segments show the trajectories of charged particles in the emulsion films. The other colored lines are interpolations, and the colors change depending on the depth in the detector.

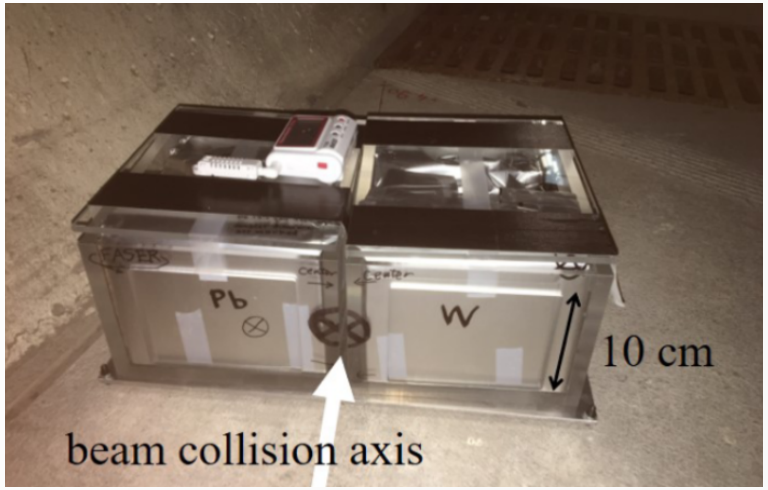
Generators		FASERν			SND@LHC		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	1501	7971	24.5	223	1316	12.6
DPMJET	DPMJET	5761	11813	161	658	1723	31
EPOSLHC	Pythia8 (Hard)	2521	9841	57	445	1871	19.2
QGSJET	Pythia8 (Soft)	1616	8918	26.8	308	1691	12
Combination (all)		2850^{+2910}_{-1348}	9636^{+2176}_{-1663}	67.5^{+94}_{-43}	408^{+248}_{-185}	1651^{+220}_{-333}	$18.8^{+12}_{-6.6}$
Combination (w/o DPMJET)		1880^{+641}_{-378}	8910^{+930}_{-938}	$36^{+20.8}_{-11.5}$	325^{+118}_{-101}	1626^{+243}_{-308}	$14.6^{+4.5}_{-2.5}$

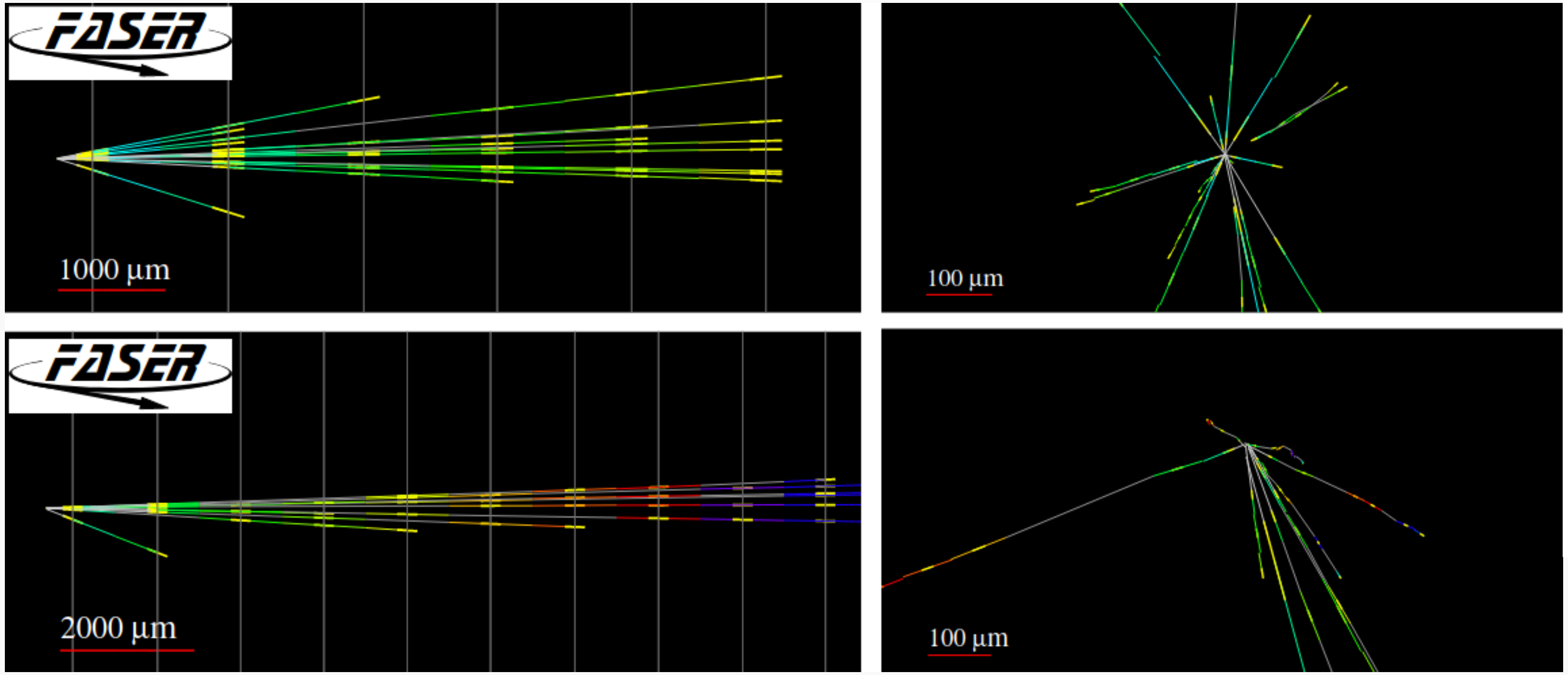
Expected number of CC neutrino interaction events occurring in FASERν and SND@LHC during LHC Run 3 with 250 fb^{-1} integrated luminosity. Predictions from different MC generators are provided.

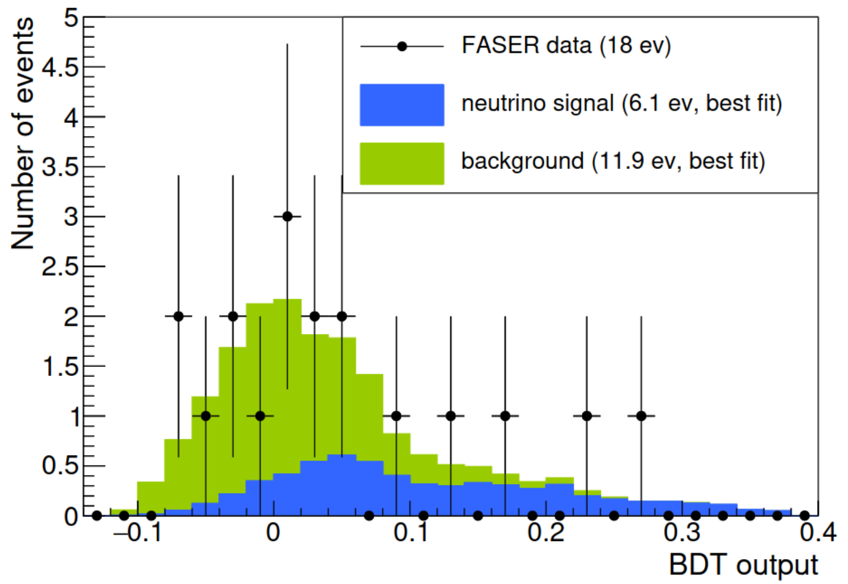
Test Beam 2018

- Pilot neutrino detector with 10 kg target was exposed in FASER location during 2018 LHC run to validate background simulation
- 12.2 fb^{-1} data collected during ~1 month, 18 neutral vertices are found
- BDT is used for signal/background separation. Best fit value of 6.1 neutrino interactions (3.3 expected) at 2.7 σ significance

First candidate collider neutrino interactions!







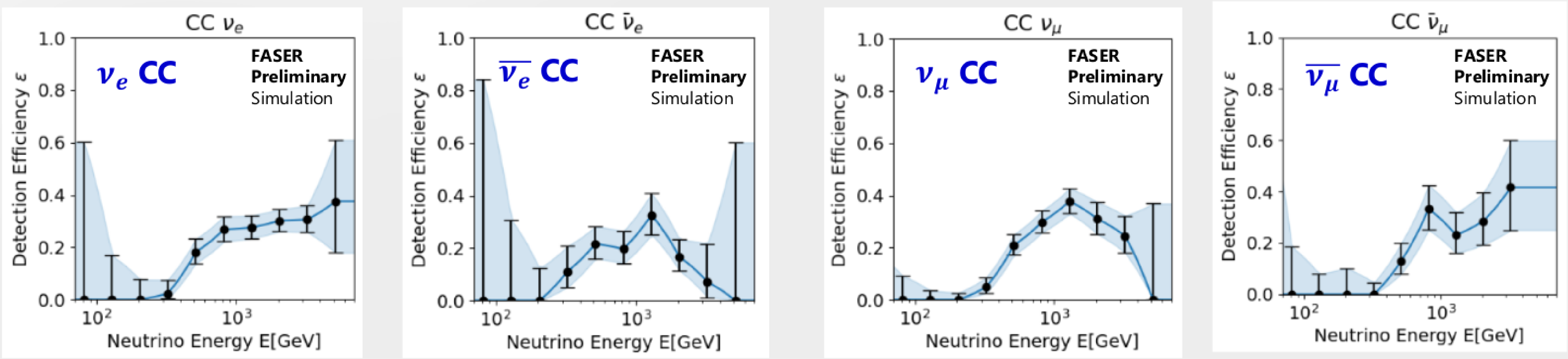
PRD.104.L091101 (2021)

FASERν: efficiencies

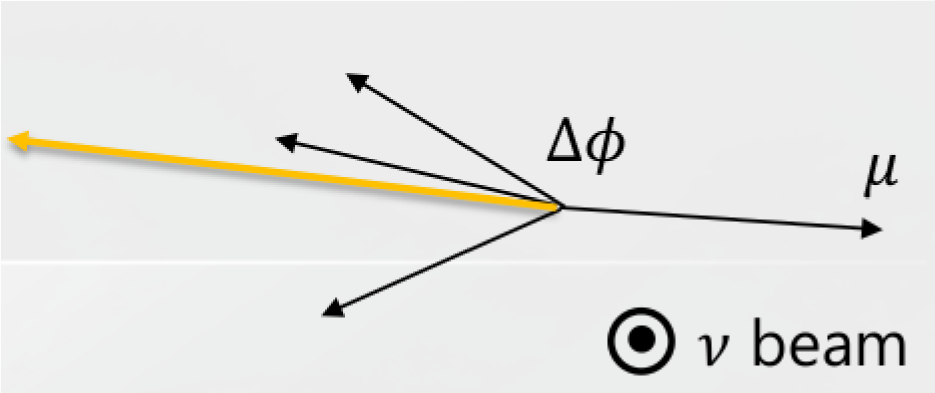
Breakdown of the efficiencies

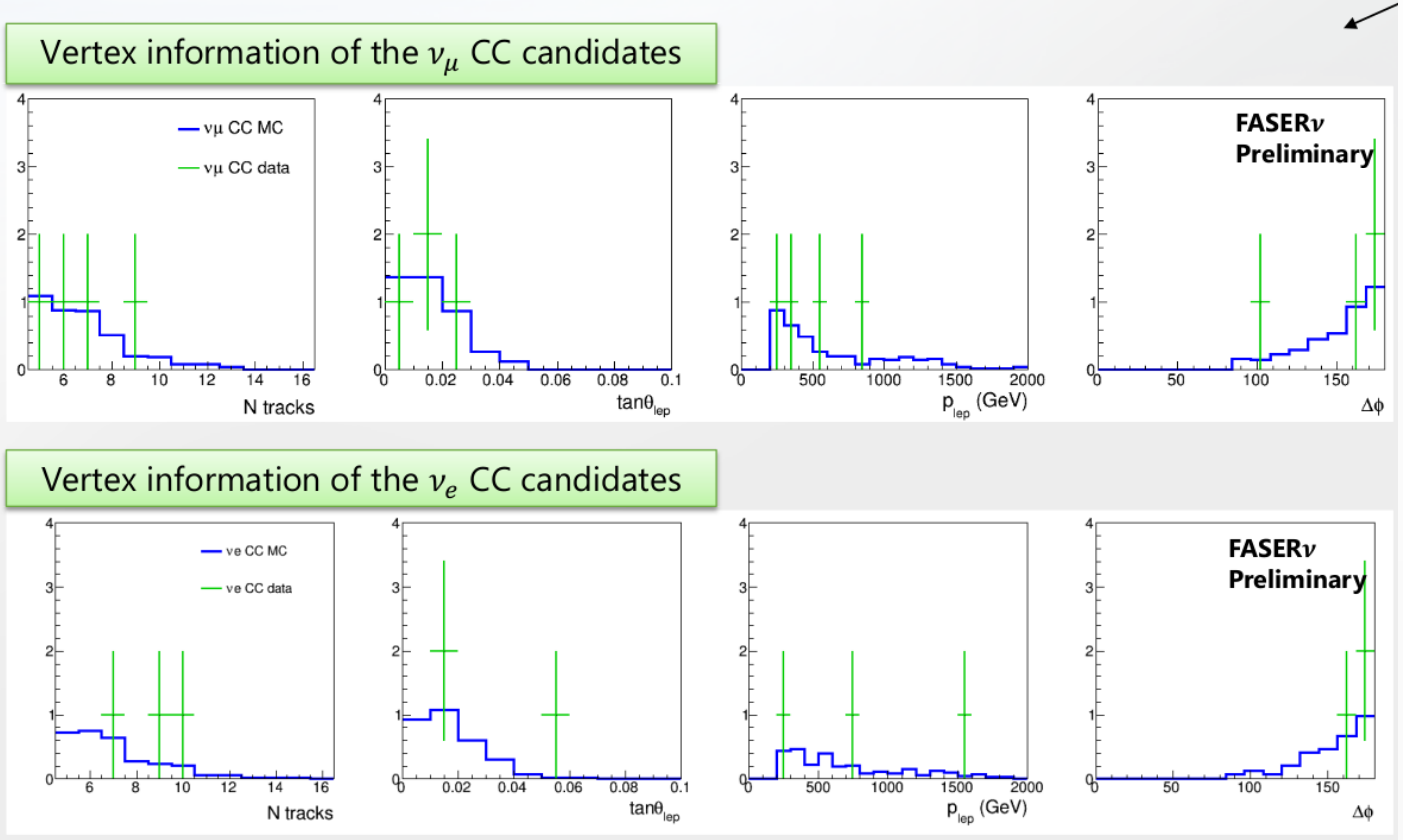
Selection	ν_e CC	ν NC	K_L	n	Λ
	1.000	1.000	1.000	1.000	1.000
Vertex reconstruction	0.516	0.336	0.813	0.803	0.753
E >200 GeV	0.340	0.001	0.000	0.000	0.000
E >200 GeV, tanθ >0.005	0.270	0.001	0.000	0.000	0.000
E >200 GeV, tanθ >0.005. $\Delta\phi$>90deg	0.226	0.000	0.000	0.000	0.000

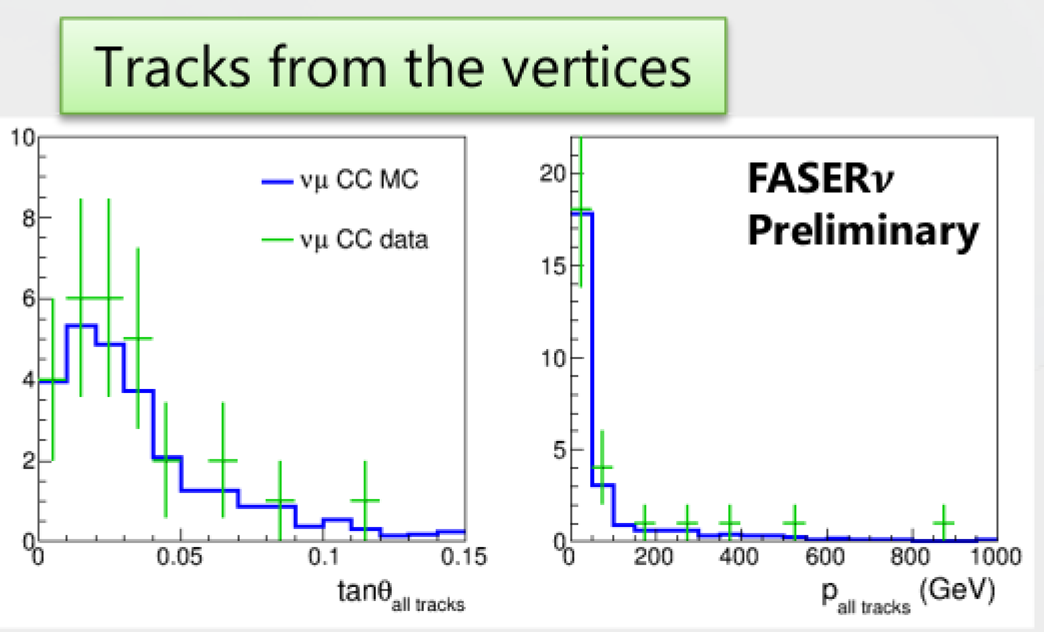
Selection	ν_μ CC	ν NC	K_L	n	Λ
	1.000	1.000	1.000	1.000	1.000
Vertex reconstruction	0.446	0.336	0.813	0.803	0.753
p >200 GeV	0.284	0.071	0.028	0.026	0.018
p >200 GeV, tanθ >0.005	0.236	0.051	0.007	0.013	0.007
p >200 GeV, tanθ >0.005. $\Delta\phi$>90deg	0.192	0.004	0.002	0.006	0.004



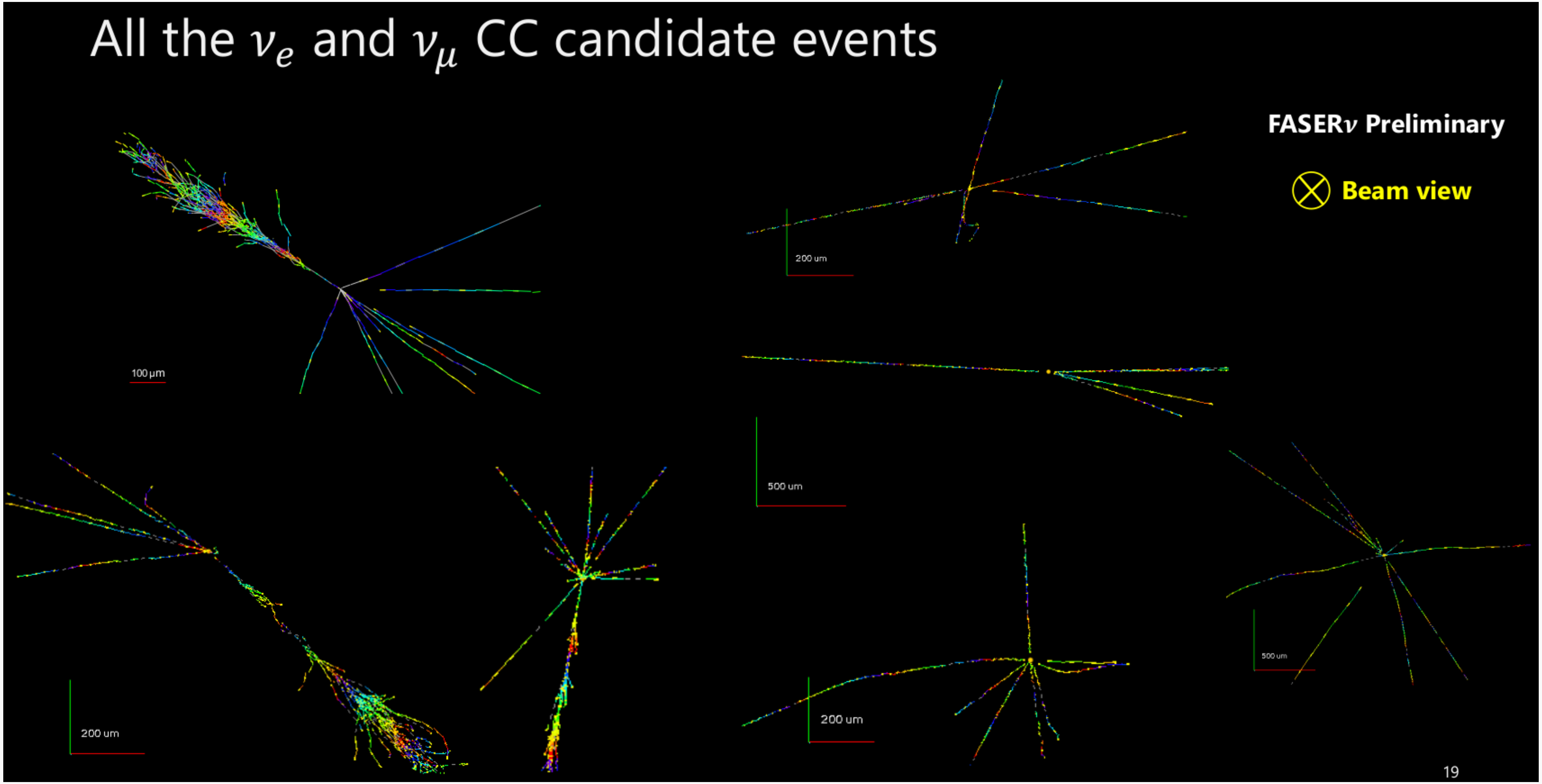
FASERν: data/MC comparison





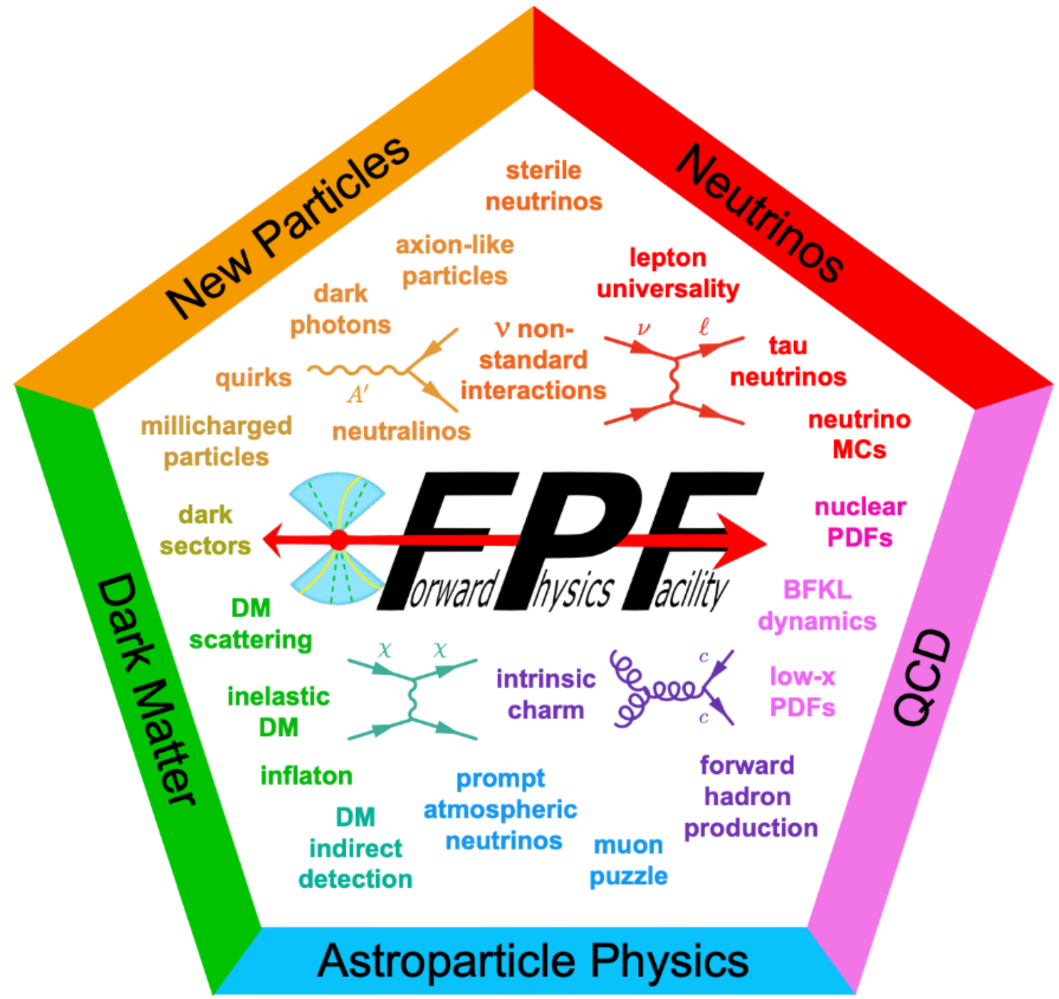


FASERν neutrino candidates



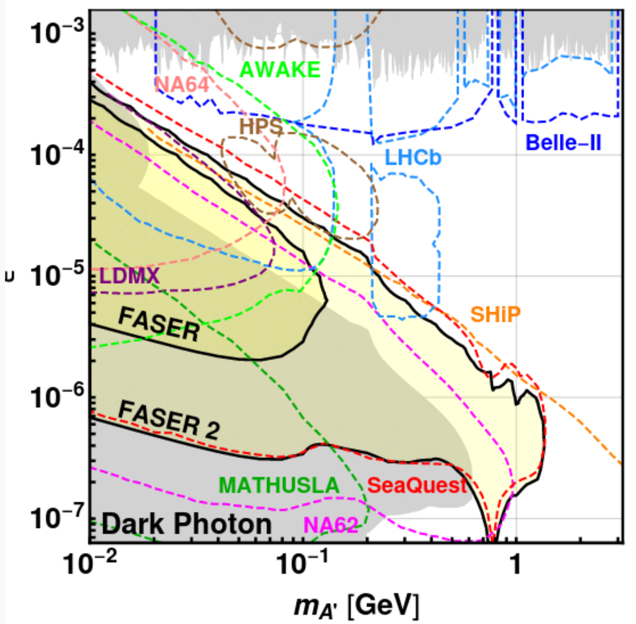
FPF

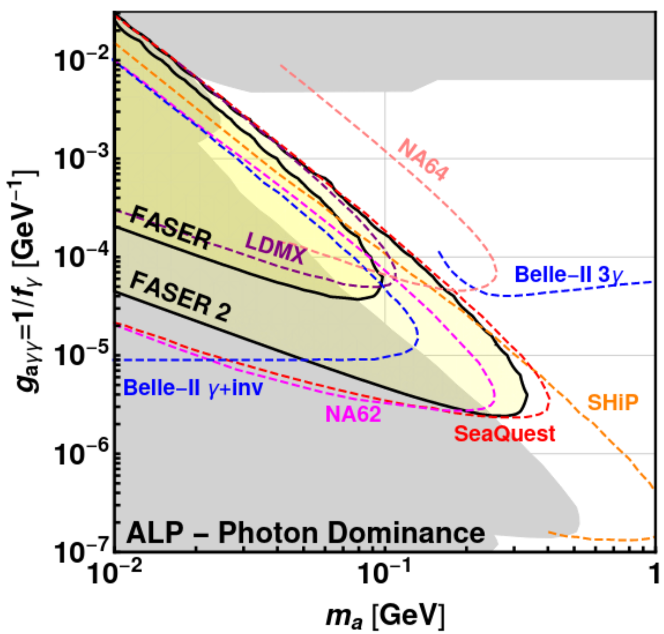
- In order to take maximum advantage of the physics in the very forward region of the LHC collisions in the HL-LHC era we need to increase the experimental capabilities
- The FASER location does not allow to install new or larger detectors on the LOS
- The Forward Physics Facility (FPF) is a proposal to create a new facility to enable a suite of new experiments to be situated on the LOS
- FTF motivations: BSM «dark sector» search, neutrino physics, QCD physics
- O(10^6) mu,O(10^5) electron and O(10^3) tau neutrino interactions expected in O(10tn) detector



arXiv:2203.05090

FASER2 vs FASER





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	—	√