First Results from FASER at the LHC

XVIth Quark Confinement and the Hadron Spectrum (QCHSC2024)

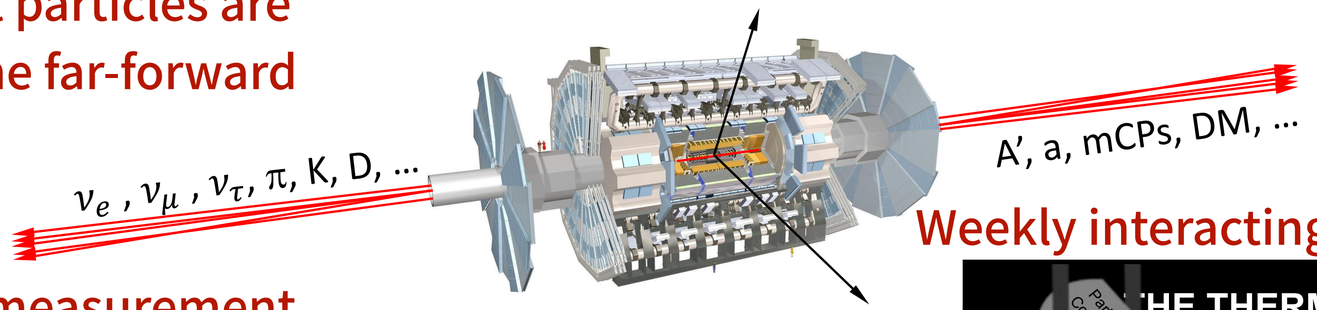
Daiki Hayakawa (Chiba University) on behalf of the FASER collaboration

Introduction

The existing collider detectors (e.g. ATLAS) were designed to find <u>strongly interacting heavy particles</u>

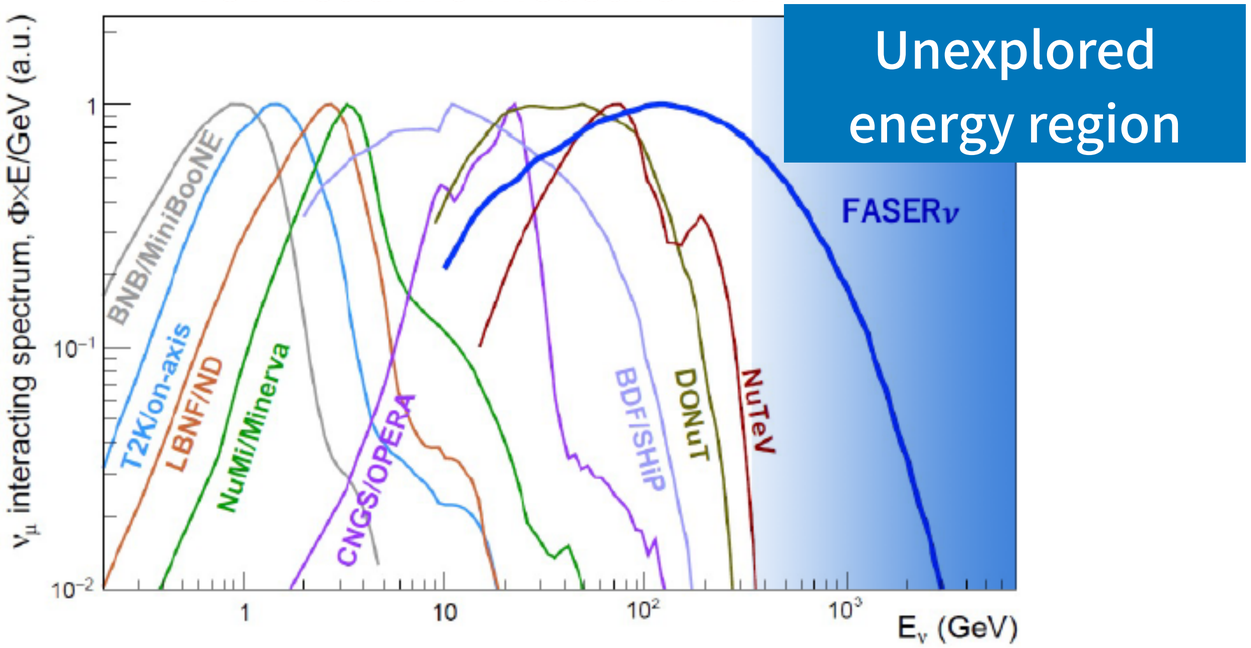
SUSY, top, Higgs, …

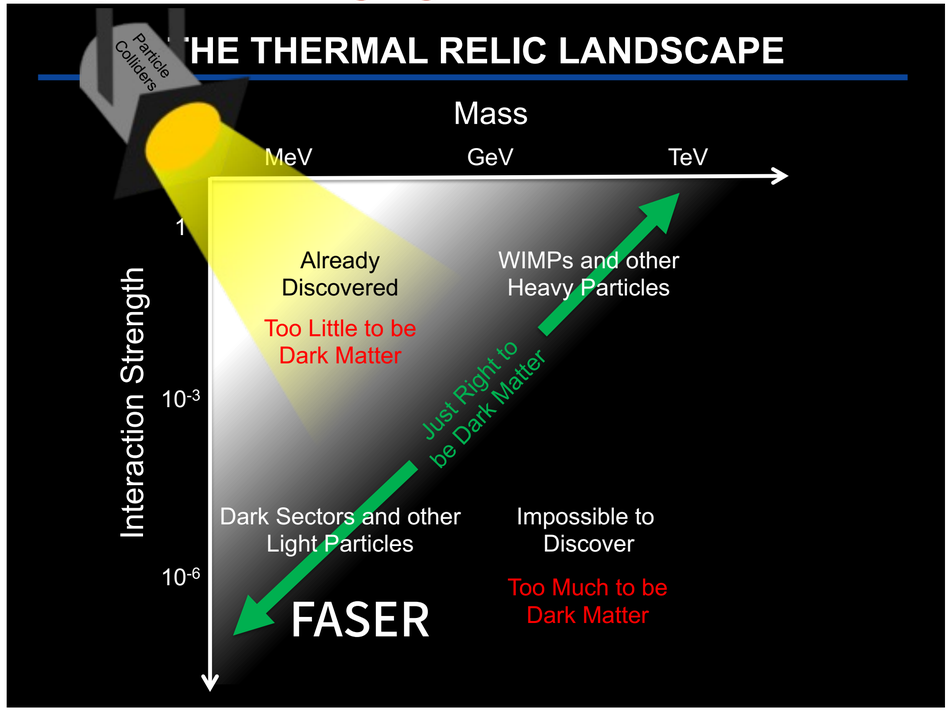
Energetic light particles are produced in the far-forward direction



Weekly interacting light particles (BSM) search

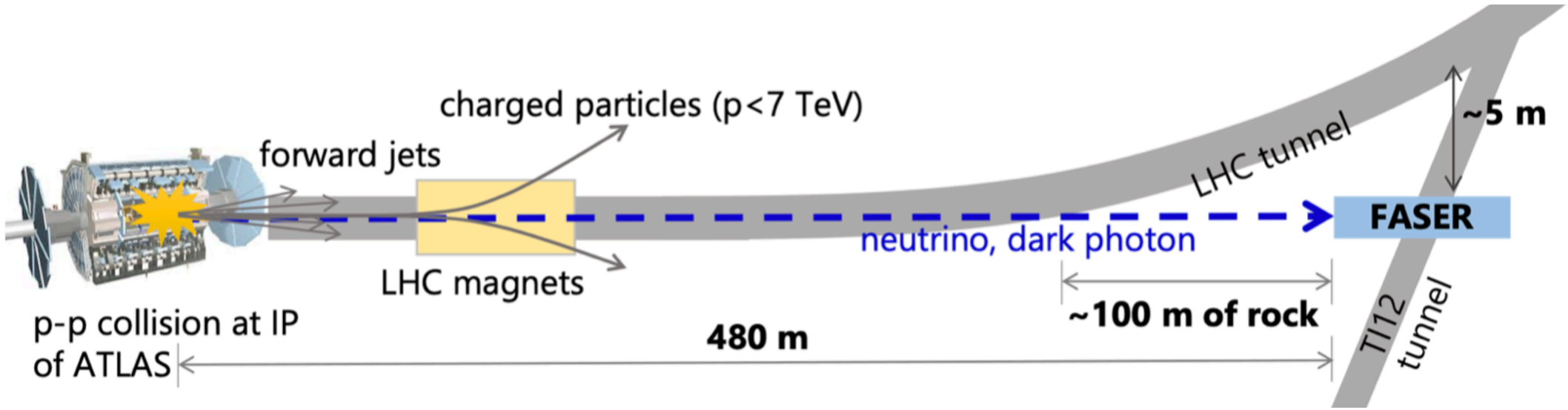
TeV neutrino measurement





There is a rich and unexplored physics program in the far forward direction!

The FASER Experiment



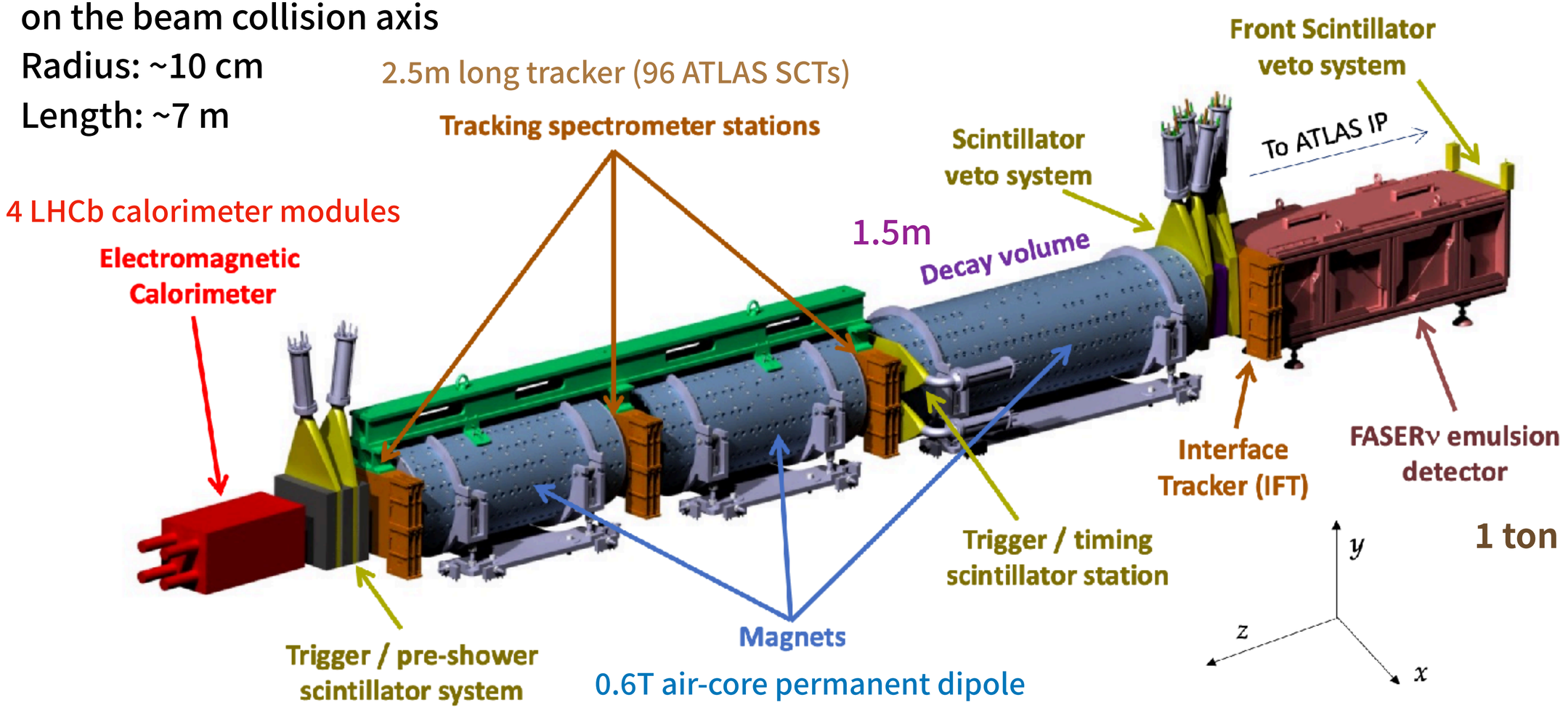
- **Large Hadron Collider (LHC)**: 27 km ring collider, 13.6 TeV proton-proton collisions
- Energetic particles (π, K, D, etc) produced in the **far-forward direction** of the collisions
- **FASER**(**F**orw**A**rd **S**earch **E**xpe**R**iment) is a new experiment at the LHC
  to search for long-lived BSM particles (dark photon, axion-like-particles)
  and study **TeV neutrinos**

FASER at TI12 Tunnel

FASER Detector

JINST 19 (2024), P05066

on the beam collision axis
Radius: ~10 cm
Length: ~7 m

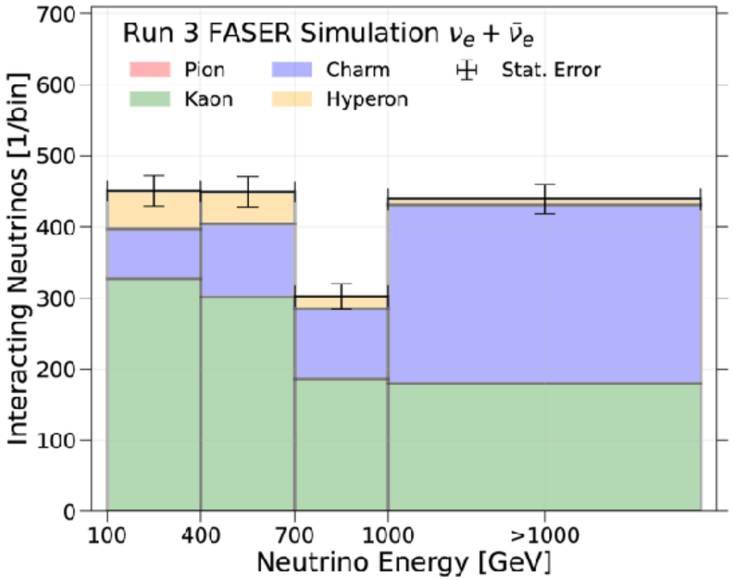


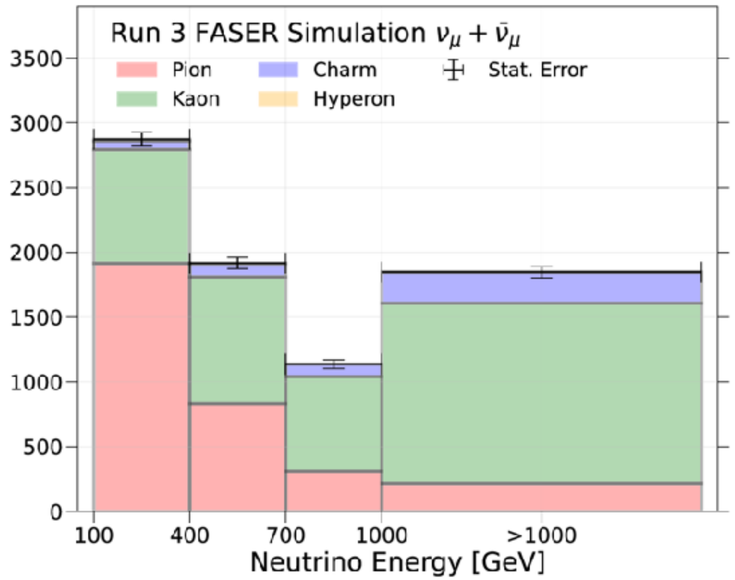
Scintillators for veto, trigger, and preshower (particle ID)

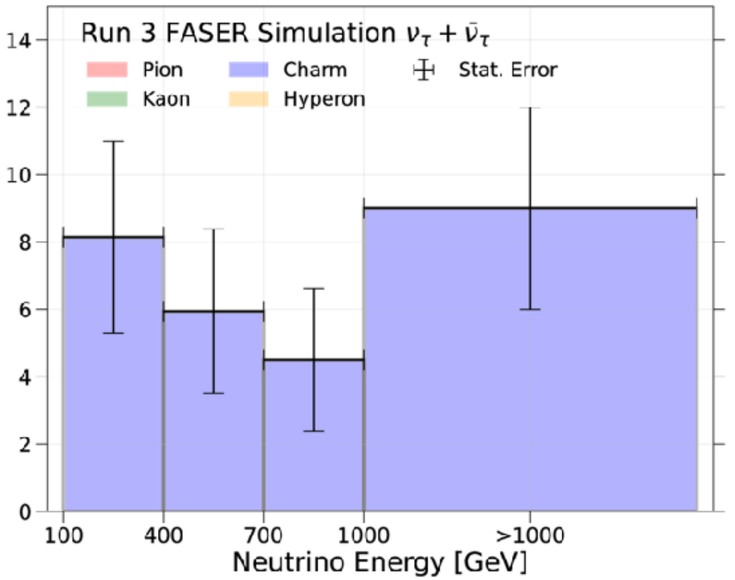
FASERν

Phys. Rev. D 110, 012009

FASERν Expected Number of Interactions







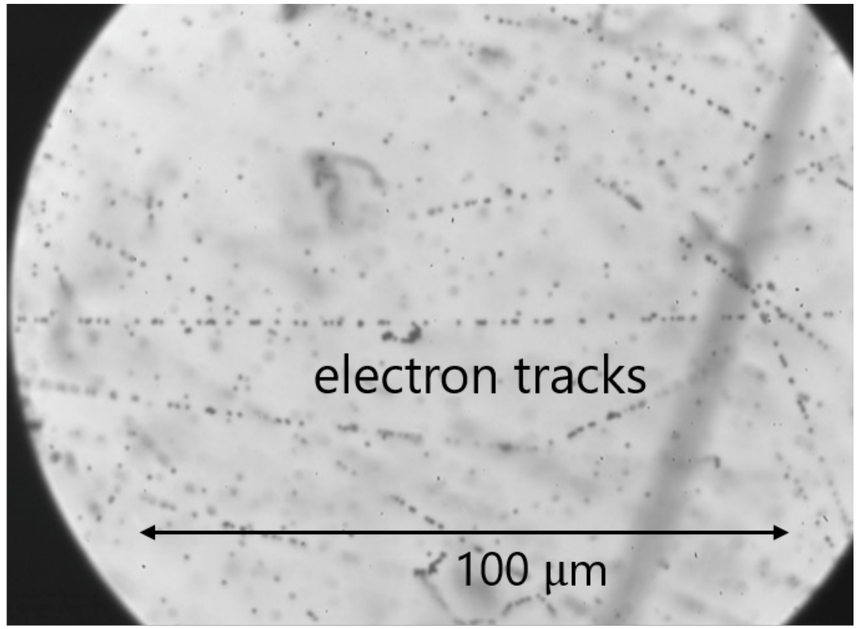
Expected CC interaction events (250 fb^{-1})

Generators		FASERν at Run 3		
light hadrons	charm hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
EPOS-LHC	–	1149	7996	–
SIBYLL 2.3d	–	1126	7261	–
QGSJET 2.04	–	1181	8126	–
PYTHIAforward	–	1008	7418	–
–	POWHEG Max	1405	1373	76
–	POWHEG	527	511	28
–	POWHEG Min	294	284	16
Combination		1675^{+911}_{-372}	8507^{+992}_{-962}	28^{+18}_{-12}

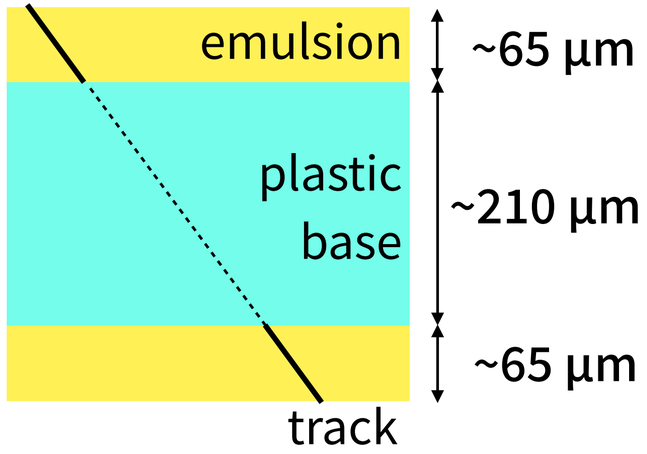
- ~10,000 ν interactions expected in LHC Run 3 (2022-2025)

Emulsion Detector

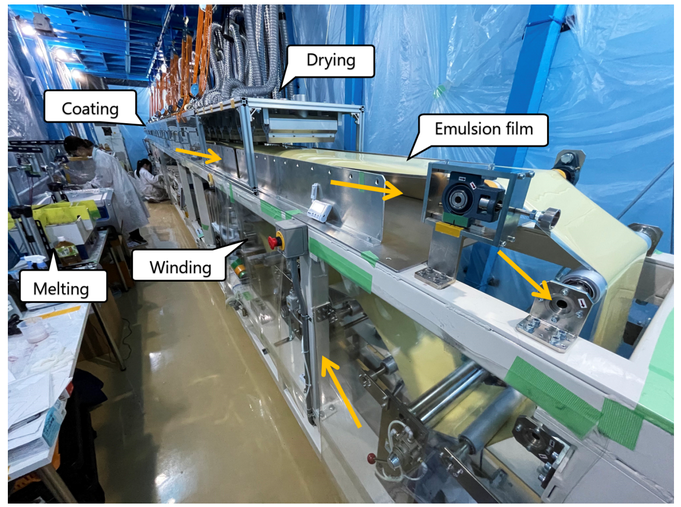
Microscopic view



Double sided emulsion coating



Emulsion film coating system



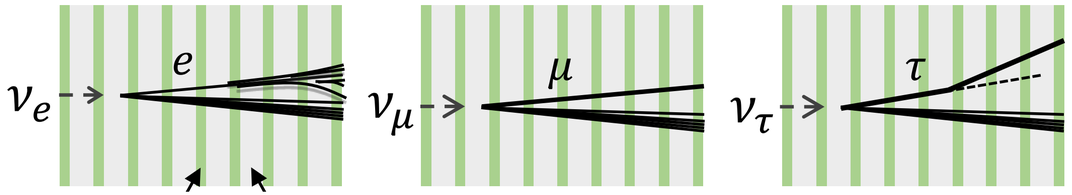
- 200 nm diameter silver halide crystals dispersed in gelatin
- O(100) nm position resolution can be achieved

- Produced gel and film at Nagoya University

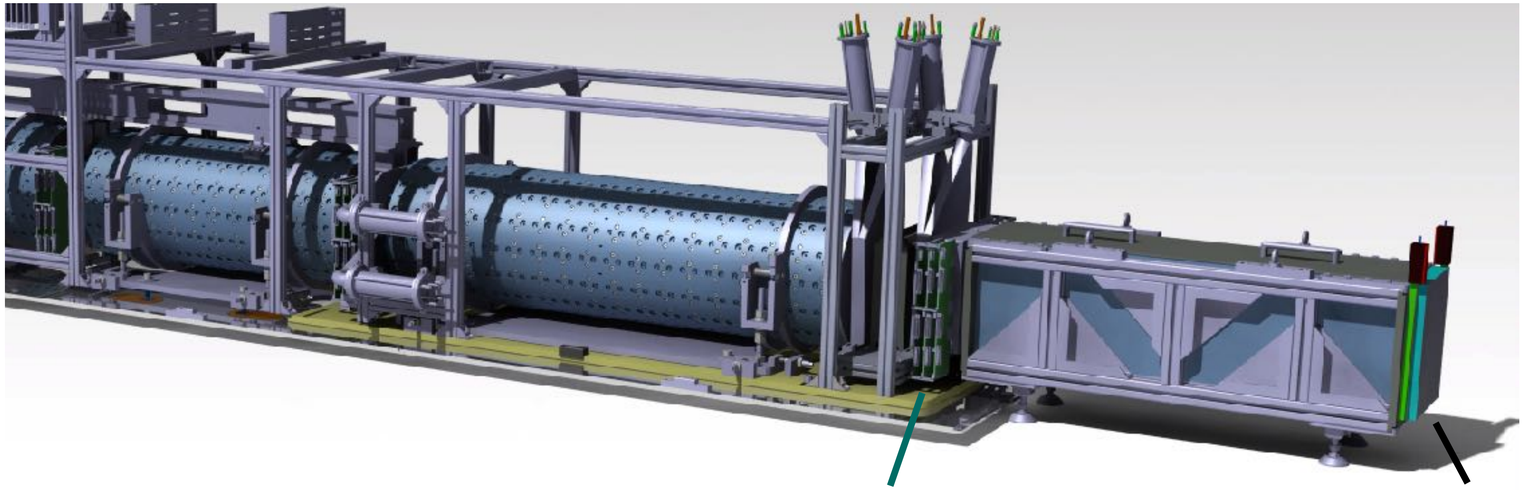
FASERν Neutrino Detector

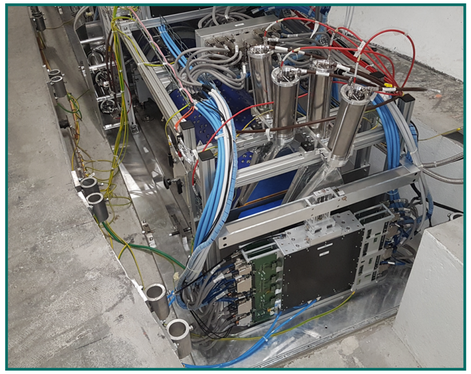
- **Emulsion-based detector**
  - 730 × [tungsten (1.1 mm thickness) + emulsion film]
  - 250 mm × 300 mm, 1 m long, 1.1 tons (220 X_0)
  - Install (exchange) emulsions 3 times a year

- **ν flavor tagging with topological/kinematical informations**



Emulsion film Tungsten plate (1.1 mm)





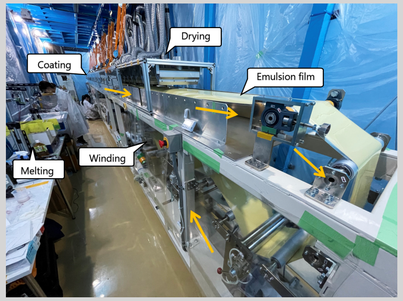
Interface Tracker: 3 layer silicon-strip tracker

Veto scintillator (2 layer)

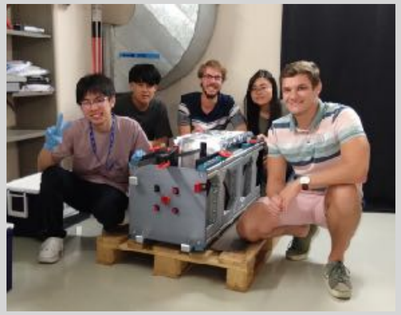
- **Global reconstruction with FASER spectrometer**
- **Muon charge identification (ν_μ)**

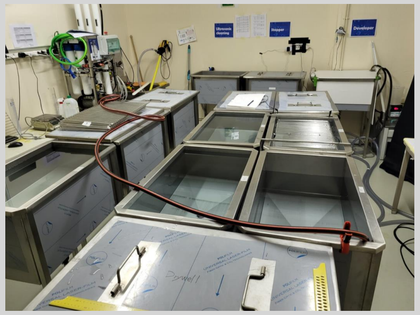
FASERν Emulsion Detector

Japan

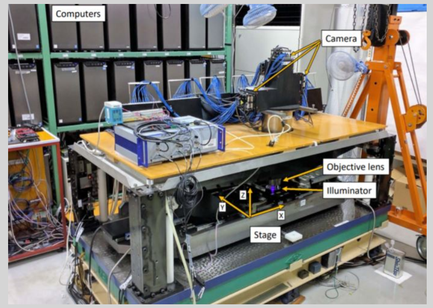


CERN





Japan

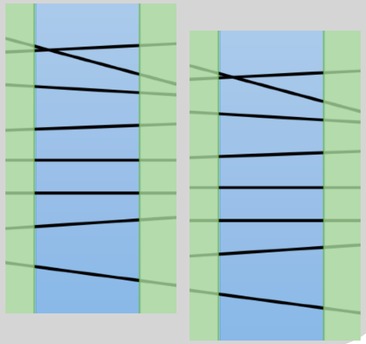


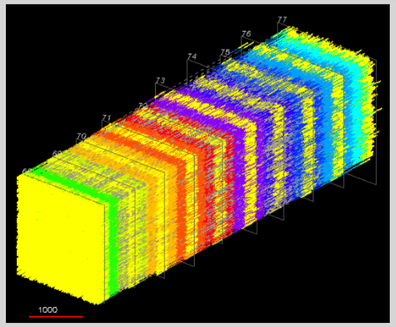
HTS-1 at Nagoya

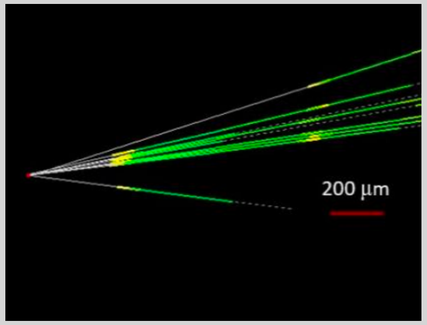
Film production → Assembly → Exposure → Disassembling → Development → Readout

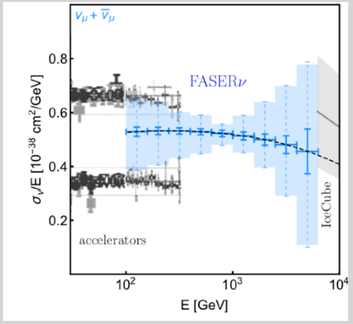
Offline analysis

Readout → Alignment → Track reconstruction → Vertex reconstruction → Kinematical analysis, Lepton ID, etc → Physics analysis



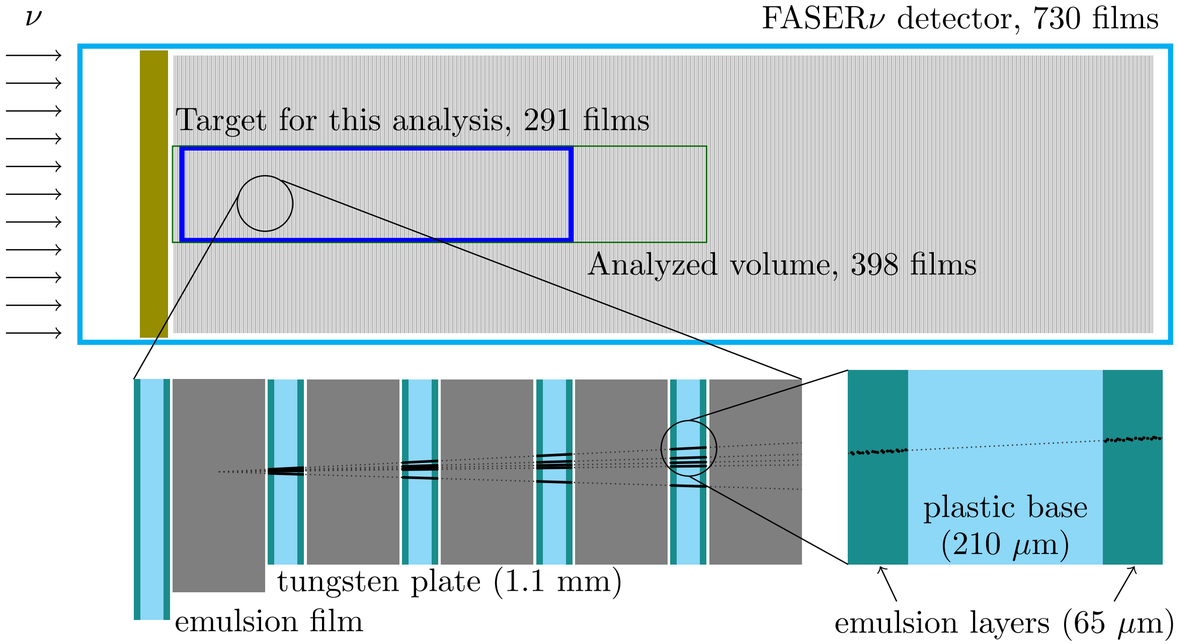


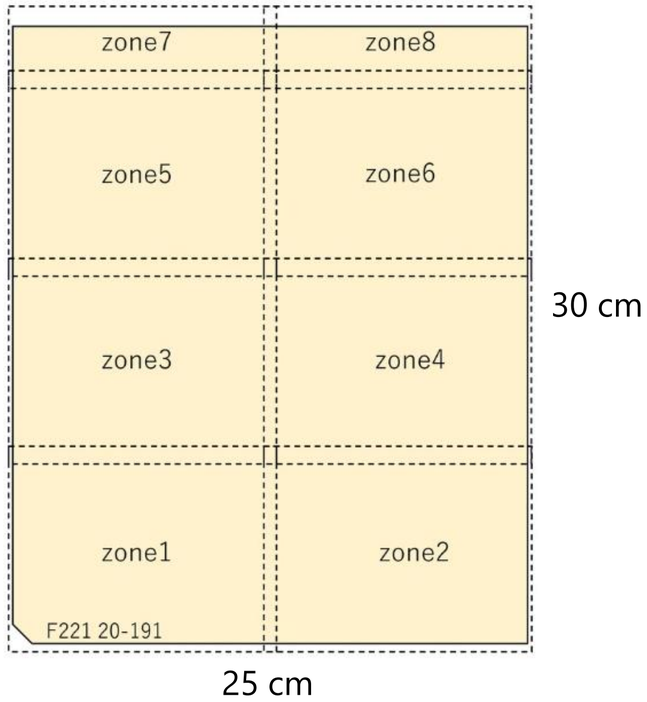




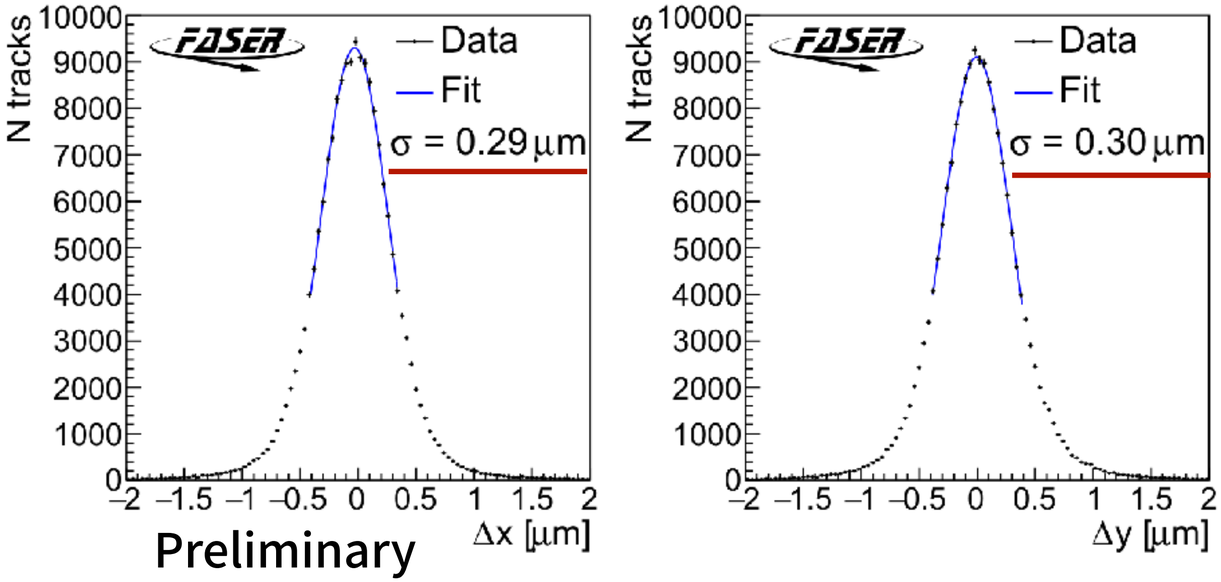
First detection of ν_e and ν_μ with FASERν detector

- **Dataset for current analysis:**
  - 9.5 fb-1 in 2022 run
  - ~1.7% of data collected so far
  - Analyzed target mass of 128.6 kg

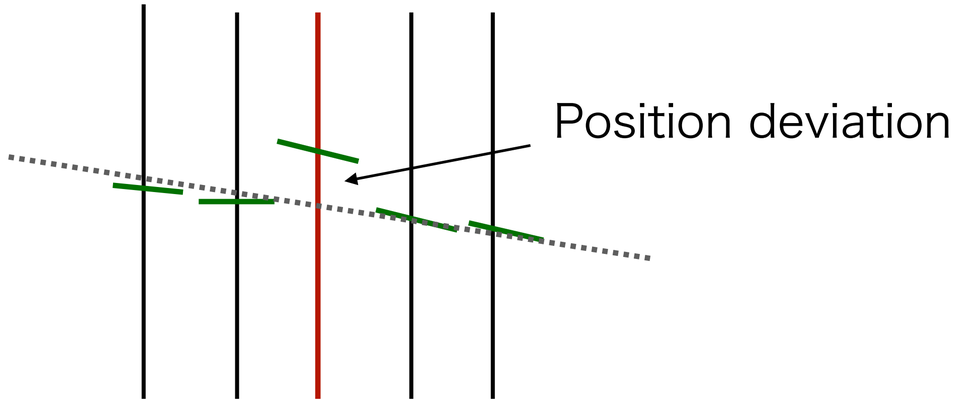


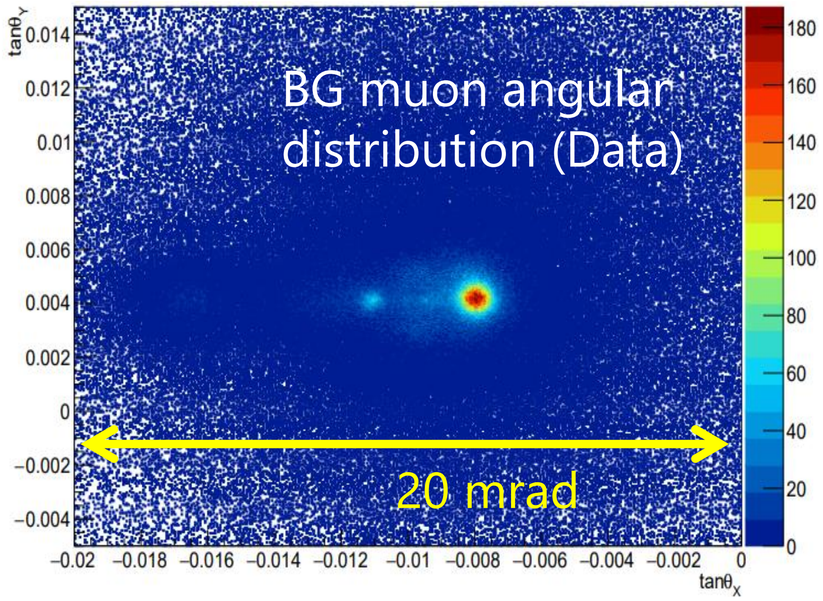


Detector Performance



~300 nm position resolution



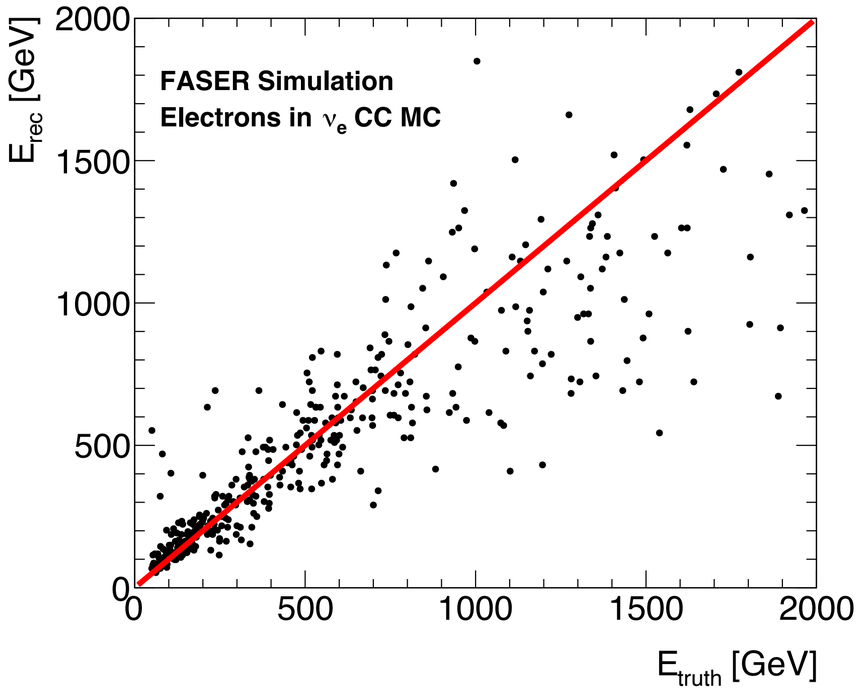


Angular spread of peaks
~ 0.4 mrad

Performance of Energy/Momentum Measurement

Electron energy measurement

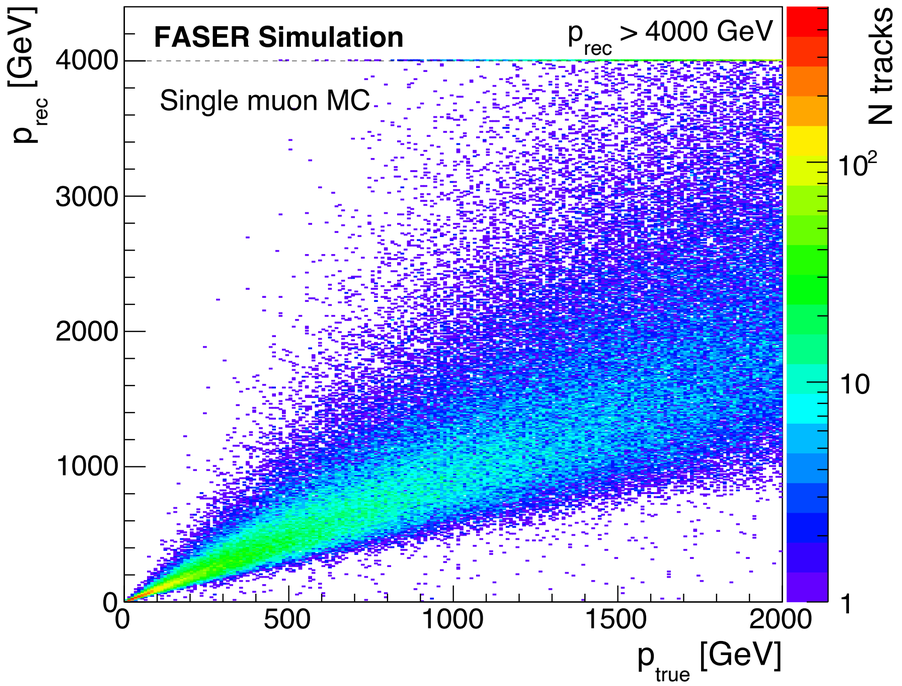
- Searching for track segments in a cylinder of radius 100 μm around the EM shower axis



- $\frac{\Delta E}{E} \sim 0.25$ for 200 GeV

Muon momentum measurement

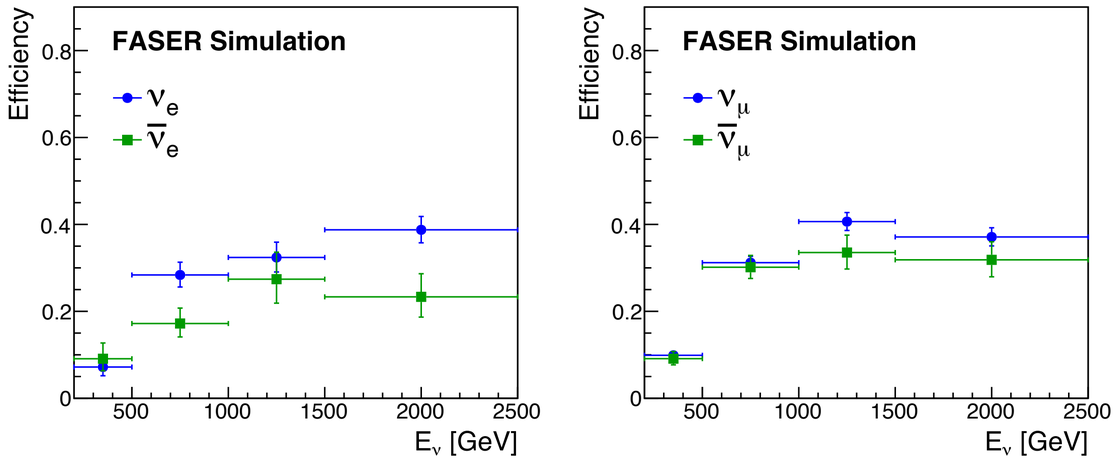
- Calculate muon momentum based on multiple Coulomb scattering using 100 plates



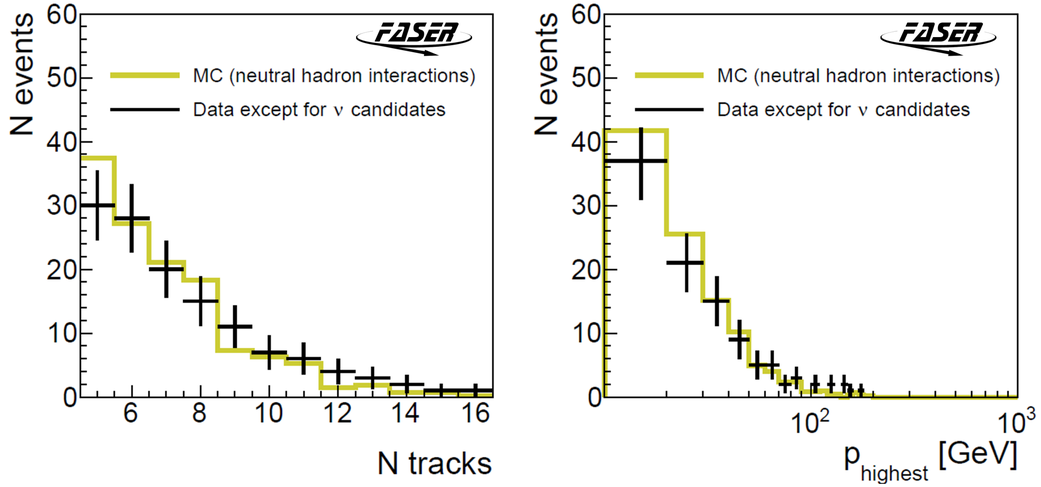
- $\frac{\Delta P_{RMS}}{P} \sim 0.3$ for 200 GeV

First detection of ν_e and ν_μ with FASERν detector

Selection



Background control



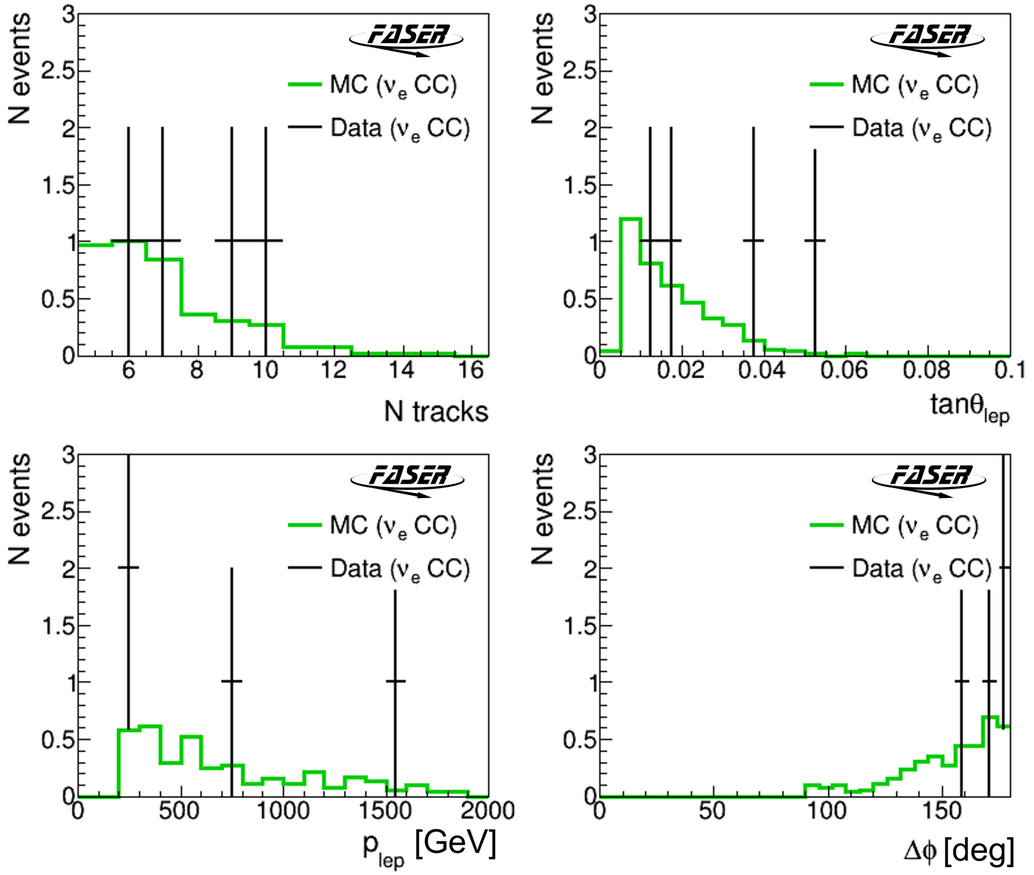
- Vertex reconstruction: ($N_{track} \geq 5$, $N_{track}(\tan\theta \leq 0.1) \geq 4$)
- E_e or p_μ >200 GeV
- $\tan\theta_e$ or $\tan\theta_\mu$ >0.005
- ϕ>90°

- The modeling of neutral-hadron backgrounds are validated using data

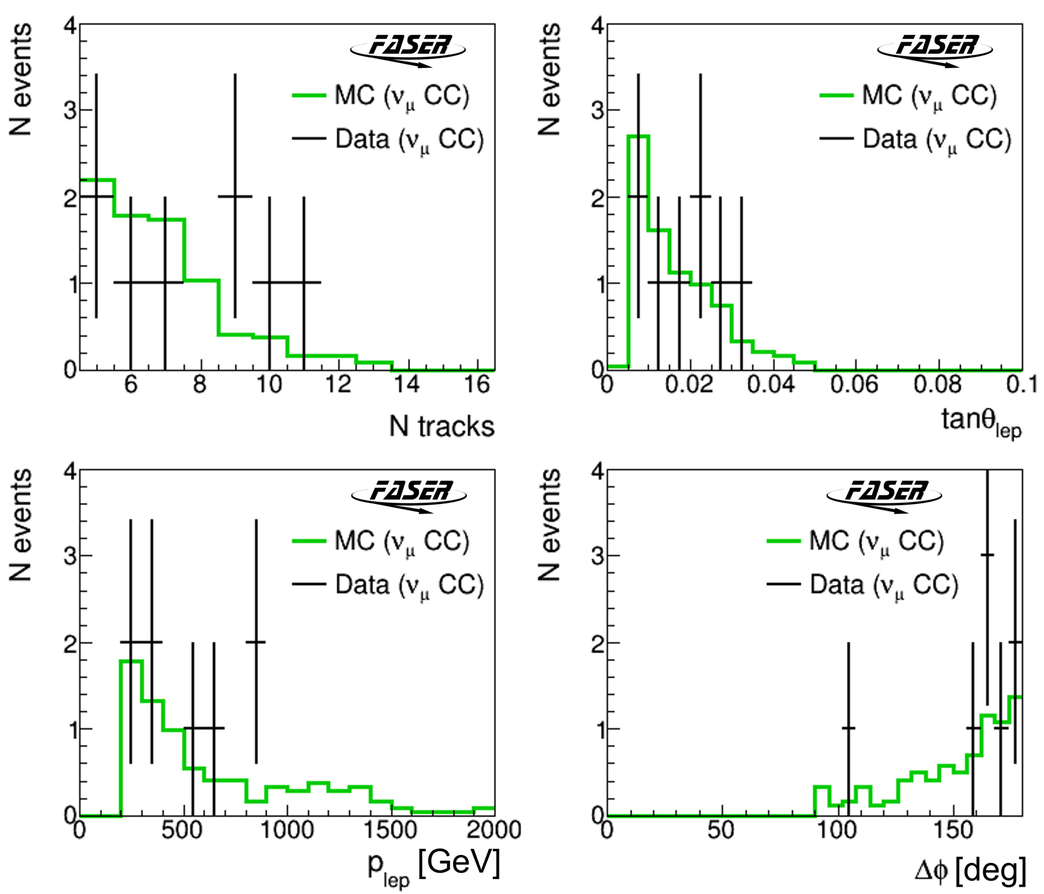
	Expected background	Expected signal	Observed	Significance
ν_eCC	$0.025^{+0.015}_{-0.010}$	1.1-3.3	4	5.2σ
ν_μCC	$0.22^{+0.09}_{-0.07}$	6.5-12.4	8	5.7σ

Neutrino Characteristic

Electron



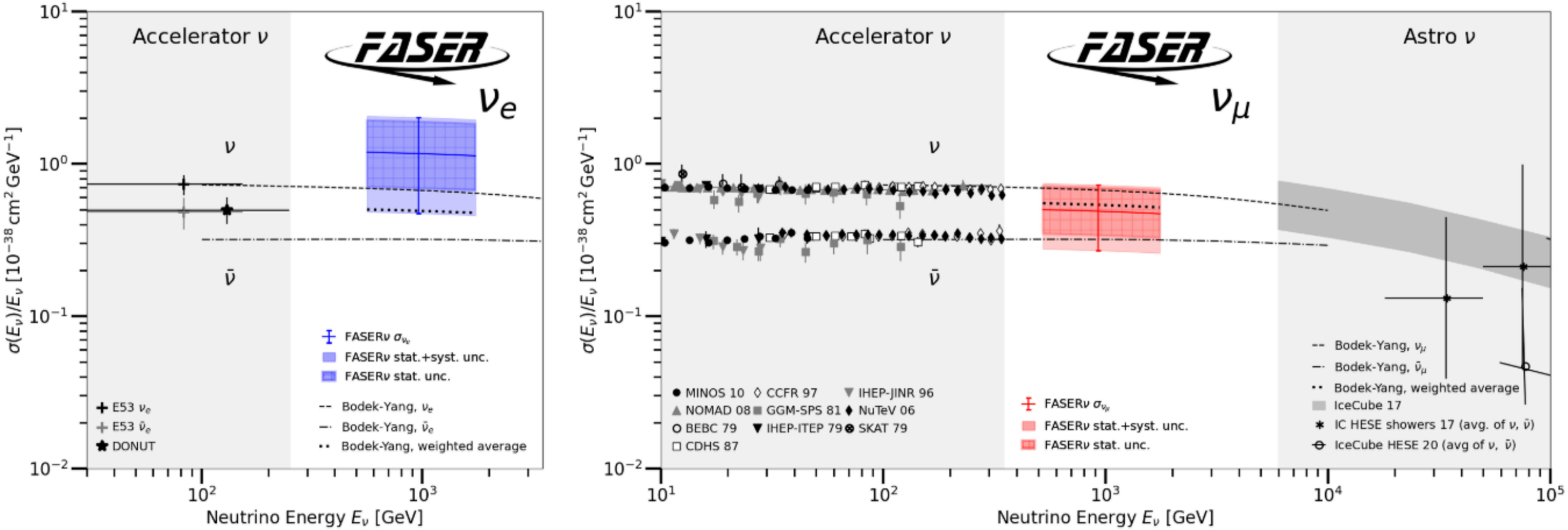
Muon



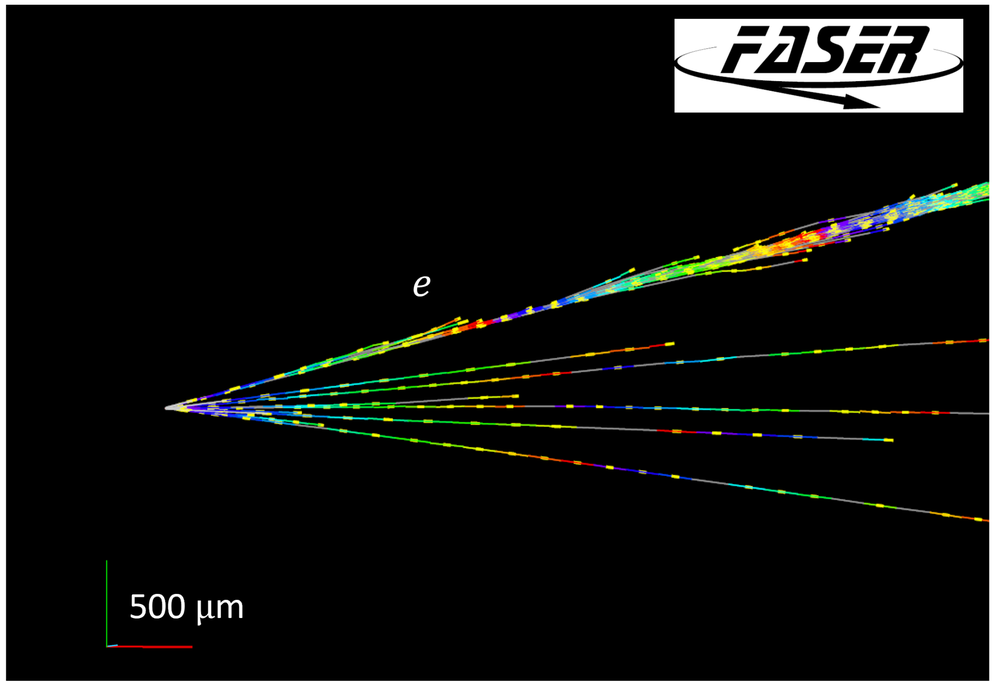
- Kinematics of observed ν interactions are in good agreement with MC
- ν interactions at TeV range

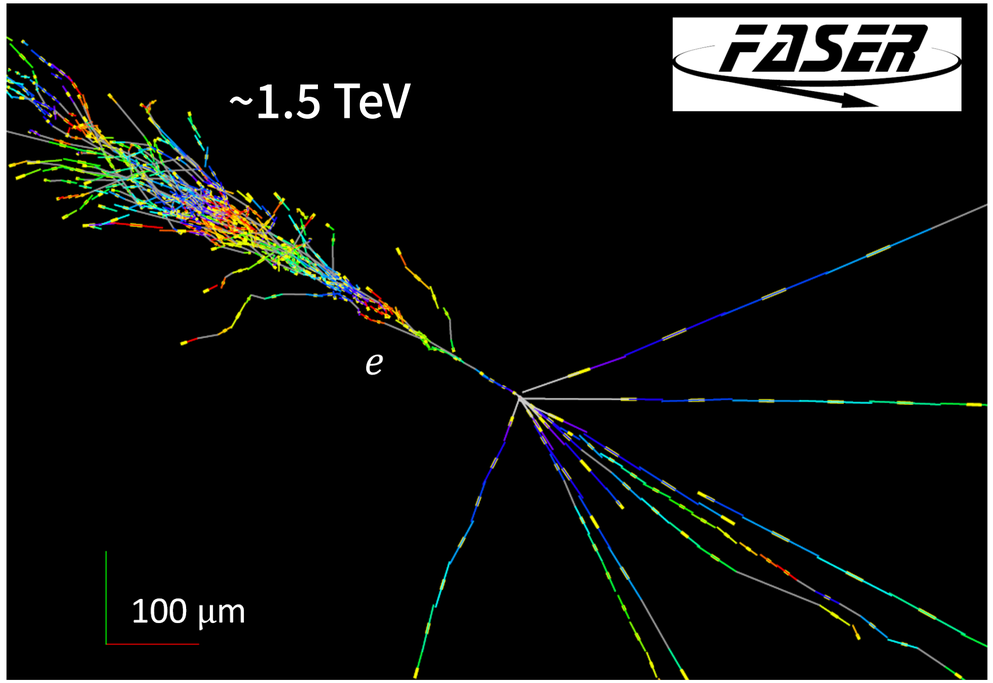
Phys. Rev. Lett. 133, 021802 (2024)

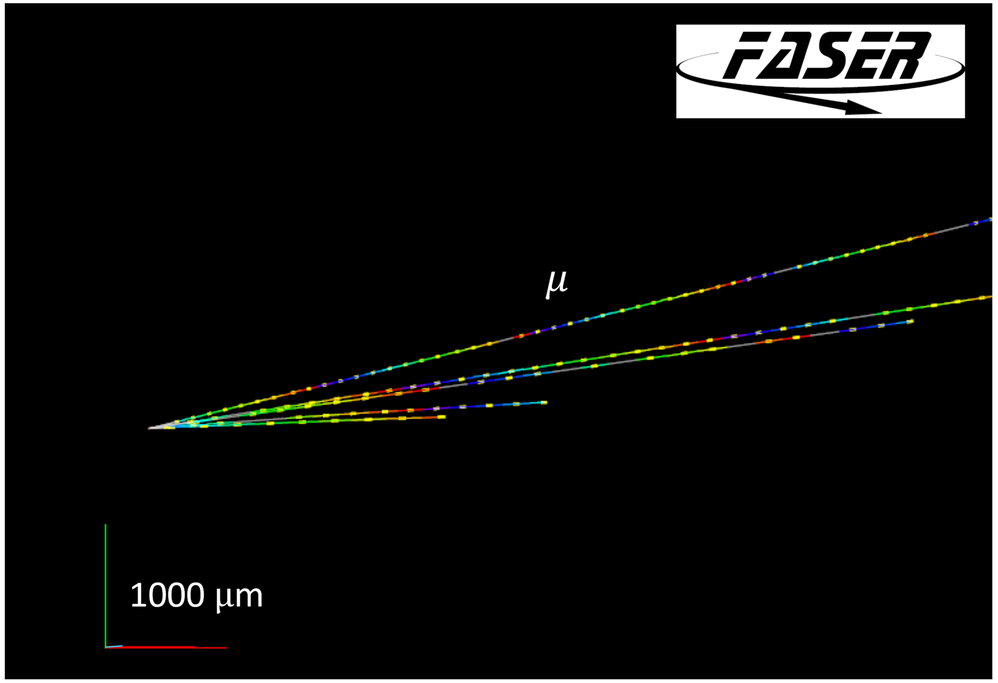
First cross section measurement at TeV energies

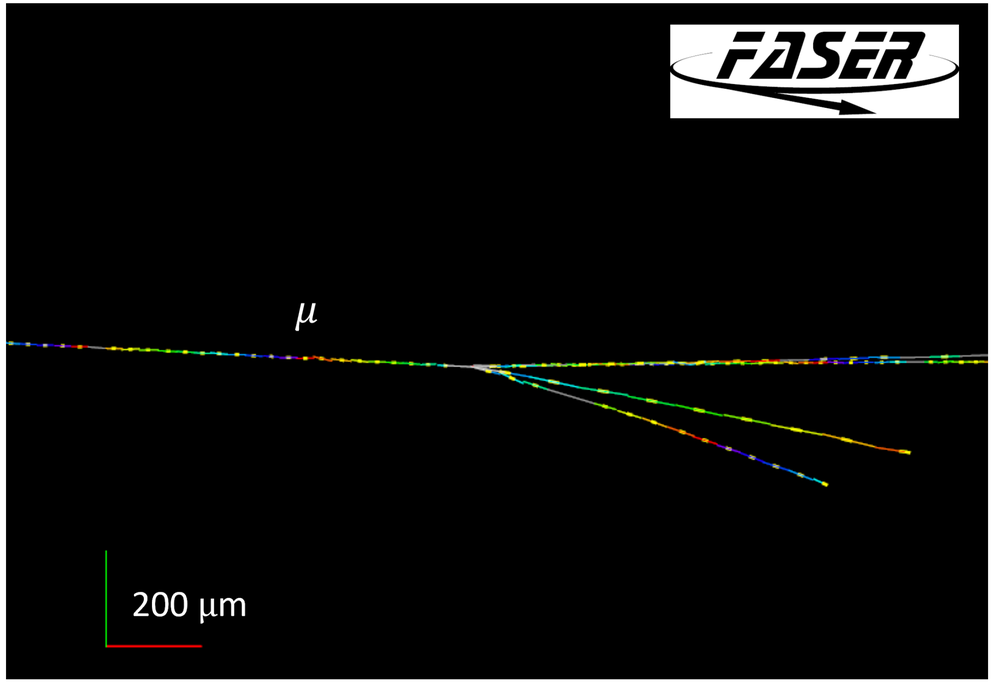


- First measurement of ν_e, ν_μ interaction cross section at the LHC with emulsion detector
- Large uncertainty from neutrino flux


FASER
e
500 μm


FASER
~1.5 TeV
e
100 μm


FASER
μ
1000 μm

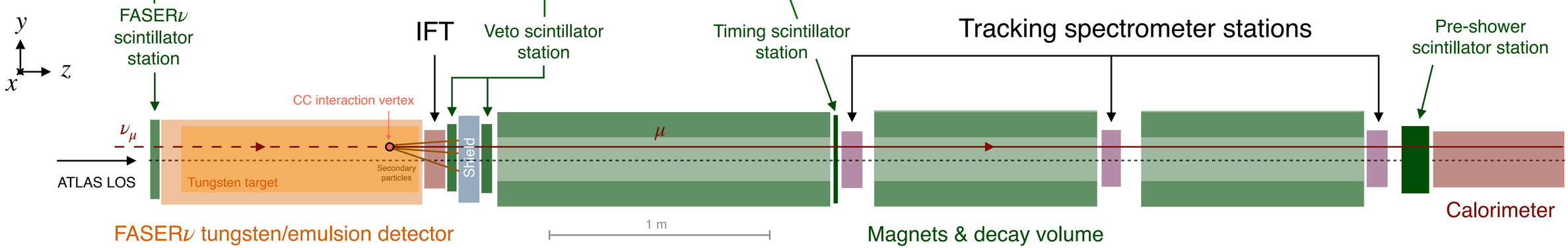

FASER
μ
200 μm

FASER

“Electronic” Neutrino search

Phys. Rev. Lett. 131 (2024), 031801

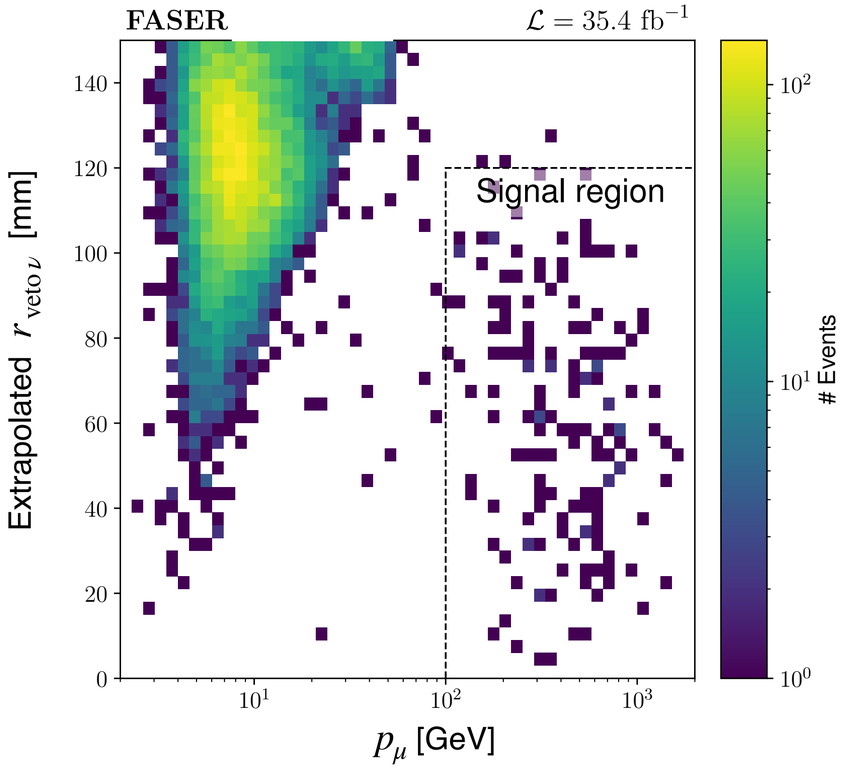
- Collision event with good data quality (35.4 fb^{-1}, 2022 data)
- No signal (<40 pC)
- Signal (>40 pC)

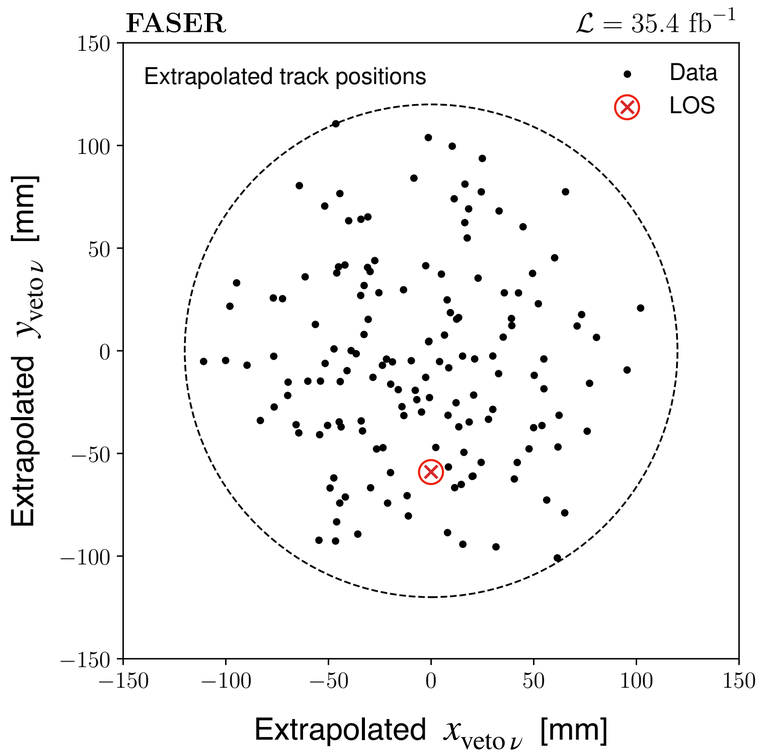


- Timing and pre-shower consistent with ≥ 1MIP
- Exactly 1 good fiducial (r < 95 mm) track
  - p > 100 GeV and θ < 25 mrad
  - Extrapolating to r < 120 mm in front veto
- **Expect 151 ± 41 events from GENIE simulation**
  - Uncertainty from DPMJET vs. SIBYLL
  - No experimental errors

Background
- **Veto inefficiency: negligible**
- **Neutral hadrons: 0.11±0.06 events (MC)**
- **Scattered large-angle muons: 0.08±1.83 events (sideband)**

Results

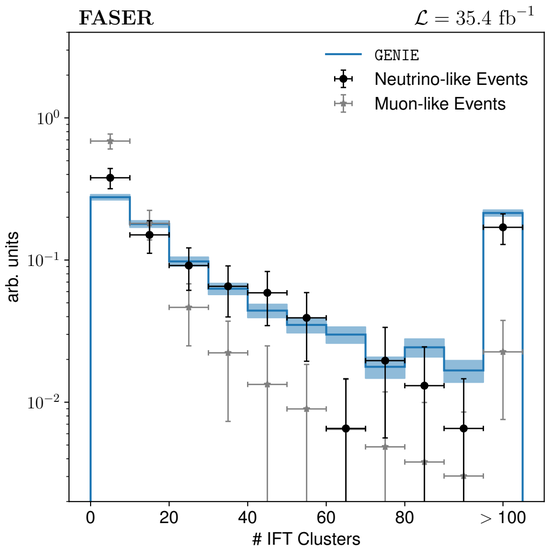




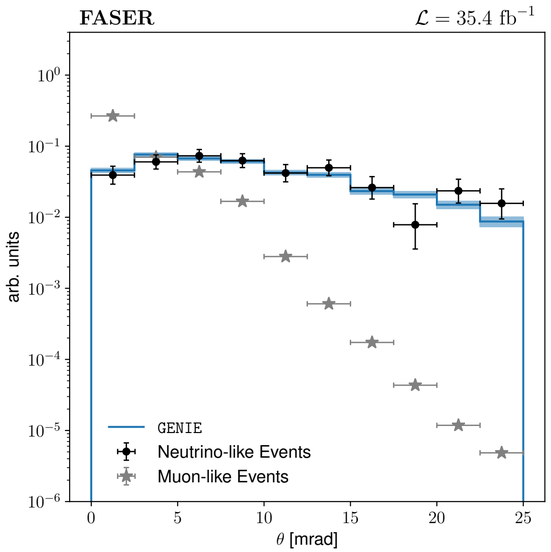
Category	Events
Signal	153
n_{10}	4
n_{01}	6
n_2	64014695

- Observed 153^{+13}_{-12} events (151 $\pm$ 41 events expected)
- Signal significance of **16σ**
- **First directory observation of collider neutrinos**

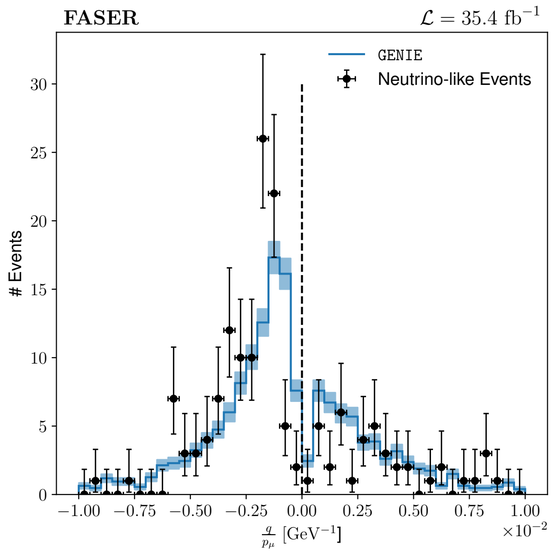
Neutrino Characteristics



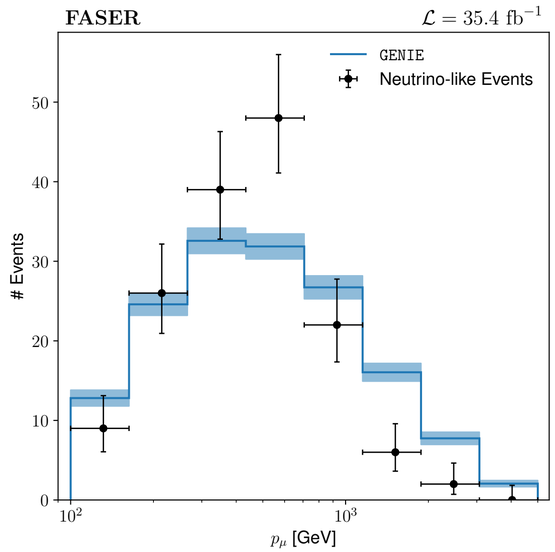
High occupancy in IFT



Large μ polar angle



More ν_μ than $\bar{\nu}_\mu$

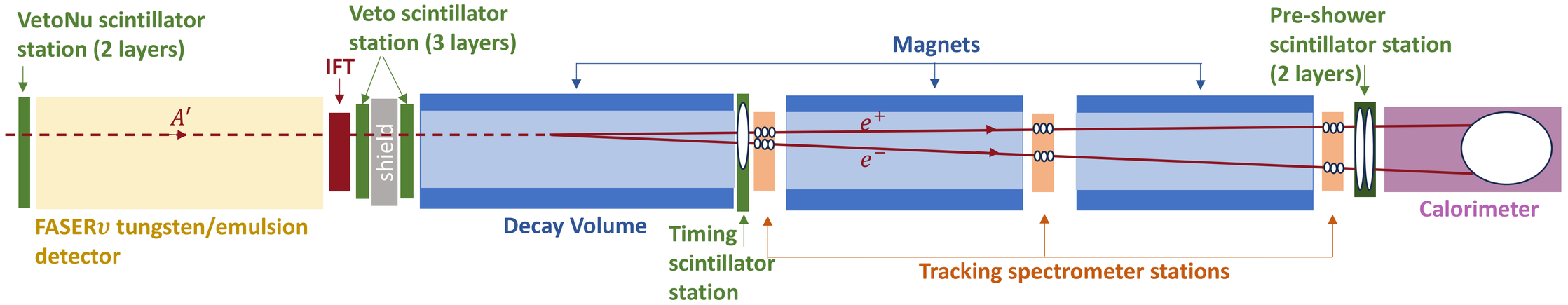


High μ momentum

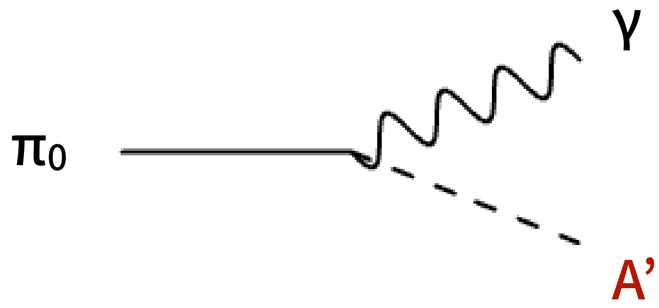
- Only statistical errors are shown
- Most events at high momentum (E_μ > 200 GeV)
- **Good agreement with expectations from simulation**

Search for Dark Photons

Phys. Lett. B 848 (2024), 138378

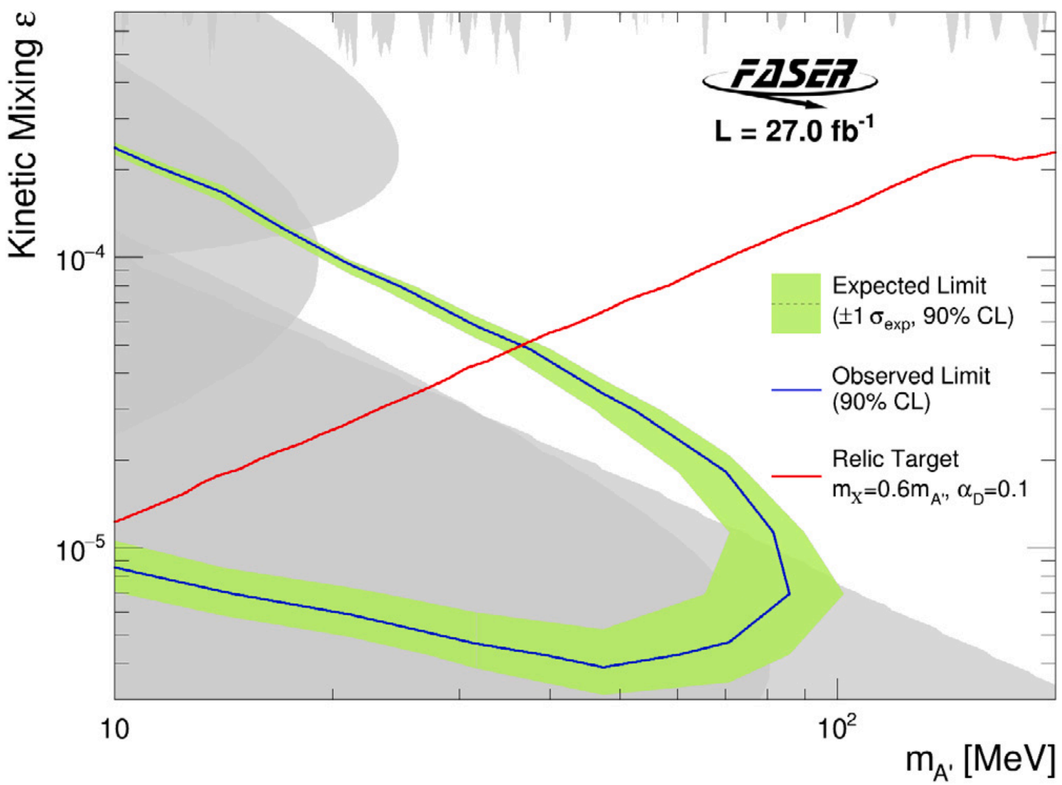


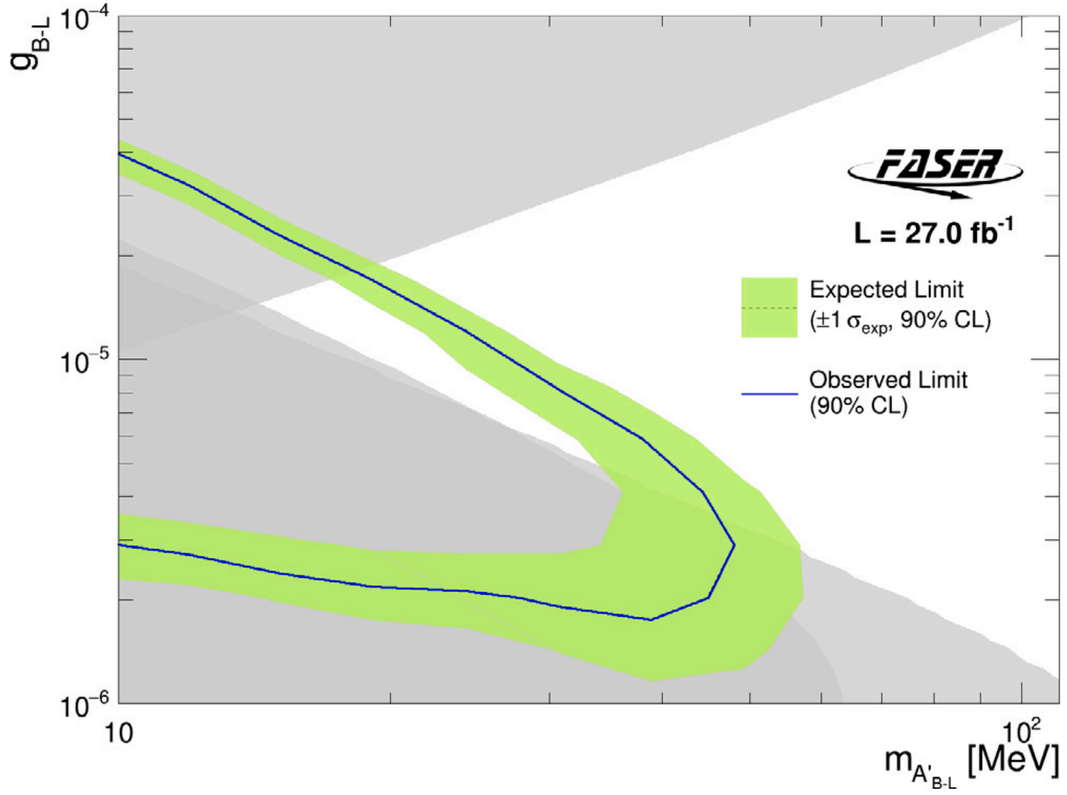
- 27.0 fb^{-1} collected in 2022
- Electron-positron pair in a decay volume
- Selection
  - 2 opposite-sign tracks
  - > 500 GeV in calorimeter
  - Nothing in all 5 veto scintillator counters
  - Something in downstream scintillators
- Negligible backgrounds: $(2.3 \pm 2.3) \times 10^{-3}$ events
  - Veto inefficiency, neutral hadrons, large-angle muons, neutrinos, non-collision events



- Dark matter from MeV-GeV can be thermal relics
- Dark photon(A’): U(1) gauge boson, hidden sector particle

Search for Dark Photons

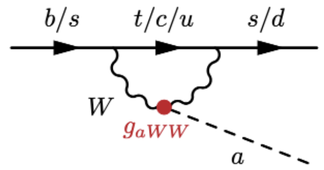


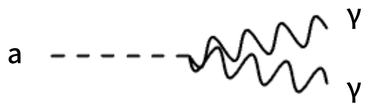


- No events observed
- New limits on unexplored parameter space
- Constrained a massive gauge boson from a $U(1)_{B-L}$ model

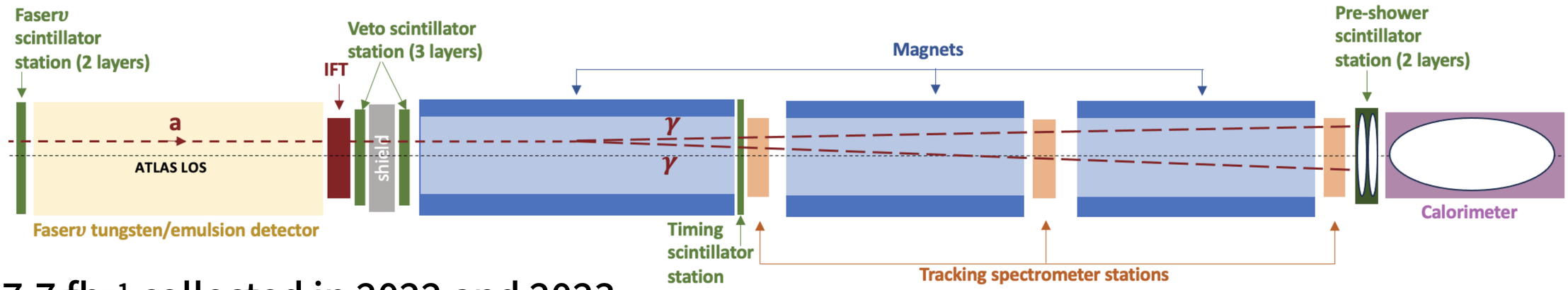
Conf note: CERN-FASER-CONF-2024-001

Search for ALPs



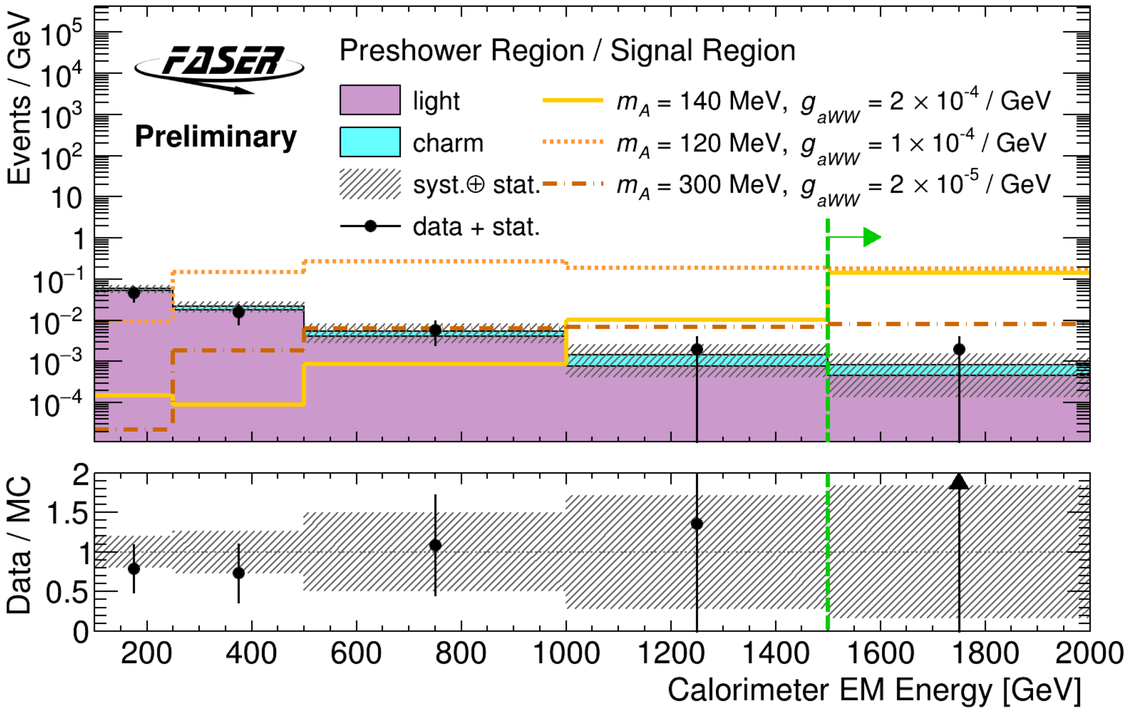


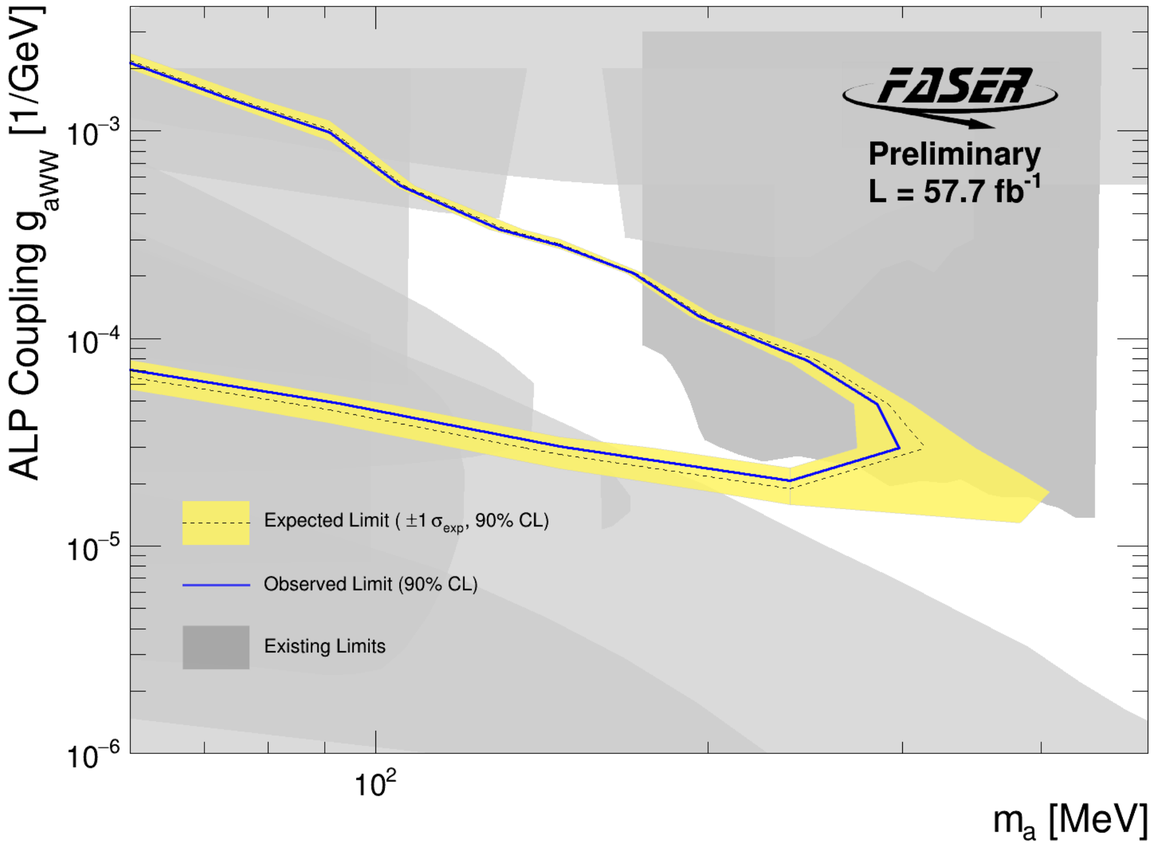
- FASER is sensitive to ALPs coupling to $SU(2)_L$ gauge bosons
- ALP decays to two photons



- 57.7 fb^{-1} collected in 2022 and 2023
- Very collimated energetic photon pair produced
  - A high energy deposit in the electromagnetic (EM) calorimeter
- Selection
  - Nothing in all 5 veto counters
  - Evidence of EM shower in preshower
  - > 1.5 TeV in calorimeter
  - In time with LHC collision
- Negligible backgrounds
  - Neutral hadrons
  - Large-angle muons
  - Non-collision / cosmics

ALPs Results

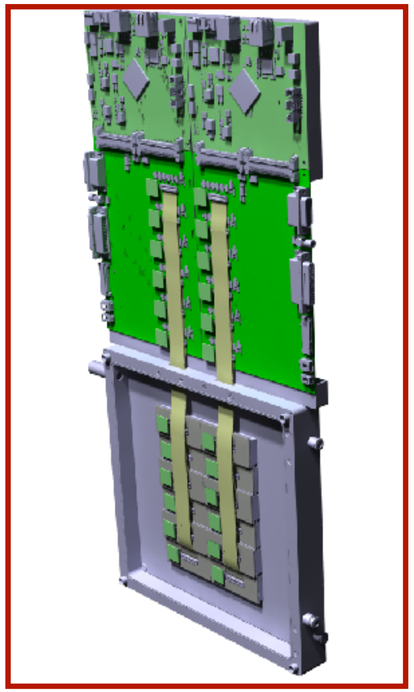




- Neutrinos produced upstream of FASER through light/charm hadron decays
  - Evaluated with MC simulations and validated in different detector regions
  - Expecting 0.42 ± 0.38 from ν CC interactions in pre-shower station
- Observed **1** event after unblinding
- Probing new parameter space of this ALPs Model

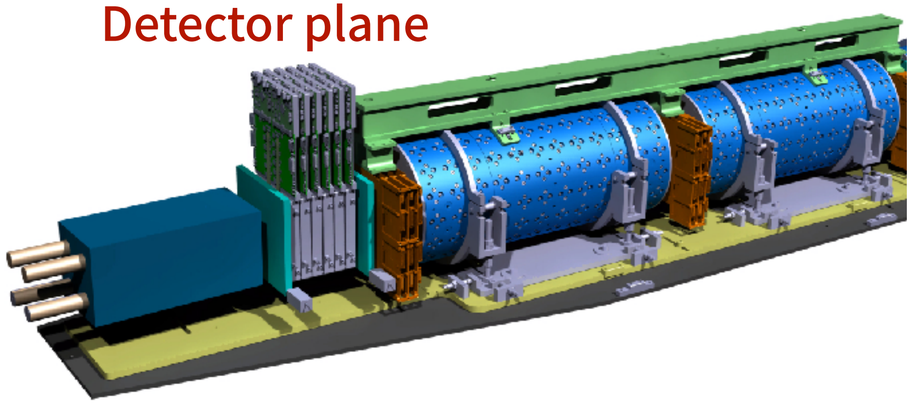
Future Prospects

New Pre-shower Calorimeter

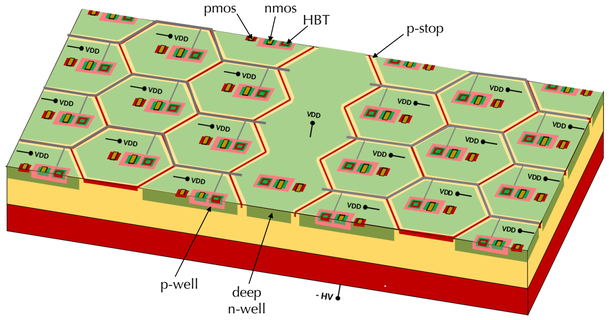


Detector plane

- **Resolve di-photon events by upgraded pre-shower calorimeter with high X-Y granularity**
  - Improve ν BG suppression in the search for ALPs
- **6 detector planes + 2 scintillators**
  - Each plane: tungsten absorber + monolithic SiGe pixel sensors
- **Project approved by CERN: CERN-LHCC-2022-006**
- **Targeting installation in December 2024**
  - Data taking during last year of LHC Run 3 and HL-LHC



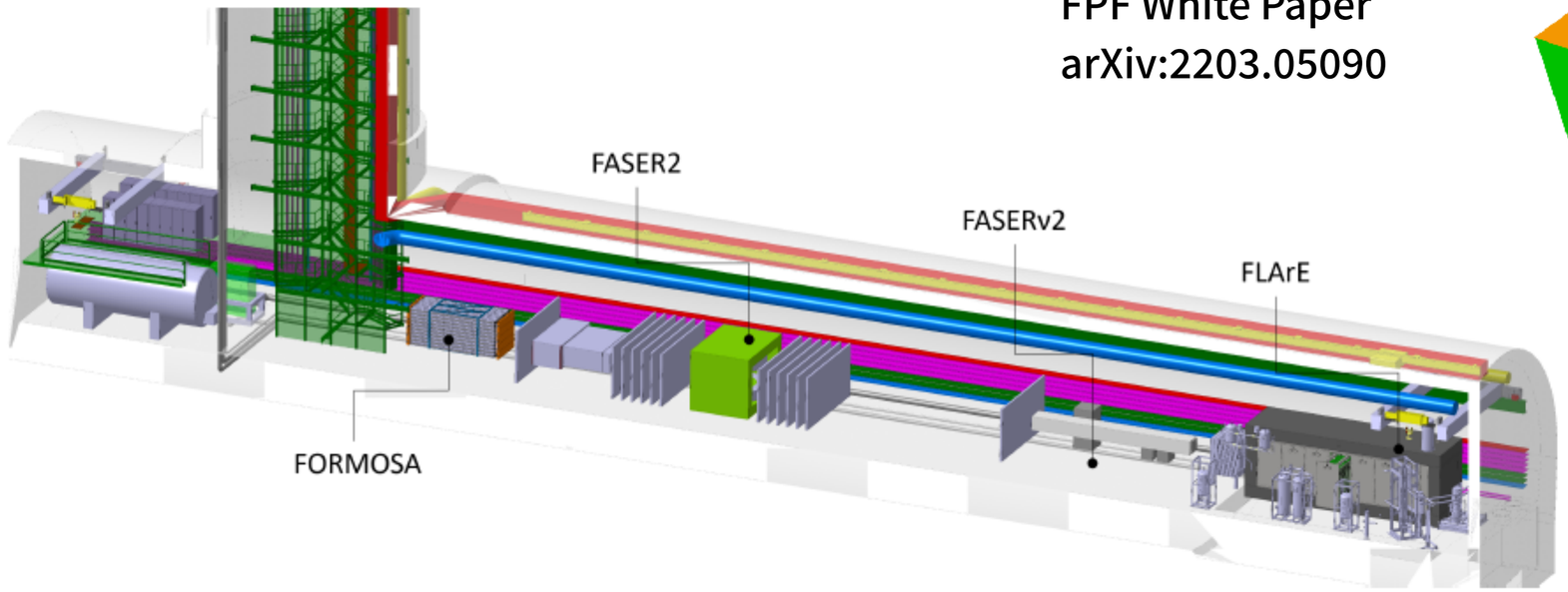
Monolithic pixel sensor: 130 nm SiGe BiCMOS technology

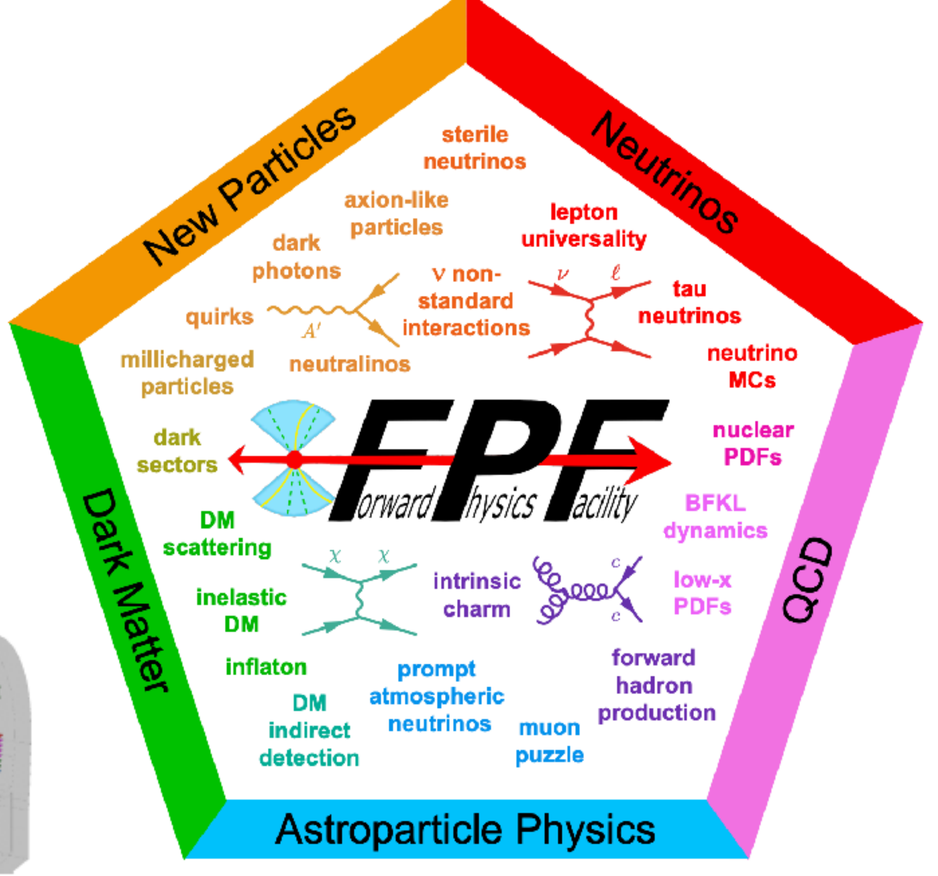


Main specifications	
Pixel Size	65 µm side (hexagonal)
Pixel dynamic range	0.5 ÷ 65 fC
Cluster size	O(1000) pixels
Readout time	< 200 µs
Power consuption	< 150 mW/cm^2
Time resolution	< 300 ps

Forward Physics Facility (FPF)

FPF White Paper
arXiv:2203.05090

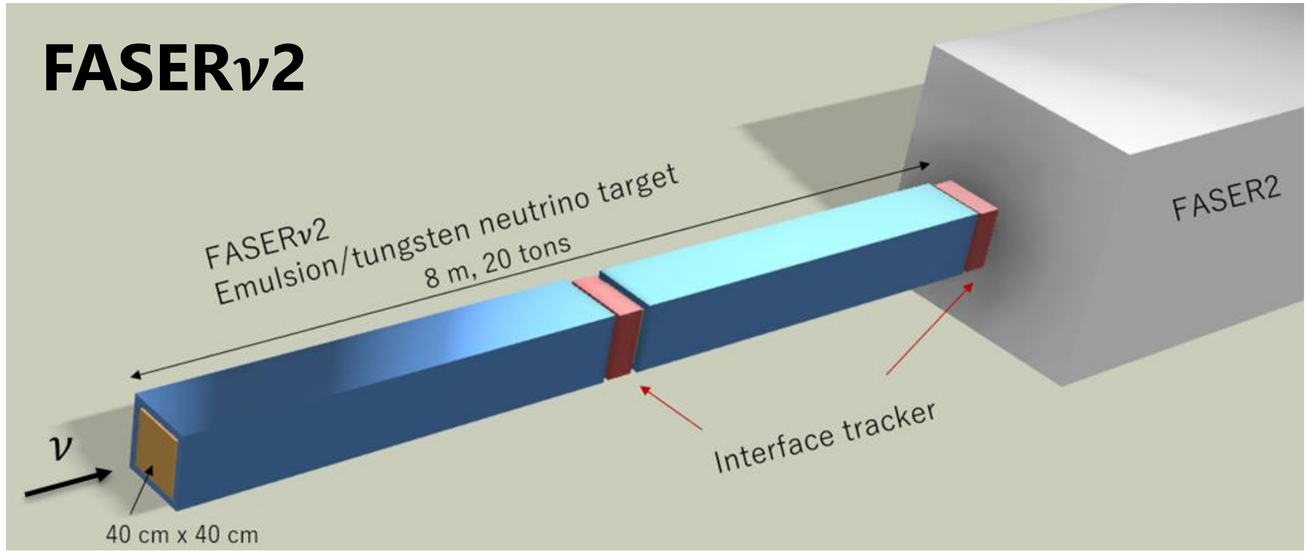




- FPF is a proposal to create a new facility ~650 m away on the LOS for HL-LHC era
- Probes topics that span multiple frontiers including QCD
- Studies proton/nuclear PDFs
  - Essential input to realizing the full potential of the HL-LHC
- Provides opportunities for interdisciplinary studies
  - Understanding hadron production related to cosmic-ray experiments

(More details in backups)

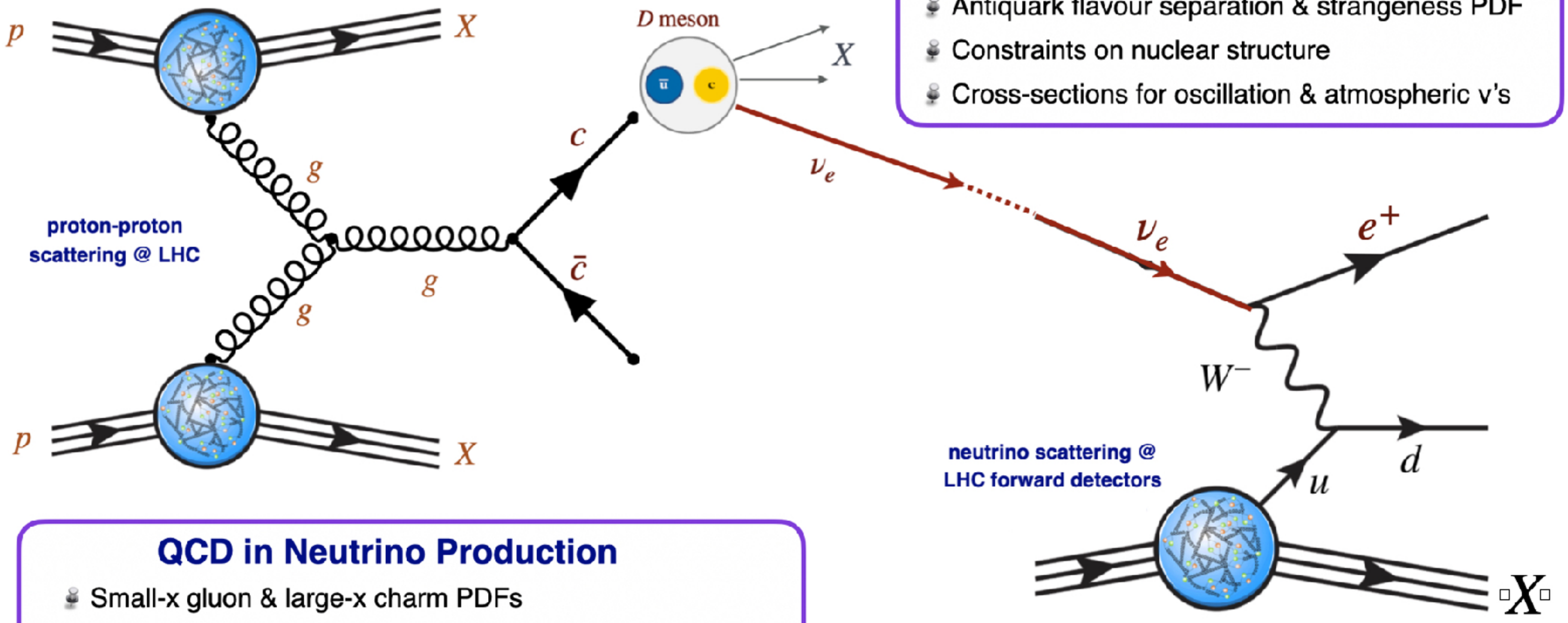
FASERν2



- 20 tons target mass emulsion neutrino detector
- Studying possibility of installing a dedicated sweeper magnet to reduce muon background
  - Emulsion detector replacement: Once per a year
- ~O(1000) expected tau neutrino interactions
  - First detection of Anti-tau neutrino

QCD at FPF

Juan Rojo (6th FPF workshop)



QCD in Neutrino Scattering

- Deep-inelastic scattering with TeV neutrinos
- Antiquark flavour separation & strangeness PDF
- Constraints on nuclear structure
- Cross-sections for oscillation & atmospheric ν's

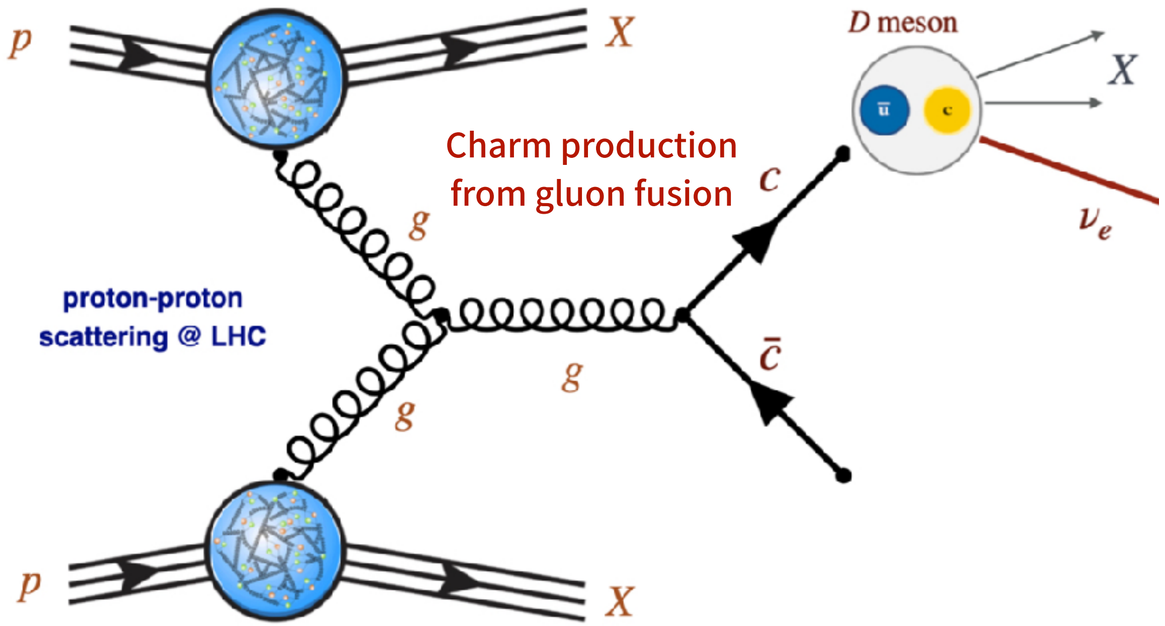
QCD in Neutrino Production

- Small-x gluon & large-x charm PDFs
- BFKL, non-linear QCD, cross-sections for UHE neutrinos
- *D*-meson fragmentation
- Forward light hadron production & cosmic ray modelling

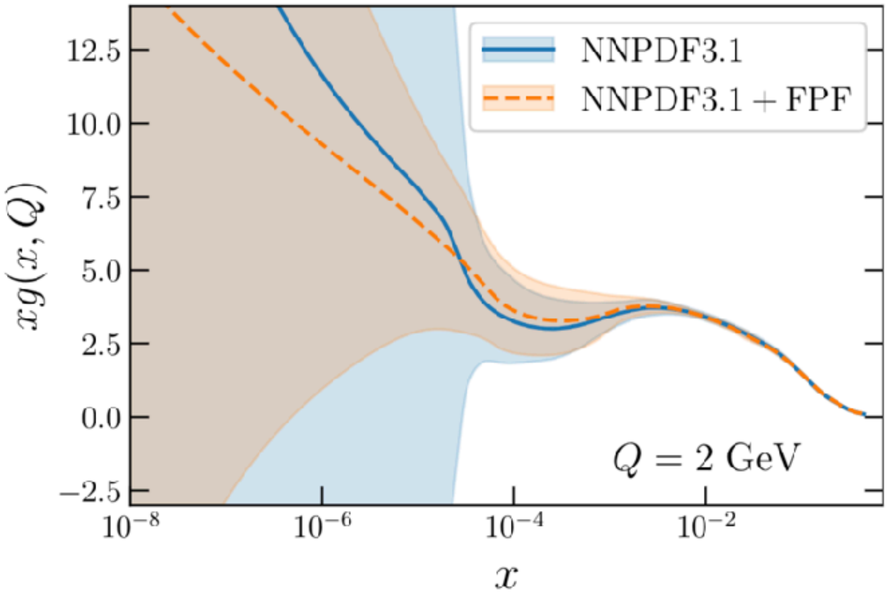
QCD at FPF

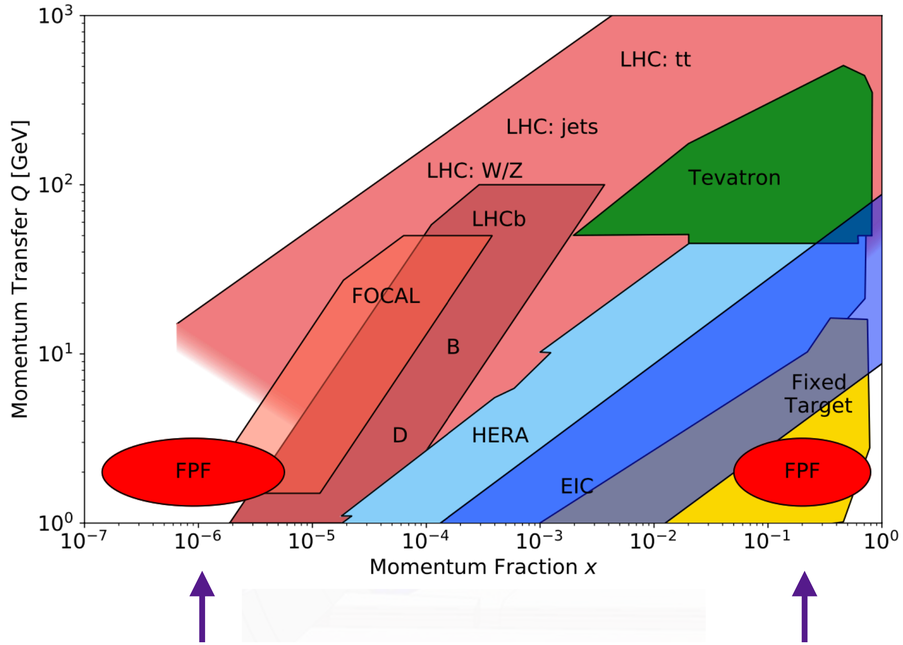
$$R_y^{(e)} \equiv \frac{N_{\nu_e}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_e}(E_\nu, 8.5 < y_\nu < 9.0)}$$

rapidity



Gluon PDF constrained by electron neutrinos, 2% uncertainty in inclusive event rates





QCD in Neutrino Production

- Small-x gluon & large-x charm PDFs
- BFKL, non-linear QCD, cross-sections for UHE neutrinos
- *D*-meson fragmentation
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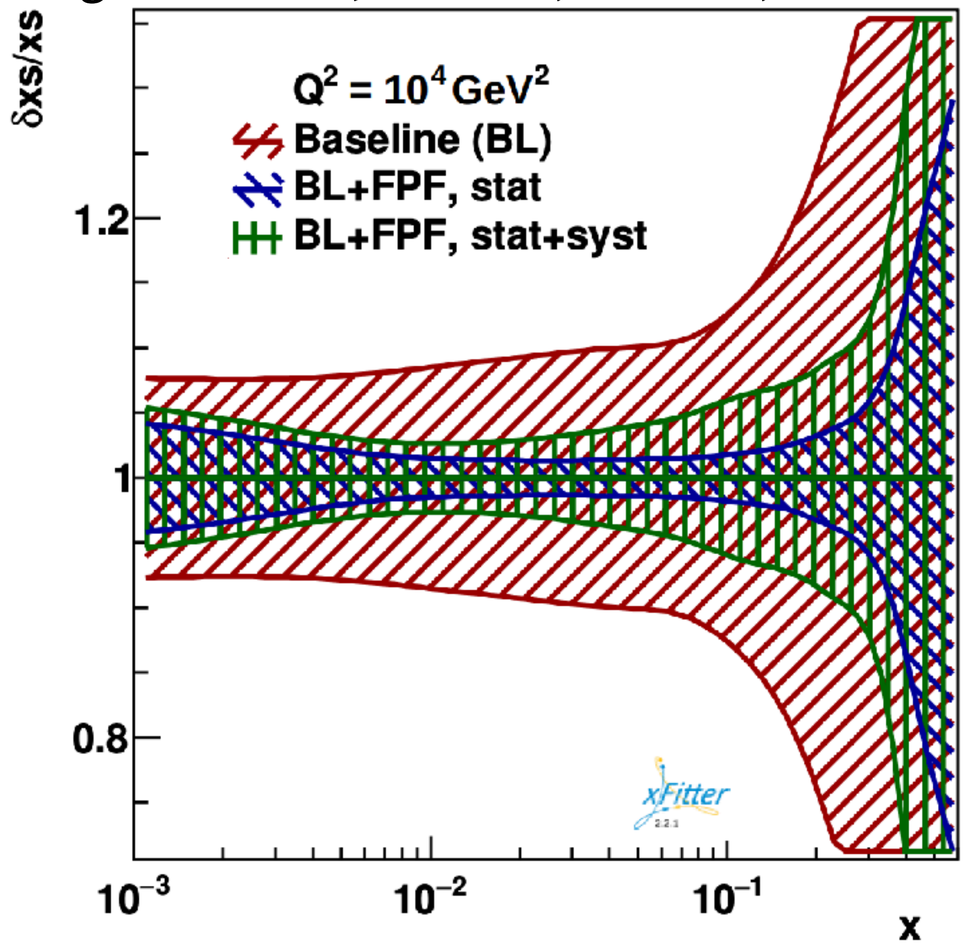
QCD at FPF

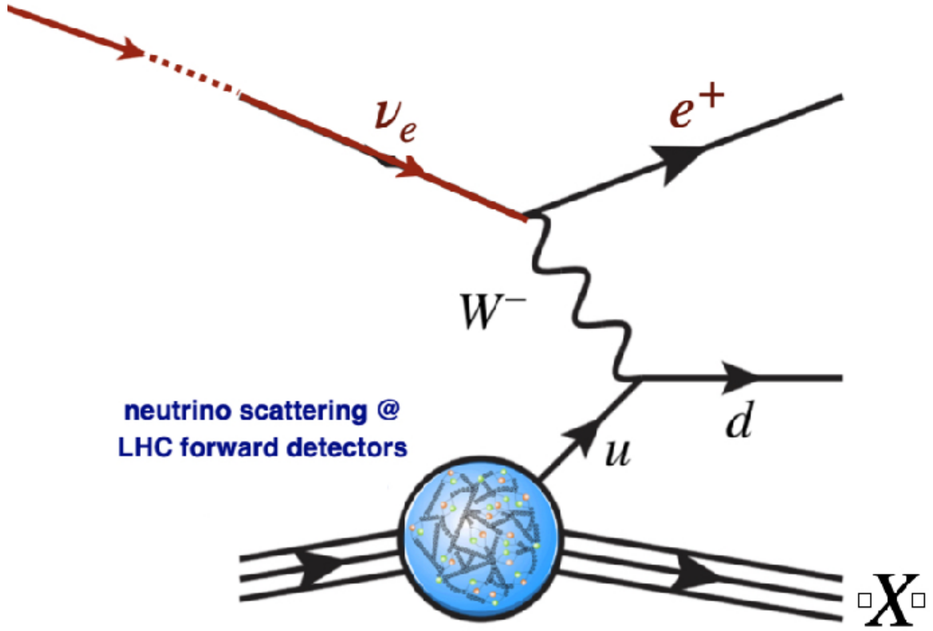
J. Cruz-Martinez et al, “The LHC as a Neutrino-Ion Collider” (2023)

strangeness PDF (FASERv2, AdvSND, and FLArE10)



QCD in Neutrino Scattering

- Deep-inelastic scattering with TeV neutrinos
- Antiquark flavour separation & strangeness PDF
- Constraints on nuclear structure
- Cross-sections for oscillation & atmospheric ν's



- Impact on proton PDFs quantified by the Hessian profiling of PDF4LHC21 (xFitter) and by direct inclusion in the global NNPDF4.0 fit

Summary

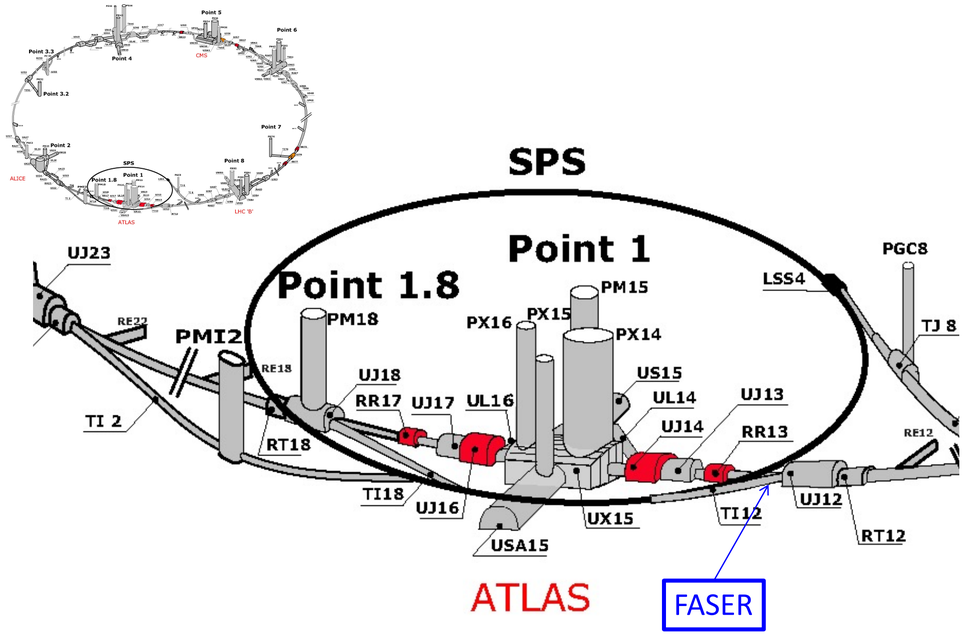
- **FASER is successfully taking data in the very forward region of the LHC from 2022**
- **Obtained physics results**
  - Dark photon limits
  - ALPs limits
  - First detection of collider neutrinos
  - First ν_e, ν_μ cross section measurements at a TeV range with emulsion detector (2% of data collected so far)
- **Pre-shower calorimeter upgrade**
- **Discussing extended physics programs in Forward Physics Facility in HL-LHC era**

Backups

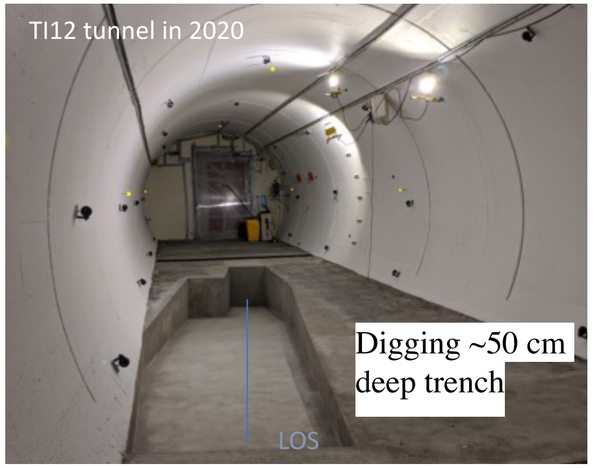
FASER Collaboration

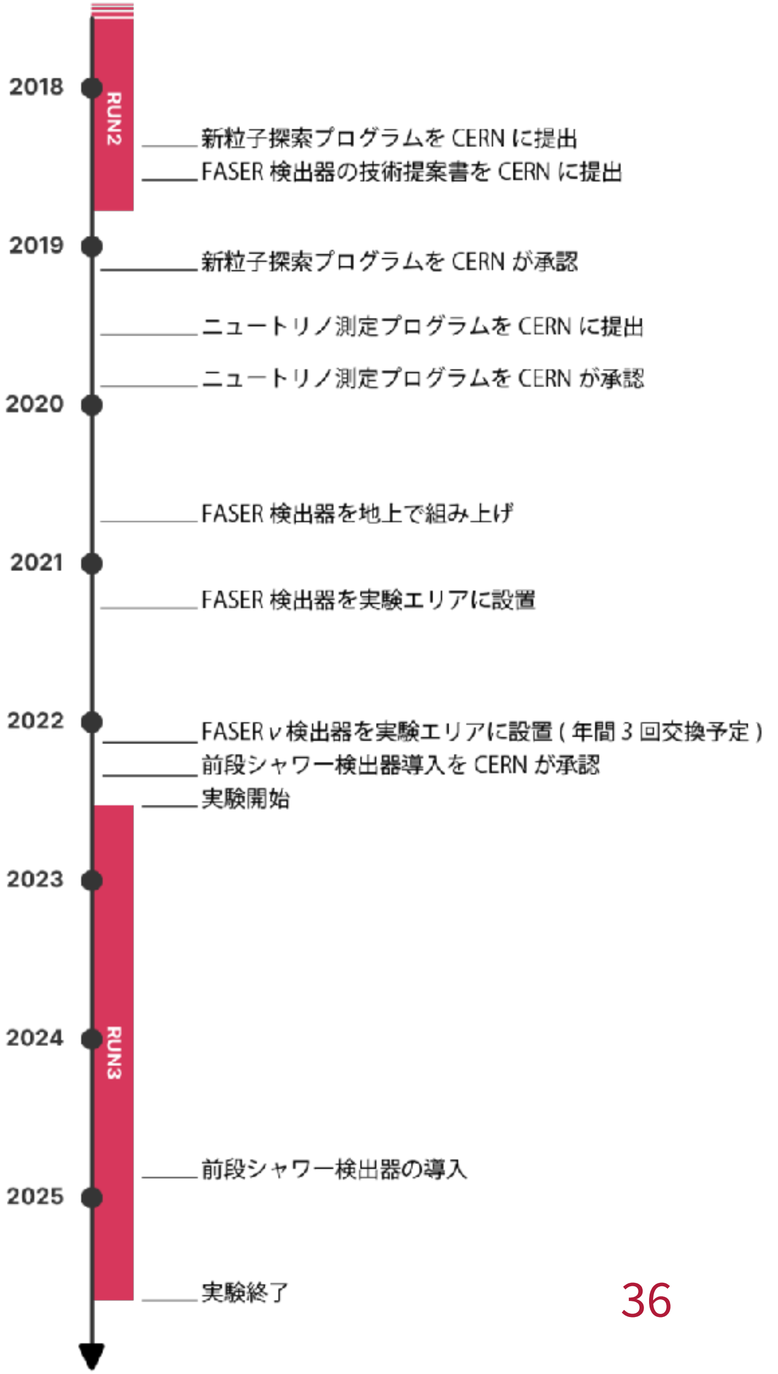
101 collaborators, 27 institutions, 11 countries

FASER



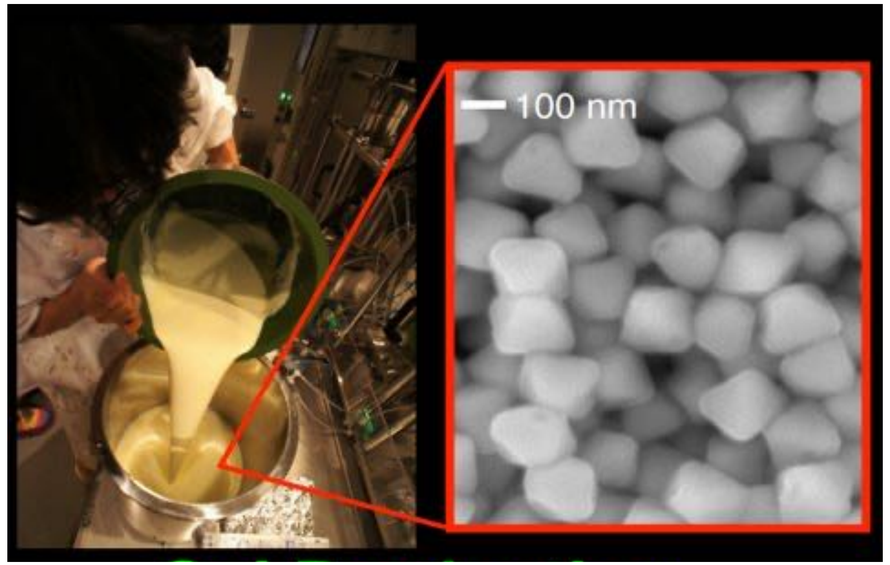
- FASER is situated in the TI12 tunnel
- Detectors were installed in 2021
- Data taking from 2022 in LHC Run3



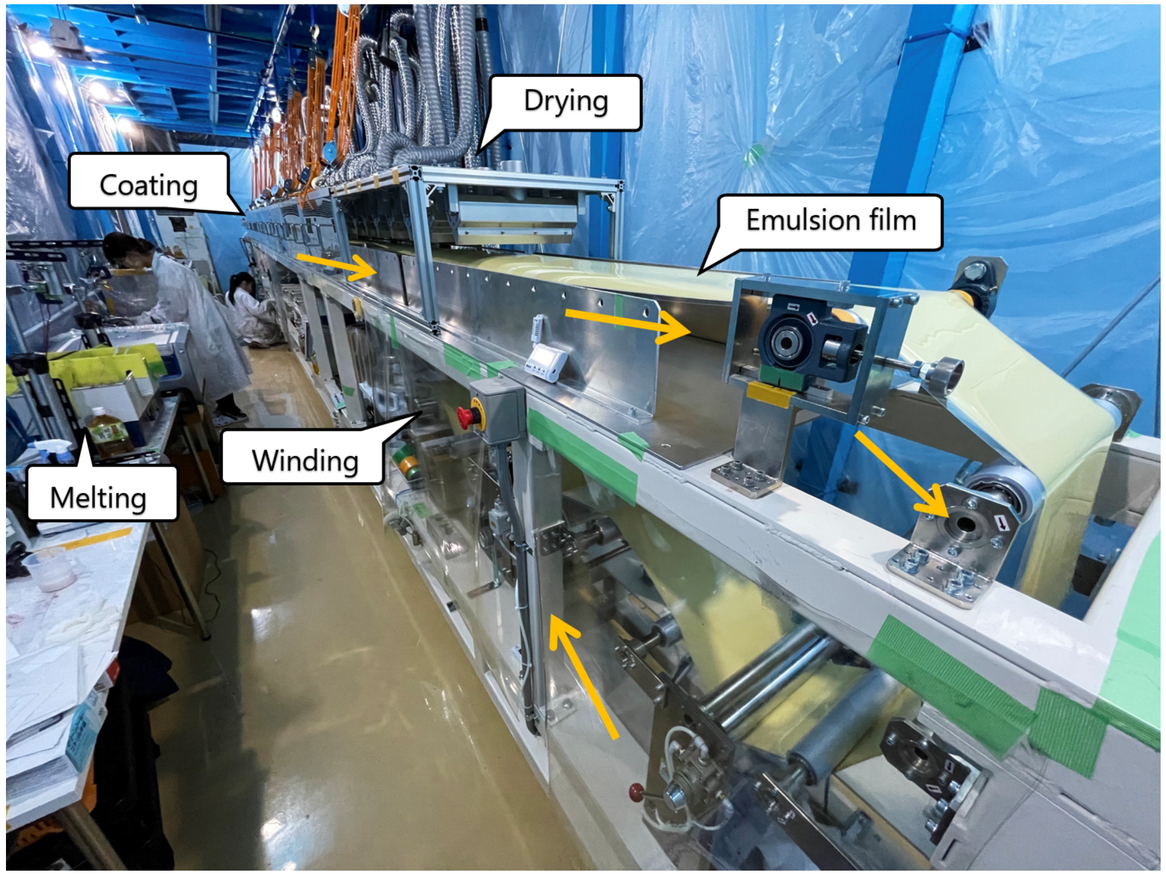


Film Production

Gel production

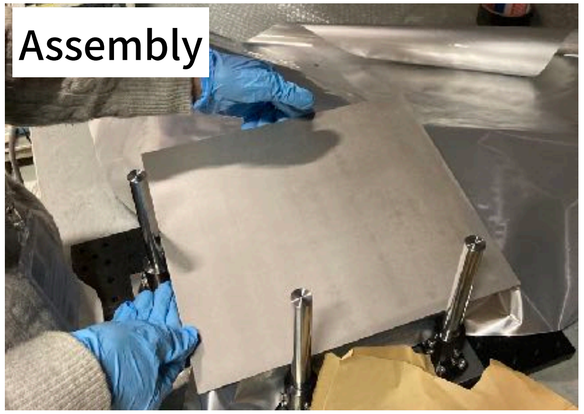


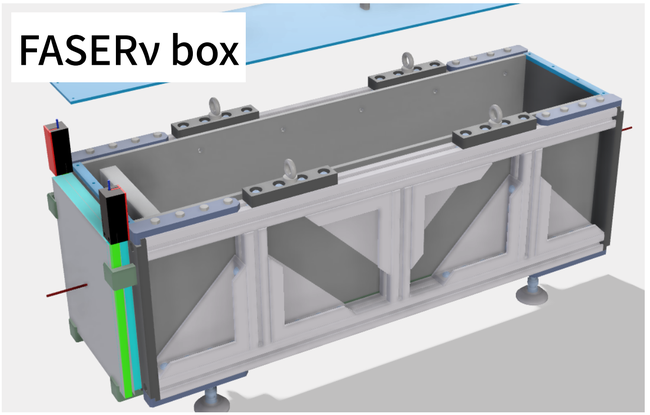
Emulsion film coating system

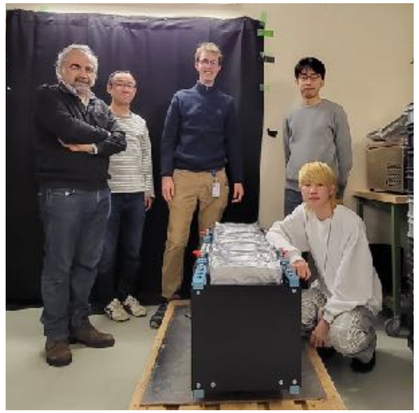


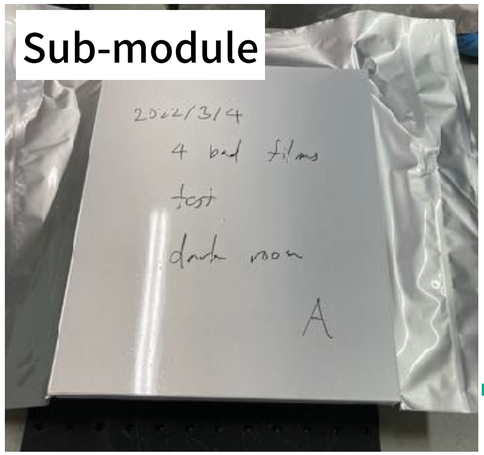
- Produced gel and film at Nagoya University
- Total area of 730 films: ~55 m^2 per replacement

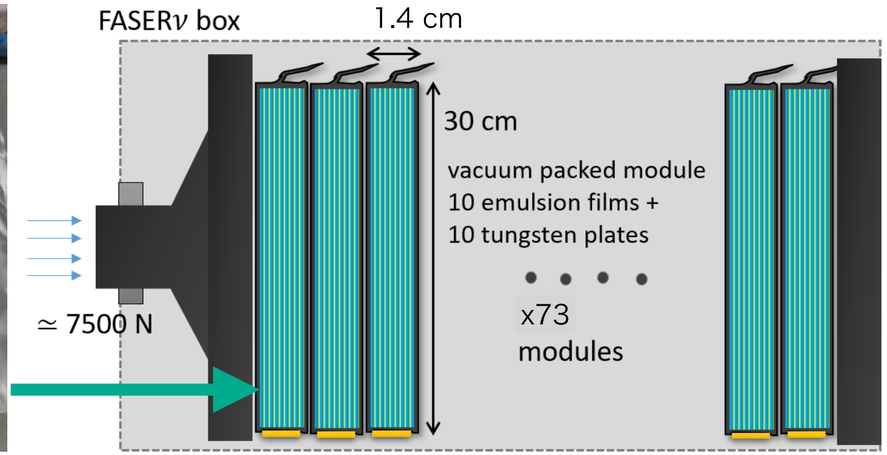
Module Assembly







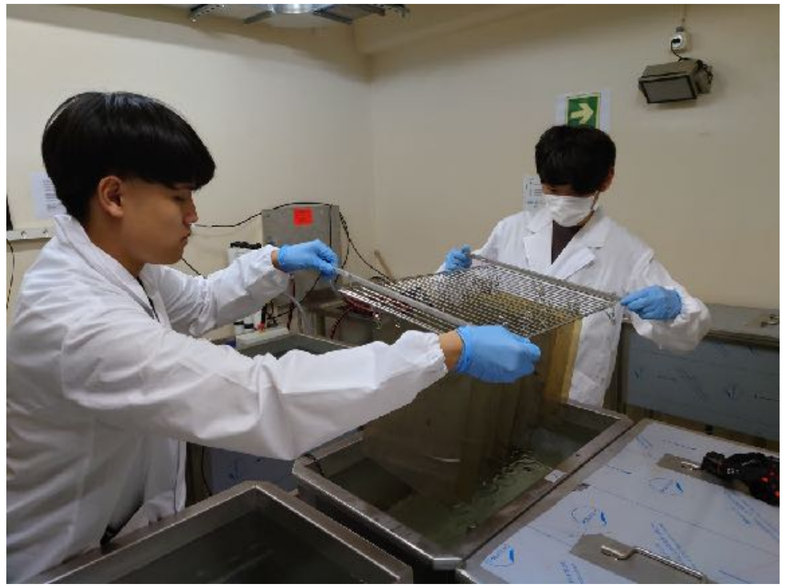


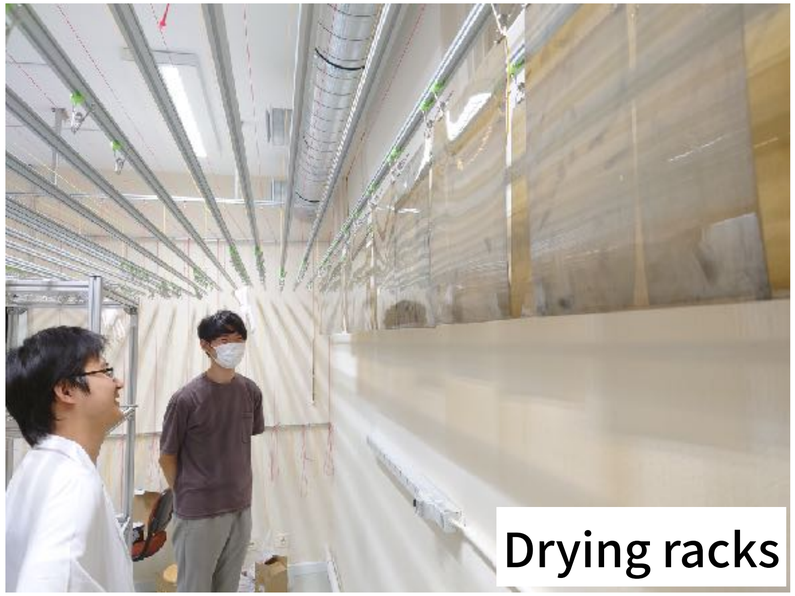


- Sub-module: 10 films + 10 tungsten plates
- Vacuum-pack to keep alignment for several months
- 10-12 days to complete 73 packs
- Apply external force (equivalent to 1 bar) to the sub-modules in the FASERv box

Film Development

Development chains

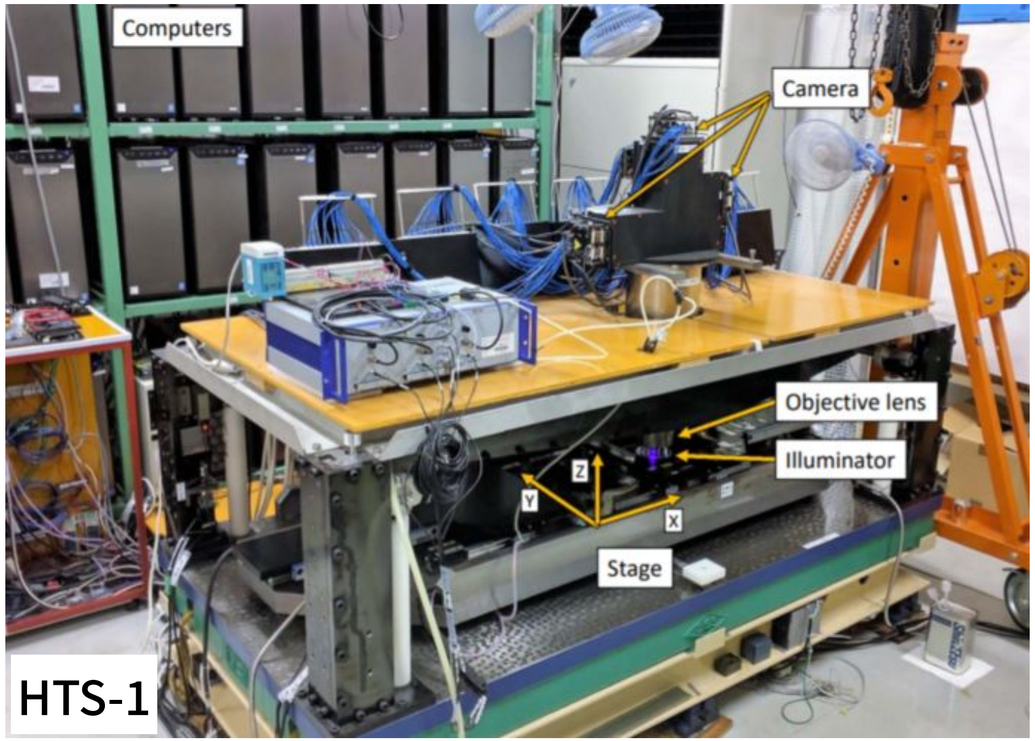


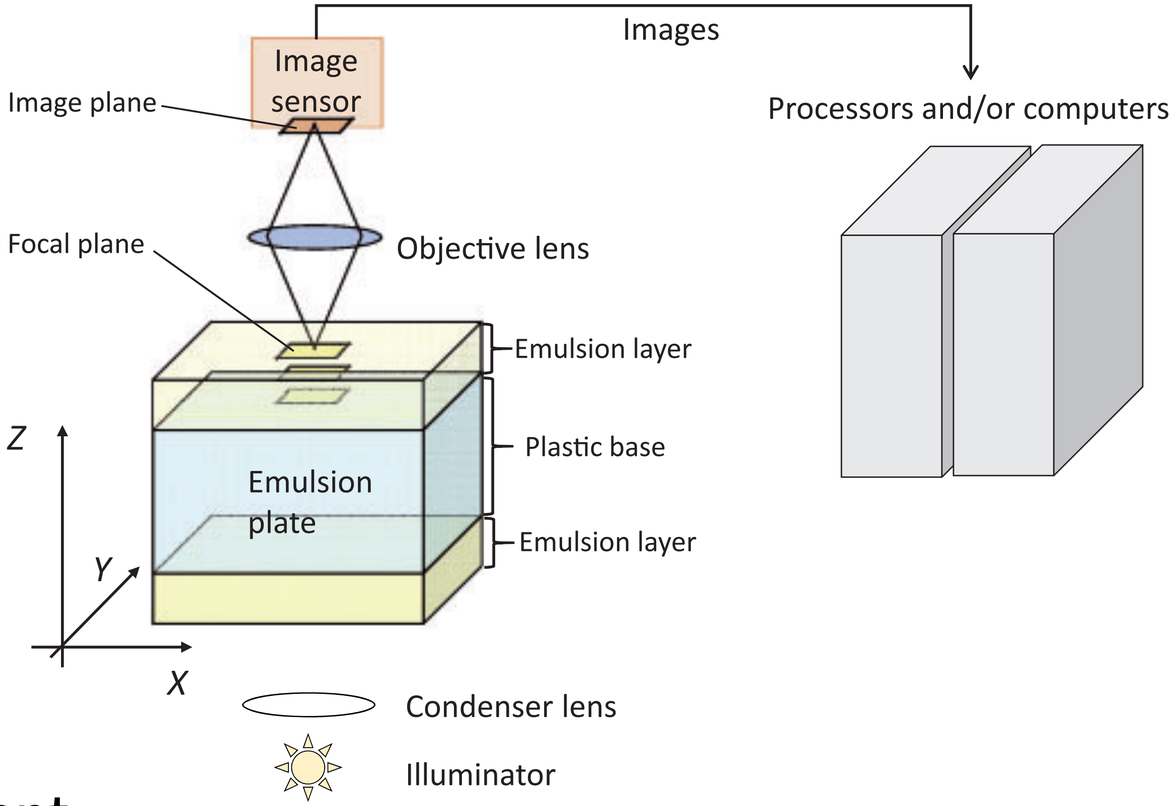

Drying racks

- **Installed new development chains and drying racks at the renovated CERN darkroom facility**
  - Sharing the facility with other emulsion experiments: NA65/DsTau, SND@LHC, etc
- **10-12 days to complete 730 films**

Readout

Prog. Theor. Exp. Phys. **10** (2017), 103H01

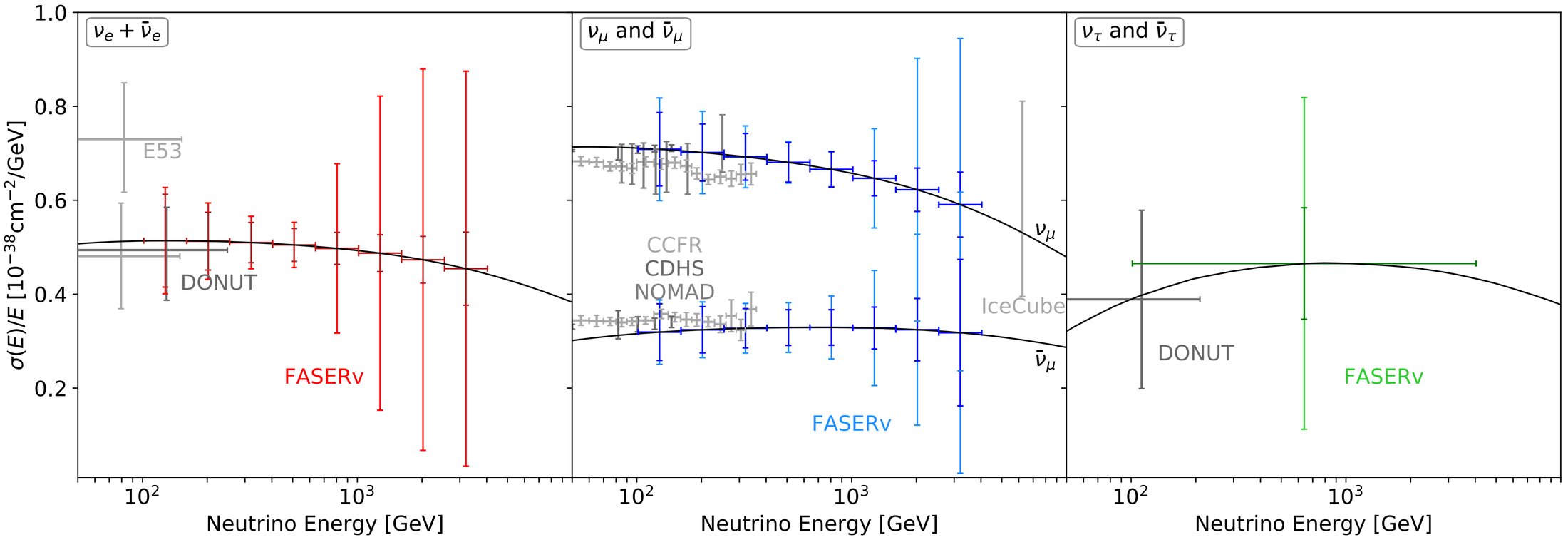




- Transport films to Japan after development
- Readout by Hyper Track Selector-1 (HTS-1)
  - Field of view: 5.1 mm × 5.1 mm
  - 60-80 minutes per a film

FASERν Cross-Section Sensitivity

(150 fb^{-1})



(inner error bars: statistical uncertainties, outer error bars: uncertainties from neutrino production rate)

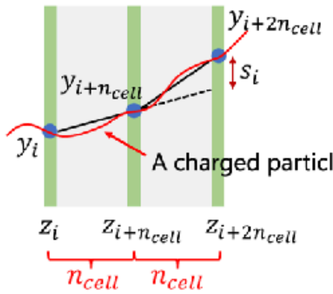
- Three flavors neutrino cross-section measurements for unexplored energy ranges
- Neutrino energy reconstruction with resolution of 30% expected from simulation studies

Momentum Measurement

Haruhi Fujimori, Neutrino 2024

Coordinate method to measure momentum

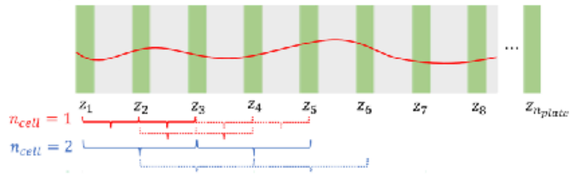
① Calculate position difference s_i



$$s^{RMS}_{plane} = \sqrt{\left(\sqrt{\frac{2}{3}}\cdot\frac{13.6MeV}{p}n_{cell}\cdot z_{cell}\sqrt{\frac{n_{cell}\cdot z_{cell}}{X_C}}\right)^2 + \left(\sqrt{6}\sigma_{pos}\right)^2} \quad ...(1)$$

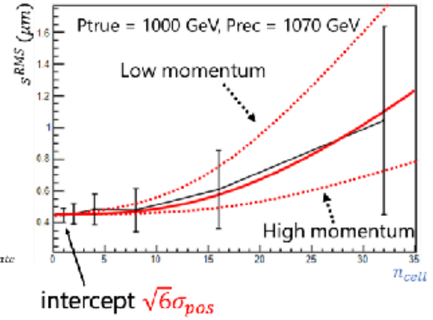
z_{cell} : The thickness of one emulsion film and tungsten plate
X_C : Compound radiation length (4.57 mm, cf: X_W=3.5 mm)
σ_{pos} : Position resolution

② Shift 1 segment and calculate s_i
③ Calculate s^{RMS} and attach error considering independent stats

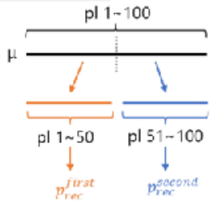


Increase n_{cell} and repeat ①~③

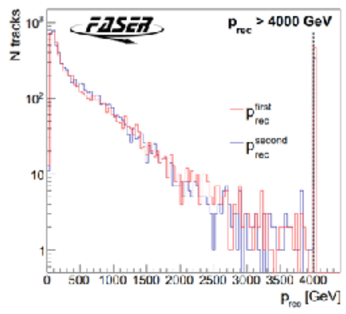
④ Plot s^{RMS} $vs.$ n_{cell}
⑤ Fit the plot with formula (1)

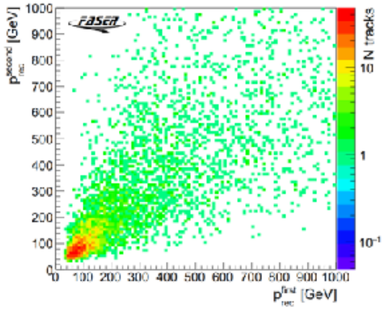


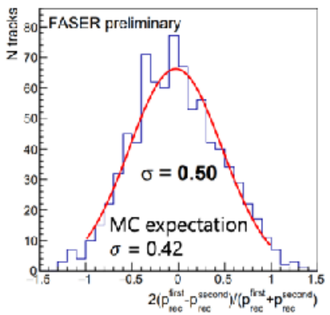
- Test reproducibility in data, by splitting long tracks into two and comparing the reconstructed momentum of the two in both data and MC.
- The uncertainty of the measurement around 200 GeV have been checked to apply momentum cut to recent FASERν analysis for removing background events
- Applied high purity selections to reject mis-connections



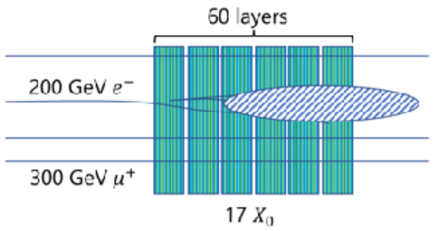
$$150 \leq \frac{p^{first}_{rec}+p^{second}_{rec}}{2} \leq 250 \text{ GeV}$$

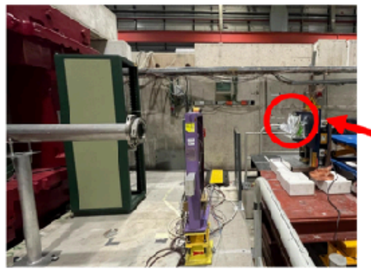


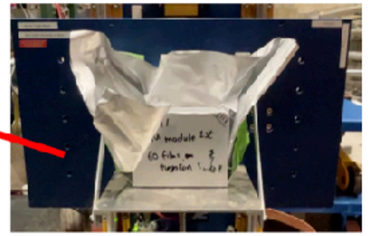




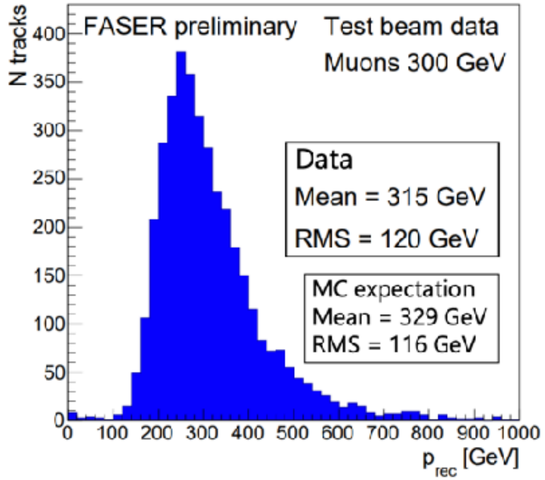
- The test beam experiment had conducted at the H4 beamline at the SPS in August 2023
- Momentum measurement with 60-layer detector, irradiated with 300 GeV muons and 200 GeV electrons
- Compared with the result of single muon MC using p_{true} = [270, 330] GeV

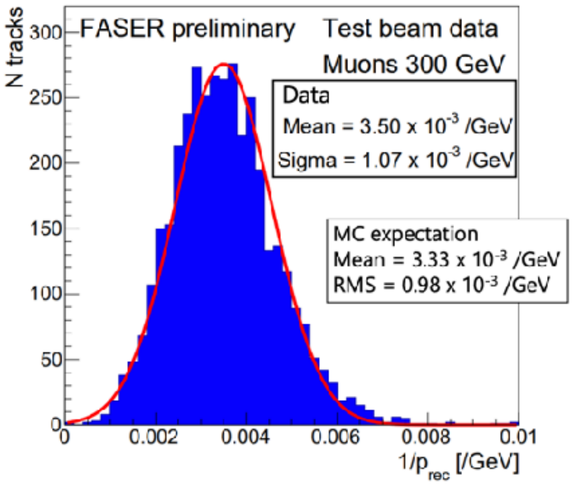






Module: 10.0 x 12.5 x 8.4 cm³





	Center value	Resolution
Test beam data	286 GeV	31%
MC expectation	300 GeV	30%

Future Prospects

Dark Photon

- Dark matter from MeV-GeV can be thermal relics
- Dark photon(A'): U(1) gauge boson, hidden sector particle

Produced in very rare meson decays:

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

- Mass $m_{A'}$
- Kinetic mixing: ε (couplings to SM fermions)

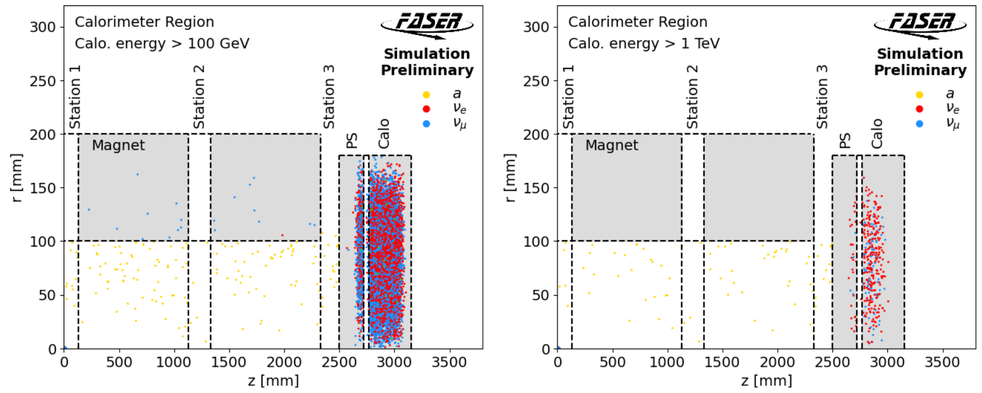
Travels long distances through matter without interacting, decays to e+e- (μ+μ-)

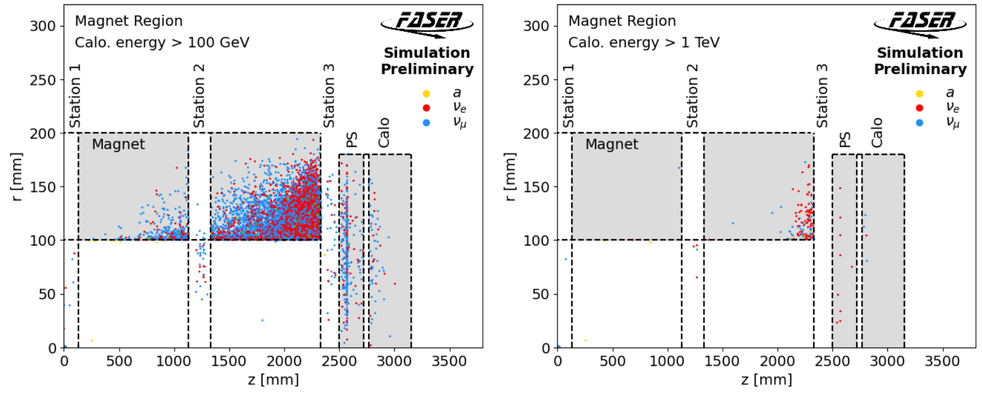
$$L = c\beta\tau\gamma \approx (80\ \mathrm{m}) \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\mathrm{TeV}}\right] \left[\frac{100\ \mathrm{MeV}}{m_{A'}}\right]^2 \qquad (E_{A'} \gg m_{A'} \gg m_e)$$

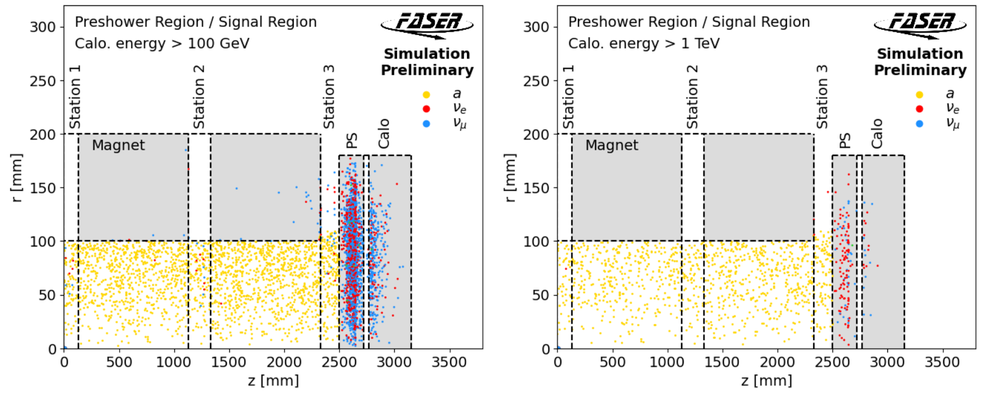
TeV energy at the LHC: **huge boost, decay lengths of ~100 m possible**

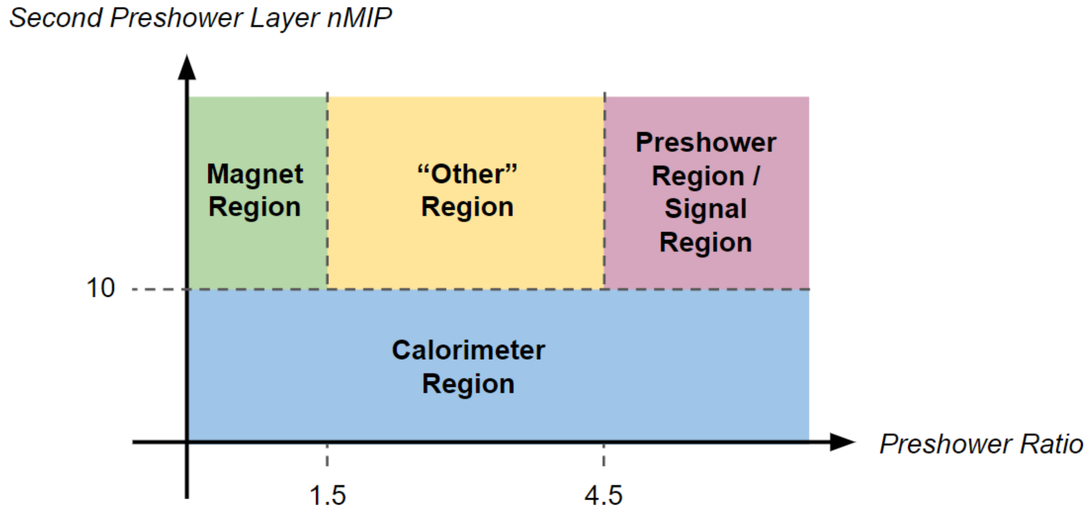
Very large number of dark photons are produced. **LHC can be a dark photon factory**

Neutrino Background (ALP)









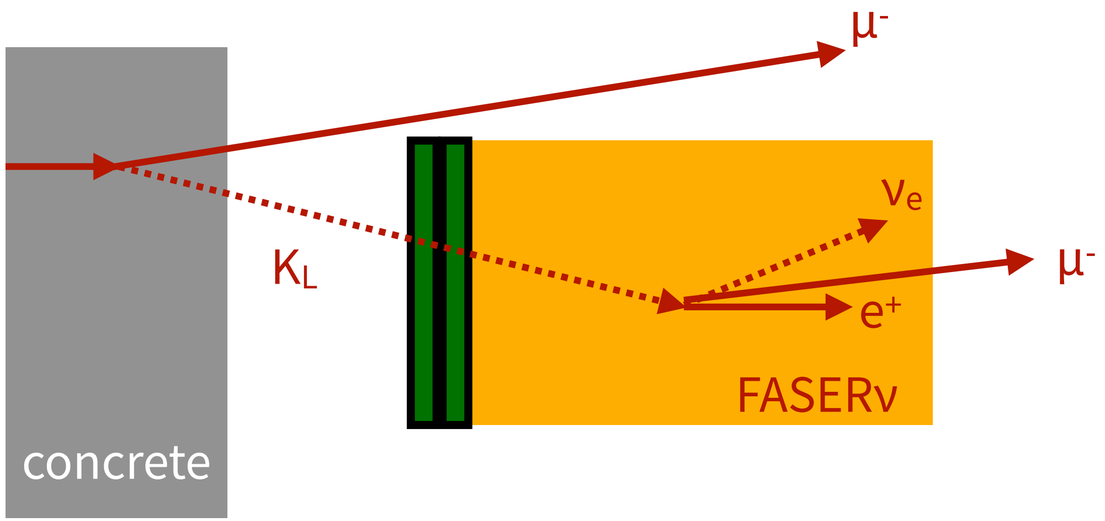
Background Estimation (1)

Veto inefficiency

Veto scintillator (2 layer)

- Estimated from events with just one veto scintillator firing
- Negligible background expected due to very high veto efficiency

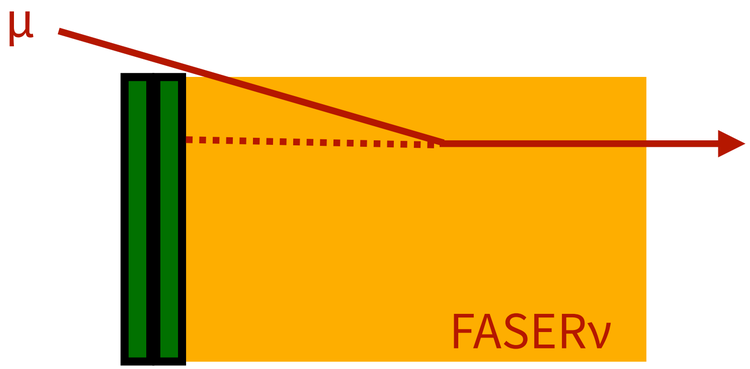
Neutral hadrons

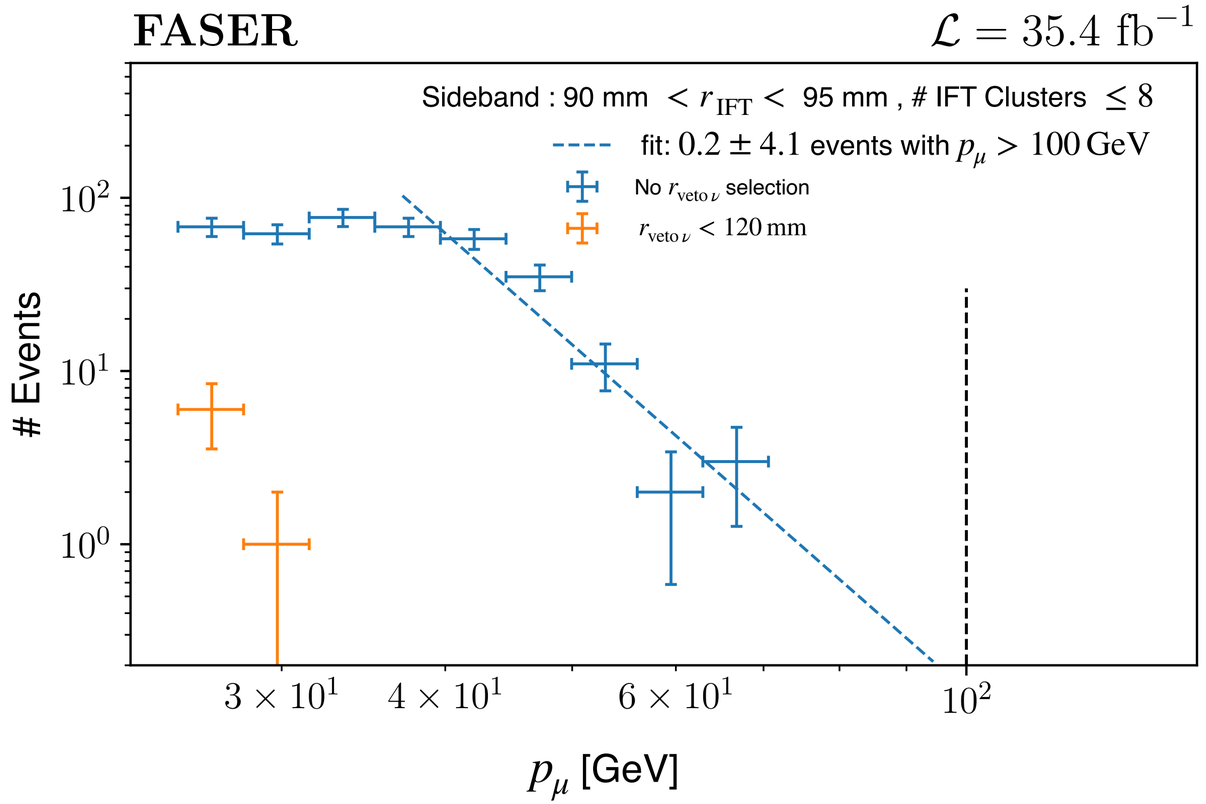


- Expect ~300 neutral hadrons with E>100 GeV
- Most are absorbed in tungsten
- Estimated from 2-step MC simulations
- Estimate 0.11 ± 0.06 events

Background Estimation (2)

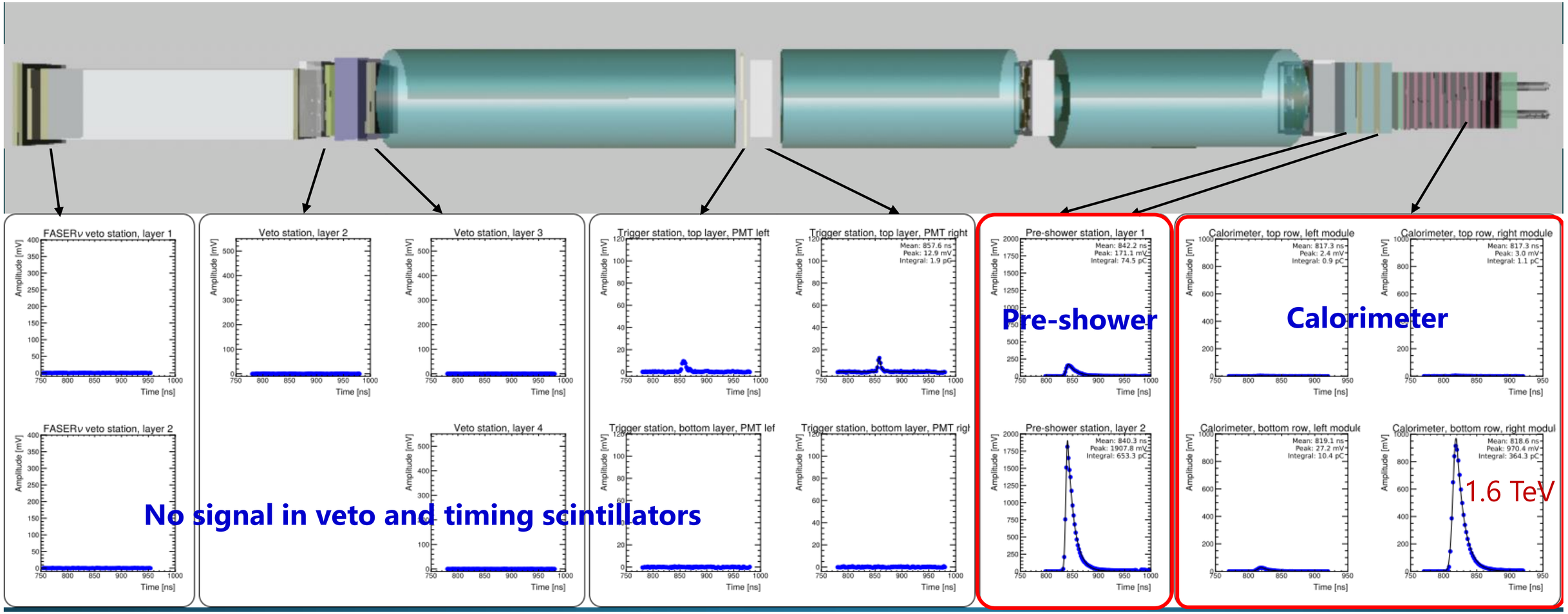
Scattered muons (geometric BG)





- Estimated from sideband
  - Fit to extrapolate to higher momentum
- Calculate scaling factor using MC simulations to extrapolate to signal region
- Estimate 0.08±1.83 events (uncertainty from varying selection)

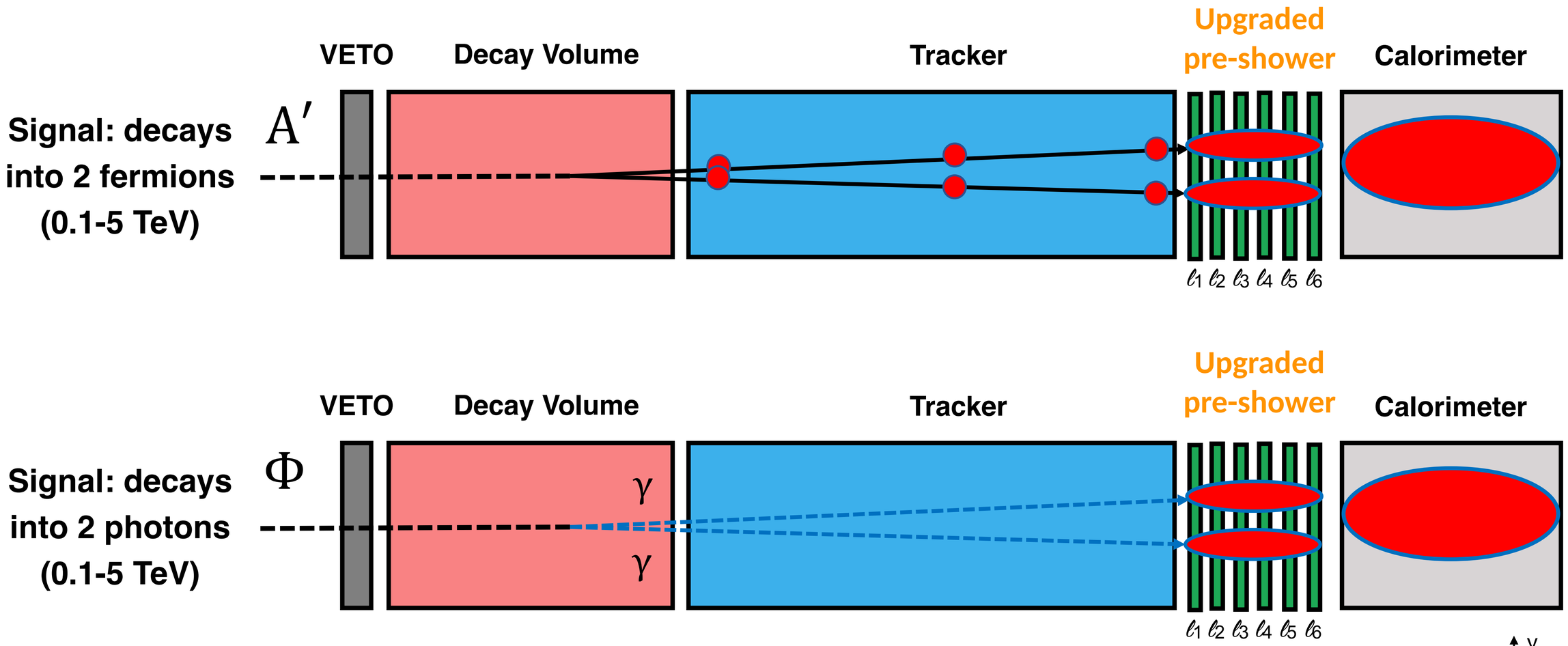
Event Display of “ALPtrino”



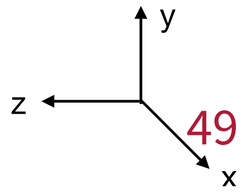
Calorimeter energy of 1.6 TeV

Upgraded Pre-shower Calorimeter

S. Zambito LHCP2023



fine X-Y granularity, high dynamic range

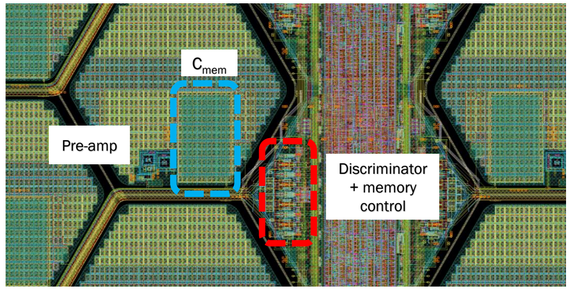


Upgraded Pre-shower Calorimeter

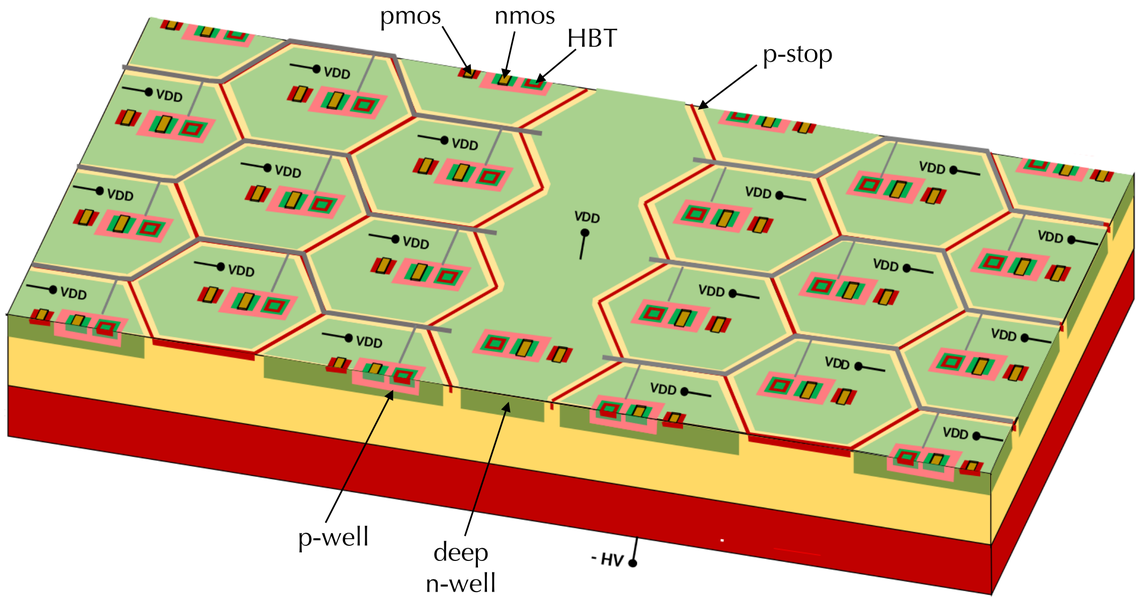
S. Zambito LHCP2023

Monolithic active pixel sensor

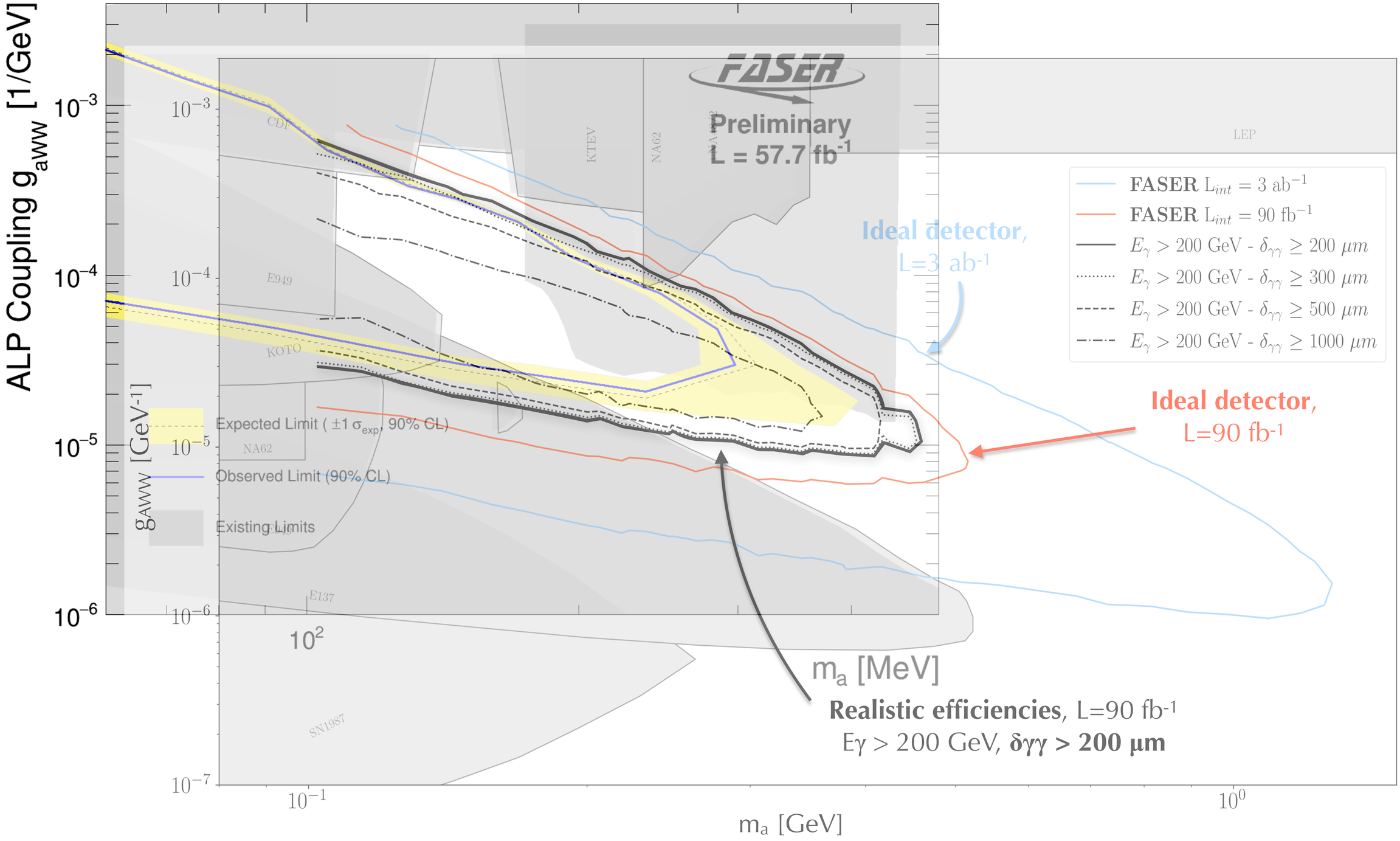
130 nm SiGe BiCMOS technology (IHP SG13G2)



- High-resistivity (220 Ω·cm) substrate, about 130 µm thickness
- Hexagonal pixels integrated as triple wells; 80 fF pixel capacitance
- High dynamic range for charge measurement (0.5÷65 fC); fast readout of many channels



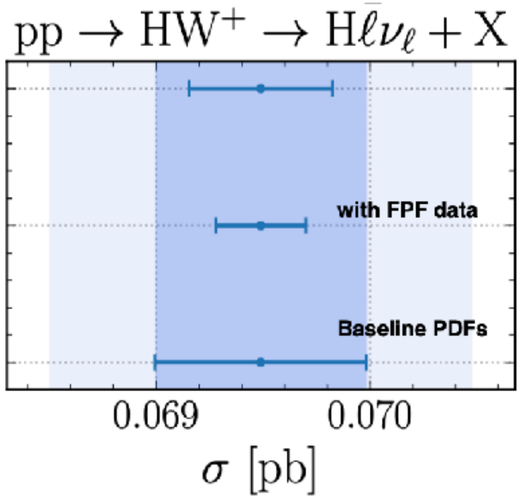
Main specifications	
Pixel Size	65 µm side (hexagonal)
Pixel dynamic range	0.5 ÷ 65 fC
Cluster size	O(1000) pixels
Readout time	< 200 µs
Power consuption	< 150 mW/cm^2
Time resolution	< 300 ps


ALP Coupling g_{aWW} [1/GeV]
g_{AWW} [GeV^{-1}]
m_a [GeV]
m_a [MeV]
FASER
Preliminary
L = 57.7 fb^{-1}
Expected Limit (±1 σ_{exp}, 90% CL)
Observed Limit (90% CL)
Existing Limits
CDF
KTEV
NA62
LEP
E949
KOTO
E137
SN1987
FASER L_{int} = 3 ab^{-1}
FASER L_{int} = 90 fb^{-1}
$E_\gamma > 200$ GeV - $\delta_{\gamma\gamma} \geq 200\ \mu m$
$E_\gamma > 200$ GeV - $\delta_{\gamma\gamma} \geq 300\ \mu m$
$E_\gamma > 200$ GeV - $\delta_{\gamma\gamma} \geq 500\ \mu m$
$E_\gamma > 200$ GeV - $\delta_{\gamma\gamma} \geq 1000\ \mu m$
Ideal detector, L=3 ab^{-1}
Ideal detector, L=90 fb^{-1}
Realistic efficiencies, L=90 fb^{-1}
Eγ > 200 GeV, δγγ > 200 μm

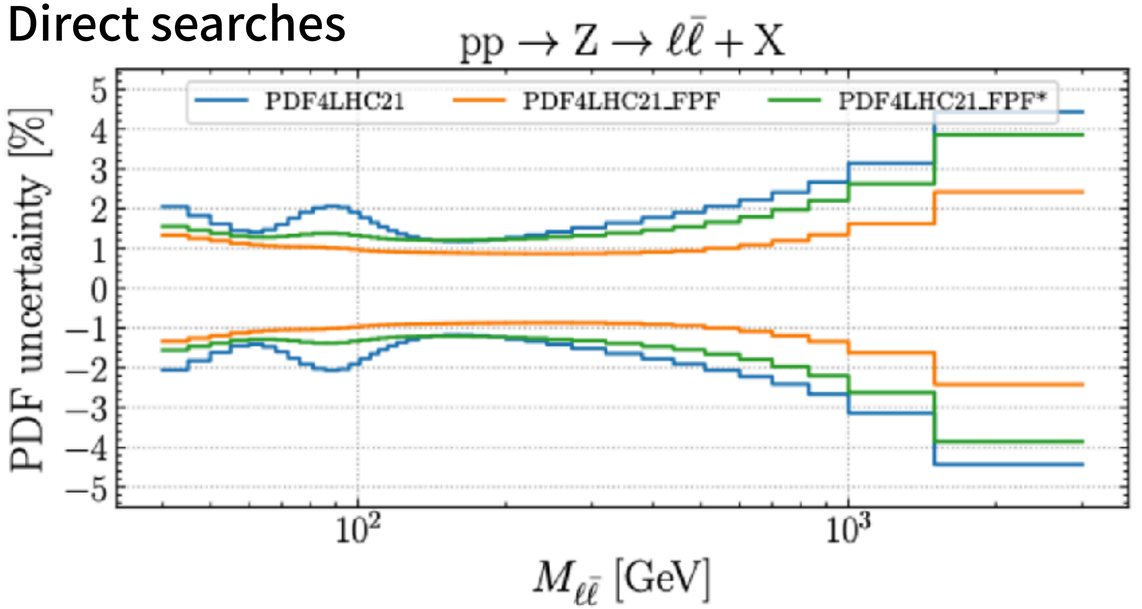
Impact on BSM Searches at the HL-LHC

Juan Rojo (LHCP2024)

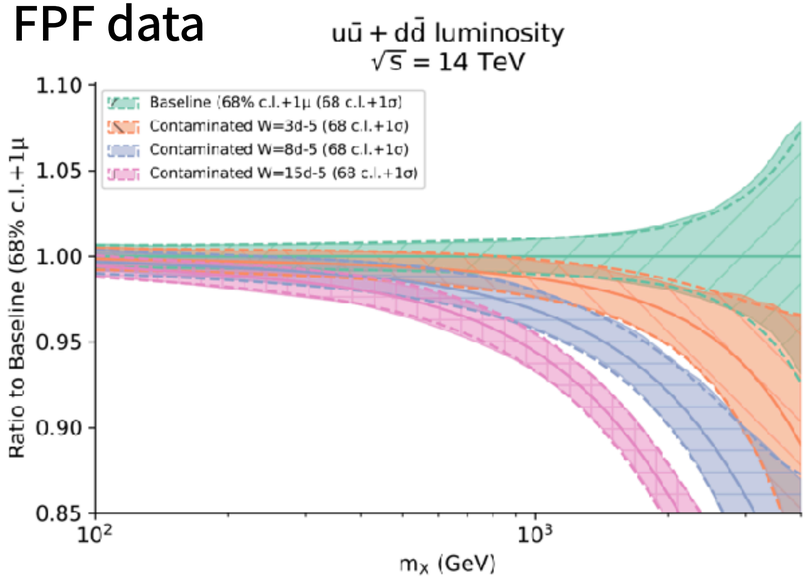
Higgs coupling

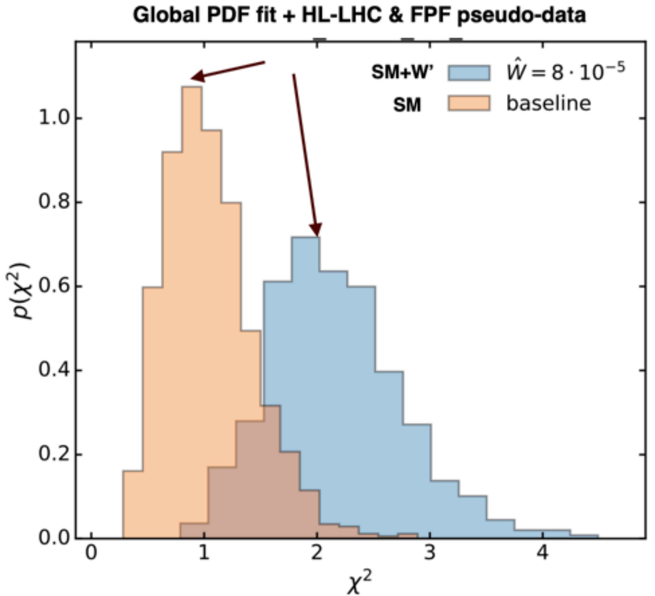


Direct searches



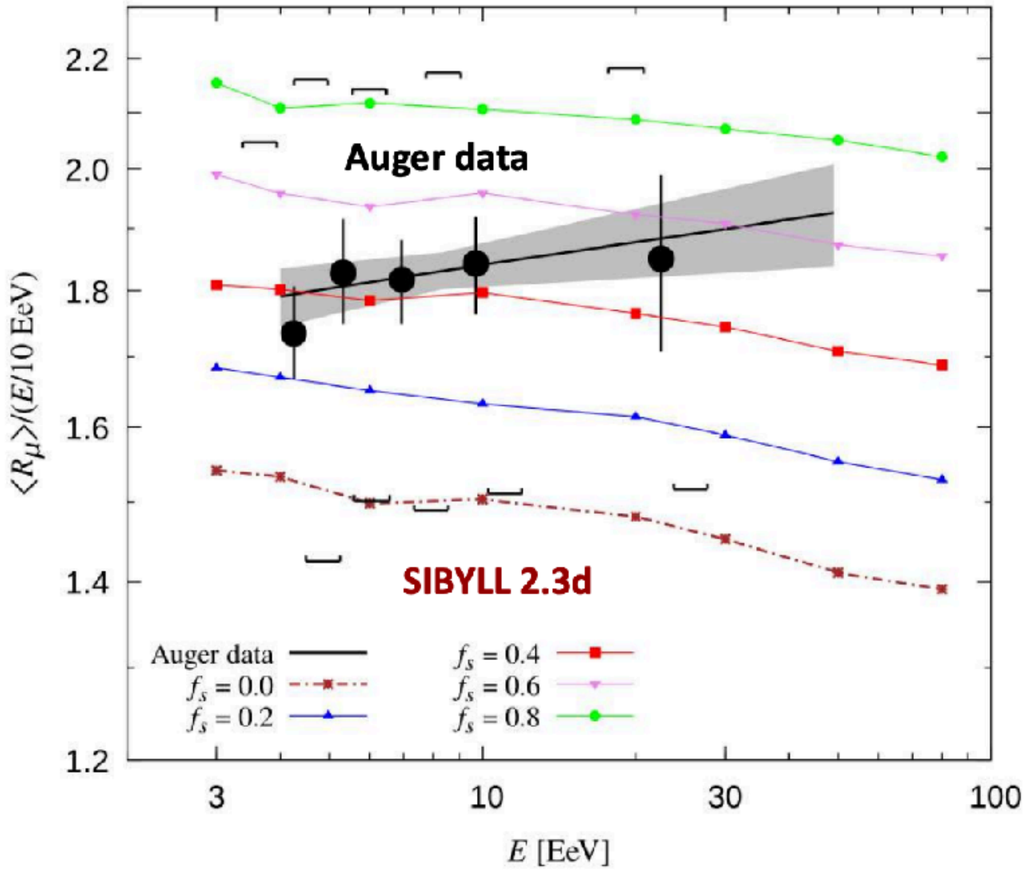
SMEFT analyses with FPF data





Muon Puzzle

Subir Sarkar (7th FPF workshop)

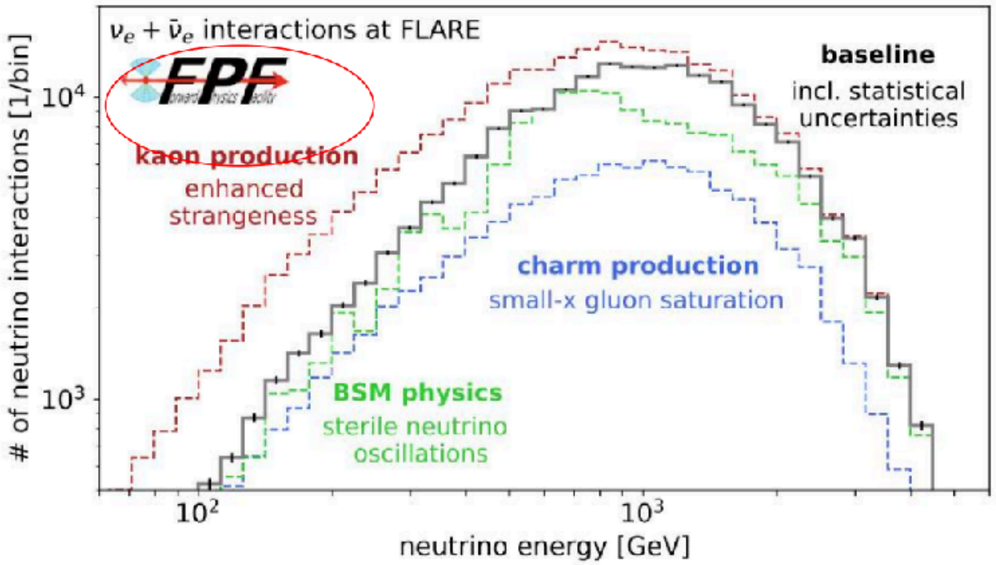


Turning a fraction *fs* of forward pions into kaons … can solve muon puzzle!

Anchordoqui *et al*, *JHEAp* **34**:19,2022

There is a suggestion of this in ALICE data …

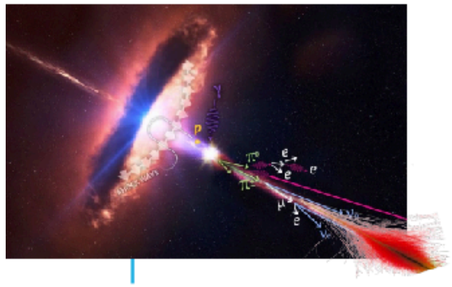
(*Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions,* ALICE collaboration, *Nature Phys.* 13:535,2017)



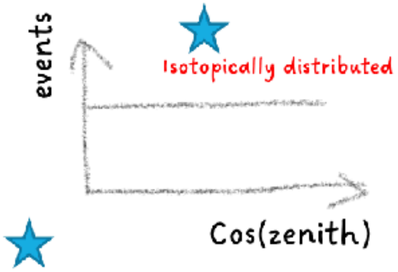
This can be tested directly at the FPF

Prompt Neutrino

Lu Lu (7th FPF Workshop)



- Hadronic interactions proton-proton or proton-gamma at source
- Super massive blackhole accelerator beam many light years of baseline
- Energy ranges from TeV to EeV



Prompt Neutrino

Lu Lu (7th FPF Workshop)