Measuring Neutrino Cross-Sections with FASERν

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DPF Meeting

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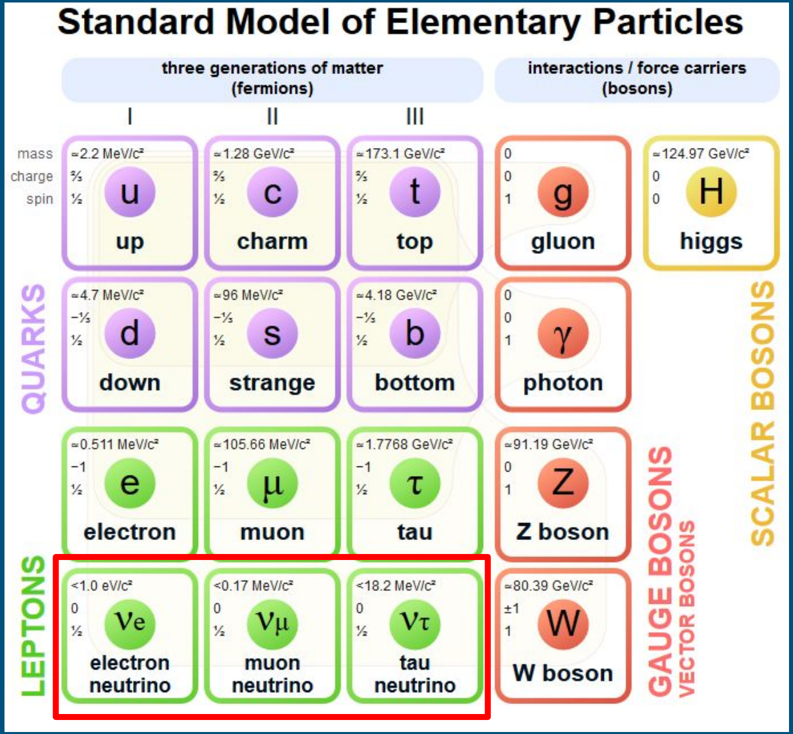
Supported by:

Background - Physics
Neutrinos

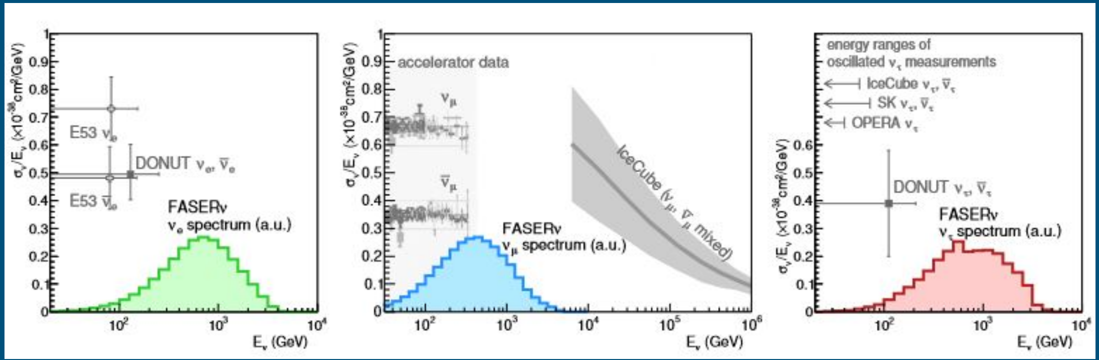
- The most elusive particles in the Standard Model (SM)
- First postulated by Enrico Fermi ~1932
  - First discovered in 1956 at nuclear reactor
- No collider-produced neutrino has ever been detected
- Many big questions about neutrinos:
  - Neutrino mass / oscillations / CP violation
- For all of these, we need to know how the neutrino interacts with the detector
  - How strongly do neutrinos interact with nucleons?

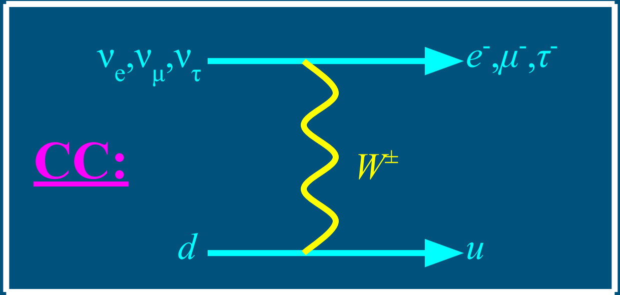


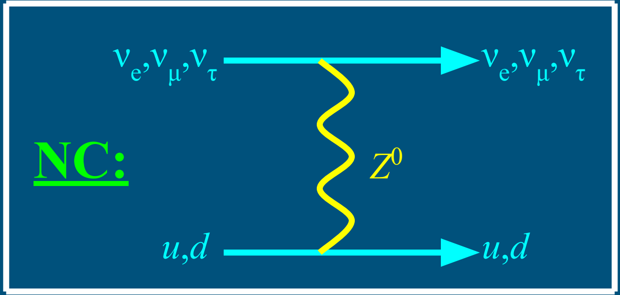
Background - Physics
Neutrino-nucleon interactions

- Neutrinos interact only weakly, via charged (CC) or neutral current (NC) interactions
- Scattering can be (quasi-)elastic (< 20 GeV) or deep inelastic (> 20 GeV)
- Big gaps in neutrino-nucleon cross section measurements!

[Source]



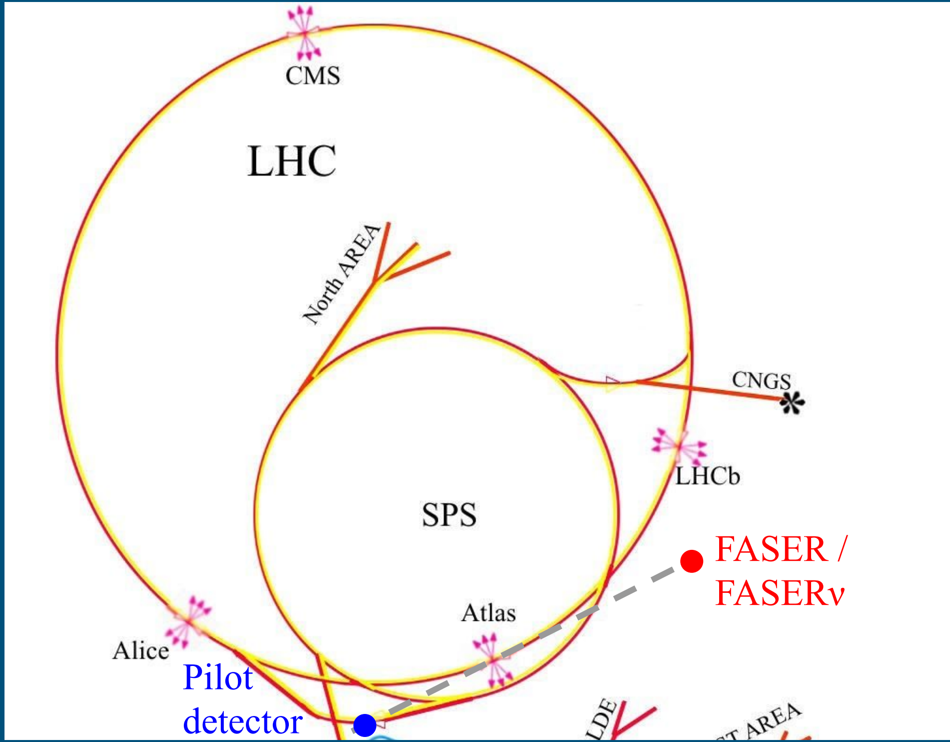




Background - Location
CERN LHC

- 27 km underground particle accelerator on border between France and Switzerland
- Accelerates protons to 7 TeV in opposite directions

[Source]

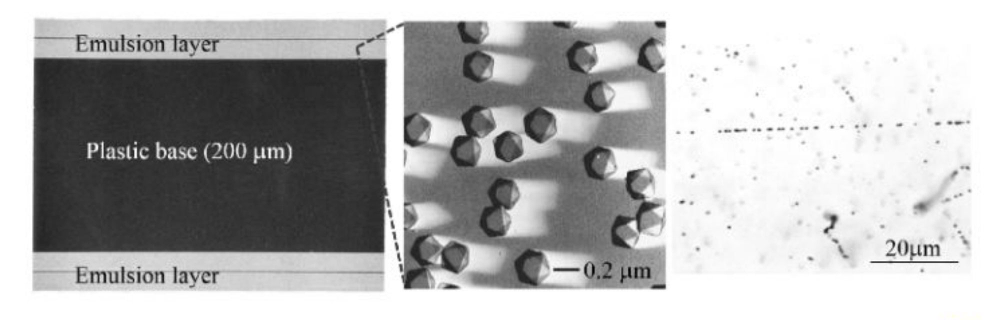


Background - Location
Production and propagation of neutrinos

- LHC uses *pp* collisions
  - Beams collide at ATLAS interaction point, producing many hadrons (e.g. π, K, D) in forward region
  - Decay products at IP include charged particles and neutrinos
  - Charged particles ($E < 7$ TeV) deflected via LHC magnets
  - Neutrinos propagate through 100 m of rock to FASERν 480 m away from ATLAS IP [ICHEP 2020]

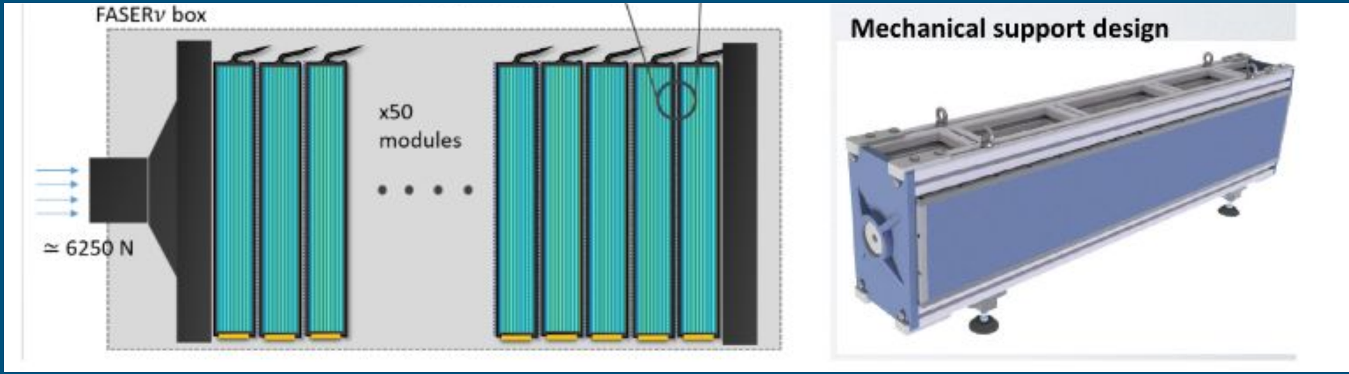
Background - Detectors
Emulsion detector - principles

[Source]



- Emulsion films: 50 μm layer of emulsion gel of AgBr crystals either side of plastic base
- Charged particle ionization recorded and can be amplified and fixed by chemical development of film
- Track position resolution ~ 50 nm
- Angular resolution ~ 0.35 mrad

[Source]

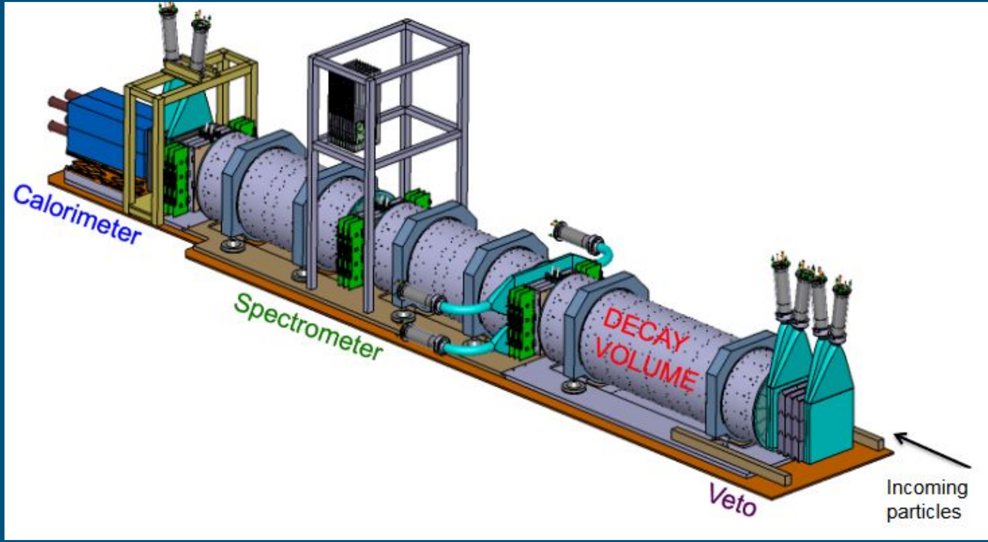


Background - Detectors

FASER - the ForwArd Search ExpeRiment

[Source]

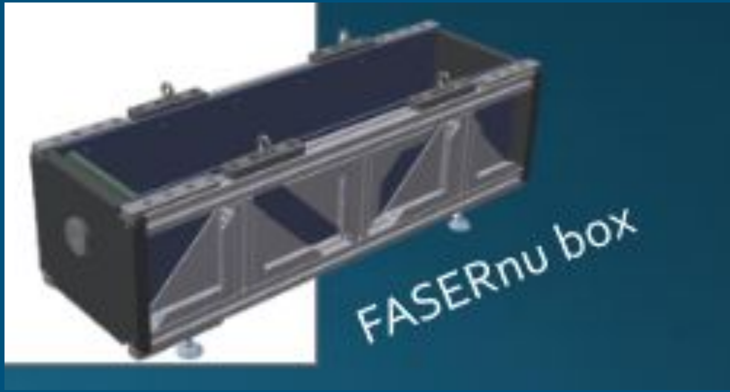
- Small detector being installed in TI12 maintenance tunnel
- Three tracking stations
  - 3 tracker planes / tracking station
  - 8 SCT modules / tracker plane
  - SCT modules tilted relative to each other
- See Savannah's talk: https://indico.cern.ch/event/1034469/contributions/4431709/



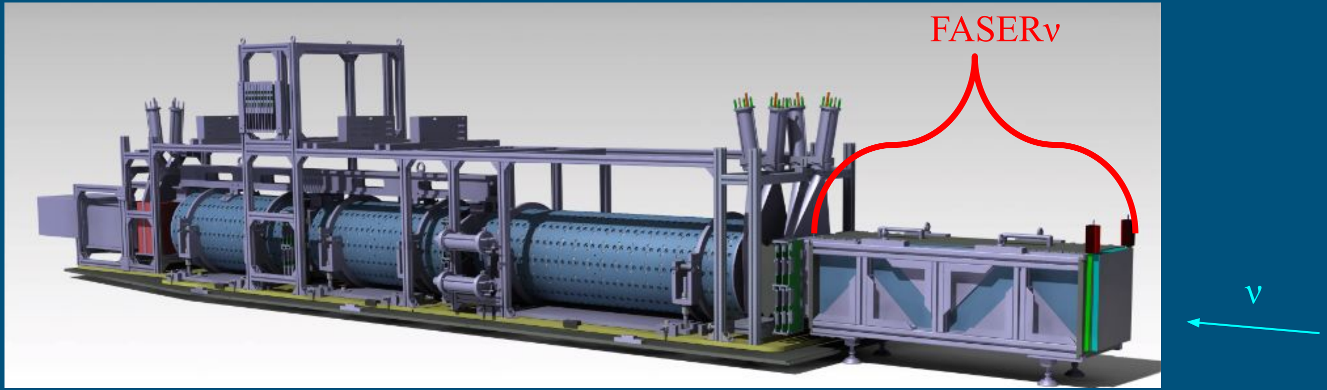
Background - Detectors

FASERν

[Source]



- Emulsion detector containing alternating tungsten plates and emulsion layers to detect collider neutrinos
    - Measure cross-sections for (anti)neutrino interactions
    - Will detect collider-produced neutrinos for the first time
- Dimensions: 0.25m × 0.20m × 1.15m
- Will be able to distinguish 3 flavours of neutrinos

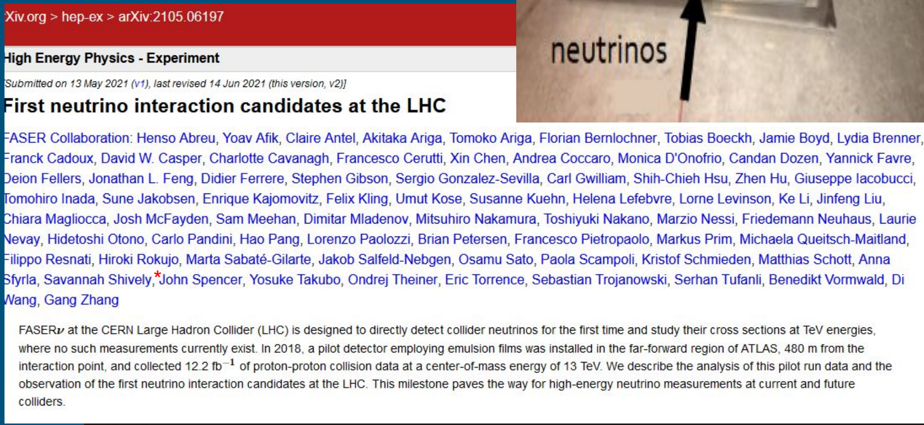


Background - Detectors

FASERν Pilot Detector

[ICHEP 2020]

- Two modules installed in TI18 in September 2018
  - Lead module (14 kg): 101 1-mm thick Pb plates
  - Tungsten module (15 kg): 120 0.5-mm thick W plates
- Absorber plates interleaved with emulsion films
- Pilot run (September-October 2018):
  - 12.2 fb^{-1} of data (integrated luminosity)
  - From data, first neutrino interaction candidates were identified at the LHC
  - https://arxiv.org/abs/2105.06197



Xiv.org > hep-ex > arXiv:2105.06197

High Energy Physics - Experiment

Submitted on 13 May 2021 (v1), last revised 14 Jun 2021 (this version, v2)]

First neutrino interaction candidates at the LHC

FASER Collaboration: Henso Abreu, Yoav Afik, Claire Antel, Akitaka Ariga, Tomoko Ariga, Florian Bernlochner, Tobias Boeckh, Jamie Boyd, Lydia Brenner, Franck Cadoux, David W. Casper, Charlotte Cavanagh, Francesco Cerutti, Xin Chen, Andrea Coccaro, Monica D'Onofrio, Candan Dozen, Yannick Favre, Deion Fellers, Jonathan L. Feng, Didier Ferrere, Stephen Gibson, Sergio Gonzalez-Sevilla, Carl Gwilliam, Shih-Chieh Hsu, Zhen Hu, Giuseppe Iacobucci, Tomohiro Inada, Sune Jakobsen, Enrique Kajomovitz, Felix Kling, Umut Kose, Susanne Kuehn, Helena Lefebvre, Lorne Levinson, Ke Li, Jinfeng Liu, Chiara Magliocca, Josh McFayden, Sam Meehan, Dimitar Mladenov, Mitsuhiro Nakamura, Toshiyuki Nakano, Marzio Nessi, Friedemann Neuhaus, Laurie Nevay, Hidetoshi Otono, Carlo Pandini, Hao Pang, Lorenzo Paolozzi, Brian Petersen, Francesco Pietropaolo, Markus Prim, Michaela Queitsch-Maitland, Filippo Resnati, Hiroki Rokujo, Marta Sabaté-Gilarte, Jakob Salfeld-Nebgen, Osamu Sato, Paola Scampoli, Kristof Schmieden, Matthias Schott, Anna Sfyrla, Savannah Shively,*John Spencer, Yosuke Takubo, Ondrej Theiner, Eric Torrence, Sebastian Trojanowski, Serhan Tufanli, Benedikt Vormwald, Di Wang, Gang Zhang

FASERν at the CERN Large Hadron Collider (LHC) is designed to directly detect collider neutrinos for the first time and study their cross sections at TeV energies, where no such measurements currently exist. In 2018, a pilot detector employing emulsion films was installed in the far-forward region of ATLAS, 480 m from the interaction point, and collected 12.2 fb^{-1} of proton-proton collision data at a center-of-mass energy of 13 TeV. We describe the analysis of this pilot run data and the observation of the first neutrino interaction candidates at the LHC. This milestone paves the way for high-energy neutrino measurements at current and future colliders.

CERN ABOUT NE

Voir en français

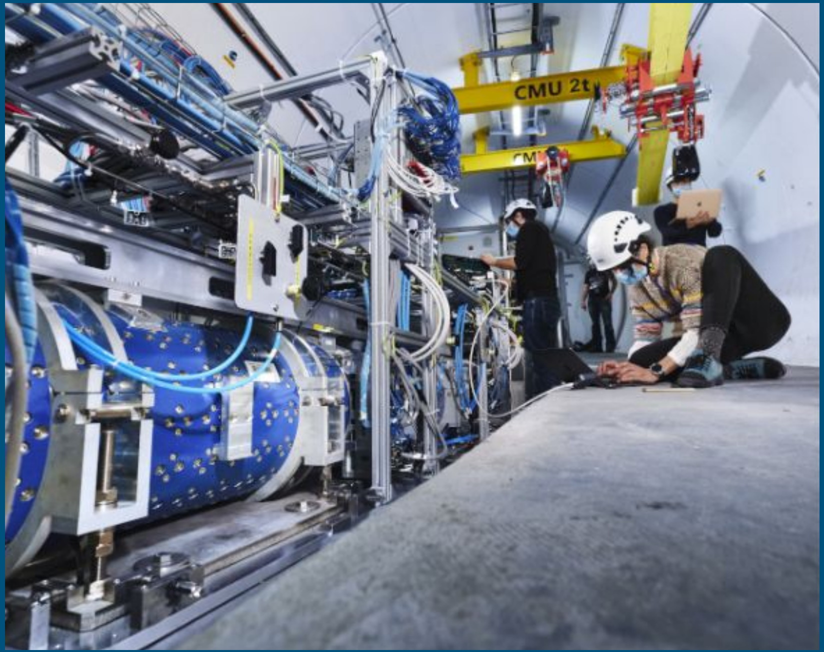
FASER catches first candidate collider neutrinos

The result paves the way for studies of high-energy neutrinos at current and future particle colliders

2 JUNE, 2021 | By Ana Lopes

Installation of FASER and FASERν

- FASER was installed March-April 2021
- FASERν approved by CERN
  - Will be installed this year
  - Run 3 begins in 2022

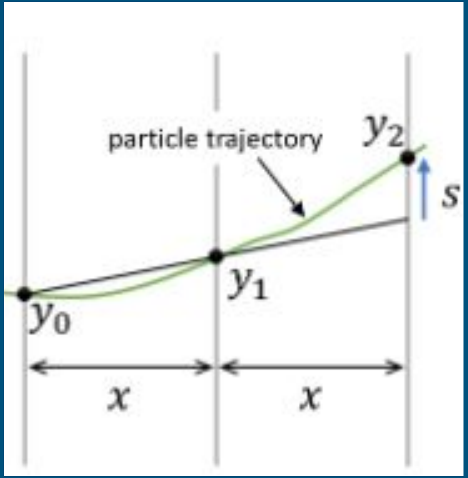


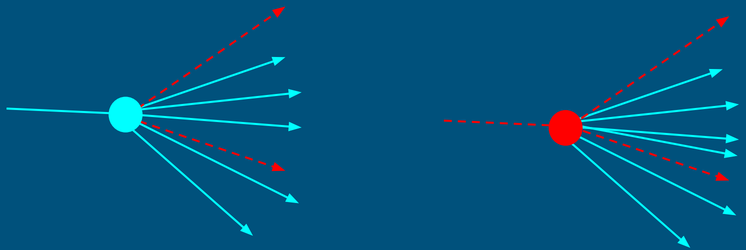
Reconstruction Algorithm

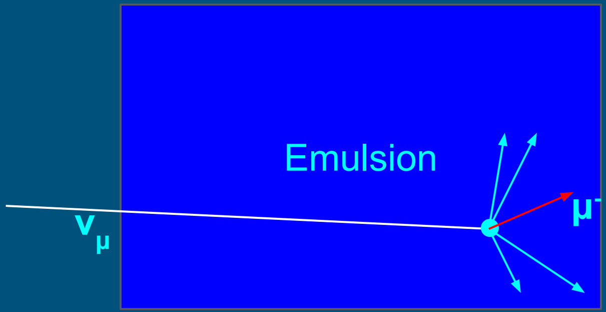
FASERν vertex and energy reconstruction

- Energy reco from multiple Coulomb scattering
  - Particle trajectory deflected by s due to MCS
  - Fit *s* to function of momentum
  - P(best fit) = reconstructed momentum
- Vertex ID: Find vertices w/ ≥5 (charged) tracks
  - One charged track is high-energy lepton
  - Reject vertices with incoming charged track
  - Require reconstructed energy > 600 GeV

[1908.02310]



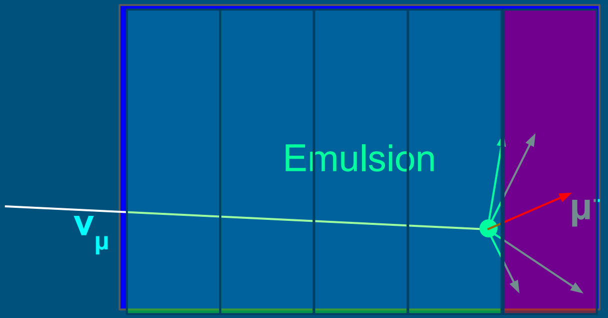




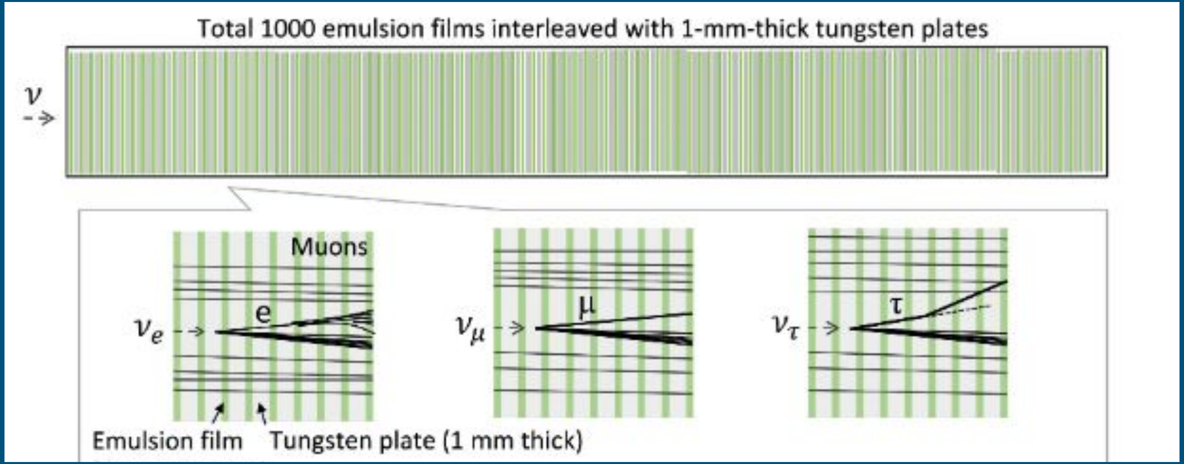
Reconstruction Algorithm

Acceptance

- FASERν is 10.1 radiation lengths long (10.1λ)
- After vertex reconstruction, we accept only vertices outside the last 2λ
- Last 2λ is used for lepton identification
- By identifying outgoing charged leptons, we determine neutrino flavour
- Signatures:
- ν_e: Electron EM shower
- ν_μ: Straight track (muon)
- ν_τ: Kinked track (decaying τ)



[2001.03073]

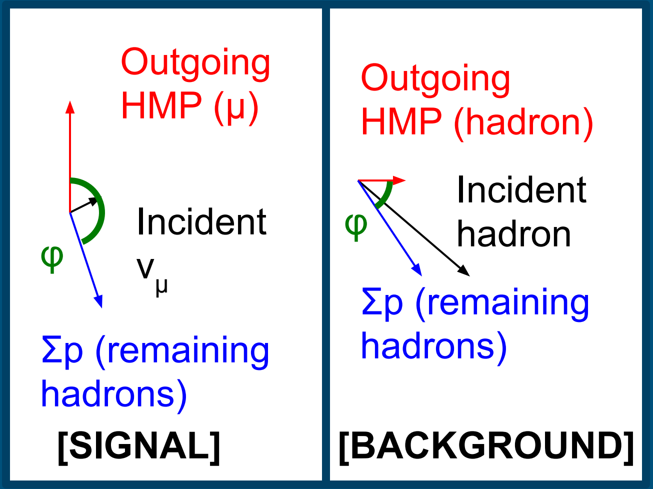


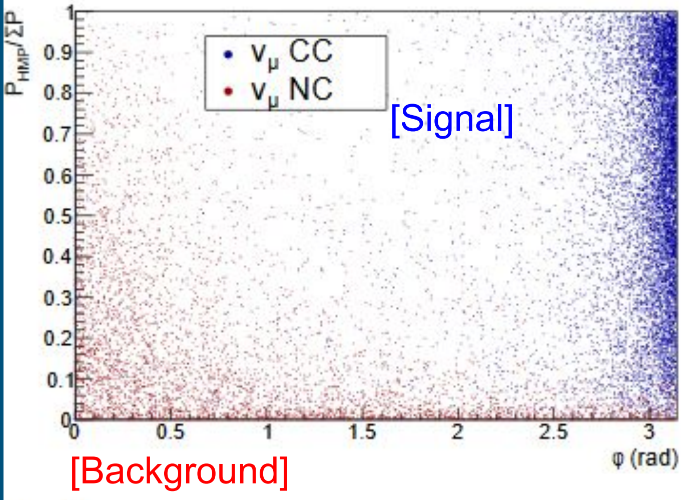
Cross Section Sensitivity Study

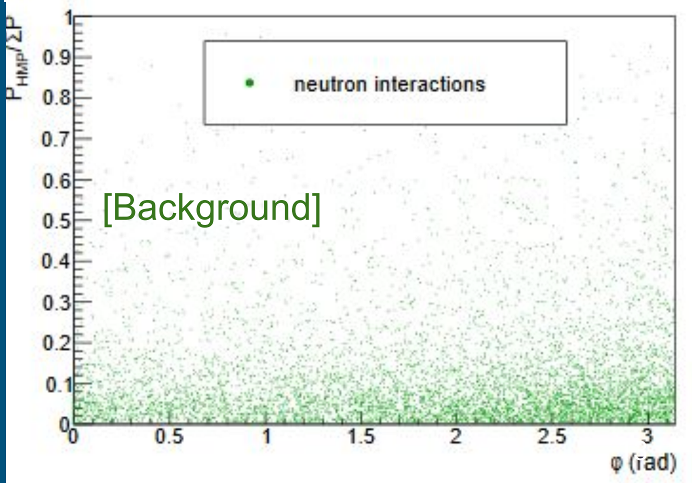
Lepton identification (μ)

- Identify muon as highest-momentum particle (HMP)
- Consider azimuth φ in transverse plane and momenta p_{HMP}, Σp shown below
- Signal: φ sharply peaked, large $p_{HMP}/\Sigma p$
- Hadronic background: φ spread out, small $p_{HMP}/\Sigma p$

[1908.02310]



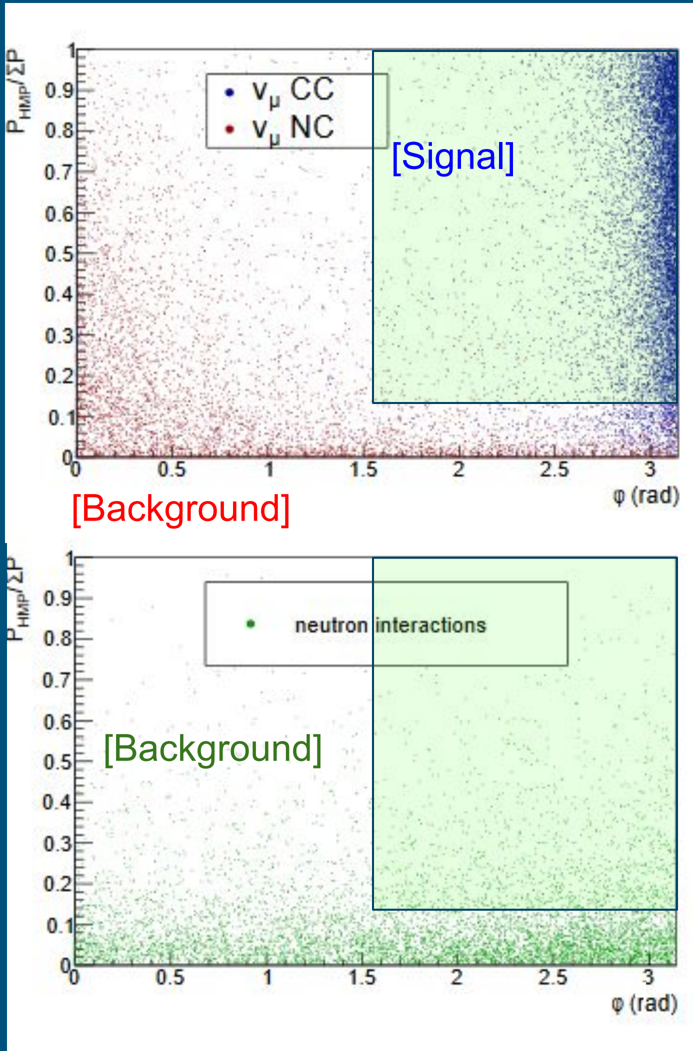




Cross Section Sensitivity Study

Muon ID efficiency

- For events passing vertex ID (≥5 charged tracks), want to separate:
  - ν_μ CC events (signal)
  - ν_μ NC events or hadron events with high-energy hadron misidentified as muon (background) [1908.02310]
- Apply cuts to φ and p_{HMP} (right) to reduce background
- Result: $\varepsilon_{\nu\mu,CC} = 0.86$
- With these cuts, can reduce background to essentially negligible

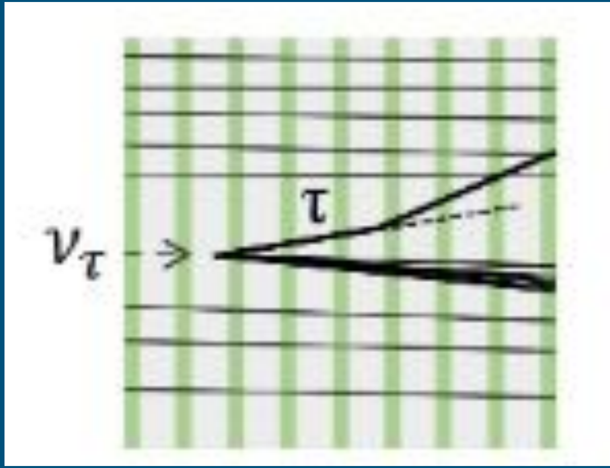


Reconstruction Algorithm

Lepton identification (τ)

[2001.03073]

- Lifetime of $\tau \sim 3 \times 10^{-13}$s
  - Will decay before end of detector
  - Mean flight length ~ 3cm
- Decays predominantly to π^- or μ^- + neutrinos
- Neutrinos carry away momentum - kink
- Identify τ decay vertex by requiring kink angle > 0.5 mrad

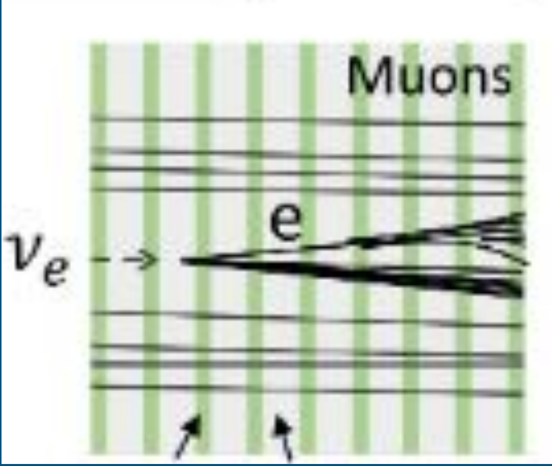


Reconstruction Algorithm

[2001.03073]

Lepton identification (e)

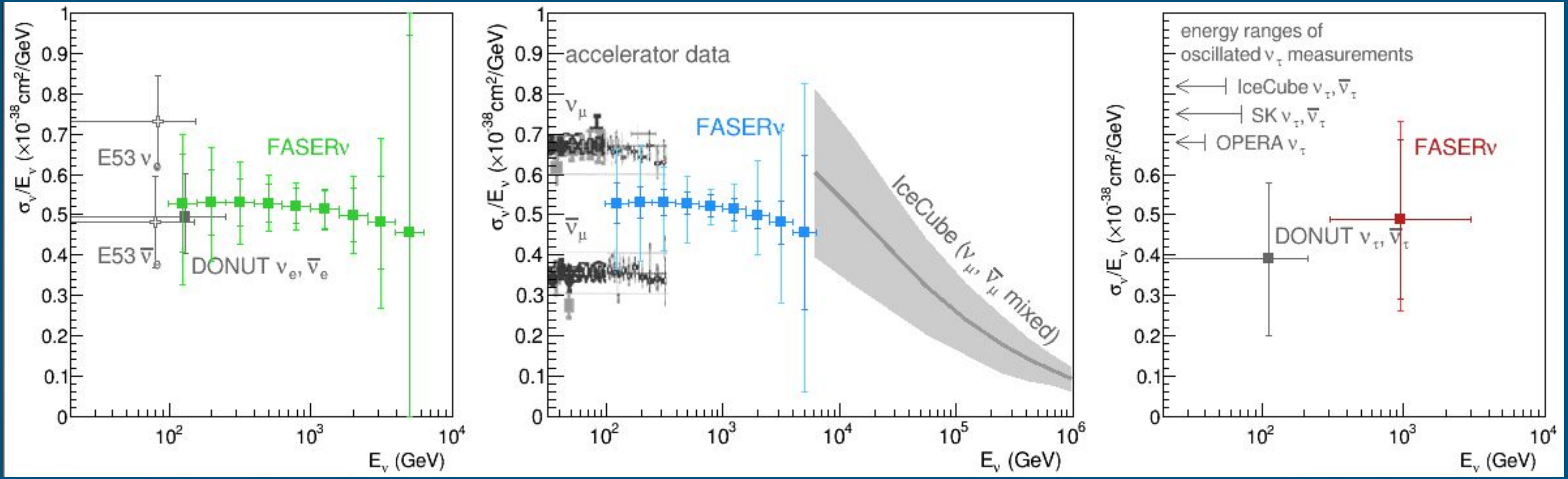
- Electrons in emulsion detector rapidly undergo electromagnetic showering, leading to cascade of e^+/e^- detected by emulsion films
- Cannot reconstruct electron energy from single track - must cluster electron shower
- Electron energy $\propto$ number of clustered tracks



Cross Section Sensitivity Study

Sensitivity plot

- Measure neutrino-nucleon cross-sections in unexplored energy regions



Summary

- FASERν will:
  - Detect collider-produced neutrinos for the first time ever
  - Measure the neutrino-nucleon CC cross section at previously unexplored energies
  - Improve our understanding of neutrinos
  - Be installed this year
- First neutrino interaction candidates from pilot detector analysis already

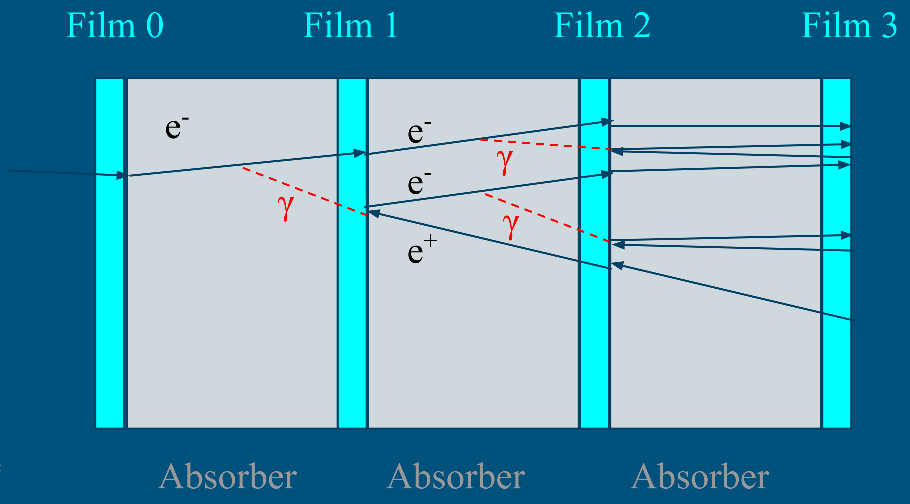
Acknowledgements

- JS is grateful to:
  - The Simons Foundation for their funding of this research project
  - His advisor Shih-Chieh Hsu (University of Washington)
  - Aki & Tomoko Ariga, Felix Kling, Dave Casper, Tomohiro Inada, Ke Li, and Jeffrey Gao
- Thank you for your attention!

BACKUP

Electron Clustering
Motivation

- Electron neutrinos produce high-energy electrons in CC interactions
- These electrons hit the absorber layers to make energetic photons (*bremsstrahlung*)
- Energetic photons hit the absorber and produce e+/e- pairs (pair-production)
- From one electron, many e+/e- detected in emulsion films - **EM shower**
- Number of BTs grows linearly with energy
- By counting e^+/e^- BTs, can reconstruct electron energy and thus neutrino energy



Electron Clustering

Clustering Algorithm

- Extrapolate BTs in layer i to layer i+1
- Calculate Δθ, Δr as shown
- If Δθ < 50mrad, Δr < 70 μm, add to cluster