Neutrino-nucleon cross section sensitivity at FASERν

General Examination

John W. Spencer
University of Washington
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Supported by:
HEISING-SIMONS FOUNDATION
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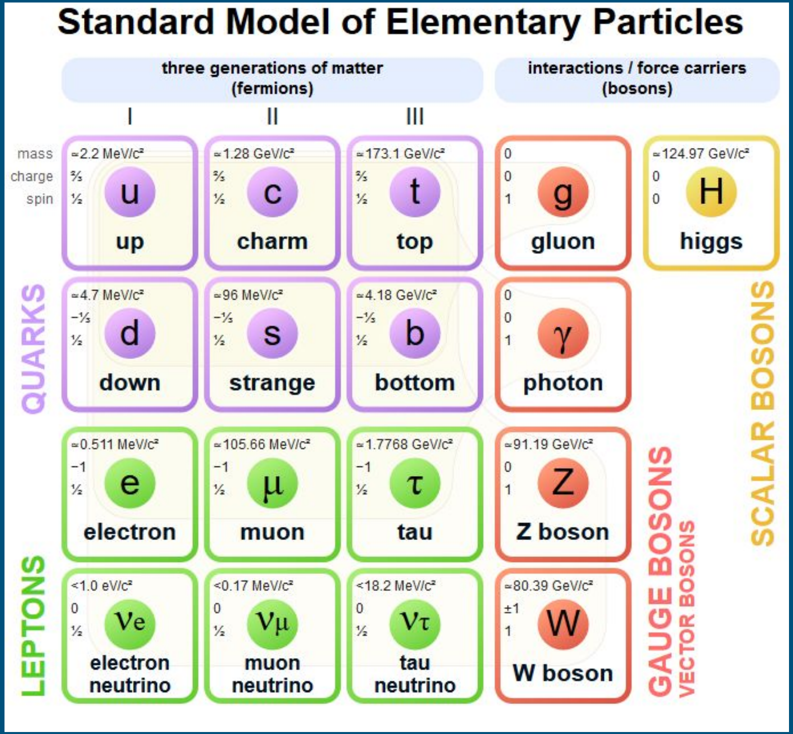
Outline

1. Introduction
2. Monte Carlo simulation
3. Reconstruction algorithm
4. Combined performance
5. Neutrino-nucleon cross sections
   - Background
   - Systematics
   - Sensitivity
6. Future work

My contributions since joining FASER/FASERν (Dec 2019)

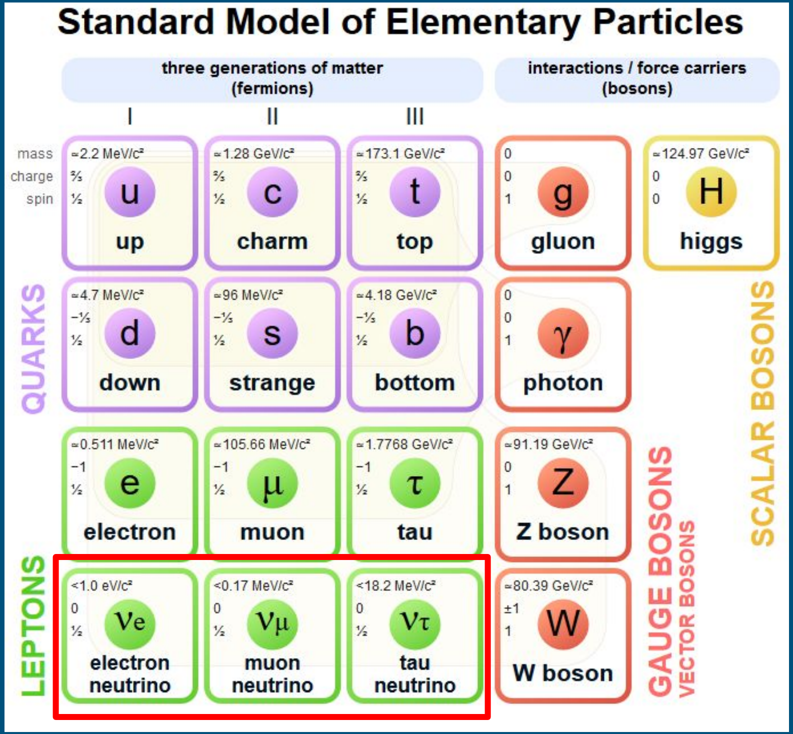
Background - Physics
Standard Model (SM)

- 12 particles of matter
- 6 quarks (u,c,t,d,s,b)
- 3 charged leptons (e,μ,τ)
- 3 neutrinos (ν_e,ν_μ,ν_τ)



Background - Physics
Neutrinos

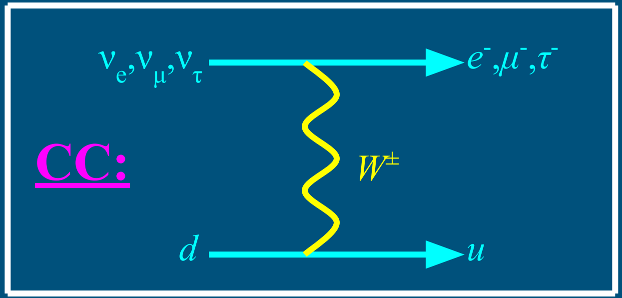
- The most elusive particles in the Standard Model (SM)
- First postulated by Enrico Fermi ~1932
  - First discovered in 1956 at nuclear reactor
- No collider-produced neutrino has ever been detected
- Many big questions about neutrinos:
  - Neutrino mass / oscillations / CP violation
- For all of these,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

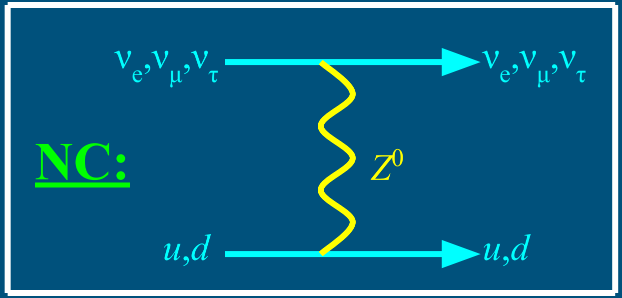


Background - Physics

Neutrino-nucleon interactions

- Nucleon: Generic name for proton or neutron
  - Composed of three quarks
  - Proton: *uud*
  - Neutron: *udd*
- Neutrinos:
  - Not quarks/antiquarks⇒no strong interactions
  - Electrically neutral⇒no EM interactions
- Can undergo two types of weak interactions
  - Charged current (CC, top-left)
  - Neutral current (NC, top-right)
- Scattering can be
  - Elastic / Quasi-Elastic (< 20 GeV)
  - Deep Inelastic (> 20 GeV)





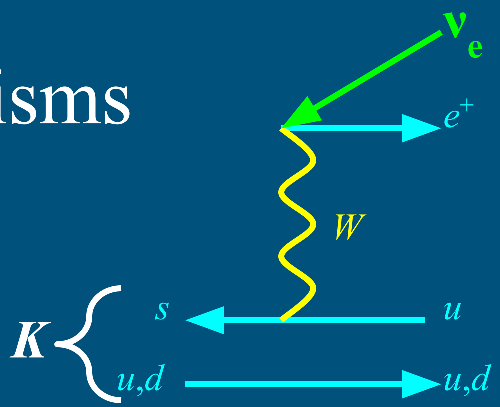
Background - Physics
Production and propagation of neutrinos

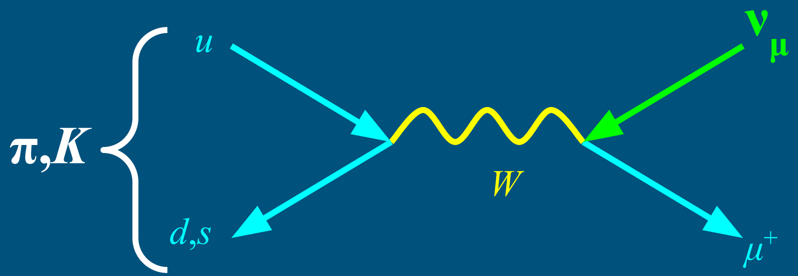
- LHC uses *pp* collisions
  - Beams collide at ATLAS interaction point, producing many hadrons (e.g. π, K, D) in forward region
  - Decay products at IP include charged particles and neutrinos
  - Charged particles (E < 7 TeV) deflected via LHC magnets
  - Neutrinos propagate through 100 m of rock to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

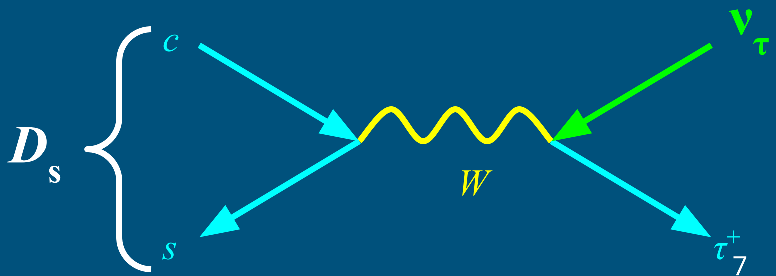
Background - Physics

Flavour-specific production mechanisms

- Dominant sources of collider neutrino production:
  - ν_e: Semileptonic kaon decays $K \to \pi e \nu_e$
  - ν_μ: Leptonic decays $\pi, K \to \mu \nu_\mu$
  - ν_τ: Leptonic decays $D_s \to \tau \nu_\tau$





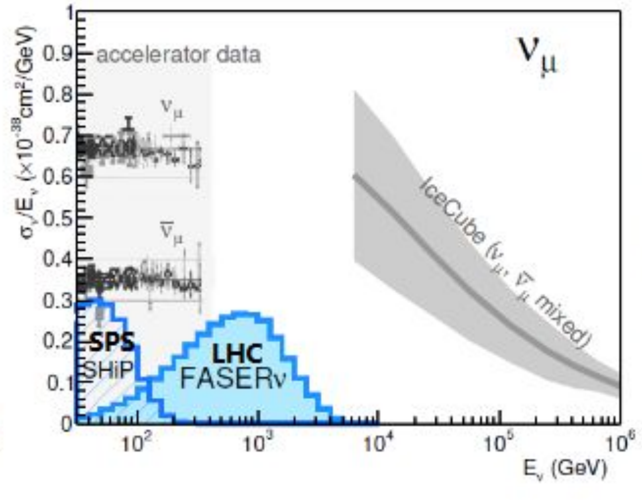


Background - Physics

Existing neutrino interaction cross section data

- We know neutrino-nucleon cross sections
  - Below 300 GeV (accelerator data)
  - Above 4 TeV (Cosmic neutrinos at IceCube)
- Gap between 300 GeV - 4 TeV

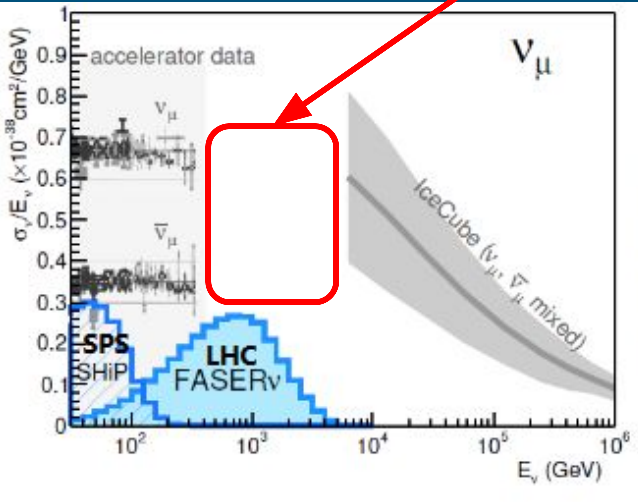
[1908.02310]



Background - Physics
FASERν and the neutrino cross section frontier

- FASERν: Unique opportunity to measure cross sections in this energy region

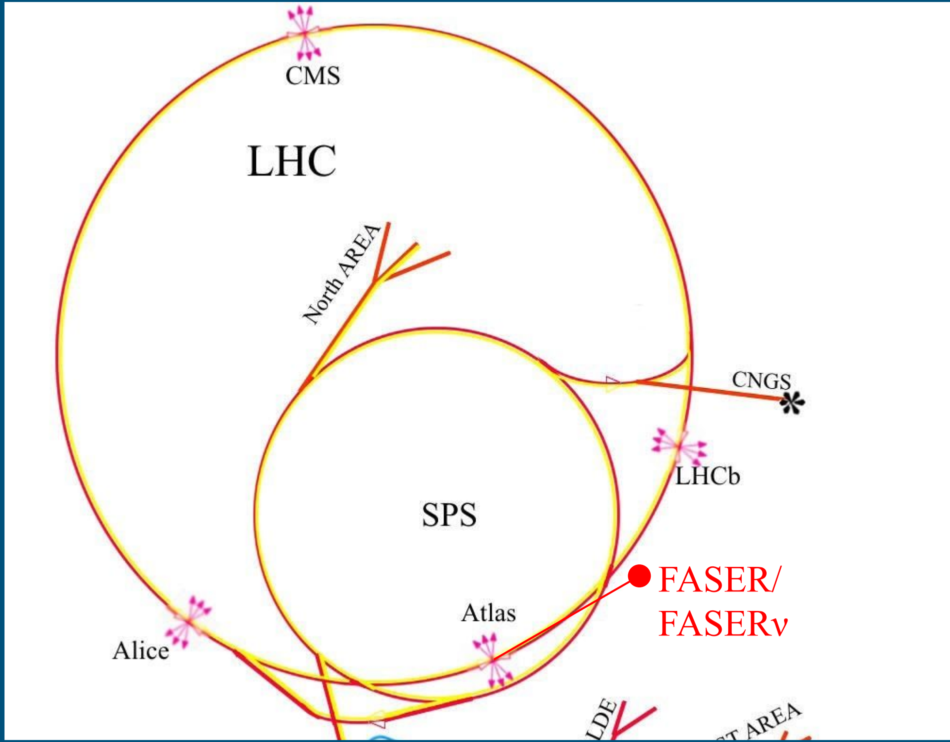
[1908.02310]



Background - Facilities
CERN

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

[Source]



Background - Facilities

FASER - the ForwArd Search ExpeRiment

- Detected cosmic neutrinos but no collider-produced neutrino has ever been detected
  - Extremely suppressed cross section for interaction with nucleons
- Being neutral elementary particles, they are unaffected by magnetic fields
- Travel in straight lines from the interaction point (IP)
- Kinematics: Lines are tangent to the collider ring
- Existing maintenance tunnel: TI12

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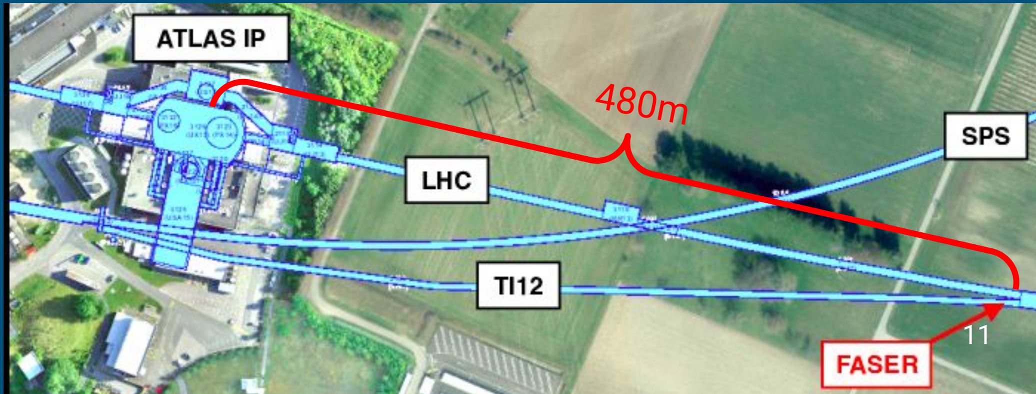

Background - Facilities

TI12 maintenance tunnel

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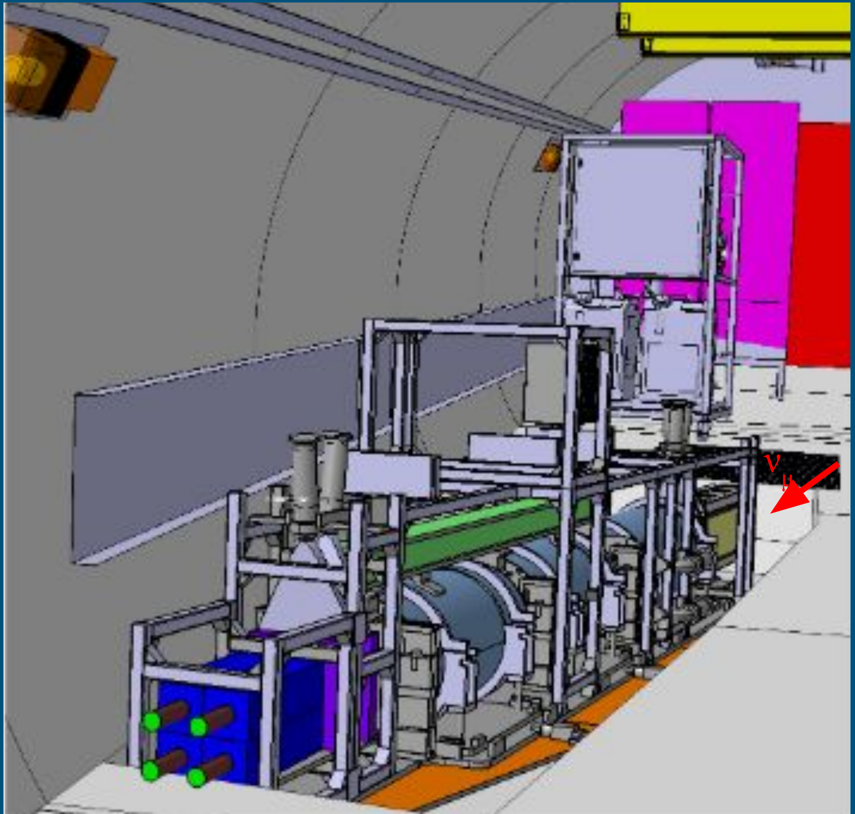
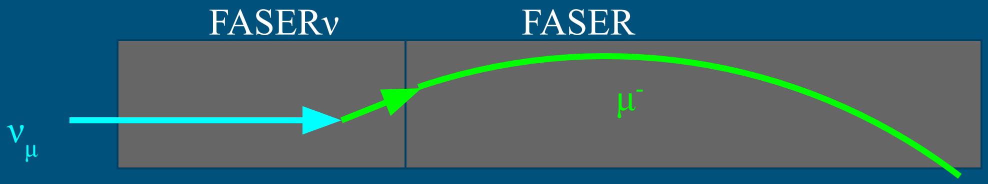


Background - Detectors
Design philosophy

- Charged leptons: Deflected with magnetic field (cyclotron motion)
  - In uniform B-field, positively (negatively) charged leptons follow right-(left-)handed helices
- Our detector must have sufficient resolution to identify two closely spaced oppositely-charged tracks (300 μm)
- Calorimeter needed for μ, e tagging
- Neutrinos: Need dense target (e.g. lead, tungsten)

[EPJC (2020) 80:61]

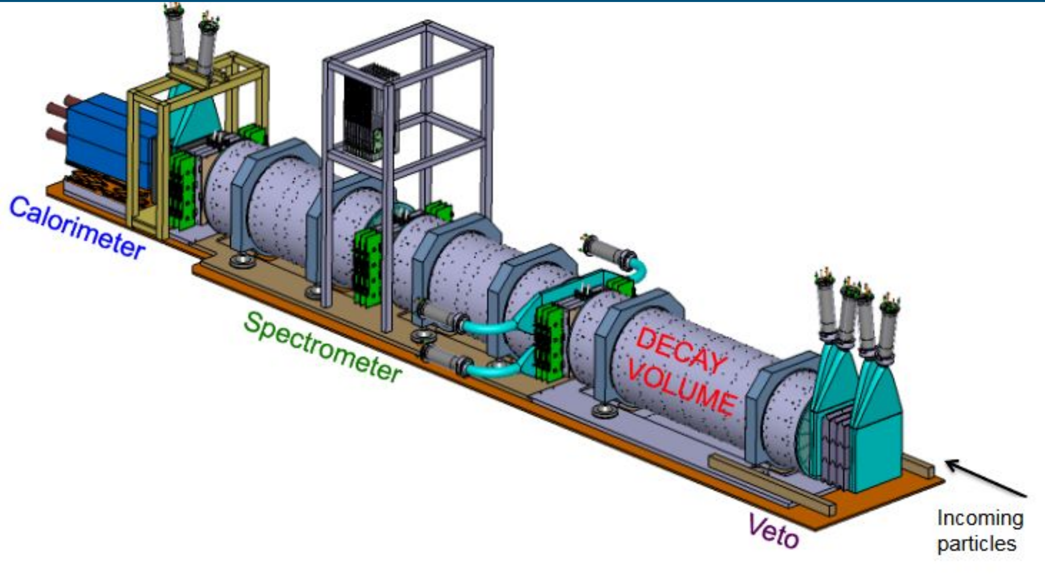
	LOI (FASER original)
$\nu_e, \bar{\nu}_e$	814, 456
$\nu_\mu, \bar{\nu}_\mu$	4452, 1366
$\nu_\tau, \bar{\nu}_\tau$	15, 7



Background - Detectors
FASER design

- Small detector to be 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

[Source]

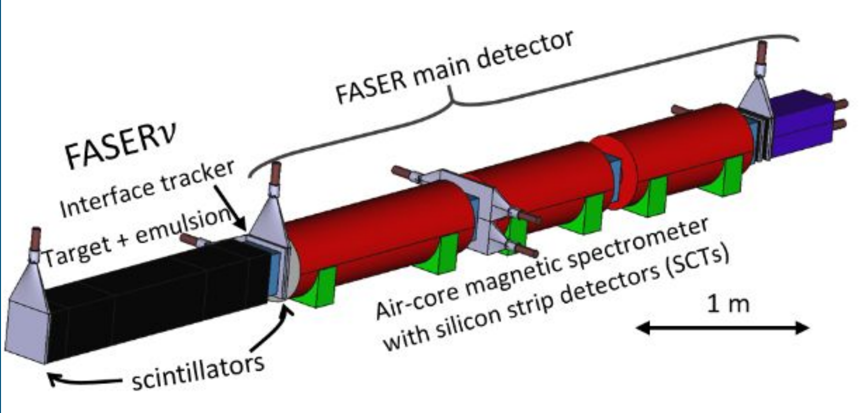


Background - Detectors

FASERν

- FASERν will be able to record but not distinguish neutrino and antineutrino interactions
- Measure average cross sections for neutrino and antineutrino interactions
- Emulsion detector containing alternating tungsten plates and emulsion layers to detect collider neutrinos
- Placed upstream from FASER
- Will detect collider-produced neutrinos for the first time
- Dimensions: 0.25m × 0.25m × 1.15m
- FASERν will be placed upstream of FASER
- Will be able to distinguish 3 flavours of neutrinos
- Can also identify charmed/beautiful hadrons

[1908.02310]



[Source]

Background - Facilities

FASER - participants

- UW contribution to FASER:
    - Offline software: Reconstruction and tracking

Background - Detectors

Emulsion detector - principles

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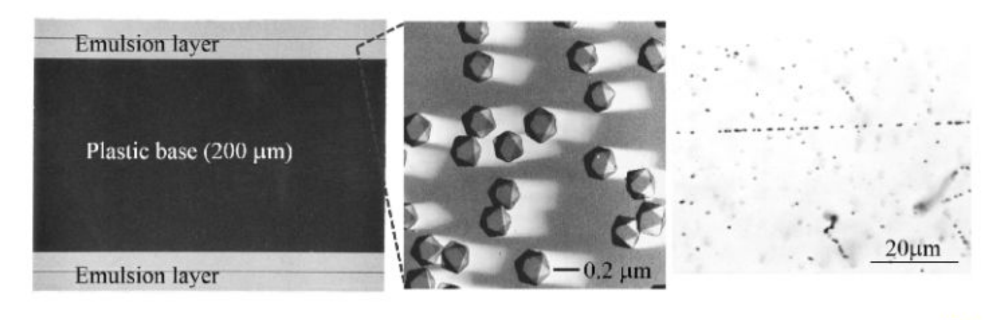

- Emulsion films: 50 μm layer of emulsion gel of AgBr crystals either side of plastic base
- Charged particle ionization recorded and can be amplified and fixed by chemical development of film
- Track position resolution ~ 50 nm
- Angular resolution ~ 0.35 mrad

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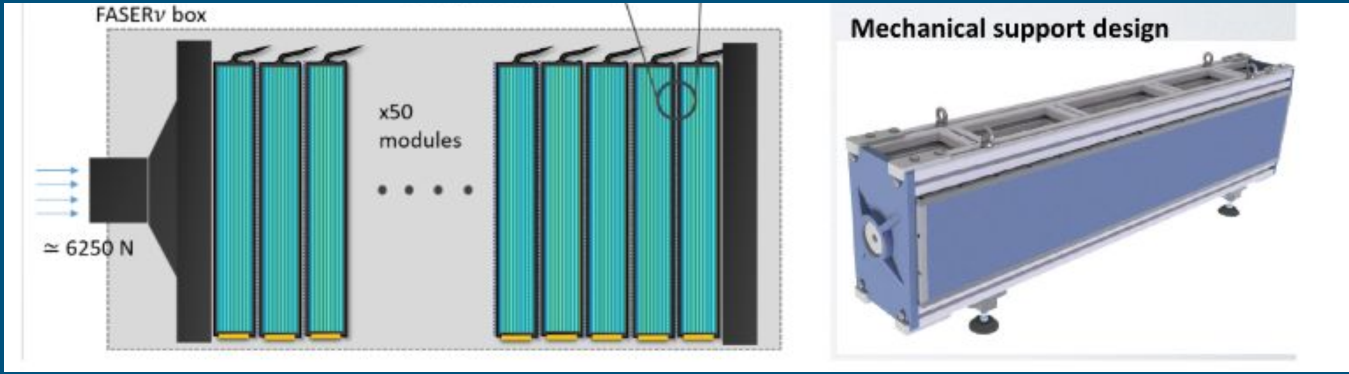
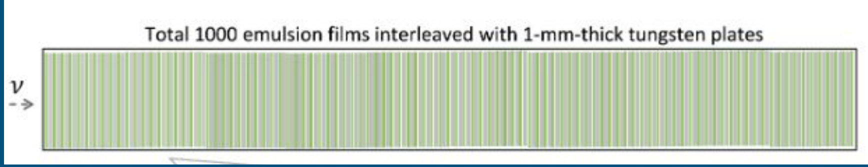


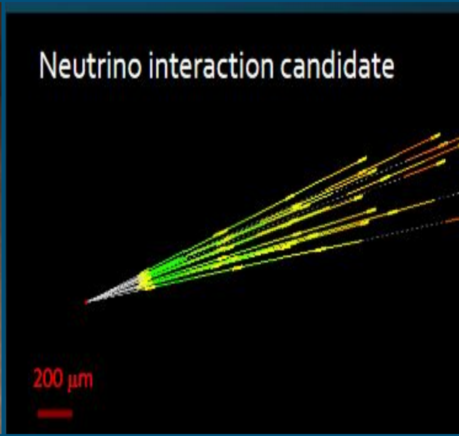
Background - Detectors

Emulsion detector - design

- Layers of tungsten plates, base and emulsion films (top)
- Tungsten film thickness = 1 mm
- Base thickness = 0.2 mm
- Emulsion film thickness = 0.05 mm × 2
- Original design had 1000 layers
- Revised design:
  - 760 layers
  - Front veto (to eliminate μ entering FASERν)
- Already have pilot run (bottom-left)
  - 30-kg detector
  - Collected 12.5fb^{-1} data Sep-Oct 2018
  - Reconstructed 11 vertices / 3 neutrino events
  - Event display shows ν CC candidate (bottom-right)

[1908.02310]





[ICHEP 2020]

Background - Detectors
Tracker

- Silicon strip detectors (left)
  - Uses spare semiconductor tracker (SCT) modules from ATLAS
  - 128 channels to record strip hits
- 8 SCT modules per tracking plane (center)
- 3 tracking planes per station (right)
- 3 tracking stations in FASER

[Source]

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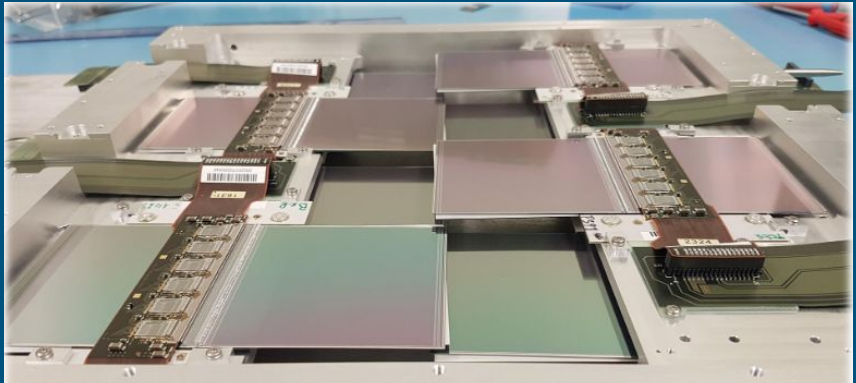
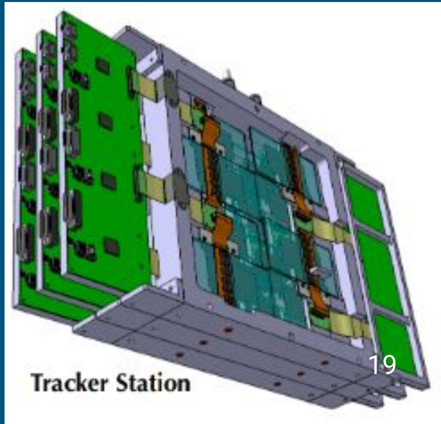


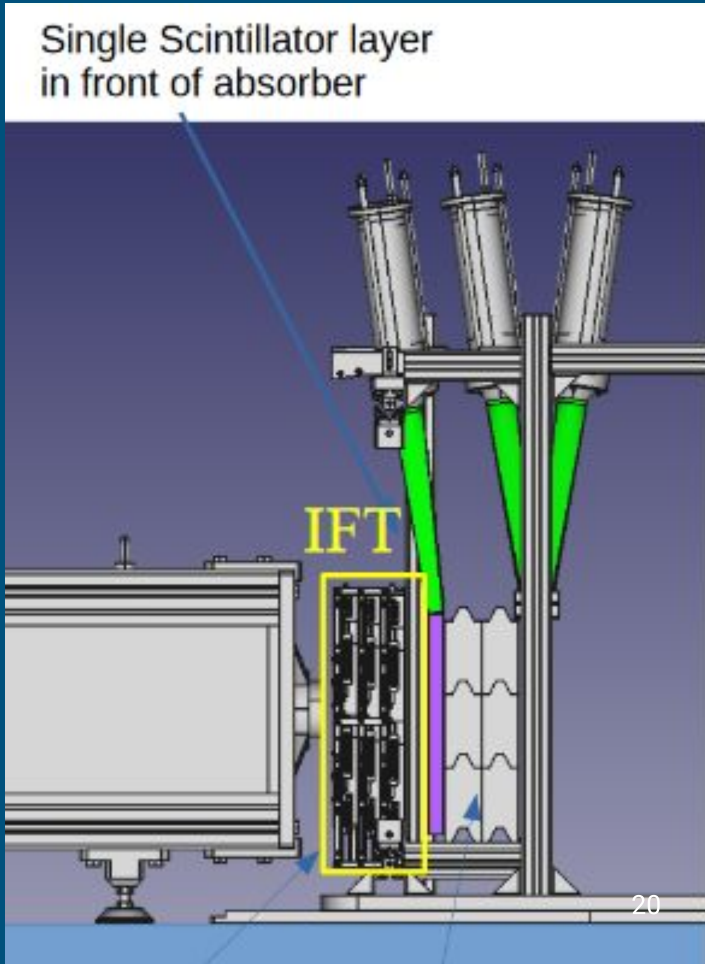


Background - Detectors

Interface Tracker (IFT)

[Source]

- Fourth tracking station placed between FASER and FASERν
- Measures charge and momentum of particles
- Muons leave helix-like tracks in tracker + IFT
- From handedness of track, we can identify μ^+ vs. μ^-
- With lepton number conservation, we can determine if a particle interacting in FASERν was a ν_μ or $\bar{\nu}_\mu$
- With FASERν+IFT, we have sensitivity to neutrino and antineutrino cross sections separately (not just the average)

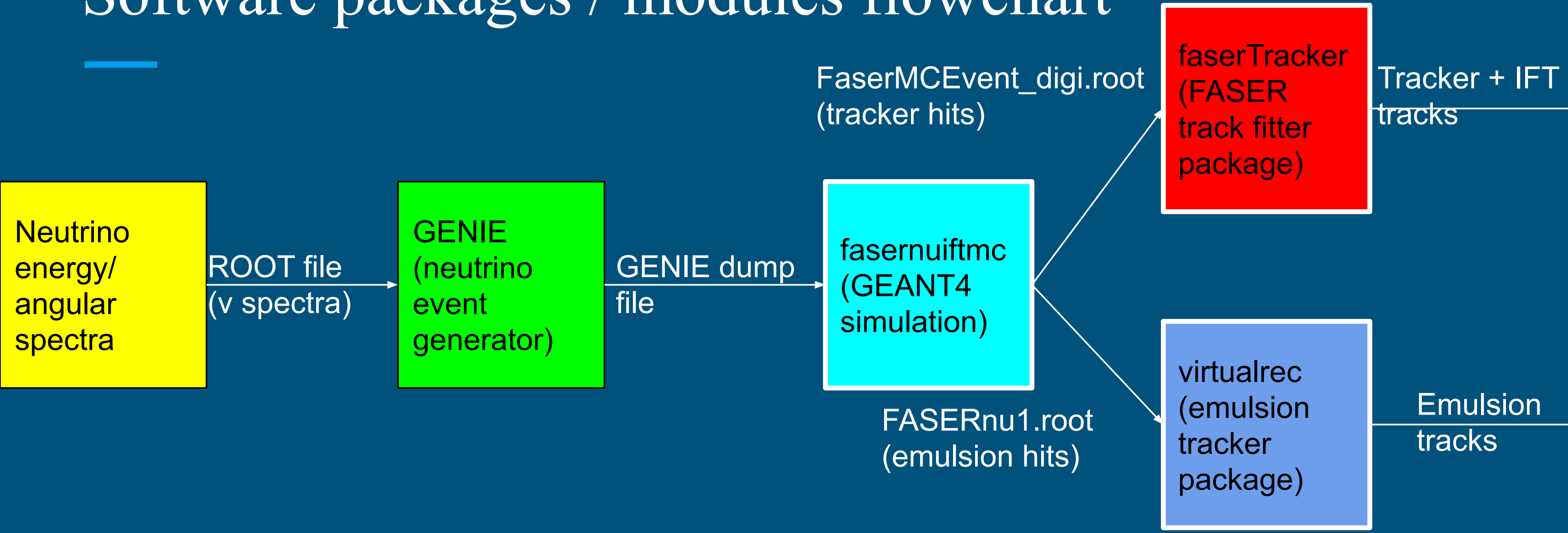


Background - Detectors
Scintillator

[Source]

- Used to veto incoming charged particles
  - Very high efficiency
- Triggering
- Timing measurement (resolution ~ 1 ns)

Software packages / modules flowchart



My major contributions

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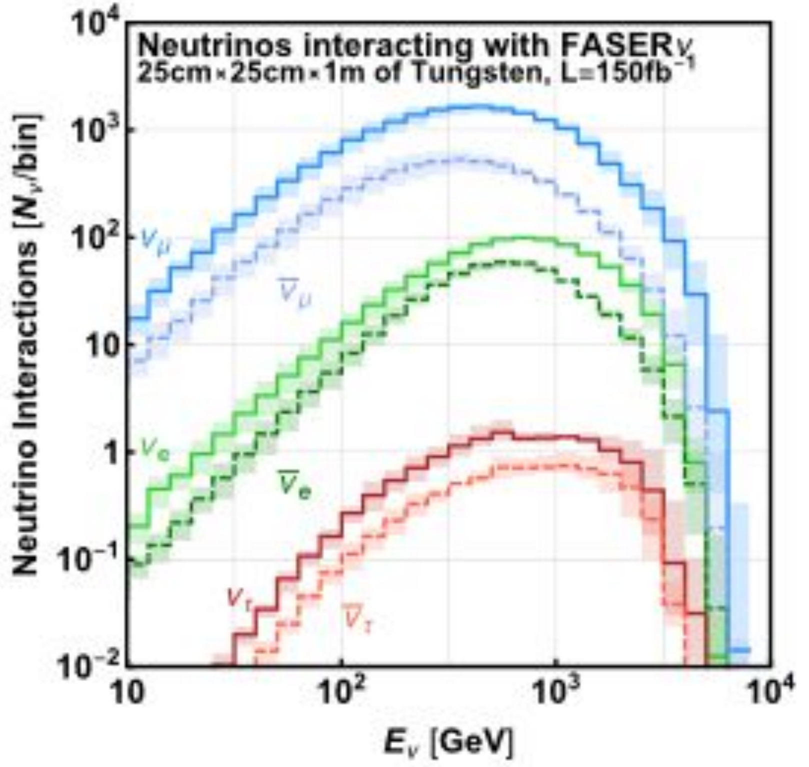
2. Monte Carlo simulation
3. Reconstruction algorithm
4. Combined performance
5. Neutrino-nucleon cross sections
   - Background
   - Systematics
   - Sensitivity
6. Future work

My contributions since joining FASER/FASERν (Dec 2019)

FASER MC Simulation
Neutrino spectrum

- Start from incoming neutrino flux data
- Prepare ROOT histogram of neutrino energies based on text files

[EPJC (2020) 80:61]



FASER MC Simulation
GENIE

[http://www.genie-mc.org/]

- Event generator to model neutrino interactions with matter
  - GEANT4 simulation does not model properly
- Use GENIE to generate events with appropriate spectra
- With GENIE, can force neutrinos to interact

FASER MC Simulation
GEANT4

[Source]

- GEometry ANd Tracking
- Simulates the passage of particles through matter
- Load detector geometry, then generate events using full detector simulation
- I modified and updated GEANT4 detector geometry:
  - Implements IFT as 4th SCT tracking station
  - Uses non-uniform spacing between tracking stations
  - Includes FASERν emulsion detector
  - https://gitlab.cern.ch/jwspence/fasernuiftmc

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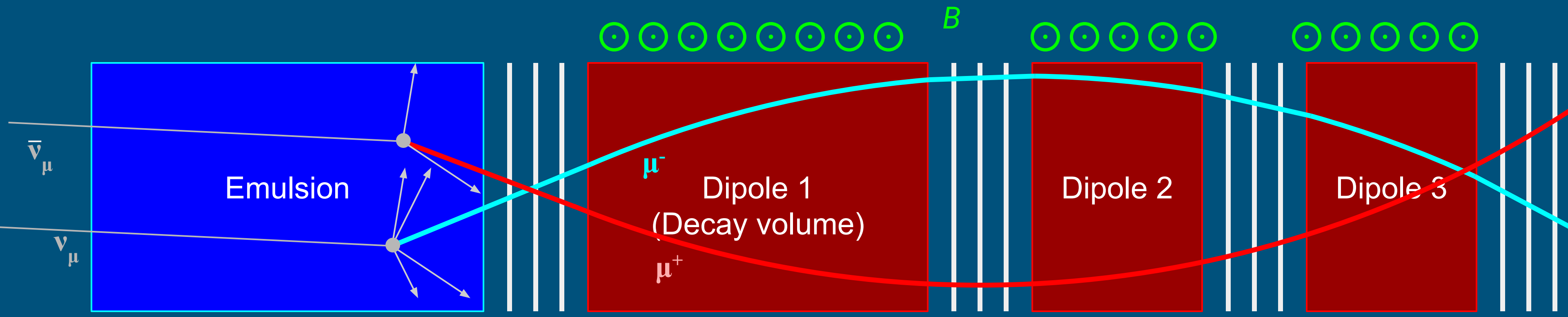
Reconstruction Algorithm

Neutrino/Antineutrino ID w/IFT+Tracker

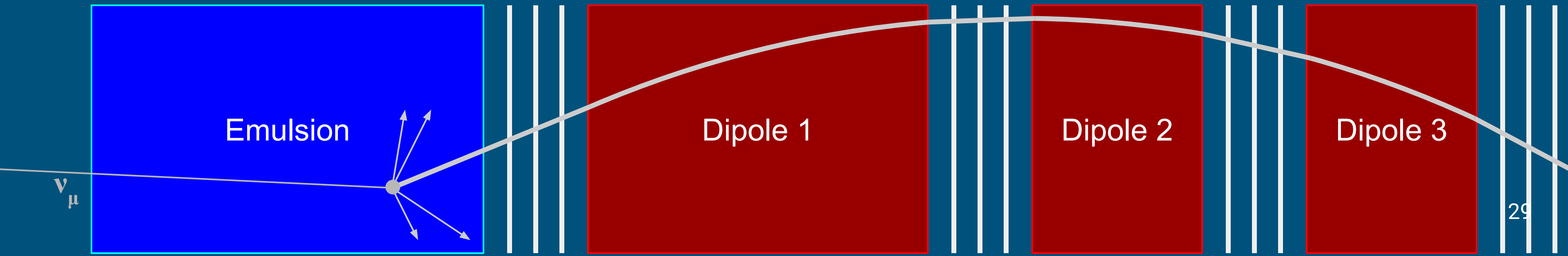
- Magnetic field in dipole volumes only (no B field in tracking stations)
- Without IFT, tracking station and FASERν are separated by decay volume
- With the IFT placed directly between FASERν and FASER, tracks in FASERν will register hits in IFT
- IFT+FASER can construct particle tracks → Charge ID from helix chirality
- Positive (negative) charge in IFT → neutrino (antineutrino) in FASERν
- Only possible for ν_μ
  - Electrons (τ) scatter (decay) before reaching IFT



Reconstruction Algorithm

Schematic of ν_μ CC event

- Emulsion reconstruction
- Tracker reconstruction
- Emulsion-IFT matching



Reconstruction Algorithm
Emulsion reconstruction

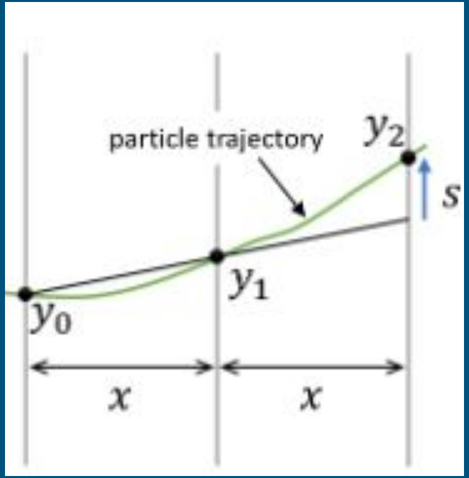
- Use hits in emulsion films to reconstruct tracks
- No B field in emulsion detector ⇒ straight line fitting
- Emulsion reconstruction efficiency:
  - Proportion of ν events with ≥1 reconstructed track
  - $\varepsilon_{Emulsion} = 0.951 \pm 0.021$

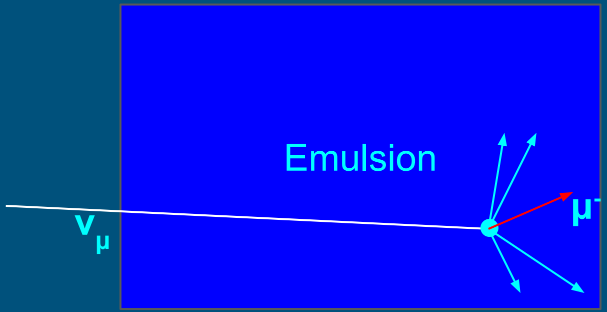
Reconstruction Algorithm

FASERν vertex and energy reconstruction

[1908.02310]

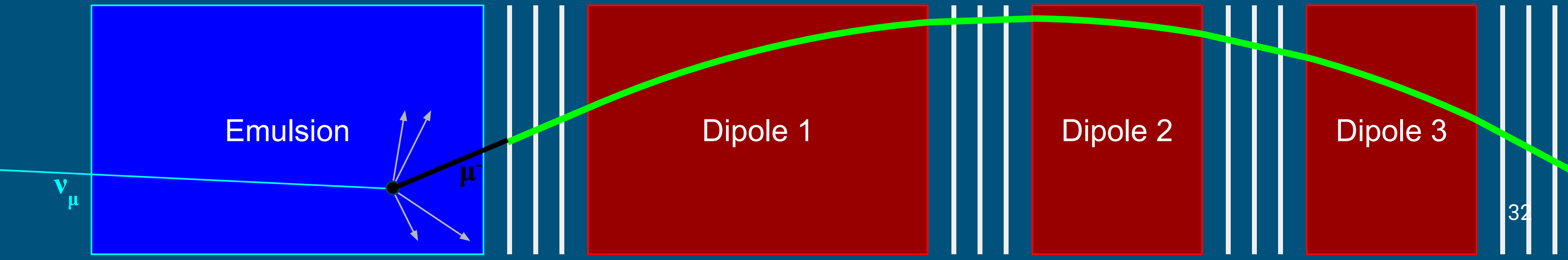
- Energy reco from multiple Coulomb scattering
  - Particle trajectory deflected by s due to MCS
  - Fit *s* to function of momentum
  - P(best fit) = reconstructed momentum
- Vertex ID: Find vertices w/ ≥5 charged tracks
- Lepton ID: Identify $\nu_e/\nu_\mu/\nu_\tau$ CC events
  - ν_e : EM showers
  - ν_μ : Track topology
  - ν_τ : Displaced decays with kink





Reconstruction Algorithm
Tracker reconstruction

- Use hits in 12 tracker planes to reconstruct μ^+/μ^- in tracker
- We will determine proportion of $\bar{\nu}_\mu/\nu_\mu$ events with reconstructed μ^+/μ^-
- Tracker reconstruction efficiency:
  - Proportion of μ events with reconstructed tracks
  - $\varepsilon_{Tracker} = 0.929 \pm 0.010$

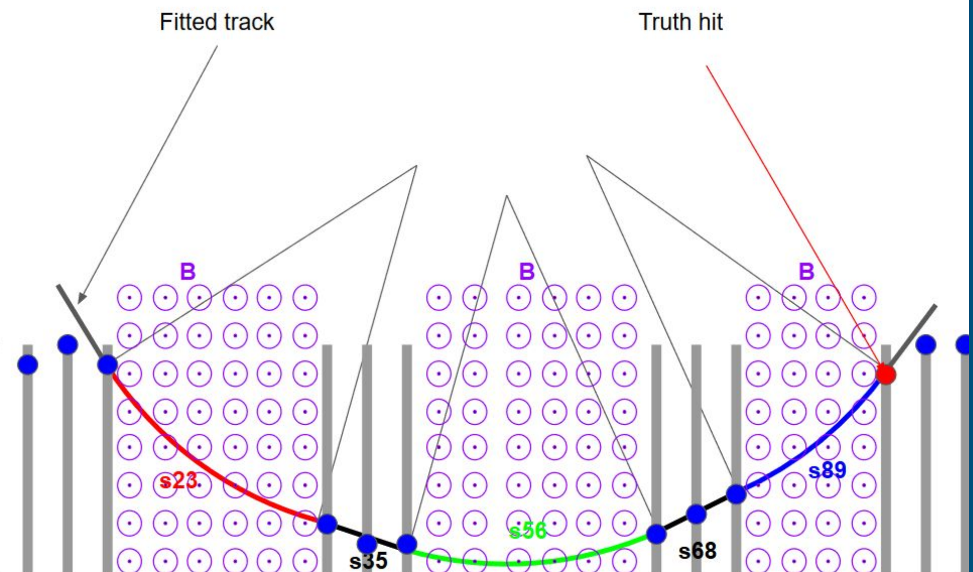


Reconstruction Algorithm

Track fitting in inhomogeneous B-field

- B-field (⇒ helix) in dipole volumes only, no field (⇒ line) everywhere else
  - Previous helix fitter assumes uniform global B-field
- Drastic revision of faserTracker to accomplish this

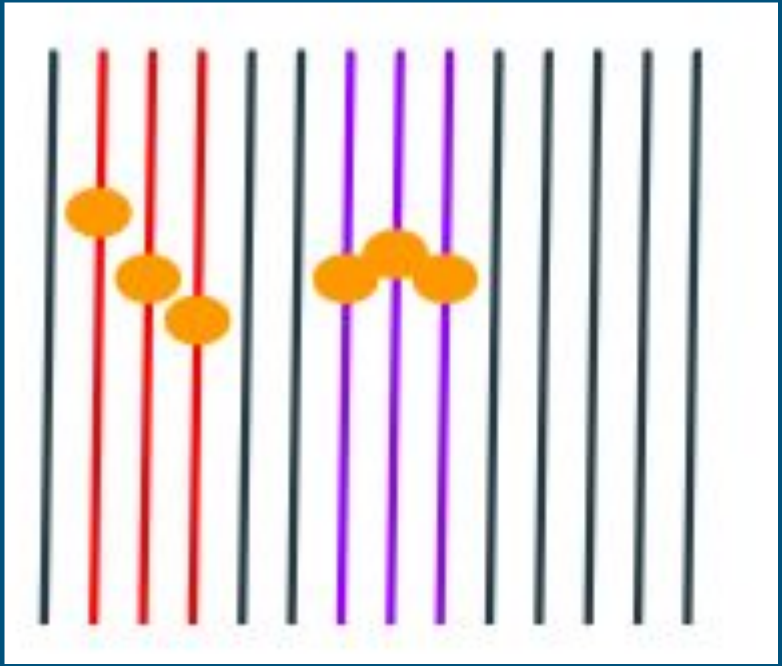
[Inhomogeneous B-field]



Reconstruction Algorithm
Clusterization

- Convert digitized SCT hits to SCT clusters
- For each strip that was hit, check if adjacent strips were hit
- For each adjacent strip that was also hit, add it to the cluster
- Hit clusters on one side of SCT are in one direction only

[Source]



Reconstruction Algorithm
Space point formation

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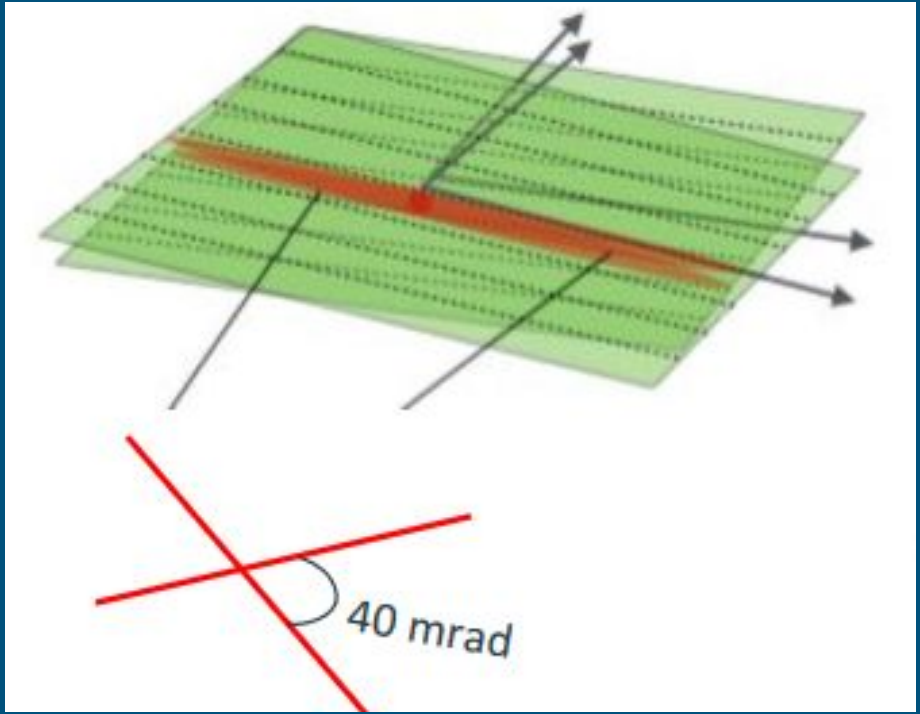
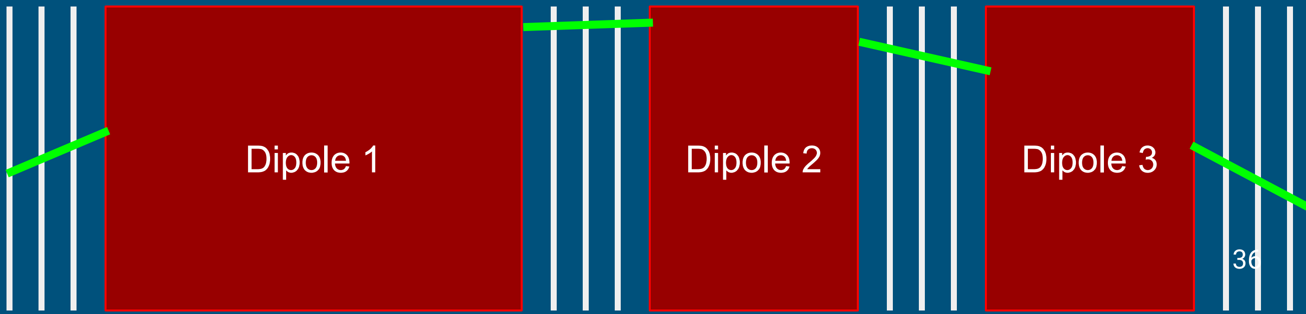


- Convert hit clusters into space points (SPs)
  - Check that there are clusters on both sides of SCT module; if so, combine them into SPs
- Strips on opposite sides are misaligned by 40 mrad
  - Two linearly independent directions
  - Two clusters intersect at SP

Reconstruction Algorithm
Track Finding

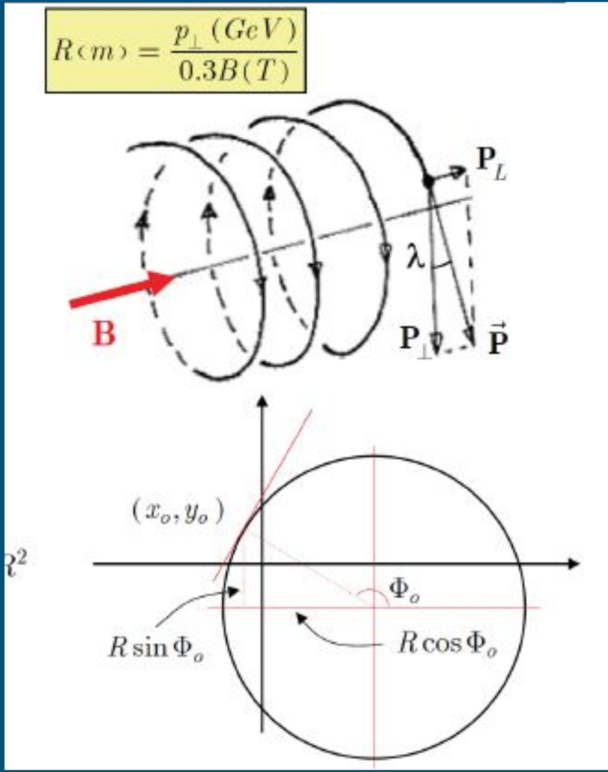
- Use 3 SPs at each tracking station + IFT to build track segment
    - Segments at each station independent



Reconstruction Algorithm
Helix track model

[*An introduction to charged particle tracking*, F. Ragusa]

- Five fit parameters
- qR - Signed helix radius
  - Charge<0 ⇒ qR<0 ⇒ left-handed helix
- (x_0, z_0) - Transverse initial position
- Φ_0 - Azimuth of center
- λ - Pitch of helix

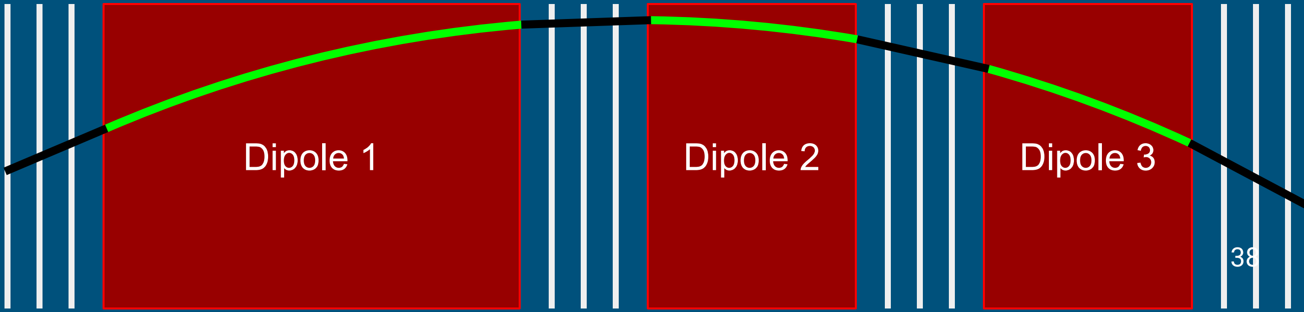


Reconstruction Algorithm

Track Fitting

- Perform global χ^2 fitting to track segments
  - Adjust fitted track parameters to minimize χ^2
- Precision: (16 µm, 580 µm)
  - SCT module has one precision direction and misaligned front/back

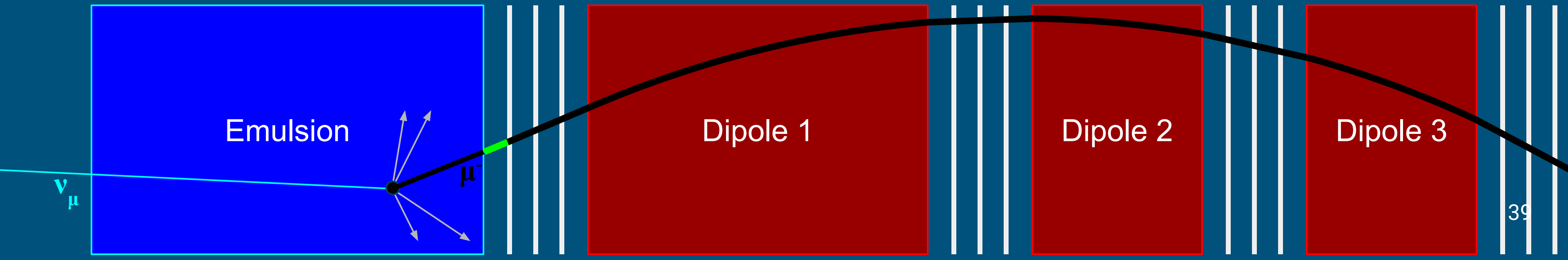
$$\chi^2 = \sum_{\text{fitted points}} \frac{(x_{\text{expected}} - x_{\text{hit}})^2}{\sigma^2_{x_{\text{hit}}}} + \frac{(y_{\text{expected}} - y_{\text{hit}})^2}{\sigma^2_{y_{\text{hit}}}}$$



Reconstruction Algorithm

Emulsion-IFT matching

- Extrapolate reconstructed FASERν emulsion track to first layer of IFT
- If$(x_{measured}, y_{measured}) = (x_{extrapolated}, y_{extrapolated})$ within (x_{reso}, y_{reso}), match the tracks
    - Note: Reject emulsion tracks which cannot match to an IFT hit because we cannot identify μ^+/μ^-



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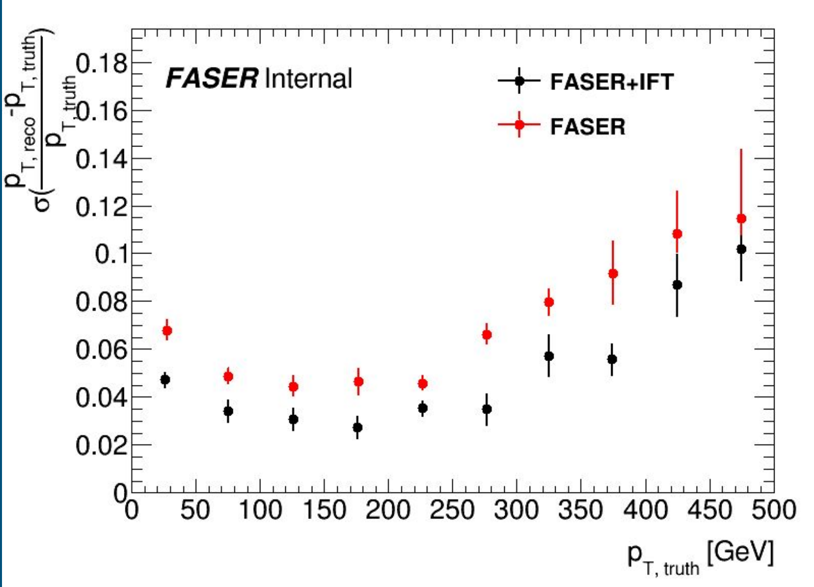
My contributions since joining FASER/FASERν (Dec 2019)

Combined Performance

p_T resolution with inhomogeneous B-field

- Improved resolution at all energies with IFT

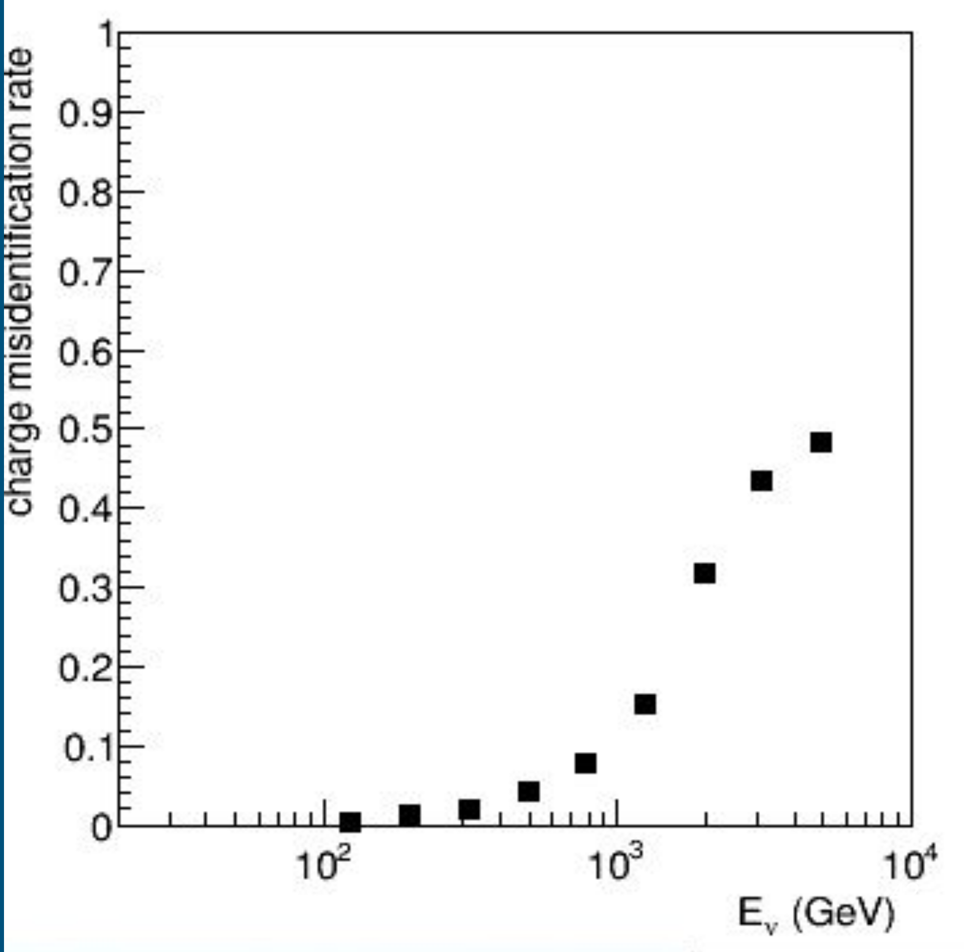


[Inhomogeneous B-field]

Combined Performance

Charge misidentification

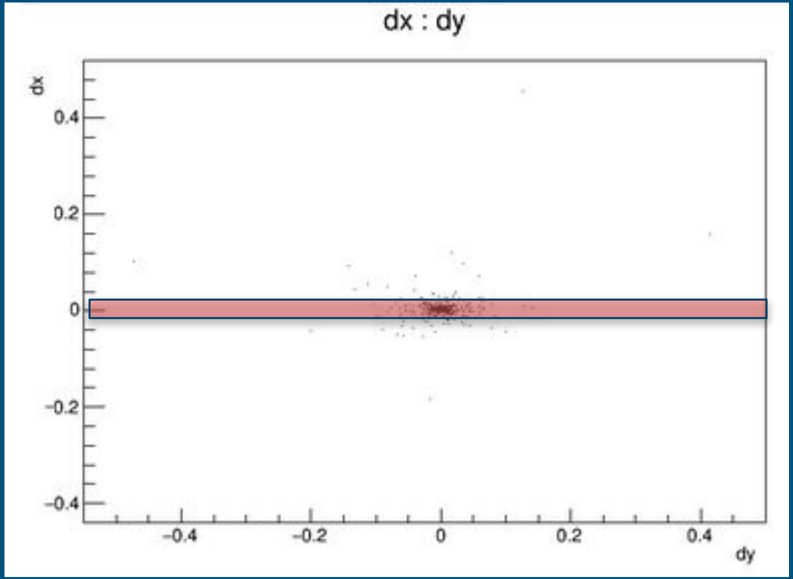
- Likelihood of misidentifying μ^+ (μ^-) as μ^- (μ^+)
- Charge misidentification rate *f* steadily increases with energy
  - Correct and incorrect charged tracks begin to approximate same straight line
  - In TeV range charge ID approaches random assignment
- Charge mis-ID rate gives systematic uncertainty contribution $\sigma_{chargeID}$
- Observed μ^+/μ^- dictates measurement of $\sigma(\nu N)$
  - $N(\mu^-)_{obs} = (1-f)N(\mu^-)_{truth} + fN(\mu^+)_{truth}$
  - $N(\mu^+)_{obs} = (1-f)N(\mu^+)_{truth} + fN(\mu^-)_{truth}$



Combined Performance

Emulsion-IFT Matching Results

- Difference in extrapolated (x,y) vs measured hit (x,y) for closest match to each track
- Track is matching if (x,y) residuals are within + / - IFT hit resolution (red band)
  - $(\sigma_x, \sigma_y) = (0.016\ \text{mm}, 0.580\ \text{mm})$
- Mu neutrinos:
  - **1017 of 1052** emulsion tracks match to the correct hit in first plane of IFT
  - $\varepsilon_{Matching}$ **0.967±0.009**
- Repeat for antineutrinos:
  - $\varepsilon_{Matching}$ **0.971±0.014**



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Cross Section Sensitivity Study

Determining cross section (part I)

$$\text{Cross Section} = \frac{N - N_{bkg}}{\mathcal{L} \times A \times \epsilon_{VertexID} \times \epsilon_{MuonID} \times \epsilon_{Emulsion} \times \epsilon_{Tracker} \times \epsilon_{Matching}}$$

- Parameters:
    - **N (events)**: Number of events observed in detector
    - L **(luminosity)**: Total number of incident neutrinos per unit area (measured by ATLAS)
    - A **(acceptance)**: Fraction of events $\geq 2\lambda_{int}$ before end of FASERν and μ^+/μ^- hitting all 12 planes
    - $\varepsilon_{VertexID}$ **(vertex ID)**: Fraction of ν vertices with ≥5 charged tracks
    - Energy-dependent
    - $\varepsilon_{Emulsion}$,$\varepsilon_{Tracker}$ **(tracking)**: Fraction of events with ≥1 reconstructed muon track
    - $\varepsilon_{Matching}$ **(matching)**: Fraction of emulsion tracks matching to signal hit in first layer of IFT

Cross Section Sensitivity Study

ν_μ CC signal vs background

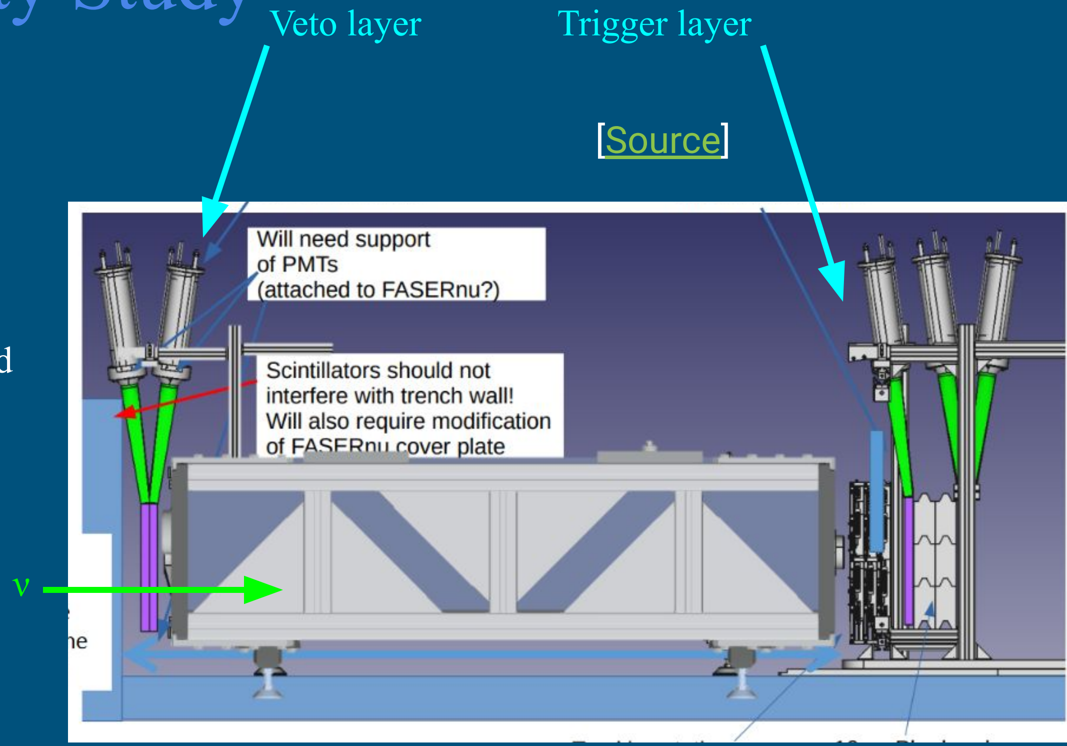
- Signal: ν_μ CC event, producing μ and other charged hadrons
- Hadronic background:
  - Neutral hadron events with highest-momentum particle (HMP) misidentified as μ
- Muon background:
  - μ propagating through FASERν and entering detector
- How do we distinguish signal and background?

Cross Section Sensitivity Study

Front Veto

- Veto scintillator to reduce background
- Muons will interact with scintillators
- Expect to remove [>99.99%] of μ background

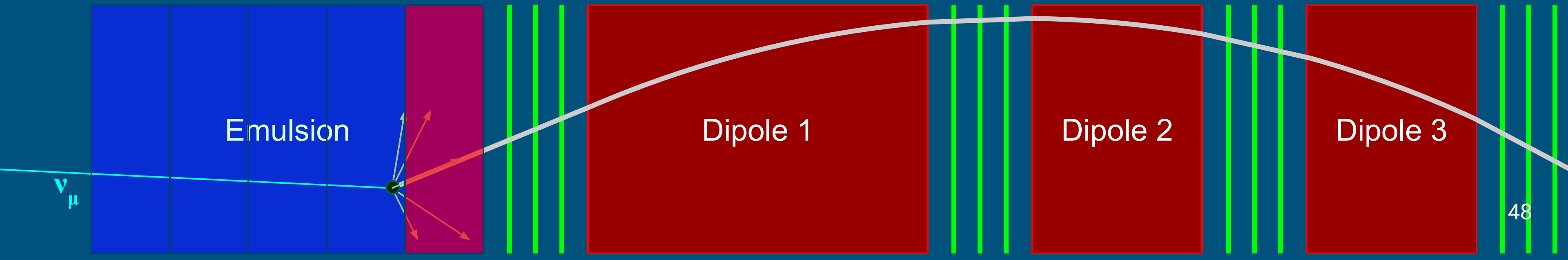
[Source]



Cross Section Sensitivity Study

FASERν acceptance

- FASERν is $10.1\lambda_{int}$ long
- Require that the neutrino interact before last $2\lambda_{int}$
  - Last $2\lambda_{int}$ used for muon ID
  - Note: If ν_μ CC vertex is in last $2\lambda_{int}$ it will be rejected
- Require that the produced μ^+/μ^- enters the tracker and hits all 12 SCT planes
  - **Acc($\bar{\nu}_\mu$) = 0.41±0.02, Acc(ν_μ) = 0.28±0.01**
  - Antineutrino + quark has different helicity from neutrino + quark, so we expect different results

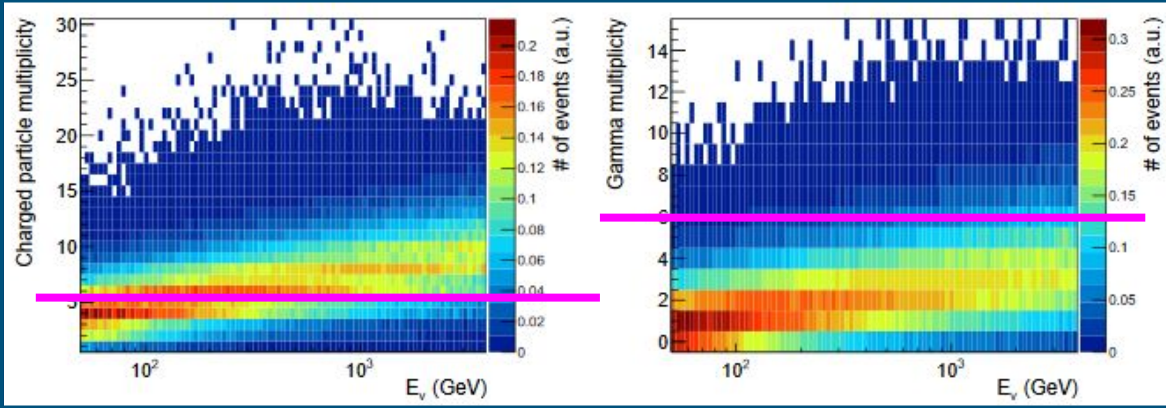


Cross Section Sensitivity Study

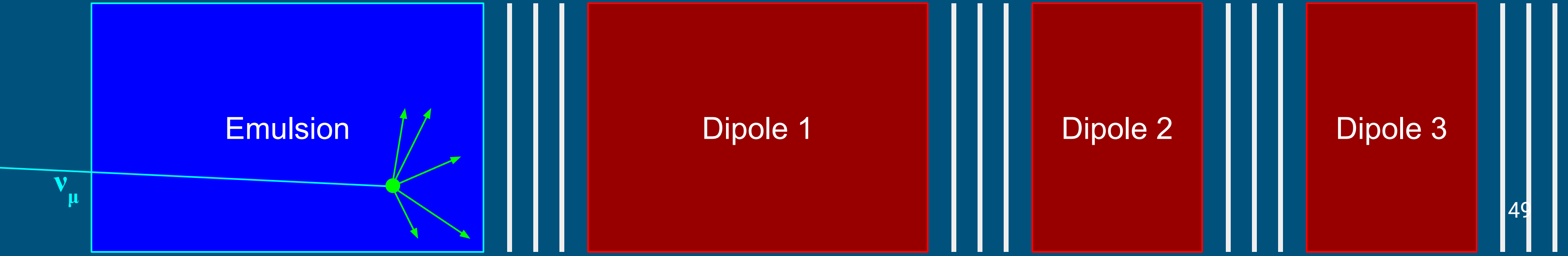
Vertex ID algorithm

[1908.02310]

- Require at least 5 charged tracks at a vertex
  - Background typically has < 5 charged tracks
  - Note: ν CC events with < 5 charged tracks not identified



[SIGNAL] [BACKGROUND]

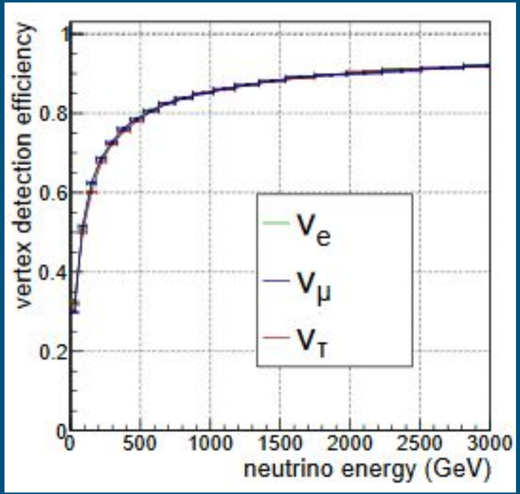


Cross Section Sensitivity Study

Vertex ID efficiency

- Energy dependent
  - Track multiplicity of ν CC events increases with energy
  - Below 100 GeV, less than 50% of neutrinos have ≥5 charged tracks

[1908.02310]



Cross Section Sensitivity Study
Muon ID algorithm

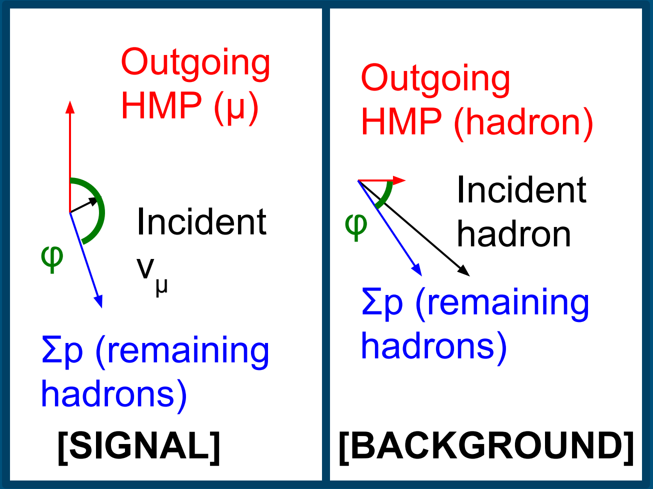
- Already identified vertex, now want to restrict to ν_μ CC vertices only
- Determine which hits were registered by muons
  - Note: Hadrons can be misidentified as muons

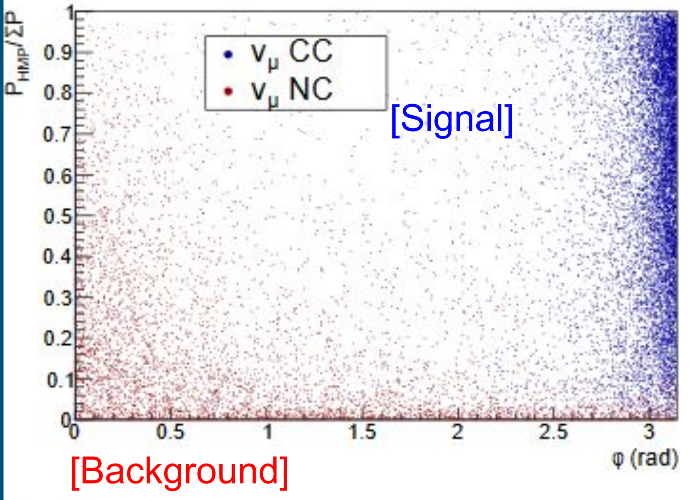
Cross Section Sensitivity Study

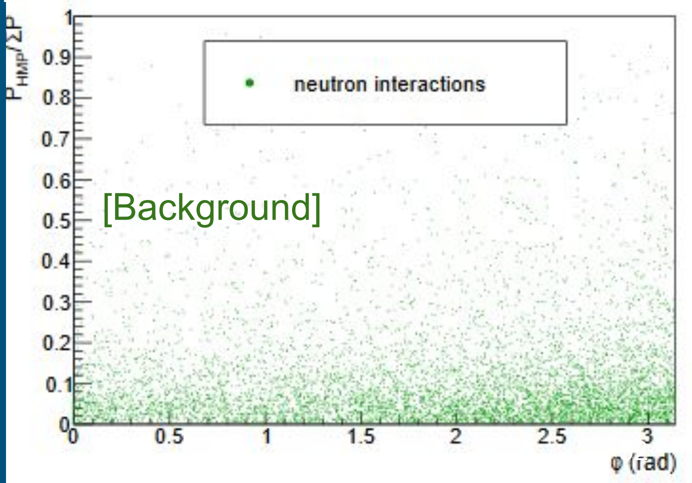
Signal / background kinematics

- 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]



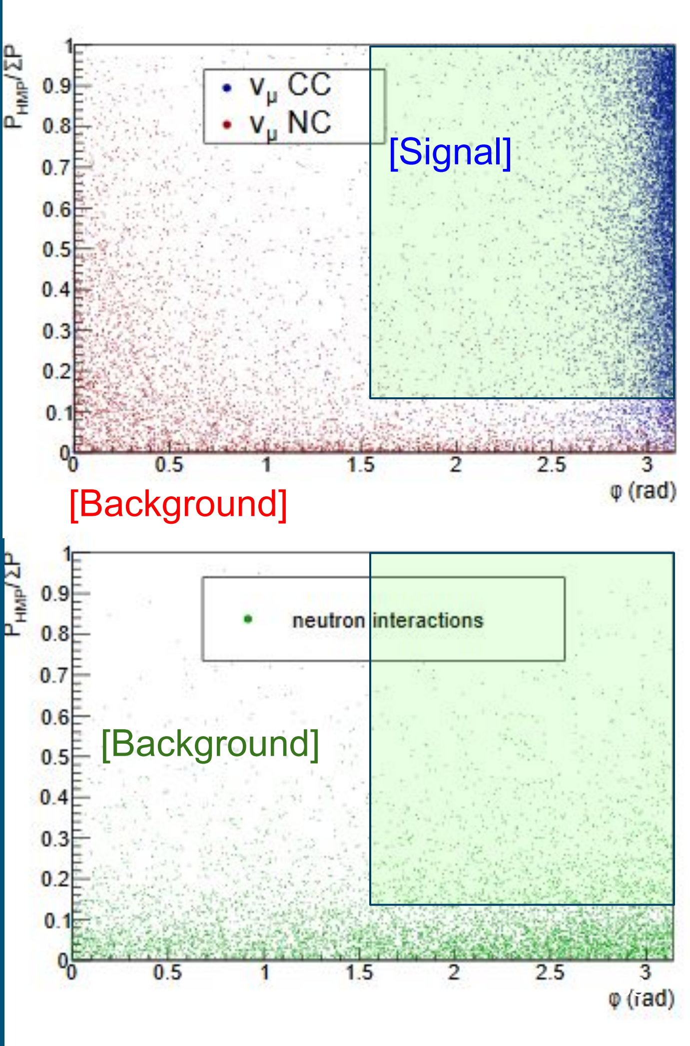




Cross Section Sensitivity Study

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



Cross Section Sensitivity Study

Determining Cross Section - Summary

$$\text{Cross Section} = \frac{N - N_{bkg}}{\mathcal{L} \times A \times \epsilon_{VertexID} \times \epsilon_{MuonID} \times \epsilon_{Emulsion} \times \epsilon_{Tracker} \times \epsilon_{Matching}}$$

Expectation	Values for ν_μ (Value for $\bar{\nu}_\mu$)
$N(\nu_\mu)$	4452 (1366)
N_{bkg}	~0
$\mathcal{L}$	139 fb^{-1} ± 1.7%
A	0.28 ± 0.01 (0.41 ± 0.02)

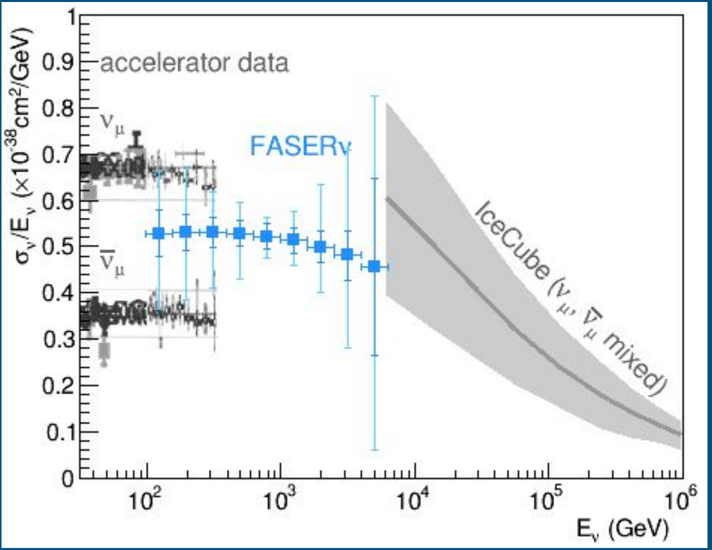
Parameters	Value for ν_μ (Value for $\bar{\nu}_\mu$)
$\epsilon_{VertexID}$	0.3 - 0.9
ϵ_{MuonID}	0.86
$\epsilon_{Emulsion}$	0.951 ± 0.021
$\epsilon_{Tracker}$	0.929 ± 0.010
$\epsilon_{Matching}$	0.967± 0.009 (0.971 ± 0.014)

Cross Section Sensitivity Study
Systematics

- Theoretical uncertainties:
    - Estimated neutrino flux (dominant source of systematic uncertainty)
    - Acceptance
- Experimental uncertainties:
    - Charge misidentification (significant above 1 TeV)
    - Misalignment of the tracker planes
    - Luminosity
    - Tracking efficiency
    - Emulsion efficiency
    - Matching efficiency
- Systematic uncertainty mainly constrained by neutrino flux and charge misID

Cross Section Sensitivity Study
Sensitivity plot

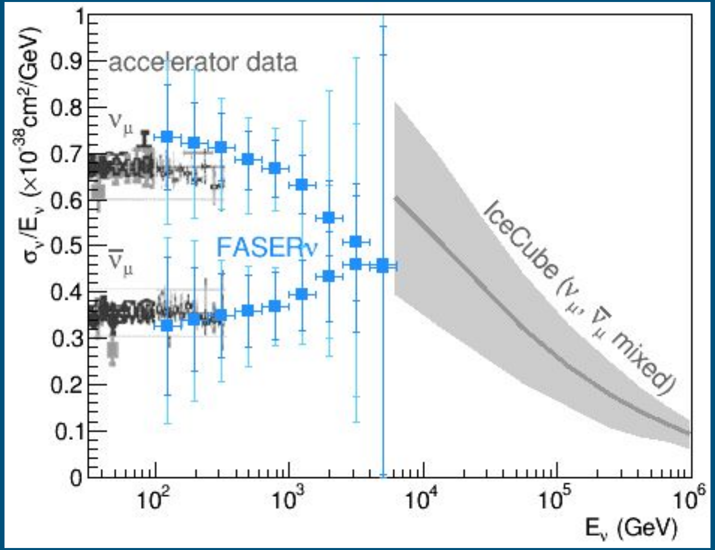
- Expected ν_μ cross section sensitivity with updated FASERν geometry (760 layers)



Cross Section Sensitivity Study

Emulsion+IFT+Tracker results

- Can distinguish νN CC cross sections for $\bar{\nu}_\mu$ vs ν_μ at lower energies (< 2 TeV)
- At higher energies (> 2 TeV), νN CC cross sections become indistinguishable



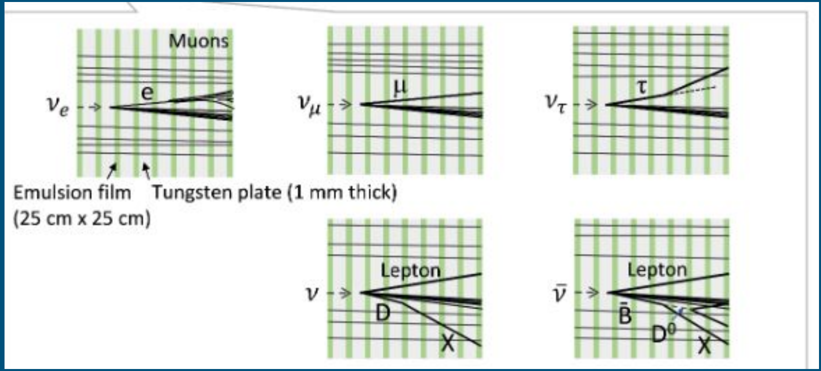
Outline

1. Introduction
2. Monte Carlo simulation
3. Reconstruction algorithm
4. Combined performance
5. Neutrino-nucleon cross sections
    - Background
    - Systematics
    - Sensitivity
6. Future work

My contributions since joining FASER/FASERν (Dec 2019)

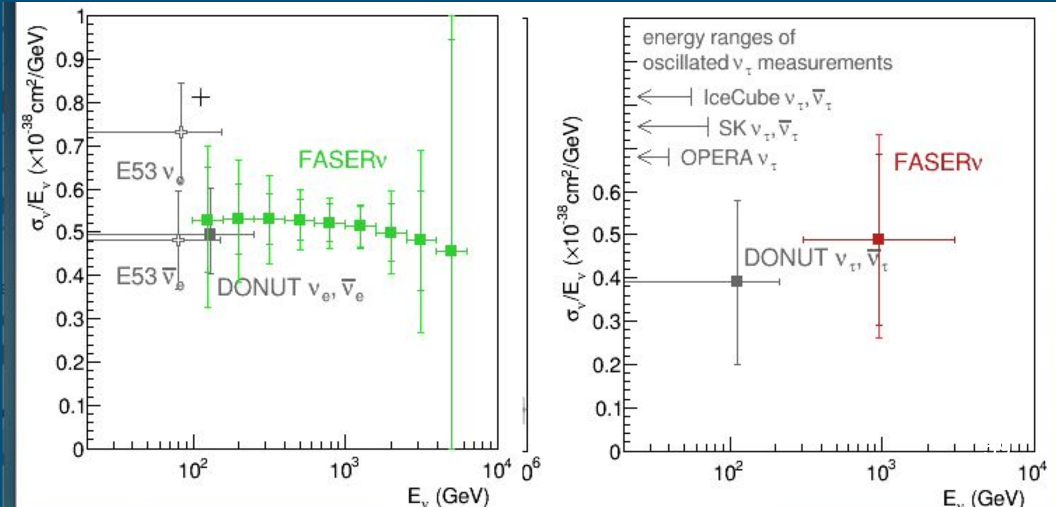
Future Work

Other capabilities of FASERν



- Can also measure ν_e / ν_τ cross section (bottom)
  - Cannot distinguish neutrinos from antineutrinos ⇒ only average cross sections
- Can identify charmed/beautiful hadrons (top)
- Other physics capabilities:
  - Heavy flavour associated channels
  - Intrinsic charm
  - Sterile neutrino oscillations
  - Probes of BSM physics

[Source]



Future Work

FASER/FASERν timeline

- Mar 2019: FASER approved by CERN Research Board ⇐ Done
- Dec 2019: FASERν approved by CERN Research Board ⇐ Done
- Jul 2020: FASER commissioned on surface ⇐ Done
- Sep 2020: Begin installation of FASER in TI12
- Nov 2020: Commission FASER in TI12
- Jun 2021: FASERν installed in TI12
- Feb 2022: Physics data taking and analysis (LHC Run 3 02/2022-2025)
- 2023: ν_μ, ν_e cross sections
- 2024: ν_μ, ν_e-induced charm production
- 2025: ν_τ cross section, other physics analysis

Future Work

Prospective tasks for JS toward Ph. D.

- Oct 2020: Material mapping, event data model
- Nov 2020: Track finder
- Dec 2020: Emulsion reconstruction
- Jan 2021: Systematics
- Mar 2021: Thesis writing
- Apr 2021: Schedule APS talk in Sacramento
- June 2021: Final Exam

Summary

- Many big questions about neutrinos which can only be answered once we know how neutrinos interact with our detector
- FASERν is an emulsion detector which will be able to detect collider neutrinos for the first time
- Using Emulsion + IFT + Tracker, we can distinguish CC νN cross sections of muon neutrinos vs antineutrinos
- FASER has been commissioned on the surface and is currently being installed in TI12
- FASERν has been approved by the CERN Research Board and will be installed starting June 2021

References

- FASER LoI: https://arxiv.org/pdf/1811.10243.pdf
- FASER TP: https://arxiv.org/pdf/1812.09139.pdf
- FASERν LoI: https://arxiv.org/pdf/1908.02310.pdf
- FASERν TP: https://arxiv.org/pdf/2001.03073.pdf
- ICHEP 2020 FASERν poster: https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-249.pdf
- RAL 2020 FASER seminar: https://indico.stfc.ac.uk/event/184/attachments/332/544/FASER_RAL-Seminar_8.7.20.pdf

Acknowledgments

- Dave Casper / Xin Chen for their FASER / FASERν simulations
- Felix Kling, Akitaka & Tomoko Ariga, Ke Li for their support and guidance in FASER- / FASERν-related projects
- Yosuke Takubo for his mathematical modeling of track performance and matching
- Gang Zhang for his work on track fitting and performance analysis
- Jeffrey Gao for his work on emulsion reconstruction and troubleshooting

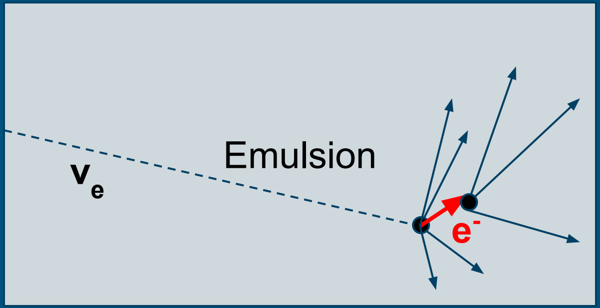
Thank you all!

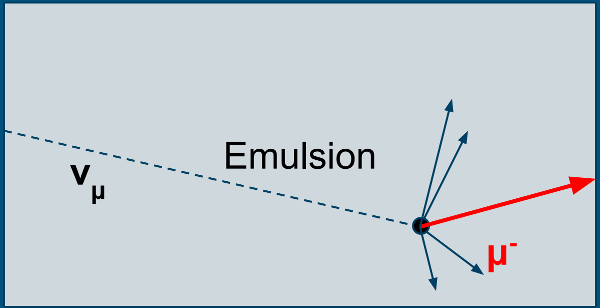
Backup

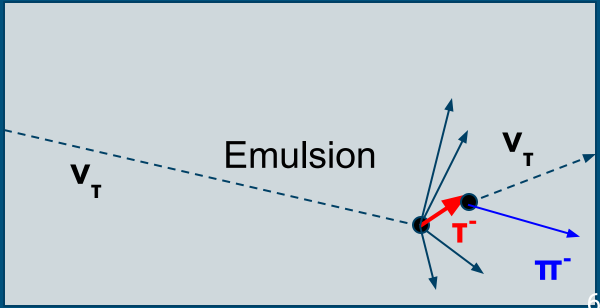
Outlook

ν / $\bar{\nu}$ features for e, μ, and τ

- Length of FASERν: 1000 ⇒ 760 emulsion films
- 285 ⇒ 217 radiation lengths (X_0)
  - Mean distance over which a high-energy e^- loses all but $^1/_e$ of its energy in EM shower (bremsstrahlung, pair production, etc.)
  - $X_0 \sim 3$ mm
- It is unfeasible to perform electron / τ ID with FASERν
  - Vertex ID can still be done
  - If we apply same geometric acceptance, remaining length of emulsion detector is $57X_0$
  - Electron will interact again by bremsstrahlung, changing direction ⇒ cannot use for electron ID
  - Similar for τ which has mean flight length ~3 cm ~ $10X_0$
  - To identify e (τ) not scattering (decaying) in FASERν, we require $z > -X_0$ (X_0) ⇒ acceptance < 0.005 (0.05)
- We will focus on μ, ν_μ for the rest of this talk



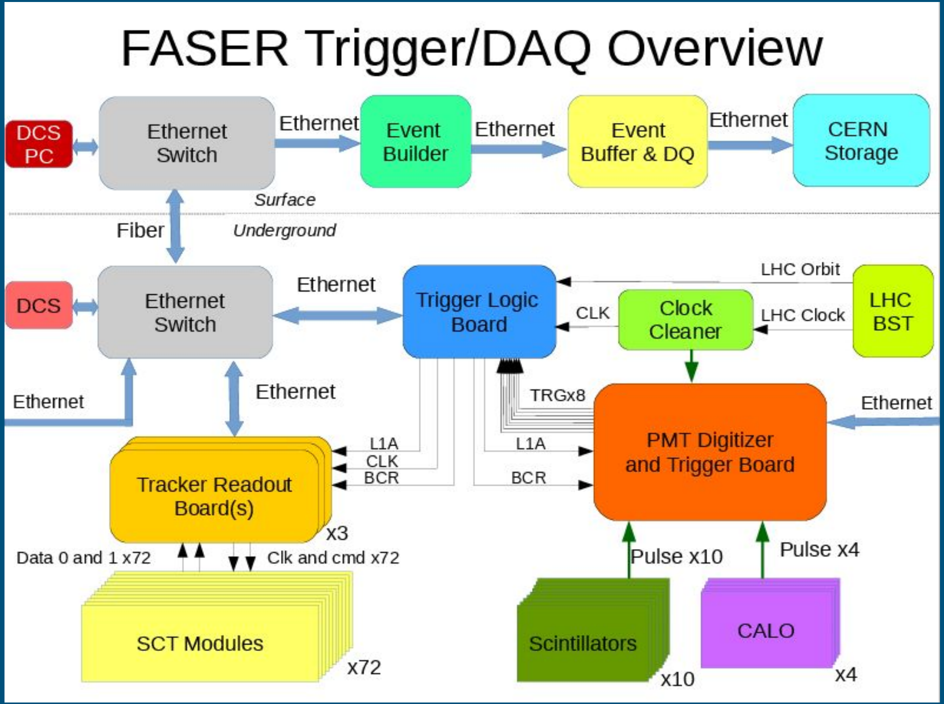




Triggering

[Source]

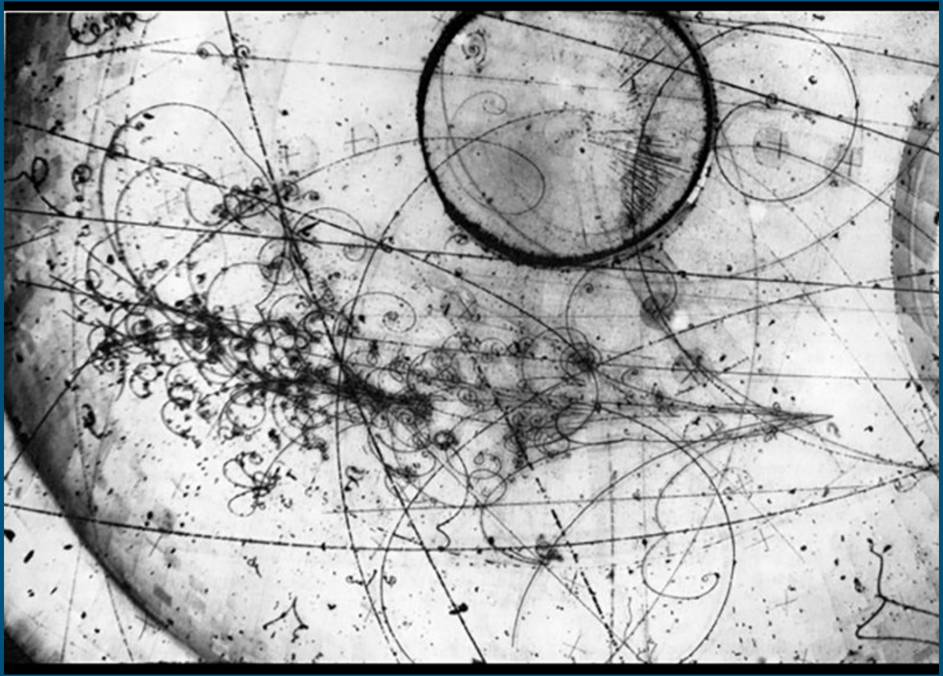
- Plan to trigger on all particles entering FASER
- Primary source of triggers: High-energy muons passing through FASER
- Decays of LLPs in FASER
- Use OR of scintillators / calorimeter
- Veto scintillators: 360 Hz,
- Timing scintillators: 640 Hz,
- Preshower scintillators: 360 Hz,
    - Scintillator threshold set below single minimum ionizing particle
- Calorimeter (E >100GeV): < 5 Hz
    - Set to trigger on any significant EM shower



E53

- Bubble chamber experiment at Fermilab
- Detected low energy electron neutrinos and antineutrinos

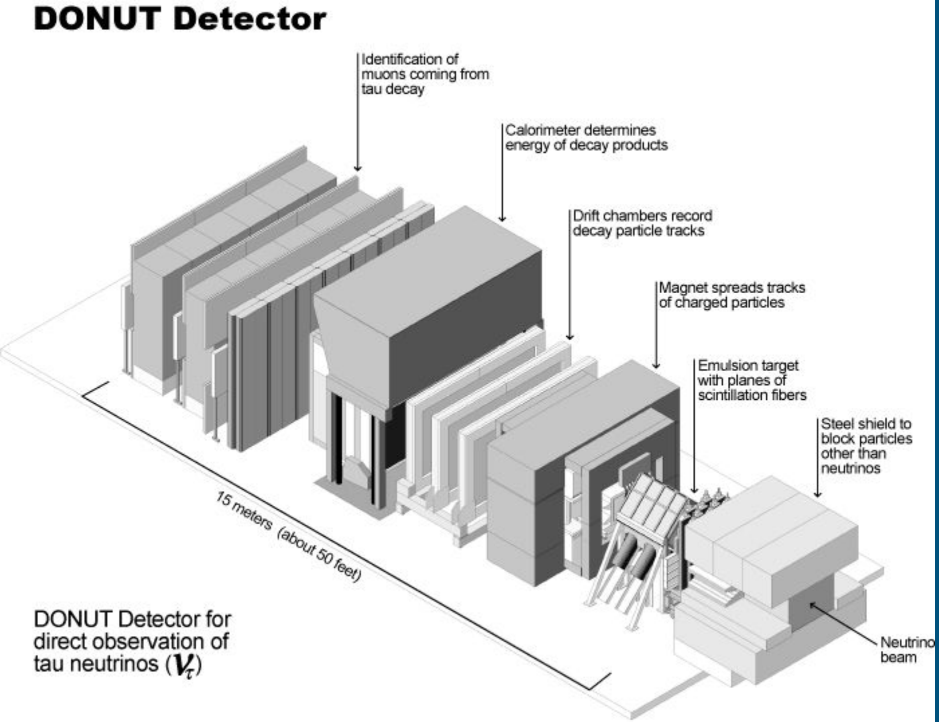
[Source]



DONUT

[Source]

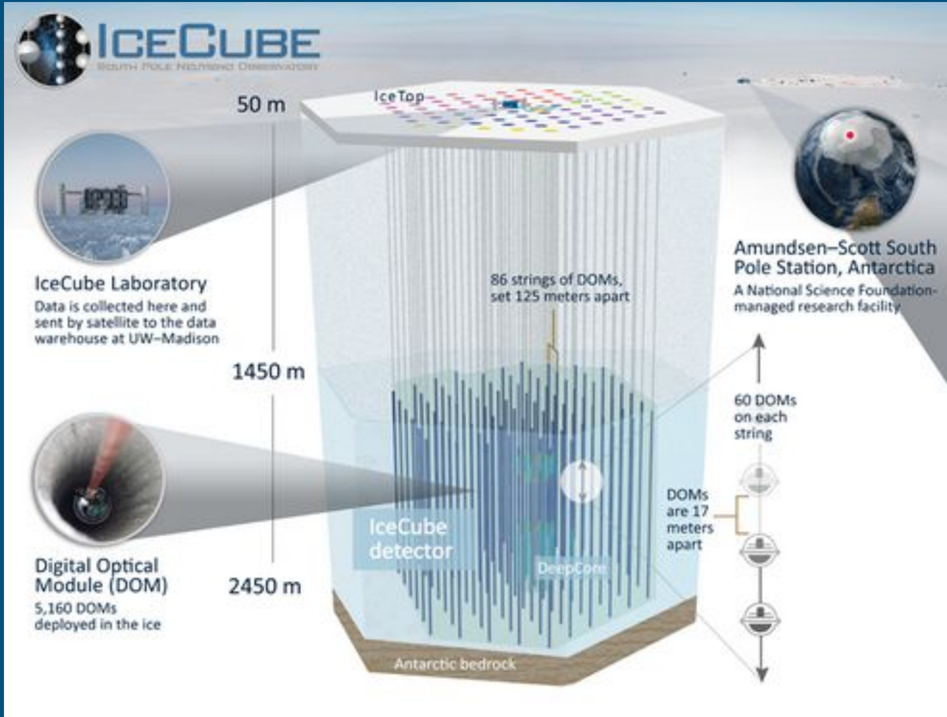
- Direct Observation of the NU Tau
- Experiment at Fermilab
- Searches for tau neutrino interactions
- 800 GeV proton beam from TeVatron
- Collides with tungsten block (beam dump)
- Produces D_s meson which decays to $\tau\nu_\tau$



IceCube

- 1 km^3 detector volume
- Maximum depth = 2.5 km
- 5160 digital optical modules
- DOMs in 86 boreholes
- Hexagonal grid with 125 m spacing
- Vertical separation of DOMs = 17 m
- First gigaton neutrino detector ever built
    - Detects cosmic rays (protons, neutrinos)
- DeepCore subdetector has horizontal (vertical) separation of 70 m (7 m)
    - Lowers ν energy threshold to 10GeV
    - Allows study of neutrino oscillations

[Source]



OPERA

- Oscillation Project with Emulsion tRacking Apparatus
- Focused on detecting v_{τ} from v_{μ} oscillations
- Fire protons from CERN Super Proton Synchrotron (SPS) at stationary carbon target to produce pions/kaons
- Pions/kaons decay to produce μ, v_{μ}
- Oscillations of v_{μ} produce v_{τ}

[Source]

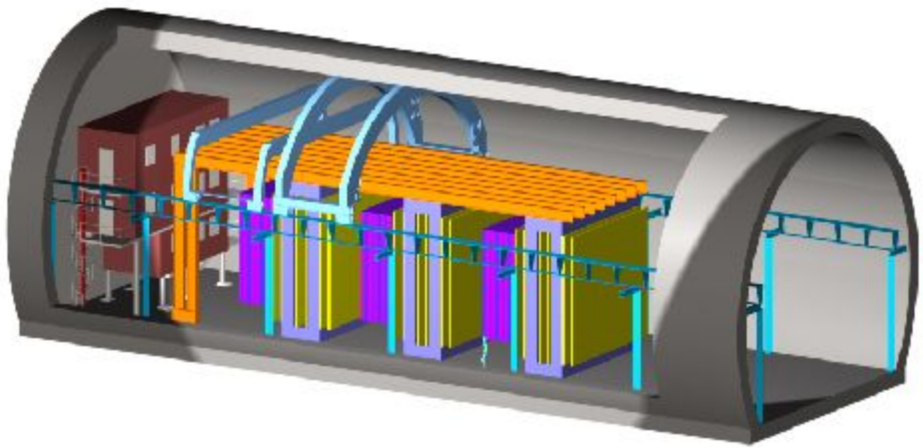


Fig. 1: The OPERA detector in the tunnel of the Gran Sasso underground laboratory.

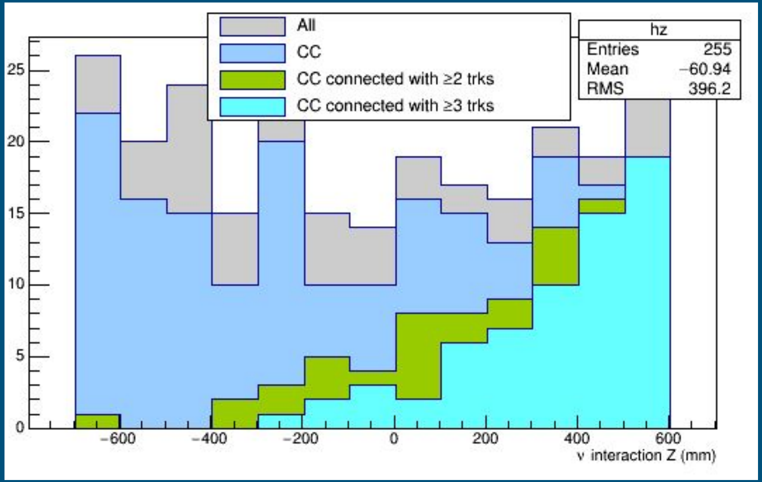
FLUKA

[Source]

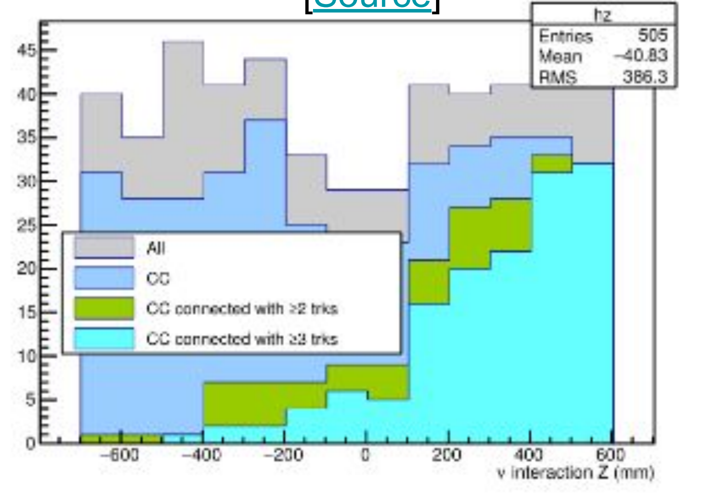
- Fully-integrated particle physics MC simulation package
- Used in high-energy experimental particle physics as well as medical physics/biology

Procedure to generate FASERnu efficiency plot

- Generate the FASERnu ROOT file using FaserNuIFTMC
  - Firing neutrinos with enhanced cross sections to record hits in FASERnu
- Copy to Windows to run virtualrec.c (FEDRA reco) and plot_hists.c
- Qualitatively consistent with Aki's results
  - Efficiency: 195 reconstructed events connected with ⩾1 track / 205 CC events = **0.951**
- [FaserNuIFTMC]



[Source]



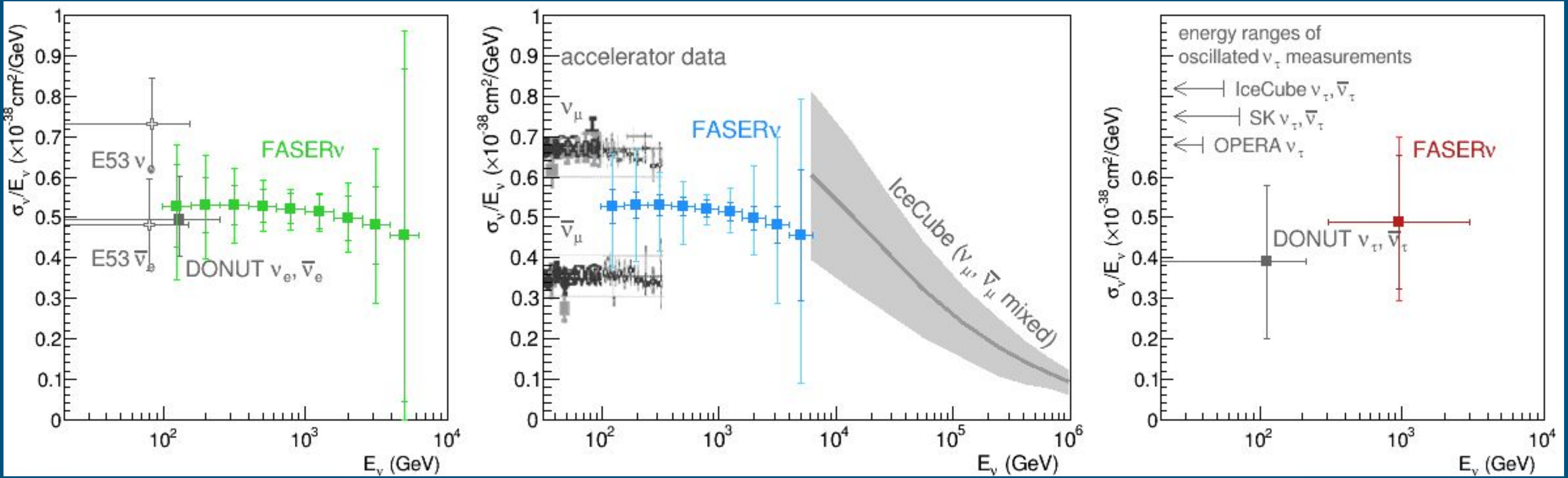
BDSIM

- Beam Delivery SIMulation
- Uses GEANT4 toolkit
- Simulates
  - Transport of particles in accelerator
  - Interaction with accelerator material

Cross Section Sensitivity Study

Reproduced sensitivity plot

- Dark blue: Statistical error   Light blue: Statistical+systematic error
- Statistical error higher in bins with fewer events



[Old geometry, 1000 planes]

To-do:

Neutrion:

- Denominator distribution of incoming particle: Energy, Eta, Theta
- Numerator distribution 1: after accepted by Emulsion
- Numerator distribution 2: after accepted by Tracker

Anti-Neutrino:

- Denominator distribution of incoming particle: Energy, Eta, Theta
- Numerator distribution 1: after accepted by Emulsion
- Numerator distribution 2: after accepted by Tracker

Cross Section Sensitivity Study

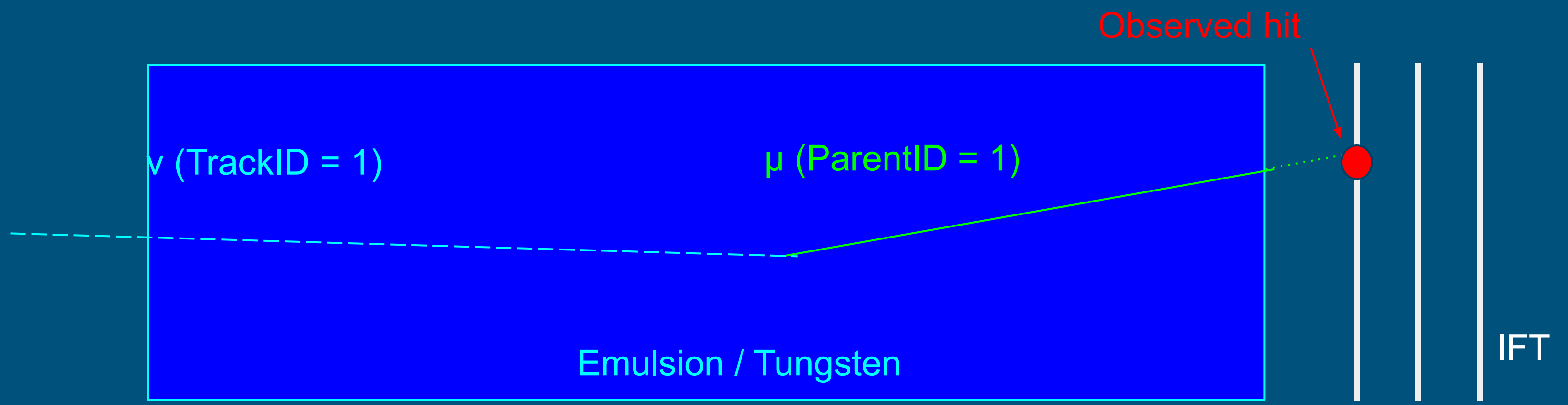
Sensitivity

- How well can we distinguish neutrinos from antineutrinos?
  - Depends on how well we can distinguish oppositely charged leptons
- There has been a preliminary study using mathematical helices
  - Add Gaussian smearing
  - Apply shifts to tracking planes
  - Perform χ^2 track fitting to shifted, smeared hits
- We want to perform similar study using simulation
  - Use correct (inhomogeneous) B-field $\Rightarrow$ piecewise line/helix tracker

Reconstruction Algorithm

Track Matching Procedure

- Collect tracker hits and reconstruct emulsion tracks
- For each emulsion track with ParentID = 1:
  - Extrapolate to the first IFT layer
  - If $(x_{extrap}, y_{extrap}) = (x_{measured}, y_{measured})$ within (σ_x, σ_y), match the tracks



Cross Section Sensitivity Study

Determining cross section (part II)

$$\text{Cross Section} = \frac{N - N_{bkg}}{\mathcal{L} \times A \times \epsilon_{VertexID} \times \epsilon_{Emulsion} \times \epsilon_{Tracker} \times \epsilon_{Matching}}$$

- Knowing theory prediction, we can determine N (# of events)
- From N we can determine statistical uncertainty = 1/sqrt(N)
- Number of events + flux uncertainty in git repo:
  - https://gitlab.cern.ch/jwspence/cross-section-sensitivity.git

Cross Section Sensitivity Study

Background estimate

- After applying specified cuts, estimated background = 0.83 events
- Our study is conducted with no-background assumption
    - Background will provide small systematic error contribution from false signal-background track matching

[Source]

	n	$\bar{n}$	K_L^0	K_S^0	Λ^0	$\bar{\Lambda}^0$	Total
Incident muons (E > 100 GeV)	6.67×10^8	6.67×10^8	6.67×10^8	6.67×10^8	6.67×10^8	6.67×10^8	
Particles (E_h > 10 GeV)	9515	4338	12190	3869	1749	1202	
Rate of events with interactions or decays	50%	51%	52%	70%	64%	66%	
Efficiency of the vertex selection (before the BDT cut)	1.4%	2.1%	2.5%	3.9%	2.8%	2.4%	
Vertex selected	68	47	157	107	32	19	
Vertex selected (normalized to 12.5 fb^{-1} and the fiducial volume)	1.3	0.9	3.0	2.1	0.6	0.4	8.3
After the BDT cut							0.83

	LOI (FASER original)
$\nu_e, \bar{\nu}_e$	814, 456
$\nu_\mu, \bar{\nu}_\mu$	4452, 1366
$\nu_\tau, \bar{\nu}_\tau$	15, 7

[EPJC (2020) 80:61]