Neutral Current Neutrino Interactions at FASERν

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FPF - Forward Physics Facility [1]

Introduction In planning for the coming decades in particle physics, it is critically important to maximize the physics potential of the High-Luminosity LHC (HL-LHC). For decades, the focus at the energy frontier has been on high-p_T physics and the production of heavy particles through processes with fb to nb cross sections. The total pp interaction cross section at the LHC is 75 mb [1, 2], however, and most of the events, and most of the highest-energy particles created, are in the far-forward region at low p_T. These low-p_T events escape down the beampipe of the LHC's large detectors, and it is important to understand now if interesting physics opportunities are currently being missed in this "wasted" cross section.

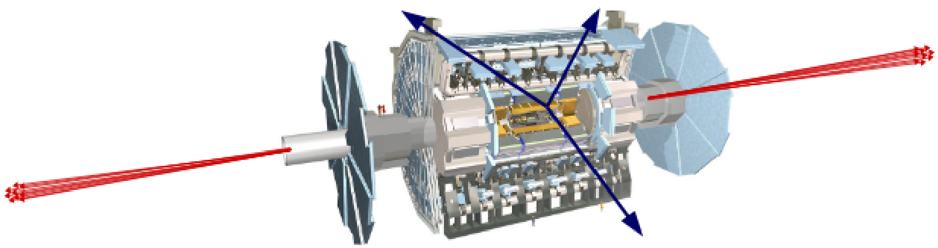
In recent years, it has become clear that this is in fact the case, and there is a rich physics program that is largely unexplored in the far-forward region at the LHC. In this Letter of Interest, we consider the possibility of creating a Forward Physics Facility (FPF) to house a diverse set of experiments dedicated to carrying out this program in the HL-LHC era.

FPF will house experiments that will study neutrinos, long-lived particles, milli-charged particles, dark matter, dark sector, cosmic rays and more.

[1] SNOWMASS 2021 Letter of Interest - DOI: 10.5281/zenodo.4009641

ForwArd Search ExpeRiment at LHC

- LHC searches/experiments focus on **central region**, which is motivated by heavy, strongly interacting particles
  * small rates: $\sigma \sim$ fb - pb or $N_H \sim 10^7$ at $\mathcal{L} = 300\ \text{fb}^{-1}$
  * high pT, produced ~ isotropical



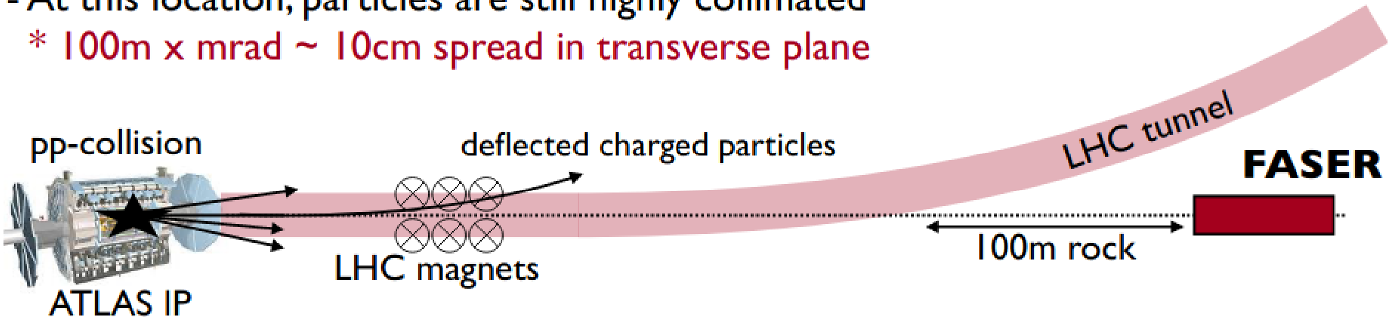
- For light and weakly interacting particles, this may be completely misguided
  * light: we can produce them in π, K, D, B decays
  * weakly-interacting: need extremely large SM event rate to see them
- We should go where the pions are: **forward region** along the beam line
  * enormous event rates: $\sigma_{\text{inel}} \sim 100$mb or $N_\pi \sim 10^{17}$ at $\mathcal{L} = 300\ \text{fb}^{-1}$
  * highly energetic beam remnants: E ~ TeV
  * low pT ~ Λ_{QCD} → particles are collimated $\theta \sim \Lambda_{QCD}/E \sim$ mrad

FASER

- We can't place a reasonably-sized detector on the beam line near the IP
  * blocks the proton beams, subject to large radiation

- However, weakly-interacting particles do not interact with matter
  → place detector few 100m away along the "collision axis" after beam curves
  * LHC infrastructure acts and rock act as shielding

- At this location, particles are still highly collimated
  * 100m x mrad ~ 10cm spread in transverse plane

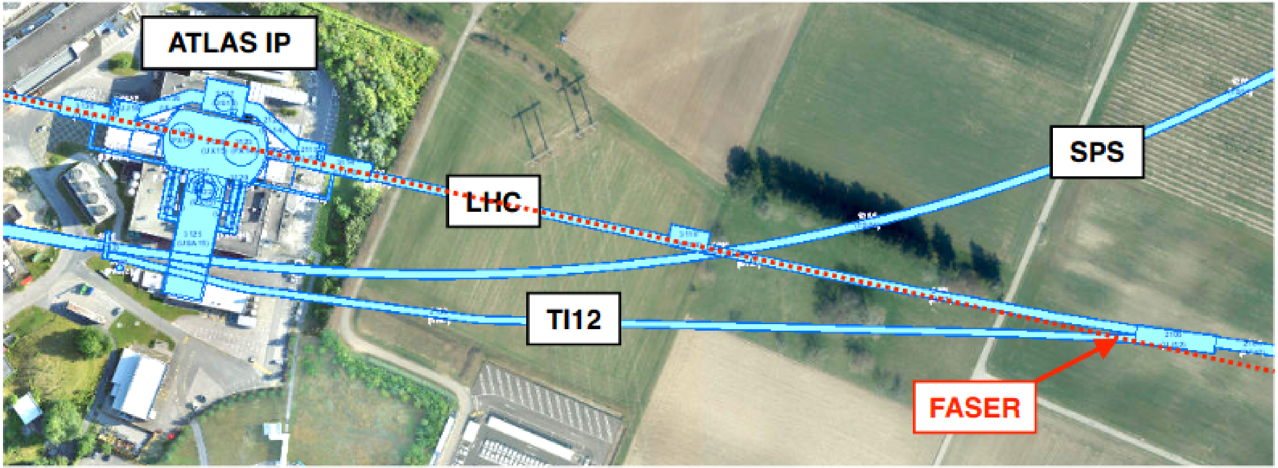


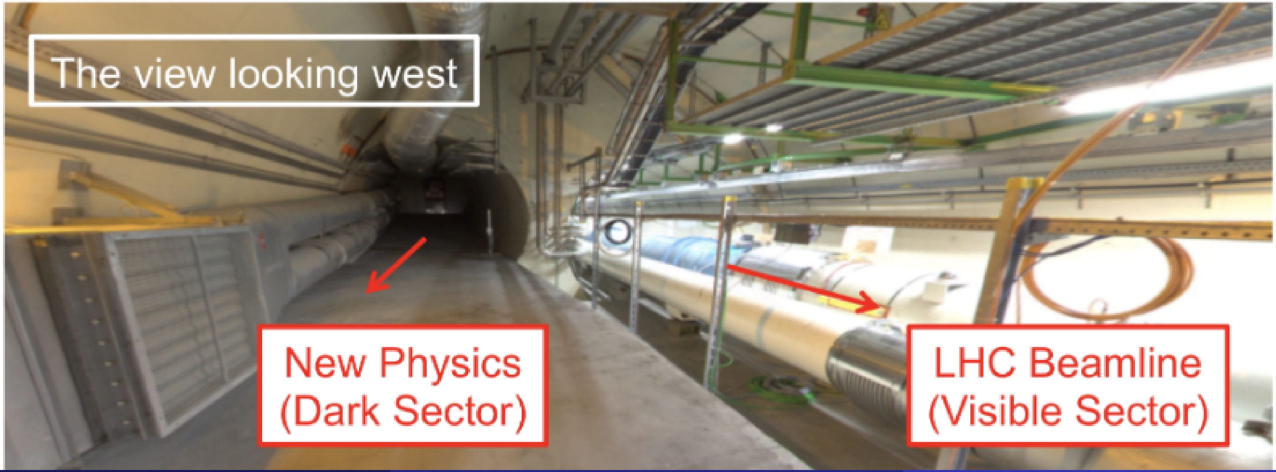
- This motivates small, fast and cheap inexpensive detector
  FASER: Forw**A**rd **S**earch **E**xpe**R**iment at the LHC

- Applications for light long-lived particles searches and neutrinos

LOI: 1811.10243, TP: 1812.09139

FASER


ATLAS IP
LHC
SPS
TI12
FASER

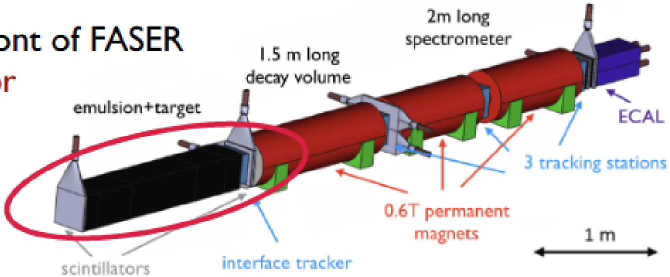

The view looking west
New Physics
(Dark Sector)
LHC Beamline
(Visible Sector)

FASERν

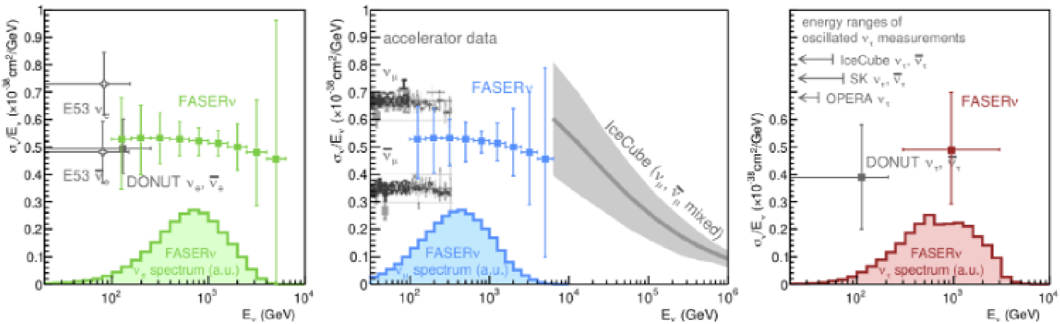
- neutrinos detected from many sources, but not from colliders

- many neutrinos at LHC produced in π, K, D meson decay
  → ATLAS provides intense highly collimated neutrino beam towards FASER
  * ~10^{12} neutrino in LHC Run 3   * highly collimated   * E~TeV

- dedicated FASERν neutrino detector in front of FASER
  * 25cm x 25cm x 1.3m emulsion detector
  * tungsten target with 1.2 ton mass
  * ~ 20000 ν_μ, ~ 2000 ν_e, ~ 20 ν_τ during LHC Run 3



- neutrino physics at TeV energies
  * probe unconstrained neutrino cross sections at TeV for all 3 flavors



LOI: 1908.02310, TP: 2001.03073

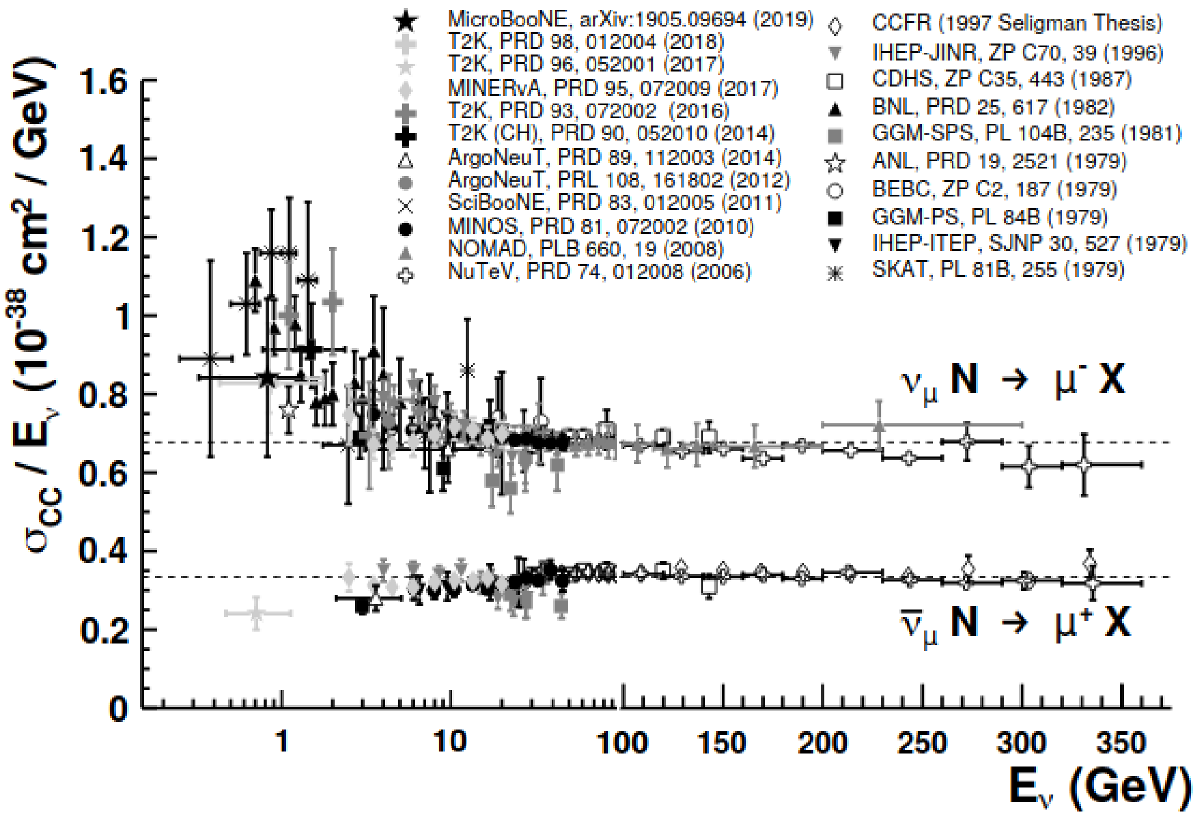
Existing Neutrino Cross Section Measurements[2]

Experiment	beam	$\langle E_\nu \rangle$, $\langle E_{\overline{\nu}} \rangle$ GeV	neutrino target(s)	run period
ArgoNeuT	$\nu, \overline{\nu}$	4.3, 3.6	Ar	2009 – 2010
ICARUS (at CNGS)	ν	20.0	Ar	2010 – 2012
K2K	ν	1.3	CH, H_2O	2003 – 2004
MicroBooNE	ν	0.8	Ar	2015 –
MINERvA	$\nu, \overline{\nu}$	3.5 (LE), 5.5 (ME)	He, C, CH, H_2O, Fe, Pb	2009 – 2019
MiniBooNE	$\nu, \overline{\nu}$	0.8, 0.7	CH_2	2002 – 2019
MINOS	$\nu, \overline{\nu}$	3.5, 6.1	Fe	2004 – 2016
NOMAD	$\nu, \overline{\nu}$	23.4, 19.7	C–based	1995 – 1998
NOvA	$\nu, \overline{\nu}$	2.0, 2.0	CH_2	2010 –
SciBooNE	$\nu, \overline{\nu}$	0.8, 0.7	CH	2007 – 2008
T2K	$\nu, \overline{\nu}$	0.6, 0.6	CH, H_2O, Fe	2010 –

And IceCube above 6.3 TeV.

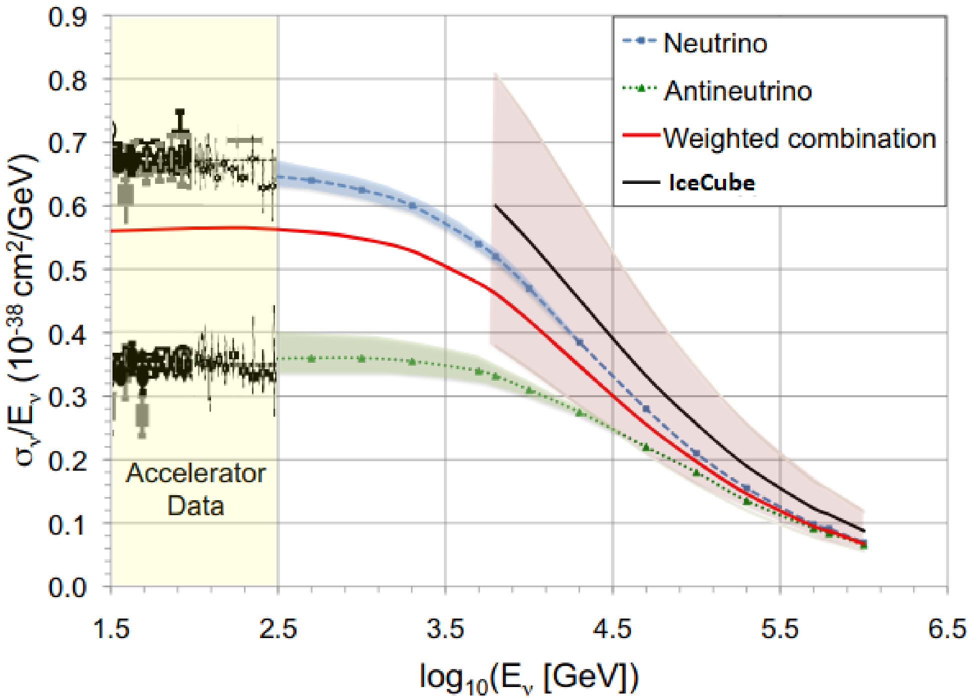
[2] https://pdg.lbl.gov/2019/reviews/rpp2019-rev-nu-cross-sections.pdf

Existing Measurements - Low Energy



Highest energies are from NuTev.

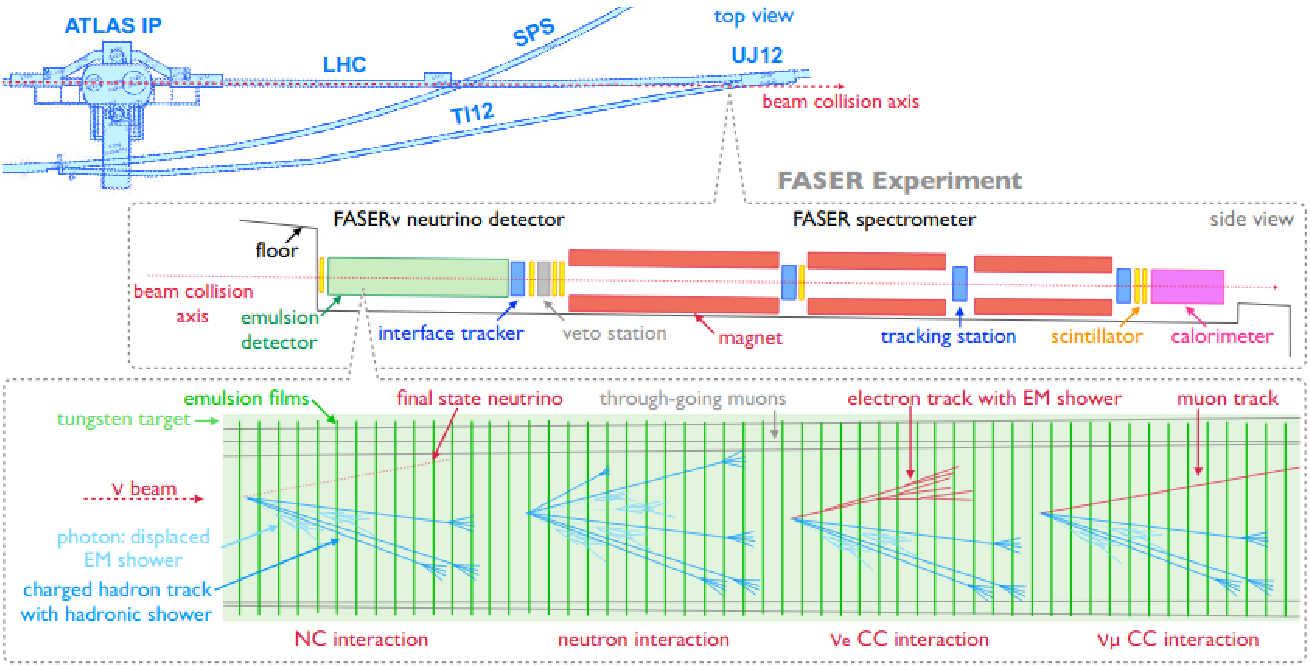
Existing Measurements - High Energy[3]



Accelerator data ≤ 350GeV and IceCube ≥ 6.3TeV. FASERν can fill in this gap.

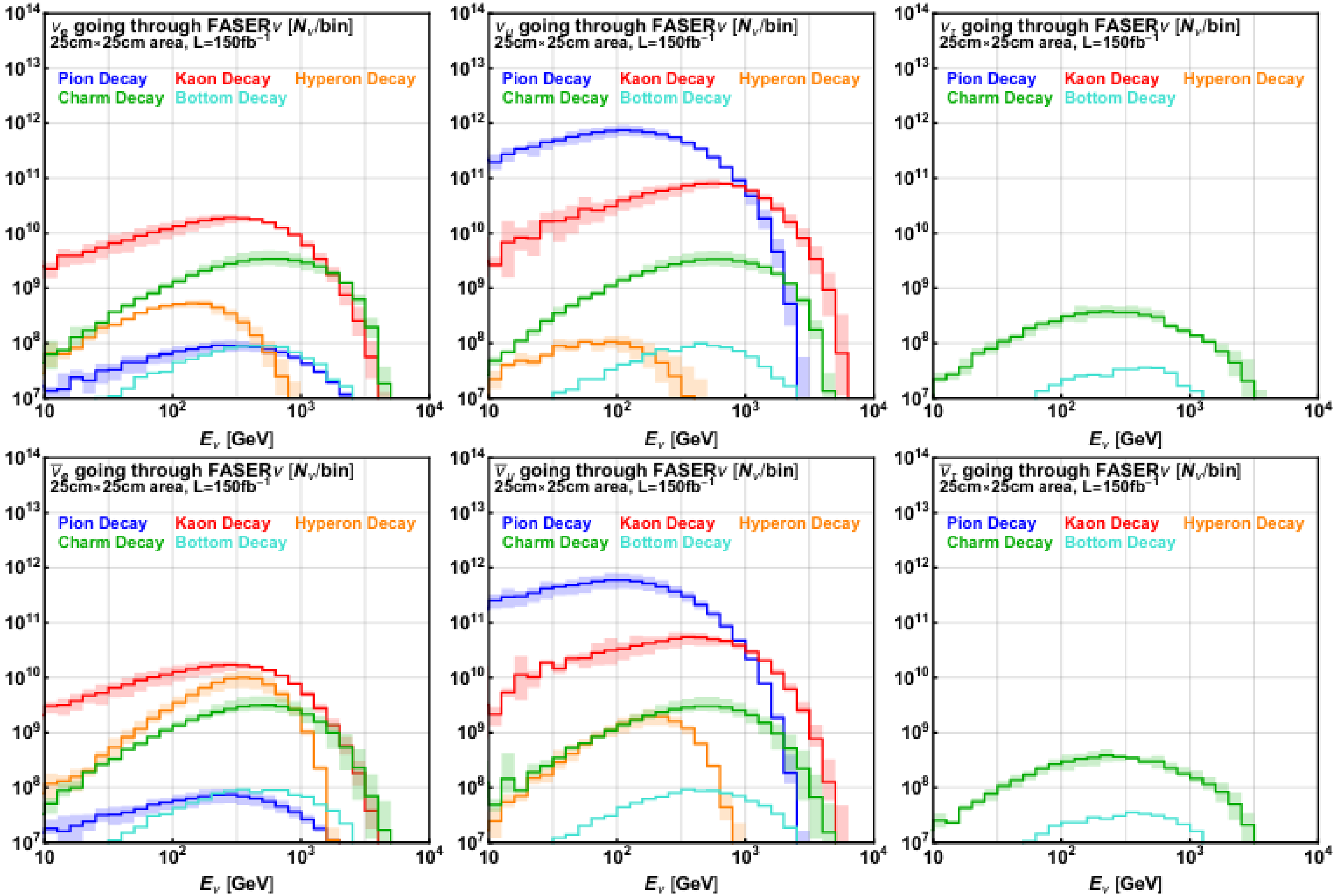
[3] 1711.08119, 1711.11043

FASERν



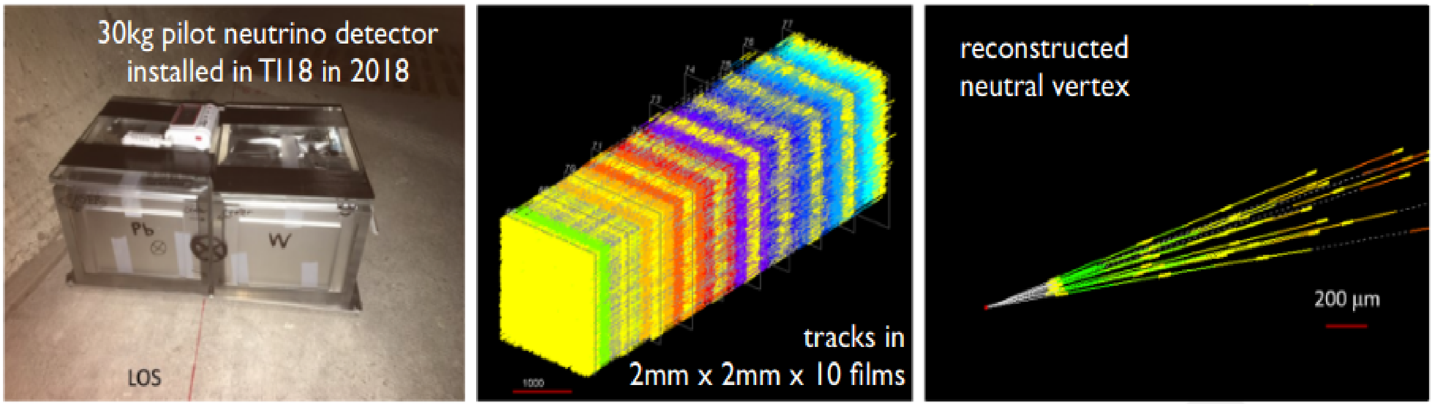
ATLAS IP
LHC
SPS
top view
UJ12
beam collision axis
TI12
FASER Experiment
FASERν neutrino detector
FASER spectrometer
side view
floor
beam collision axis
emulsion detector
interface tracker
veto station
magnet
tracking station
scintillator
calorimeter
emulsion films
tungsten target
final state neutrino
through-going muons
electron track with EM shower
muon track
ν beam
photon: displaced EM shower
charged hadron track with hadronic shower
NC interaction
neutron interaction
νe CC interaction
νμ CC interaction

FASERν neutrino flux



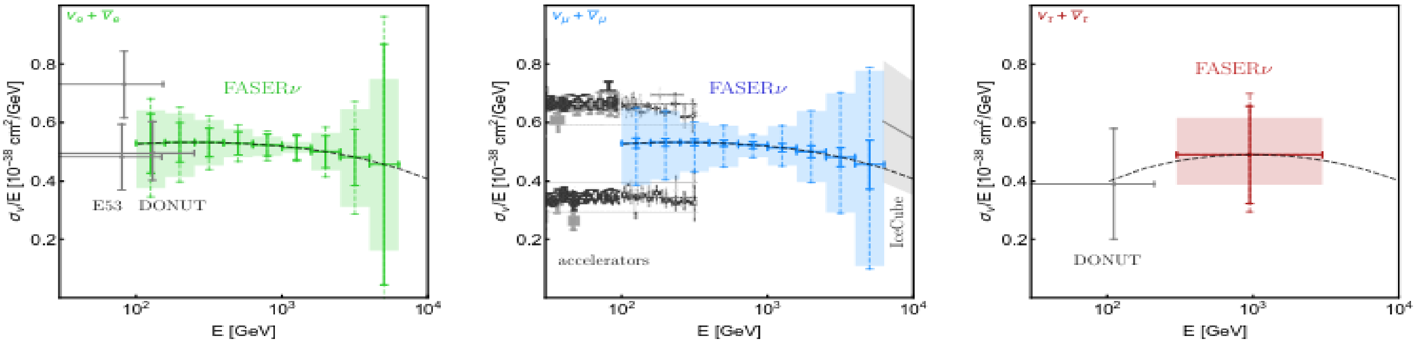
FASERν Test Run

A pilot neutrino detector collected 12.5 fb^{-1} of data from September to October 2018.



A track density of 3×10^5 tracks/cm^2 was observed. To find vertices in this data multiple signal selection cuts have to be imposed (more later).

Charged Current Cross-Section at FASERν [4]



	Number of CC Interactions	Number of Reconstructed Vertices	Mean Energy
$\nu_e+\bar{\nu}_e$	1296^{+77}_{-58}	1037^{+52}_{-36}	827 GeV
$\nu_\mu+\bar{\nu}_\mu$	20439^{+1545}_{-2314}	15561^{+1103}_{-1514}	631 GeV
$\nu_\tau+\bar{\nu}_\tau$	$21^{+3.3}_{-2.9}$	$17^{+2.6}_{-2.6}$	965 GeV

Expected numbers without considering geometrical acceptance and lepton identification efficiency. Globally there have been $\sim 20\ \nu_\tau$'s observed directly at DONut and OPERA. FASERν can detect $\sim 10\nu_\tau$ during LHC Run 3 with 150 fb^-1.

[4] 1908.02310

Neutral Current Cross-Section at FASERν [5]

- FASERν will give us a unique opportunity to measure ν cross-section in the $\sim$ [100GeV – few TeV] range. Charged Current (CC) cross-sections were studied earlier.
- Here we present an analysis strategy to identify and reconstruct Neutral Current (NC) interactions and hence constrain neutral current ν cross-sections.

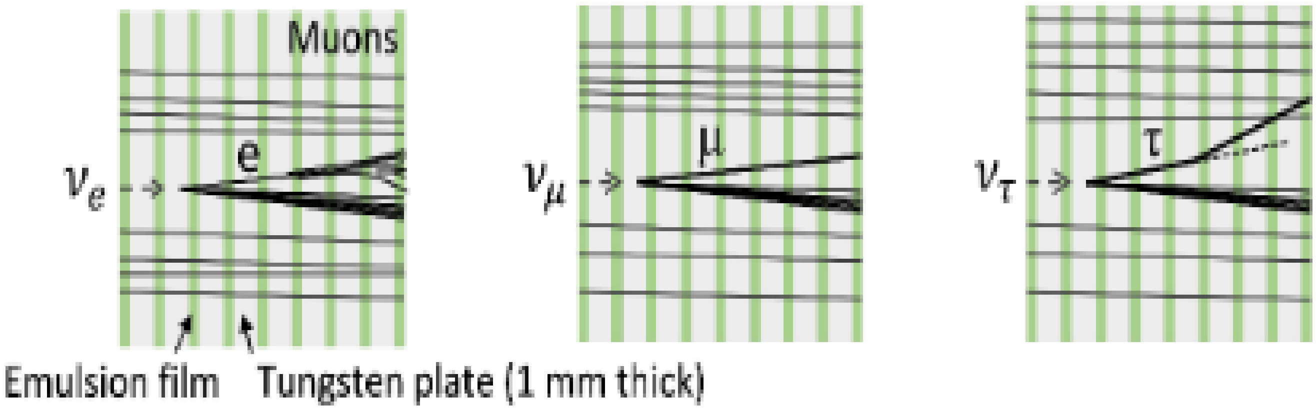
ν NC studies face two main obstacles at FASERν :

- The missing energy in the final state (carried away by the ν) makes event energy reconstruction very difficult. This is a problem shared by all ν NC studies.
- The main background for NC events at FASERν are
  - CC events (*one person's treasure is another's background*). This is a less severe problem.
  - Neutral Hadrons (NH), mainly induced by μ's.

[5] 2012.10500

Backgrounds - CC

CC: Different event topology allow us to discriminate between them and the signal.



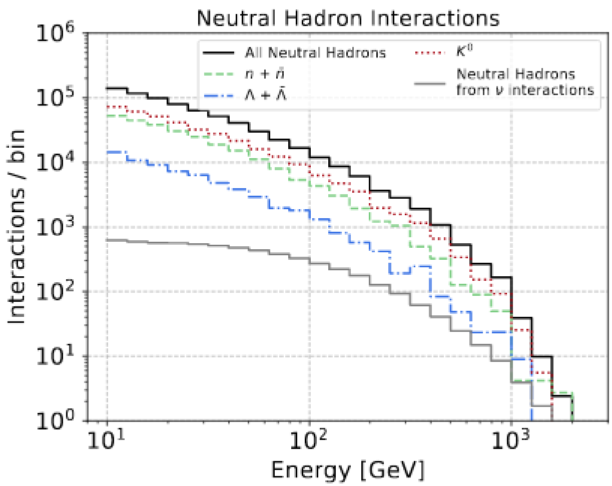
Backgrounds - CC

ν CC events have a lepton in the final state which can be used to identify these events.

- ν_e: The e in the final state initiates an EM shower in the detector that can easily be identified.
- ν_μ: μ's usually live long enough to NOT decay in the detector. The presence of a charge track that doesn't decay in the detector volume can be used to identify a μ-CC event. Sometimes charged hadrons in the final state of a NC event can mimic this signature.
- ν_τ: The almost immediate decay of τ results in a secondary displaced interaction vertex a short distance from the primary interaction vertex. This is a good discriminator.

Backgrounds - NH

Apart from the ν's we are interested in, only μ's can travel all the way through rock to the FASERν detector. The μ's interact with the rock in front of the detector and within the detector producing NHs, our most dominant background. NH interactions look very similar to our signal events. Below we show the interaction spectrum for NHs estimated using FLUKA simulations. Neutral hadrons are also produced by neutrino NC (and CC) events themselves, but these are a subdominant contribution to the total flux.



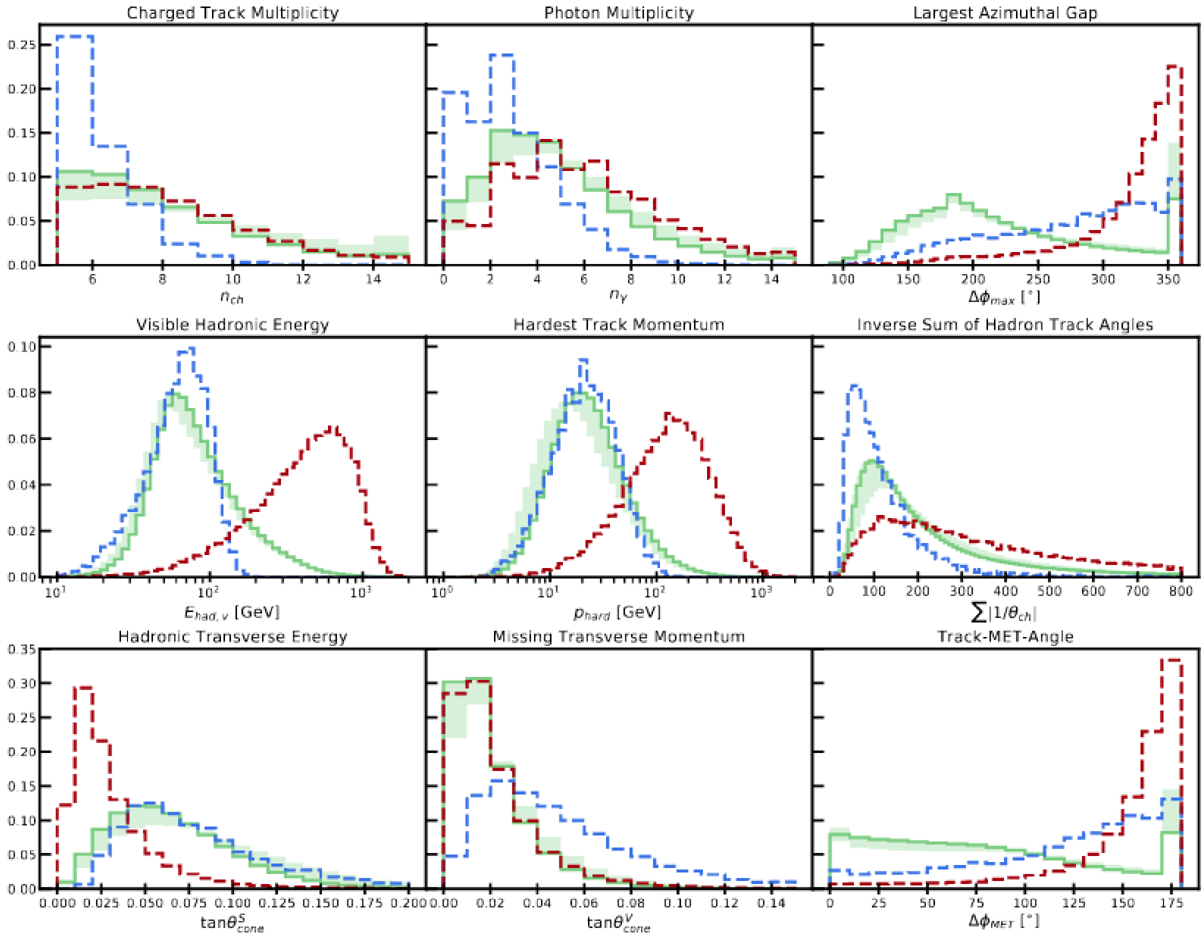
Event Generation and NN training

- *Event Generation:* We use Pythia to simulate ν-W and NH-W collision. Other generators were compared with Pythia and were in agreement.
- *Event Selection:* We select events with ≥ 5 charged tracks, each charged track has energy ≥ 1 GeV, and $\theta < \pi/4$ w.r.t incoming particle direction.
- *Detector Simulation:*
  - Track momentum and energy smearing.
  - Identifies each visible track as electron, photon or a normal track.
  - Determines if the track interacts within the detector.
- *NN training:* We use 2 NN's:
  - Classifier N/W: Distinguishes signal(NC) and background(NH) events.
  - Regression N/W: Estimates the incoming particle energy. Only on identified signal events.

Observables - Characterizing an Event

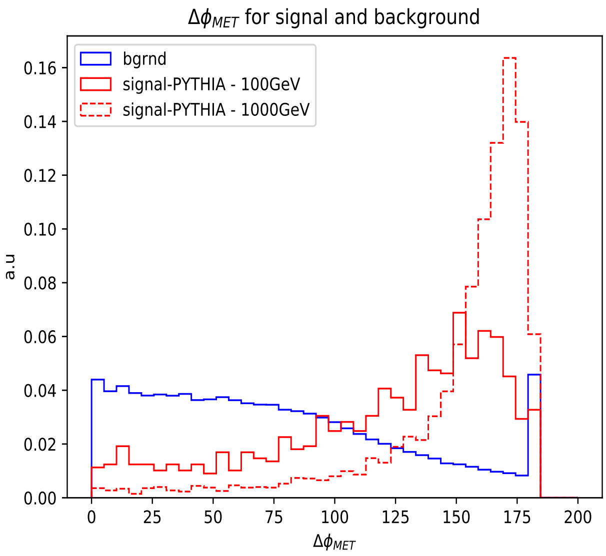
- **Charged Track Multiplicity:** $n_{ch} \sim \log E_{\text{had}}$
- **Photon Multiplicity:** $n_{\gamma} \sim 2n_{\pi^0} \sim \log E_{\text{had}}$
- **Visible Hadronic Energy:** $E_{had,v} \sim \sum E_{\text{ch}} + \sum E_{\gamma}$
- **Momentum of Hardest Track:** $p_{\text{hard}} \sim E_{\text{had}}$
- **Inverse Sum of Track Angles:** $\sum |1/\theta_{\text{ch}}| \sim E_{\text{had}}$
- **Scalar Cone Angle:** $\tan \theta^{S}_{\text{cone}} = (\sum p_{T,i})/(\sum p_i) \sim H_T/E_{\text{had}}$
- **Vector Cone Angle:** $\tan \theta^{V}_{\text{cone}} = (\sum \vec{p}_{T,i})/(\sum p_i) \sim \vec{p}_T/E_{\text{had}}$
- **Largest Azimuthal Gap:** The largest difference in azimuthal angle between two neighbouring tracks, $\Delta\phi_{\text{max}}$ (large for events where a ν recoils all other hadronic activity).
- **Track-MET-Angle:** The azimuthal angle between the reconstructed missing transverse momentum, $\not{\vec{p}}_T$ and the nearest track, $\Delta\phi_{MET}$.

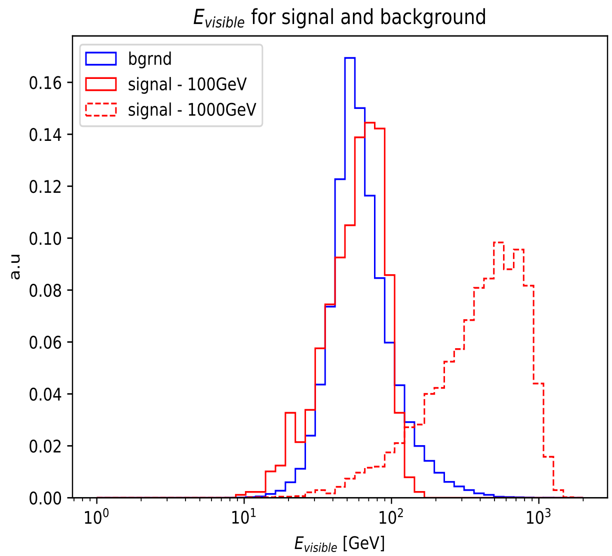
Observables - Signal vs Background



Observables (cont.)

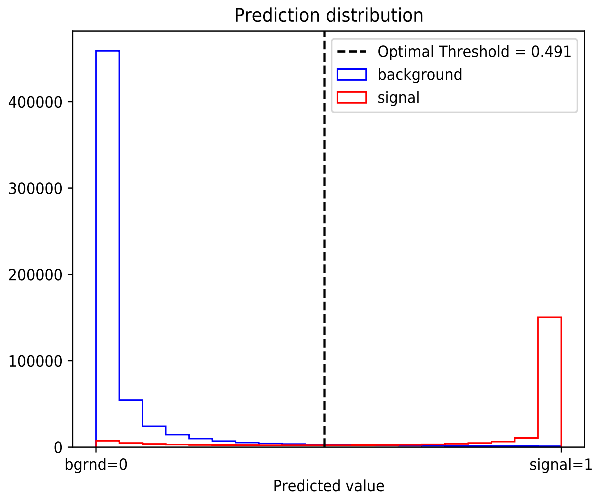
These observables capture the kinematic differences between signal and background events. Statistically, NH background (following the expected spectrum) resemble low energy signal. It is patterns like these that we try to learn using neural networks.

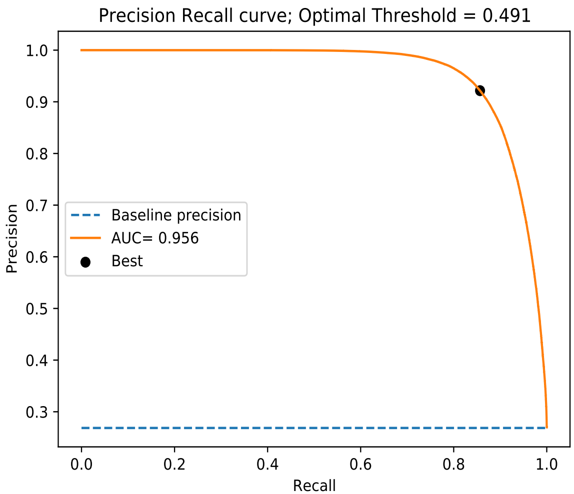




Training Neural Networks - Classifier

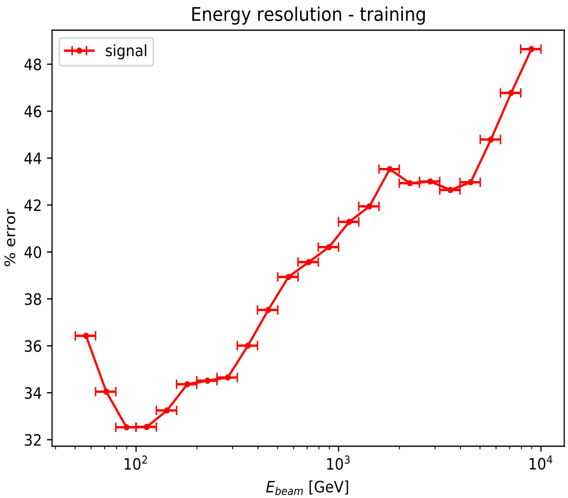
- We simulate 100 times the **expected Run 3 event rate** for both the NC signal and the NH background interaction to train a classifier neural network with binary cross-entropy loss function. It assigns a score to each event.
- Optimal Threshold is that which maximizes F score, harmonic mean of precision and recall.
  Precision $= \frac{TP}{TP+FP}$, Recall $= \frac{TP}{TP+FN}$

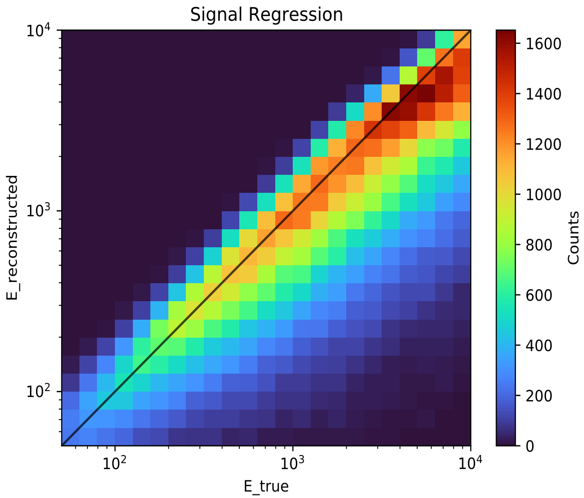




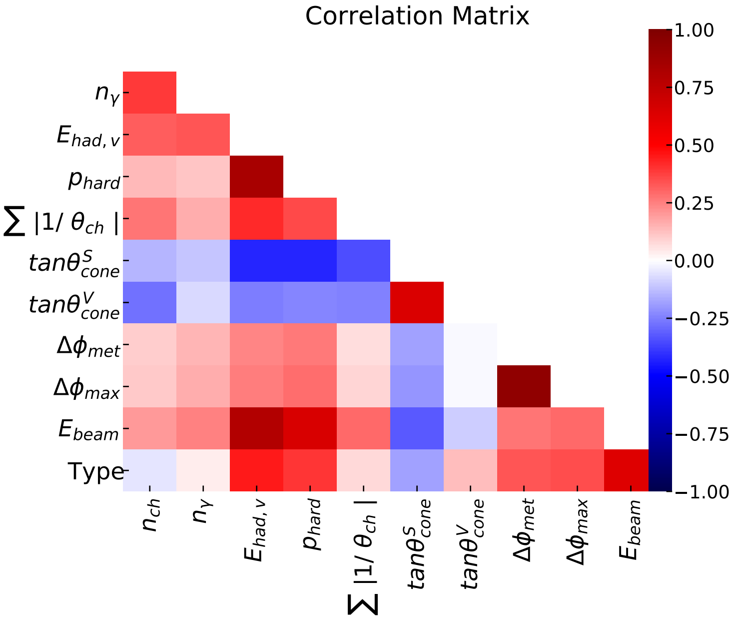
Training Neural Networks - Regression

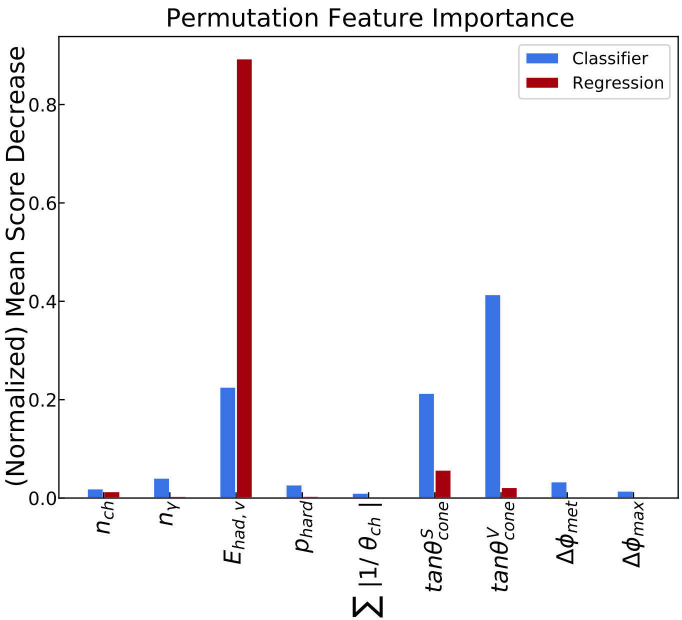
- Here we train a regression network using mean absolute error loss function on a **flat distribution** of only NC signal events.
- Only NC signal events are used here as we do not attempt to reconstruct NH background event energies in our analysis.





Feature Importance





Feature Importance (cont.)

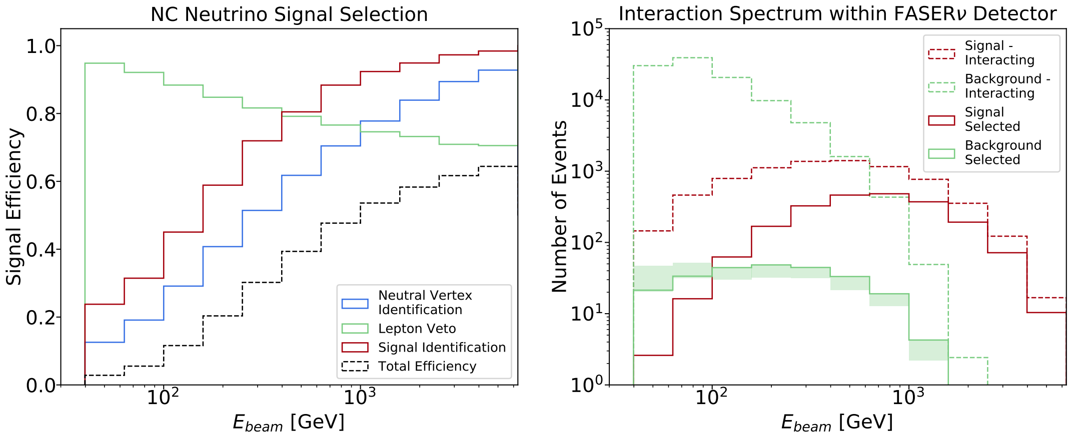
Correlation Matrix:

- Event type is most strongly correlated with $E_{had,v}, p_{hard}$. This is expected as the incoming neutrinos which interact with the detector tend to be harder than the neutral hadrons.
- More energy associated with an event (larger $E_{beam}, E_{had,v}, p_{hard}$) $\longrightarrow$ more tightly collimated its reaction products are (smaller cone angles θ_{cone}, larger azimuthal angles $\Delta\phi$).

Permutation Feature Importance:

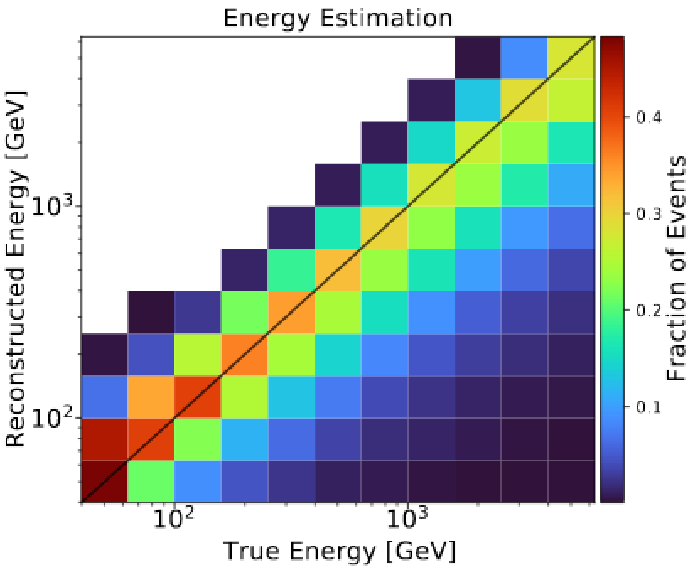
- Shows the score degradation if you randomly shuffle the values of one observable.
- Large decreases $\longrightarrow$ important observable.

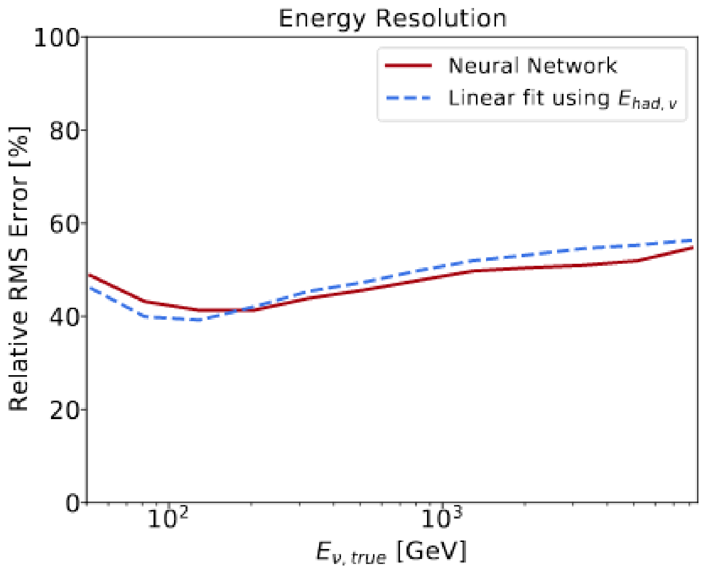
Neural Network Results - Classifier



- Neutral vertex identification (blue) requiring ≥ 5 charged tracks: Small at low energies as there isn't enough energy to produce many charged tracks.
- Lepton veto (green) requiring no electron candidate and no non-interacting charged track (this is for muons): Decreases as energetic charged hadrons have more chance to escape detector without interacting.
- Signal identification (red) as performed by the NN classifier: At low energies there are more background events.

Neural Network Results - Regression

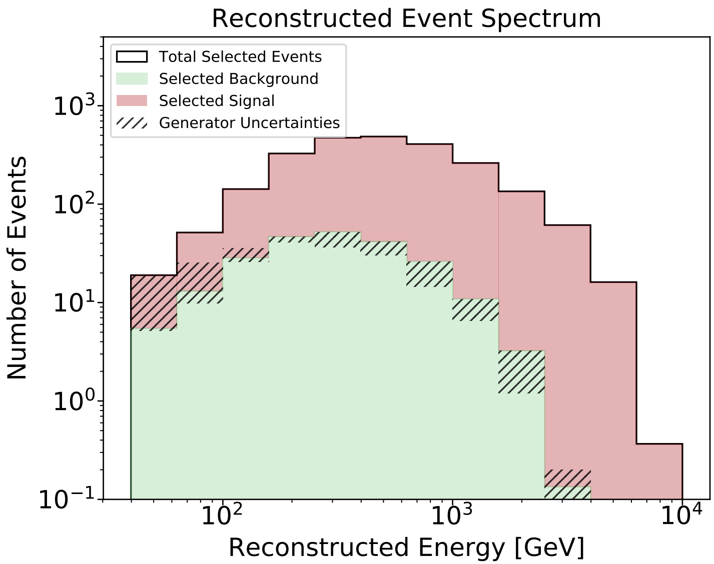


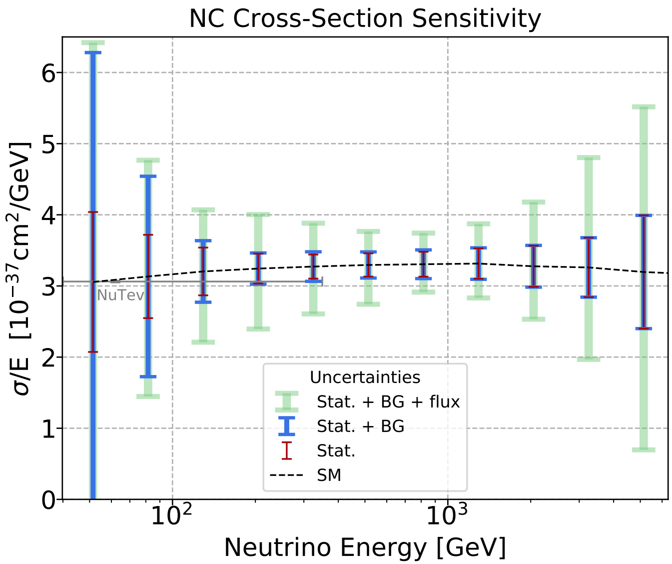


Energy Resolution:
CC $\sim$ 30% (1908.02310)
NC $\sim$ 50%

Cross-Section Results

O/p of the NN's gives us the number of reconstructed events in each energy bin (for a total of $\sim$ 7000 events). This gives us size of statistical uncertainty on ν NC interaction cross-section. The other sources of uncertainty are background uncertainty and incoming ν flux uncertainty (dominant one).





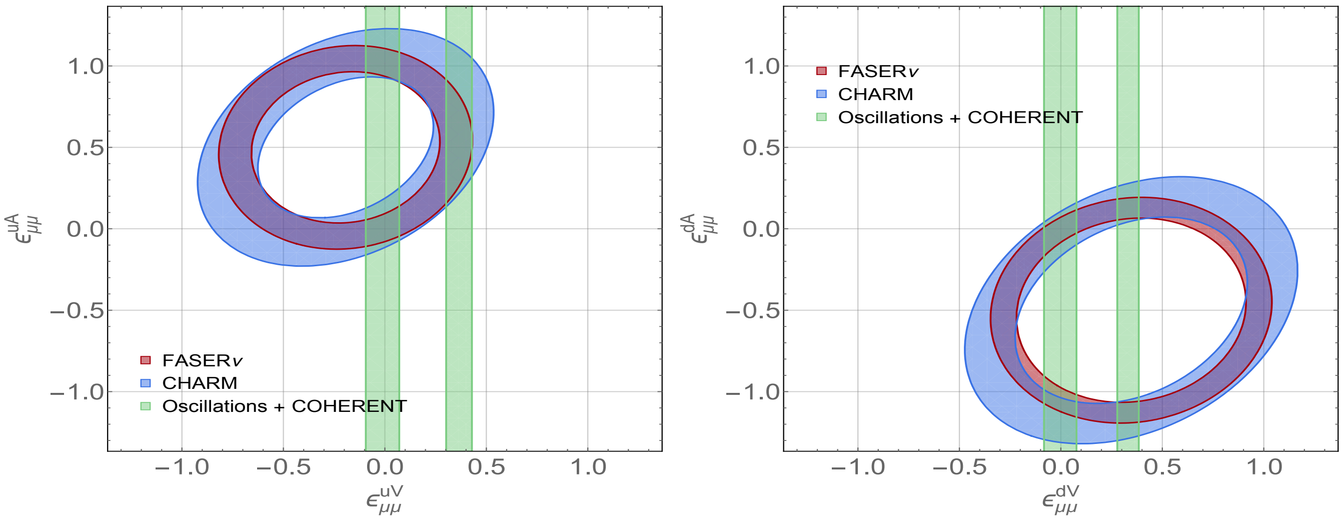
Constraining NSI

$$\mathcal{L} \supset -\sqrt{2}G_F \sum_{f,\alpha,\beta} [\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta][\epsilon^{f,V}_{\alpha\beta} \bar{f}\gamma_\mu f + \epsilon^{f,A}_{\alpha\beta} \bar{f}\gamma_\mu \gamma^5 f] \quad (1)$$

- Neutrino oscillations [6] and coherent neutrino-nucleus scattering [7] probe vector couplings, $\epsilon^{f,V}_{\alpha,\beta}$ but are insensitive to axial couplings.
- By contrast, high-energy experiments can probe NSI regardless of the underlying spin structure and hence sensitive to $\epsilon^{f,V}_{\alpha,\beta}$ and $\epsilon^{f,A}_{\alpha,\beta}$. [8]
- We take the ratio of the NC to CC cross section assuming that the flux uncertainties will largely cancel, which was our dominant uncertainty.

[6] L. Wolfenstein, "Phys. Rev. D17(1978) 2369–2374.
[7] arXiv:hep-ph/0508299
[8] K. Babu, D. Goncalves, S. Jana, and P. A. Machado, arXiv:2003.03383

Constraining NSI - Bounds from FASERν



NSI bounds from CHARM(400GeV)(blue) and FASERν (red) for (**left:**) up quark and (**right:**) down quark in the Vector-Axial vector coupling plane. Vertical lines are bounds from oscillations and COHERENT that constrain only vector NSI. (The ellipses are differently shaped as we probe $\nu, \overline{\nu}$ whereas CHARM probed only ν.)

Summary

- There is much physics to be studied in the forward region at LHC.
- Hitherto unstudied the FPF aims to probe this region in a variety of ways.
- FASERν is the dedicated experiment to study collider neutrinos at few GeV to few TeV range, new for neutrino physics.
- We show here a strategy to overcome the usual difficulties with NC studies using machine learning.
- Both event identification and energy reconstruction were done to constrain ν NC cross-section.
- This sensitivity to NC interactions (combined with earlier CC studies) was used to constraining NSI.