Measurement of TeV neutrinos with *FASER*ν at the LHC

ForwArd Search ExpeRiment at the LHC

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for the FASER Collaboration

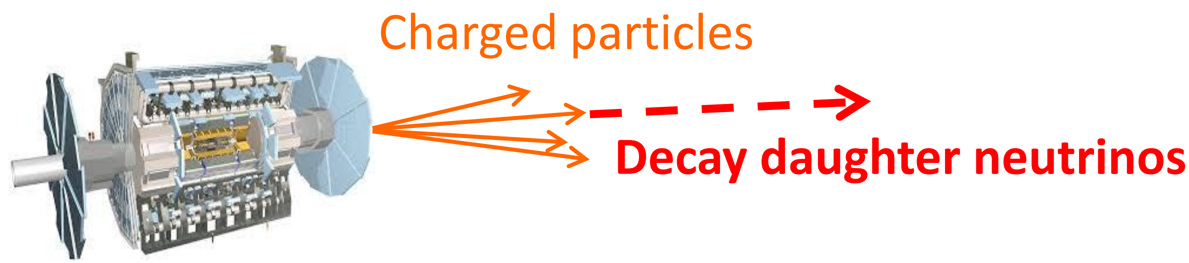
3rd May 2022

FASER

Supported by

CERN erc HEISING-SIMONS FOUNDATION SIMONS FOUNDATION 科研費 KAKENHI

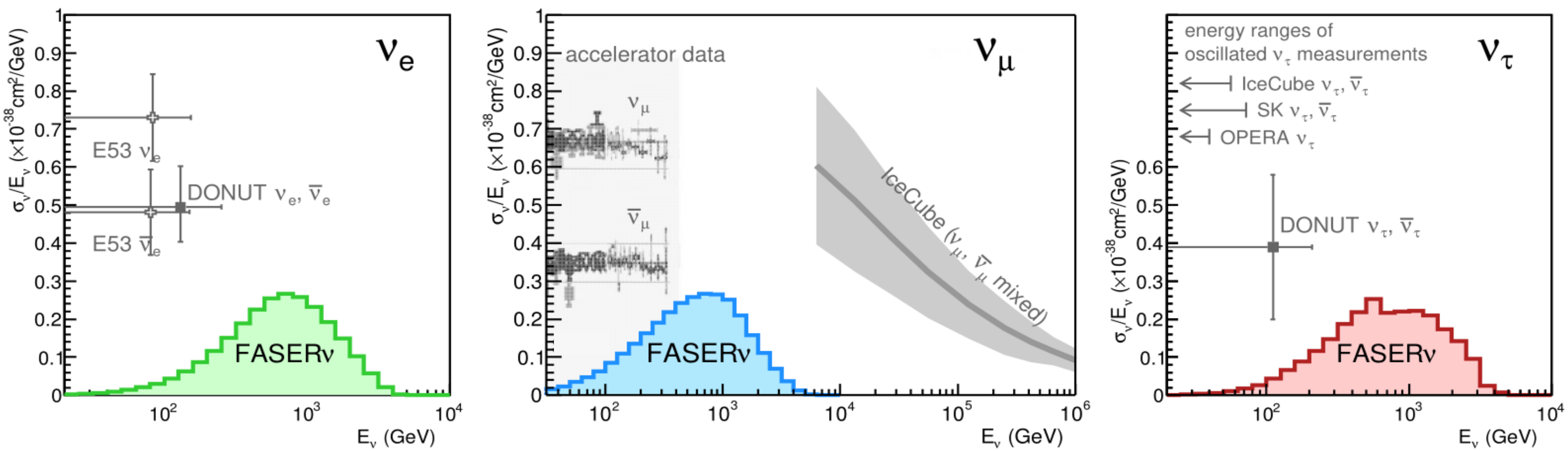
Motivation



- LHC collision products in forward direction can be high energy neutrino source.
- No data on the neutrino interactions at Eν in several 100 GeV to several TeV.
- The interaction cross section at ~TeV region is the knee point of its energy dependence and start behave sigma ≠ $\sigma_0 E$.
- **Measuring neutrino cross section of 3 type of neutrinos at unexplored enegy.**

- **Lepton Universality check, especially tau neutrino interactions and others, possible anomaly indication by B mesons.**

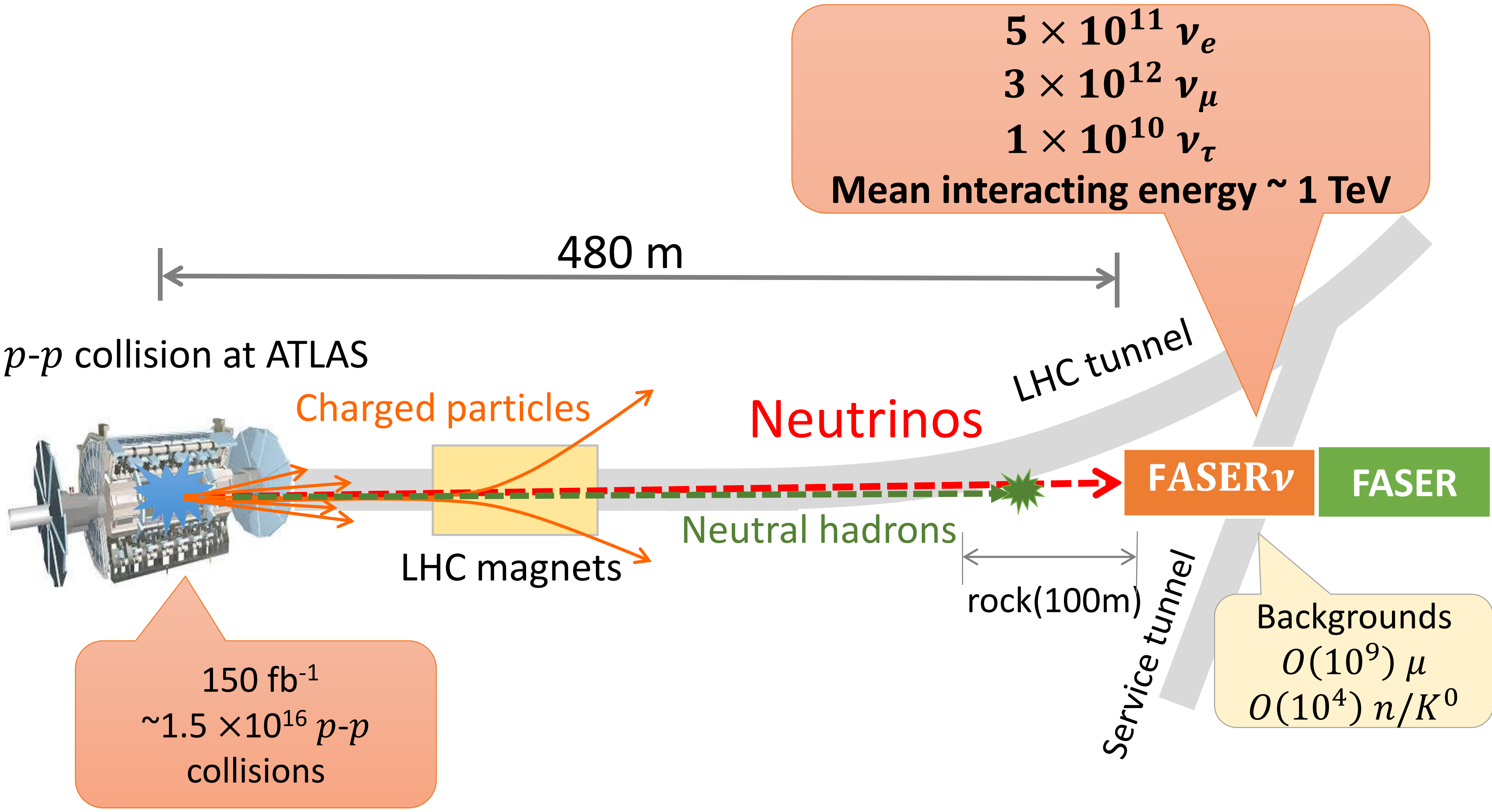
$$R(D) = \frac{\mathcal{B}(B \to \tau\nu_\tau D)}{\mathcal{B}(B \to \mu\nu_\mu D)}$$



Another Motivation

- Charm hadron production properties study through detection of especially tau neutrinos.
- Very forward going Charm production from LHC collision point is not well studied.
- Tau neutrinos in forward direction is the decay product of such Charm and contain information of Charm energy or its production flux.
- Measuring the neutrino flux as a function of energy , lateral position will provide charm differential cross section $d\sigma/ dx_F$.

FASERν layout

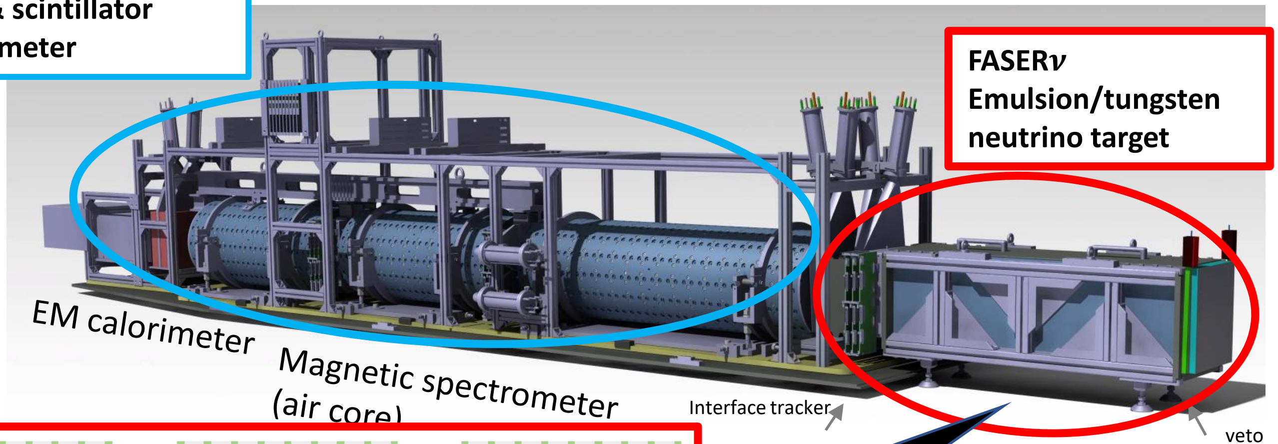


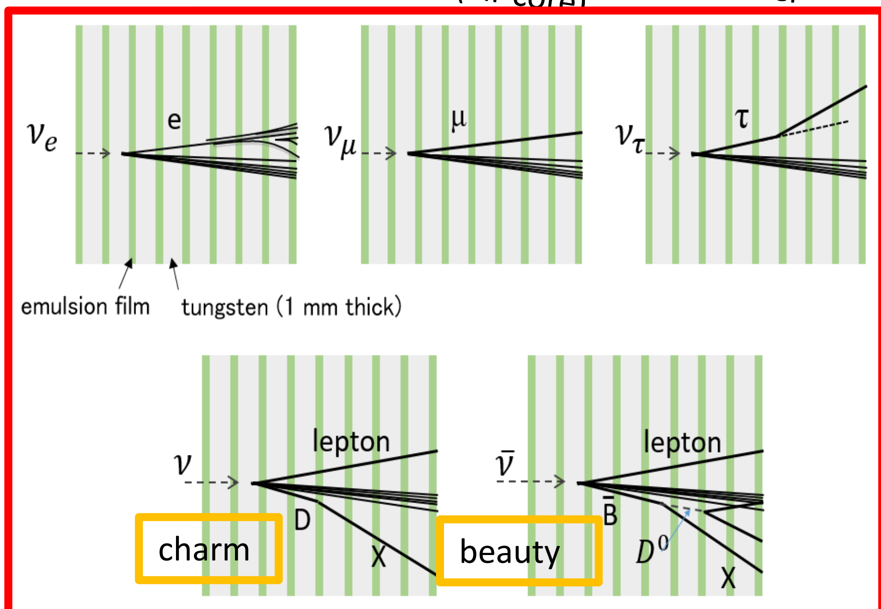
FASER/FASERν detector in Run3 (2022-2025)

FASER
Decay volume & tracking
Spectrometer & scintillator system & calorimeter

~7m long detector

FASERν
Emulsion/tungsten neutrino target





- **Tungsten** as neutrino interacting target.
- **Emulsion trackers**
  sub-micron spatial resolution, $\sigma \simeq 0.4\ \mu m$
- 770 1-mm-thick tungsten target and emulsion films
- 25x30 cm^2, 1.1 m, **1.1 tons** ($8\ \lambda_{int}$, $220X_0$)

- **Sensitive to 3 flavor** neutrinos
- **Muon ID** in track length in tungsten
- Replace emulsions 3 times a year

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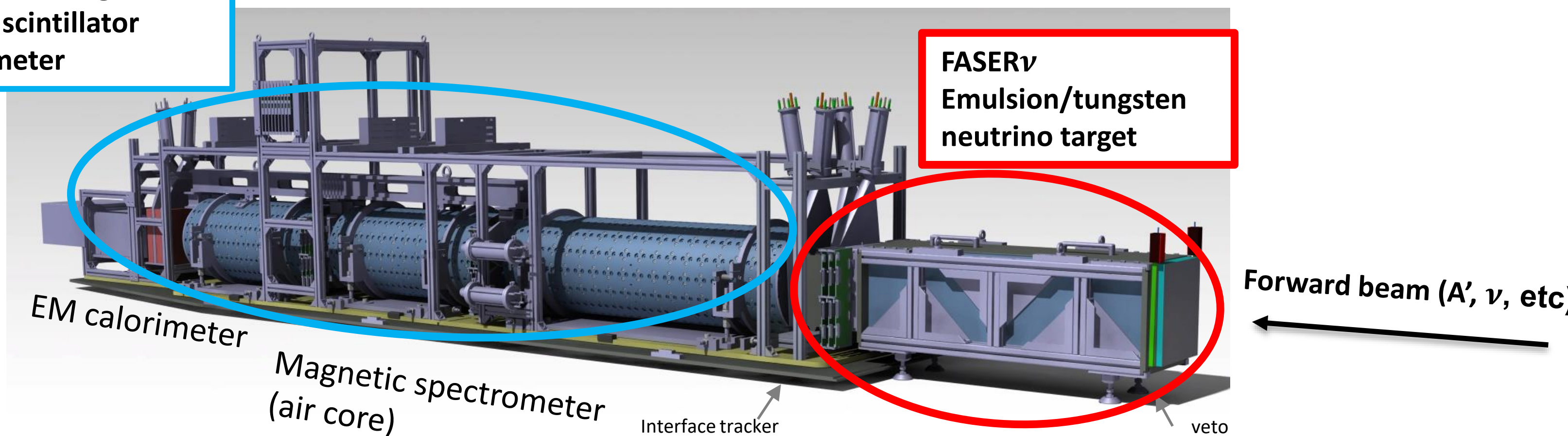
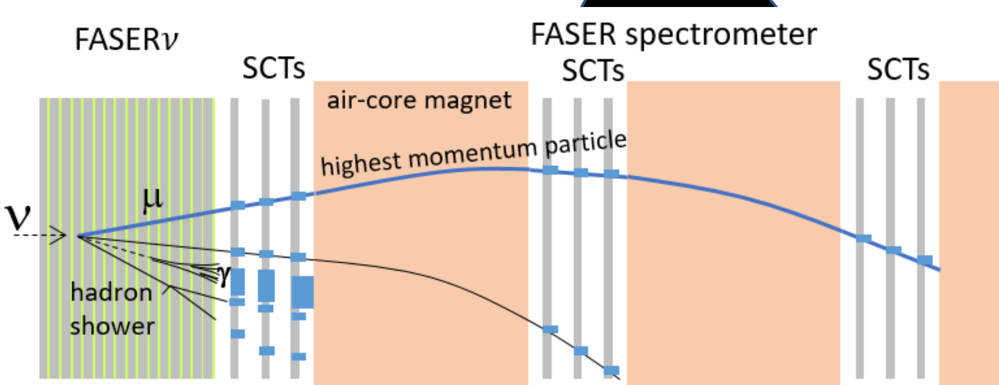




- Global reconstruction with FASER spectrometer with silicon (80um pitch) microstrip detectors (SCTs)
  → muon charge identification
  → $\nu_\mu/\bar{\nu}_\mu$ separation
- Improve energy resolution

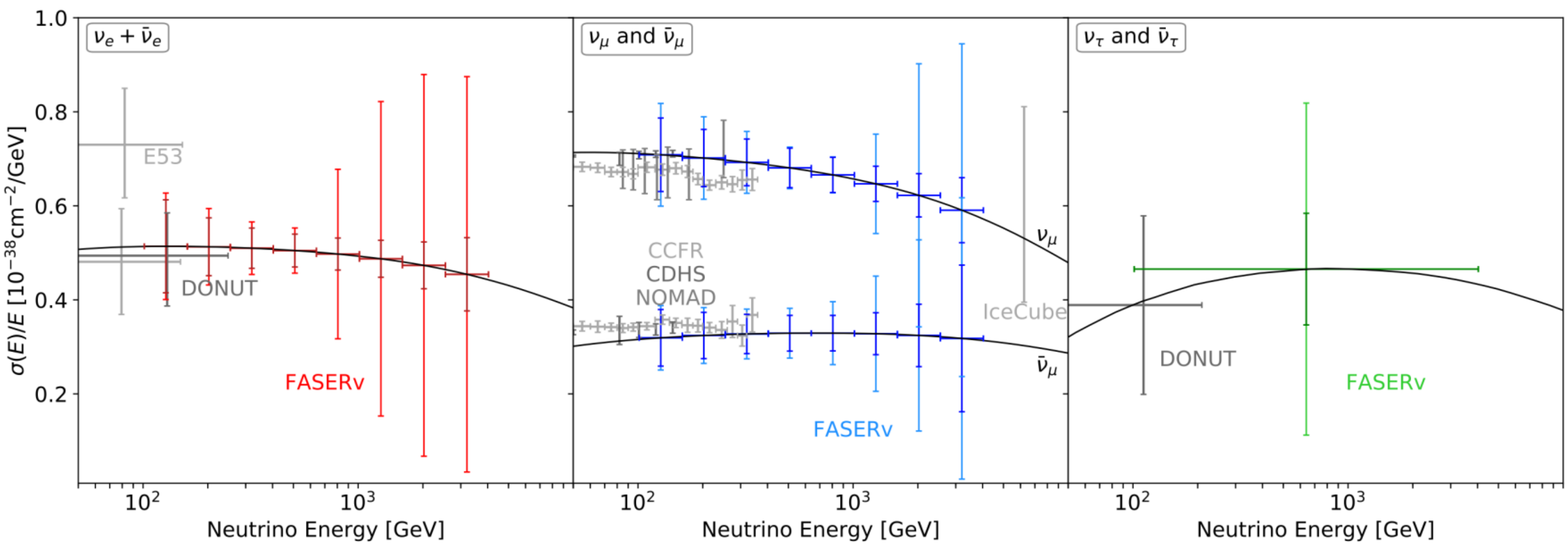
Physics studies in the LHC Run 3 (1):
Cross sections

- **Three flavors neutrino cross section measurements** at unexplored energies
- ~10,000 ν interactions expected in LHC Run 3
- **Large differences in the expected neutrino rates between MC generators, due to large uncertainties in very forward high energy hadron production**

arXiv:2105.08270

Generators		FASERν		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	901	4783	14.7
DPMJET	DPMJET	3457	7088	97
EPOSLHC	Pythia8 (Hard)	1513	5905	34.2
QGSJET	Pythia8 (Soft)	970	5351	16.1
Combination (all)		1710^{+1746}_{-809}	5782^{+1306}_{-998}	$40.5^{+56.6}_{-25.8}$
Combination (w/o DPMJET)		1128^{+385}_{-227}	5346^{+558}_{-563}	$21.6^{+12.5}_{-6.9}$

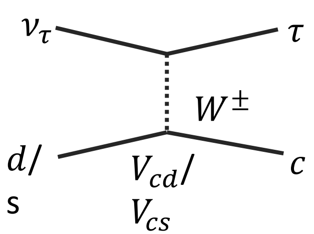
Expected CC interactions with 150 fb^{-1}



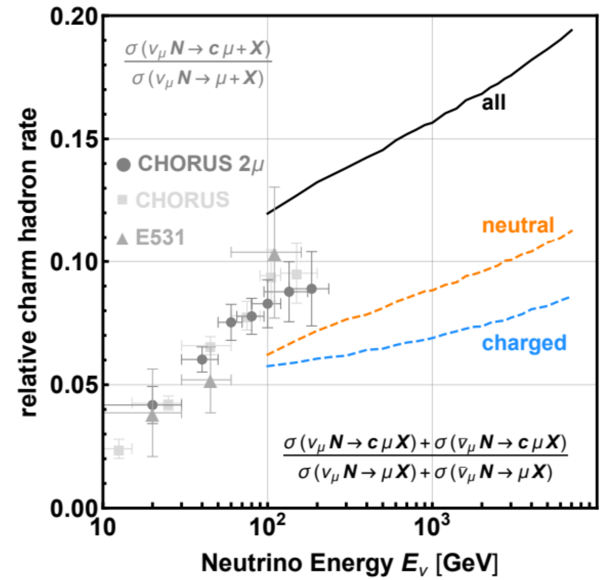
Physics studies in the LHC Run 3 (2):

Heavy-flavor-associated channels

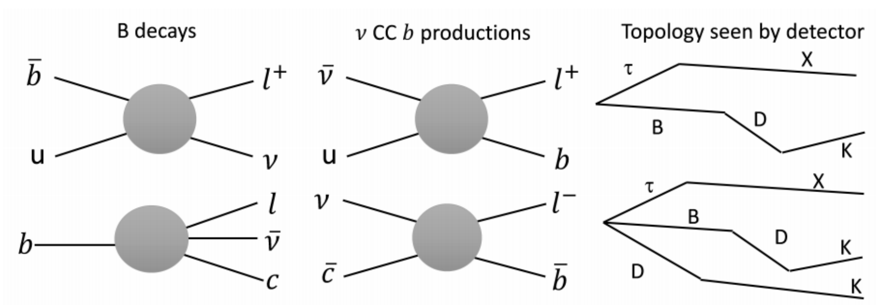
- Measure charm production channels
  - Large rate ~ 15% ν CC events, $\mathcal{O}(1000)$ events
  - First measurement of ν_e induced charm prod.



$$\frac{\sigma(\nu_\ell N \to \ell\, X_c + X)}{\sigma(\nu_\ell N \to \ell + X)} \quad \ell = e, \mu, \tau$$



- Search for Beauty production channels
  - Expected SM events (ν_μ CC b production) are $\mathcal{O}(0.1)$ events due to CKM suppression, $V_{ub}^2 \simeq 10^{-5}$

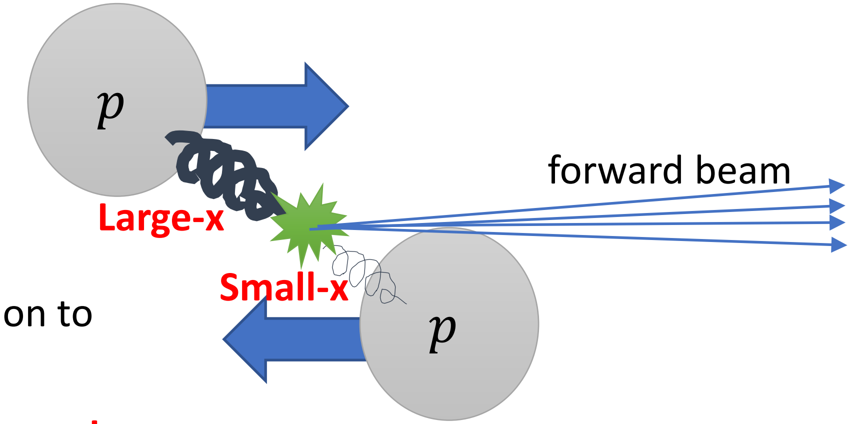


$\bar{\nu} N \to \ell \bar{B} X$

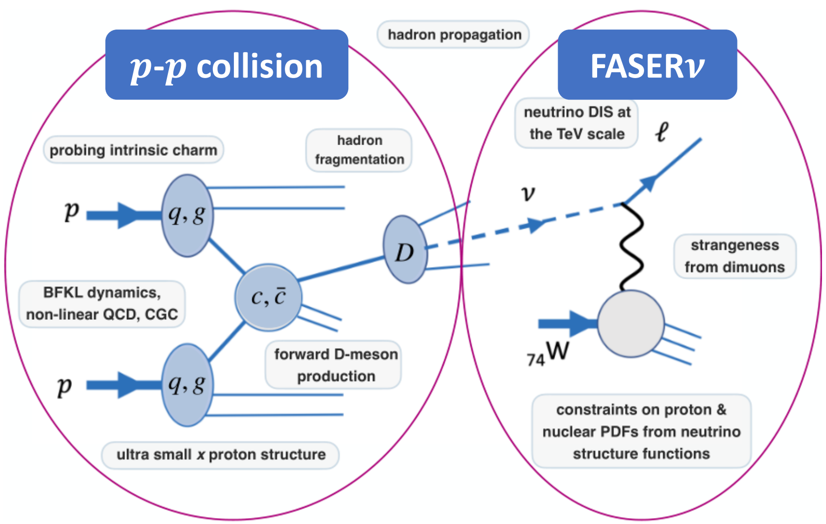
$\nu N \to \ell B D X$

Eur. Phys. J. C (2020) **80**: 61

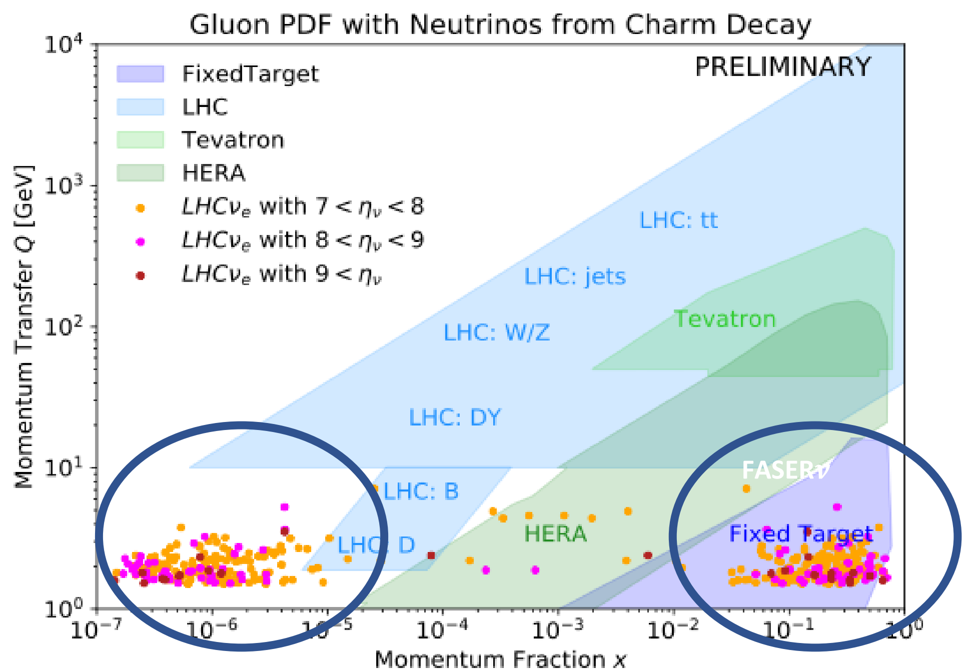
Physics studies in the LHC Run 3 (3): Further insights on QCD



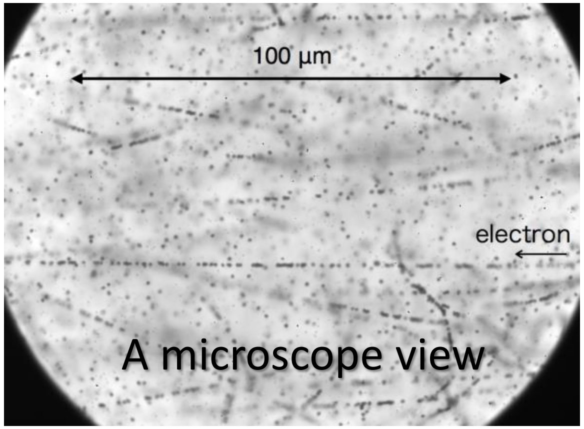
- Asymmetric gluon-gluon interaction, **small-x × large-x**
- **Neutrinos from charm decay** could allow to test transition to small-x factorization, probe intrinsic charm
- Deep understanding of neutrinos from charm decays (**prompt neutrinos)** is important for astrophysical neutrino observations



2203.05090



Status of pre-analysis



1. Feasibility test

Background track density acceptable for emulsion detector ?

Concern: Emulsion accumulate all charged particle tracks before its chemical -development.
More than $10^6/cm^2$ make emulsion detector analysis difficult.
Is track density in situ acceptable for analyzing neutrino interaction by emulsion detector ?

2. Pilot neutrino detector run in 2018

Demonstrating neutrino interaction detection at realistic background track density.
FASER detector was not yet ready .
→ Test with small size **Emulsion detector alone**.

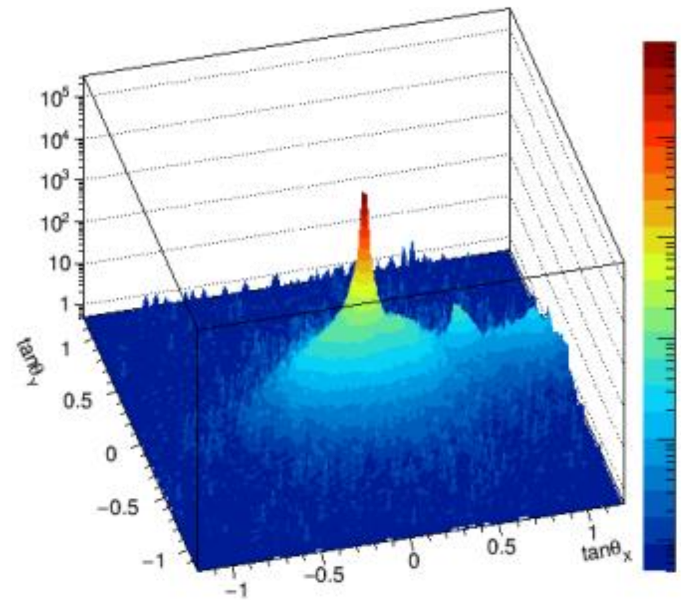
1. Feasibility test
back ground track flux at the site

- *In-situ* measurements in 2018

No problem with emulsion analysis

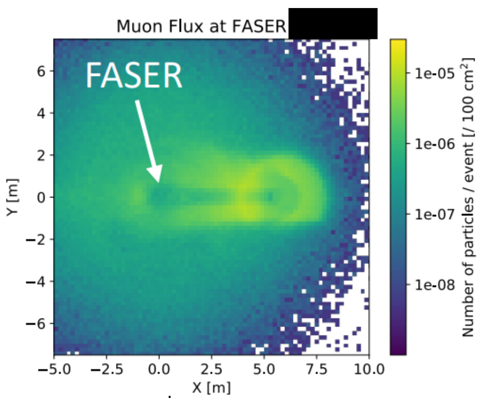
	Flux in main peak [fb/cm^2]
TI18 data	$1.7 \pm 0.1 \times 10^4$
TI12 data	$1.9 \pm 0.2 \times 10^4$
FLUKA MC	2.5×10^4

(uncertainty 50%)

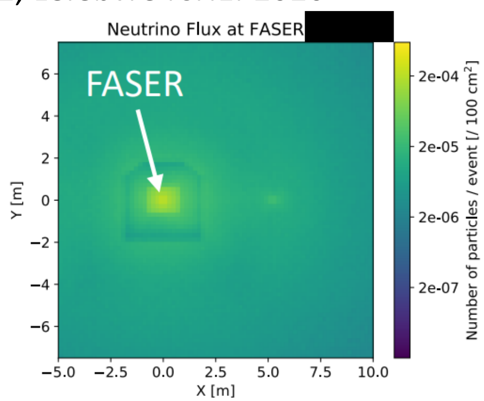


Observed angular distribution of background tracks

BDSim result for TI12, Lefebvre ICHEP2020

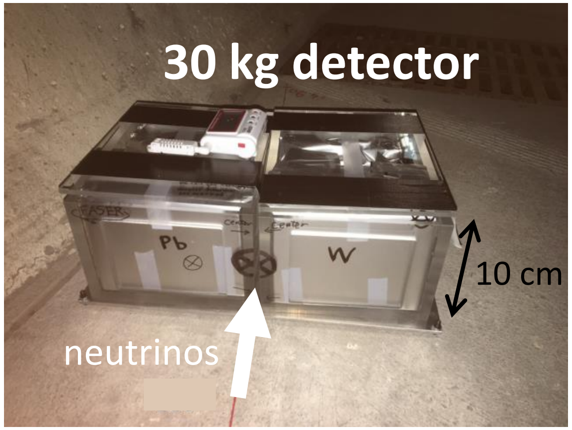


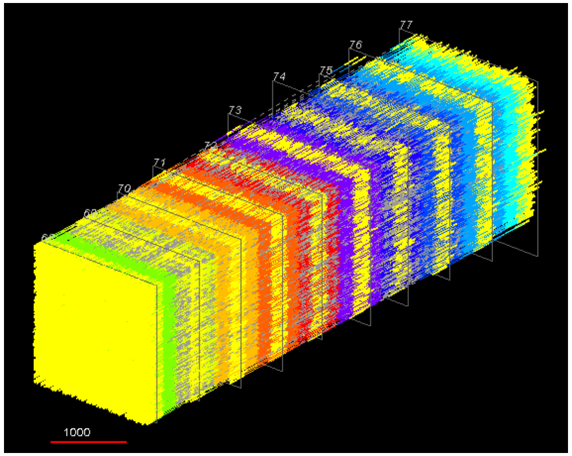
$\mu^{\pm}$



ν

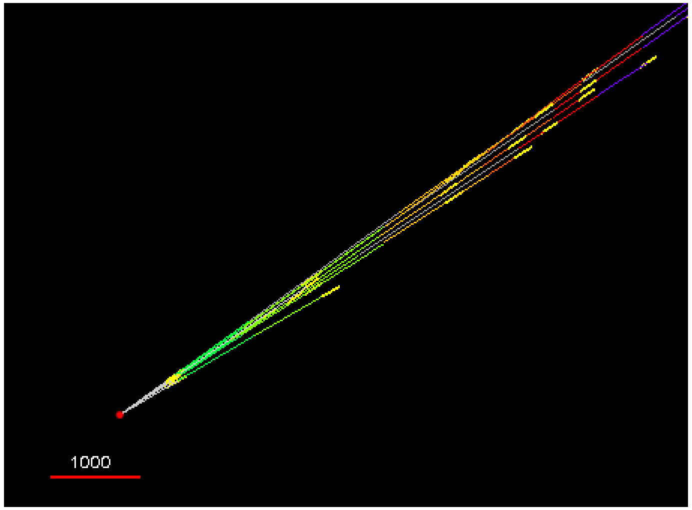
2. Pilot neutrino detector in 2018





$\simeq 3 \times 10^5$ tracks/cm^2

Proof of principle in Emulsion detector



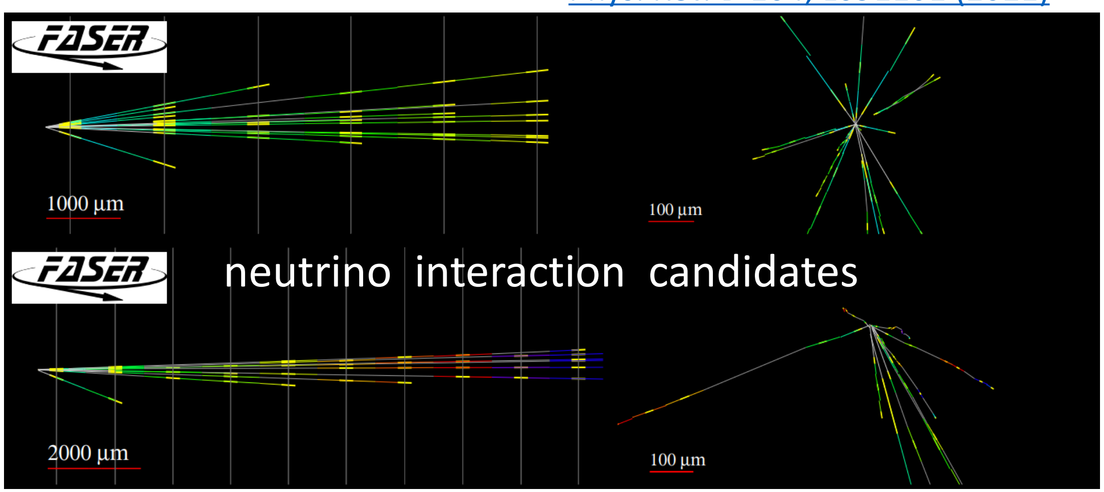
- A 30 kg emulsion based (lead, tungsten target) detector was installed on axis, 12.2 fb^{-1} of data was collected in Sep-Oct 2018 (4 weeks)
- Proof of principle by just Emulsion detector.
- Combined analysis with FASER for Muon ID/charge in Physics run.

Pilot run result

- Analyzed target mass of **11 kg** and luminosity of **12.2 fb^{-1}**
- **18** neutral vertices were selected
  - by applying # of charged particle ≥ 5, etc.
  - **Expected signal = $3.3^{+1.7}_{-0.95}$ events, BG = 11.0 events**
- Note: no lepton ID in the pilot run → High BG
- In BDT analysis, **an excess of neutrino signal** (6.1 events) is observed.
  Statistical significance = 2.7 σ from null hypothesis
- This result demonstrates the detection of neutrinos from the LHC

Succeed to analyzing vertices

Phys. Rev. D 104, L091101 (2021)



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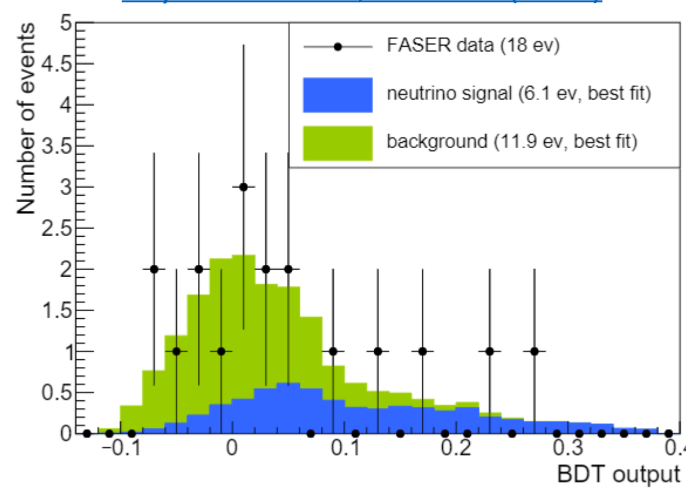
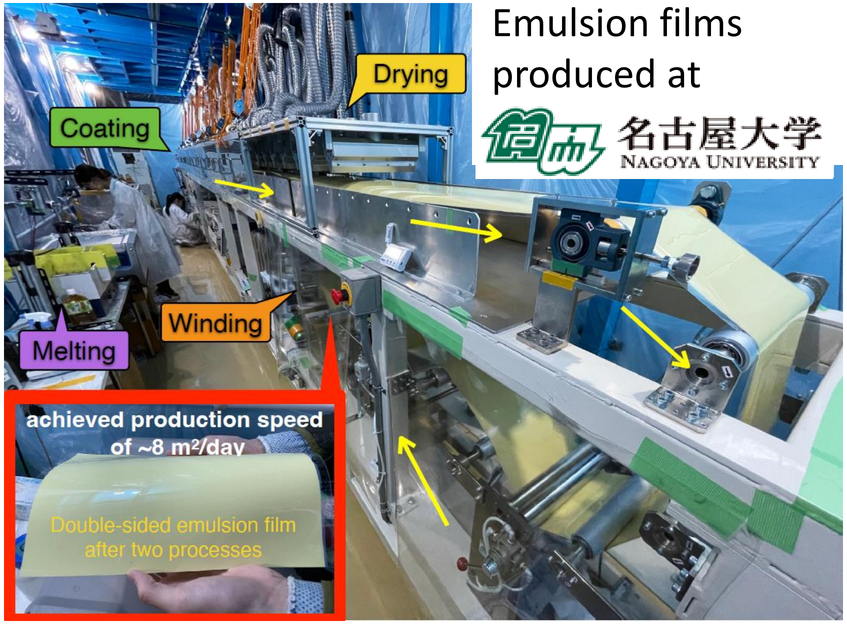
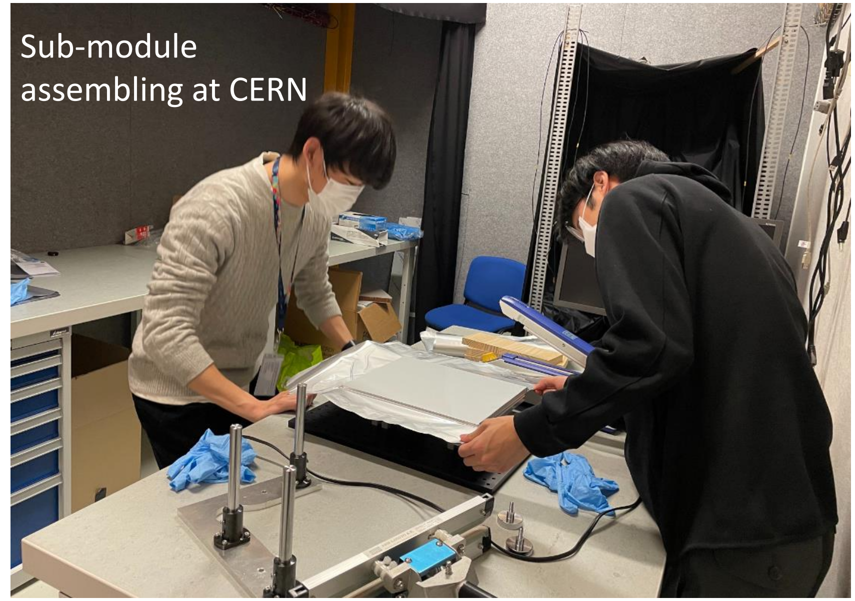
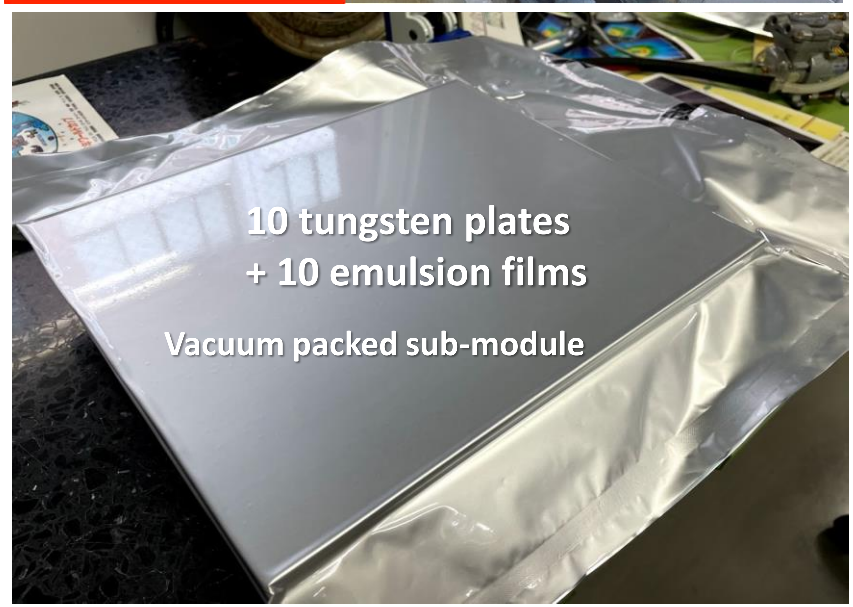
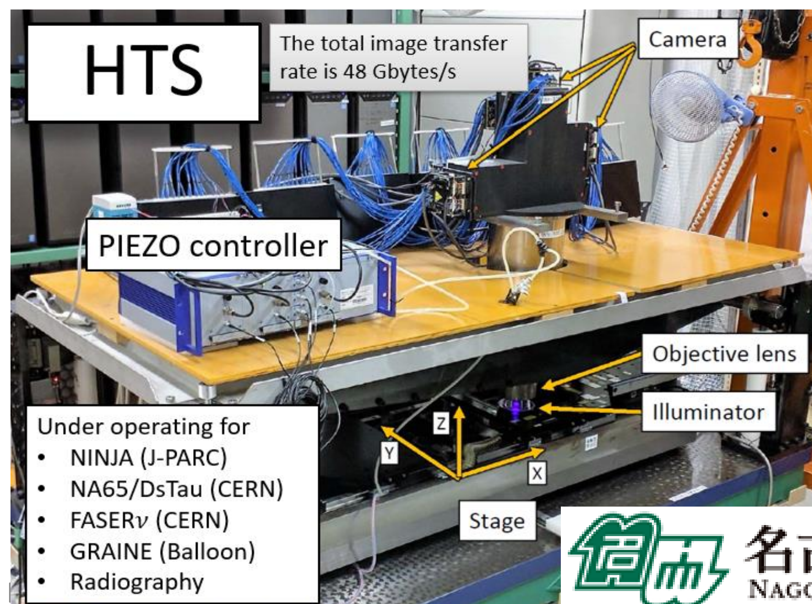


Preparation for Run 3: FASERν detector









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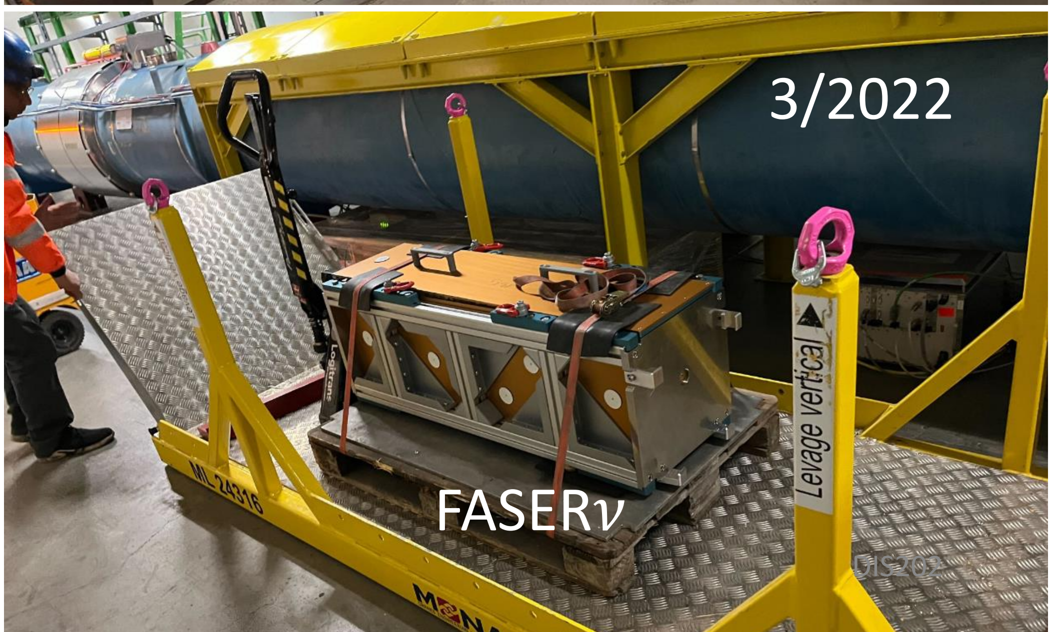
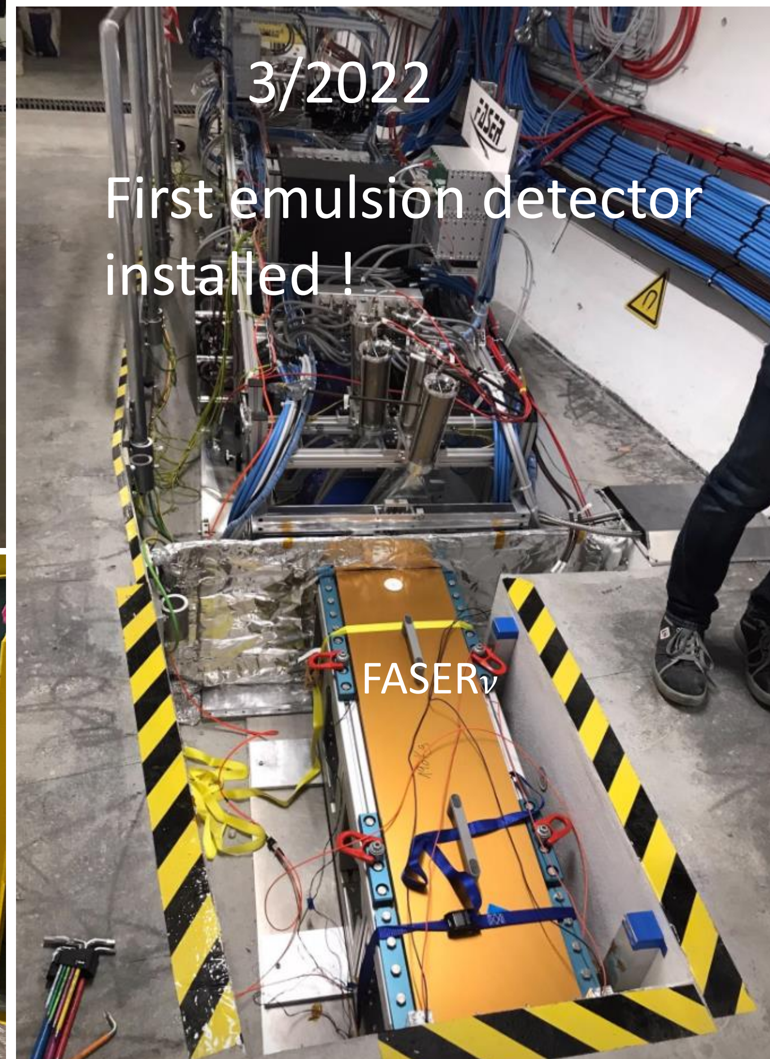
NAGOYA UNIVERSITY

Preparation for Run 3 at site

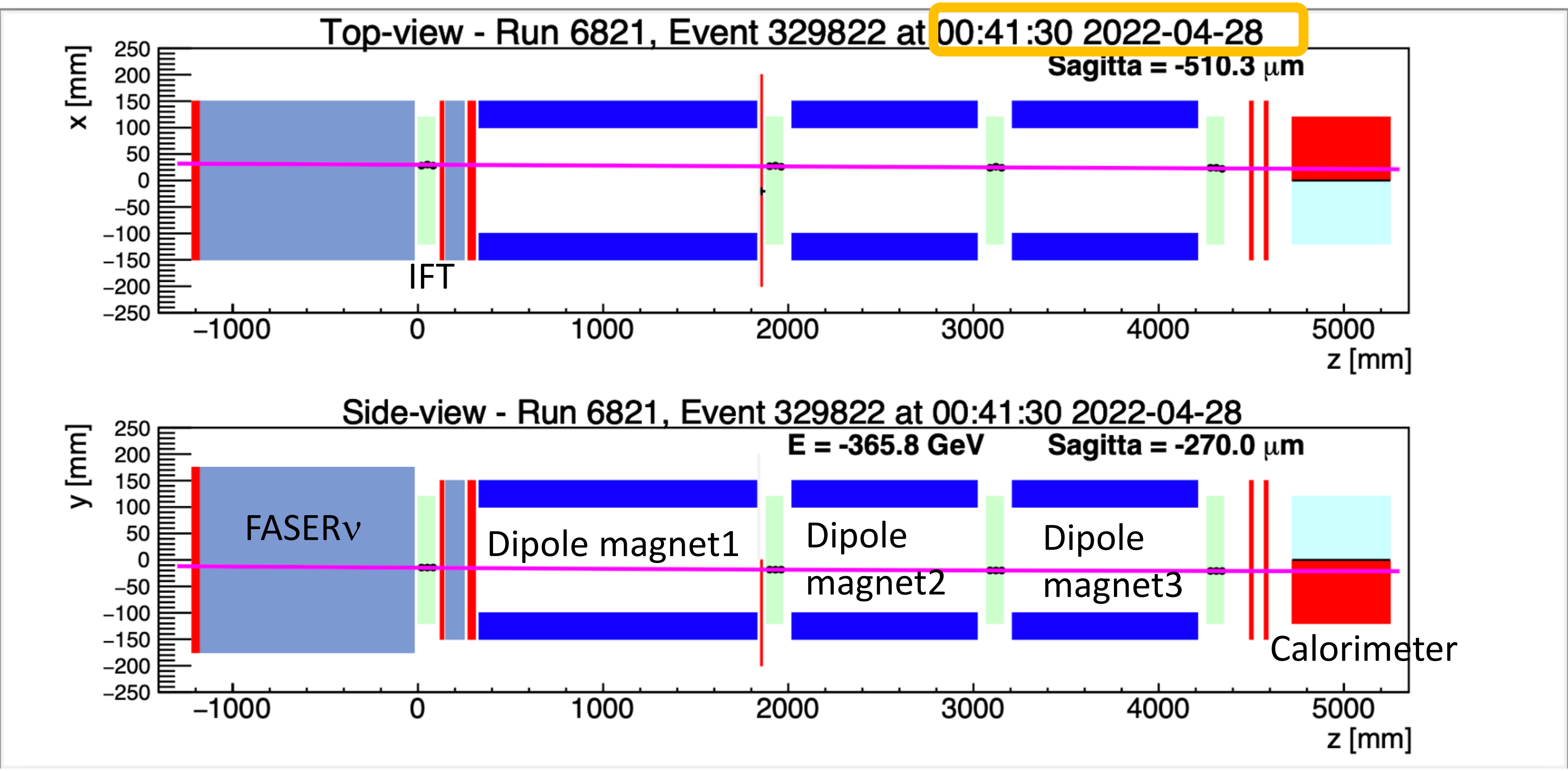




ν

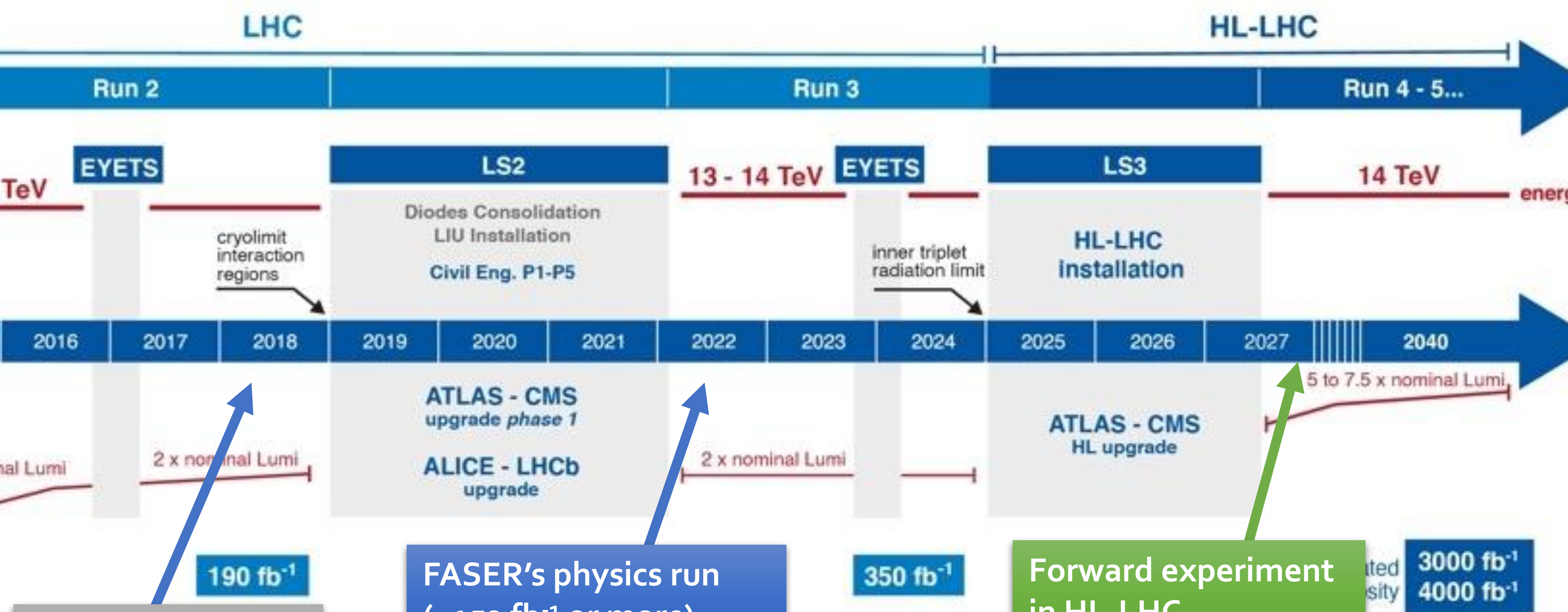
First light of Physics run : LHC run3
The Beam commissioning just started.

- All detector components have been installed.
- We are observing the first “events”, beam background muons.



FASERν/FASERν2 schedule

- LHC Run-3 will start in 2022, FASERν.
- HL-LHC, starting in 2028, 10 times more integrated luminosity
  → FASERν2



Pilot run & background measurements in 2018

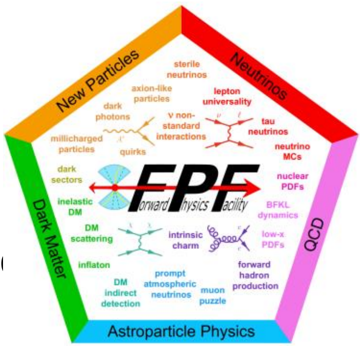
FASER's physics run (~150 fb^{-1} or more)

Forward experiment in HL-LHC

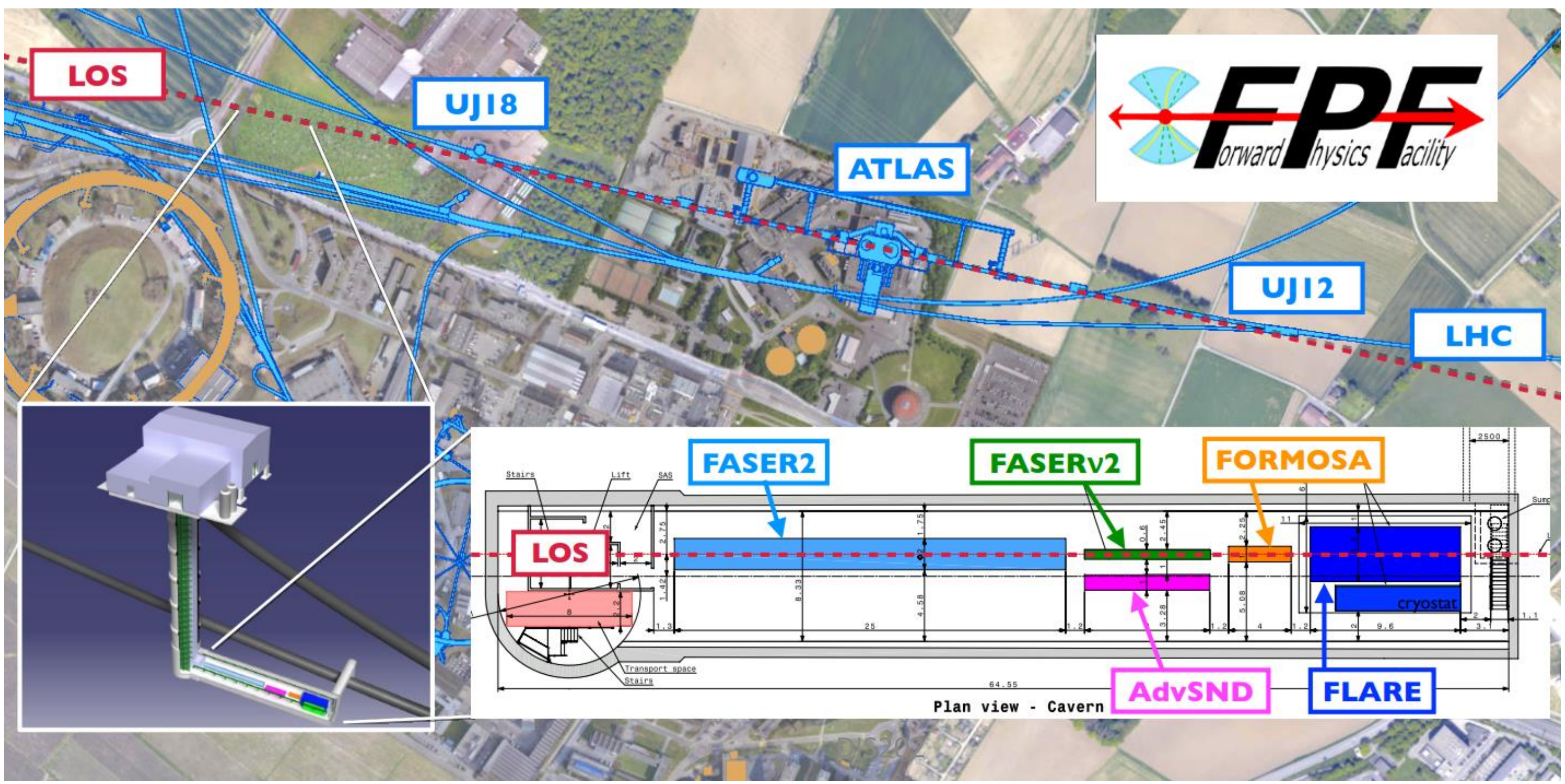
2022-25 physics run in LHC RUN3,
1.1 tons, a total area of film 720 m^2

2028- FASERν2@FPF
in HL-LHC, **10-20 tons**

Forward Physics Facility (*FPF*) at the HL-LHC



- HL-LHC will give × 20 more collisions.
- FPF is proposed new facility to house larger experiments in the very forwar region (neutrino target mass x10 FASERν).
- Extending sensitivities for new particle searches and neutrino physics by two orders of magnitude → FASER2, FASERν2, … much more
- FPF White Paper (429 pages, 236 authors, 156 endorsers) http://arxiv.org/abs/2203.05090



Summary

- FASERν is a project to analyze high energy **neutrinos coming from LHC collision products**.
- Study neutrino interactions at the **unexplored energy region by each neutrino species**.
- **Charm / Beauty production analysis in neutrino CC interactions** is a Physics target.
- It is also study on **decaying parent especially Charms properties in Forward direction**.

- After confirmation of track density in situ as well acceptable for emulsion detector who can identify 3 types of neutrino CC interactions.
- In 2018 a small sized emulsion detector succeed to detect some neutrino candidates under the realistic background track density condition (ie. In situ.)
- In 2022, Tungsten target with emulsion detector 1.1 ton will detect unexplored energy region neutrinos.

- FASERν physics run just started .
- All detector components are installed in time, and observed first light of LHC run3 recently.
- Emulsion detector and FASER detector are waiting for detecting forward “neutral particles”.

arXiv:2105.08270

Generators		FASERν		
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Expected CC interactions with 150 fb^{-1}

BACK UP

FASER INSTITUTIONS

77 collaborators, 21 institutions, 9 countries

CERN

UNIVERSITÉ DE GENÈVE

KYUSHU UNIVERSITY

UC IRVINE

u^b UNIVERSITÄT BERN

Technion Israel Institute of Technology

NAGOYA UNIVERSITY

UNIVERSITY of WASHINGTON

JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U

מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE

KEK

UNIVERSITY OF OREGON

UNIVERSITÄT BONN

INFN

清華大學 Tsinghua University

SLAC NATIONAL ACCELERATOR LABORATORY

ROYAL HOLLOWAY UNIVERSITY OF LONDON

UNIVERSITY OF LIVERPOOL

CHIBA UNIVERSITY

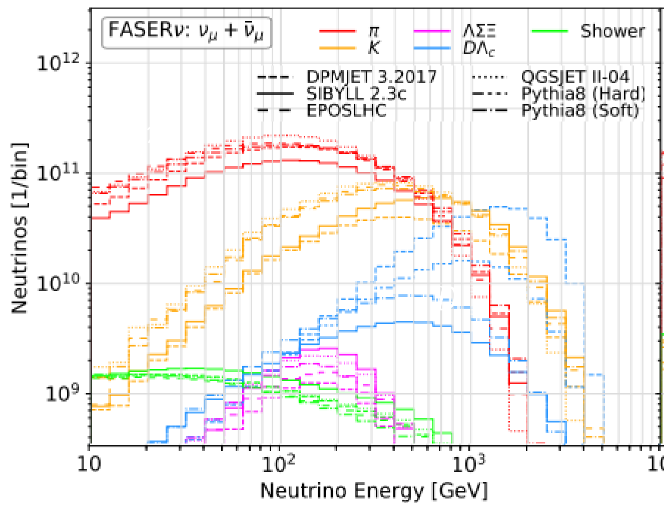
US UNIVERSITY OF SUSSEX

JINR

Neutrinos = proxy of forward hadron production

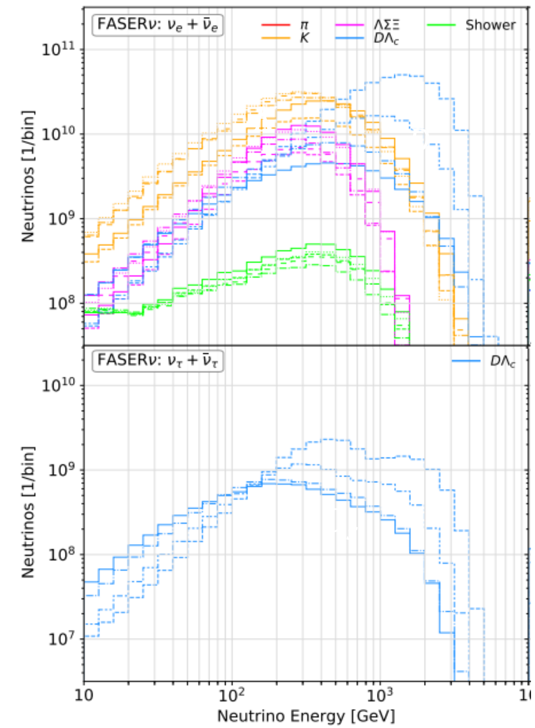
- Pion, Kaon, charm contribute to different part of energy spectra and flavor

ν_μ



ν_e

ν_τ



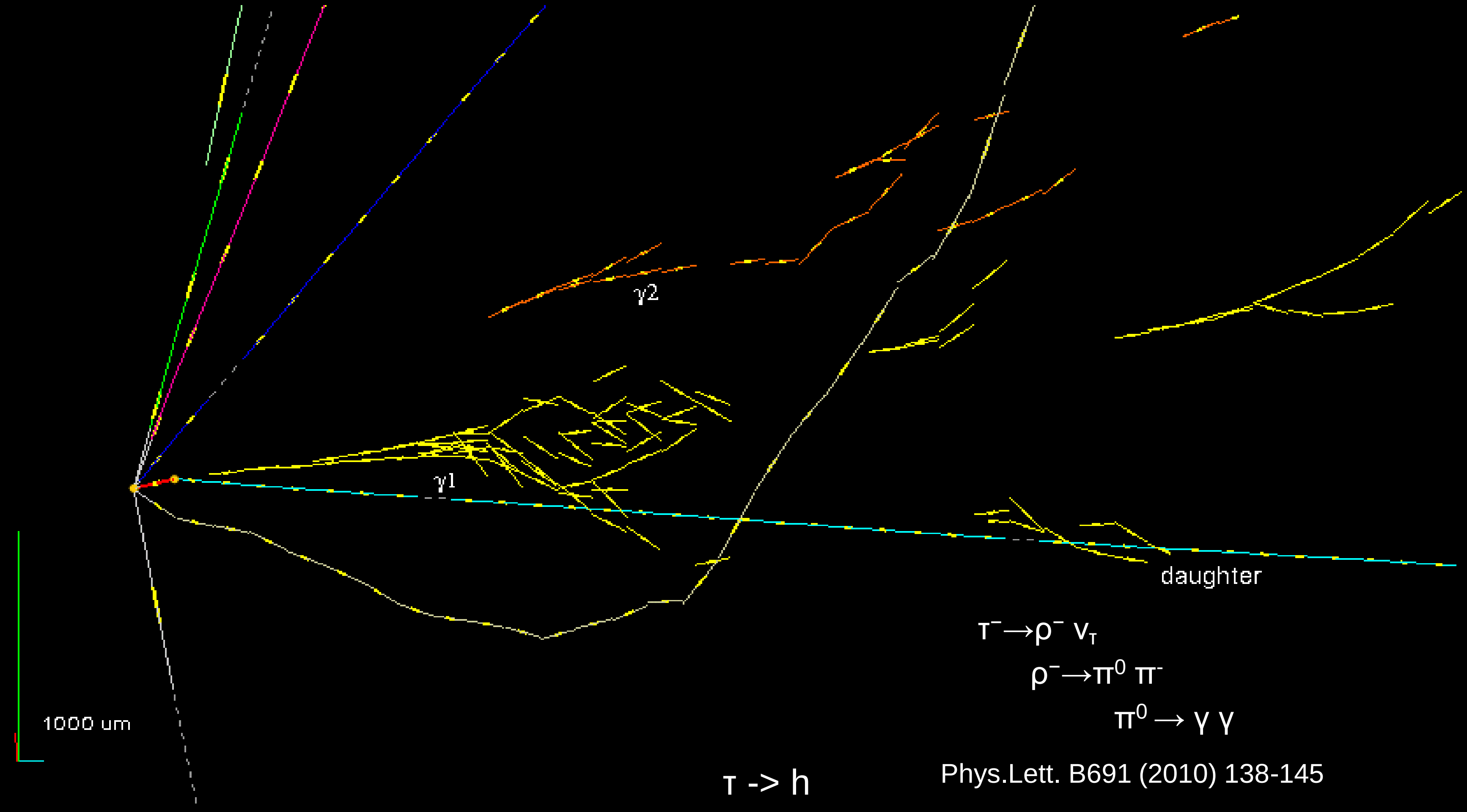
- FASERν provides important inputs to validate/improve generators → Muon excess, prompt neutrinos

The 1st ν_τ candidate OPERA

NEUTRINO2010

5 candidates till 2015 Sep, 5.1σ

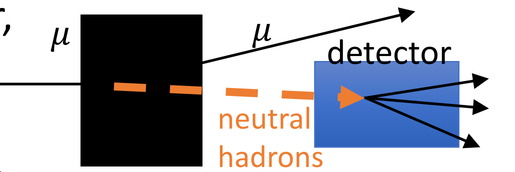
10 candidates final 2018 May, 6.1σ



Phys.Lett. B691 (2010) 138-145

Background for neutrino analysis

- Muons rarely produce neutral hadrons in upstream rock or in detector, which can mimic neutrino interaction vertices
  - Probability of O(10^{-5})



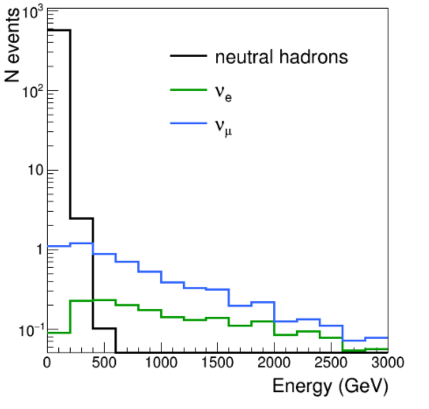
- Pilot neutrino detector doesn't have lepton ID

→ Separation from neutral hadron BG (produced by muons) is challenging

→ tighter cuts

- The produced neutral hadrons are low energy

→ Discriminate by event topology



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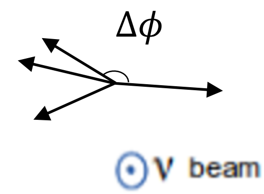
Production rate per muon (E_{had}>10 GeV)

	Negative Muons	Positive Muons
K_L	3.3×10^{-5}	9.4×10^{-6}
K_S	8.0×10^{-6}	2.3×10^{-6}
n	2.6×10^{-5}	7.7×10^{-6}
$\bar{n}$	1.1×10^{-5}	3.2×10^{-6}
Λ	3.5×10^{-6}	1.8×10^{-6}
$\bar{\Lambda}$	2.8×10^{-6}	8.7×10^{-7}

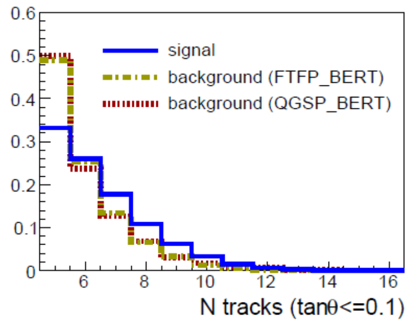
Vertex detection efficiency

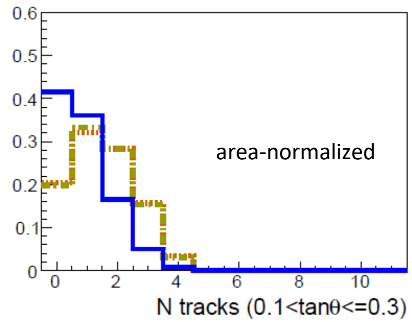
Signal		Background		
			FTFP_BERT	QGSP_BERT
ν_e	0.490	K_L	0.017	0.015
$\bar{\nu_e}$	0.343	K_S	0.037	0.031
ν_μ	0.377	n	0.011	0.012
$\bar{\nu_\mu}$	0.266	$\bar{n}$	0.013	0.013
ν_τ	0.454	Λ	0.020	0.021
$\bar{\nu_\tau}$	0.368	$\bar{\Lambda}$	0.018	0.018

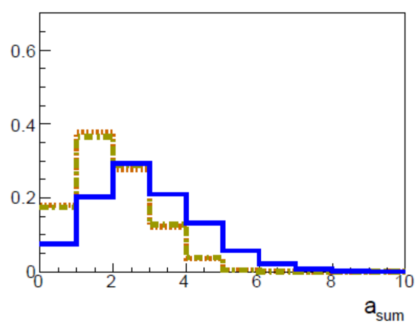
Variables for MVA

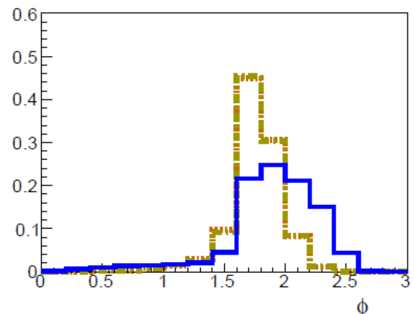


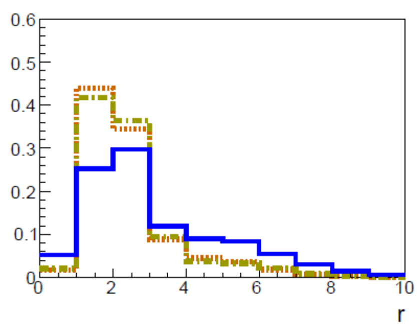
Expected distributions of the variables











5 variables used in the analysis

1. the number of tracks with tanθ<=0.1 with respect to the beam direction
2. the number of tracks with 0.1<tanθ<=0.3 with respect to the beam direction
3. the absolute value of vector sum of transverse angles calculated considering all the tracks as unit vectors in the plane transverse to the beam direction (a_{sum})
4. for each track in the event, calculate the mean value of opening angles between the track and the others in the plane transverse to the beam direction, and then take the maximum value in the event (ϕ_{mean})
5. for each track in the event, calculate the ratio of the number of tracks with opening angle <=90 degrees and >90 degrees in the plane transverse to the beam direction, and then take the maximum value in the event (r).

Variables 1–2: Multiplicity and Pseud rapidity distribution

Variable 3: Momentum balance

Variables 4–5: Back-to-back kinematics at vertex

Conceptually why these variables are good:

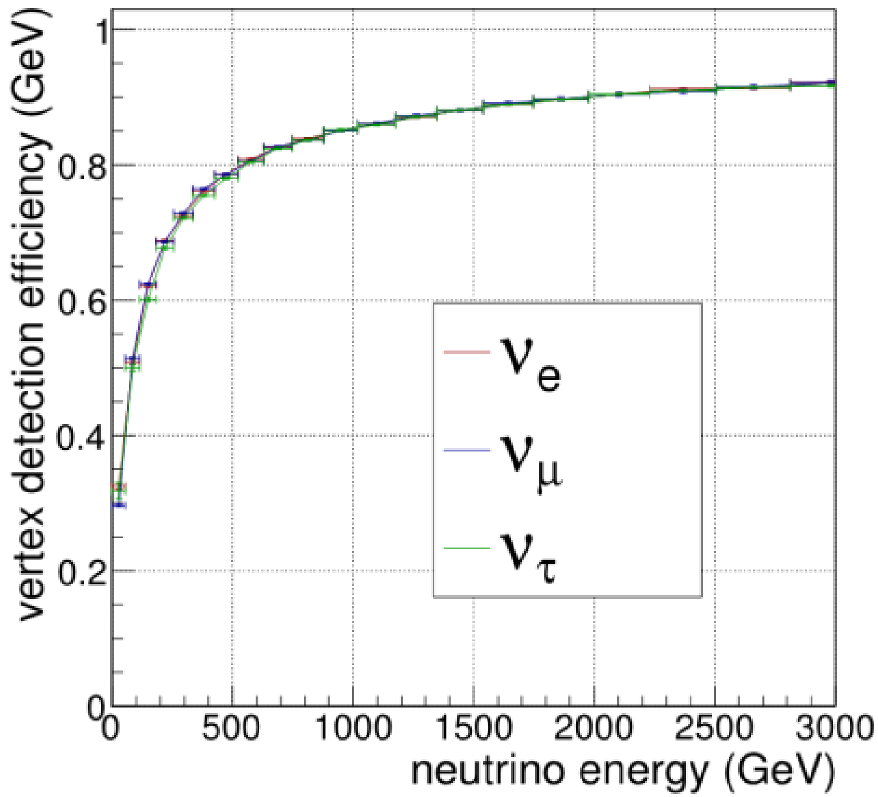
Variable 1, 2: The neutrino energy is higher than the neutral hadron energy. Higher energy, more particles are produced in forward direction, i.e. tan(theta)<0.1 (var 1), and higher ratio of var1/var2.

Variable 3: Momentum in the transverse plane is more balanced in hadron interactions than neutrino CC and NC interactions. Outgoing leptons in neutrino interactions take a major energy, which distorts this variable.

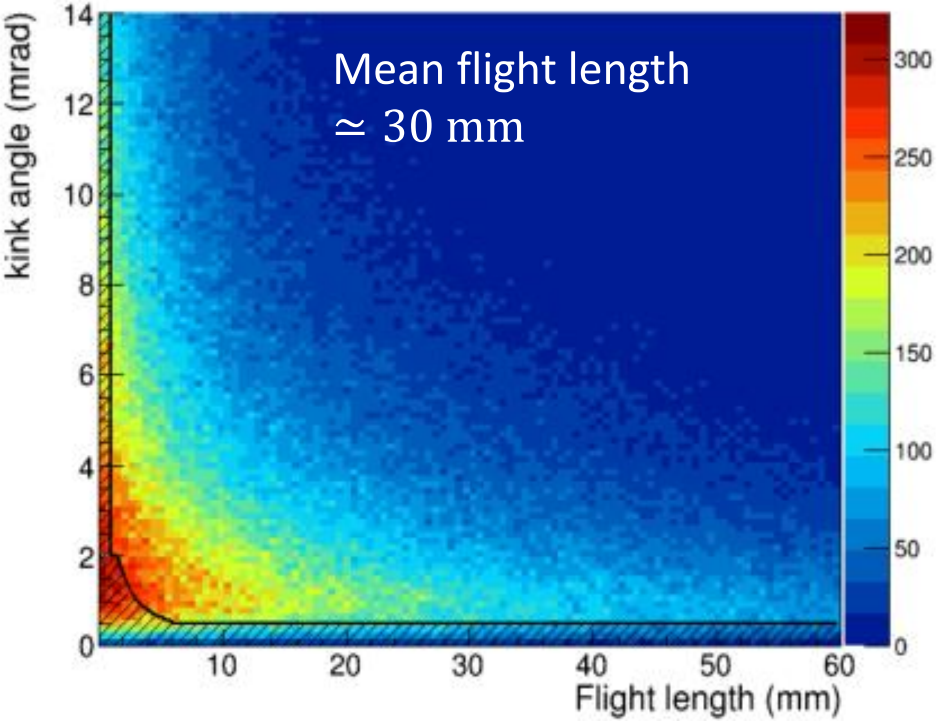
Variable 4, 5: For CC interactions, we expect the outgoing lepton and hadron system are back to back in the transverse plane.

Detection efficiency

Vertex detection efficiency
(charged multiplicity>=5)



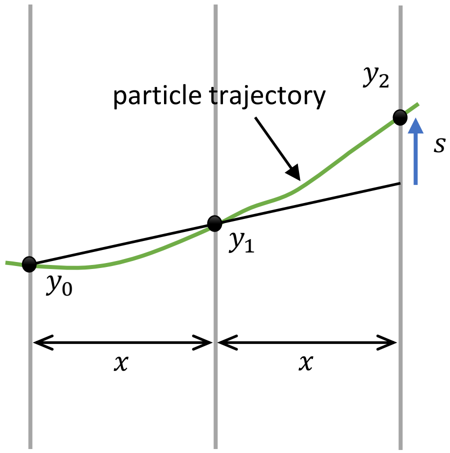
Tau decay detection efficiency
=75% ($\tau \to 1$ prong)



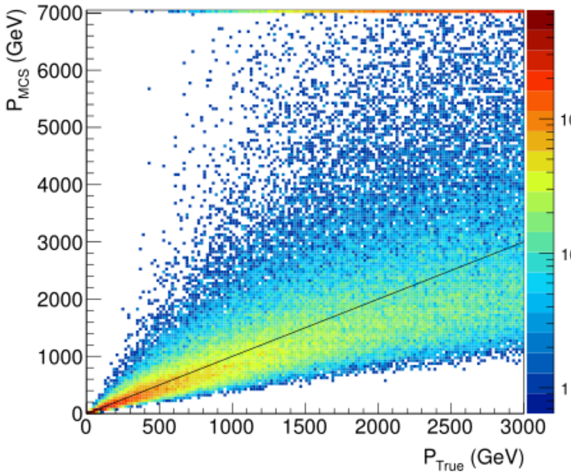
Particle momentum measurement

by multiple Coulomb scattering (MCS)

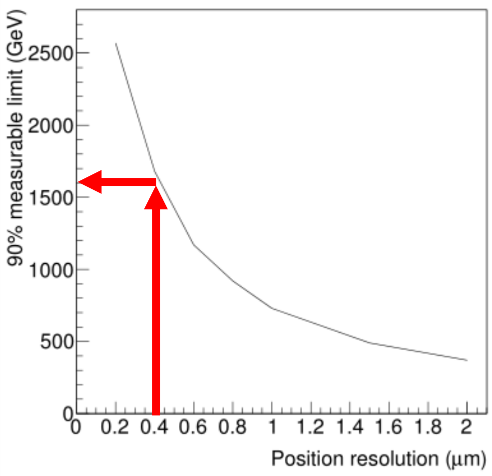
- Sub-micron precision alignment using muon tracks
  - Our experience = 0.4 μm (in the DsTau experiment)
- This allow to measure particle **momenta by MCS, even above 1 TeV.**



$$(s^{\mathrm{RMS}})^2 = \left(\sqrt{\frac{2}{3}}\frac{13.6(\mathrm{MeV})}{\beta P}x\sqrt{\frac{x}{X_0}}\right)^2 + \left(\sqrt{6}\ \sigma_{\mathrm{pos}}\right)^2$$



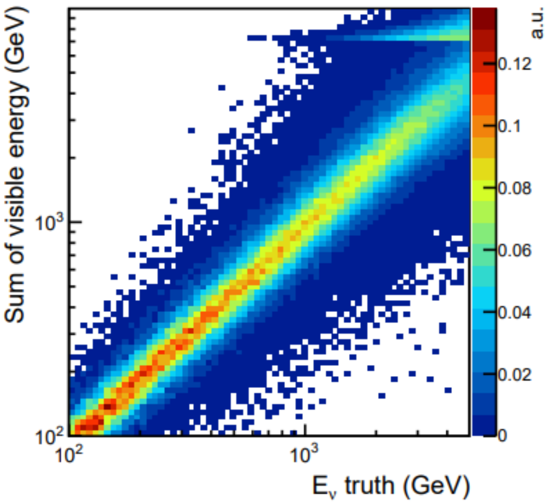
Performance with position resolution of 0.4 μm, in 100 tungsten plates (MC)



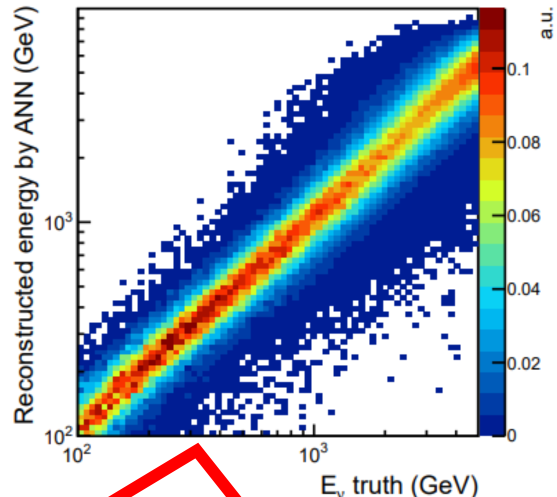
Measurable energy vs position resolution

Energy reconstruction ($\nu_\mu\ CC$)

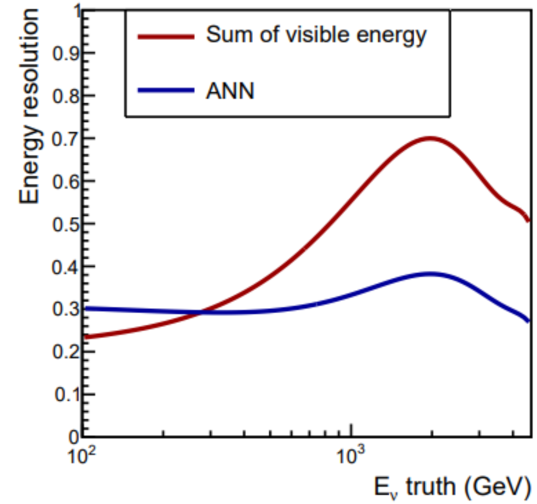
Sum of visible energy



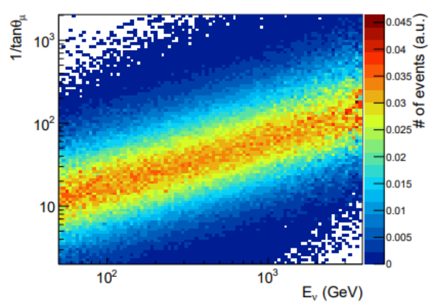
ANN method



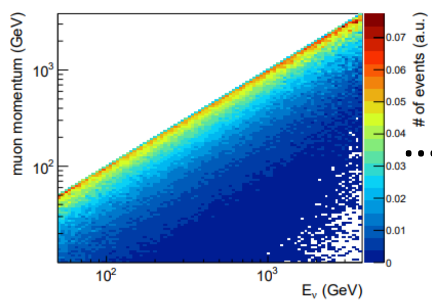
$\Delta E/E$



inputs for ANN, simulated by GENIE (MC truth)



Angular info



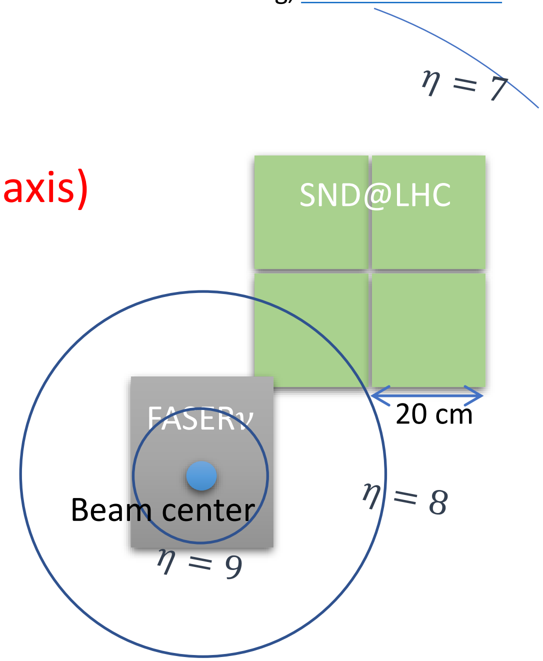
Momentum

…

- Sum of visible energy (model independent) already gives a reasonable resolution
- ANN can solve problem at high energy and gives about 30% resolution at relevant energy range.

- Neutrino spectra at unexplored energy range
    - Study production / propagation / interaction
    - CC Cross section measurements of ν_e, ν_μ, ν_τ
    - Heavy flavor physics, NC, QCD, NSI, oscillations
    - Complementarity between FASERν (on axis) and SND (off axis)

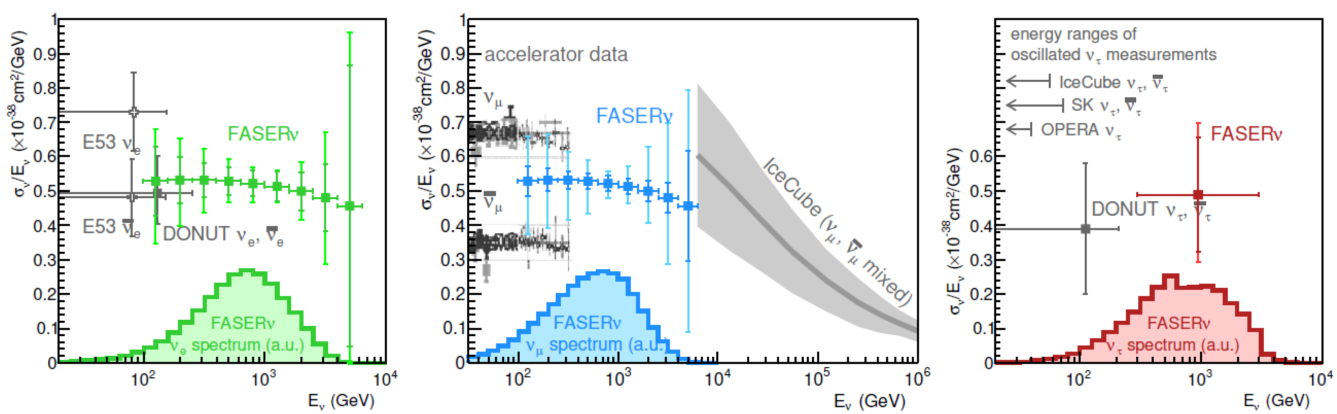
F. Kling, arXiv:2105.08270



Expected CC event statistics

Generators		FASERν			SND@LHC		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	1343	6072	21.2	184	965	10.1
DPMJET	DPMJET	4614	9198	131	547	1345	22.4
EPOSLHC	Pythia8 (Hard)	2109	7763	48.9	367	1459	16.1
QGSJET	Pythia8 (Soft)	1437	7162	24.5	259	1328	10.7
Combination (all)		2376^{+2238}_{-1032}	7549^{+1649}_{-1476}	$56.4^{+74.5}_{-35.1}$	339^{+208}_{-155}	1274^{+184}_{-308}	$14.8^{+7.5}_{-4.7}$
Combination (w/o DPMJET)		1630^{+479}_{-286}	7000^{+763}_{-926}	$31.5^{+17.3}_{-10.3}$	270^{+96}_{-85}	1251^{+208}_{-285}	$12.3^{+3.8}_{-2.1}$

Projected precision of FASERν measurement at 14-TeV LHC (150 fb^{-1})

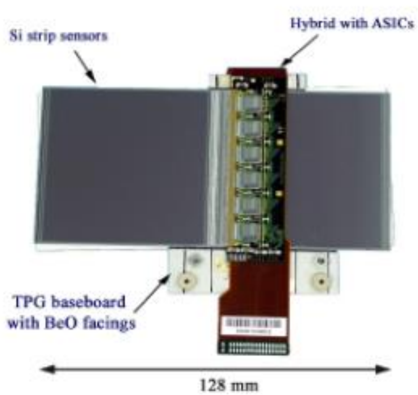


inner error bars: statistical uncertainties, outer error bars: uncertainties from neutrino production rate corresponding to the range of predictions obtained from different MC generators.

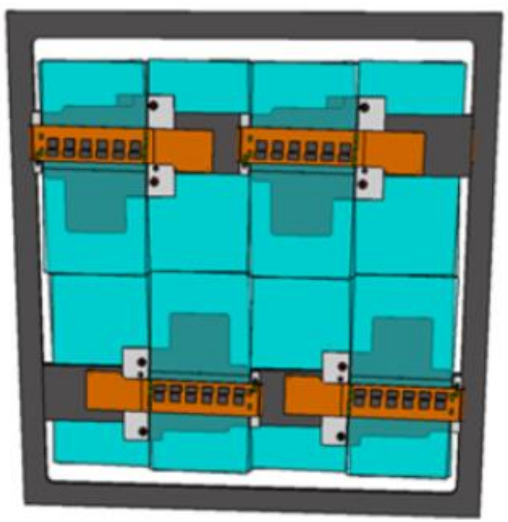
FASER Collaboration, Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310

Tracking device of FASER

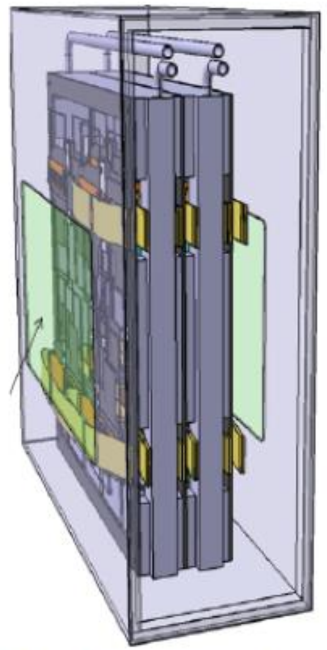
- Thee tracking station and a interface tracker to FASERnu.
- Each containing 3 layers of double sided silicon micro-strip detectors
- Spare ATLAS SCT modules, 80um strip pitch, 40mrad stereo angle.
- SCT modules a 24cm x 24cm tracking layers by 8 SCT modules.



SCT module



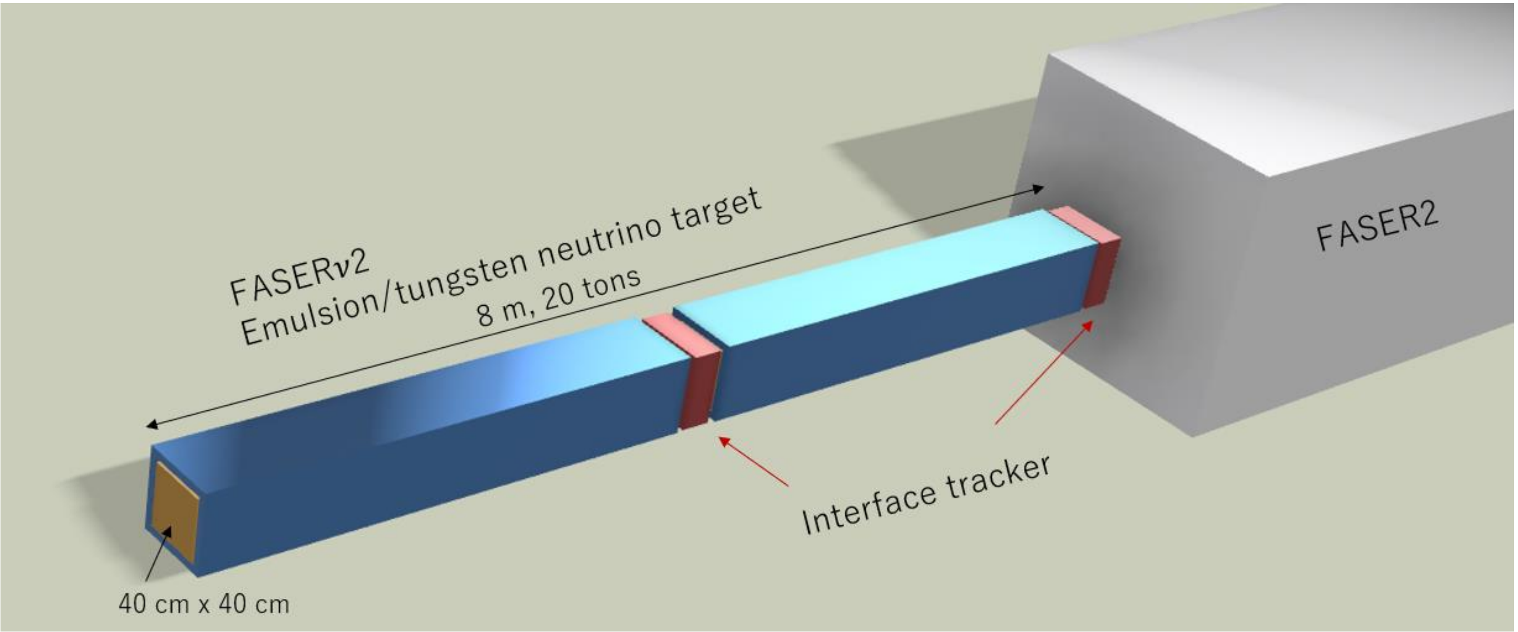
Tracking layer



Tracking station

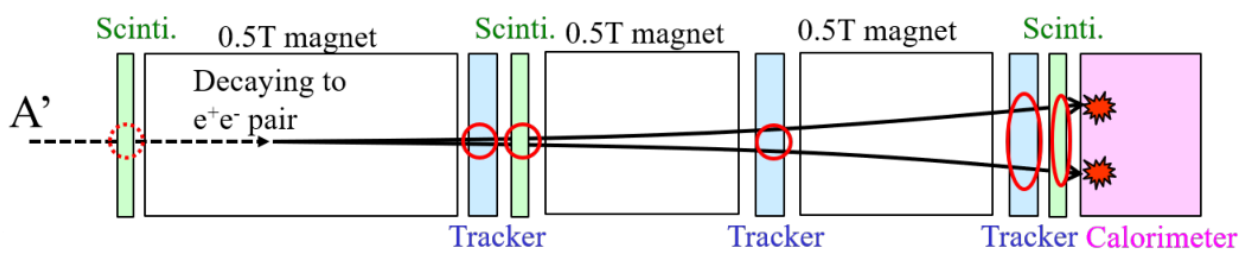
FASERν2 at the FPF

- **Tau neutrino physics, with >100 times statistics of FASERν**
  - FASERν2: Beam x 20, 20 tons mass
  - $\sim 10^5\ \nu_e,\ 10^6\ \nu_\mu,\ 10^3\ \nu_\tau$ CC events
- **Rich physics programs in neutrino physics, flavor physics, QCD and cosmic-rays**

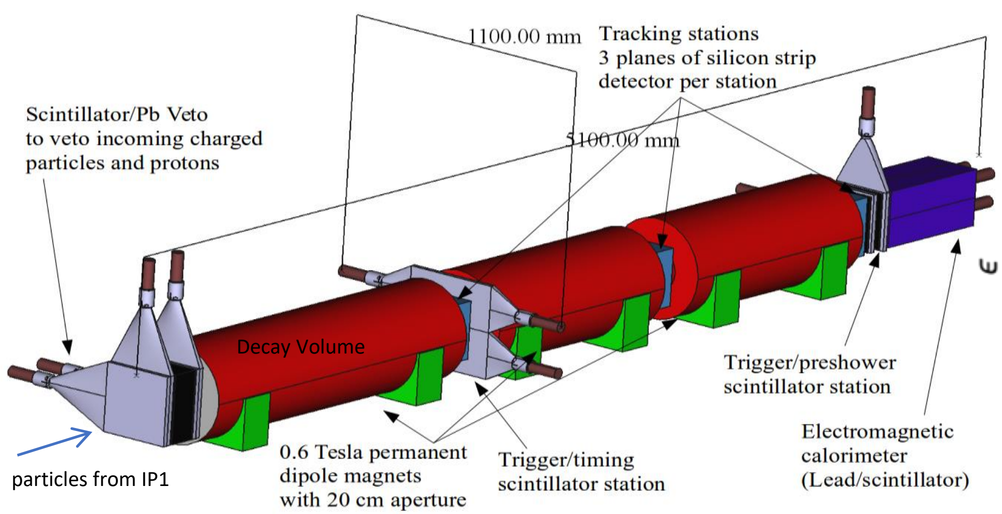


FASER detector & sensitivity

- Dark photon: Photon in dark sector, and it has mass
- Signal: Dark photon decay into e^+e^- pair



Detector schematic (original one without FASERnu)



Sensitivity for dark photon search in Run 3