

Detecting and studying high-energy neutrinos with FASER ν at the LHC

Akitaka Ariga PD Dr., University of Bern
on behalf of the FASER collaboration



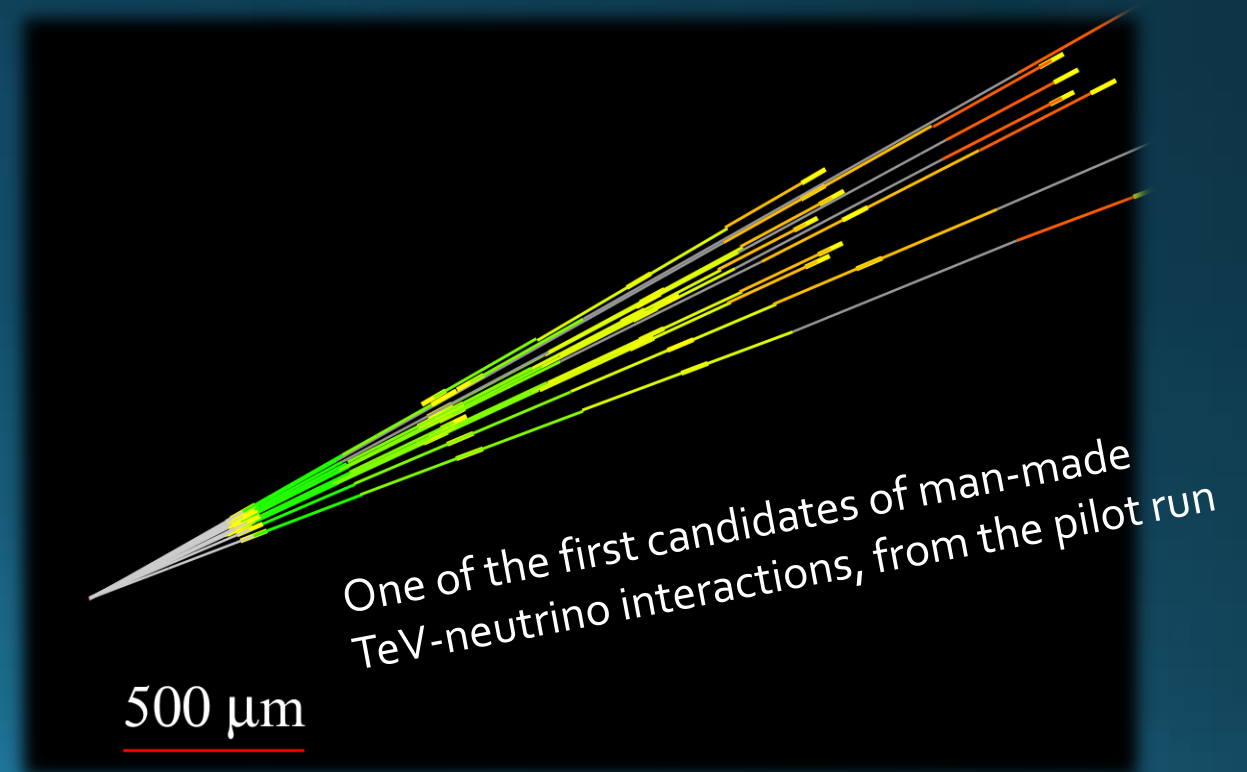
FASER ν physics paper:
Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310

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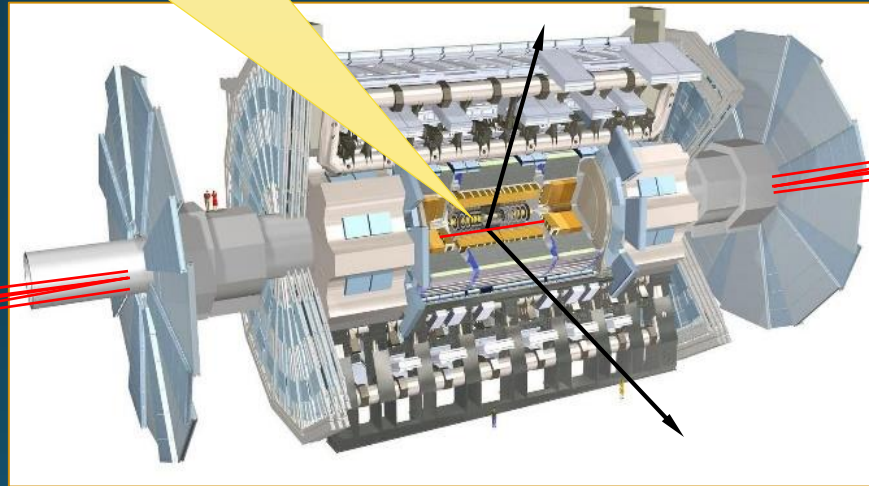
SIMONS
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The **FASER** experiment

ForwArd Search ExpeRiment at the LHC

14 TeV p-p collision



No experiment has sought neutrinos at the LHC so far!

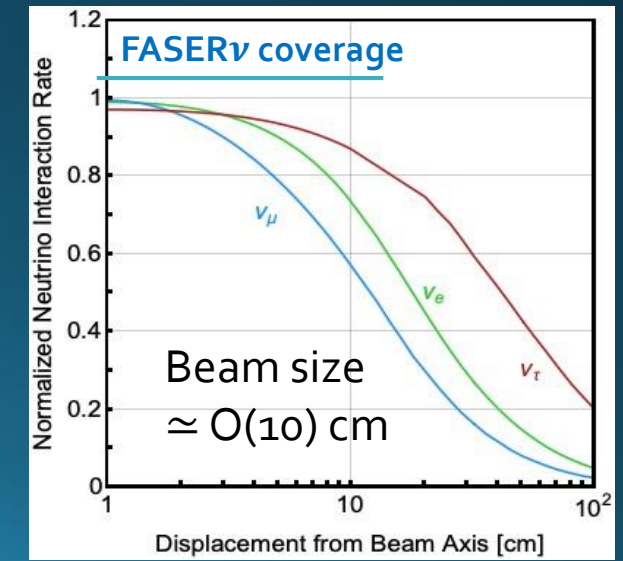
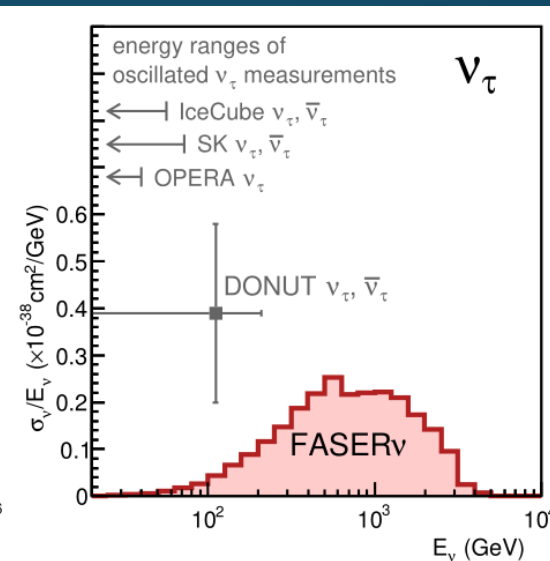
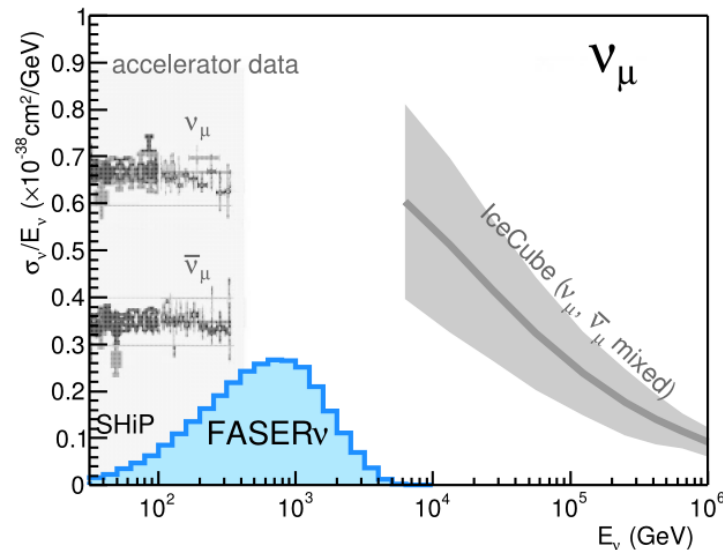
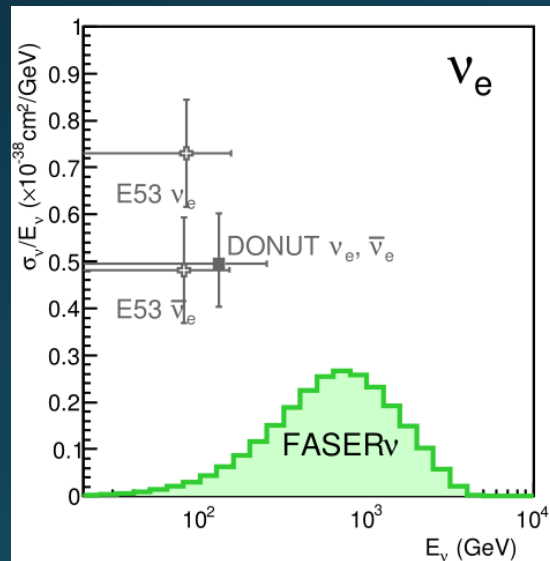
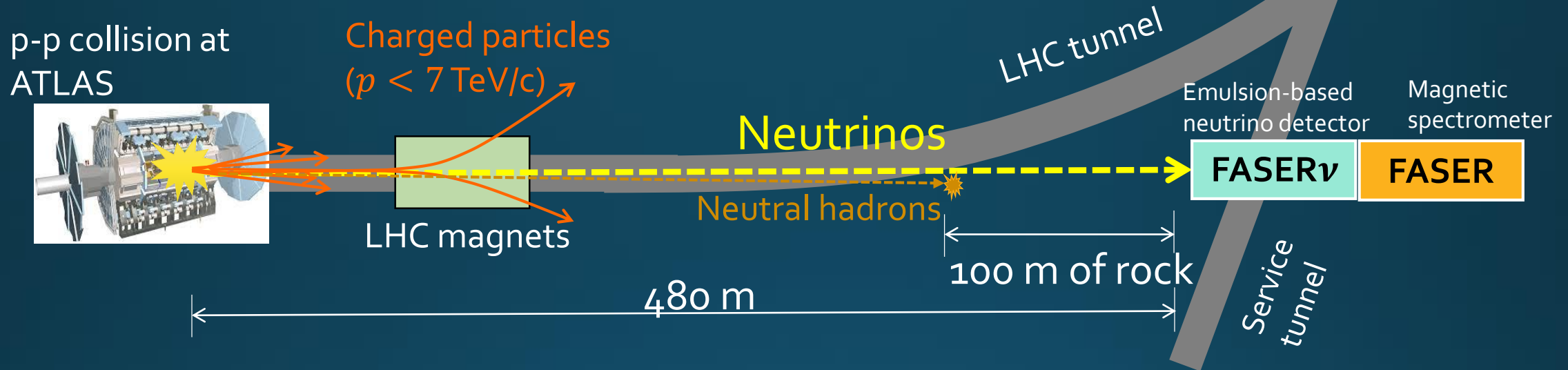
Intense neutrino beam (+ long lived particles, LLPs) here!



FASER (new particle searches) was approved by CERN in Mar 2019
FASER ν (neutrino program) was approved by CERN in Dec 2019

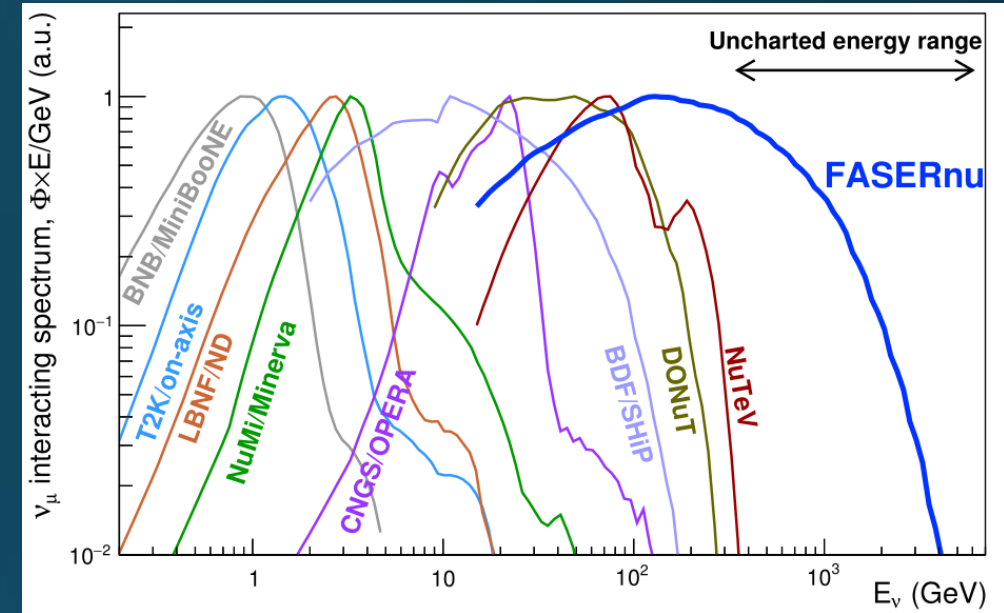
*FASER general talk
on Friday 31st in BSM
by M. Queitsch-Maitland*

LHC high energy neutrino “beamline”



Neutrinos at the LHC: New domain of neutrino research!

- High energy frontier ~ TeV
- Neutrinos by collider method
- Study of production, propagation and interactions of high energy neutrinos



Production

14 TeV p-p collision \equiv 100 PeV int
in fixed target ($\sqrt{s} \sim 10$ TeV)

Prompt neutrino production \rightarrow
Input for neutrino telescopes

QCD (charm/gluon PDF,
intrinsic charm)

Propagation

Unique energy and baseline,
 $L/E \sim 10^{-3}$ m/MeV

Neutrino oscillation at
 $\Delta m^2 \sim 1000$ eV²

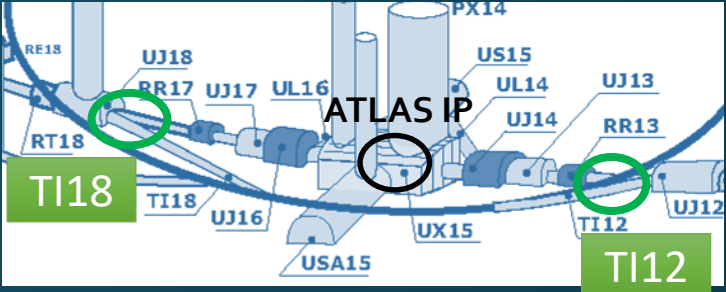
Interaction

3-flavor neutrino cross sections
in unexplored energy range

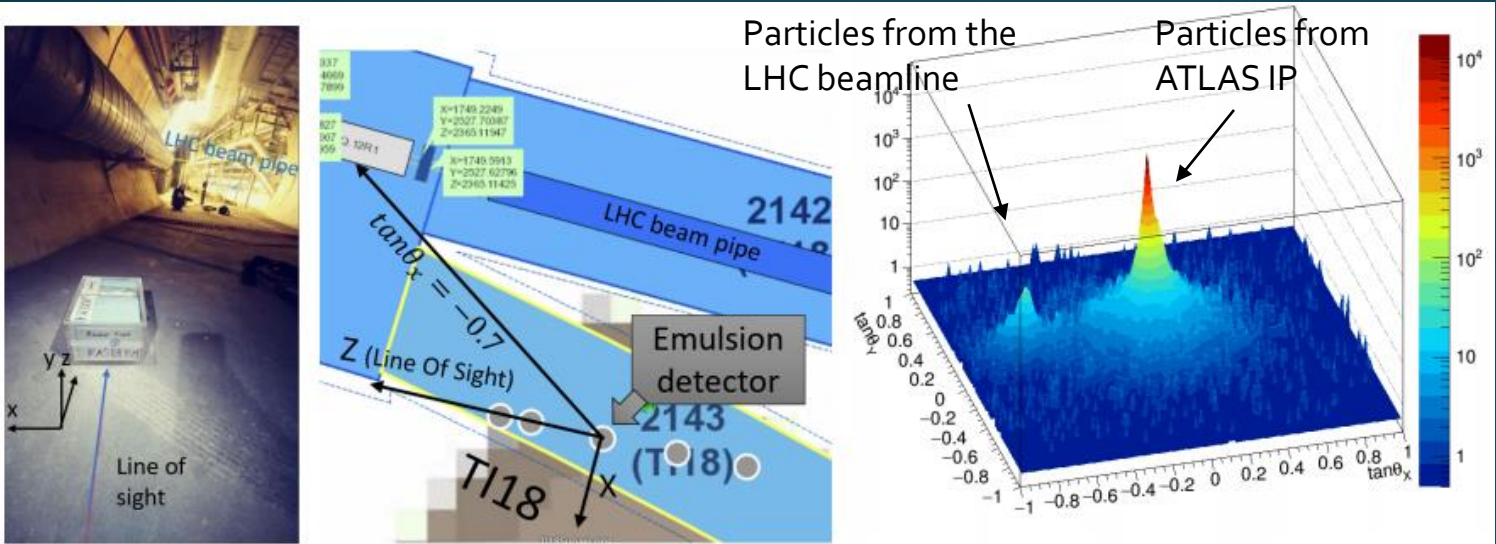
Neutrino induced heavy quark
productions

New physics effects

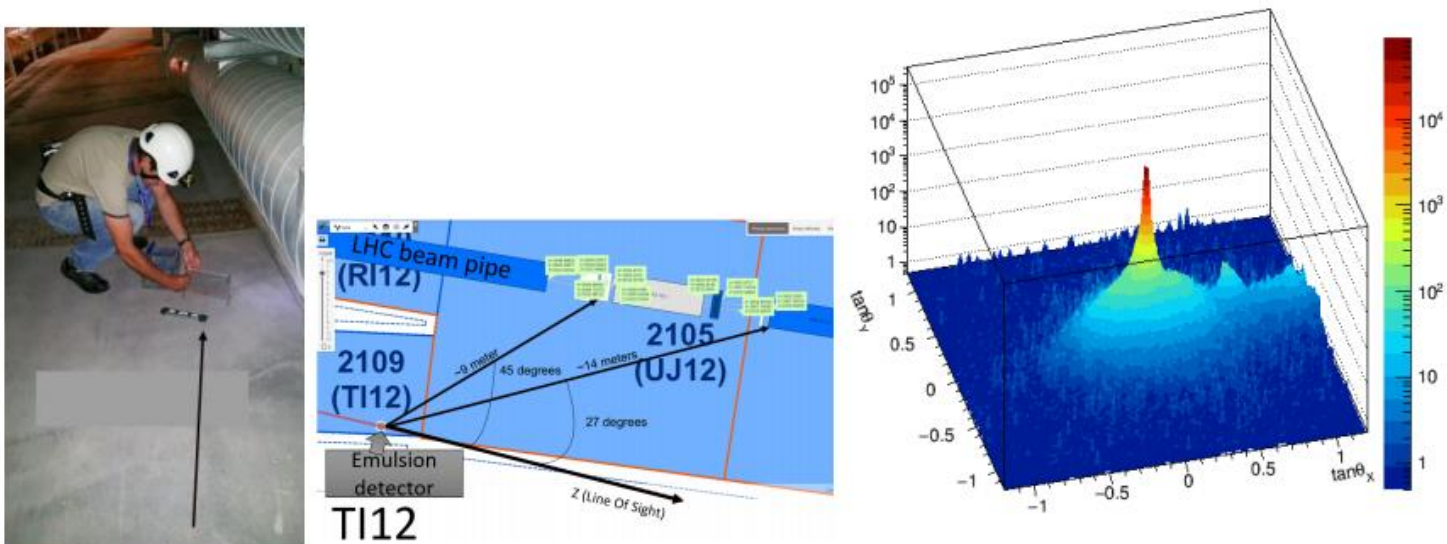
Feasibility studies in 2018: In-situ measurements of charged particle BG



TI18



TI12



- Emulsion detectors were installed to investigate TI18 and TI12
 - flux and angular distribution

	Normalized flux (tracks/fb ⁻¹ /cm ²)
TI18	$(2.6 \pm 0.7) \times 10^4$
TI12	$(3.0 \pm 0.3) \times 10^4$
FLUKA	2×10^4 (muons only)

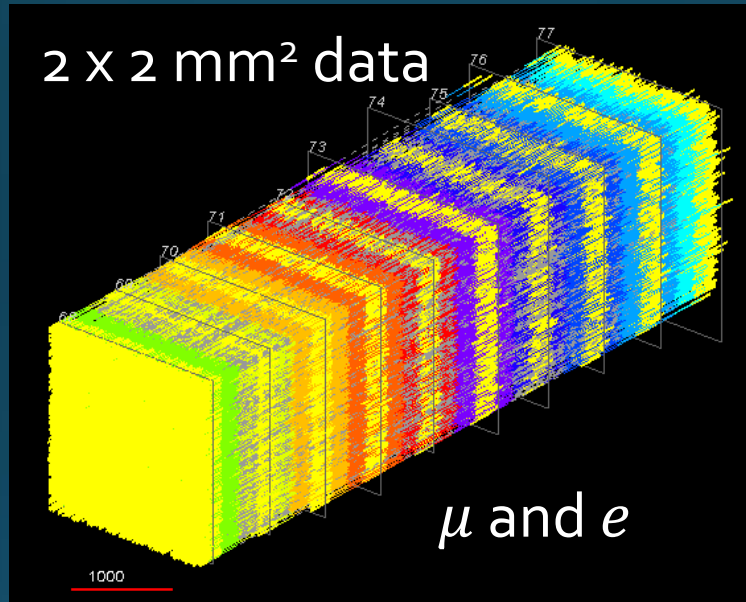
- Low background was confirmed
- Consistent with the FLUKA prediction.

Emulsion detectors can work at the actual environment!
(up to $\sim 10^6/\text{cm}^2 \simeq 30 \text{ fb}^{-1}$ of data)

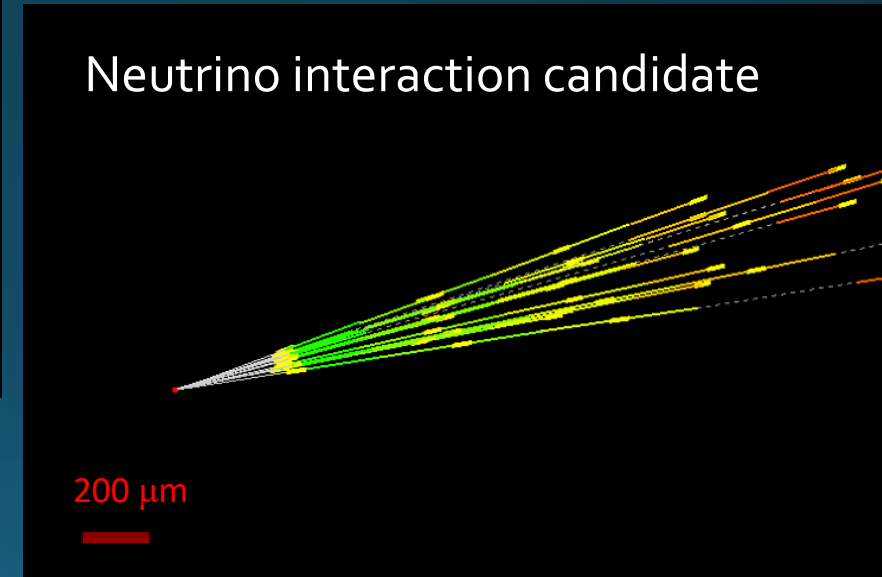
Pilot run in 2018



30 kg detector in T18, 12.5 fb^{-1}



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

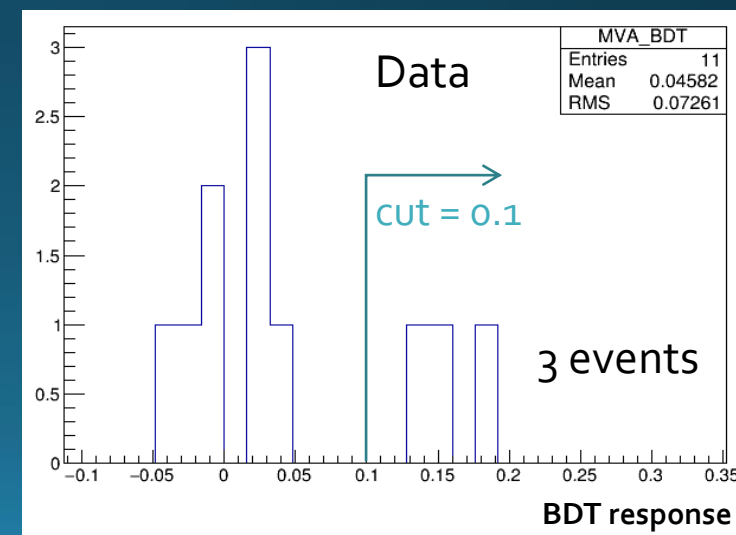
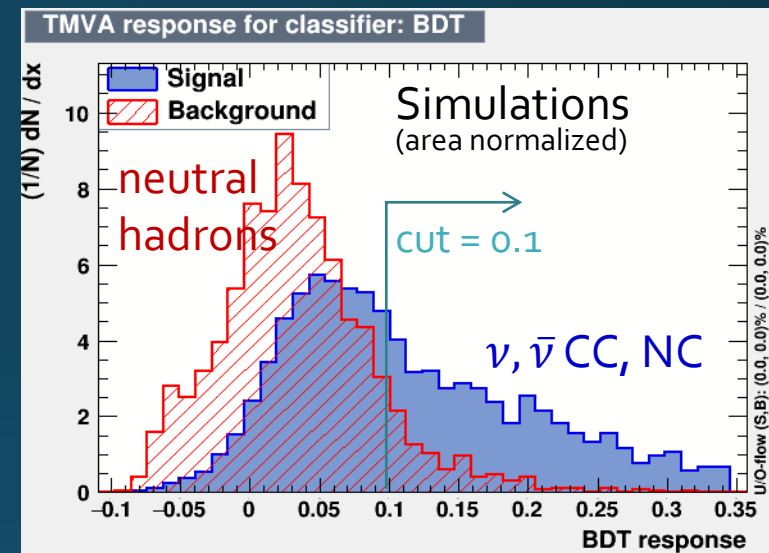


- Aiming to demonstrate the feasibility of detection of collider neutrinos
- A 30 kg emulsion based (lead, tungsten target) detector was installed on axis, 12.5 fb^{-1} of data was collected in Sep-Oct 2018 (6 weeks)

Pilot run event statistics

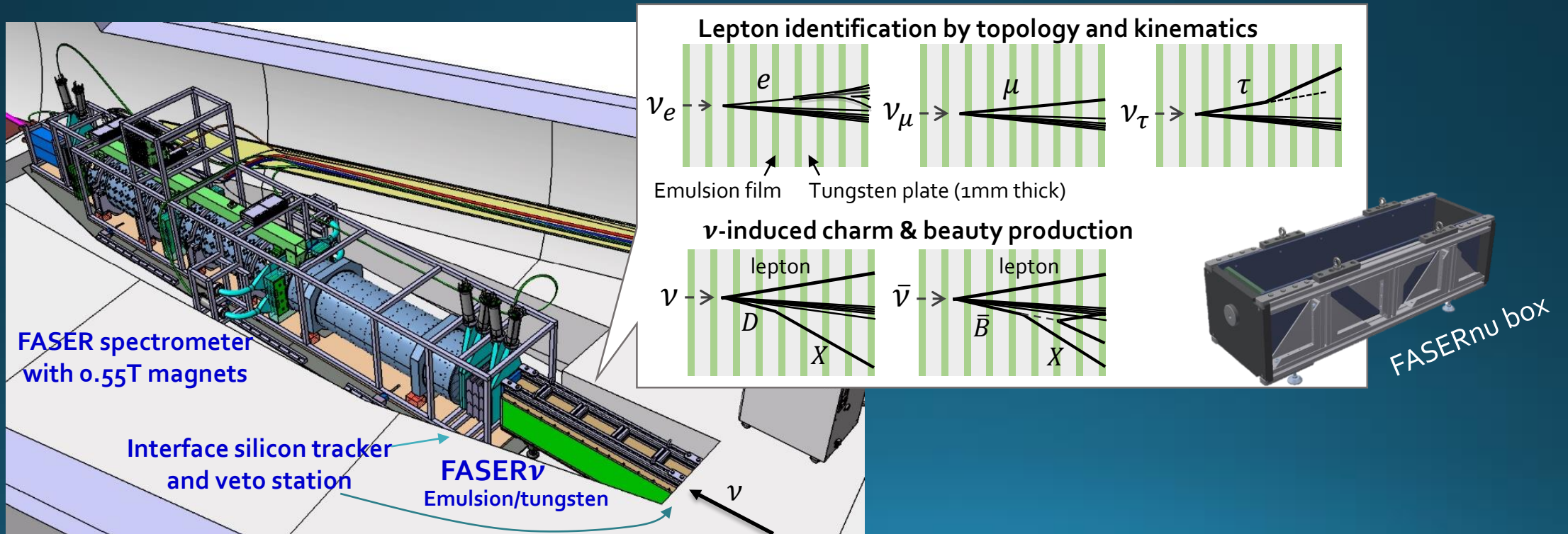
Preliminary

- Analyzed target mass of **12.3 kg**
- Pilot neutrino detector doesn't have lepton ID
 - Separation from neutral hadron BG (produced by muons) is challenging → tighter cuts
- 11 neutral vertices were selected
 - by applying # of charged particle ≥ 5 , etc.
- After BDT analysis, **3 events** remained with **0.83 expected background**
 - A few signal events expected
 - Consistent with the signal + background expectation
 - BG only hypothesis: **p-value = 0.051**
- This result demonstrates the detection of neutrinos from the LHC



FASER ν : Flavor-sensitive ν detector, design for Run 3

- **Emulsion + tungsten detector**, placed **on axis**, in front of the **FASER magnetic spectrometer**
- 1000 layers of 1-mm-thick tungsten target, 25 cm x 25 cm x 130 cm, **1.2 ton** detector (**$285X_0$** , **$10 \lambda_{int}$**)
 - **Emulsion film = high precision tracker** (0.4 μm position accuracy, 2 mrad angular resolution)
 - Films will be replaced every 15-50 fb^{-1} during LHC's technical stops (10 times in Run 3)
- **Lepton identification** by topology in detector
- **Muon charge identification** with FASER spectrometer \rightarrow **distinguishing ν_μ and $\bar{\nu}_\mu$**
- **Neutrino energy** measurement by combining topological and kinematical variables (**$\Delta E/E \sim 30\%$**)



Neutrino event rate (2021-2024)

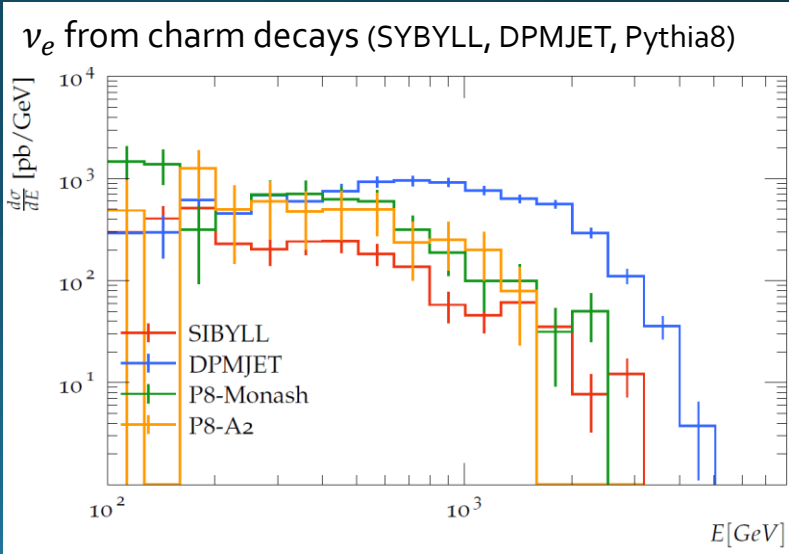
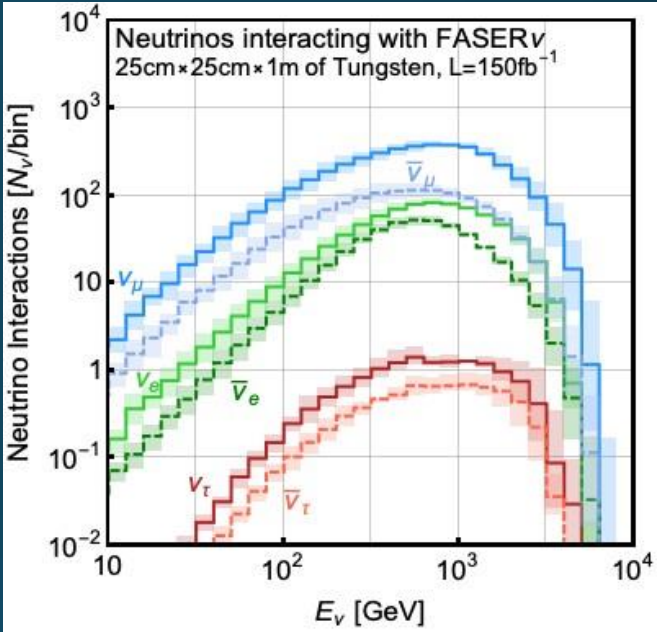
- Small detector, but a lot of interactions ($\sim 10^4$ CC) are expected during Run3

Expected number of CC interactions in FASER ν in Run3 (14 TeV LHC, 150 fb $^{-1}$)

	LOI (FASER original)	FLUKA-based (CERN STI)	Mean int. energy (LOI)
$\nu_e, \bar{\nu}_e$	814 , 456	2986 , 1261	830 GeV
$\nu_\mu, \bar{\nu}_mu$	4452 , 1366	8437 , 2737	840 GeV
$\nu_\tau, \bar{\nu}_\tau$	15 , 7	110 , 55	970 GeV

Letter of Intent (LOI): EPOS-LHC, QGSJET, SIBYLL, Pythia8
FLUKA simulation: DPMJET Thanks to CERN STI group for the FLUKA simulation
Work with BDSim in progress ([Poster](#) on 30th Thu by H. Lefebvre)

- Neutrino fluxes are being cross-checked among different simulations
 - Differences due to hadron generators and beamline infrastructure reproduction were identified. Updating the flux estimates
- Work in progress for quantifying and reducing these uncertainties
 - Creating a dedicated forward physics tune with Pythia8, using forward data (LHCf, FASER's muon measurements, etc.)



Large variation between different hadron production models (at p-p collision)

Prospects for 2021-2024

- **Cross section measurements at TeV energy regime**

- Three flavors in an energy range where cross sections are unconstrained

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

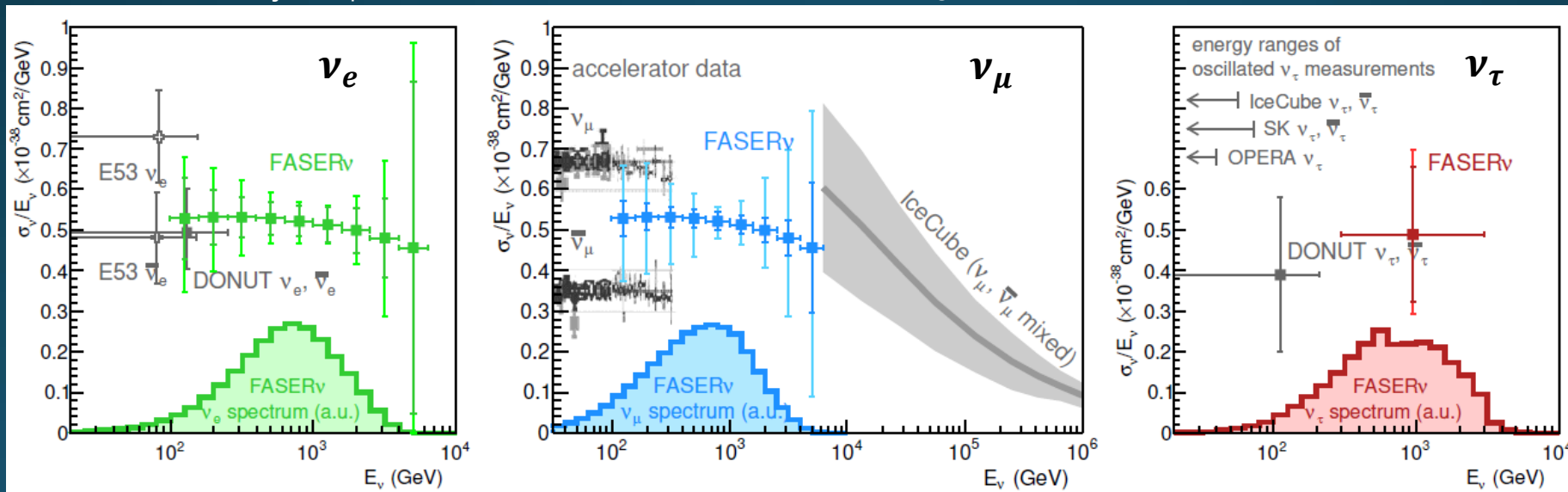
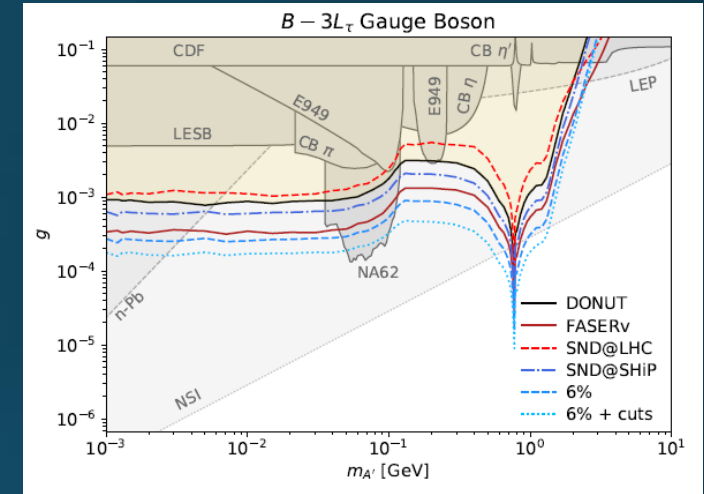
- **Additional physics studies**

- Neutrino-induced charm/beauty production channels
- Neutrino production via heavy meson decays → Prompt neutrino and QCD (intrinsic charm) study
- Sterile neutrino oscillations
- Further possibility to study new physics models

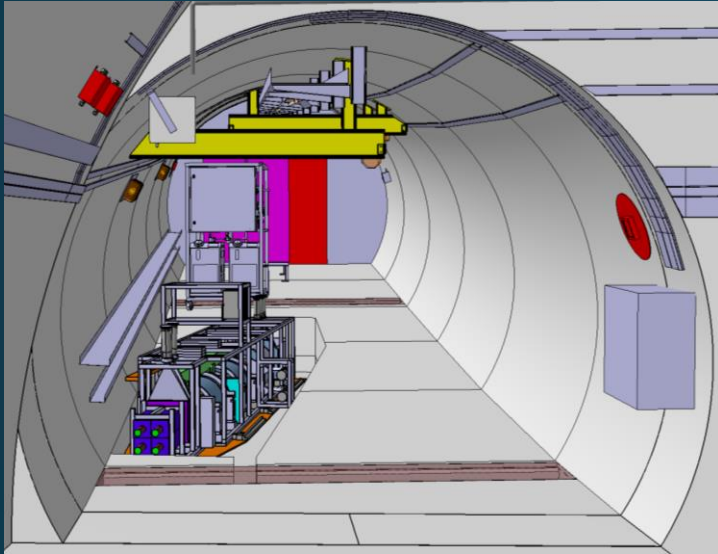
Projected precision of FASERν measurement at 14-TeV LHC (150 fb⁻¹)

Possibility of probing tau neutrino production from the decay of light gauge bosons,

arXiv:2005.03594



Civil engineering and infrastructure work



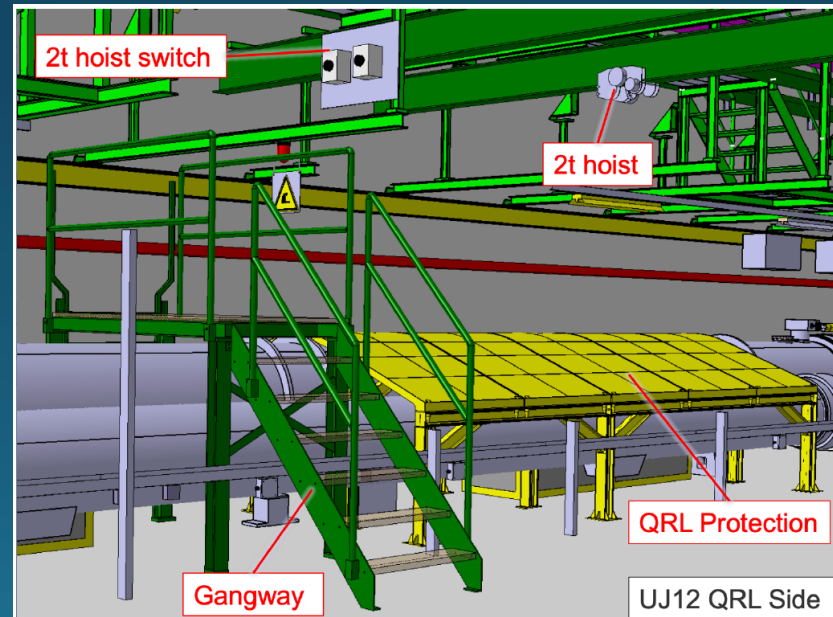
2019



Trench to install the detectors

March 2020

- TI12 area was cleaned up
- **Civil engineering work** for FASER/FASER ν installation finished on schedule, just before the CERN shutdown
- Access to TI12 over the LHC machine is prepared



Protection of the LHC beam pipe

March 2020

Summary



- **FASER ν** at the LHC: The first experiment with “Collider neutrinos”
 - High energy frontier of man-made neutrinos at 1 TeV scale
 - New knowledge in unexplored energy regime, BSM!?
 - Small experiment, but high impact to neutrino physics
- We identified a good location for neutrino programs, a synergy with the FASER dark sector searches
- Detection of neutrinos was demonstrated by the 2018 pilot run
- Data taking in Run 3 (2021-2024) can collect $\mathcal{O}(10^4)$ neutrino interactions
 - Emulsion-based detector to study flavors (ν_e , ν_μ , ν_τ , charm and beauty).
- Discussing for neutrino measurements in the HL-LHC era

THE FASER COLLABORATION

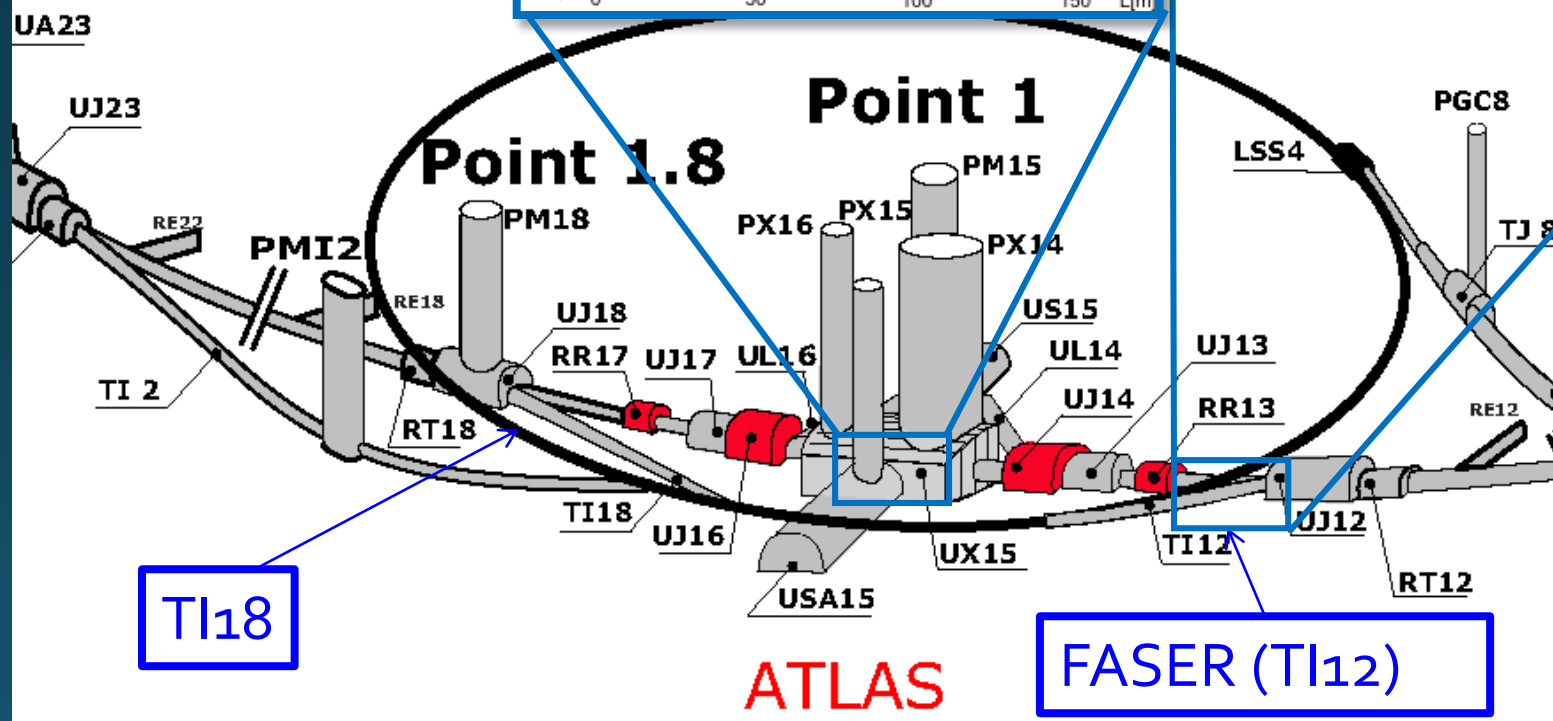
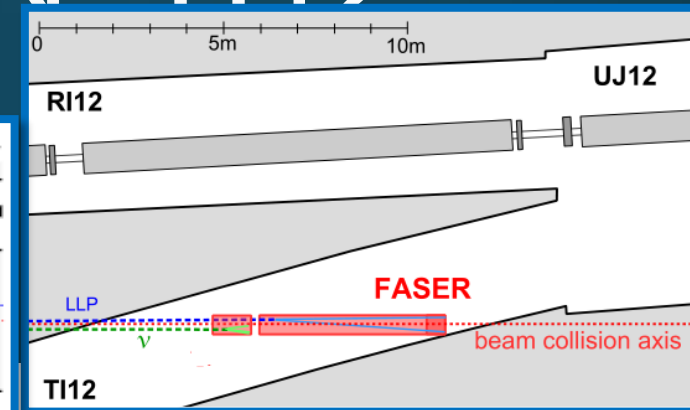
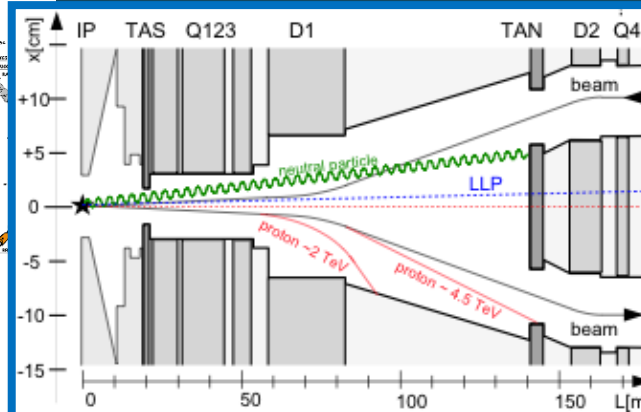
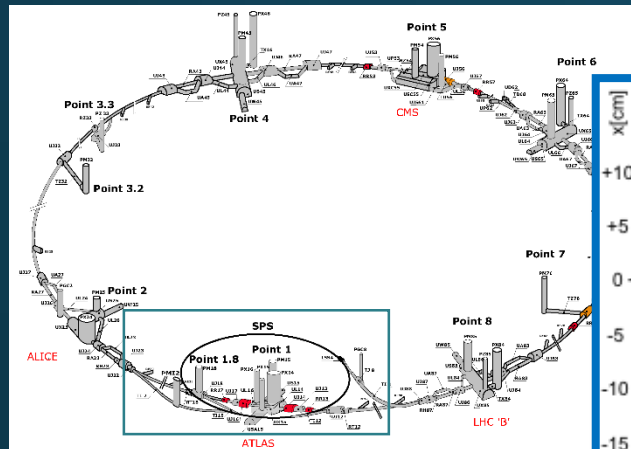
- 64 collaborators, 20 institutions, 8 countries

Henso Abreu (Technion), Yoav Afik (Technion), Claire Antel (Geneva), Akitaka Ariga (Bern), Tomoko Ariga (Kyushu/Bern), Florian Bernlochner (Bonn), Jamie Boyd (CERN), Lydia Brenner (CERN), Dave Casper (UC Irvine), Franck Cadoux (Geneva), Xin Chen (Tsinghua), Andrea Coccaro (INFN), Candan Dozen (Tsinghua), Yannick Favre (Geneva), Deion Fellers (Oregon), Jonathan Feng (UC Irvine), Didier Ferrere (Geneva), Iftah Galon (Rutgers), Stephen Gibson (Royal Holloway), Sergio Gonzalez-Sevilla (Geneva), Shih-Chieh Hsu (Washington), Zhen Hu (Tsinghua), Peppe Iacobucci (Geneva), Sune Jakobsen (CERN), Enrique Kajomovitz (Technion), Felix Kling (SLAC), Umut Kose (CERN), Susanne Kuehn (CERN), Helena Lefebvre (Royal Holloway), Lorne Levinson (Weizmann), Ke Li (Washington), Jinfeng Liu (Tsinghua), Chiara Magliocca (Geneva), Josh McFayden (CERN), Sam Meehan (CERN), Dimitar Mladenov (CERN), Mitsuhiro Nakamura (Nagoya), Toshiyuki Nakano (Nagoya), Marzio Nessi (CERN), Friedemann Neuhaus (Mainz), Hidetoshi Otono (Kyushu), Carlo Pandini (Geneva), Hao Pang (Tsinghua), Brian Petersen (CERN), Francesco Pietropaolo (CERN), Markus Prim (Bonn), Michaela Queitsch-Maitland (CERN), Filippo Resnati (CERN), Jakob Salfeld-Nebgen (CERN), Osamu Sato (Nagoya), Paola Scampoli (Bern), Kristof Schmieden (Mainz), Matthias Schott (Mainz), Anna Sfyrlla (Geneva), Savannah Shively (UC Irvine), Jordan Smolinsky (Florida), Yosuke Takubo (KEK), Ondrej Theiner (Geneva), Eric Torrence (Oregon), Sebastian Trojanowski (Sheffield), Serhan Tufanli (CERN), Benedikt Vormwald (CERN), Dengfeng Zhang (Tsinghua), Gang Zhang (Tsinghua)



Backup

FASER LOCATION- TI12



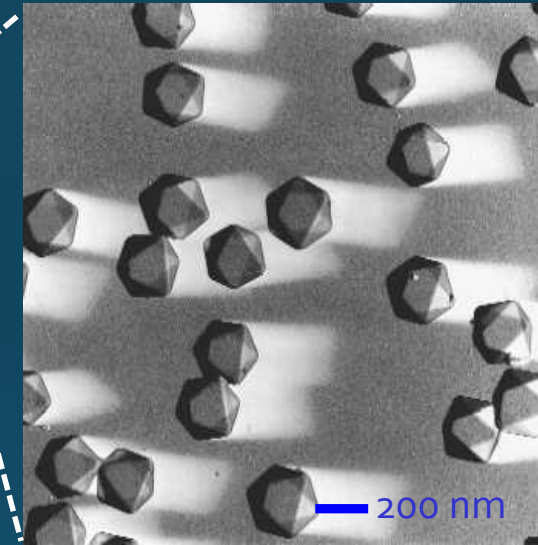
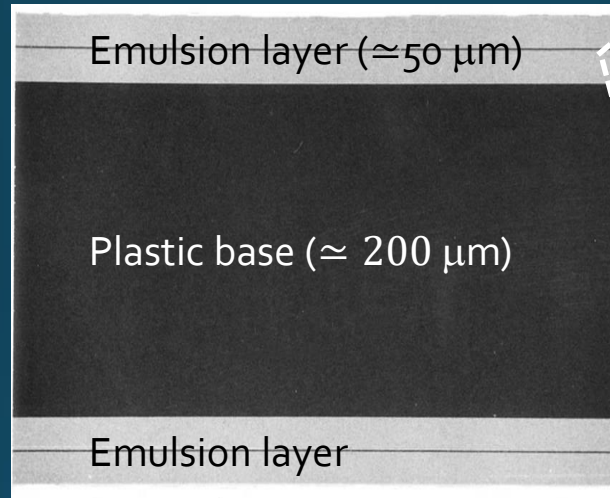
Emulsion detectors: 3D tracking device with 50 nm precision

AgBr crystal = detector
 10^{14} channels/film or 10^{14} channels/cm³

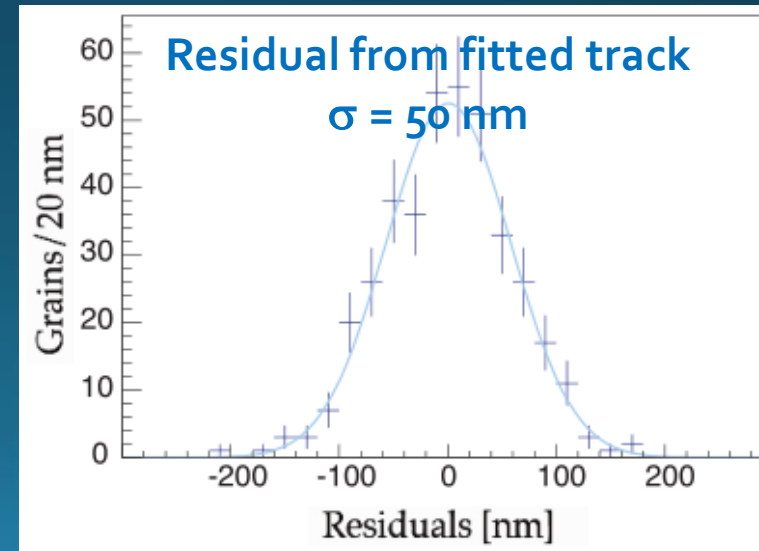
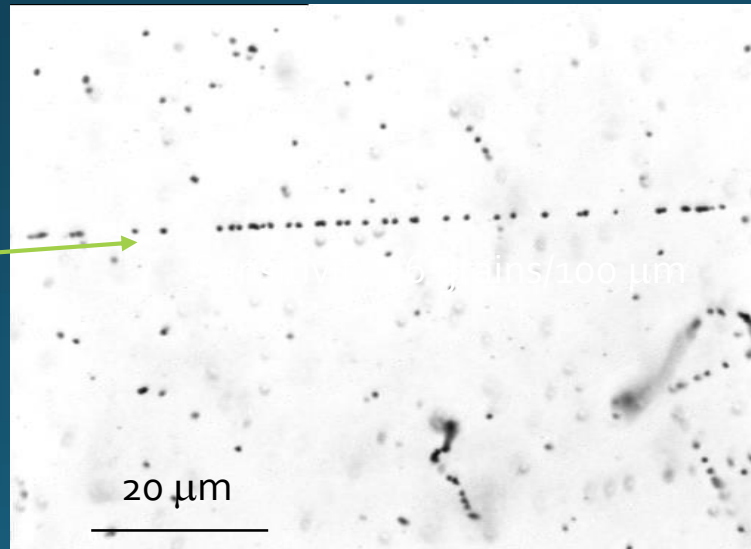
Emulsion film



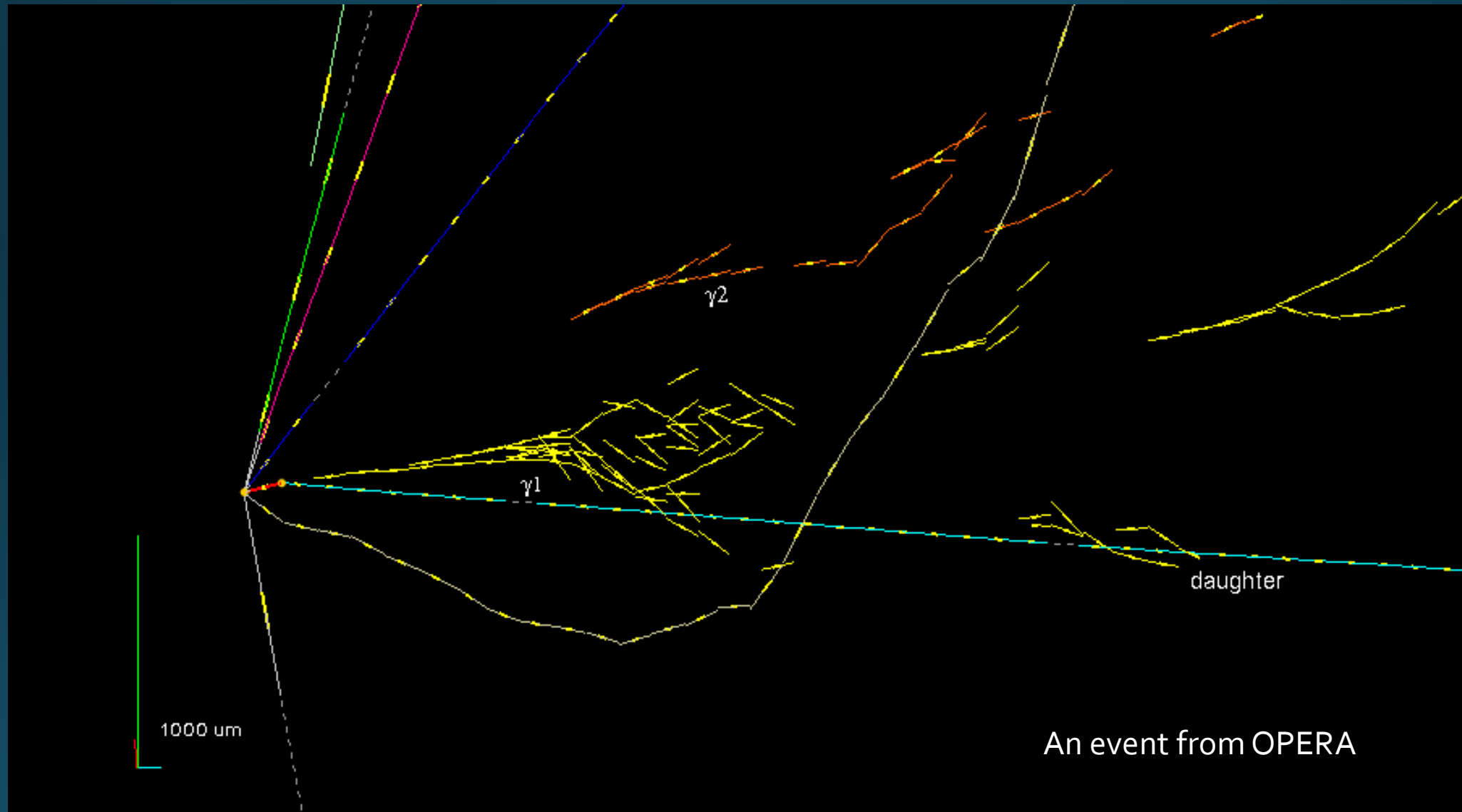
Cross-sectional view



10 GeV/c π
beam



Emulsion-based neutrino detector

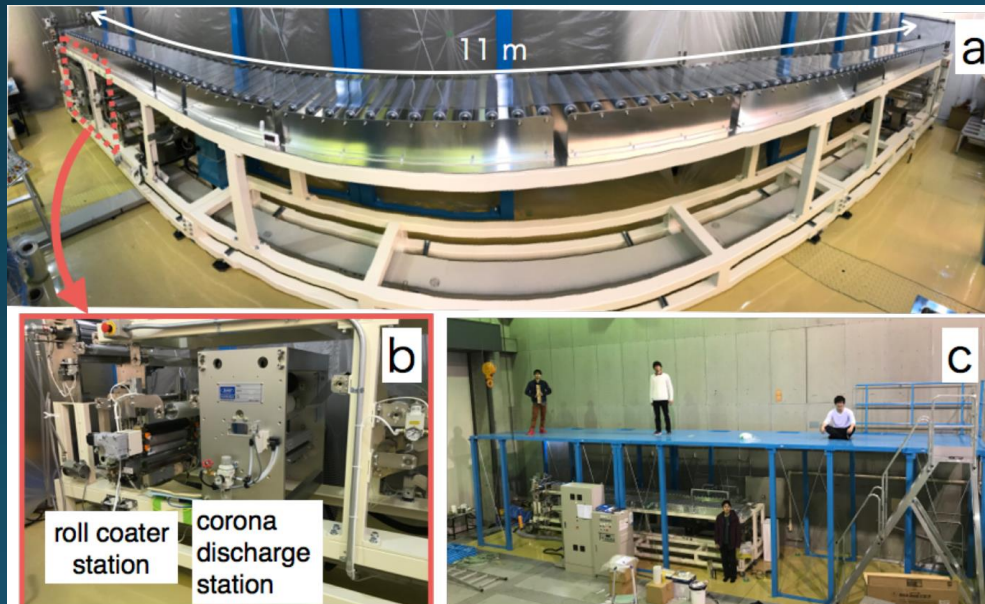


An event from OPERA

Emulsion detector technology

- **Detector production**

- Upgrading the emulsion facility in Nagoya University
 - Large-scale gel production machine and film production system
- Targeted performance of the film production system: 12.5 m²/day
- Would be ready for mass production in July-August 2020

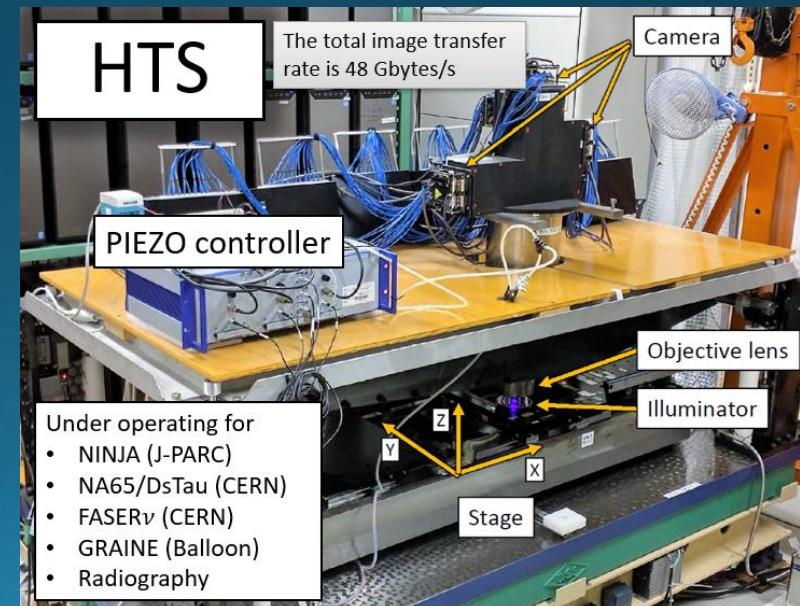


- **Fast readout of emulsion films**

- **Great progress in the readout speed**
- ~100 times faster than OPERA

HTS paper: M. Yoshimoto, T. Nakano, R. Komatani, H. Kawahara, PTEP 10 (2017) 103H01.

	Start year	Field of view (mm ²)	Readout speed (cm ² /h/layer)
S-UTS	2006	0.05	72
HTS-1	2015	25	4700
HTS-2	2021	50	25000

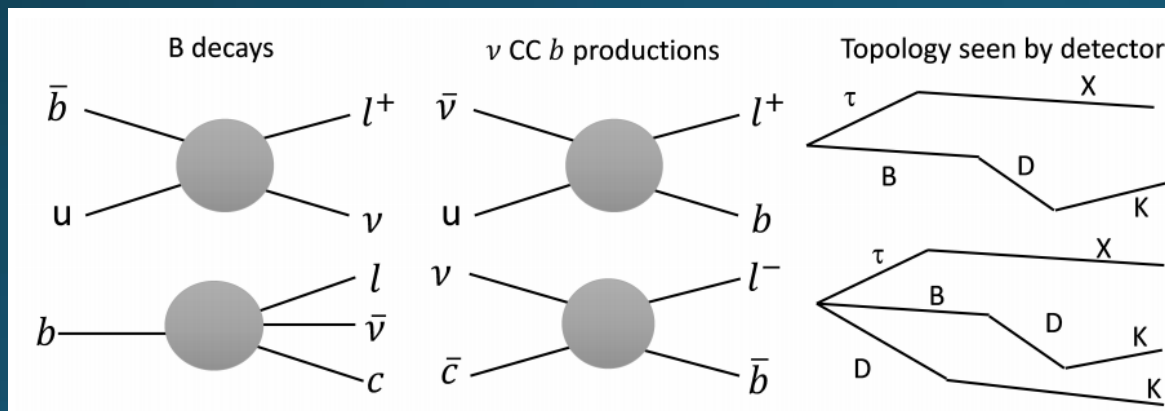
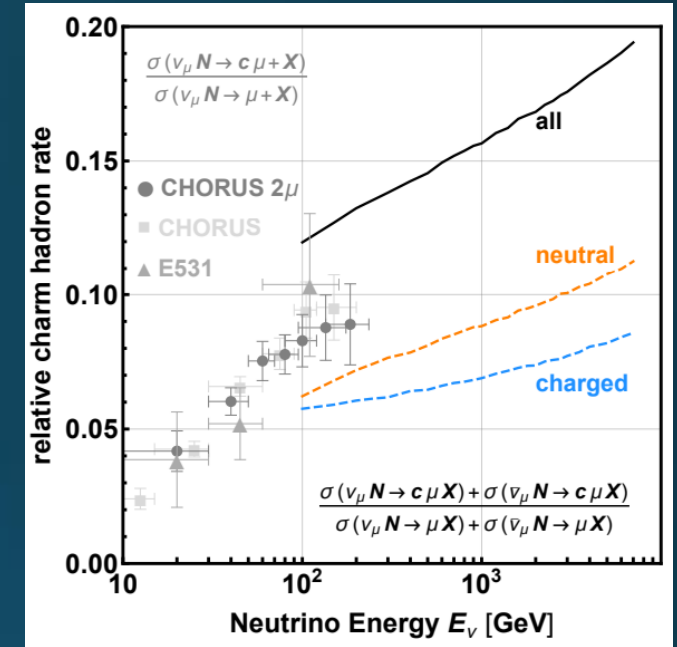


Heavy-flavor-associated channels

- **Measure charm** production channels
 - Large rate $\sim 10\%$ ν CC events, $\mathcal{O}(1000)$ events
 - First measurement of ν_e induced charm prod.

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

- Search for Beauty production channels
 - Expected SM events (ν_μ CC b production) are $\mathcal{O}(0.1)$ events in Run 3, due to CKM suppression, $V_{ub}^2 \simeq 10^{-5}$

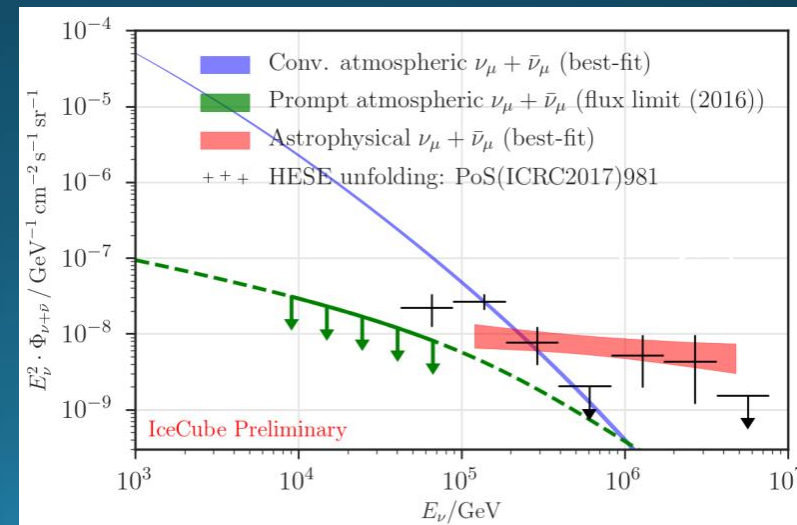
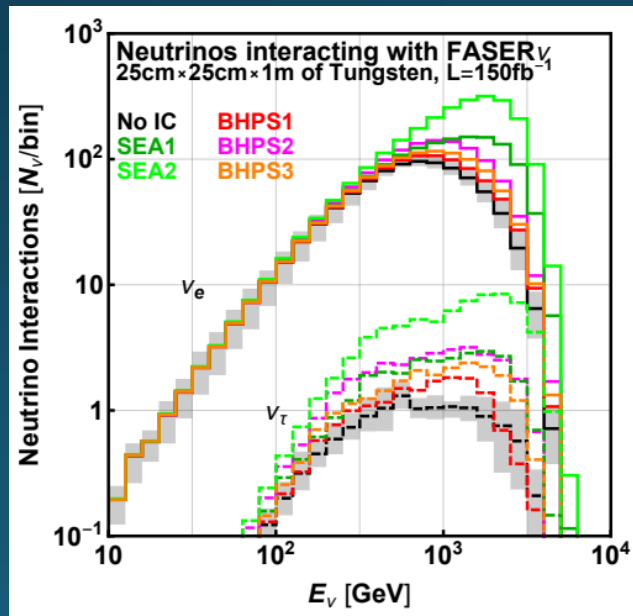


$$\bar{\nu} N \rightarrow \ell \bar{B} X$$

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

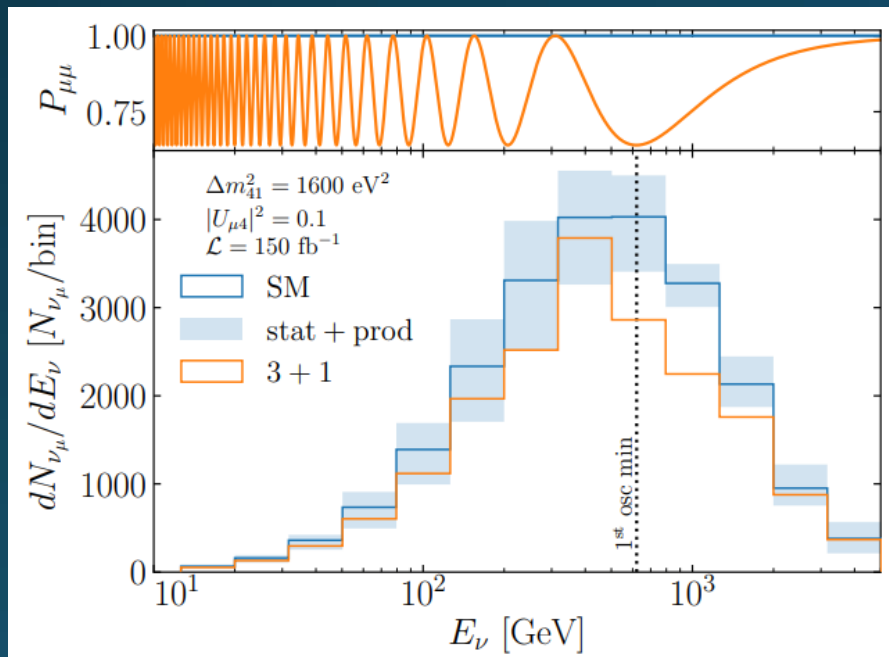
Prompt neutrino production

- Forward charm production in p - p collision is not well understood → Large uncertainty in “prompt neutrino” production.
 - 14 TeV p - p collision \equiv 100 PeV proton interaction in lab frame
 - Intrinsic Charm could change it by a factor of 10 at high energy
 - Important input to extraterrestrial neutrinos measurements, e.g. by IceCube. Synergy with IceCube.
- Sensitivity in ν_e , and ν_τ channels.

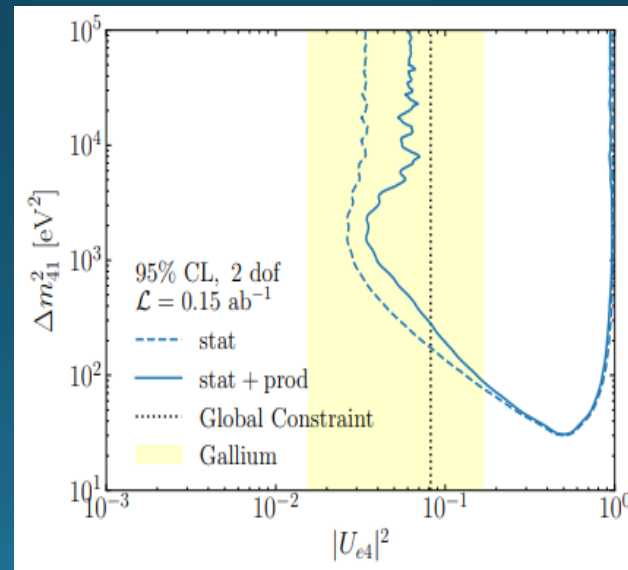


Sterile neutrino oscillation

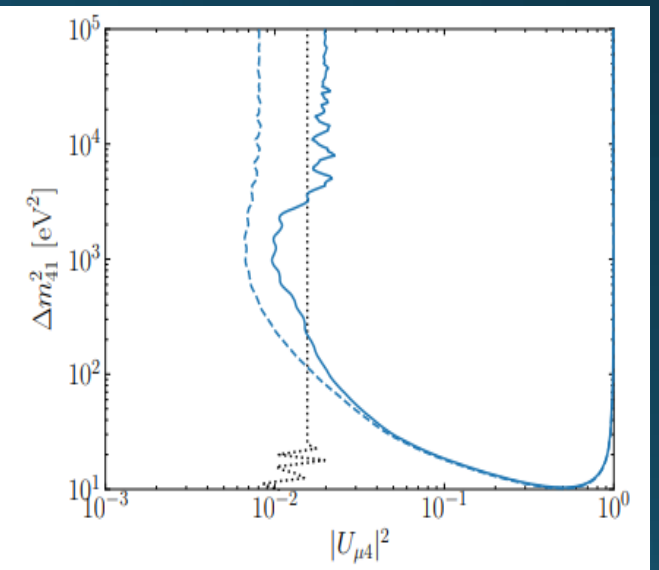
- Due to unique energy and baseline ($L/E \sim 10^{-3}$ m/MeV), FASER ν is sensitive to large $\Delta m^2 \sim 10^3$ eV 2 .
- Neutrino spectrum deformation
- Competitive in disappearance channels.



ν_e disappearance

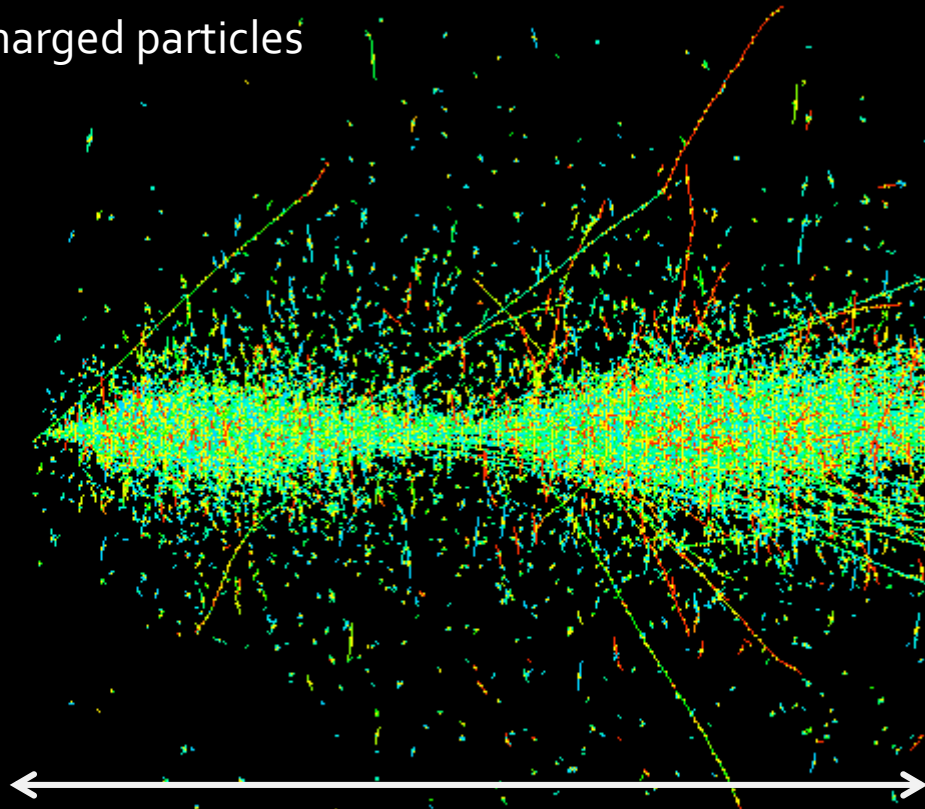


ν_μ disappearance



Simulated $1\text{ TeV } \nu_\mu$ CC interaction

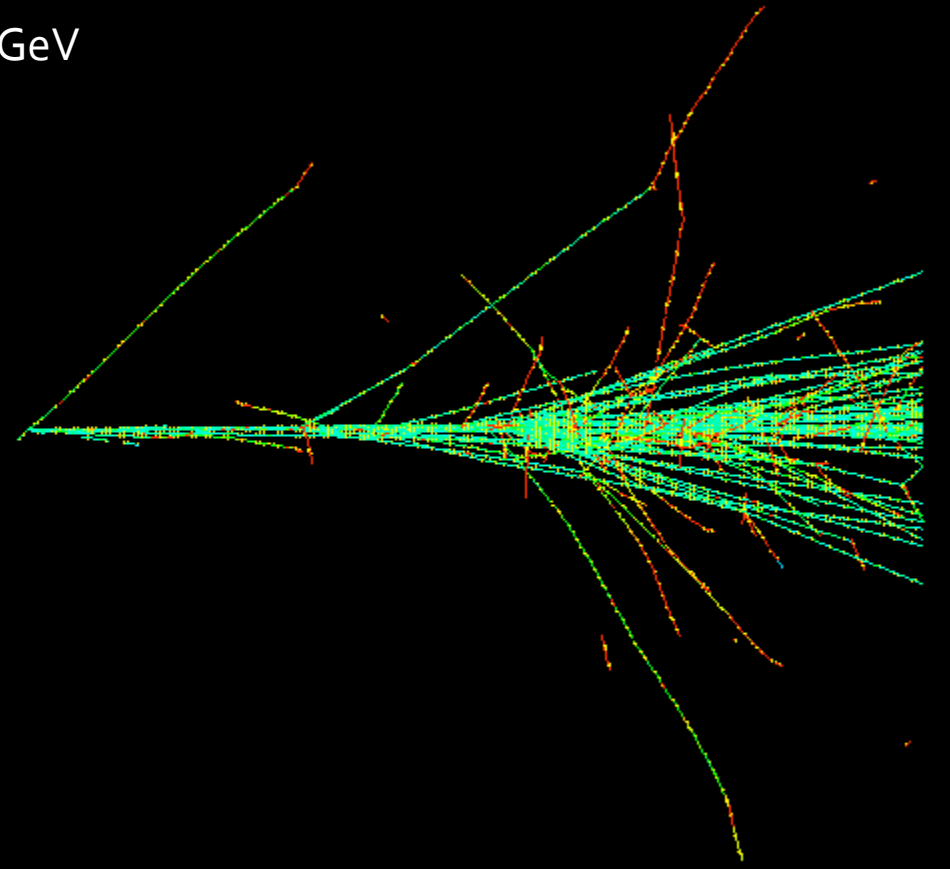
All charged particles



200 tungsten plates (27 cm)
 $\sim 57 X_0, \sim 2 \lambda_{int}$

50000 μm

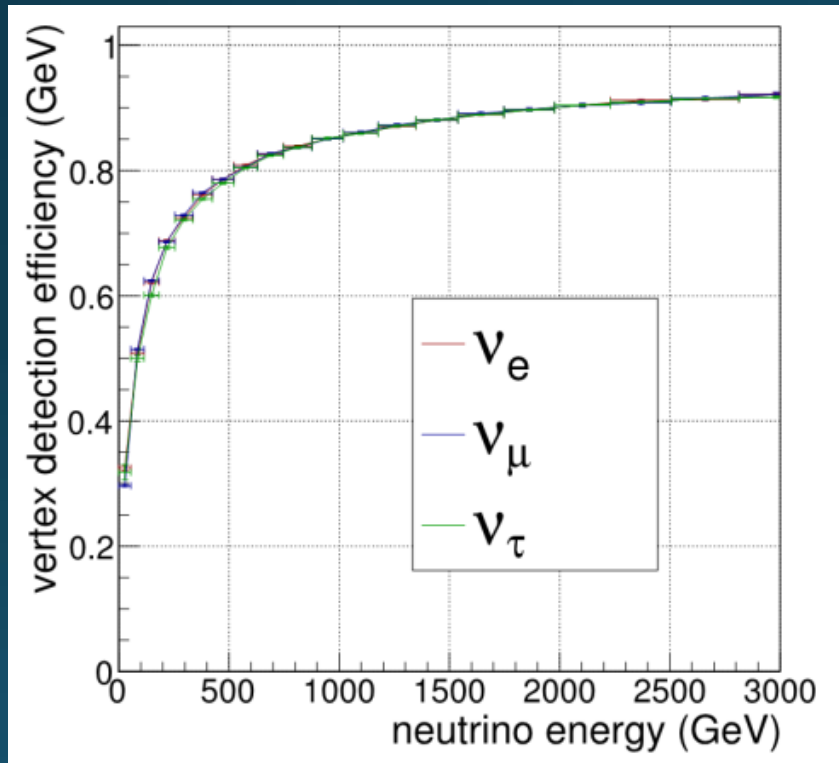
$P > 0.3\text{ GeV}$



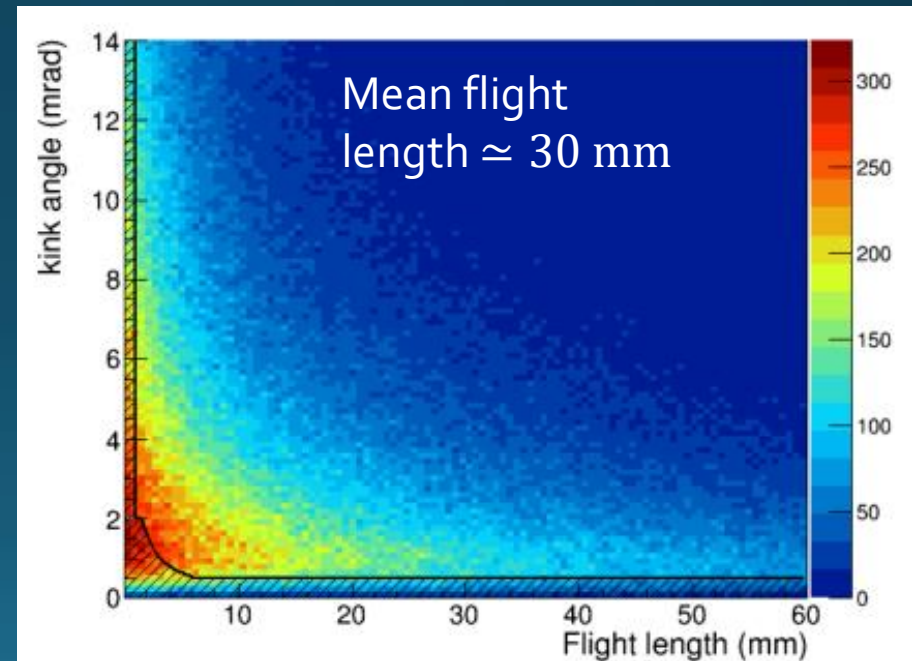
50000 μm

Detection efficiency

Vertex detection efficiency
(charged multiplicity ≥ 5)



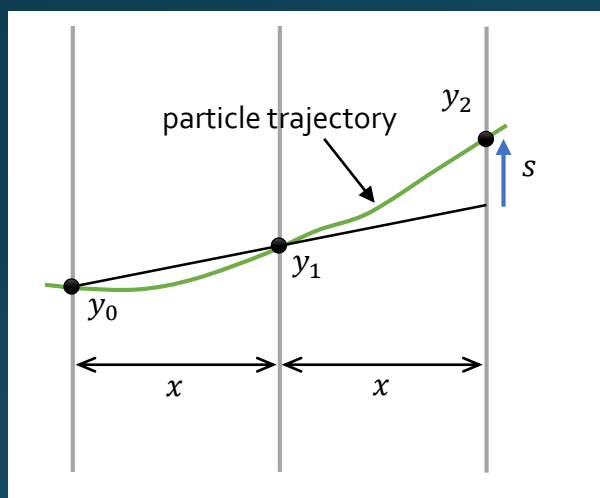
Tau decay detection efficiency
 $\approx 75\%$ ($\tau \rightarrow 1$ prong)



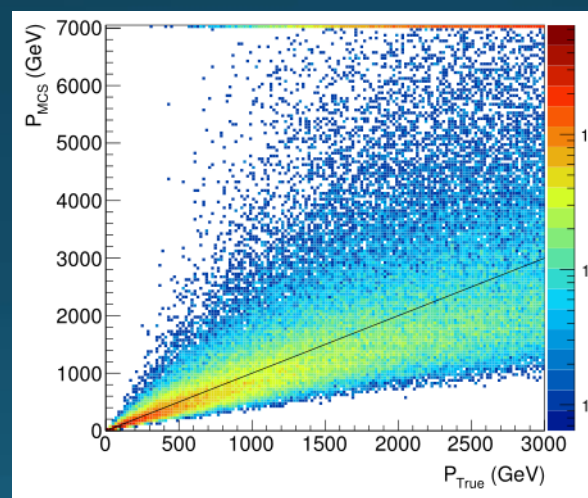
Particle momentum measurement

by multiple Coulomb scattering (MCS)

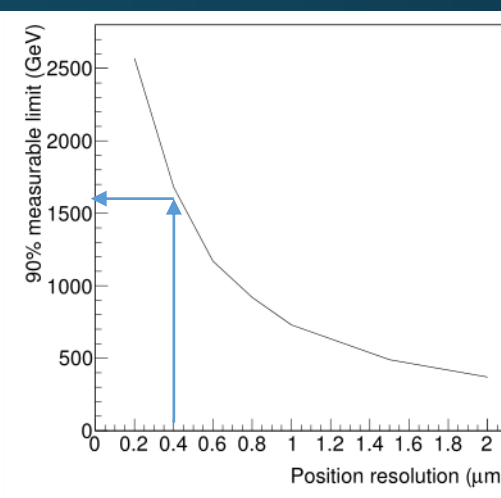
- Sub-micron precision alignment using muon tracks
 - Our experience = 0.4 μm (in the DsTau experiment)
- This allow to measure particle momenta by MCS, even above 1 TeV.



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



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



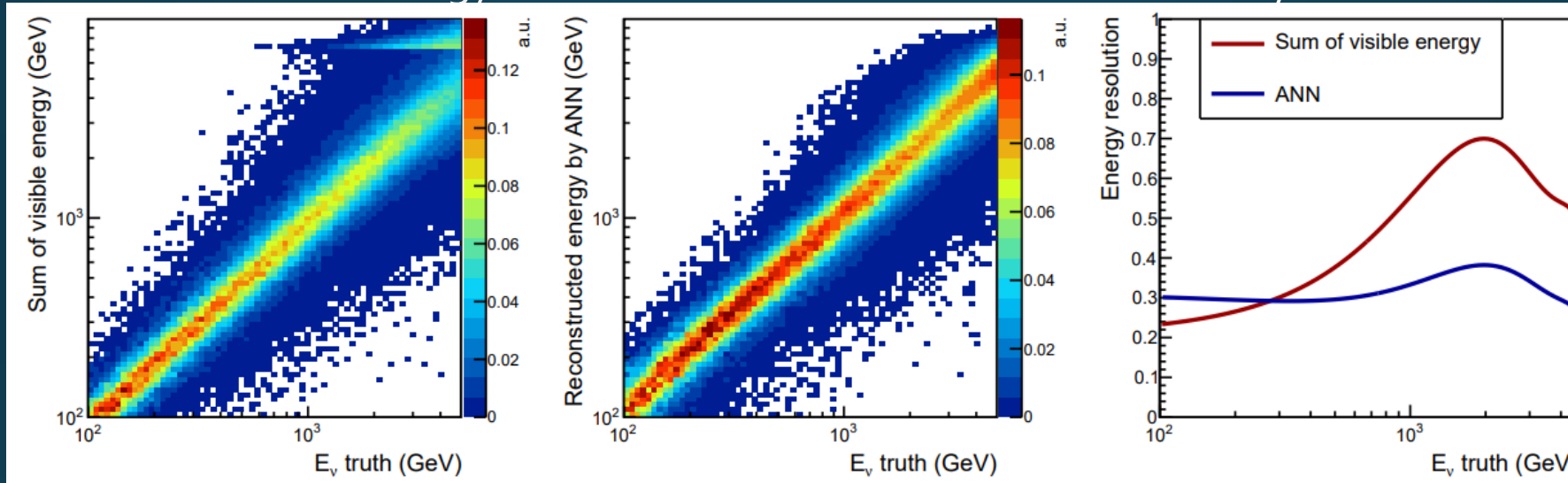
Measurable energy vs position resolution

Energy reconstruction (ν_μ CC)

Sum of visible energy

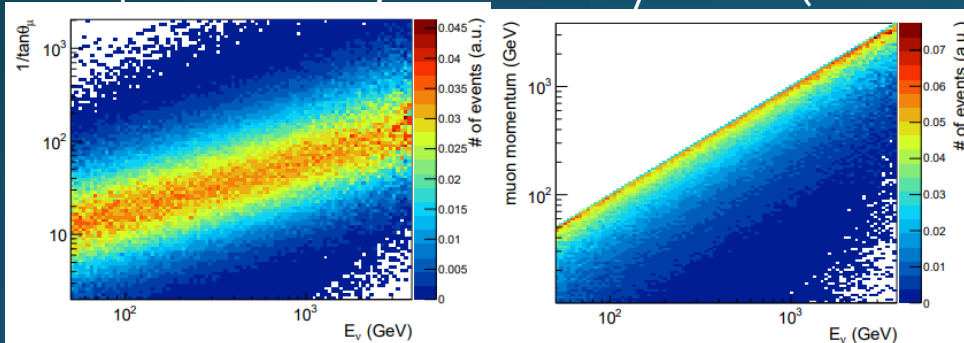
ANN method

$\Delta E/E$



(smeared)

inputs for ANN, simulated by GENIE (MC truth)



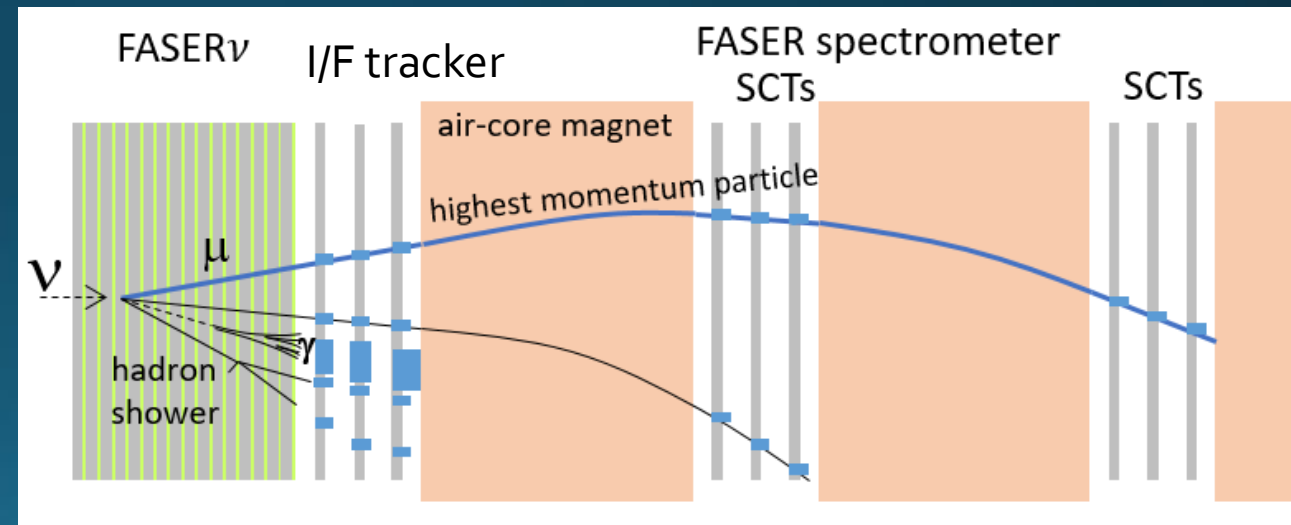
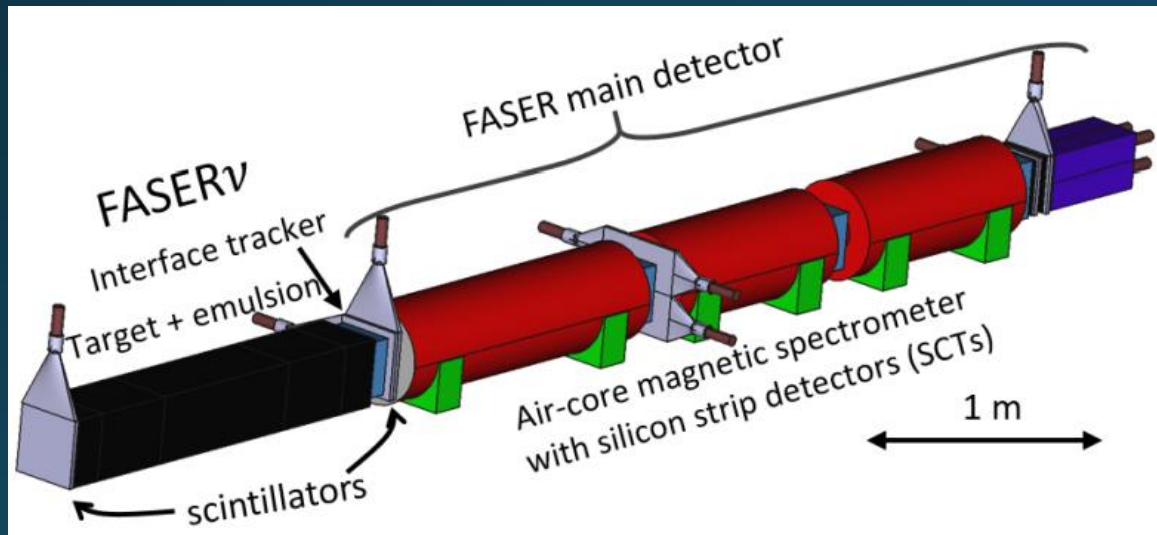
Angular info

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.

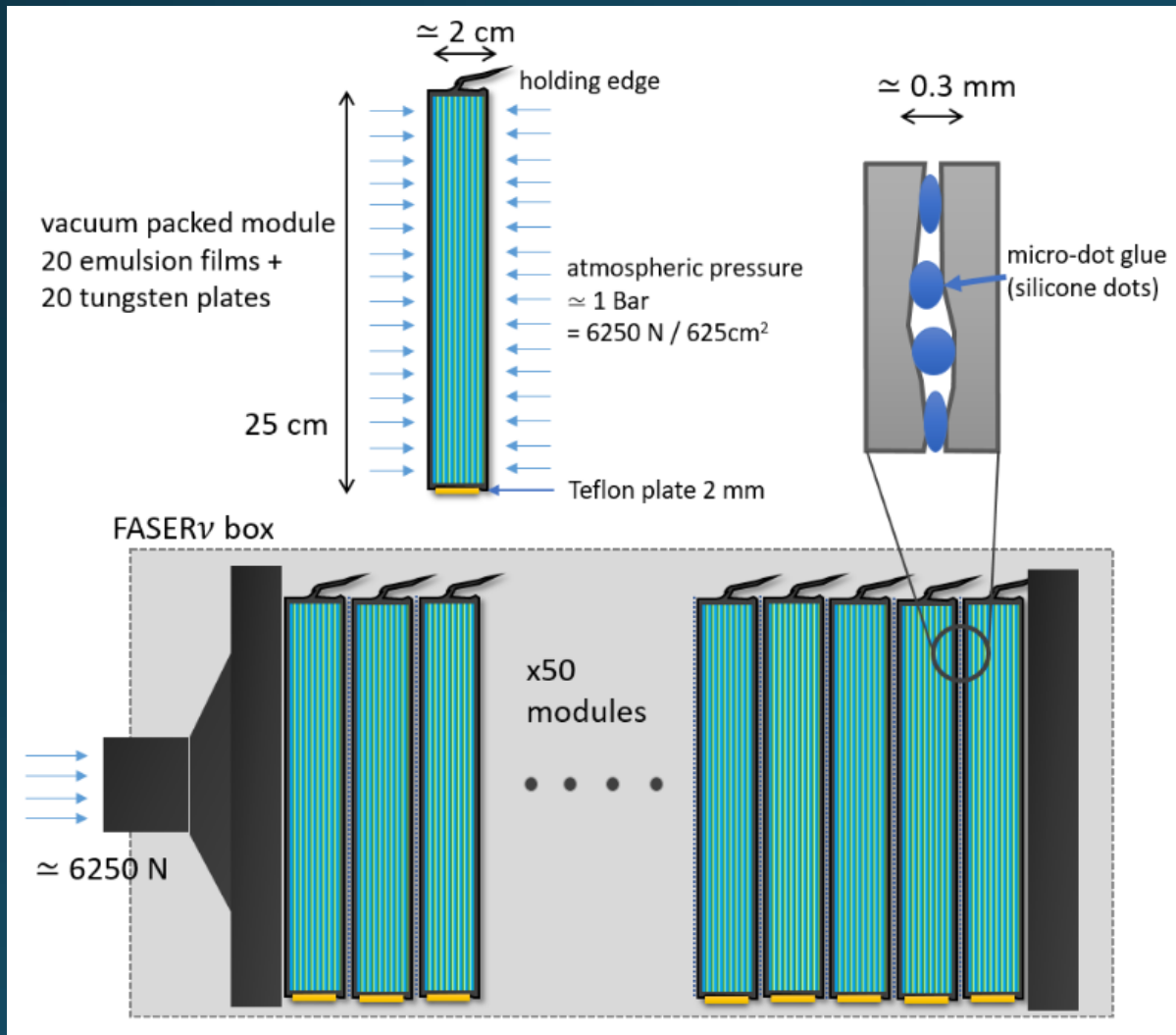
FASER ν + FASER, hybrid configuration

- Muon charge identification
- Distinguish ν_μ and $\bar{\nu}_\mu \rightarrow$ Wider physics cases
- Improve neutrino energy reconstruction



Position and angular matching between
FASER ν and electronic detectors

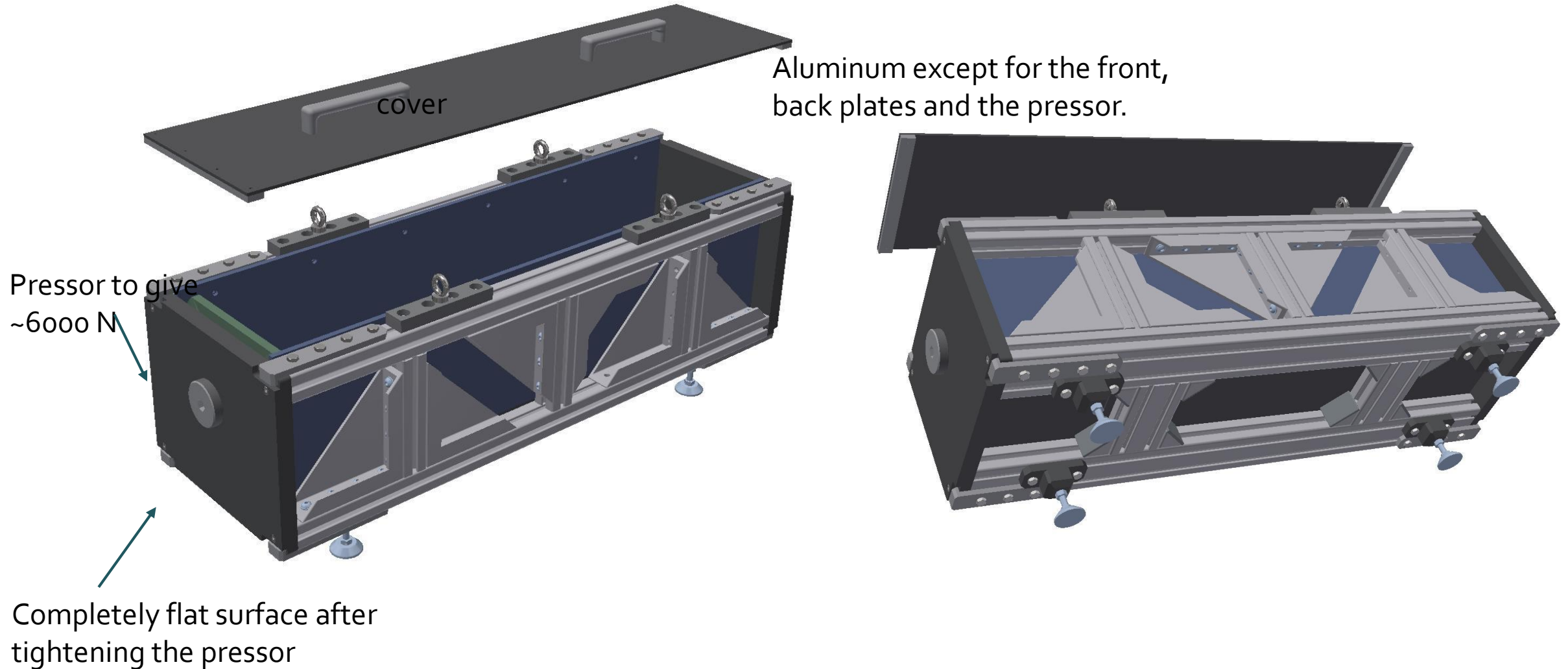
Module structure



Vacuum-packed module

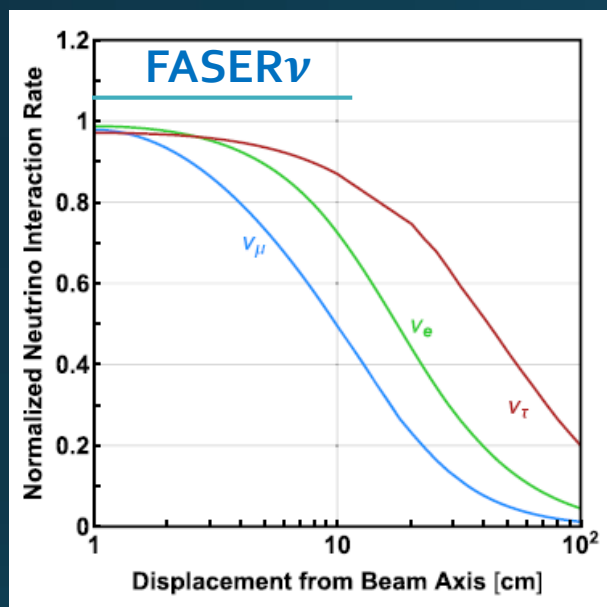


New design by Roger Haenni



Neutrino event rates

- **FASER ν will be centered on the LOS** (in the FASER trench) to maximize flux of all neutrino flavors

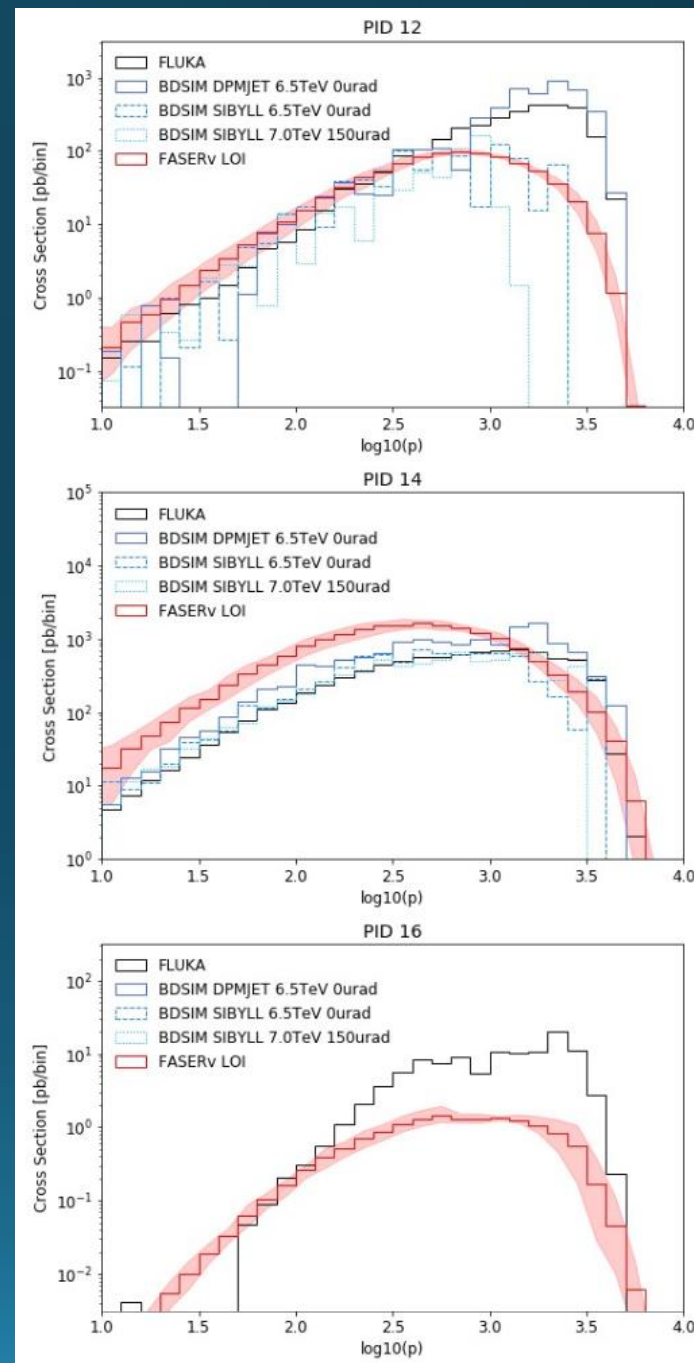


Expected number of CC interactions in Run3

	LOI	FLUKA
$\nu_e, \bar{\nu}_e$	908, 479	2986, 1261
$\nu_\mu, \bar{\nu}_\mu$	18344, 8437	8437, 2737
$\nu_\tau, \bar{\nu}_\tau$	15, 7	110, 55

Large uncertainty for the moment

- **Working on the evaluation of the uncertainties and the possible improvements**
 - Creating a dedicated forward physics tune with Pythia8
 - Studying the systematic uncertainties



BG expectation

BG source = photo-nuclear interactions of high energy muons, occurred upstream rock/concrete, that generate neutral hadrons

Background event rate

- Simulations for neutral hadron production and interactions
 - **Previous estimate:** FLUKA+QGSJET by Sebastian and Felix
 - **New estimate:** G4 (FTFP_BERT) by Xin. QGSP_BERT, QGSP_BIC were also checked.

	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 ($E_n > 10$ 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

0.83 BG events