

Neutrinos and beyond

with LHC's forward beam



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Supported by:

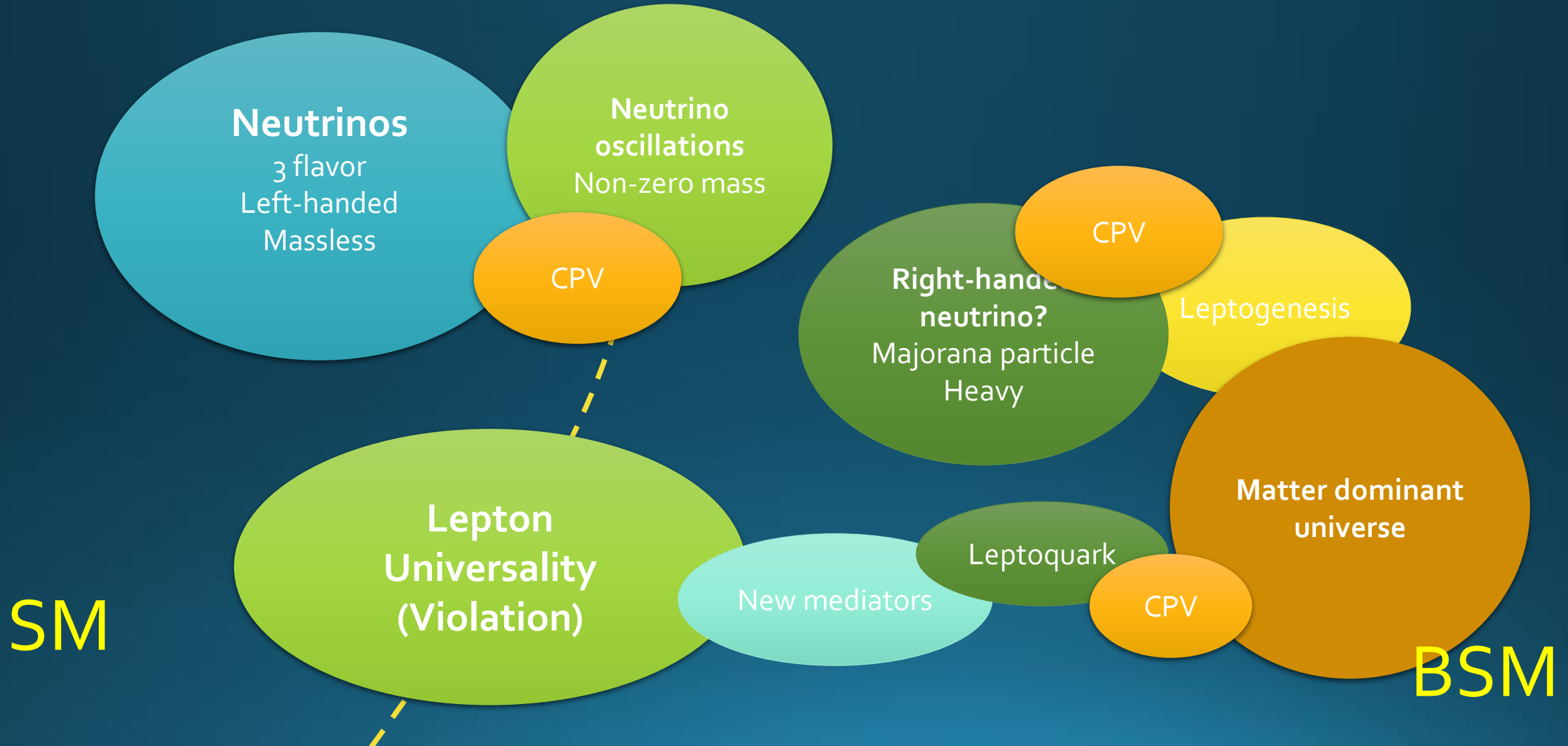


HEISING-SIMONS
FOUNDATION

SIMONS
FOUNDATION

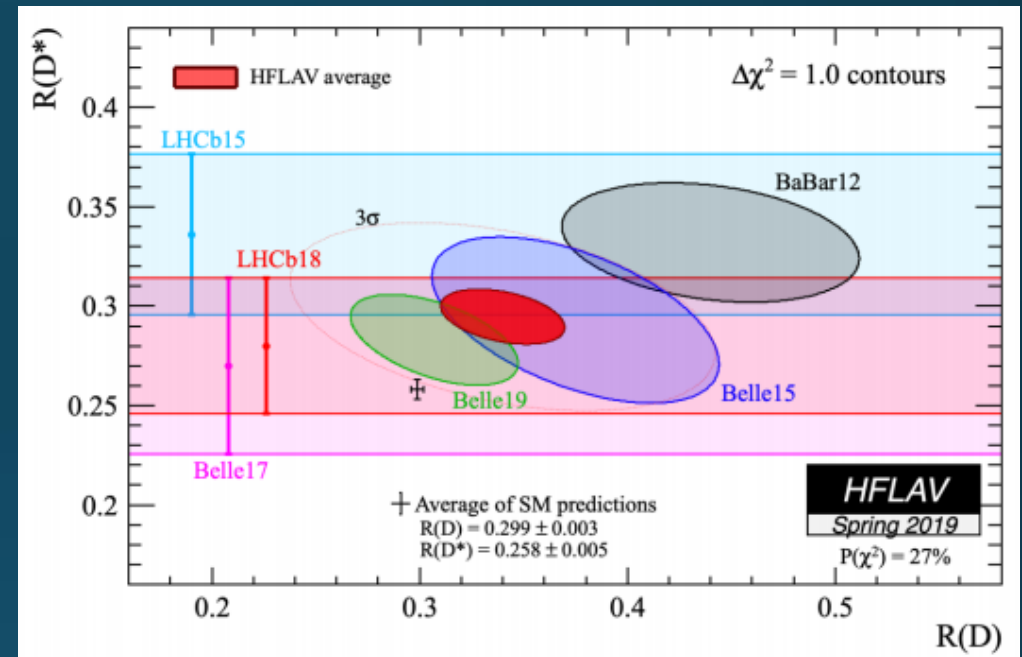
科研費
KAKENHI

Neutrino physics



“Flavor anomaly”

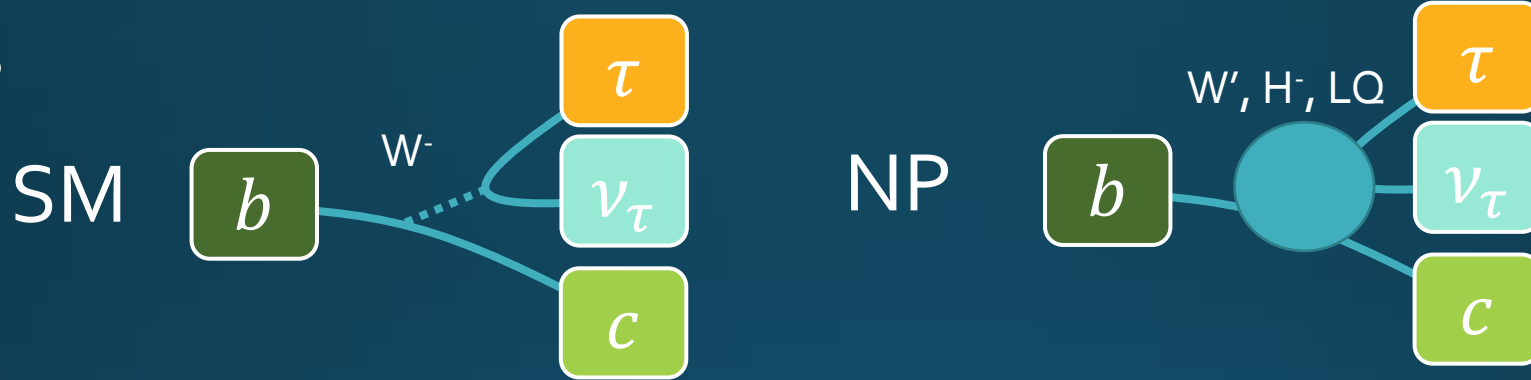
$$R(D) = \frac{\mathcal{B}(B \rightarrow \tau \nu_\tau D)}{\mathcal{B}(B \rightarrow \mu \nu_\mu D)}$$



Possible contribution from new physics in heavy flavors!?

New physics effect?

B decays



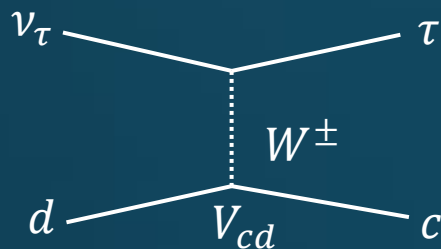
Neutrino CC beauty production



Why leptons are universal?
Why we have 3 generations?
Anything special for 3rd generation?

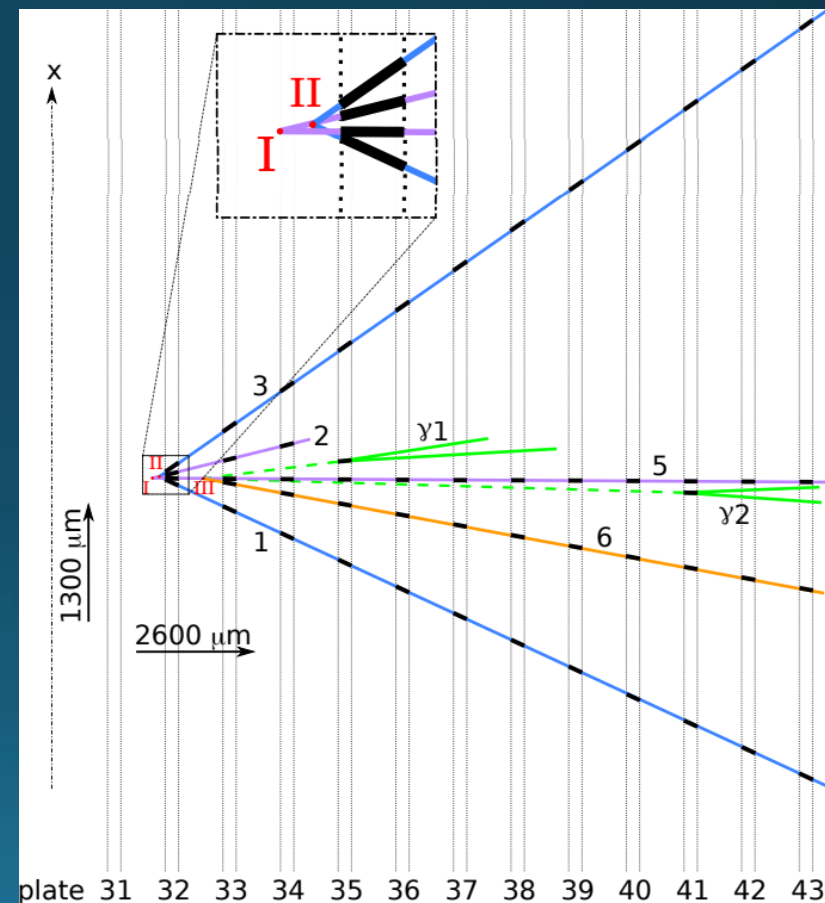
OPERA's ν_τ induced charm production event

SM process,
charm production
via mixing

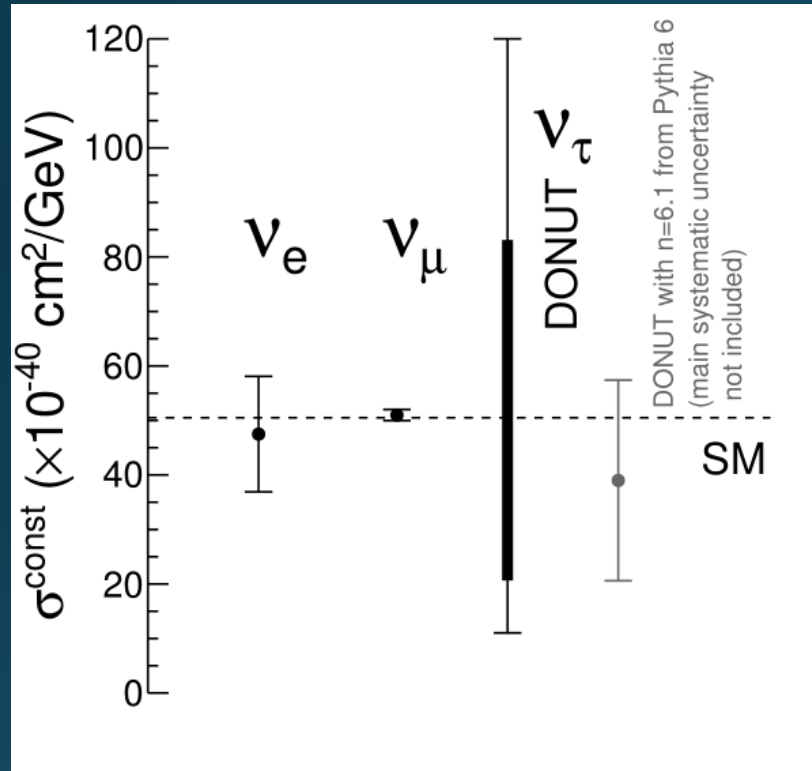


Well measured for ν_μ

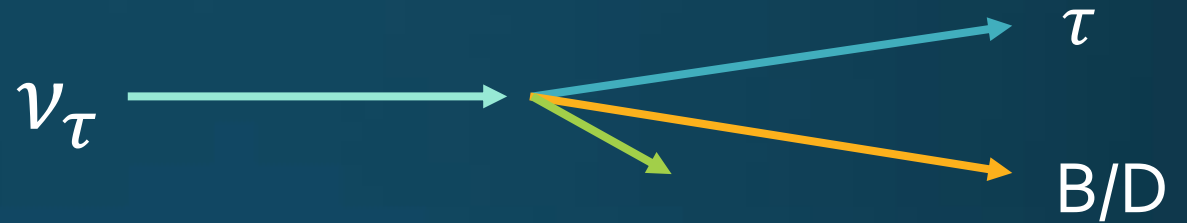
- 1 event was observed with surprise
- Expectation:
 - Signal 0.04
 - Background < 0.05
- Could also be a hint of new physics!?



Status of Lepton Universality testing in neutrino scattering



Poor constraint for ν_τ



High energy neutrinos ($E_\nu > 100 \text{ GeV}$) is required to access heavy flavor channels

→ Need high statistics and high energy beam experiment!

LHC as neutrino source?

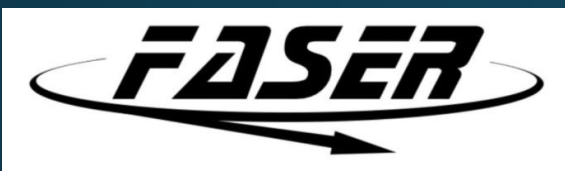
Large Hadron Collider

27 km circumference

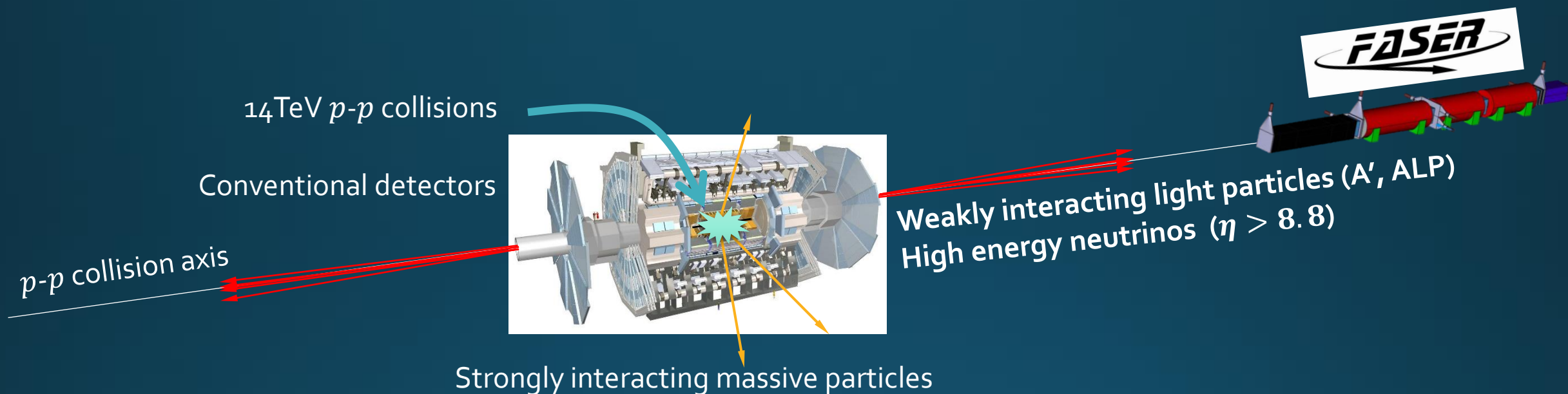
7 TeV + 7 TeV

Let's open new domain of research! **Neutrino**





experiment: LLPs and neutrinos



No neutrino has ever been detected at the LHC, nor at any colliders

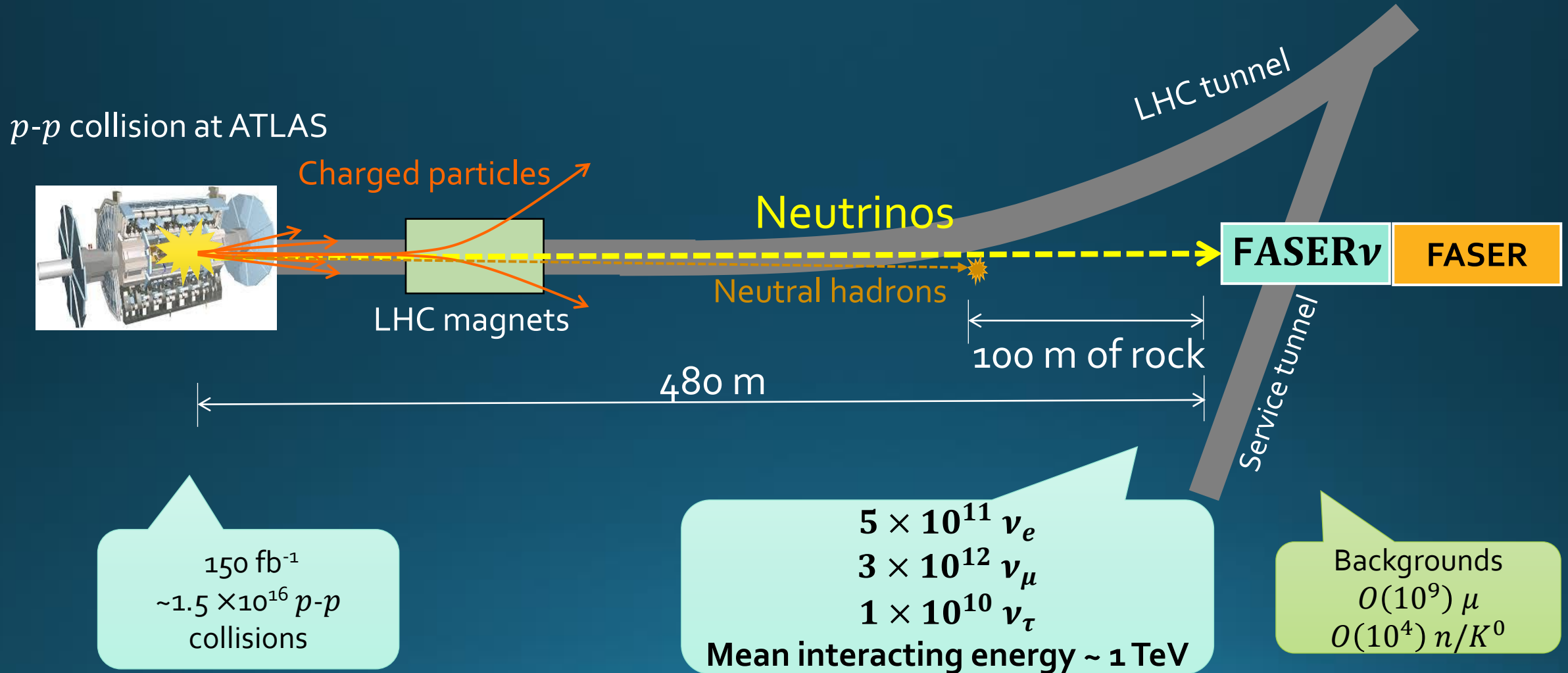
FASER (new particle searches) was approved by CERN in Mar 2019 [arXiv:1812.09139](https://arxiv.org/abs/1812.09139)

FASER ν (neutrino program) was approved in Dec 2019 [Eur. Phys. J. C \(2020\) 80: 61](https://arxiv.org/abs/1912.01407)

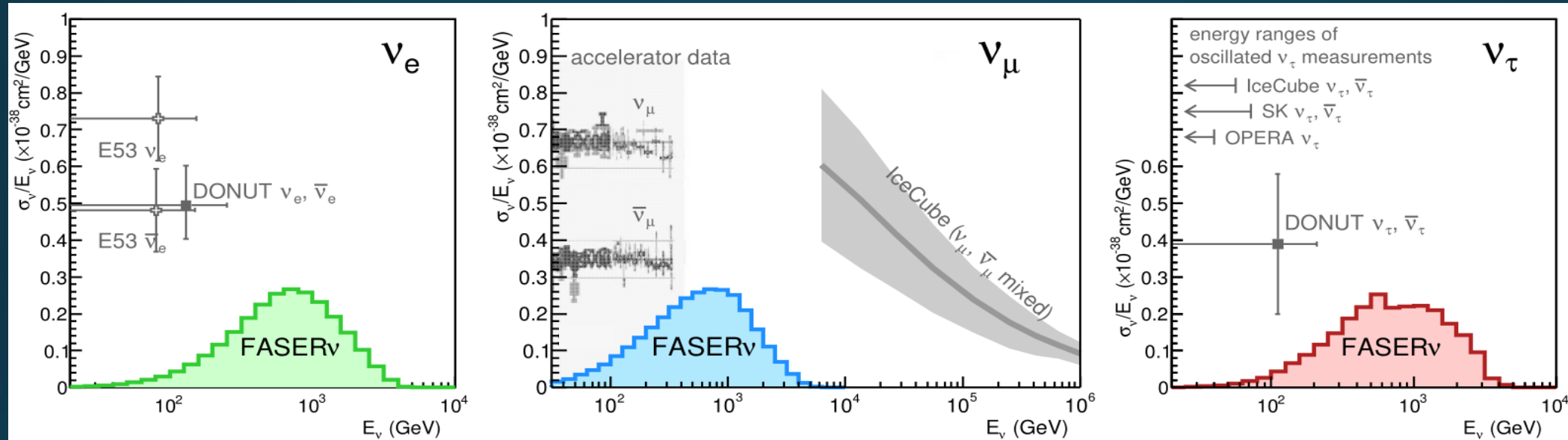
Data taking is starting in 2022!

More $\rightarrow$ FASER web page: <https://faser.web.cern.ch/>

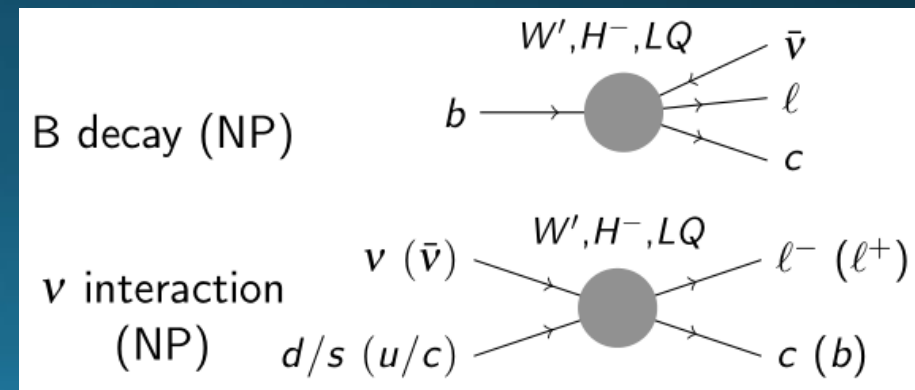
LHC's "neutrino beamline"



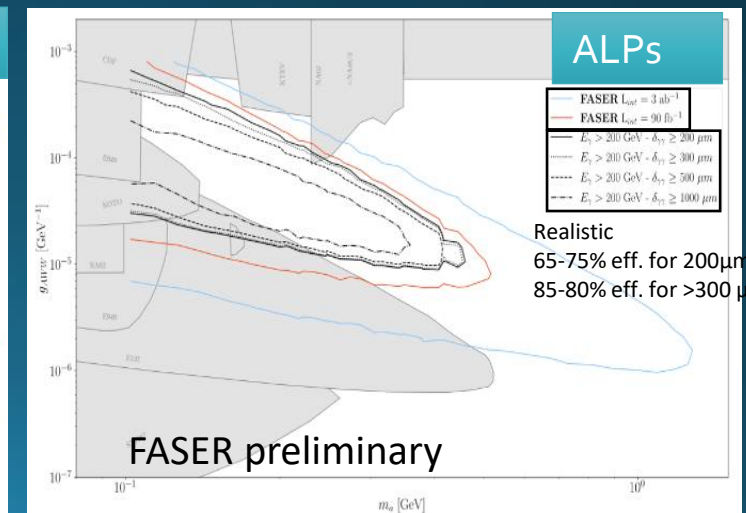
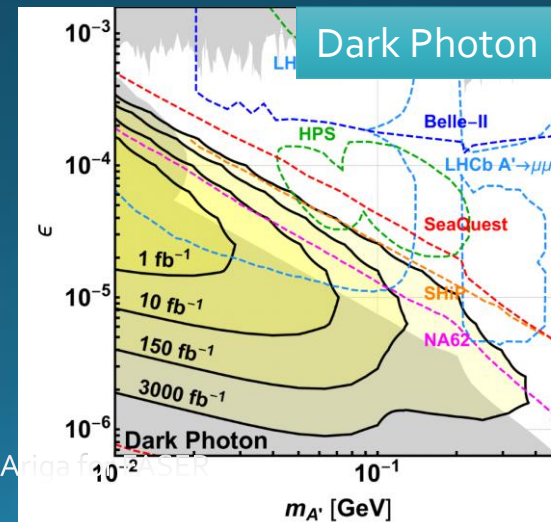
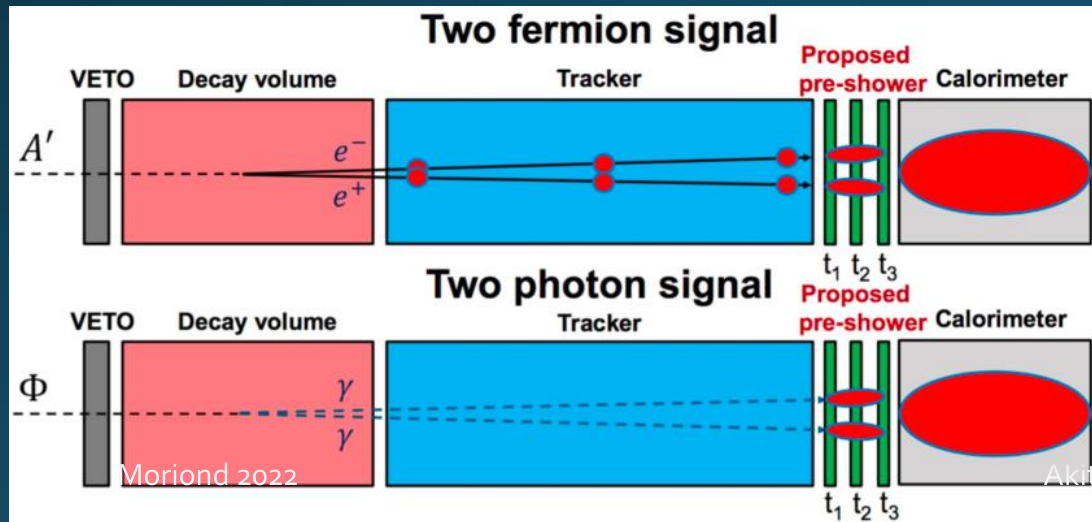
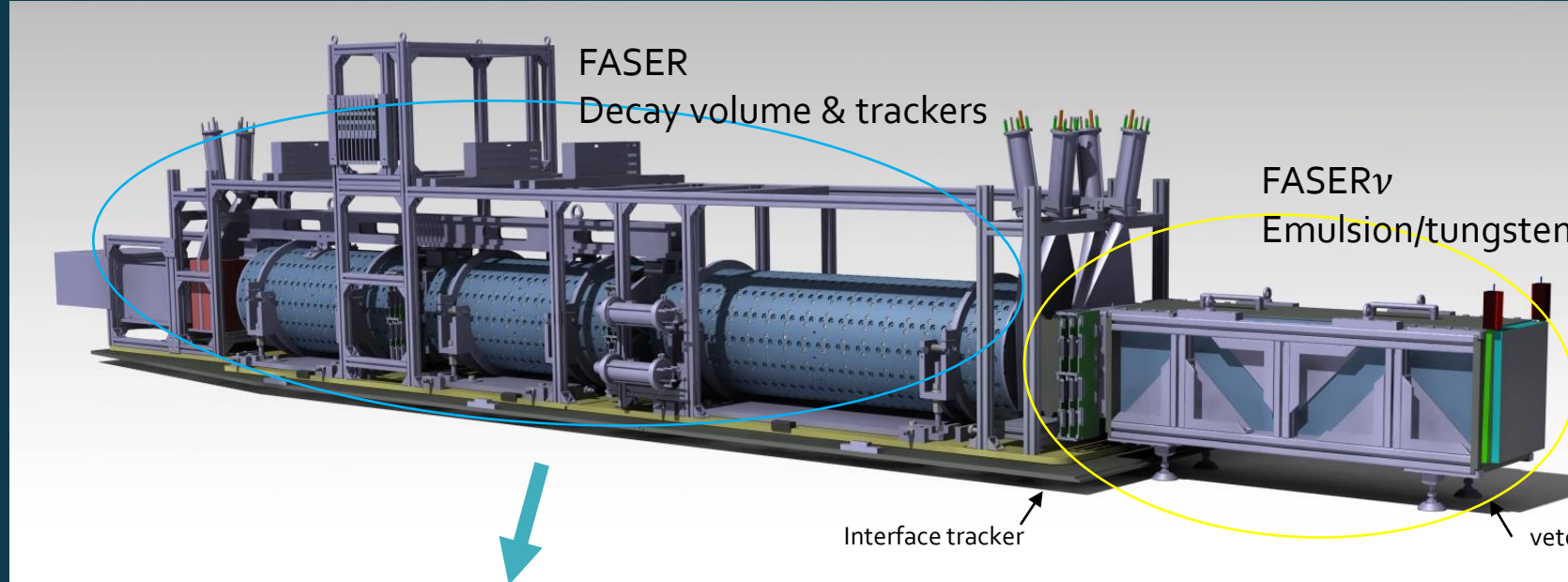
Motivations for high energy neutrinos



- Behavior of neutrinos at TeV energies?
- Lepton Universality in neutrino scattering?
 - ν_τ and heavy quarks $\rightarrow$ Flavor anomaly e.g. R_D
- Any new physics effects at high energy?
- **$\rightarrow$ High energy neutrinos from the LHC!**

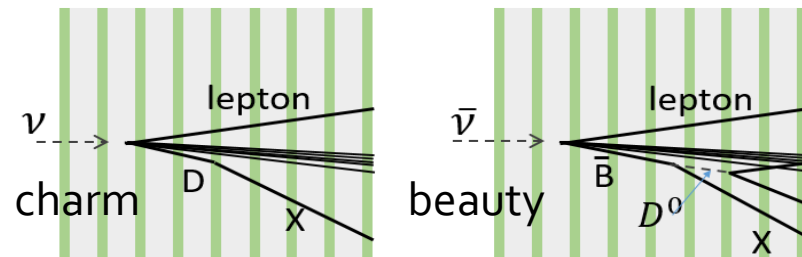
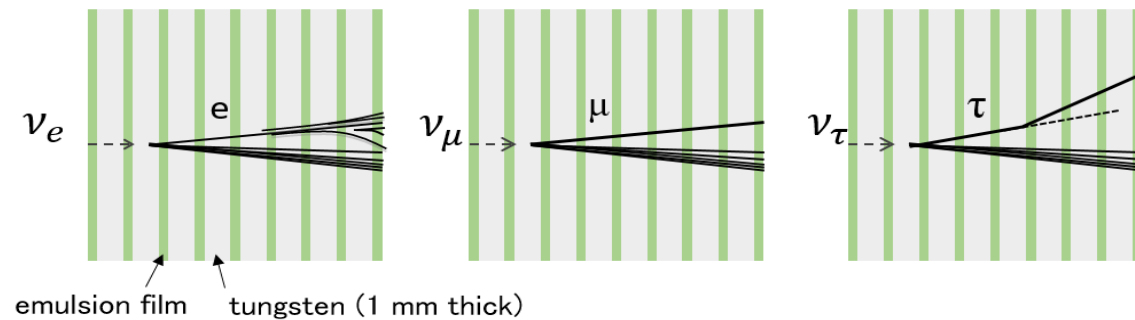
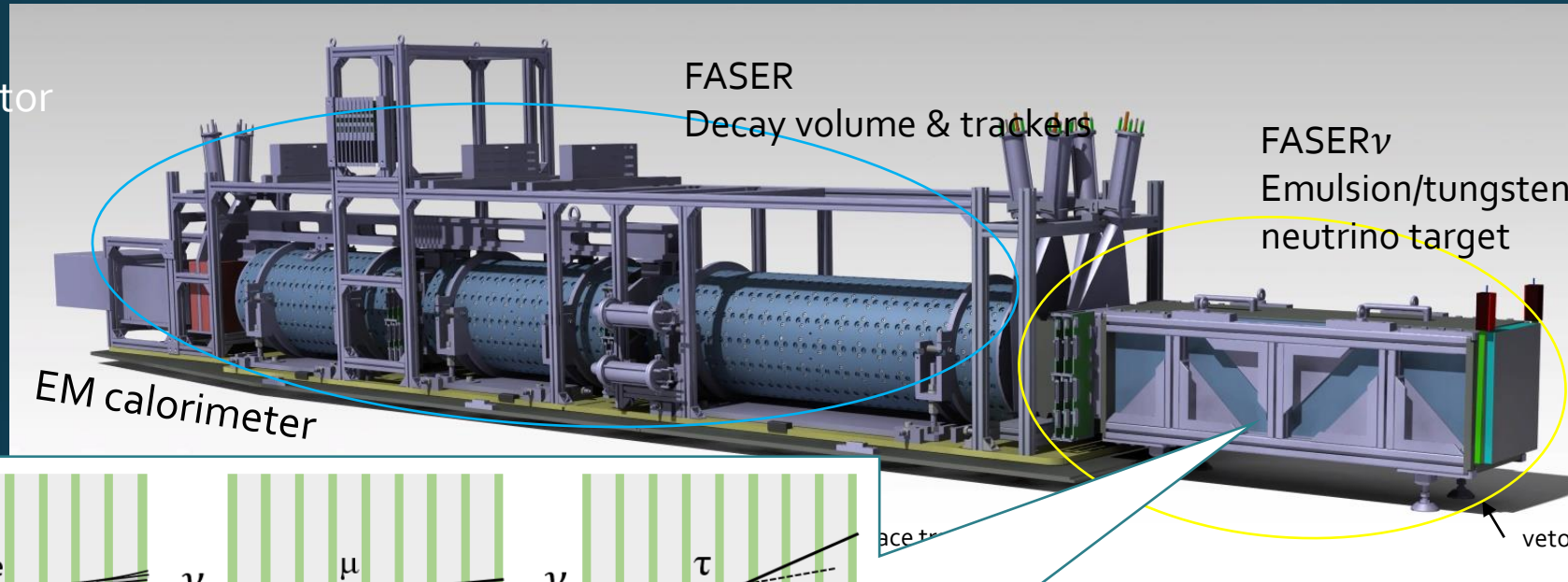


FASER/FASER ν detector



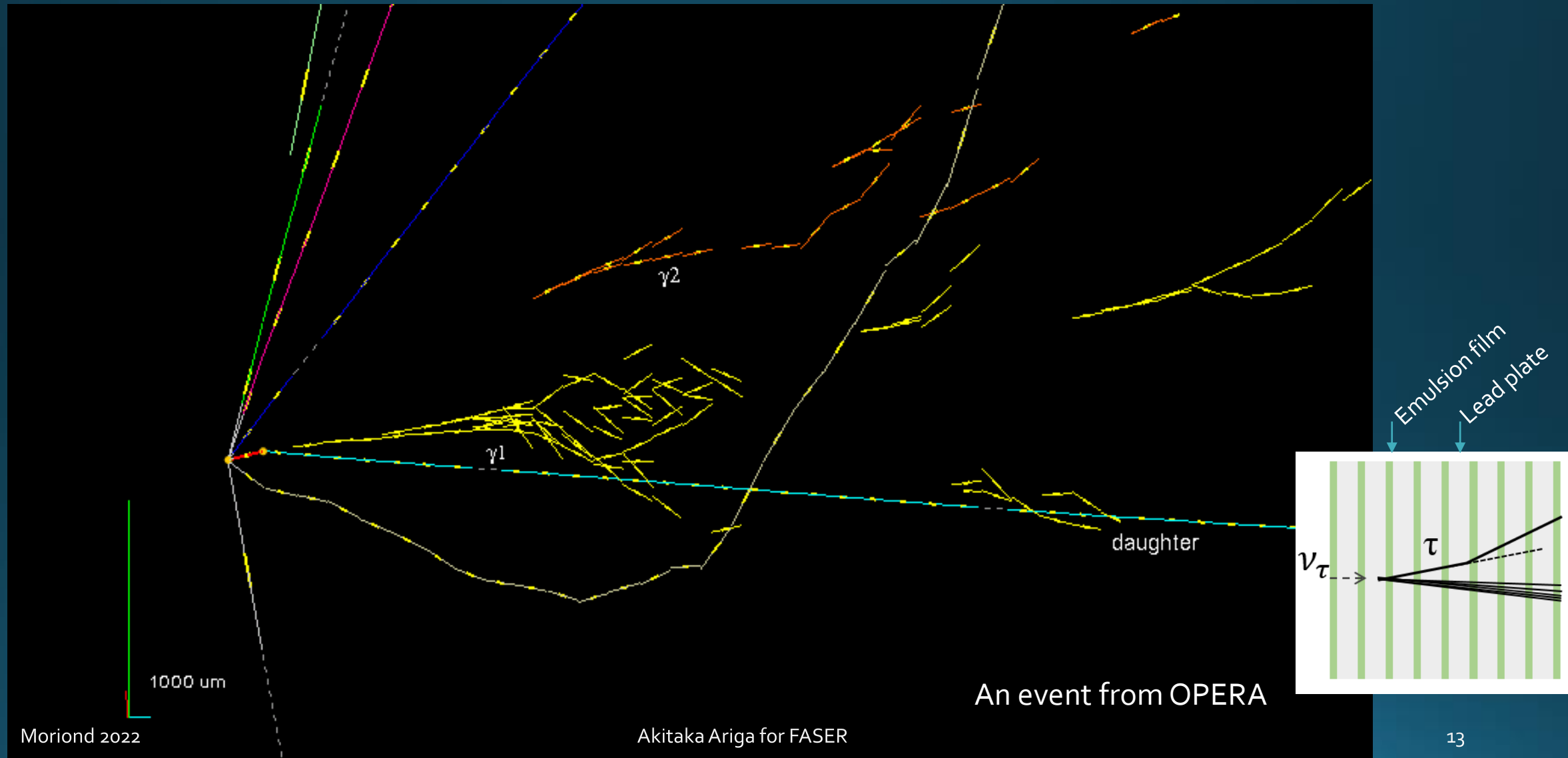
FASER+FASER ν detector in Run3 (2022-2025)

5m long detector

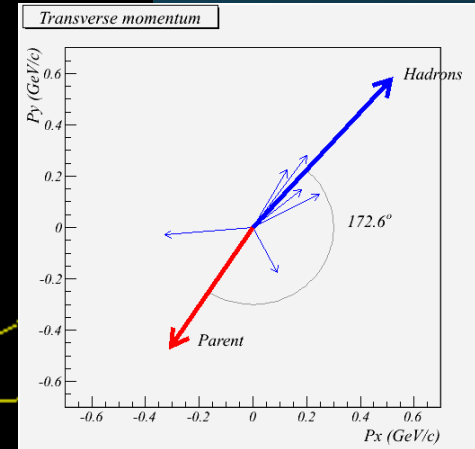
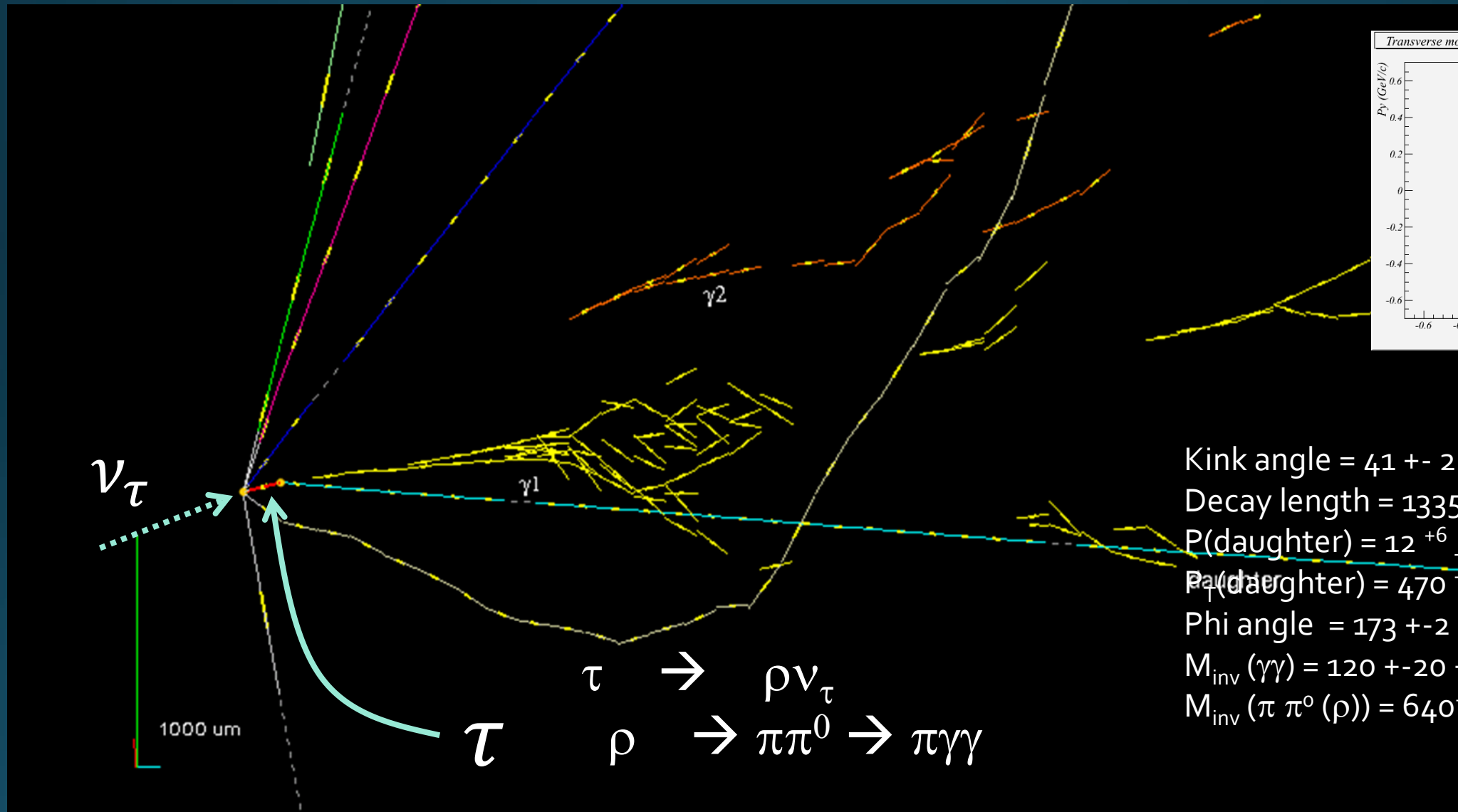


- Emulsion films = trackers with sub-micron spatial resolution, $\sigma_{intrinsic} \simeq 50 \text{ nm}$, $\sigma_{practical} \simeq 0.4 \mu\text{m}$
- 770 1-mm-thick tungsten target and emulsion films
- $25 \times 30 \text{ cm}^2$, 1.1 m, 1.1 tons ($8 \lambda_{int}$, $220 X_0$)
- Sensitive to 3 flavor neutrinos
- Muon ID in track length in tungsten
- Replace emulsions 3 times a year

Emulsion-based neutrino detector

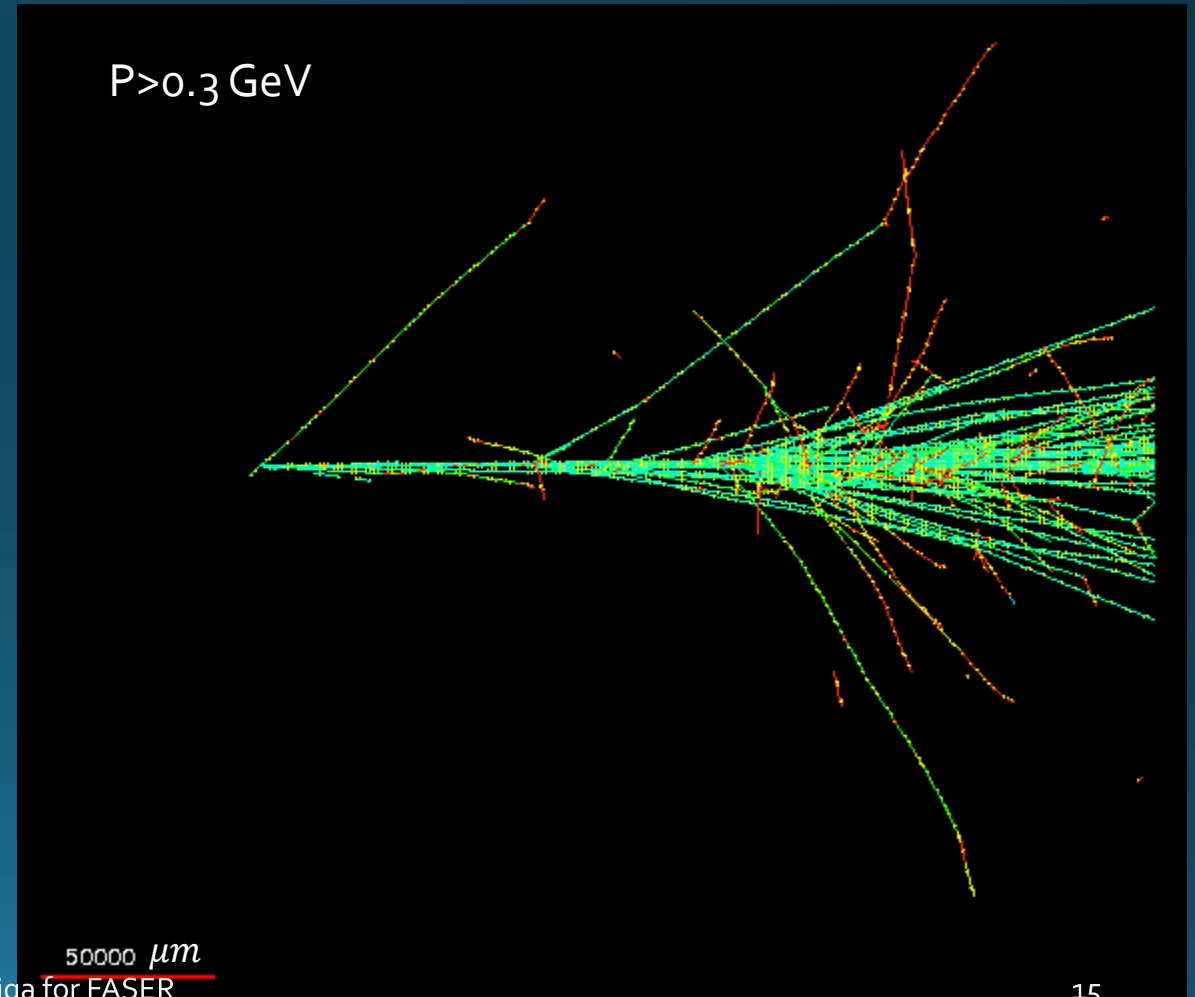
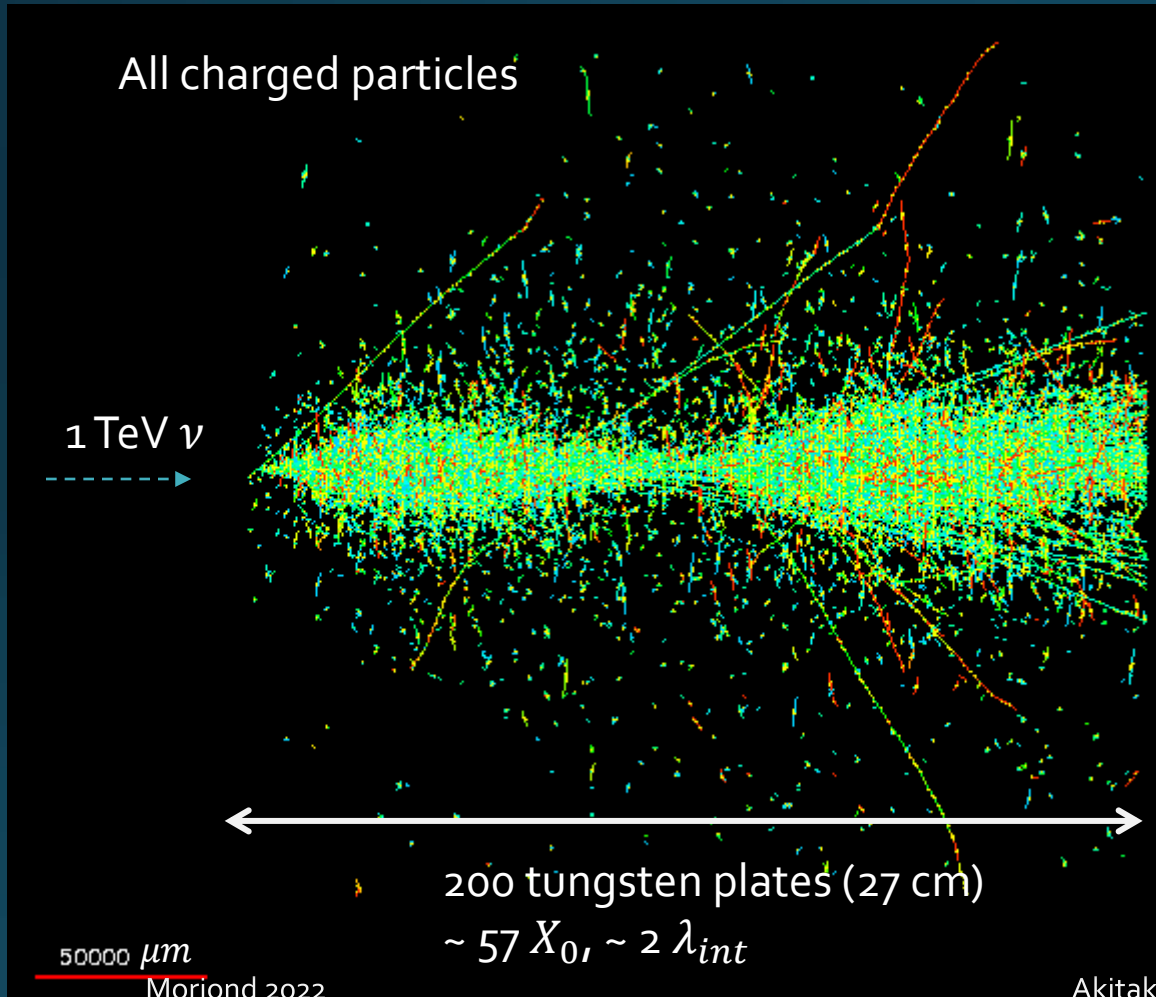


Emulsion-based neutrino detector

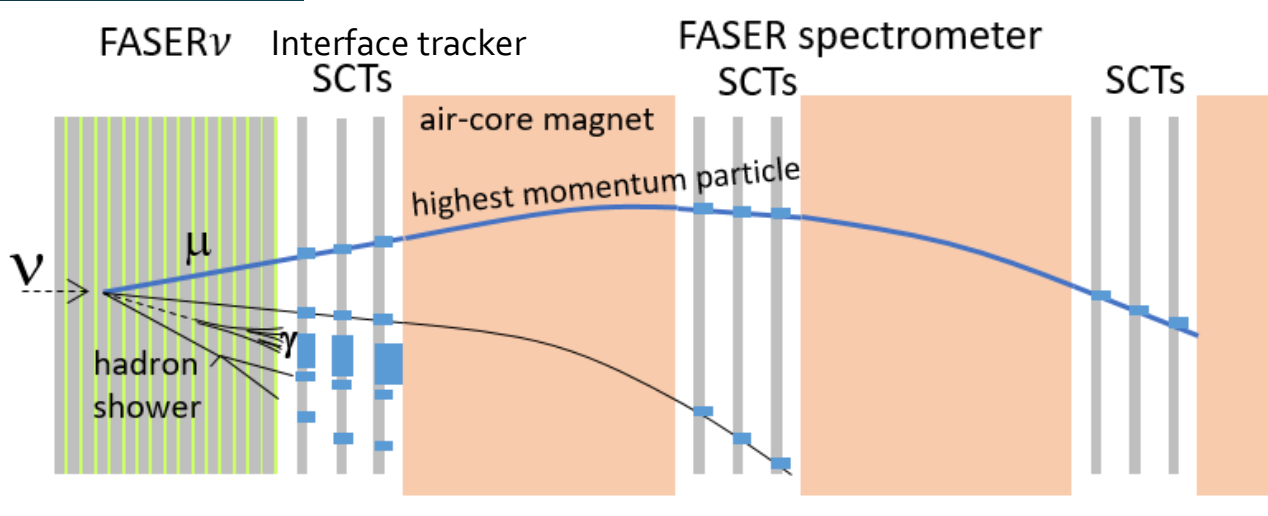
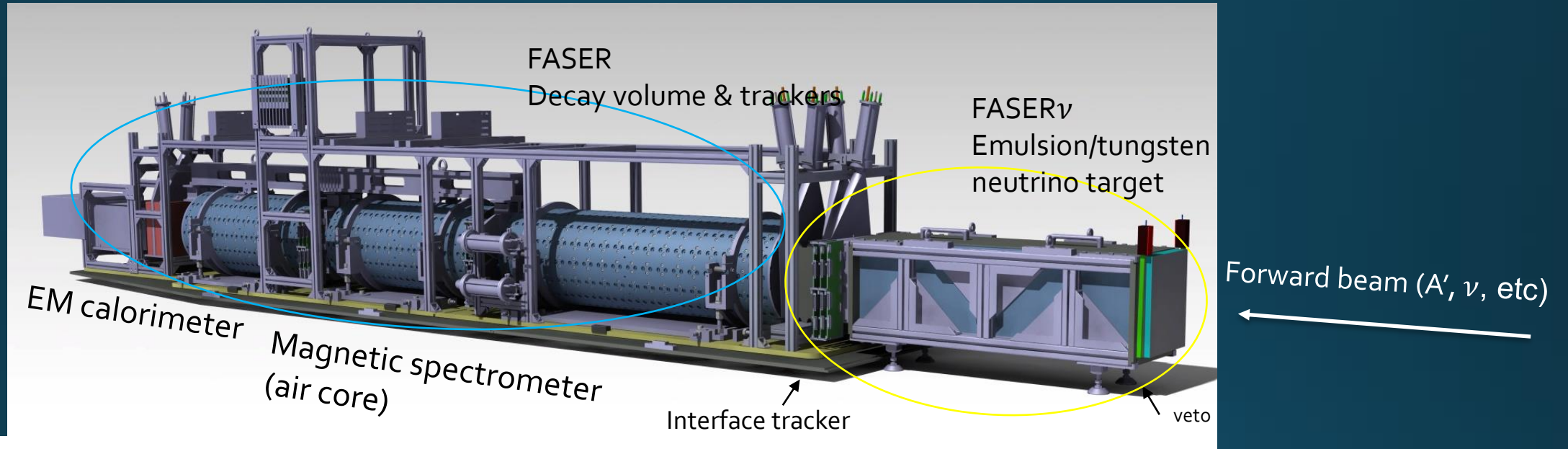


Kink angle = 41 ± 2 mrad
 Decay length = 1335 ± 35 μm
 $P(\text{daughter}) = 12^{+6}_{-3}$ GeV
 $P(\text{daughter}) = 470^{+230}_{-120}$ MeV
 Phi angle = 173 ± 2 deg
 $M_{\text{inv}}(\gamma\gamma) = 120 \pm 20 \pm 35$ MeV
 $M_{\text{inv}}(\pi\pi^0(\rho)) = 640^{+125}_{-80} {}^{+100}_{-90}$ MeV

Simulated 1 TeV ν_μ CC interaction



FASER+FASER ν detector in Run3 (2022-2025)



- Global reconstruction with FASER spectrometer
→ muon charge identification
→ $\nu_\mu/\bar{\nu}_\mu$ separation
- Improve energy resolution

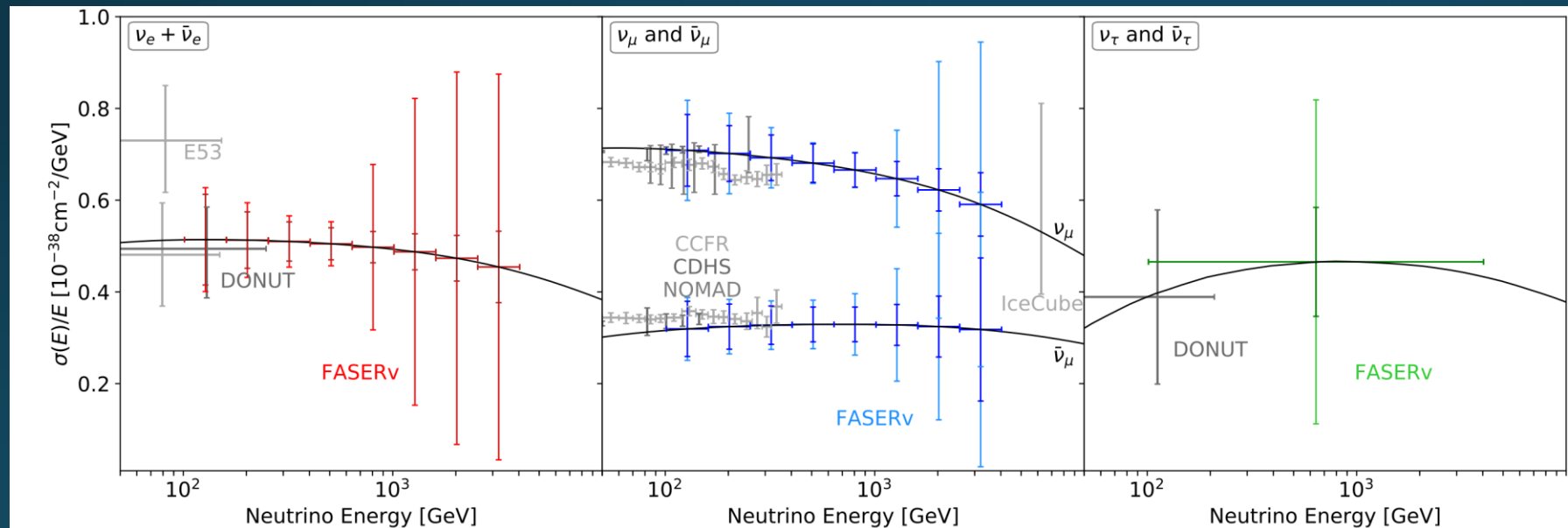
Neutrino cross sections

arXiv:[2105.08270](https://arxiv.org/abs/2105.08270)

- Three flavors neutrino cross section measurements at unexplored energies
- ~10,000 ν interactions expected in LHC Run 3
- NC interaction studies

Generators		FASER ν		
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
EPOS LHC	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}

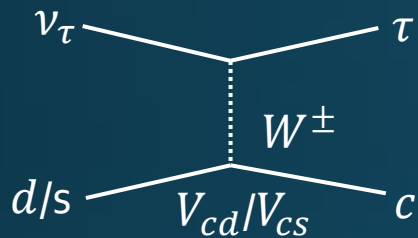


Projected cross section sensitivities

Heavy-flavor-associated channels

- **Measure charm** production channels

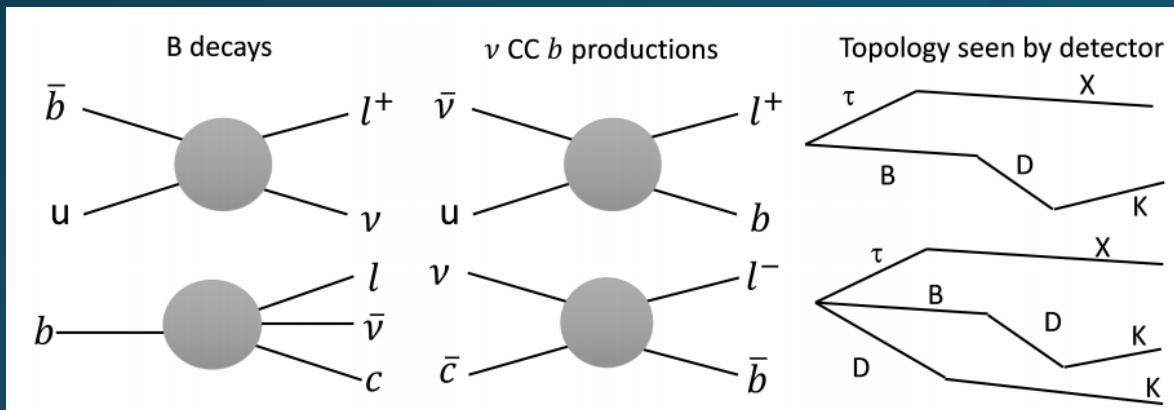
- Large rate $\sim 15\%$ ν CC events, $\mathcal{O}(1000)$ events
- First measurement of ν_e induced charm prod.



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

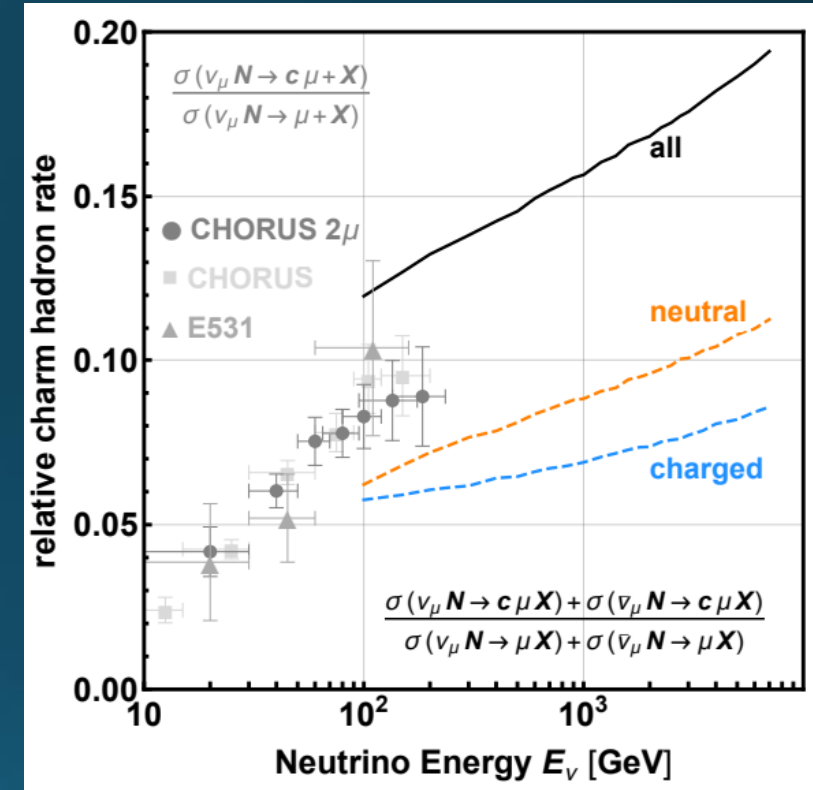
- **Search for beauty** production channels

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



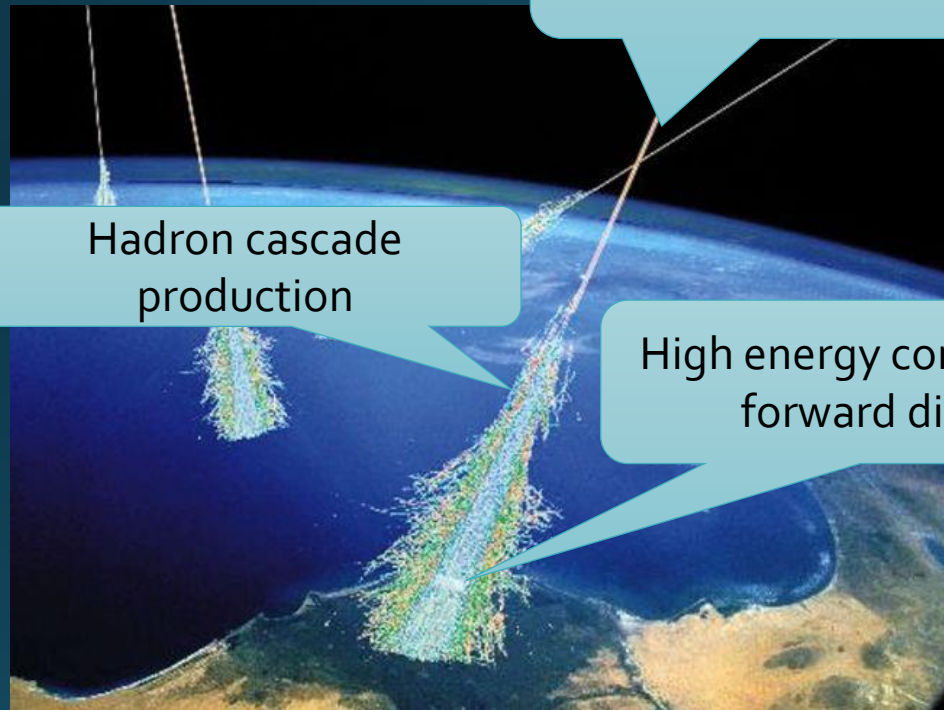
$$\bar{\nu} N \rightarrow \ell \bar{B} X$$

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



[Eur. Phys. J. C \(2020\) 80: 61](#)

Relation to cosmic rays, atmospheric leptons



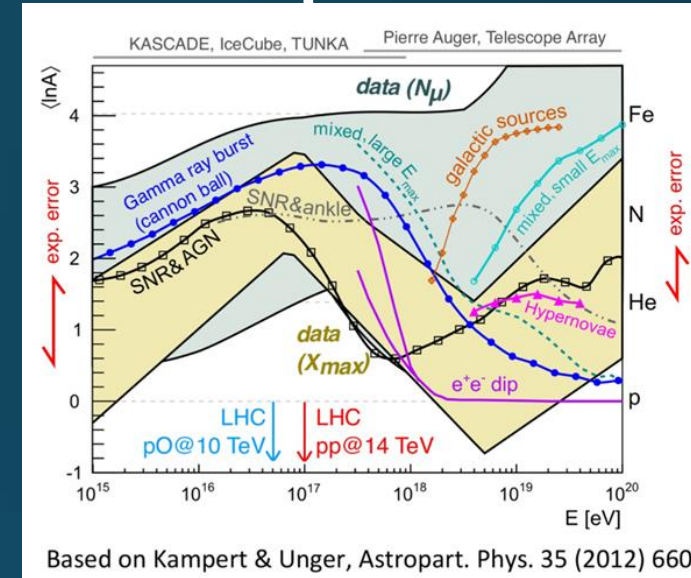
Primary cosmic ray from extrasolar source

Hadron cascade production

High energy components in forward direction

14 TeV collision = 100 PeV interaction in fixed target mode

Understanding of “Forward particle production with flavor sensitivity” is the key for future cosmic ray experiments



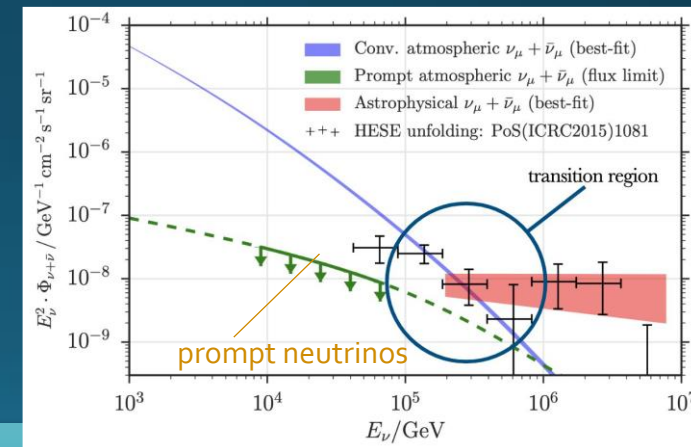
Muon excess

π/K

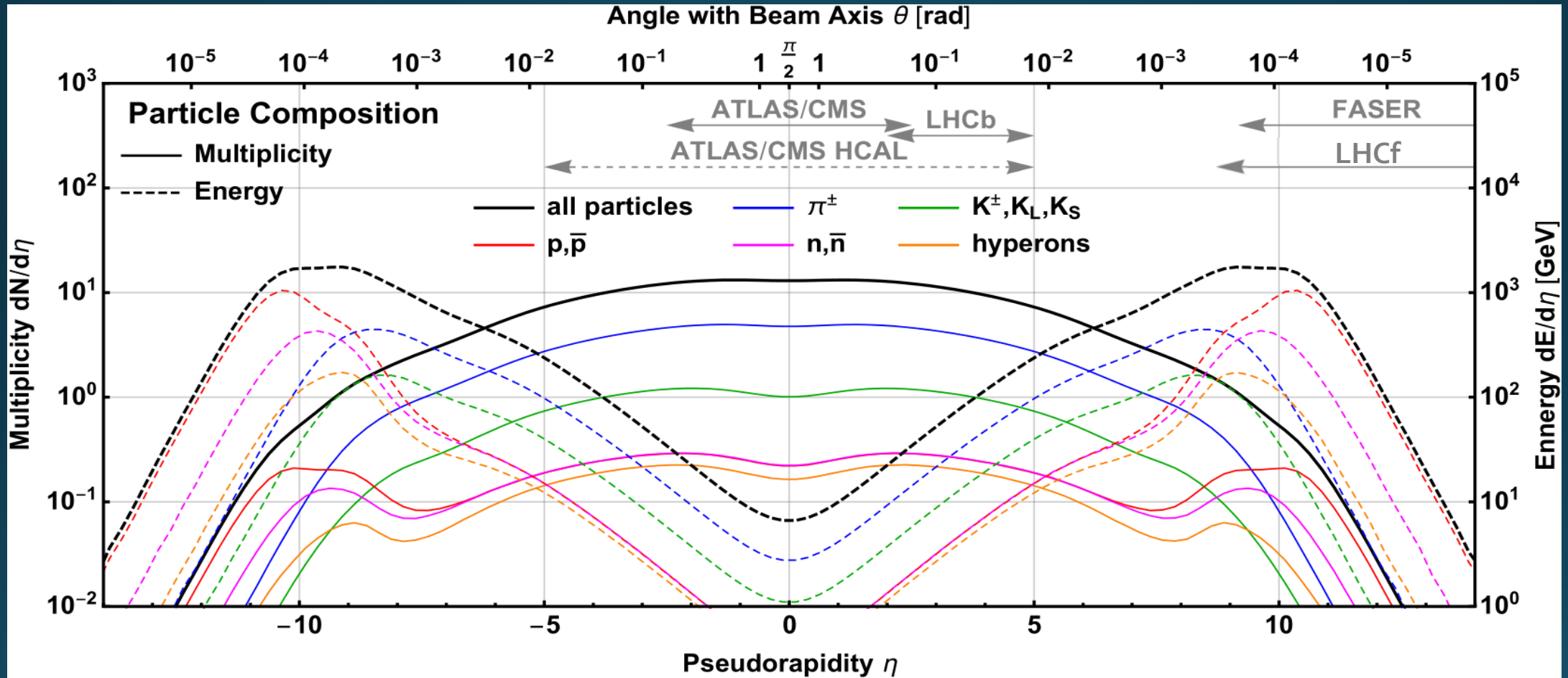
Prompt neutrinos

IceCube Collaboration, Astrophys. J. 833 (2016)

Charm



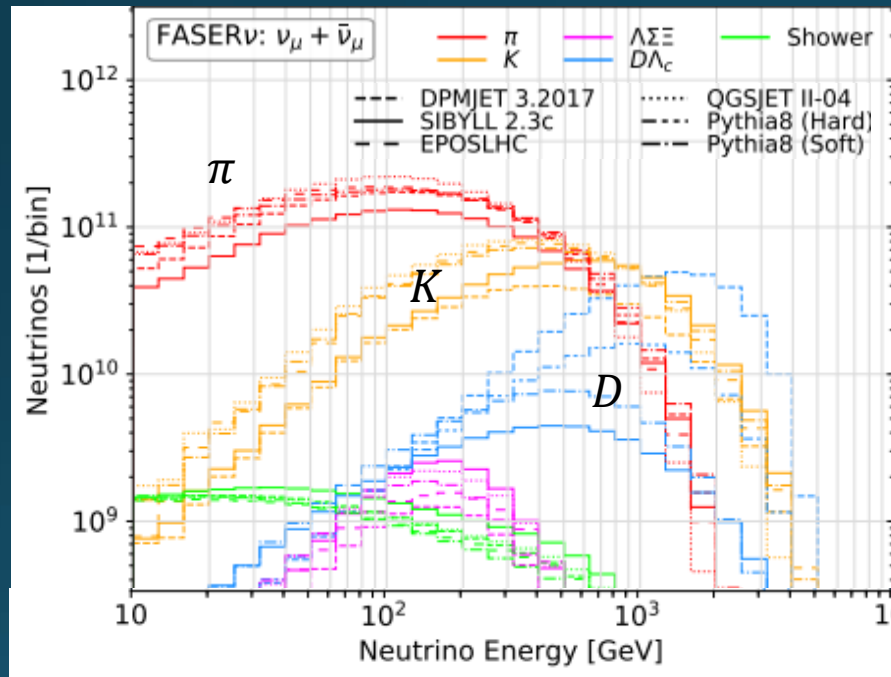
Neutrinos = proxy of forward hadron production



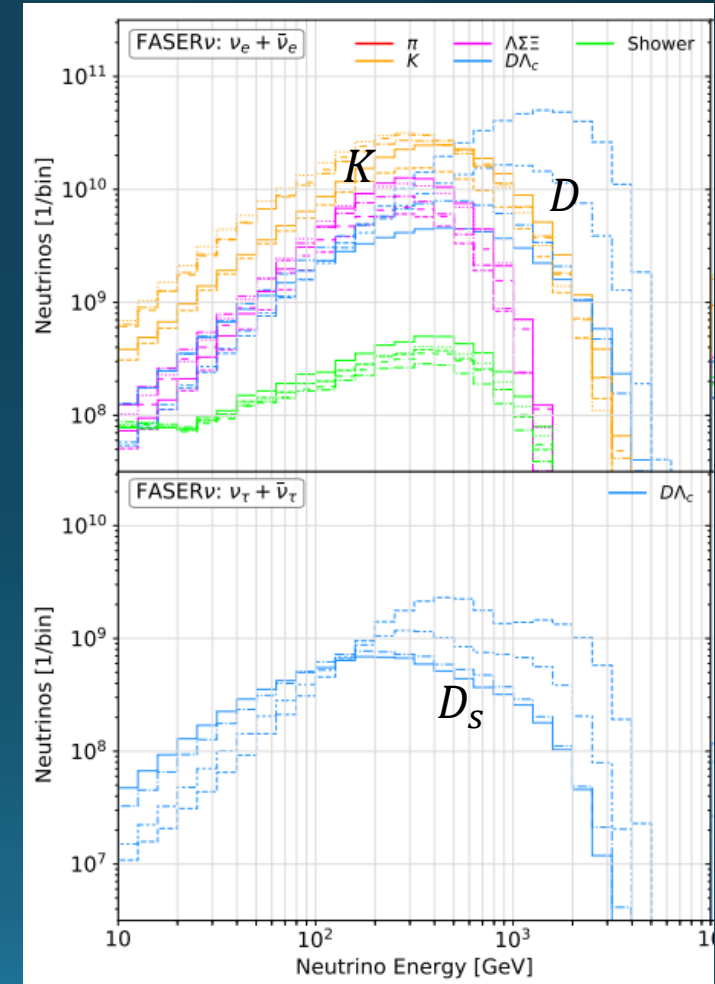
Neutrinos = proxy of forward hadron production

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

ν_μ



ν_e

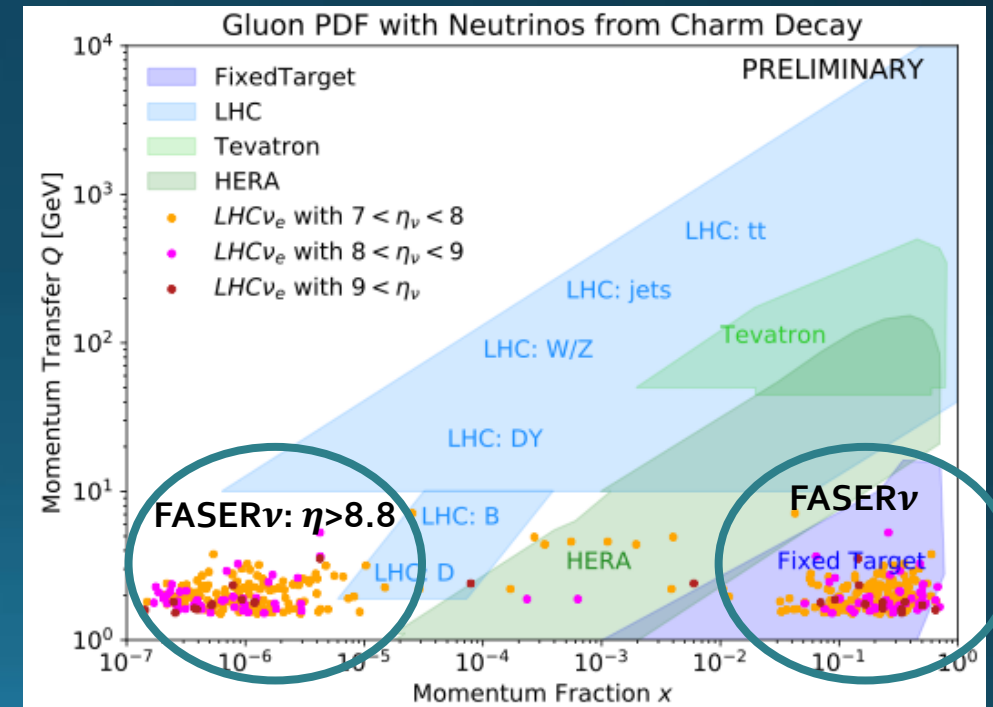
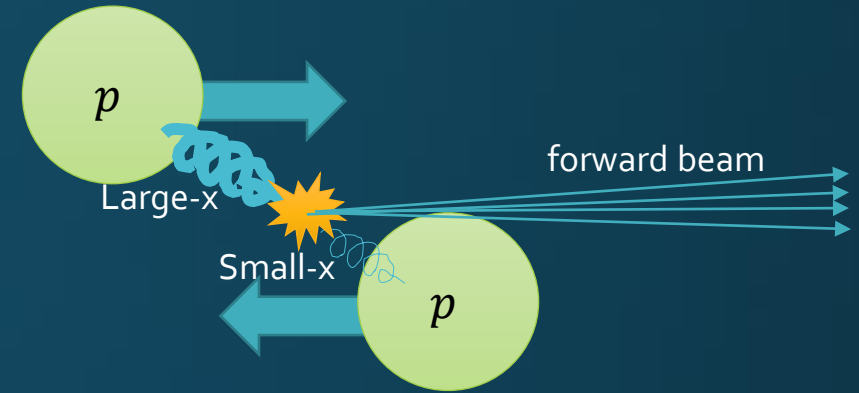


ν_τ

- FASER ν provides important inputs to validate/improve generators $\rightarrow$ Muon excess, prompt neutrinos

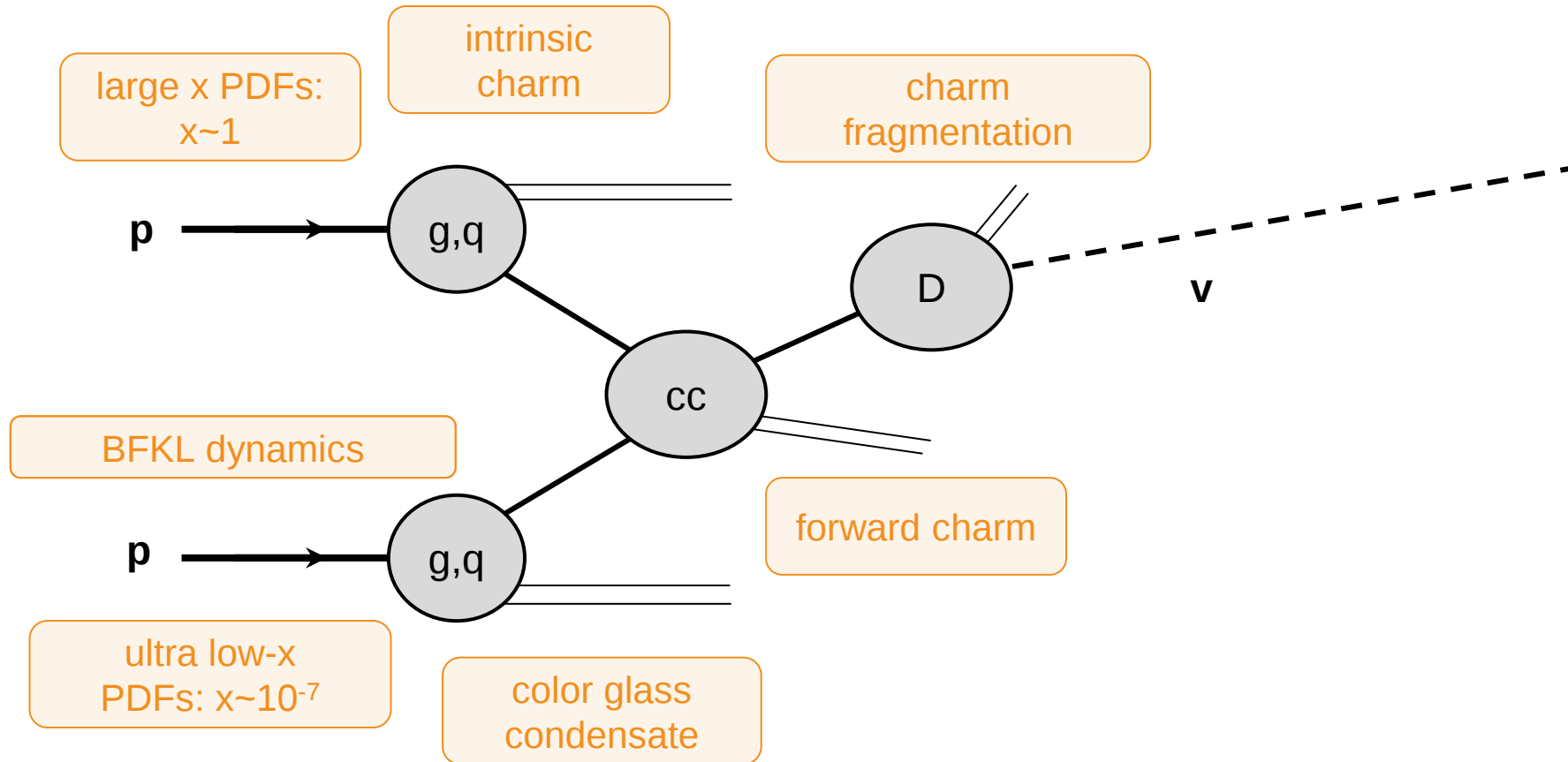
Further insights on QCD

- Asymmetric gluon-gluon interaction, **small- x $\times$ 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

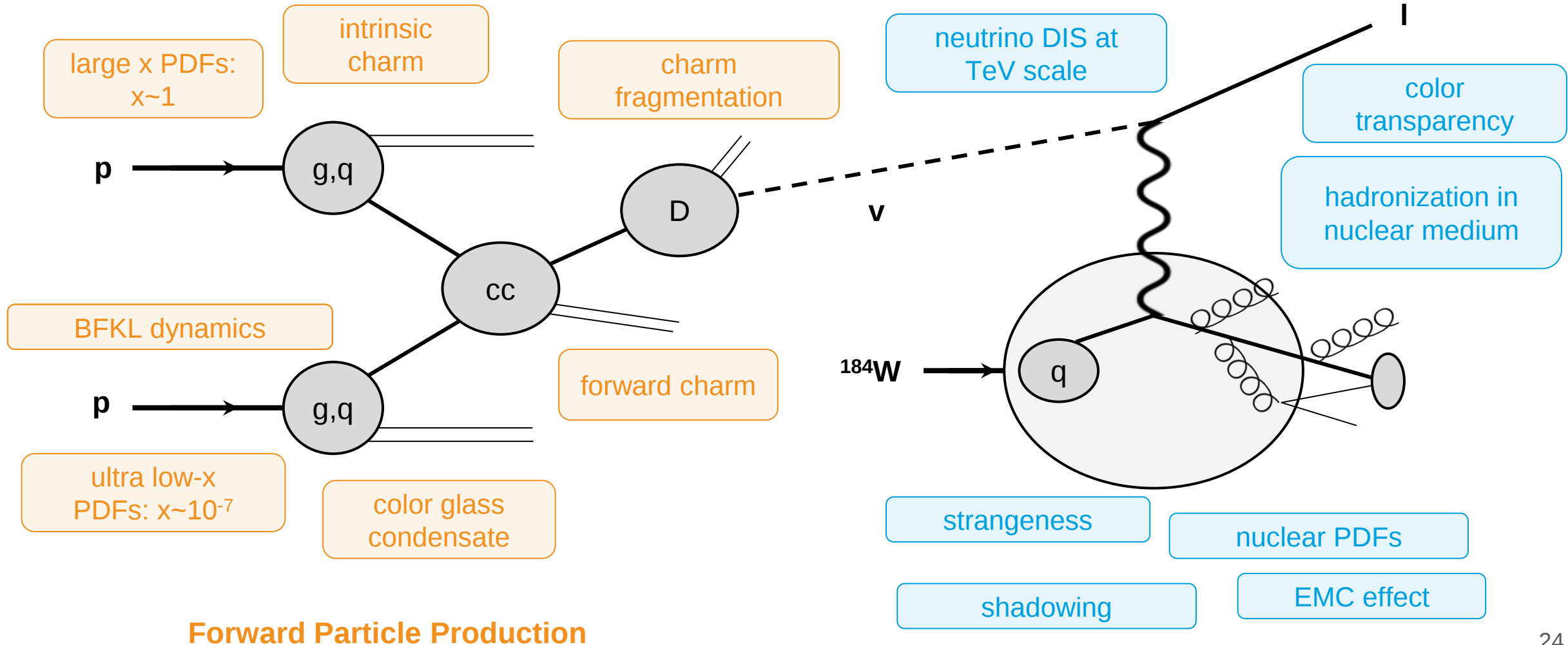
QCD using LHC Neutrinos



Forward Particle Production

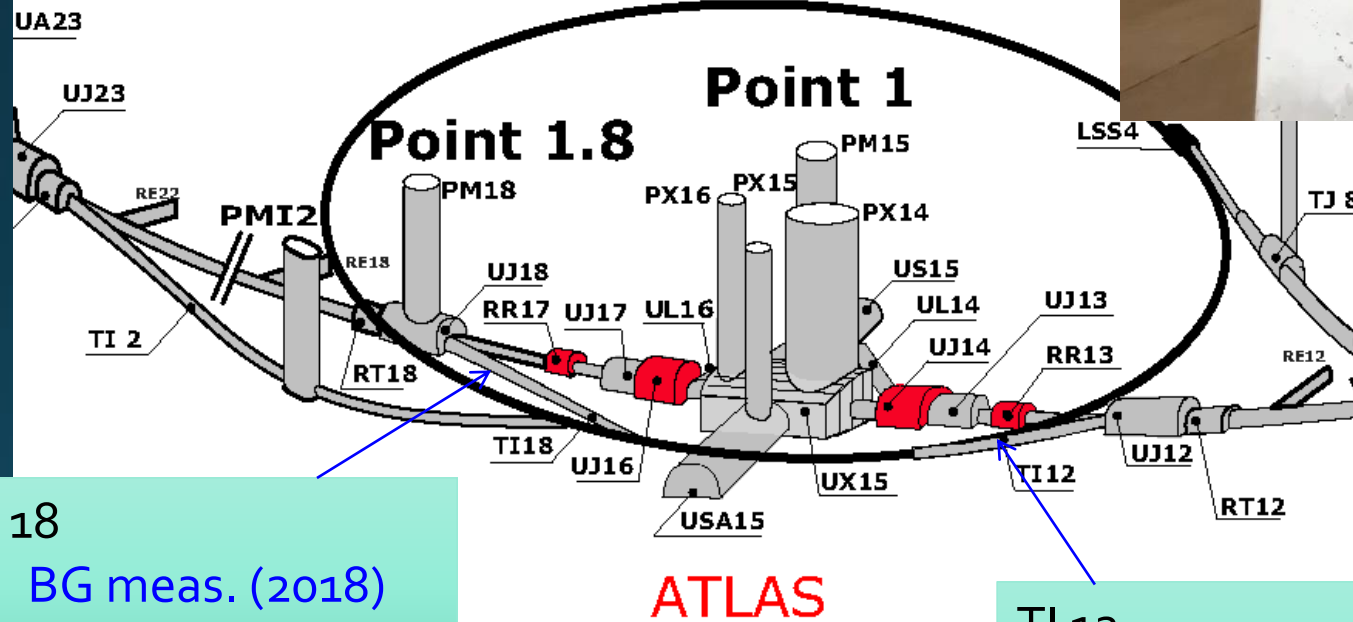
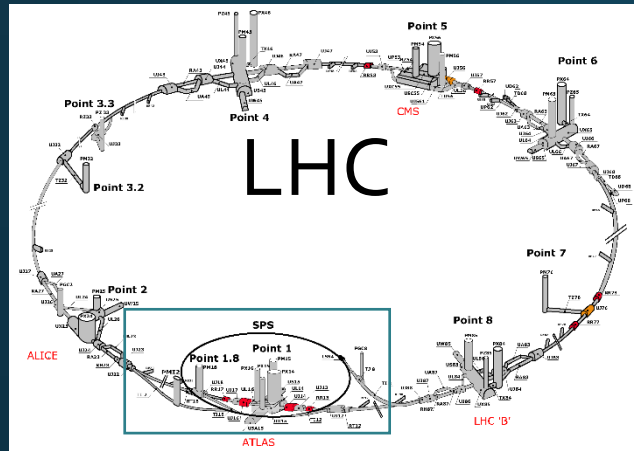
QCD using LHC Neutrinos

TeV Energy Neutrino Interaction



Results from 2018 run

FASER sites



TI 18

- BG meas. (2018)
- Pilot run (2018)

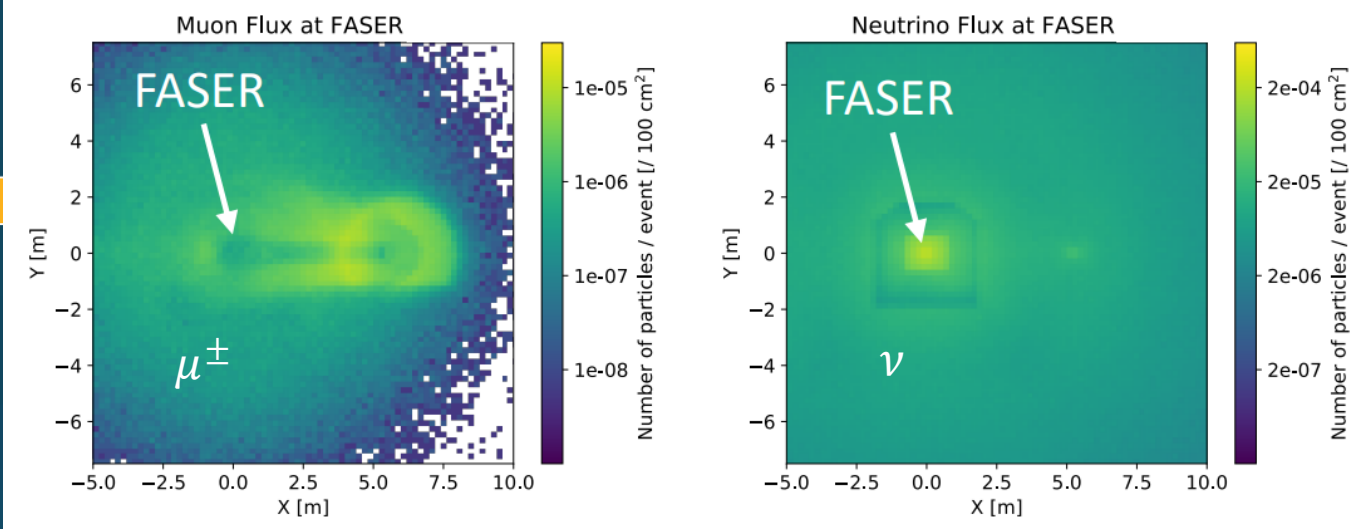
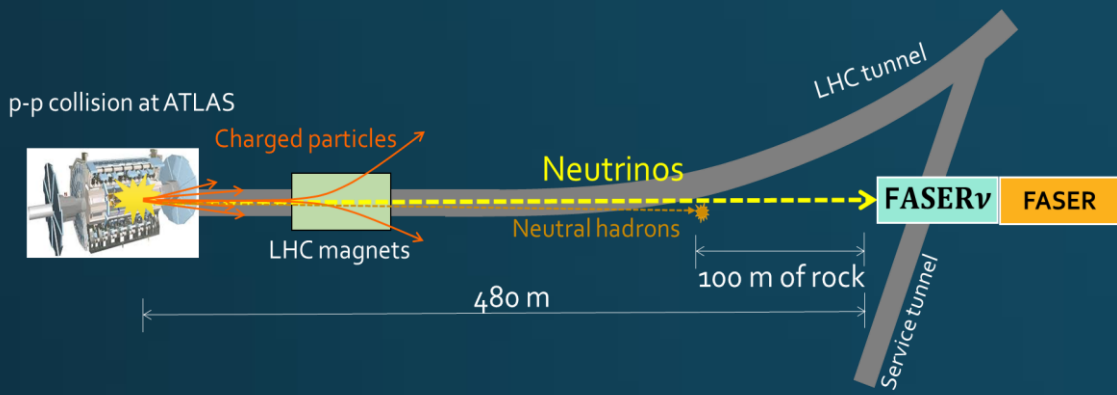
TI 12

- BG meas. (2018)
- Physics run (2022-)

BG measurements, pilot run in 2018

Particle fluence at the site

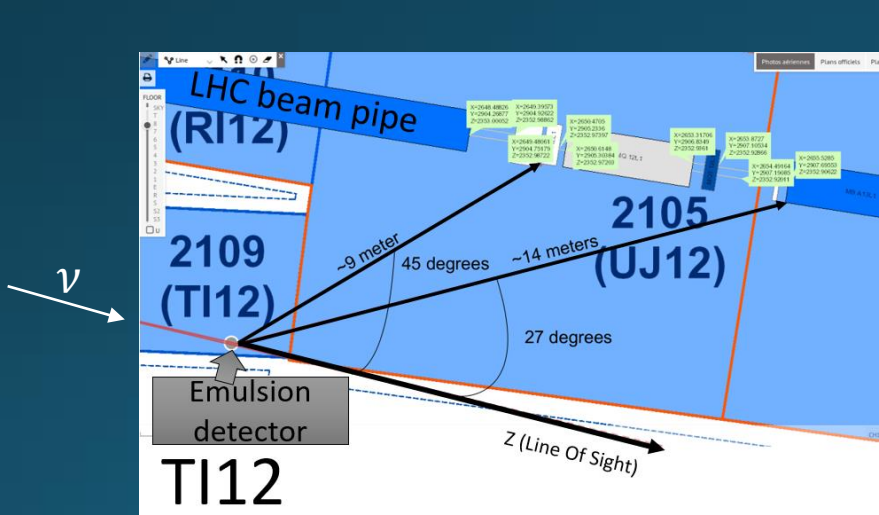
BDSim result for Tl12, Lefebvre ICHEP2020



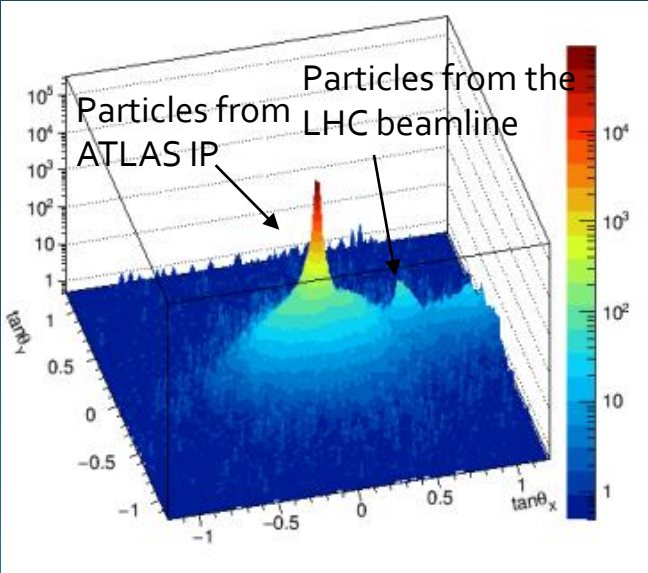
- *In-situ* measurements in 2018



Moriond 2022



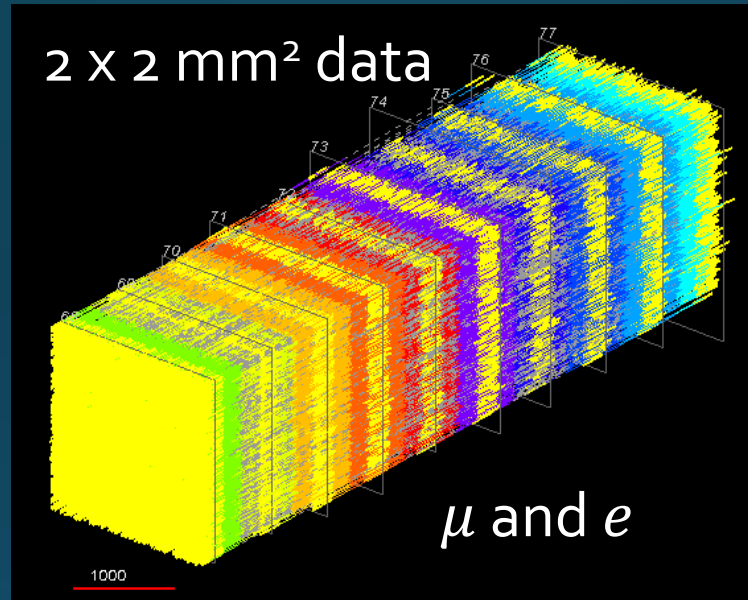
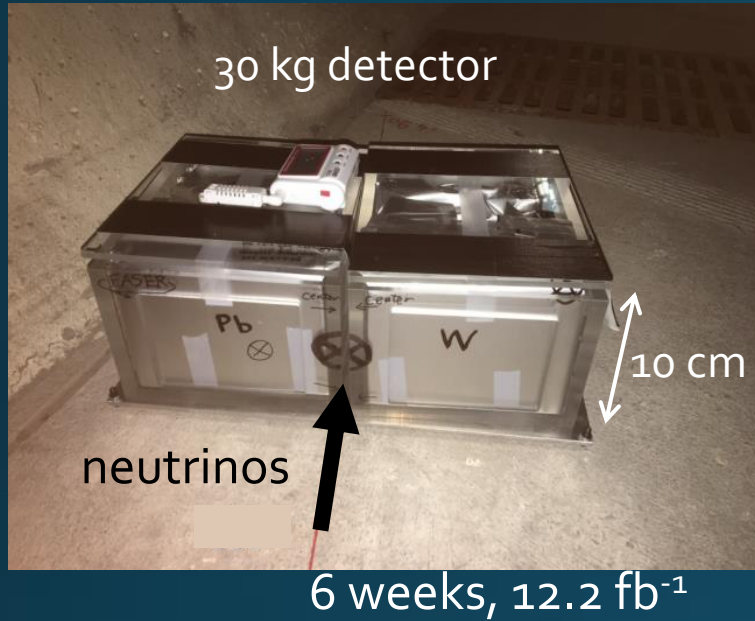
Akitaka Ariga for FASER



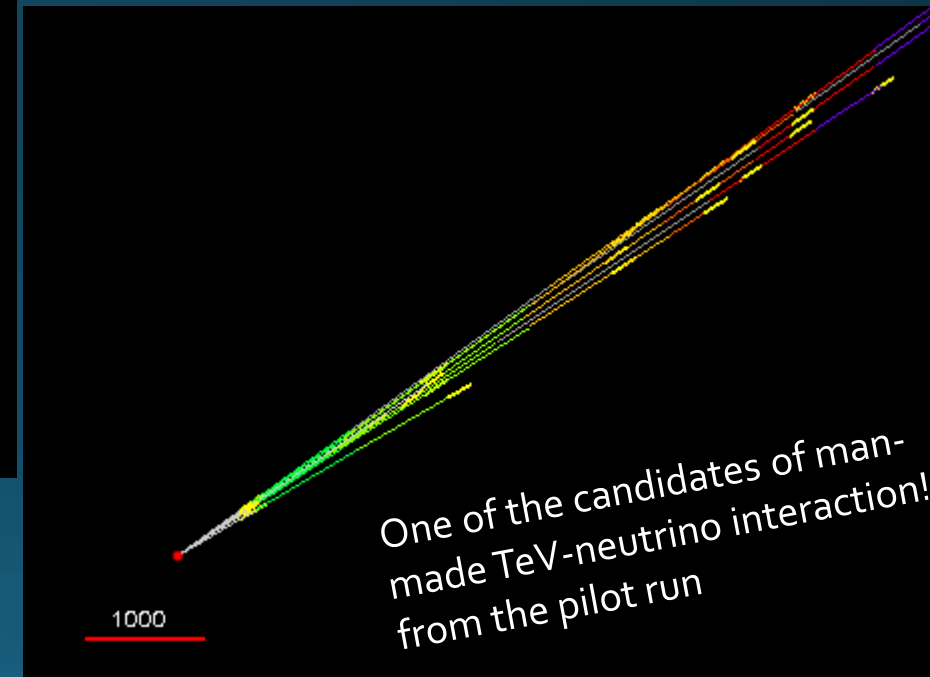
	Flux in main peak [fb/cm ²]
Tl18 data	$1.7 \pm 0.1 \times 10^4$
Tl12 data	$1.9 \pm 0.2 \times 10^4$
FLUKA MC	2.5×10^4 (uncertainty 50%)

Pilot neutrino detector in 2018

Proof of principle



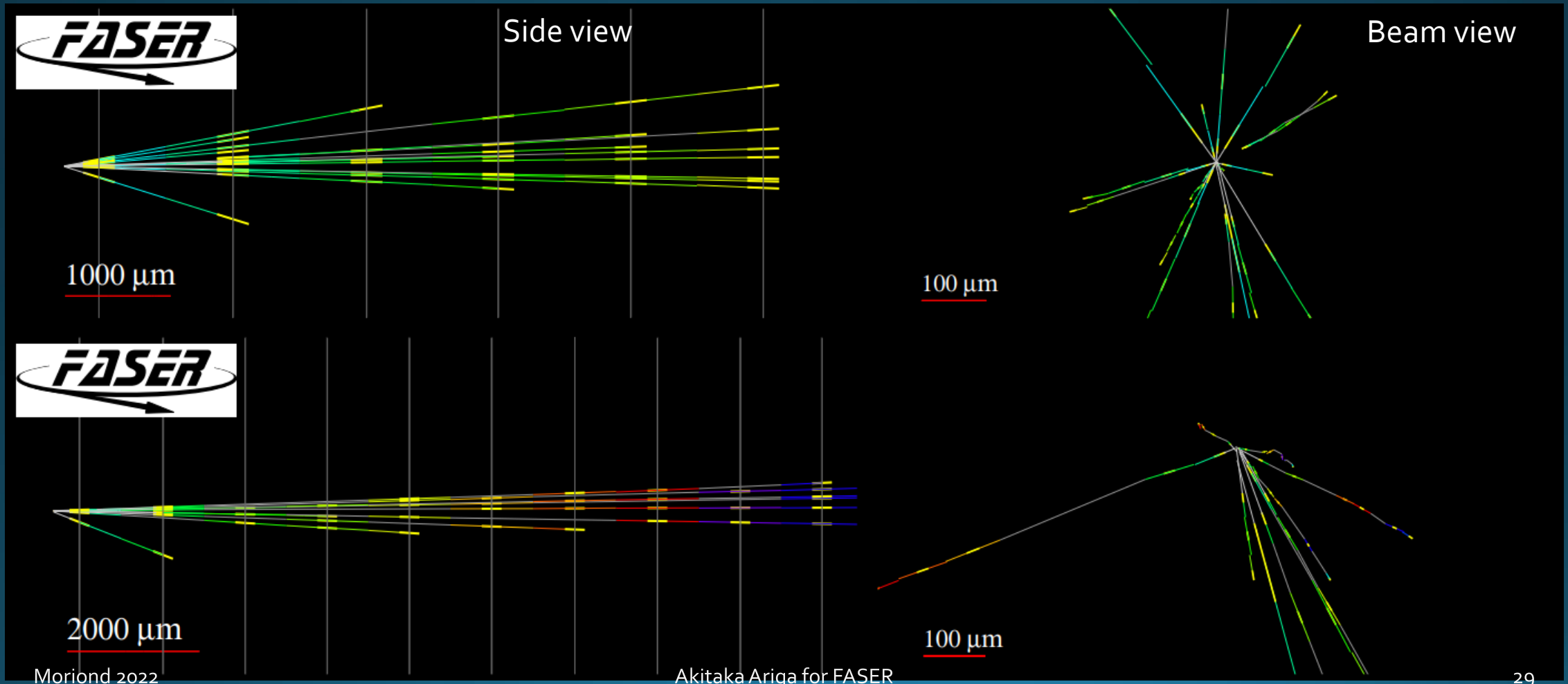
$\simeq 3 \times 10^5 \text{ tracks/cm}^2$



- 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 (6 weeks)

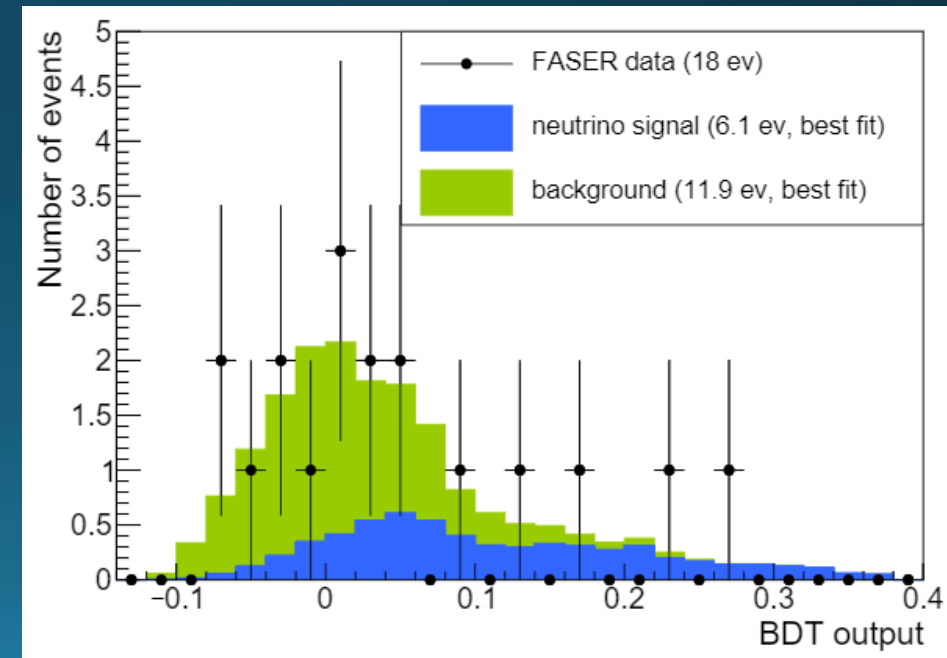


Neutrino interaction candidates



Pilot run event statistics

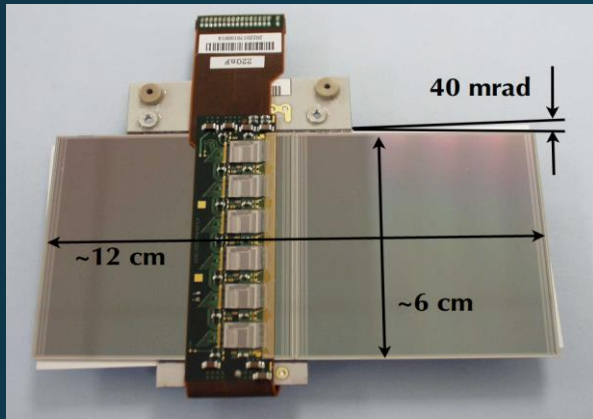
- Analyzed target mass of **11 kg** and luminosity of **12.2 fb^{-1}**
- 18 neutral vertices were selected
 - by applying # of charged particle ≥ 5 , etc.
 - Expected signal = $3.3^{+1.7}_{-0.95}$ events, BG = 11.0 events
- **Note: no lepton ID in the pilot run $\rightarrow$ High BG**
- In BDT analysis,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



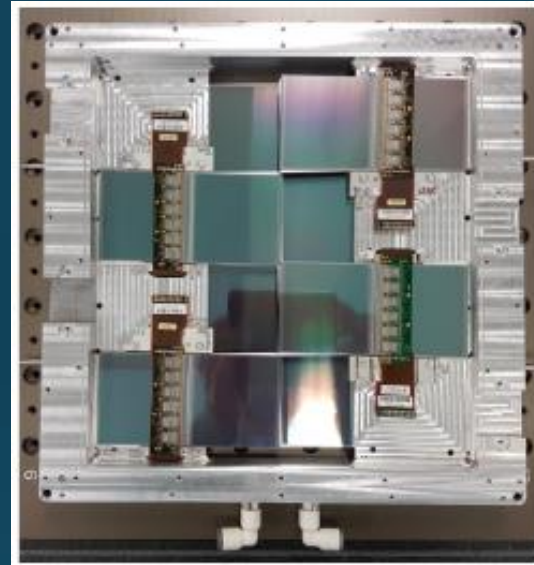
Preparation for LHC Run 3 (2022-)



FASER detector components



SCT module from ATLAS, 80 μm silicon strip detector



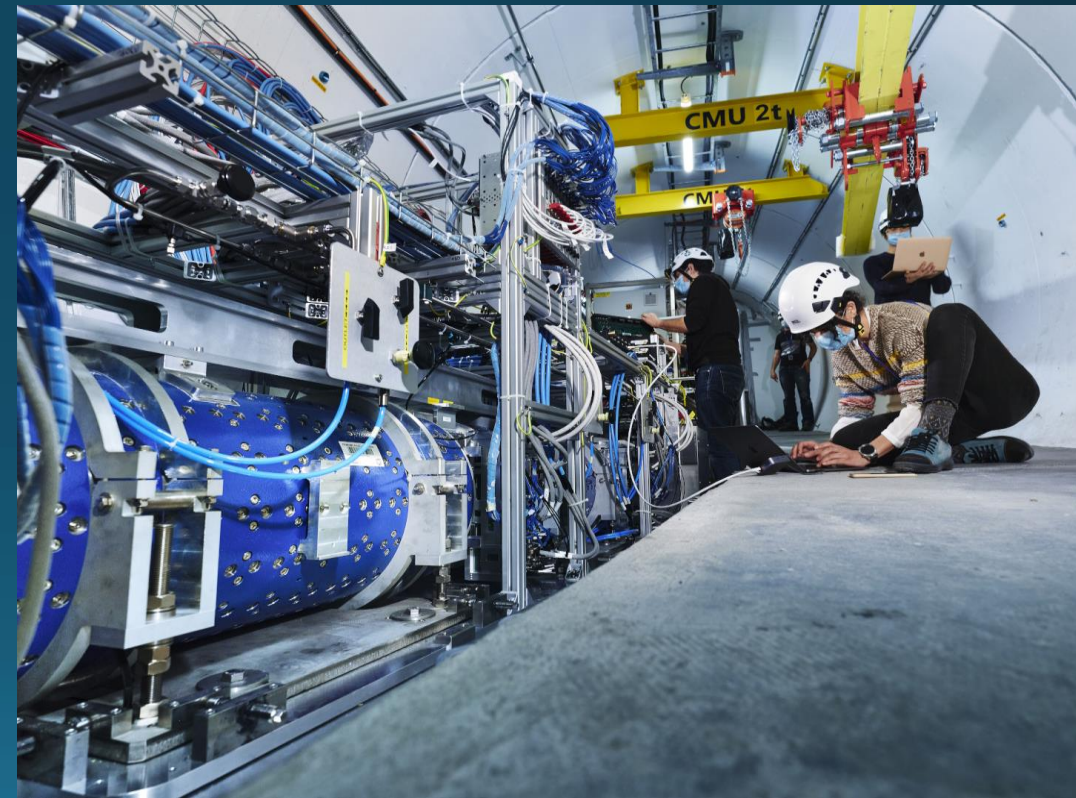
Tracking layer = 8 SCT modules



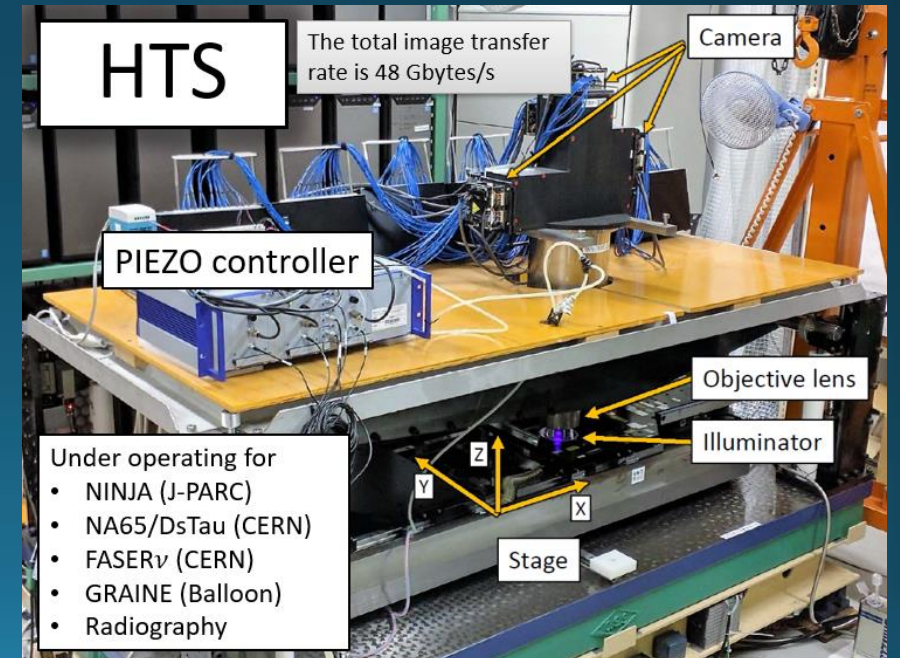
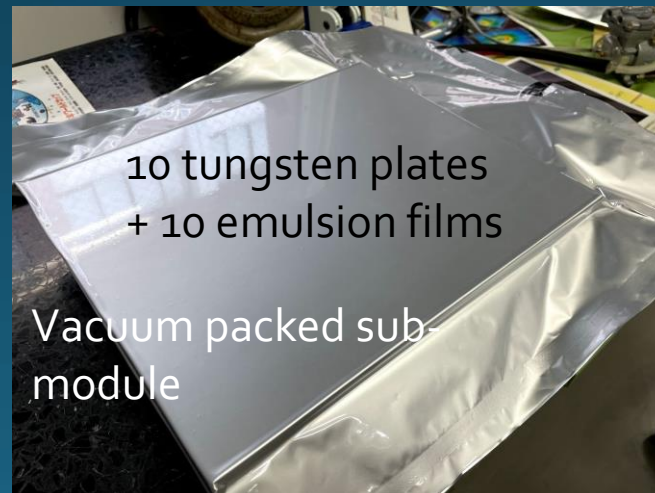
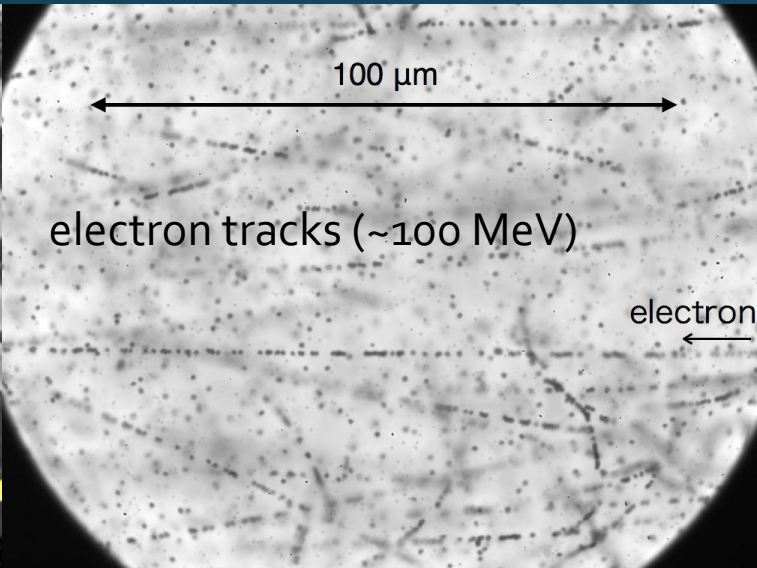
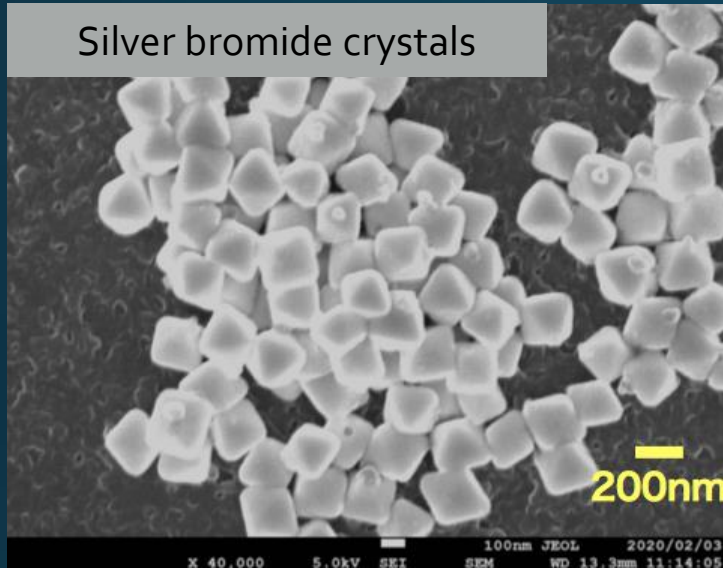
Calorimeter module from LHCb



Scintillators

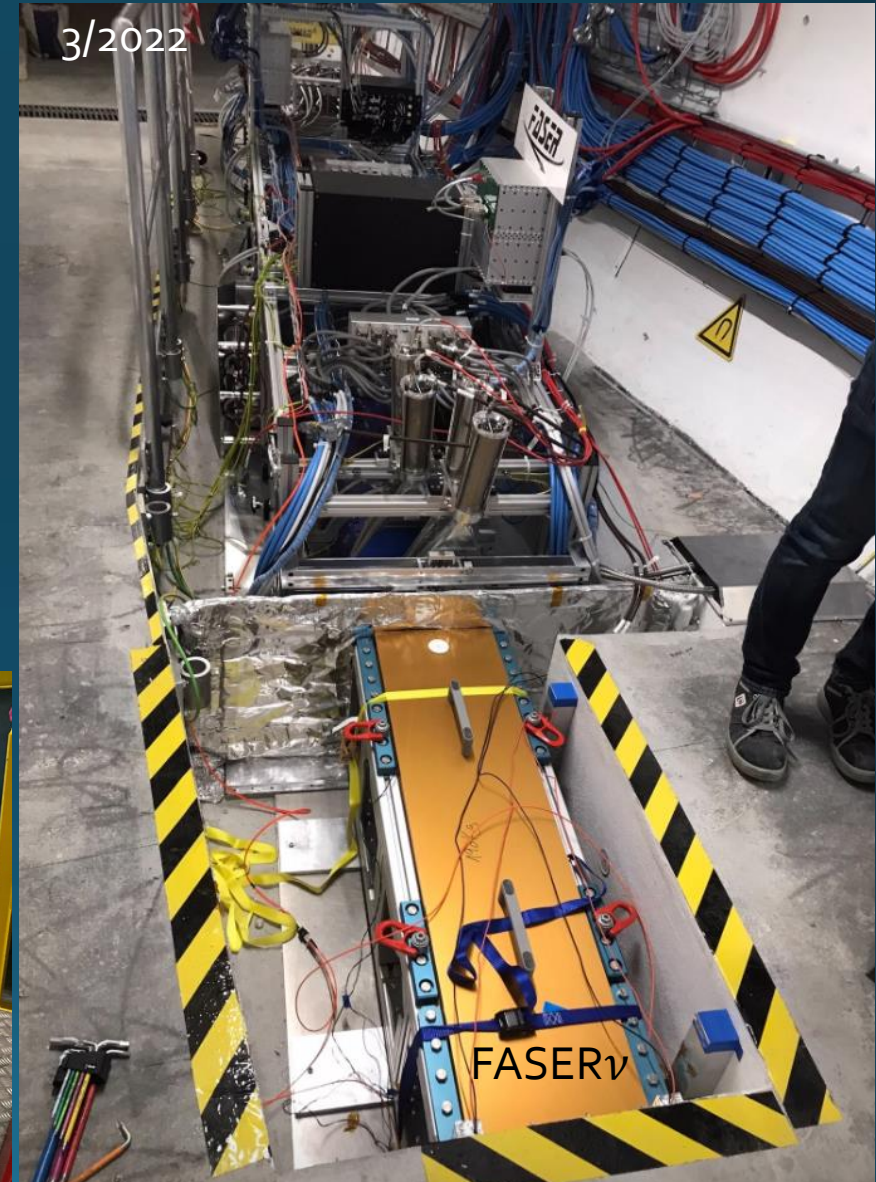
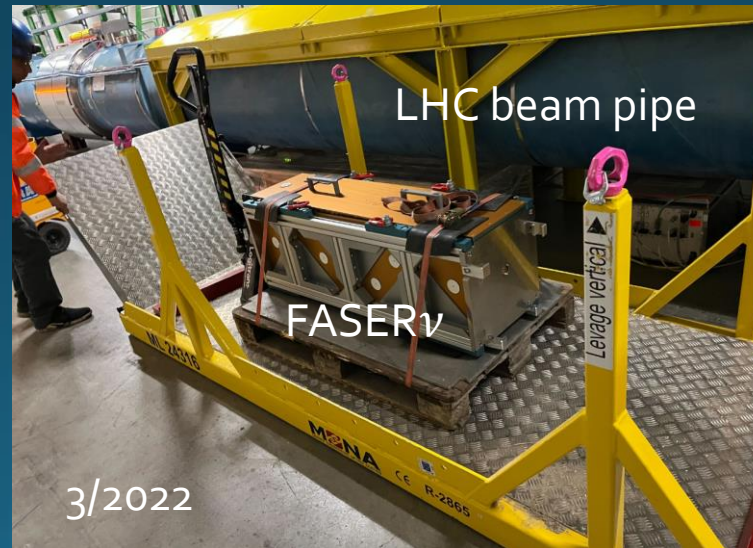
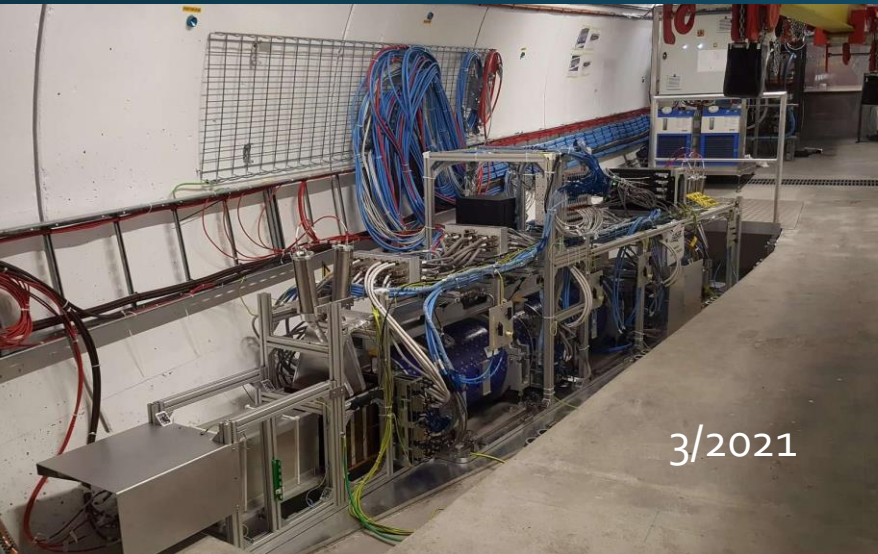


Preparation for Run 3: FASER ν detector

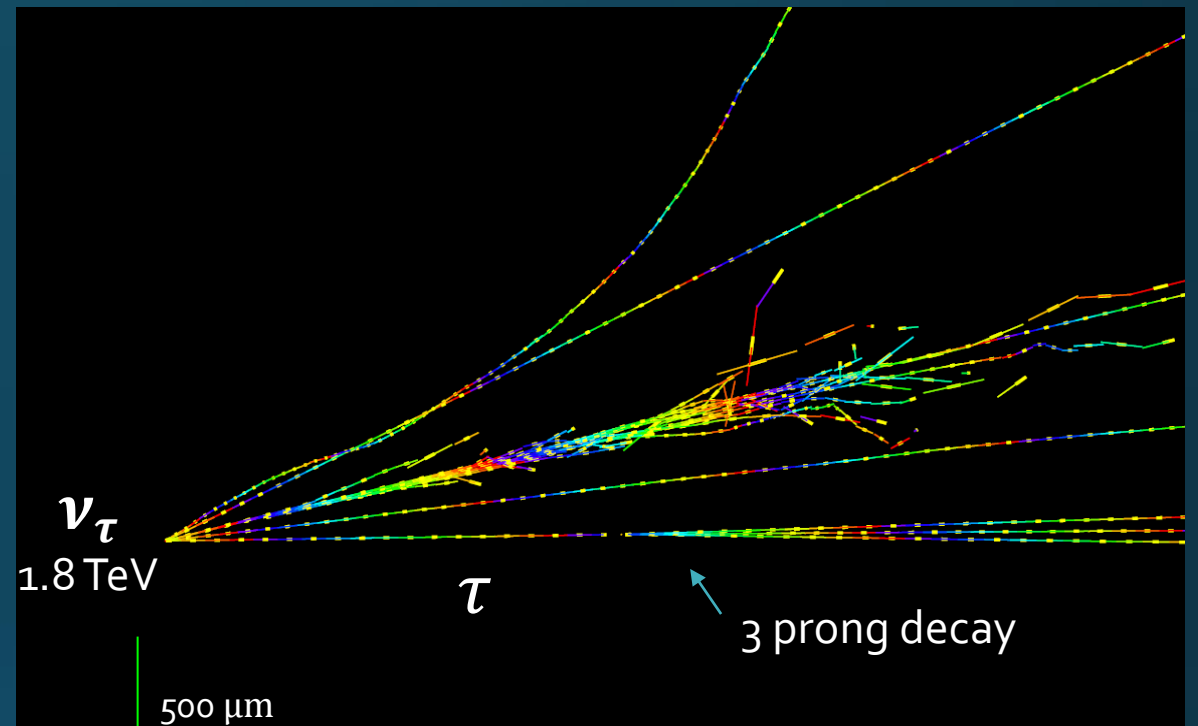
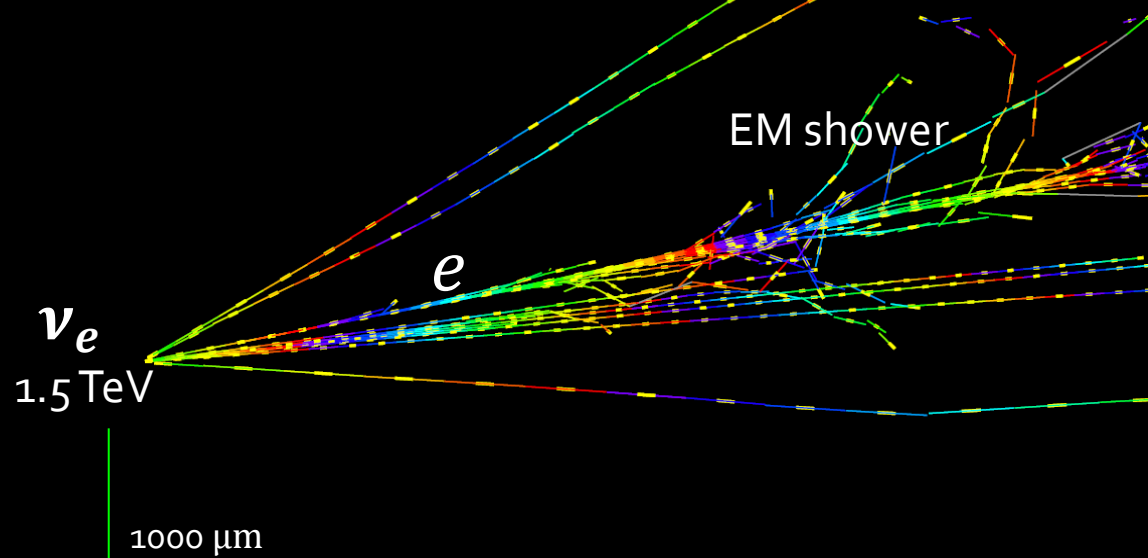


Preparation for Run 3 at site

First emulsion detector installed this week!



Simulated ν_e and ν_τ events



ν_τ interaction (τ^- decaying to μ^-)

Interactions in emulsion detector

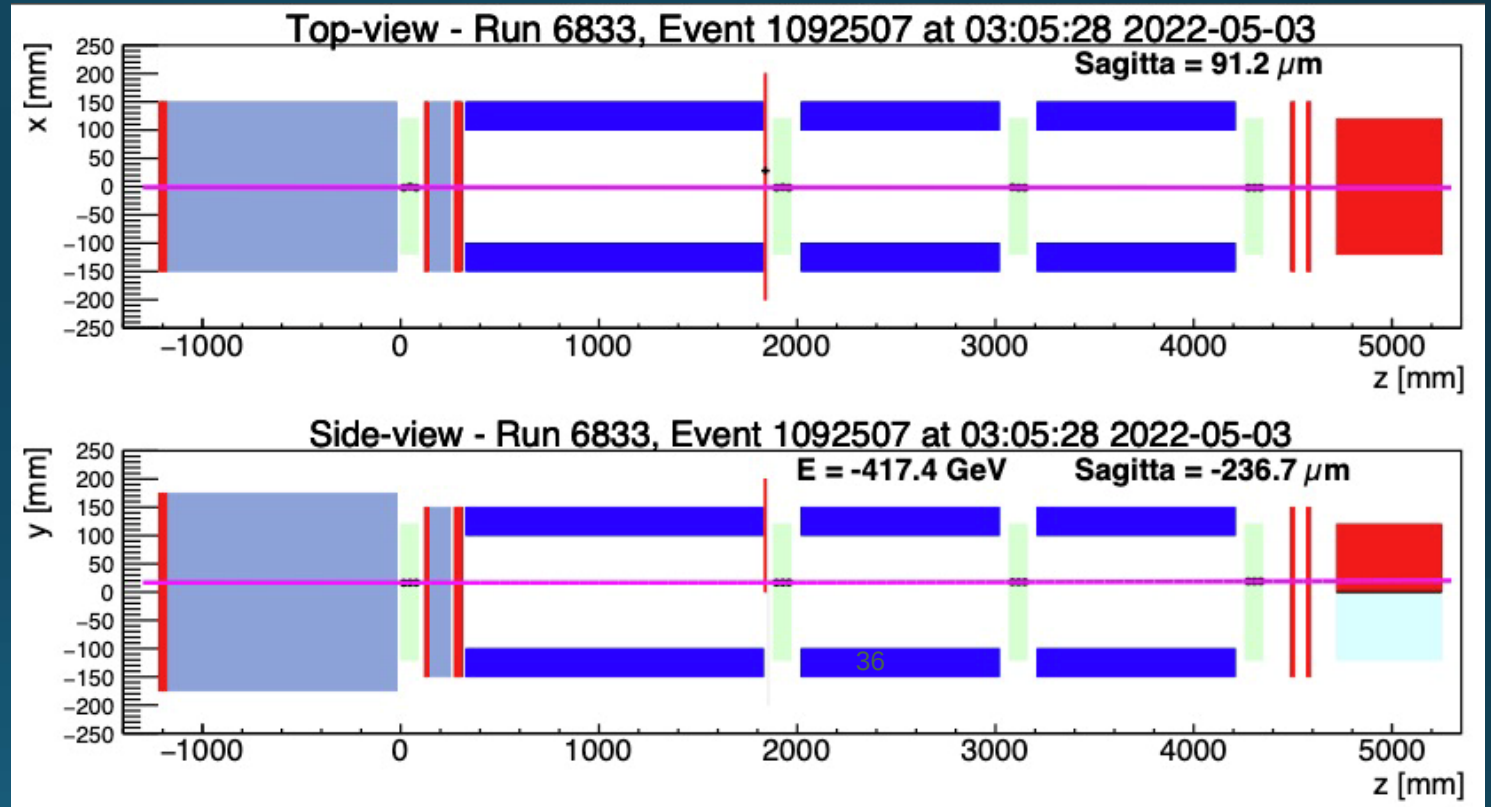
Moriond 2022

Akitaka Ariga for FASER

Hit events in tracker of FASER spectrometer

First beam particles in May 2022

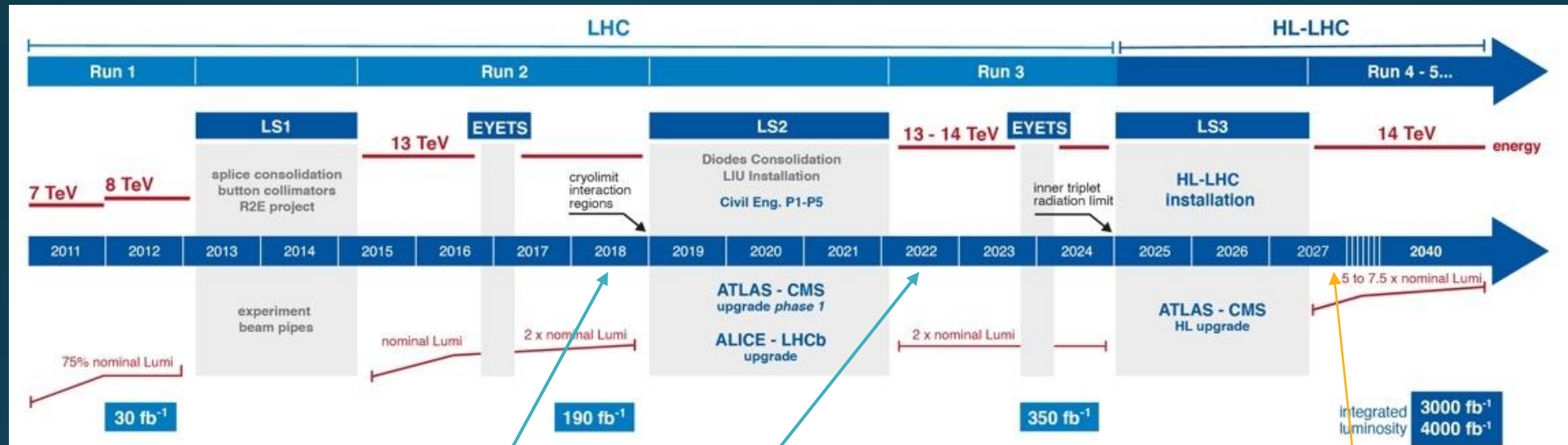
- Saw first beam particles from recent 6.8 TeV beam optics tests!
- First particles traversing full detector, including Fwd Veto and IFT
- Good readiness confirmed toward Run 3



First neutrino interactions will be reported within this year

FASER ν /FASER ν 2 schedule

- LHC Run-3 will start in 2022, FASER ν .
- HL-LHC, starting in 2028, will deliver 10 times more integrated luminosity $\rightarrow$ FASER ν 2



Pilot run & background measurements in 2018

FASER's physics run (~150 fb⁻¹ or more)

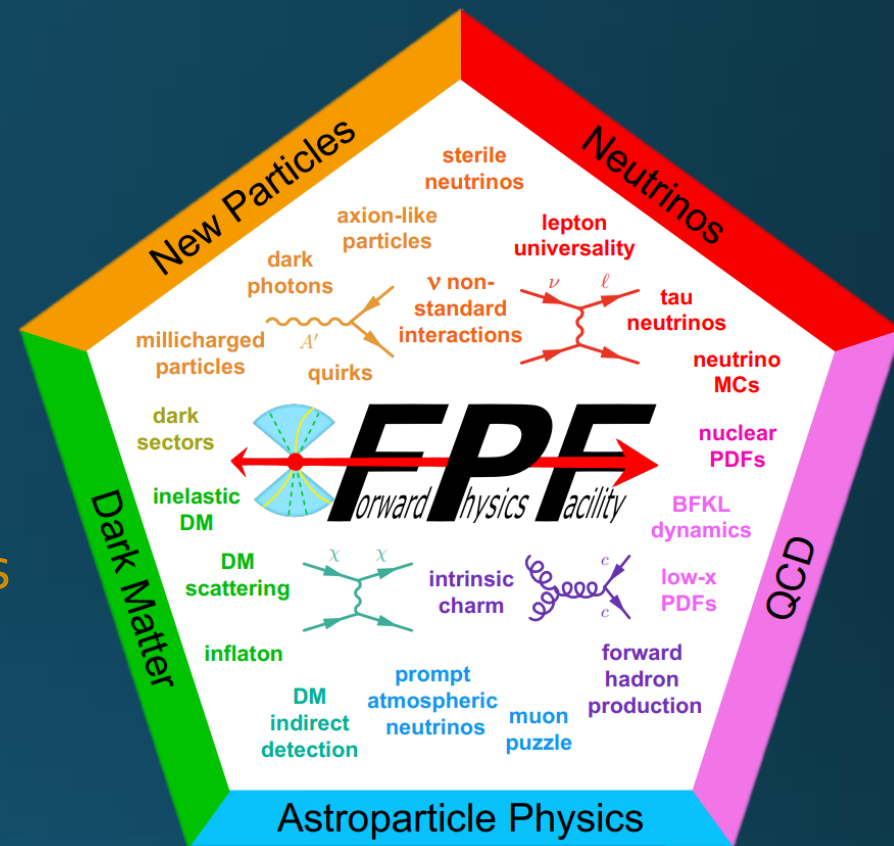
Forward experiment in HL-LHC

2022-25 physics run in LHC RUN3, 1.1 tons, a total area of film 720 m²

2028- FASER ν 2@FPF in HL-LHC, 10-20 tons

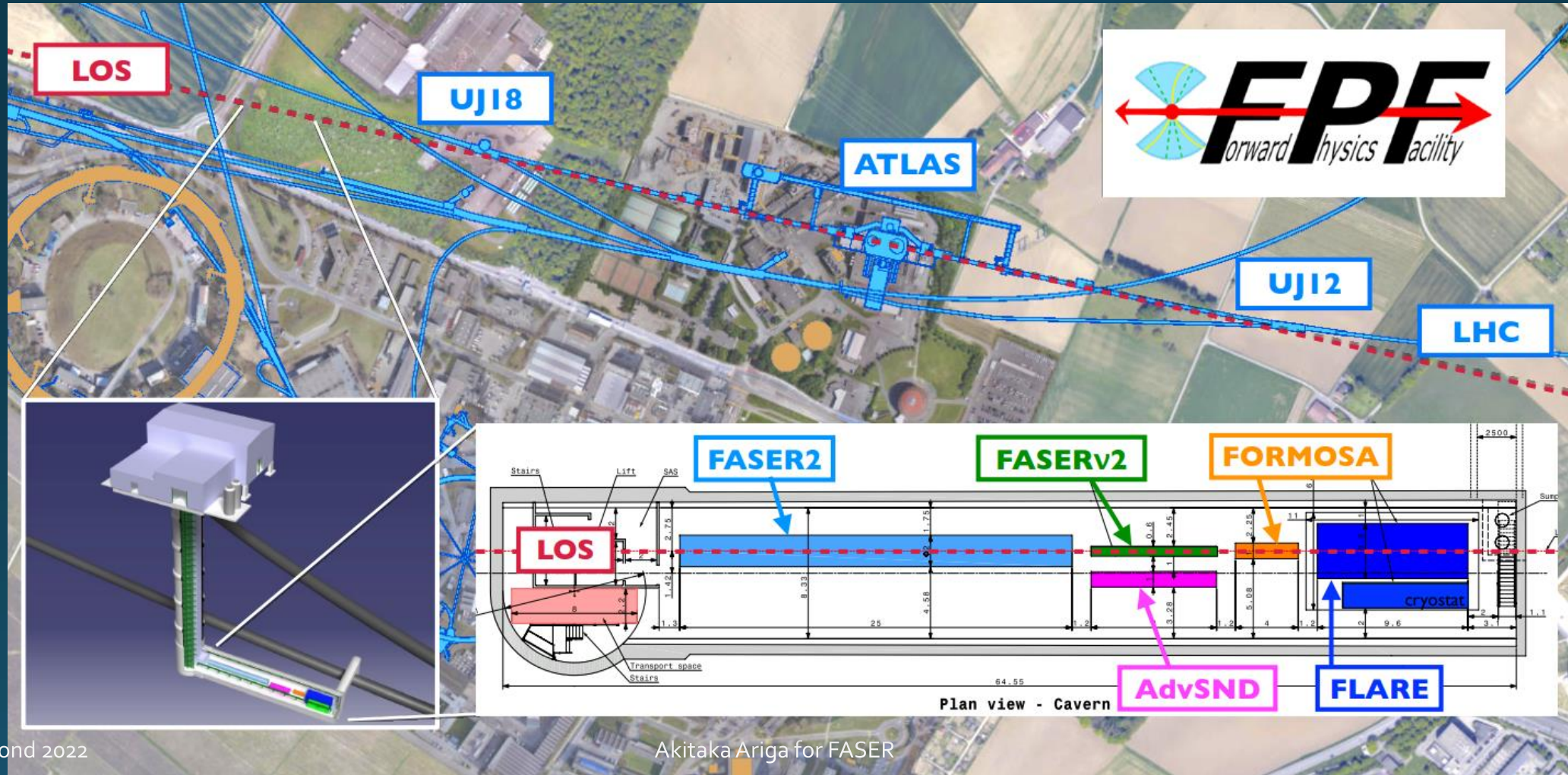
Physics Motivation

- The FPF has a rich and broad physics programme
- Three main physics motivations
 - Beyond Standard Model (BSM) “dark sector” searches
 - Neutrino physics
 - QCD physics
- In order to fully benefit from the increase in luminosity from the HL-LHC, the FPF will allow:
 - Longer detectors to increase target/decay volume
 - Wider detectors to increase sensitivity to heavy flavour produced particles
 - Space for new detectors with complementary physics capabilities

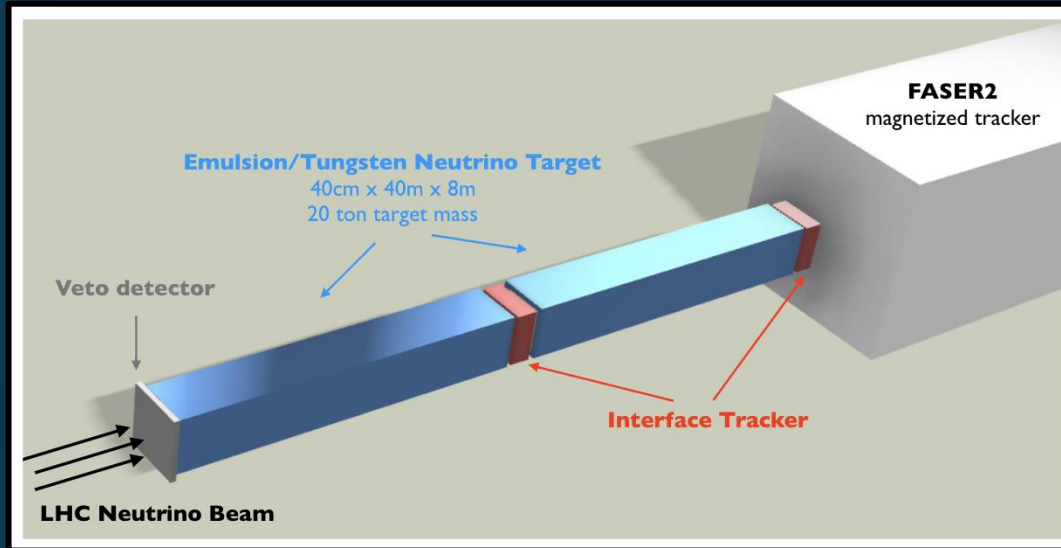


Forward Physics Facility (*FPF*) at the HL-LHC

- FPF White Paper (429 pages, 236 authors, 156 endorsers)
<http://arxiv.org/abs/2203.05090>

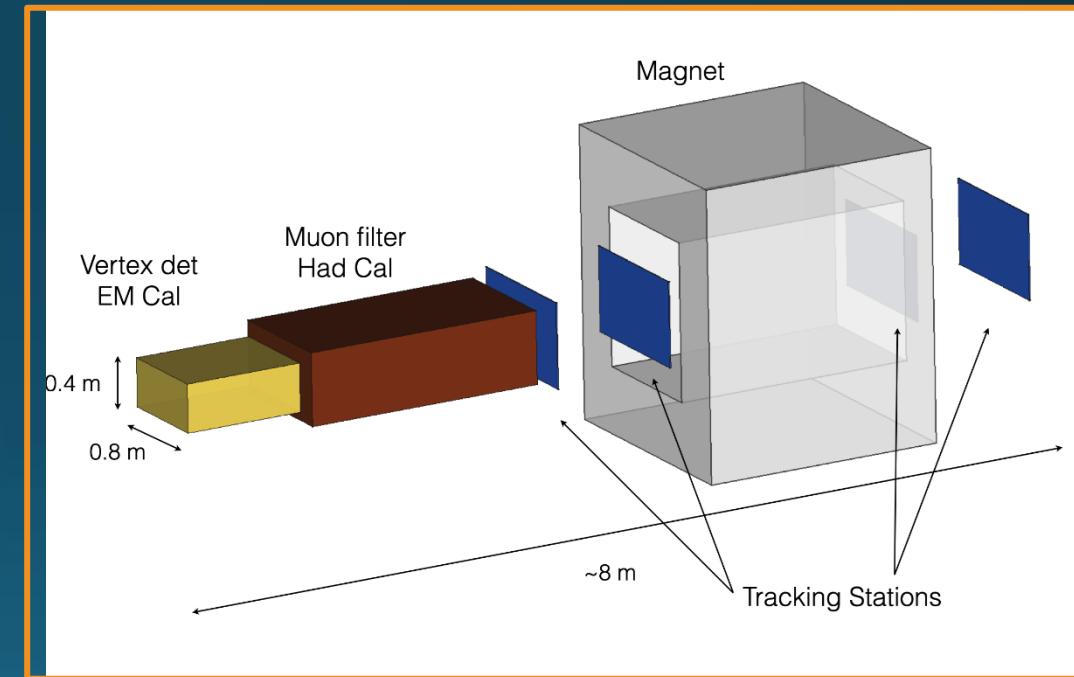


Neutrino Detector at the FPF



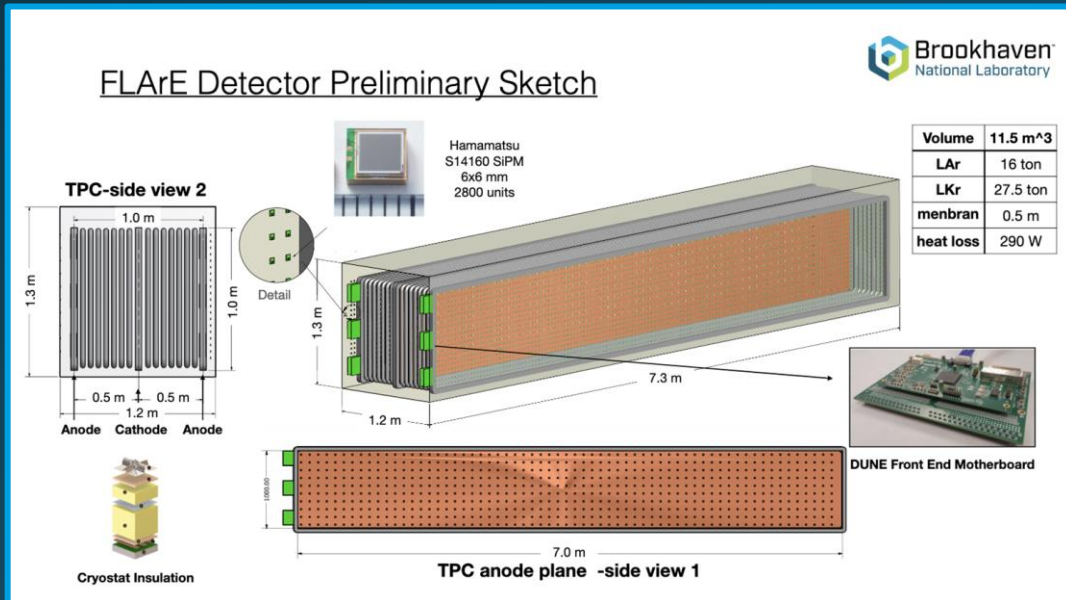
FASERv2

emulsion neutrino detector
followed by FASER spectrometer



AdvSND

electronic detector
near detector at $\eta \sim 5$
far detector at FPF



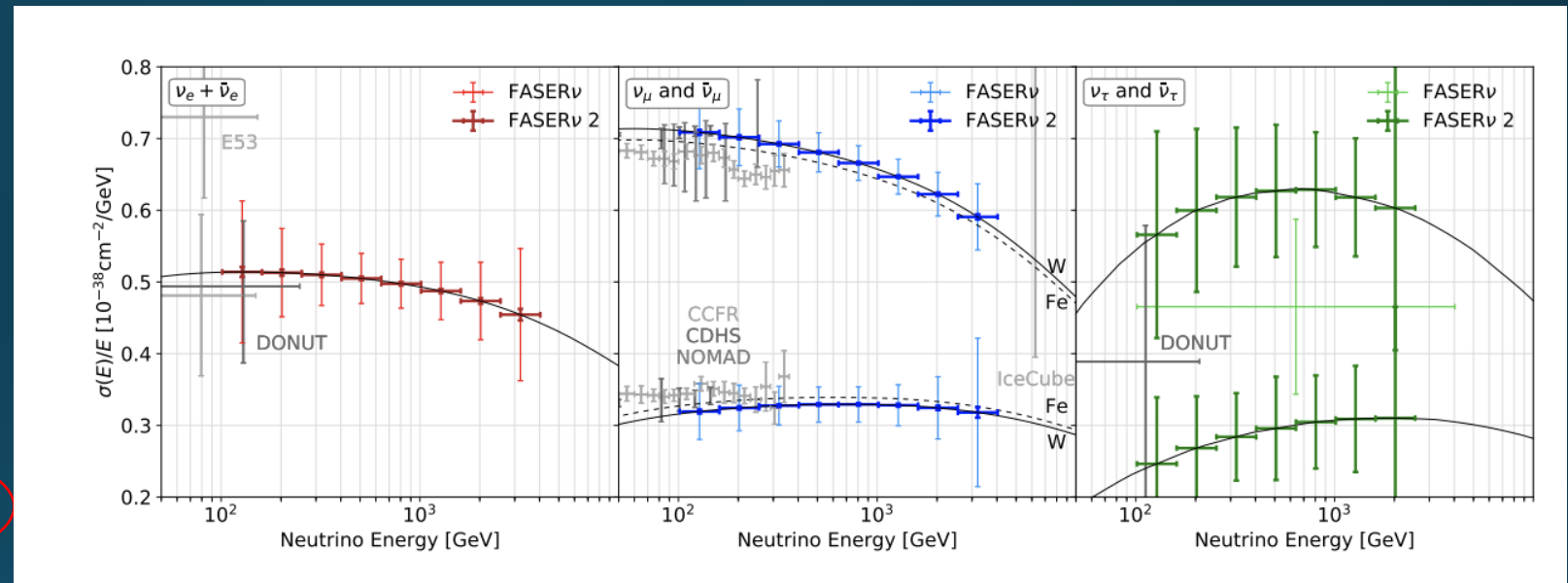
FLArE

liquid noble gas detector

A huge number of high-energy neutrinos of all flavours will be detected by experiments at the

<https://arxiv.org/pdf/2105.08270.pdf> (F. Kling)

Species	#evts (20tn, 3/ab)	
ν_e	64k	~100k
$\bar{\nu}_e$	36k	
ν_μ	430k	~500k
$\bar{\nu}_\mu$	120k	
ν_τ	2k	~3k
$\bar{\nu}_\tau$	0.8k	



Tau neutrino:

- FPF experiments will **increase this number by over two orders of magnitude**, enabling precision ν_τ studies:
- Measure high energy $\nu_\tau/\bar{\nu}_\tau$ charge-current cross sections
- Study $\nu_\tau \rightarrow$ heavy flavour – towards probing same diagrams as LHCb lepton-flavour violation anomalies

Large sample of ν_e, ν_μ :

- Sterile neutrino, NSI, constrain SM EFT, s-channel resonance,,,

QCD studies → Cosmic-ray

Physics Program of Forward Physics Facility

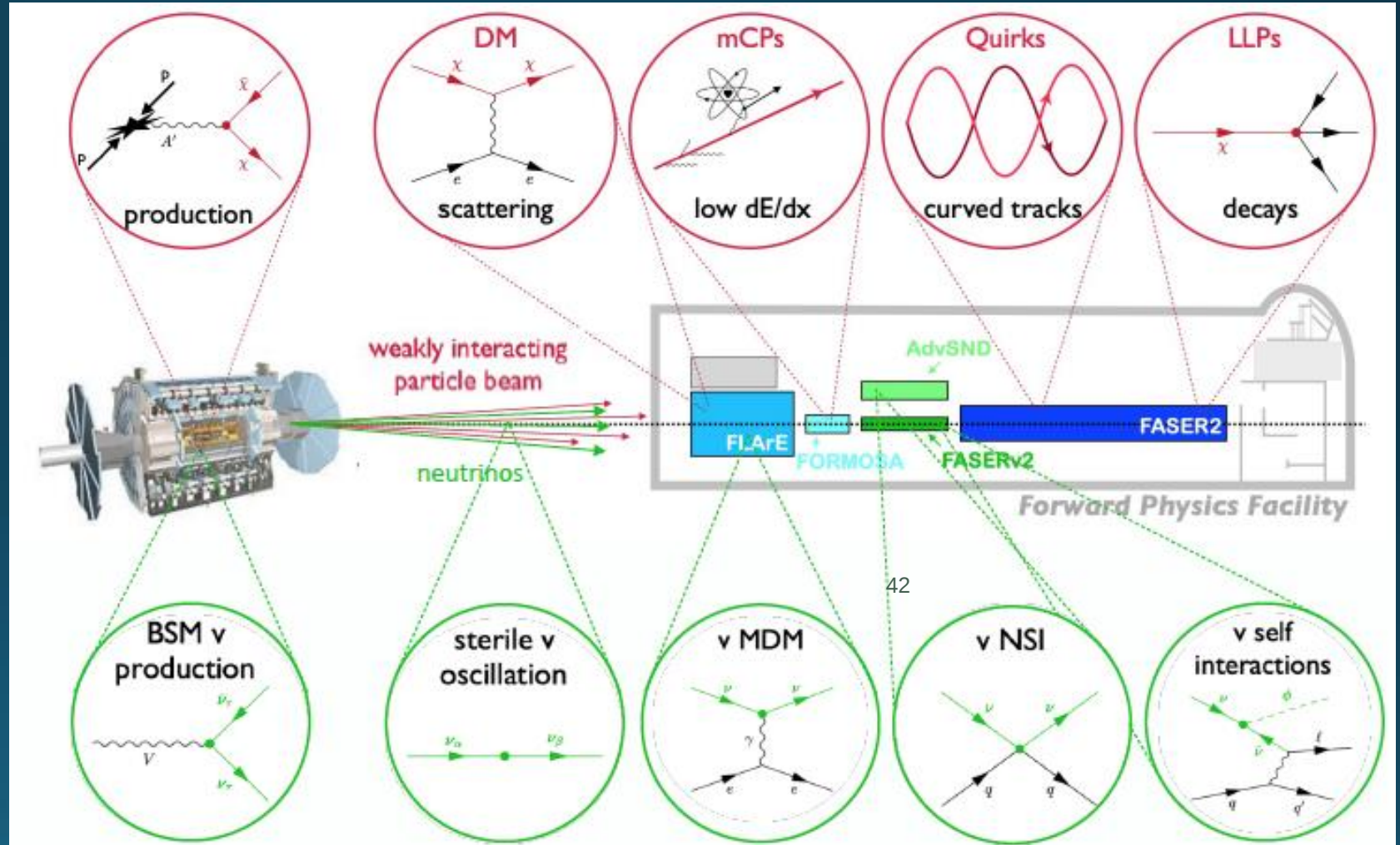


BSM particles can be detected in various ways

- Giving access to wide range of models

Neutrinos can be used to search for BSM effects

- Production
- Propagation
- Interaction



Forward Physics Facility

FPF workshop series:
FPF₁, FPF₂, FPF₃, FPF₄

FPF Paper:

2109.10905

~75 pages, ~80 authors

Snowmass Whitepaper:

2203.05090

~450 pages, ~250 authors

4th Forward Physics Facility Meeting

31 January 2022 to 1 February 2022
Europe/Zurich timezone

Enter your search term

Overview

Call for Abstracts

Timetable

Contribution List

My Conference

My Contributions

Book of Abstracts

Registration

Participant List

Starts 31 Jan 2022, 16:00
Ends 1 Feb 2022, 21:00
Europe/Zurich

There are no materials yet.

The Forward Physics Facility (FPF) project is moving forward!

At the 4th Forward Physics Facility Meeting we will discuss the facility, experiments, and physics goals of the proposed FPF at the HL-LHC. The meeting takes place just before the completion of the FPF Snowmass White Paper and will provide an opportunity to summarize the current status of the White Paper and the final steps in its preparation. The whole event will be held online.

The Zoom links are:
Plenary sessions (both Monday and Tuesday): <https://uci.zoom.us/j/91591021575>
<https://vu-live.zoom.us/j/9RQnRzTJpdz09>
<https://uiowa.zoom.us/j/94645515841>
<https://zoom.us/j/97280888150>

**The Forward Physics Facility:
Sites, Experiments, and Physics Potential**

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The Forward Physics Facility (FPF) is a proposal to create a cavern with the space infrastructure to support a suite of far-forward experiments at the Large Hadron Collider during the High Luminosity era. Located along the beam collision axis and shielded the interaction point by at least 100 m of concrete and rock, the FPF will house experiments that will detect particles outside the acceptance of the existing large LHC experiments that will observe rare and exotic processes in an extremely low-background environment. In this work, we summarize the current status of plans for the FPF, including recent progress in civil engineering in identifying promising sites for the FPF; the FPF experiments envisioned to realize the FPF's physics potential; and the many Standard Model and beyond physics topics that will be advanced by the FPF, including searches for long-lived particles, probes of dark matter and dark sectors, high-statistics studies of TeV neutrinos of all flavors, aspects of perturbative and non-perturbative QCD, and high-energy astrophysics.



**The Forward Physics Facility
at the High-Luminosity LHC**

High energy collisions at the High-Luminosity Large Hadron Collider (LHC) produce a large number of particles along the beam collision axis, outside of the acceptance of existing LHC experiments. The proposed Forward Physics Facility (FPF), to be located several hundred meters from an LHC interaction point and shielded by concrete and rock, will host a suite of experiments to probe standard model processes and search for physics beyond the standard model (BSM). In this report, we review the status of the civil engineering plans and the experiments to explore the diverse physics signals that can be uniquely probed in the forward region. FPF experiments will be sensitive to a broad range of BSM physics through searches for new particle scattering or decay signatures and deviations from standard model expectations in high statistics analyses with TeV neutrinos in this low-background environment. High statistics neutrino detection will trace back to fundamental topics in perturbative and non-perturbative QCD and in weak interactions. Experiments at the FPF will enable synergies between forward particle production at the LHC and astroparticle physics to be exploited. We report here on these physics topics, on infrastructure, detector and simulation studies, and on future directions to realize the FPF's physics potential.

Summary

- Neutrinos at the LHC, a new domain of particle physics research!
- The **FASER** experiment at the LHC: **neutrinos and LLPs**
- **FASER ν** is the first neutrino experiment with a collider
 - Beam at new kinematical regime, including 3 flavors
 - Not only neutrino physics, but **flavor physics, cosmic-ray physics**
 - Data taking in 2022-2025
- **Detection of neutrinos from the LHC was demonstrated with pilot run in 2018**
- **FASER is starting data taking in next months!** (Collisions in June)
- Future projects (FPF) at the HL-LHC are under discussion
 - Strong and broad physics motivation with significant interest from the community
 - We invite people from neutrino and wider fields!

FASER Collaboration

74 collaborators, 21 institutions, 9 countries (as of Jan. 2022)



