Neutrinos and beyond with LHC's forward beam

FASER

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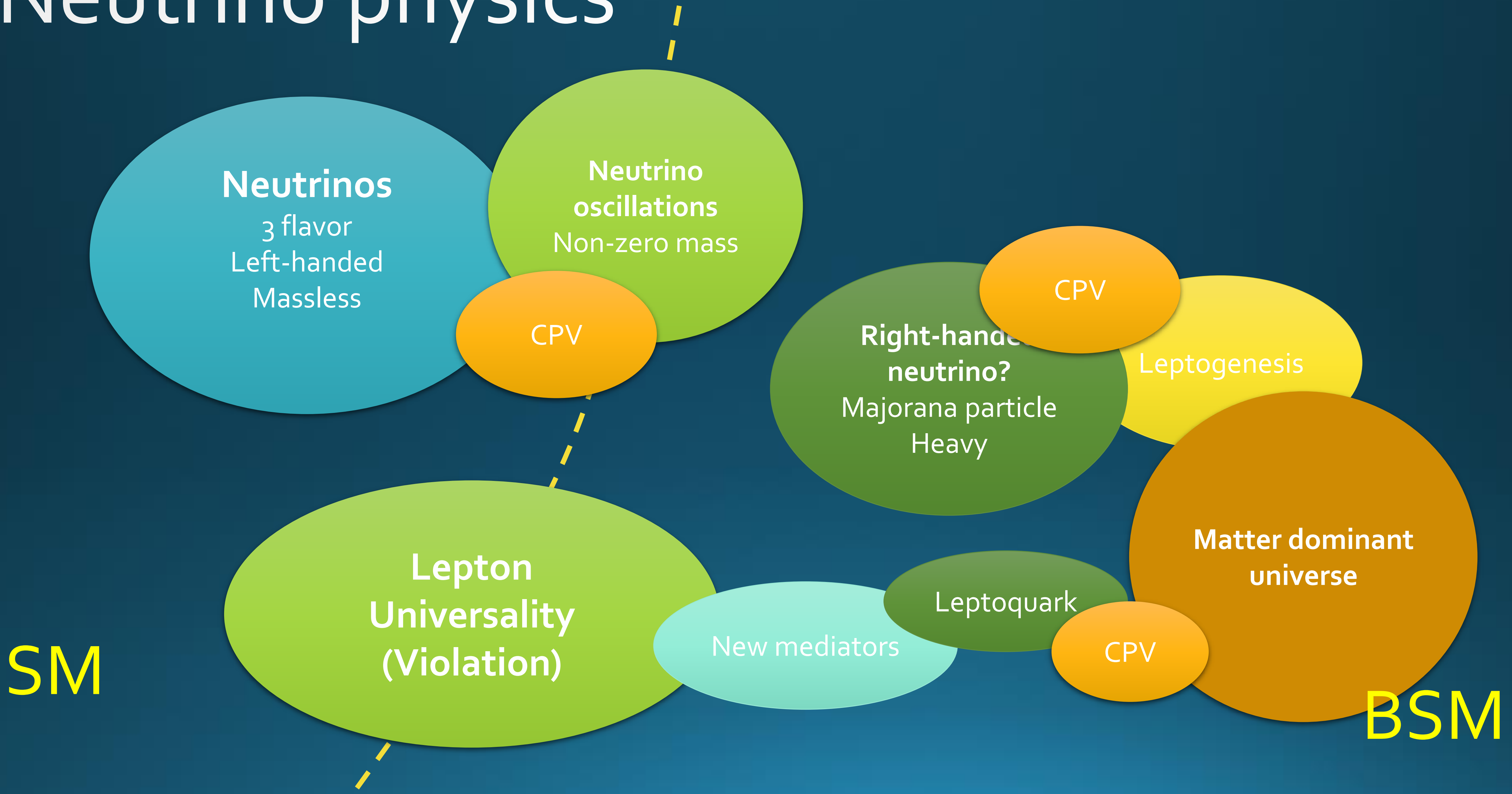
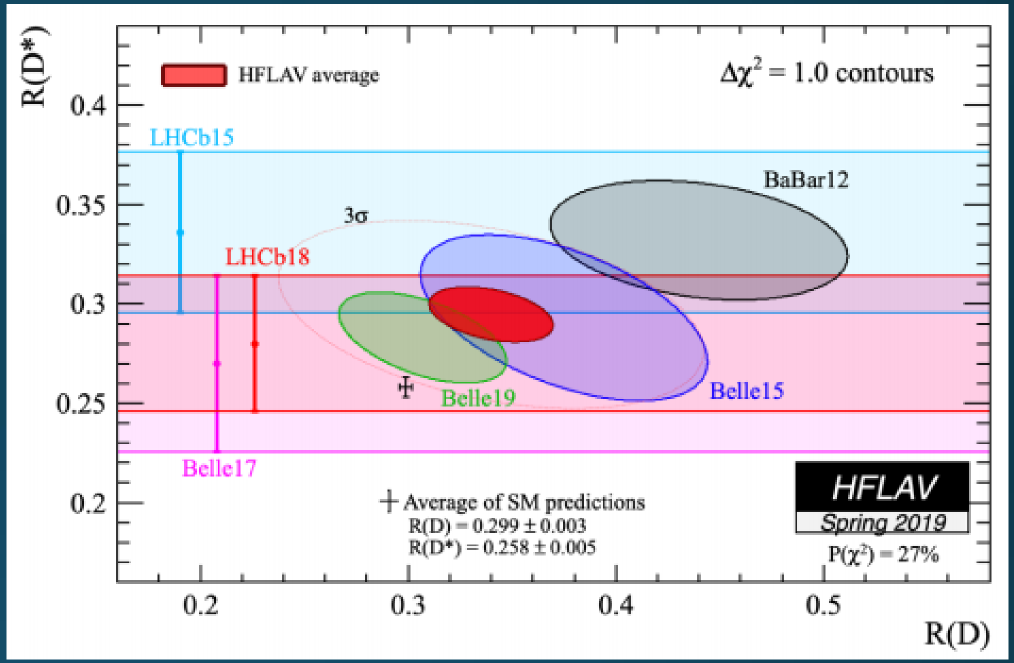
Neutrino physics



“Flavor anomaly”

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

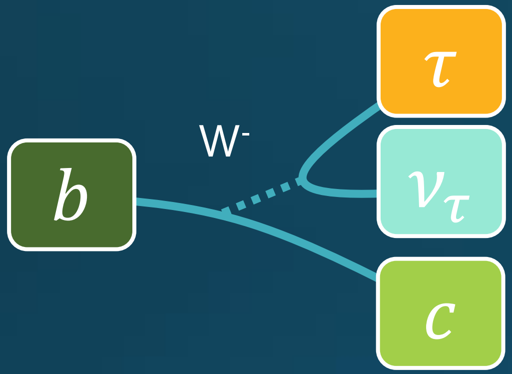


Possible contribution from new physics in heavy flavors!?

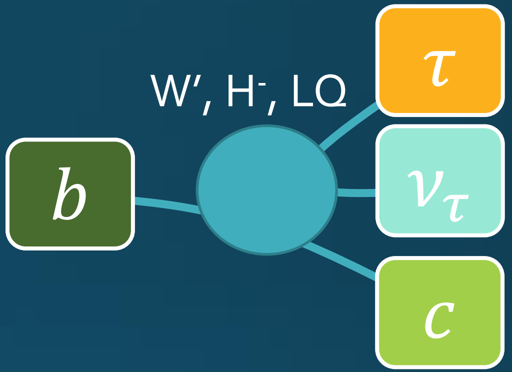
New physics effect?

B decays

SM



NP

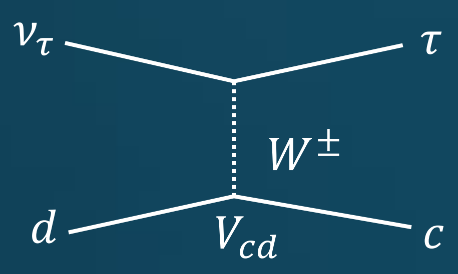


Neutrino CC beauty production

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

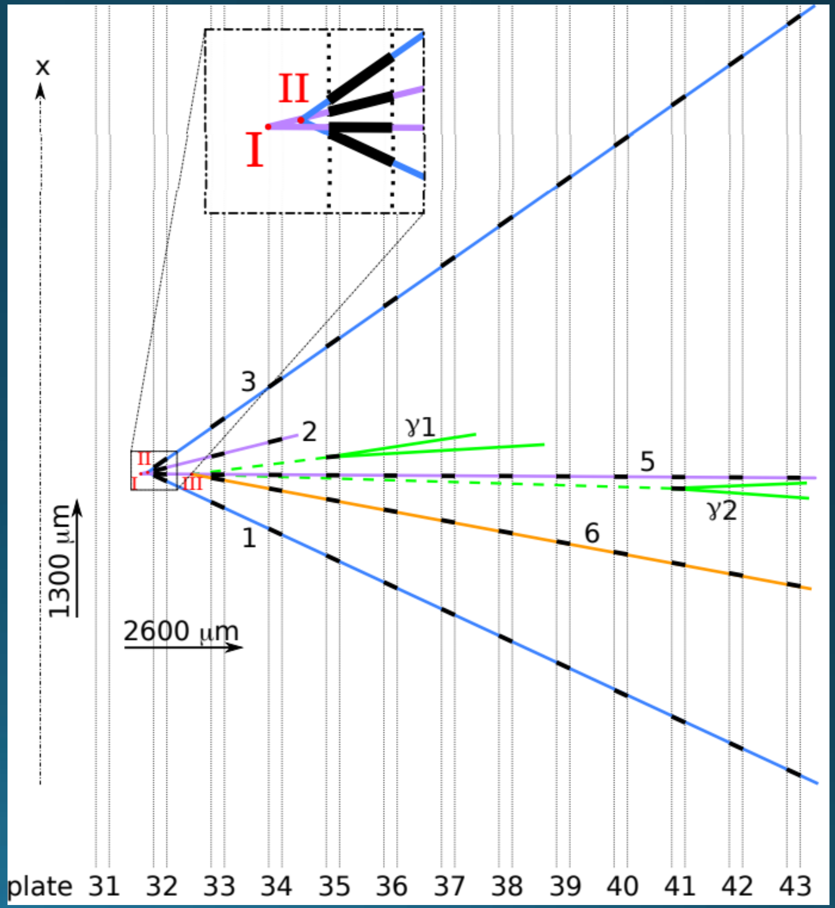
OPERA's ν_τ induced charm production event

SM process,
charm production
via mixing

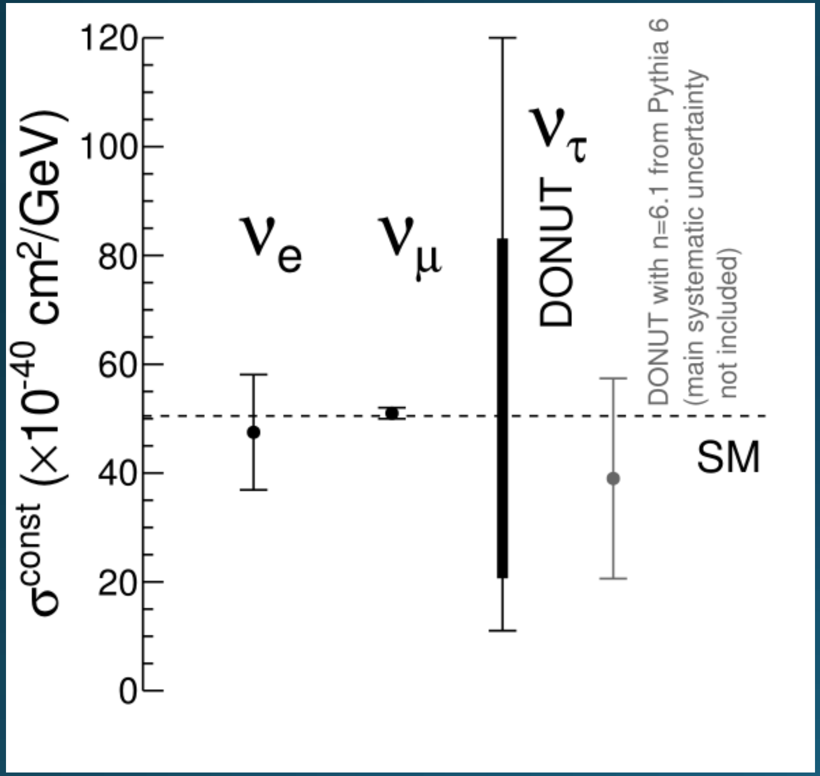


Well measured for ν_μ

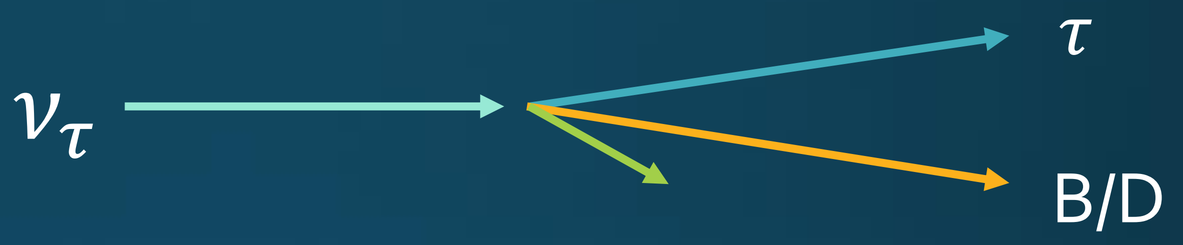
- 1 event was observed <u>with surprise</u>
- Expectation:
  - Signal 0.04
  - Background <0.05
- Could also be a hint of new physics!?



Status of Lepton Universality testing in neutrino scattering



Poor constraint for ν_τ



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

→ Need high statistics and high energy beam experiment!

LHC as neutrino source?

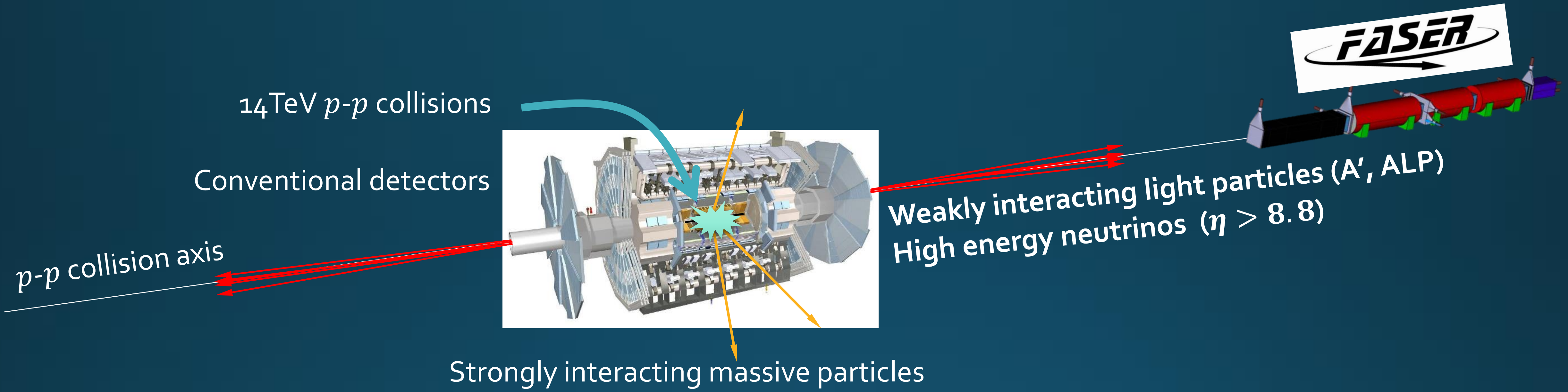
Large Hadron Collider

27 km circumference

7 TeV + 7 TeV

Let's open new domain of research! Neutrino

FASER experiment: LLPs and neutrinos



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

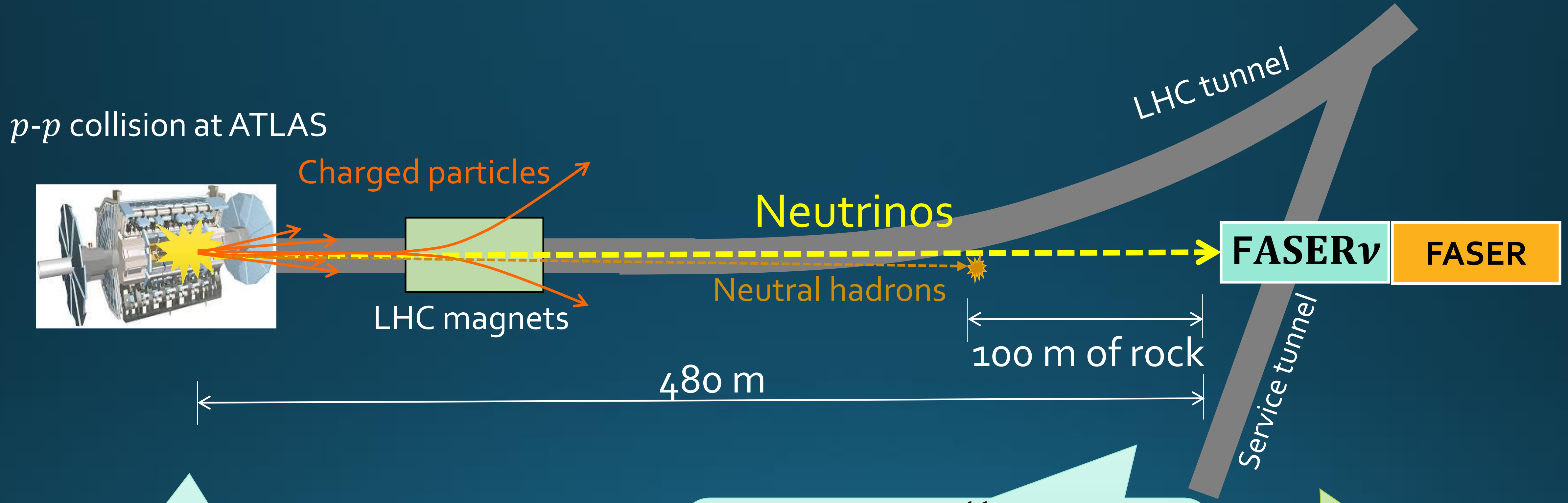
FASER (new particle searches) was approved by CERN in Mar 2019 arXiv:1812.09139

FASERν (neutrino program) was approved in Dec 2019 Eur. Phys. J. C (2020) **80**: 61

Data taking is starting in 2022!

More → FASER web page: https://faser.web.cern.ch/

LHC's "neutrino beamline"

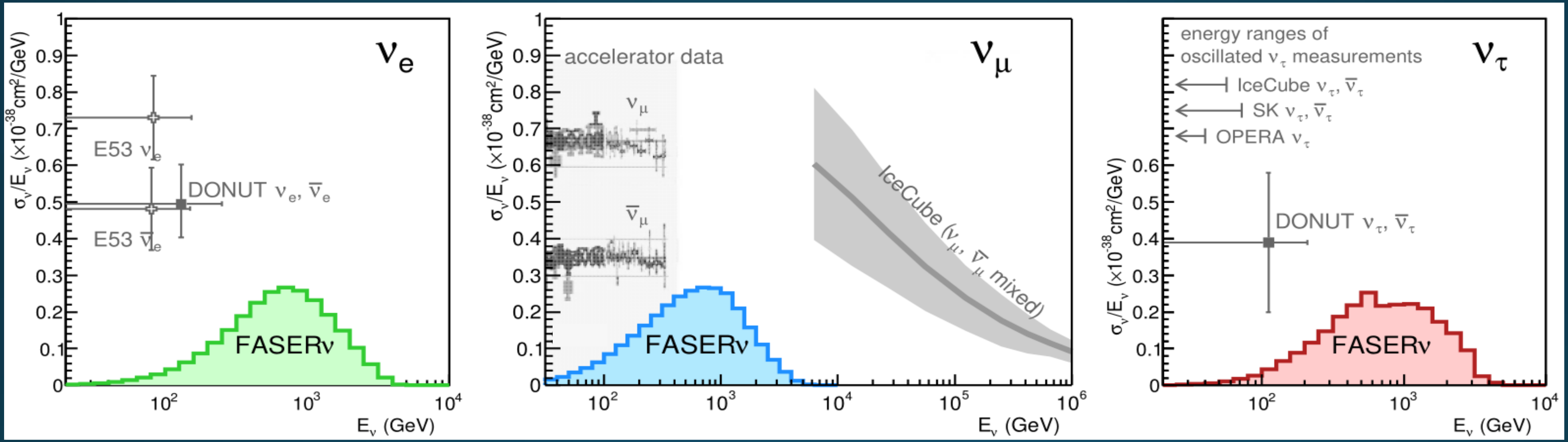


150 fb^{-1}
~1.5 ×10^{16} p-p collisions

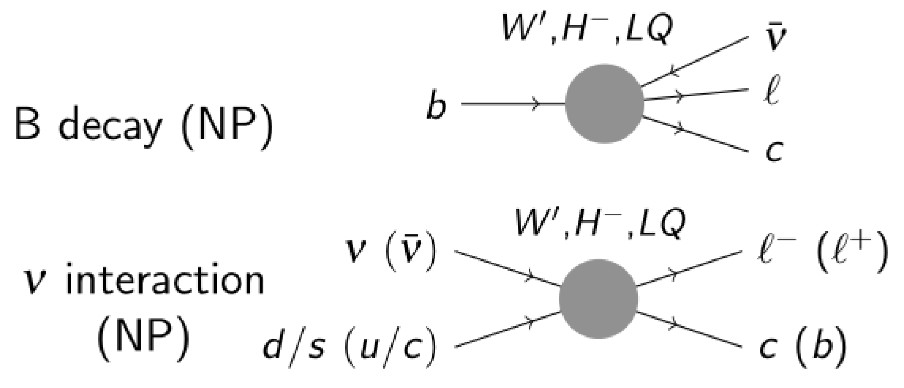
$\mathbf{5 \times 10^{11}\ \nu_e}$
$\mathbf{3 \times 10^{12}\ \nu_\mu}$
$\mathbf{1 \times 10^{10}\ \nu_\tau}$
Mean interacting energy ~ 1 TeV

Backgrounds
$O(10^9)\ \mu$
$O(10^4)\ n/K^0$

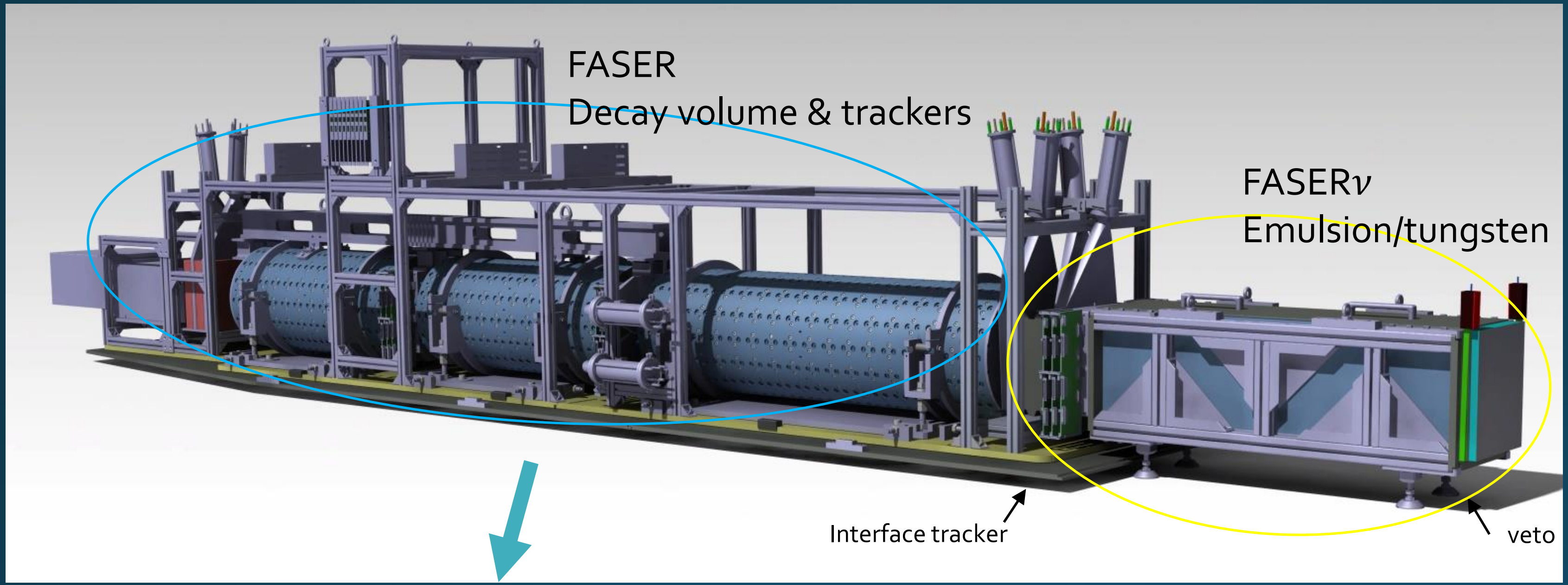
Motivations for high energy neutrinos

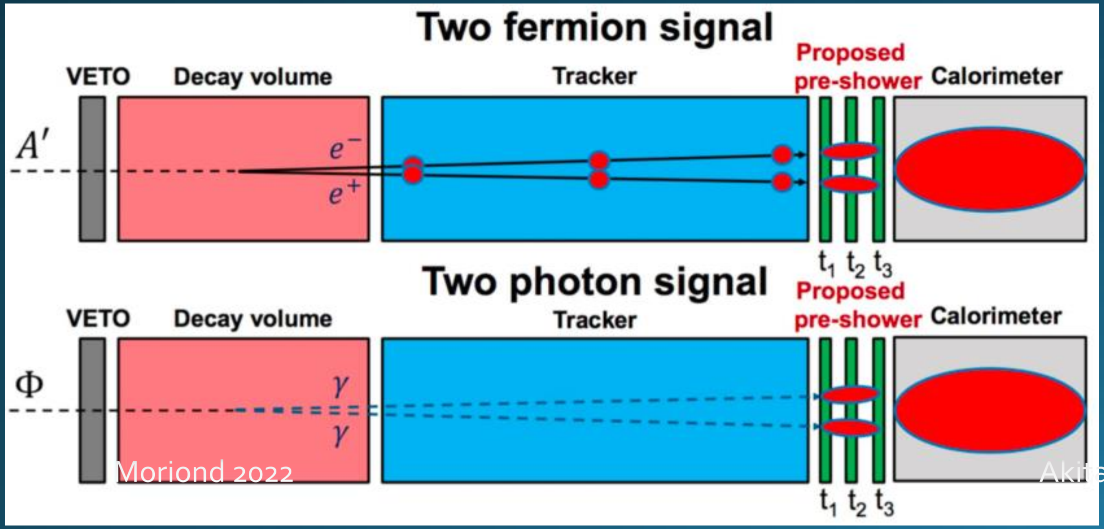


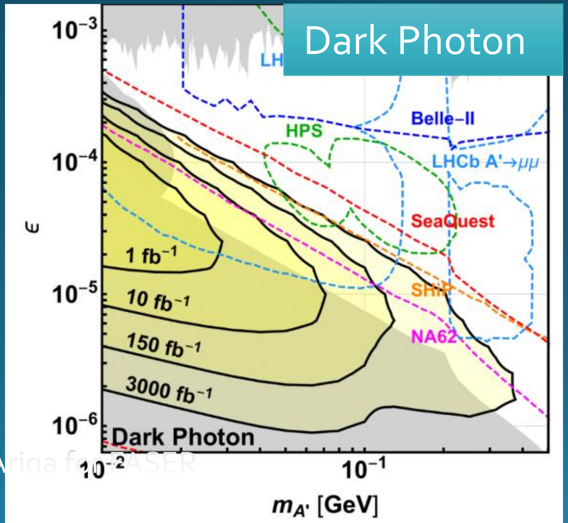
- Behavior of neutrinos at TeV energies?
- Lepton Universality in neutrino scattering?
  - ν_τ and heavy quarks → Flavor anomaly e.g. R_D
- Any new physics effects at high energy?
- →High energy neutrinos from the LHC!

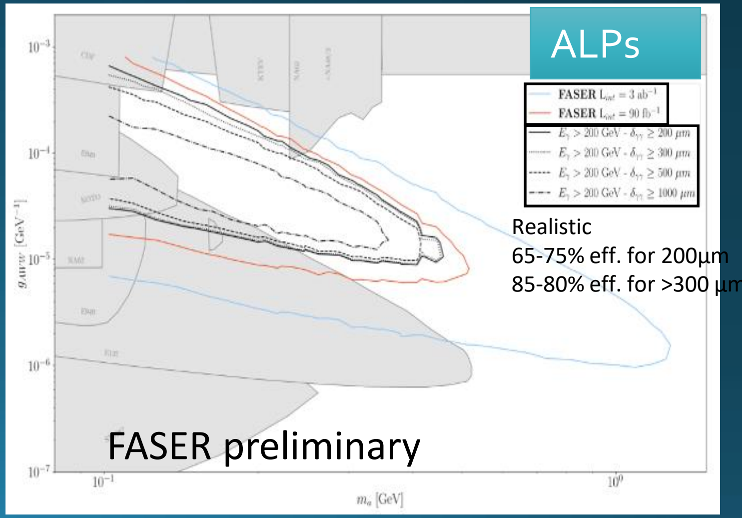


FASER/FASERν detector



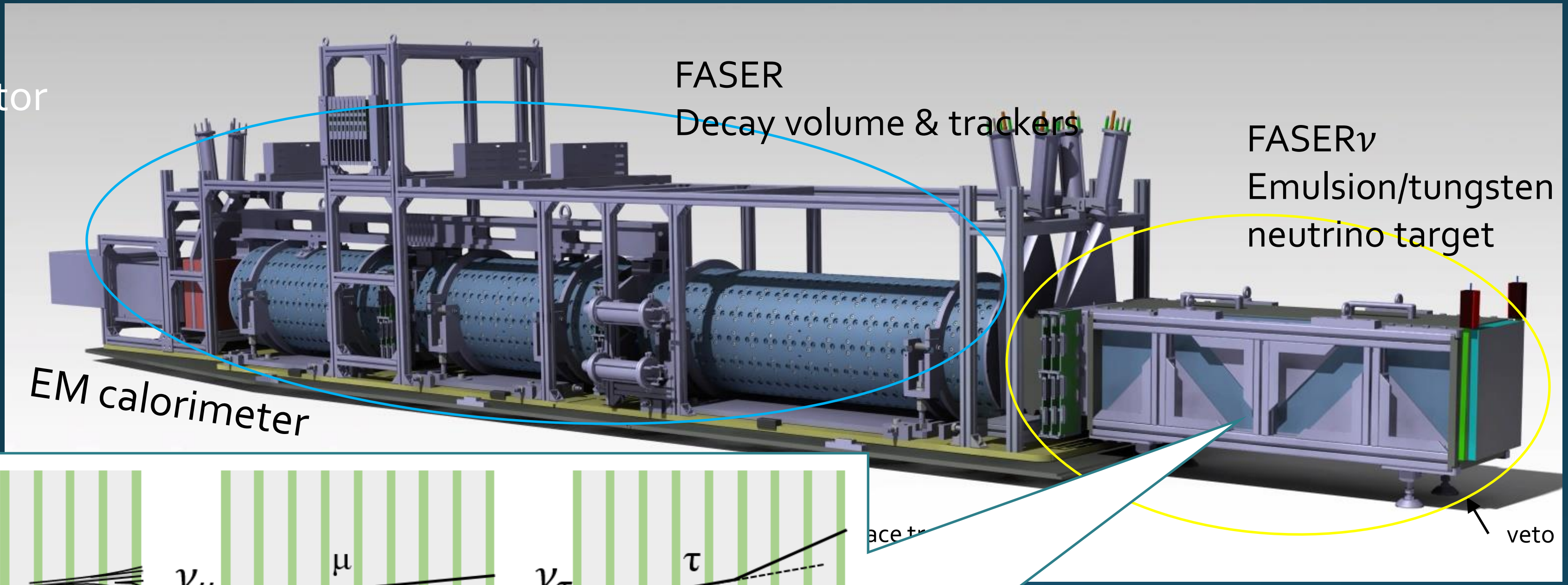




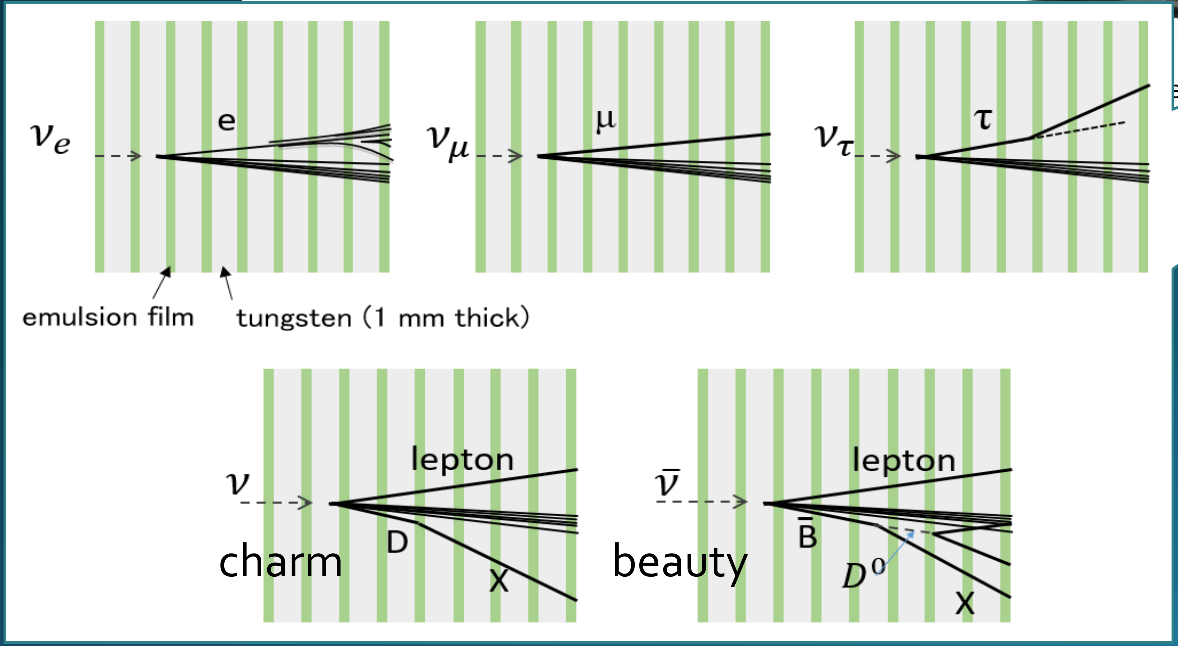


FASER+FASERν detector in Run3 (2022-2025)

5m long detector

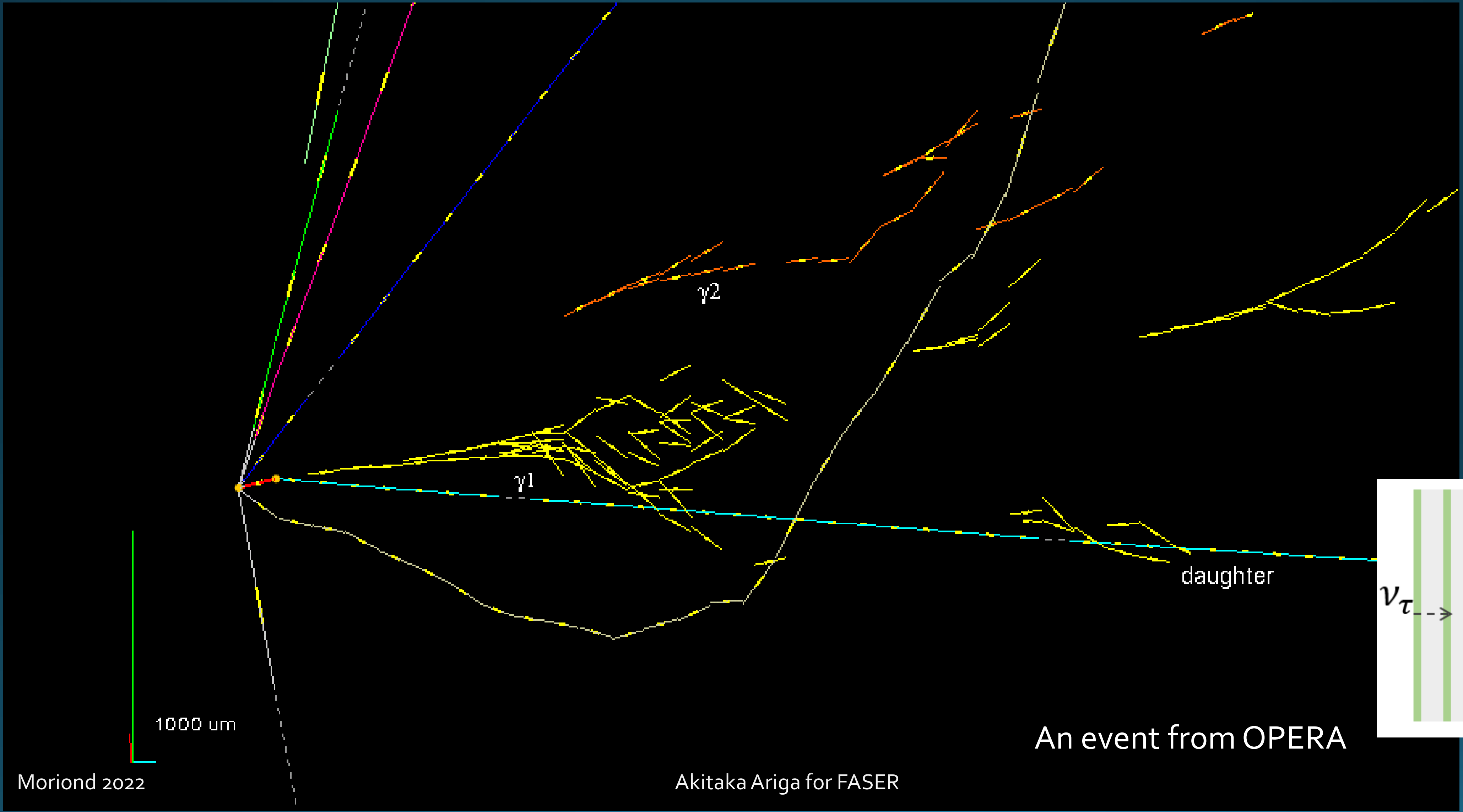


Forward beam (A′, ν, etc)

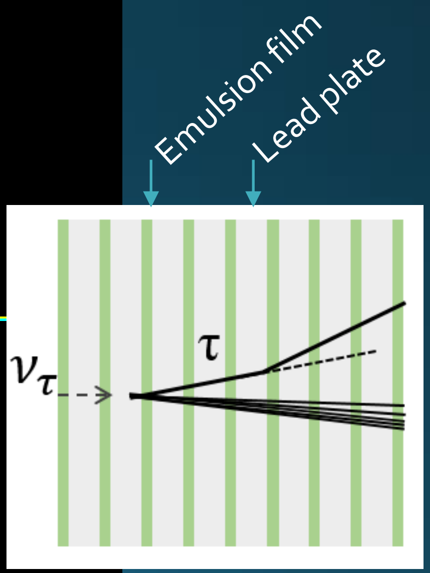


- Emulsion films = trackers with sub-micron spatial resolution, $\sigma_{intrinsic} \simeq 50\ nm$, $\sigma_{practical} \simeq 0.4\ \mu m$
- 770 1-mm-thick tungsten target and emulsion films
- 25x30 cm², 1.1 m, 1.1 tons (8 λ_{int}, 220X_0)
- Sensitive to 3 flavor neutrinos
- Muon ID in track length in tungsten
- Replace emulsions 3 times a year

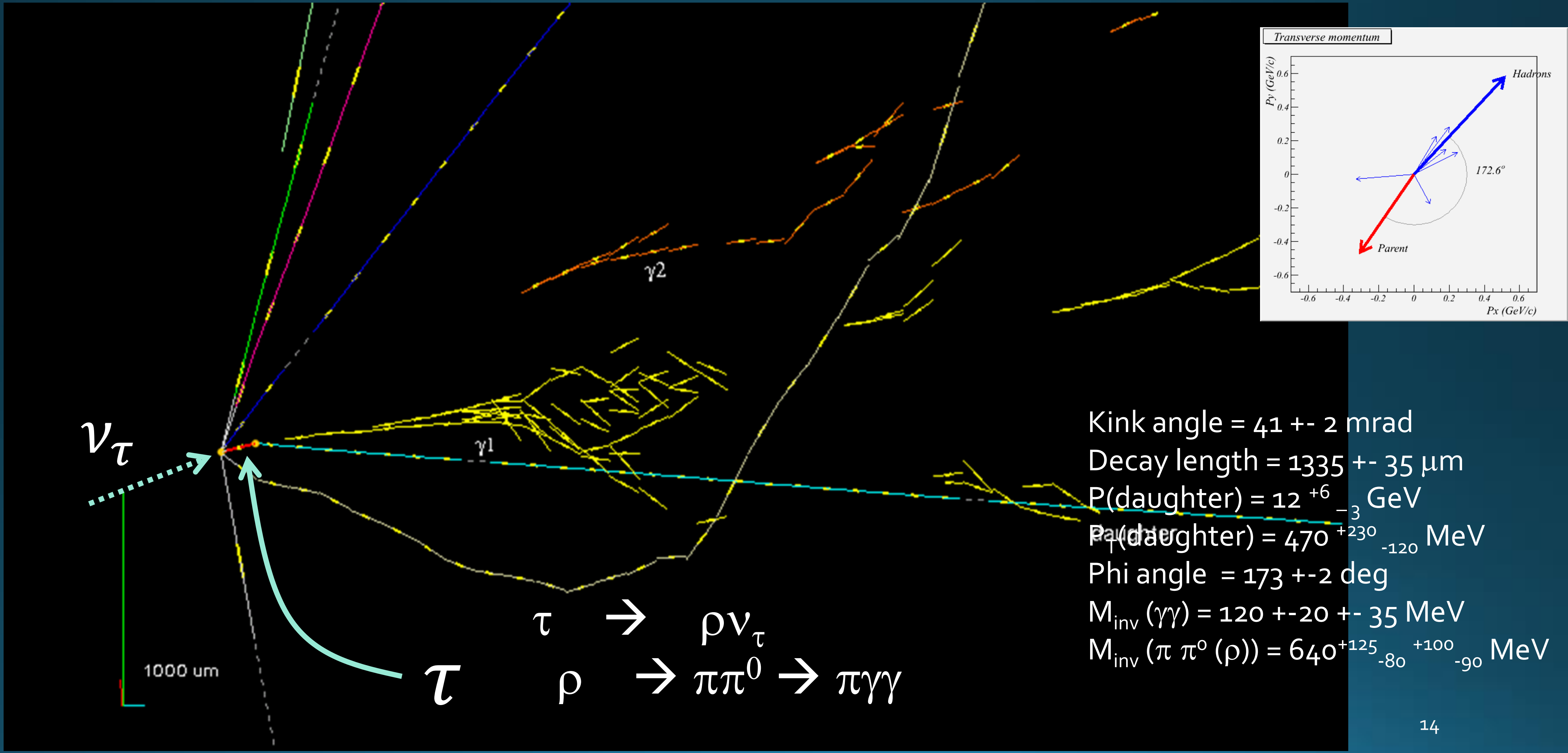
Emulsion-based neutrino detector



An event from OPERA



Emulsion-based neutrino detector



Kink angle = 41 +- 2 mrad

Decay length = 1335 +- 35 μm

P(daughter) = 12^{+6}_{-3} GeV

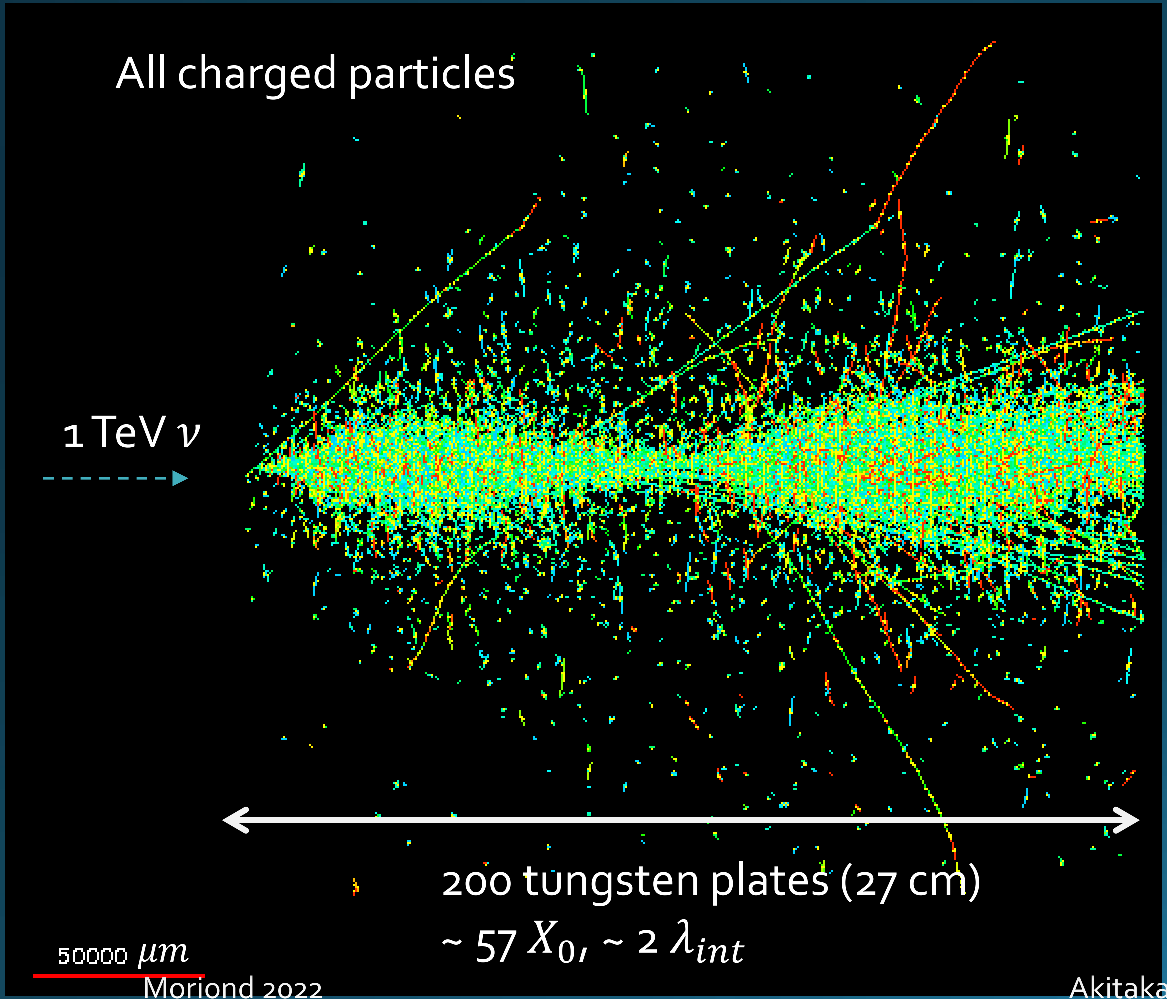
P_T(daughter) = 470^{+230}_{-120} MeV

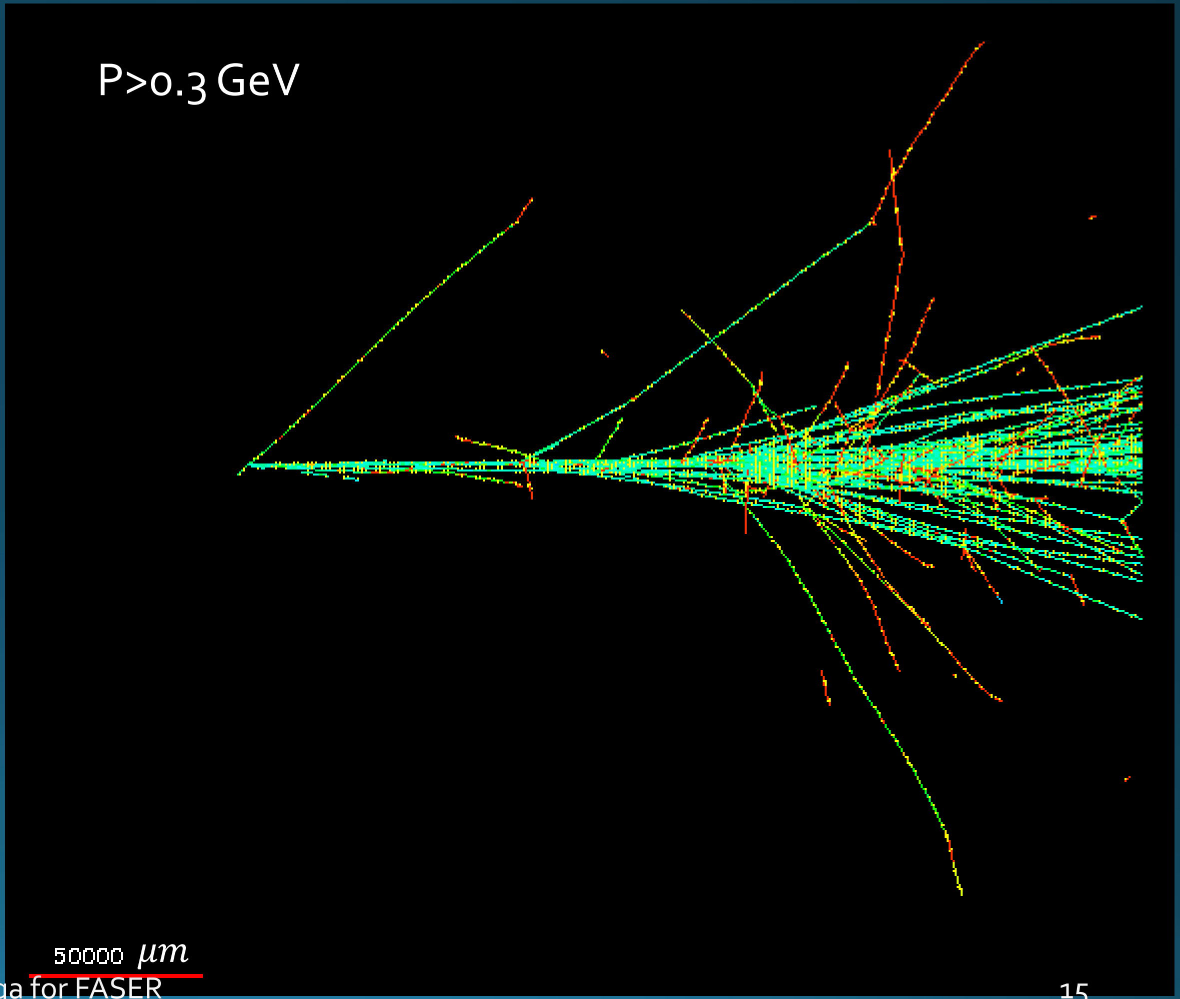
Phi angle = 173 +-2 deg

M_{inv} (γγ) = 120 +-20 +- 35 MeV

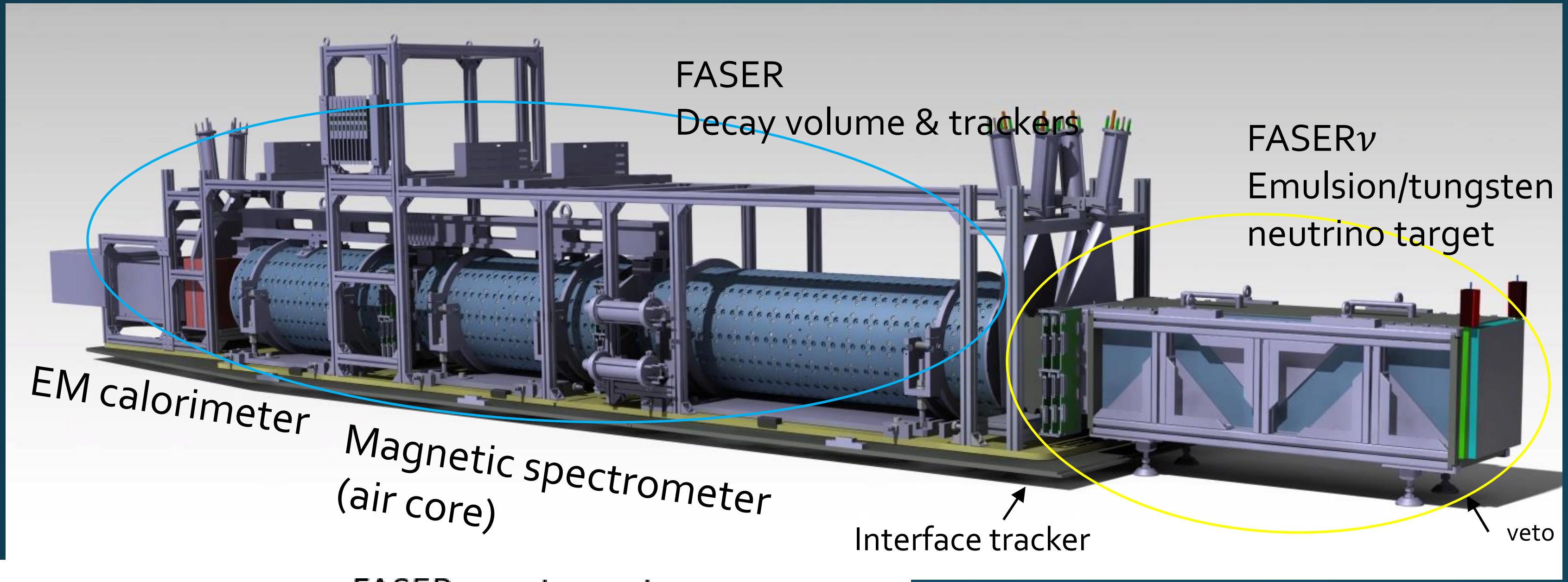
M_{inv} (π π° (ρ)) = 640^{+125}_{-80} $^{+100}_{-90}$ MeV

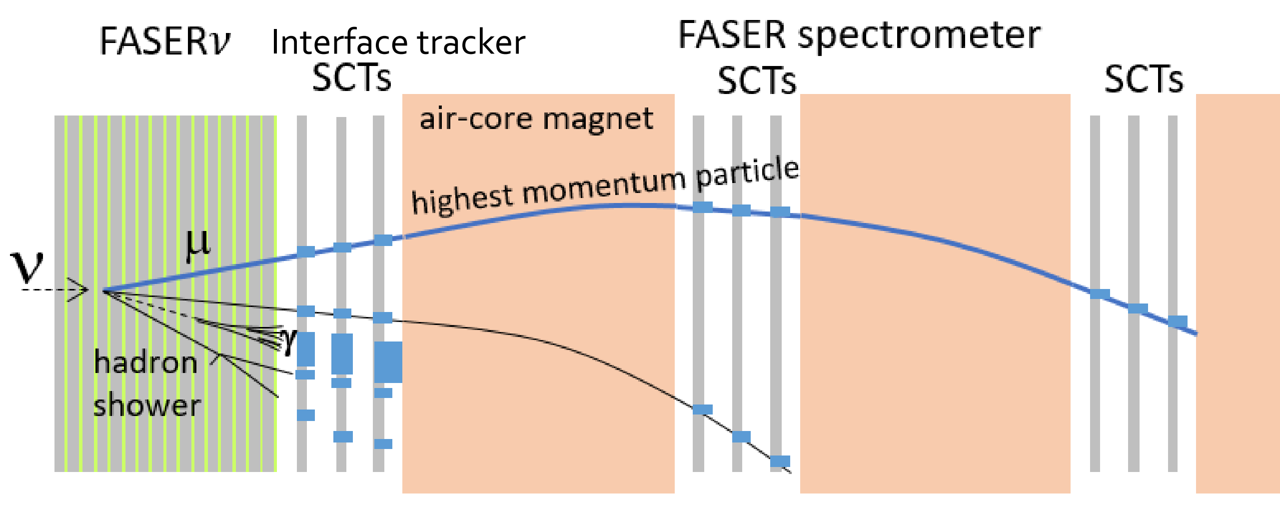
Simulated 1 TeV ν_μ CC interaction





FASER+FASERν detector in Run3 (2022-2025)





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

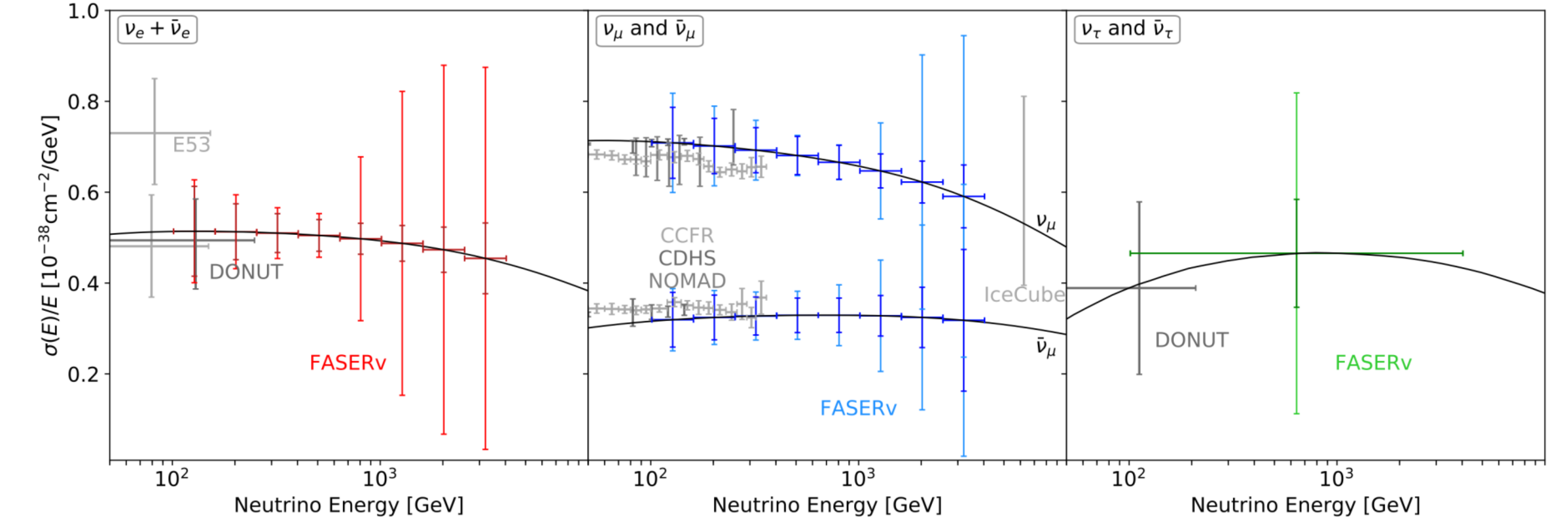
Neutrino cross sections

arXiv:2105.08270

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

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}	$21.6^{+12.5}_{-6.9}$

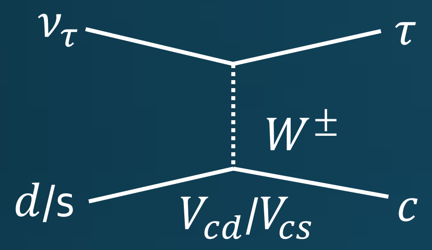
Expected CC interactions with 150 fb^{-1}



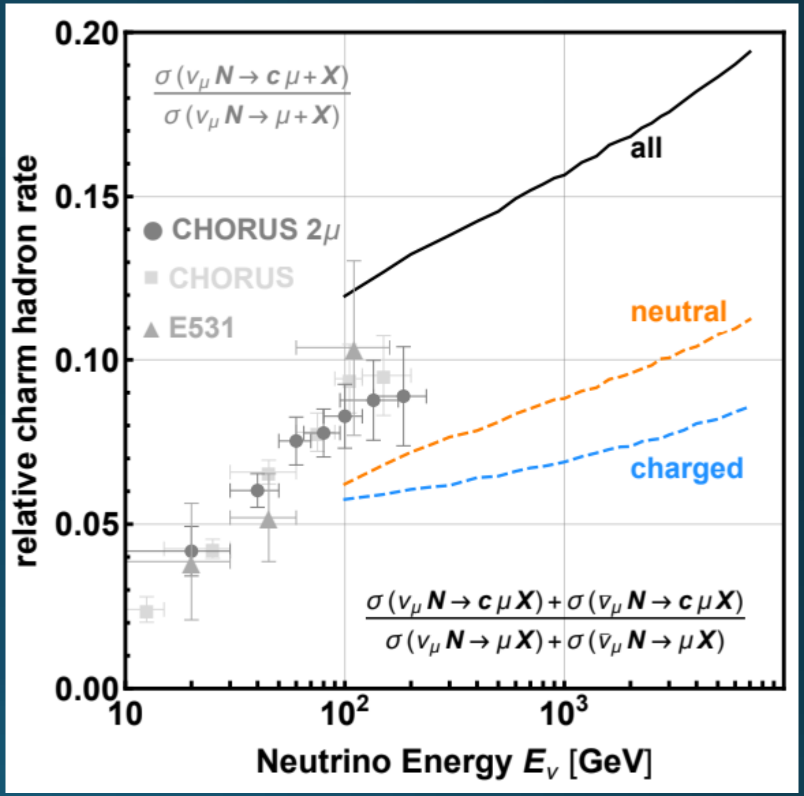
Projected cross section sensitivities

Heavy-flavor-associated channels

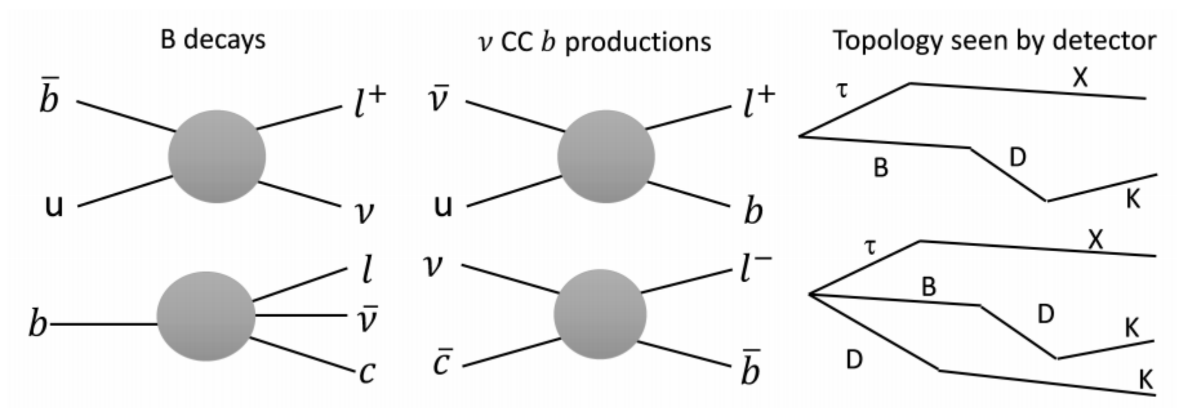
- Measure charm production channels
  - Large rate ~ 15% ν CC events, $\mathcal{O}(1000)$ events
  - First measurement of ν_e induced charm prod.



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



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



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

$\nu N \to \ell BDX$

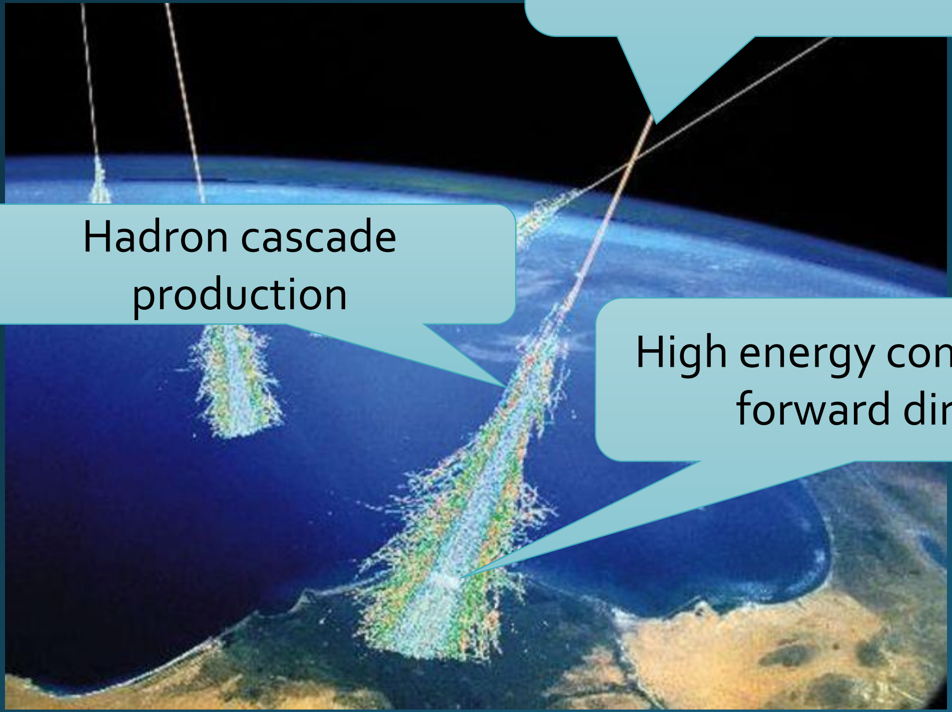
Eur. Phys. J. C (2020) **80**: 61

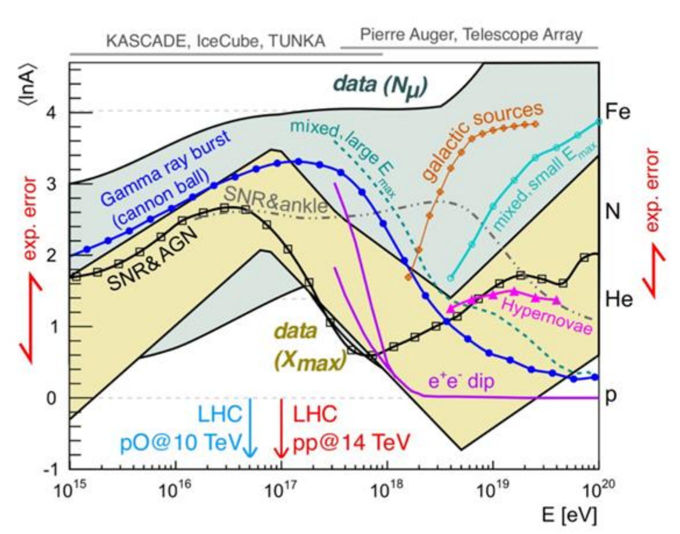
Relation to cosmic rays, atmospheric leptons

Primary cosmic ray from extrasolar source

Hadron cascade production

High energy components in forward direction

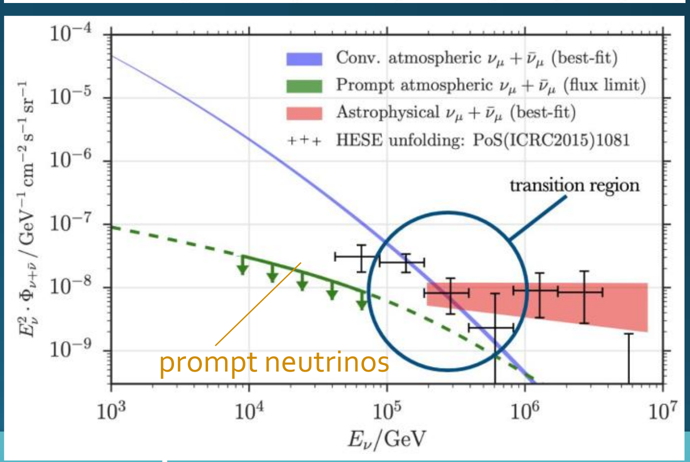




Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

Muon excess

π / K



Prompt neutrinos

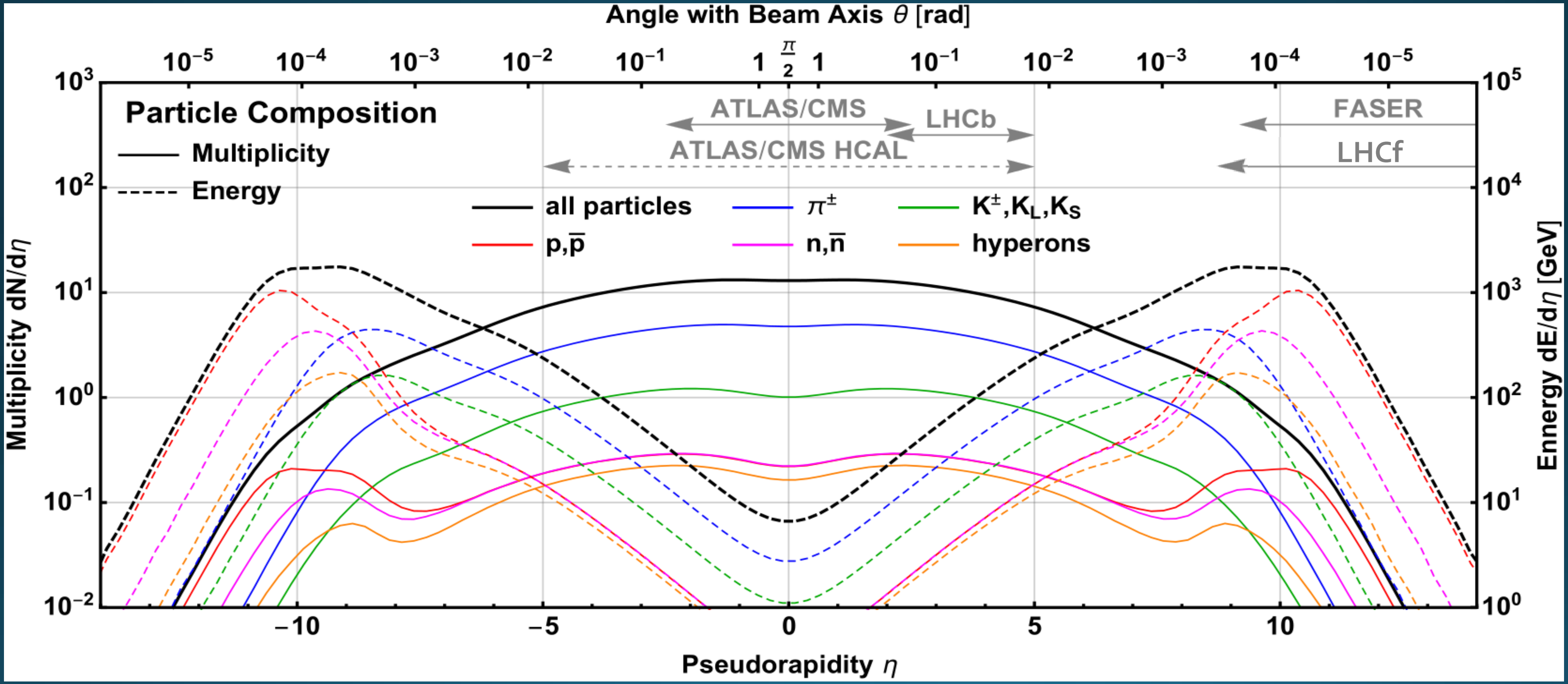
IceCube Collaboration, Astrophys. J. 833 (2016)

Charm

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

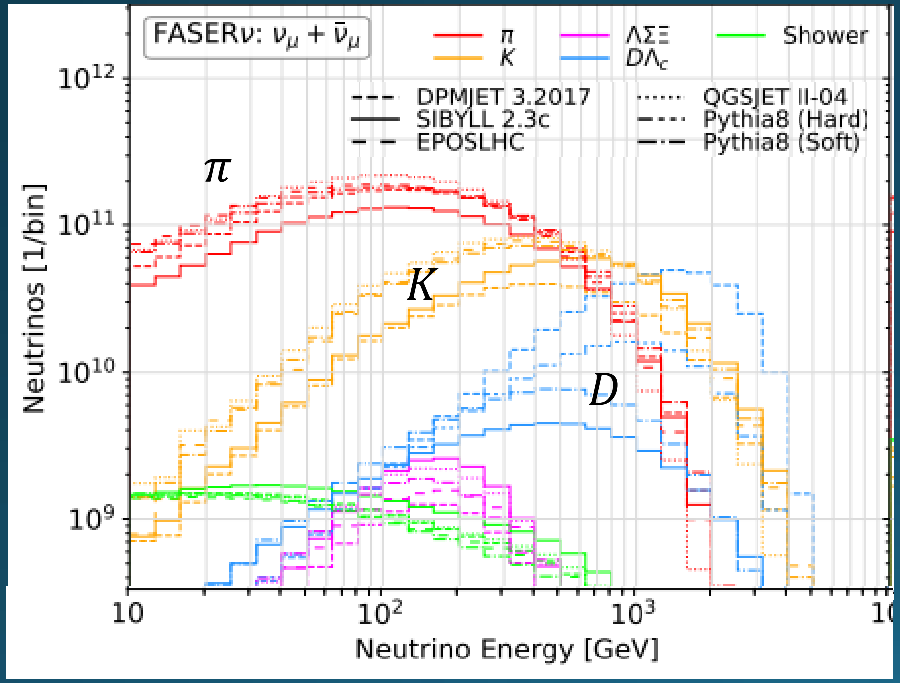
Neutrinos = proxy of forward hadron production



Neutrinos = proxy of forward hadron production

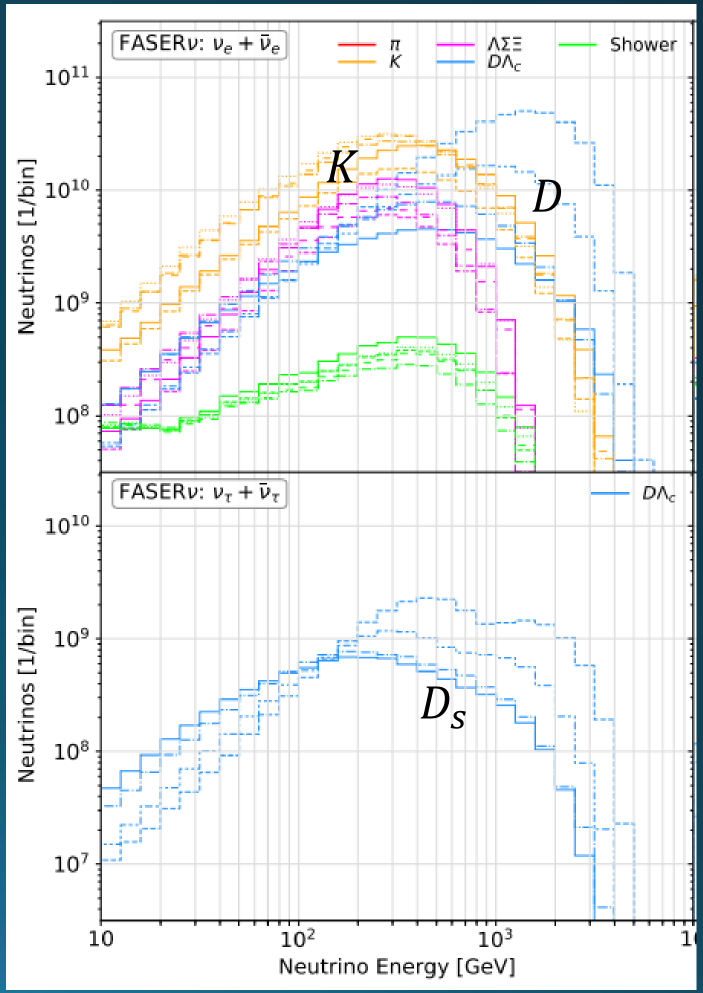
- Pion, Kaon, charm contribute to different part of energy spectra and flavor

ν_μ



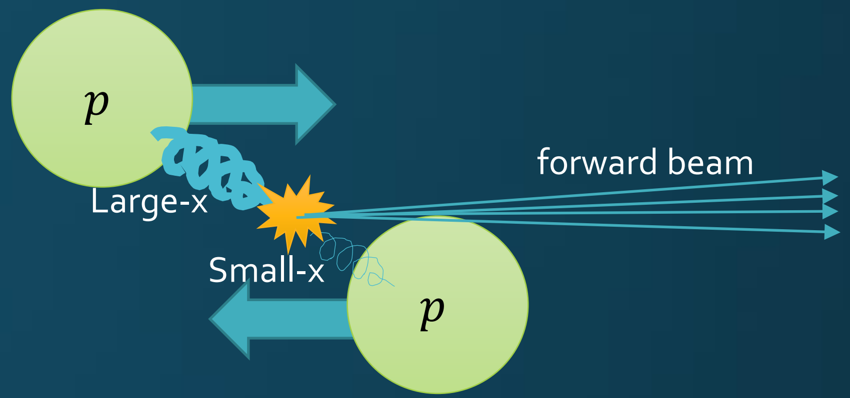
ν_e

ν_τ



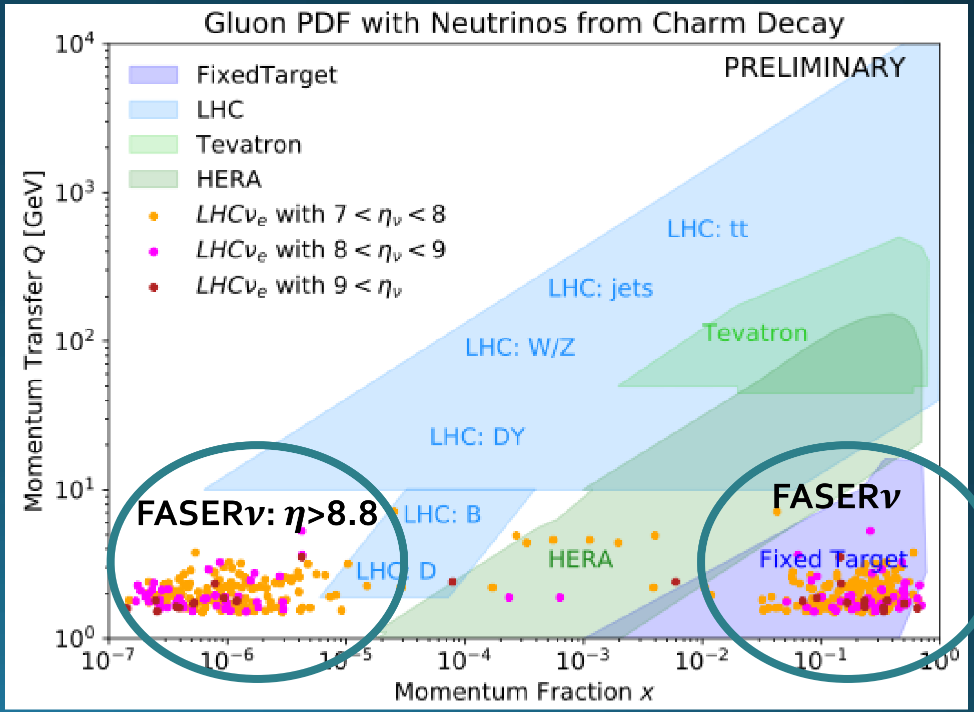
- FASERν provides important inputs to validate/improve generators → Muon excess, prompt neutrinos

Further insights on QCD

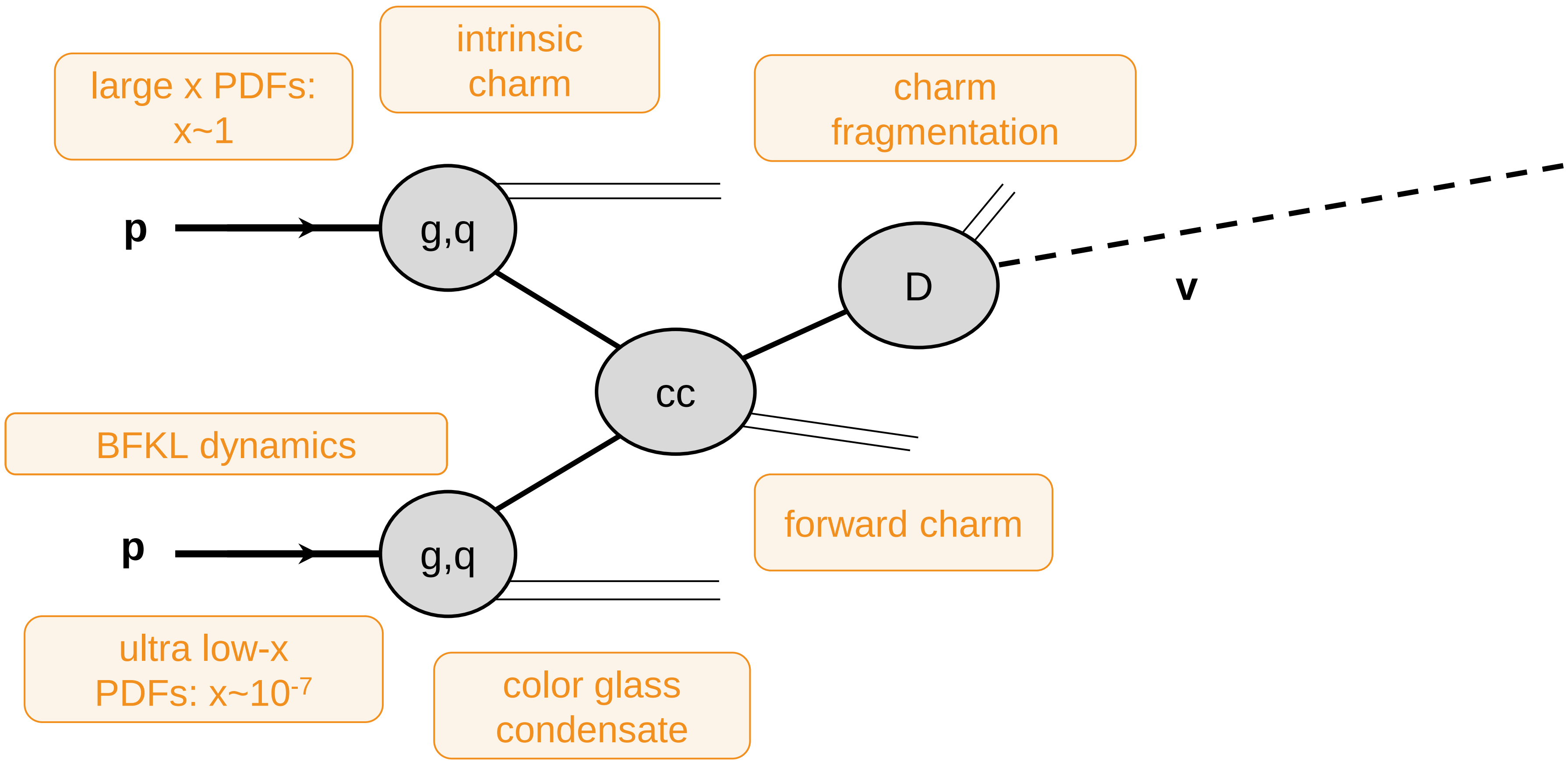


- Asymmetric gluon-gluon interaction, small-x × large-x
- Neutrinos from charm decay could allow to test transition to small-x factorization, probe intrinsic charm
- Deep understanding of neutrinos from charm decays (prompt neutrinos) is important for astrophysical neutrino observations

2203.05090



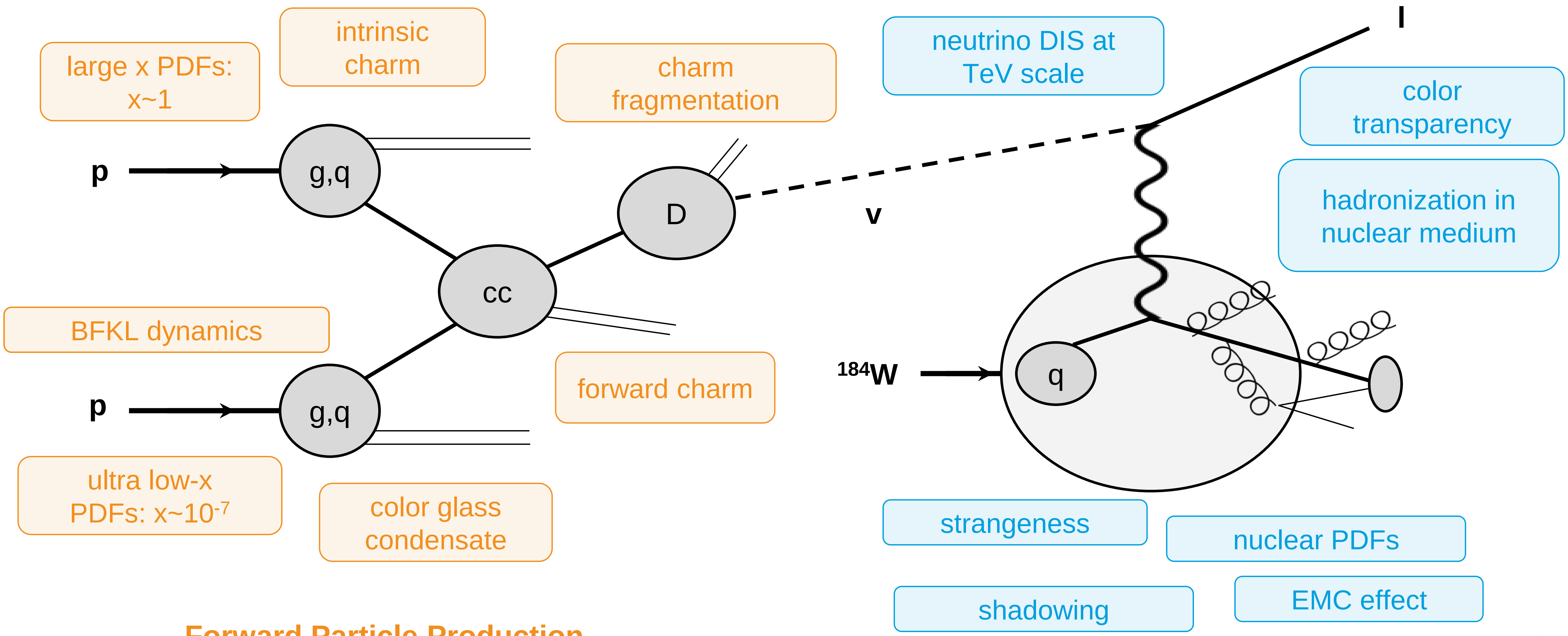
QCD using LHC Neutrinos



Forward Particle Production

QCD using LHC Neutrinos

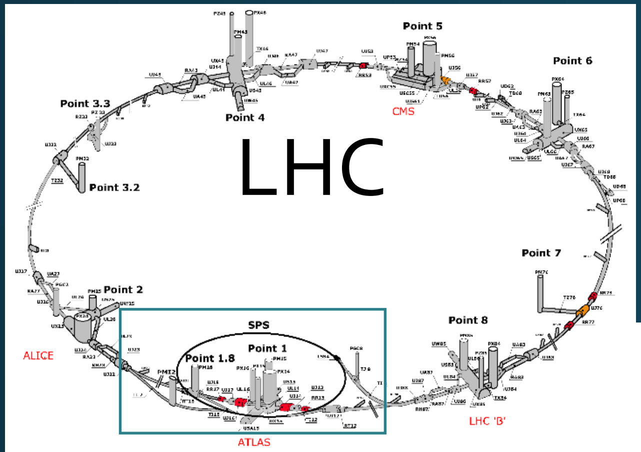
TeV Energy Neutrino Interaction

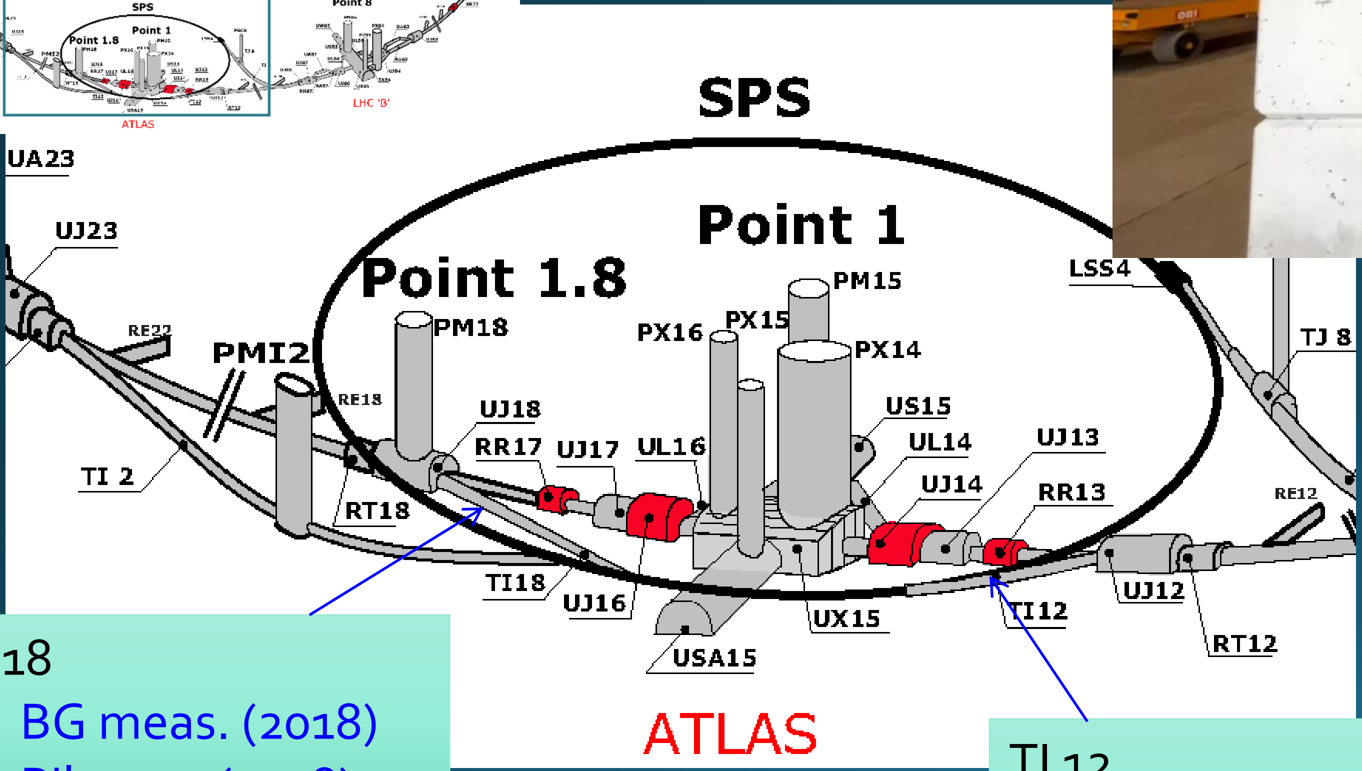


Forward Particle Production

Results from 2018 run

FASER sites



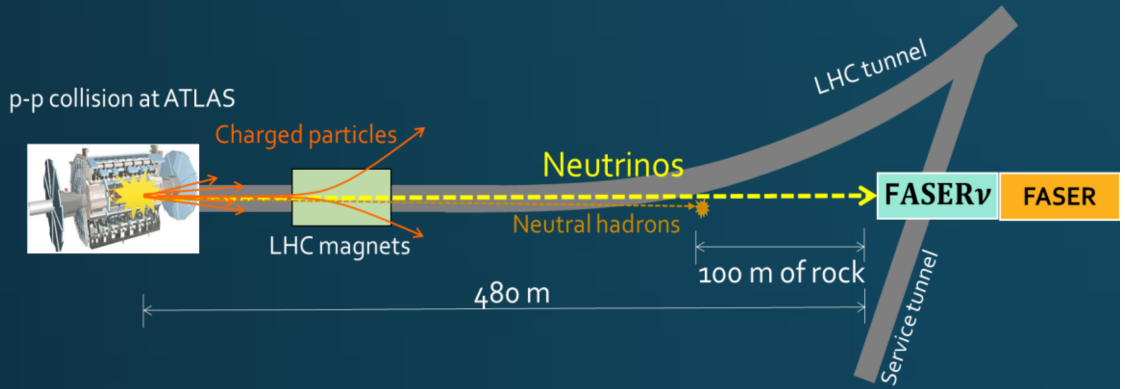


TI 18
- BG meas. (2018)
- Pilot run (2018)

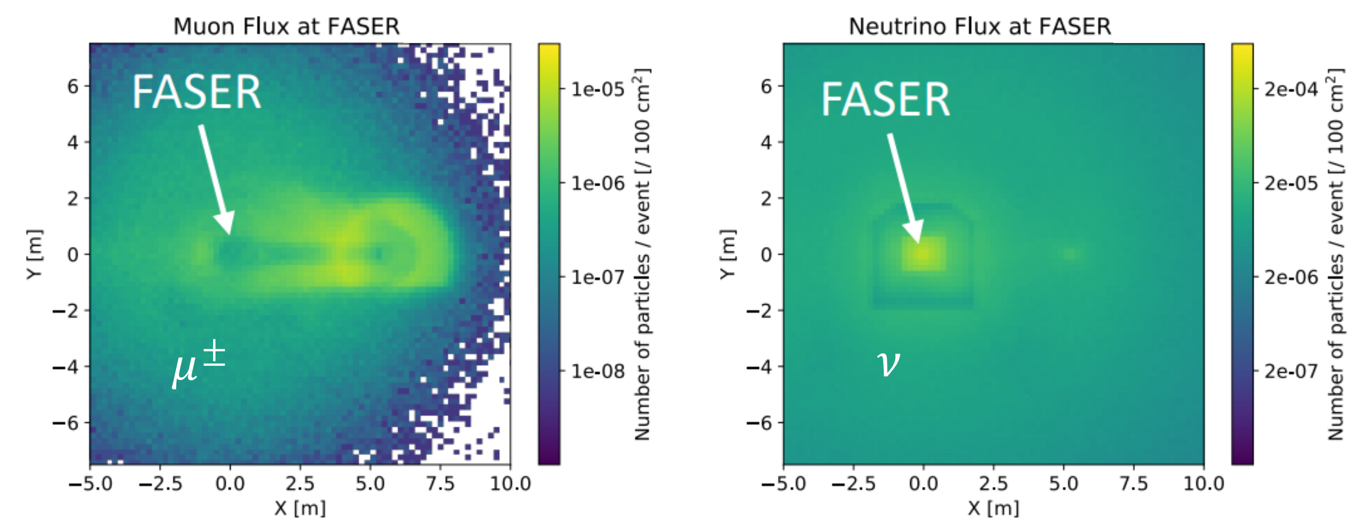
BG measurements, pilot run in 2018

TI 12
- BG meas. (2018)
- Physics run (2022-)

Particle fluence at the site

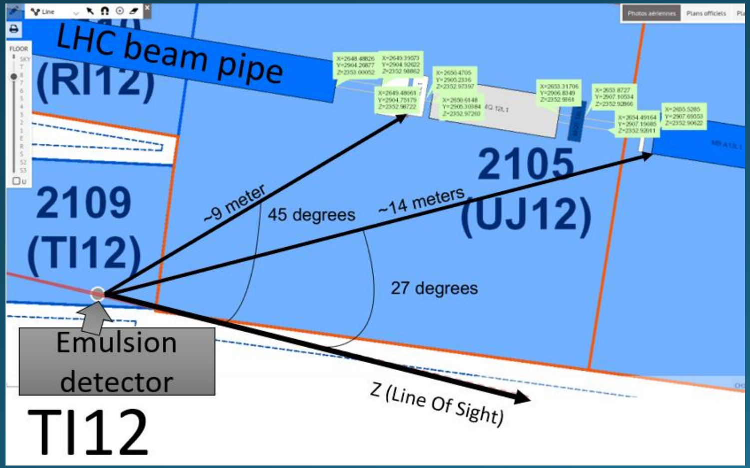


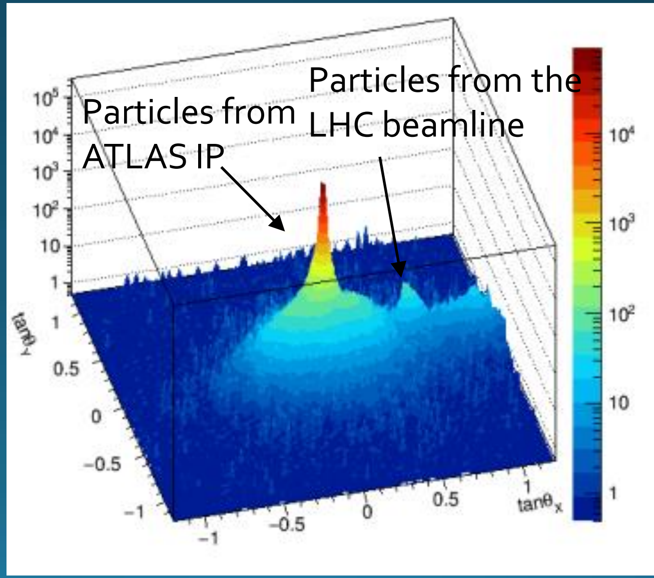
BDSim result for TI12, Lefebvre ICHEP2020



- *In-situ* measurements in 2018

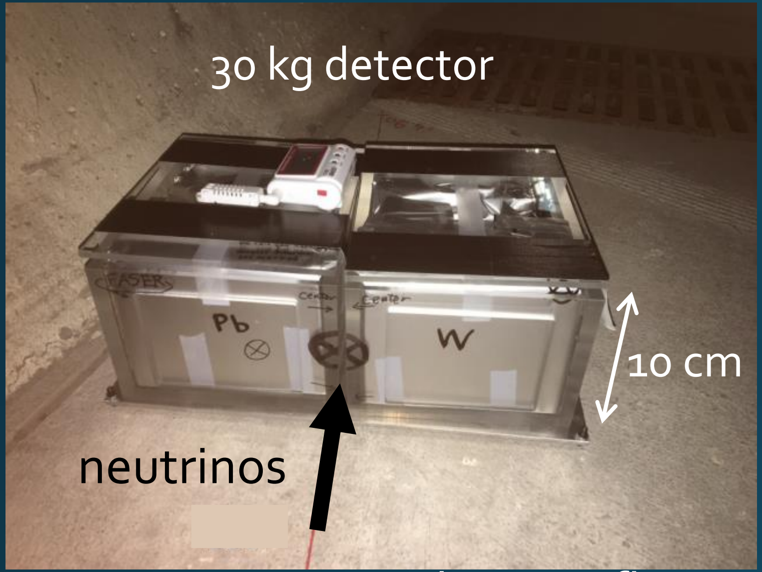
ν





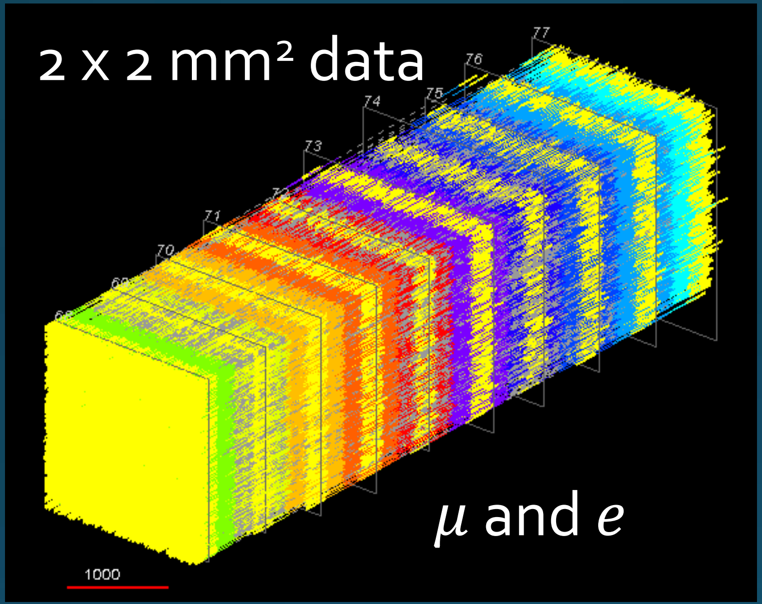
	Flux in main peak [fb/cm²]
TI18 data	$1.7 \pm 0.1 \times 10^4$
TI12 data	$1.9 \pm 0.2 \times 10^4$
FLUKA MC	2.5×10^4 (uncertainty 50%)

Pilot neutrino detector in 2018

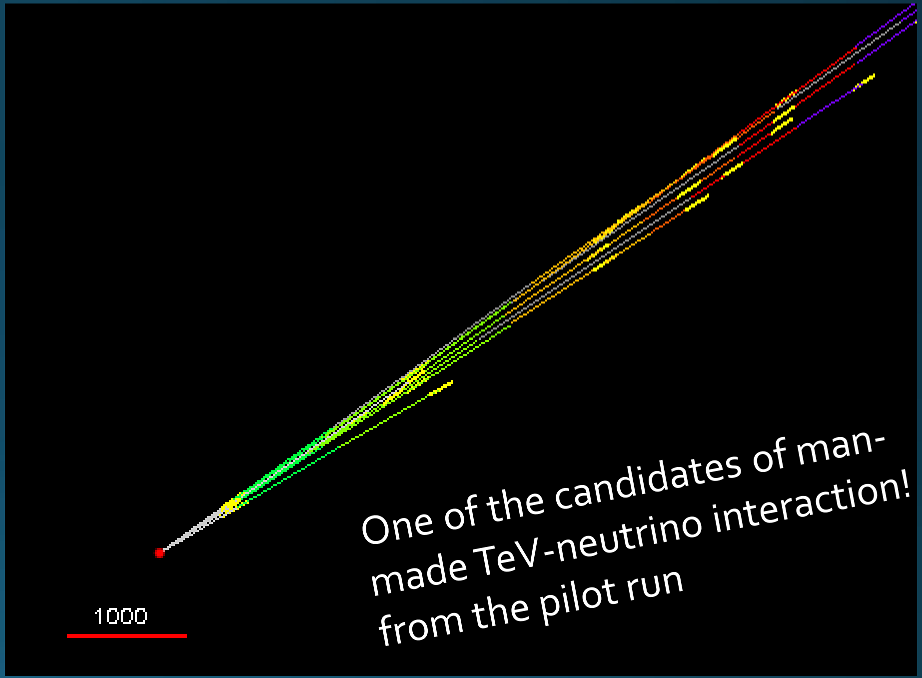


6 weeks, 12.2 fb^{-1}

Proof of principle



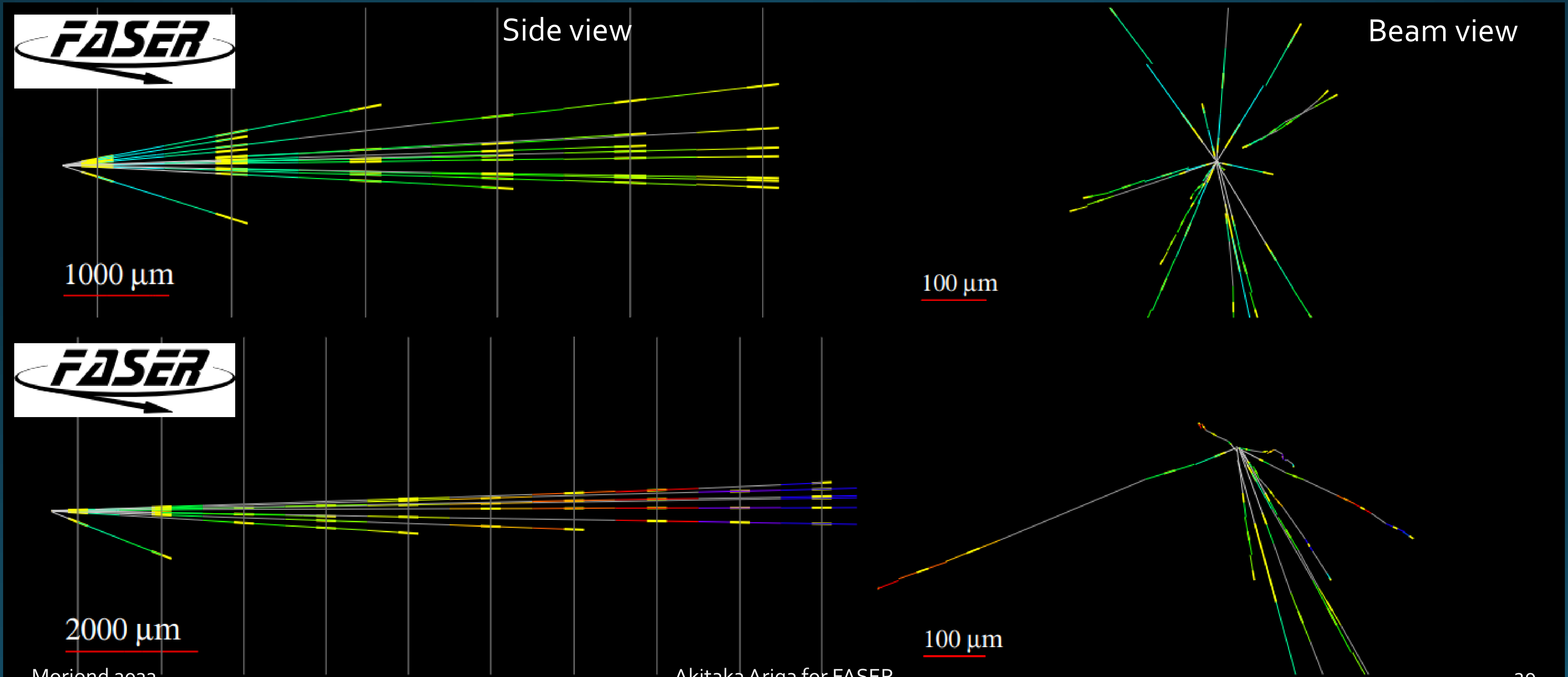
$\simeq 3 \times 10^5$ tracks/cm²



- 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)

Phys. Rev. D 104, L091101 (2021)

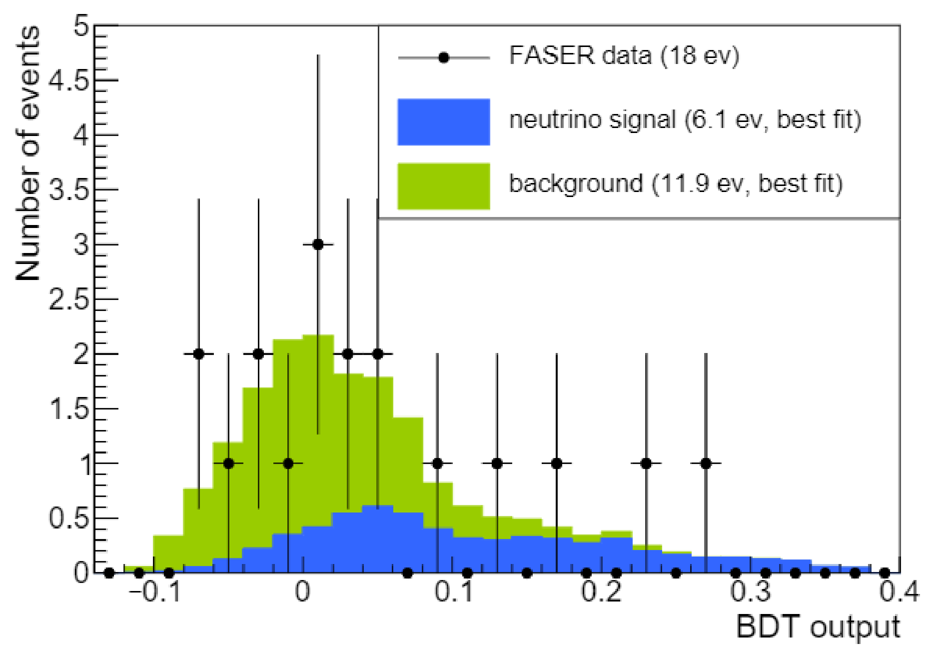
Neutrino interaction candidates



[Phys. Rev. D 104, L091101 (2021)]

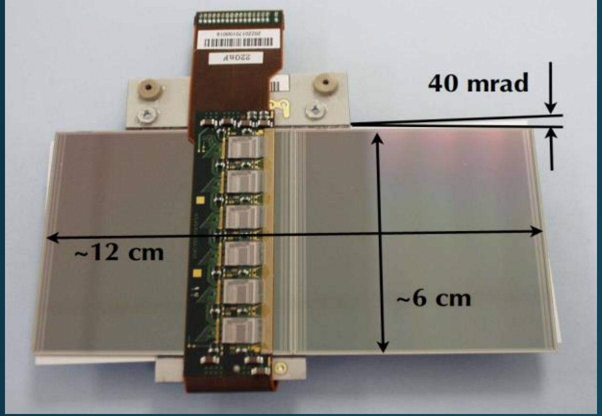
Pilot run event statistics

- 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 → 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

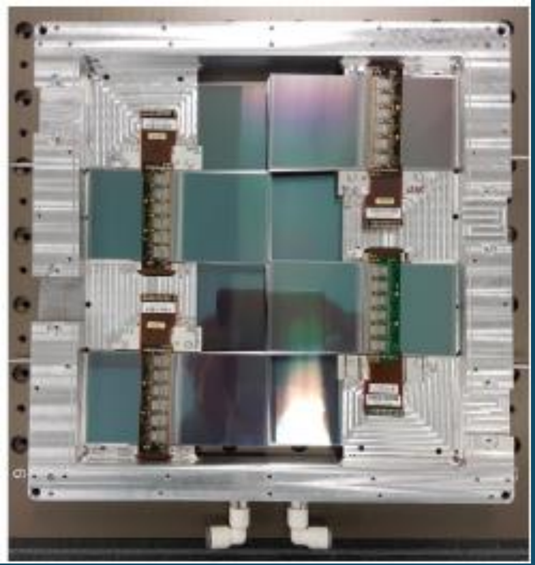


Preparation for LHC Run 3 (2022-)

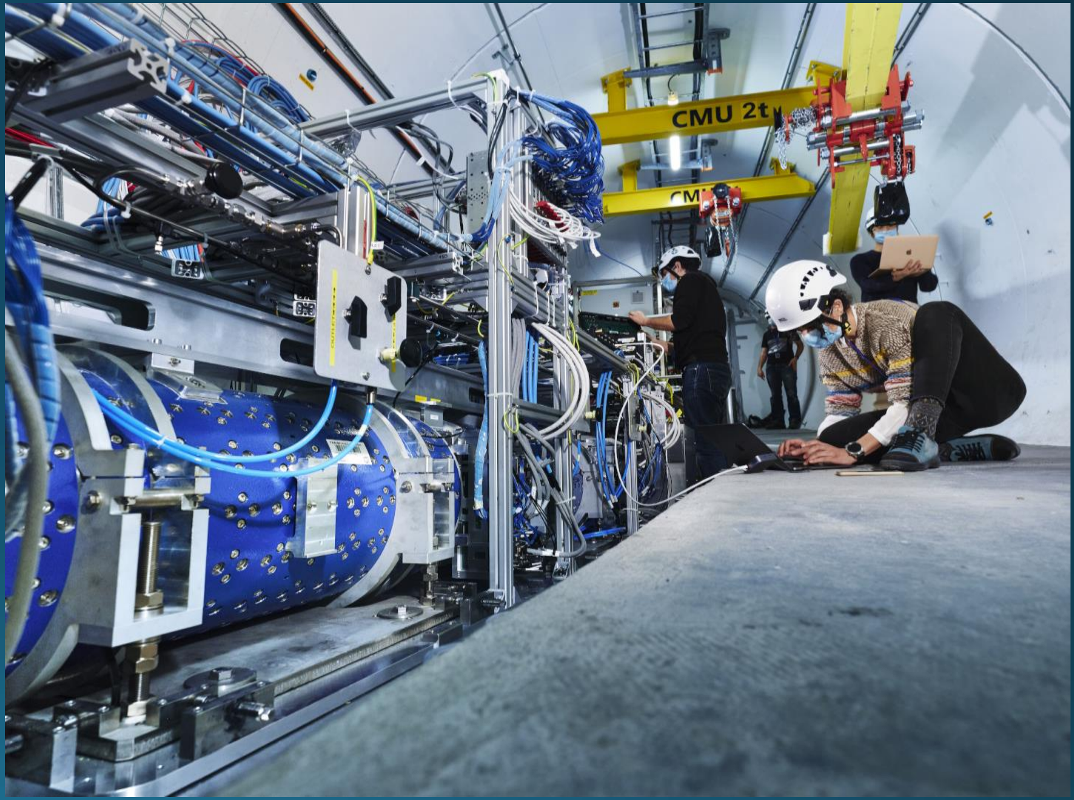
FASER detector components

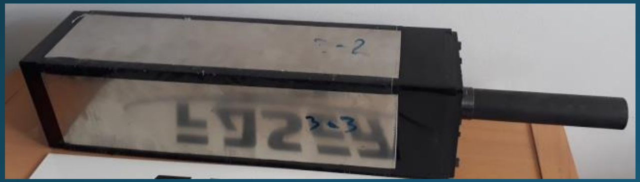


SCT module from ATLAS, 80 um silicon strip detector



Tracking layer = 8 SCT modules

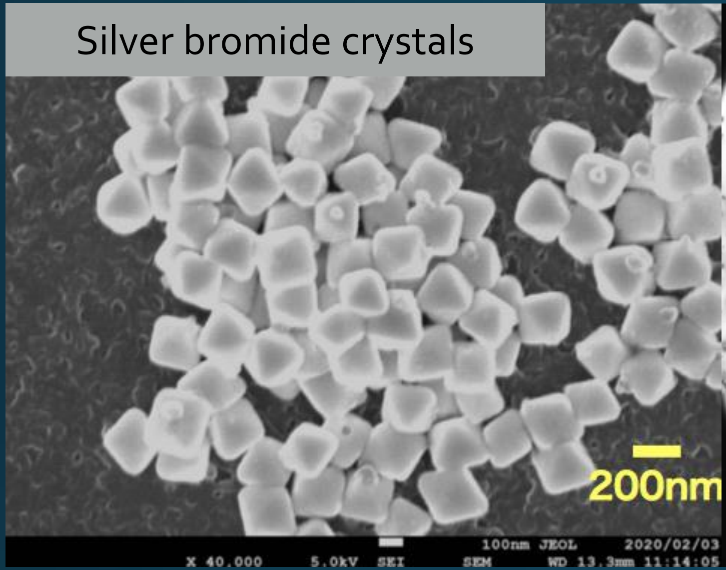


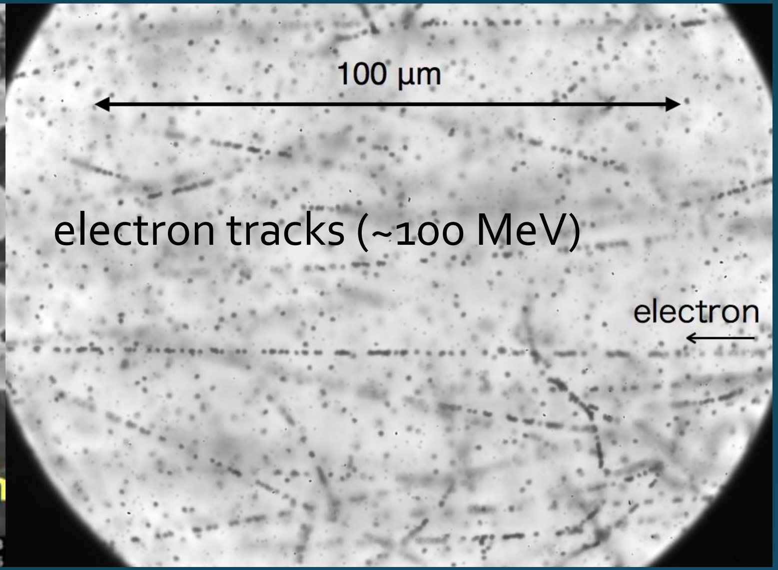


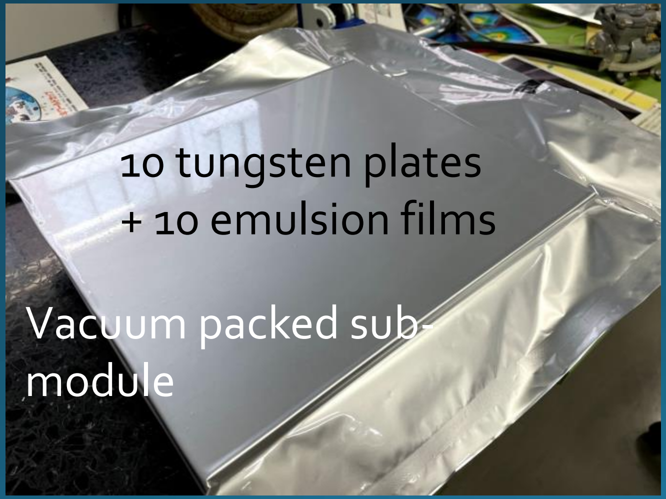
Calorimeter module from LHCb

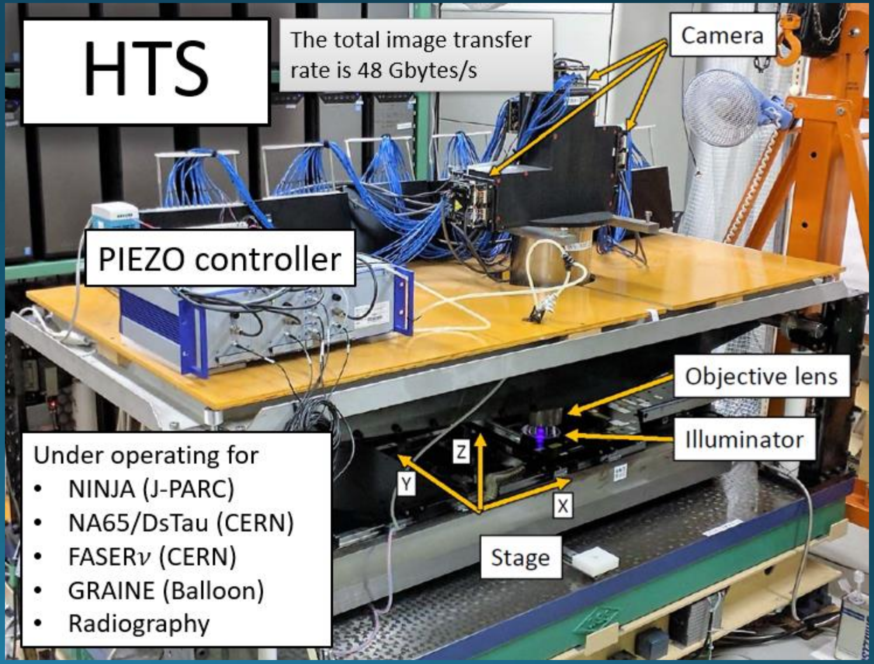
Scintillators

Preparation for Run 3: FASERν detector



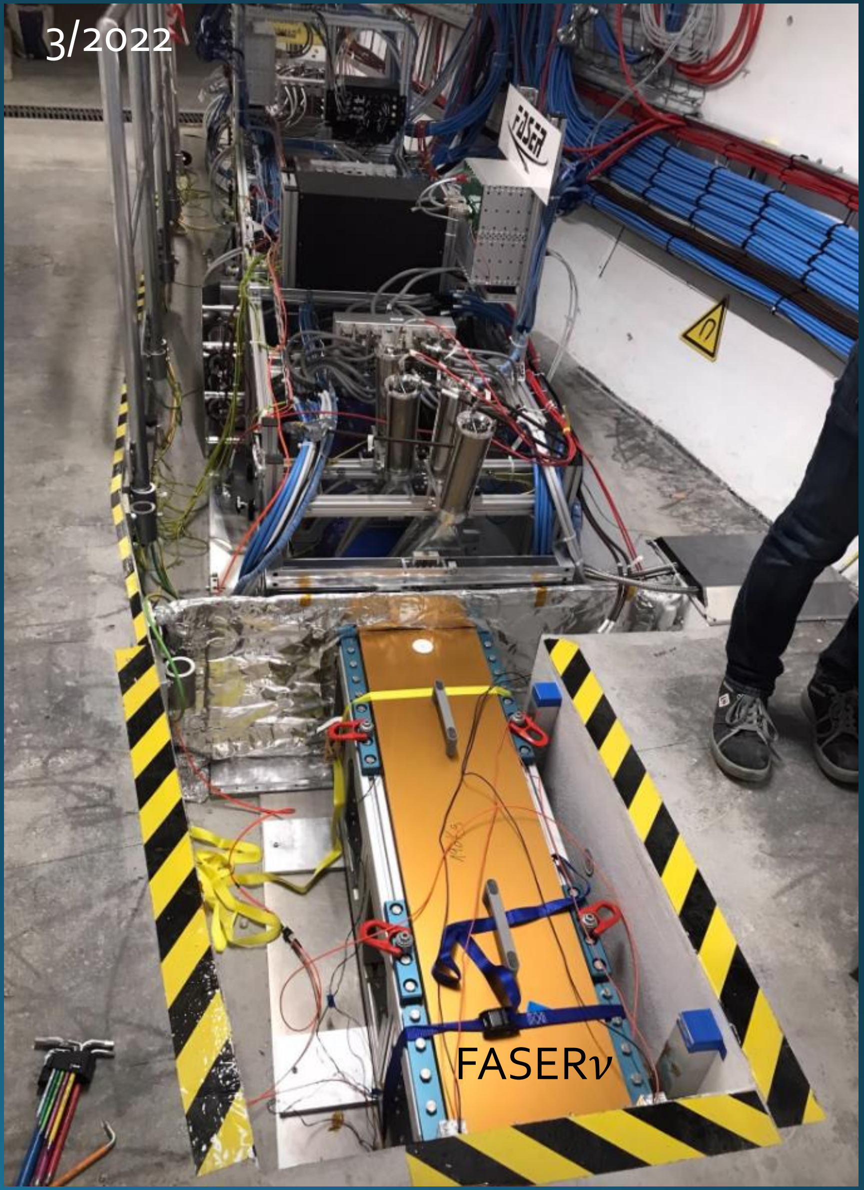


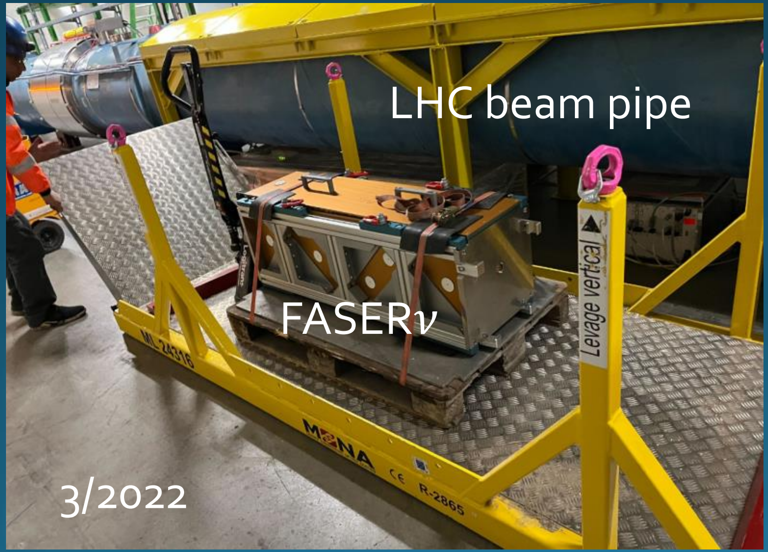




Preparation for Run 3 at site

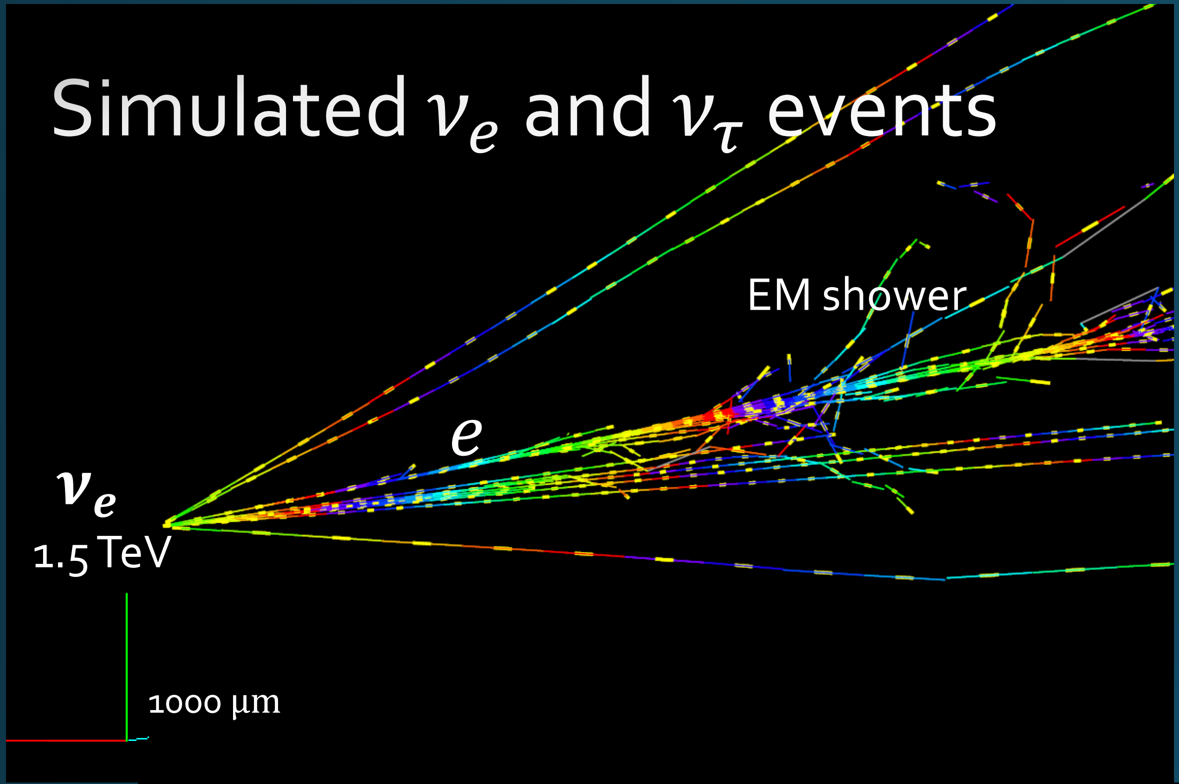
First emulsion detector installed this week!

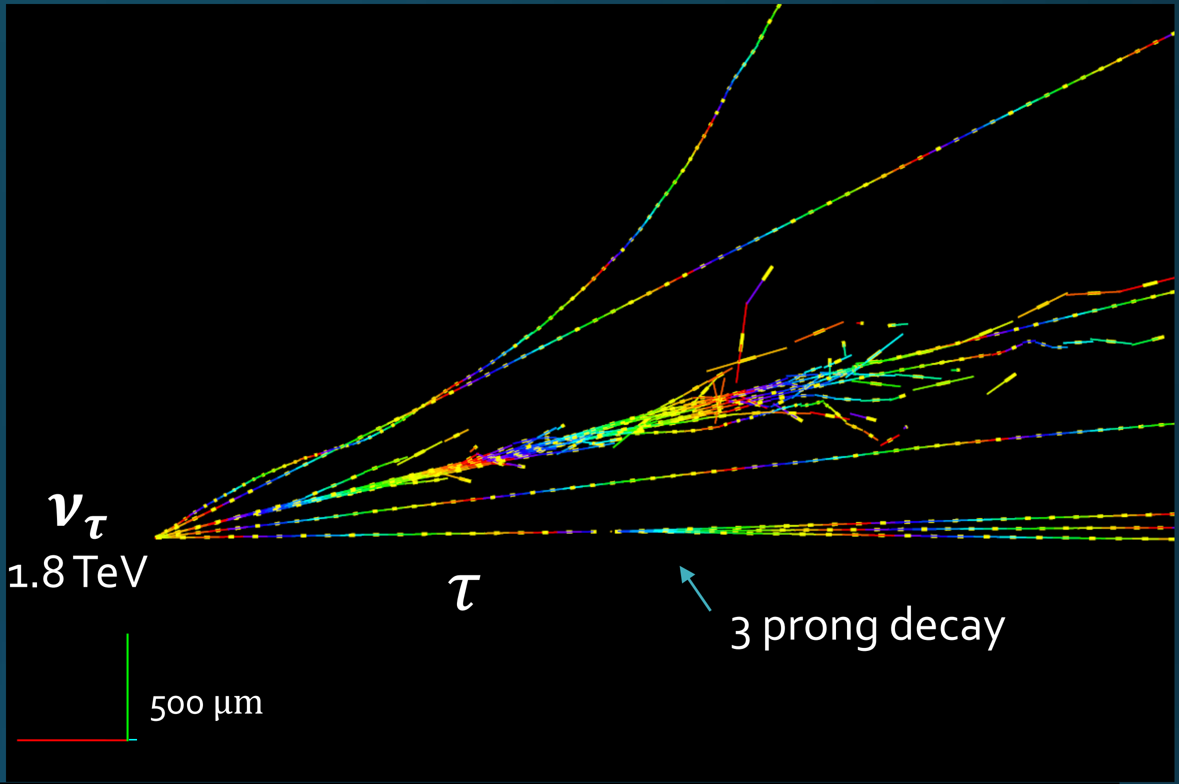


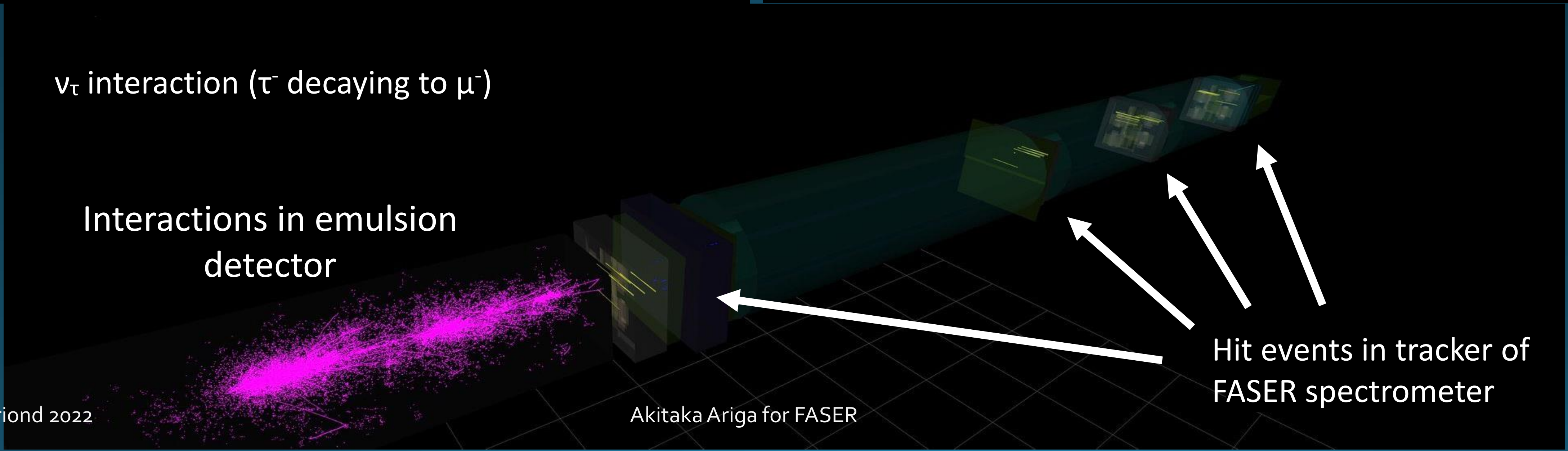


ν

Simulated ν_e and ν_τ events

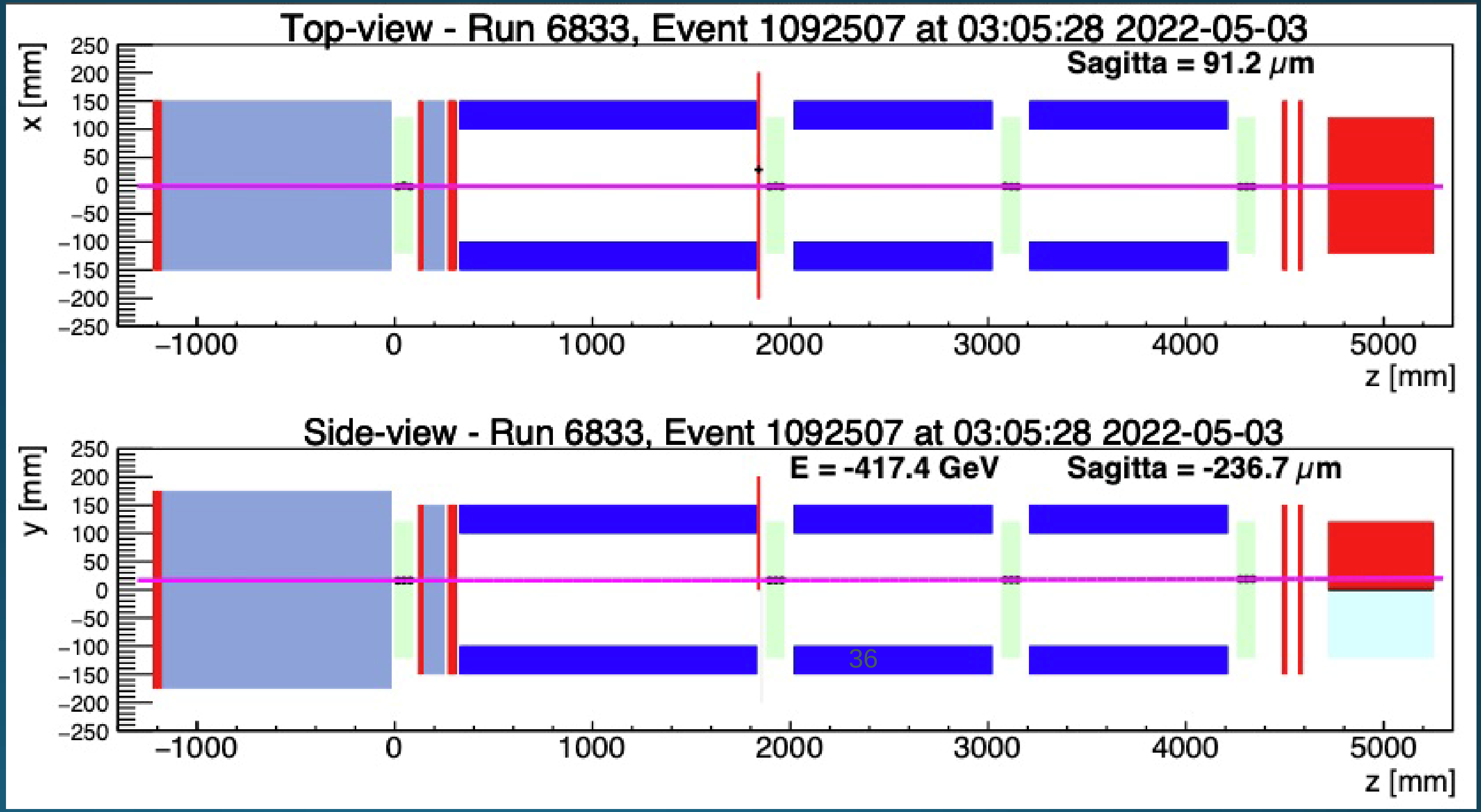






First beam particles in May 2022

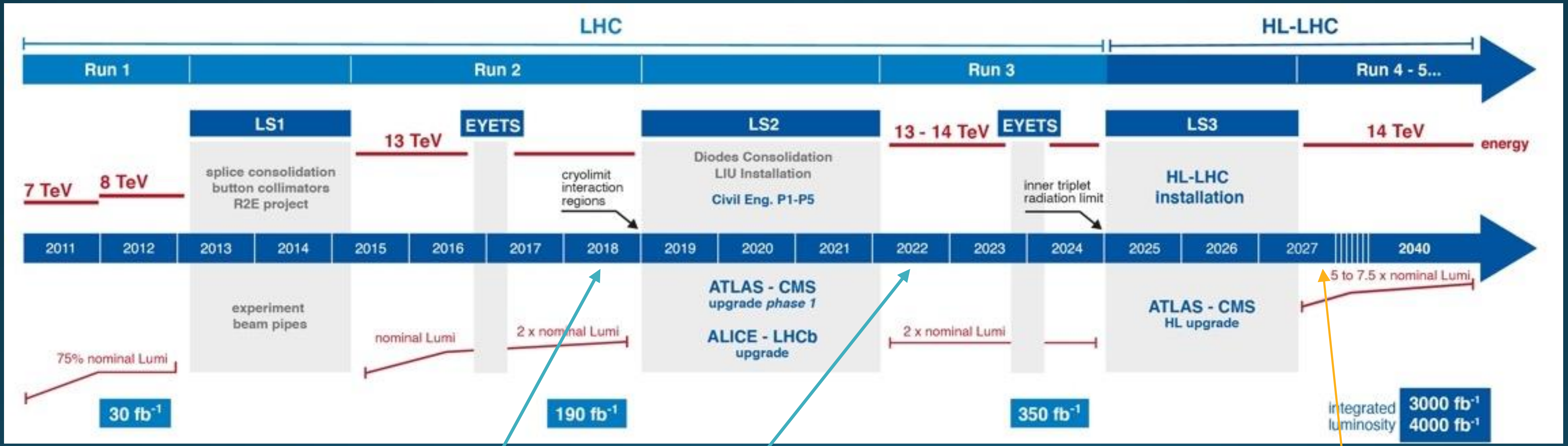
- Saw first beam particles from recent 6.8 TeV beam optics tests!
- First particles traversing full detector, including Fwd Veto and IFT
- Good readiness confirmed toward Run 3



First neutrino interactions will be reported within this year

FASERν/FASERν2 schedule

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



Pilot run & background measurements in 2018

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

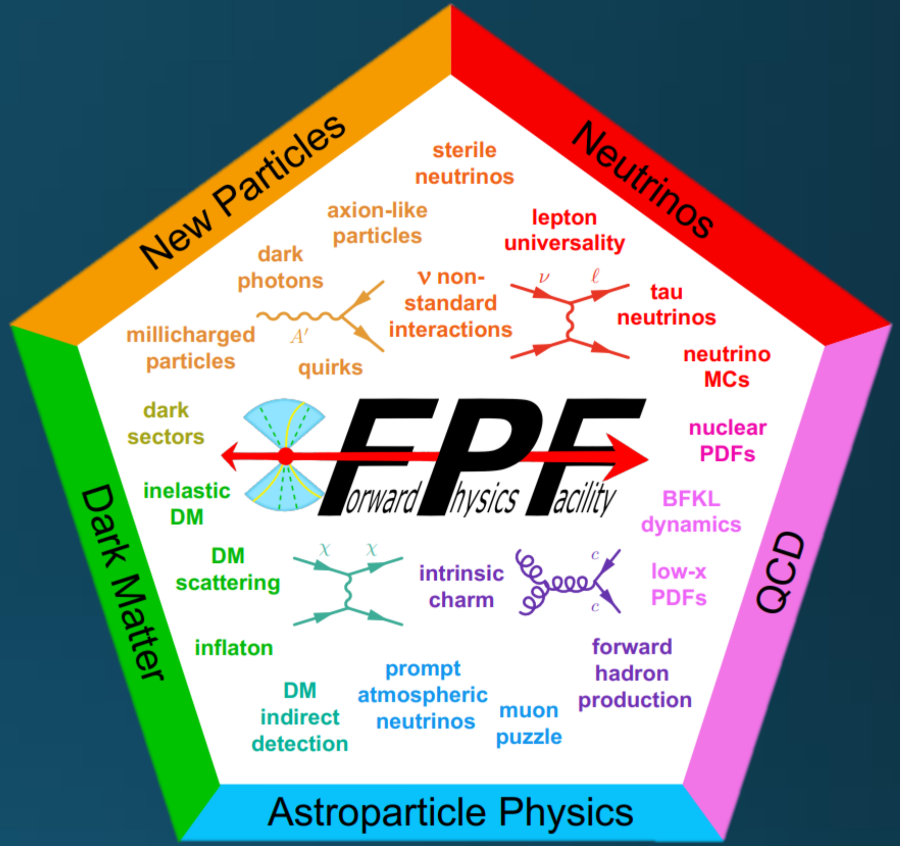
Forward experiment in HL-LHC

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

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

Physics Motivation

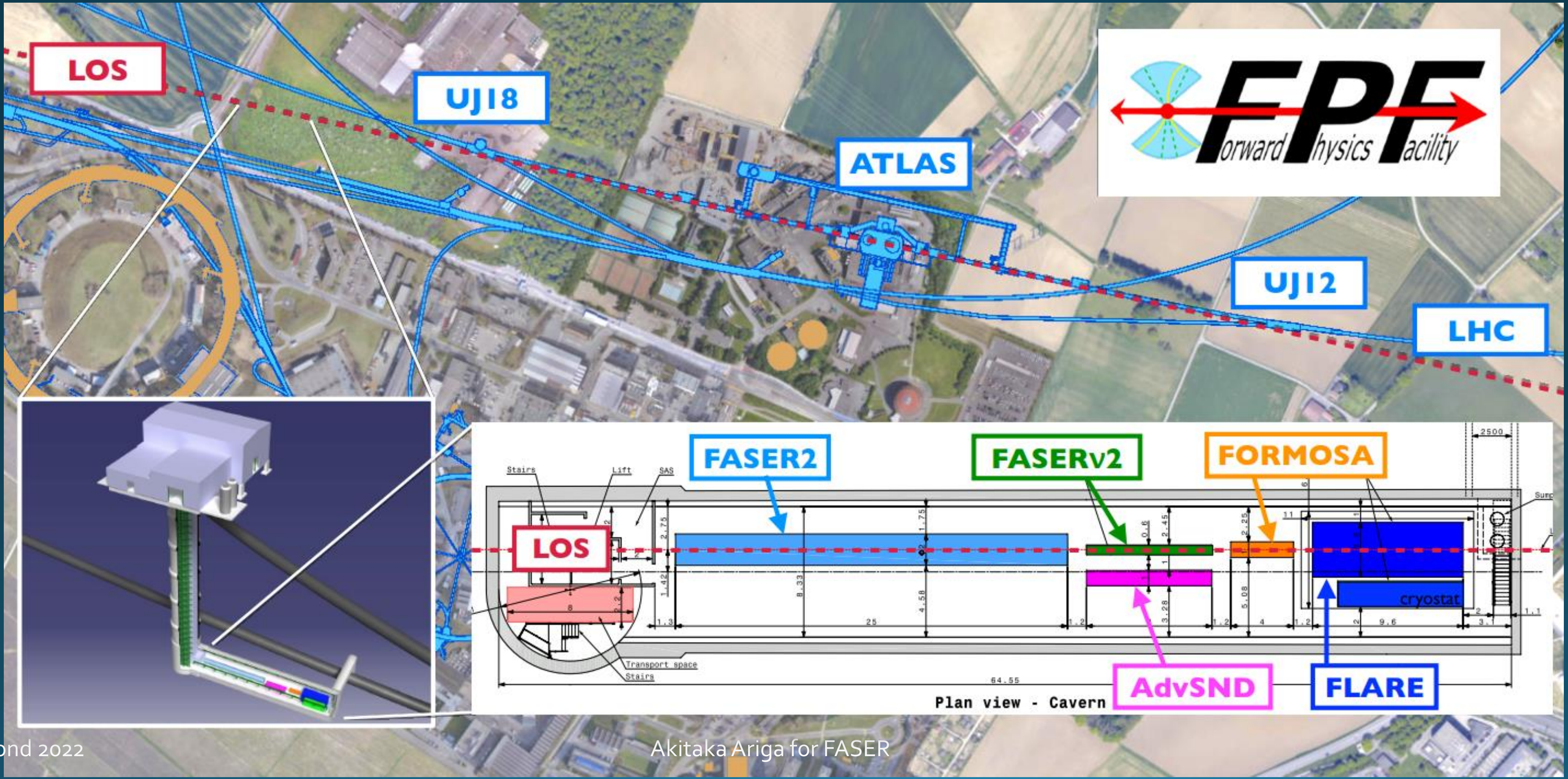
- The FPF has a rich and broad physics programme
- Three main physics motivations
  - Beyond Standard Model (BSM) “dark sector” searches
  - Neutrino physics
  - QCD physics



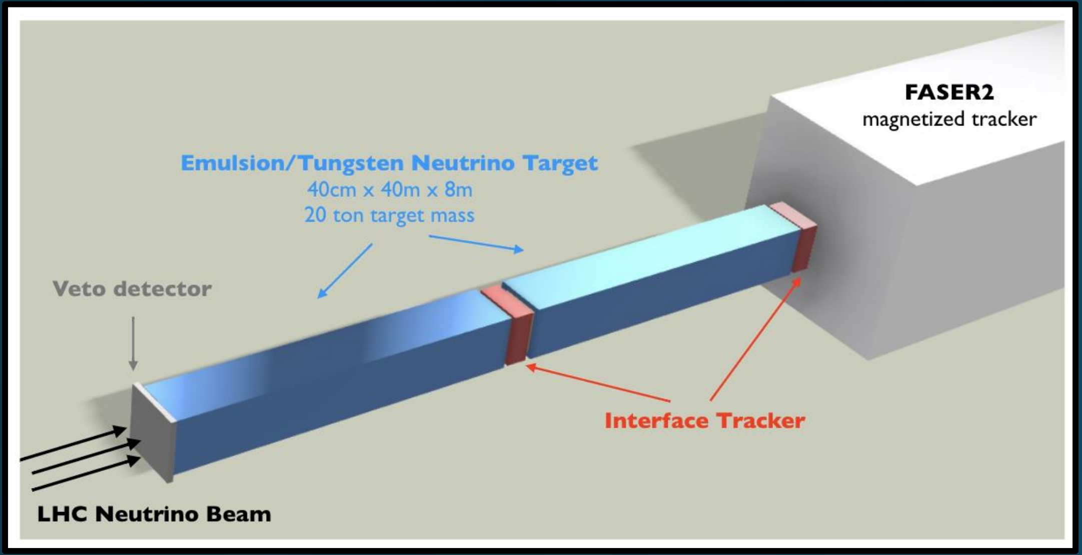
- In order to fully benefit from the increase in luminosity from the HL-LHC, the FPF will allow:
  - Longer detectors to increase target/decay volume
  - Wider detectors to increase sensitivity to heavy flavour produced particles
  - Space for new detectors with complementary physics capabilities

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

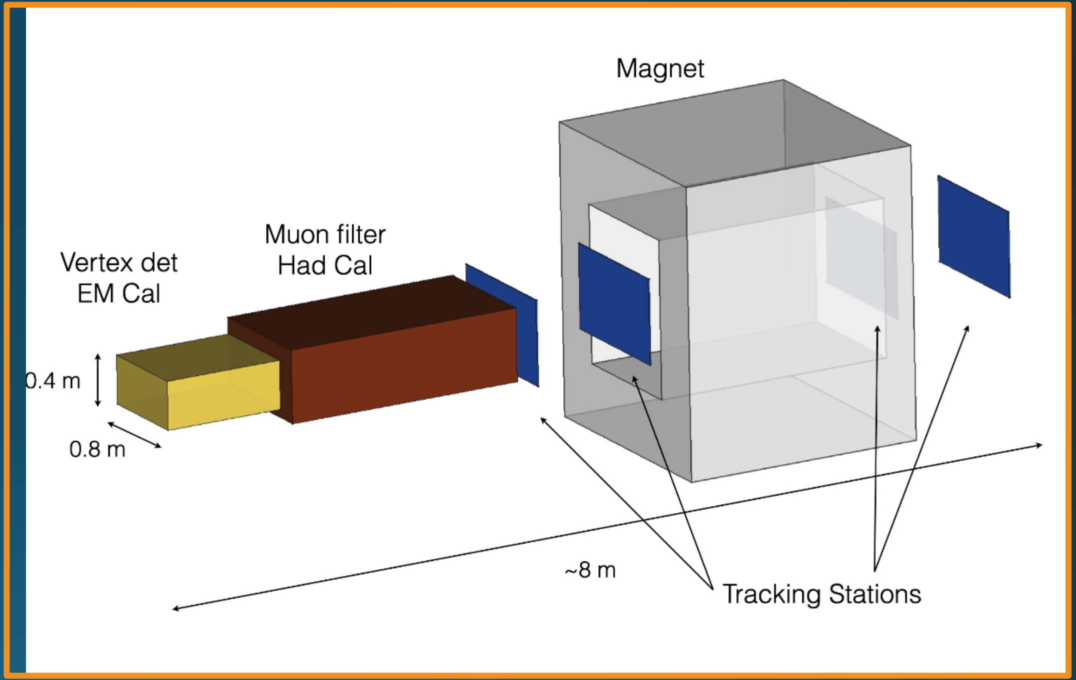
- FPF White Paper (429 pages, 236 authors, 156 endorsers)
  http://arxiv.org/abs/2203.05090

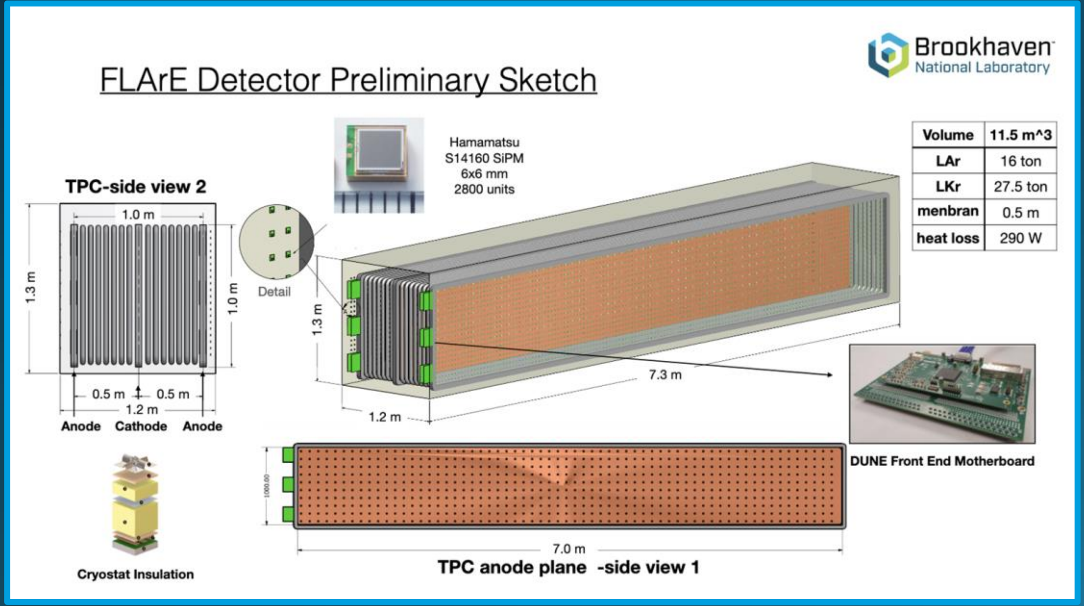


Neutrino Detector at the FPF



FASERv2
emulsion neutrino detector
followed by FASER spectrometer





Volume	11.5 m^3
LAr	16 ton
LKr	27.5 ton
menbran	0.5 m
heat loss	290 W

FLArE
liquid noble gas detector

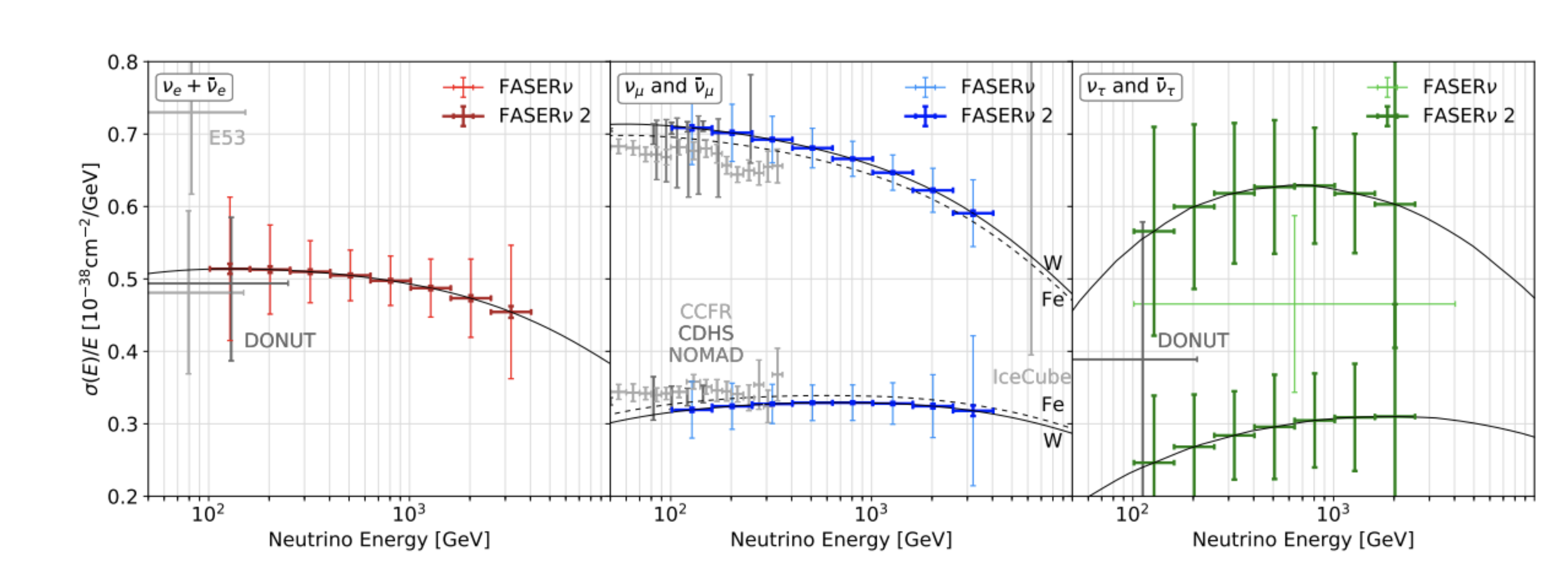
AdvSND
electronic detector
near detector at η~5
far detector at FPF

Neutrinos at the FPF

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

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

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 ν_τ/ $\bar{\nu}_\tau$ charge-current cross sections
- Study ν_τ → 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

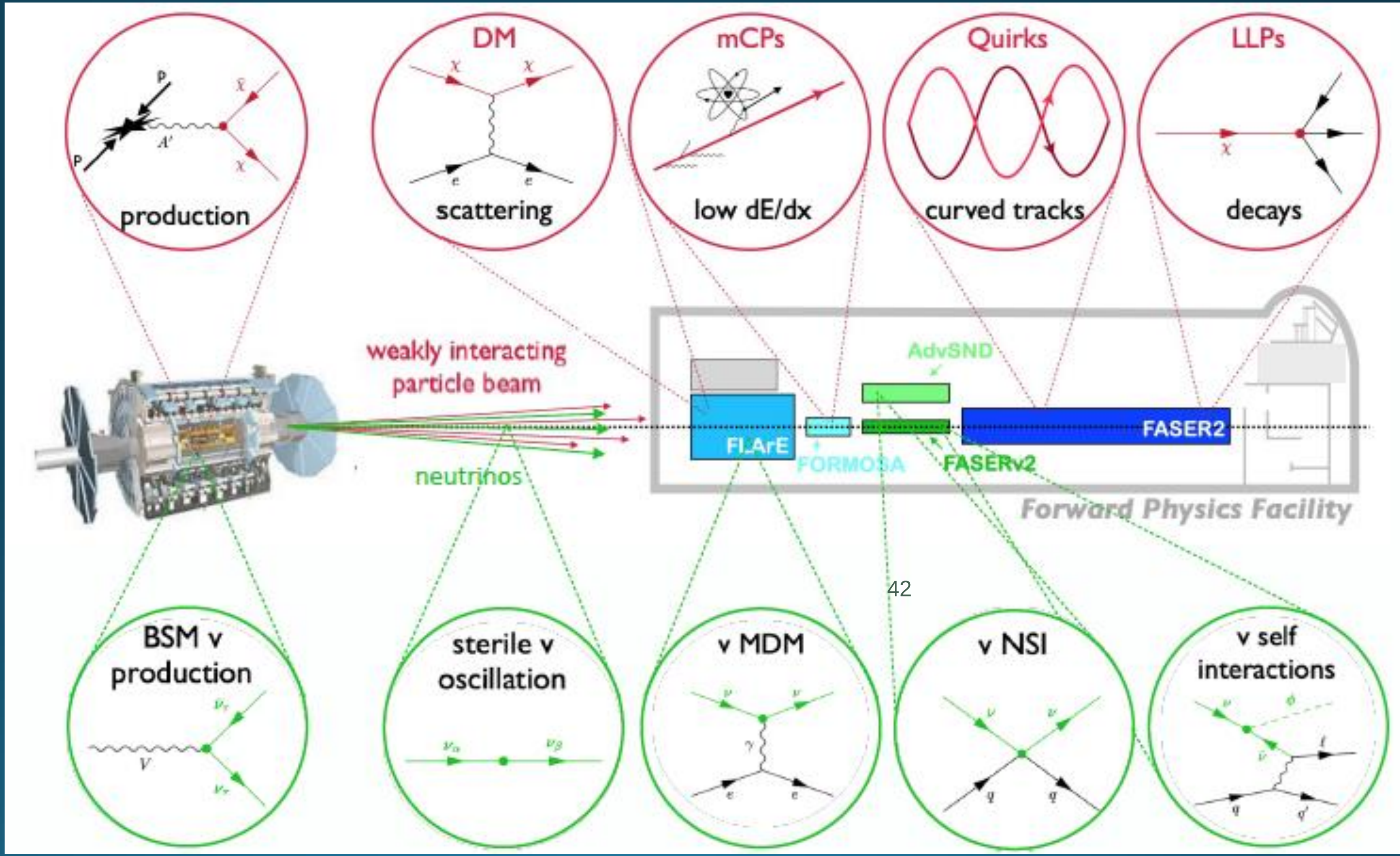
Physics Program of Forward Physics Facility

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

Summary

- Neutrinos at the LHC, a new domain of particle physics research!
- The FASER experiment at the LHC: neutrinos and LLPs
- FASERν 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

FASER Collaboration

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

- CERN
- Université de Genève
- Kyushu University
- UC Irvine
- Universität Bern
- Technion – Israel Institute of Technology
- Nagoya University
- University of Washington
- Johannes Gutenberg Universität Mainz (JGU)
- 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
- University of Sussex
- JINR