QCD AT A FORWARD PHYSICS FACILITY AT THE HIGH-LUMINOSITY LHC

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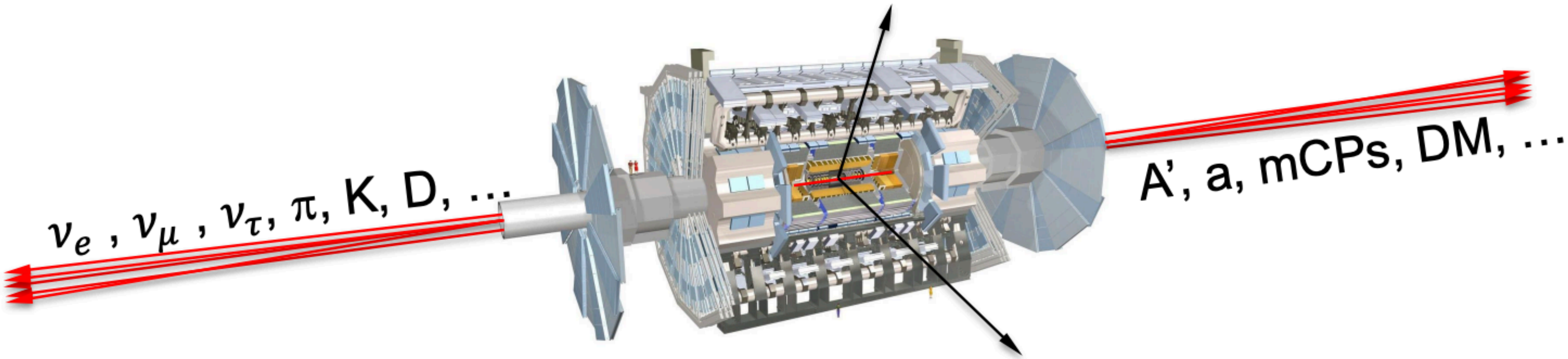
Diffraction and Low-x 2022 - Sept 25-30, 2022

MOTIVATION

- The existing large LHC detectors are beautifully designed to find strongly interacting heavy particle
- But they are also perfectly designed to not find weakly-interacting light particles
- These are dominantly produced in the rare decays of light particles: π, η, K, D and B mesons along the forward direction, and so the new particles escape through the blind spots down the beamline
- There are both SM and BSM motivations to explore these blind spots in the far forward region
- We cannot block the beams, but if we go far away, the proton beams are bent by magnets, whereas light, weakly-interacting particles go straight
- High energy neutrinos can be used as a probe of QCD in the forward region



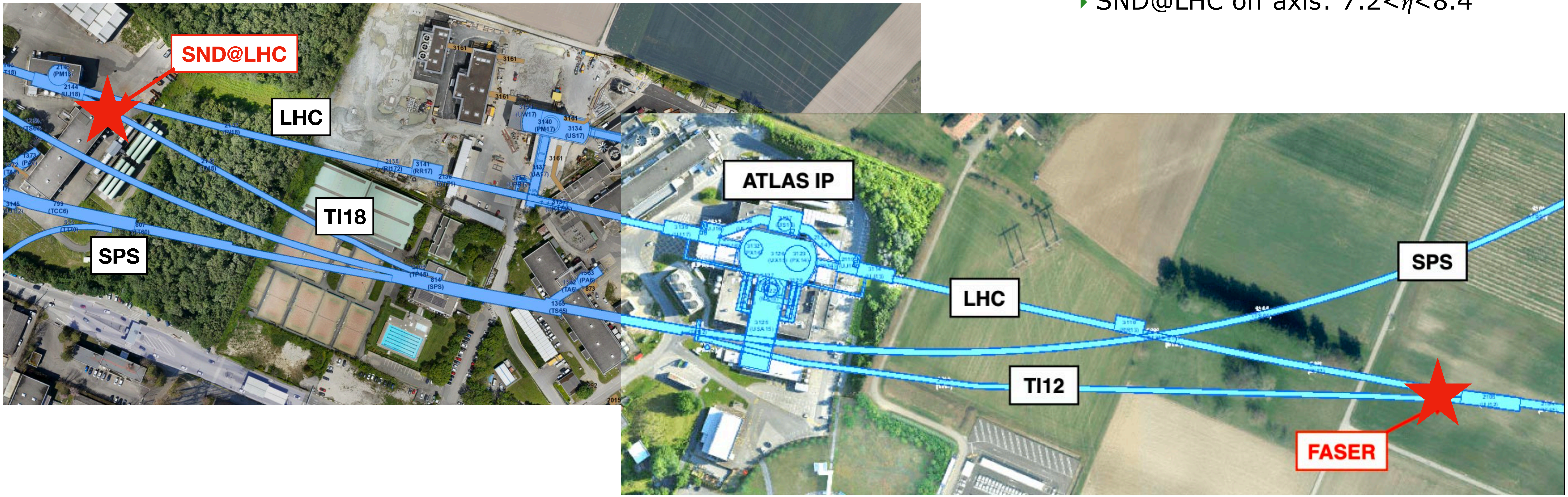
- Currently, FASERv and SND@LHC installed for Run3 based on this idea

TWO RECENTLY APPROVED EXPERIMENTS: SND@LHC and FASERν

- SND@LHC and FASER located in two symmetric locations: TI18 and TI12
- About 480 m away from the ATLAS IP
- TI18 and TI12 tunnels: former service tunnel connecting SPS to LEP

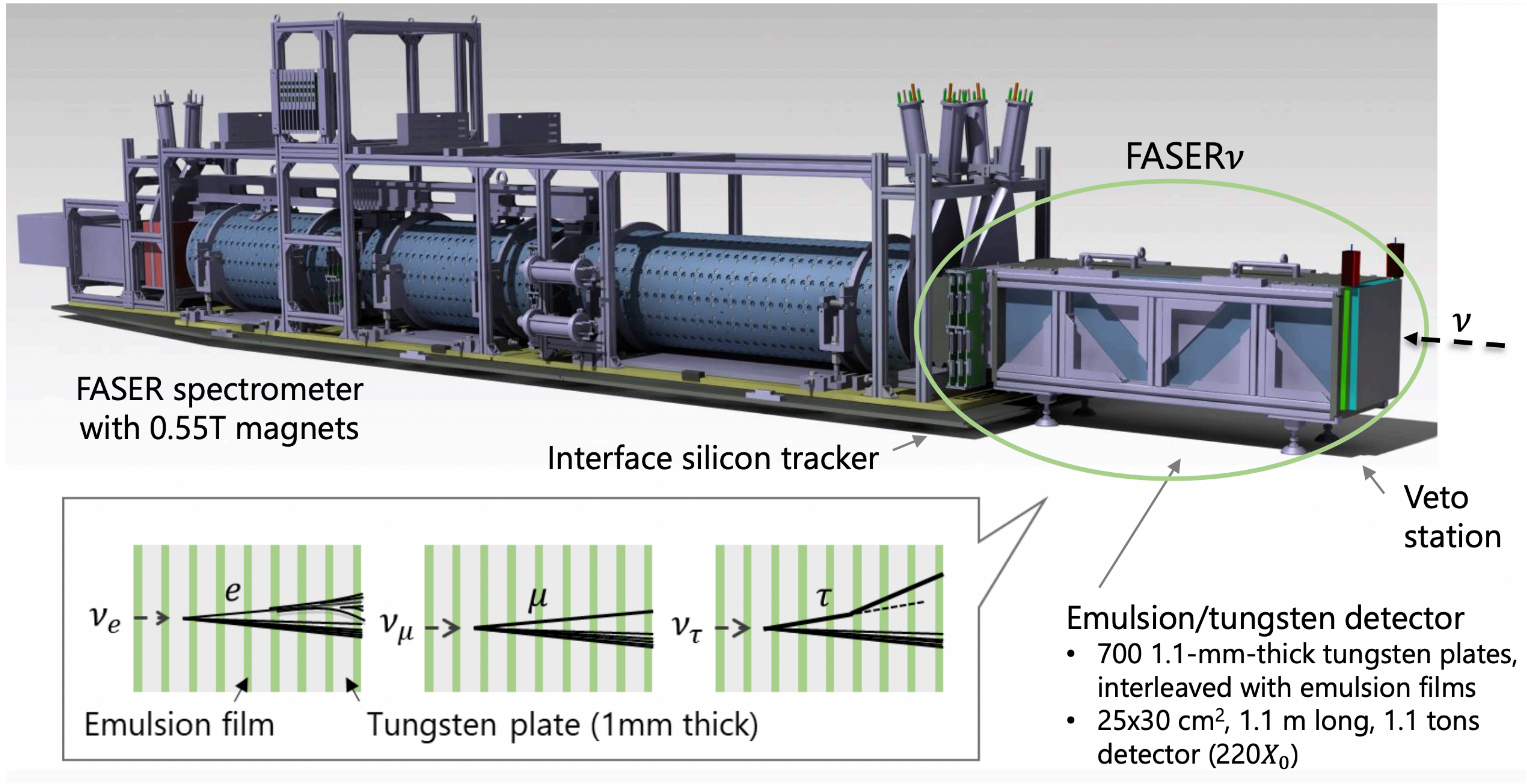
- Charged particles deflected by LHC magnets
- Shielding from the IP provided by 100 m rock
- Aim: collect more than 200 fb^{-1} in LHC Run3 (2022-2025)

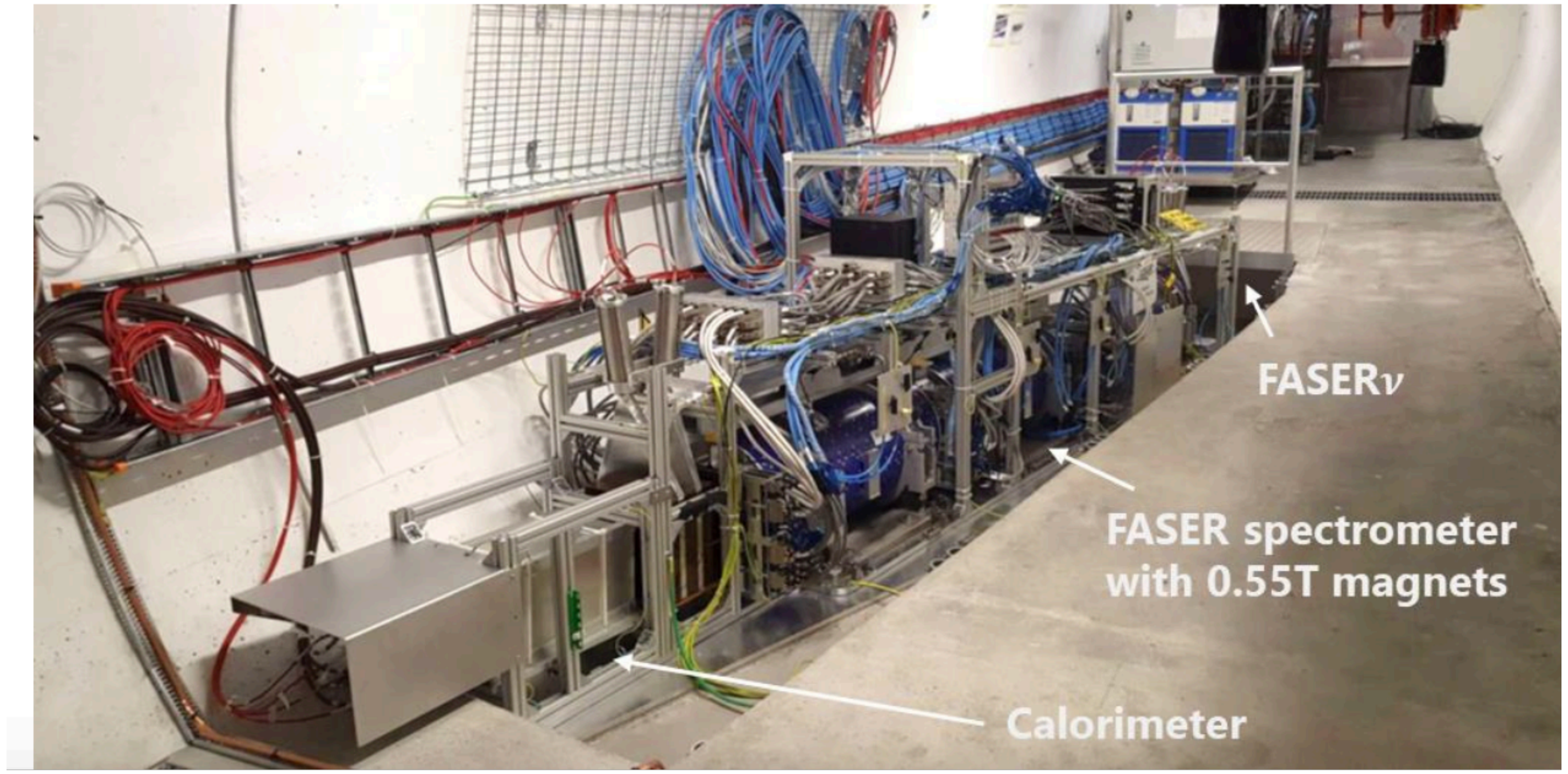
Complementarity:
- FASERν on axis: η>8.8
- SND@LHC off axis: 7.2<η<8.4



THE FASERν CONCEPT

- Emulsion/tungsten detector, interface silicon tracker, and veto station placed in front of the FASER main detector
- Allow to distinguish all flavor of neutrino interactions
  - Muon identification by their track length in the detector (8λ)
  - Muon charge identification with hybrid configuration to distinguish ν_μ and $\bar{\nu}_\mu$
  - Neutrino energy measurement with ANN by combining topological and kinematical variables





FASER and FASERν in the TI12 tunnel

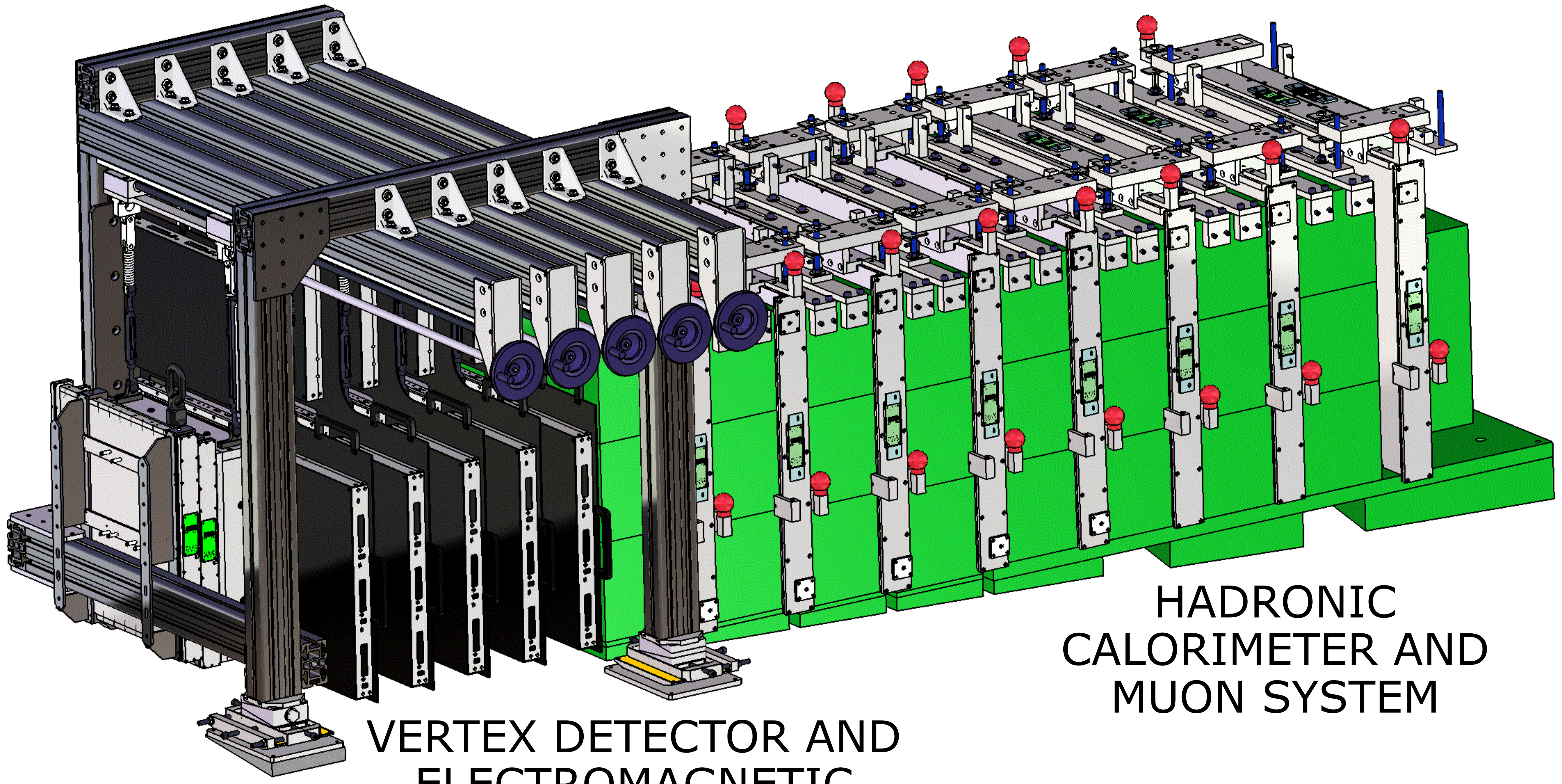
THE SND@LHC CONCEPT

Hybrid detector optimised for the identification of three neutrino flavours and for the detection of feebly interacting particles

VETO PLANE:
tag penetrating muons

TARGET REGION + ECAL:
- Emulsion cloud chambers (Emulsion+Tungsten) for neutrino interaction detection
- Scintillating fibers for timing information and energy measurement

MUON SYSTEM + HCAL:
iron walls interleaved with plastic scintillator planes for fast time resolution and energy measurement

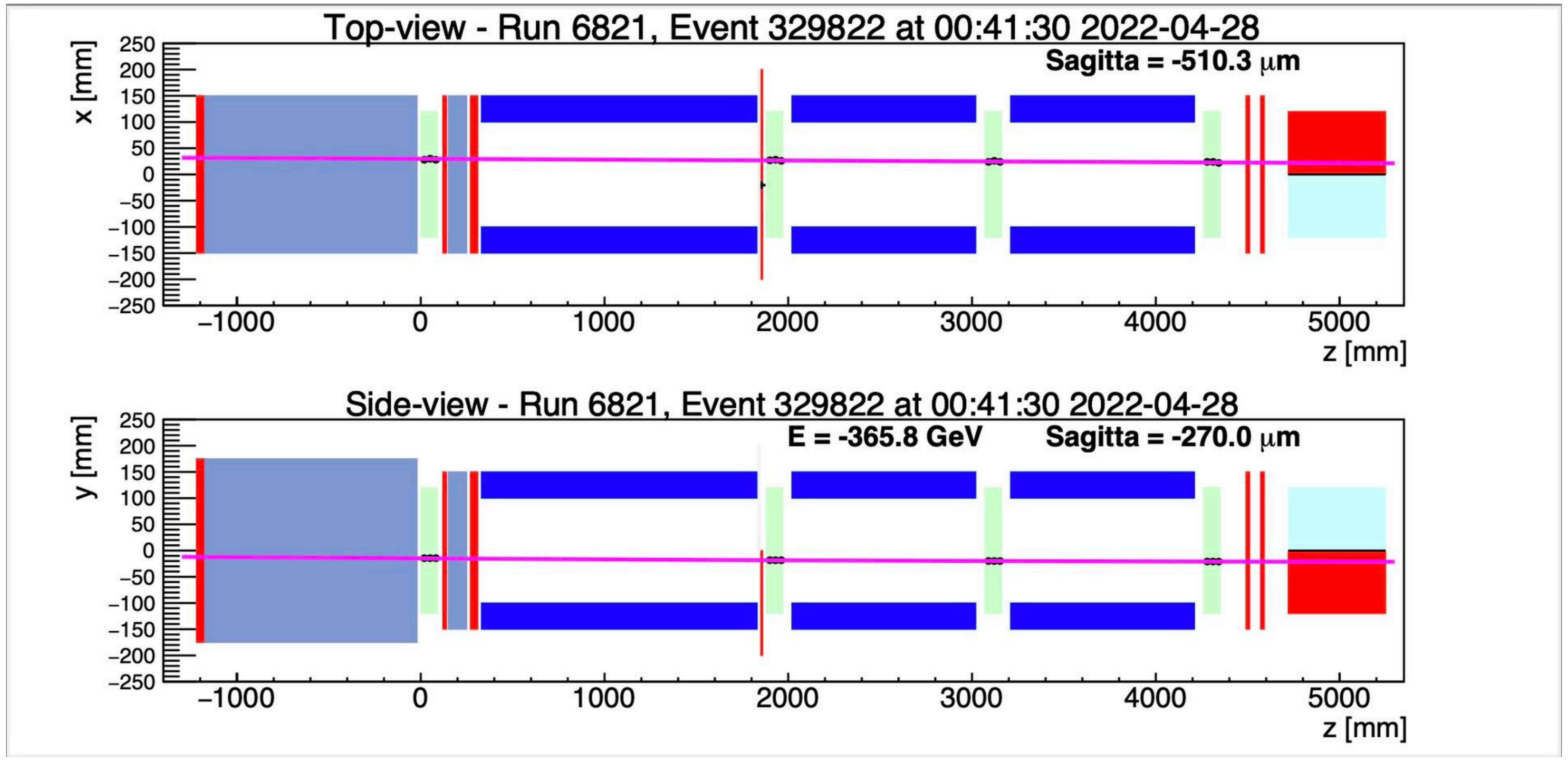


SND@LHC in the TI18 tunnel

EXPERIMENT DATA TAKING

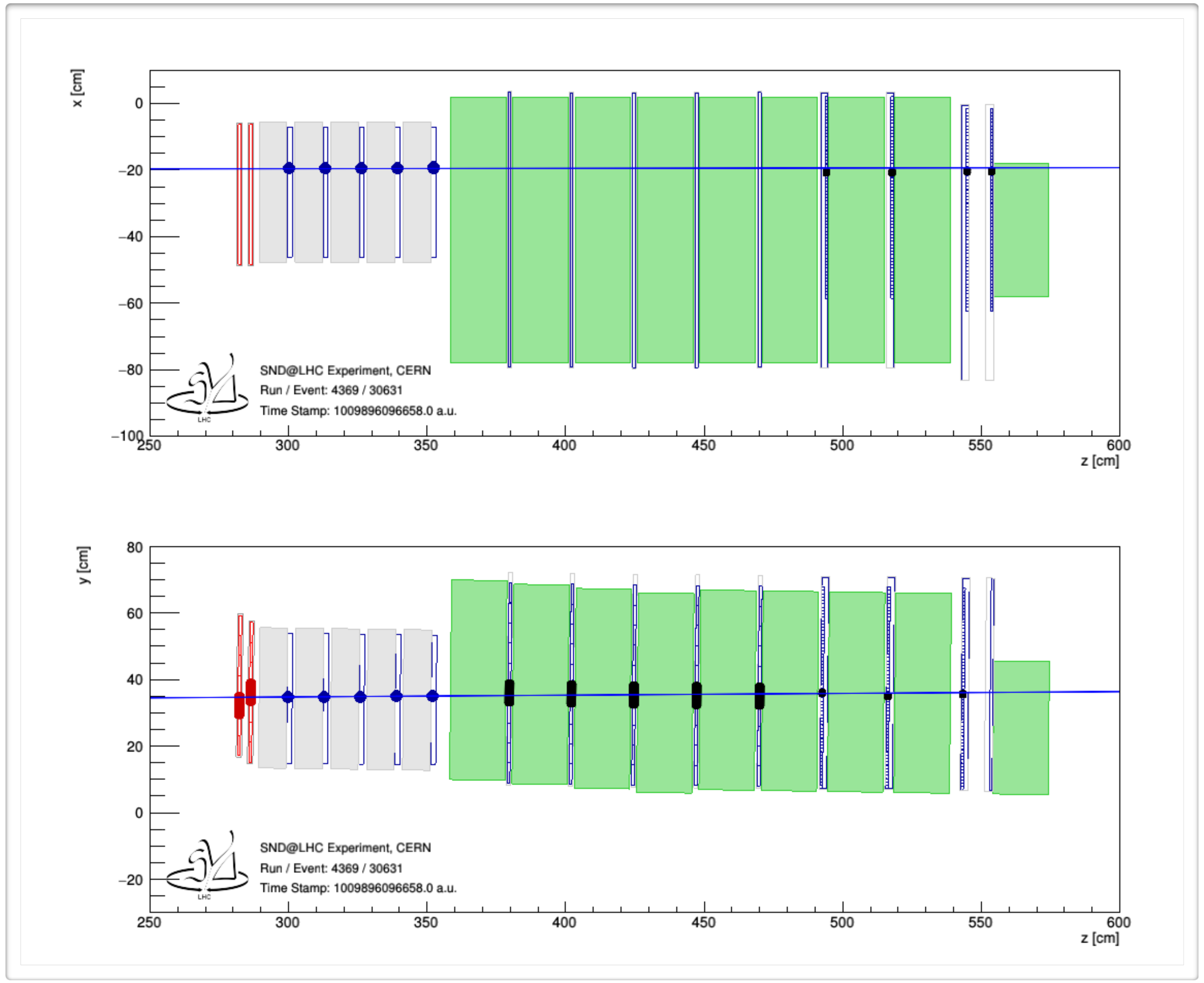
FASER

Muon from ATLAS IP
(April 2022)



SND@LHC

Muon from ATLAS IP
(May 2022)



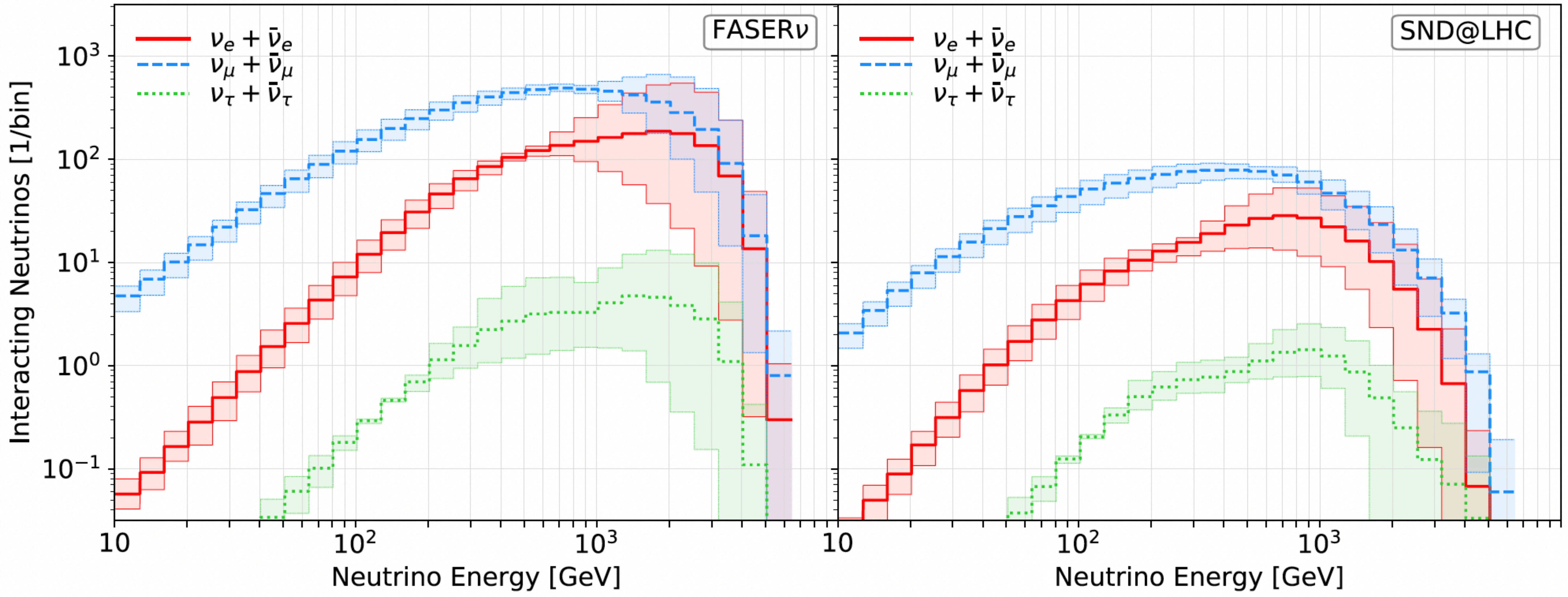
NEUTRINO PHYSICS PROGRAMME

- First detection of TeV neutrinos produced at colliders
- Neutrinos produced in the forward direction at the LHC originate from the decay of hadrons, mainly pions, kaons, and charm particles
- FASERν and SND@LHC measurements provide novel input to validate/improve generators
- First data on forward charm, hyperon, kaon

Complementarity

- SND@LHC: off axis location (7.2<η<8.4)
- FASERν: on axis (η>8.8)

- Expected neutrino interactions in 150 fb^{-1}
  → More than 200 fb^{-1} expected in Run3

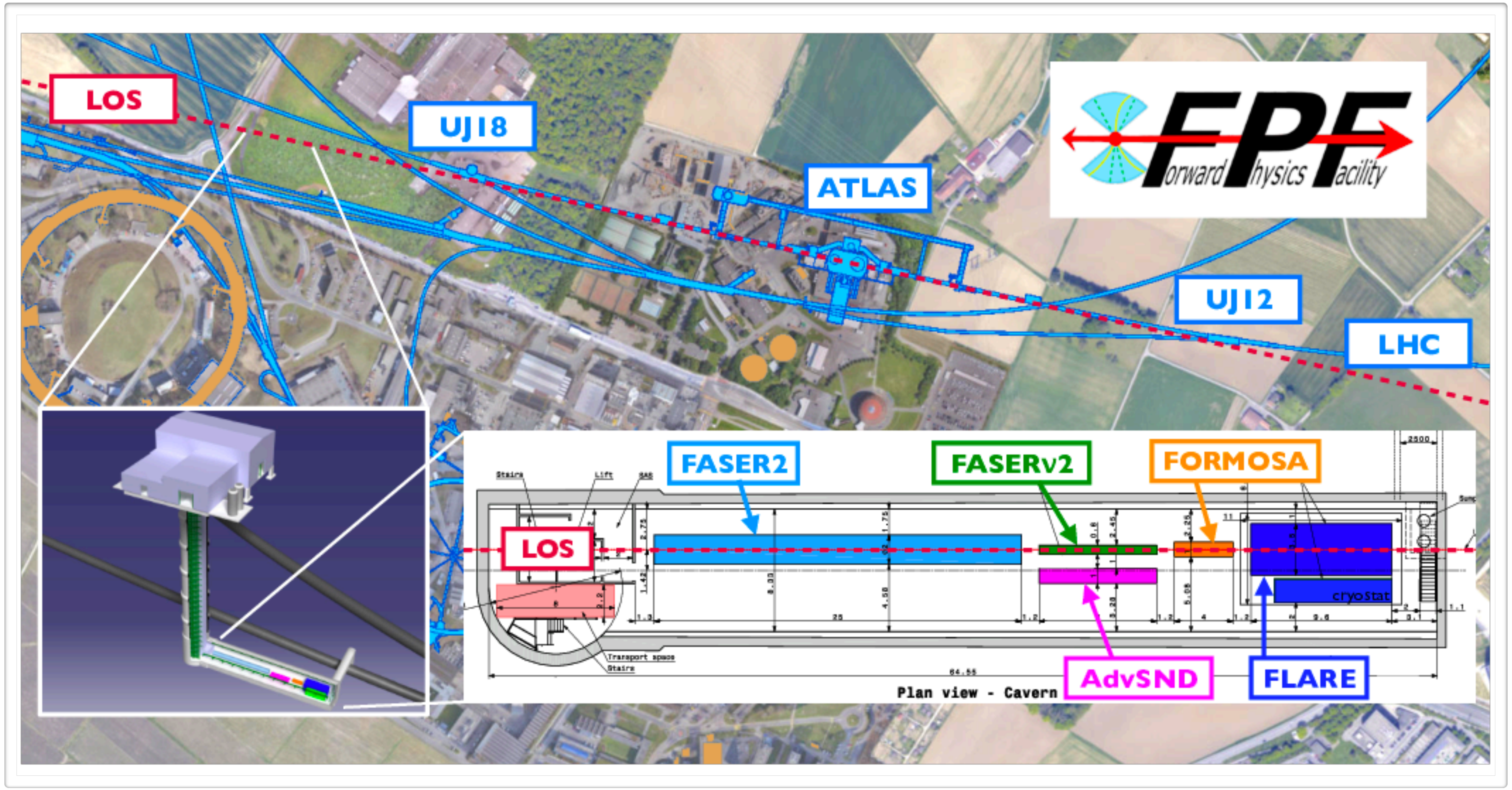


Generators		FASERν			SND@LHC		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	901	4783	14.7	134	790	7.6
DPMJET	DPMJET	3457	7088	97	395	1034	18.6
EPOSLHC	Pythia8 (Hard)	1513	5905	34.2	267	1123	11.5
QGSJET	Pythia8 (Soft)	970	5351	16.1	185	1015	7.2
Combination (all)		1710^{+1746}_{-809}	5782^{+1306}_{-998}	$40.5^{+56.6}_{-25.8}$	245^{+149}_{-111}	991^{+132}_{-200}	$11.3^{+7.3}_{-4.0}$
Combination (w/o DPMJET)		1128^{+385}_{-227}	5346^{+558}_{-563}	$21.6^{+12.5}_{-6.9}$	195^{+71}_{-61}	976^{+146}_{-185}	$8.8^{+2.7}_{-1.5}$

[Phys. Rev. D 104, 113008, arXiv:2105.08270]

FORWARD PHYSICS FACILITY

- FASER, FASERν, and SND@LHC are currently highly constrained by 1980's (LEP!) infrastructure that was never intended to support experiments
- The rich physics program in the far-forward region therefore strongly motivates creating a dedicated **Forward Physics Facility** to house far forward experiments for the HL-LHC era from 2029-2040

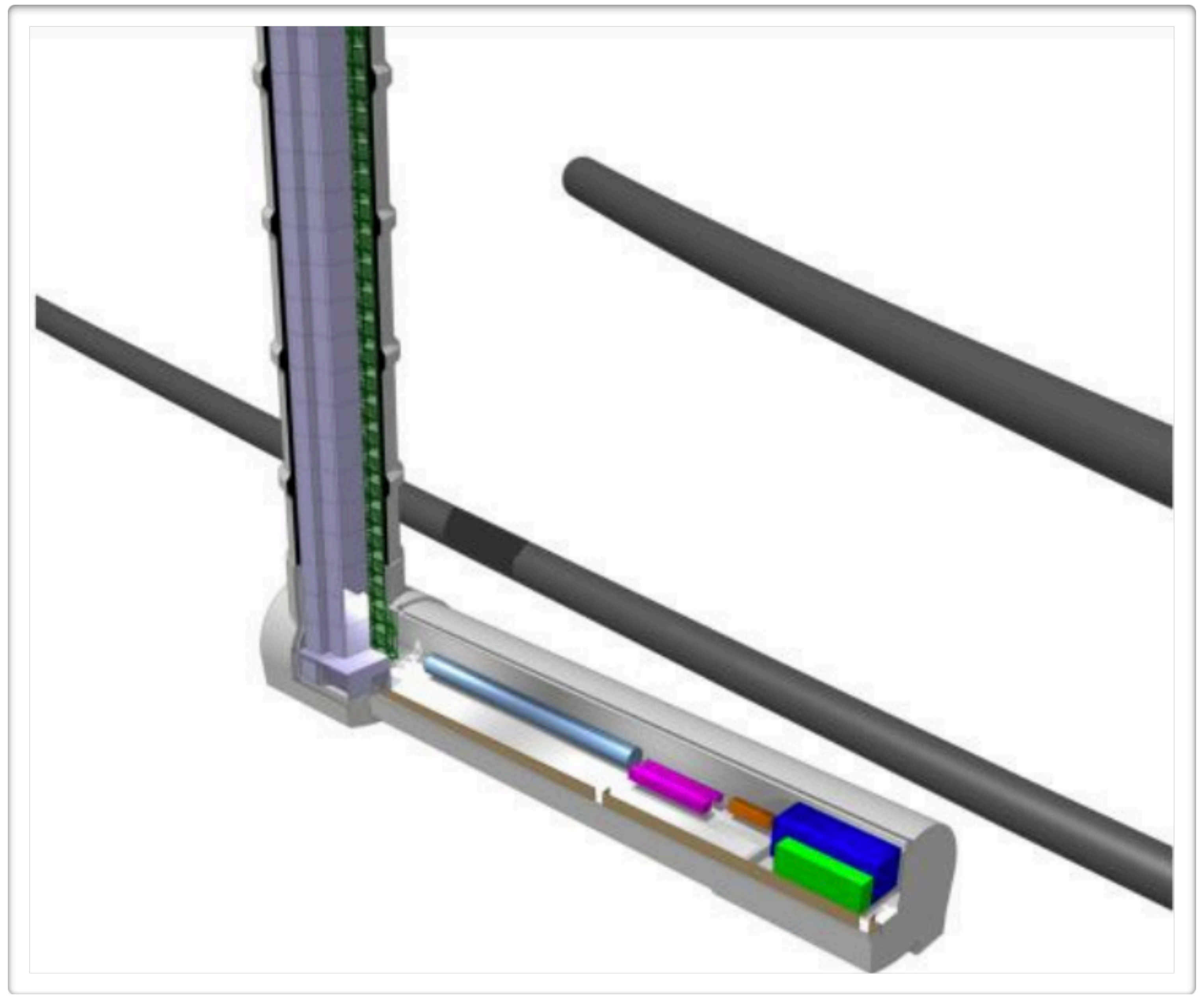


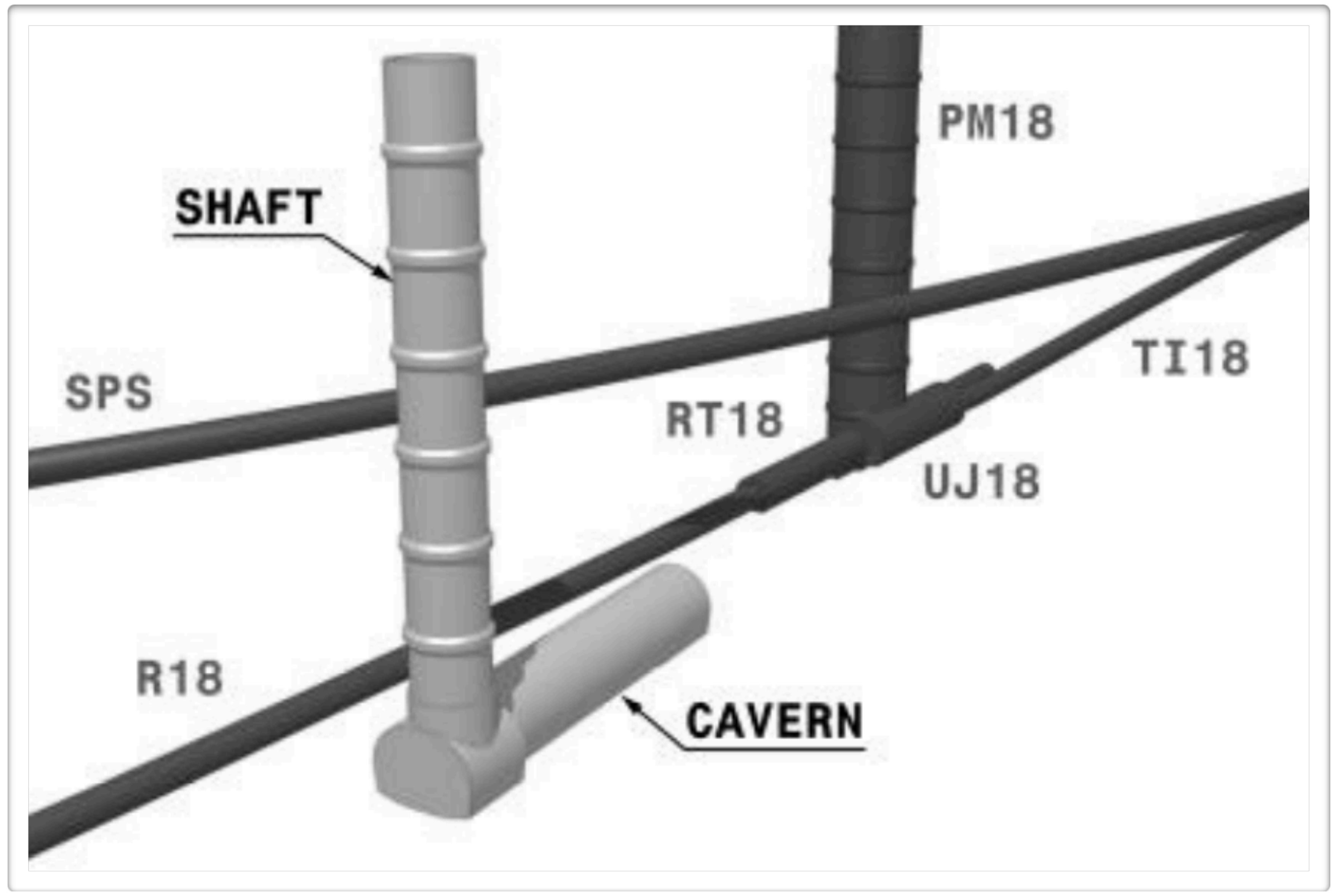
[https://pbc.web.cern.ch/fpf-resources]

- FPF Meetings
  - FPF Kickoff Meeting, 9-10 Nov 2020, https://indico.cern.ch/event/955956
  - FPF2 Meeting, 27-28 May 2021, https://indico.cern.ch/event/1022352
  - FPF3 Meeting, 25-26 Oct 2021, https://indico.cern.ch/event/1076733
  - FPF4 Meeting, 31 Jan-1 Feb 2022, https://indico.cern.ch/event/1110746
- FPF Short Paper: 75 pages, 80 authors completed in Sep 2021 (2109.10905, Physics Reports 968, 1 (2022))
- FPF Snowmass White Paper: Feng, Kling, Reno, Rojo, Soldin et al. A comprehensive, 429-page, 392-author+endorser summary (2203.05090)

LOCATION, TIMELINE, COST

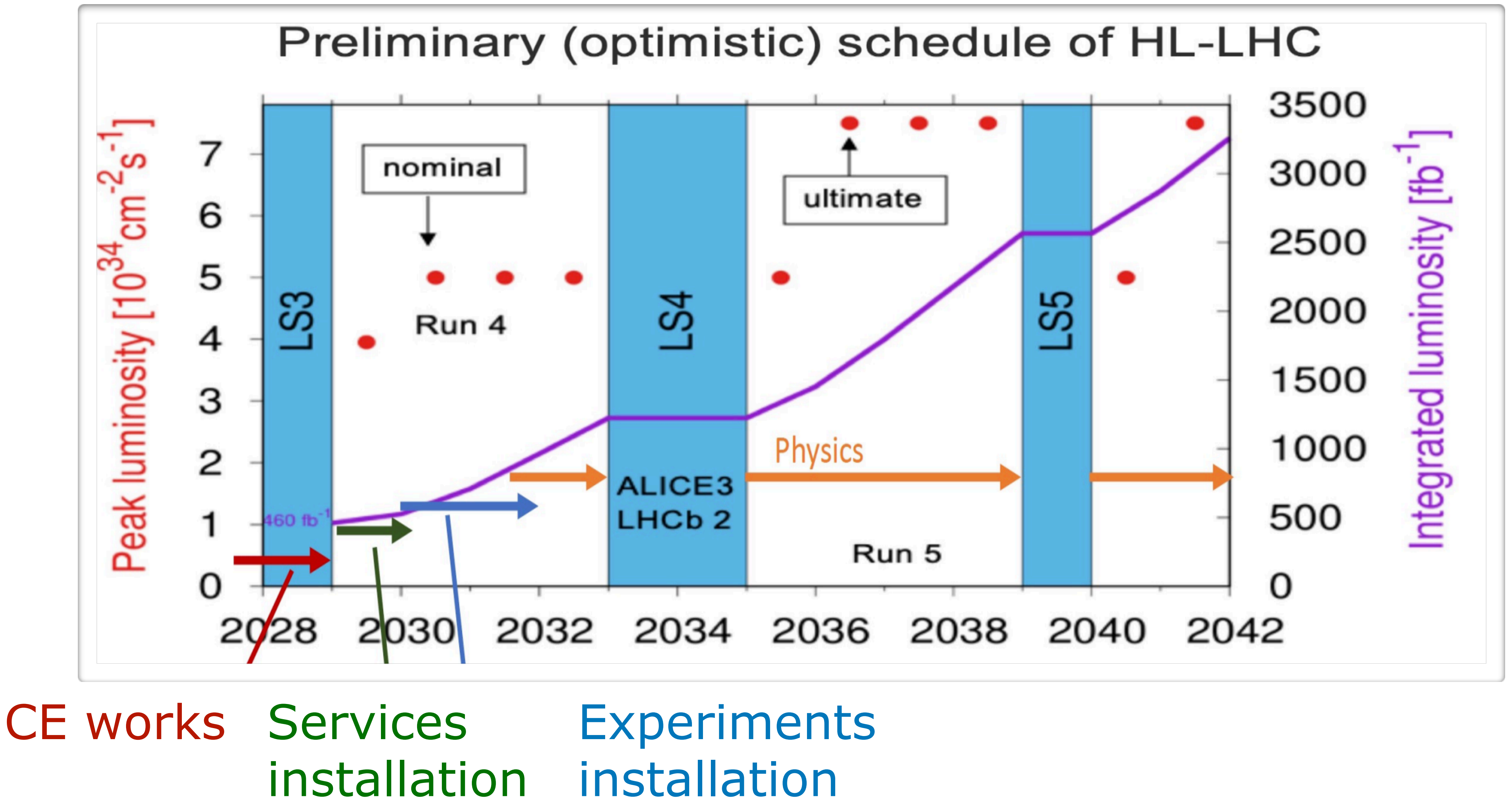
- 620-680 m west of the ATLAS IP
- Shielded by ~200 m of rock
- Cavern: 65m long, 8m wide/high
- Shaft: 88m-deep, 9.1m-diameter
- Surface Buildings





- Construction end of this decade
- Operation in the 2030s

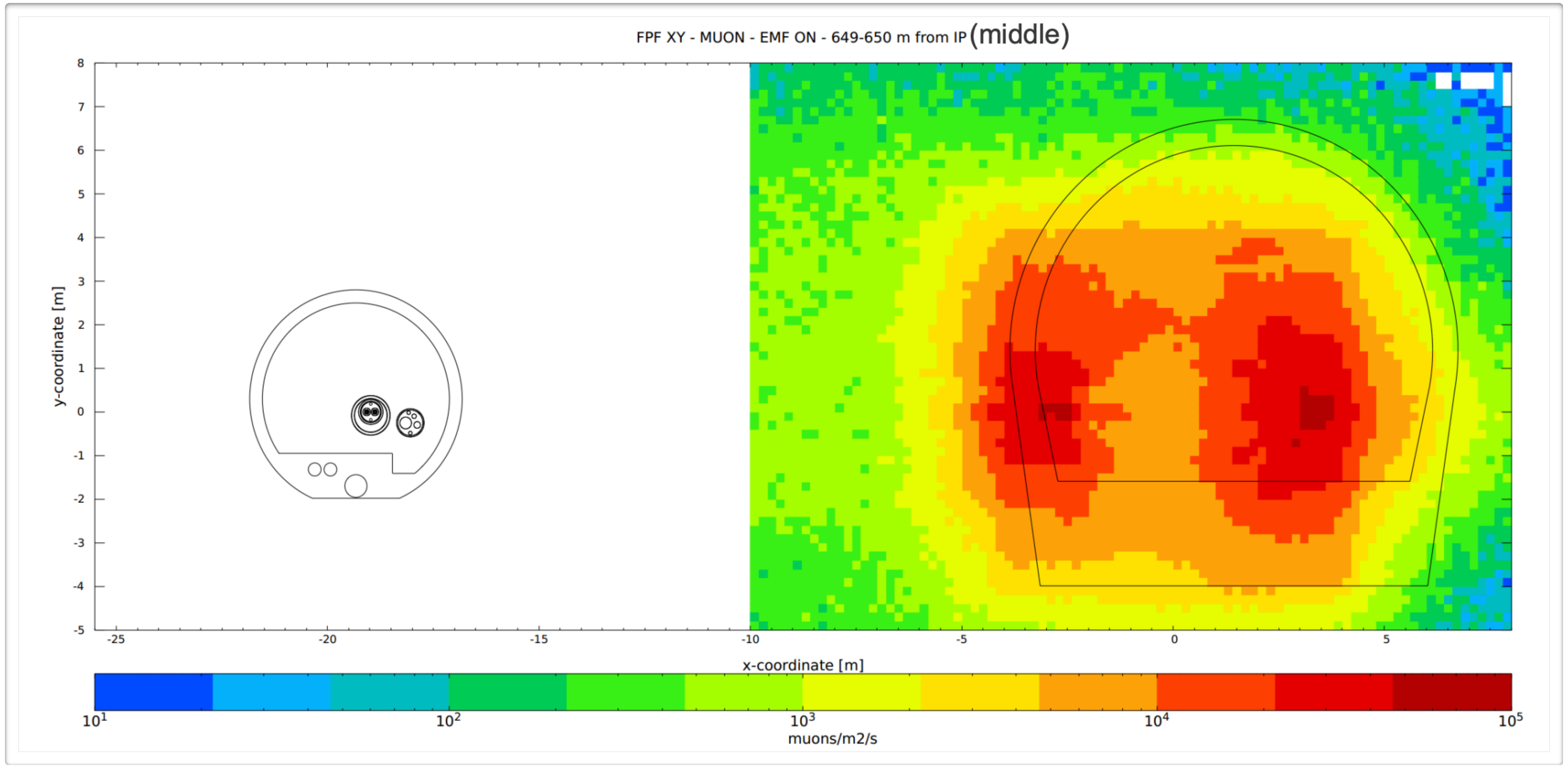
- Very preliminary (class 4) cost estimate:
  - 23 MCHF (CE) + 15 MCHF (services) ≈ 40 MCHF (+50%/-30%), not including experiments



DESIGN STUDIES

- The FPF is completely decoupled from the LHC: no need for a safety corridor connecting the FPF to the LHC
- Preliminary RP and vibration studies indicate that FPF construction will have no significant impact on LHC operation
- RP study suggests access to the FPF cavern possible during HL-LHC operations

- FLUKA studies of expected muon rate at FPF of **~1.5Hz/cm²** at HL-LHC (L=5e34) close to LOS
- FLUKA agrees well with observed rate at FASER and SND@LHC
- Studies ongoing to see if the background rate can be reduced with a sweeper magnet



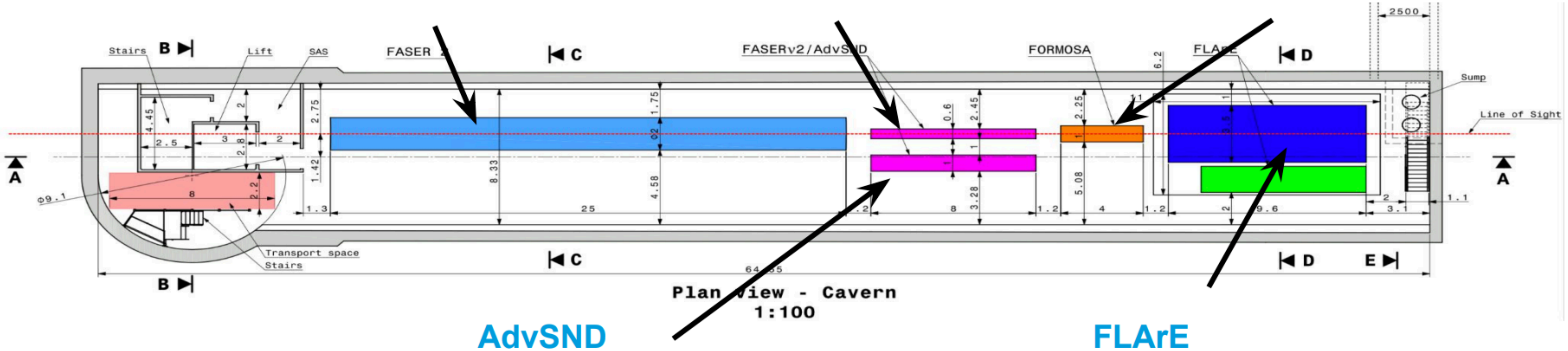
EXPERIMENTS

The FPF would house a suite of experiments that will greatly enhance the LHC's physics potential for **BSM physics searches** and **neutrino physics** and **QCD**

FASER2
magnetized spectrometer
for BSM searches

FASERν2
emulsion-based
neutrino detector

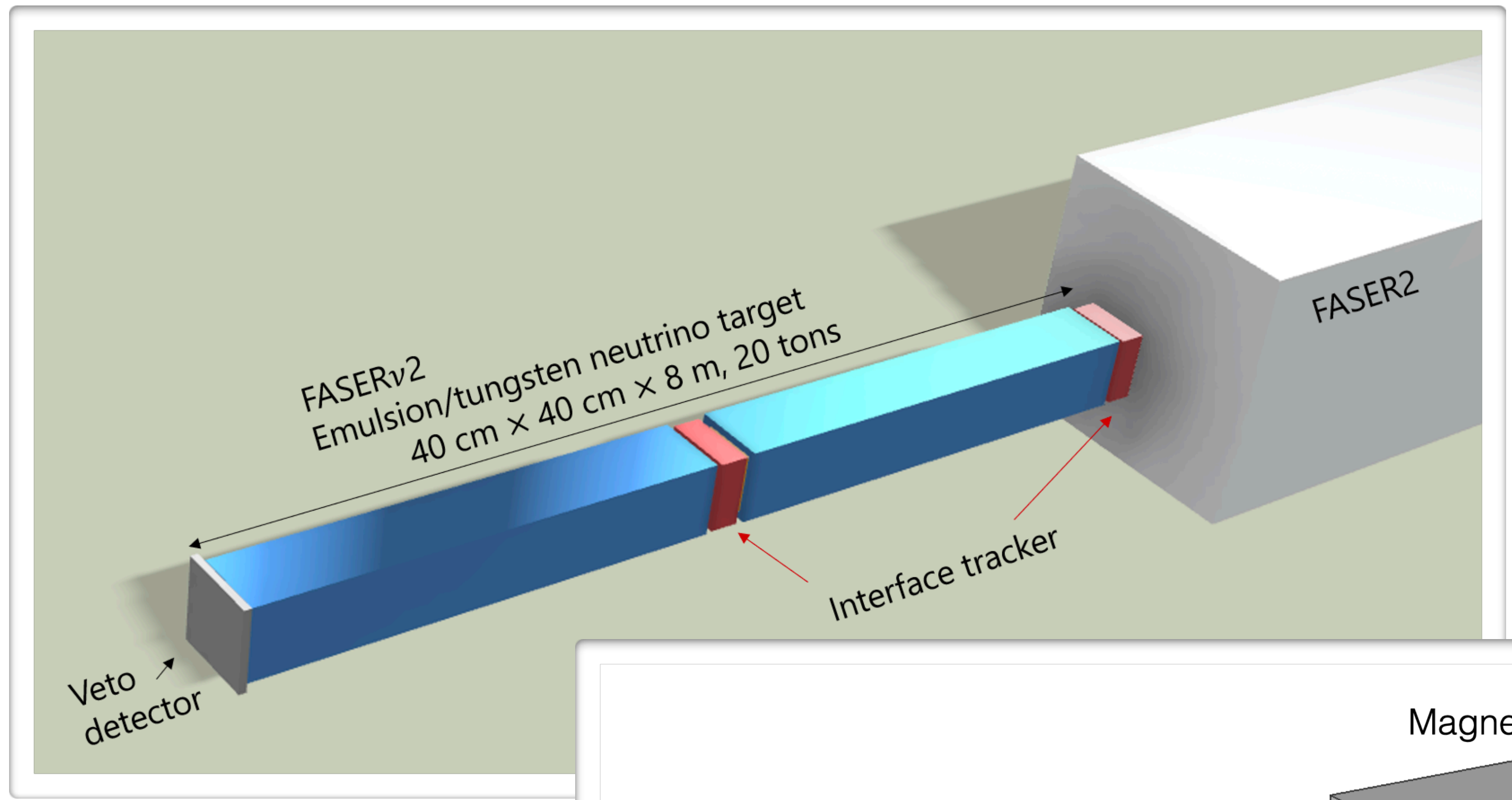
FORMOSA
plastic scintillator array for
BSM searches



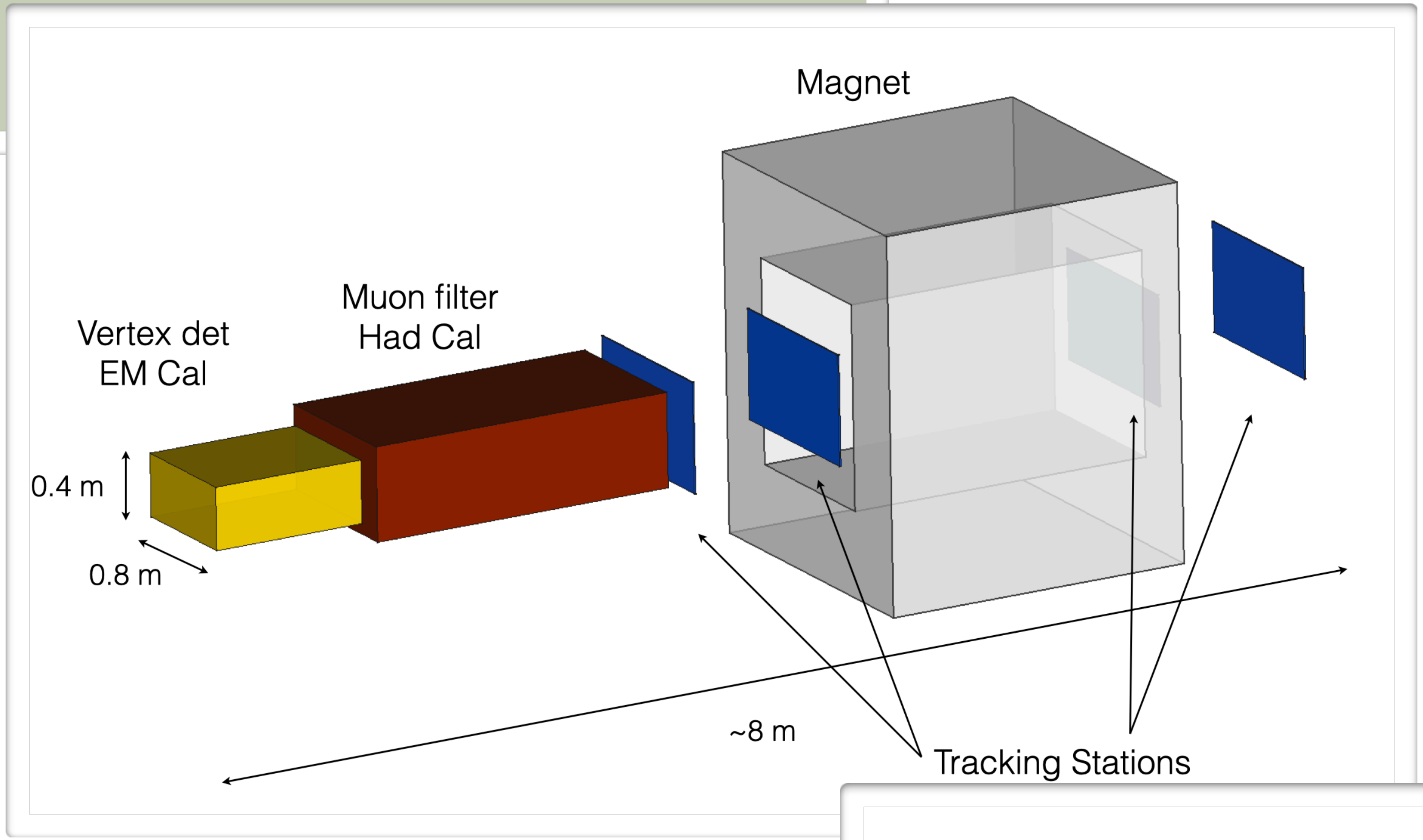
AdvSND
electronic
neutrino detector

FLArE
LAr based
neutrino detector

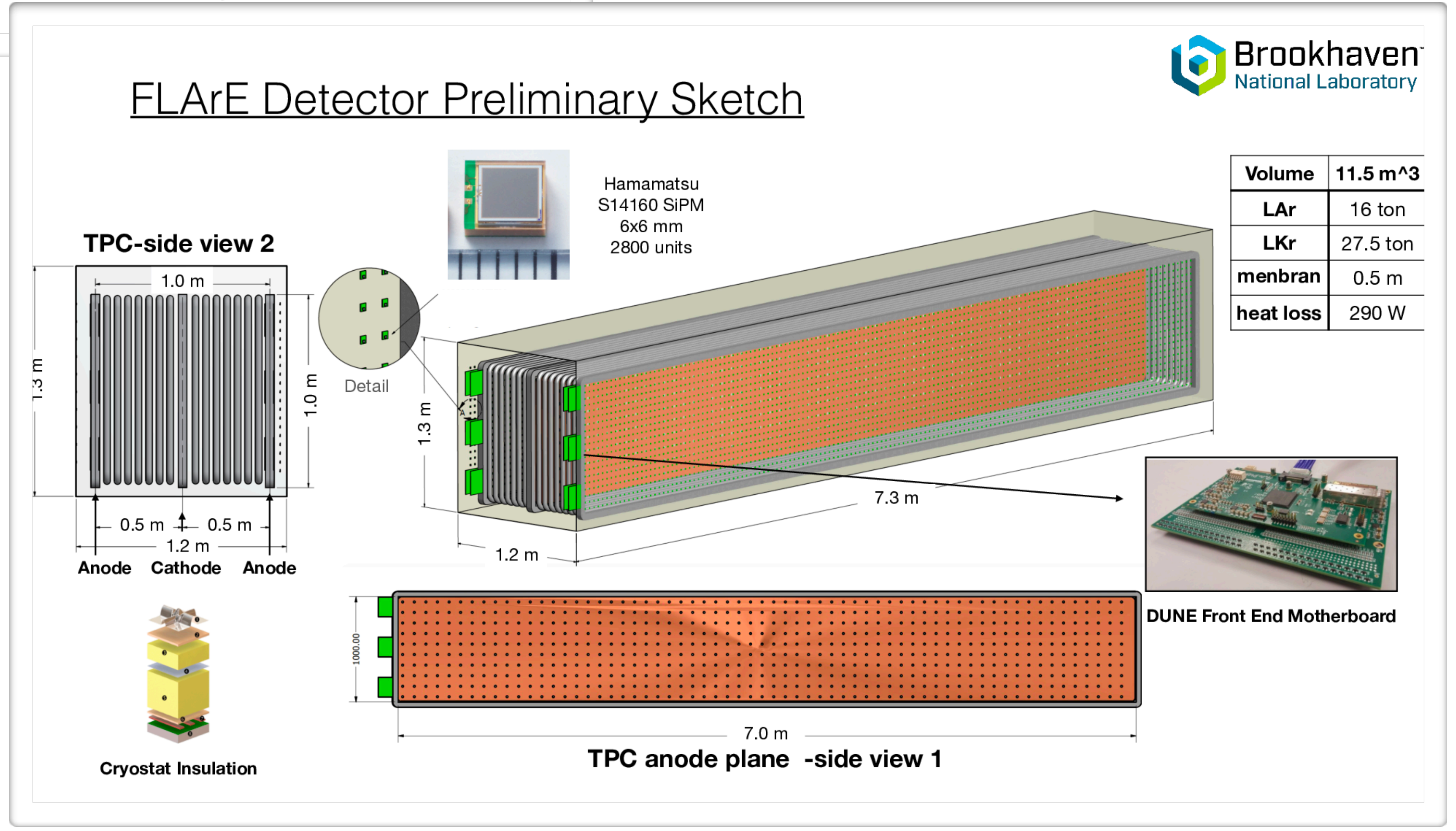
NEUTRINO DETECTORS AT FPF



FASERν2 (η>8.5)
Emulsion neutrino detector
Target mass: 20 tons
Followed downstream by FASER spectrometer

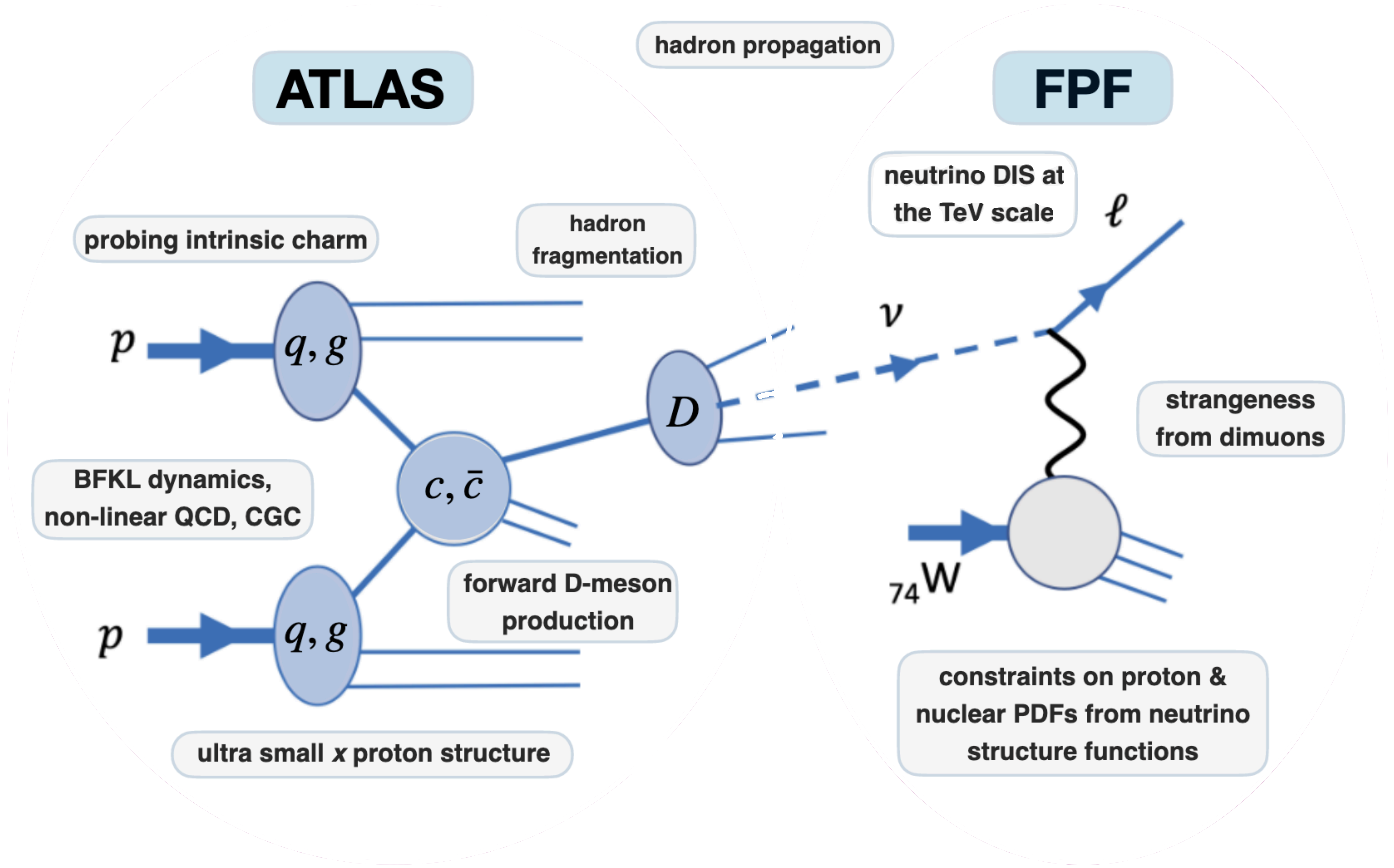


AdvSND-Far (7.2<η<8.5)
Electronic detector and magnetic spectrometer
Target mass: 5 tons
Associated to AdvSND-Near at η~5



FLArE (η>8.5)
LAr TPC neutrino detector
Target mass: 10 tons

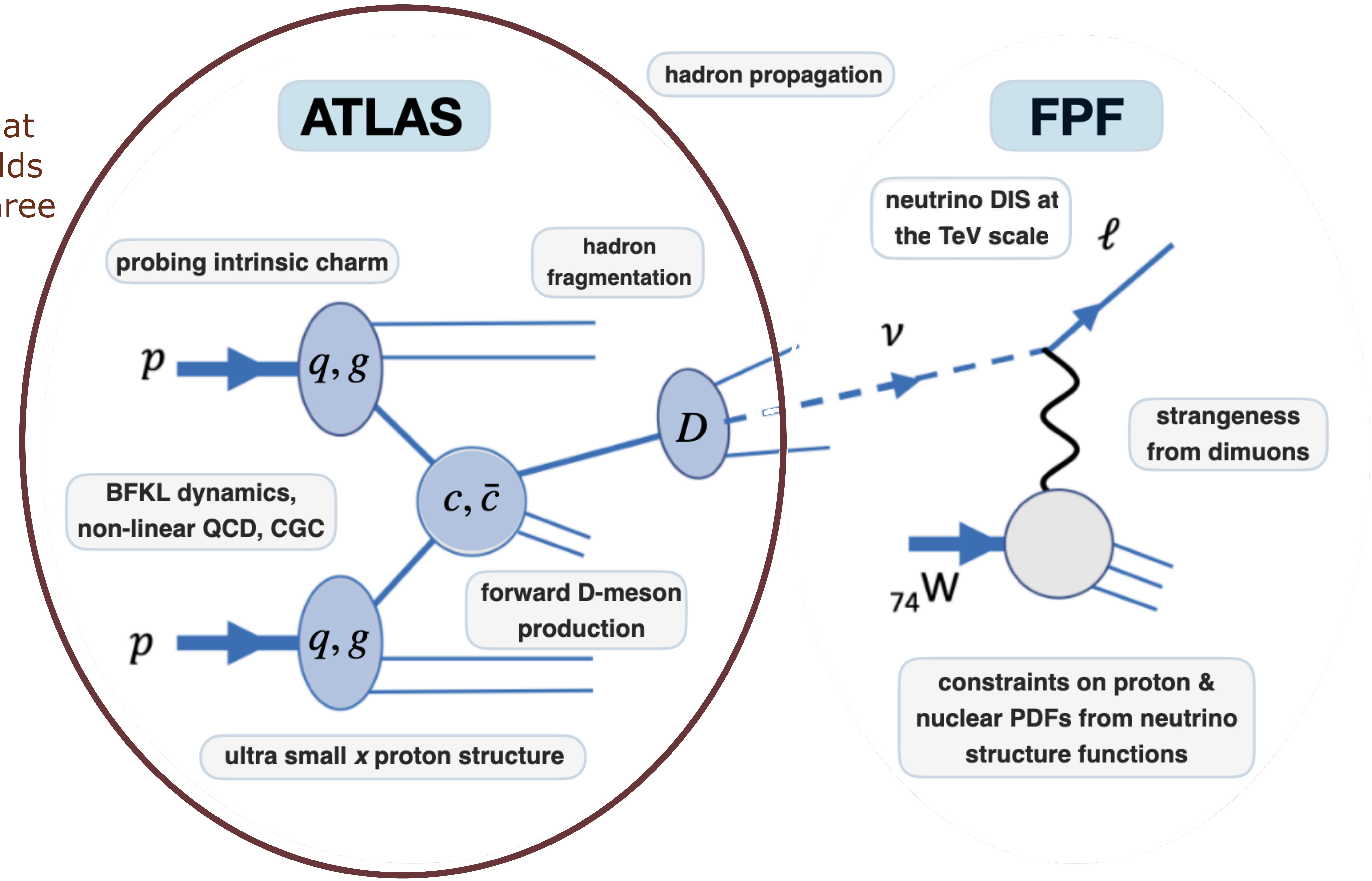
QCD IN pp AND νA COLLISIONS



[FPF Snowmass white paper (2203.05090)]

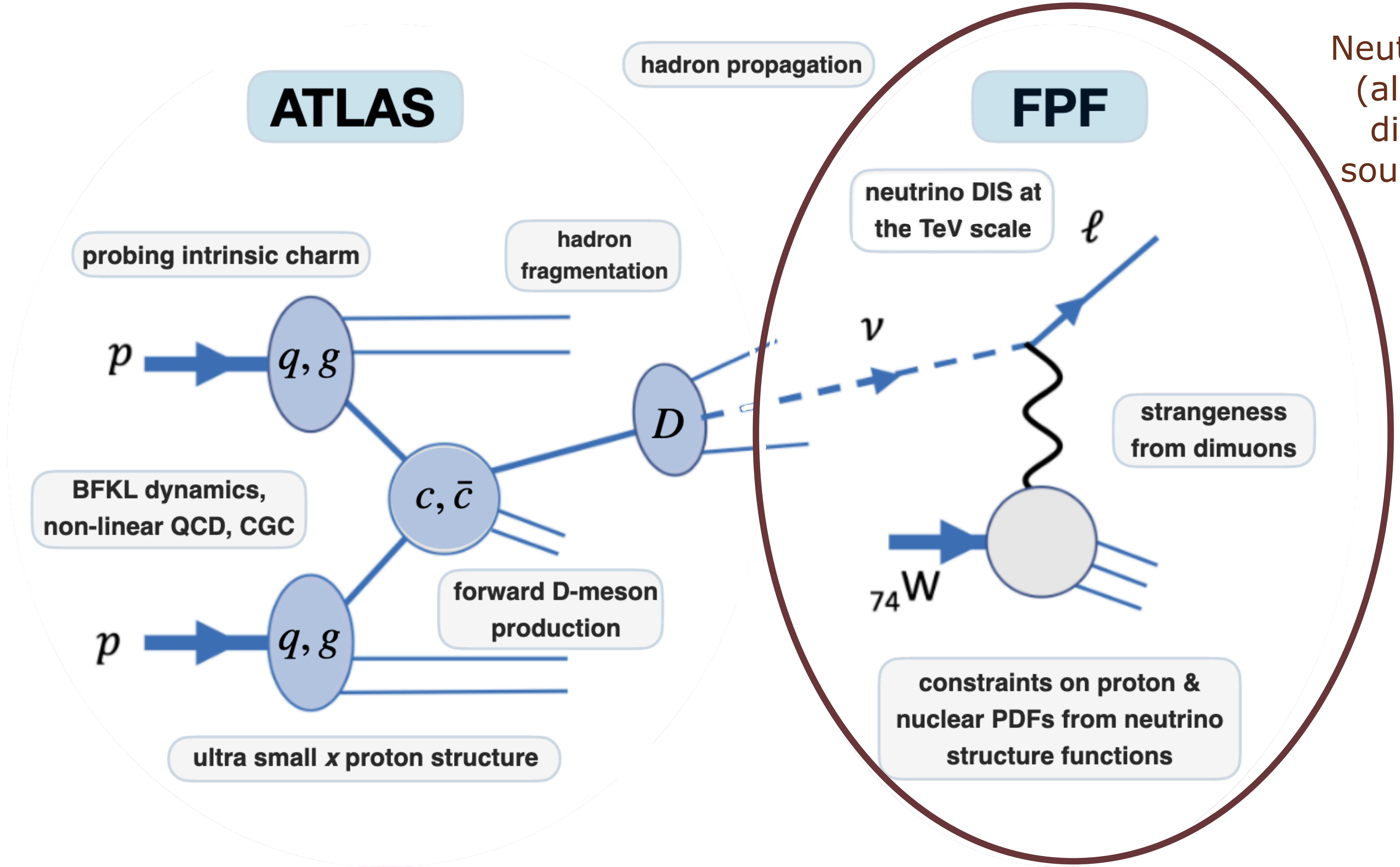
QCD IN pp AND νA COLLISIONS

Hadron production that ultimately yields neutrinos of three flavours



[FPF Snowmass white paper (2203.05090)]

QCD IN pp AND νA COLLISIONS

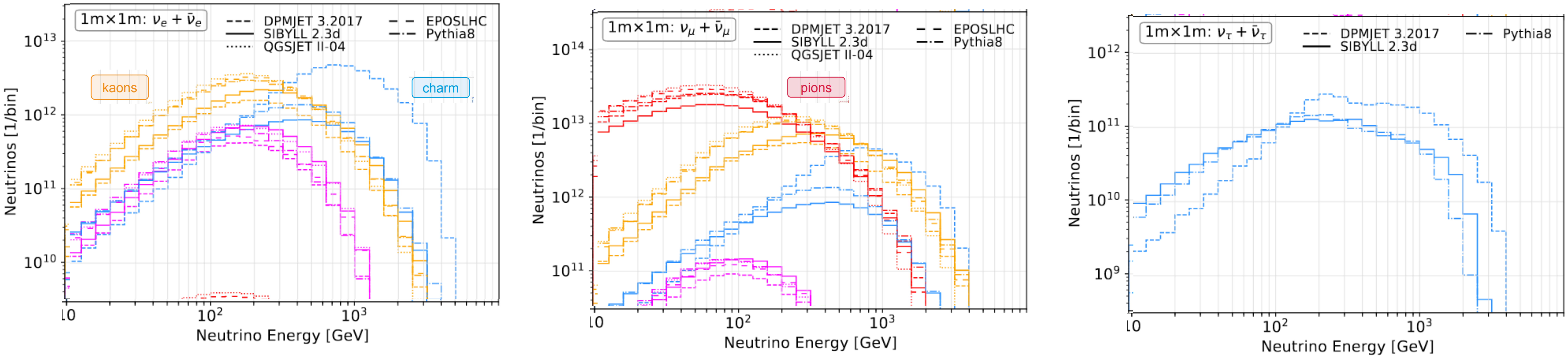


Neutrino interactions (all flavours, from different hadron sources) on nuclear targets

[FPF Snowmass white paper (2203.05090)]

NEUTRINOS FLUXES AT THE DETECTOR

- Fluxes in forward region evaluated with several MC generators of hadronic interactions for cosmic rays and forward physics + Pythia 8.2 Monash
- Kaons dominate lower energy $\nu_e + \bar{\nu}_e$
- Pions dominate lower energy $\nu_\mu + \bar{\nu}_\mu$
- High energy neutrino fluxes from charm – perturbative QCD
- $\nu_\tau + \bar{\nu}_\tau$ all from charm



[FPF Snowmass white paper (2203.05090)]

NEUTRINOS FLUXES AND RATES

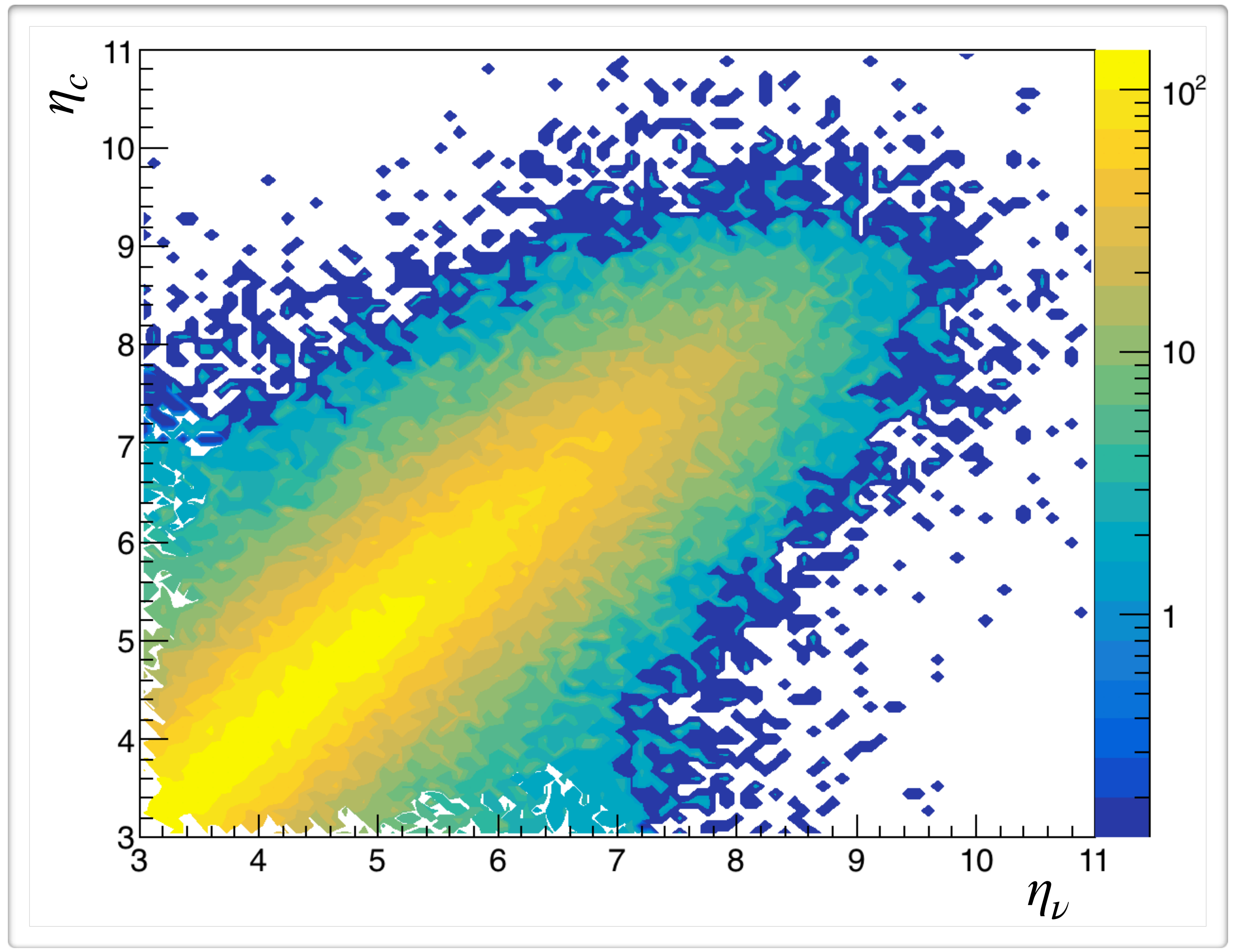
- Event rates at LHC neutrino experiments estimated with two LO MC generators: SIBYLL / DPMJET

	Detector			Number of CC Interactions		
	Name	Mass	Coverage	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
LHC Run3	FASERν	1 ton	$\eta \gtrsim 8.5$	1.3k / 4.6k	6.1k / 9.1k	21 / 131
	SND@LHC	800kg	$7 < \eta < 8.5$	180 / 500	1k / 1.3k	10 / 22
HL-LHC	FASERν2	20 tons	$\eta \gtrsim 8$	178k / 668k	943k / 1.4M	2.3k / 20k
	FLArE	10 tons	$\eta \gtrsim 7.5$	36k / 113k	203k / 268k	1.5k / 4k
	AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	6.5k / 20k	41k / 53k	190 / 754

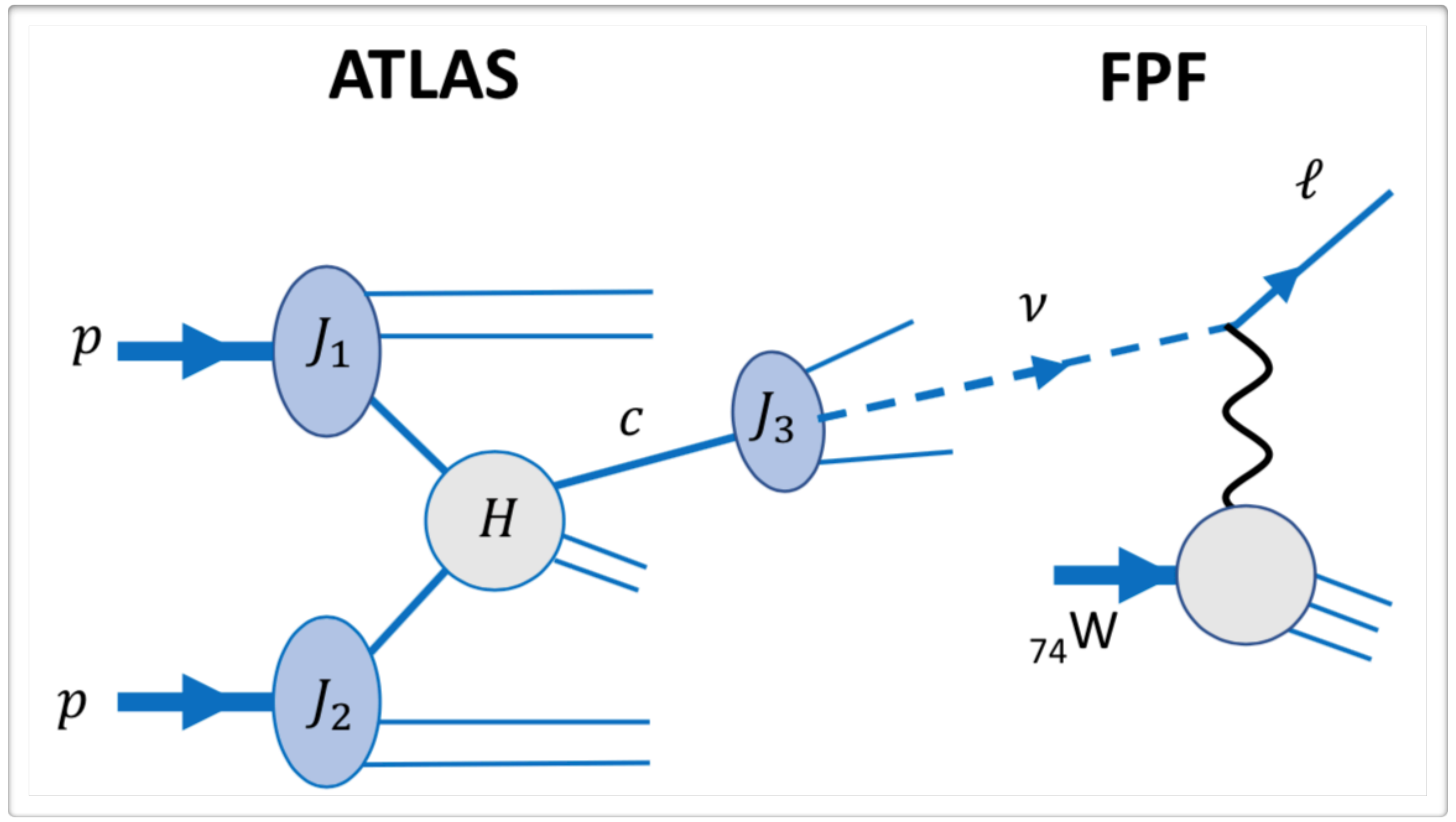
- Large spread in current generator predictions:
  - Challenge: for neutrino physics measurement we need to quantify and reduce neutrino flux uncertainties
  - Opportunity: forward neutrino flux measurement can help to improve our understanding of underlying physics

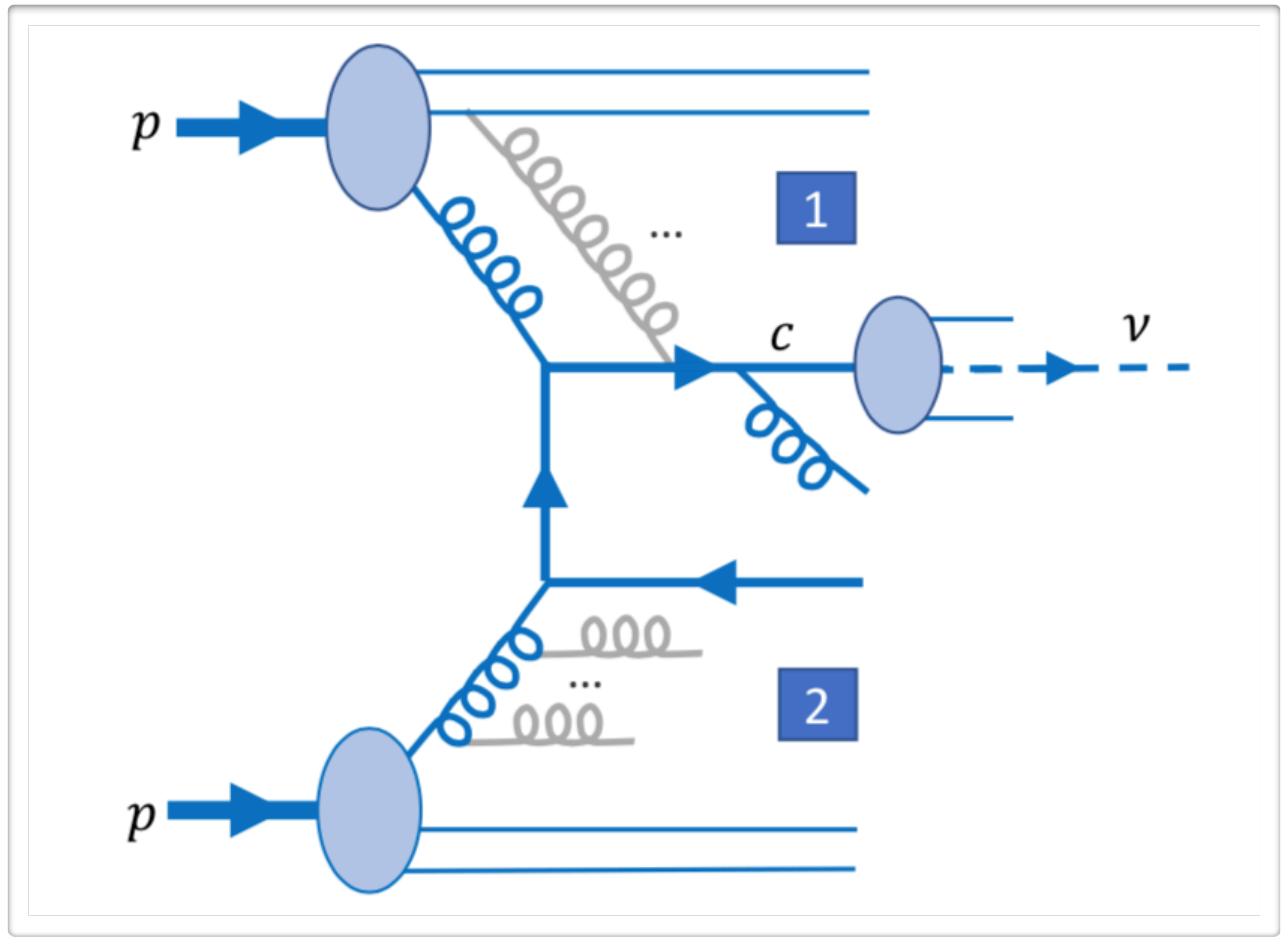
CHARM PRODUCTION

- Forward neutrino η_ν is correlated to charmed hadron η_c



- Many opportunities:
  - PDFs, small x and large x
  - PDFs, intrinsic charm
  - Treatment of heavy flavour
  - Fragmentation, spectator effects, forward baryon production
  - Higher order effects, intrinsic k_T
  - Particle/antiparticle asymmetries

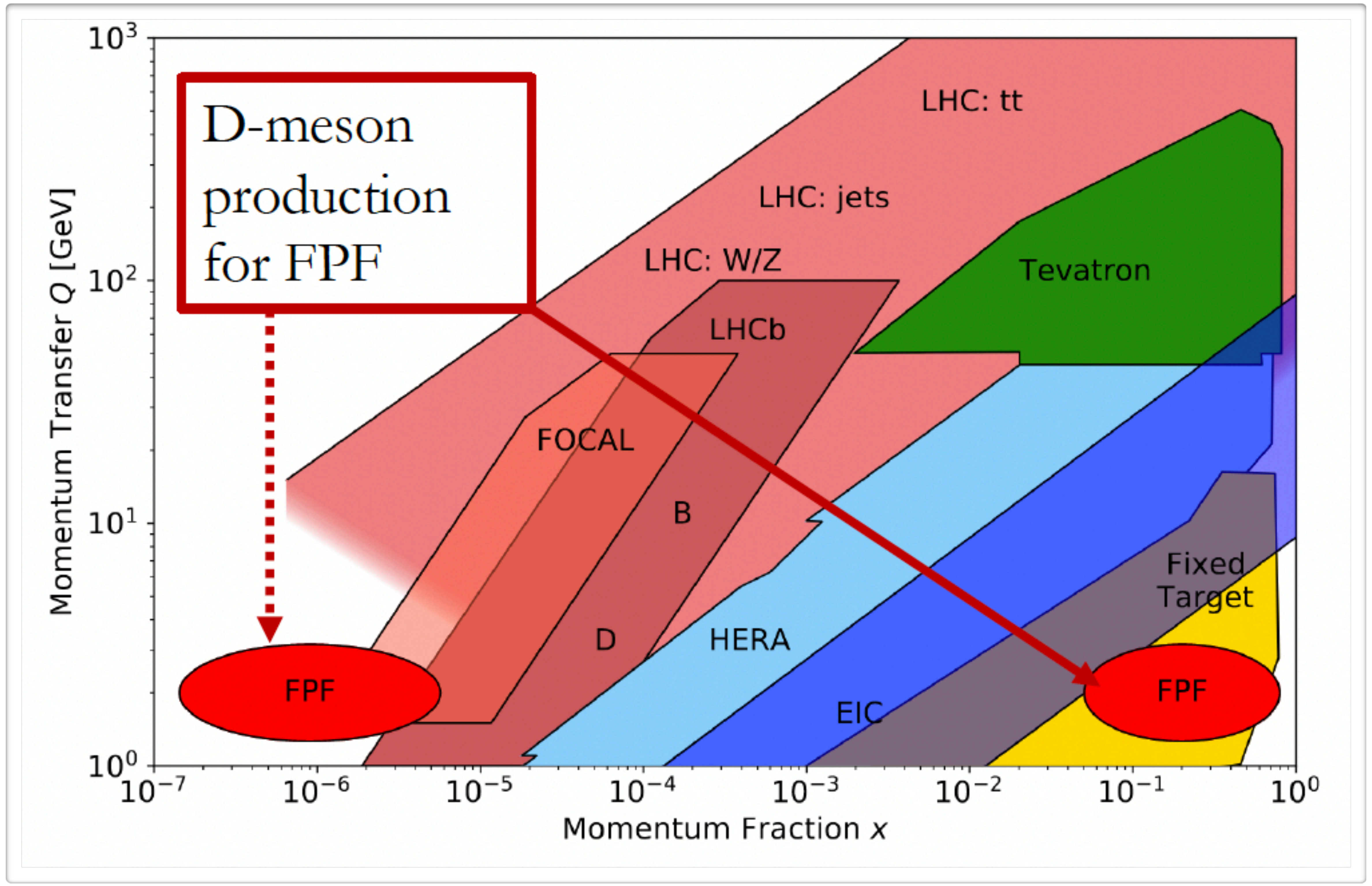




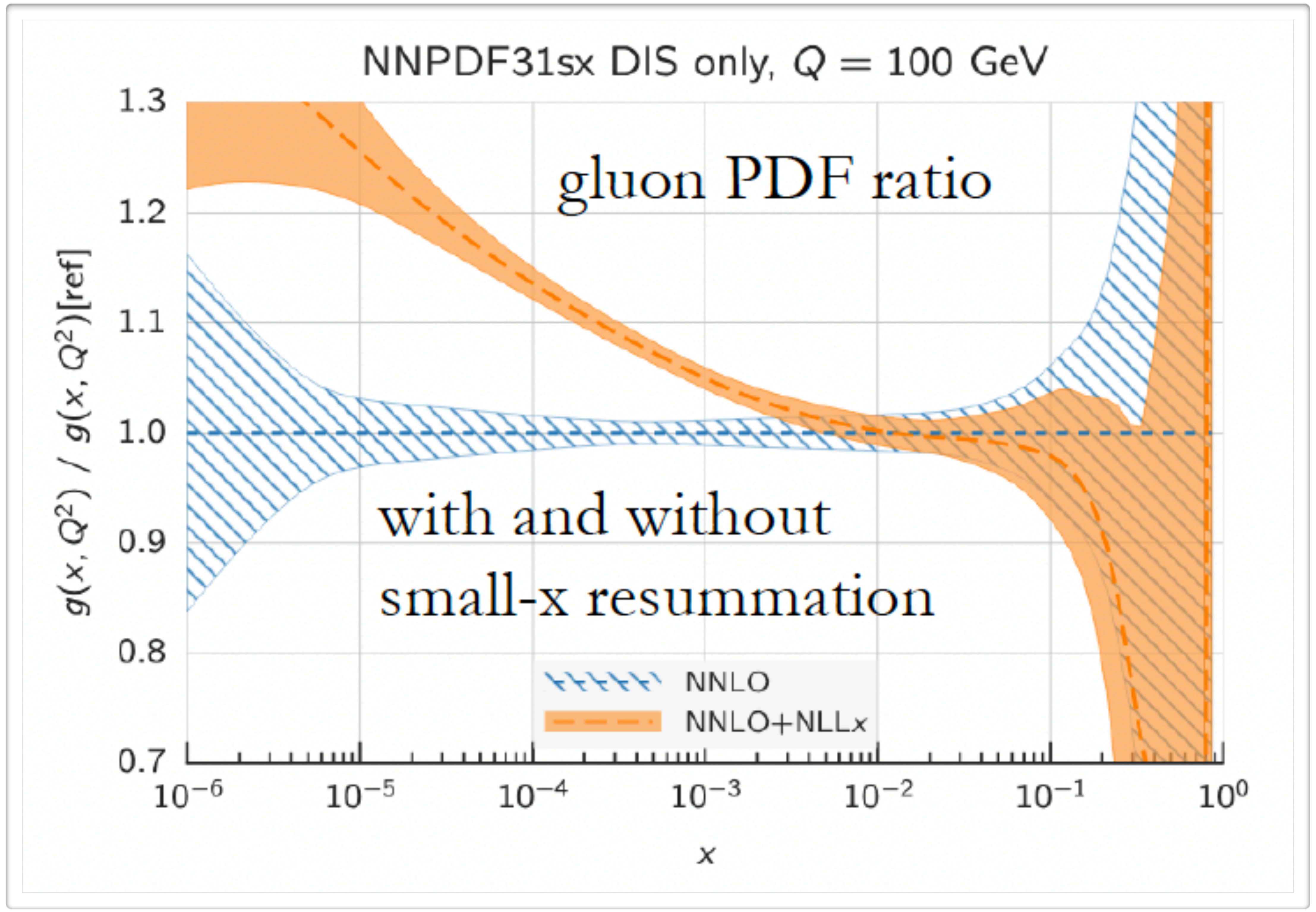
[Short white paper 2109.10905]

QCD USING LHC NEUTRINOS

- Forward charm: high rapidity, $x_1 >> x_2$ in gluon PDF



- Small-x reggono for PDFs
  - PDF fits and uncertainties
  - large ln(1/x) and resummation
  - collinear and kT factorization approaches
  - small-x gluon saturation



[FPF Snowmass white paper (2203.05090)]

CONCLUSIONS

- Forward Physics Facility – a relatively low cost facility and experiments can leverage the HL-LHC interactions to do interesting physics to better understand the fundamental physics of elementary particles, and perhaps, discover new particles and forces
- FASER and SND@LHC just started to take data in LHC’s forward direction
- The FPF is proposed to continue this program during the HL LHC era
- Significant extension of the LHC’s physics program

Thanks to the CERN Physics Beyond Colliders group for technical studies on the FPF design/feasibility

BACKUP SLIDES

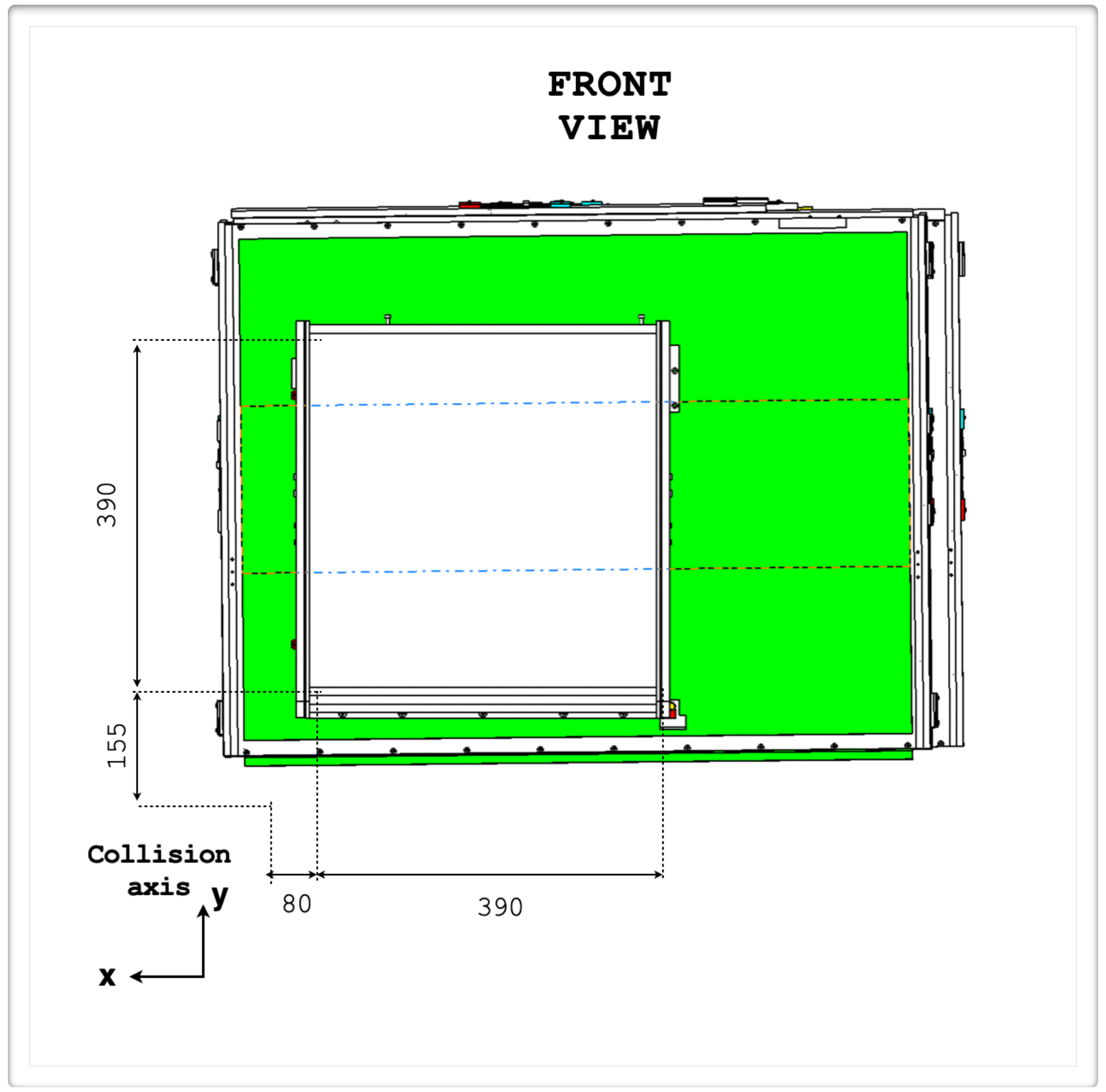
THE SND@LHC DETECTOR LAYOUT

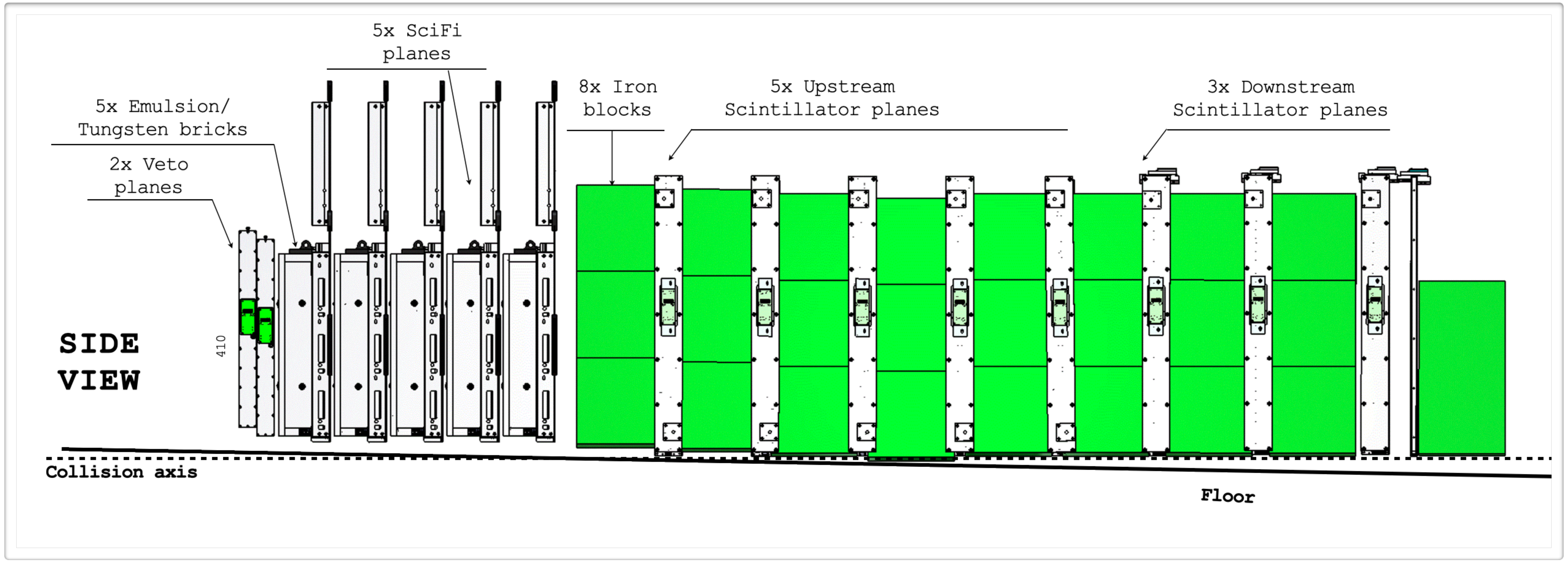
- Angular acceptance: 7.2< η < 8.4
- Target material: Tungsten
- Target mass: 830 kg
- Surface: 390x390 mm^2

Off axis location

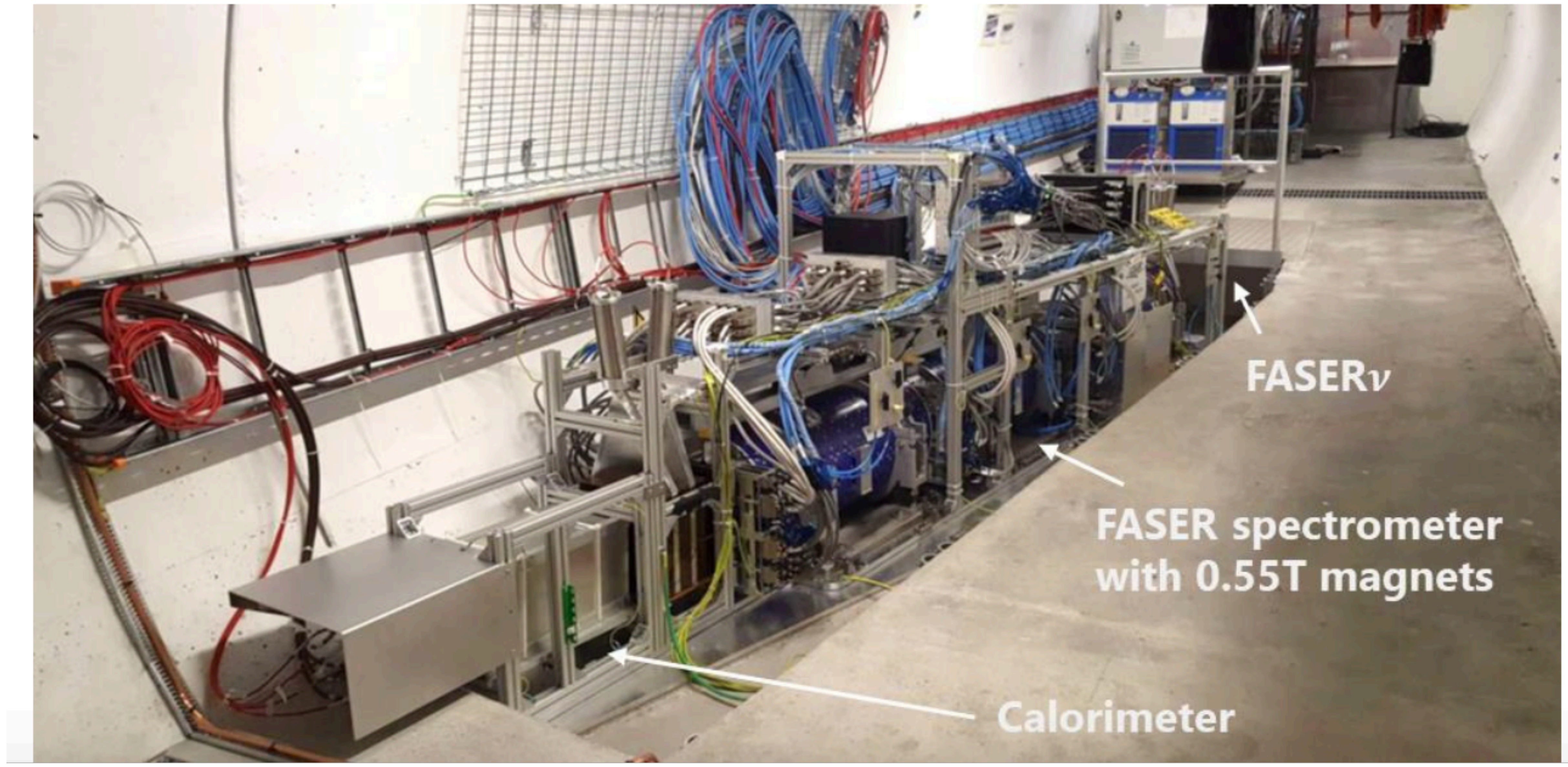
Electromagnetic calorimeter
~40 X_0

Hadronic calorimeter
~10 λ





FASERν INSTALLATION IN TI12



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SND@LHC INSTALLATION IN TI18

- Detector commissioning on surface (North Area @CERN) in September and October 2021
- Installation in TI18 started on November 1st 2021
  - Electronic detector installation completed on December 3rd 2021
  - Installation of the neutron shield completed on March 15th 2022
  - Installation of the first emulsion wall on April 7th 2022

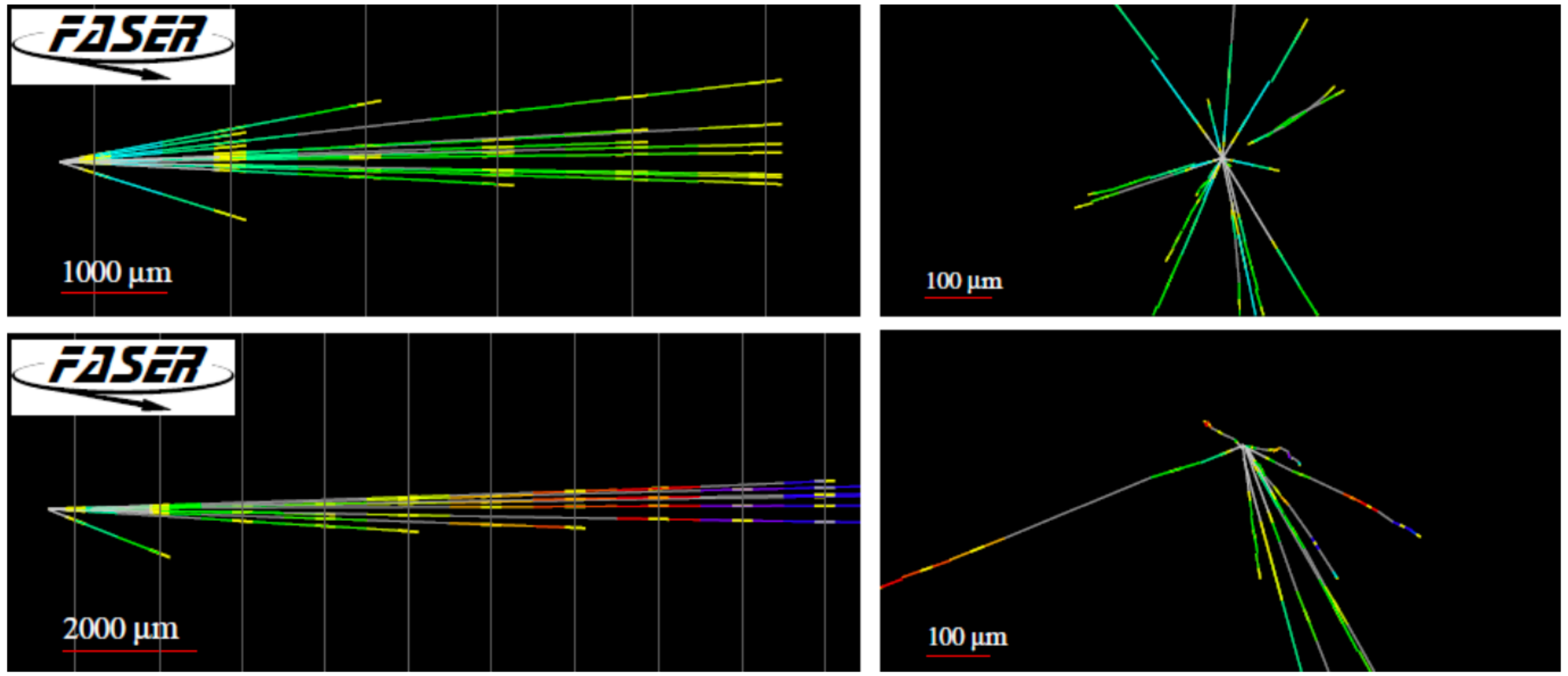
September 2021

December 2021

March 2022

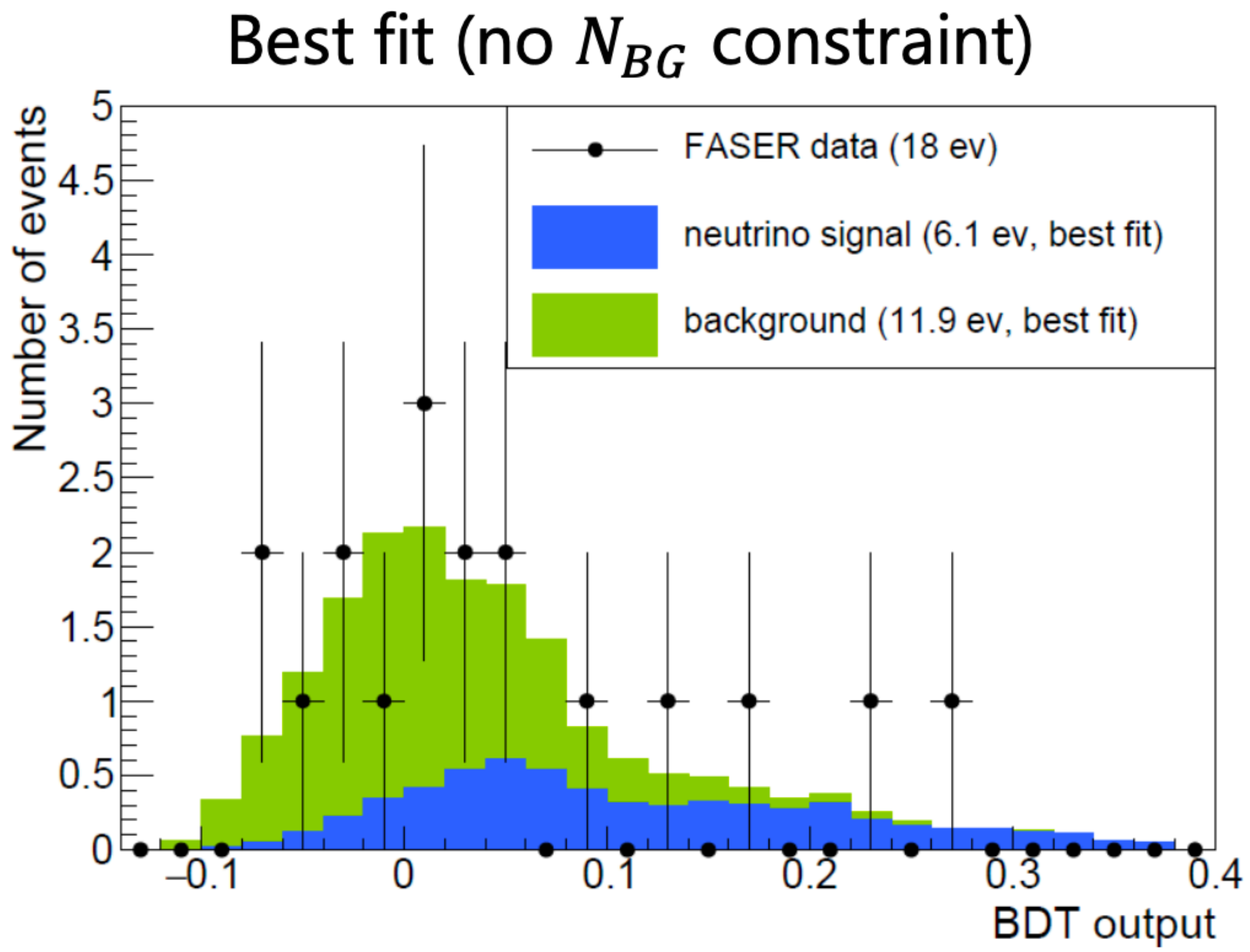
FIRST NEUTRINO INTERACTION CANDIDATES AT THE LHC

[Phys. Rev. D 104, L091101]



2018 FASERν Pilot run

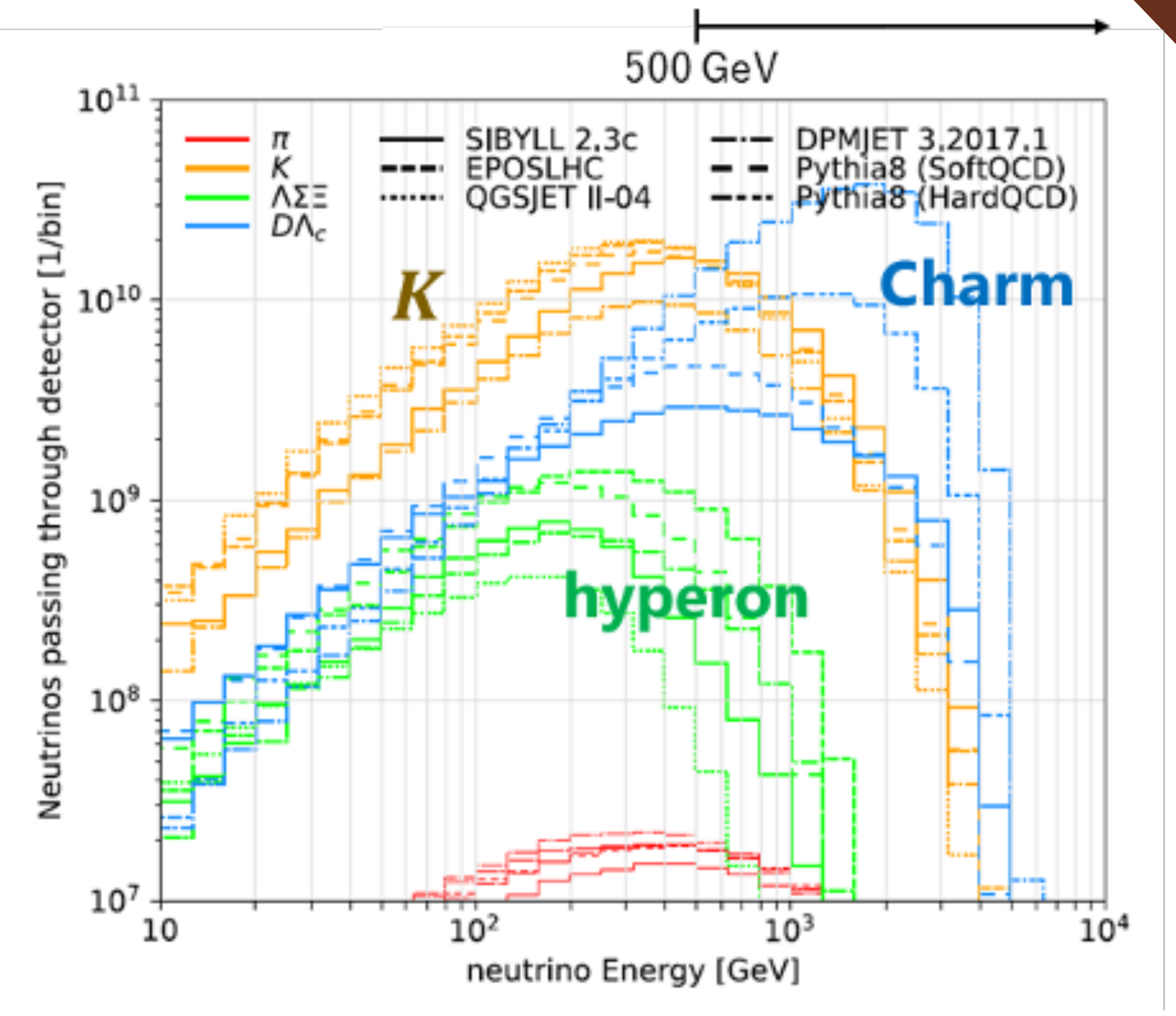
- Analyzed target mass of 11 kg and luminosity of 12.2 fb^{-1}
- 18 neutral vertices selected
  - By applying topological cuts
  - Expected signal $3.3^{+1.7}_{-0.9}$ events, background 11.0 events
- no lepton ID in the pilot detector, high BG
- In the BDT analysis, excess of neutrino signal observed
- Statistical significance 2.7 σ from null hypothesis
- This result demonstrates detection of neutrinos at the LHC

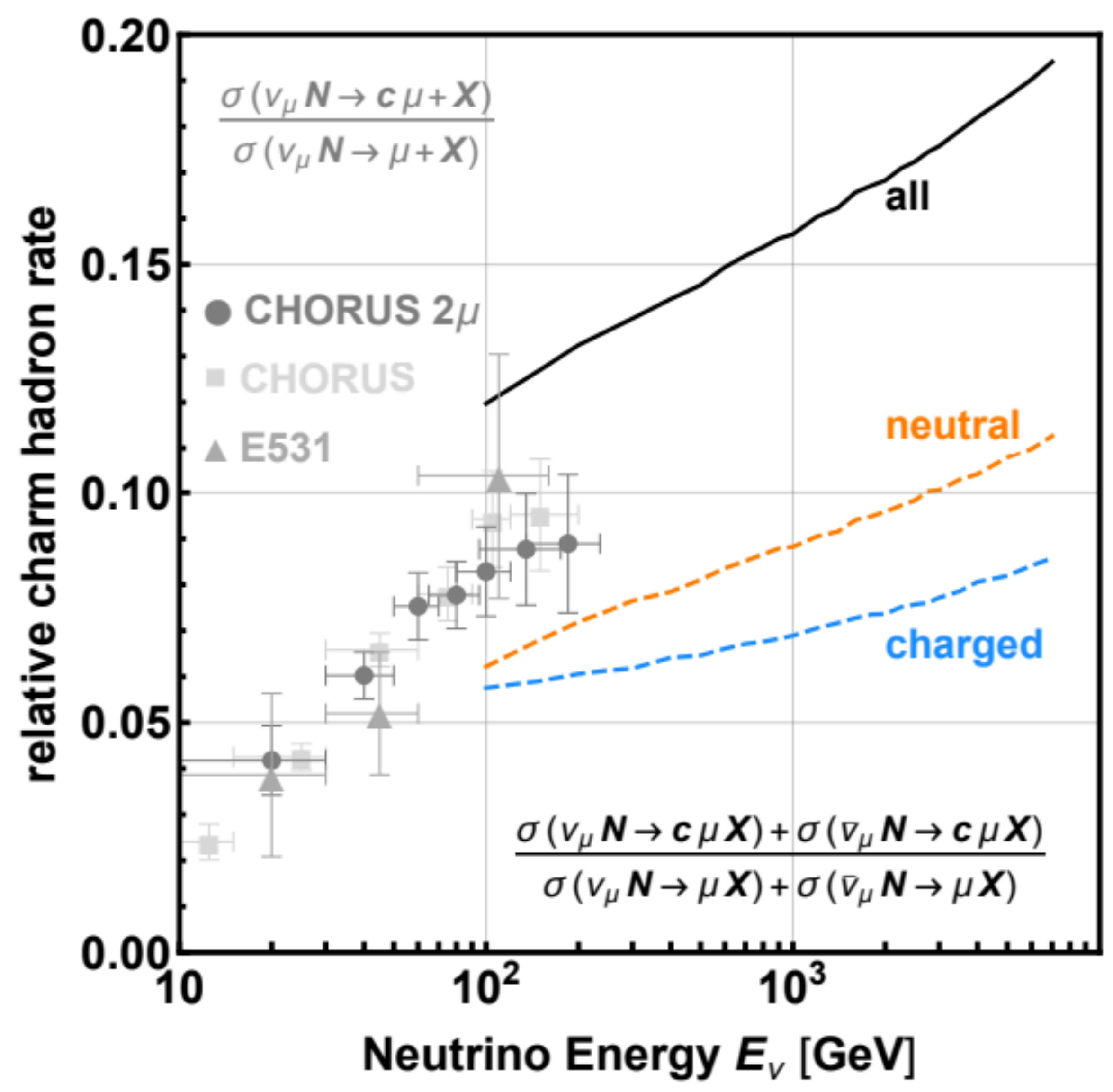


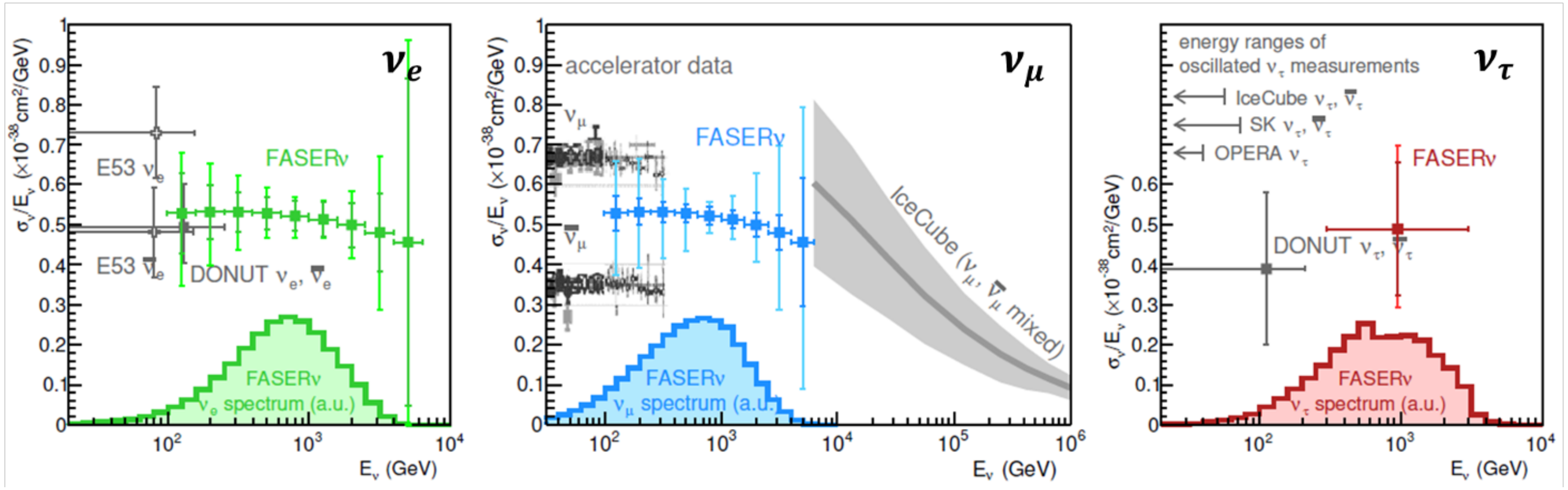
FASERν PHYSICS PROGRAMME

- Neutrino cross-section measurement of three flavors at TeV energies
- Neutrino CC interactions with charm production ($\nu s \rightarrow lc$):
  - study strange quark content
  - probe inconsistency between predictions and LHC data
- Neutrino NC measurements could constraint non-standard interactions
- High energy electron neutrinos (E>500 GeV) mainly produced in charmed hadron decays:
  - measurement of forward charm production

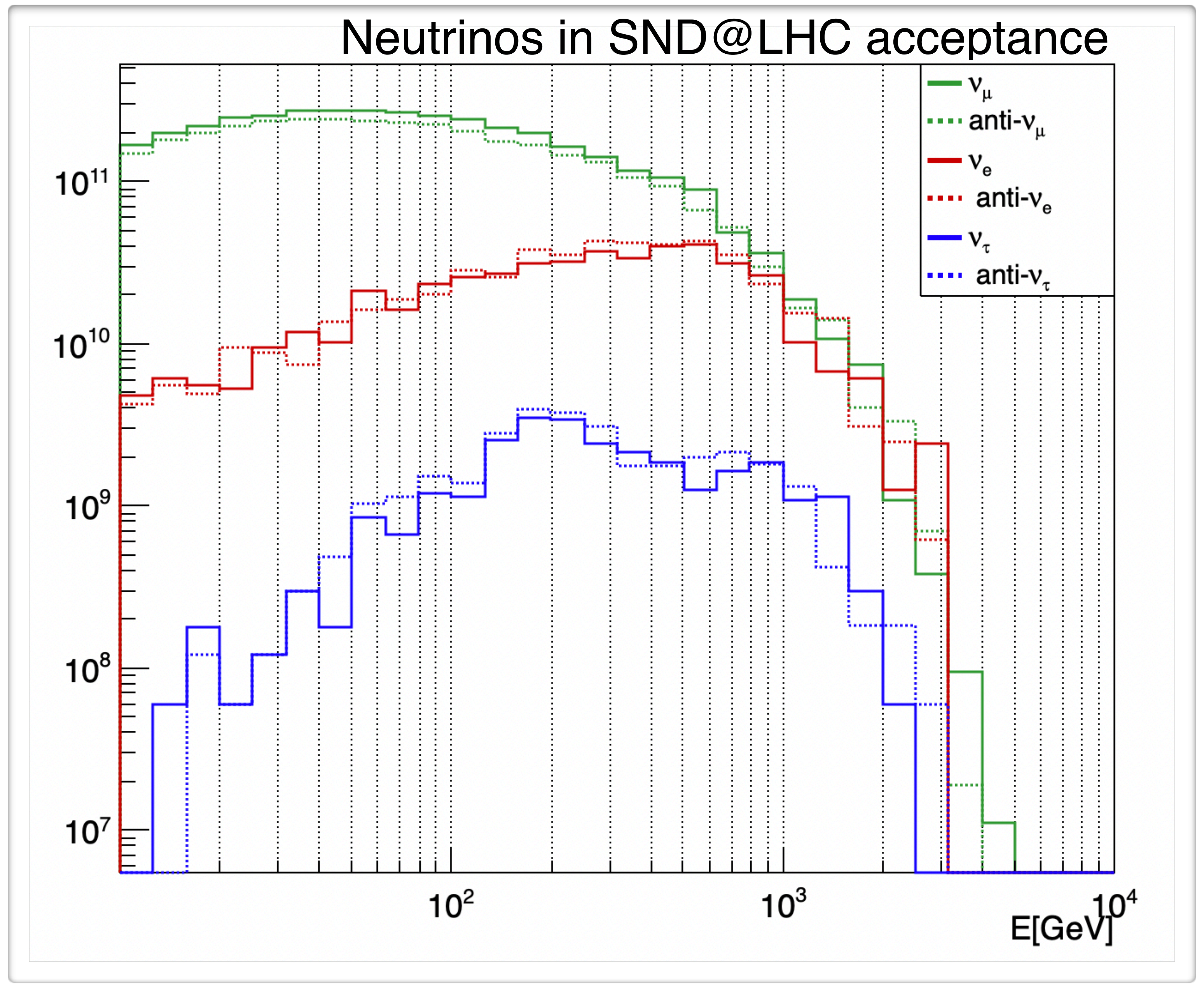
Electron neutrino in FASERν





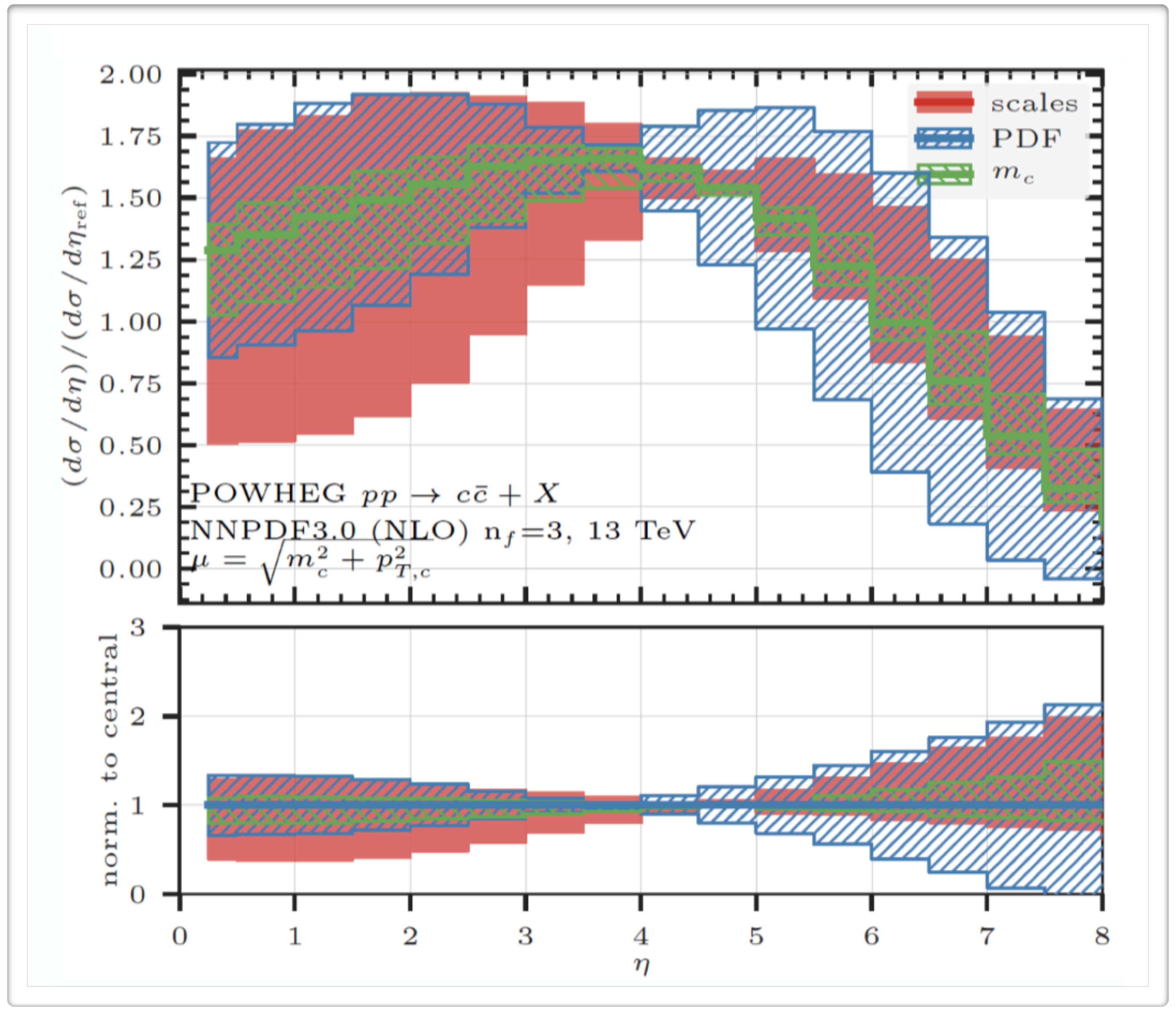


SND@LHC PHYSICS PROGRAMME



- Study neutrino of different flavors at TeV energies
- Electron neutrinos mostly produced by charm decays
- ν_e ca be used as a probe of **charm production** in a region where charm yield has large uncertainties
- Measure the charmed hadron yield in an unexplored pseudo-rapidity range:
  - extraction of gluon PDF in very small x-region
- Test lepton flavor universality measuring ν_e/ν_τ and ν_e/ν_μ ratios

Measurement	Uncertainty Stat.	Uncertainty Sys.
$pp \to \nu_e X$ cross-section	5%	15%
Charmed hadron yield	5%	35%
ν_e/ν_τ ratio for LFU test	30%	22%
ν_e/ν_μ ratio for LFU test	10%	10%



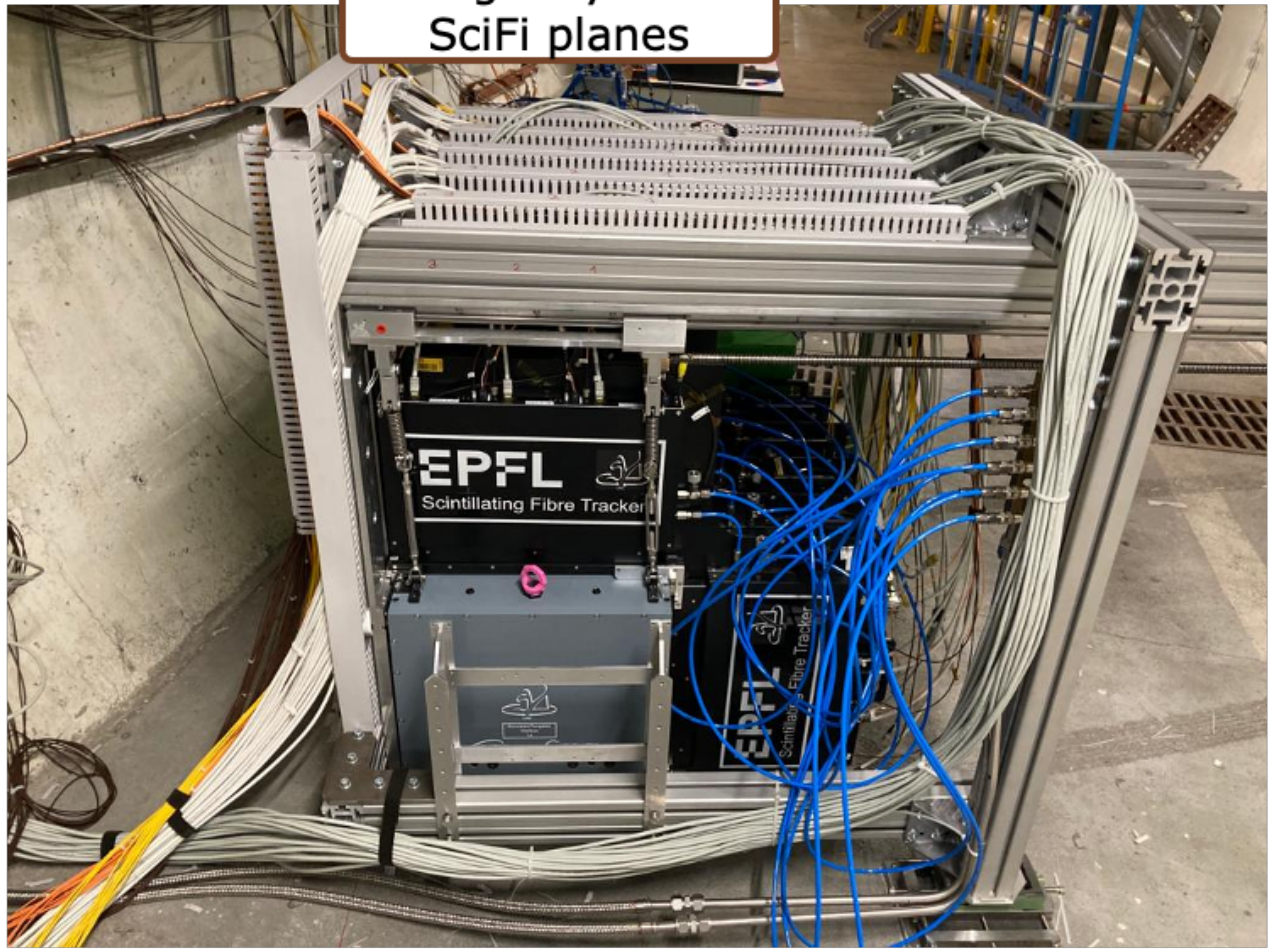
Ratio between the cross-section measurements at different pseudo-rapidities, normalised to LHCb measurements

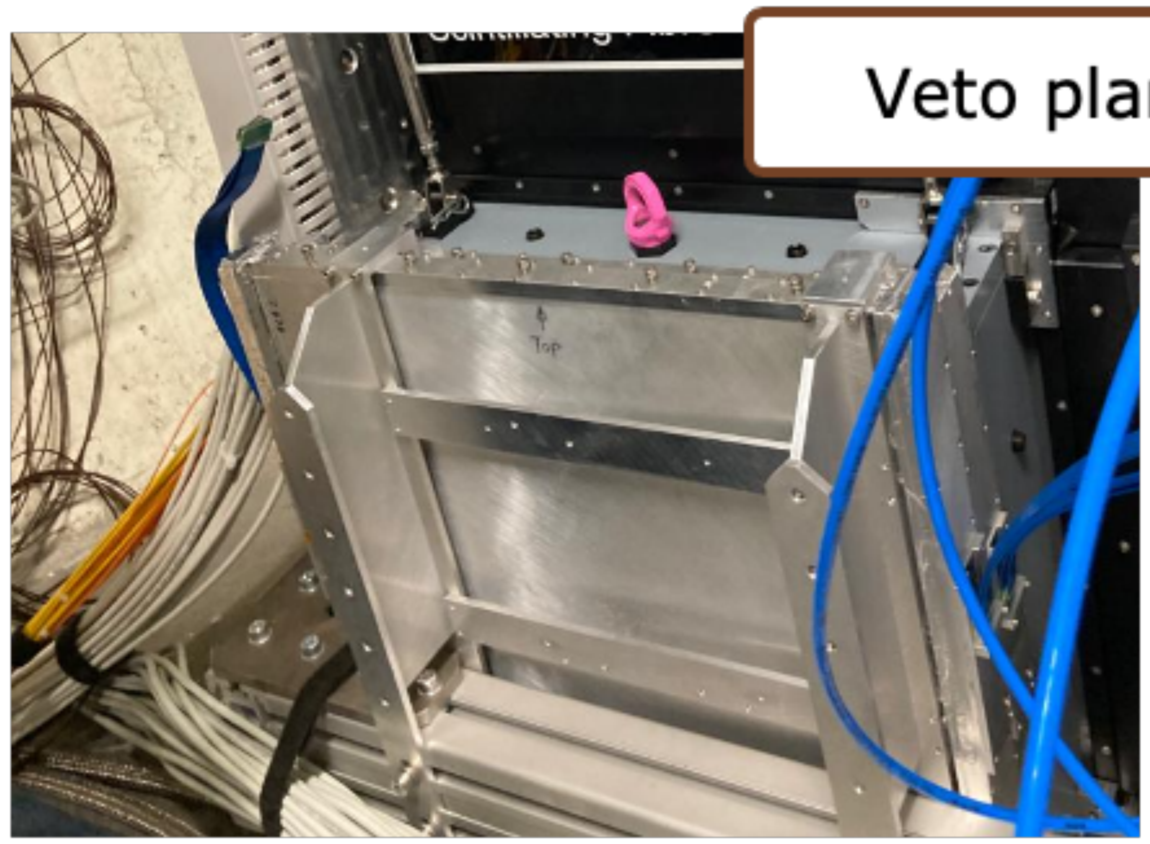
$$R = \frac{d\sigma/d\eta(13\,TeV)}{d\sigma/d\eta_{ref}(7\,TeV)}$$

$\eta_{ref} = [4,4.5]$

arxiv:1510.01707

SND@LHC INSTALLATION IN TI18





FASERν PREPARATION FOR RUN3