Swiss National
Science Foundation

Neutrinos at the LHC

In context

Symposium on Science at PAUL (Paarl Africa Underground Laboratory)
14th - 18th January 2024

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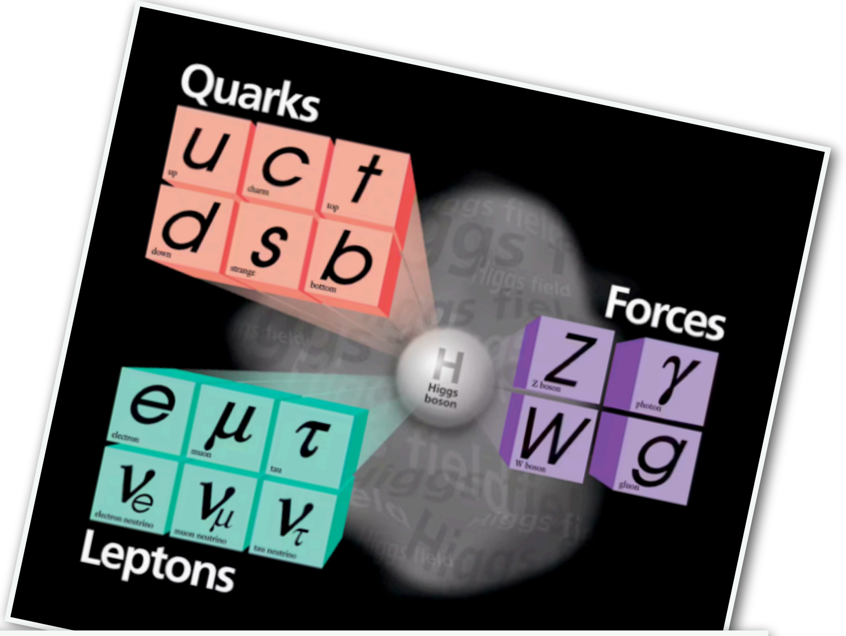
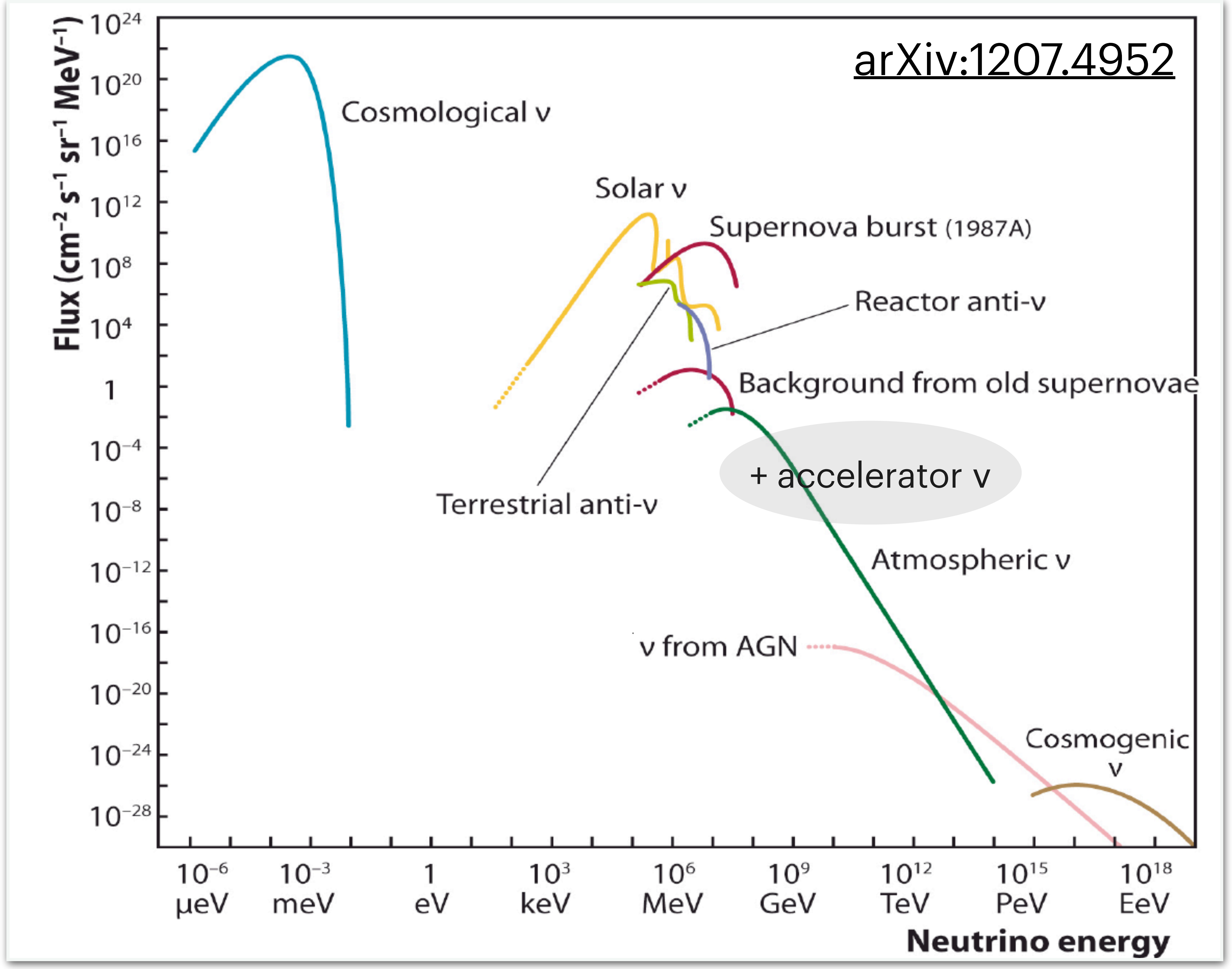
Why neutrinos are cool: Abundant, unsolved & challenging

Second most abundant particle in universe after photons, yet least understood Standard Model particle

Difficult to detect due to very low interaction cross-section.



- Intriguingly, represent New Physics: Don’t fit in Standard Model, as proven to have mass but no way of generating these in SM.
- Neutrinos produced from many sources across wide energy spectrum: From hardly interacting eV relic neutrinos - yet to be detected - to Peta-eV scale neutrinos from currently unknown (extra)galactic sources.


arXiv:1207.4952

Why neutrinos are cool: Versatile tools

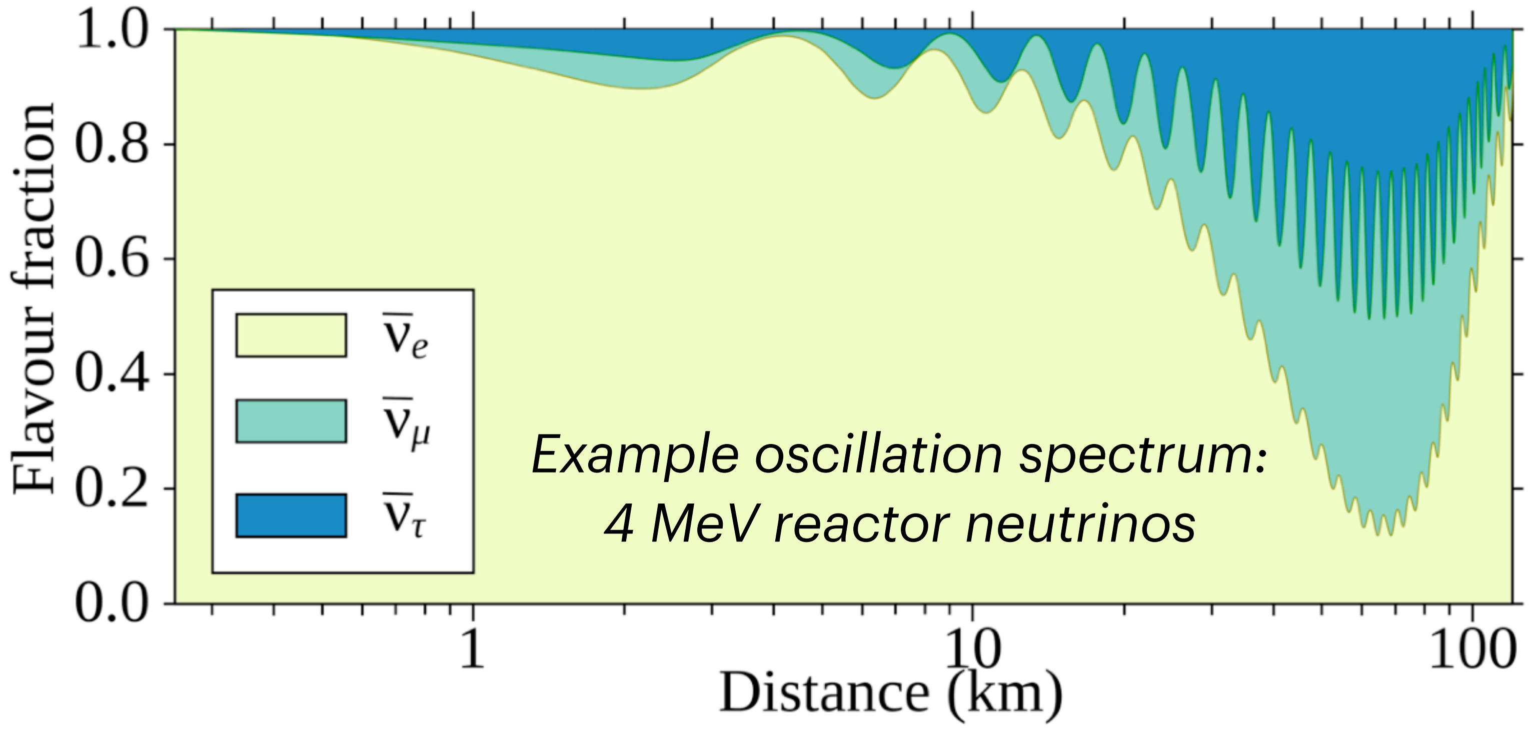
Neutrinos can teach us more about themselves *and* their sources.

Neutrino properties

Neutrino flavour oscillation measurements have allowed determination of neutrino mixing parameters,

$$\Delta m^2_{2,1}, |\Delta m^2_{3,1}|, \theta_{1,3/1,2/2,3}$$

And constraints on new physics (sterile neutrino states)



Key has been access to large range in ν propagation distance & energy

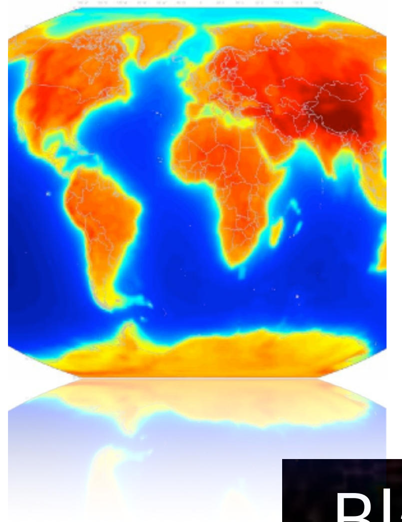
From 1 MeV: Solar (10^7 km), reactor (0.01-100 km) ν

to 100 GeV : atmospheric (10-10^4 km), accelerator (0.1-1000 km) ν

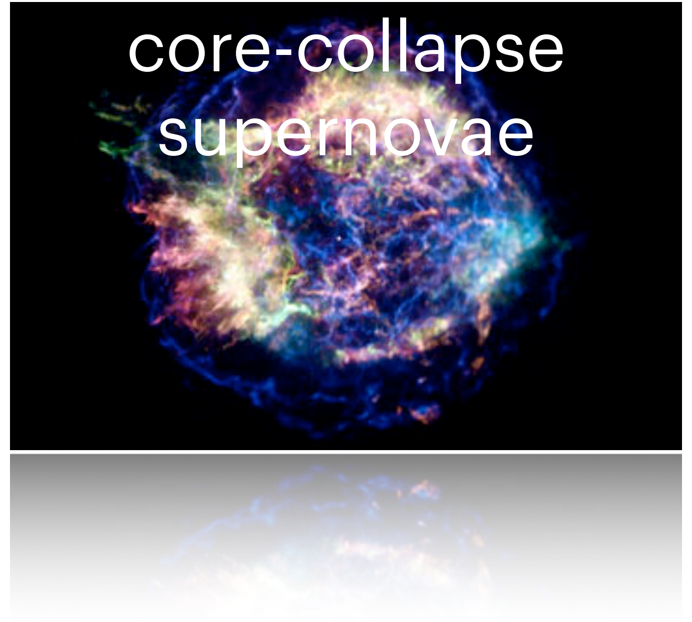
While work ongoing on unknowns: Neutrino nature & mass generation, neutrino masses & ordering, CP violating phase

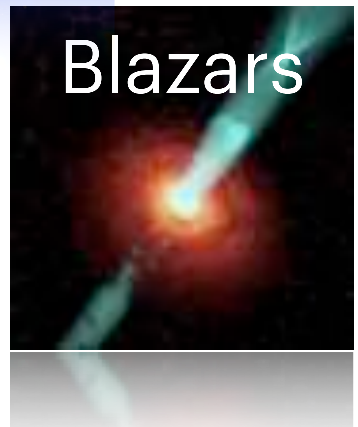
Probes to originators

Geoneutrinos -> Earth interior



Astroparticle neutrinos ->





Ultra high energy astroparticle neutrinos -> cosmic accelerators

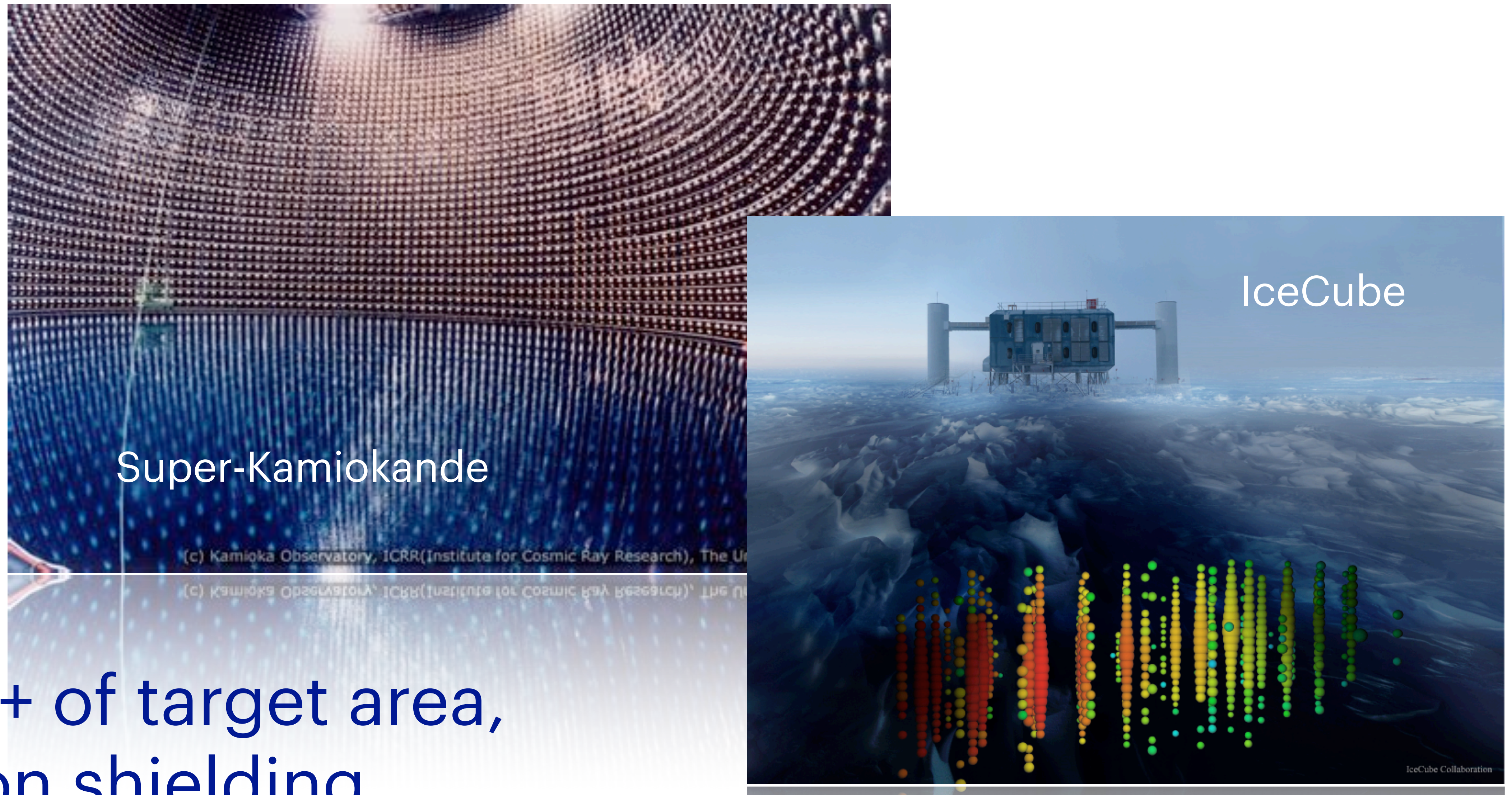
Alert systems

Rare supernova events

Nuclear reactor activity monitoring

Characteristics of neutrino experiments

When one thinks of a neutrino experiment, something large usually comes to mind…

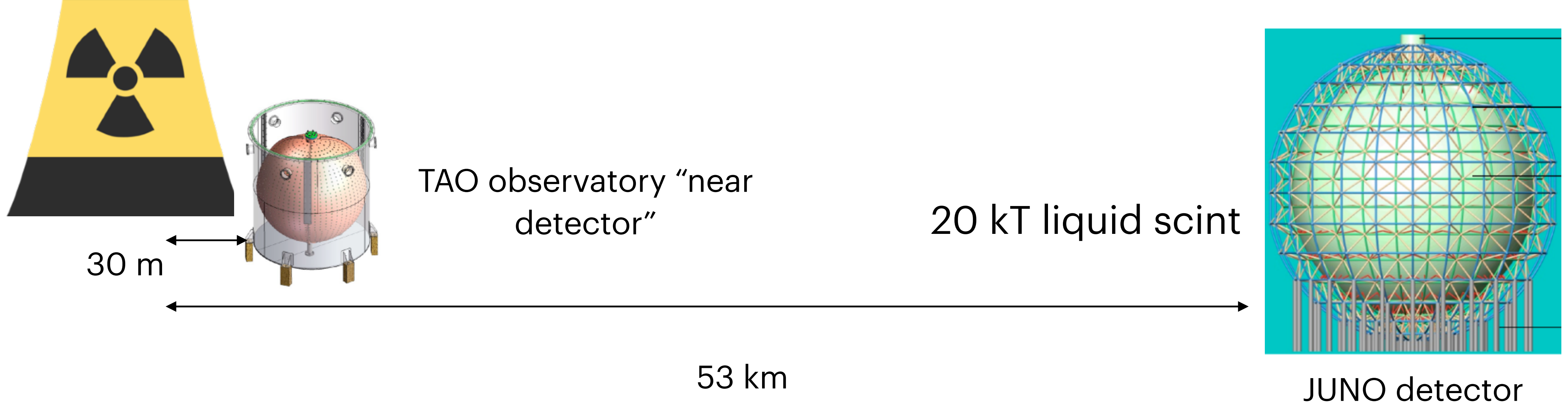


We have used the entire Earth as a way of suppressing background for neutrino detection.

- **Rely on**: Typically kilotonnes++ of target area, excellent background/radiation shielding.

- **Keys to precision:**
  - Knowledge of *original neutrino flux* (production dependent).
  - Knowledge of neutrino *interaction cross-sections* at relevant energies.

Planned JUNO observatory: Requires high precision to resolve neutrino mass ordering

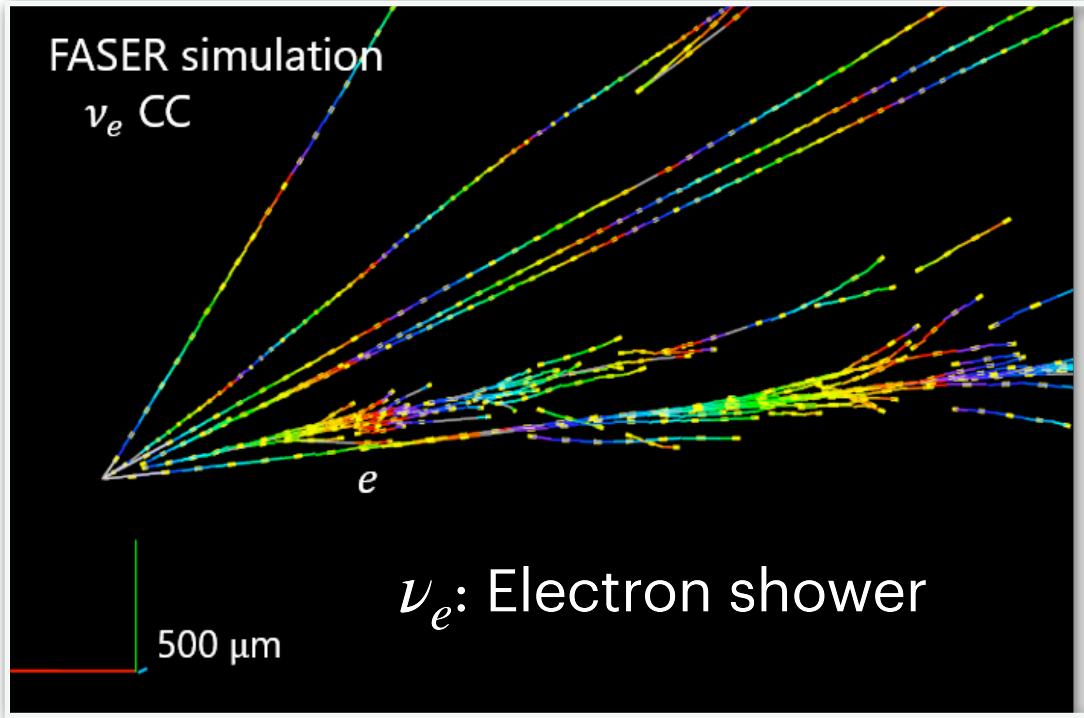


Oscillation experiments typically have a near detector to measure original spectrum.

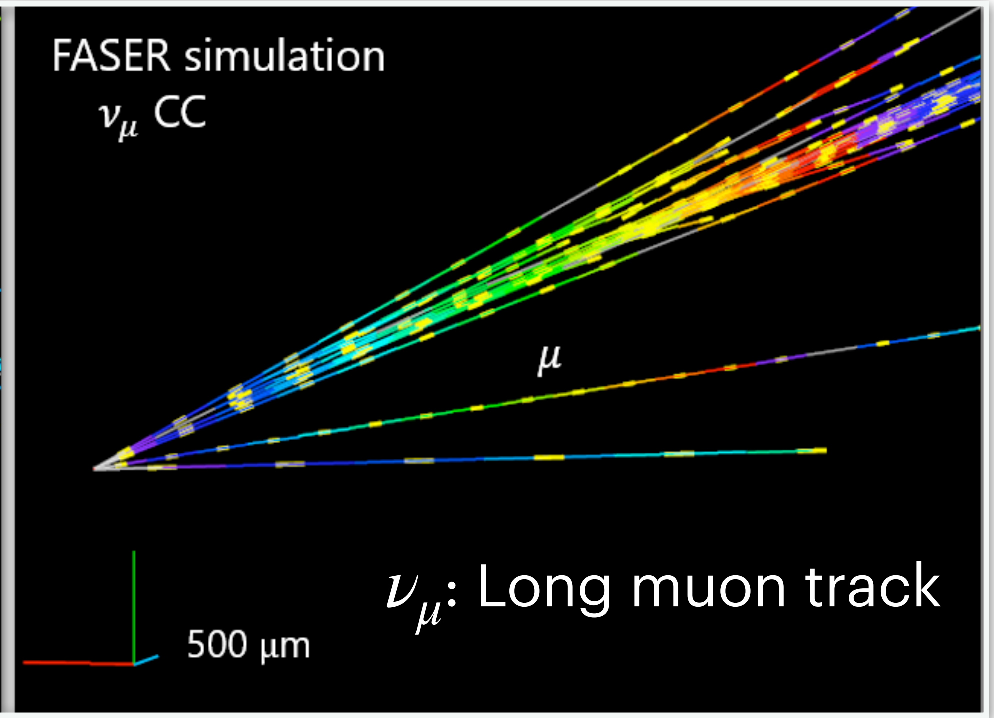
Characteristics of neutrino experiments

- **Challenging detector capabilities:** Good energy resolution, pointing, flavour identification.

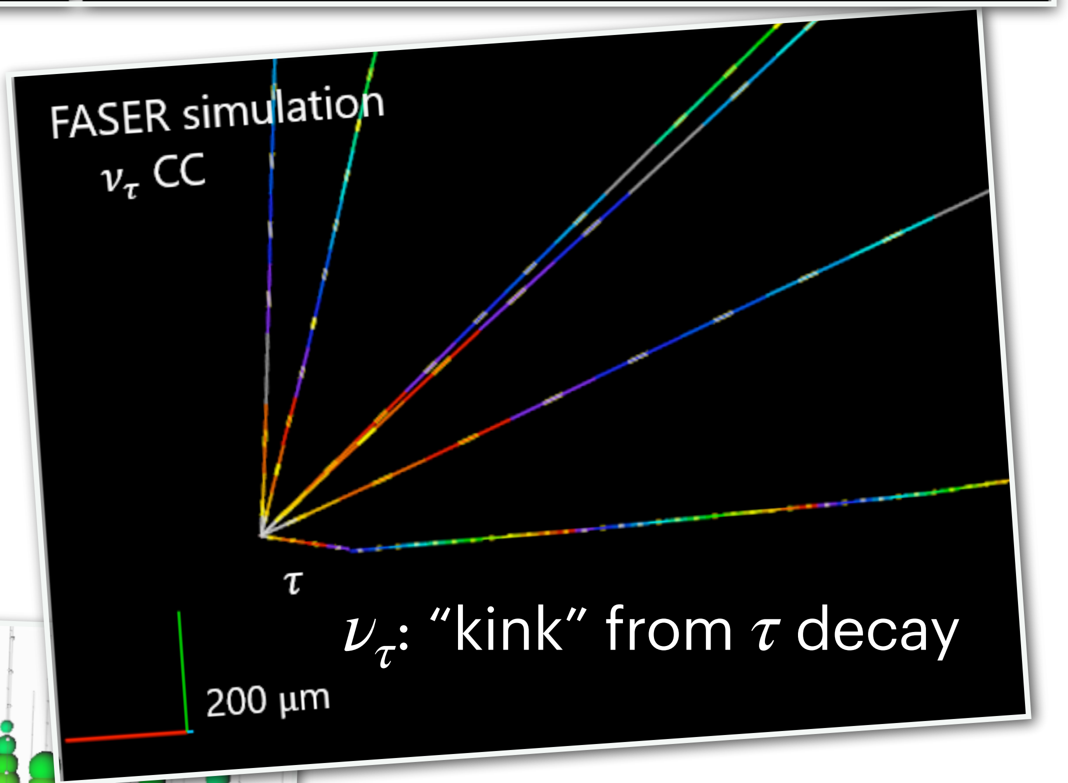
- **Popular detector technologies:**
  - Use of *scintillating liquid for detection of inverse β decay,* popular in reactor experiments (KamLAND, JUNO).
  - Array of PMTs in large body of water, ice (…) to detect Cherenkov light from energetic charged lepton; Large area can cost-effectively be equipped for low rate high energy astro-neutrino flux (SuperK, IceCube).
  - *Emulsion* interleaved with target material for precise measurements of interaction topologies, e.g. for lepton ID, in particular identifying tau decays (OPERA).
  - Up & coming: *LAr TPCs* for high res 3D imaging of neutrino interaction at lower energy w.r.t. Cherenkov (MicroBooNE, DUNE).



ν_e: Electron shower

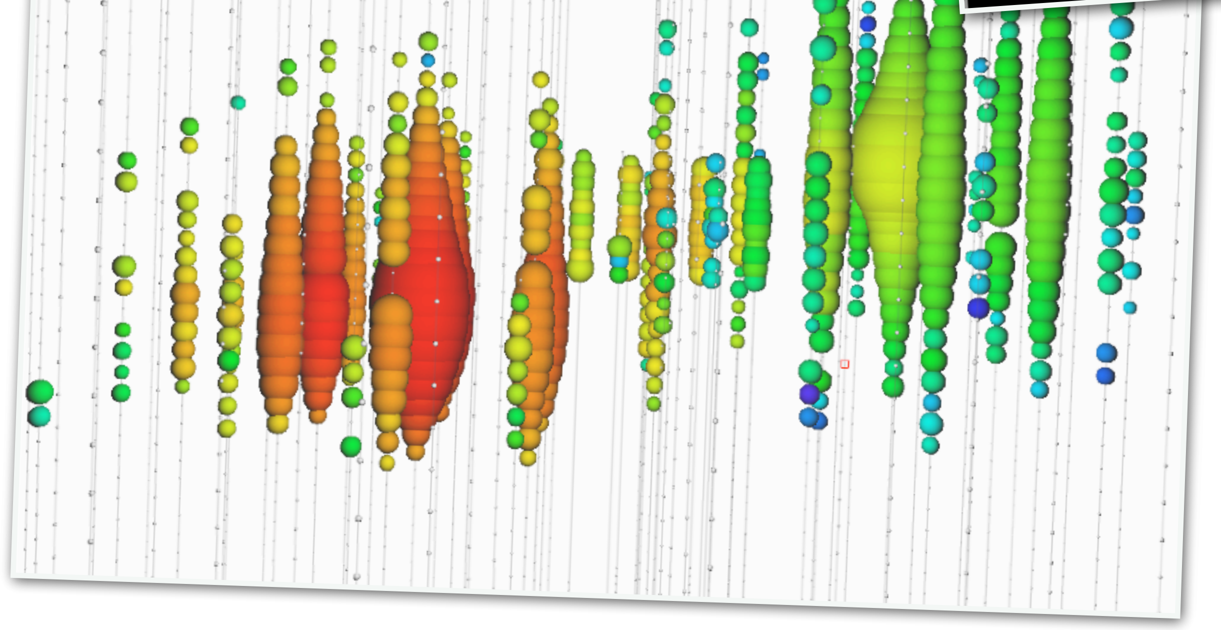


ν_μ: Long muon track



ν_τ: "kink" from τ decay

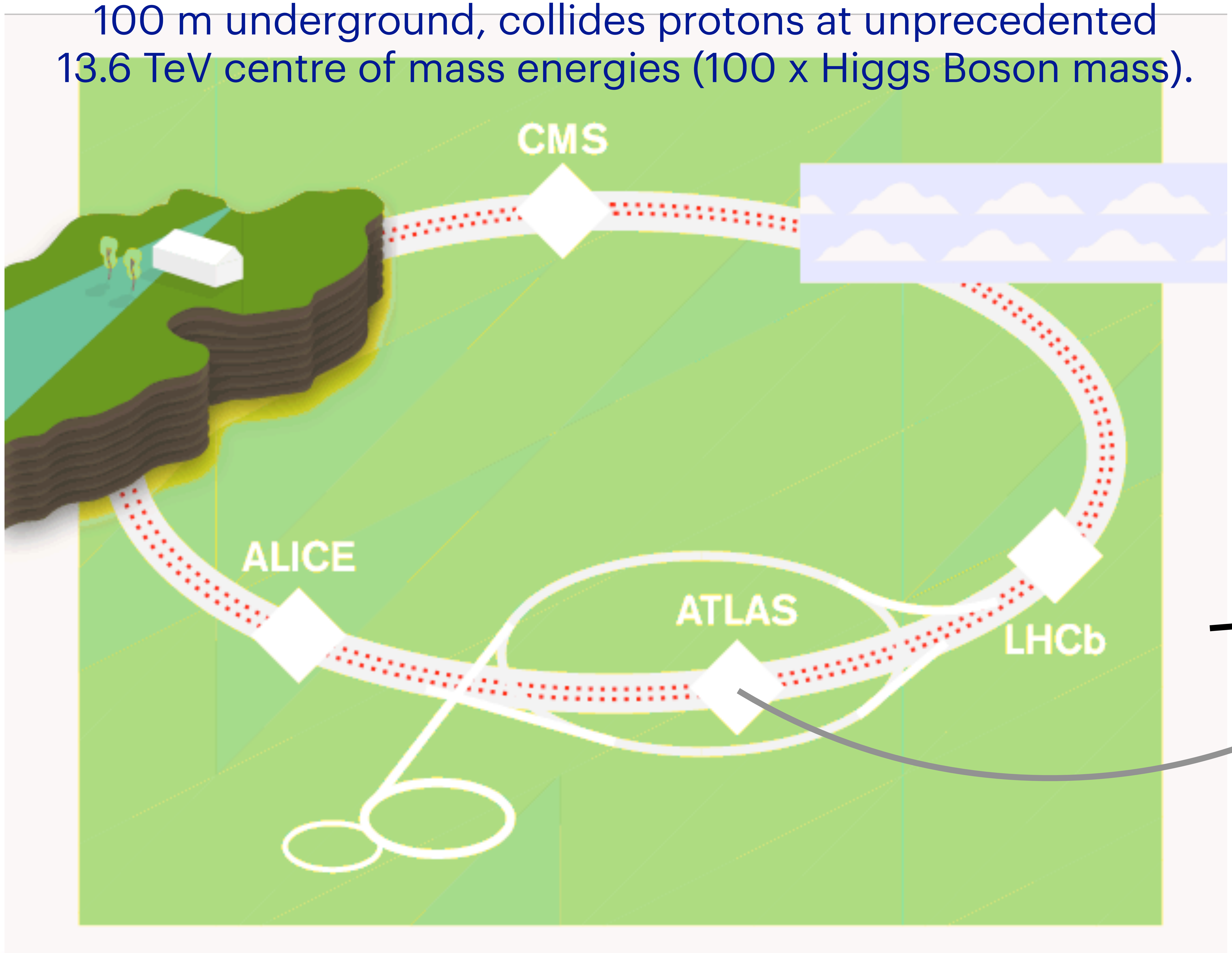
Lepton identification with imaging detector in deep inelastic scattering events.



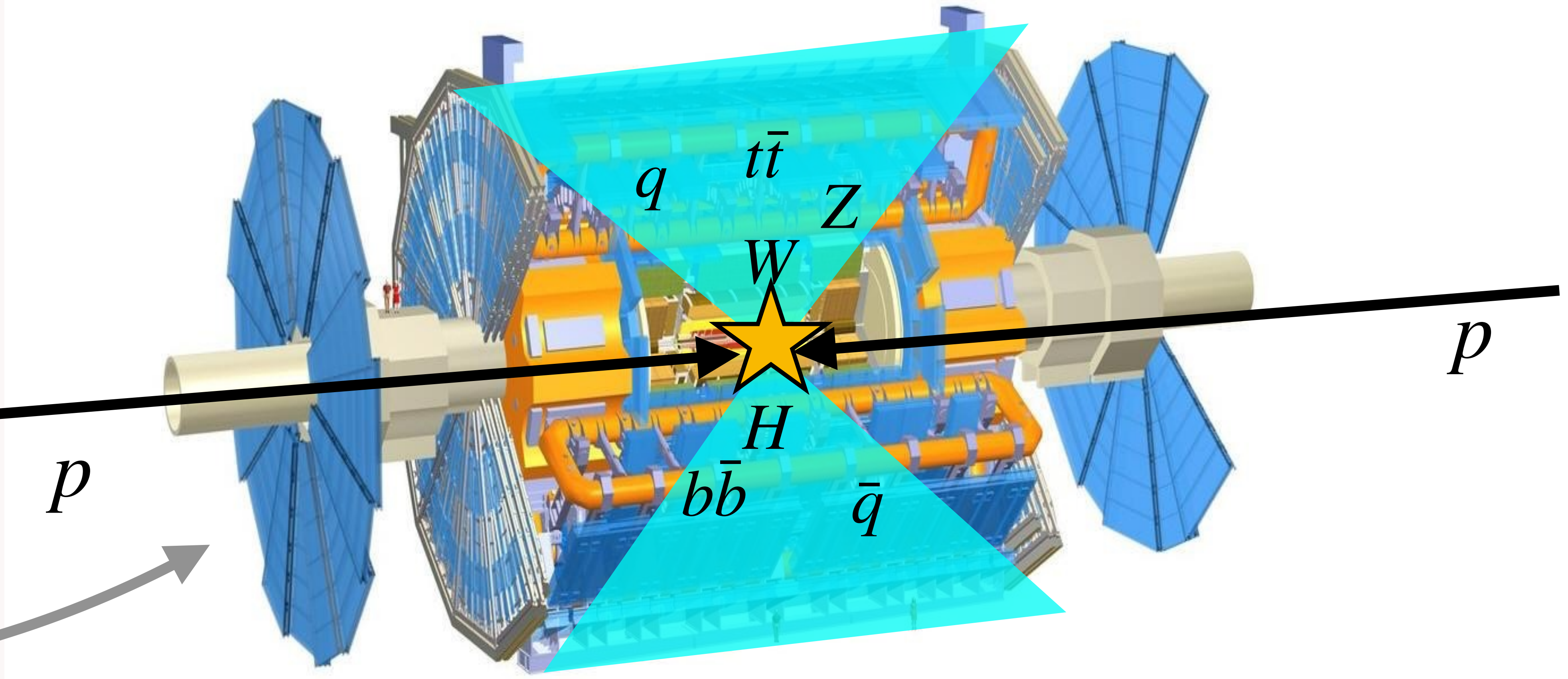
Simulated τ "double bang" decay Cherenkov signature in IceCube

A new door to neutrino physics, at the LHC

Large Hadron Collider @ CERN:
100 m underground, collides protons at unprecedented
13.6 TeV centre of mass energies (100 x Higgs Boson mass).



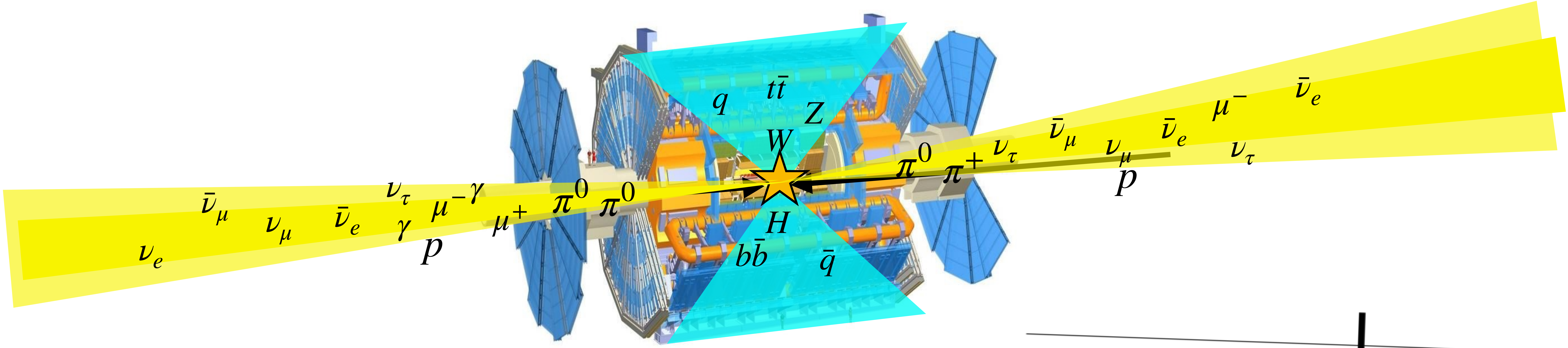
Main experiments large:
Up to 25 m Ø, focus on heavy
products produced perpendicular
to beam axis.



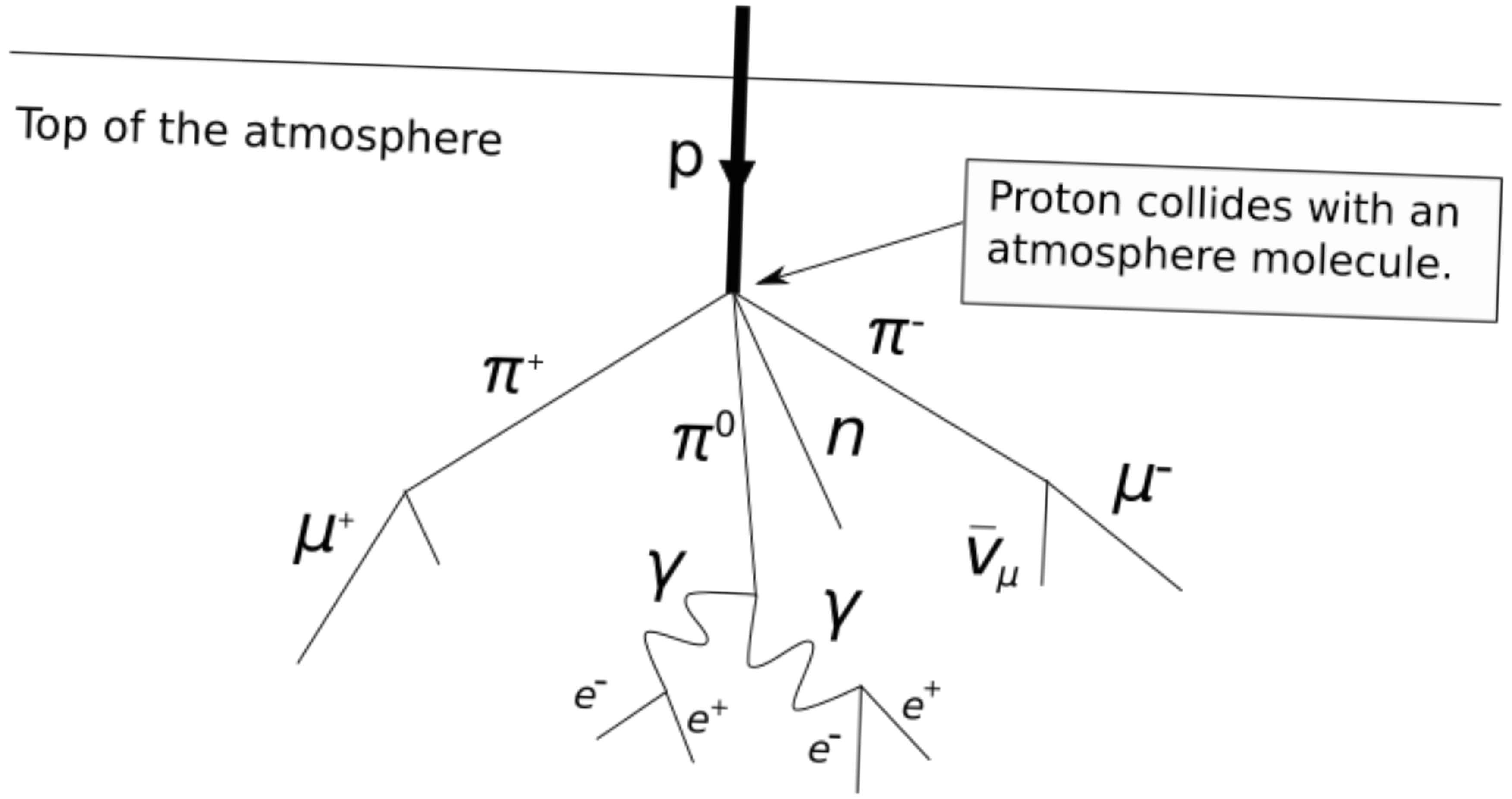
ATLAS detector

A new door to neutrino physics, at the LHC

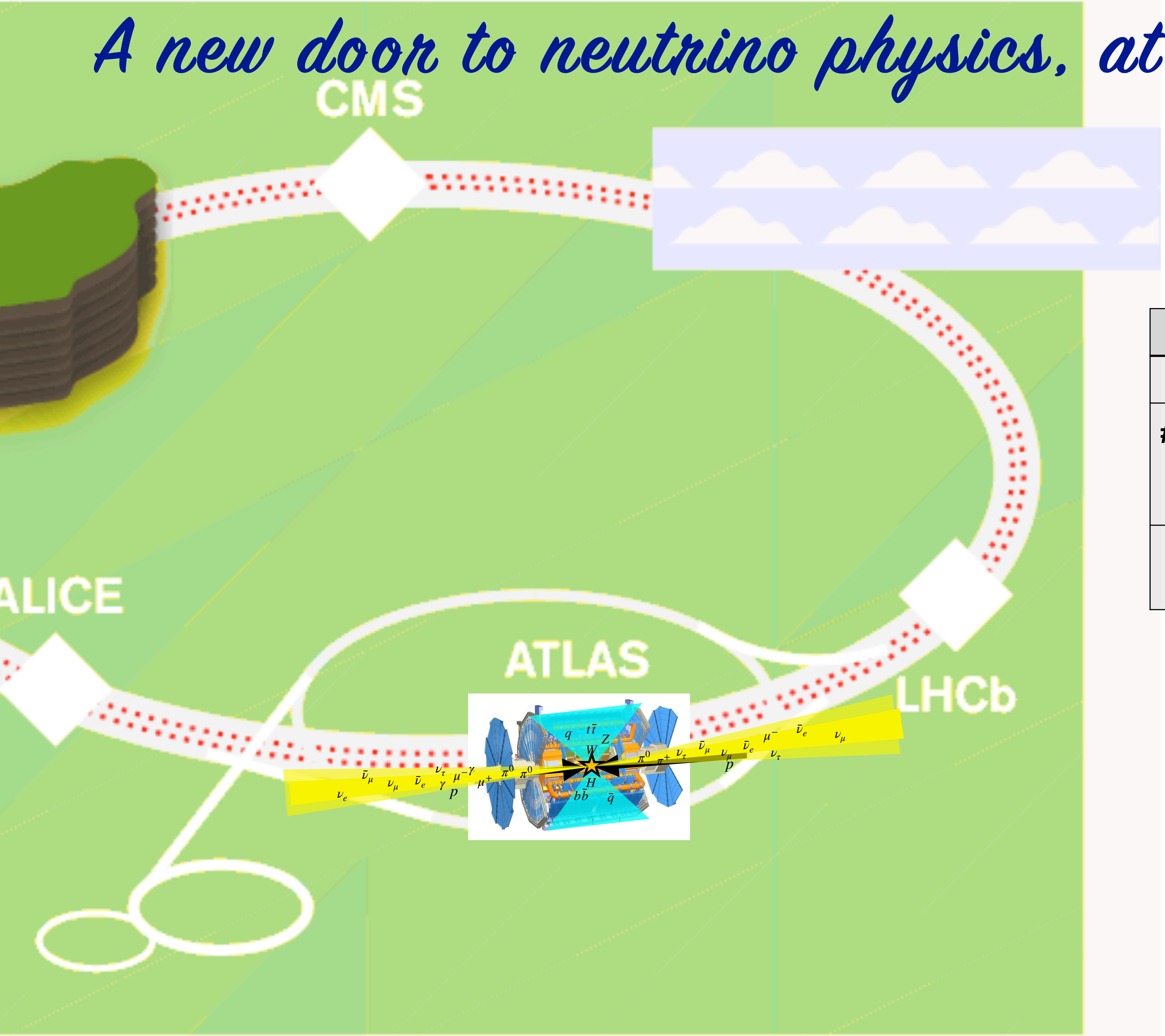
However, also have high flux of *highly* energetic (TeV scale) light mesons produced parallel to beam axis: After meson decay and shielding, ultimately becomes a high intensity high energy beam of muons and neutrinos.



Processes akin to cosmic ray showers produced in atmosphere.



A new door to neutrino physics, at the LHC



Low background far from collision point
+ high flux & energy
—> significant number of TeV energy neutrinos
measurable in small area with just 1 tonne material.

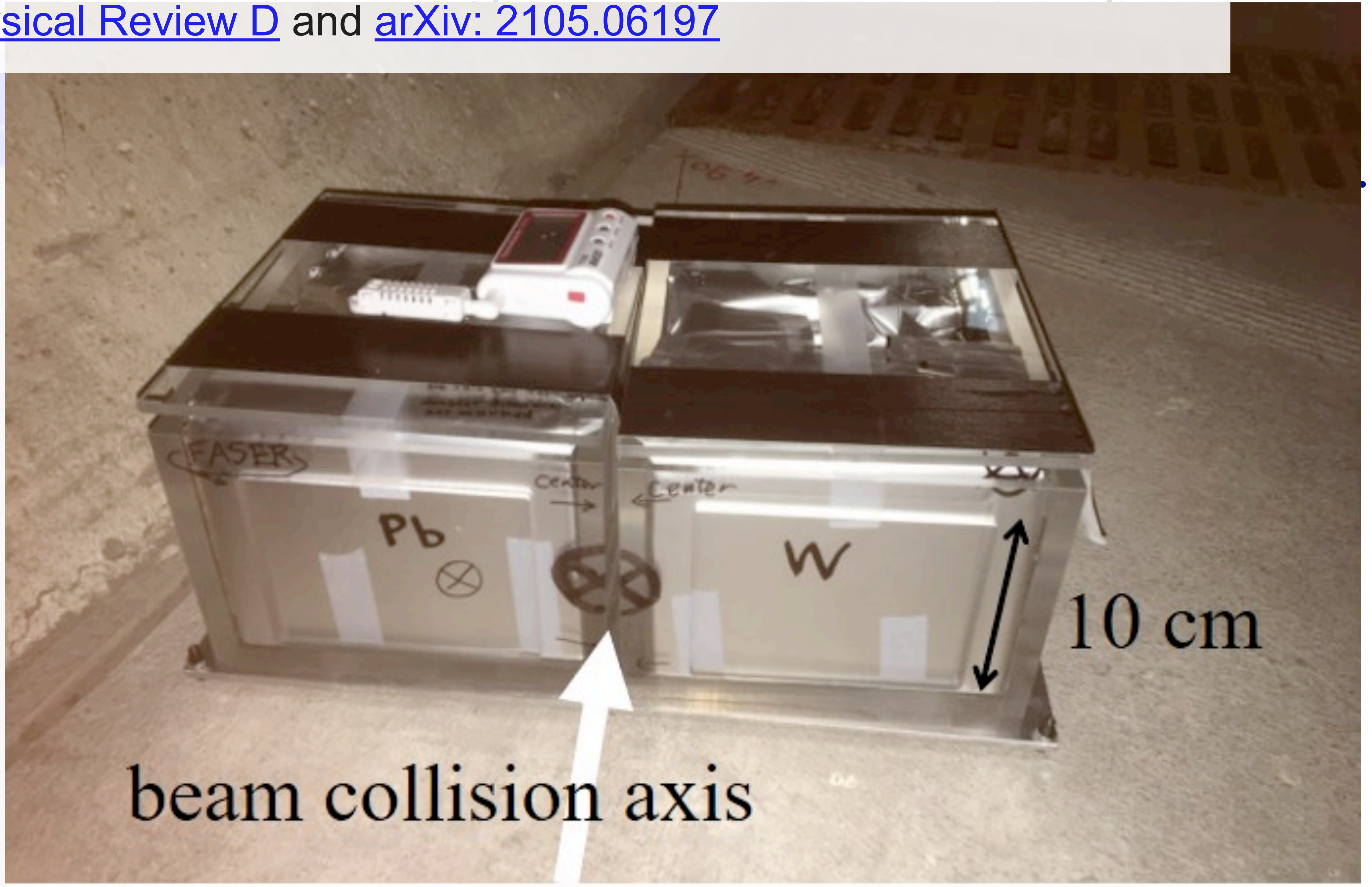
@ LHC 2022-2025	ν_e	ν_μ	ν_τ
Main source	Kaon decay	Pion decay	Charm decay
# neutrinos in 25cmx25 cm area, 0.5 km from collision point	$\mathcal{O}(10^{11})$	$\mathcal{O}(10^{12})$	$\mathcal{O}(10^{9})$
Of those, interacting in 1 tn tungsten	~3000	~10000	~70

A new door to neutrino physics, at the LHC

For the First Time Ever, Physicists Detect Signs of Neutrinos at Large Hadron Collider

First neutrino interaction candidates at the LHC
Physical Review D and arXiv: 2105.06197

Low background far from collision point



In fact, first evidence of "collider neutrinos" measured at LHC or elsewhere, with 10 x 12.5 cm2 11 kg emulsion/tungsten box on the floor of a decommissioned LHC side tunnel!

A new door to neutrino physics, at the LHC

Now replaced by FASER
(ForwArd Search ExpeRiment)
20 cm Ø, 7 m long,
2 million swiss francs.

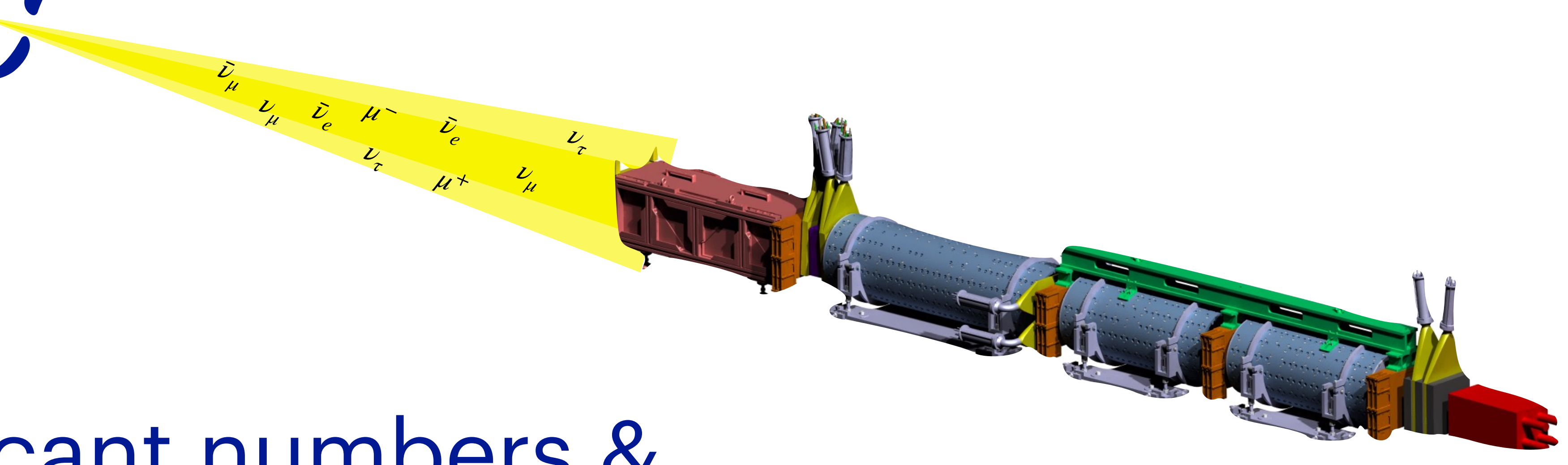
FASER 100 m underground
(+ me for scale)

Focus of today

FASERν: “Passive” **emulsion/tungsten** detector
for neutrino interaction measurements.

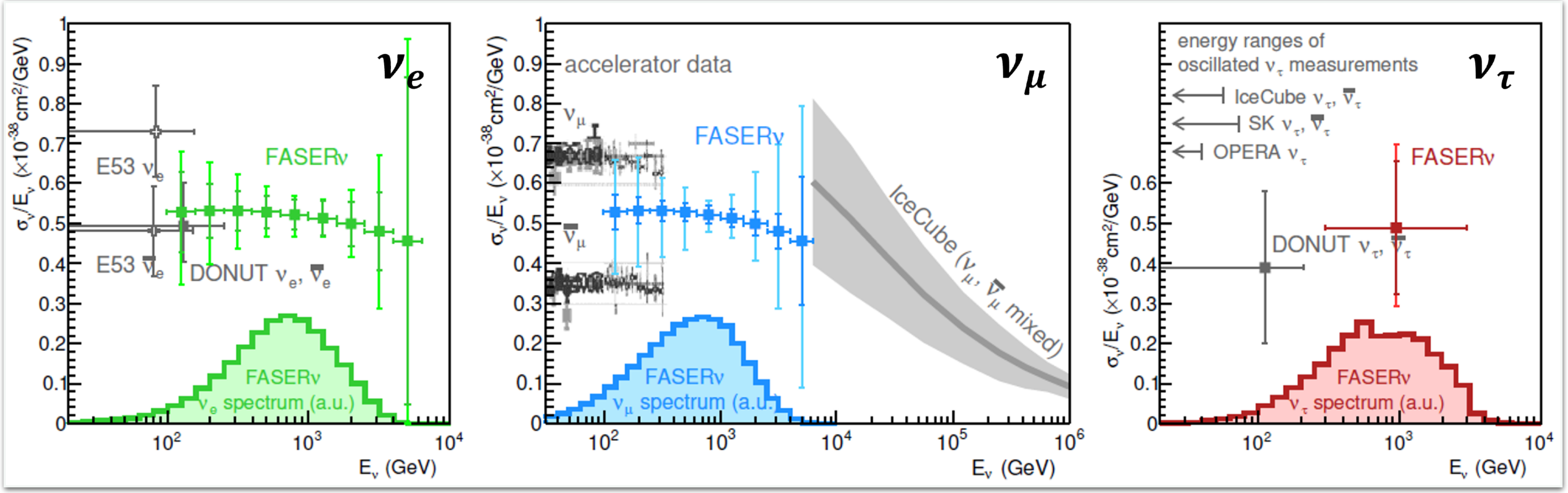
FASER main detector: “Active” **electronic** detector:
Magnets, tracker + scintillators, as muon spectrometer &
search for decays of new physics.

A new door to neutrino physics, at the LHC



What makes FASERν neutrino measurements interesting?

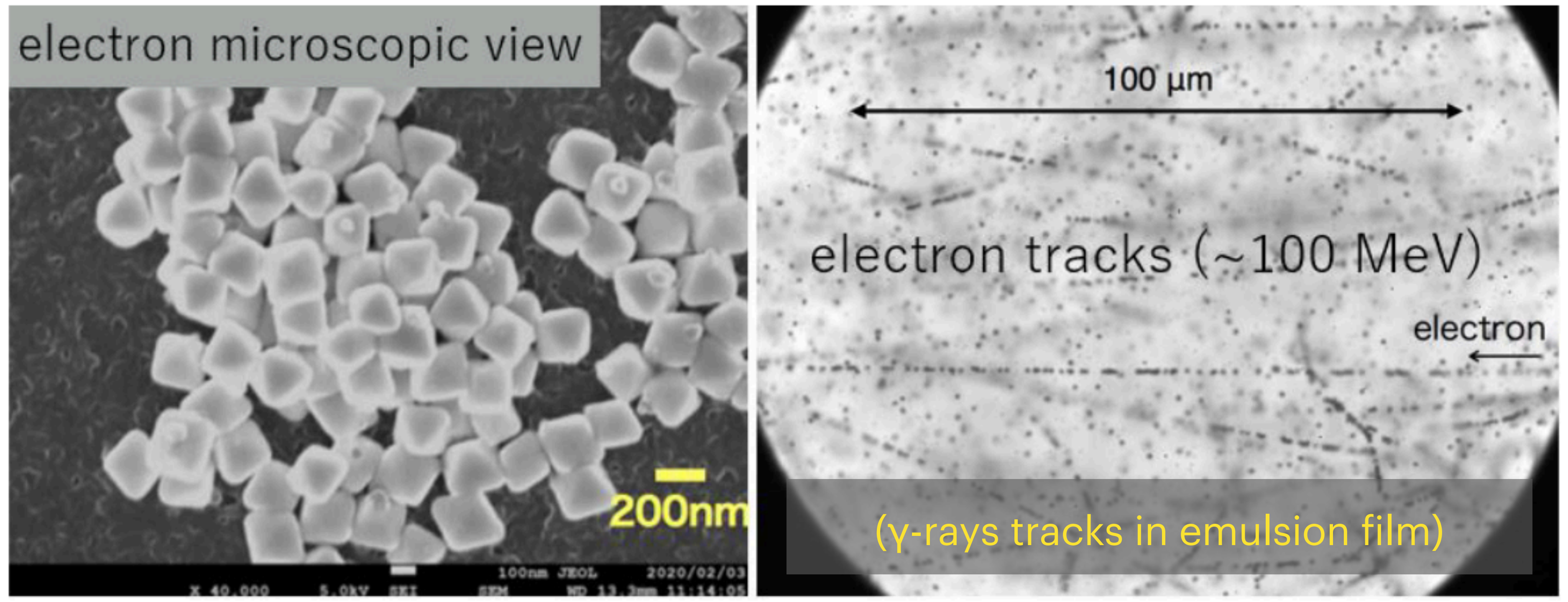
(1) All flavour neutrinos produced in significant numbers &
(2) at unique energies compared to other experiments.



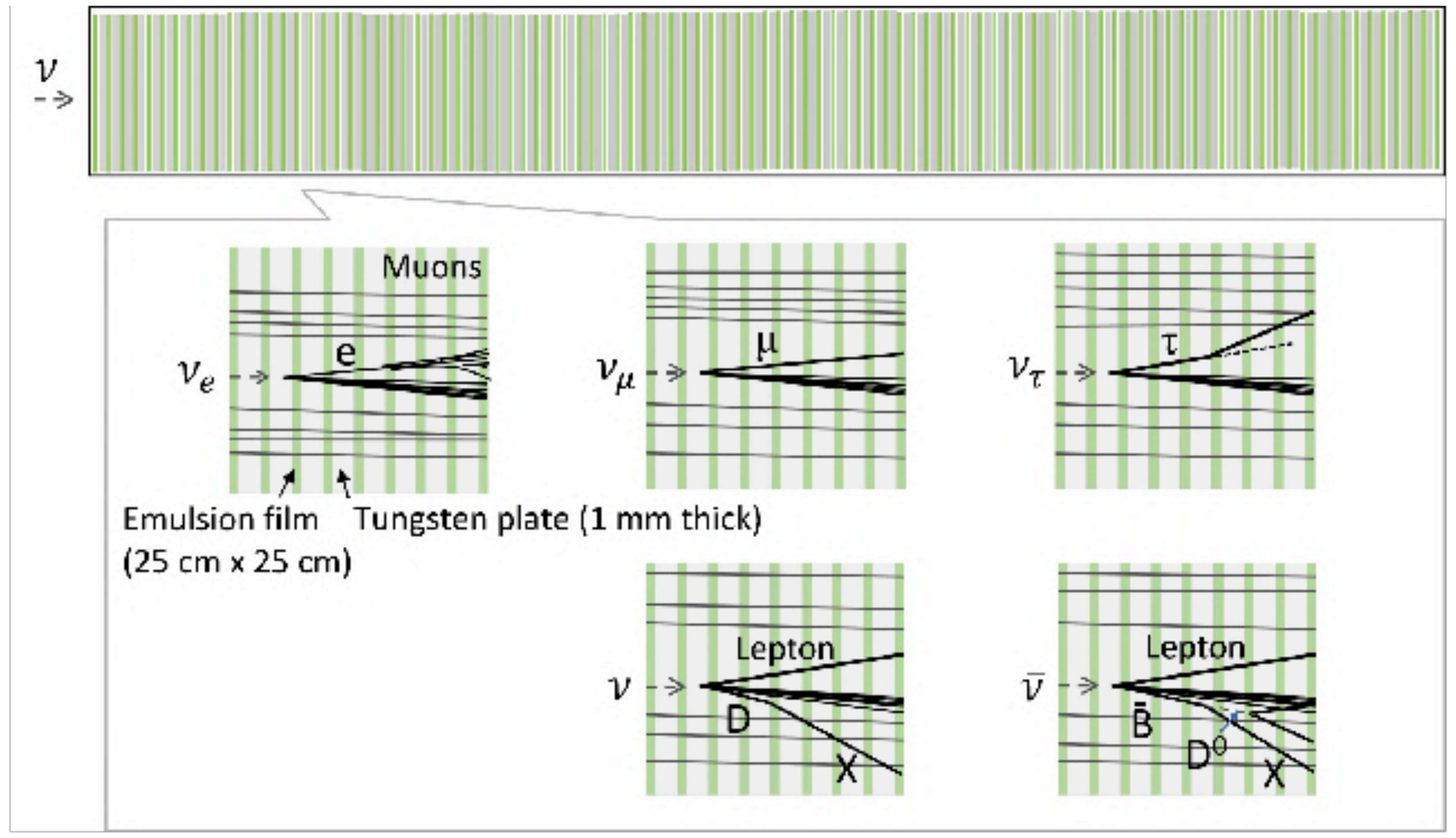
-> New information on neutrino interaction cross-sections with stat σ < syst σ.
-> Valuable input to forward hadron flux modelling, with implications for neutrino telescopes when estimating atmospheric neutrino background.

FASERν detector technology

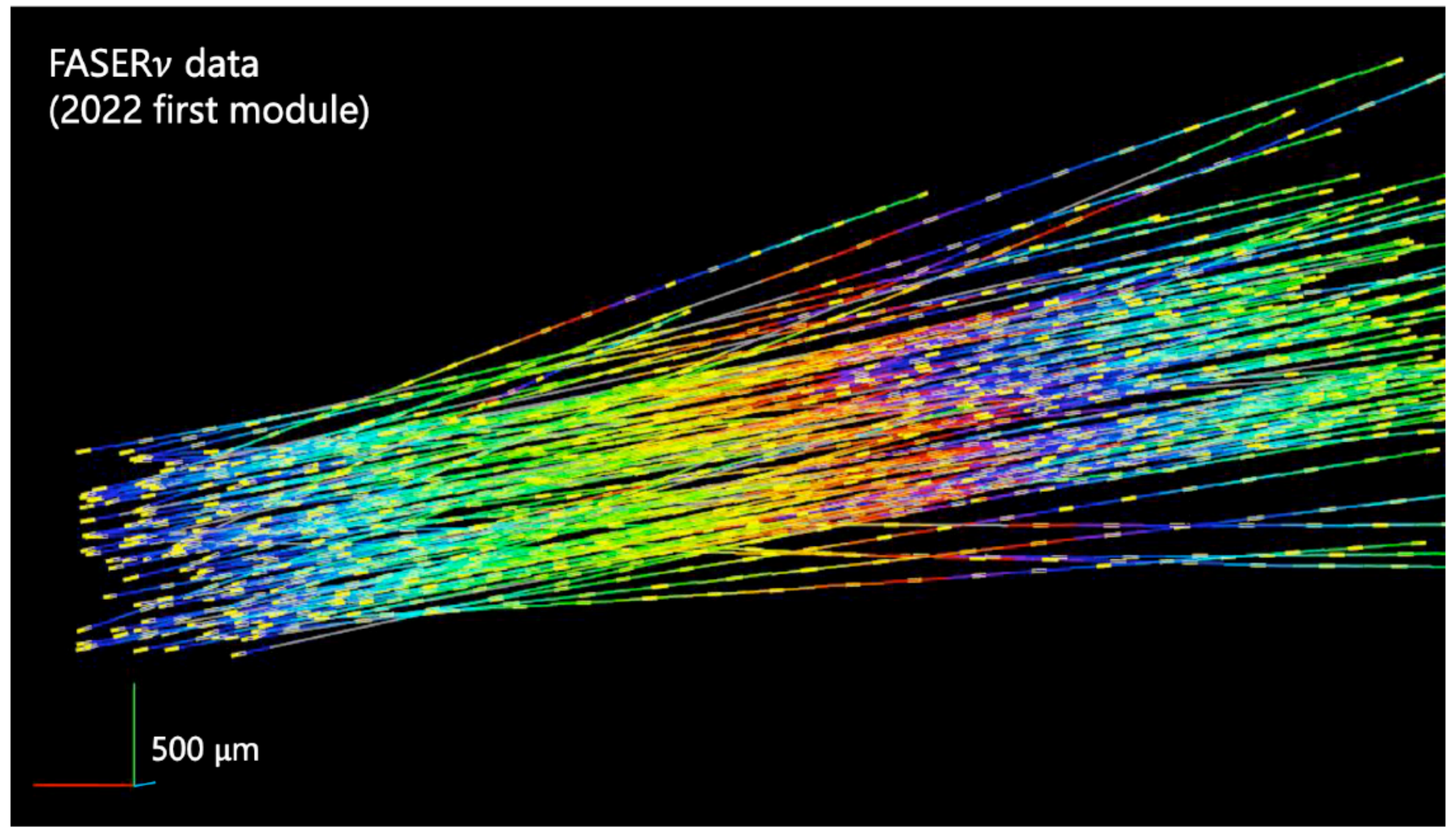
- Use emulsion film for extremely high spatial and angular resolution.



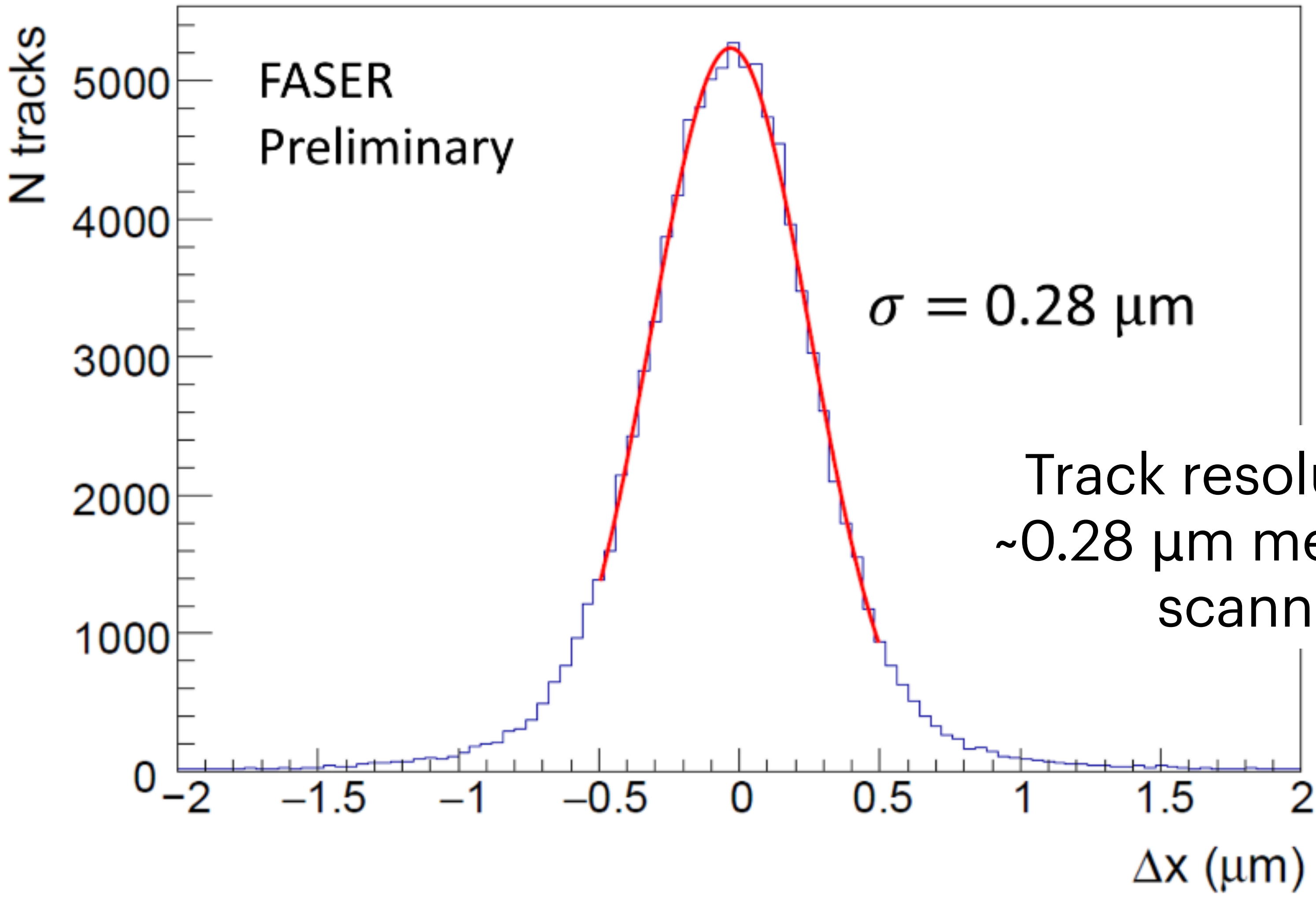
Silver bromide crystals of 200 nm Ø give intrinsic detection resolution of 50 nm, total 8.1 x 10^{14} channels/film.



730 emulsion layers interleaved with tungsten (220 χ_0 , 7.8 λ_0) allows tracking each interaction.



Main background is impeding muon flux. Track density of $10^6/cm^2$ still allows to resolve interactions, but modules replaced several times a year to avoid higher densities!

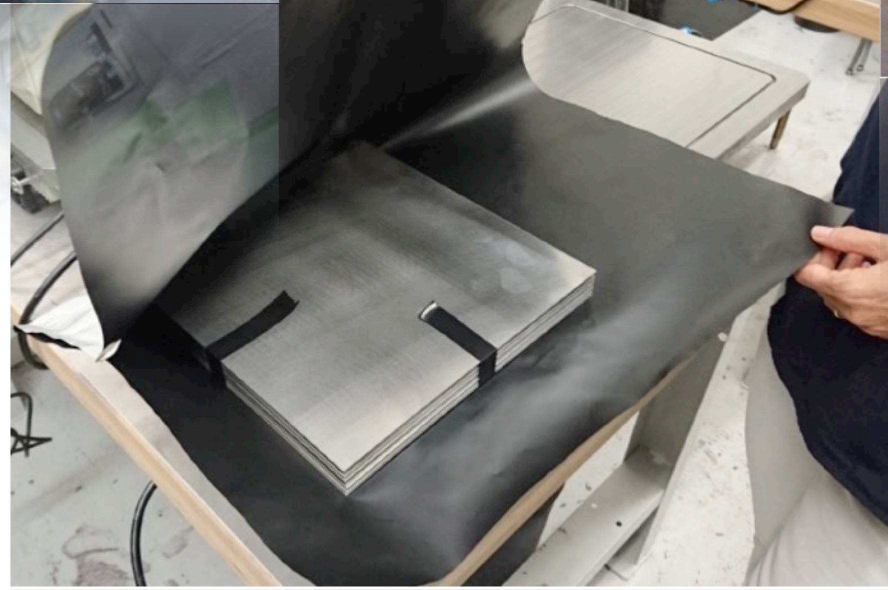


Track resolution in Δx of ~0.28 µm measured in first scanned data.

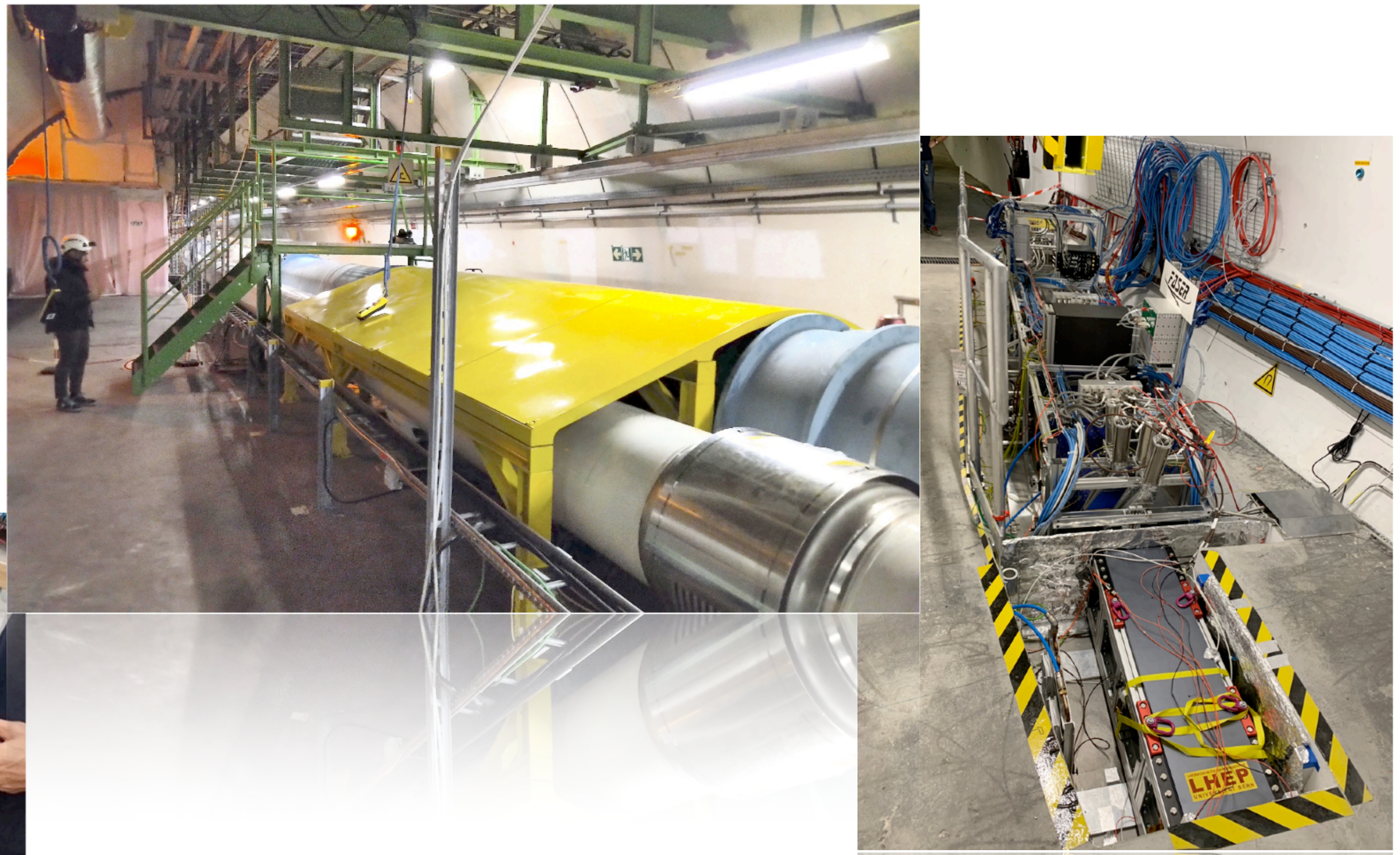
FASERν detector technology

- But excellent spatial resolution at cost of labour intensive processes.

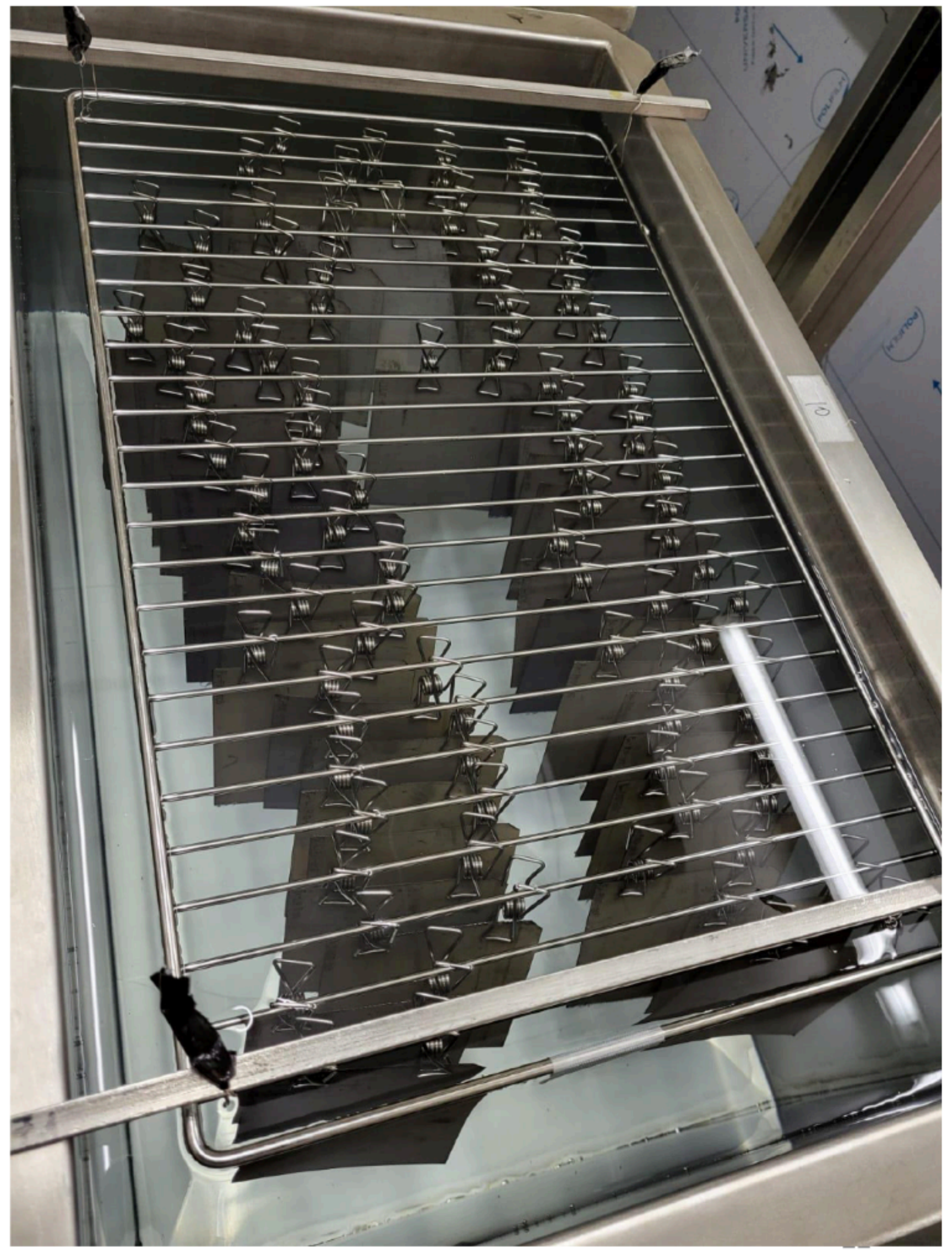
Emulsion gel production & coating in Nagoya, Japan. Emulsion film resetting in Kyushu Uni.
~ 1.5 month



Emulsion/Tungsten module vacuum packing in CERN dark room- 24 kg each.
~ 2 weeks



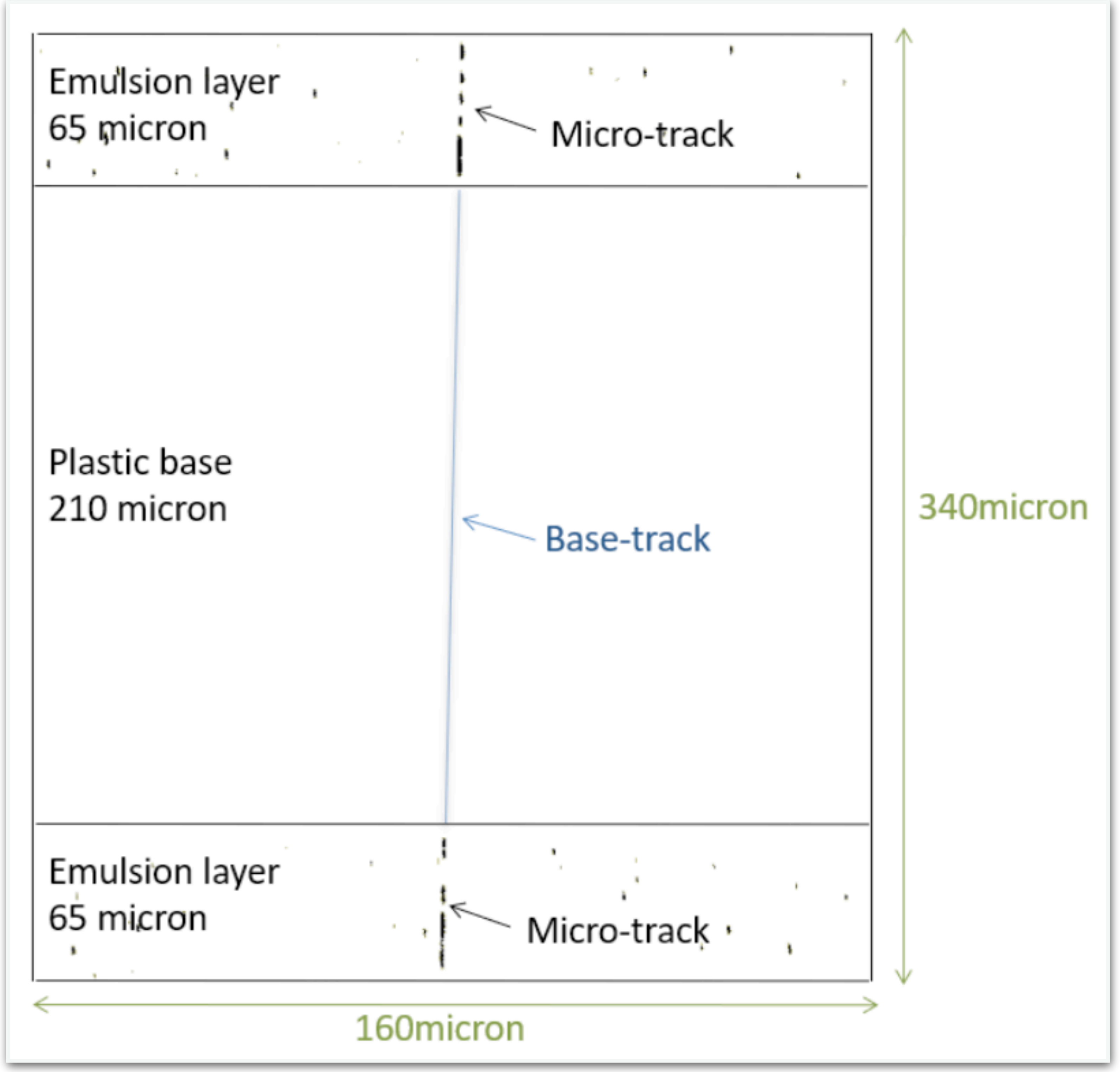
Careful transportation of 1 tonne box over LHC beam line, and installation in trench.



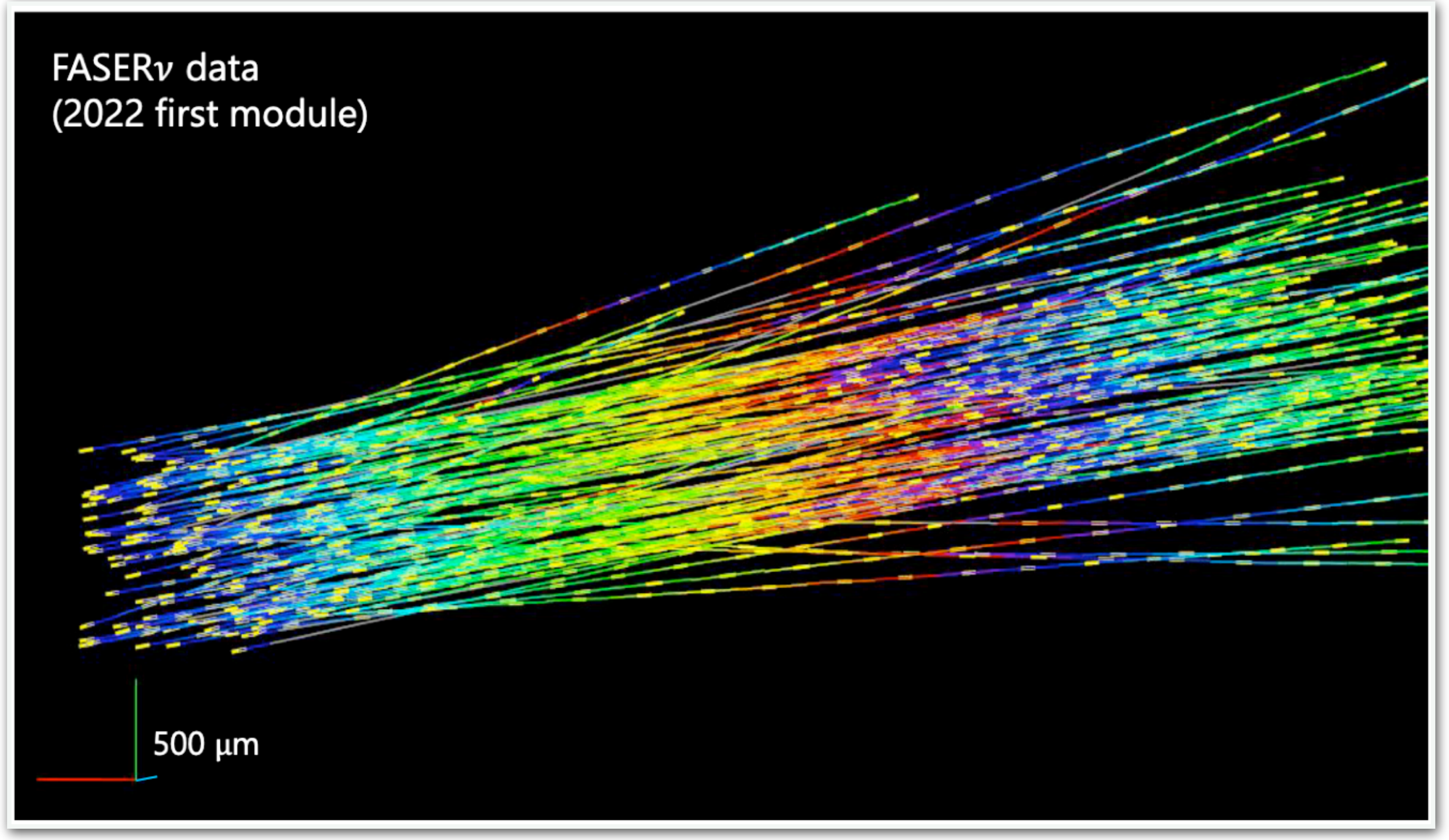
Emulsion film development via application of: Developer, stopper, fixer, wash, thickener and dryer.
~ 2 week

FASERν detector technology

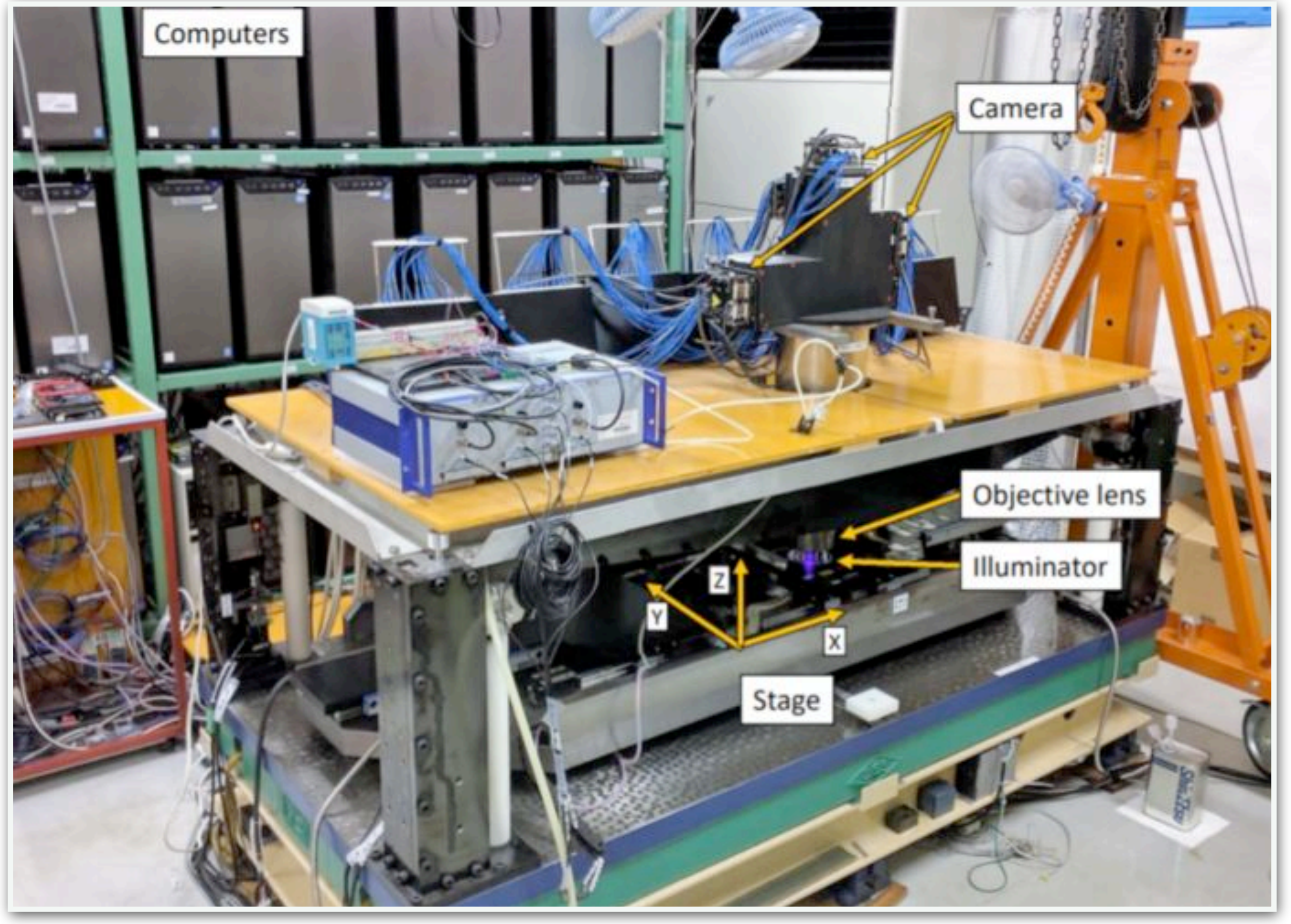
- But excellent spatial resolution at cost of labour intensive processes.



Emulsion readout: Tomographic images read out at 16 images/film (16 TB/film), “micro tracks” reconstructed in real-time and stored on file.

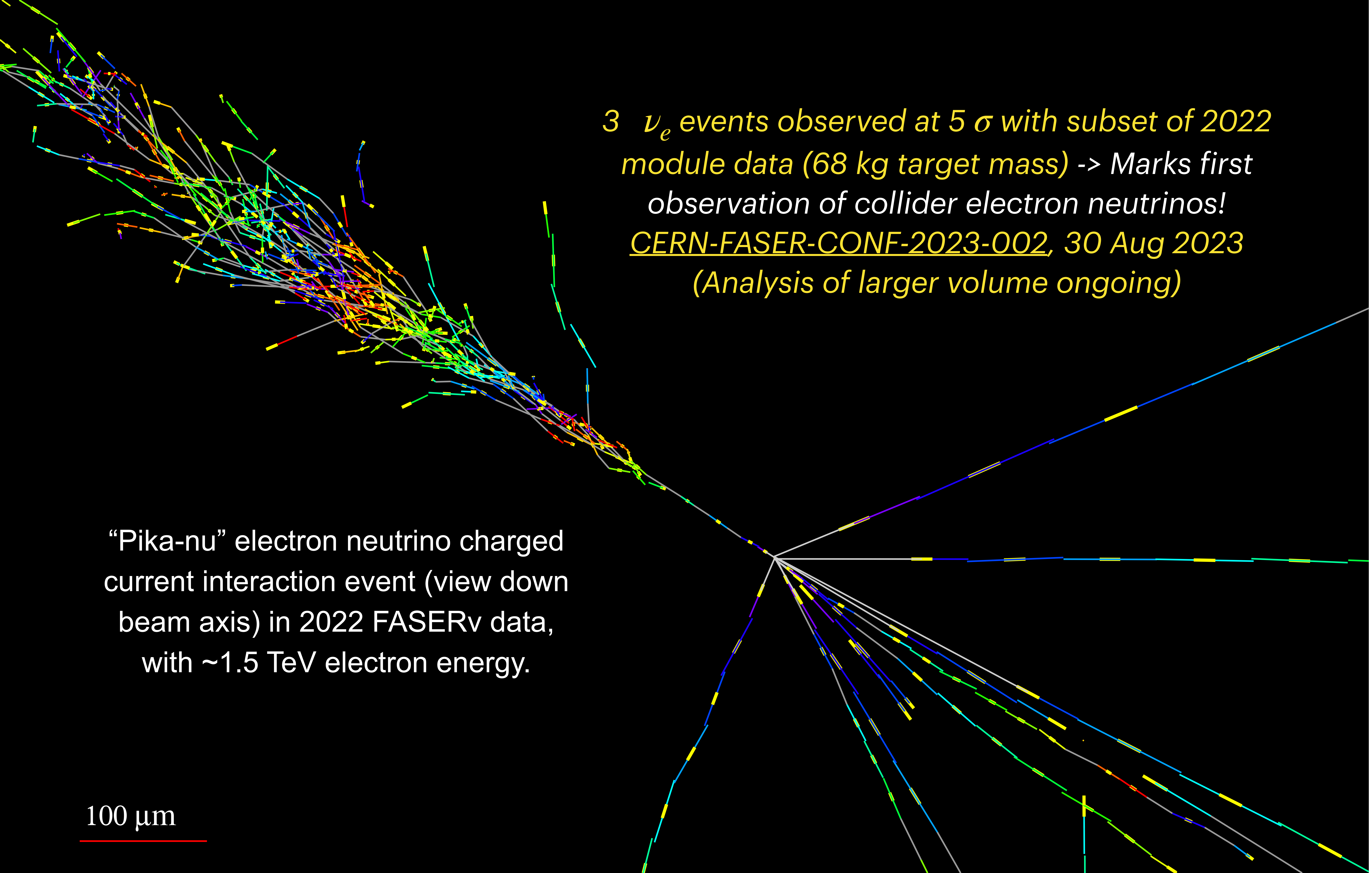


Data reconstruction:
Reconstruction of base tracks + alignment, full tracks



Hyper Track Selector (HTS) used to scan emulsion layers (Nagoya Uni, Japan)

Total data processing:
(24 parallel processing thread), 200 TB storage,
~7 months for one box



3 ν_e events observed at 5 σ with subset of 2022 module data (68 kg target mass) -> Marks first observation of collider electron neutrinos! CERN-FASER-CONF-2023-002, 30 Aug 2023 (Analysis of larger volume ongoing)

“Pika-nu” electron neutrino charged current interaction event (view down beam axis) in 2022 FASERν data, with ~1.5 TeV electron energy.

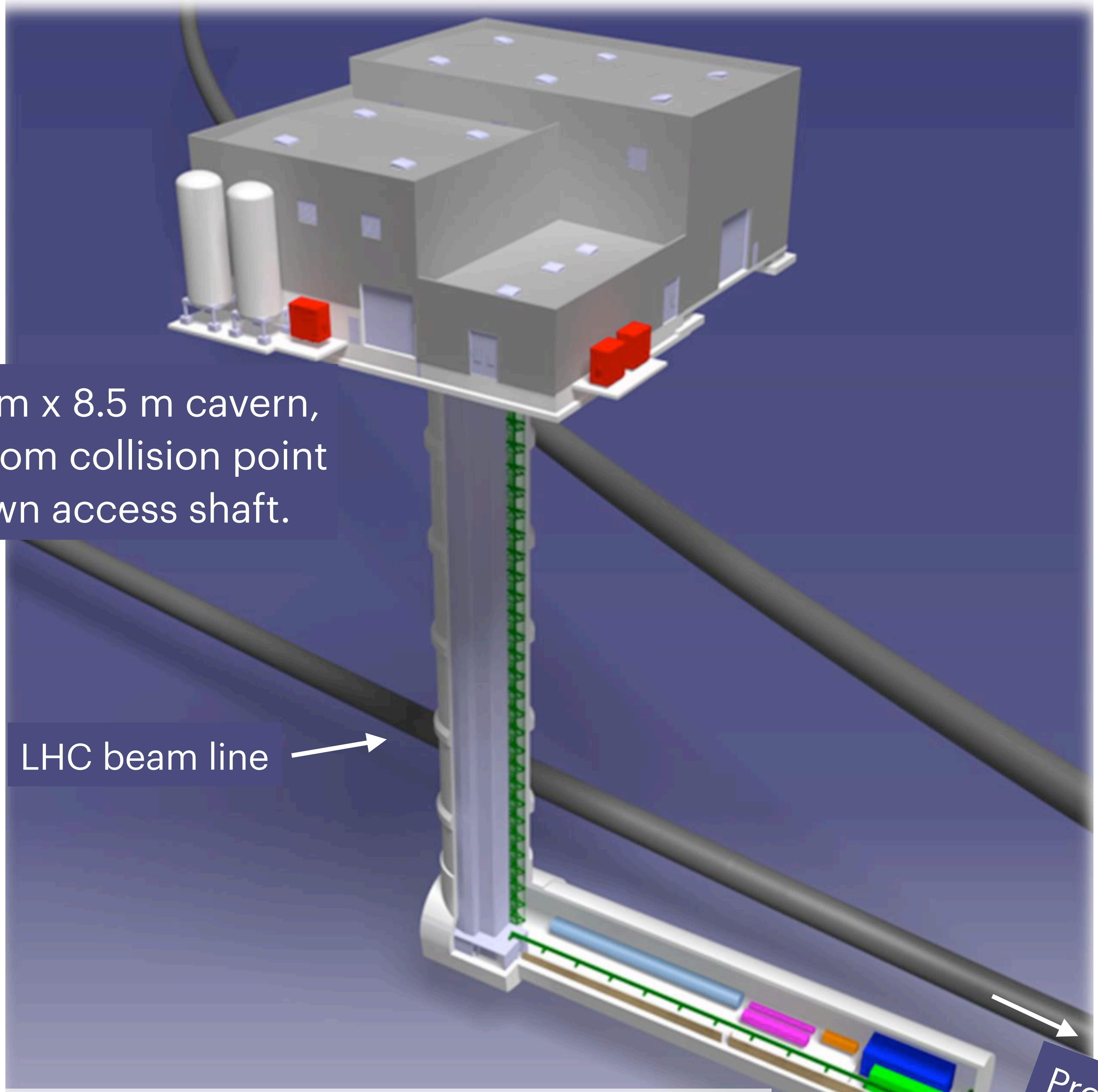
Important ν measurements with emulsion elsewhere

Emulsion-based neutrino detectors have made important measurements in neutrino physics elsewhere as well!

- **DONUT @ Fermilab (1997)**: First direct observation of tau neutrinos (9 total) using emulsion interleaved with iron.
- **OPERA @ Gran Sasso (2008-2012)**: First observation of tau neutrino *appearance* in muon neutrino beam from CERN 730 km away.
- Ongoing:
  - **NINJA @ J-PARC** to improve systematic uncertainties for accelerator-based long baseline oscillation experiments using accelerator based water target detector to precisely measure neutrino-nuclear interaction cross-sections in sub-multi-GeV region.
  - **NEWSdm @ Gran Sasso**: Directional DM detection via nuclear recoil in high granularity emulsion.

OPERA: 1.25 kt emulsion/lead target + muon spectrometer

Future neutrino physics @ LHC



New 65 m x 8.5 m cavern, 600 m from collision point with own access shaft.

LHC beam line

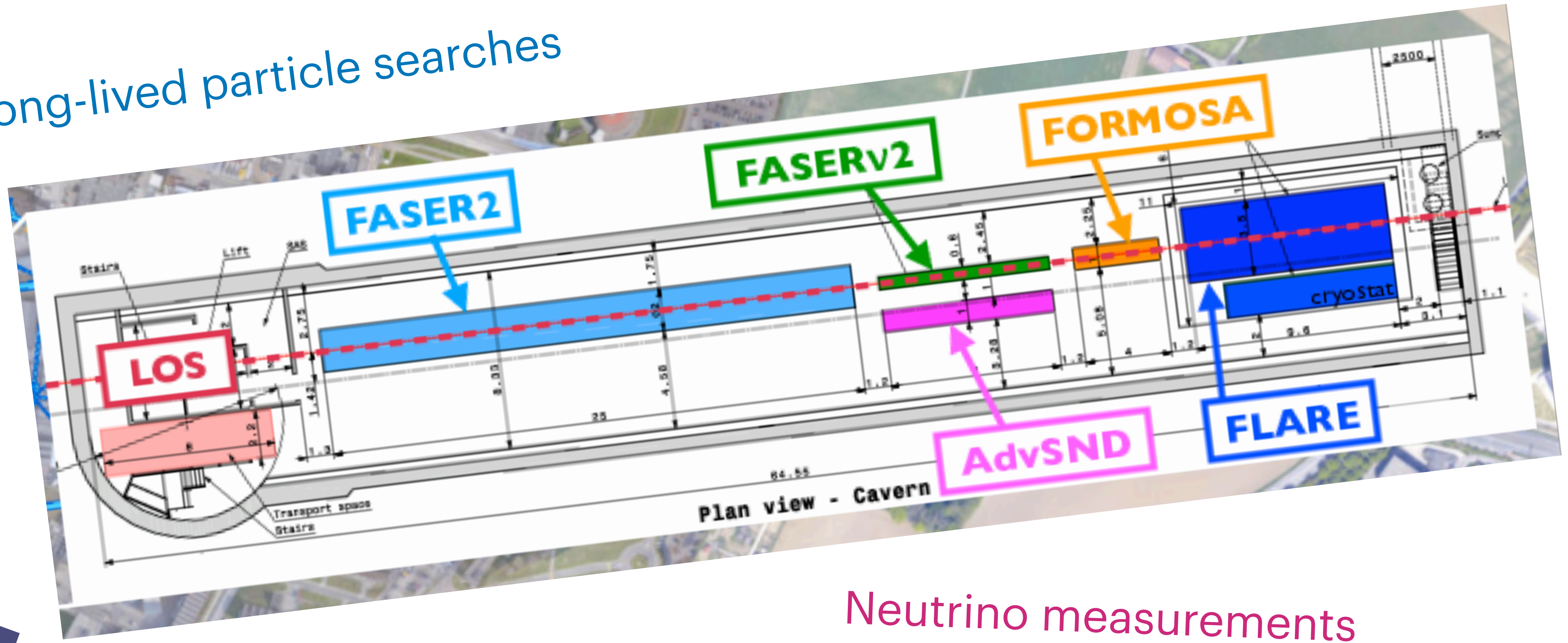
Proton-proton collision point

"The Forward Physics Facility at the High-Luminosity LHC", arXiv:2203.05090

Proposal to make further use of LHC neutrinos with new **Forward Physics Facility (FPF)** at High Lumi LHC, where 10 times more proton collision data to be collected.

Millicharged particle searches

Long-lived particle searches

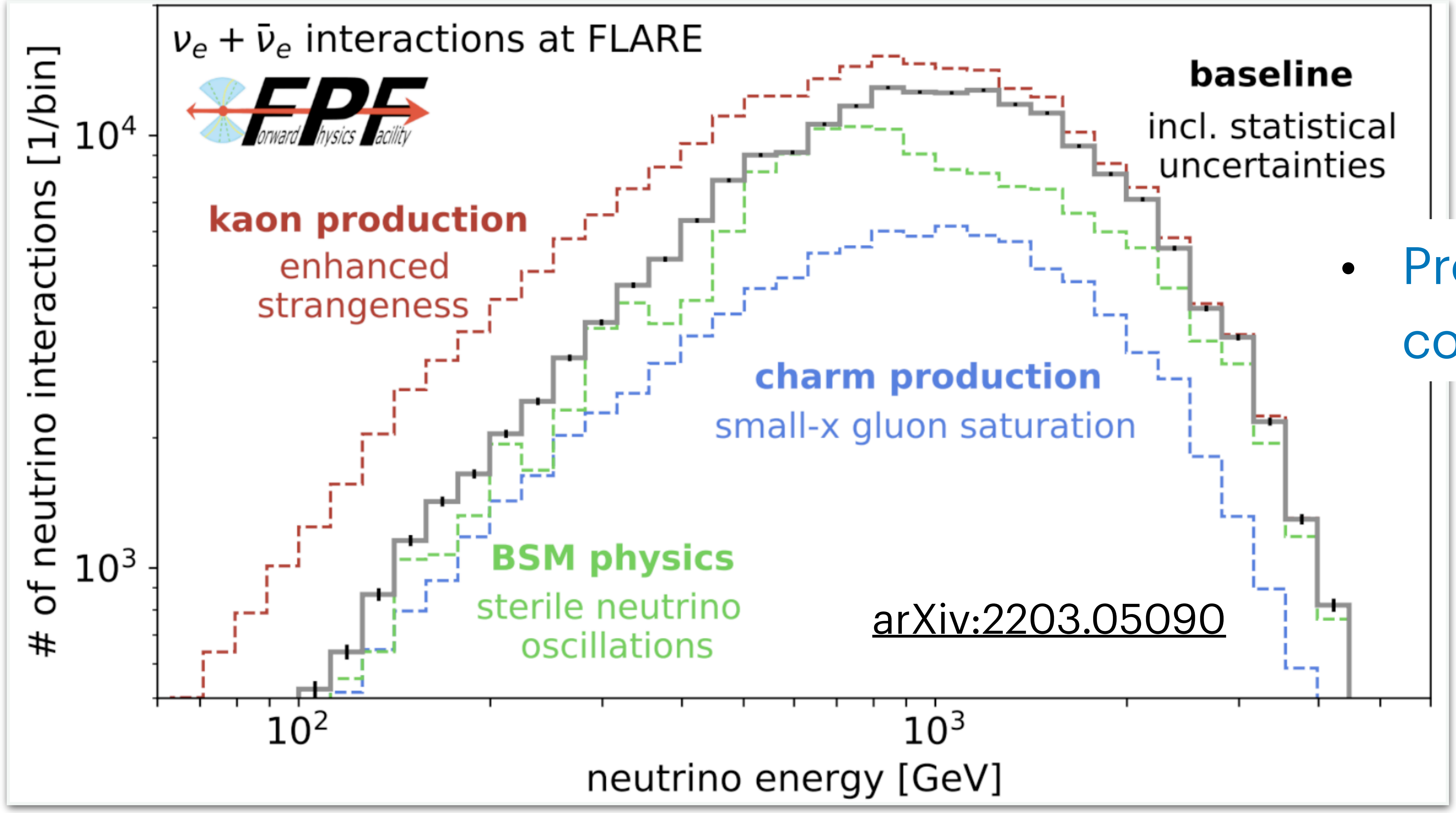


Neutrino measurements (emulsion & LAr TPC based)

Future neutrino physics @ LHC

200 x more neutrino data at a HL-LHC Forward Physics Facility (higher lumi, larger detectors) enables many interesting measurements as physics effects on neutrino flux become larger than statistical uncertainty:

- Tests & constraints for *atmospheric cosmic ray shower physics*:
  - Probe "prompt neutrino flux" (ν from heavy meson decay) that dominates cosmic ray high energy spectrum
  - Address "muon puzzle" - a muon deficit in simulations compared to cosmic ray data: More muons from enhanced kaon production?



- Proton & nuclear PDF constraints from ν DIS

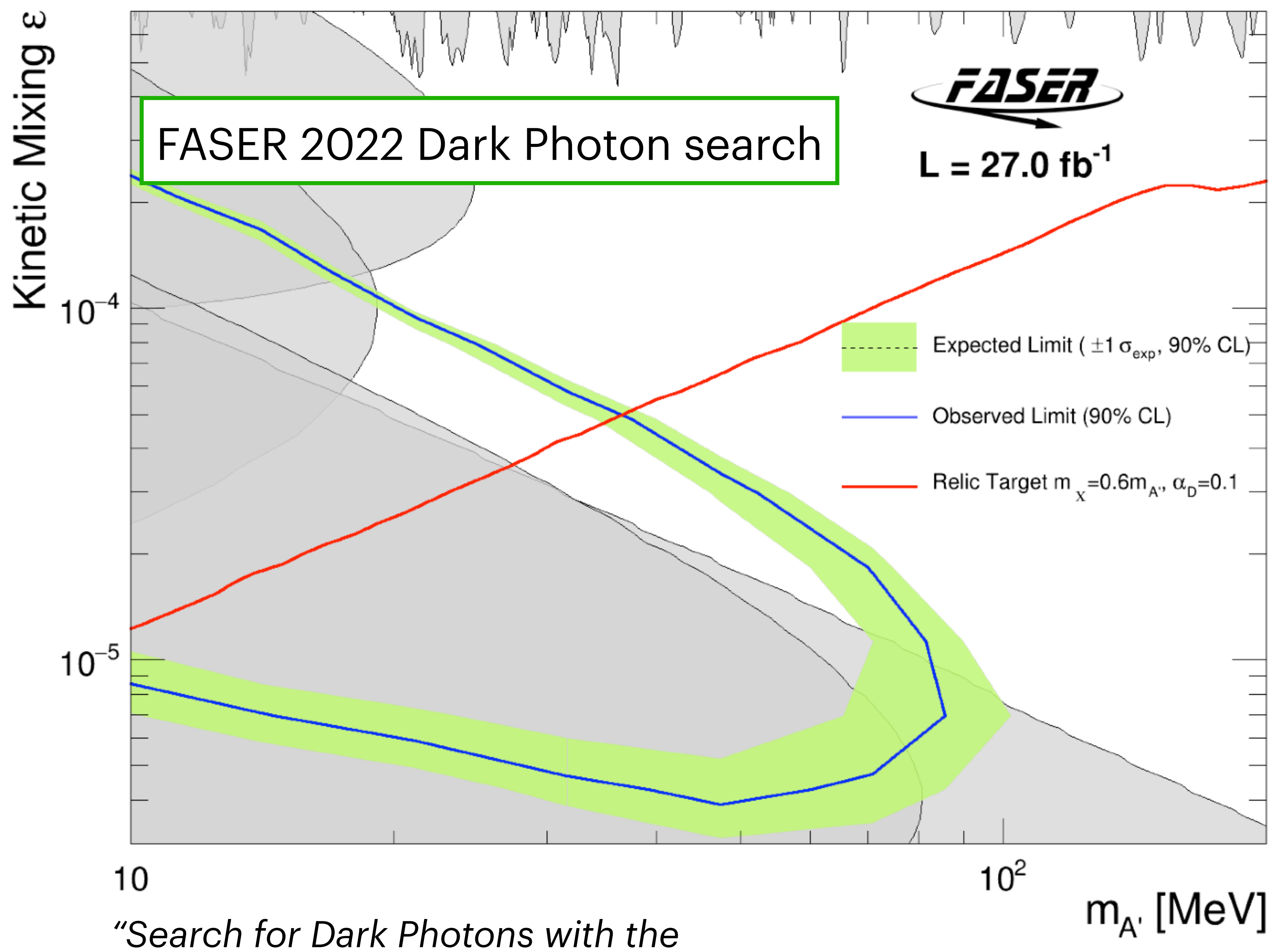
- Sensitivity to new physics: Constraints on sterile neutrinos at ~30 eV mass.

Dark matter with LHC forward neutrino experiments

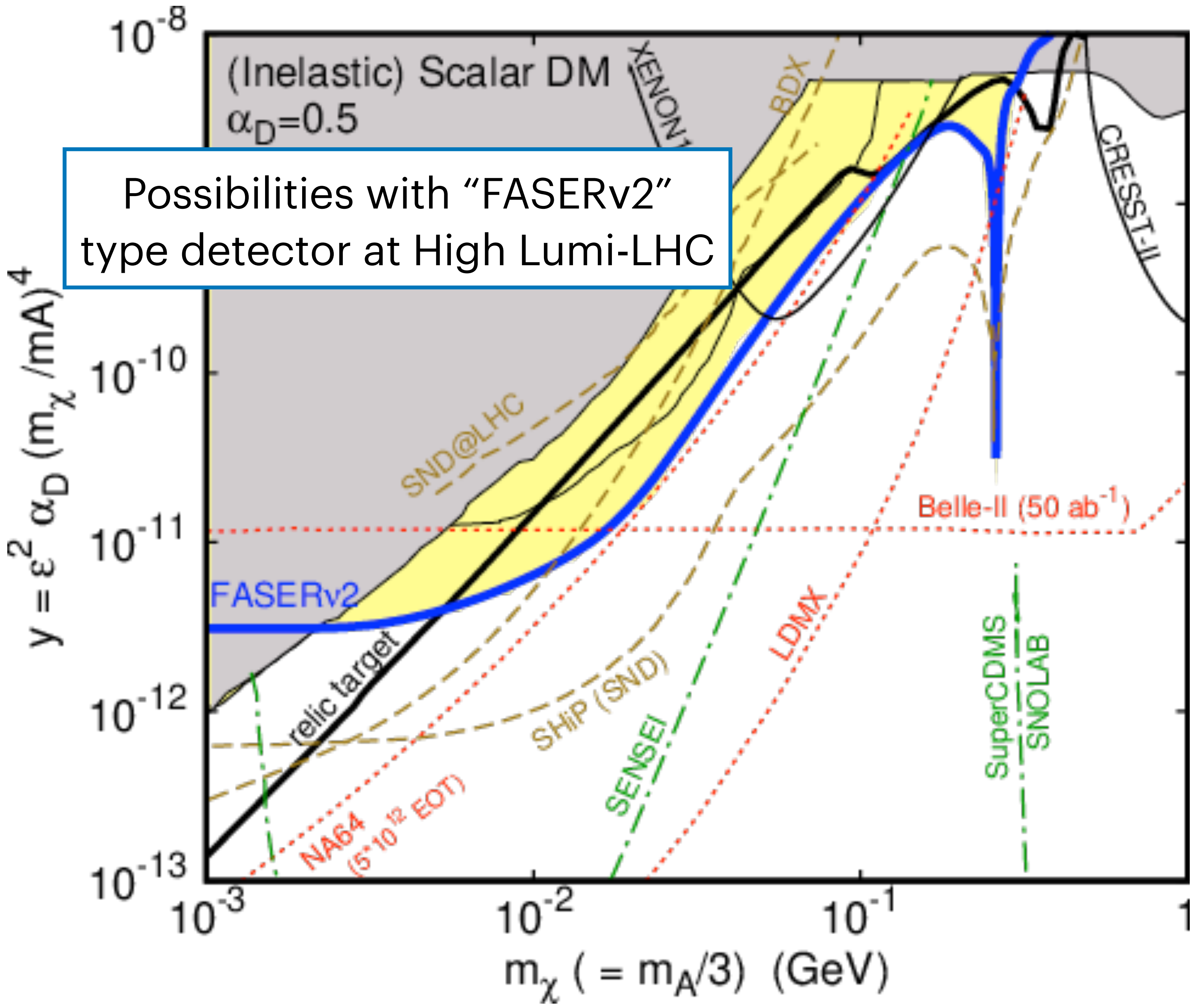
If neutrinos, why not dark matter? Light DM with masses at < ~GeV scale famously hard to detect directly.
But LHC might similarly be generating highly energetic dark matter in collisions in far forward region…

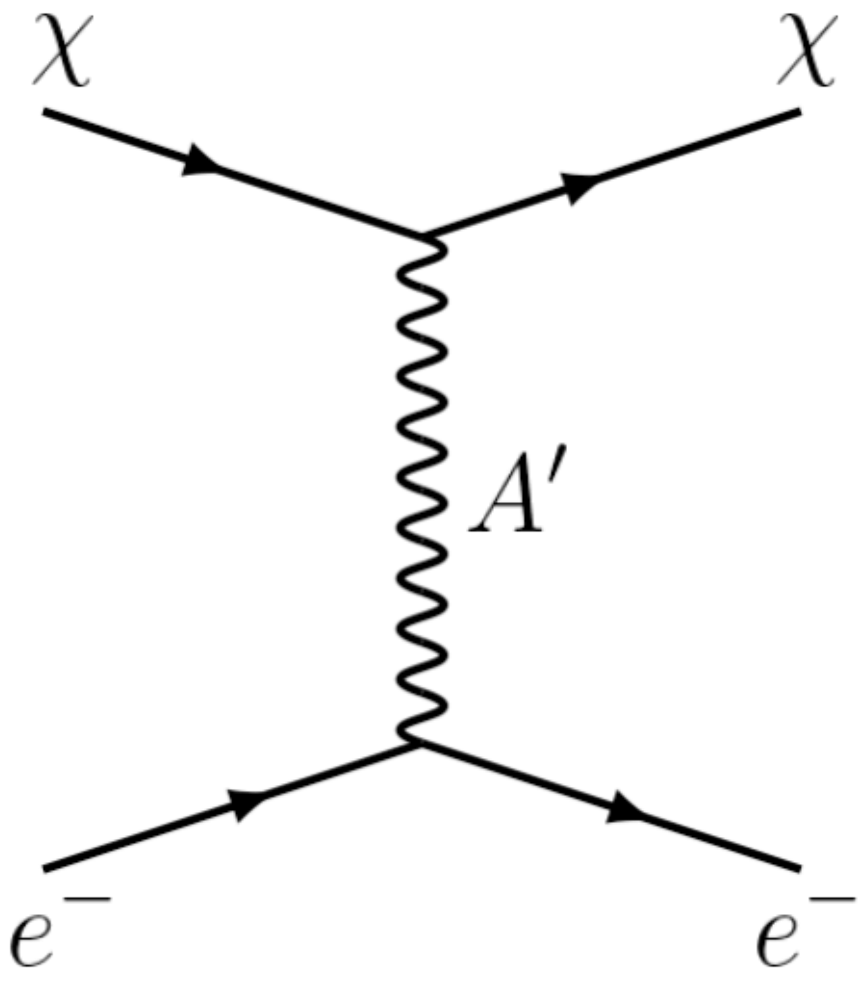
FASER already paving way by probing light DM mediators in region of parameter space motivated by DM thermal relic density.

FPF experiments at High Lumi LHC may allow *direct* detection of low-mass dark matter.


FASER 2022 Dark Photon search

"Search for Dark Photons with the FASER Detector at the LHC": arXiv: 2308.05587


Possibilities with "FASERv2" type detector at High Lumi-LHC



"Detecting Dark Matter with Far-Forward Emulsion and Liquid Argon Detectors at the LHC": arXiv:2101.10338

Sensitivity complimentary to non-accelerator Dark Matter Detection experiments such as SENSEI and superCDMS.
All of these experiments are not particularly big but use technology and strategy to their advantage.

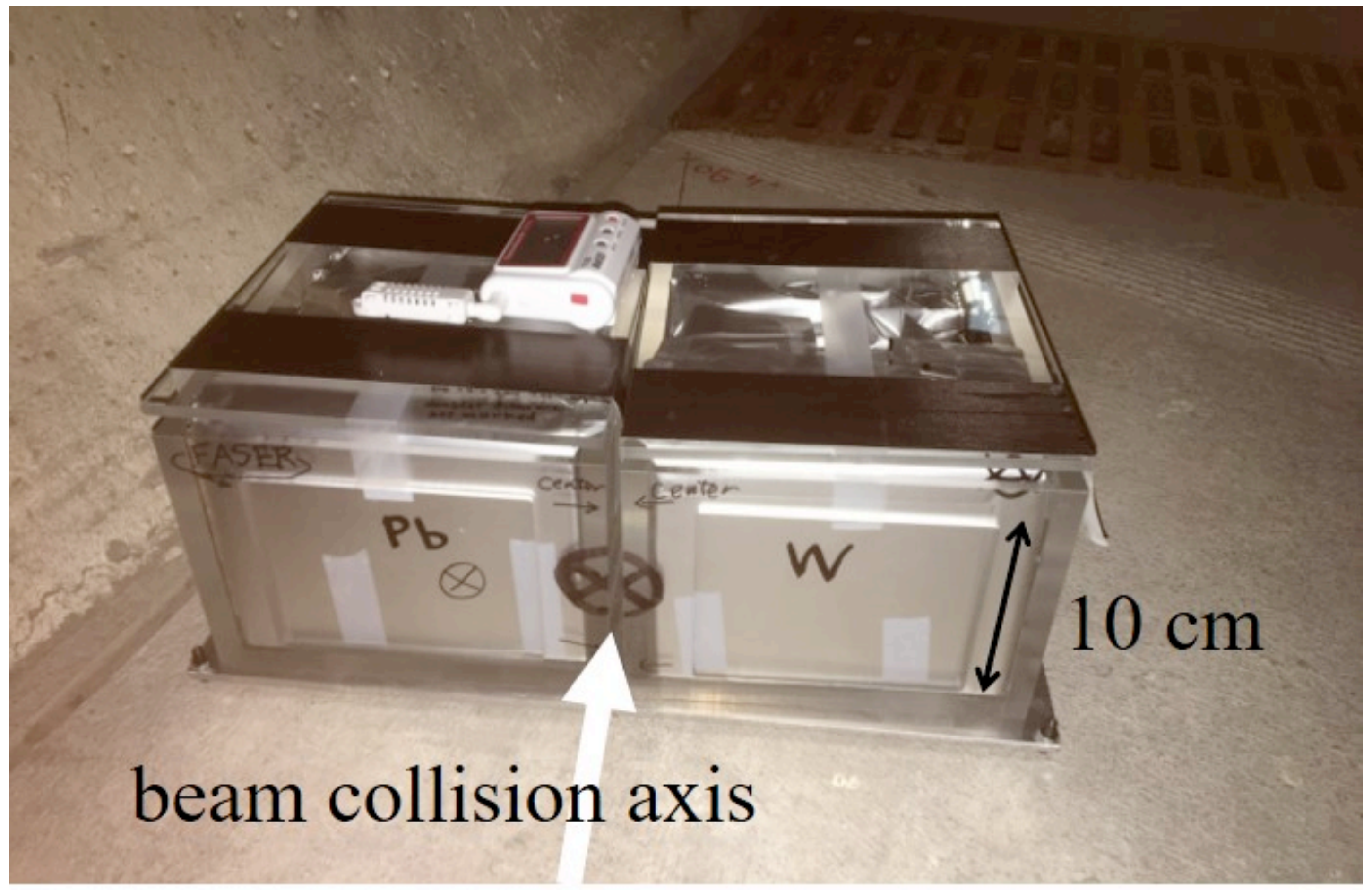
In Summary

Stories for inspiration?

Neutrinos are an intriguing area of physics and versatile tools (although challenging)!

Small detectors can do *great* things when in the *right* location.

Given the right strategy, sensitivity to unchartered search space can come from many types of large and small experiments.



Thanks for listening!

Back up

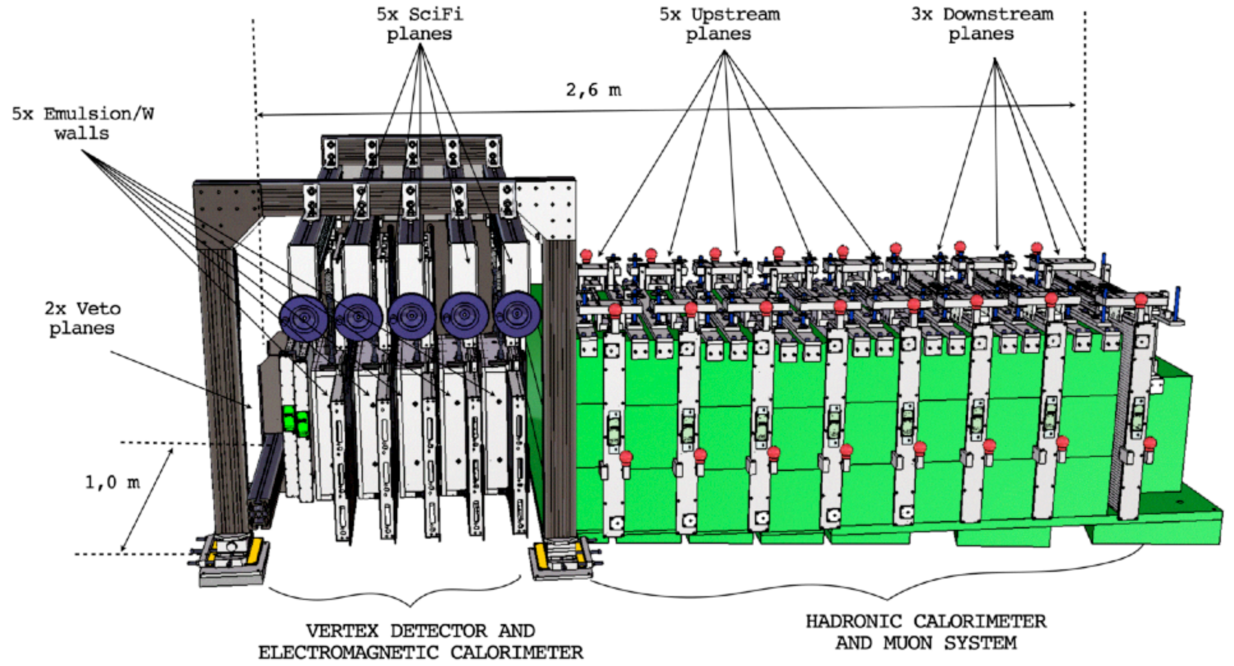
Neutrino experiments at LHC Run 3

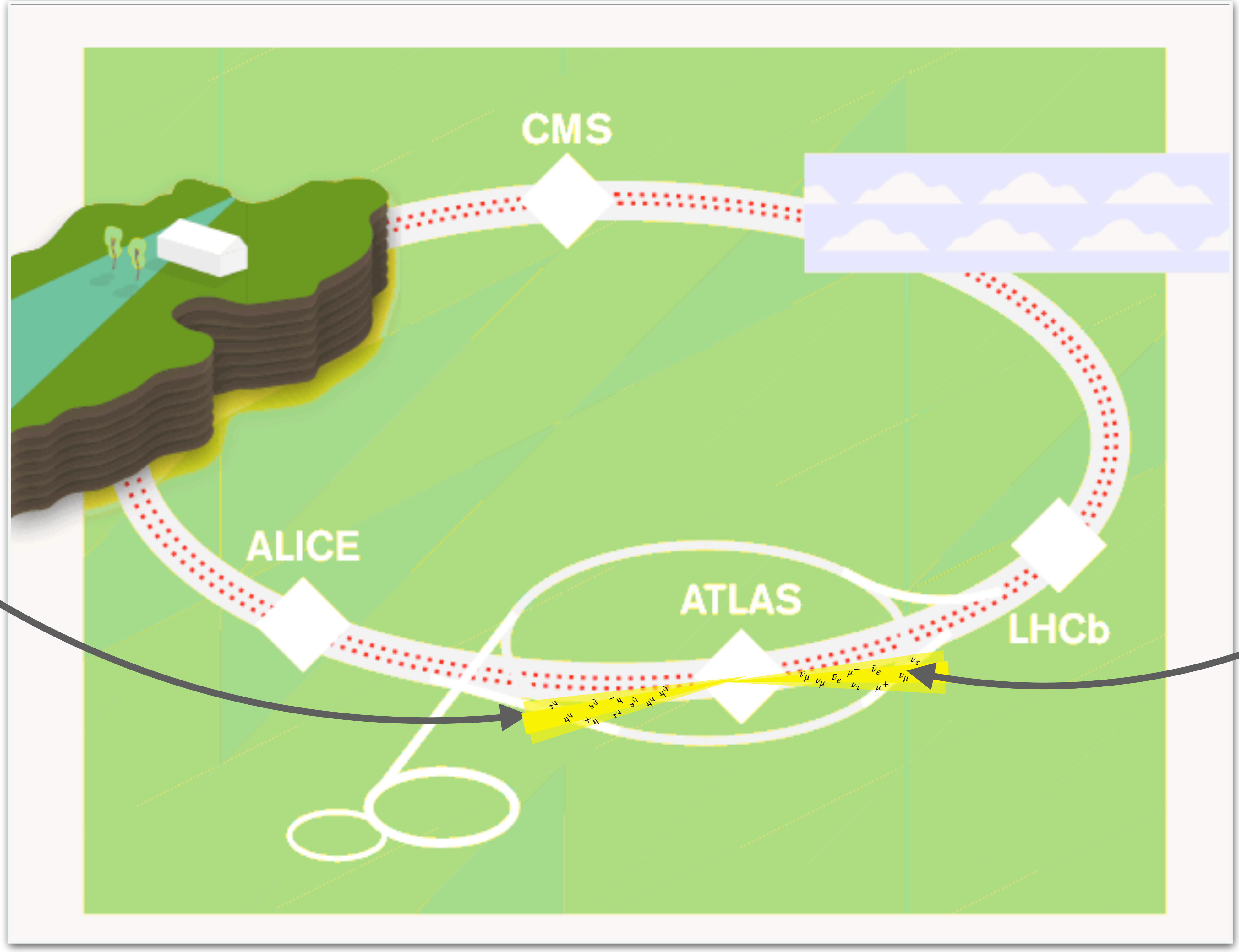
Now replaced by 2 new LHC experiments on either side of ATLAS collision point:

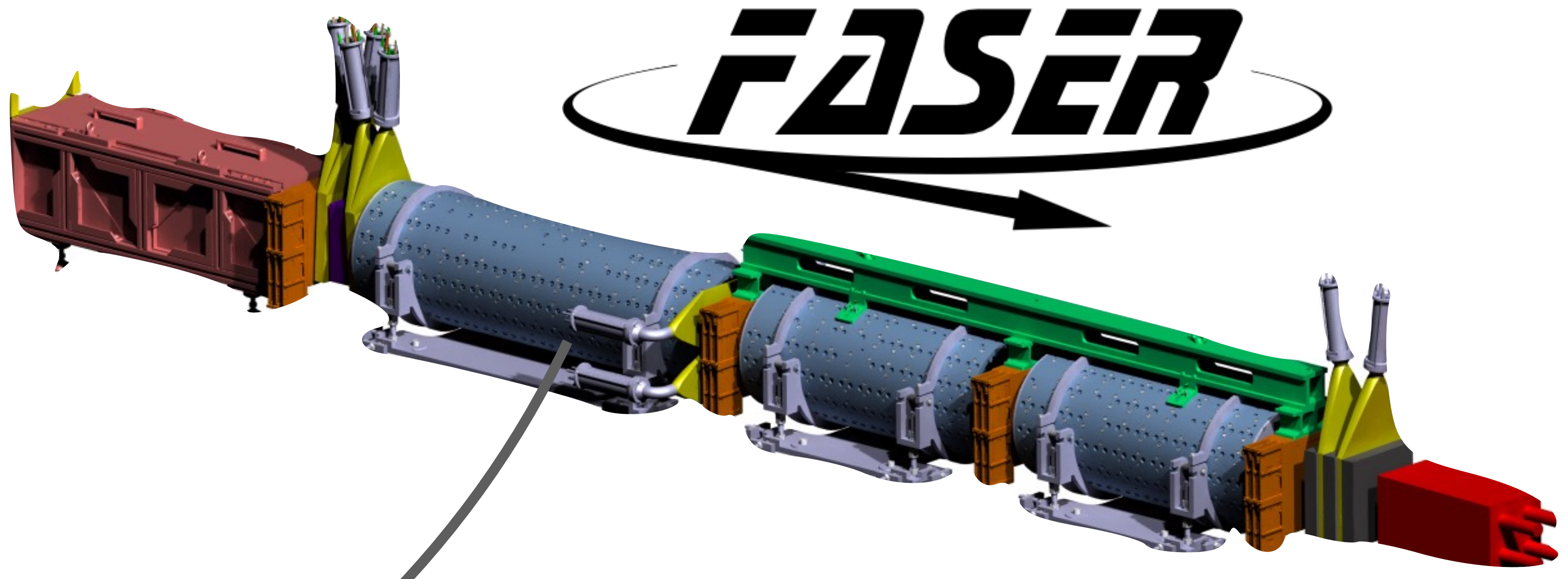
- **FASER** (ForwArd Search ExpeRiment) Long-lived particle search & emulsion-based neutrino detector, 20 cm Ø, 7 m long.
- **SND@LHC**: 1 m x 2.6 m off-axis emulsion/electronic neutrino detector with sci-fi tracker planes.

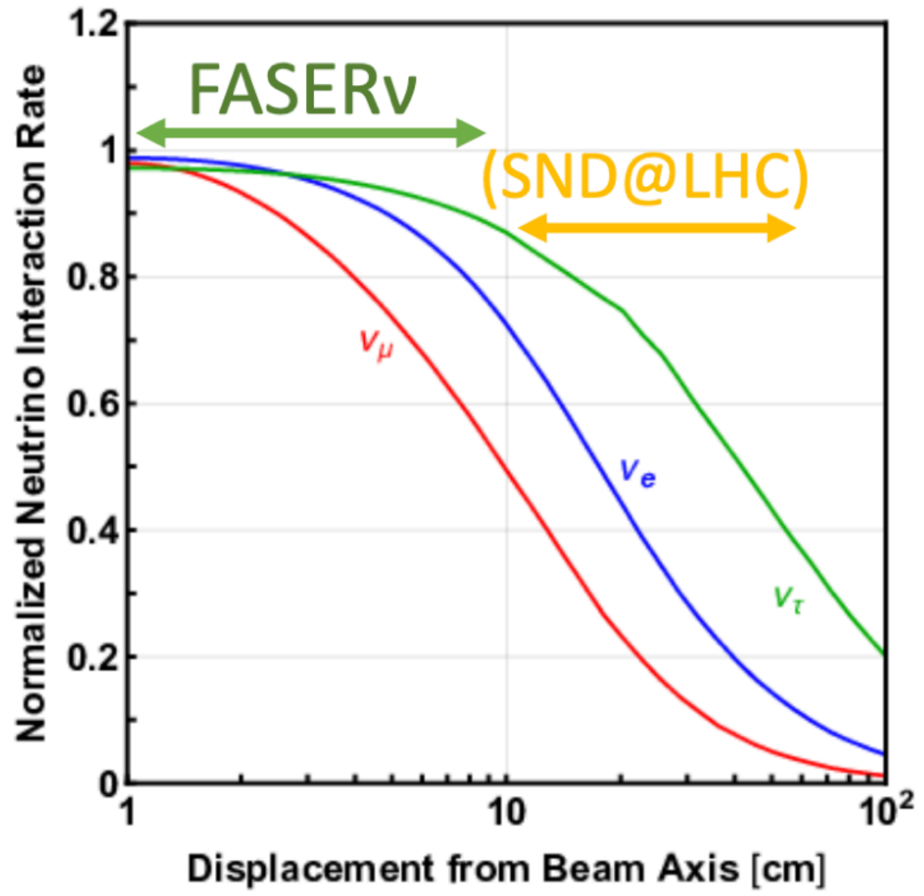
LHC

Scattering and Neutrino Detector
at the LHC





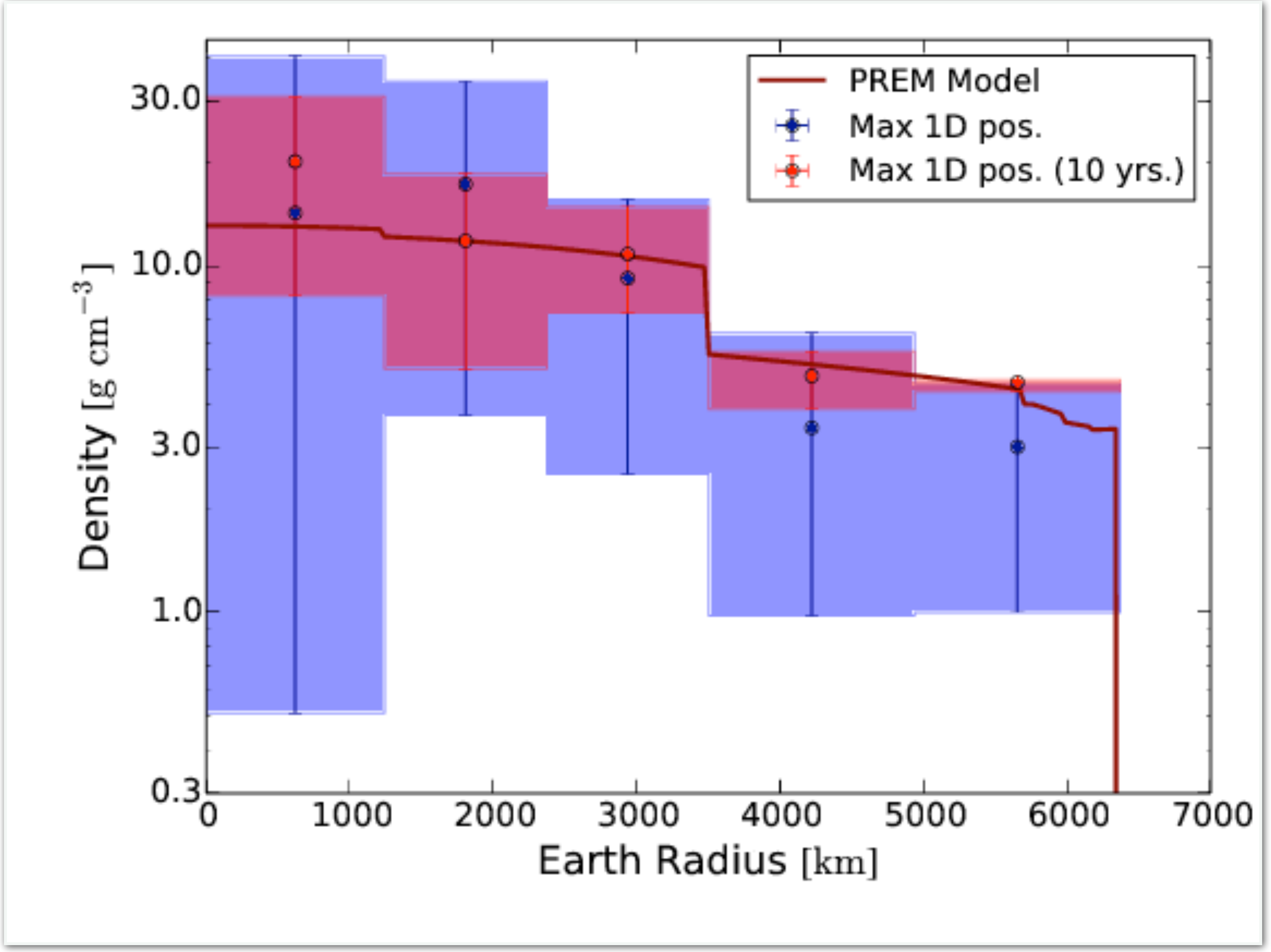




Measuring Earth's density profile

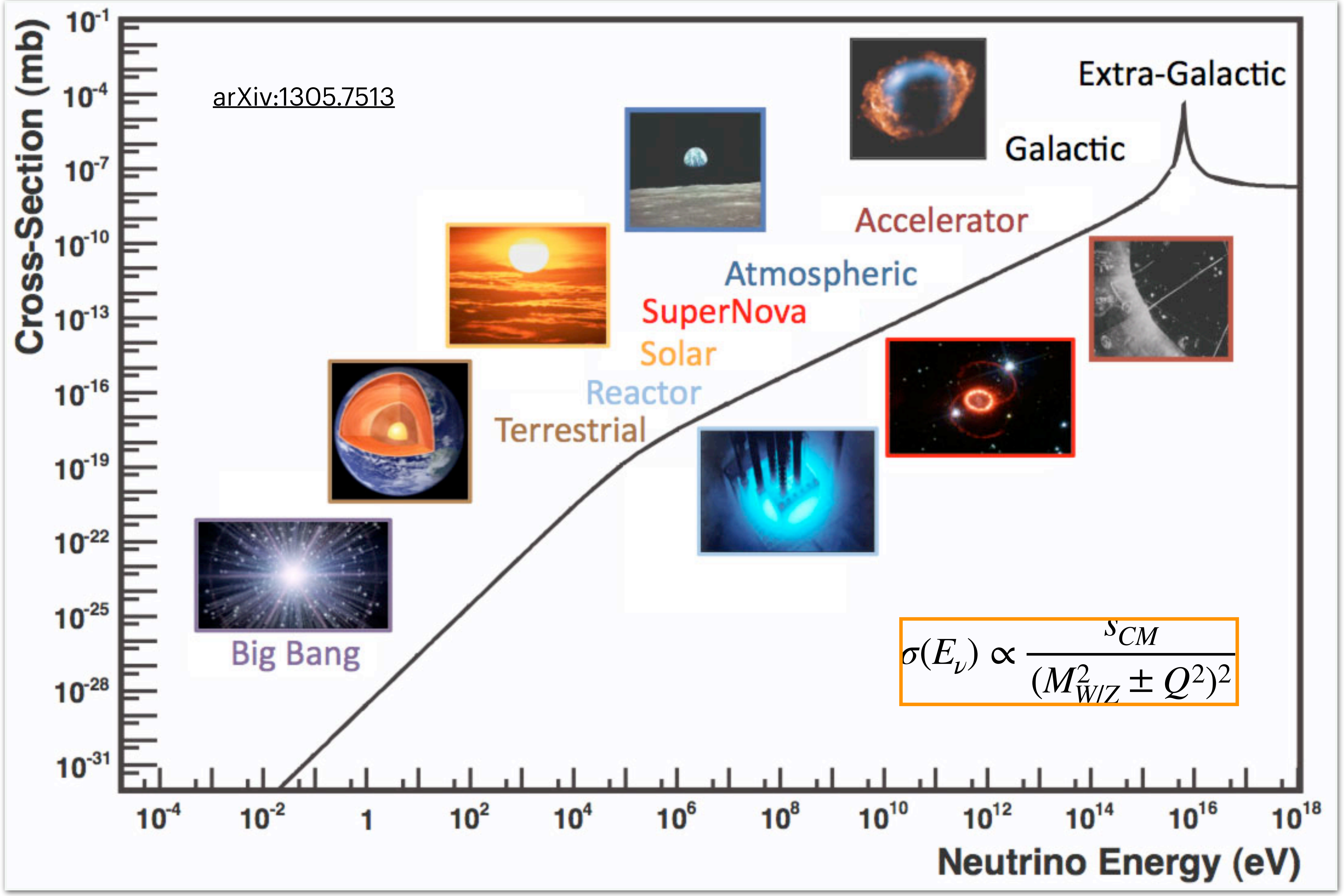
Example: Neutrinos at LHC could help in improved measurement of Earth density profile.

- Can use most accurate high energy neutrino modelling to probe Earth's density profile with IceCube data. Improved modelling of atmospheric neutrino flux hadronic interaction significantly reduces sys. uncertainty for future 10 yr timescale analyses.



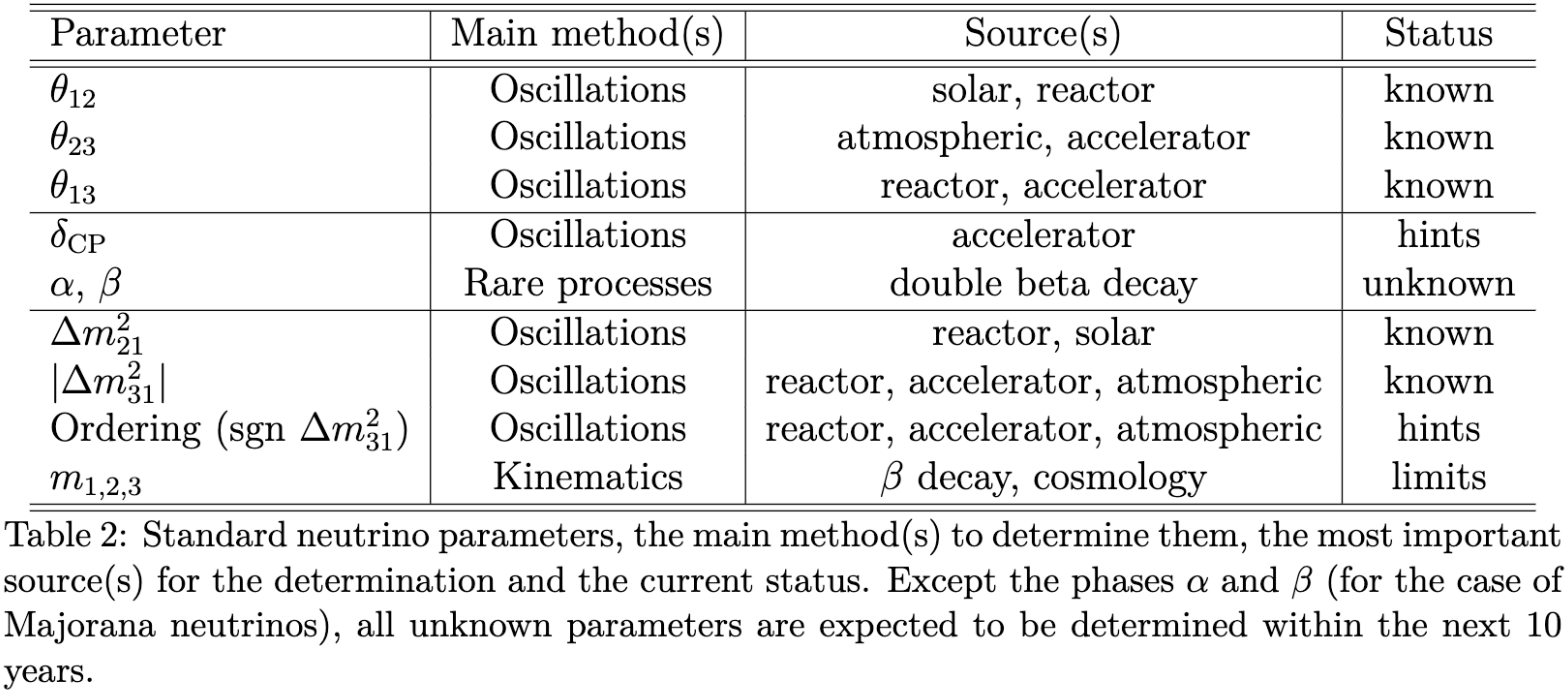
arXiv:1803.05901,*"Neutrino tomography of Earth"*

Neutrino cross-section from different sources



$$\sigma(E_\nu) \propto \frac{s_{CM}}{(M^2_{W/Z} \pm Q^2)^2}$$

Neutrino physics parameters & status



Parameter	Main method(s)	Source(s)	Status
θ_{12}	Oscillations	solar, reactor	known
θ_{23}	Oscillations	atmospheric, accelerator	known
θ_{13}	Oscillations	reactor, accelerator	known
$\delta_{\rm CP}$	Oscillations	accelerator	hints
α, β	Rare processes	double beta decay	unknown
Δm^2_{21}	Oscillations	reactor, solar	known
$\lvert\Delta m^2_{31}\rvert$	Oscillations	reactor, accelerator, atmospheric	known
Ordering (sgn Δm^2_{31})	Oscillations	reactor, accelerator, atmospheric	hints
$m_{1,2,3}$	Kinematics	β decay, cosmology	limits

Table 2: Standard neutrino parameters, the main method(s) to determine them, the most important source(s) for the determination and the current status. Except the phases α and β (for the case of Majorana neutrinos), all unknown parameters are expected to be determined within the next 10 years.

arXiv:2111.07586

Neutrino oscillation relation to L/E

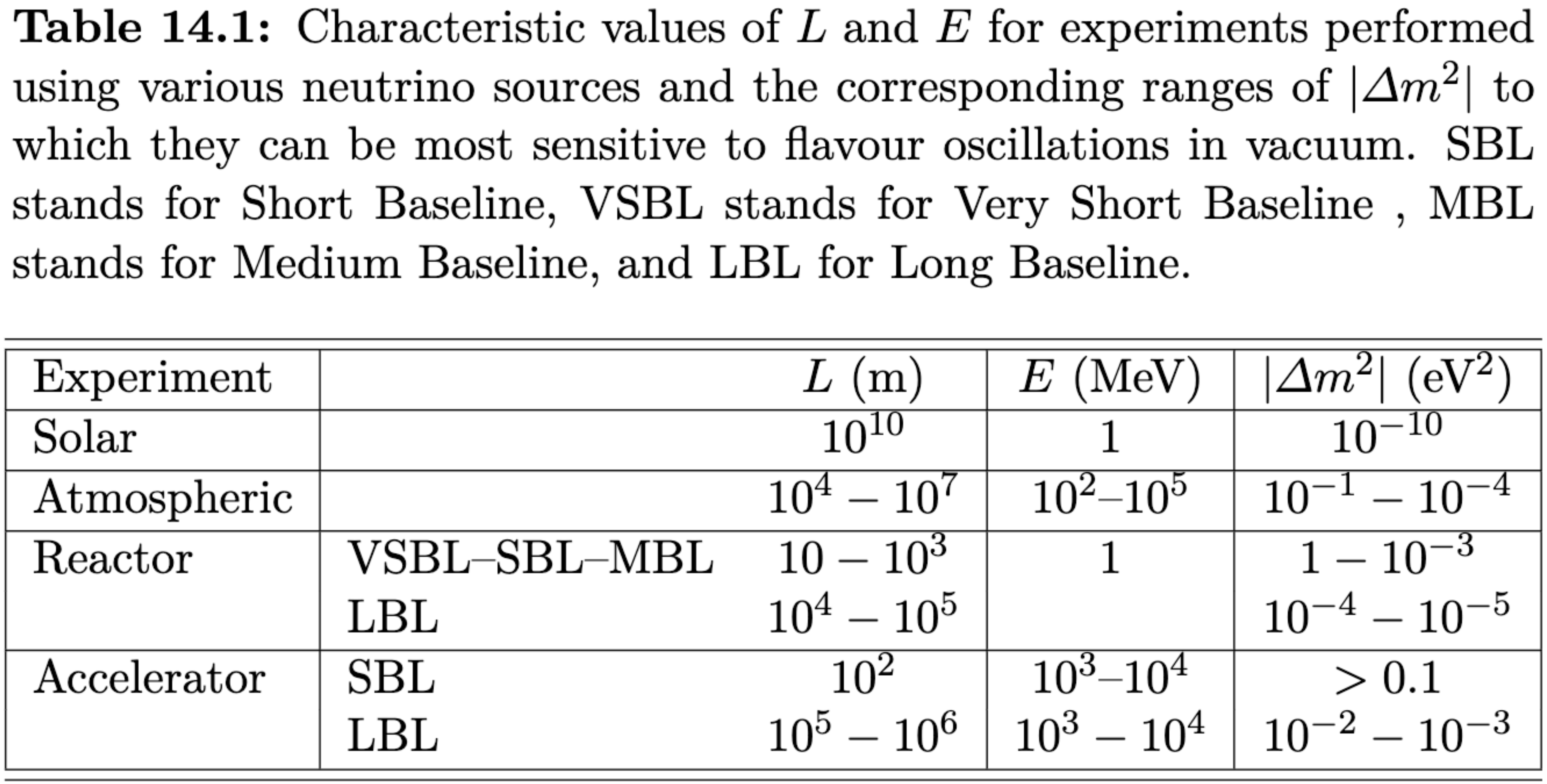
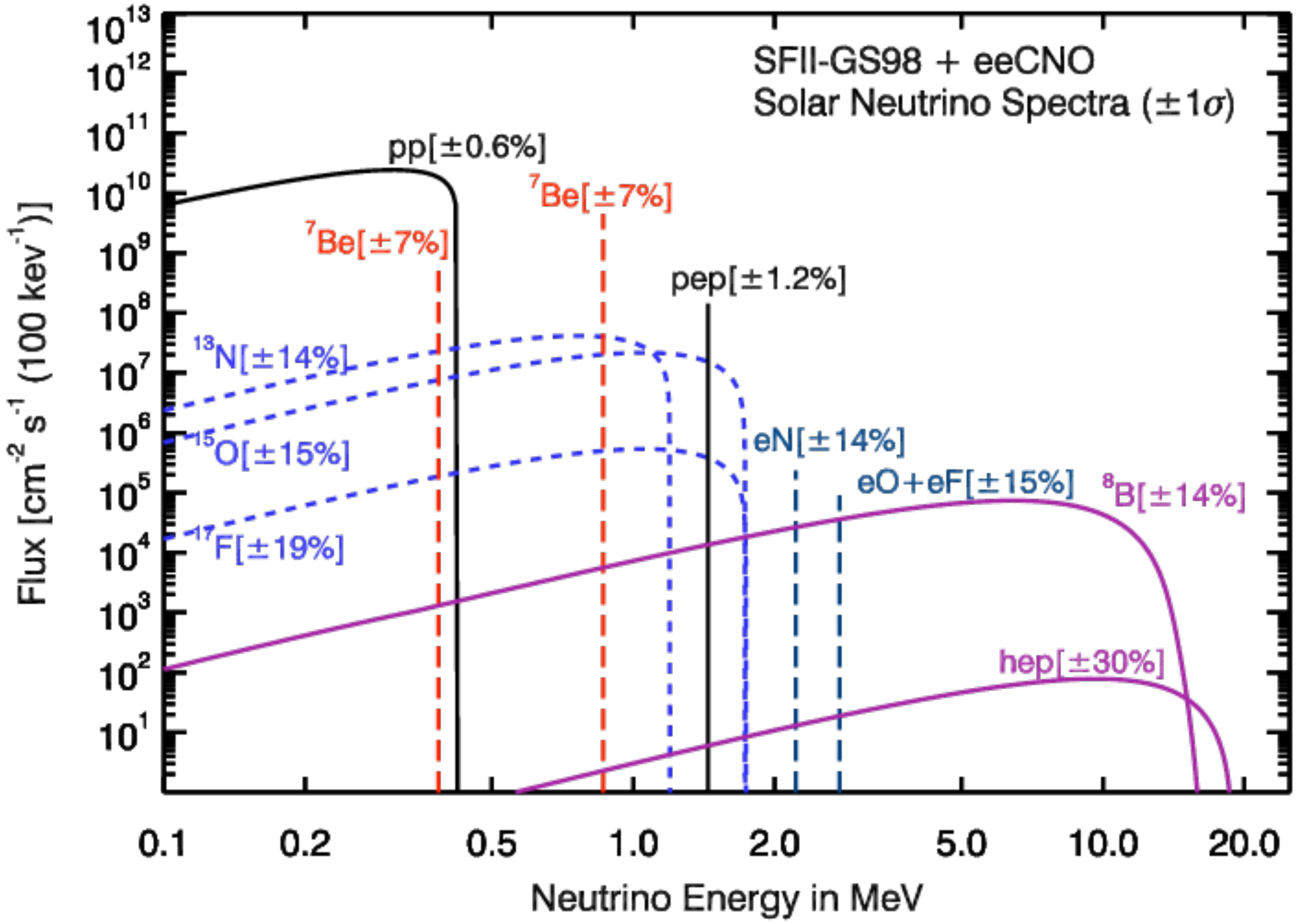


Table 14.1: Characteristic values of L and E for experiments performed using various neutrino sources and the corresponding ranges of $|\Delta m^2|$ to which they can be most sensitive to flavour oscillations in vacuum. SBL stands for Short Baseline, VSBL stands for Very Short Baseline , MBL stands for Medium Baseline, and LBL for Long Baseline.

Experiment		L (m)	E (MeV)	$\|\Delta m^2\|$ (eV^2)
Solar		10^{10}	1	10^{-10}
Atmospheric		$10^4 - 10^7$	10^2–10^5	$10^{-1} - 10^{-4}$
Reactor	VSBL–SBL–MBL	$10 - 10^3$	1	$1 - 10^{-3}$
	LBL	$10^4 - 10^5$		$10^{-4} - 10^{-5}$
Accelerator	SBL	10^2	10^3–10^4	> 0.1
	LBL	$10^5 - 10^6$	$10^3 - 10^4$	$10^{-2} - 10^{-3}$

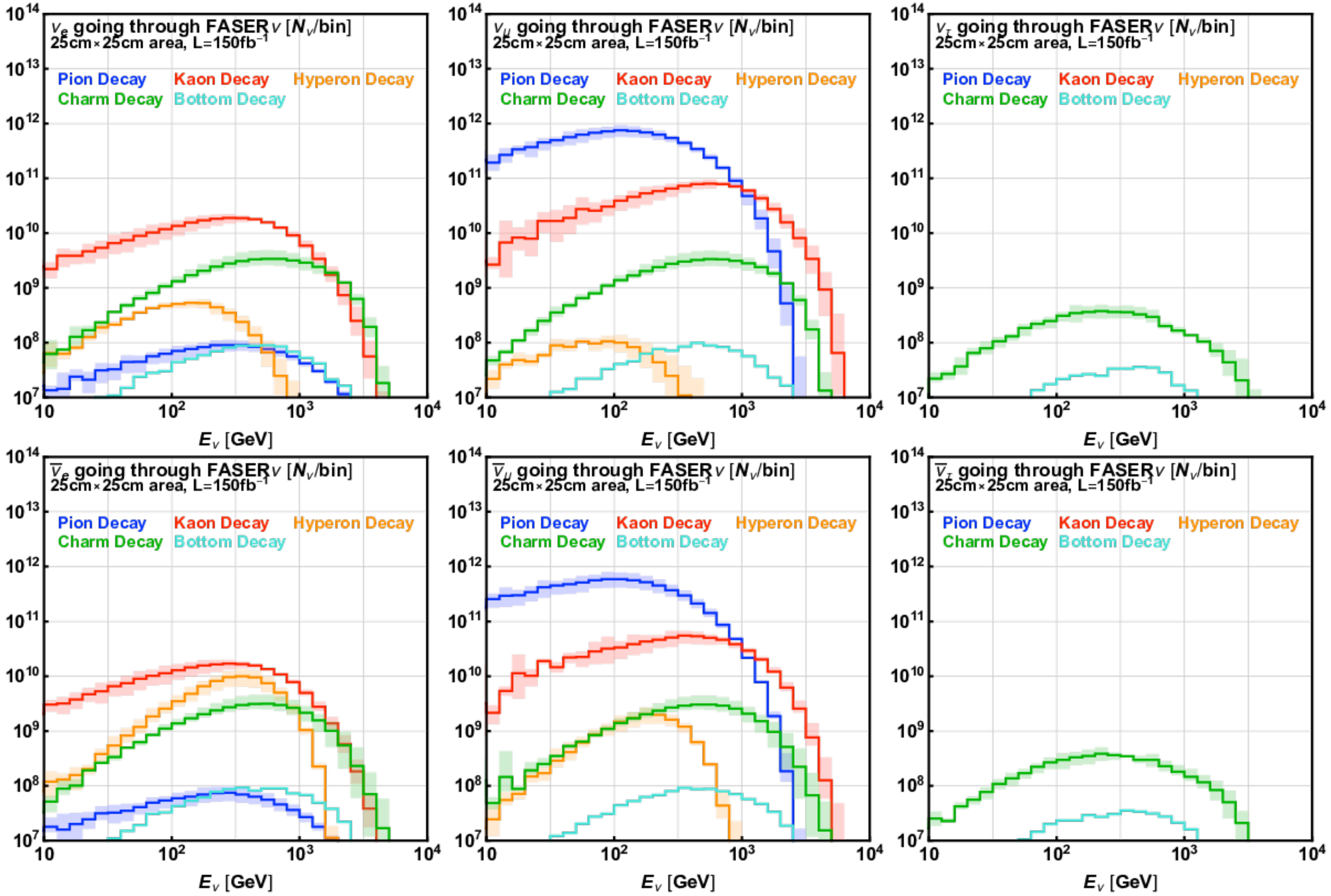
https://pdg.lbl.gov/2023/reviews/rpp2023-rev-neutrino-mixing.pdf

Solar neutrino spectrum

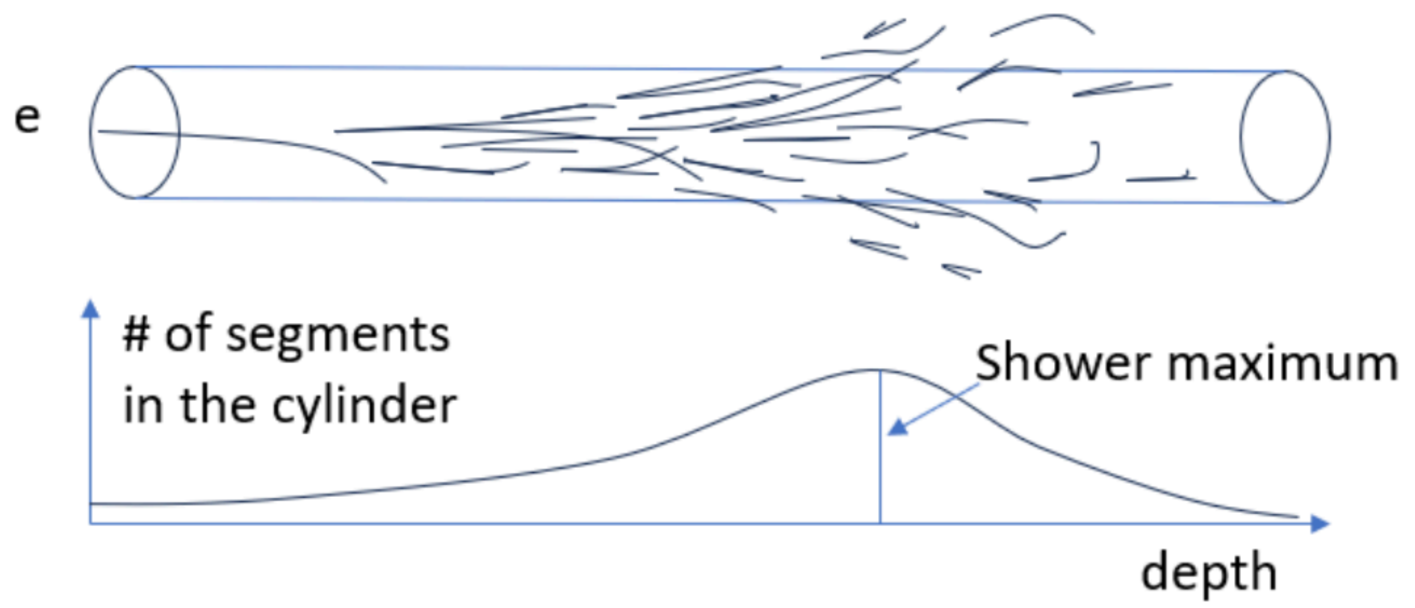


arXiv:1601.07179 : Spectrum of solar neutrino fluxes corresponding to the SFII-GS98 model. ecCNO neutrinos have been added in addition to standard fluxes. Electron capture fluxes are given in cm−2 s−1.

Simulated neutrino flux at LHC

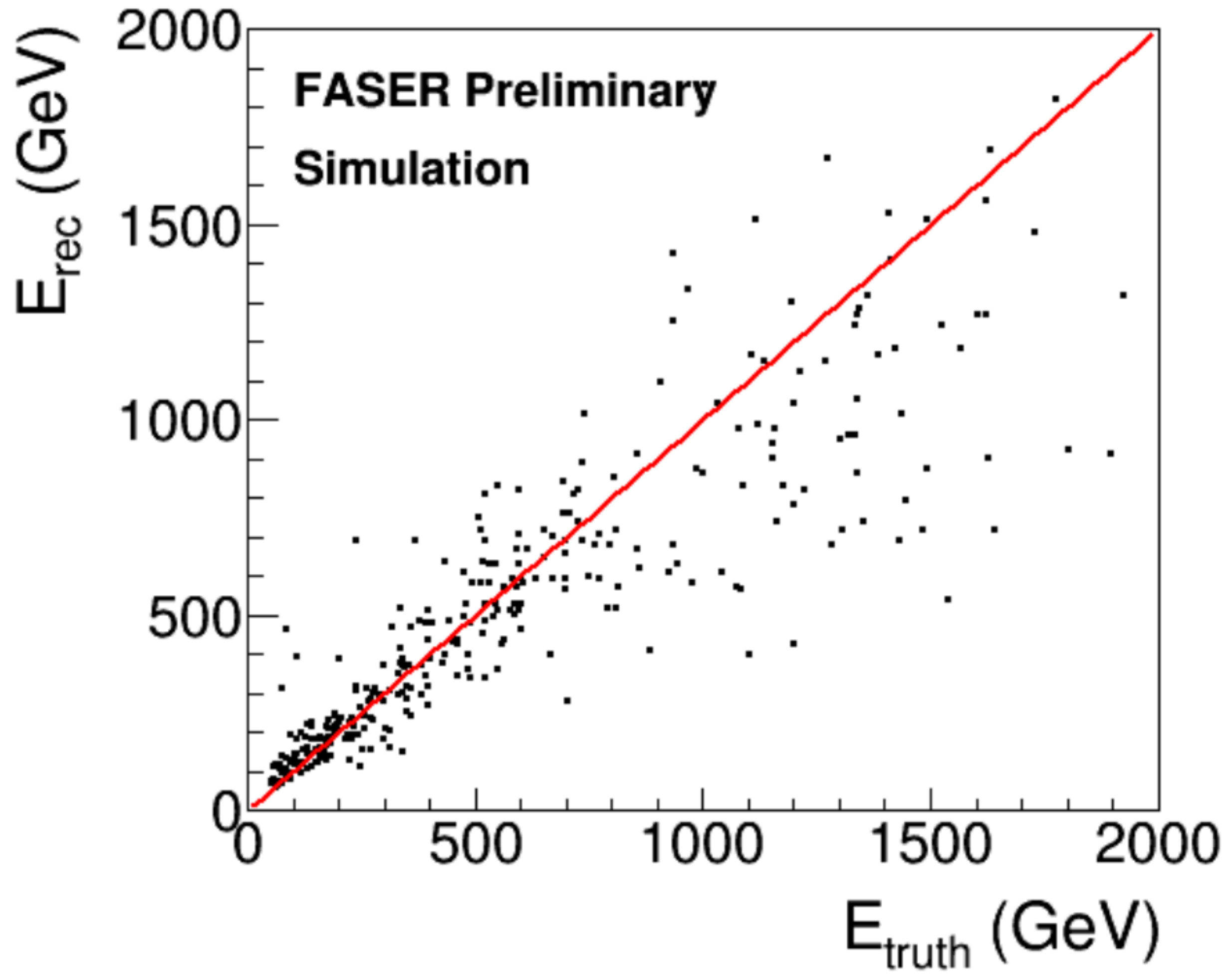


FASERν lepton energy measurement



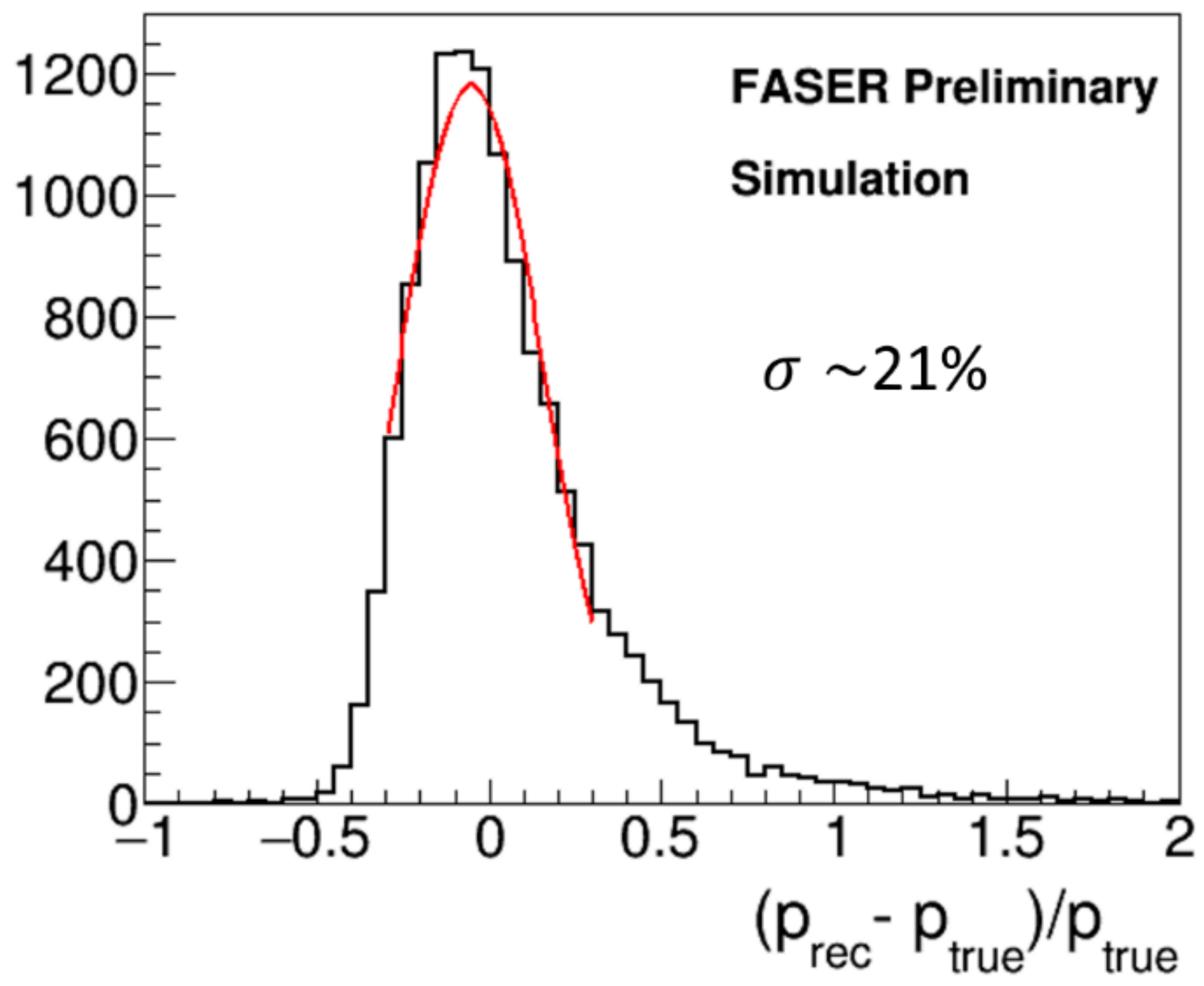
$\delta\text{pos} < 100\ \mu\text{m}$
$\delta\theta < 10\ \text{mrad}$
$d\text{min} < 50\ \mu\text{m}$

Electron energy reconstructed from tracing electromagnetic shower shape from track segment count.



Electron energy resolution:
25-40% resolution at >200 GeV.
Will be improved with test beam data.

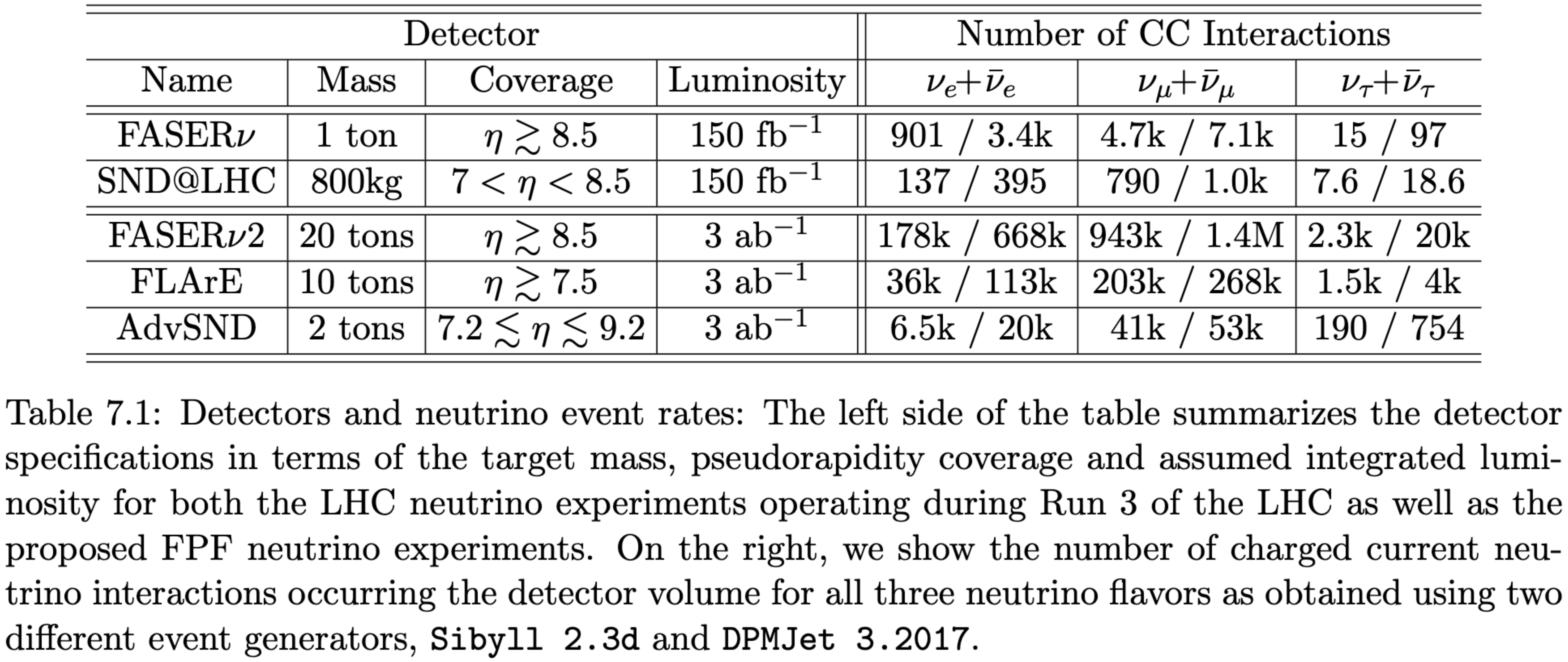
Muon momentum reconstructed from measuring multiple coulomb scattering on muon track. Validated in data by taking two halves of 1 long track, and comparing momentum measurement.



Muon momentum resolution:
20% resolution at 200 GeV.

Forward Physics Facility: Neutrino numbers

- Neutrino numbers for current LHC Run 3 detectors (FASERν & SND@LHC) as well as proposed detectors during HL-LHC.



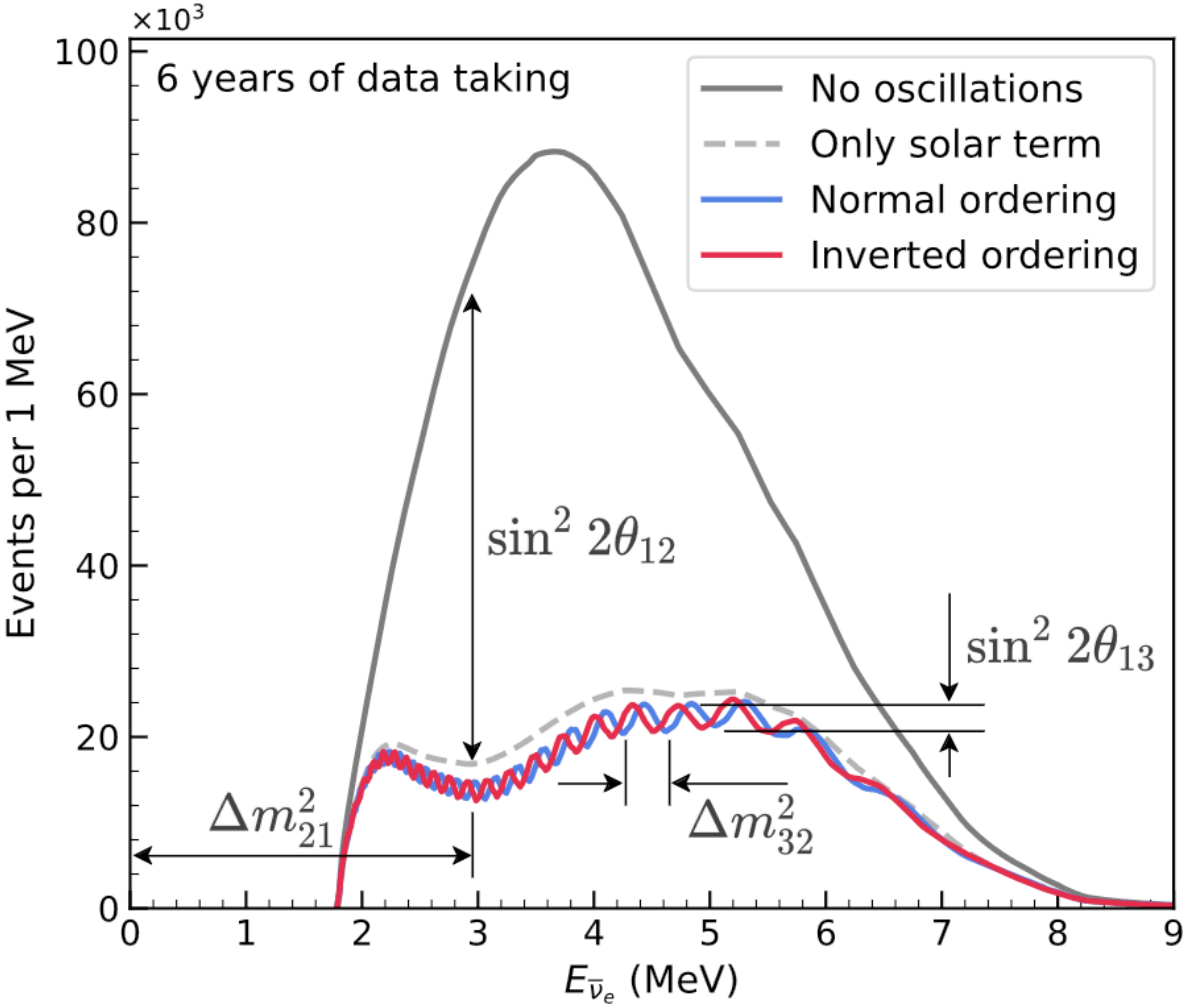
Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k / 20k	41k / 53k	190 / 754

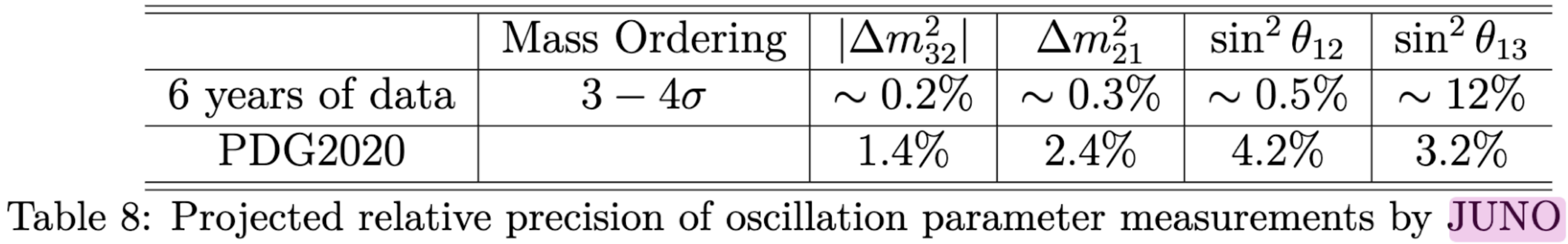
Table 7.1: Detectors and neutrino event rates: The left side of the table summarizes the detector specifications in terms of the target mass, pseudorapidity coverage and assumed integrated luminosity for both the LHC neutrino experiments operating during Run 3 of the LHC as well as the proposed FPF neutrino experiments. On the right, we show the number of charged current neutrino interactions occurring the detector volume for all three neutrino flavors as obtained using two different event generators, `Sibyll 2.3d` and `DPMJet 3.2017`.

arXiv:2203.05090

JUNO experiment

- Aims to resolve mass ordering
- Energy resolution < 3% @ 1 MeV





	Mass Ordering	$\lvert\Delta m^2_{32}\rvert$	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
6 years of data	$3-4\sigma$	$\sim 0.2\%$	$\sim 0.3\%$	$\sim 0.5\%$	$\sim 12\%$
PDG2020		1.4%	2.4%	4.2%	3.2%

Table 8: Projected relative precision of oscillation parameter measurements by JUNO