Far forward neutrino detectors at the high luminosity LHC

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May 2, 2022 Seminar at the University of Pennsylvania Physics Department.

Outline

Introduction to forward geometry at the LHC

Reminder of LHC forward parameters

Status of the plan for the forward physics facility.

Possible schedule for FPF and its relation to the HL-LHC

Current program for forward physics.

- Physics case and topics for the FPF: dark matter, neutrino physics.

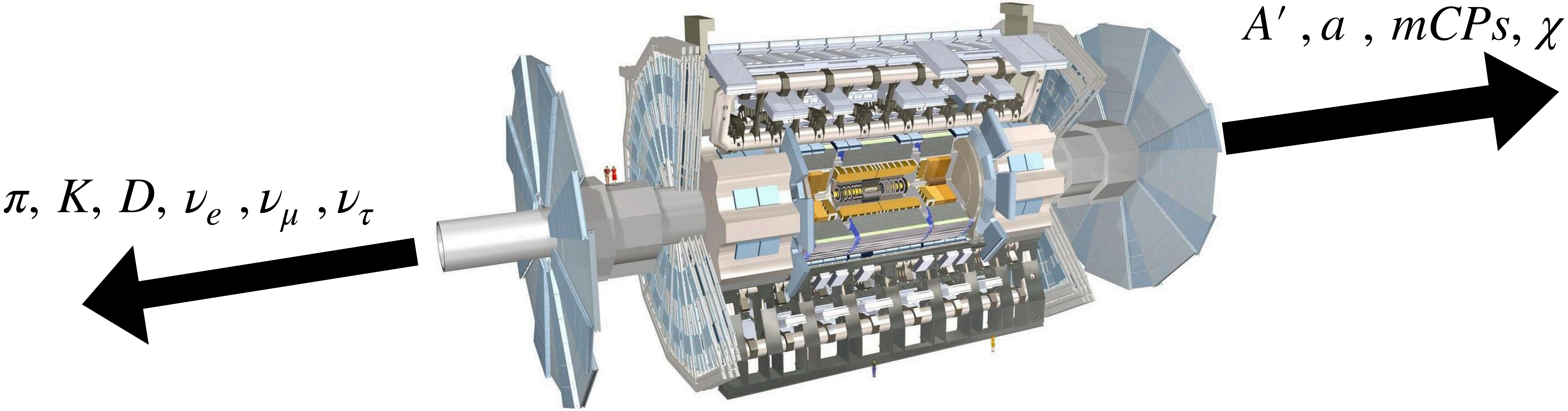
Muon flux at the FPF.

Detector requirements for a noble liquid detector.

Design options for a liquid argon TPC (Forward Liquid Argon Experiment)

Prospects.

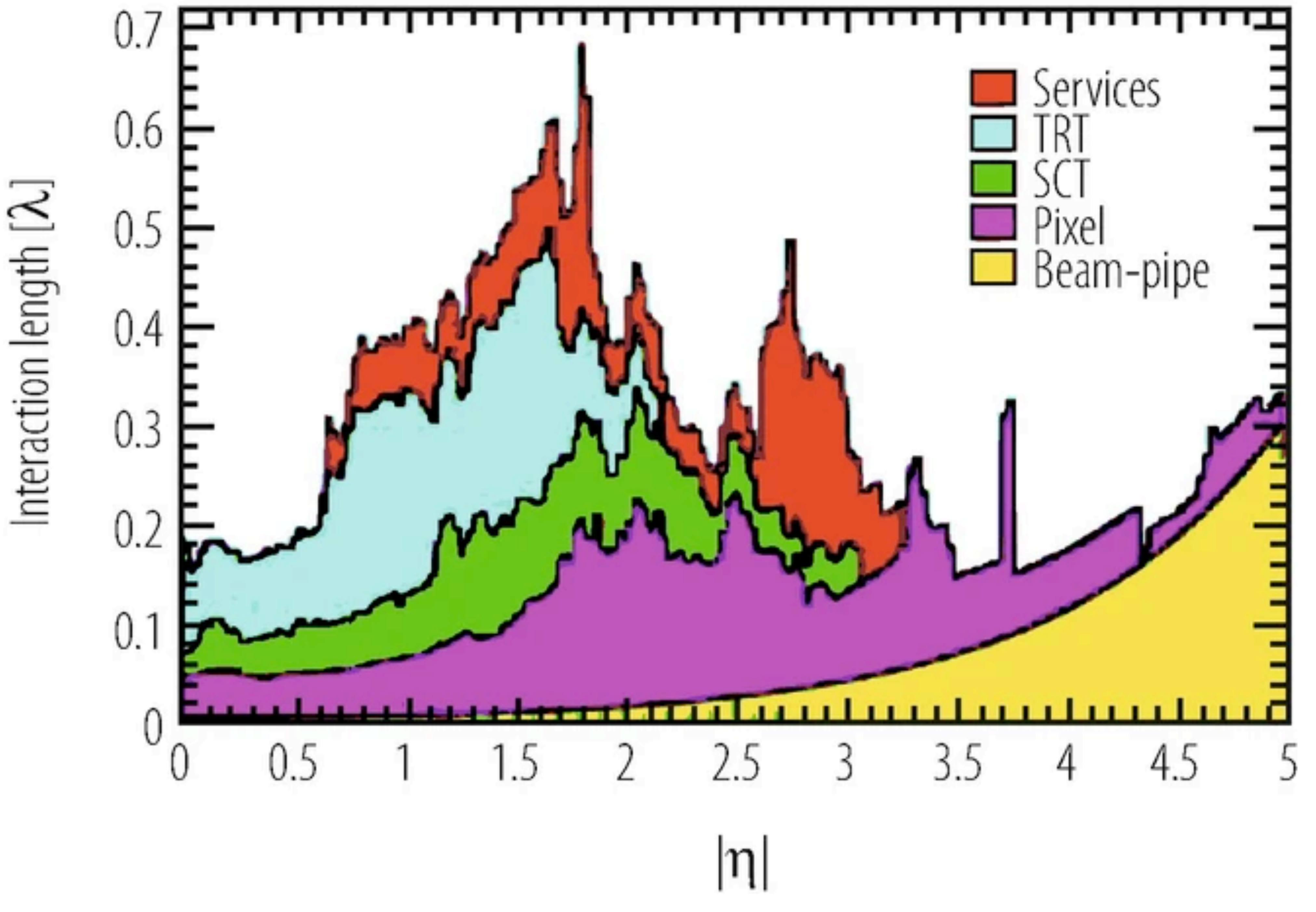
What are we missing ?



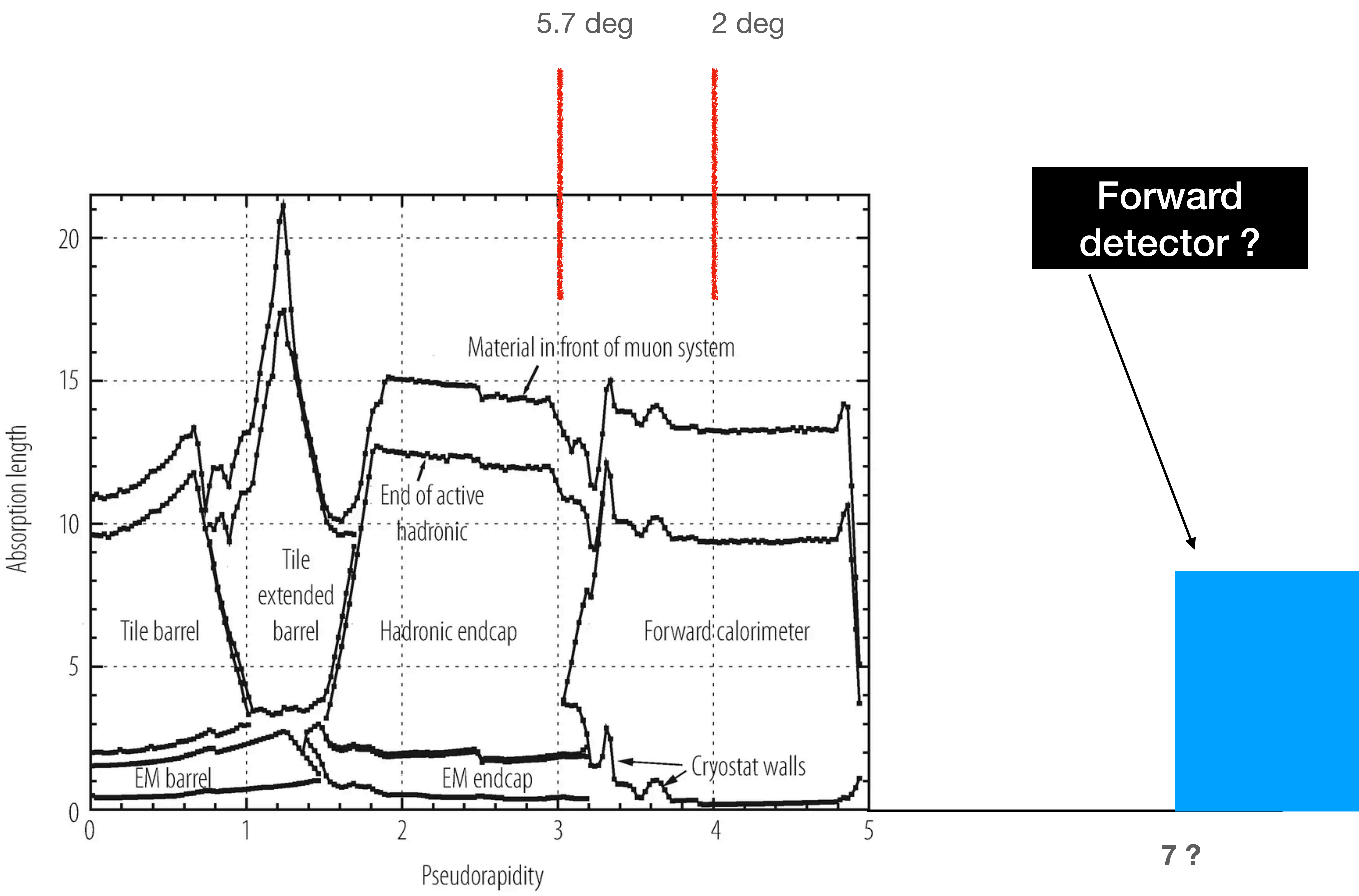
- ***Most interesting physics is believed to be at high pT, and so are we missing physics in the forward direction ?***
- ***The largest flux of high energy light particles, pions, kaons, D-mesons, and neutrinos of all flavors is in the forward direction.***
- ***This could be true of new particles also: dark photons, axion-like particles, millicharged particles, light dark matter, etc.***
- ***The high laboratory energies (>100 GeV), and kinematically focused nature of the particles presents a unique opportunity that should not be missed with the high-luminosity LHC.***

ATLAS coverage

Physics coverage $\eta \leq 3.5$

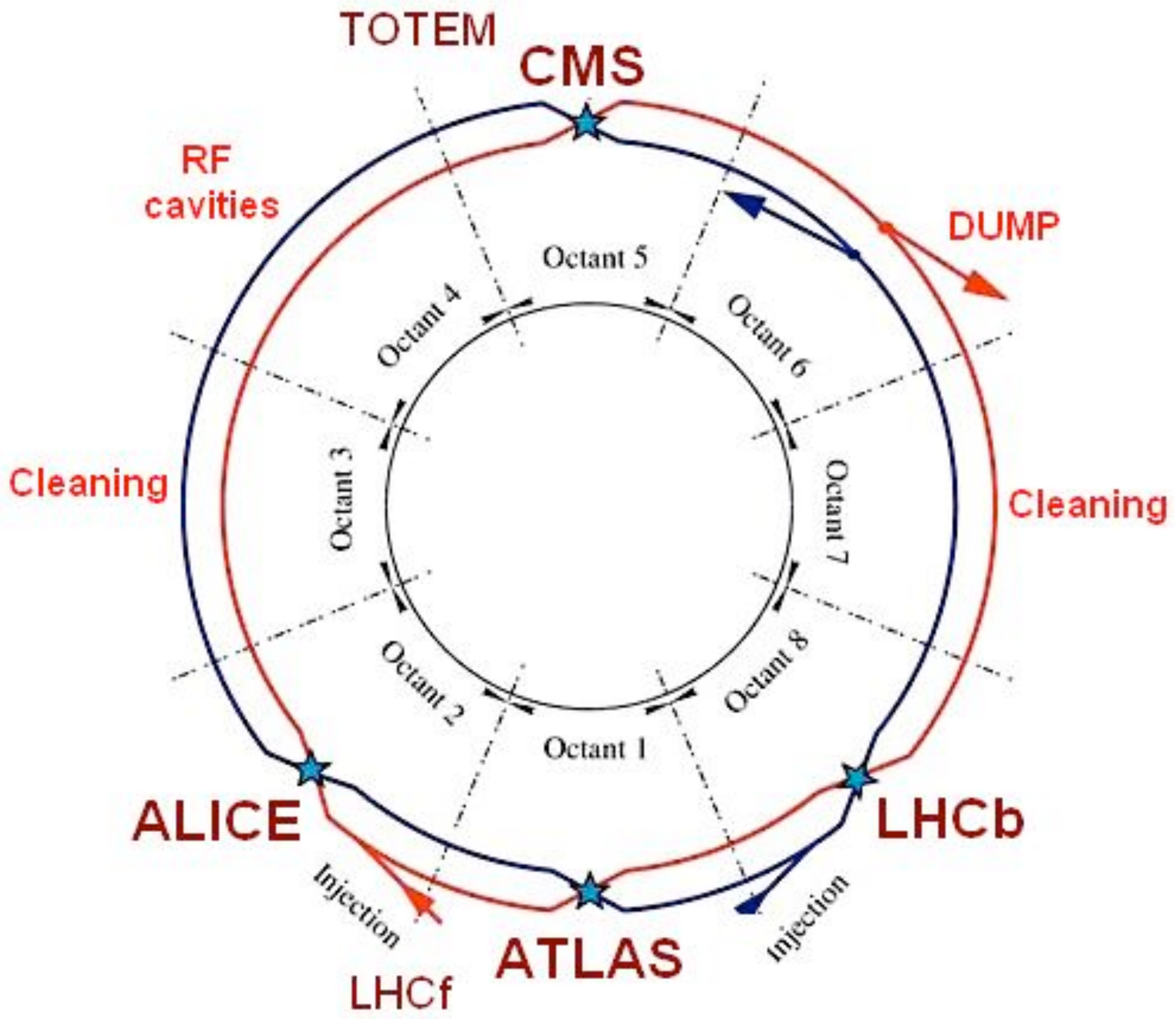


$\eta \equiv -ln[\tan(\theta/2)]$



Froidevaux, D. (2020). Integration of Detectors into a Large Experiment

The LHC description and operation for run 3 and (HL)-LHC

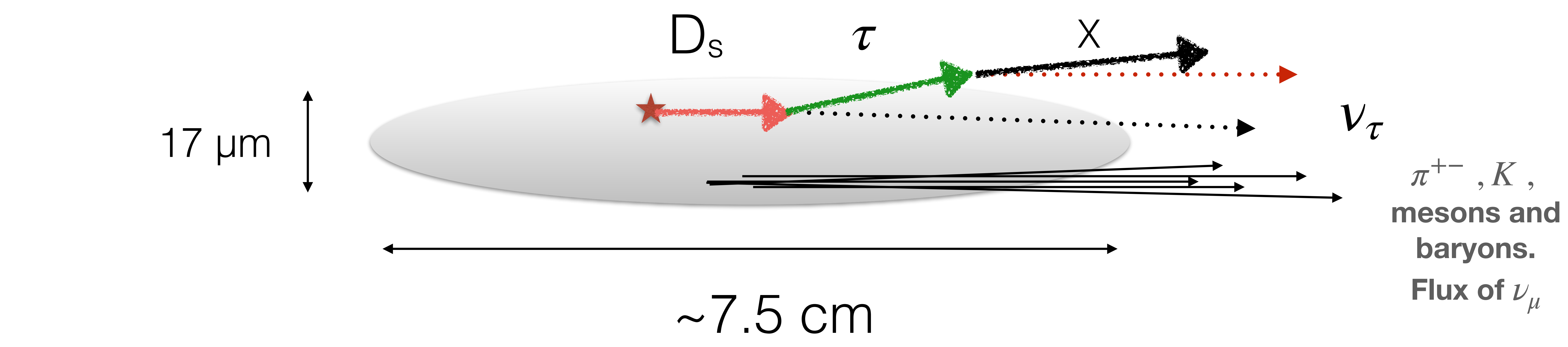


- For a forward experiment a ***well shielded location tangent*** to an IP must be found.
- The HL-Luminosity projections are to increase up to 7.5 10^34 cm^{-2} s^{-1}
- Source: Jamie Boyd (2001.04370)

parameter	Design	Run-3	HL-LHC
Circumference	27 km (r=4243 m)		
depth	100 m		
arcs	8 arcs; each has 23 cells; cell is 106.9 m		
insertions	8 insertions: insertion is a straight section with transition regions at each end.		
energy	14 TeV	14 TeV	14 TeV
bunches	3550 (with 7.5 m/25 ns) spacing)		
effective bunches	2808	2808	2808
protons/bunch	1.15E+11	<1.8E+11	2.2E+11
crossing	40 Mhz (25 ns)	25 ns	25 ns
Peak Luminosity	10^34 cm^{-2} s^{-1}	2. 10^34 cm^{-2} s^{-1}	5. 10^34
Min-bias event rate	50/crossing=1.6 GHz	3.2 GMhz	8 Ghz
inelastic rate	~20/crossing = 0.6 GHz	1.2 GHz	3 Ghz
inelastic cross sec	60 mbarn		
bunch transverse size at IP	17 mu-m		
bunch length at 7 TeV	7.5 cm		
crossing angle	285 microrad	300-> 260	TBD
Peak pileup	25	55	150
Total plan		150 fb^{-1}	3000 fb^{-1}

Production geometry

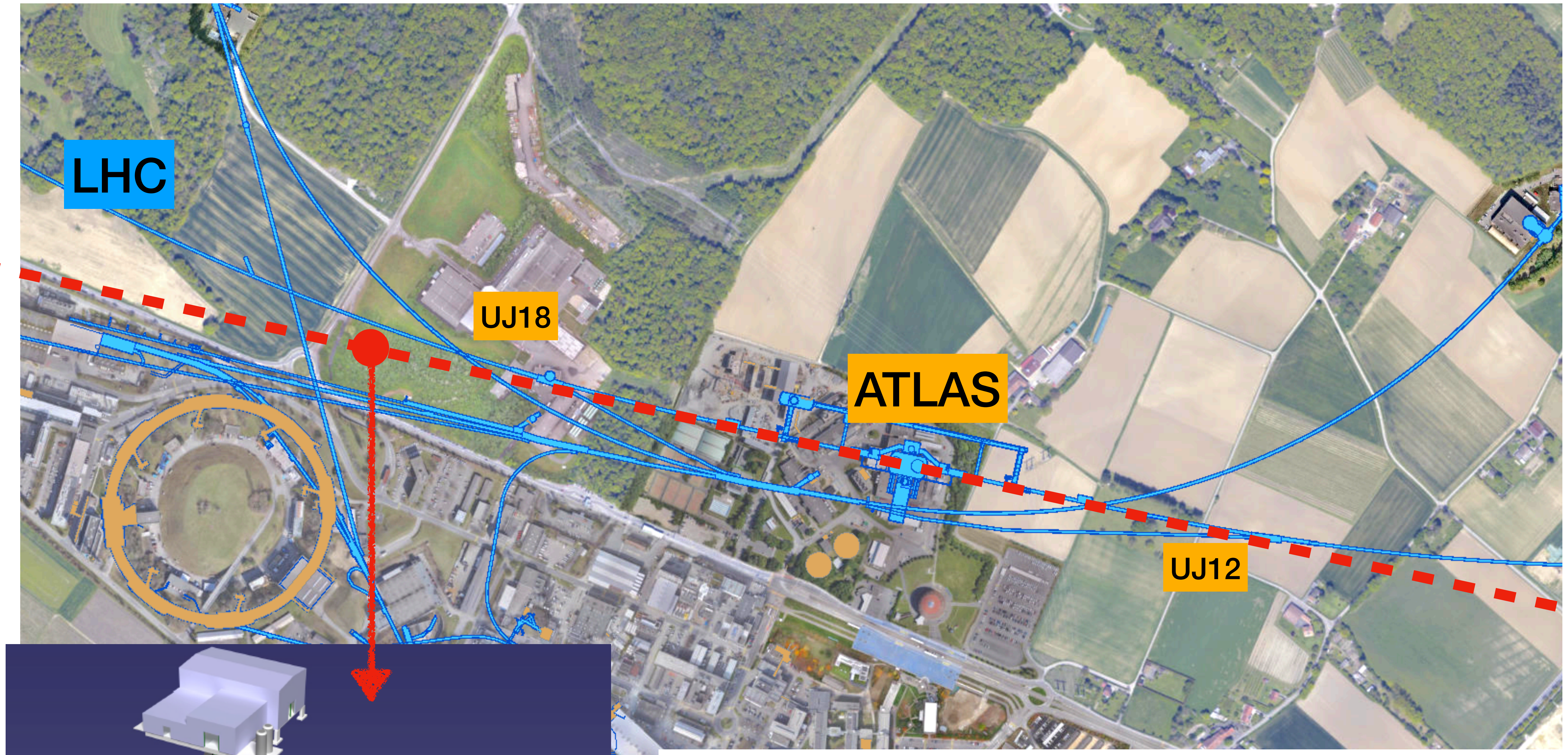
~4 GeV/14 TeV (momentum due to the crossing angle, ignored for calculations) will shift the Line of Sight (LOS) by ~17 cm at 600 meters.

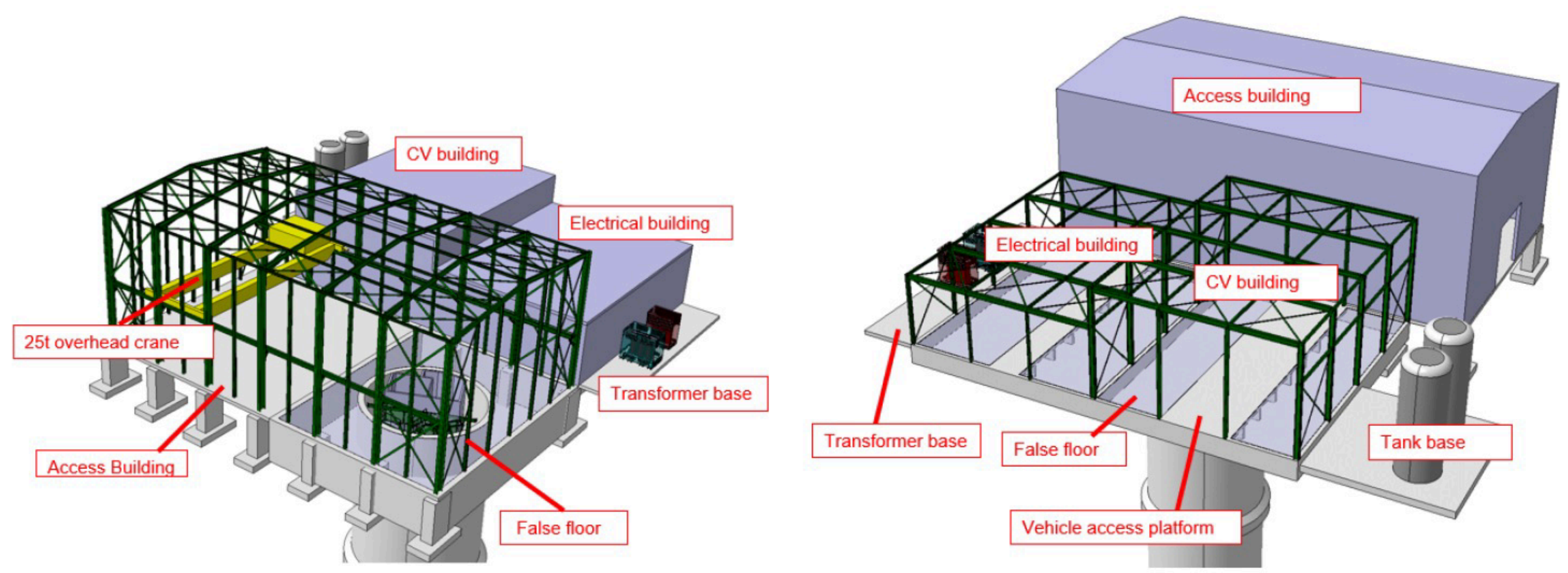


For γ~100, decay distances will be ~1.5 cm for Ds and ~0.87 cm for tau lepton $\Longrightarrow$ size of the neutrino source for the LHC is ~7.5 cm. The LHC collision region is the most compact neutrino source ever made.

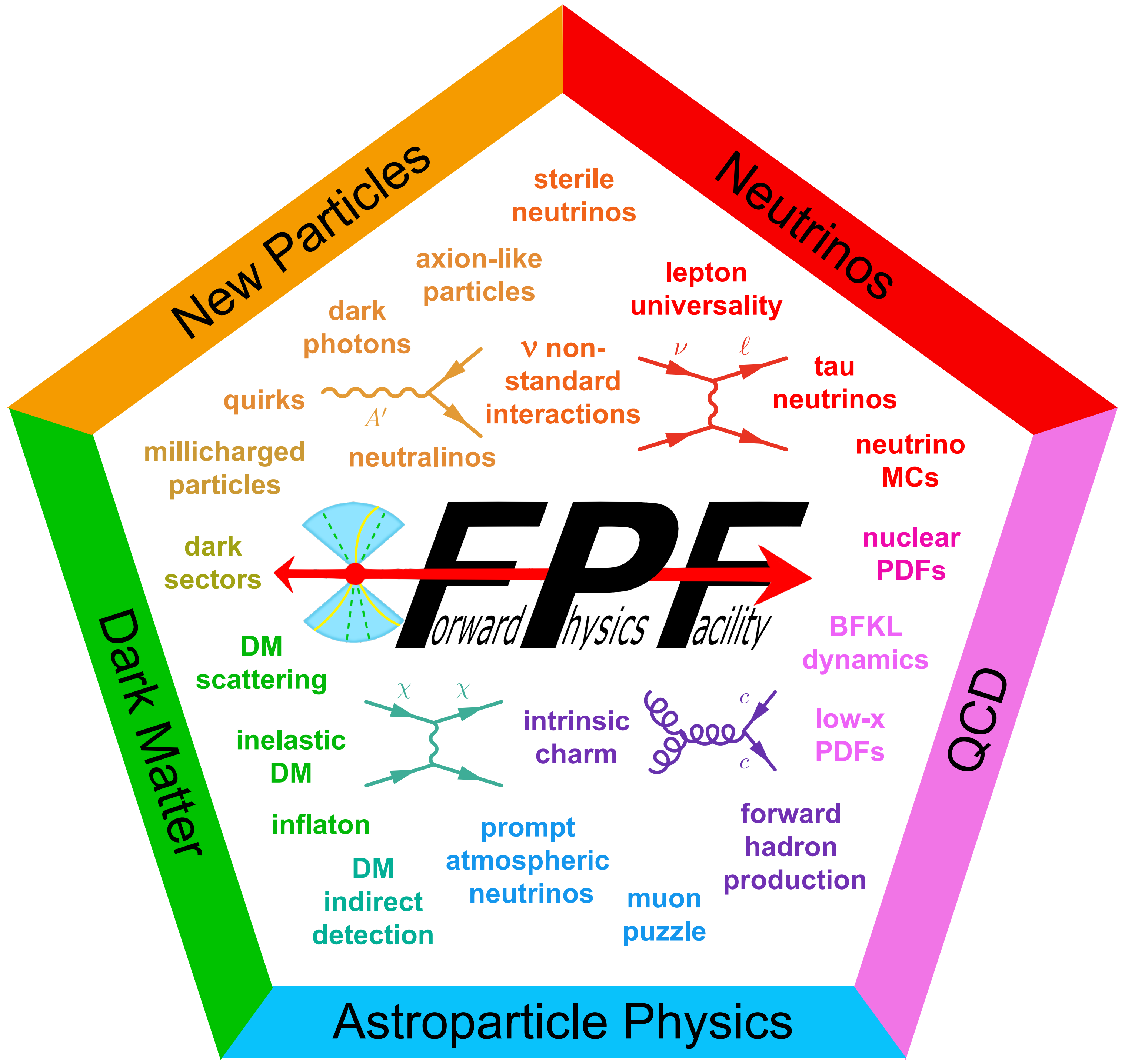
Forward Physics Facility (FPF)

Proposal to create forward underground space for experiments during HL-LHC.

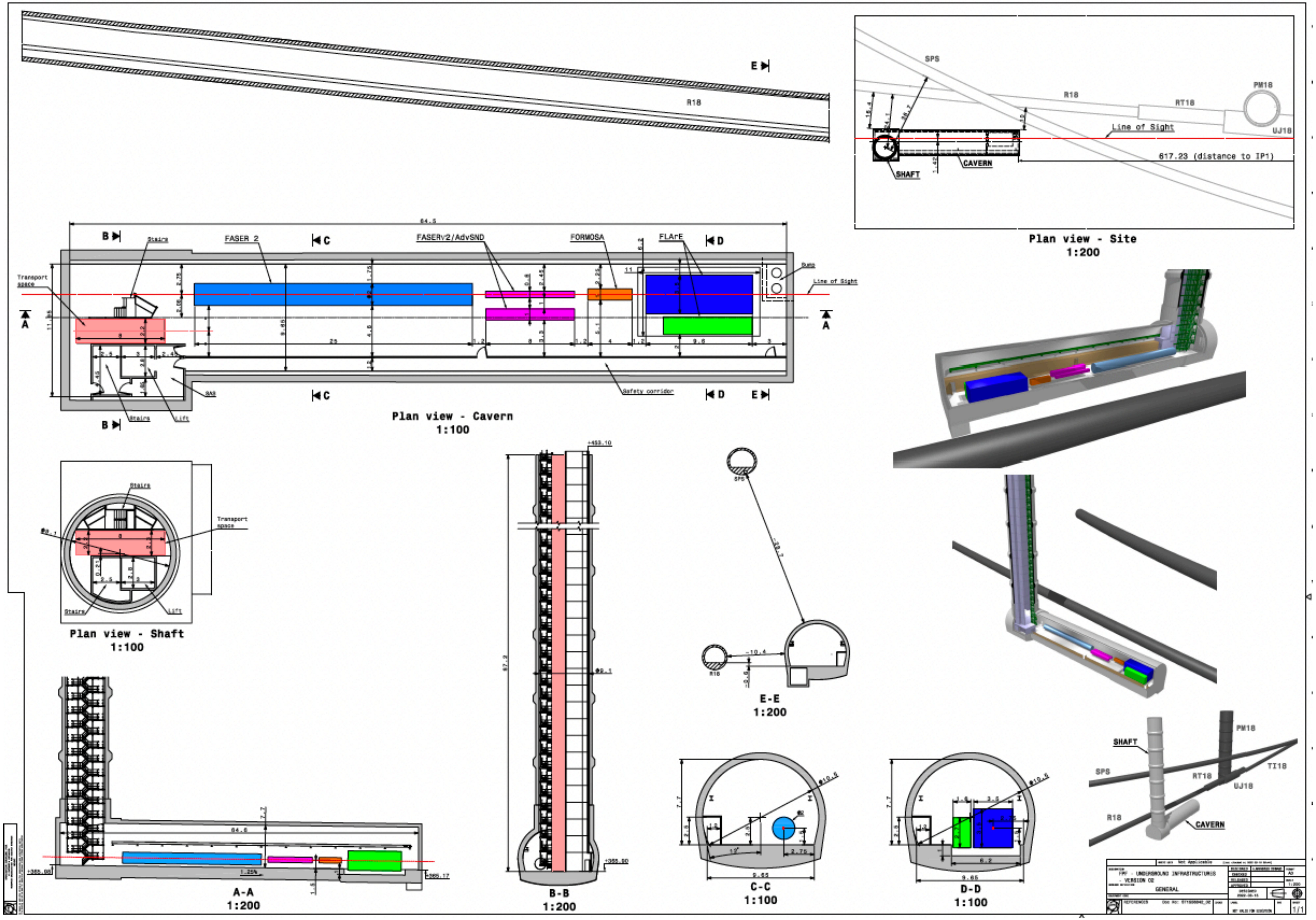




- The cavern is not connected to the LHC and no impact on HL-LHC running is foreseen.
- General purpose facility with broad SM and BSM program; spans all HEP frontiers.



Experiment	Science Priority	Technology
Faser 2	Long-live neutral particles decay	Large decay volume (super-conducting) magnetic spectrometer
FASERnu2	Neutrino Interactions	Tungsten/Emulsion 20 tons. Veto and interface tracker for muons
AdvSND	Neutrino Interactions on/off axis	Hybrid electronic and tungsten/emulsion detector with had. cal.
FORMOSA	Milicharged particles	Scintillation bars with photomultiplier readout.
FLArE	DM scattering and neutrino interactions	Noble liquid TPC (liquid argon or krypton) 10-20 tons



Class 4 cost of this has been estimated: 23 MCHF (CE)+ 15 MCHF (services) + additional items = 40 MCHF

Class 4 means: -30% +50%

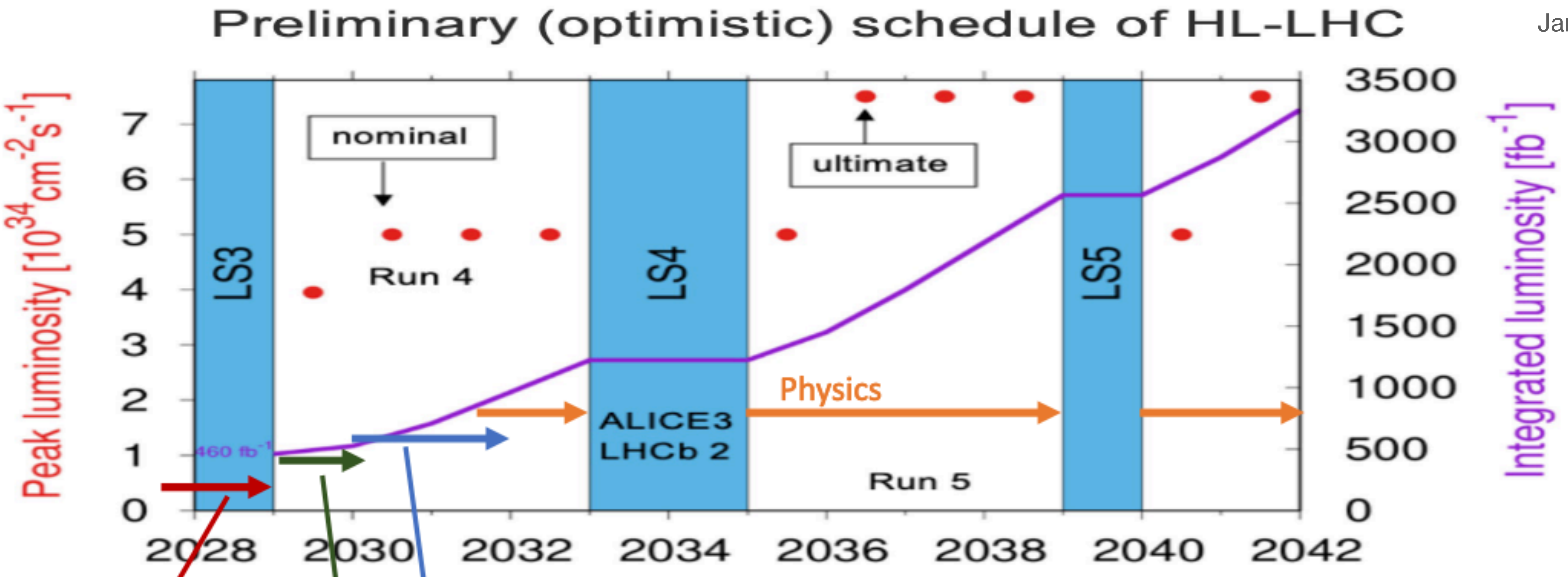
Important development April 22:

- safety gallery allows no connection to the LHC for secondary exit.

Possible FPF schedule

HL-LHC schedule from DG presentation,
New-Year (on-line) meeting, 13/1/22

Jamie Boyd



Pure CE works (including ~~connection to LHC)~~

Installation and commissioning of the experiments

Installation of services (CERN technical teams, busy during LS3)

Such a schedule would:

- Allow physics data taking for most of the luminosity of the HL-LHC
- Not overload CERN technical teams during LS3
- Design of facility would allow different experiments to come online at different times

Requirements:

- Can access the facility during LHC operations (RP study ongoing)
- Can complete CE works before the end of LS3

Forward physics facility progress

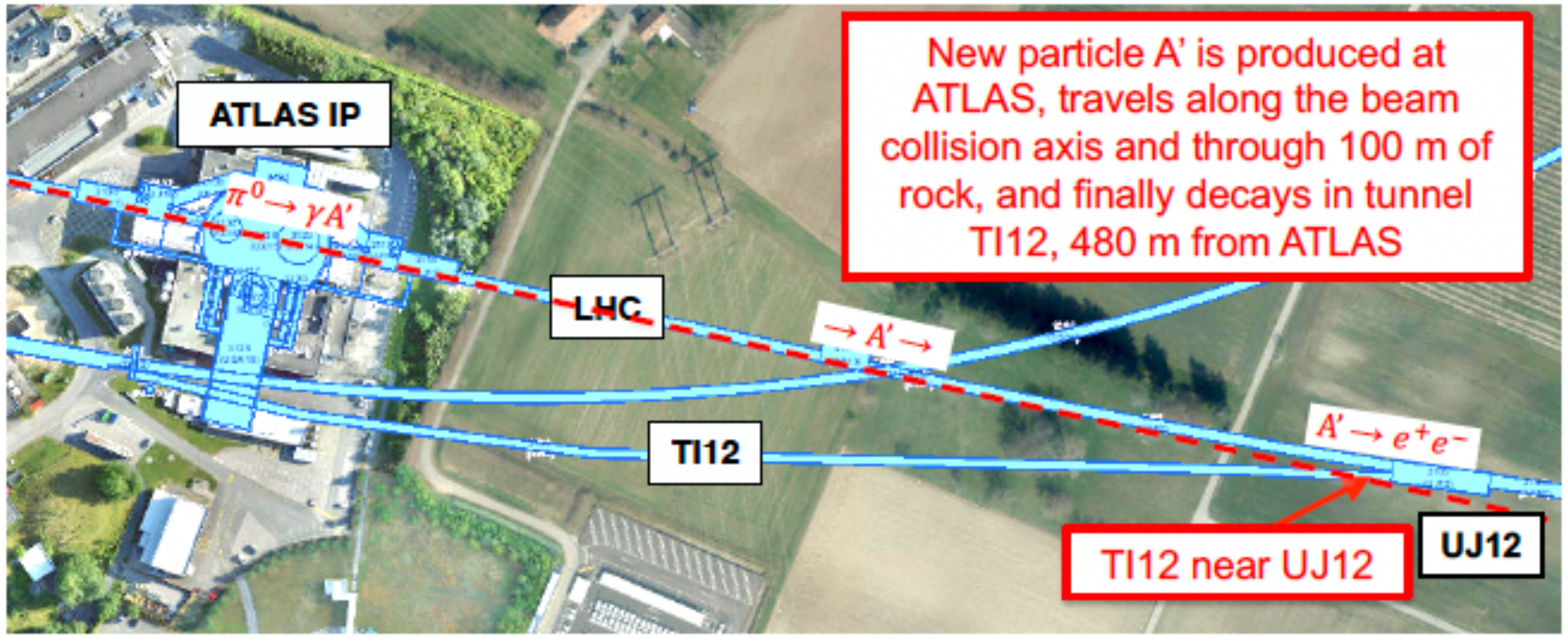
Workshops and technical working groups.

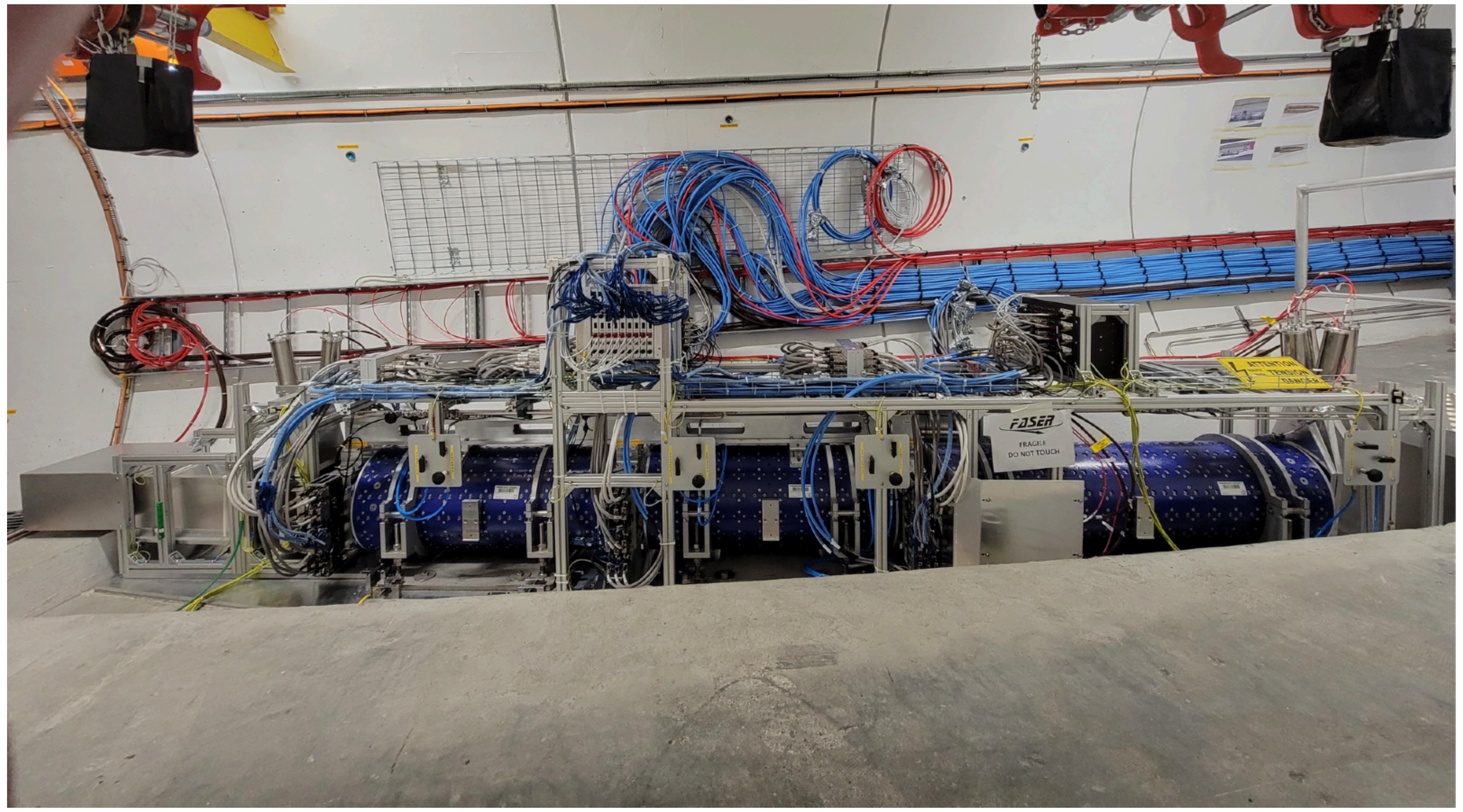
- There have been 4 workshops so far starting in 2020. Workshops have taken account of the Physics Beyond Colliders (PBC) and Snowmass frameworks.
  - FPF1 Meeting, 9-10 Nov 2020, https://indico.cern.ch/event/955956
  - FPF2 Meeting, 27-28 May 2021, https://indico.cern.ch/event/1022352
  - FPF3 Meeting, 25-26 Oct 2021, https://indico.cern.ch/event/1076733
  - FPF4 Meeting, 31 Jan-1 Feb 2022, https://indico.cern.ch/event/1110746
- A short and focused document was produced.
  - "The Forward Physics Facility: Sites, Experiments, and Physics Potential" (2109.10905), a 75-page, 80-author document distilling key progress on the FPF.
- A long Snowmass white paper also has been produced.
  - "The Forward Physics Facility at the High-Luminosity LHC." (2203.05090), Jonathan Feng, et al., 429 pages contribution to Snowmass 2021.
- An informal US working group has been launched by some of us. It is serving as a platform to inform and organize a US collaboration.
  - Forward physics working group: https://indico.cern.ch/category/14011/

Current program with Run 3

Recent progress on forward physics

- 4 experiments in progress for LHC-run3 for 150fb^{-1} 2022-24.
- FASER (March 2019), Magnetic spectrometer for neutral decays.
- FASERnu (Dec 2019), Emulsion/tungsten detector (~1 ton)
- SND@LHC (Mar. 2021) Hybrid Emulsion/active target. (~1 ton)
- Also MilliQan located near CMS (not forward); scintillation bars to see milli-charged particles.
- This program will provide excellent experience for the FPF.





FASERnu pilot run

First collider neutrinos detected at 2.7 sig

- 2018 pilot emulsion detector with 11 kg was deployed for 12.2/fb
- May 2021, announced 6 candidates with 12 backgrounds.
- Same stack able to measure the muon rate at that location.
- muon and neutrino rates in rough agreement with expectations.
- https://arxiv.org/abs/2105.06197

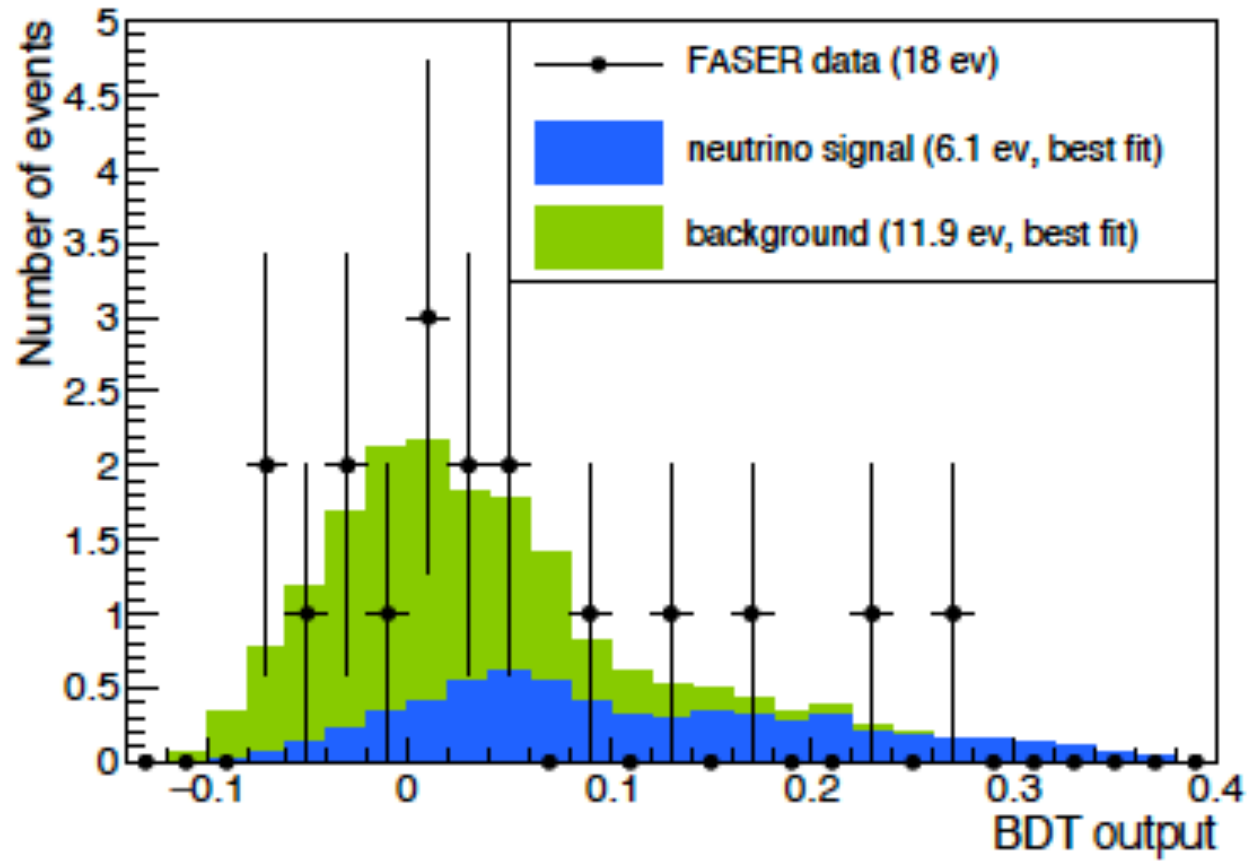
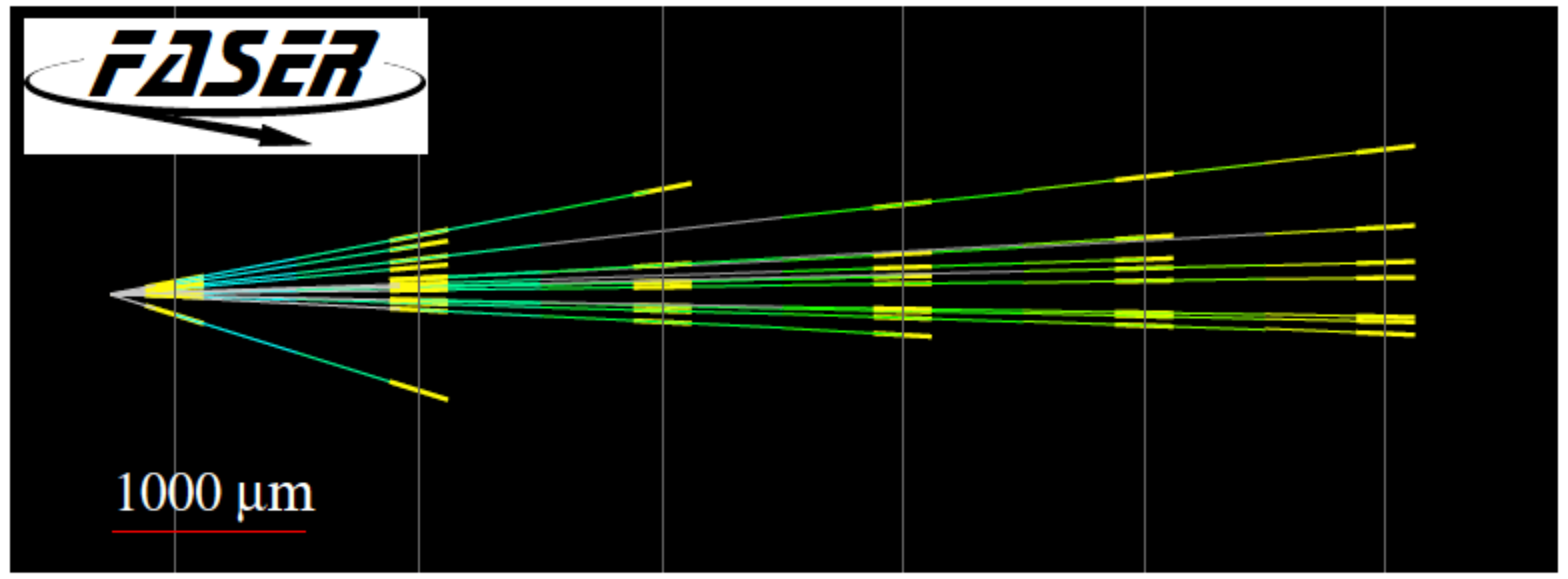
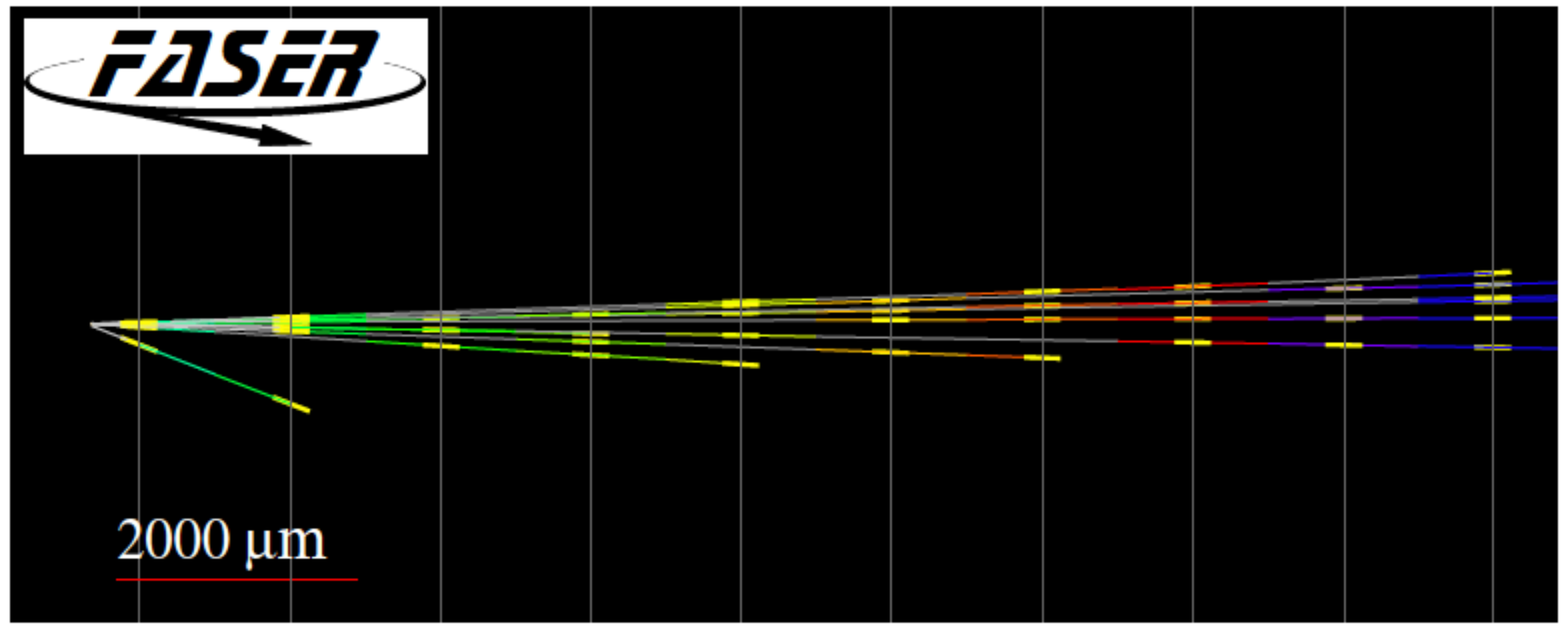


FIG. 6. The BDT outputs of the observed neutral vertices, and the expected signal and background distributions (stacked) fitted to data. Higher BDT output values are associated with neutrino-like vertex features.





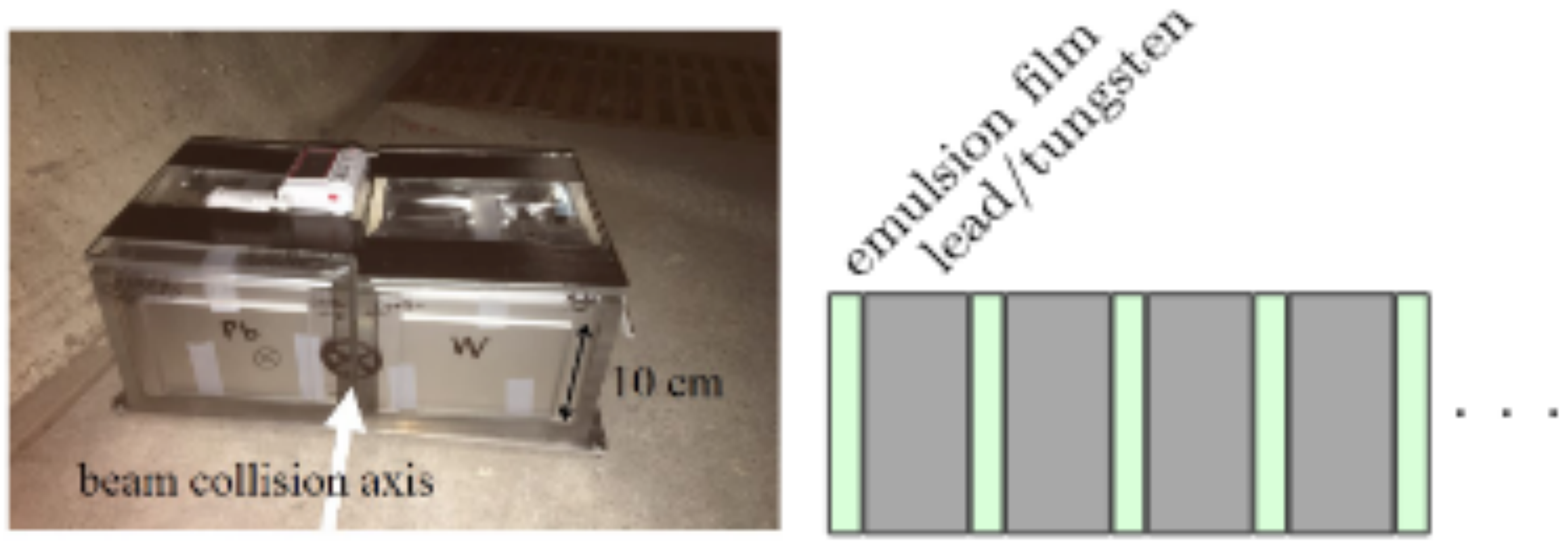
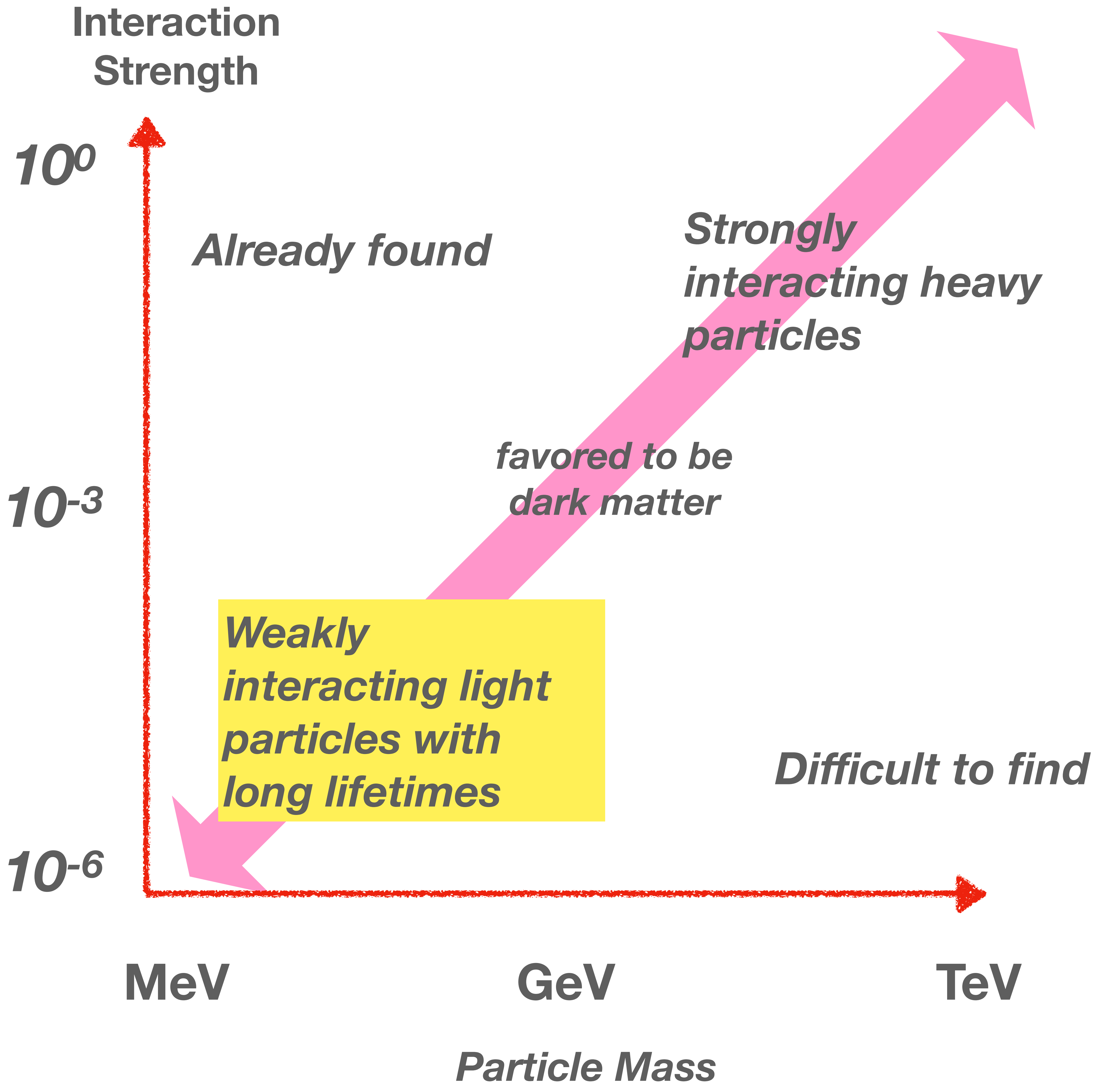


FIG. 1. Structure of the pilot emulsion detector. Metallic plates (1-mm-thick lead or 0.5-mm-thick tungsten) are interleaved with 0.3-mm-thick emulsion films. Only a schematic slice of the detector is depicted.

New particles and beyond the standard model

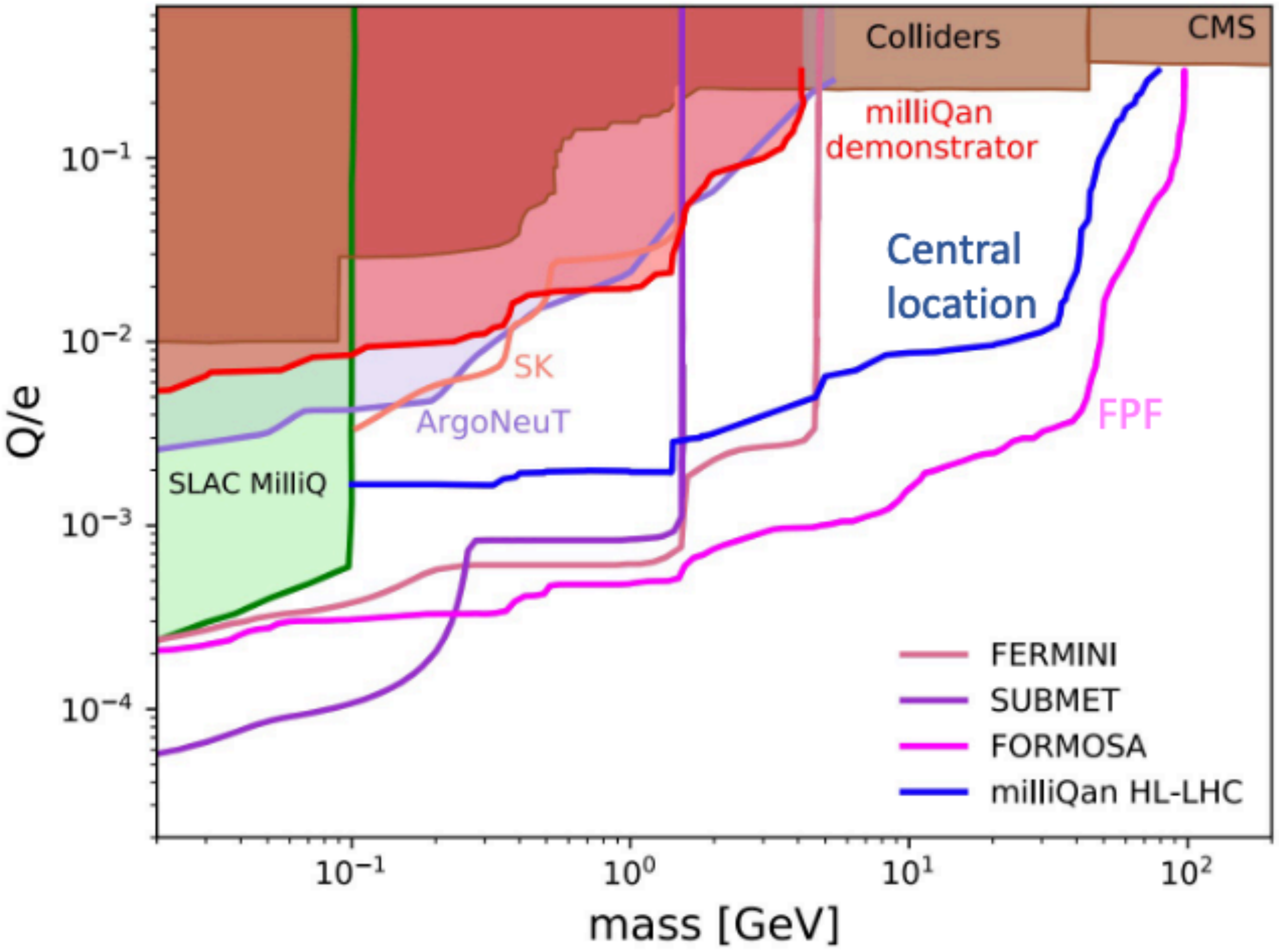
General considerations

- Focus is on weakly interacting light particles from the dark section.
- Produced in rare SM decays which LHC would provide in copious number in p-p in-elastic collisions.
- Particles are long lived and either decay or scatter in FPF detectors.
  - Boost from the energy helps the sensitivity
  - The high energies help with scattering cross section
- There are a lot of models. They are getting discussed in the physics beyond colliders venue.



Milicharged particles

- These emerge in models with massless dark photons which couple weakly to dark particles.
- The idea is to see them using dE/dx in a low noise detector.
- Deep bars of scintillator coupled to PMTs: milliQan (central location) and FORMOSA (at FPF)
- The FPF sensitivity assumes high efficiency light sensitivity in 1 meter bars of plastic scintillator with coincidence of 4.
- How can we do better ? Is it possible to use a liquid argon TPC with very good single electron sensitivity (with 2phase)

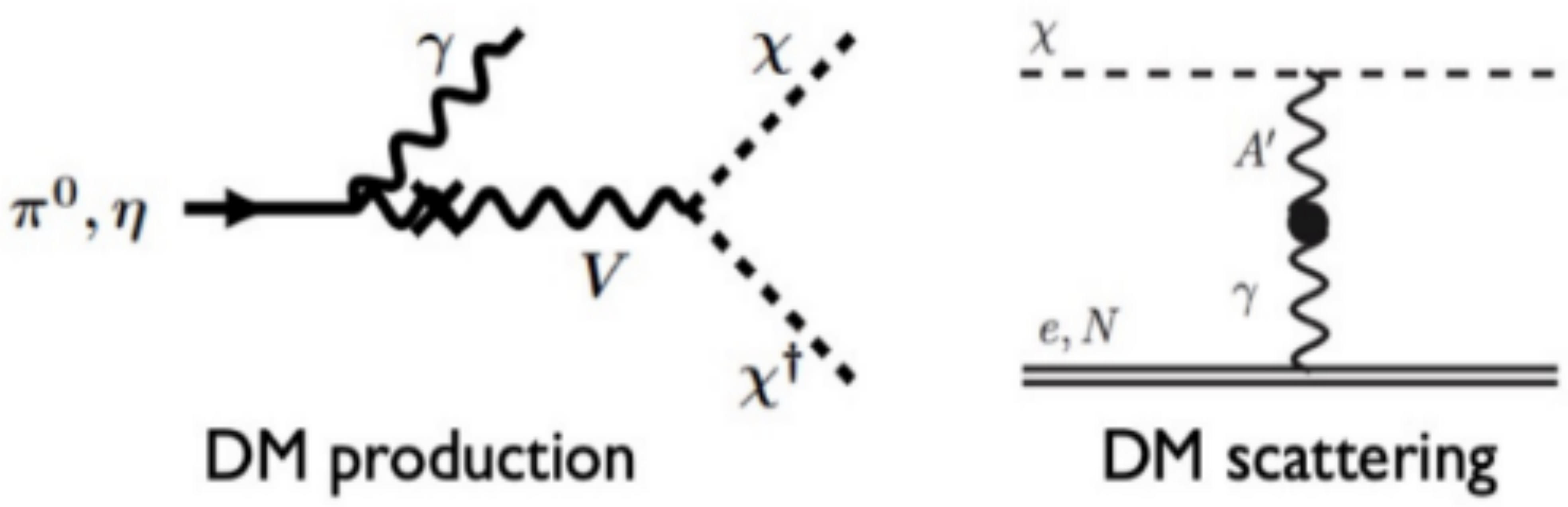


Foroughi-Abari-Kling (2020)

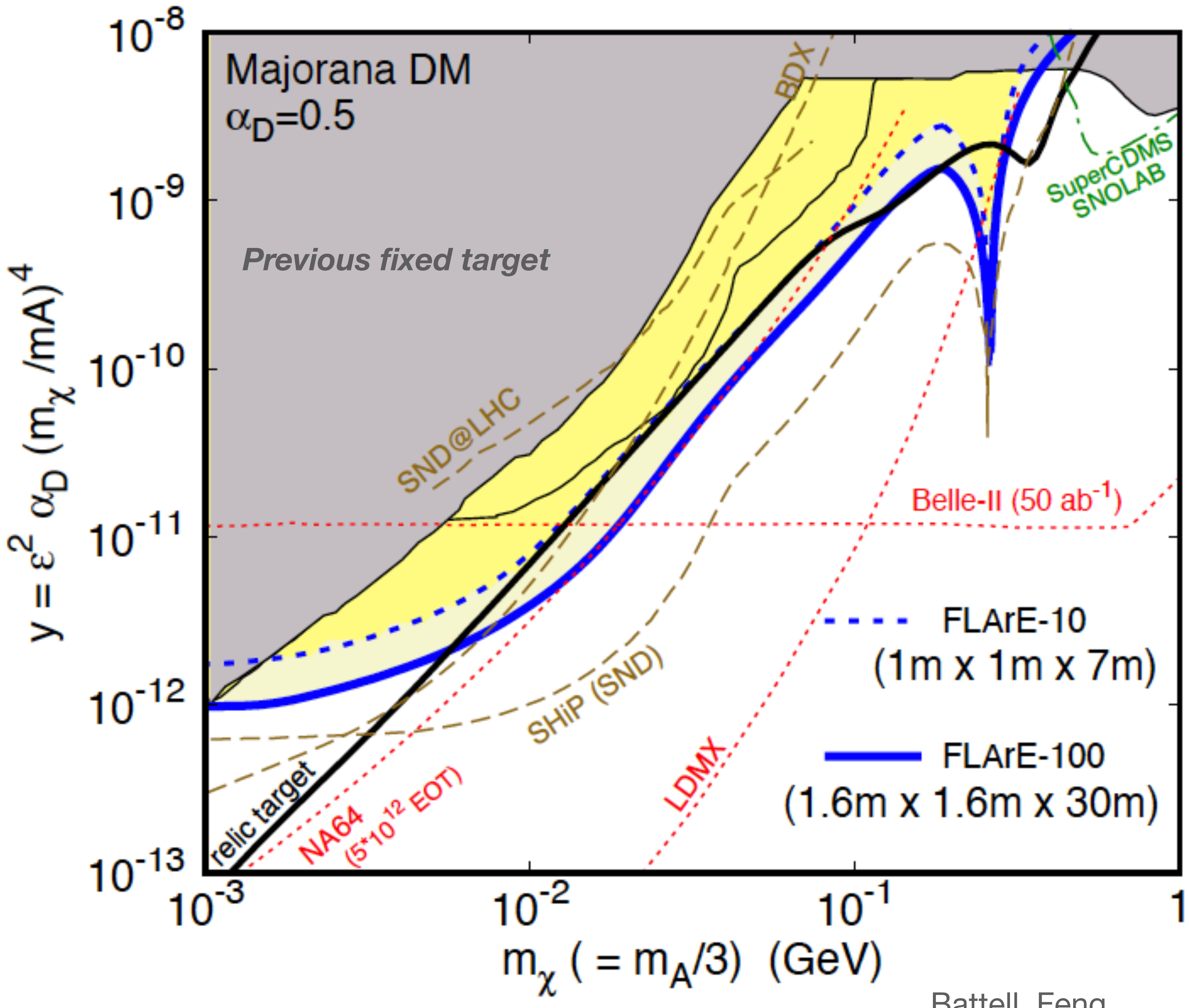
Light Dark Matter scattering (FPF@HL-LHC)

Elastic scattering from electrons or nuclei

- Mass of the χ alters the kinematics of the outgoing electron or nucleus.
- Signal is at low energy (~1 GeV)
- Background is from neutrino interactions and muons.
- The sensitivity plot assumes reasonable cuts for background suppression
- Needs a huge flux of mesons for this ***direct detection*** technique to get to the relic density target.



Both production and scattering cross sections are suppressed by mass.



Battell, Feng, Trojanowski (2021)

Neutrinos at FPF

**Uncertainties are large. 2105.08270 (Kling) is standard simulations.
2002.03012 (Bai et al.) and 2112.11605 is deep analysis of the tau neutrino flux.**

- $c\tau(\pi, K^{\pm}, K_L) = 7.8m,\ 3.7m,\ 15m$
- $\pi \to \nu_\mu, K \to \nu_\mu, K \to \nu_e$ will be affected by the LHC magnets and shielding

Needs detailed Monte Carlo

$D^{\pm} \to e/\mu$ (semi)leptonic (33%) m=1870MeV, $c\tau$=311 μm (decay to τ is very small)

$D^{0} \to e/\mu$ (semi)leptonic (13%) m=1865MeV, $c\tau$=122 μm (no decay to τ due to mass)

$D_s^{\pm} \to e/\mu$ (semi)leptonic (6%) $m = 1968 MeV$, $c\tau = 150 \mu m$

$D_s^{\pm} \to \tau\nu_\tau$ (5.5%) $p_{cm} = 182$ MeV. This would be the main source of ν_τ

$B^{\pm} \to l^{\pm}\nu_l X$ (11 %) m=5279 MeV, $c\tau$=491 μm (most decays are to D which decay to neutrinos)

$B^{\pm} \to D\ X(>95\%)$

$B^0, \bar{B}^0 \to l^{\pm}\nu_l X$ (11 %) m=5279MeV, $c\tau$=455μm

$B^0, \bar{B}^0 \to D\ X$ (>90%)

$\Lambda_c \to l\nu_l X(\sim 10\%)$ m=2286MeV, $c\tau$=60μm (e/μ modes only)

$\tau^{+} \to X\bar{\nu}_\tau$ (100%) m=1776 MeV, $c\tau$=87μm

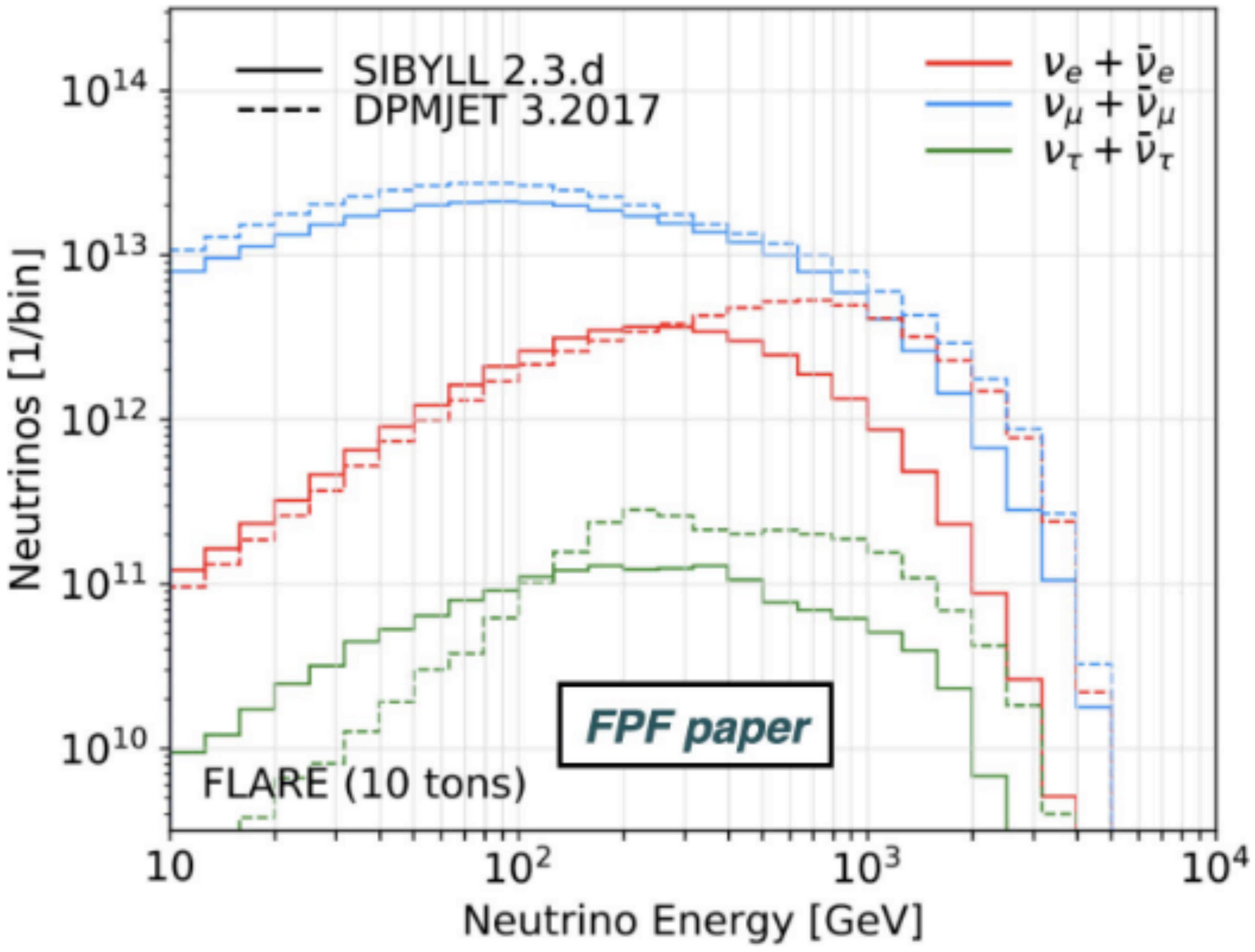
Electron neutrino flux above 300 GeV is charm dominated.

Needs modeling of forward production in the PP interaction

Neutrino event rates (with large uncertainties)

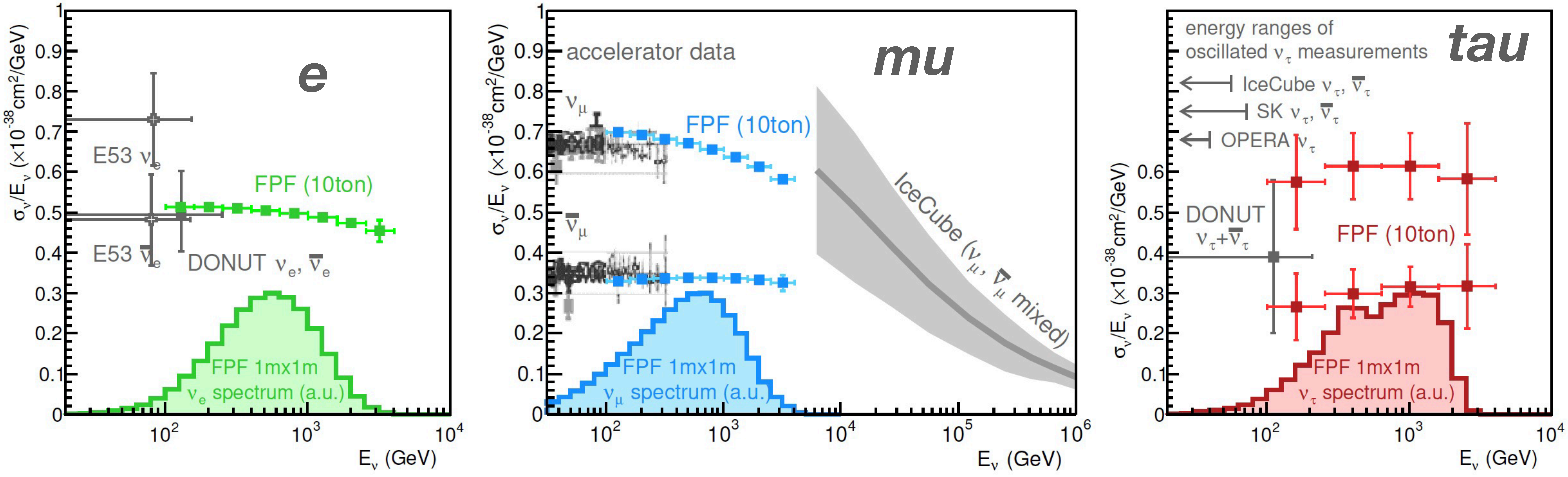
evts/ ton/fb-1	ν	$\bar{\nu}$	Total
e	2.1	1.0	3.1
mu	15	5	20
tau	0.1	0.05	0.15

During HL-LHC fb⁻¹ is approximately per day.



Mean energy of interactions is ~500 GeV

Neutrino physics



- The current data from accelerators ends around 300 GeV. FPF would provide data that fills in the gap between accelerators and atmospheric neutrinos.
- There are three proposed detectors at 10 ton each: FASERnu2 (emulsion), SND(TBD), and FLARE.
- Total rate will be ~100k electron neutrinos, ~1M muon, and ~few thousand tau neutrino events.

Tau neutrino calculations

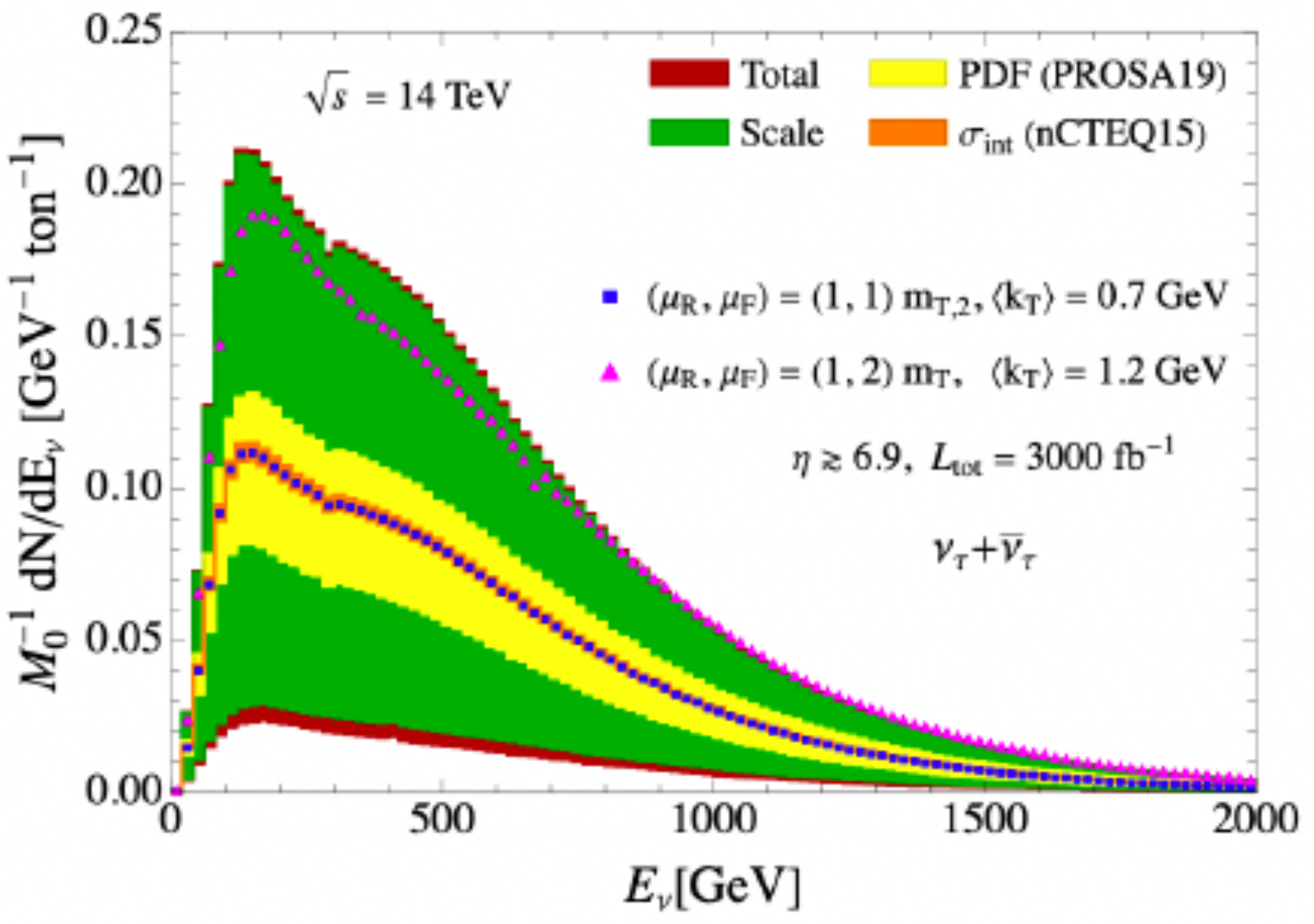
Parton distribution function uncertainties in theoretical predictions for far-forward tau neutrinos at the Large Hadron Collider,
Weidong Bai, Milind Diwan, Maria Vittoria Garzelli, Yu Seon Jeong, Karan Kumar, Mary Hall Reno,

https://arxiv.org/abs/2112.11605

$\mathcal{L} = 3000$ fb^{-1}, 1 m	ν_τ	$\bar{\nu}_\tau$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_\tau + \bar{\nu}_\tau$		
$(\mu_R,\ \mu_F)$, $\langle k_T \rangle$	(1, 1) $m_{T,2}$, 0.7 GeV					
				scale (u/l)	PDF (u/l)	σ_{int}
$\eta \gtrsim 6.9$	3260	1515	4775^{+4307}_{-3763}	+4205/-3494	+926/-1391	±112
$(\mu_R,\ \mu_F)$, $\langle k_T \rangle$	(1, 2) m_T, 1.2 GeV			(1, 1) $m_{T,2}$, 0.7 GeV		
PDF	PROSA FFNS			NNPDF3.1	CT14	ABMP16
$\eta \gtrsim 6.9$	5877	2739	8616	4545	7304	5735

normalized for ~60 ton of tungsten

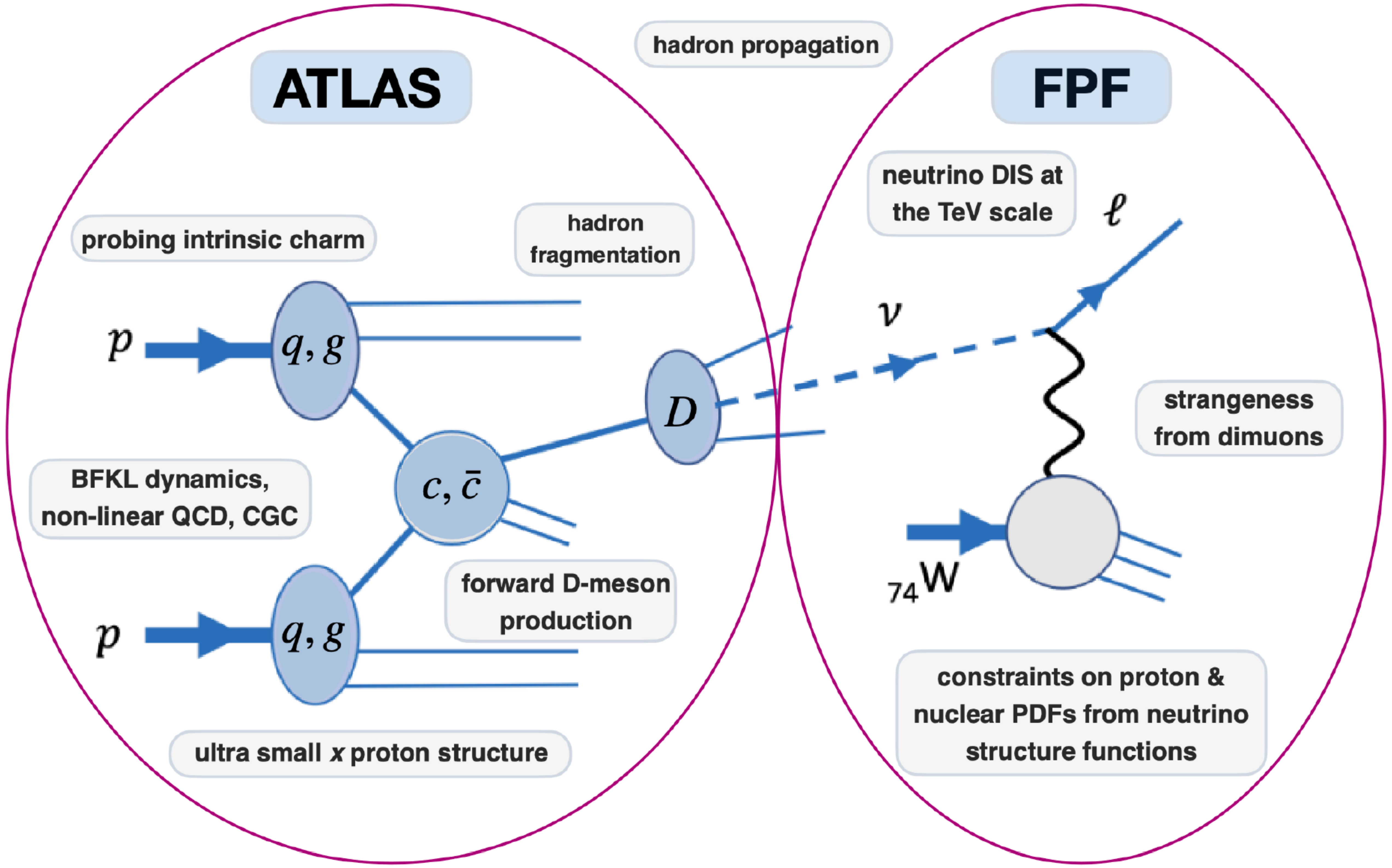
Events per GeV per ton

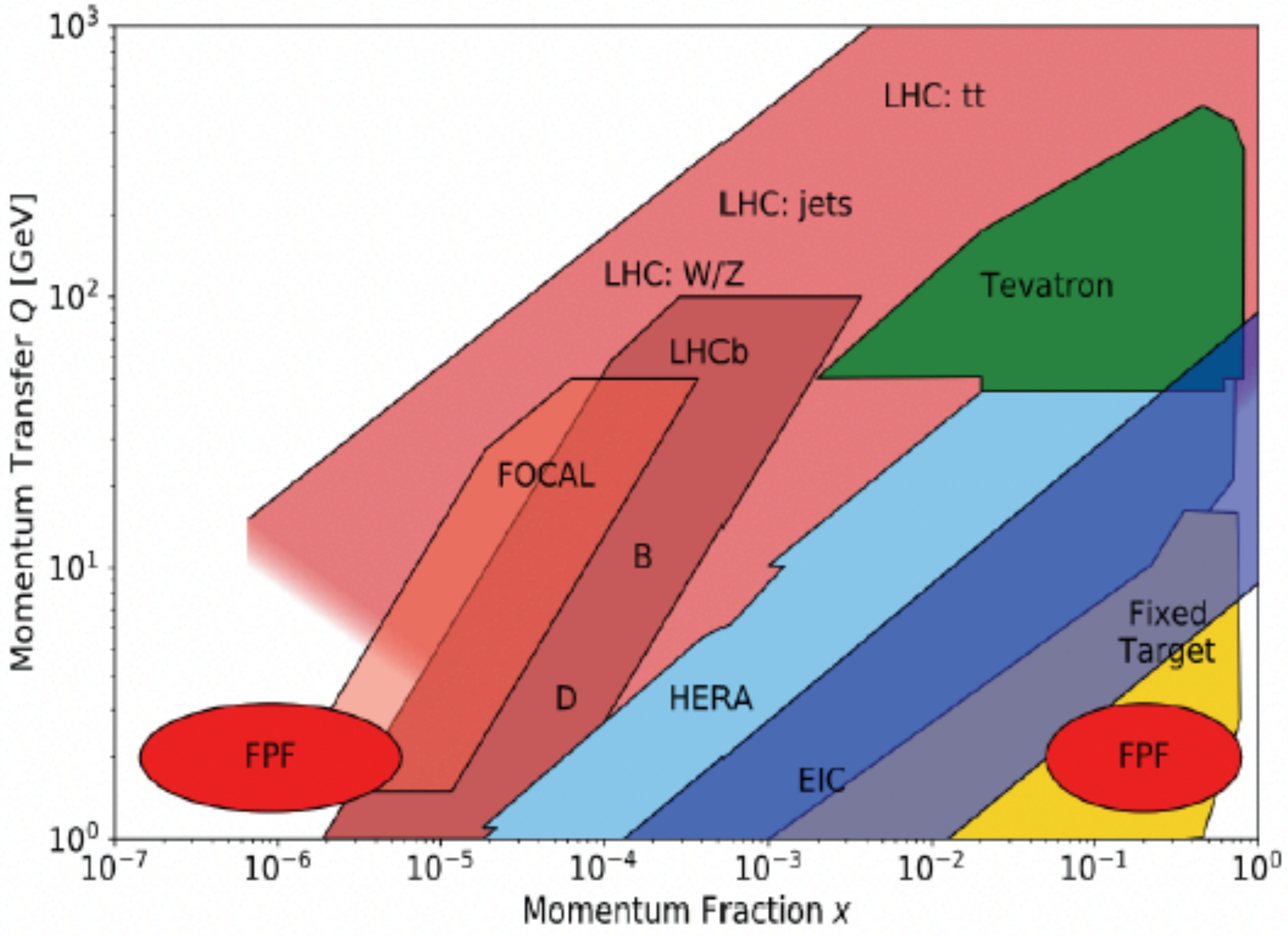


- Largest uncertainties are from scale variation.
- Measuring this rate could be important for forward charm production.

QCD interest

Neutrino interactions neutrino-ion collisions at $\sqrt{s} \approx 50 GeV$



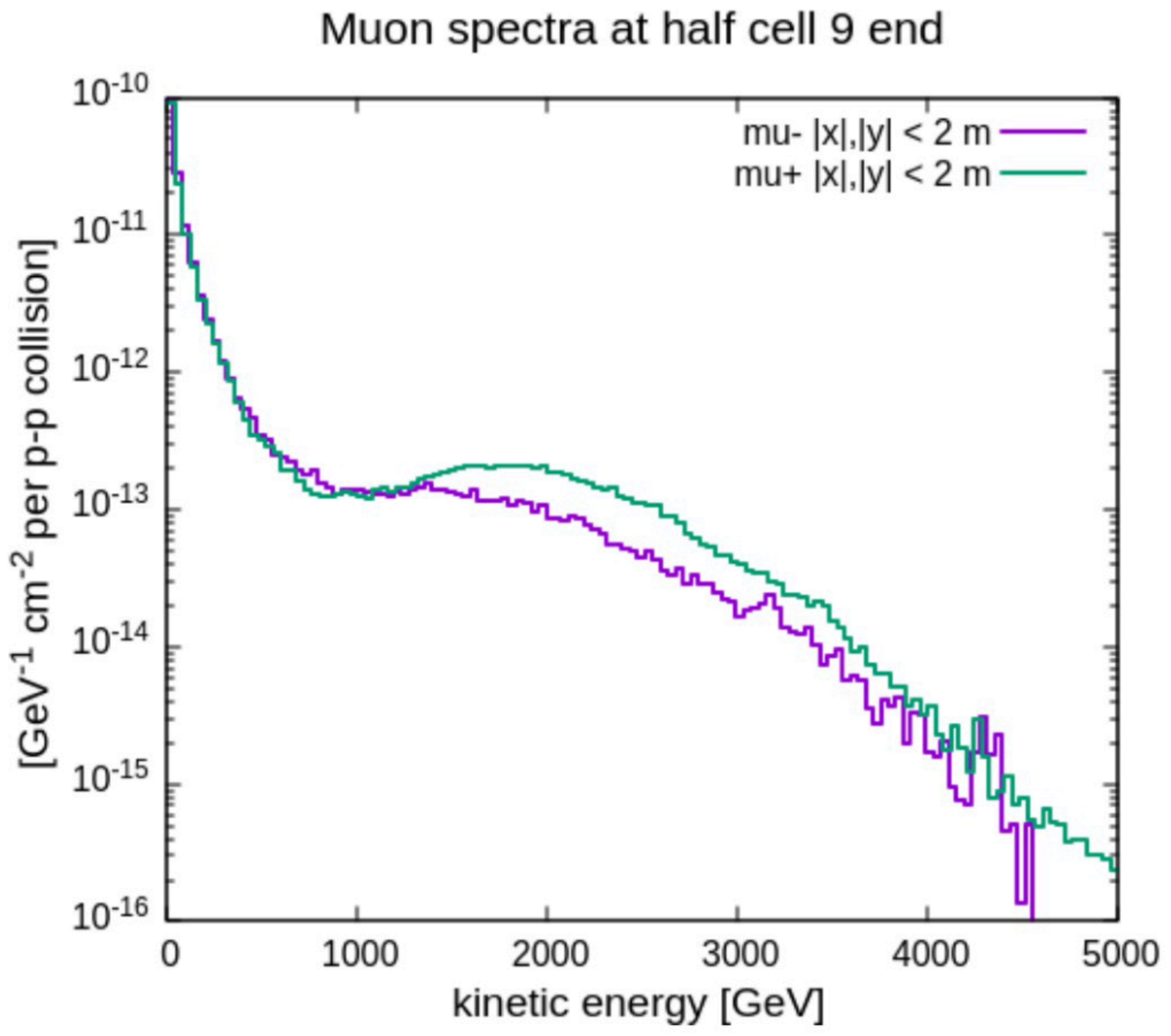


- ***Forward hadron production, instrinsic charm (large-x), ultra-small x proton structure***
- ***Extremely well motivated by the astrophysics UHE cosmic rays.***

Experimental conditions (without sweeping magnet)

Approximate fluxes, rates of backgrounds

348.5 m
from IP1



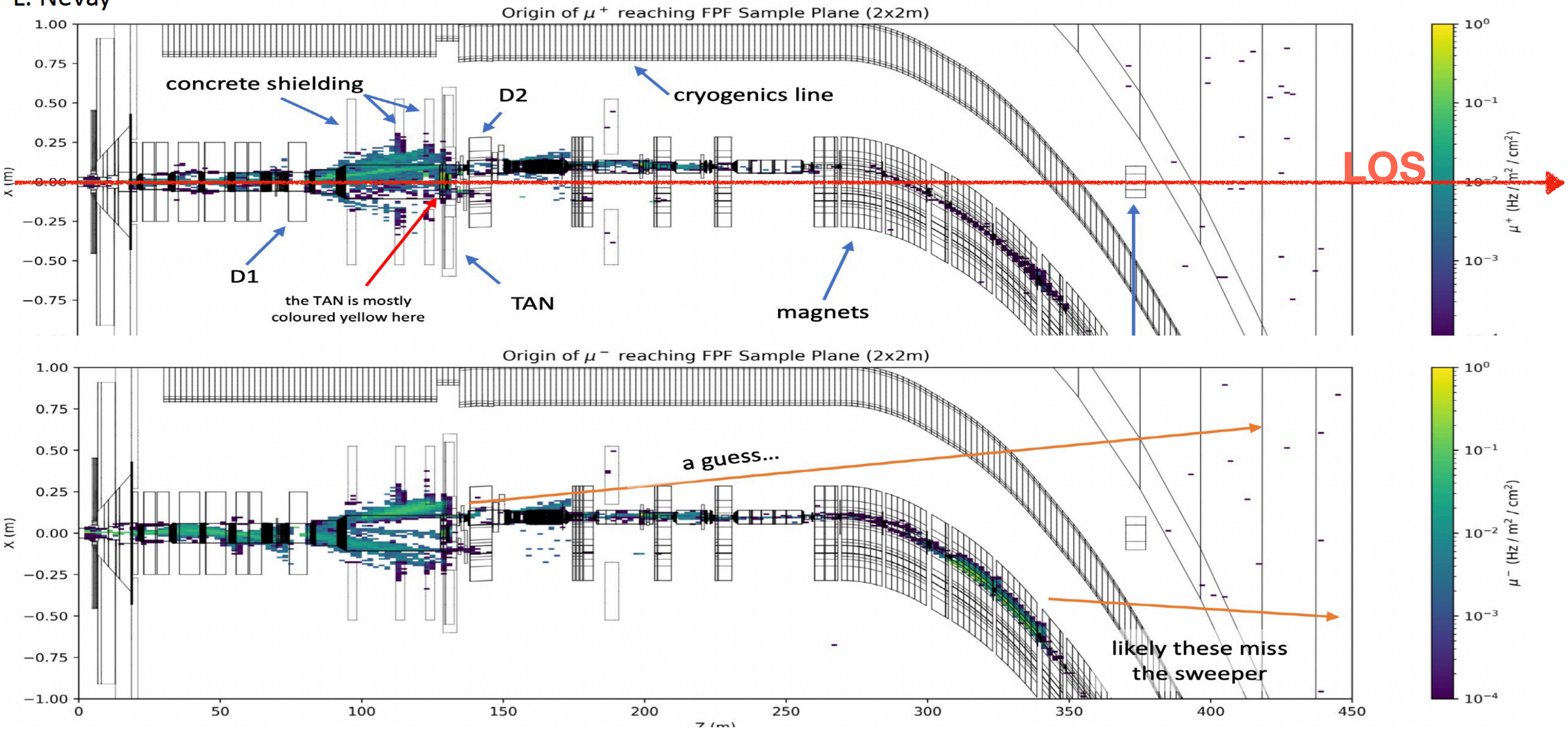
- **Rate inside 50 cm circle (mu+ 2.7Hz/cm2, mu- 7.4 Hz/cm2. This rate will be lower at 612 m.**
- **Rate is much higher than FASERnu pilot data. A sweeping magnet is required.**
- **Both charged and neutral hadron interactions present significant background.**
- **Total neutrino interaction rate normalized to per ton per fb^{-1}**
- **Observed nu rate from pilot run: ~45/ton/fb^{-1} at 480 m**

Minimum distance	612 m
Total Lumi/max lumi	3000/fb ; $5x10^{34}$ /cm2/sec
Lumi per day	~1 /fb assuming 10 year running
pseudorapidity coverage	>6.4, (~5.4-6.0 for off-axis)
track density (from pilot data)	1.7x $10^4/cm^2/fb^{-1}$
max track density per sec (per crossing)	~3/cm^2/sec ($6x10^{-8}$/cm2/crossing)
Tracks in detector/1 ms	~30/m^2/1msec
Neutral hadron flux > 10 GeV (10^{-4} of muons)	~few /cm^2/fb^{-1}
Total neutrino rate (all flavors)	~25-50/ton/fb^{-1}

updated with new information on HL-LHC configuration 2105.06197

New HL-LHC geometry BDSIM simulation. Where to place a sweeper magnet ?
Any Placement requires movement of cryogenic lines and other services. But so far possible.

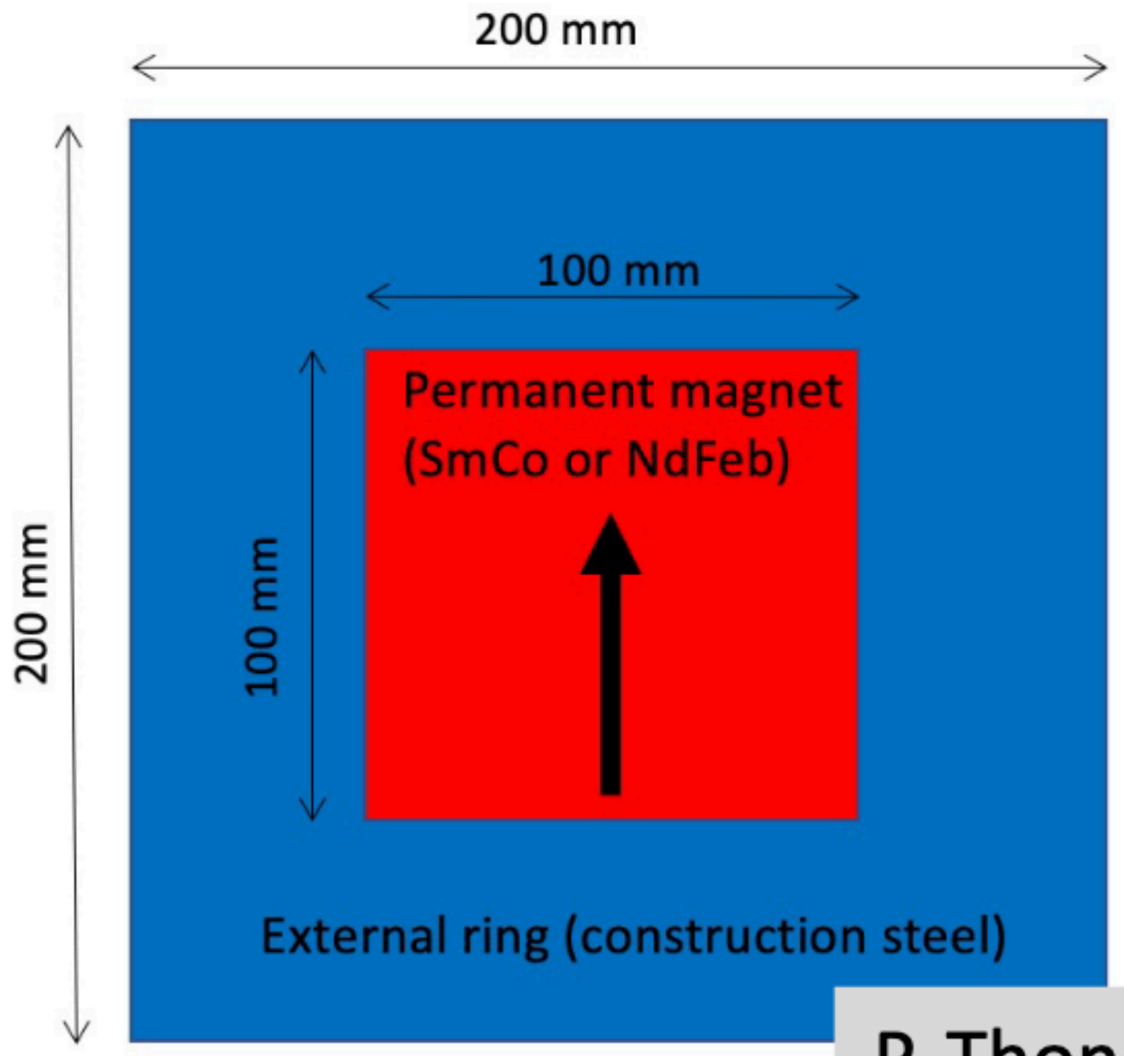
L. Nevay



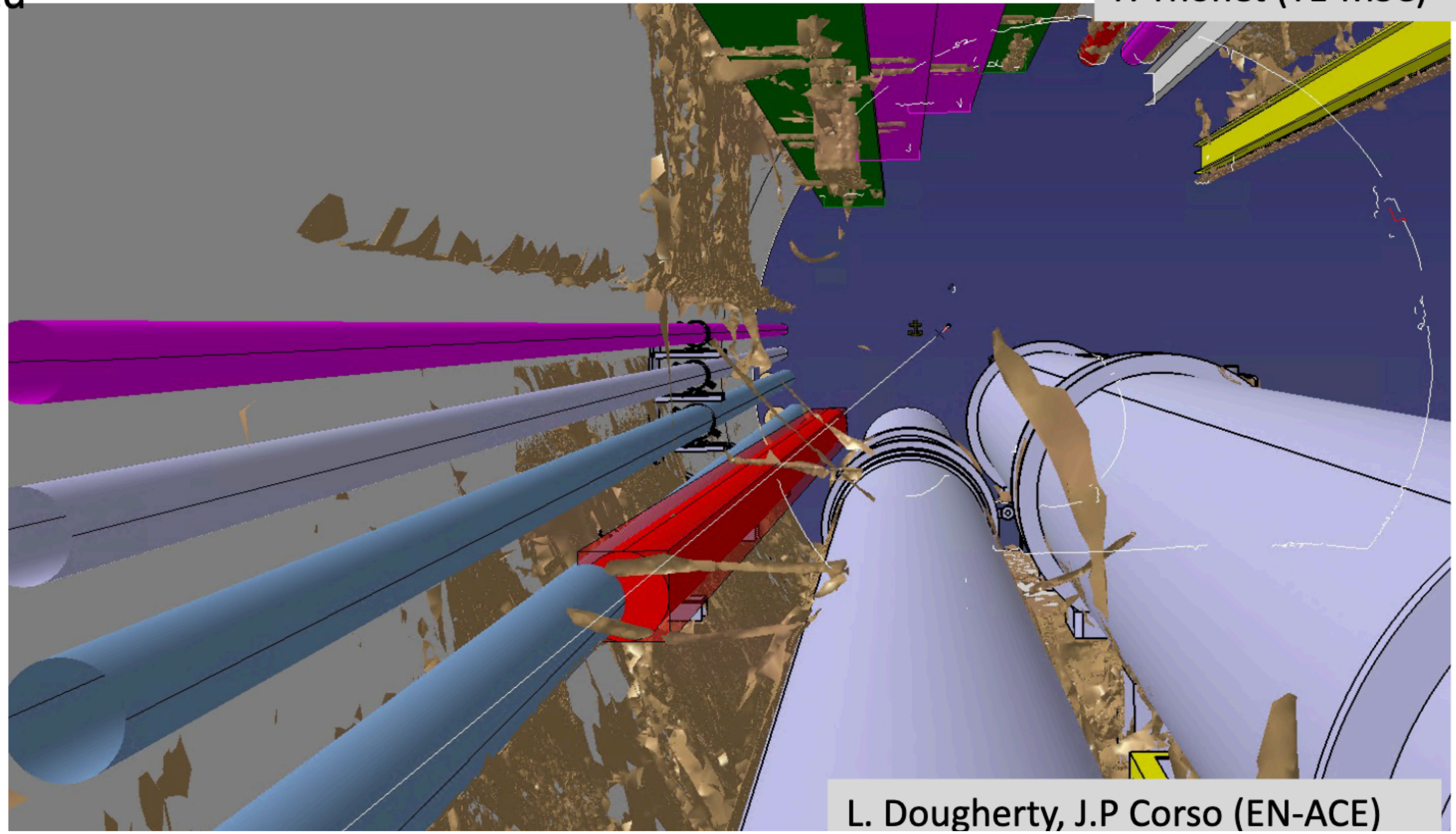
The MU+ and MU- have very different spatial distributions. And the rate is actually higher away from the LOS. We have to assume that this will be solved with ultimate rate of << 1 Hz/cm2 at the FPF. it will need more people !

Sweeper Magnet: Ongoing Studies

- Preliminary design of sweeper magnet by TE-MSC
  - Based on permanent magnet to avoid power converter in radiation area
  - Consider 7m long (20x20cm^2 in transverse plane) magnet, 7Tm bending power
- To install such a magnet would require some modifications to cryogenic lines in relevant area
  - Possibility of modifications to be investigated with LHC cryo
  - Integration/installation aspects to be studied
- FLUKA and BDSIM studies ongoing to assess effectiveness of such a magnet in reducing the muon background in the FPF

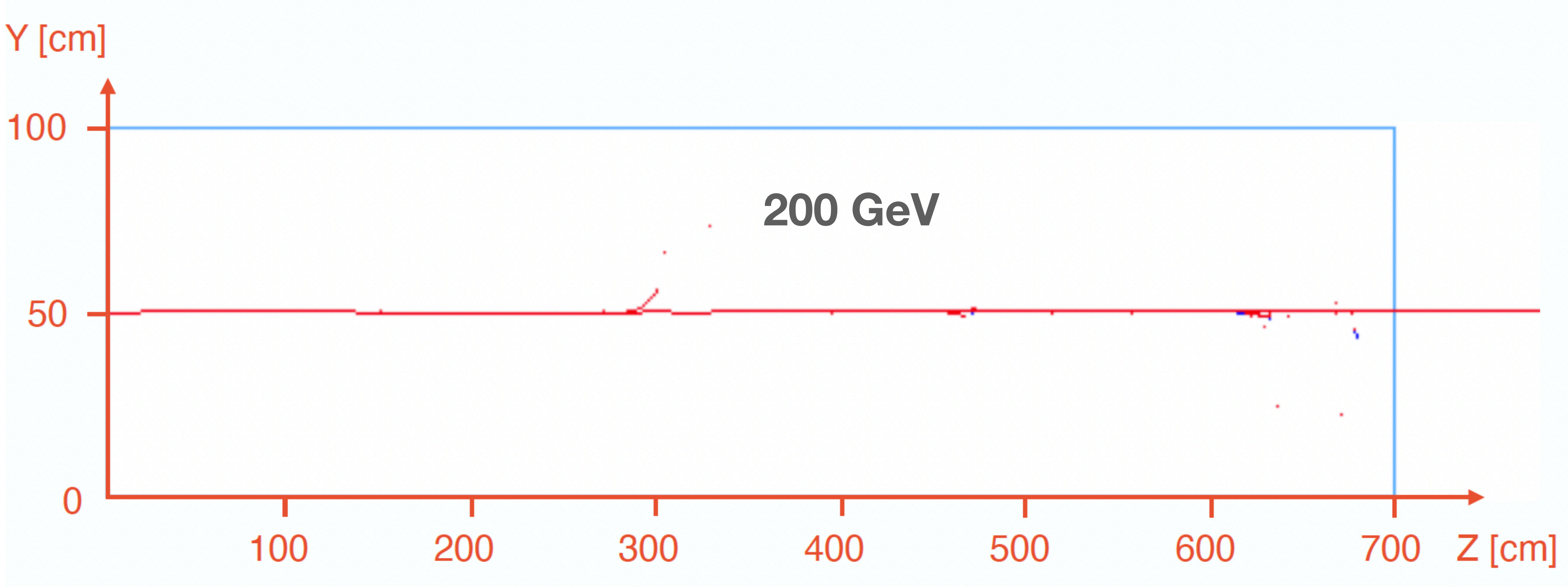


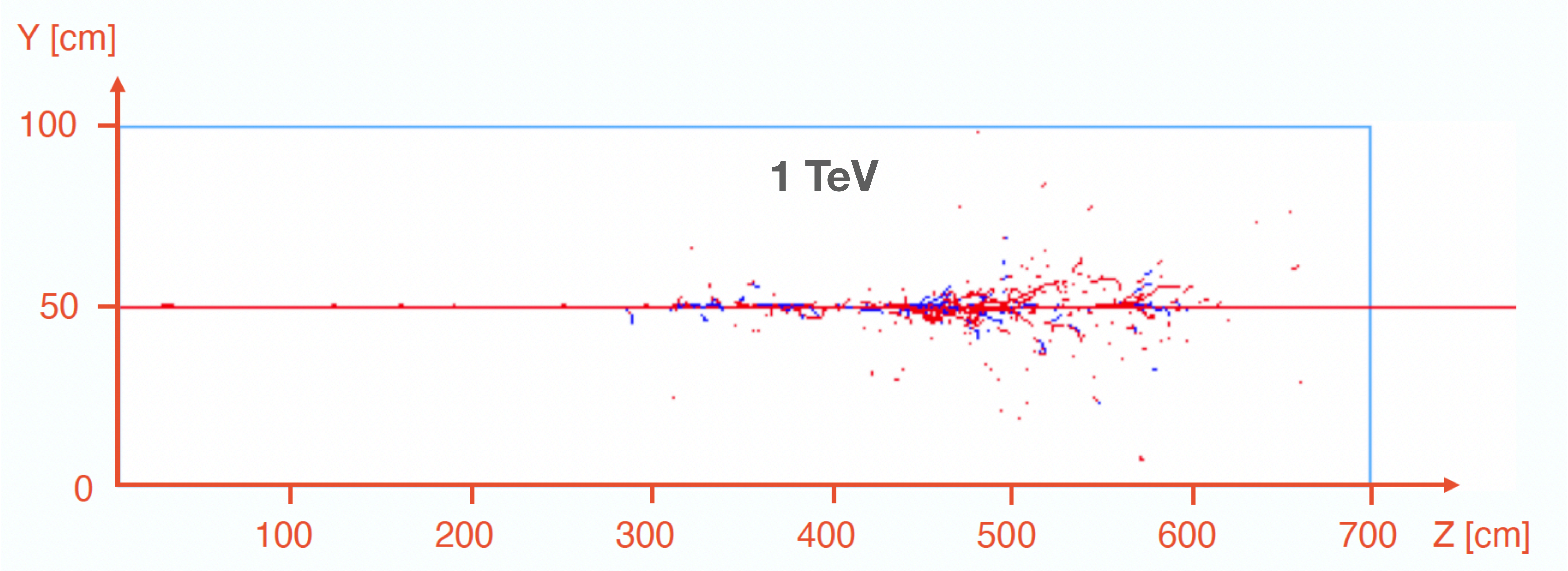
P. Thonet (TE-MSC)



L. Dougherty, J.P Corso (EN-ACE)

Muon simulation in liquid argon.





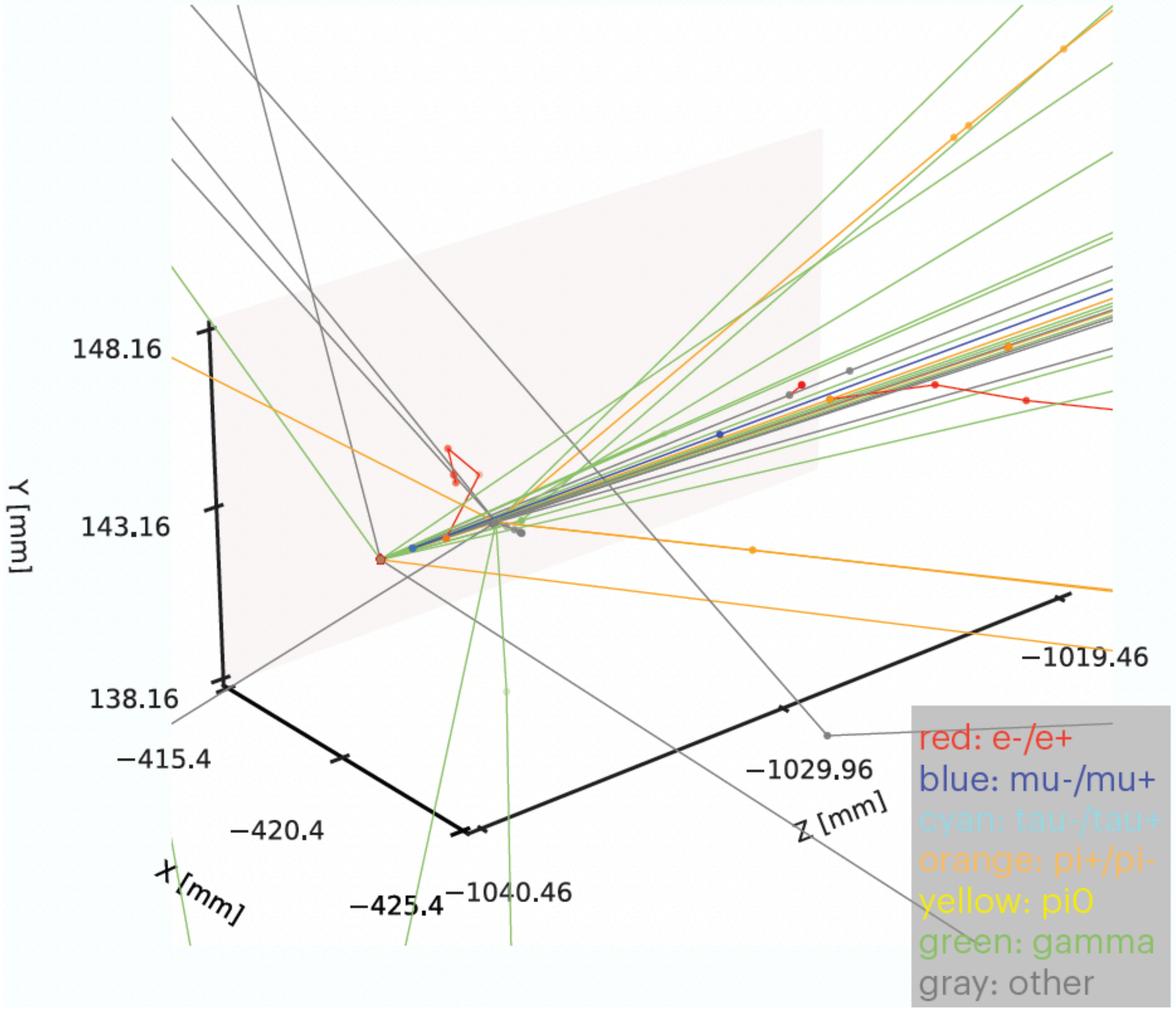
- *Muon flux above 1 Hz/cm2 presents a difficult problem for all detectors.*
- *For Liquid argon TPC, the flux also presents a space charge problem for large gaps.*
- *Showering muons will also present a trigger problem since if the incoming muon is missed the event will look like a neutrino.*

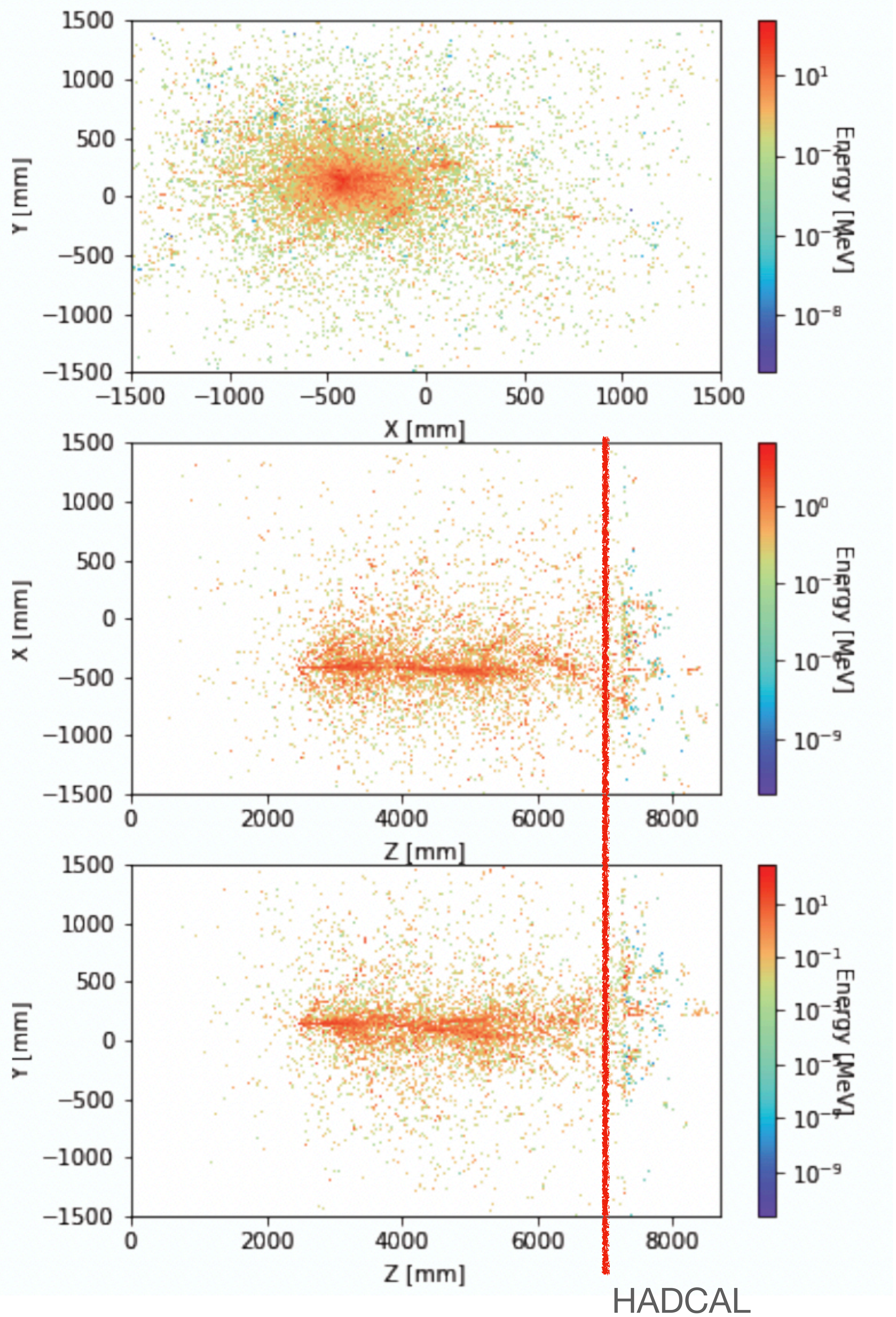
Wenjie Wu (UCI)

Tau Neutrino event simulation in a LAR TPC

ν_τ CC (E_ν = 230.7 GeV)

$\tau^-(102.9\ \text{GeV}) \rightarrow \nu_\tau + \bar{\nu}_\mu + \mu^-(74.7\ \text{GeV})$





First conclusions from simulations:

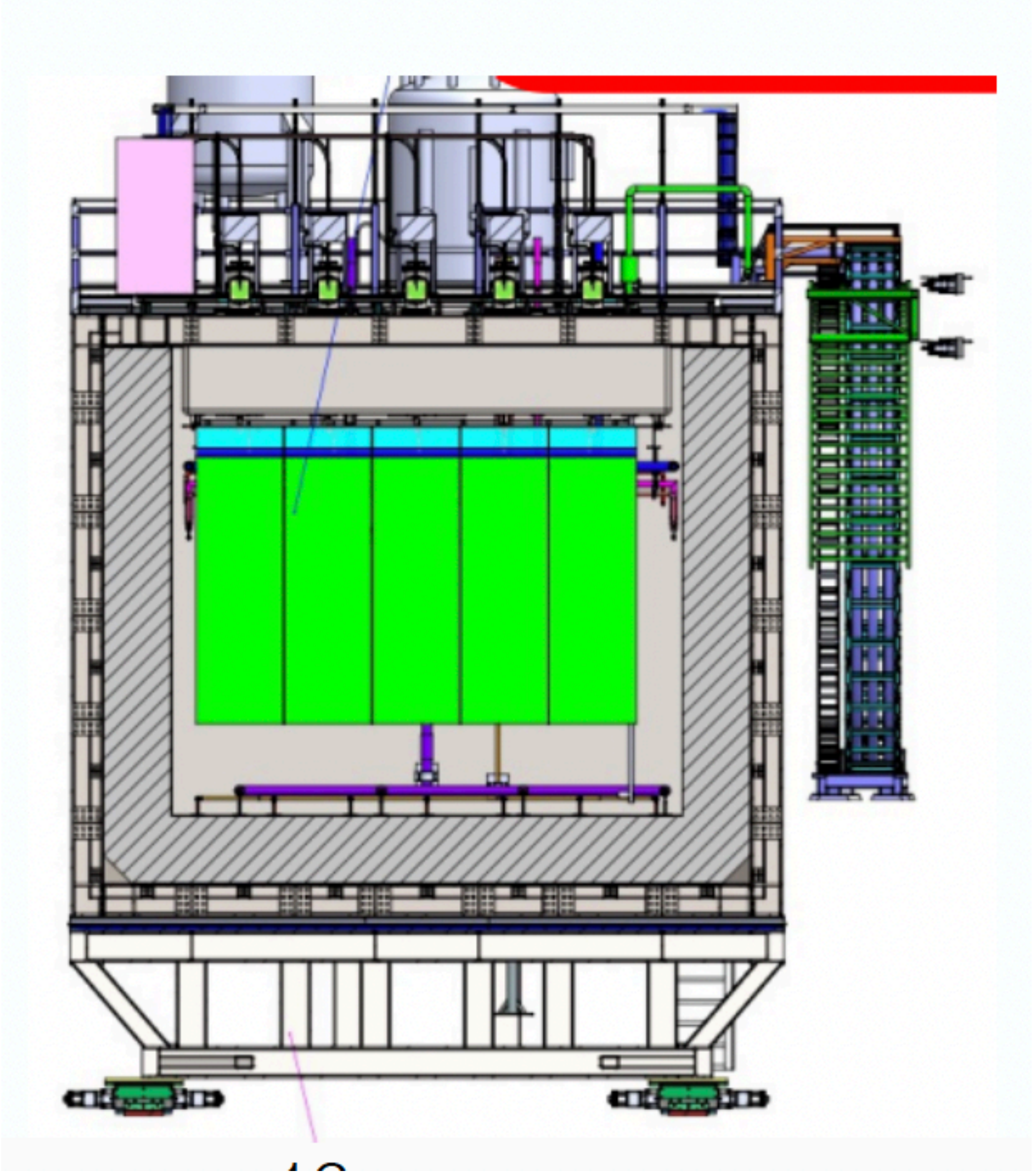
1) Need 1.8 X 1.8 to contain transverse events in fiducial of 1 m x 1 m x 7 m.
2) Need Hadronic calorimeter to contain showers that start downstream.
3) Even a modest resolution is sufficient.
4) excellent muon identification could result in quick selection of nut events.
5) Studies: can we combine spatial resolution in drift dimension with kinematics to get good S/N ?

Basic detector requirements for FLARE

Item	Choice	Comments
Liquid fill	LAr or LKr or LAr/LXe mix	LKr allows compact events and EM showers, but radioactivity may limit utility.
Cryostat and TPC dimensions	Keep the total to active volume ratio small. Need to fit into FPF space.	Cryostat, field cage, HV design must be integrated.
Cathode/anode and gap size	Central cathode with two anode planes. (makes two drift volumes). Gap < 0.5 m	more channels, better for HV safety and space charge. cathode must be transparent to light
Photon readout	SiPM's. Cannot use PMTs to keep the unused volume small.	Will need large number of channels.
Wavelength shifter for scintillation light	LAr: 128 nm, LKr: 150 nm, LXe: 170nm	DUNE development of ARAPUCA.
SiPM density, timing resolution and trigger	This requires detailed simulations and R&D. **A minimum density is needed for recognizing contained events versus muons for trigger.** Timing resolution is needed to associate with LHC bunch.	
Anode electrode design	Pixels versus wires	Simple wire geometry may not be possible because of straight thru muons. Need Simulation input.
Anode readout pitch	2 to 5 mm	Depends on kinematic resolution needed and also signal to noise.
Electronics	Cold electronics for low noise; how do we optimize for best drift resolution	Need < 1 mm resolution in drift dimension

Cryostat options

Very important for space considerations.



	Cryostat Inner Dimensions	Insulation Type	Insulation Thickness	Insulation density	Heat leak	Cold shield
MicroBooNE	3.8m dia x 12 m	Polyurethane Foam	**400mm**	32 kg/m³	**~13 W/m²**	No
ICARUS-GS	3.9m x 3.6m x 19.6m	Nomex honeycomb+perforated Al	**665 mm+ (combined)**	25-35 kg/m³	**7-22 W/m²**	Yes
ICARUS-SBN	3.9m x 3.6m x 19.6m	Al extrusion+GTT foam	**665 mm+ (combined)**	25-35 kg/m³	**10-15 W/m²**	Yes
ProtoDUNE	7.9m x 8.55m x 8.55 m	GTT membranc	**800mm**	90 kg/m³	**~8 W/m²**	No
ND-LAr	3m x 5m x7m	GTT membrance	800mm	90 kg/m³	**~8 W/m²**	No
FLArE	~(1m x 1m x 7m)					No?

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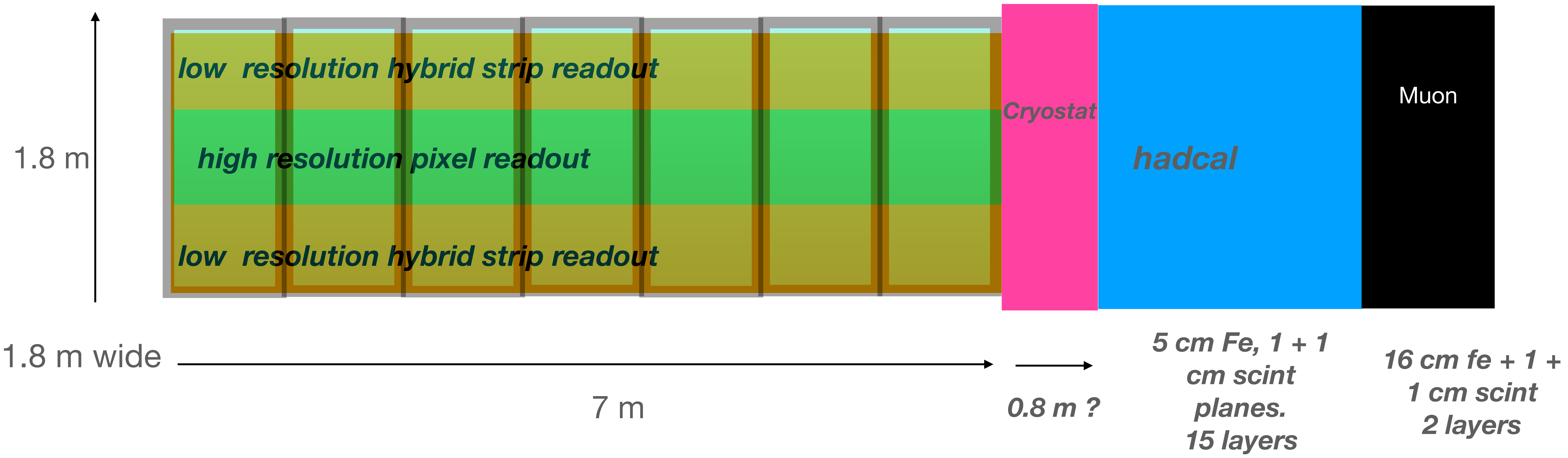
- *Space in FPF hall currently is limited to 3.5 m X 3.5 m X 9.6 m for FLARE.*
- *80 cm GTT membrane occupies 1.6 m out of 3.5 m. More space might be needed for corrugations.*
- *But despite the installation for th GTT membrane would be much easier.*
- *The DUNE ND-LAR design has installation from top. This would also simplify things.*
- *Further engineering might be needed, but we can settle on this option for now.*

Simulations have confirmed that these dimensions allow reasonable containment of neutrino events in LAr and total energy measurement.

They also fit within the cryostat allowed transverse space.



Carry two options into Conceptual Design

either 2 X 7 vertical modules with 0.45 m gap
or 3 x 7 vertical modules or with 0.3 m gap

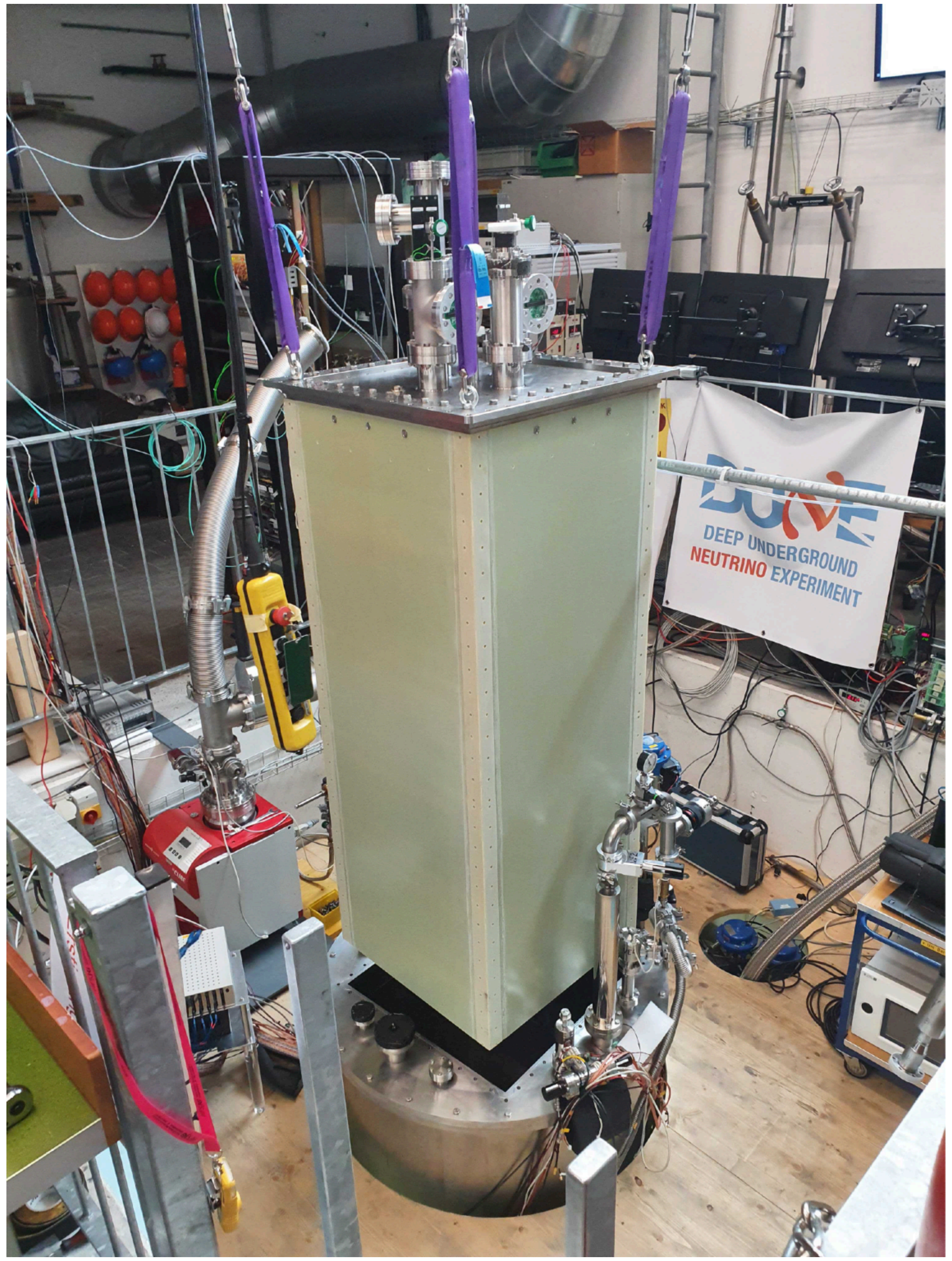
None of this is optimized

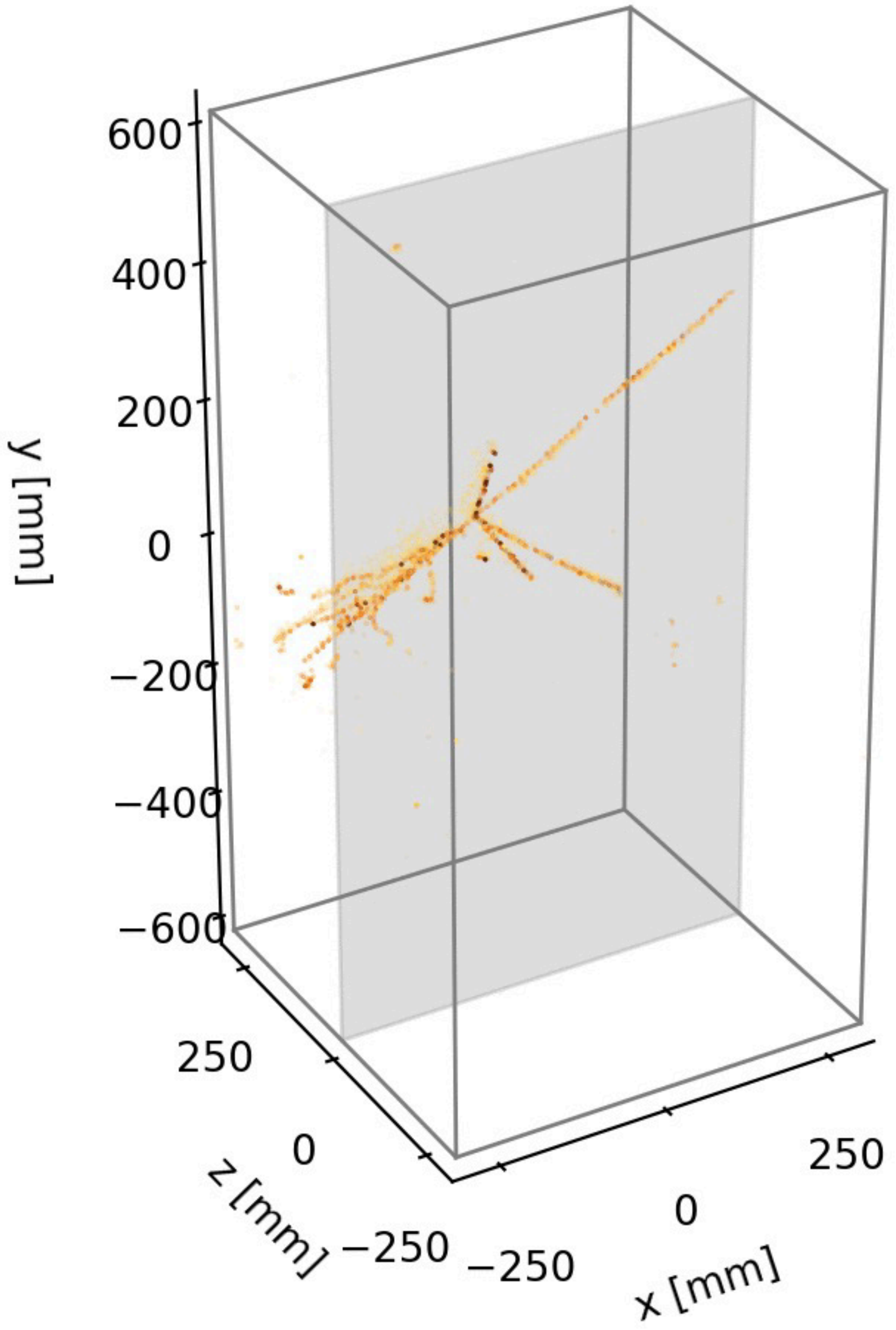
Nominal configuration

To be detailed in a spread sheet and developed into a detail for a conceptual design parameters.

Cryostat outer	**3.5 m X 3.5 m X 9.6 m**	**Membrane**
Insulation thickness	0.8 m	including corrugations
Detector dimension	1.8 m X 1.8m x 7 m	good for >90 % containment
Fiducial volume	1 m x 1m x 7 m (10 tons)	Length may be adjusted later
TPC Modules	2 X 7 or 3 X 7	Keep two options
Module opt1 dimensions	0.9 m (W) X 1.8 m (H) X 1 m (L)	Central cathode: gap: 0.45 m
Module opt2 dimensions	0.6 m (W) X 1.8 m (H) X 1 m (L)	gap: 0.3 m
Anode design fiducial region	5 mm x 5 mm for 1 m x 1 m	80000 chan/mod
Anode design containment region	10 mm x 10 mm for 0.8 m x 1 m	16000 chan/mod
photon sensor	Bare SiPM or X-ARAPUCA	~50 chan/mod
Downstream cryo wall	80 cm	Can it be thinned down
HADCAL	2 m x 2 m x (5 cm Fe + 1+1 cm scint, 15 layers) x (1.05 m)	Optimize for resolution
Murange	•2 m x 2 m x (16 cm Fe + 1 + 1 cm scint, 2 layers) x (0.36 m)	Increase to 1 m to get clean muID

Benefit from the DUNE near detector design





Conclusion

- A forward physics facility FPF is being considered at CERN for neutrino and dark matter physics.
- HL-LHC will start running in 2029. The FPF is decoupled from the LHC sufficiently that its schedule could be independent of the HL-LHC upgrades.
  - The physics interest is
    - Neutrino cross sections in the 1 TeV range: ~20-50 events/ton/day
    - Tau neutrino flux and associated heavy flavor physics: ~0.1-0.2 events/ton/day
    - Light dark matter search with decays and interactions.
- Noble liquid detector for FPF is being considered along with other technologies.
- Preliminary examination of event rates and backgrounds suggests that a LAr detector is feasible and ground-breaking.
- A LAr TPC for FPF would require much more advanced readout for ultimate spatial resolution, and a trigger system that can find contained events in the presence of muons.
- A strong US collaboration for FLArE is obviously welcome.
- Cost of the detector ? We now have a very modest project at BNL to produce a conceptual design and make an estimate. DUNE R&D investment has made this much easier.