Far forward neutrino detectors at the high luminosity LHC

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Snowmass/Seattle Community Summer Study, July 22, 2022

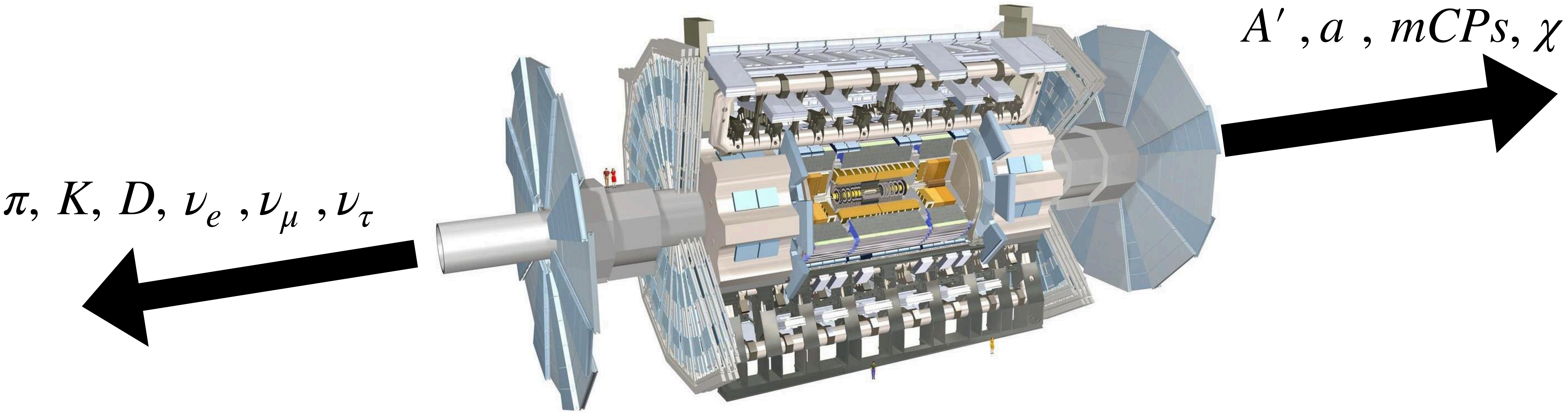
Brookhaven National Laboratory

Snowmass engagement for the forward physics facility (FPF) and organization

- Snowmass LOI from 2020
- Nov 2020 (FPF1), May 2021 (FPF2), Oct 2021 (FPF3), Jan 2022 (FPF4): 4 dedicated, interdisciplinary meetings to develop the FPF's potential. 5 physics themes: BSM, neutrinos, QCD, DM, and astroparticle physics.
- FPF Short Paper: 75 pages, 80 authors, Anchordoqui et al., 2109.10905, Phys. Rept. 968, 1 (2022).
- FPF Snowmass White Paper: 429 pages, 392 authors+endorsers, Feng, Kling, Reno, Rojo, Soldin et al., 2203.05090, J. Phys. G.
- Physics Beyond Colliders working group at CERN: PBC@CERN. There are many resources here.
- US working groups on FPF physics (Brian Battell, Sebastian Trojanowski) and FLARE Technical design (Steve Linden, Jianming Bian, MVD) group.
- There is modest funding in place with a mandate to produce a conceptual design report by early 2023.
- FPF-related talks at Snowmass

– Monday July 18: EF05-07, Hallsie Reno
– Wednesday, July 20: EF09/RF06, Jonathan Feng
– Thursday, July 21: NF02, Felix Kling
– Friday, July 22: EF/NF: Milind Diwan
– Sunday, July 24: NF04/CF07, Ina Sarcevic
– Tuesday, July 26: Small- and Mid-Scale Experiments/Facilities, Jonathan Feng
– Summary discussions, talks, panels.

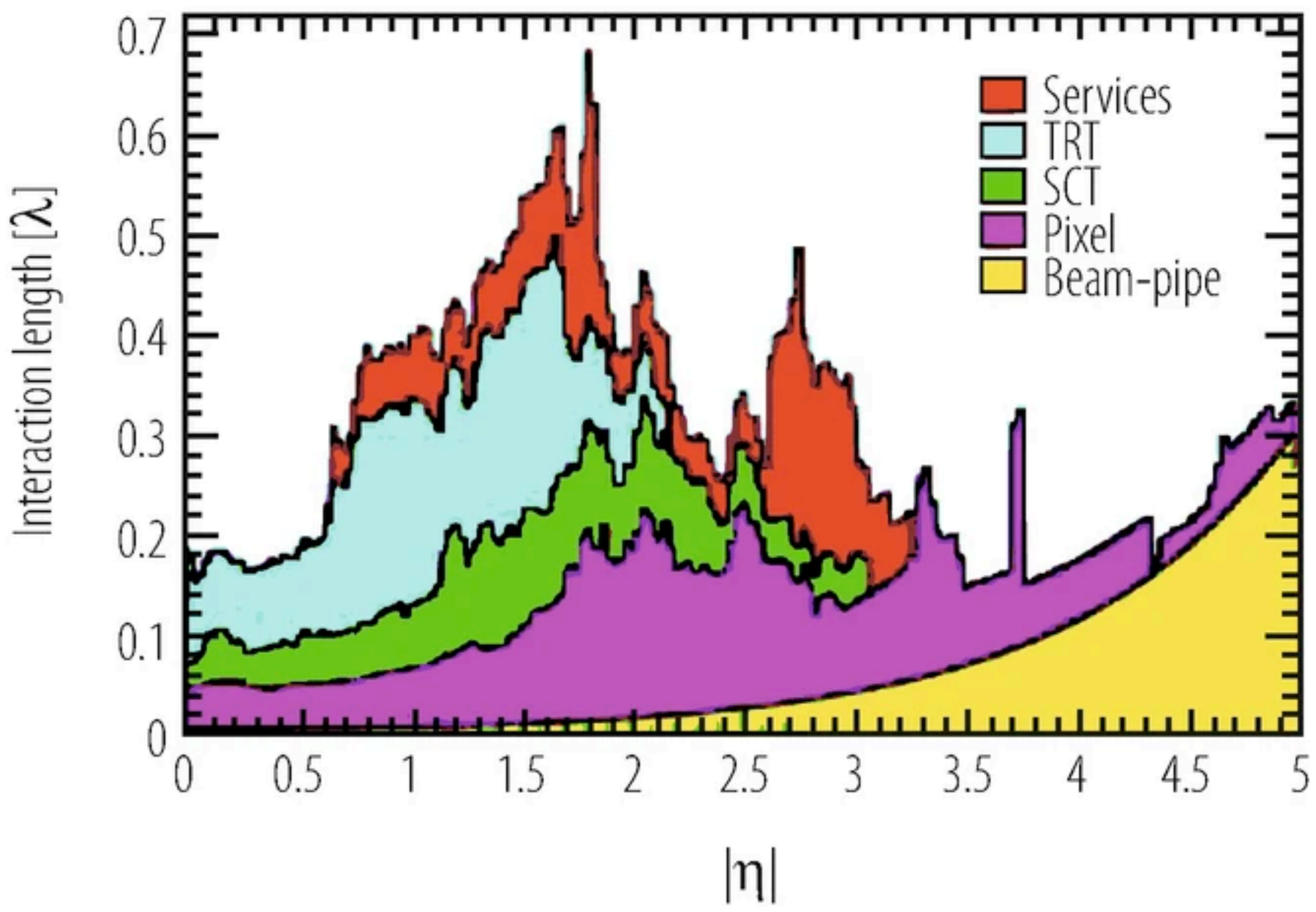
High luminosity LHC is a unique opportunity, and so what are we missing ?



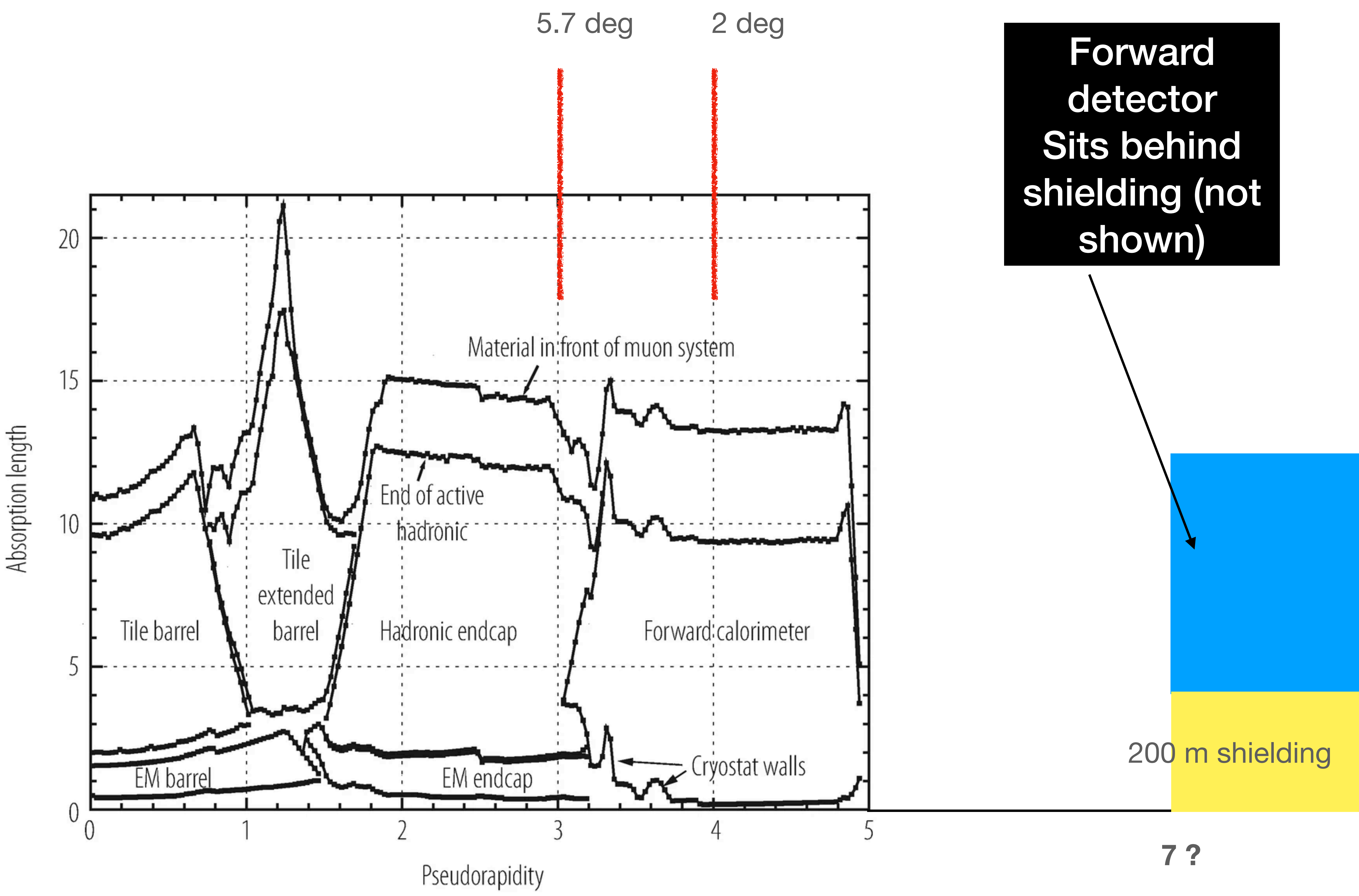
- *Most interesting physics is believed to be at high pT, and so are we missing physics in the forward direction ?*
- *The largest flux of high energy light particles, pions, kaons, D-mesons, and neutrinos of all flavors is in the forward direction.*
- *This could be true of new particles also: dark 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 (for modest sized detectors) that should not be missed with the high-luminosity LHC.*
- *A program has started at LHC: 4 experiments are FASER, FASERnu, SND, and MilliQan. Please see Jonathan Feng's talk.*

ATLAS coverage

Physics coverage $\eta \leq 3.5$

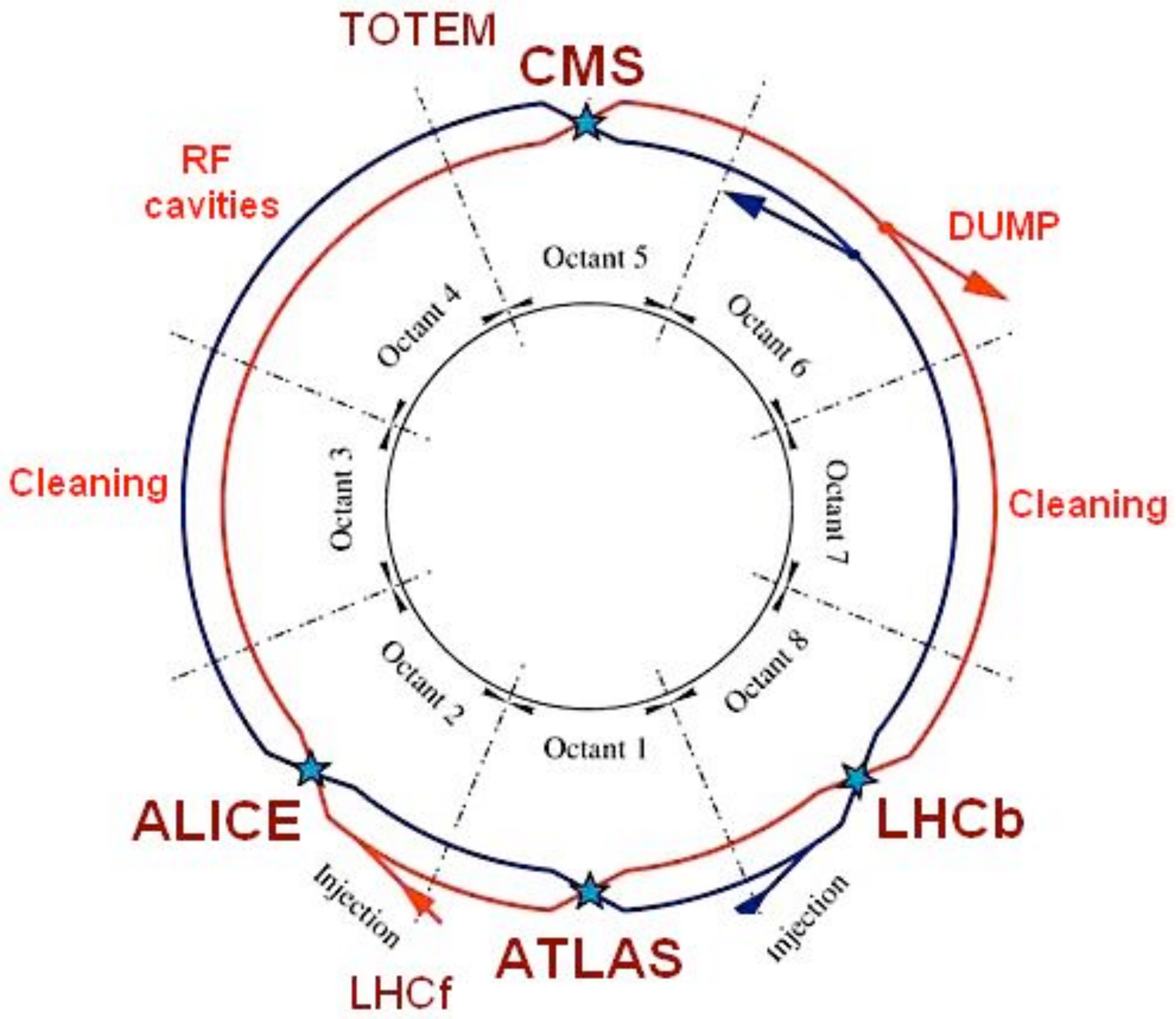


$\eta \equiv -ln[\tan(\theta/2)]$



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

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

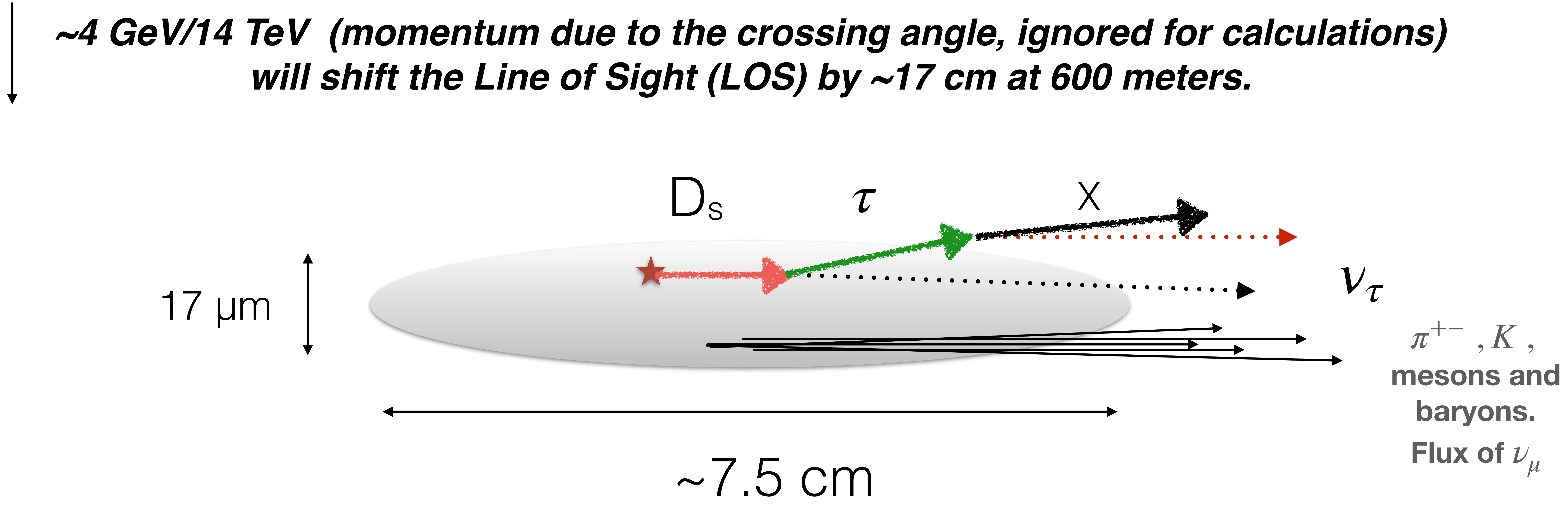


parameter	Design	Run-3	HL-LHC
Circumference	27 km (r=4243 m)		
depth	100 m		
arcs	8 arcs; each has 23 cells; cell is 106.9 m		
insertions	8 insertions: insertion is a straight section with transition regions at each end.		
energy	14 TeV	14 TeV	14 TeV
bunches	3550 (with 7.5 m/25 ns) spacing)		
effective 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}

- 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)

Production geometry

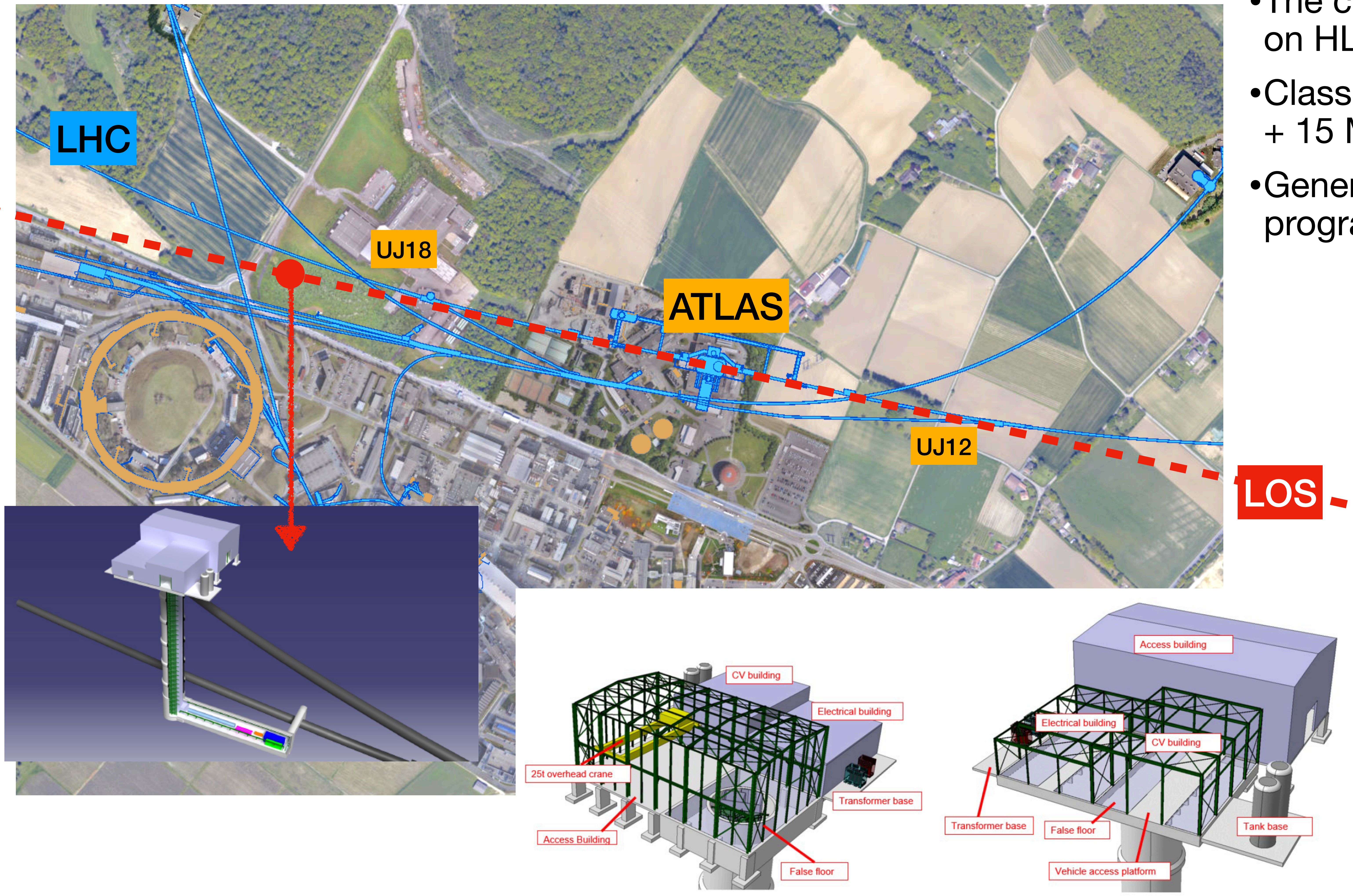
~4 GeV/14 TeV (momentum due to the crossing angle, ignored for calculations) will shift the Line of Sight (LOS) by ~17 cm at 600 meters.



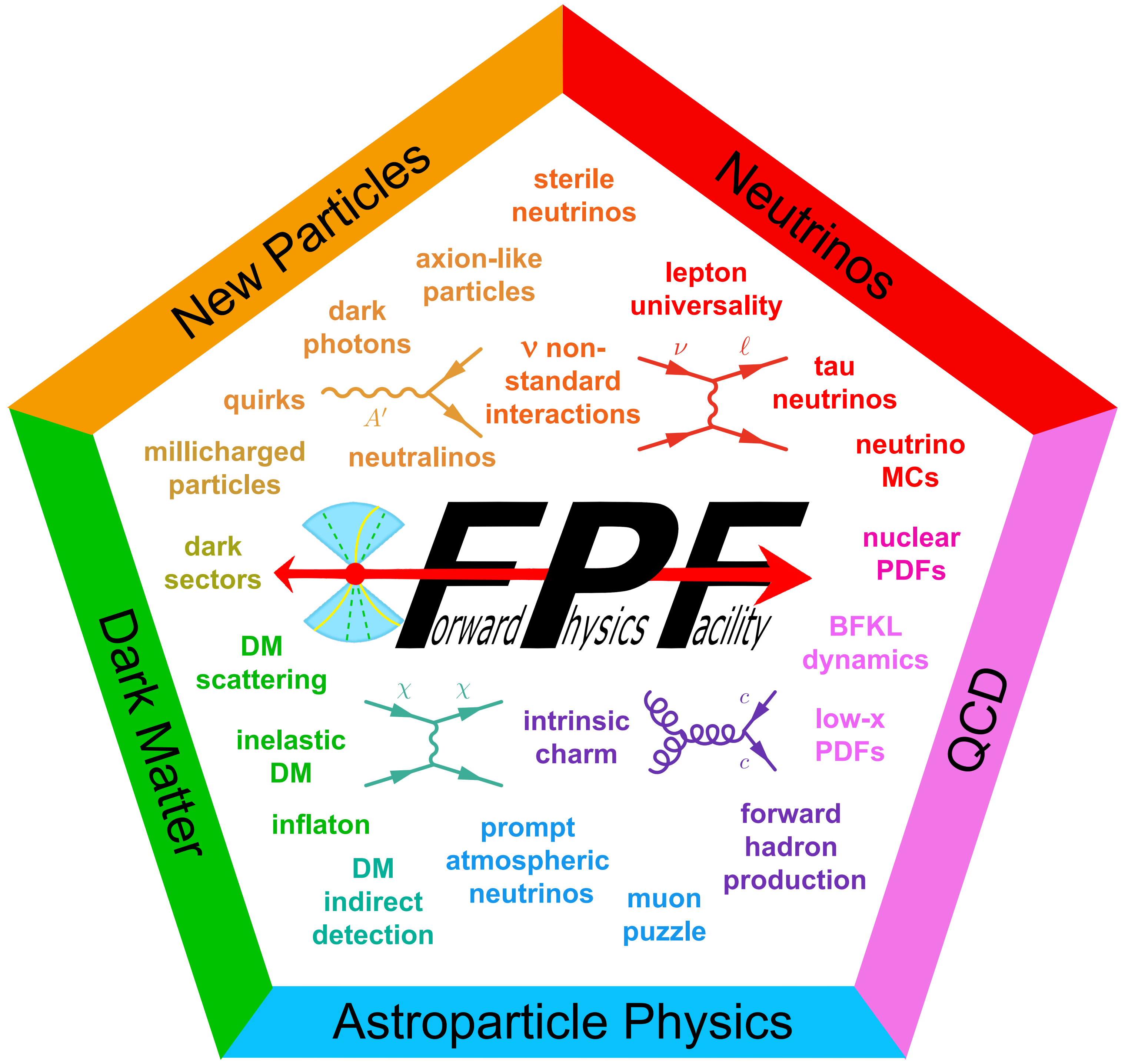
For γ~100, decay distances will be ~1.5 cm for Ds and ~0.87 cm for tau lepton $\Rightarrow$ size of the neutrino source for the LHC is ~7.5 cm. The LHC collision region is the most compact neutrino source ever made.

Forward Physics Facility (FPF)

Proposal to create forward underground space for experiments during HL-LHC. Expand the program that has started with FASER, FASERnu, SND, MilliQan.

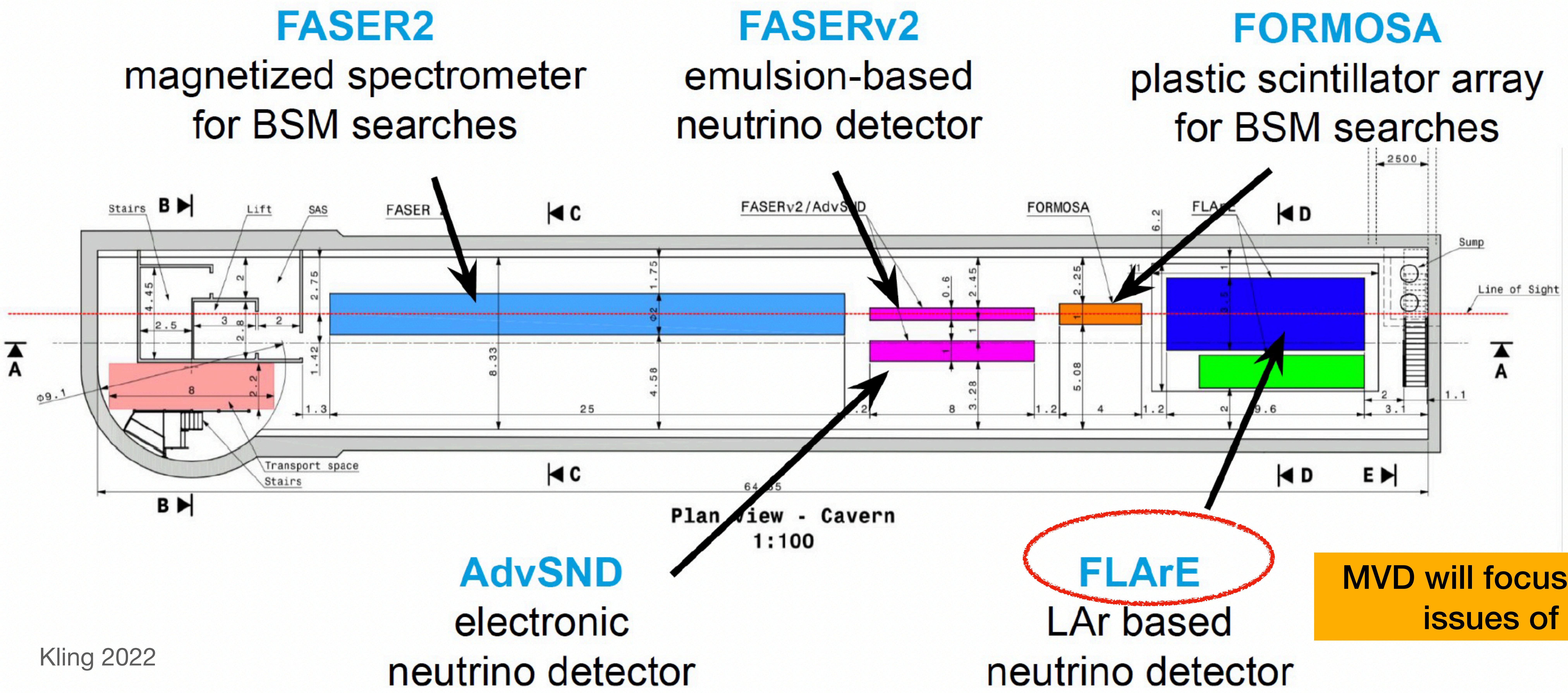


- The cavern is not connected to the LHC and no impact on HL-LHC running is foreseen.
- Class 4 cost of this has been estimated: 23 MCHF (CE) + 15 MCHF (services) +additional items = 40 MCHF
- General purpose facility with broad SM and BSM program; spans all HEP frontiers.



- At present there are 5 experiments being developed for the FPF.
- Pseudo-rapidity coverage in the FPF is $\eta > 5.5$, with most experiments on the LOS covering $\eta > 7$.

A strong experimental program is needed to make a decision on the FPF



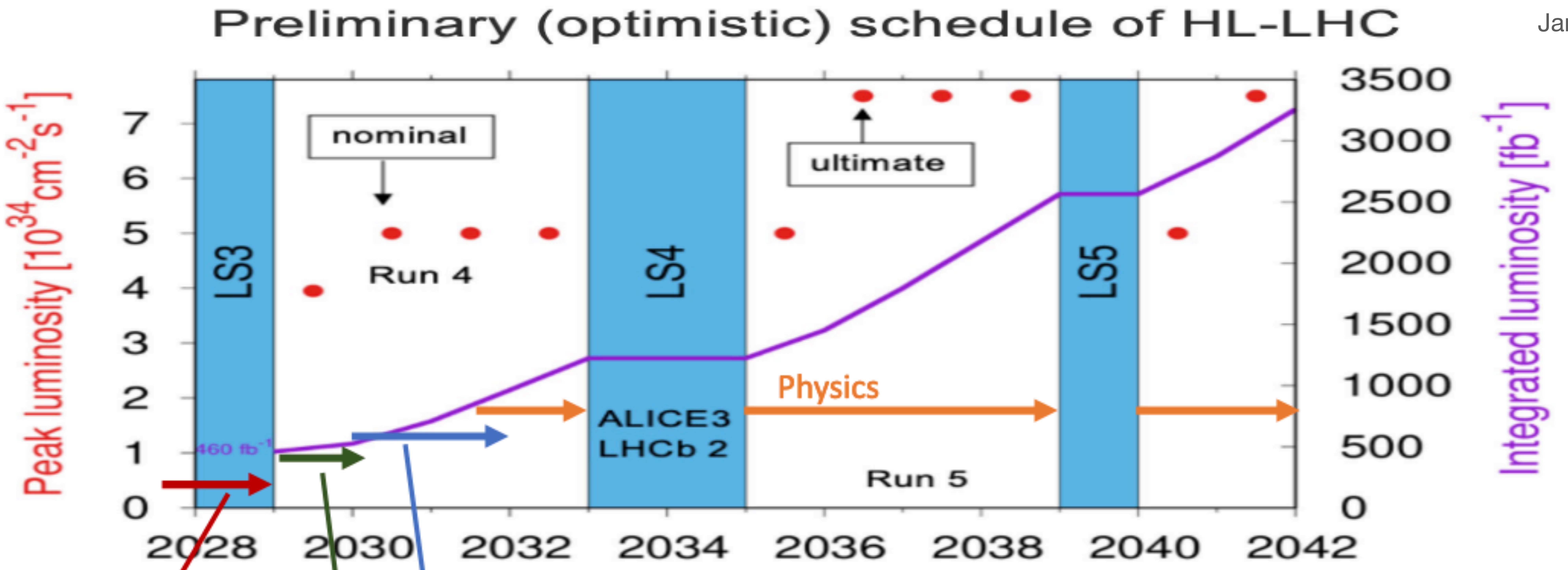
MVD will focus on technical issues of FLARE.

Kling 2022

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

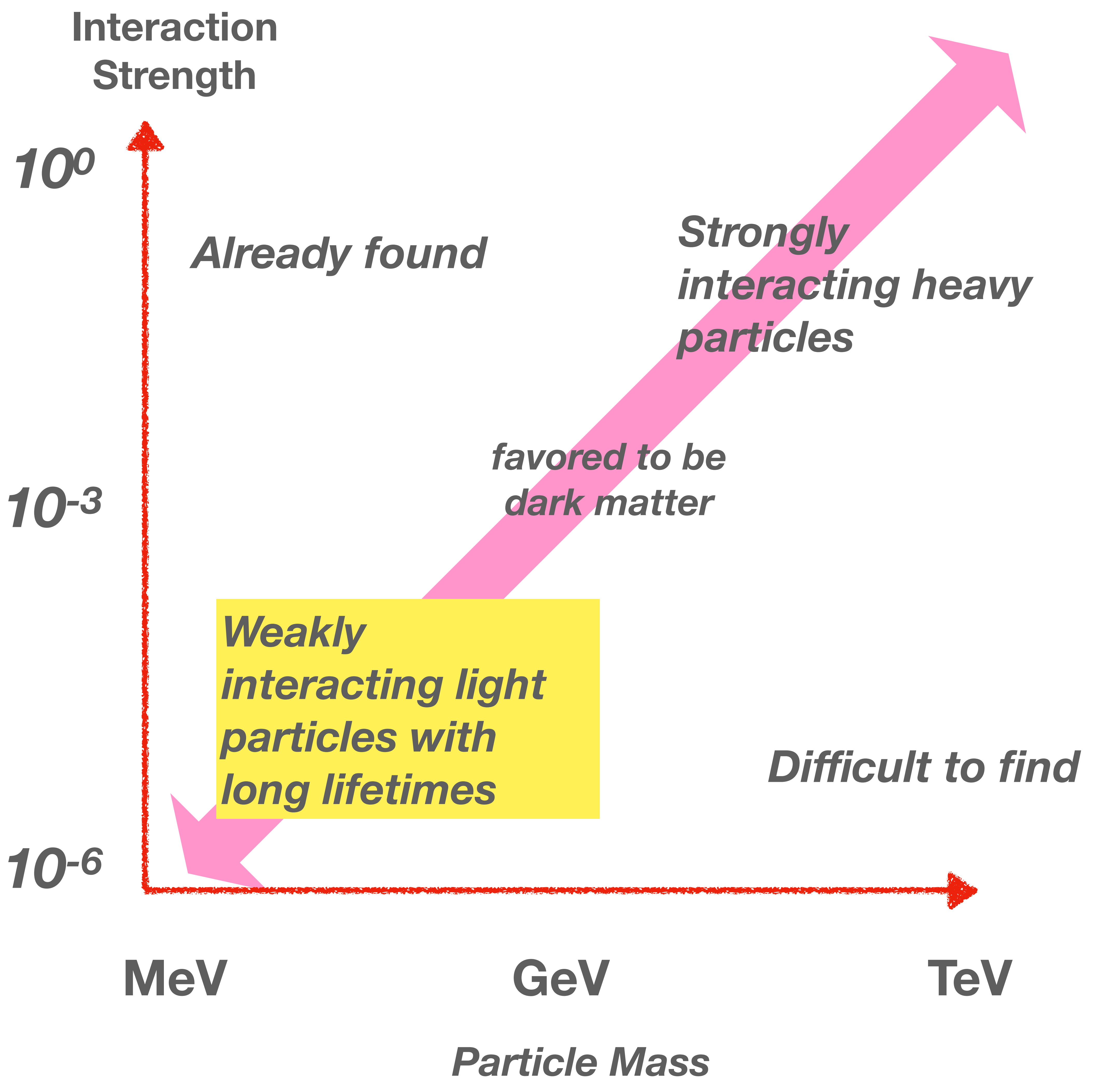
Requirements:

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

Standard model and BSM science program

General considerations

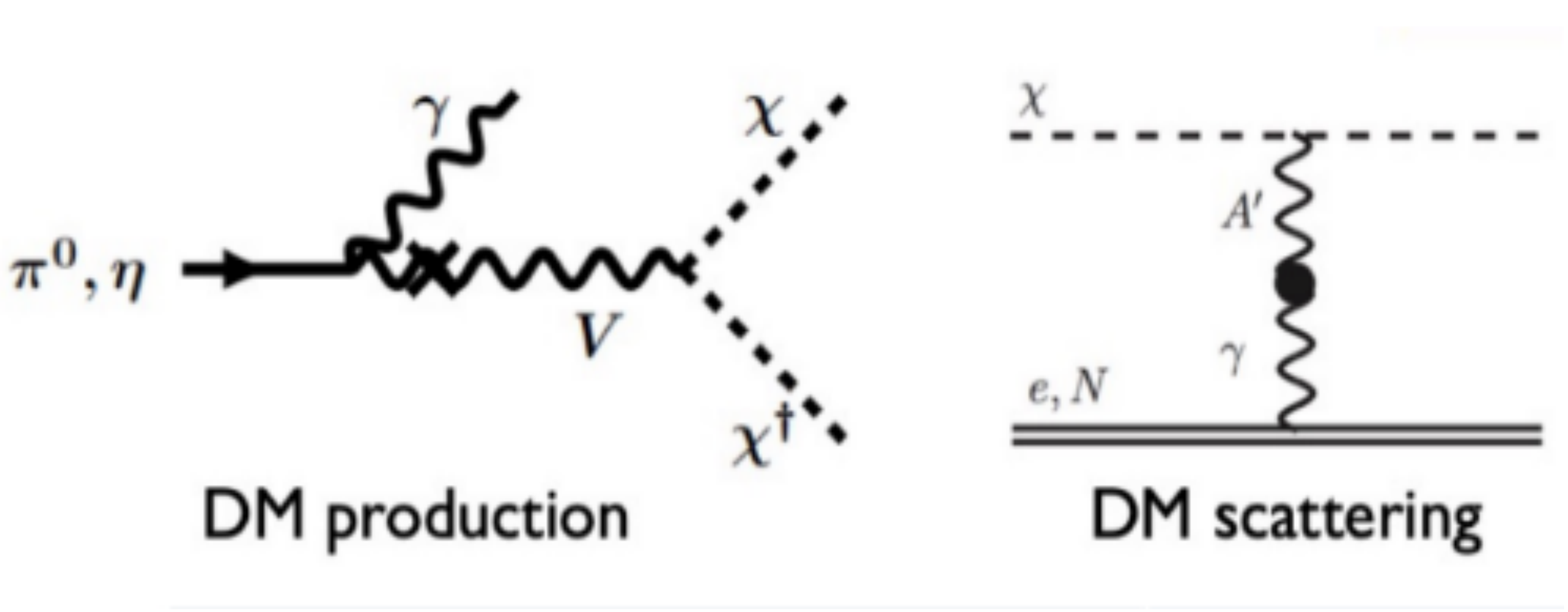
- SM program - Focus on very high energy neutrinos and their interactions.
  - First large statistics for tau neutrino interactions.
- BSM program - Focus on weakly interacting light particles from the dark sector.
  - Produced in rare SM decays of copiously produced forward mesons
  - Particles are long lived and either decay or scatter in FPF detectors. Boost from the energy helps the sensitivity
- QCD program — Focus on prompt neutrinos (both tau and electron) to understand the charm content of the proton. Deep connections to nuclear physics and the EIC.

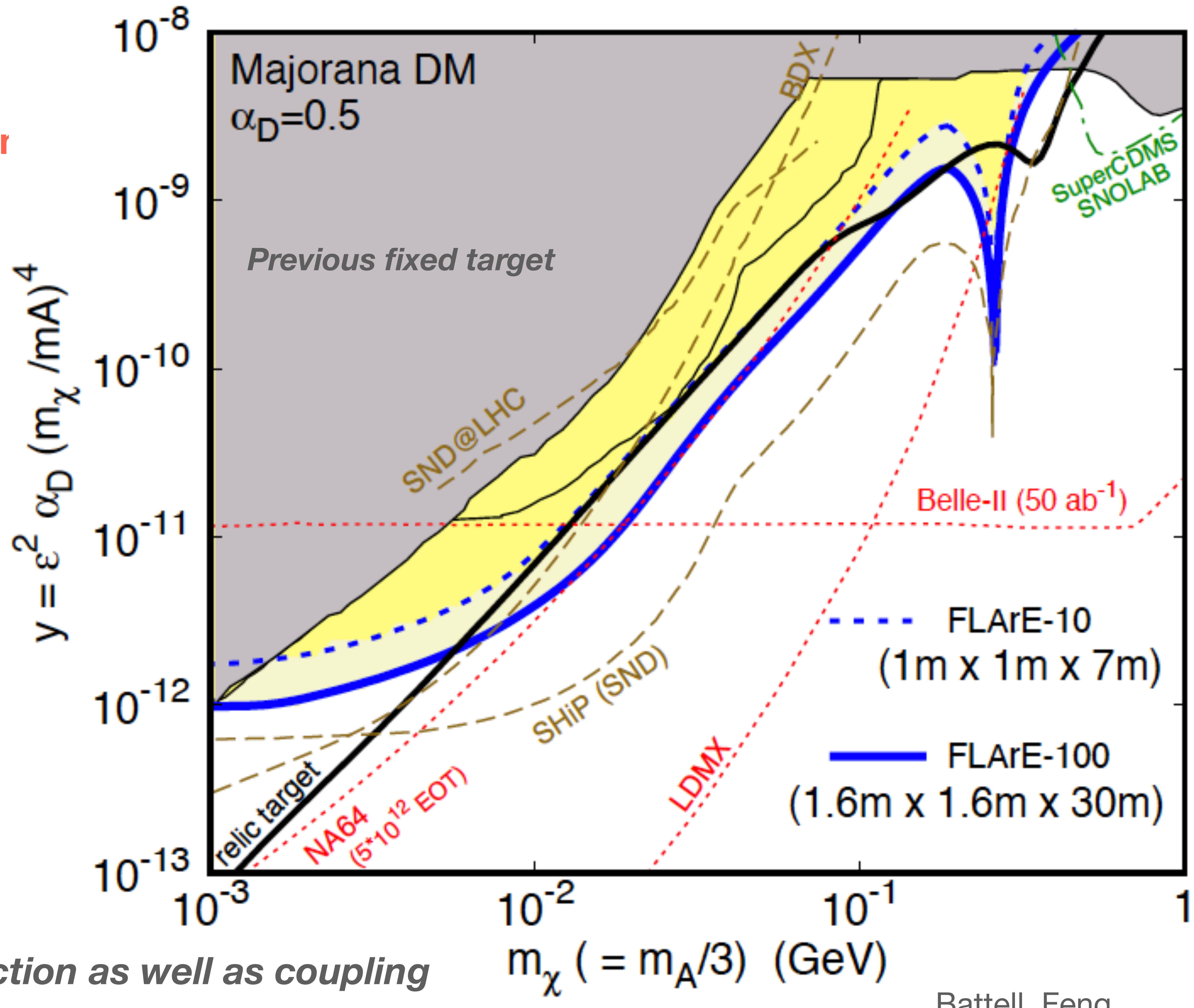


Light Dark Matter scattering (FPF@HL-LHC)

Direct detection with 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). **Need high kinematic resolutior**
- Background is from neutrino interactions (elastic scattering) and muons.
- The sensitivity plot assumes reasonable cuts for background suppression
- ***10 ton detector will reach the target sensitivity indicated by Relic density.***





Plot attempts to compare both missing mass and direct detection as well as coupling with electrons and nucleons.

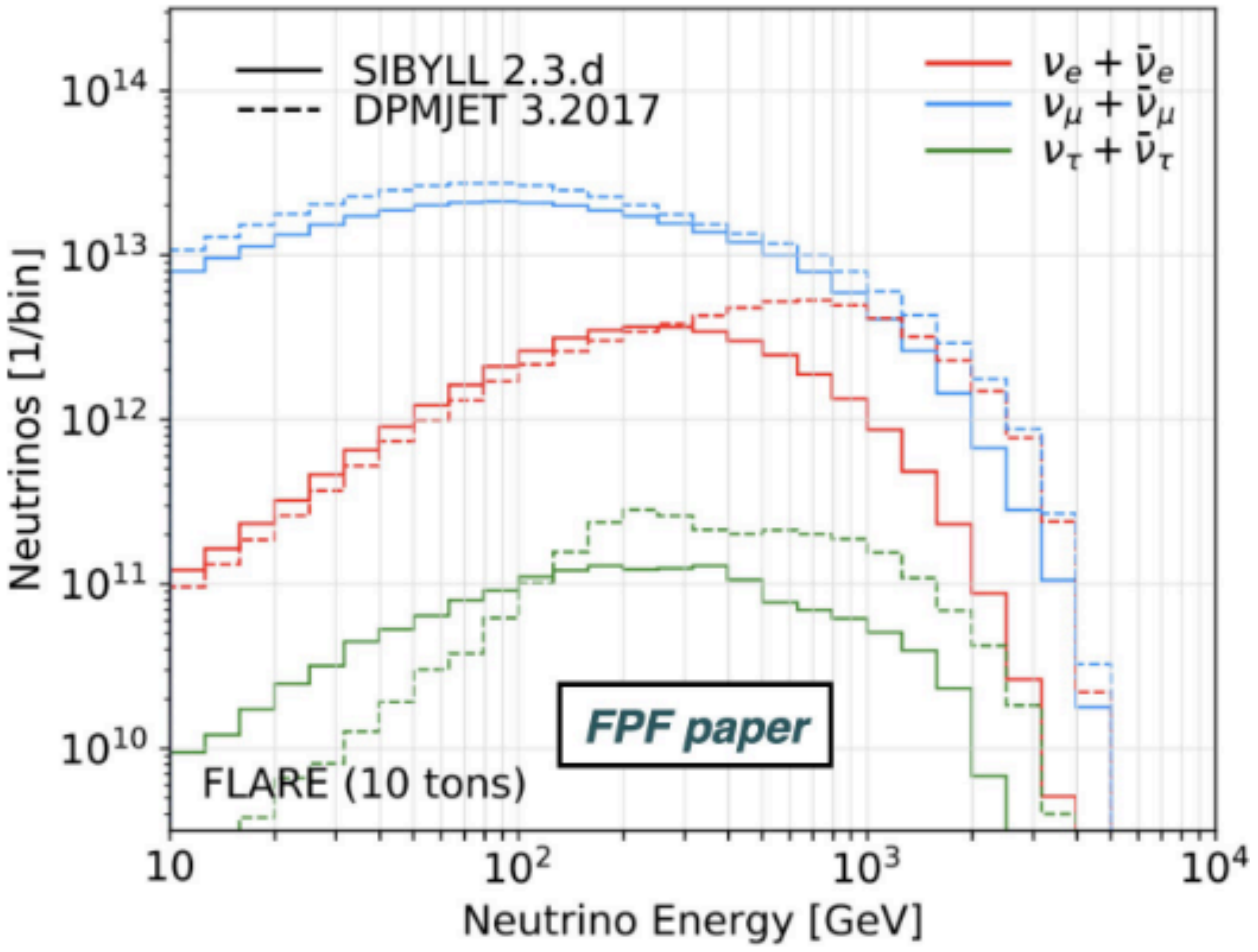
Battell, Feng, Trojanowski (2021)

Neutrino event rates (with large uncertainties)

Muon and electron neutrino spectra require detailed simulation of the beam line. The tau flux requires deeper understanding of charm production in the pp collision.

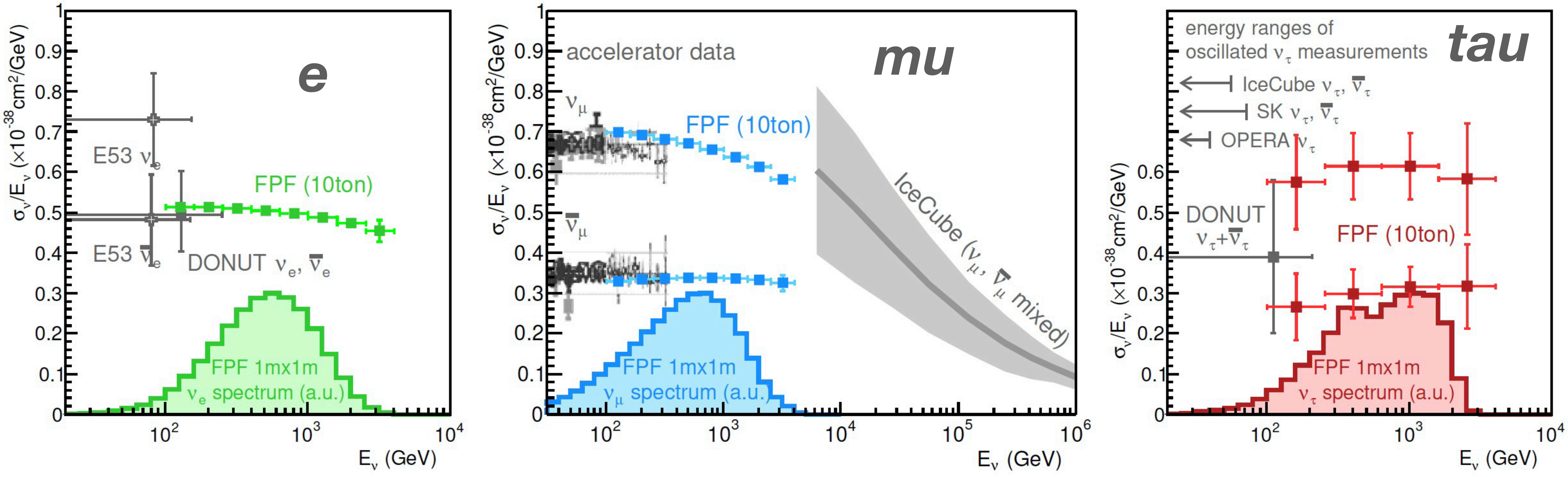
evts/ ton/fb-1	ν	$\bar{\nu}$	***Total***
e	*2.1*	*1.0*	*3.1*
mu	*15*	*5*	*20*
tau	*0.1*	*0.05*	*0.15*

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

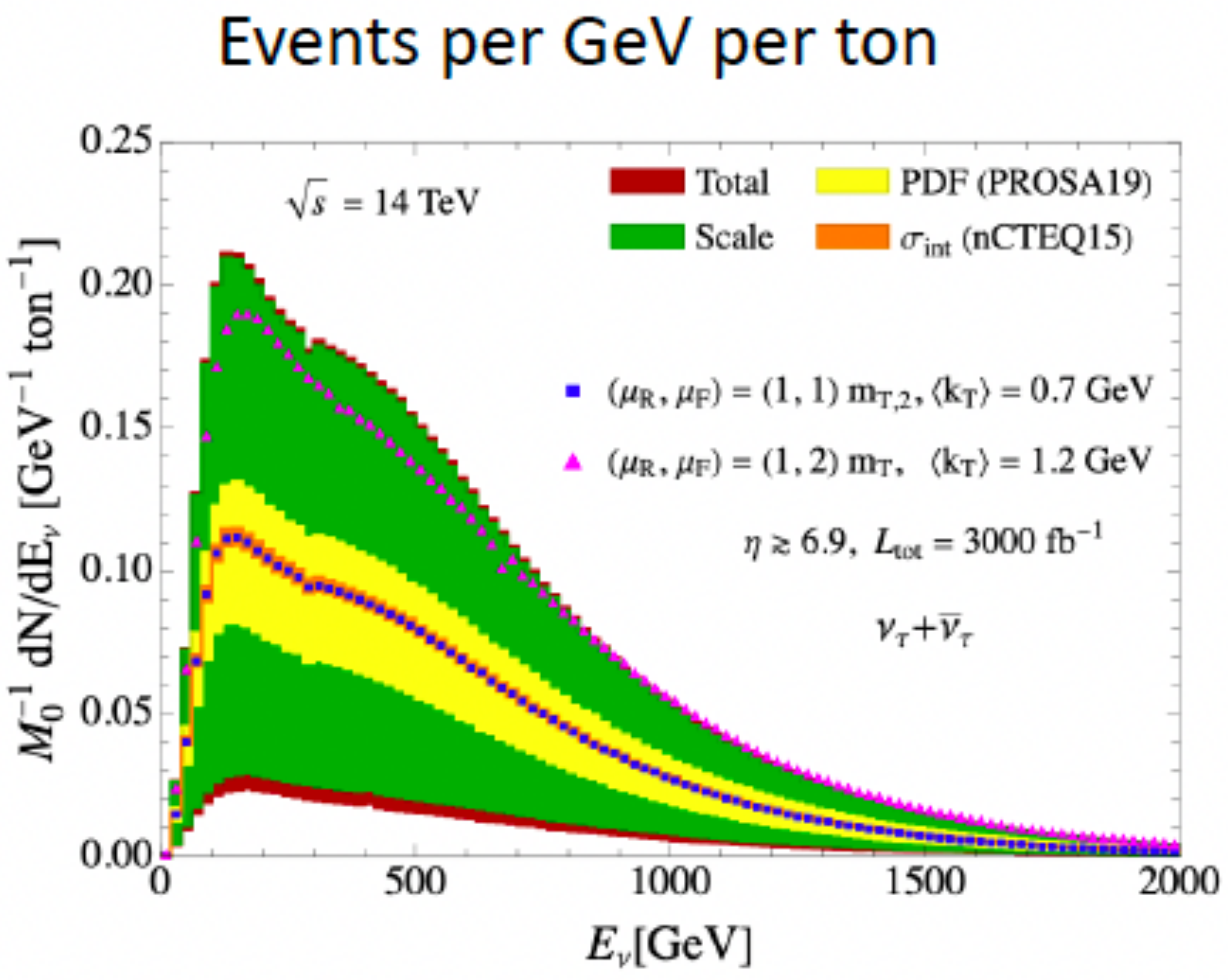
Parton distribution function uncertainties in theoretical predictions for far-forward tau neutrinos at the Large Hadron Collider,
Weidong Bai, Milind Diwan, Maria Vittoria Garzelli, Yu Seon Jeong, Karan Kumar, Mary Hall Reno,

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)	$\sigma_{\rm int}$
$\eta \gtrsim 6.9$	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

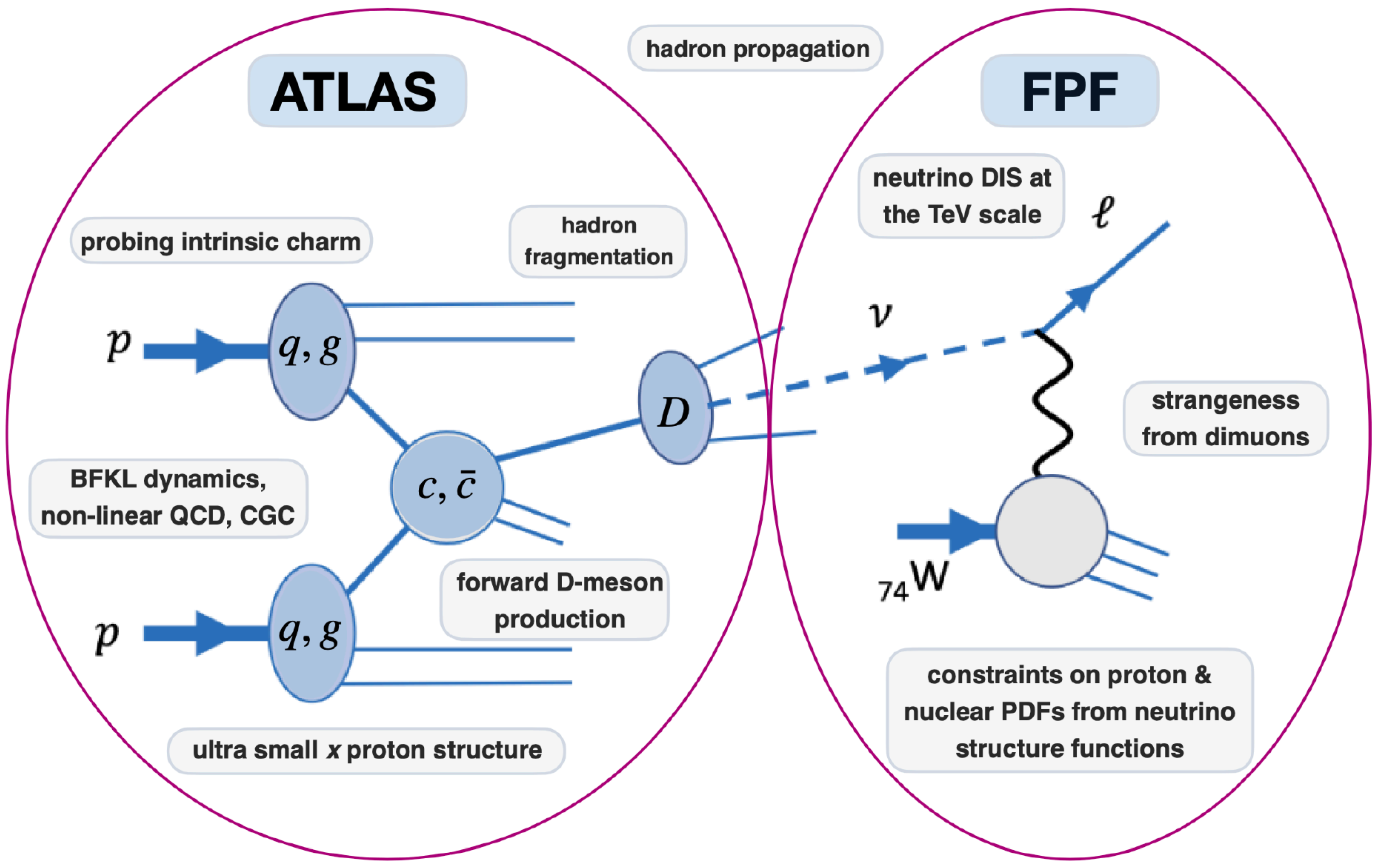
normalized for ~60 ton of tungsten

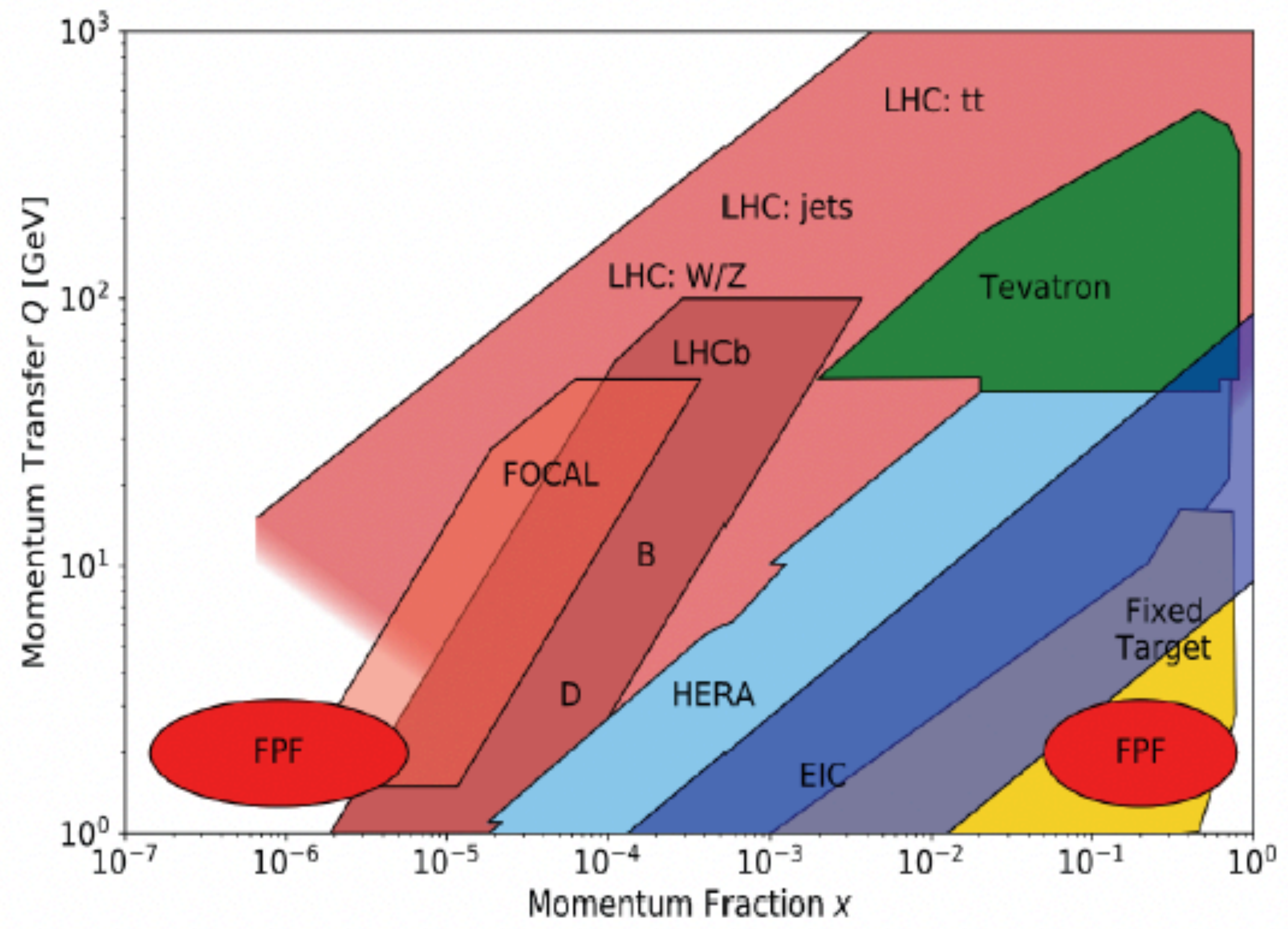
- Largest uncertainties are from scale variation.
- Measuring this rate could be important for forward charm production.



QCD interest

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





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

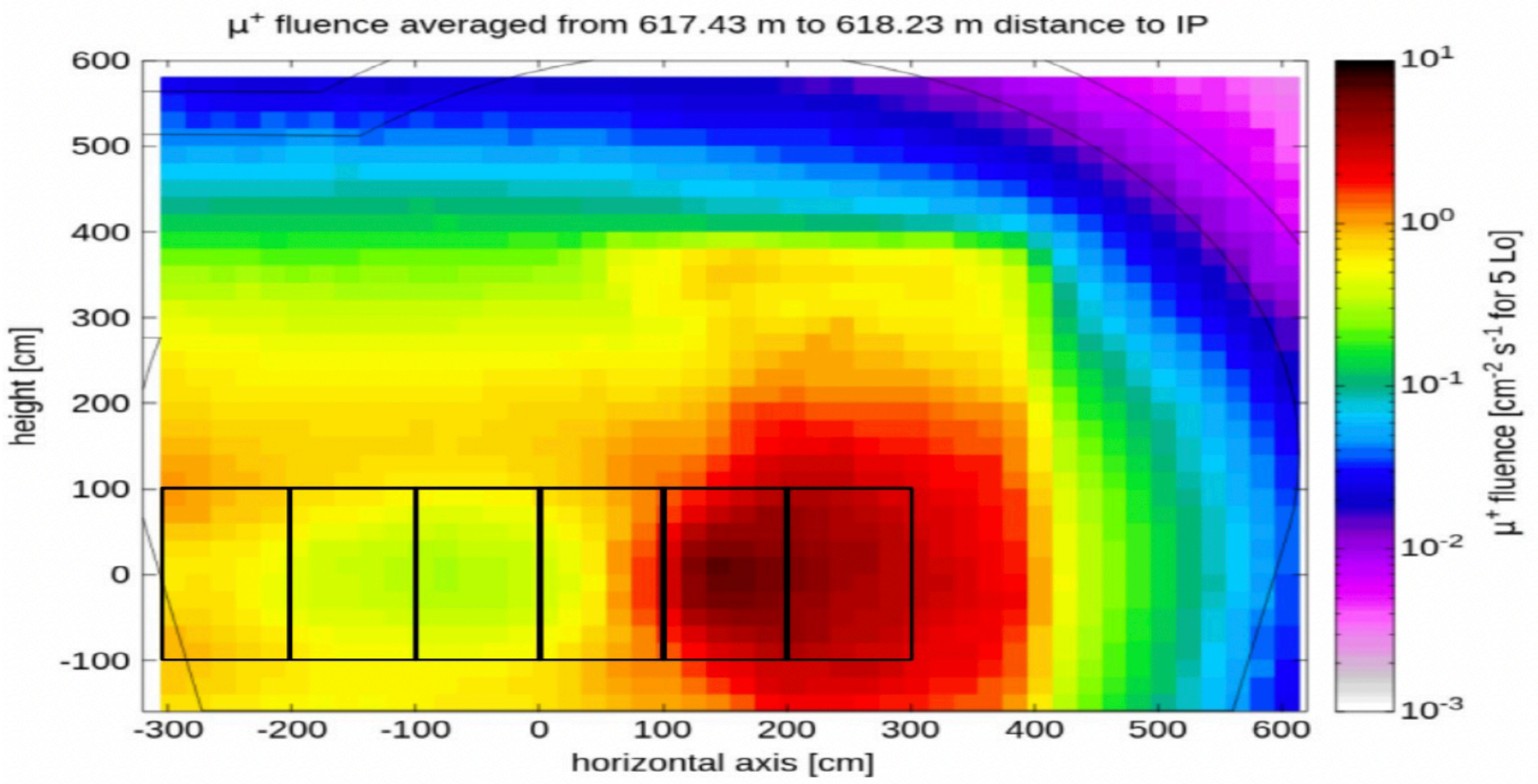
Flux and cross section errors.

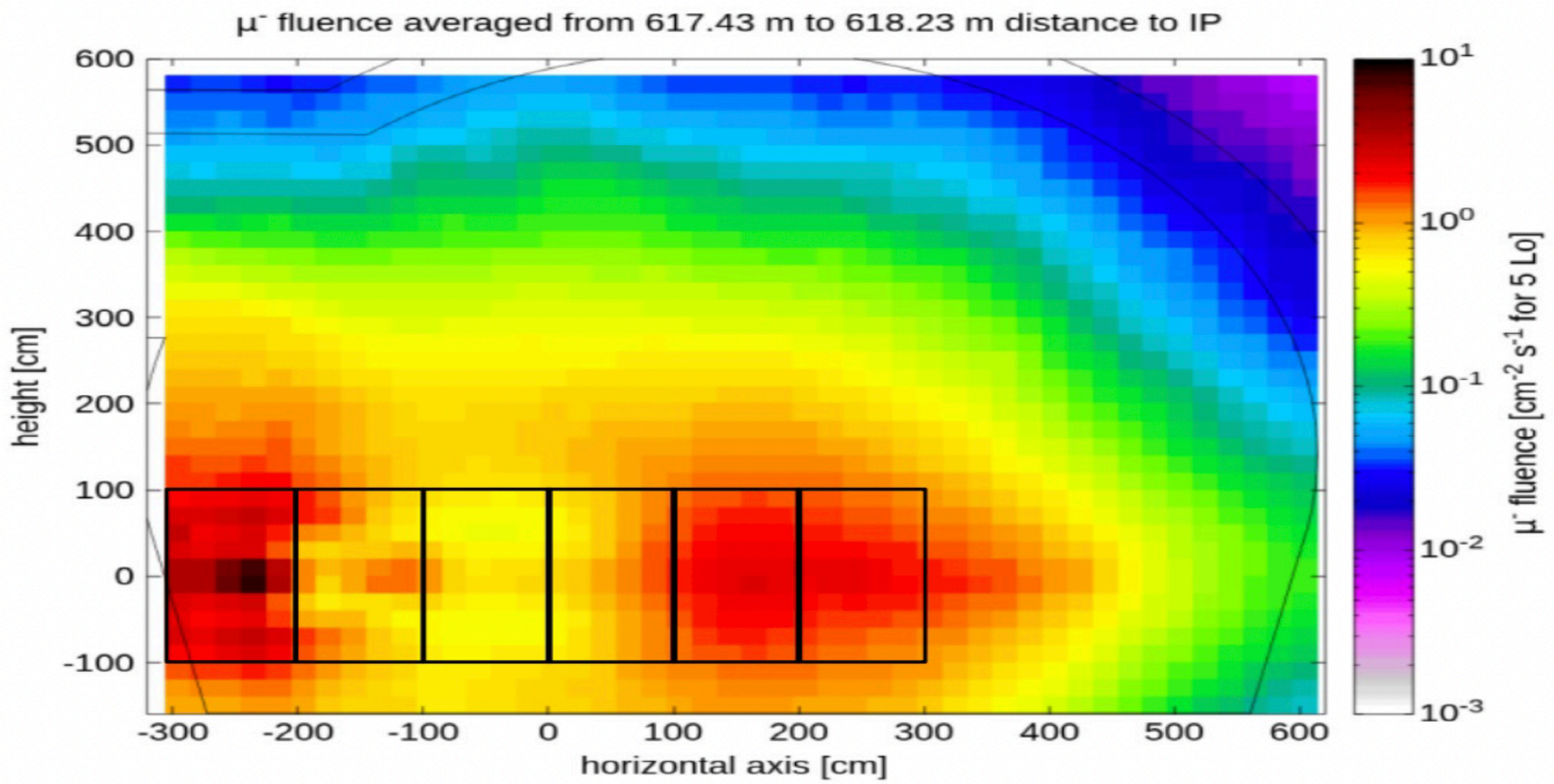
How do we deal with unknown flux and cross sections ?

- The cross section and flux determination will be in a joint theoretical and experimental program. Evolving step by step like any other program.
  - Detailed simulations of the beam are needed for muon and electron components.
  - Well known cross sections (lo-nu and elastic scattering) can be used to extract flux.
  - The ratio of high energy electron and tau neutrinos can be well constrained.
  - Theoretical advances are needed in next to leading order calculations.
- External data will be needed on charm production
- ***FPF and EIC would be running at the same time and informing each other.***

Muon fluence estimates

Jamie Boyd June 27, 2022





First FLUKA results shown at last meeting. Flux in ~1m from LOS <1.5Hz/cm^2.

Ongoing FLUKA studies:

- Using the full magnetic field maps of Q4 and D2 had some impact on the results, so the full magnetic field maps of Q5/6/7 will be considered in further simulations as soon as they are available from the magnet group
  - Likely to slightly reduce flux

- The sweeping magnet is now implemented in the simulations, placed on the line of sight. Preliminary calculations show a mild effect on the muon fluence in the FPF cavern. Investigating different locations for the magnet (position and alignment), to maximize its effect.

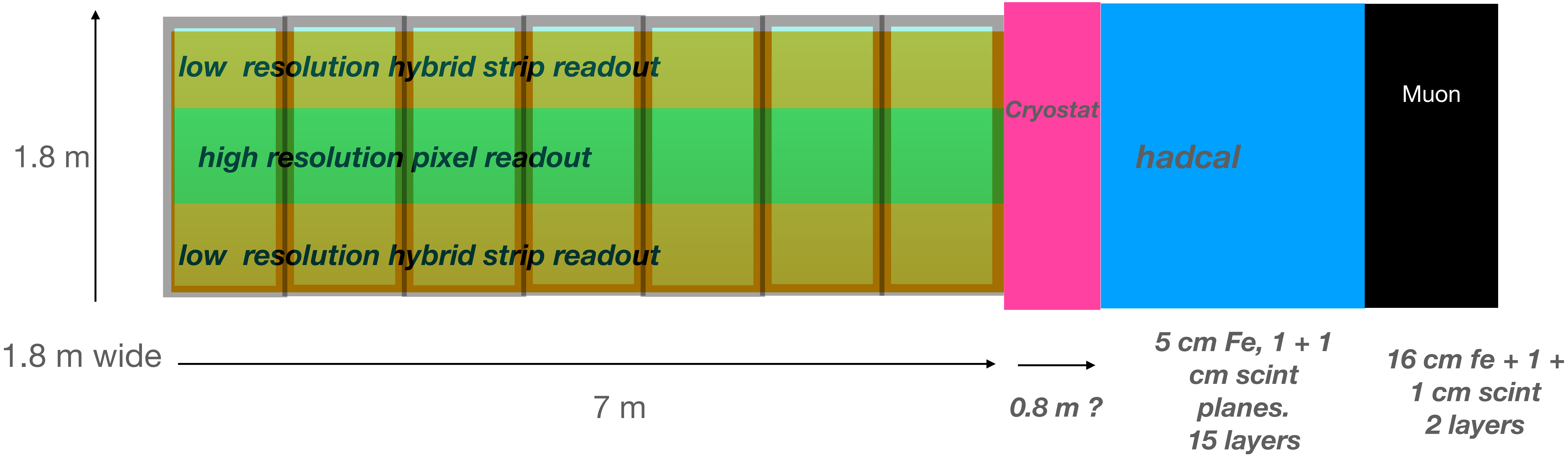
- The particle threshold set at 10 GeV will be lowered since the detectors are sensitive to muons below that energy
  - Will increase the flux

Basic detector requirements for FLARE from studies

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	1-2 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

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.

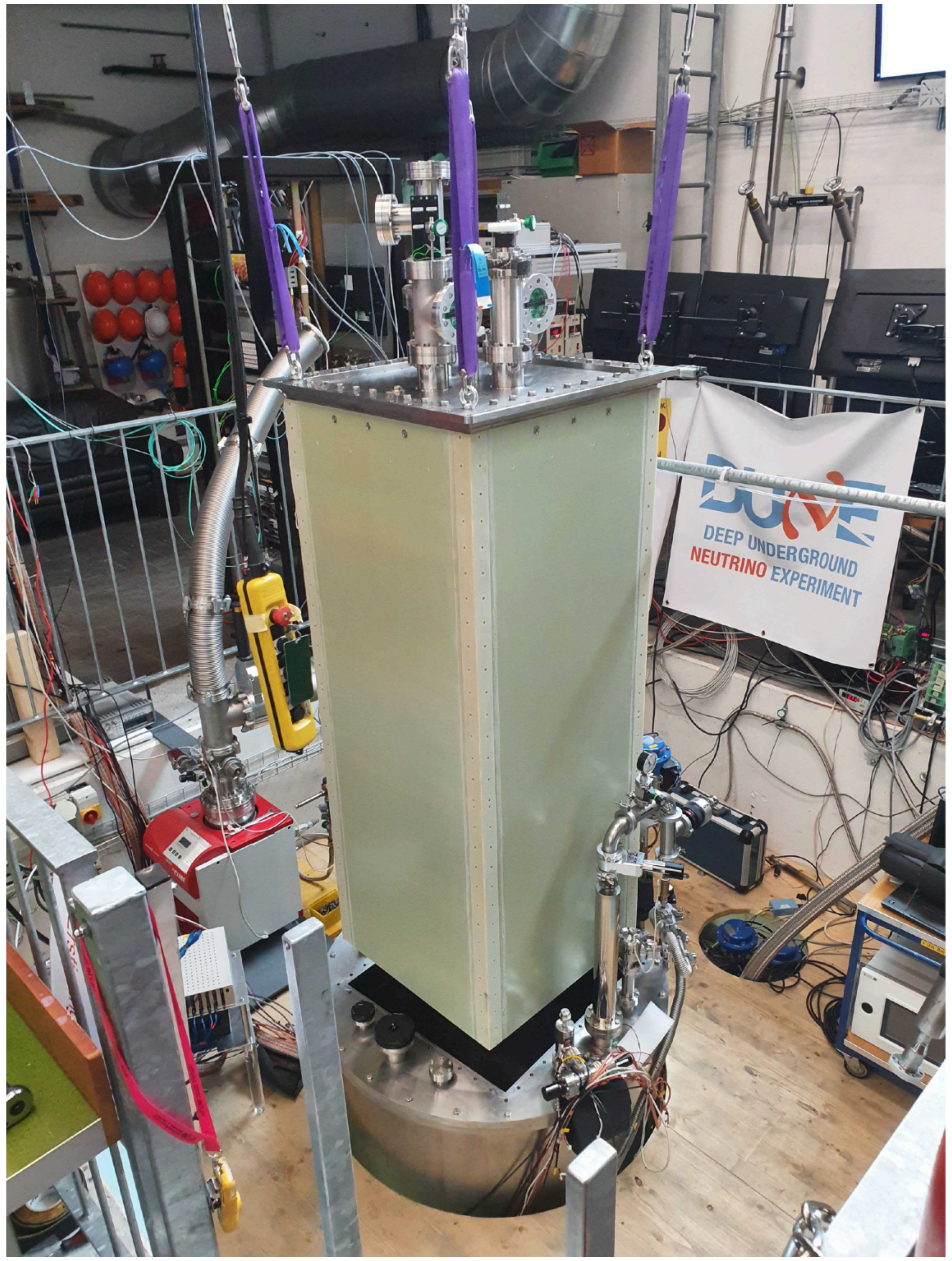


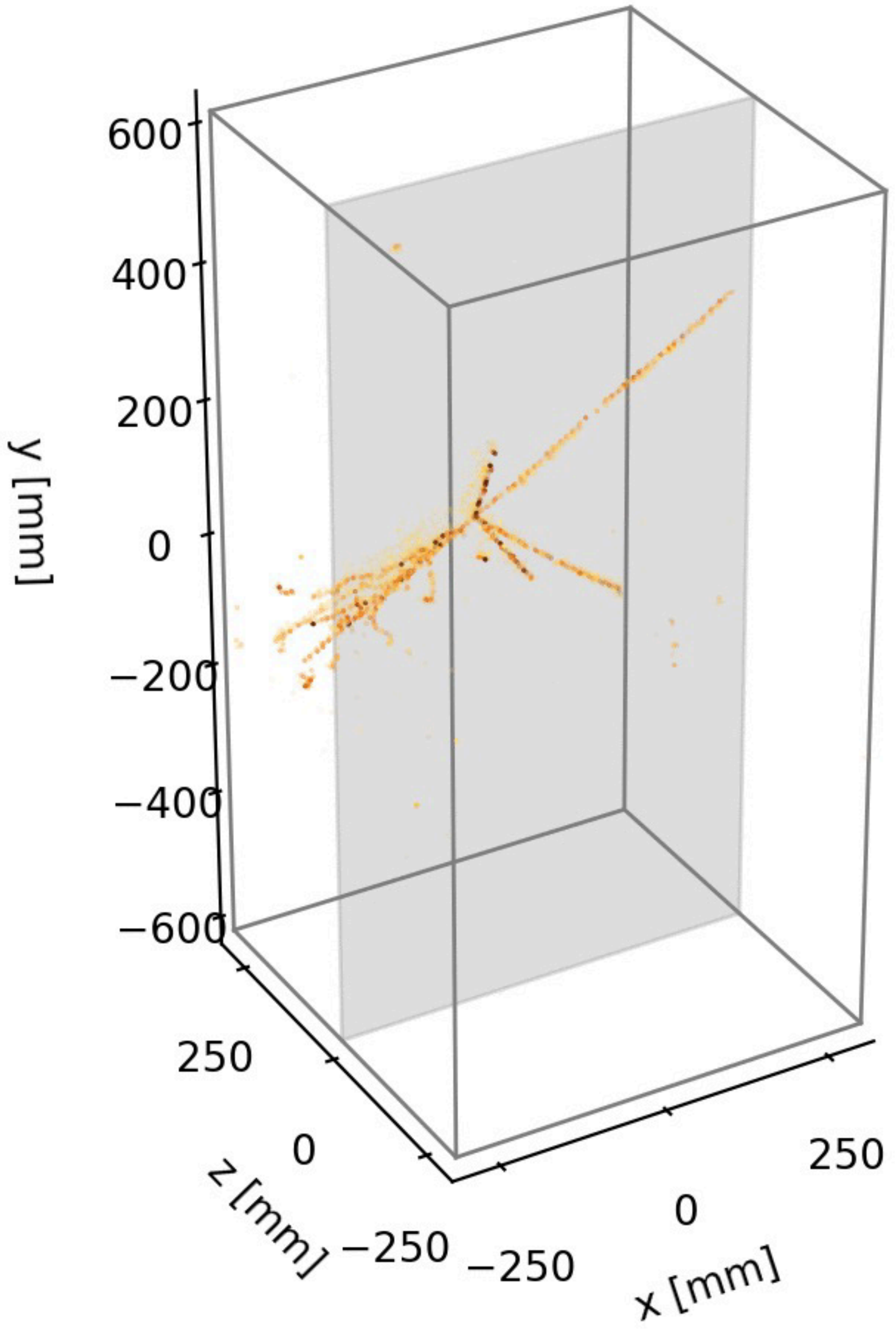
Carry two options into Conceptual Design

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

FLARE will Benefit from the DUNE near detector concepts.

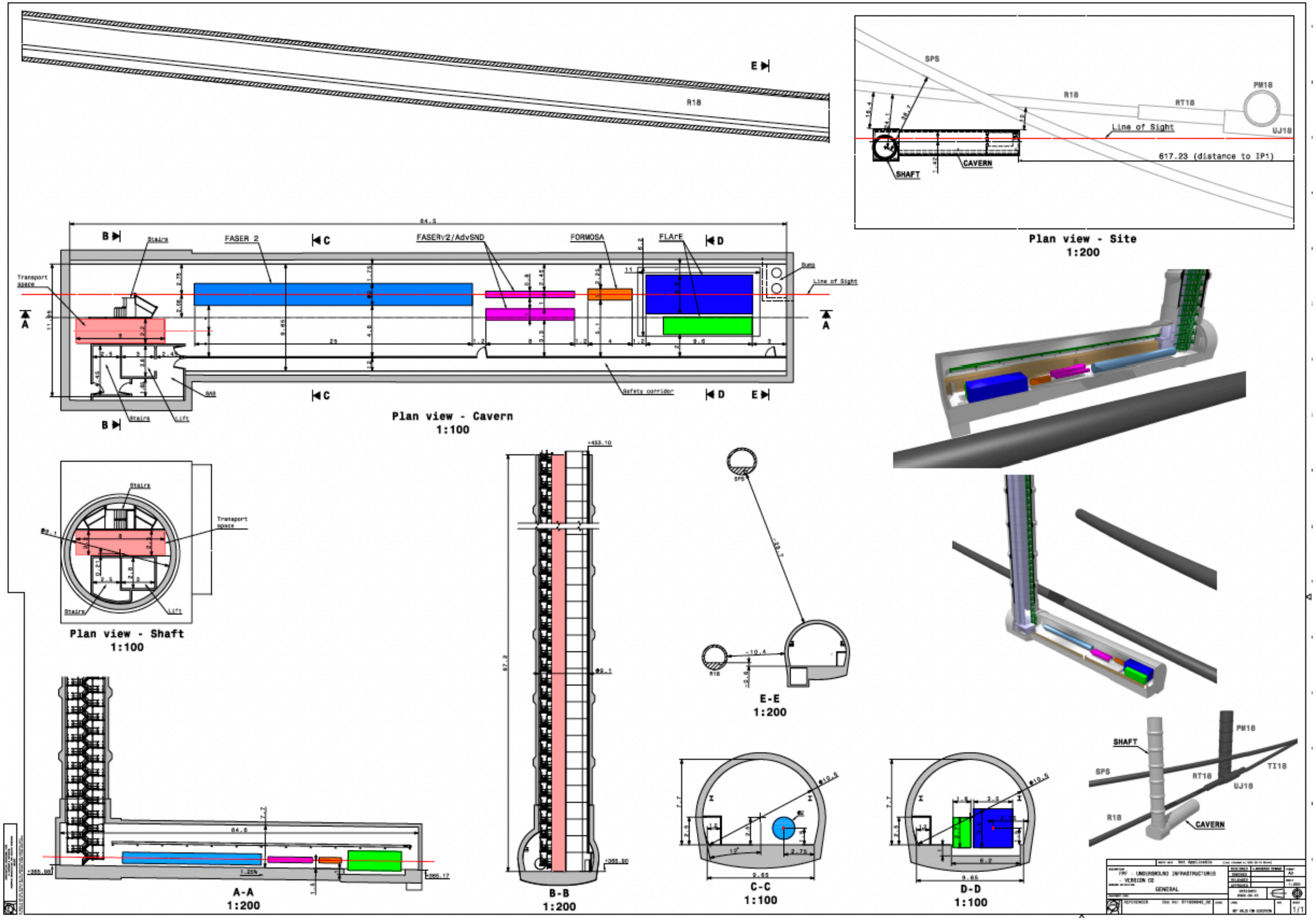




Conclusion

- 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 headline physics interest is
    - Neutrinos 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.
- Muon backgrounds, and engineering considerations necessitates a modular TPC detector.
- A LAr TPC requires much more advanced readout for ultimate spatial resolution, and a trigger system that can find contained events in the presence of muons. Timing could associate events with the ATLAS bunch crossing (studies are needed).
- Cost ? We now have a very modest project at (BNL and collaborators) to produce a conceptual design by mid-2023. DUNE R&D investment has made this much easier.
- ***FPF/FLARE is an intellectually challenging modest project with excellent advanced technologies. It would be a welcome outcome of this Snowmass.***

Backups



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

Class 4 means: -30% +50%

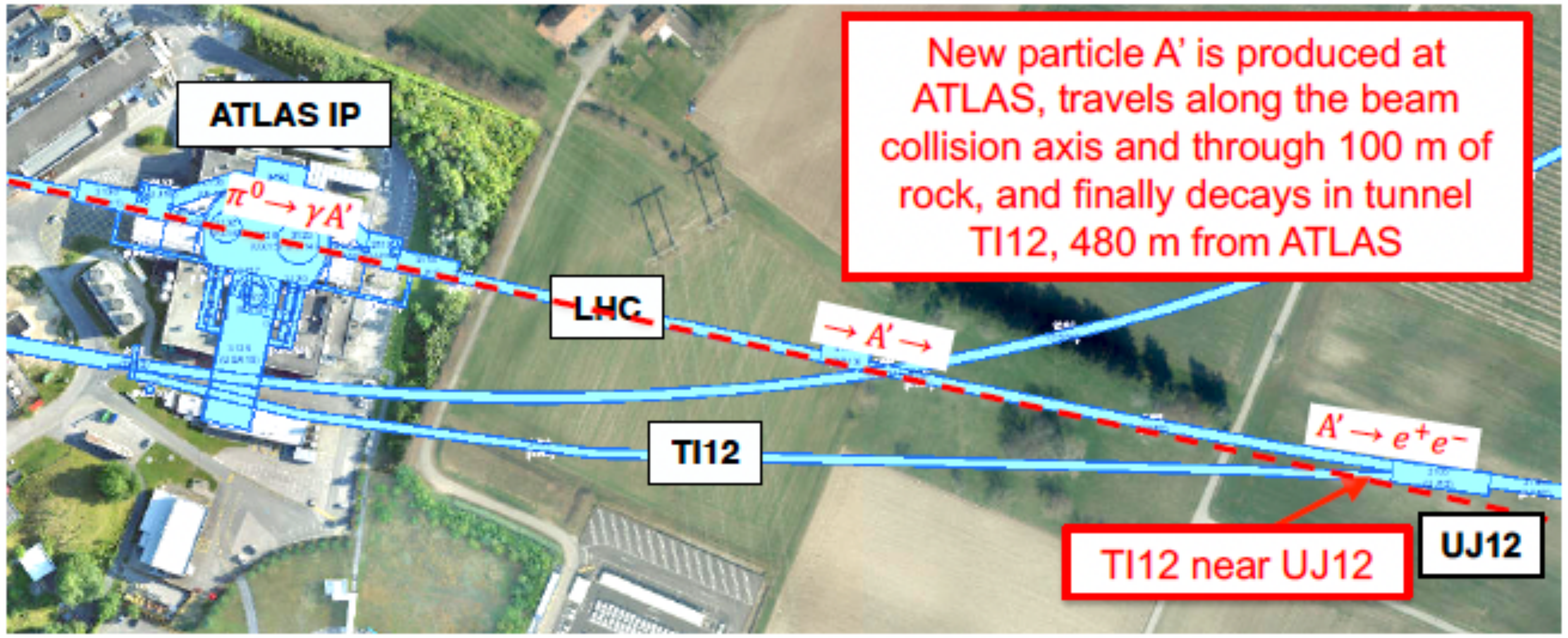
Important development April 22:

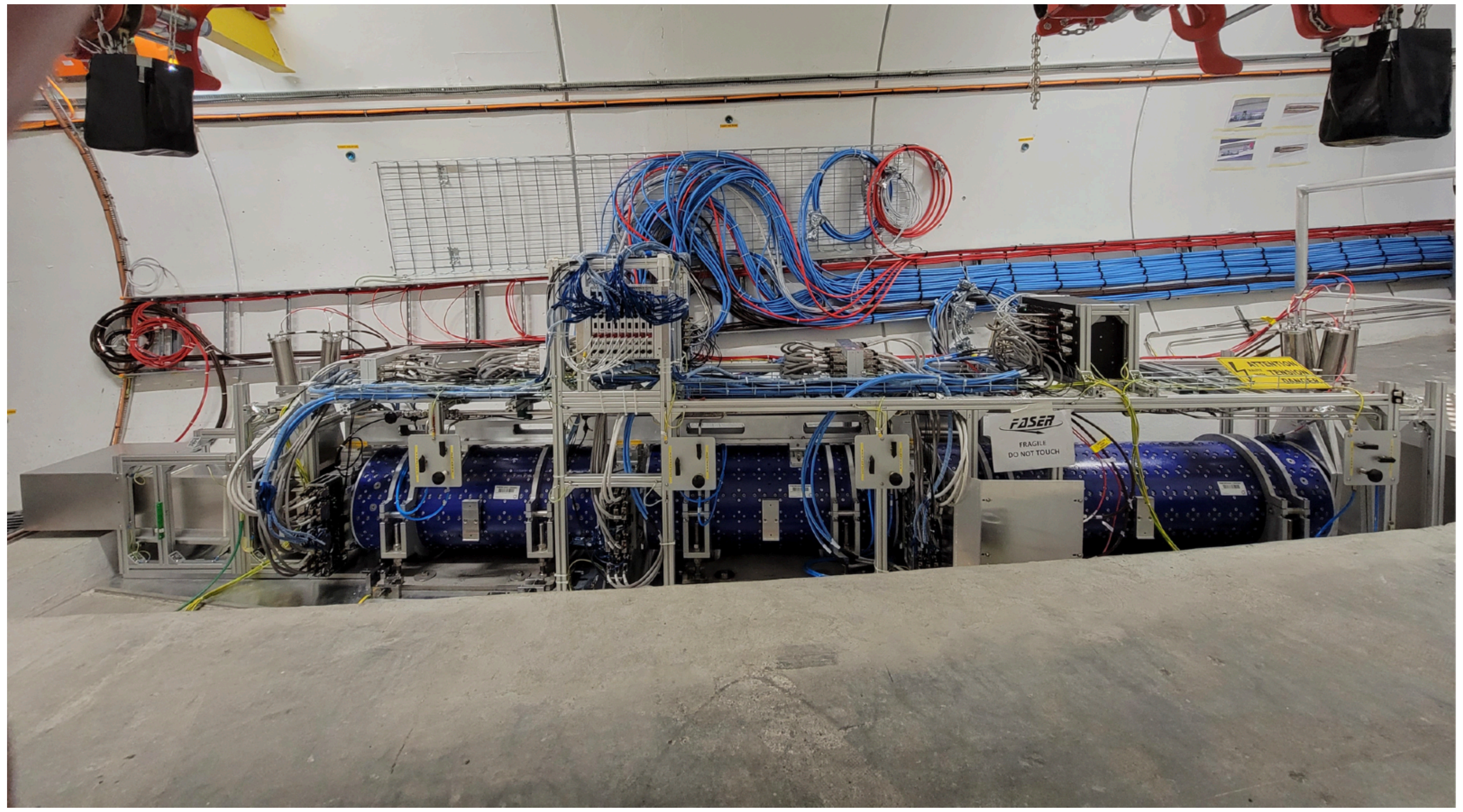
- safety gallery allows no connection to the LHC for secondary exit.

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.





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

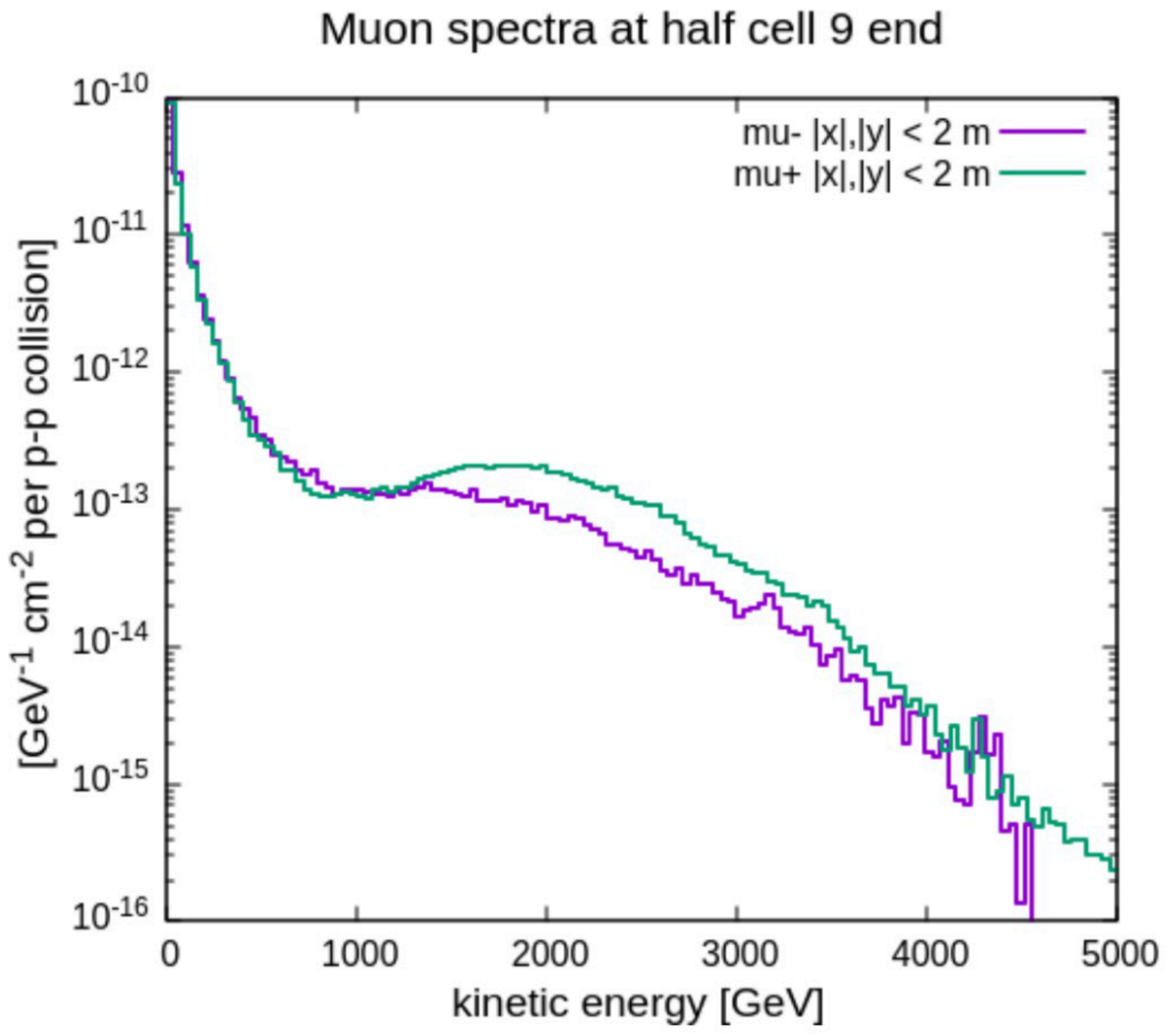
Electron neutrino flux above 300 GeV is charm dominated.

Needs modeling of forward production in the PP interaction

Experimental conditions (without sweeping magnet)

Approximate fluxes, rates of backgrounds

348.5 m from IP1



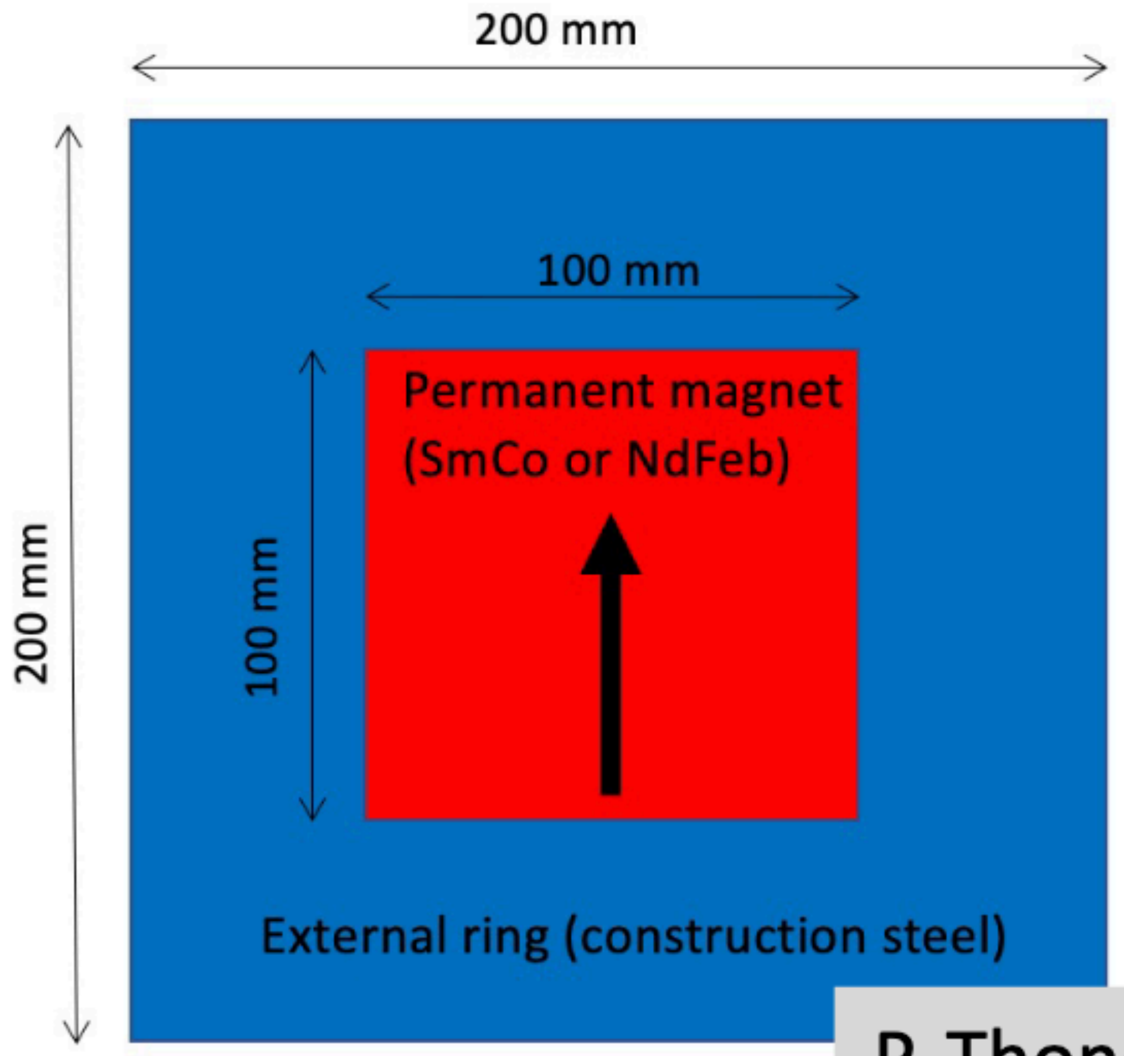
- **Both charged and neutral hadron interactions present significant background.**
- **Total neutrino interaction rate normalized to per ton per fb^{-1}**
- **Observed nu rate from pilot run: ~45/ton/ fb^{-1} at 480 m**

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)	~1.5cm^2/sec (6x10^{-8}/cm2/crossing)
Tracks in detector/1 ms	~15/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}

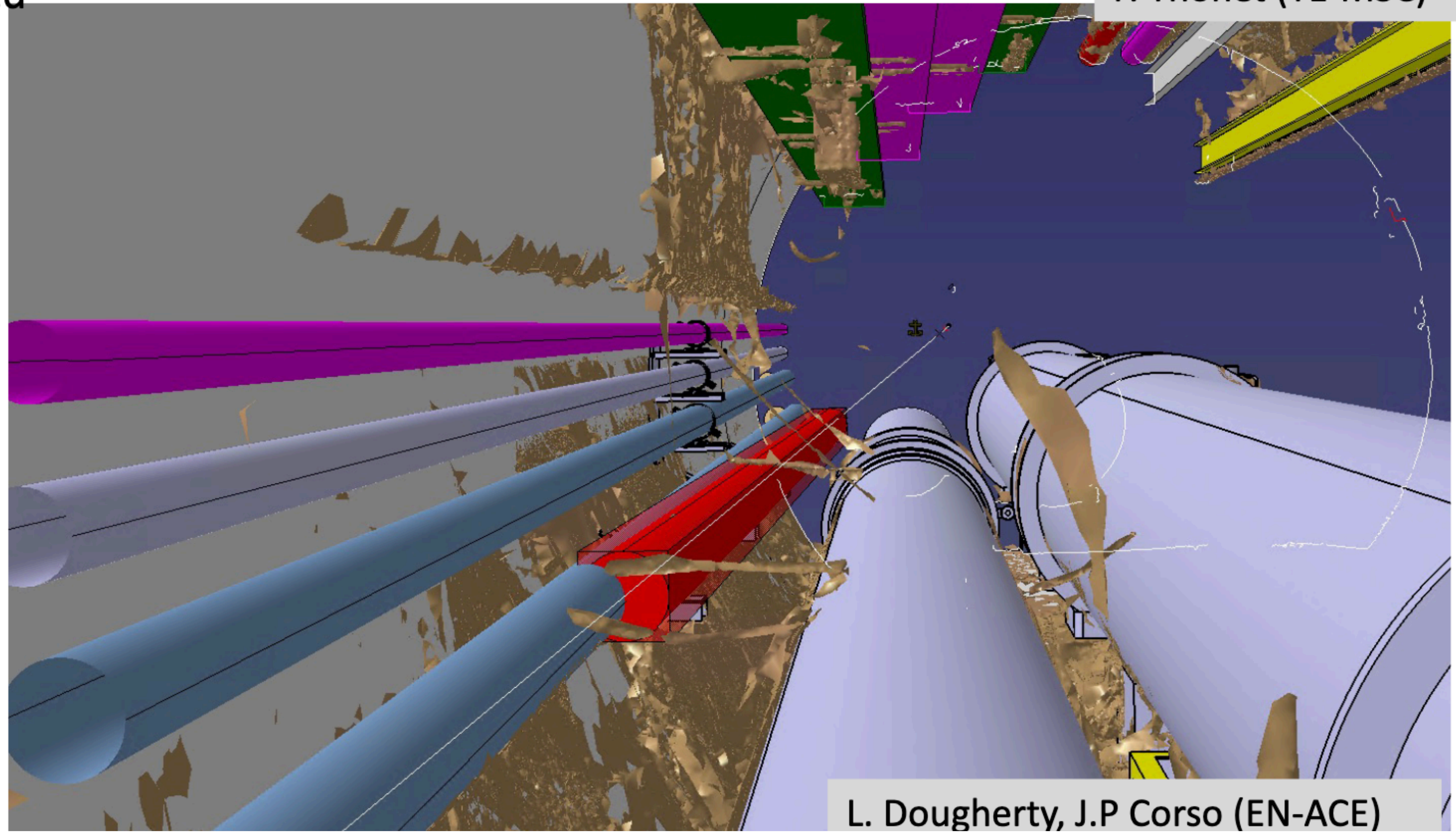
updated with new information on HL-LHC configuration 2105.06197

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 ($20 \times 20 cm^2$ 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

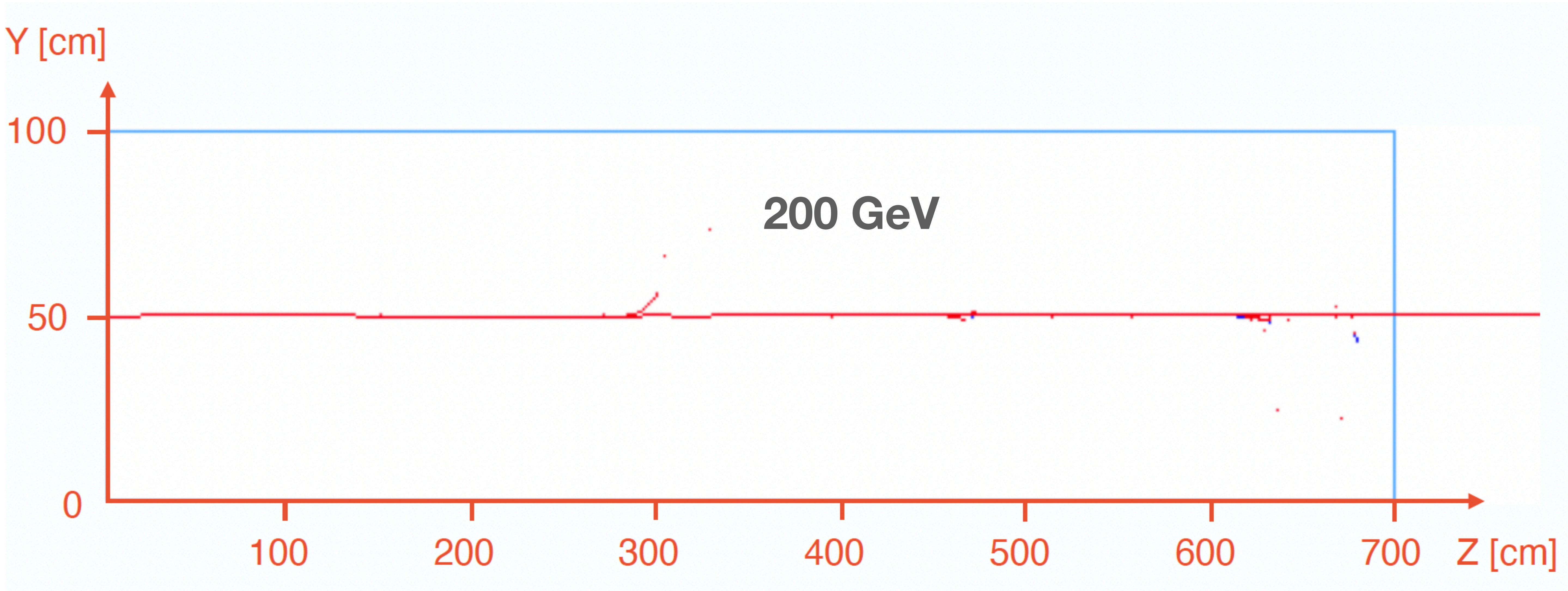


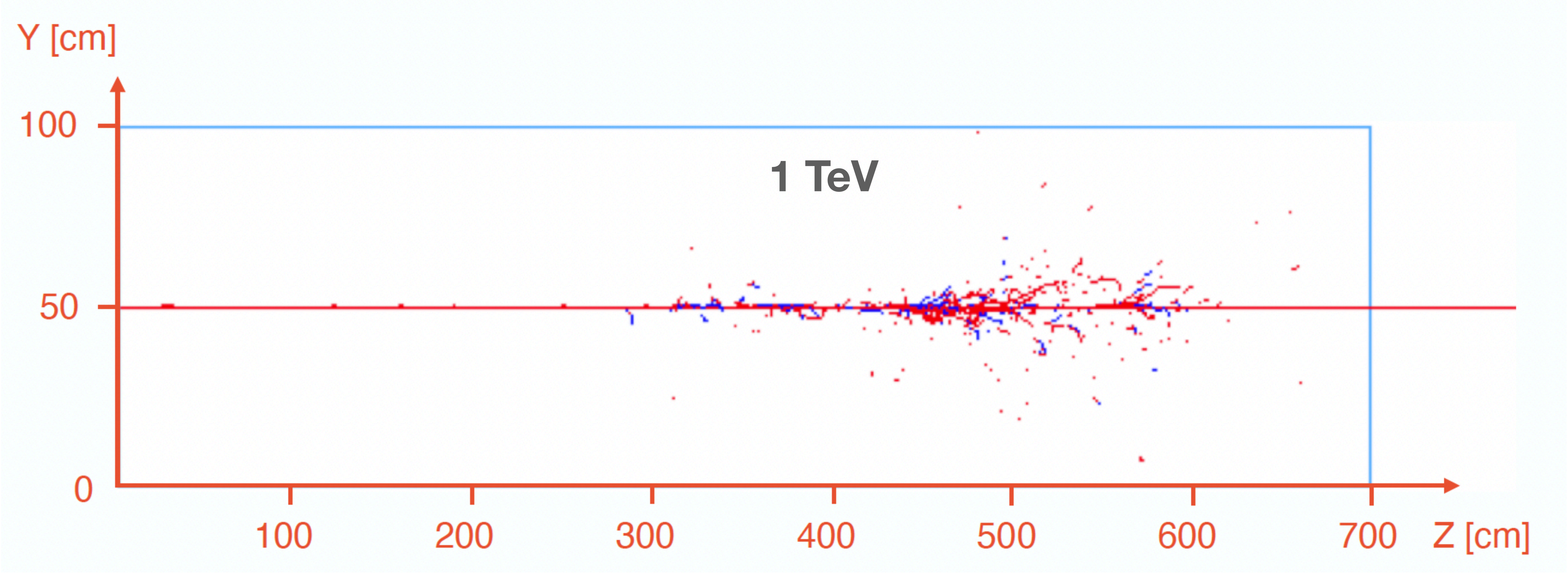
P. Thonet (TE-MSC)



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

Muon simulation in liquid argon.



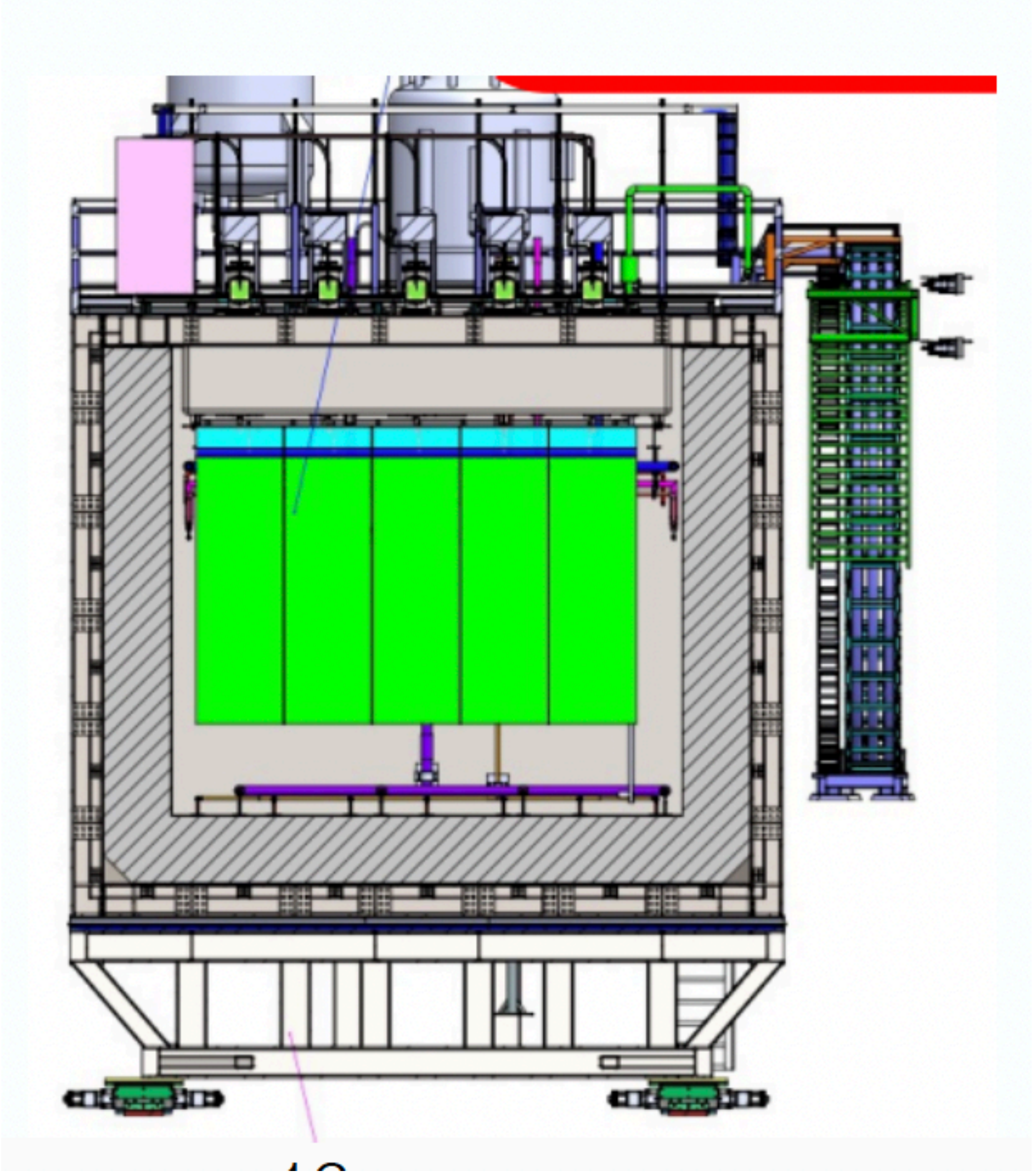


- *Muon flux above 1 Hz/cm2 presents a difficult problem for all detectors.*
- *For Liquid argon TPC, the flux also presents a space charge problem for large gaps.*
- *Showering muons will also present a trigger problem since if the incoming muon is missed the event will look like a neutrino.*

Wenjie Wu (UCI)

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.*

Nominal configuration

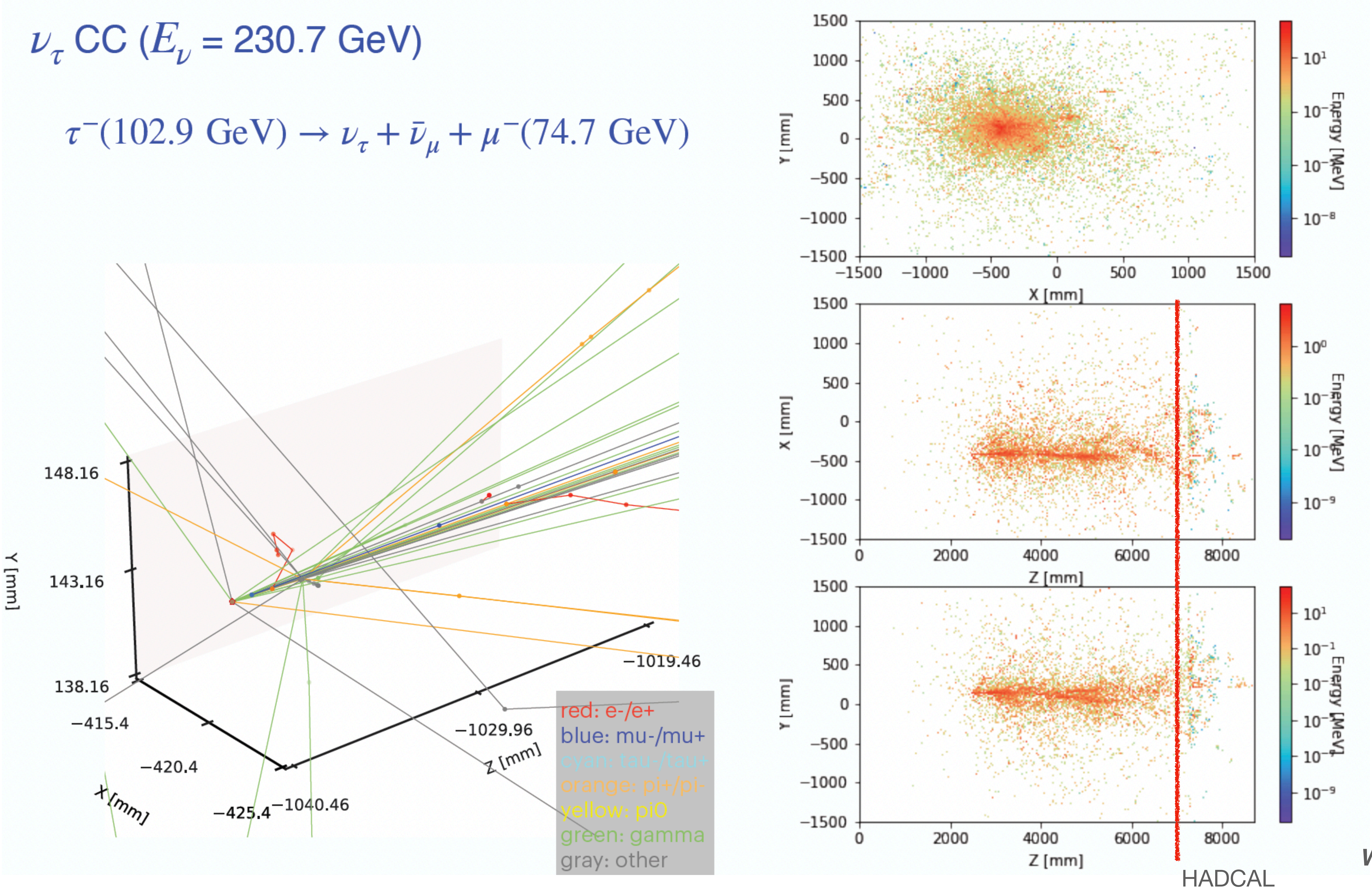
To be detailed in a spread sheet and developed into a detail for a conceptual design parameters.

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

Tau Neutrino event simulation in a LAR TPC. Kinematic separation combined with high vertex resolution seems to be very promising. But a lot of work is needed.

ν_τ CC (E_ν = 230.7 GeV)

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



1. 1.8 X 1.8 to contain transverse events in fiducial of 1m x 1m x 7m.
2. Hadronic calorimeter to contain showers that start downstream.
3. Even a modest energy resolution is sufficient.
4. Excellent muon identification results in quick selection of nutau events.
5. We will combine spatial resolution in drift dimension with kinematics to get good S/N.

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