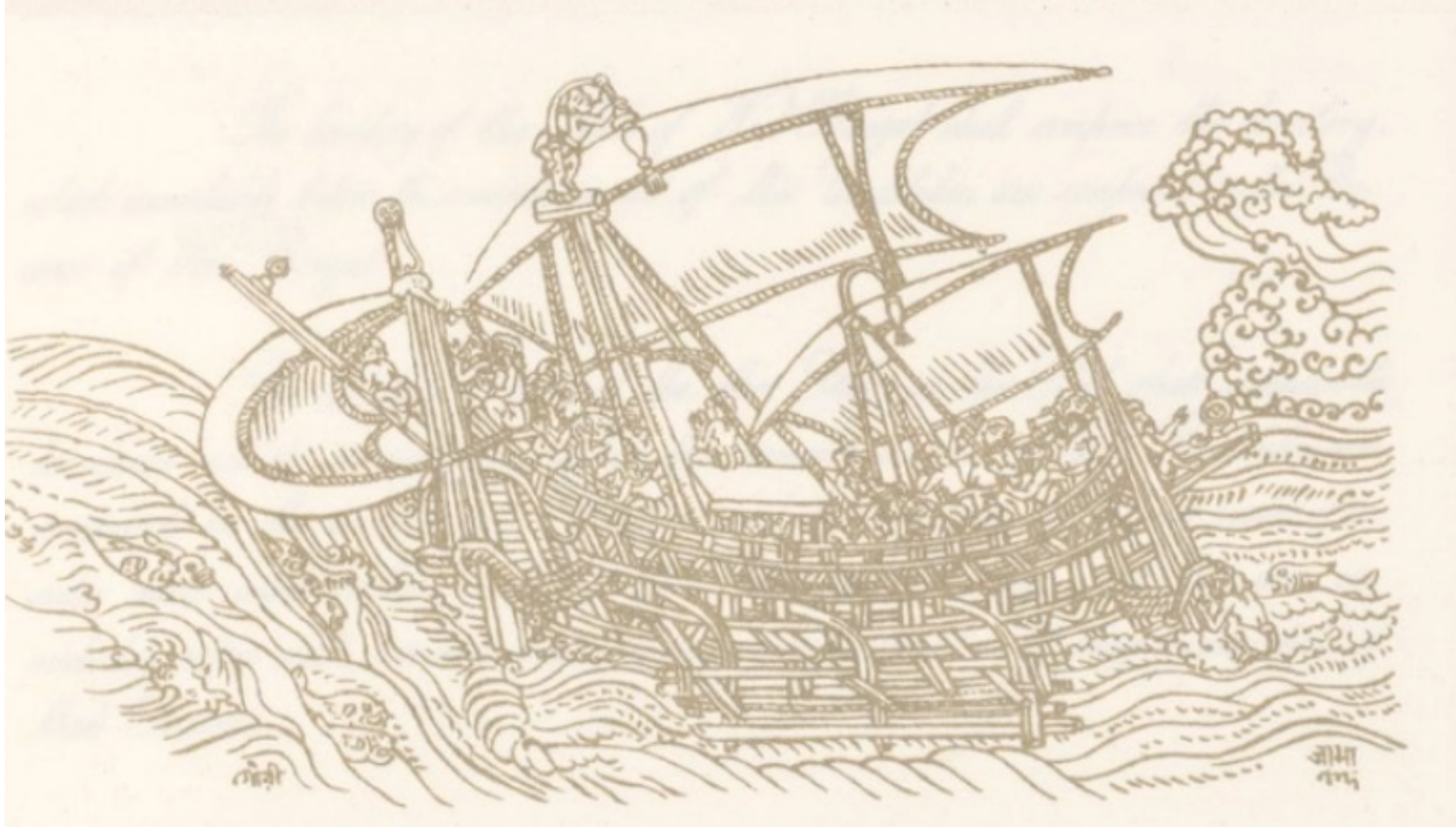
Far forward neutrino detectors at the high luminosity LHC

Milind V. Diwan (Brookhaven National Laboratory)

Fermilab Wine and Cheese Colloquium, March 3, 2023



Gauri Bhanja, Jabha, and Nandalal

Dedication

Thank you for the accidental coincidence of this talk being after a symposium for my dear friend Meenakshi Narain.

She was very much engaged in placing this scientific opportunity in the snowmass energy frontier report.

Our highest immediate priority accelerator and project is the HL-LHC, the successful completion of the detector upgrades, operations of the detectors at the HL-LHC, data taking and analysis, including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades. — Energy Frontier Report (2022)

References for forward physics facility (FPF) and organization

- Snowmass LOI from 2020 (community study)
- Nov 2020 (FPF1), May 2021 (FPF2), Oct 2021 (FPF3), Jan 2022 (FPF4): 5 dedicated, interdisciplinary meetings to develop the FPF's potential. 5 physics themes: BSM, neutrinos, QCD, DM, and astroparticle physics. Nov 2023 (FPF5), fcoordination of experimental program
- 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, MVD) 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. (BNL-LDRD, HSF, BNL-program development, etc.)
- FPF-related talks at Snowmass in Seattle (July16-26). All are recorded.

Outline

The LHC and its parameters.

Geometry of the LHC

Geometry of the collision and the forward region.

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.

Liquid argon detector for the forward physics facility.

Muon flux at the FPF.

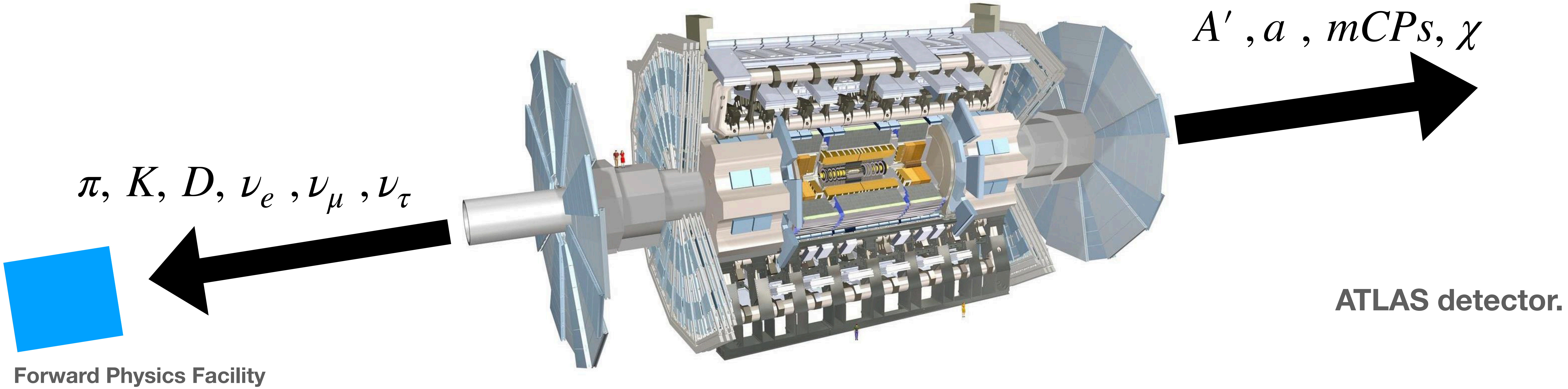
Detector requirements for a noble liquid detector.

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

Prospects.

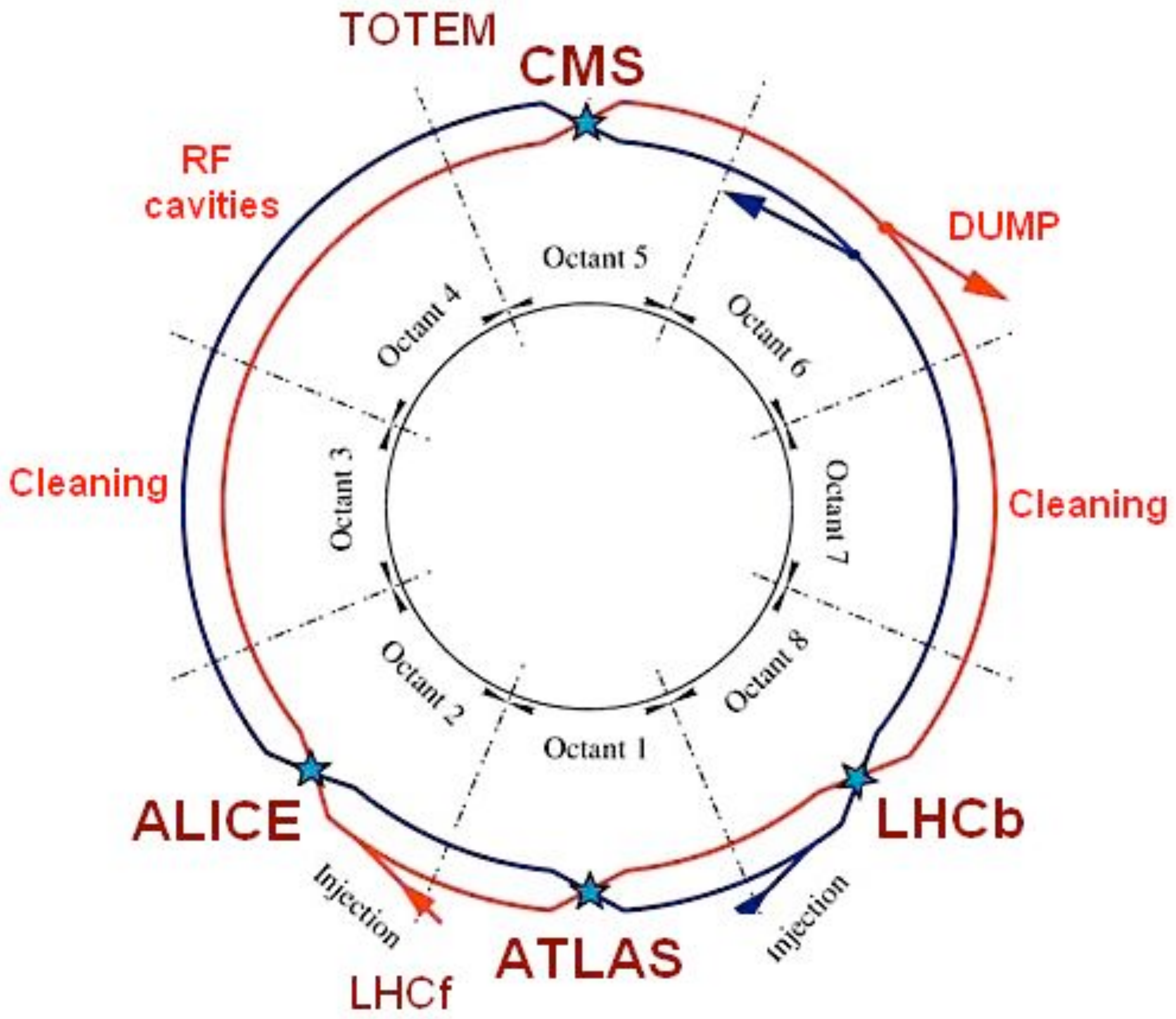
The LHC, ATLAS and forward geometry

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.***
- ***Is it 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. See Jonathan Feng's W&C talk from last year.***

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

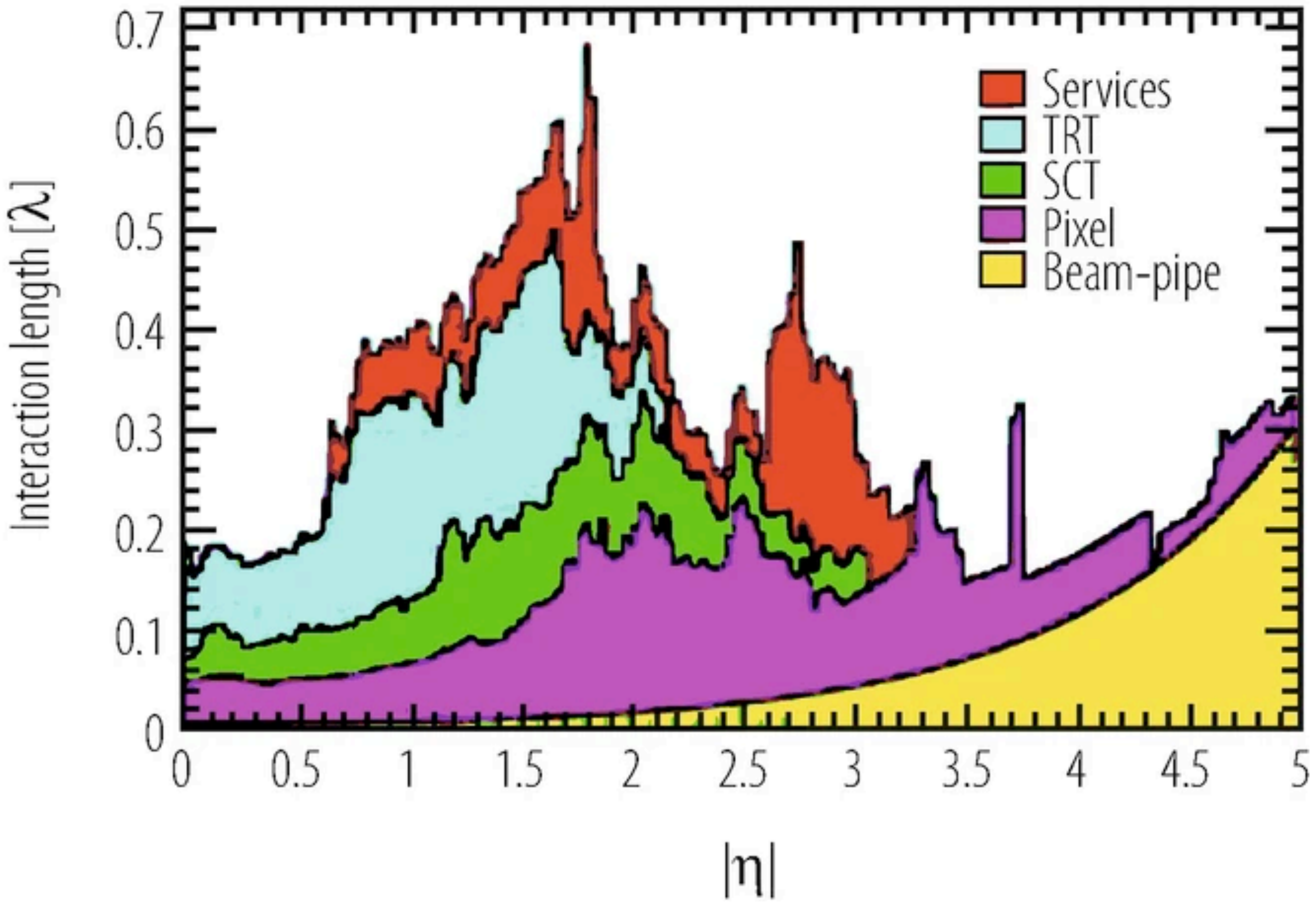


parameter	Design	Run-3	HL-LHC
Circumference	27 km (r=4243 m)		
depth	100 m		
arcs	8 arcs; each has 23 cells; cell is 106.9 m		
insertions	8 insertions: insertion is a straight section with transition regions at each end.		
energy	14 TeV	14 TeV	14 TeV
bunches	3550 (with 7.5 m/25 ns) spacing)		
effective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

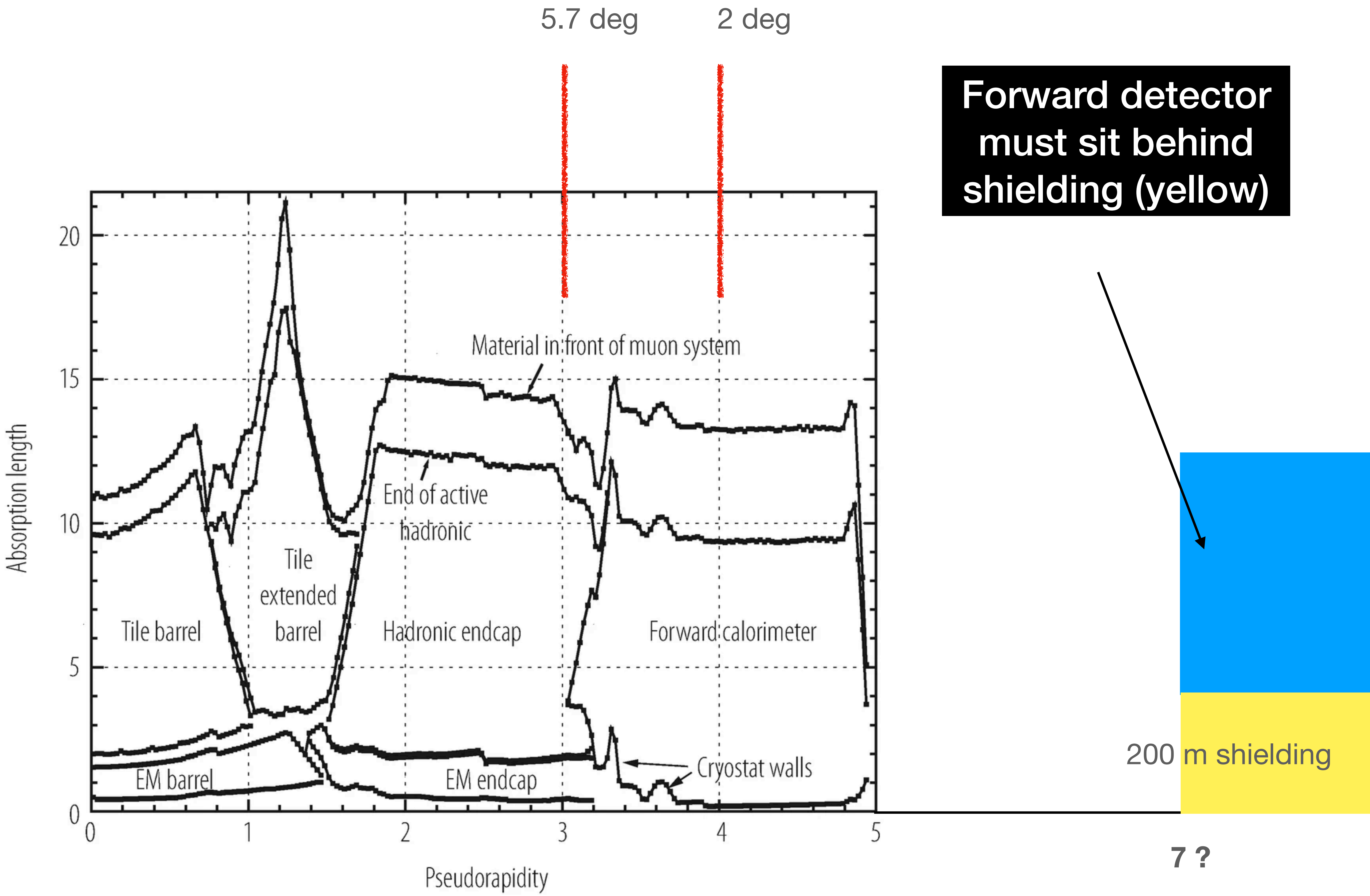
- For a forward experiment a ***well shielded location tangent*** to an IP must be found.
- The HL-Luminosity projections are to increase up to 7.5 10^34 cm^{-2} s^{-1}
- Source: Jamie Boyd (2001.04370)

ATLAS coverage

Physics coverage $\eta \leq 3.5$



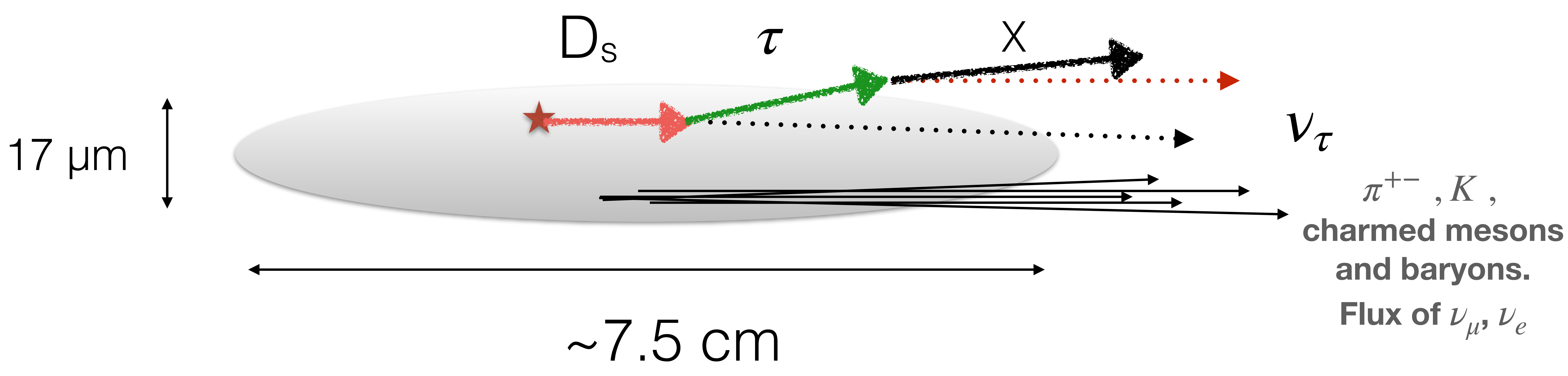
$\eta \equiv -ln[\tan(\theta/2)]$



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

Production geometry

~4 GeV/14 TeV (momentum due to the crossing angle, ignored for most 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.

Recall heavy particles lile W, Z, Higgs do not contribute much here. Their decay products are at high PT

Neutrinos at FPF

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

Two types of calculations needed

- $c\tau(\pi, K^{\pm}, K_L) = 7.8m,\ 3.7m,\ 15m$
- $\pi \to \nu_\mu, K \to \nu_\mu, K \to \nu_e$ 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.

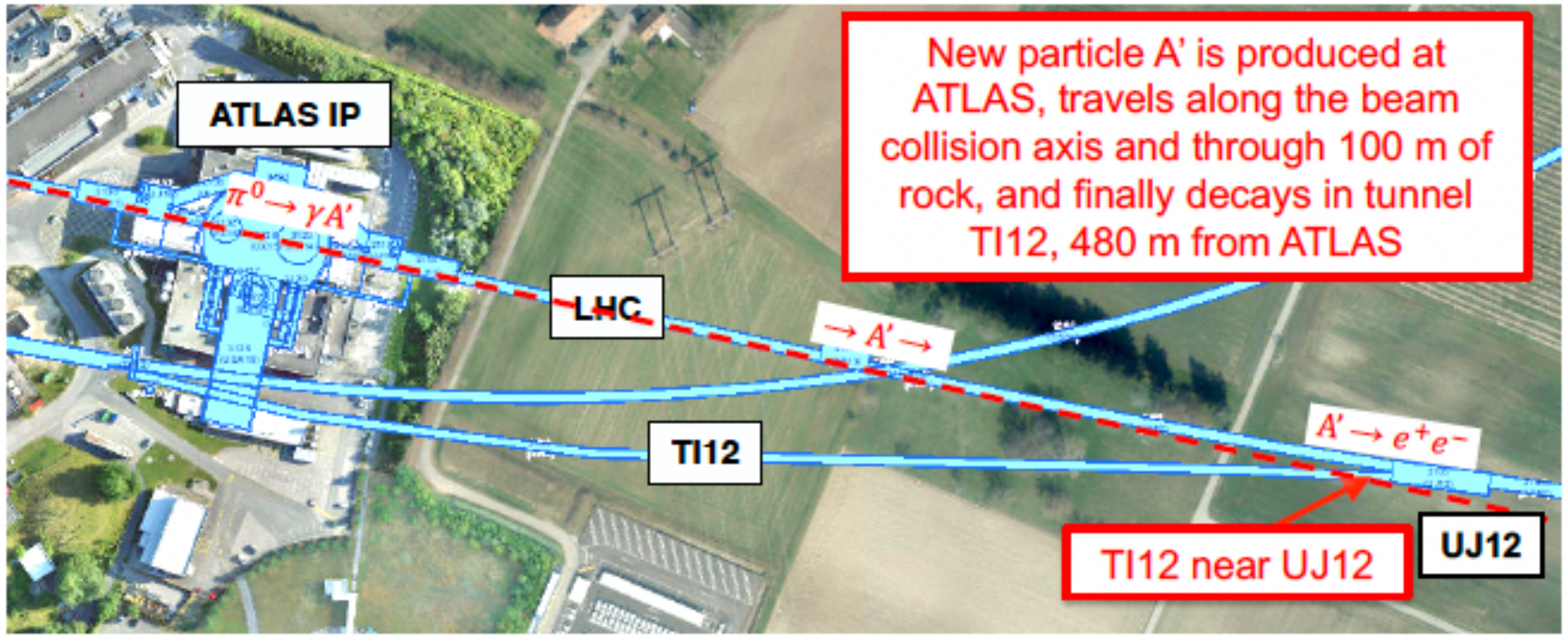
Needs modeling of forward production in the PP interaction

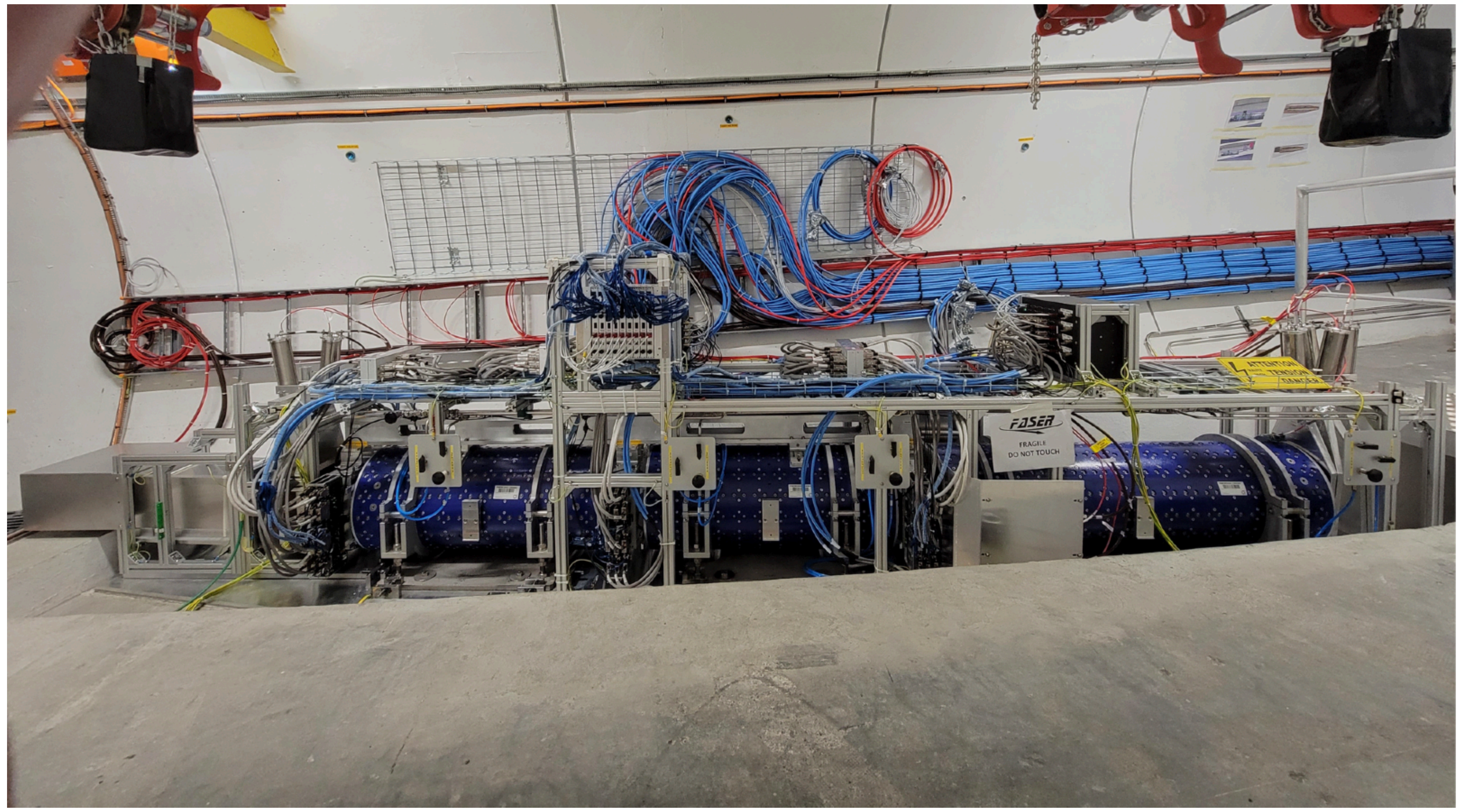
Current program

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. (also builds a community)





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

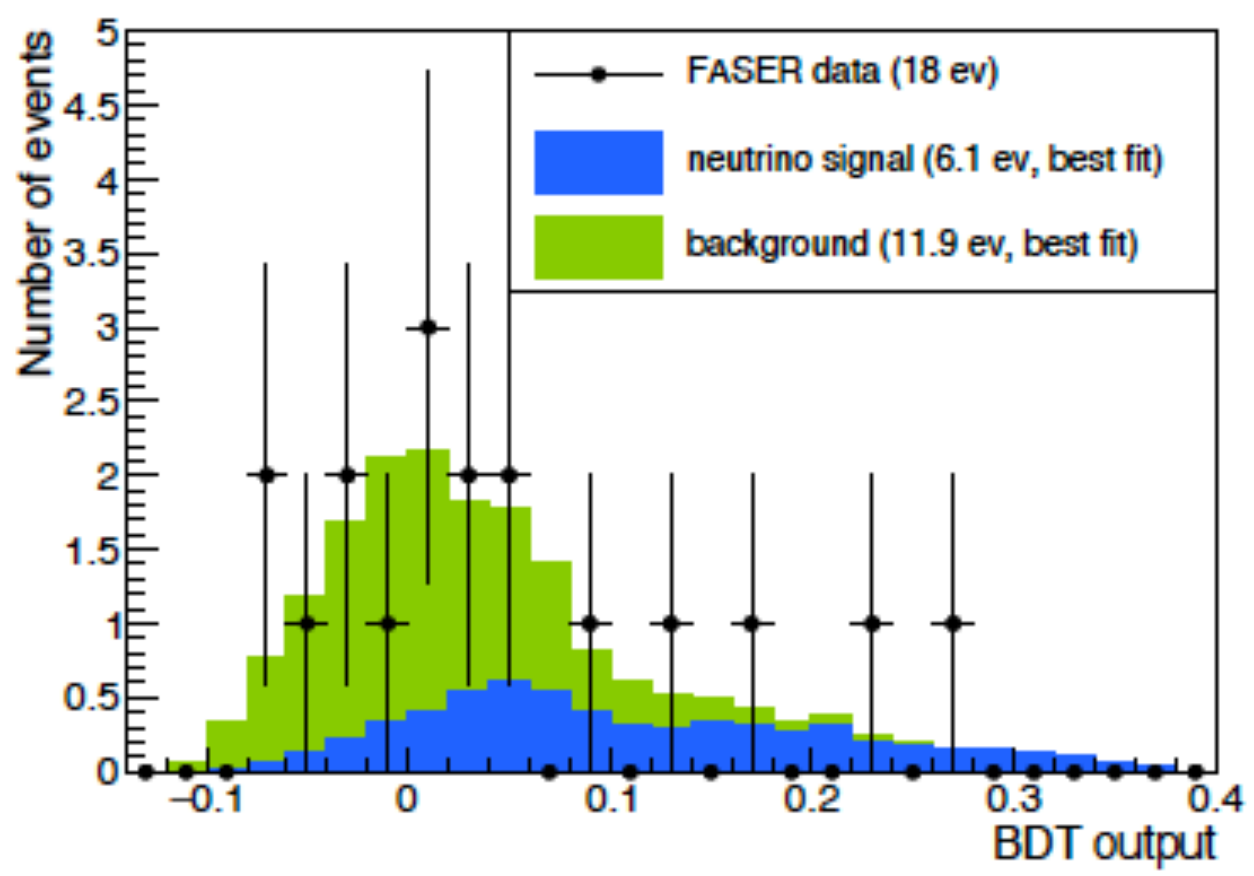
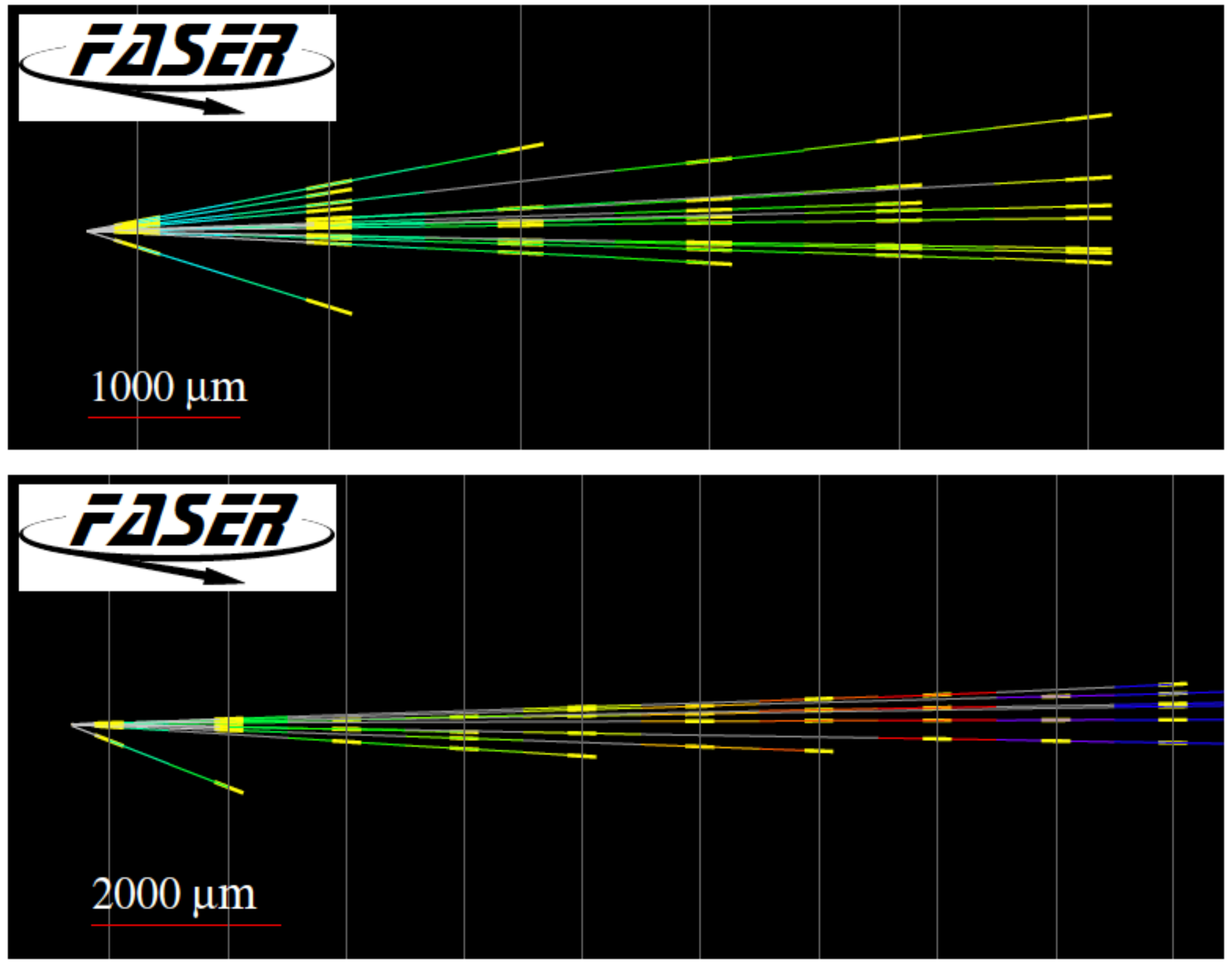


FIG. 6. The BDT outputs of the observed neutral vertices, and the expected signal and background distributions (stacked) fitted to data. Higher BDT output values are associated with neutrino-like vertex features.



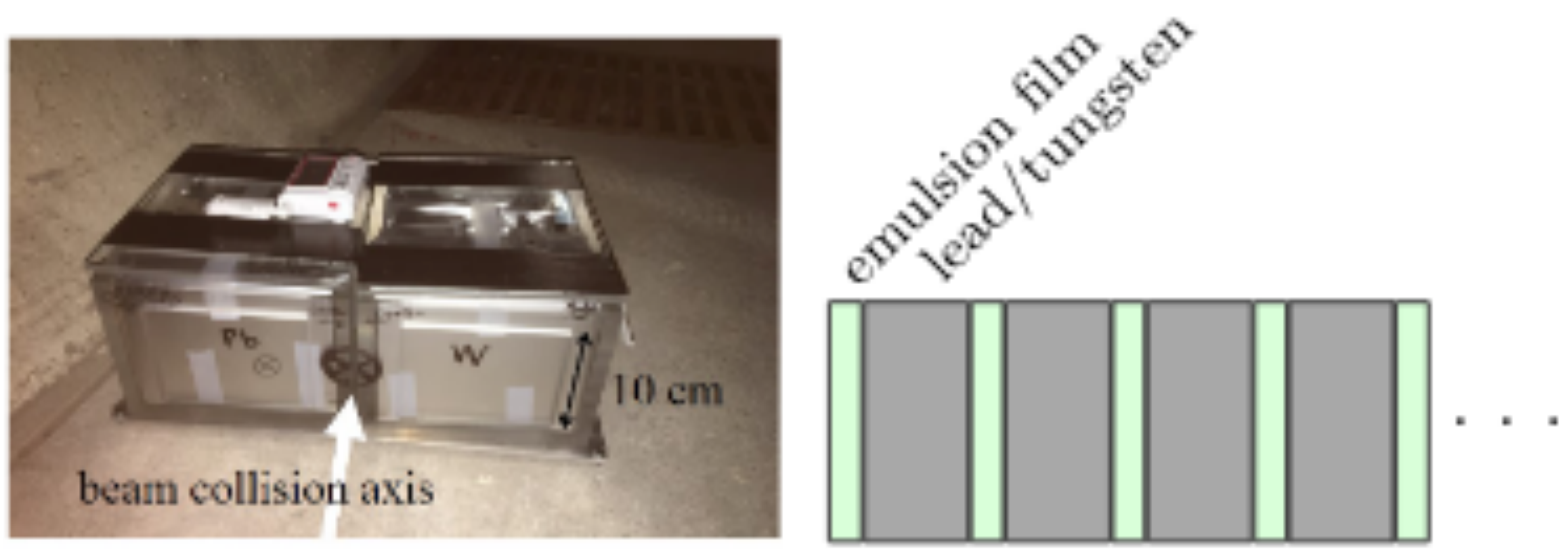


FIG. 1. Structure of the pilot emulsion detector. Metallic plates (1-mm-thick lead or 0.5-mm-thick tungsten) are interleaved with 0.3-mm-thick emulsion films. Only a schematic slice of the detector is depicted.

A forward program with much larger detectors is clearly well-justified.

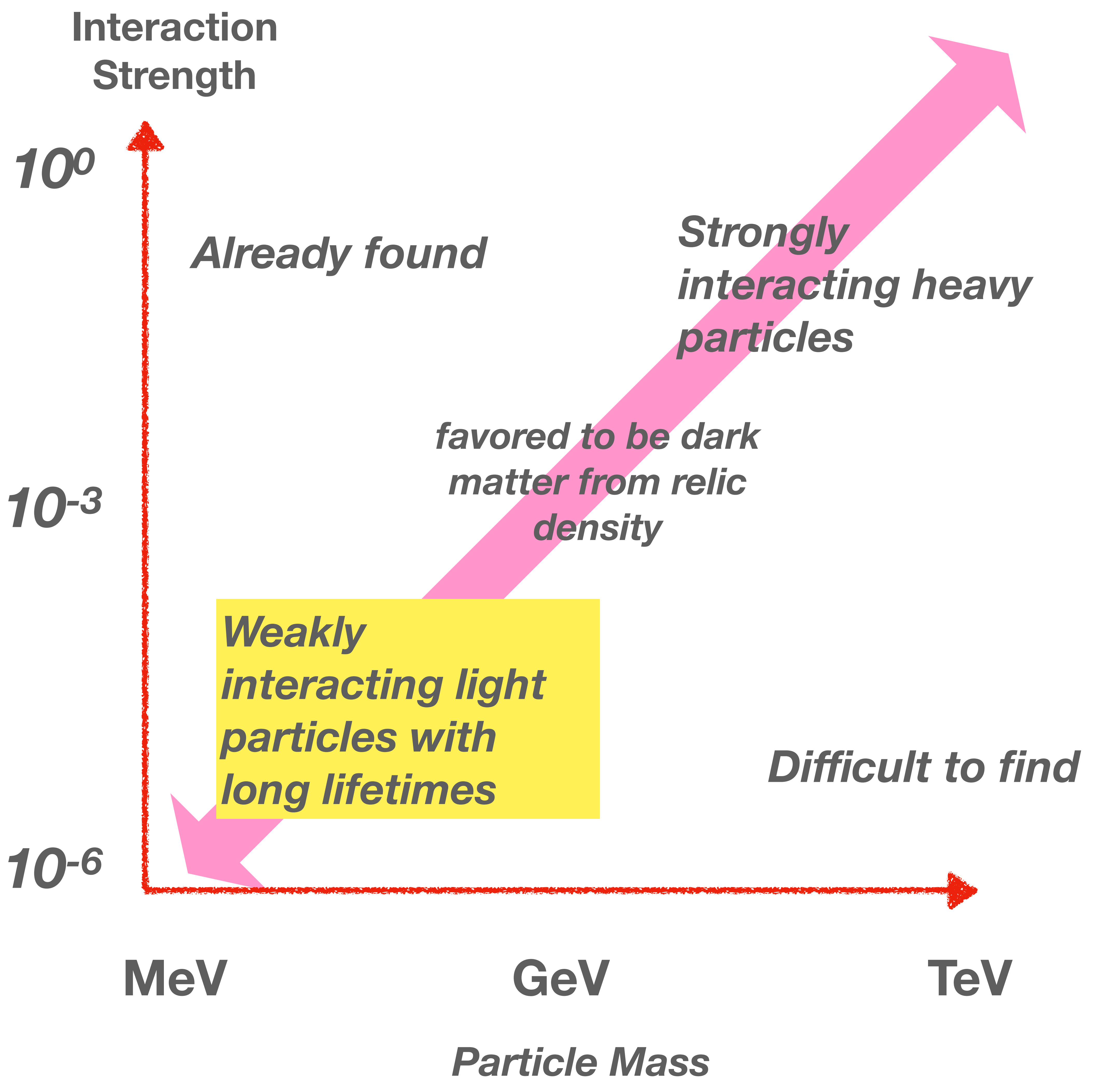
Physics topics for a new program of forward physics.

(from the abstract to the specific)

Standard model and BSM science program

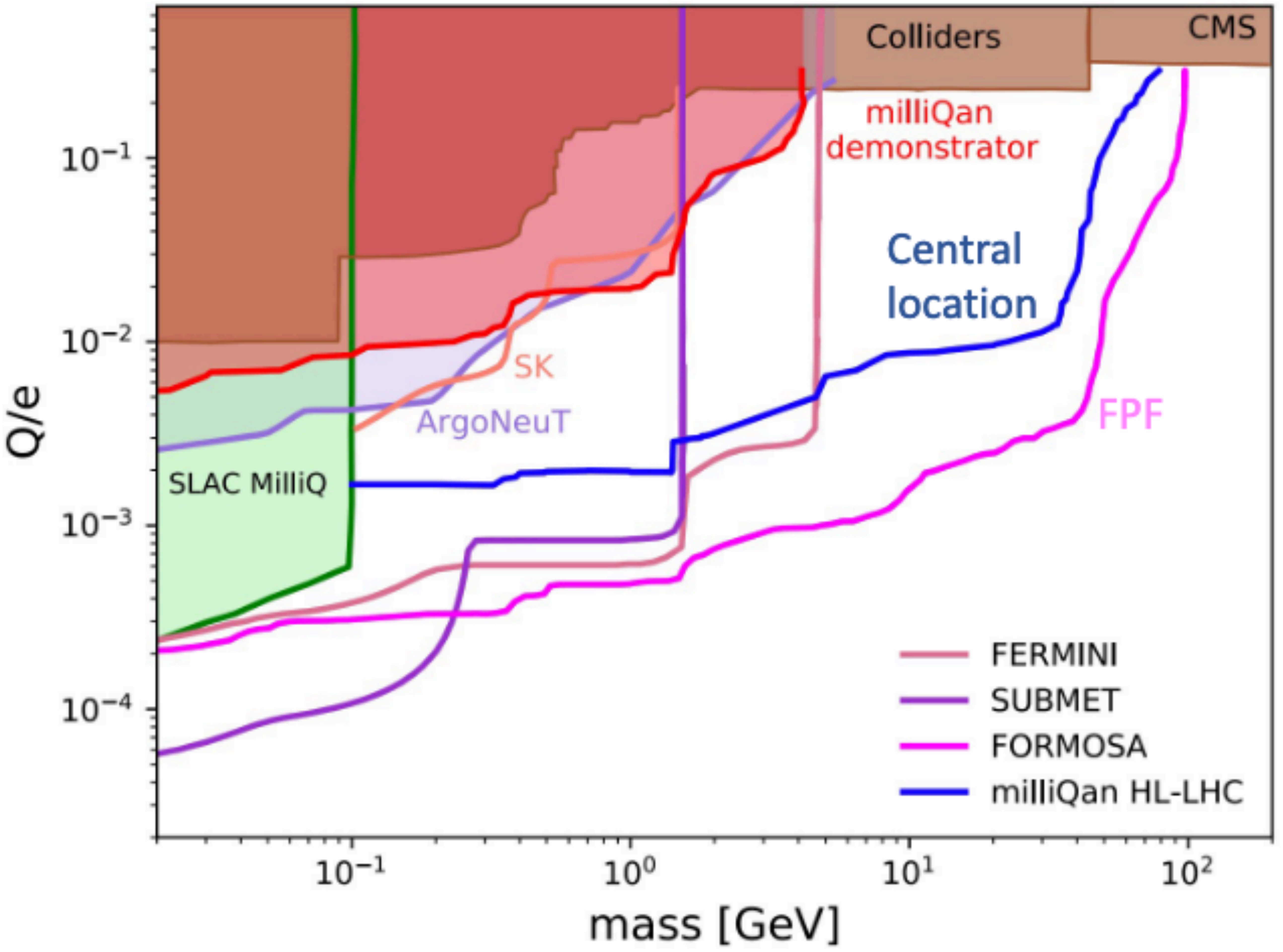
General considerations

- 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.



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)

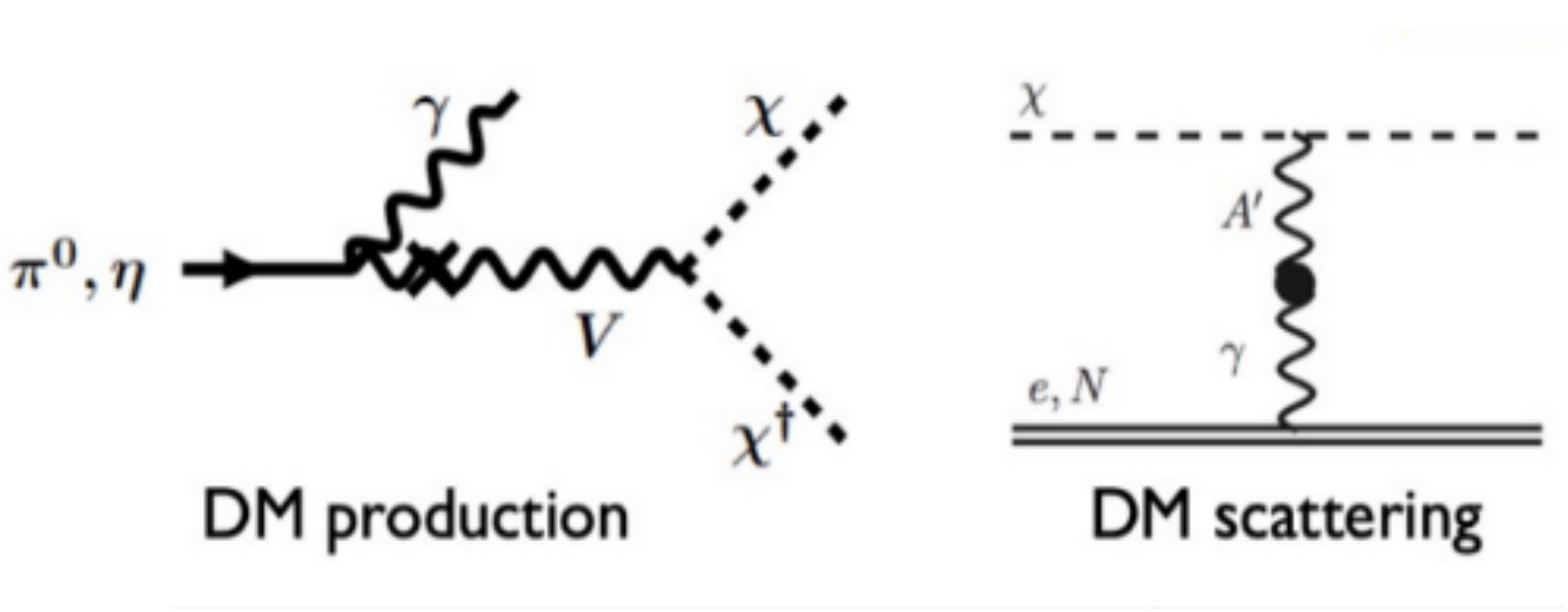


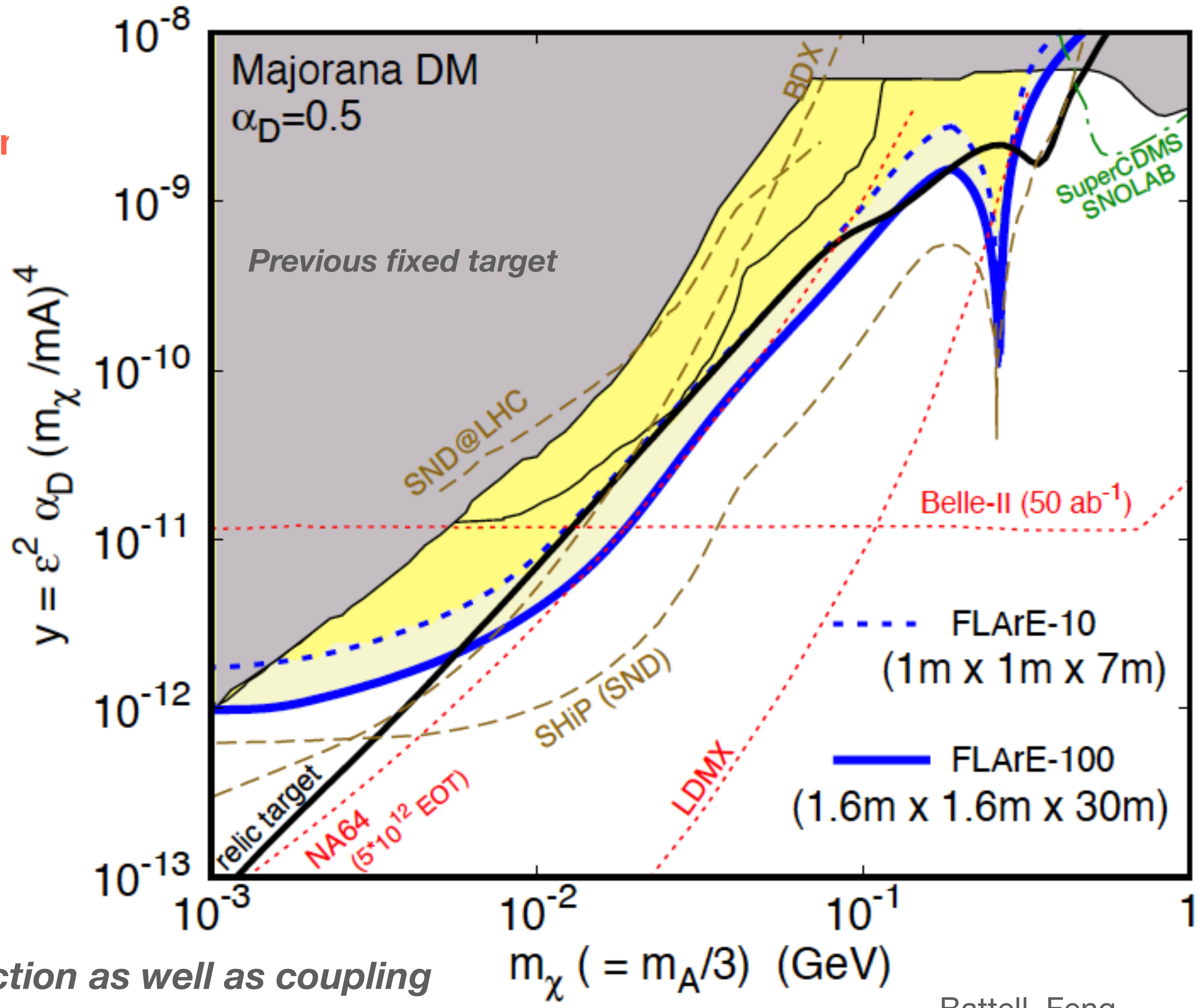
Foroughi-Abari-Kling (2020)

Light Dark Matter scattering (FPF@HL-LHC)

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.

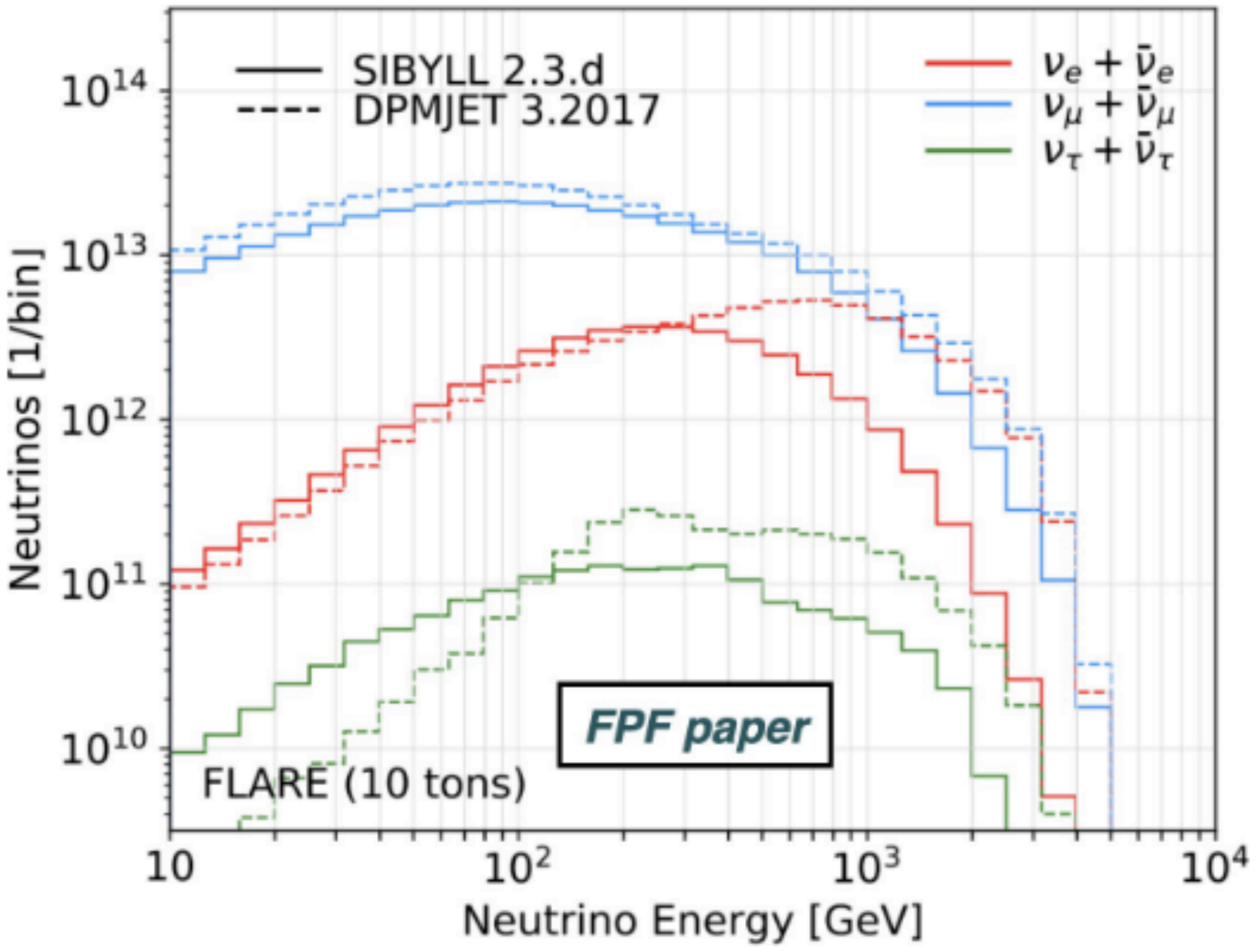
Battell, Feng, Trojanowski (2021)

Neutrino event rates @600 meters (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.

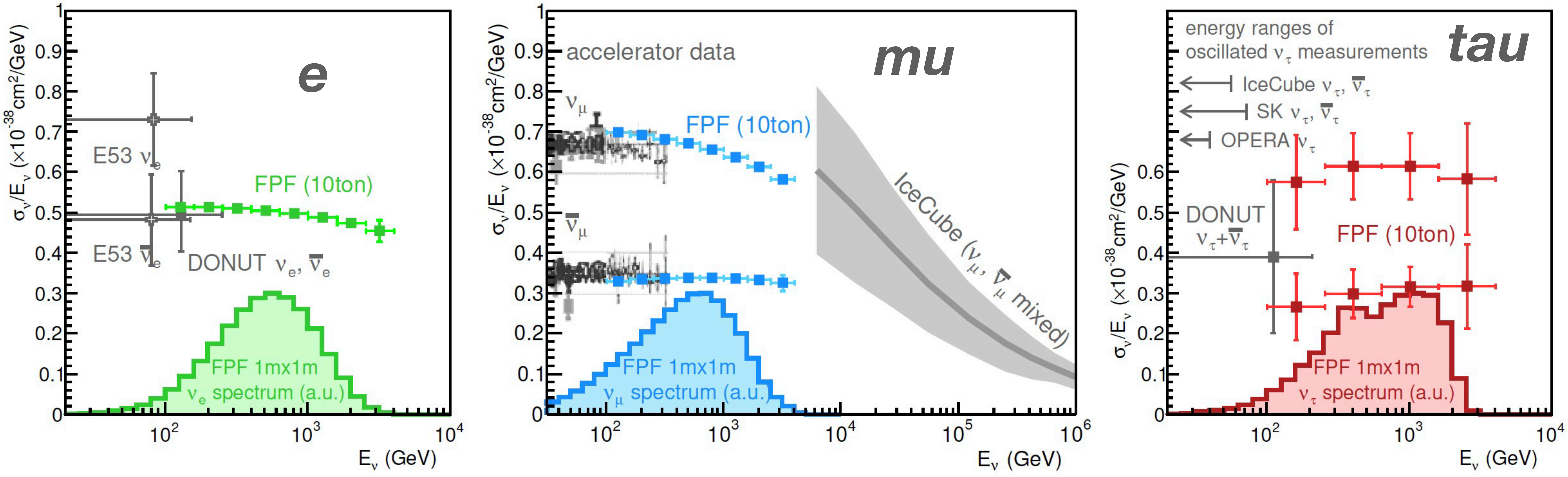
evts/ ton/fb-1	ν	$\bar{\nu}$	Total
e	2.1	1.0	3.1
mu	15	5	20
tau	0.1	0.05	0.15

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

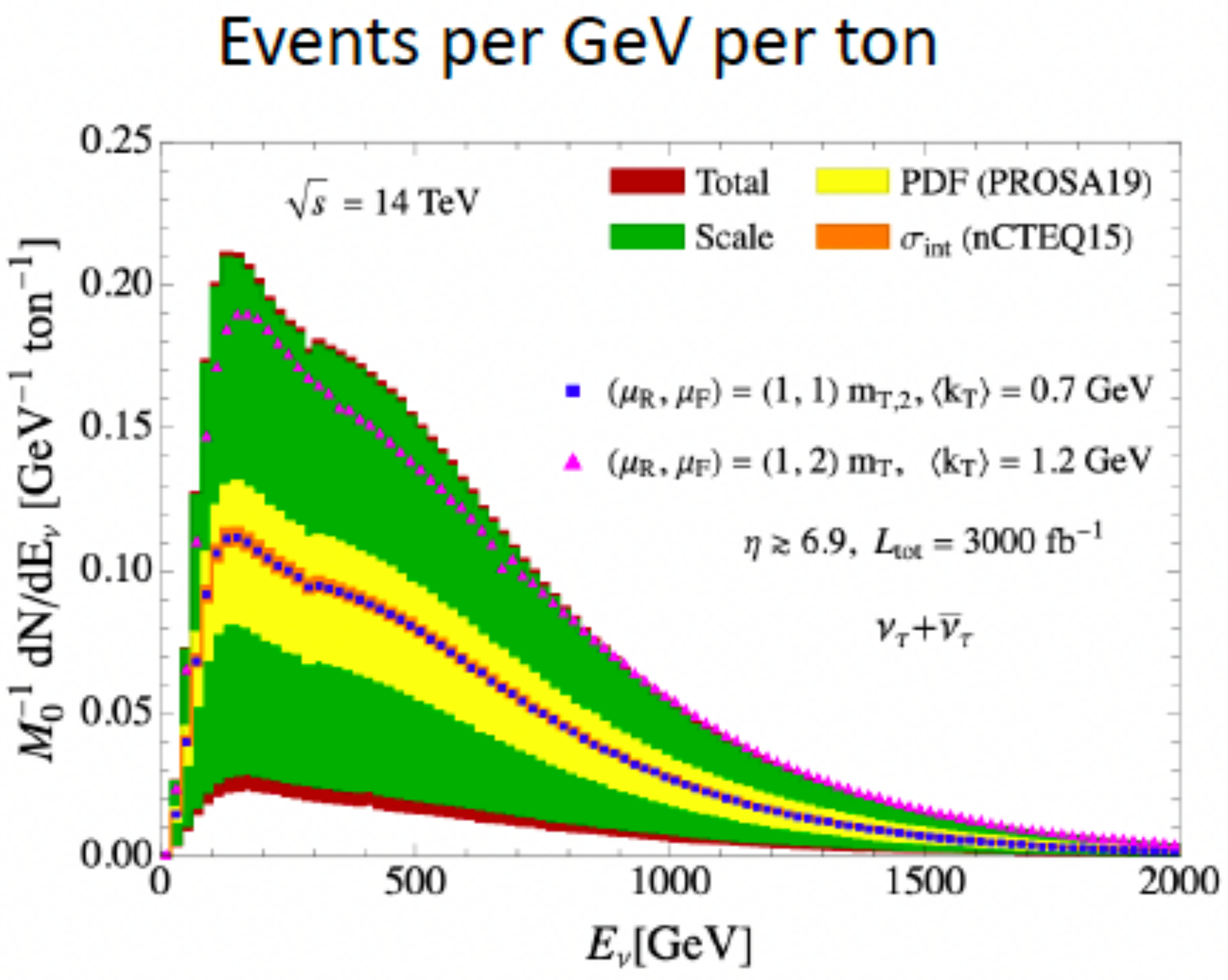
Parton distribution function uncertainties in theoretical predictions for far-forward tau neutrinos at the Large Hadron Collider,
Weidong Bai, Milind Diwan, Maria Vittoria Garzelli, Yu Seon Jeong, Karan Kumar, Mary Hall Reno,

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

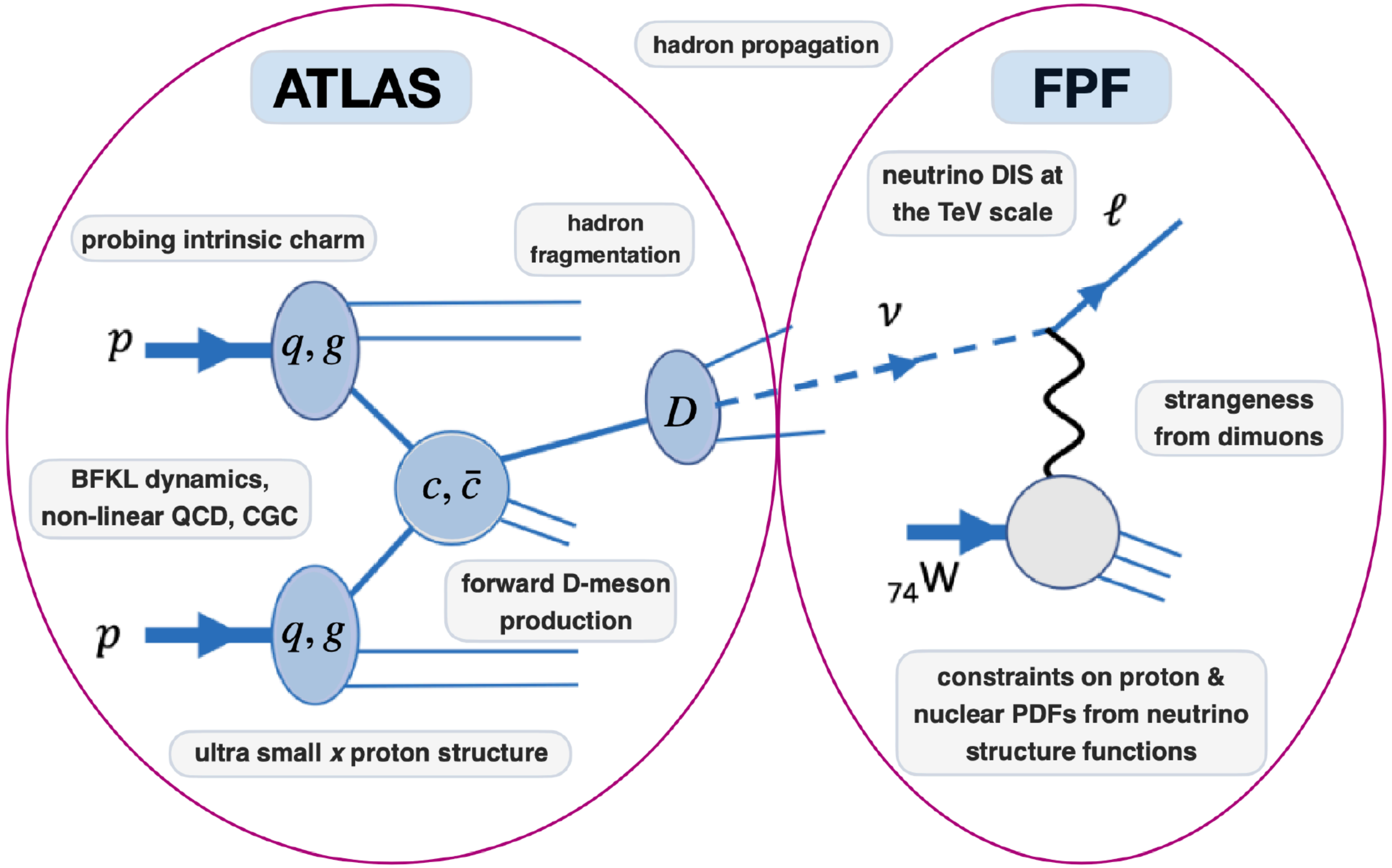
normalized for ~60 ton of tungsten

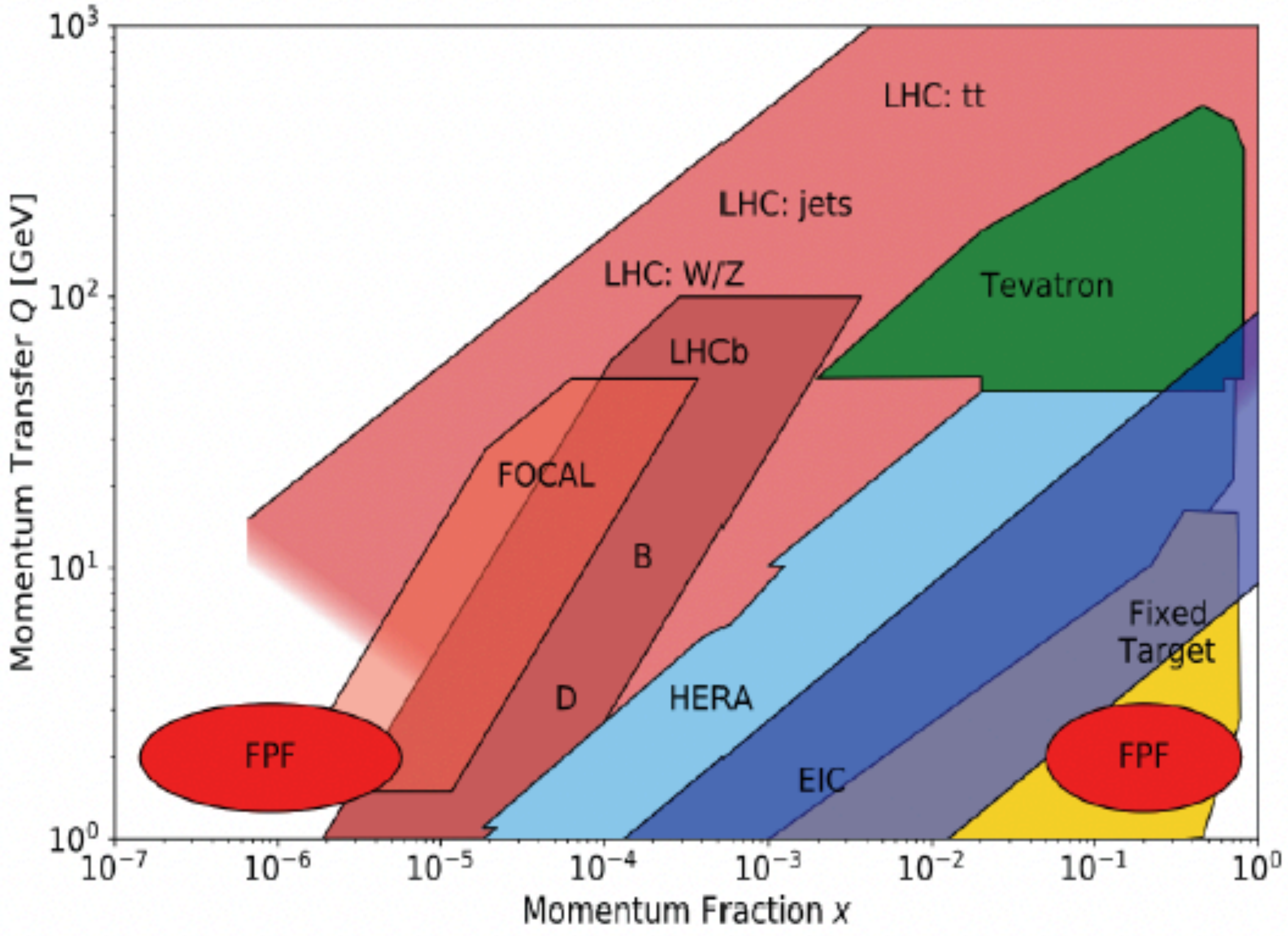
- This result uses LHC-b data on charm to extrapolate to large rapidities.
- Still, the largest uncertainties are from scale variation.
- Measuring this rate will pin down forward charm production.



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. New work shows significant reach for astrophysics with CM ~14 TeV***

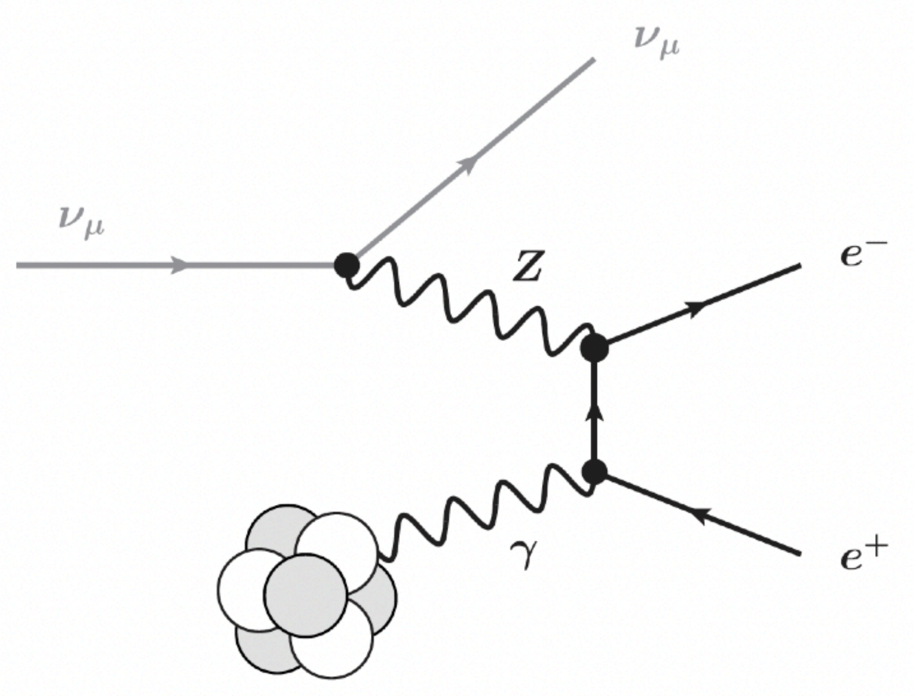
Flux and cross section errors.

How do we deal with unknown flux and cross sections ?

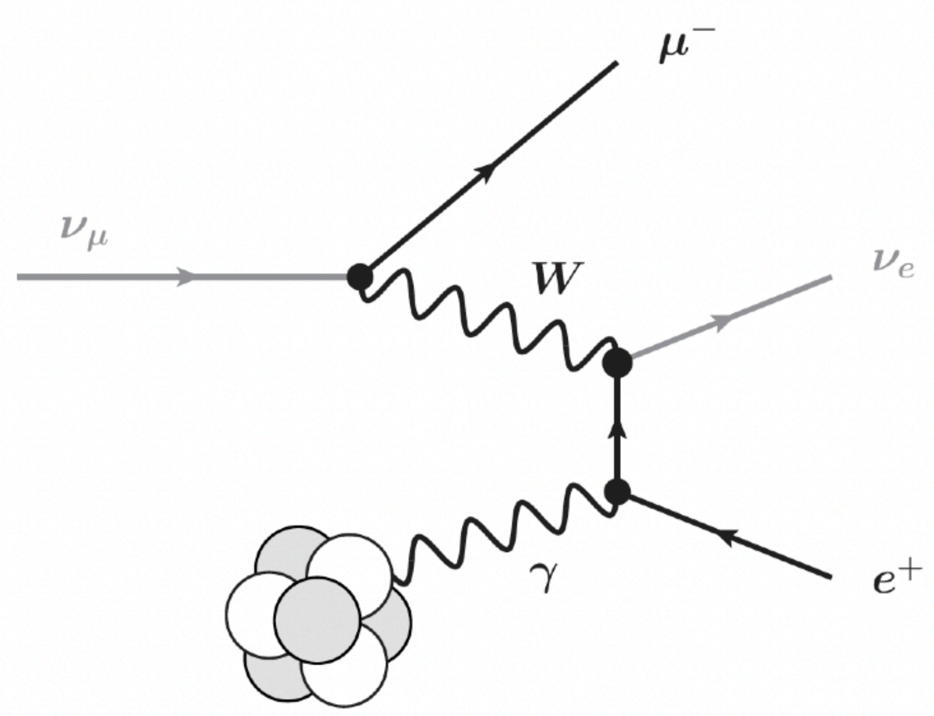
- The cross section and flux determination will be in a joint theoretical and experimental program. Evolving step by step like any other program.
  - Detailed simulations of the beam are needed for muon and electron components.
  - Well known cross sections (lo-nu and elastic scattering) can be used 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.***

Neutrino Tridents

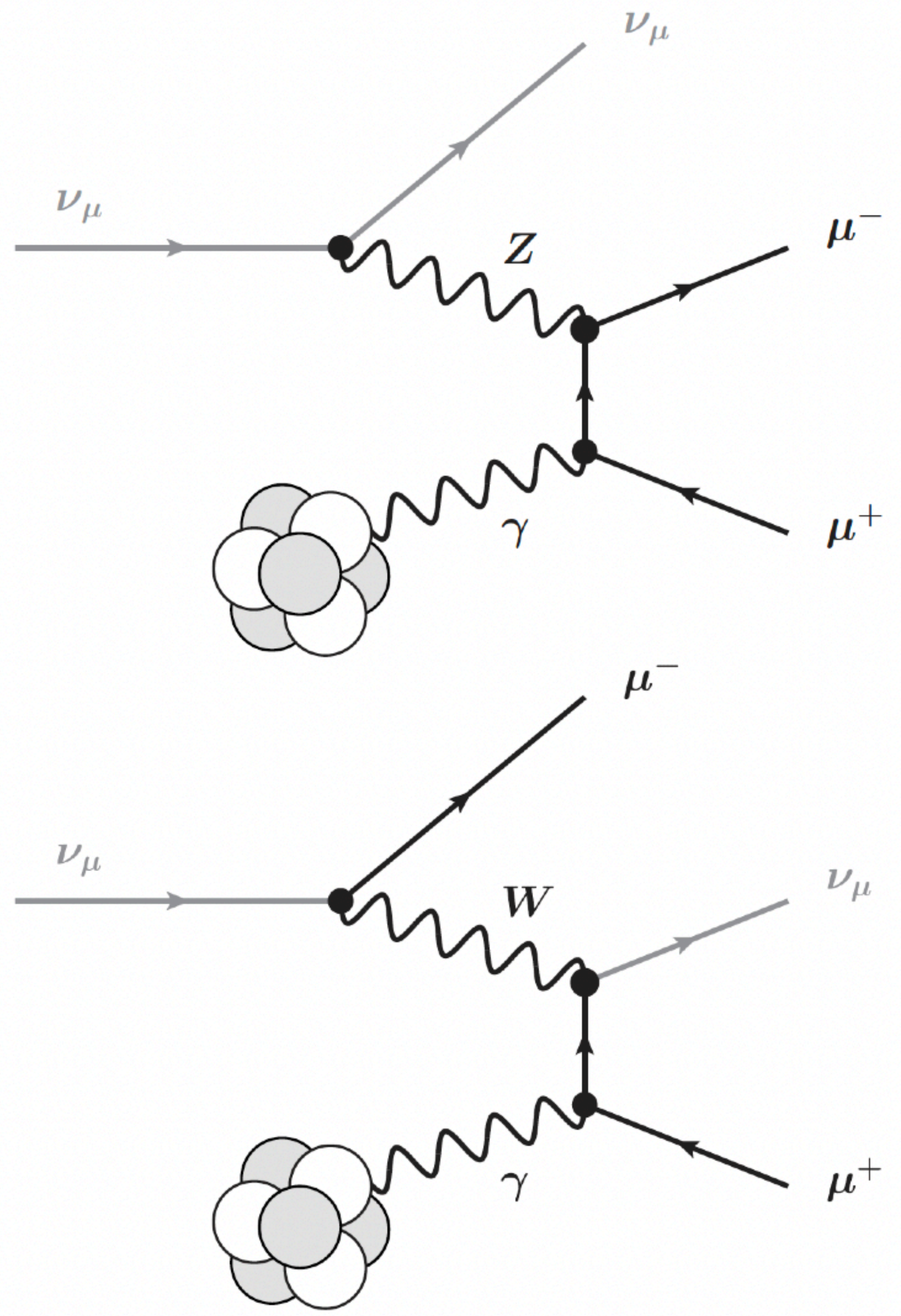
- *Neutrino induced production of charged lepton pairs in the presence of a nucleus.*
- *Mediated by electroweak interactions at tree level and sensitive to new physics.*
- *Rare process.   Mu+mu- has evidence from (CHARM-II) and CCFR.*
- *Coherent cross section strongly enhanced by Z and energy. The LHC flux would open up tau channels as well.*



ee



mue



mumu

$\sigma \approx 1\ fb$ at 200 GeV on Ar
Rate is much larger on larger Z.
Ar-18, Kr-36, Xe-54, W-74

Process	$g^V_{\rm SM}$	$g^A_{\rm SM}$
$\nu_e \to \nu_e e^+ e^-$	$1 + 4\sin^2\theta_W$	-1
$\nu_e \to \nu_e \mu^+ \mu^-$	$-1 + 4\sin^2\theta_W$	$+1$
$\nu_e \to \nu_\mu \mu^+ e^-$	2	-2
$\nu_\mu \to \nu_\mu e^+ e^-$	$-1 + 4\sin^2\theta_W$	$+1$
$\nu_\mu \to \nu_\mu \mu^+ \mu^-$	$1 + 4\sin^2\theta_W$	-1
$\nu_\mu \to \nu_e e^+ \mu^-$	2	-2

$$d\sigma_{\rm coh.} \propto Z^2 \alpha_{\rm em}^2 G_F^2 |F_N(q^2)|$$

See 1406.2332, Altmannshofer, Gori, Pospelov, Yavin
and 1902.06765, Altmannshofer, Gori, Martin-Albo, Sousa, Wallbank.

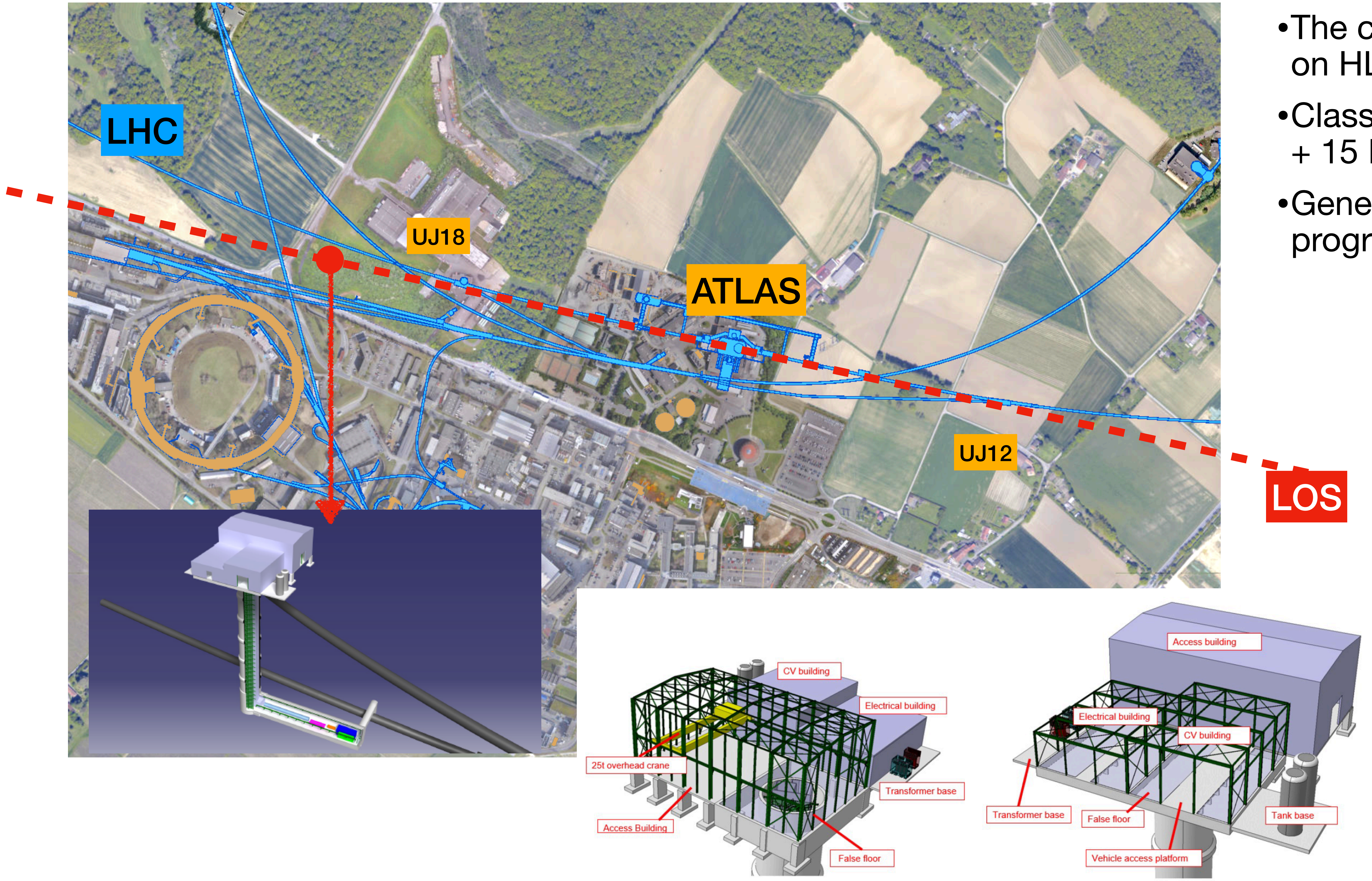
Forward Physics Facility and FLARE (forward liquid argon experiment)

Basic requirements for far forward detectors.

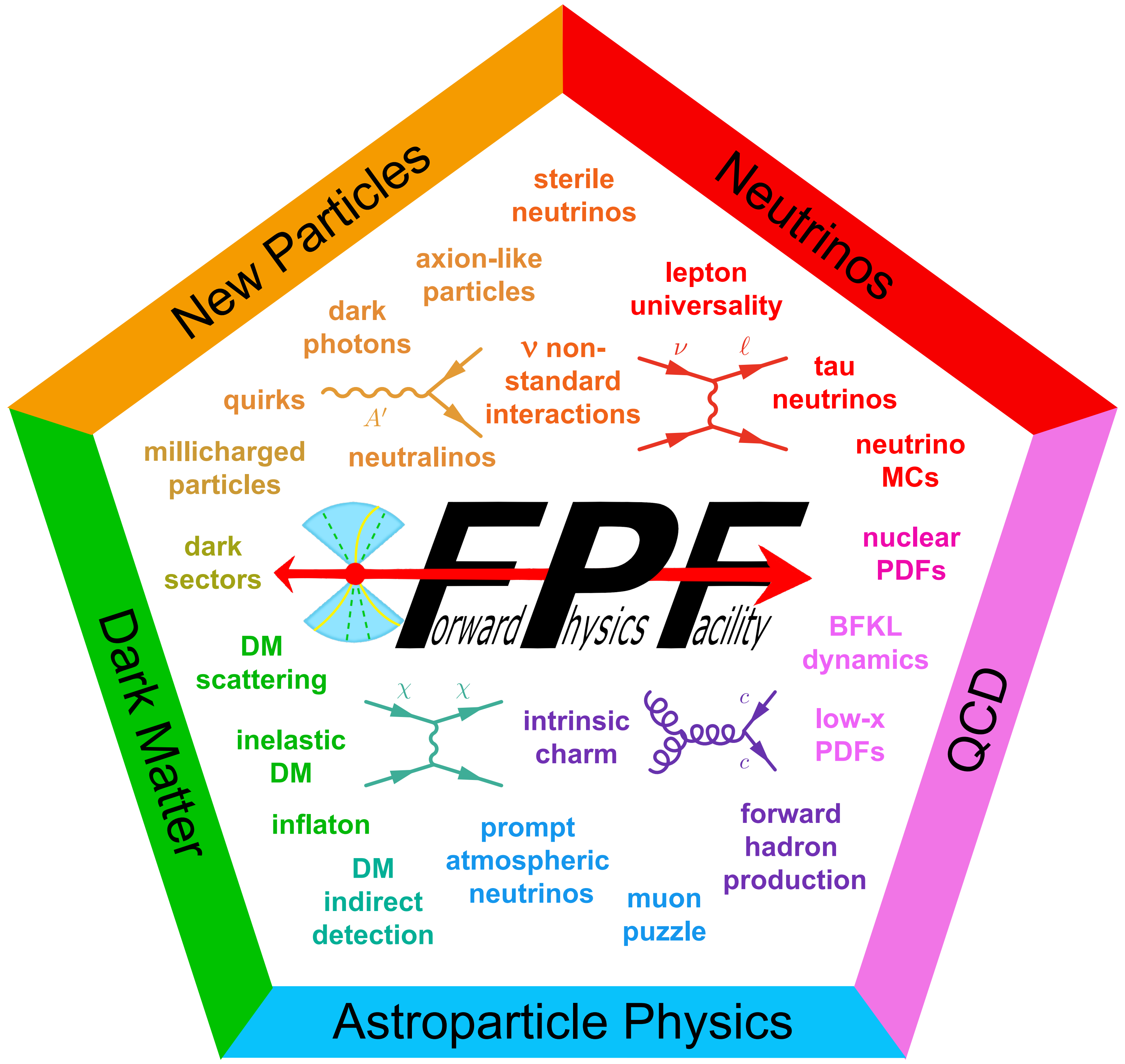
- Detector needs to be at 0 degrees to the collision axis.
- Some off-axis data might be very useful for neutrinos from high mass particles.
- Fiducial mass of 10 tons at few hundred meters is needed for good statistics and sensitivity to dark matter.
- Detectors need to have good energy containment (high density) and resolution (~10 interaction lengths, live detector) for neutrino physics.
- Detectors need low (~100 MeV) threshold for dark matter elastic scattering
- Detectors need <1 mm scale spatial resolution if we want to detect tau neutrinos with low backgrounds.
    - Only emulsion is guaranteed for this scale, but emulsion/tungsten stack will not have great total energy resolution. And it cannot be triggered.
    - The only other detector with this possibility is a liquid argon time projection chamber.

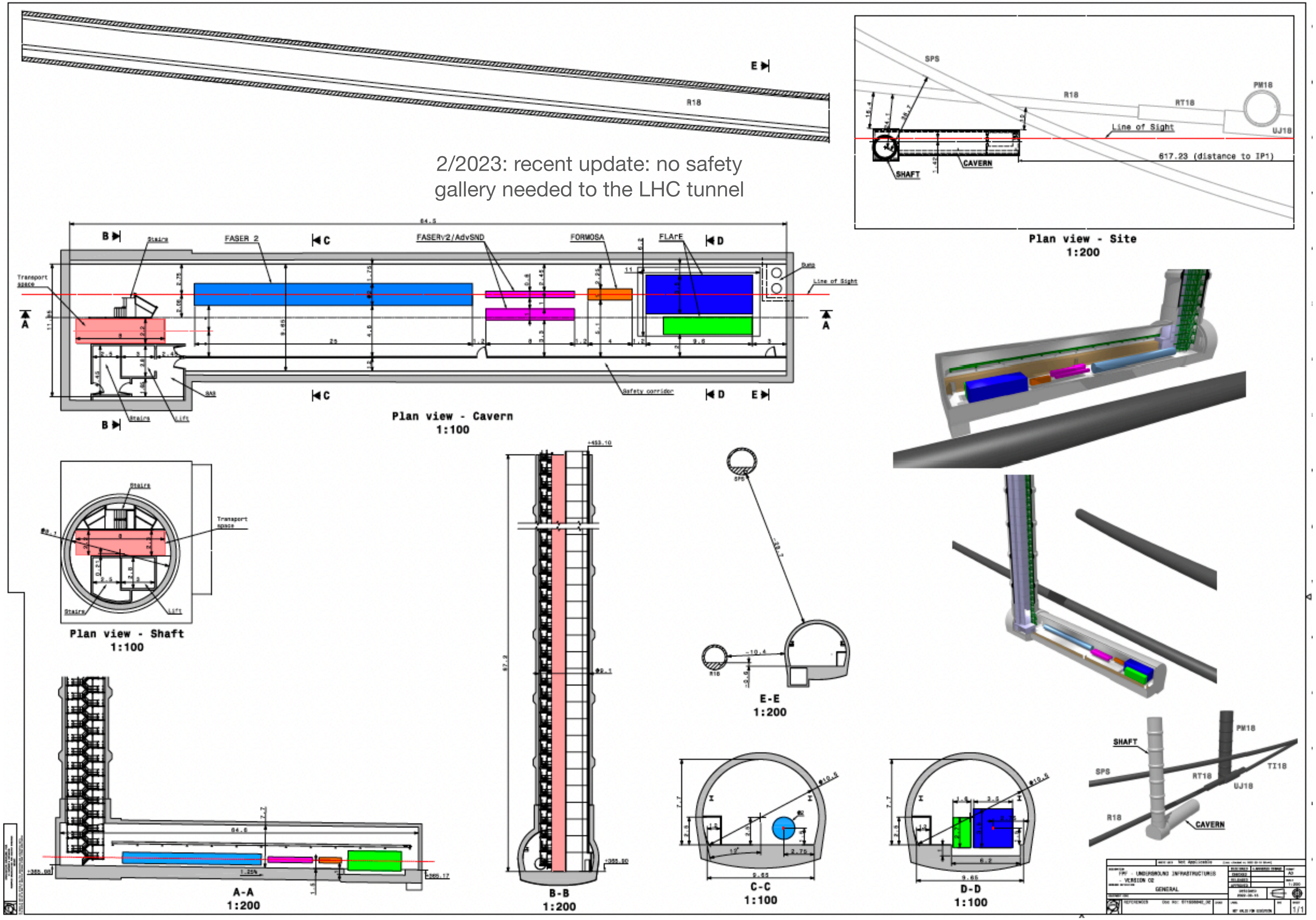
Forward Physics Facility (FPF)

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.





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

Class 4 means: -30% +50%

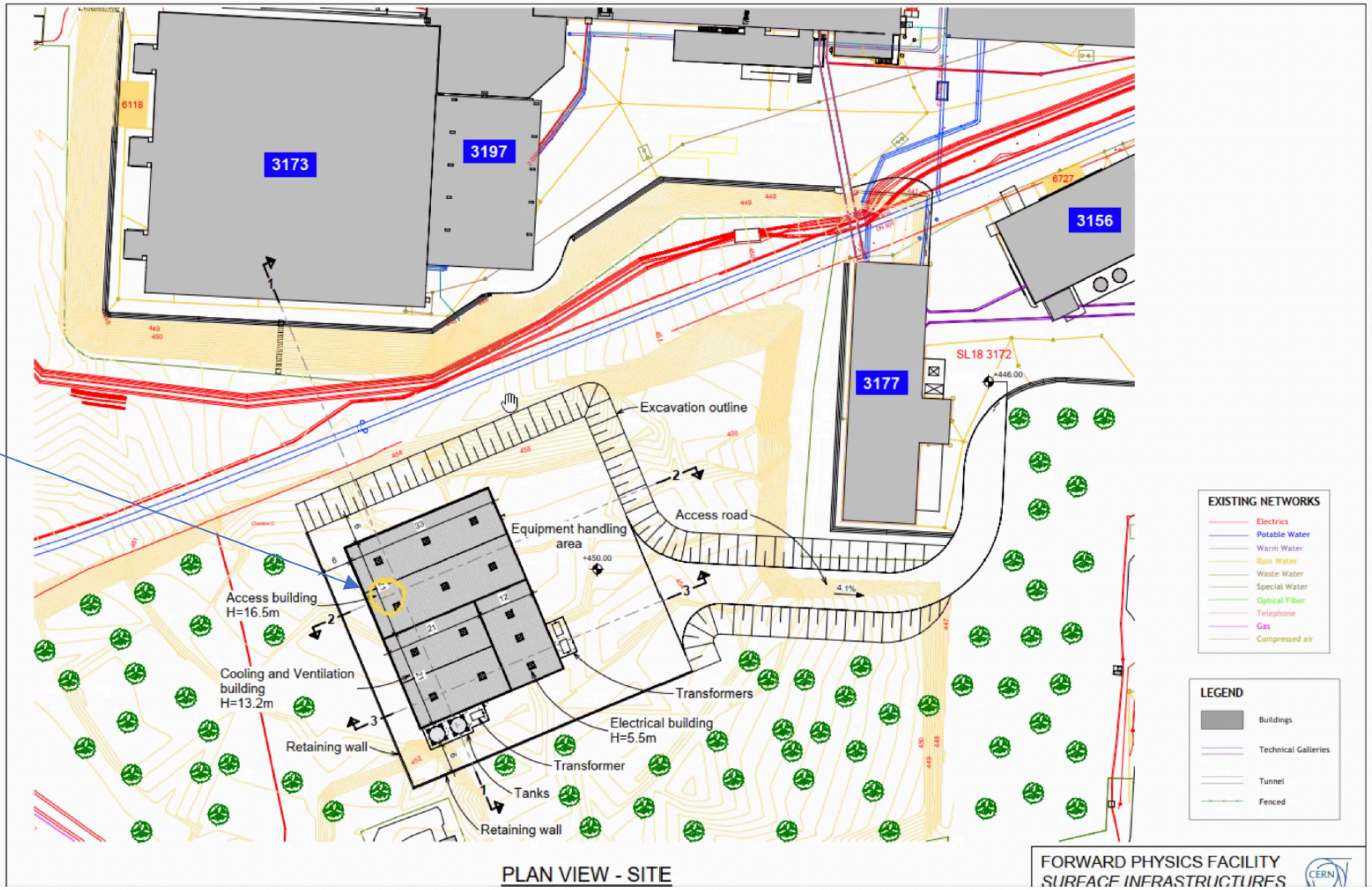
Important development April 22:

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

Civil Engineering: Site Investigation

Civil engineering team are starting a site investigation study.
With external consultant are planning to drill a core down to proposed FPF cavern level (90m) at location of shaft.
Will provide important information on on the structural strength of the rock at the cavern location, as well as understanding any contaminates in the rock, and would be fed into a revised design/costing.
Hope to have drilling and analysis carried out before the end of the year.

Planned drilling location



From: Jamie Boyd 2/2023

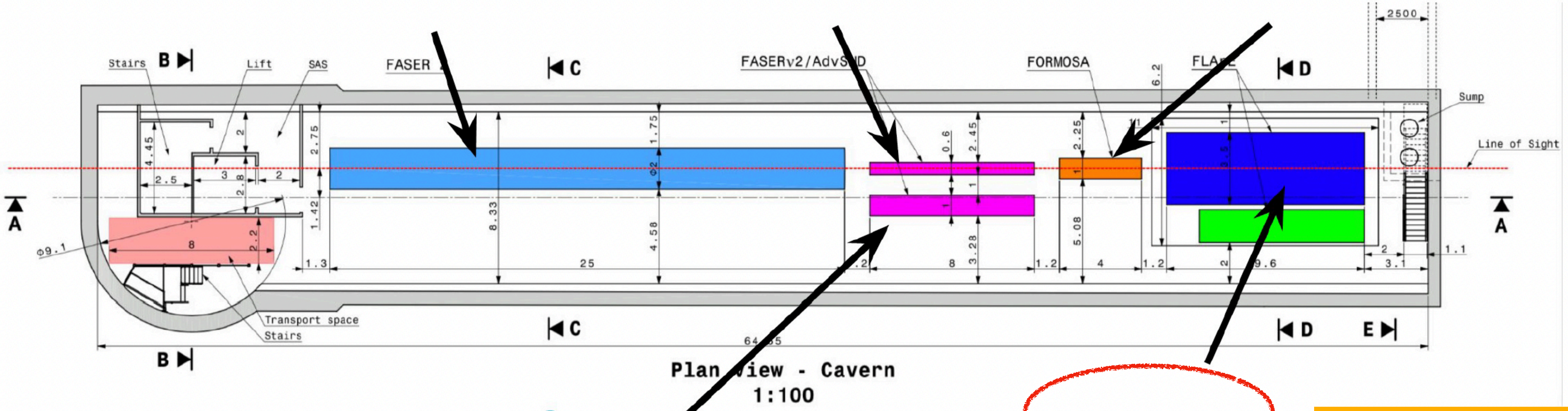
- At present there are 5 experiments being developed for the FPF.
- Pseudo-rapidity coverage in the FPF is $\eta > 5.5$, with most experiments on the LOS covering $\eta > 7$.

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

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

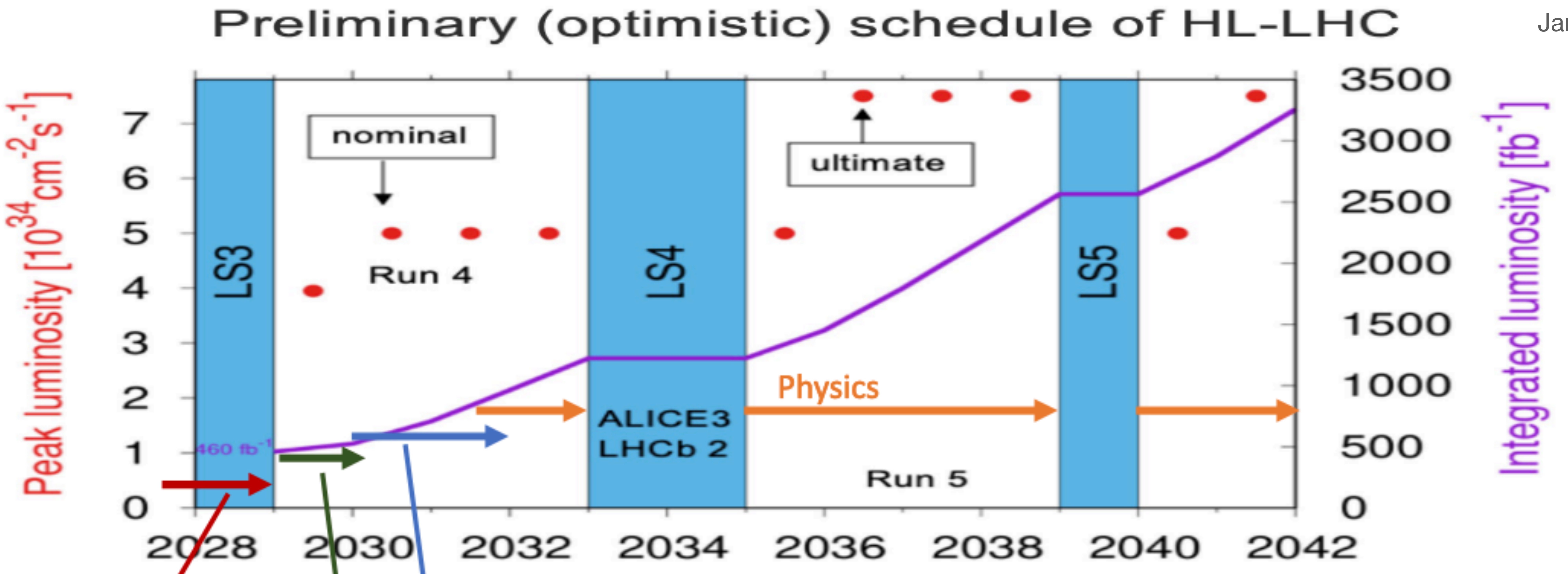
MVD will focus on technical issues of FLARE.

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

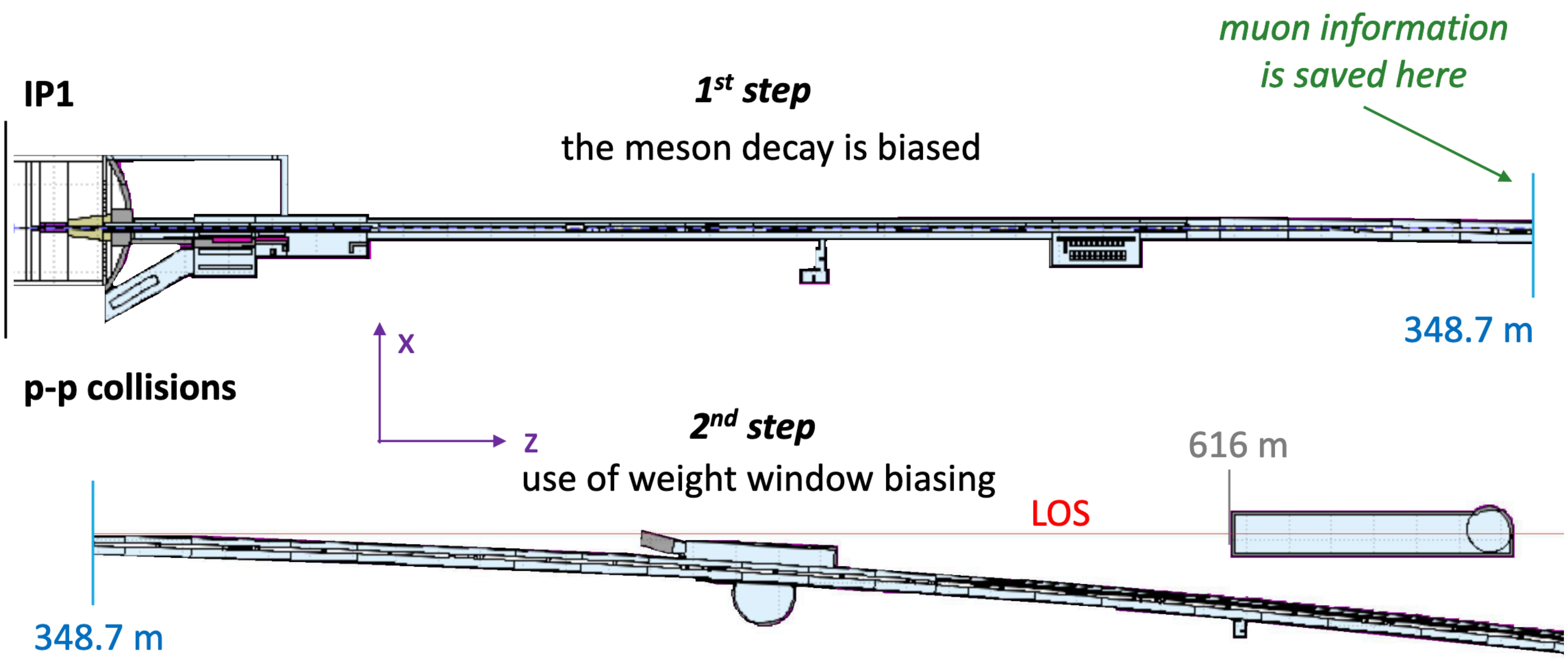
Radiation issues.

FLUKA simulations overview

BDSIM simulations have also been developed.

IR1 - HL-LHC
Horizontal crossing
+250 μrad half crossing angle

- In order to get the muon fluence in the FPF cavern:



LHC magnets

Important recent improvement is the inclusion of the full magnetic field of the LHC magnets.

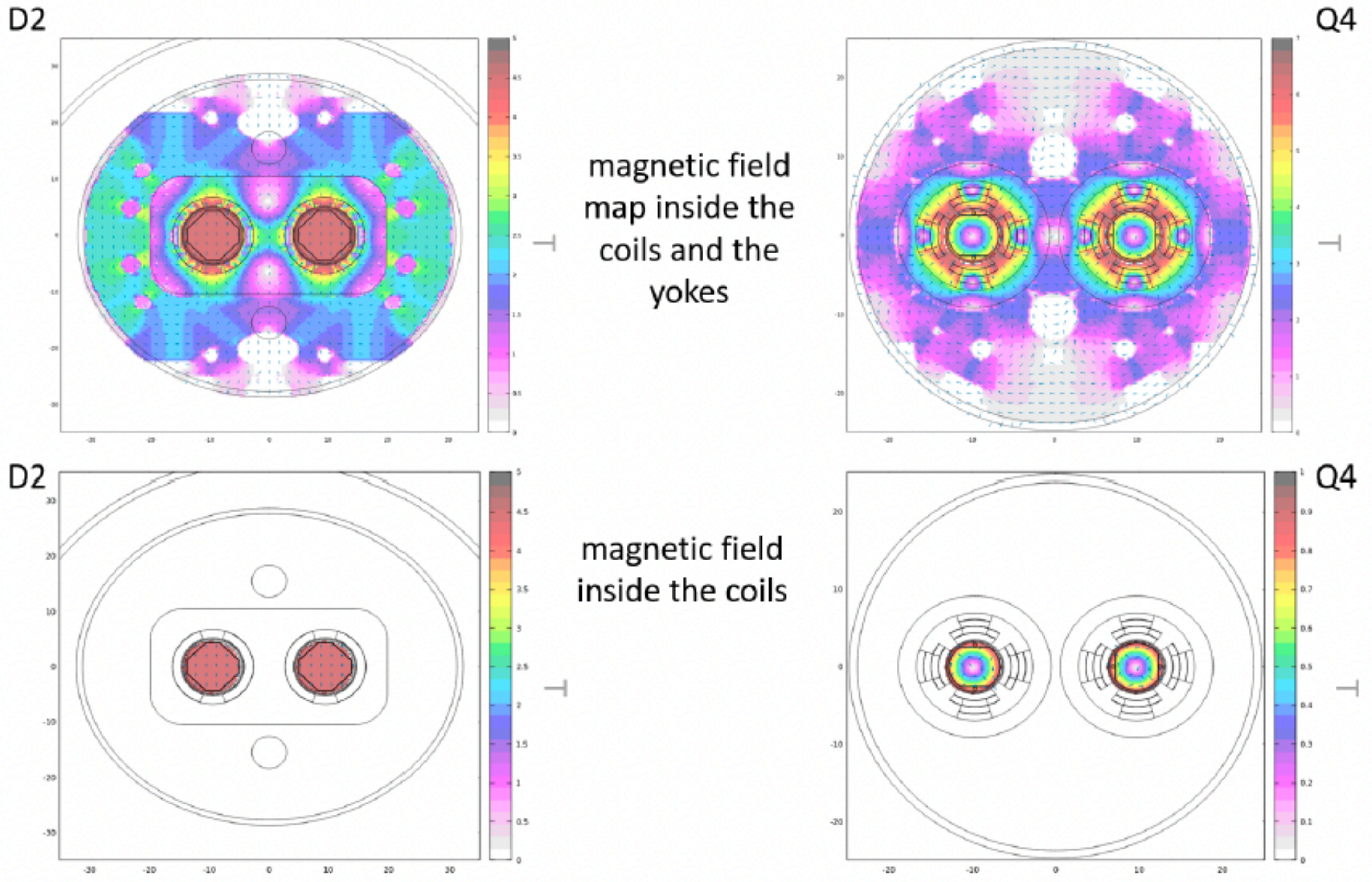


Figure 7: Magnetic field maps of the D2 recombination dipole (left) and Q4 matching section quadrupole (right). On the bottom it is shown the magnetic field in the two-bore region limited by the coils, as considered in previous simulations, while on the top the magnetic field region covers the whole magnet (courtesy of Susana Izquierdo Bermudez).

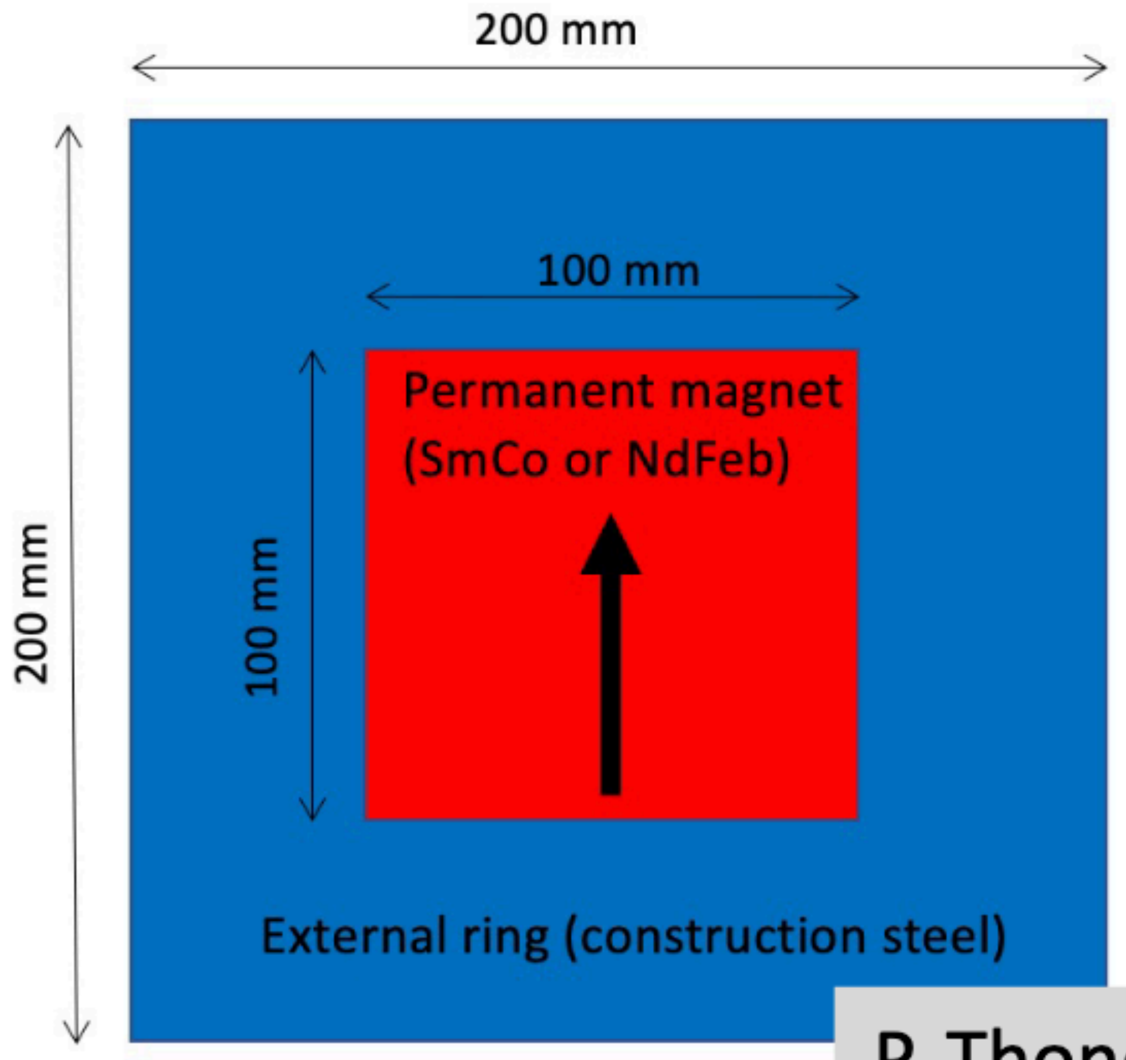
The LHC magnetic field effectively acts as a sweeper to move muons out of the way from the LOS.

Sweeper Magnet: Ongoing Studies

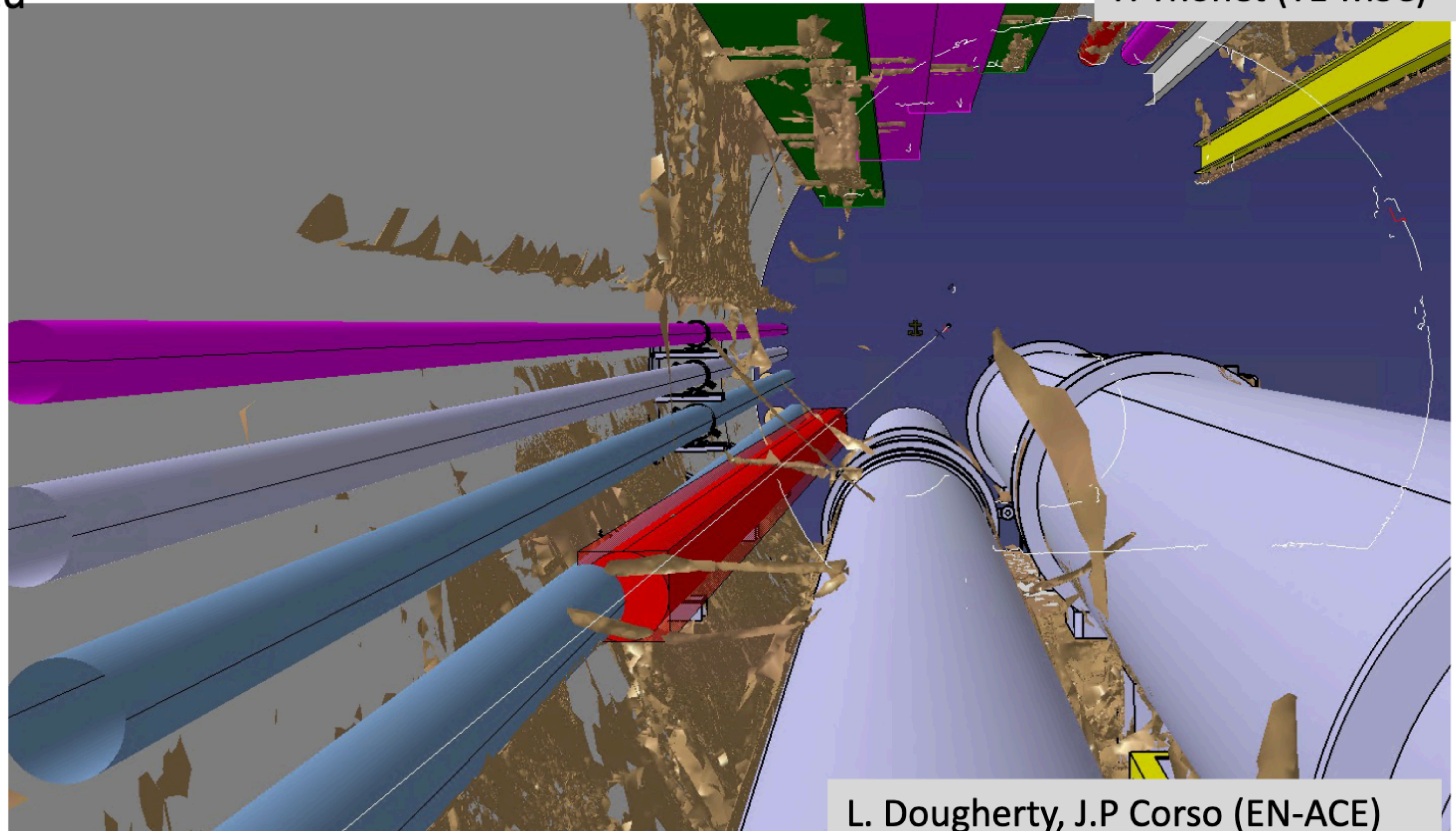
- Preliminary design of sweeper magnet by TE-MSC
  - Based on permanent magnet to avoid power converter in radiation area
  - Consider 7m long ($20x20cm^2$ in transverse plane) magnet, 7Tm bending power
- To install such a magnet would require some modifications to cryogenic lines in relevant area
  - 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

2/23: update

Current studies do no show appreciable reduction from variations of the sweeper magnet beyond what is achieved with appropriate calculations including the LHC magnets.



P. Thonet (TE-MSC)



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

Muon fluence at the FPF.

Muon flux: 0.6 Hz/cm^2 at 5*10^34/cm2/sec, 0.15mu+, 0.45mu-

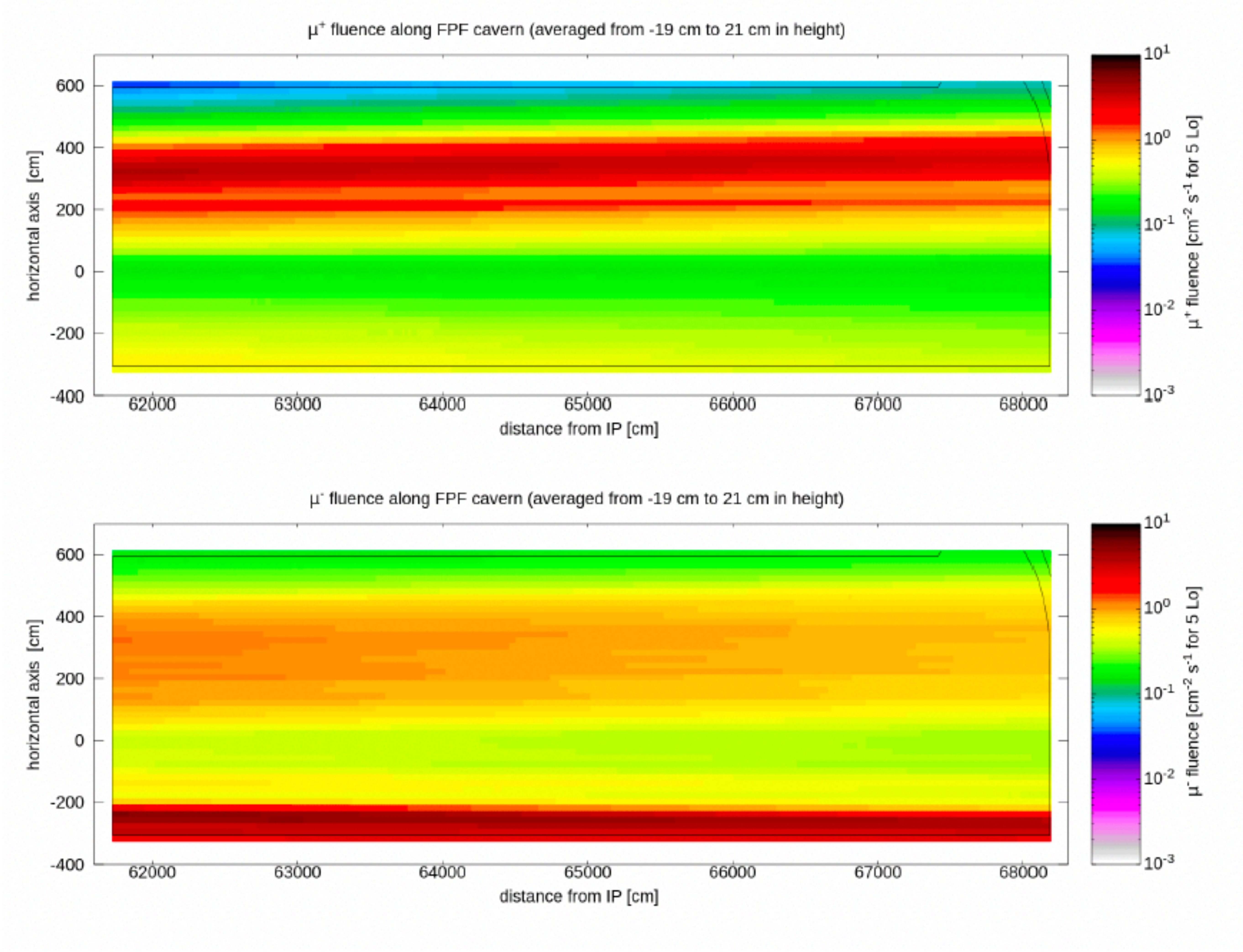


Figure 8: Spatial distribution of positive (top) and negative (bottom) muon fluence rate along the FPF cavern for 5 L0 instantaneous luminosity. The 2D view is on the horizontal xz plane, with values averaged from -19 cm to 21 cm in the missing vertical dimension, being y=0 the beam height.

0 is the ATLAS axis. Crossing angle in the horizontal plane is included.

Neutron flux ~0.1 Hz/cm2 is mostly at low energies.

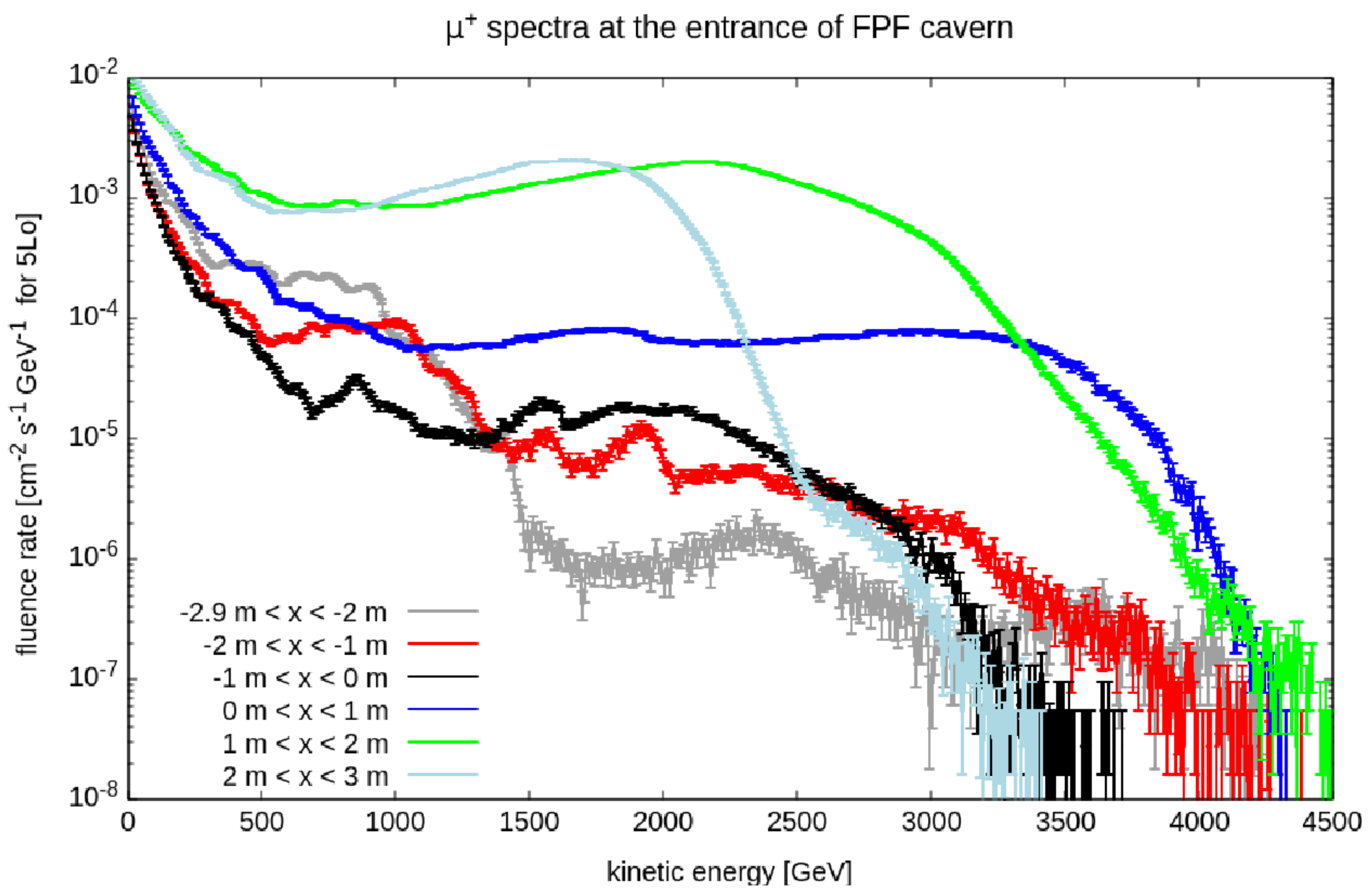
Radiation protection preliminary conclusions

- From studies in [9, 10]: Direct contribution from muons coming from IP1/LSS1 can limit the accessibility to the cavern during LHC operation, i.e. > 6 mSv/year may be achieved locally;
- Classification of the cavern as Simple Controlled/Supervised Radiation Area (low-occupancy, i.e. $< 20\%$ working time) seems possible;
- Access to the cavern during LHC beam operation will be limited to Radiation Workers [2].;
- No permanent control rooms are foreseen underground. During installation and commissioning there might people in the cavern for an extended period: this time shall be quantified to finalize the RP risk assessment;
- Final study to be done considering a full integration model, i.e. including detectors, service equipment, and more;
- External personnel involved in the excavation (of the cavern and the lower part of the shaft) have to be classified as “Radiation Workers”.

Detector design for FLArE

Experimental conditions (without sweeping magnet)

Approximate fluxes, rates of backgrounds



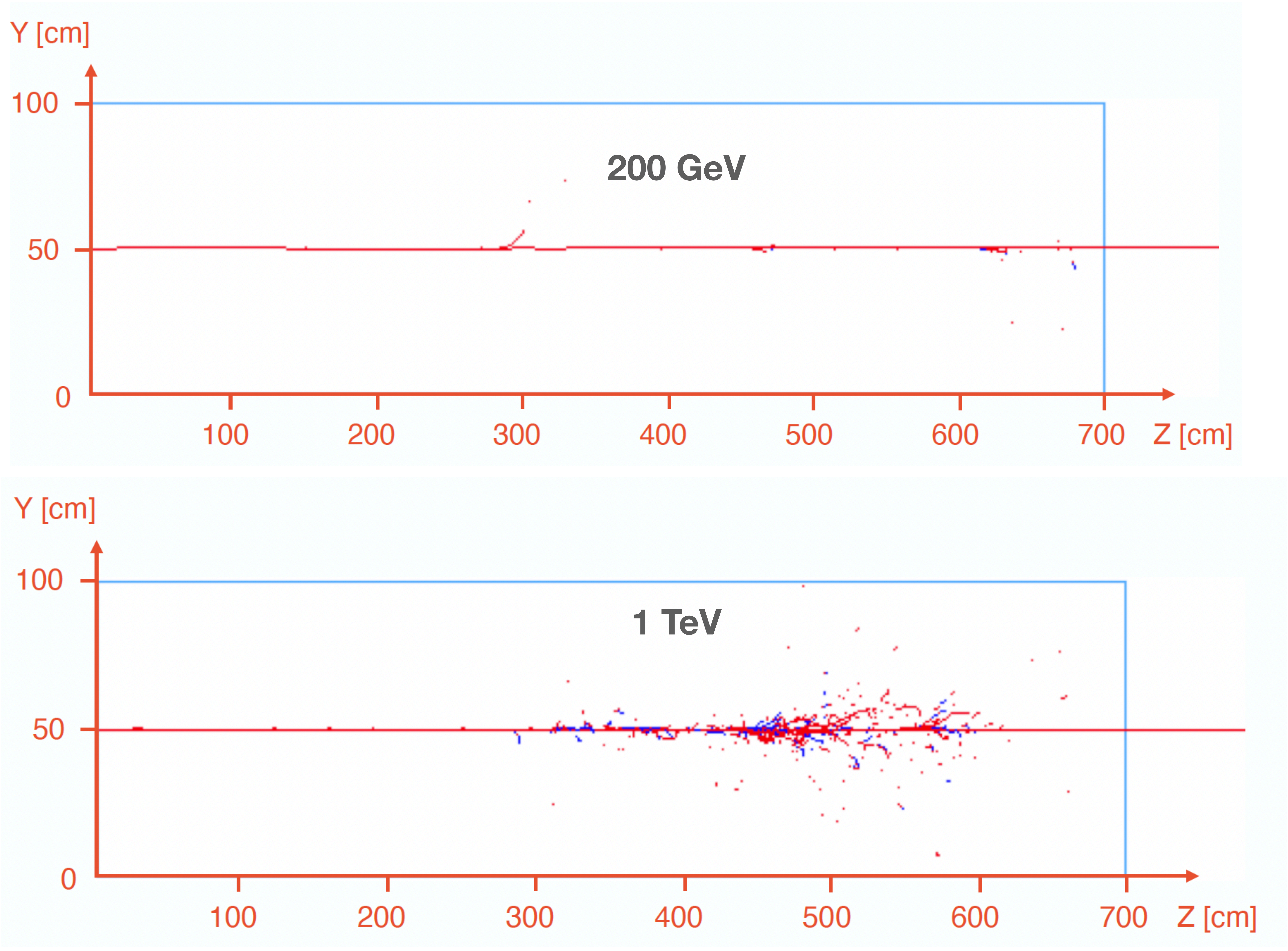
Sabate-Gilarte, Cerutti

- **Muon flux at FPF is calculated to be 0.6/cm2/sec at HL-LHC**
- **Mean muon energy ~300 GeV**
- **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
LHC collision energy	14 TeV
LHC bunch crossing	25 ns (40 MHz)
LHC crossing angle	280 micro-rad (TBD for HL-LHC)
Total Lumi/ instantaneous 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)	~0.6/cm^{2}/sec (1.5x10^{-8}/cm2/crossing)
Tracks in 1 m^2 detector/1 ms	~6/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}

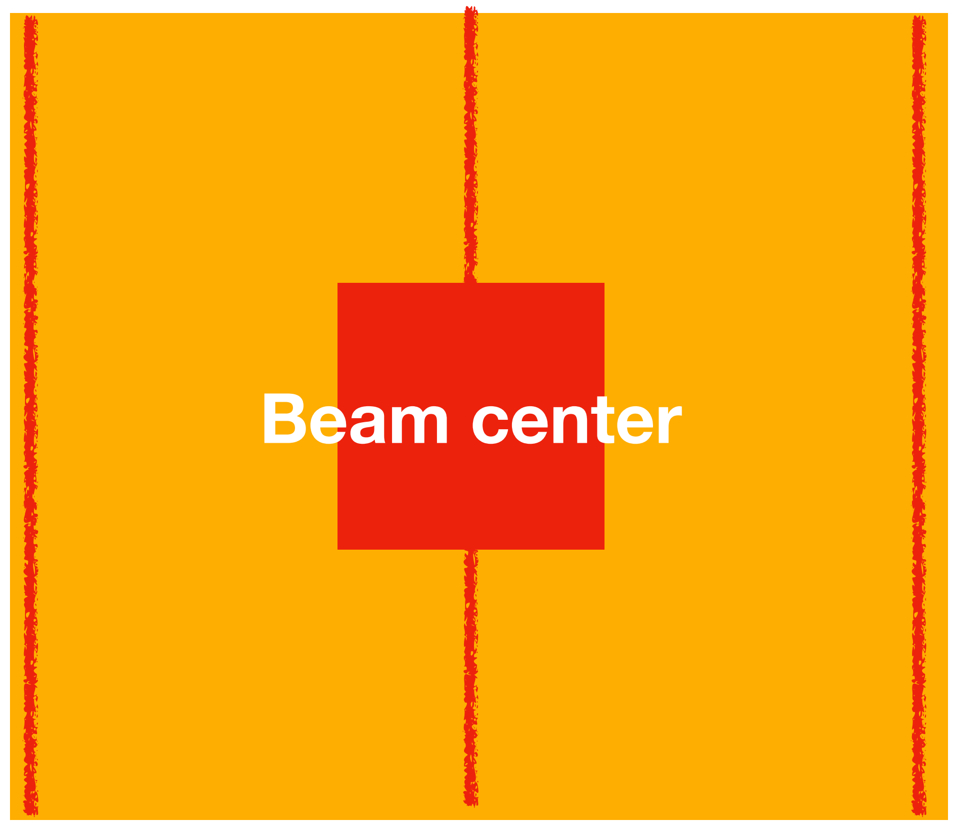
updated with new information on HL-LHC configuration 2105.06197

Muon simulation in liquid argon.



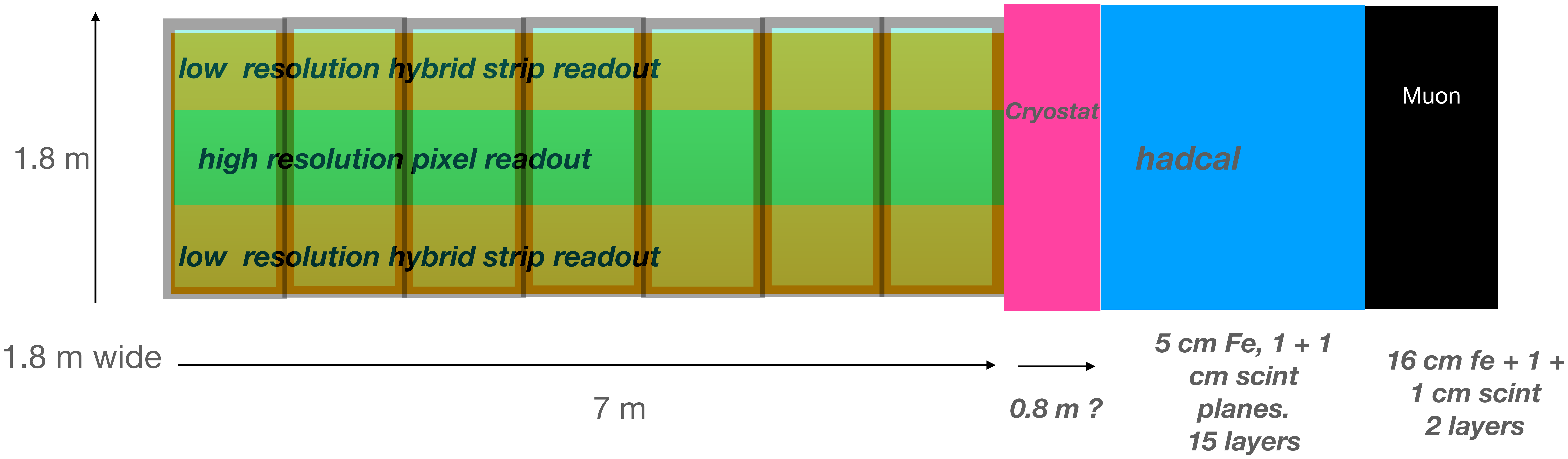
- ***Muon flux above 1 Hz/cm2 presents a difficult problem for all detectors.***
- ***For Liquid argon TPC, the flux also presents a space charge problem for large gaps.***
- ***Showering muons will also present a trigger problem since if the incoming muon is missed the event will look like a neutrino.***

Wenjie Wu (UCI)



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.

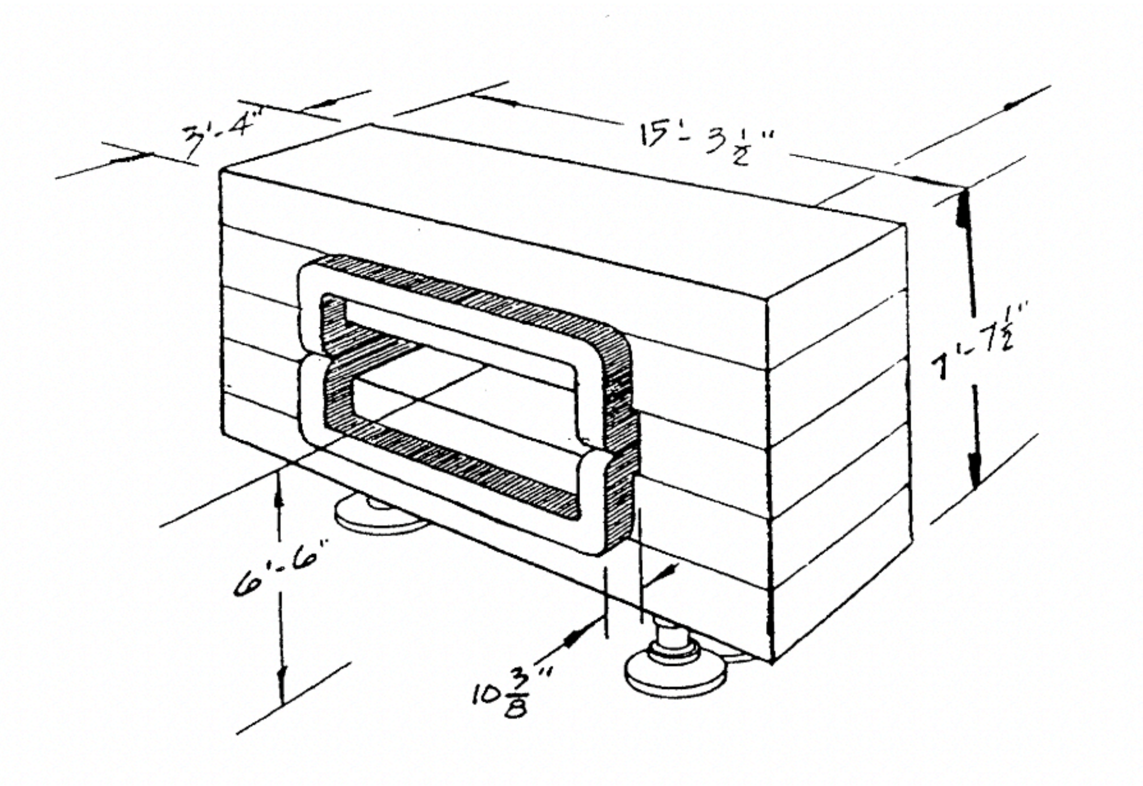


Carry two options into Conceptual Design

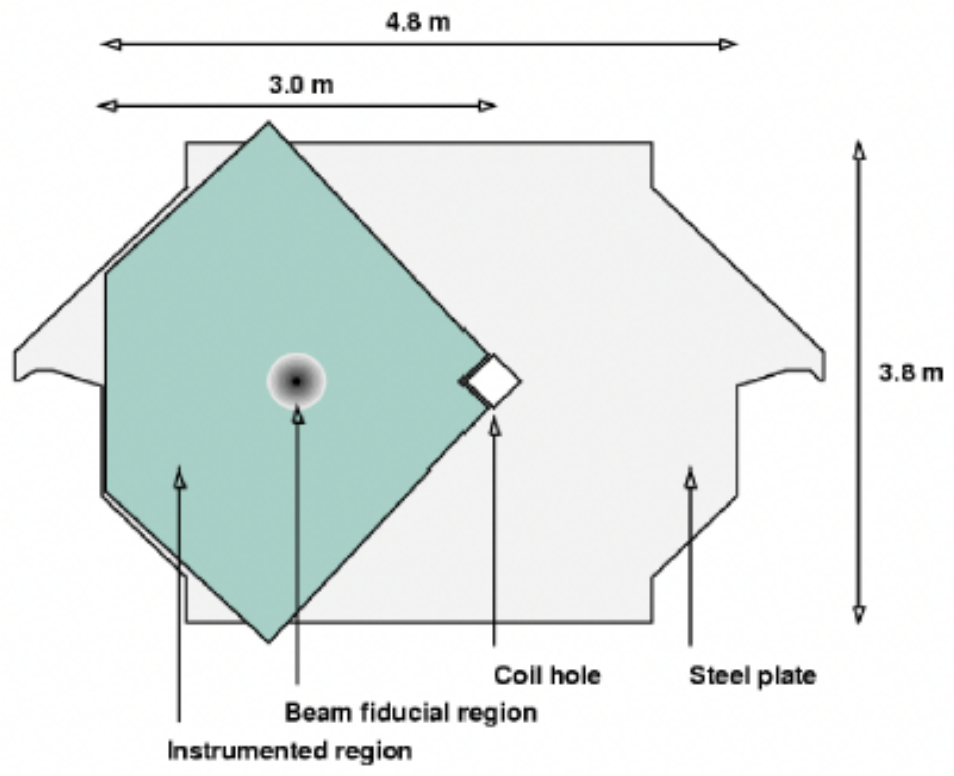
either 2 X 7 vertical modules with 0.45 m gap
or 3 x 7 vertical modules or with 0.3 m gap

None of this is optimized

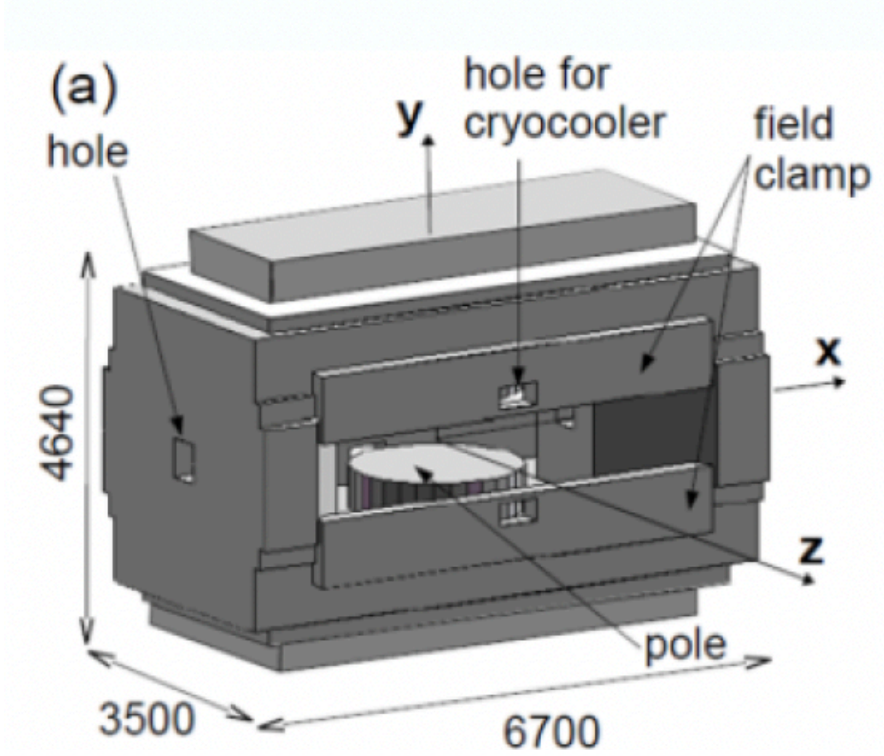
Goals and options for the magnetic spectrometer design



BNL 96D40



Minos near detector toroidal



SAMURAI (**S**uperconducting **A**nalyzer for **Mu**lti-particles from **Ra**dio**i**sotope beams) RI beam at RIKEN, Japan

- *Create the scientific and technical requirements for the magnetic systems. (scientific input is independently supported) - based on muon neutrino detection, trident detection, and decays of dark particles.*
- *Perform preliminary analysis of possible magnet configurations, and installation plans in the FPF cavern.*
- *Communicate with the CERN transport group and civil engineering to narrow down options for magnet(s)*
- *Superconduting coils for these magnets add considerable level of complexity, but may be necessary to reduce power costs.*

Brookhaven National Laboratory

Simulations Status (Wenjie Wu from UCI)

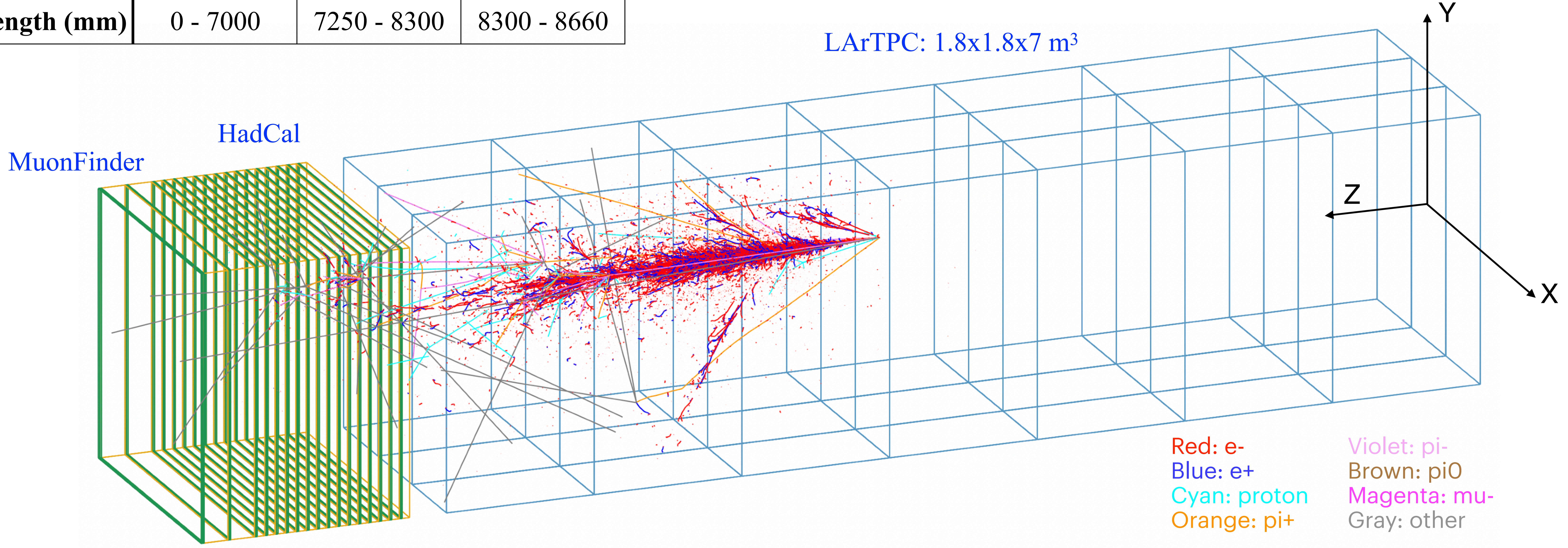
- We're developing simulation and reconstruction for
  - Detector design optimization: geometry, pixel size, trigger…
  - Detector performance: spatial/energy resolution, containment, thresholds…
  - Physics sensitivity: tau neutrino, light dark matter scattering…
- Previous studies (https://indico.cern.ch/event/1160758/#2-progress-and-status-of-flare)
  - The detector size is optimized for energy containment.
  - The event classifiers trained based on pseudo-reconstructed variables for tau's hadron decay look promising.
- Work in progress
  - Phase space coverage (muon neutrino): energy and angle acceptance.
  - More on tau neutrino identification.
  - Study the effects of pixel size on event identification.

Thanks to: Jianming Bian(UCI), Alejandro Yankelevich (UCI),
Matteo Vicenzi (BNL), and many others now.

Detector configuration in simulation

- Fiducial mass of 10 tons (1x1x7 m^3) is needed for good statistics and sensitivity to dark matter.
- Detector needs to have good energy containment and resolution for neutrino physics.
- Muon and electron ID. Very good spatial resolution (~1 mm) for tau neutrino detection.

	LArTPC	HadCal	MuonFinder
Length (mm)	0 - 7000	7250 - 8300	8300 - 8660

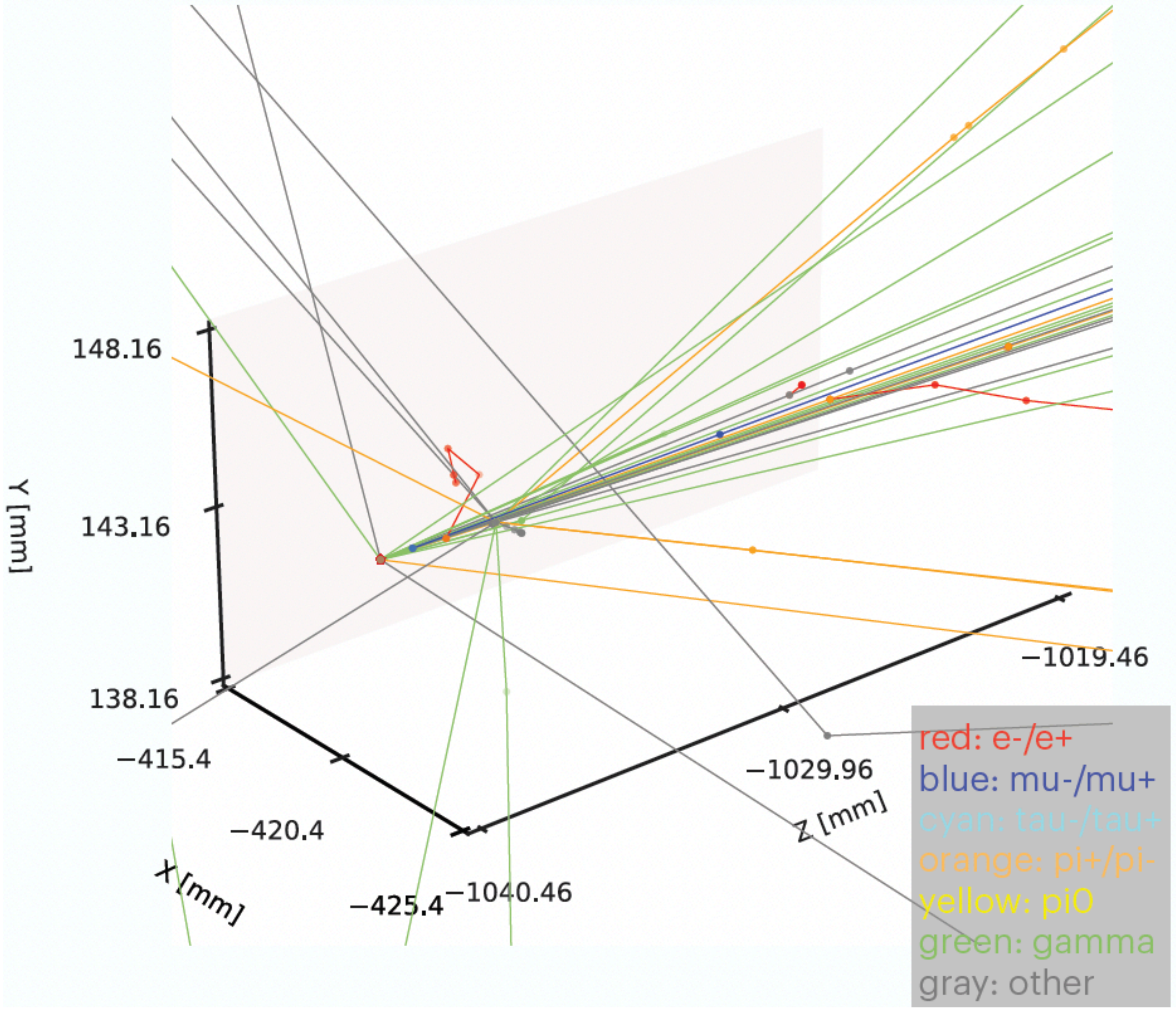


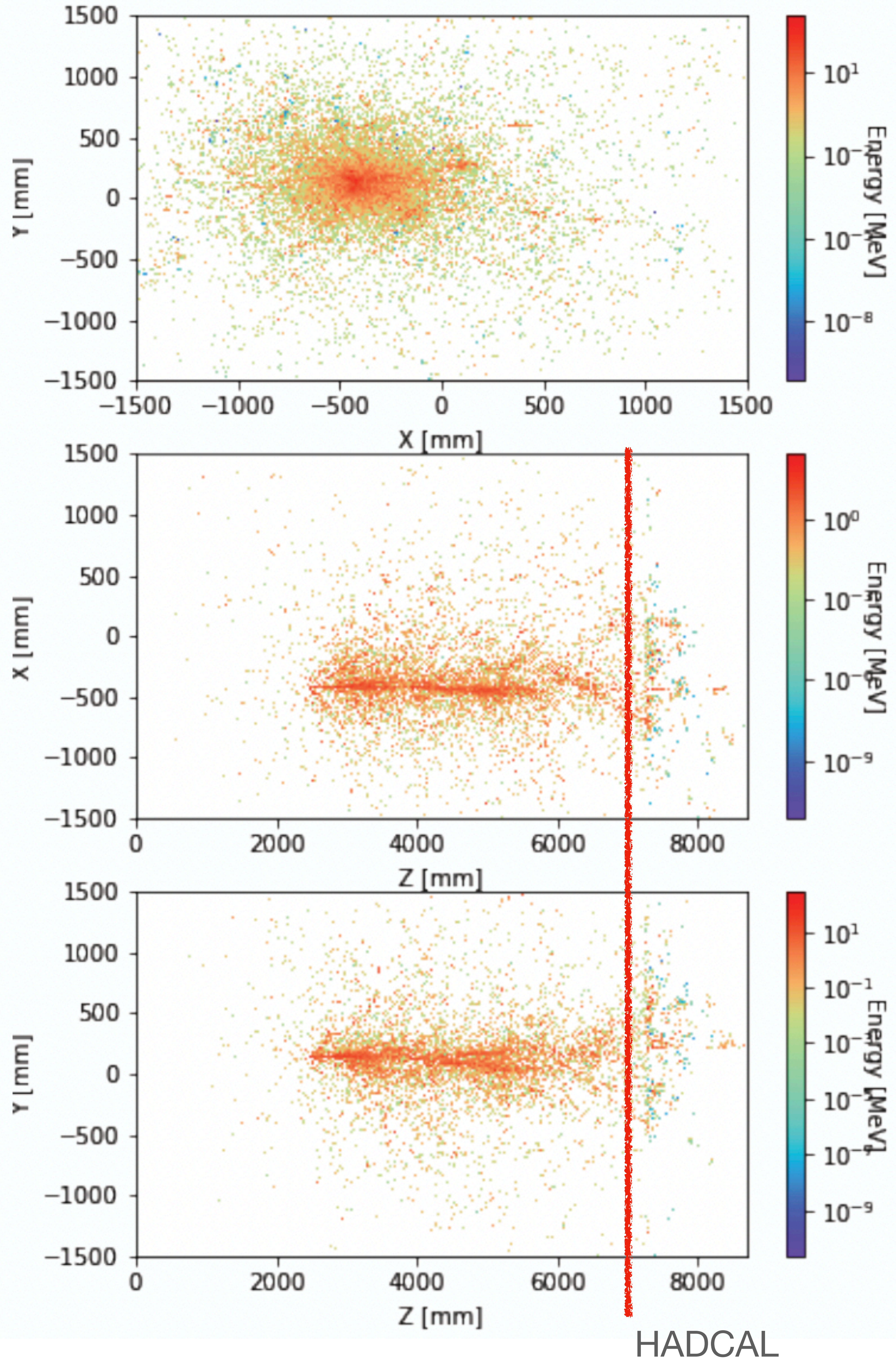
UCIRVINE

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)

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



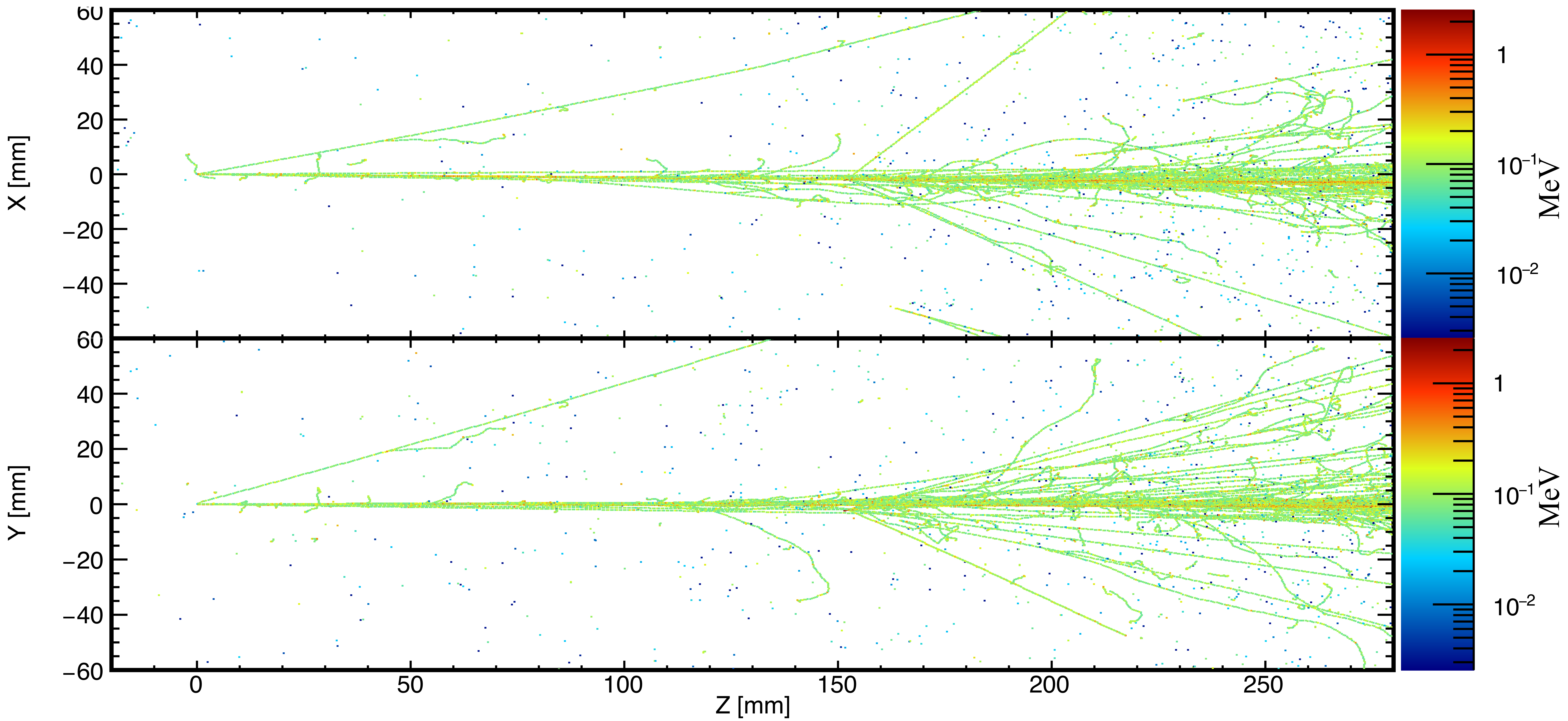


1. 1.8 X 1.8 to contain transverse events in fiducial of 1m x 1m x 7m.
2. Hadronic calorimeter to contain showers that start downstream.
3. Even a modest energy resolution is sufficient.
4. Excellent muon identification results in quick selection of nutau events.
5. We will combine spatial resolution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

Wenjie Wu/ Jianming Bian UCI

Muon neutrino

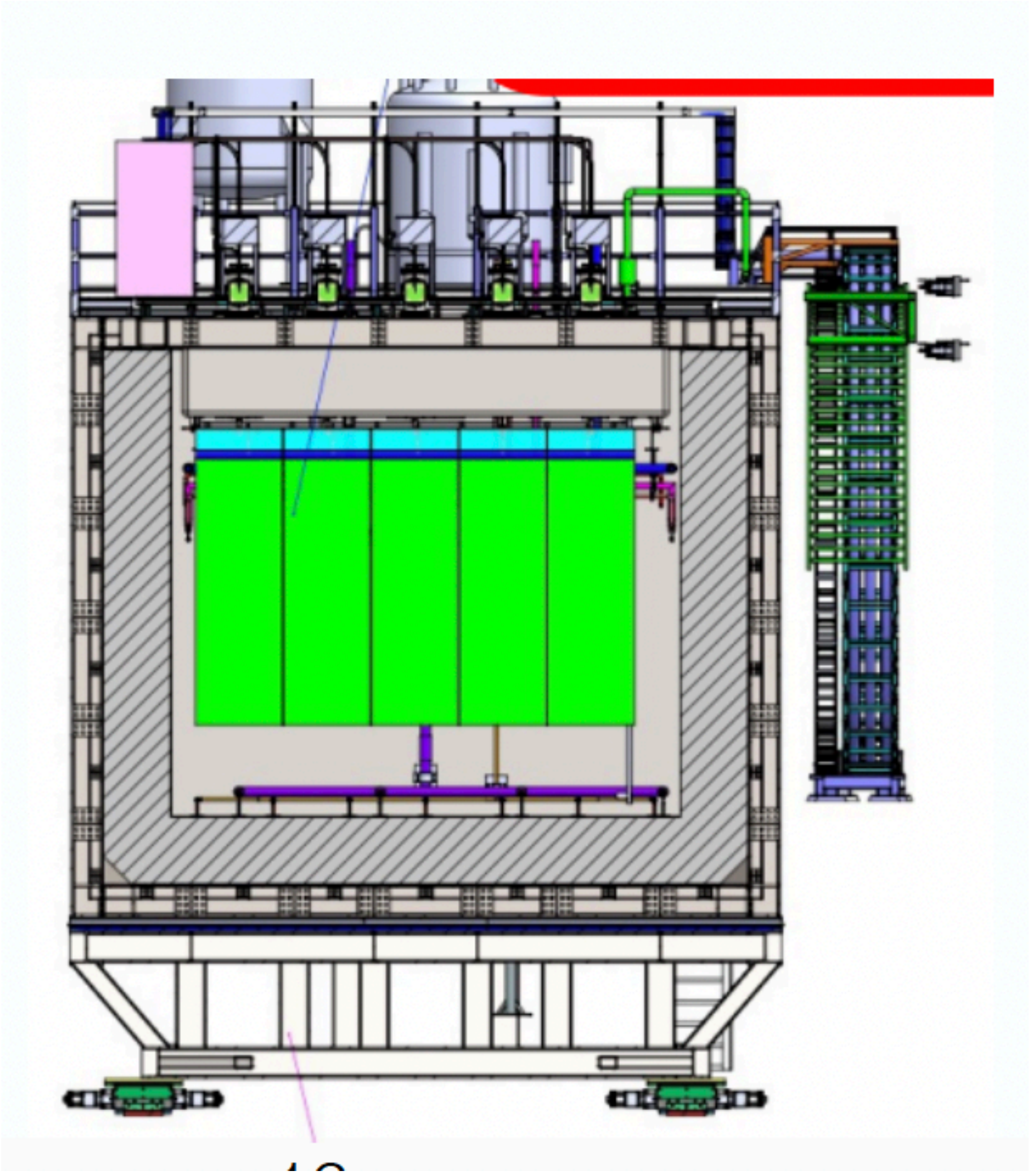
Vertex activities: $0.2 \times 0.2 \times 0.2\ \mathrm{mm}^3$



EvtID 2 nuPDG 14 nuE 907.49 GeV nuVtx (247.7, 59.9, 2372.7) mm

Cryostat options

Very important for space considerations.



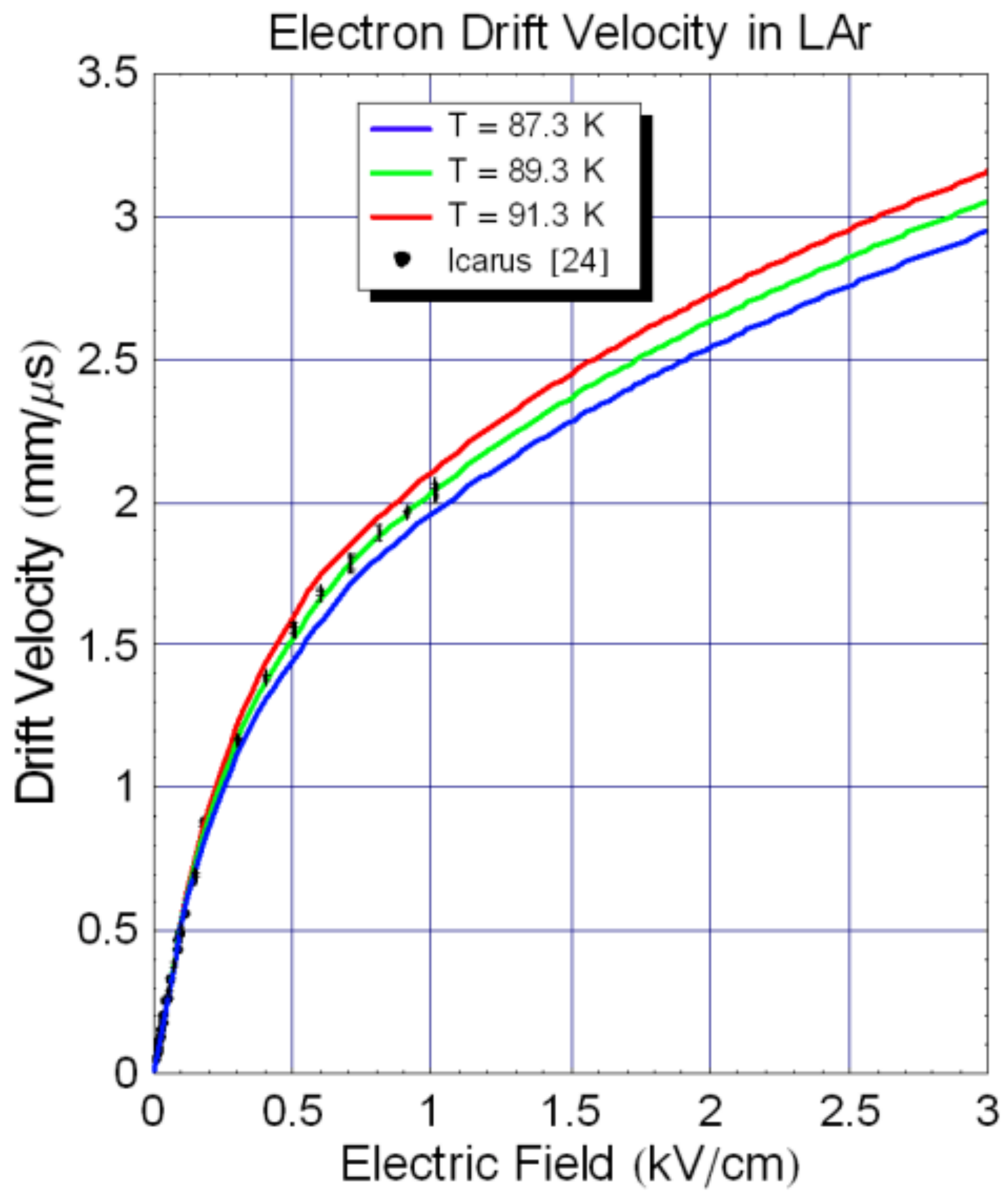
	Cryostat Inner Dimensions	Insulation Type	Insulation Thickness	Insulation density	Heat leak	Cold shield
MicroBooNE	3.8m dia x 12 m	Polyurethane Foam	**400mm**	32 kg/m^3	**~13 W/m^2**	No
ICARUS-GS	3.9m x 3.6m x 19.6m	Nomex honeycomb+perforated Al	**665 mm+ (combined)**	25-35 kg/m^3	**7-22 W/m^2**	Yes
ICARUS-SBN	3.9m x 3.6m x 19.6m	Al extrusion+GTT foam	**665 mm+ (combined)**	25-35 kg/m^3	**10-15 W/m^2**	Yes
ProtoDUNE	7.9m x 8.55m x 8.55 m	GTT membranc	**800mm**	90 kg/m^3	**~8 W/m^2**	No
ND-LAr	3m x 5m x7m	GTT membrance	800mm	90 kg/m^3	**~8 W/m^2**	No
FLArE	~(1m x 1m x 7m)					No?

Yichen Li

- *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 this installation for the GTT membrane would be much easier.*
- *The DUNE ND-LAR design has installation from top. This would also simplify things.*
- *Further engineering will be needed, but we have chosen this option for now.*

Drift velocity and diffusion

Electron drift velocity [22, 23, 24, 25]



Electron transverse diffusion coefficient: . D_t = 13 cm² /s
Electron longitude diffusion coefficient: D_l = 5 cm² /s

t = 500 [mm] / 2.0 [mm/us] = 250 us
T = 250 [mm] / 2.5 [mm/us] = 100 us
1D case $\sigma_l = \sqrt{2D_l t}$ = 0.5 [mm]
2D case $\sigma_t = \sqrt{4D_t t}$ = 1.1 [mm]

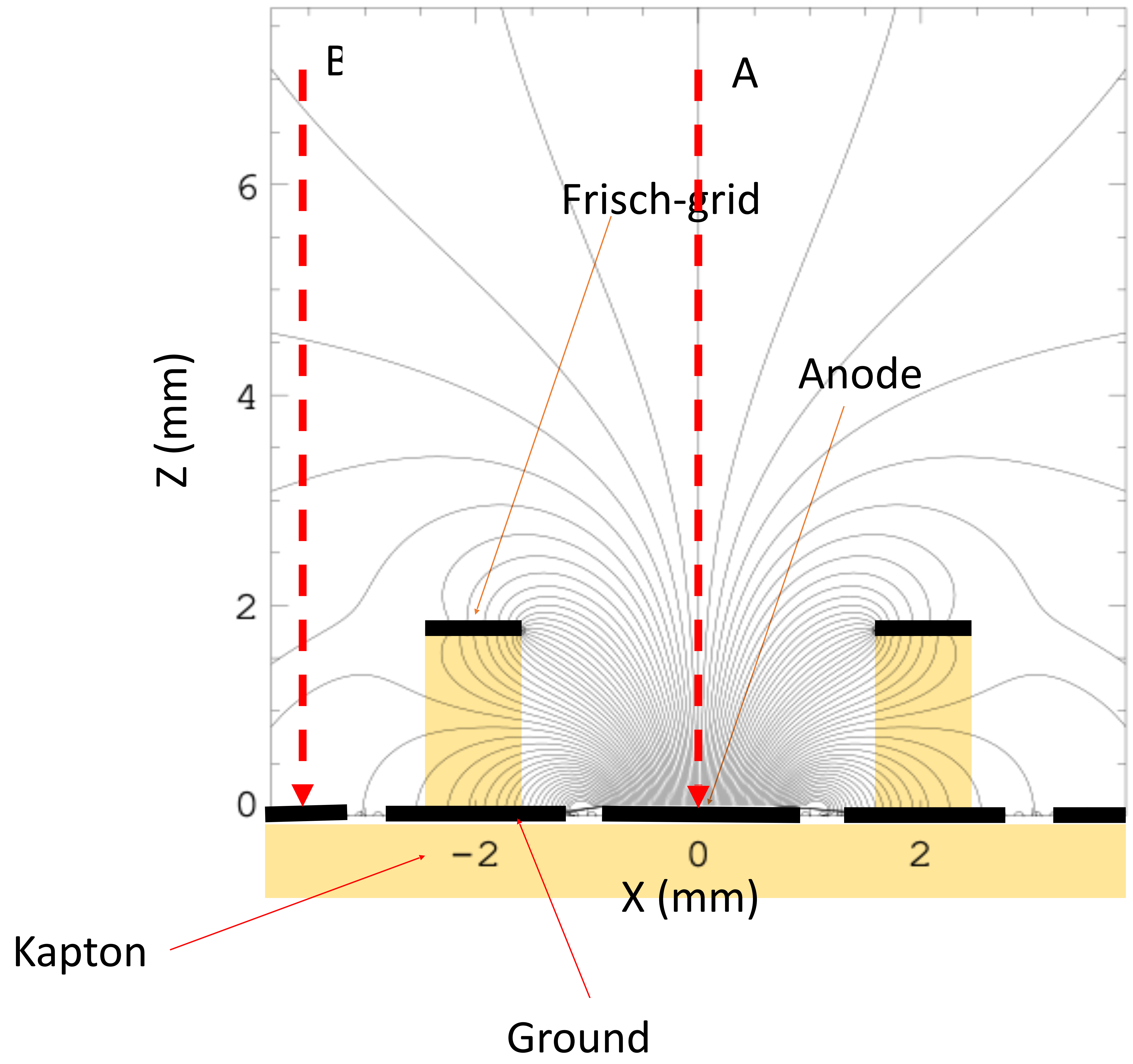
	500 mm at 1 KV/cm, 250 us	250 mm at 2 KV/cm, 100 us
Long. (FWHM)	0.5 (1.2) mm	0.3 (0.7) mm
Transverse (FFHM)	1.1 (2.6) mm	0.7 (1.7) mm

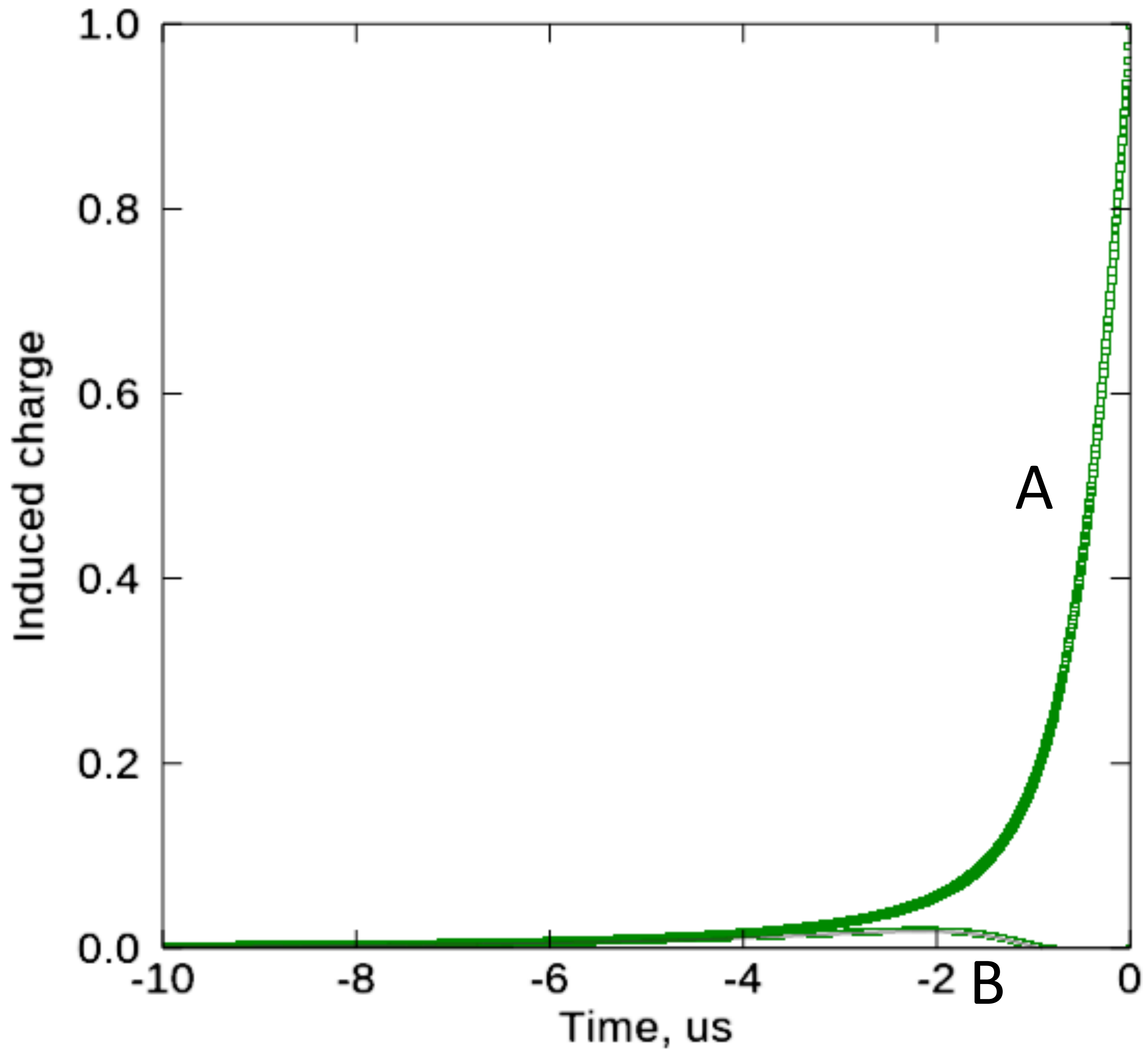
There should be no fundamental limit to getting < 1 mm resolution

Bolotnikov

Use Frisch-grid

Weighting field for GEM-like structure with pixel anode, 4 mm pitch



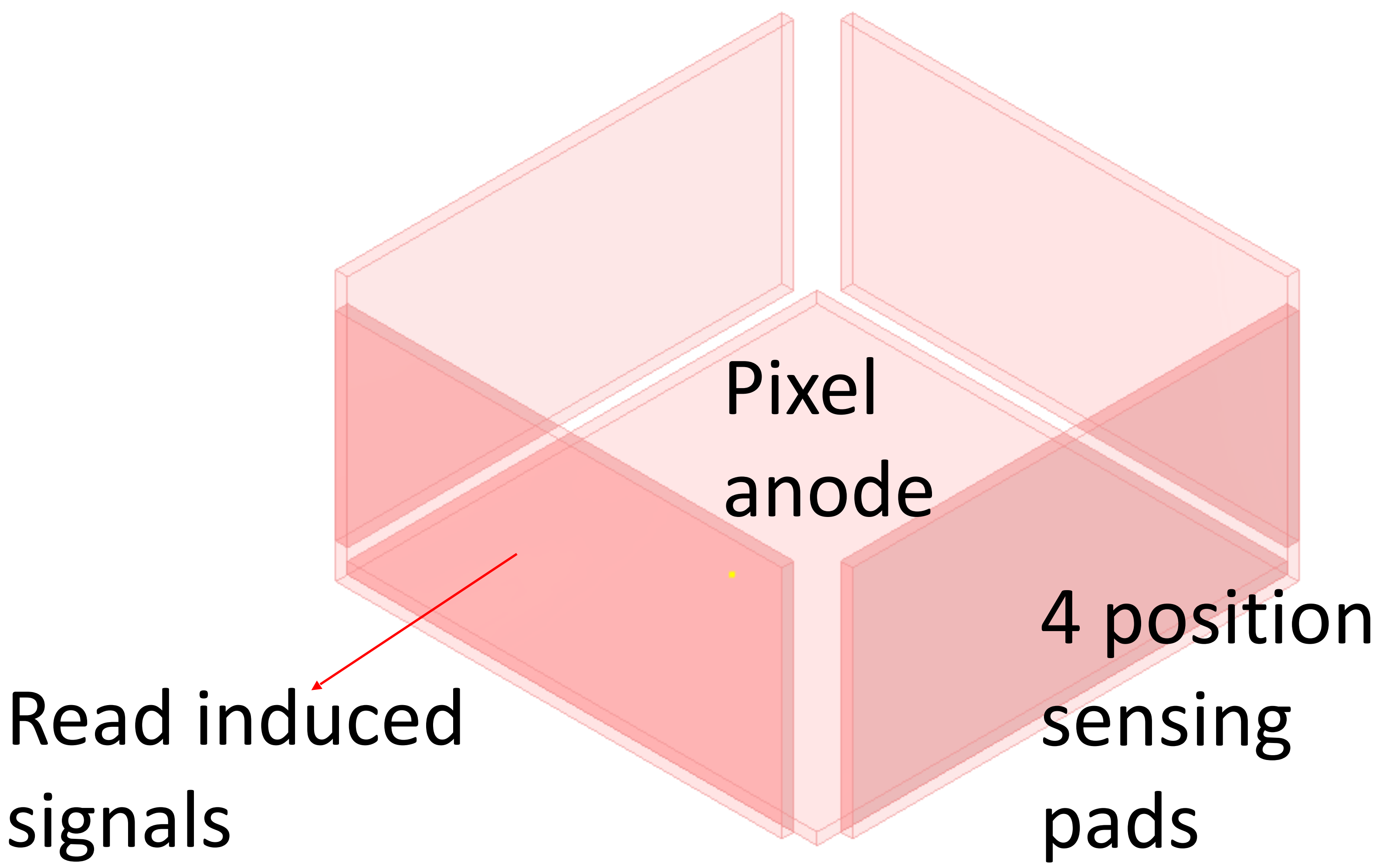


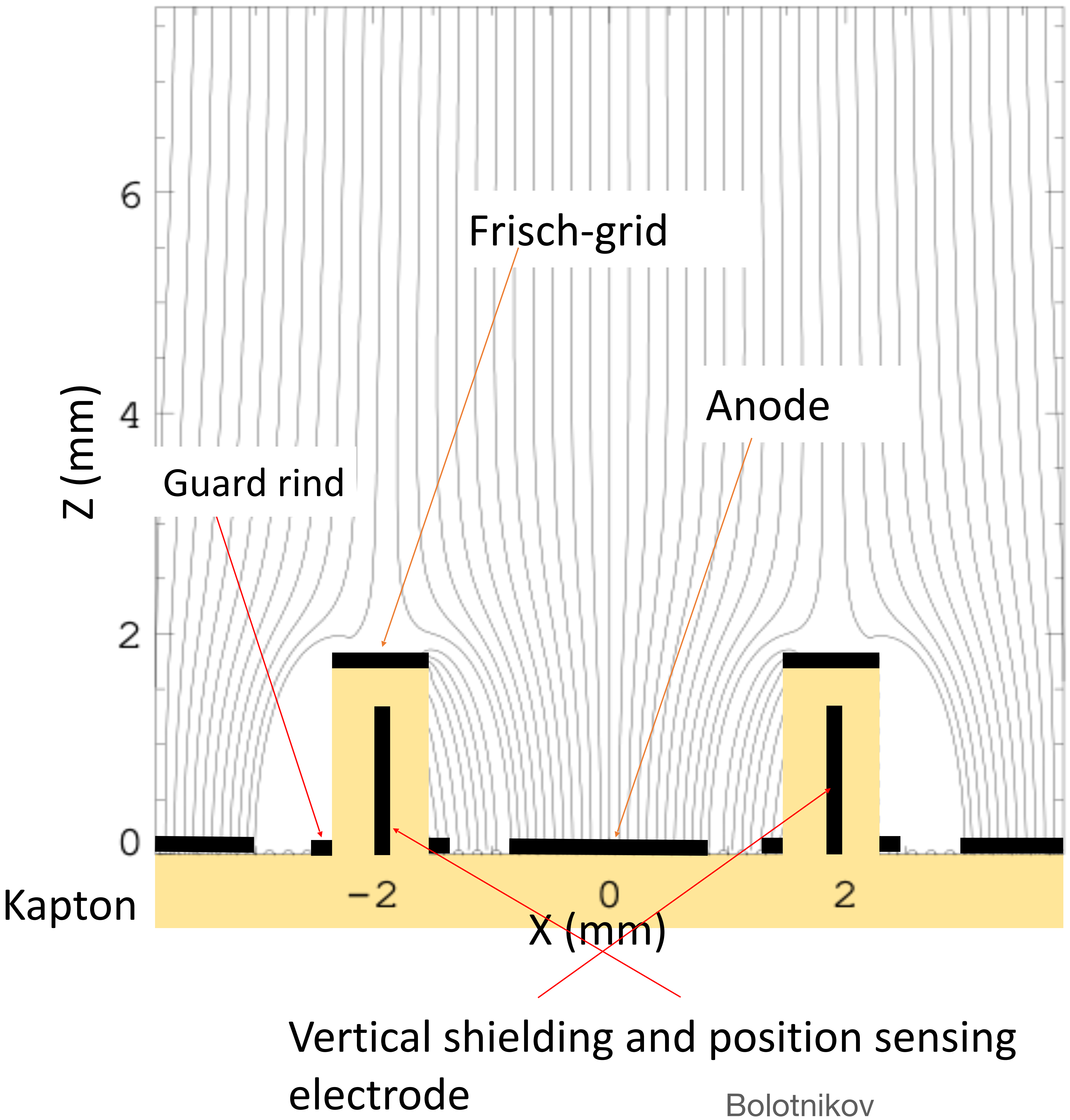
Most of the field lines terminate on the grounding electrodes

Bolotnikov

Using the Frisch-grid or GEM-like structure with pixelated anode (cont.)

- Vertical shielding electrodes
- They can also be used as position sensitive electrodes to refine position withing a pixel -- position resolution of < 100 um was demonstrated in the case of 8-mm pitch for a point-like charge



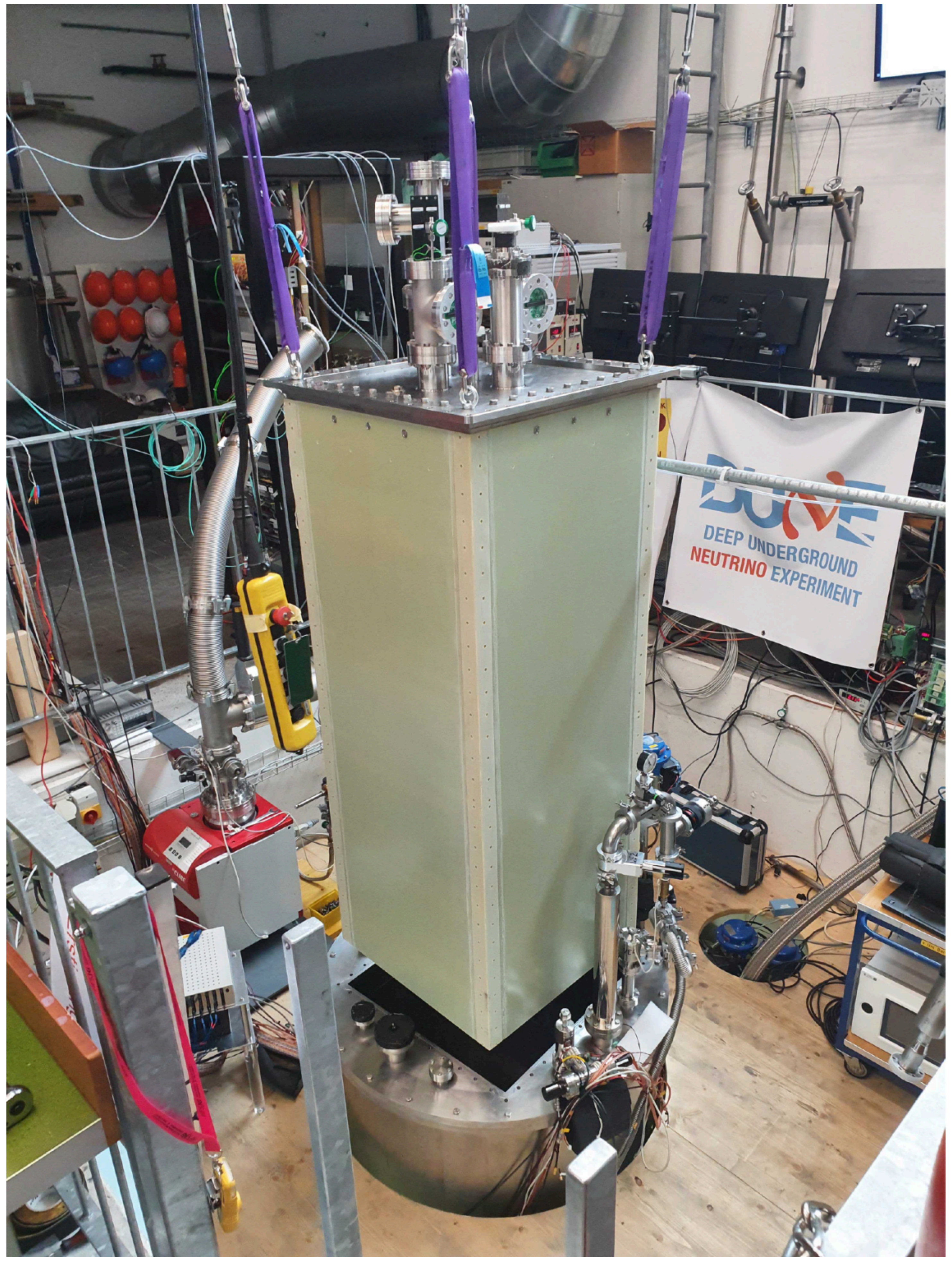


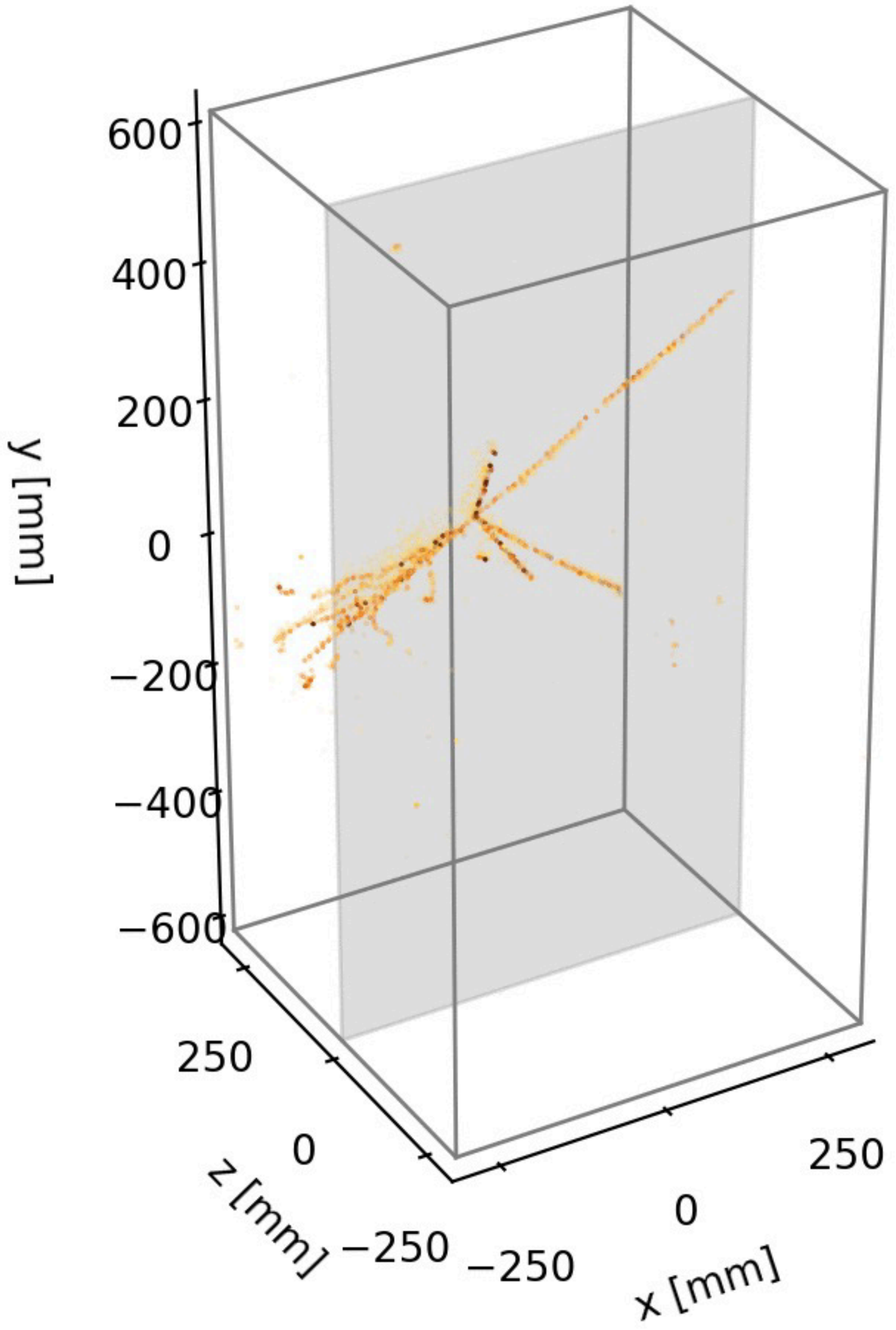
Bolotnikov

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 < 0.3 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

FLARE will Benefit from the DUNE near detector concepts.





Conclusion

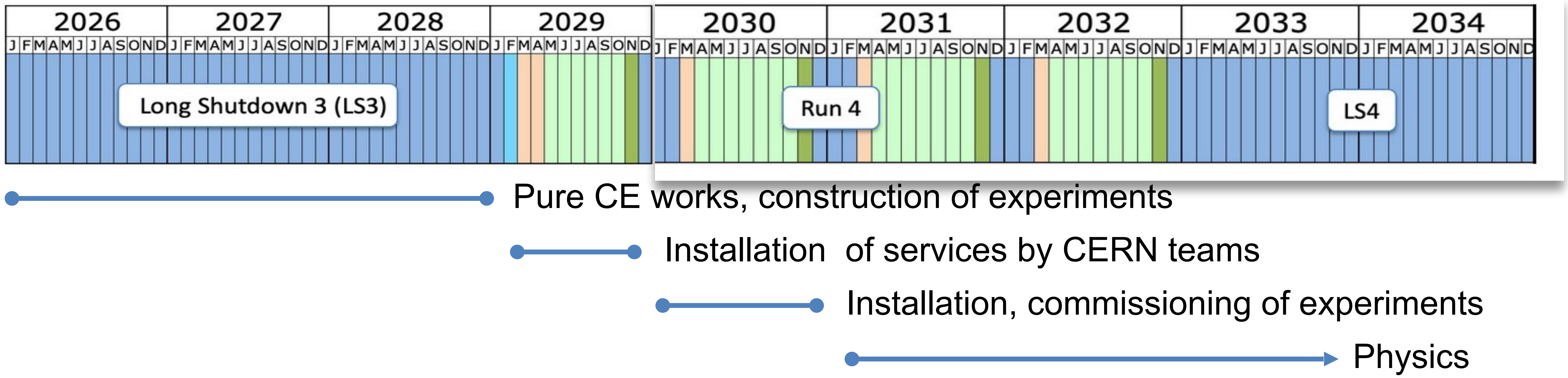
- A forward physics facility(FPF) is being considered at CERN for neutrino and dark matter physics. It will unlock a new source of neutrinos => the LHC.
- HL-LHC will start running in 2029-2030. The FPF is decoupled from the LHC sufficiently that its schedule could be independent of the HL-LHC upgrades.
    - 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 funding to produce a conceptual design by mid-2023. DUNE R&D investment has made this much easier.

COST AND TIMELINE

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

- Conceptual designs for the FPF and its 5 experiments ready by mid-2023.
  - FASER2, FASERnu2, AdvSND, FORMOSA build on existing experiments and collaborations.
  - FLArE R&D is currently supported by BNL LDRD, PD, and Heising-Simons Foundation funds.

- Timeline: begin CE works, installation of services in LS3, followed by installation and commissioning of experiments in early Run 4. Physics begins in Run 4 and continues to the end of the HL-LHC era (~2031-42).



Backups

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


Hall Ceiling height
CRANE COVERAGE
FLARE TPCs
1.8 m
7 m
Muon
FASERnu2
(tungsten/
emulsion)
FASER2 magnet