FPF Forward Physics Facility

Physics Colloquium at DESY, Hamburg

13/9/22

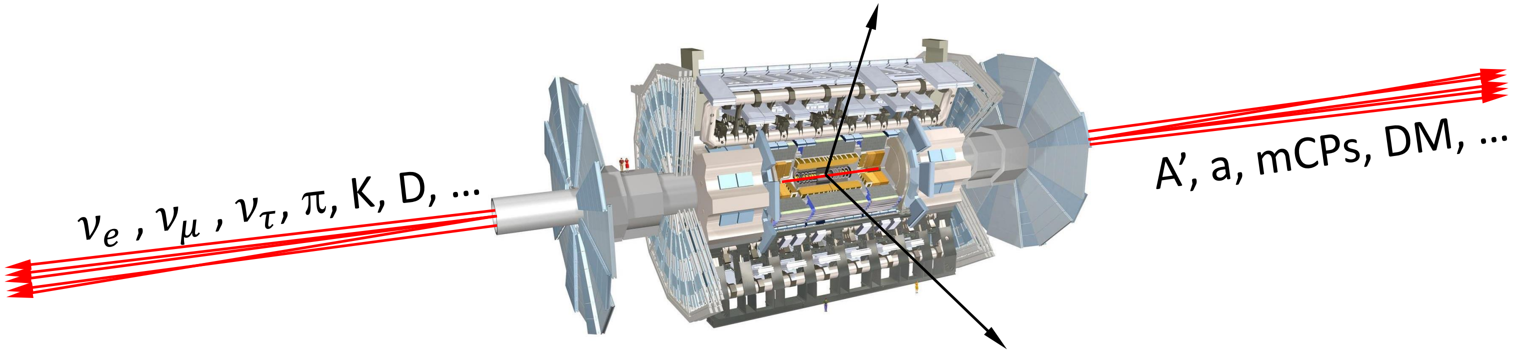
Jamie Boyd (CERN)

Overview:
- Physics motivation
- Experiments
- Facility

Much more information in FPF White paper: arxiv:2203.05090
and links from : https://pbc.web.cern.ch/fpf-resources

Introduction

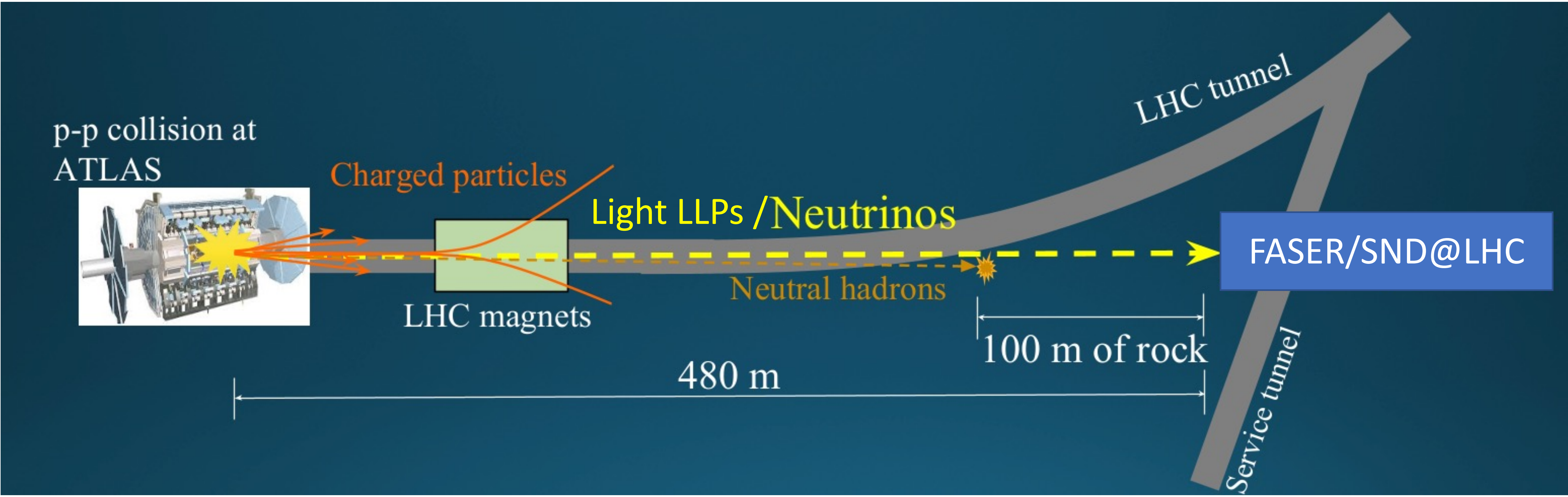
- The existing large LHC detectors were designed to find strongly interacting heavy particles.



- But energetic light particles are primarily produced in the far-forward direction, and all particles with η > 4.5 escape down the beampipe
  - e.g. 1% of pions with E > 10 GeV are produced in the forward 0.000001% of the solid angle (η > 9.2)

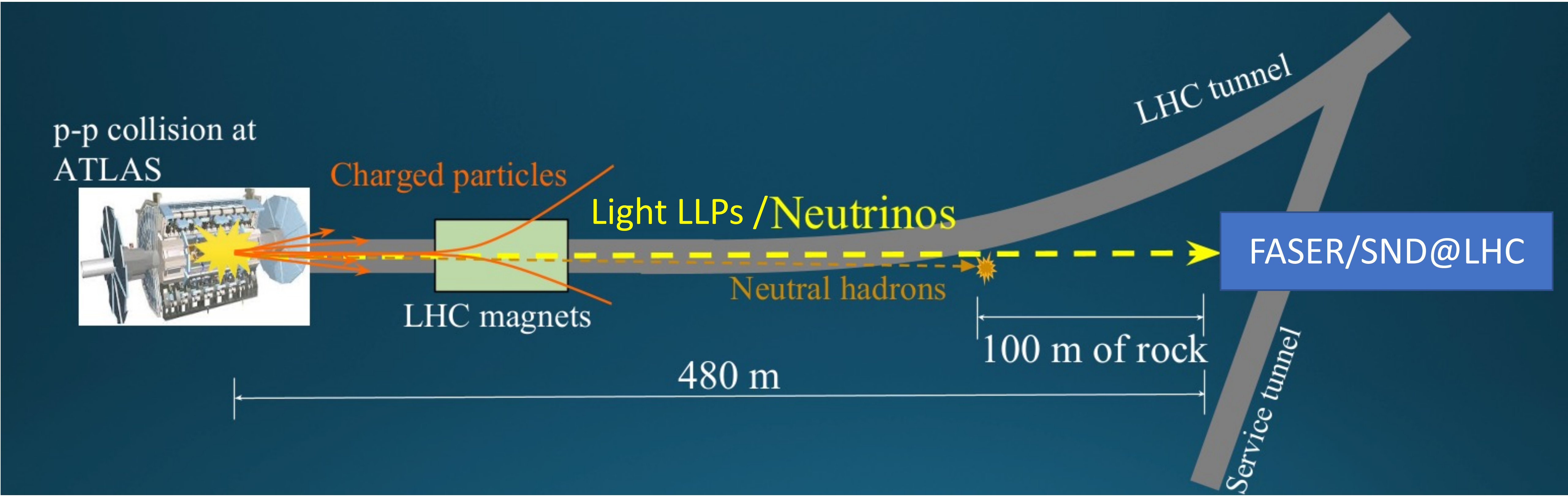
- There is therefore a rich and unexplored physics program in the far forward direction for weakly interacting light particles.
  - **SM**: TeV neutrinos of all flavours at the highest energies from a human-made source. Neutrinos also enable probes of QCD, proton and nuclear structure.
  - **BSM**: world-leading sensitivities to LLPs, FIPs, dark sectors, including dark photons, axion-like particles, milli-charged particles, dark matter, …

Existing Experiments



FASER and SND@LHC experiments designed to take advatage of this and to search for new, light, long-lived particles (LLPs), and study neutrinos. These experiments are situated ~500m either side of the ATLAS collision point, on the beam collision axis line-of-sight (LOS), and have just started taking physics data with the start of LHC Run 3.

Existing Experiments



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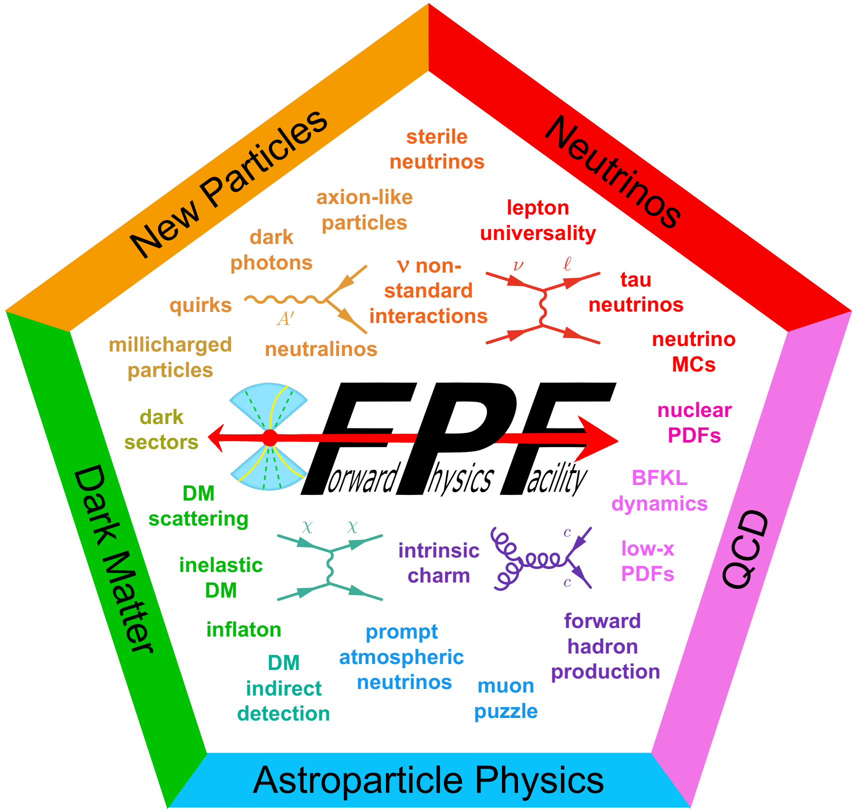
However, strong physics case to scale these type of experiments up by >1 order of magnitude, as well as to add new types of detectors in this special location.

Unfortunately, the existing infrastructure used by FASER/SND (unused tunnels) does not allow for larger and more experiments to be installed. The FPF is a proposed new facility to allow such experiments to be installed for the HL-LHC.

Physics Motivation

- The FPF has a rich and broad physics programme
- Three main physics motivations
  - Beyond Standard Model (BSM) “dark sector” searches
  - Neutrino physics
  - QCD physics



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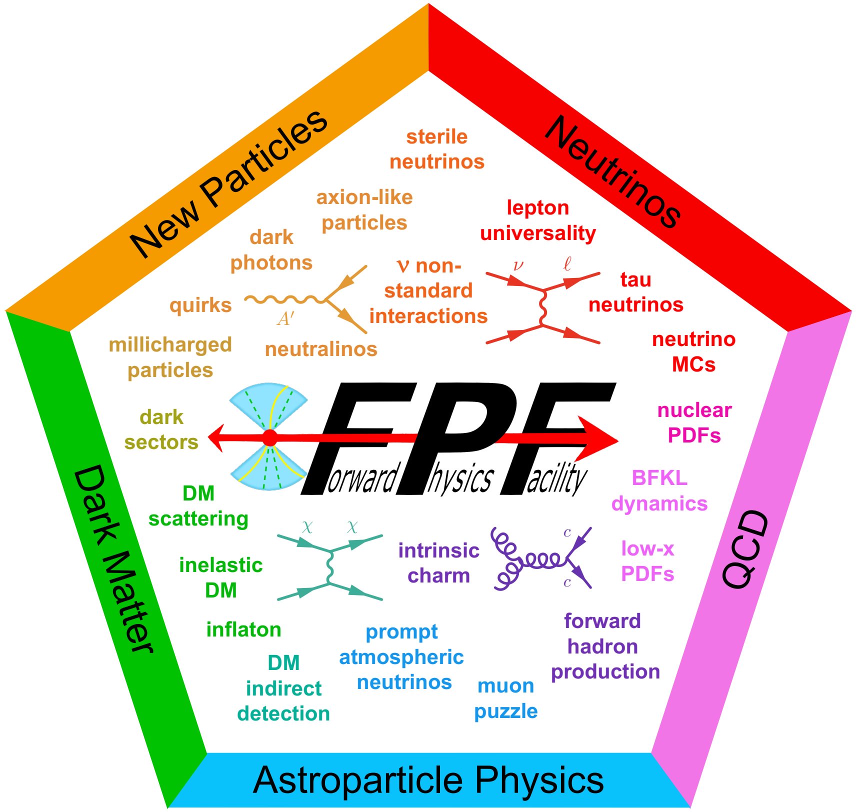
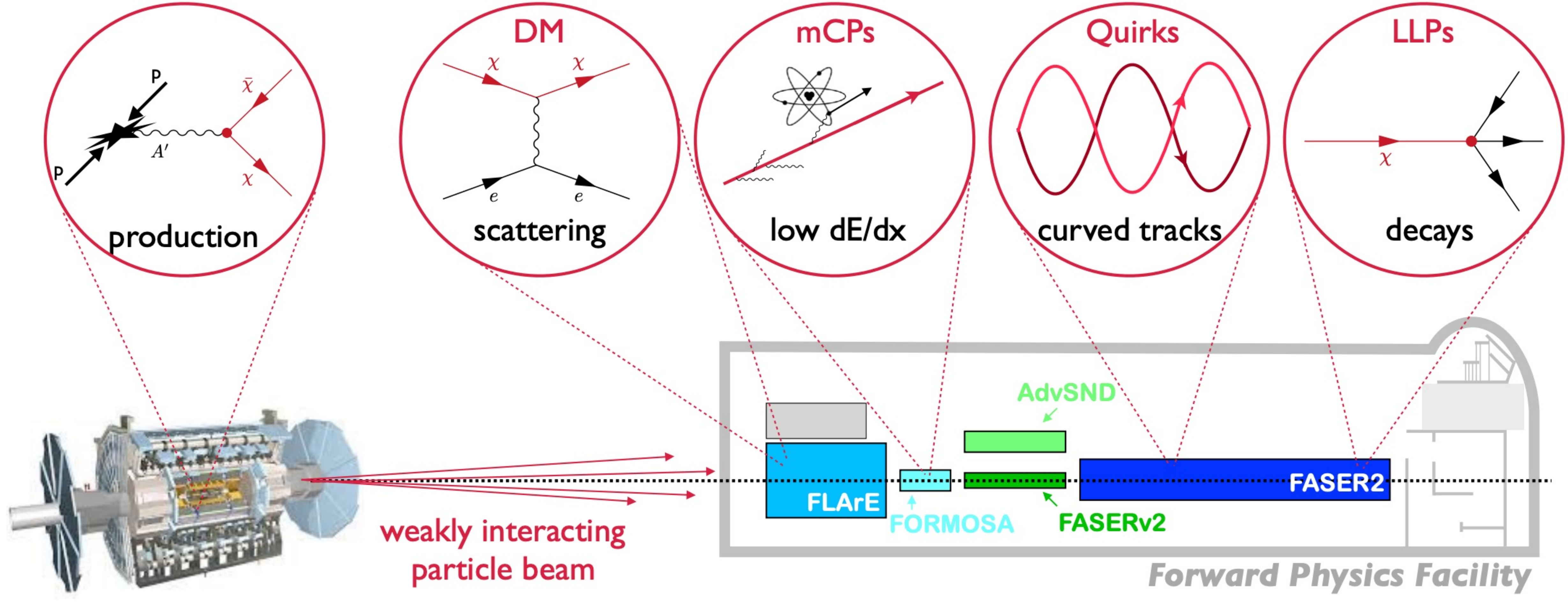


- In order to fully benefit from the increase in luminosity from the HL-LHC, the FPF will allow:
  - **Longer detectors** to increase target/decay volume
  - **Wider detectors** to increase sensitivity to heavy flavour produced particles
  - Space for **new detectors** with complementary physics capabilities

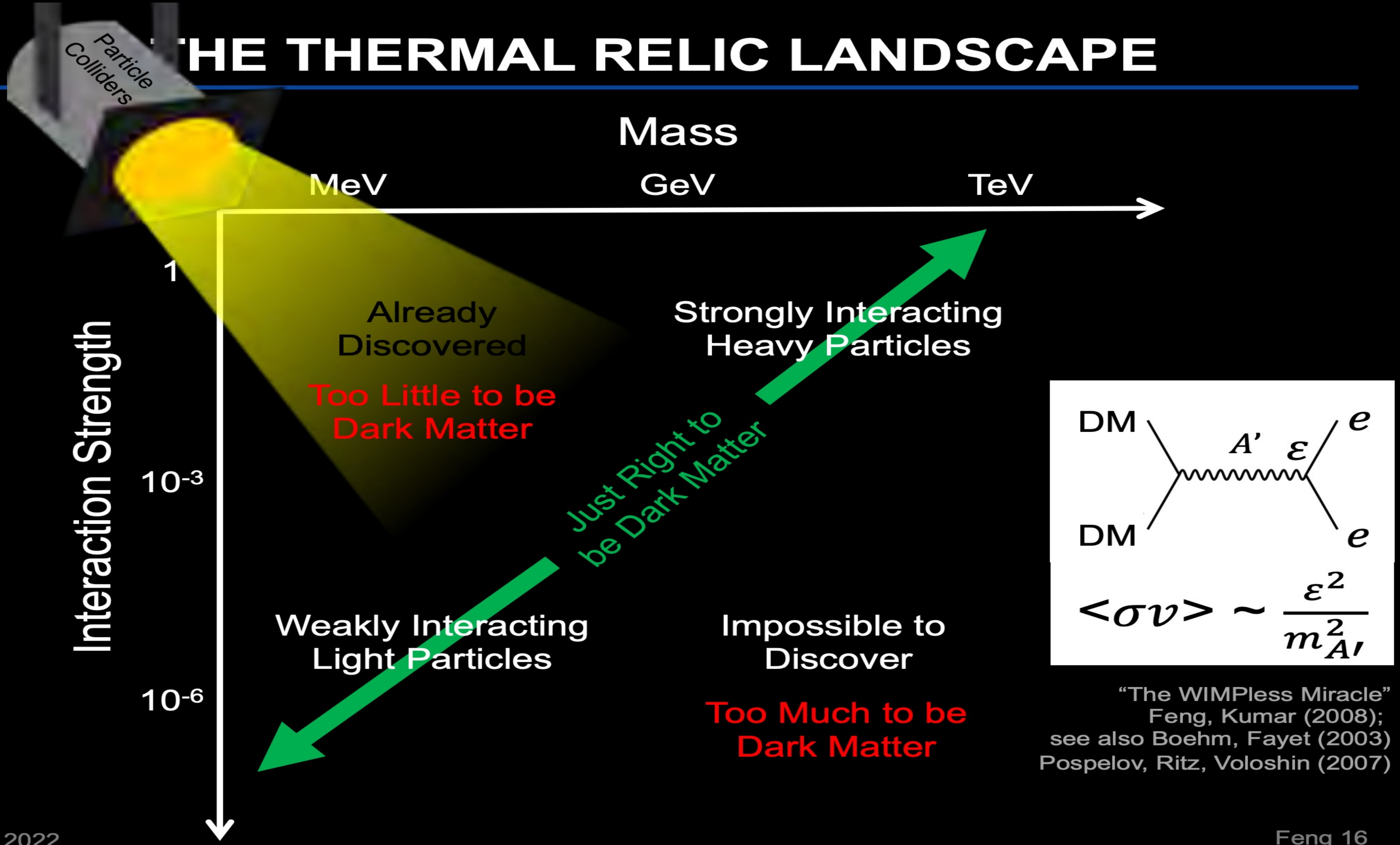
Beyond the Standard Model Physics

BSM particles can be detected in different ways in FPF experiments:



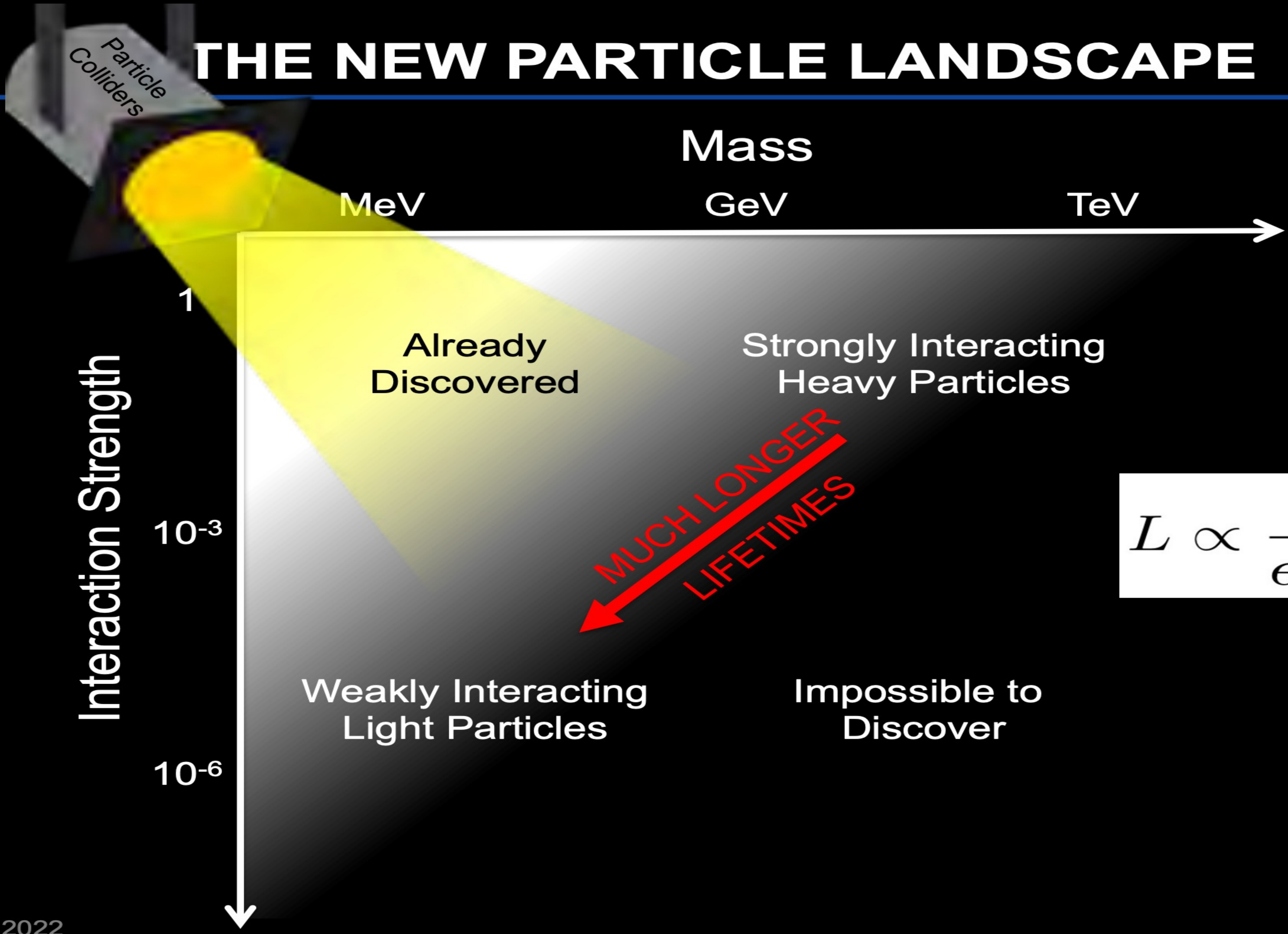
Many of these particles motivated by dark matter and more generally dark sectors.

THE THERMAL RELIC LANDSCAPE



"The WIMPless Miracle"
Feng, Kumar (2008);
see also Boehm, Fayet (2003)
Pospelov, Ritz, Voloshin (2007)

THE NEW PARTICLE LANDSCAPE



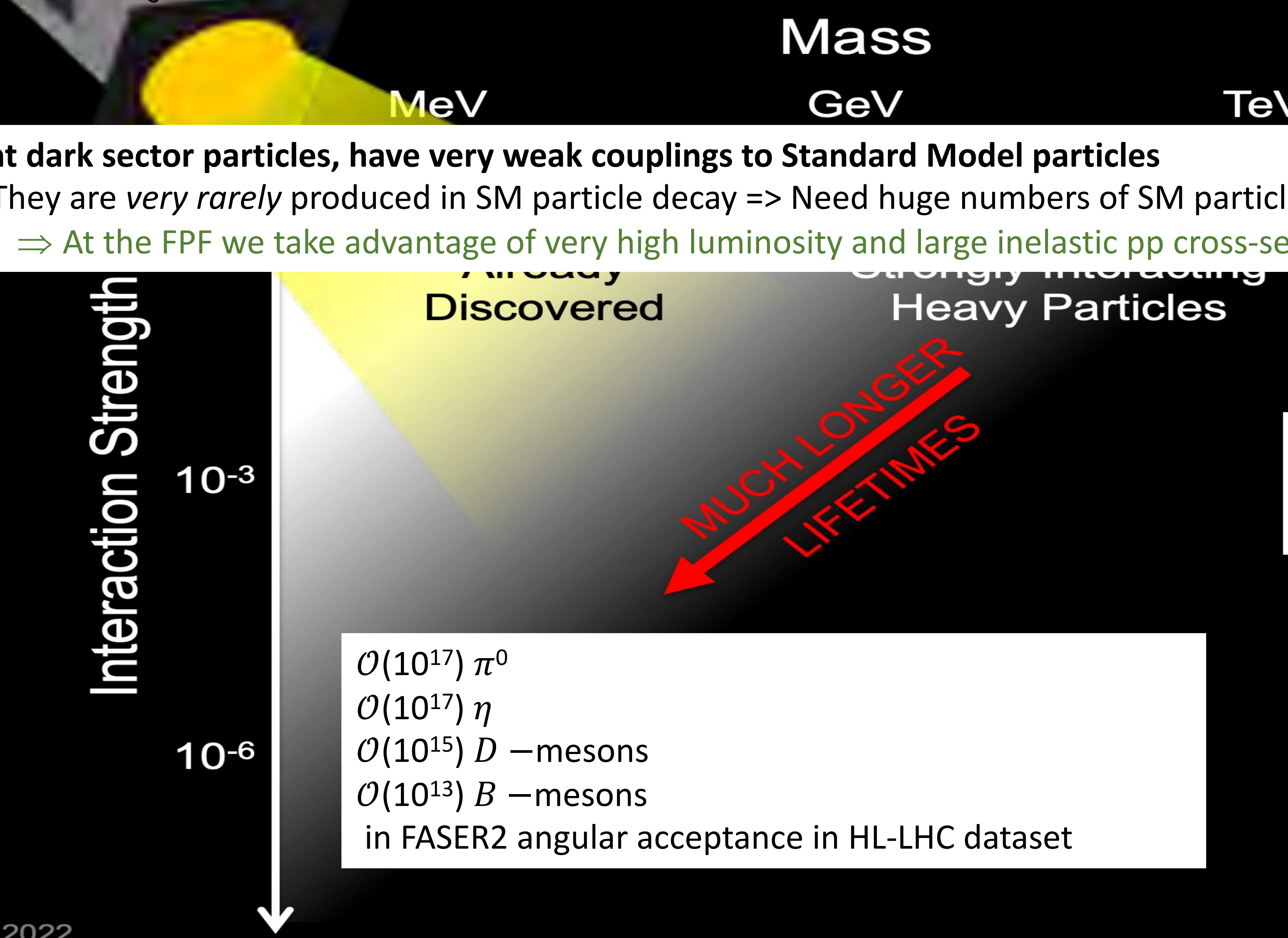
$$L \propto \frac{1}{\epsilon^2 m^2}$$

THE NEW PARTICLE LANDSCAPE

Light dark sector particles, have very weak couplings to Standard Model particles

$\Rightarrow$ They are *very rarely* produced in SM particle decay => Need huge numbers of SM particles for sensitive searches

$\Rightarrow$ At the FPF we take advantage of very high luminosity and large inelastic pp cross-section at HL-LHC



$$L \propto \frac{1}{\epsilon^2 m^2}$$

$\mathcal{O}(10^{17})\ \pi^0$
$\mathcal{O}(10^{17})\ \eta$
$\mathcal{O}(10^{15})\ D$ −mesons
$\mathcal{O}(10^{13})\ B$ −mesons
in FASER2 angular acceptance in HL-LHC dataset

THE NEW PARTICLE LANDSCAPE

Mass

MeV GeV TeV

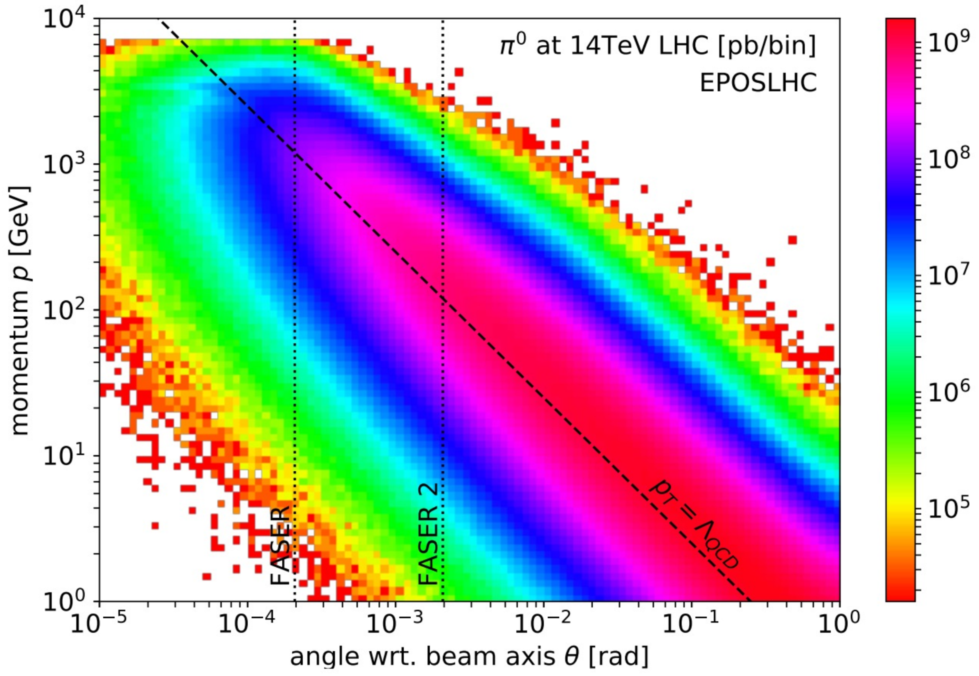
Light dark sector particles, have very weak couplings to Standard Model particles

⇒ They are *very rarely* produced in SM particle decay => Need huge numbers of SM particles for sensitive searches

⇒ At the FPF we take advantage of very high luminosity and large inelastic pp cross-section at HL-LHC

⇒ They are long-lived:

⇒ The FPF is $\mathcal{O}$(100's)m from IP, the distance to decay is increased by the large boost of forward particle production at LHC



MUCH LON

LIFETIMES

$$L \propto \frac{1}{\epsilon^2 m^2}$$

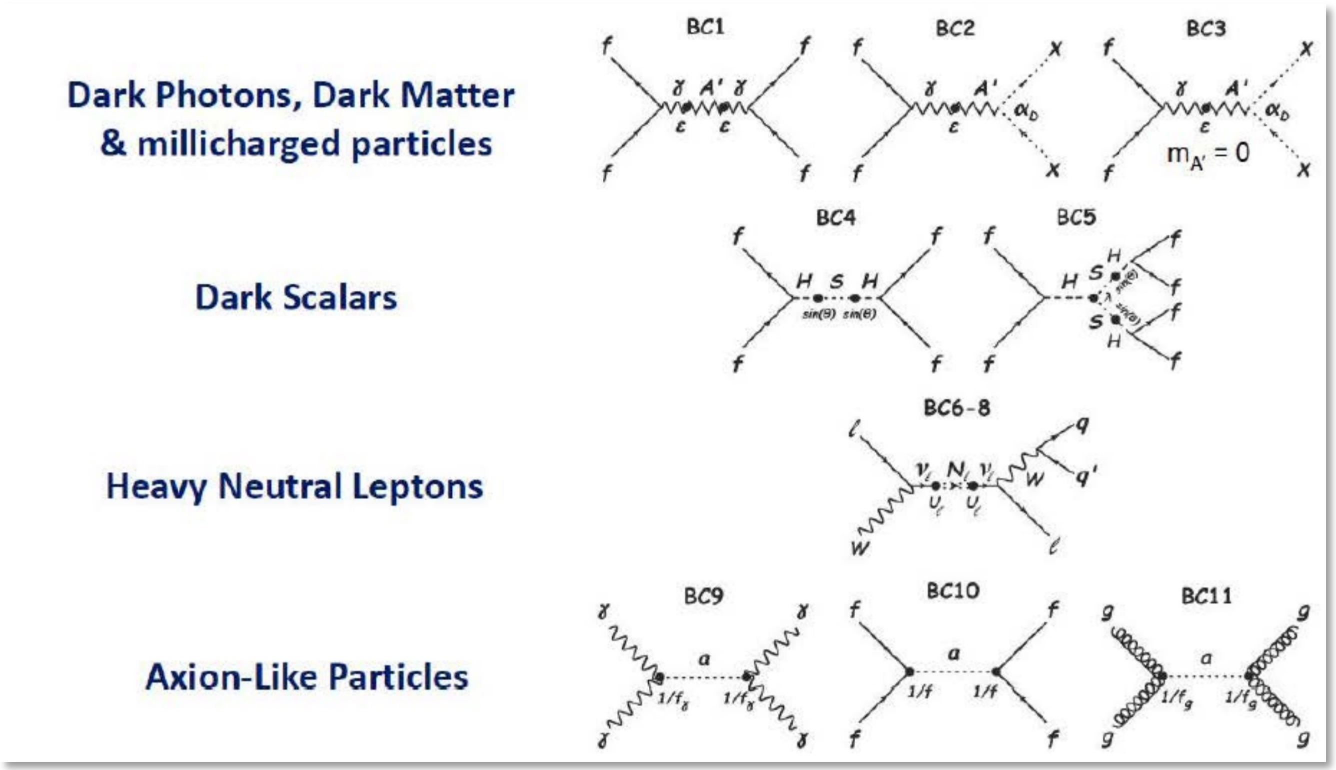
ng

Impossible to Discover

Typical momentum of π^0 in FASER2 angular acceptance $\mathcal{O}$(100s) GeV

BSM at FPF

The set of most popular dark-sector models compiled as benchmarks by CERN Physics Beyond Colliders (PBC) group:

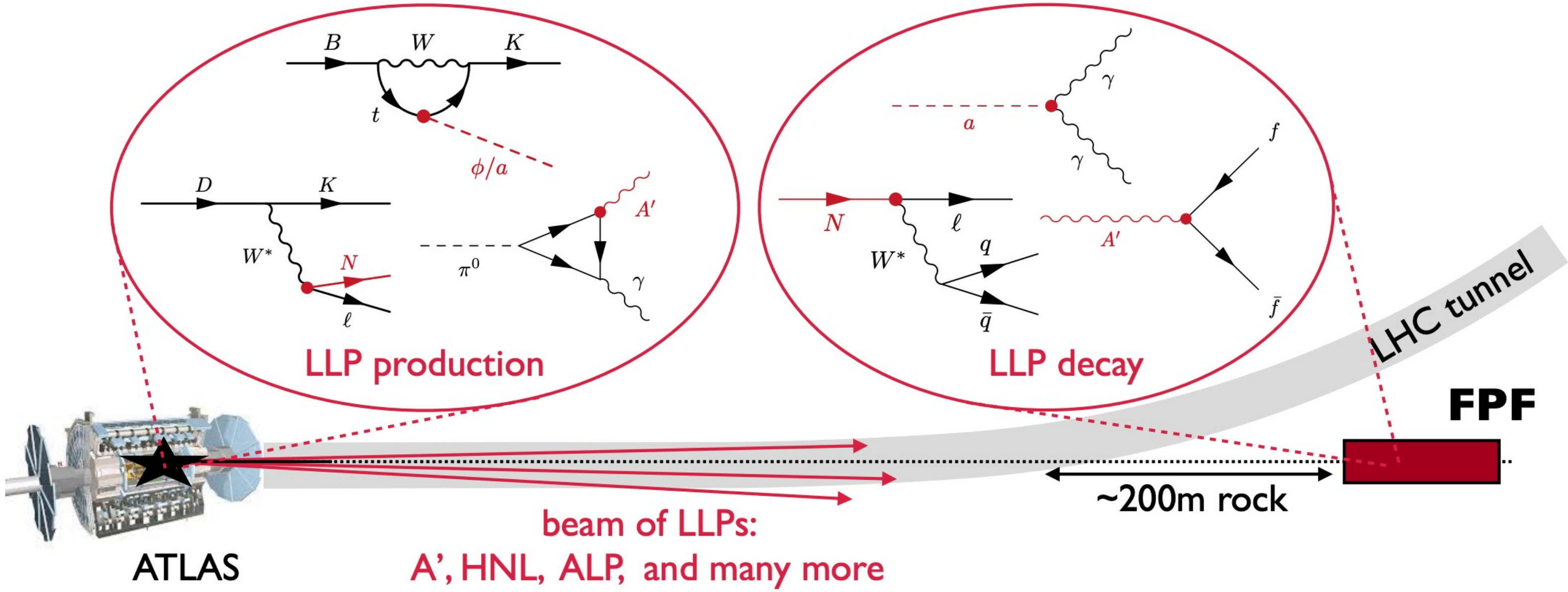


FPF experiments would give significant new sensitivity in all of these models. A few examples on next slides…

Benchmark Model	FPF
BC1: Dark Photon	FASER 2
BC1': $U(1)_{B-L}$ Gauge Boson	FASER 2
BC2: Dark Matter	FLArE
BC3: Milli-Charged Particle	FORMOSA
BC4: Dark Higgs Boson	FASER 2
BC5: Dark Higgs with hSS	FASER 2
BC6: HNL with e	FASER 2
BC7: HNL with μ	FASER 2
BC8: HNL with τ	FASER 2
BC9: ALP with photon	FASER 2
BC10: ALP with fermion	FASER 2
BC11: ALP with gluon	FASER 2

BSM at FPF

FASER2 experiment designed to search for dark sector particles decaying inside the detector. FPF has excellent shielding from collisions (200m rock and strong LHC magnets) – background free searches should be possible.



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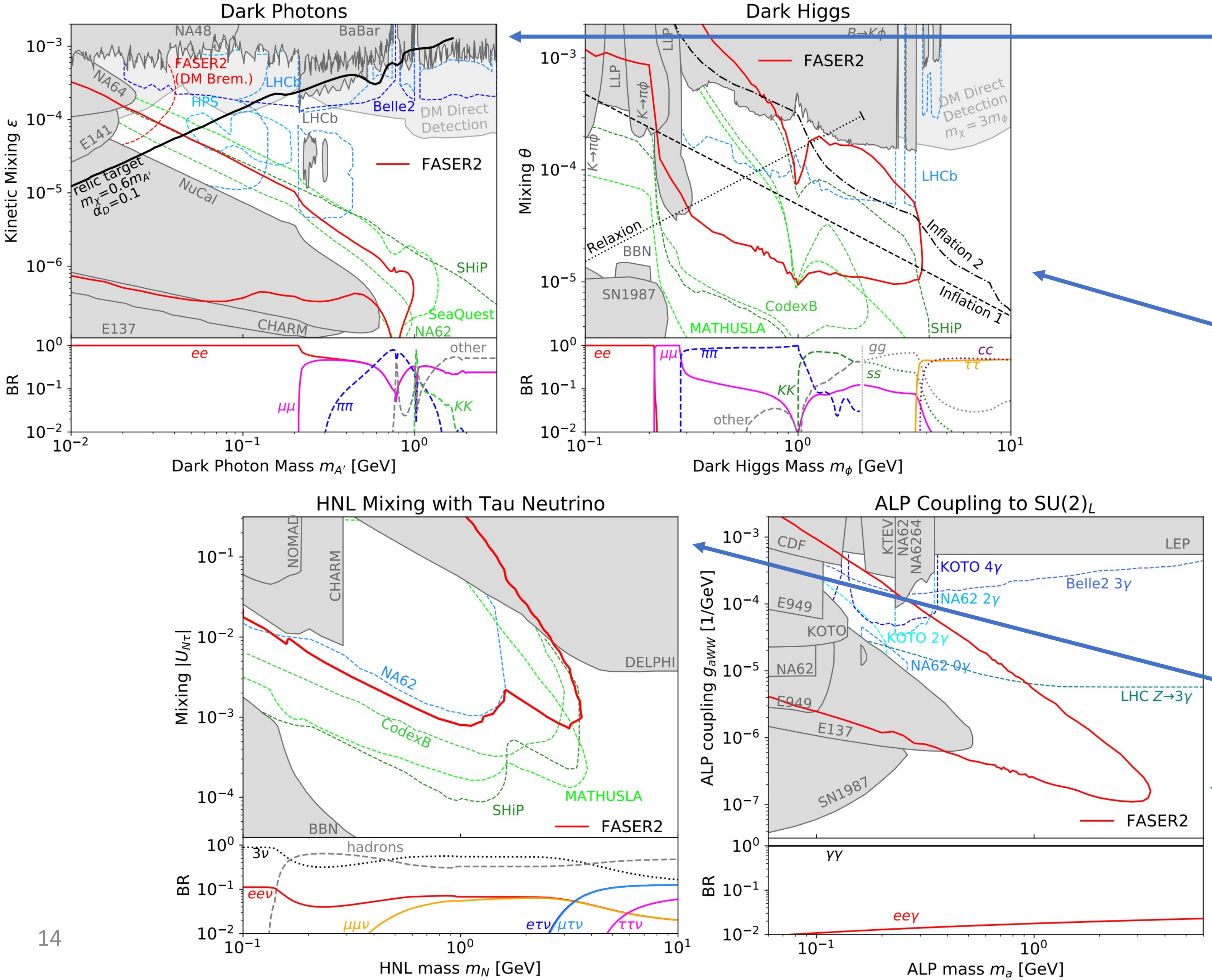

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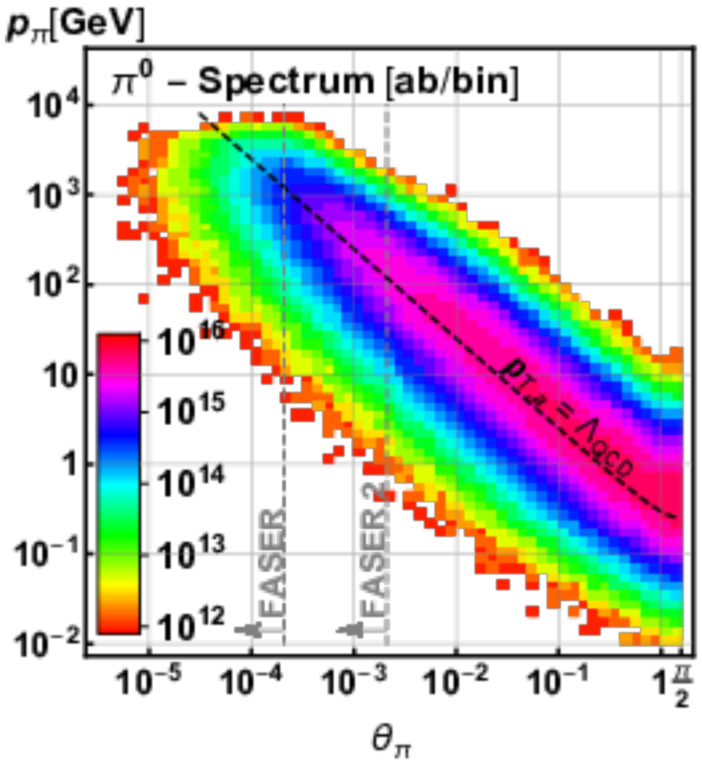
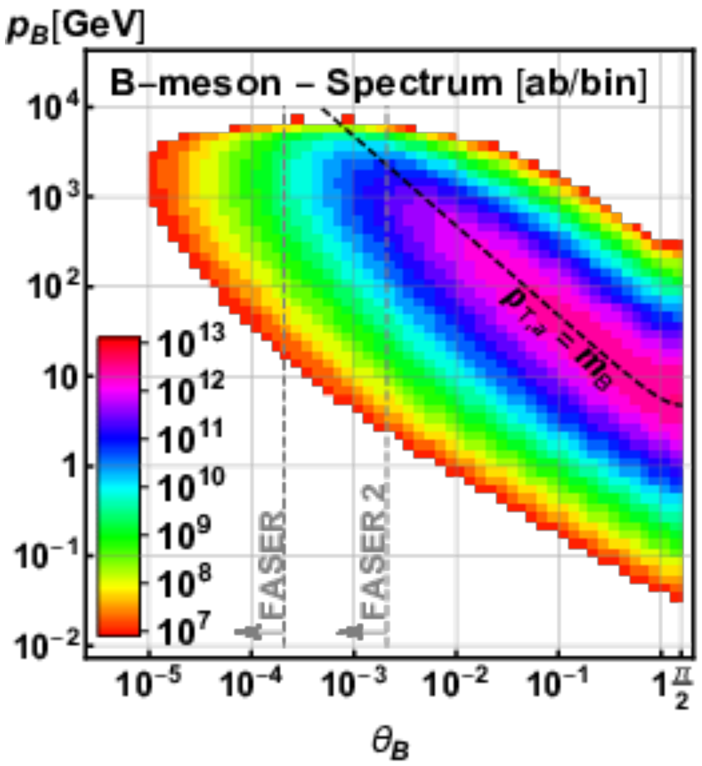
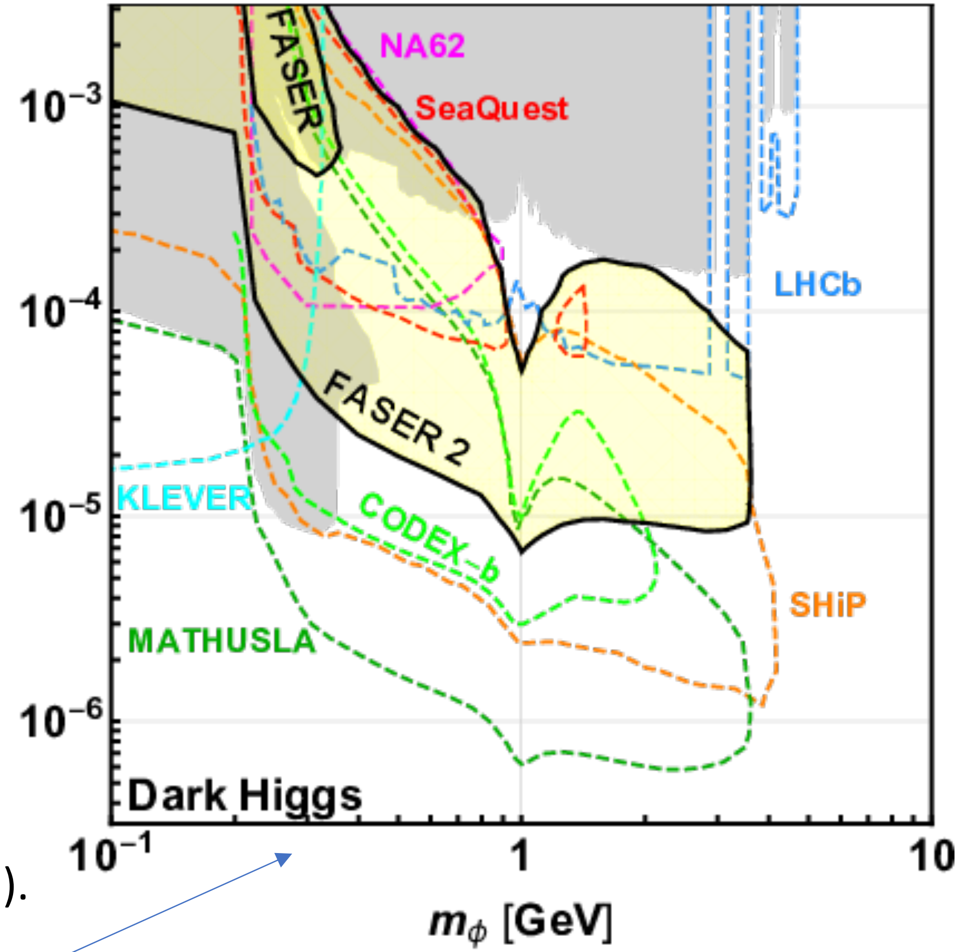
Aside: Signals from heavy flavour decay



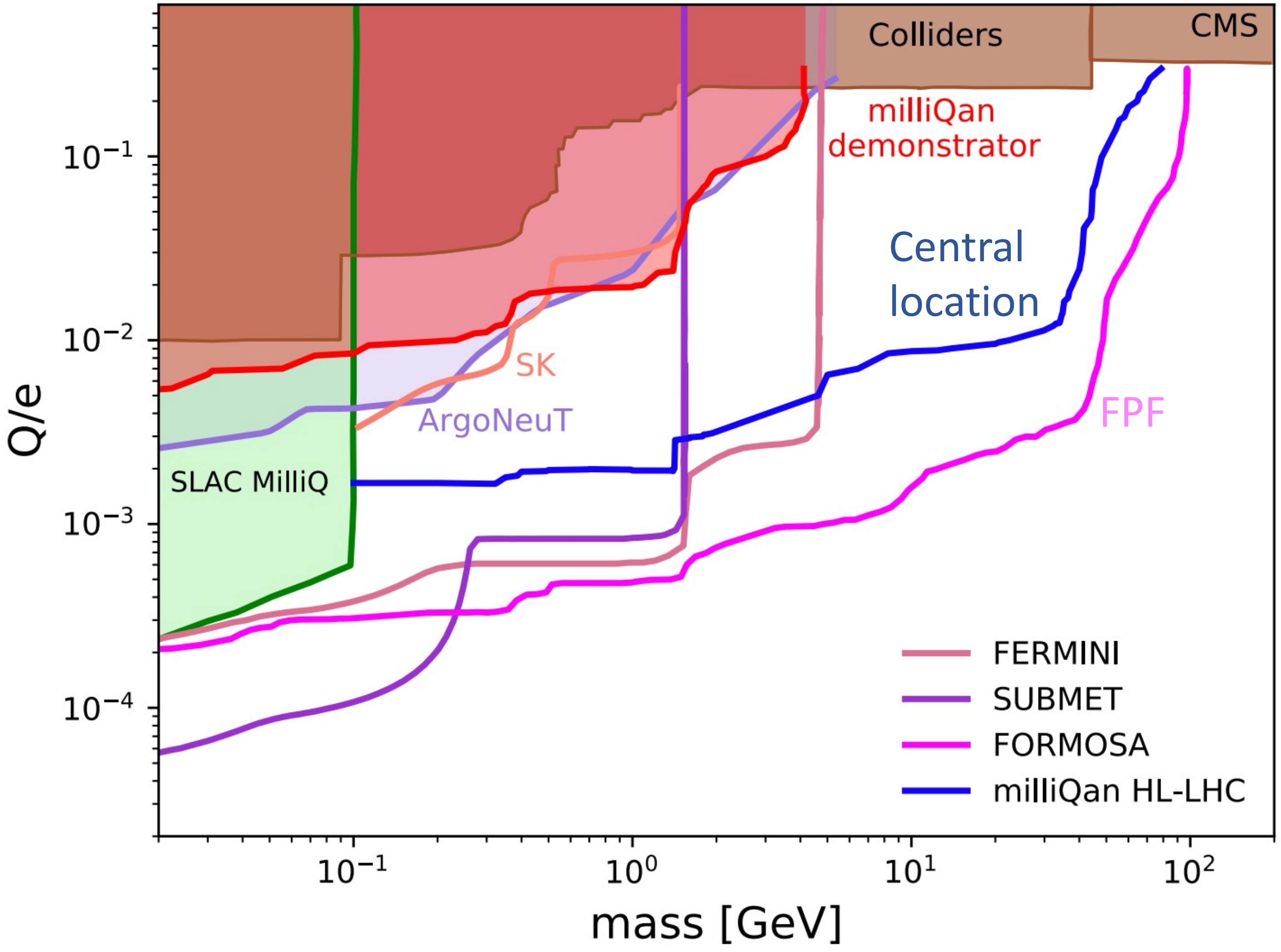




Number of π^0 and B mesons as function of angle wrt LOS and energy (for 150/fb). Heavier B-mesons are more spreadout around the LOS => only small fraction in FASER acceptance, but FASER2 starts to get into the bulk of the distribution. Much better sensitivity for new LLPs produced in B decays (such as Dark Higgs) at FASER2 than FASER.

BSM at FPF

Milicharged particles appear in models with massless dark photons. Improvement in sensitivity for this scenario by FORMOSA at the FPF, compared to milliQan detector installed as a central detector. FORMOSA sees up to ~250x signal rate compared to central detector location.



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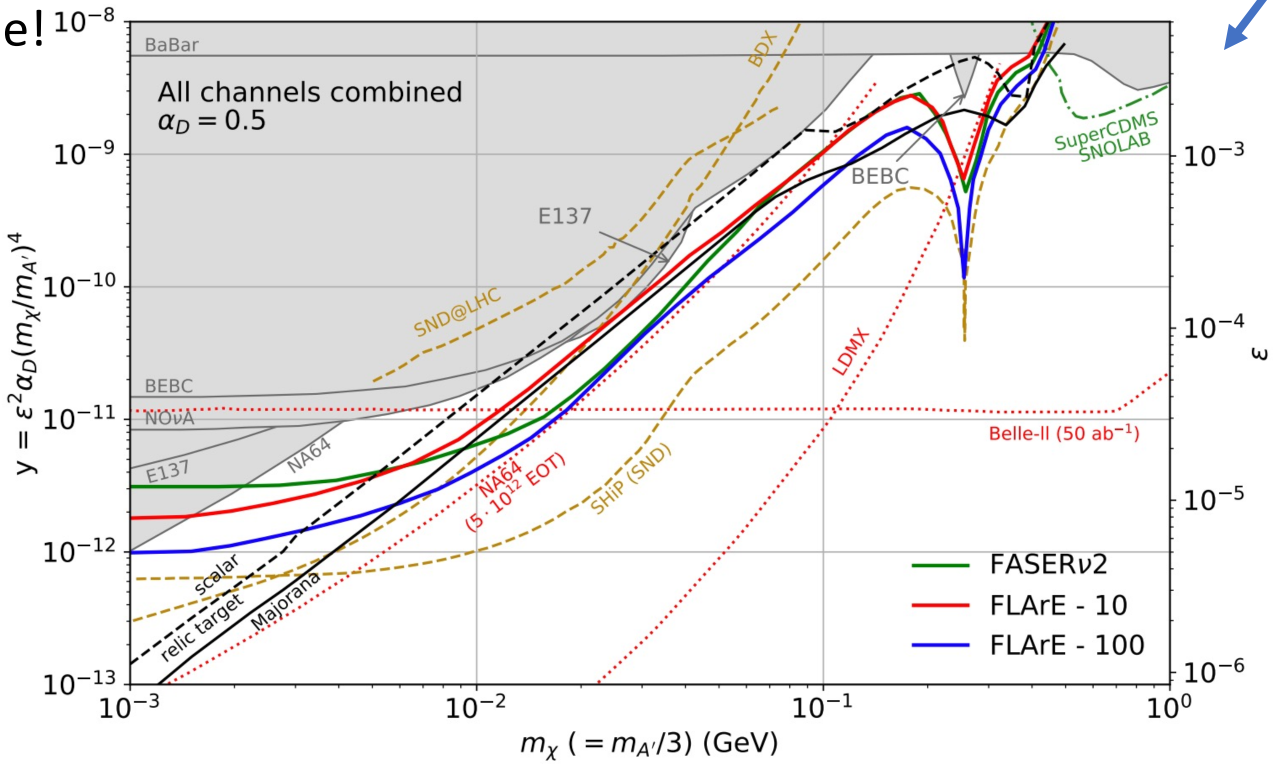
BSM at FPF

- Recent theory level studies on sensitivity to DM scattering in a LArTPC at the FPF (FLArE)
  - Consider both DM-electron and DM-nucleus scattering
- Very interesting sensitivity, probing the thermal relic region with the "right amount" of Dark Matter
  - Direct scattering, complementary method to "missing energy" (NA64/LDMX) signatures
- Opens door to direct-detection type DM search at a collider for the first time!



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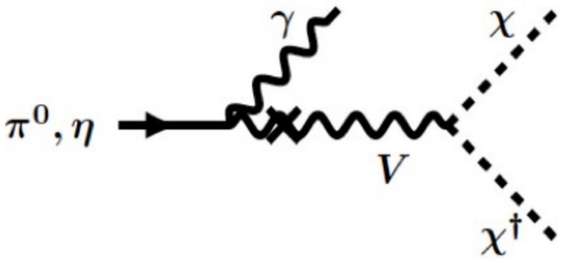
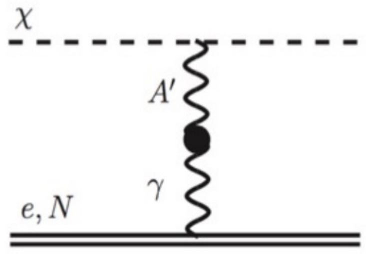


DM production



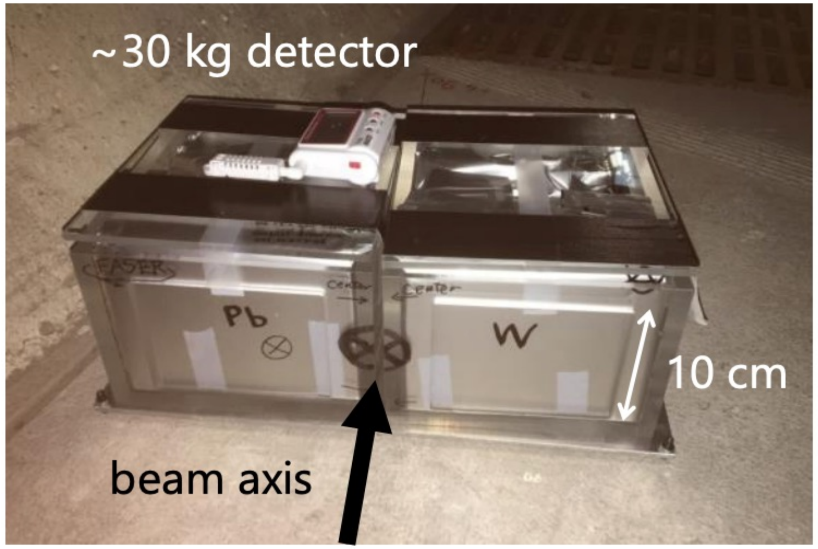
DM scattering

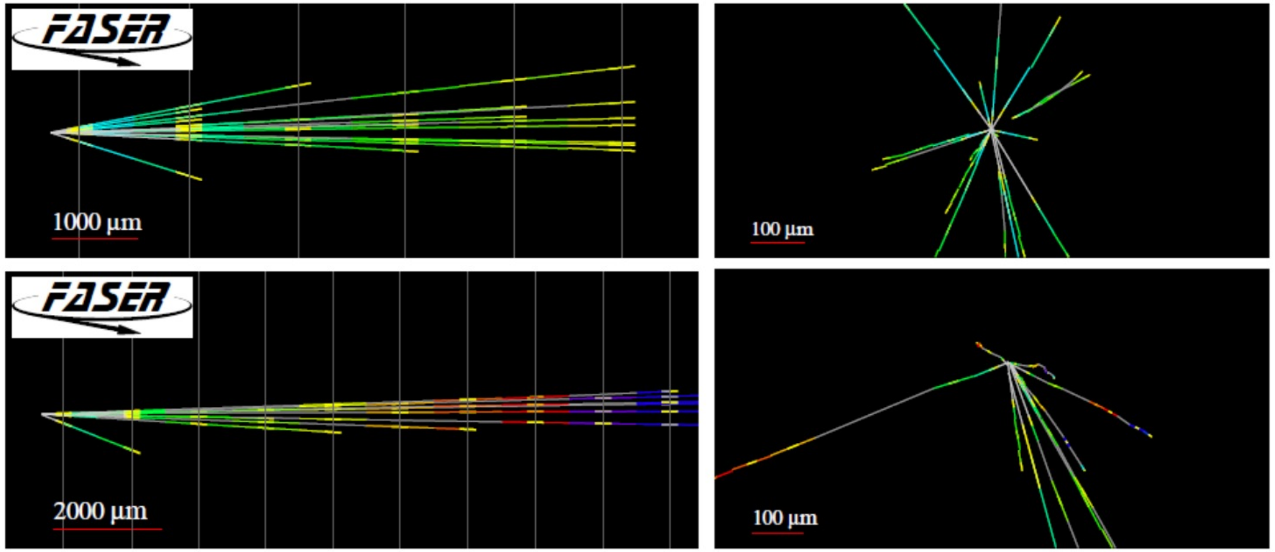
Collider Neutrinos

PRD.104.L091101

- Studying neutrinos produced at colliders has been proposed nearly 40 years ago: *De Rujula, Ruckl (1984); Winter (1990)* but so far has not been realised
- LHC collisions produce a huge flux of high energy neutrinos (from hadron decay) extremely collimated with the LHC beam
- FASERnu and SND@LHC experiments approved to for Run 3 datataking to detect and study such neutrinos for the first time

As part of the preparation of FASER, in 2018 LHC running a small emulsion detector (30kg / 11kg fiducial) was installed into the TI18 tunnel on the LOS, for 4 weeks (~12/fb of data).
Analysis of this led to the observation of neutrino interaction candidates from a collider for the first time.





Highlights the potential of the LOS location for neutrino physics!

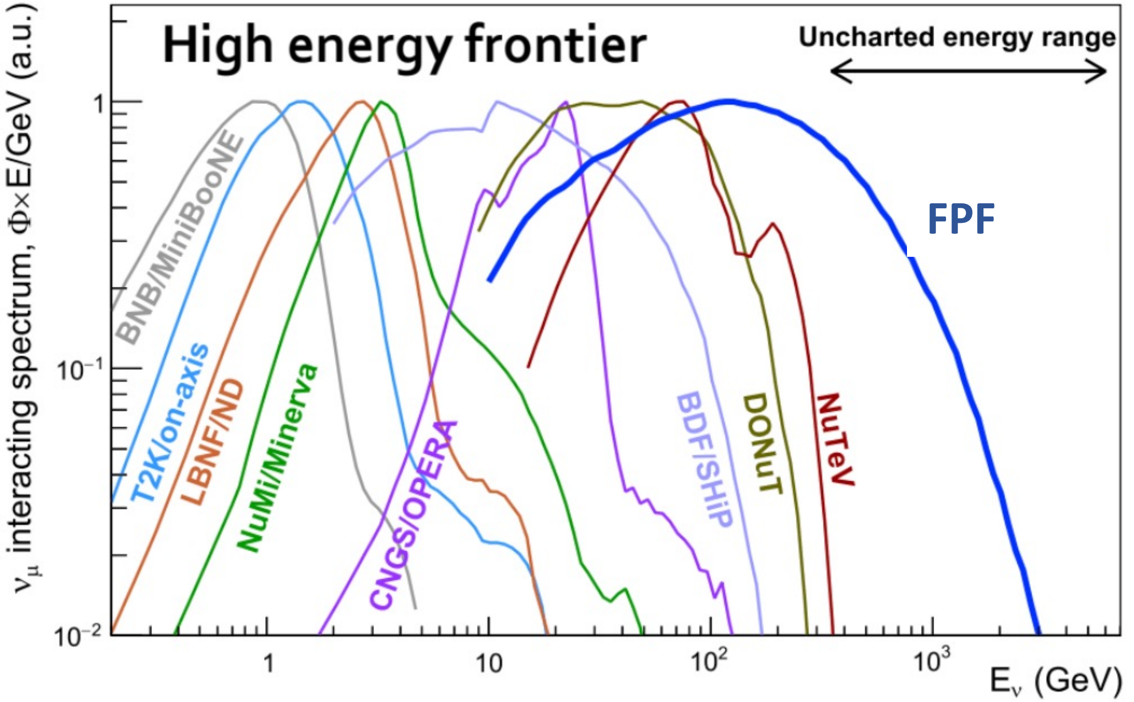
https://arxiv.org/pdf/2105.08270.pdf (F. Kling, DESY)

Neutrinos at the FPF

A ***huge number of high-energy neutrinos of all flavours*** will be detected by experiments at the FPF.

Species	#evts* (20tn, 3/ab)	
ν_e	115k	~180k
$\bar{\nu}_e$	65k	
ν_μ	875k	~1M
$\bar{\nu}_\mu$	225k	
ν_τ	1.7k	~2.5k
$\bar{\nu}_\tau$	0.7k	

Highest energy neutrinos from a terrestrial source.
Typical energy of interacting neutrinos on LOS ~900 GeV.



- \- large differences in expectations between different generators – numbers shown here the most conservative particularly for ν_τ where some generators predict more than a factor of two larger numbers

More detailed calculations for tau neutrinos in: https://arxiv.org/abs/2112.11605 (M. Garzelli, DESY – et al.)

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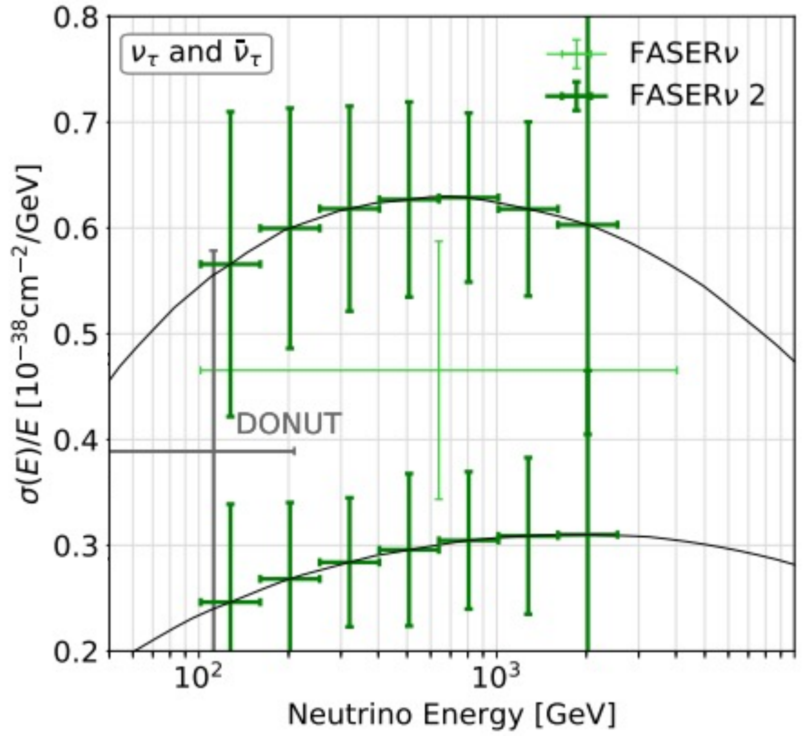

The tau neutrino is the **least well studied SM particle**, with only $\mathcal{O}(20)$ directly detected interactions. FPF experiments will **increase this number by over two orders of magnitude**, enabling precision ν_τ studies:

- Separately identify $\nu_\tau / \bar{\nu}_\tau$ for the first time
- Constrain the ν_τ magnetic dipole moment
- Measure high energy $\nu_\tau / \bar{\nu}_\tau$ charge-current cross sections
- Study $\nu_\tau \rightarrow$ heavy flavour – towards probing same diagrams as LHCb lepton-flavour violation anomalies

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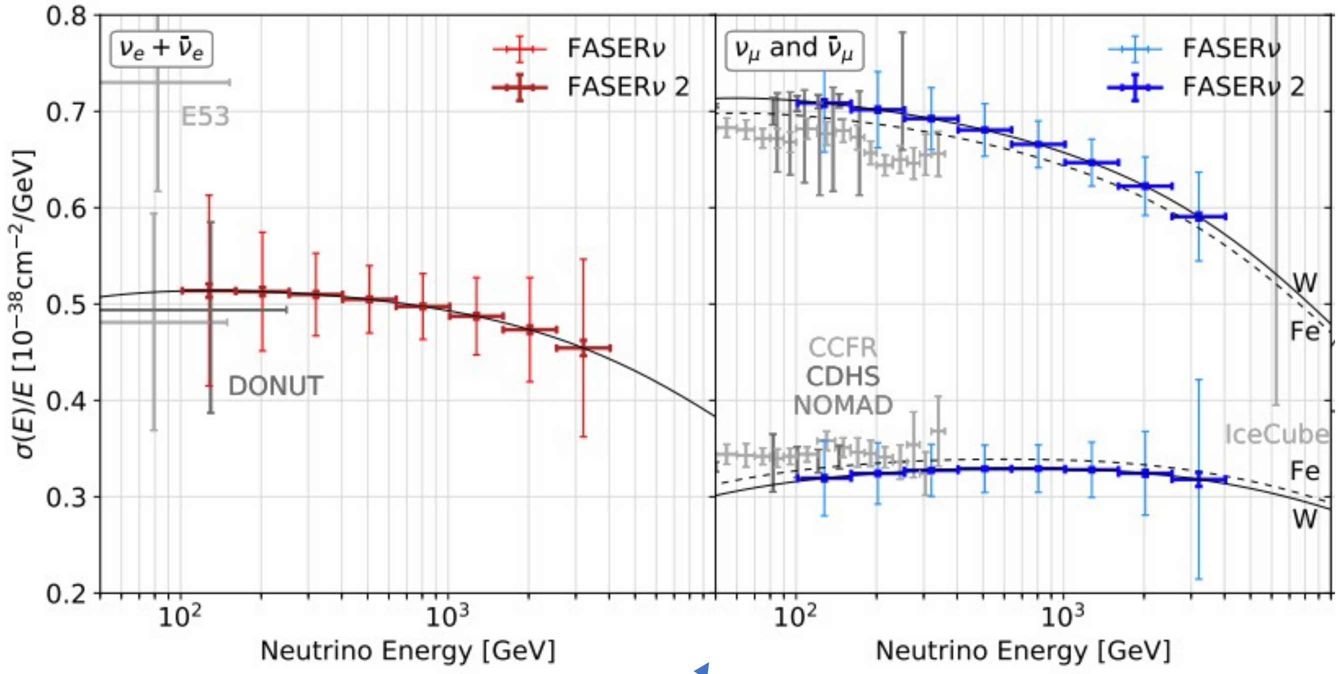
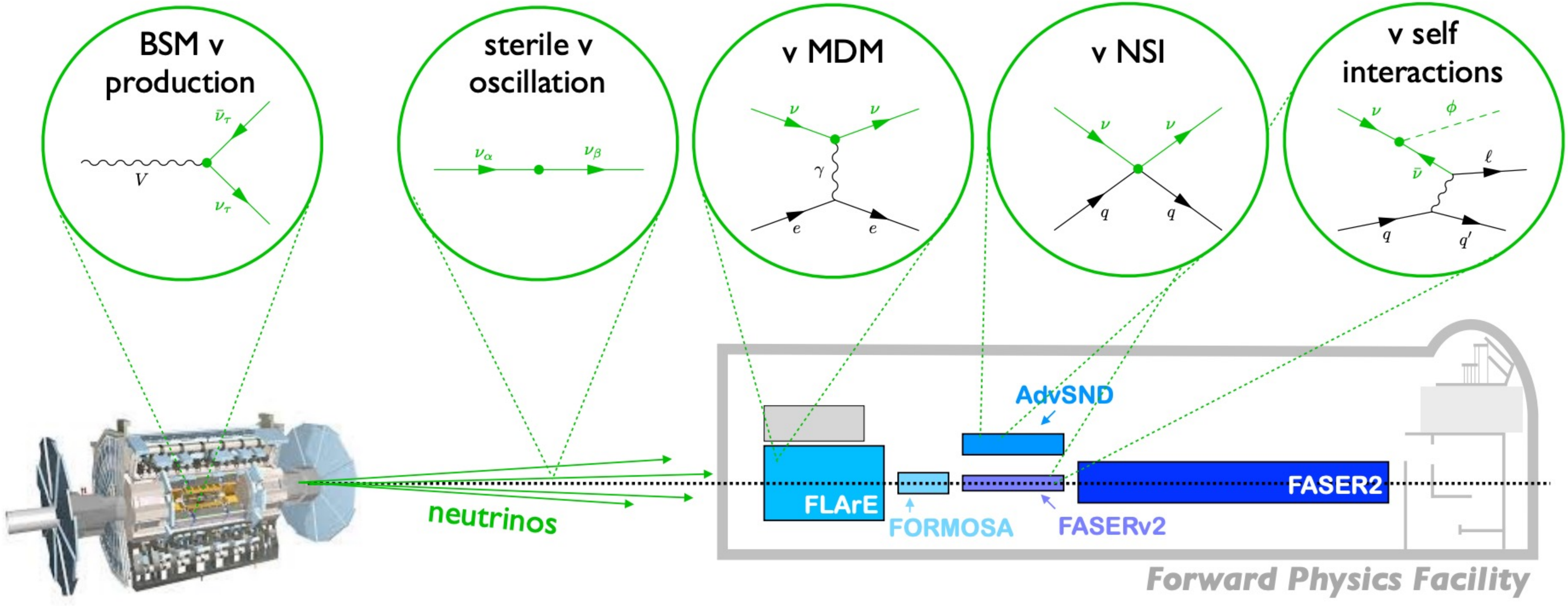


Other FPF neutrino physics, take advantage of the **huge ν_μ/ν_e datasets**, include:

- Constrain non-standard neutrino interactions with neutral current events
- Constrain SM EFT coefficients using neutrino data
- Search for sterile neutrinos via oscillations over short baseline
- Precise measurement of charge-current cross-sections in unexplored energy regime
- s-channel resonance production is $\bar{\nu}_e$ - e scattering

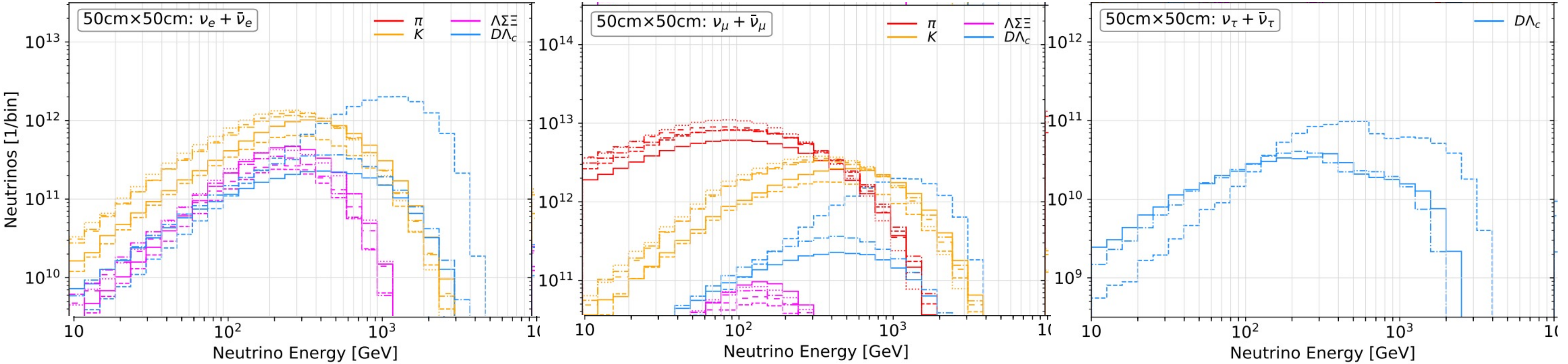
Neutrinos at the FPF

FPF neutrinos can be used to search for BSM effects, in production, propagation, and interactions:



QCD at the FPF

- Neutrinos detected at FPF experiments can also be used to study QCD both in the neutrino production, and in neutrino interaction
- Production mechanism, depends on neutrino flavour, rapidity and energy
  - $\pi \rightarrow \nu\mu$, K $\rightarrow \nu_e$ (at high-energy/off-axis D $\rightarrow \nu_e$), D $\rightarrow \nu\tau$



Large differences between generators on rate of forward hadron production, especially for charm:
SIBYLL 2.3d (solid), DPMJet 3.2017 (short dashed), EPOS-LHC (long dashed), QGSJet II-04(dotted), and Pythia 8.2 (dot-dashed)

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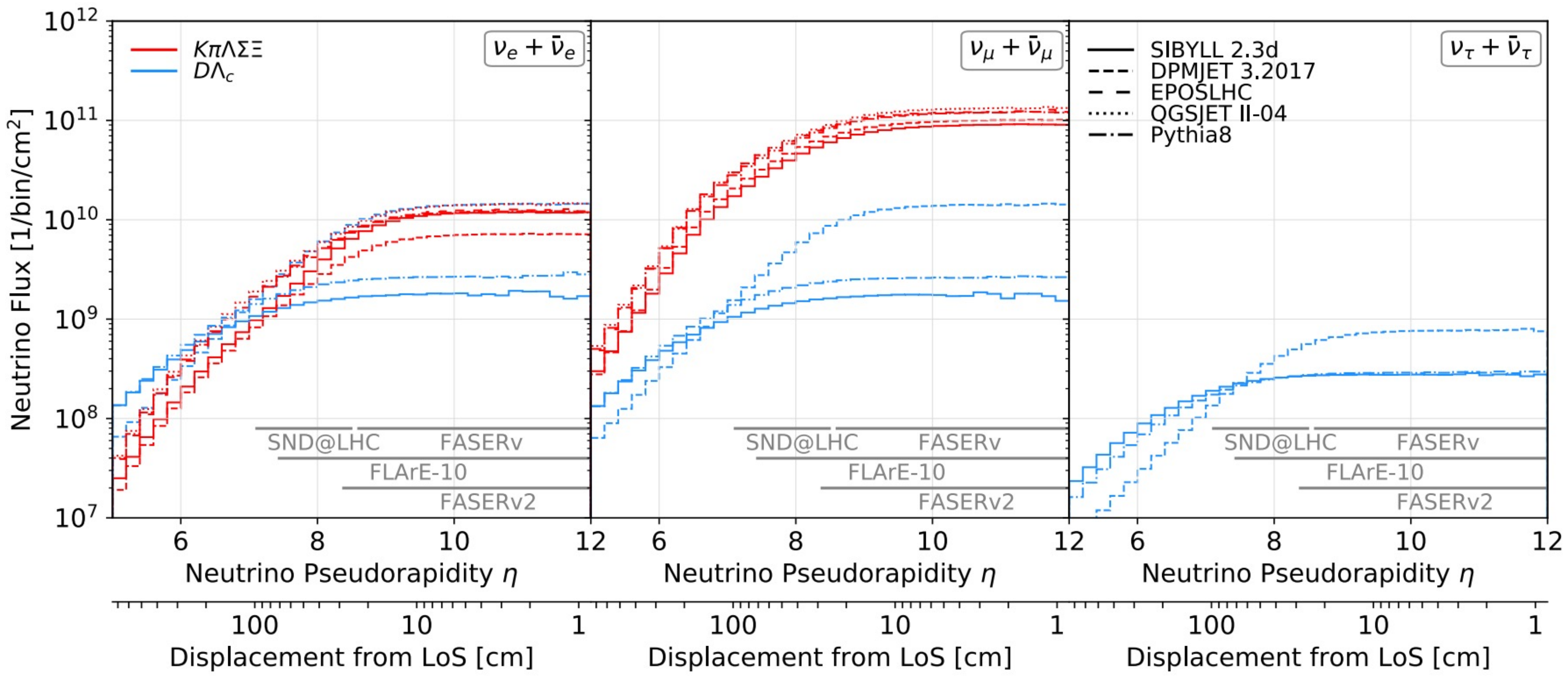
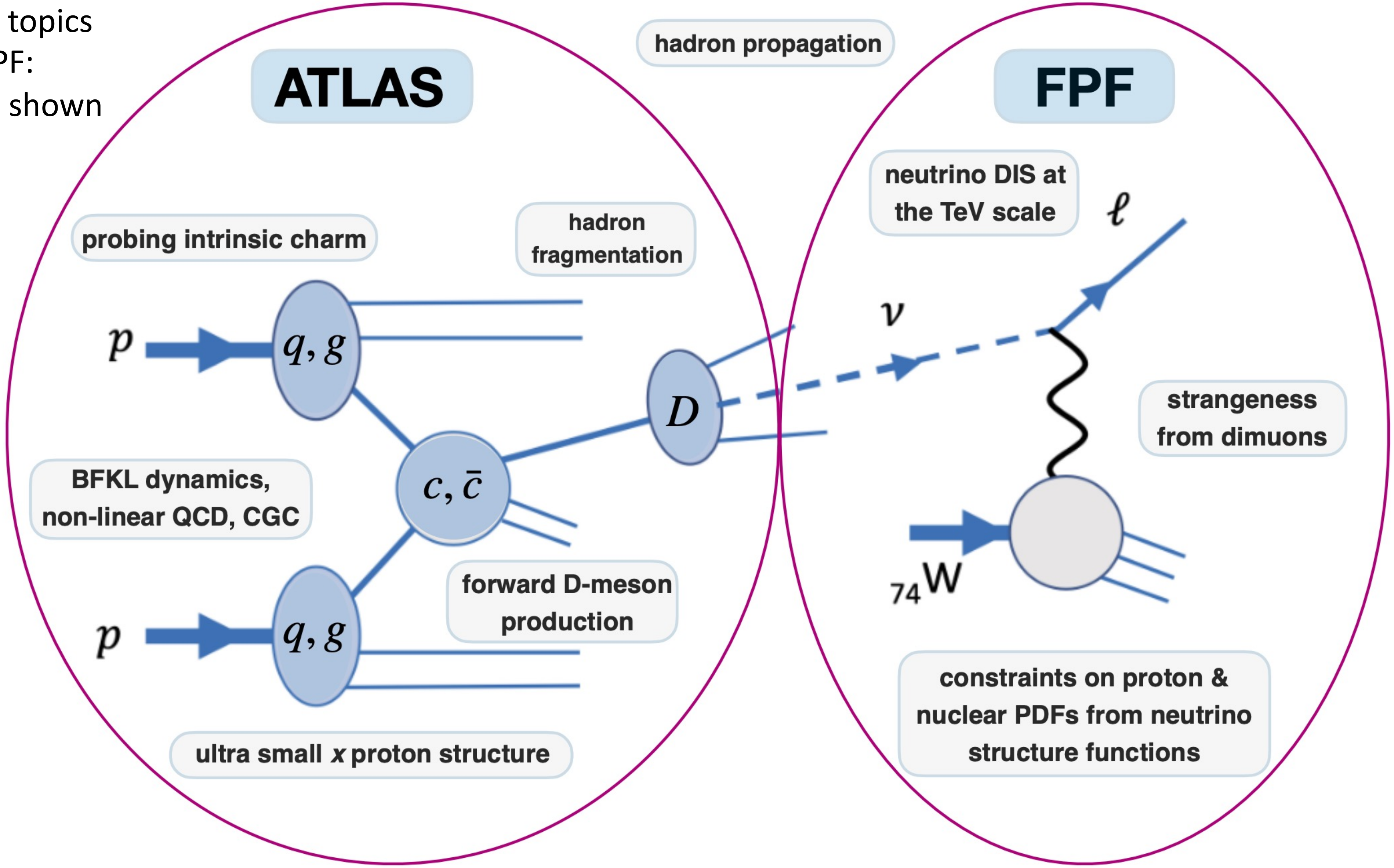


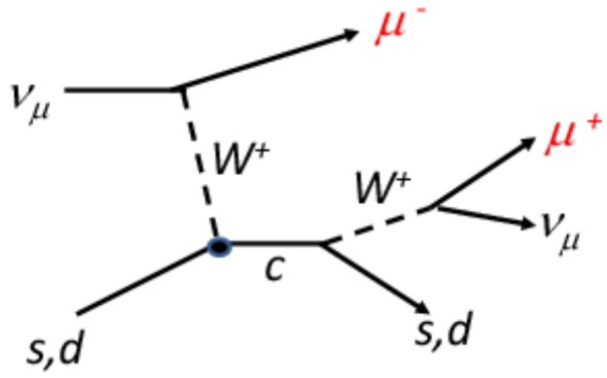
QCD at the FPF

Many interesting QCD topics to be studied at the FPF:
(A couple of examples shown on next slides)



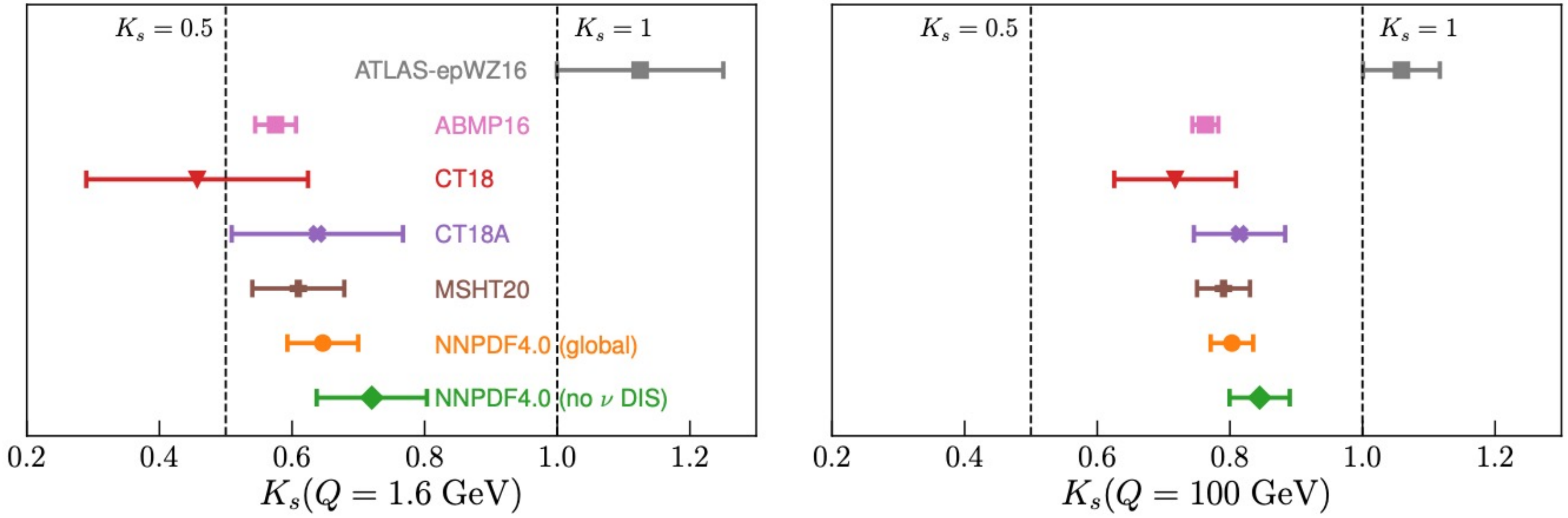
PDFs - strange

The FPF is essentially a ν-ion collider with sqrt(s)~50GeV.
Can be used to study e.g. strange quark PDF through neutrino interaction producing charm (can be tagged in emulsion detector):



$$K_s \equiv \frac{\int_0^1 dx x[s(x,Q)+\bar{s}(x,Q)]}{\int_0^1 dx x[\bar{u}(x,Q)+\bar{d}(x,Q)]}$$

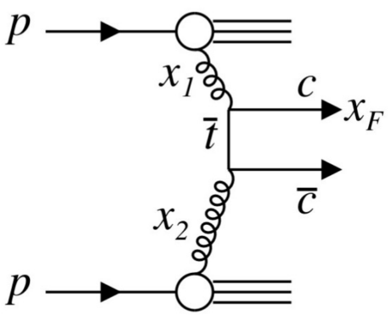
Could help to resolve observed tension between different measurements of strange component of PDF with recent ATLAS measurement:



PDFs - gluon

- **QCD of charm pair production**
  - Probes extremely low-x

$$\sigma(pp \to c\bar{c}X) \simeq \int dx_1\, dx_2\, G(x_1,\mu)G(x_2,\mu)\hat{\sigma}_{GG\to c\bar{c}}(x_1 x_2 s)$$



$x_1,\ x_2:$

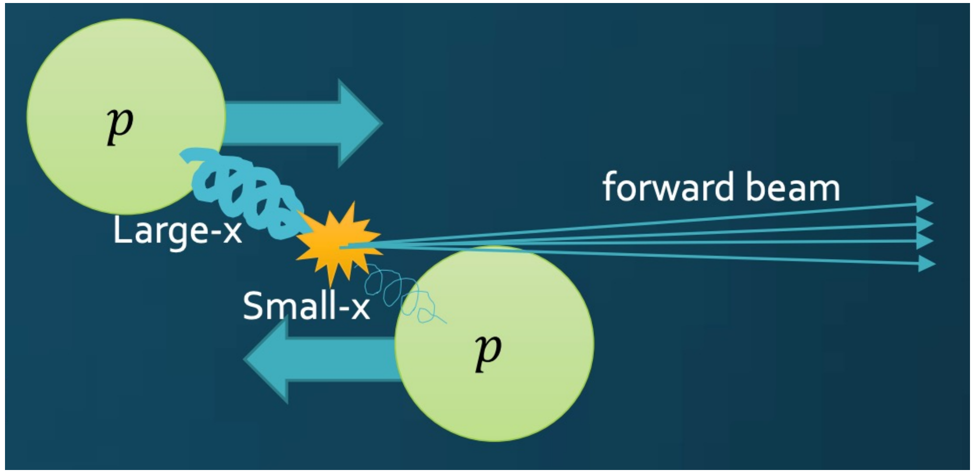
$$x_F = x_1 - x_2$$

$$x_F \simeq x_E = E/E'$$

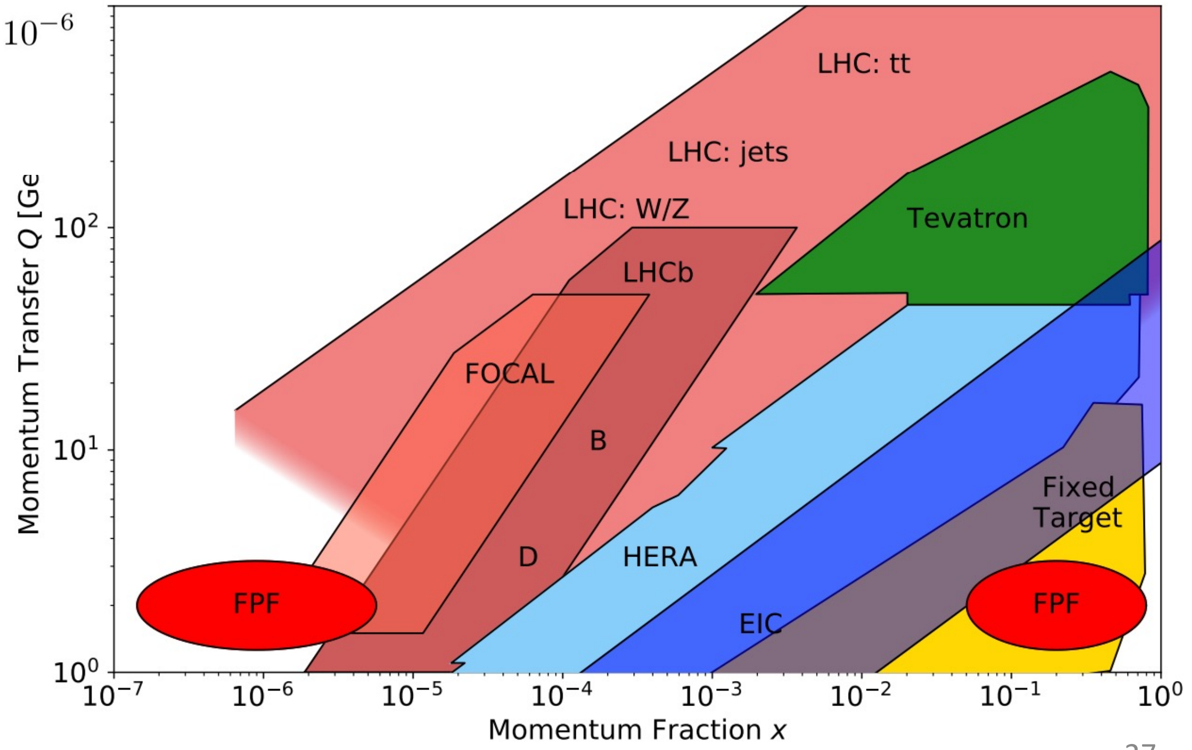
$$x_1 \simeq x_F \sim 0.1, \quad x_2 \ll 1 \qquad E \sim 10^7\ \text{GeV} \to x_2 \sim 10^{-6}$$

$$x_{1,2} = \frac{1}{2}\left(\sqrt{x_F^2 + \frac{4M_{c\bar{c}}}{s}} \pm x_F\right)$$

Taken from: A. Bhattacharya



Detecting neutrinos from D (c-quark) decays allow to probe the gluon PDF in very high- and low- x regimes, and to constrain intrinisc charm in the proton.



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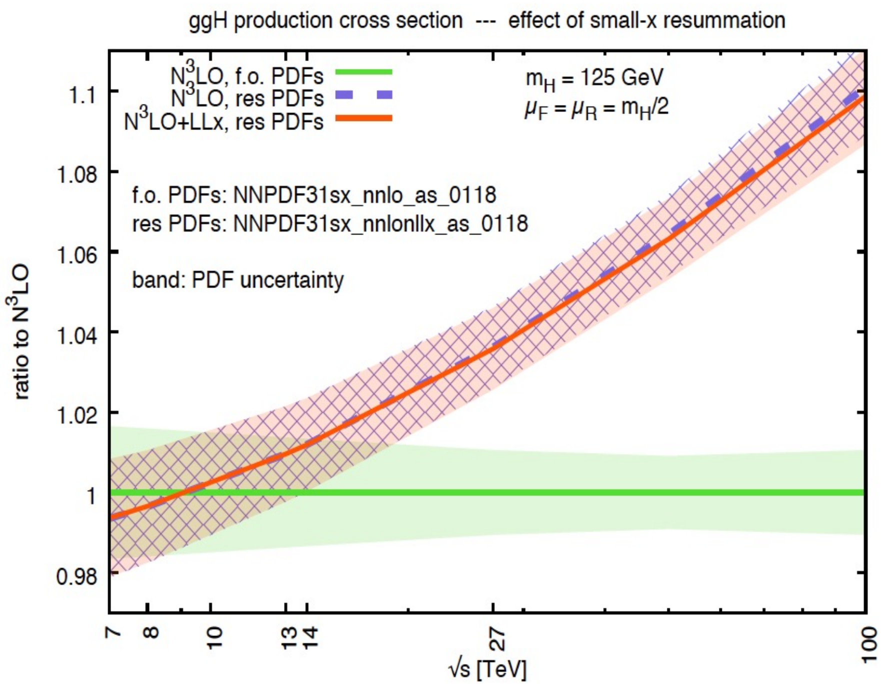

Low-x gluon PDF measurement important for ggH production at FCC collider.

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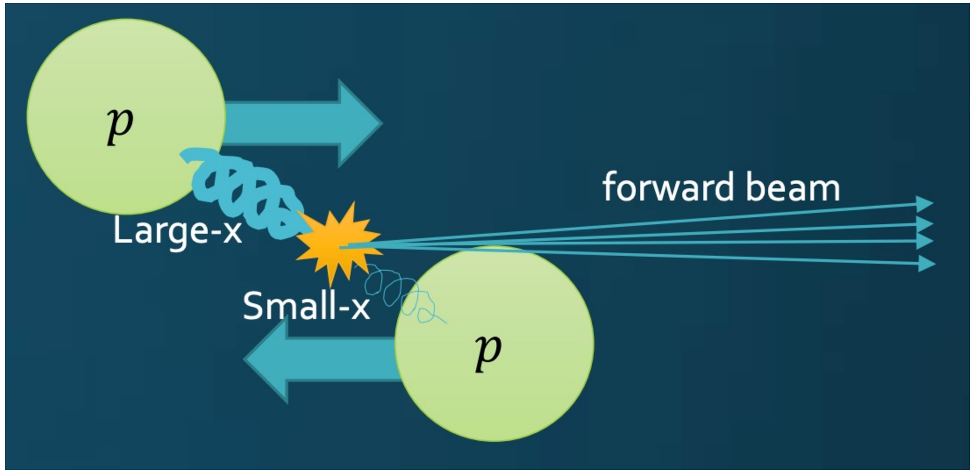
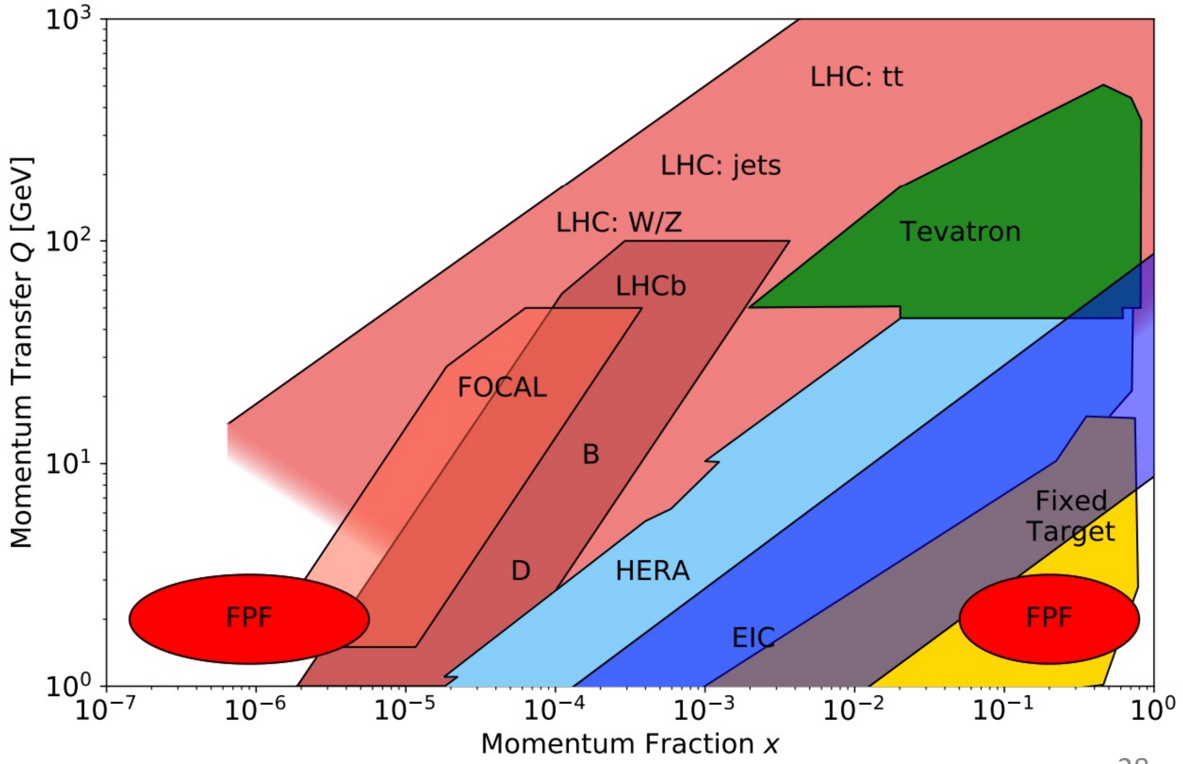
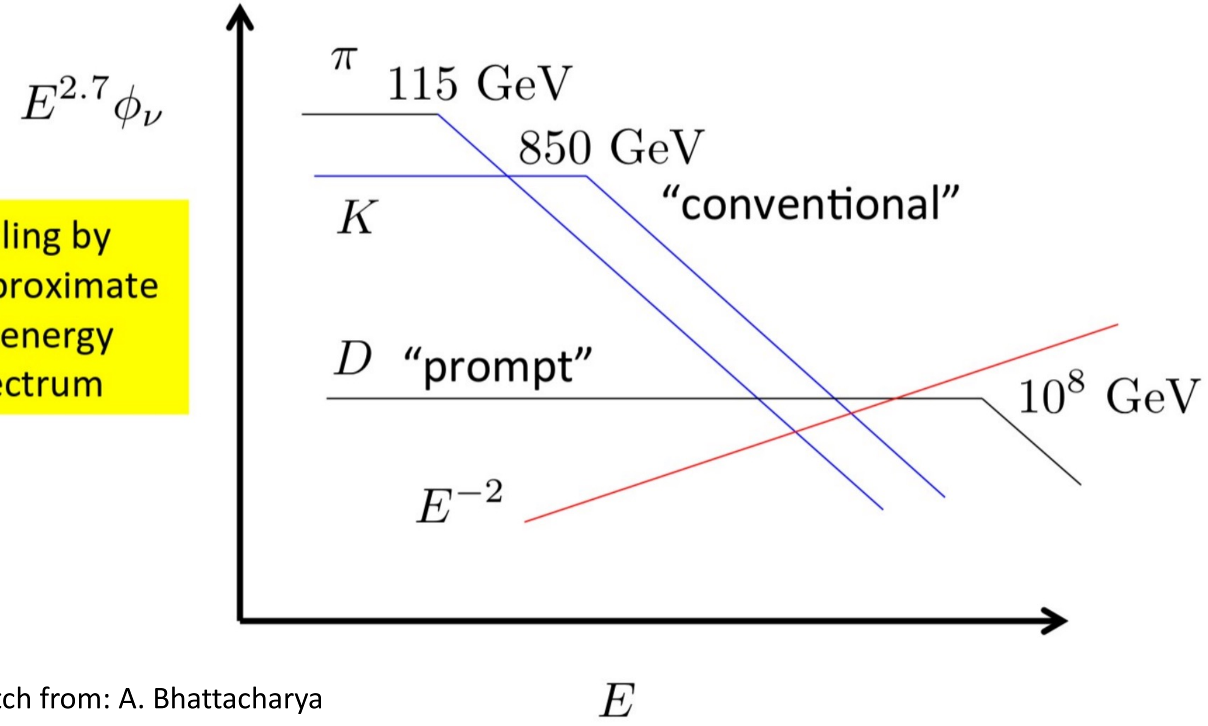




Input for astroparticle experiments

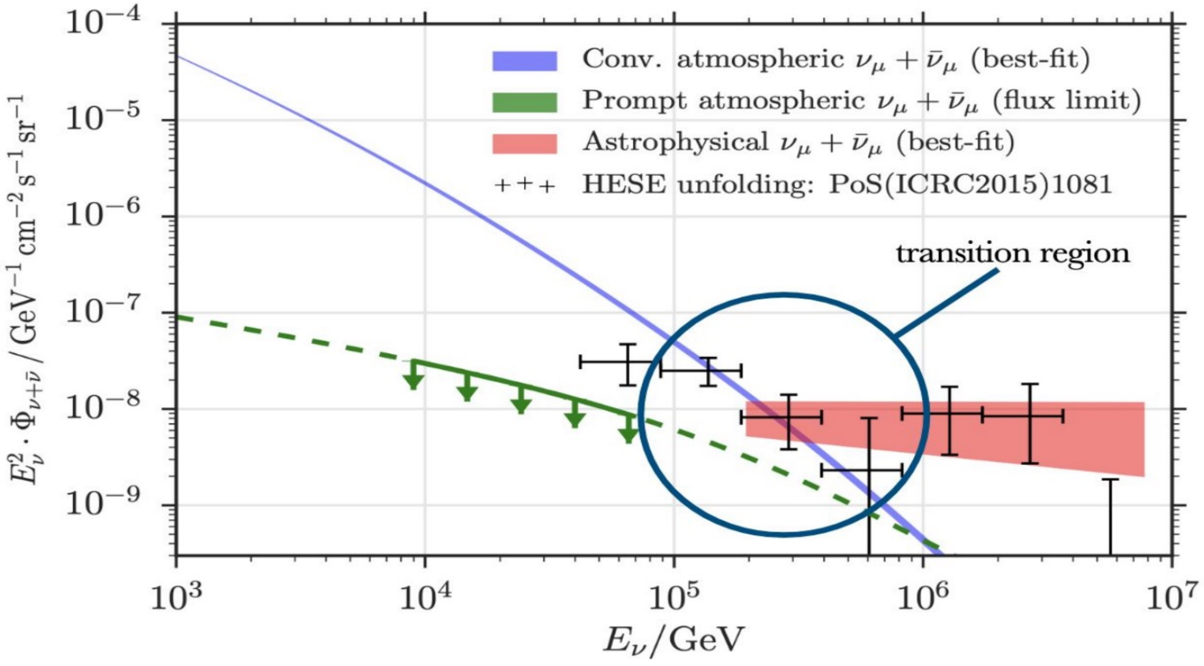
Studies of high-energy astrophysical neutrinos with large-scale neutrino telescopes (e.g. IceCube), suffer from backgrounds from atmospheric neutrinos from charm-decay (charm produced in hadronic shower initiated by cosmic rays hitting the atmosphere).
At ultra high-energy light hadrons travel far through the atmosphere, losing energy, and hence produce lower energy neutrinos. Neutrinos produced in charm decay ("prompt neutrinos") are therefore the key background at high energy.
This prompt background has a large associated uncertainty which limits the study of astrophysical neutrinos.
Measurements of neutrinos from charm at the FPF can provide important information to constrain this background.

Scaling by approximate CR energy spectrum



Sketch from: A. Bhattacharya

IceCube, PoS (ICRC2017) 1005



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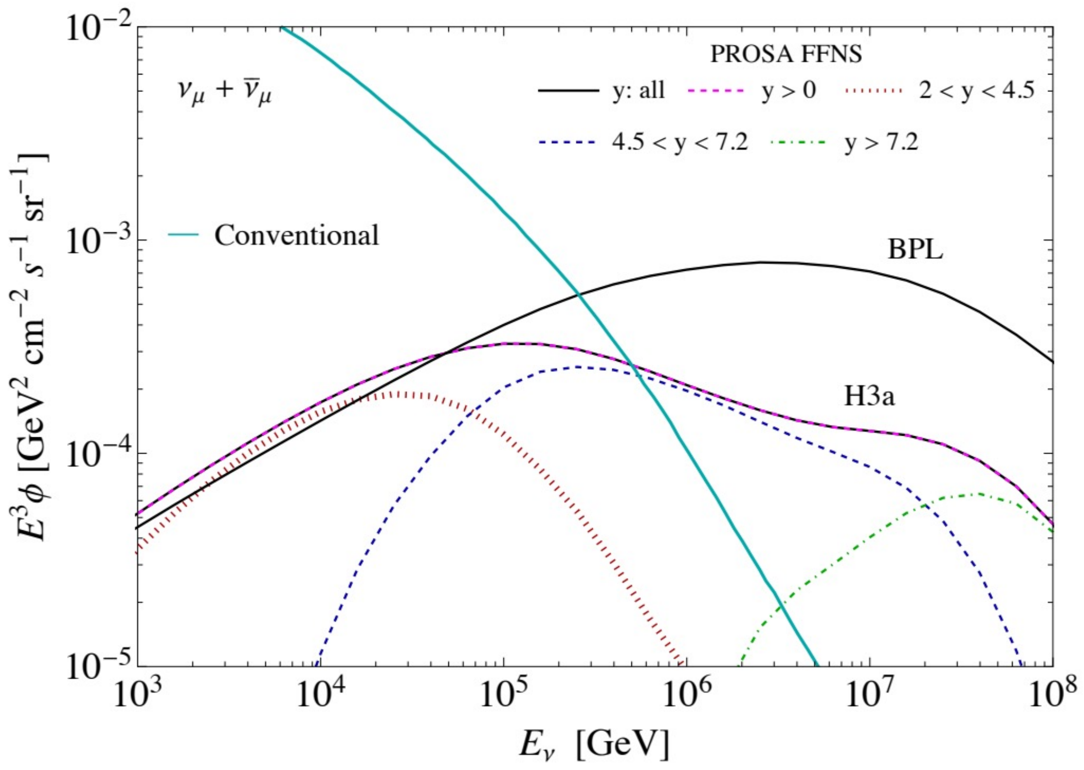


Figure shows what is the relevant rapidity range of LHC charm measurements to correspond to the IceCube neutrino energy:
Rapidity regions $4.5<y<7.2$ and $y>7.2$ both (currently unexplored) in relevant energy range.

The Experiments

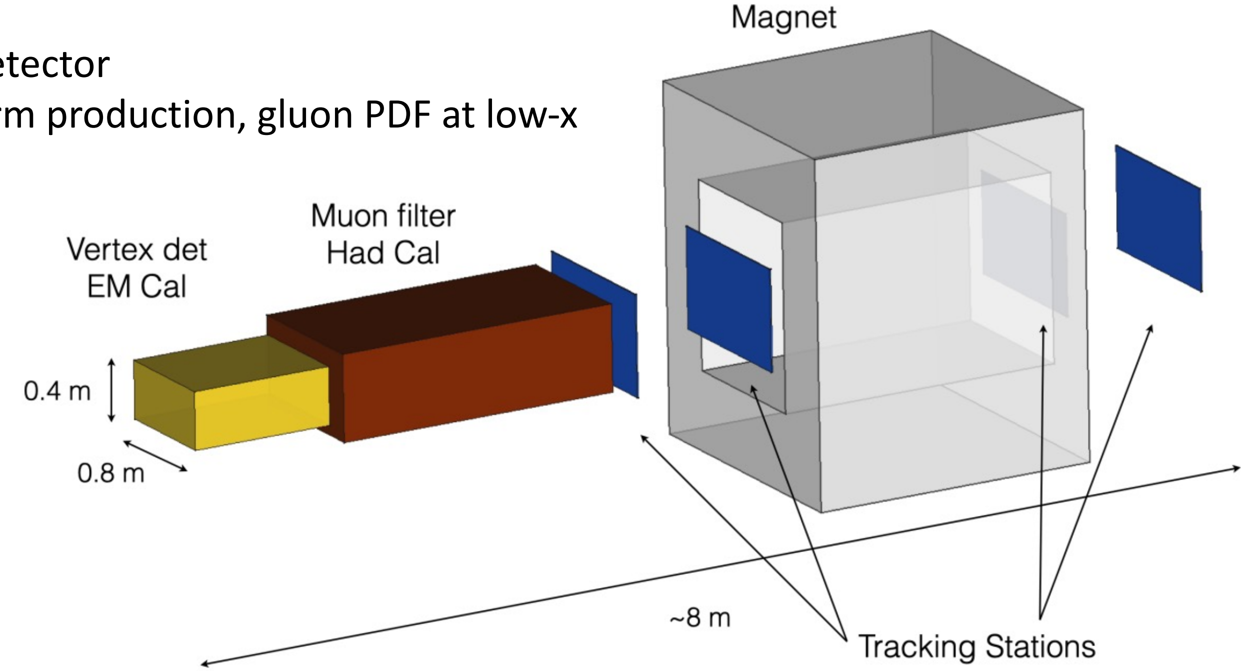
Currently proposed FPF experiments

- FLArE
  - $\mathcal{O}$(10tn) LAr TPC detector
  - DM scattering
  - Neutrino physics (ν_μ/ν_e , capabilitty for ν_τ under study)
    - Full view of neutrino interaction event
- FASERnu2
  - $\mathcal{O}$(20tn) emulsion/tungsten detector (FASERnu x20)
    - Mostly for tau neutrino physics
  - Interfaced to FASER2 spectrometer for muon charge ID ($\nu_\tau/\ \overline{\nu}_\tau$ separation)
- AdvSND
  - Neutrino detector slightly off-axis
    - Provides complementary sensitvity for PDFs from covering different rapidity to FASERnu2
- FASER2
  - Detector for observing decays of light dark-sector particles
  - Similar to scaled up version of FASER (1m radius vs 0.1m)
    - Increases sensitivity to particles produced in heavy flavour decay
  - Larger size requires change in detector and magnet technology: Superconducting magnet
- FORMOSA
  - Milicharged particle detector
  - Scintillator based, similar to miliQan

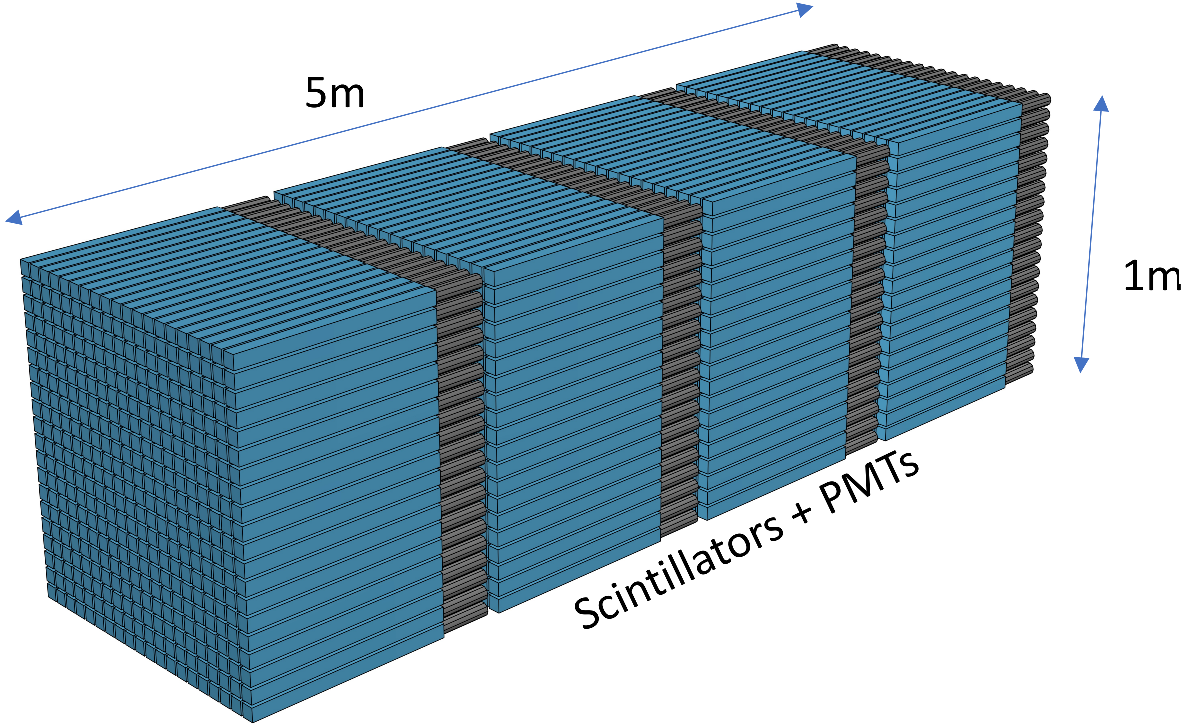
No detailed design for any of these experiments yet!

Currently proposed FPF experiments

AdvSND:
Off-axis neutrino detector
Target forward charm production, gluon PDF at low-x



FORMOSA:
For milicharged particles

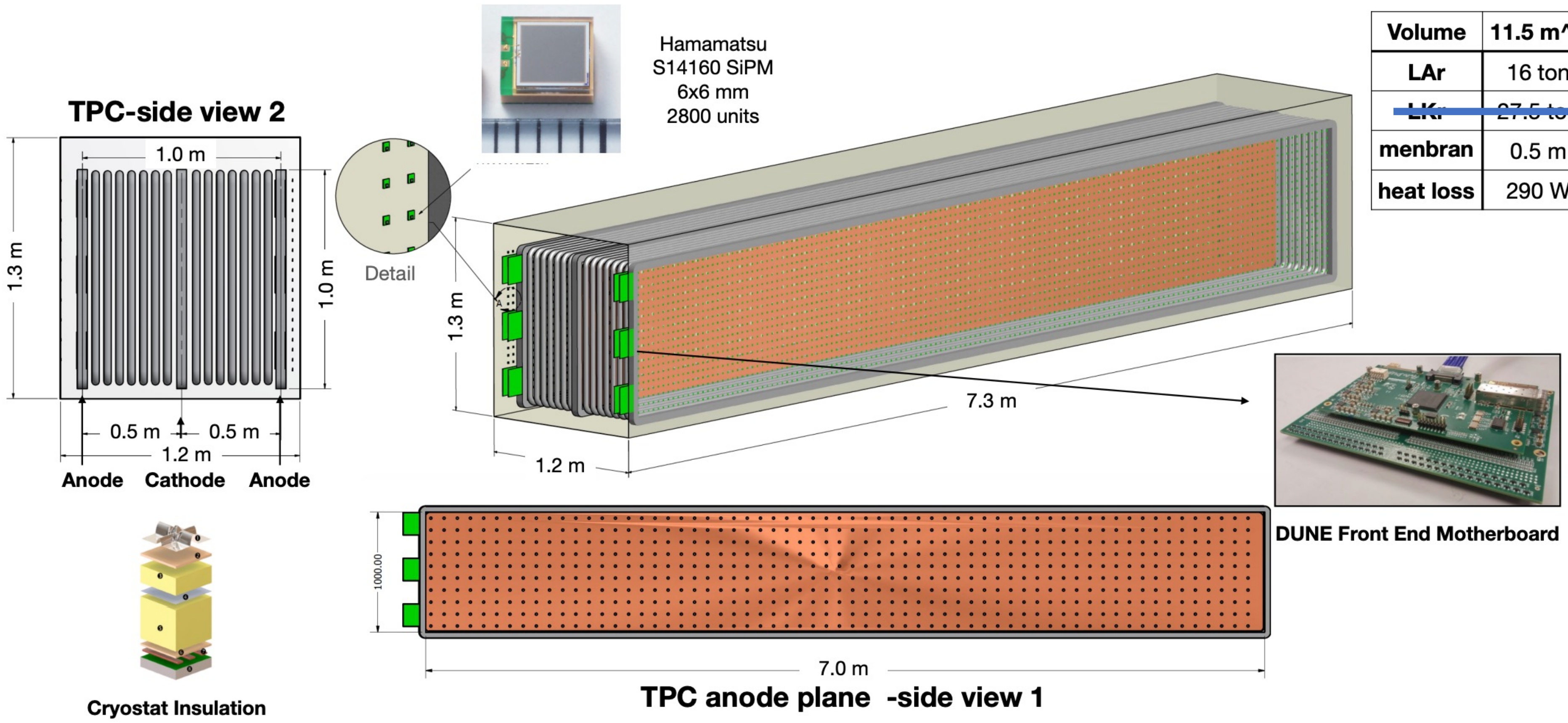


FLArE: LAr TPC detector

Proposed LAr TPC for DM scattering and neutrino physics: $\mathcal{O}$(10tn) fiducial target mass.
Cryostat and cryogenics discussed with protoDune experts in the CERN neutrino platform.
Significant detector design effort ongoing at BNL, with dedicated resources.

Brookhaven National Laboratory

FLArE Detector Preliminary Sketch



Volume	11.5 m^3
LAr	16 ton
~~LKr~~	~~27.5 ton~~
menbran	0.5 m
heat loss	290 W

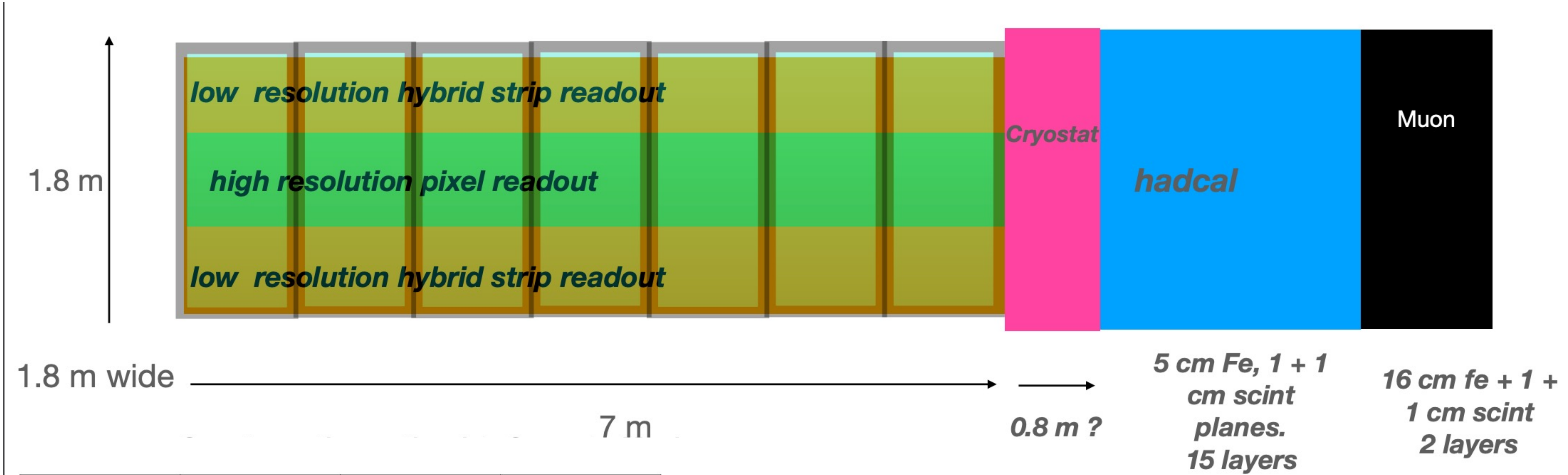
FLArE is the FPF detector which needs the most novel design and drives much of FPF services/infrastructure and safety needs.

FLArE: LAr TPC detector

M. Diwan, S. Linden (BNL)

Proposed LAr TPC for DM scattering and neutrino physics: $\mathcal{O}(10\text{tn})$ fiducial target mass.
Cryostat and cryogenics discussed with protoDune experts in the CERN neutrino platform.
Significant detector design effort ongoing at BNL, with dedicated resources.

Simulation studies on containment of high energy neutrino showers have led to the following conceptual design of the detector. With central fiducial region of 1mx1m in the transverse plane. More detailed studies are starting to ramp-up.



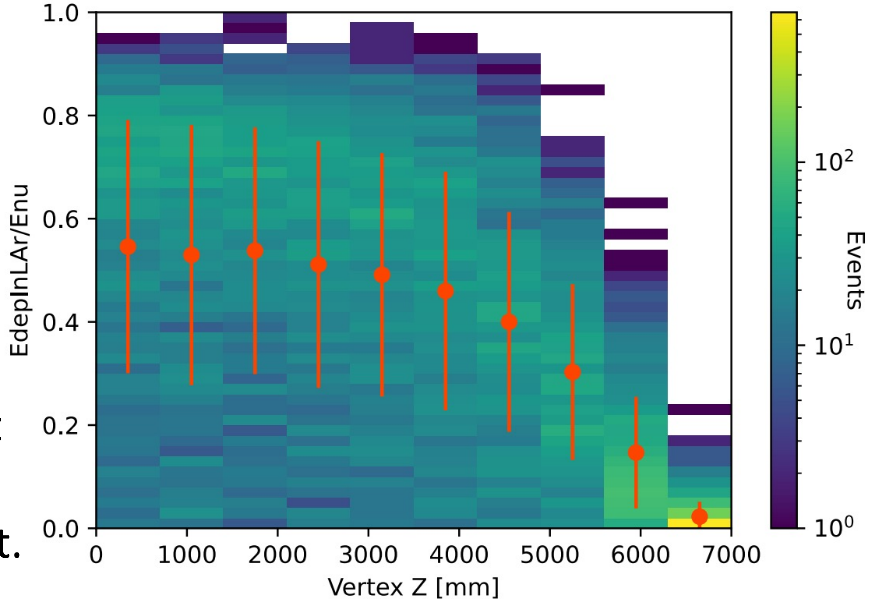
	LArTPC	HadCal	MuonFinder
Length (mm)	0 - 7000	7250 - 8300	8300 - 9340

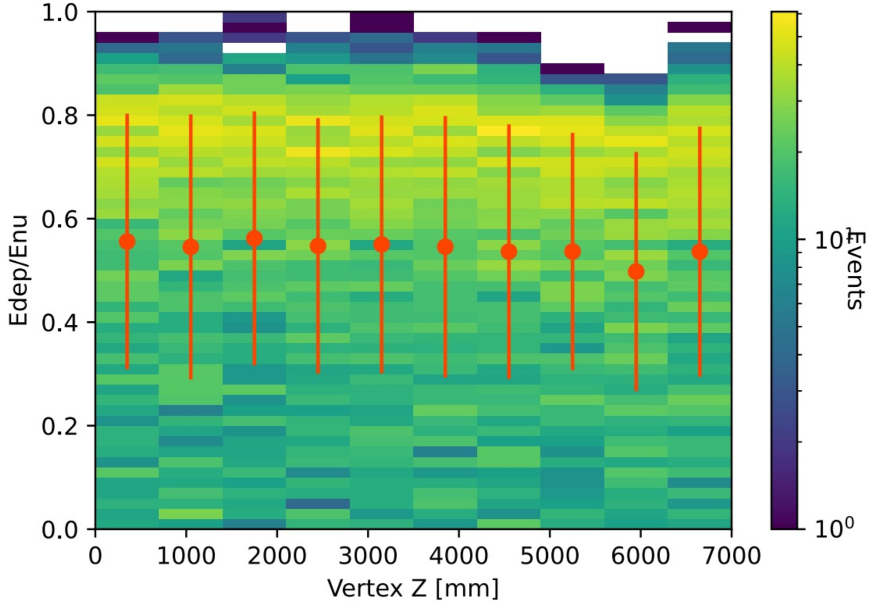
Design similar to Dune Near Detector

FLArE: Simulation Studies…

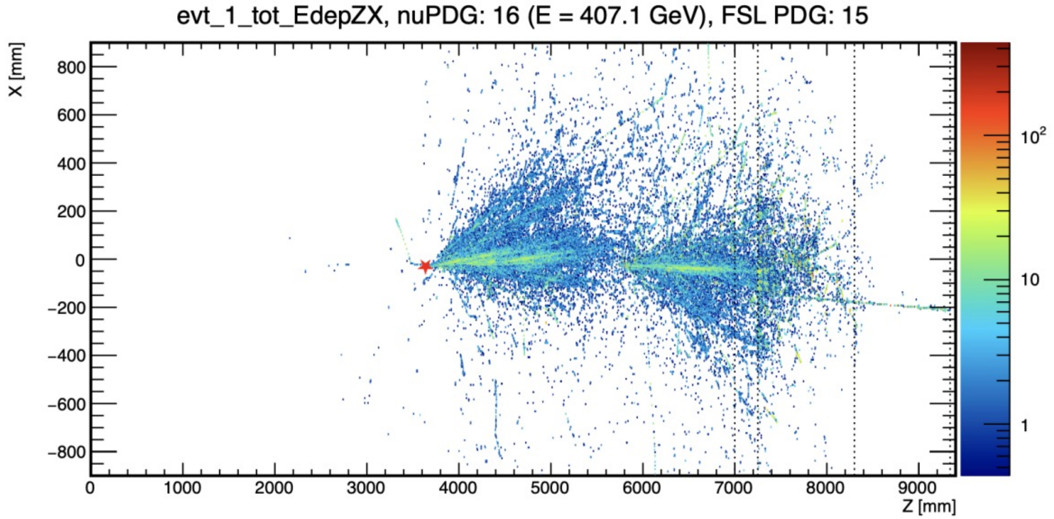
Neutrino event energy containment versus neutrino interaction position:
- without HCAL (top),
- with HCAL (bottom).

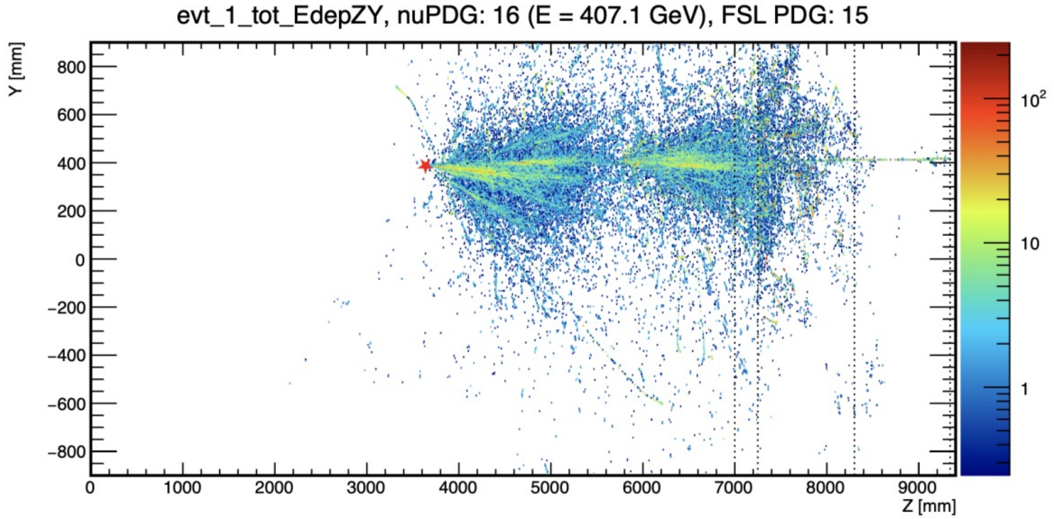
Reasonable containement shows 1.8mx1.8m transverse size is sufficient.





Simulated ν_τ -> τ -> μ interaction

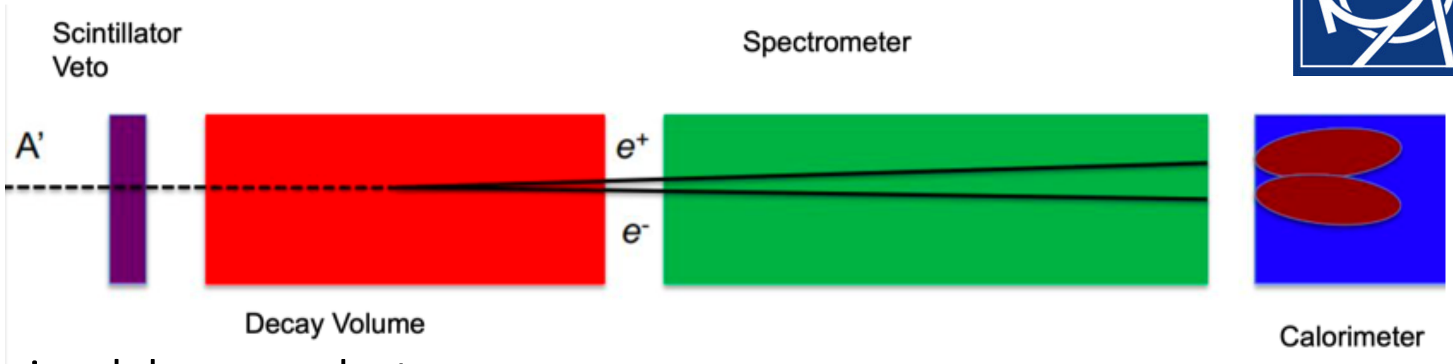




FASER2

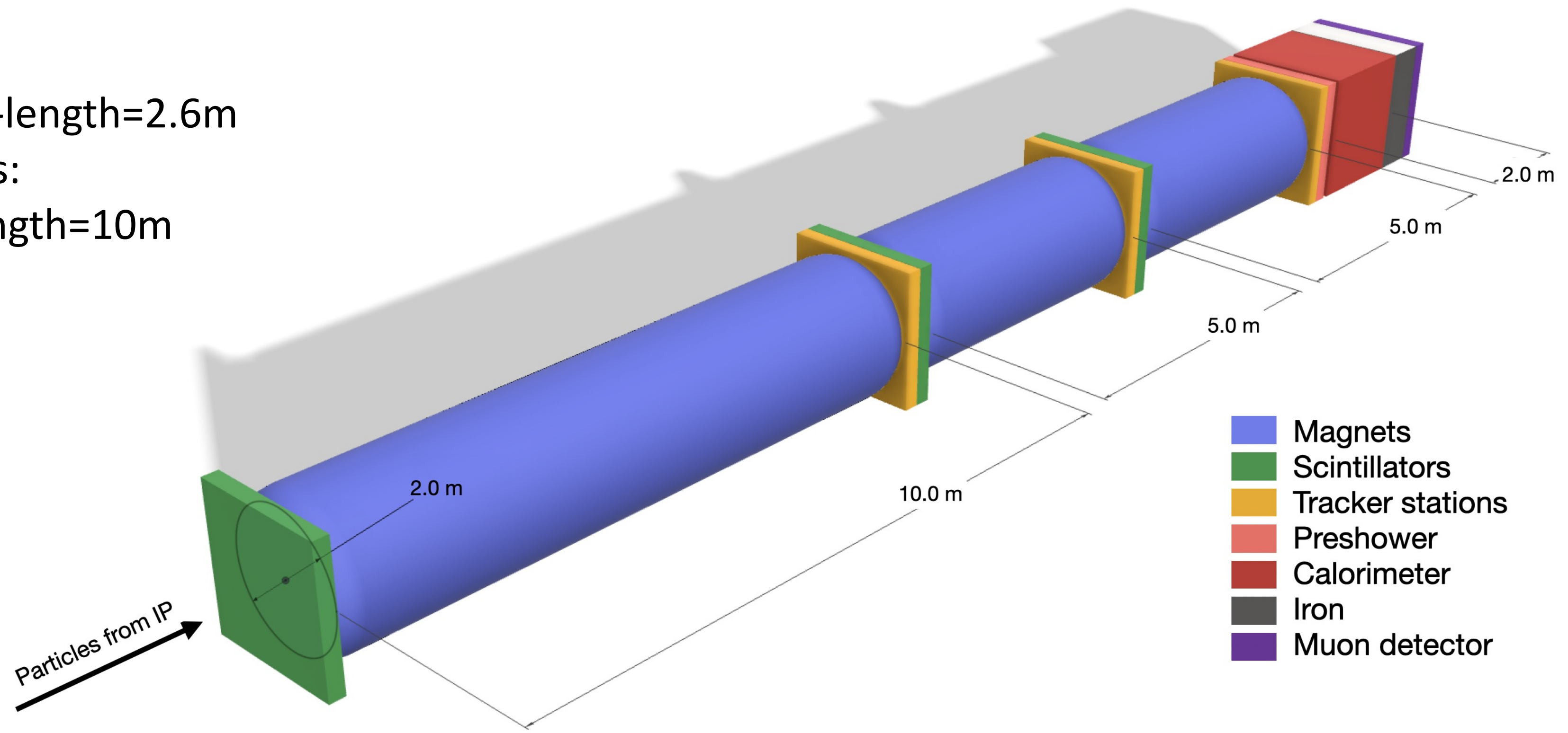
FASER2 is conceptually a scaled-up version of FASER:

- Scintillator based veto system
- Decay Volume (DV)
- Tracking spectrometer (TS)
- Calorimeter



Magnetic field needed to separate the closely-spaced signal decay products.

FASER dimension:
r=10cm, DV-length=1.5m, TS-length=2.6m
FASER2 proposed dimensions:
r=1m, DV-length=10m, TS-length=10m



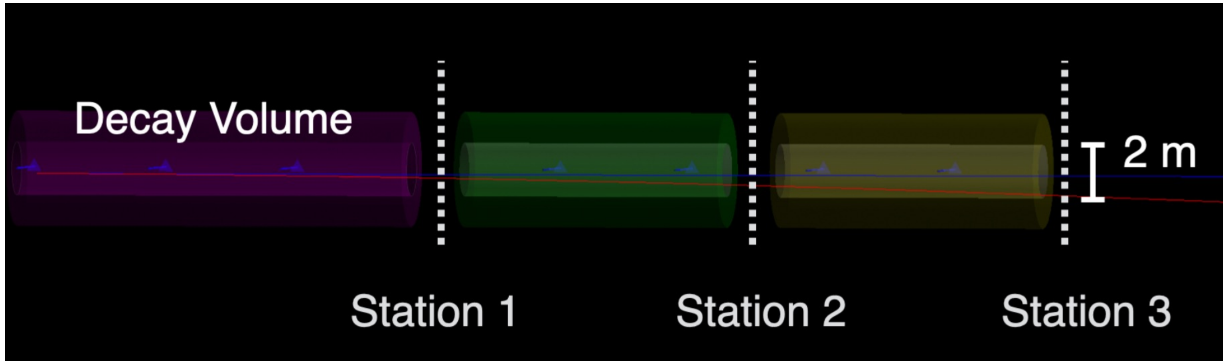
FASER2

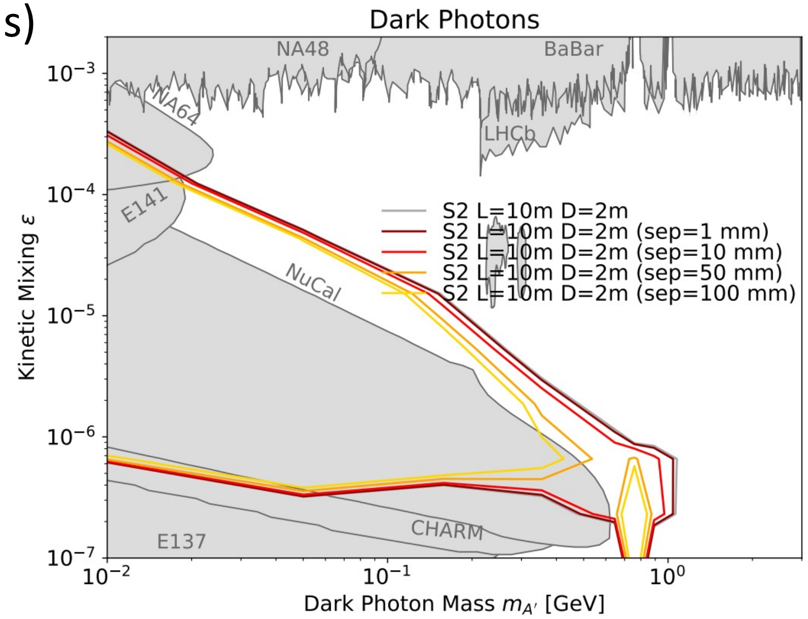
Huge ($\mathcal{O}(100)$) increase in instrumented area, and magnetic field volume. Can not use same detector design/technology as FASER.

Studies starting to optimize overall layout, with main open questions:

- Magnetic field strength, and volume
    - Likely untilize superconducting magnet technology
    - Likely only 1 magnet in the spectrometer
- Tracker detector technology
    - Performance given by interplay with resolution, magnetic field strength and alignment
    - SciFi tracker (ala LHCb upgrade 1) seems a good possible technology
- Calorimeter/Muon system
    - PID capability and good position resolution important for physics goals (more-so than at FASER due to sensitivity to higher mass states, and additional signals)

Simplified GEANT4 setup used for current studies:

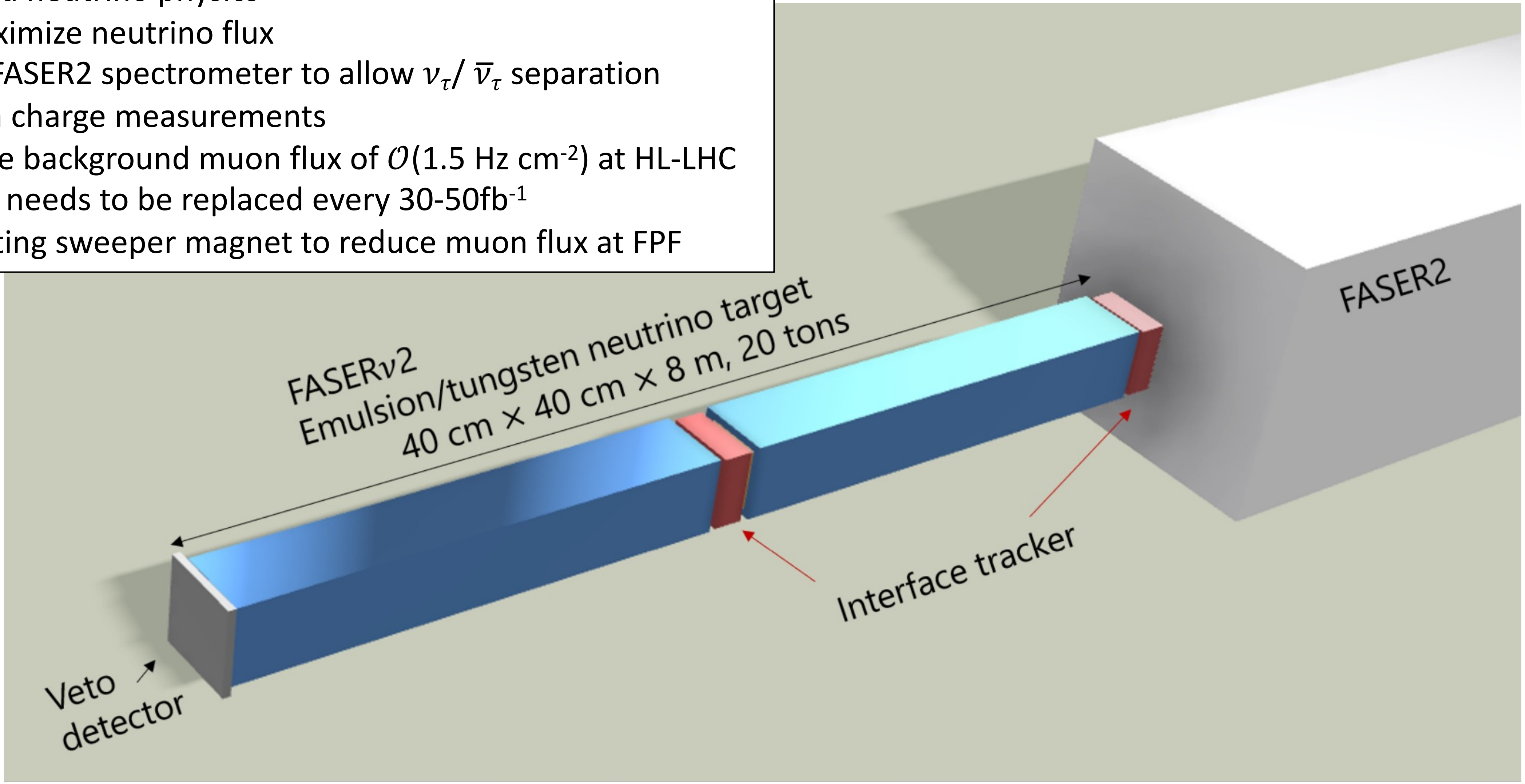




Example study looking at dark-photon sensitivity for different requirements on the separation of the 2 tracks at the 1st tracking station.

FASERnu2

- Proposed $\mathcal{O}$(20tn) emulsion/tungsten neutrino detector
  - Scaled up version of $\mathcal{O}$(1tn) FASERnu detector
- Main target tau neutrino physics
- On-axis to maximize neutrino flux
- Interfaced to FASER2 spectrometer to allow ν_τ/ $\bar{\nu}_\tau$ separation through muon charge measurements
- Main challenge background muon flux of $\mathcal{O}$(1.5 Hz cm^{-2}) at HL-LHC
  - Emulsion needs to be replaced every 30-50fb^{-1}
  - Investigating sweeper magnet to reduce muon flux at FPF



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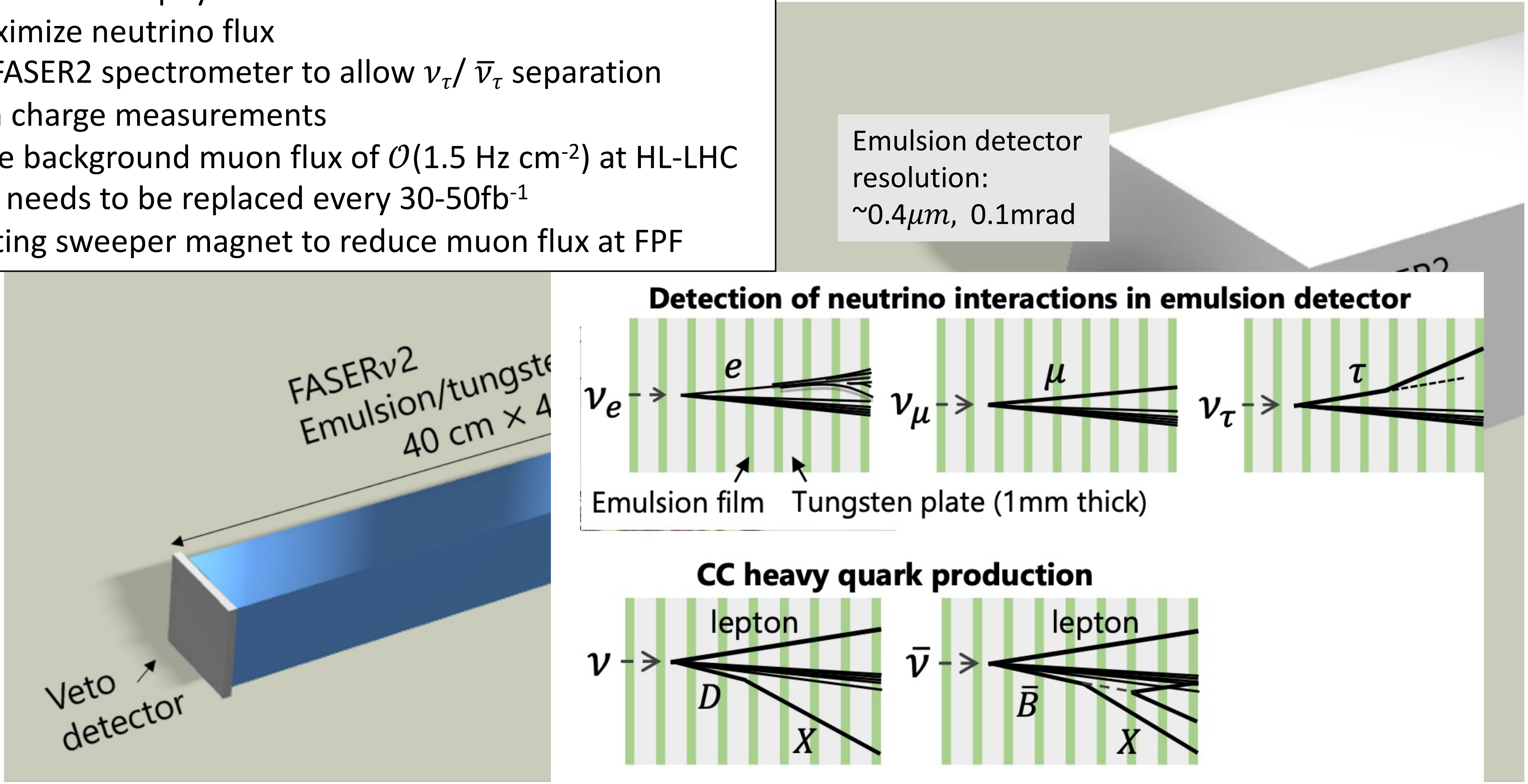
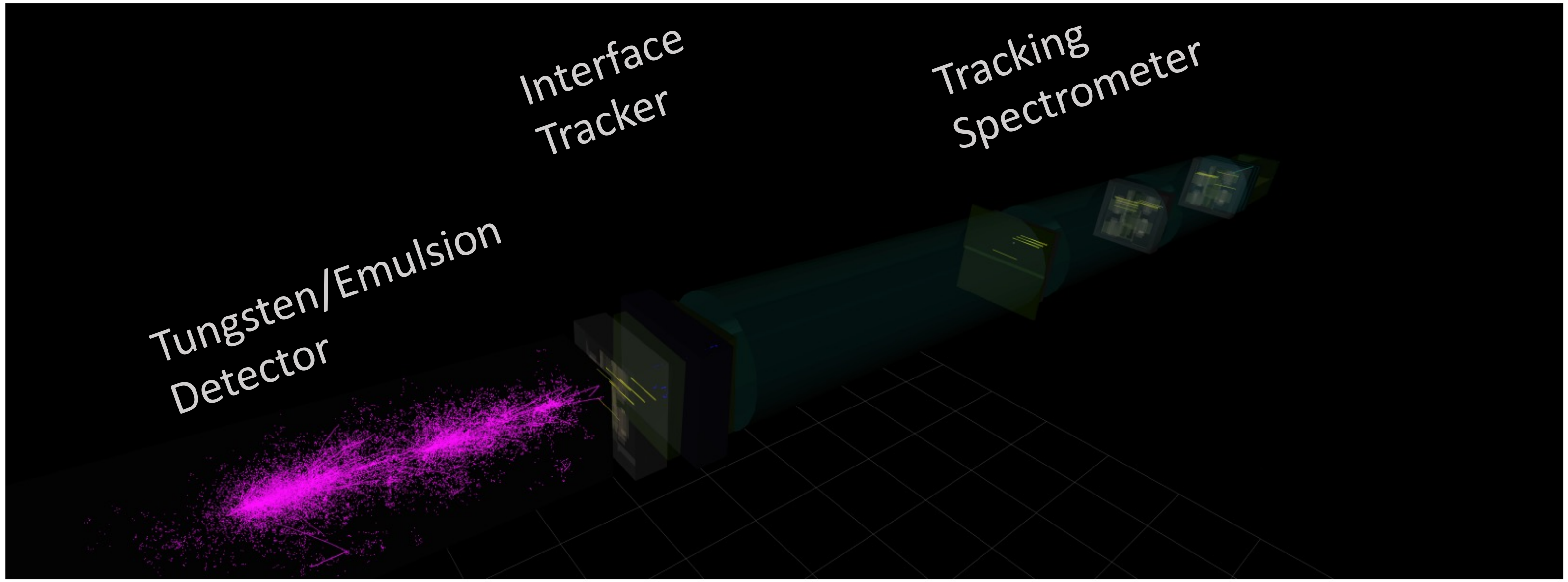
Emulsion detector resolution: ~0.4μm, 0.1mrad

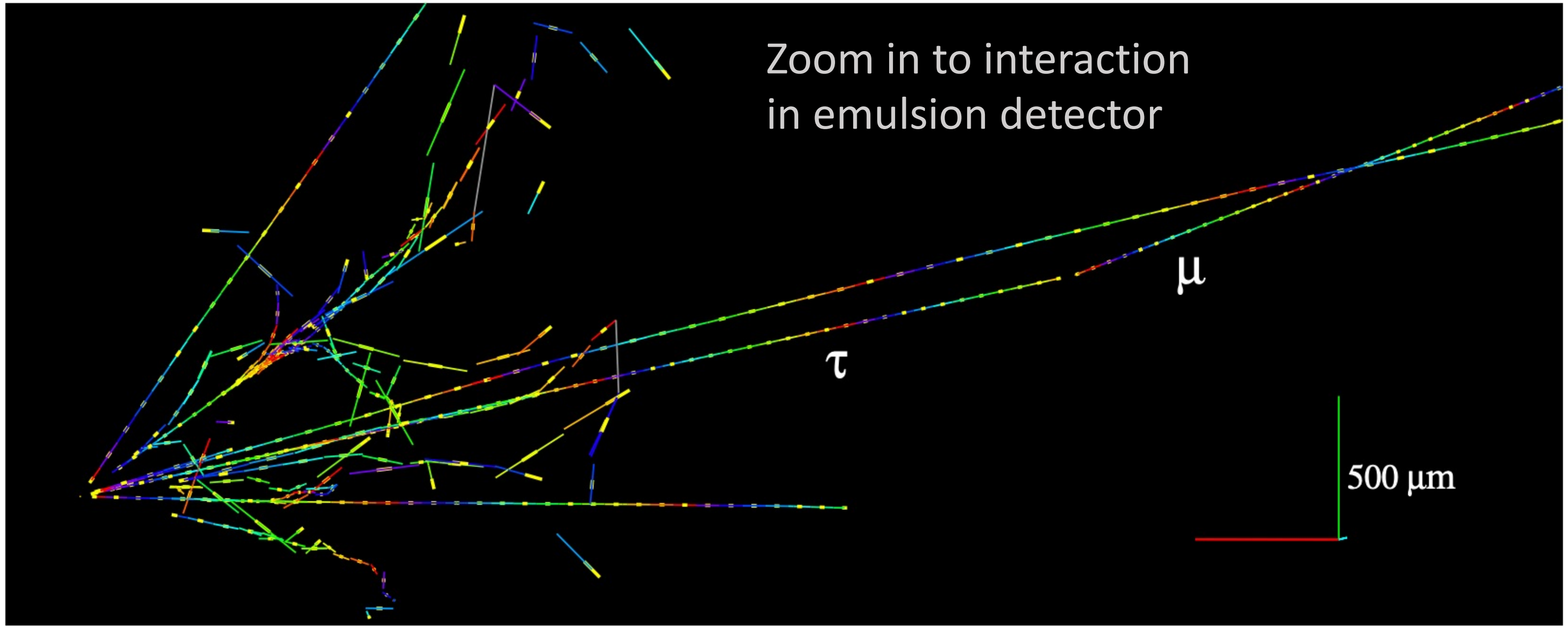


FASERnu2

Simulated tau neutrino interaction in FASERnu, with muon traversing the FASER spectrometer (to allow ν_τ/ $\bar{\nu}_\tau$ separation)

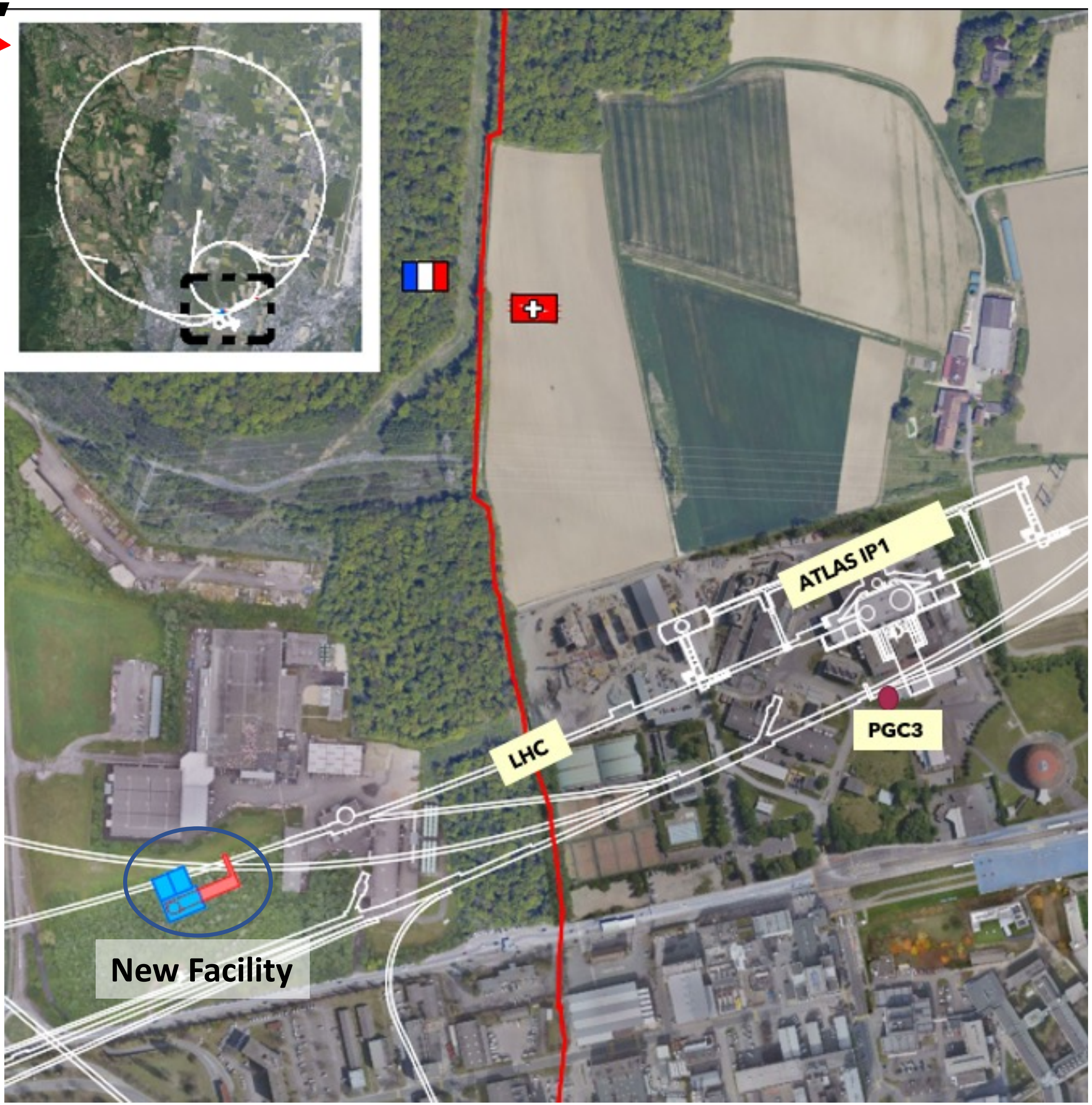


FASER2 tracker/magnet design, essential for FASERnu2 physics!



The Facility

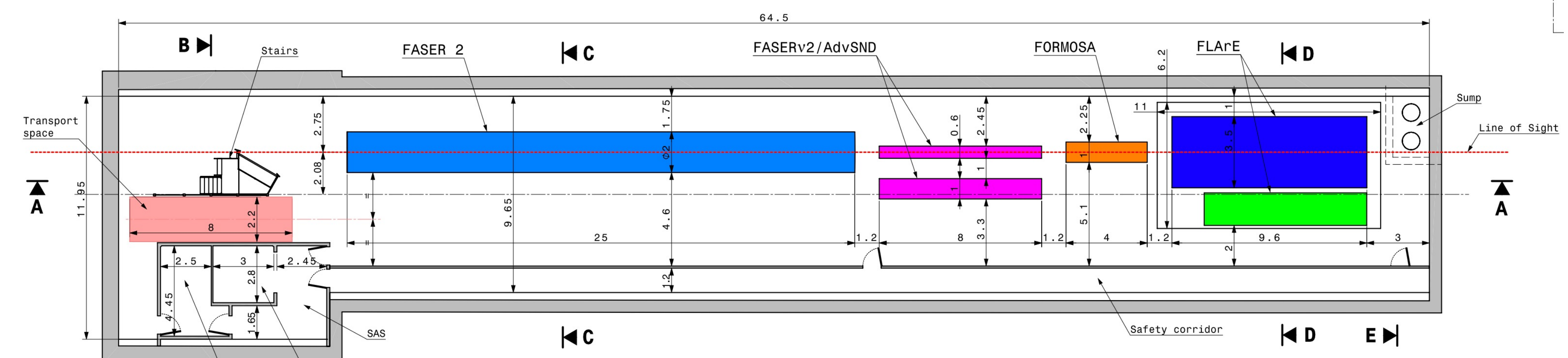
K. Balazs, J. Osborne, J. Gall - CERN SCE



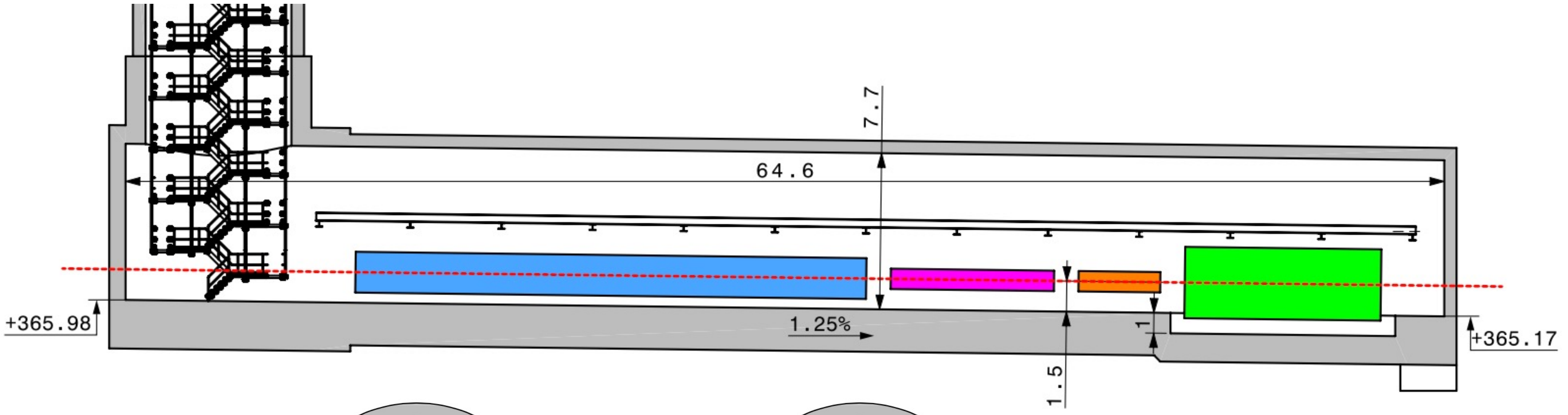
After several studies by CERN civil engineering team, looking at options around both the ATLAS and CMS interaction points, the best option for the FPF facility is chosen as a dedicated new facility ~600m from the ATLAS IP (to the west).

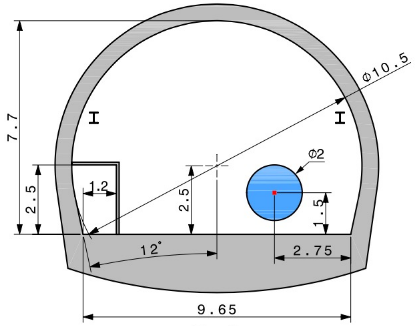
FPF Facility:

65m long, 8m wide/high cavern
Connected to surface through
88m high shaft (9.1m diameter):
617m from IP1.

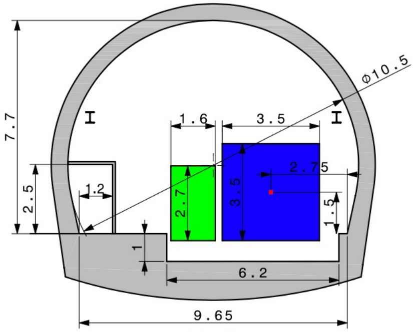


Plan view - Cavern
1:100





C-C
1:100



D-D
1:100

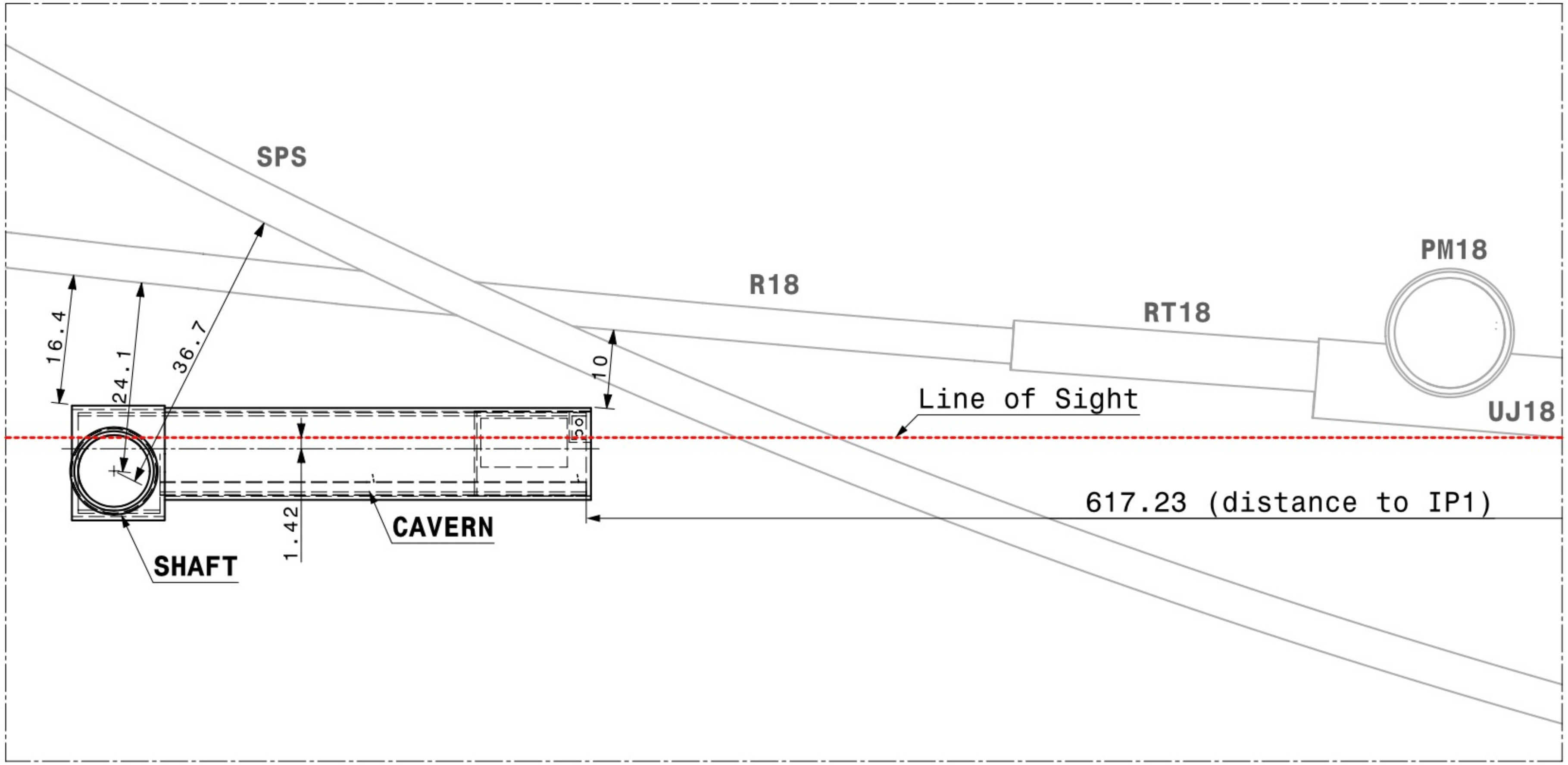
K. Balazs, J. Osborne
CERN SCE

FPF Facility:

65m long, 8m wide/high cavern
Connected to surface through 88m high shaft (9.1m diameter): 617m from IP1.

Require that cavern is at least 10m from LHC for structural stability during digging.

Previous design had a connection from FPF to LHC (as an emergency escape route) recently dropped after discussions with CERN safety.



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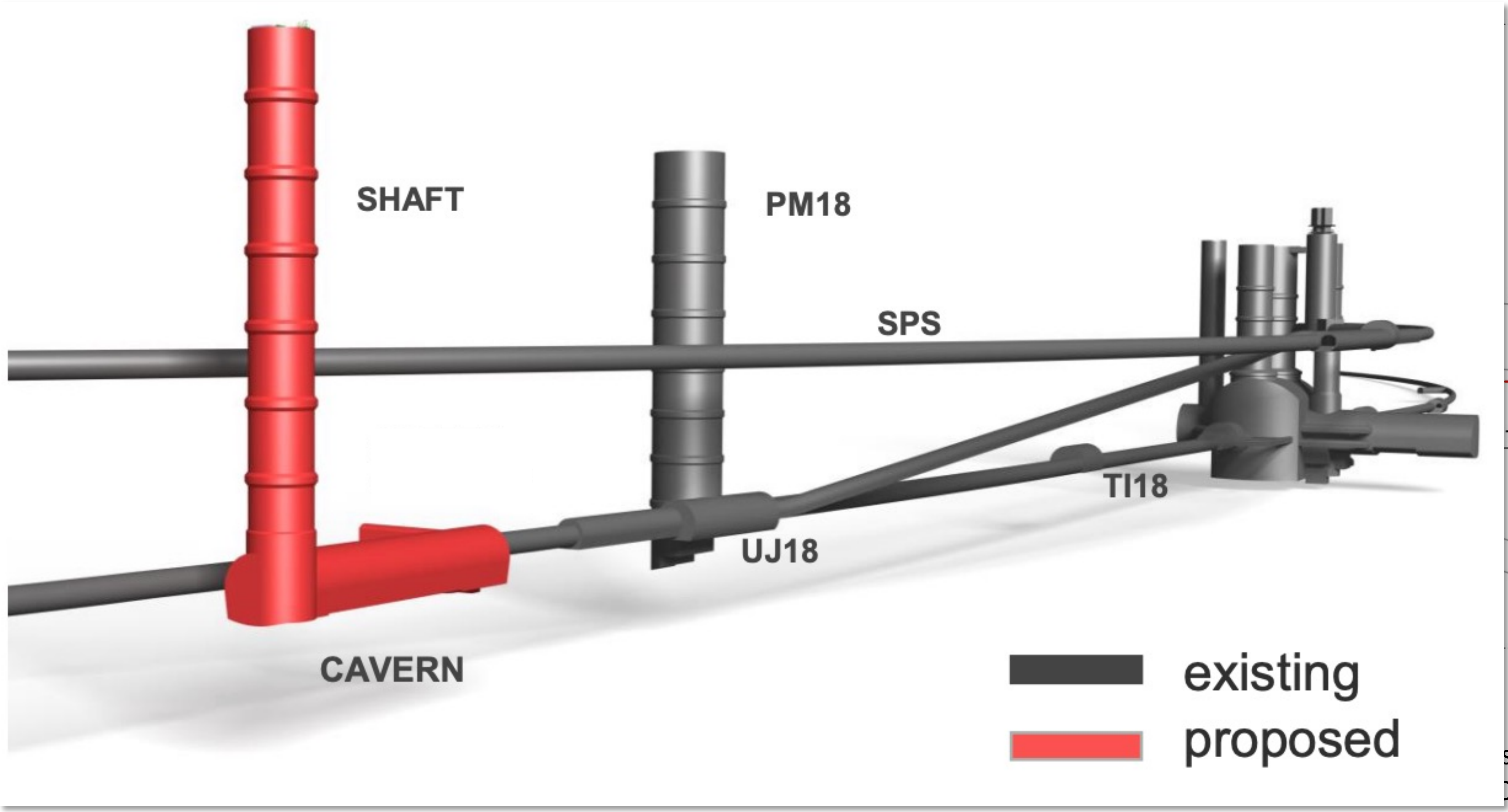
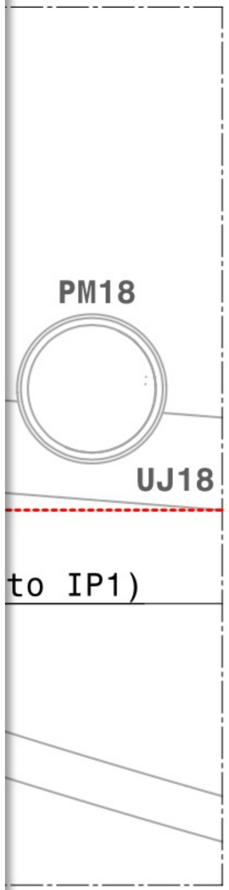
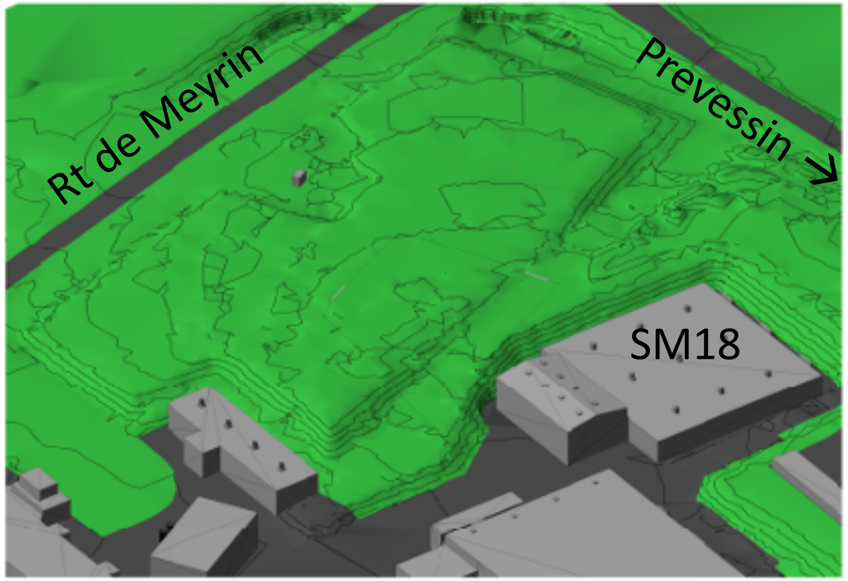




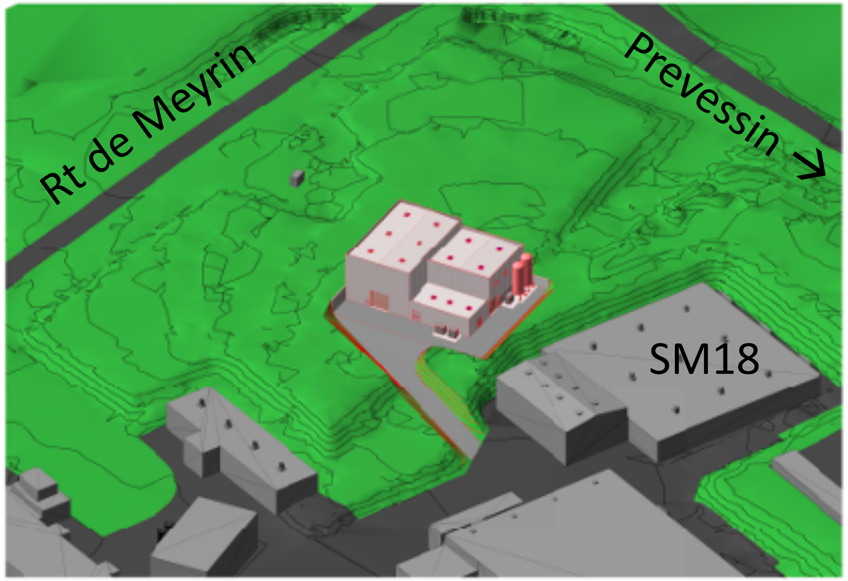
s, J. Osborne
CE

New Cavern: Surface works

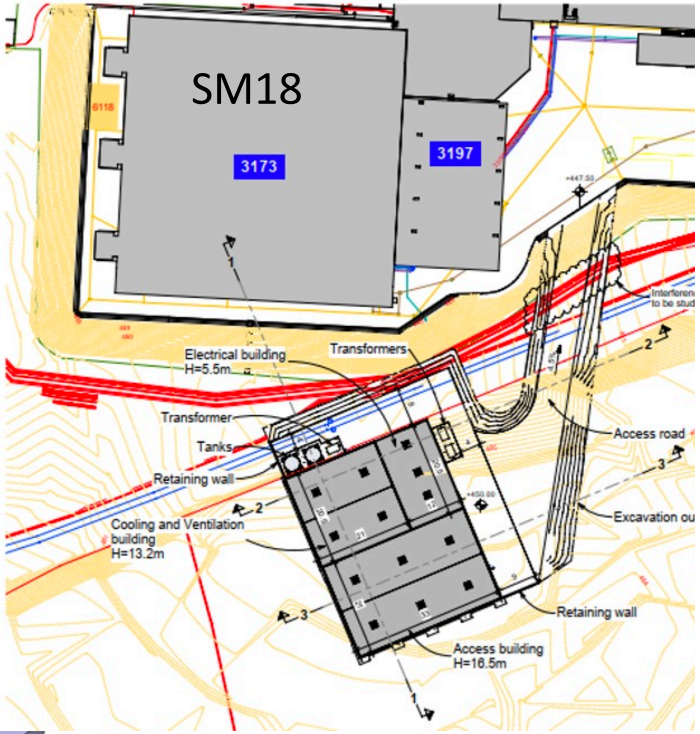
K. Balazs, J. Osborne

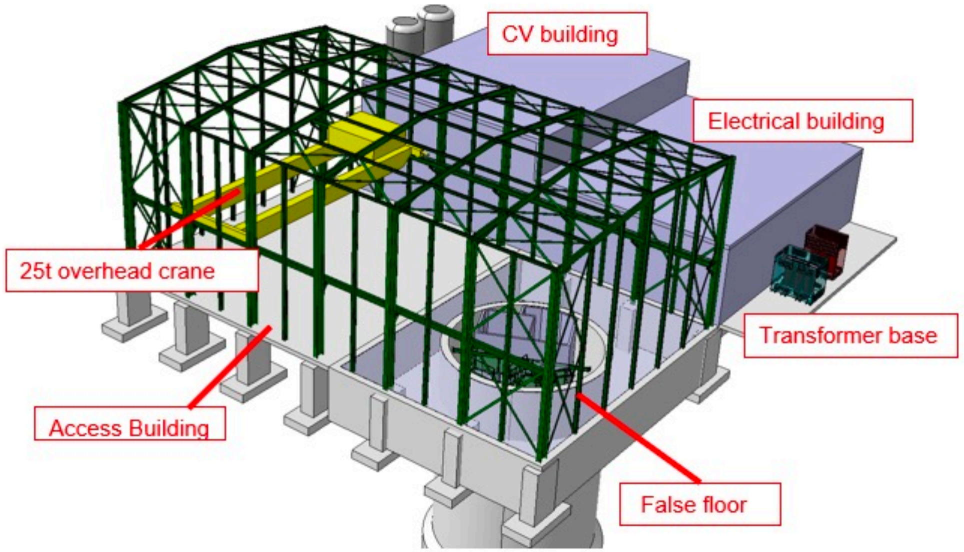


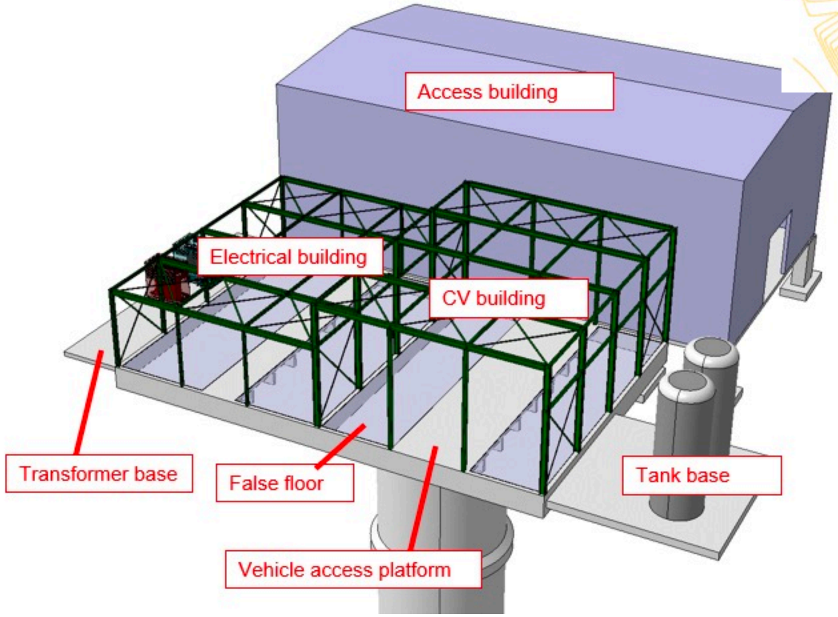
3D EXISTING



3D NEW

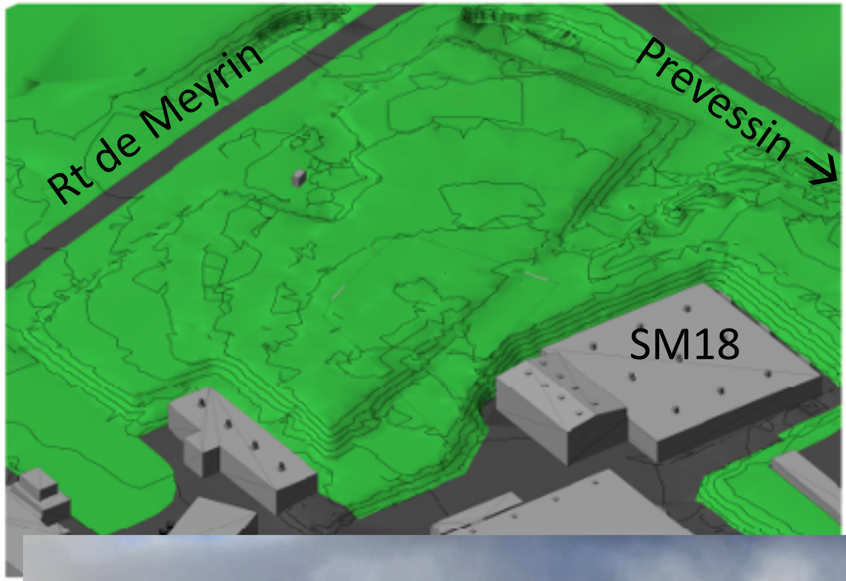


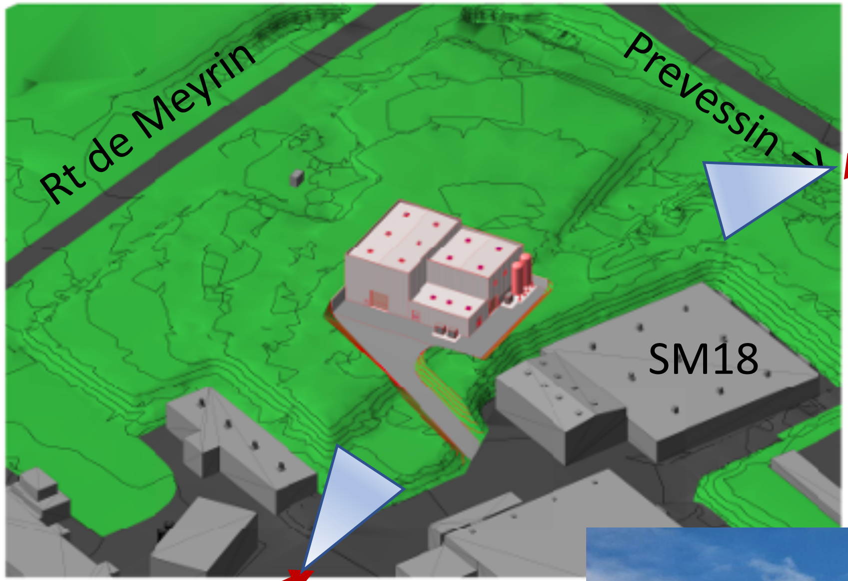




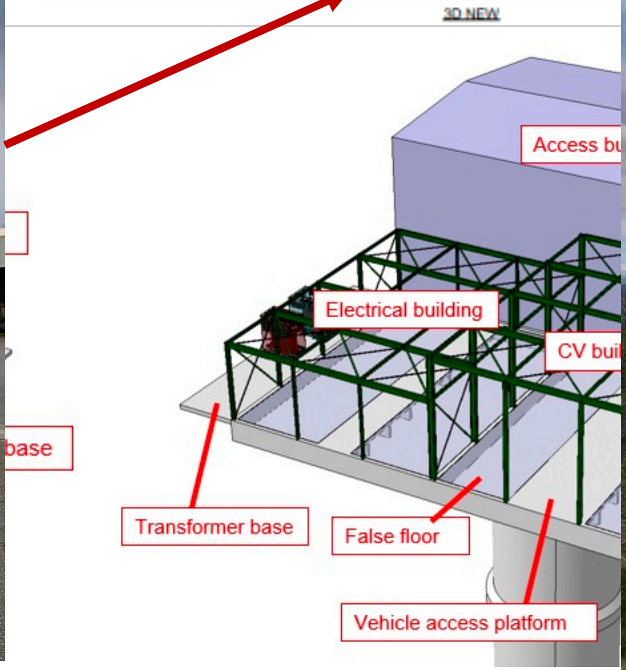
New Cavern: Surface works

K. Balazs, J. Osborne





Photos of the current situation



Technical Services

Based on previous similar projects at CERN the main cost drivers for services, with approximate costing are:

Item	**Details**	**Approximate cost (MCHF)**
Electrical Installation	2MVA electrical power	1.5
Ventillation	Based on HL-LHC underground installation	7.0
Access/Safety Systems	Access system Oxygen deficiency hazard Fire safety Evacuation	2.5
Transport/Handling Infrastructure	Shaft crane (25 t) Cavern crane (25 t) Lift	1.9
Total		**12.9**

Round up to 15MCHF to account for some missing items.

K. Balazs, J. Osborne
CERN SCE

First costing of CE works & services

- Preliminary costing of civil engineering works, based on comparative costing to similar project:
  - HL-LHC Point 1 as reference point for new facility option
- Cost Estimates Class 4
  - Total could be 50% higher and 30% lower than the given estimate
- Pure civil engineering cost estimate 23MCHF
- Additional cost for services ~15MCHF
- **Total cost: ~40MCHF**

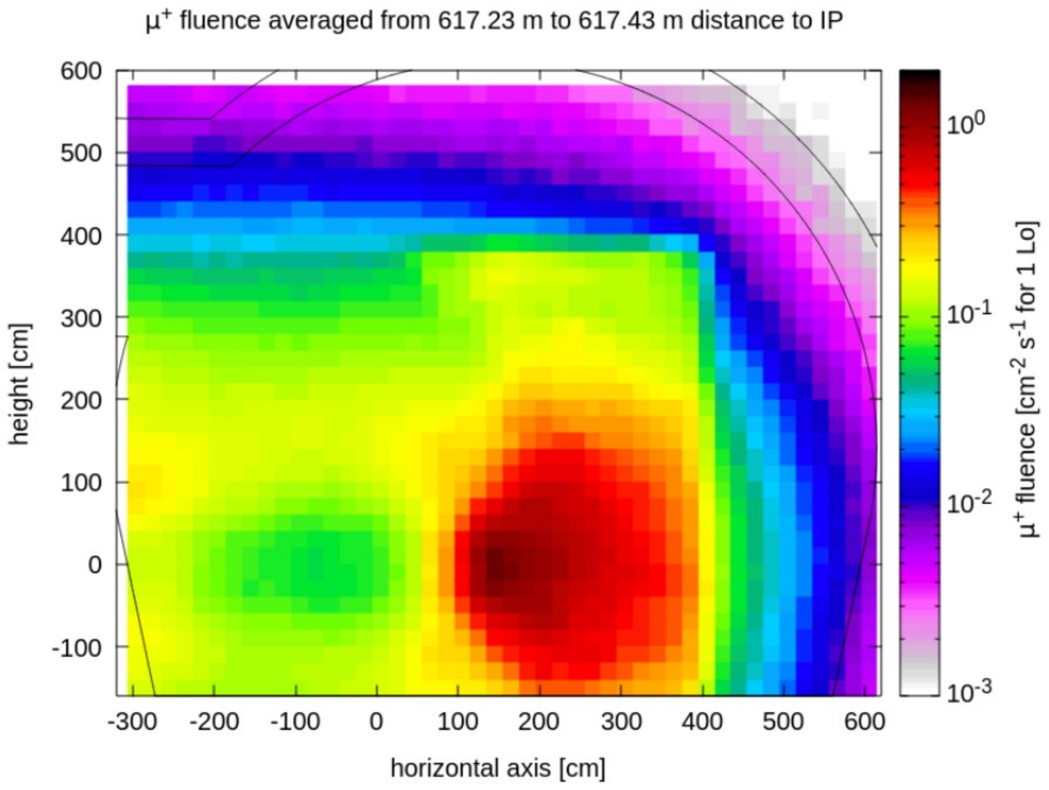
Muon background at FPF

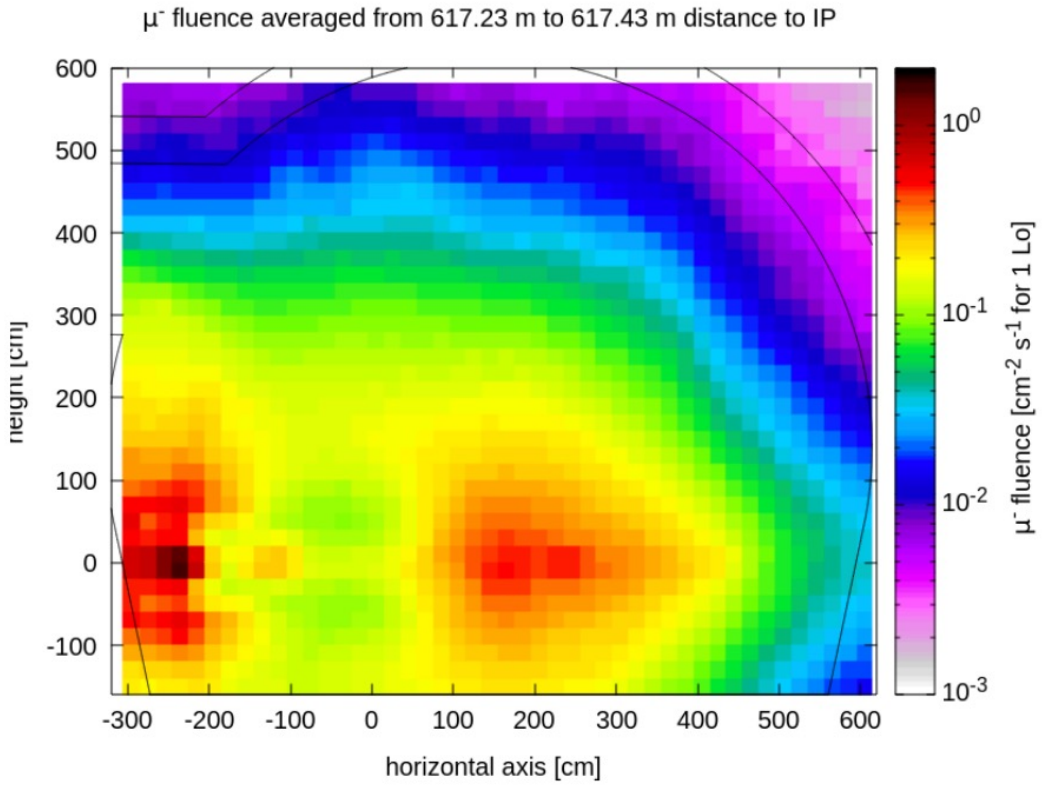
F. Cerutti, M. Sabate-Gilarte
CERN STI

FLUKA simulation predicts a muon flux of ~1.5Hz/cm^2 (@ 5e34cm^{-2}s^{-1}) for ~1m around the LOS at the FPF. Flux raises by an order of magnitude once you go further than ~1m in horizontal direction.

Muons that reach the FPF come from hadronic showers in the long straight section, or start of the arc from collision debris or off-momentum protons hitting the beam pipe apperture. Sophisticated modelling of LHC components in simulation needed.

Measured rate of particles by FASER (on the LOS) in Run 3 within ~25% of the FLUKA expectation – gives confidence that the rates for FPF should be reasonable.

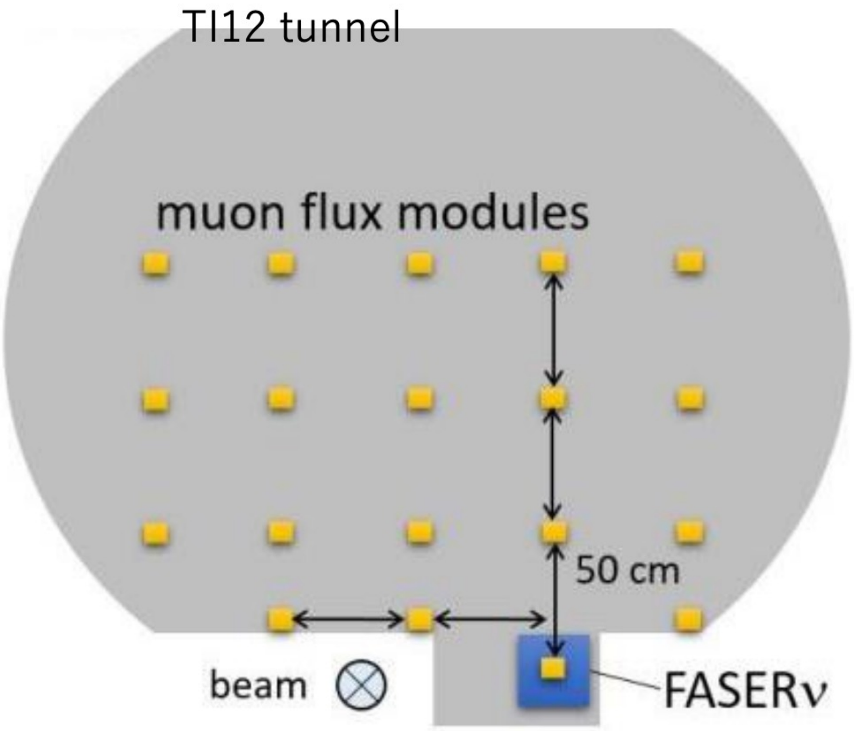


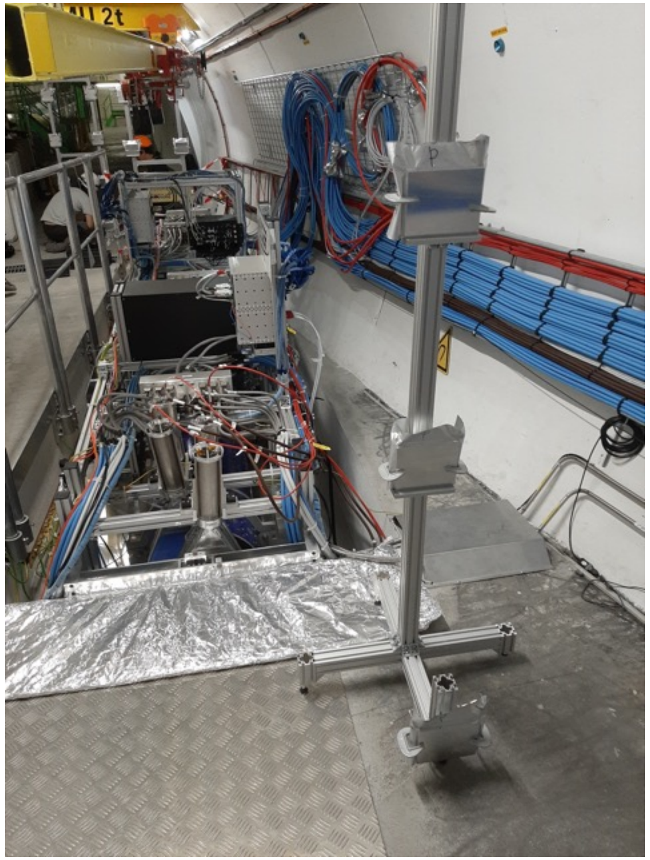


LHC tunnel would be at at -1300cm on these plots scale

Muon background at FPF

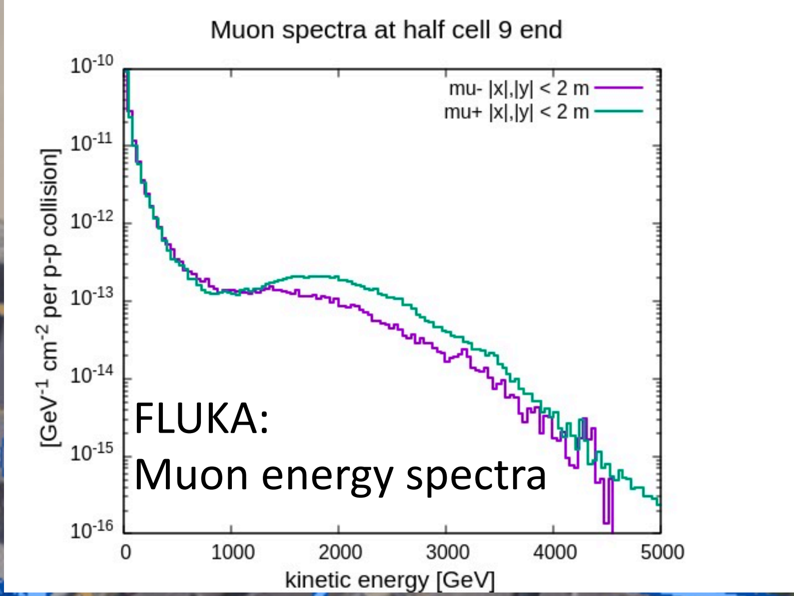
In order to measure the muon rate away from the LOS in Run 3, we recently installed 20 small emulsion detectors within 2m of FASER. These were installed on 23/7 and removed on 2/9, having been exposed to ~10/fb of data. Tyhey will provide a useful validation of the FLUKA estimate further from the LOS.





Results should be available in the next months.

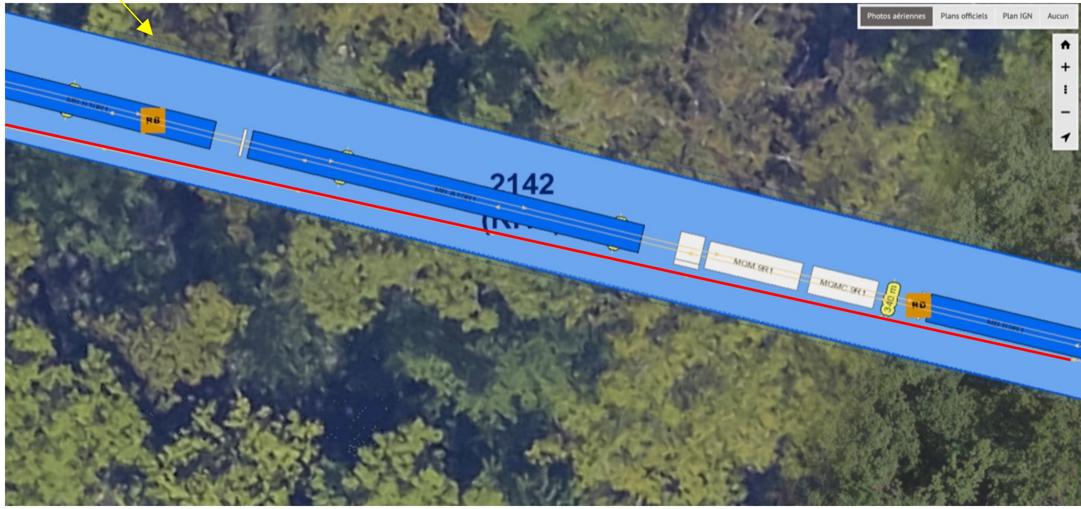
Muon Background: Sweeper Magnet



Although muon rate of ~1.5Hz/cm^2 is very low compared to LHC collision rate, reducing this background would be beneficial for the FPF experiments (both for physics and costs - e.g. reducing the number of times emulsion would need to be replaced.)

Placing a sweeper magnet on the LOS can deflect these muons and reduce the background.

Best place for such a magnet would be between where LOS leaves LHC magnets and where it leaves the LHC tunnel (200m lever-arm for deflected muons). Studies ongoing….



Recent and ongoing FPF facility studies

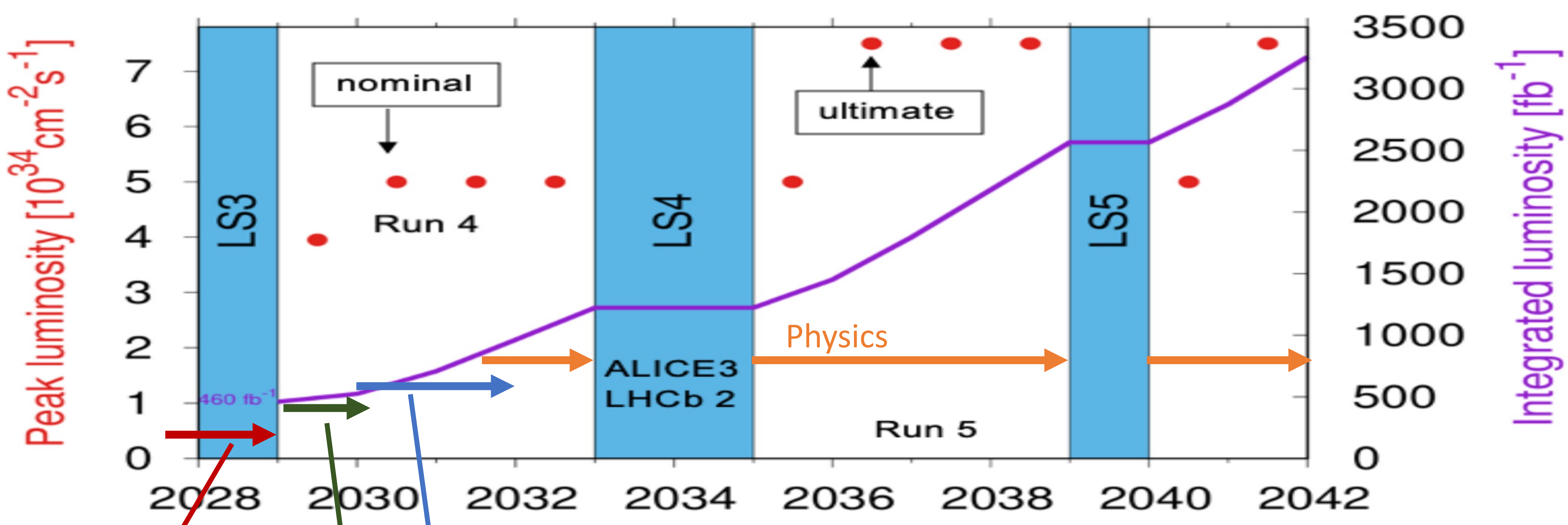
Access to the cavern during HL-LHC operations:
The CERN Radio-Protection group has recently completed a detailed FLUKA study to see if people can access the cavern during HL-LHC operations. The conclusion of this study is that access should be possible during operations with an occupancy of <20% of the time in a year, and with some possible local restrictions.
Very important result for allowing successful implementation of the FPF!

Civil Engineering site investigation:
CERN will provide resources for a core to be drilled to the depth of the cavern (90m) at the location of the shaft. This will provide important information on the rock composition to allow refining the facility design and cost.
Aiming for results before the end of the year.

Civil engineering works during HL-LHC operations:
A study is ongoing to assess if the civil engineering works can be done during HL-LHC operations, in terms of beam stability due to vibrations. Initial studies, based on recent civil engineering for HL-LHC, suggest that this should not be problematic.

Progress in design/costing of needed services:
There are continuing studies in the design and refined costing of the needed services for the FPF, where possible. However, in many cases the requirements from the experiments are lacking and this is an area where rapid progress in needed.

Possible FPF schedule



Pure CE works

Installation and commissioning of the experiments

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

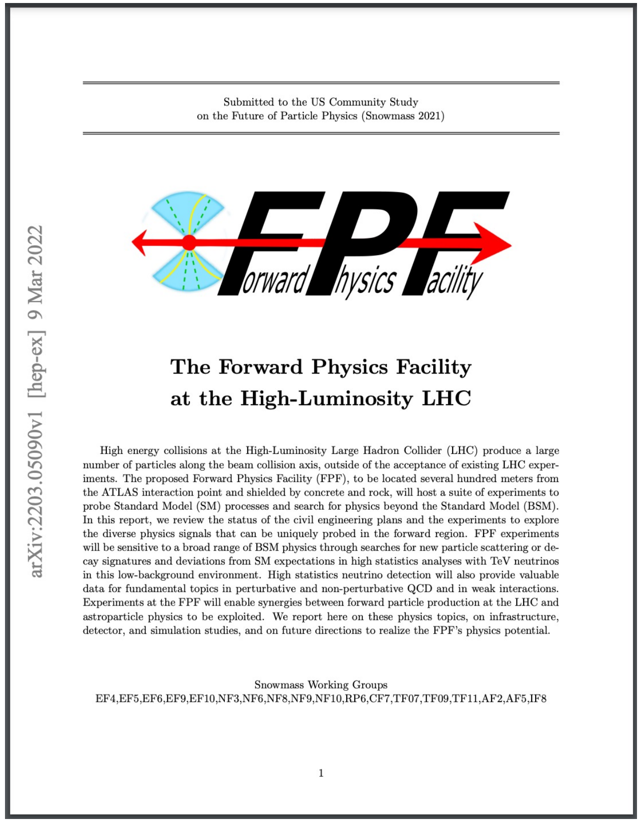
Such a schedule would:

- 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

Time is tight: Need to move fast towards CDR/TDR for funding and approval

FPF workshops & papers

- There have been four FPF workshops over the last two years
  - https://indico.cern.ch/category/14436/
  - Mostly reporting progress on theory level physics studies for FPF, and evolution of the physics case
  - 5th worksgop being planned for November
- The FPF was actively discussed in many of the different tracks in the US Snowmass process, with significant interest expressed by the community
- As part of that process two papers have been released:
  - Phys.Rept. 968 (2022) 1-50 (2109.10905) ("short" paper ~70 pages, 80 authors from 68 institutes)
  - https://arxiv.org/abs/2203.05090 ("long" paper ~430 pages, $\mathcal{O}(300)$ authors + endorsers)
    - Lots of details on physics case for FPF
    - To appear in Journal of Physics G
- The FPF is being activiely studied as part of the CERN Physics Beyond Colliders study group
  - Provides technical resources for facility design study
  - Provides a forum for physics discussions, and comparisons to other proposed future projects
- The project needs to transition towards more detailed designs of the experiments and how these effect the facility design and required infrastructure and services


Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)

arXiv:2203.05090v1 [hep-ex] 9 Mar 2022

The Forward Physics Facility
at the High-Luminosity LHC

High energy collisions at the High-Luminosity Large Hadron Collider (LHC) produce a large number of particles along the beam collision axis, outside of the acceptance of existing LHC experiments. The proposed Forward Physics Facility (FPF), to be located several hundred meters from the ATLAS interaction point and shielded by concrete and rock, will host a suite of experiments to probe Standard Model (SM) processes and search for physics beyond the Standard Model (BSM). In this report, we review the status of the civil engineering plans and the experiments to explore the diverse physics signals that can be uniquely probed in the forward region. FPF experiments will be sensitive to a broad range of BSM physics through searches for new particle scattering or decay signatures and deviations from SM expectations in high statistics analyses with TeV neutrinos in this low-background environment. High statistics neutrino detection will also provide valuable data for fundamental topics in perturbative and non-perturbative QCD and in weak interactions. Experiments at the FPF will enable synergies between forward particle production at the LHC and astroparticle physics to be exploited. We report here on these physics topics, on infrastructure, detector, and simulation studies, and on future directions to realize the FPF's physics potential.

Snowmass Working Groups
EF4,EF5,EF6,EF9,EF10,NF3,NF6,NF8,NF9,NF10,RP6,CF7,TF07,TF09,TF11,AF2,AF5,IF8

1

Summary

- The FPF is a proposed facility to house several BSM and neutrino experiments on the ATLAS collision axis line of sight
- **Strong and broad physics motivation** with **significant interest from the community**:
  - BSM, neutrino physics, QCD and input for astroparticle experiments
    - Much of it only possible at the LHC
  - Maximizing the physics potential of the LHC in the high-luminosity era:
    - **Opening new areas of physics**: Precision tau neutrino studies
      Collider produced dark matter scattering experiment
- Fully consistent with European Strategy 2020 recommendation:

"*The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.*"

- Baseline design of dedicated new facility
  - Preliminary costing of ~40MCHF (without experiments)
  - To be implemented during LS3, for physics during the HL-LHC era
  - No large modification to the LHC beam/infrastructure needed
  - Parasitic running wityh LHC so energy-efficient / sustainable compared to other new projects
- Great progress on FPF studies in last 2 years, but a lot of work to do to realise this exciting project
  - Especially related to detector design studies
  - Please **contact me** if you are interested to get involved (Jamie.Boyd@cern.ch)

More information and references: https://pbc.web.cern.ch/fpf-resources

Backup...

Acknowledgements

Most figures/tables shown in this seminar have been taken from:

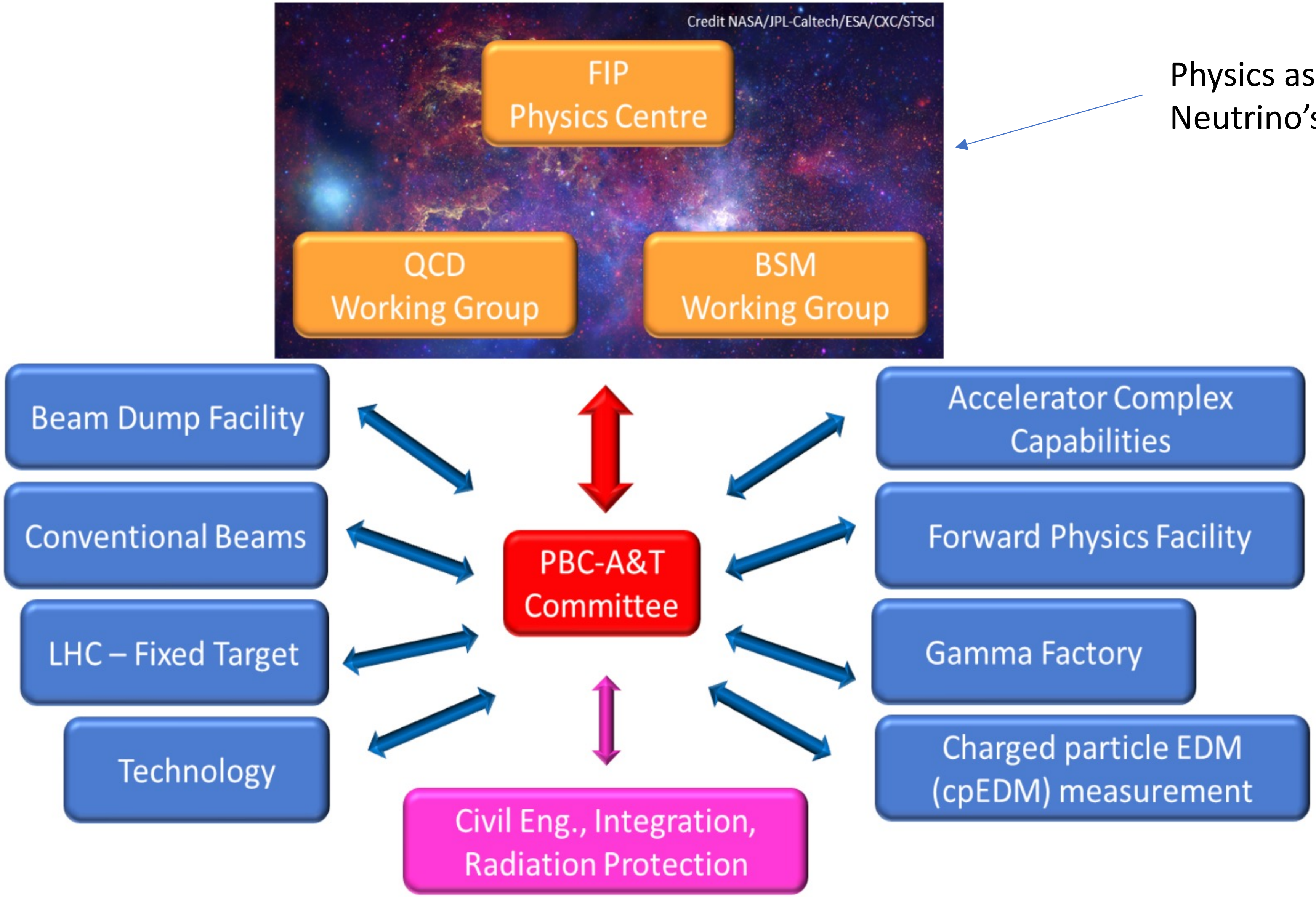
- FPF White paper - https://arxiv.org/pdf/2203.05090.pdf (Many thanks to the authors)
- Talks given at the FPF workshops

Many thanks to the authors of this material.

In addition, many thanks to all the CERN teams who have contributed to FPF studies:

- PBC: G. Arduini, C. Vallee, J. Jaeckel
- SCE-DOD-FS: K. Balazs, J. Osborne
- HSE-RP: L. Elie, A. Infantino, H. Vincke
- SY-STI-BMI: F. Cerutti, M. Sabate Gilarte
- EN-ACE-INT: J. P. Corso
- EN-HE: C. Bertone
- EN-CV: G. Peon, R. Bozzi
- EN-EL: M. Lonjon
- EN-AA: P. Ninin, S. Grau, T. Hakulinen, R. Nunes
- HSE-OHS: M. Andreini
- BE-ABP – D. Gamba
- TE-MSC-NCM: P. Thonet

The Physics Beyond Colliders Projects



Physics aspects of the FPF discussed here: Neutrino's mostly discussed in the QCD WG

Technical aspects on the FPF discussed here https://pbc.web.cern.ch/fpf-mandate

Forward Physics Facility

Mandate

A Forward Physics Facility at the LHC could house a suite of experiments enhancing the LHC's potential for both BSM and SM physics extending the capabilities of the FASER detector installed in the line of sight of the interaction point IP1. The Working Group is mandated to provide a Conceptual Design of the facility after an analysis of the possible options and taking into account the impact on the LHC Machine during construction and installation and the HL-LHC operational scenario.

Objectives

Determine the experimental set-up based on the physics requirements identified by the Physics Working Groups. Study the possible civil engineering scenarios, their impact on the LHC machine and its infrastructure, and study the integration of the experiment in the LHC tunnel. Evaluate the performance based on the expected HL-LHC operational scenario.

Conceptual design report of the facility.

Working Group Core Members

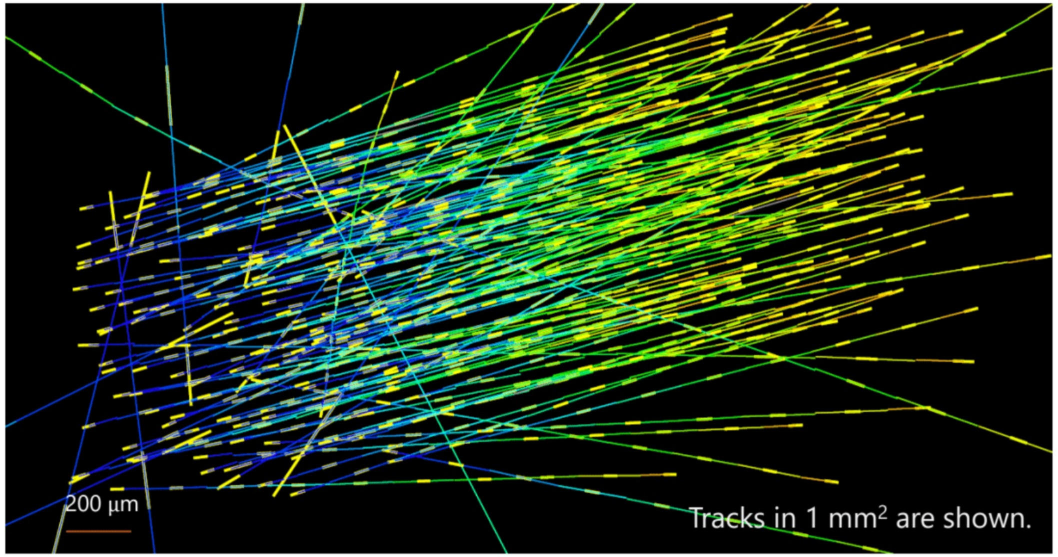
Convener: Jamie Boyd

Core Members: Marco Andreini, Kincso Balazs, Jean-Pierre Corso, Jonathan Feng (UCI), John Osborne.

Current far forward experiments

FASER

FASERν data (2022-module1) ($0.5\ fb^{-1}$)



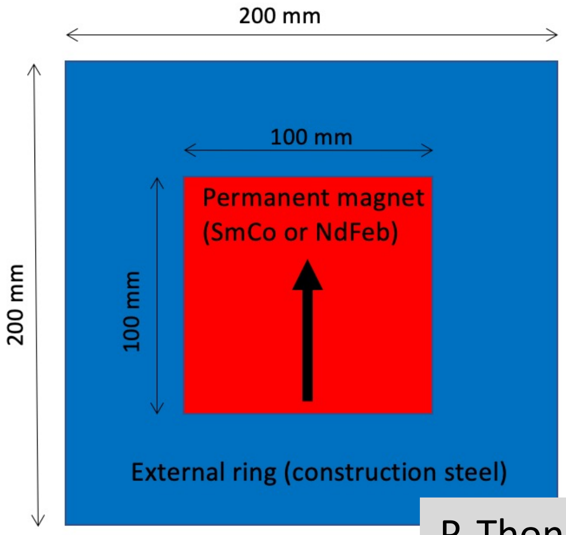
SND@LHC

SND: $7.2 < \eta < 8.4$

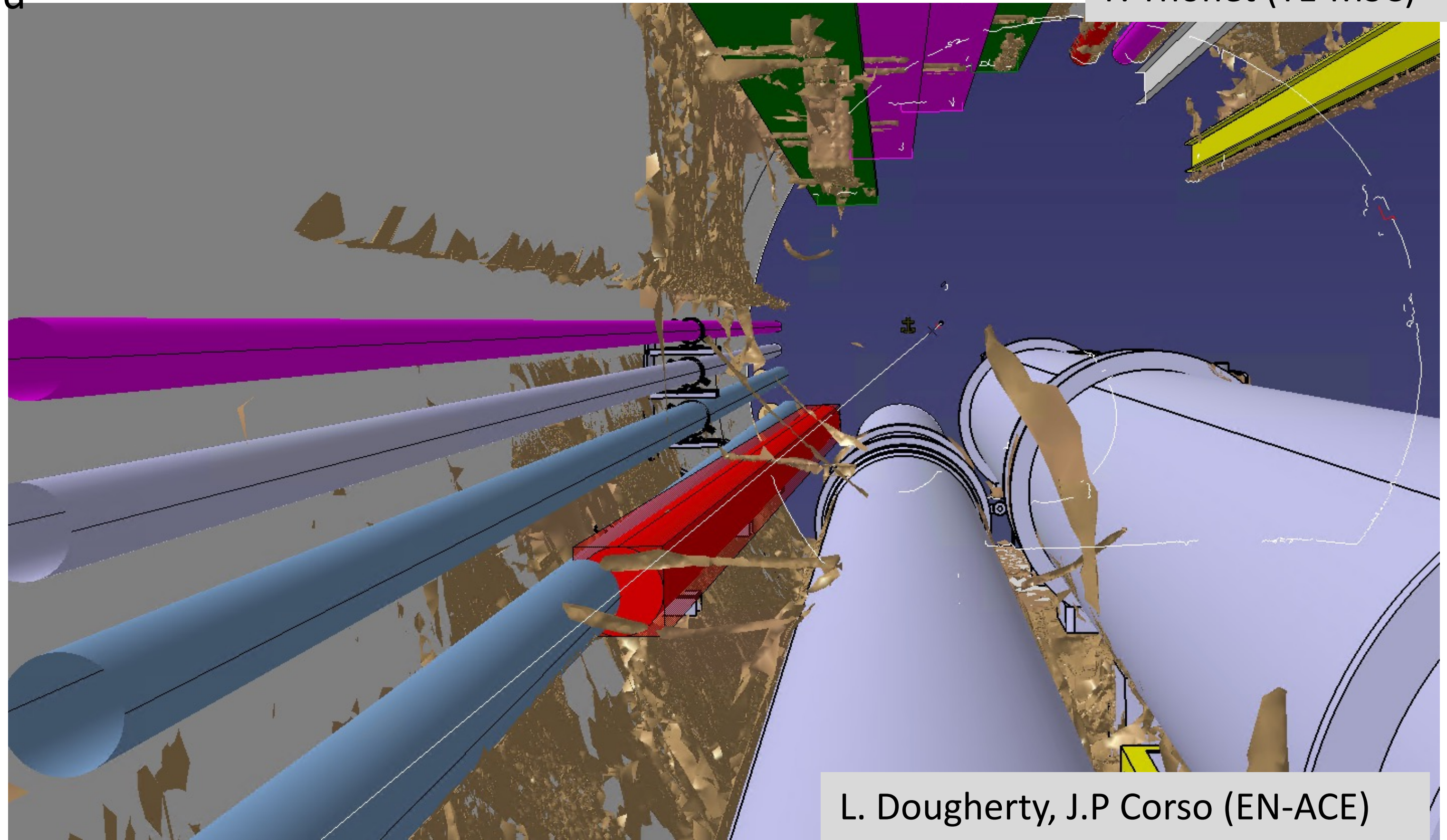
FASER(nu): $\eta > 9.2$

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



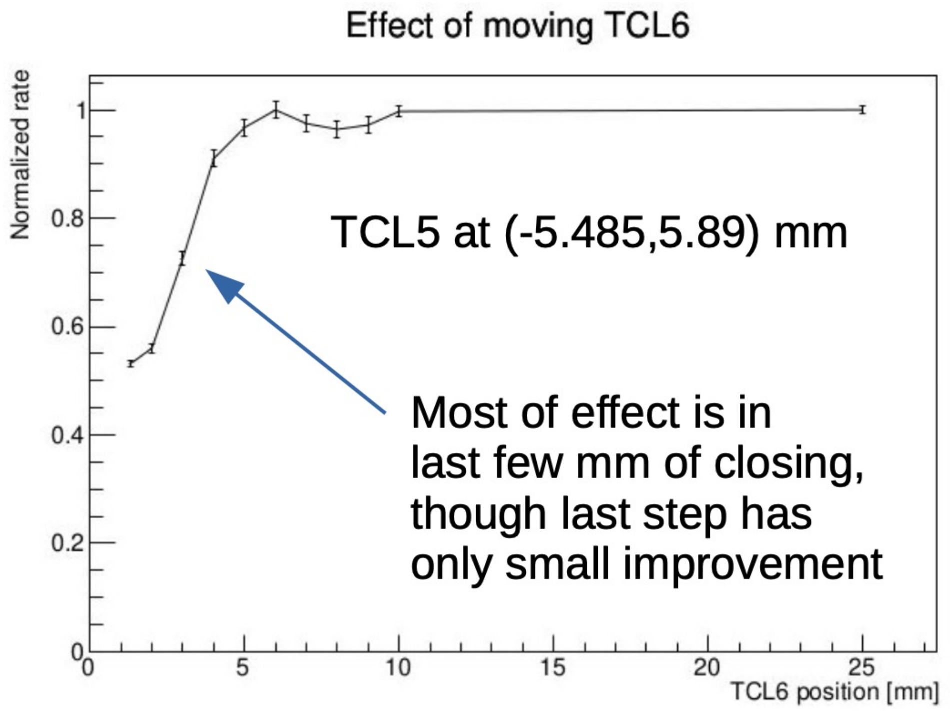
P. Thonet (TE-MSC)

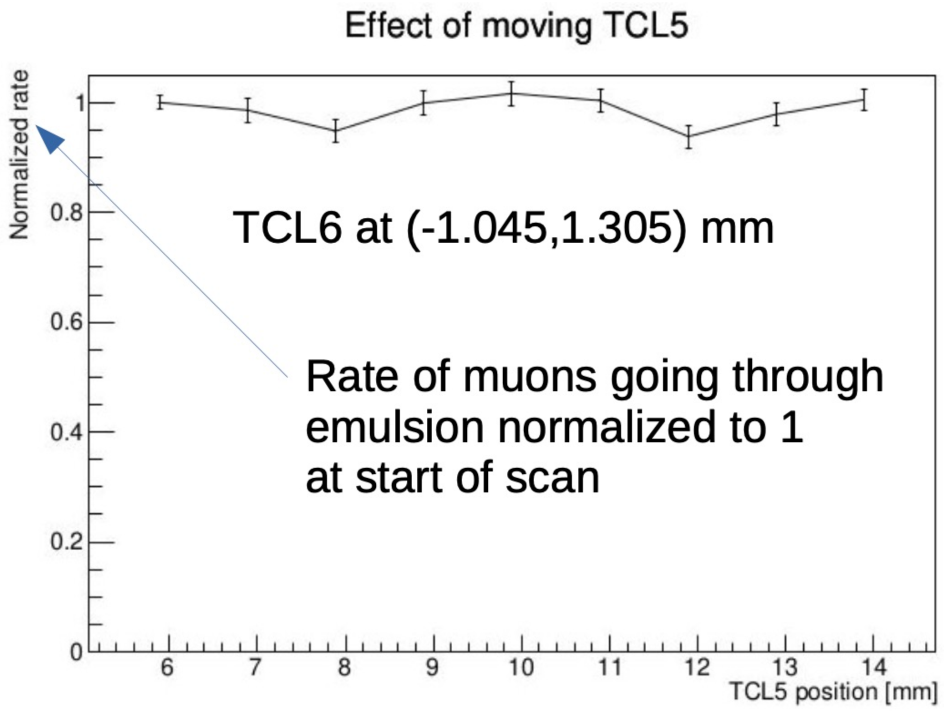


L. Dougherty, J.P Corso (EN-ACE)

Muon fluence at FASER (on the LOS)

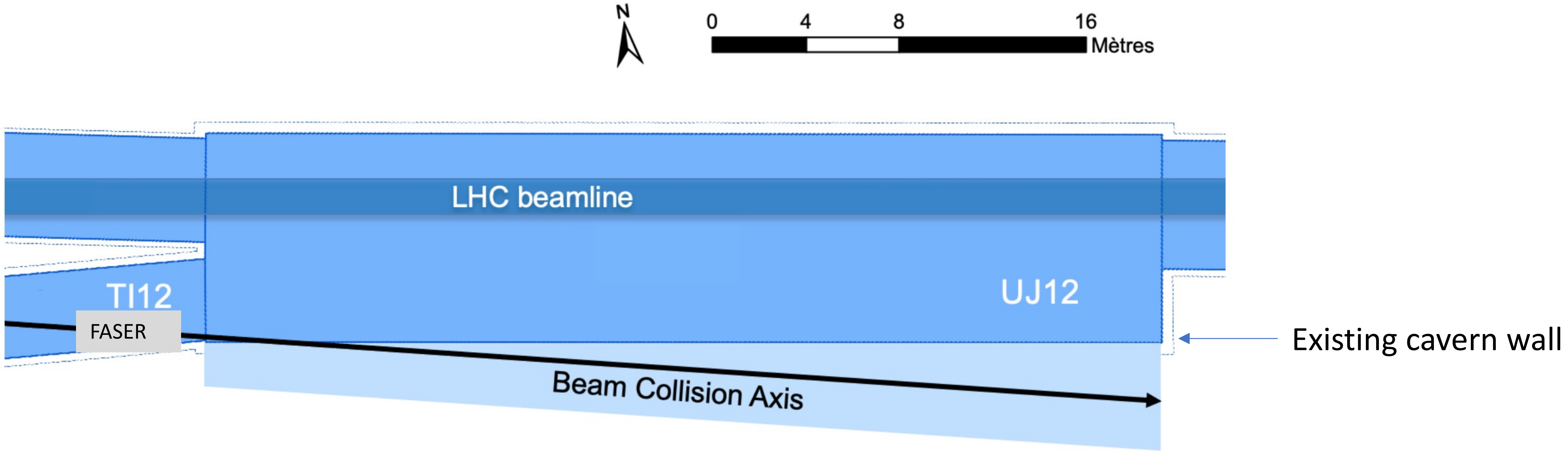
FASER experiment has been taking physics data since July 5th. Measures the rate of muon on the LOS.
In general the observed rate is broadly consistent with the expectation from FLUKA and previous in situ measurements. Observe ~0.6Hz/cm^2 (FLUKA estimate ~0.5Hz/cm^2). Also see evidence for rate increasing away from LOS as predicted by FLUKA.
However, noticed a significant dependence on the TCL collimator settings (which are changed when the AFP Roman Pot detectors are inserted a few minutes into the fill). In order to understand this we did a dedicated scan of the TCL5 and TCL6 collimator settings to see how they effect the FASER trigger rate.





Strong dependence on TCL6 settings. FLUKA simulations for FPF used HL-LHC baseline TCL6 settings – may be interesting to simulate possible other options to see sensitivity for FPF.

First idea:
Widen UJ12 cavern by 2-4m to allow ~50 area for experiments to be installed along the LOS



Not possible from civil engineering side.
Impossible to get sufficiently large excavation machine here, without dismantling ~500m of the LHC machine.

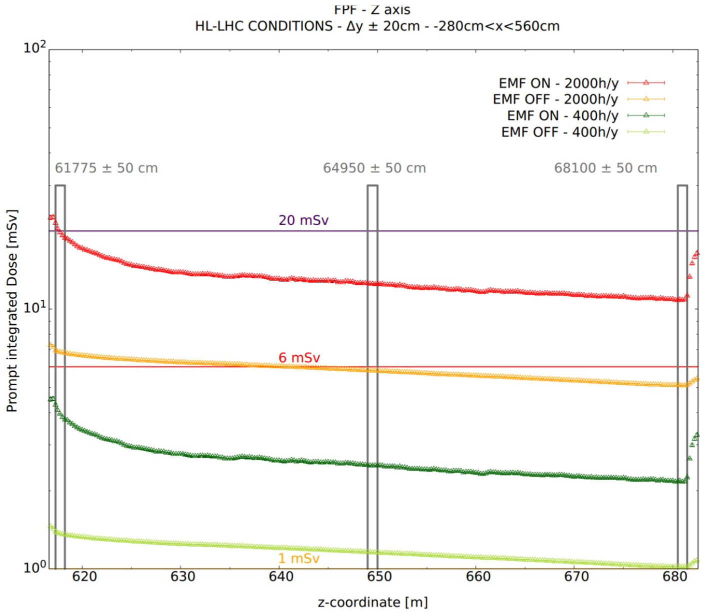
A. Infantino, L. Elie - CERN RP

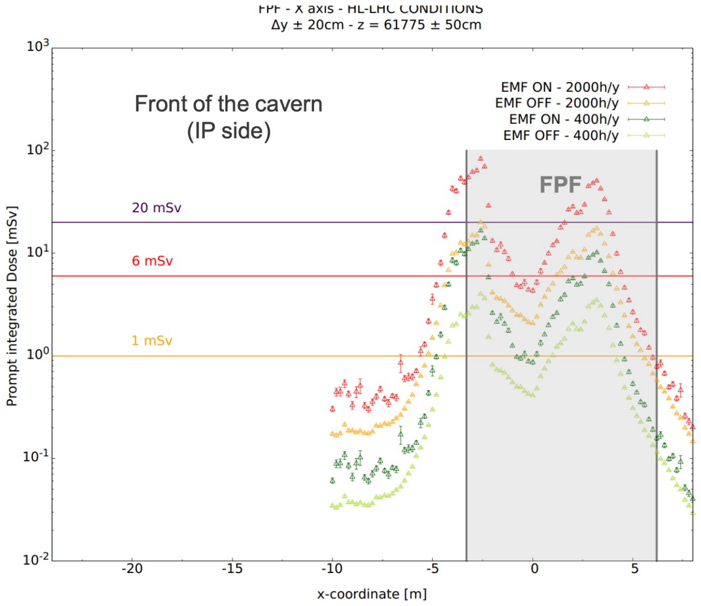
Access to the FPF during HL-LHC operations

The CERN Radio-Protection group has recently completed a detailed FLUKA study to see if people can access the cavern during HL-LHC operations. They have studied radiation from:

- Accidental beam loss close in the LHC or SPS close to the FPF,
- Radiation from beam-gas interactions in the LHC,
- Radiation dose from the prompt muons passing through the FPF

For the ultimate HL-LHC performance ($L=7.5e34 cm^{-2}s^{-1}$) only the last of these is seen to be close to the limit. Assuming <20% occupancy, and with some restrictions for local hotspots in the cavern, access should be possible during operations.





Yearly dose (assuming 7.5e34 lumi for full year). (EMF-ON, is better modelling in FLUKA).
Accumulated yearly dose limit is 6mSv for an area occupied <20% of the time. (Green is 20% of red curve).
Exceeded locally in limited number of locations (in muon hot spots).

Important encouraging result for feasibility of FPF implementation.

Radiation Areas classification

EDMS 810149

Area	Annual dose limit (year)	Ambient dose equivalent rate		Sign
		permanent occupancy	low occupancy	RADIATION
Non-designated	1 mSv	0.5 µSv/h	2.5 µSv/h	
Supervised	6 mSv	3 µSv/h	15 µSv/h	Dosimeter obligatory / Dosimètre obligatoire
Simple Controlled	20 mSv	10 µSv/h	50 µSv/h	SIMPLE CONTROLLED / CONTRÔLÉE SIMPLE – Dosimeter obligatory / Dosimètre obligatoire
Limited Stay	20 mSv	-	2 mSv/h	LIMITED STAY / SÉJOUR LIMITÉ – Dosimeters obligatory / Dosimètres obligatoires
High Radiation	20 mSv	-	100 mSv/h	HIGH RADIATION / HAUTE RADIATION – Dosimeters obligatory / Dosimètres obligatoires
Prohibited	20 mSv	-	> 100 mSv/h	NO ENTRY / DÉFENSE D'ENTRER

Radiation Area (Supervised to Prohibited)

Controlled Area (Simple Controlled to Prohibited)

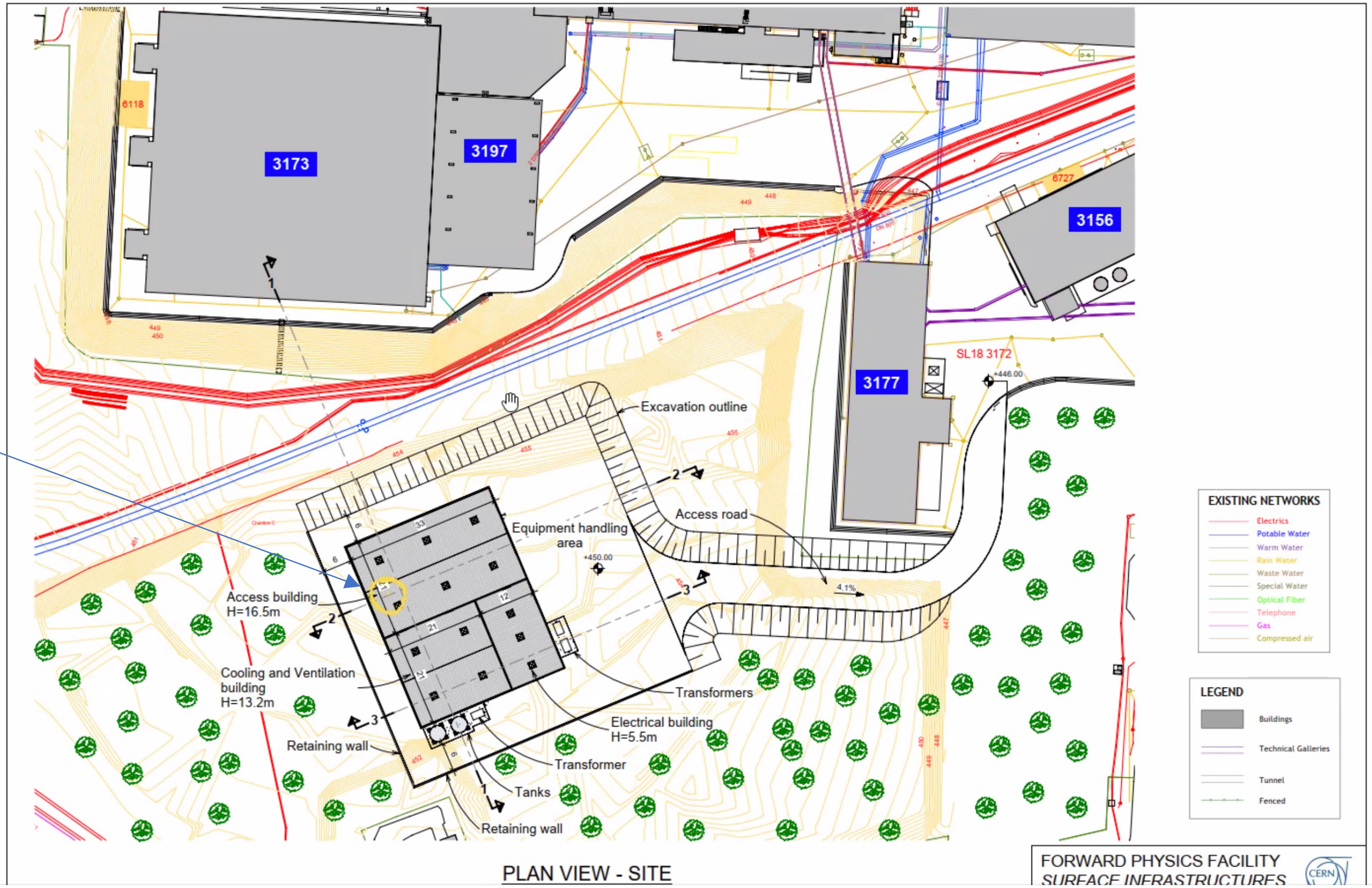
Low-occupancy:
< 20% working time

- ✓ The CERN RP group has reviewed the signage used in radiation areas, by introducing a new colour code for better visualizing the radiological risk level
- ✓ The RP rules determining the area classification were not changed

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



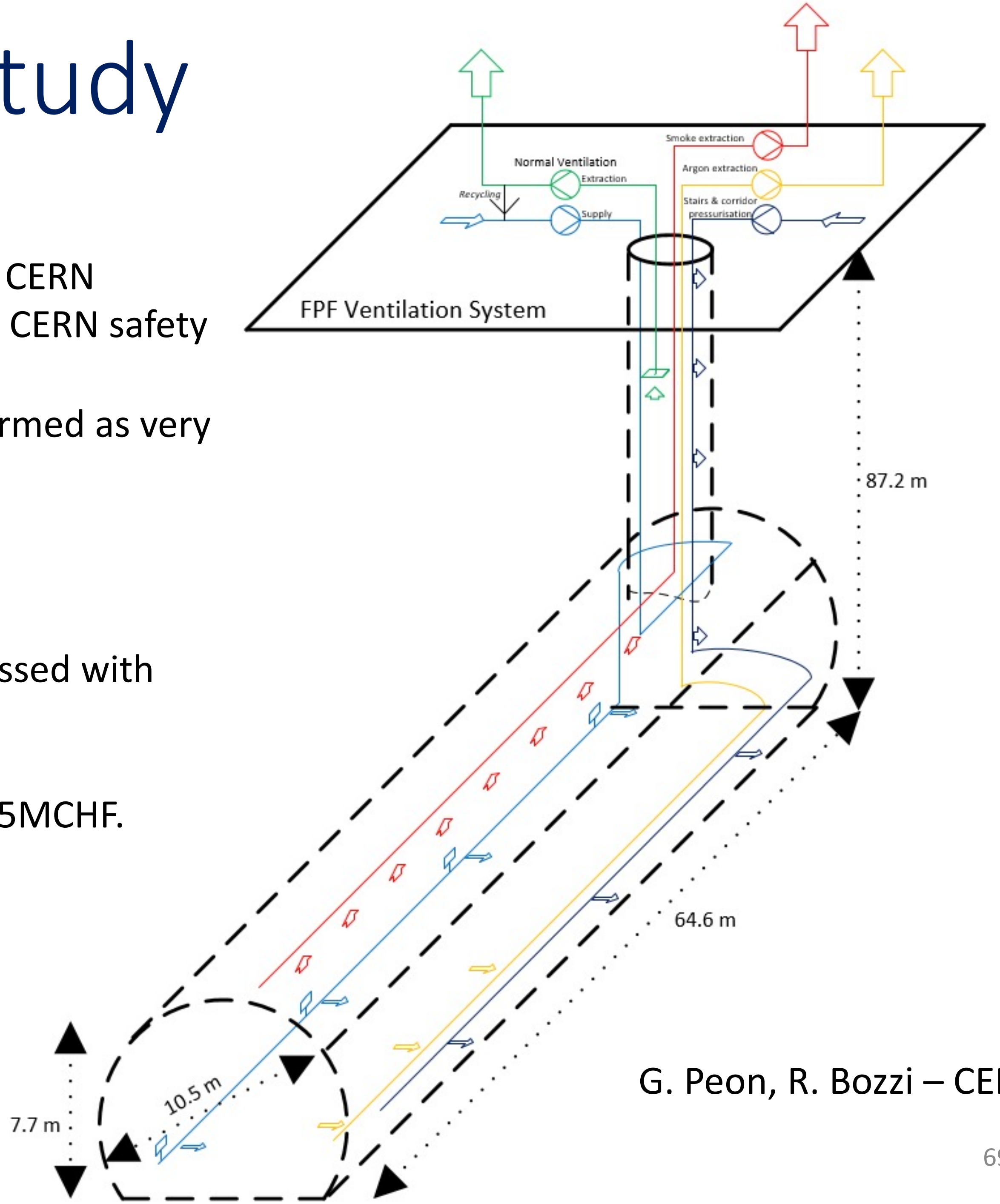
Ventillation Study

More detailed study on ventillation being carried out by CERN cooling/ventilation group (EN-CV), after discussion with CERN safety (HSE).

Current design, assmues shaft will not be covered (confirmed as very likely by RP), and includes separate system for:

- Fresh air
- Pressurization
- Smoke extraction
- LAr evacuation included, but details need to be discussed with safety.

Preliminary costing of ventillation system (no cooling) 2.5MCHF.



G. Peon, R. Bozzi – CERN EN-CV

Cost breakdown compared to HL-LHC works

Rough comparison of cost breakdown with HL-LHC works (assuming FPF total cost is 40MCHF).
Clear that CV is more expensive and EL is less expensive than corresponding HL-LHC works fraction.

Infrastructures	**[% of WP17]**	**% for FPF costing**
Civil engineering	67	25/40 = 62.5
Electrical distribution	13	1.5/40 = 3.8
Cooling & ventilation	12	7./40 = 17.5
Alarm & access system	2.4	2.5/40 = 6.3
Handling equipment	2.2	1.5/40 = 3.8
Operational safety	1.6	
Logistics & storage	1.4	
Technical monitoring	0.6	

This is based on 25MCHF for pure CE, and 15MCHF for services

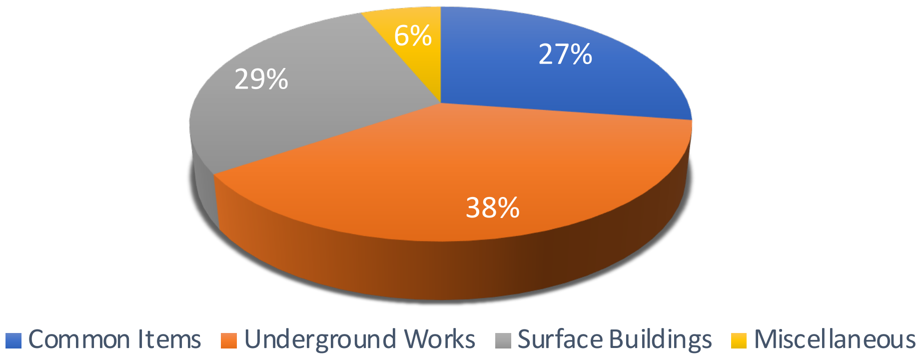
K. Balazs, J. Osborne

New Cavern – Very Preliminary Cost Estimate for CE

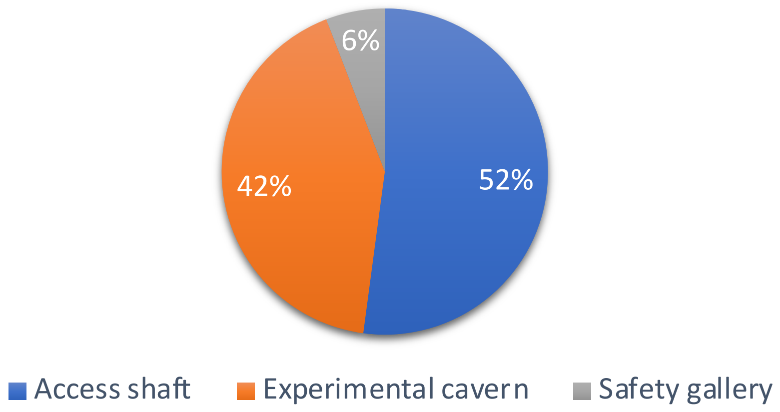
Ref.	Description of works	Cost [CHF]
1	**Common Items**	**6,356,824**
1.1	Contractual requirements (performance guarantee, insurances)	163,473
1.2	Specified requirements (Installation of barracks, Access road, Services etc.)	1,055,263
1..3	Method-related charges (Accommodations, Services, Site supervision, Project drawings)	5,054,772
1.4	Provisional sums	83,316
2	**Underground Works**	**8,859,608**
2.1	Site installation and equipment	3,689,097
2.2	Underground works	5,170,511
3	**Surface Buildings**	**6,598,589**
3.1	Generality	636,485
3.2	Top soils and Earthworks	882,051
3.3	Roads and Network	850,725
3.4	Buildings	4,229,328
4	**Miscellaneous**	**1,436,656**
4.1	Site investigation prior works	200,000
4.2	Project Management	1,236,656
	TOTAL CE WORKS	**23,251,677**

Draft

Split of the CE cost

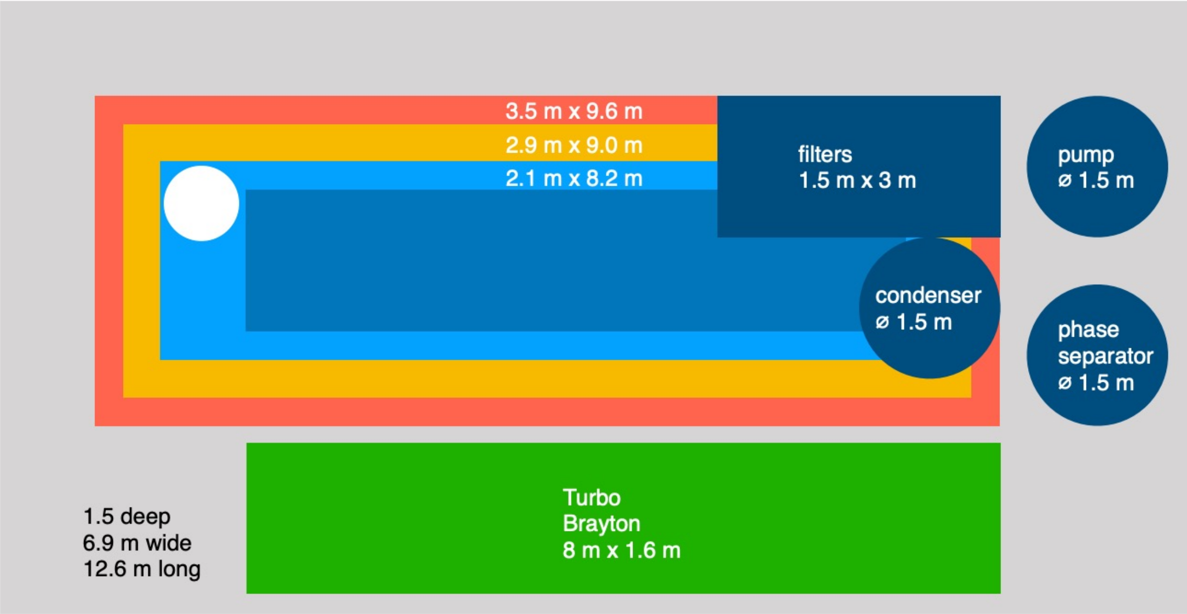


Split of underground work

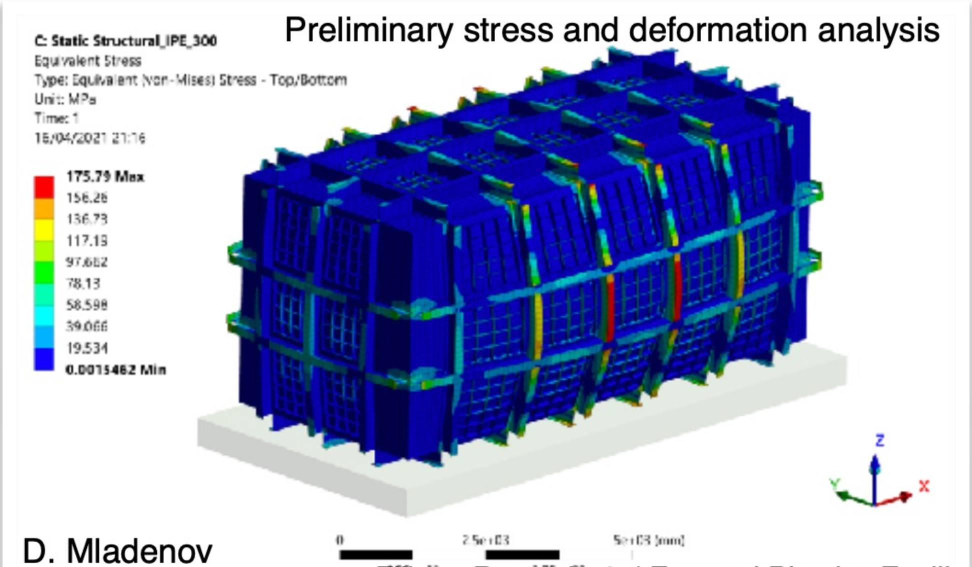


LAr TPC cryogenics and cryostat

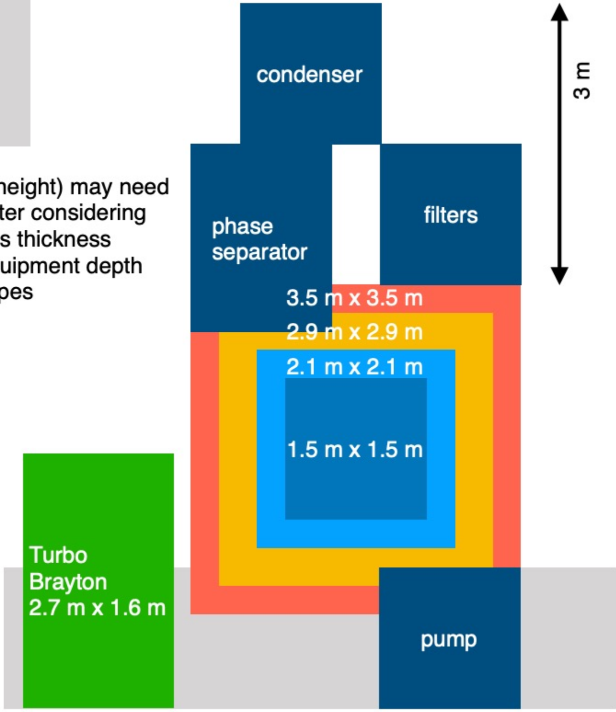
LAr TPC detector drives many aspects of services/infrastructure and safety systems.
Rough design of cryostat and cryogenics by F. Resnati based on proto-Dune experience in the neutrino platform.



- Reduced to 30 cm the non-instrumented LAr layer.
- Insulation thickness reduced to 40 cm (~increase the heat input (*O*(4 kW)).
- Reduce structural thickness.
- Manhole for egress added.



Dimensions (height) may need to increase after considering
- minimum gas thickness
- minimum equipment depth
- cryogenic pipes



Neutrinos at the FPF

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

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

Neutrinos at the FPF

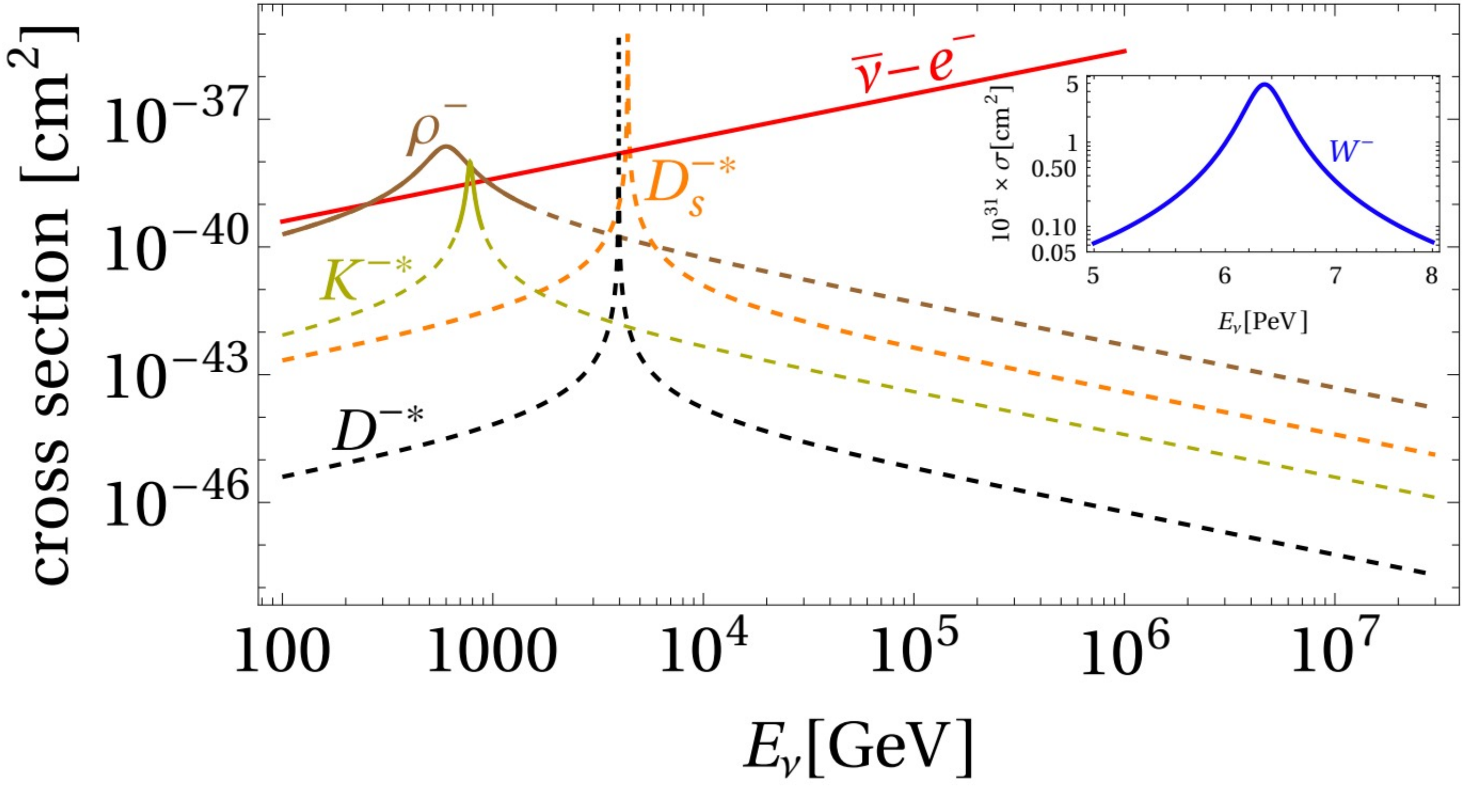
https://arxiv.org/abs/2112.03283

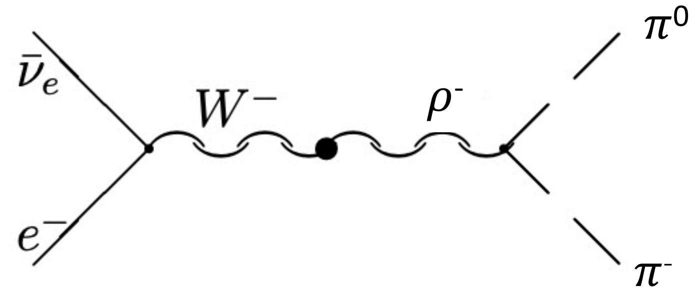
Can also look for electron-antineutrino – electron resonance production, TeV scale neutrinos at the FPF give access to resonances at the ~1 GeV scale.

cf. 6 PeV neutrinos at ICECUBE, sensitive to resonant W production (Glashow resonance) – 1 event observed in last year.

Recent paper suggests ρ^- production could be observed at FPF, with $\mathcal{O}(50)$ events in FPF experiments.

(ρ mass equivalent to neutrino energy of 580 GeV)

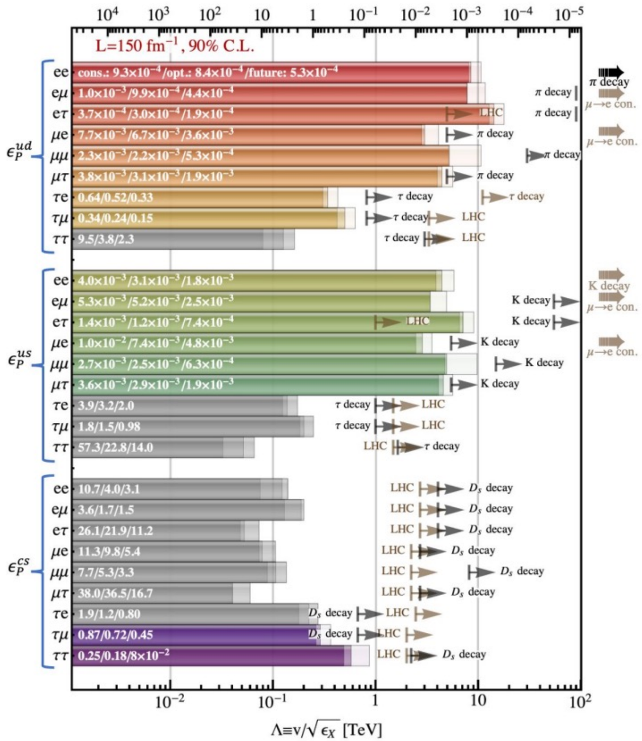




Neutrino Physics

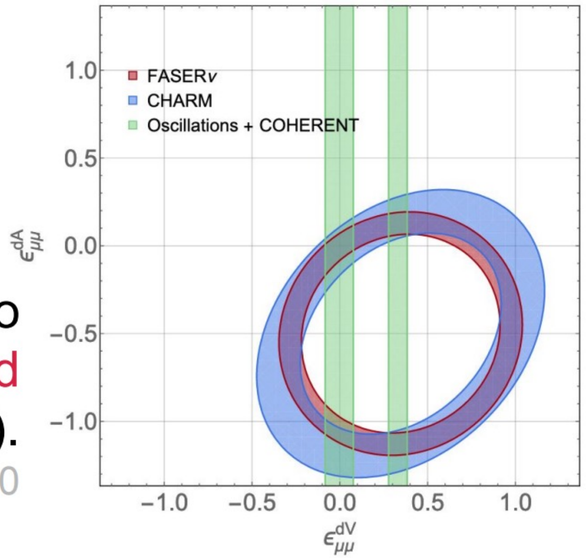
Interactions of LHC neutrino can also be used to constrain SM EFT coefficients

Falkowski, González-Alonso, Kopp, Soreq, Tabrizi 2105.12136



NC measurements could also constrain neutrino non-standard interactions (NSI).

Abraham, Ismail, Kling 2012.10500



SM neutrino oscillations are expected to be negligible at FASERv. However, sterile neutrinos with mass ~40eV can cause oscillations. FASERv could act as a short-baseline neutrino experiment.