FPF Forward Physics Facility

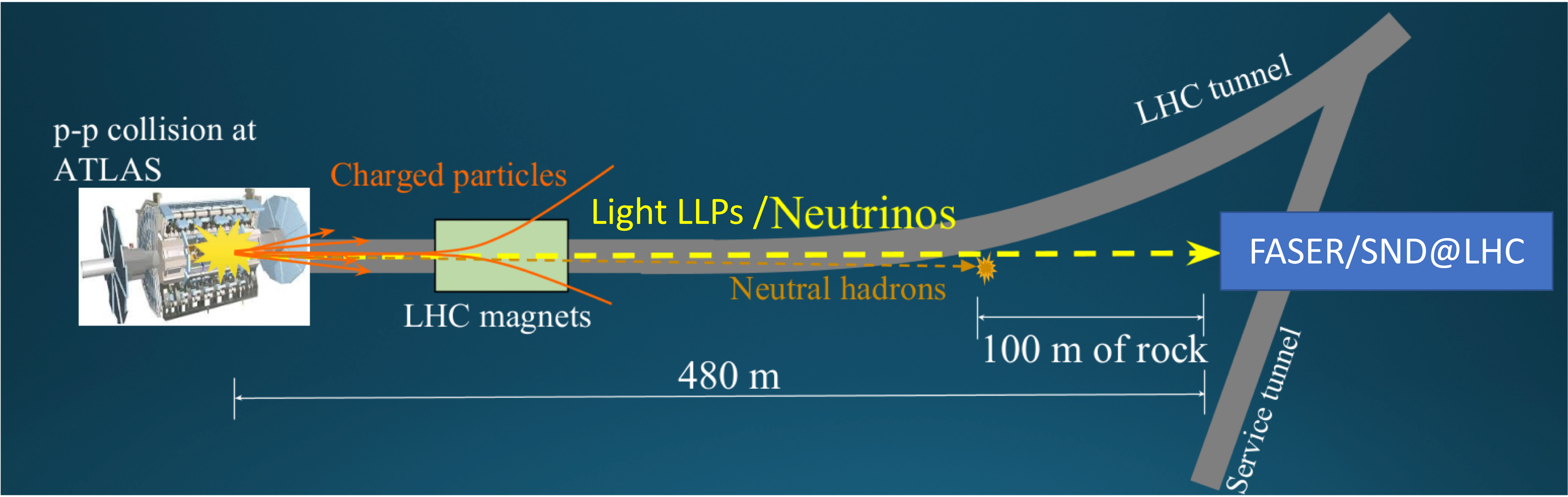
Seminar at University of Geneva

30/3/22

Jamie Boyd (CERN)

Overview:
- Physics motivation
- Experiments
- Facility

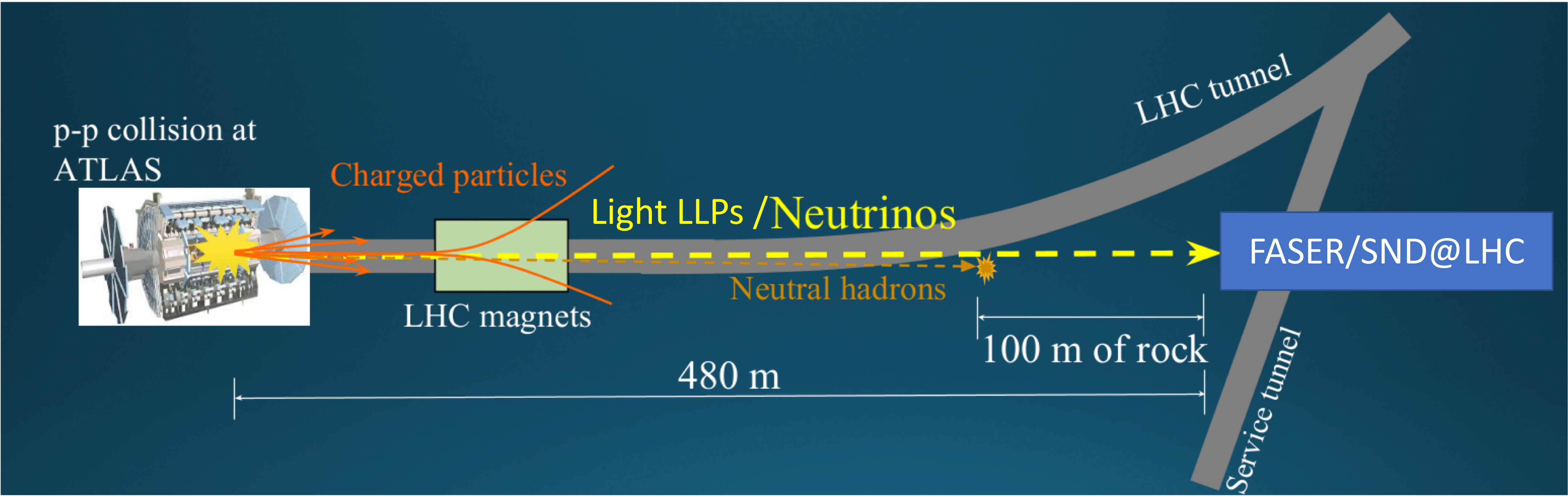
Introduction



FASER and SND@LHC experiments designed to search for new, light, long-lived particles (LLPs), and study neutrinos. These are produced in the decay of light hadrons which are produced in the LHC collisions.

Light hadron production is very peaked in the forward direction, extremely collimated with the beam collision axis line of sight (LOS), hence even small detectors covering the angular region less than a miliradian around the LOS have good physics sensitivity.

Introduction

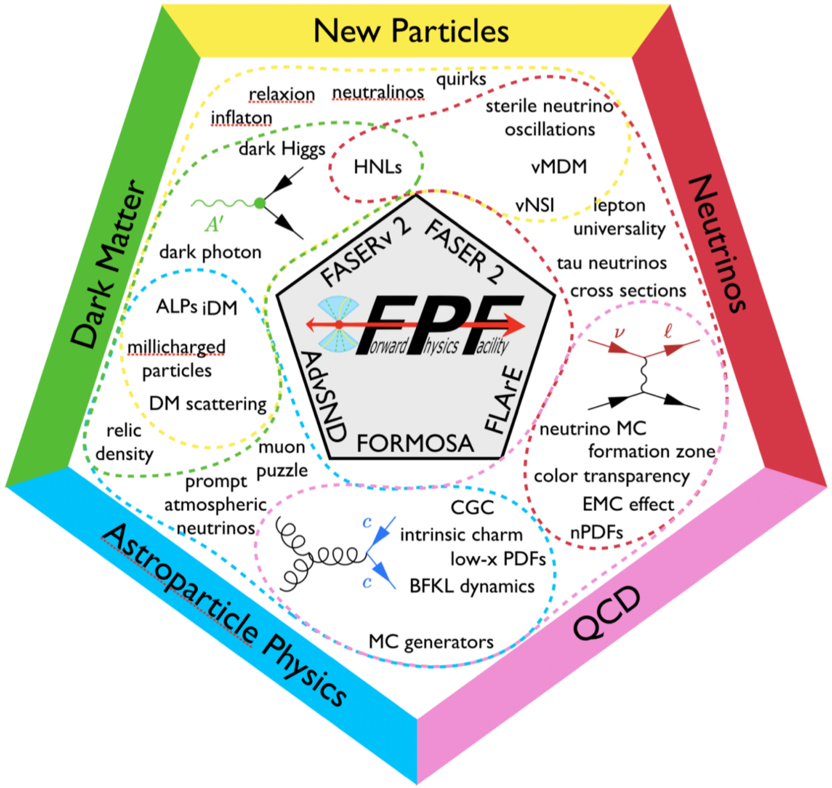


However, strong physics case to scale these type of experiments up by >1 order of magnitude, as well as to add new types of detectors in this special location.

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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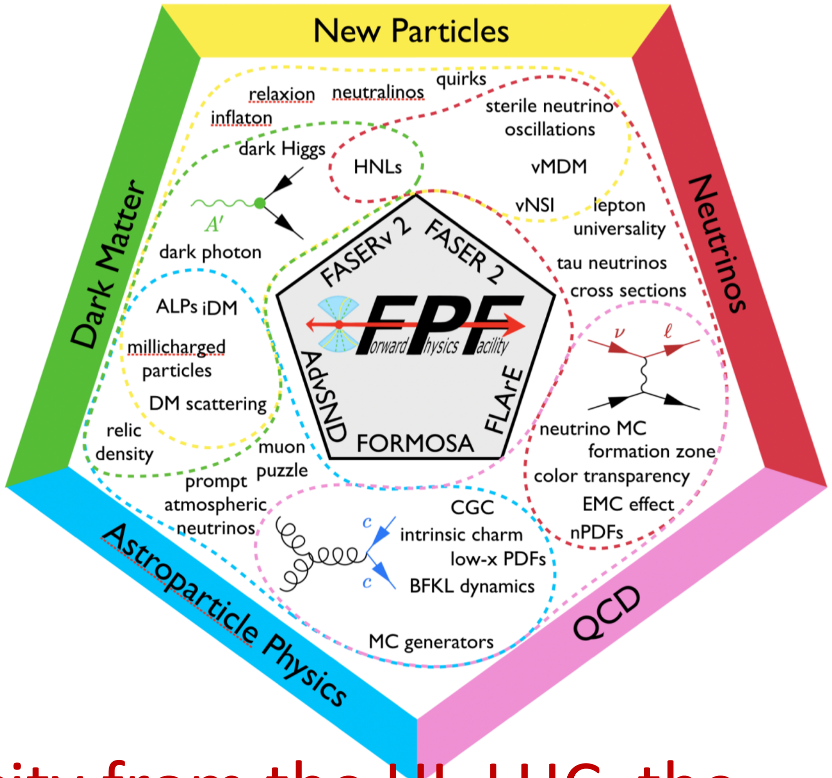
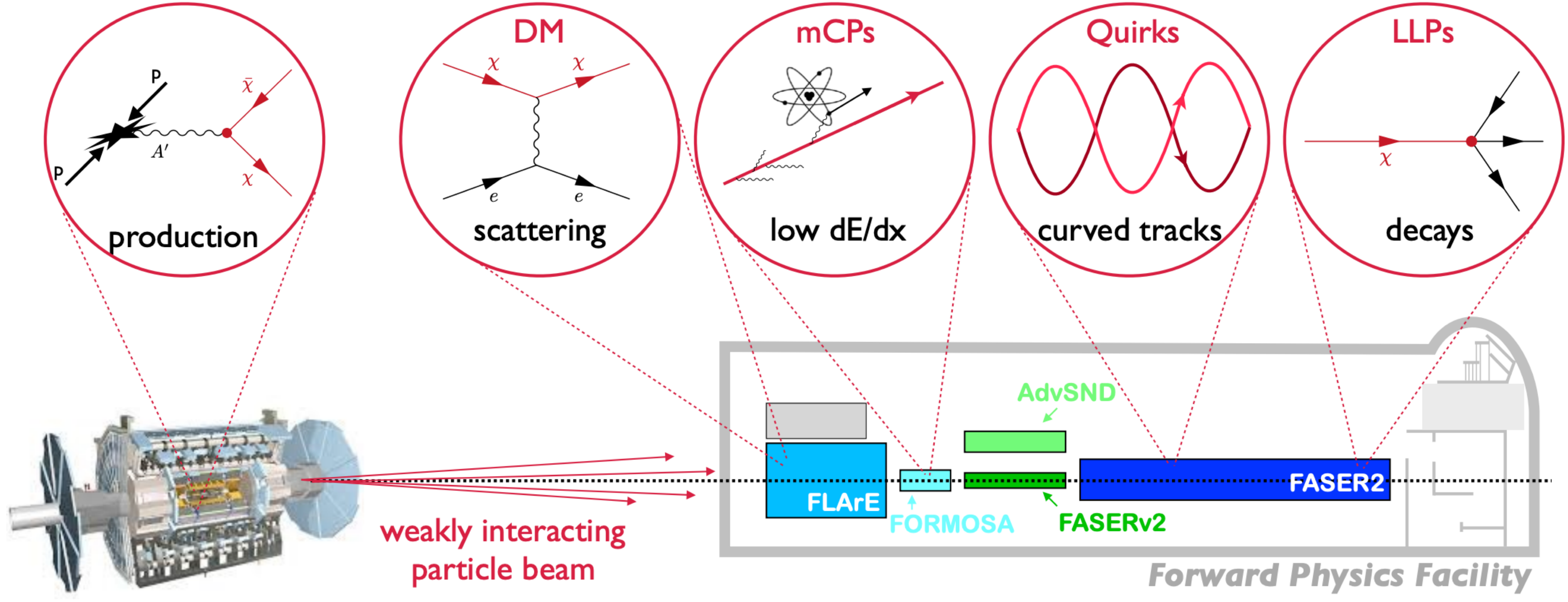


- In order to fully benefit from the increase in luminosity from the HL-LHC, the FPF will allow:
  - Longer detectors to increase target/decay volume
  - Wider detectors to increase sensitivity to heavy flavour produced particles
  - Space for new detectors with complementary physics capabilities

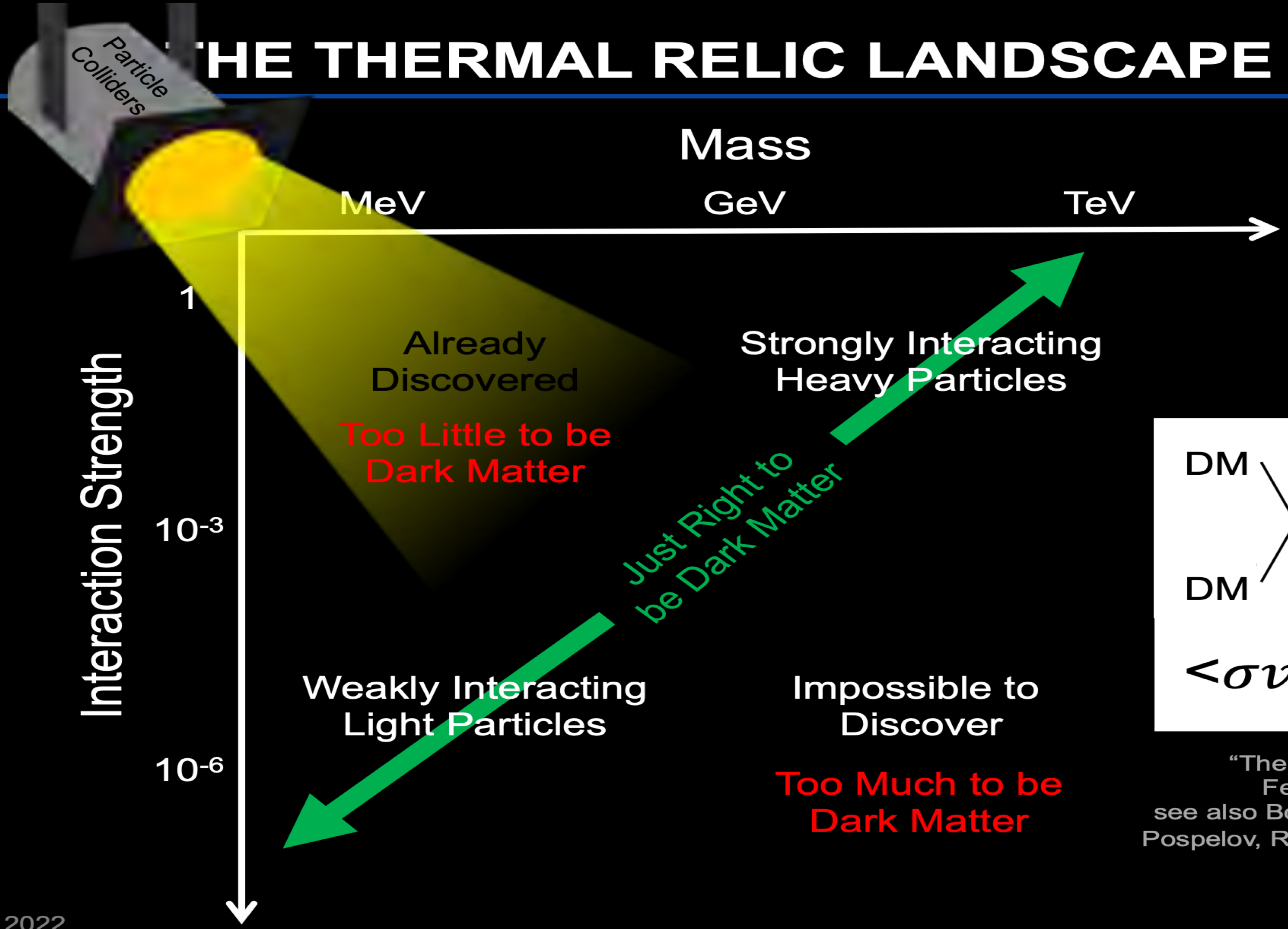
Beyond the Standard Model Physics

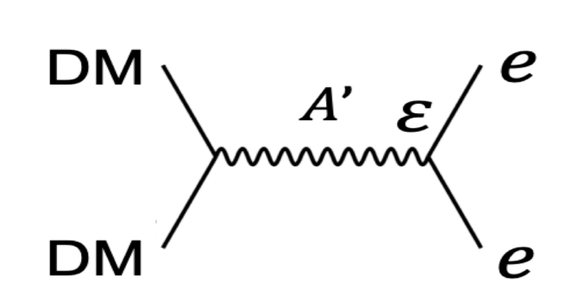
BSM particles can be detected in different ways in FPF experiments:



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

THE THERMAL RELIC LANDSCAPE

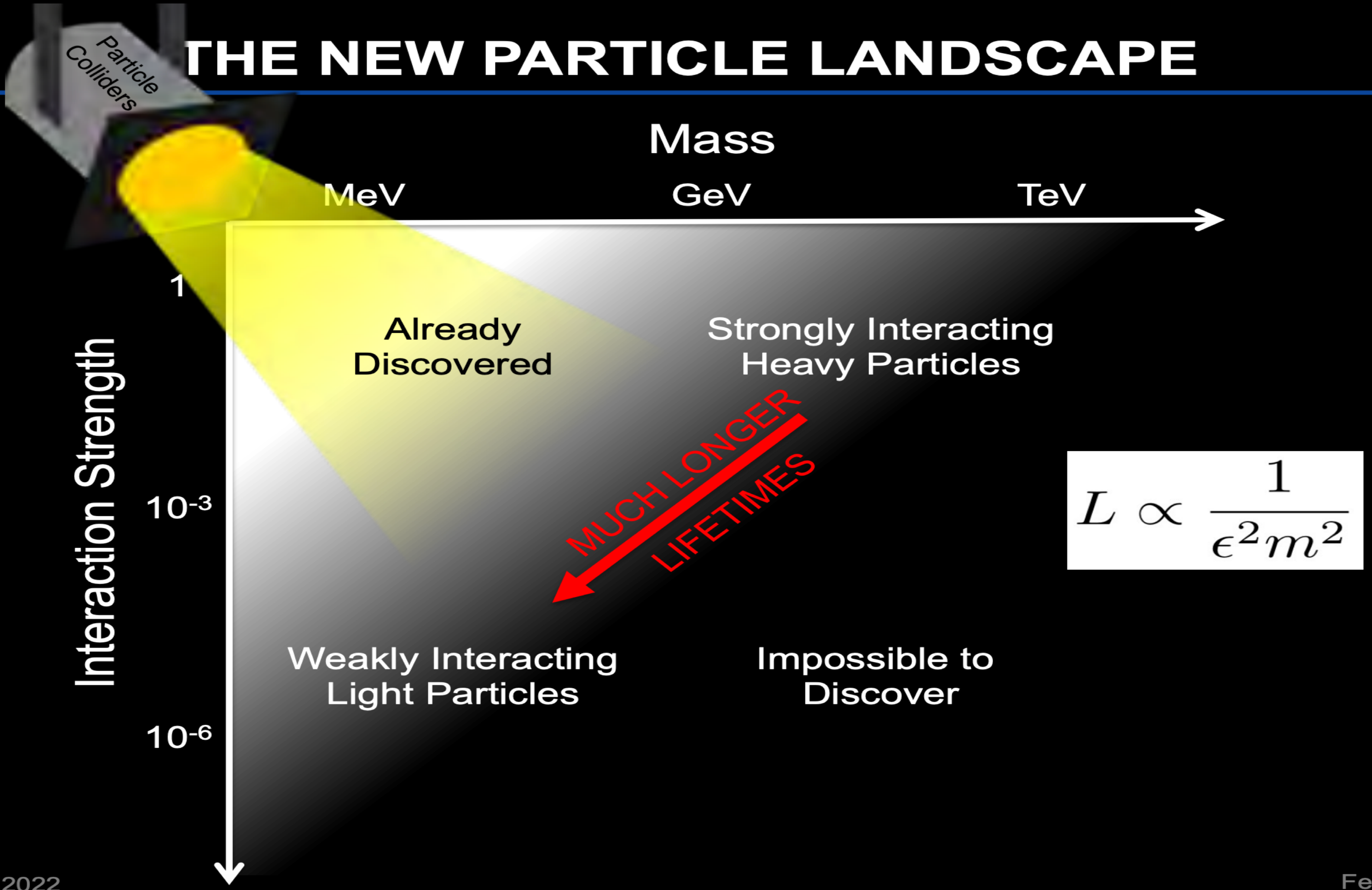




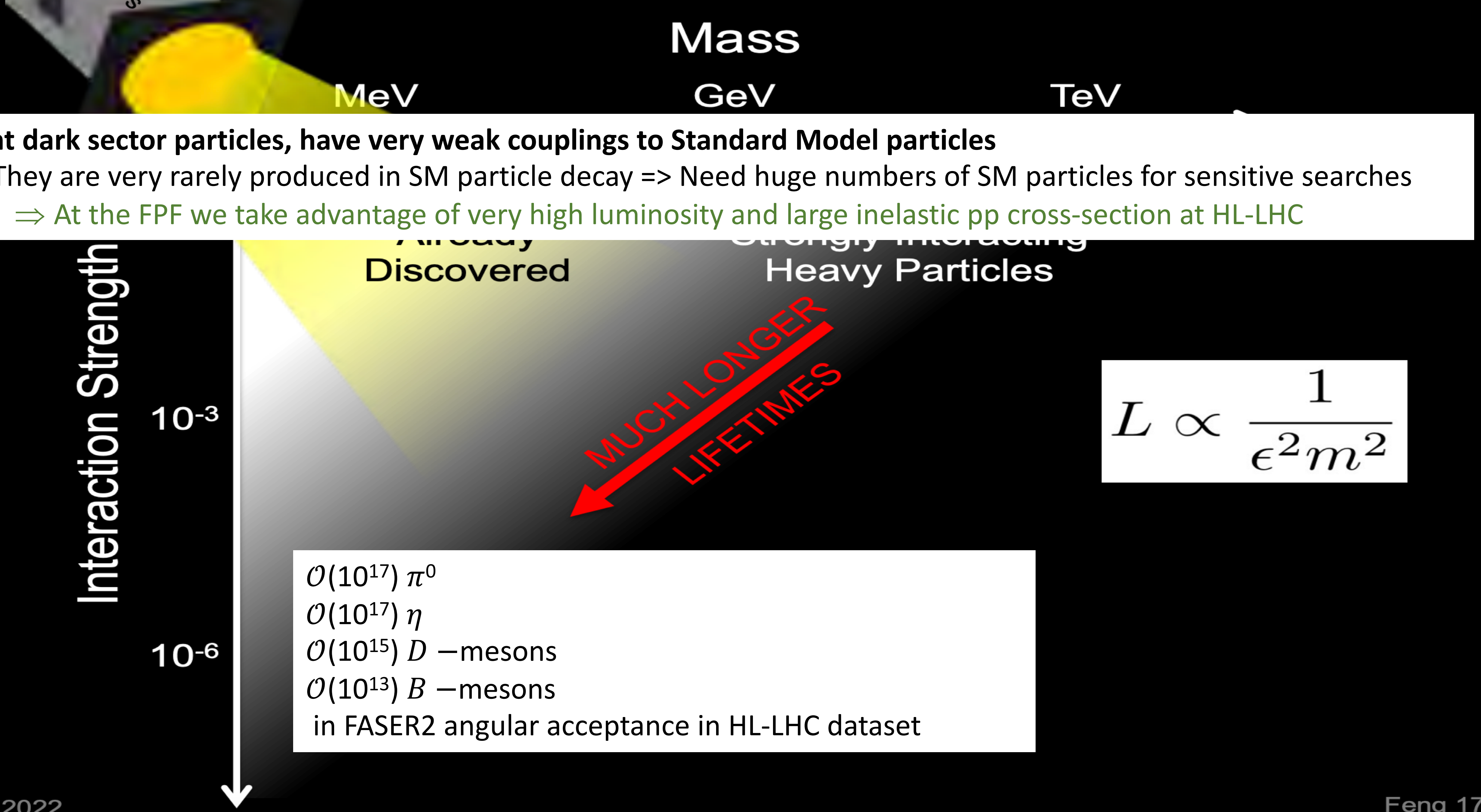
$$<\sigma v> \sim \frac{\varepsilon^2}{m_{A'}^2}$$

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

THE NEW PARTICLE LANDSCAPE



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

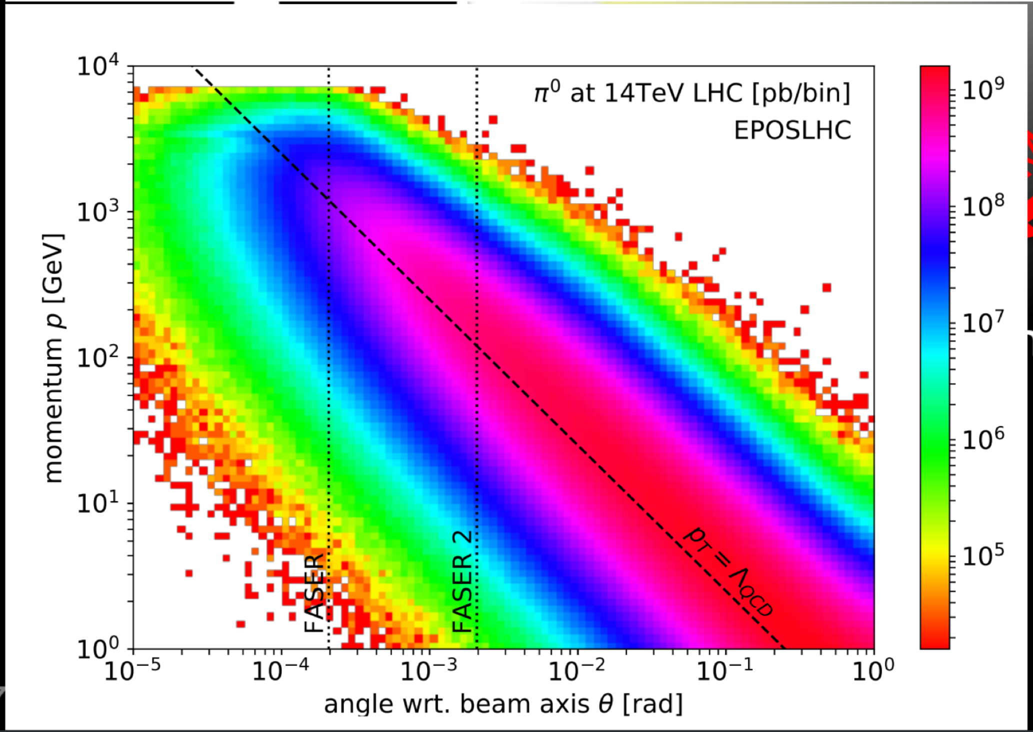
Light dark sector particles, have very weak couplings to Standard Model particles

⇒ 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

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

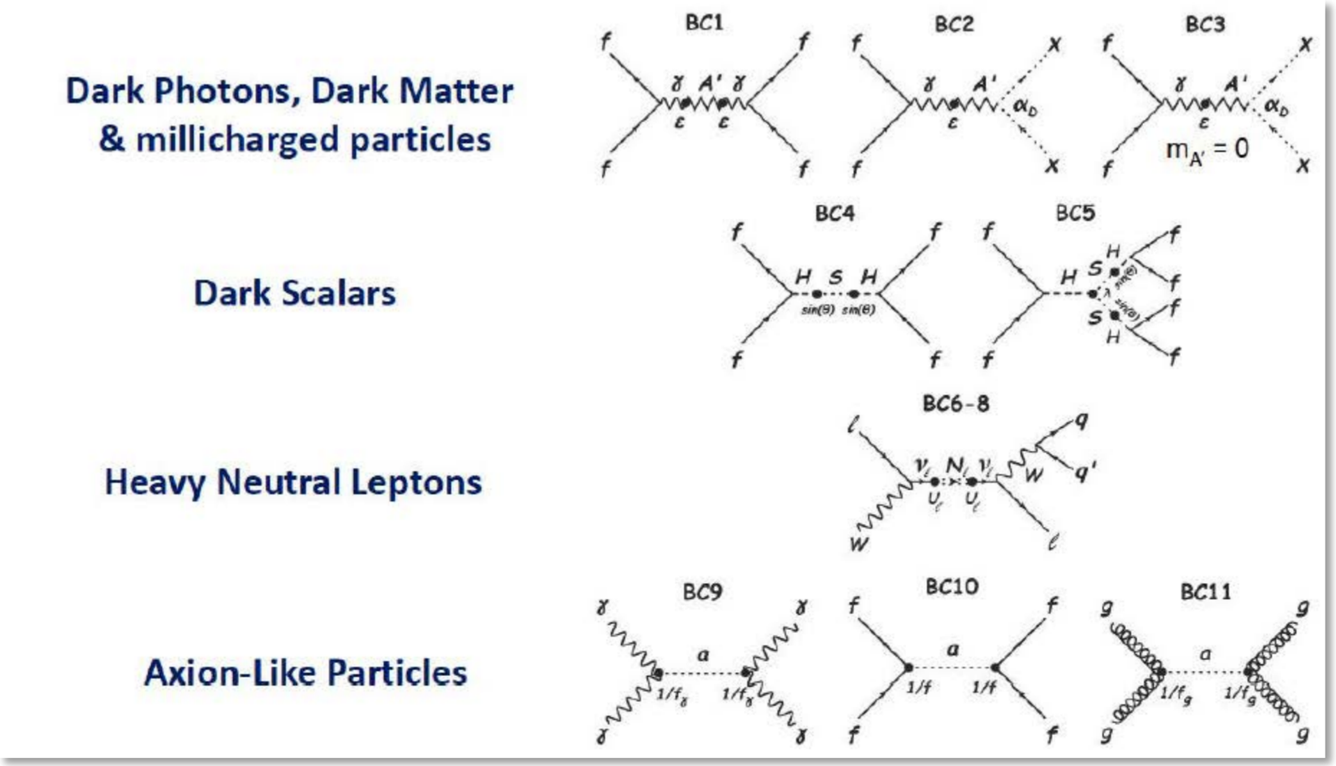
...ng

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 PBC:

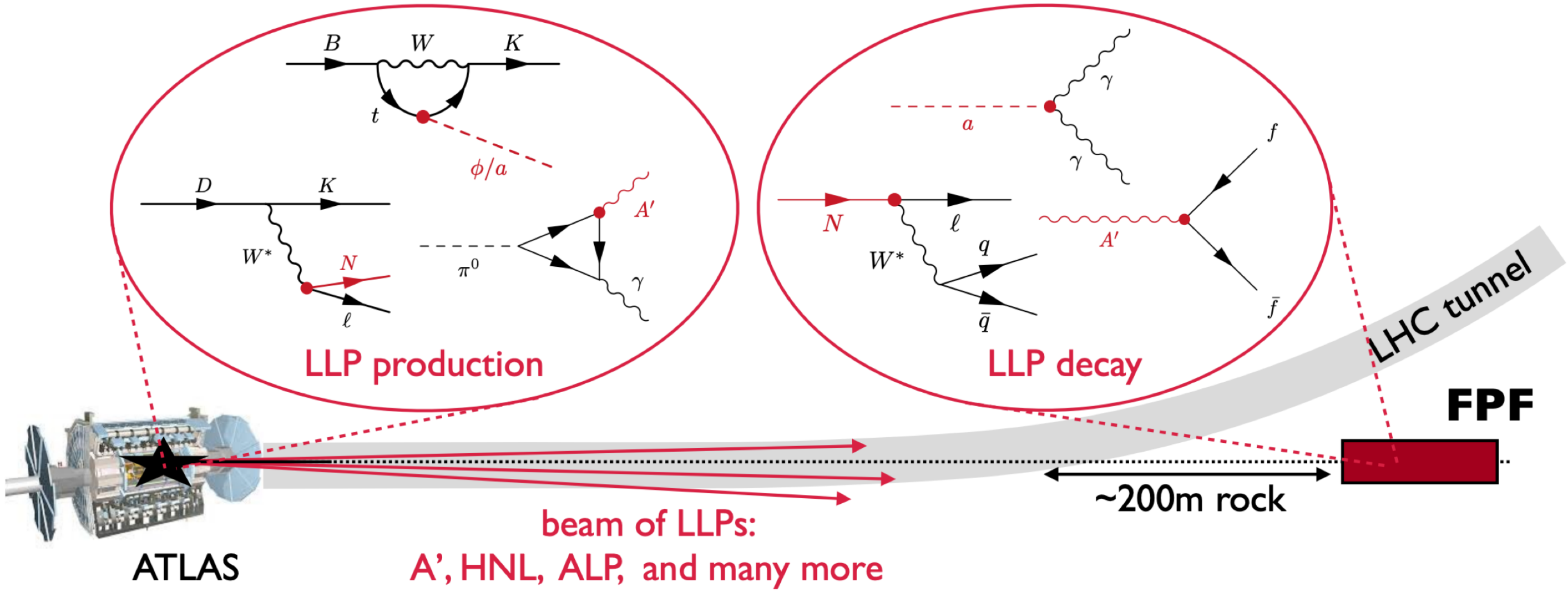


FPF experiments would give significant new sensitivity in all of these models. A few examples on next slides…

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.



Benchmark Model	FPF
BC1: Dark Photon	FASER 2
BC1’: $U(1)_{B-L}$ Gauge Boson	FASER 2
BC2: Dark Matter	FLArE
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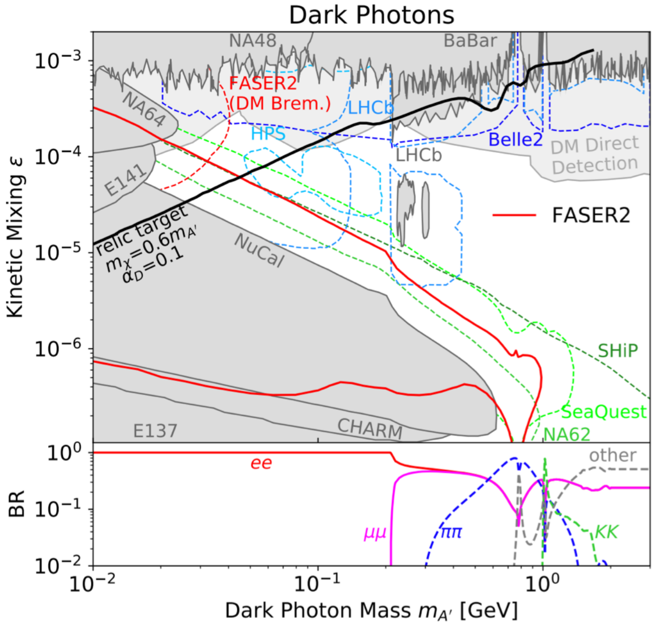
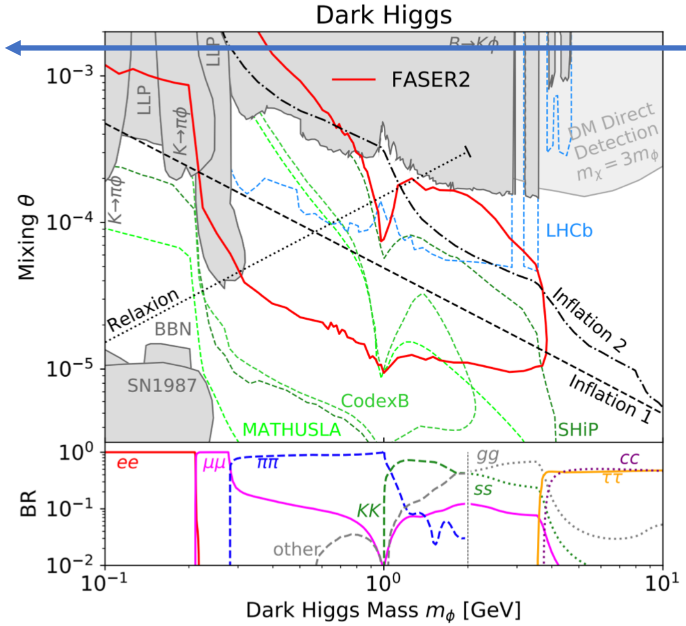
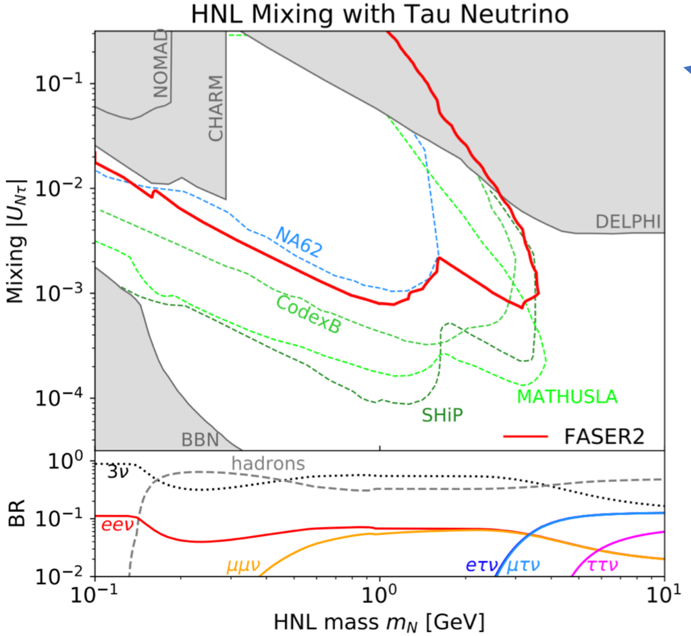
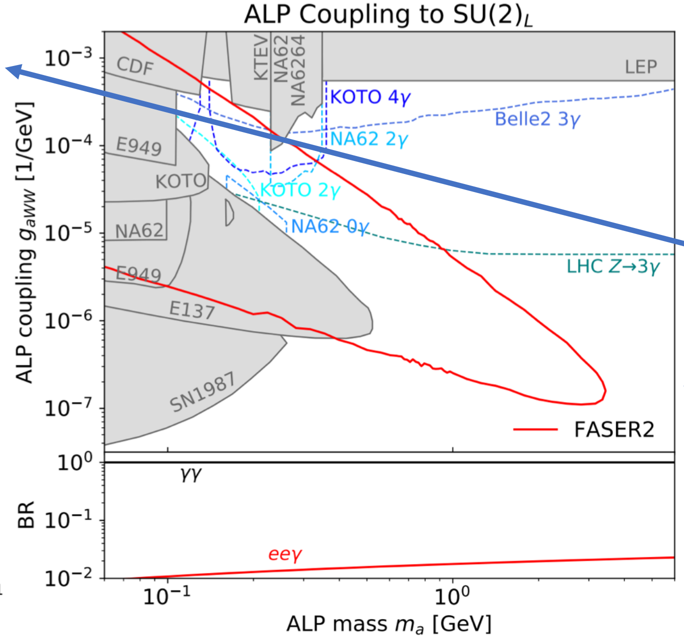
BSM at FPF









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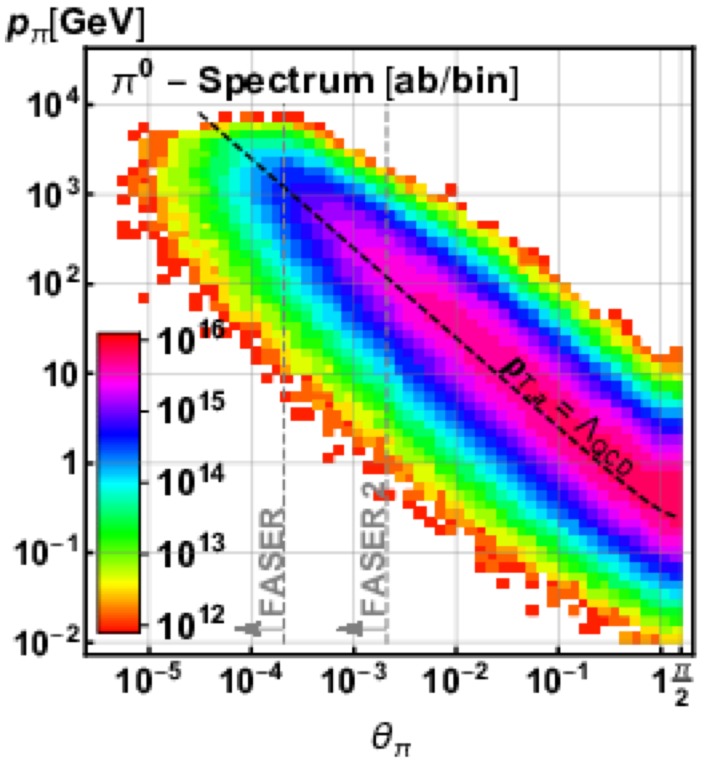
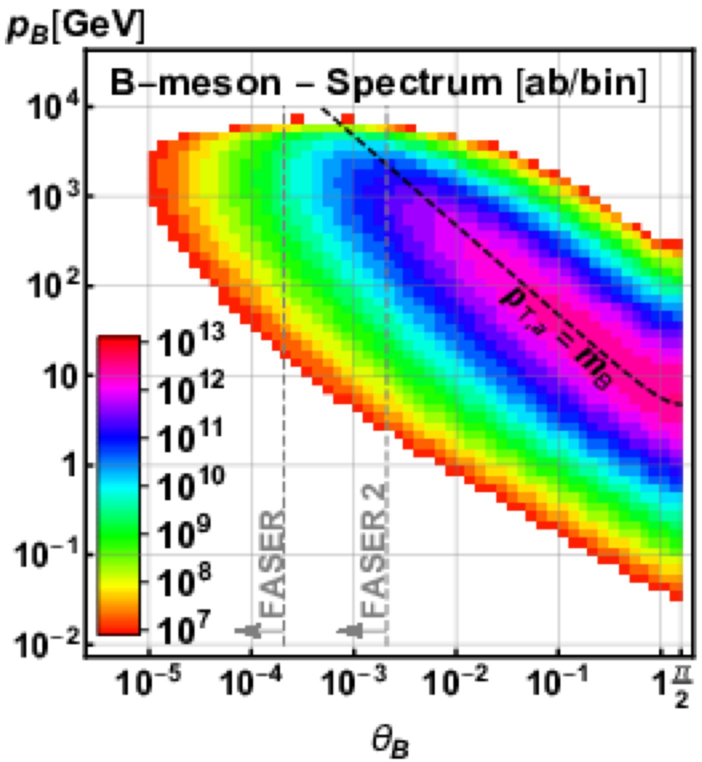
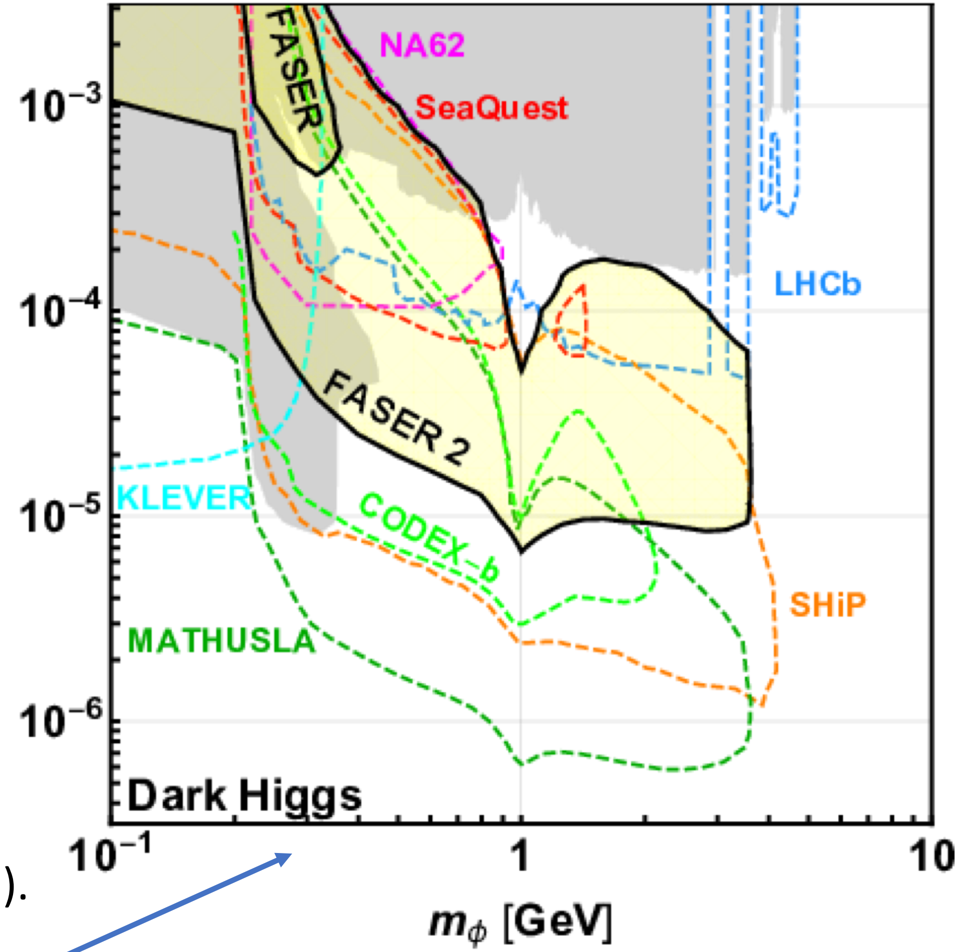
Aside: Signals from heavy flavour decay



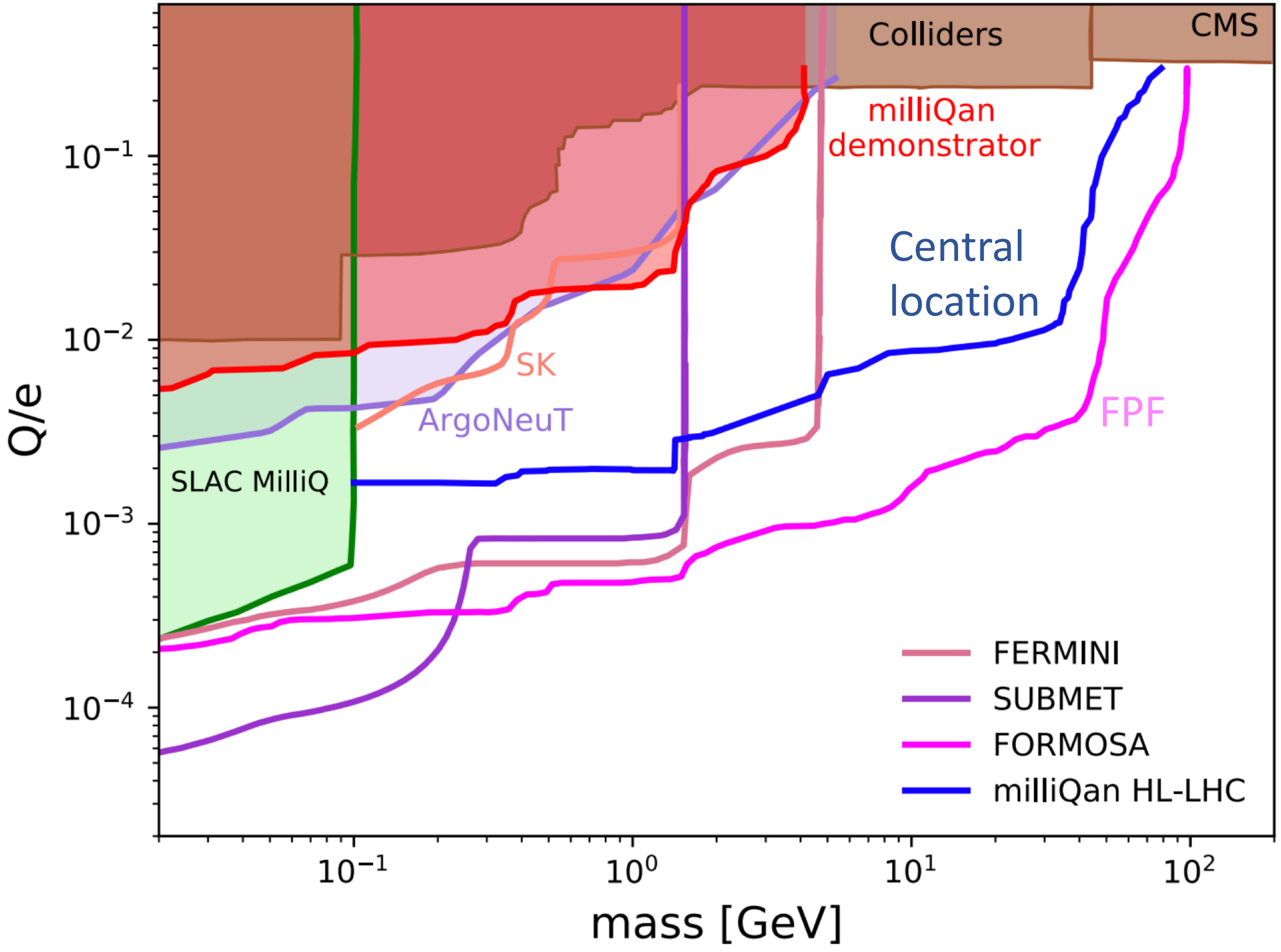




Number of π^0 and B mesons as function of angle wrt LOS and energy (for 150/fb). Heavier B-mesons are more spreadout around the LOS => only small fraction in FASER acceptance, but FASER2 starts to get into the bulk of the distribution. Much better sensitivity for new LLPs produced in B decays (such as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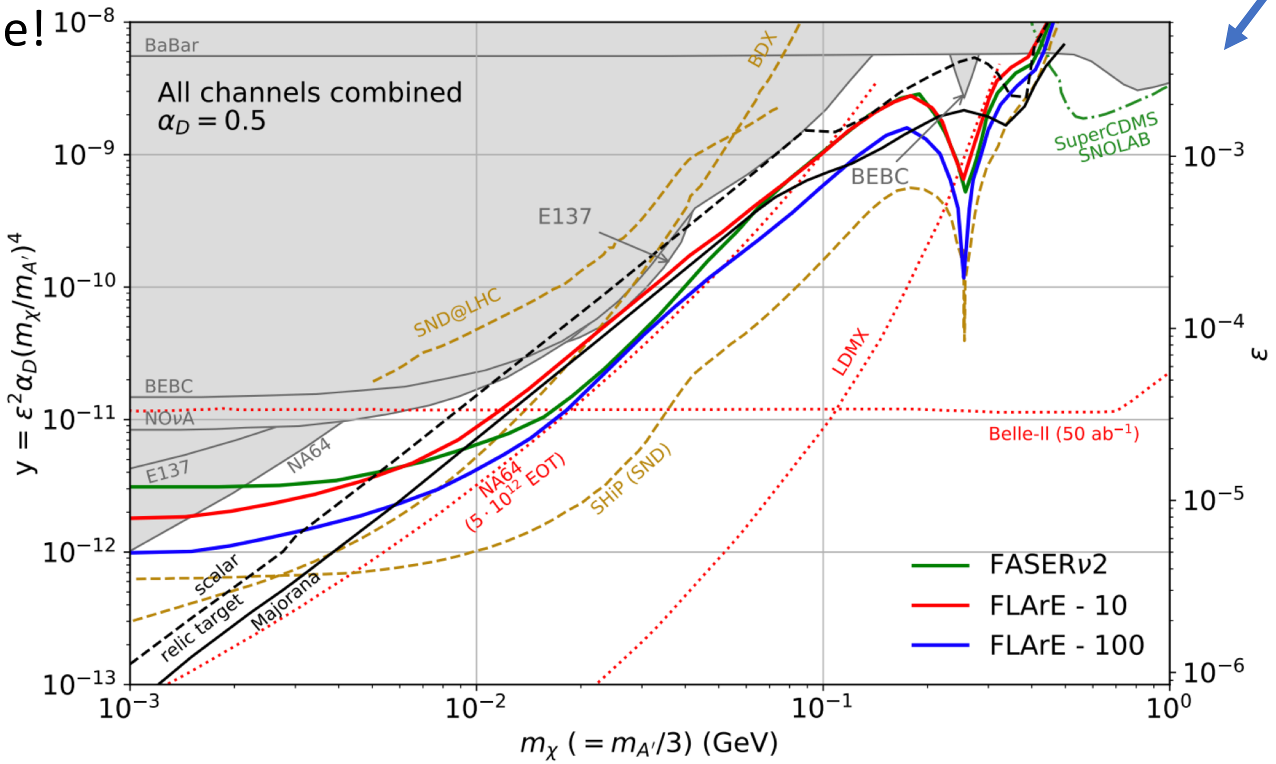
BSM at FPF

- 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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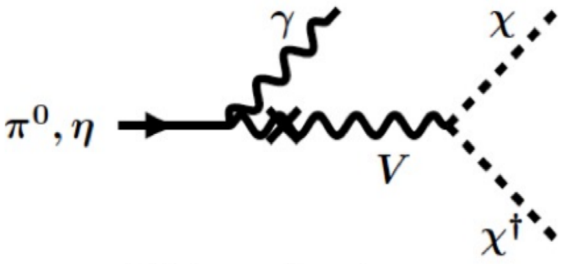
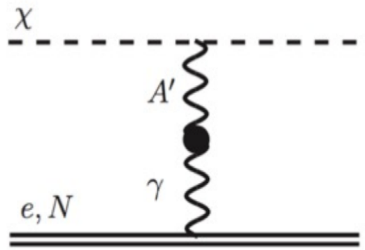


DM production



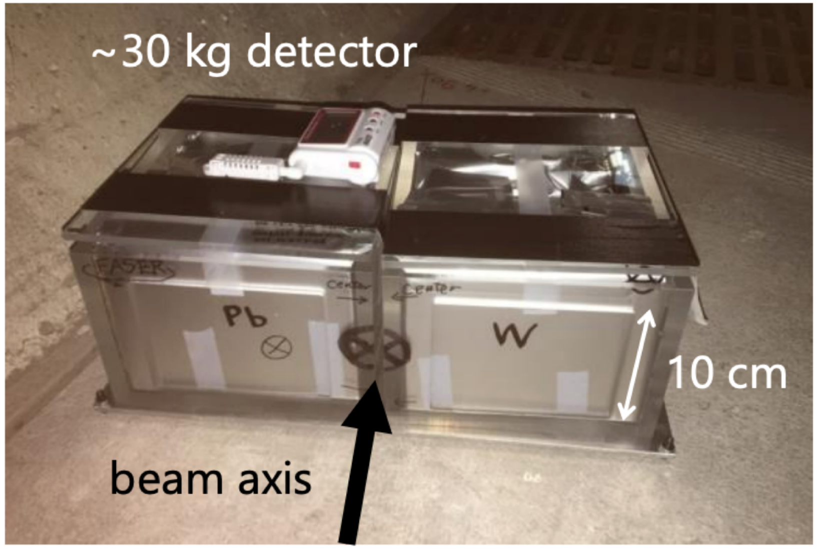
DM scattering

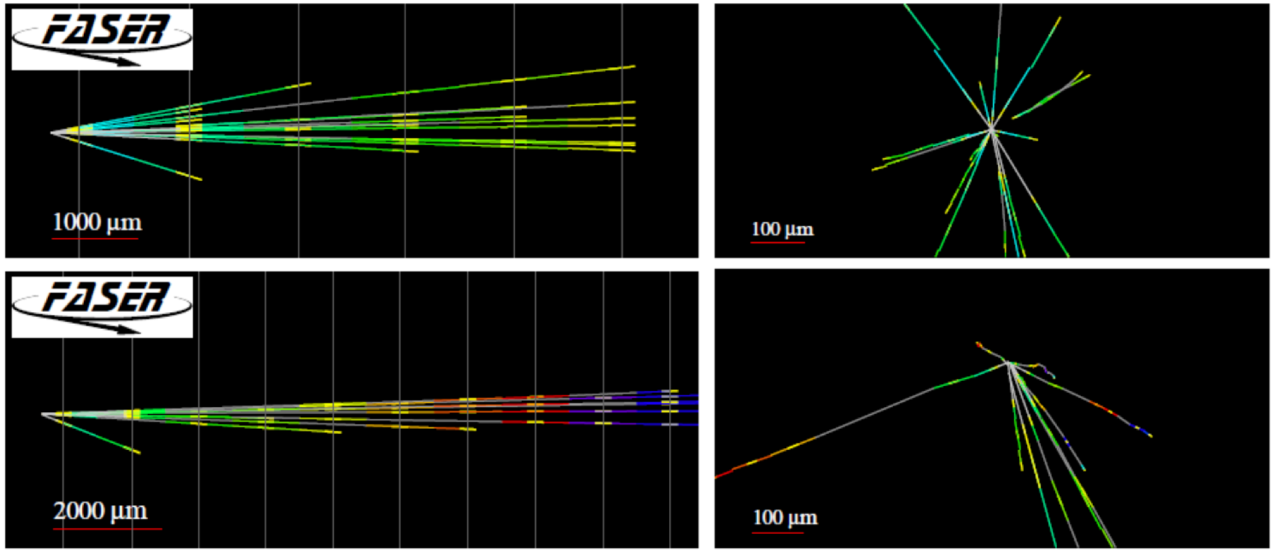
Collider Neutrinos

[PRD.104.L091101](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.





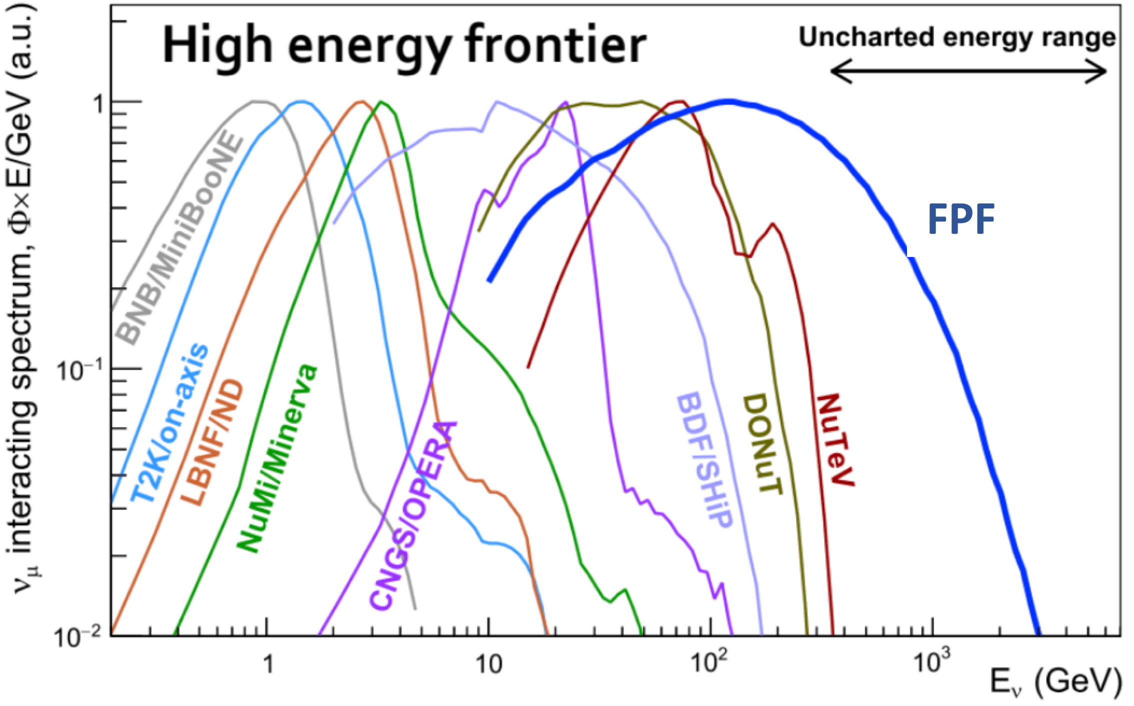
Highlights the potential of the LOS location for neutrino physics!

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	64k	~100k
$\bar{\nu}_e$	36k	
ν_μ	430k	~500k
$\bar{\nu}_\mu$	120k	
ν_τ	2k	~3k
$\bar{\nu}_\tau$	0.8k	

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



Neutrinos at the FPF

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

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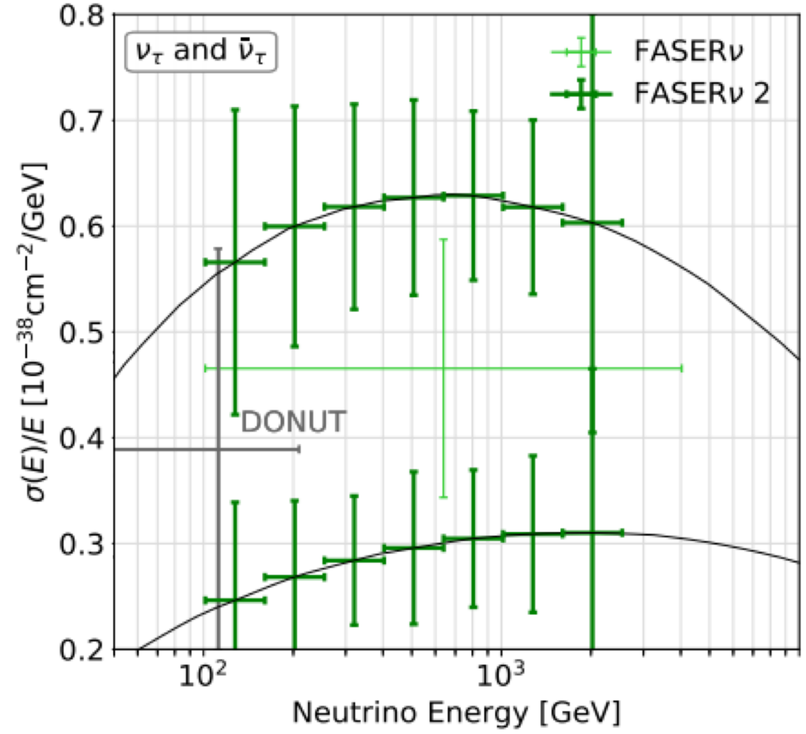

The tau neutrino is the **least well studied SM particle**, with only $\mathcal{O}(20)$ directly detected interactions. FPF experiments will **increase this number by over two orders of magnitude**, enabling precision ν_τ studies:

- 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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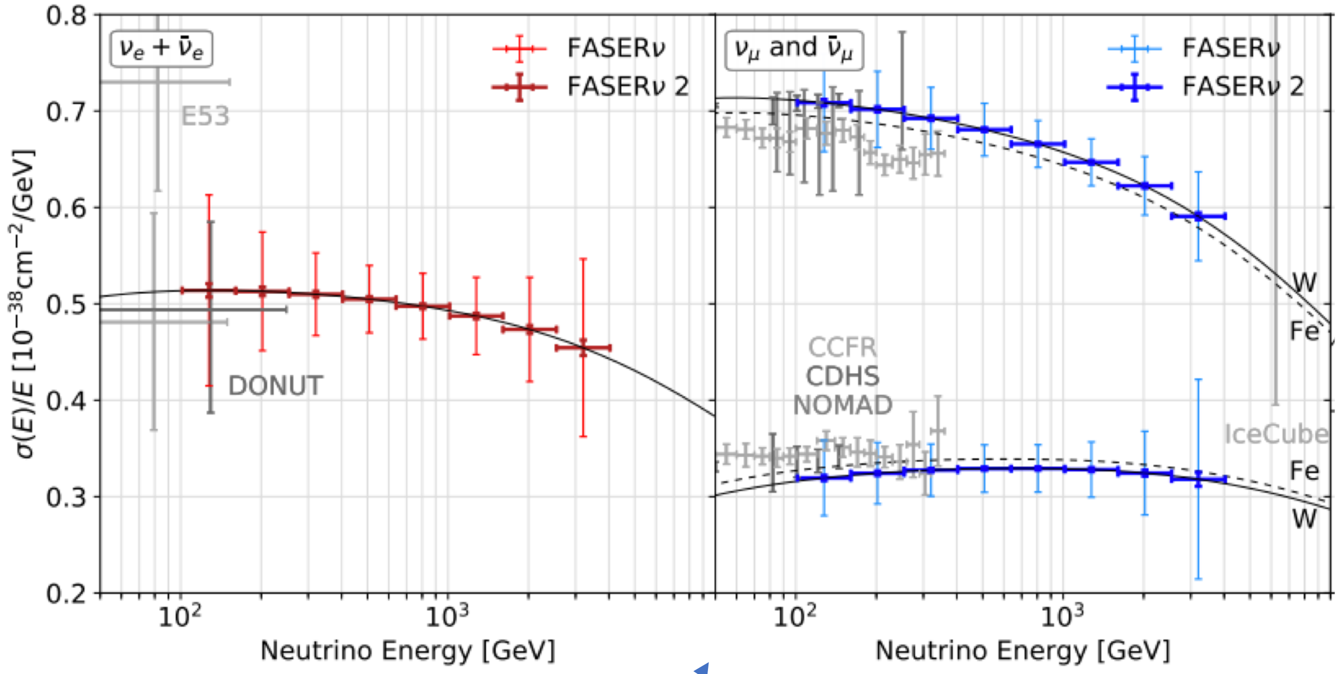
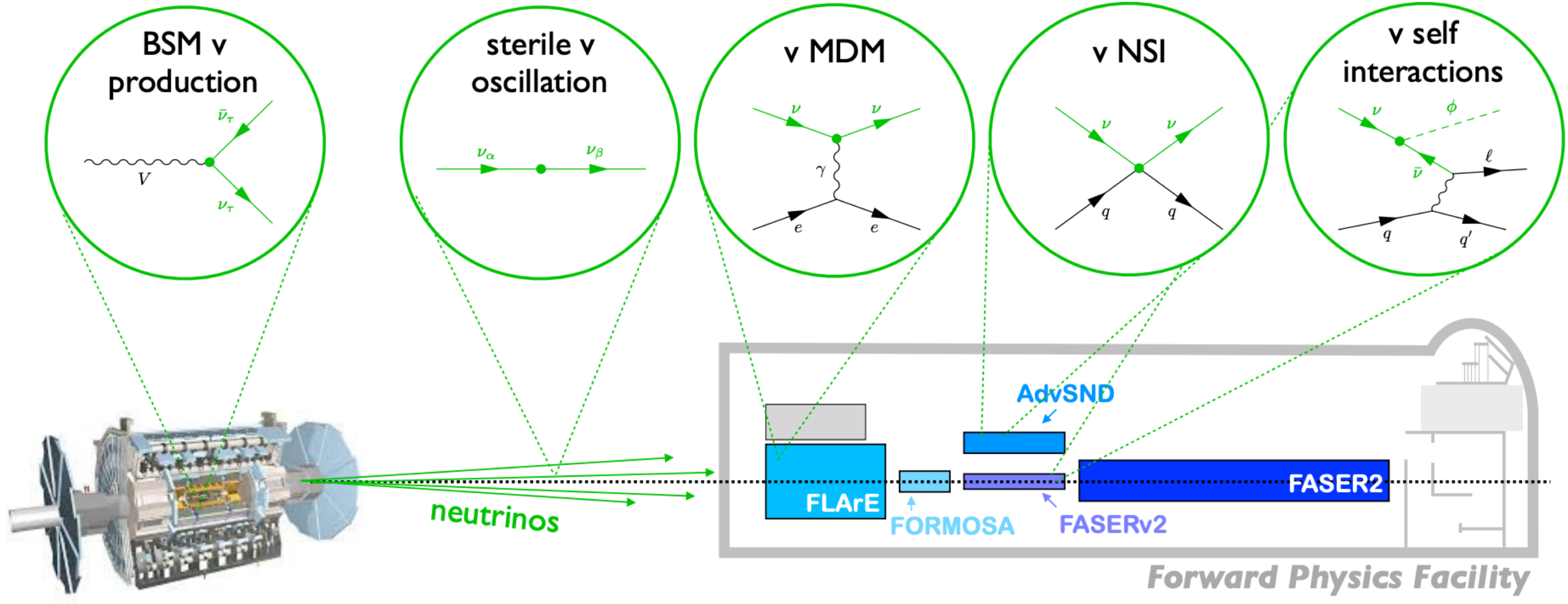


Other FPF neutrino physics, take advantage of the **huge ν_μ/ν_e datasets**, include:

- 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

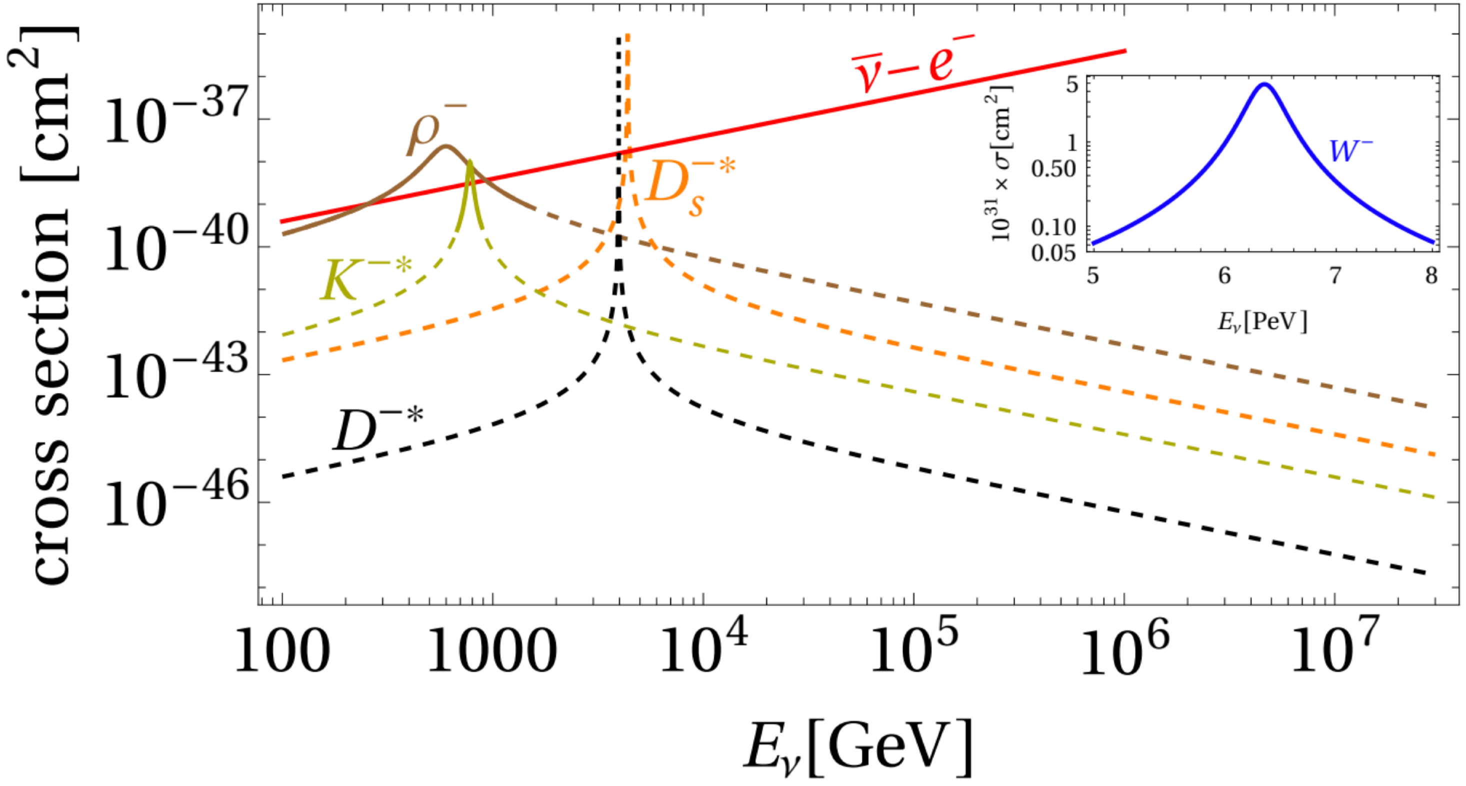
FPF neutrinos can be used to search for BSM effects, in production, propagation, and interactions:

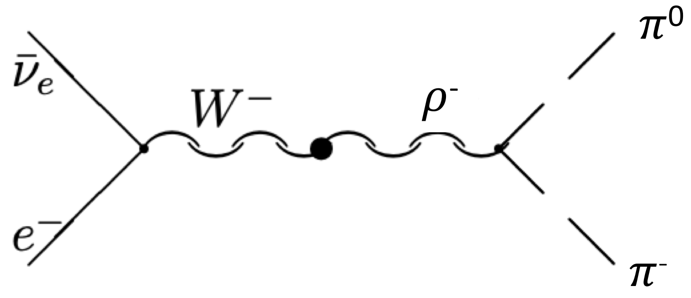


Neutrinos at the FPF

https://arxiv.org/abs/2112.03283

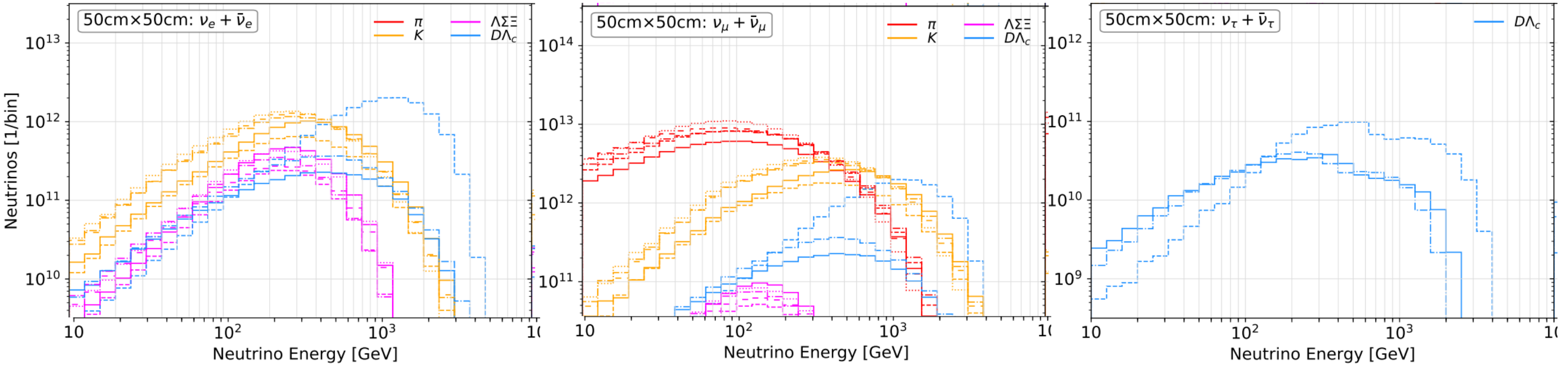
Can also look for electron-antineutrino – electron resonance production, TeV scale neutrinos at the FPF give access to resonances at the ~1 GeV scale.
cf. 6 PeV neutrinos at ICECUBE, sensitive to resonant W production (Glashow resonance) – 1 event observed in last year.
Recent paper suggests ρ^- production could be observed at FPF, with $\mathcal{O}(50)$ events in FPF experiments.
(ρ mass equivalent to neutrino energy of 580 GeV)





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
  - $\pi \to \nu\mu$, K $\to \nu_e$ (at high-energy/off-axis D $\to \nu_e$), D $\to \nu\tau$



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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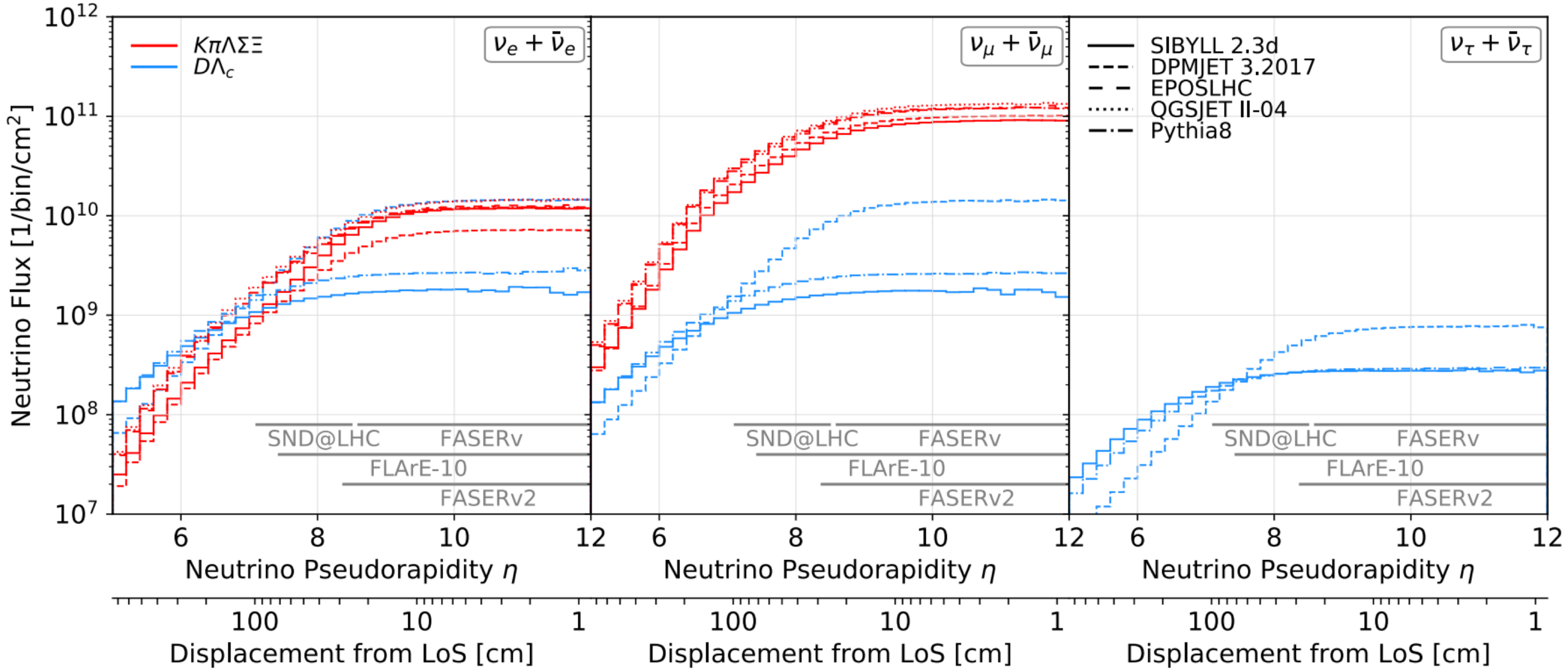
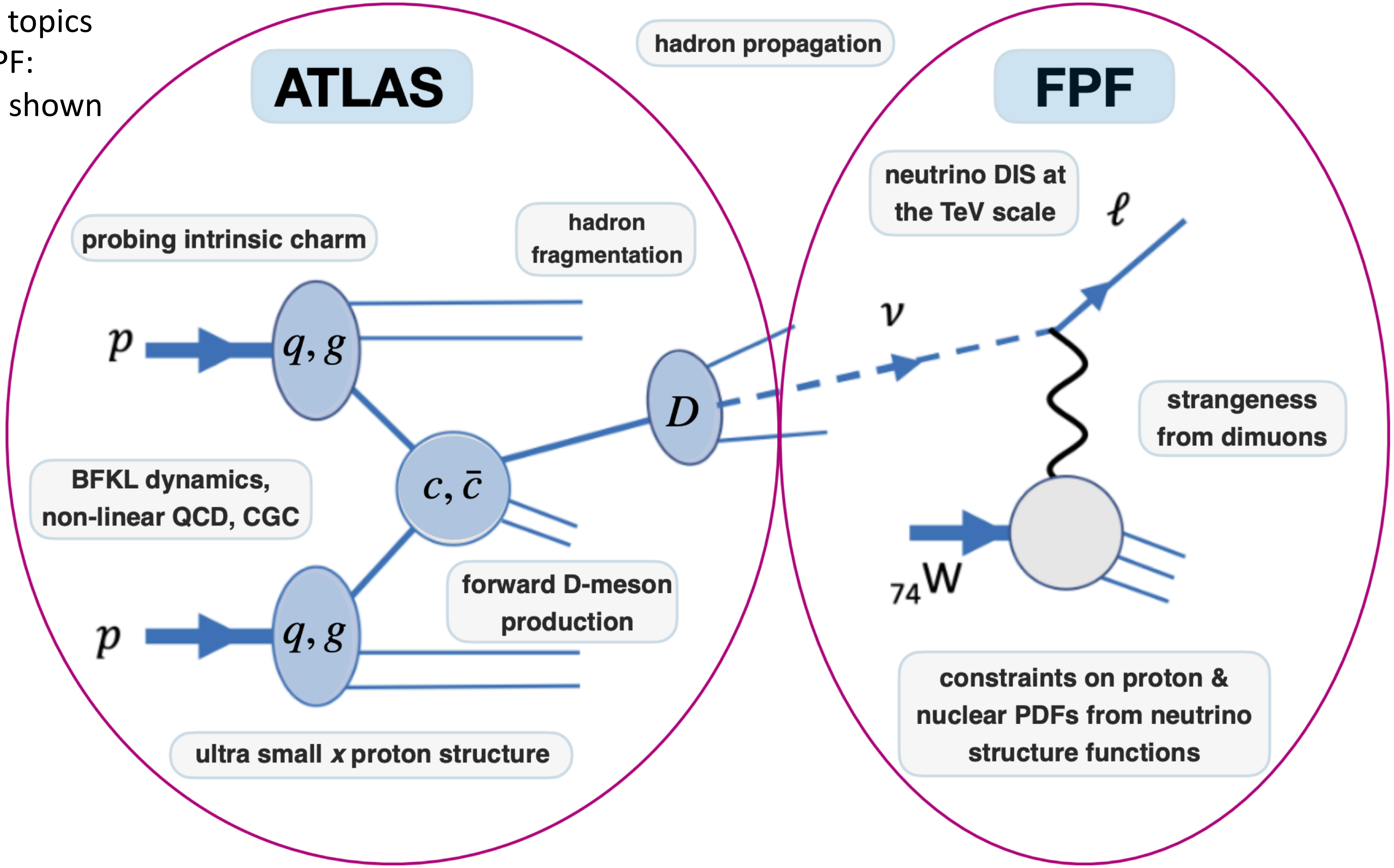


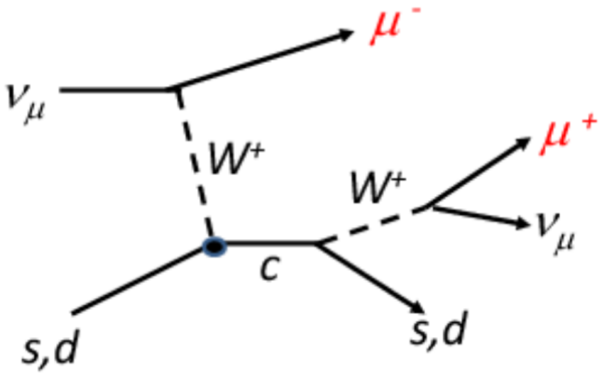
QCD at the FPF

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



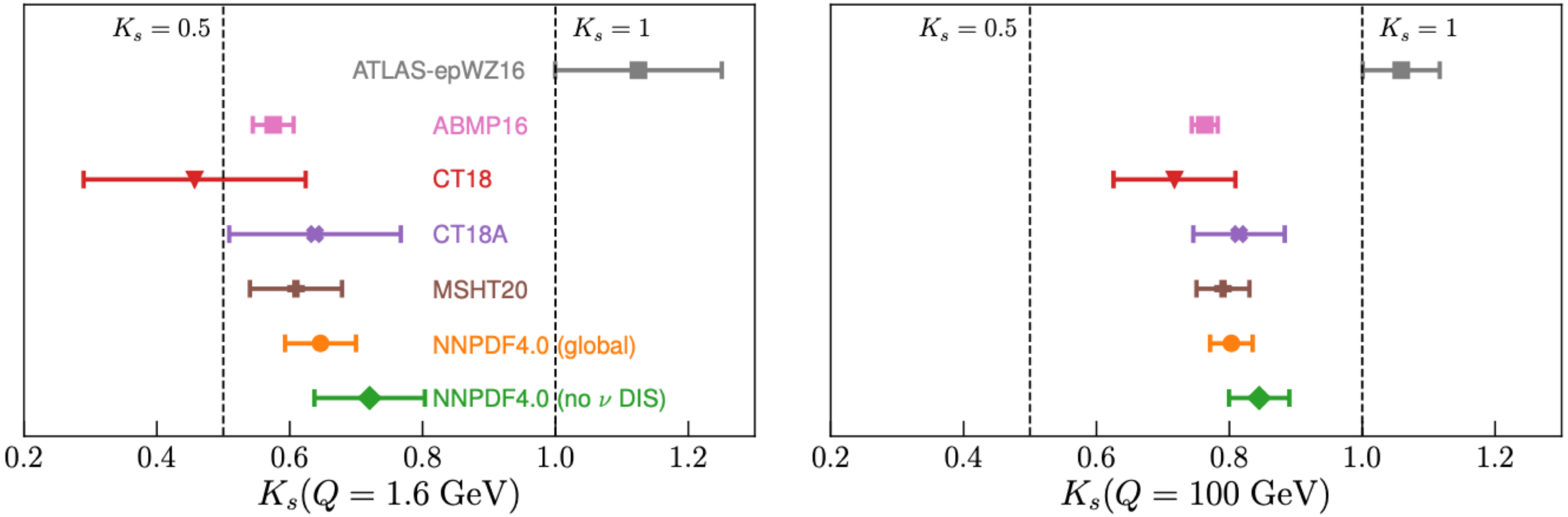
PDFs - strange

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:

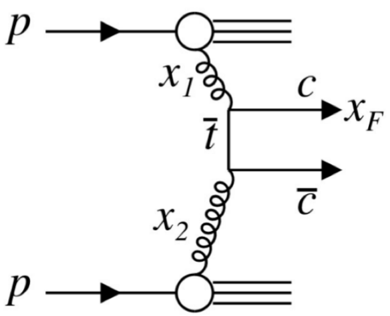


PDFs - gluon

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

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

Detecting at the FPF 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.



$x_1,\ x_2$:

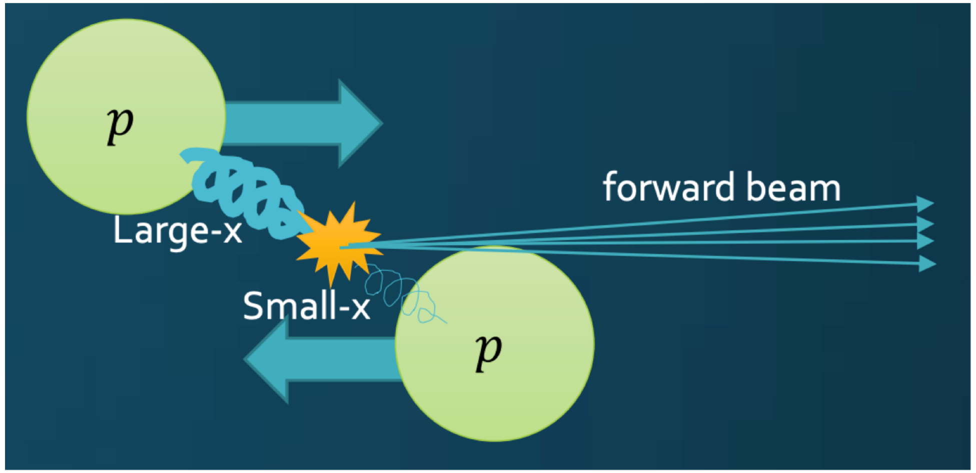
$$x_{1,2} = \frac{1}{2}\left(\sqrt{x_F^2 + \frac{4M_{c\bar{c}}}{s}} \pm x_F\right)$$

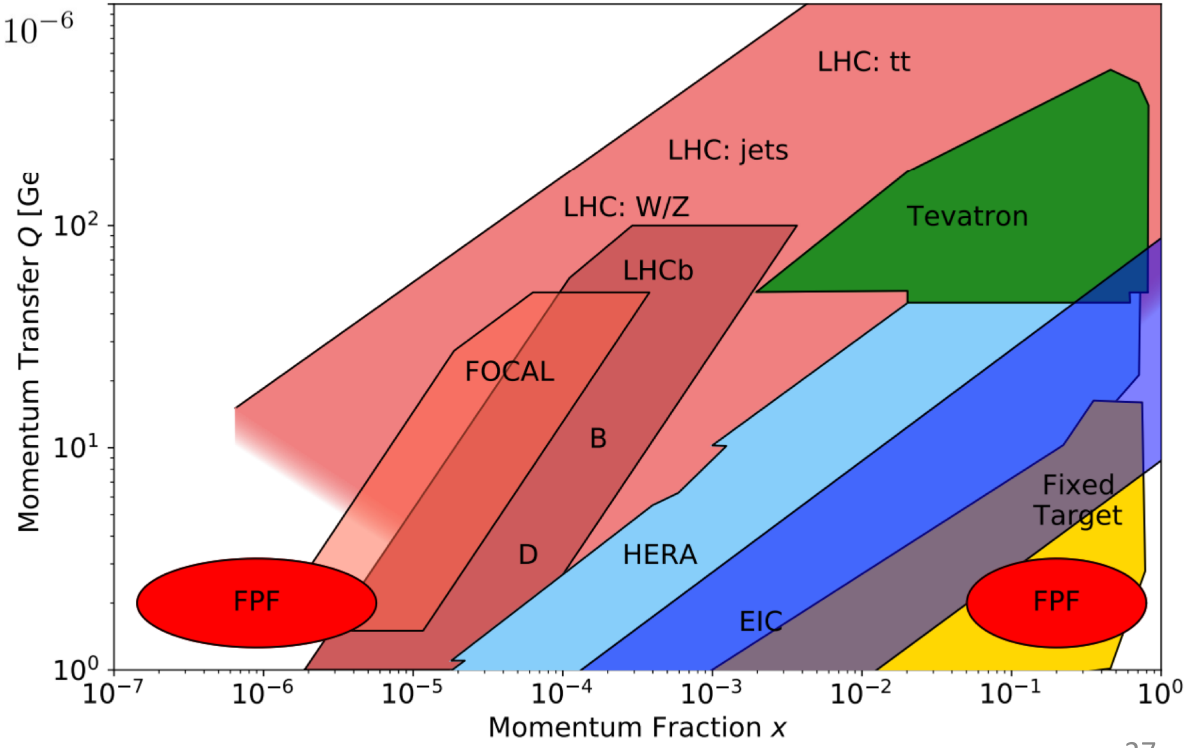
$$x_F = x_1 - x_2$$

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

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

Taken from: A. Bhattacharya

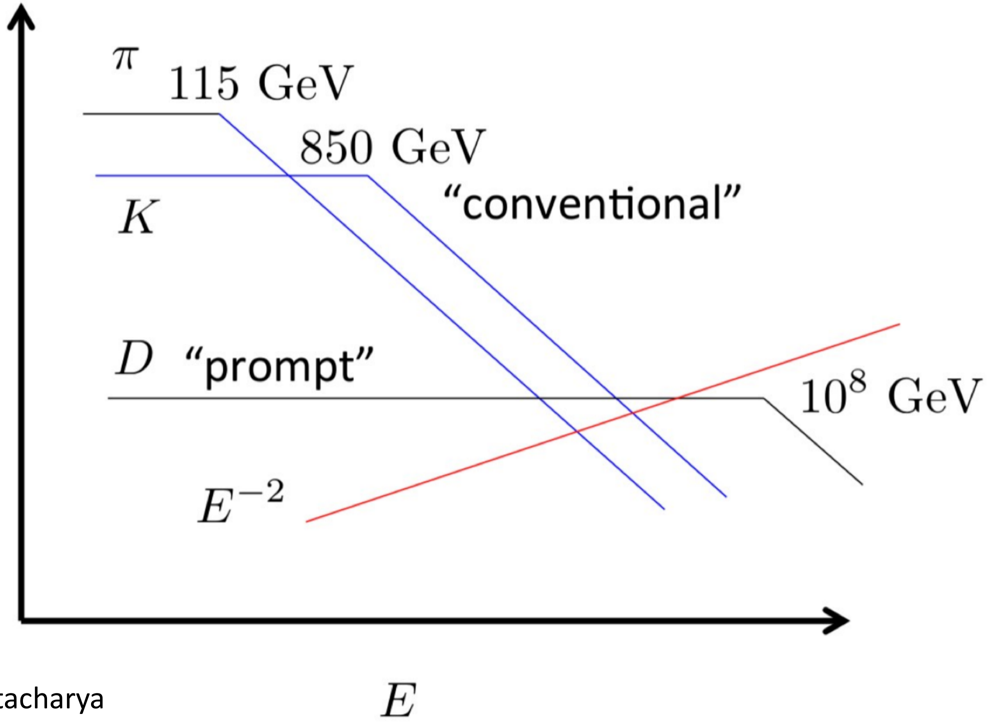




Input for astroparticle experiments

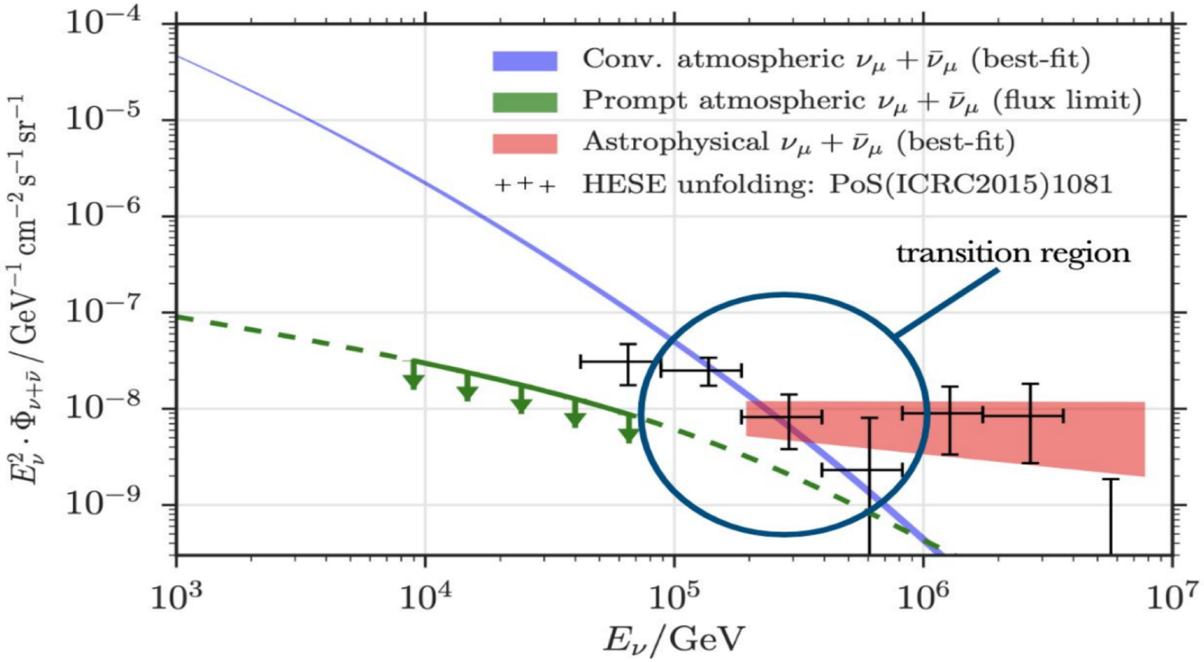
Studies of high-energy astrophysical neutrinos with large-scale neutrino telescopes (e.g. IceCube), suffer from backgrounds from atmospheric neutrinos from charm-decay (charm produced in hadronic shower initiated by cosmic rays hitting the atmosphere).
At ultra high-energy light hadrons travel far through the atmosphere, losing energy, and therefore 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



Input for astroparticle experiments

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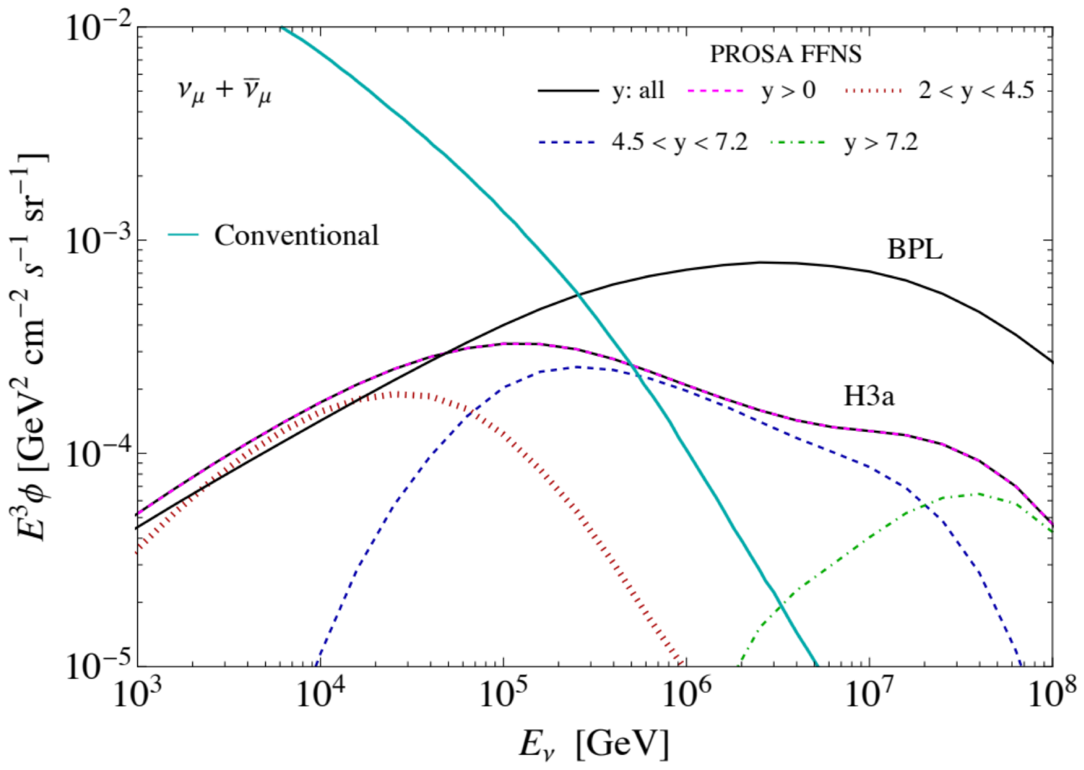

Figure shows what is the relevant rapidity range of LHC charm measurements to correspond to the IceCube neutrino energy:
Rapidity regions 4.5<y<7.2 and y>7.2 both (currently unexplored) in relevant energy range.

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!

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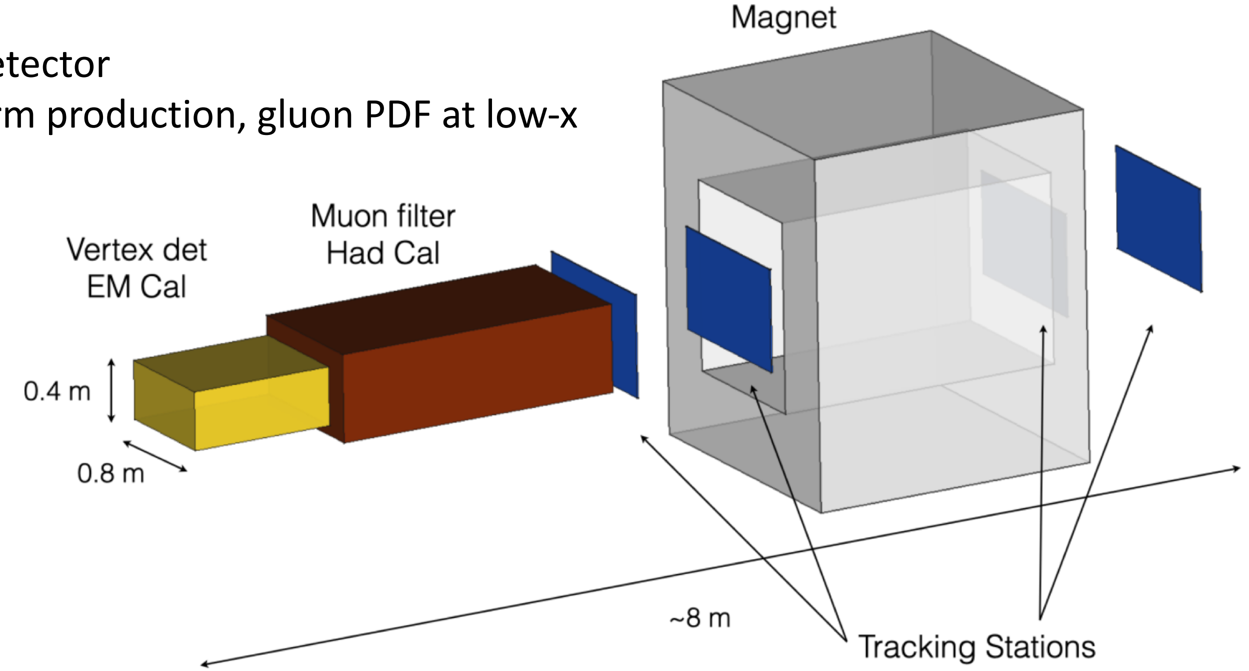
Given my knowledge and interest I will give more details on FASER2 and FASERnu2.

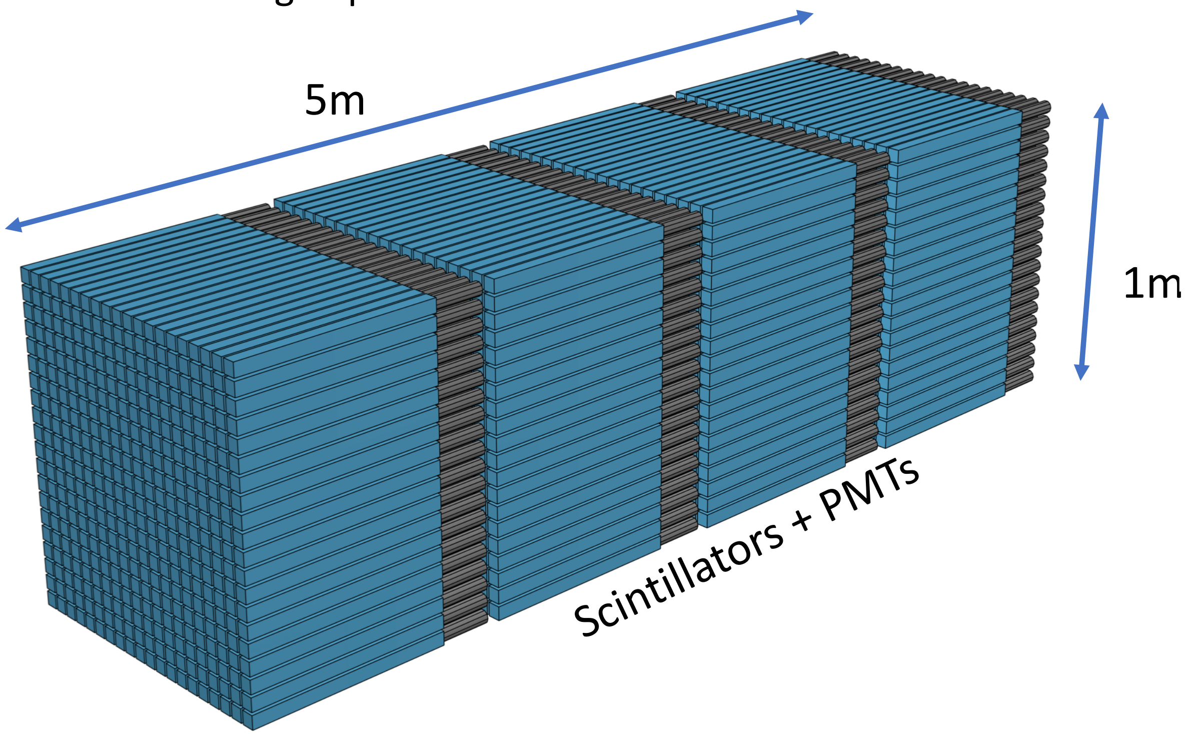
No detailed design for any of these experiments yet!

Currently proposed FPF experiments

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



FORMOSA:
For milicharged particles



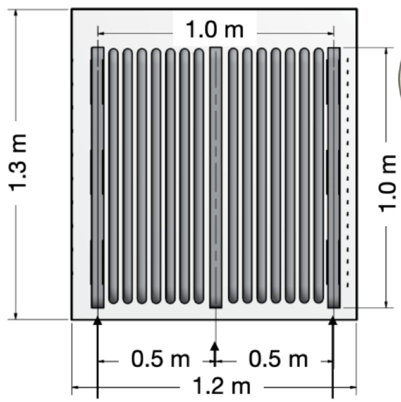
FLArE: LAr TPC detector

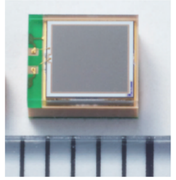
Proposed LAr TPC for DM scattering and neutrino physics: $\mathcal{O}(10\text{tn})$ fiducial target mass.
Cryostat and cryogenics discussed with protoDune experts at CERN (see backup). Detector design studies ongoing at BNL.
FLArE is the FPF detector which needs the most novel design and drives much of FPF services/infrastructure and safety needs!

Brookhaven National Laboratory

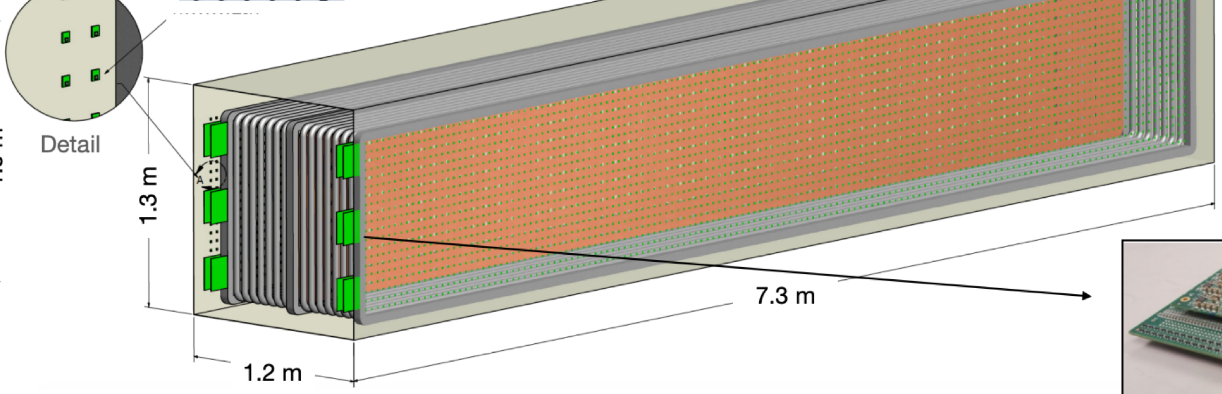
FLArE Detector Preliminary Sketch

TPC-side view 2

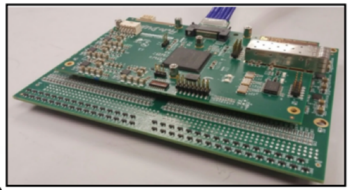




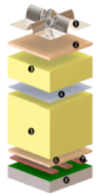
Hamamatsu
S14160 SiPM
6x6 mm
2800 units



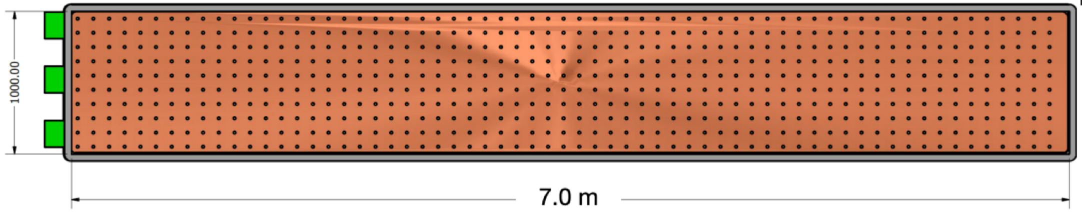
Volume	11.5 m^3
LAr	16 ton
LKr	27.5 ton
menbran	0.5 m
heat loss	290 W



DUNE Front End Motherboard



Cryostat Insulation



TPC anode plane -side view 1

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 at CERN (see backup). Detector design studies ongoing at BNL.
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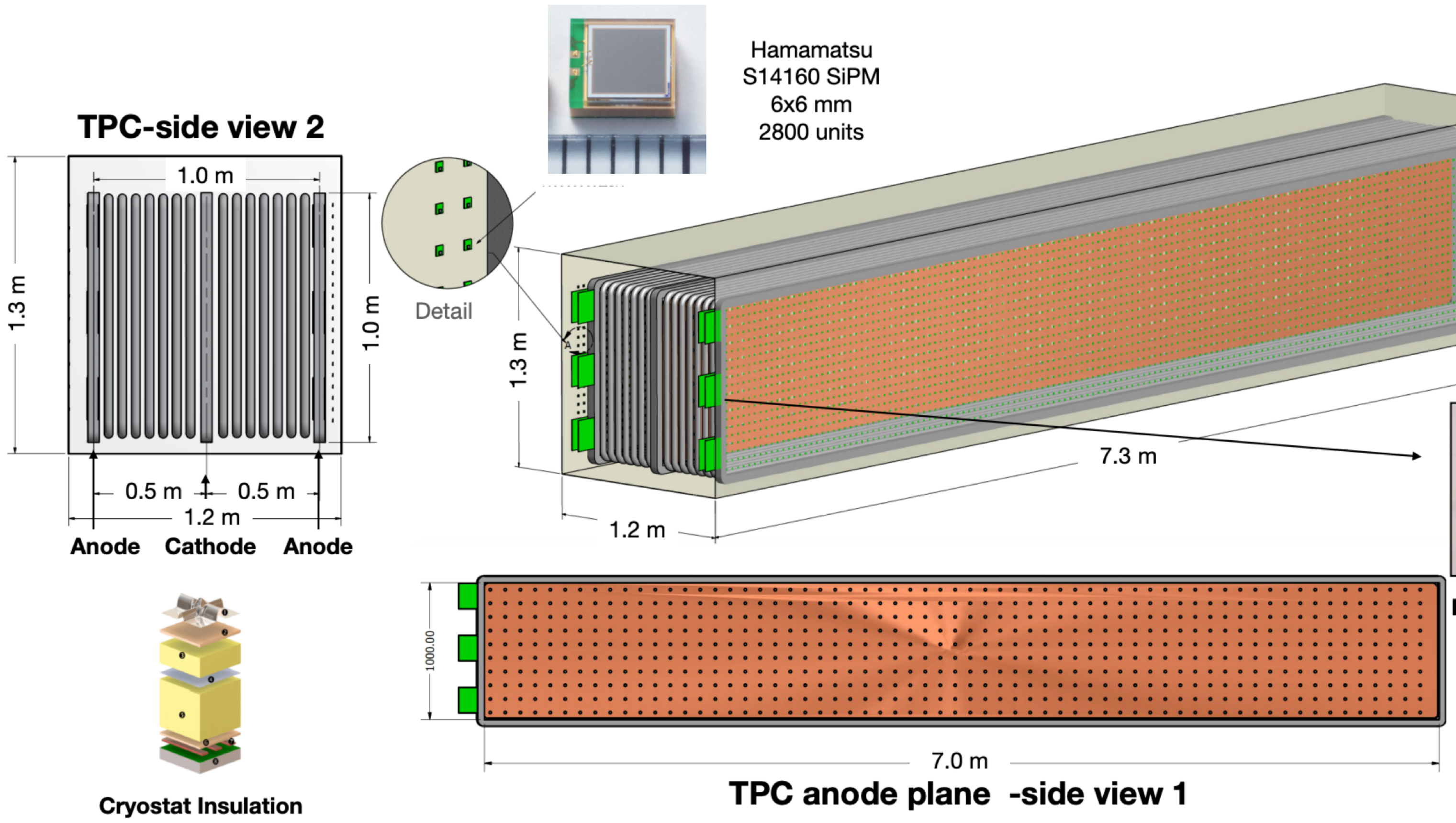
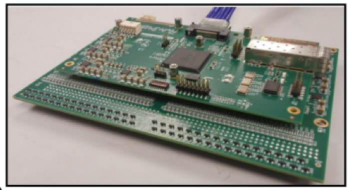
FLArE Detector Preliminary Sketch

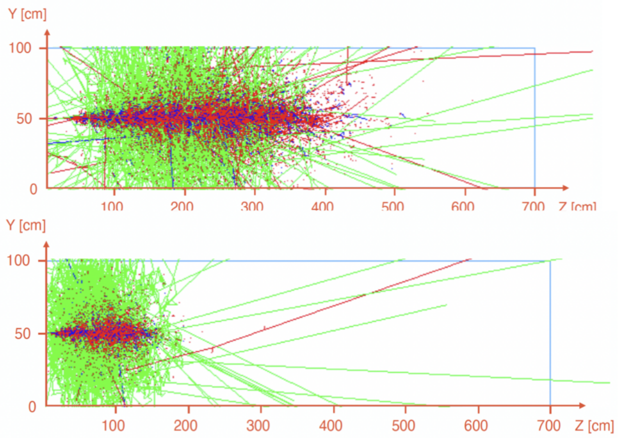




DUNE Front End Motherboard

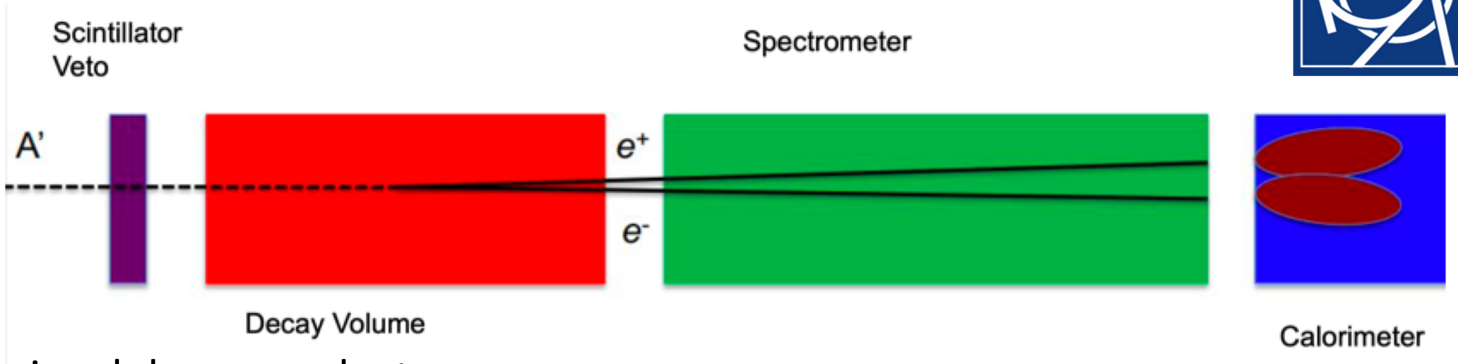
Volume	11.5 m^3
LAr	16 ton
LKr	27.5 ton
menbran	0.5 m
heat loss	290 W

Recent development:
Considering LKr as well as LAr – better shower containment for high energy showers.
Example from simulated 1 TeV electron shower in LAr and LKr



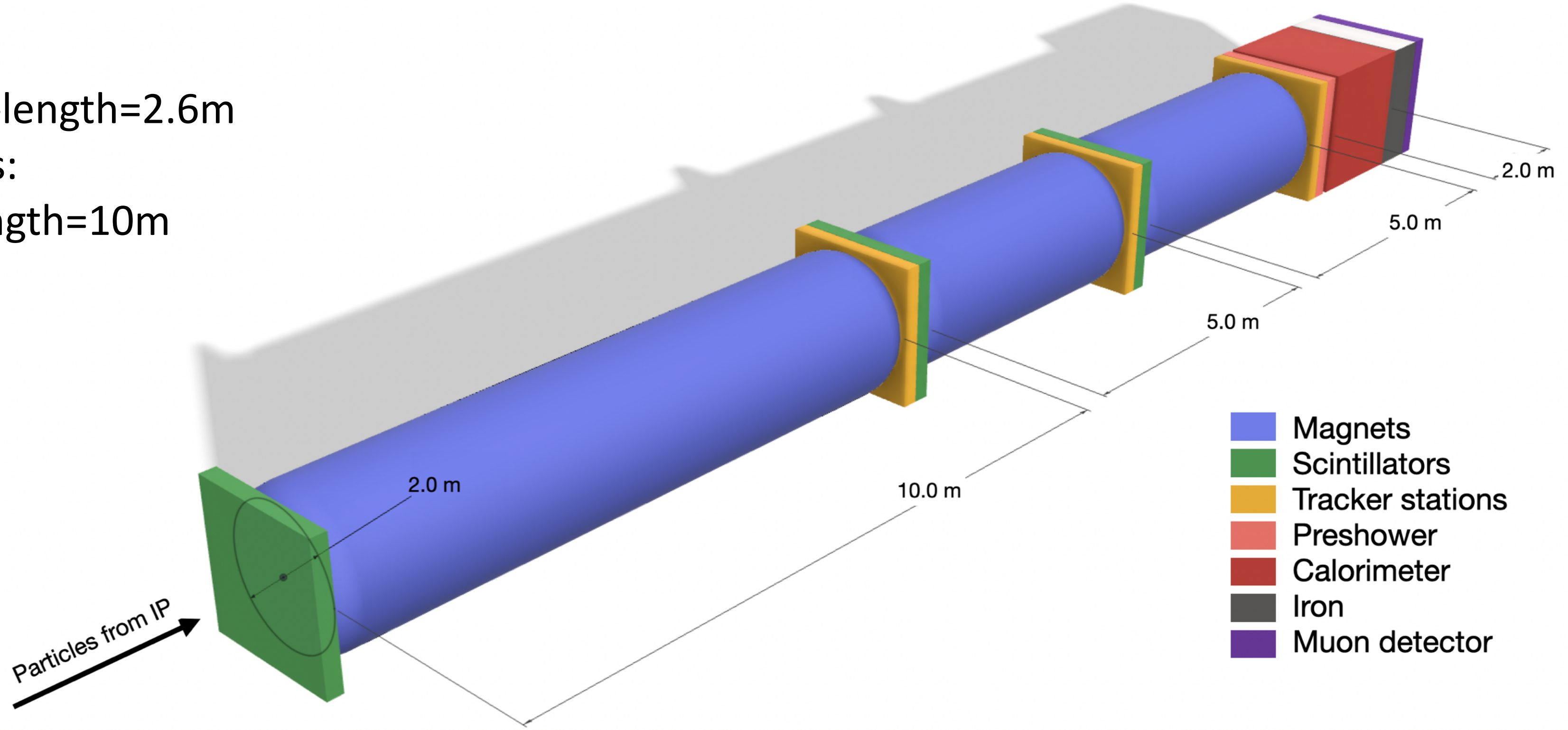
FASER2

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



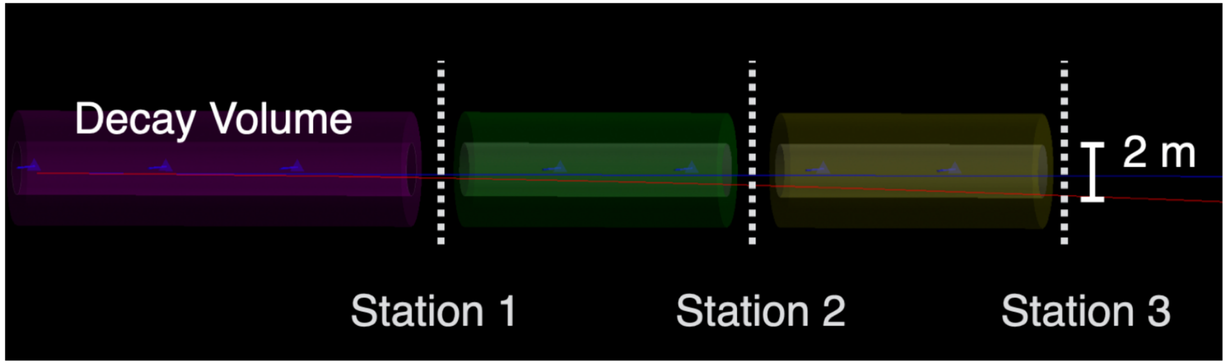
FASER2

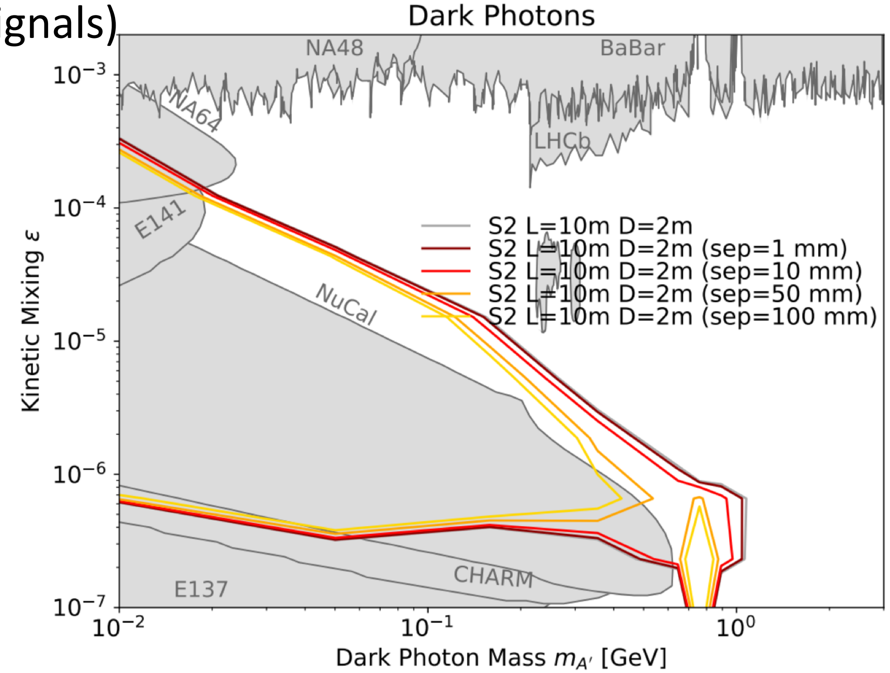
Huge ($\mathcal{O}(100)$) increase in instrumented area, and magnetic field volume. Can not use same detector design/technology as FASER.

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

- Magnetic field strength, and volume
  - Likely untilize superconducting magnet technology
- 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:

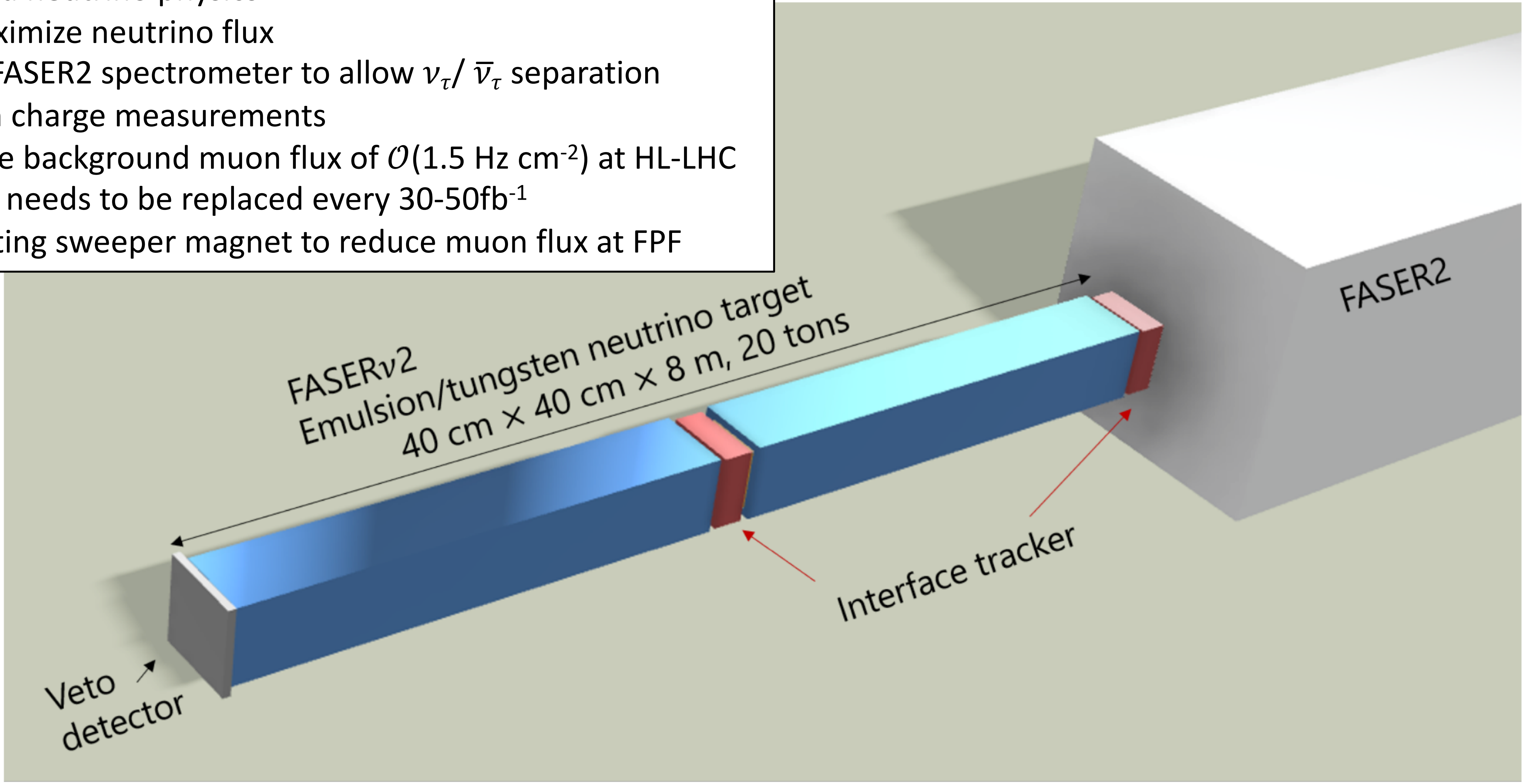




Example study looking at dark-photon sensitivity for different requirements on the separation of the 2 tracks at the 1st tracking station.

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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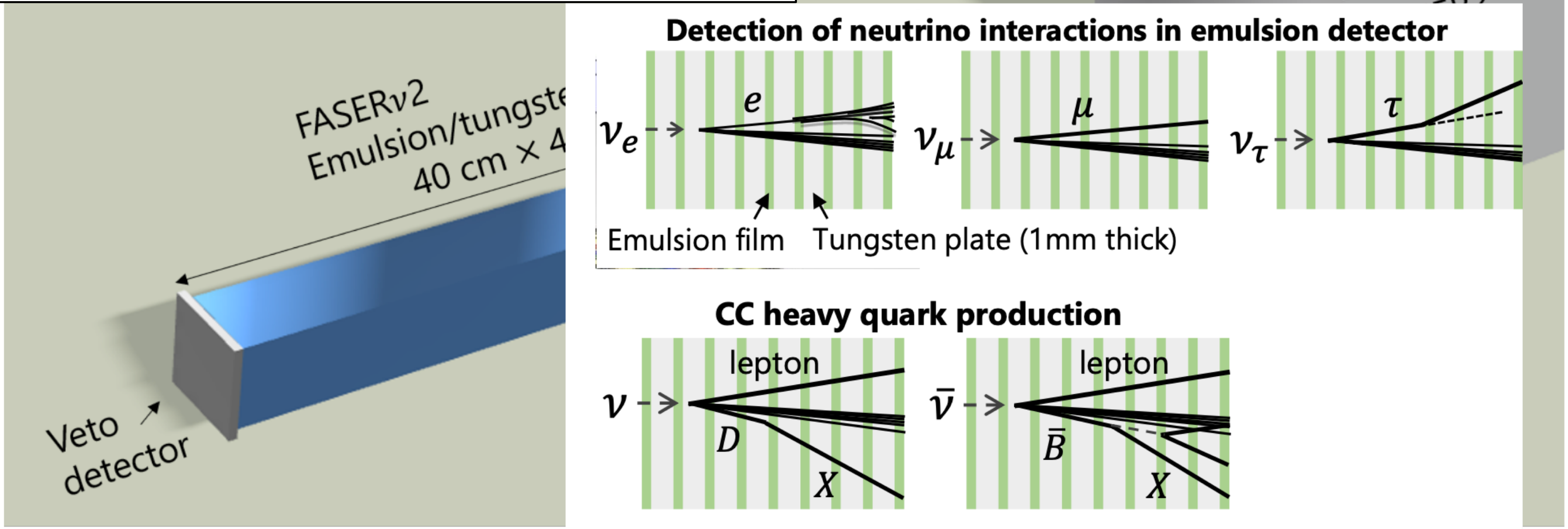
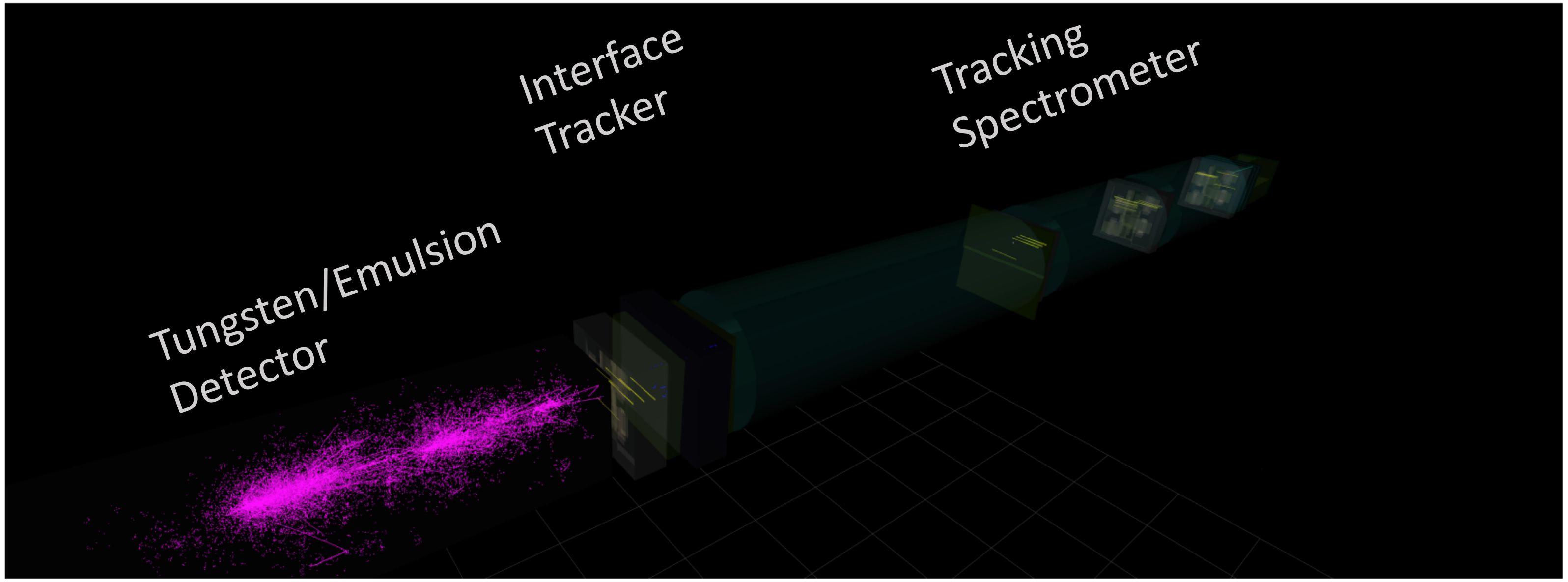
Emulsion detector resolution: ~$0.4\mu m$, 0.1mrad

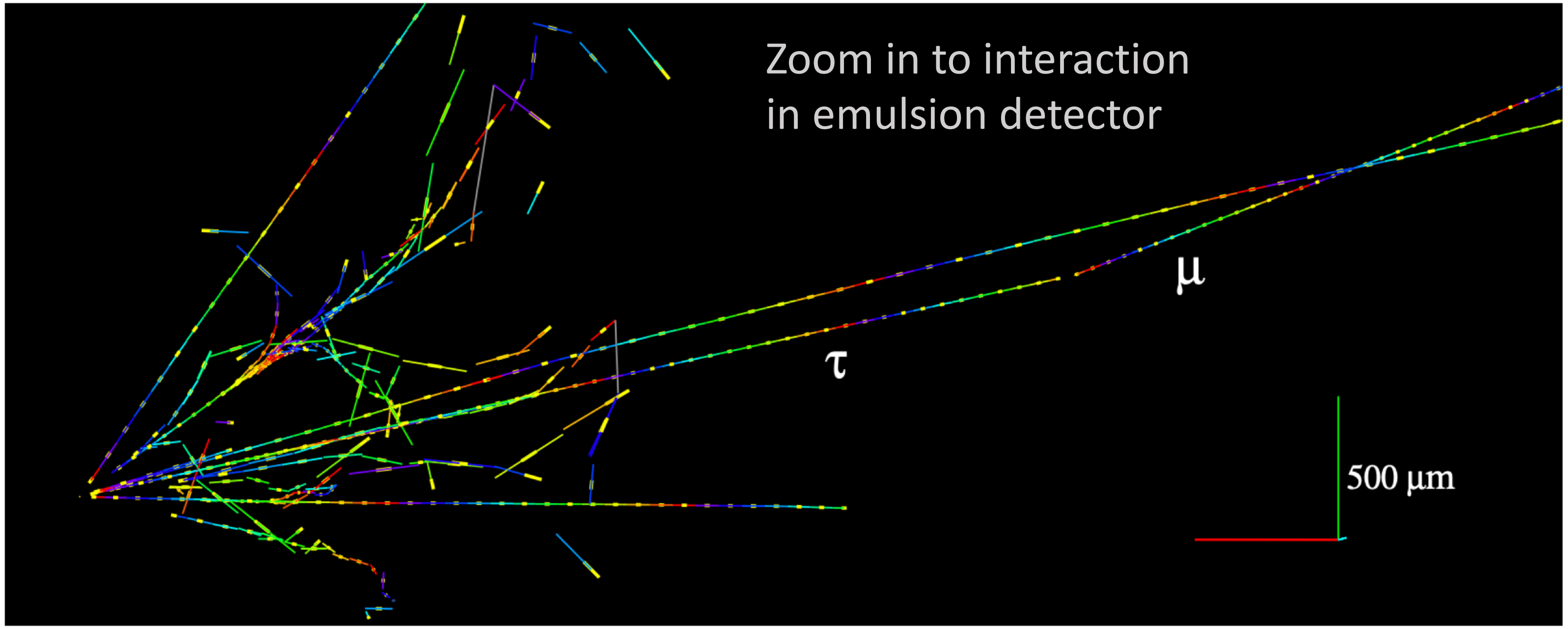


FASERnu2

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

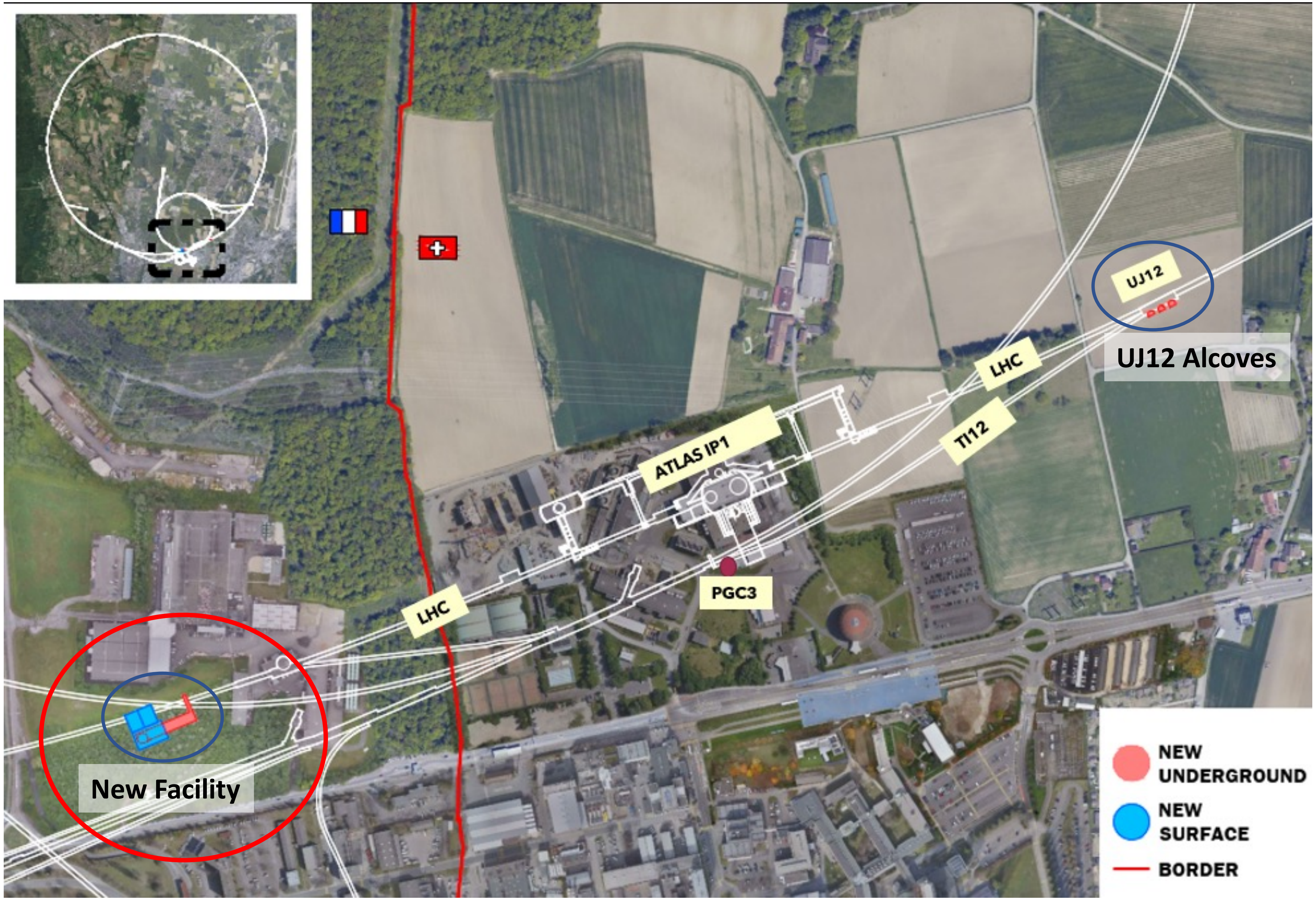
FASER2 tracker/magnet design, essential for FASERnu2 physics!





The Facility

After several studies by CERN civil engineering team, the baseline option is a dedicated new facility ~600m from the ATLAS IP (to the west).



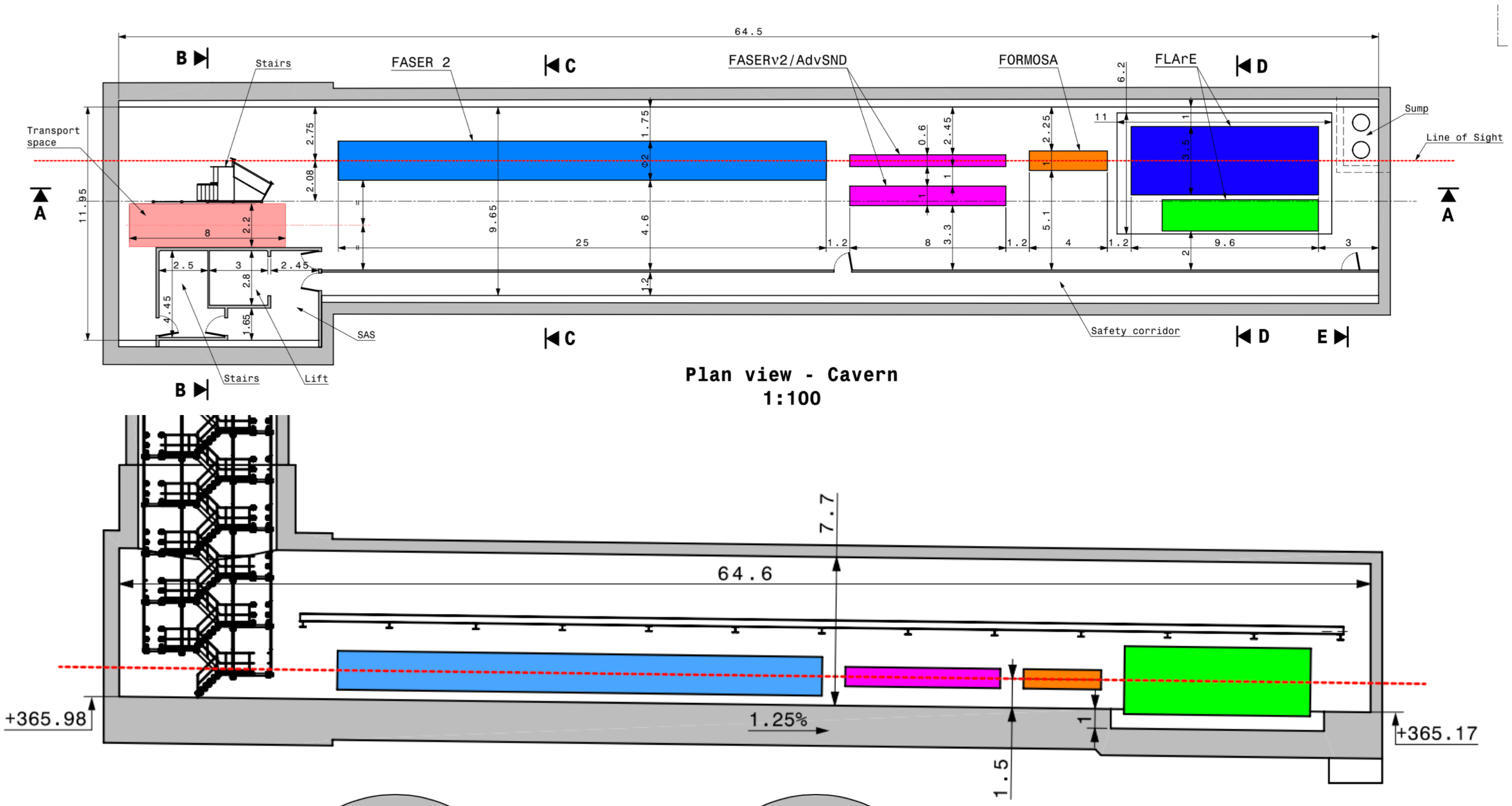
Alcoves in UJ12 cavern considered as an alternative option, but not retained – see backup for more details

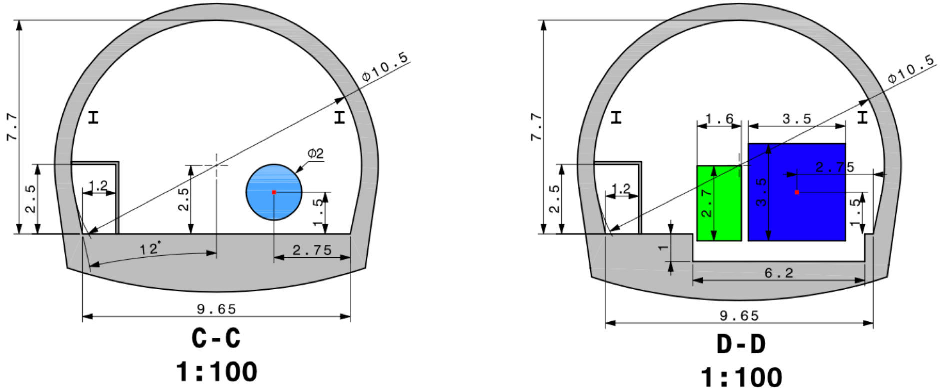
K. Balazs, J. Osborne, J. Gall - CERN SCE

New Facility:

65m long, 8m wide/high cavern

Connected to surface through 88m high shaft (9.1m diameter): 617m from IP1.





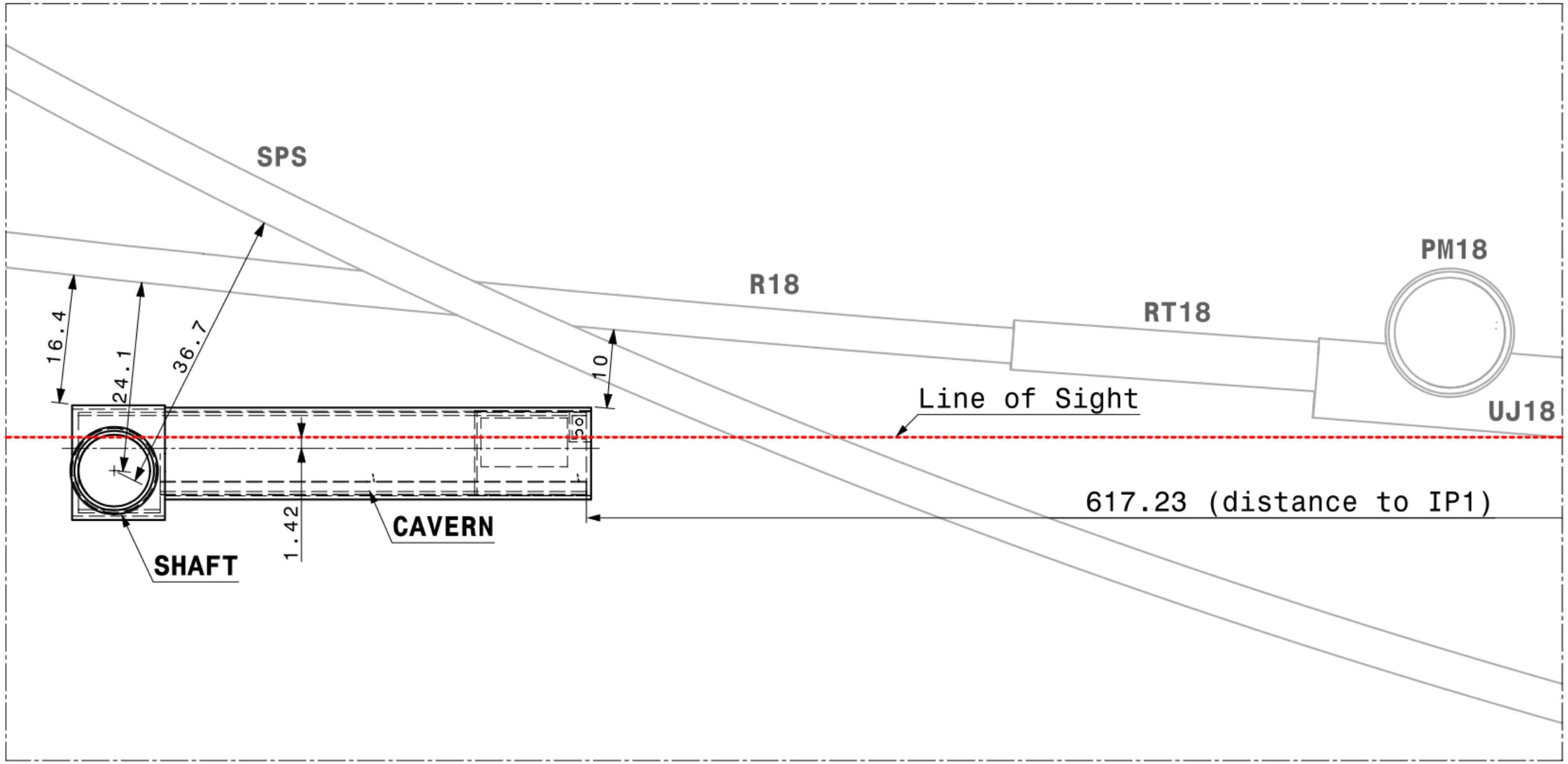
K. Balazs, J. Osborne
CERN SCE

New 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.



K. Balazs, J. Osborne
CERN SCE

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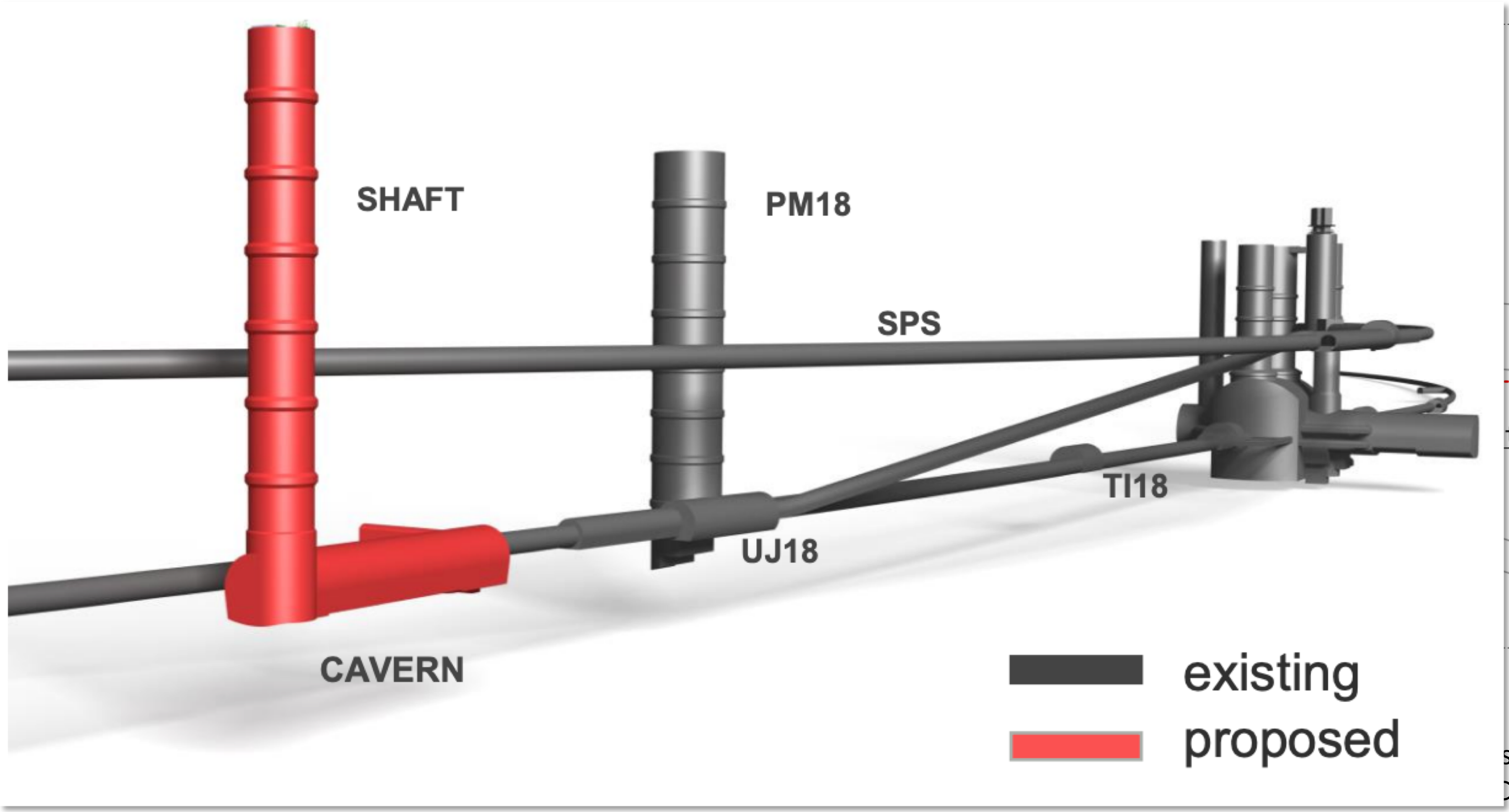
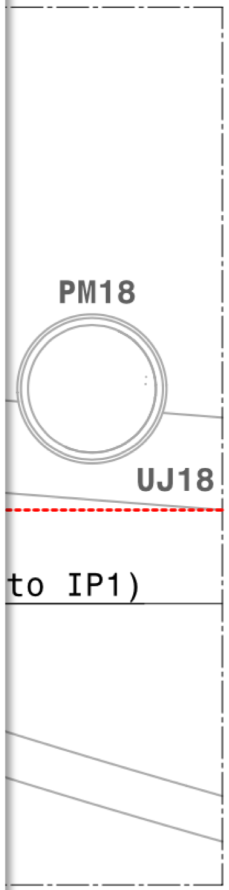
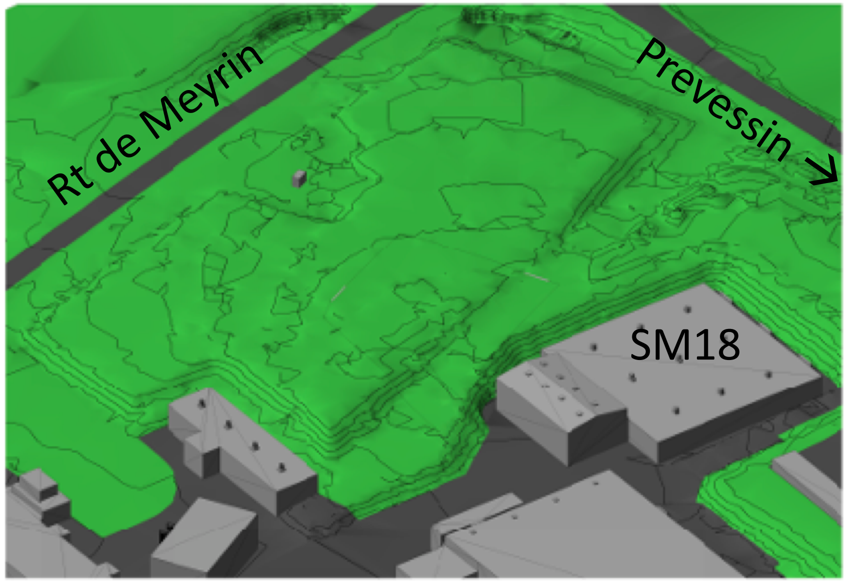




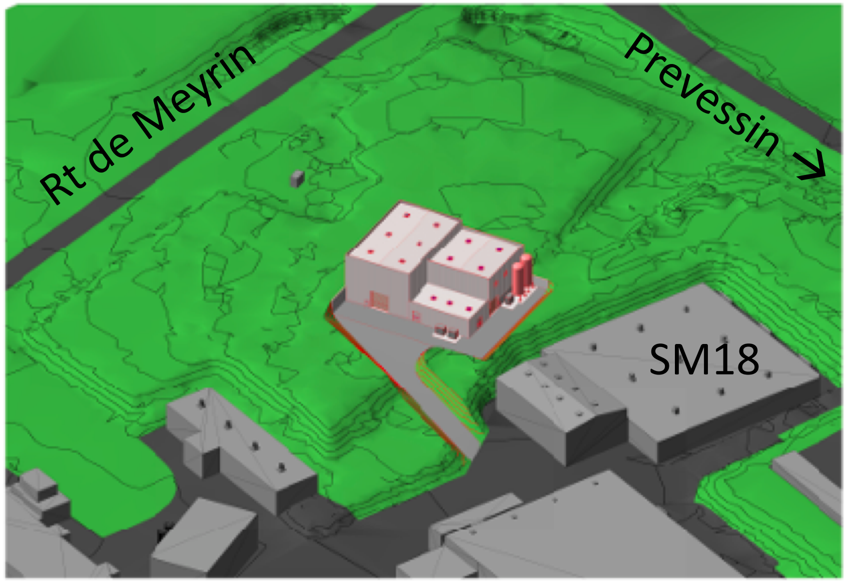
s, J. Osborne
CE

New Cavern: Surface works

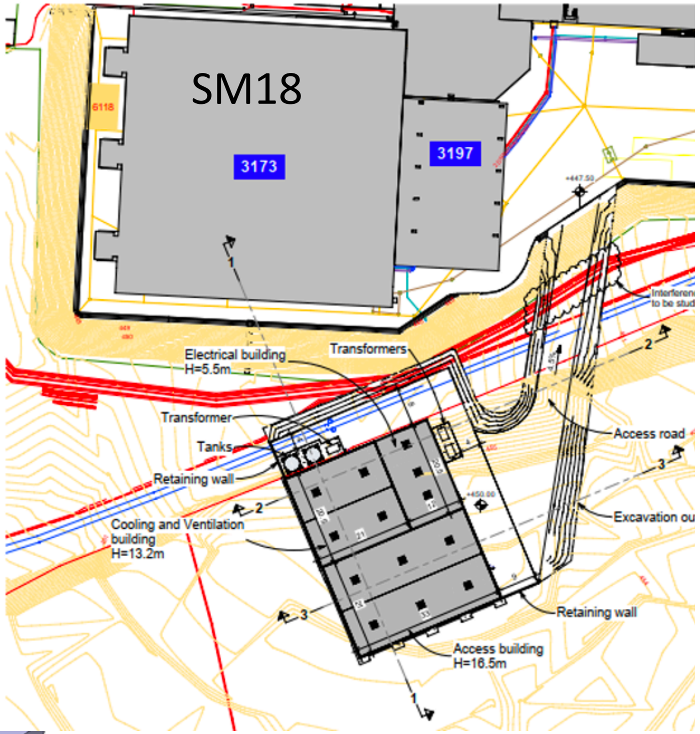
K. Balazs, J. Osborne

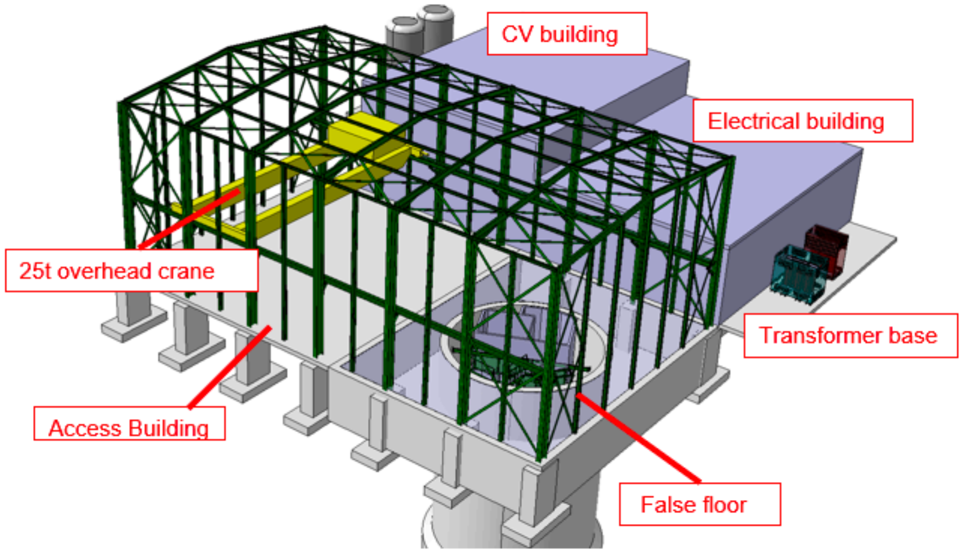


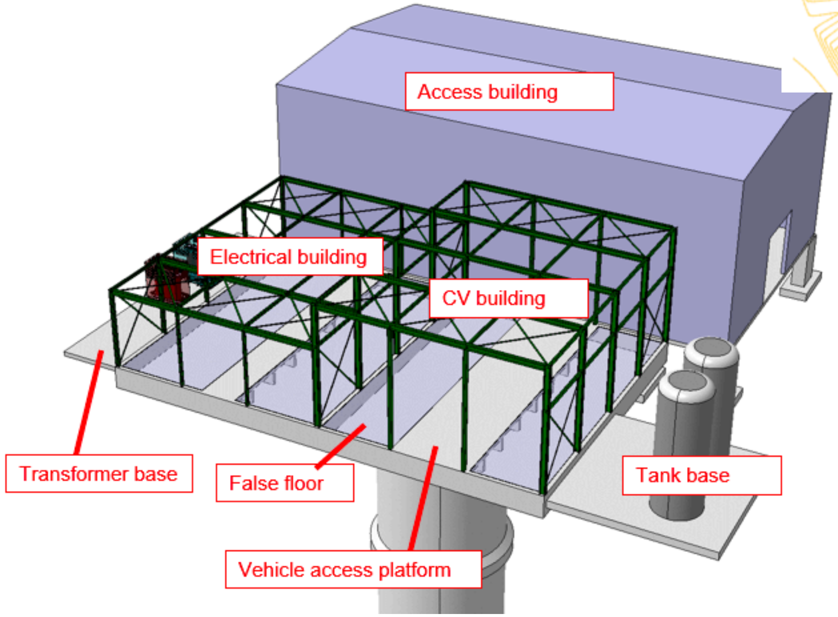
3D EXISTING



3D NEW

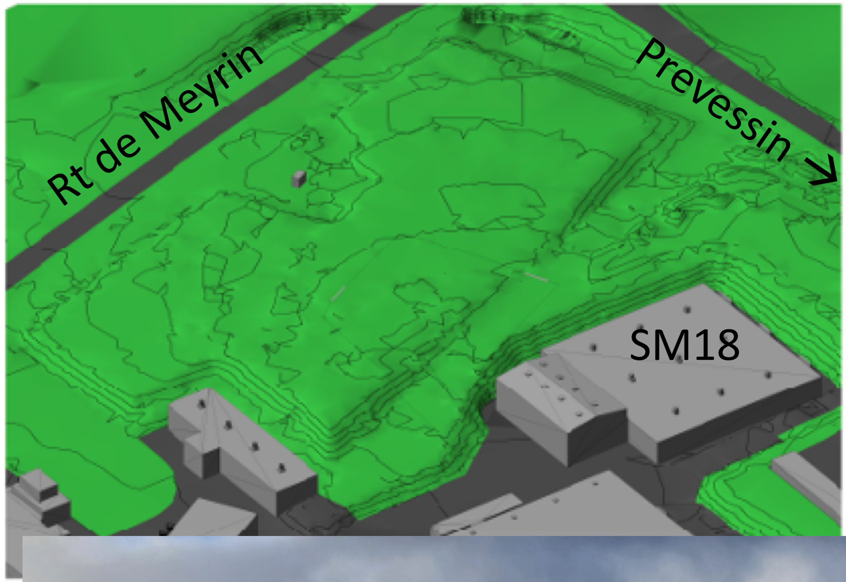


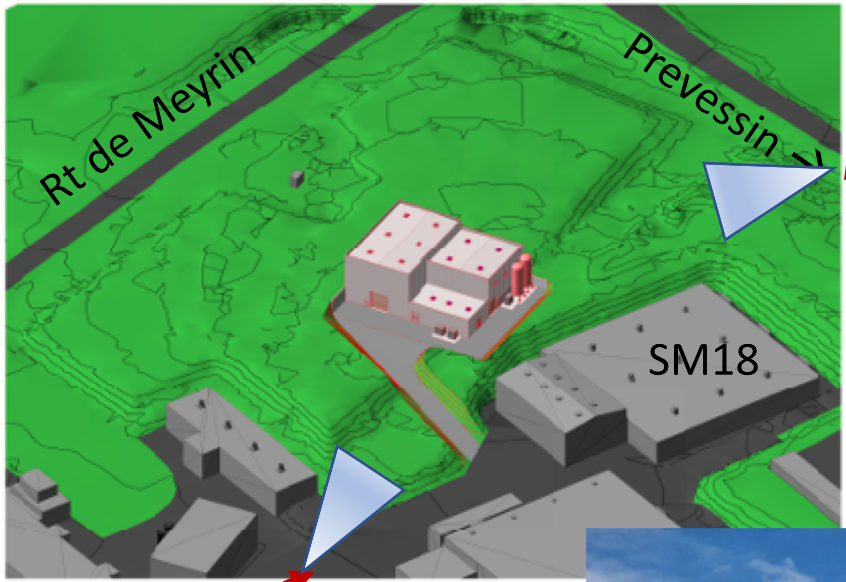




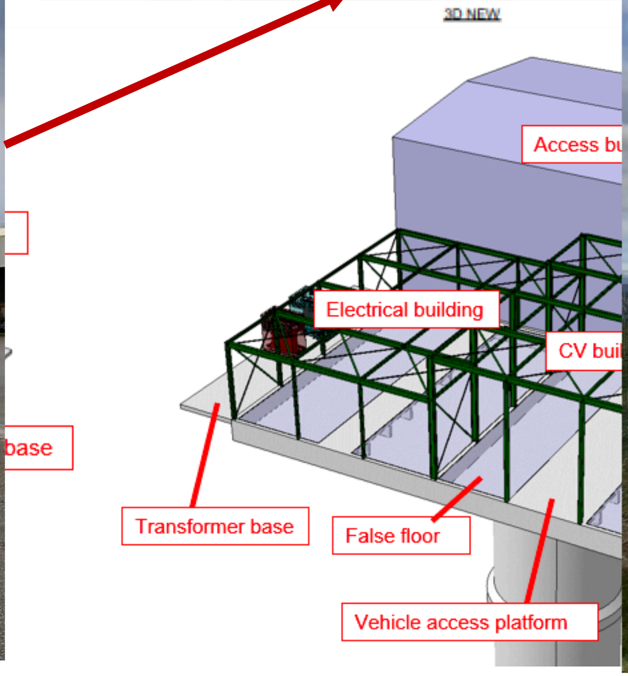
K. Balazs, J. Osborne

New Cavern: Surface works





Photos of the current situation



EN-EL, EN-CV, EN-AA, EN-HE
CERN groups

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**

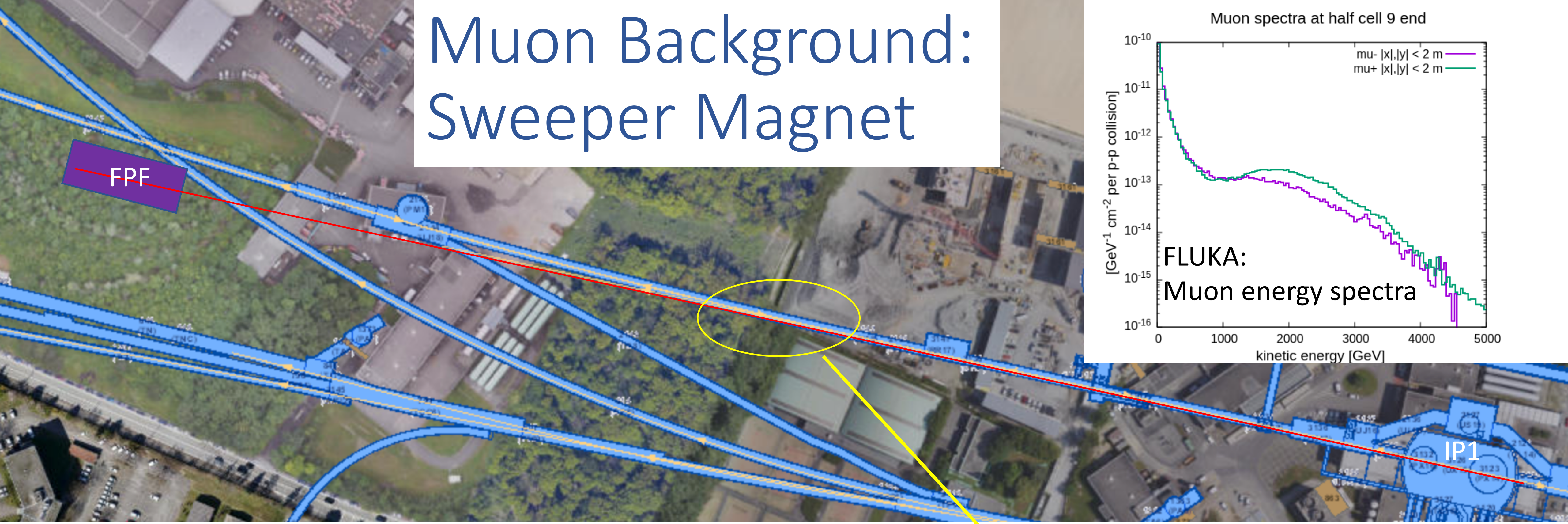
Round up to 15MCHF to account for some missing items.

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**

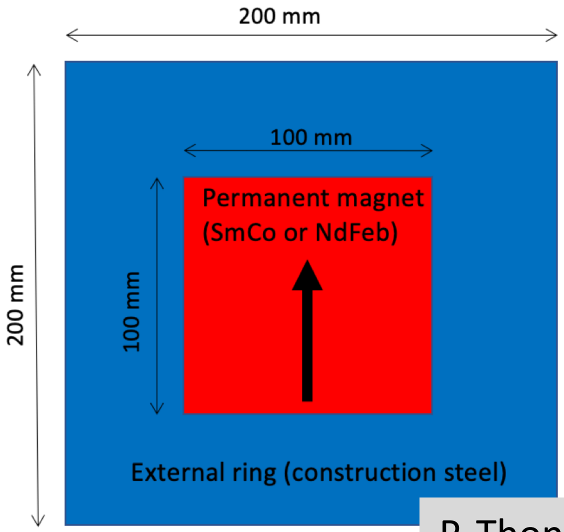
Muon Background: Sweeper Magnet



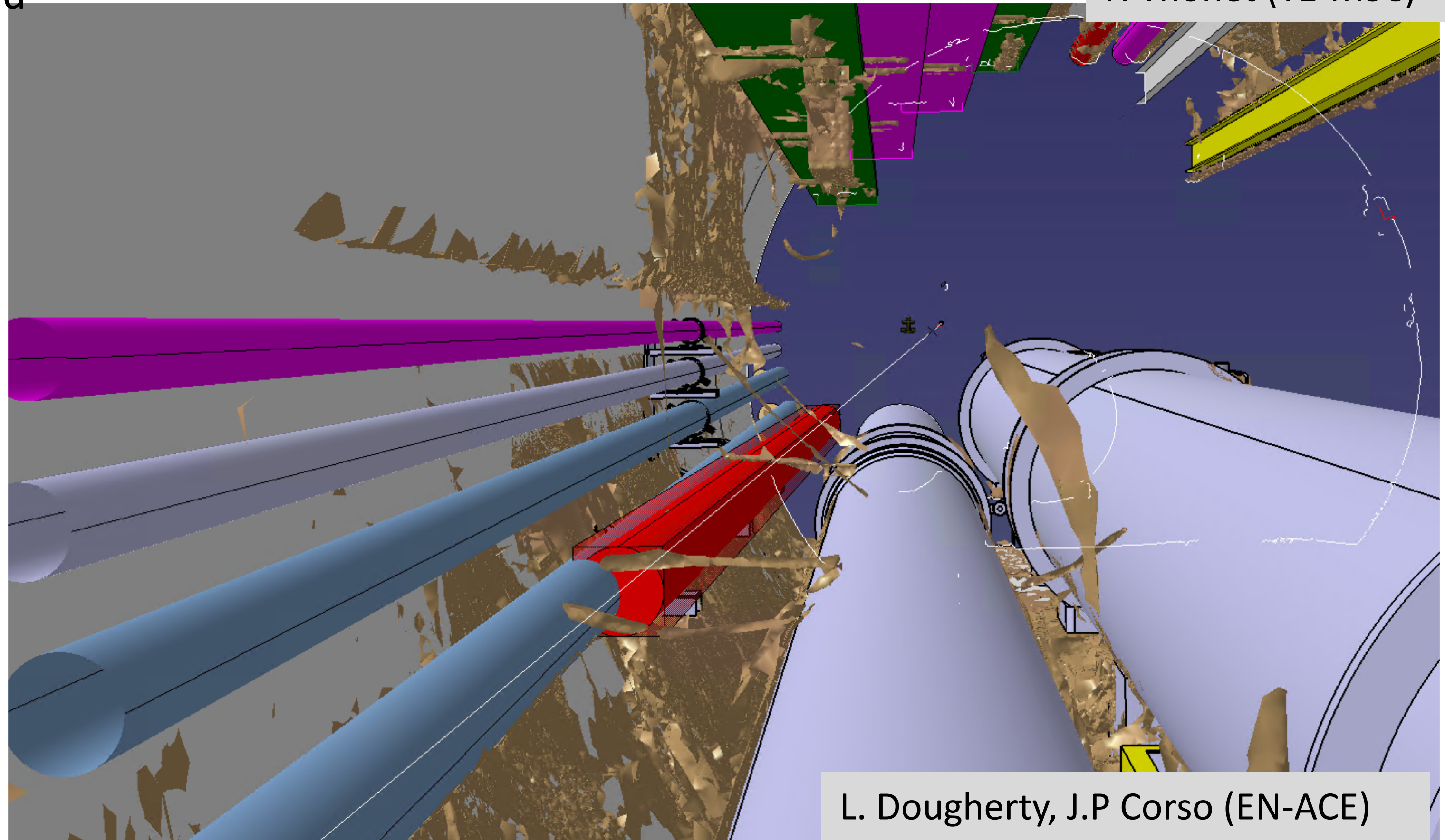
Background muons coming from IP1 collisions go through FPF (~1.5Hz/cm^2) on LOS, higher away from LOS.
Placing a sweeper magnet on the LOS can deflect these muons and reduce the background – which could be very important for physics - e.g. reducing the number of times emulsion would need to be replaced.
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).

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



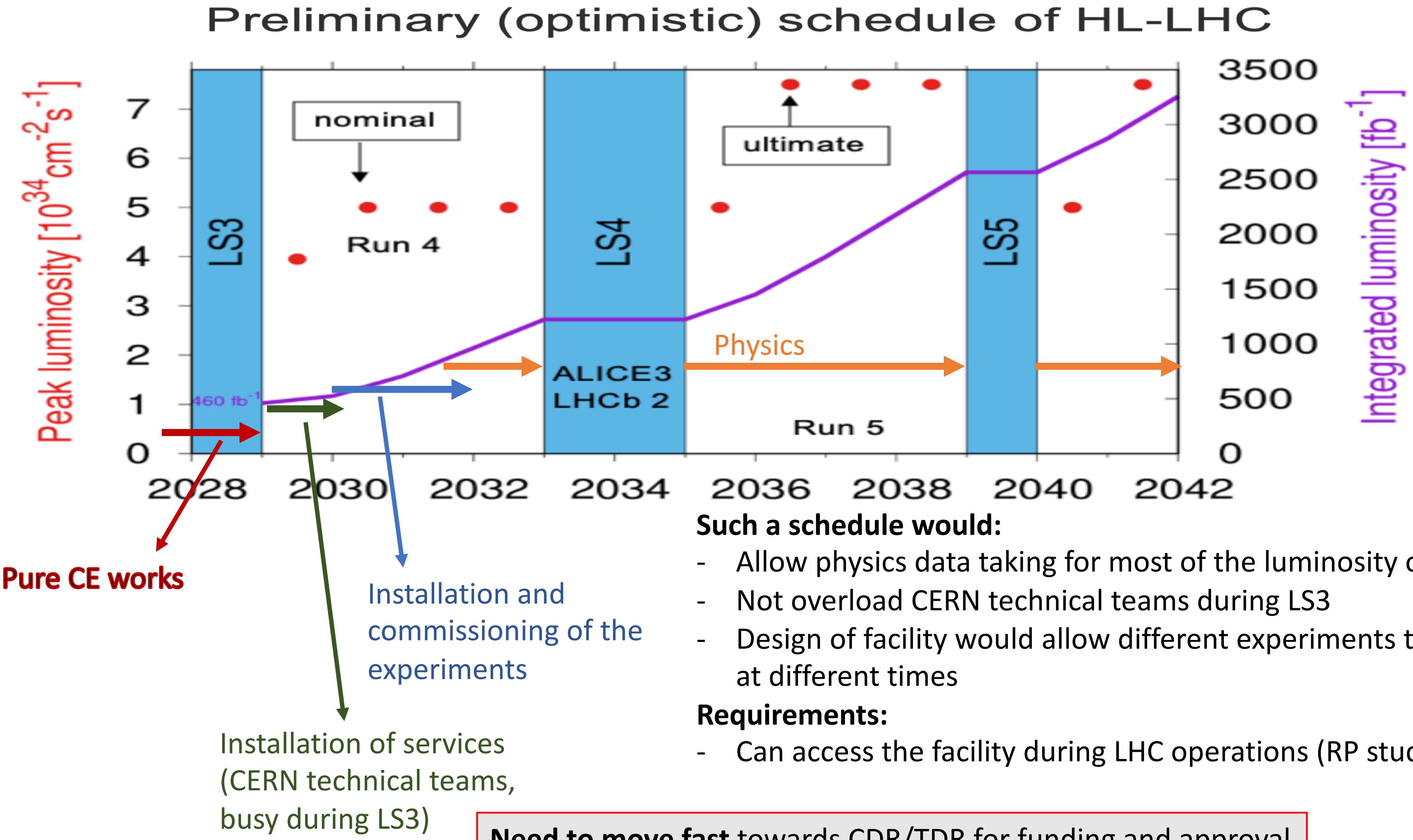
P. Thonet (TE-MSC)



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

Possible FPF schedule

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



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

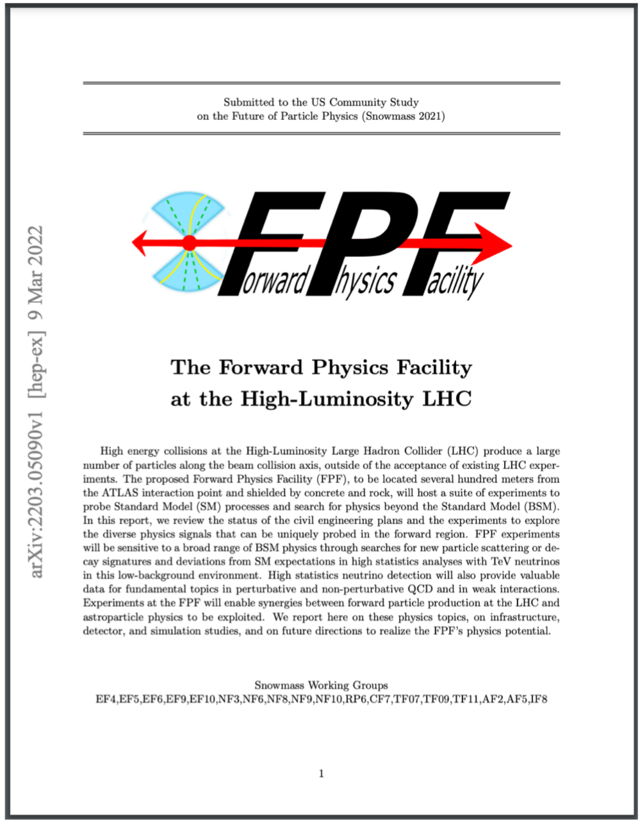
Requirements:

- Can access the facility during LHC operations (RP study ongoing)

Need to move fast towards CDR/TDR for funding and approval

FPF workshops & papers

- There have been four FPF workshops over the last year
  - https://indico.cern.ch/category/14436/
  - Mostly reporting progress on theory level physics studies for FPF, and evolution of the physics case
- The FPF is being actively discussed in many of the different tracks in the US Snowmass process, with significant interest expressed by the community
- As part of this process two papers have been released, with a 3rd long paper in preparation:
  - https://zenodo.org/record/4009641 Letter of Interest (signed by ~300 people)
  - https://arxiv.org/pdf/2109.10905.pdf ("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
- 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


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

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

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

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Physics Beyond Colliders

Snowmass 2021

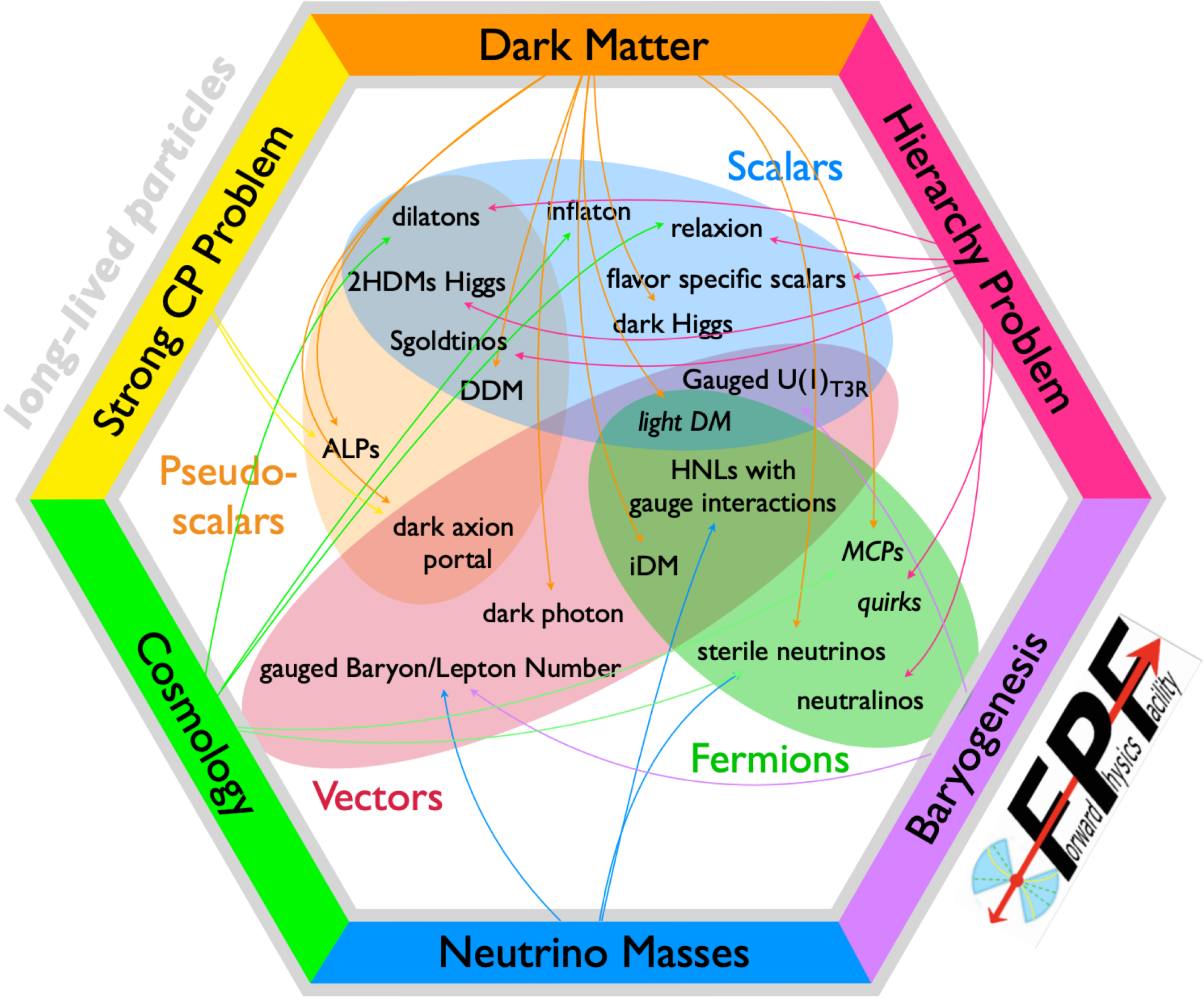
Summary

- The FPF is a proposed facility to house several BSM and neutrino experiments on the IP1 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 is a 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
- Great progress on FPF studies in last year, but lots 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)

Backup…


Dark Matter
Hierarchy Problem
Baryogenesis
Neutrino Masses
Cosmology
Strong CP Problem
long-lived particles
Scalars
dilatons
inflaton
relaxion
2HDMs Higgs
flavor specific scalars
dark Higgs
Sgoldtinos
DDM
Gauged U(1)T3R
light DM
ALPs
Pseudo-scalars
HNLs with gauge interactions
dark axion portal
iDM
MCPs
quirks
dark photon
sterile neutrinos
gauged Baryon/Lepton Number
neutralinos
Fermions
Vectors

References…

- FORMOSA:
  - https://arxiv.org/abs/2010.07941 (S. Foroughi-Abari, F. Kling, Y. Tsai)
- FLArE:
  - https://arxiv.org/abs/2107.00666 (B. Batell, J. L. Feng, A. Ismail, F. Kling, R. M. Abraham, S. Trojanowski)
  - https://arxiv.org/abs/2101.10338 (B. Batell, J. L. Feng, S. Trojanowski)
- FASER2 physics reach:
  - https://arxiv.org/abs/1811.12522 (FASER Collaboration)
- LHC Neutrino fluxes:
  - https://arxiv.org/pdf/2105.08270.pdf (F. Kling)
- Neutrinos EFT:
  - https://arxiv.org/pdf/2105.12136.pdf (Falkowski, González-Alonso, Kopp, Soreq, Tabriz)
- Non-standard interactions with NC neutrino events:
  - https://arxiv.org/abs/2012.10500 (Abraham, Ismail, Kling)
- Resonances in $\nu_e - e^-$ scattering:
  - https://arxiv.org/pdf/2112.03283.pdf (V. Brdar, A. de Gouvea, P. Machado, R. Plestid)
- FPF papers:
  - https://zenodo.org/record/4009641 (FPF community)
  - https://arxiv.org/pdf/2109.10905.pdf (FPF community)

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, M. Maietta, H. Vincke
- SY-STI-BMI: F. Cerutti, M. Sabate Gilarte
- EN-ACE-INT: J. P. Corso
- EN-HE: C. Bertone
- EN-CV: M. Battistin, O. Crespo-Lopez
- EN-EL: M. Lonjon
- EN-AA: P. Ninin, S. Grau, T. Hakulinen, R. Nunes
- HSE-OHS: M. Andreini
- BE-ABP
- TE-MSC-NCM: P. Thonet

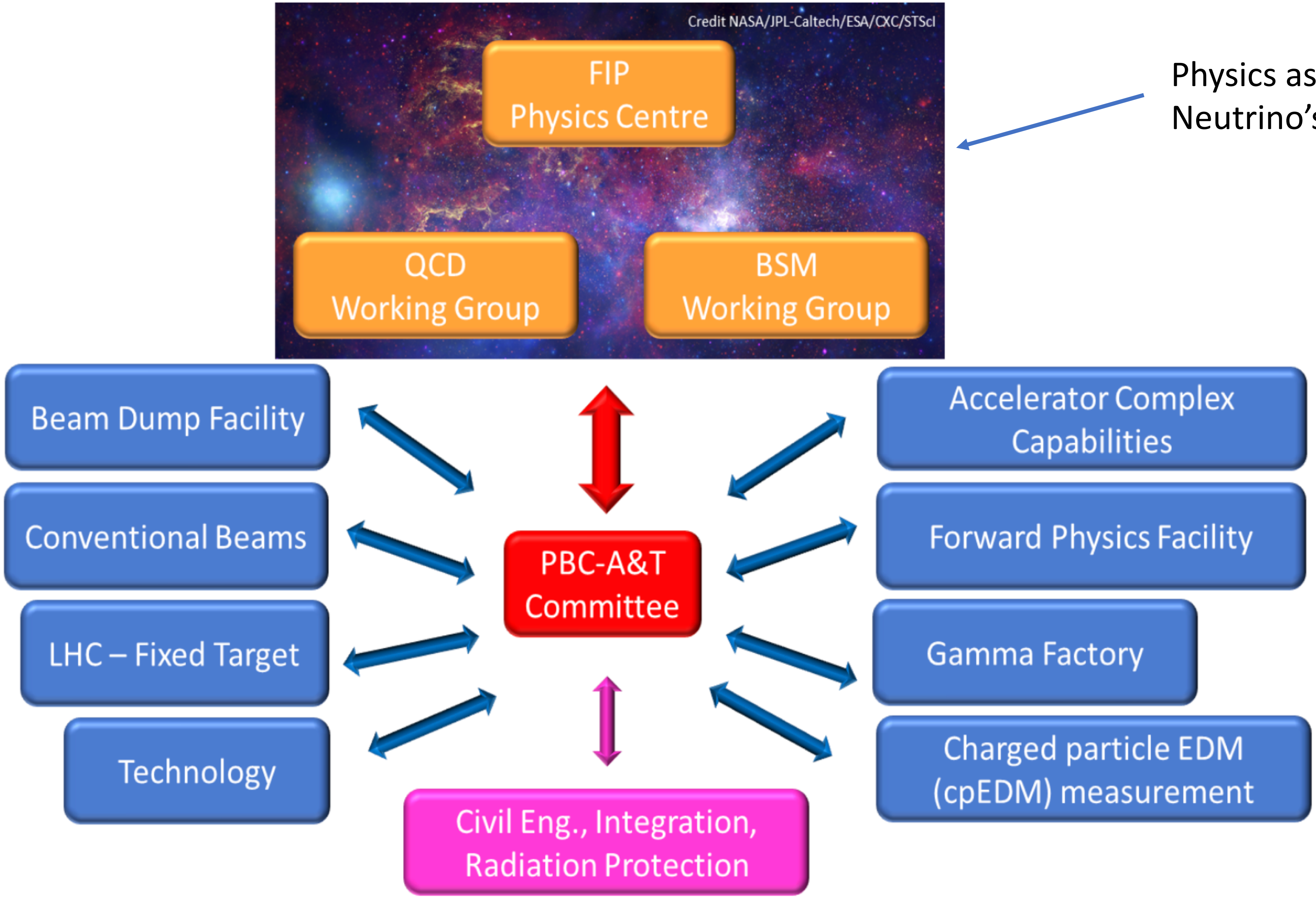
Areas where experimental effort is needed: FASER2

- Detector design
  - Main parameters: size of decay volume, size of spectrometer, magnetic field configuration, tracker technology, other detector technologies…
  - Note FASER2 spectrometer will be interfaced to FASERnu2 to allow to distinguish $\nu_\tau / \bar{\nu}_\tau$ – this needs to be considered in the design
- Physics studies based on realistic conceptual design
- First work started by J. McFayden (Sussex), and interest shown by a few other groups - but no big work started yet
  - SciFi tracker seems good option for tracker technology, considering: size of area to instrument, needed resolution/efficiency, cost and services constraints
- Need to feed main parameters (size, services, safety aspects) into design of facility as soon as possible to be able to converge on facility design and costing (by end of year)

Areas where experimental effort is needed: FLArE

- Detector design
  - Effort started by BNL/UCI teams for detector design
  - CERN Neutrino Platform expertize (from protoDUNE) very helpful for cryostat / cryogenics
  - FLArE most novel detector, that requires most R&D and studies to converge on final design
- Muon background rate important for optimizing FLArE design – coupled with sweeper magnet studies
- From QCD physics side, interest to be able to trigger ATLAS based on neutrino in FLArE
  - Unclear if this is technically possible, but could be interesting to study this as will effect design of FLArE trigger and possible detector design
- Physics studies based on realistic conceptual design will be important, especially for:
  - Tau neutrino physics
  - DM scattering
- Need to feed main parameters (size, services, safety aspects) into design of facility as soon as possible to be able to converge on facility design and costing (by end of year)

The PBC 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

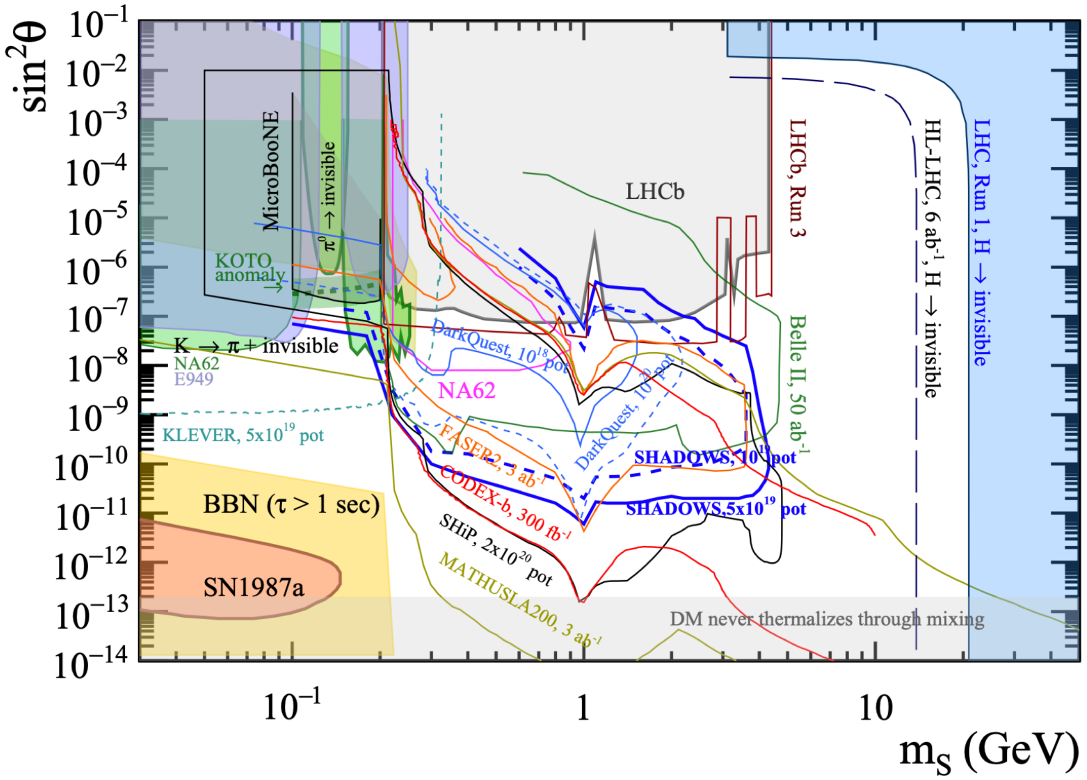
Convener: Jamie Boyd

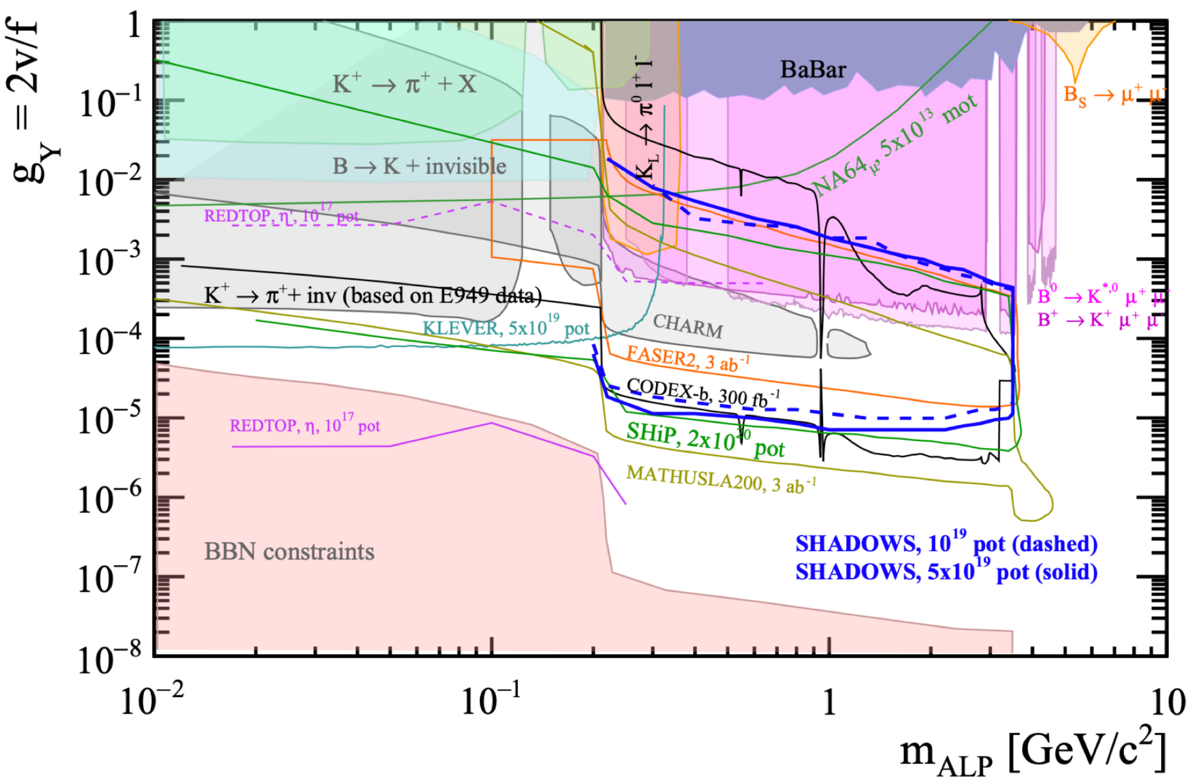
Core Members: Marco Andreini, Kincso Balazs, Jean-Pierre Corso, Jonathan Feng (UCI), John Osborne.

Contents of the “Long” FPF white paper

Contents

Comparison to other proposed projects



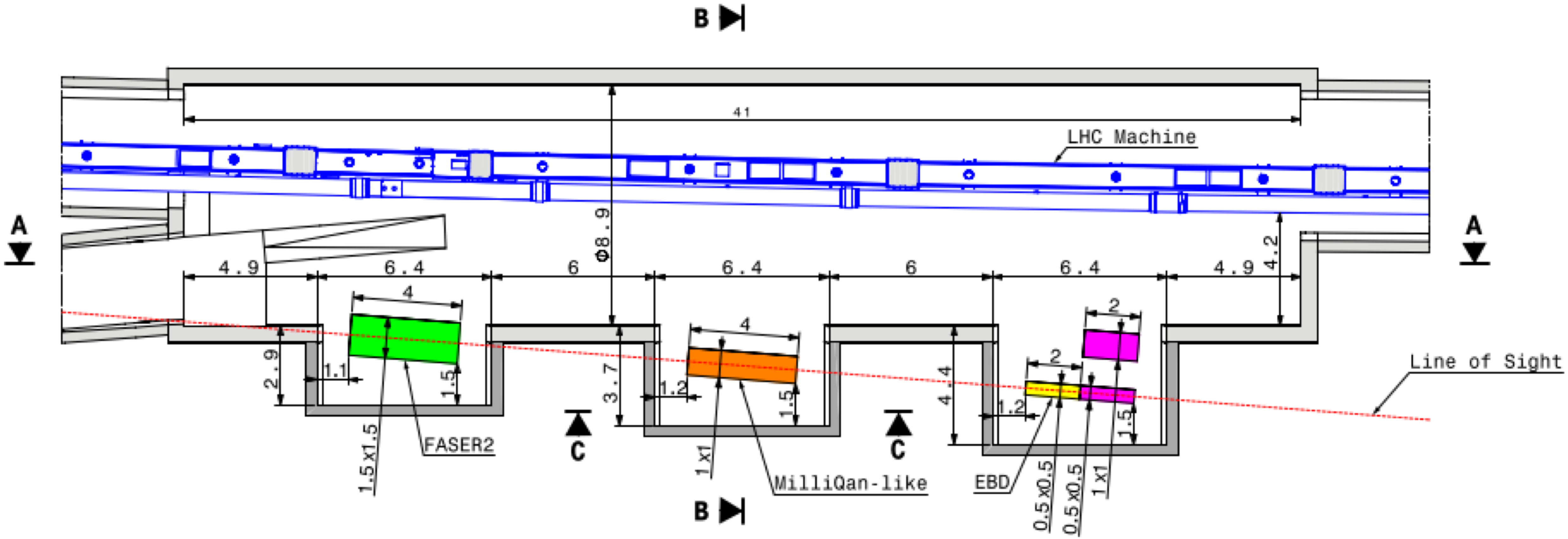


Example reach plots from SHADOWS proposed SPS beam dump experiment LOI:
https://cds.cern.ch/record/2799412/files/SPSC-EOI-022.pdf
Shows somewhat better sensitivity to FASER2, although background considerations are very different and I would expect backgrounds to be far simpler for FASER2 (~600m from partticle source + ~200m of rock shielding).
Physics reach of SHiP significnatly stronger than FASER2, although SHiP+BDF cost ~250MCHF much higher than FPF.

UJ12 Alcoves

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

Three 'alcoves' in UJ12 cavern wall, would allow some more room on the LOS for experiments.
For works the full UJ12 area would need to be emptied out (LHC magnets, QRL, EN-EL/CV equipment etc…).
Seems possible but significant work.
Background / radiation from beamline may be problematic for experiments.



K. Balazs, J. Osborne
CERN SCE

First costing of CE works & services

- Preliminary costing of civil engineering works for the two options
- Based on comparative costing to similar projects:
  - SPS Dump Facility Tunnel eye enlargement as reference point for UJ12 alcoves
  - 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 13MCHF for UJ12 alcoves, 23MCHF for new cavern
- Additional cost for services ~15MCHF for new cavern (see backup), much less for UJ12 alcoves
- **Total cost: ~40MCHF (new cavern), ~15MCHF (UJ12 alcoves)**

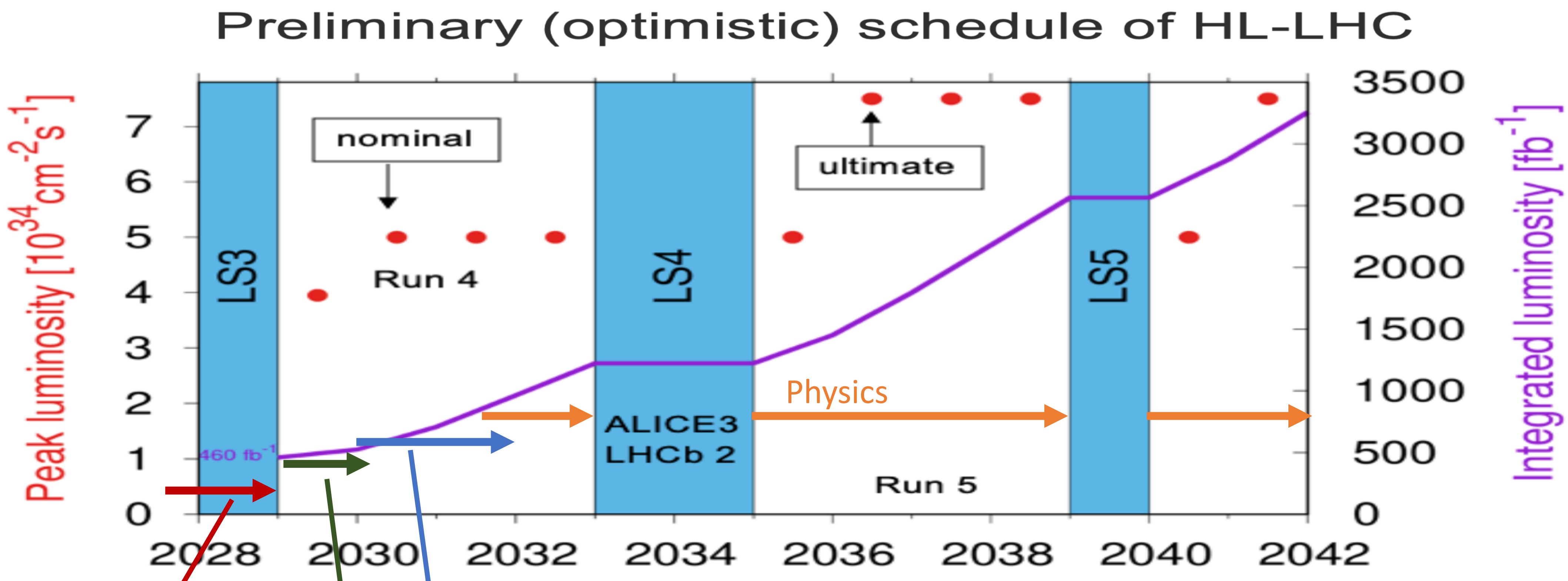
Contrasting the two options

- UJ12 alcoves advantages:
  - Cost
- New Facility advantages:
  - No size constraints on the experiments
    - FASER2 physics would be much reduced if restricted to a 6m long alcove
  - New facility would allow a LAr based detector, not possible in LHC tunnel due to safety constraints
  - Access to the experimental area much easier for new facility option
    - Requirements on size/weight of apparatus for installation
    - Access for maintenance during beam operation (RP study ongoing – but looks possible)
  - Radiation and beam backgrounds negligible for separate cavern compared to UJ12 alcoves
  - Much of the excavation work and the installation of services/experiments could be done during LHC operations for the new facility – reducing possible schedule pressure during LSs

Given the only factor of ~2.5 difference in costs between the two options there is a strong preference from the physics side towards the new facility option.

Possible FPF schedule

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



Pure CE works (including connection to LHC)

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

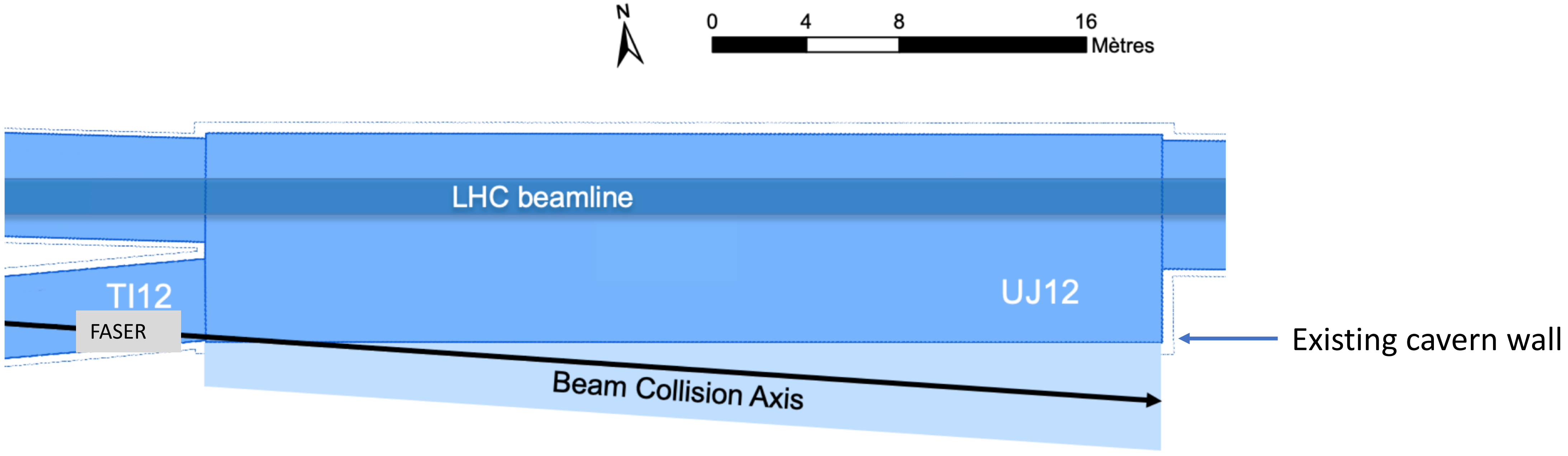
Installation and commissioning of the experiments

If the above schedule becomes unachievable we would aim to implement the facility during Run 4:

- Ongoing study within ABP to understand what digging is compatible with HL-LHC operations (significantly further from IP than UPR works, so likely much of digging can be done)
- To investigate if connection of safety gallery compatible with (E)YETS during Run 4

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.

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

UJ12 Alcoves – Very Preliminary Cost Estimate for CE works

Preliminary Cost Estimate

Ref.	Description of works	Cost [CHF]
1.	**CE Works Alcoves**	**10,866,870**
1.1	Alcove 6.4*2.9 m	2,864,902
1.2	Alcove 6.4*3.7 m	3,655,220
1.3	Alcove 6.4*4.4 m	4,346,748
2.	**Engineering and consultancy**	**1,630,031**
3.	**Minor Works**	**287,281**
3.1	Site investigation	74,524
3.2	Miscellaneous	212,757
	Total Cost	**12,784,182**

Methodology

- Comparative Costing
- SPS Dump Facility Tunnel eye enlargement as reference point
- Cost Estimate Class 4 – total could be 50% higher and 30% lower than the given estimate

Assumptions

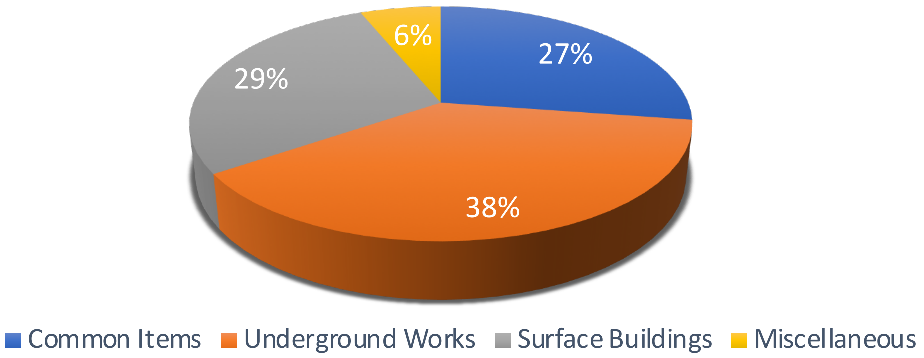
- Removal of the existing services and equipment from the UJ12 not included
- Services (CV, electricity etc.) not included

New Cavern – Very Preliminary Cost Estimate for CE

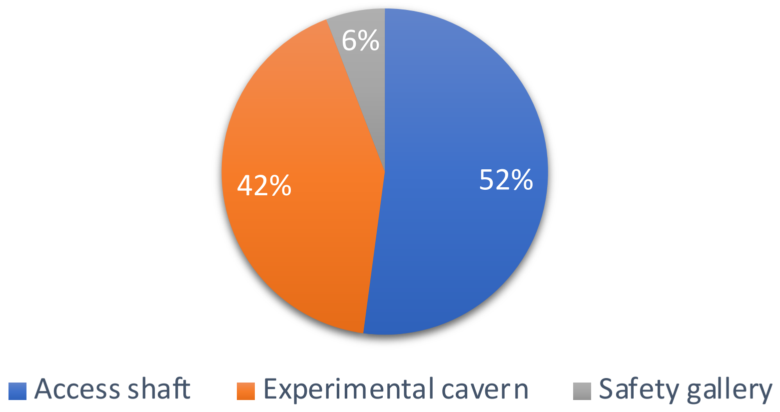
Ref.	Description of works	Cost [CHF]
1	**Common Items**	**6,356,824**
1.1	Contractual requirements (performance guarantee, insurances)	163,473
1.2	Specified requirements (Installation of barracks, Access road, Services etc.)	1,055,263
1..3	Method-related charges (Accommodations, Services, Site supervision, 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



What needs to be removed from UJ12 for alcoves option

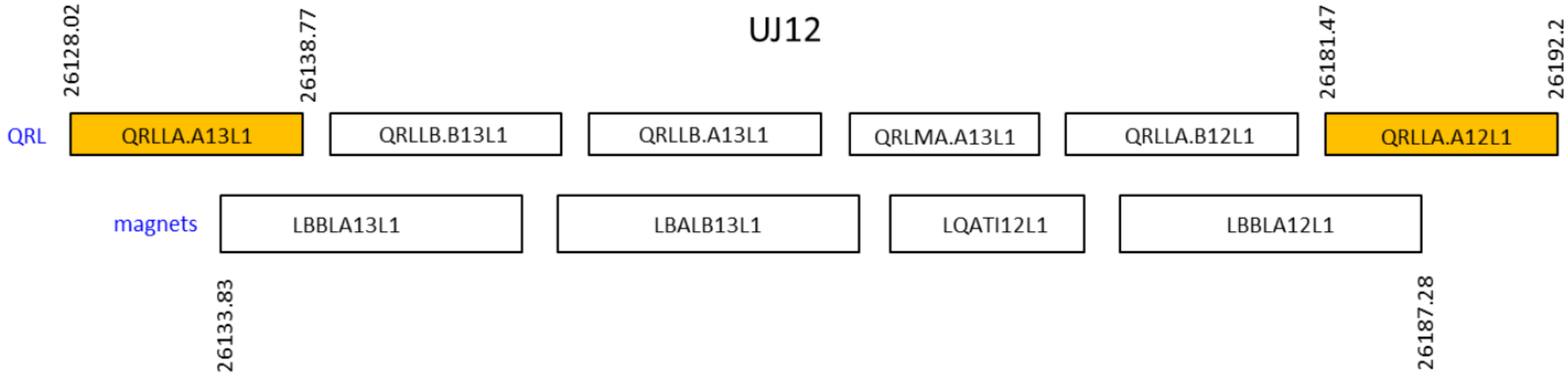
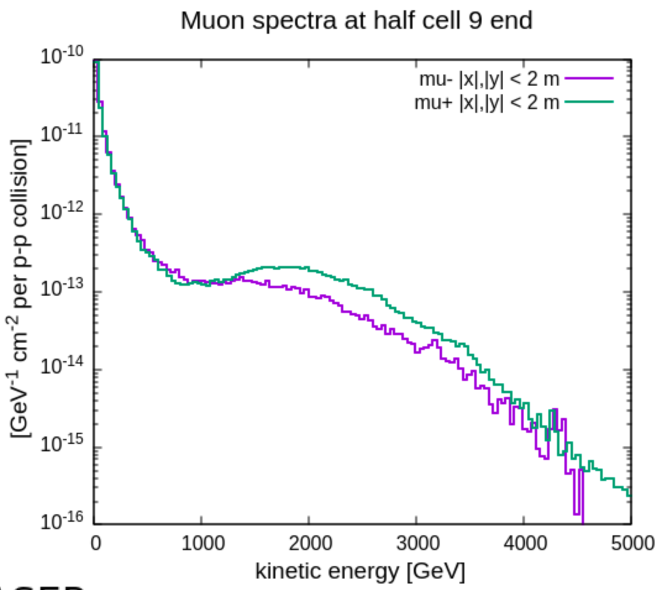


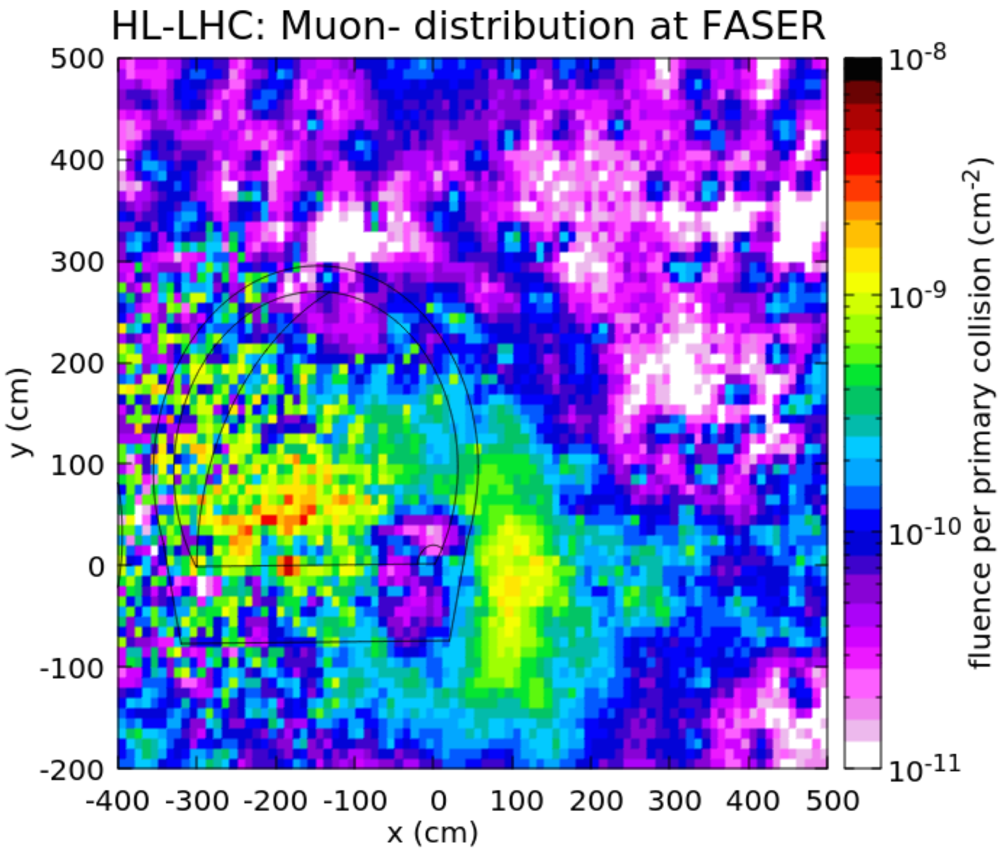
Figure 1; Sketch of UJ12 machine layout (magnets and the QRL) with main Dcum values.

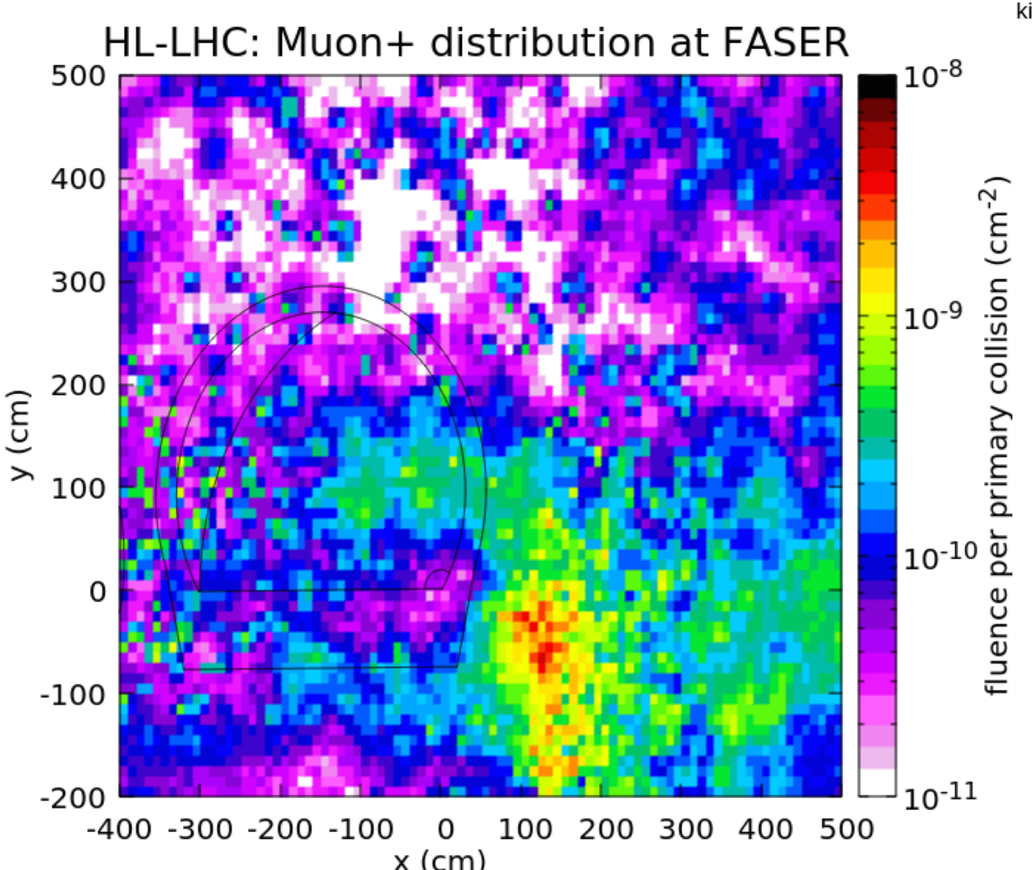
Muon Backgrounds

F. Cerutti, M. Sabate Gilarte, SY-STI

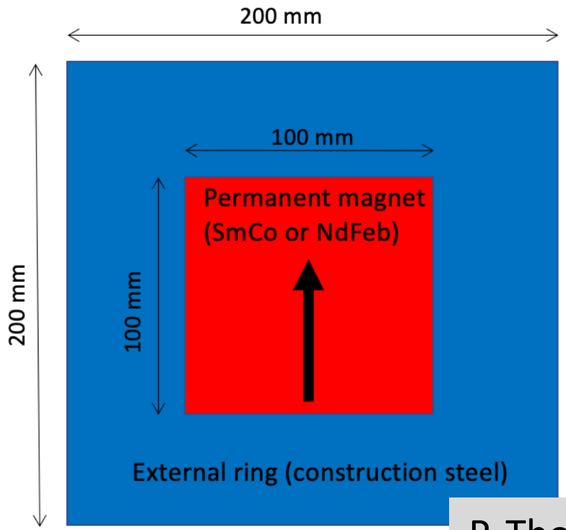


FLUKA distribution of muon flux in tranverse plane around LOS.
The flux is lowest on the LOS.





Sweeper Magnet: Ongoing Studies

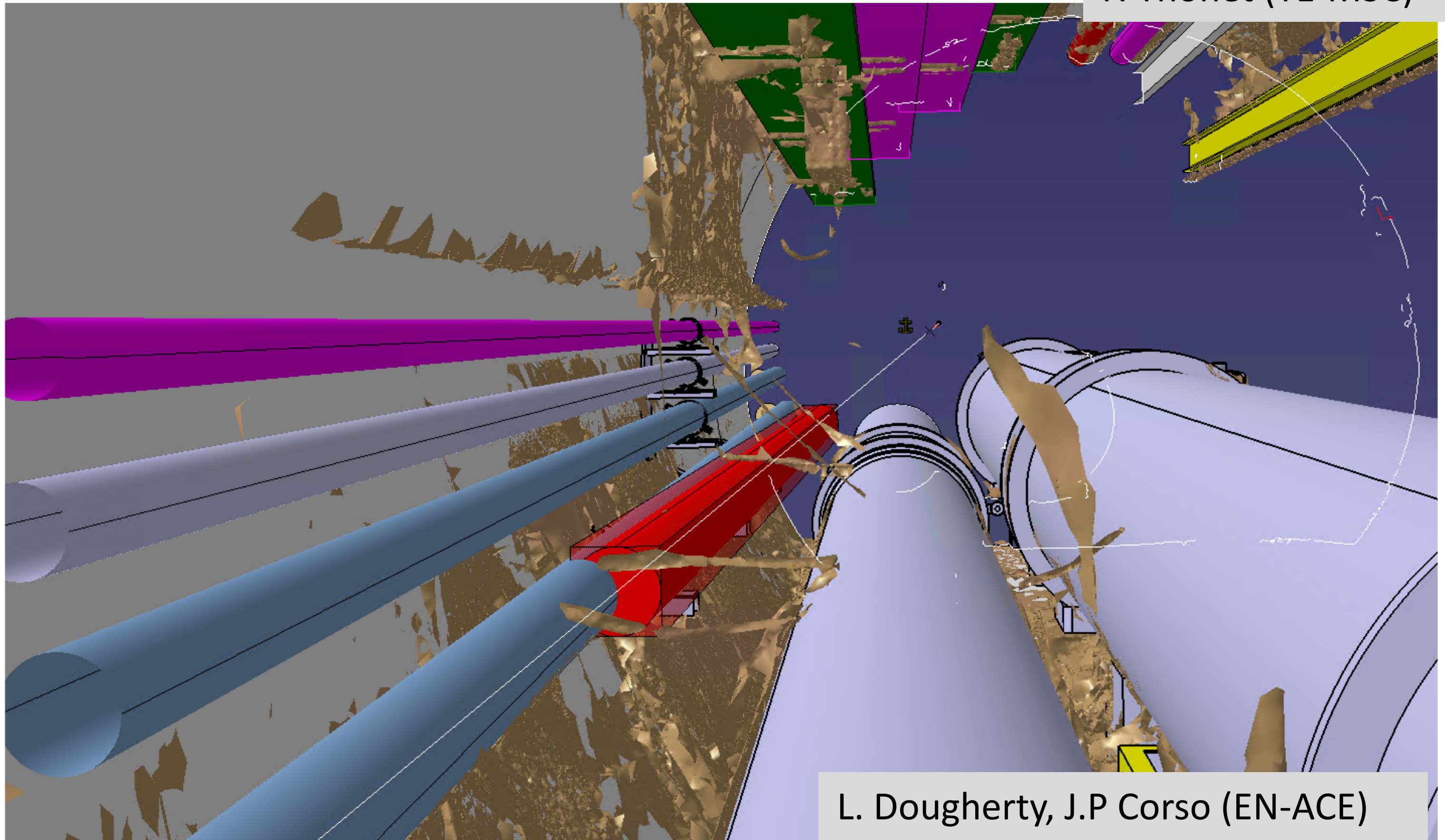


P. Thonet (TE-MSC)

- Preliminary design of sweeper magnet by TE-MSC
  - Based on permanent magnet to avoid power converter in radiation area
  - Simple / cheap design with 1T bending power (~150kCHF)
  - Consider total length ~7m, 2.3tonnes
  - 7Tm magnet would deflect a 100 GeV muon 4.2m from the LOS at the FPF
  - Handling, support structure not yet considered

- Integration have looked at placement of sweeper magnet on the LOS in the LHC tunnel
  - Laser scan of relevant area taken in 2020
  - Would need some minor modifications to cryogenic lines (warm return line) in relevant area to allow sufficiently long magnet to be installed
  - Possibility of modifications to be investigated with LHC cryo

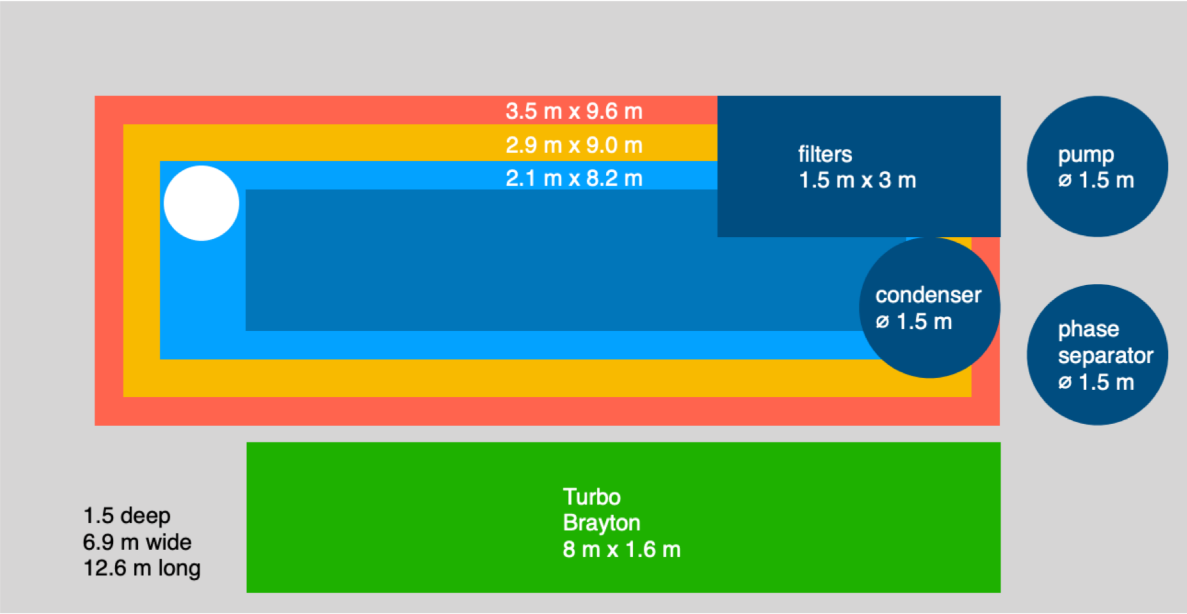
- FLUKA and BDSIM studies ongoing to assess effectiveness of such a magnet in reducing the muon background in the FPF



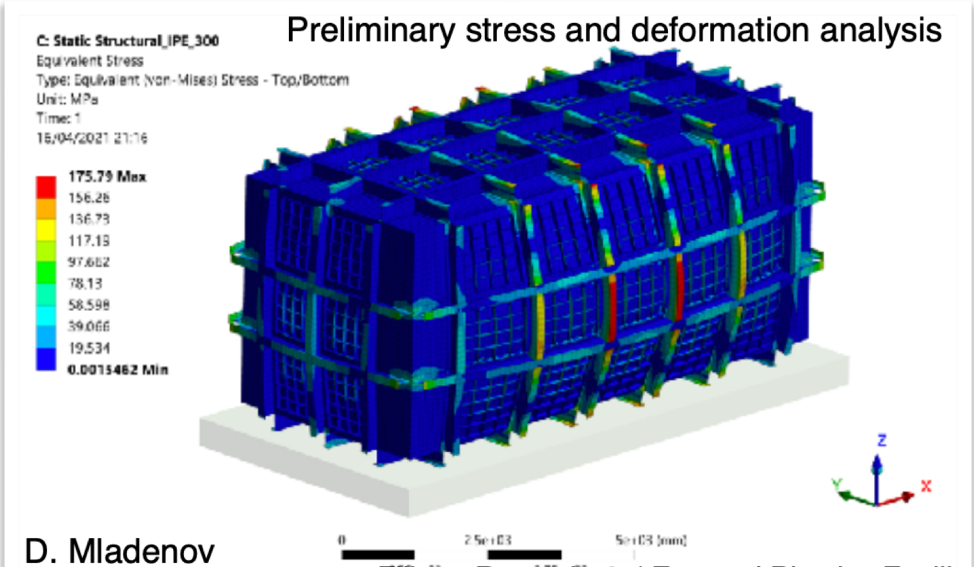
L. Dougherty, J.P Corso (EN-ACE)

LAr TPC cryogenics and cryostat

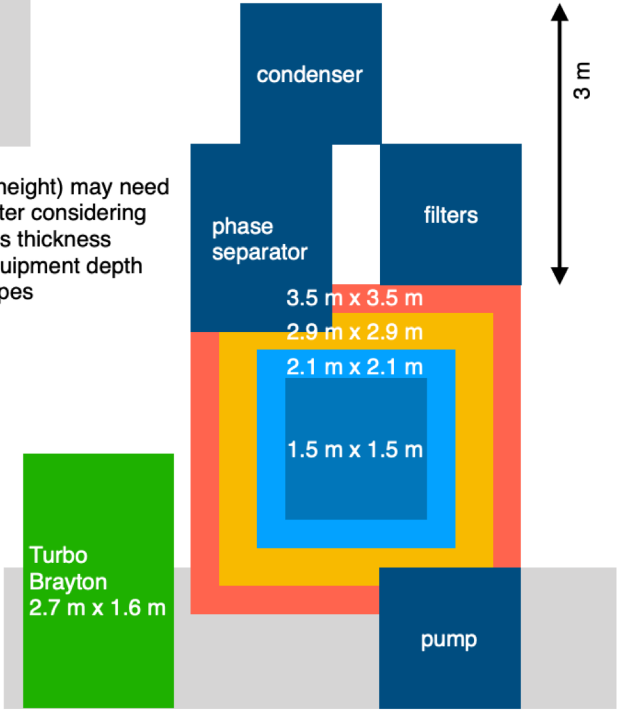
LAr TPC detector drives many aspects of services/infrastructure and safety systems.
Rough design of cryostat and cryogenics by F. Resnati based on proto-Dune experience in the neutrino platform.



- 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.



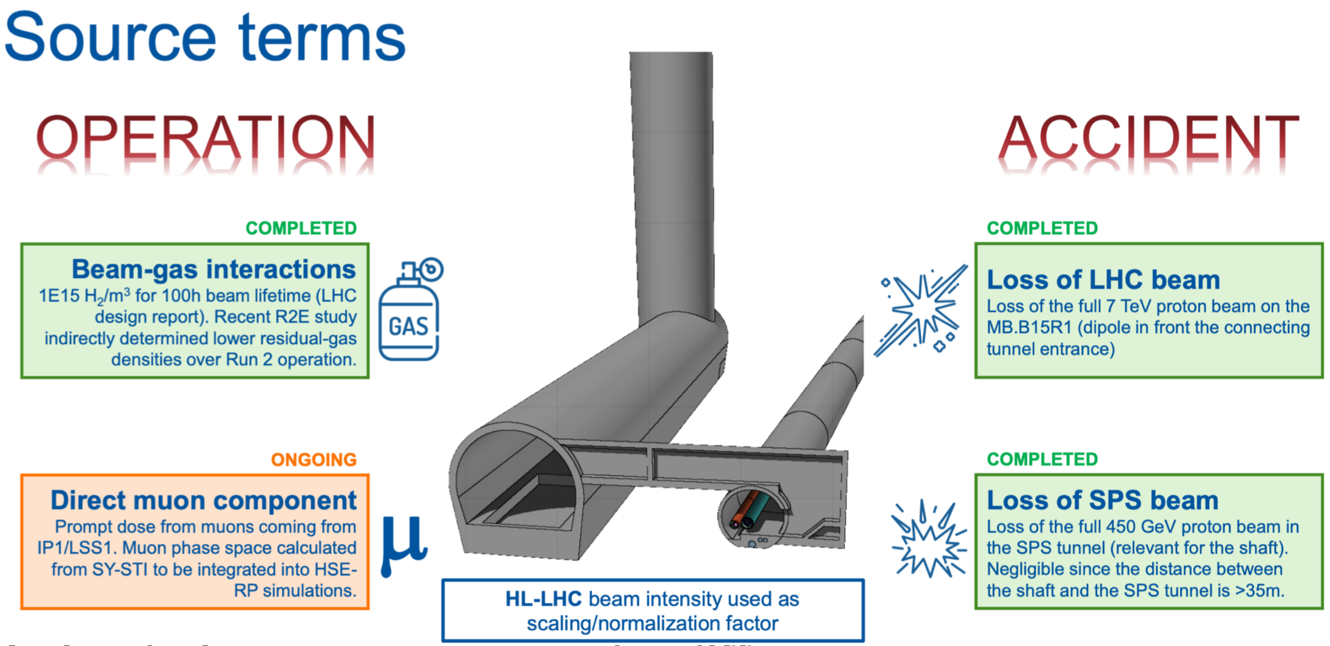
Dimensions (height) may need to increase after considering
- minimum gas thickness
- minimum equipment depth
- cryogenic pipes



L. Elie, A. Infantino, M. Maietta, H. Vincke (HSE-RP)

RP Study

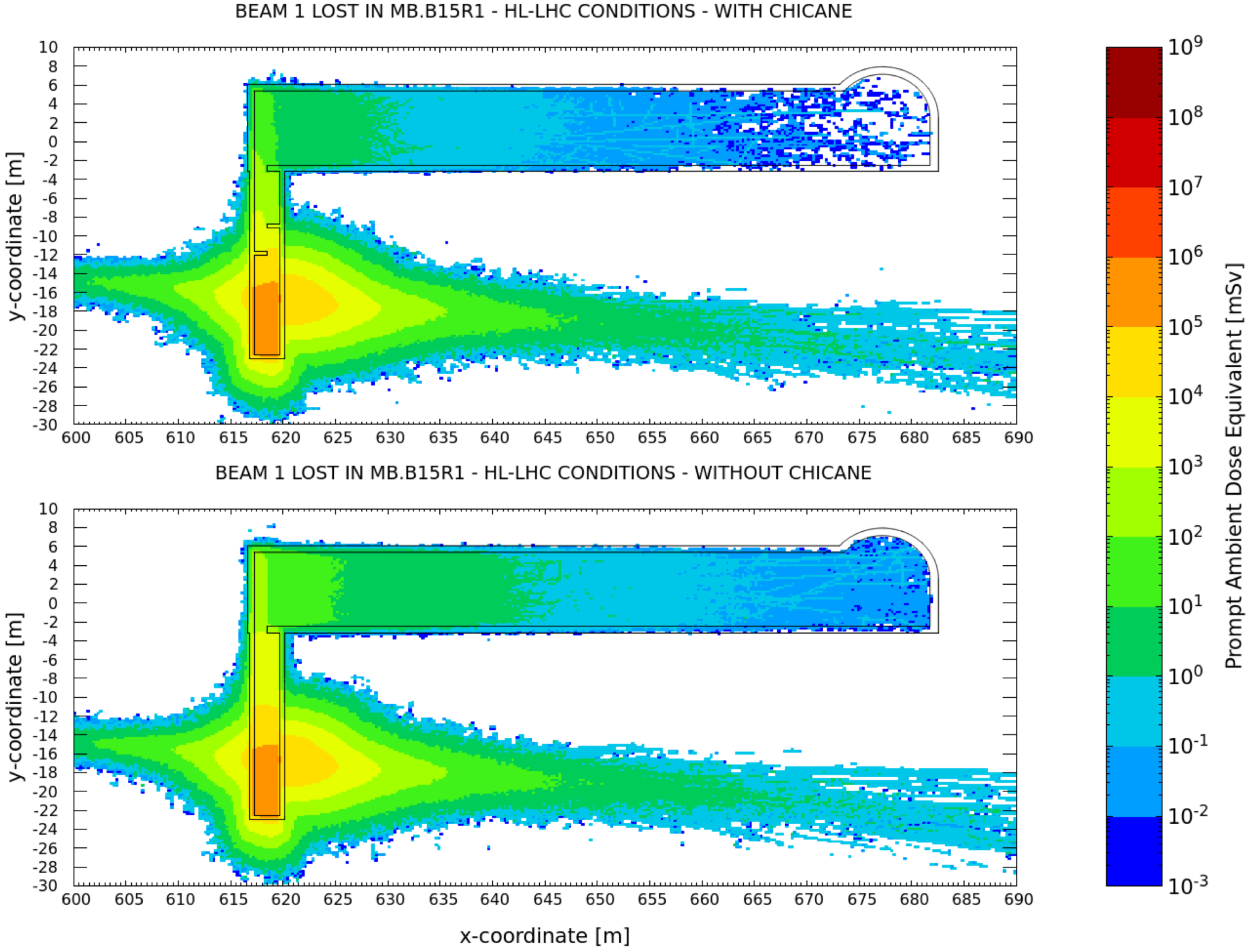
- An RP study has been carried out to assess if people can access the FPF cavern during HL-LHC operations which would be a significant benefit

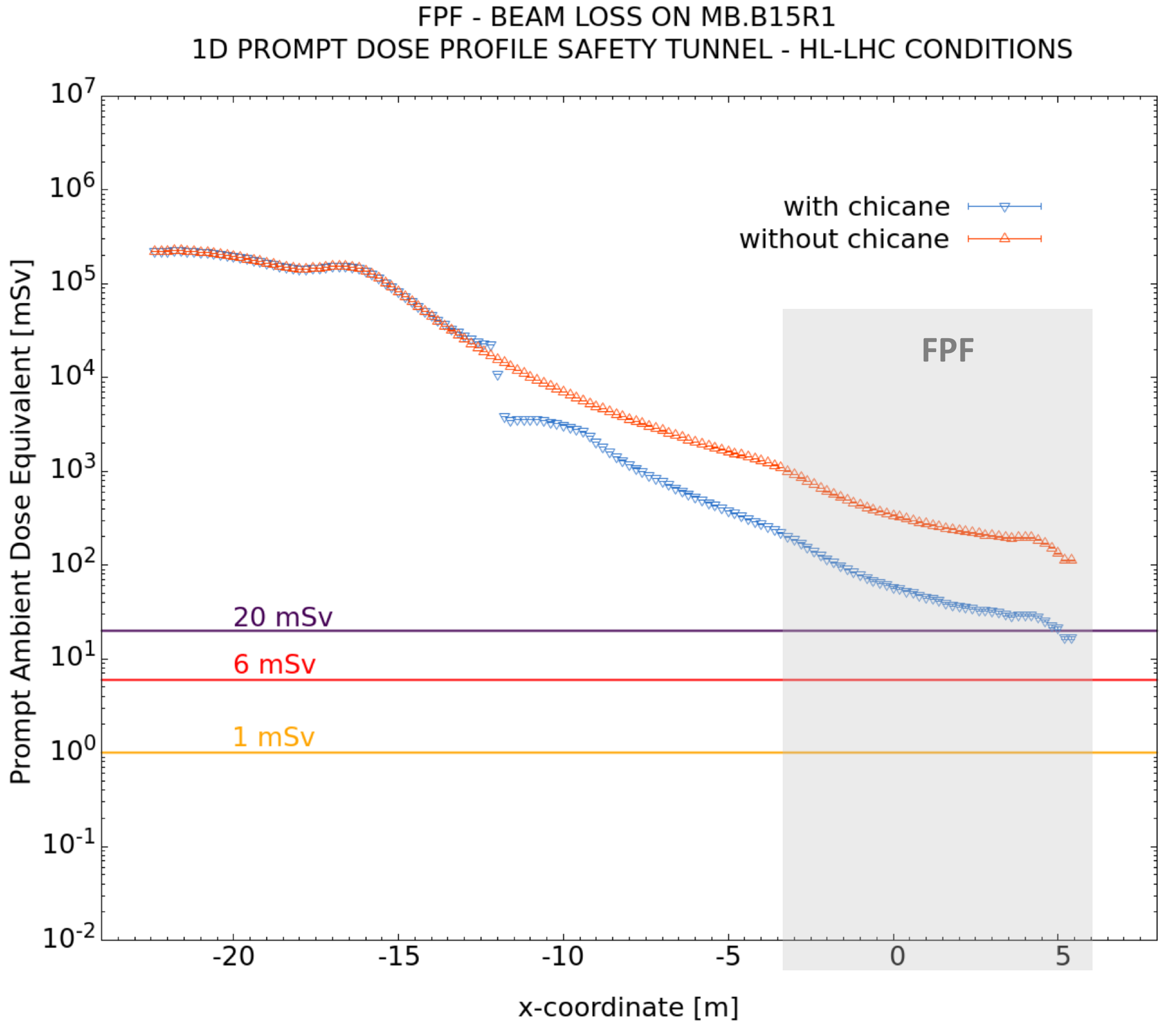


- Detailed FLUKA simulations run to assess the different components
  - SPS losses not a problem
  - Beam-gas not a problem
  - Accidental loss of full LHC beam in worst place – radaiation level too high, updates to chicane in safety gallery being studies
  - Prompt muon dose – under study

L. Elie, A. Infantino, M. Maietta, H. Vincke (HSE-RP)

RP Study – Accidental LHC beam loss



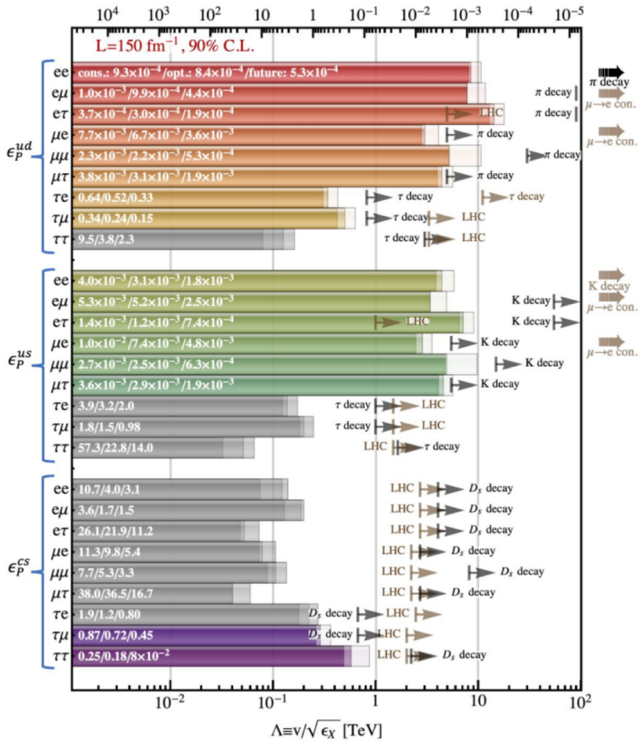


Chicane in safety gallery reduces the dose but not enough. Chicane being redesigned to address this (thicker/more walls)

Neutrino Physics

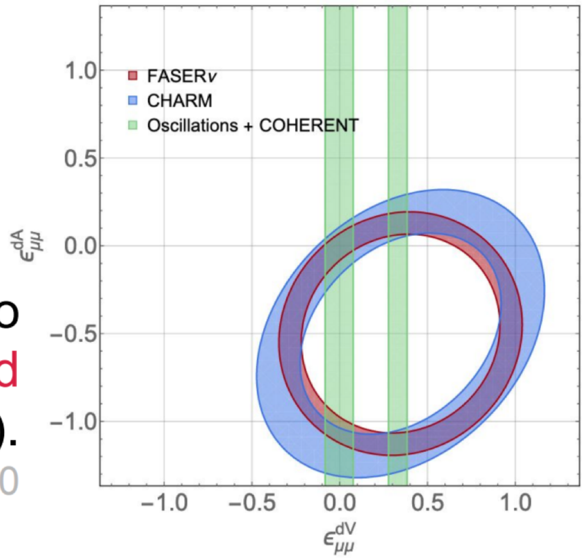
Interactions of LHC neutrino can also be used to constrain SM EFT coefficients

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 FASERν. However, sterile neutrinos with mass ~40eV can cause oscillations. FASERν could act as a short-baseline neutrino experiment.