F A C E T:

Forward **A**perture **C**MS **E**x**T**ension

Proposal for **LLP** searches (cτ ≈ 0.1 – 100 m)

- with a new detector 100 m from CMS
- fiducial volume ≈ 14 m^3 – high vacuum (10^{-10} mbar)
- forward direction ($7.6 > \eta > 6.2$)
- phase-2 upgrade equipment (tracker, calorimeter)

LLP-13: 13th Workshop of LLP community - June 22, 2023

A. Penzo, Univ. of Iowa

(On behalf of **FACET** Team)

JHEP06(2022)110

FACET: A new long-lived particle detector in the very forward region of the CMS experiment

S. Cerci,[a,1] D. Sunar Cerci,[a,1] D. Lazic,[b] G. Landsberg,[c,2] F. Cerutti,[d] M. Sabaté-Gilarte,[d] M.G. Albrow,[e,2] J. Berryhill,[e] D.R. Green,[e] J. Hirschauer,[e] S. Kulkarni,[f] J.E. Brücken,[g] L. Emediato,[h] A. Mestvirishvili,[h] J. Nachtman,[h] Y. Onel,[h] A. Penzo,[h] O. Aydilek,[i] B. Hacisahinoglu,[i] S. Ozkorucuklu,[i,2] H. Sert,[i] C. Simsek,[i] C. Zorbilmez,[i] I. Hos,[j,1] N. Hadley,[k] A. Skuja,[k] M. Du,[l] R. Fang,[l] Z. Liu,[l] B. Isildak[m,1] and V.Q. Tran[n,o]

arXiv:2201.00019v2 [hep-ex] 18 Jun 2022

https://doi.org/10.1007/JHEP06(2022)110

Former FACET Talks

Workshops of LHC LLP Community:

LLP – 08 (Nov 16, 2020) : Mike Albrow, Forward Multiparticle Spectrometer
https://indico.cern.ch/event/922632/

LLP – 09 (May 25, 2021) : Bora Isildak, FACET
https://indico.cern.ch/event/980853/

LLP – 10 (Nov 09, 2021) : Dan Green, Status of FACET
https://indico.cern.ch/event/1042226/

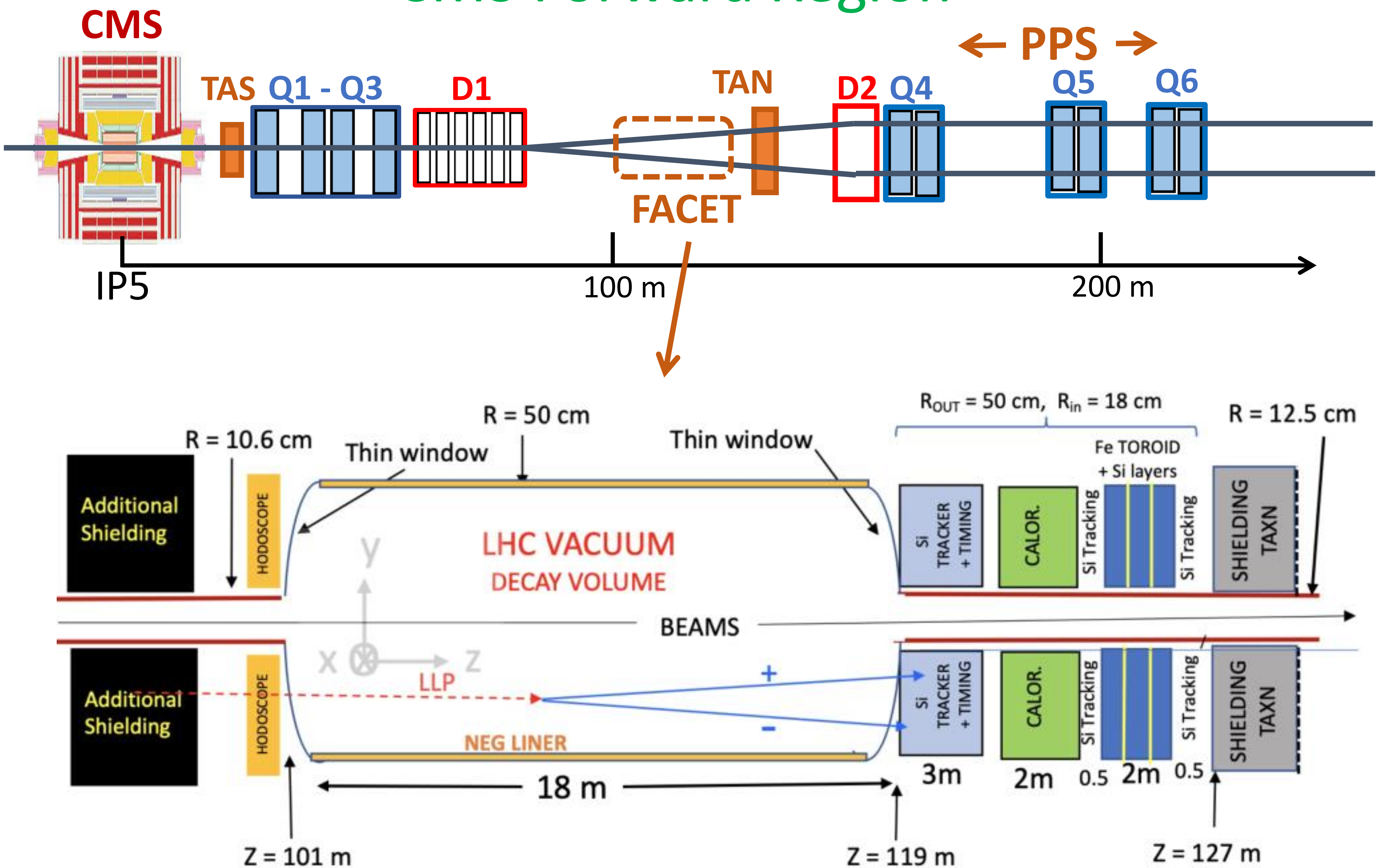
LLP – 11 (June 01, 2022) : Ilknur Hos, FACET
https://indico.cern.ch/event/1128662/

LLP – 12 (Nov 03, 2022) : Keith Ulmer, Status of FACET
https://indico.cern.ch/event/1166678/

Other FACET talks (f. i.):

FNAL LPC (Jan 26, 2021) : Greg Landsberg, Searches for new physics with FACET
https://indico.cern.ch/event/994582/

CMS Forward Region



FACET

Detector conceived as remote CMS subsystem, in a region of Pt5 housing other CMS systems (f.i. ZDC in TAN absorber)

Large decay volume (D= 1m, L = 18 m)

- expanded section of LHC beampipe (high vacuum ≈ low background)
- polar angles from 1 – 4 mrad ($6.2 < \eta < 7.6$)
- shielding upstream ≈ 35 – 50 m of iron (LHC magnets ≈ 200 – 300 interaction lengths)

Detector design based on CMS Phase-2 technology

- High precision Si - tracking
- High granularity calorimeter
- High granularity hodoscopes
- Rad-hard and fast detectors

Physics Goals

Detect penetrating neutral particles decaying to ≥2 charged particles (or photons) in fiducial volume

Possible LLP candidates:

- dark photons,
- heavy neutral leptons,
- axion-like particles,
- dark Higgs bosons

Lifetime sensitivity $\gamma c\tau \approx$ 10 – 10,000 m, peak ≈ 100m

Explore specific regions in parameter space, largely complementary to other searches (ongoing/proposed)

Examples: Recent Papers discussing FACET

Dark Photons

Mingxuan Du, Rundong Fang, Zuowei Liu and Van Que Tran, Enhanced long-lived dark photon signals at lifetime frontier detectors, arXiv:2111.15503v1 [hep-ph] 30 Nov 2021

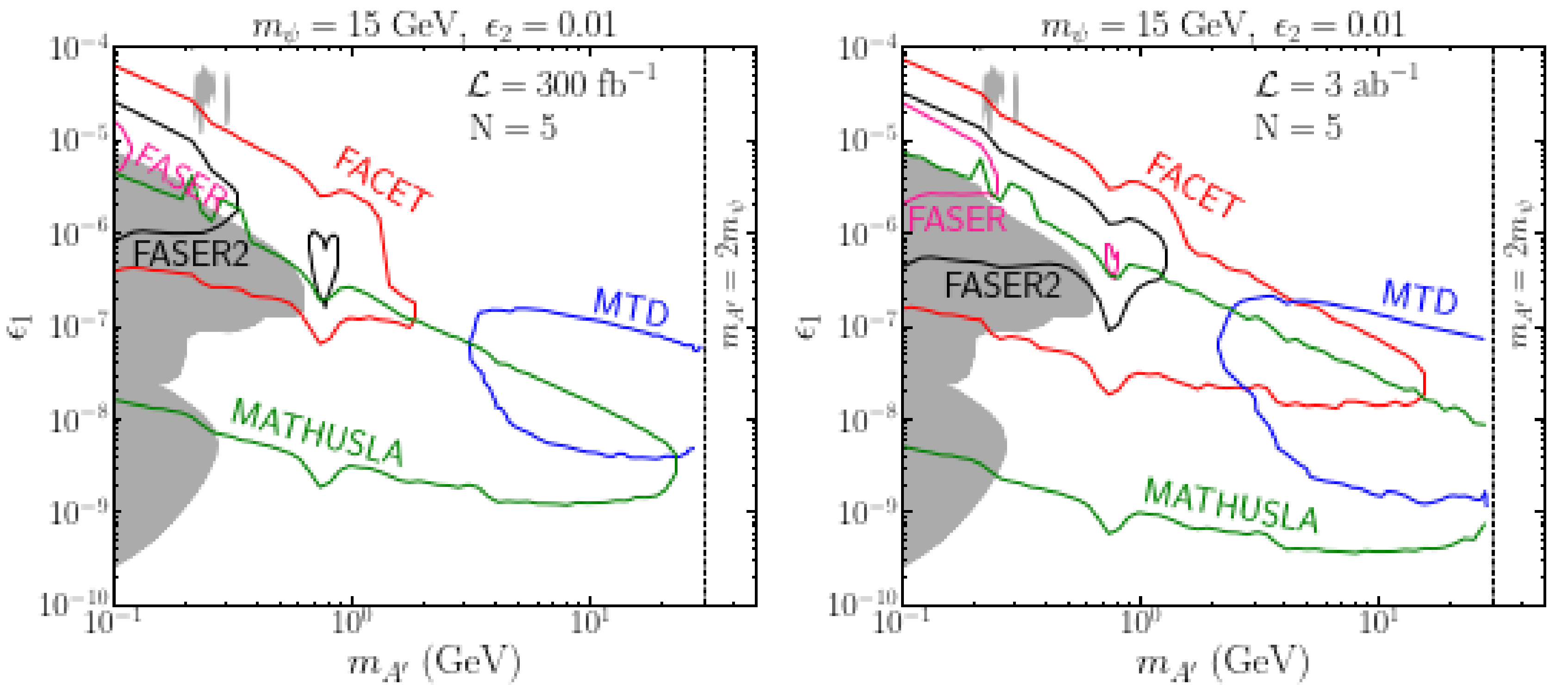


Figure 8: Projected sensitivities from FACET (red), FASER (magenta), FASER2 (black), and MATHUSLA (green), at the HL-LHC with the integrated luminosities of $\mathcal{L} = 300$ fb^{-1} (left panel) and $\mathcal{L} = 3$ ab^{-1} (right panel) to our dark photon model in which all the three dark photon production channels (MD, PB, and HR) contribute to the signals. Here we fix $m_\psi = 15$ GeV and $\epsilon_2 = 0.01$, and require $m_{A'} < 2m_\psi$ so that the dark photon cannot decay into invisible final states. Contours correspond to the expected signal events $N = 5$. The dark gray shaded region indicates the excluded dark photon parameter space by various experiments where the HR process is not considered; the limits are obtained with the Darkcast package [101].

Heavy Neutral Leptons - HNL

Asli M. Abdullahi et al., The Present and Future Status of Heavy Neutral Leptons
arXiv:2203.08039v1 [hep-ph] 15 Mar 2022 **(Heavy Neutral Leptons - HNL)**

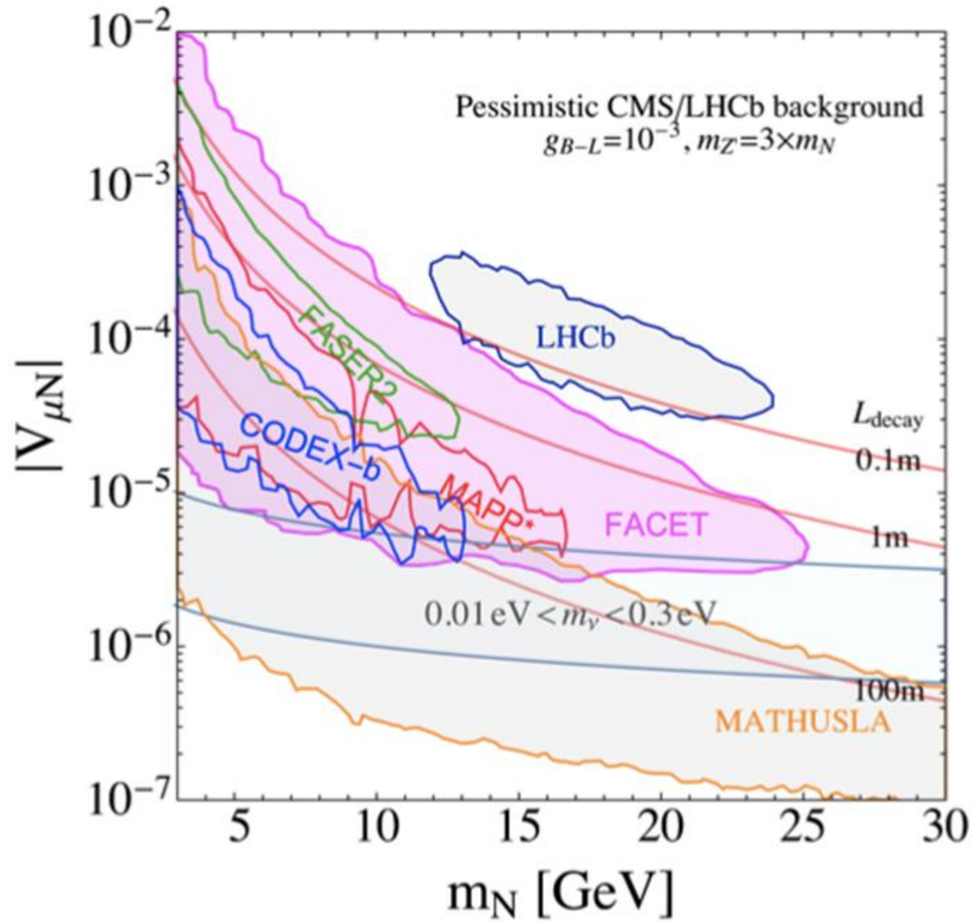


Figure 19: FACET reach compared to other future experiments in the context of the U(1)B−L HNL scenario, with one generation of N mixing [428].

Maksym Ovchynnikov, Viktor Kryshtal and Kyrylo Bondarenko, Sensitivity of the FACET experiment to Heavy Neutral Leptons and Dark Scalars, JHEP02(2023)056
arXiv:2209.14870v2 [hep-ph] 6 Feb 2023

Higgs-Like Dark Scalars (HLDS) — Heavy Neutral Leptons (HNL)

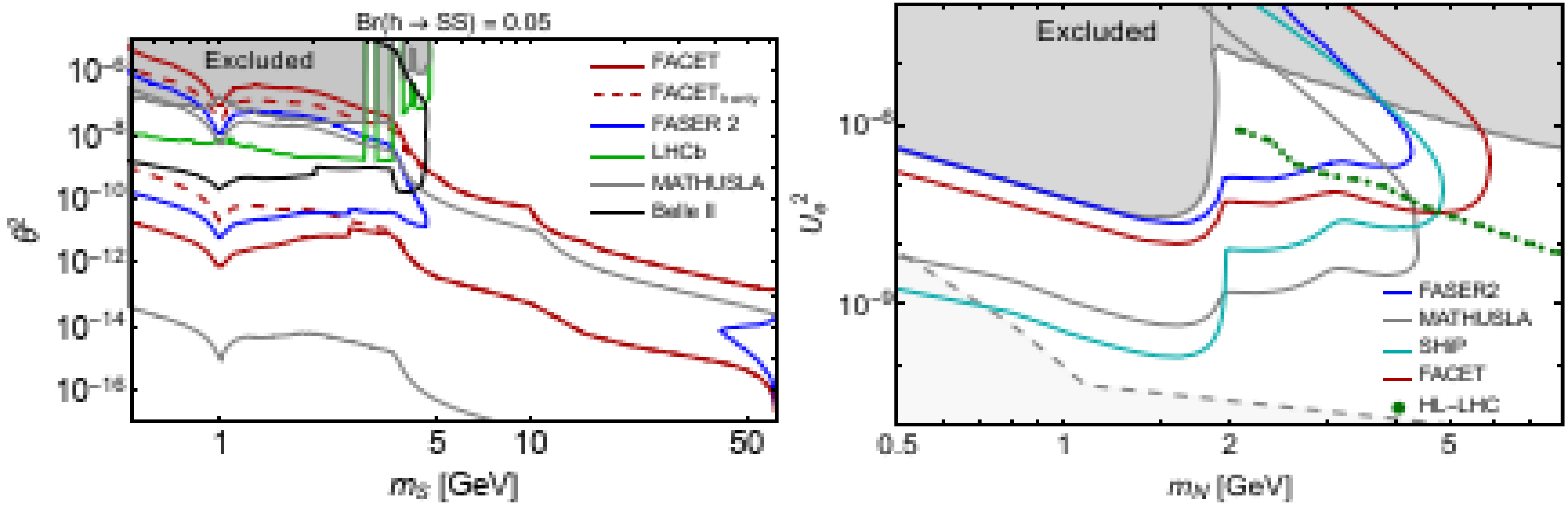


Figure 1. Sensitivity of FACET and FASER2 to the models of HNLs and Higgs-like scalars. Left panel: Higgs-like scalars, assuming $\mathrm{Br}(h \to SS) = 0.05$. The solid red line shows the sensitivity of FACET including the production of scalars from h and B, while the dashed line denotes the sensitivity to scalars from h only. We also include the sensitivity of Belle II from [20] (see also [21]). Right panel: HNLs that mix predominantly with ν_e. For comparison, we also show the sensitivity of SHiP and MATHUSLA experiments from [2], as well as the optimistic estimate of the sensitivity of HL-LHC from [22]. The region excluded by the previous experiments is given from [23] for HNLs and from [2] for Higgs-like scalars.

Takumi Kuwahara and Shu-Run Yuan, **Dark Vector Mesons** at LHC Forward Detector Searches

arXiv:2303.03736v1 [hep-ph] 7 Mar 2023

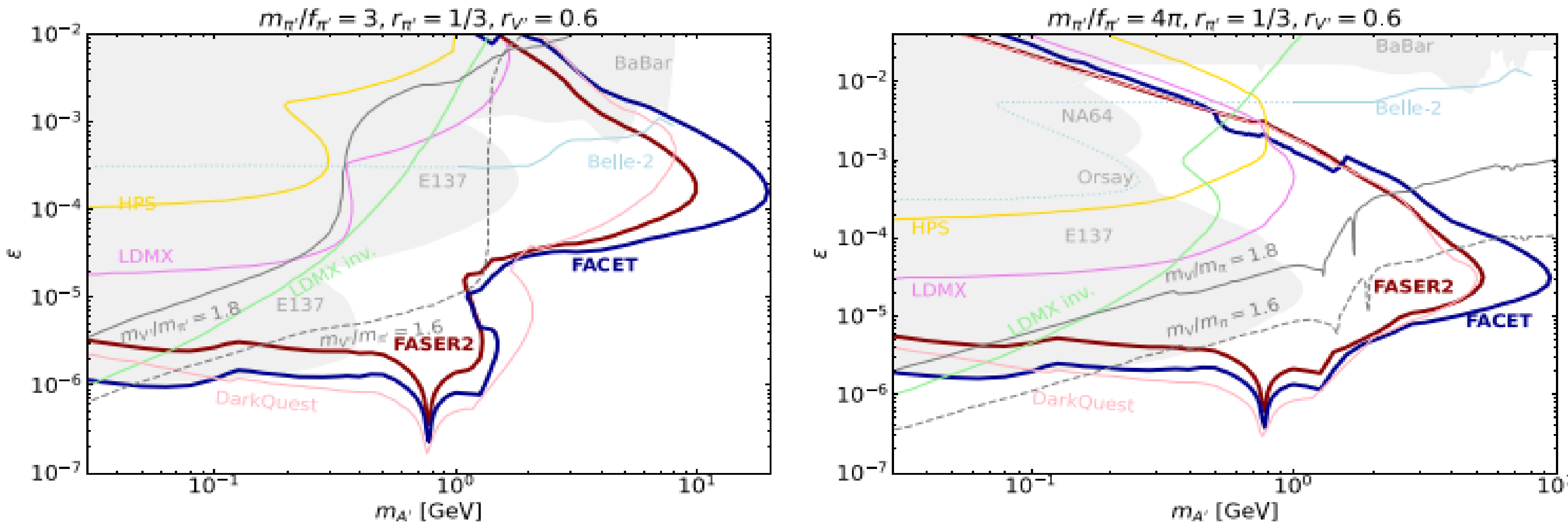


Figure 2: Existing constraints and sensitivity of future searches to signals of dark vector mesons. The shaded regions are excluded by mono-photon search at BaBar [57]; invisible decay search at NA64 [59]; and visible decay signals at E137 [21, 87], Orsay [63, 88]. The light-color contours correspond to the projected reach of Belle-II [58], HPS [22], Dark-Quest [24], LDMX [23]. The future sensitivity of dark vector mesons at the LHC forward-detector searches during HL-LHC are shown as thick lines: FASER2 [25] (dark red) and FACET [26] (dark blue). The parameters are fixed to be $\alpha_D = 0.01$, $r_{\pi'} = m_{\pi'}/m_{A'} = 1/3$, and $r_{V'} = m_{V'}/m_{A'} = 3/5$. We take the pion self-coupling to be $m_{\pi'}/f_{\pi'} = 3\,(4\pi)$ in the left (right) panel.

Background Issues

Interest for FACET approach to LLP search:

- close to the beam(s)
- not too far from IP vertex
- large volume with LHC vacuum

→ **enhanced signal sensitivity**

In parallel, increased **backgrounds** may override the positive features of FACET… a balance is necessary!

Extensive **FLUKA studies** for FACET have been done by **Marta Sabatè-Gilarte** and **Francesco Cerutti**, with **Dan Green** using their results to estimate particles' fluxes in FACET region, and to mitigate their effects.

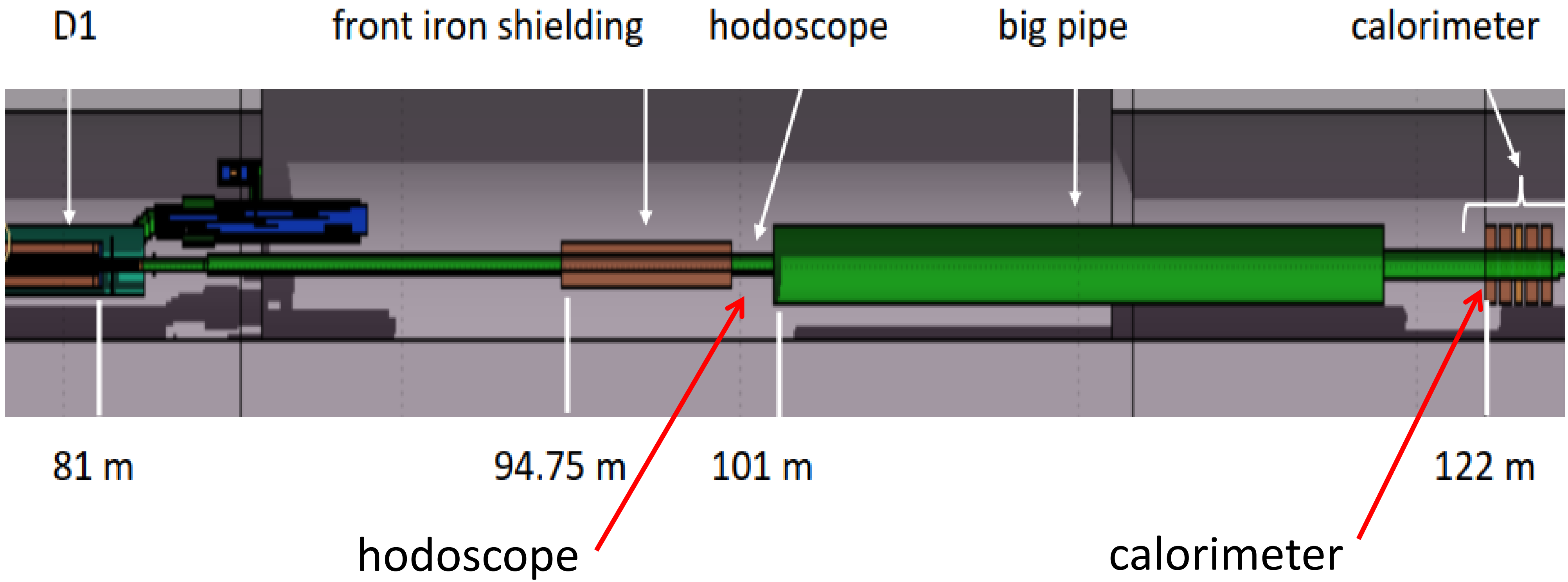
FLUKA Studies

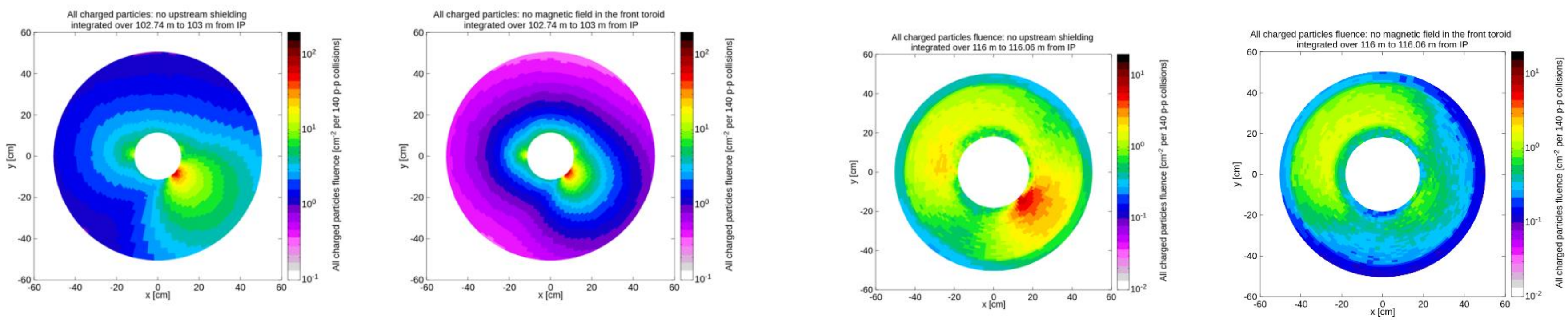
Since April 2020, Marta Sabatè-Gilarte has regularly reported on (work with Francesco Cerutti):

- Machine conditions for the HL-LHC
- particle distributions, and fluences
- acceptances for FACET
- signal and background estimates
- shielding configurations

The results produced were interpreted by Dan Green to evaluate FACET operating conditions

Typically:





no - shield   with - shield   no - shield   with - shield

Interim conclusions on radiation issues

Beam Pipe

- 12.5 cm radius in the front pipe is better to minimize the radiation levels in the front detectors (hodoscope)
- 10.6 cm allows reducing radiation levels on the back detectors
- the reduction from 12.5 cm to 10.6 cm of the front vacuum chamber may limit acceptance of back detectors
- **Main point - protect back detectors: smaller pipe best option**
- Hodoscope may be more exposed and acceptance of back detectors may be reduced

(M. Sabaté-Gilarte & F. Cerutti) (04/08/2021) slides # 7, 8)

Front Shielding

With stainless steel shielding (SSS):

- Electromagnetic dose decreases:
  (15 MGy -> 0.7 Mgy)
- 1 MeV neq fluence no change : $4{\cdot}10^{15}$ cm^{-2}
  (Increases at R=50cm)
- Thermal neutrons no change: ~ $2{\cdot}10^{14}$ cm^{-2}

In conclusion:

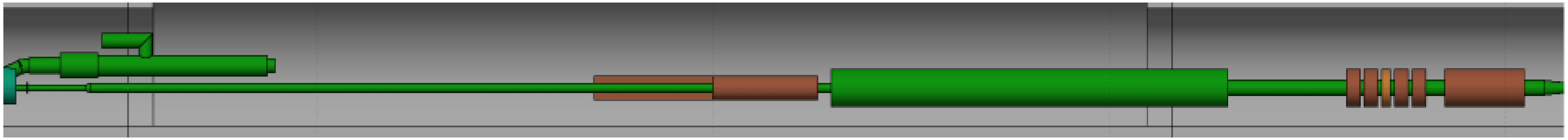
- *Inner SSS reduces EM dose.*
- *Non-ionizing dose increases*
- *Radiation field dominated by HE hadrons (charged/neutrons)*
- *Flux of charged hadrons ≈ 200/BX*

(M. Sabaté-Gilarte & F. Cerutti) (13/10/2021) slides # 4, 5, 8)

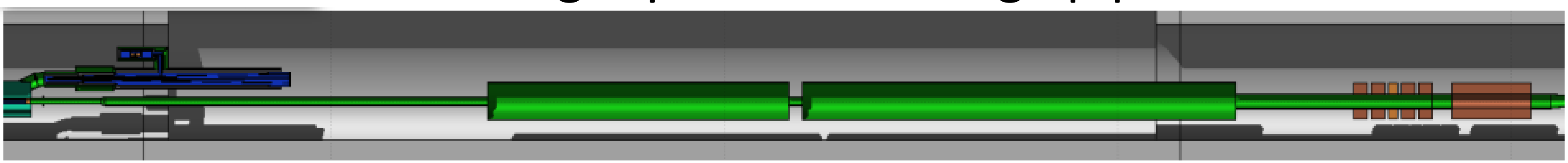
Unlikely hodoscopes survive whole HL-LHC (4000 fb^{-1}): should consider (partial/total) replacement every ≈ 1000 fb^{-1} : still reasonable/comfortable turnaround…

Conclusions confirmed... (May 3rd,2023)
(after systematic study...)

"standard" configuration with large pipe and shielding

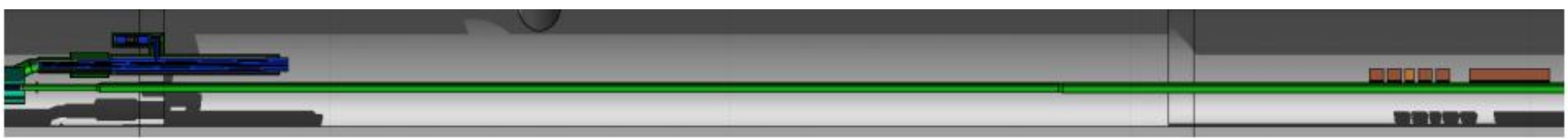


shielding replaced with large pipe



no shielding - conical shape – large pipe

"baseline" configuration - "standard" pipe



Conclusions

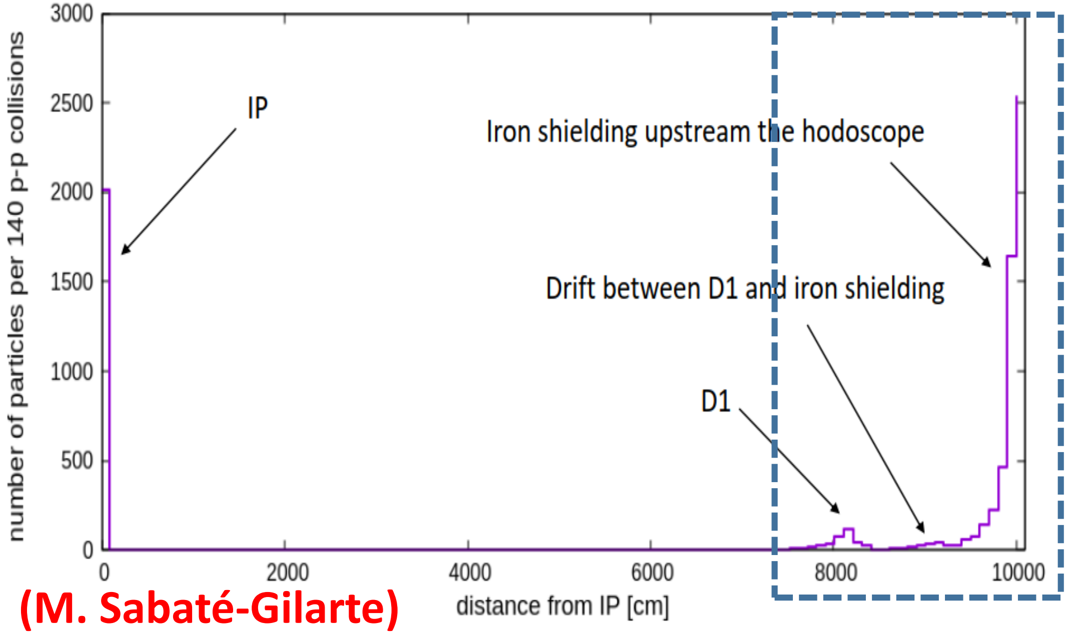
- The upstream shielding is needed to protect the calorimeter placed downstream the big-pipe.

[AP: Main point - protect back detectors (tracker, calorimeter)]

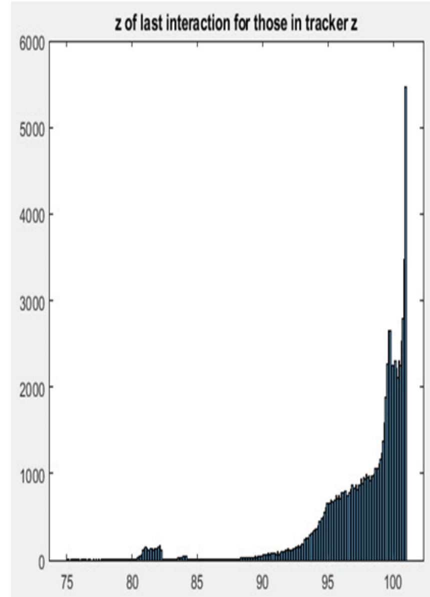
- The removal of the upstream shielding allows reducing the radiation levels and particle fluences at the hodoscope position when increasing the upstream pipe internal radius from 10.6 cm to 46 cm. However, the radiation levels at the calorimeter highly worsen.

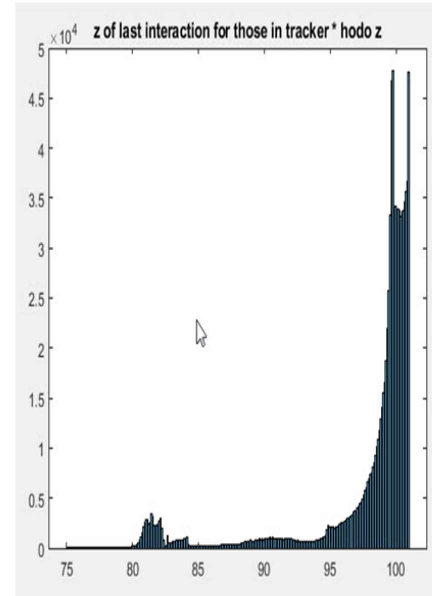
- *The vacuum chamber from D1 to the entrance of the big pipe was replaced by a series of pipes with increasing radius, emulating a conical shape. Additionally, the reserved space for the hodoscope was removed. These changes in the layout do not show an improvement in the radiation levels at the calorimeter compared to the case of removing the shielding upstream the big pipe.* [AP: Trying to replace "heavy" shielding with “tapered“ pipe doesn’t really help…. where are background particles coming from…?]

Position of "last interaction"

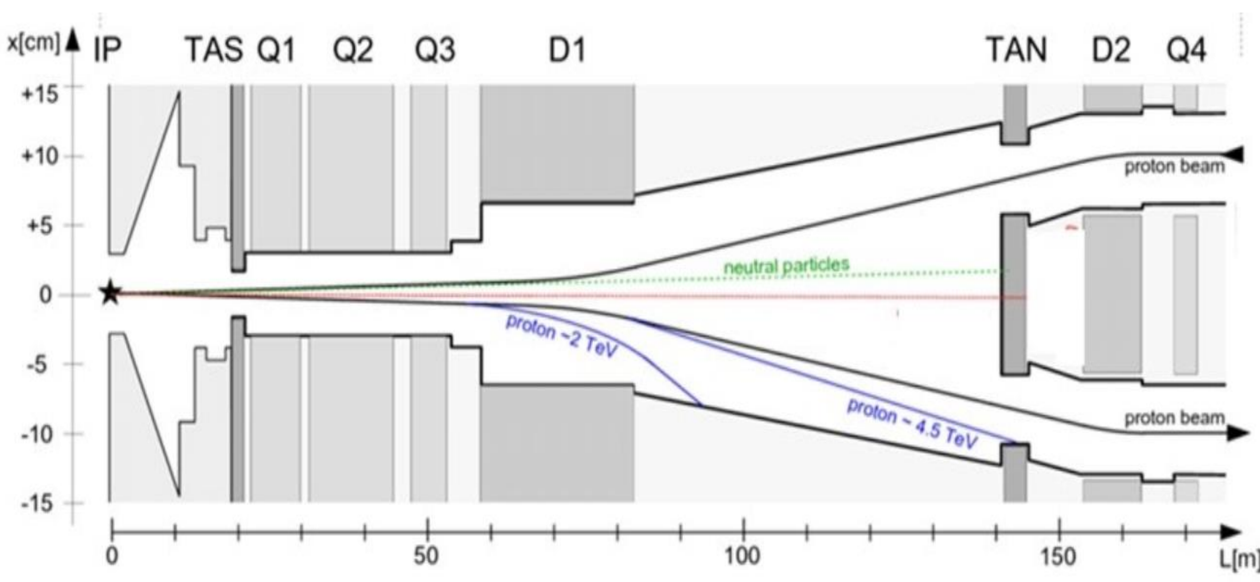


(M. Sabaté-Gilarte)





(D. Green)



Origin of particles reaching FACET:

- from IP (collision)
- from D1 edges
- from shielding

Left: neutrals
Right: charged
in tracker & hodoscope

A possible configuration for Run 4 that does not require the modification of the vacuum layout

- The latest configuration implies:
  - Going back to baseline vacuum layout.
  - Removal of the big pipe (45 cm diameter).
  - Removal of the upstream shielding.
  - Decrease of the pipe at the detector location from 18 cm to 12.5 cm Rin.
- Quantities are shown here for a fraction of the expected integrated luminosity for HL-LHC, i.e., 1000 fb^{-1} instead of 4000 fb^{-1}.
- All these modifications showed an important increase of the dose, high energy hadron fluence, charged and neutral particle fluences.

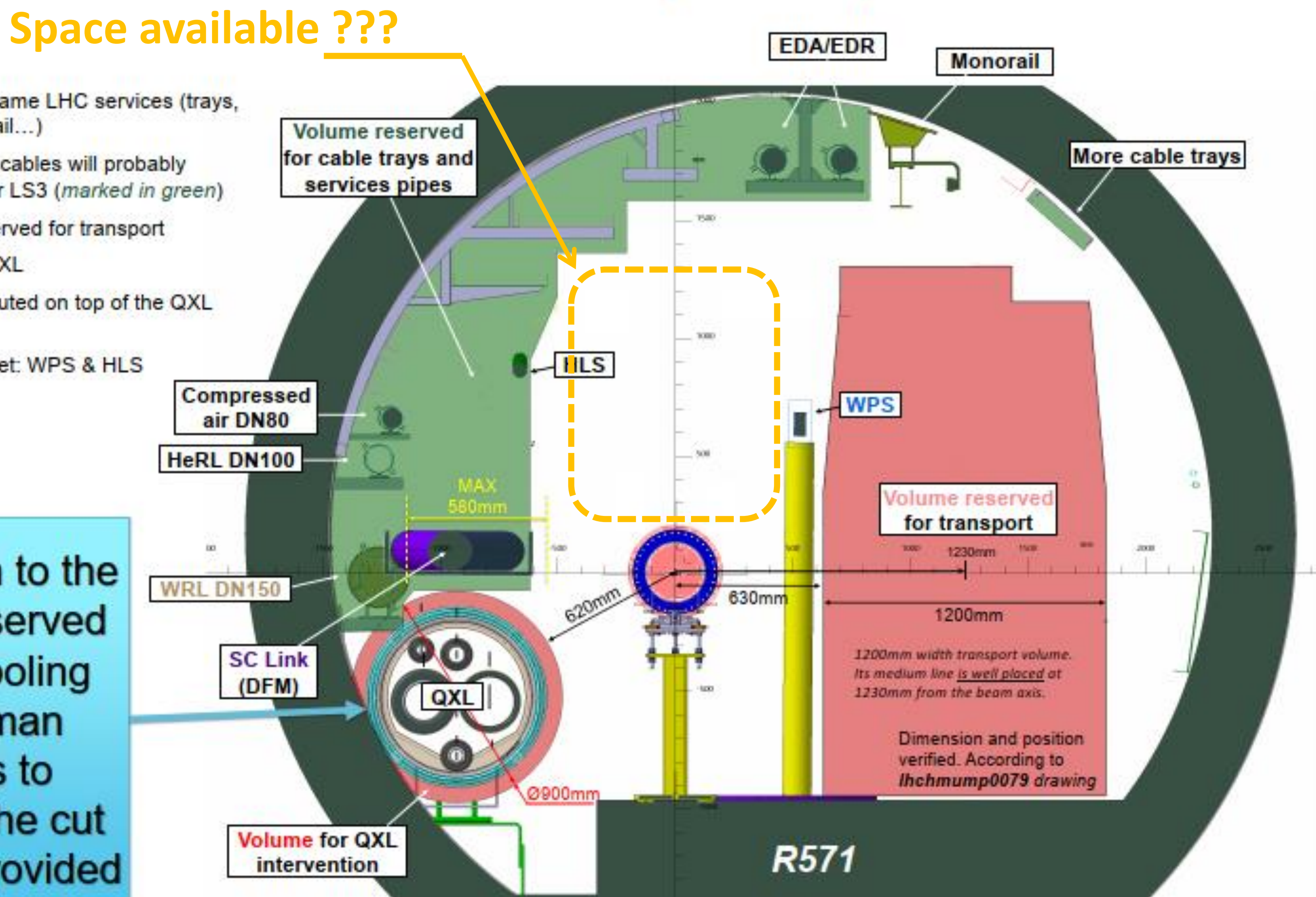
[AP: Maybe we should consider keeping the shielding?]

Cross Section 1 (120m/IP):

At least the same LHC services (trays, pipes, monorail…)

- Volume for cables will probably increase for LS3 (*marked in green*)
- Space reserved for transport
- The new QXL
- SC Link routed on top of the QXL (baseline)
- Do not forget: WPS & HLS

In addition to the space reserved for the tooling the human access to perform the cut shall be provided

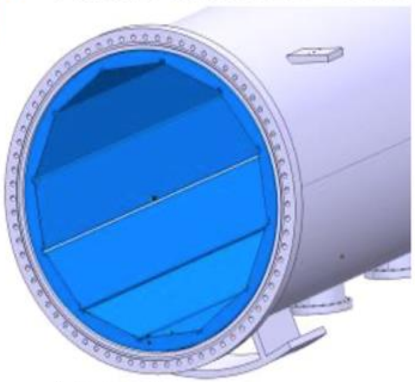


Give up large vacuum chamber ??

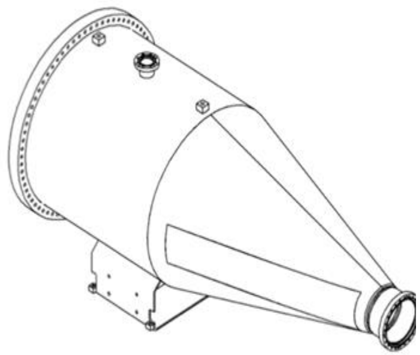
A wide aperture vacuum chamber in LHC: case of ALICE ZDC beam pipe in LSS2

- Circular Stainless Steel beam pipe with transitions from 800 to 212.7 mm
- Length over 25.7 m
- Vacuum Transition Chambers (VCT) with 15° tapering angle (impedance)
- Frame with NEG coated liners

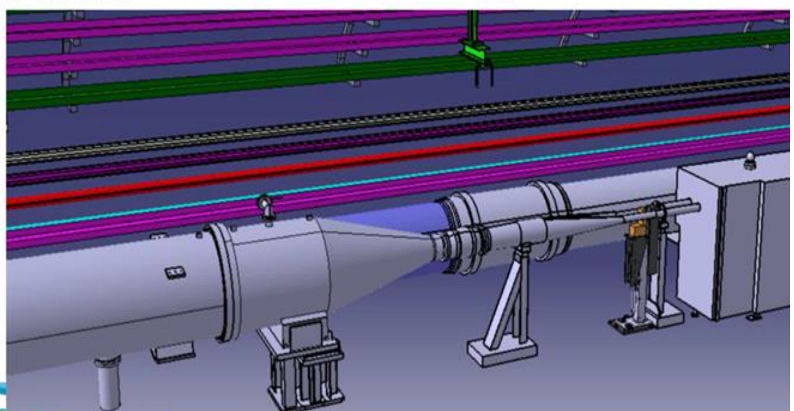
NO!
It’s already here…

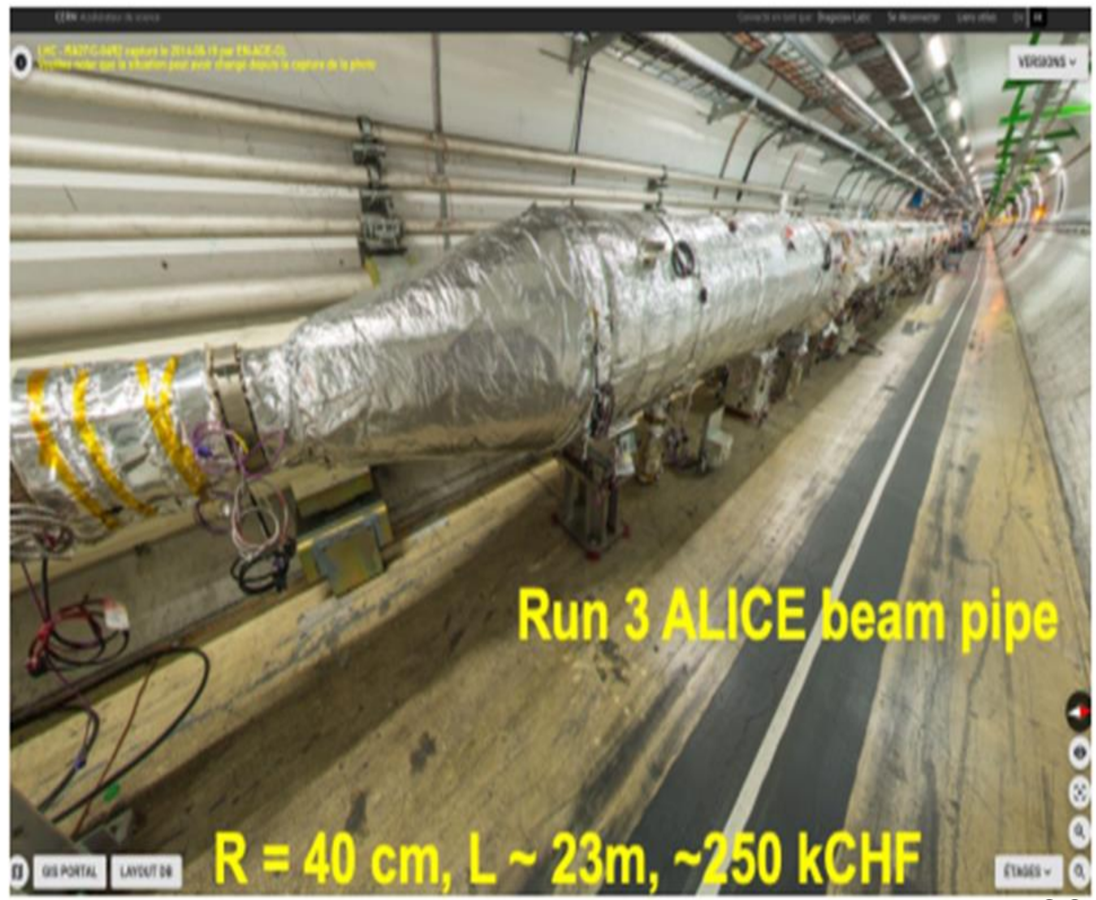


NEG liners



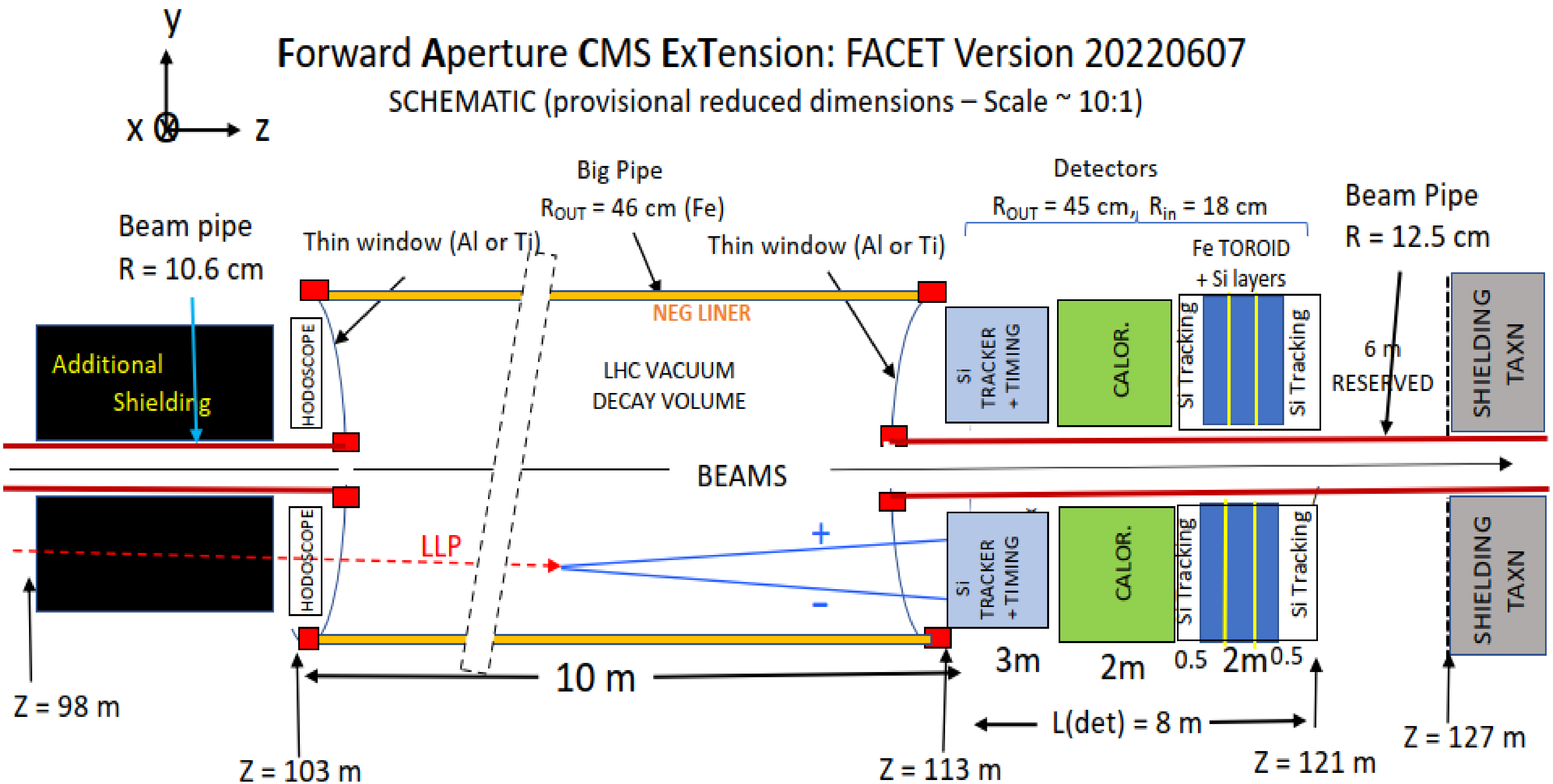
VCTCH





Forward Aperture CMS ExTension: FACET Version 20220607

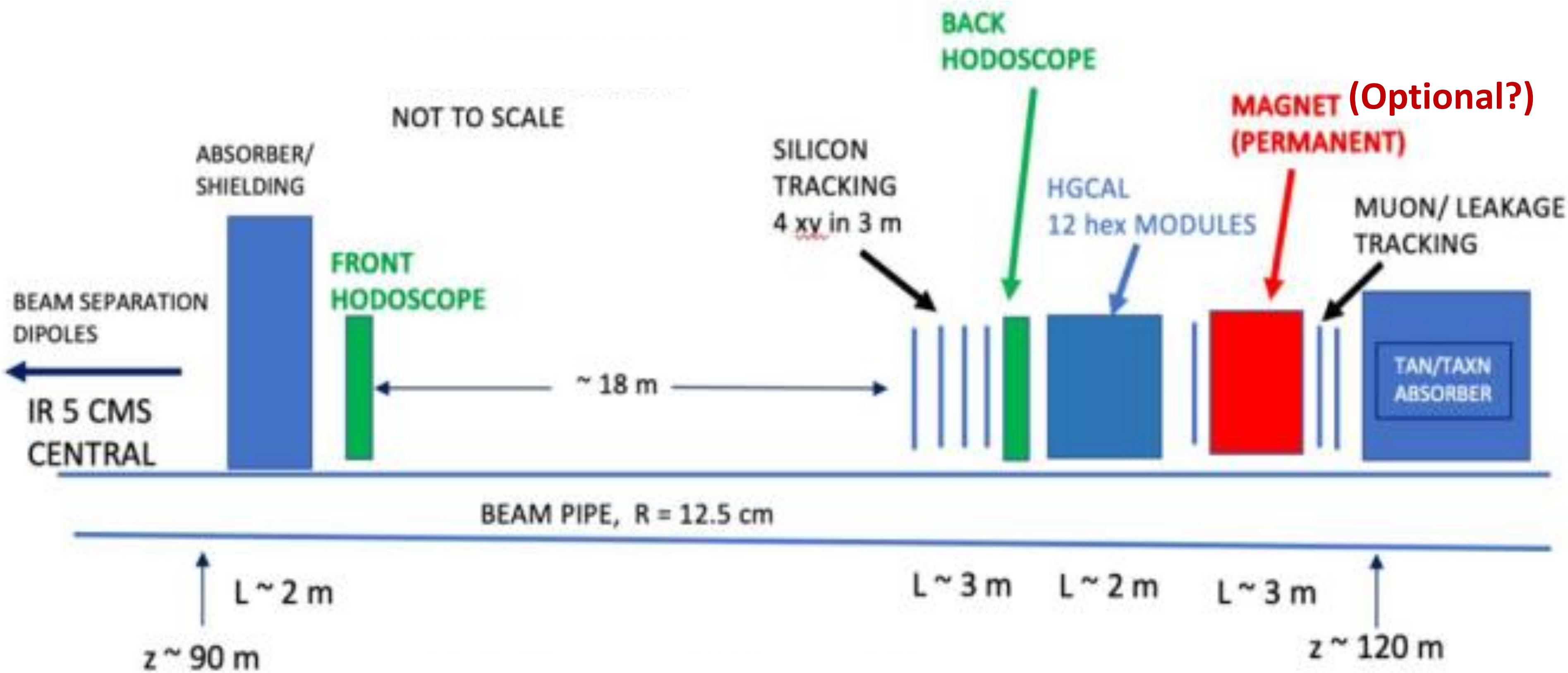
SCHEMATIC (provisional reduced dimensions – Scale ~ 10:1)



Present situation in LSS5....

Waiting for....

PRE-FACE(T)



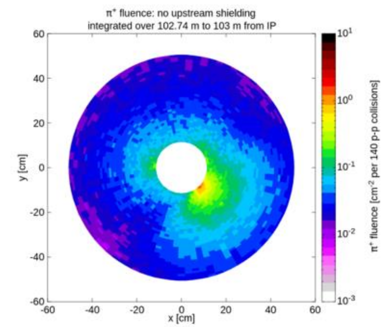
NOT TO SCALE
BACK HODOSCOPE
MAGNET (PERMANENT)
(Optional?)
ABSORBER/ SHIELDING
SILICON TRACKING 4 xy in 3 m
HGCAL 12 hex MODULES
MUON/ LEAKAGE TRACKING
FRONT HODOSCOPE
BEAM SEPARATION DIPOLES
IR 5 CMS CENTRAL
~ 18 m
TAN/TAXN ABSORBER
BEAM PIPE, R = 12.5 cm
L ~ 2 m
L ~ 3 m
L ~ 2 m
L ~ 3 m
z ~ 90 m
z ~ 120 m

Wrap up…

- FACET project gaining interest and momentum

Good balance of sensitivity - background mitigation

Actively seeking financing…



- Main issues:

Hot spot at 4 o' clock:

- mitigated for back detectors with shielding
- optimized hodoscope (rad hard, fast, segmented)
- exclude 4 o' clock azimuth

- Big vacuum chamber "timed out" for Run 4:

- wait for Run 5? *(a bit too late for some collaborators…)*
- aim to Run 4 without big pipe …
  (study acceptance, background, new signals…)

Backup slides

Dark Photons

Maksym Ovchynnikov et al., Sensitivities to **Feebly Interacting Particles (FIP)**
arXiv:2305.13383v1 [hep-ph] 22 May 2023 *(submitted to JHEP)*

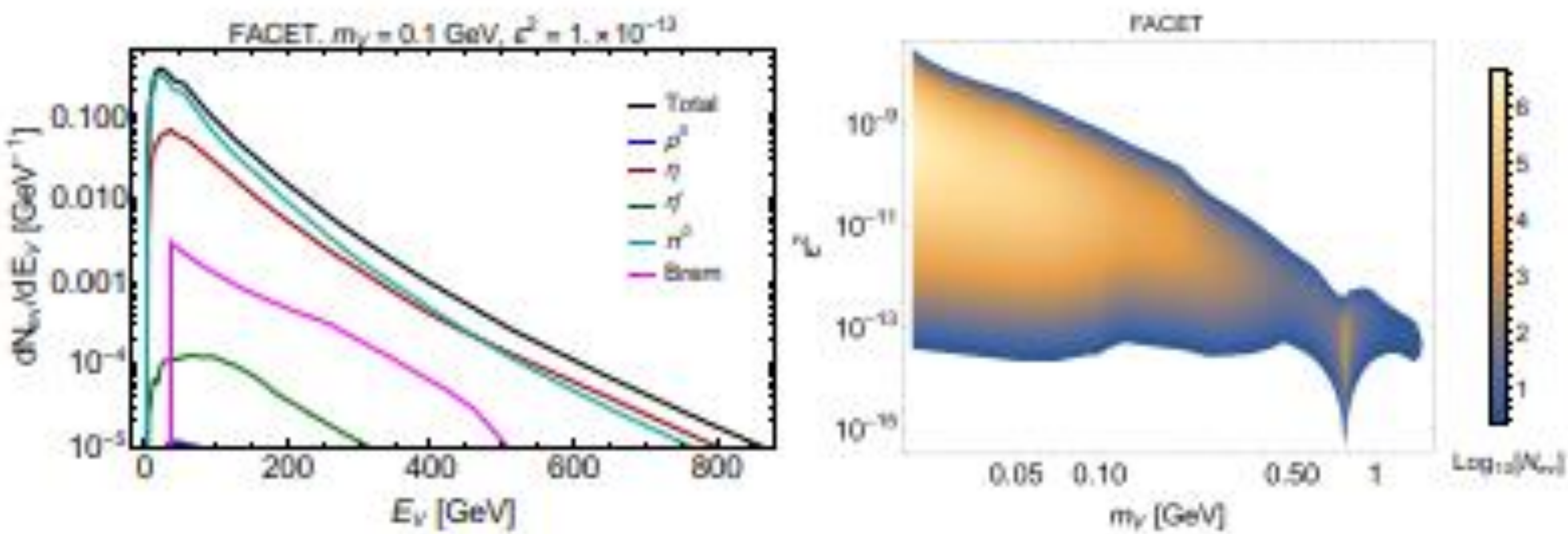


Figure 8. Examples of the output produced by the notebook `FIP sensitivity.nb`. **Left panel**: differential number of events with respect to the FIP's energy for various production channels. **Right panel**: density plot of the total number of events as a function of the FIP mass and coupling. As an example, dark photons at FACET are considered. No cuts on the decay products other than the geometric acceptance have been applied.

Brian Batell et al., Exploring Dark Sector Portals with High Intensity Experiments
arXiv:2207.06905v3 [hep-ph] 29 Sep 2022

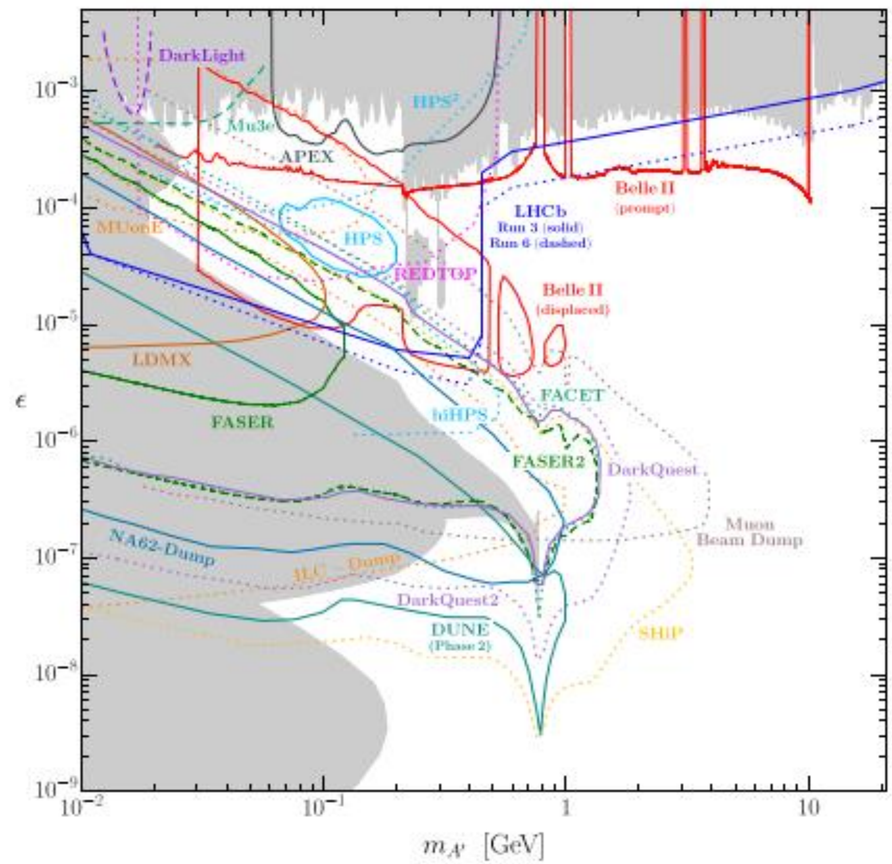


FIG. 3: *Minimal vector portal model.* Existing constraints (gray shaded region) and future experimental projections (colored contours) are shown in the $m_{A'} - \epsilon$ plane. The existing bounds are from Refs. [13–32]. Also shown are projections from a number of existing and proposed future experiments, including DUNE [33], Belle II [34–36], LHCb [37], FASER and FASER2 [38, 39], HPS [40], NA62-Dump [6], LDMX [41], DarkQuest [42], APEX [43], Mu3e [44], DarkLight [45], FACET [46], REDTOP [47], MUonE [48], SHiP [49], an ILC beam dump experiment [50, 51], and a muon beam dump experiment [52].

Enrico Bertuzzo et al., Searching for inelastic dark matter with future LHC experiments

arXiv:2201.12253v2 [hep-ph] 12 Jul 2022

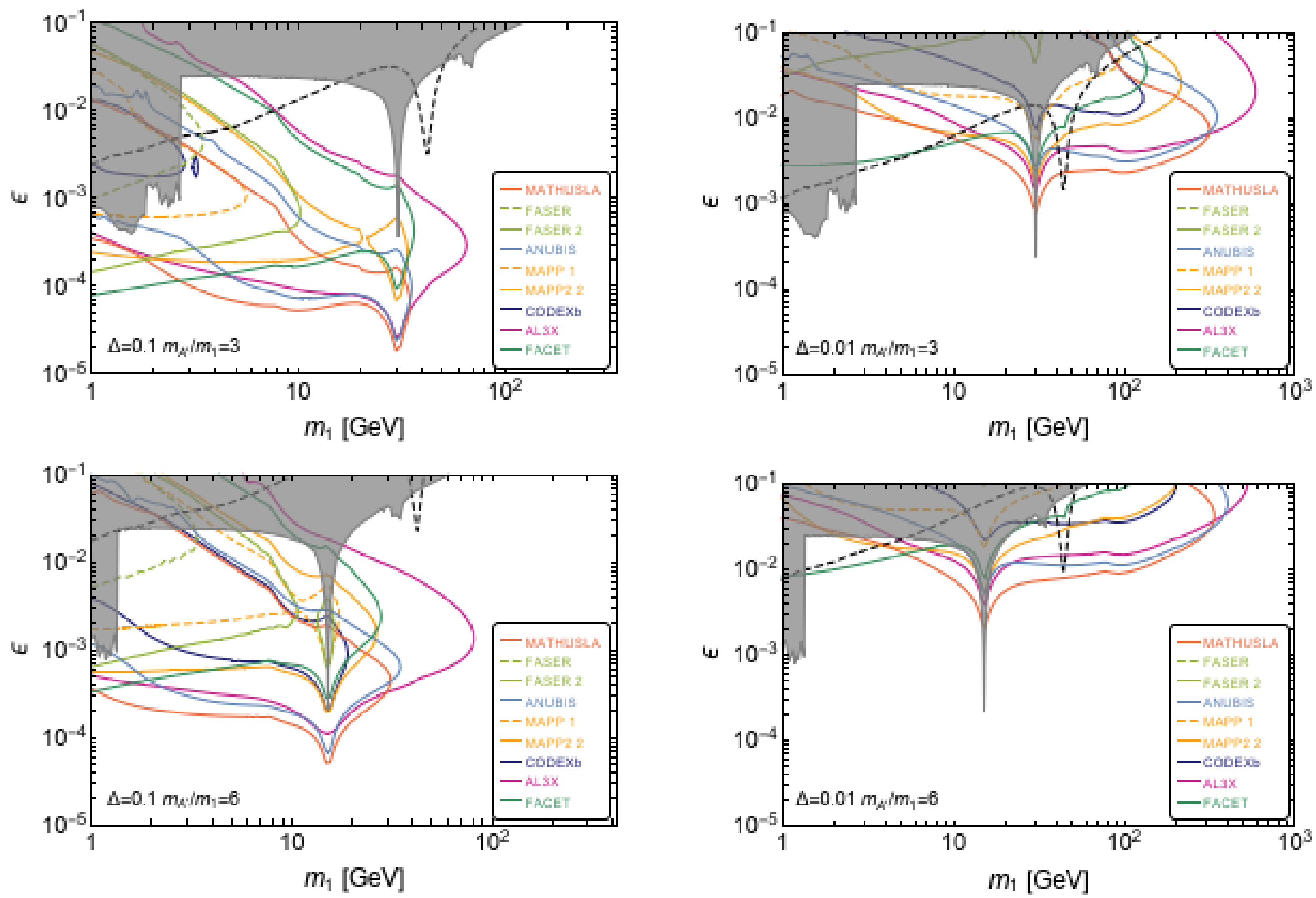
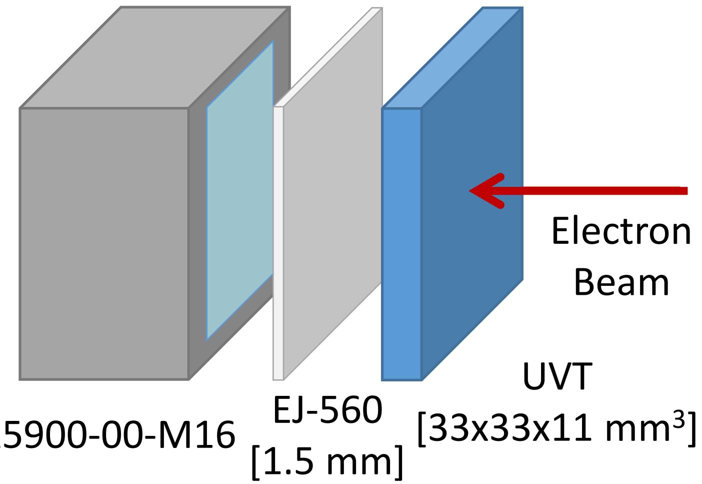


Figure 1: Projected sensitivities of proposed future experiments (coloured lines) and existing constraints (grey regions) on the model of fermionic iDM described in Sec. 2.1 in the $m_1 - \epsilon$ plane for $\Delta = \{0.1, 0.01\}$ and $m_{A'}/m_1 = \{3, 6\}$. The dashed black contour depicts where the abundance of the χ_1 matches the observed dark matter energy density.

Beam tests of Pad Hodoscope

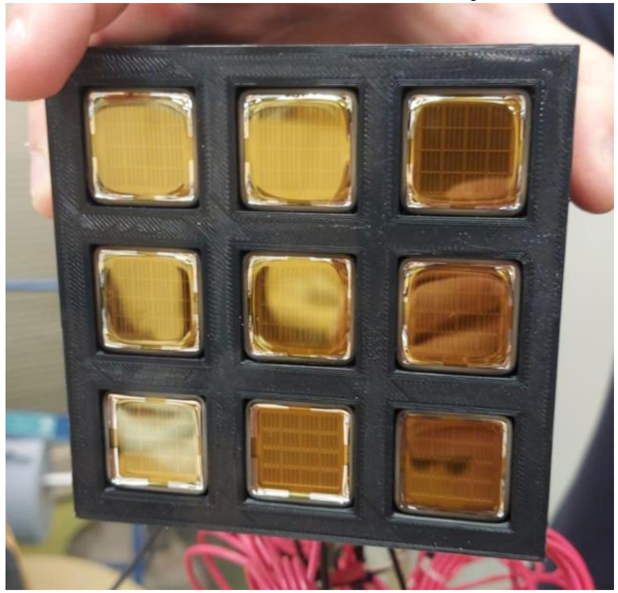
Beam: Electron (40,60,80,100 GeV), Pion (100 GeV)
Radiators: UVT($33x33x11\ mm^3$)
PMTs: Hamamatsu R5900-00-M16 (Sum of 16 ch)

Assembly of PMT and Radiators



Single PMT+ UVT

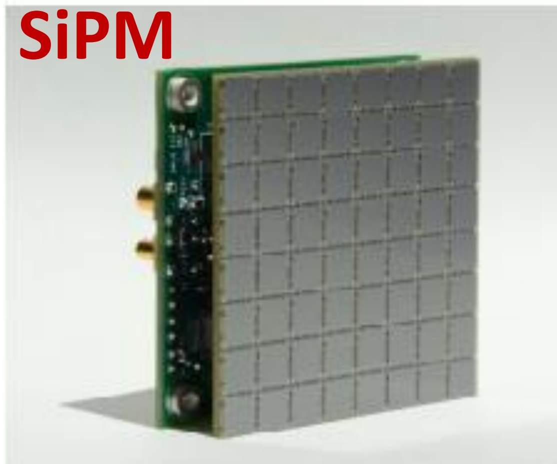
Array of 3x3 PMT+UVT



Front side - PMT windows

Back side - Cables

SiPM



SiPM arrays with glass radiators also available

Vertilon