BSM and SM signals and backgrounds in Far-Forward Experiments at the LHC

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with input from many authors of the FPF Snowmass reports:
- arXiv:2109.10905, published in Phys. Rept. 968 (2022), 1-50,
- arXiv:2203.05090, to be published in J. Phys G.: Nuclear and Particle Physics

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Diffraction and Low-x 2022
Corigliano Calabro + zoom, Italy, September 24 - 30, 2022

Far-forward LHC experiments

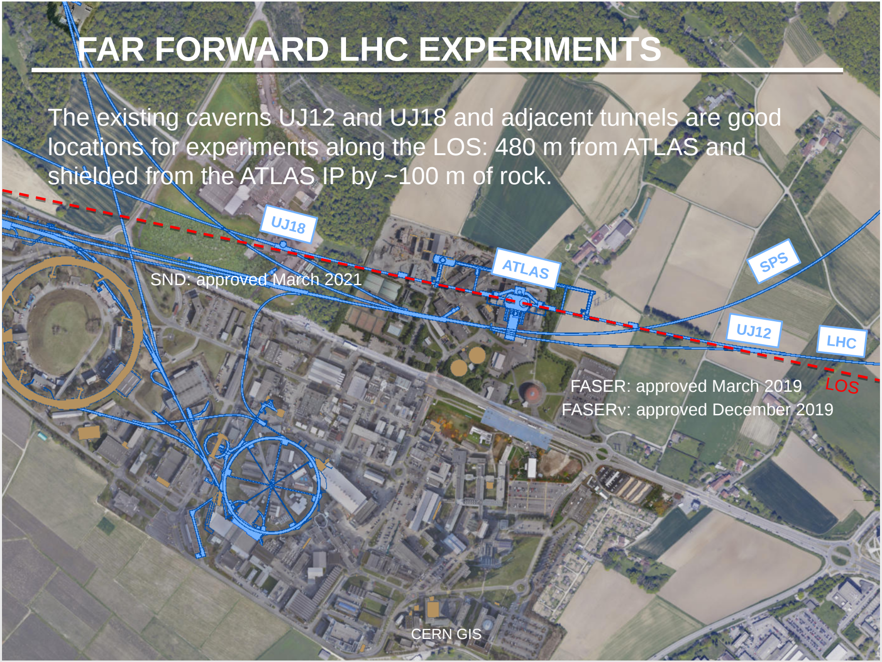
* Various projects to exploit beams of particles produced in the interactions points at the LHC, propagating in the direction tangent to the accelerator arc.

* Let these beams propagating for some distance, until they interact either with the material on the way or with the material of one or more detectors.

* Pilot experiments, on the tangent to the LHC beam line, at $\sim$ 480 m from ATLAS IP:
  - FASER, Faserν and SND@LHC, all active in taking data during Run 3.

FAR FORWARD LHC EXPERIMENTS

The existing caverns UJ12 and UJ18 and adjacent tunnels are good locations for experiments along the LOS: 480 m from ATLAS and shielded from the ATLAS IP by ~100 m of rock.



Particle Fluxes at far-forward LHC experiments

$*$ Not all kinds of particles produced in the forward region of the LHC IP can be seen at the location of the experiments: LHC optical elements and rock are on the way.

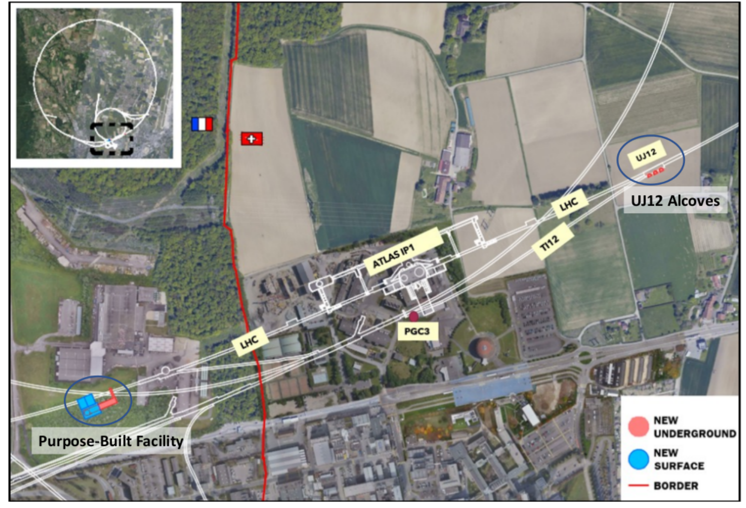
$*$ Among the particles produced at the IP or nearby, forward ν, μ and some kinds of BSM particles will reach the detectors.

$*$ ν forward fluxes: intense and very energetic, with $\mathcal{O}$(TeV) particles (peak in the energy spectrum much larger than for fluxes seen in other accelerator neutrino experiments, like e.g. DUNE).
Unique energetic regime $\Rightarrow$ Unique Measurements $\Rightarrow$ Interesting SM physics program.

$*$ BSM LLPs: searches in the low mass / large $c\tau^0$ domain, complementary to searches at ATLAS/CMS/LHCb for which LLPs decaying beyond the spatial limits of the detector infrastructure are "missing energy".

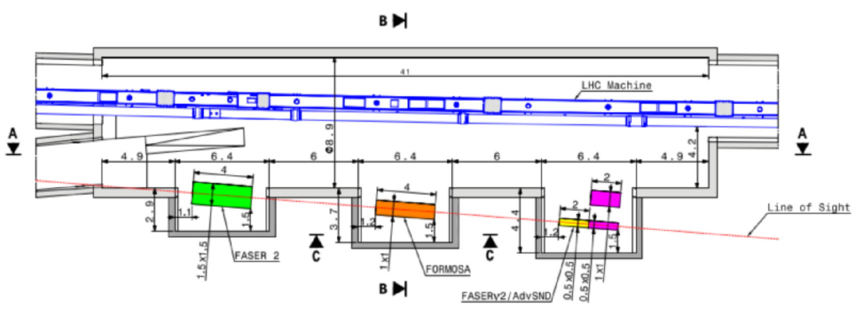
$*$ Present far-forward experiments limitations: space for positioning bigger detectors and increase sensitivity for SM and BSM searches is missing!

Possibilities for a FPF at the LHC



- dedicated facility
- enlargement of one of the existing caverns with alcoves

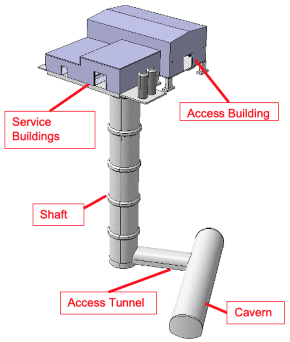
Alcove option

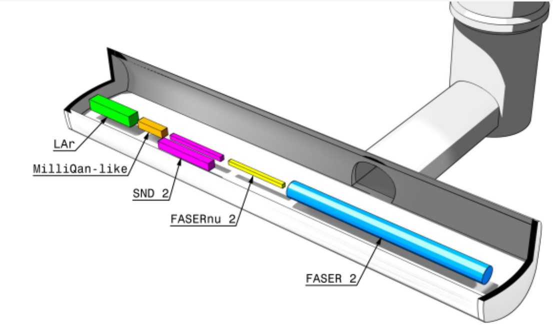


The LoS touch marginally UJ12. One could envisage to enlarge UJ12 to better encompass the LoS, with alcoves for different experiments.

The Forward Physics dedicated Facility @ HL-LHC

A new large infrastructure, capable of simultaneously hosting a suite of experiments dealing with forward ν, μ and BSM particles interacting with the targets and/or decaying.





- Access possible during LHC operation
- Easier access than in LHC side caverns.
- It might be designed around the need of the experiments.

The Forward Physics Facility @ HL-LHC

A new large infrastructure, capable of simultaneously hosting a suite of experiments dealing with forward ν, (μ) and BSM particles.

Questions currently under study:
- size and lenght ?
- at which angle positioning the various detectors ? ($6 \lesssim \eta \lesssim 10$)
- which detection technology and materials ?
- how to control the backgrounds ?

$\Rightarrow$ The answers partly depend on the physics one wants to explore, partly on the morphology of the experimental environment.

E.g. ν interactions are signals for SM searches,
whereas act as a background for BSM searches!

Experience built on top of experiments active during Run-3 will help!

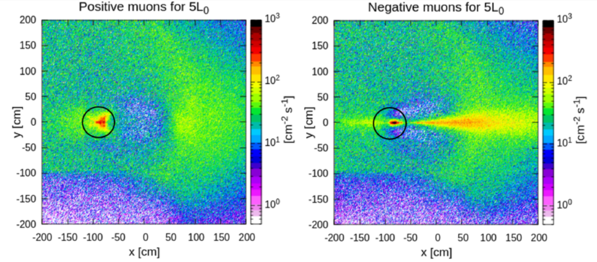
The experiments

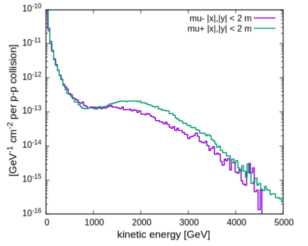
- advanced SND@LHC: neutrinos, light DM
- Faserν2: neutrinos, light DM
- FLArE: neutrinos, light DM and mCP
- FASER2: decays of LLPs (dark bosons, dark scalars, HNLs, ALPs....)
- FORMOSA: mCP

Some additional studies for heavy BSM particles (e.g. SUSY neutralinos) have also been carried out.

As for forward muons, they are currently considered more as a background disturbing the searches, than as a resource to enlarge the physics program.

Muon fluence rate and fluence energy spectra in the transverse plane, on the way to the FPF

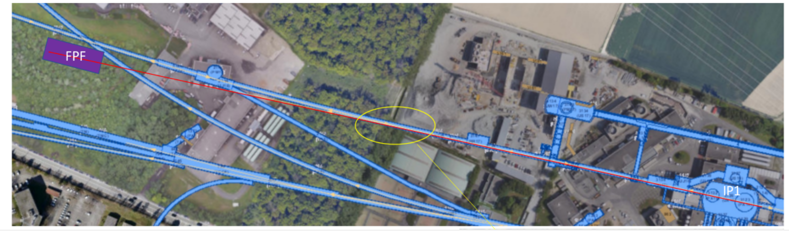


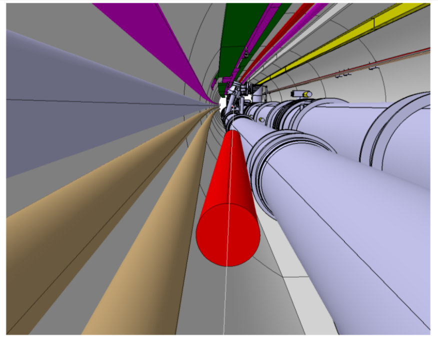


∗ FLUKA simulations on a 4 x 4 m^2 area transverse to the LoS at 348 m from the ATLAS IP, for the nominal HL-LHC integrated luminosity.

∗ Proposal to deflect as much muons as possible through a sweeper magnet.

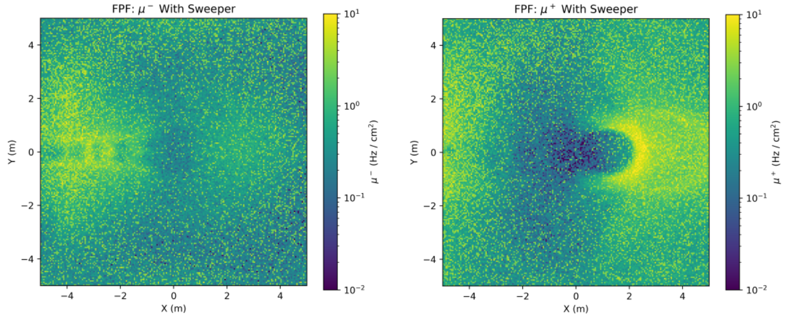
The sweeper magnet location





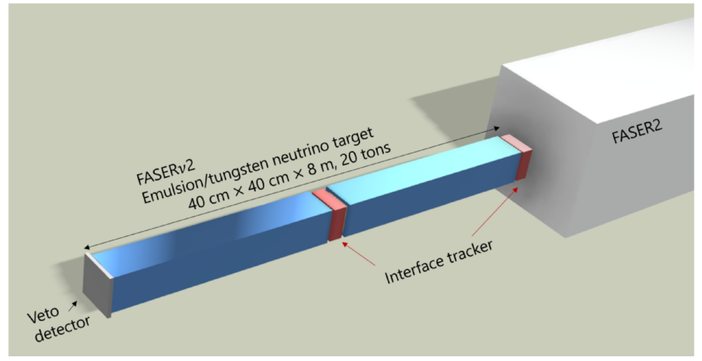
Side view of the sweeper magnet along the LoS, at the location where the LOS leaves the beampipe.

Muon fluence rate at the entrance of the FPF



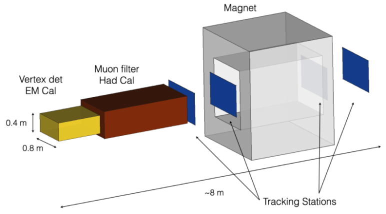
$\ast$ BDSIM simulations on a 4 x 4 m^2 area transverse to the LoS at 617 m from the ATLAS IP, including sweeper magnet effects, for the nominal HL-LHC integrated luminosity.

Faserν2 for ν Physics / QCD / BSM (light DM)



- on-axis ($\eta \gtrsim 8.5$),
- large target mass (20 tons) to maximize ν interaction rates,
- possibility to identify different lepton flavours,
- capability to reconstruct the EM shower energy / muon momentum $\rightarrow E_\nu$
- μ^+ and μ^- distinguished thanks to the interface to FASER2.

Advanced SND@LHC for ν Physics / QCD / BSM

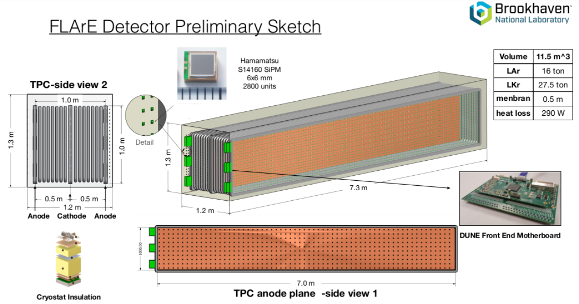


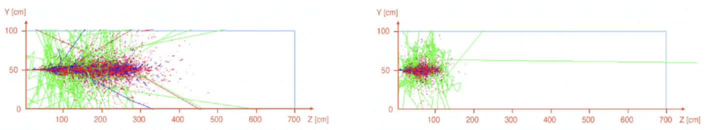
AdvSND - FAR				
	ν in acceptance		CC DIS	
Flavour	hardQCD: $c\bar{c}$	hardQCD: $b\bar{b}$	hardQCD: $c\bar{c}$	hardQCD: $b\bar{b}$
$\nu_\mu + \bar{\nu}_\mu$	6.3×10^{12}	1.5×10^{11}	1.2×10^4	200
$\nu_e + \bar{\nu}_e$	6.7×10^{12}	1.7×10^{11}	1.2×10^4	220
$\nu_\tau + \bar{\nu}_\tau$	7.1×10^{11}	4.7×10^{10}	880	40
Tot	1.4×10^{13}		2.5×10^4	

AdvSND - NEAR				
	ν in acceptance		CC DIS	
Flavour	hardQCD: $c\bar{c}$	hardQCD: $b\bar{b}$	hardQCD: $c\bar{c}$	hardQCD: $b\bar{b}$
$\nu_\mu + \bar{\nu}_\mu$	2.1×10^{12}	3.3×10^{11}	980	200
$\nu_e + \bar{\nu}_e$	2.2×10^{12}	3.3×10^{11}	1000	200
$\nu_\tau + \bar{\nu}_\tau$	2.7×10^{11}	1.4×10^{11}	80	50
Tot	5.4×10^{12}		2.5×10^3	

- two off-axis detectors, with coverage $4 < \eta_\nu < 5$ (NEAR) and $7.2 < \eta_\nu < 8.4$ (FAR)
- vertex reconstruction and EM energy measurement (electronic trackers),
- 5 ton target mass,
- hadronic calorimeter and muon identification,
- magnet to separate μ^+ and μ^-,

FLArE for ν Physics / QCD / BSM (light DM, mCP)





- On axis,
- large target mass (15 - 30 tons) to maximize ν interaction rates,
- either LArTPC or LKrTPC, with excellent spatial/kinematic resolution over energies from 10 MeV to hundreds of Gev, to identify particles, ν flavour and measure DM and ν cross-sections
- excellent time resolution (coincidences with ATLAS ?)

QCD opportunities with forward neutrinos during the HL-LHC phase

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New facility: Forward Physics Facility @ CERN capable of hosting a suite of experiments exploiting forward neutrinos produced at one of the LHC interaction points and propagating for several hundred meters in the direction tangent to the accelerator arc

New pilot experiments:
Faser2, Faser-ν, SND@LHC, MilliQan

Physics Opportunities:
* Proton Parton Distribution Functions
* Nuclear Parton Distribution Functions
* NP QCD and Tuning of Monte Carlo event generators
* Forward charged pions and kaons
* Forward heavy-flavoured hadrons

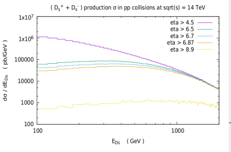
Proton Parton Distribution Functio
* Low x ($x < 10^{-6}$) gluon at $Q^2 > 1$ GeV^2 probed by other experiments so far!

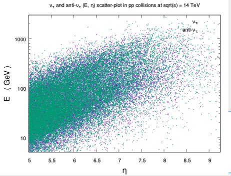
Nuclear Parton Distribution Functions
* Measurements of CC and NC ν - A and $\bar{\nu}$ - A DIS cross-sections using various targets
* u and d quark flavour separation
* DIsentangling strange sea asymmetries
* Complementary to EIC e-A scattering studi

NP QCD and Tuning of MC event generat
* New data for testing the robustness of phenomenological models describing NP physics in MC (e.g. NP MPI, beam remnant effects, hadronization, branching fractions) and tuning their parameters.

Forward heavy-flavour
* NP effects in heavy-flavour production
* Interplay with perturbative effects
* Universality of FF
* Intrinsic heavy-flavour and higher-twist

Forward charged pions and kaons
* NP effects in light-flavour production
* Cosmic Ray EAS applications





Open questions:
* how to disentangle SM and BSM effects ?
* how to measure forward lepton fluxes and disentangle them from cross-sections ?

Work supported by BMBF contract 05H18GU

See also W. Bai, M. Diwan, M.V. Garzelli, Y.-S. Jeong, M.H. Reno, *"Far-forward neutrinos at the LHC"*, hep-ph/2002.03012, JHEP **2006** (2020) 032.

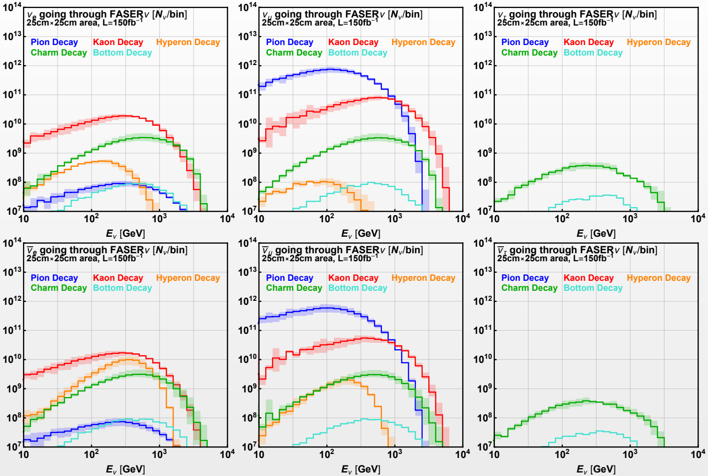
For further info:
* 2nd Forward Physics Facility Meeting online – 27 – 28 May 20
https://indico.cern.ch/event/1022352 !Registration ope
* Forward Physics Facility Kick-off meeting – 9 – 10 Nov 2020

presented at the APS Meeting "Quarks to Cosmos", April 2021

How to disentangle particle fluxes from particle cross-sections ?

* The detectors will measure observables from the **convolution** of **fluxes** (production + propagation) and **interaction** σ with target.
* Capability to distinguish might be more important for SM precision constraints than for BSM searches...
* For example, SM objectives of the FPF experiments may include:
    - Constraining forward particle production in *pp* collisions (of interest for better modelling soft physics and tuning the related parameters in MC event generators): it works well under the assumption: *"we precisely know neutrino cross-sections"*.
    - constraining PDFs/nPDFs through neutrino DIS with target in detector (of interest for ALICE/ATLAS/CMS/LHCb SM and BSM programs at HL-LHC): it works under the assumption: *"we precisely know neutrino fluxes"*.

Examples of MC predictions of forward ($\nu + \bar{\nu}$) fluxes



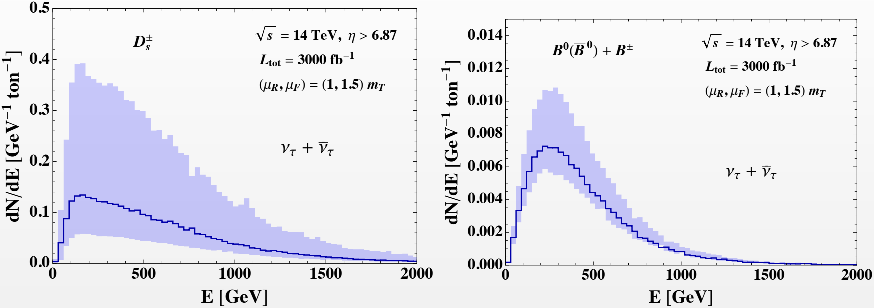
from Faserν collab. [arXiv:1908.02310]

Estimated number of ν impinging on the transverse area of the FASERν detector.

Uncertainty band: envelope of the central predictions of different MC generators.

How to estimate a more reliable uncertainty band ?

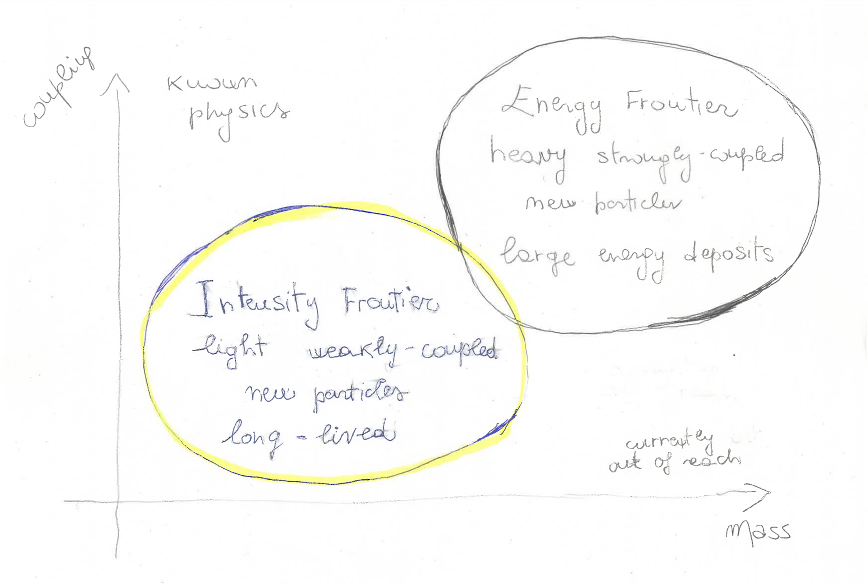
Energy distribution of CC $(\nu_\tau + \bar{\nu}_\tau)$ events



, *from W. Bai et al. [arXiv:2002.03012]*

- Huge uncertainty band from state-of-the-art QCD calculations.
- Missing higher-order pQCD contributions are probably large.
- In case of bottom production, uncertainty is smaller (+60%, -20%) than for charm (+300%, -60%) in relation to the fact that $m_b > m_c$ $\Rightarrow \alpha_S(\mu_R = m_b) < \alpha_S(\mu_R = m_c)$.
- Additional uncertainties due to focus in forward region.

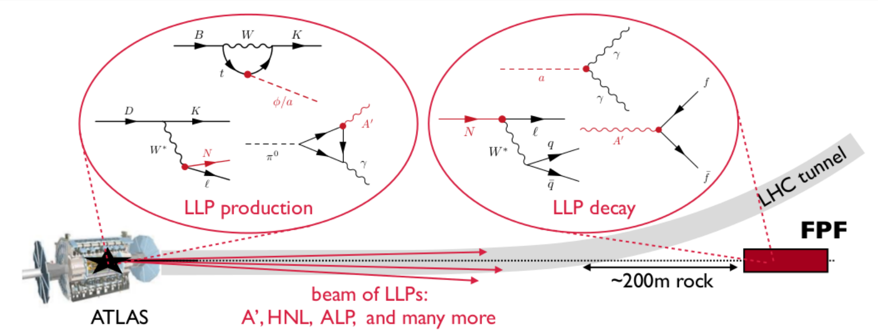
Which BSM particles can be better studied in the LHC forward region ?



Search for light BSM particles

Most (but not all) BSM searches at the FPF focus on:

- LLPs (vectors, scalars, fermions, pseudoscalars) exclusively coupled to the SM in minimal models, decaying in the FPF detectors:



- LLPs in non-minimal models

- LLPs coupled to light DM, with DM decaying or interacting in the FPF detectors.

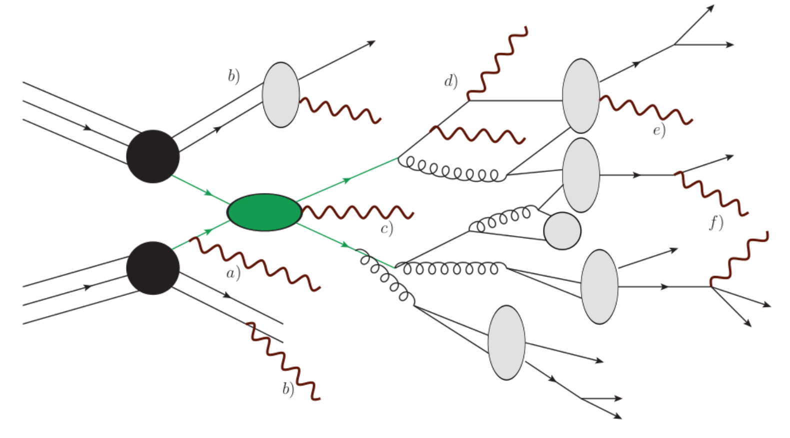
How are LLP produced ?

Depending on the LLP, the production mechanism can be:

- Meson decays at the IP
- proton bremsstrahlung
- Drell-Yan
- ISR, FSR
- hadronization
- emissions from beam remnants

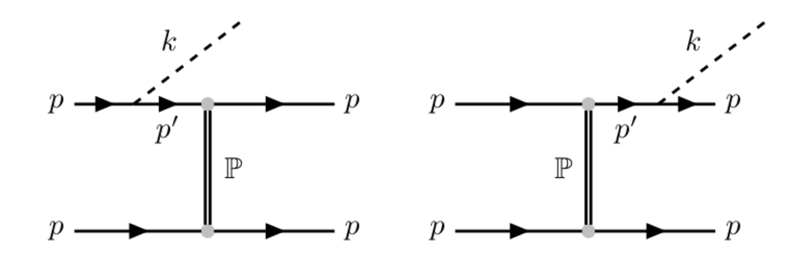
To have reliable production for the LLP flux, we need to control all these processes, starting from reliable predictions in the forward region for the SM case, and extending them to BSM !

Example: dark photon production



Dark photons are under incorporation in Shower Monte Carlo event generators

Example: dark scalar radiation from proton bremsstrahlung



- ISR and FSR in *pp* quasi-elastic scattering (*t*-channel pomeron exchange)

- ISR-FSR interference suppress dark scalar emission.

- On the other hand in non-single diffractive scattering, interference is not expected.
- Analogous considerations work for dark photons.

PBC BSM Benchmark Cases

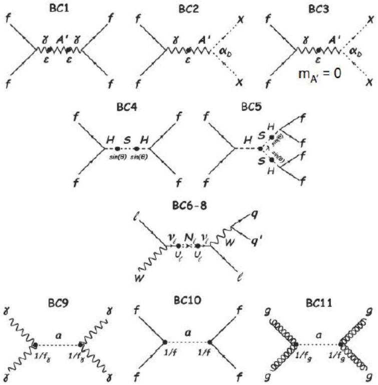
The BSM WG selected a set of theoretically and phenomenologically motivated target areas used as benchmarks models to explore the physics reach of the received proposals and put them into the worldwide landscape.

Dark Photons, Dark Matter & millicharged particles

Dark Scalars

Heavy Neutral Leptons

Axion-Like Particles

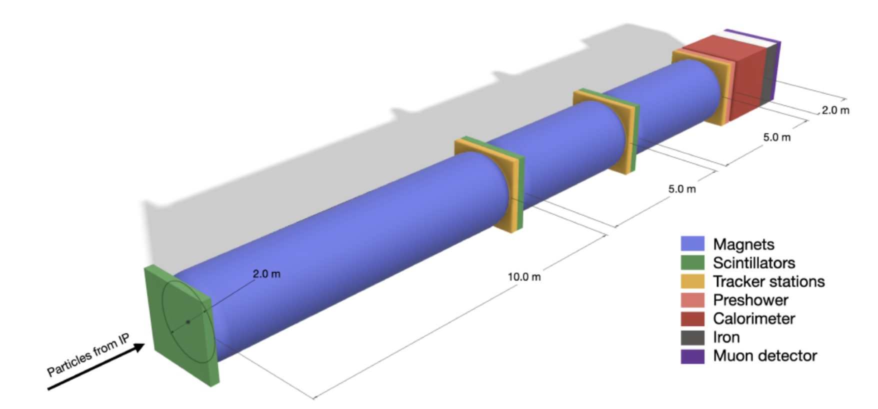


from M. Lamont, PBC presentation @ MITP, november 2020

∗ 11 models for light, weakly-interacting particles (LLPs, FIPs)

∗ BC1, BC4-11 covered by FASER, FASER2; BC2 and BC3: other FPF exper..

FASER2 for BSM physics



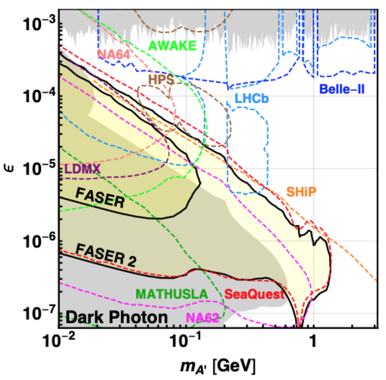
w.r.t. FASER, FASER2 has:

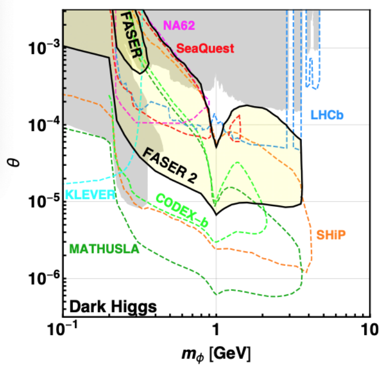
- larger radius → improved sensitivity on LLP's with larger mass
- large detector lenght → larger separation between LLP's decay products
- larger background → need for more advanced trigger and data analysis techniques

BCs 1, 4-11: LLPs at FASER and FASER2

∗ Run-3 integrated luminosity is enough for FASER to discover new physics for some of the Benchmark Cases.

∗ FPF will provide space to upgrade FASER (R = 10 cm, L = 1.5 m) to FASER2 (R = 1.0 m, L = 5 m), either greatly enhancing sensitivity (e.g. for A' - visible mode) or by providing new prospects (e.g. for S), complementary to other experiments.

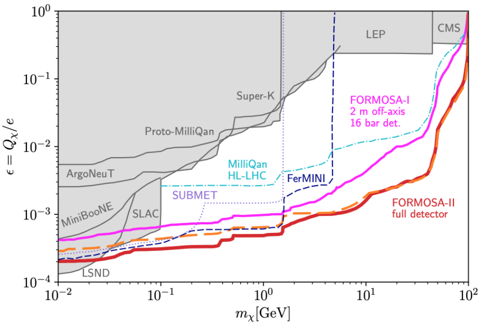




from FASER Collaboration, [arXiv:1811.12522]

BC3: Milli-charged particles

* This is currently the target of the MilliQan experiment, near the CMS IP.
* MilliQan Demonstrator already probes an otherwise uncovered region. Full MilliQan planned to run in the same location at HL-LHC. However, sensitivity can be improved significantly at the FPF (FORMOSA)



from MilliQan/FORMOSA

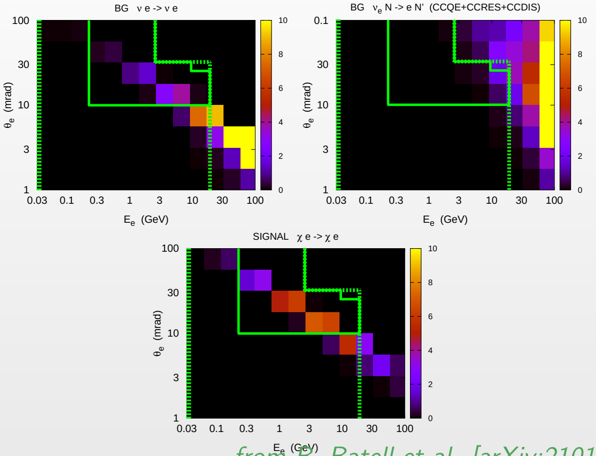
Light DM searches at the FPF: a simple testable model

* Hypothesis: DM particles χ in a hidden sector coupled to the SM through a dark photon A' with $m_\chi < m_{A'} << m_{EW}$.
  Parameter space $\{m_{A'}, \epsilon, m_\chi, \alpha_D\}$
* A' produced either by $pp \to ppA'$ (proton bremsstrahlung) or through $pp \to \pi^0, \eta, ... + X \to A'\gamma + X$
* followed by $A' \to \chi\,\chi$ decay.
* Signal at FPF detectors (LAr TPC or emulsion detector): $\chi e^- \to \chi e^-$
* Backgrounds at FPF detectors:
  - CC $\nu_e e^- \to \nu_e e^-$, $\bar{\nu}_e e^- \to \bar{\nu}_e e^-$
  - NC $\nu_i e^- \to \nu_i e^-$, $\bar{\nu}_i e^- \to \bar{\nu}_i e^-$
  - CC and NC νN interactions.
  - $\mu \to \mu\gamma \to \mu e^+ e^-$

from B. Batell et al. [arXiv:2101.10338]

Light DM searches: signal/background discrimination

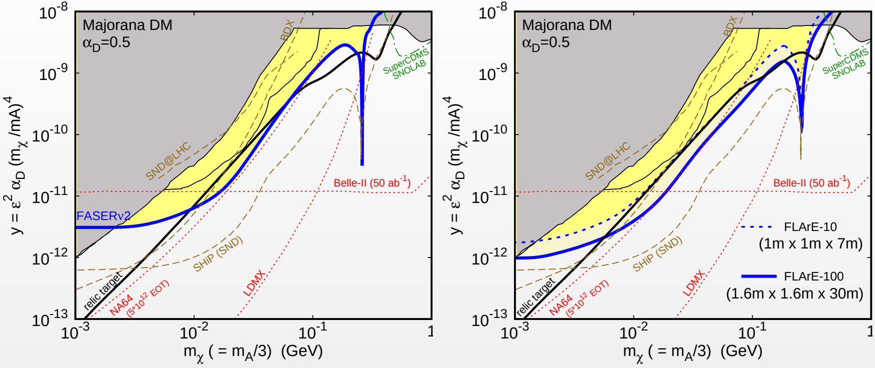
* ν induced background can be eliminated because signal and background occupy different regions of the $(E_{e,rec}, \theta_{e,rec})$ plane.



from B. Batell et al. [arXiv:2101.10338]

* μ induced background can strongly be reduced by sweeper magnets or active μ vetos.

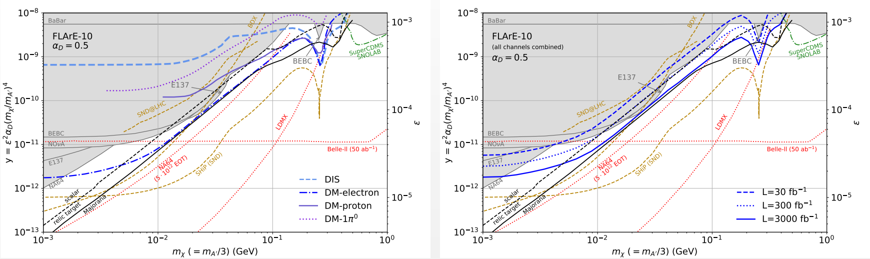
Exclusion bounds for light Majorana DM search



from B. Batell et al. [arXiv:2101.10338]

- LArTPC 10-ton detector increases exclusion bounds w.r.t. emulsion (Faserν2).
- Sensitivity to the region where χ has the correct thermal relic density.
- Complementary info w.r.t. missing energy experiments, that do not see χ scattering.

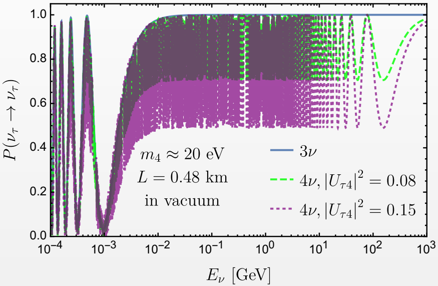
Exclusion bounds for light Majorana DM search

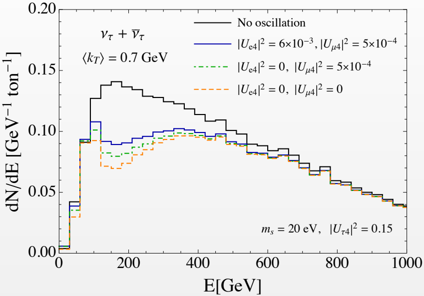


from B. Batell et al. [arXiv:2107.00666]

∗ Extension of the previously considered exclusion bounds in the large m_χ region, thanks to the additional identification and analysis of $\chi + A$ collisions.

Other physics opportunities/complications for HNL searches: ν oscillations





from W. Bai et al. [arXiv:2002.03012]

∗ For the baseline and the neutrino energy range of the Forward Physics Facility, oscillations between active neutrinos in the SM are suppressed.

∗ Oscillation of ν_τ in heavy sterile neutrinos ($m_4 \sim 20$ eV) can be probed, by looking at deficit or excess in the observed event spectrum.

Conclusions

$*$ Far-forward experiments offer the opportunity for a reach BSM (and SM) program, exploiting the production of LLPs at the LHC IPs, their decay in SM or DM, and DM + e and DM + A scatterings in the detectors.

$*$ FASER/FASERν/SND@LHC already able to provide competitive limits in exclusion plots during Run 3.

$*$ A Forward Physics Facility, ready for the HL-LHC phase, can offer a unique opportunity to expand the program of LLP/FIP/DM searches in the "forward" direction.

$*$ First civil Engineering studies and cost estimates for the facility.

$*$ Crucial questions, considering the BSM production and decay mechanisms:

- how well do we control forward SM particle production and decay ?
- how well do we control SM ν + e and ν + A backgrounds ?