2nd Forward Physics at the LHC informal get together

Physics with a LAr detector at the FPF

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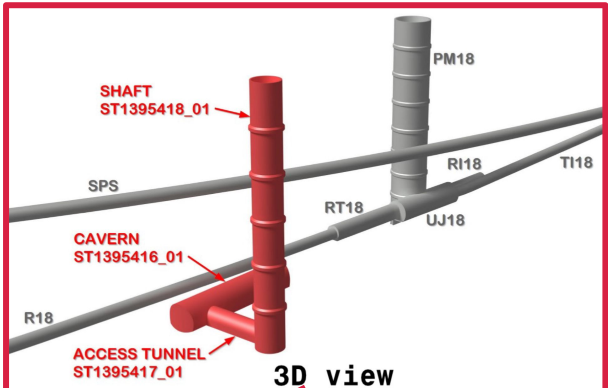
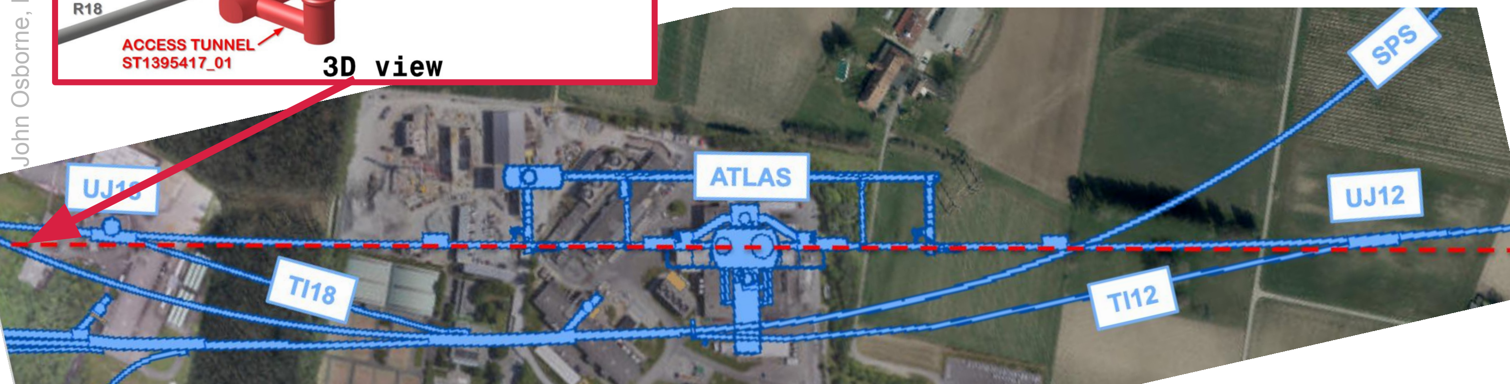
Overview

There is a large flux of light weakly interacting particles (neutrinos, possibly new particles) produced along the LHC's beam collision axis.

The proposal: create a Forward Physics Facility (FPF) for the HL-LHC to house a suite of experiments utilizing this flux.



What physics can probe with an LAr detector at the FPF?



John Osborne, Kincso Balazs, Jonathan Gall

Overview

A LAr experiment at the FPF would greatly enhance the LHC's physics potential for BSM physics searches, neutrino physics and QCD.

Neutrino Physics
v fluxes
v cross sections
tau neutrinos

BSM Physics
Dark Matter
Long Lived Particles
Millicharged Particles

QCD
Hadronic Interaction Models
PDFs via v-production
PDFs via v-scattering
IceCube / Cosmic Rays

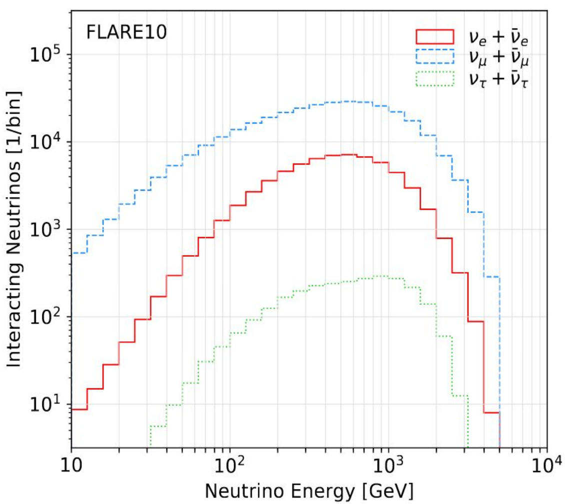
Neutrinos: Fluxes

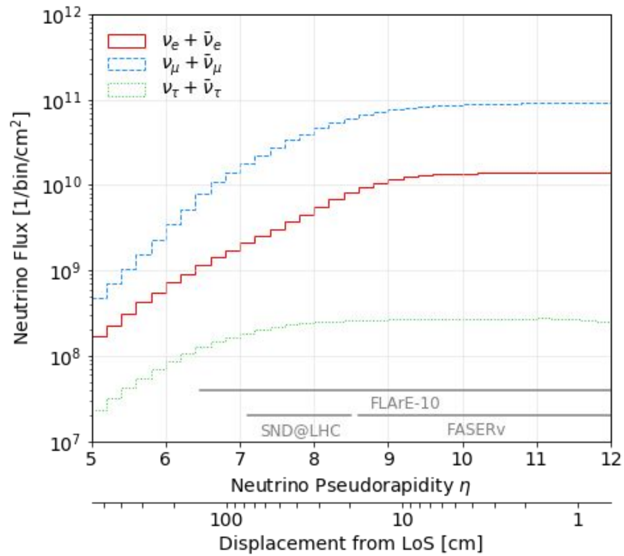
We estimated the neutrino event rates for the FLArE-10 benchmark detector:

dimensions:	1m x 1m x 7m
mass:	10 ton
luminosity:	3000/fb (full HL-LHC)
distance to ATLAS:	620m
event generator:	SIBYLL 2.3d

expected event rates

νe CC	~ 50k
νμ CC	~ 250k
ντ CC	~ 2k
NC	~ 130k





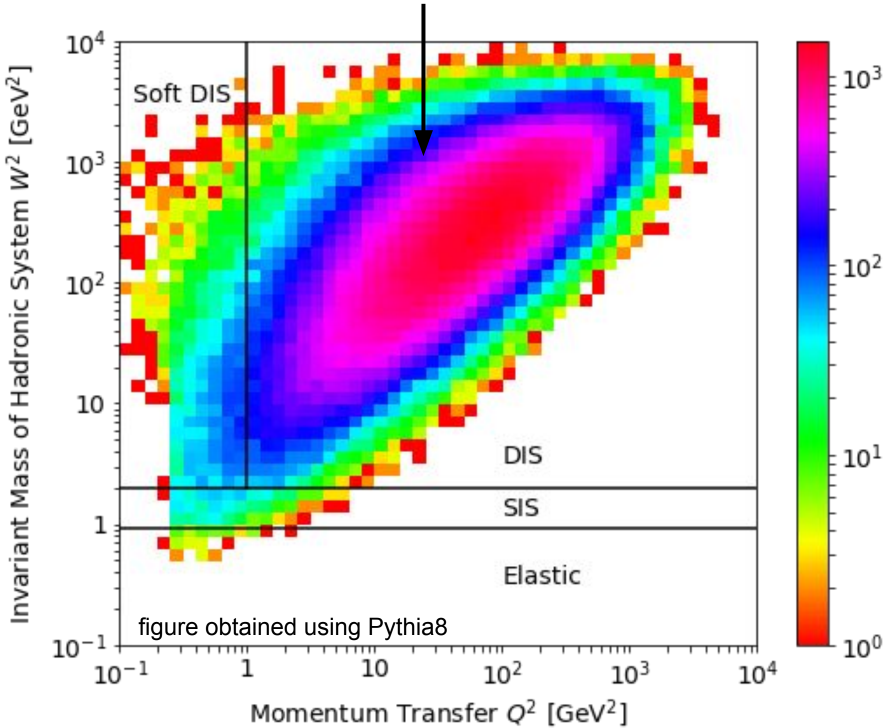
Neutrinos: Interactions

Due to the high energy, most interactions are described by DIS: ν q → l q’

invariant mass of hadronic system ~ hadronic system particle multiplicity

DIS: O(10) particles in final state

SIS: transition between resonance production to DIS



typical momentum transfer |Q| ~ 10GeV

Neutrinos: Event Rates

Event rates for FLArE-10 setup separated by process (estimated using GENIE):

	CC						NC
	ν_e	ν_μ	ν_τ	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$	all
Event Rate	31516	209197	1488	16140	62429	594	132991

TABLE I. Expected total event rates for charged current (CC) and neutral current (NC) neutrino scattering.

	CCQE				CCRES				NCEL	NCRES
	ν_e	ν_μ	$\bar{\nu}_e$	$\bar{\nu}_\mu$	ν_e	ν_μ	$\bar{\nu}_e$	$\bar{\nu}_\mu$	all	all
Event Rate	58	590	47	366	167	1673	184	1219	175	1206

TABLE II. Expected event rates for charged current quasi elastic (CCQE), charged current resonant (CCRES), neutral current elastic (NCEL) and neutral current resonant (NCRES) interactions neutrinos.

	$\nu_\mu e^- \to \nu_\mu e^-$	$\nu_e e^- \to \nu_e e^-$	$\nu_\mu e^- \to \nu_e \mu^-$	$\bar{\nu}_e e^- \to \nu_\mu \mu^-$	$\nu_\tau e^- \to \nu_e \tau^-$
Event rate	28	29	211	11	$< 10^{-4}$

TABLE III. Expected event rates for neutrino scatterings off electrons.

Neutrinos: Cross Section Measurements

One can measure the total DIS cross section at TeV energies for all flavours!

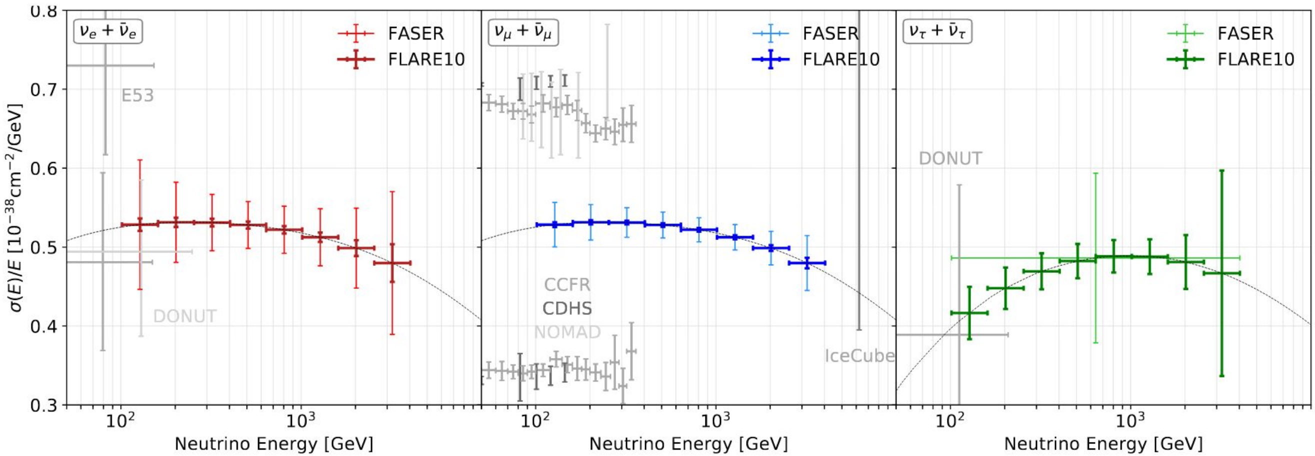


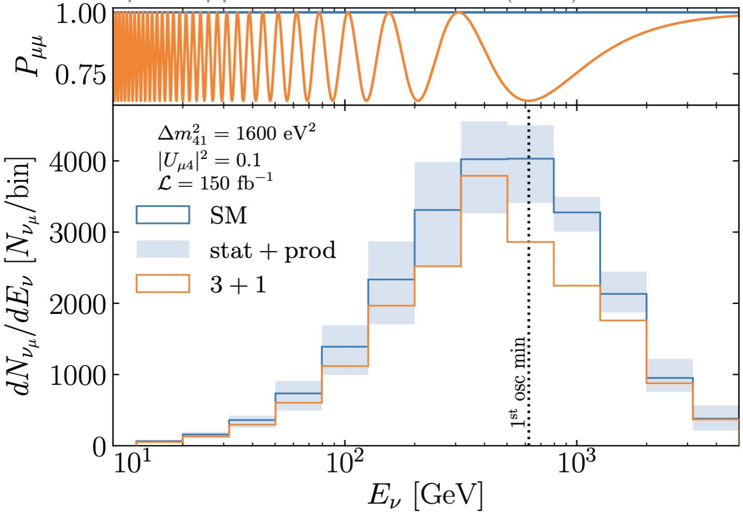
FIG. 2. Estimated ν-nucleon CC cross section sensitivity for ν_e (left), ν_μ (center), and ν_τ(right) at FLArE-10 at the HL-LHC with an integrated luminosity of 3 ab^{-1} collected. Here we consider only statistical uncertainties (meaning that we assume a perfect knowledge of the neutrino flux). Existing constraints are shown in gray. The black dashed curve is the theoretical prediction for the average DIS cross section per tungsten-weighted nucleon.

We expect 200 tau neutrino interactions → tau neutrino precision physics

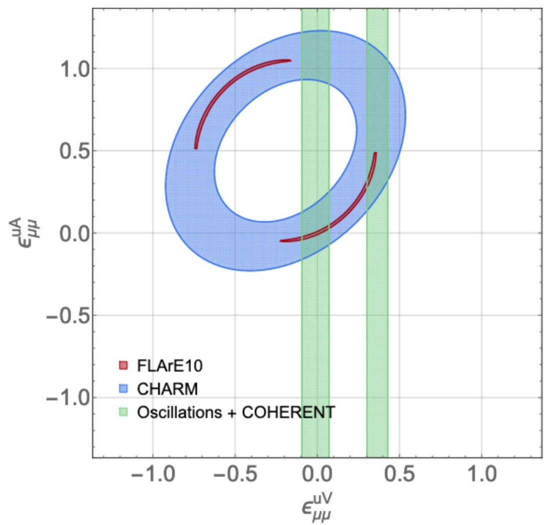
Can one distinguish neutrino/anti-neutrino?

Neutrinos: More Physics Potential

νμ disappearance at FASERν (1ton) with 300/fb



Sterile neutrinos with mass ~40eV can cause oscillations. FLArE could act as a short-baseline neutrino experiment (1908.02310)



NSI using νμ NC scattering at FLARE (10 ton) with 3000/fb

NC measurements at FLArE could constrain Weinberg Angle or neutrino non-standard interactions or NSIs (see 2012.10500).

and more neutrino related new physics (under investigation): neutrino magnetic moments, neutrino-philic DM, sterile neutrino decays ...

QCD and Astroparticle Physics

QCD: Forward Particle Production

Forward neutrino fluxes are sensitive to forward particle production and can be used to improve/validate hadronic interaction models.

O(1) differences for light hadron production

larger differences for charm production

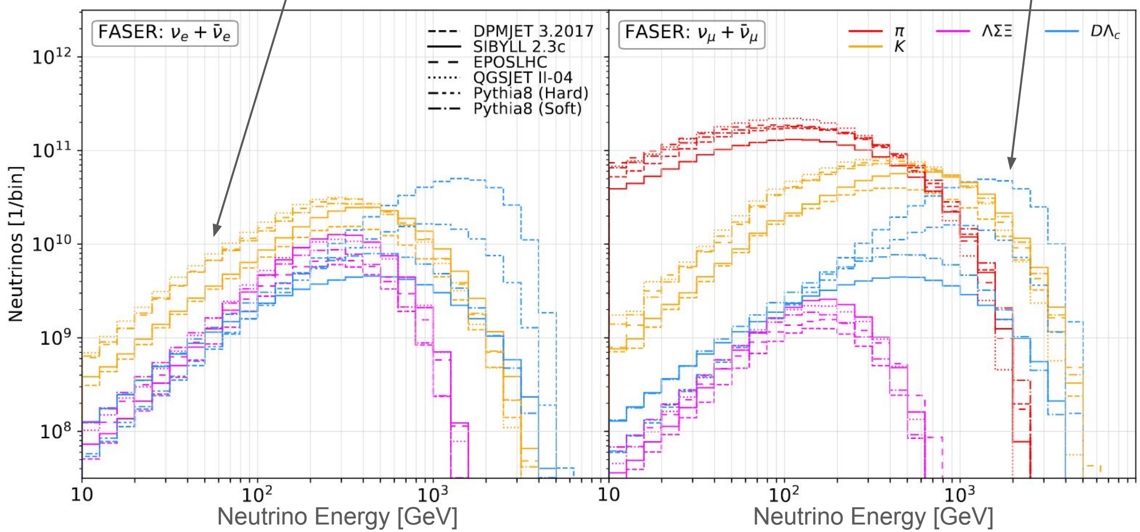


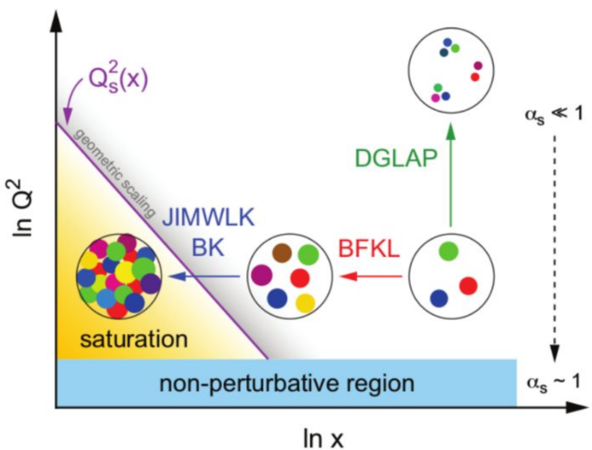
FIG. 5. Neutrino energy spectrum for electron neutrinos (left) and muon neutrinos (right) passing through FASERν. The vertical axis shows the number of neutrinos per energy bin that go through the detector's cross sectional area for an integrated luminosity of 150 fb^{-1}. We separate the different production modes: pion decays (red), kaon decays (orange), hyperon decays (magenta) and charm decays (blue). The different linestyles correspond to predictions obtained from different commonly used event generators.

Results for FLArE will be qualitatively similar

QCD: Forward Charm

Electron neutrinos at high energy and tau neutrinos are mainly produced in charm decays: g g → c c , c → D, D → K l v

Neutrinos from charm decay could allow to test transition to small-x factorization, constrain low-x gluon PDF, probe gluon saturation, and probe intrinsic charm.



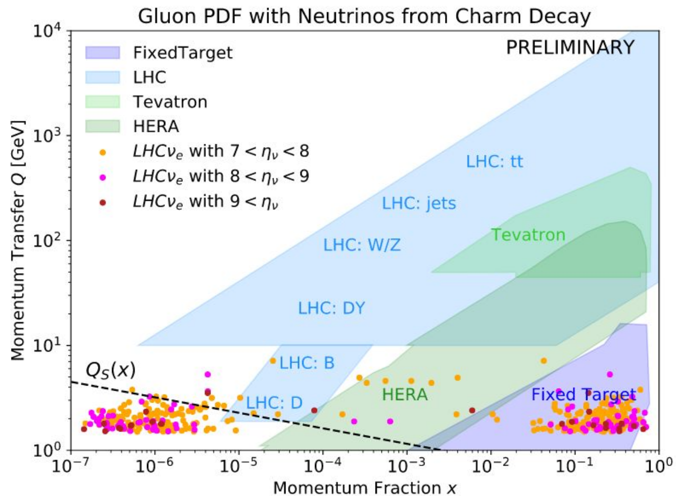
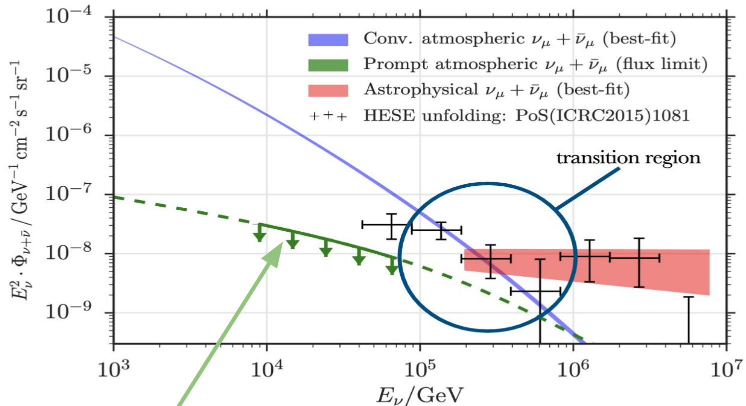


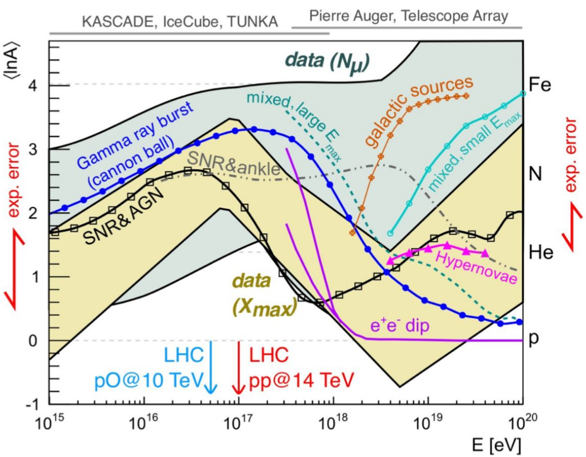
FIG. 6. **Left:** Theoretical description of the gluon PDF. **Right:** PDF landscape in terms of Q^2 bs x. Data from previous measurements is available in the shaded regions. Forward charm production resulting in far-forward is sensitive to $x_1 \sim 0.5$ and $x_2 \sim 10^-6$ for $Q \sim 2$ GeV, which is currently unconstrained.

Application in Astroparticle Physics

Measuring forward charm production at the LHC would help to constrain the (currently very poorly constrained) prompt atmospheric neutrino flux at IceCube.



prompt atmospheric neutrinos



Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

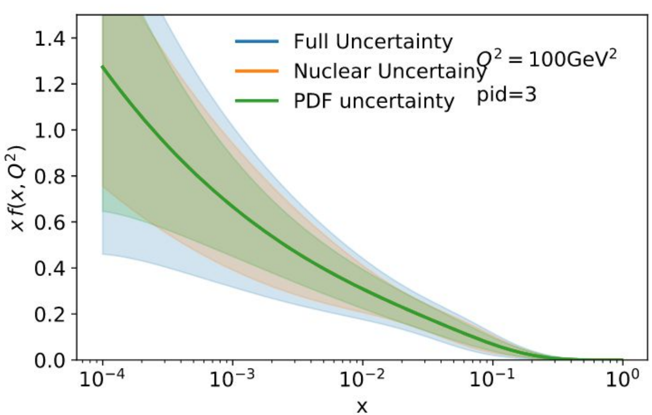
Cosmic Ray experiments have reported an excess in the number of muons over expectations computed using extrapolations of hadronic interaction models tuned to LHC data at the few σ level (muon problem in CR physics).

Measurements of forward hadron production (kaons) at the LHC are crucial to solve this issue.

QCD: PDFs and ν Scattering

One can also use DIS neutrino scattering to probe (nuclear) PDFs:

In particular, charm associated neutrino events (ν s → l c) are sensitive to the poorly constrained strange quark PDF, and can help to resolve existing tension between different measurements.



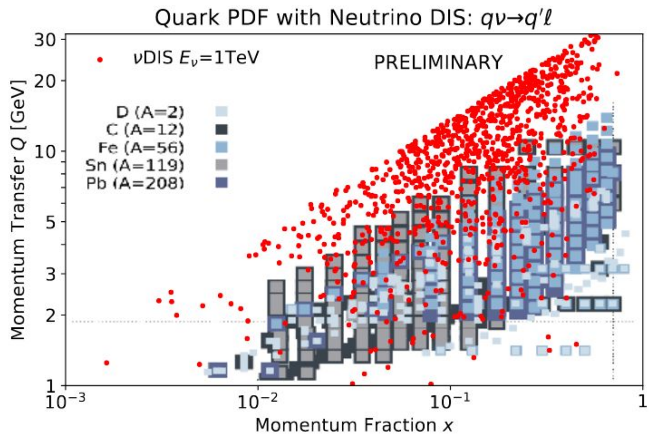


FIG. 4. **Left:** Strange quark PDF for $Q^2 = (10\text{ GeV})^2$ using EPPS16 (for aluminum, since they don't have argon). We can see that there are currently $\mathcal{O}(1)$ uncertainties on the strange quark PDF. **Right:** PDF landscape in terms of Q^2 vs x. The boxes correspond to regions where existing data is available. The red dots show the parameter space that could be accessed by forward neutrino experiments with $E = 1$ TeV neutrinos.

New Physics
(motivated by Dark Matter)

Motivaion: Dark Sectors

Simple Model: Dark Matter charged under U(1) $_D$

$$\mathcal{L} \supset -\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} - \frac{1}{2} m^2_{A'} A'^2 - m^2_\chi \chi^2 - i g_D A' \chi^2$$

coupling to SM via small mixing with SM photon

massive gauge boson: dark photon

dark photon couples to DM

Phenomenology depends on masses:

mA’ > 2mX : dark photon promptly decays in DM → LHC produces DM beam

mA’ < 2mX : dark photon can only decay to SM → A’ is long-lived

mA’ = 0 : dark matter becomes millicharged

DM Scattering

1. A huge number of high-energy mesons are produced in forward direction (hadronization of beam remnants)

2. Produce A' via decays π0 → A'γ or A' Bremsstrahlung pp → ppA'

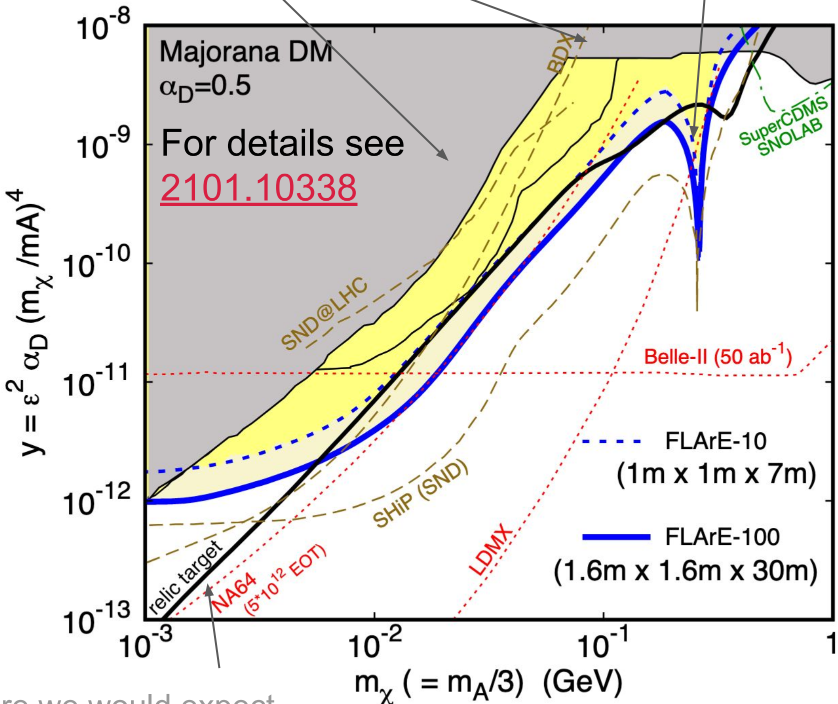
3. Prompt decay A'→ XX produces DM beam

4. SM scatters on electrons: X e → X e
Typical electron energy ~ 1-10 GeV

5. Possible background: ν e → ν e
Typical electron energy ~ 0.1-1 TeV

existing constraints from MicroBoone, BaBar

A' mixes resonantly with ω meson



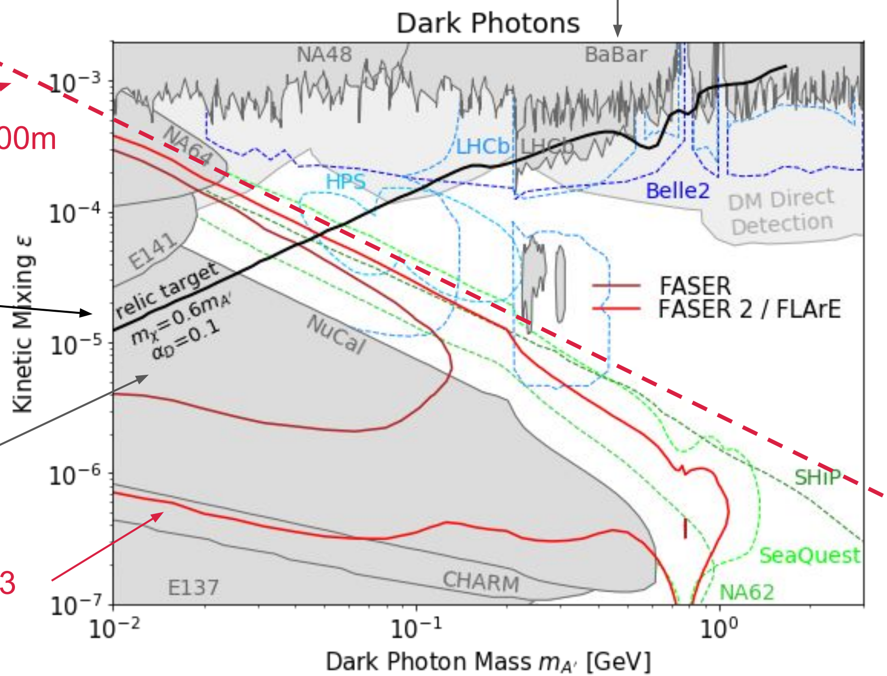
where we would expect DM in this model

Assumptions: full HL-LHC with 3/ab.

Long-Lived Particle Decays

If mA’ < 2mX: A’ decays to SM particles

searches for prompt di-electron resonance



lifetime cτ ~ 1cm → decay length cτγ ~ 100m
A’ is longlived

region than can explain observed amount of DM

searches for displaced decays at beam dump experiments

number of A’ decays in detector volume = 3

For details and many more models see 1811.12522.

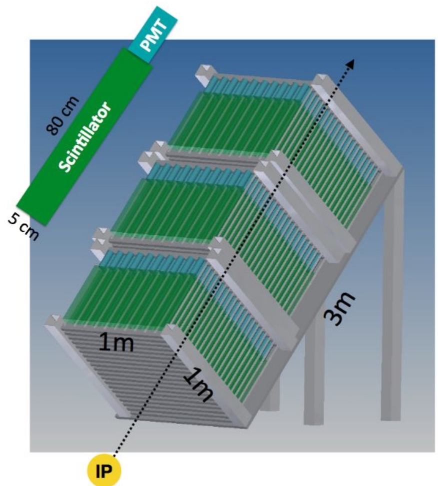
Assumptions: full HL-LHC with 3/ab.
All decays are detectable, no BG.

MilliCharged Particles (MCPs)

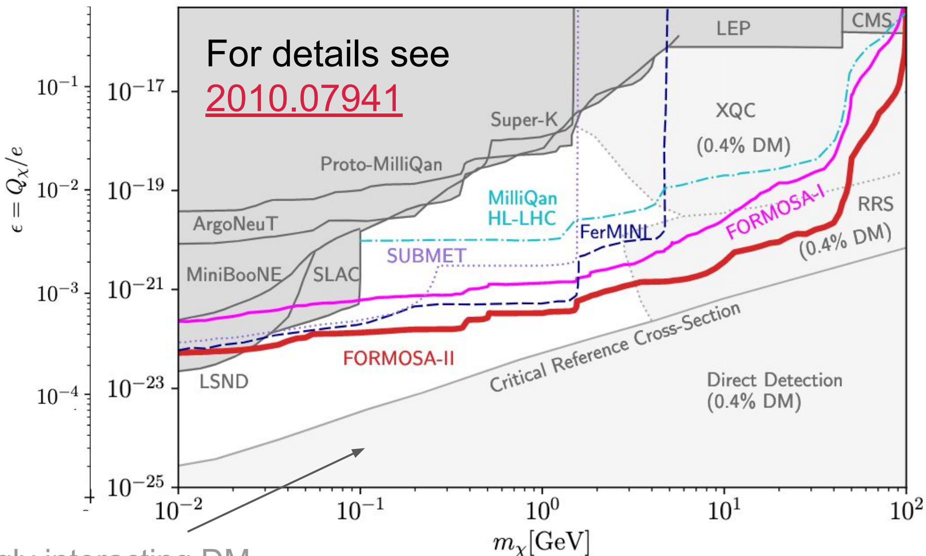
If mA'=0: X is effectively milli-charged with Q=εe → search for minimum ionizing particle with very small dE/dx

MilliQan was proposed as dedicated LHC experiment to search for MCPs near CMS. But it was noted that sigal flux is ~100 times larger in forward direction.

LAr detector could in principle also look for MCPs (example: ArgoNeuT).



milliQan detector: 1607.04669



MCPs are an example of strongly interacting DM.
Above DD bounds: DM absorbed in earth crust.
Popular model to explain EDGES anomaly.

Assumptions: full HL-LHC with 3/ab.
1mx1m cross sectional area, no BG.

Next FPF Meeting

Upcoming 2nd FPF workshop on May 27th/28th will discuss these topics in great detail.

https://indico.cern.ch/event/1022352

You are invited to join!