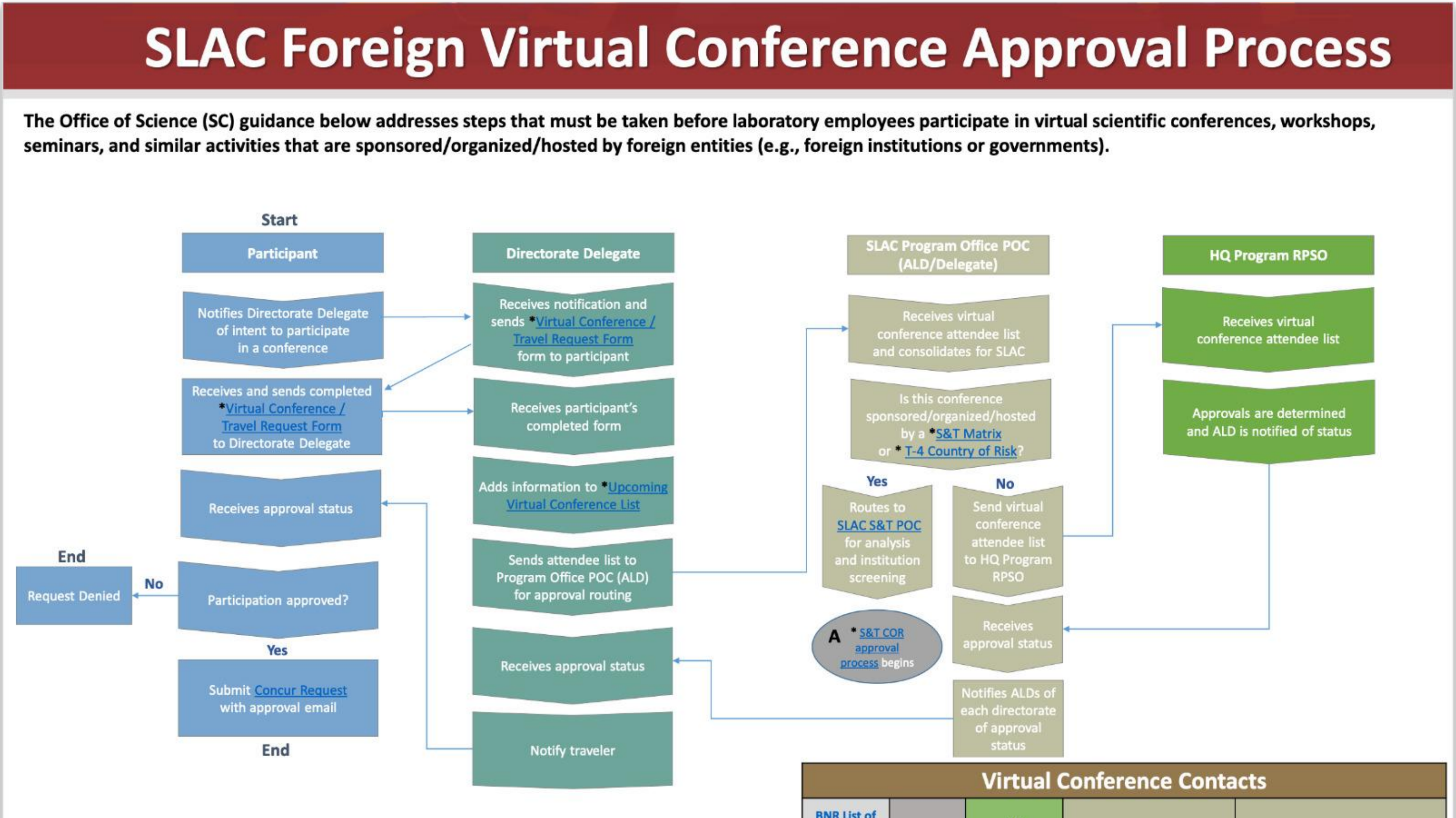
Physics with Forward LHC Neutrino Detectors

Invisibles 2021

Felix Kling

SLAC NATIONAL ACCELERATOR LABORATORY

Administration required to attend this conference



the entire process took about 2 months …

Neutrinos at the LHC

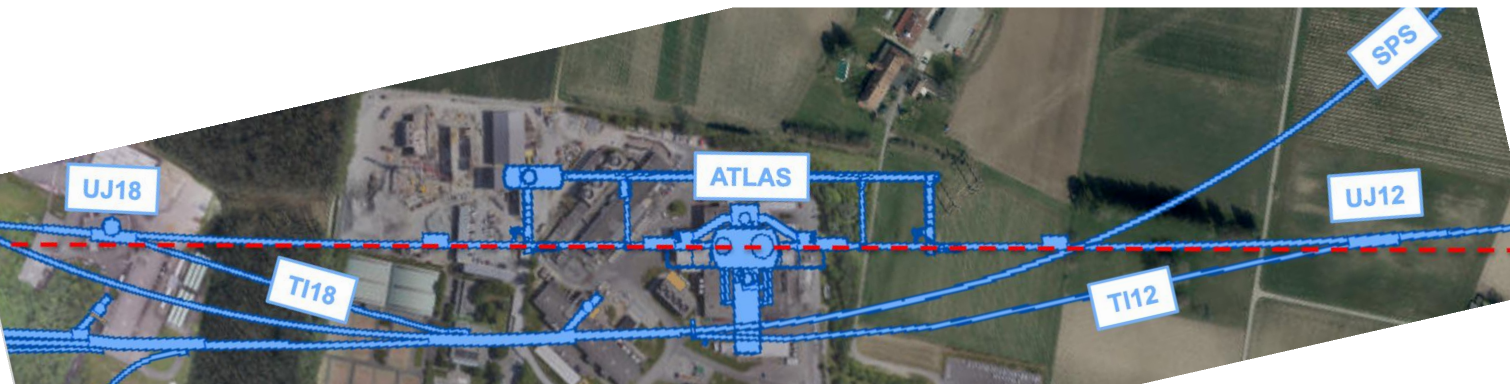
Neutrinos at the LHC

1984 2018 2022 2028

Neutrinos detected from many sources, but not from colliders.

But there is a huge flux of neutrinos in the forward direction, mainly from π, K and D meson decay. De Rujula et al. (1984)

ATLAS provides an intense and strongly collimated beam of TeV-energy neutrinos along beam collision axis.

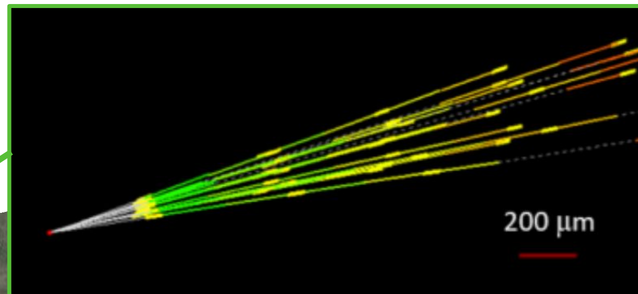


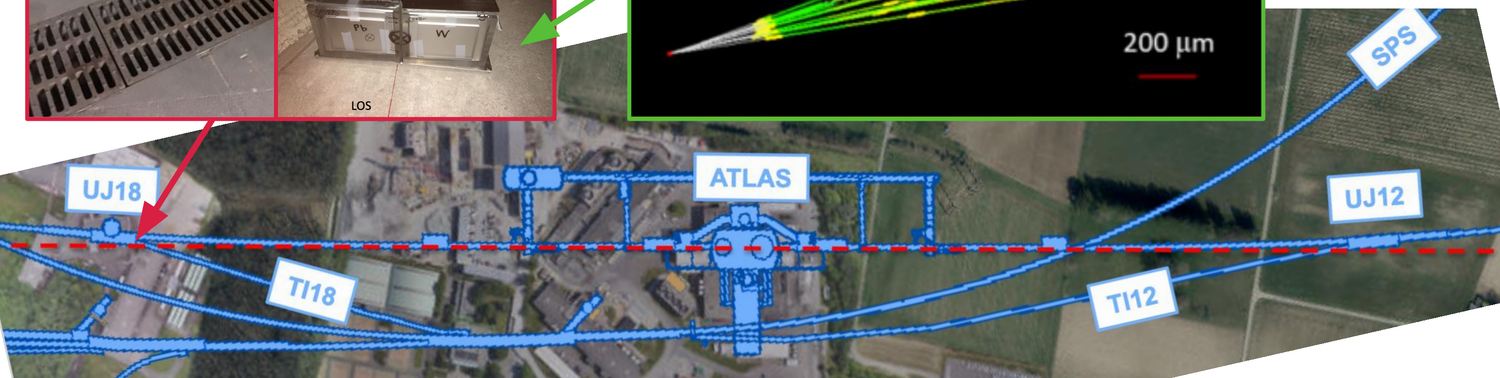
Neutrinos at the LHC

1984 — **2018** — 2022 — 2028

In 2018, the FASER collaboration placed ~30 kg pilot emulsion detectors in TI18 for a few weeks. O(10) neutrino interactions expected

First neutrino interaction candidates were [recently reported](#).



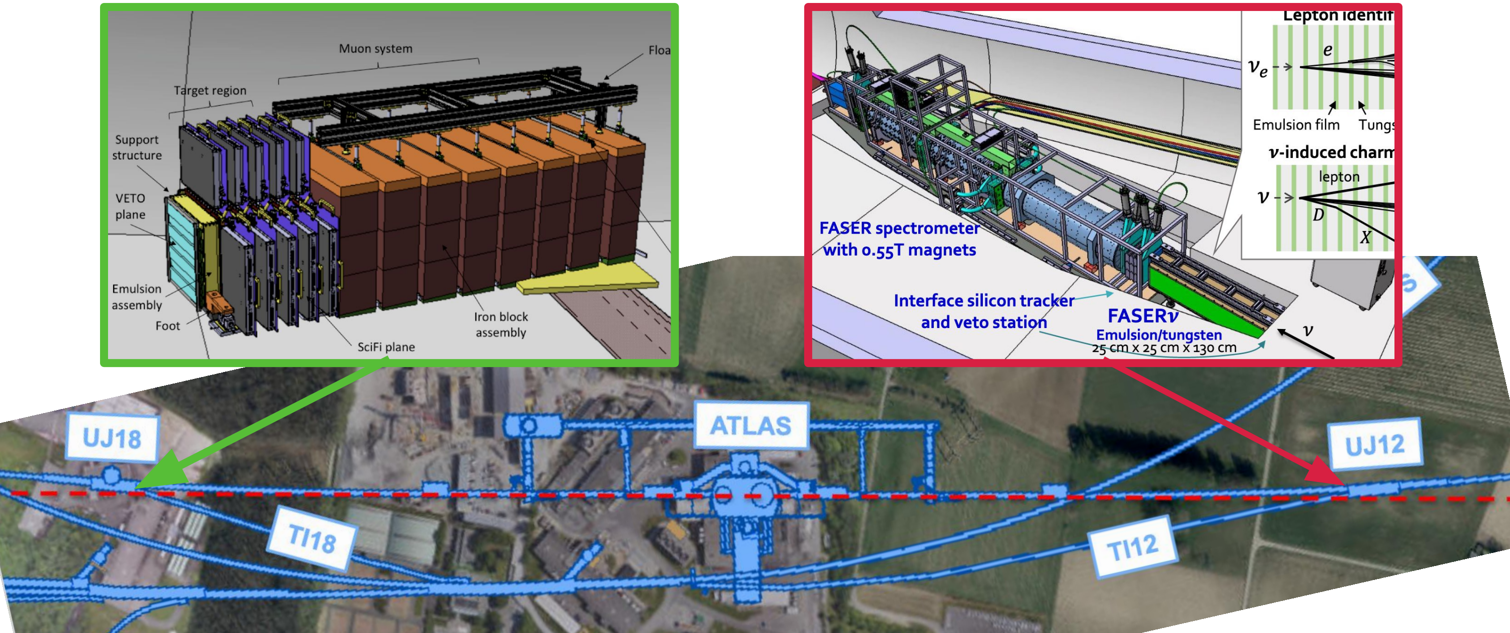


Neutrinos at the LHC

1984 — 2018 — 2022 — 2028

During Run 3 of the LHC, two new experiments will detect LHC neutrinos. FASERv: 1000 neutrinos, 10000 muon neutrinos and 10 tau neutrino CC interactions.

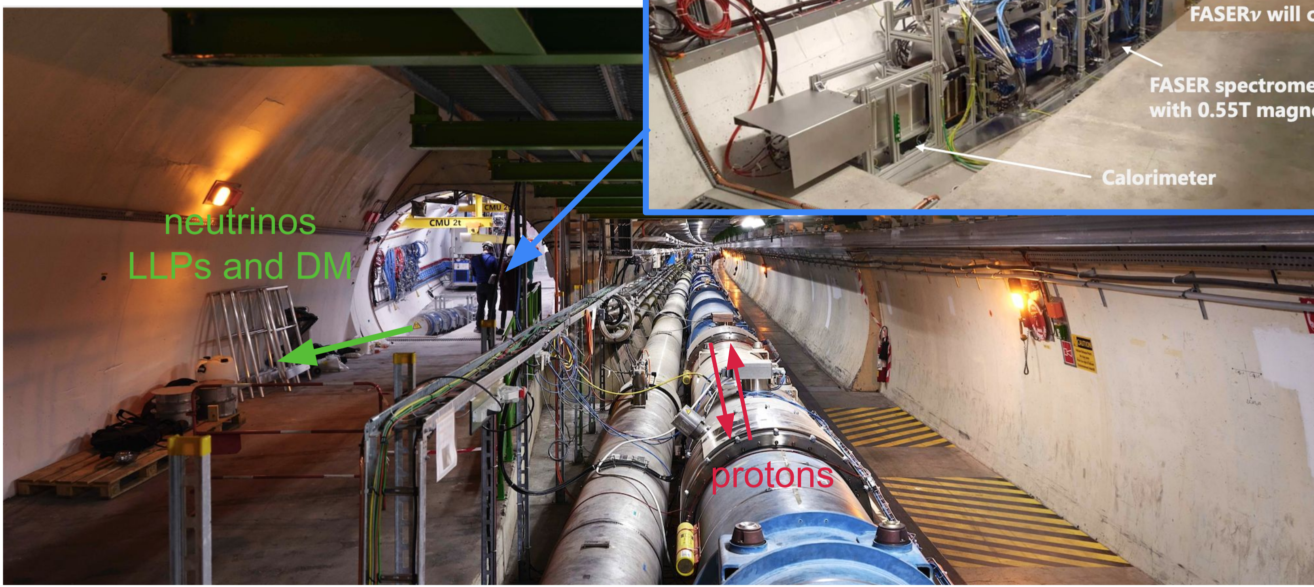
SND@LHC **FASERnu**



Neutrinos at the LHC

1984 — 2018 — 2022 — 2028

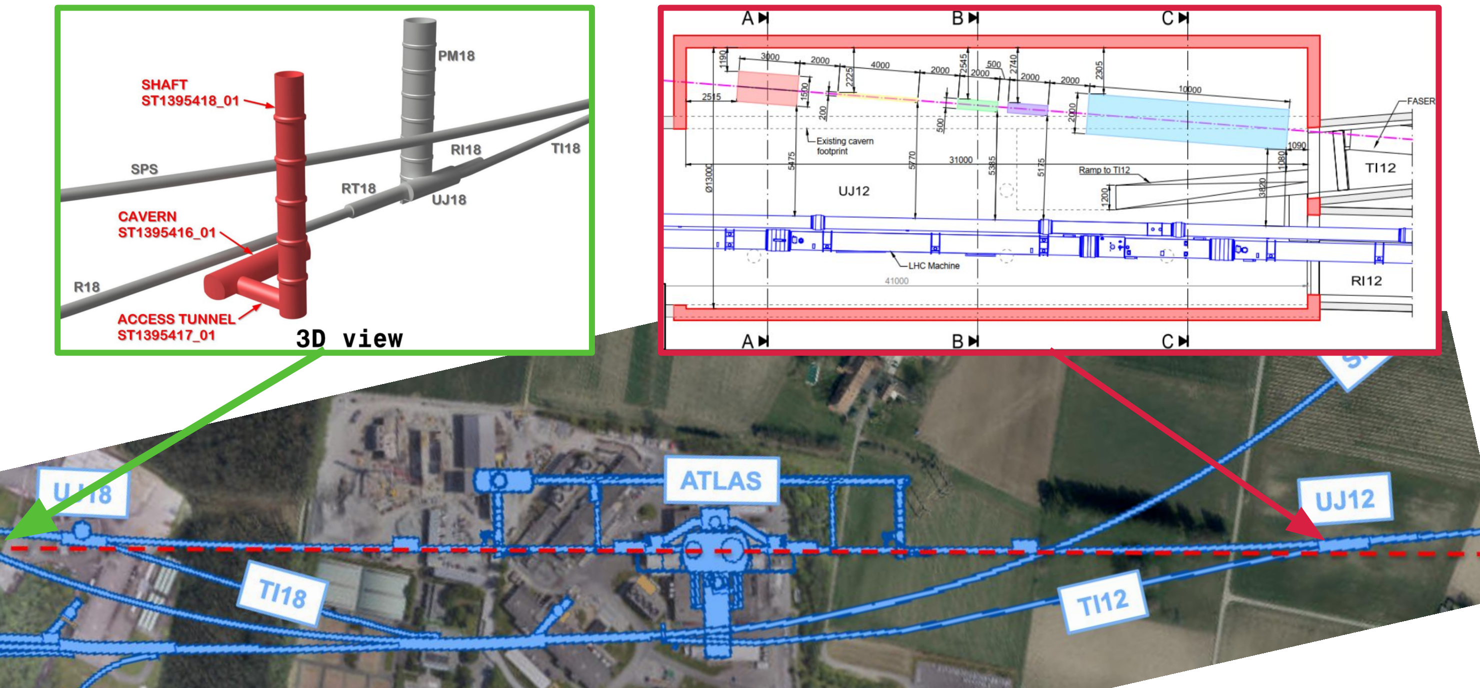
FASER detector was successfully installed into the TI12 tunnel in March 2021



Neutrinos at the LHC

1984 — 2018 — 2022 — 2028

The proposal: create a Forward Physics Facility (FPF) for the HL-LHC to house a suite of experiments. Two promising locations were identified.

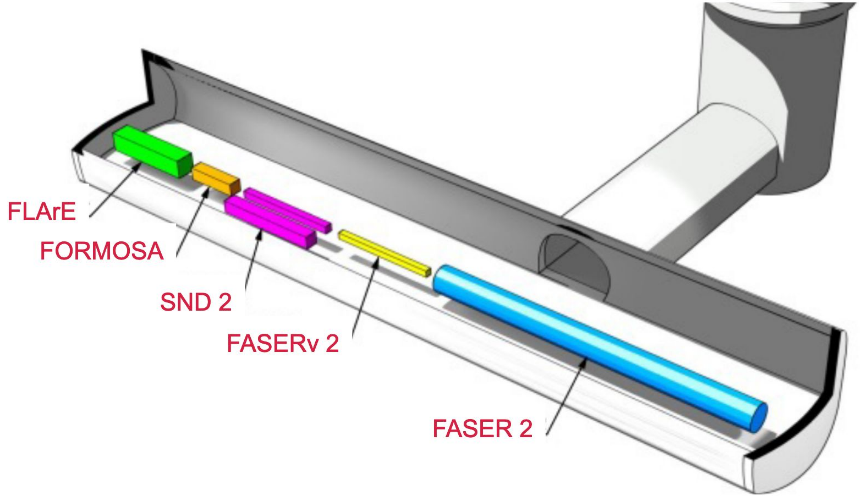


John Osborne, Kincso Balazs, Jonathan Gall

Neutrinos at the LHC

A suite of experiments were proposed for the FPF.

We are currently writing a physics potential summary. You are welcome to join!



Snowmass LOI: https://zenodo.org/record/4059893

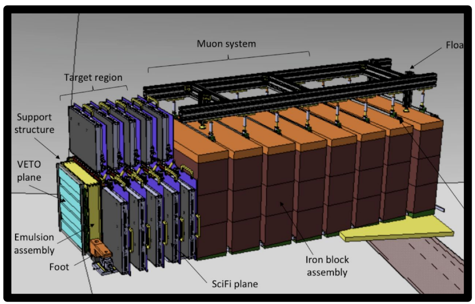
Kickoff Meeting: https://indico.cern.ch/event/955956/

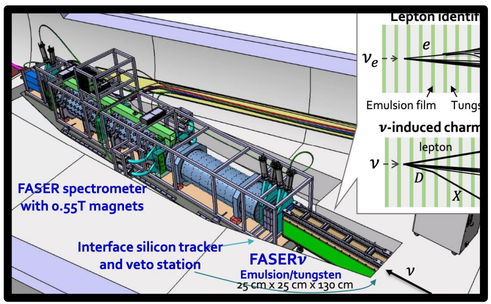
2nd Workshop (last week): https://indico.cern.ch/event/1022352

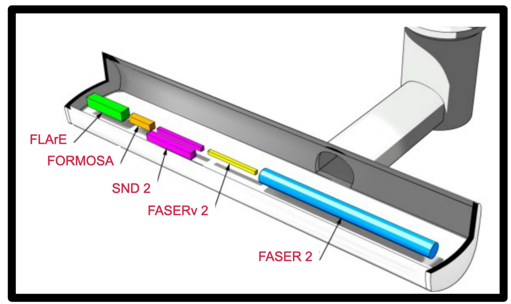
Neutrinos at the LHC

Neutrino experiments at the LHC will greatly enhance the LHC's physics potential for BSM physics searches, neutrino physics and QCD.

In this talk, I will highlight some exciting examples.







Neutrino Physics

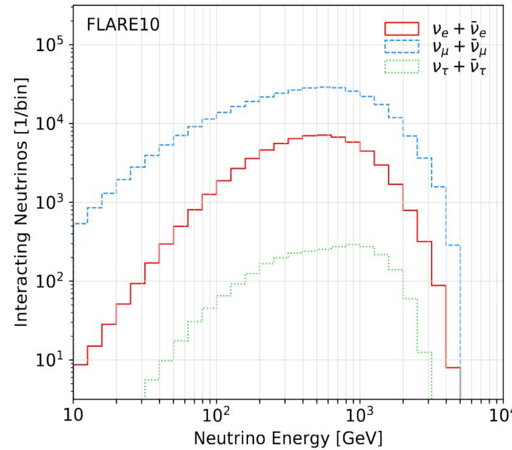
Neutrino Physics

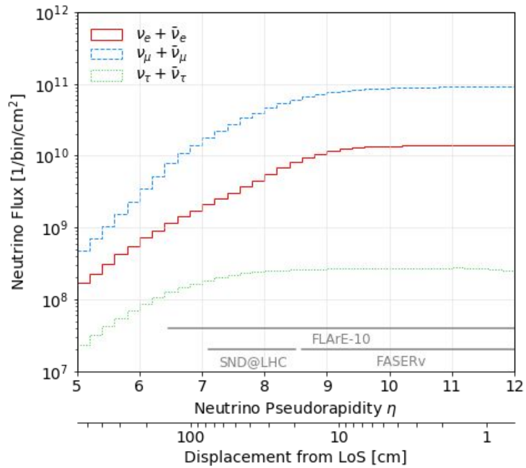
The LHC neutrino beam is broad, with mean energies around 1 TeV, exceeding the energies of all other artificial neutrino sources.

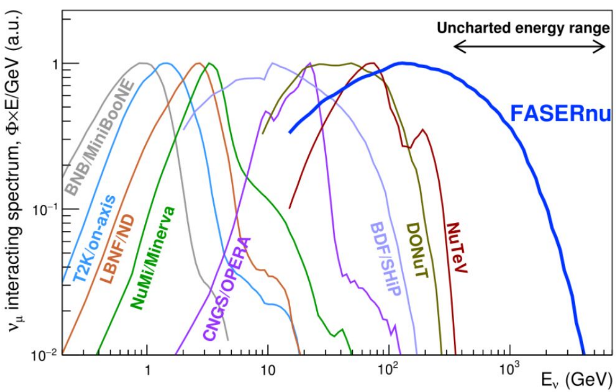
It originates from a variety of sources: pion, kaon, hyperon and charm decays.

FASERν (~1ton, 150/fb):
1k νe, 10k νμ, 10 ντ interactions

FPF (~10ton, 3000/fb):
100k νe, 1M νμ, 1k ντ interactions







for details on simulation see F.Kling 2105.08270

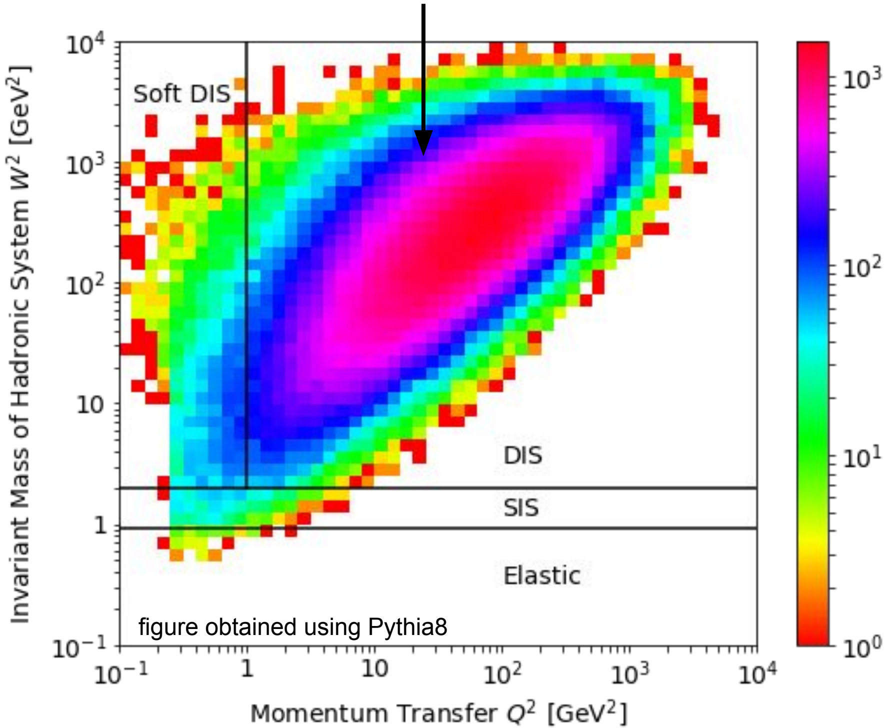
Neutrino Physics

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

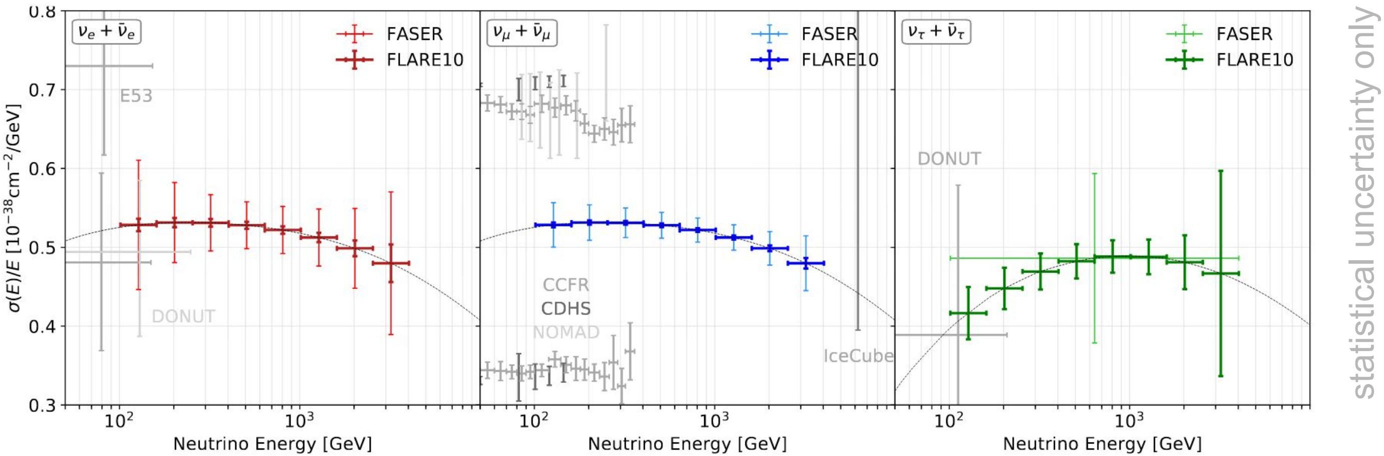
SIS: transition between resonance production to DIS



typical momentum transfer |Q| ~ 10GeV

Neutrino Physics

Using LHC neutrinos, one can measure neutrino cross section at unexplored TeV energies for all three flavors. Both CC and NC are possible.

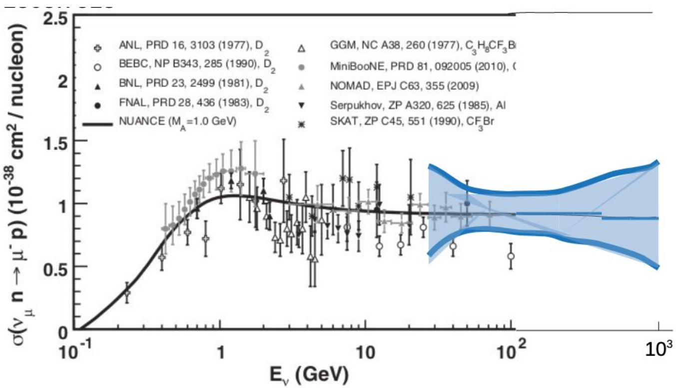


FASERν will detect ~10 tau neutrino interactions, which is similar to DONuT and OPERA. Thousands of tau neutrino events possible at HL-LHC, allowing for precision studies of tau neutrino properties.

Neutrino Physics

more than 1k quasi-elastic and resonant events expected

	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



Measurement of inclusive interaction cross section possible

For high-energy neutrinos, typically >95% of Ev goes into the outgoing lepton

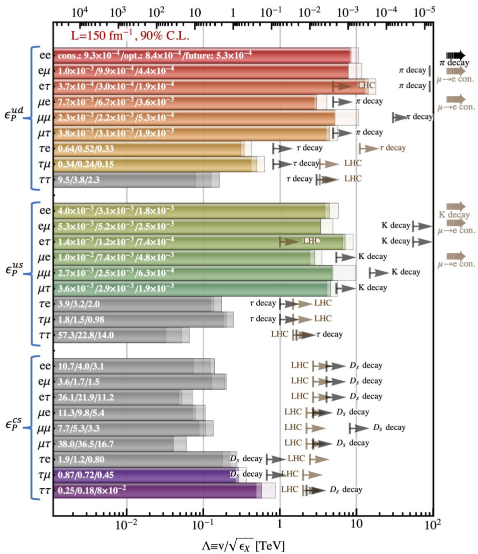
Consistency check of the neutrino spectrum & cross section measurements

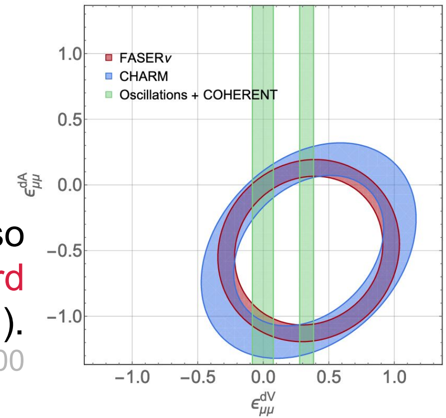
table/figure by Sebastian Trojanowski

Neutrino Physics

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

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

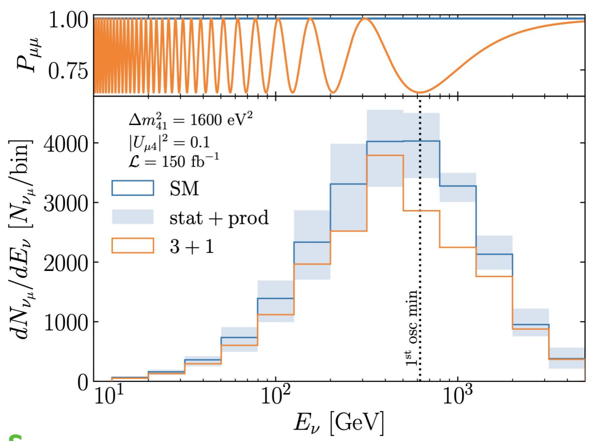




NC measurements could also constrain neutrino non-standard interactions (NSI).

Abraham, Ismail, Kling 2012.10500

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



QCD and Cosmic Rays

QCD and Cosmic Rays

Forward particle production is poorly constrained by other LHC experiments. FASERν's neutrinos flux measurements will provide novel complimentary constraints that can be used to validate/improve MC generators.

We need to quantify and reduce these uncertainties.

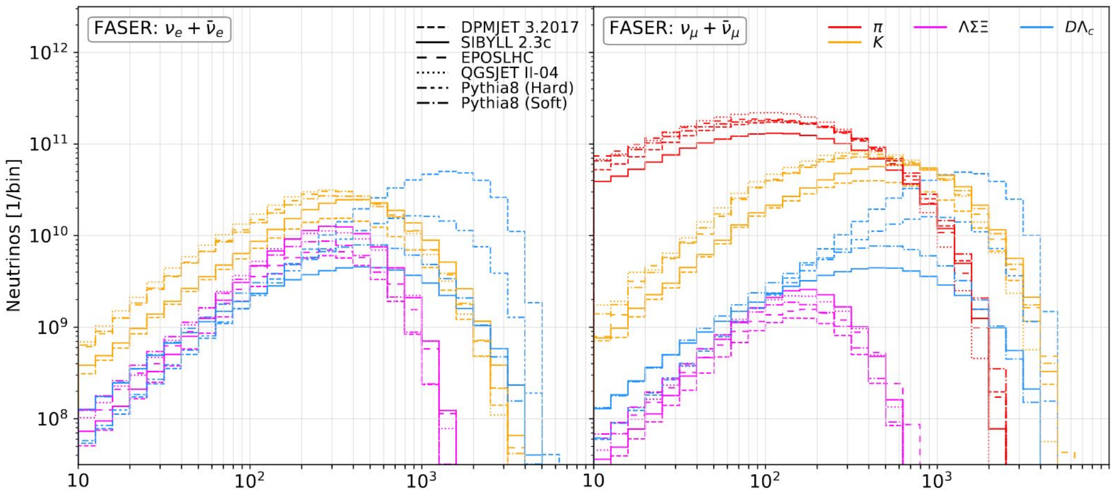
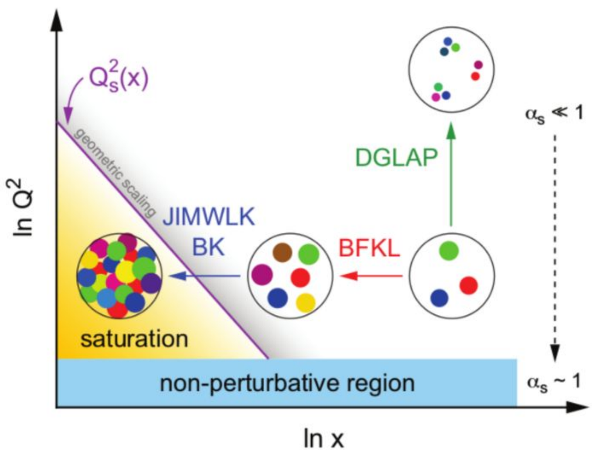


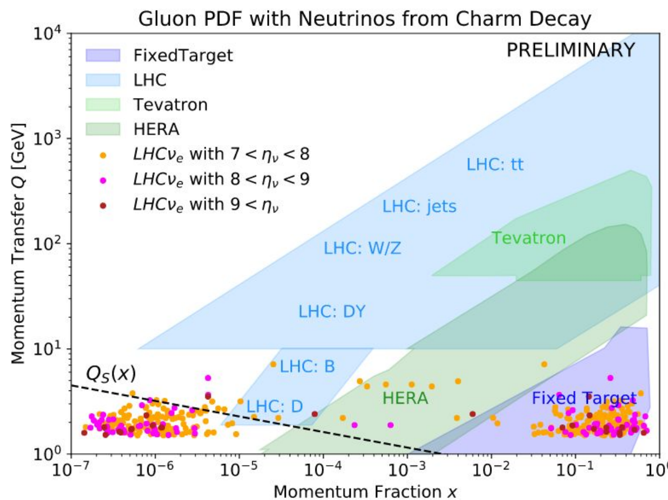
FIG. 5. Neutrino energy spectrum for electron neutrinos (left) and muon neutrinos (right) passing through FASERν. The vertical axis shows the number of neutrinos per energy bin that go through the detector's cross sectional area for an integrated luminosity of 150 fb^{-1}. We separate the different production 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.

QCD and Cosmic Rays

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

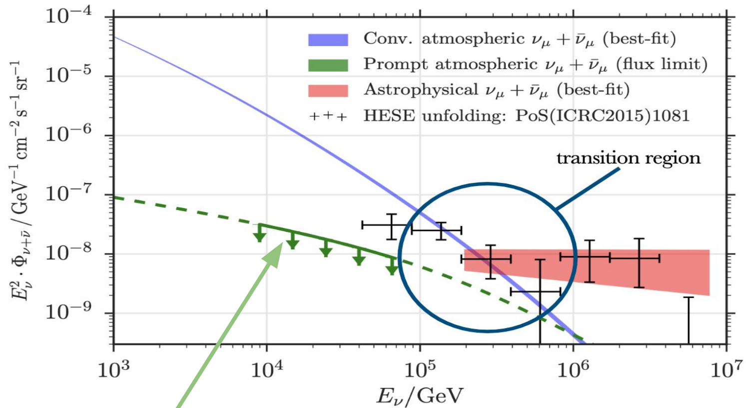
Neutrinos from charm decay could allow to test transition to small-x factorization, constrain low-x gluon PDF, probe gluon saturation, and probe intrinsic charm.



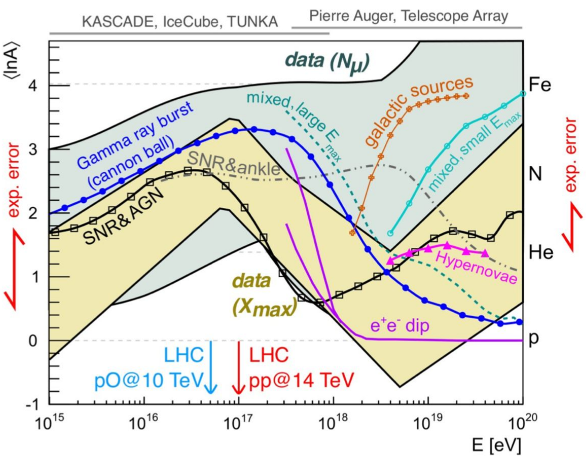


QCD and Cosmic Rays

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

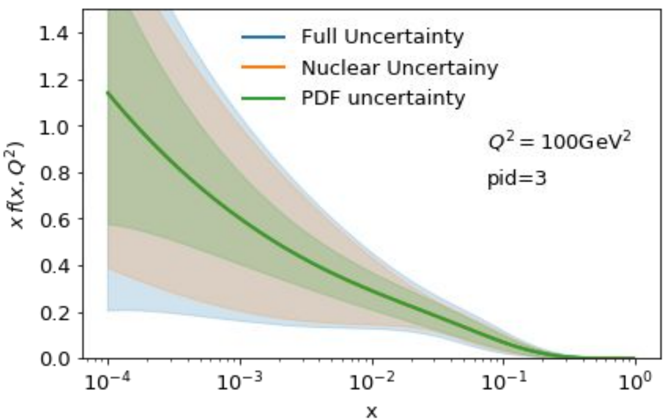
Cosmic Ray experiments have reported an excess in the number of muons over expectations computed using extrapolations of hadronic interaction models tuned to LHC data at the few σ level (muon problem in CR physics).

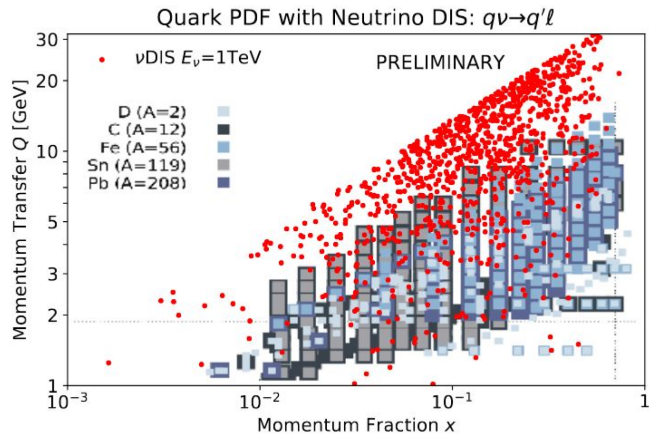
Measurements of forward hadron production (kaons) at the LHC are crucial to solve this issue.

QCD and Cosmic Rays

One can also use DIS neutrino scattering to probe (nuclear) PDFs: shadowing, anti-shadowing, EMC effect for different nuclear targets

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.





BSM Physics

BSM Physics

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

BSM Physics - Dark Matter

DM Scattering in Neutrino Detector

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

A' produced via decays $\pi0 \rightarrow A'\gamma$ or A' Bremsstrahlung $pp \rightarrow ppA'$

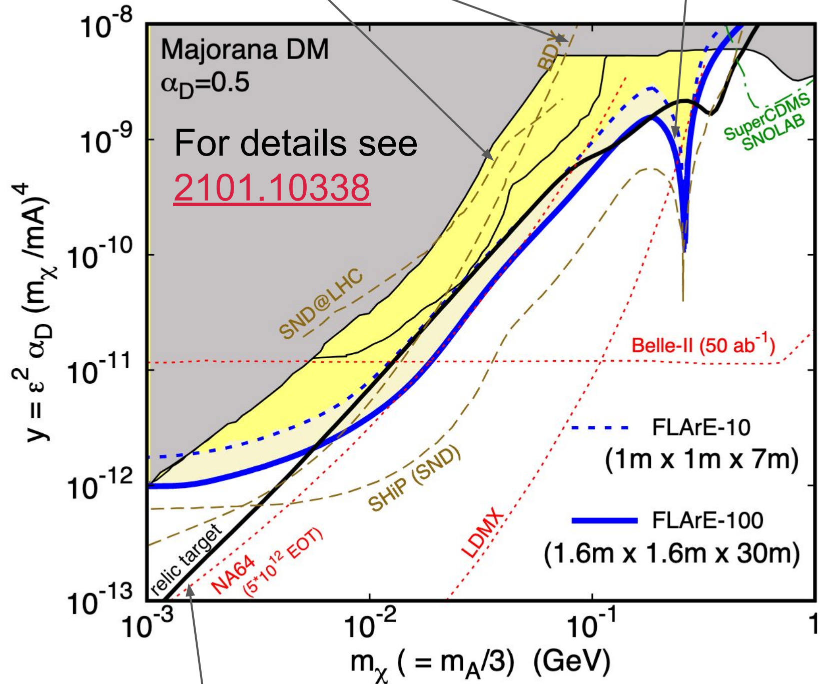
Prompt decay $A' \rightarrow XX$ produces DM beam

DM scatters on electrons: $X e \rightarrow X e$. Typical electron energy ~ 1-10 GeV

possible background: $\nu e \rightarrow \nu e$ with 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

BSM Physics - LLPs

If mA’ < 2mX: A’ decays to SM particles → Long lived particle decays

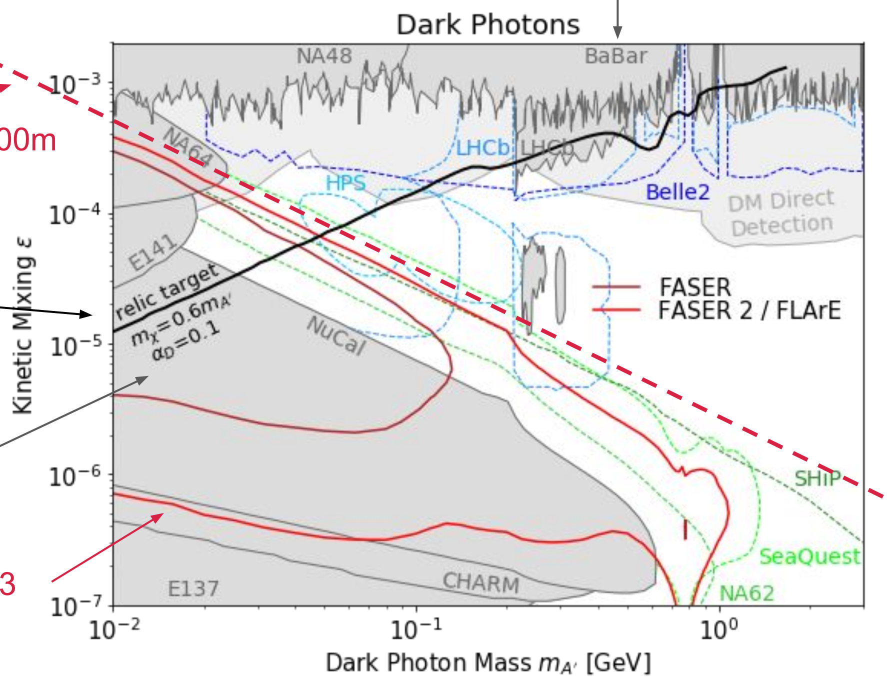
searches for prompt di-electron resonance

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



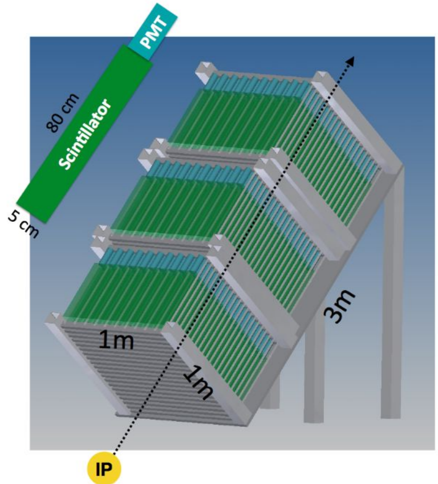
For details and many more models see [1811.12522](1811.12522).

BSM Physics: MCPs

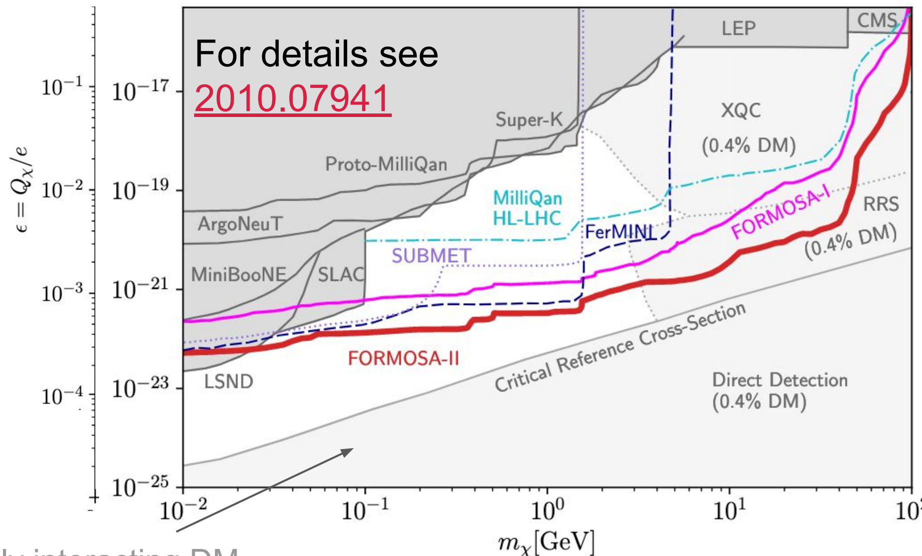
If mA'=0: X is effectively milli-charged with Q=εe → search for minimum ionizing particle with very small dE/dx

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.

Summary

With FASER and SND@LHC, two new experiment will soon start to perform neutrino measurements at the LHC.

They also paves the way for a forward search and neutrino program at the HL-LHC, opening up many many new opportunities for neutrino physics, BSM physics searches and QCD measurements, significantly extending the LHC's physics program.

We would like to invite the Invisibles 2021 community to help us explore and better understand the physics potential of this program.

We are currently writing a physics potential summary.
You are welcome to join!

↓

contact me via felixk@slac.stanford.edu or
visit our workshop page https://indico.cern.ch/event/1022352