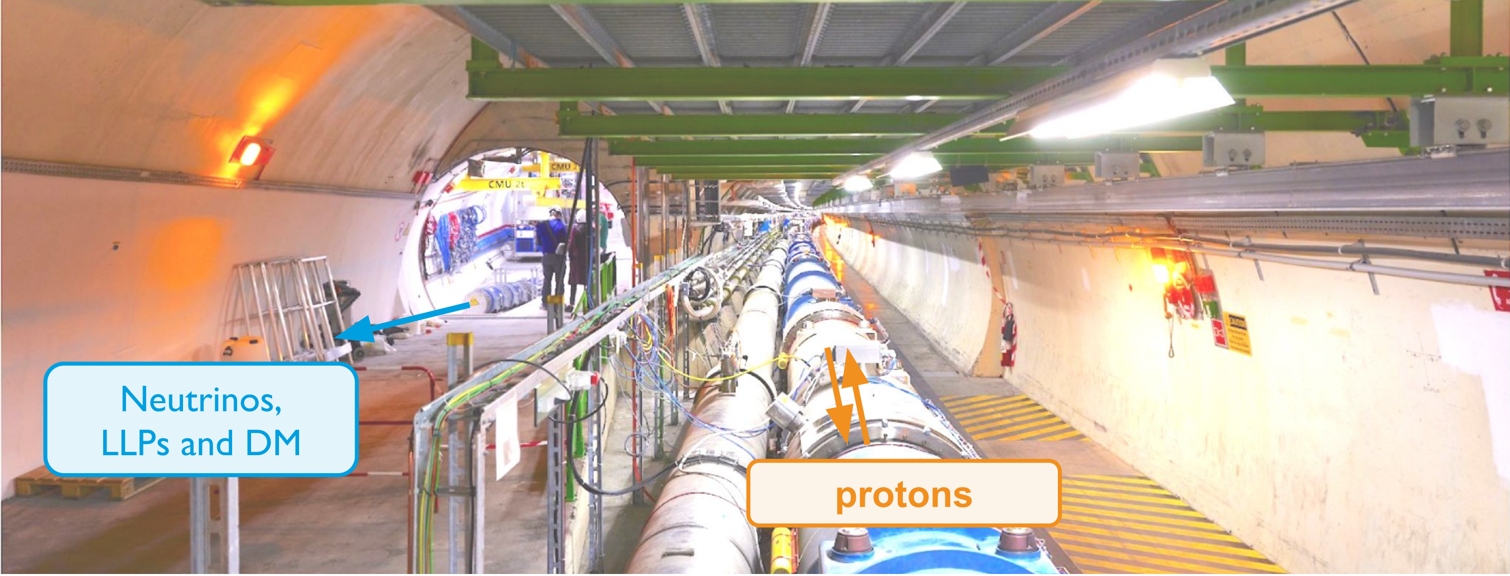


Physics at the Forward Physics Facility.

Felix Kling
Pheno 2022
05/11/2022

Why Forward Physics?

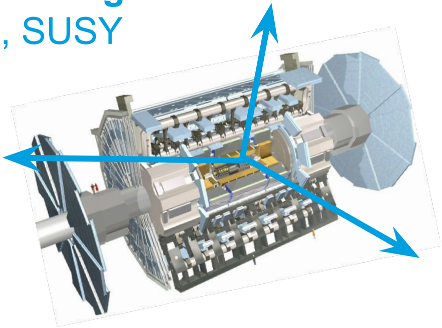
Main focus of LHC are heavy particles: Higgs, SUSY … .

Their decay products have high pT and are distributed almost isotropically.

ATLAS/CMS were constructed to catch them.

Central Region

H, SUSY

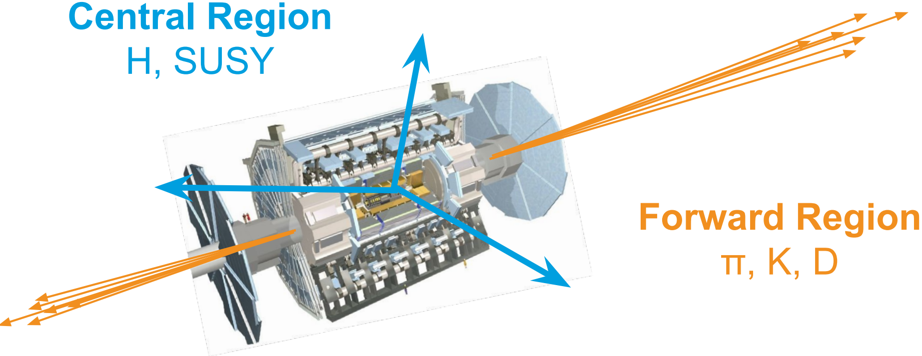


Why Forward Physics?

The LHC produces a huge number of hadrons in the forward direction:
10^{17} π0, 10^{16} η, 10^{15} D, 10^{13} B within 1 mrad of beam.

Typically low pT but large energy.

Can we do something with that?

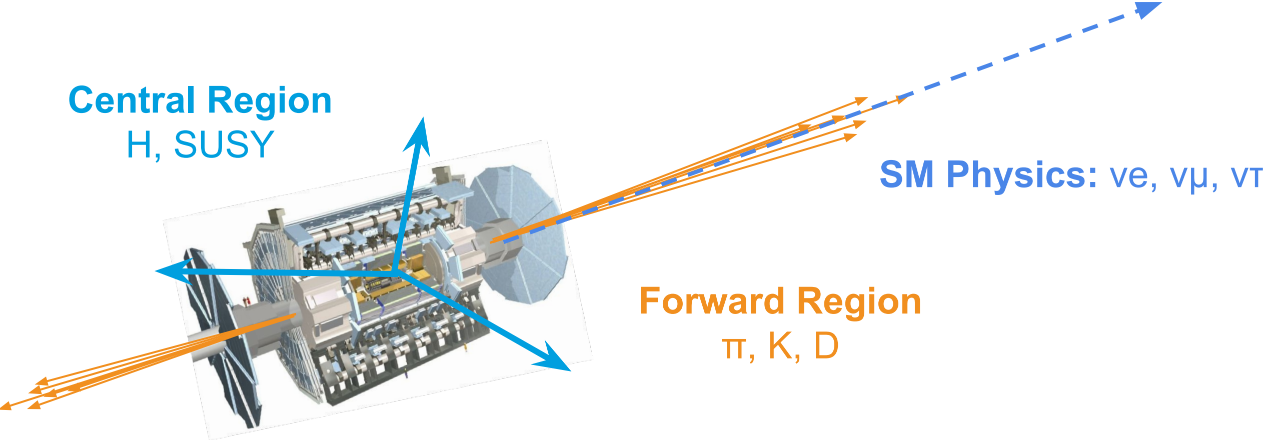


Central Region
H, SUSY

Forward Region
π, K, D

Why Forward Physics?

The LHC produces an intense and strongly collimated beam of neutrinos with TeV energies in the forward direction.



Central Region

H, SUSY

SM Physics: νe, νμ, ντ

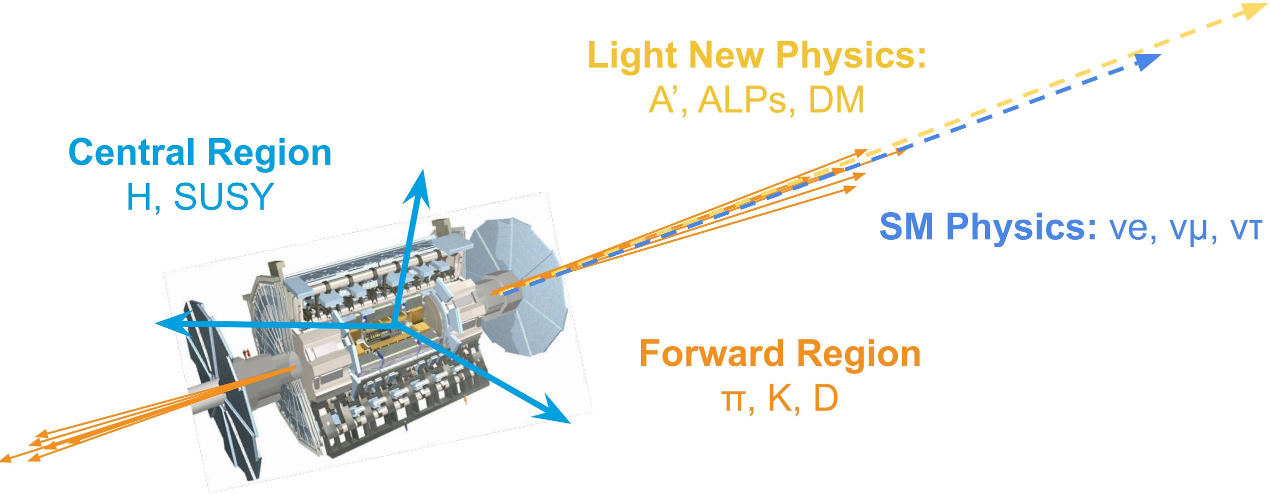
Forward Region

π, K, D

Why Forward Physics?

The LHC produces an intense and strongly collimated beam of neutrinos with TeV energies in the forward direction.

This may also be true for many interesting new particle candidates: dark photons, axion-like particles, dark matter.



Light New Physics:
A', ALPs, DM

Central Region
H, SUSY

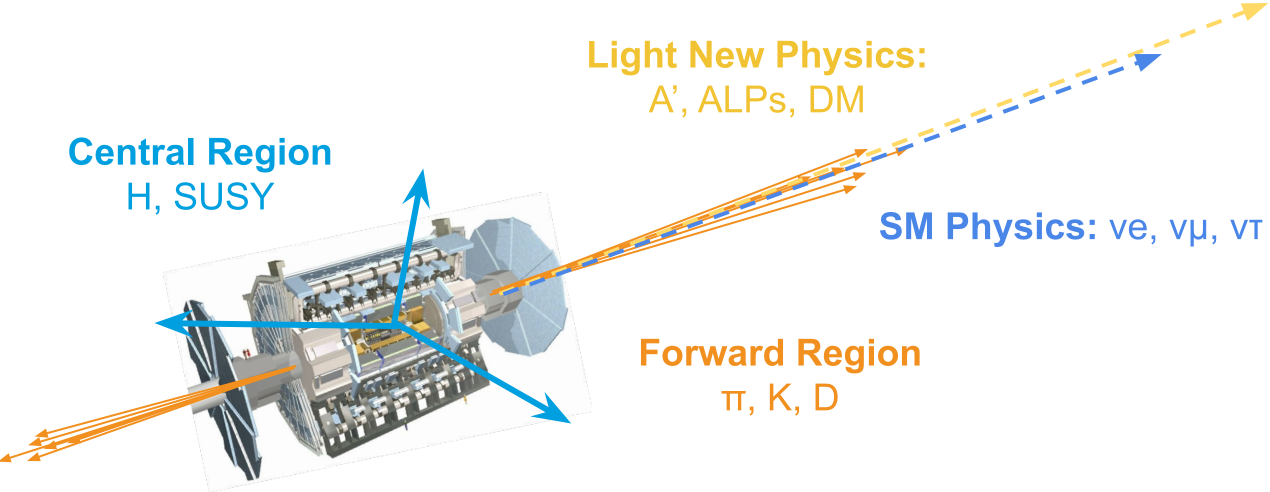
SM Physics: νe, $\nu \mu$, $\nu \tau$

Forward Region
π, K, D

Why Forward Physics?

These particles escape down the beam pipe and remain undetected.

Indeed, the existing big LHC detectors are perfectly designed NOT to see them.



Light New Physics:
A', ALPs, DM

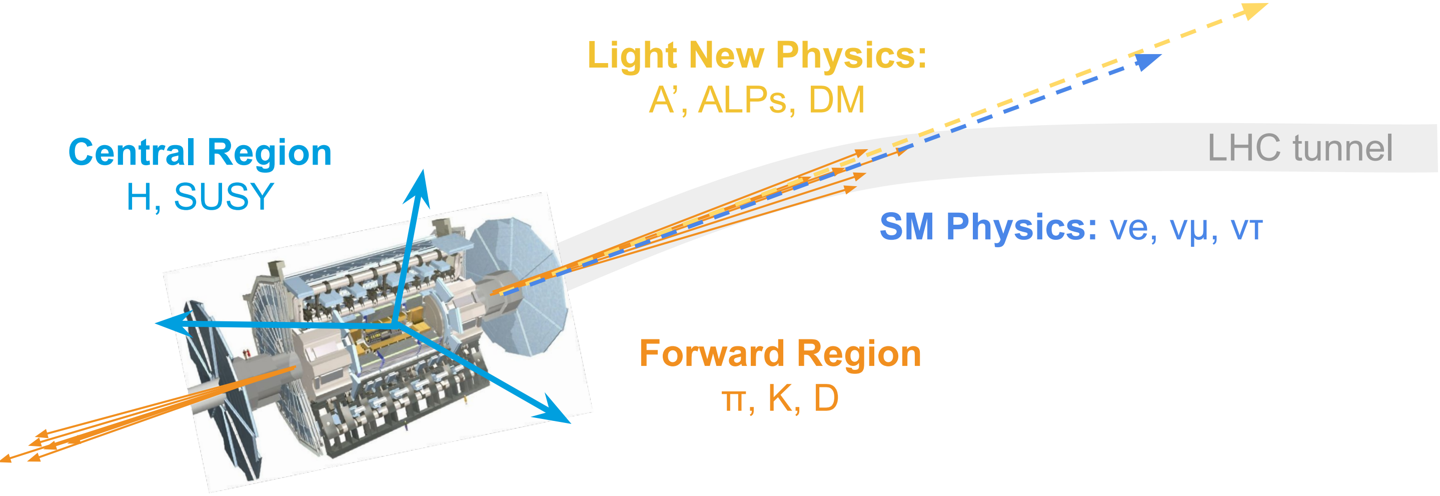
Central Region
H, SUSY

SM Physics: νe, νμ, ντ

Forward Region
π, K, D

Why Forward Physics?

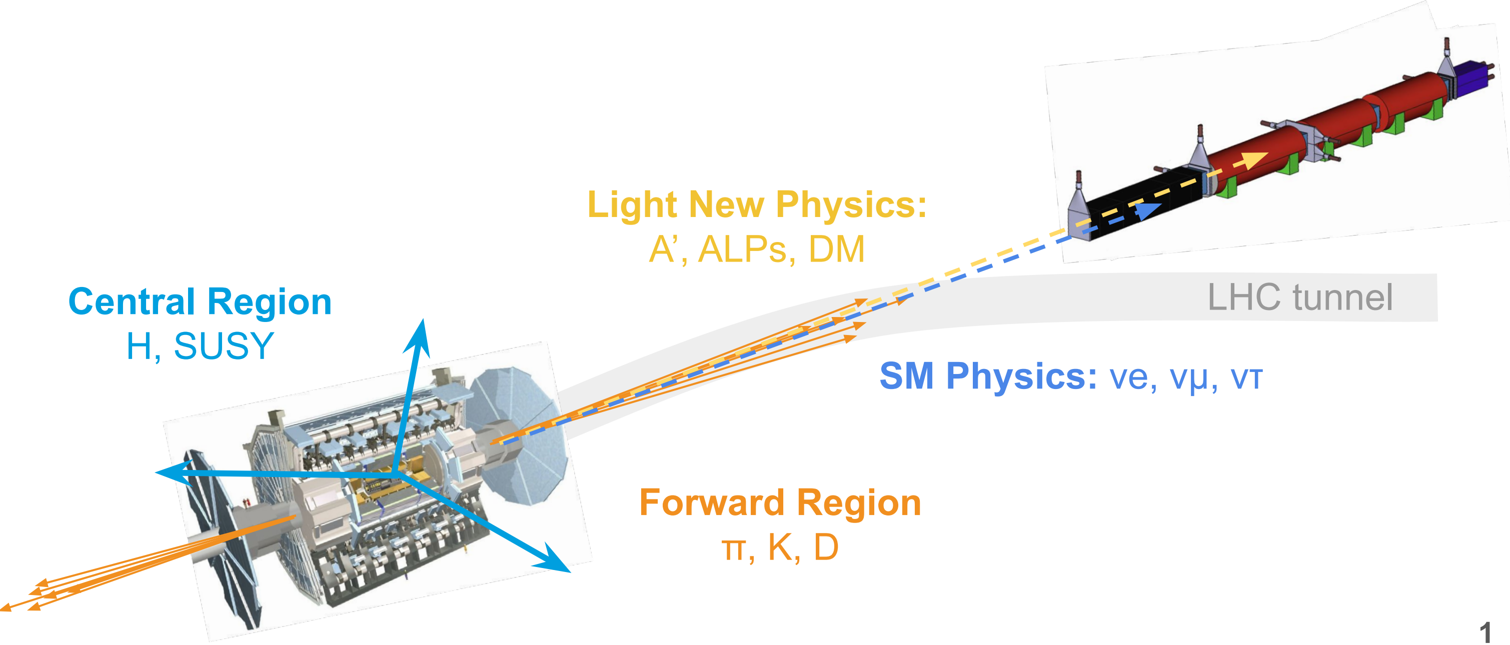
LHC tunnel will eventually curve away, but the beam of neutral particles will continue along the beam collision axis.



Why Forward Physics?

LHC tunnel will eventually curve away, but the beam of neutral particles will continue along the beam collision axis.

Idea: Placed experiment in this beam to detect them.



Light New Physics:
A', ALPs, DM

Central Region
H, SUSY

LHC tunnel

SM Physics: νe, νμ, ντ

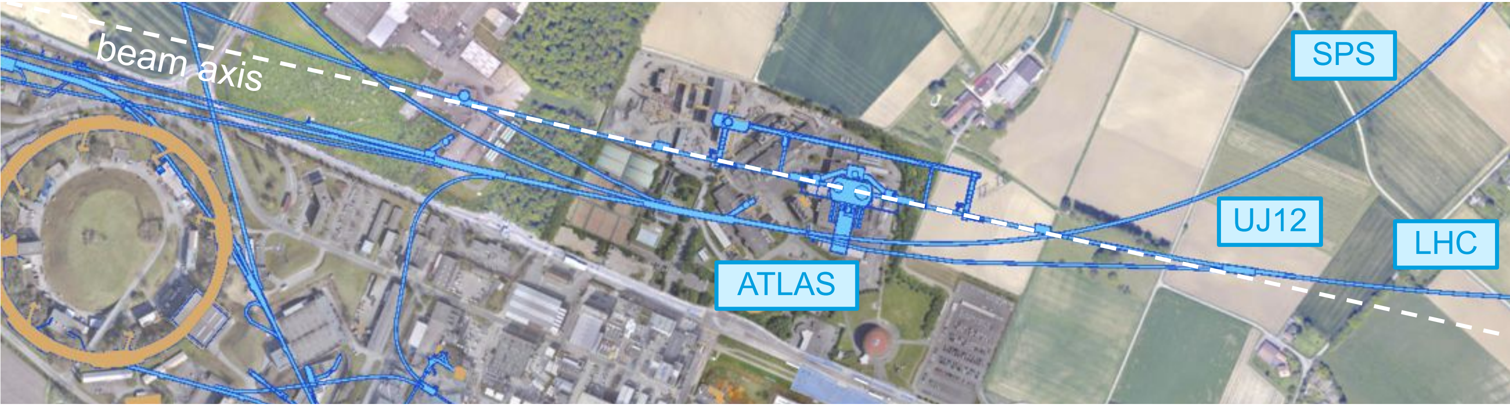
Forward Region
π, K, D

Experimental Program:
FASER — FASERν — SND@LHC — FPF

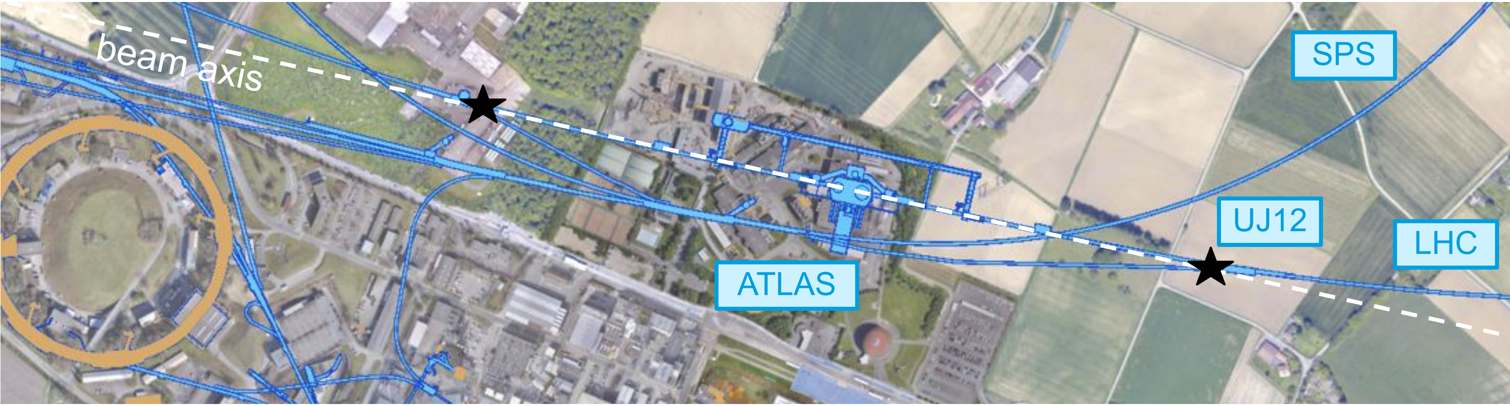
Searches for BSM physics:
LLP Decays — DM Scattering — Millicharged Particles

SM Measurements:
Neutrinos — QCD — Cosmic Rays

Location.

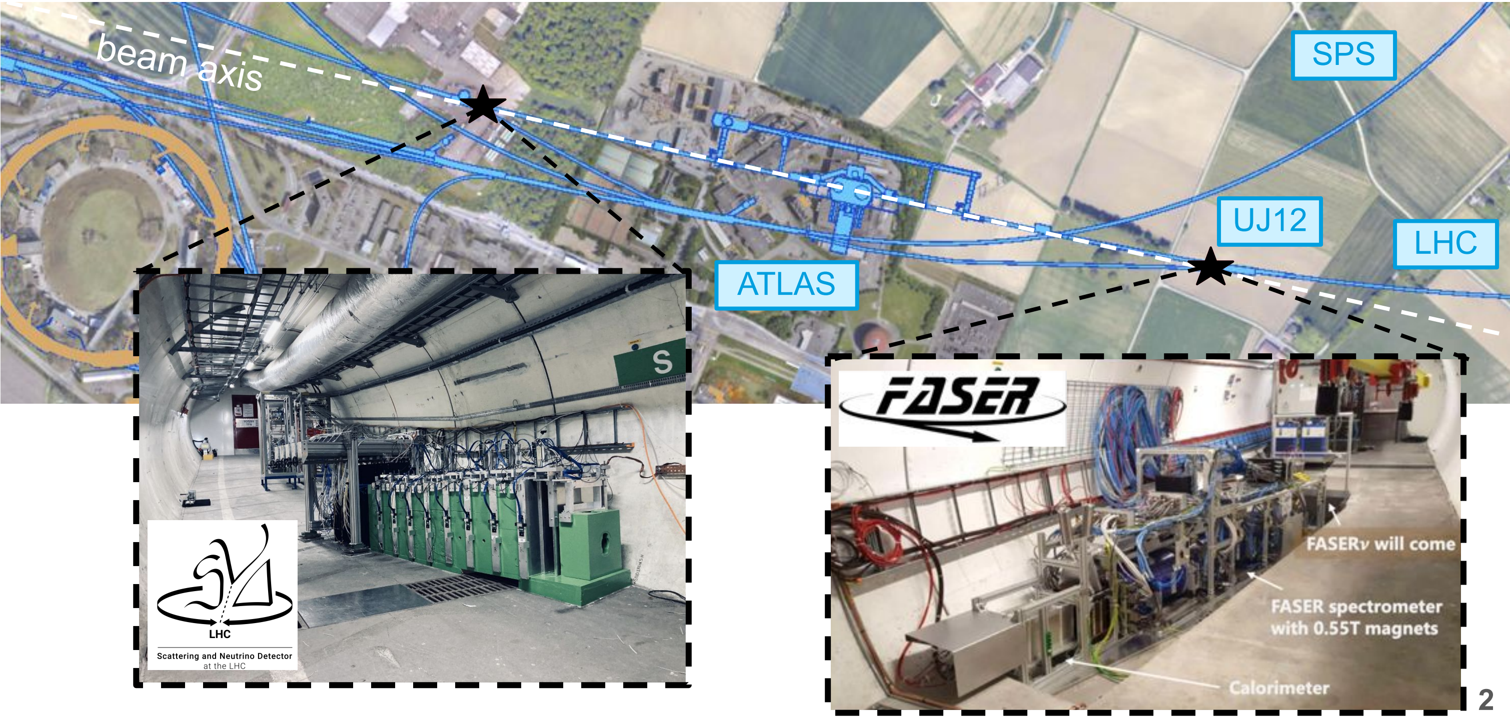


Location.



Location.

Two new experiments will exploit this potential during run 3 of the LHC:
SND@LHC and FASER.



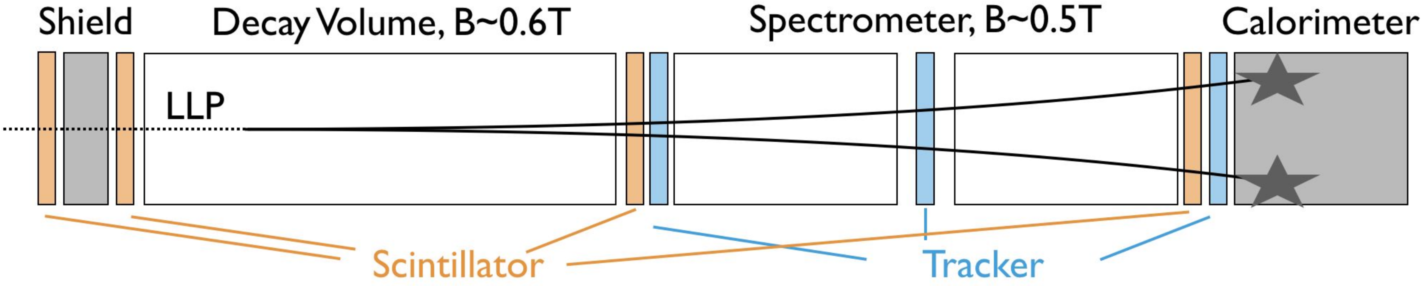
FASER.

Main Goal: Search for light long-lived particles

pp → LLP + X, LLP travels ~ 480m, LLP → charged tracks + X

Signal is striking:

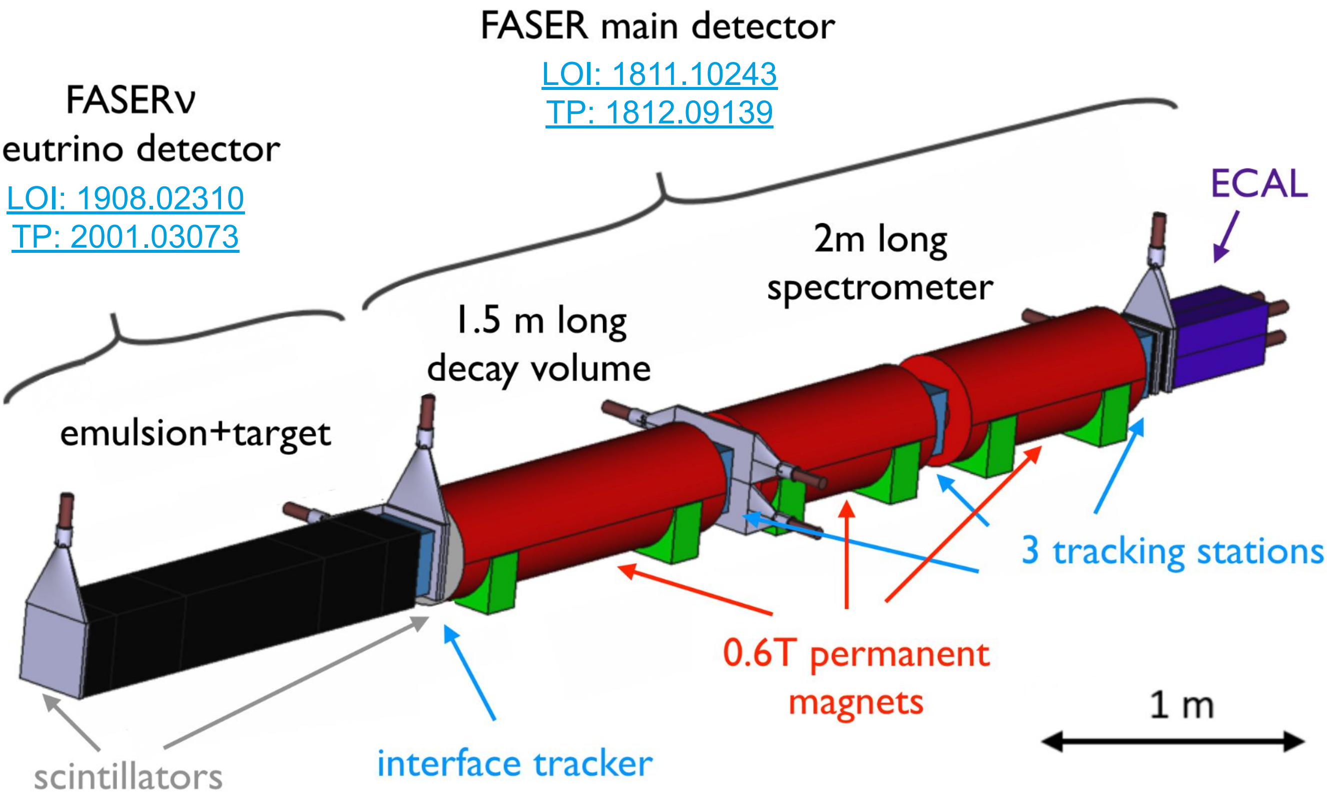
- highly energetic charged particles (E ~ TeV)
- emerging from an empty decay volume
- point back to the IP through 90 m of rock



Background considerations:

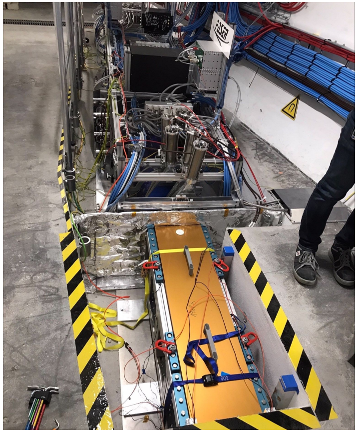
- large flux of muons from the LHC cause muon-associated radiative events
- use scintillators veto to reduce BG to negligible levels

FASER.


FASER main detector
LOI: 1811.10243
TP: 1812.09139
FASERν
neutrino detector
LOI: 1908.02310
TP: 2001.03073
ECAL
2m long
spectrometer
1.5 m long
decay volume
emulsion+target
3 tracking stations
0.6T permanent
magnets
1 m
scintillators
interface tracker

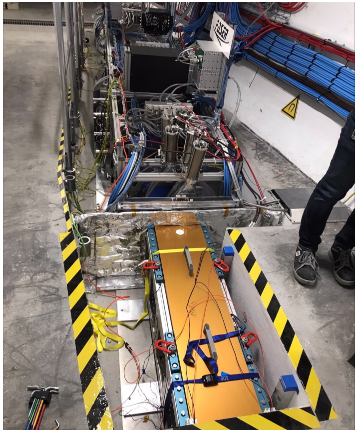
FASERν.

FASERν neutrino detector in front of FASER
- 25cm x 25cm x 1.3m, 1.2 ton mass
- placed on axis: η > 9
- ~10000 neutrinos during LHC Run 3



FASERν.

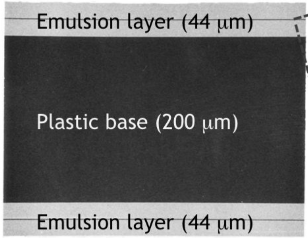
FASERν neutrino detector in front of FASER
- 25cm x 25cm x 1.3m, 1.2 ton mass
- placed on axis: η > 9
- ~10000 neutrinos during LHC Run 3



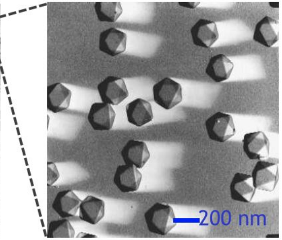
Emulsion detectors technology

- used by CHORUS, DONUT, OPERA
- 1000 emulsion films interleaved with 1mm tungsten plates
- global reconstruction with the FASER detector possible

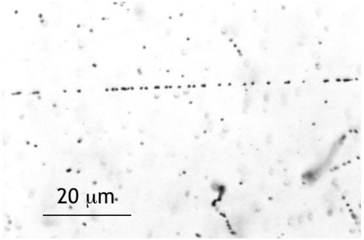

Emulsion film



Cross-sectional view



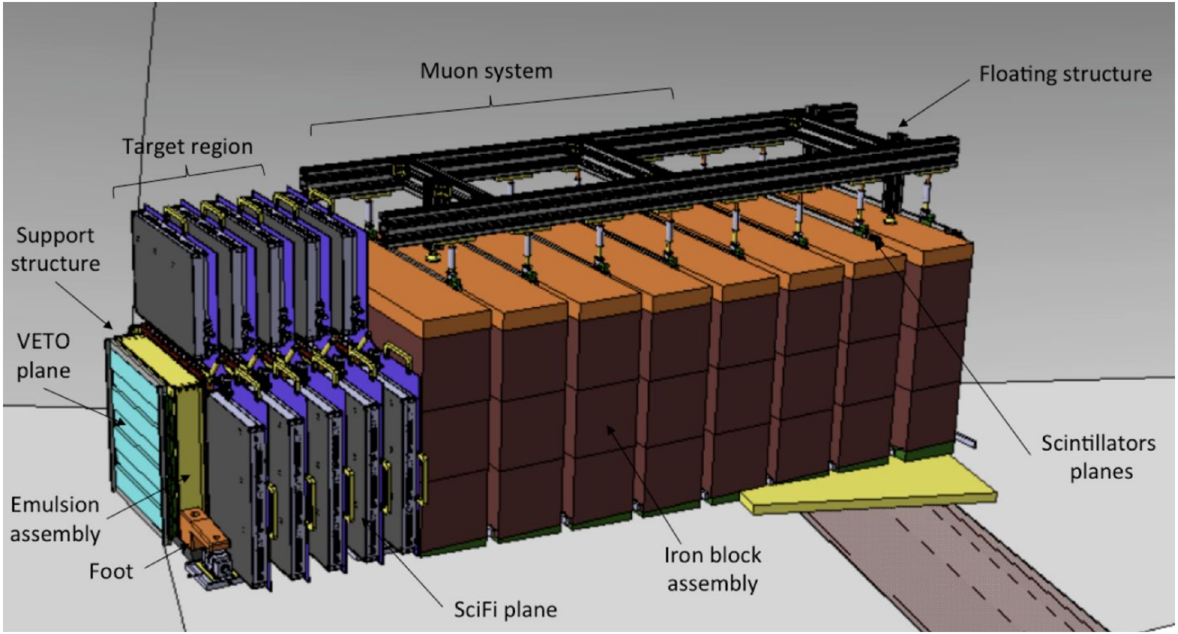
AgBr crystal



Track in emulsion film

SND@LHC.

SND@LHC: second LHC neutrino experiment

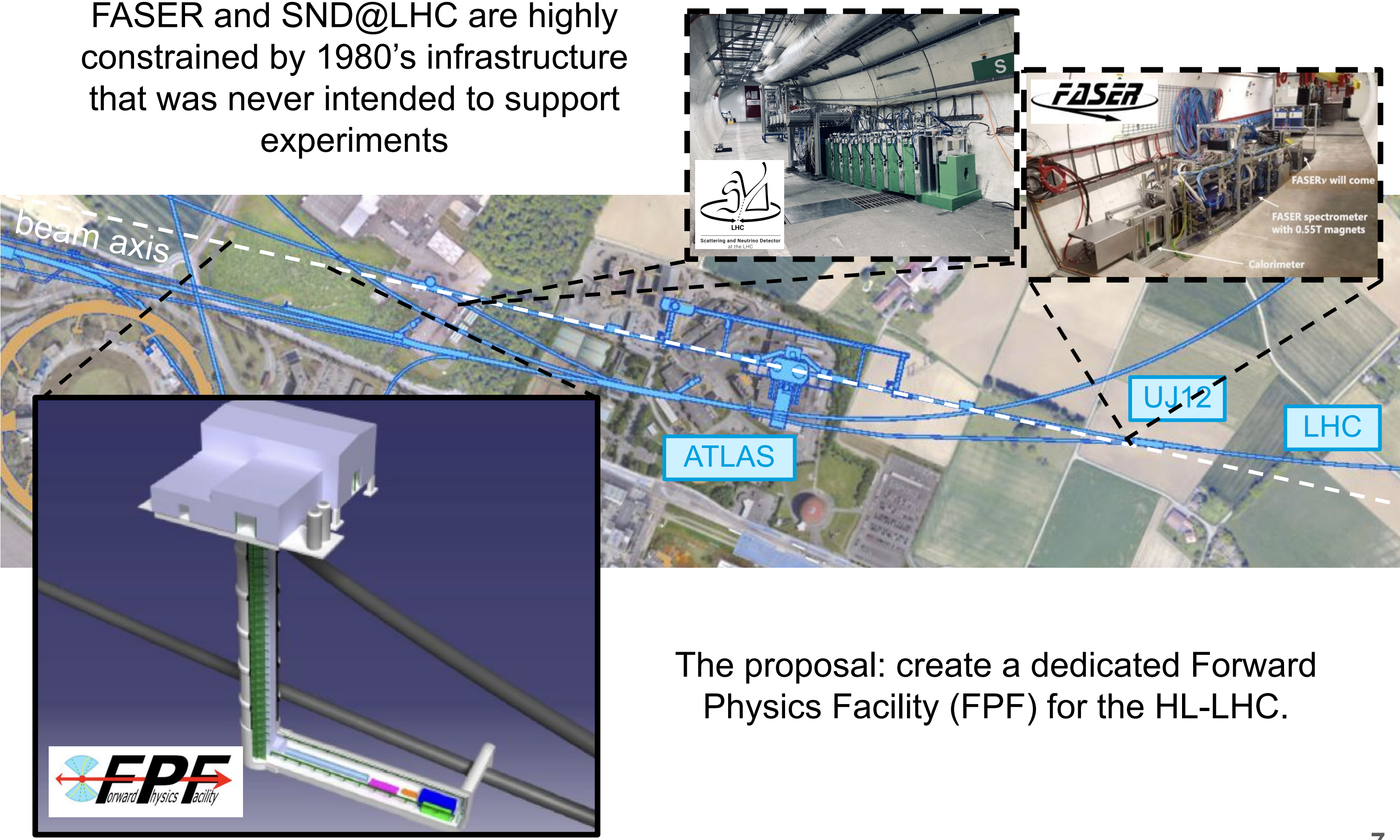


- located on other side of ATLAS
- used emulsion and electronic components

- slightly off-axis location: $7.2 < \eta < 8.7$
- target: 830 kg of tungsten

Forward Physics Facility.

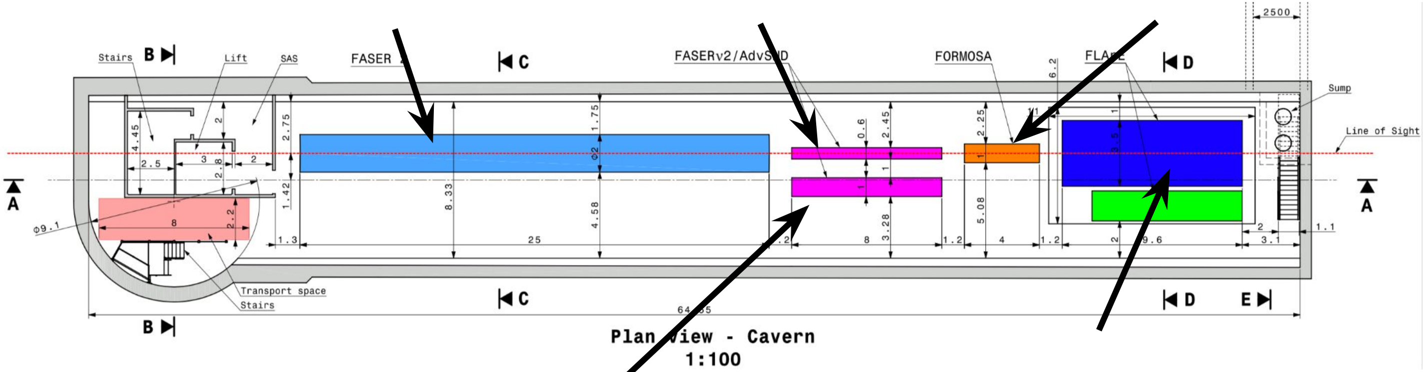
FASER and SND@LHC are highly constrained by 1980’s infrastructure that was never intended to support experiments



The proposal: create a dedicated Forward Physics Facility (FPF) for the HL-LHC.

Forward Physics Facility.

The FPF would house a suite of experiments that will greatly enhance the LHC's physics potential for BSM physics searches, neutrino physics and QCD.



FASER2
magnetized spectrometer
for BSM searches

FASERν2
emulsion-based
neutrino detector

FORMOSA
plastic scintillator array
for BSM searches

AdvSND
electronic
neutrino detector

FLArE
LAr based
neutrino detector

Forward Physics Facility.

FPF workshop series:
FPF1, FPF2, FPF3, FPF4

FPF Paper:
2109.10905
~75 pages, ~80 authors

Snowmass Whitepaper:
2203.05090
~450 pages, ~250 authors

4th Forward Physics Facility Meeting

31 January 2022 to 1 February 2022
Europe/Zurich timezone

Starts 31 Jan 2022, 16:00
Ends 1 Feb 2022, 21:00
Europe/Zurich

There are no materials yet.

The Forward Physics Facility (FPF) project is moving forward!

At the 4th Forward Physics Facility Meeting we will discuss the facility, experiments, and physics goals of the proposed FPF at the HL-LHC. The meeting takes place just before the completion of the FPF Snowmass White Paper and will provide an opportunity to summarize the current status of the White Paper and the final steps in its preparation. The whole event will be held online.

The Zoom links are:
Plenary sessions (both Monday and Tuesday): https://uci.zoom.us/j/91591021575
u-live.zoom.us
RQnRzTjlpdz09
s://uiowa.zoom.us/j/94645515841
oom.us/j/97280888150

The Forward Physics Facility:
Sites, Experiments, and Physics Potential

Luis A. Anchordoqui,[1,*] Akitaka Ariga,[2,3] Tomoko Ariga,[4] Weidong Bai,[5] Kincso Balazs,[6]
Brian Batell,[7] Jamie Boyd,[6] Joseph Bramante,[8] Adrian Carmona
Francesco G. Celiberto,[11,12,13] Grigorios Chachamis,[14] Matthew Citr
Albert de Roeck,[6] Hans Dembinski,[18] Peter B. Denton,[19] Anto
Milind V. Diwan,[20] Liam Dougherty,[21] Herbi K. Dreiner,[22] Yong
Yasaman Farzan,[25] Jonathan L. Feng,[26,†] Max Fieg,[26] Patric
Foroughi-Abari,[28] Alexander Friedland,[29,*] Michael Fucilla,
Maria Vittoria Garzelli,[33,‡] Francesco Giuli,[34] Victor P. Gonca
Francis Halzen,[37] Juan Carlos Helo,[38,39] Christopher S. Hill,
Ameen Ismail,[42] Sudip Jana,[43] Yu Seon Jeong,[44] Krzysztof Jo
Kumar,[20] Kevin J. Kelly,[46] Felix Kling,[29,47,§] Rafał Maciuła,
Abraham,[41] Julien Manshanden,[33] Josh McFayden,[49] Mohammed
Pavel M. Nadolsky,[50,*] Nobuchika Okada,[51] John Osborne,[6] Hi
Pandey,[52,46,*] Alessandro Papa,[30,31] Digesh Raut,[53] Mary Hall R
Adam Ritz,[28] Juan Rojo,[55] Ina Sarcevic,[56,*] Christiane Scher
Holger Schulz,[59] Dipan Sengupta,[60] Torbjörn Sjöstrand,[61,*] Tyler B.
Anna Stasto,[62] Antoni Szczurek,[48] Zahra Tabrizi,[63] Sebastia
Yu-Dai Tsai,[26,46] Douglas Tuckler,[66] Martin W. Winkler,[67] Kepin

The Forward Physics Facility (FPF) is a proposal to create a
infrastructure to support a suite of far-forward experiments at
during the High Luminosity era. Located along the beam collis
the interaction point by at least 100 m of concrete and rock, the F
that will detect particles outside the acceptance of the existing l
will observe rare and exotic processes in an extremely low-backg
work, we summarize the current status of plans for the FPF, i
civil engineering in identifying promising sites for the FPF; the
envisioned to realize the FPF's physics potential; and the many
physics topics that will be advanced by the FPF, including searc
probes of dark matter and dark sectors, high-statistics studies of
flavors, aspects of perturbative and non-perturbative QCD, and
physics.

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 an LHC interaction point and shielded by concrete and rock, will host a suite of experiments to probe standard model 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 standard model expectations in high statistics analyses with TeV neutrinos in this low-background environment. High statistics neutrino detection will trace back to 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.

Experimental Program:
FASER — FASERν — SND@LHC — FPF

Searches for BSM physics:
LLP Decays — DM Scattering — Millicharged Particles

SM Measurements:
Neutrinos — QCD — Cosmic Rays

Motivation: Dark Sectors.

SM Sector

Mediator

Dark Sector

Motivation: Dark Sectors.

Simple Model: Dark Matter charged under U(1)D

$$\mathcal{L} \supset -\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2 A'^2 - m_\chi^2\chi^2 - ig_D A'\chi^2$$

coupling to SM via small mixing with SM photon

dark photon can be massive

massive DM

dark photon couples to DM

Motivation: Dark Sectors.

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

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

coupling to SM via small mixing with SM photon

dark photon can be massive

massive DM

dark photon couples to DM

Phenomenology depends on masses:

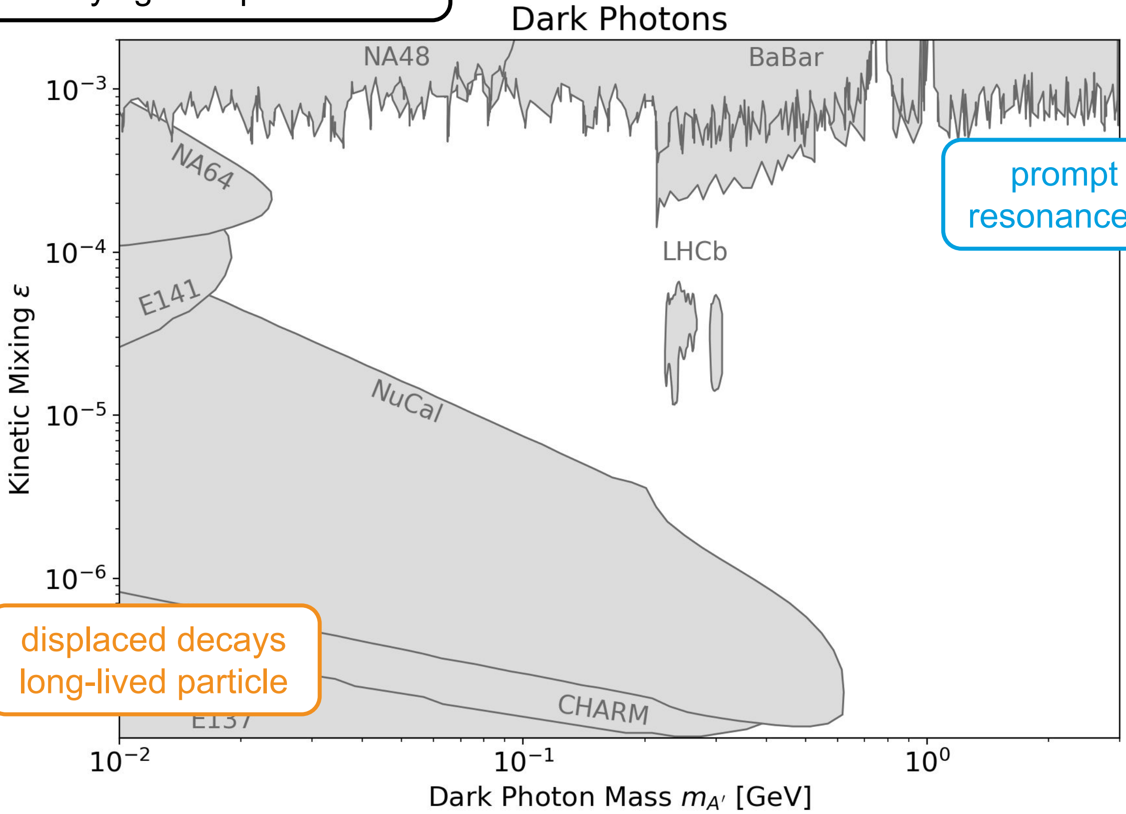
$m_{A'} > 2m_X$:
A' → XX

$m_{A'} < 2m_X$:
A' → SM SM
long-lived

$m_{A'} = 0$:
milli-charged X

Long-Lived Particles: Dark Photon.

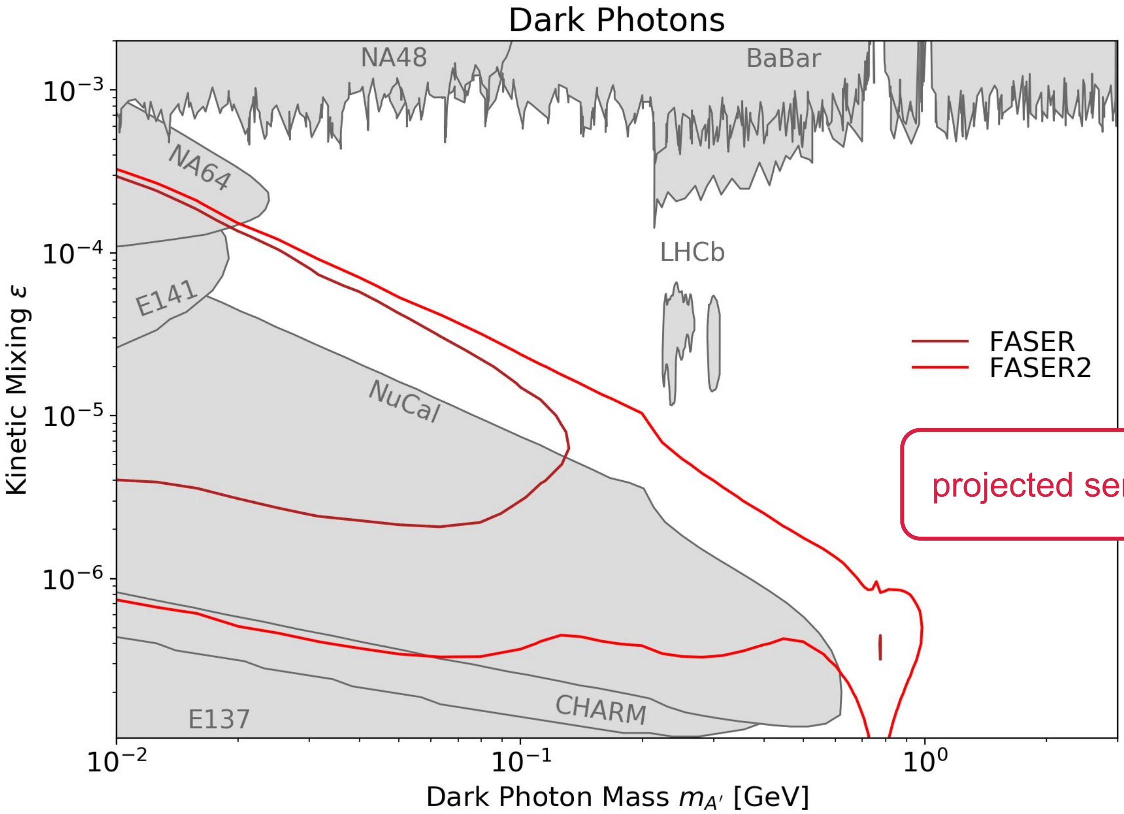
parameter space of **visibly** decaying dark photon



prompt decays resonance searches

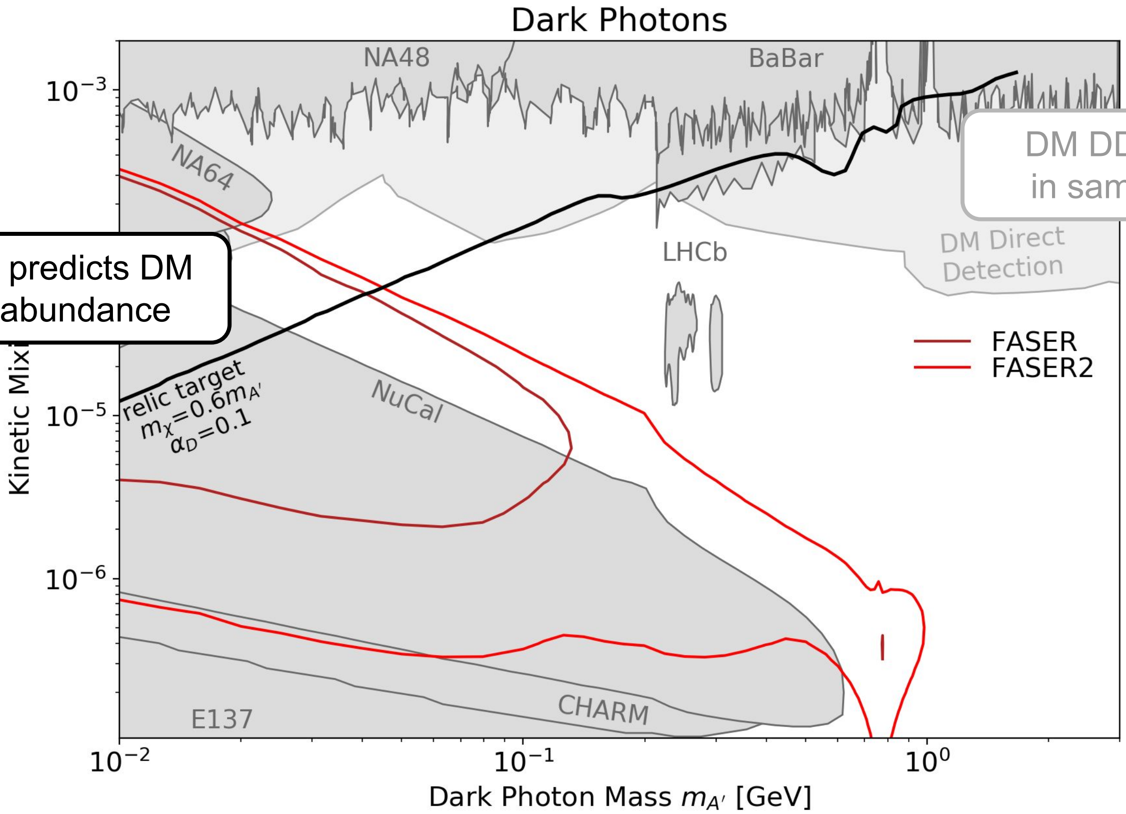
displaced decays long-lived particle

Long-Lived Particles: Dark Photon.



projected sensitivity

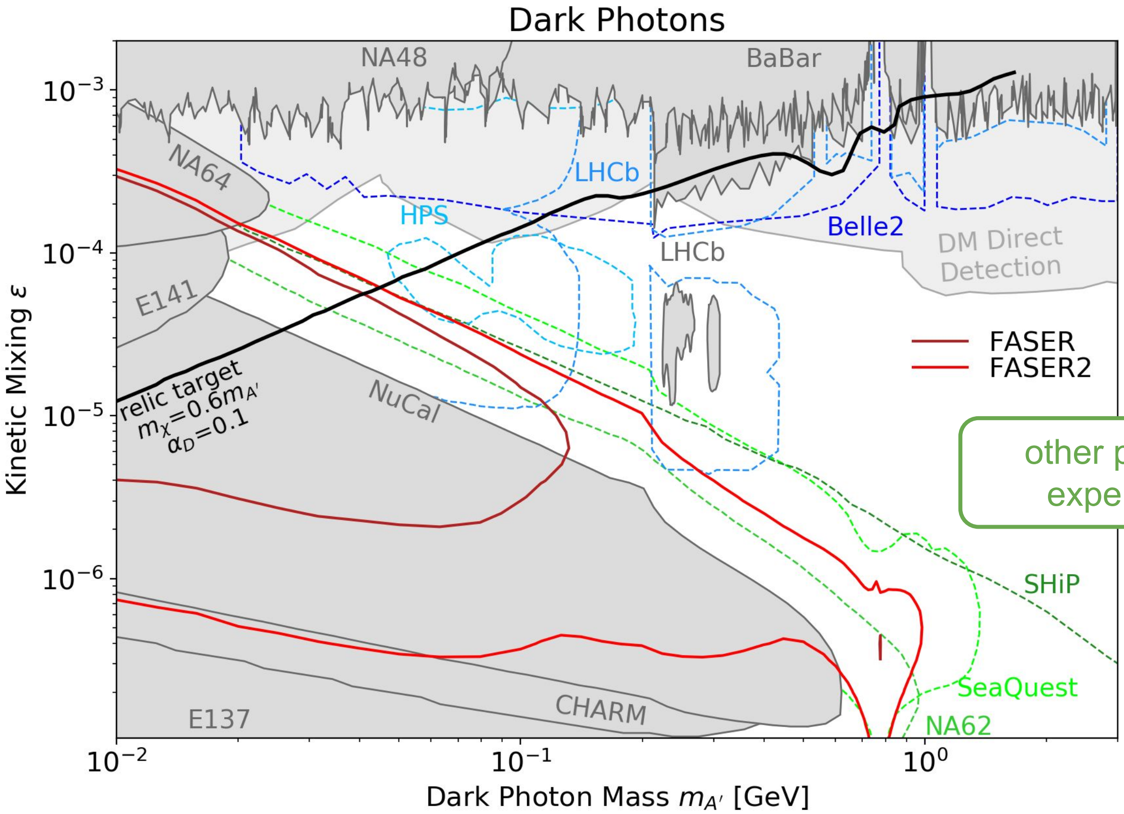
Long-Lived Particles: Dark Photon.



model predicts DM relic abundance

DM DD bounds in same model

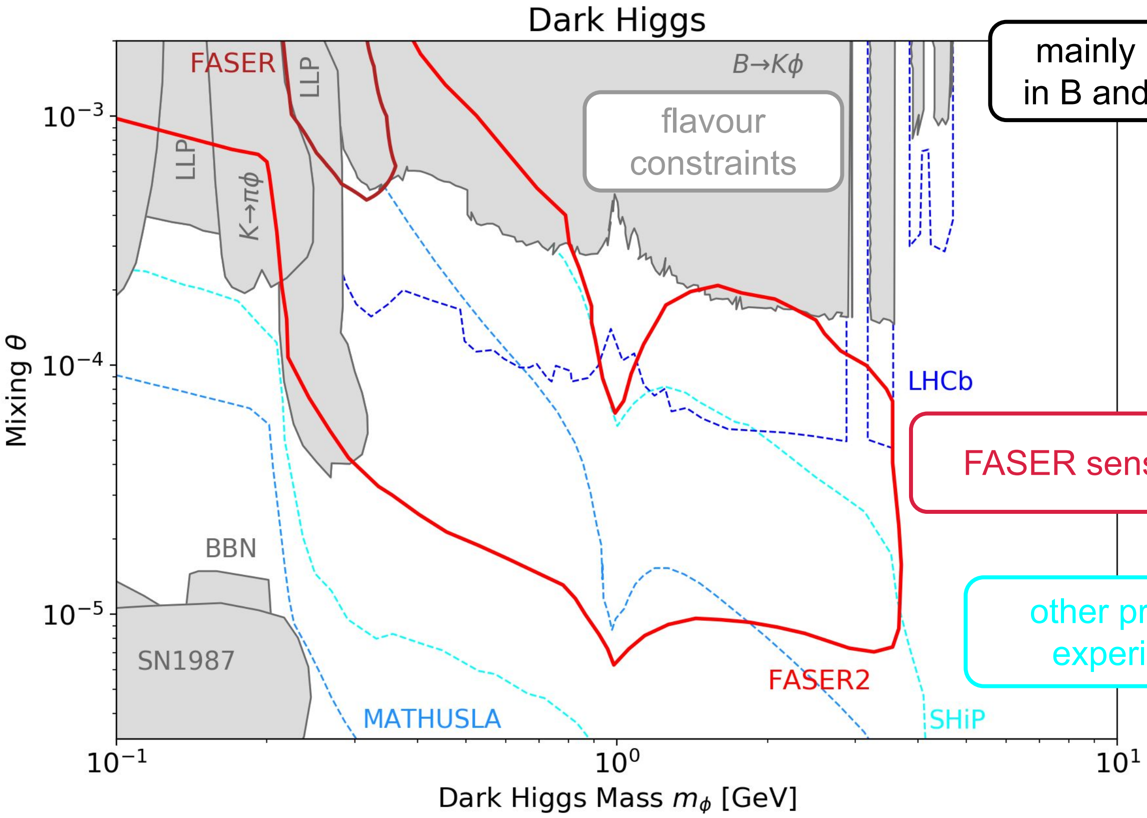
Long-Lived Particles: Dark Photon.



other proposed experiments

Long-Lived Particles: Dark Higgs.

Dark Higgs = light scalar mixing with SM Higgs: $\mathcal{L} \supset {m_\phi}^2 \phi^2 + \sin\theta \, y_f \phi \bar{f} f$

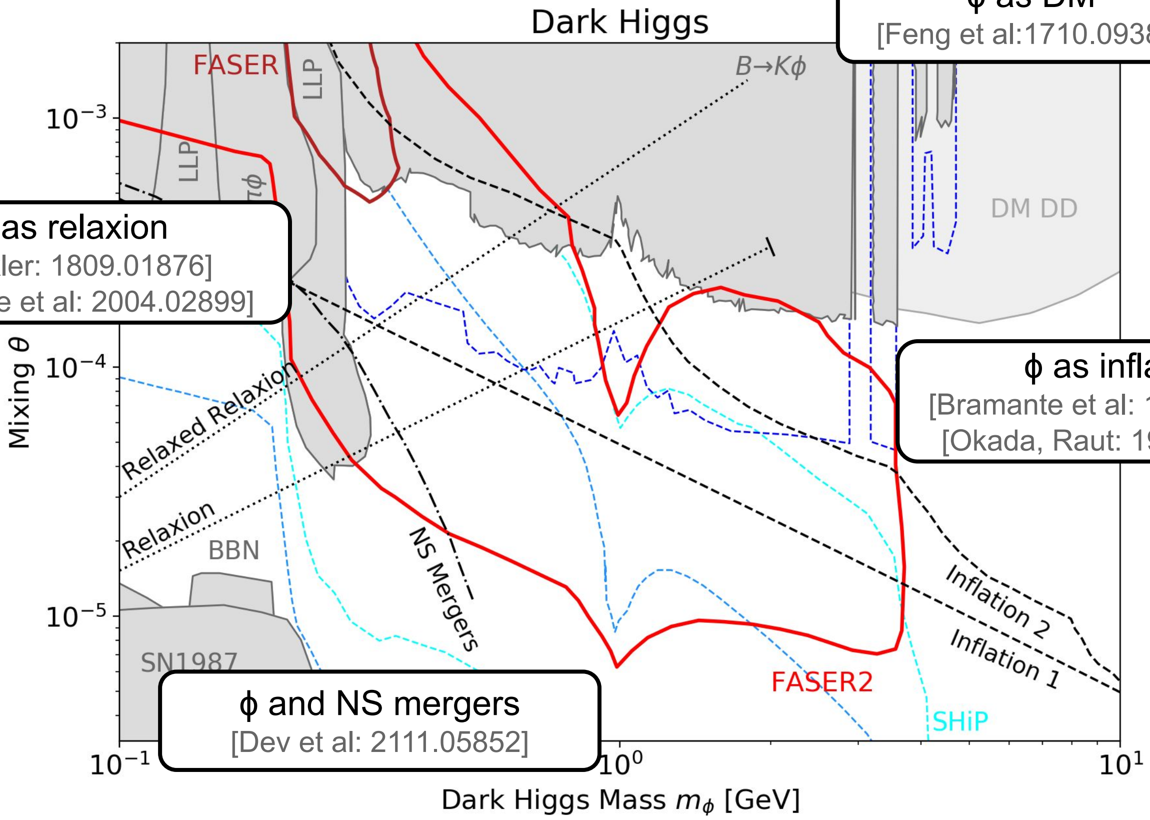


mainly produced in B and K decays

FASER sensitivity

other proposed experiments

Long-Lived Particles: Dark Higgs.



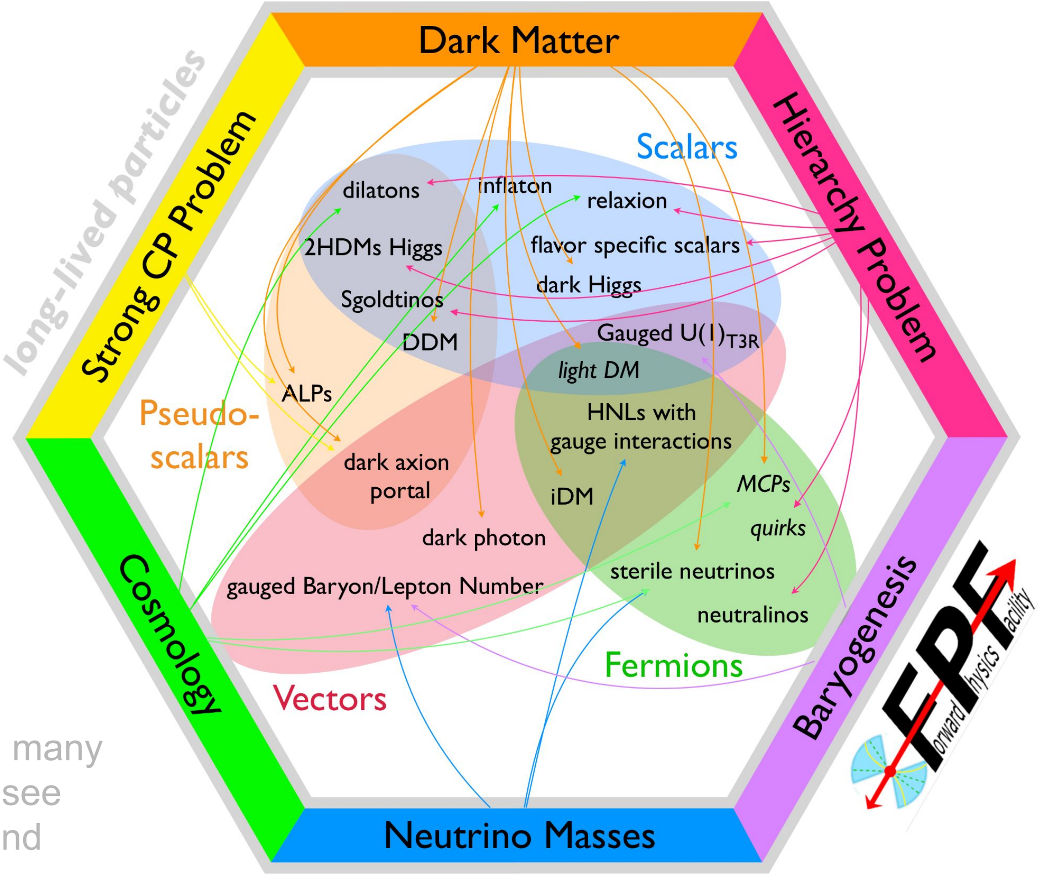
ϕ as DM
[Feng et al:1710.09387]

ϕ as relaxion
[Winkler: 1809.01876]
[Banerjee et al: 2004.02899]

ϕ as inflaton
[Bramante et al: 1608.08625]
[Okada, Raut: 1910.09663]

ϕ and NS mergers
[Dev et al: 2111.05852]

Long-Lived Particles.

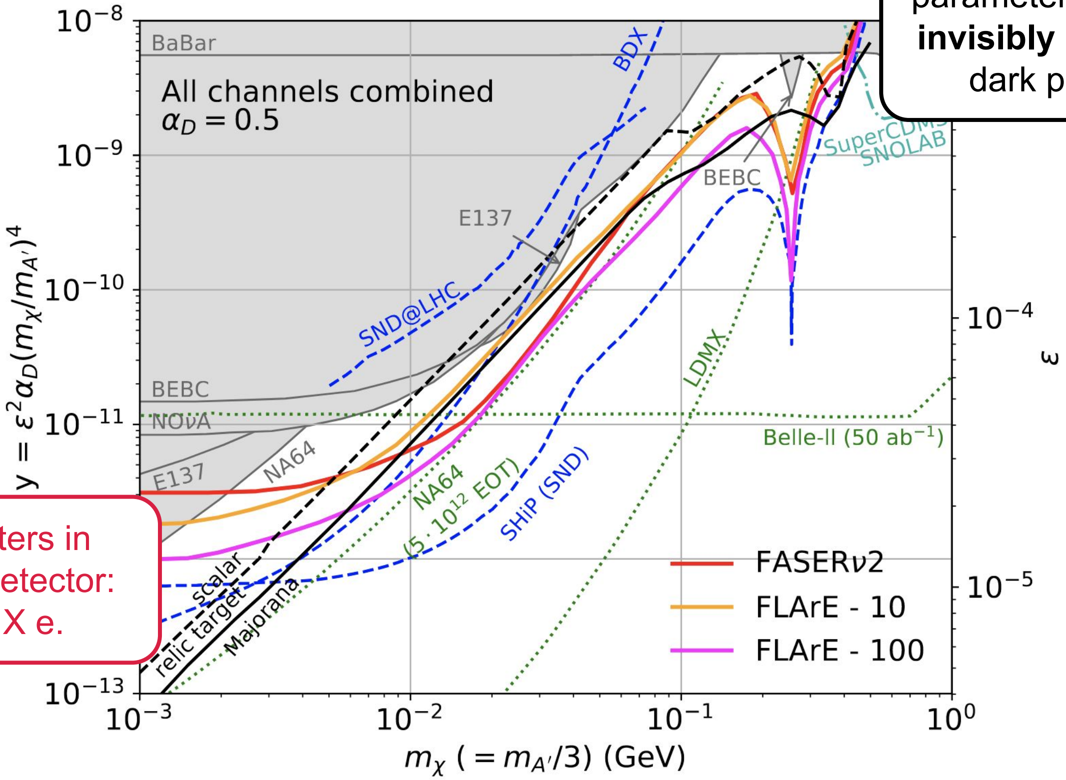


For details on many more models see 1811.12522 and 2203.05090.

Dark Matter Scattering.

if mA’ > 2mX : A’ decays to DM → LHC produces energetic DM beam

[Batell et al: 2101.10338]



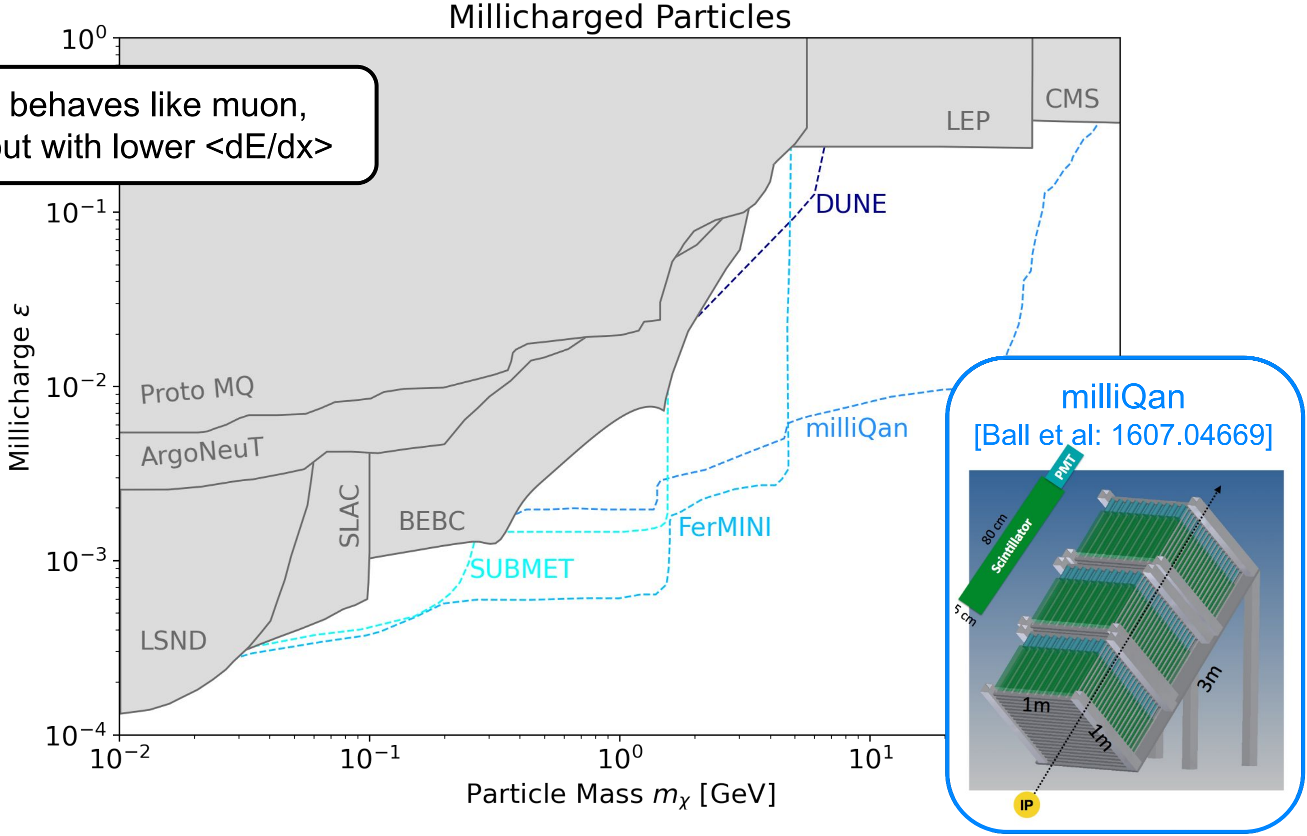
parameter space of **invisibly** decaying dark photon

DM scatters in neutrino detector:
X e → X e.

MilliCharged Particles.

If mA’=0: X is effectively milli-charged with Q=εe

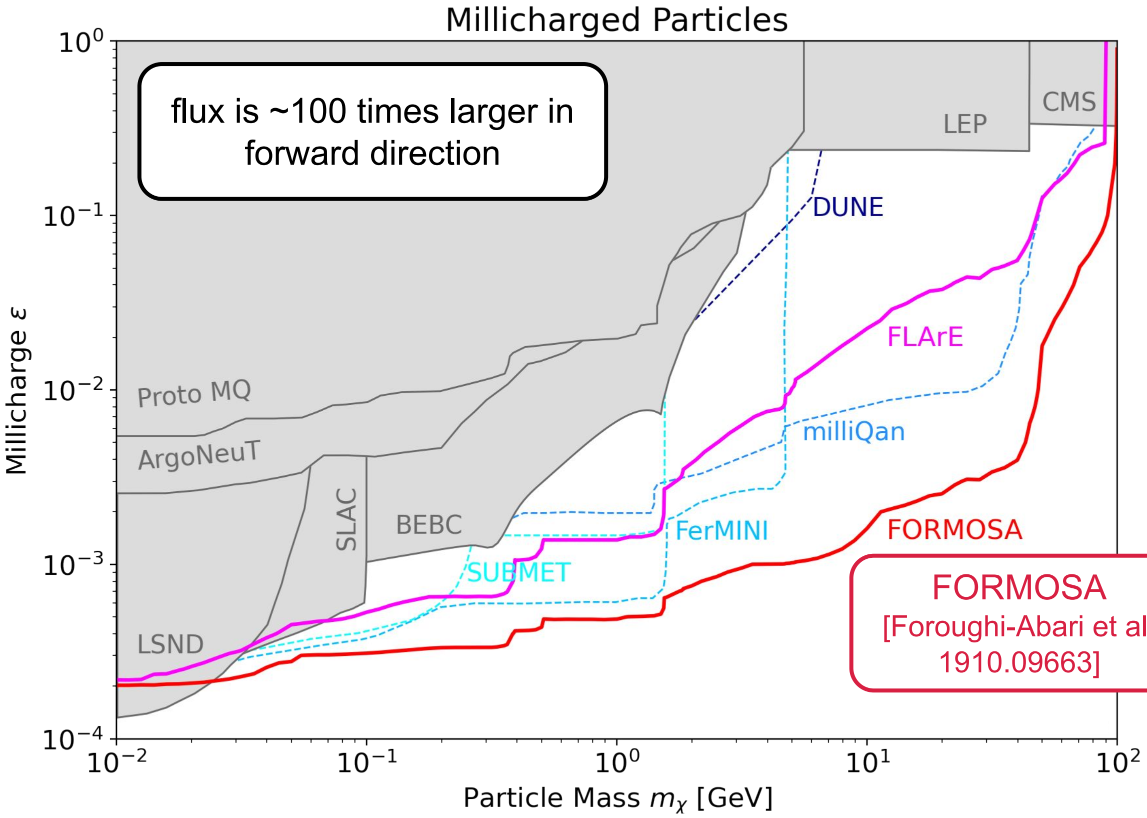
behaves like muon,
but with lower <dE/dx>



milliQan
[Ball et al: 1607.04669]

MilliCharged Particles.

If mA’=0: X is effectively milli-charged with Q=εe

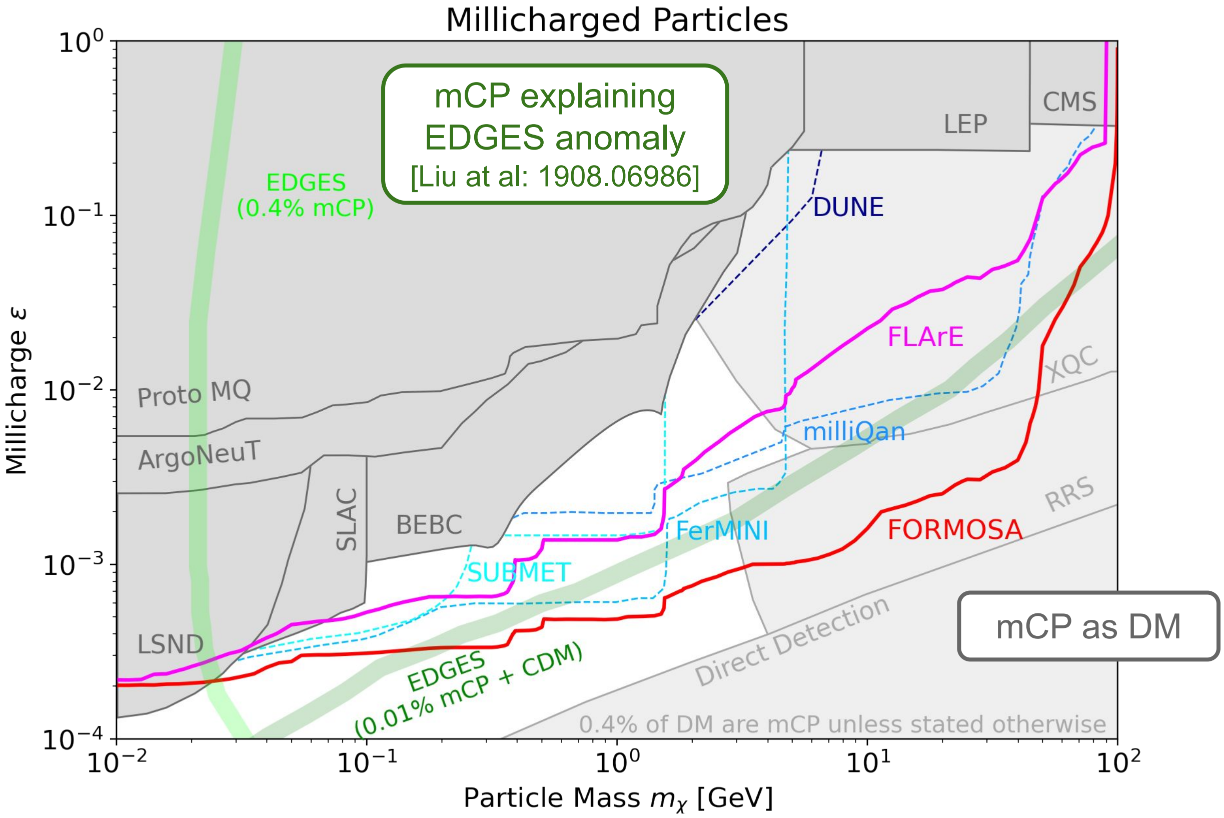


flux is ~100 times larger in forward direction

FORMOSA
[Foroughi-Abari et al: 1910.09663]

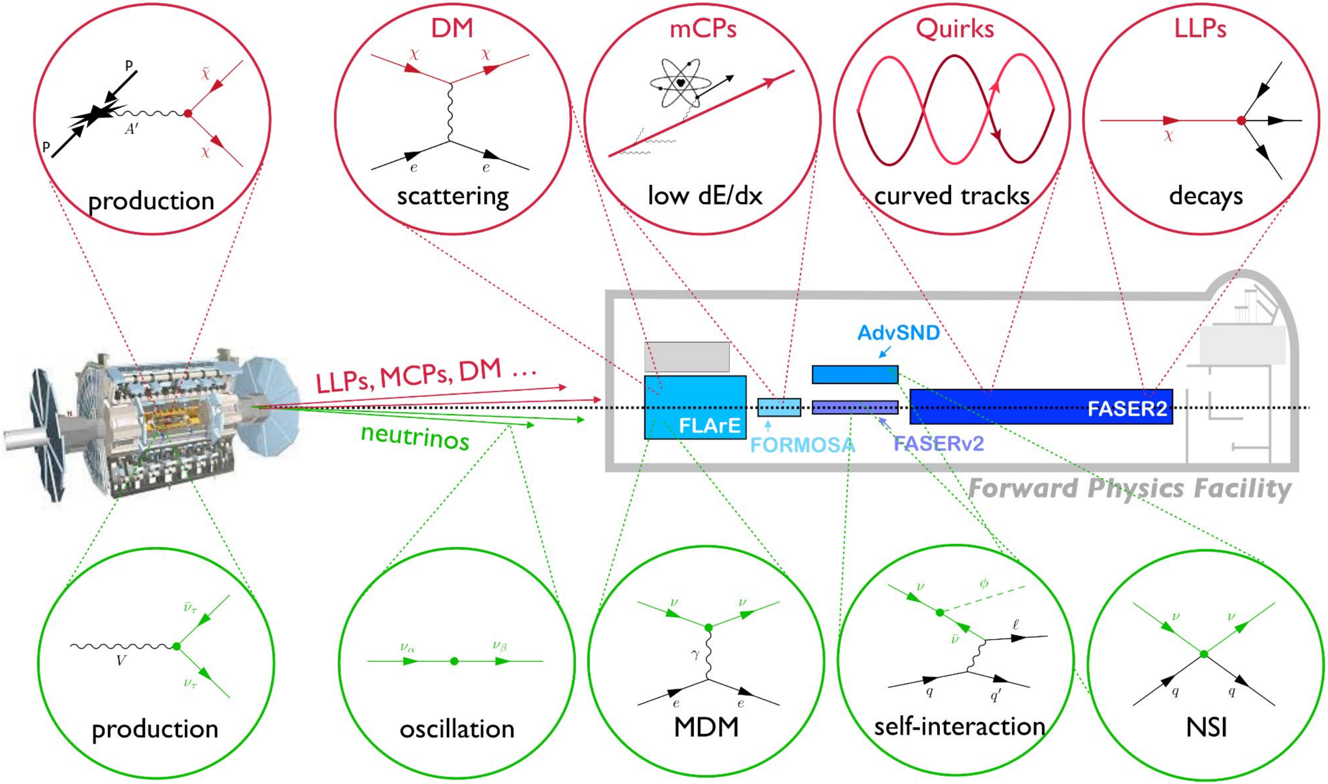
MilliCharged Particles.

If mA’=0: X is effectively milli-charged with Q=εe



Searches for BSM Physics

dark sector searches



BSM neutrino physics

Experimental Program:
FASER — FASERν — SND@LHC — FPF

Searches for BSM physics:
LLP Decays — DM Scattering — Millicharged Particles

SM Measurements:
Neutrinos — QCD — Cosmic Rays

Neutrinos at the LHC.

There is a huge flux of neutrinos in the forward direction, mainly from π, K and D meson decays.
[De Rujula et al. (1984)]

NEUTRINO AND MUON PHYSICS IN THE COLLIDER MODE OF FUTURE ACCELERATORS*)

A. De Rújula and R. Rückl
CERN, Geneva, Switzerland

ABSTRACT

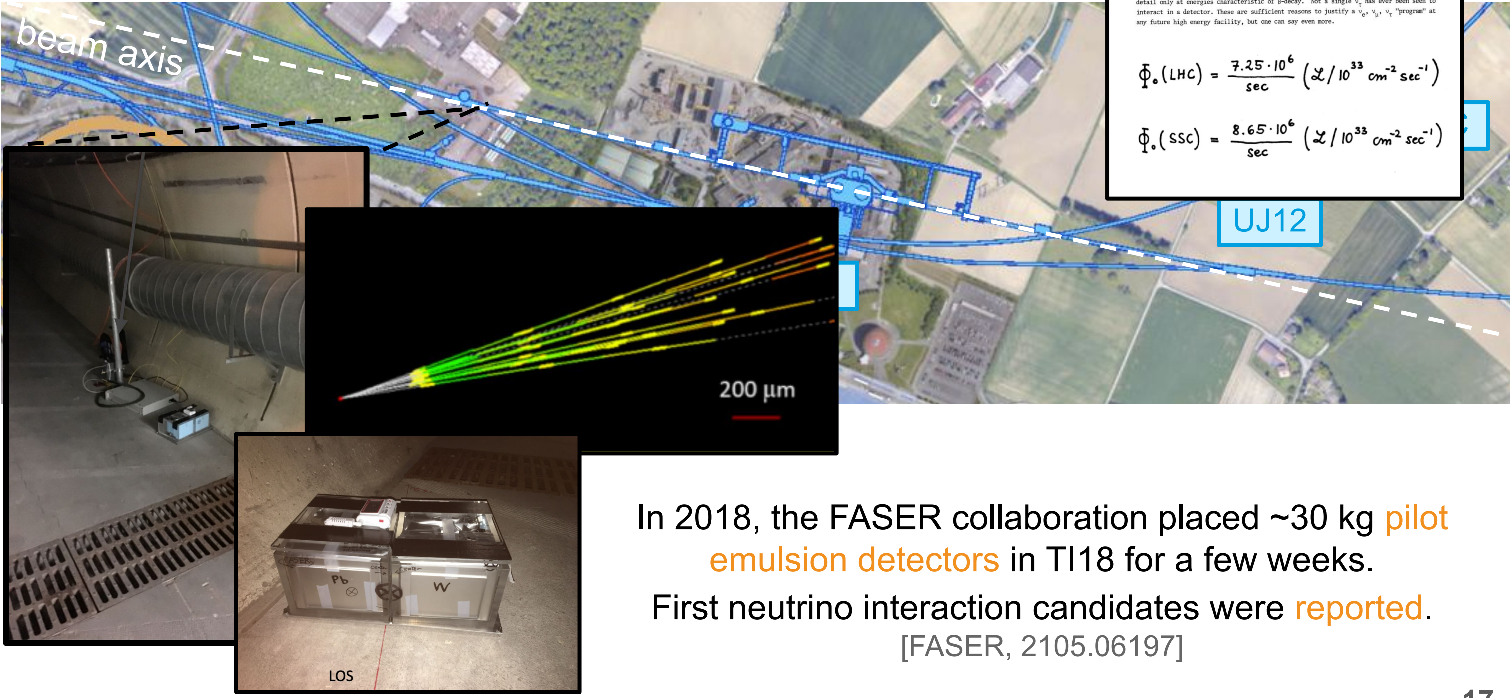
Extracted beams and fixed target facilities at future colliders (the SSC and the LHC) may be (respectively) impaired by economic and "ecological" considerations. Neutrino and muon physics in the multi-TeV range would appear not to be an option for these machines. We partially reverse this conclusion by estimating the characteristics of the "prompt" ν_μ, ν_e, ν_τ and μ beams necessarily produced (for free) at the pp or $\bar{p}p$ intersections. The neutrino beams from a high luminosity (pp) collider are not much less intense than the neutrino beam from the collider's dump, but require no muon shielding. The muon beams from the same intersections are intense and energetic enough to study μp and μN interactions with considerable statistics and a Q^2-coverage well beyond the presently available one. The physics program allowed by these lepton beams is a strong advocate of machines with the highest possible luminosity: pp (not $\bar{p}p$) colliders.

I. INTRODUCTION

The interactions of muons and muon-neutrinos with nucleons have not been experimentally studied with beams of energy in the TeV range. The $\nu_e N$ interactions have been analysed in detail only at energies characteristic of β-decay. Not a single ν_τ has ever been seen to interact in a detector. These are sufficient reasons to justify a ν_e, ν_μ, ν_τ "program" at any future high energy facility, but one can say even more.

$$\Phi_0(\mathrm{LHC}) = \frac{7.25\cdot 10^6}{\mathrm{sec}} \left(\mathcal{L}/10^{33}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\right)$$

$$\Phi_0(\mathrm{SSC}) = \frac{8.65\cdot 10^6}{\mathrm{sec}} \left(\mathcal{L}/10^{33}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\right)$$



In 2018, the FASER collaboration placed ~30 kg pilot emulsion detectors in TI18 for a few weeks.

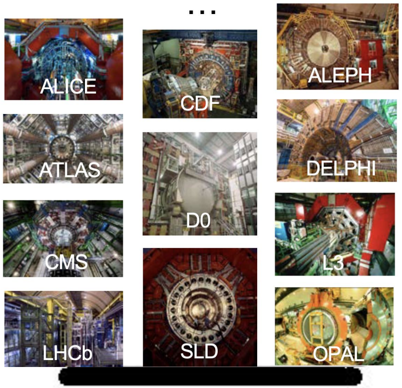
First neutrino interaction candidates were reported.
[FASER, 2105.06197]

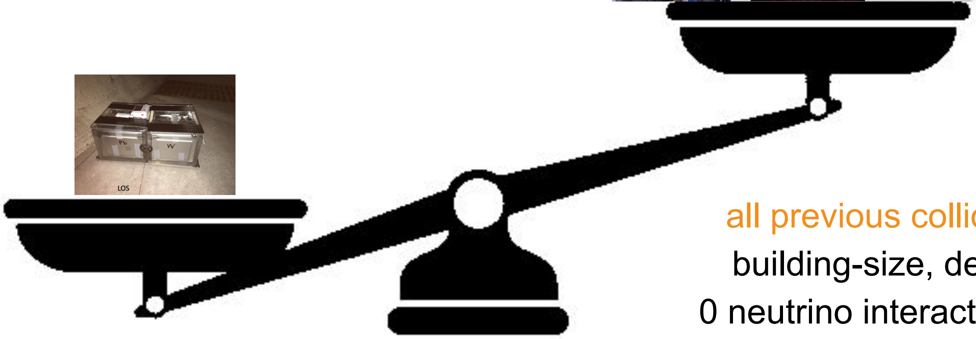
Neutrinos at the LHC.

FASER Pilot Detector

lunchbox-size, 4 weeks
$0 (recycled parts)

6 neutrino interaction candidates





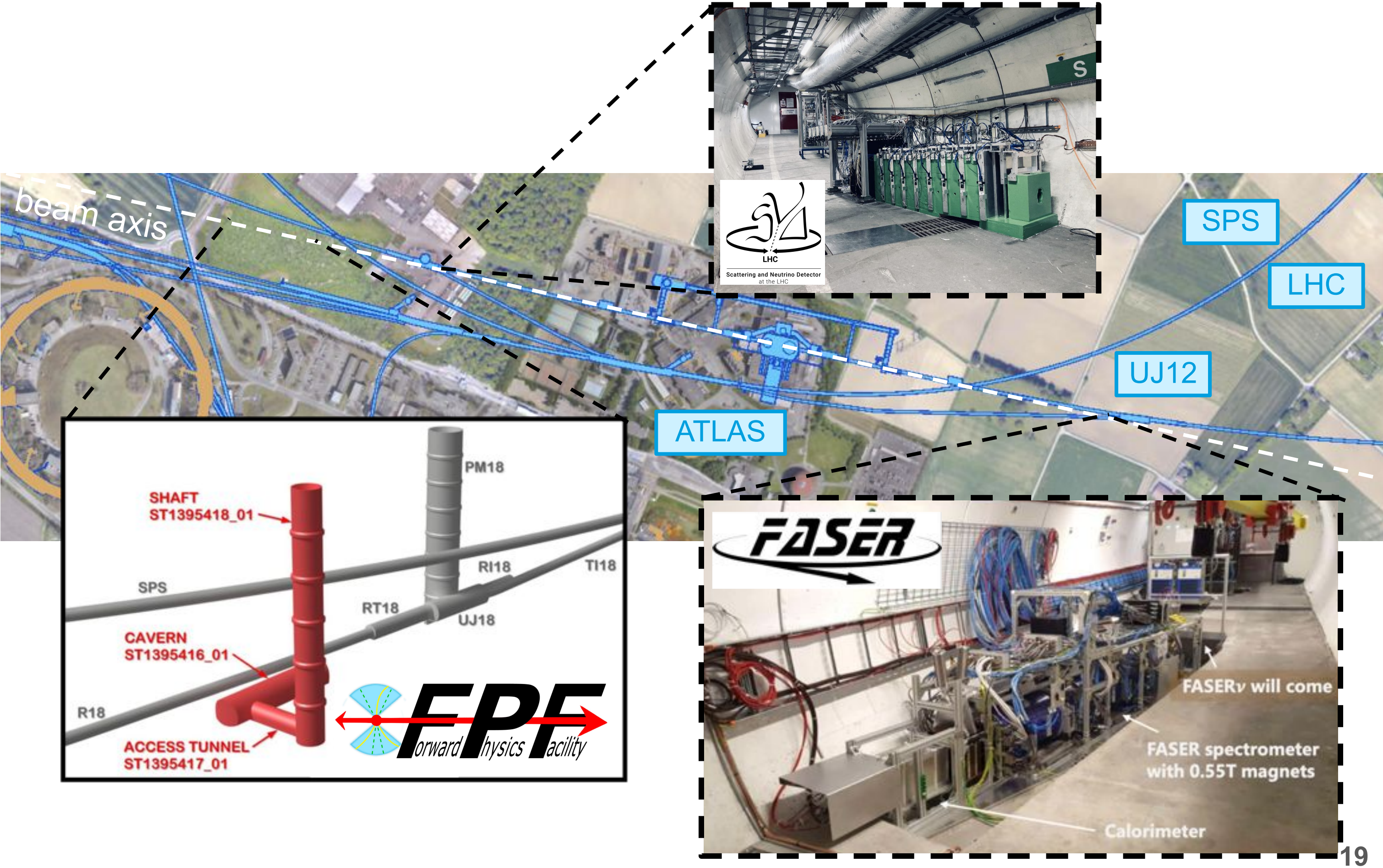
all previous collider detectors

building-size, decades ~$1B

0 neutrino interaction candidates

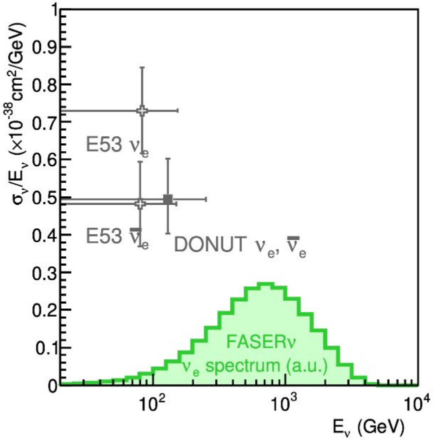
slide by Jonathan Feng

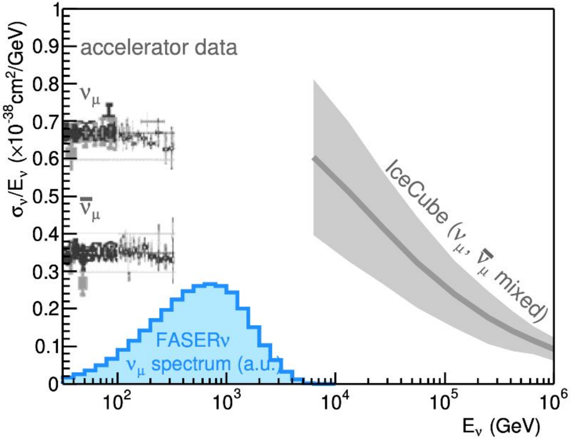
Neutrinos at the LHC.

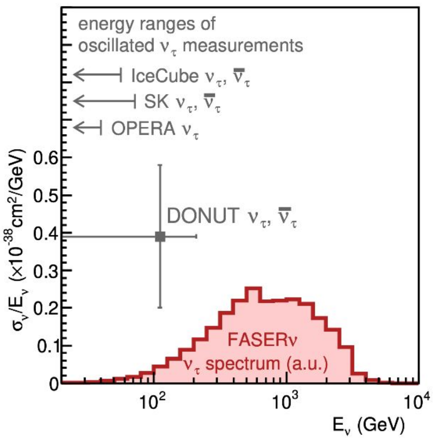


Neutrinos at the LHC.

LHC provides a strongly collimated beam of TeV energy neutrinos of all three flavours in the far forward direction.

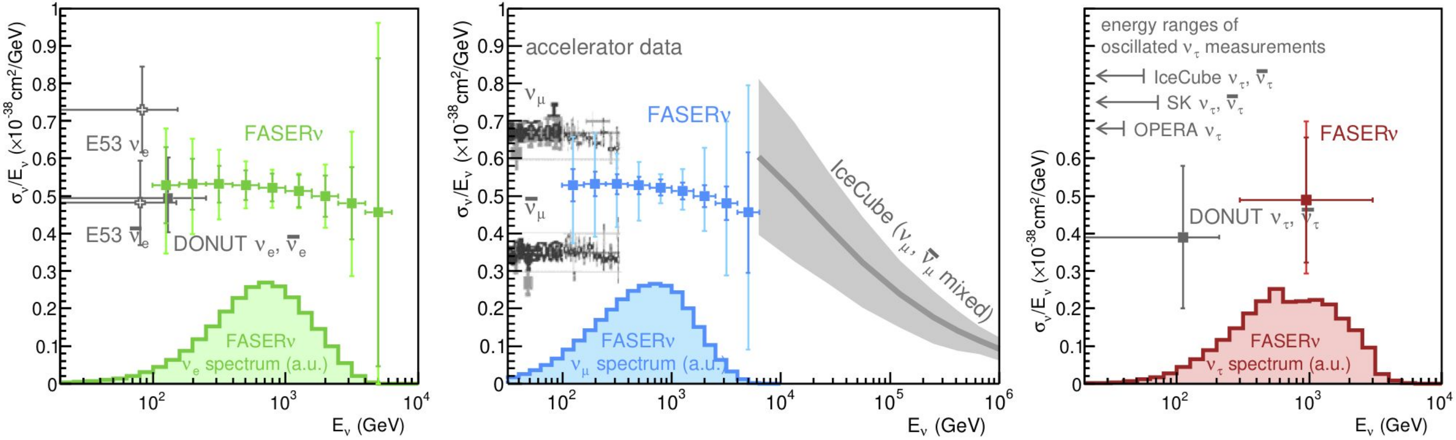






Neutrinos at the LHC.

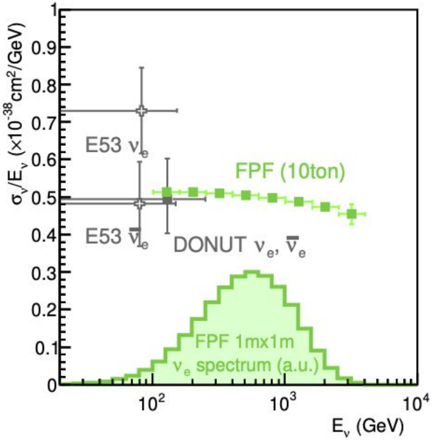
LHC provides a strongly collimated beam of TeV energy neutrinos of all three flavours in the far forward direction.

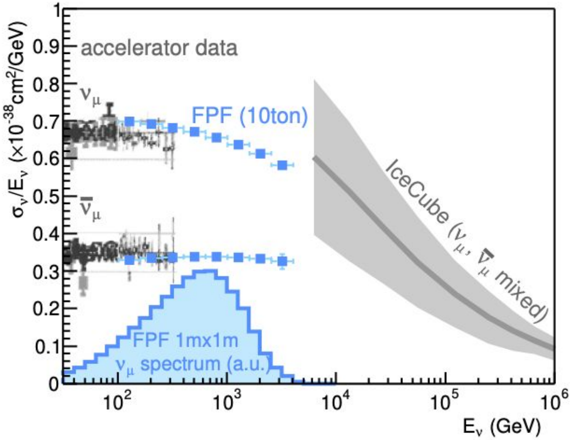


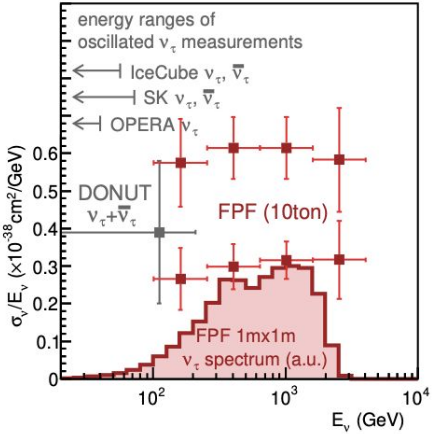
FASERν and SND@LHC will detect O(10k) neutrinos.

Neutrinos at the LHC.

LHC provides a strongly collimated beam of TeV energy neutrinos of all three flavours in the far forward direction.





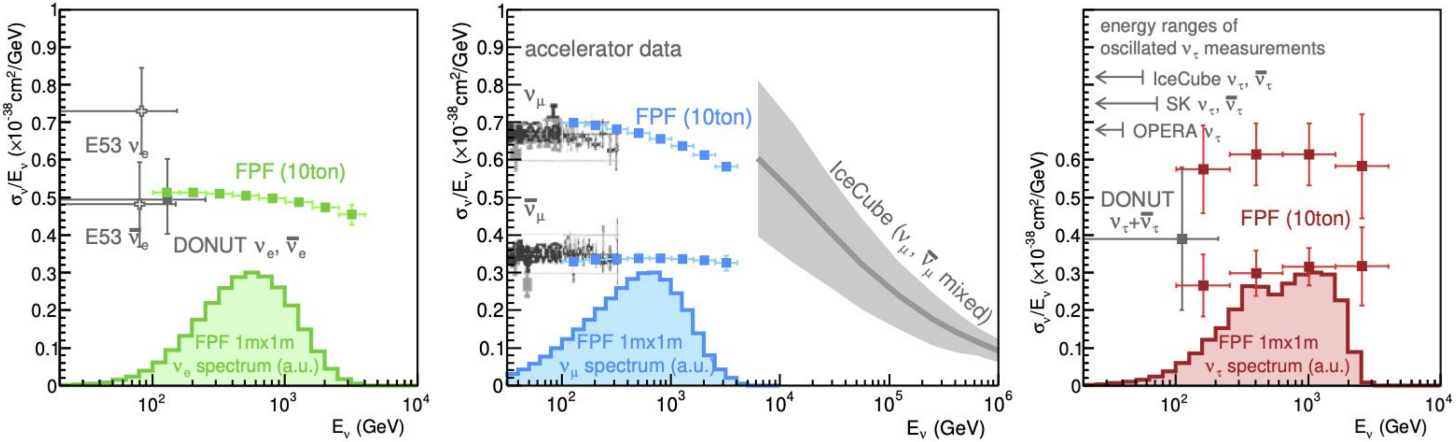


FASERν and SND@LHC will detect O(10k) neutrinos.

Proposed FPF experiment have potential to detect O(1M) neutrinos.

Neutrinos at the LHC.

LHC provides a strongly collimated beam of TeV energy neutrinos of all three flavours in the far forward direction.



FASERν and SND@LHC will detect O(10k) neutrinos.

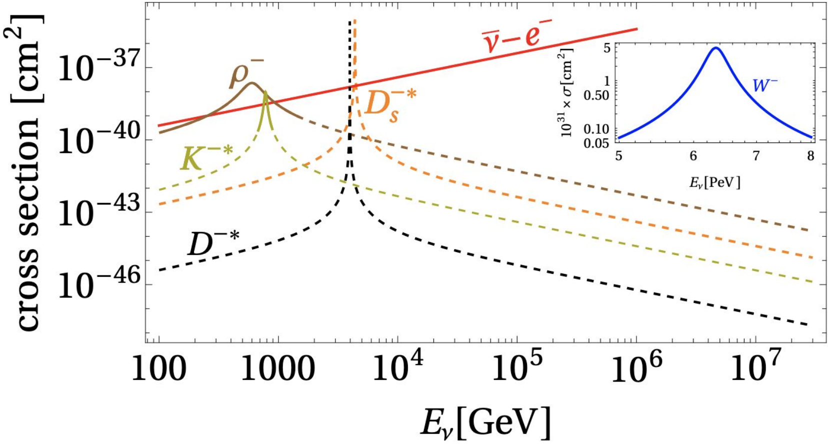
Proposed FPF experiment have potential to detect O(1M) neutrinos.

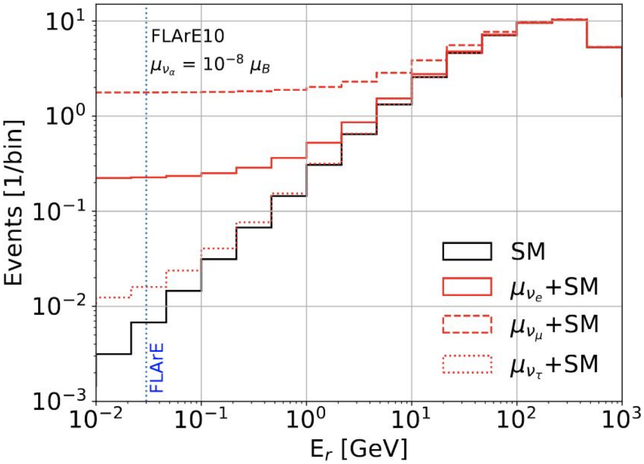
Neutrinos at the LHC.

two applications from: PHENO2022

indico.cern.ch/e/pheno22

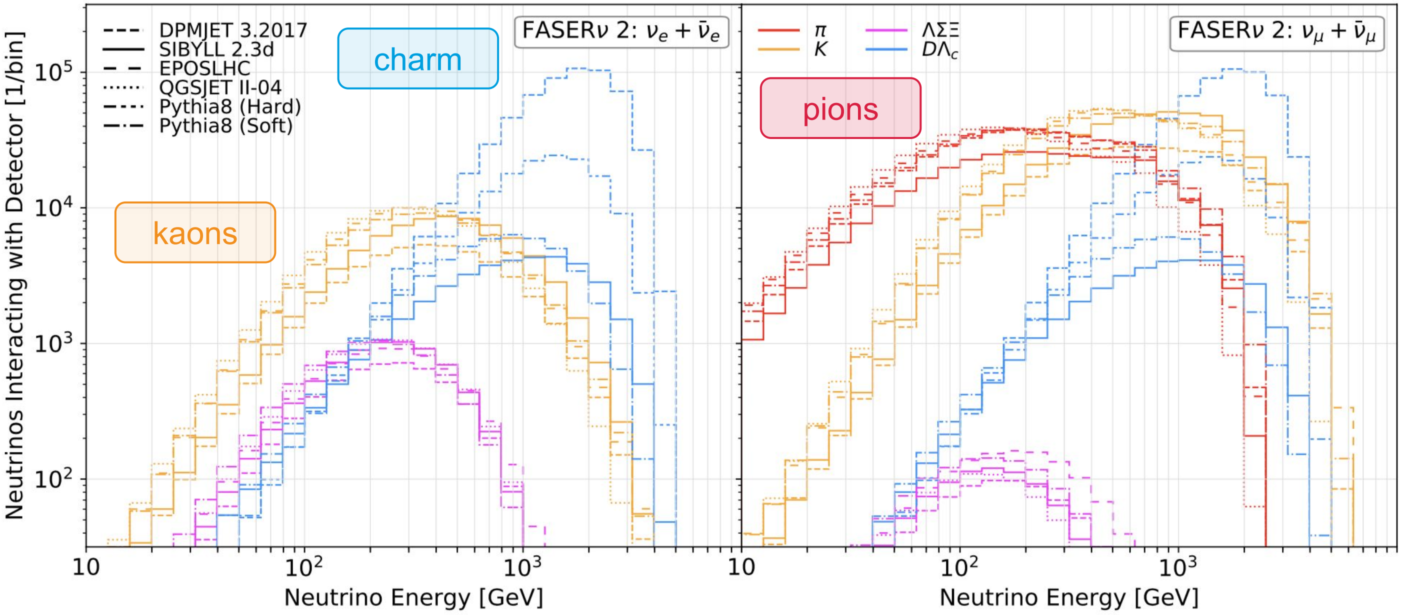
hadronic hesonances in v-e scsattering
Vedran Brdar's talk on Tuesday
[Brdar et al: 2112.03283]



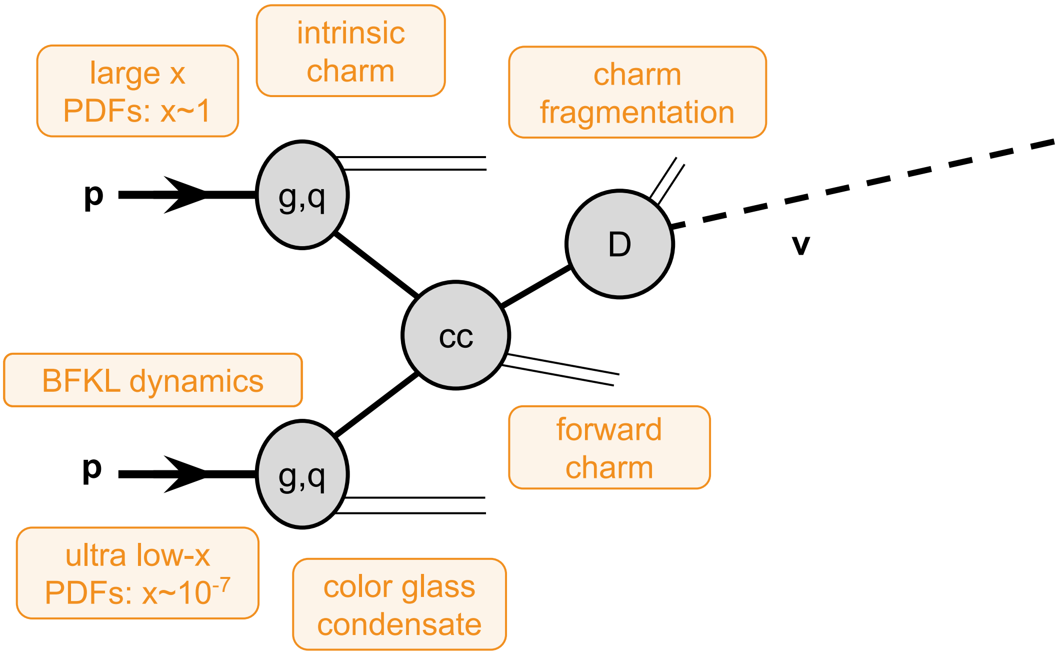


Neutrino electromagnetic properties
Roshan Mammen Abraham's talk on Monday
[Ismail et al: 2012.10500], [Ismail et al: 2109.05032]

Where do the LHC neutrinos come from?



LHC neutrinos = probe of forward particle production



large x
PDFs: x~1

intrinsic
charm

charm
fragmentation

BFKL dynamics

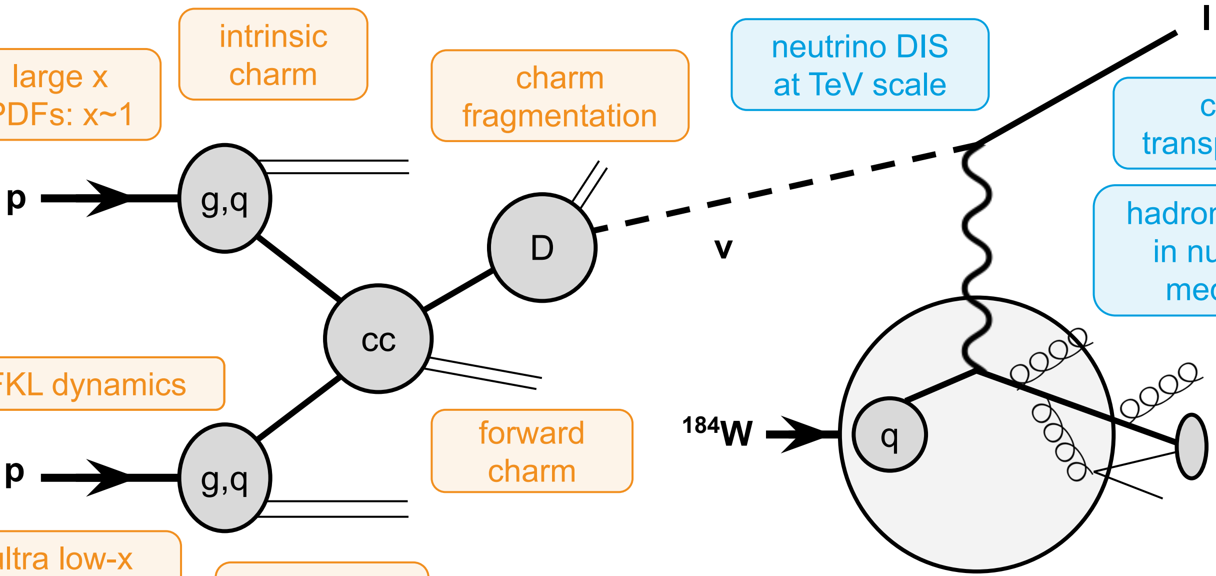
forward
charm

ultra low-x
PDFs: x~10^{-7}

color glass
condensate

Forward Particle Production

QCD.



Forward Particle Production

large x PDFs: x~1

intrinsic charm

charm fragmentation

BFKL dynamics

forward charm

ultra low-x PDFs: $x \sim 10^{-7}$

color glass condensate

TeV Energy Neutrino Interaction

neutrino DIS at TeV scale

color transparency

hadronization in nuclear medium

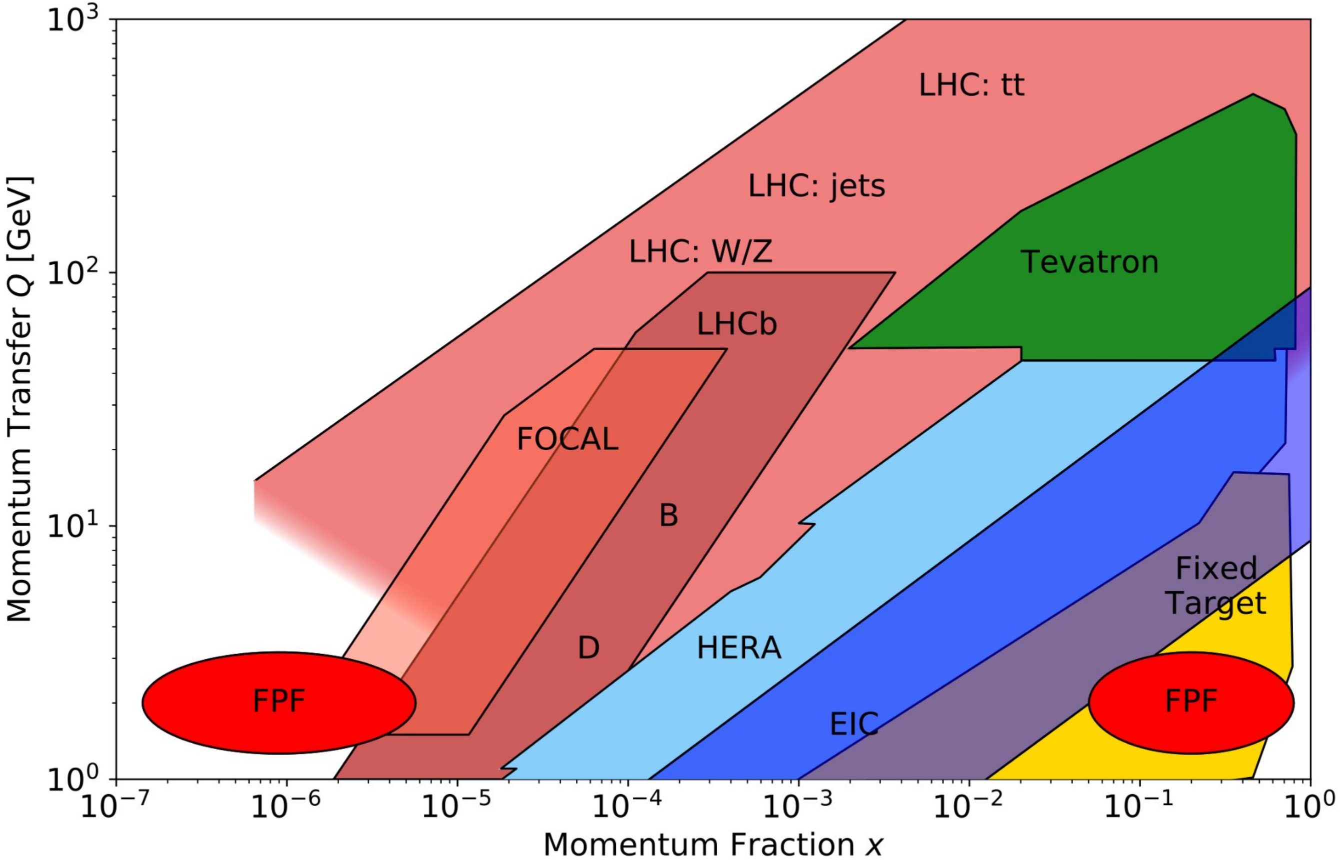
strangeness

nuclear PDFs

shadowing

EMC effect

QCD.

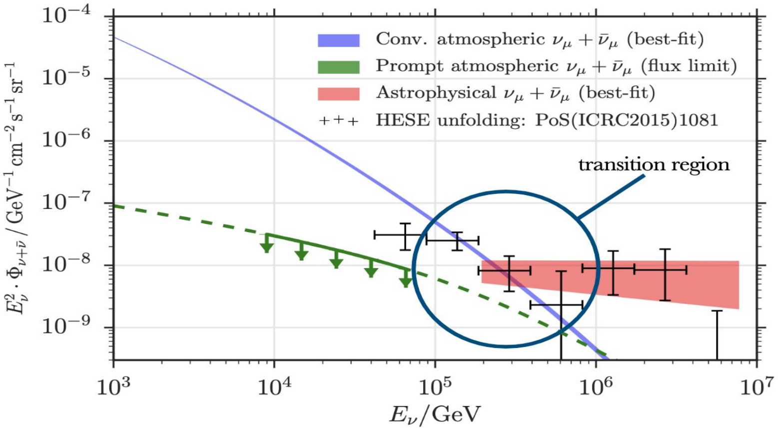

LHC: tt
LHC: jets
LHC: W/Z
LHCb
Tevatron
FOCAL
B
D
HERA
EIC
Fixed Target
FPF
FPF
Momentum Transfer Q [GeV]
Momentum Fraction x
10^3
10^2
10^1
10^0
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0

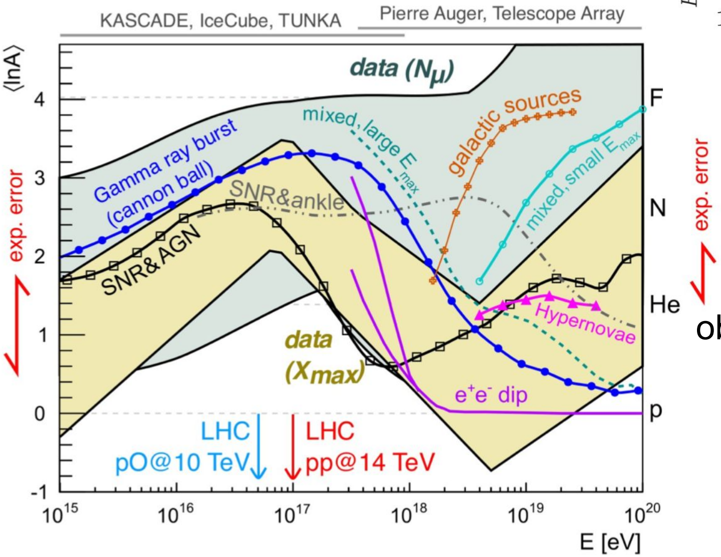
Astroparticle Physics.

forward charm production at the LHC

↓

constraints on prompt atmospheric neutrino flux at IceCube





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

cosmic ray muon puzzle:
observed excess of muons compared to hadronic interaction models

forward pion/kaons fluxes will provide crucial input

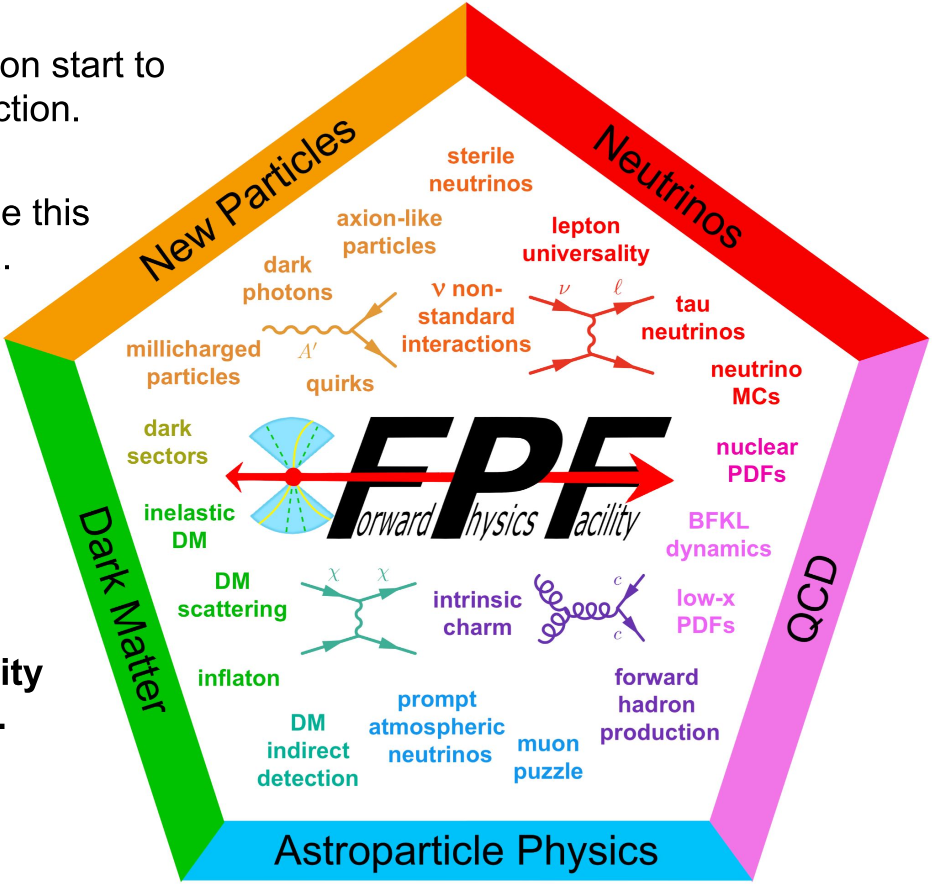
Summary.

FASER and SND@LHC will soon start to take data in LHC's forward direction.

The FPF is proposed to continue this program during the HL LHC era.

Significant extension of the LHC's physics program.

We invite the Pheno community to participate in this program.
You are welcome to join!


New Particles

Neutrinos

QCD

Astroparticle Physics

Dark Matter

FPF

Forward Physics Facility

sterile neutrinos

axion-like particles

lepton universality

dark photons

ν non-standard interactions

tau neutrinos

millicharged particles

quirks

neutrino MCs

dark sectors

nuclear PDFs

inelastic DM

BFKL dynamics

DM scattering

intrinsic charm

low-x PDFs

inflaton

forward hadron production

DM indirect detection

prompt atmospheric neutrinos

muon puzzle

Backup.

Neutrino Fluxes and Rates.

Event rates at LHC neutrino experiments
estimated with two LO MC generators: SIBYLL / DPMJET

	Detector			Number of CC Interactions		
	Name	Mass	Coverage	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
LHC Run3	FASERν	1 ton	$\eta \gtrsim 8.5$	1.3k / 4.6k	6.1k / 9.1k	21 / 131
	SND@LHC	800kg	$7 < \eta < 8.5$	180 / 500	1k / 1.3k	10 / 22
HL-LHC	FASERν2	20 tons	$\eta \gtrsim 8$	178k / 668k	943k / 1.4M	2.3k / 20k
	FLArE	10 tons	$\eta \gtrsim 7.5$	36k / 113k	203k / 268k	1.5k / 4k
	AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	6.5k / 20k	41k / 53k	190 / 754

Large spread in current generator predictions

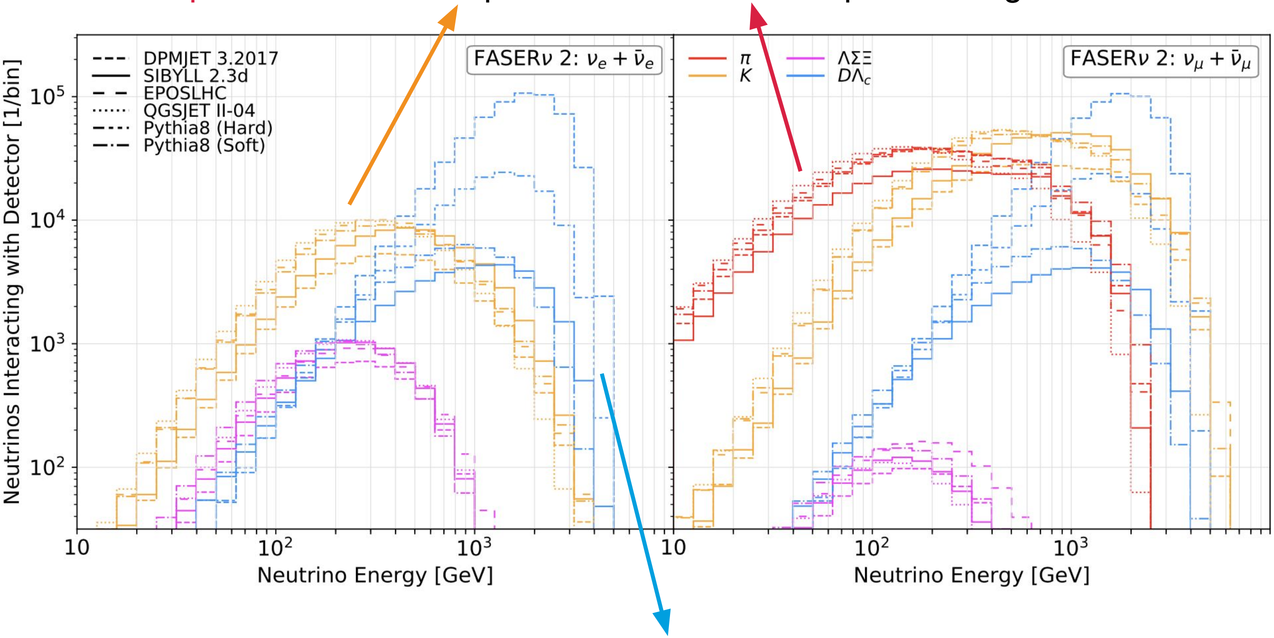
Challenge:
For neutrino physics measurement
we need to quantify and reduce
neutrino flux uncertainties

Opportunity:
Forward neutrino flux measurement
can help to improve our
understanding of underlying physics.

QCD.

Forward particle production is poorly constrained by other LHC experiments.
LHC neutrinos fluxes measurement will provide novel complimentary information.

pions & kaons: nonperturbative QDC → improve MC generators



charm: perturbative QCD → test BFKL dynamics, constrain low-x PDFs, probe gluon saturation and intrinsic charm