From Neutrinos to QCD and Dark Matter: Looking Forward for Exciting Physics.

Felix Kling (DESY)
Bonn Physics Colloquium
04.03.2023

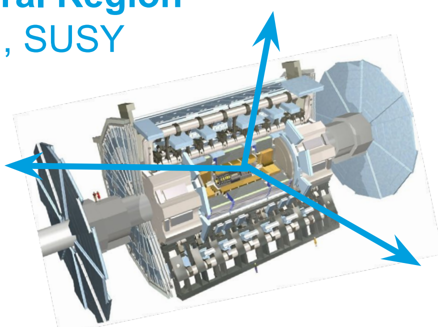
Idea and Motivation.

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



Idea and Motivation.

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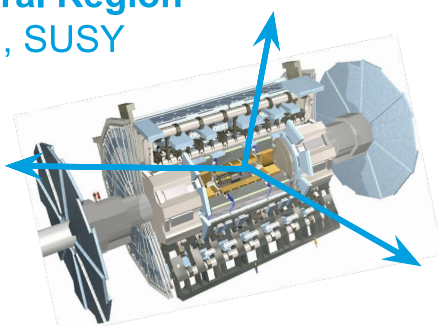
Their decay products have high pT and are distributed almost isotropically.

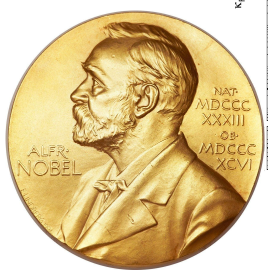
ATLAS/CMS were constructed to catch them.

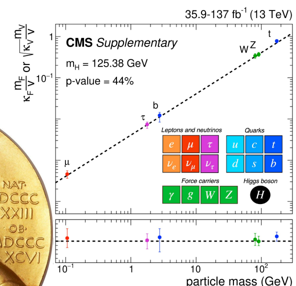
LHC experiments perform amazingly well!

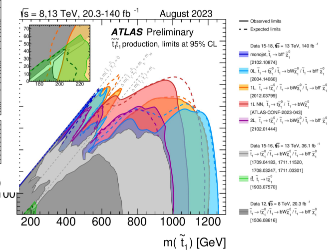
Central Region

H, SUSY









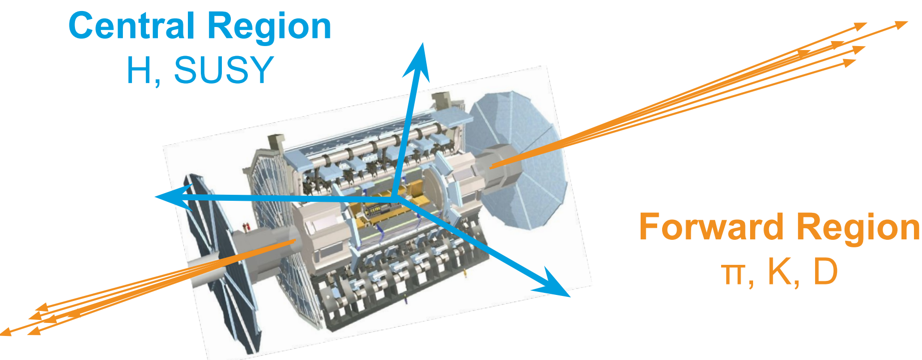
What else can we do to exploit the LHC?

Idea and Motivation.

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.

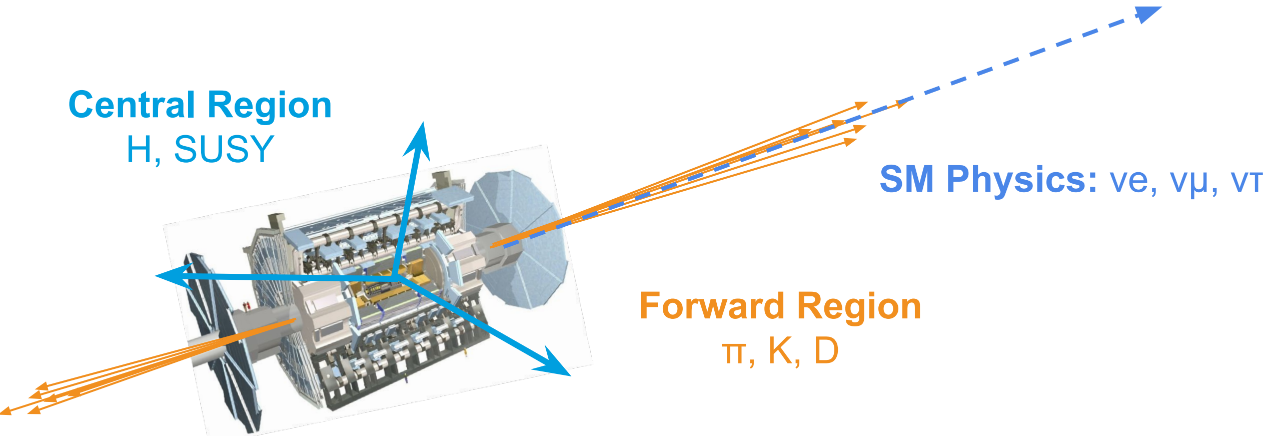
Typically low pT but large energy.

Can we do something with that?



Idea and Motivation.

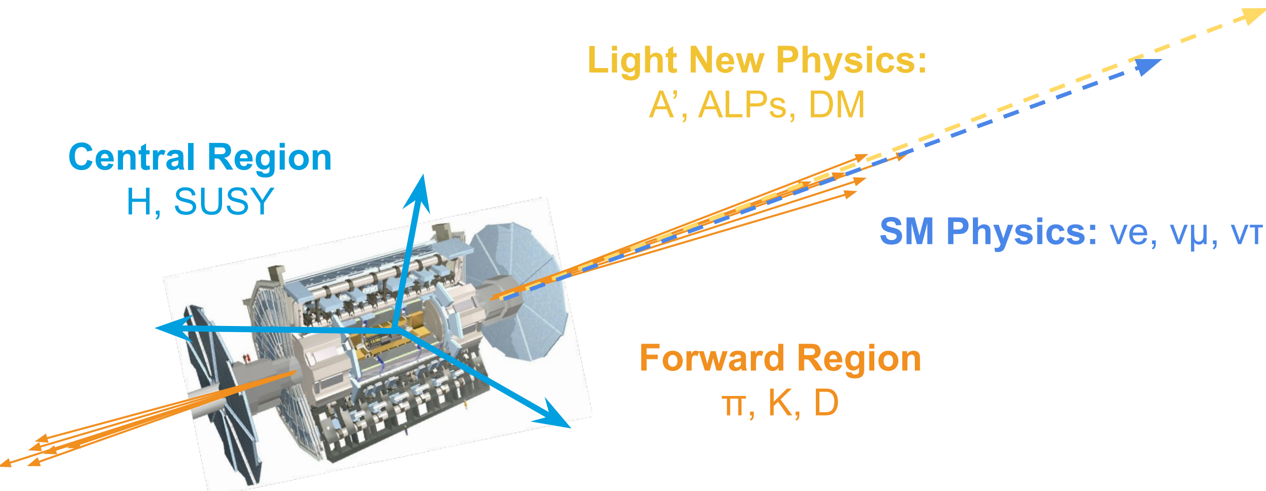
The LHC produces an intense and strongly collimated beam of neutrinos with TeV energies in the forward direction.



Idea and Motivation.

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

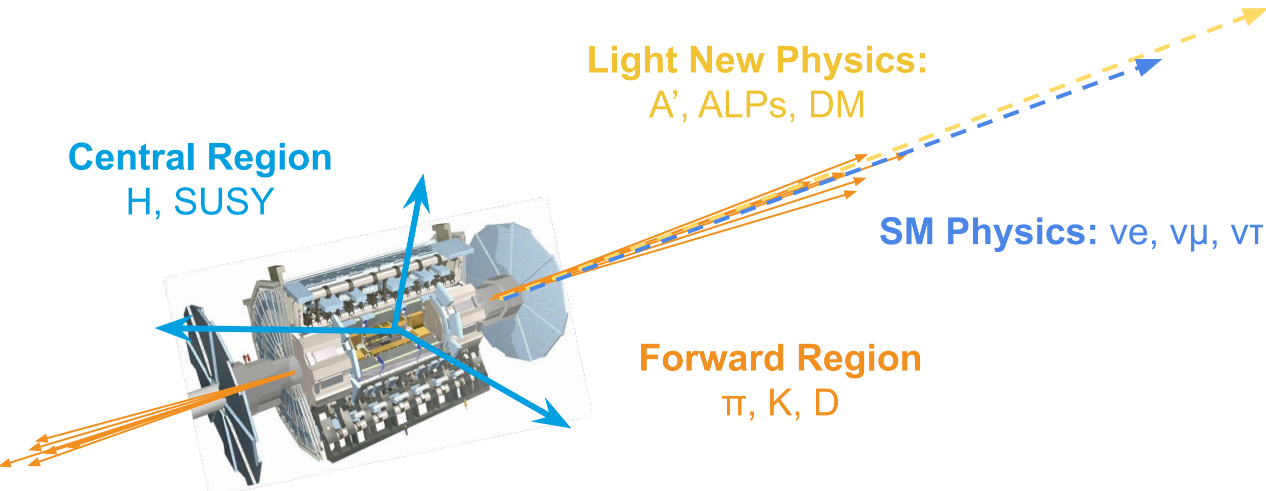
This may also be true for many interesting new particle candidates: dark photons, axion-like particles, dark matter.



Idea and Motivation.

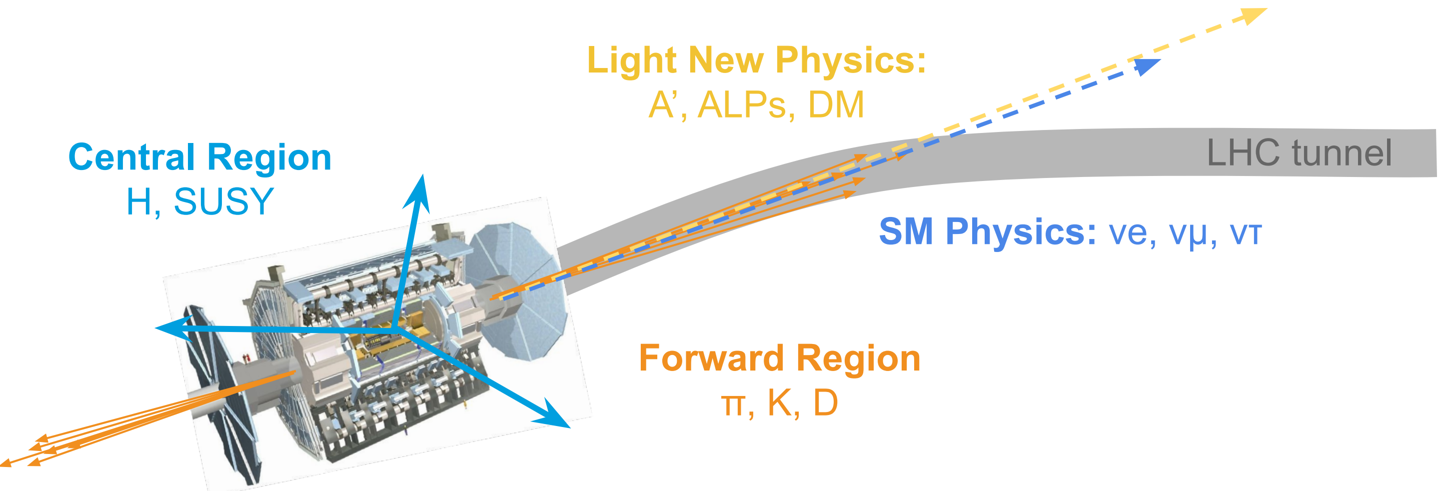
These particles escape down the beam pipe and remain undetected.

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



Idea and Motivation.

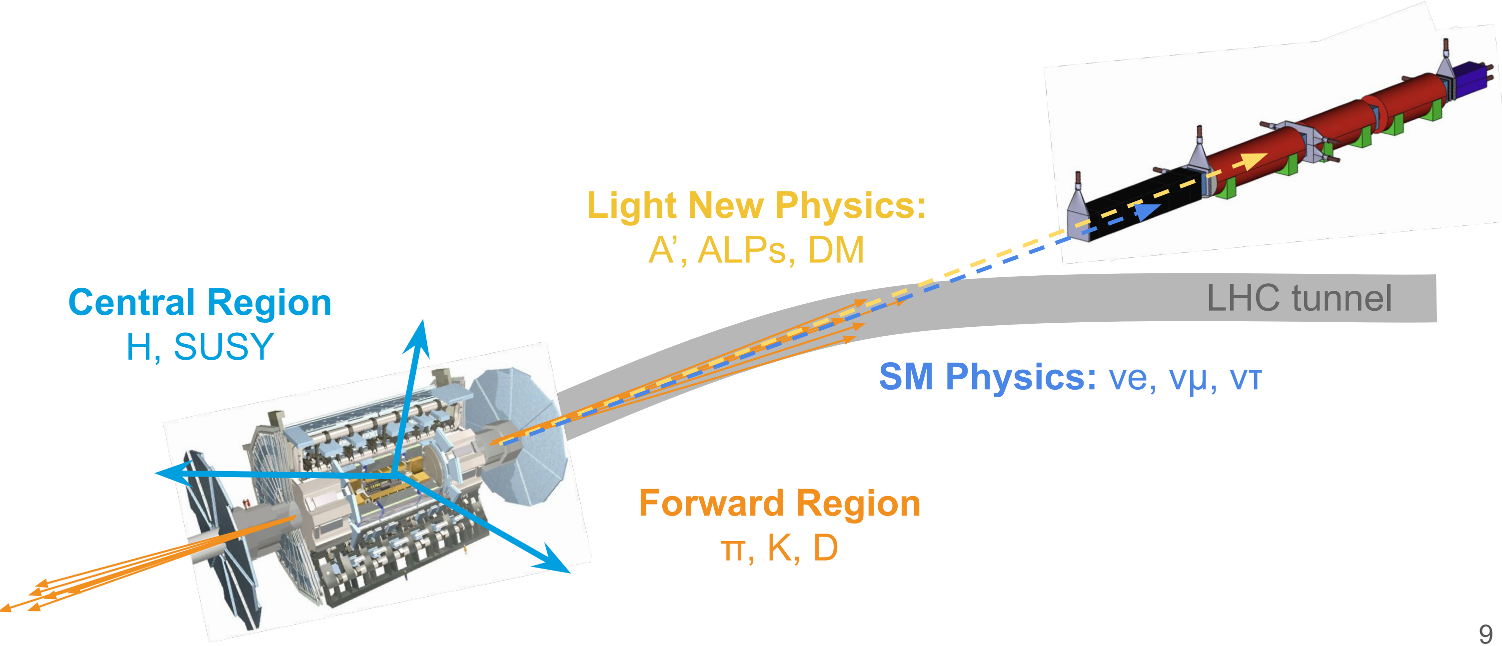
LHC tunnel will eventually curve away, but the beam of neutral particles will continue along the beam collision axis.



Idea and Motivation.

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

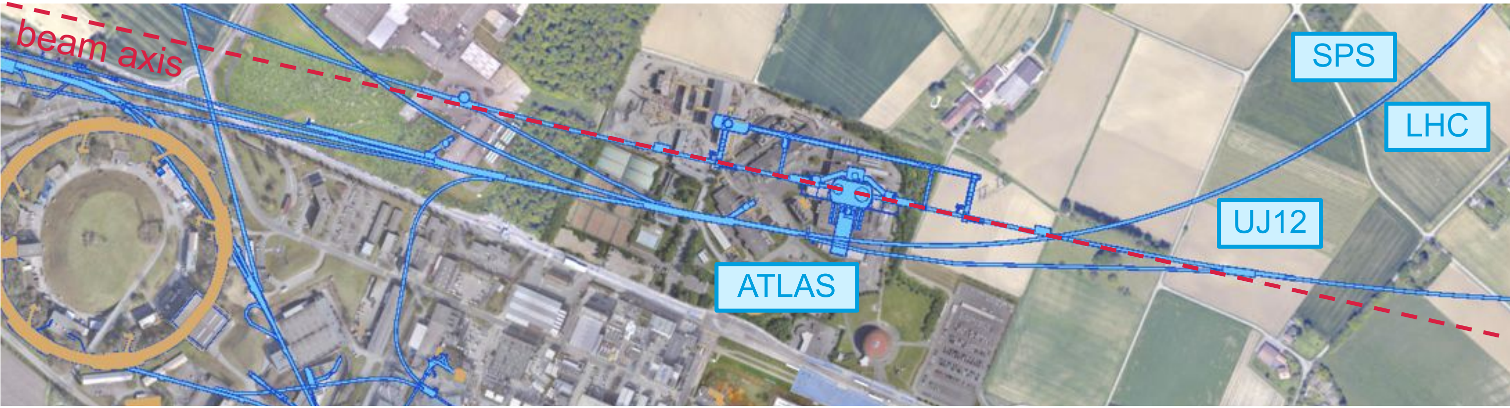
Idea: Placed experiment in this beam to detect them.
[Feng, Galon, FK, Trojanwoski, 1708.09389]



Experimental Program

Experimental Program.

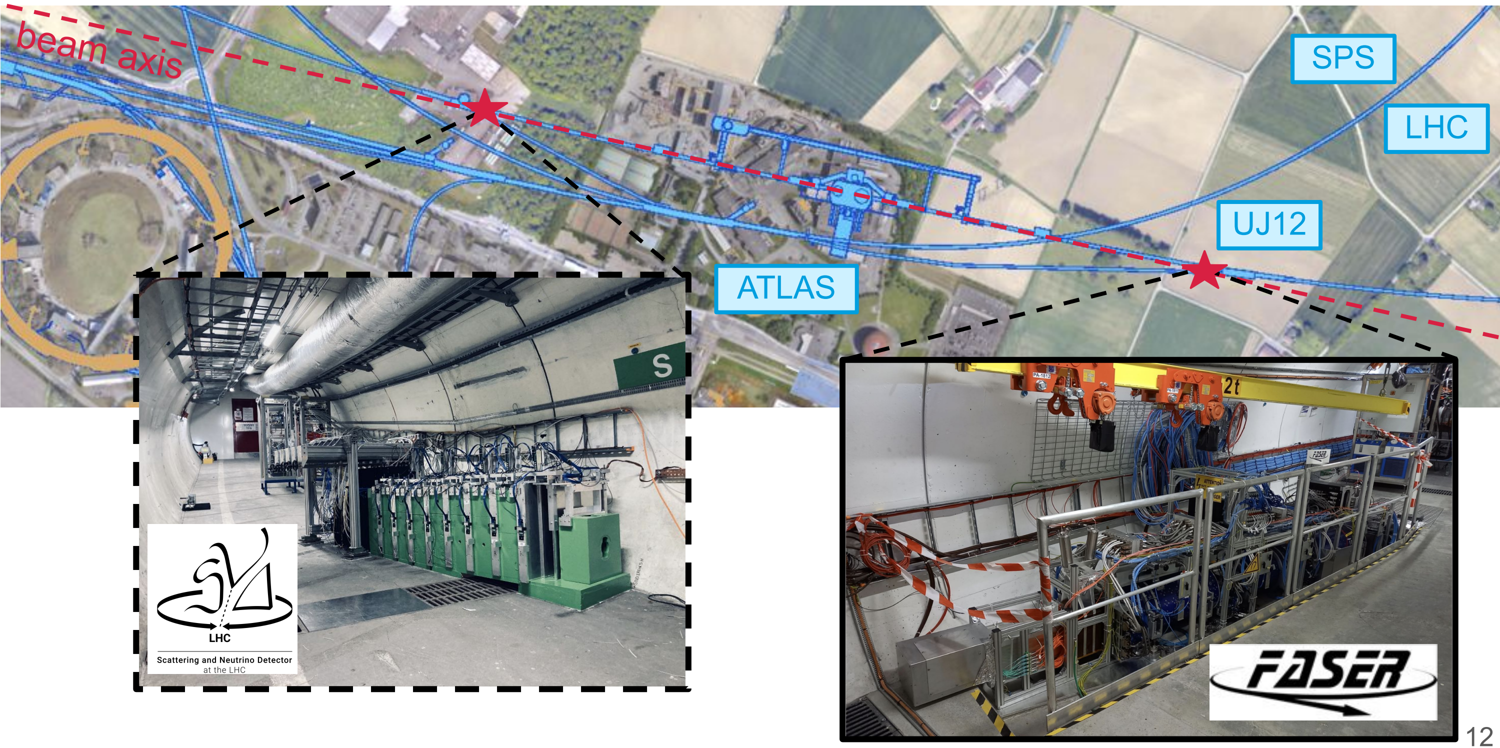
There is potential for forward physics experiments along beam axis.



Experimental Program.

There is potential for forward physics experiments along beam axis.

Two new experiments started operation in 2022 to exploit this potential: SND@LHC and FASER.

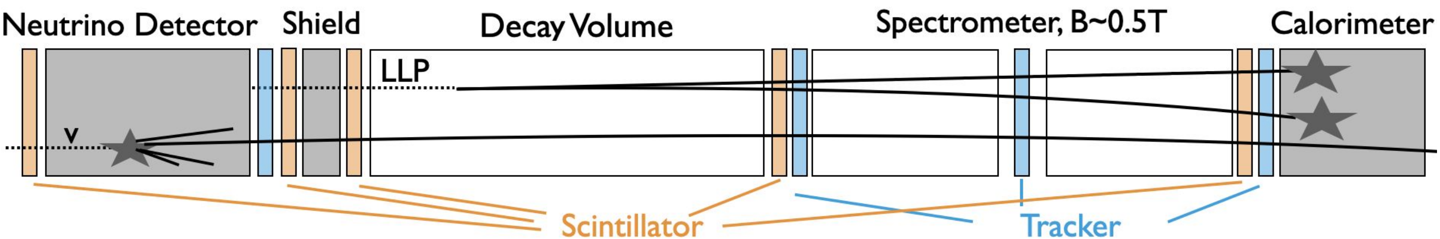


FASER Experiment.

(as imagined by a theorist)

Goal 1: Search for New Physics:

- decay of long-lived particles, e.g. A' → e e
- highly energetic particles emerge from empty decay volume
- need front veto, tracker, calorimeter

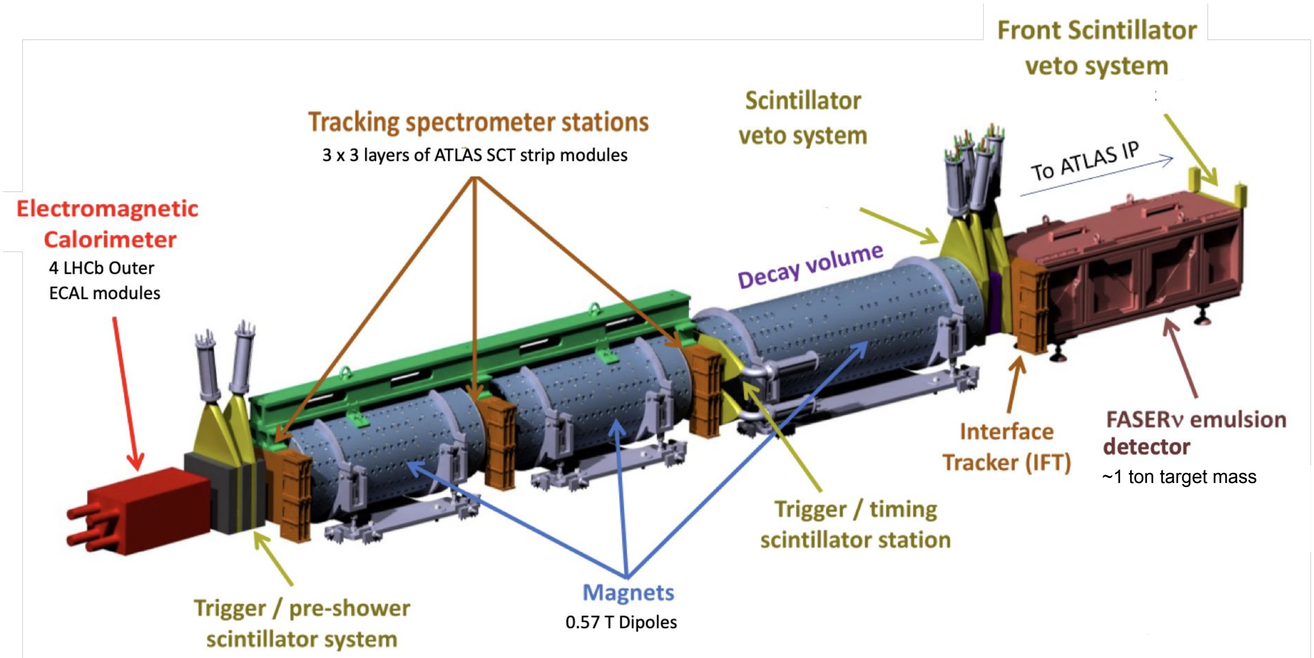


Goal 2: Neutrino Measurements

- interactions of collider neutrinos, e.g. ν N → μ + hadrons
- highly energetic particles emerge from dense material
- dedicated emulsion neutrino detector in front

FASER Experiment.

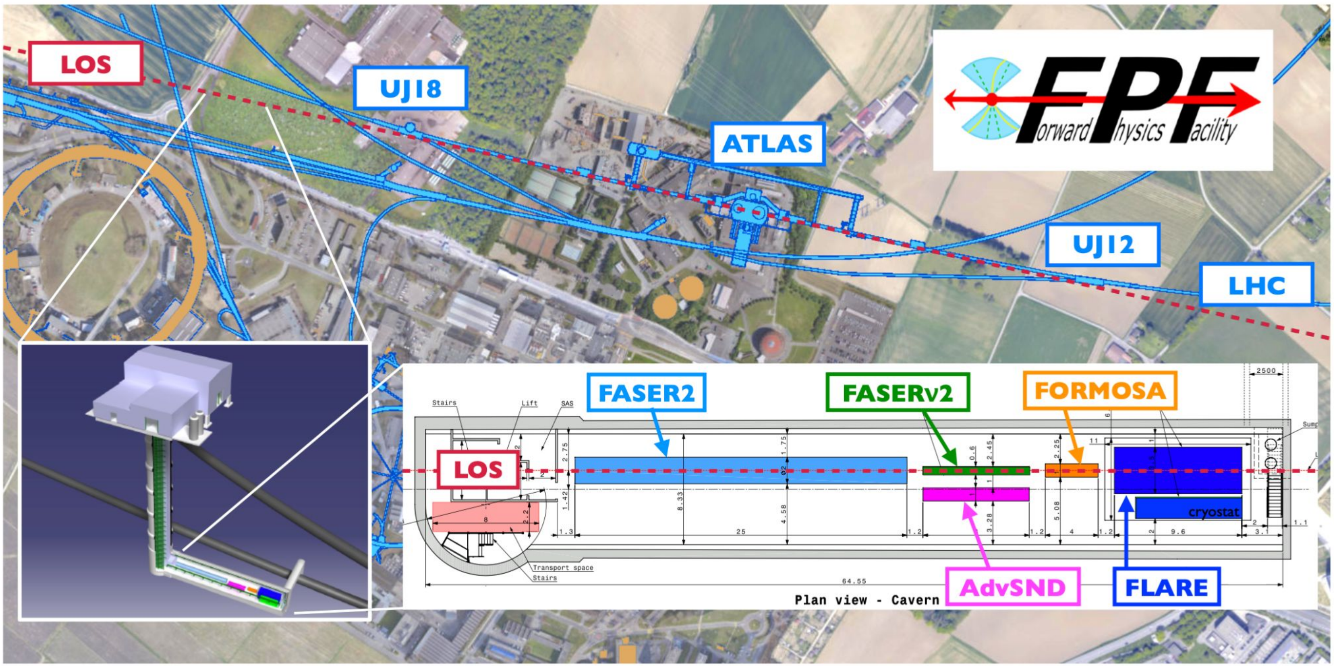
(as realized by the experimentalists)
[FASER, arXiv:2207.11427]



Forward Physics Facility.

Continuation of this program envisioned for HL-LHC era (2030s).

Proposal to create a dedicated **Forward Physics Facility (FPF)** for the HL-LHC: suite of experiments that will greatly enhance the LHC's physics potential for BSM physics searches, neutrino physics, QCD and astro-particle physics.



Forward Physics Facility.

FPF workshop series:
[FPF1], [FPF2], [FPF3], [FPF4],
[FPF5], [FPF6], [FPF7]
[FPF Theory Day]

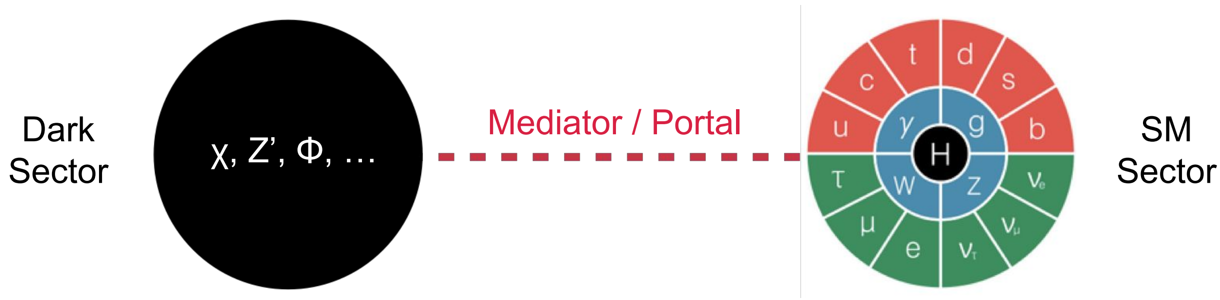
FPF Paper:
2109.10905
~75 pages, ~80 authors

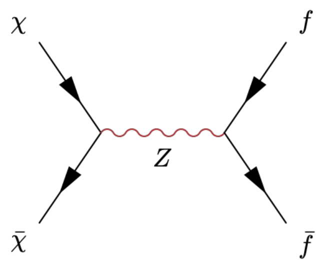
Snowmass Whitepaper:
2203.05090
~450 pages, ~250 authors

Recent Summary:
FPF Update

Searches for Light New Physics

Light New Physics.

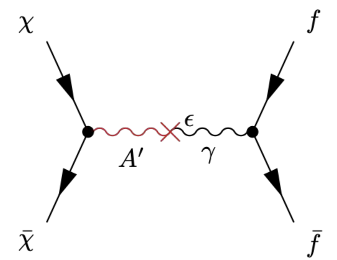




Z/H Portal

too much DM for $M_X \lesssim$ GeV
[Lee, Weinberg, 1977]

BR(Z/H→XX) too big for $M_X \lesssim M_{Z/H}/2$
[Berlin, FK 1810.01879]



New Portal

dark photon: $\epsilon F^{\mu\nu} F'_{\mu\nu}$

dark Higgs: $\epsilon |H|^2 \phi^2$

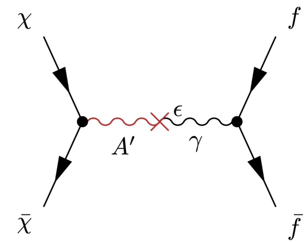
neutrino: $yLHN$

axion: $g a F^{\mu\nu} \tilde{F}_{\mu\nu}$

Example: The Dark Photon.

The Dark Photon (A') Portal

- arise in many hidden sector models
- (massive) gauge boson of a $U(1)_D$ gauge group
- weakly coupled to SM via kinetic mixing with photon

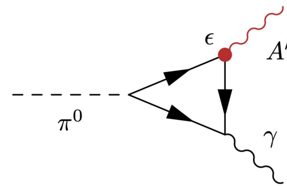


$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu + \sum_f \epsilon e q_f \, \bar{f} \not{A}' f + g_D \, \bar{\chi} \not{A}' \chi$$

A' phenomenology at FASER

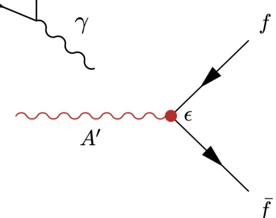
- MeV A' s produced mainly in meson decays

$$\mathrm{BR}(\pi^0 \to \gamma A') = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_\pi^2}\right)^3$$



- mA'<2mX: A' is long-lived

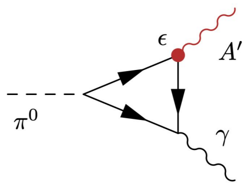
$$\bar{d} \approx 80\mathrm{m}\ B_e \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\mathrm{TeV}}\right] \left[\frac{100\ \mathrm{MeV}}{m_{A'}}\right]^2$$

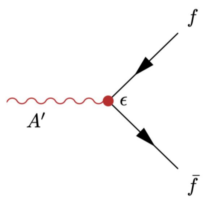


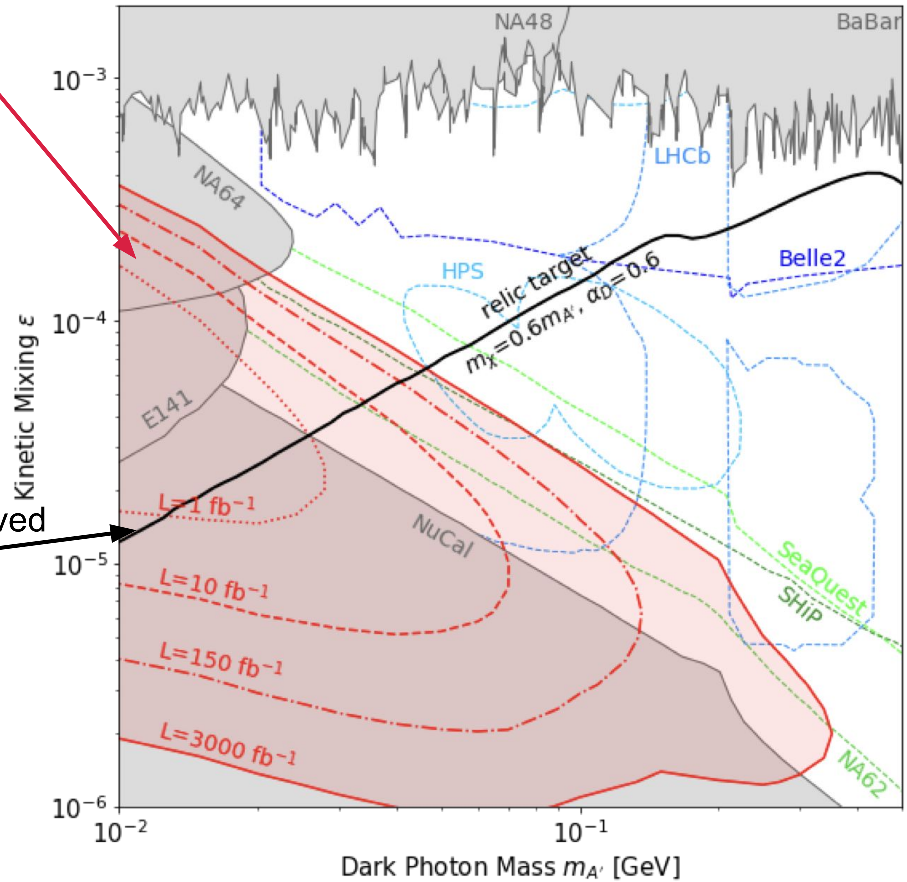
- for mA'<2mμ: A' only decays to e+e- pair

Example: The Dark Photon.

estimated FASER sensitivity

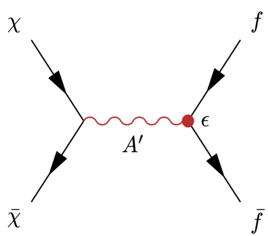






dark photon portal explains observed abundance of dark matter

[FK, Trojanowski, arXiv:2105.07077]



Simulations: FORESEE.

FORESEE: python based simulation tool for forward new physics searches

[FK, Trojanowski, arXiv:2105.07077]

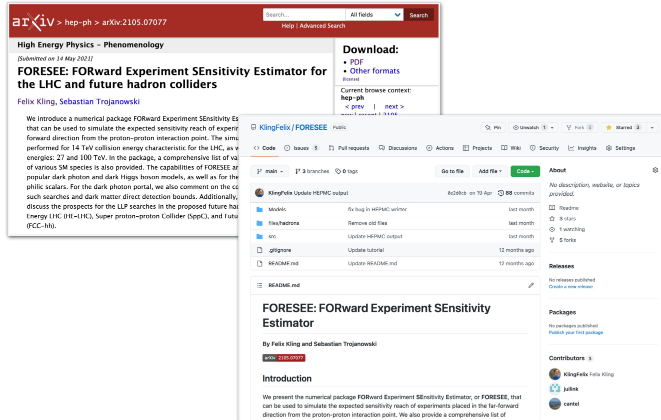
- event generator: HepMC output
- reach estimator: sensitivity curves

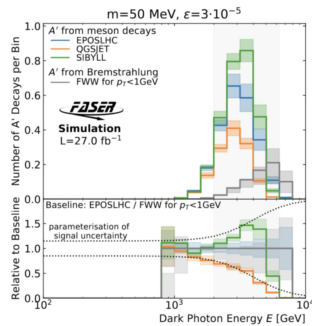
- contains model library
- allows user to define new models
- ideal interface between theory and experiment

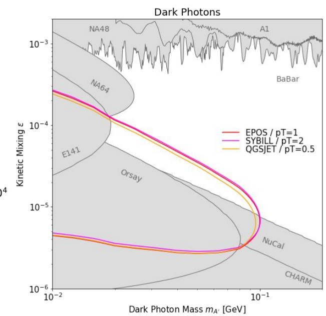
- utilizes forward hadrons fluxes provided by various dedicated generators
- can provide theory/flux uncertainties

… more on this later

- optimized for performance / useability
- available on GitHub

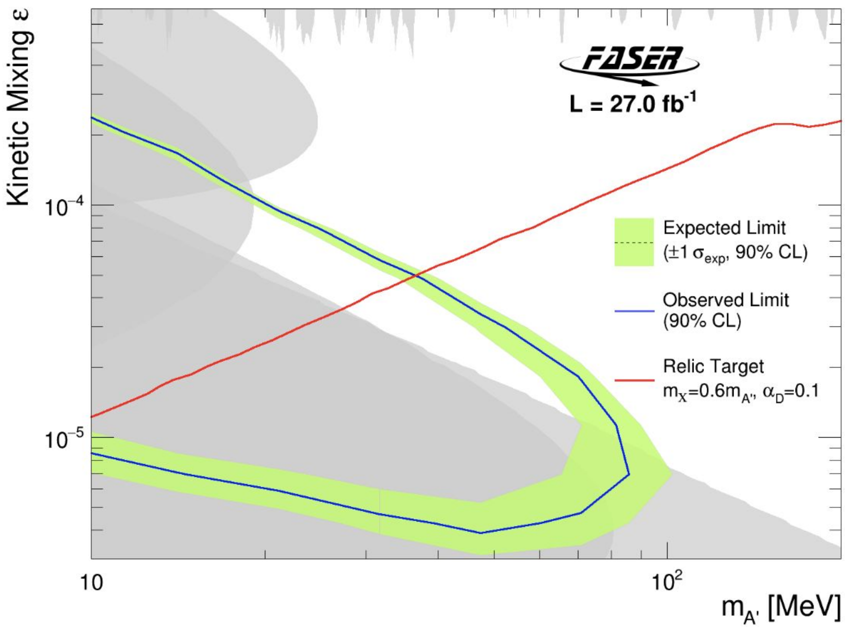






FASER Dark Photon Search.

FASER performed a first search for dark photons: [FASER, arXiv:2308.05587]
- simple and robust A’ e+e- selection, optimised for discovery



No events found in signal region.

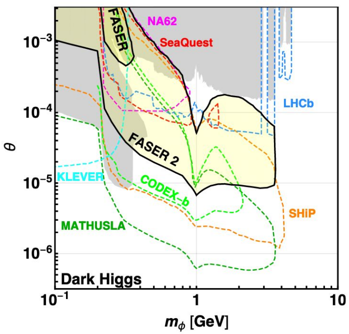
Based on this null results, FASER sets limits in previously unexplored parameter space

Probing region interesting from thermal relic target.

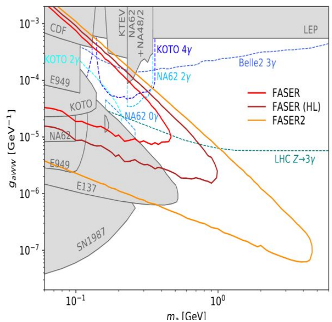
More Long-Lived Particles.

FASER has sensitivity in a large variety of long-lived particle models

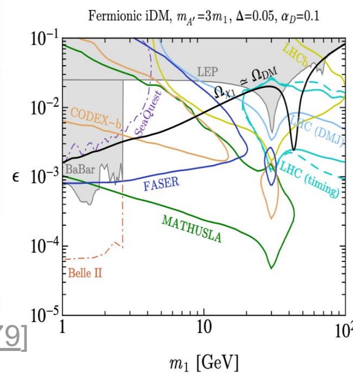
FASER Physics Case for LLPs: [FASER, 1811.12522]
PBC BSM WG Report: [Beacham et al. 1901.09966]



dark Higgs: $\mathcal{L} \supset \sin\theta \, \frac{m_f}{v} \bar{f} f$

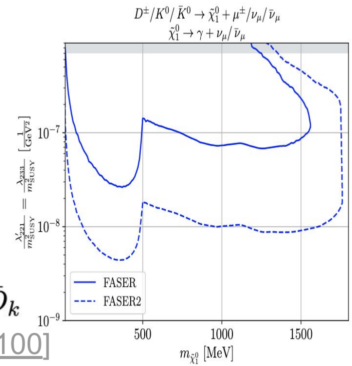


axions: $\mathcal{L} \supset \frac{1}{4} g a W^{\mu\nu} W_{\mu\nu}$



inelastic DM: $\mathcal{L} \supset \epsilon e q_f \, \bar{f} \not{A}' f + i e_D \bar{\chi}_1 \not{A}' \chi_2$

[Berlin, FK 1810.01879]



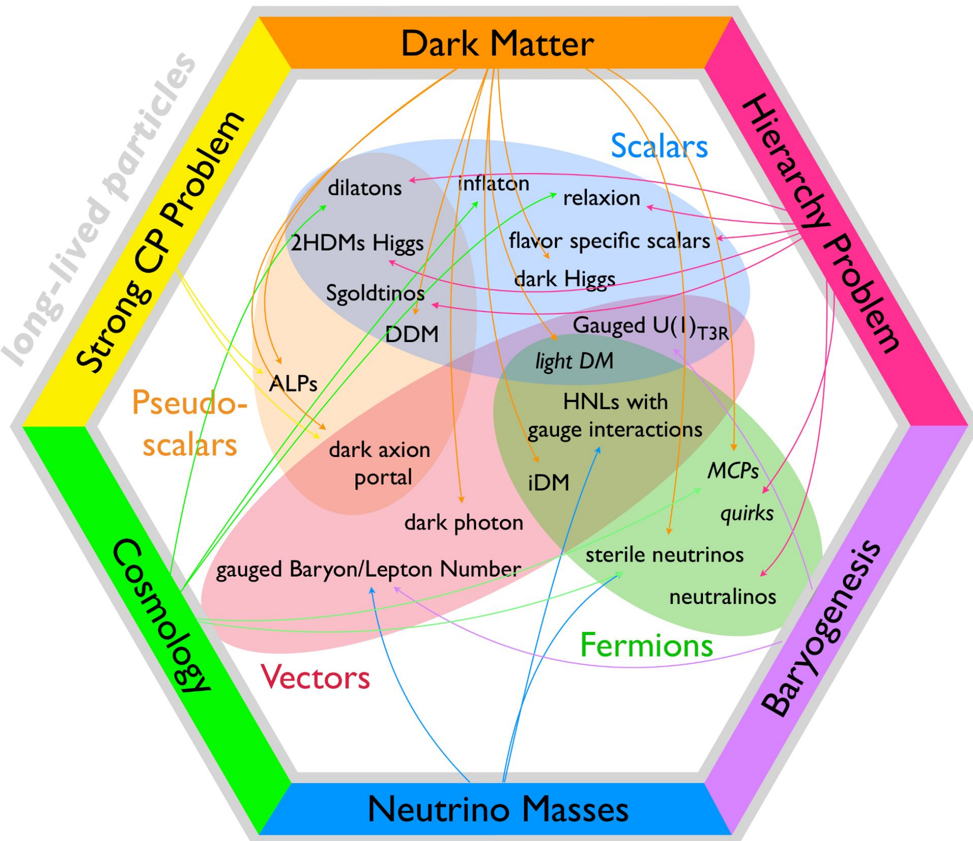
RPV neutralino: $W_{\rm LNV} = \frac{1}{2} \lambda^{ijk} L_i L_j \bar{E}_k + \lambda'^{ijk} L_i Q_j \bar{D}_k$

[Dreiner, Köhler, Nangia, Wang, 2207.05100]

More Long-Lived Particles.

Light new physics models can address many outstanding problems in particle physics

[Feng, FK, Reno, Rojo, Soldin et al. 2203.05090]



Other Dark Sector Signatures.

[Abraham, Batell, Feng, Ismail, FK, Trojanowski, 2107.00666]

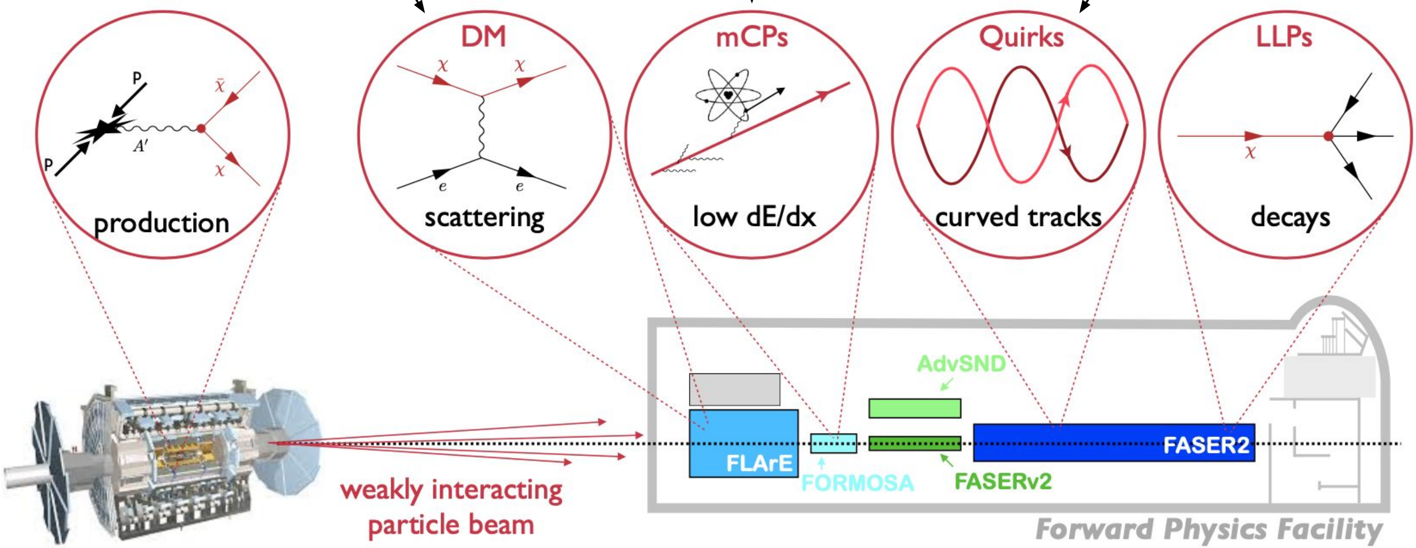
mA’<2mX: LHC produces DM beam

[Abari, FK, Tsai, 2010.07941]

mA’=0: X is millicharged

[Li, Pei, Ran, Zhang, 2108.06748]

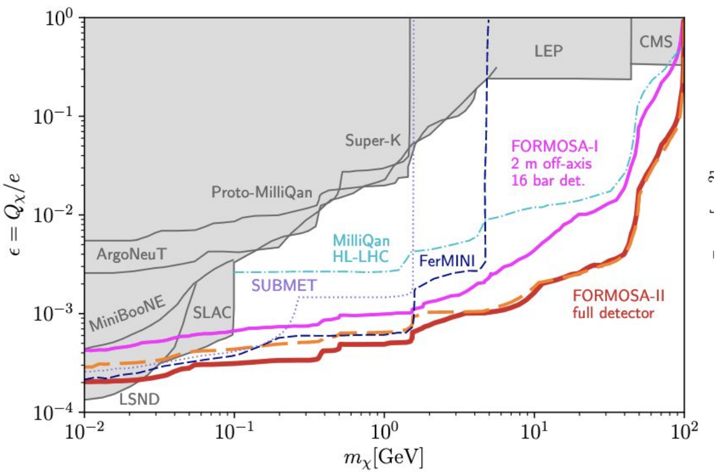
X charged under SU(N) with Λ ≪ mX



Other Dark Sector Signatures.

FORMOSA reach
for millicharged particles

[Abari, FK, Tsai, 2010.07941]



Demonstrator installed a few weeks ago.

Collider Neutrino Physics

Collider Neutrino Observation.

The LHC produces a huge flux of TeV energy neutrinos of all three flavours in the forward direction, mainly from π, K and D meson decays. [De Rujula et al. (1984)]

FASER is uniquely placed to exploit this neutrino beam. The FASERν emulsion neutrino detector was added for this purpose. [FASER, 1908.02310]. But FASER could also detect them using only electronic components. [Arakawa, Feng, Ismail, FK, Waterbury, 2206.09932].

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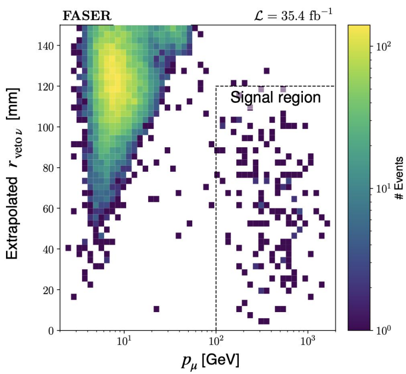
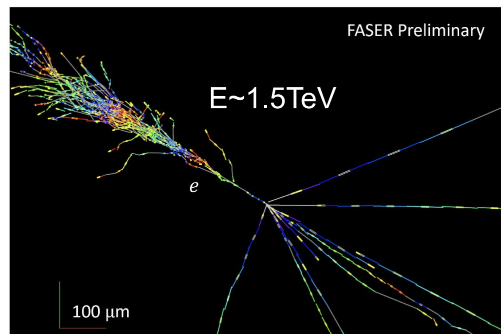
first observation of collider νμ
search for charged current νμ events through muon appearance: 153 events (16σ)
[FASER, 2303.14185]



first observation of collider νe
search for charged current νe events in emulsion detector: 3 events (5σ)
[FASER, CERN-FASER-CONF-2023-002]



The Dawn of Collider Neutrino Physics.

Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

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Research team detects first neutrinos made by a particle collider

The discovery promises to help physicists understand the nature of the elusive particle

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VIEWPOINT

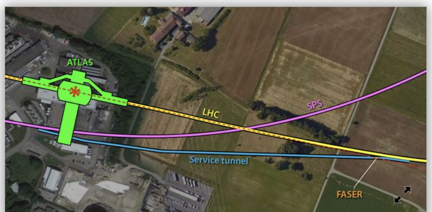
The Dawn of Collider Neutrino Physics

Elizabeth Worcester

Brookhaven National Laboratory, Upton, New York, US

July 19, 2023 • *Physics* 16, 113

The first observation of neutrinos produced at a particle collider opens a new field of study and offers ways to test the limits of the standard model.



Google Earth, imagery (c)2023 Maxar Technologies, map data (c)2023; CERN; adapted by APS/Alan Stonebraker

Figure 1: The Forward Search Experiment (FASER) is installed in a service tunnel that connects the Large Hadron Collider (LHC) and the Super Proton Synchrotron (SPS). Proton collisions at the ATLAS experiment's interaction point (red star) generate beams of neutrinos (dashed red lines) that escape along a tangent to the LHC.

UNIVERSITÄT BONN

UNIVERSITÄT STUDIUM FORSCHUNG UND

20. März 2023

Erstmals Neutrinos aus einem Teilchenbeschleuniger beobachtet

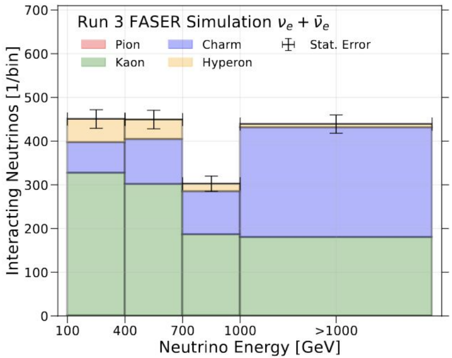
Internationale Studie hilft, die Natur des fast masselosen Elementarteilchens besser zu verstehen

Neutrinos gehören zu den am häufigsten vorkommenden Teilchen im Kosmos, geben Forschenden jedoch nach wie vor viele Rätsel auf. Ein internationales Team unter Beteiligung der Universität Bonn hat jetzt zum ersten Mal Neutrinos direkt beobachtet, die in einem Teilchenbeschleuniger erzeugt wurden. Die Physikerinnen und Physiker erhoffen sich, durch ihre neue Entdeckung die Natur dieser fast masselosen Elementarteilchen besser verstehen zu können. Die Ergebnisse wurden am vergangenen Wochenende bei der 57. Moriond-Konferenz in Italien vorgestellt und werden demnächst in der Fachzeitschrift Physical Review Letters zur wissenschaftlichen Begutachtung eingereicht.

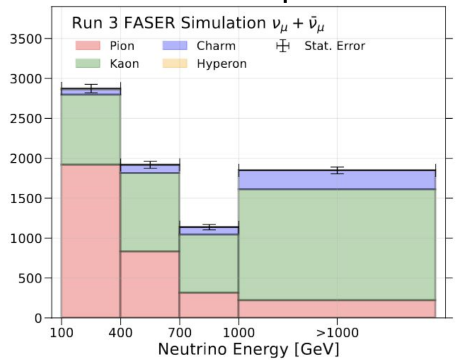
YouTube DE Suchen

The Dawn of Collider Neutrino Physics.

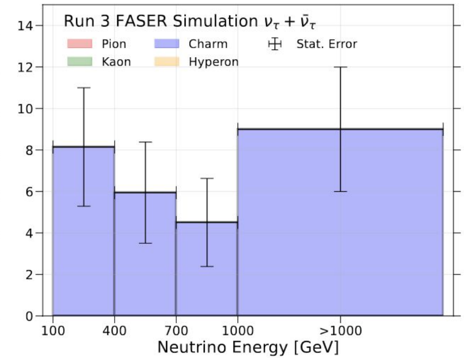
1.5k νe



8.5k νμ



30 ντ

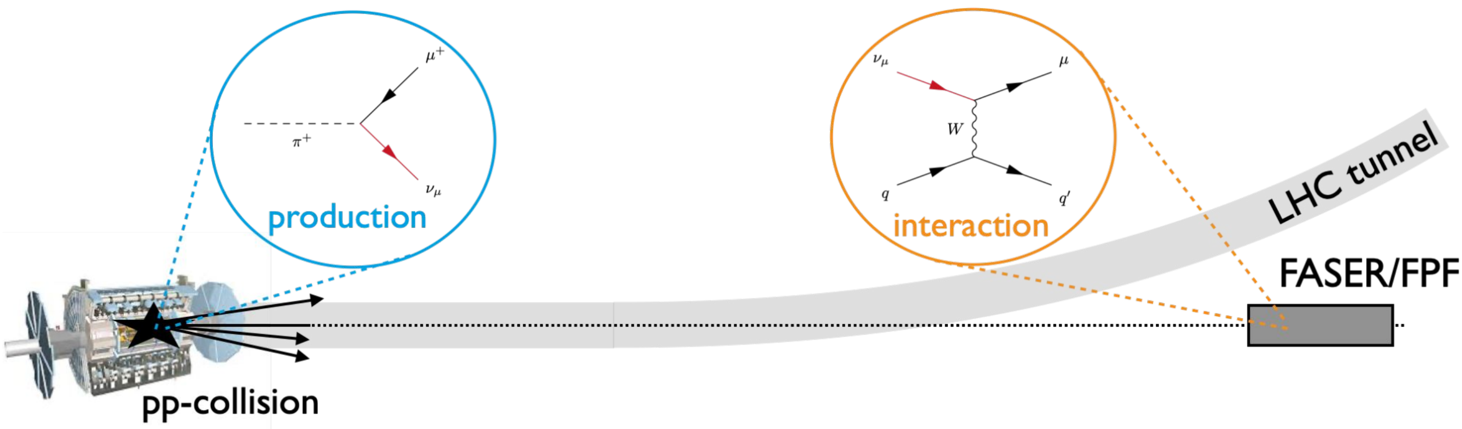


[*Neutrino Rate Predictions for FASER*, FASER, 2402.13318]

Current LHC experiments will detect thousands of neutrinos
The FPF experiments will detect millions of neutrinos.

What physics can we probe with them?

The Dawn of Collider Neutrino Physics.



complementary probe of
forward particle production

light and charm hadrons

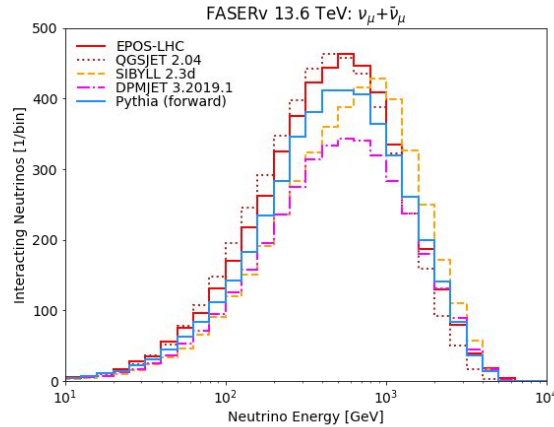
unique laboratory probe of
TeV energy neutrino interactions

cross sections and nuclear structure

Neutrinos from Light Hadrons.

Forward Light Hadron Production

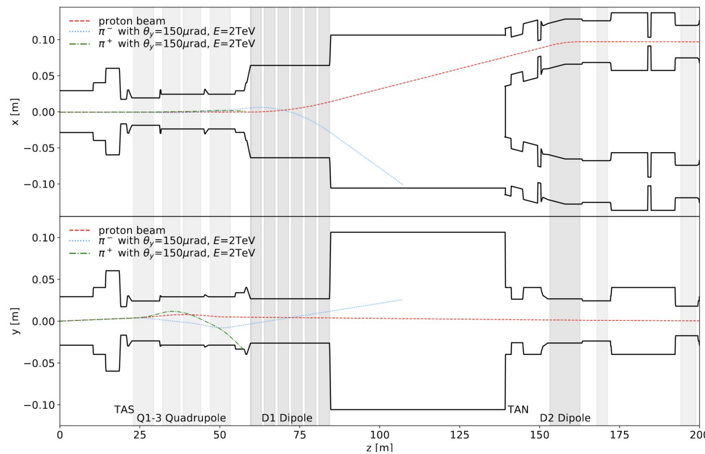
- low pT / low Q ≲ GeV
- described by non-perturbative QCD
- several hadronic interaction models available, often from cosmic ray physics
- typically spread of generators used to parameterize uncertainty
- also used in FORESEE



Simulation

- pions/kaons decay downstream of IP
- simulation of propagation/decay of hadrons needed
- established tools FLUKA/BDSIM computationally expensive: 10^4 CPU hours
- introduced in fast neutrino flux simulation
- available as RIVET module on GitHub

[FK, Nevay, 2105.08270]



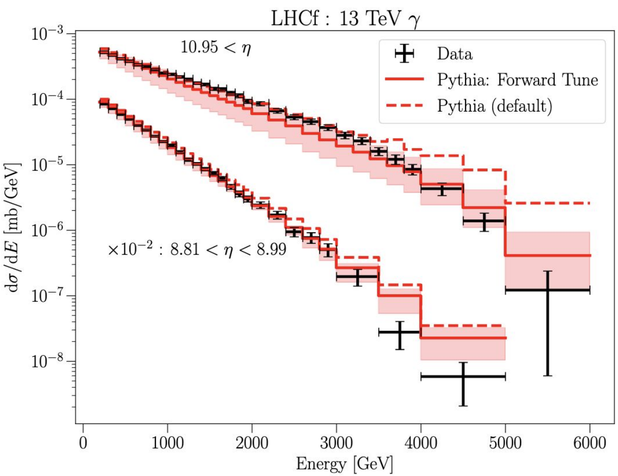
Neutrinos from Light Hadrons.

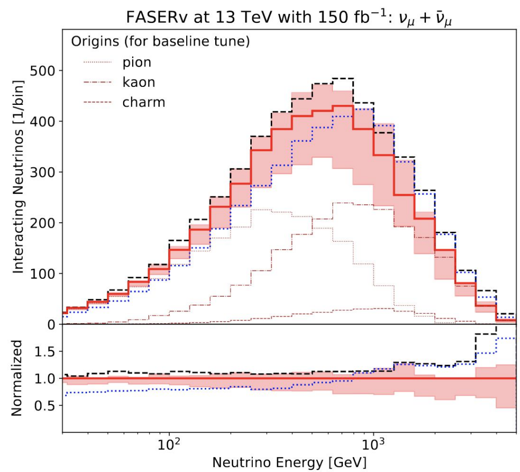
Multi-purpose MC generator can also be used to simulate forward particle production

Default version of **Pythia** overestimates forward photon production compared to LHCf data

Dedicated **forward physics tune**: [Fieg, FK, Schulz, Sjöstrand, 2309.08604]
- more flexible modelling of beam remnant hadronization
- tune fragmentation parameters and primordial kT to LHCf data

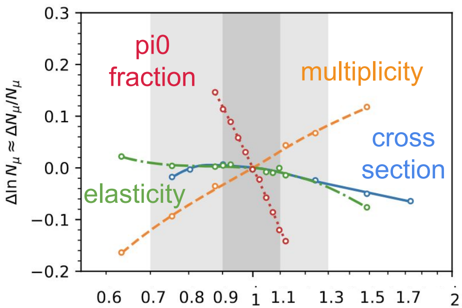
Data-driven parameterization of flux uncertainties using tuning variations.



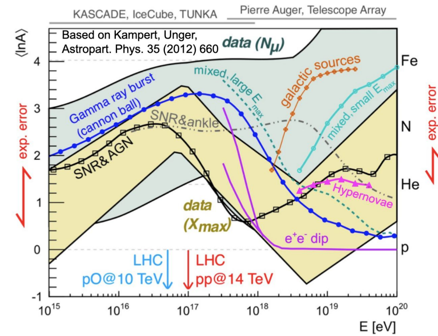


Light Hadrons and Muon Puzzle.

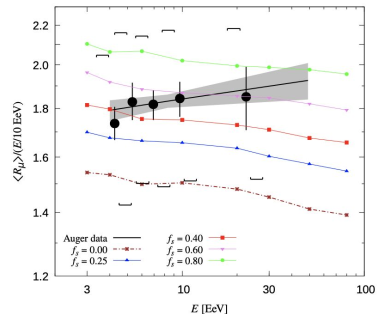
cosmic ray muon puzzle: observed 8σ excess of muons compared to predictions from hadronic interaction models



possible solutions:
studies show that enhanced forward strangeness explains discrepancy
→ measure forward π/K at LHC

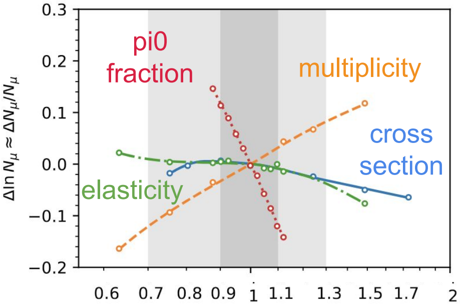


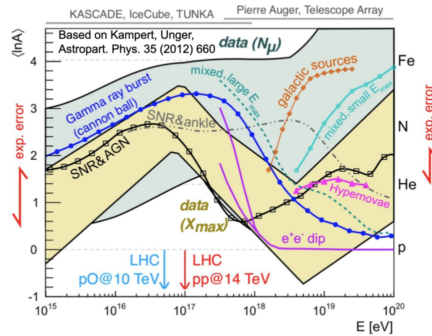
toy model: turn a fraction f_s of forward pions into kaons:solves muon puzzle and testable at LHC
[Anchordoqui, Garcia Canal, FK, Sciutto, Soriano, 2202.03095]



Light Hadrons and Muon Puzzle.

cosmic ray muon puzzle: observed 8σ excess of muons compared to predictions from hadronic interaction models





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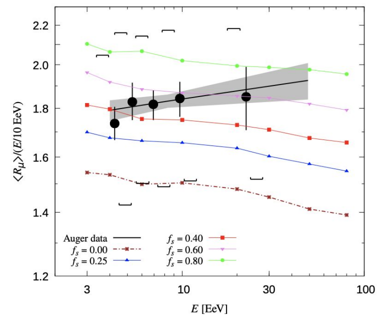
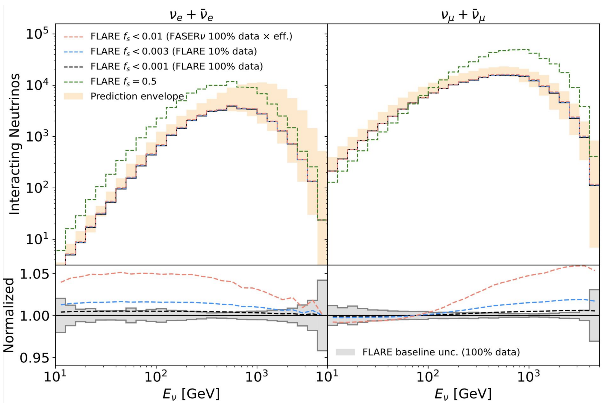
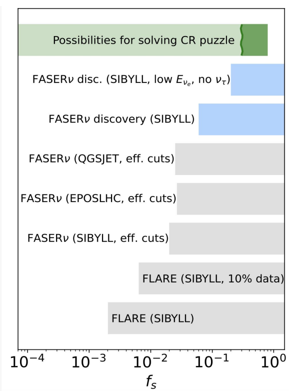






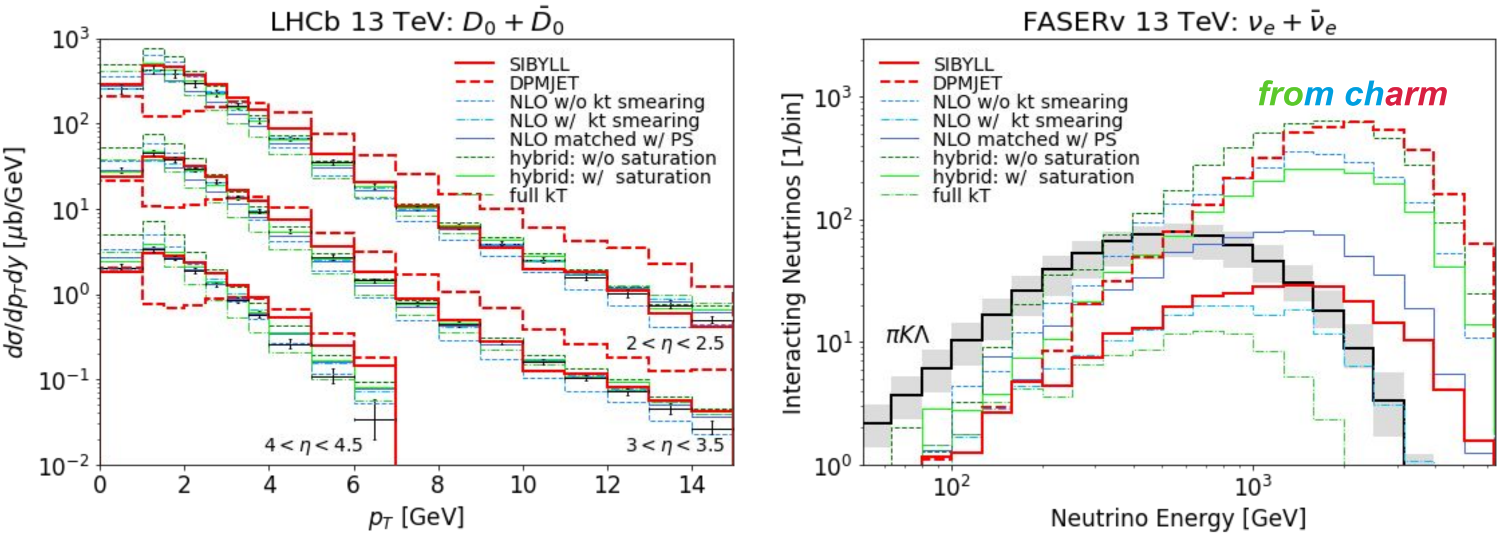
quantitative sensitivity study:
model testable at FASER
[FK, Mäkelä, Trojanowski, 2309.10417]

Neutrinos from Charm Hadrons.

forward charm hadron production can, in principle, be calculated using perturbative QCD

several predictions available based on hadronic interaction models, NLO collinear factorization and kT factorization: guided by LHCb data

[Bai, Diwan, Garzelli, Jeong, Reno, 2002.03012] [Maciula, Szczurek, 2210.08890] [Bhattacharya, FK, Sarcevic, Stasto, 2306.01578] [Buonocore, FK, Rottoli, Sominka, 2309.12793]



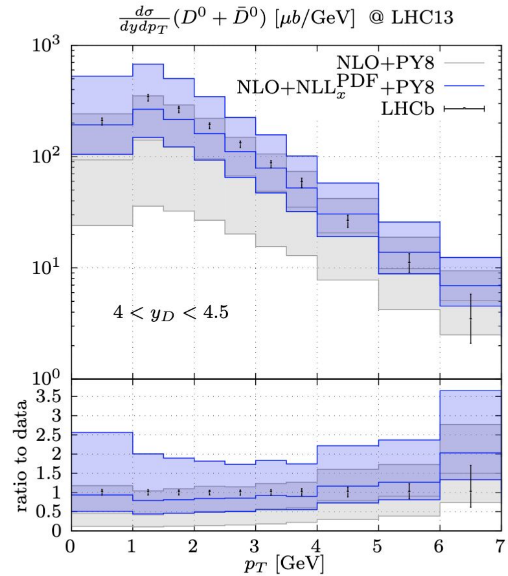
large spread of predictions at FASER

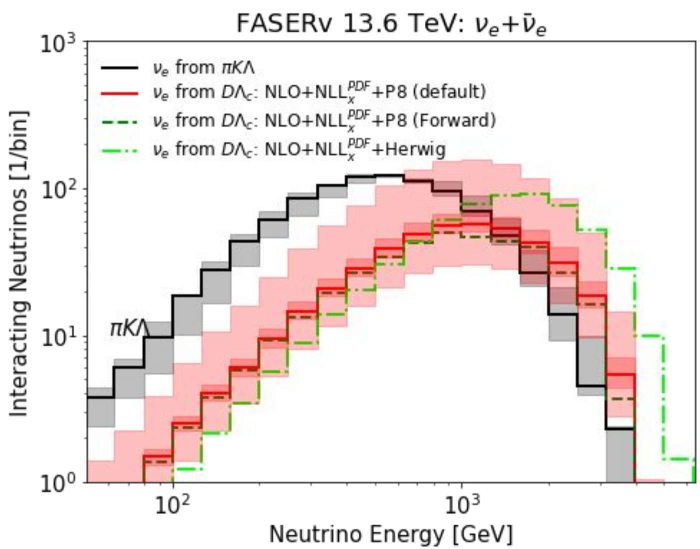
approximate descriptions of hard scattering/hadronization may affect reliability

Neutrinos from Charm Hadrons.

state-of-the-art QCD predictions for charm an bottom using POWHEG+Pythia: NLO+NLLx accuracy
[Buonocore, FK, Rottoli, Sominka, 2309.12793]

NNPDF3.1sx + LHCb PDF set: includes small-x resummation at NLLx and fit to LHCb D-meson data
[Ball et al. 1710.05935] [Bertone, Gauld, Rojo, 1808.02034]





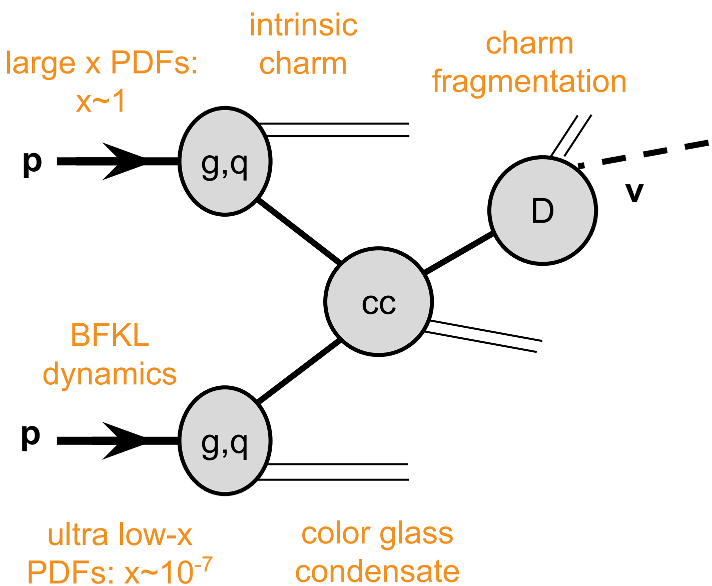
matching with Pythia for shower and hadronization

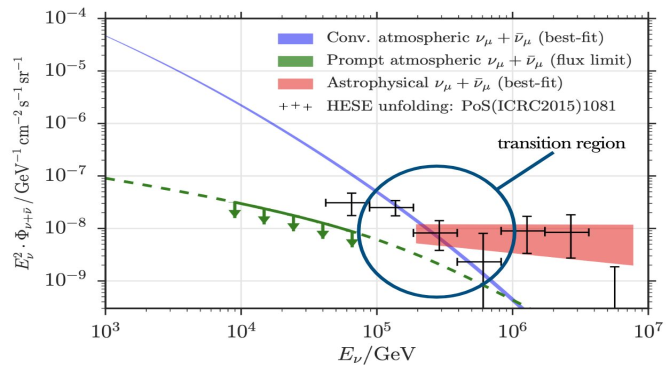
scale uncertainties dominate: roughly factor 2

Charm in QCD and Astroparticle Physics.

Neutrinos from forward charm production are an valuable laboratory for QCD, with applications in astroparticle physics

[FPF Paper, 2109.10905], [Feng, FK, Reno, Rojo, Soldin et al. 2203.05090]





forward charm production at the LHC

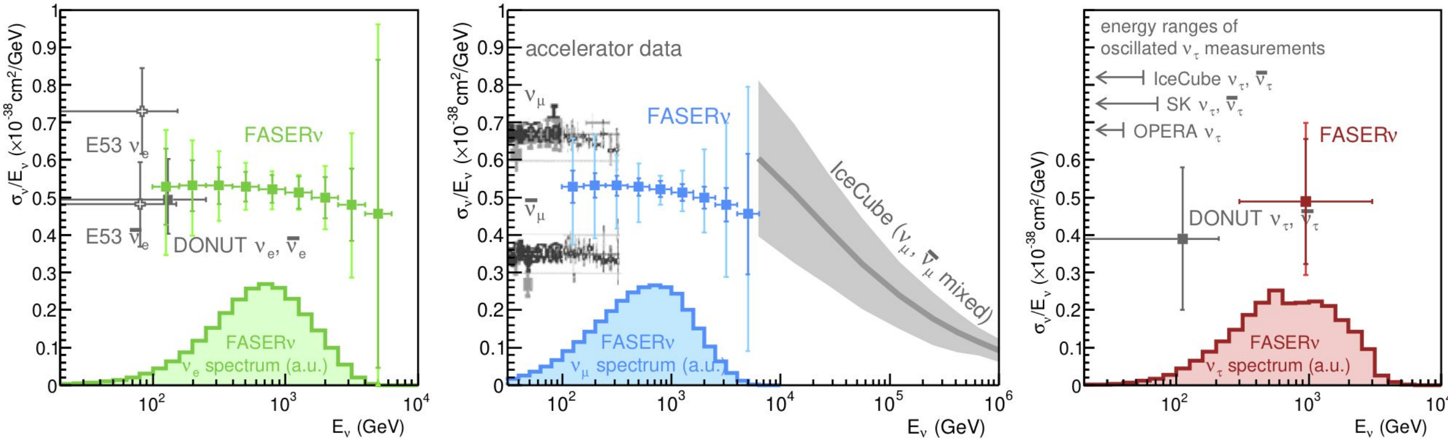
↓

constraints on prompt atmospheric neutrino flux at IceCube

(currently very poorly constrained/understood)

Collider Neutrinos: Interactions.

LHC provides a unique beam of TeV energy neutrinos of all three flavours.



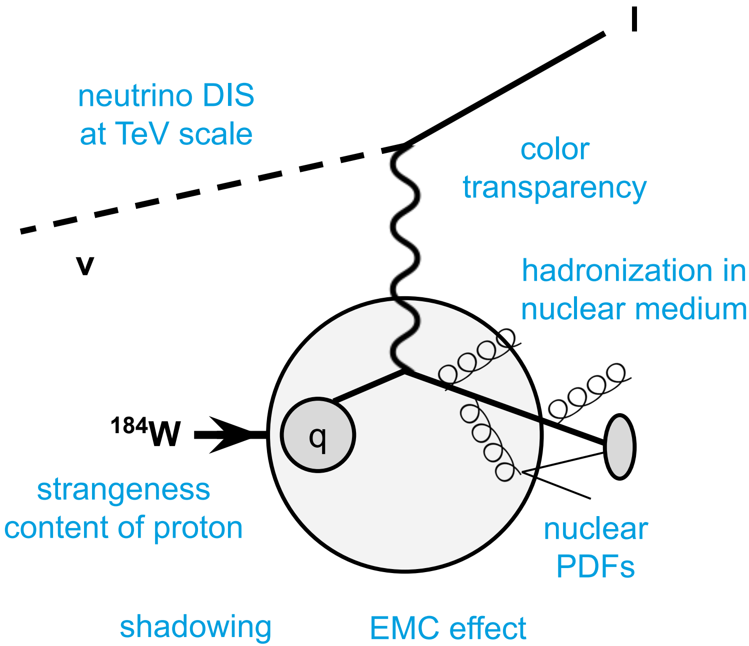
Collider neutrino experiments will measure cross section in unconstrained regime

[FASERν LOI, 1908.02310]

Test of SM: Lepton Flavor Universality

Collider Neutrinos: Interactions.

Collider Neutrino Experiments
are a Neutrino-Ion Collider
at EIC center of mass energies



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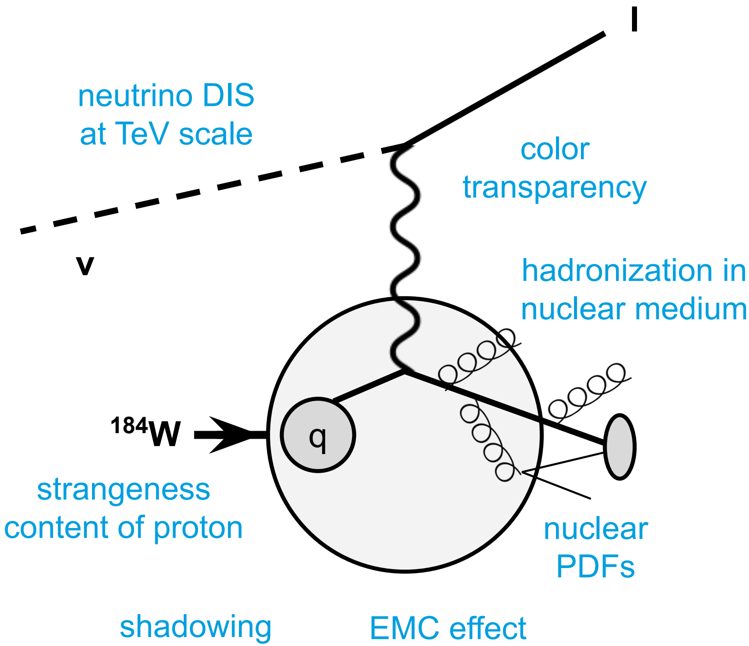
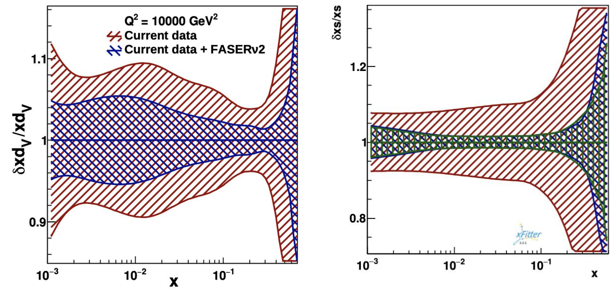
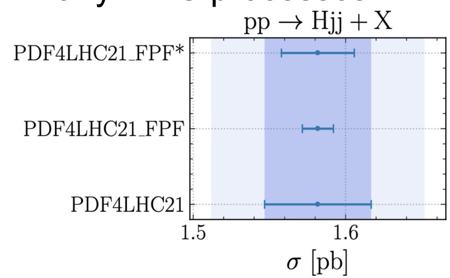


neutrino DIS data will improve PDFs

[FPF, P5 Input] [Cruz-Martinez et al. 2309.09581]



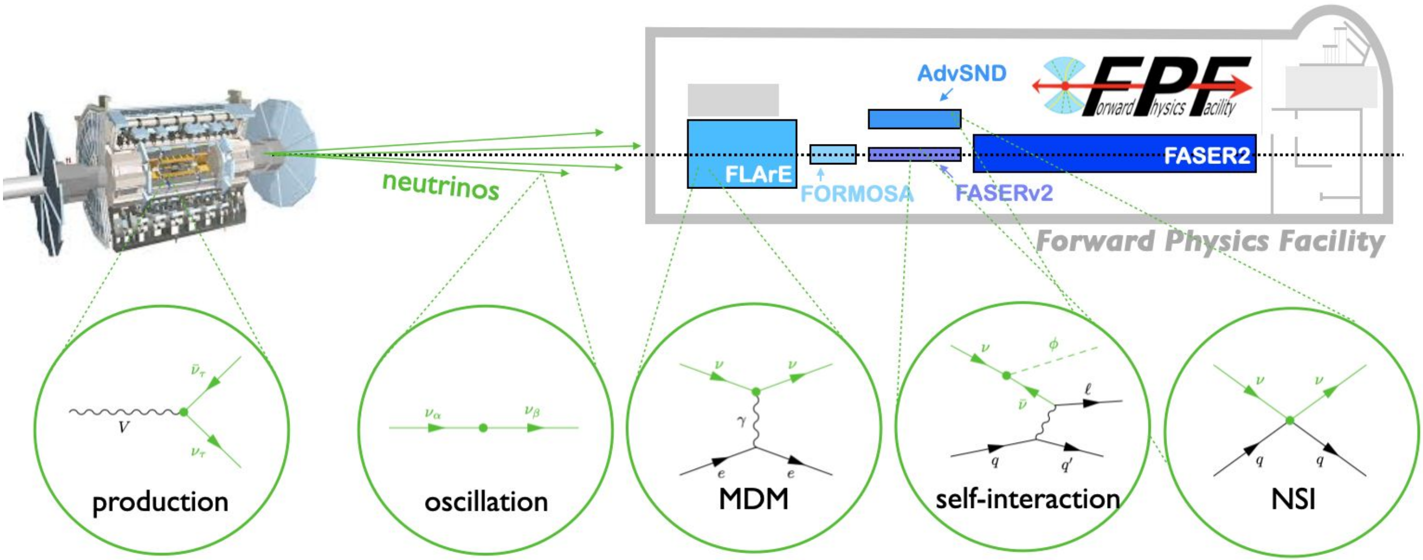
reduced PDF uncertainties for
many LHC processes



breaks PDF/BSM degeneracy

[Rojo, FPF7 Talk]

Collider Neutrinos: BSM Physics.



[FK, 2005.03594]

[FASER, 1908.02310]

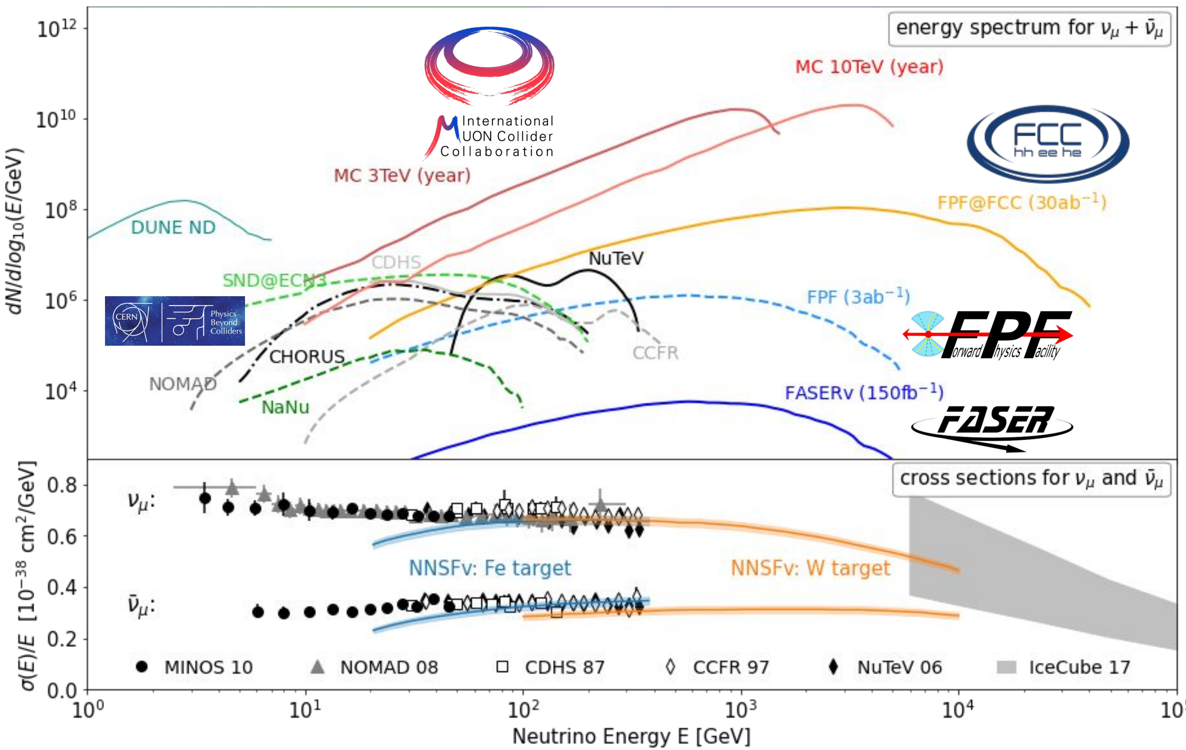
[Abraham, Abari, FK, Tsai, 2301.10254]

[Kelly, FK, Tuckler, Zhang, 2111.05868]

[Abraham, Ismail, FK, 2012.10500]

Outlook and Summary

Forward Physics beyond LHC.



[Ahdida et al., 2203.05090] [Abraham, Adhikary, Feng, Fieg, FK, Rojo, Trojanowski, *in progress*] [Fieg, FK, Meloni, Rabemananjara, Rojo, Wulzer, *in progress*]

Summary.

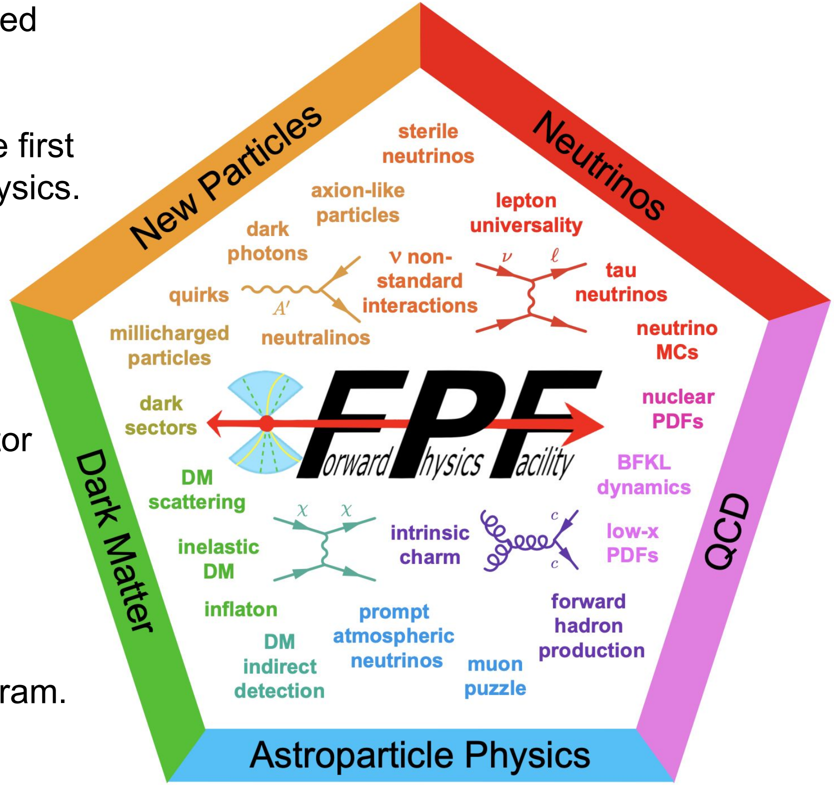
A novel forward physics program emerged to fully exploit the LHC.

Already success: FASER discovered the first neutrinos in the 50+ years of collider physics.

This is just the beginning of a time of multi-messenger collider physics
- neutrinos: messenger to QCD
- new particles: messenger to dark sector

Many more exciting results to come.

Theoretical and phenomenological efforts play an essential role in this program.



[Feng, FK, Reno, Rojo, Soldin et al. 2203.05090]

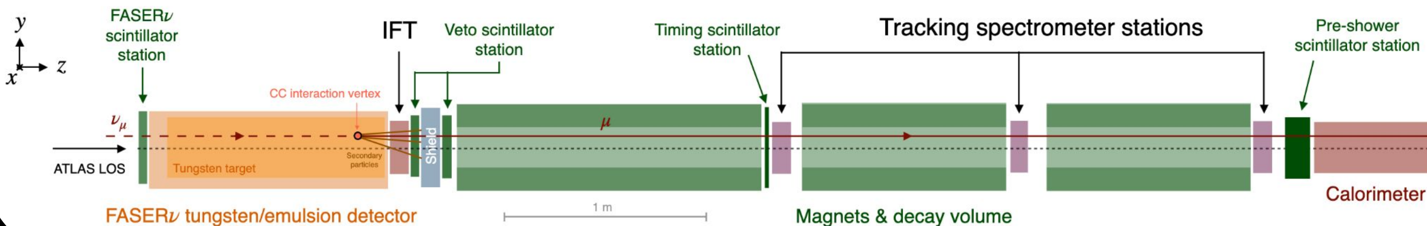
Backup

First Neutrino Observation.

Search for charged current νμ events through muon appearance
using FASER spectrometer and veto systems!

[FASER, 2303.14185]

1. Collision event with good data quality
2. no activity in 2 front scintillators
3. activity in all other scintillators
4. exactly 1 good high-momentum track
   - r < 95 mm at IFT
   - extrapolating to r < 120 mm in front veto
   - p > 100 GeV and θ < 25 mrad



Signal: expect 151 ± 41 events
- using CRMC + transport + GENIE
- uncertainty from DPMJET vs SIBYLL
- no experimental errors
- currently not trying to measure cross section

Background: expect 0.19 ± 1.89 events
- front veto inefficiency: negligible
- neutral hadrons: 0.11 ± 0.06
- scattered muons: 0.08 ± 1.83

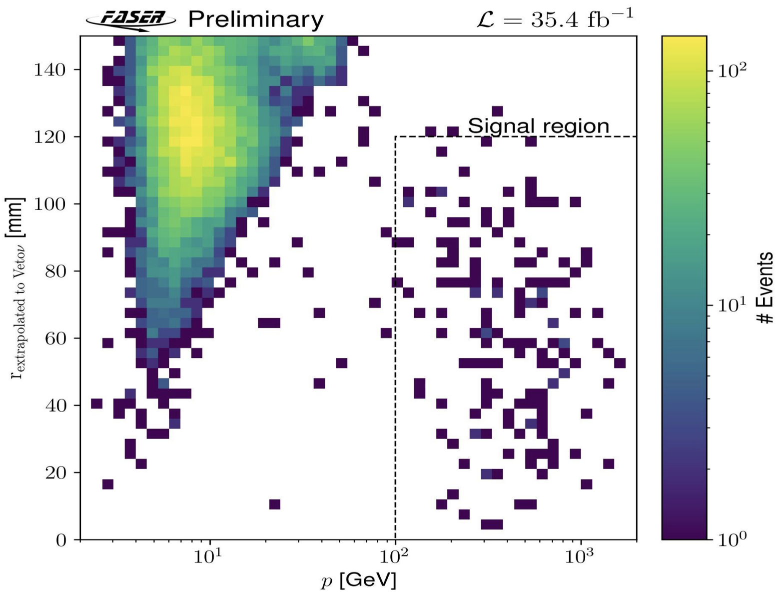
(see backup for details)

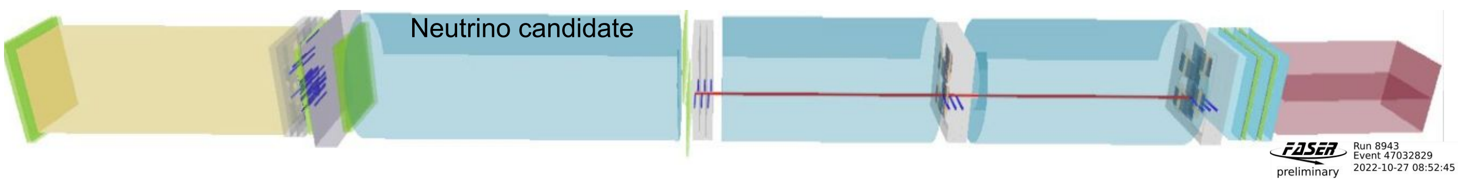
First Neutrino Observation.

~0.2 background events expected in signal region

Upon unblinding find 153 events with no veto signal

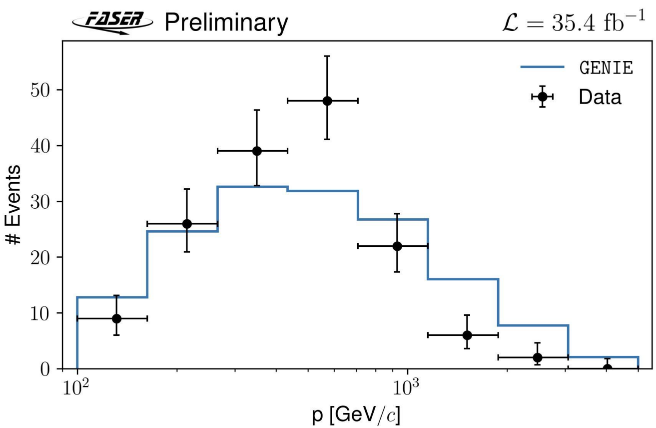
First direct detection of collider neutrinos: signal significance of 16σ



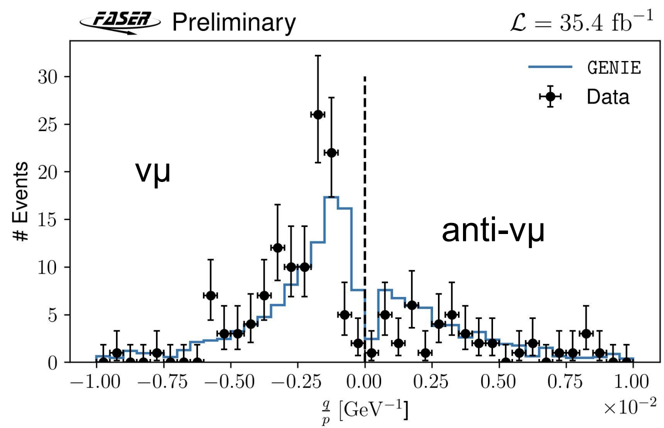


First Neutrino Observation.

candidate neutrino events match expectation



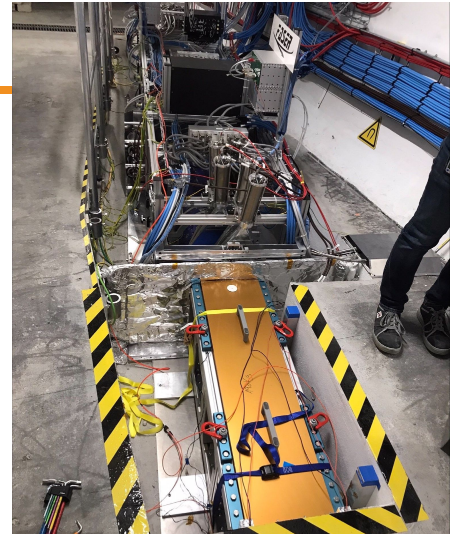
most events have high μ momentum



more νμ than anti-νμ

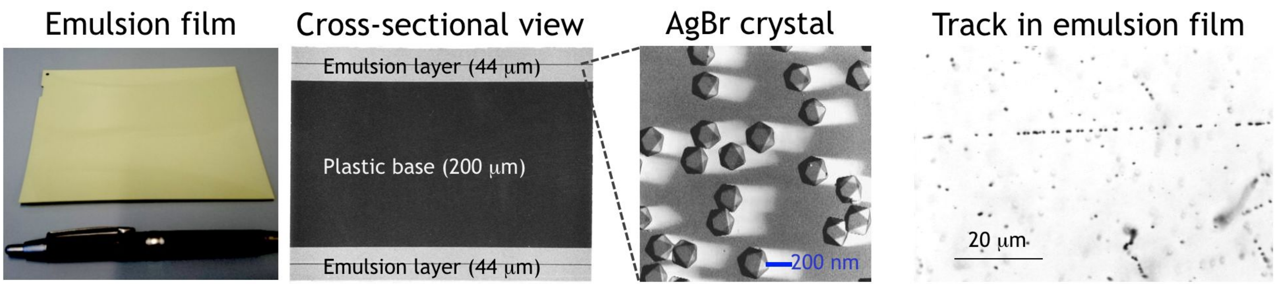
Note: no acceptance corrections nor any systematic uncertainties in these plots.

FASERν.

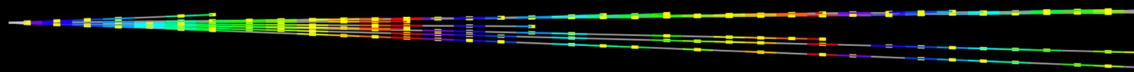


FASERν neutrino detector in front of FASER
- 25cm x 25cm x 1.3m, 1.2 ton mass
- expect 10000 neutrinos during LHC Run 3

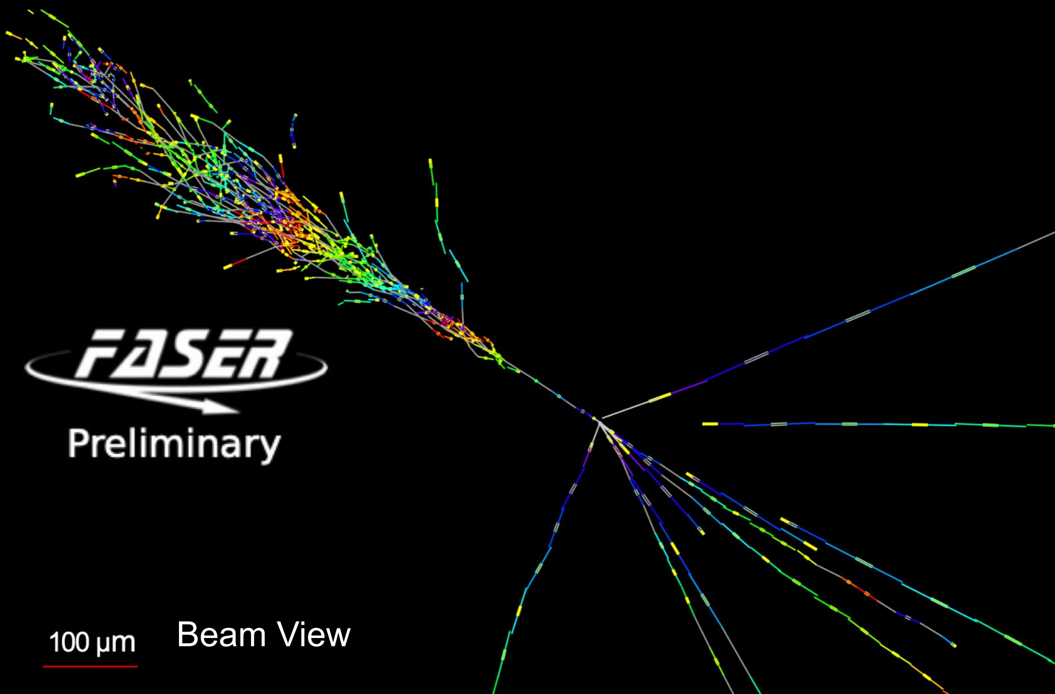
Emulsion detectors technology
- used by CHORUS, DONUT, OPERA
- 1000 emulsion films interleaved with 1mm tungsten plates
- provide 3D image of interaction with sub-μm resolution
- global reconstruction with the FASER detector possible



Highly ν_e-like CC Candidate Event.



5000 µm Side View (without EM shower)



100 µm Beam View

vertex with 11 tracks
- 615 µm inside tungsten

e-like track from vertex
- single track for 2X0
- shower max at 7.8X0
- θ_e = 11 mrad to beam

Back-to-back topology
- 175° between e & rest

Analysis of FASERν emulsion detector data underway

LHC Neutrino Fluxes.

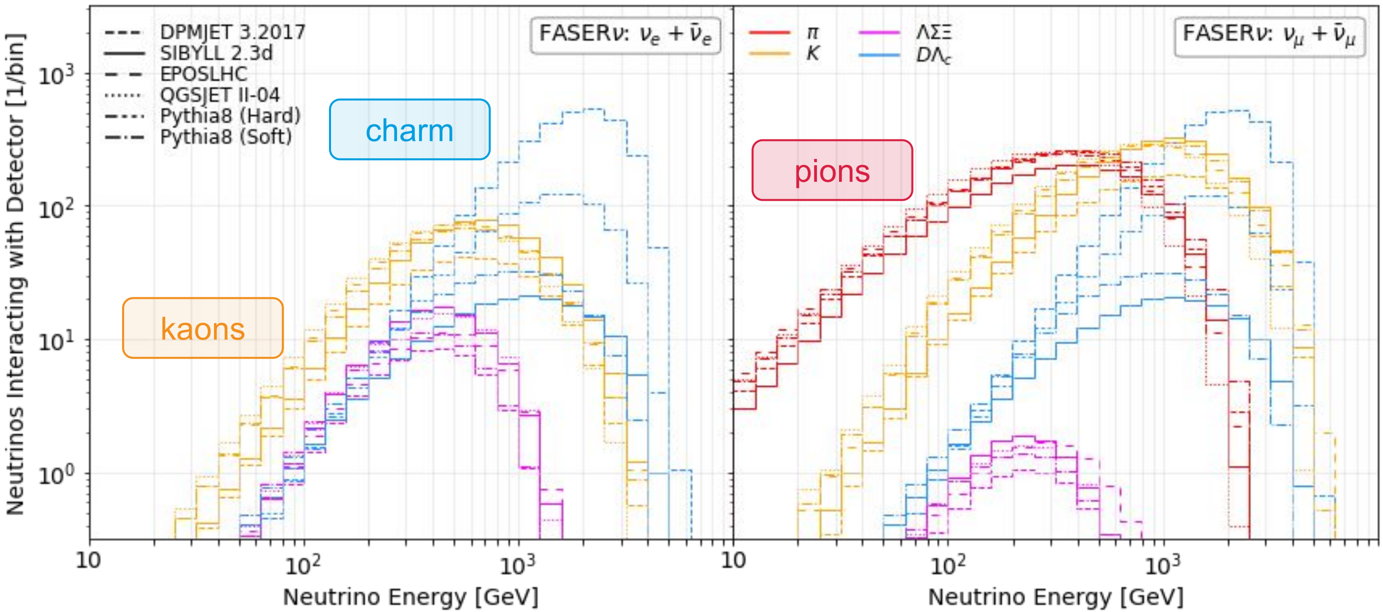
Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k / 20k	41k / 53k	190 / 754

Current LHC experiments will detect thousands of neutrinos

The FPF experiments will detect millions of neutrinos.
This will provide the necessary statistics for precision studies.

LHC Neutrino Fluxes Origin.

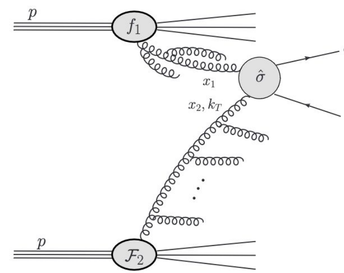
Where do the LHC neutrinos come from?

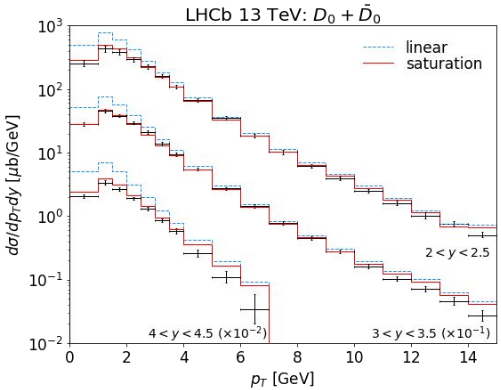


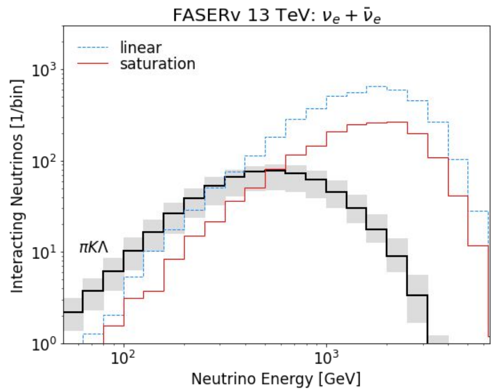
LHC neutrinos = probe of forward particle production

Forward Charm and Prompt Neutrinos.

Prediction using kT-factorization (hybrid approach)
[Bhattacharya, FK, Stato, Sarcevic: 2306.01578]

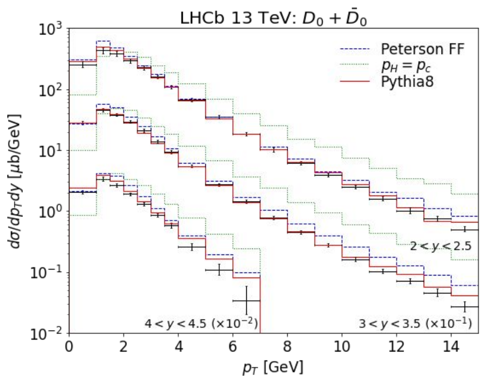


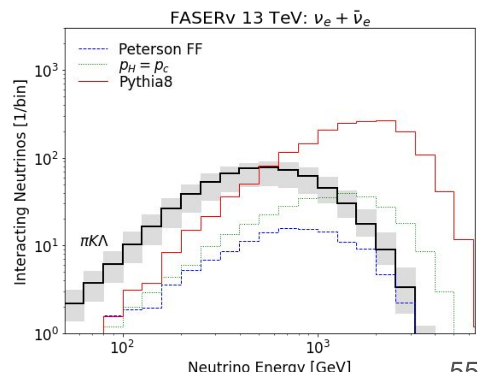




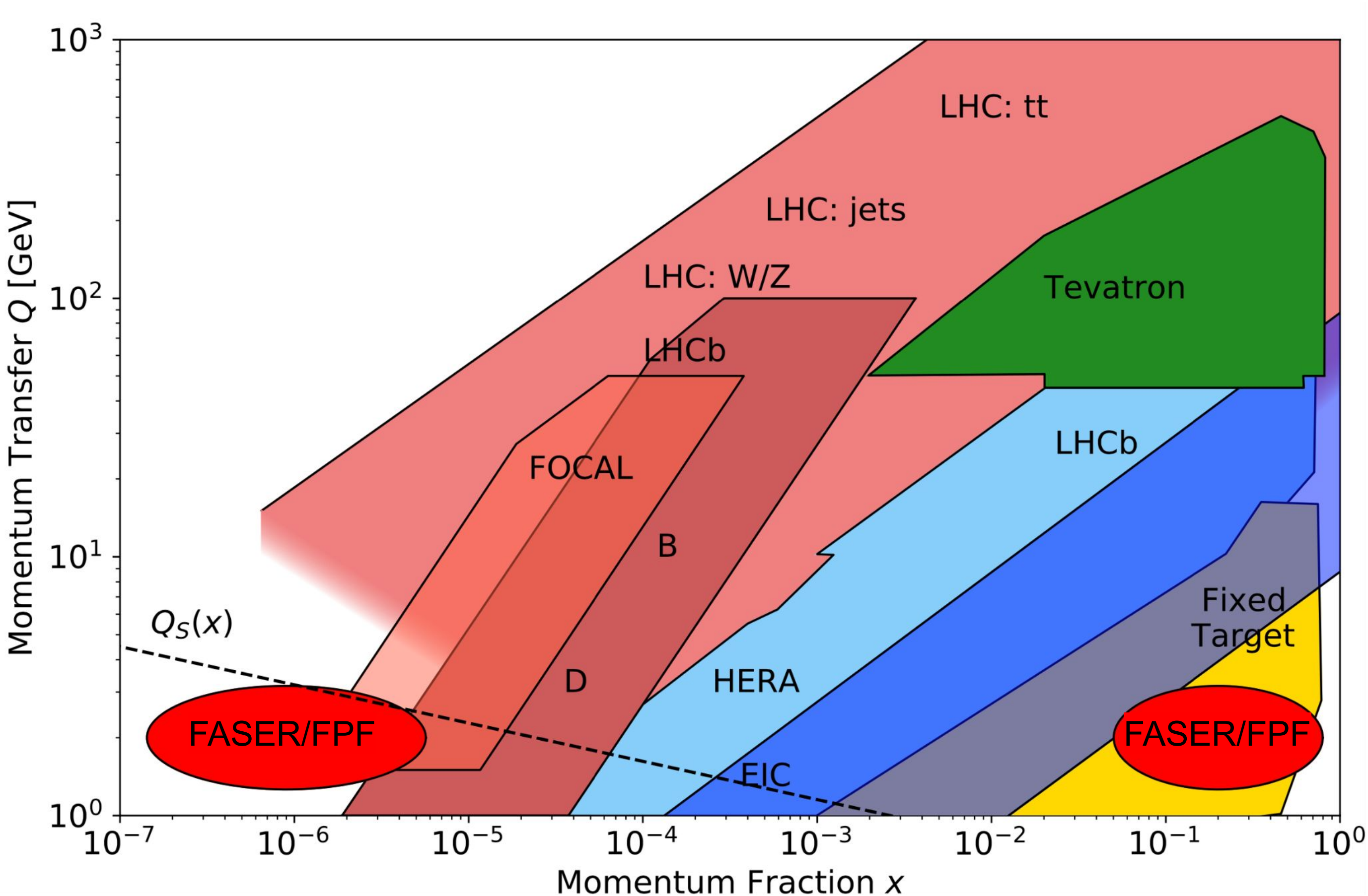
study of **gluon saturation** at low-x

dominating modelling uncertainty at the moment: **hadronization**

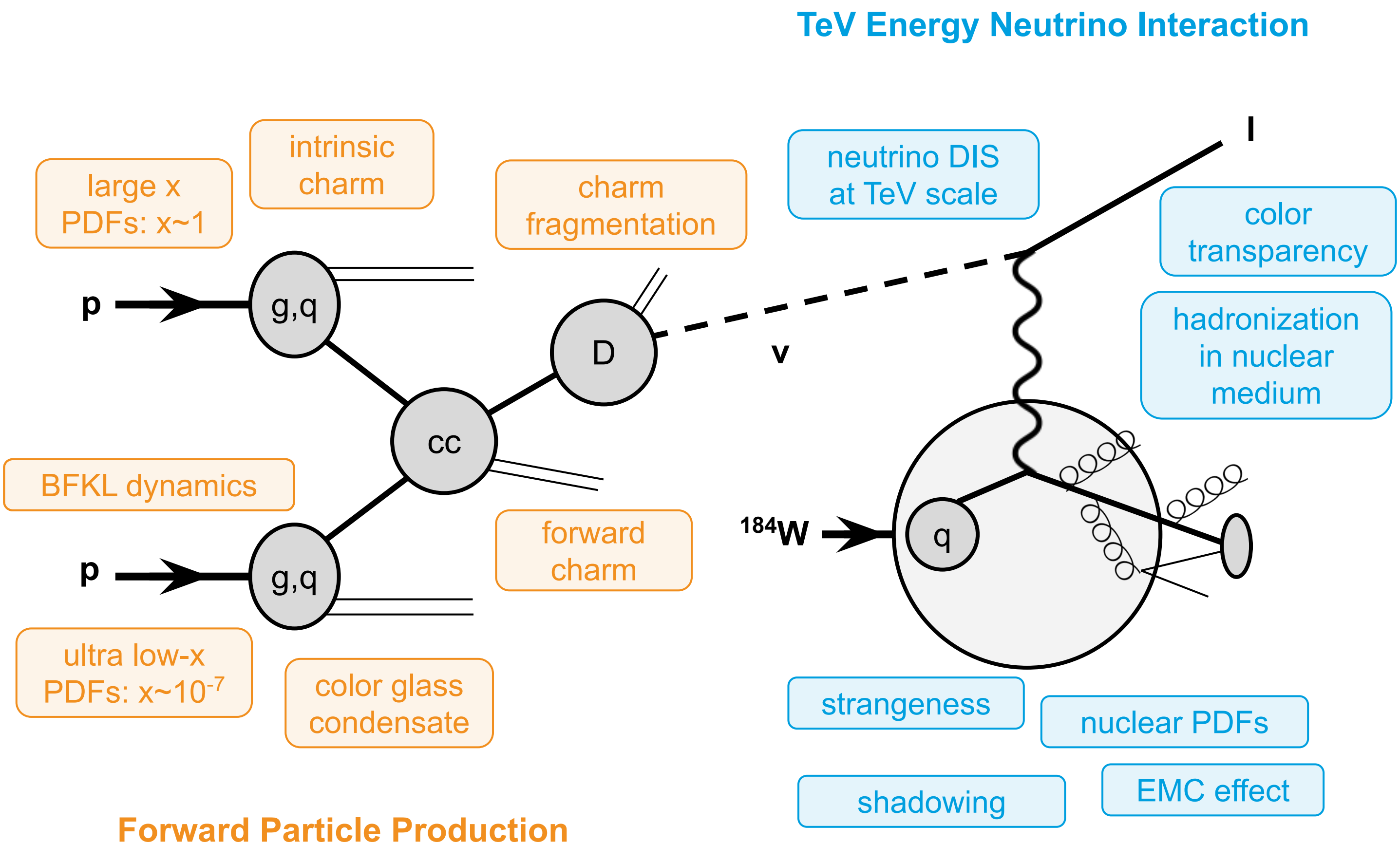




Forward Charm and Prompt Neutrinos.



LHC Neutrino Physics Opportunity.



Neutrinos at the LHC.

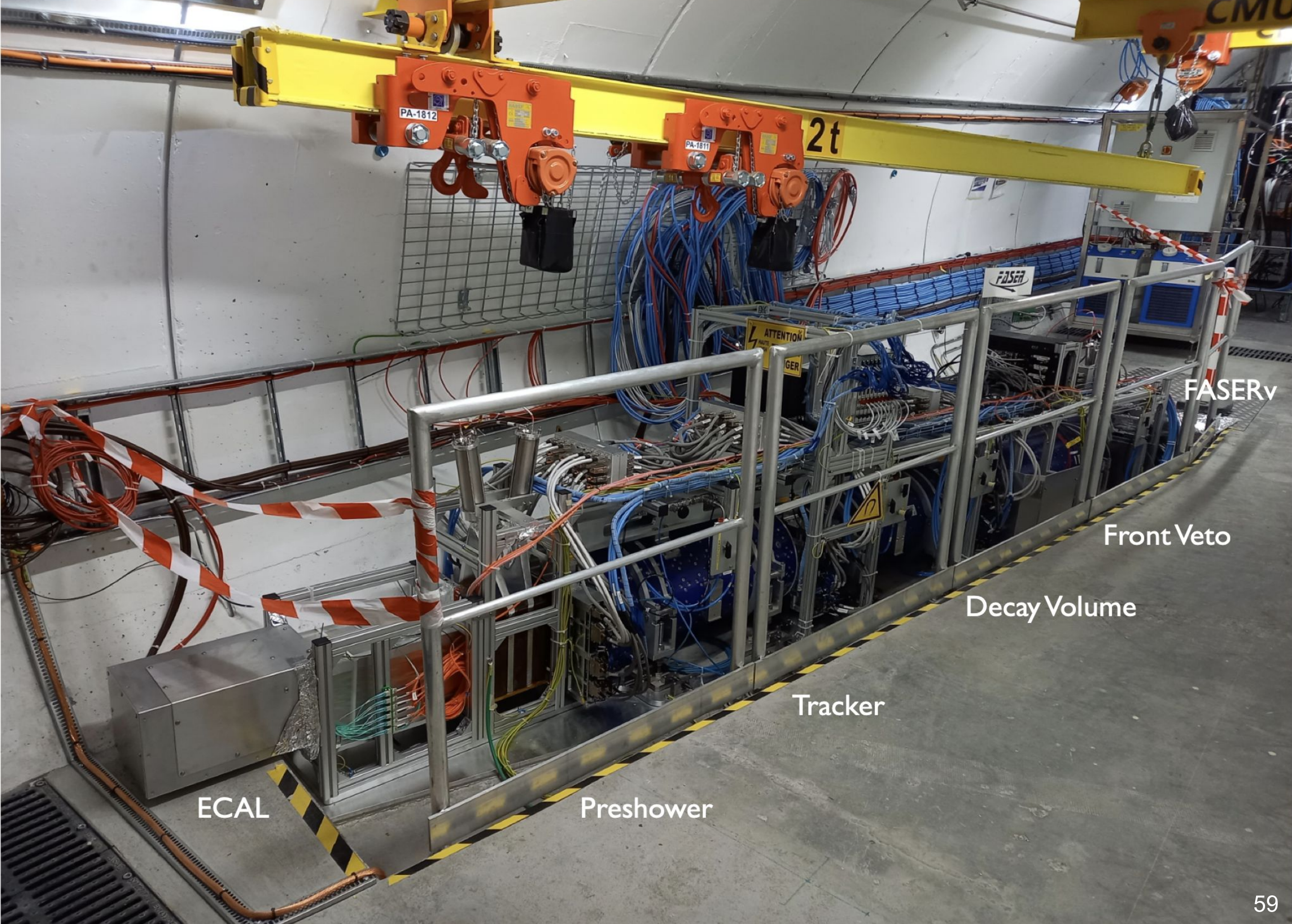
FASER Pilot Detector

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

6 neutrino candidates

all previous collider detectors
building-size, decades ~$1B
0 neutrino candidates

slide by Jonathan Feng


FASERν
Front Veto
Decay Volume
Tracker
Preshower
ECAL

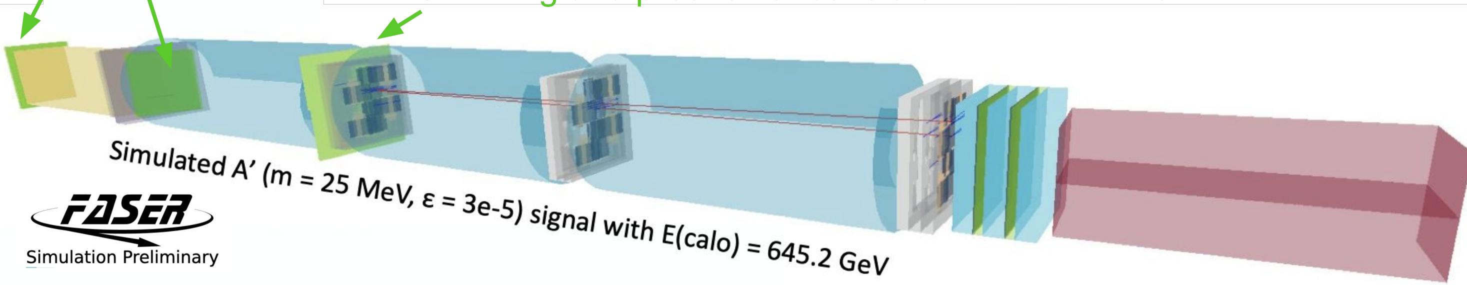
FASER's Dark Photon Search.

FASER performed a first search for dark photons: [FASER, CERN-FASER-CONF-2023-001]
- simple and robust A' e+e- selection, optimised for discovery
- blind events with no veto signal and E(calo) > 100 GeV
- efficiency of ~40% across region sensitive to

1. Collision event with good data quality

2. No signal in any veto scintillator

3. Timing and preshower consistent with ≥2 MIPs



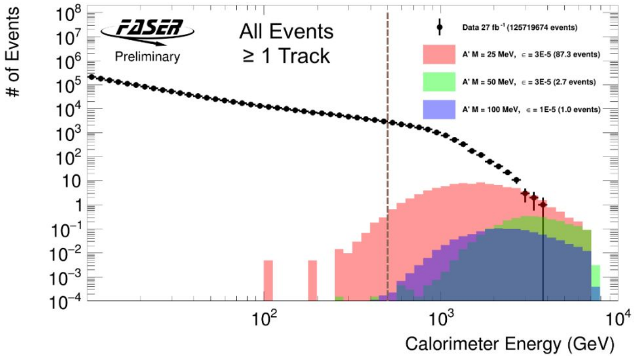
4. Exactly 2 good fiducial tracks

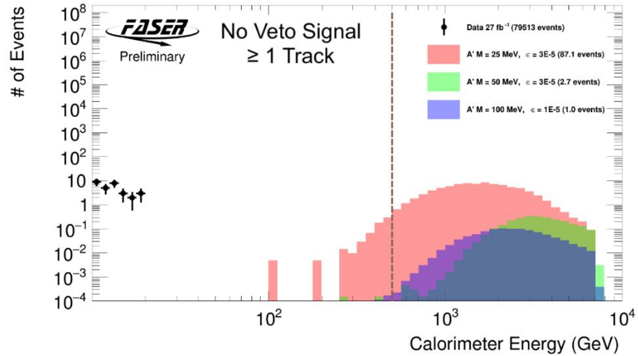
5. Calo E > 500 GeV

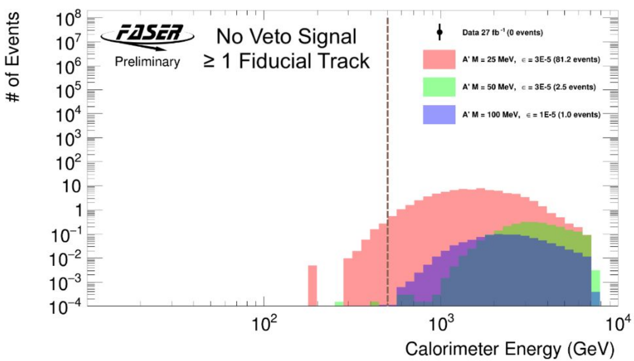
Background: expect (2.0 ± 2.7) x 10^{-3} events
- veto inefficiency, non-collision backgrounds, neutrino interactions, neutral hadrons

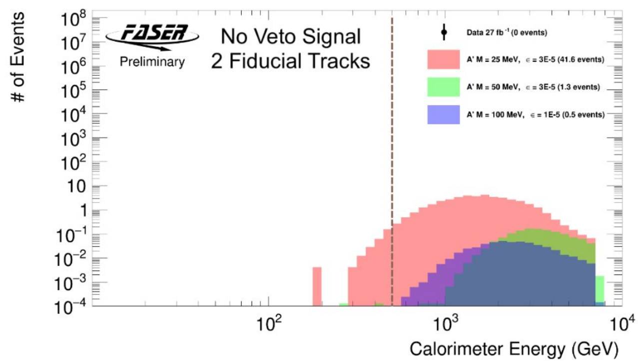
FASER's Dark Photon Search.

No events in unblinded signal region
Not even any with ≥1 fiducial track



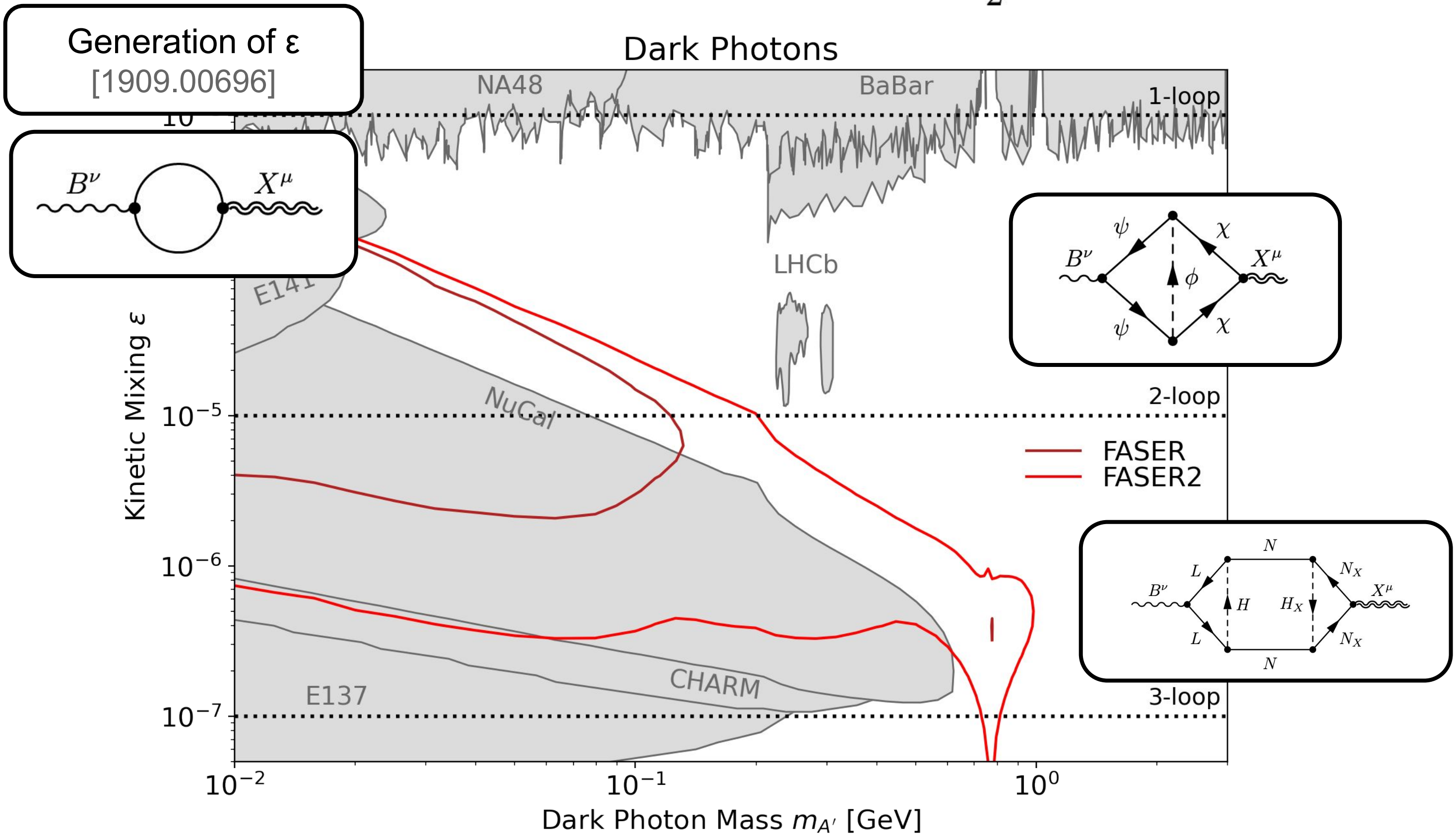






Long-Lived Particles: Dark Photon.

Dark Photon = gauge boson mixing with photon: $\mathcal{L} \sim -\frac{1}{2} m_{A'}{}^2 A'^2 - \epsilon e q_f \bar{f} \not{A}' f$



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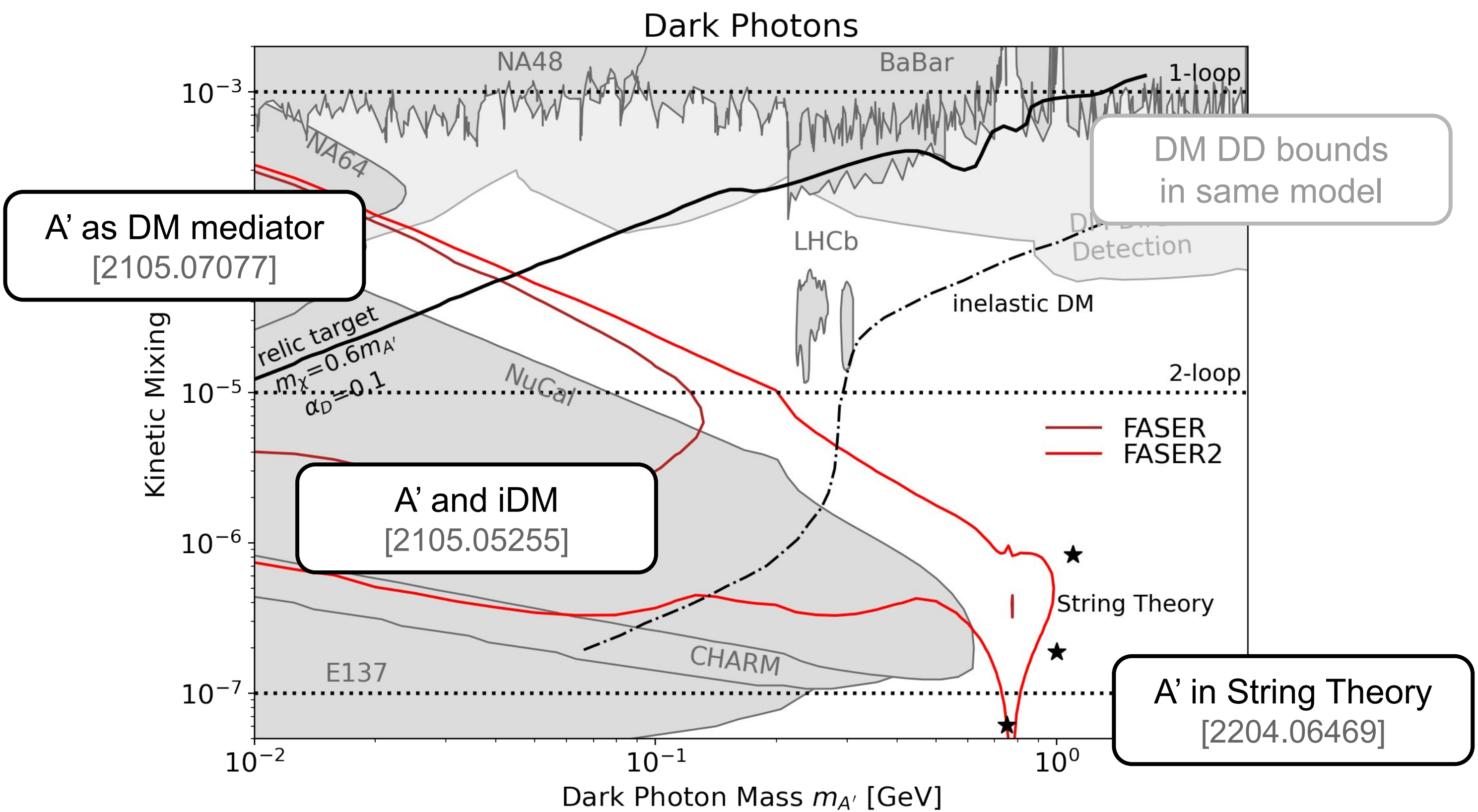
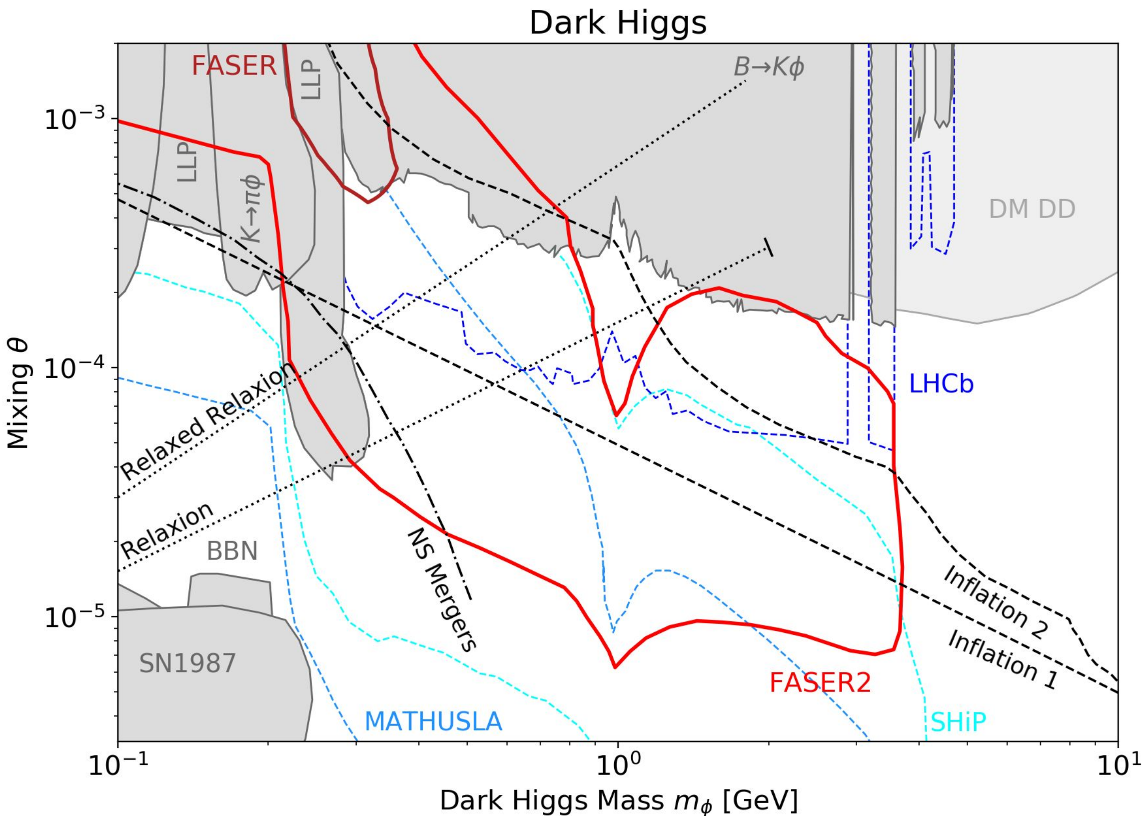


Long-Lived Particles: Dark Higgs.

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

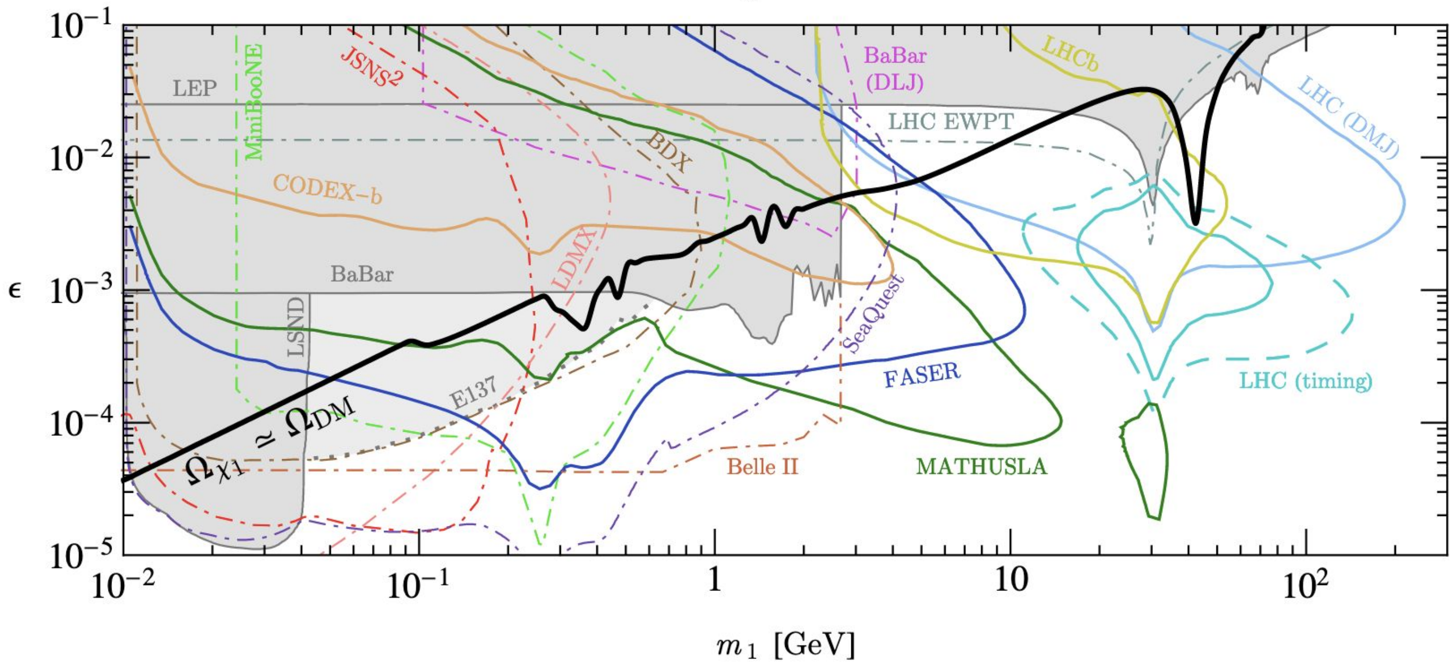


Long-Lived Particles: inelastic DM.

non-minimal model: here higher energy can really help

qq → A' → X1 X2   X2→X1+SM

Fermionic iDM, $m_{A'} = 3m_1$, Δ=0.1, α_D=0.1



For details see [1810.01879](1810.01879)

Dark Matter Scattering.

mA' > 2mX

↓

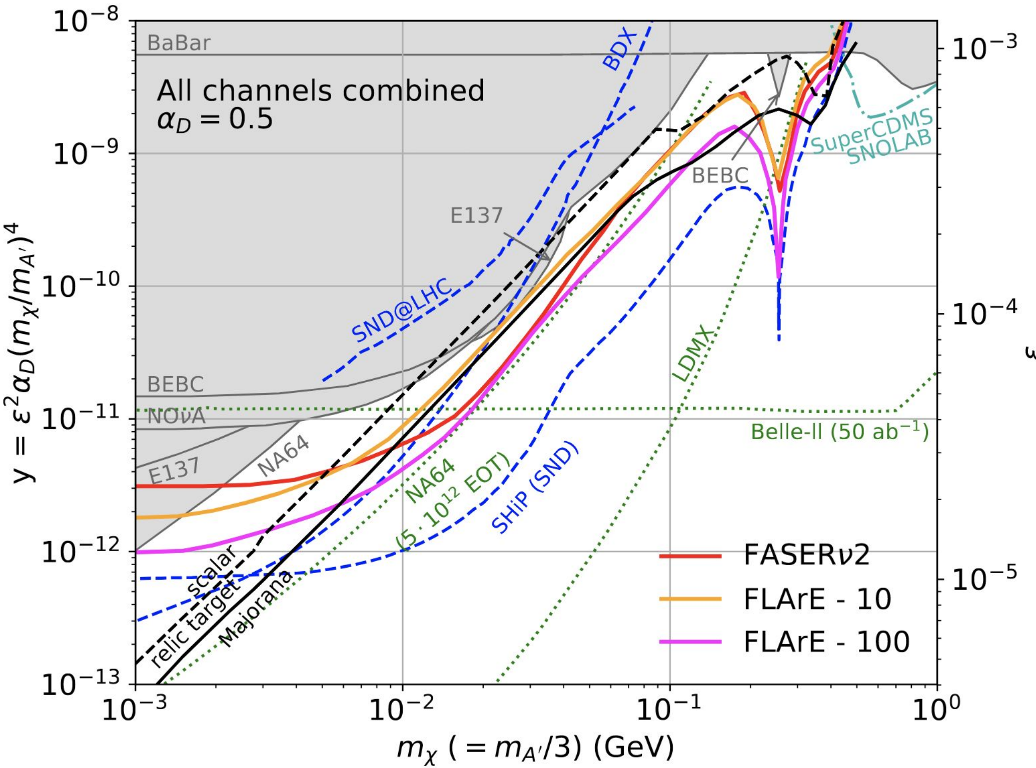
dark photon promptly decays in DM

↓

LHC produces DM beam

↓

DM scattering in neutrino detector



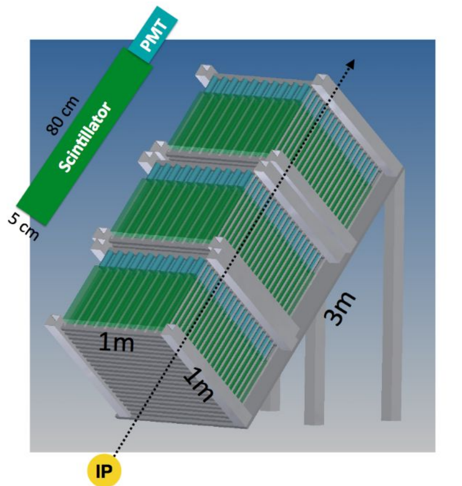
for more details see: [2101.10338]

More Searches for BSM Physics.

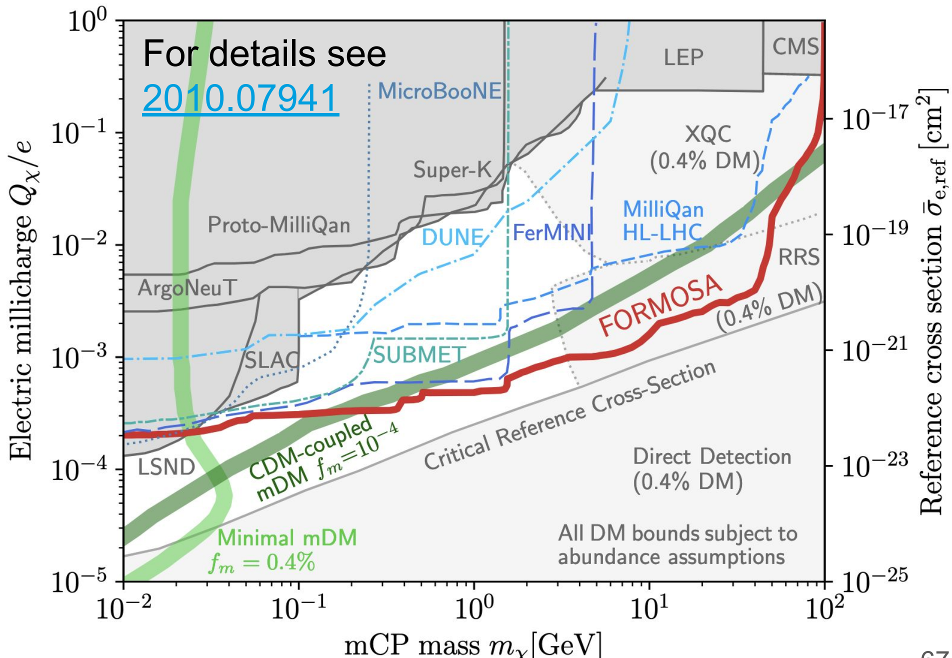
milli-charged particle Q=εe
→ search for minimum ionizing particle with very small dE/dx

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.



milliQan detector: 1607.04669



More Searches for BSM Physics.