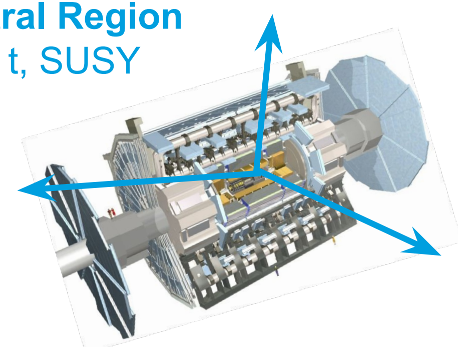
First Observation of Collider Neutrinos with FASER and Implications for Astroparticle Physics.

Felix Kling
KIT Seminar
05/11/2023

DESY.

Motivation.

Central Region
H, t, SUSY

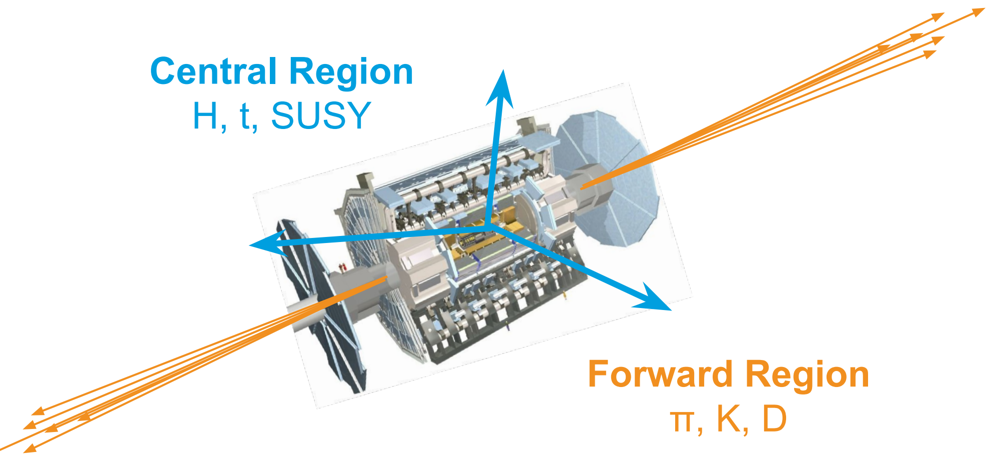


Motivation.

The LHC produces an intense and strongly collimated beam of highly energetic particles in the forward direction.

10^{17} π0, 10^{16} η, 10^{15} D, 10^{13} B within 1 mrad of beam

Can we do something with that?



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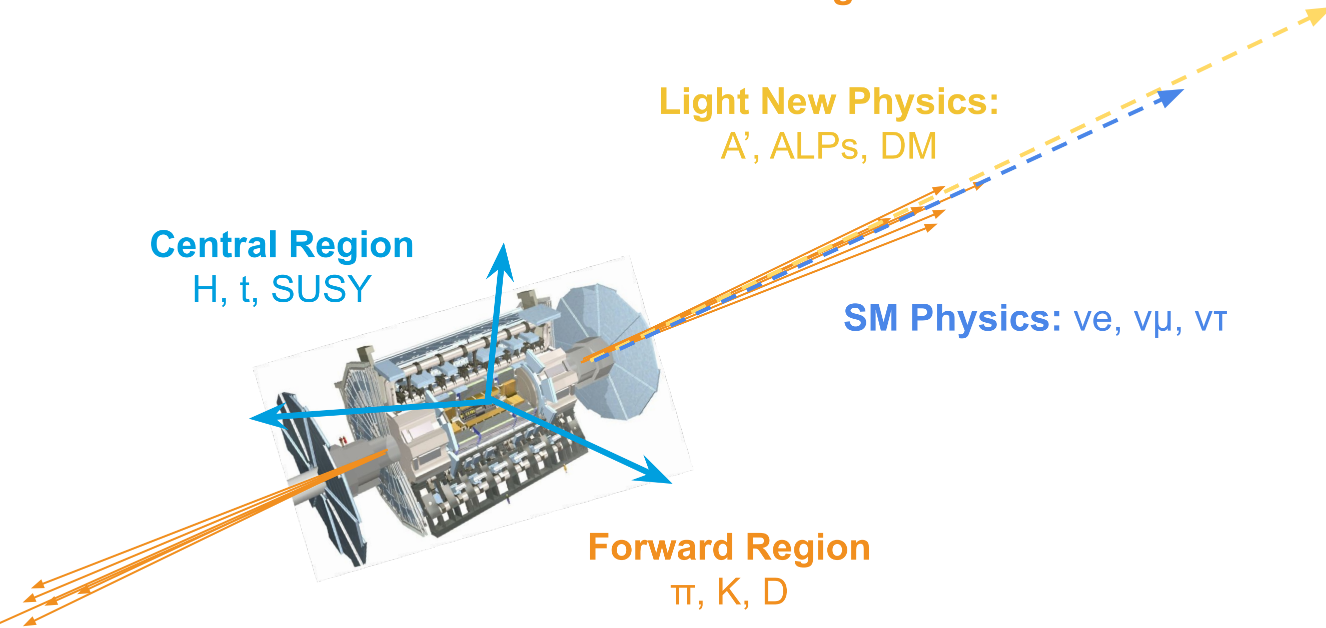

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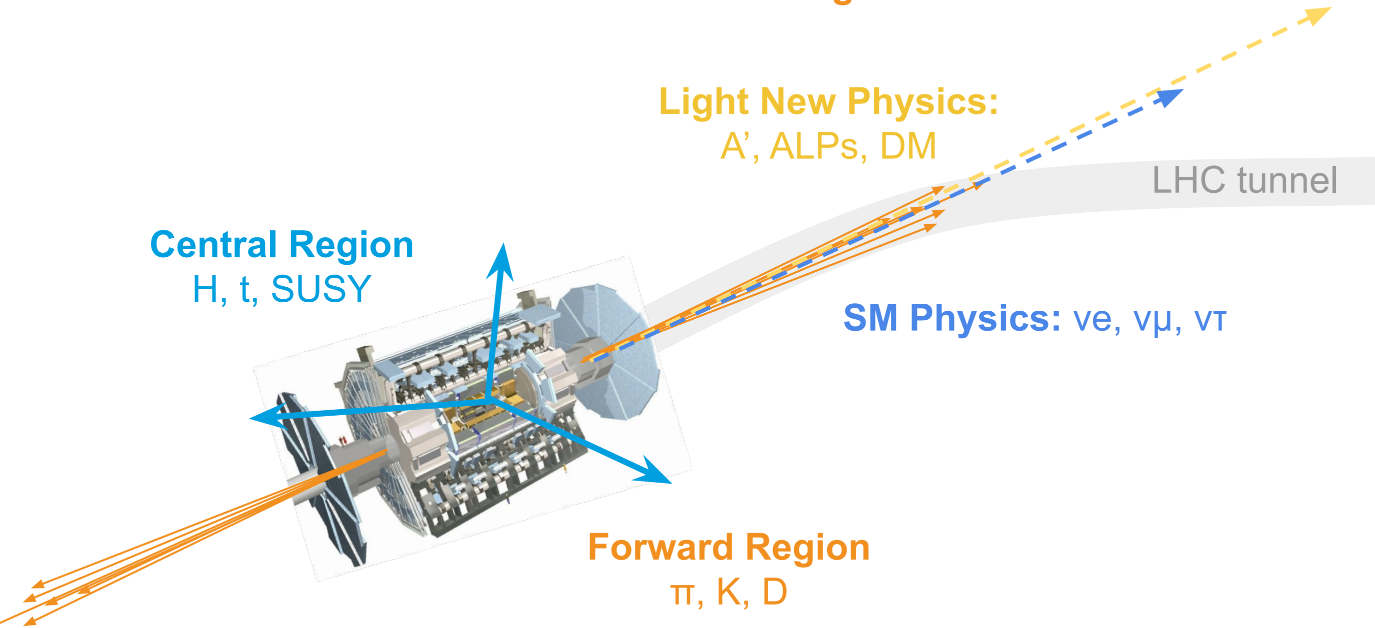

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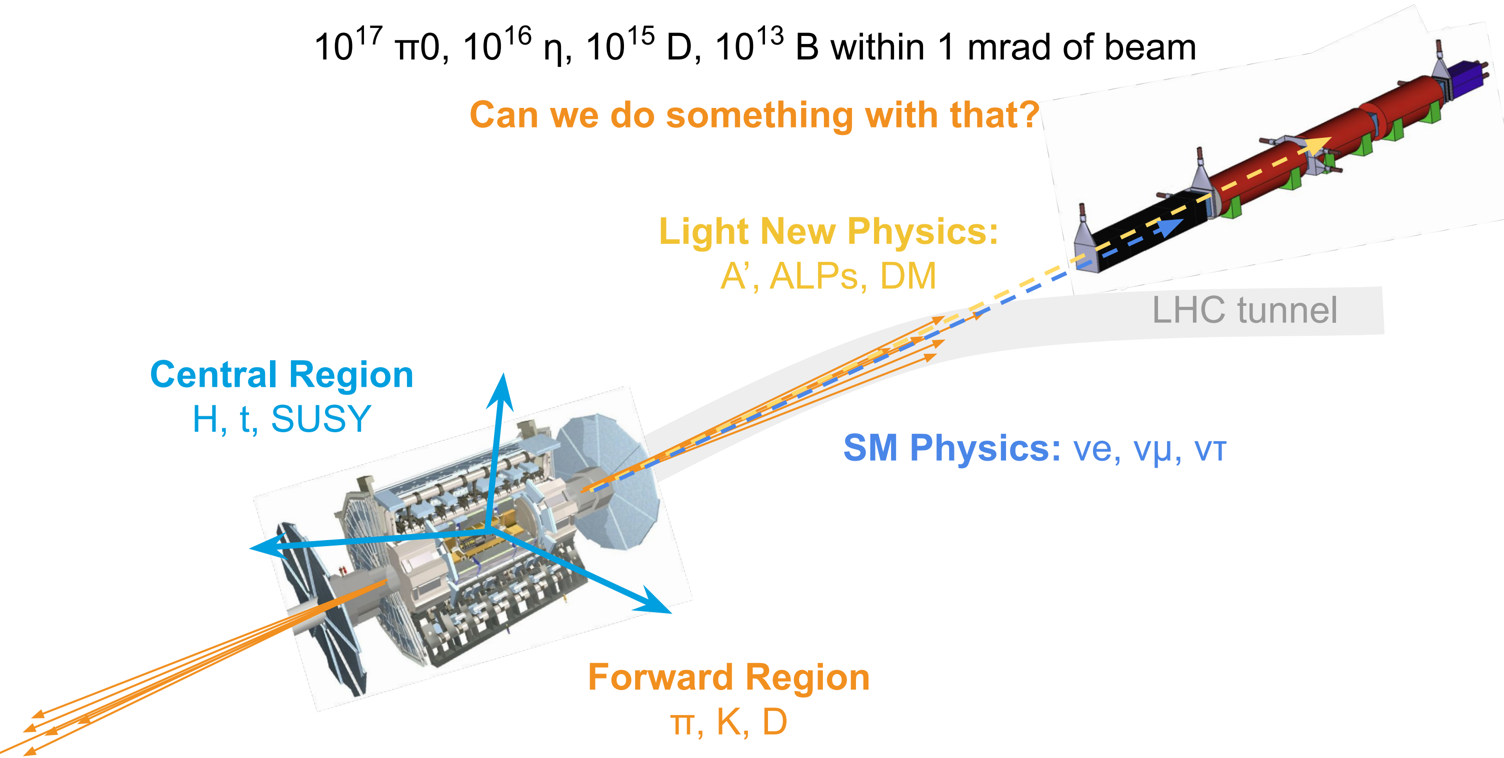
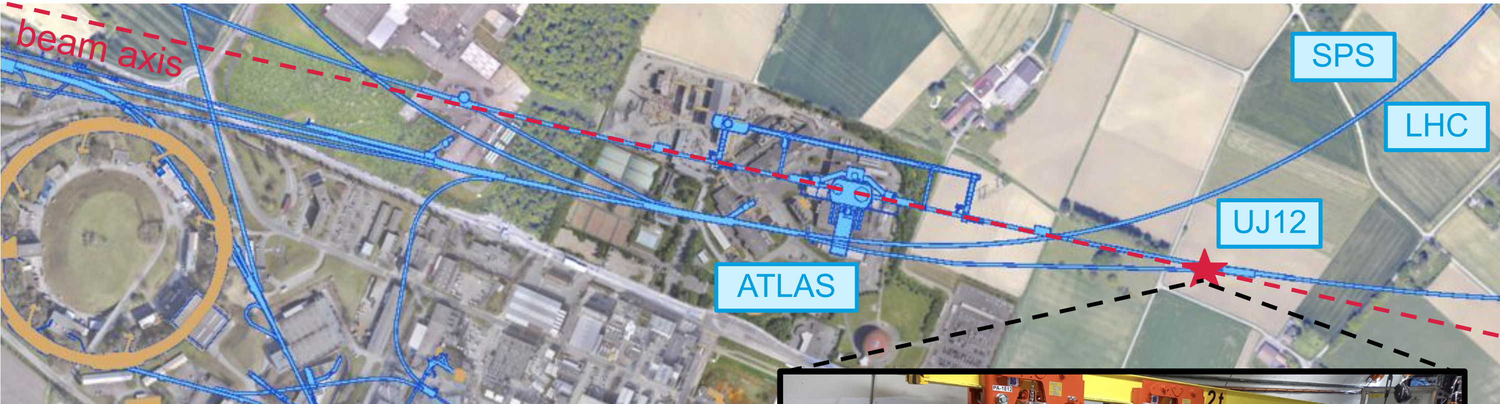


The FASER Experiment

FASER Location.

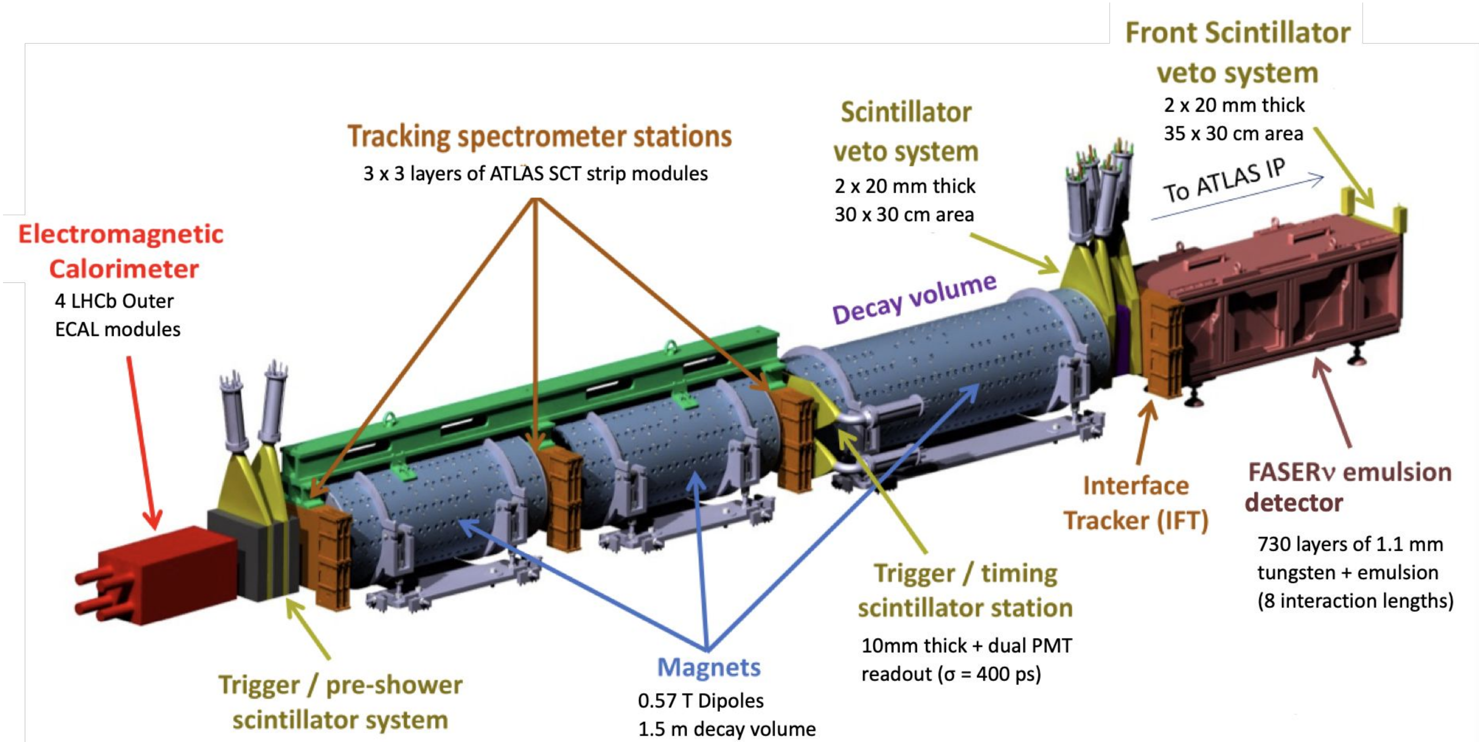


FASER is a new forward LHC experiment to detect light long-lived BSM particles and neutrinos

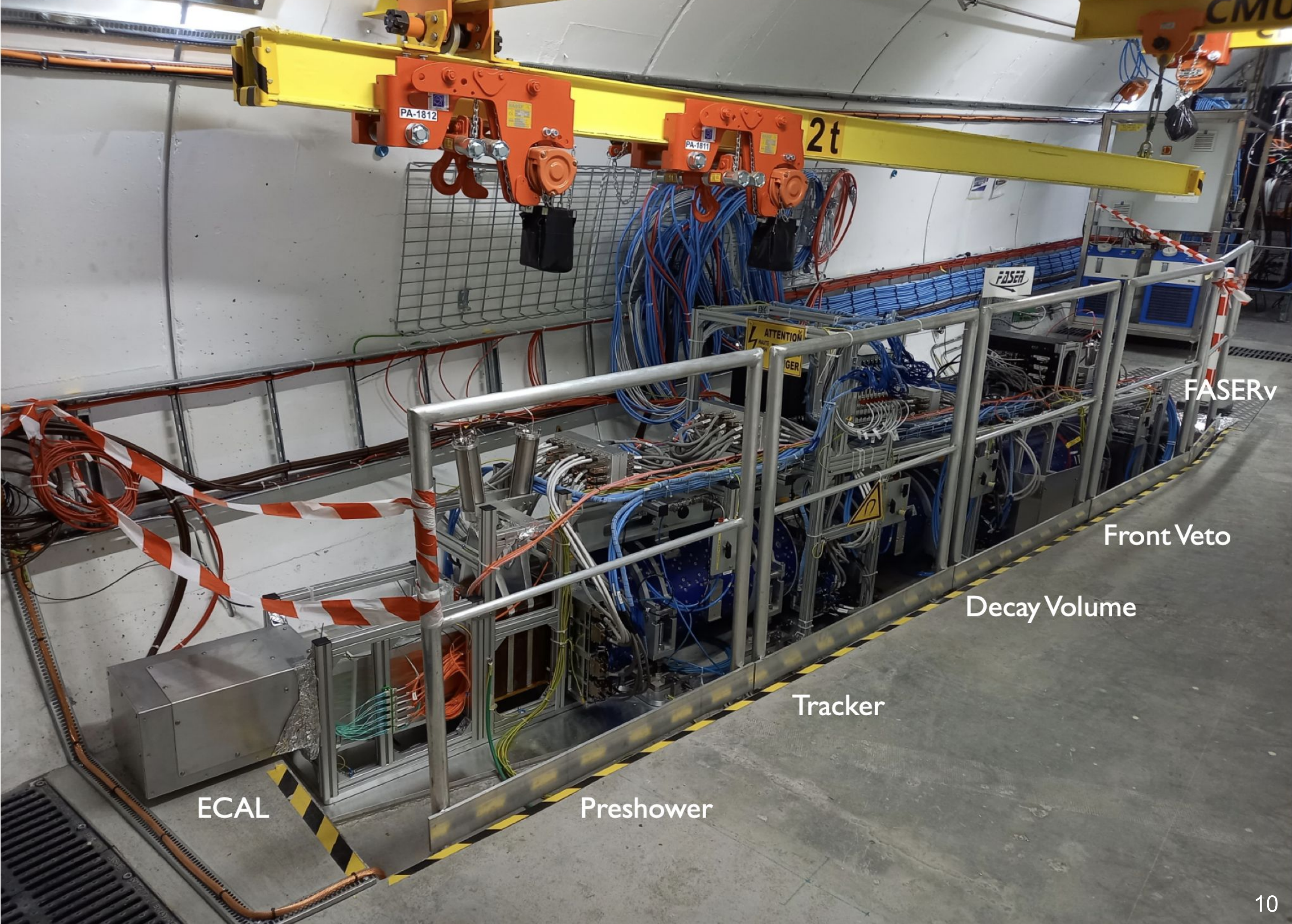
Located along beam axis about 480m downstream of ATLAS IP: covers $\eta > 9$

Shielded from IP by ~100m of rock

FASER Detector.



[*The FASER Detector*, arXiv:2207.11427]



PA-1812
PA-1811
2t
FASER
ATTENTION
FASERν
Front Veto
Decay Volume
Tracker
Preshower
ECAL

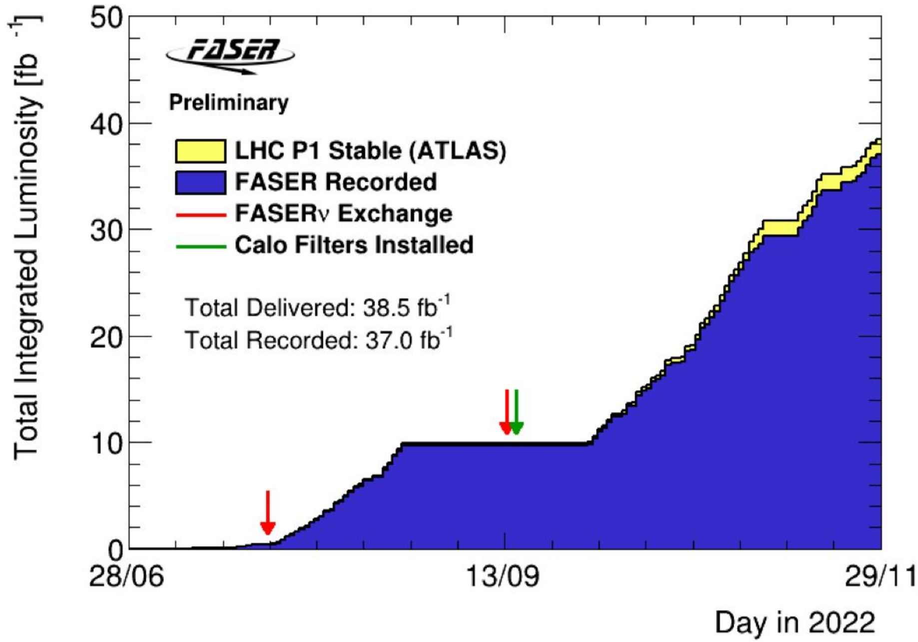
FASER Operation.

Data taking started in summer 2022

Successfully operation throughout 2022

Recorded 96.1% of delivered luminosity

Analyses presented use
- 27.0/fb (dark photons)
- 35.4/fb (neutrinos)



All detector components performing excellently

More than 350M single-muon events recorded

FASER Operation.

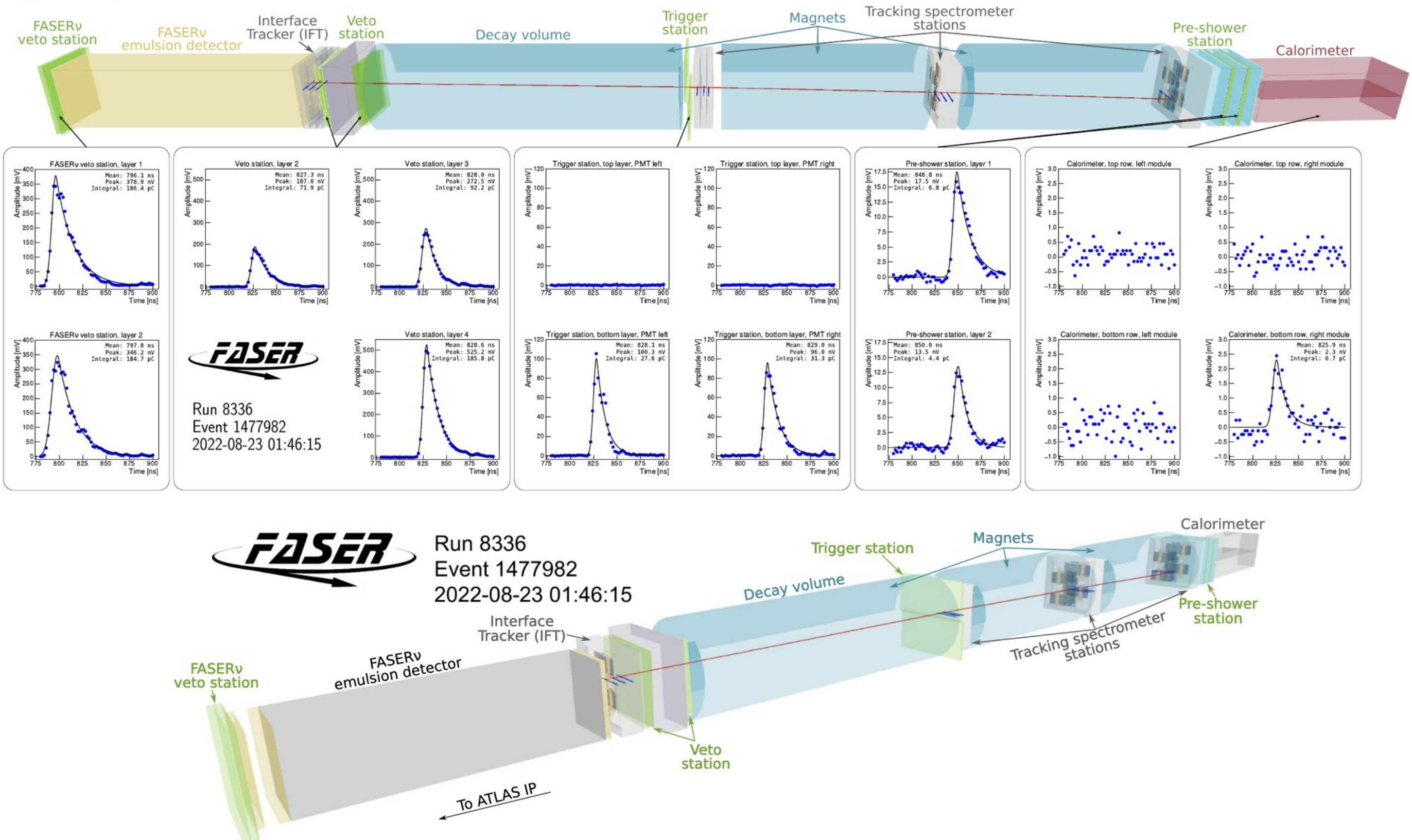


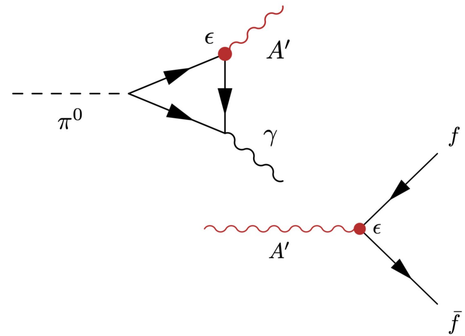
Figure 4: Collision event with a muon traversing FASER. Measured momentum of 21.9 GeV. The ATLAS interaction point is on the picture in the left direction. The detected hits in the semiconductor tracker modules are shown with blue lines and the reconstructed track is shown with a red line.

Search for Dark Photons with FASER

Dark Photon Model.

Dark photons (A’) 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

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon\, e \sum_f q_f \bar{f} \not{A}' f$$



A’ phenomenology at FASER
- MeV A’ s produced mainly in meson decays

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

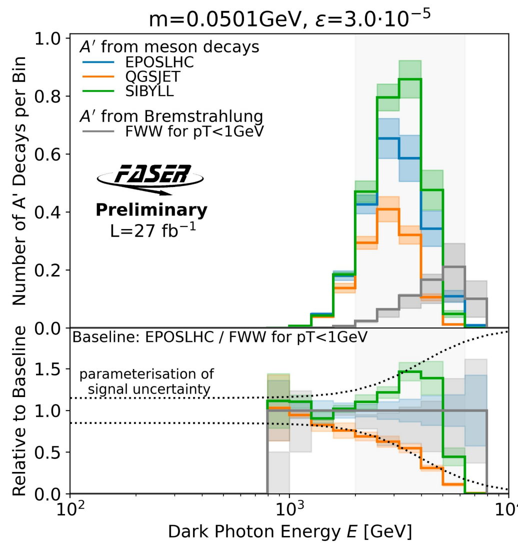
- FASER targets small ε, where A’ has long decay length

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

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

Signal simulation
- use hadron fluxes from CRMCs as input
- A’ spectra simulated using FORESEE

[FK, Trojanowski: 2105.07077]



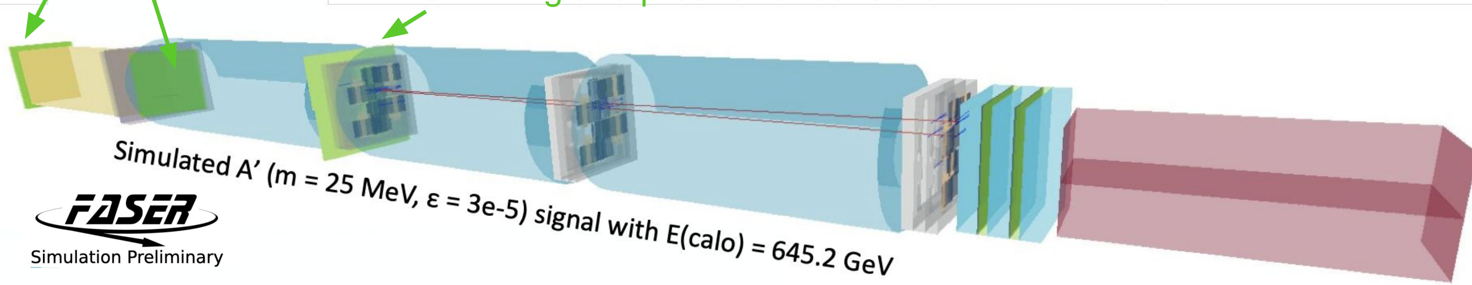
Dark Photon Analysis.

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 (< 40 pc) in any veto scintillator

3. Timing and preshower consistent with ≥2 MIPs

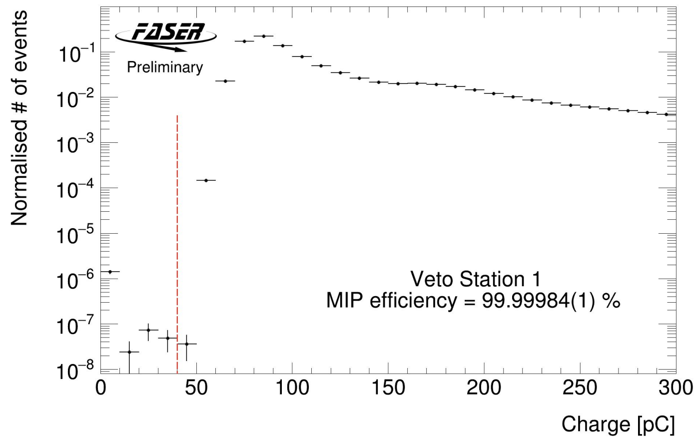


4. Exactly 2 good fiducial tracks
   p > 20 GeV and r < 95 mm
   Extrapolating to r < 95 mm at vetos

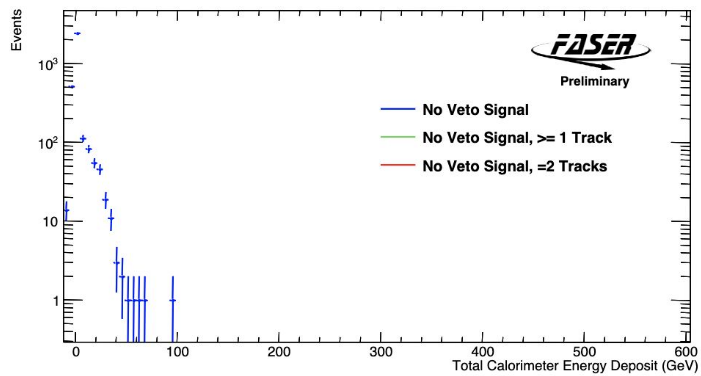
5. Calo E > 500 GeV

Backgrounds.

1. Veto inefficiency
 - measured layer-by-layer via muons with tracks pointing back to vetos
 - layer efficiency > 99.998%
 - 5 layers reduce expected 100M muons to negligible level (even before cuts)



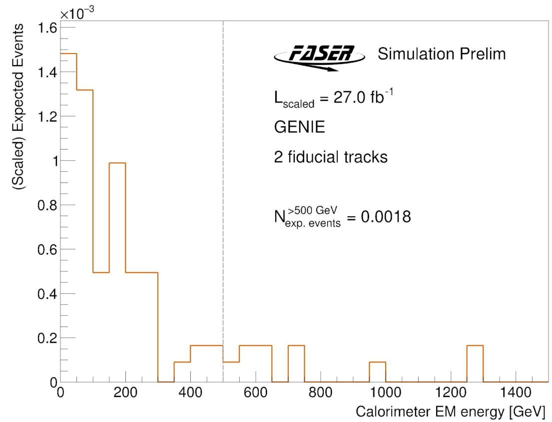
2. Non-collision backgrounds
 - cosmics measured in runs with no beam
 - near-by beam debris measured in non-colliding bunches
 - no events observed with ≥1 track or E(calo) > 500 GeV individually



Backgrounds.

3. Neutrino interactions
- primarily coming from vicinity of timing layer
- estimated from GENIE simulation (300/ab)
- uncertainties from neutrino flux & mismodelling
- predicted events with E(calo) > 500 GeV

$N = (1.8 \pm 2.4) \times 10^{-3}$

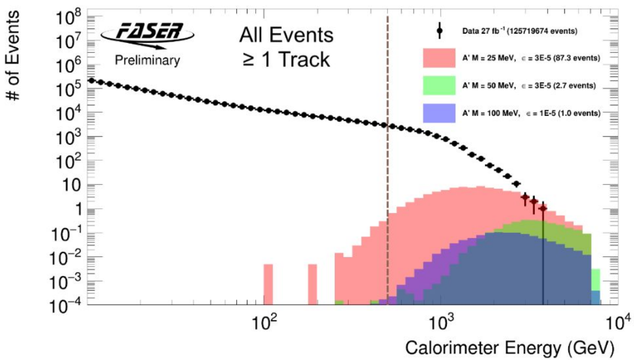


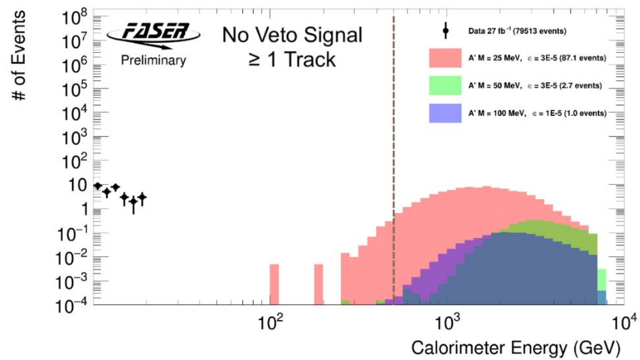
4. Neutral hadrons
- (e.g. Ks) from upstream muons interacting in rock in front of FASER
- heavily suppressed since
  * muon nearly always continues after interaction
  * has to pass through 8 interaction lengths (FASERν)
  * decay products have to leave E(calo) > 500 GeV
- estimated from lower energy events with 2/3 tracks and different veto conditions

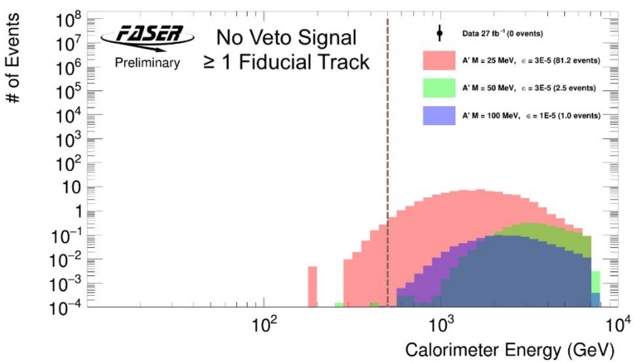
$N = (2.2 \pm 3.1) \times 10^{-4}$

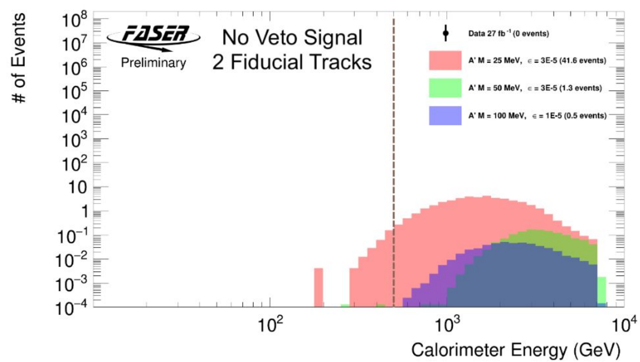
Results.

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





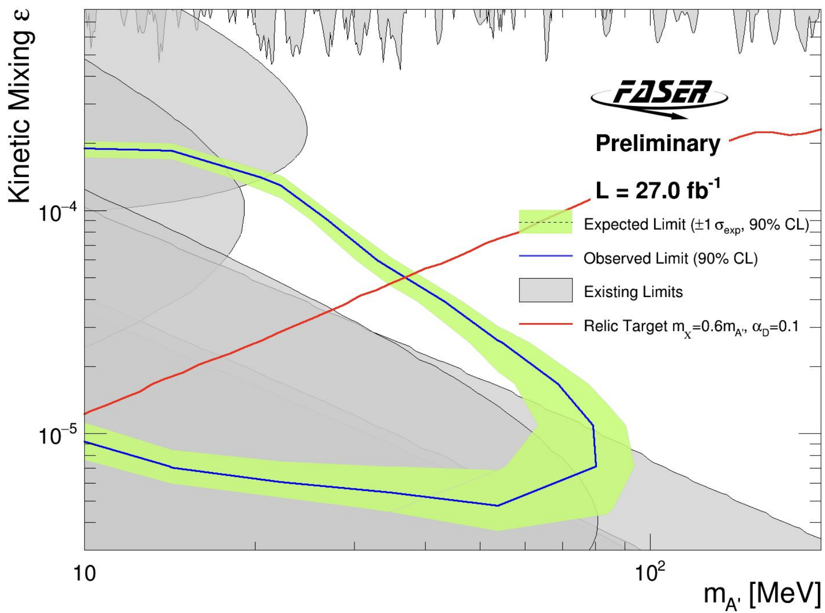




Results.

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

Probing region interesting from thermal relic target.

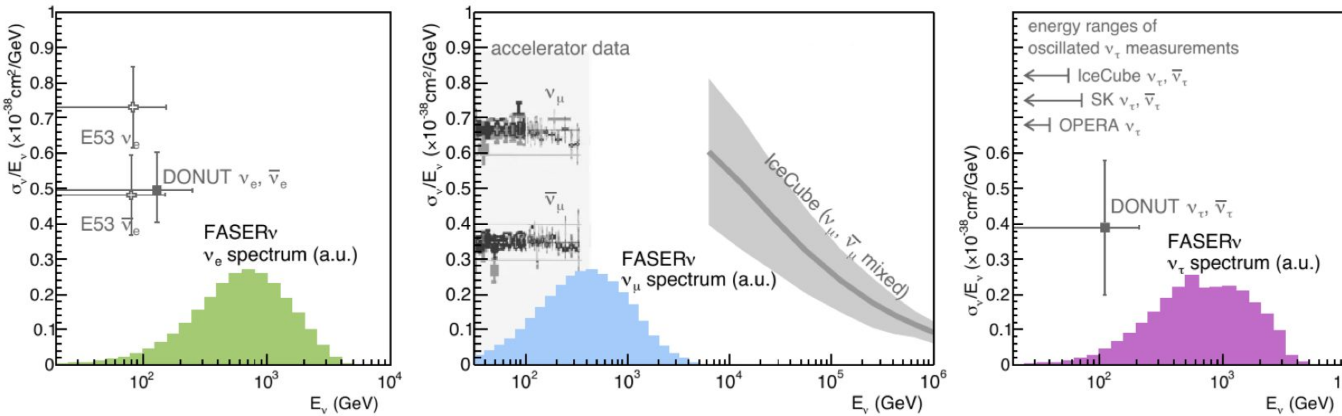


First Neutrino Observation with FASER

Collider Neutrinos.

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]



FASER can also detect CC νμ using just the spectrometer and veto systems!

Analysis.

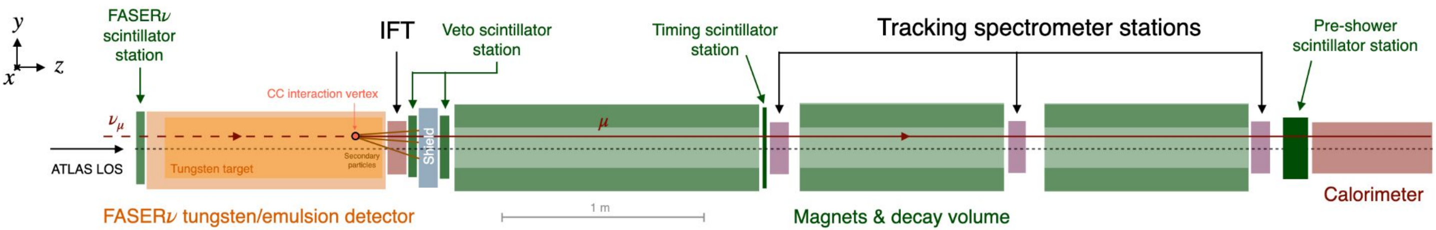
FASER can also detect CC νμ using just the spectrometer and veto systems!

[FASER, 2303.14185]

1. Collision event with good data quality

2. No signal (<40 pc) in 2 front vetos
3. Signal (>40 pC) in other 3 scintillators
4. Timing and preshower consistent with ≥1 MIP

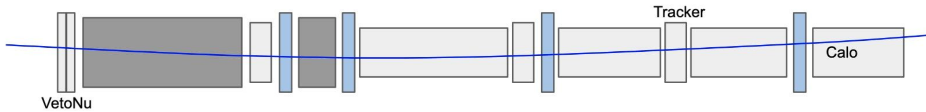
5. Exactly 1 good fiducial (r < 95 mm) track
 - p > 100 GeV and θ < 25 mrad
 - extrapolating to r < 120 mm in front veto



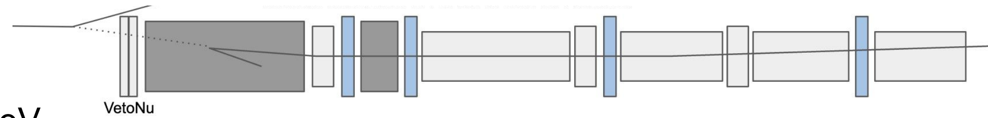
expect 151 ± 41 events (using CRMC + Particle Transport + GENIE)
- uncertainty from DPMJET vs SIBYLL
- no experimental errors
- currently not trying to measure cross section

Backgrounds.

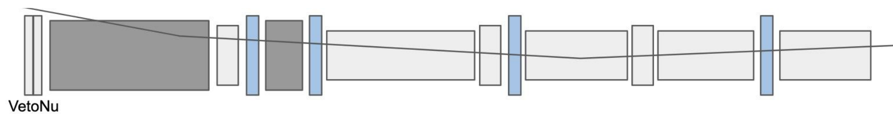
1. front veto inefficiency
 - muon passes
   front veto undetected
 - background found negligible due to very high veto efficiency



2. Neutral hadrons
 - simulation predicts ~300
   neutral hadrons with E>100 GeV
 - most accompanied by μ but conservatively assume missed
 - estimate fraction of these passing event selection
 - most are absorbed in tungsten with no high-momentum track
 - pedict N = 0.11 ± 0.06 events



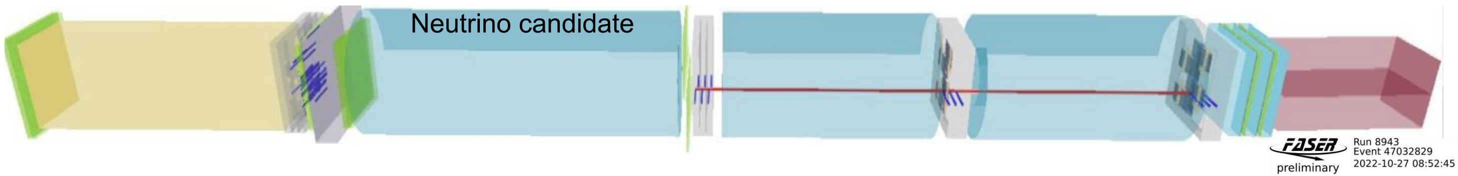
3. Scattered muons
 - estimated using extrapolation
   from sideband region
 - predict N = 0.08 ± 1.83 events
 - uncertainty from varying selection/extrapolation procedure

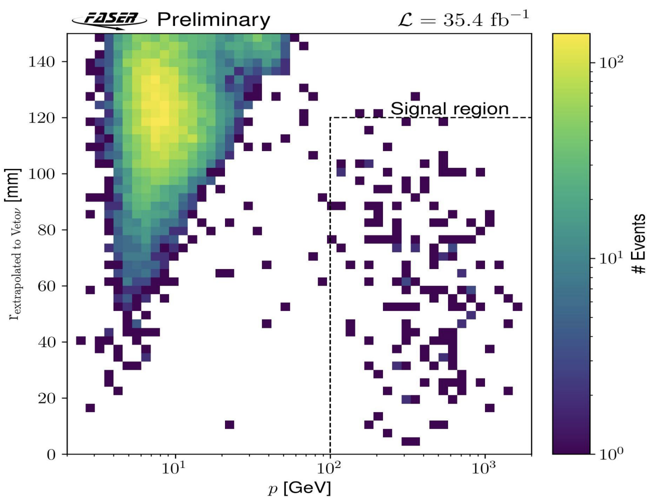


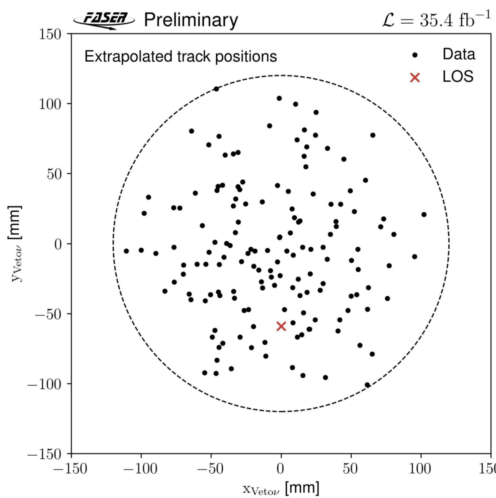
Results.

Upon unblinding find 153 events with no veto signal

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



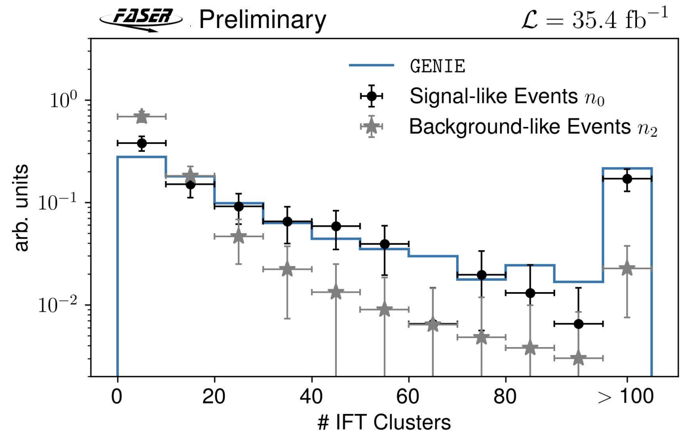


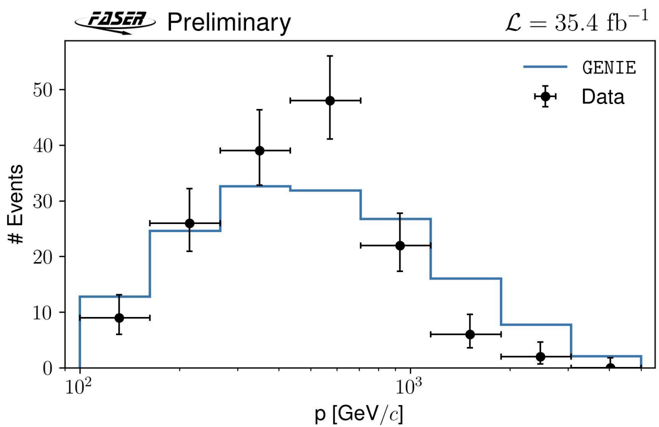


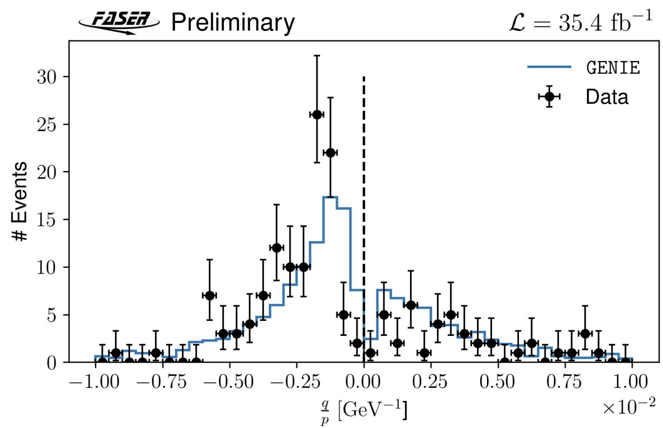
Neutrino Characteristics.

candidate neutrino events match expectation
- high occupancy in front tracker station
- most events have high μ momentum
- more νμ than anti-νμ

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

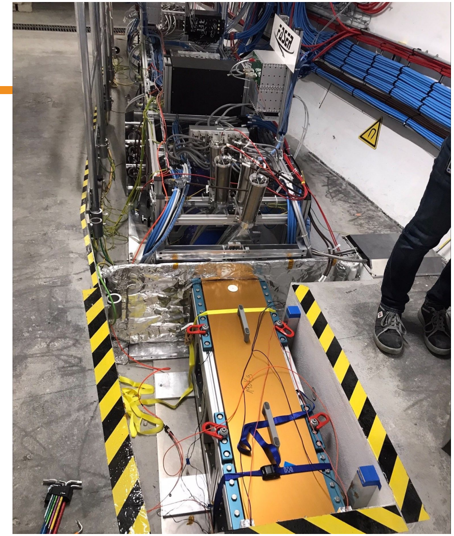






FASERν Neutrino Detector

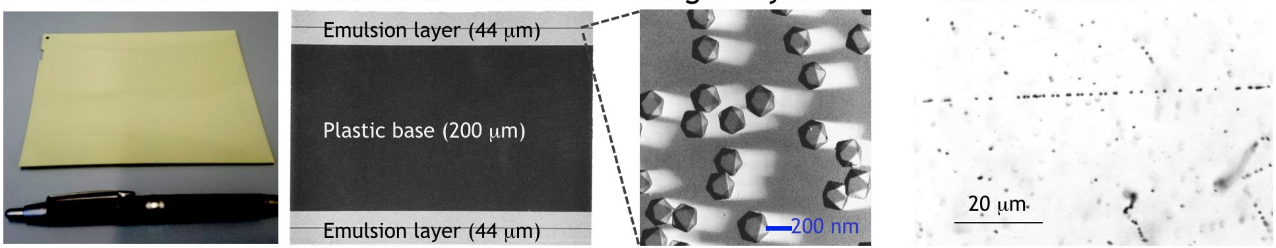
FASERν.



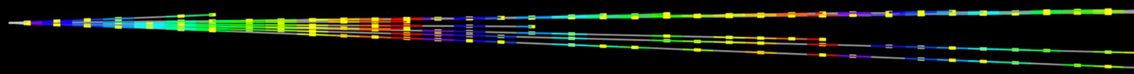
FASERν neutrino detector in front of FASER
- 25cm x 25cm x 1.3m, 1.2 ton mass
- expect 10000 neutrinos during LHC Run 3

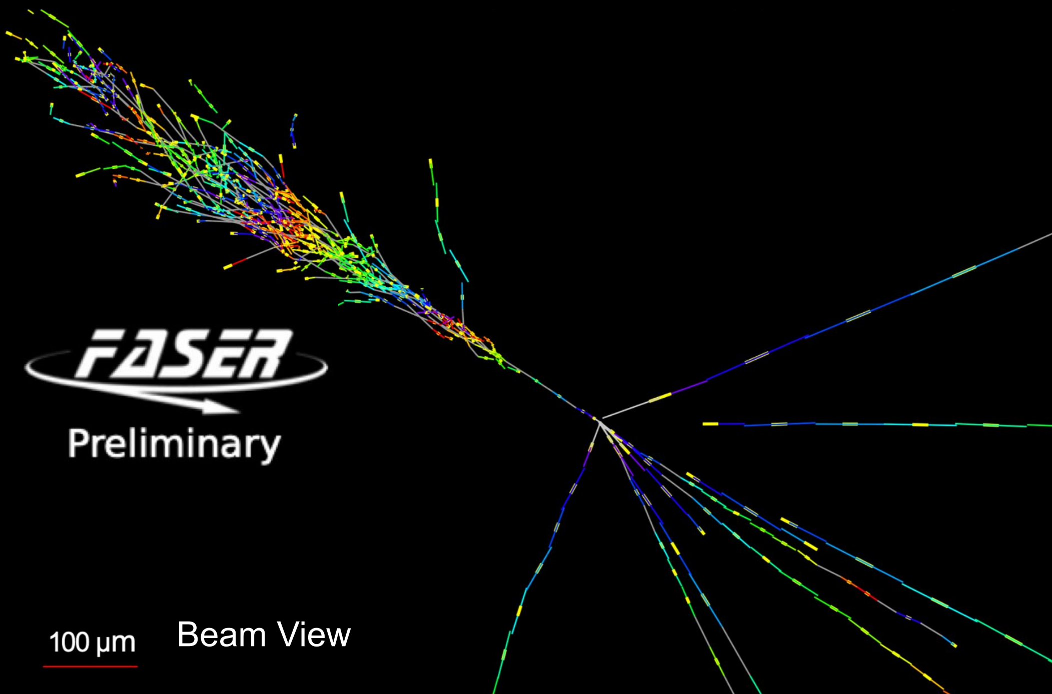
Emulsion detectors technology
- used by CHORUS, DONUT, OPERA
- 1000 emulsion films interleaved with 1mm tungsten plates
- provide 3D image of interaction with sub-μm resolution
- global reconstruction with the FASER detector possible

Emulsion film | Cross-sectional view | AgBr crystal | Track in emulsion film



Highly ν_e-like CC Candidate Event.





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 FAESRν emulsion detector data underway

Connection to Astroparticle Physics

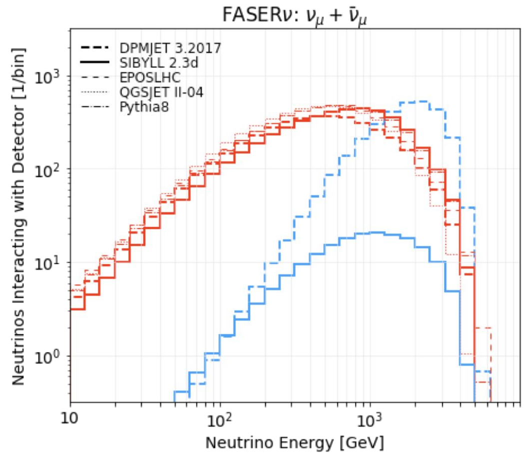
Neutrino Flux Simulation.

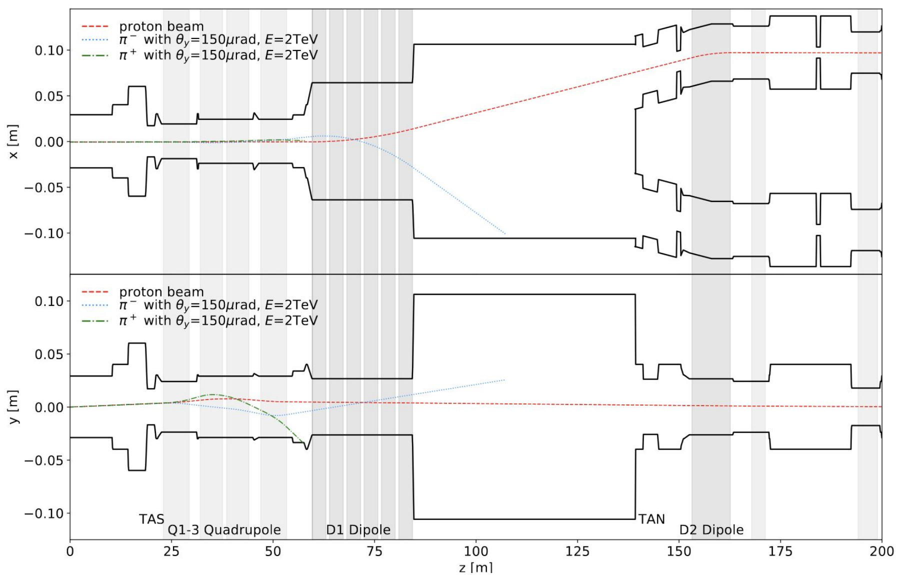
simulation and analysis

- flux + GENIE + Geant4 + cuts
- no experimental uncertainties included at the moment
- presented analysis was not a flux measurement

So one cannot really say anything, except that it roughly matches expectations.

- follow-up flux / cross section measurement planned



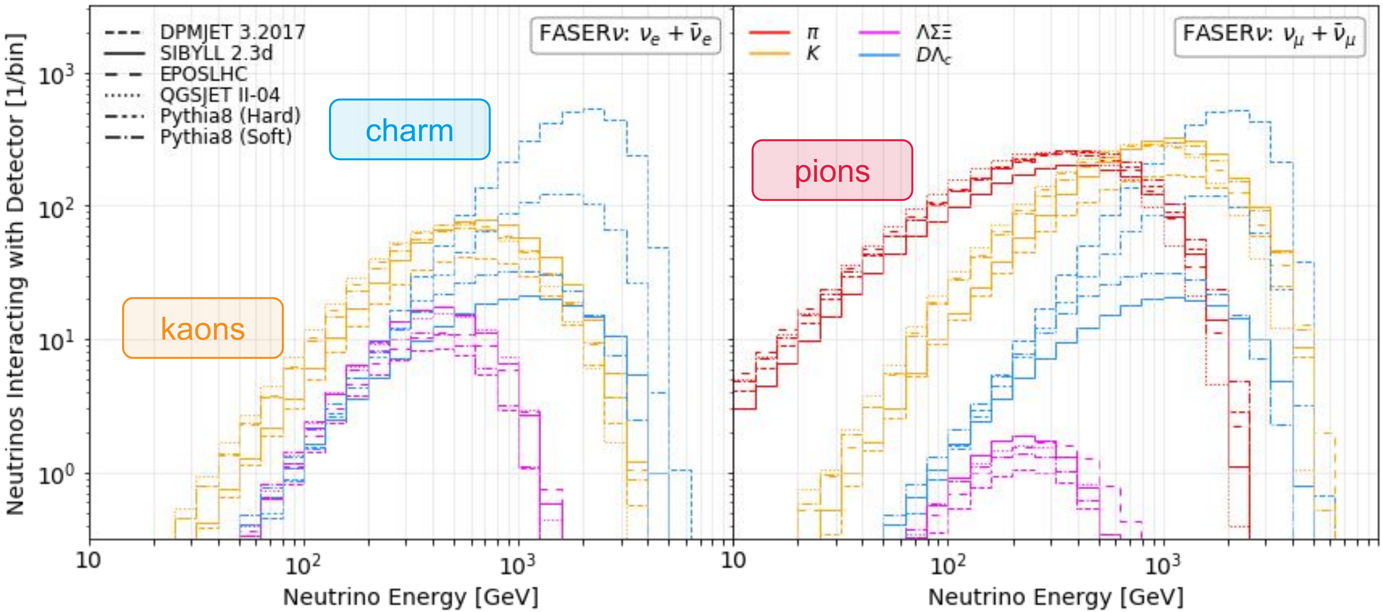


neutrino flux simulation

- introduced in 2105.08270
- hadrons from CRMC generators (SIBYLL and DPMJET)
- propagation of light hadrons through LHC infrastructure
- hadron decays into neutrinos (following Pythia)

Neutrino Flux Origin.

Where do the LHC neutrinos come from?



LHC neutrinos = probe of forward particle production

Neutrino Fluxes and Muon Puzzle.

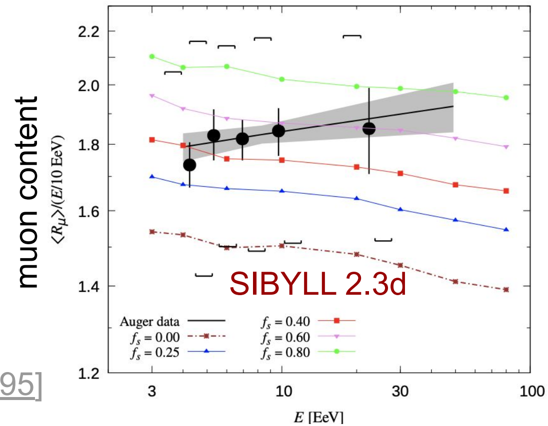
cosmic ray muon puzzle: observed excess of muons compared to predictions from hadronic interaction models

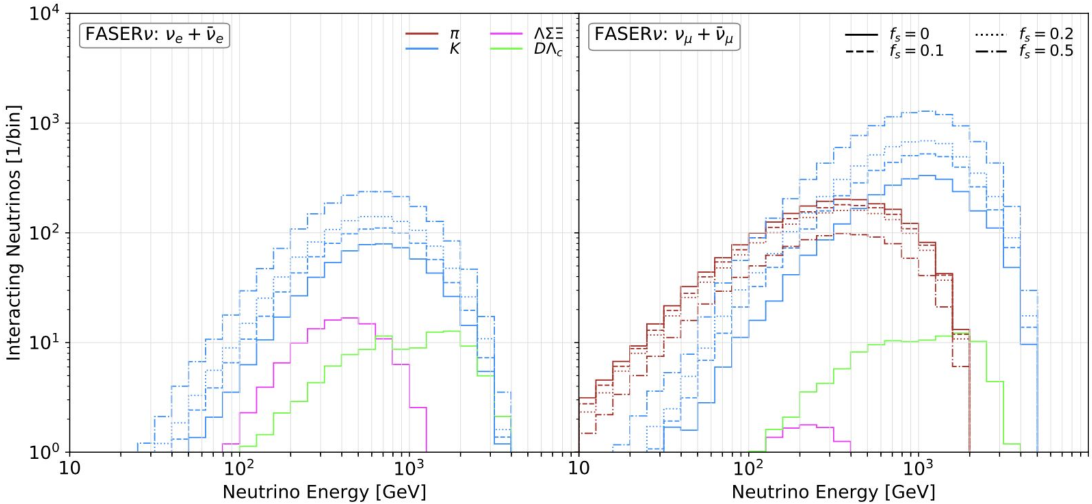
solutions: extensive studies suggest that an enhanced forward strangeness could explain the discrepancy

[Albrecht et al, 2105.06148]

toy model: turn a fraction f_s of forward pions into kaons: solves muon puzzle and testable at FASER

[Anchordoqui, Garcia Canal, FK, Sciutto, Soriano, 2202.03095]





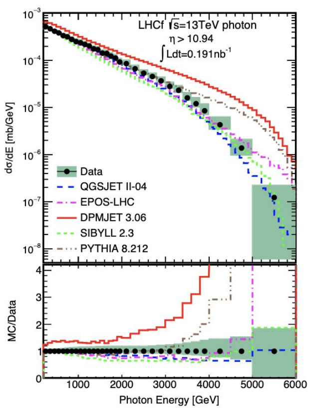
Predictions with Pythia.

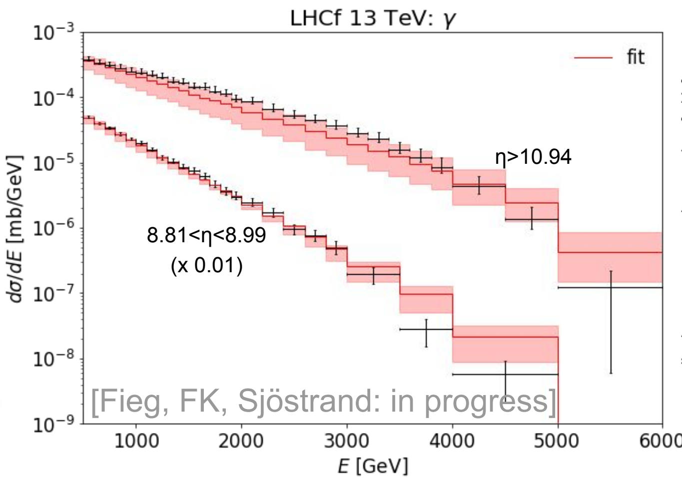
Multi-purpose MC generators can also be used to simulate forward particle production

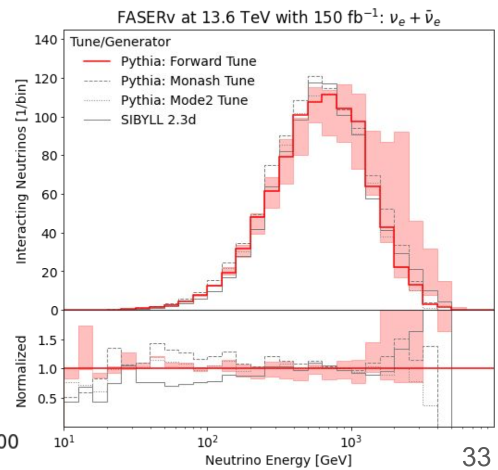
Default version of Pythia overestimates forward photon production compared to LHCf data

Dedicated forward physics tune:
- modify modelling of beam remnant fragmentation
- tune fragmentation parameters and primordial kT to LHCf data

Parameterization of flux uncertainties using tuning variations (mainly kT).



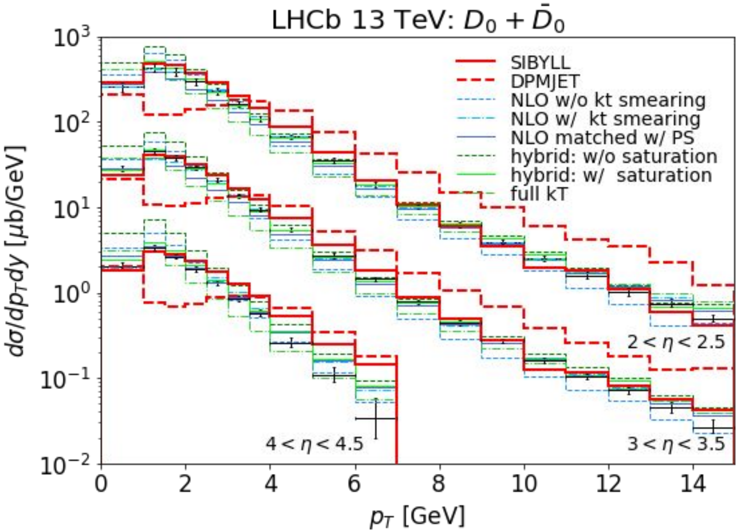


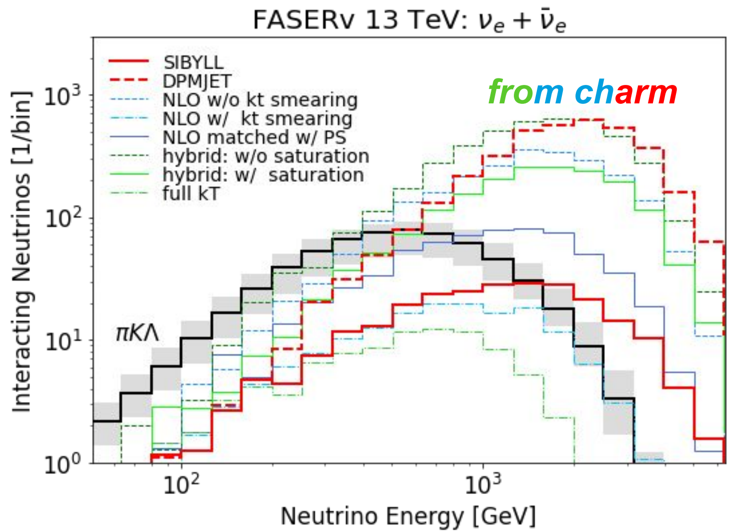


Forward Charm Production.

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

Predictions from 5 theory groups, using using different approaches on physics modeling

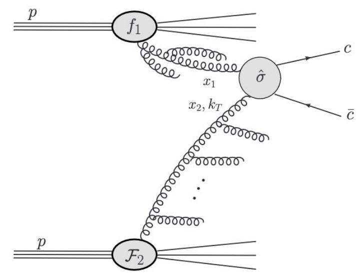


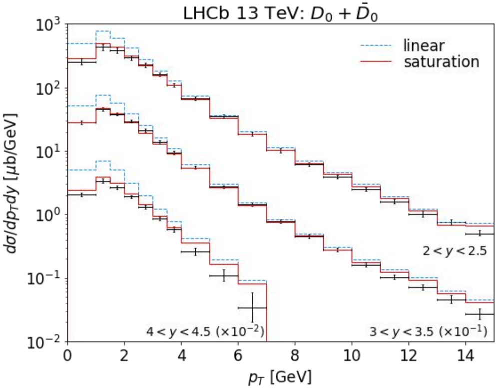


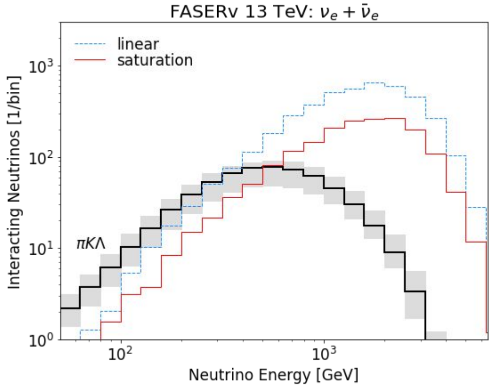
FASER will be able to distinguish predictions that LHCb cannot.

Forward Charm Production.

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

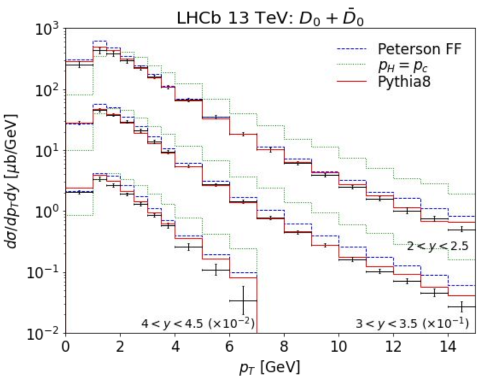


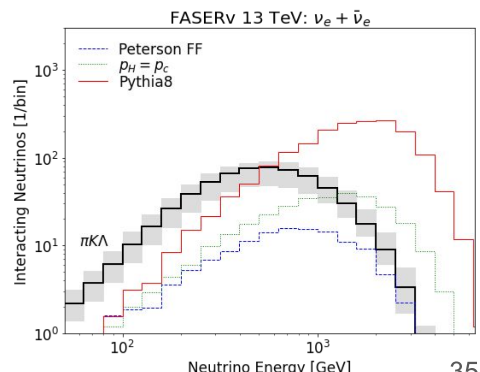




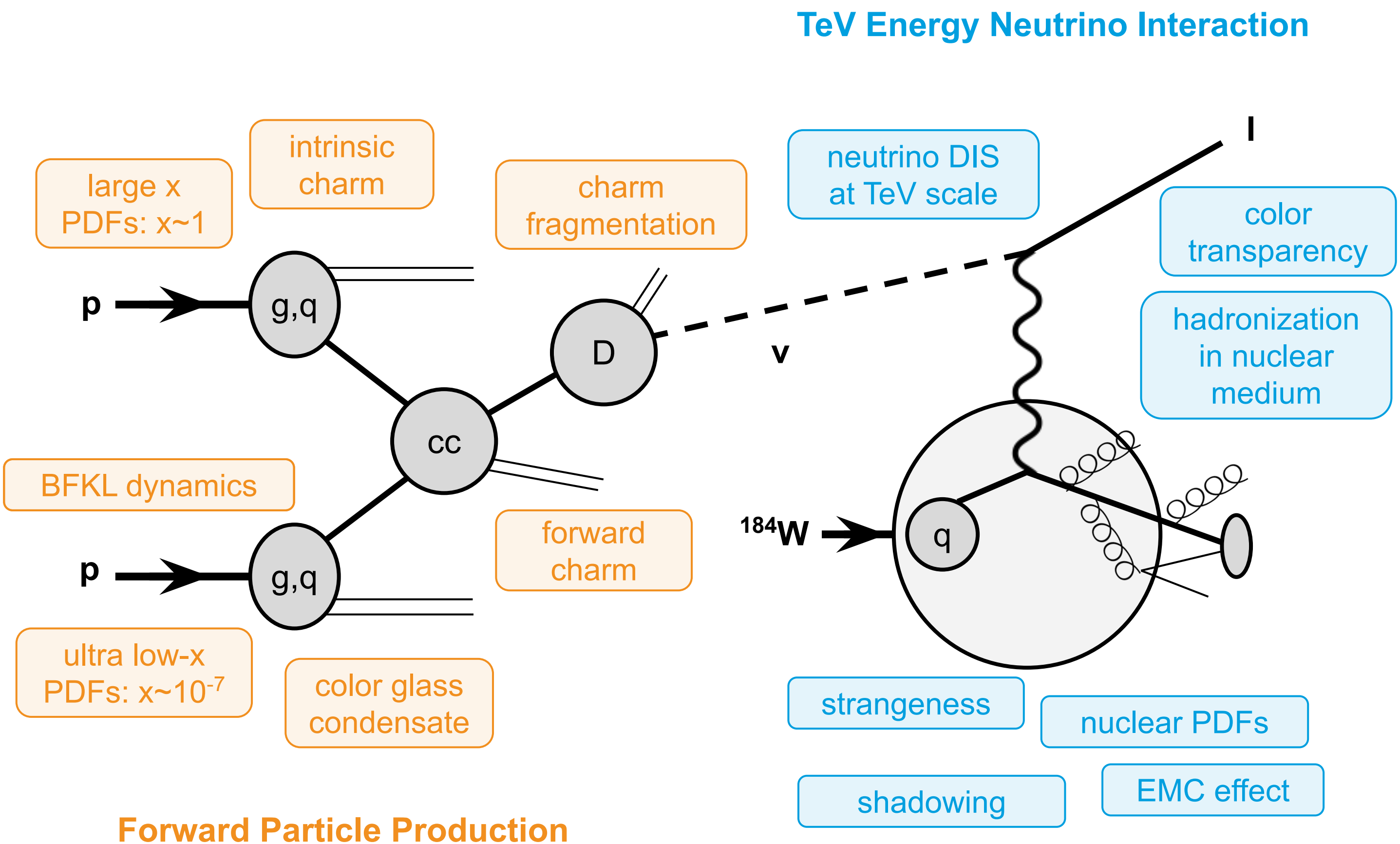
study of **gluon saturation** at low-x

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





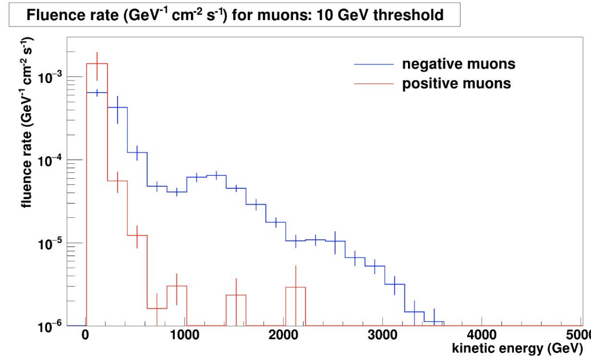
Collider Neutrino Physics.



LHC Muon Measurements

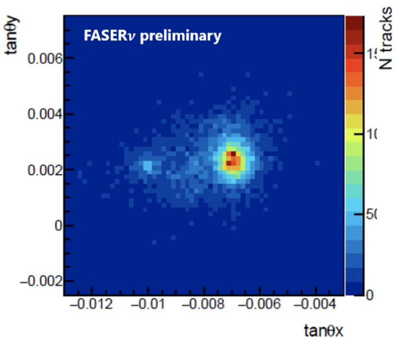
Data on Muons.

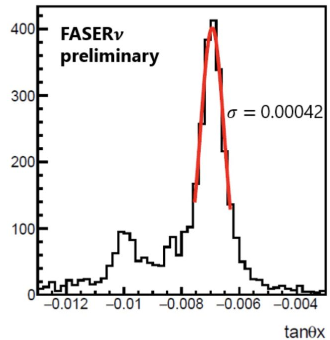
FASER spectrometer:
muon charge and energy spectrum



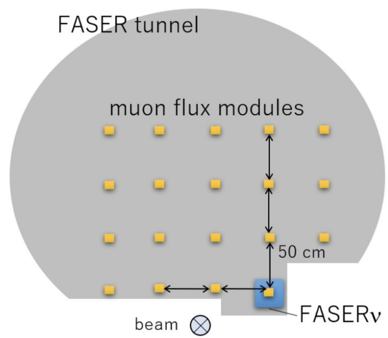
[FLUKA Simulation, 1812.09139]

[Jamie Boyd, FPF5 talk]





FASERν: precision angular distribution around LOS



flux modules: spatial and angular distribution away from beam axis

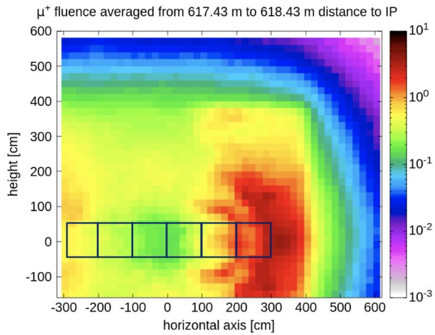
Muon Simulation.

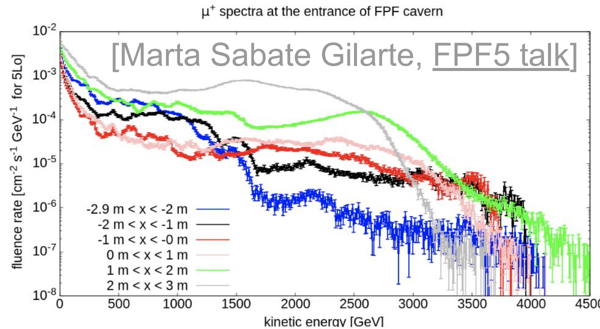
forward muons originate from various sources: hadron decay, secondary interactions

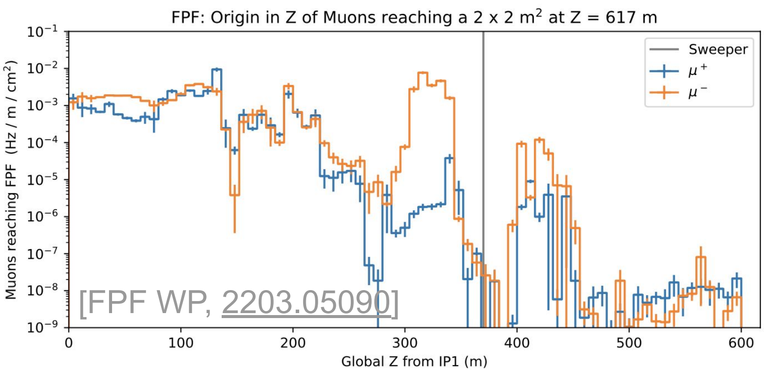
full simulation of particle transport through LHC needed

FLUKA simulation (by CERN EN-STI team)

fluences of mu+ and mu- MC sample available







BDSIM simulation (by Laurie Nevay)

full trajectory and event history of muons

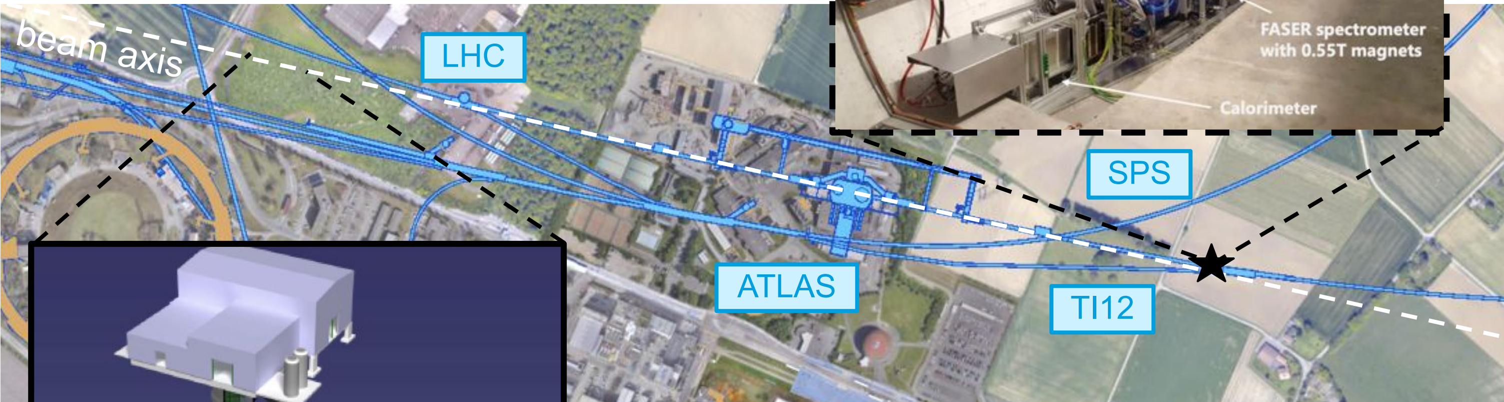
Animation of Muon Flux Origin

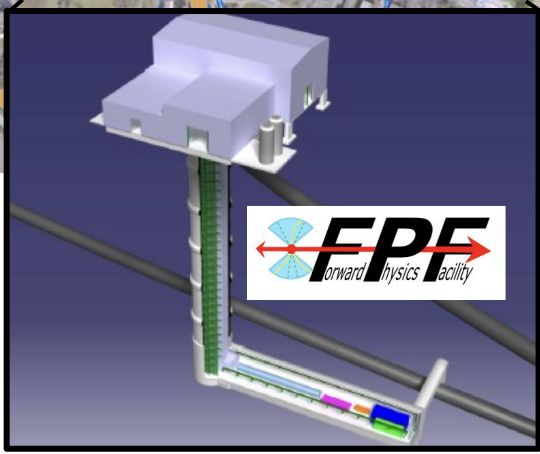
The Forward Physics Facility

The Forward Physics Facility.

FASER just started operation with beginning LHC Run 3

few 10^3 neutrinos





proposal to create a dedicated **Forward Physics Facility** for the HL-LHC

few 10^6 neutrinos

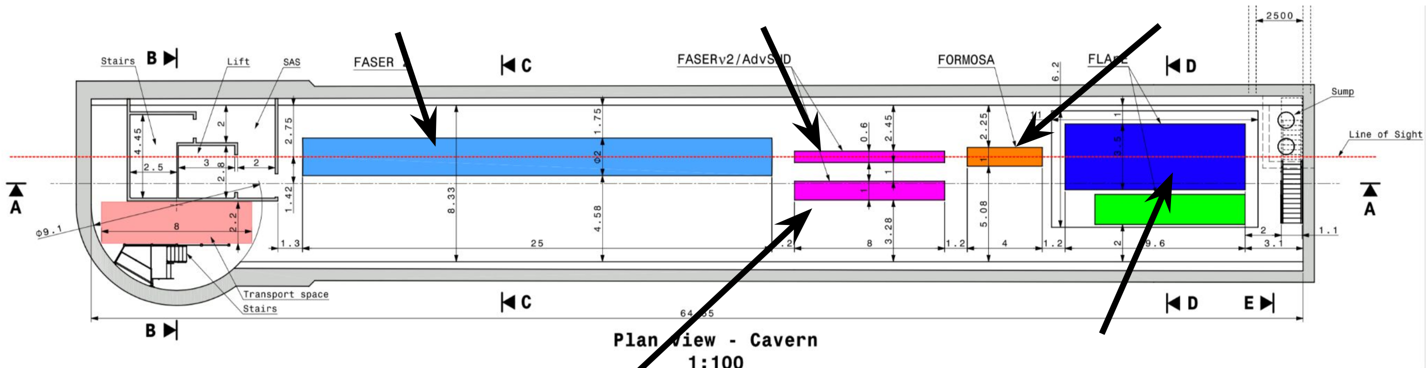
FPF Experiments.

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

FPF Documentation.

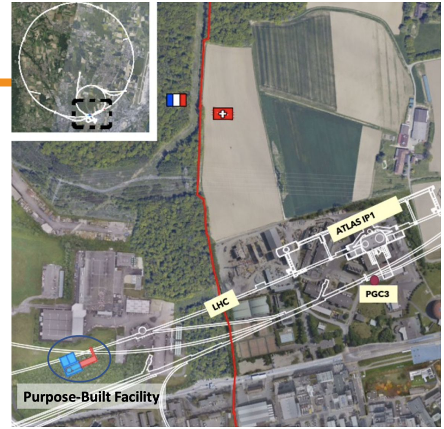
FPF workshop series:
FPF1, FPF2, FPF3, FPF4,
FPF5, FPF6 (June 8/9)

FPF Paper:
2109.10905
~75 pages, ~80 authors

Snowmass Whitepaper:
2203.05090
~450 pages, ~250 authors

Recent Summary:
FPF Update

FPF Facility.

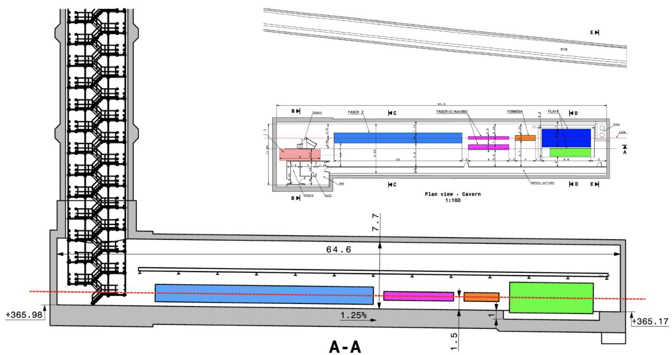


site selection completed: several sites considered by the CERN civil engineering team preferred location on CERN land in France, 620-685 m west of the ATLAS IP

65 m-long, 8 m-wide cavern:
10 m from the LHC and disconnected from it

preliminary (class 4) cost estimate:
25 MCHF (CE) + 13 MCHF (services)

site investigation study was performed
(take core at the FPF site)

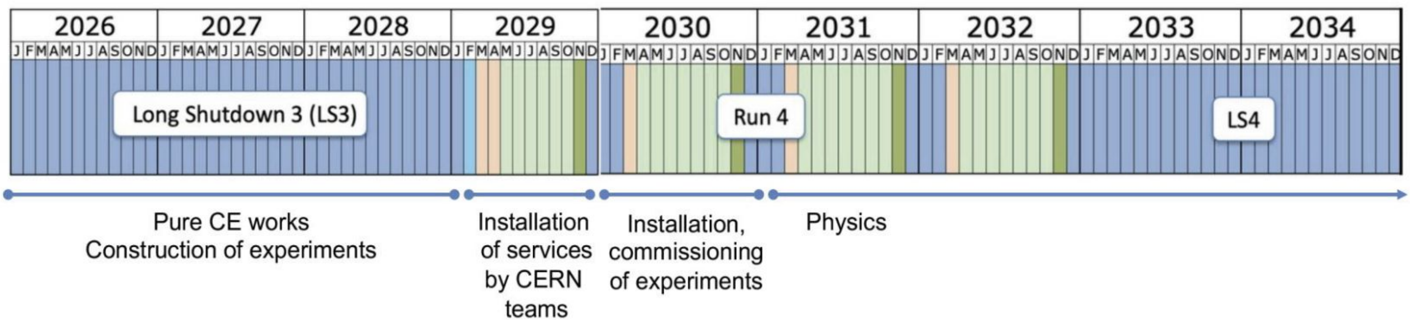


FPF Timeline.

radiation protection studies indicate that there is no danger from working in the FPF while the LHC is running

vibration studies indicate that construction of the FPF, installation of services, experiments, will not interfere with LHC operations

envisioned timeline presented at Chamonix (Jan 2022)

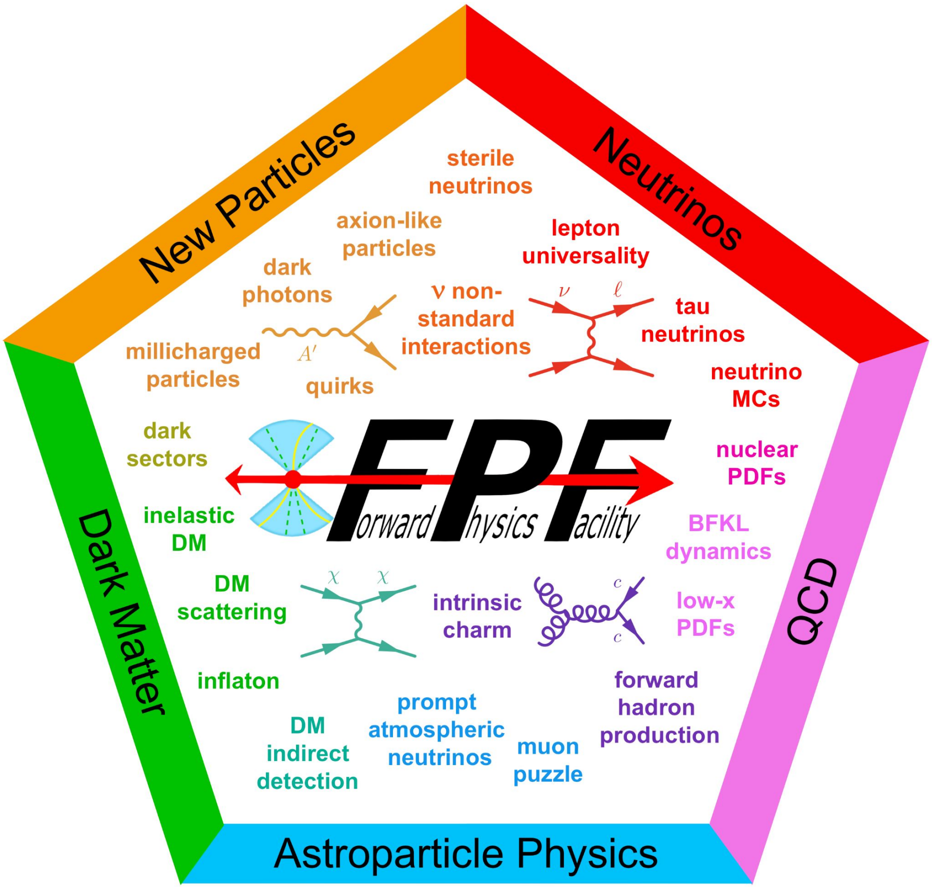


FPF Neutrino Fluxes.

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

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

FPF: Physics Summary.



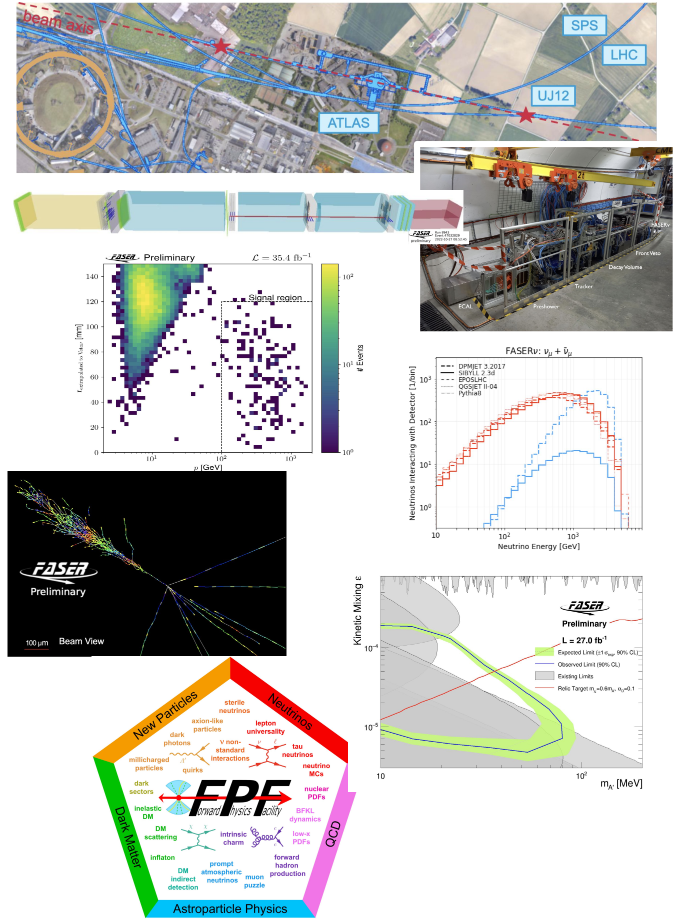
Summary.

FASER is a dedicated experiment to search for light LLPs and detect high energy neutrinos at the LHC.

FASER has recently observed the collider neutrinos for the first time!

Broad physics potential associated with collider neutrinos.

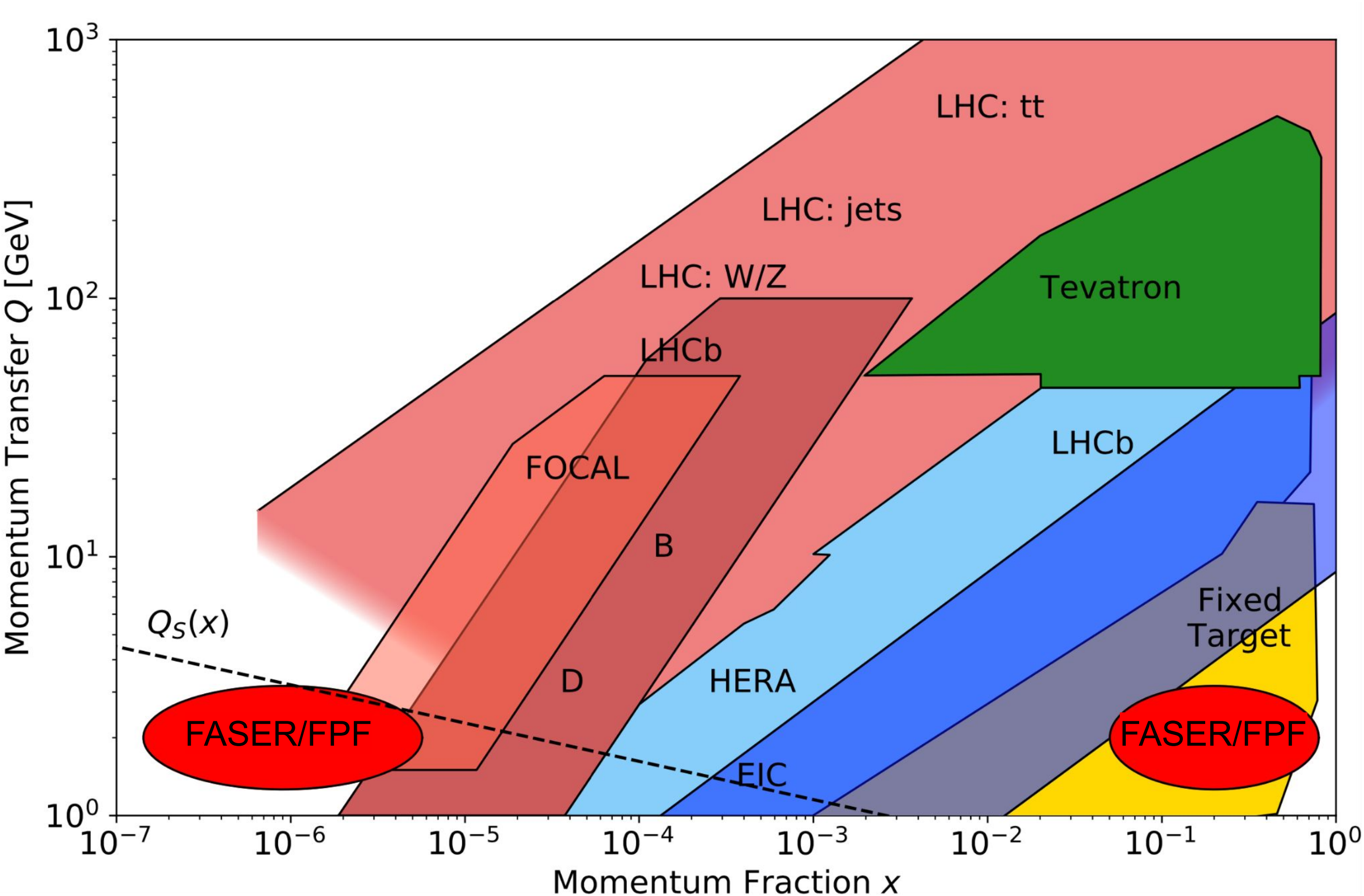
The FPF is proposed to continue this program during the HL LHC era and significantly extent the LHC’s physics programme.



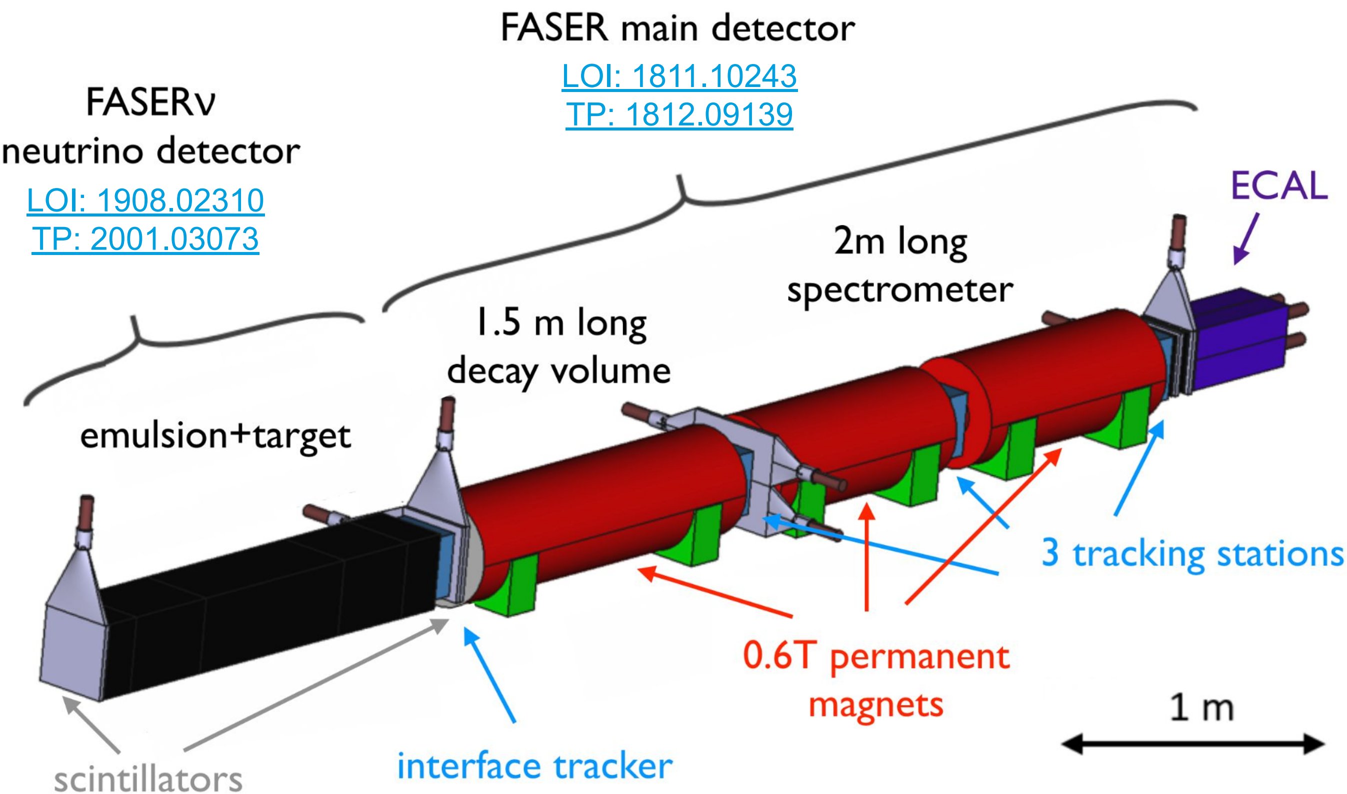
For questions and comments, please contact me via felix.kling@desy.de

Backup

Collider Neutrino Physics.



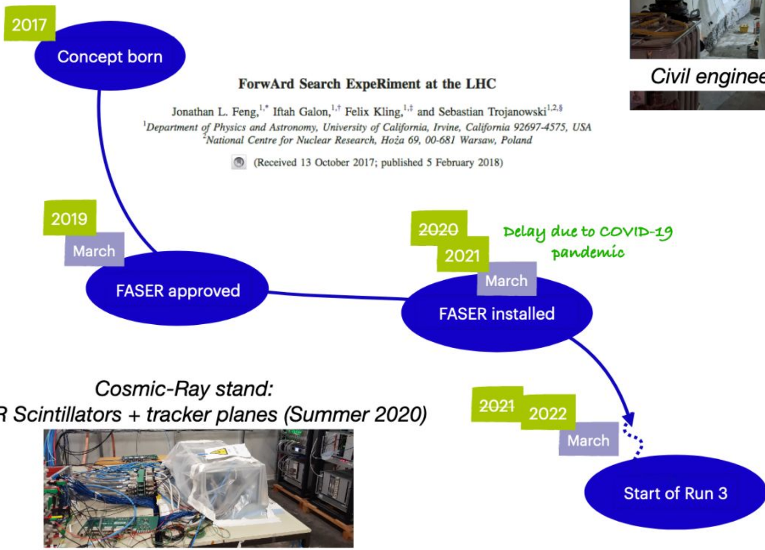
FASER Detector.



FASER Construction.

A snapshot

The challenge: Short time scale!



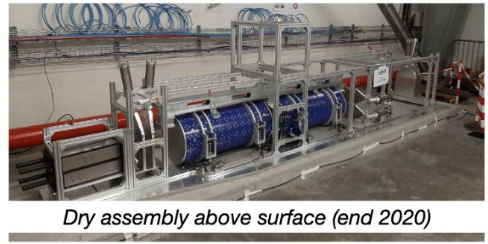
ForwArd Search ExpeRiment at the LHC

Jonathan L. Feng,[1,*] Iftah Galon,[1,†] Felix Kling,[1,‡] and Sebastian Trojanowski[1,2,§]
[1]*Department of Physics and Astronomy, University of California, Irvine, California 92697-4575, USA*
[2]*National Centre for Nuclear Research, Hoża 69, 00-681 Warsaw, Poland*

(Received 13 October 2017; published 5 February 2018)

Cosmic-Ray stand:
FASER Scintillators + tracker planes (Summer 2020)

Civil engineering (2019)



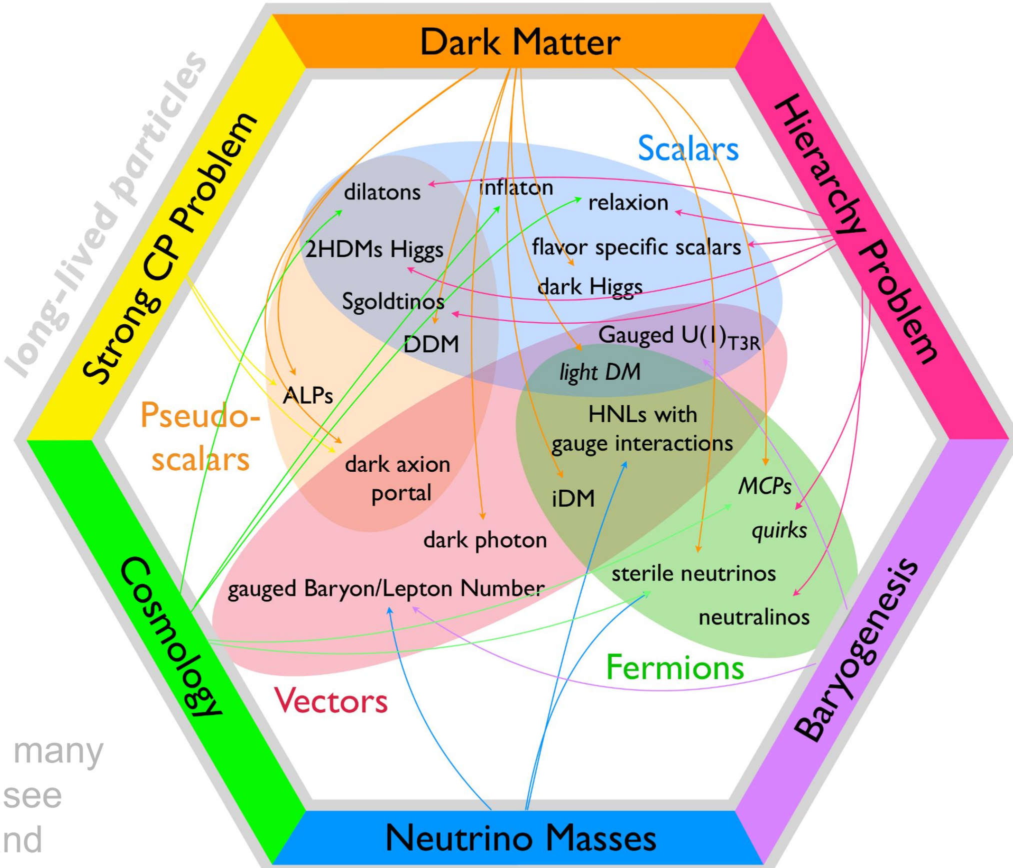
Dry assembly above surface (end 2020)

Installation in tunnel (March 2021)

Trigger	Rate (Hz)
Veto scintillator station	3.5
Timing scintillator station	10
Pre-shower scintillator station	0.25
Calorimeter	0.25
Random	1
Total rate	15

2021 in tunnel: 125 Million cosmic ray/noise induced events collected

Long-Lived Particles.

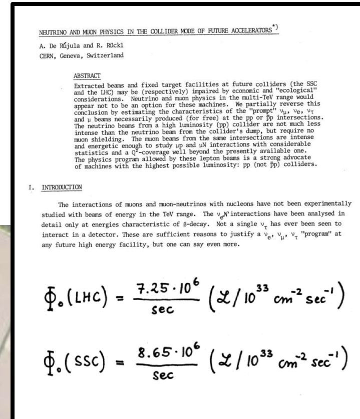


For details on many more models see [1811.12522](1811.12522) and [2203.05090](2203.05090).

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

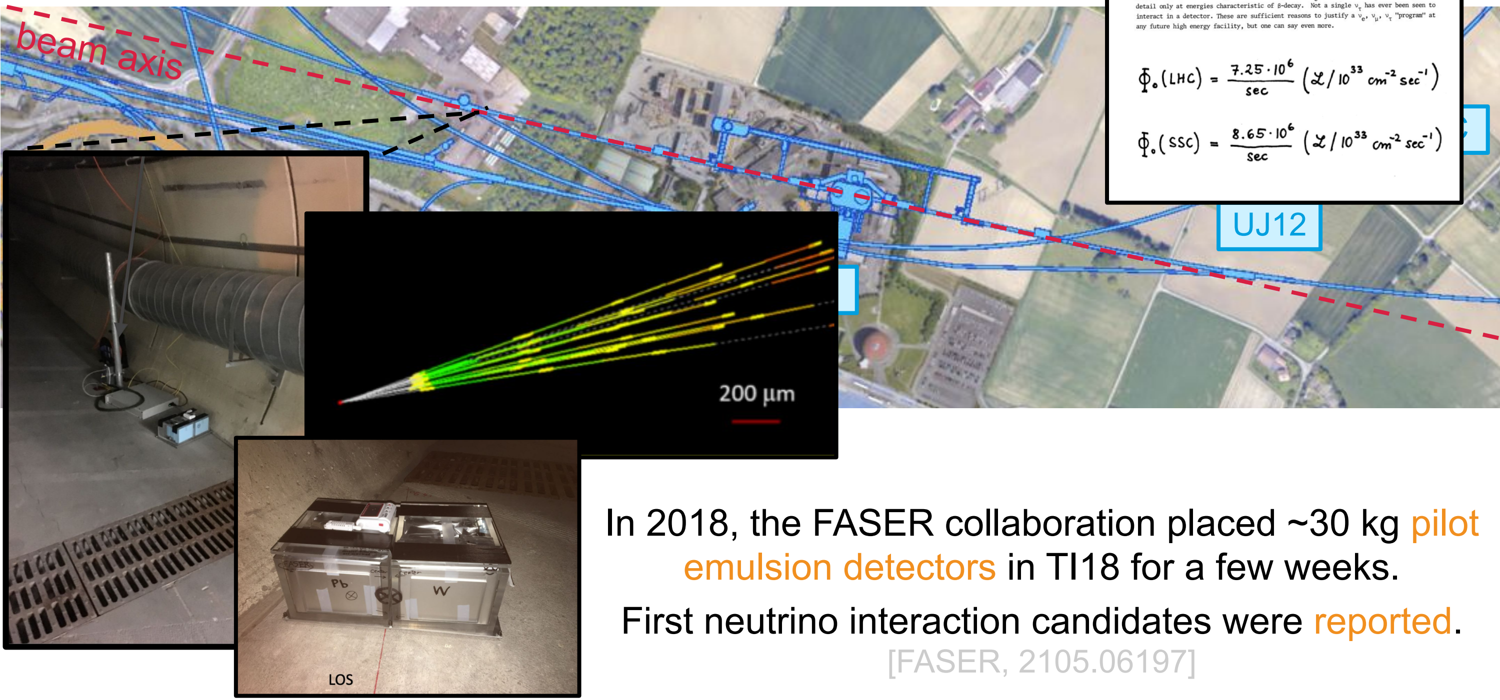
Extracted beams and fixed target facilities at future colliders (the SSC and the LHC) may be (respectively) impaired by economic and "ecological" considerations. Neutrino and muon physics in the multi-TeV range would appear not to be an option for these machines. We partially reverse this conclusion 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.

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

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



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

First neutrino interaction candidates were reported.

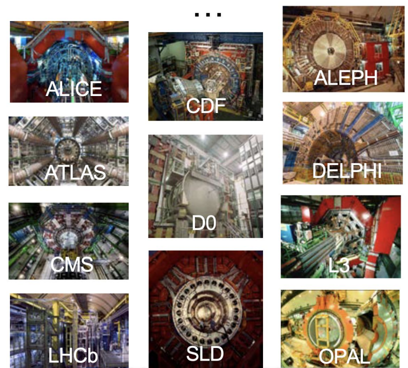
[FASER, 2105.06197]

Neutrinos at the LHC.

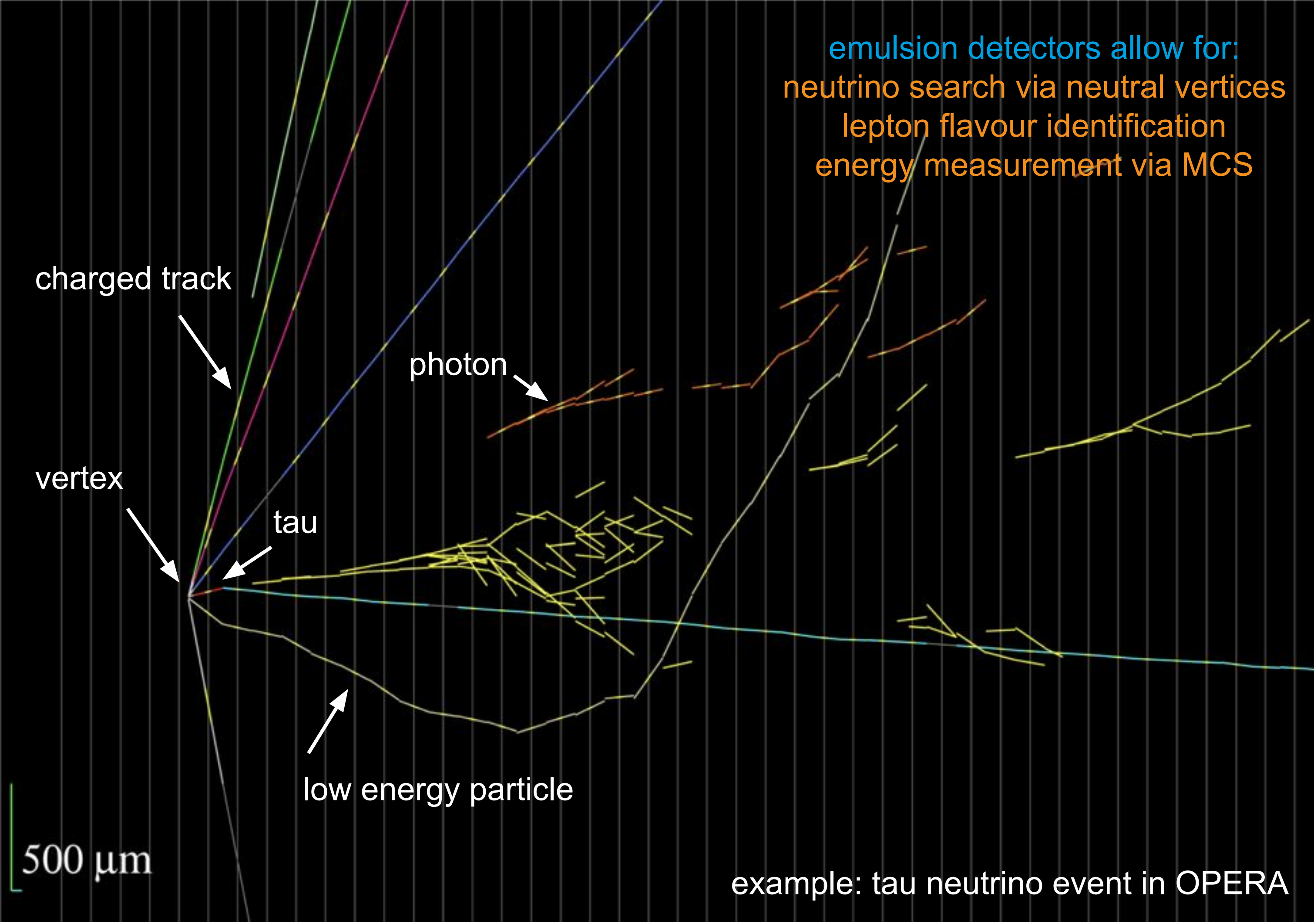
FASER Pilot Detector

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

6 neutrino candidates



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

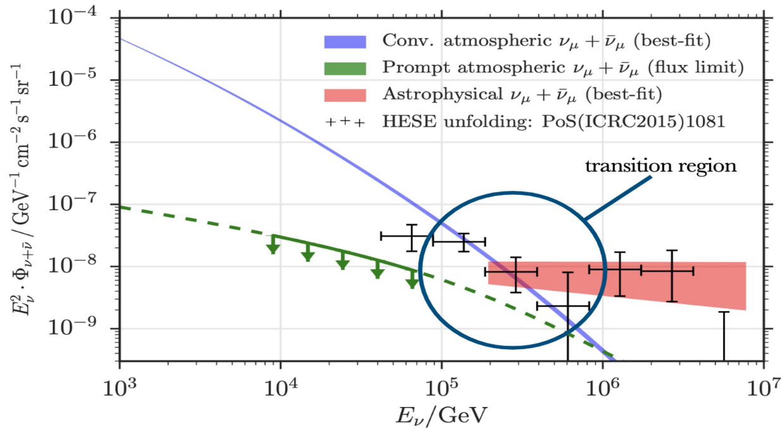

emulsion detectors allow for:
neutrino search via neutral vertices
lepton flavour identification
energy measurement via MCS
charged track
photon
vertex
tau
low energy particle
500 μm
example: tau neutrino event in OPERA

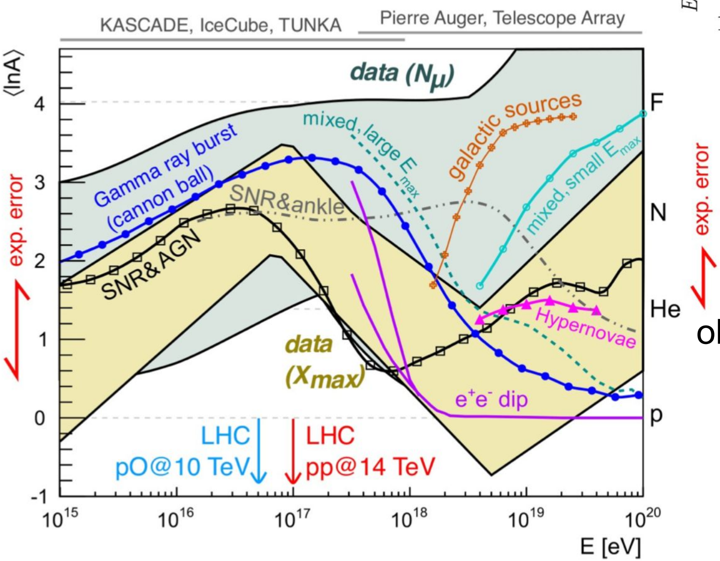
Application in Astroparticle Physics.

forward charm production at the LHC

↓

constraints on prompt atmospheric neutrino flux at IceCube



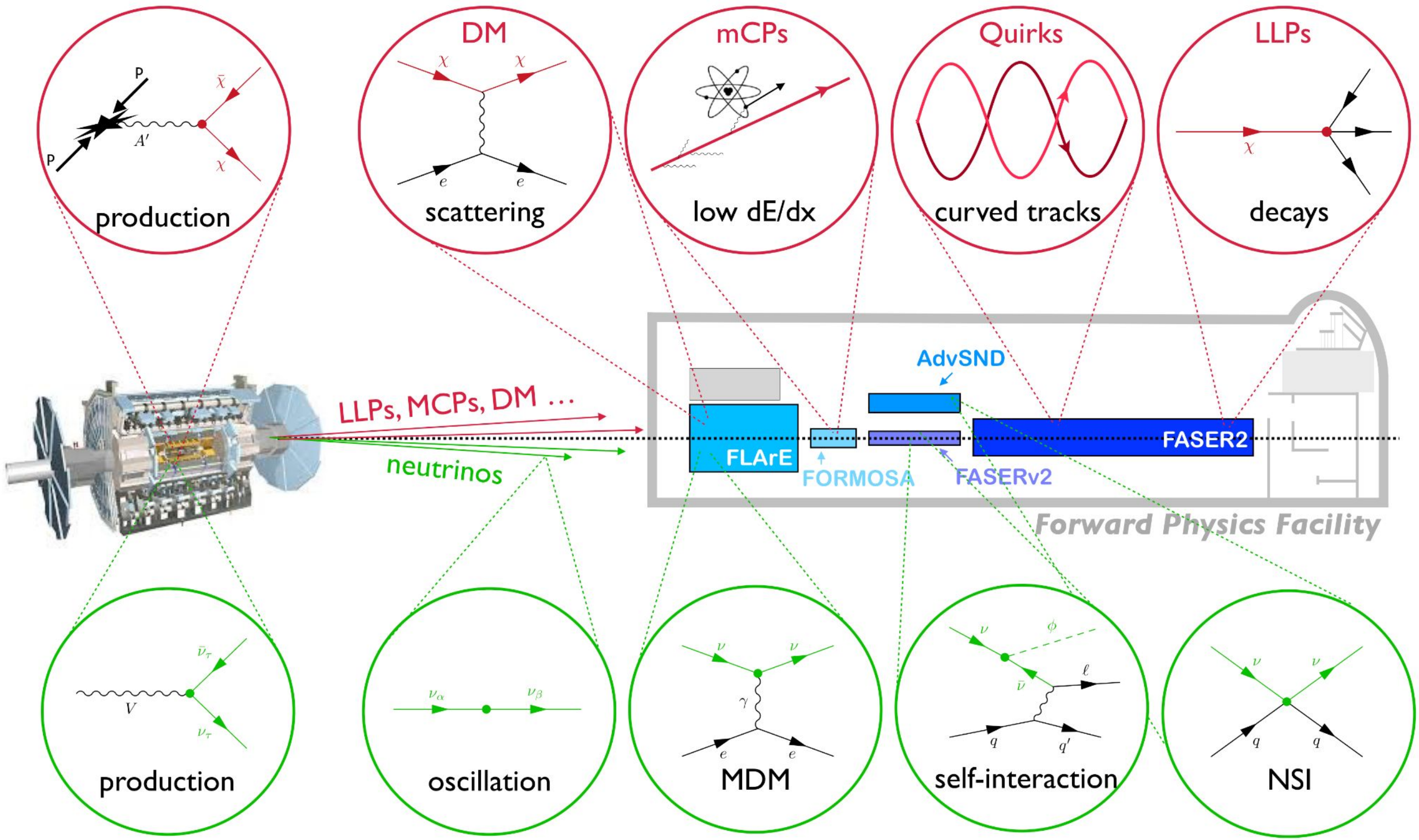


Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

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

forward pion/kaons fluxes will provide crucial input

FPF: BSM Physics.

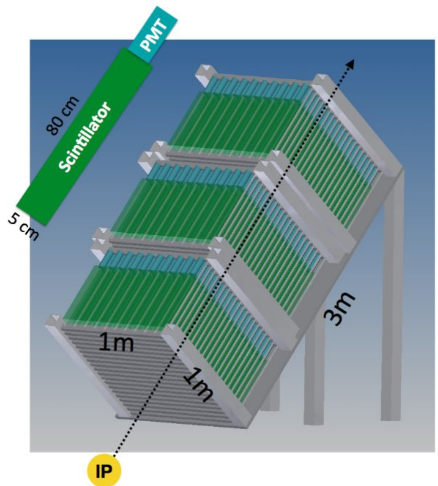


FPF: BSM Physics.

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.



milliQan detector: 1607.04669