FIRST FASER PHYSICS RESULTS
AND
THE FORWARD PHYSICS FACILITY

Jonathan Feng, UC Irvine

on behalf of the FASER Collaboration and the FPF Working Groups

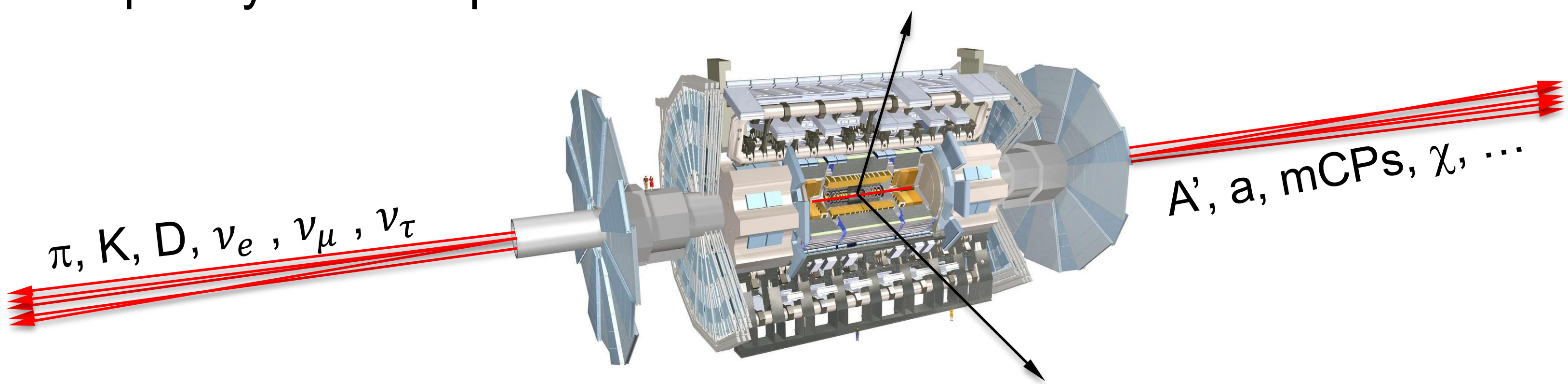
Aspen Winter Conference, 27 March 2023

LOOKING FORWARD

- In the last few years, we've increasingly realized that LHC detectors are beautifully optimized to discover heavy particles, but not light particles.

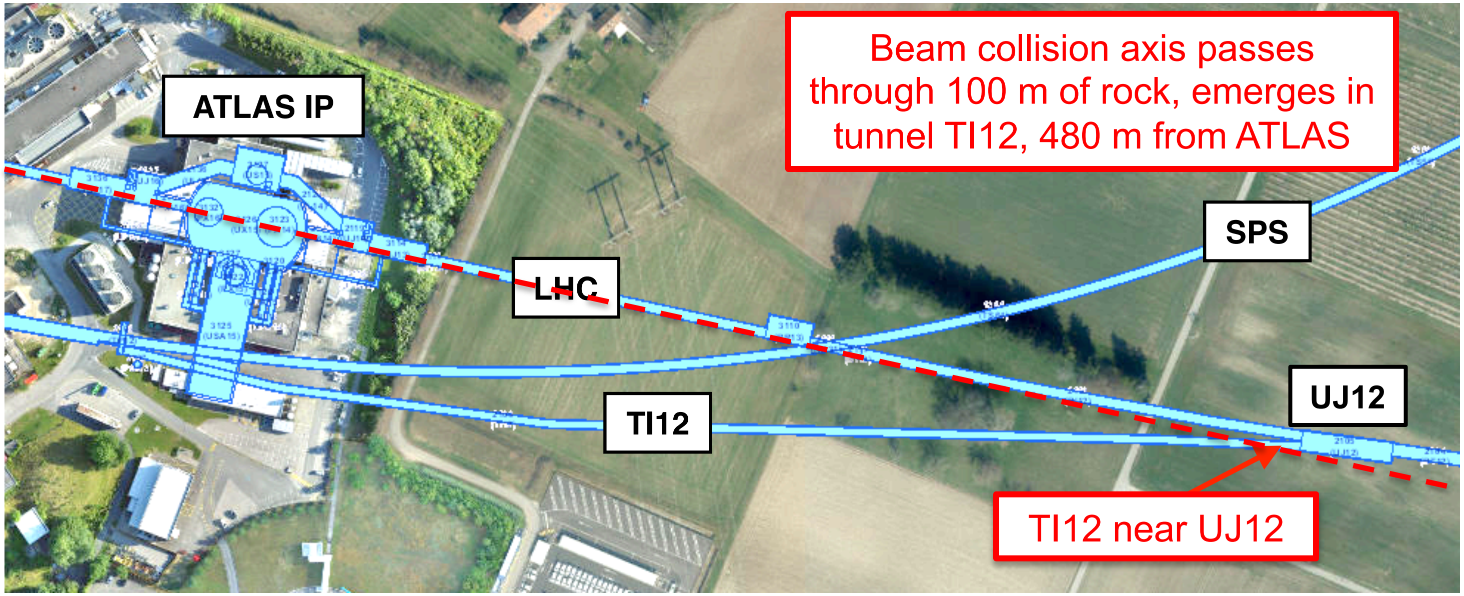
De Rujula, Ruckl (1984)

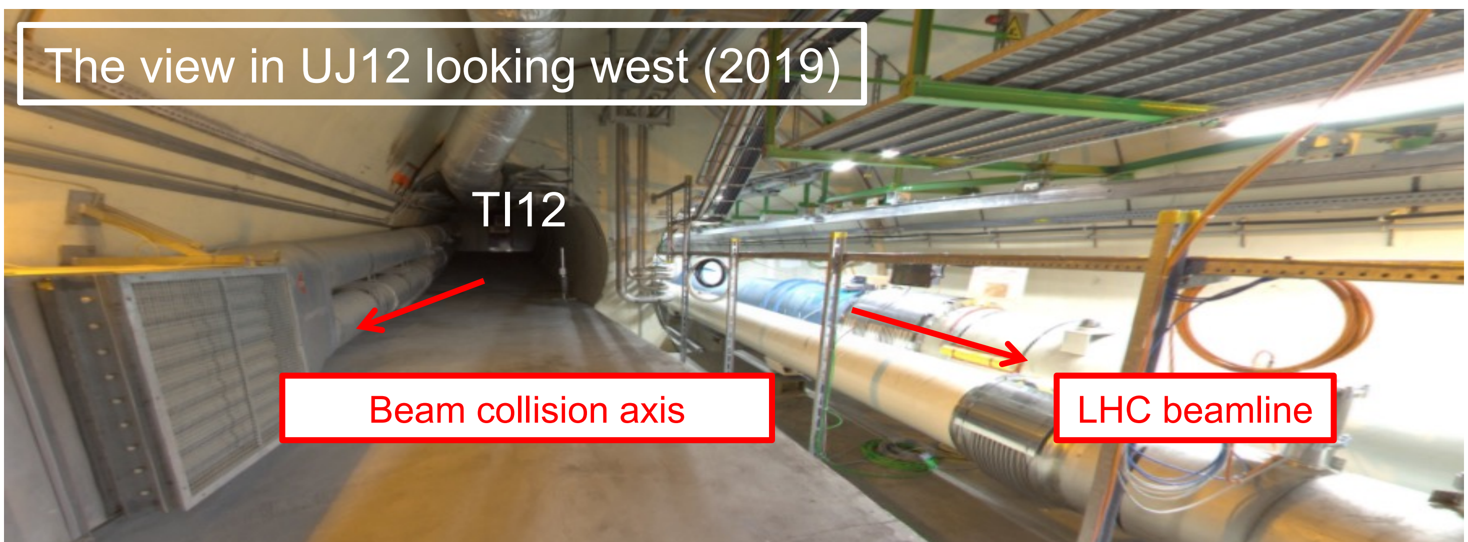
- Heavy particles are produced at low velocity and then decay roughly isotropically to other particles.



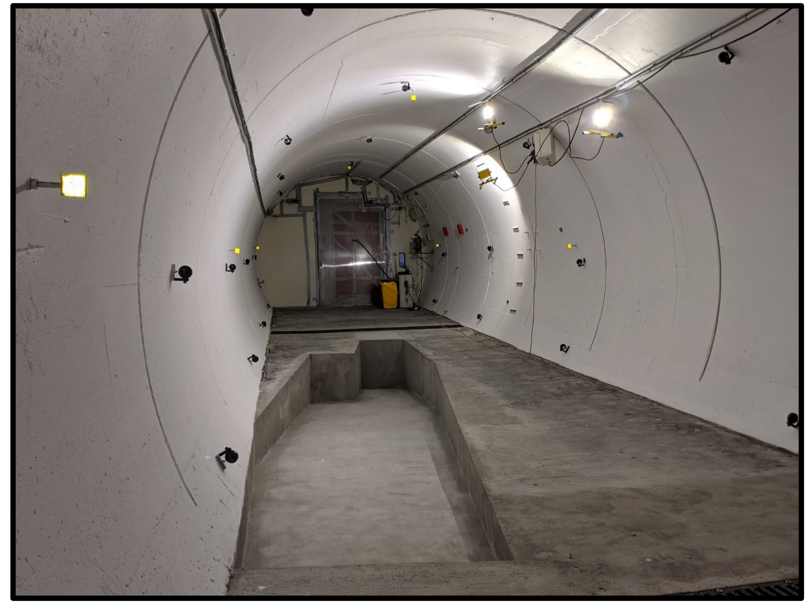
- But high-energy light particles are dominantly produced in the forward direction, escape through un-instrumented regions of existing detectors.
  - The existing large detectors are blind to neutrinos.
  - They are also blind to many other new physics possibilities: dark photons, dark Higgs bosons, sterile neutrinos, ALPs, millicharged particles, new force carriers, dark matter, dark sectors, LLPs, FIPs,… (see PBC benchmarks).

THE FAR-FORWARD REGION





FASER PROGRESS 2019-21



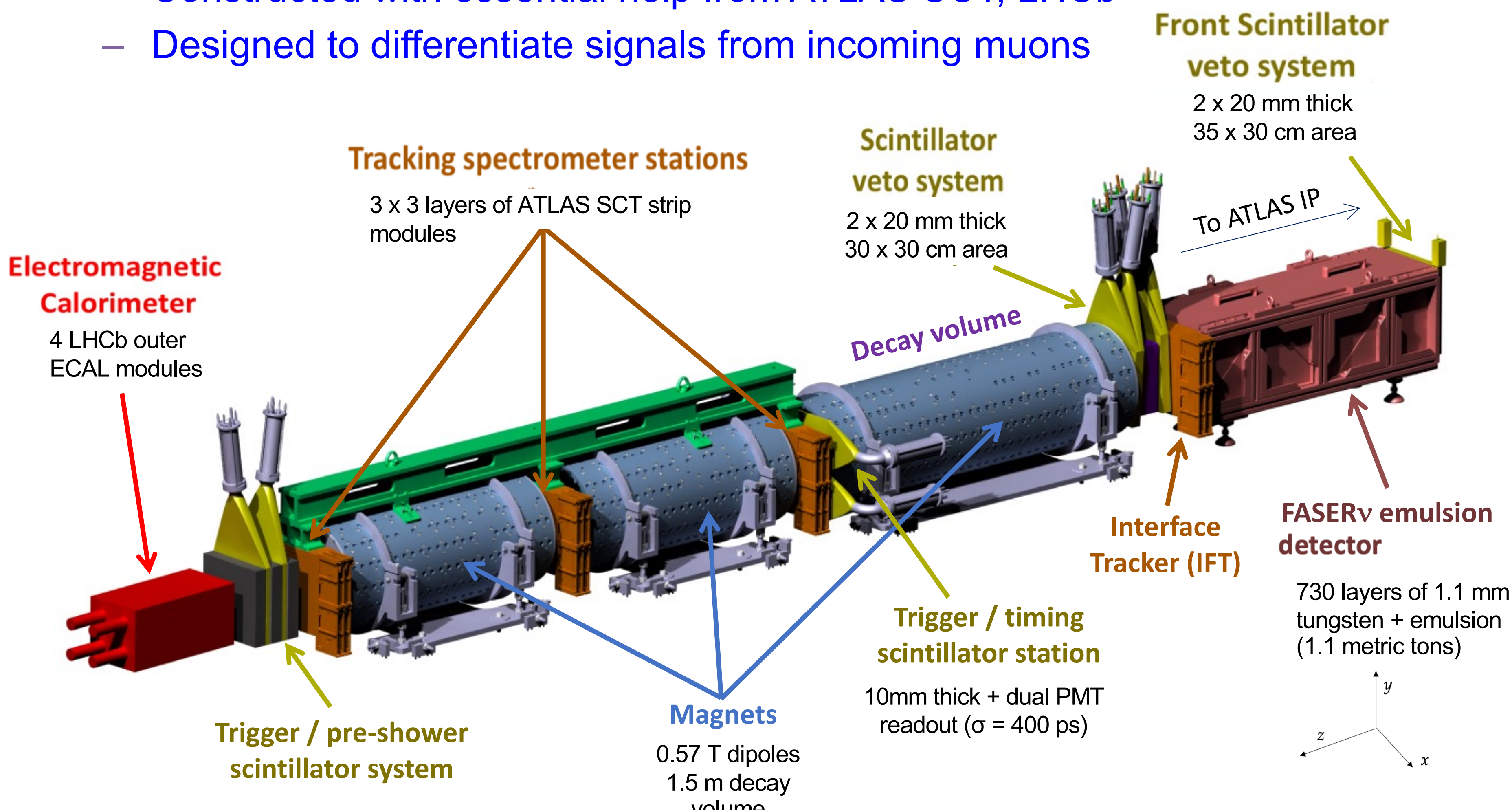
Jamie Boyd, FASER Co-Spokesperson

FASER NOW

THE FASER DETECTOR

- Small, fast, inexpensive
  - 10 cm radius, 7 m long
  - Constructed with essential help from ATLAS SCT, LHCb
  - Designed to differentiate signals from incoming muons

FASER Collaboration (2207.11427)



FIRST PHYSICS RESULTS FROM FASER

- With 2022 Run 3 data
  - First direct observation of collider neutrinos (2303.14185, last night!)
  - New dark photon limits in the thermal relic region
- See full talks at other winter conferences
  - Brian Petersen, Moriond EW, 19 March 2023
  - Carl Gwilliam, Moriond QCD, 29 March 2023
  - Dave Casper, UCLA DM, 30 March 2023

CERN-EP-2023-056

arXiv:2303.14185v1 [hep-ex] 24 Mar 2023

First Direct Observation of Collider Neutrinos with FASER at the LHC

FASER Collaboration

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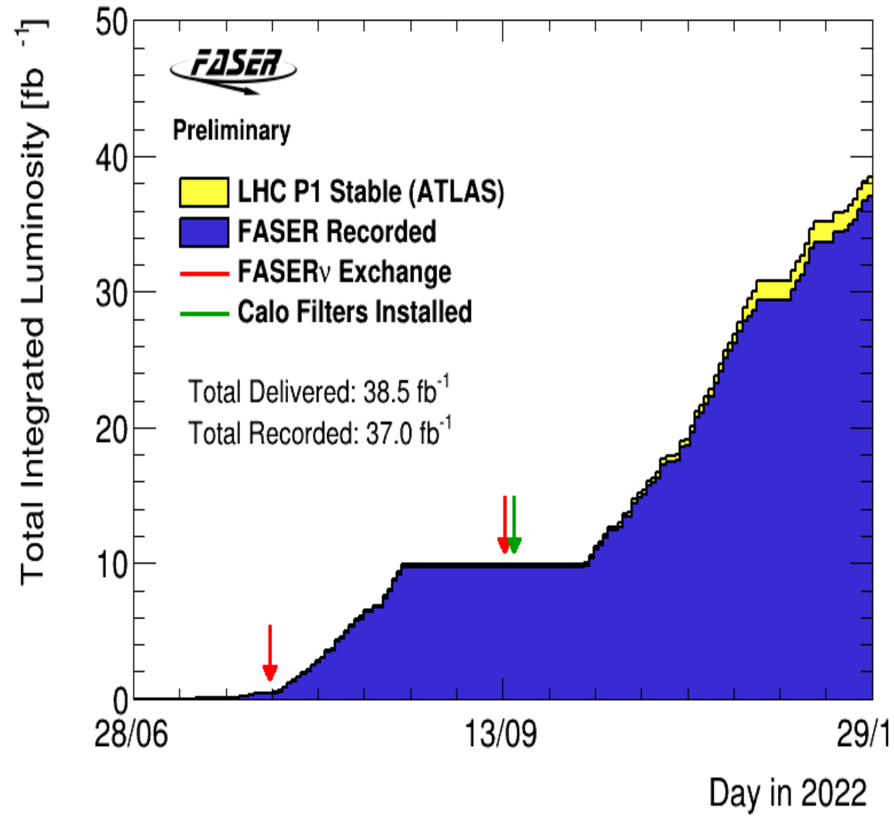
(Dated: March 24, 2023)

FASER OPERATIONS

- Successfully operated throughout 2022
  - Continuous data taking
  - Largely automated
  - Up to 1.3 kHz
  - 350M single muons recorded
- Recorded 96.1% of delivered lumi.
  - DAQ dead-time of 1.3%
  - A couple of DAQ crashes
- Emulsion detector exchanged twice
  - Needed to manage occupancy
  - First box only partially filled
- Calorimeter gain optimised for:
  - Low E (< 300 GeV) before 2nd exchange
  - High E (up to 3 TeV) after 2nd exchange

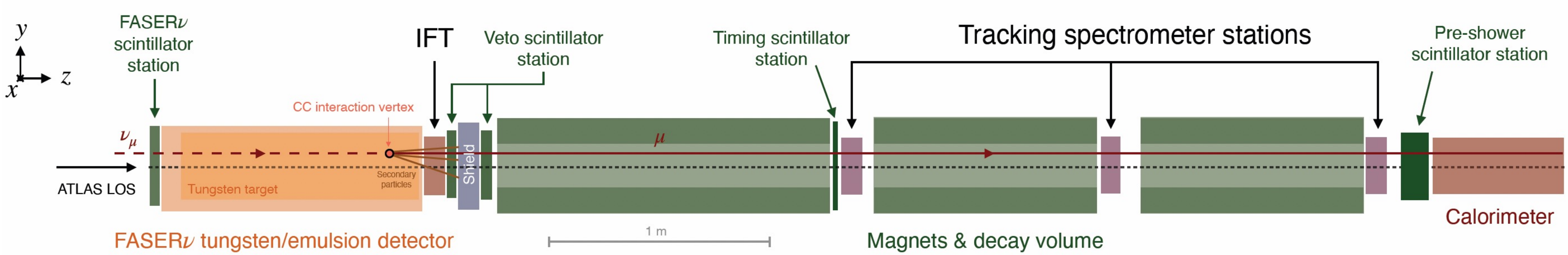


Analyses presented use $27.0\ fb^{-1}$ or $35.4\ fb^{-1}$

COLLIDER NEUTRINO SEARCH

- Signal: ~TeV neutrinos produced in meson decays, interact in FASERν. Focus on CC interactions $\nu_\mu N \rightarrow \mu X$, producing a high-energy muon.
- Aim for observation, currently not trying to measure cross section. Use electronic components only, FASERν only as a 1.1 ton target.

Arakawa, Feng, Ismail, Kling, Waterbury (2022)



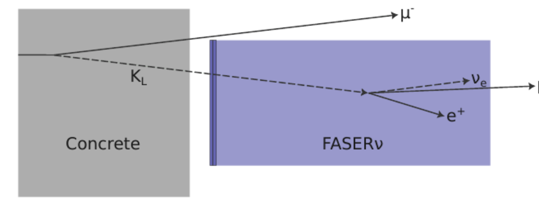
- Collider neutrino selection

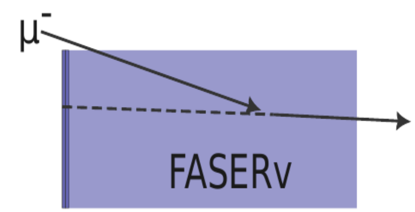
FASER Collaboration (2303.14185)

  - Collision event with good data quality
  - No signal (< 40 pC) in front veto station
  - Signal (> 40 pC) in other 3 scintillator stations
  - Timing and preshower consistent with ≥ 1 MIP
  - Exactly 1 good fiducial track (r < 95 mm, p > 100 GeV and θ < 25 mrad, extrapolating to r < 120 mm in front veto station)
- Expect 151 ± 41 events from GENIE simulation, uncertainty from forward hadron production, spans DPMJET vs. SIBYLL range

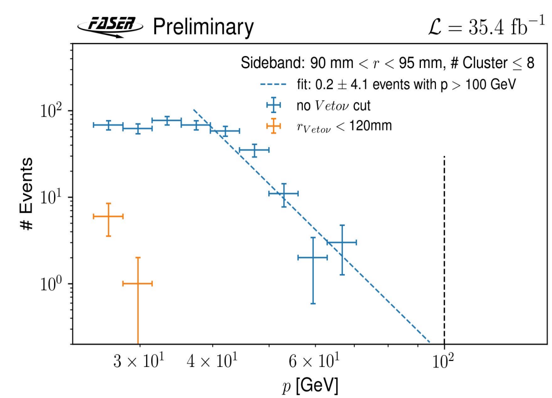
COLLIDER NEUTRINO BACKGROUNDS

- Neutral hadrons estimated from simulation
  - Expect ~300 neutral hadrons with E > 100 GeV reaching FASERν, 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
  - Predict N = 0.11 ± 0.06 events





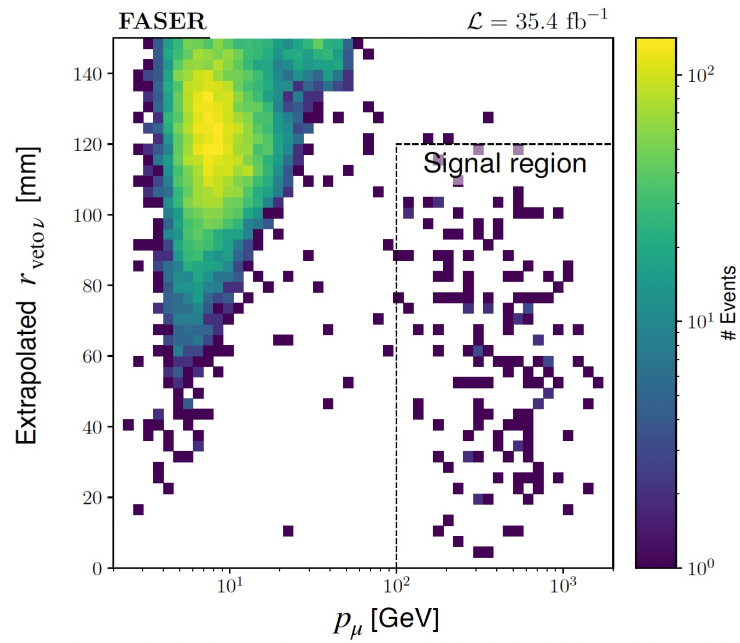
- Scattered muons estimated from data sideband
  - Take events w/o front veto radius requirement and single track segment in first tracker station with 90 < r < 95 mm, extrapolate to higher momentum
  - Scale by number of events with front veto cut, use MC to extrapolate to signal region
  - Predict N = 0.08 ± 1.83 events

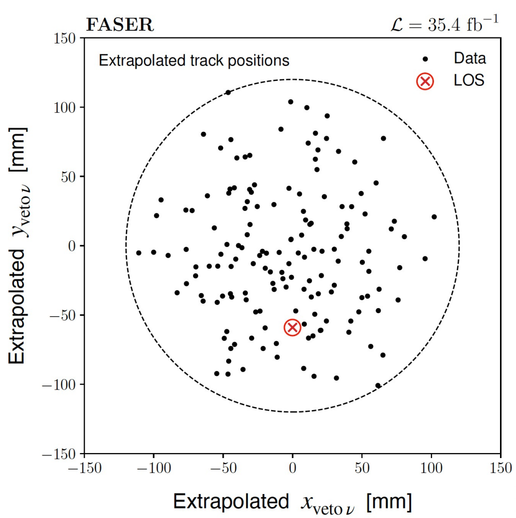


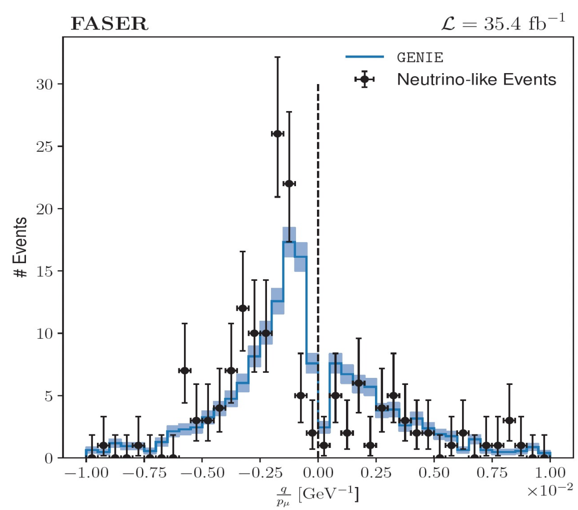
- Veto inefficiency estimated from final fit
  - Scintillator eff. > 99.999%, bkgrd is negligible

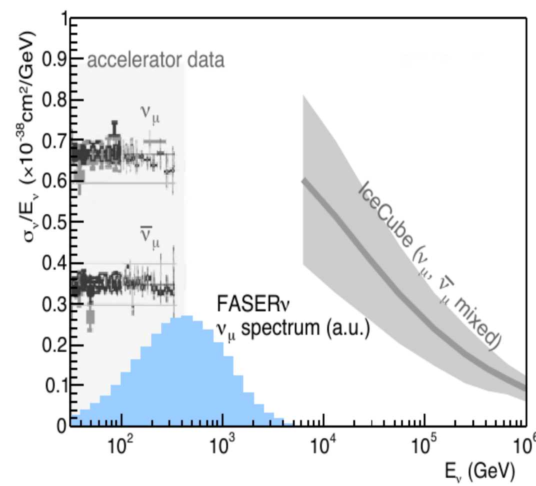
COLLIDER NEUTRINO RESULTS

- After unblinding, find 153 signal events with no veto signal
  - Just 10 events with one veto signal
- 1st direct observation of collider neutrinos
  - Signal significance of ~16σ
  - Muon charge → both ν and $\bar{\nu}$
  - Almost certainly these include the highest energy ν and $\bar{\nu}$ from a human source





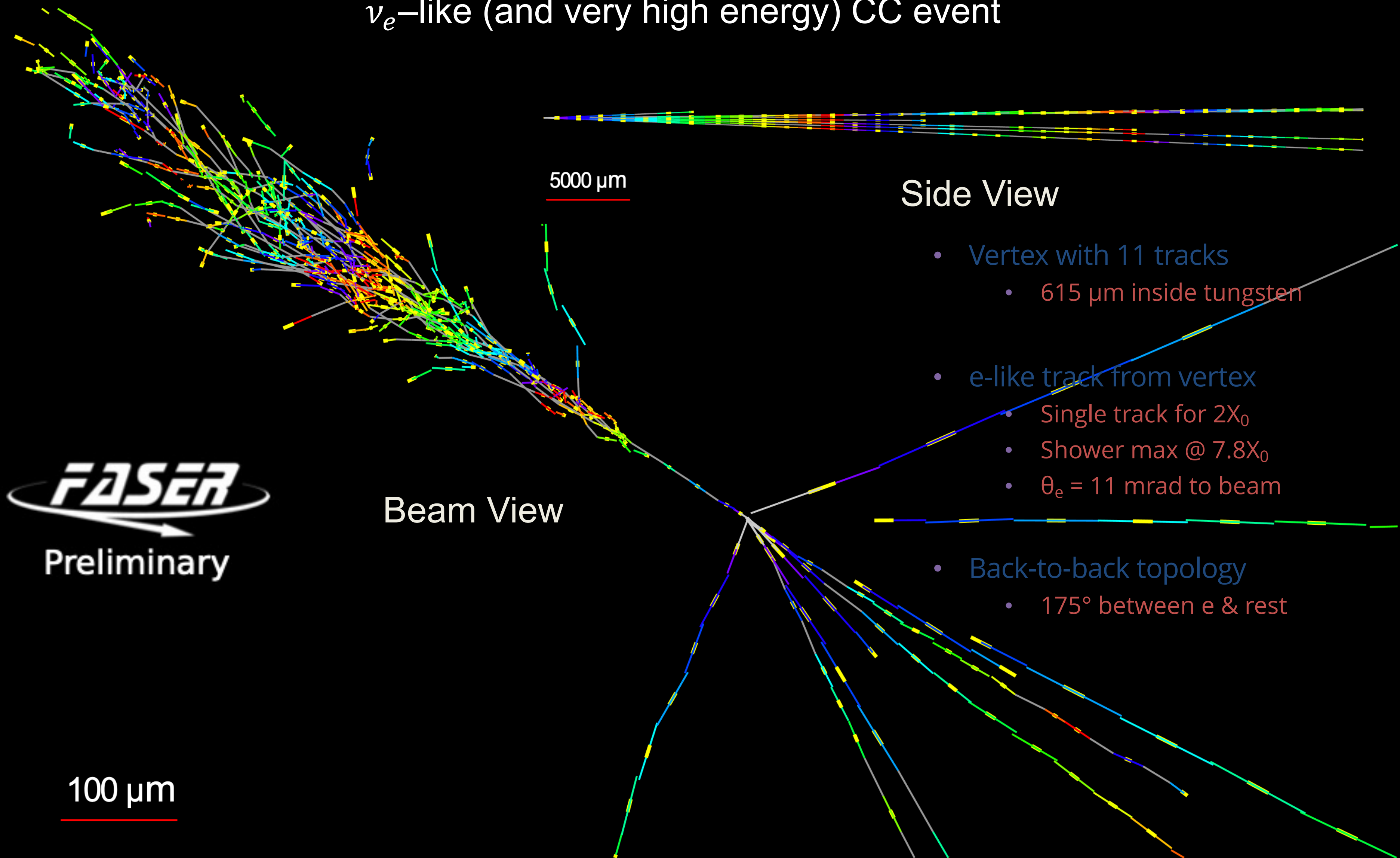




FASER Collaboration (2303.14185)

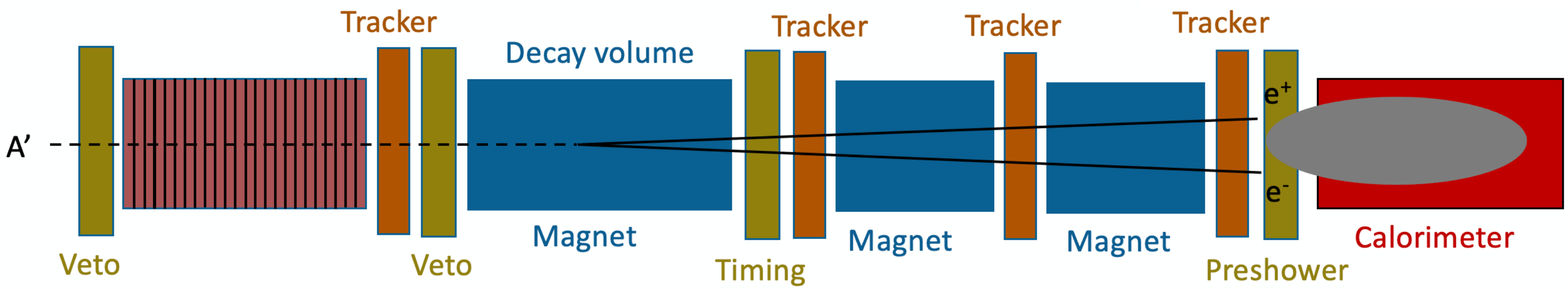
NEUTRINOS FROM EMULSION IN FASERν

Much more to come: this analysis does not even use the emulsion data!
Analysis underway, but already many neutrino candidates, including this highly ν_e–like (and very high energy) CC event



DARK PHOTON SEARCH

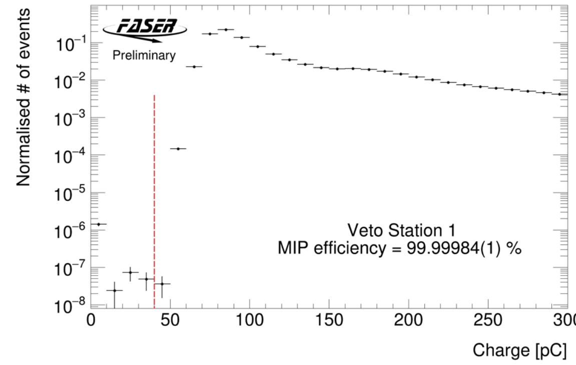
- Signal: $\pi/\eta \to A'\gamma$ or $pp \to ppA'$, A' travels 476 m through rock/concrete, then decays $A' \to e^+e^-$. Probes thermal target: m ~ $10 - 100$ MeV, $\varepsilon \sim 10^{-5} - 10^{-4}$.

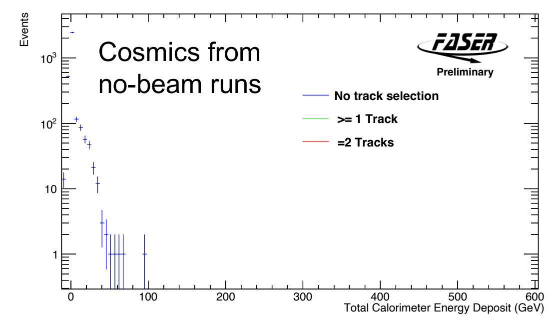


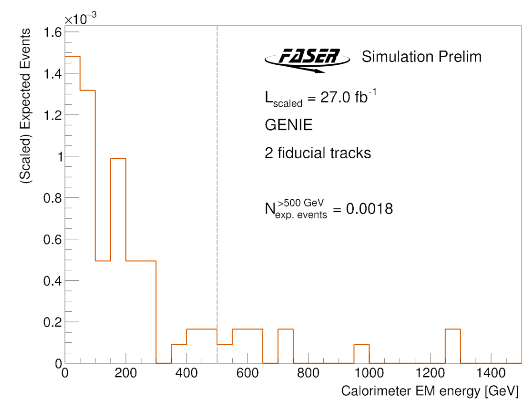
- Dark photon selection: simple and robust, optimized for discovery
  - Collision event with good data quality
  - No signal (< 40 pC) in any veto scintillator
  - Timing and preshower consistent with > 2 MIPs
  - Exactly 2 good fiducial tracks (p > 20 GeV and r < 95 mm, extrapolating to r < 95 mm at vetos)
  - Calorimeter energy > 500 GeV
- Blinded events with no veto signal and calorimeter energy > 100 GeV
- Signal efficiency was ≈ 40% across entire parameter space of sensitivity

DARK PHOTON BACKGROUNDS

- Veto inefficiency
  - Measured layer by layer with muons, completely negligible: $10^8 (10^{-5})^4 \sim 10^{-12}$
- Non-collision backgrounds
  - Cosmics measured in runs with no beams, nearby beam debris measured in runs with non-colliding bunches, all negligible
- Neutral hadrons, e.g., K_S, from muons interacting in rock in front of FASER
  - Heavily suppressed since muons typically trigger veto, hadrons have to pass through FASERν and still leave E>500 GeV in calo
- Neutrino interactions
  - Estimated from GENIE simulation with 300 ab^{-1}, uncertainties from ν flux
  - Dominant background: N = (1.8 ± 2.4) x 10^{-3}

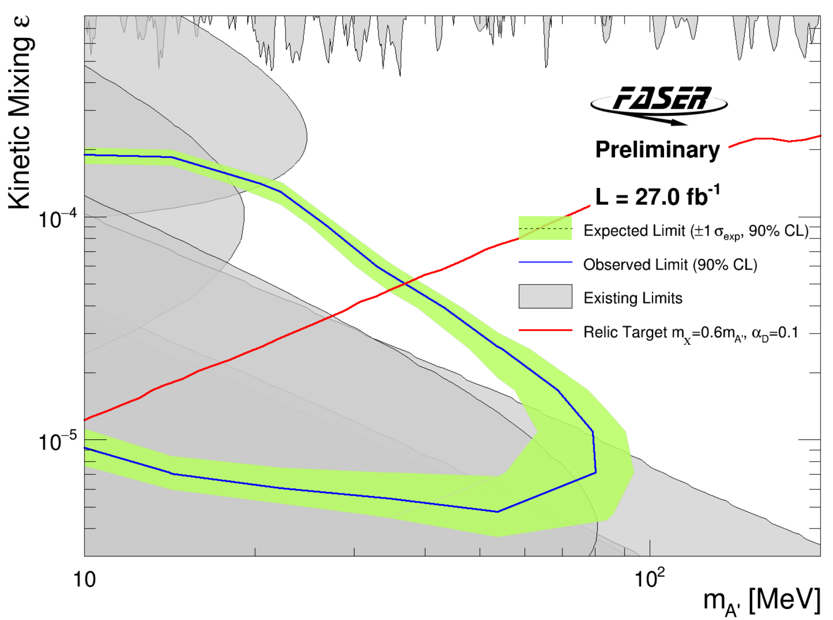


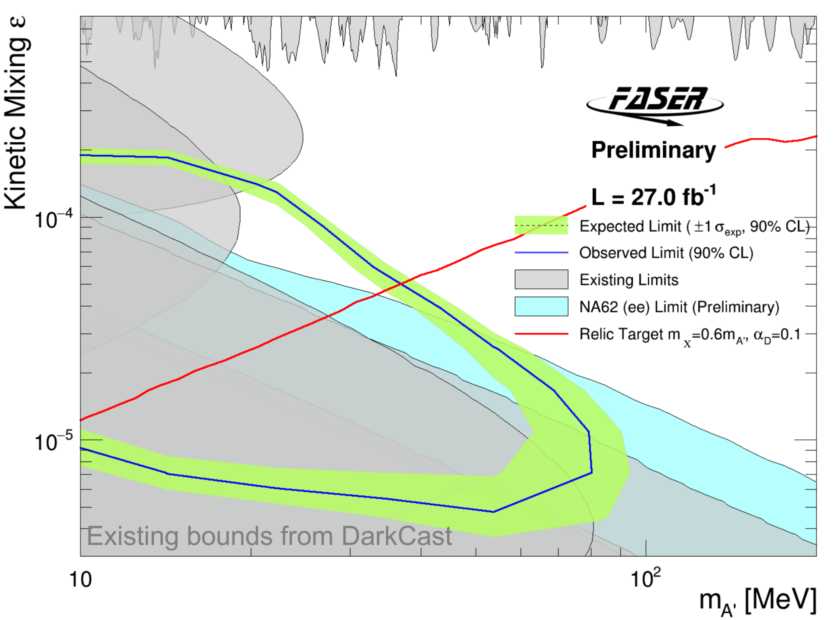




DARK PHOTON RESULTS

- After unblinding, no events seen in signal region, FASER sets limits on previously unexplored parameter space.
- First incursion (along with NA62, announced at La Thuile) into the thermal relic region from low coupling since the 1990's.
- Background-free analysis bodes well for future sensitivity. Expect factor of ~10 more luminosity in Run 3 from 2022-25.

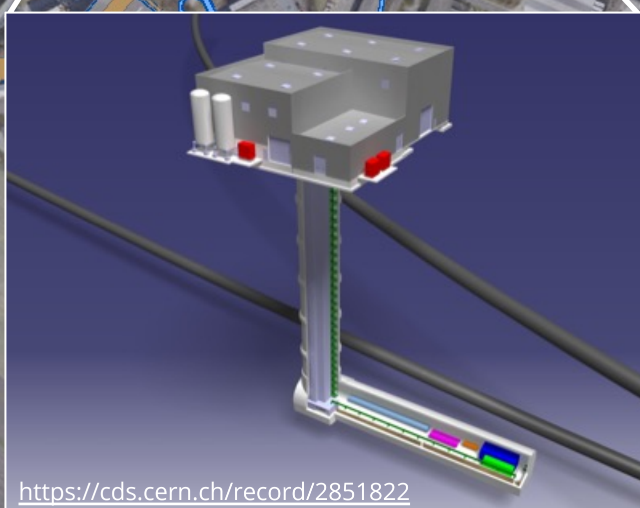


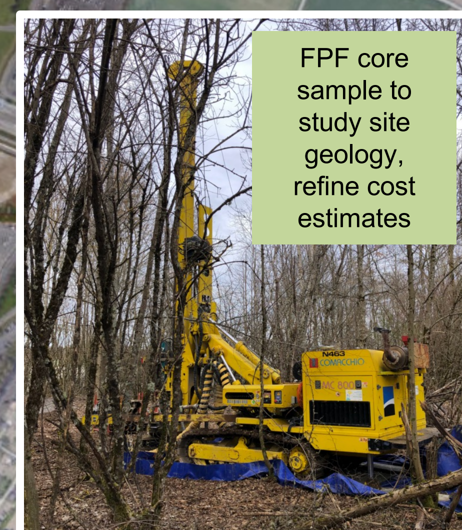


FORWARD PHYSICS FACILITY

- The rich physics program in the far-forward region strongly motivates creating a dedicated Forward Physics Facility to house far-forward experiments for the HL-LHC era from 2028-2040s.

UJ18 ATLAS SPS FASER LHC LOS

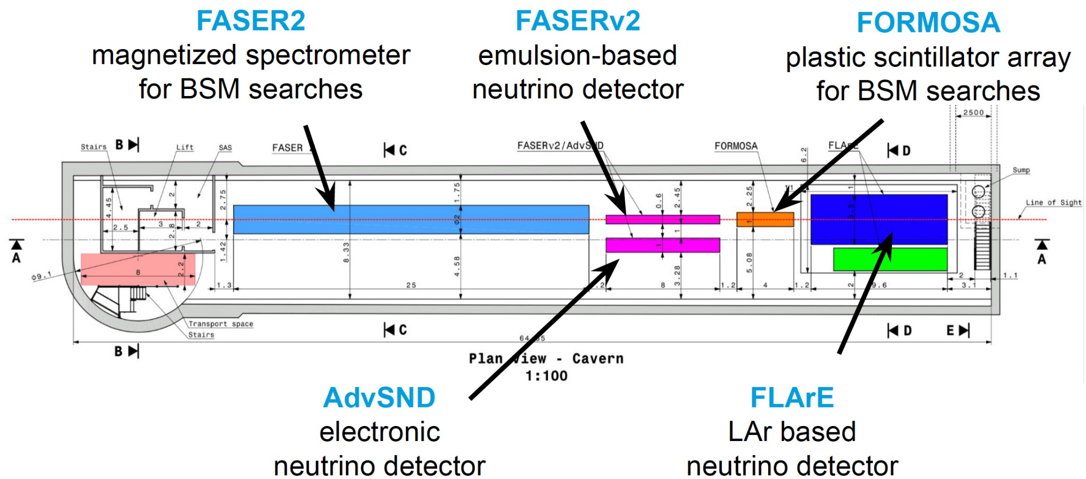




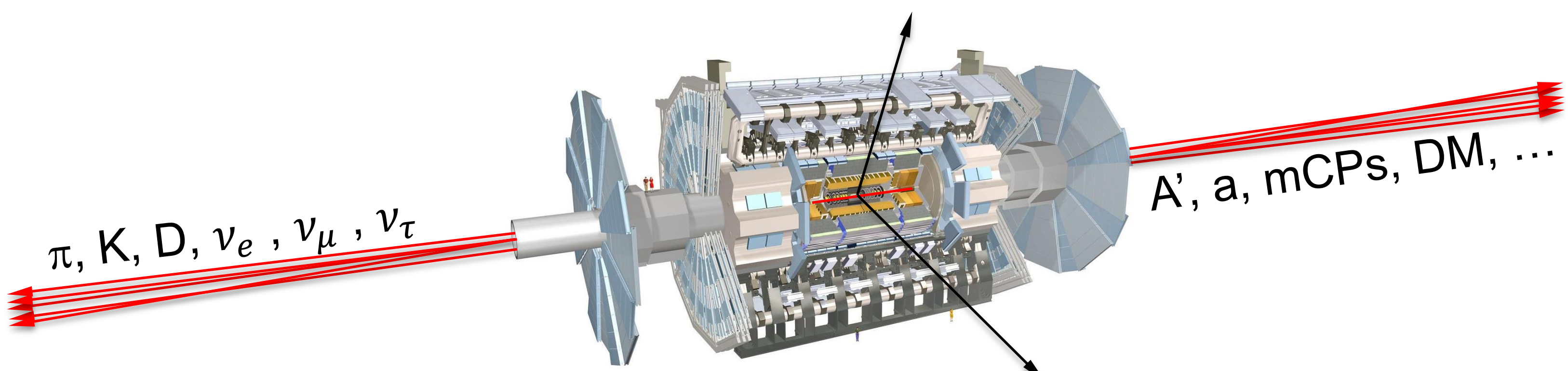
CERN GIS

FPF EXPERIMENTS

- At present there are 5 experiments being designed to explore the breadth of SM and BSM topics. FPF covers η > 5.5, experiments on LOS cover η ≳ 7.

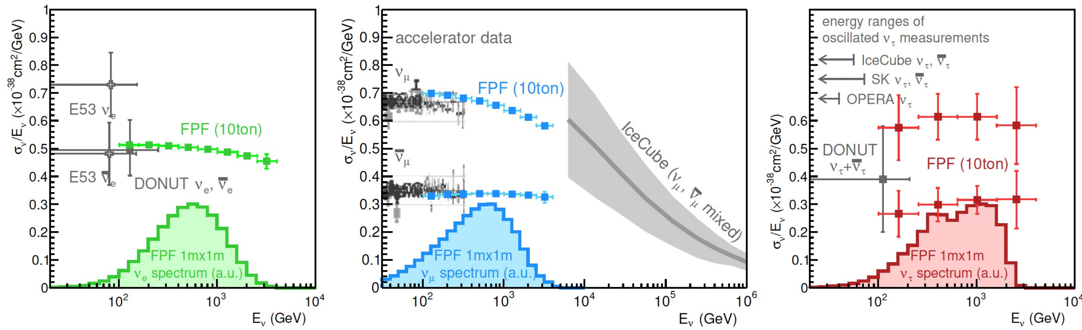


- Large far-forward fluxes are automatically provided by the LHC and can be exploited with small and inexpensive detectors. For example,
  - ~10^6 TeV-neutrino interactions per 10 tons.
  - ~10^4 dark photon decays can be observed in currently viable regions of param space.

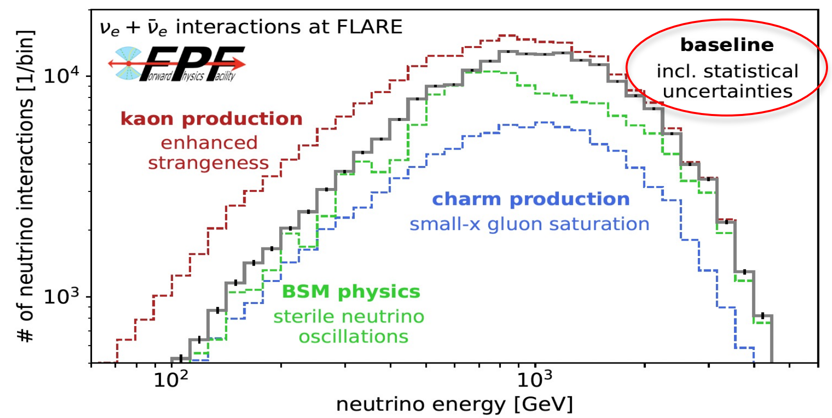


THE FPF NEUTRINO PROGRAM

- The FPF experiments will see $10^5\ \nu_e$, $10^6\ \nu_\mu$, and $10^4\ \nu_\tau$ interactions at ~ TeV energies where there is currently no data.

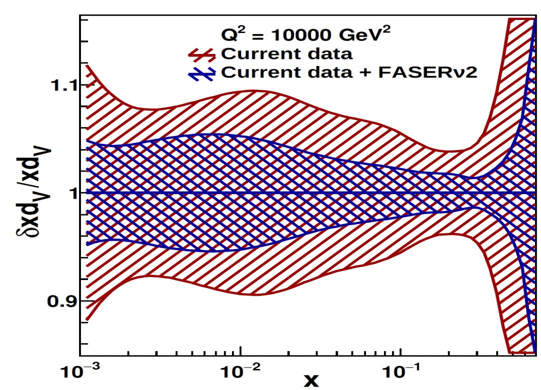


- Neutrinos are produced by forward hadron production: $\pi, K, D, \ldots$. Energy spectra will inform
  - Astroparticle physics: muon puzzle, …
  - QCD: pdfs at x ~ 10^{-1}, x ~ 10^{-7} , intrinsic charm, small-x gluon saturation, …
  - Neutrino properties: ν_s w/ $\Delta m^2 \sim 10^3\ \mathrm{eV}^2$



- Fully differential neutrino DIS scattering cross sections will improve constraints on pdfs by up to a factor of ~2.

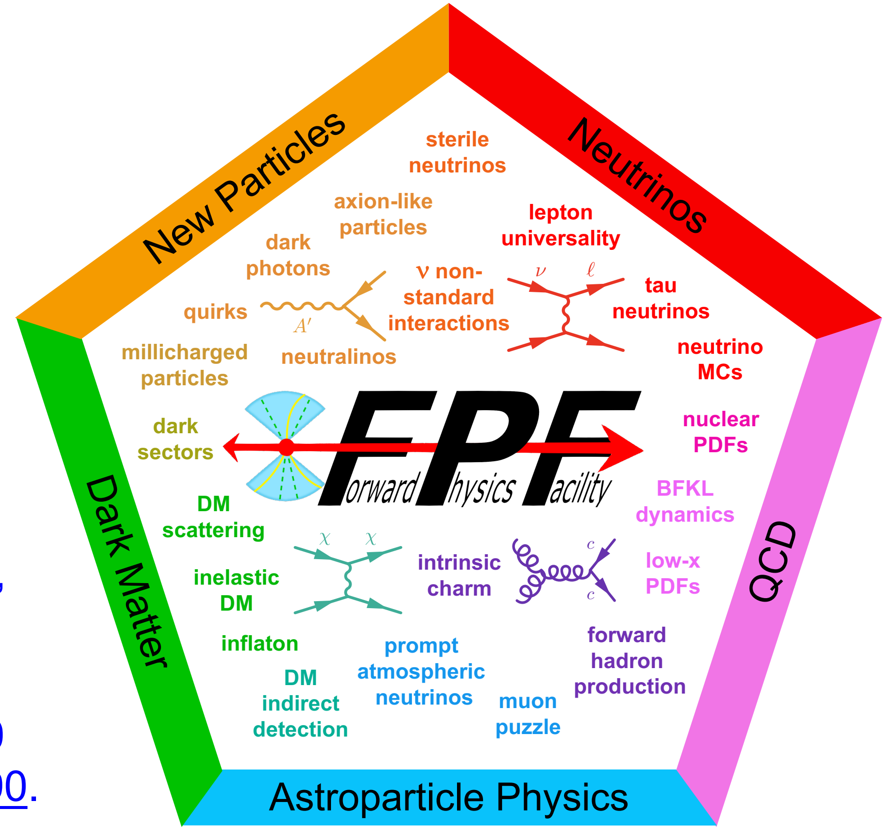
- What else?



FPF WGs, PDF4LHC21, stat uncertainty only

FORWARD PHYSICS FACILITY

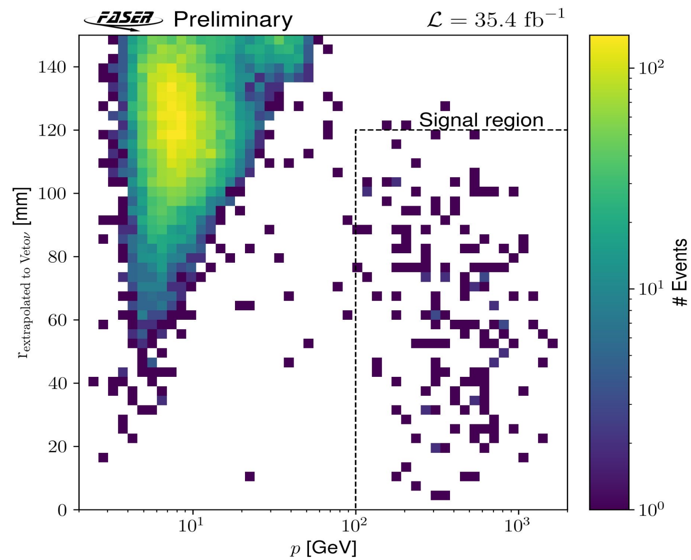
- The physics program in the far-forward region has been developed in a series of meetings and papers.
- FPF Meetings
  - FPF Kickoff Meeting, 9-10 Nov 2020
  - FPF2 Meeting, 27-28 May 2021
  - FPF3 Meeting, 25-26 Oct 2021
  - FPF4 Meeting, 31 Jan-1 Feb 2022
  - FPF5 Meeting, 15-16 Nov 2022
- FPF Papers
  - FPF "Short" Paper: 75 pages, 80 authors, Phys. Rept. 968, 1 (2022), 2109.10905.
  - FPF White Paper: 429 pages, 392 authors+endorsers representing over 200 institutions, J. Phys. G (2022), 2203.05090.

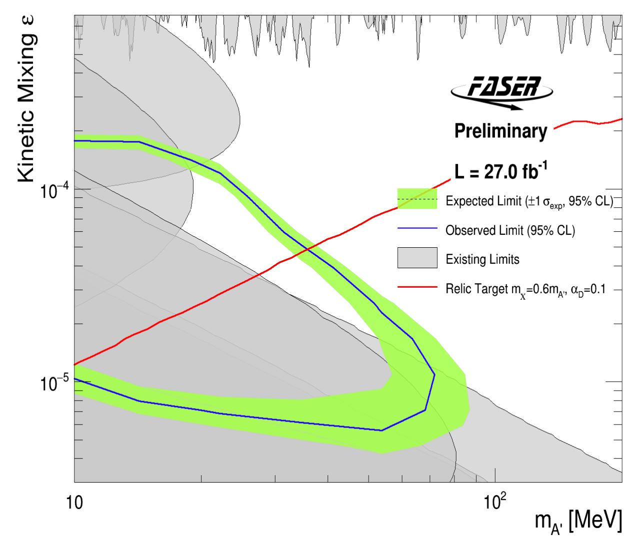


- Snowmass 2022: "Our highest immediate priority accelerator and project is the HL-LHC, … including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades."

SUMMARY

- FASER successfully took data in 1st year of Run 3
  - Running with fully functional detector and very good efficiency
- First direct observation of collider neutrinos
  - ~153 events with ~0 background, 16 sigma
  - Opens a new field: neutrino physics at the LHC
- Excluded A' in region of 10-100 MeV mass and really small coupling
  - First incursion into the thermal relic region from low coupling in 30 years
- More neutrino studies and BSM searches to come
  - Including first results from emulsion detector
  - Searches for ALPs, light gauge bosons, …
- Strongly motivates FPF for the HL-LHC era





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- The LHC for excellent performance in 2022
- ATLAS for luminosity information
- ATLAS for use of ATHENA s/w framework
- ATLAS SCT for spare tracker modules
- LHCb for spare ECLA modules
- CERN FLUKA team for bkgrd simulations
- CERN PBC and technical infrastructure groups for excellent support during FASER's design, construction, installation