MULTI-MESSENGER COLLIDER PHYSICS AT THE

FPF Forward Physics Facility

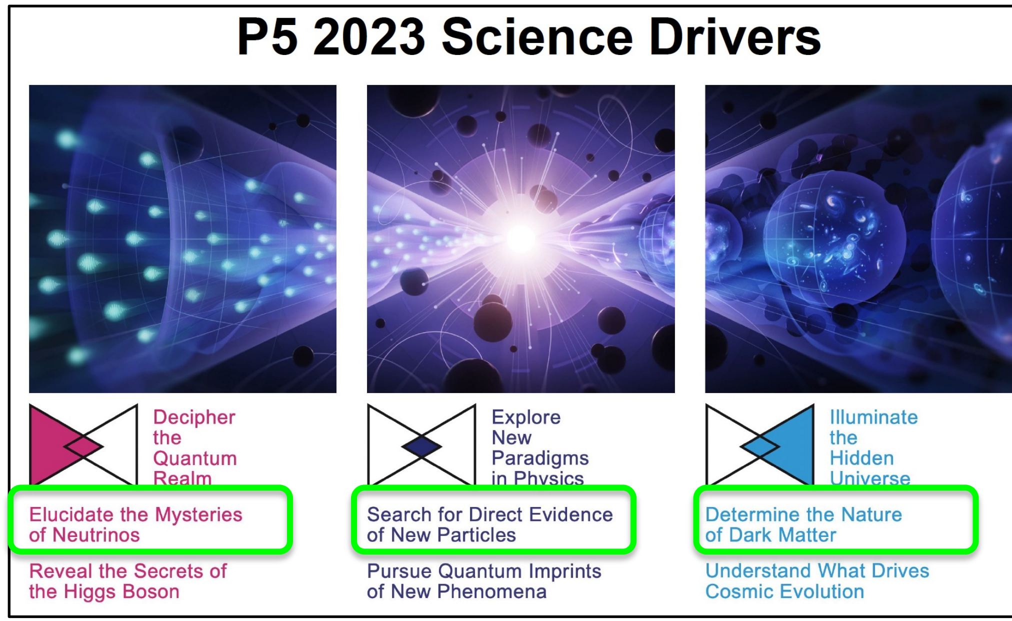
DPF-PHENO 2024: Mini-Symposium on Forward Physics

Jonathan Feng, UC Irvine, 15 May 2024

NSF SIMONS FOUNDATION HEISING-SIMONS FOUNDATION UC IRVINE CERN

EXECUTIVE SUMMARY

- In the last few years, there has been a complete transformation in our understanding of forward physics at colliders.
- Previously: luminosity measurements, pomerons, odderons, …
- Now: we understand that the forward region contains a treasure trove of both SM and BSM physics, addressing all of our top science drivers.
- We have entered the era of multi-messenger collider physics with the discovery of collider neutrinos.



- To fully exploit the physics potential of the LHC, neutrino detectors are required, just like trackers and calorimeters. The Forward Physics Facility is proposed to house a suite of such detectors at the HL-LHC.

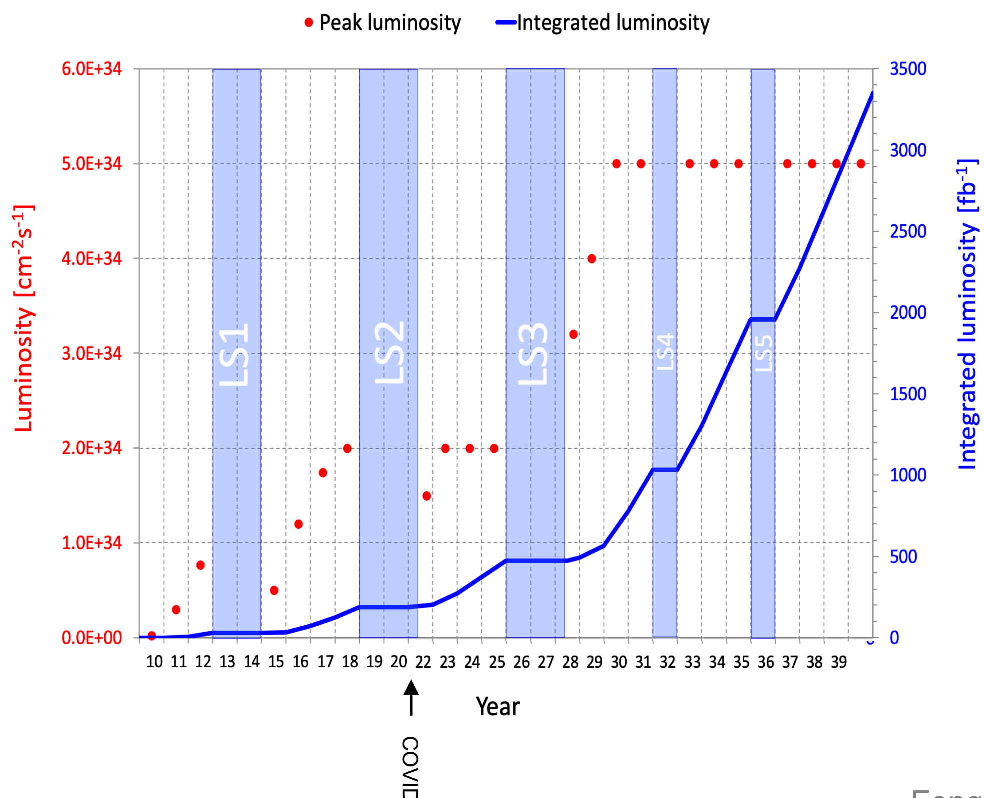
LIFETIME OF THE LHC

- The LHC is an amazing achievement.

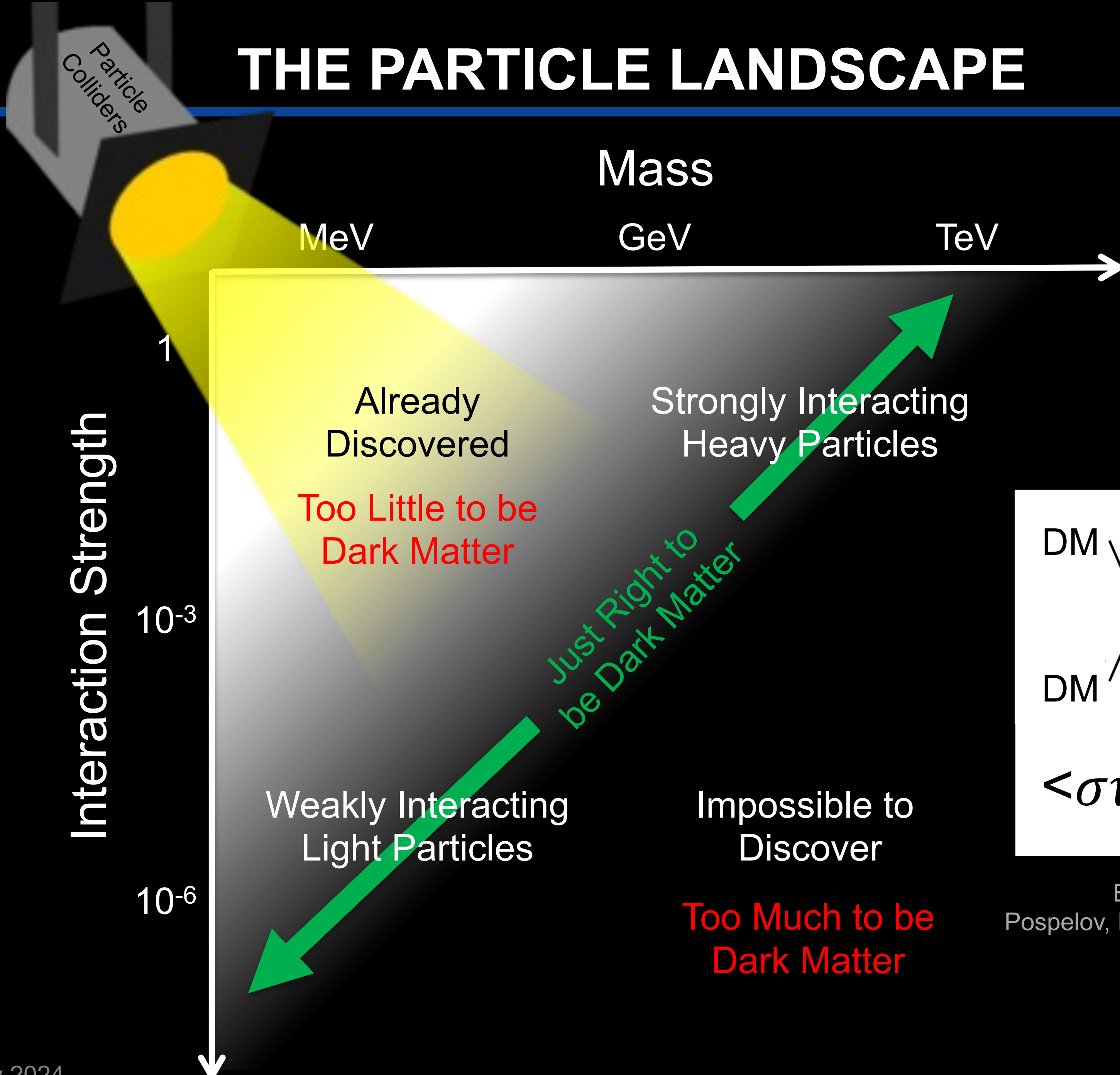
- While we are planning for colliders to build in the rest of the century, we should also make sure we are using the LHC well. By doing so, we advance physics now, and we may also discover something new that will greatly clarify and smooth the path forward.

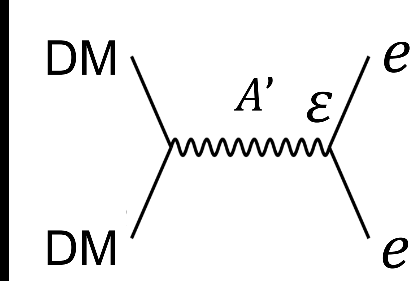
- The LHC is still in its youth!
  - a postdoc in terms of years
  - a kindergartener in terms of integrated luminosity

- Are we using the LHC to its full potential? If not, what can we do to enhance its discovery prospects?



THE PARTICLE LANDSCAPE





$$<\sigma v> \sim \frac{\varepsilon^2}{m_{A'}^2}$$

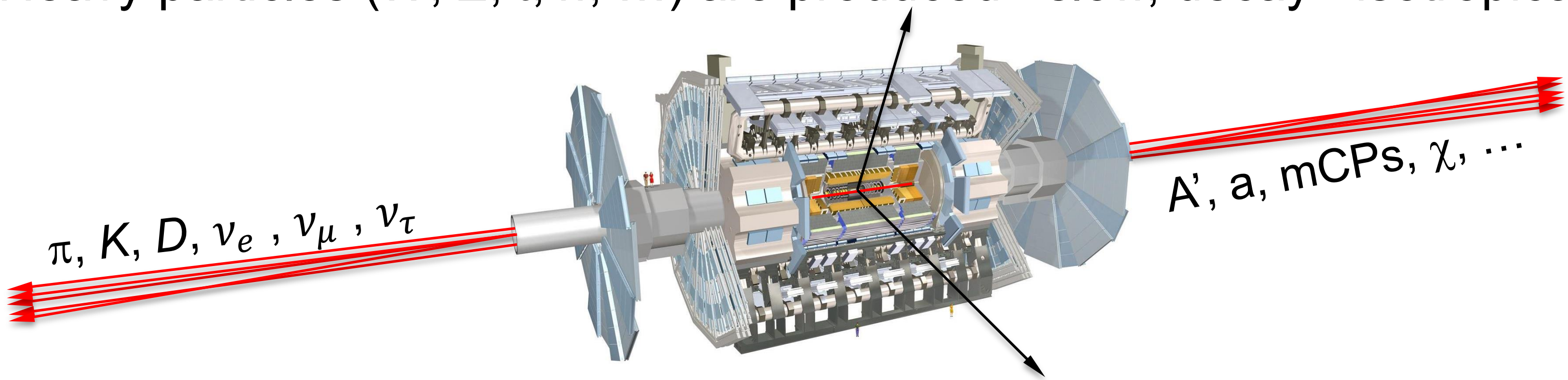
Boehm, Fayet (2003)
Pospelov, Ritz, Voloshin (2007)
Feng, Kumar (2008)

FORWARD PHYSICS

- We now know that the large LHC detectors, while beautifully optimized to discover and study heavy particles, are not at all optimally configured to discover and study light particles.

Feng, Galon, Kling, Trojanowski (2017)

- Heavy particles (*W*, *Z*, *t*, *h*, …) are produced ~slow, decay ~isotropically.

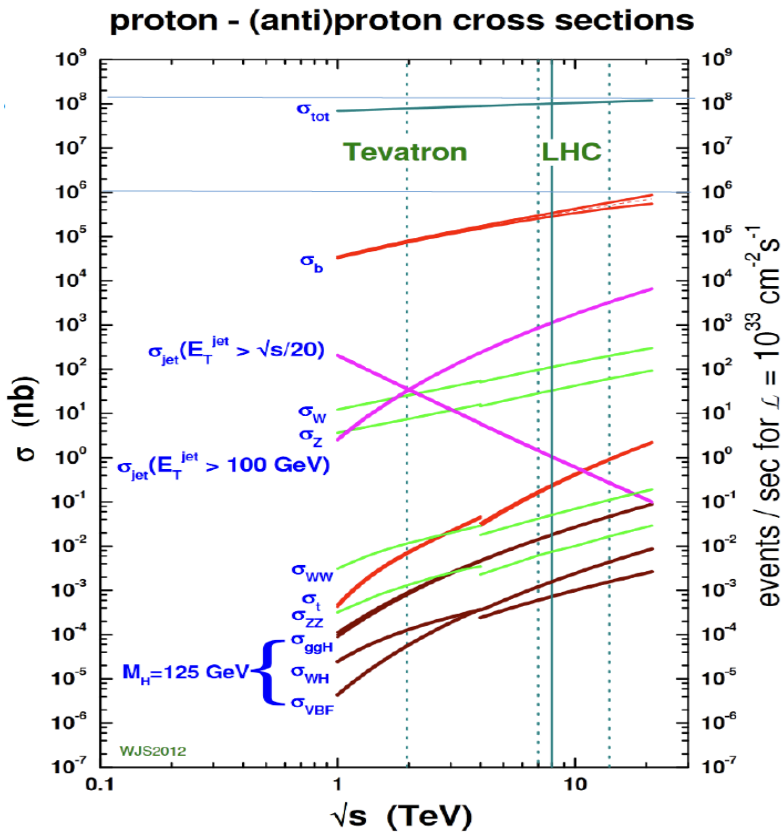


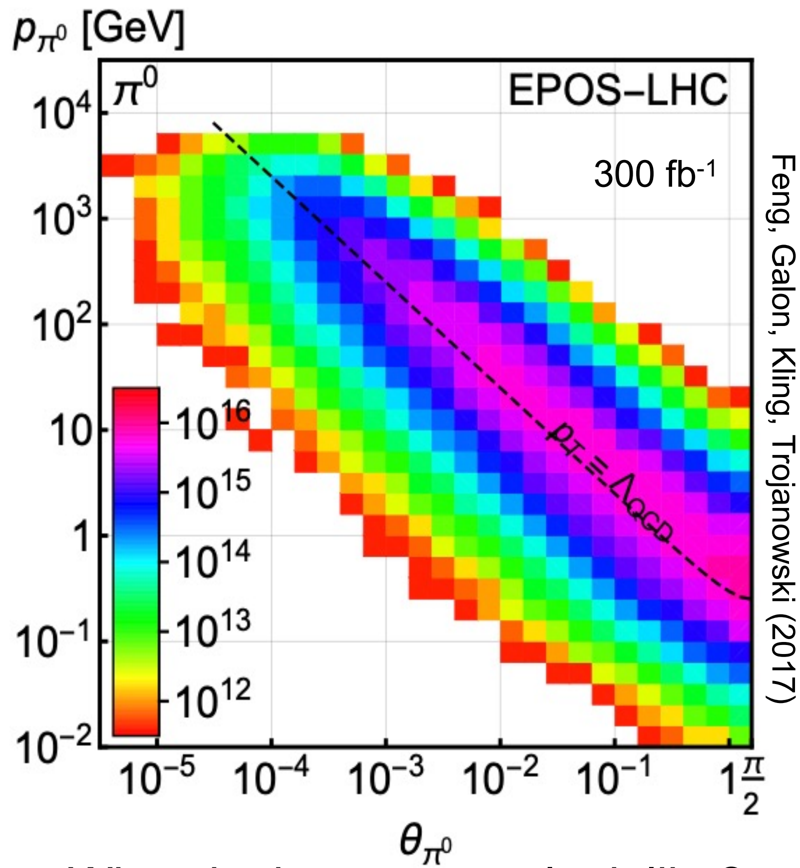
- But high-energy light particles are dominantly produced in the forward direction and escape through the blind spots of these large detectors.
  - This is true for all known light particles, including neutrinos, which had never been directly detected at a collider before 2023.
  - It is also true for many proposed new particles, especially those motivated by neutrino mass and dark matter.

De Rujula, Ruckl (1984)

- These blind spots are the Achilles heels of the large LHC detectors.

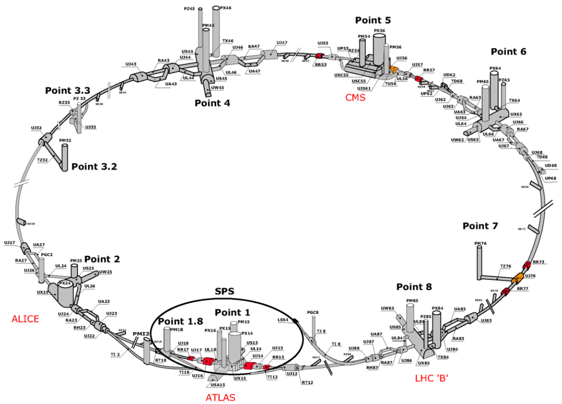
LIGHT PARTICLES AT THE LHC



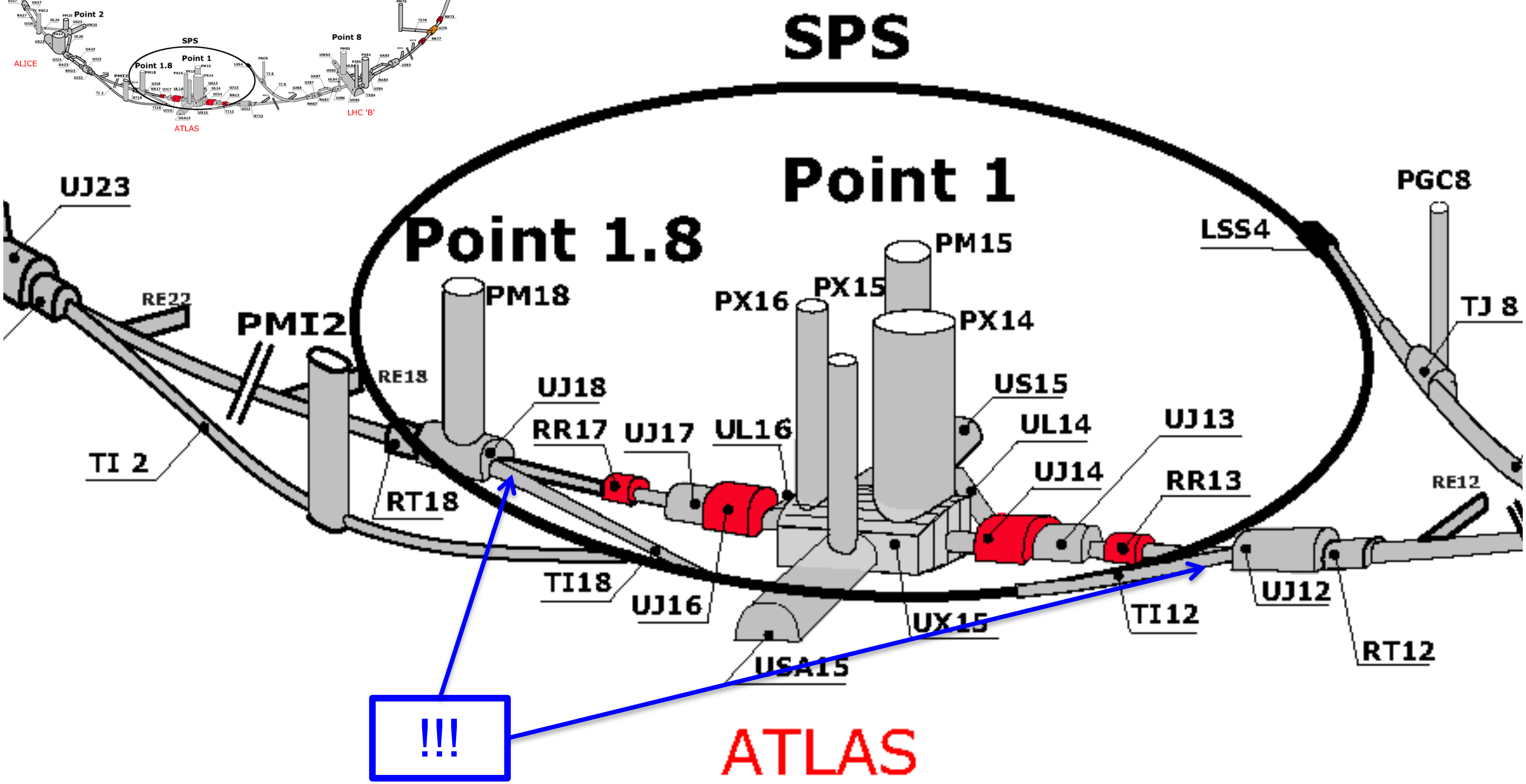


- Most searches have focused on processes with σ ~ fb, pb.
- But the total cross section is σ_{tot} ~ 100 mb and has been largely neglected.
- What do these events look like? Consider pions (decays to ν, BSM).
- Enormous event rates: IF at the EF! Typical p_T ~ 250 MeV, but p ~ TeV within 1 mrad (η > 7.6) of the beamline.

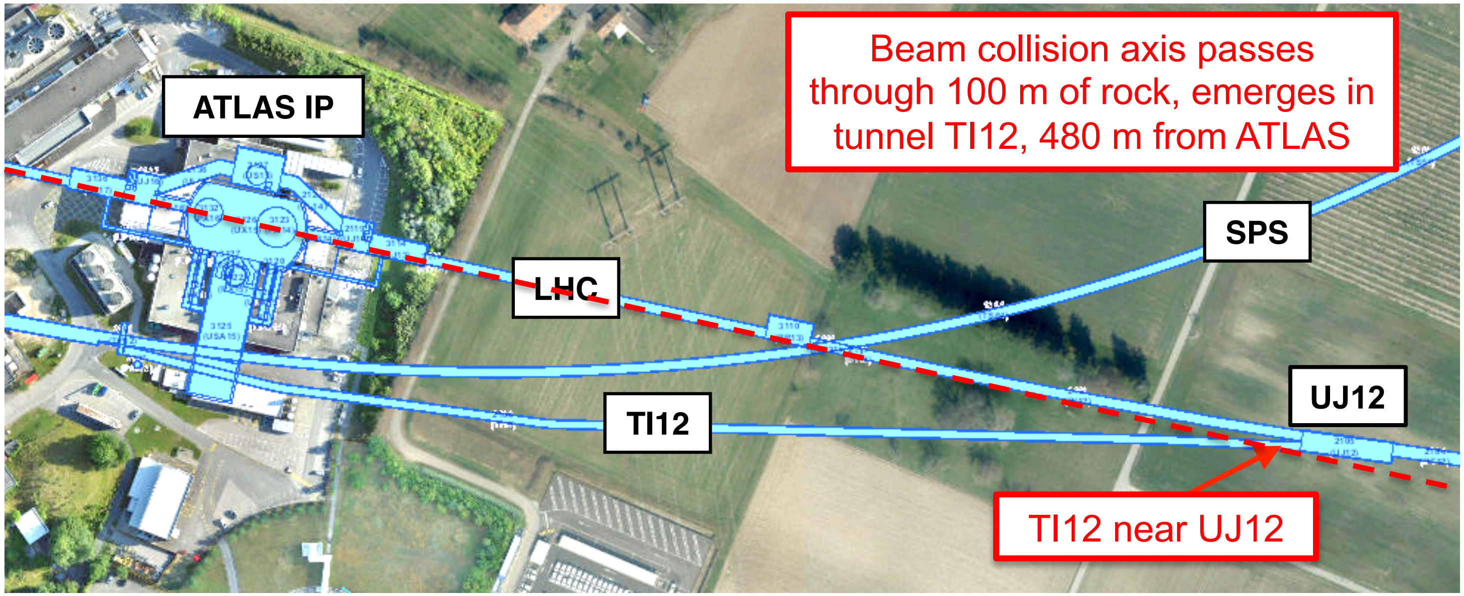
MAP OF THE LHC



To instrument the forward region, one can't simply plug up the holes – we need to let the protons in. But the LHC is a circular collider!



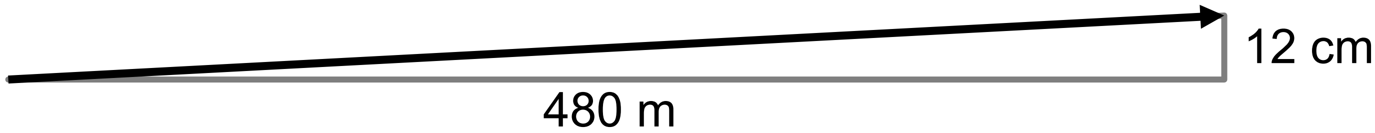
THE FORWARD REGION



HOW BIG DOES THE DETECTOR HAVE TO BE?

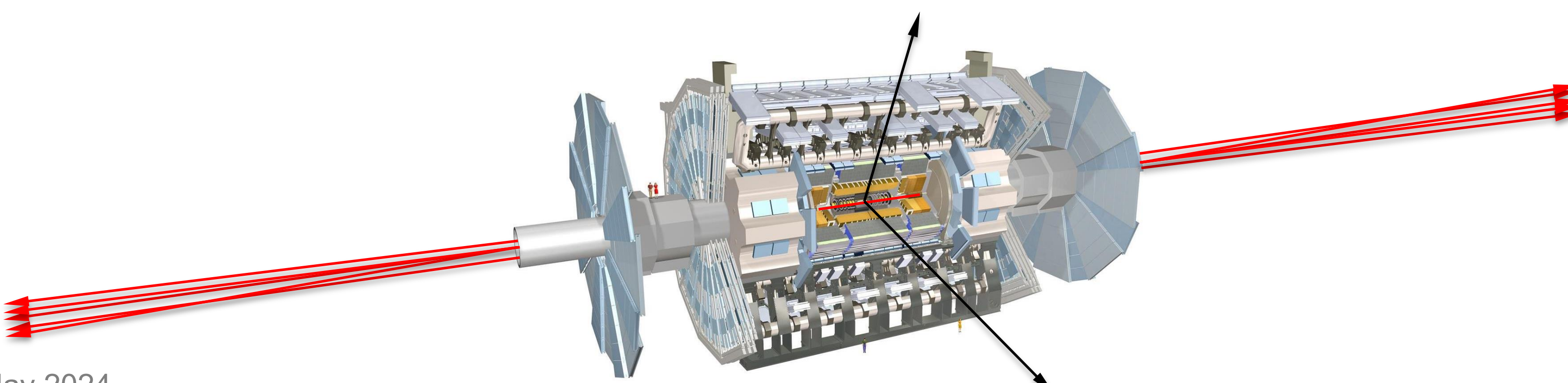
- Momentum:

- Space:



- The opening angle is 0.2 mrad (the moon is 7 mrad). Even 480 m away, most of the signal passes through an 8.5” x 11” (A4) sheet of paper.

- Neutrinos and many new particles are therefore much more collimated than shown below, motivating a relatively small, fast, and inexpensive experiment at the LHC: the ForwArd Search ExpeRiment (FASER).



FASER AT THE LHC

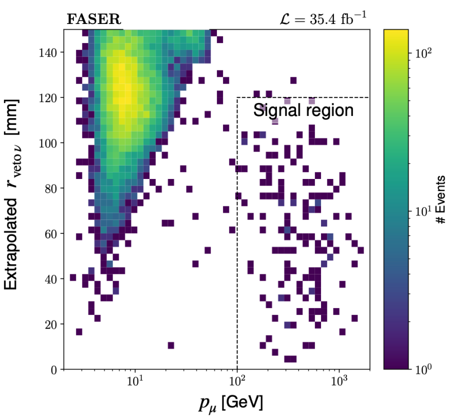
THE FASER DETECTOR

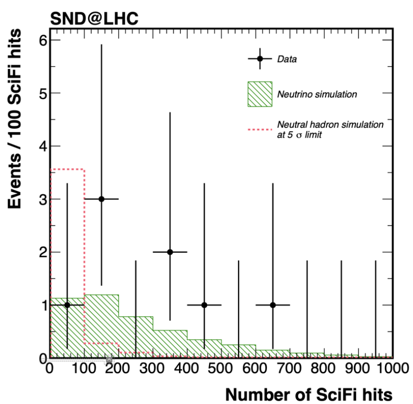
FIRST RESULTS FROM RUN 3

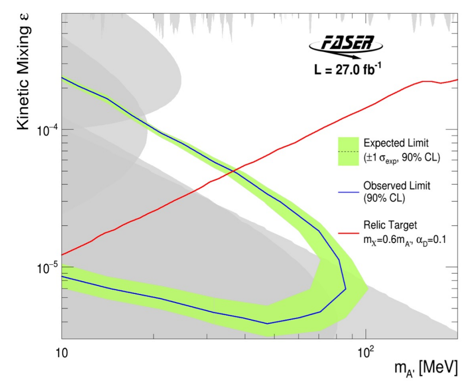
An exciting year for FPF pathfinder experiments. Some highlights:

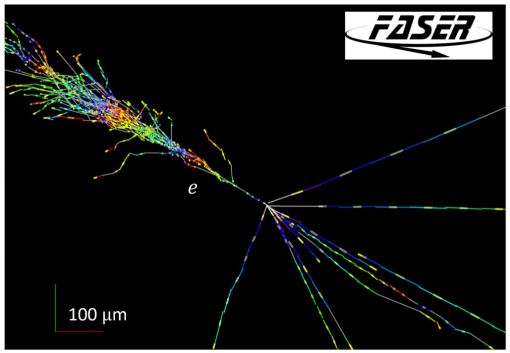
- First Direct Observation of Collider Neutrinos with FASER at the LHC, PRL, 2303.14185
- Observation of Collider Muon Neutrinos with SND@LHC, PRL, 2305.09383
- Search for Dark Photons at FASER, CERN-FASER-CONF-2023-001, PLB, 2308.05587
- Observation of High-Energy Electron Neutrinos with FASERν, CERN-FASER-CONF-2023-002
- Search for U(1)B-L Gauge Bosons at FASER, PLB, 2308.05587
- First Measurement of the ν_e and ν_μ Interaction Cross Sections at the LHC with FASERν, 2403.12520
- Search for ALPs in Photonic Final States with FASER CERN-FASER-CONF-2024-001

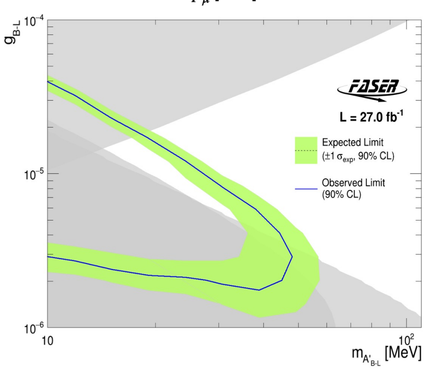
See the following talks

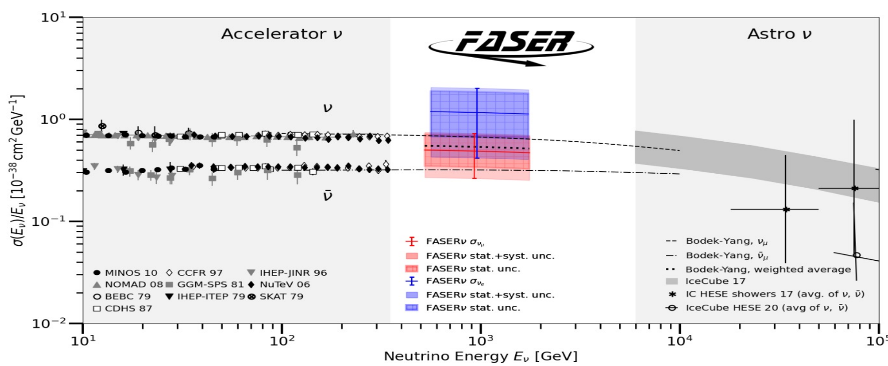


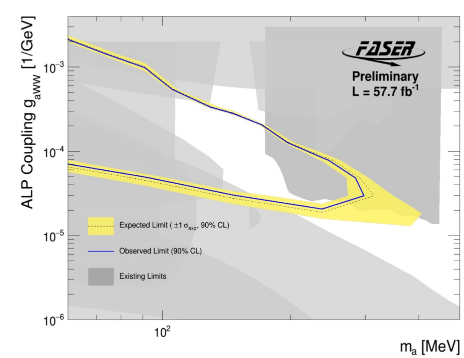










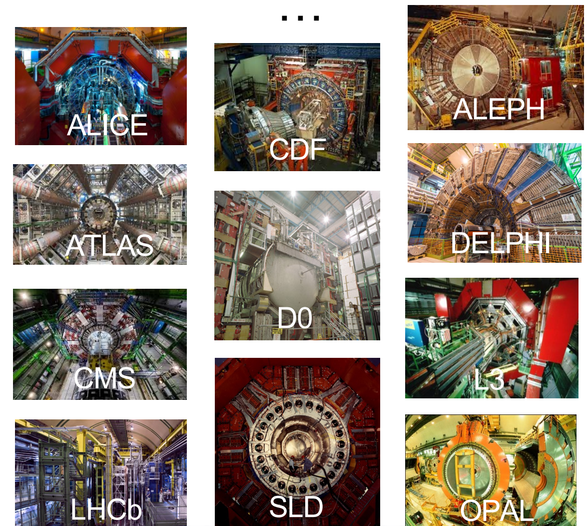


LOCATION, LOCATION, LOCATION

FASER

“Tabletop,” 18 months,
~$1M

153 neutrinos



All previous
collider detectors

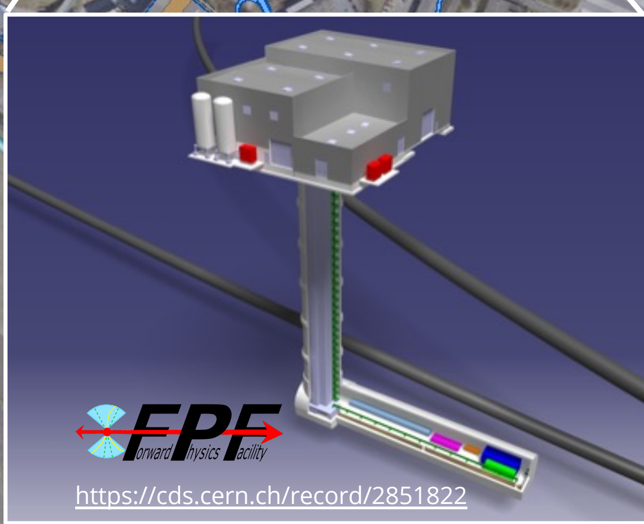
Building-size, decades,
~$1B

0 neutrinos

16σ discovery, opening a new window
at the high energy frontier

FORWARD PHYSICS FACILITY

- Following the results of FASER and SND@LHC, CERN is considering the possibility of creating a dedicated Forward Physics Facility to house far-forward experiments for the rest of the LHC era from 2028-2040s.

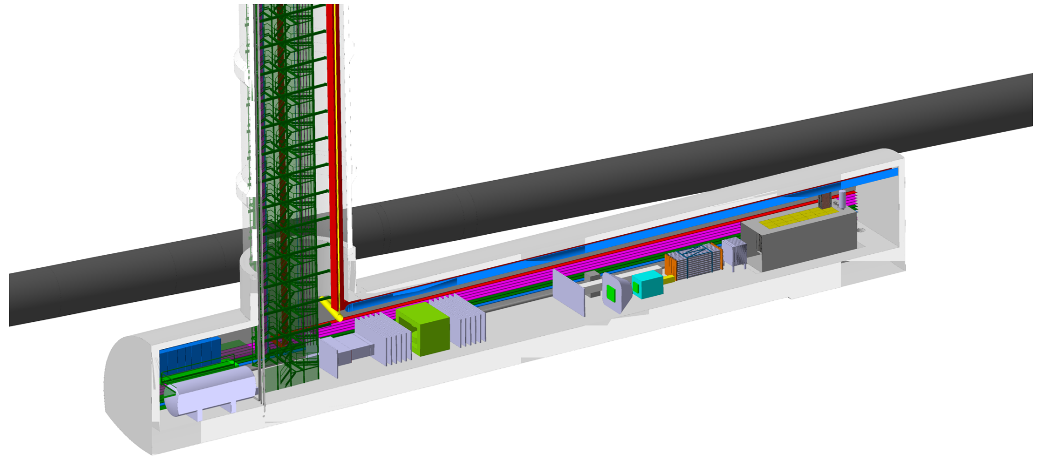


FPF site selection study and core study have identified an ideal site in France just outside the CERN main gate

CERN GIS

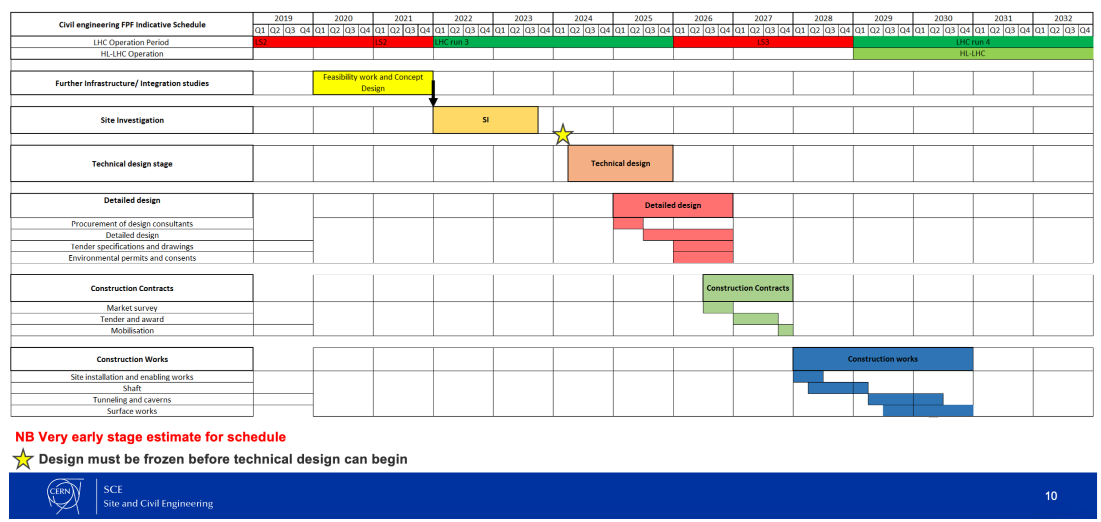
THE FACILITY

- A cylindrical cavern surrounding the LOS, 620-695 m west of the ATLAS IP.
- 75 m long, 12.5 m in diameter, covers $\eta > 5.1$.
- Preliminary (Class 4) cost estimate: 30 MCHF.
- Can be constructed independently of the LHC, does not disrupt LHC running.
- Timeline: construct in LS3/early Run 4, physics starts in late Run 4. Capture as much HL-LHC luminosity as possible.



Bud, Magazinik, Pál, Osborne, et al. CERN CE (2024)

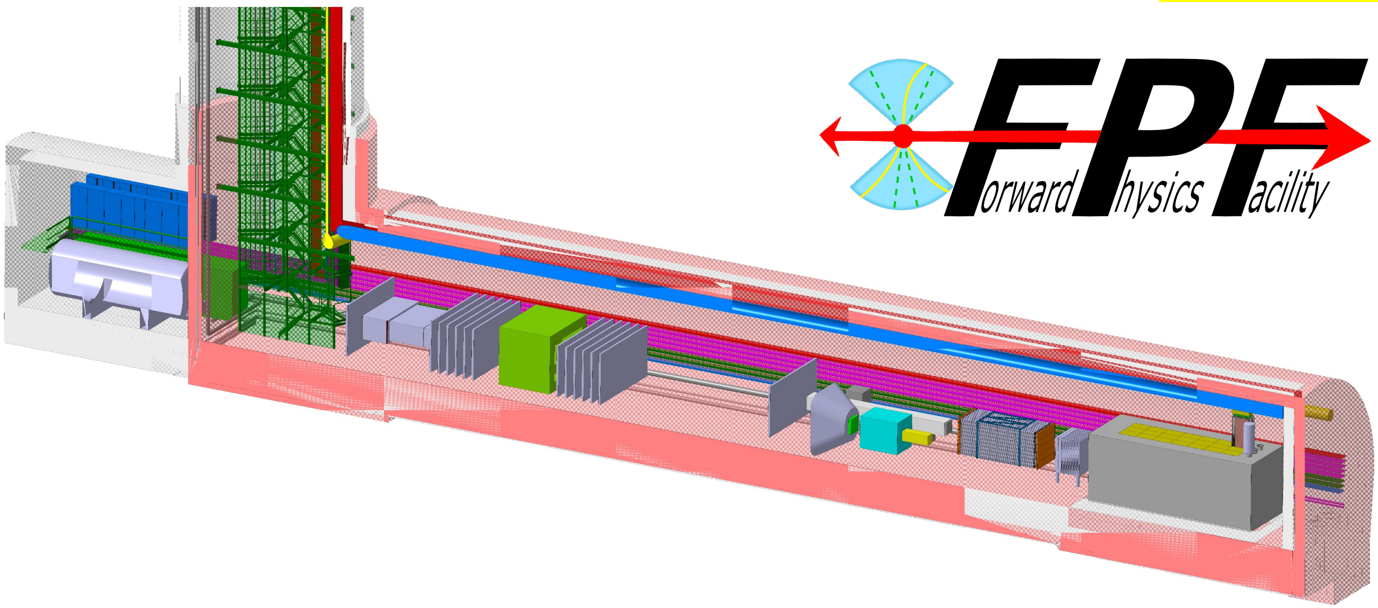
Proposed Civil Engineering Schedule



FPF EXPERIMENTS

- At present there are 4 experiments being designed for the FPF
  - FASER2: magnetized spectrometer for BSM searches
  - FASERν2: 10-ton emulsion-based neutrino detector
  - FLArE: 10-ton LArTPC neutrino detector
  - FORMOSA: scintillator array for BSM searches (successor to MilliQan)

See the following talks



- These represent a huge jump relative to the existing experiments:
  - 10,000 times greater (decay volume * luminosity) for BSM searches.
  - Will detect miilions of TeV neutrinos, ~1000 neutrinos/day!

FPF ORGANIZATION

- The FPF activities are organized into 9 WGs consisting of hundreds of experimentalists on pathfinder experiments, theorists, and multiple CERN technical teams, with active exp/th interactions and optimization between experiments. For more, see fpf.web.cern.ch.

Forward Physics Facility

THE FACILITY · EXPERIMENTS · PHYSICS · PAPERS · TALKS · EVENTS · ORGANIZATION · PRESS · WEB UPDATES

Organization

FPF Working Group Conveners

- **Steering Committee:** Jamie Boyd (CERN), Albert De Roeck (CERN), Milind Diwan (Brookhaven), Jonathan Feng (UC Irvine), Juan Rojo (Nikhef)
- **Coordination Panel:** Aki Ariga (Chiba), Alan Barr (Oxford), Brian Batell (Pittsburgh), Jianming Bian (UC Irvine), Jamie Boyd (CERN), Albert De Roeck (CERN), Milind Diwan (Brookhaven), Jonathan Feng (UC Irvine), Chris Hill (Ohio State), Felix Kling (DESY), Juan Rojo (Nikhef), Dennis Soldin (Utah), Anna Stasto (Penn State)
- **WG0 Facility:** Jamie Boyd (CERN)
- **WG1 Neutrino Interactions**: Juan Rojo (Nikhef)
- **WG2 Charm Production:** Anna Stasto (Penn State)
- **WG3 Light Hadron Production and Astroparticle Connections:** Luis Anchordoqui (Lehman), Dennis Soldin (Utah)
- **WG4 New Physics:** Brian Batell (Pittsburgh), Sebastian Trojanowski (Warsaw)
- **WG5 FASER2:** Alan Barr (Oxford), Josh McFayden (Sussex), Hide Otono (Kyushu)
- **WG6 FASERv2** :Aki Ariga (Chiba), Tomoko Ariga (Kyushu)
- **WG7 FLArE:** Jianming Bian (UC Irvine), Milind Diwan (Brookhaven)
- **WG8 FORMOSA:** Matthew Citron (UC Davis), Chris Hill (Ohio State)

Exp/Th Working Group Liaisons

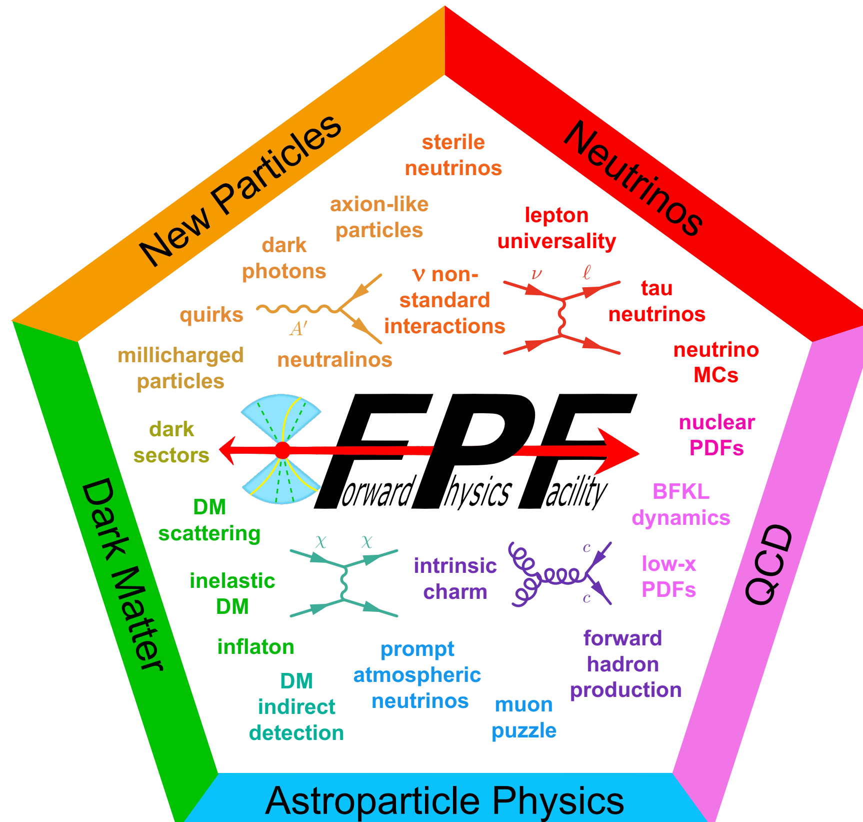
- **WG5 FASER2:** Josh McFayden (Sussex)
- **WG6 FASERnu2:** Aki Ariga (Chiba), Tomoko Ariga (Kyushu)
- **WG7 FLArE:** Steve Linden (Brookhaven), Wenjie Wu (UC Irvine)
- **WG8 FORMOSA:** Matthew Citron (UC Davis)

PBC FPF Subgroup

- **Convener:** Jamie Boyd (CERN)
- **Core Members**: Marco Andreini (CERN), Kincso Balazs (CERN), Jean-Pierre Corso (CERN), Jonathan Feng (UC Irvine), John Osborne (CERN)

FORWARD PHYSICS FACILITY

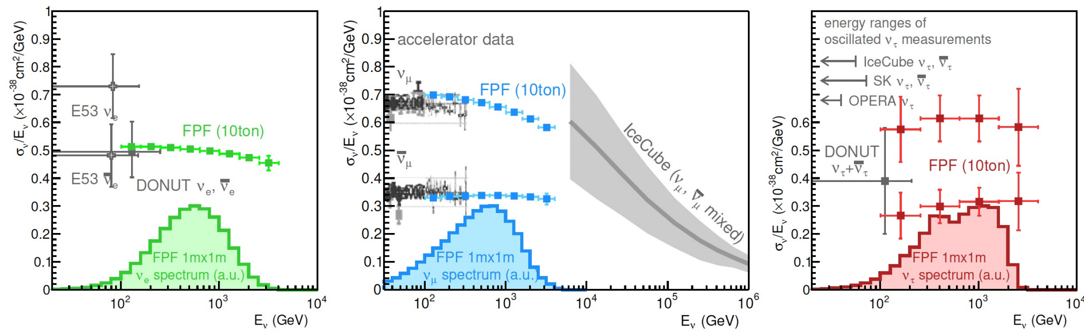
- The physics program has been defined by a large and broad community.
- FPF Meetings
  - FPF Kickoff Meeting, 9-10 Nov 2020
  - FPF2 Meeting, 27-28 May 2021
  - FPF3 Meeting, 25-26 Oct 2021
  - FPF4 Meeting, 31 Jan - 1 Feb 2022
  - FPF5 Meeting, 15-16 Nov 2022
  - FPF6 Meeting, 8-9 Jun 2023
  - FPF Theory Workshop, 19-20 Sep 2023
  - FPF7 Meeting, 29 Feb – 1 Mar 2024
- 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 (2023), 2203.05090.



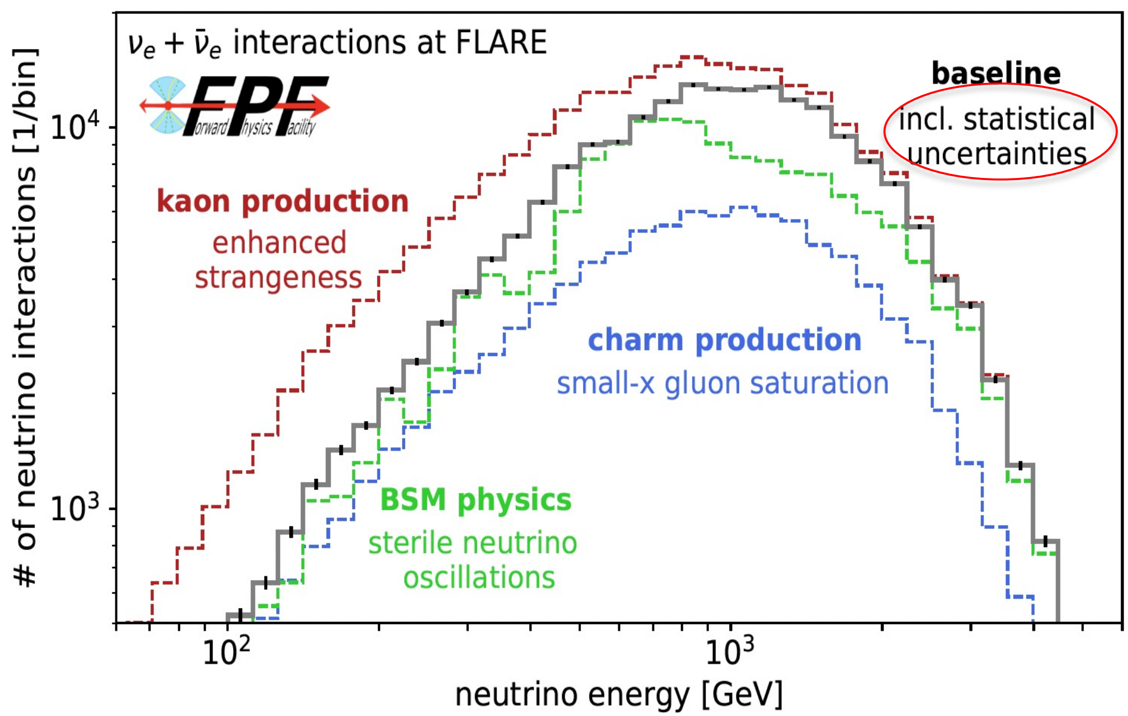
- Far too much physics to discuss comprehensively here – I will give some fun examples, but for more, see these papers and meeting indico pages.

NEUTRINOS AT THE FPF

- 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 almost no data.

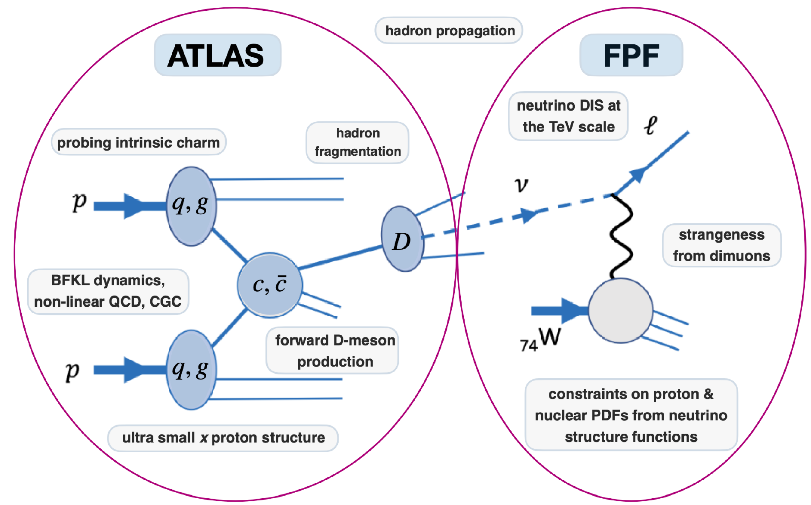


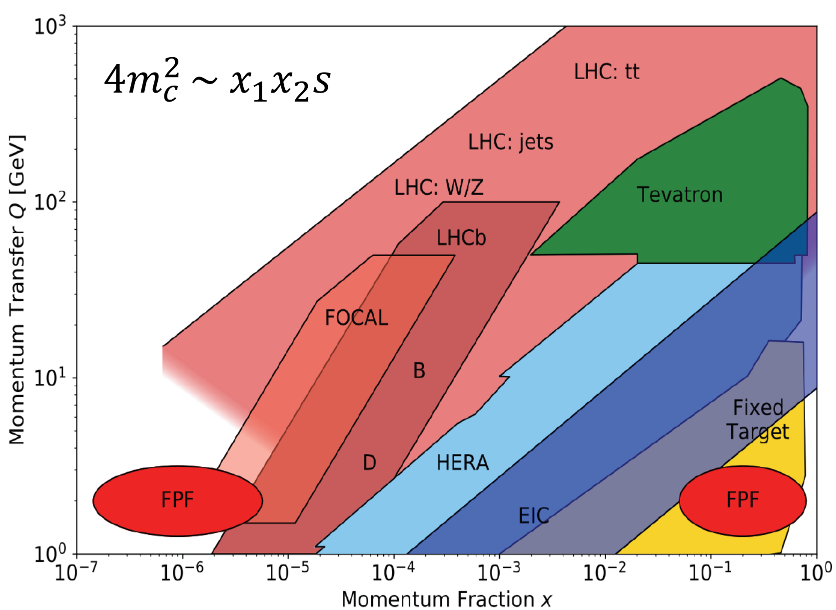
- Neutrinos are produced by forward hadron production: $\pi, K, D, \ldots$. Dependence on E, η will inform
  - Astroparticle physics: muon puzzle, …
  - QCD: pdfs at x ~ 10^{-1}, x ~ 10^{-7} , intrinsic charm, small-x gluon saturation, …
  - Neutrino oscillations: ν_s with $\Delta m^2 \sim 10^3\ \text{eV}^2$

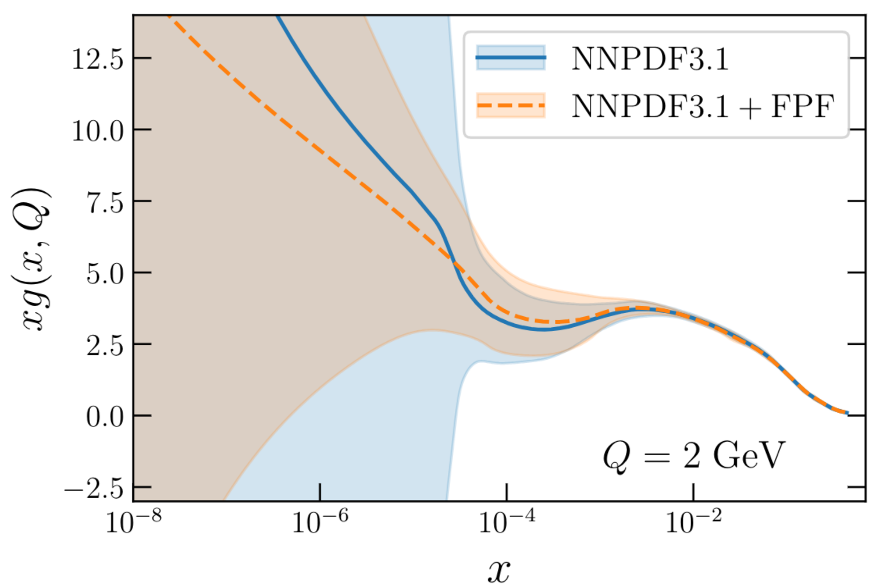


QCD AT THE FPF

- The FPF will enable a rich program of QCD and hadron structure studies.
- Forward neutrino production is a probe of forward hadron production, BFKL dynamics, intrinsic charm, and proton structure at ultra small x ~ 10^{-7} to 10^{-6}.
- Important implications for UHE cosmic ray experiments, ATLAS/CMS at HL-LHC, …



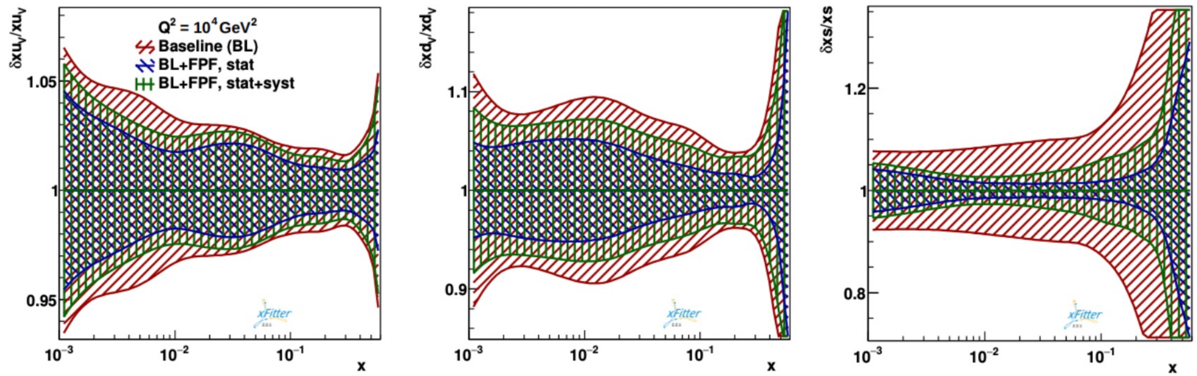




FASER White Paper (2022); Rojo et al. (2024)

OPTIMIZING HIGH P_T STUDIES AND SEARCHES

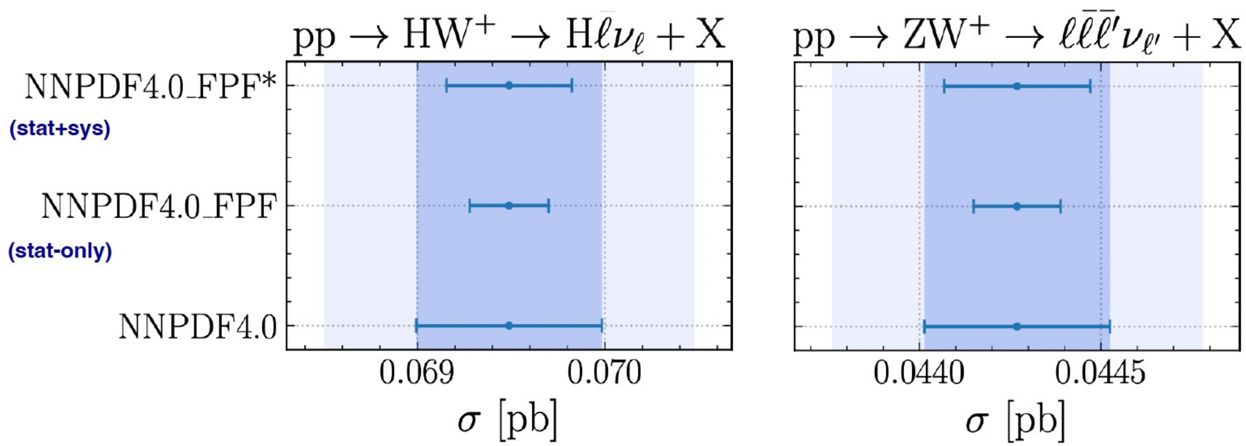
- The FPF will provide new constraints on pdfs that will sharpen studies at ATLAS and CMS.



Cruz-Martinez, Fieg, Giani, Krack, Makela, Rabemananjara, Rojo (2023);
see talk by Max Fieg

- For example, W, Z, and Higgs boson studies.

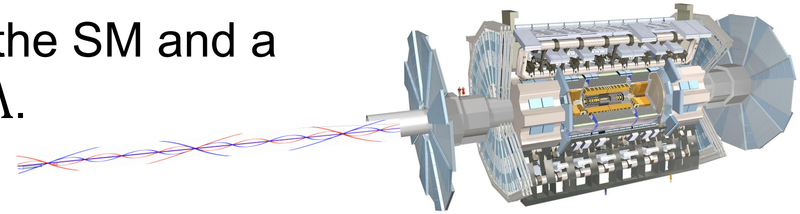
- Will also remove degeneracies between pdfs and new physics ("fitting away new physics"), enhancing the reach for new particle searches.



Ubiali et al., in progress

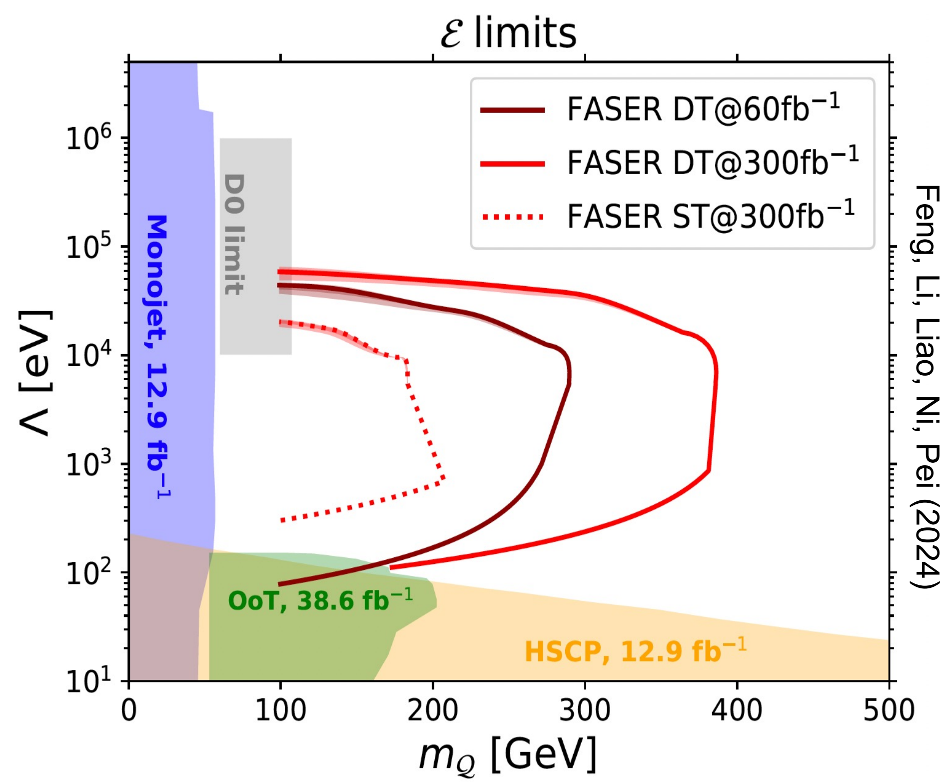
QUIRKS: STRONGLY-INTERACTING DARK SECTORS

- Quirks are particles charged under both the SM and a strong-interacting dark force, with $m \gg \Lambda$.



- Quirks can be pair-produced at the LHC, but the quirk-anti-quirk pair is bound together and has $p_T \approx 0$. They therefore preferentially travel down the beampipe, and may pass through FPF detectors.

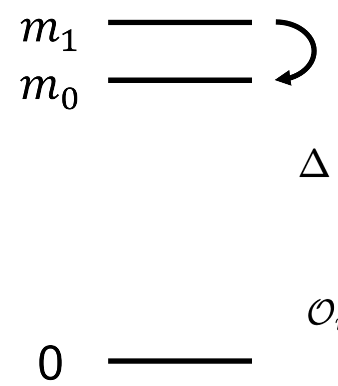
- By looking for 2 coincident slow or delayed tracks (out of time with the bunch crossing), FASER and FASER2 can discover quirks with masses up to ~ hundreds of GeV to TeV, as motivated by neutral naturalness solutions to the gauge hierarchy problem.



- Only possible at the EF, not at fixed target experiments.

LLPS FROM COMPRESSED SPECTRA

- LLPs can result from weak couplings.
- But they can also arise generically from compressed spectra (e.g., inelastic DM), where decays are phase-space suppressed by degeneracies.

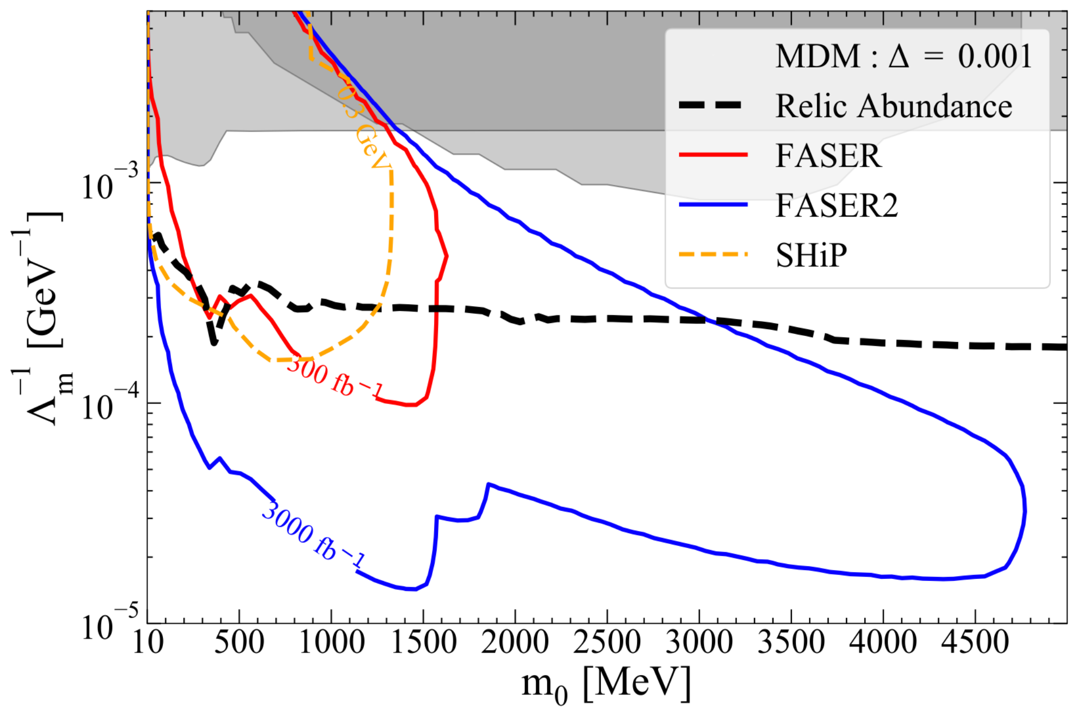


$\chi_1 \to \chi_0 \gamma$

$$\Delta \equiv \frac{\Delta m}{m_0} \equiv \frac{m_1 - m_0}{m_0}$$

$$\mathcal{O}_m = \frac{1}{\Lambda_m} \overline{\chi}_1 \sigma^{\mu\nu} \chi_0 F_{\mu\nu}$$

- In this case, decays $\chi_1 \to \chi_0 \gamma$ lead to very soft photons that can be difficult to detect.
- But these are boosted at the LHC by $\gamma \sim 1000$, FASER2 can detect GeV particles with even ~MeV mass splittings, thermal relic target.
- Difficult at SHiP (sensitivity contour assumes E_γ threshold of 300 MeV, 2 10^{20} POT).

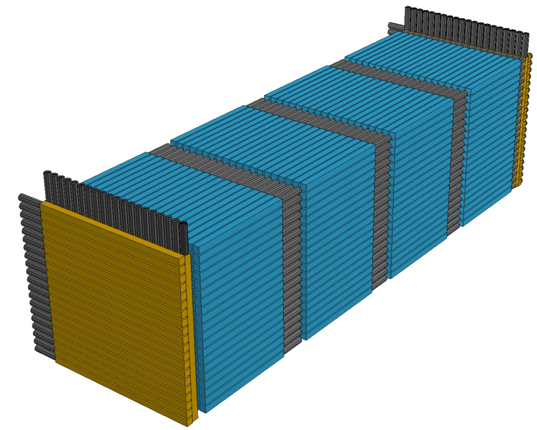


Dienes et al. (2023)

MILLI-CHARGED PARTICLES

- The FPF accommodates a suite of experiments that can be optimized for various physics cases. This diversity is essential in probing a broad range of BSM physics possibilities.

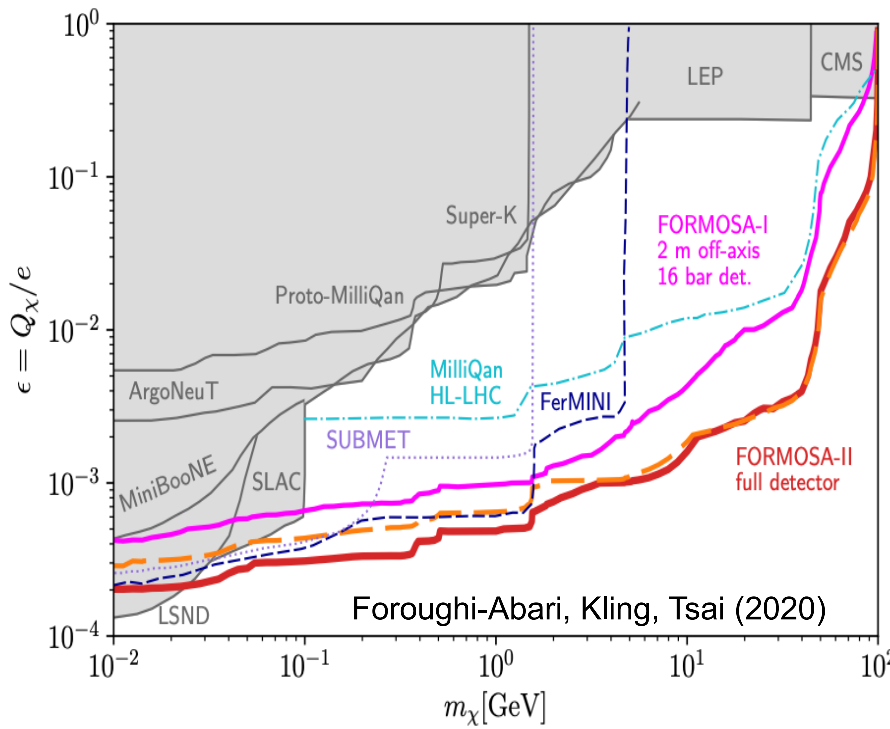
- For example: FORMOSA, targeting milli-charged particles.



- Motivated by dark sectors with massless dark photons, but also new particles with magnetic or electric dipole moments, …

- World-leading sensitivity for masses from ~100 MeV to 100 GeV.

- Will not be probed by SHiP (and no fixed target experiment can produce particles with mass > 10-20 GeV).



SUMMARY

- The forward region, previously largely neglected, is in fact a treasure trove of interesting physics.
  - Collider neutrinos at TeV energies, opening a new window on neutrino properties, QCD, astroparticle physics, and high p_T physics.
  - World-leading searches for light (and also heavy) BSM particles, including many motivated by dark matter.
- The multi-messenger era in collider physics: FASER and SND@LHC have shown that this treasure can be mined by small, fast, and cheap detectors, producing world-leading, background-free results on budget and on time.
- These results imply a paradigm shift: forward experiments are not auxiliary experiments hunting for exotica; they are neutrino detectors that are integral to fully exploiting the energy frontier, just like trackers and calorimeters.
- The Forward Physics Facility is now being considered to fully exploit this new capability for the HL-LHC era from 2028-2042. Without it, the LHC will be blind to neutrinos. With it, we will see 1000's of TeV neutrinos each day.