NEW EYES FOR THE LHC

Minnesota Physics and Astronomy Colloquium

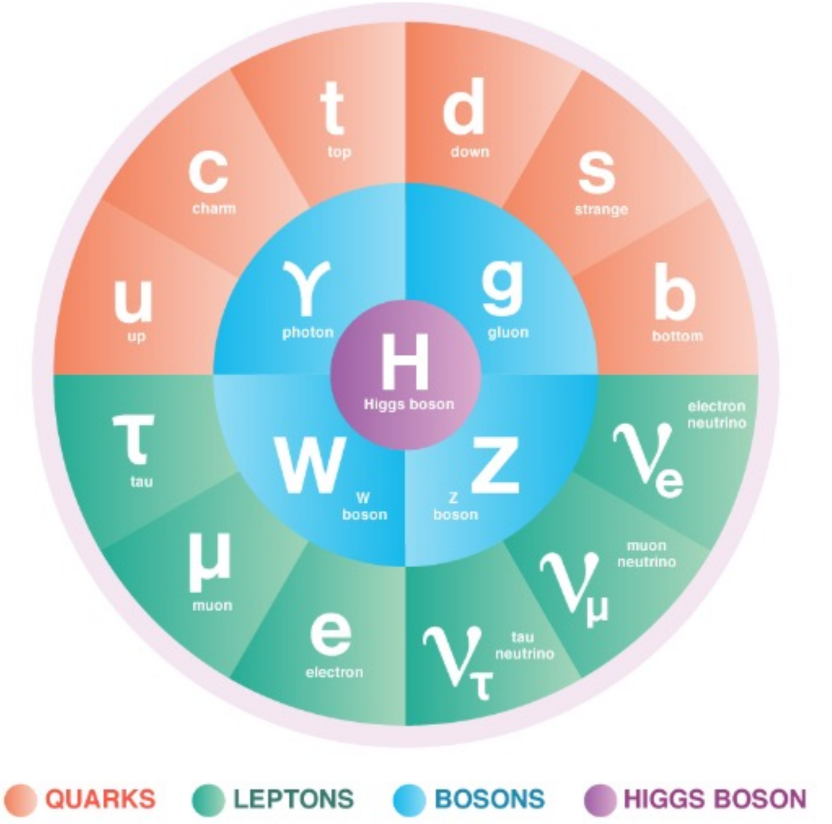
Jonathan Feng, UC Irvine, 21 November 2024

THE STANDARD MODEL OF PARTICLE PHYSICS

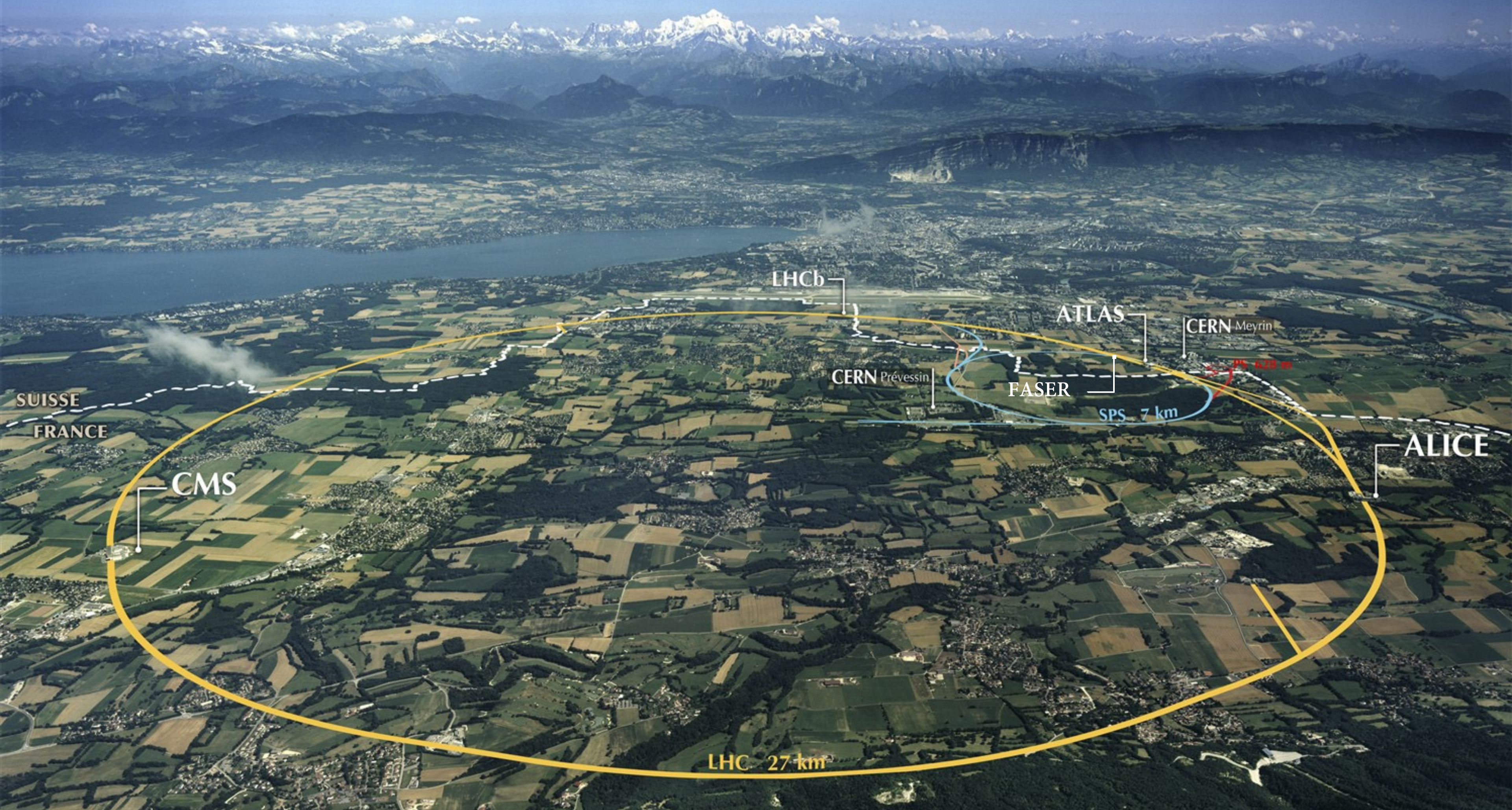
- The Standard Model is the reigning theory of fundamental particles and their interactions. The last particle predicted by the SM, the Higgs boson, was discovered at CERN in 2012.

- But the SM is not the last word, because many fundamental questions remain. For example:
  - Neutrino Masses: the SM predicts that neutrinos are massless, but they aren't.
  - Dark Matter: The particles of the SM make up only ~15% of the matter in the universe.

- These questions imply that there are more particles left to discover, and probably many more.



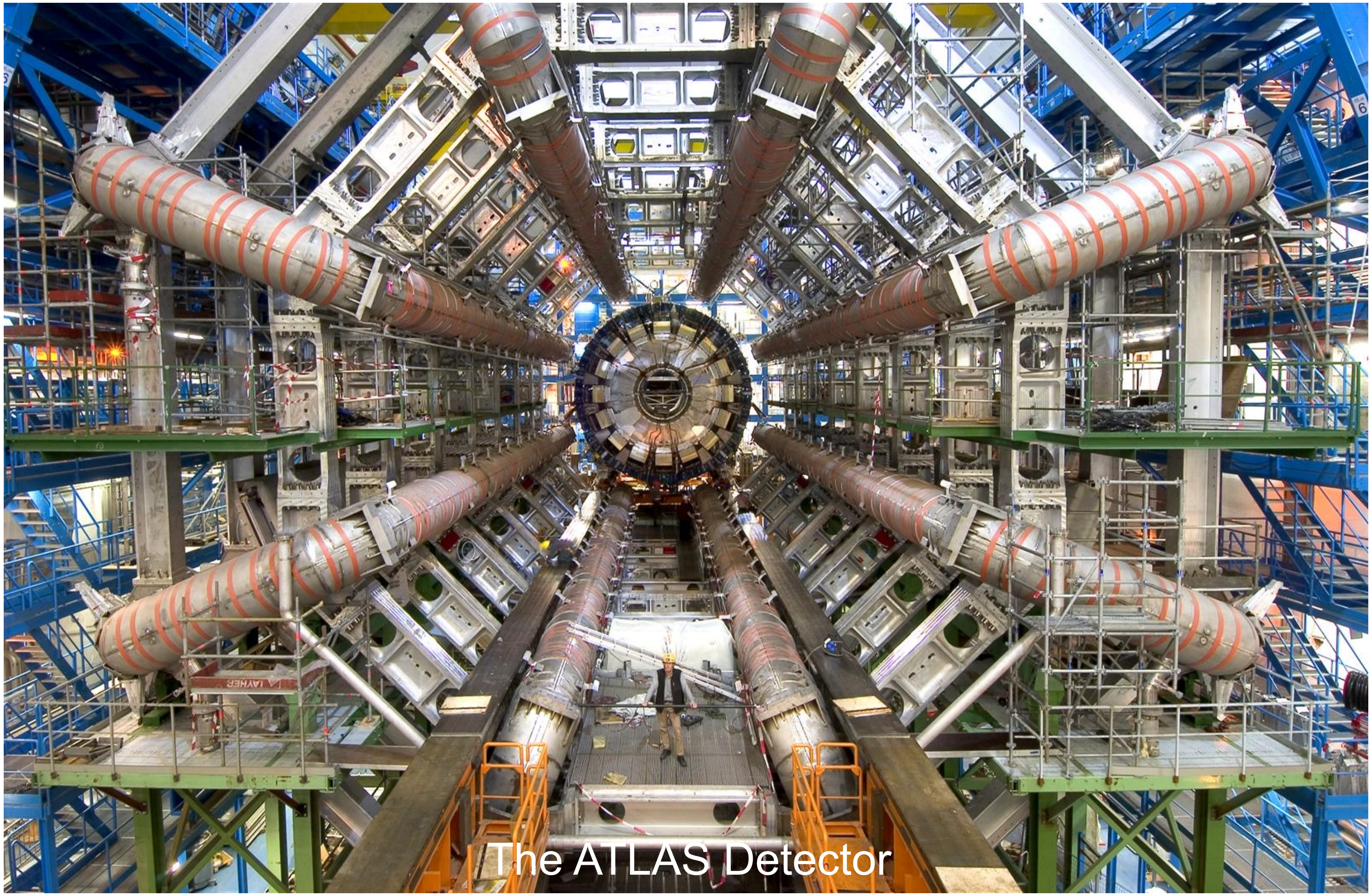
THE LARGE HADRON COLLIDER



Particle colliders have been key to progress for many decades. The state of the art is currently the LHC, which collides protons with protons at a center-of-mass energy of 13.6 TeV ($v \approx 0.9999999905\,c$).

LHC DETECTORS

The protons collide at 4 points around the LHC, and each point is surrounded by a large detector to view the results of the collisions. These detectors are were constructed over decades by thousands of collaborators.

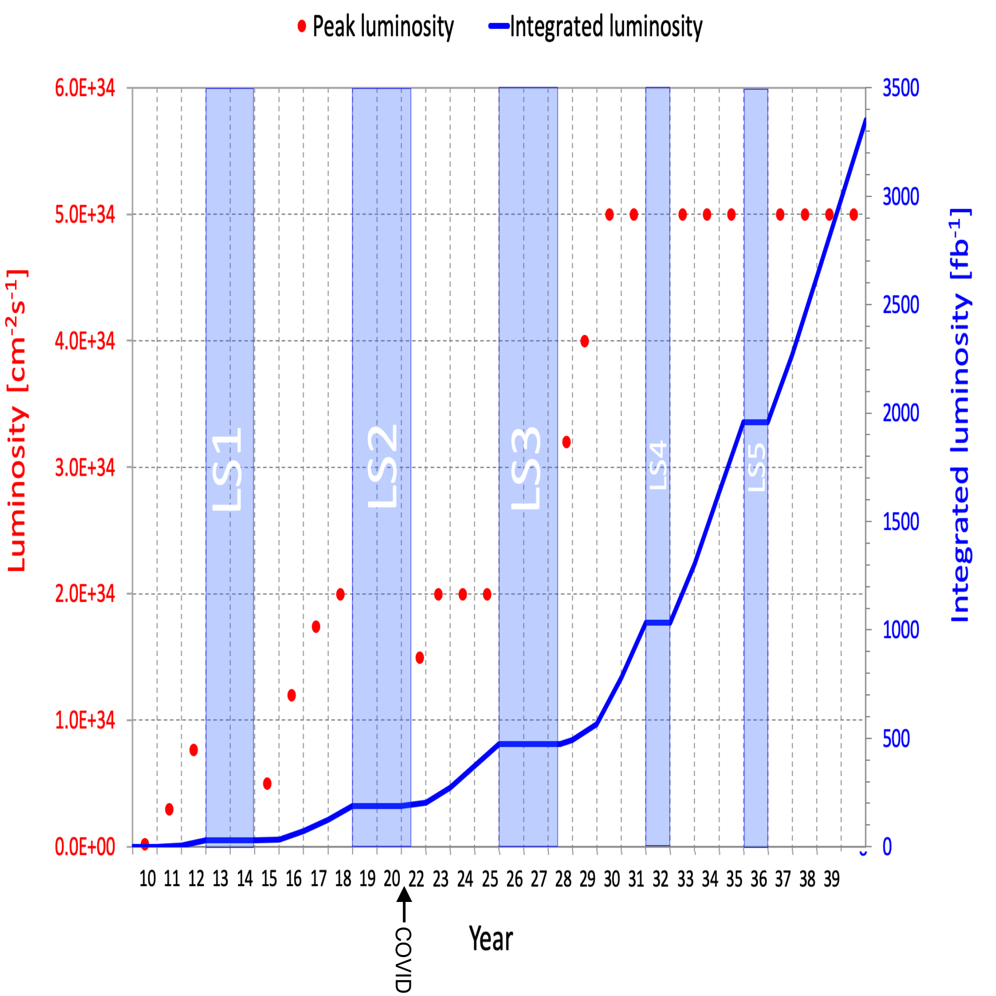


LIFETIME OF THE LHC

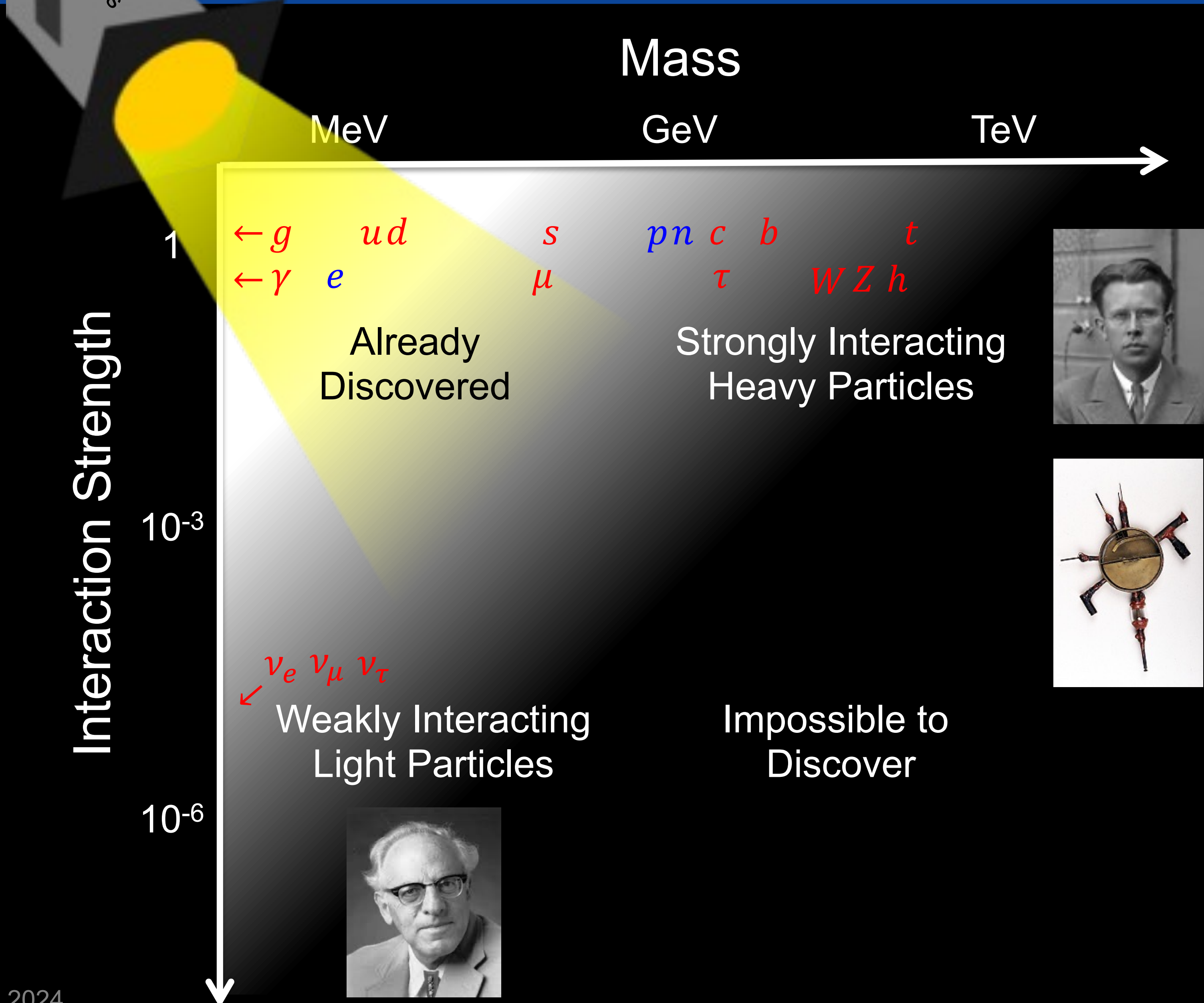
- The LHC became the future of particle colliders in 1993 when the US canceled the SSC, which was being built in Texas.

- The LHC started running in 2010 and is scheduled to run until the 2040s.
  - Middle-aged in terms of years
  - But a 4th grader in terms of number of collisions (integrated luminosity)

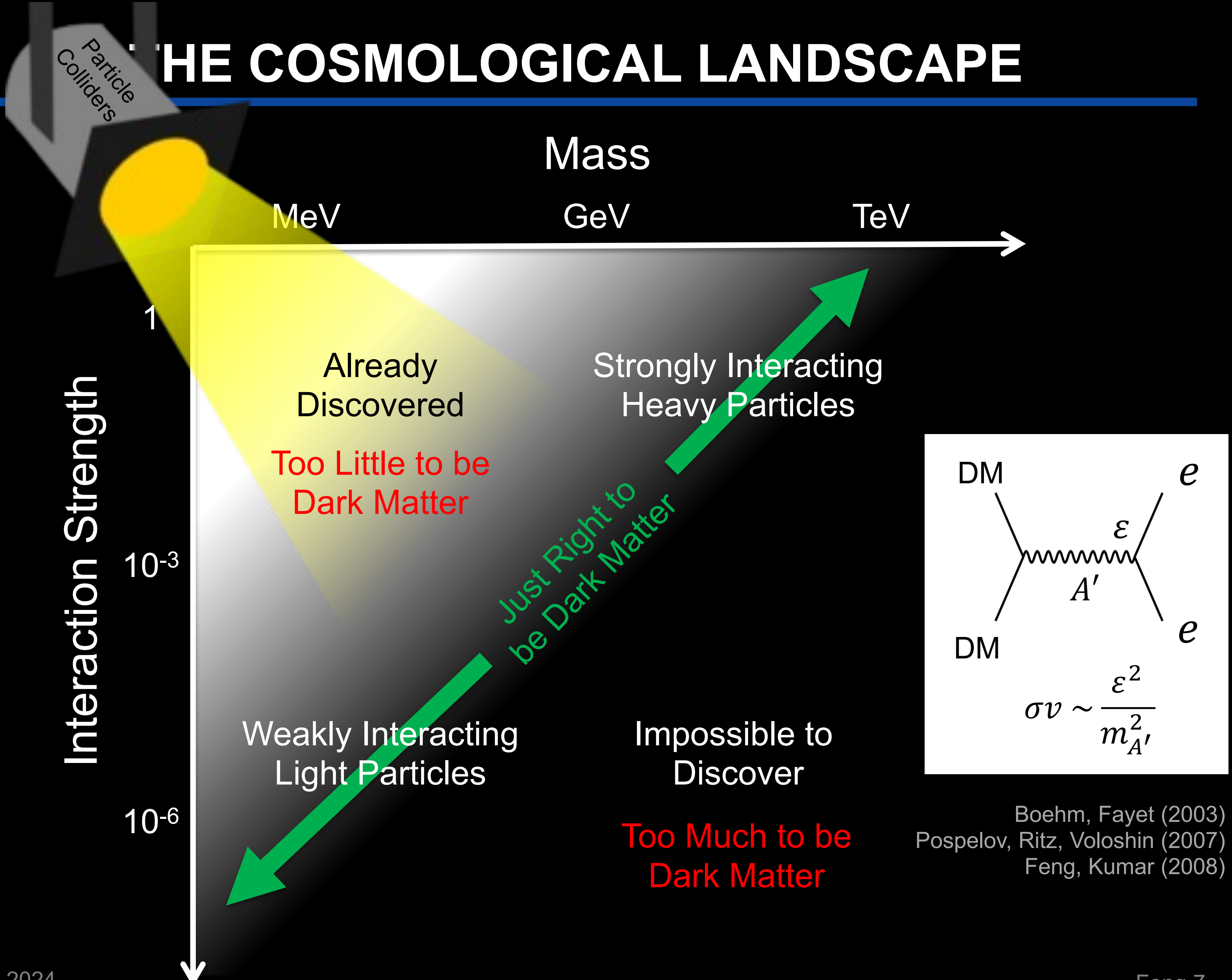
- Are we using the LHC to its full potential? If not, what can we do to enhance its discovery prospects?



THE PARTICLE LANDSCAPE



THE COSMOLOGICAL LANDSCAPE

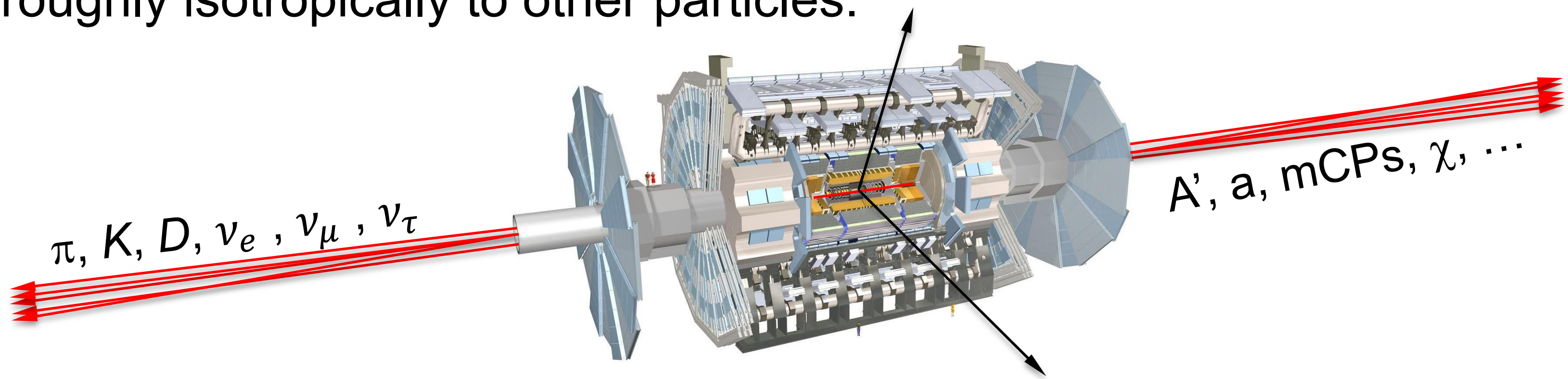


Boehm, Fayet (2003)
Pospelov, Ritz, Voloshin (2007)
Feng, Kumar (2008)

FORWARD PHYSICS

- In 2017, we realized that the large LHC detectors, while beautifully optimized to discover new heavy particles, are also almost optimally configured NOT to find new light particles. Feng, Galon, Kling, Trojanowski (2017)

- Heavy particles (*W*, *Z*, *t*, *h*, …) are produced at low velocity and decay roughly isotropically to other particles.

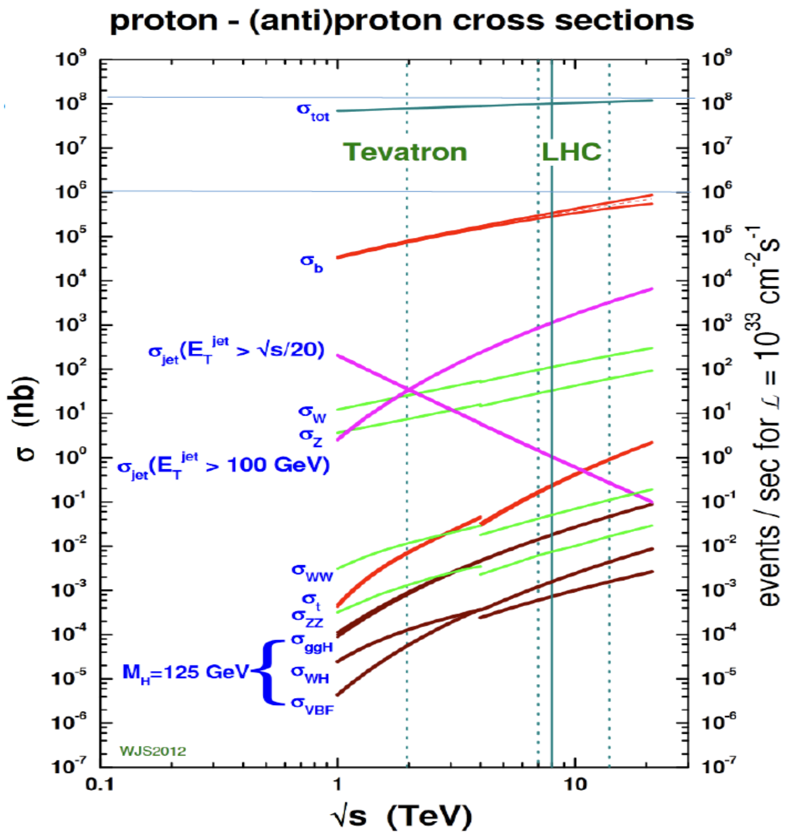


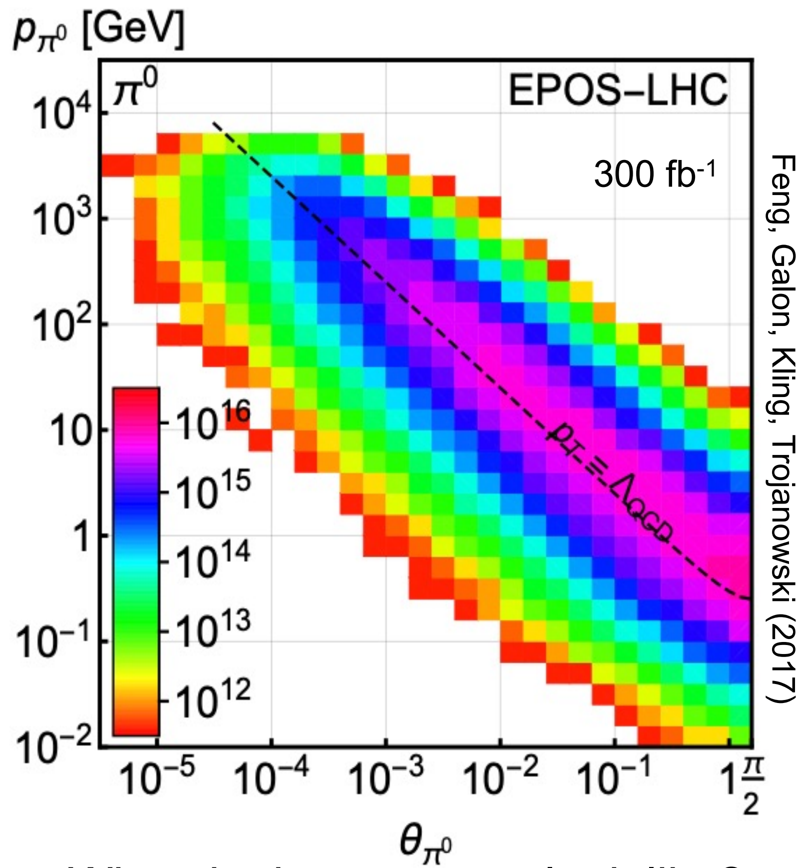
- But high-energy light particles are dominantly produced in the forward direction and escape through the blind spots of these large detectors.
  - This is true for all known light particles: pions, kaons, *D* mesons, all neutrinos.
  - It is also true for many proposed new particles, especially those 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



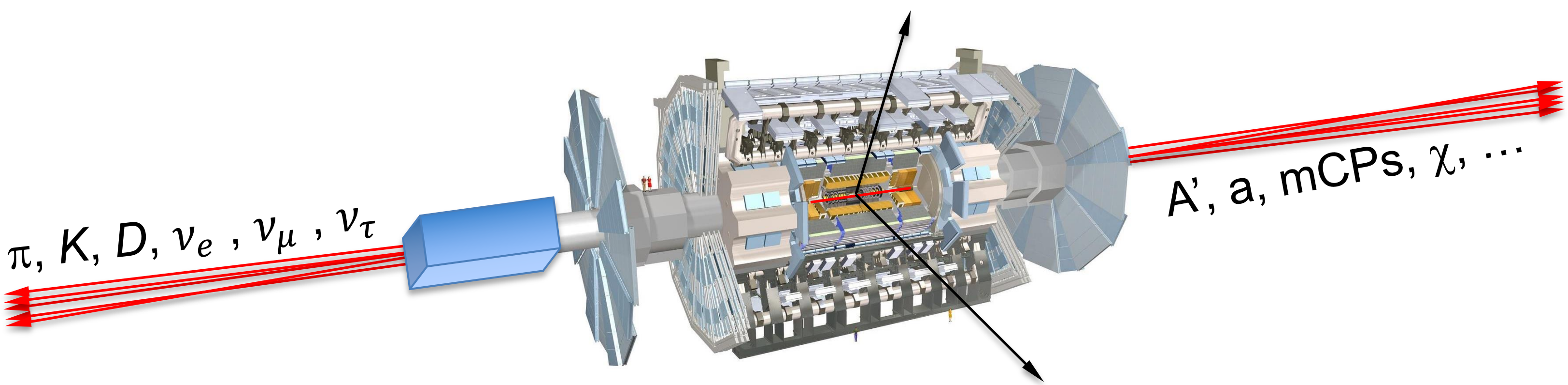


- Most searches have focused on processes with σ ~ fb, pb.
- But the total cross section is σ_{tot} ~ 100 mb and most of it is typically treated as useless.
- What do these events look like? Consider pions (decays to ν, BSM).
- Enormous event rates. Typical p_T ~ 250 MeV, but many with p ~ TeV within 1 mrad ($\eta > 7.6$) of the beamline.

DETECTING FORWARD PARTICLES

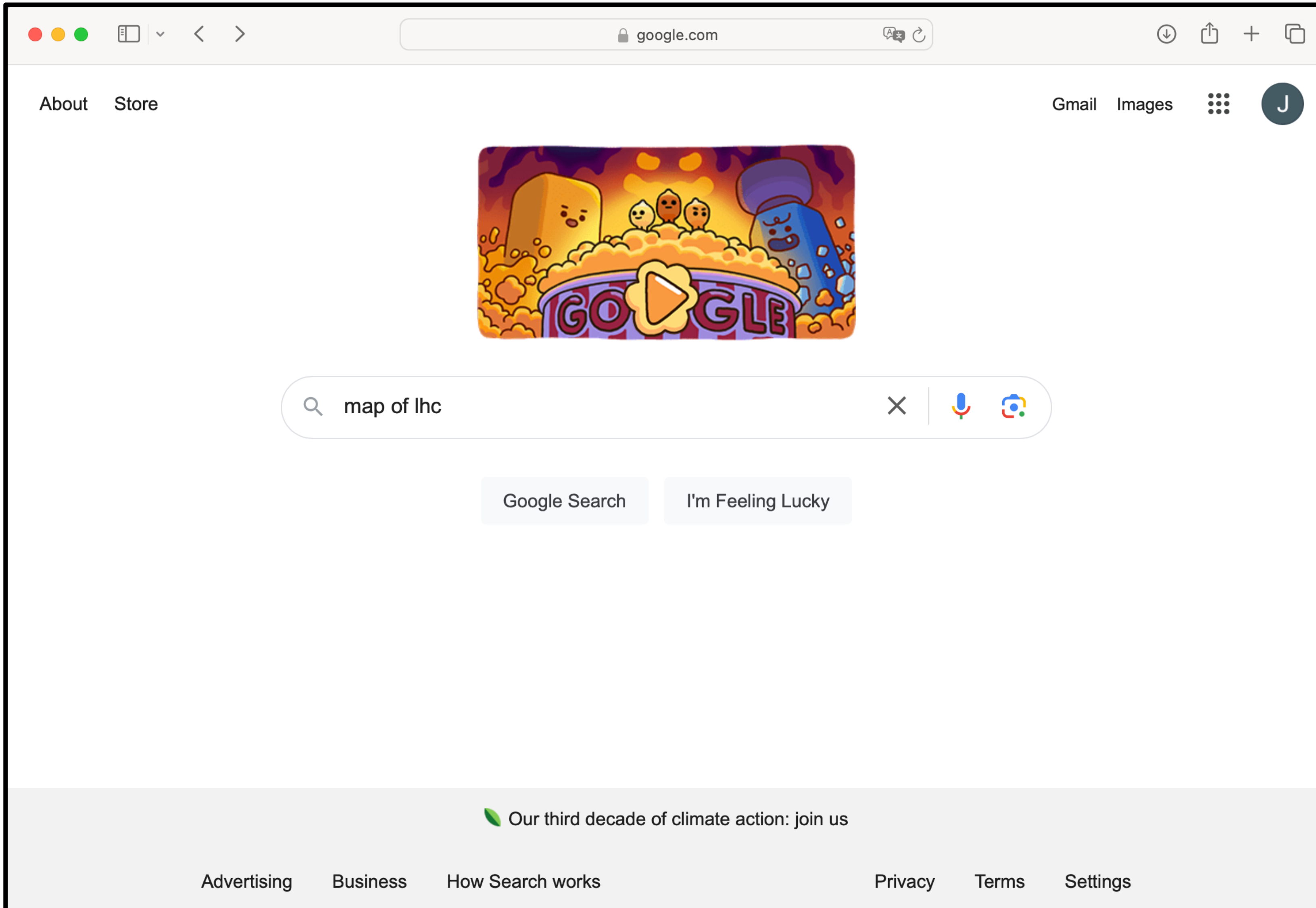
- To capture the enormous forward flux, we need to detect particles that are produced in the forward direction along the beamline.

- Problem: we can't just put the detector there: they will block the protons from coming in.

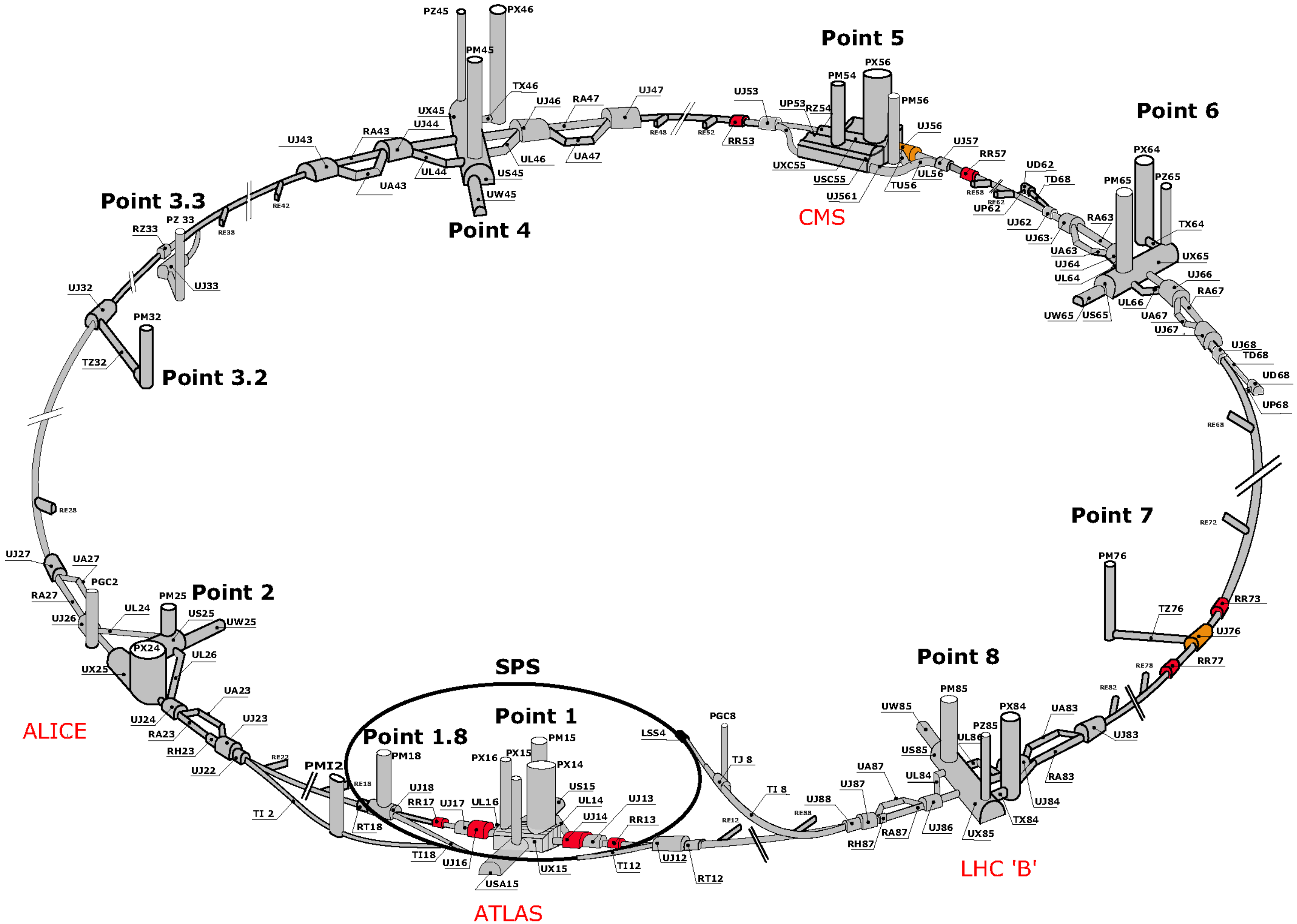


- Solution: the LHC is a circular collider! If we go far enough away, the LHC proton beam will curl away, while all the light, weakly-interacting particles we are looking for will go straight.

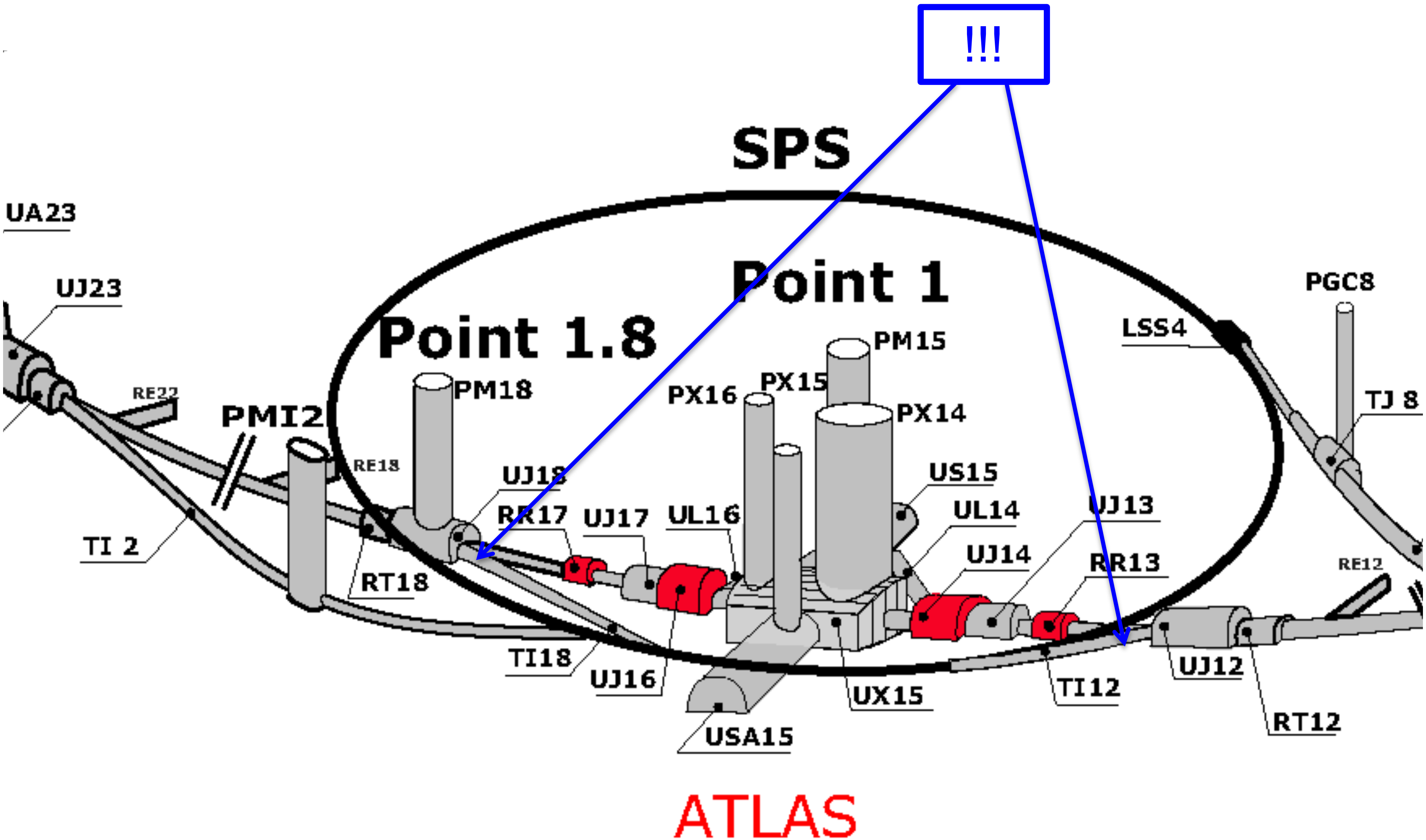
SOPHISTICATED RESEARCH



SOPHISTICATED RESEARCH



MAP OF LHC



!!!
SPS
Point 1
Point 1.8
UA23
UJ23
RE22
PMI2
RE18
TI 2
PM18
UJ18
RR17
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UL16
PX16
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PM15
PX14
US15
UL14
UJ14
UJ13
RR13
LSS4
PGC8
TJ 8
RE12
RT18
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UJ16
USA15
UX15
TI12
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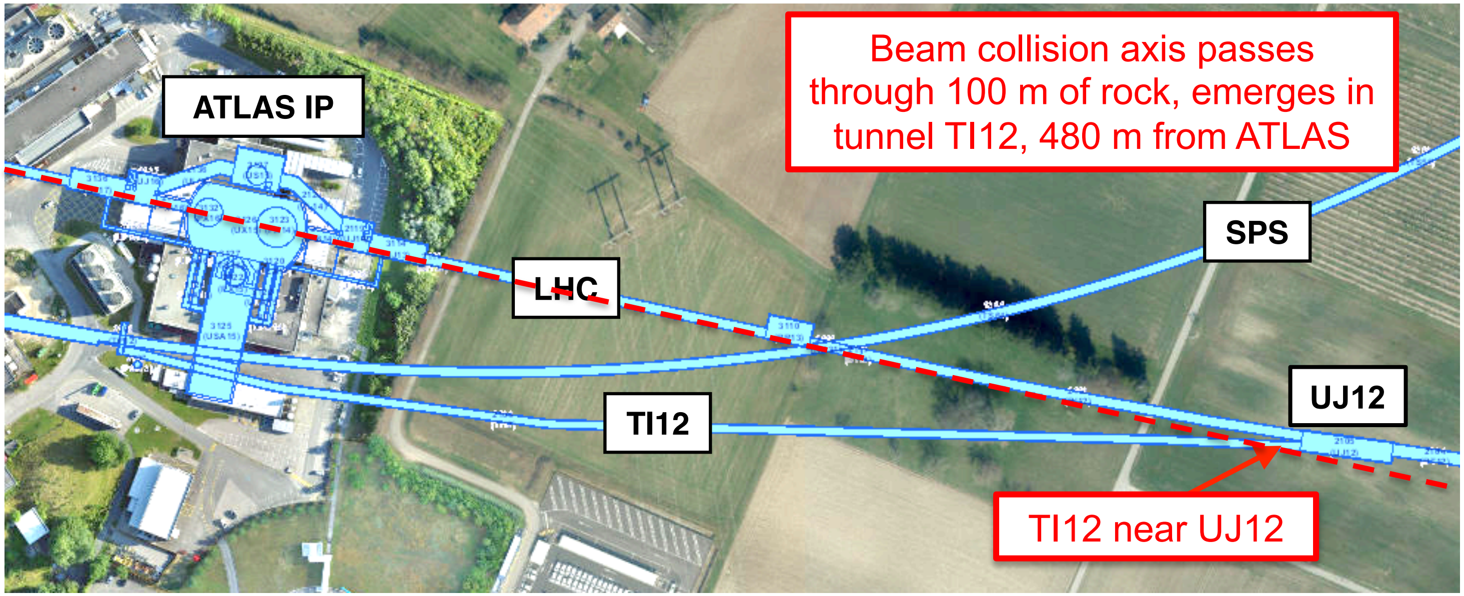
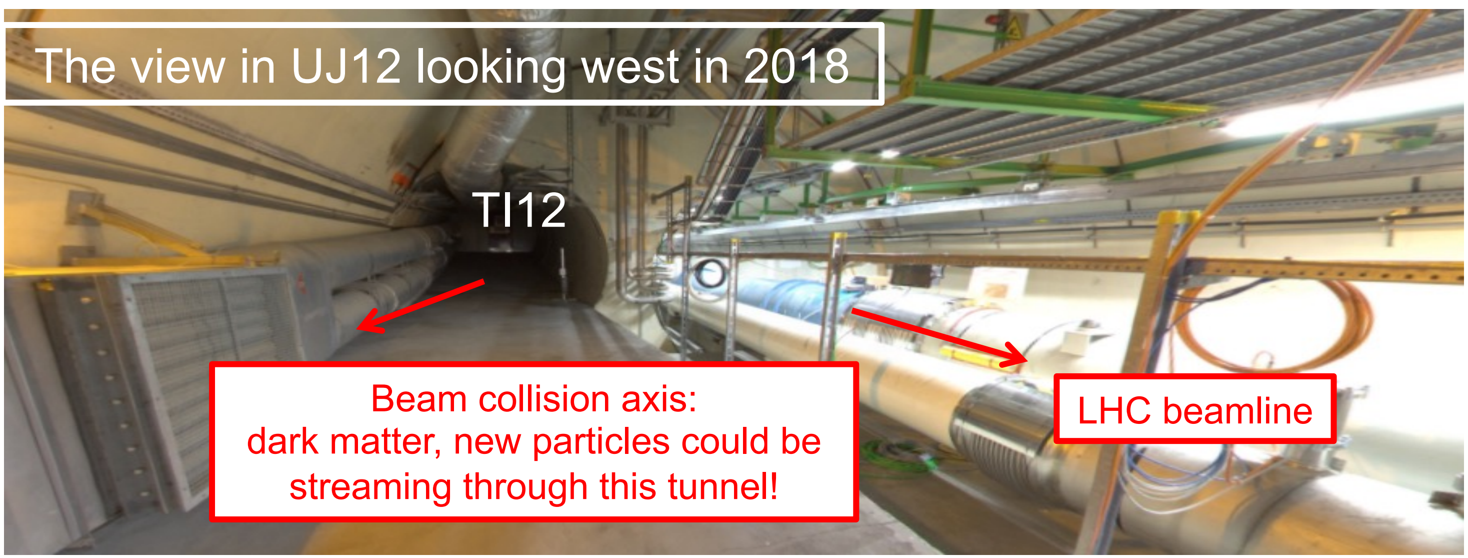
RT12
ATLAS

THE FORWARD REGION





HISTORY: THE FALL OF FORWARD PHYSICS

- Is it really possible that a collider is making new particles, and we are missing them simply because we are looking in the wrong place?
- Yes. In fact, it happened before at CERN.
- In 1971, the first hadron collider, CERN's Intersecting Storage Rings (ISR), began operation.
- It had a circumference of ~1 km, collided protons with protons at center-of-mass energy 30 GeV.

HISTORY: THE FALL OF FORWARD PHYSICS

- During ISR's 50th anniversary, there were many fascinating articles and talks by eminent physicists
  - "Enormous impact on accelerator physics, but sadly little effect on particle physics." – Steve Myers, talk at "The 50th Anniversary of Hadron Colliders at CERN," October 2021.
  - "There was initially a broad belief that physics action would be in the forward directions at a hadron collider…. It is easy to say after the fact, still with regrets, that with an earlier availability of more complete… experiments at the ISR, CERN would not have been left as a spectator during the famous November revolution of 1974 with the J/ψ discoveries at Brookhaven and SLAC ." – Lyn Evans and Peter Jenni, "Discovery Machines," CERN Courier (2021).

- Bottom line: The collider was creating charm quarks, but, based on theoretical prejudice, experimentalists focused on the forward region and so missed them.

- Since that time, forward physics at colliders has been almost completely ignored for new particle searches.

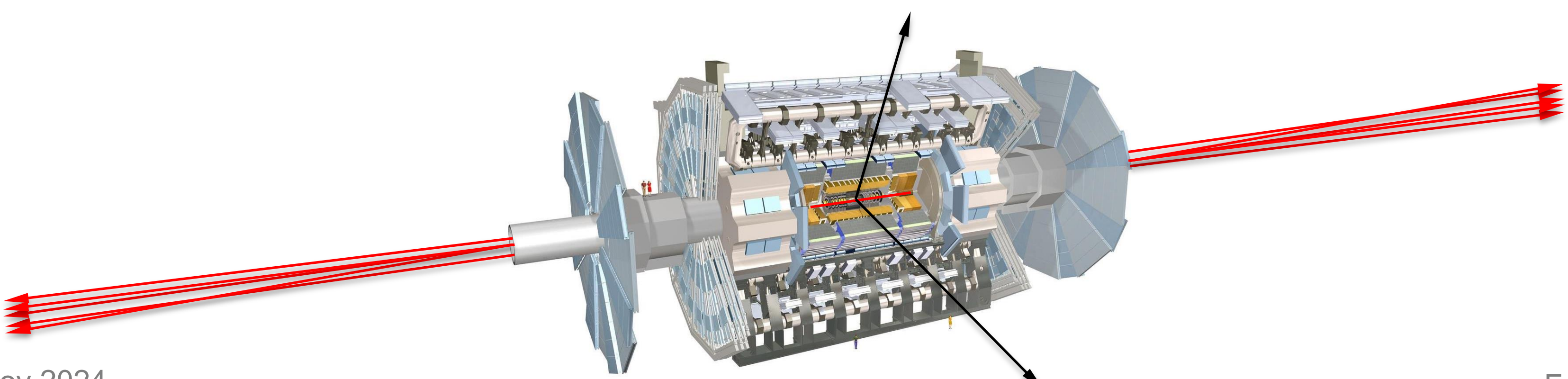
- But are we making the same mistake now (in reverse)? And could there be another November revolution waiting for us in the forward direction?

HOW BIG DOES THE DETECTOR HAVE TO BE?

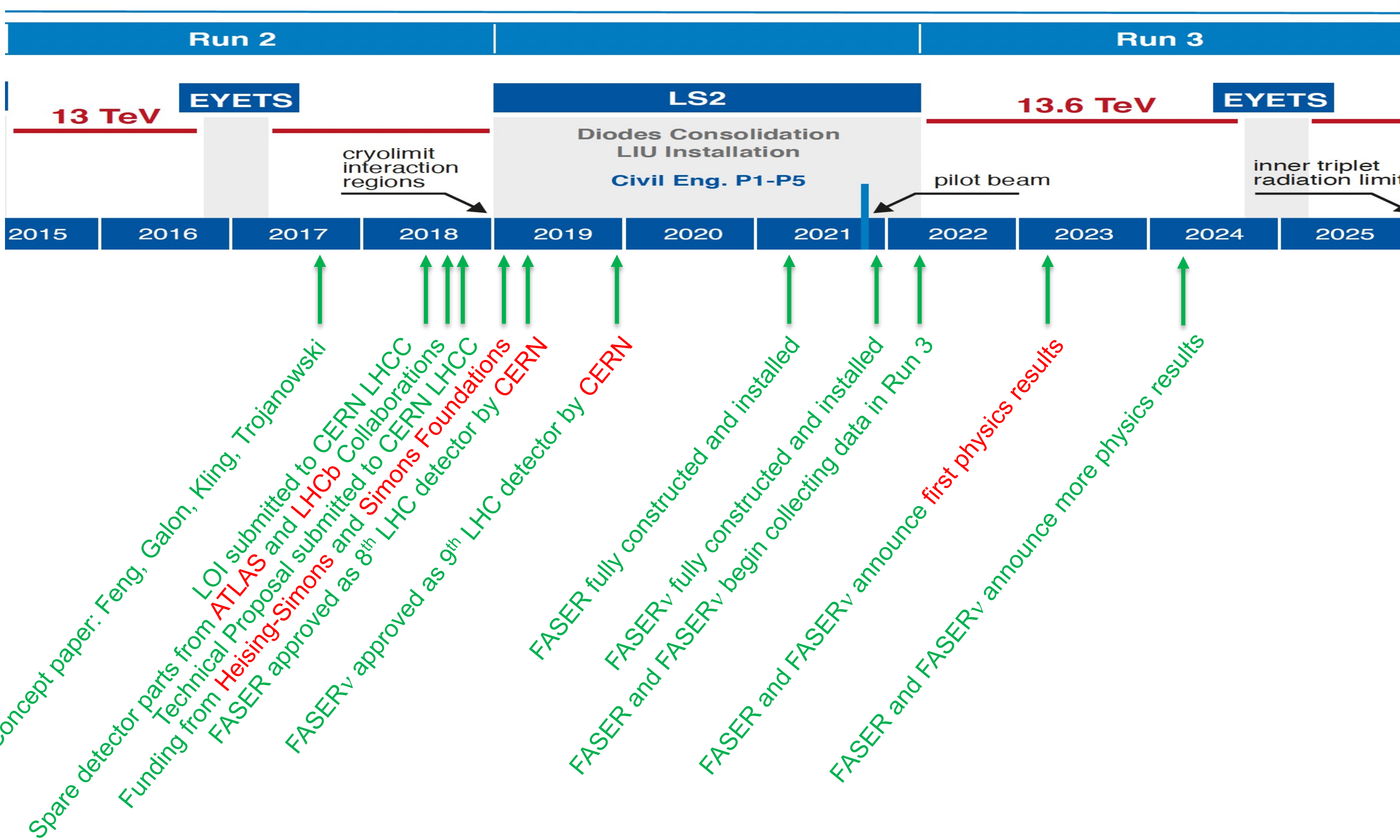
- Momentum: 250 MeV / 1 TeV
- Space: 12 cm / 480 m

- 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 AND FASERν TIMELINE



FASER COLLABORATION

112 collaborators, 28 institutions, 11 countries

CERN
UNIVERSITÉ DE GENÈVE
KYUSHU UNIVERSITY
UC IRVINE

UNIVERSITÄT BERN
Technion Israel Institute of Technology
NAGOYA UNIVERSITY
UNIVERSITY of WASHINGTON

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE
CHIBA UNIVERSITY
UNIVERSITY OF OREGON

DESY.
INFN
ISS
International laboratory covered by a cooperation agreement with CERN
清華大學
Tsinghua University
ROYAL HOLLOWAY UNIVERSITY OF LONDON

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II
UNIVERSITY OF LIVERPOOL
ZHENGZHOU UNIVERSITY
NATIONAL INSTITUTE OF TECHNOLOGY (KOSEN), NIIHAMA COLLEGE
UNIVERSITY OF SUSSEX

Nikhef
UNIVERSITÄT BONN
ETH zürich
UKRI Science and Technology Facilities Council
Rutherford Appleton Laboratory
MANCHESTER 1824
The University of Manchester

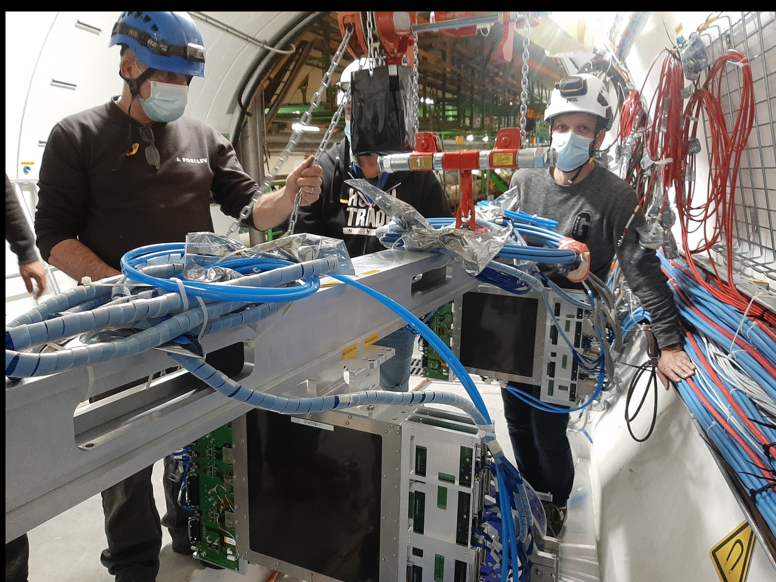
PREPARATION OF THE FASER LOCATION

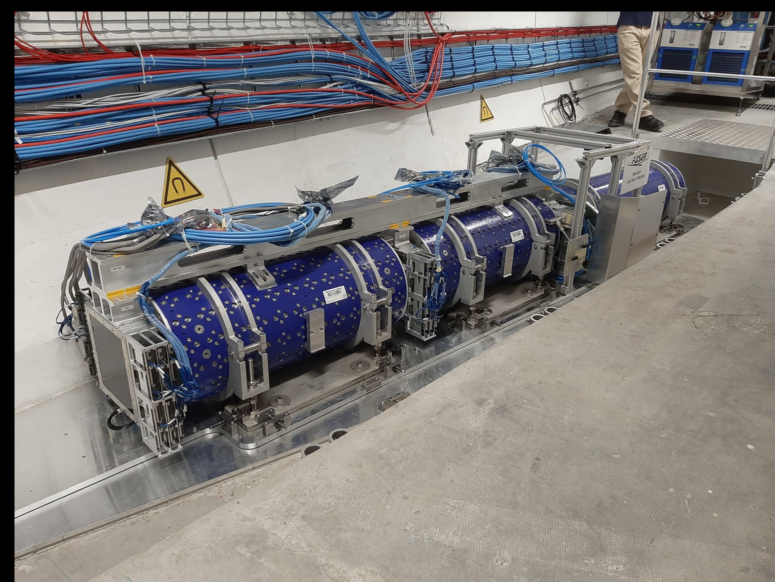
- The nominal beam collision axis was located to mm accuracy by the CERN survey department. (In fact, it goes up and down by a few cm, depending on the beam crossing angle.) To place FASER on this axis, a trench was required to lower the floor by 46 cm.

- The trench was completed by an Italian firm just hours before COVID shut down CERN in March 2020.

FASER AND THE LHC

FASER INSTALLATION





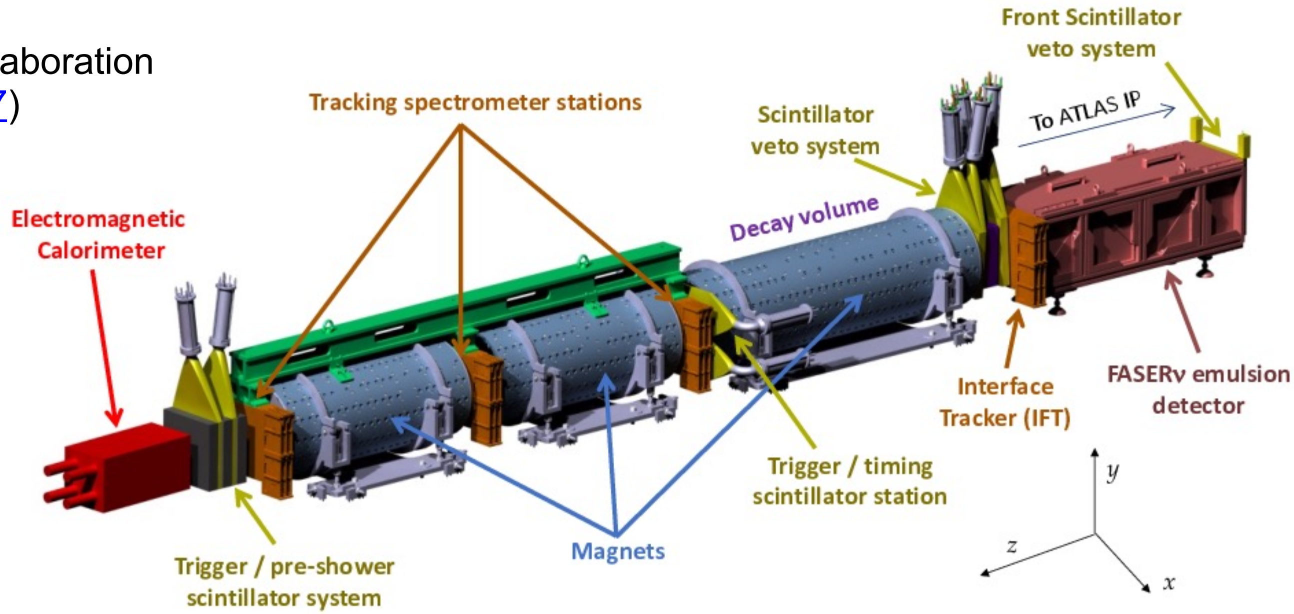
THE FASER DETECTOR

THE FASER DETECTOR

- Design challenges: small (no room), low maintenance (no access), fast (no time).
  - Size: Total length ~ 5 m, decay volume: R = 10 cm, L = 1.5 m.
  - Magnets: 3 permanent dipoles (Halbach design), 0.57 T, deflect charged particles in y.
  - Tracker: composed of 4 stations x 3 layers x 8 mod. = 96 ATLAS SCT modules.
  - Calorimeter: composed of 2 x 2 LHCb ECAL modules.
  - Scintillators: 4 stations, each 1-2 cm thick, >99.999% efficient. 4-layer veto ~ $(10^{-5})^4 \sim 10^{-20}$.
  - FASERν: 770 interleaved sheets of tungsten + emulsion. 1 m long, 1.1 ton total mass. Micron-level spatial resolution, but no timing. Becomes over-exposed from muons, must be replaced after ~30 fb^{-1}.

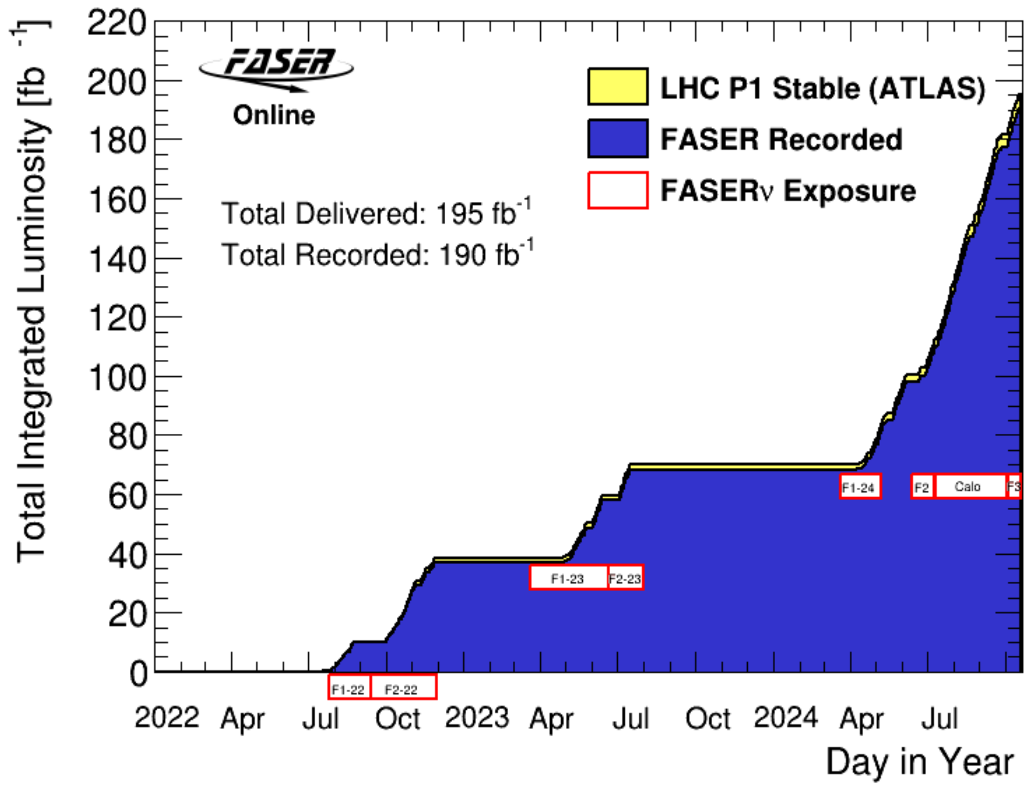
- The experimental environment: 88 m underground, shielded from ATLAS by 100 m of rock → extremely quiet. Trigger on everything, ~kHz trigger rate dominated by muons from ATLAS.

FASER Collaboration
(2207.11427)



FASER DATA TAKING IN 2022 AND 2023

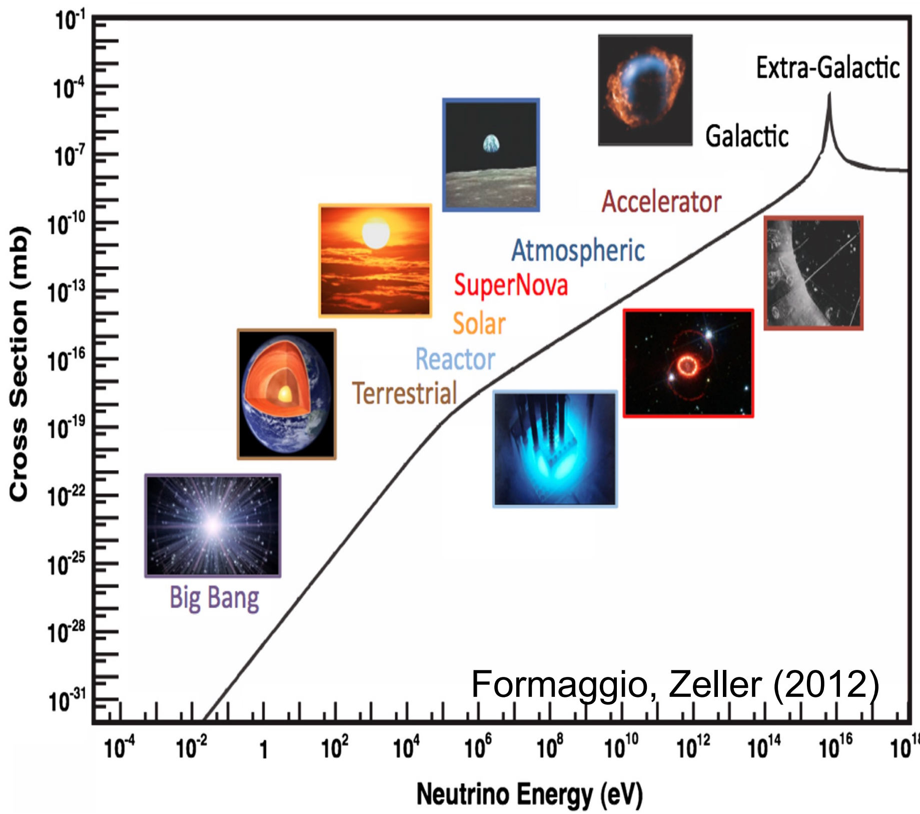
- FASER was constructed in 18 months and was ready to go when LHC Run 3 started in 2022.
- FASER has now been running for 3 years.
  - Recorded 97% of delivered luminosity.
  - Largely automated: no control room, 2 shifters controlling and monitoring the expt from their laptops.



- FASERν emulsion exchanged periodically to prevent overexposure
  - 2 boxes in 2022 (10, 30 fb^{-1})
  - 2 boxes in 2023 (20, 10 fb^{-1})
  - 3 boxes in 2024 (10, 10, 10 fb^{-1})

COLLIDER NEUTRINOS

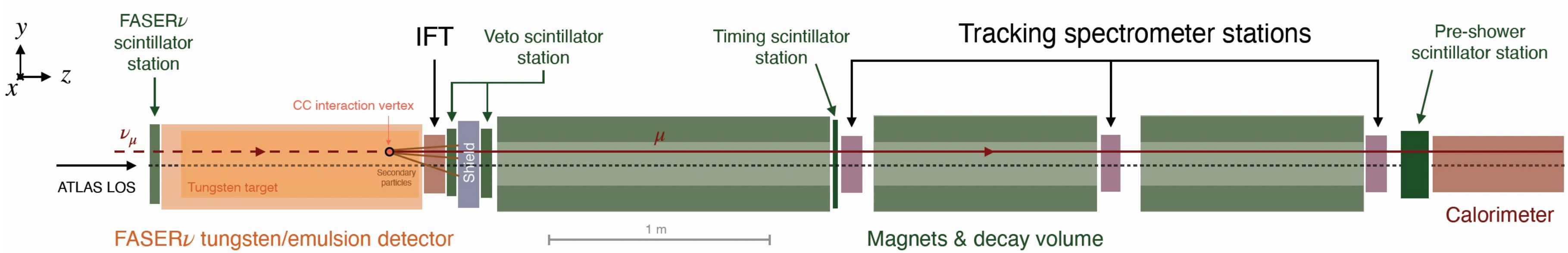
- Neutrinos are the least understood of all known particles, and the only ones with confirmed BSM properties.
- They have been discovered from many sources, each time with stunning implications for particle physics, astrophysics, and cosmology.



- But before FASER, neutrinos produced at a particle collider had never been directly observed.
  - Conventional wisdom: neutrinos interact very weakly so cannot be detected.
  - The truth: the highest energy ones, which are most likely to interact, pass through the blind spots of existing detectors.

COLLIDER NEUTRINO SEARCH

- Neutrinos produced at the ATLAS IP travel 480 m and pass through FASERν. Occasionally, they can interact through $\nu_\mu N \to \mu X$, producing a high-energy muon, which travels through the rest of the detector.



FASER Collaboration (2303.14185, PRL)

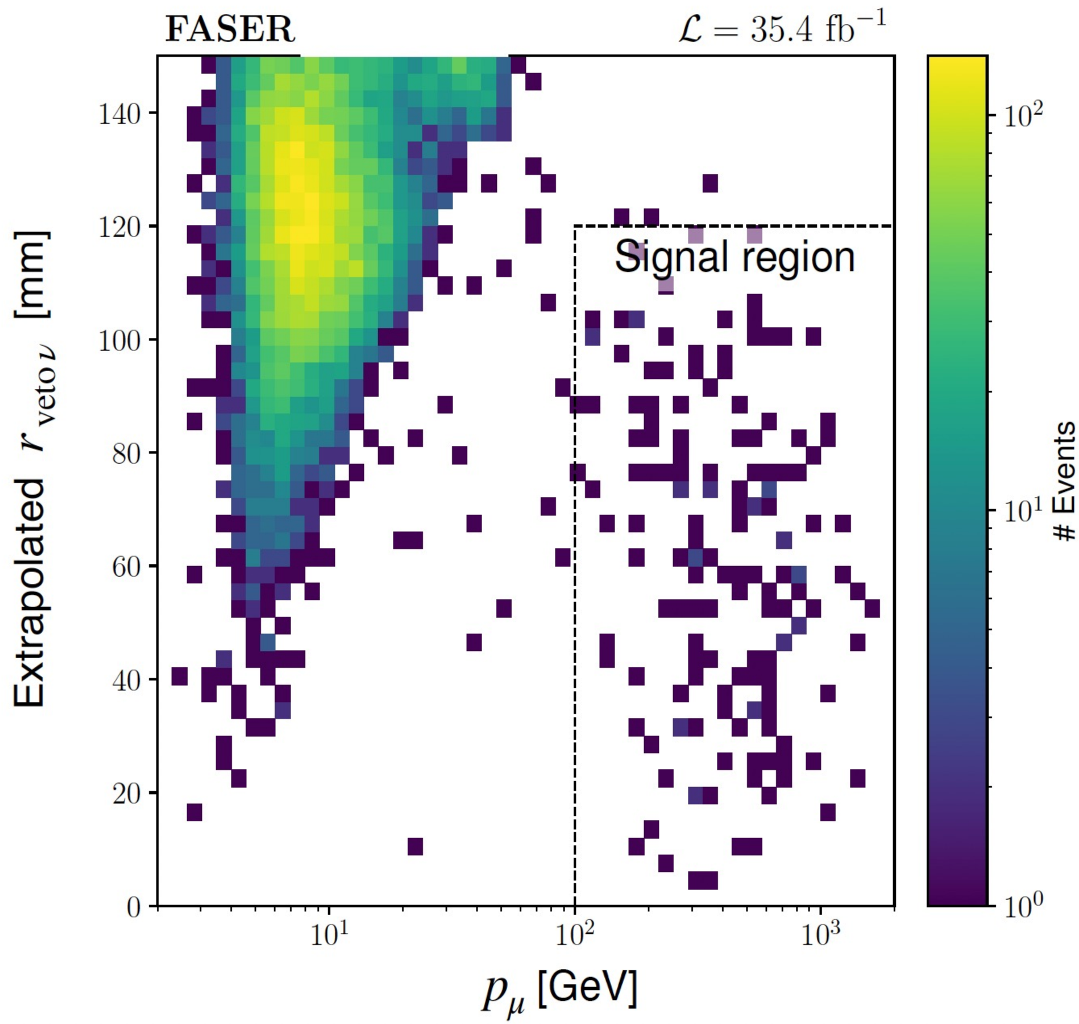
- The signal is no charged particle passing through the upstream veto scintillators, hits in the downstream scintillators, and a single charged track, >100 GeV, in the central region of downstream trackers.

- Leading backgrounds from neutral hadrons produced in the rock, muons that enter from the side, or beam 1 background contribute $\lesssim 1$ event.

- Expect 151 ± 41 events from simulations, with the large uncertainty arising from the poorly understood flux of forward hadrons.

COLLIDER NEUTRINO RESULTS

- After unblinding, we found 153 signal events.
- 1st direct detection of collider neutrinos.
  - Signal significance of ~16σ
  - Muon charge → ν and $\bar{\nu}$
  - These include the highest energy ν and $\bar{\nu}$ interactions ever observed from a human source
- Following the FASER observation, SND@LHC, a complementary experiment in the "other" forward direction, discovered an additional 8 neutrinos.



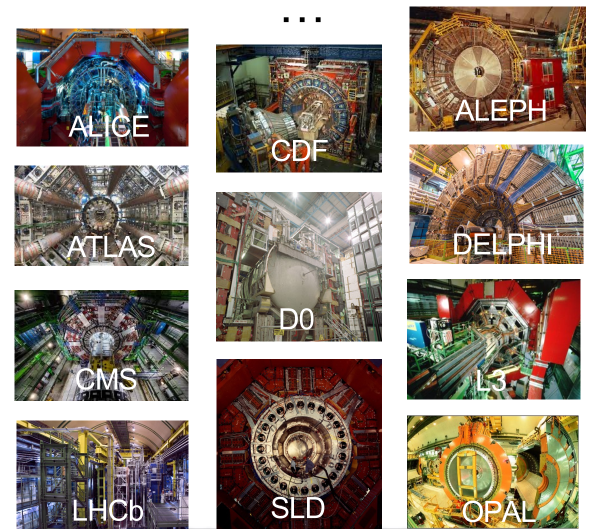
FASER Collaboration (2303.14185, PRL)

LOCATION, LOCATION, LOCATION

FASER

“Tabletop,” 18 months,
~$1M

153 neutrinos



All previous
collider detectors

Building-size, decades,
~$1B

0 neutrinos

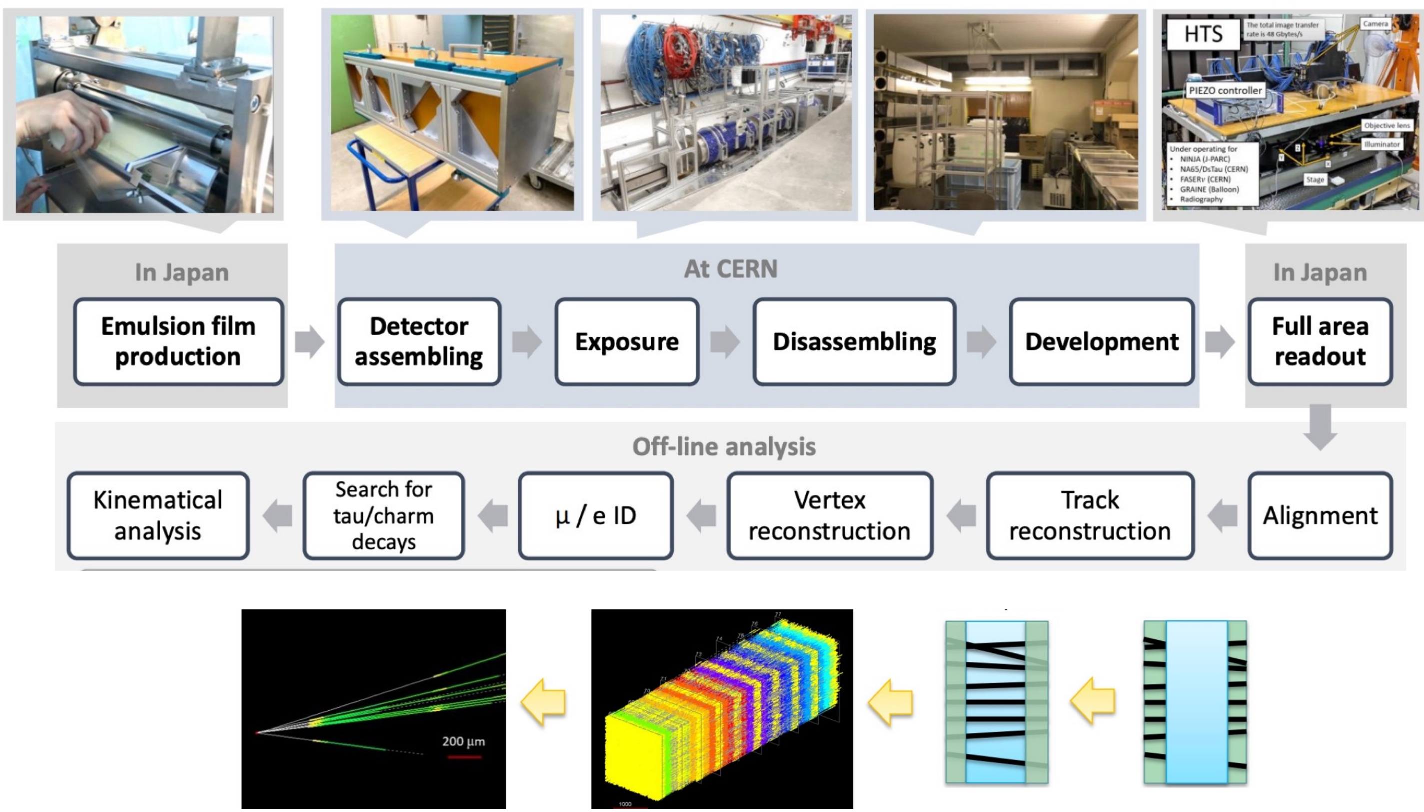
16σ discovery, opening a new window
at the high energy frontier

DISCOVERY OF COLLIDER NEUTRINOS

NEUTRINOS IN FASERν

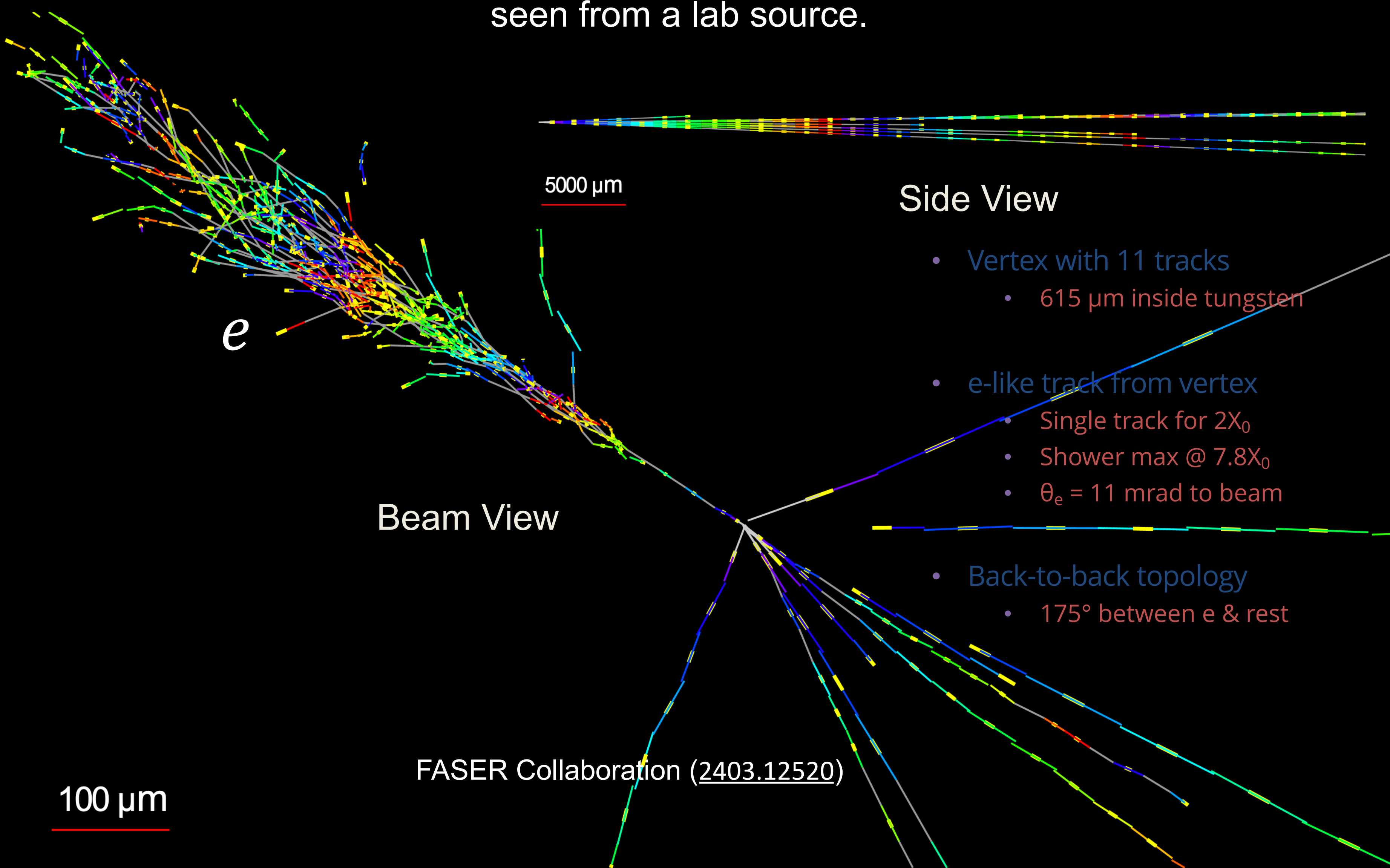
- At the front of FASER is FASERν, a 1.1-ton block of interleaved tungsten and emulsion plates. The first neutrino analysis treated this as a big block of matter, but the emulsion provides far more detailed information.

- Emulsion is essentially old-fashioned photographic film, has unmatched spatial resolution (~0.5 microns).



NEUTRINOS IN FASERν

With the emulsion, we have now observed the first collider electron neutrinos, including the "Pika-ν" event, the highest energy (1.5 TeV) electron neutrino ever seen from a lab source.

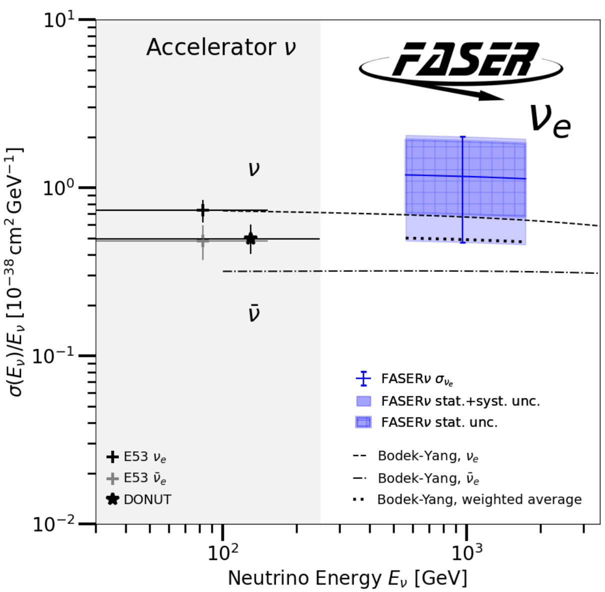


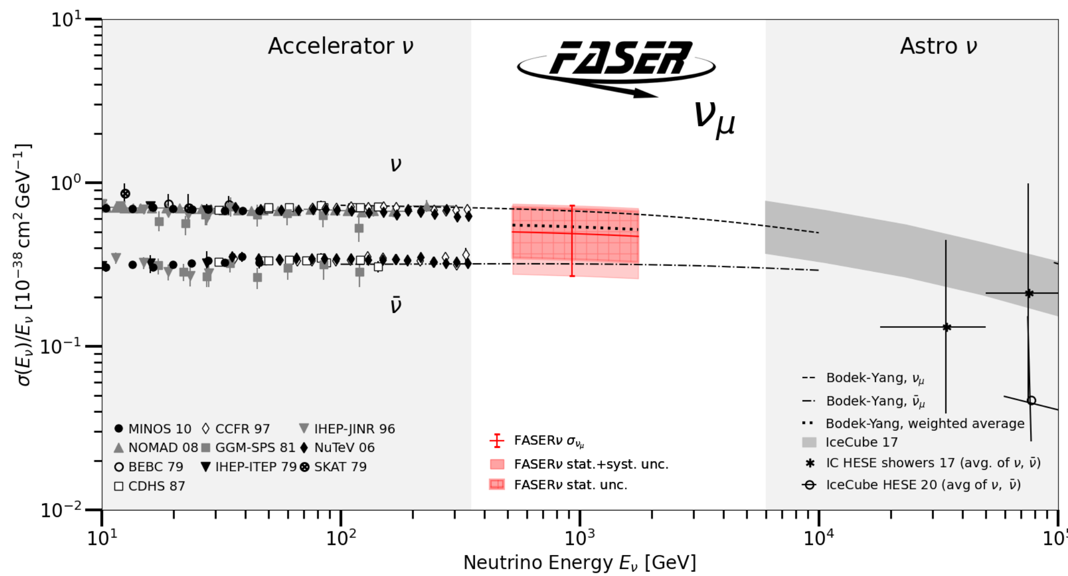
- Vertex with 11 tracks
  - 615 μm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max @ $7.8X_0$
  - θ_e = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest

FASER Collaboration (2403.12520)

TEV NEUTRINO CROSS SECTIONS

- Following these discoveries, we can then move on to studies, including the first measurement of neutrino cross sections at TeV energies.
- Results are consistent with SM DIS predictions.



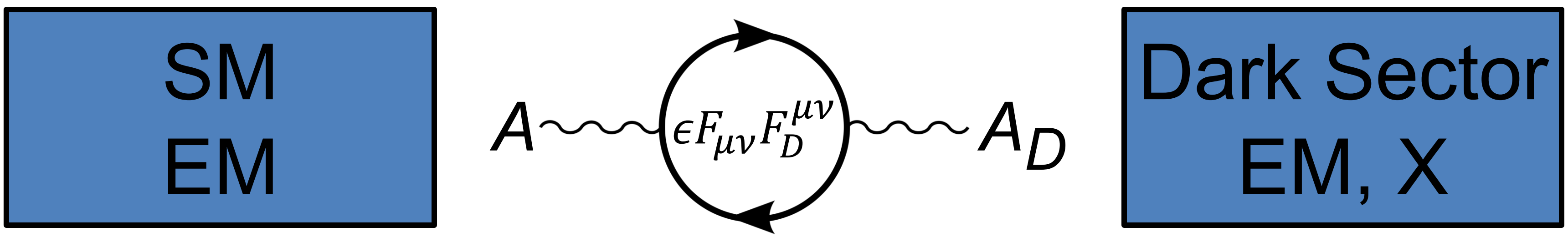


FASER Collaboration (2403.12520)

- These measurements use only 1.1% of the data already collected so far. Much more to come; we expect to triple the world’s supply of tau neutrinos, identify the first anti-tau neutrino, …

NEW PARTICLE SEARCHES

- FASER can also look for new light and weakly-interacting particles.
- For example: suppose there is a dark sector that contains dark matter X and also a dark force: dark electromagnetism.



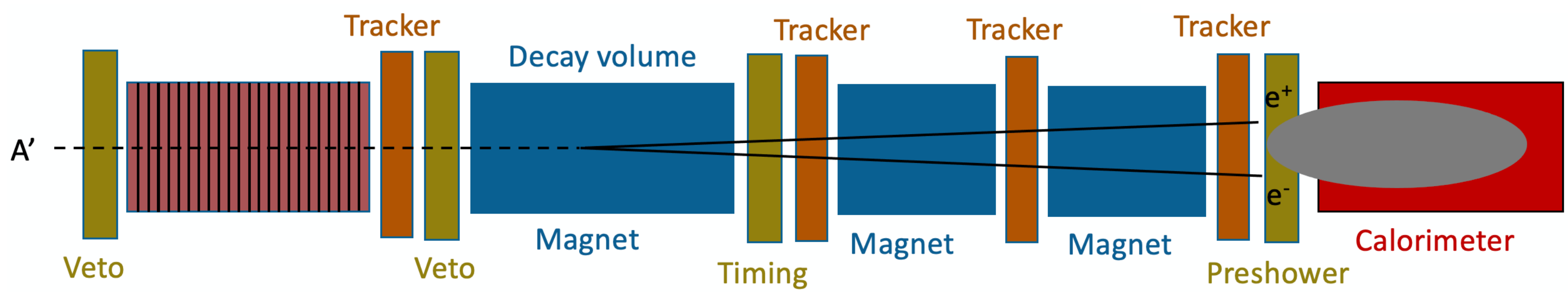
- The result? Dark photons A' , like photons, but with mass $m_{A'}$, couplings suppressed by ϵ.

Holdom (1986)

- For low ϵ, dark photons are long-lived particles (LLPs), can be produced in ATLAS, pass through rock and magnetic fields unhindered, and decay in FASER.

DARK PHOTON SIGNAL

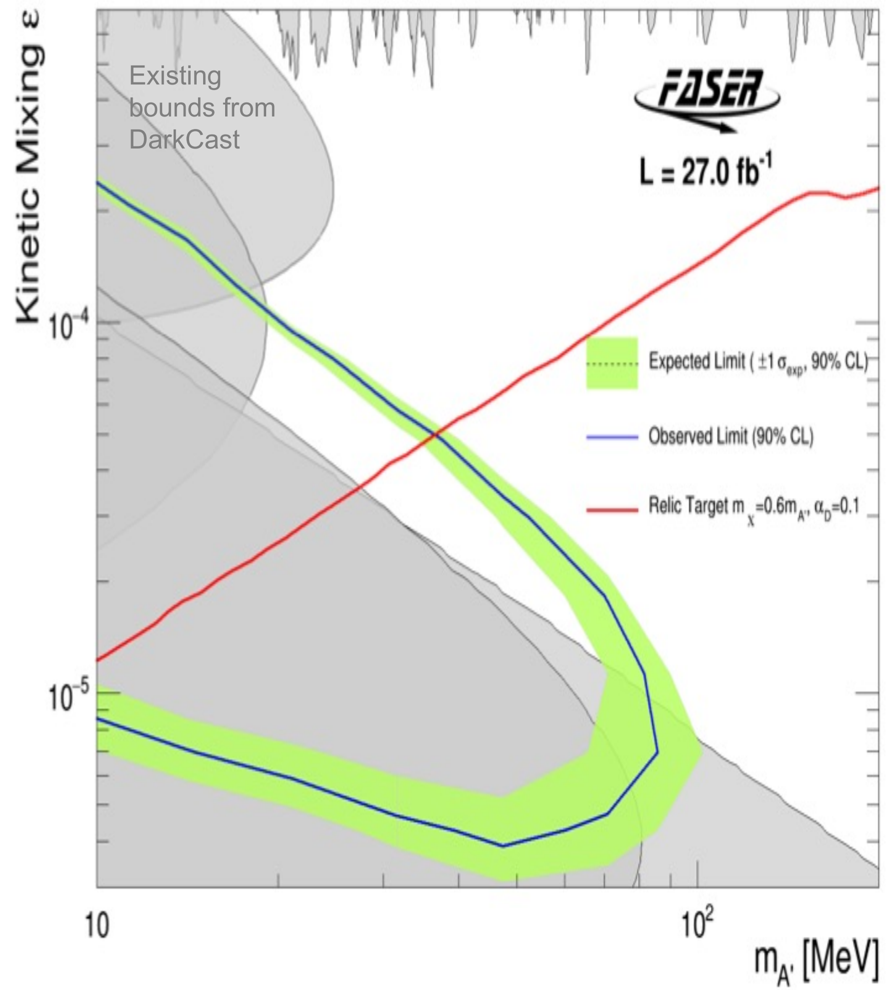
- Focus on masses in the 10-100 MeV range.
- Produced through meson decay $\pi/\eta \to A'\gamma$ or "dark bremsstrahlung" $pp \to ppA'$.
- Travel straight and unimpeded through 480 m of rock/concrete.
- Then decay through $A' \to e^+e^-$.



- The signal is no charged particle passing through the upstream veto scintillator detectors, followed by two very energetic (100s of GeV) charged tracks in downstream trackers. Tracks are very collimated, but magnet splits them sufficiently to be seen as 2 tracks in trackers.

DARK PHOTON RESULTS

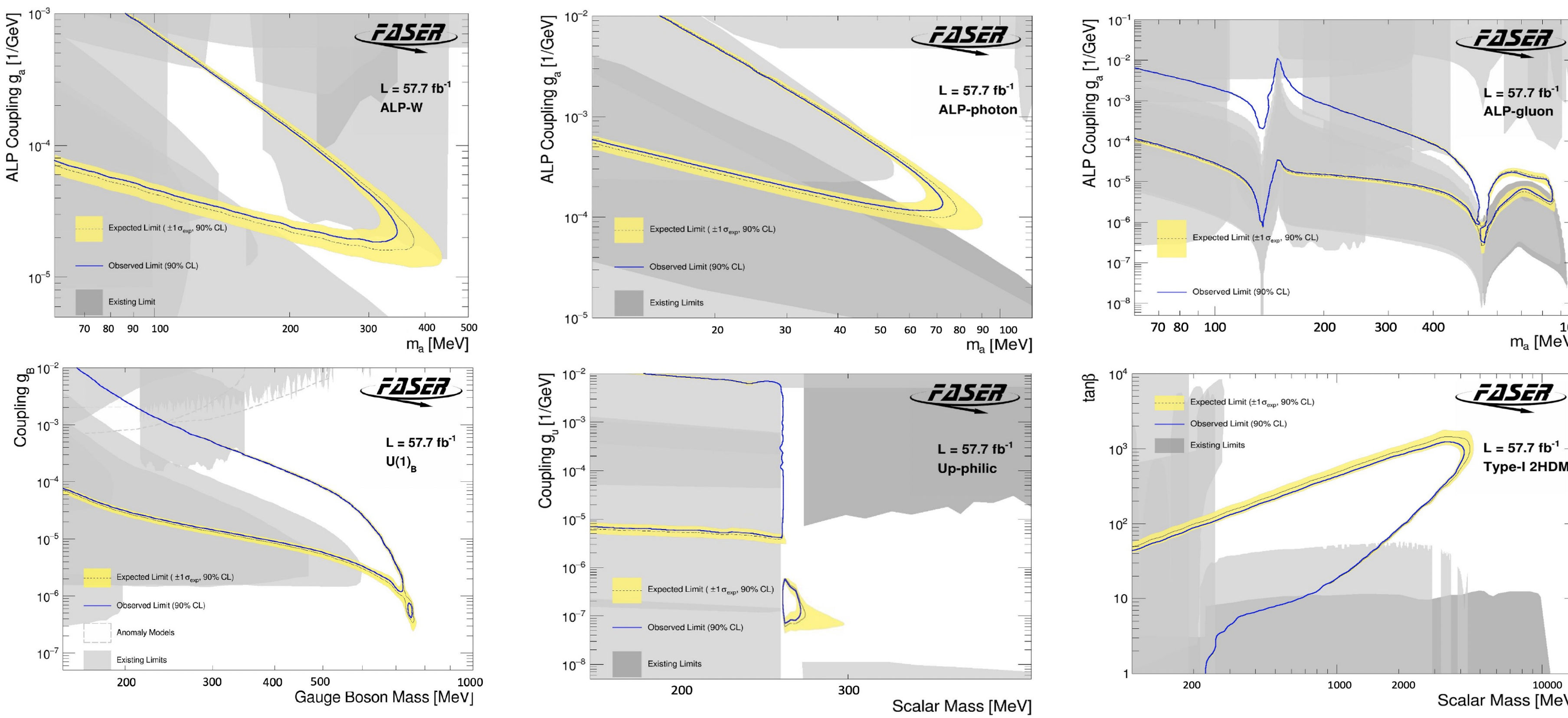
- After unblinding, no events seen, FASER sets limits on previously unexplored parameter space.
- First new probe of the parameter space favored by dark matter from low coupling since the 1990's.
- Bodes well for the future
  - Background-free analysis
  - Started probing new parameter space with the first day of data
  - Ended up ~100 times more sensitive than previous experiments
  - Improvements in analysis and 40 times more data to come



FASER Collaboration (2308.05587, PLB)

MORE SEARCH RESULTS

- Also many other search results: axion-like particles with *W*, photon, gluon couplings, $U(1)_B$ gauge bosons, up-philic scalars, two Higgs doublet models.
- Qualitatively different signals: some with charged tracks, some with only photons, some mainly produced in pion decay, some mainly produced in B decay. Shows the characteristic versatility of searches at high-energy colliders.



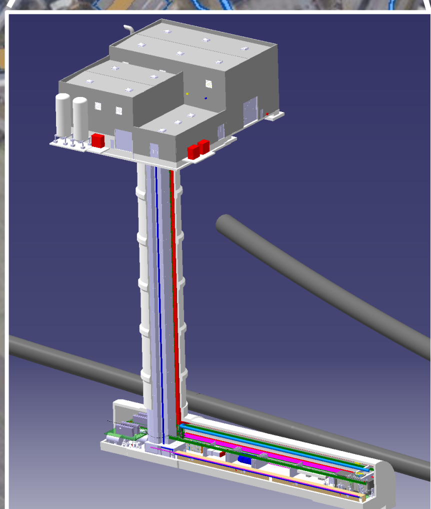
FASER Collaboration [2410.10363](2410.10363)

FPF

Forward Physics Facility

FORWARD PHYSICS FACILITY

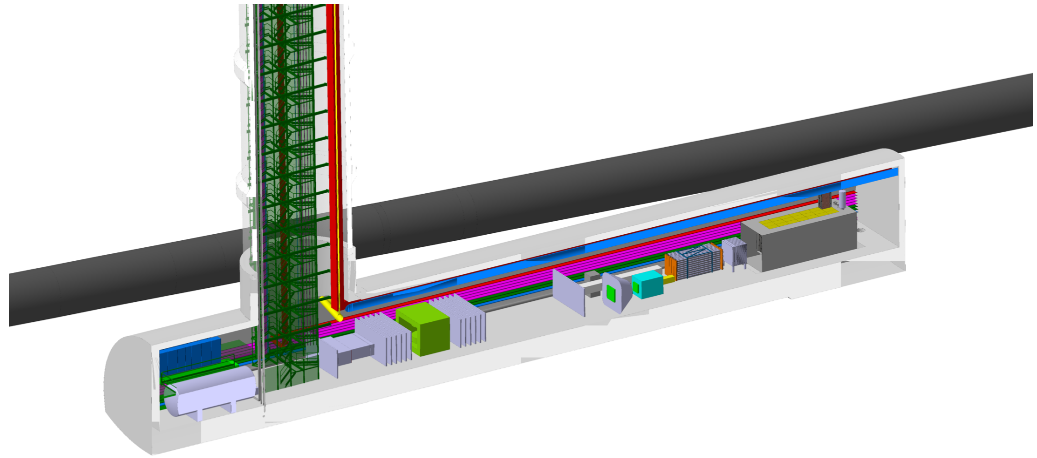
- Following the results of FASER and SND@LHC, CERN is considering the possibility of creating a dedicated Forward Physics Facility to house far-forward experiments for the rest of the LHC era from 2028-2040s.



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

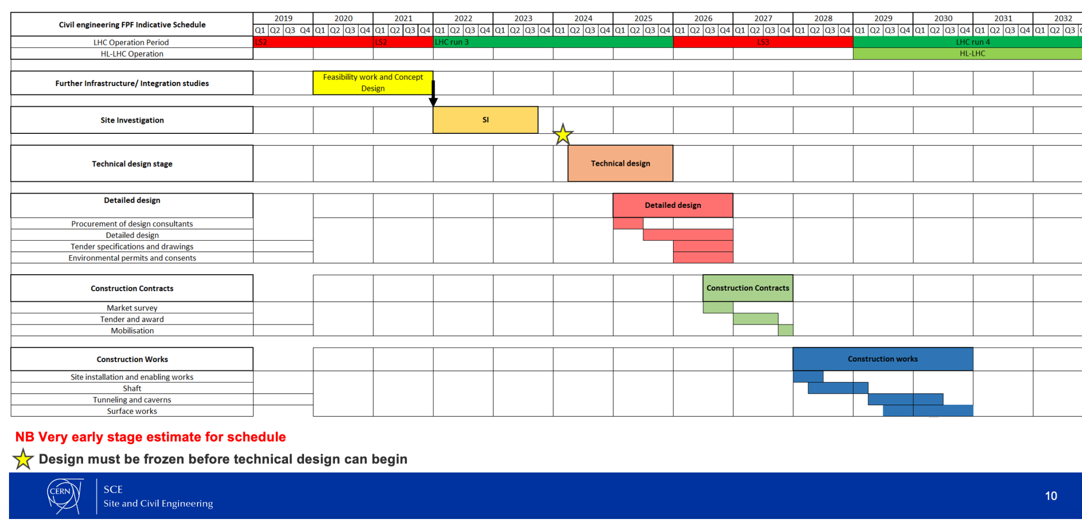
THE FACILITY

- A cylindrical cavern surrounding the LOS, 620-695 m west of the ATLAS IP.
- 75 m long, 12 m in diameter, covers $\eta > 5.1$.
- Preliminary (Class 4) cost estimate: 35 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.



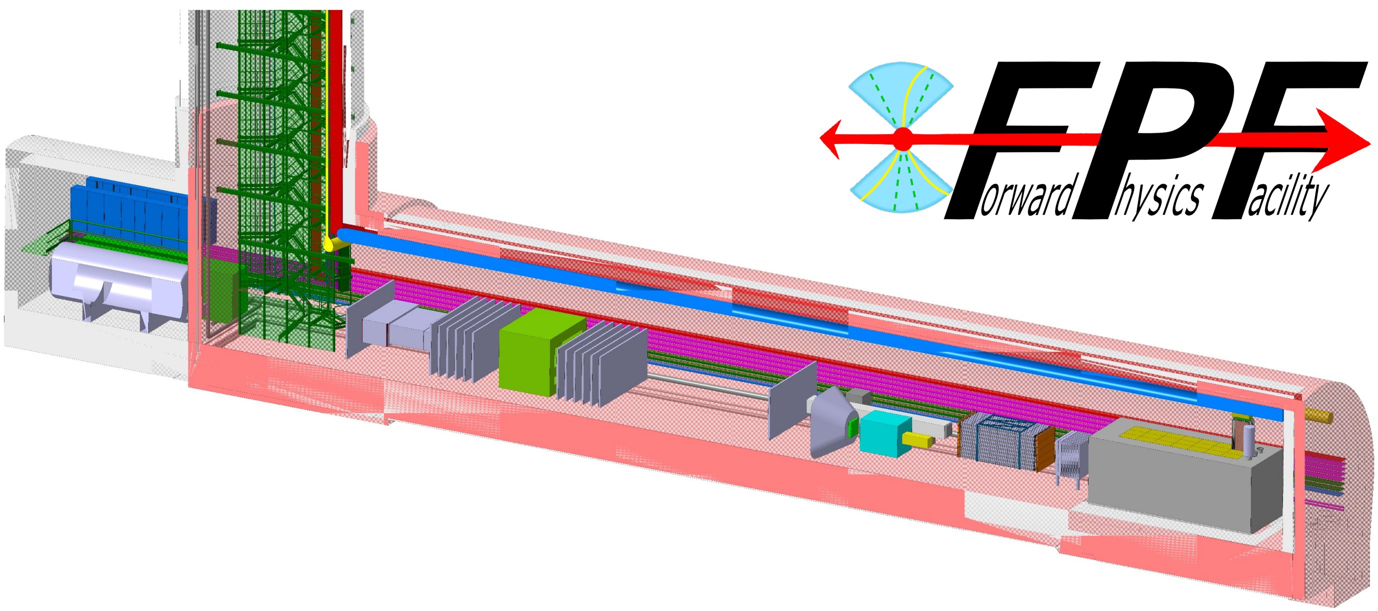
Bud, Magazinik, Pál, Osborne, et al. CERN CE (2024)

Proposed Civil Engineering Schedule



FPF EXPERIMENTS

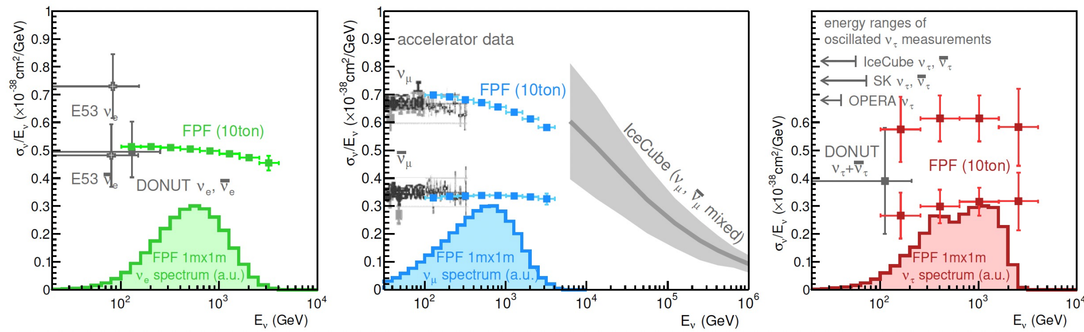
- At present there are 4 experiments being designed for the FPF
  - FASER2: magnetized spectrometer for BSM searches
  - FASERν2: emulsion-based neutrino detector
  - FLArE: LArTPC neutrino detector
  - FORMOSA: scintillator array for BSM searches (successor to MilliQan)



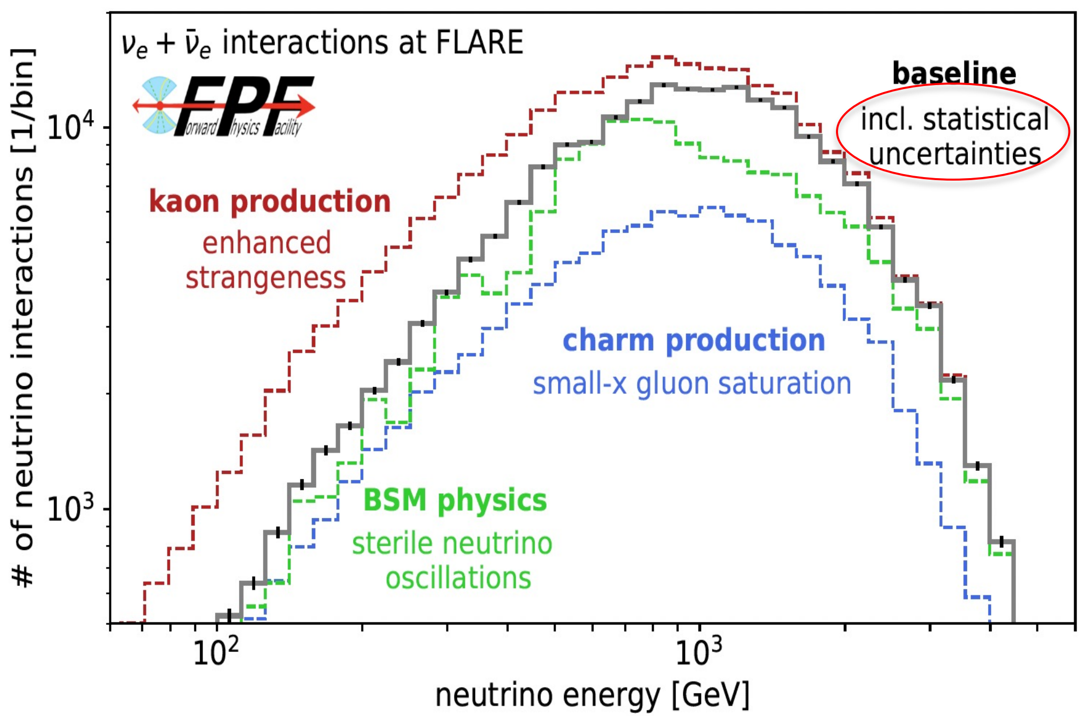
- These represent a huge jump relative to the existing experiments:
  - 10,000 times greater (decay volume * luminosity) for BSM searches.
  - Will detect miilions of TeV neutrinos (~1000 neutrinos/day!), including 10,000 ν_τ

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. The last chance to probe this in a controlled environment for at least 50 years.



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



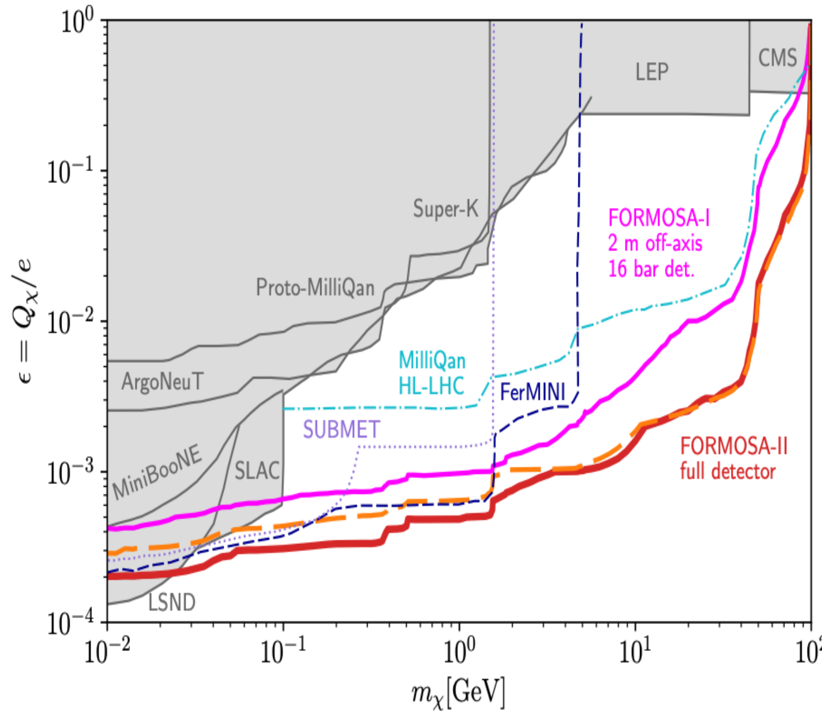
UNIQUE DISCOVERY OPPORTUNTIES

- FPF experiments will enhance the LHC's discovery potential, looking somewhere new where no other LHC experiments (or any other experiments) can look. Many examples:

- Millicharged particles: a completely generic possibility motivated by dark matter, dark sectors. Currently the target of the MilliQan experiment, located at the LHC near the CMS experiment in a "non-forward" tunnel.

- FORMOSA is a dedicated experiment in the forward region with much greater sensitivity for a wide range of masses from 10 MeV to 100 GeV.

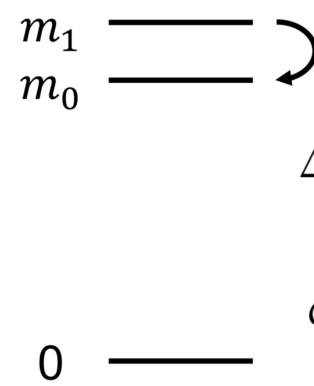
- Currently being explored with the FORMOSA Demonstrator behind FASER.



Foroughi-Abari, Kling, Tsai (2020)

DARK MATTER

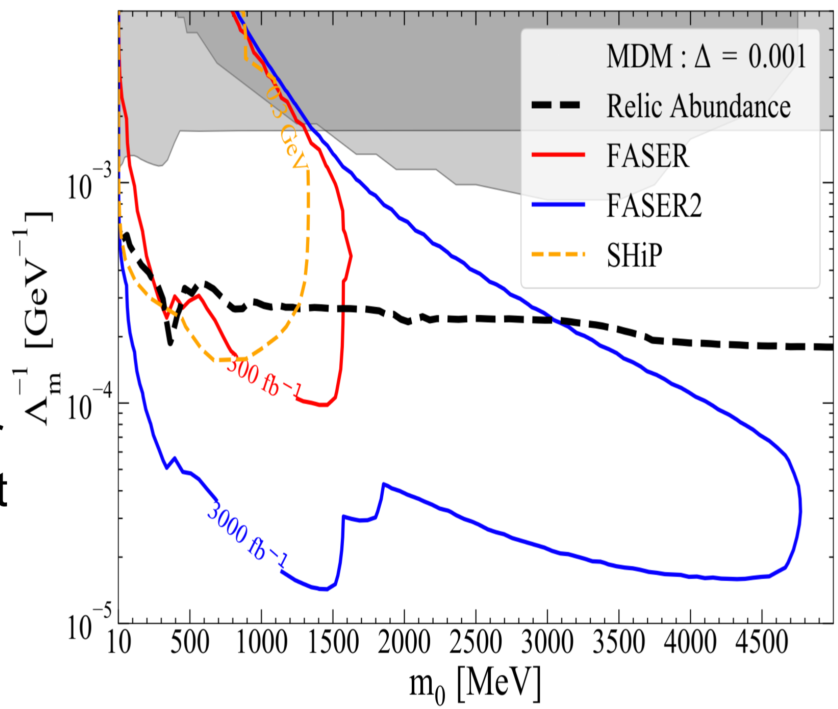
- In the last few decades, there has been an intense effort to detect dark matter through non-gravitational couplings, all yielding null results.
- One generic possibility that is infamously hard to detect: inelastic dark matter, where there are two nearly-degenerate dark states with off-diagonal couplings to the SM.
- These generically lead to long-lived particles, but with soft decay products, but these are highly boosted to observable levels at the FPF.
- Bottom line: the FPF can discover DM (or any compressed spectrum), which cannot be seen anywhere else (ATLAS/CMS, SHiP and other fixed target expts, direct and indirect DM searches, …)



$\chi_1 \to \chi_0 \gamma$

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

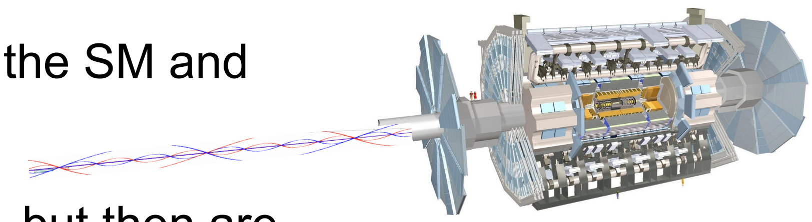
$$\mathcal{O}_m = \frac{1}{\Lambda_m} \overline{\chi}_1 \sigma^{\mu\nu} \chi_0 F_{\mu\nu}$$



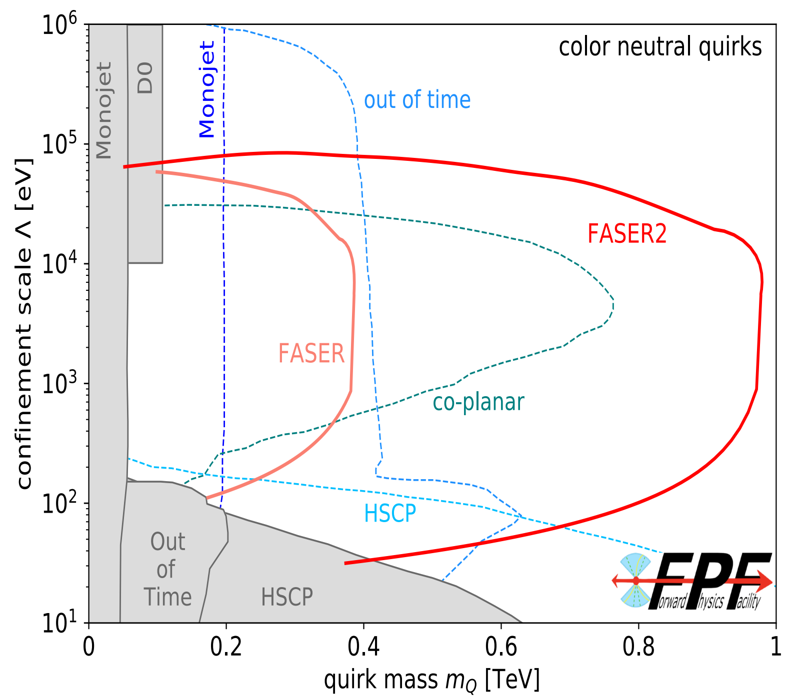
Dienes et al. (2023)

QUIRKS

- There may be another strong (non-Abelian) force.
- Quirks are particles charged under both the SM and another strong force, with $m \gg \Lambda$.



- Quirks can be pair-produced at the LHC, but then are bound by a color string, oscillate about their center-of-mass and travel down the beamline.
- By looking for 2 coincident slow or delayed tracks (out of time with the bunch crossing), FPF experiments can discover quirks with masses up to ~TeV, as motivated by neutral naturalness solutions to the gauge hierarchy problem.

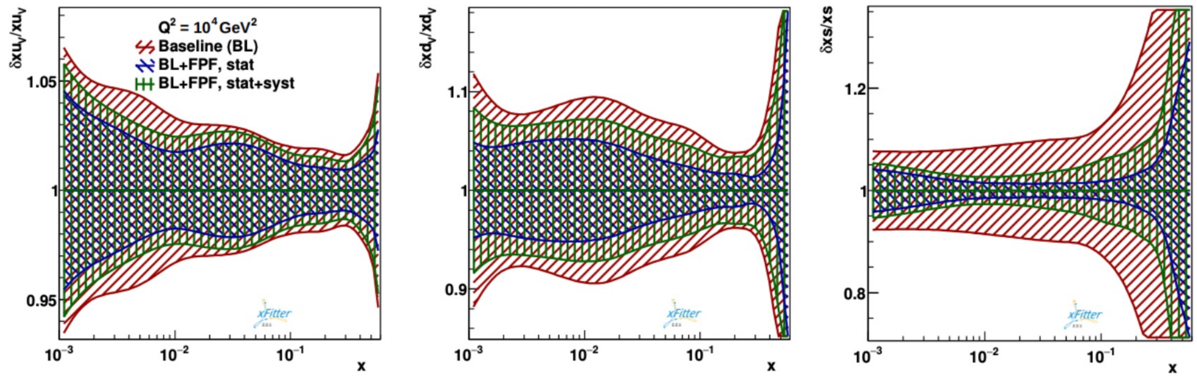


Feng, Li, Liao, Ni, Pei (2024)

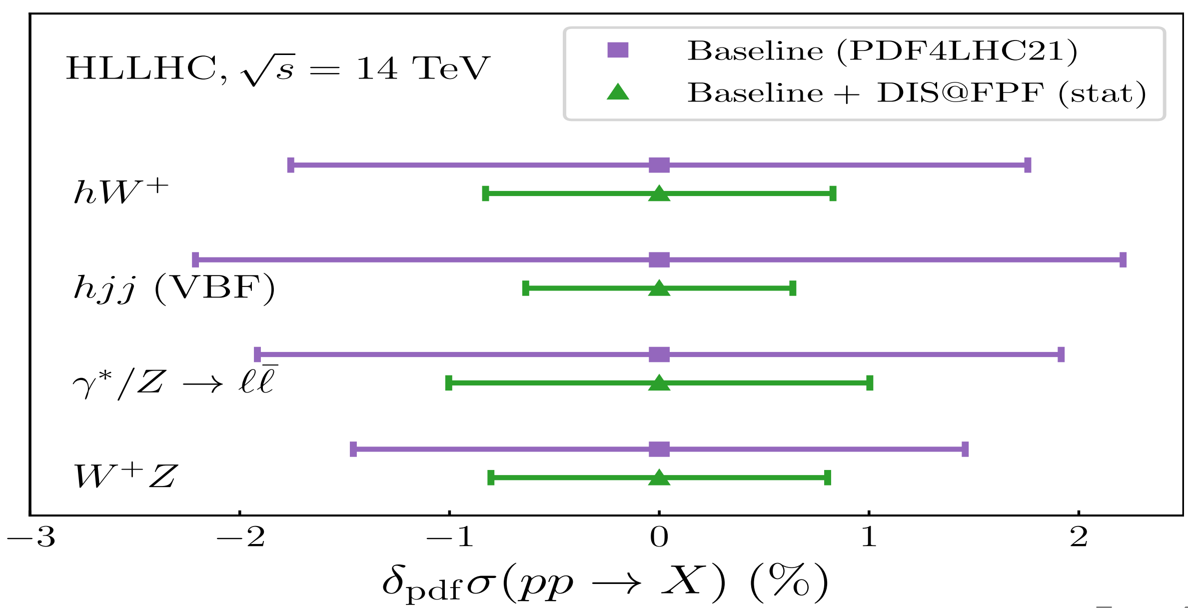
- Unique discovery potential at the FPF: very challenging at ATLAS/CMS, not possible at fixed target experiments.

COMPLEMENTARITY WITH HIGH P_T PHYSICS

- The FPF will provide new constraints on pdfs that will sharpen studies at ATLAS and CMS.
- For example, W, Z, and Higgs boson studies.
- Will remove degeneracies between pdfs and new physics (“fitting away new physics”), enhancing the reach for new particle searches.



Cruz-Martinez, Fieg, Giani, Krack, Makela, Rabemananjara, Rojo (2023)



FPF Working Groups (2024)

SUMMARY

- Neglected for decades, the forward region at particle colliders turns out to be a treasure trove of interesting physics that can be mined with small, fast, inexpensive experiments. Much more to come!