FORWARD-LOOKING PHYSICS AT CERN'S LARGE HADRON COLLIDER

Colloquium, Department of Physics, University of New Mexico

Jonathan Feng, UC Irvine, 2 September 2022

OUTLINE

MOTIVATIONS

FORWARD PHYSICS

CURRENT: FASER AND FASERν

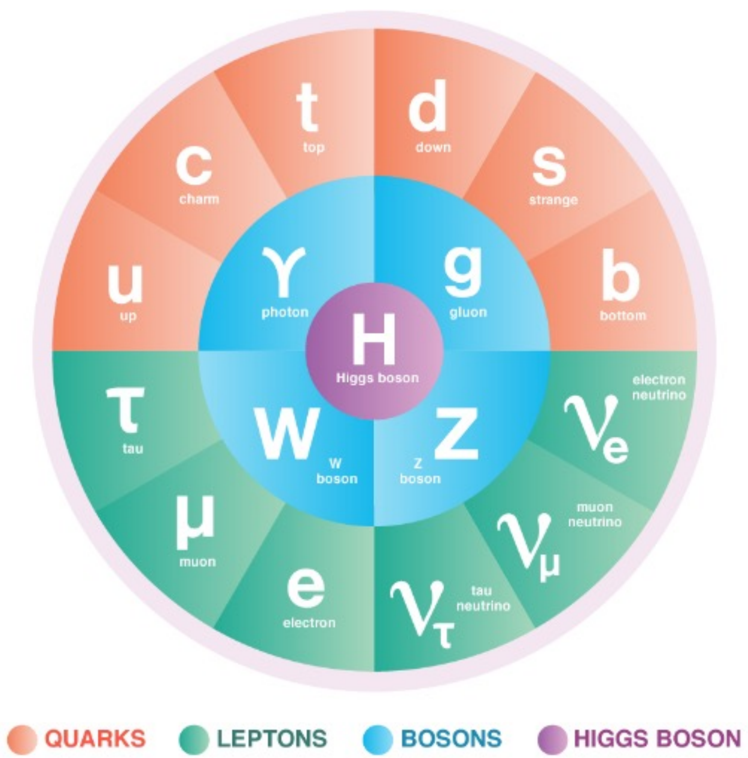
THE FUTURE: FORWARD PHYSICS FACILITY

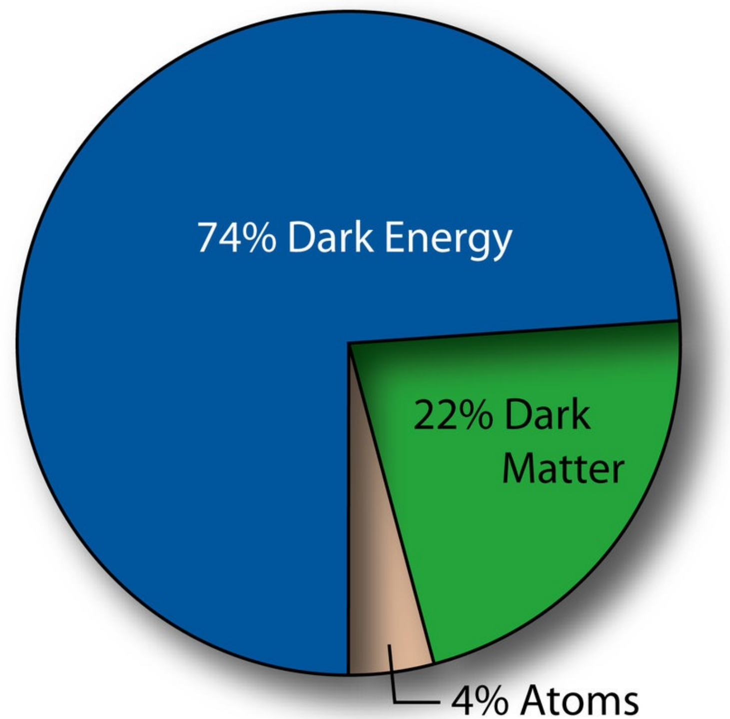
SUMMARY

MOTIVATIONS

PARTICLE PHYSICS: CURRENT STATUS

- This is a critical time in particle physics
  - the Higgs boson was discovered in 2012, completing the standard model
  - but many fascinating problems remain: dark matter, dark energy, matter–anti-matter asymmetry, strong CP problem, neutrino masses, grand unification, gauge and flavor hierarchy problems, ...

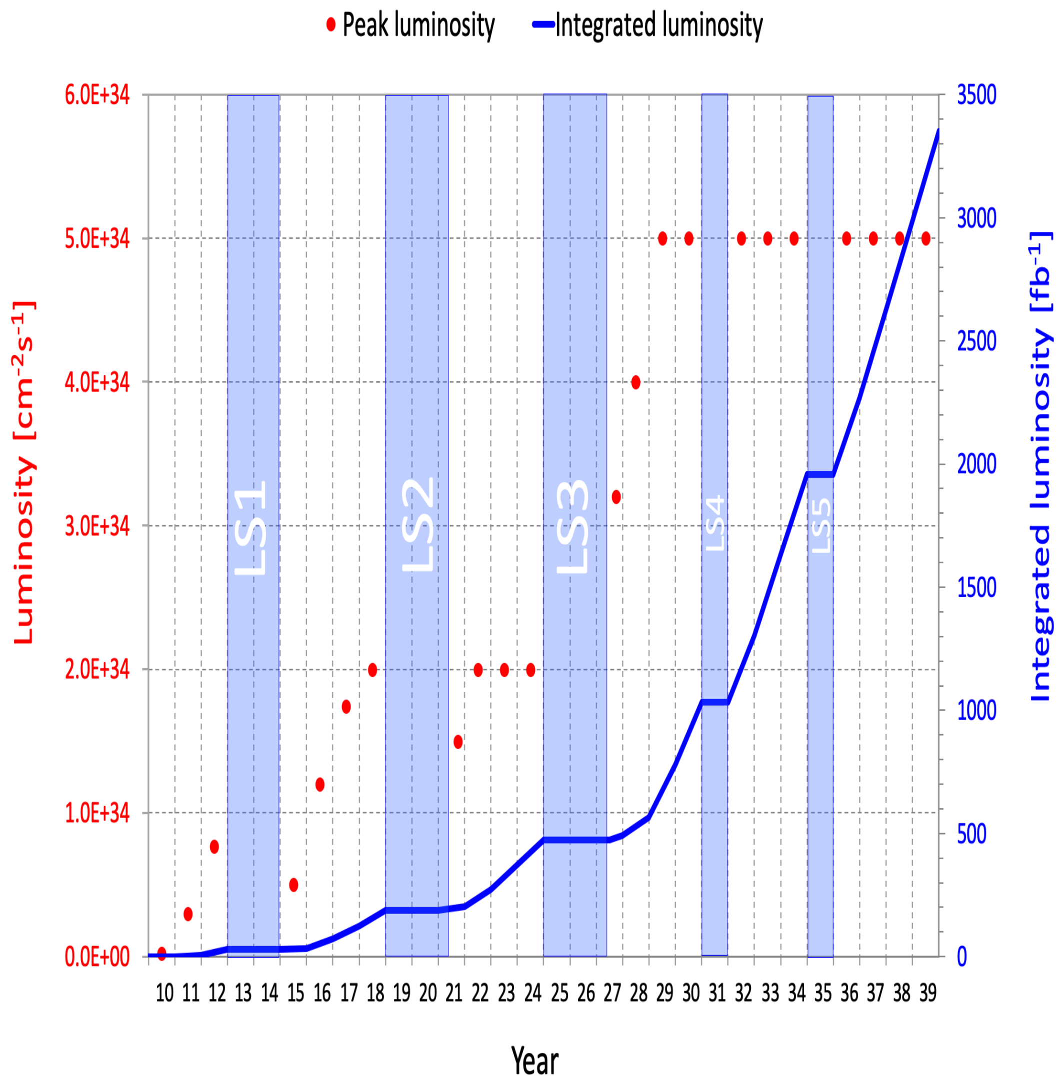




PARTICLE PHYSICS: CURRENT STATUS

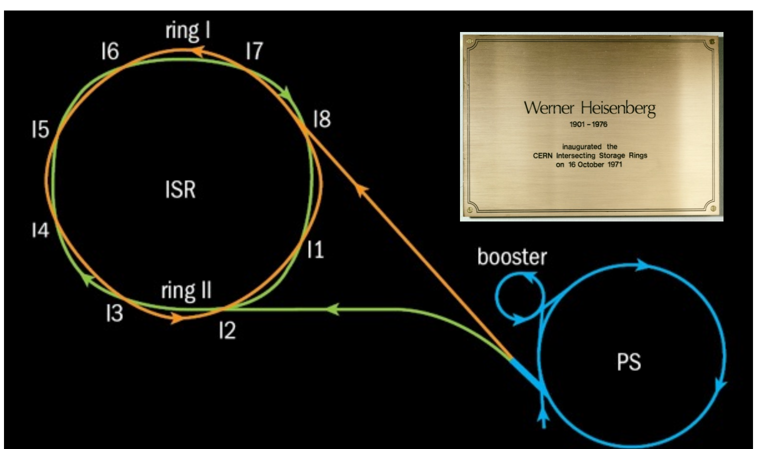
- At the energy frontier, the Large Hadron Collider at CERN just started running again and will run until the 2040's.

- What can we do to enhance the prospects for discovering new particles and shedding light on the many outstanding problems?



SOME HISTORY

- Sometimes to look forward, it pays to first look back.
- Last year was the 50th anniversary of the birth of hadron colliders.
- In 1971, CERN's Intersecting Storage Rings (ISR), with a circumference of ~1 km, collided protons with protons at center-of-mass energy 30 GeV.

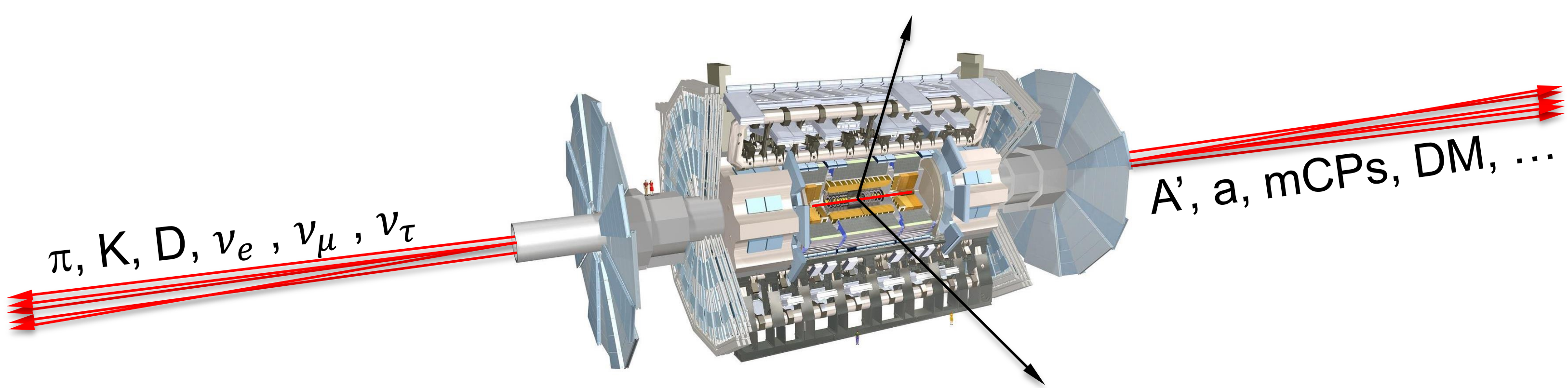


ISR'S LEGACY

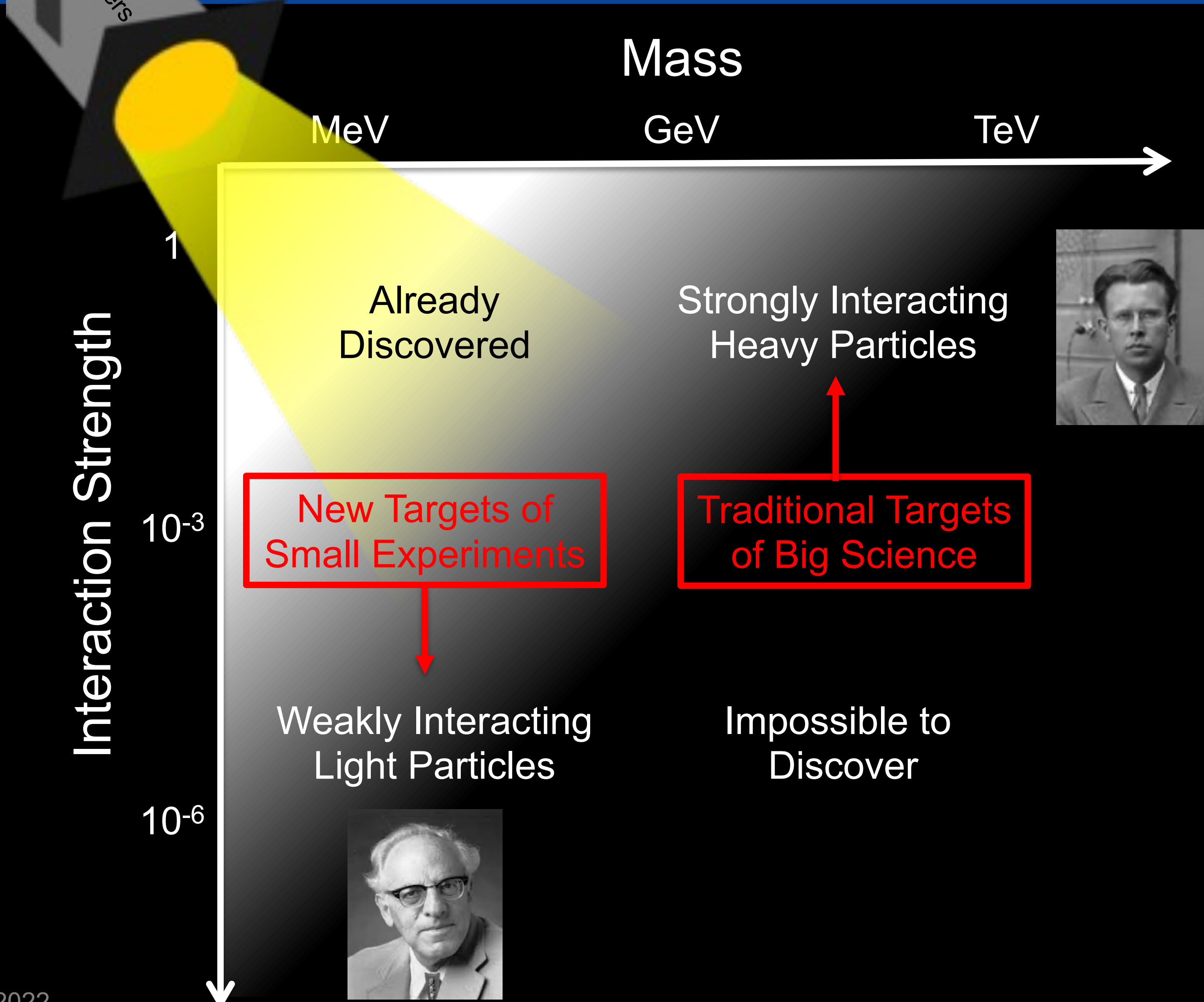
- On the occasion of the 50th anniversary of CERN's ISR, there have been many fascinating articles and talks by eminent physicists looking back on the ISR's legacy.
  - "Enormous impact on accelerator physics, but sadly little effect on particle physics." – Steve Myers, talk at "The 50th Anniversary 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 new forms of matter, but the detectors focused on the forward region (along the beamline) and missed them.

AN OBVIOUS QUESTION

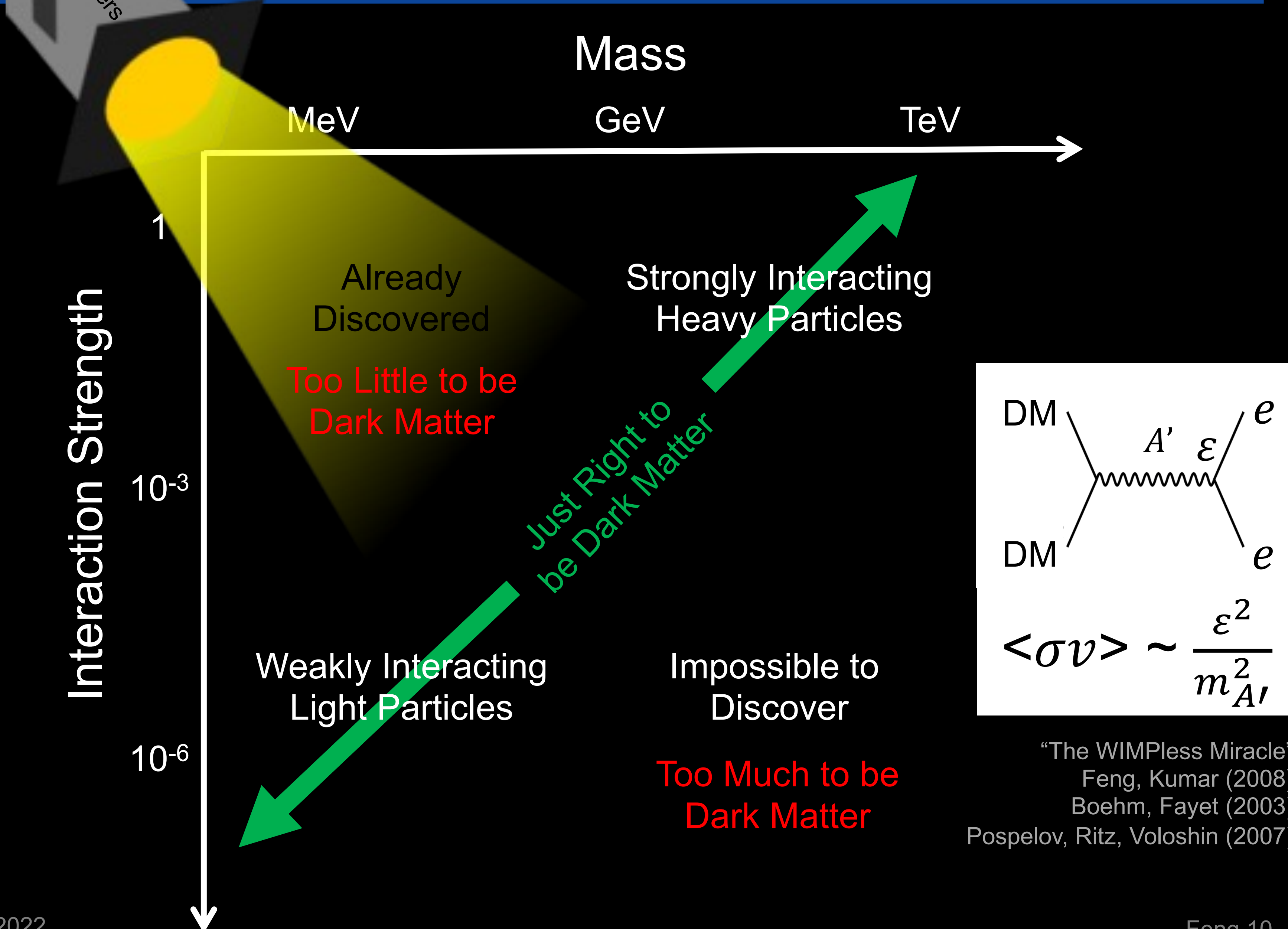
- Are we missing opportunities in a similar way at the LHC?
- In contrast to the ISR days, there is now broad belief that the most interesting physics is at large angles relative to the beamline. But are we now missing revolutionary discoveries in the forward direction?
- By far the largest fluxes of high-energy light particles (e.g., pions, kaons, D mesons, neutrinos of all flavors) are in the far-forward direction.
- This may also be true of new particles if they are light: dark photons, axion-like particles, millicharged particles, dark matter, …



THE NEW PARTICLE LANDSCAPE



THE THERMAL RELIC LANDSCAPE

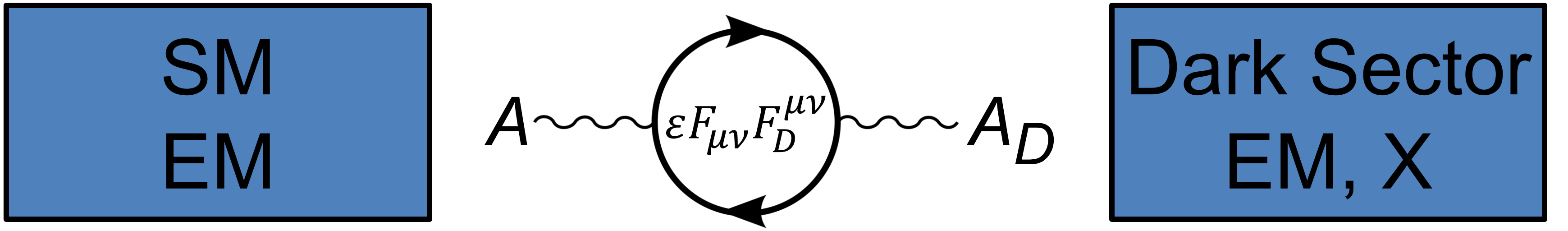


"The WIMPless Miracle"
Feng, Kumar (2008)
Boehm, Fayet (2003)
Pospelov, Ritz, Voloshin (2007)

SPECIFIC EXAMPLES

- Suppose there is a dark sector that contains dark matter X and also a dark force: dark electromagnetism.

- The force carriers of our sector and the dark sector will mix
  - perhaps suppressed, but completely generic, since a renormalizable operator



- The result? A new particle, the dark photon A': like a normal photon, but with a non-zero mass $m_{A'}$ and couplings suppressed by ε. It travels through matter without interacting, but eventually decays through $A' \to e^+ e^-$

Holdom (1986)

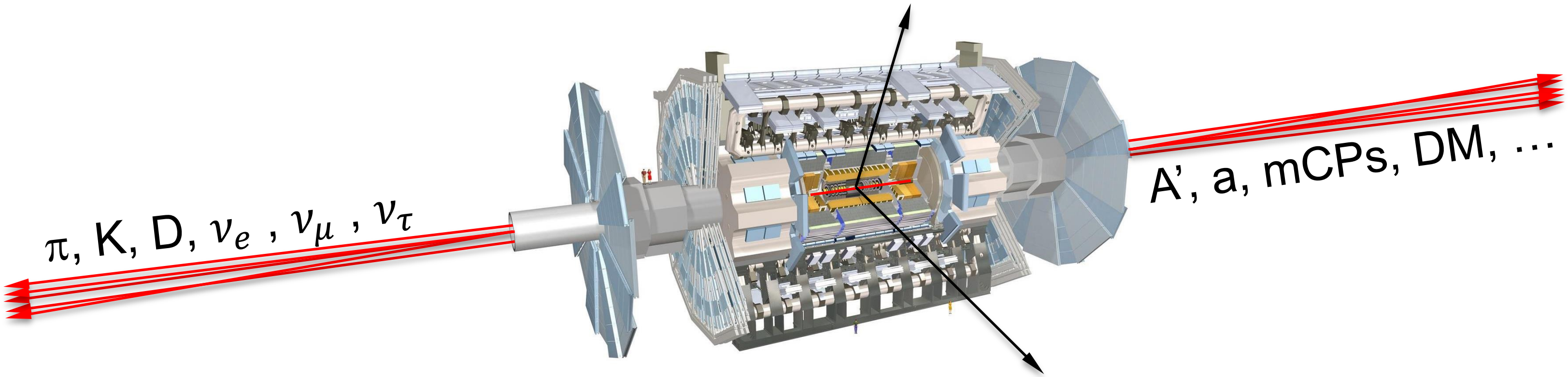
- Many other similar particles with other signatures: dark Higgs bosons $X \to K^+ K^-$, axion-like particles $a \to \gamma\gamma$, sterile neutrinos $N \to l^+ l^- \nu$, millicharged particles, …

FORWARD PHYSICS

SEARCHES FOR NEW LIGHT PARTICLES

- If new particles are light and weakly interacting, the existing big LHC detectors are perfectly designed NOT to see them.

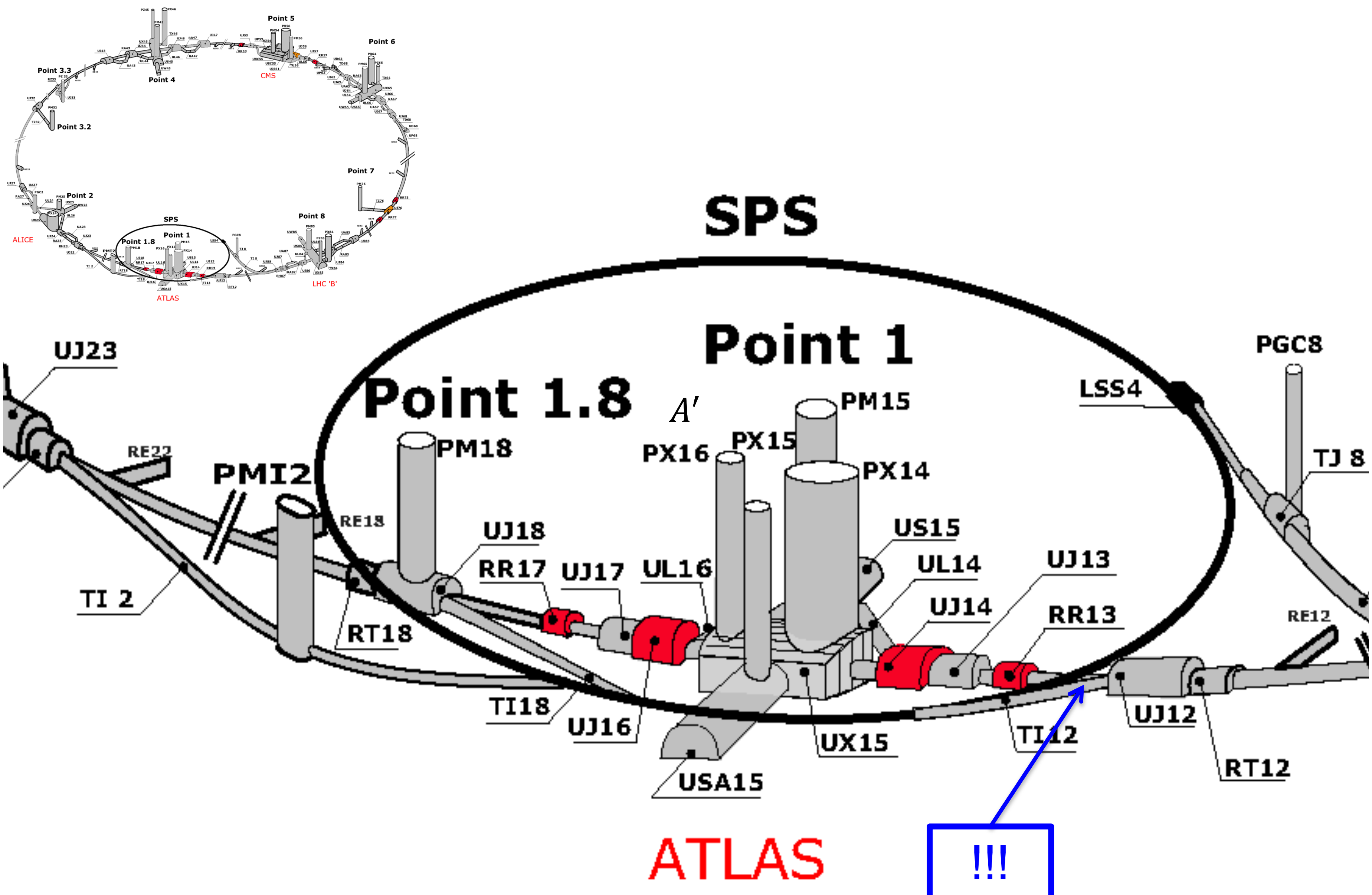
- Existing detectors are designed to find new heavy particles. These particles are produced at low velocities and decay roughly isotropically.



- But new light particles are mainly produced in the decays of light particles: π, η, K, D and B mesons. These are mainly produced along the beamline, and so the new particles disappear through the holes that let the beams in.

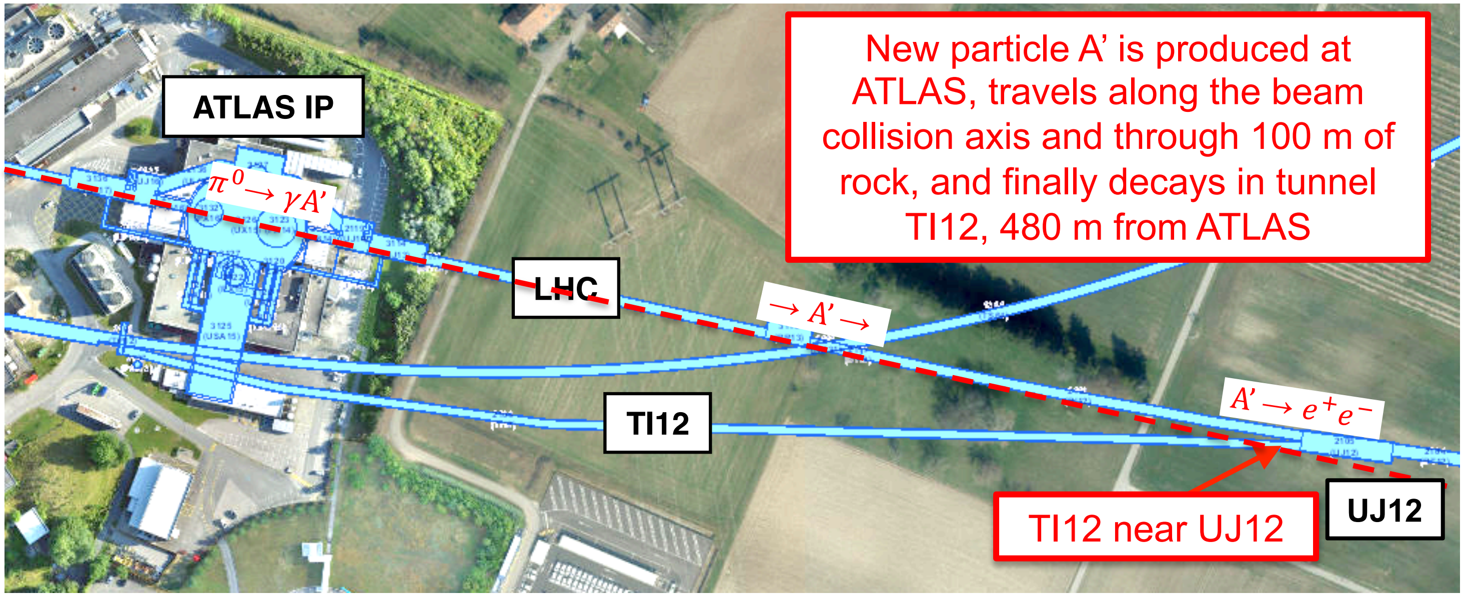
- Clearly we need a detector to exploit the "wasted" σ_{inel} ~ 100 mb and cover these "blind spots" in the forward region. If we go far enough away, the proton beams are bent by magnets (it's a circular collider!), whereas the new light particles will go straight.

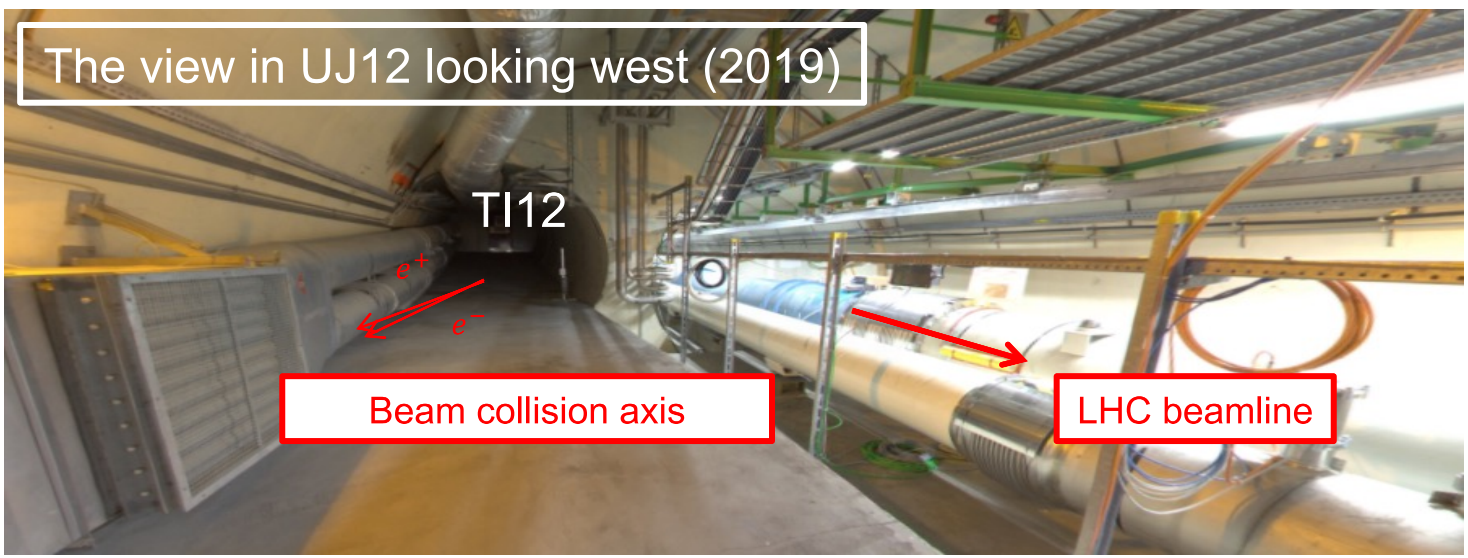
MAP OF LHC



SPS
Point 1
Point 1.8
A'
PM15
PX15
PX16
PM18
PX14
PMI2
UJ23
RE22
RE18
LSS4
PGC8
TJ 8
UJ18
US15
RR17
UJ17
UL16
UL14
UJ13
UJ14
RR13
TI 2
RT18
RE12
TI18
UJ16
UX15
TI12
UJ12
RT12
USA15
ATLAS
!!!

THE FAR-FORWARD REGION



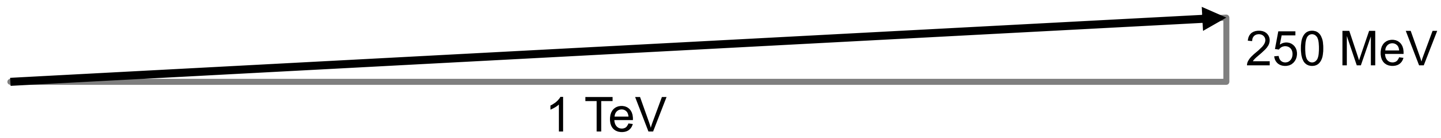


PARTICLE PATH FROM ATLAS TO TI12

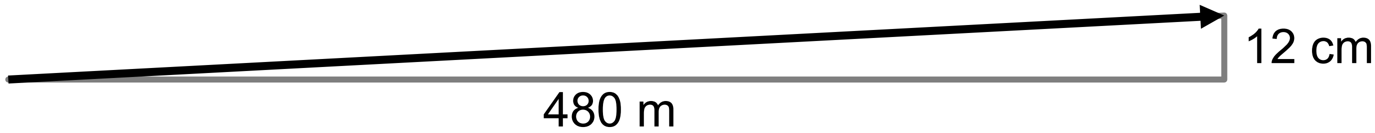
Dougherty, CERN Integration (2019)

HOW BIG DOES THE DETECTOR HAVE TO BE?

- Momentum:

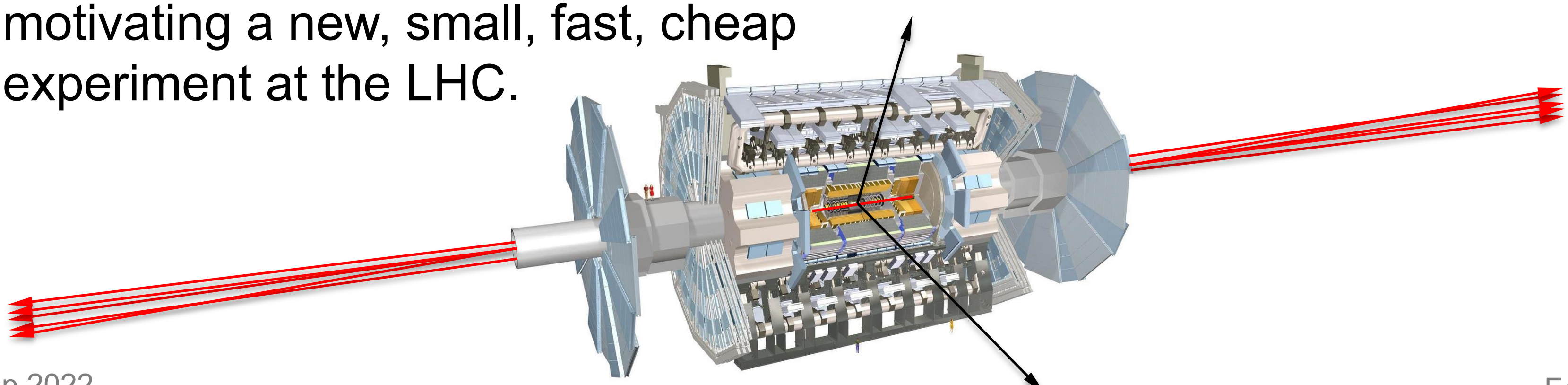


- Space:



- The opening angle is 0.2 mrad (η ~ 9); cf. the moon (7 mrad). Most of the signal passes through 1 sheet of paper at 480 m.

- TeV dark photons (or any other new particles produced in π, η, K, D, B decay) are far more collimated than shown below, motivating a new, small, fast, cheap experiment at the LHC.



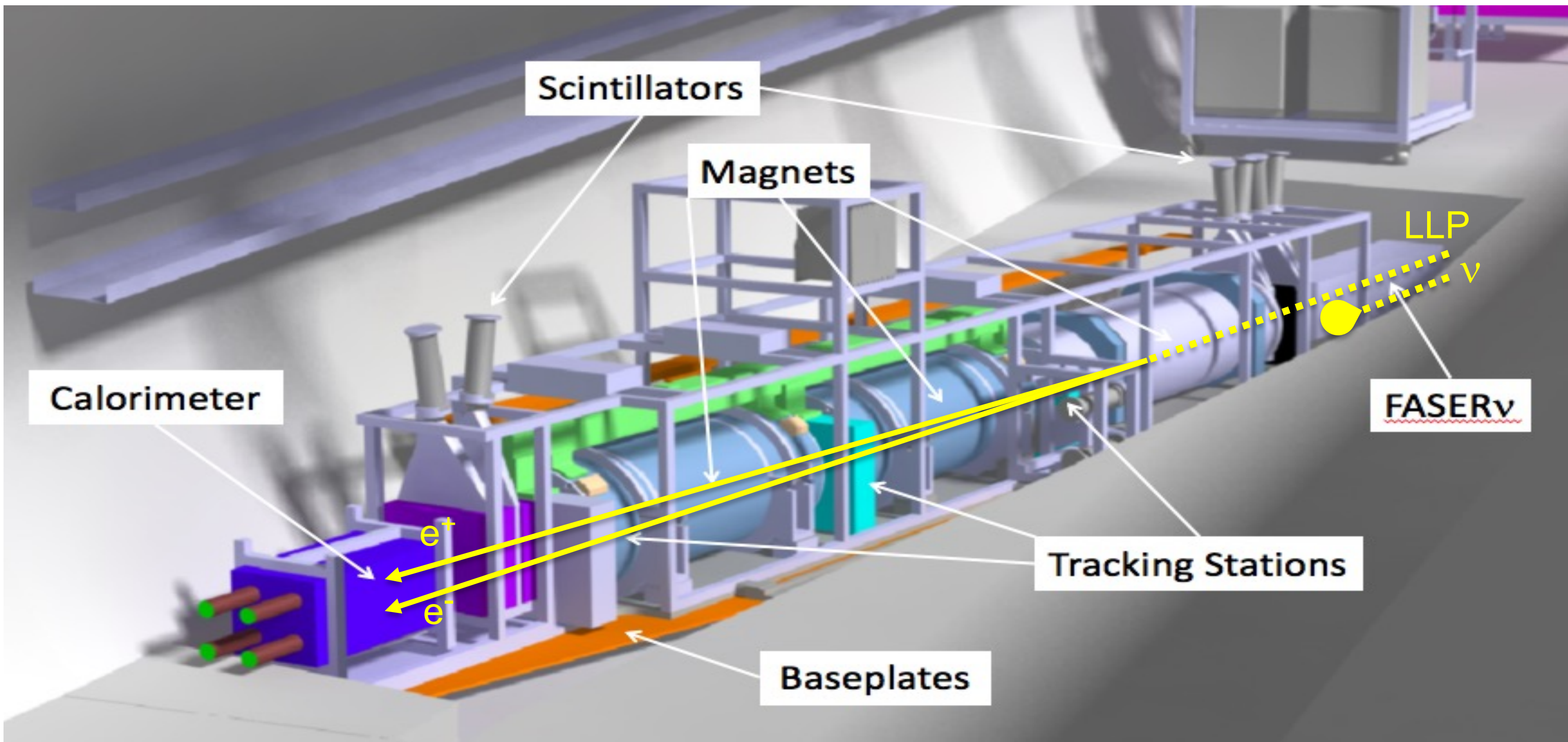
FASER

FASER TIMELINE

- September 2017: Initial proposal (Feng, Galon, Kling, Trojanowski)
- July 2018: Submitted LOI to CERN LHCC
- October 2018: Approval from ATLAS SCT and LHCb Collaborations for use of spare detector modules
- November 2018: Submitted Technical Proposal to LHCC
- November 2018 – January 2019: Experiment funded by the Heising-Simons and Simons Foundations
- March 2019: FASER approved as 8^{th} LHC detector by CERN
- December 2019: FASERν approved as 9^{th} LHC detector by CERN
- March 2021: FASER fully installed, commissioning of the detector begins
- May 2021: FASERν announces first candidate collider neutrinos
- June 2022: FASER and FASERν begin collecting data in Run 3

THE FASER DETECTOR

- Nothing incoming and 2 ~TeV, opposite-sign charged tracks pointing back to the ATLAS IP: a "light shining through (100 m-thick) wall" experiment.
- Scintillators veto incoming charged tracks (muons), magnets split the charged tracks, which are detected by tracking stations and a calorimeter.



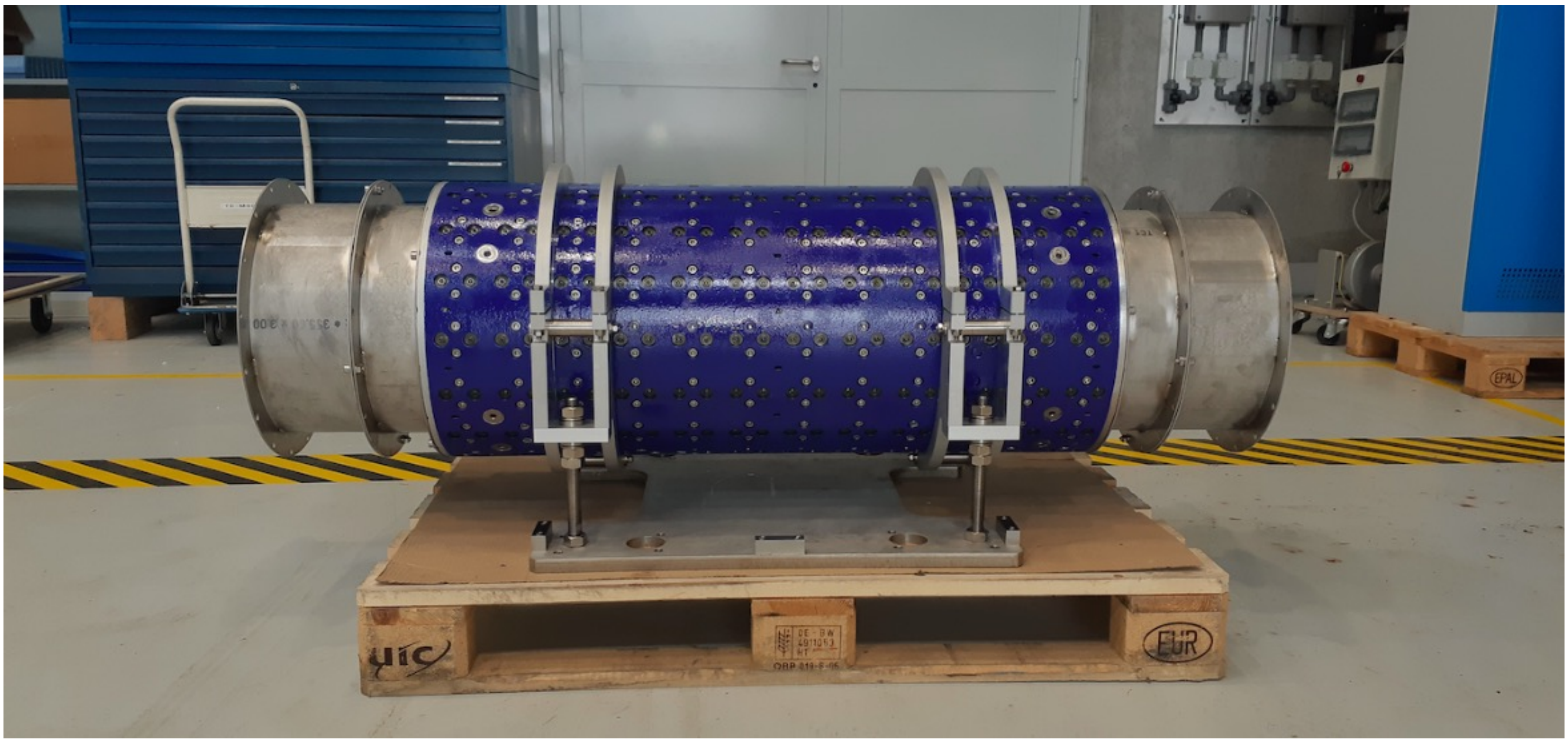
FASER IN TUNNEL TI12

- The beam collision axis was located to mm accuracy by the CERN survey department. 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 Spring 2020.

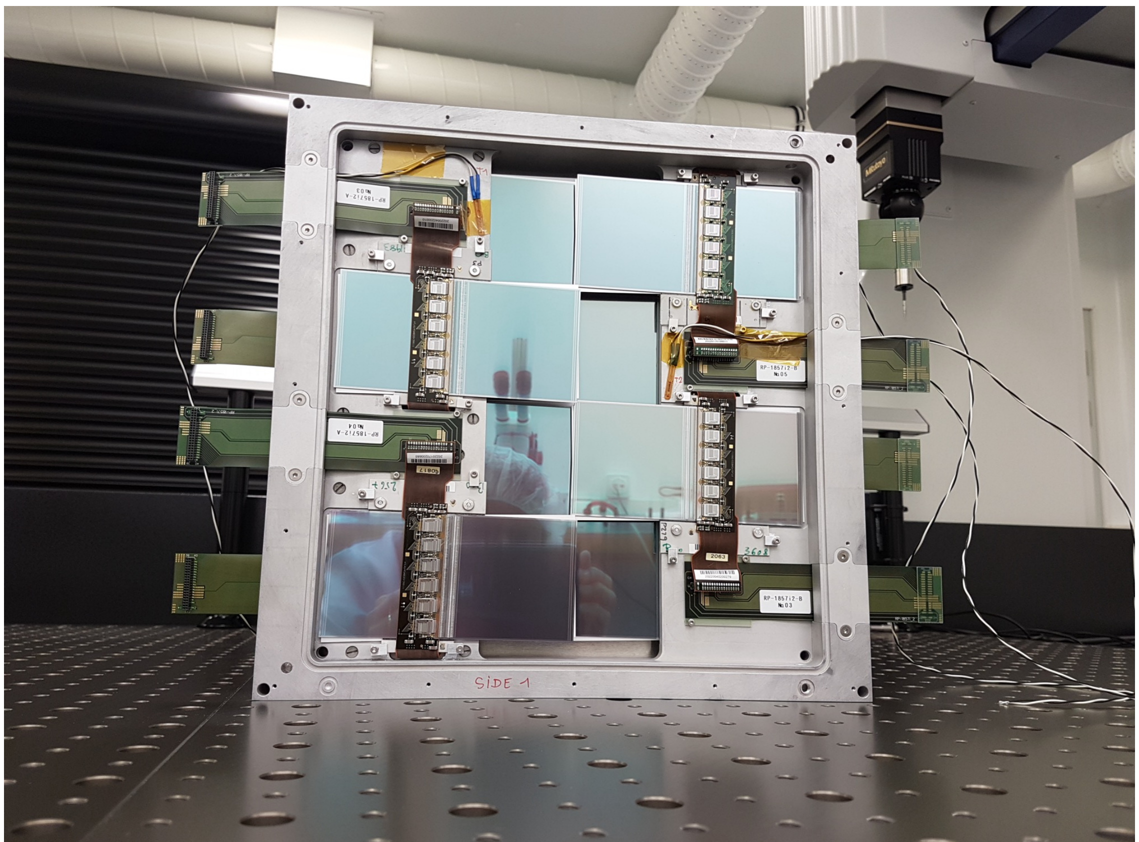
MAGNETS

- FASER includes 3 magnets: 1.5 m, 1 m, and 1m long.
- 0.57 T permanent dipoles with an inner diameter of 20 cm, require little maintenance.
- Constructed by the CERN magnet group.



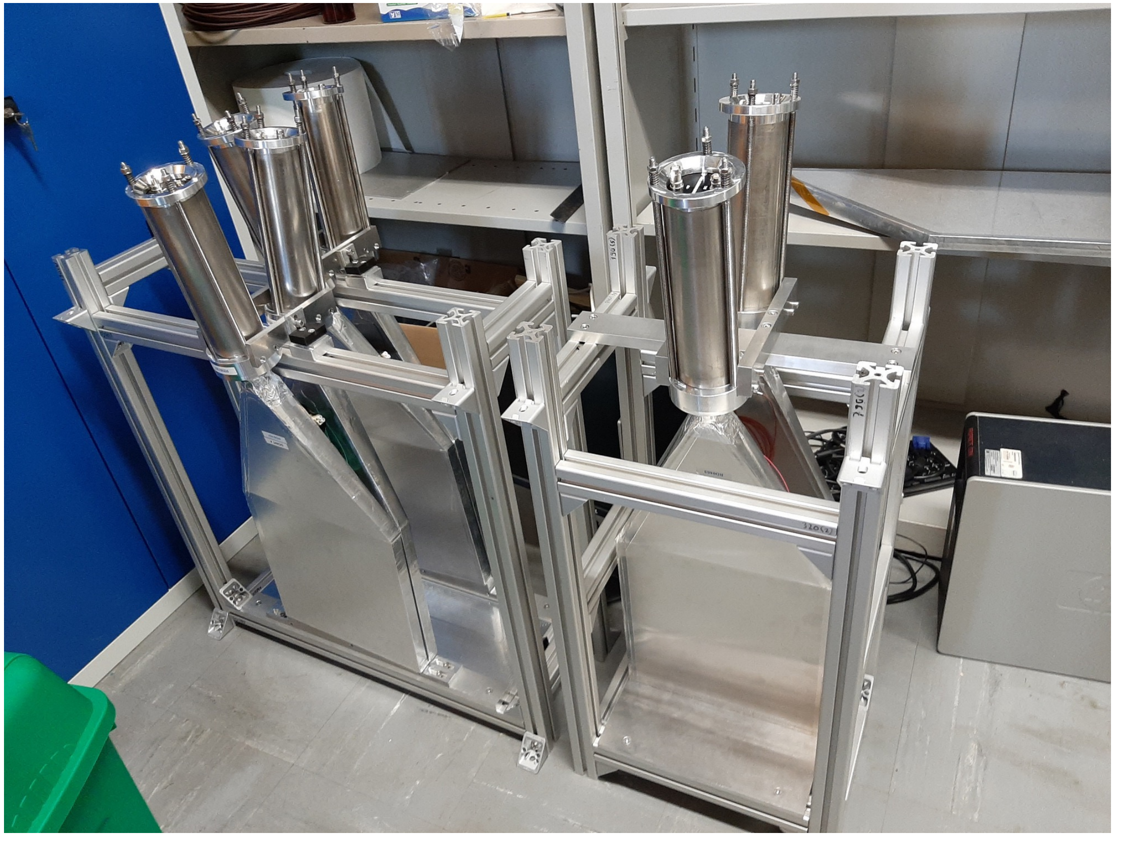
TRACKERS

- ATLAS tracker consists of ~3000 SCT modules.
- ~300 spares were never used. ~100 of these were generously donated to FASER: 8 modules x 3 tracking planes x 4 tracking stations at FASER.

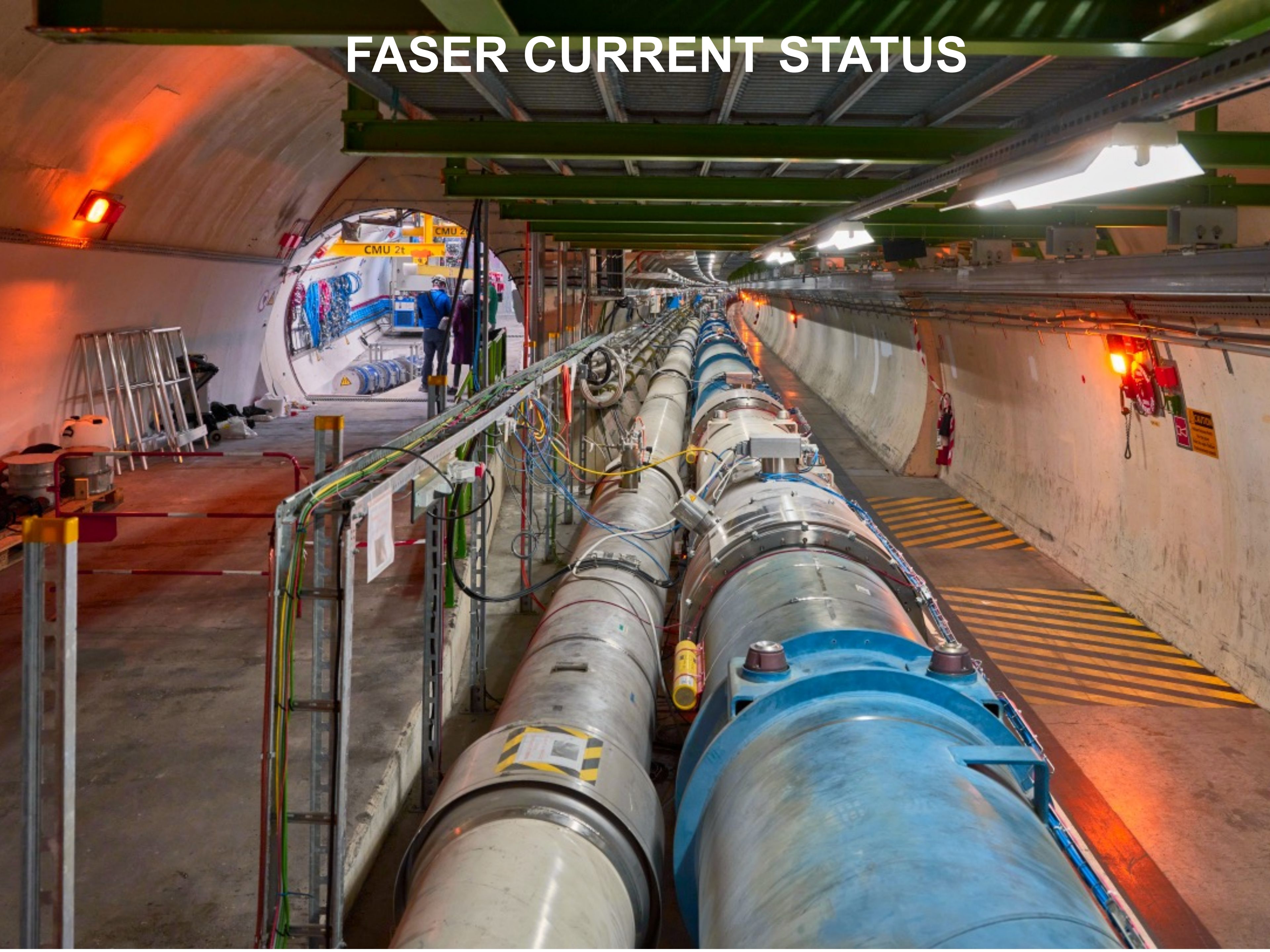


SCINTILLATORS

- 4 veto scintillators, each 2cm x 30cm x 30cm, upstream of the detector. Efficiency of each one is > 99.99%, makes muon background negligible.
- Additional beam backgrounds, simulated with FLUKA and validated with pilot detectors in 2018, are also expected to be negligible.



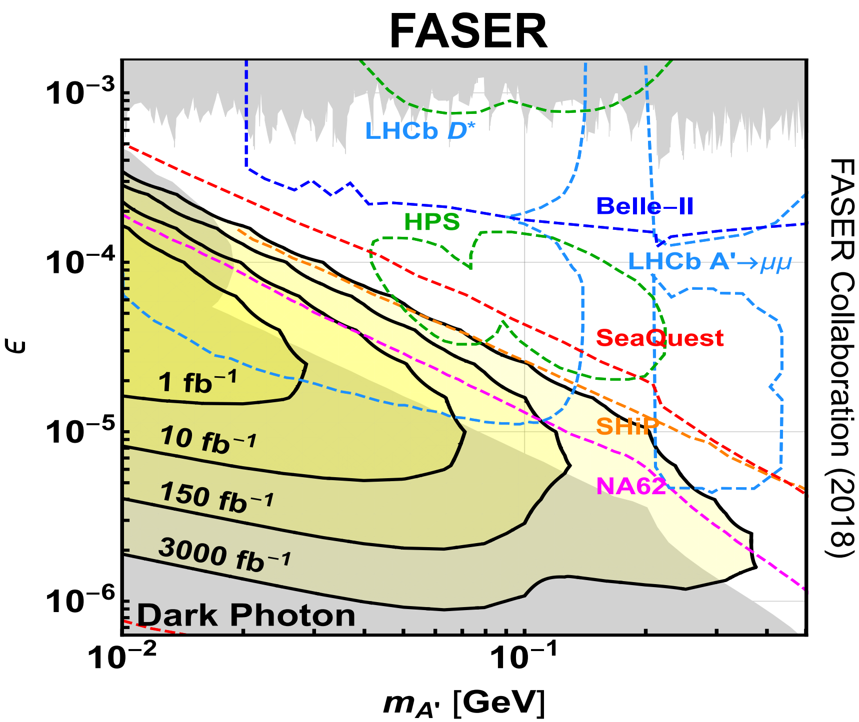
FASER CURRENT STATUS

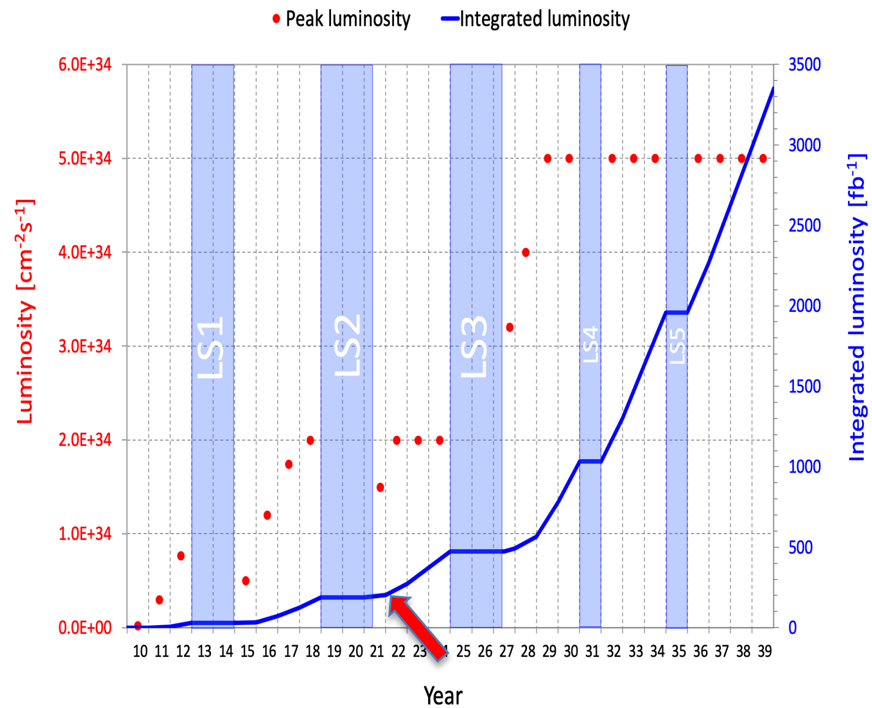


FASER CURRENT STATUS

LHC Run 3 started (officially) on 5 July 2022. Muon backgrounds are within ~30% of expectations (i.e., negligible), and FASER already has enough data to exclude or discover proposed LLPs in new regions parameter space.

DARK PHOTON SENSITIVITY REACH





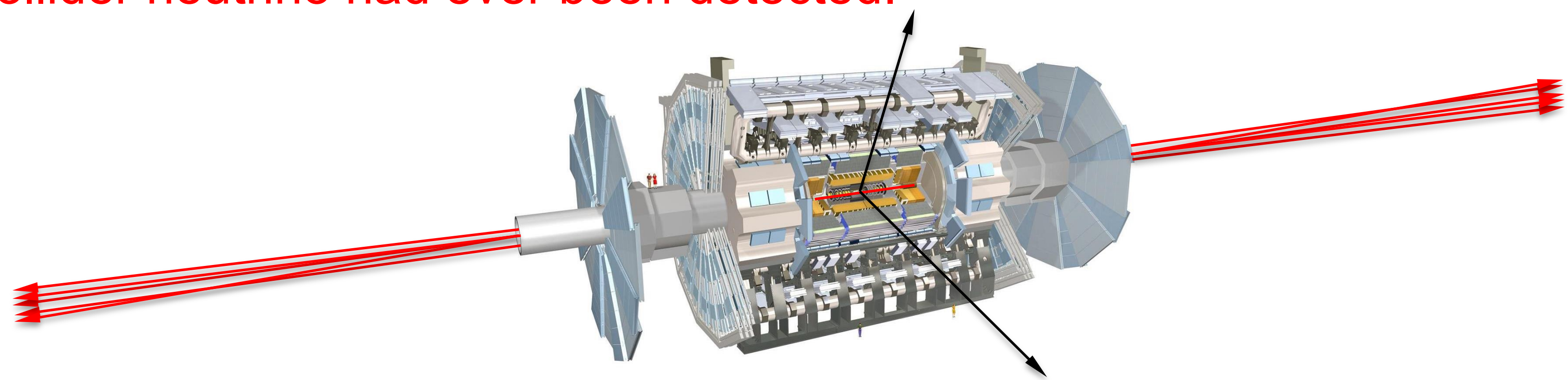
- FASER has collected 10 fb^{-1} and has started probing many new models.
- Without upgrade, HL-LHC extends (Luminosity*Vol) by factor of 3000 – could detect as many as 10,000 dark photons.
- Possible upgrade to FASER 2 (R=1m, L=20m) extends (Luminosity*Vol) by factor of ~10^6 – could detect as many as 3 x 10^6 dark photons.

FASERν

COLLIDER NEUTRINOS

- In addition to the possibility of hypothetical new light, weakly-interacting particles, there are also known light, weakly-interacting particles: neutrinos.

- The high-energy ones, which interact most strongly, are overwhelmingly produced in the far forward direction. Before May 2021, no candidate collider neutrino had ever been detected.

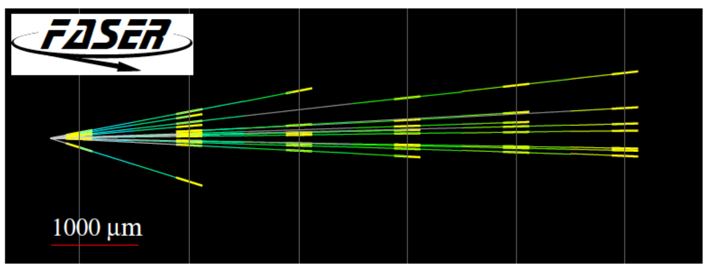


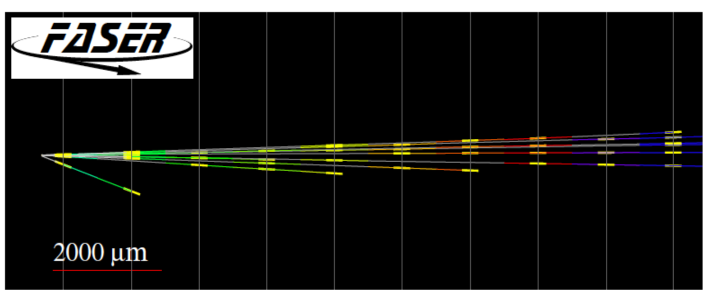
- If they can be detected, there is a fascinating new world of LHC neutrinos that can be explored.
  - The neutrino energies are ~TeV, highest human-made energies ever.
  - All flavors are produced ($\pi \to \nu_\mu$, $K \to \nu_e$, $D \to \nu_\tau$) and both neutrinos and anti-neutrinos.

De Rujula, Ruckl (1984); Winter (1990); Vannucci (1993)

FIRST COLLIDER NEUTRINOS

- In 2018 a FASER pilot emulsion detector with 11 kg fiducial mass collected 12.2 fb^{-1} on the beam collision axis (installed and removed during Technical Stops).
- In May 2021, the FASER Collaboration announced the direct detection of 6 candidate neutrinos above 12 expected neutral hadron background events (2.7σ).
- This opens up a new field: neutrino physics at colliders.



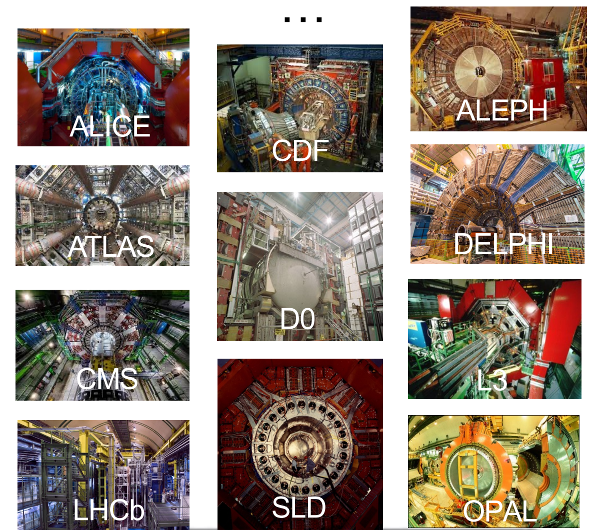


LOCATION, LOCATION, LOCATION

FASER Pilot Detector

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

6 candidate neutrinos



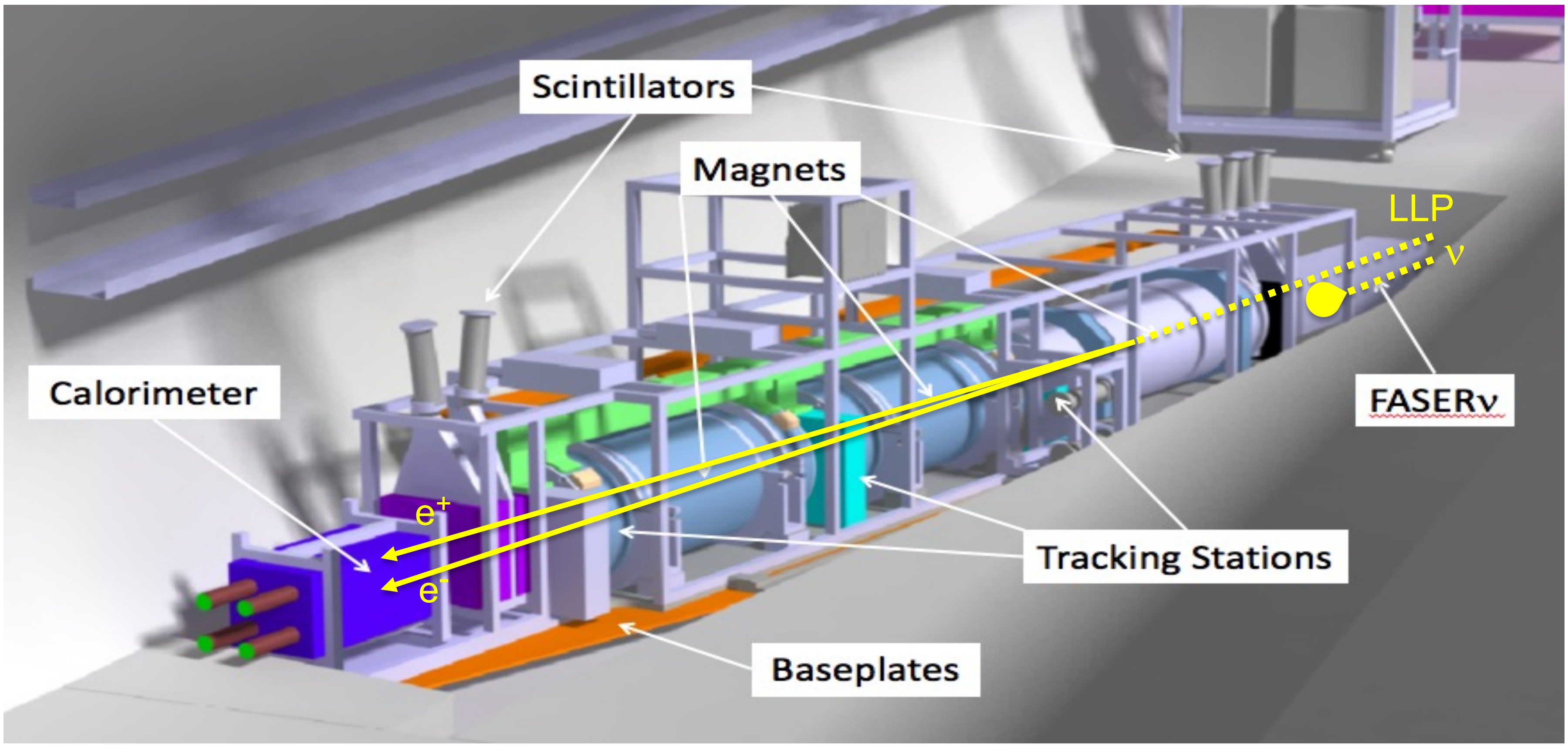
All previous
collider detectors

Building-size, decades
~$$10^9$

0 candidate neutrinos

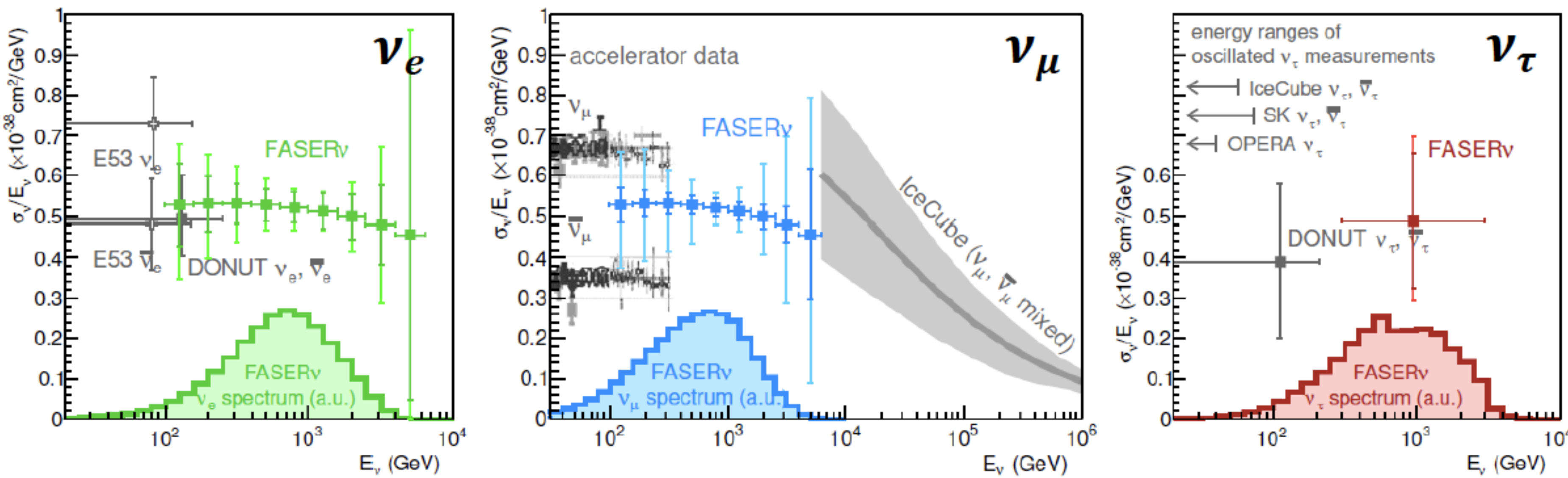
THE FASERν DETECTOR

- FASERν is designed to detect neutrinos of all flavors.
  - 25cm x 30cm x 1.1m detector consisting of 770 emulsion layers interleaved with 1 mm-thick tungsten plates; target mass = 1.1 tonnes.
  - Emulsion swapped out every ~10-30 fb^{-1}, total 10 sets of emulsion for Run 3.



NEUTRINO PHYSICS

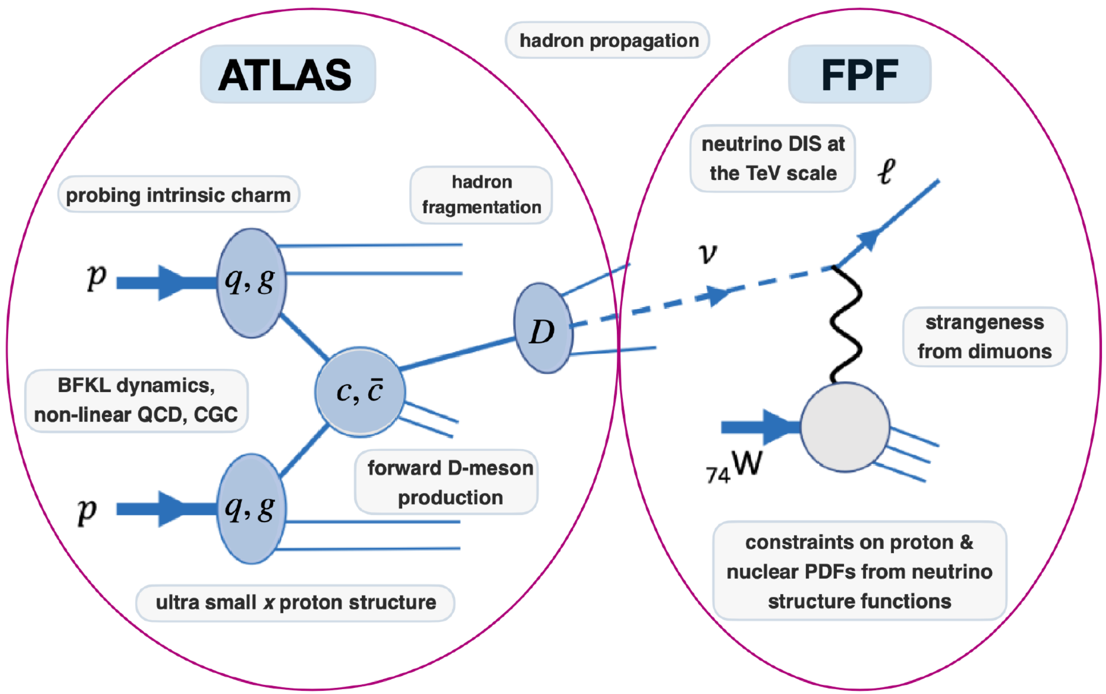
- In Run 3 (2022-24), the goals of FASERν are to
  - Detect the first collider neutrino.
  - Record ~1000 ν_e, ~10,000 ν_μ, and ~10 ν_τ interactions at TeV energies, the first direct exploration of this energy range for all 3 flavors.
  - Distinguish muon neutrinos from anti-neutrinos by combining FASER and FASERν data, and so measure their cross sections independently.
  - Add significantly to the number of ν_τ and detect the first anti-ν_τ .



FASER Collaboration 1908.02310 (2019)

QCD

- FASER will also have a rich program of QCD and hadron structure studies.
- Forward neutrino production is a a probe of forward hadron production, BFKL dynamics, intrinsic charm, ultra small x proton structure, with important implications for UHE cosmic ray experiments.
- Neutrino interactions will probe DIS at the TeV-scale, constrain proton and nuclear structure, pdfs.

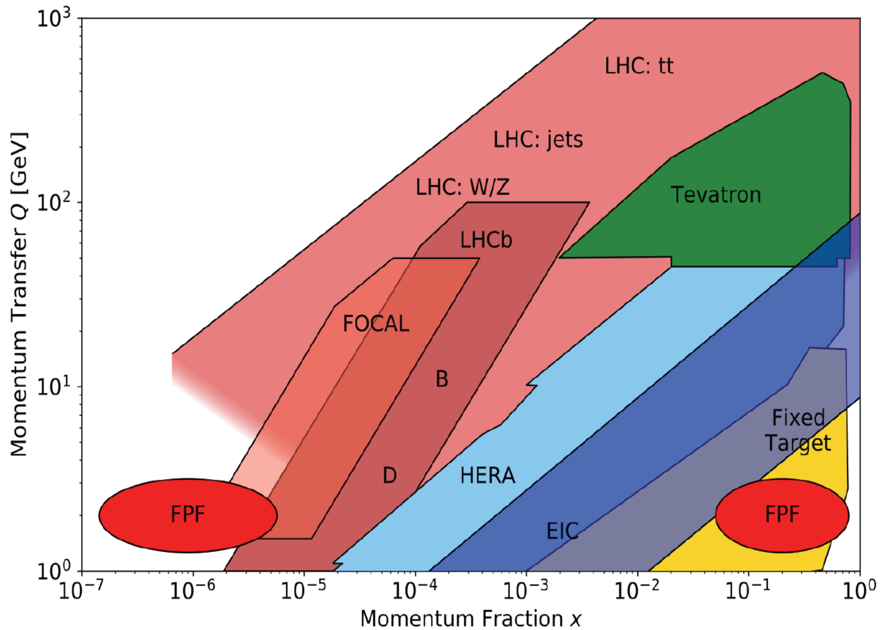


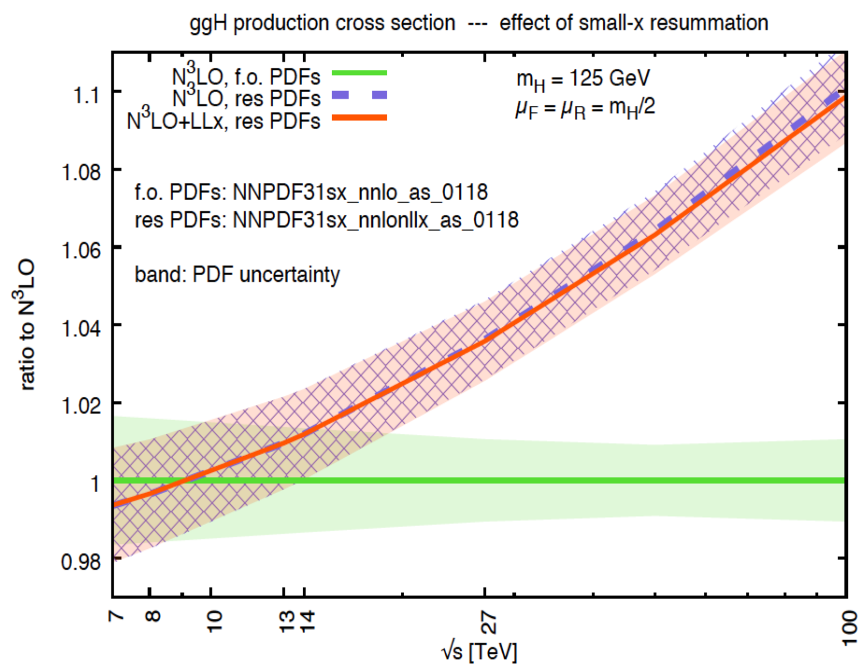
FPF White Paper (2022)

QCD

- FASER and FASERν will probe proton structure at ultra small $x \sim 10^{-7}$ (and also high $x \sim 1$).

- In addition to the intrinsic interest in QCD, ultra small-x physics will become more and more important at higher energies, for example, in making precise predictions for $\sigma(gg \to h)$ at a 100 TeV pp collider.





FPF White Paper (2022)

FPF

Forward Physics Facility

FORWARD PHYSICS FACILITY

- FASER, FASERν, and other proposed far-forward detectors are currently highly constrained by 1980's infrastructure that was never intended to support experiments.

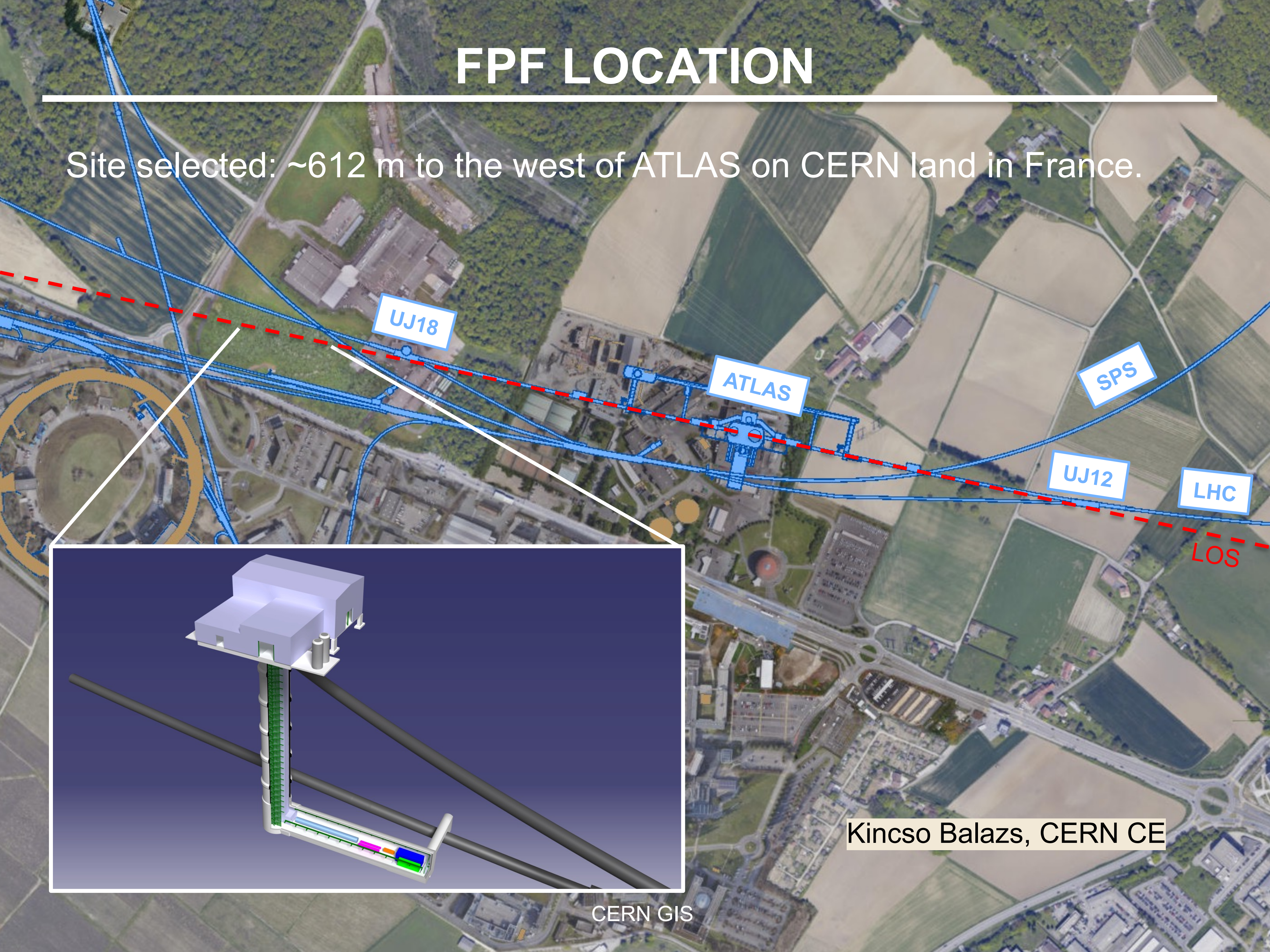
- The rich physics program in the far-forward region therefore strongly motivates creating a dedicated Forward Physics Facility to house far-forward experiments for the HL-LHC era from 2029-40.

- FPF Meetings
  - FPF Kickoff Meeting, 9-10 Nov 2020, https://indico.cern.ch/event/955956
  - FPF2 Meeting, 27-28 May 2021, https://indico.cern.ch/event/1022352
  - FPF3 Meeting, 25-26 Oct 2021, https://indico.cern.ch/event/1076733
  - FPF4 Meeting, 31 Jan-1 Feb 2022, https://indico.cern.ch/event/1110746

- FPF Papers
  - "Short" Paper: 75 pages, 80 authors (2109.10905, Phys. Rept. 968, 1 (2022)).
  - Snowmass White Paper: 429 pages, 392-authors+endorsers (2203.05090, J. Phys. G).

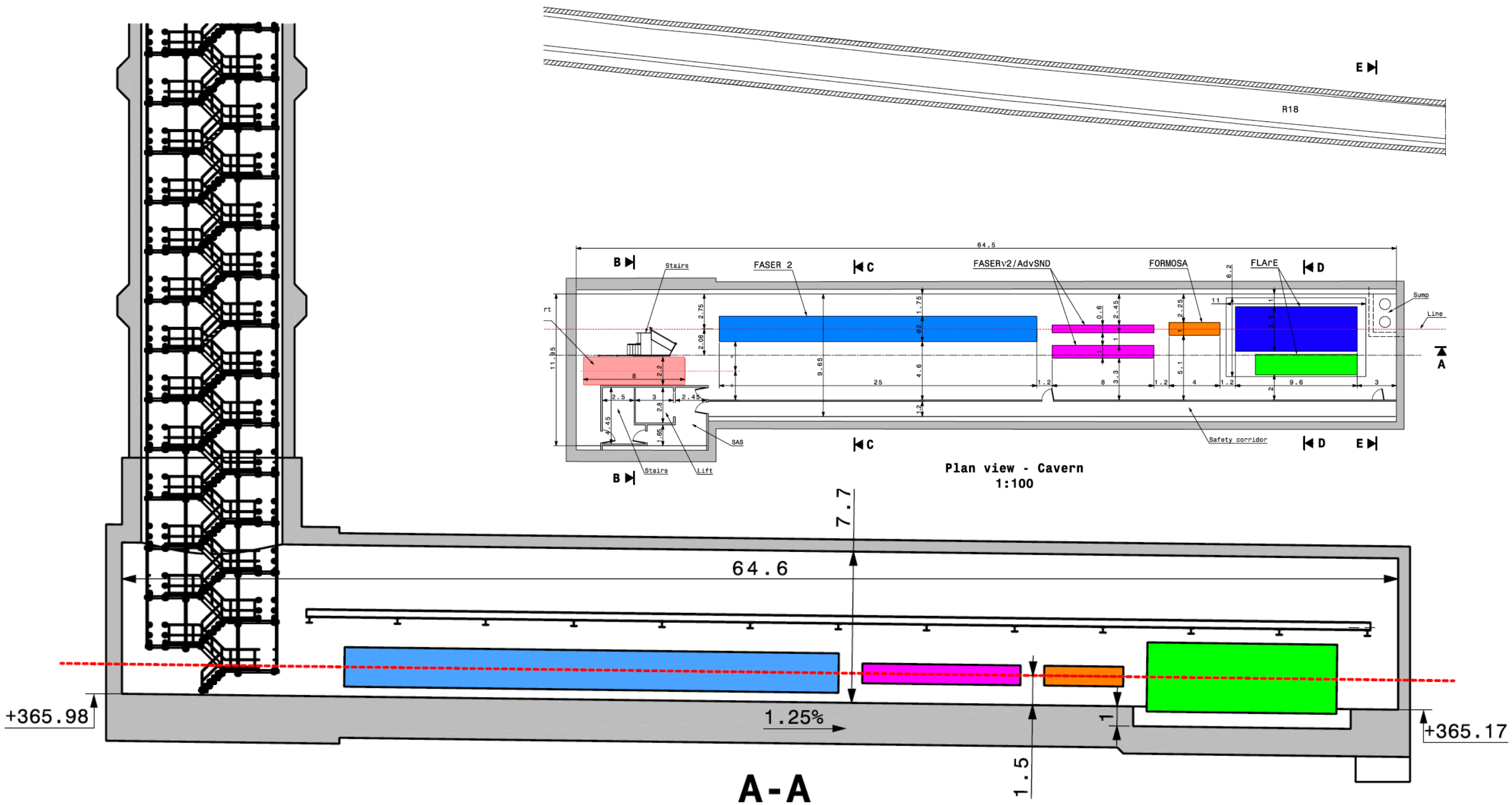
FPF LOCATION

Site selected: ~612 m to the west of ATLAS on CERN land in France.

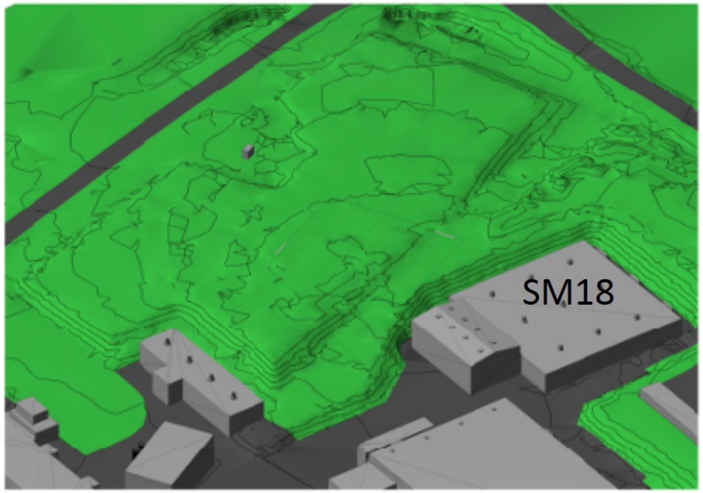


CAVERN AND SHAFT

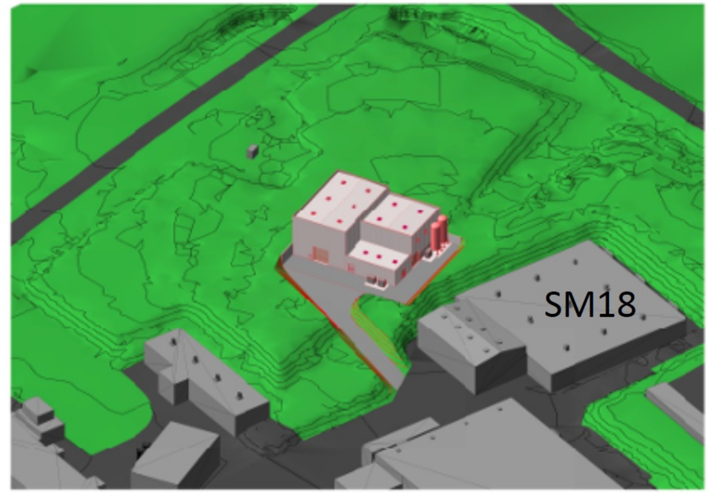
- Cavern: 65m long, 8m wide/high. Shaft: 88m-deep, 9.1m-diameter.
- The FPF is completely decoupled from the LHC (as of today, no need for a safety corridor connecting FPF to the LHC).



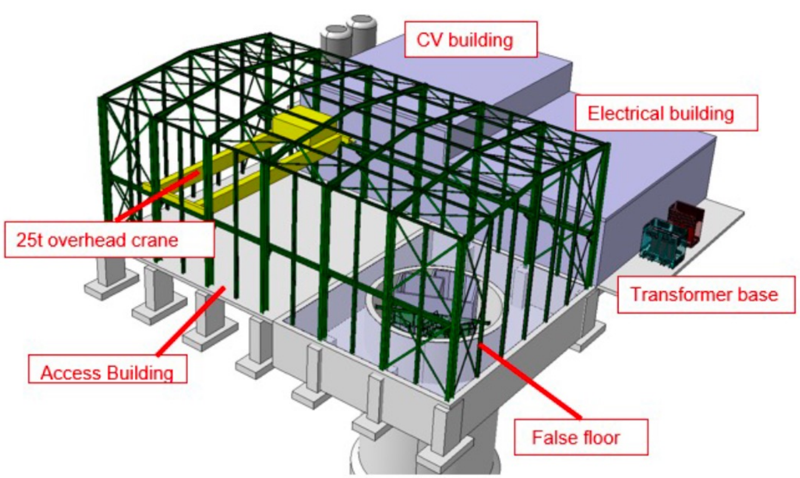
SURFACE BUILDINGS

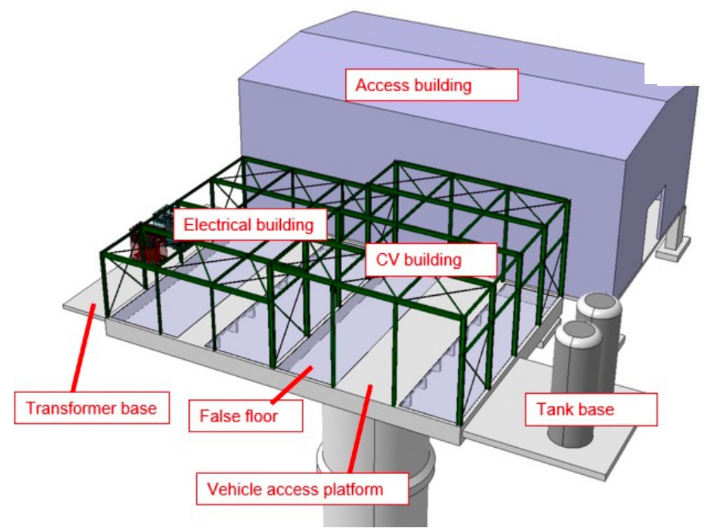


3D EXISTING



3D NEW

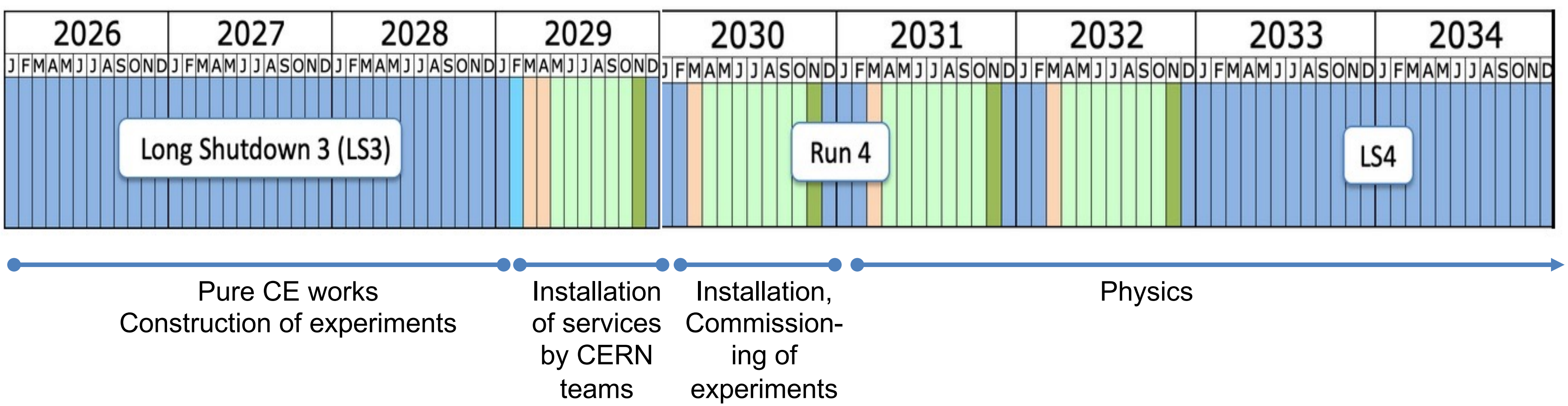




COST AND TIMELINE

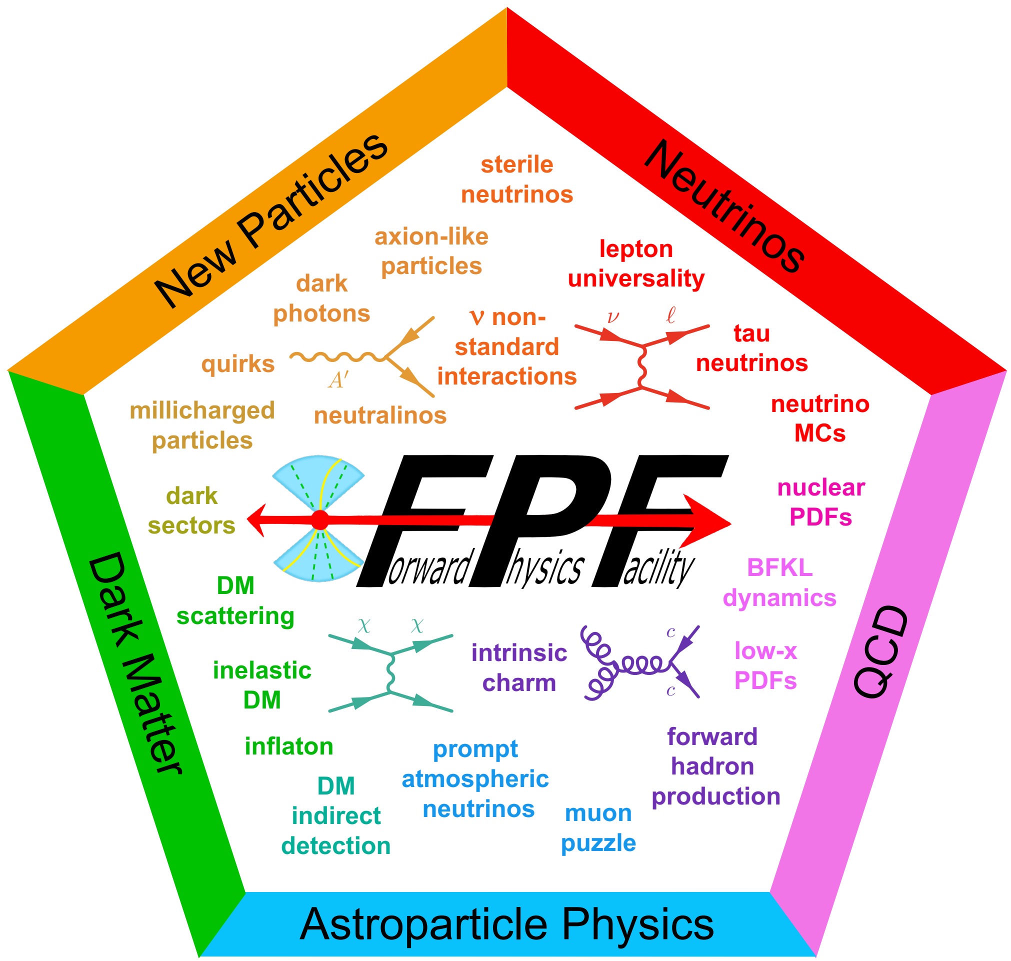
- Very preliminary (class 4) cost estimate: 23 MCHF (CE) + 15 MCHF (services) ≈ 40 MCHF (+50%/-30%), not including experiments.

- Timeline considerations
  - Can construct and service the FPF and its experiments while the LHC is running.
  - Timeline set by the HL-LHC.
  - Possible timeline presented at Chamonix (Jan 2022) allowing physics from 2031-42:



FPF PHYSICS

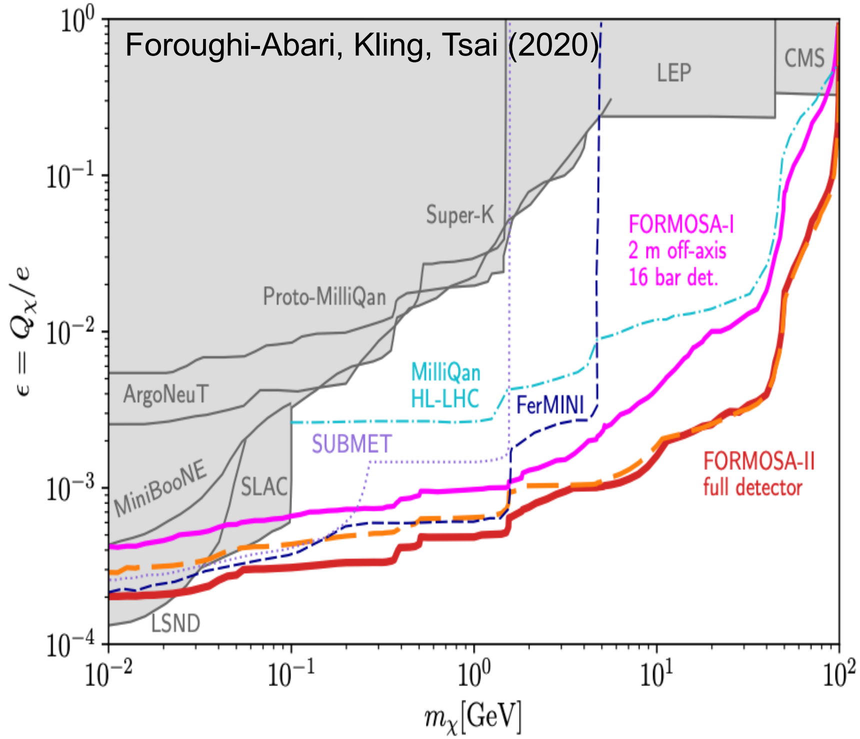
- The FPF is a general purpose facility with a broad SM and BSM physics program that expands on the physics of FASER and FASERν. Here I will just give a few additional examples. For more details, see the FPF White Paper.



MILLI-CHARGED PARTICLES

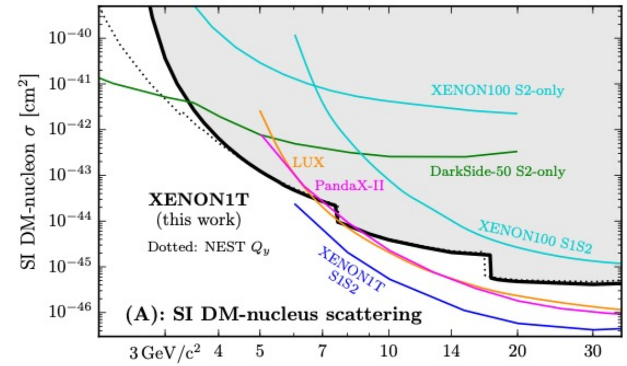
- A completely generic possibility motivated by dark matter, dark sectors. Currently the target of the MilliQan experiment, located at the LHC near the CMS experiment in a “non-forward” tunnel.

- The MilliQan Demonstrator (Proto-MilliQan) already probes new region. Full MilliQan can also run in this location in the HL-LHC era, but the sensitivity may be improved significantly by moving it to the FPF (FORMOSA).

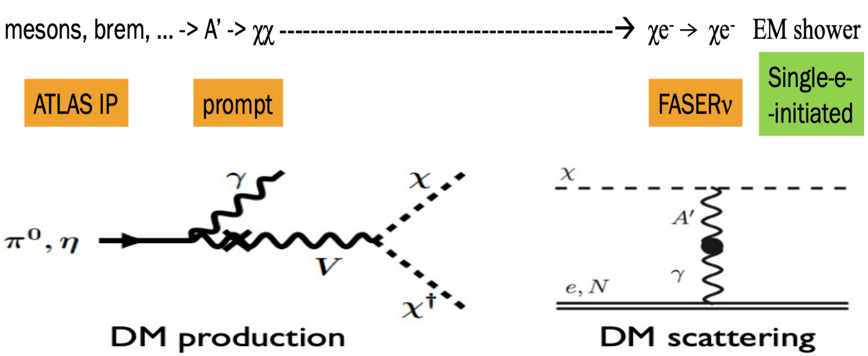


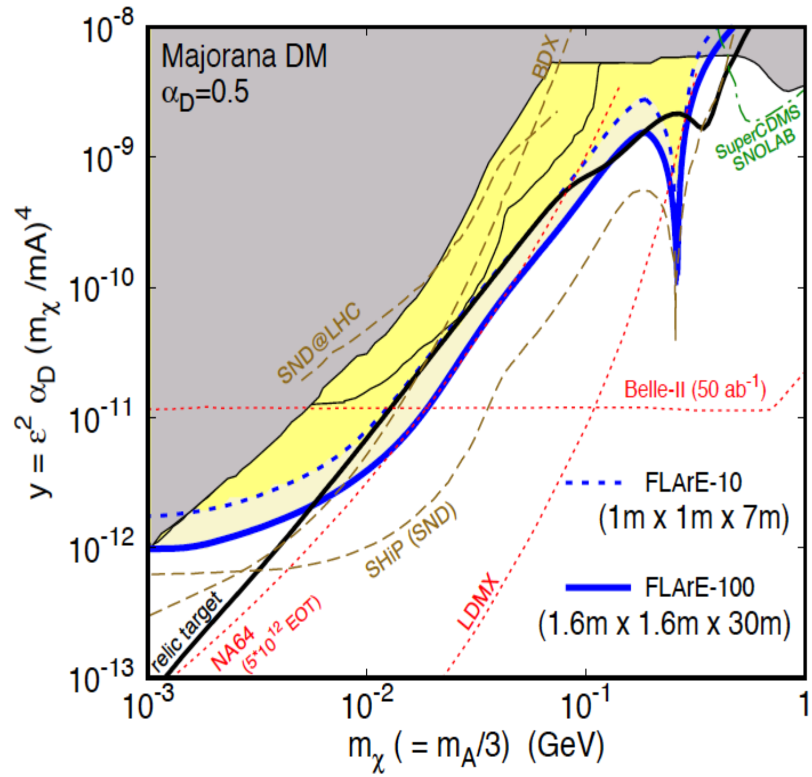
DARK MATTER

- Light DM with masses at the GeV scale and below is famously hard to detect.
  - Galactic halo velocity ~ 10^{-3} c, so kinetic energy ~ keV or below.



- At the LHC, we can produce DM at high energies, look for the resulting DM to scatter in FLArE, Forward Liquid Argon Experiment, a proposed 10 to 100 tonne LArTPC.



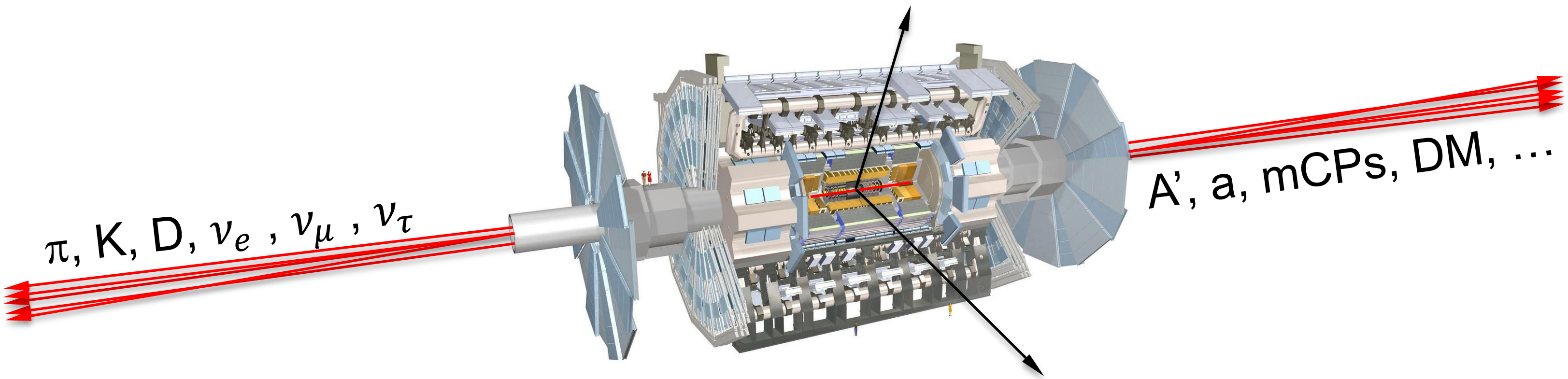


Batell, Feng, Trojanowski (2021)

- FLArE is powerful in the region favored/allowed by thermal freezeout.

SUMMARY

- SM and new physics opportunities are currently being missed in the far-forward region at the LHC.



- Modest investment in a few small experiments can solve this problem

- FASER and FASERν: 5 m long, ~$2M. Along with SND@LHC, will soon create the new field of LHC neutrino physics, and also look for many new particles.

- In the future, the FPF and its experiments will carry this research program into the 2040's.

FIRST FASER COLLABORATION MEETING

FASER COLLABORATION TODAY

75 collaborators, 22 institutions, 9 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 JG|U
מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE
KEK
UNIVERSITY OF OREGON

UNIVERSITÄT BONN
INFN
清華大學
Tsinghua University
MANCHESTER 1824
The University of Manchester

ROYAL HOLLOWAY UNIVERSITY OF LONDON
UNIVERSITY OF LIVERPOOL
CHIBA UNIVERSITY
UNIVERSITY OF SUSSEX

DESY.
JINR