LOOKING FORWARD TO FORWARD PHYSICS

Physics Colloquium, The Ohio State University

Jonathan Feng, UC Irvine, 7 December 2021

OUTLINE

MOTIVATIONS

FORWARD PHYSICS

FASER

FASERν

FORWARD PHYSICS FACILITY

SUMMARY

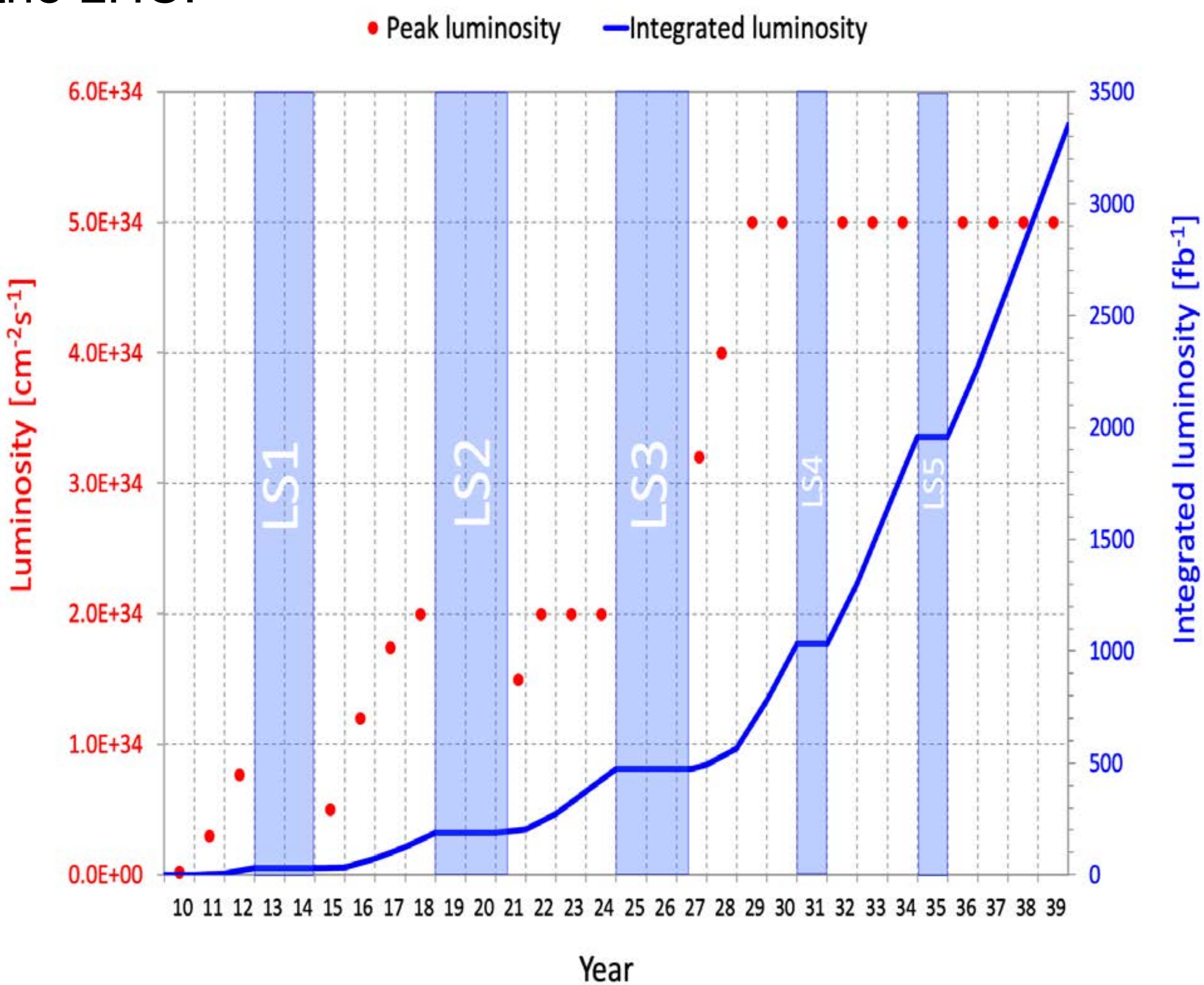
MOTIVATIONS

LHC: CURRENT STATUS

- This is a critical time in particle physics: the Higgs boson was discovered in 2012, but there has been no evidence of new particles beyond the Standard Model from the LHC.

- The LHC is currently in Long Shutdown 2, but will start up again in 2022 and run until ~2037. Will we find new particles?

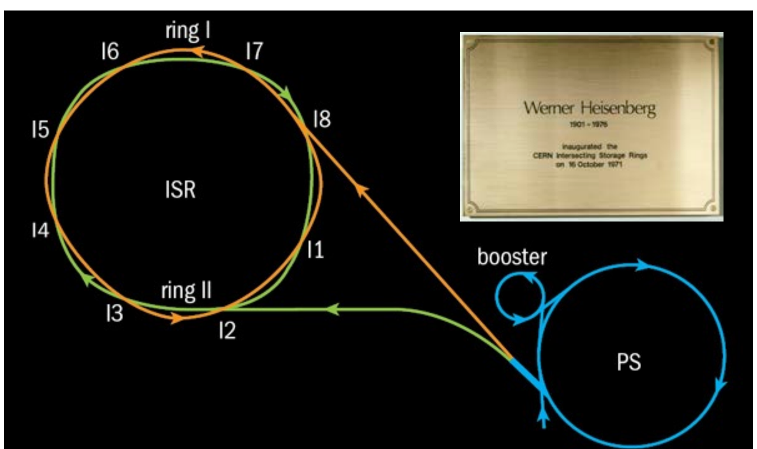
- More importantly, what can we do to enhance the prospects for discovering new physics?

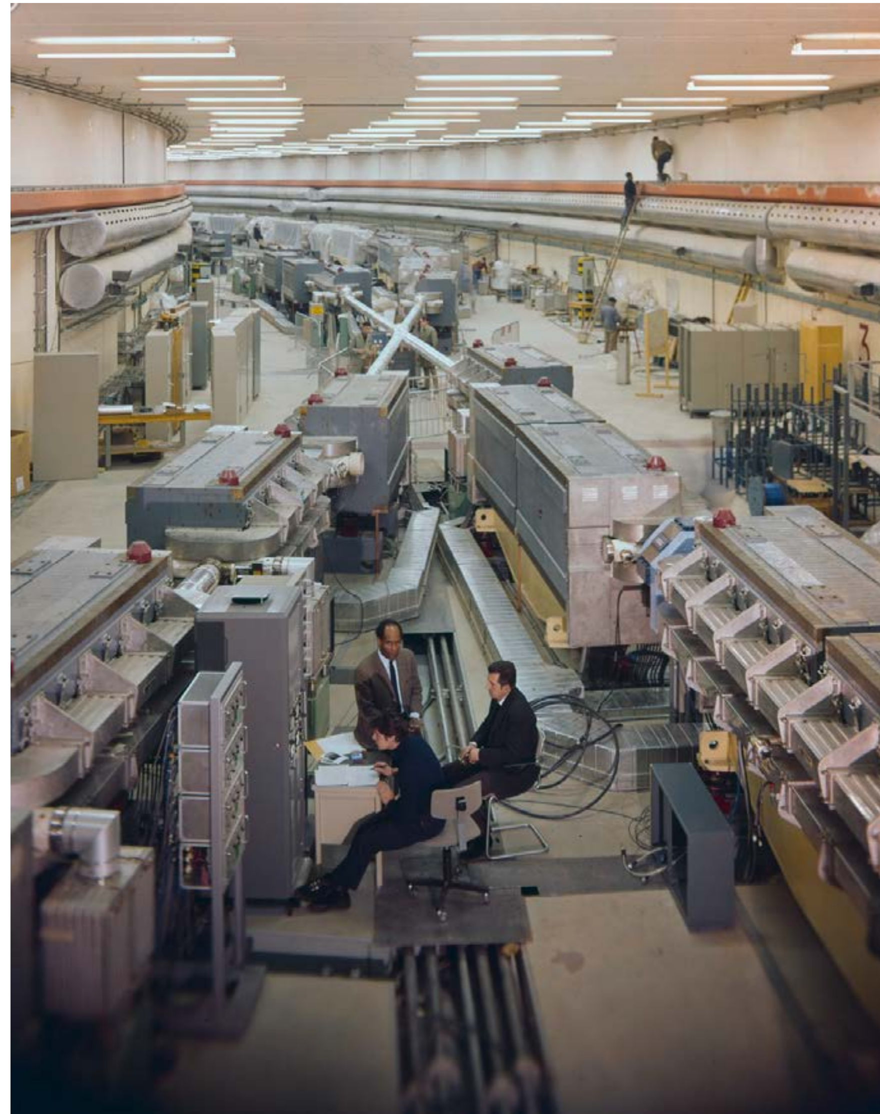


SOME HISTORY

- This is the 50th anniversary of the birth of hadron colliders.

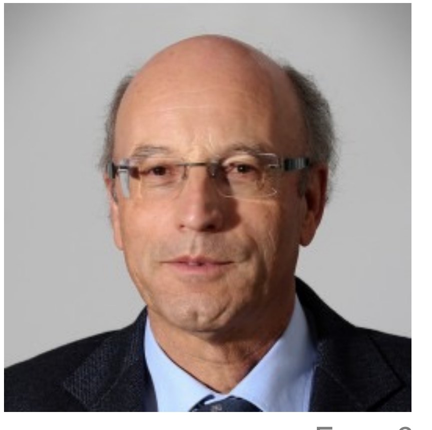
- In 1971, CERN's Intersecting Storage Rings (ISR), with a circumference of ~1 km, collided protons with protons at center-of-mass energy 30 GeV (later raised to 62 GeV).





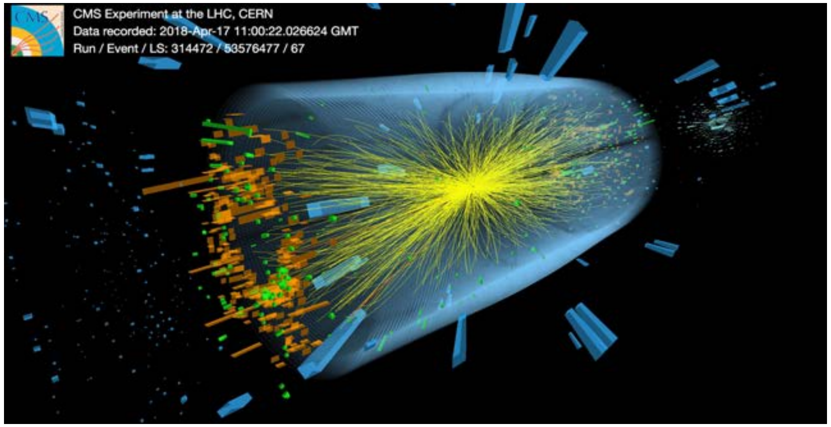
ISR'S LEGACY

- 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).

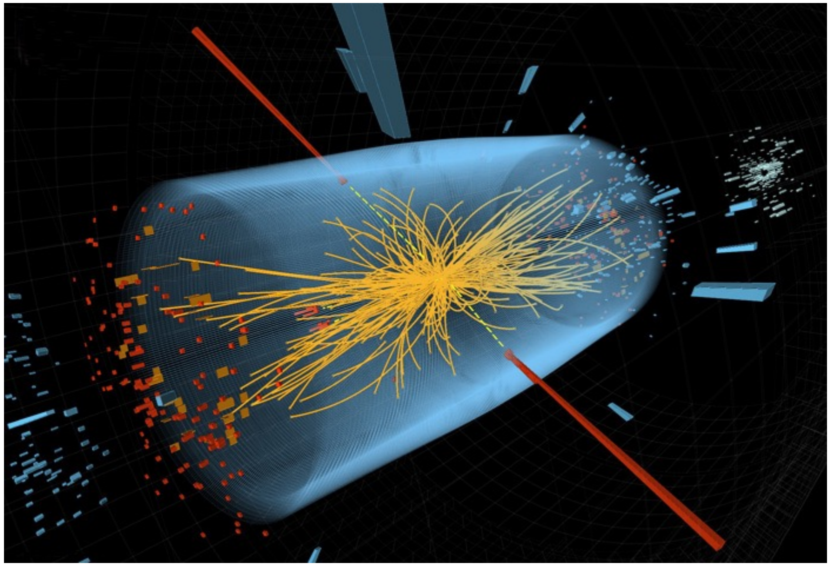


A CAUTIONARY TALE

- Expected
  - In 1971, physicists expected the most interesting events to be from the soft, glancing collisions of protons.
  - These produce particles in the forward direction, along the beam line.



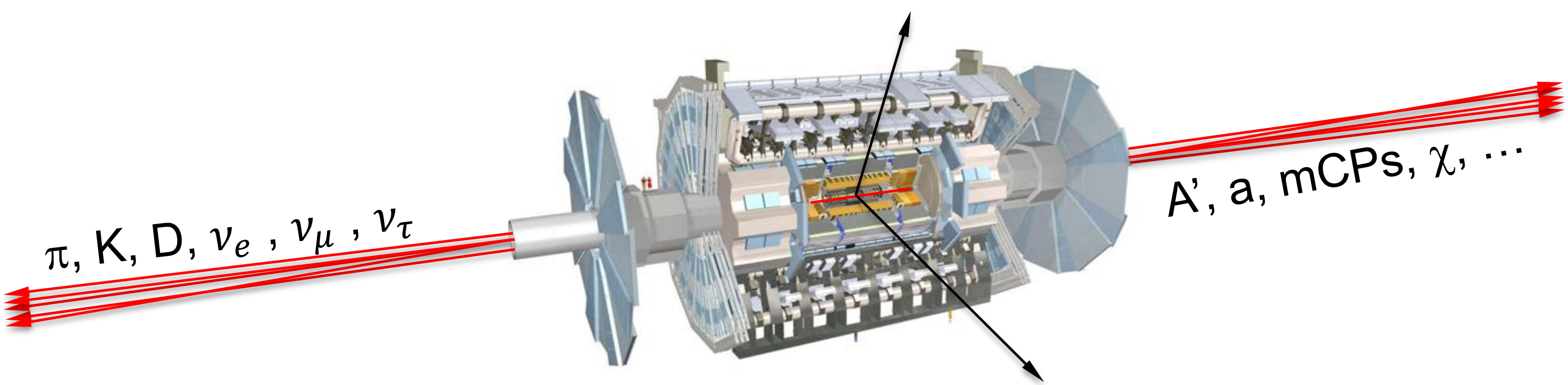
- Actual
  - In fact, the most interesting collisions were from hard collisions of quarks.
  - These produced heavy particles, like charm and bottom quarks, that decayed to particles at large angles relative to the beamline.



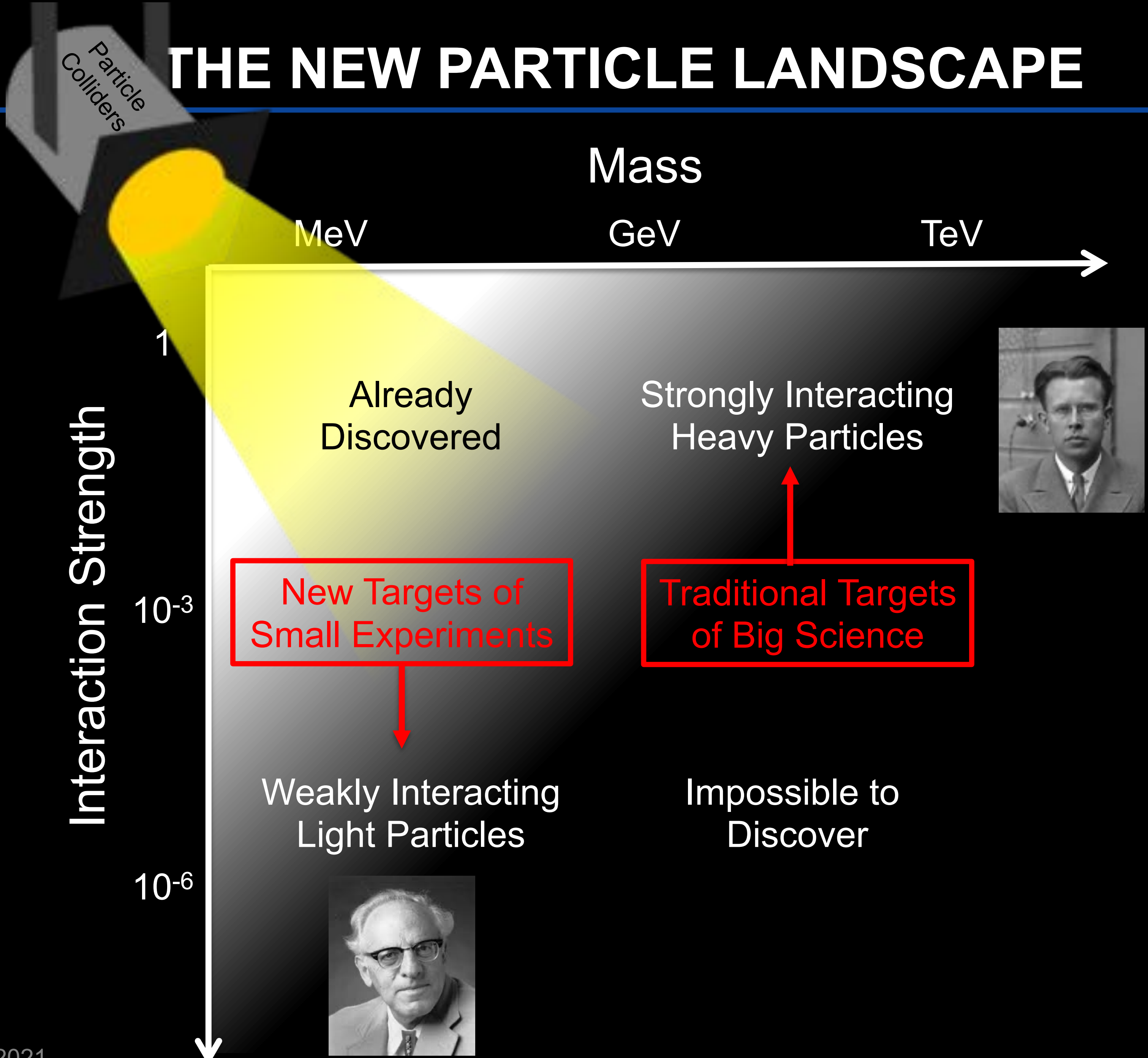
- The collider was creating new forms of matter, but the detectors focused on the forward region and missed them.

AN OBVIOUS QUESTION

- Are we missing opportunities in a similar (but opposite) way at the LHC?
- In contrast to the ISR days, there is now broad belief that the most interesting physics is at high p_T . 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) are in the far-forward direction.
- This may also be true of many interesting new particle candidates: dark photons, axion-like particles, millicharged particles, dark matter, …



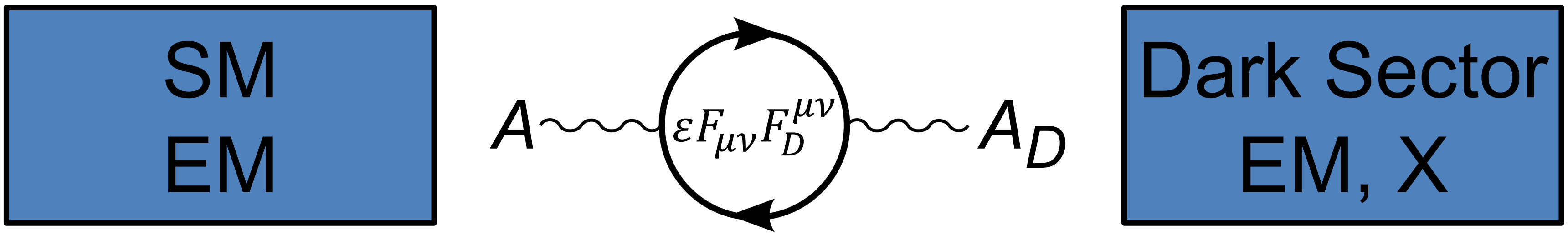
THE NEW PARTICLE LANDSCAPE



AN EXAMPLE: DARK SECTORS

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

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

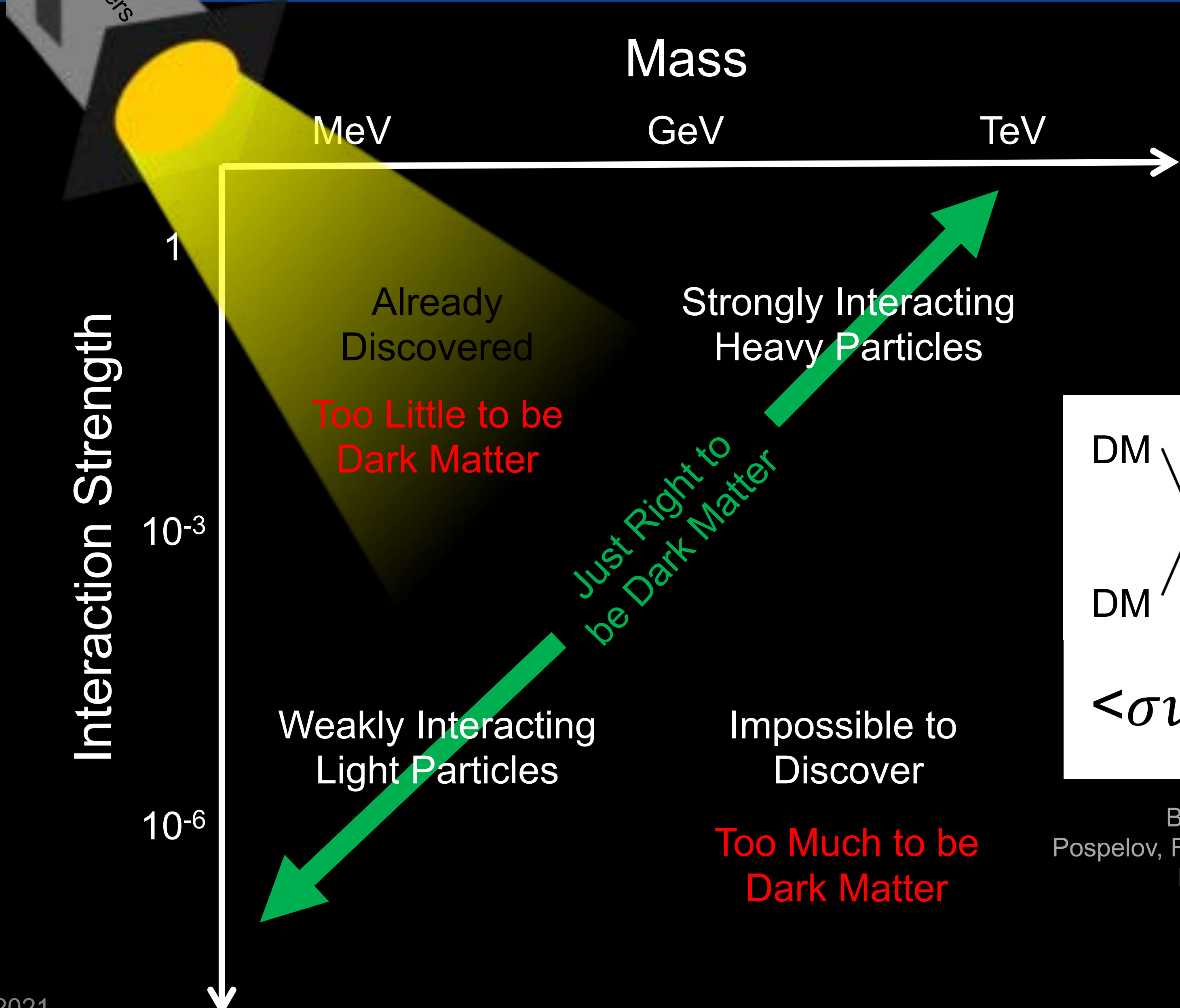


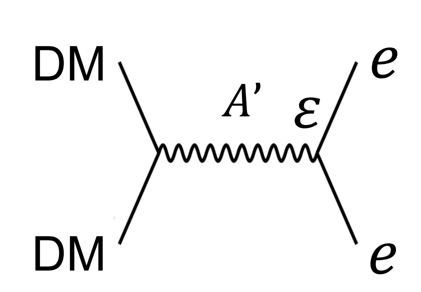
- The result? Two possibilities:
  - Dark photons A', like photons, but with mass $m_{A'}$, couplings suppressed by ε.
  - Milli-charged particles (mCPs), with charges suppressed by ε.

Holdom (1986)

- Finding either of these would imply new fundamental forces or new matter particles, possibly a "portal" to the dark sector.

THE THERMAL RELIC LANDSCAPE





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

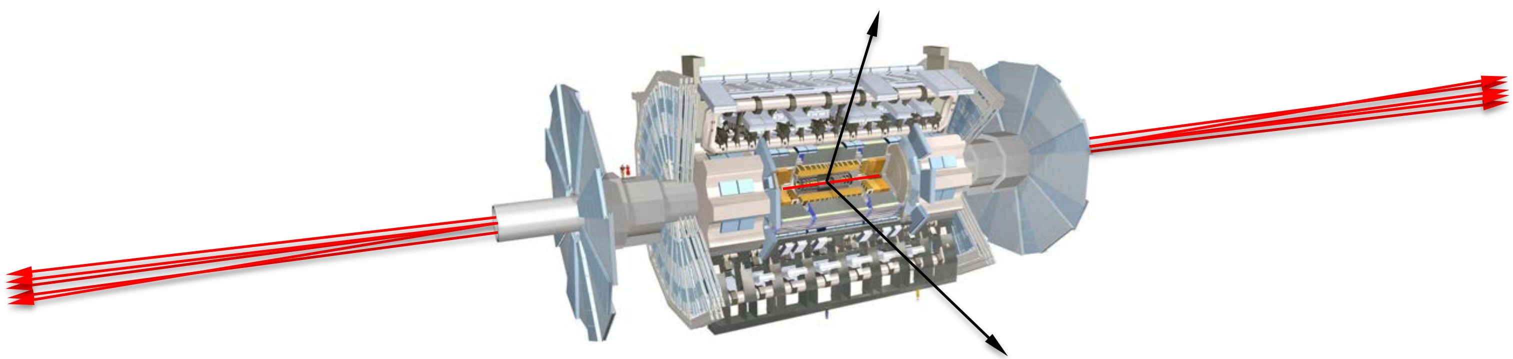
Boehm, Fayet (2003)
Pospelov, Ritz, Voloshin (2007)
Feng, Kumar (2008)

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.

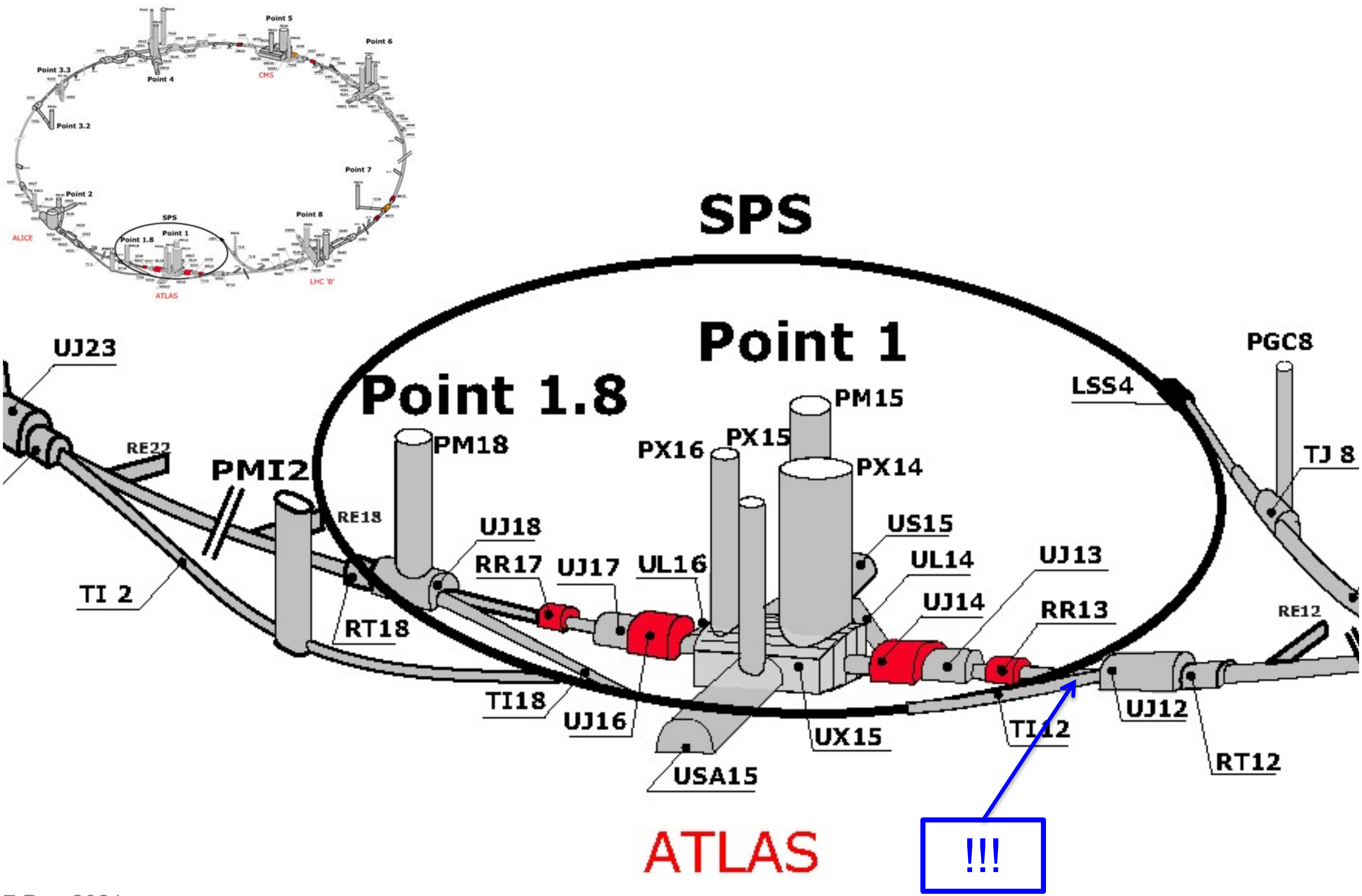
- Existing detectors are designed to find new heavy particles. These particles are produced almost at rest and decay isotropically.



- 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.

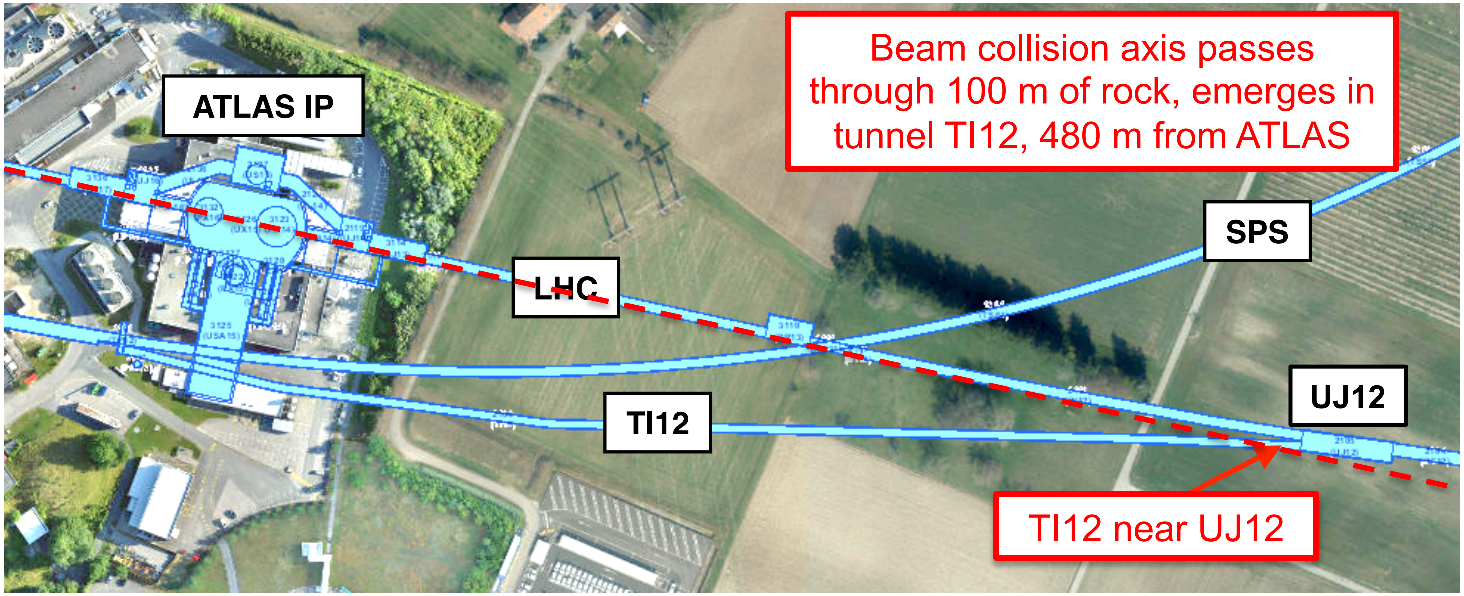
- Clearly we need a detector to exploit the "wasted" $\sigma_{inel} \sim 100$ mb and cover these "blind spots" in the forward region. If we go far enough away, the proton beams are bent by magnets (it's a circular collider!), whereas the new light particles will go straight.

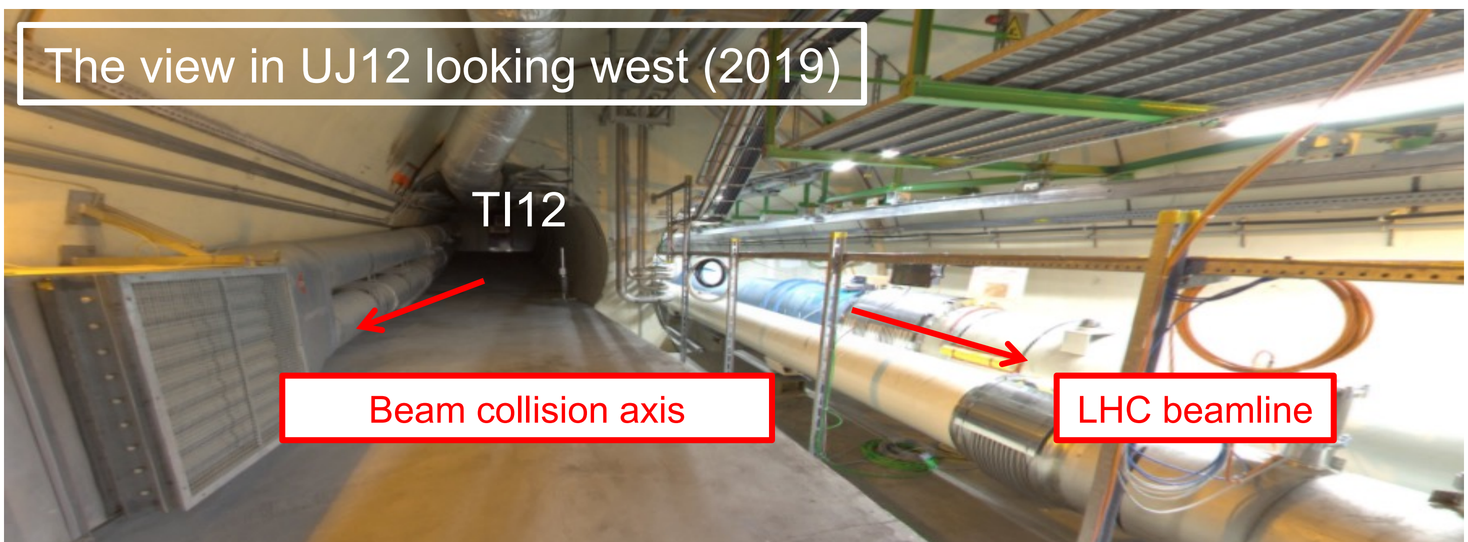
MAP OF LHC



Point 5
Point 6
Point 3.3
Point 4
CMS
Point 3.2
Point 7
Point 2
Point 8
ALICE
SPS
Point 1
Point 1.8
LHC 'B'
ATLAS
SPS
Point 1
Point 1.8
UJ23
PGC8
LSS4
PM15
PX15
PX16
PM18
PX14
TJ 8
RE22
PMI2
RE18
UJ18
US15
UL14
UJ13
RR17
UJ17
UL16
UJ14
RR13
TI 2
RE12
RT18
TI18
UJ16
UX15
TI12
UJ12
RT12
USA15
ATLAS
!!!

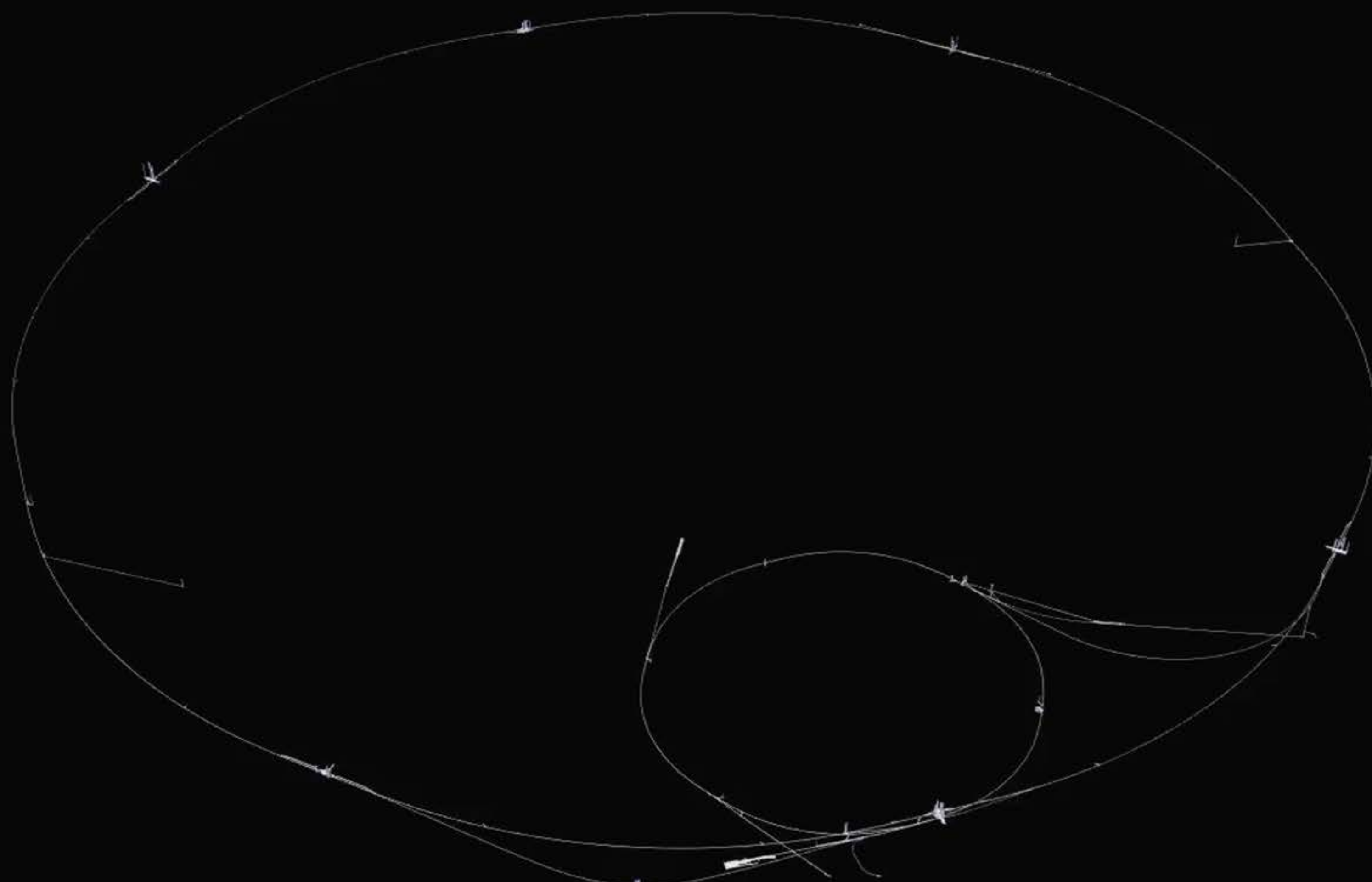
THE FAR-FORWARD REGION



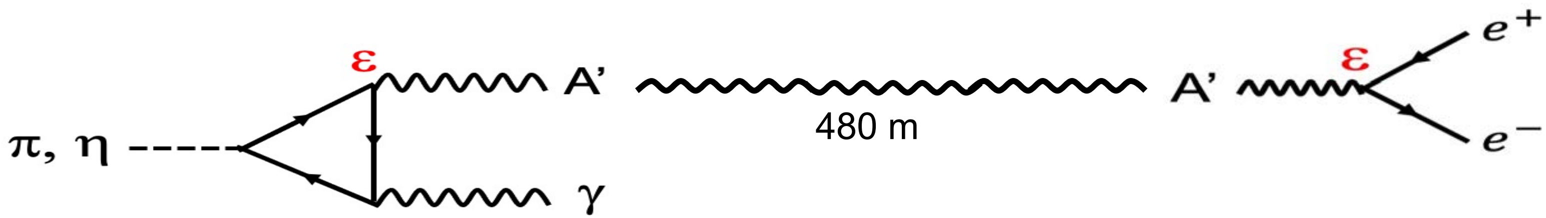


PARTICLE PATH FROM ATLAS TO TI12

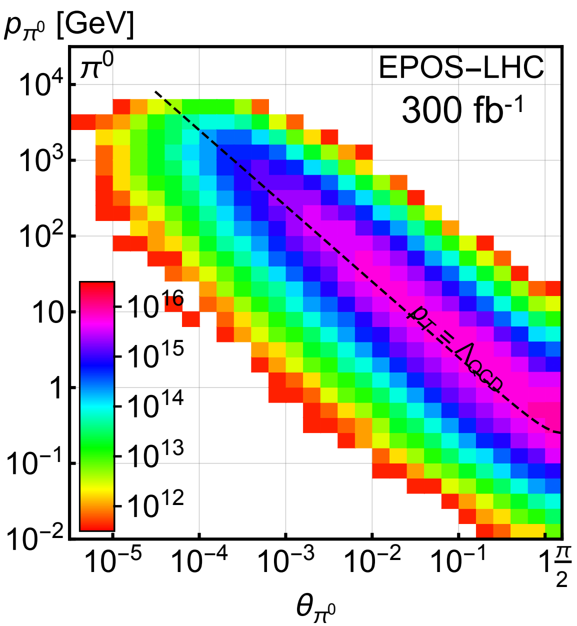
Dougherty, CERN Integration (2019)



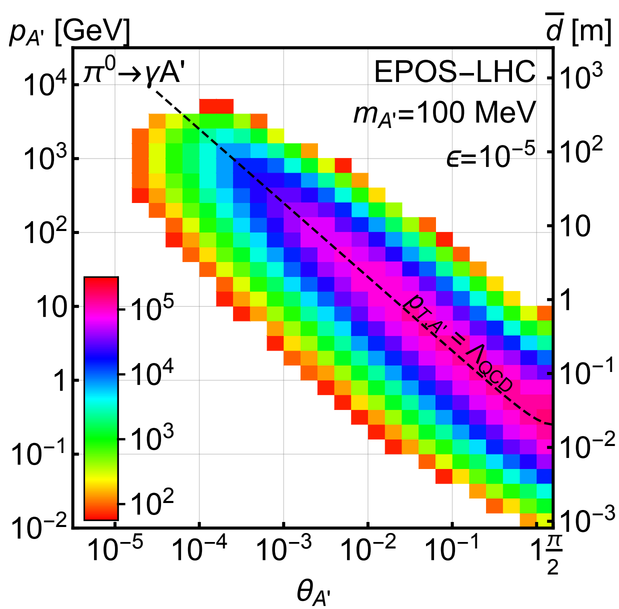
AN EXAMPLE SIGNAL: DARK PHOTONS



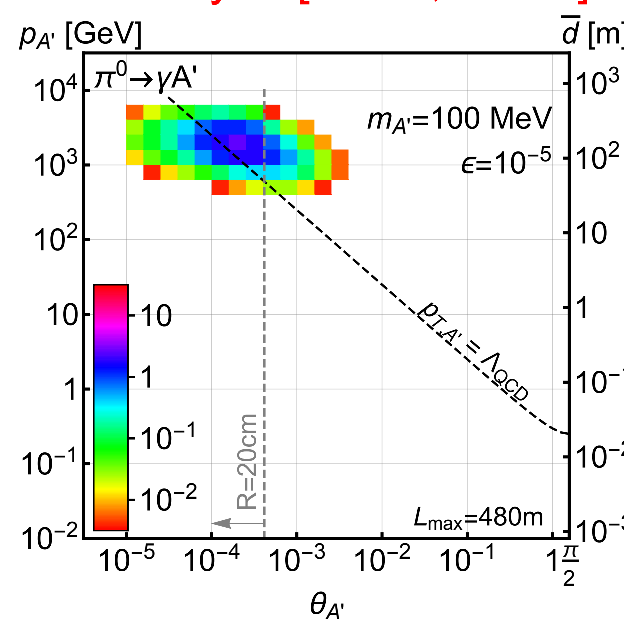
Produced Pions



Produced A's



A's decay in [480m, 483m]



- Enormous event rates: $N_\pi \sim 10^{15}$ per bin
- Huge range of p, but p_T is peaked at ~250 MeV

- Decays to A' are rare: $N_{A'} \sim \varepsilon^2 N_\pi$
- But still $N_{A'} \sim 10^5$ per bin, these travel straight

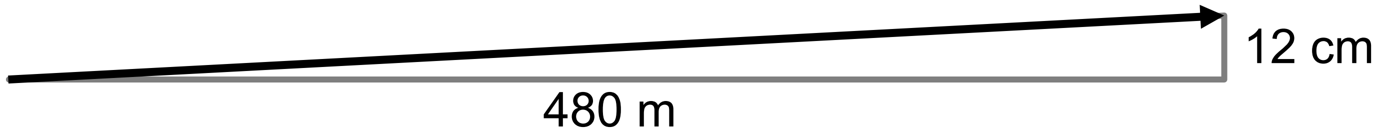
- Only highly boosted, ~TeV A's decay in the tunnel
- But these are highly collimated, and there are still many events

Feng, Galon, Kling, Trojanowski (2017)

HOW BIG DOES THE DETECTOR HAVE TO BE?

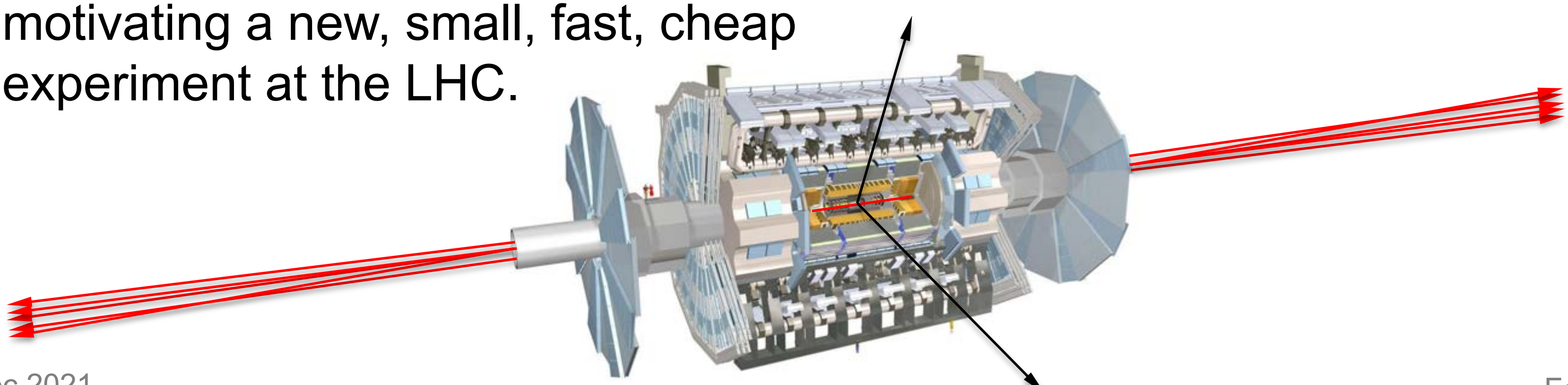
- Momentum:

- 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 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 8th LHC detector by CERN
- December 2019: FASERν approved as 9th LHC detector by CERN
- March 2021: FASER fully installed, commissioning of the detector begins
- May 2021: FASERν announces first candidate collider neutrinos
- Mid-2022: FASER and FASERν begin collecting data in Run 3

FIRST FASER COLLABORATION MEETING

FASER INSTITUTIONS TODAY

77 collaborators, 21 institutions, 9 countries

CERN

UNIVERSITÉ DE GENÈVE

KYUSHU UNIVERSITY

UC IRVINE

u^b 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

US UNIVERSITY OF SUSSEX

DESY.

ROYAL HOLLOWAY UNIVERSITY OF LONDON

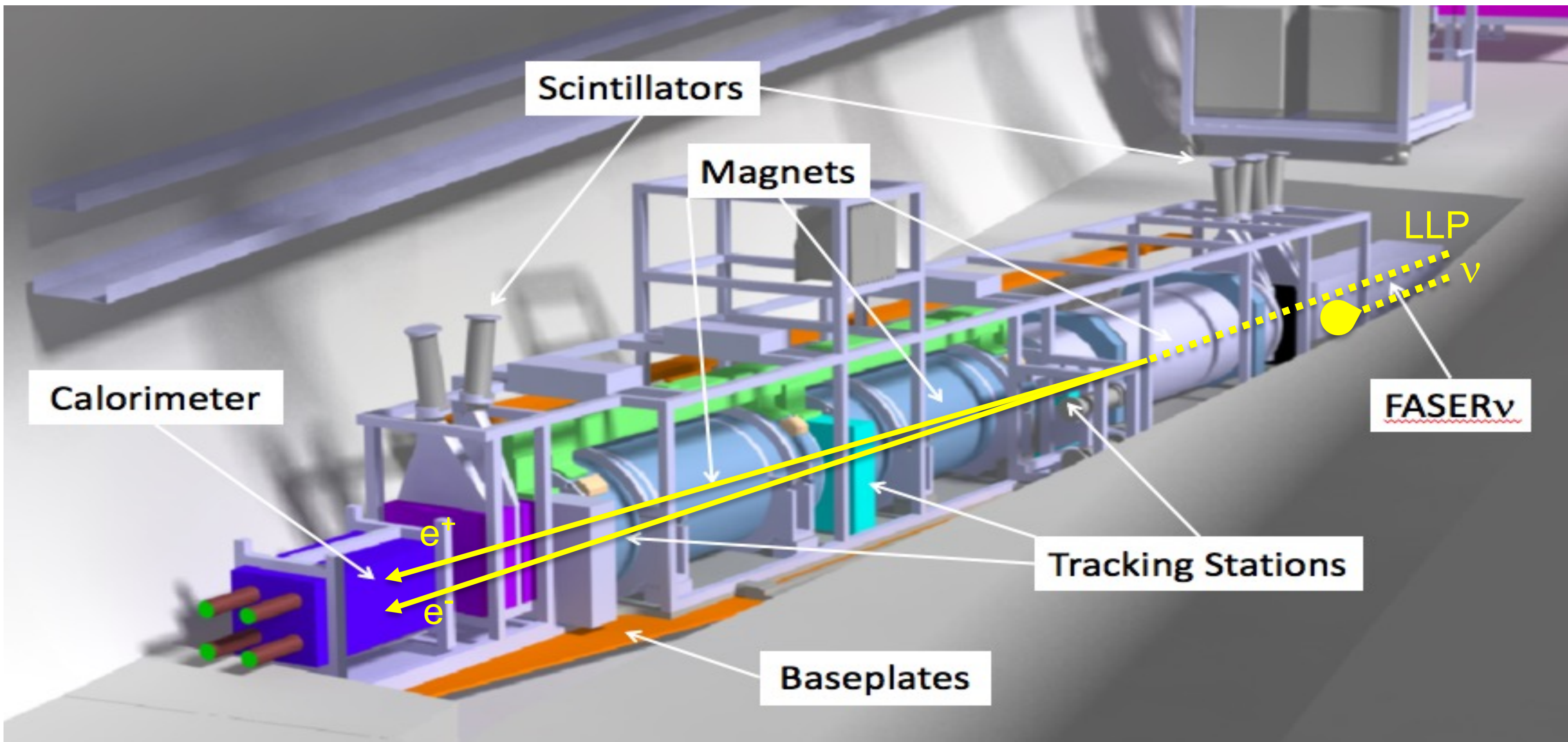
UNIVERSITY OF LIVERPOOL

CHIBA UNIVERSITY

JINR

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.

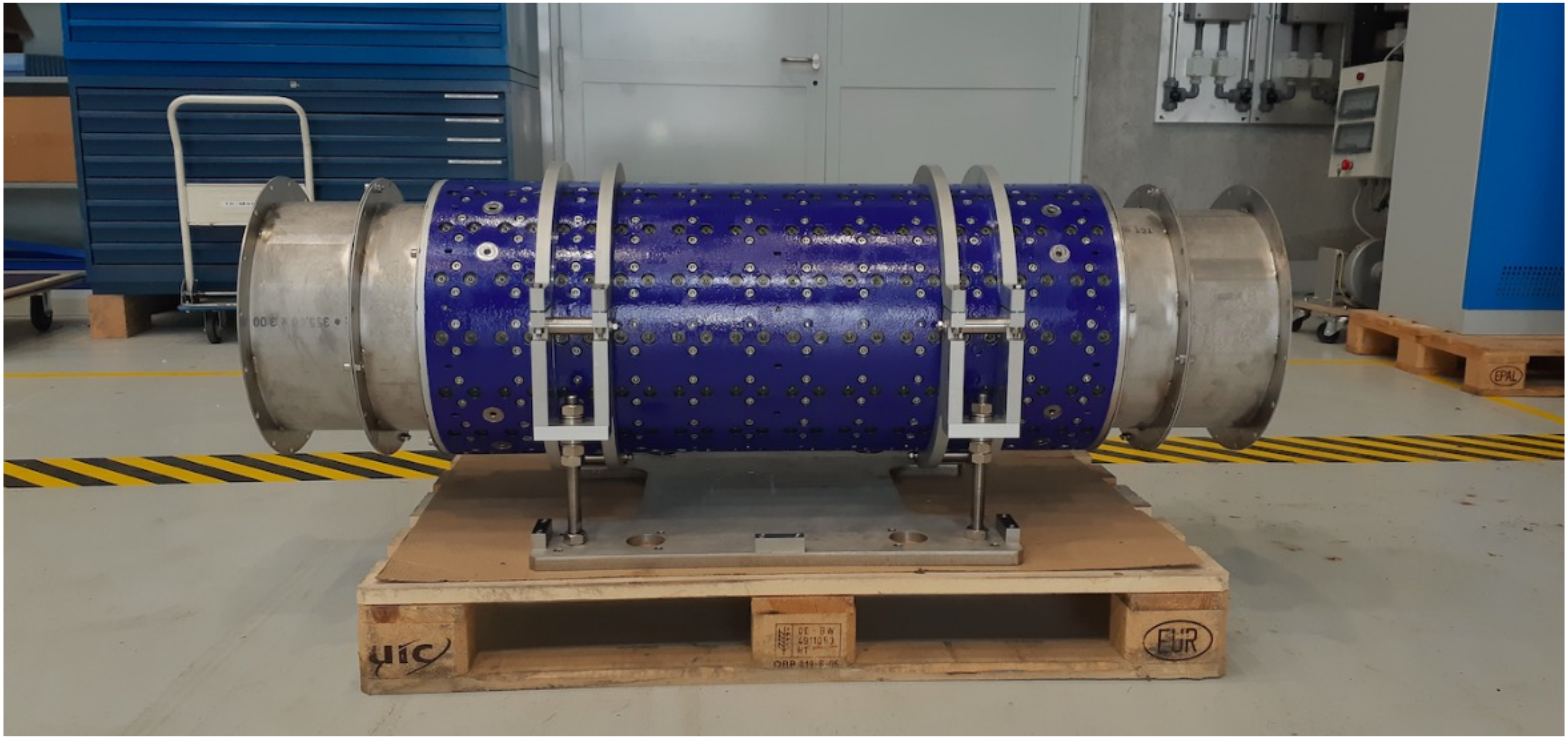


FASER IN TUNNEL TI12

- 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.

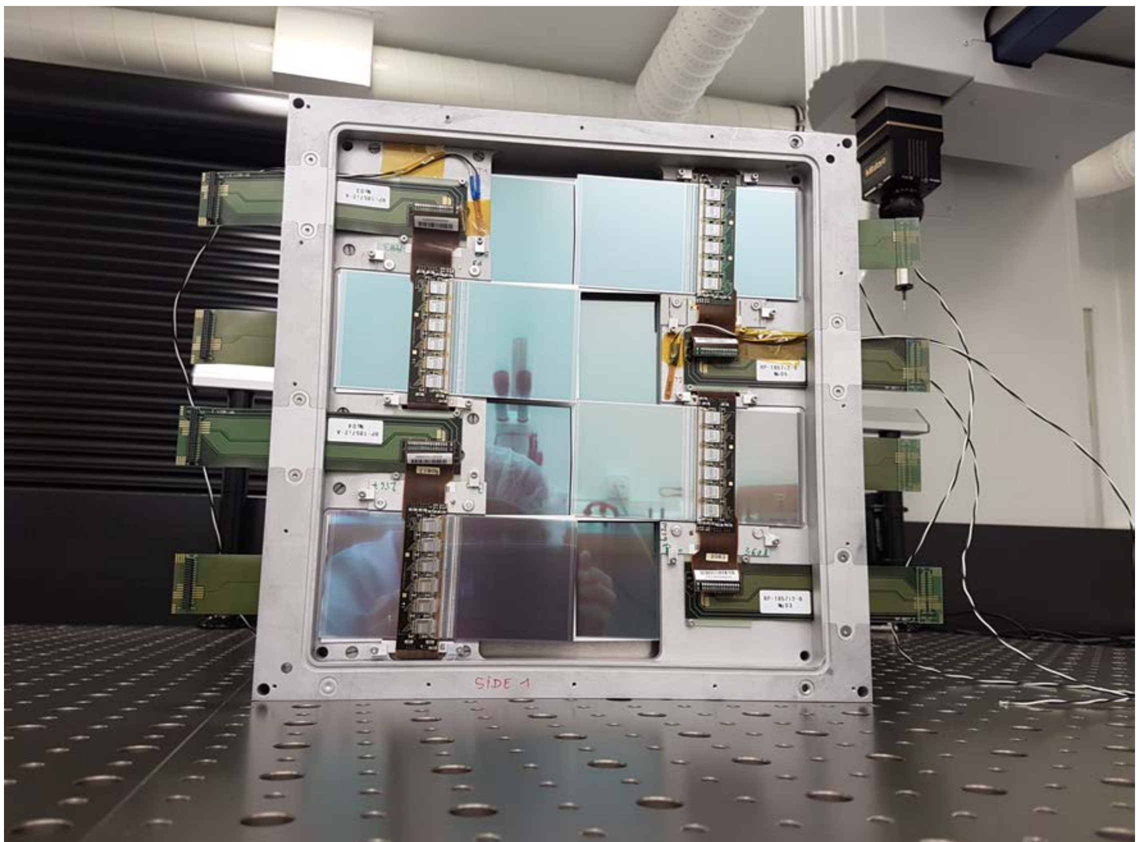
MAGNETS

- 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

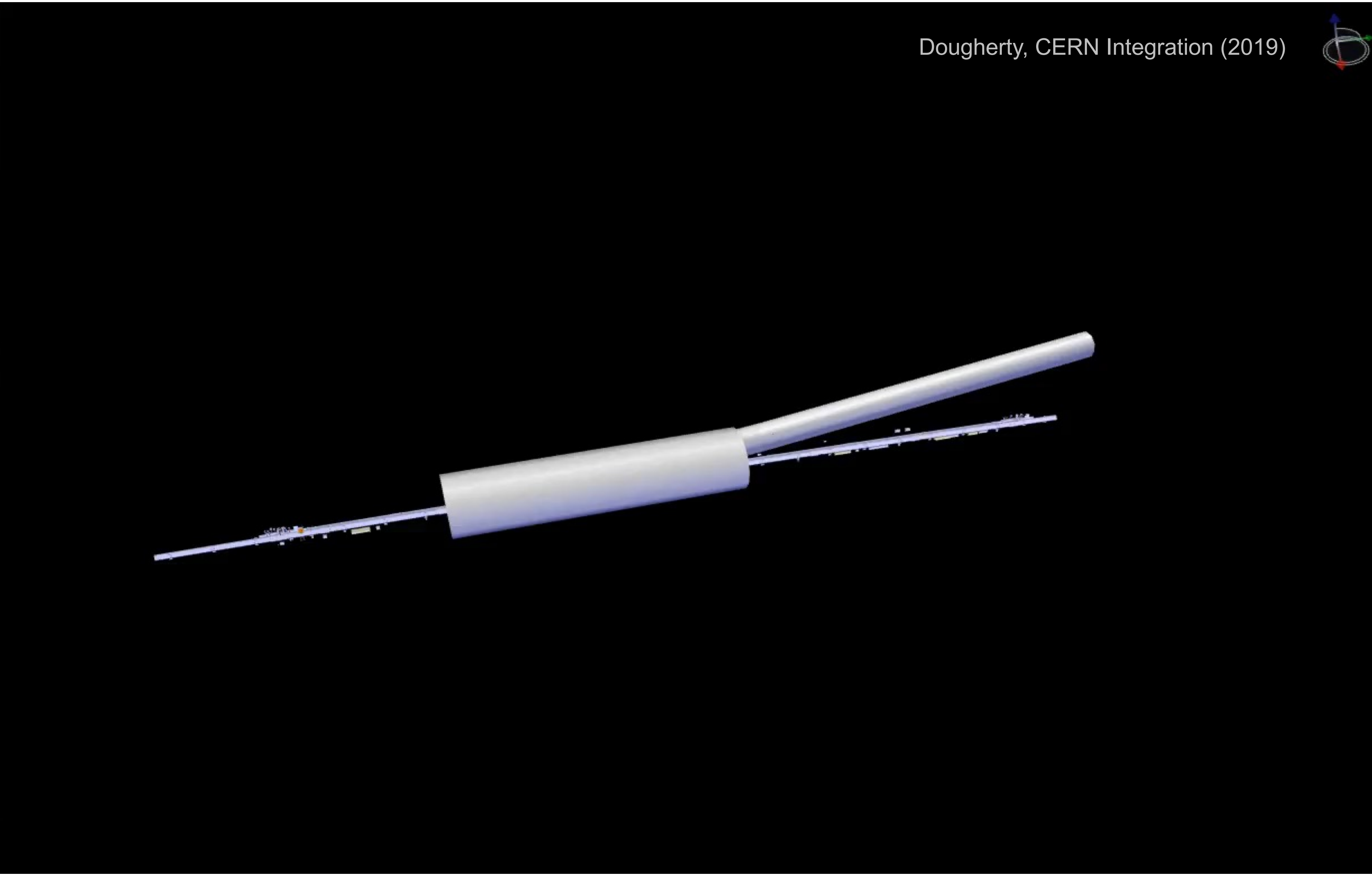
- ATLAS tracker consists of ~3000 SCT modules.
- ~300 spares were never used. ~100 of these were generously donated to FASER: 8 modules x 3 tracking planes x 4 tracking stations at FASER.



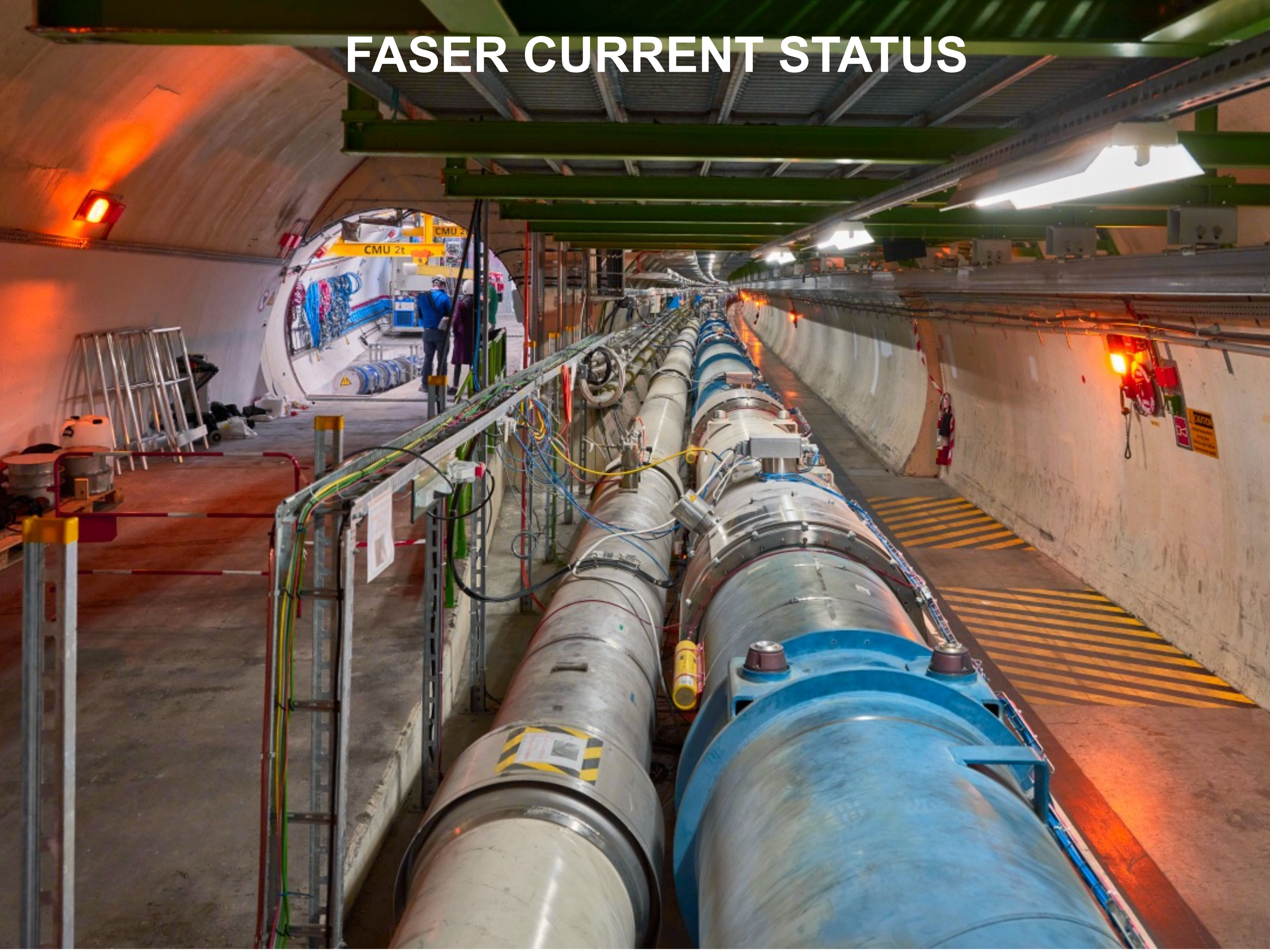
SCINTILLATORS

- 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.

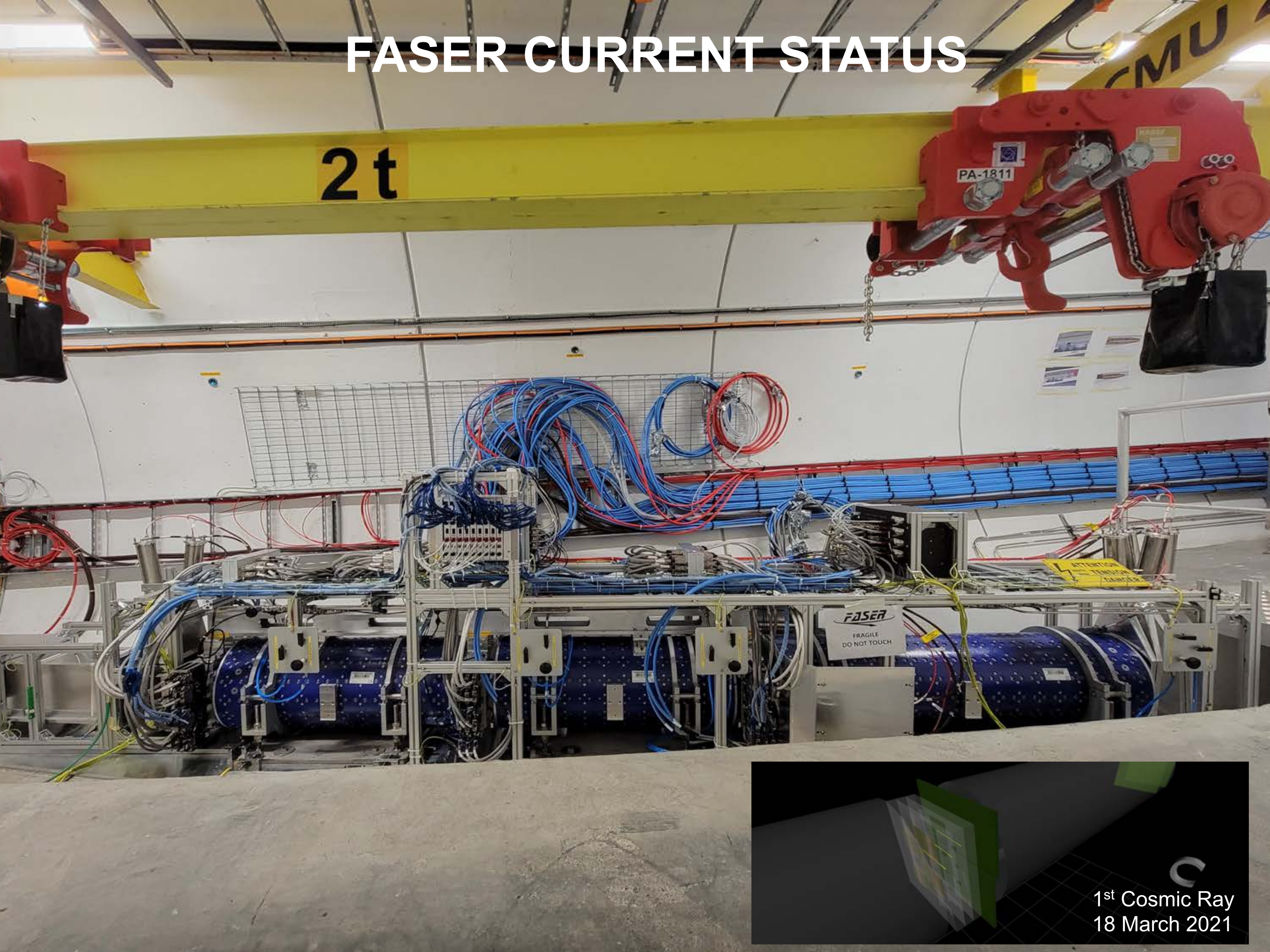
FASER INSTALLATION



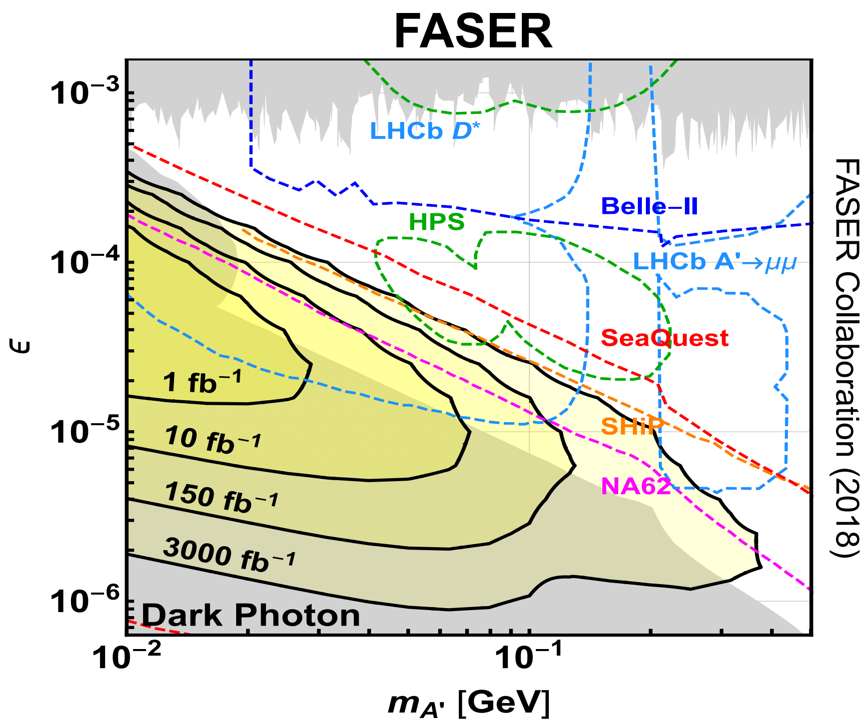
FASER CURRENT STATUS

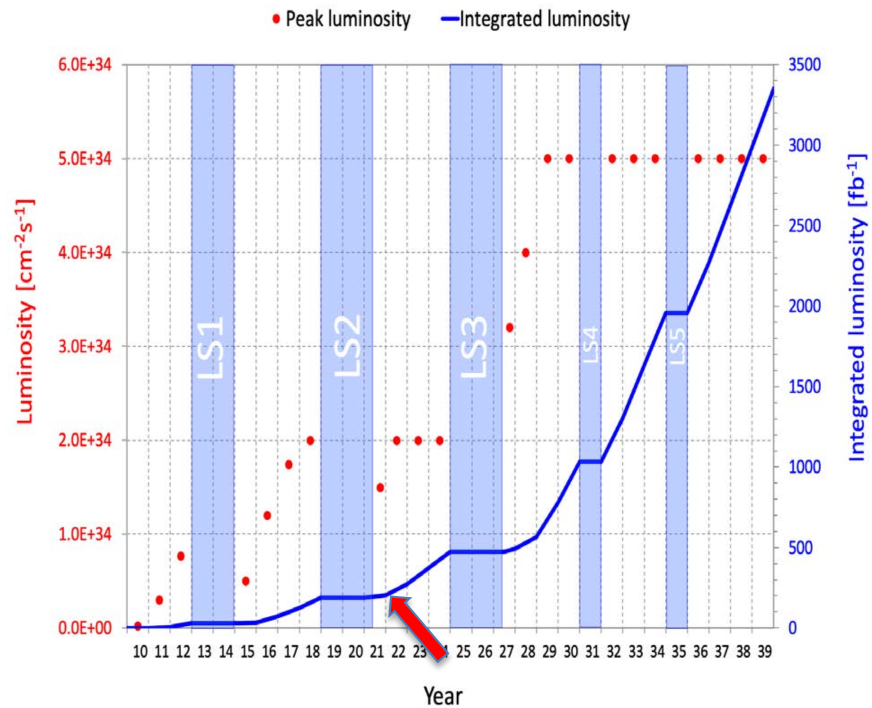


FASER CURRENT STATUS



DARK PHOTON SENSITIVITY REACH





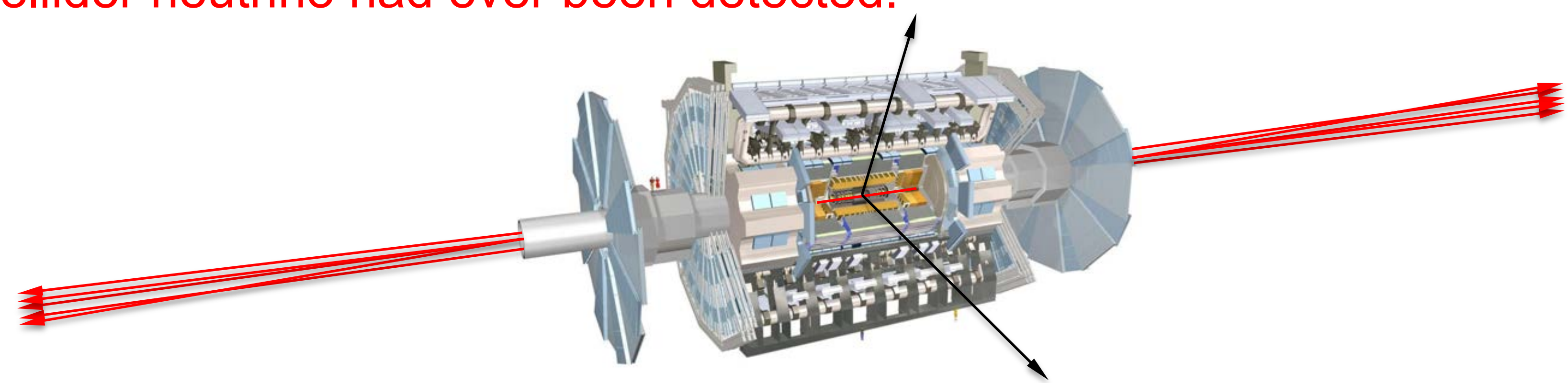
- FASER probes new parameter space with just 1 fb^{-1} starting in 2022.
- Without upgrade, HL-LHC extends (Luminosity*Vol) by factor of 3000 – could detect as many as 10,000 dark photons.
- Possible upgrade to FASER 2 (R=1m, L=20m) extends (Luminosity*Vol) by factor of ~10^6 – could detect as many as 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.

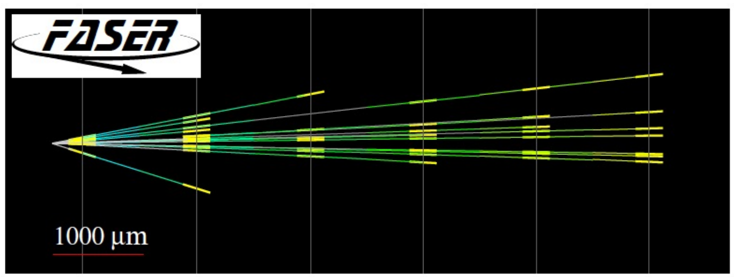
De Rujula, Ruckl (1984); Winter (1990); Vannucci (1993)

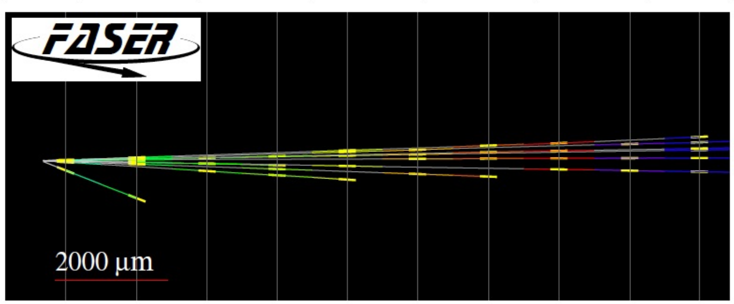
FIRST COLLIDER NEUTRINOS

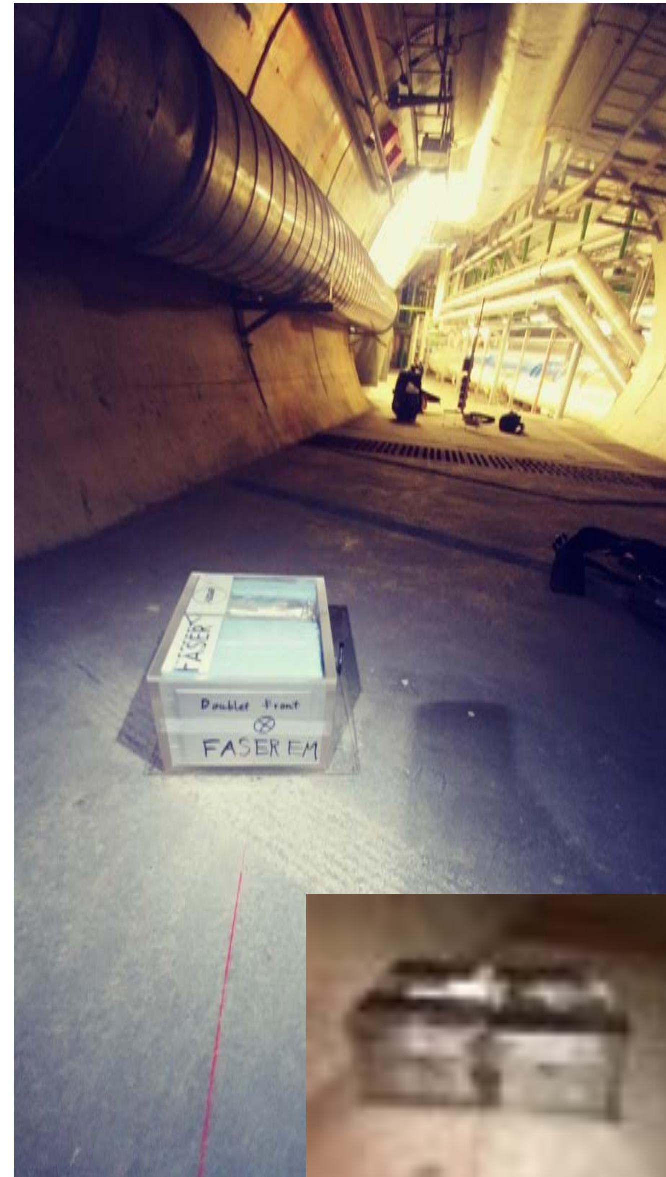
- In 2018 a FASER pilot emulsion detector with 11 kg fiducial mass collected 12.2 fb^{-1} on the beam collision axis (installed and removed during Technical Stops).

- In May 2021, the FASER Collaboration announced the direct detection of 6 candidate neutrinos above 12 expected neutral hadron background events (2.7σ).

- Not the discovery of collider neutrinos, but a sign of things to come.





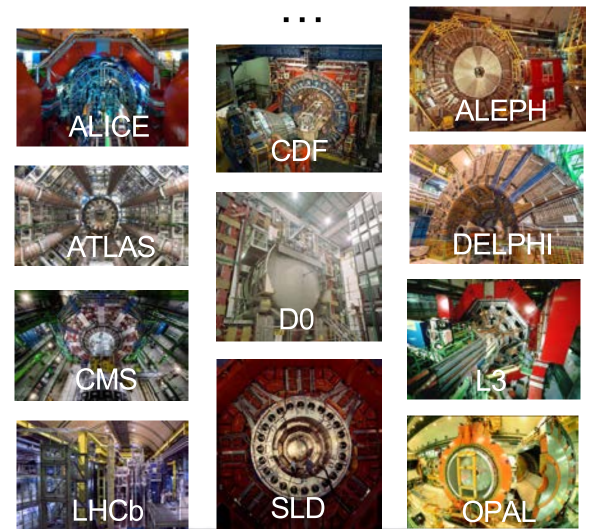


LOCATION, LOCATION, LOCATION

FASER Pilot Detector

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

6 candidate neutrinos



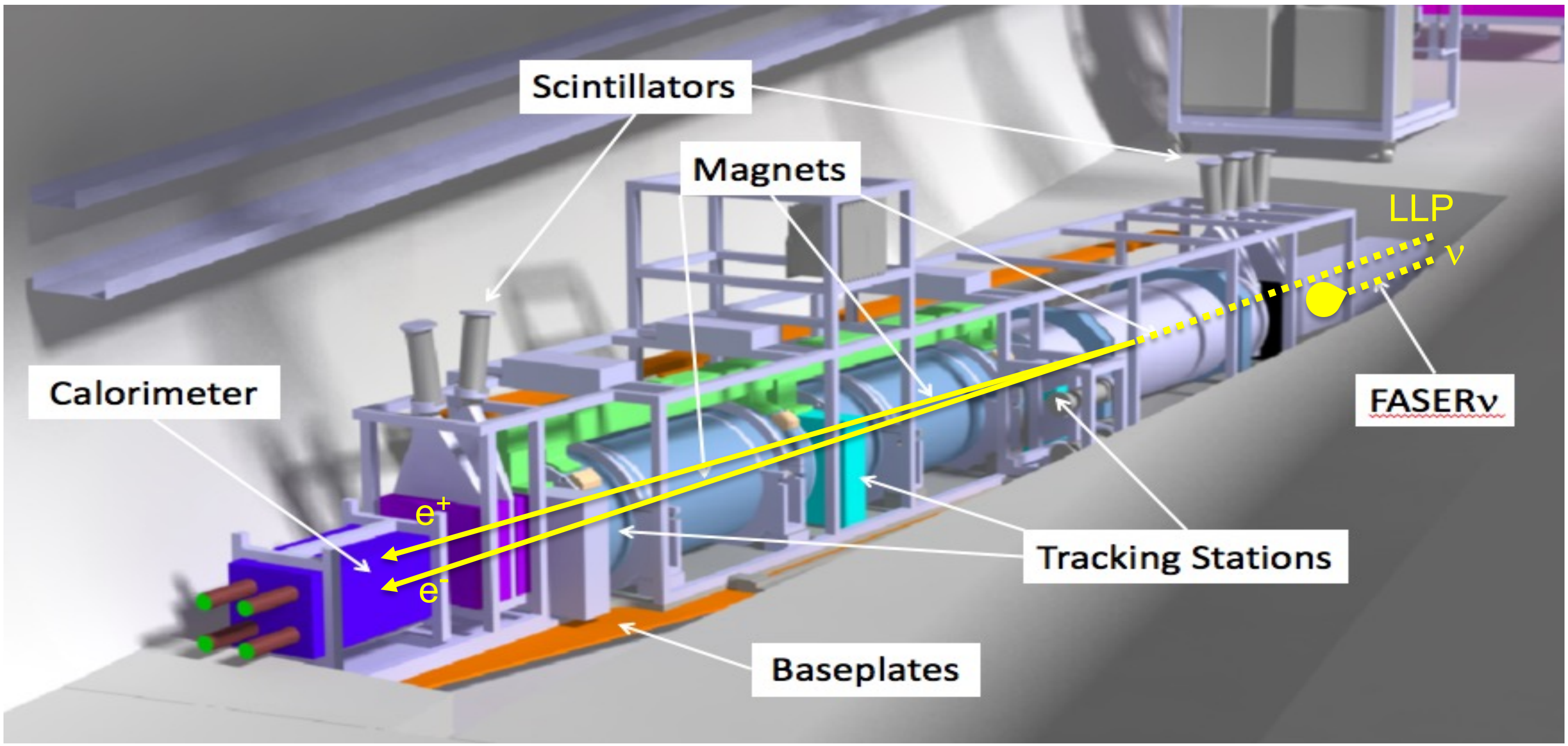
All previous
collider detectors

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

0 candidate neutrinos

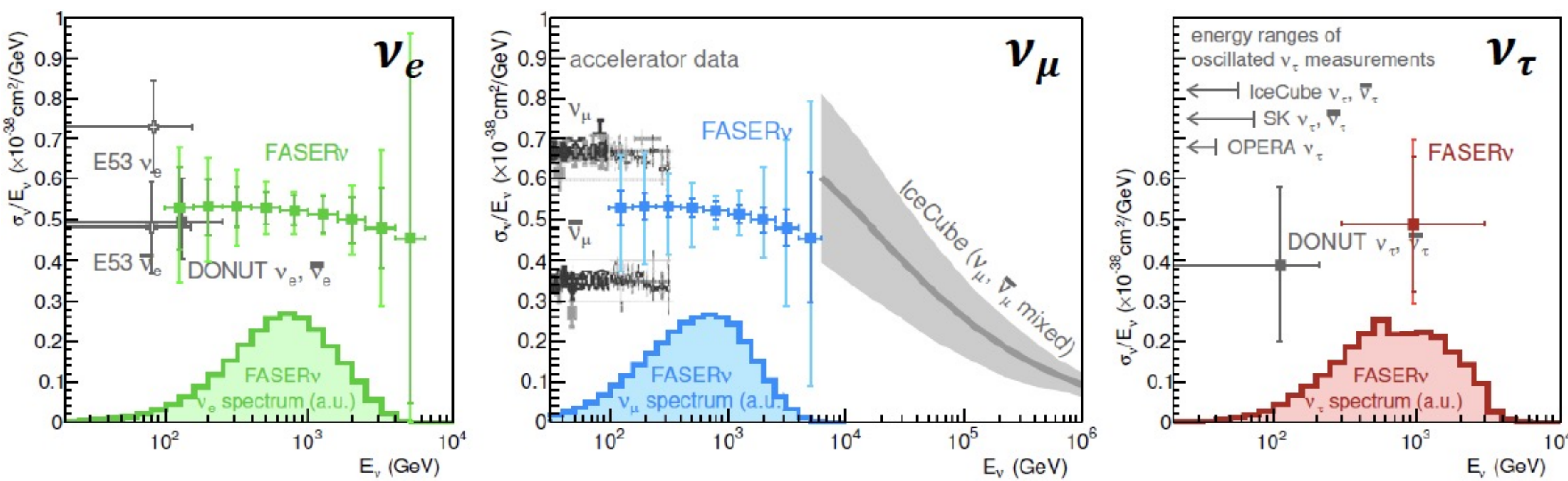
THE FASERν DETECTOR

- 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

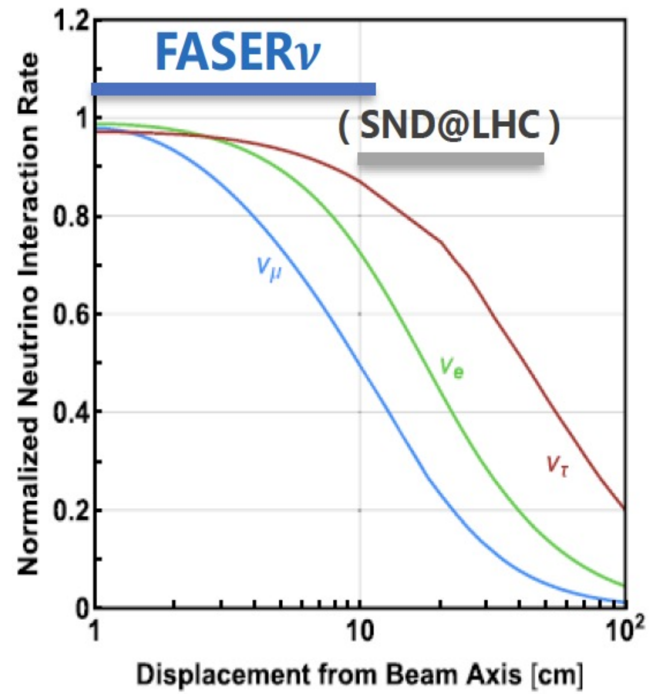
- In Run 3 (2022-24), the goals of FASERν are to
  - Detect the first collider neutrino.
  - Record ~1000 ν_e, ~10,000 ν_μ, and ~10 ν_τ interactions at TeV energies, the first direct exploration of this energy range for all 3 flavors.
  - Distinguish muon neutrinos from anti-neutrinos by combining FASER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

- The forward production of hadrons is currently subject to large uncertainties. Forward ν experiments will provide useful insights.
  - On- and off-axis neutrino detectors provide complementary information ($\pi \rightarrow \nu_\mu$, $K \rightarrow \nu_e$, $D \rightarrow \nu_\tau$).
  - Different target nuclei (lead, tungsten) probe different nuclear pdfs.
  - Strange quark pdf through $\nu s \rightarrow lc$.
  - Forward charm production, intrinsic charm.
  - Refine simulations that currently vary greatly (EPOS-LHC, QGSJET, DPMJET, SIBYLL, PYTHIA…).
  - Provide essential input to astroparticle experiments; e.g., distinguish galactic neutrino signal from atmospheric neutrino background at IceCube.



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 2027-37.

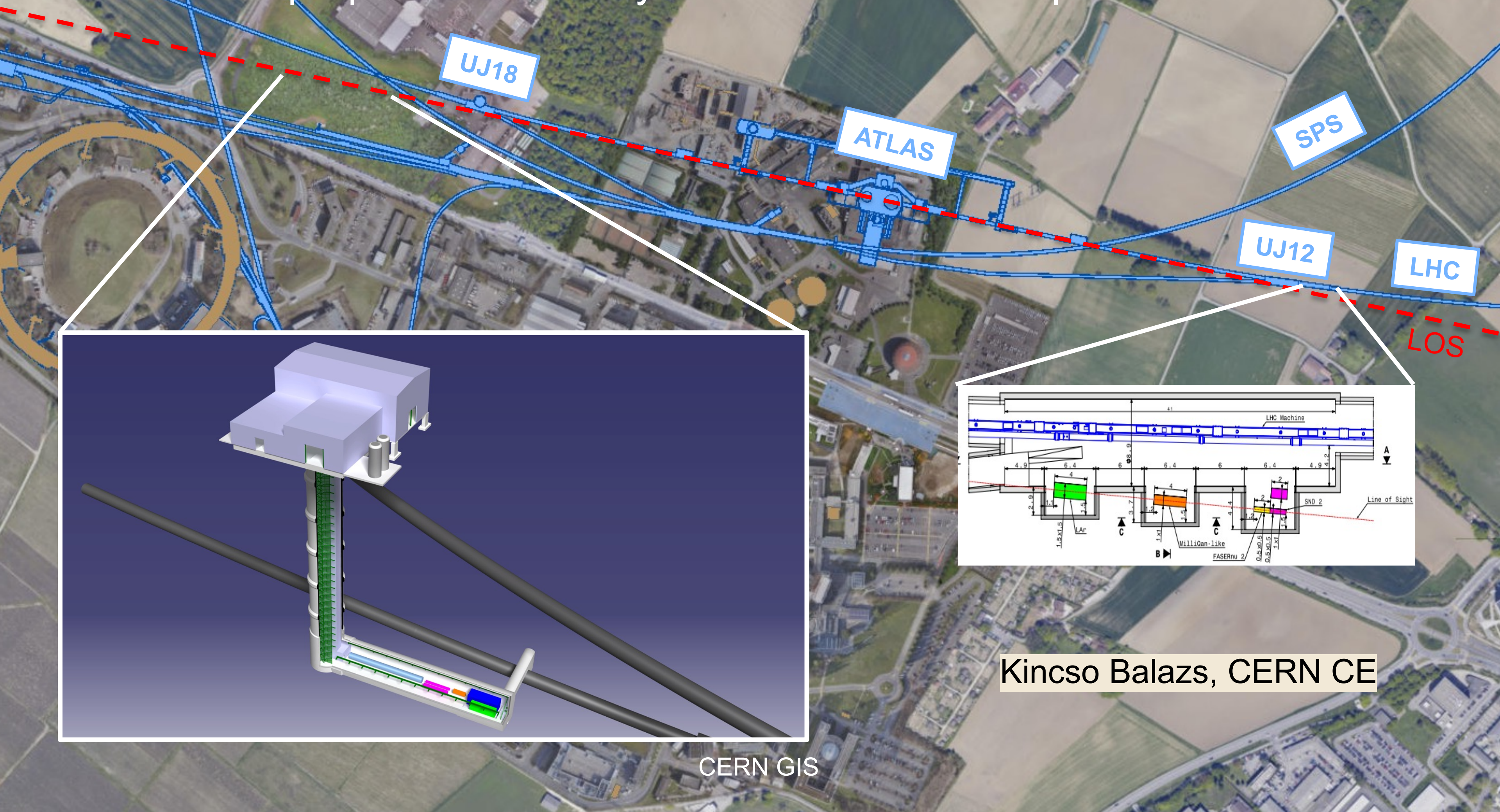
- FPF Meetings
  - FPF Kickoff Meeting, 9-10 Nov 2020, https://indico.cern.ch/event/955956
  - FPF2 Meeting, 27-28 May 2021, https://indico.cern.ch/event/1022352
  - FPF3 Meeting, 25-26 Oct 2021, https://indico.cern.ch/event/1076733

- FPF Short Paper: 75 pages, 80 authors completed in Sep 2021 (2109.10905).

- The FPF White Paper (~300 pages) is being prepared for submission to Snowmass in Feb 2022 (conveners: Feng, Kling, Rojo, Reno, Soldin).

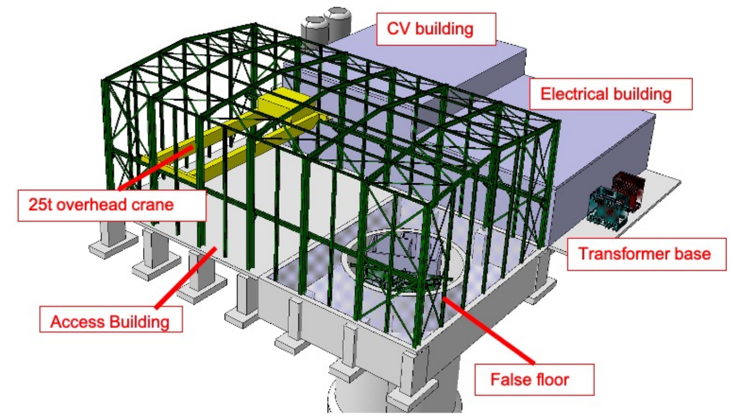
FPF LOCATION

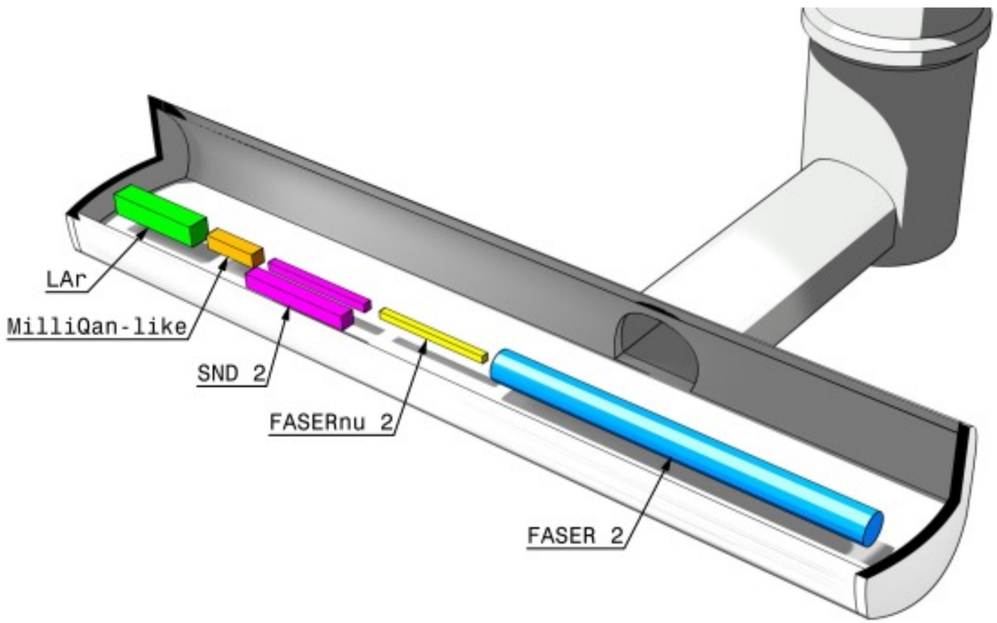
Possibilities under active investigation: enlarge existing cavern UJ12, 480 m from ATLAS and shielded from the ATLAS IP by ~100 m of rock; or create a purpose-built facility ~612 m from ATLAS past UJ18.

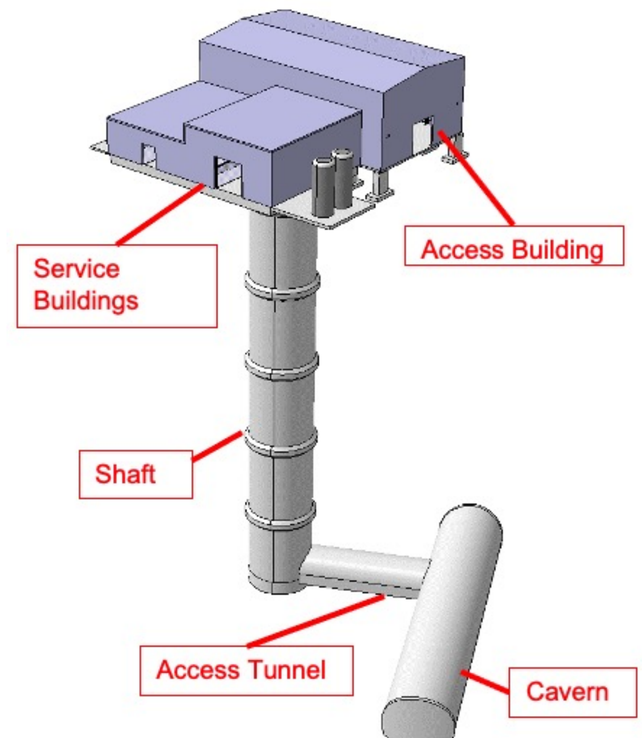


PURPOSE-BUILT FACILITY

- Many advantages
  - Construction access far easier
  - Access possible during LHC operations
  - Size and length of cavern more flexible
  - Designed around needs of the experiments







Design by Liam Dougherty (EN-ACE-INT)

NEW PHYSICS SEARCHES AT THE FPF

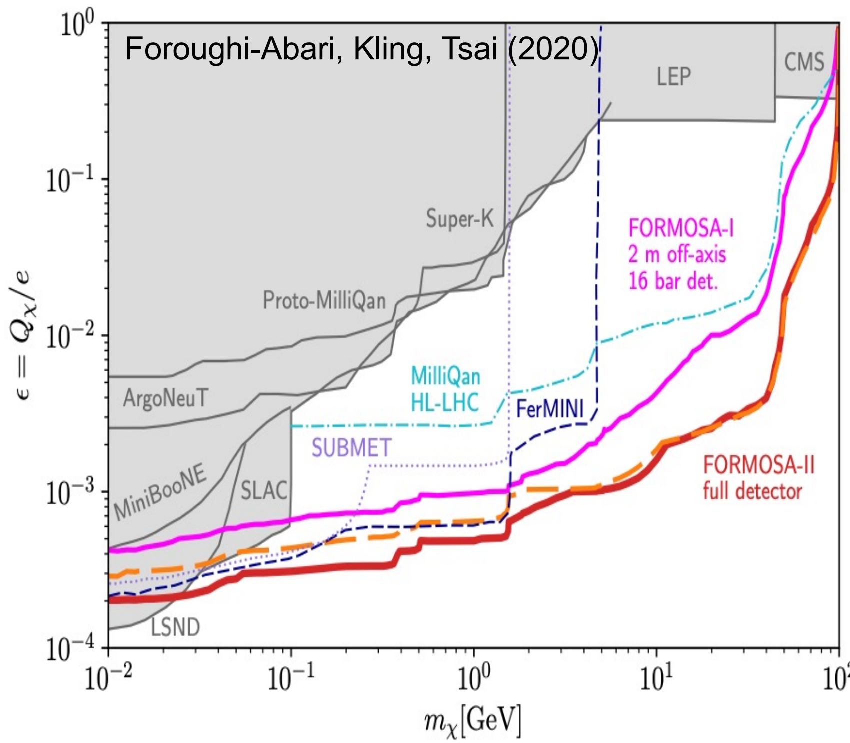
- The FPF will extend the current far-forward program by housing larger and a more diverse array of experiments.
- FASER 2, with R = 1 m, L = 20 m, can discover all candidates with renormalizable couplings (dark photon, dark Higgs, HNL); ALPs with all types of couplings (γ, f, g); and many other particles.
- Other experiments can discover mCPs, dark matter, and many other interesting ideas.

Benchmark Model	Underway	FPF
BC1: Dark Photon	FASER	FASER 2
BC1': $U(1)_{B-L}$ Gauge Boson	FASER	FASER 2
BC2: Dark Matter	–	FLArE
BC3: Milli-Charged Particle	–	FORMOSA
BC4: Dark Higgs Boson	–	FASER 2
BC5: Dark Higgs with hSS	–	FASER 2
BC6: HNL with e	–	FASER 2
BC7: HNL with μ	–	FASER 2
BC8: HNL with τ	–	FASER 2
BC9: ALP with photon	FASER	FASER 2
BC10: ALP with fermion	FASER	FASER 2
BC11: ALP with gluon	FASER	FASER 2

MILLI-CHARGED PARTICLES

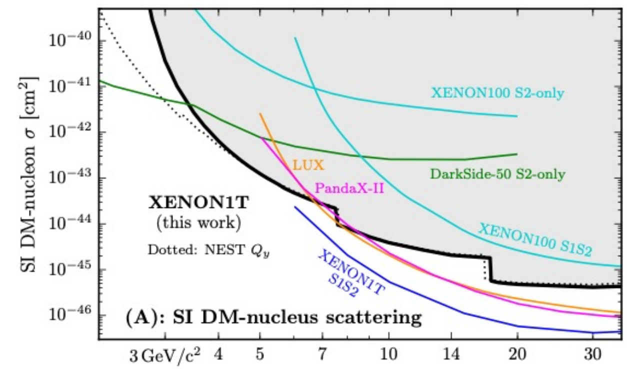
- A completely generic possibility motivated by dark matter, dark sectors. Currently the target of the MilliQan experiment, located at the LHC near the CMS experiment in a "non-forward" tunnel.

- 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).

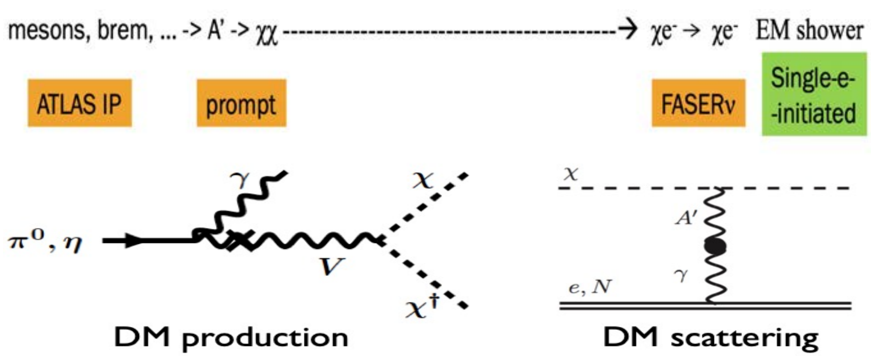


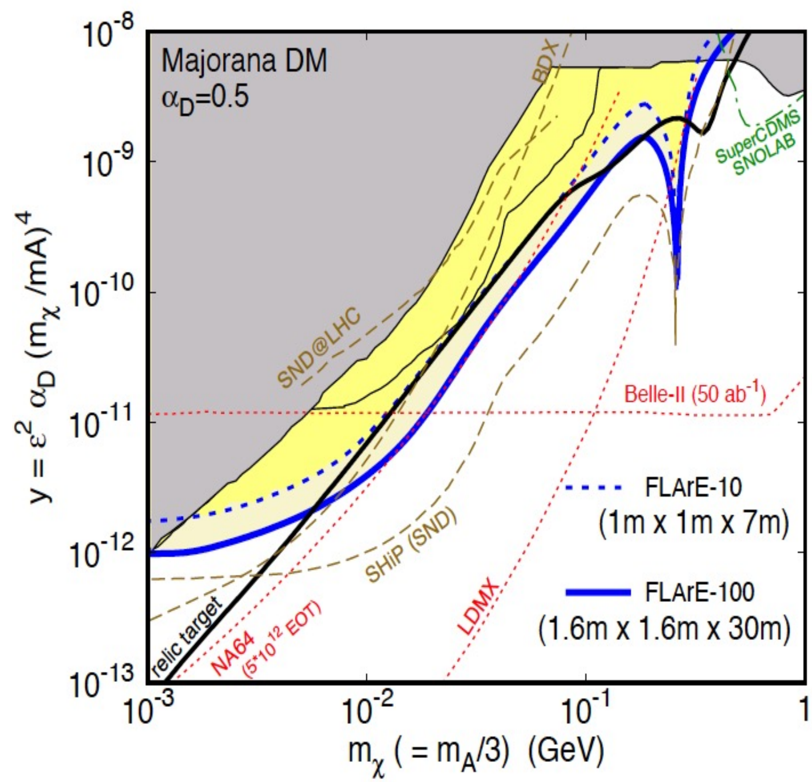
DARK MATTER

- 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.

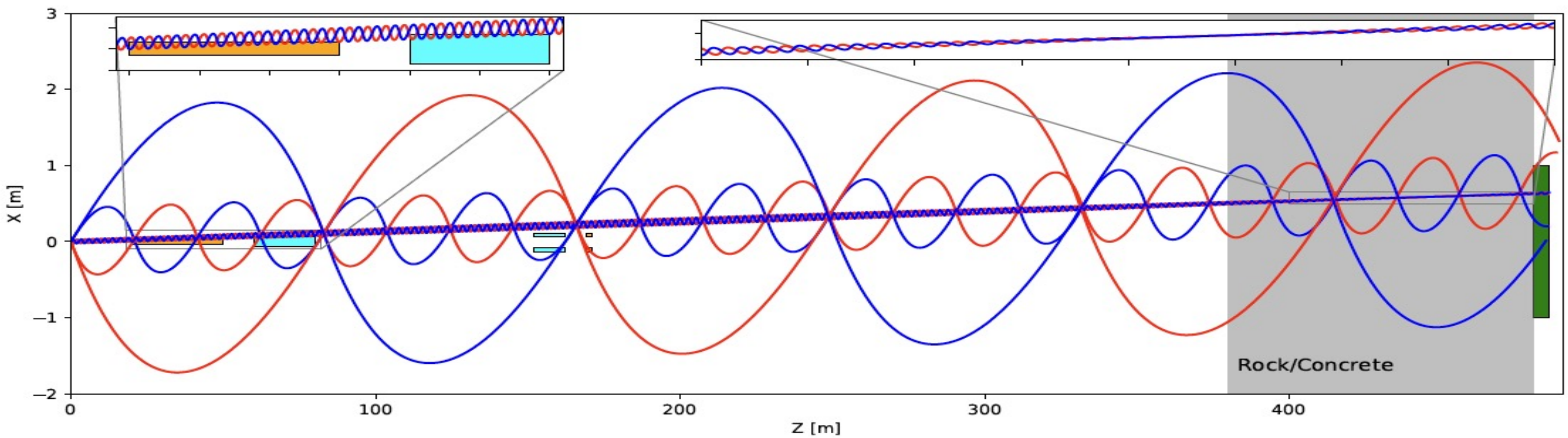
QUIRKS

Kang, Luty (2008)

- Quirks are new particles charged under a hidden strong force with mass m >> Λ_{hidden}. E.g., m ~ 500 GeV, Λ_{hidden} ~ keV.

- Once produced a quirk-anti-quirk pair does not hadronize, but rather oscillates, with length scale ~ 1/ Λ_{hidden}.

- The quirk-anti-quirk system has no p_T, and so travels down the beamline, escaping most LHC detectors, but ultimately leaving (strange!) tracks in FASER.



Li, Pei, Ran, Zhang, 2108.06748

SUMMARY

- Coverage of the “blind spot” in the far-forward region is required to realize the physics potential of the LHC.
  - Standard Model: opens a new field of neutrino physics at colliders, with ~1000 ν_e, ~10,000 ν_μ, ~10 ν_τ at TeV energies in Run 3, ~100 times more in HL-LHC. Implications for neutrino properties, forward hadron production, cosmic rays and cosmic neutrino physics.
  - Beyond the Standard Model: dark photons, sterile neutrinos, dark scalars, axion-like particles, milli-charged particles, dark matter, new forces.
- FASER and FASERν: 3.5 years from idea to completion, 5 m long, ~$2M. Along with SND@LHC, data-taking starts in mid-2022 with a rich physics program.
- Forward Physics Facility: Proposed facility to house far-forward experiments in the HL-LHC era from 2027-37, including FASER2, FASERν2, Advanced SND, FORMOSA (MilliQan successor), and the Forward Liquid Argon Experiment (FLArE).