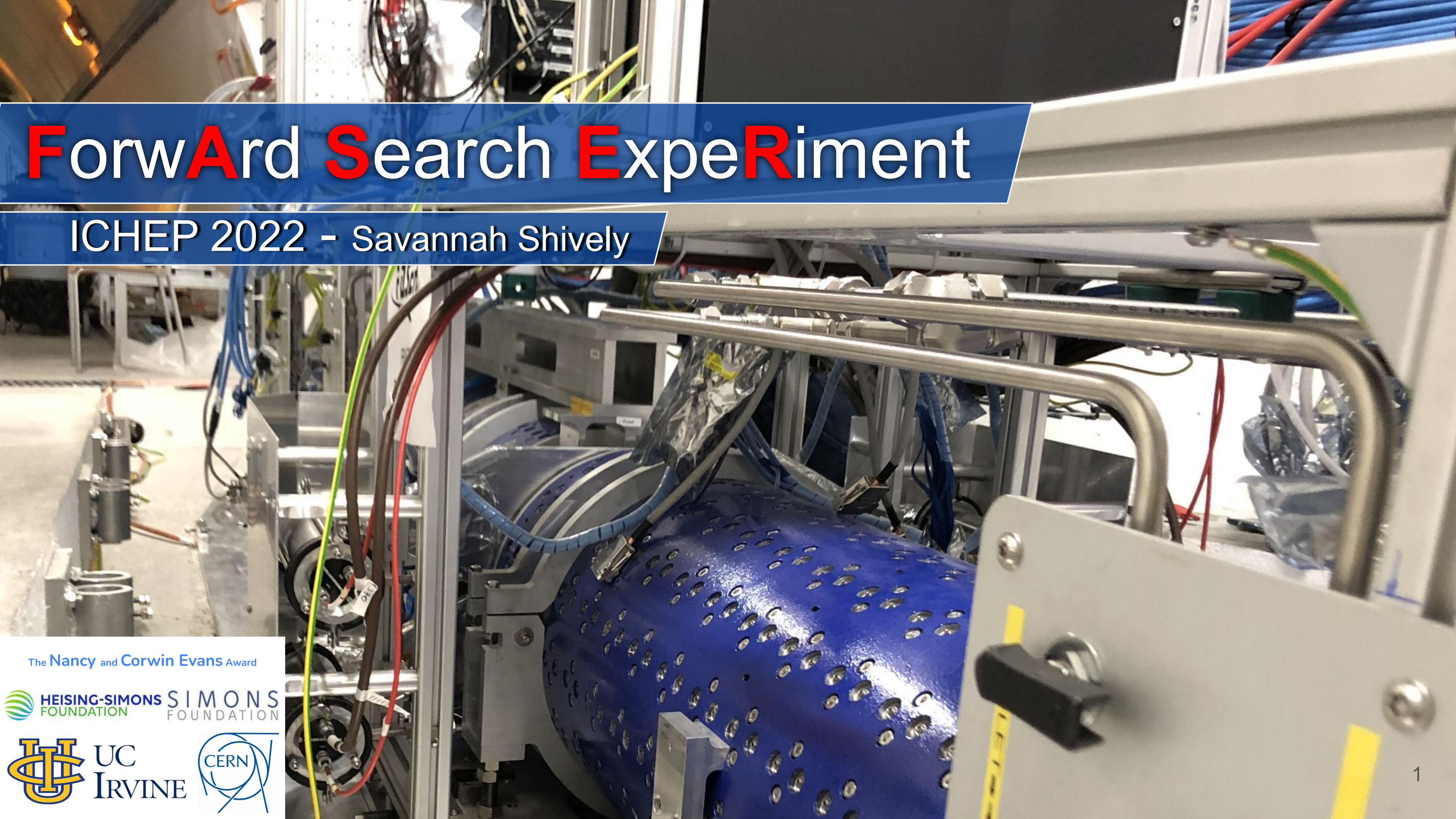
# ForwArd Search ExpeRiment

## ICHEP 2022 - Savannah Shively



The Nancy and Corwin Evans Award
HEISING-SIMONS FOUNDATION
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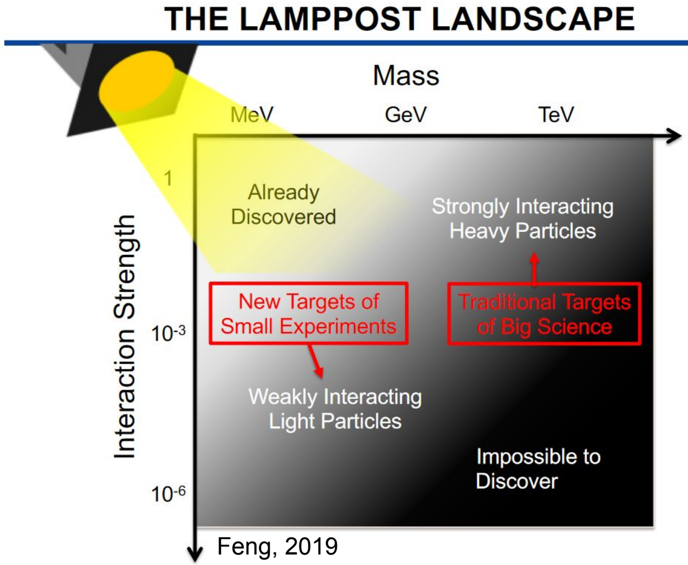
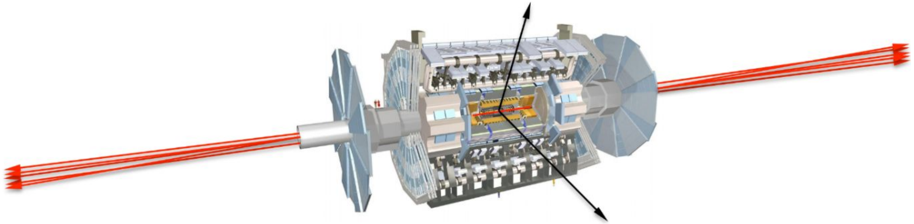
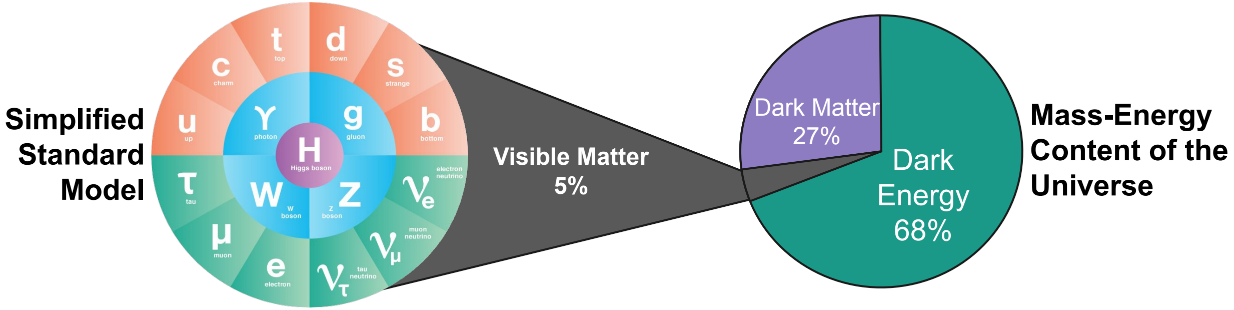
# The Far Forward Region

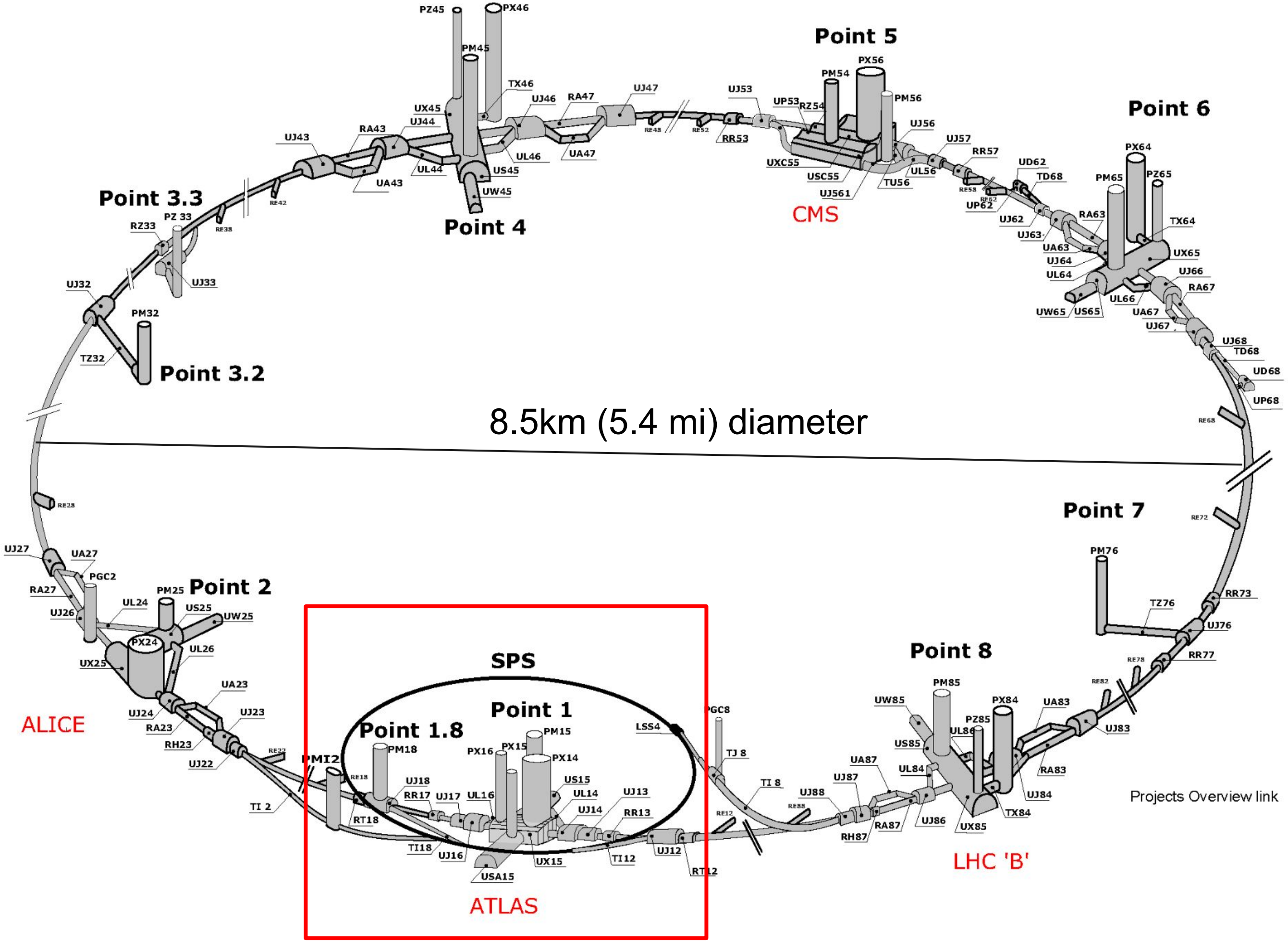


- Last new particle detection - Higgs Boson - 10 years ago 🎂
- Dark Matter & Dark Energy still unexplained (among other things)
- Standard Model not enough; no interactions with DM or DE known
- Most experiments measure particles emitted transverse to the beamline (ATLAS, CMS...)
- Long Lived Particles (LLPs) - low mass, long life → High pseudorapidity
- Need complementary experiments like FASER

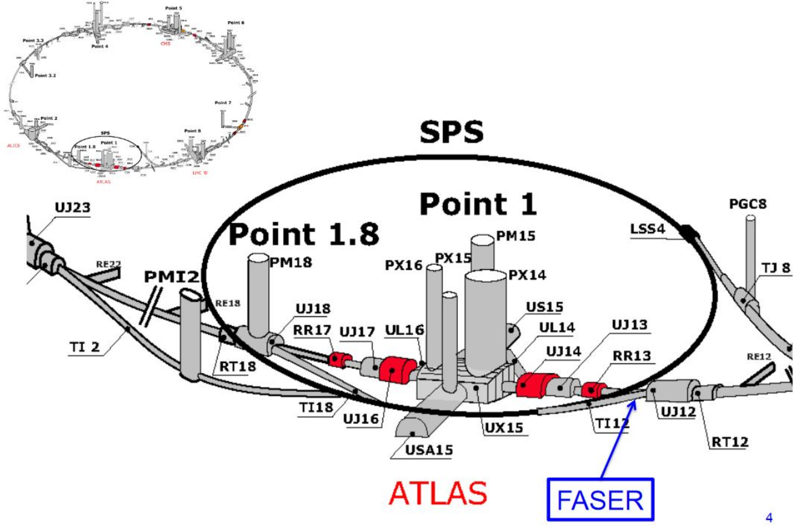


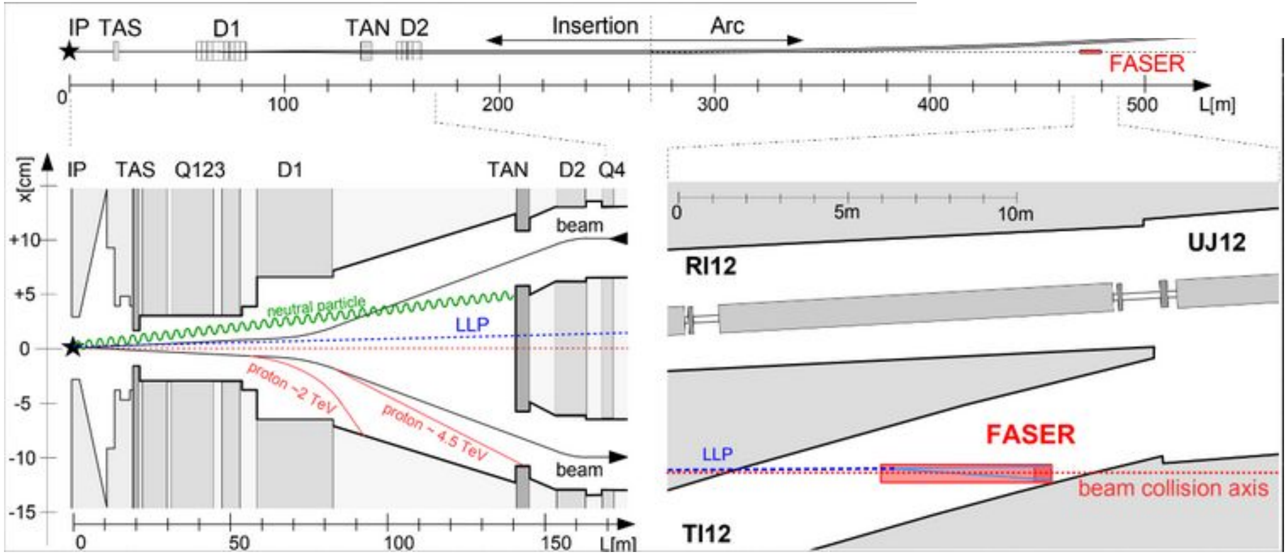
# Location


Point 1
Point 1.8
Point 2
Point 3.2
Point 3.3
Point 4
Point 5
Point 6
Point 7
Point 8
SPS
8.5km (5.4 mi) diameter
CMS
ALICE
ATLAS
LHC 'B'
Projects Overview link

# Location

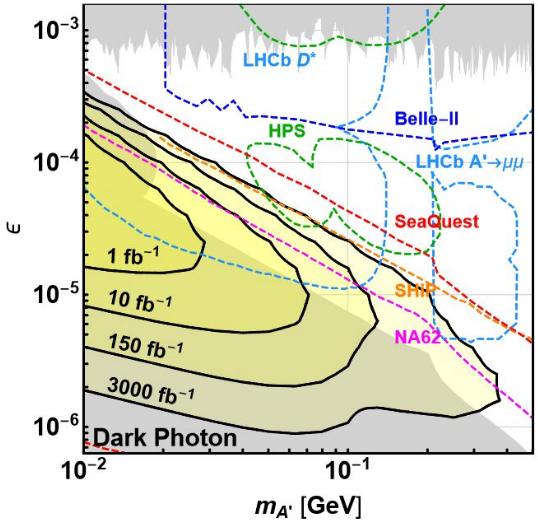
- TI12 - unused SPS maintenance tunnel intersecting collision axis
- ~480m from IP
- Highly Collimated beam (mrad diameter) → only small detector needed
  - Magnet aperture 20cm diameter
- Infrastructure & rock catches most collision products



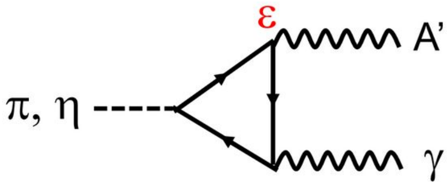



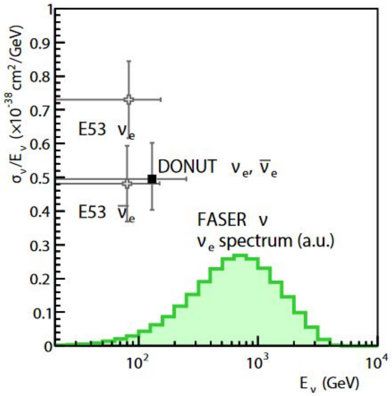
# Physics reach

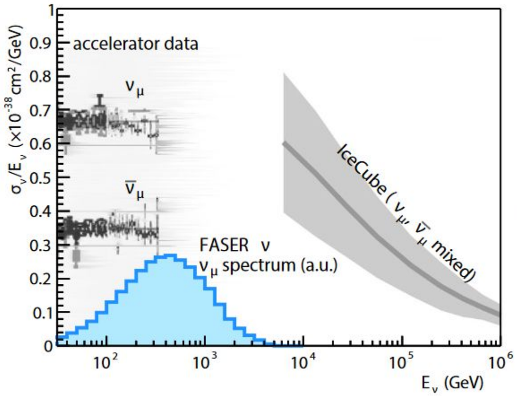
- Dark Photon
  - Run 3 has integrated luminosity of 290$fb^{-1}$
    - 13.6 TeV center-of-mass energy
  - Plot assumes no background for dark photon search
    - Probes regions favored by many considerations, such as muon g-2, dark matter, and ATOMKI anomalies
    - FASER starts probing LLP candidates with the first few $fb^{-1}$
- Neutrinos
  - Highest energy neutrinos produced along beamline - blindspot strikes again!
  - All lepton variations to be studied with distinction of $\nu_\mu$ from $\nu_\mu$.
  - FASER$\nu$ dedicated talk by Yosuke Takubo

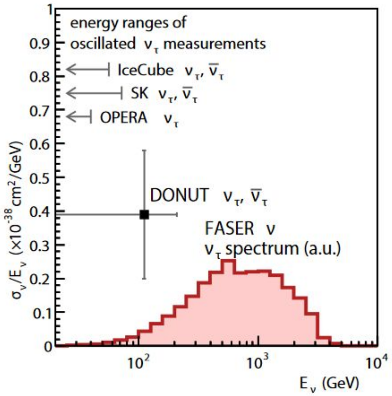


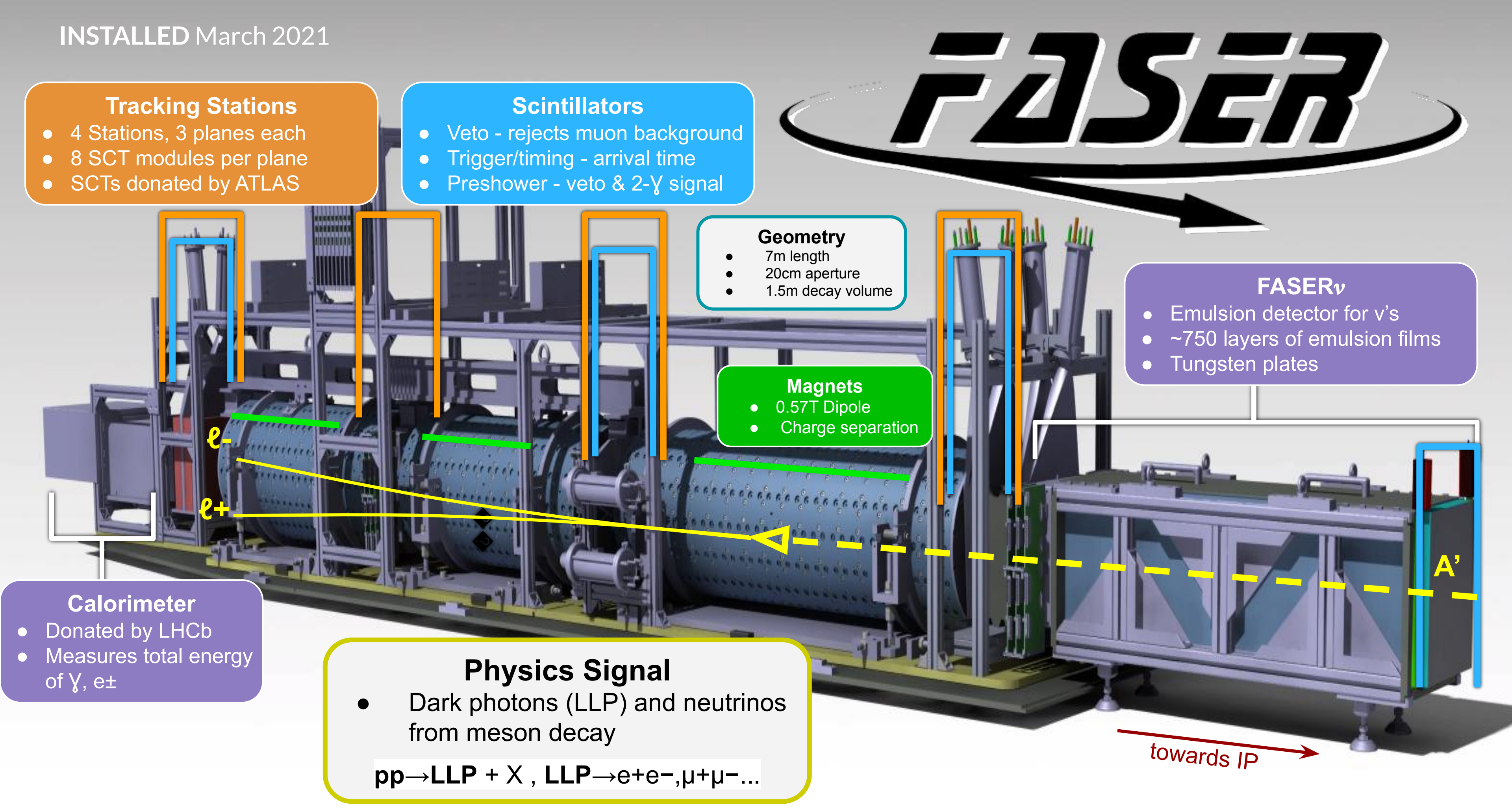

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon\, e \sum_f q_f \bar{f} \not{A}' f$$



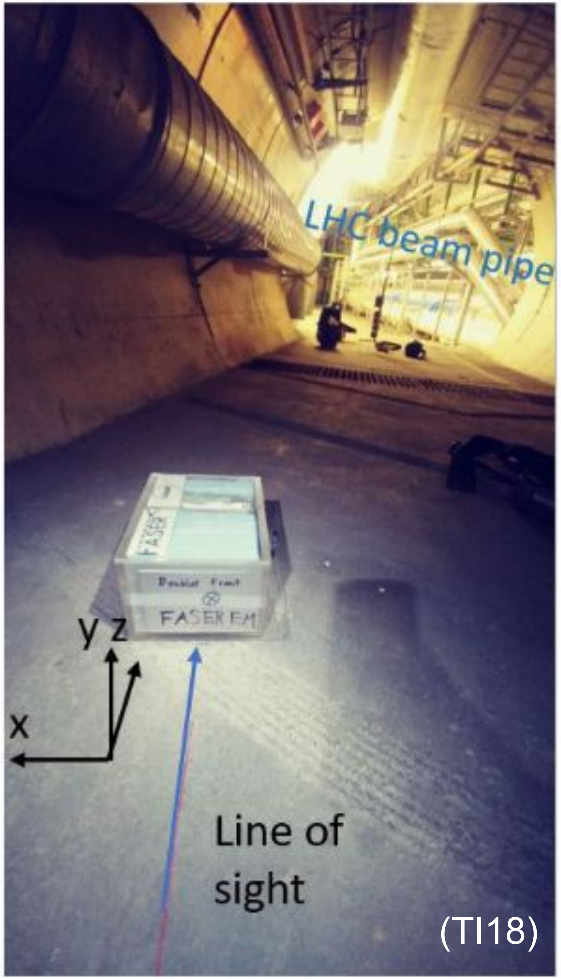

INSTALLED March 2021
FASER
Tracking Stations
• 4 Stations, 3 planes each
• 8 SCT modules per plane
• SCTs donated by ATLAS
Scintillators
• Veto - rejects muon background
• Trigger/timing - arrival time
• Preshower - veto & 2-ɣ signal
Geometry
• 7m length
• 20cm aperture
• 1.5m decay volume
FASERν
• Emulsion detector for ν's
• ~750 layers of emulsion films
• Tungsten plates
Magnets
• 0.57T Dipole
• Charge separation
ℓ-
ℓ+
A'
Calorimeter
• Donated by LHCb
• Measures total energy of ɣ, e±
Physics Signal
• Dark photons (LLP) and neutrinos from meson decay
pp→LLP + X , LLP→e+e−,μ+μ−...
towards IP

# Background/noise

- Emulsion detector Particle flux tests
  - Installed during 2018 LHC Technical stops
  - Measured muon flux agrees with FLUKA simulation
  - Mostly **μ-** and neutrinos expected & measured
  - **First neutrino interaction candidates at a particle collider!** (Paper here)
- Neutrinos produced primarily at IP
  - Neutrino-rock interactions negligible (<0.01Hz)
- Non-radiation-hard electronics ok
- Cosmics accounted for by direction and timing

Muon flux (FLUKA)

| Energy threshold [GeV] | Charged particle flux [$cm^{-2}\ s^{-1}$] |
|---|---|
| 10 | 0.40 |
| 100 | 0.20 |
| 1000 | 0.06 |



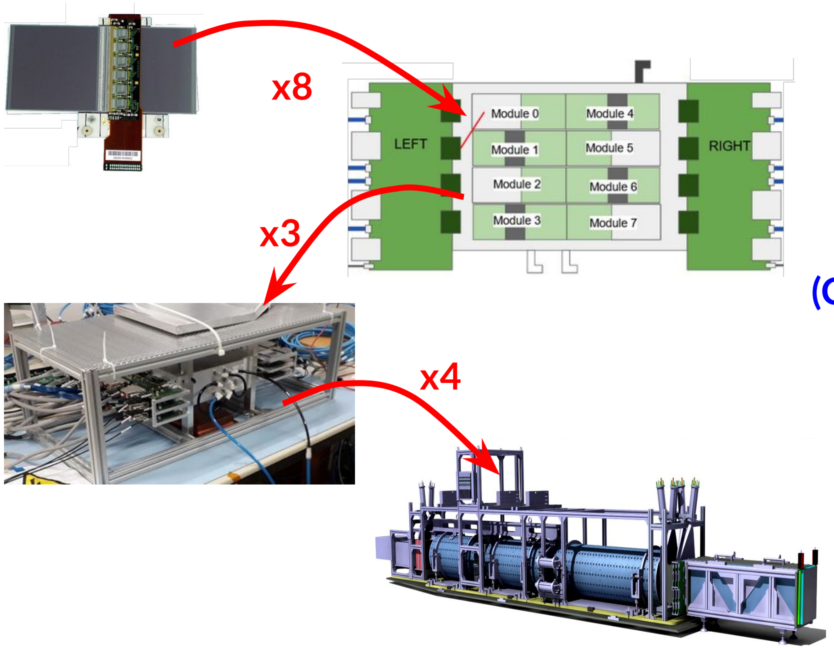
# The FASER Tracker

## Stages of Commissioning

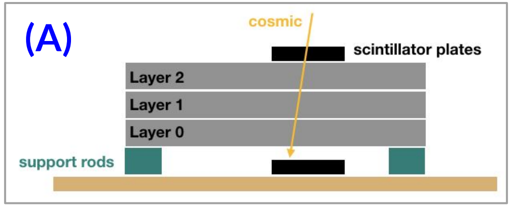
1. *SCT Module* - 8 per tracker plane
2. *Plane* - 3 per station (12 total)
3. *Station* - 4 stations in the detector
4. *Detector* - Final configuration

- Long term stability and control
  - Temperature, humidity, electric...
- Quantifying noisy/dead strips
- Electronics stability
  - IV Scans, ENC, Gain...

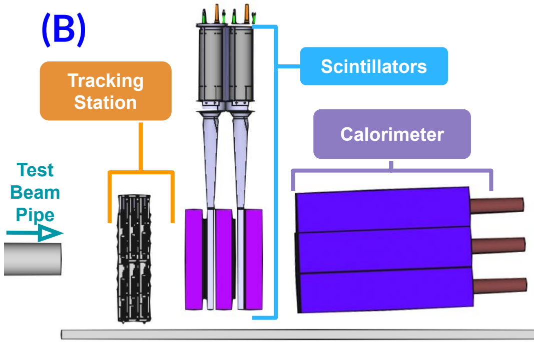
Paper released here!



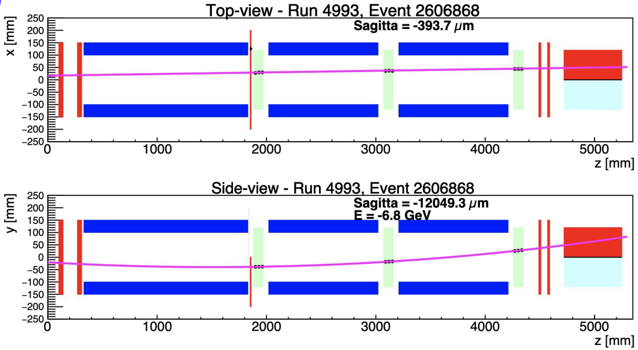

(A)




(B)




(C)



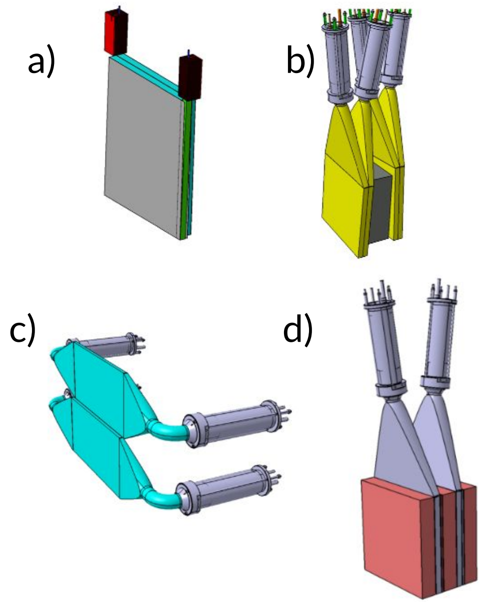

**(A)** EHN1 Single station cosmics setup

**(B)** EHN1 Test Beam setup

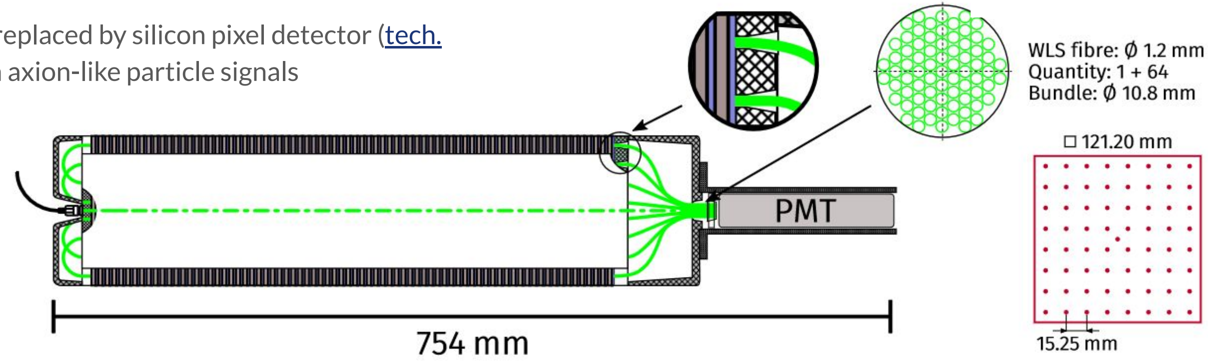
**(C)** TI12 LHC Pilot beam event reconstruction (900 GeV, Oct 2021)

# Calorimeter & Scintillators

- 4 Scintillator stations commissioned & installed, including for FASER$\nu$
  - (a) FASER$\nu$ Veto, (b) Interface Veto, (c) Timing, & (d) Preshower
  - >99.9% efficiency, enough to trigger when an LLP decays inside FASER
  - Installed muon metal shield to reduce noise, light leaks, and discharge
- 4 LHCb ECAL modules selected & tested
  - Energy resolution of ~1%, dependent on calibration
- Both tested with light and cosmic sources; acceptable, expected rates found
  - To be detailed in upcoming detector paper
  - All channels working well
- SPS Test beam - Summer 2021
  - Along with tracker (see previous slide for setup)
  - Analysis nearing completion
  - Few-% energy resolution confirmed

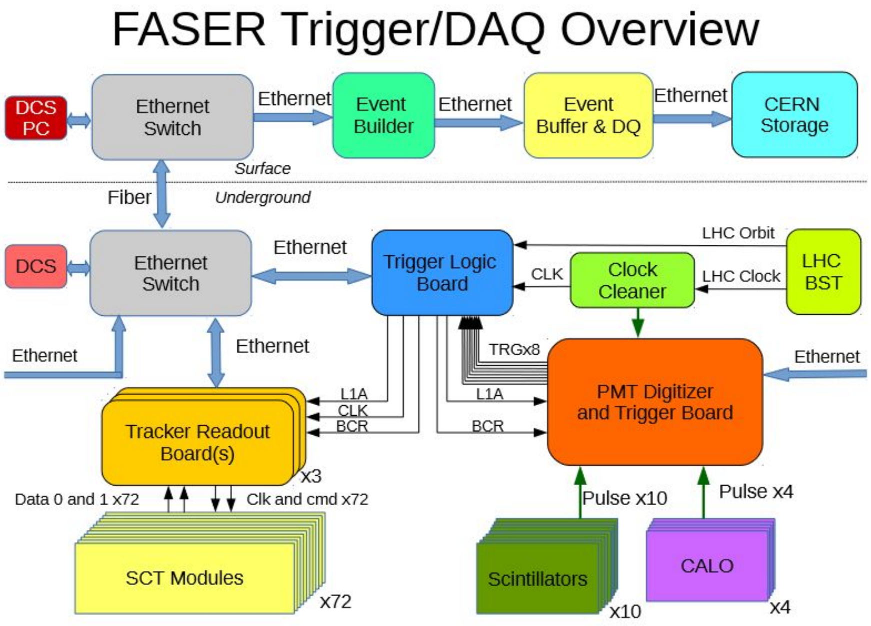



Preshower scintillator to be replaced by silicon pixel detector (tech. proposal) To detect 2-photon axion-like particle signals



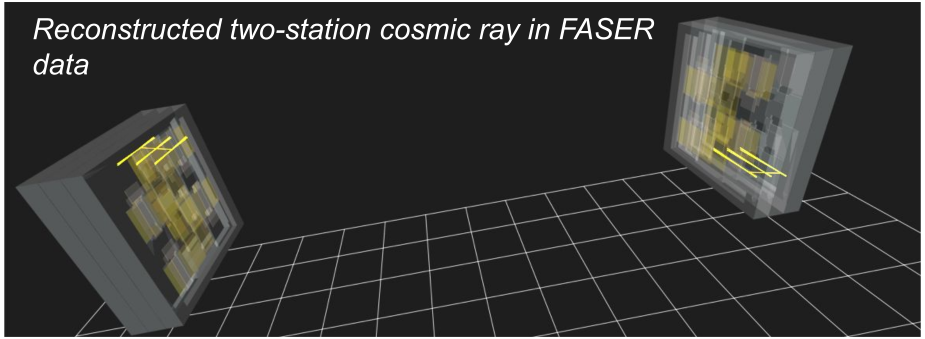
# Trigger & Data Acquisition

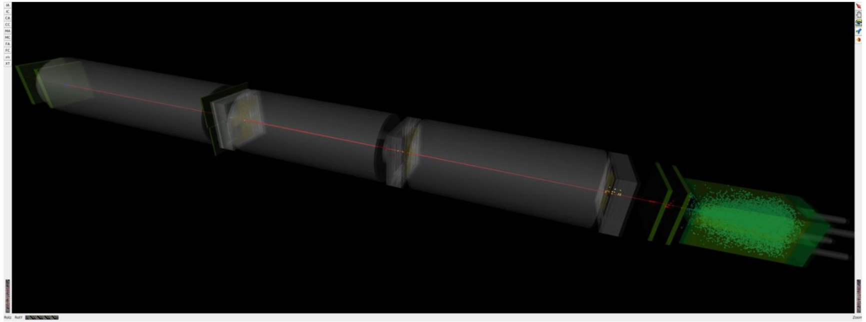
- PMTs from scintillators and calorimeter provide trigger signals
  - Trigger system run synchronously to the 40.08 MHz LHC clock
- Data Acquisition (DAQ): Configuration & readout
- Data Control & Safety (DCS): powers detector and protects it from unusual conditions
- Monitoring: checking data flow, detector conditions, and data quality to spot/resolve problems
- FASER Trigger rate: 650 Hz expected (dominated by muons)
- Paper published: [2021 JINST 16 P12028]



# Offline Software

- **Calypso** software package based on ATLAS framework (Gaudi and Athena)
  - Uses Geant4, ROOT, etc
  - Borrows much from ATLAS, now open-source
- Reconstruction, simulation, event display
- Includes Tracker, Scintillators, ECAL, magnetic field, FASERν, and non-active material in detector
- Physics generators - Dark Photons, Cosmic Rays, neutrino interactions, single muons
  - More robust far-forward simulation than ATLAS' models
  - Work ongoing to refine the event generator description of far forward hadron production (mostly relevant for



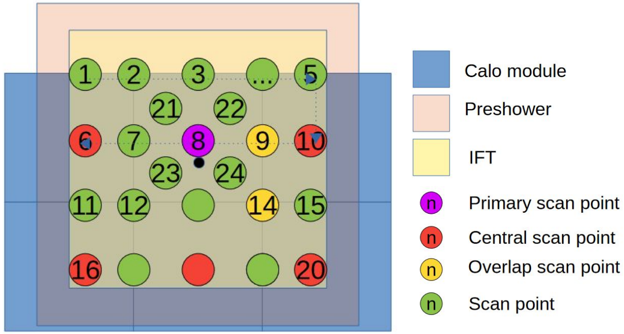



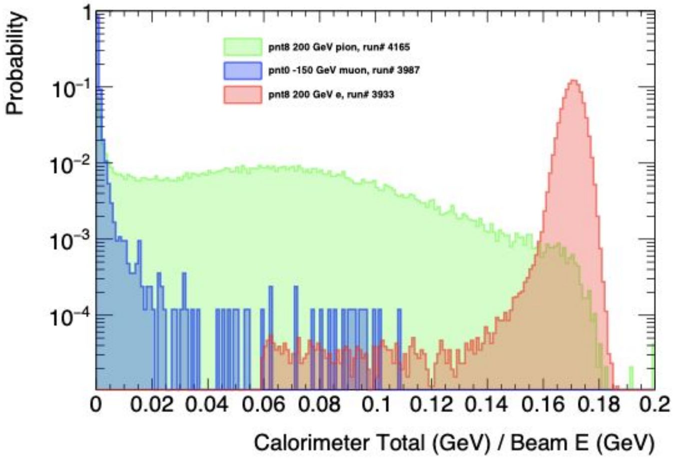
D. Casper

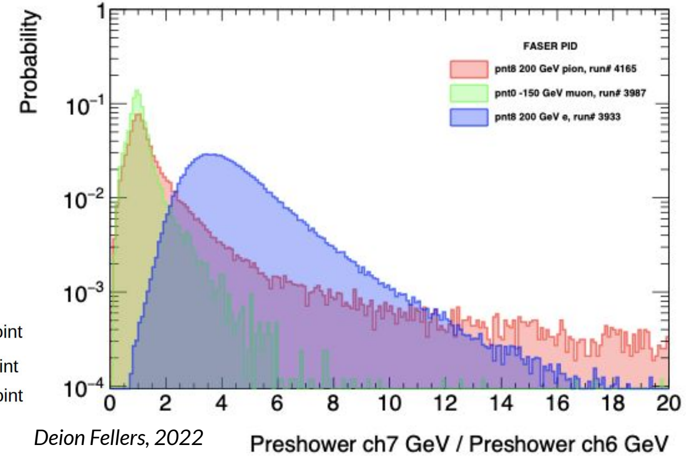
# Test Beam (Summer 2021)

- Goals:
  - Calibrate preshower & calorimeter modules
  - Develop and validate calibration procedure for TI12
  - Operation and performance measurements of IFT tracker station and scintillators in actual beam conditions
- Different beams, at various energies
  - Electrons: 5-300 GeV; Muons: 150 GeV; Pions: 200 GeV
  - Now we could practice particle identification →
- Tracker cluster efficiency measured: 99.86 ± 0.04 % , agreeing well with MC and ATLAS (99.74±0.04 %)
- Correction to gains improves calorimeter resolution by accounting for charges lost to preshower scintillator
- Calorimeter response uniform within a few percent across different beam positions

Paper in progress!



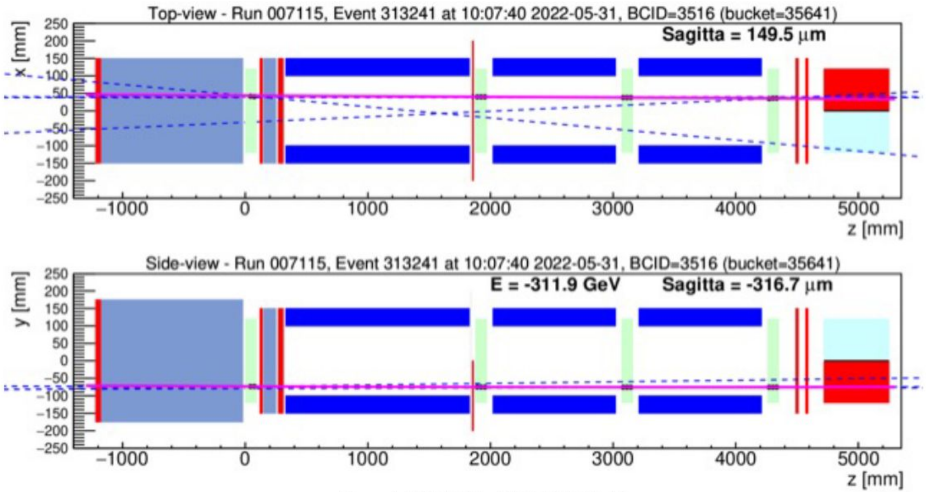



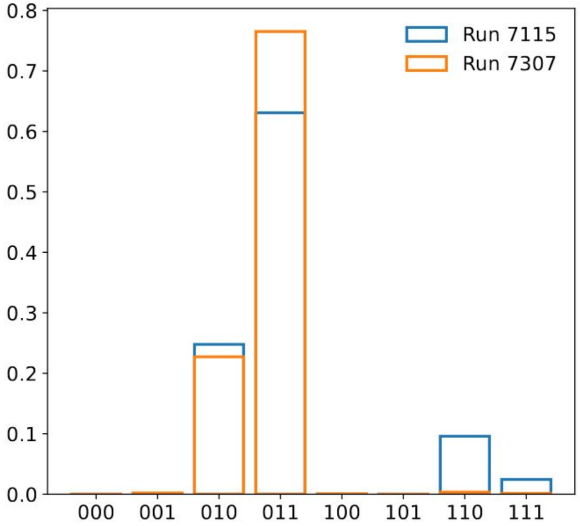

*Deion Fellers, 2022*

# First Beam Data

- Continual data taking during beam commissioning since late-April.
- Thousands of events collected with charged particle tracks traversing the detector.
    - Great for performance studies, optimizing operation procedures, & commissioning reconstruction software.
- First 13.6 TeV collisions on July 5th. Saw good events in the detector consistent with coming from collisions.
- Ideally all hits have 010 or 011 timing; after timing corrections, large improvement in the fraction with these hit patterns.



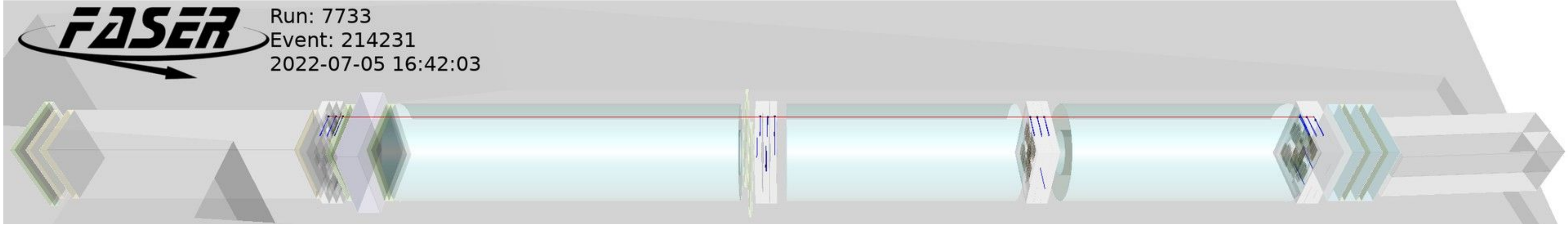

Event 313241, 829.546 GeV

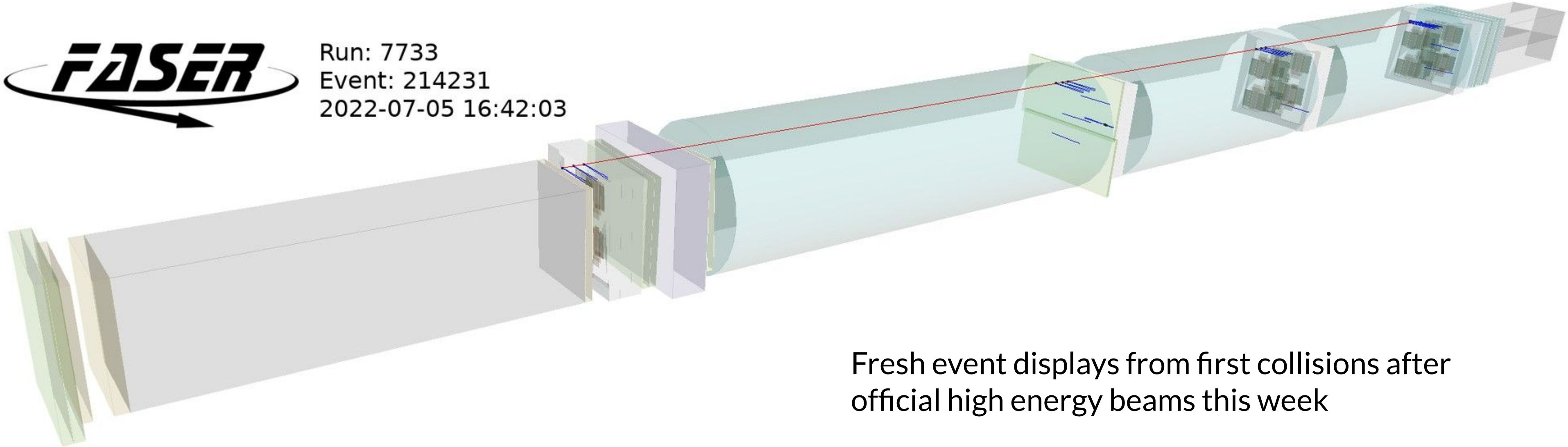



T. Böckh, 2022

Hit Pattern

# Run 3 Officially Begins!

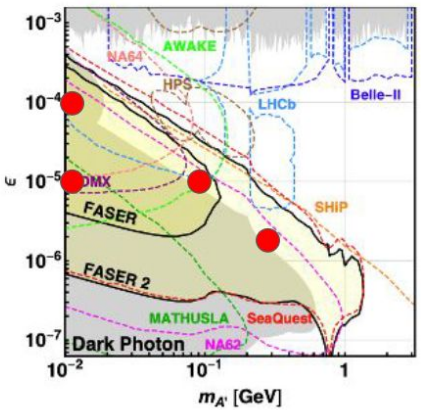


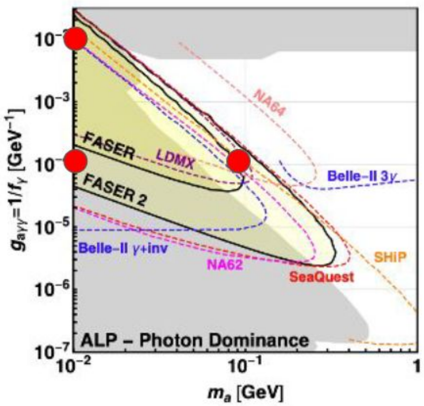




Fresh event displays from first collisions after official high energy beams this week

# Mock Data Challenge

- Exercise to generate, reconstruct, and analyze specific signal and background samples
- Springboard for development of analysis protocols and procedures
- Samples generated for a variety of signals:
  - Dark photons/ALPs, neutrinos, photons, charged pions...
  - Genie & FLUKA
- Sample generation began in May; improved after collaborators begin to use them and regenerated as needed
- Good exercise of MC production




- Validation of samples produced for single particle and physics signal carried out at different levels, things look good
- Tests with track reconstruction allow studies of momentum resolution
- Can also study & improve upon Track finding and fitting

An ongoing exercise!

# Summary & FASER Looking Forward

- All FASER Publications - 3 published this year, with two more planned! (Detector & Test Beam)
- FASER and FASER$\nu$ installed and operational
  - Preshower upgrade approved March 2022 for installation in 2023/2024
  - Data collection has started with Run 3!
  - FASER$\nu$: guaranteed neutrino physics results
  - At the end of Run 3 (~2026): dark photon evidence or model constraints
- Development of analysis tools ongoing
  - Begun with earliest commissioning phases & cosmics
  - Assisted & focused by the ongoing Mock Data Challenge

# EXTRAS

# FASER INSTITUTIONS

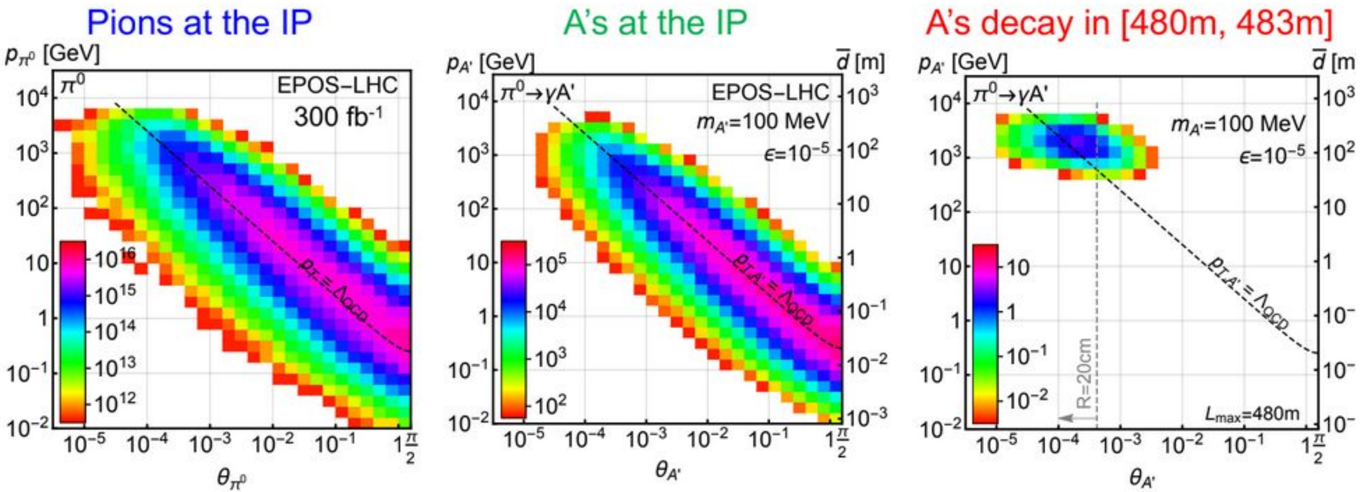
## 75 collaborators, 22 institutions, 9 countries

Henso Abreu (Technion), Claire Antel (Geneva), Akitaka Ariga (Chiba/Bern), Tomoko Ariga (Kyushu/Bern), Florian Bernlochner (Bonn), Tobias Boeckh (Bonn), Jamie Boyd (CERN), Lydia Brenner (NIKHEF), Franck Cadoux (Geneva), Dave Casper (UC Irvine), Charlotte Cavanagh (Liverpool), Xin Chen (Tsinghua), Andrea Coccaro (INFN), Sergey Dmitrievsky (JINR), Monica D’Onofrio (Liverpool), Yannick Favre (Geneva), Deion Fellers (Oregon), Jonathan Feng (UC Irvine), Didier Ferrere (Geneva), Stephen Gibson (Royal Holloway), Sergio Gonzalez-Sevilla (Geneva), Yuri Gornushkin (JINR), Carl Gwilliam (Liverpool), Daiki Hayakawa (Chiba), Shih-Chieh Hsu (Washington), Zhen Hu (Tsinghua), Peppe Iacobucci (Geneva), Tomohiro Inada (Tsinghua), Sune Jakobsen (CERN), Enrique Kajomovitz (Technion), Felix Kling (DESY), Umut Kose (CERN), Rafaella Eleni Kotitsa (Geneva), Susanne Kuehn (CERN), Helena Lefebvre (Royal Holloway), Lorne Levinson (Weizmann), Ke Li (Washington), Jinfeng Liu (Tsinghua), Chiara Magliocca (Geneva), Josh McFayden (Sussex), Matteo Milanesio (Geneva), Dimitar Mladenov (CERN), Theo Moretti (Geneva), Magdalena Munker (Geneva), Mitsuhiro Nakamura (Nagoya), Toshiyuki Nakano (Nagoya), Marzio Nessi (CERN), Friedemann Neuhaus (Mainz), Laurie Nevay (Royal Holloway), Hidetoshi Otono (Kyushu), Hao Pang (Tsinghua), Lorenzo Paolozzi (Geneva), Brian Petersen (CERN), Francesco Pietropaolo (CERN), Markus Prim (Bonn), Michaela Queitsch-Maitland (Manchester), Filippo Resnati (CERN), Hiroki Rokujo (Nagoya), Elisa Ruiz Choliz (Mainz), Jorge Sabater-Iglesias (Geneva), Osamu Sato (Nagoya), Paola Scampoli (Bern), Kristof Schmieden (Mainz), Matthias Schott (Mainz), Anna Sfyrla (Geneva), Savannah Shively (UC Irvine), Yosuke Takubo (KEK), Noshin Tarannum (Geneva), Ondrej Theiner (Geneva), Eric Torrence (Oregon), Serhan Tufanli (CERN), Svetlana Vasina (JINR), Benedikt Vormvald (CERN), Di Wang (Tsinghua), Eli Welch (UC Irvine)

# The Signal

**pp→LLP** + X , **LLP**→$e^+e^-, \mu^+\mu^-, \pi^+\pi^-$...

- 2 oppositely charged tracks. E~1TeV
- Combined momentum points back to IP



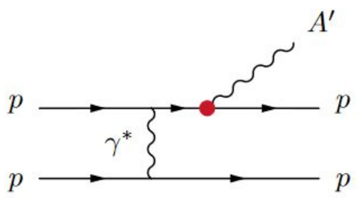

- Production is peaked at $p_T \sim m_\pi, \Lambda_{QCD}$~250 MeV
- Enormous event rates: $N_\pi \sim 10^{15}$ per bin

- Rates highly suppressed by $\varepsilon^2 \sim 10^{-10}$
- But still $N_{A'} \sim 10^5$ per bin

- Only highly boosted ~TeV A's decay in FASER
- $N_{A'} \sim 100$ $e^+e^-$ events, within 20 cm of "on axis"

Feng, Galon, Kling, Trojanowski (2017)

# Other production modes -LLPs




- Dark Bremsstrahlung
  - For LLPs heavier than thresholds for the decays of the lightest mesons
  - [Fermi-Weizsacker-Williams approximation]
  - Dominant for $m > m_\pi$
- LLPs from Hard Scattering
  - Technically possible, but large uncertainties from:
    - determination of PDFs at low momentum transfer
    - low parton momentum fraction
  - Becomes relevant: m>2 GeV with [Drell-Yan process]
- Beam dump from TAN
  - Sort of fixed target experiment
  - Also could produce dark gauge boson via dark compton