HEISING-SIMONS FOUNDATION SIMONS FOUNDATION

UC IRVINE

CERN

FASER

ForwArd Search ExpeRiment

Savannah Shively

July 2021

THE FASER COLLABORATION

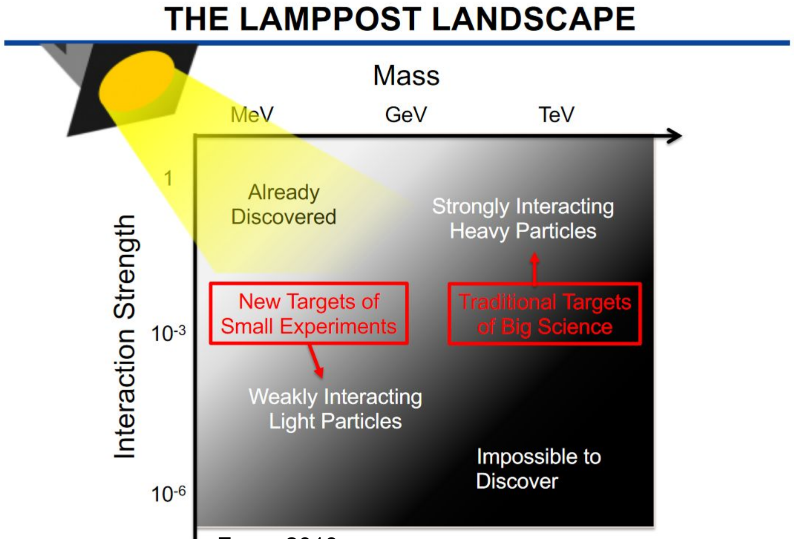
71 collaborators, 19 institutions, 8 countries

Henso Abreu (Technion), Yoav Afik (Technion), Claire Antel (Geneva), Akitaka Ariga (Bern), Tomoko Ariga (Kyushu/Bern), Florian Bernlochner (Bonn), Tobias Boeckh (Bonn), Jamie Boyd (CERN), Lydia Brenner (CERN), Franck Cadoux (Geneva), Dave Casper (UC Irvine), Charlotte Cavanagh (Liverpool), Xin Chen (Tsinghua), Andrea Coccaro (INFN), Monica D'Onofrio (Liverpool), Candan Dozen (Tsinghua), Yannick Favre (Geneva), Deion Fellers (Oregon), Jonathan Feng (UC Irvine), Didier Ferrere (Geneva), Stephen Gibson (Royal Holloway), Sergio Gonzalez-Sevilla (Geneva), Carl Gwilliam (Liverpool), Shih-Chieh Hsu (Washington), Zhen Hu (Tsinghua), Peppe Iacobucci (Geneva), Tomohiro Inada (Tsinghua), Sune Jakobsen (CERN), Enrique Kajomovitz (Technion), Felix Kling (SLAC), Umut Kose (CERN), Susanne Kuehn (CERN), Helena Lefebvre (Royal Holloway), Lorne Levinson (Weizmann), Ke Li (Washington), Jinfeng Liu (Tsinghua), Chiara Magliocca (Geneva), Josh McFayden (CERN), Dimitar Mladenov (CERN), Mitsuhiro Nakamura (Nagoya), Toshiyuki Nakano (Nagoya), Marzio Nessi (CERN), Friedemann Neuhaus (Mainz), Laurie Nevay (Royal Holloway), Hidetoshi Otono (Kyushu), Lorenzo Paolozzi (Geneva), Carlo Pandini (Geneva), Hao Pang (Tsinghua), Brian Petersen (CERN), Francesco Pietropaolo (CERN), Johanna Price (UC Irvine), Markus Prim (Bonn), Michaela Queitsch-Maitland (CERN), Filippo Resnati (CERN), Chiara Rizzi (Geneva), Hiroki Rokujo (Nagoya), Jakob Salfeld-Nebgen (CERN), Osamu Sato (Nagoya), Paola Scampoli (Bern), Kristof Schmieden (Mainz), Matthias Schott (Mainz), Anna Sfyrla (Geneva), Savannah Shively (UC Irvine), John Spencer (Washington), Yosuke Takubo (KEK), Ondrej Theiner (Geneva), Eric Torrence (Oregon), Serhan Tufanli (CERN), Benedikt Vormvald (CERN), Di Wang (Tsinghua), Gang Zhang (Tsinghua)

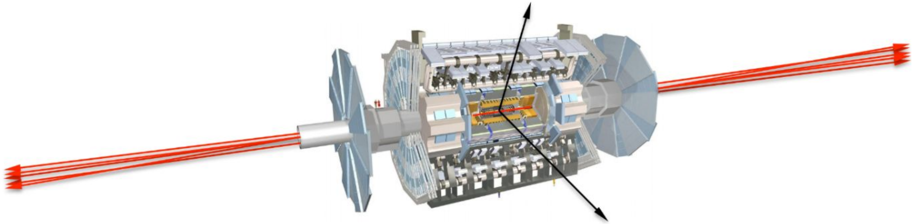
Outline

- Motivation
- The Experiment
- Sensitivity
- Commissioning
  - Tracker
  - Cosmics
- Summary/Timeline

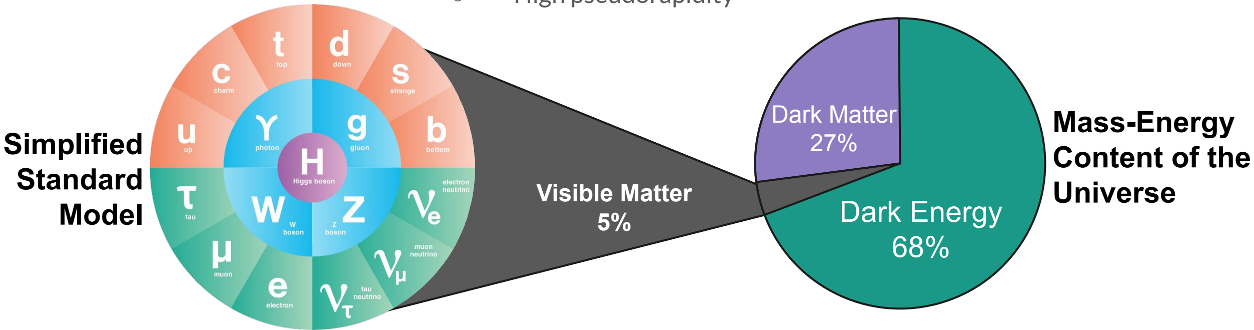
The Far Forward Region

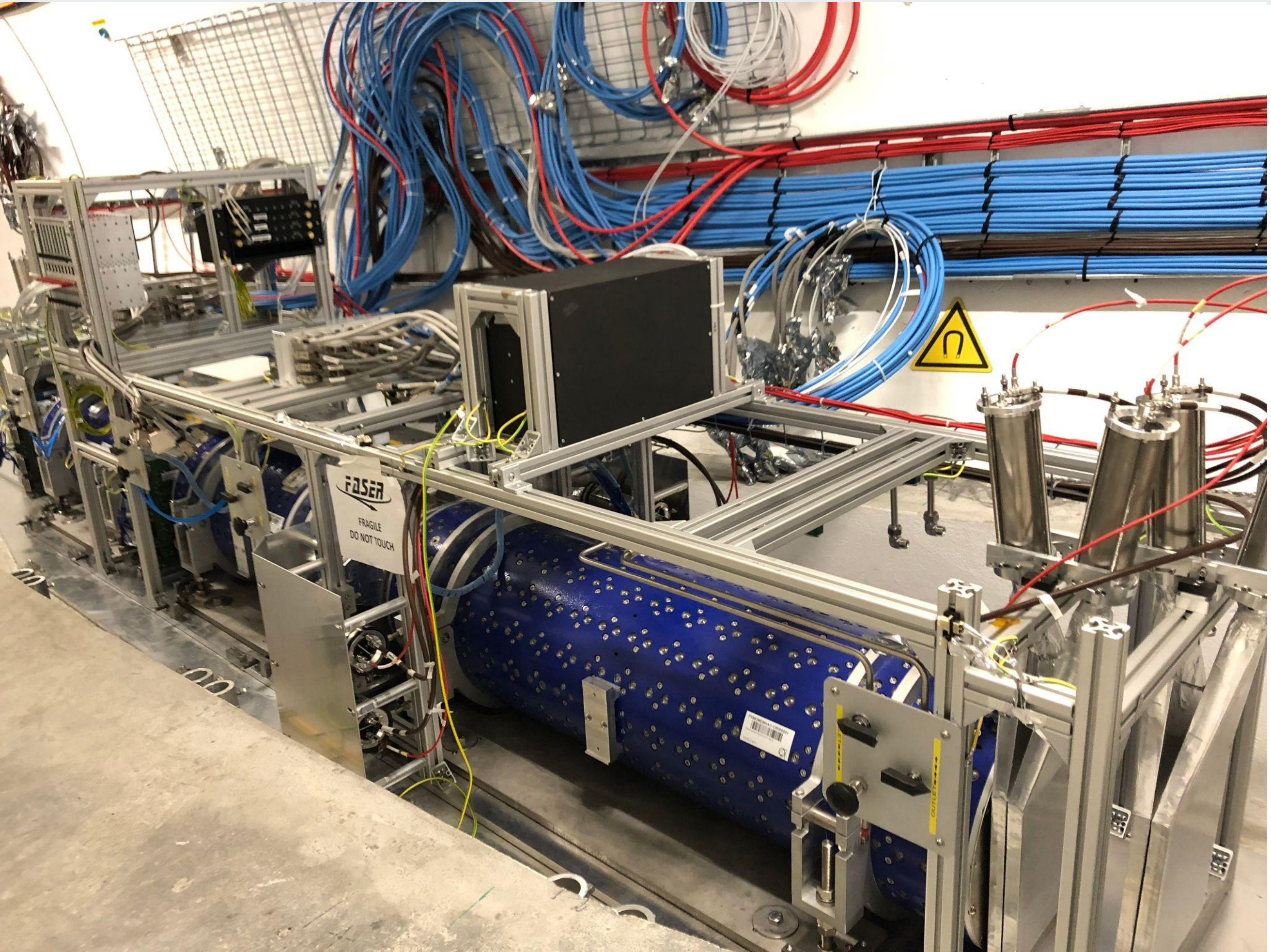


Feng, 2019



- Last new particle detection - Higgs Boson - almost 10 years ago
- Dark Matter & Dark Energy still unexplained (among other things)
- Standard Model not enough
- Large Hadron Collider (LHC) currently at the end of Long Shutdown 2 (LS2)
- Most experiments measure particles emitted transverse to the beamline
  - ATLAS, CMS...
- FASER complementary to larger experiments
- LLPs - low mass, long life
  - High pseudorapidity

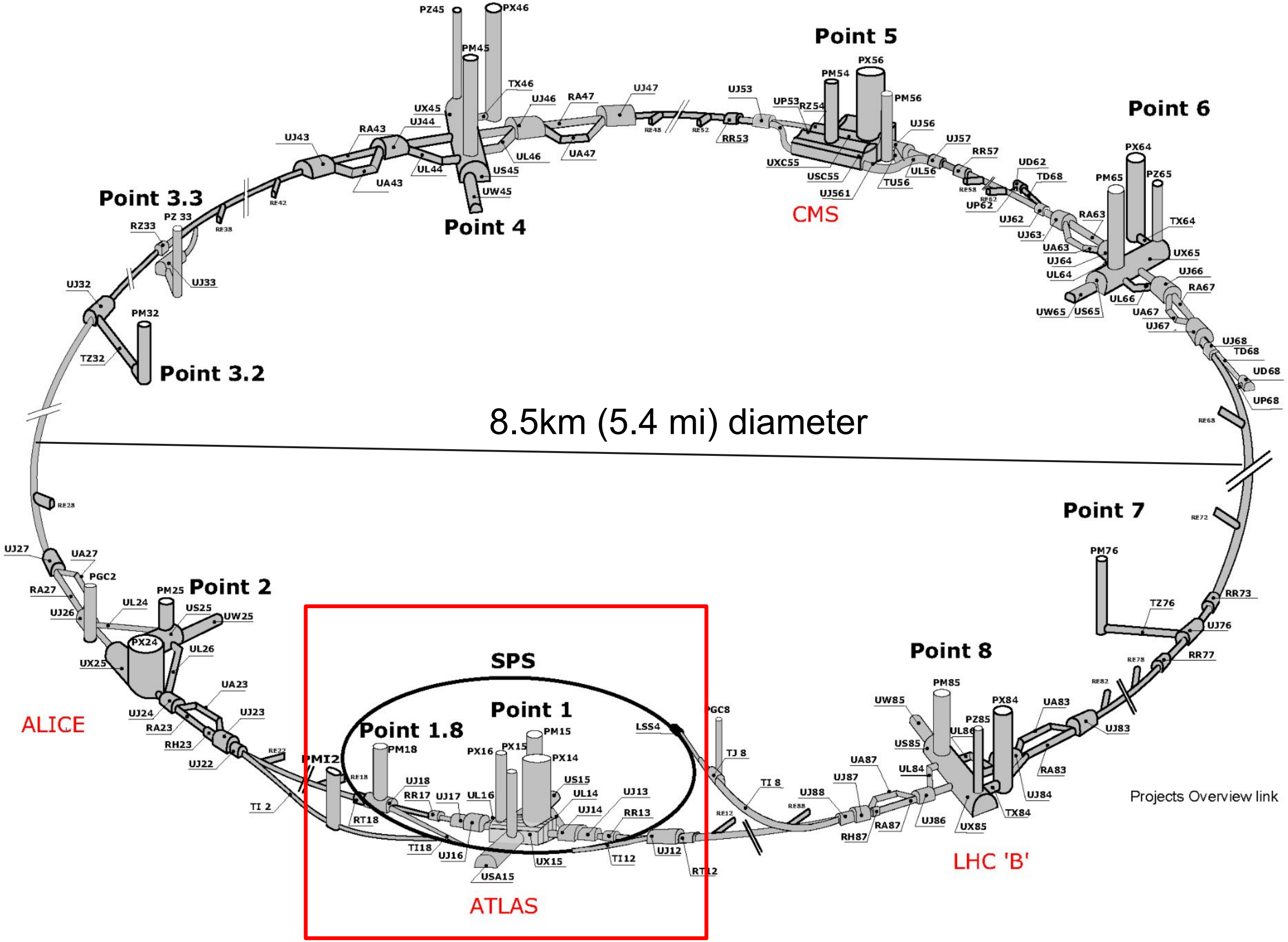




Introducing...

FASER

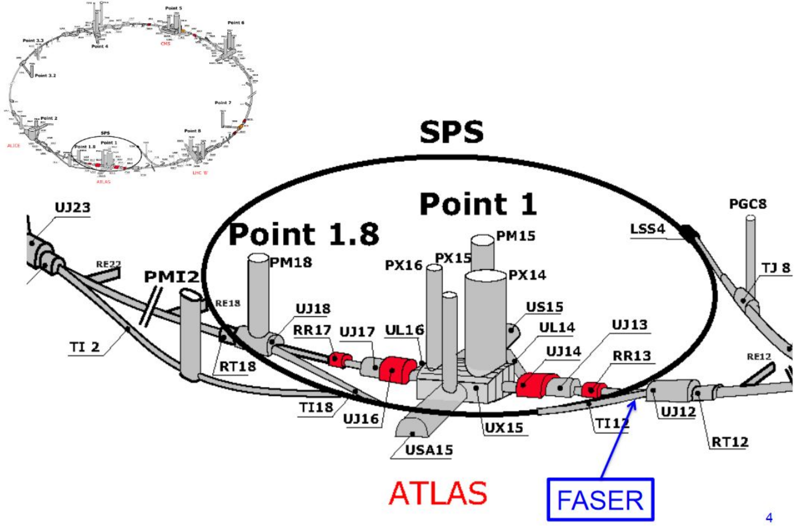
Location

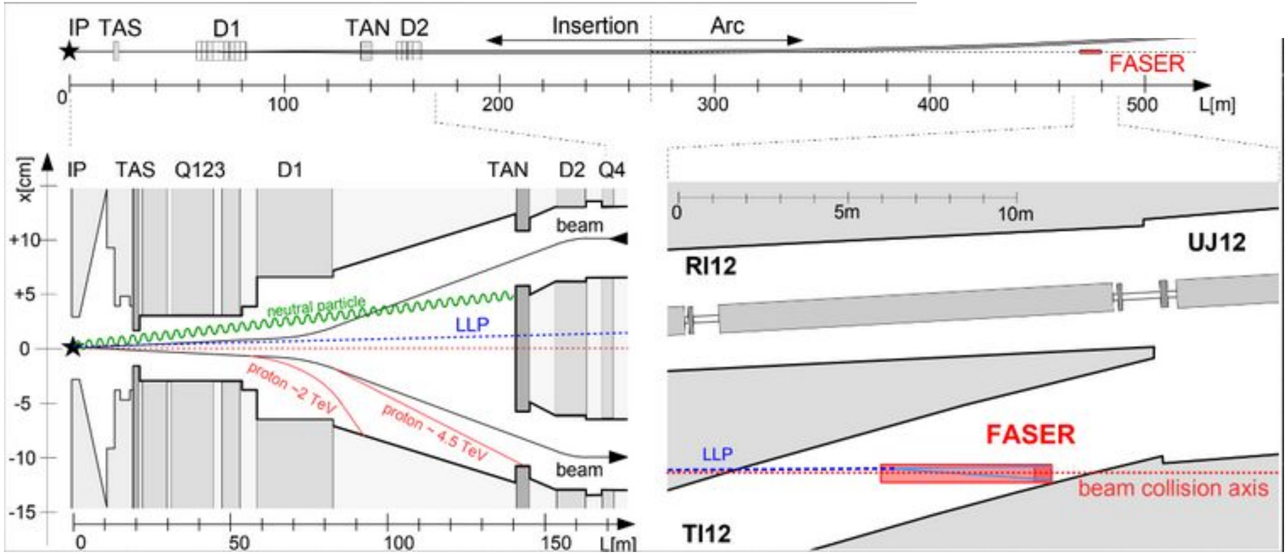


Projects Overview link

Location

- TI12 - unused maintenance tunnel intersecting collision axis
- ~480m from IP
- Highly Collimated beam (mrad diameter) → only small detector needed





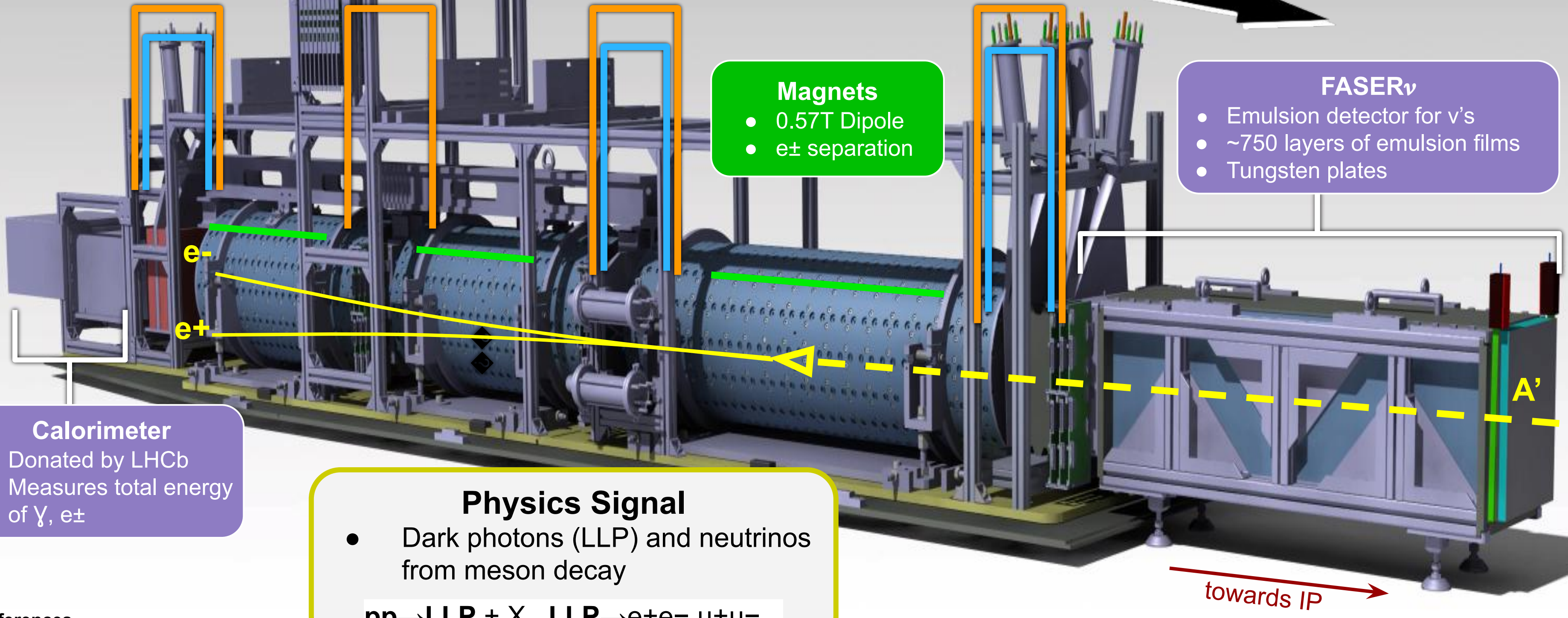
Tracking Stations
- 4 Stations, 3 planes each
- 8 SCT modules per plane
- SCTs donated by ATLAS

Scintillators
- Veto - rejects muon background
- Trigger/timing - arrival time
- Preshower - veto & 2-ɣ signal

FASER

Magnets
- 0.57T Dipole
- e± separation

FASERν
- Emulsion detector for ν's
- ~750 layers of emulsion films
- Tungsten plates



Calorimeter
- Donated by LHCb
- Measures total energy of ɣ, e±

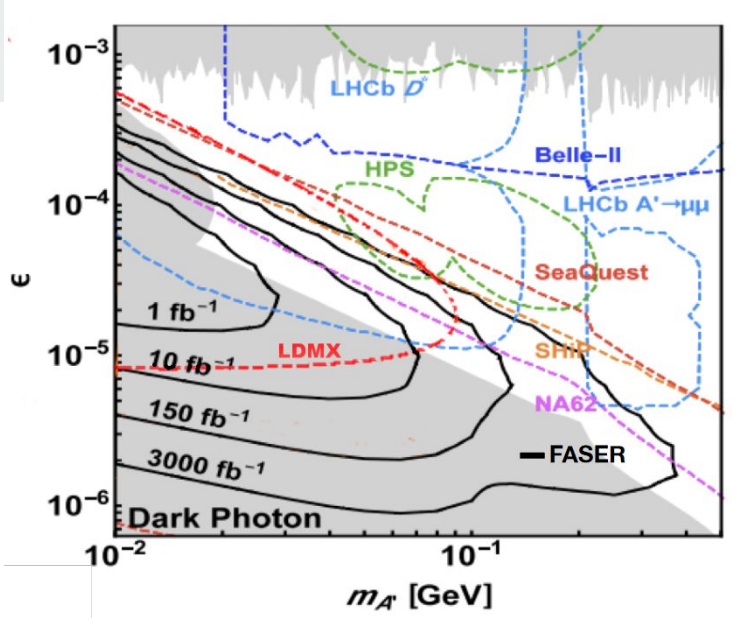
Physics Signal
- Dark photons (LLP) and neutrinos from meson decay

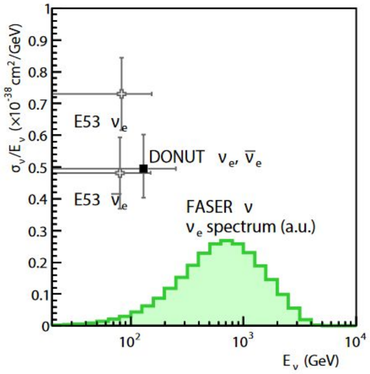
pp→LLP + X , **LLP**→e+e−,μ+μ−...

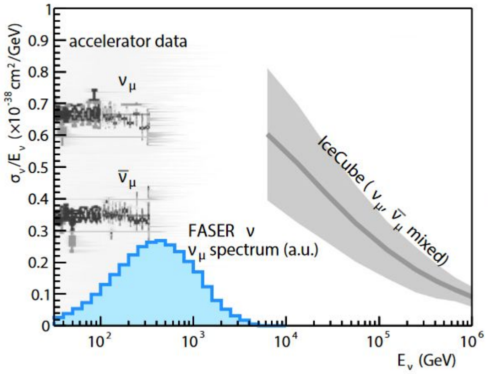
References
[1] https://arxiv.org/pdf/1811.12522.pdf
[2] https://arxiv.org/pdf/1812.09139.pdf

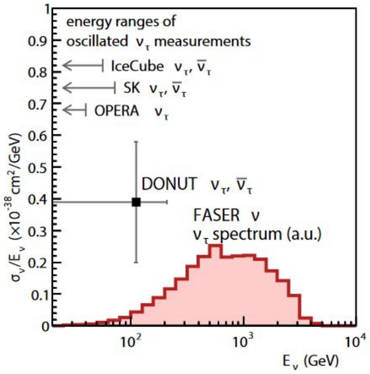
Physics reach

- Dark Photon
  - Gray-shaded regions - excluded by current bounds
  - Run 3 has integrated luminosity of 150 fb^{-1}
    - Run 5 (2030+) ends above 3000
  - Plot assumes no background for dark photon search
    - FASER starts excluding currently allowed models with first fb^{-1}
- Neutrinos
  - Typical sizes of colliders and coverage of detectors means neutrinos escape undetected
  - Highest energy neutrinos produced along beamline - blindspot strikes again!
  - **For FASERν See John Spencer's talk HERE at 4:30pm in Track K**

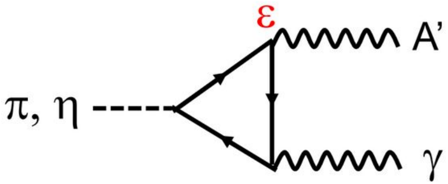








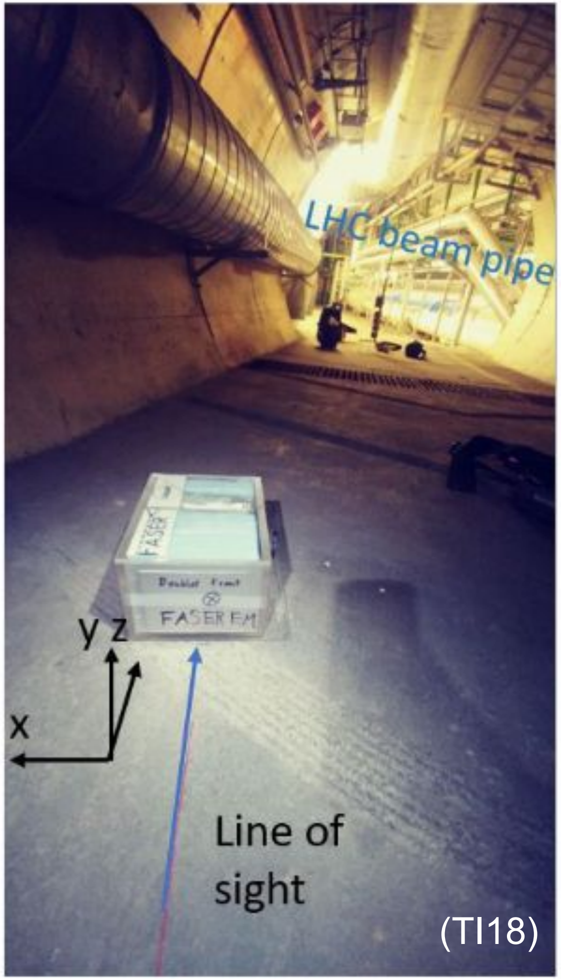
$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon e \sum_f q_f \bar{f} \not{A}' f$$



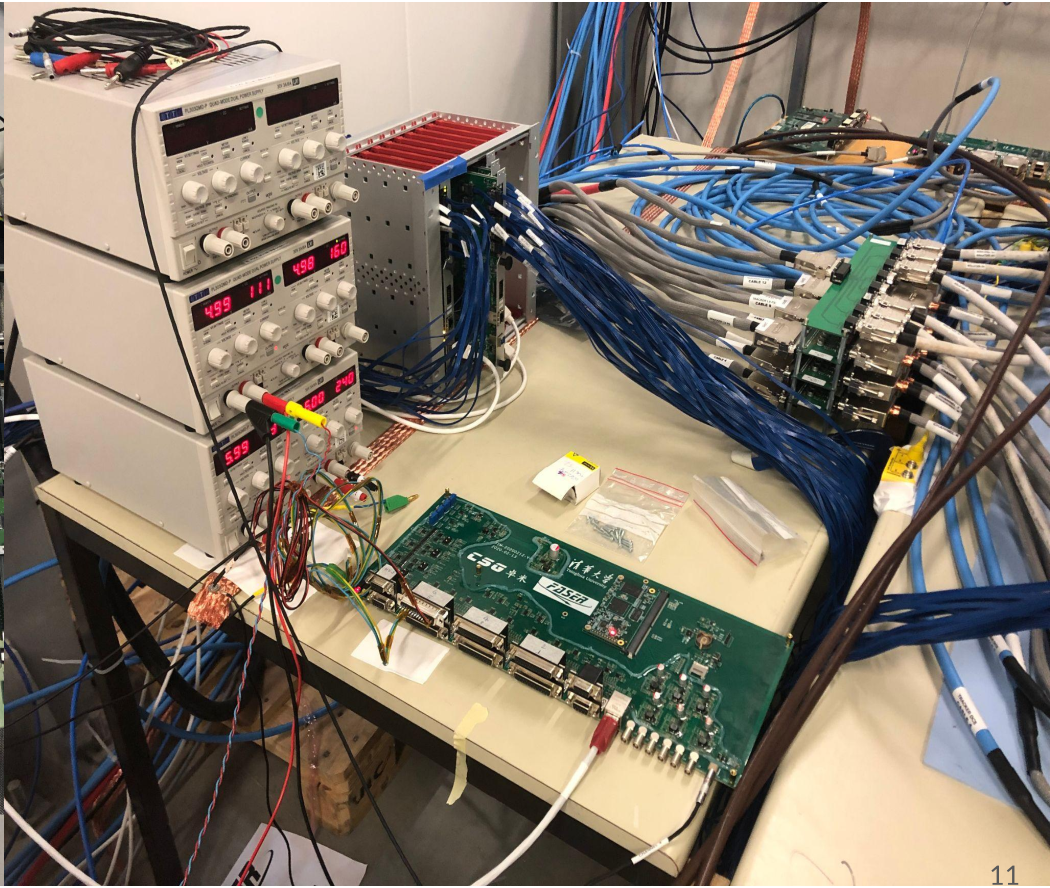
Background/noise

- Particle flux tests
- Emulsion detectors
  - Installed during 2018 LHC Technical stops
  - Agrees with FLUKA simulation
  - Mostly muons and neutrinos passing through - upstream or from other high energy products hitting machine parts
- Mostly **μ**- due to LHC magnet bending
- Neutrinos produced primarily at IP
  - Neutrino-rock interactions negligible (<0.01Hz)
- Non-radiation-hard electronics ok
- Cosmics accounted for by direction and timing

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

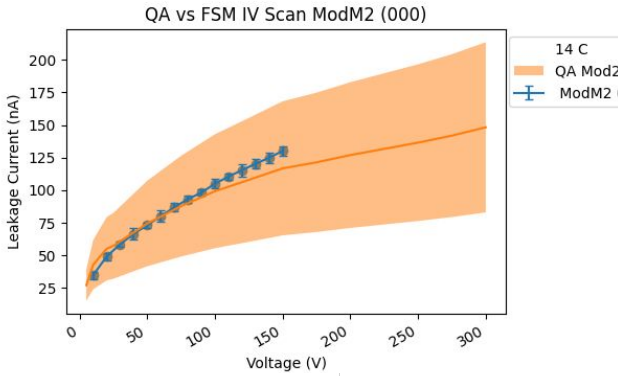


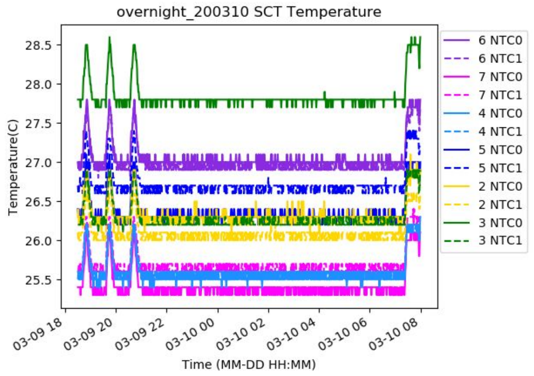
Commissioning



Standard Tracker Commissioning

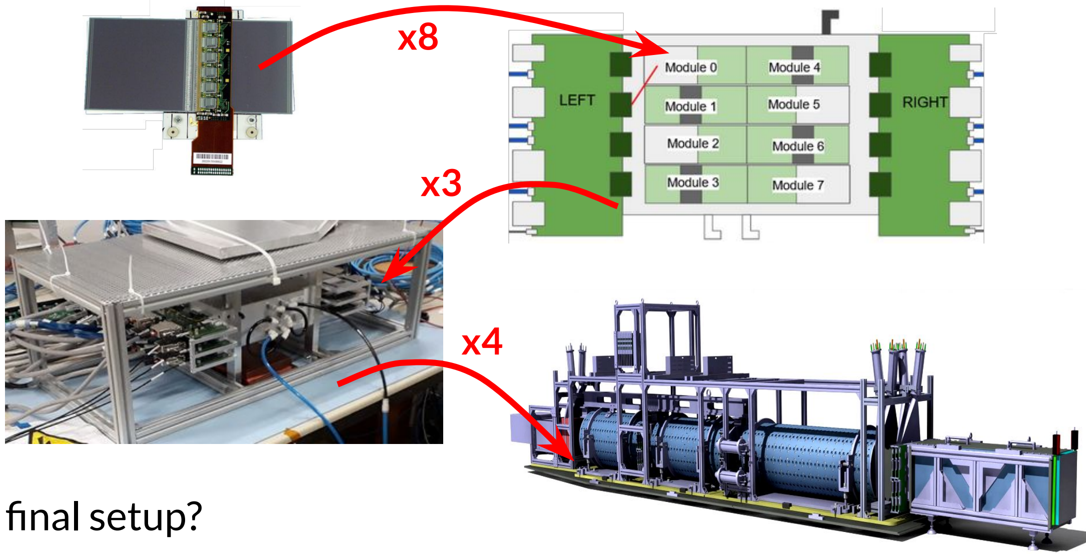
- Voltage vs Leakage current behavior (IV scans)
- Long term stability and control
  - Temperature, humidity, electric…
- Quantifying noisy/dead strips
  - Do they work as well in the first stage as in the final stage?





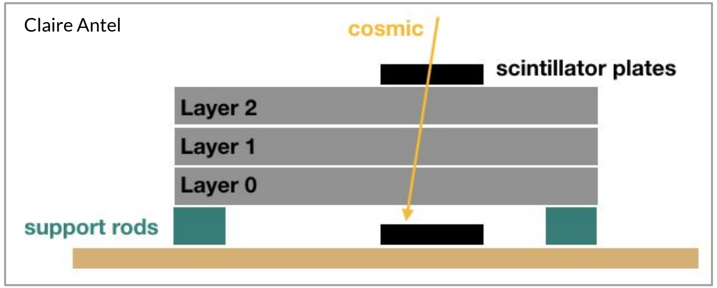
Stages of Commissioning

- Module QA - 8 per tracker plane
- Plane - 3 per station (12 total)
- Station - 4 stations in the detector
- Detector - Does everything work in the final setup?

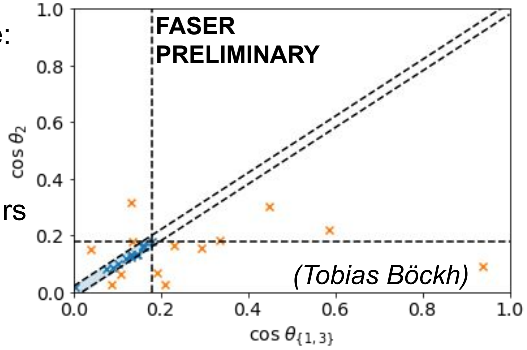


Cosmics Tests

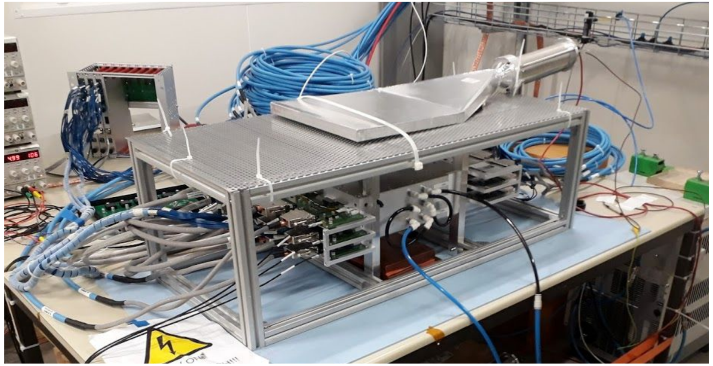
- Cosmic ray muons used to test tracker functionality
- Single station on surface (Winter 2020)
- Full detector underground (Ongoing)
- CR simulation vs Measurement
- Helpful for testing reconstruction

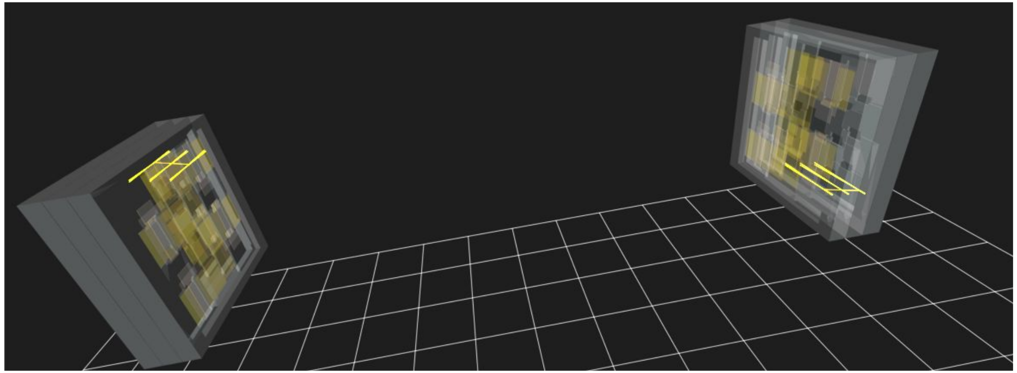


- Estimate of cosmic trigger rate: *276 mHz*
- **Two-station tracks**
  - Prediction: *1/(28 hrs)*
  - 14 good tracks in 469 hours of data
  - Measured rate: *1/(33.5 +/- 8.9 hrs)*
- **Three-station tracks**
  - Prediction: *1/(82 days)*
  - *Not yet measured*



"Good" tracks shown in blue traverse two adjacent stations at compatible angles.





FASER Looking Forward

- Ongoing tracker tests with CR
- Beam test upcoming in early August - collection and analysis
- Actively building data analysis tools to be ready for Run3 data
- Data collection officially begins in Spring 2022 with Run 3
- At the end of Run 3 (~2024): dark photon evidence or model constraints

- Baseline installed - FASERν and interface tracker installed by end of year
- FASERν - guaranteed neutrino physics results
- **FASER papers to be published this year**
  - **TDAQ, tracker, full detector, FASERν pilot**

Summary

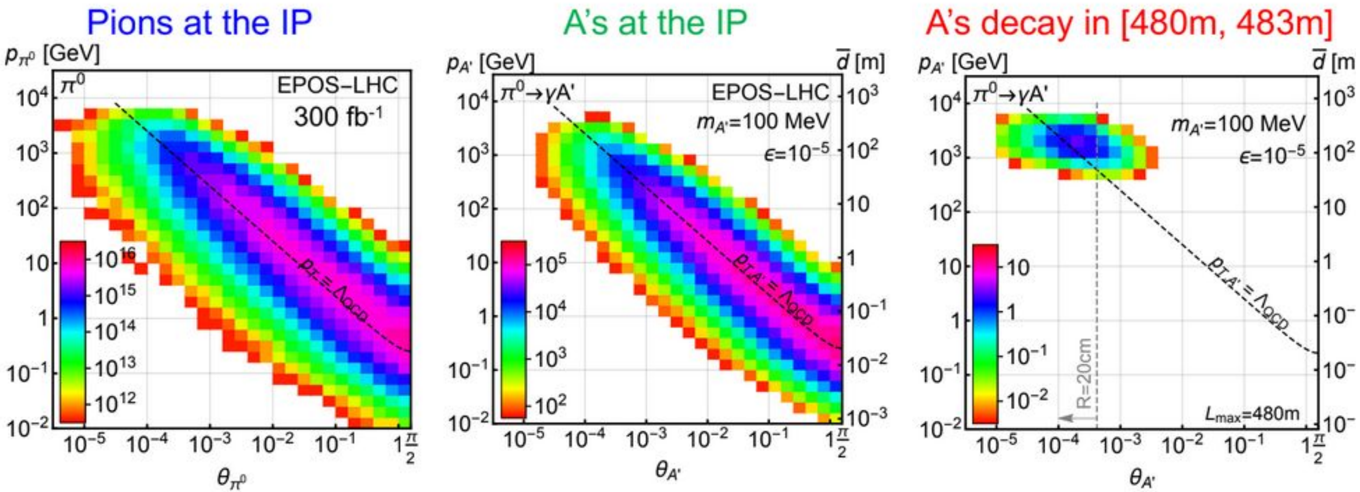
- Other LHC detectors have an axial “blind spot” that low-mass, long-lived particles may escape through, undetected
- FASER will be looking there for BSM physics in Run-3
  - Dark Photons
  - Neutrino high energy cross-section
- FASER baseline currently installed
- Continued commissioning of final components ongoing
- Cosmic rays and upcoming beam test analysis to do
- Run-3 data analysis development for dark photon search

EXTRAS

The Signal

pp→**LLP** + X , **LLP**→e+e−,μ+μ−,π⁺π−...

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



- Production is peaked at $p_T \sim m_\pi, \Lambda_{QCD} \sim 250$ 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 Physics Signals

- Dark Vectors
  - Other than DP: if one of the anomaly-free global symmetries of the SM is gauged
  - Requires RH-neutrino
  - new GB can couple to SM currents and kinetically mix with hypercharge GB
  - As with DP, any light dark sector GB produced in light meson decays and dark bremsstrahlung
  - B-L, Li-Lj
- Dark Scalars
  - Higgs/dark higgs
  - From rare B-meson decay → Larger angular spread
  - Higgs-dark Higgs mixing generates Yukawa-like couplings between the SM fermions and the dark Higgs boson
- Heavy Neutral Leptons aka sterile neutrinos
  - Produced through heavy meson and τ decay
  - Decay modes: 3 neutrinos OR charged particle pairs like other ones
- Axion-like Particles (ALP)
  - couple to the SM through dimension-5 operators.
- Dark Pseudoscalars
  - mainly produced through the flavor-changing heavy meson decay $B \to X_s a$.
  - dominant decay modes are typically pairs of the heaviest kinematically available SM fermions

Calculation of rates - LLP

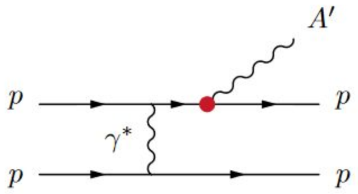
Angular acceptance enforcement

$$\mathcal{P}(p,\theta) = \left(e^{-(L-\Delta)/d} - e^{-L/d}\right)\Theta(R - \tan\theta L) \approx \frac{\Delta}{d}e^{-L/d}\Theta(R-\theta L)$$

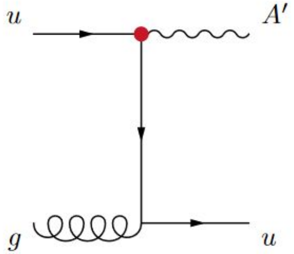
- Probability of LLP decaying in FASER
  - L, R, delta from detector geometry
  - d = decay length
  - Total LLP decays given P:
    - Assume decay into DM absent due to kinematics or suppressed
    - Assume 100% detection efficiency for visible decay modes
  - Most LLPs would come from Light Hadron Decays
    - π^0 = , 1.6×10^{12}pb , $\eta=1.7\times10^{11}$pb
    - 0.6% of π^0 produced within 0.2 mrad of beam collision axis (higher % for higher energy)
  - In Run3, expect:
    - 3×10^{17} π^0, $2.5\times10^{16}\eta$, 1.1×10^{15}D, and 7.1×10^{13}B

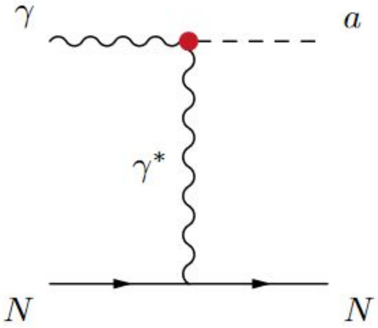
$$N = \mathcal{L}\int dp\, d\theta\, \frac{d\sigma_{pp\to \mathrm{LLP}+X}}{dp\, d\theta} \times \mathcal{P}(p,\theta)$$

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





Tracker DAQ Tests

Circuitry allows to inject a specific charge (voltage pulse through a 100 fF internal capacitor) simultaneously in 1/4th of all chip channels

Tracker Calibration:

- **Mask Scan** - identify dead and noisy strips
- **Strobe Delay** - optimize delay between the calibration charge and the clock, so that sampling is at the max of the input signal
- **Three Point Gain** (x2) - how much input noise is there? (3 different charges)
- **Trim Scan** - threshold correction offsets to achieve a uniform threshold distribution within module
- **Response Curve** - measure input noise for 10 different charges
- **Noise Occupancy** - fraction of channels giving rise to a signal only due to noise; for module performance

To evaluate and quantify how each module reads out data

Derive calibration constants for close as possible uniform response across all planes

DAQ Tests in detail

- **Strobe Delay**: An optimal setting of the strobe delay for each chip is important for the accuracy of the threshold calibration.
- **Threshold scans**: A threshold scan forms the basis of all analog tests, with or without charge injection.
- **Three Point Gain:** Threshold scan with injected charges of 1.5, 2 and 2.5 fC to verify the analog performance of the modules but not to calibrate it. The 3 point gain test summary reports the offset, gain, input and output noise as well as their RMS values for each chip, as well as the 3 point fit values, the defects, and the slopes for offset, gain, and noise for each chip.
- **The equivalent noise charge (ENC):** Measured by converting noise in fC to electrons. The conversion is done by multiplying the noise by the number of electrons in 1 fC.
- **Response Curve:** This test extends the three point gain test to 10 scan points where the injected charge is varied over a larger range to 0.5, 0.75, 1.0, 1.25, 1.5, 2, 3, 4, 6, and 8 fC points.This test is also known as a 10-Point Gain scan. It gives a precise measurement of gains and offsets with which to update the configuration. This test is crucial for the long term stability and performance of the SCT as with irradiation, the characteristics of the modules are expected to change.
- **TrimRange**: The main aim of trimming is to minimize the variations in the optimal 1 fC threshold setting for physics running so that the efficiency for all channels is the same. This test is also crucial for the long-term stability and performance of the SCT as the channel-to-channel variations will increase with irradiation and stable operation of the SCT will require the chips to be set in higher trim ranges. The trim range scan injects a charge of 1 fC for all events and does threshold scans for different trim DAC settings. Usually, it is performed after a 3-point gain scan has checked that charge injection works and before a 10-point gain scan which sets the threshold for 1 fC.
- **Noise Occupancy**:This test measures the noise occupancy as a function of threshold. As the threshold is increased, the occupancy of noise hits decrease

FASER Trigger/DAQ Overview