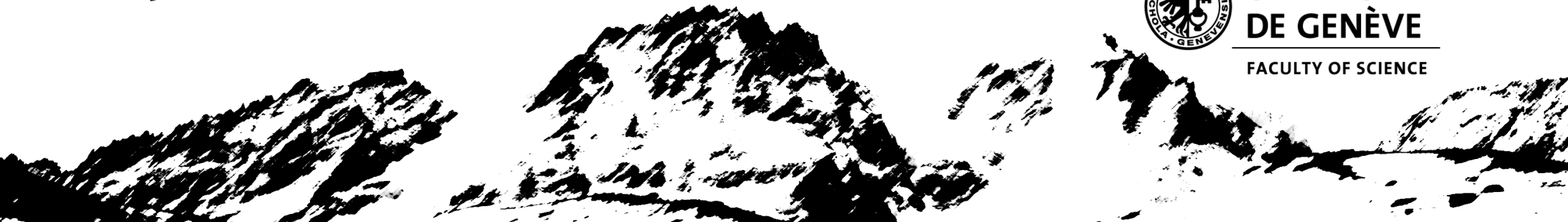
# Looking forward to new physics: The FASER experiment at the CERN LHC

## From searches for weakly interacting particles to first measurements of collider neutrinos

La Thuile Conference
9-11 March 2021

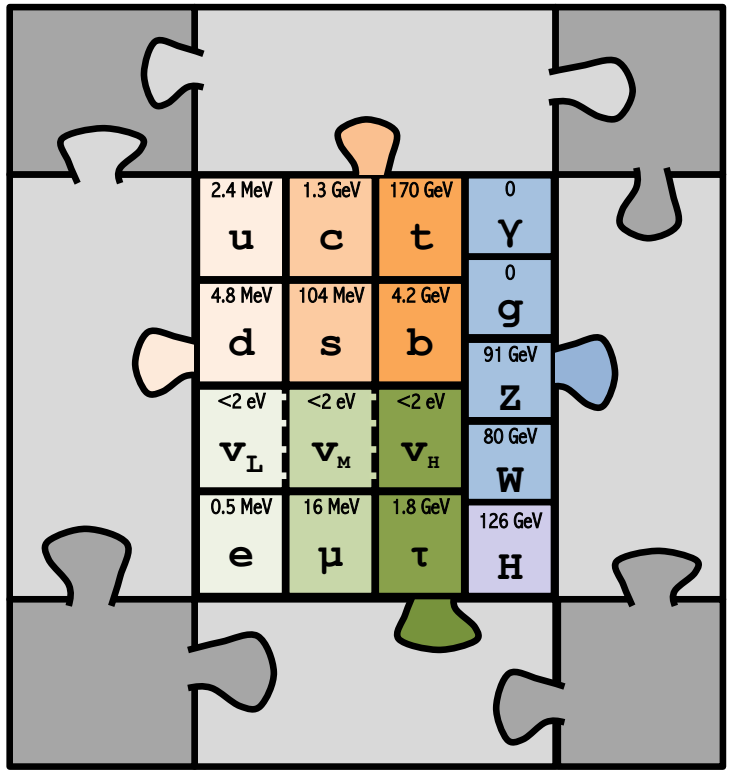
Anna Sfyrla
UNIVERSITÉ DE GENÈVE
FACULTY OF SCIENCE

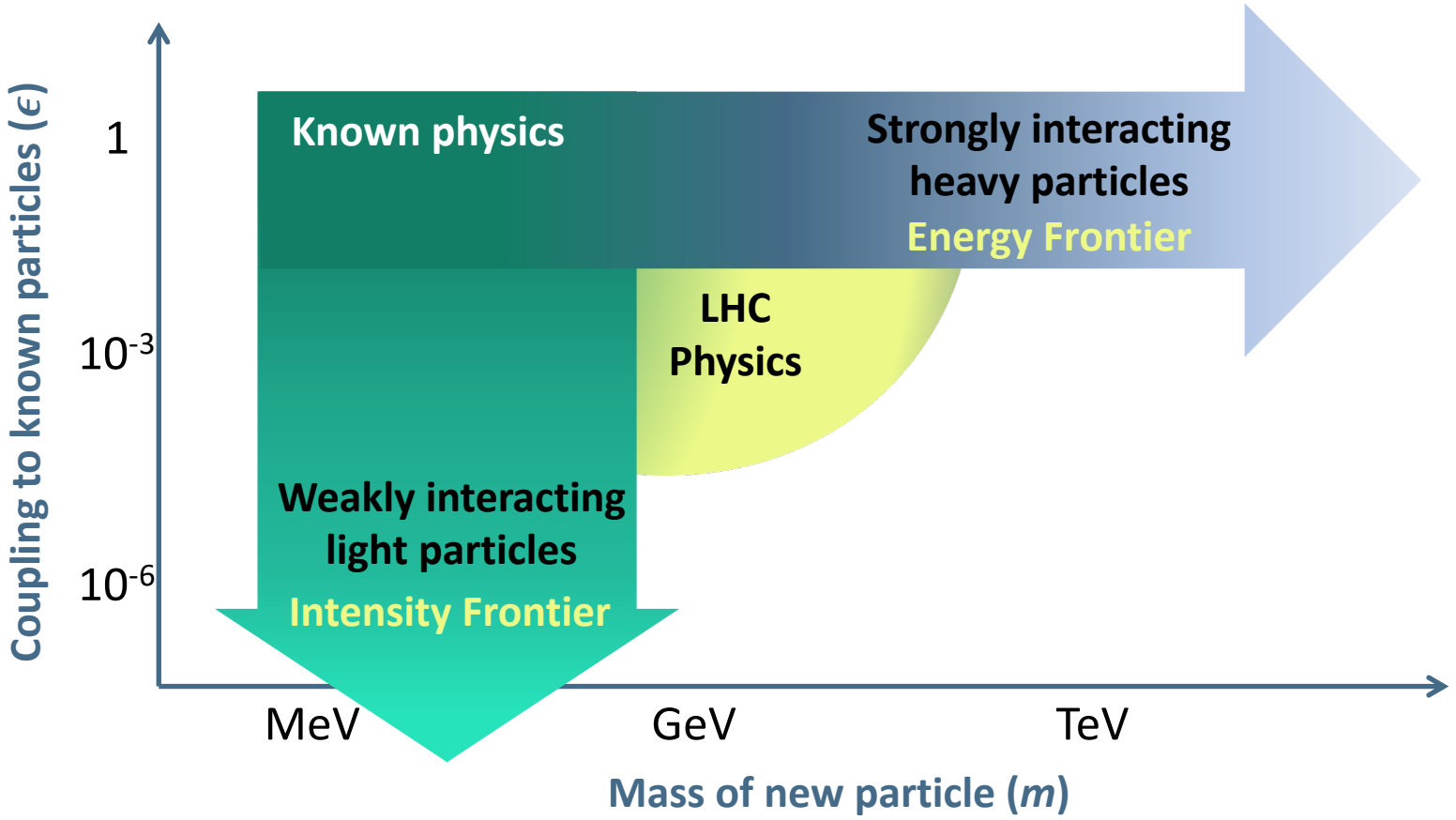


# The landscape of new particles @ colliders

# The landscape of new particles @ colliders

- Collider physics: a plethora of measurements and searches
- The Standard Model is complete and confirmed; Burning questions still remain!



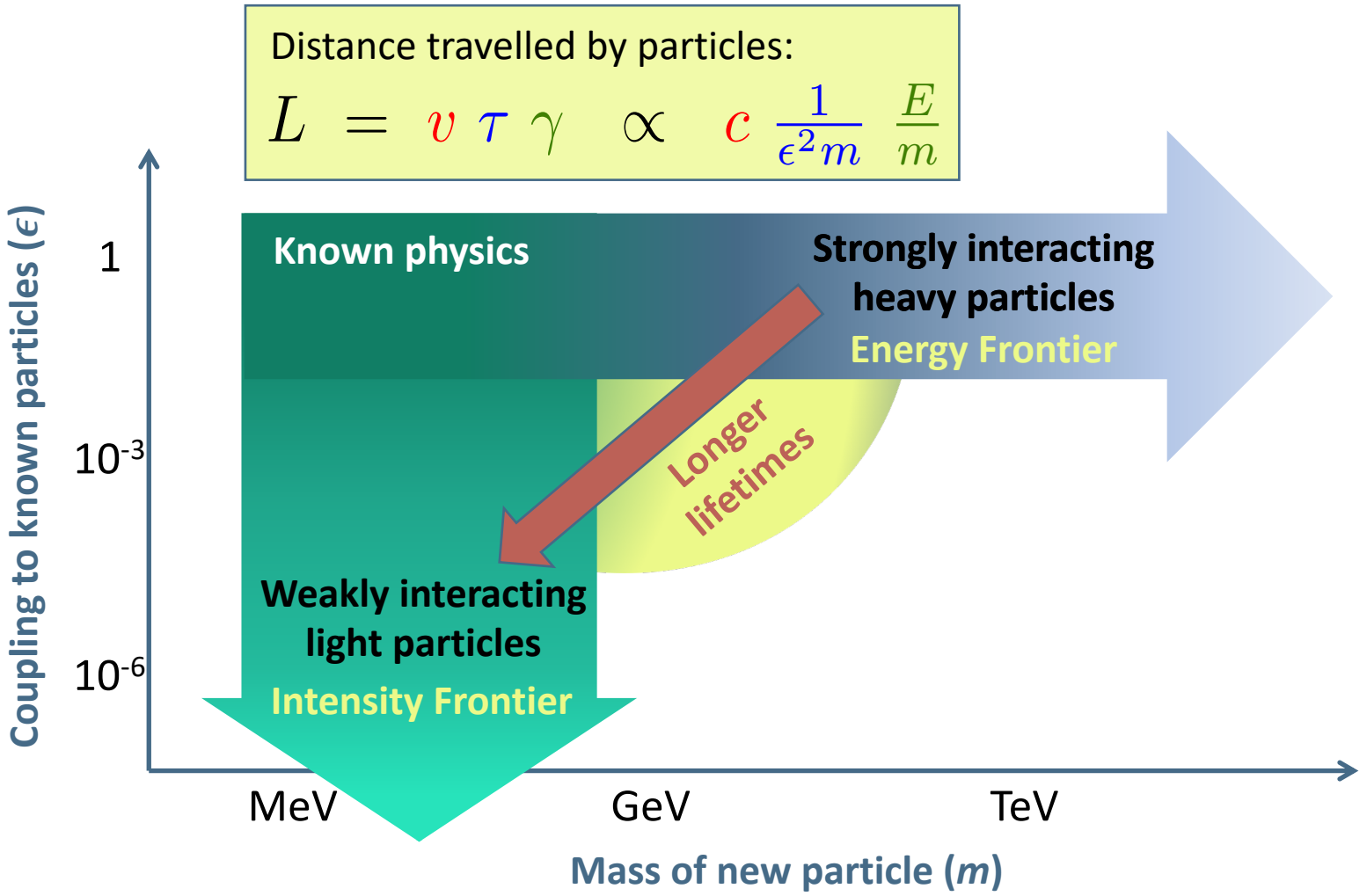



# The landscape of new particles @ colliders

**Lifetime**
a characteristic of weakly interacting light particles

Distinct signatures

**Opportunity for exploration!**



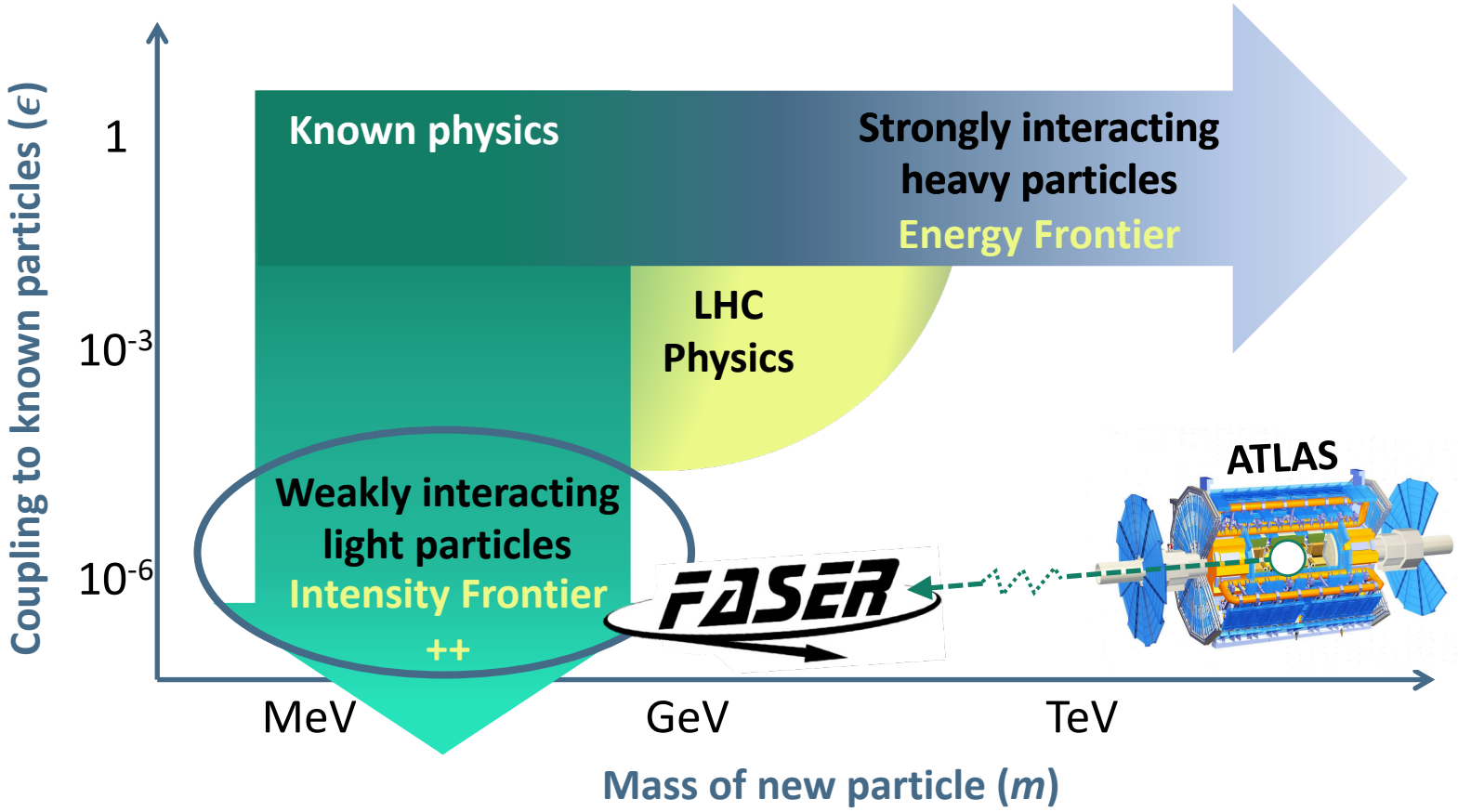

Feng, Galon, Kling, Trojanowski - Phys. Rev. D 97, 035001 (2018)

# The FASER experiment

**Searches for new weakly-interacting light particles**

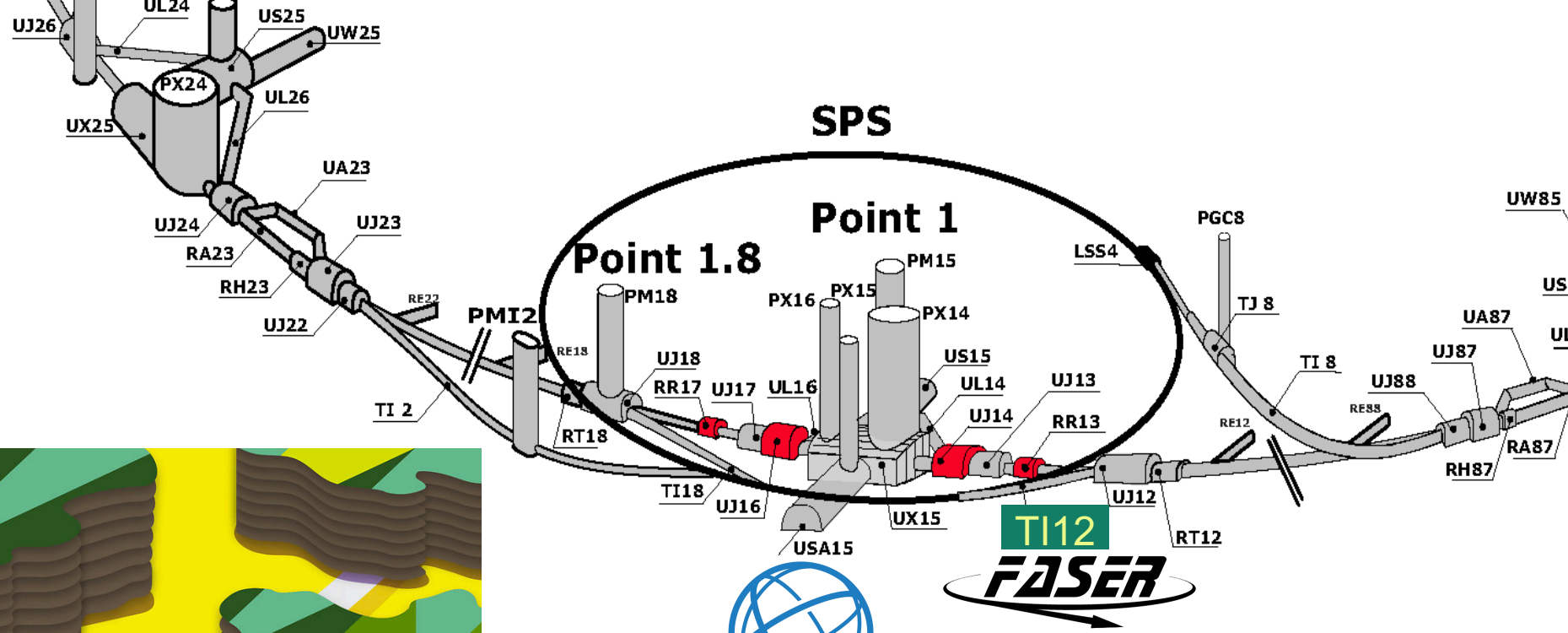
New particles produced in decays of light mesons (e.g. π, K), copiously present at zero angle, escaping detection in ATLAS/CMS

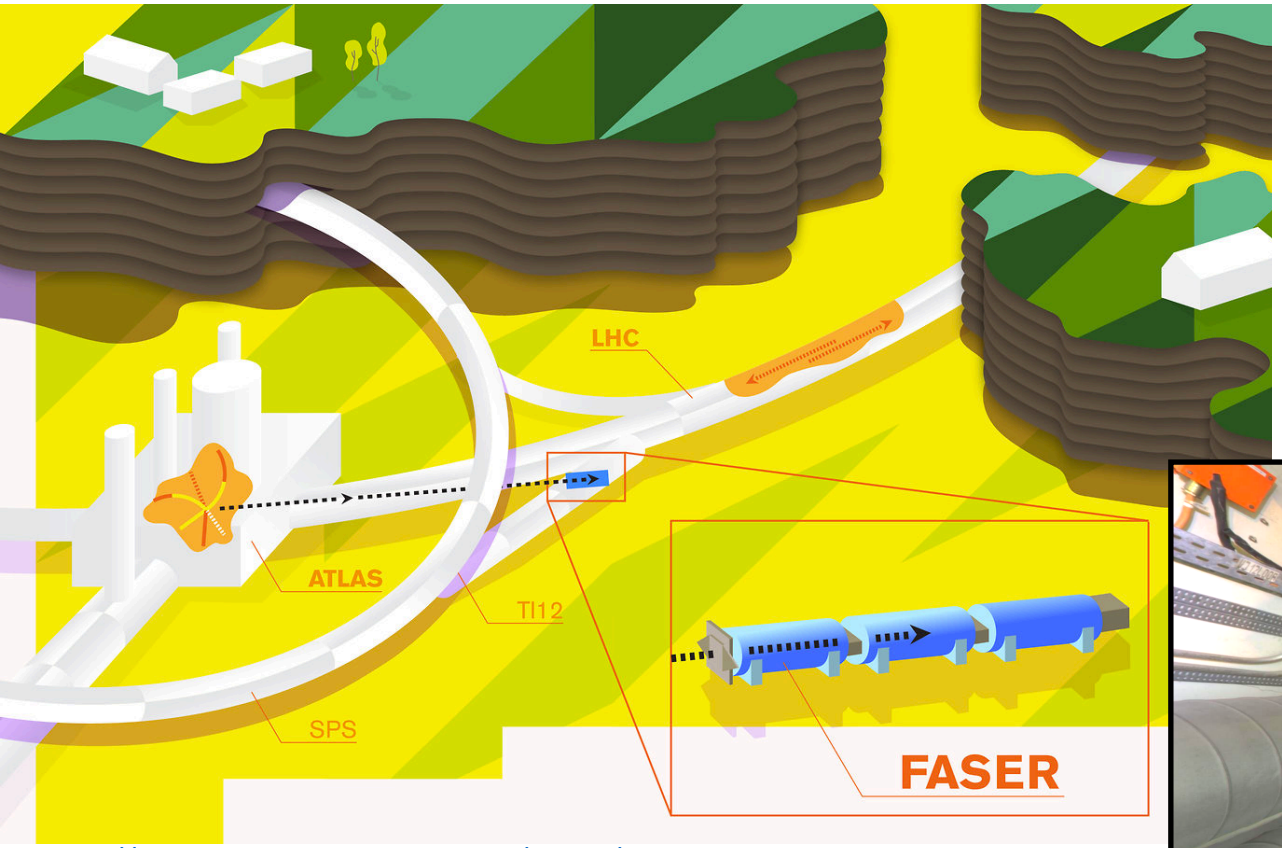
2x10$^{-6}$% solid angle but still O(10$^{16}$) π per year!




Feng, Galon, Kling, Trojanowski - Phys. Rev. D 97, 035001 (2018)

# The  experiment



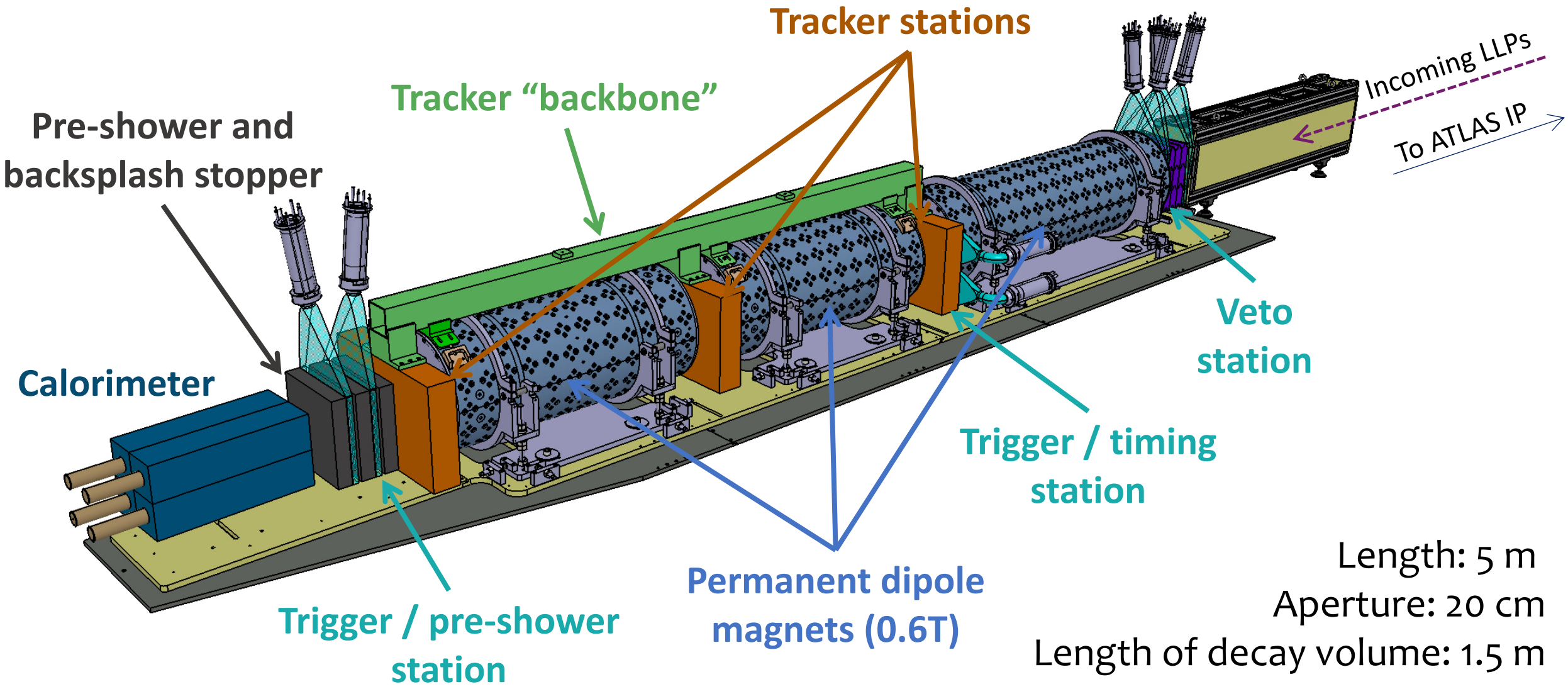




ATLAS EXPERIMENT



https://www.symmetrymagazine.org/article/a-tiny-new-experiment-at-the-lhc

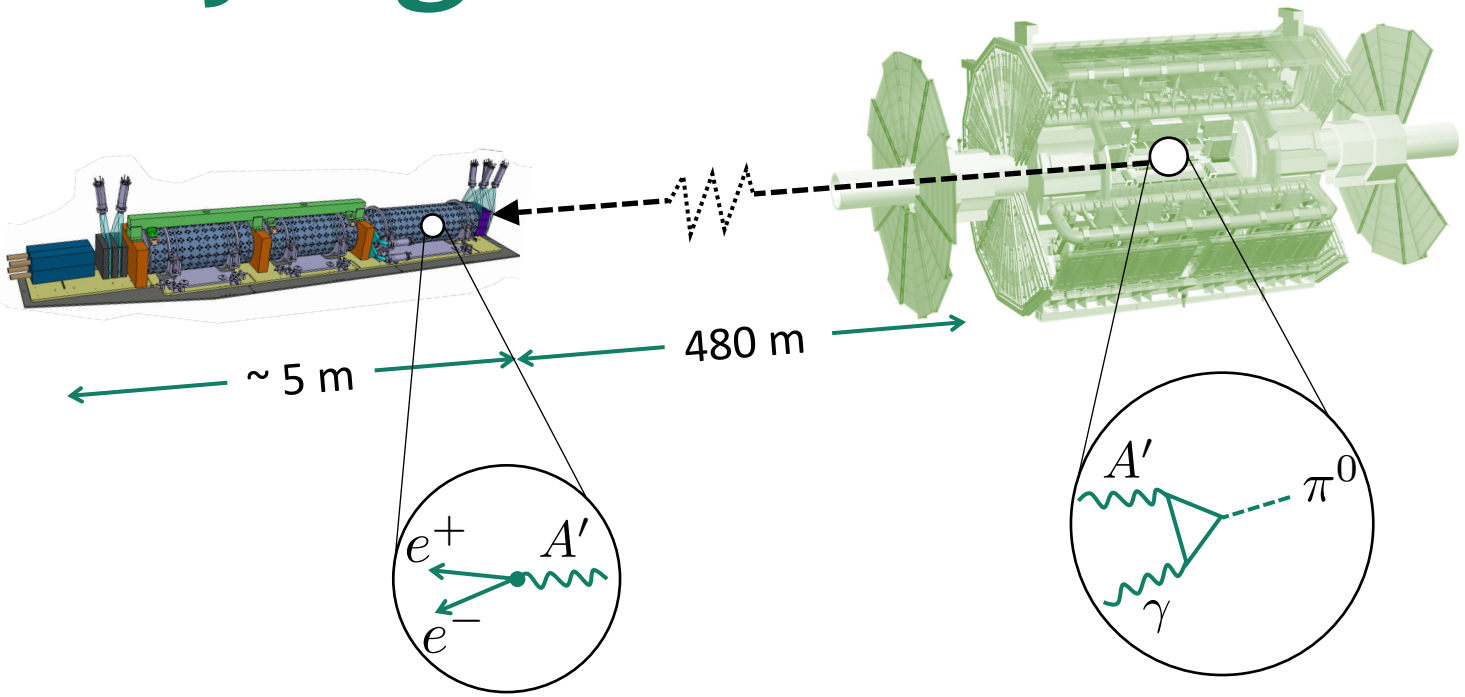
# FASER Detector

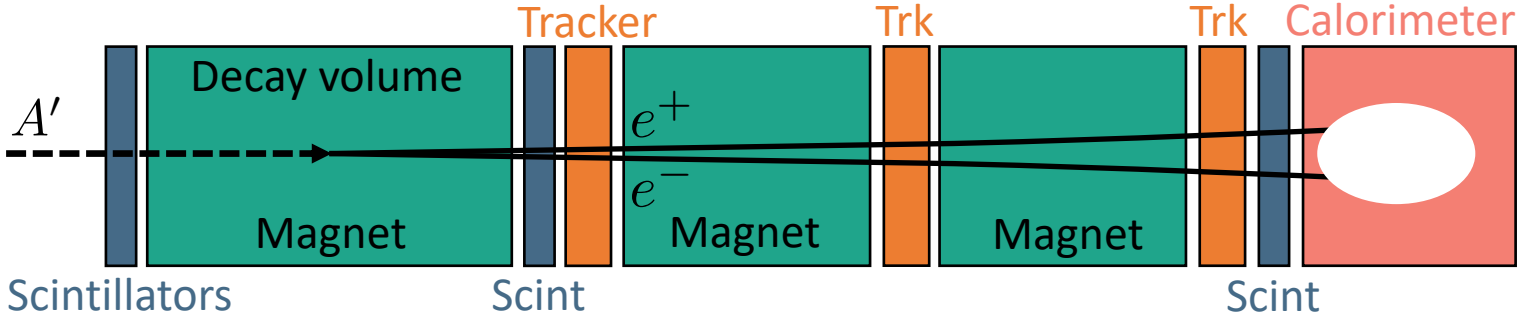



Length: 5 m
Aperture: 20 cm
Length of decay volume: 1.5 m

# Key signatures

## Dark photon ($A'$)



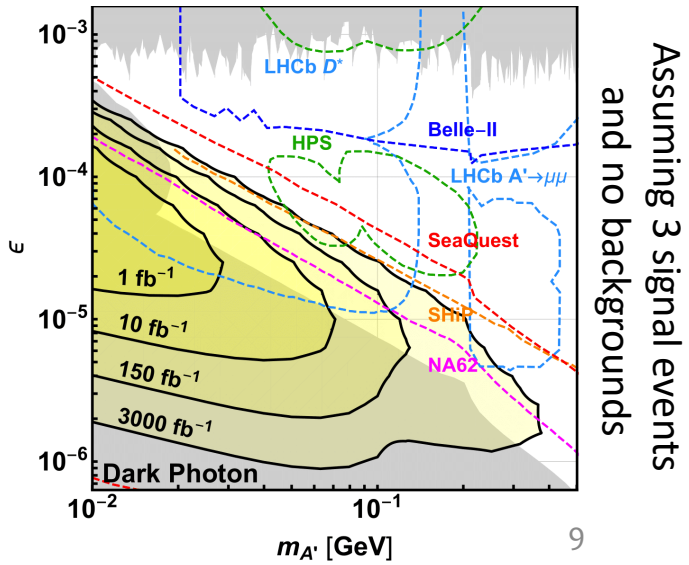




Ballpark numbers for *A'*:

- Momentum of 1 TeV
- Mass of 100 MeV

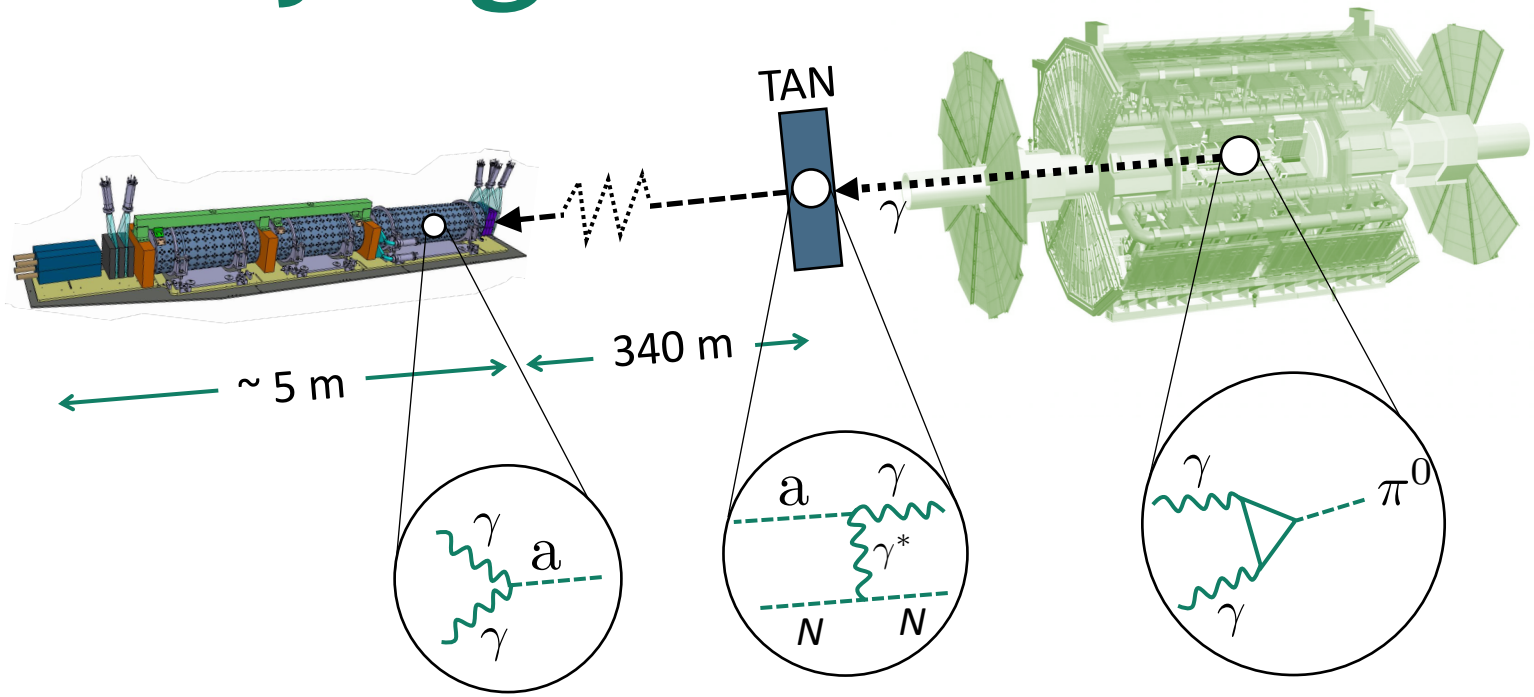
Decay products collimated

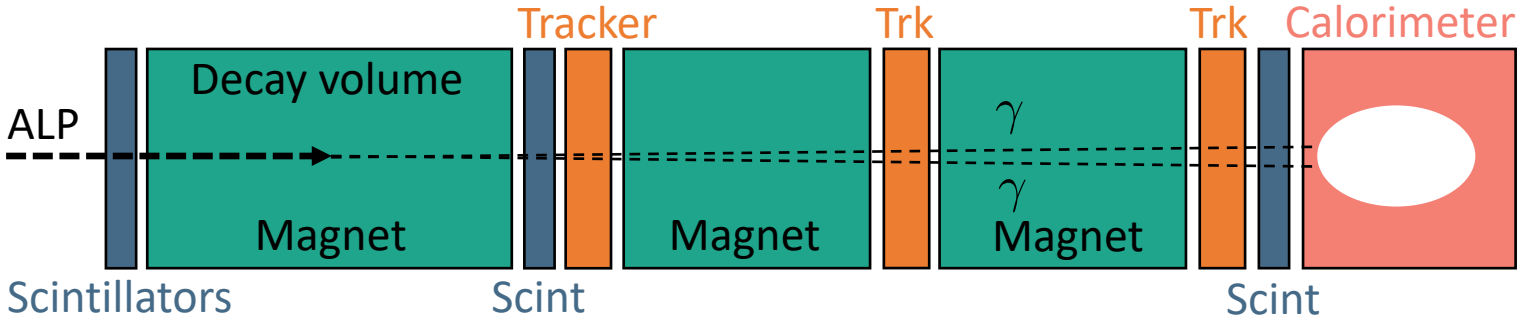
requirements for magnetic field & high resolution tracker



# Key signatures

## Axion-like particle (ALP, a)



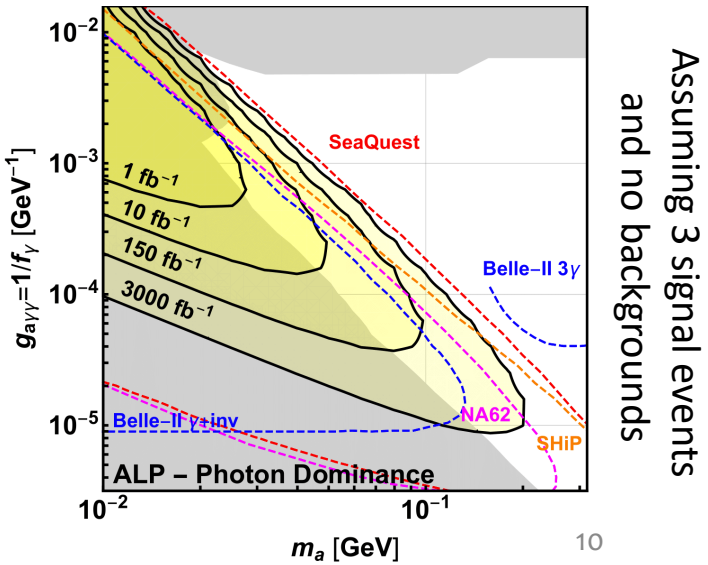




Ballpark numbers for ALPs:

- Momentum of 1 TeV
- Mass of 100 MeV

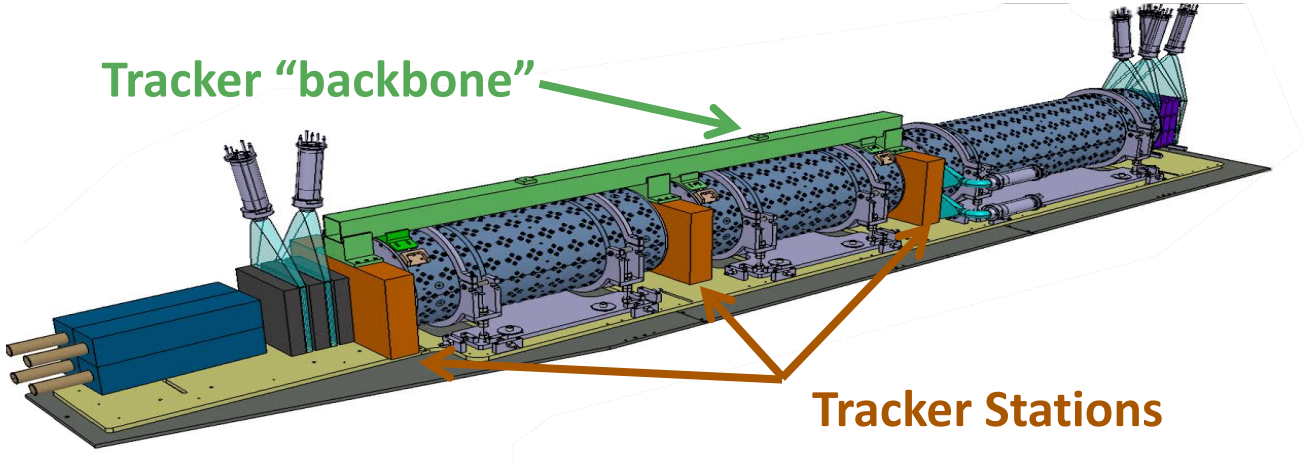
Decay products collimated

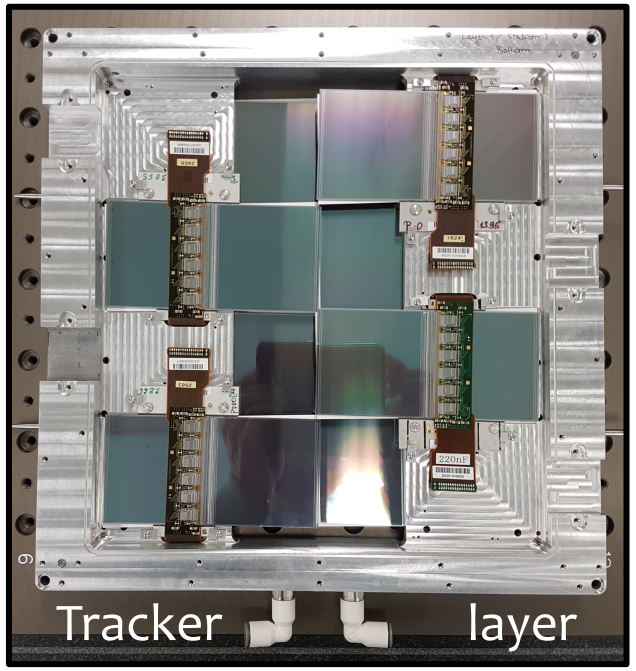
2-γ signature can't be resolved with present detector: upgrade

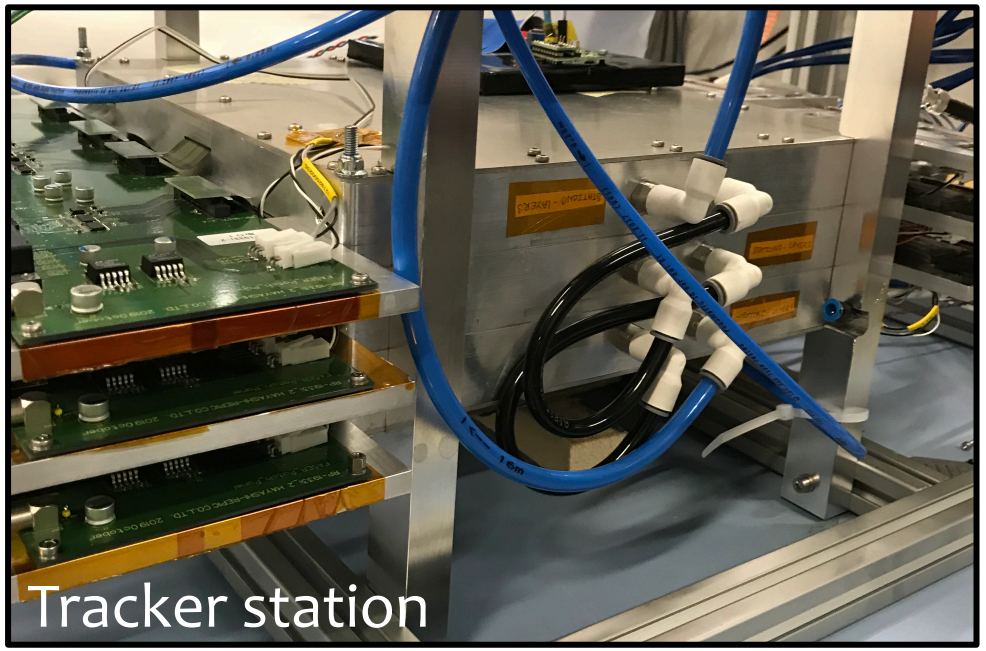


# Tracker

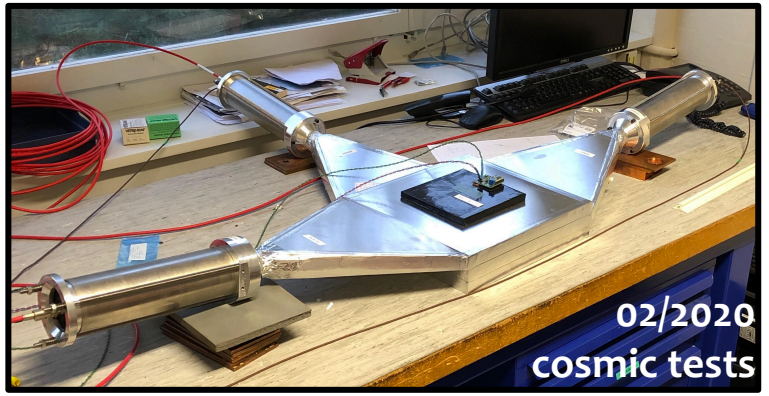
- FASER uses ATLAS SCT spare modules THANKS!
- 3 tracker stations x 3 tracker layers x 8 modules
  - 72 modules and O($10^5$) channels in total
- Mechanical stability by “backbone” fixed on magnets
- Water cooling at 15° for on-board electronics
- Read out with custom GPIO board



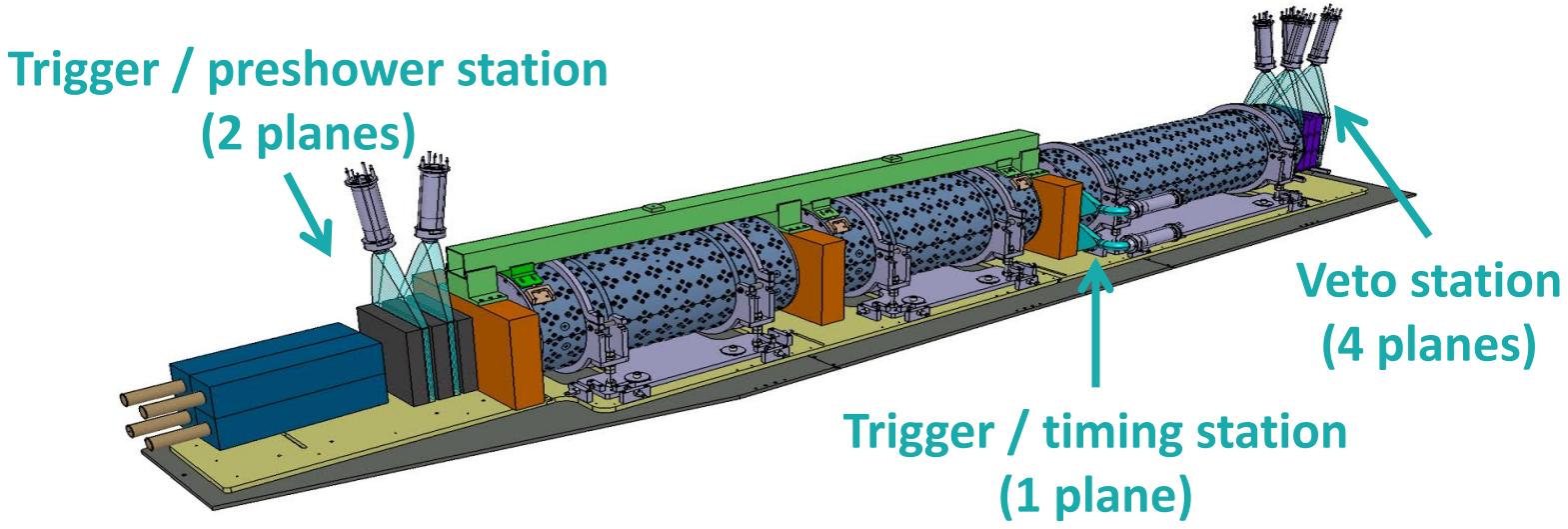



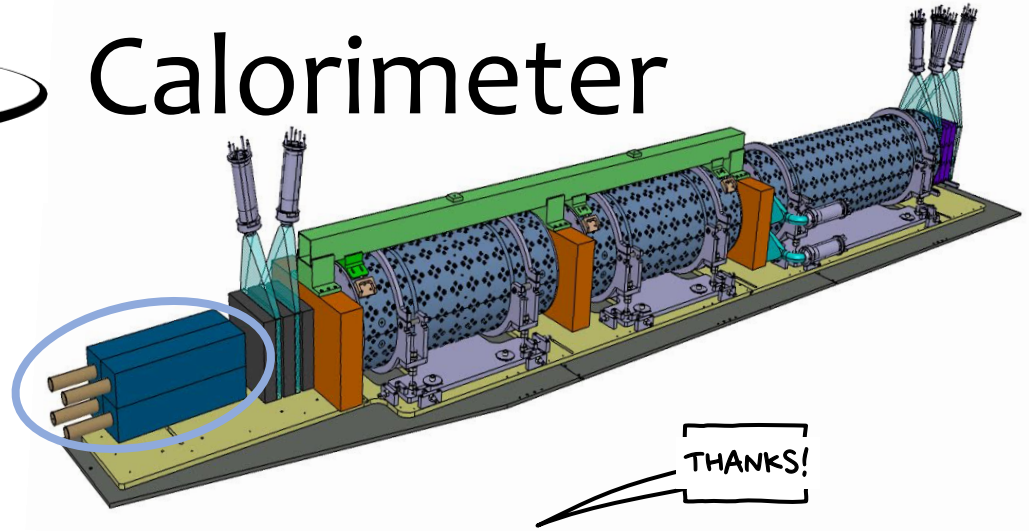
# Scintillators




- Three stations all providing triggering capability:
  - Very high efficiency veto station for incoming charged particles ($10^8$ muons in Run3)
    - Efficiency/scintillator measured with cosmics: > 0.999
  - Timing station; precise timing (~ ns) wrt IP
  - Preshower station; coincidence with timing station
- Read out with PMTs and CAEN digitizer

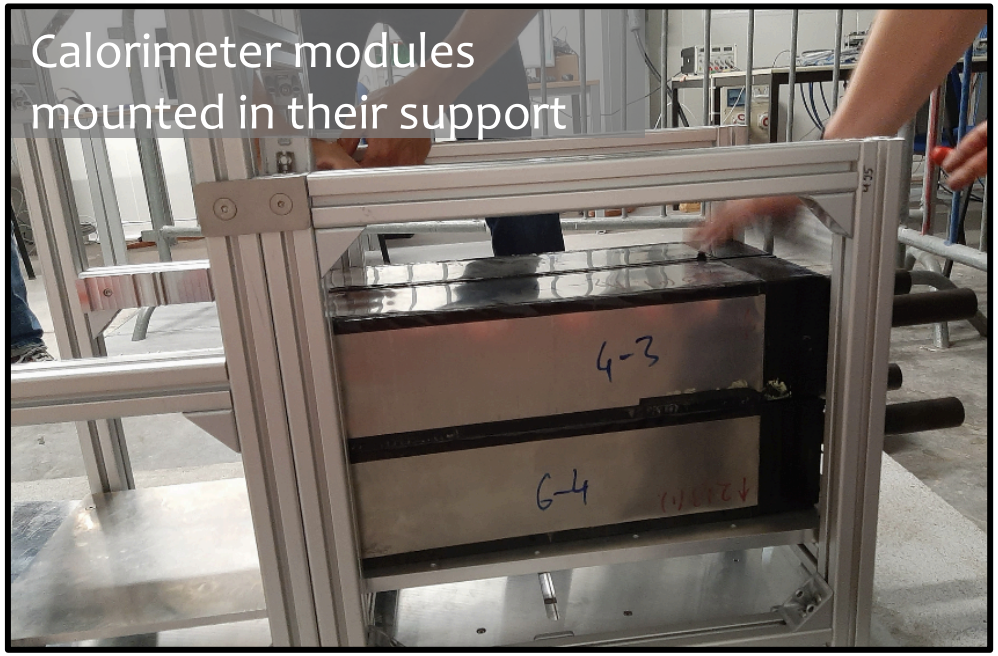



# Calorimeter




A calorimeter module

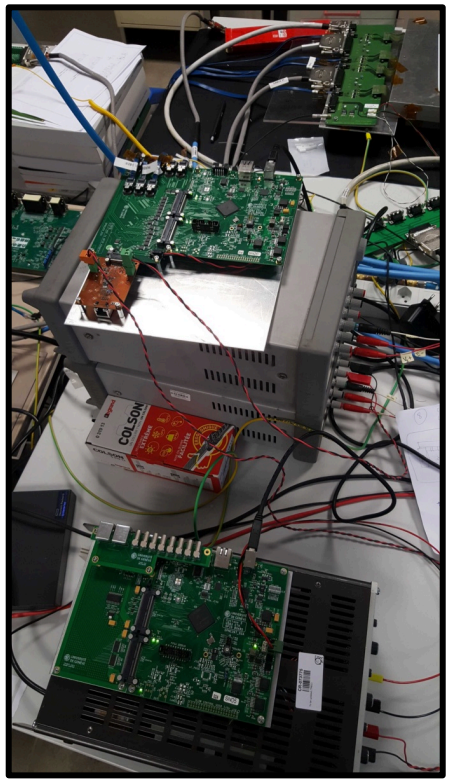
- FASER uses 4 LHCb spare outer ECAL modules
  - 25 radiation lengths long
  - 12x12cm$^2$ in transverse plane x 4 channels
  - Lead/scintillator calorimeter
- Energy resolution ~ 1% for TeV deposits
  - No longitudinal shower information
- Provides triggering capability
- Read out with PMTs and CAEN digitizer



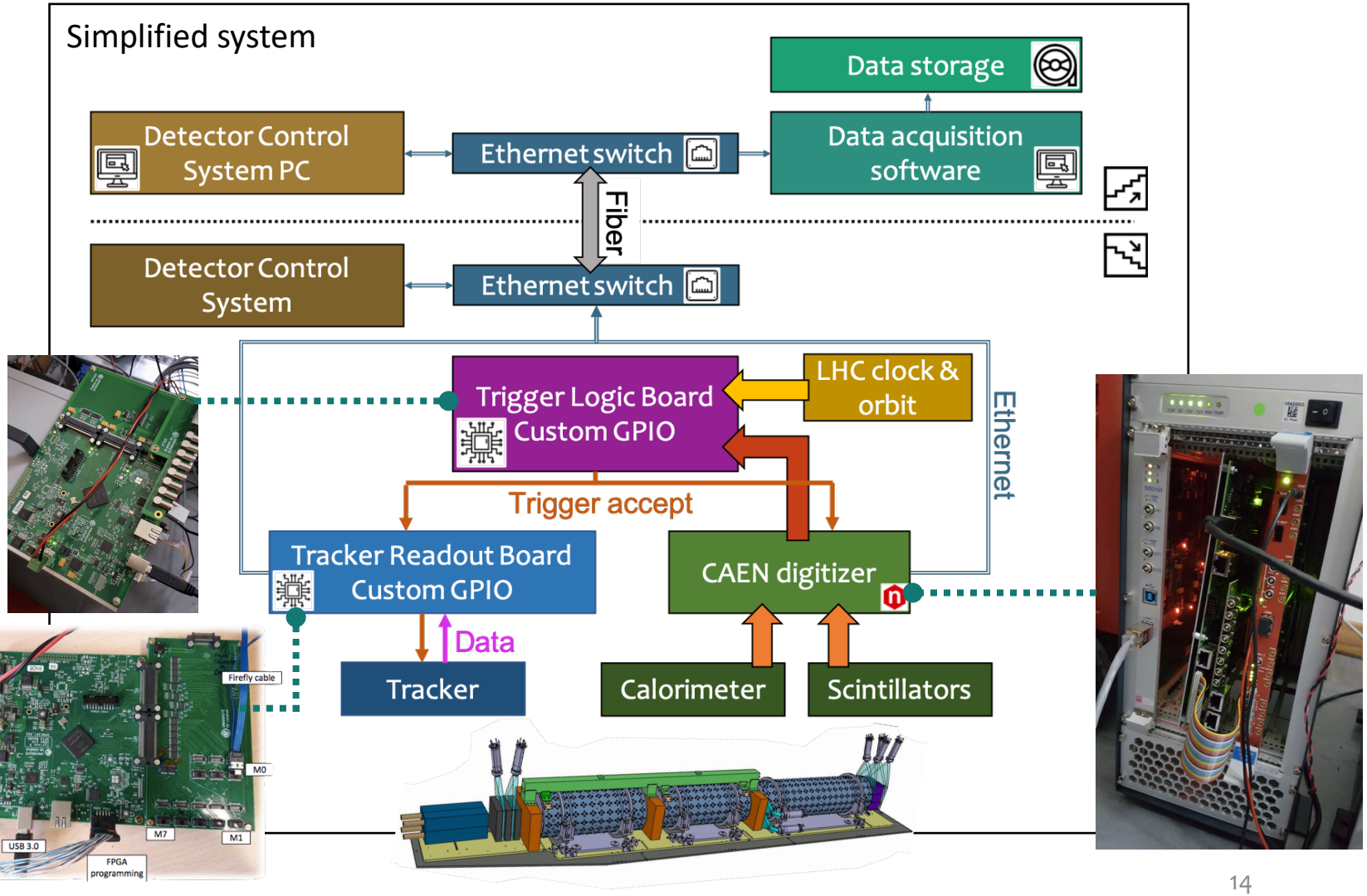
Calorimeter modules mounted in their support

# Trigger & Data acquisition

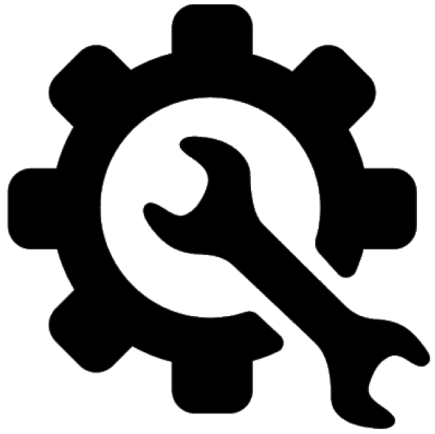
- Expected **trigger rate** about **500 Hz,** dominated by muons from the IP



All boards connected together for tests




experiment



construction and commissioning

# Commissioning

- Dedicated labs available at CERN for individual component testing
- Dedicated area at CERN's Prevessin site ("EHN1") for full-detector commissioning

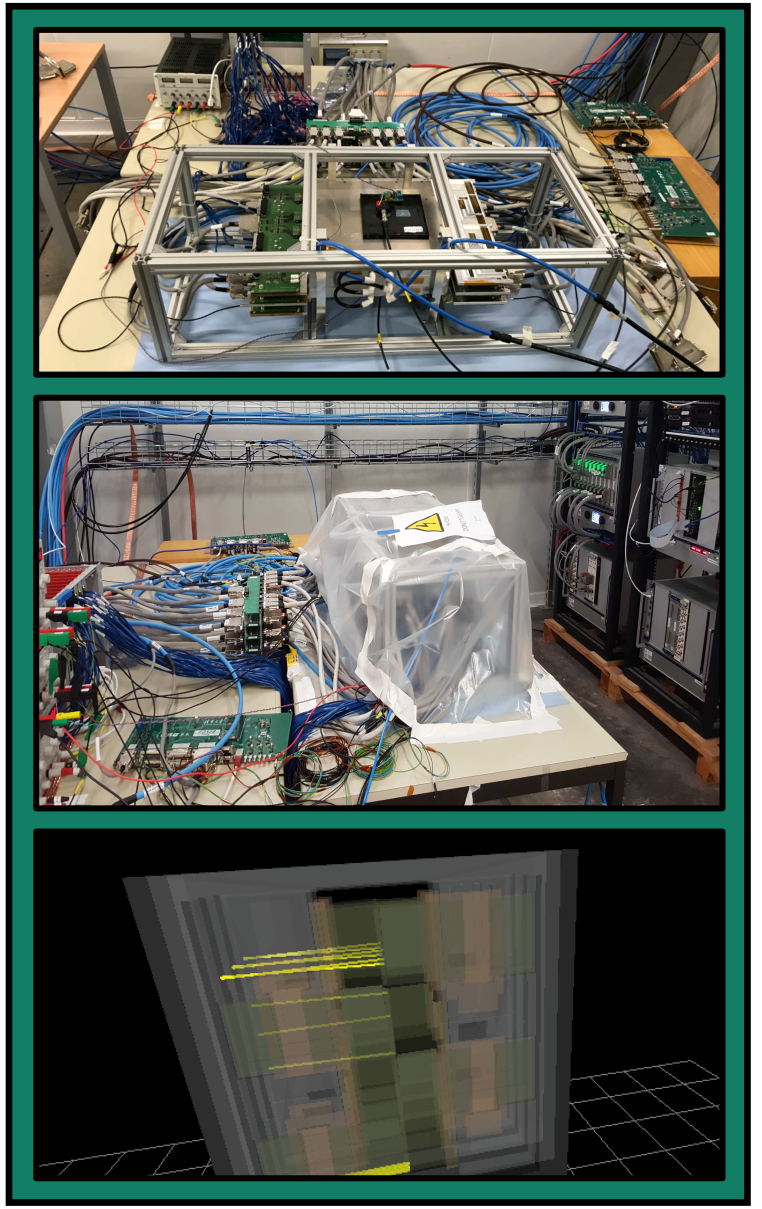
| Milestone | Where | When |
|---|---|---|
| Individual component commissioning | CERN labs | July 2020 |
| Detector commissioning | EHN1 | Sept 2020 |
| Installation of magnets | EHN1 | Sept 2020 |
| Surface commissioning – part 1 | EHN1 | Oct 2020 |
| Detector installation – part 1 | TI12 | Nov 2020 |
| Surface commissioning – part 2 | EHN1 | Feb 2021 |
| Detector installation – part 2 | TI12 | March 2021 |
| In-situ dry commissioning | TI12 | During 2021 |

# Commissioning

- Dedicated labs available at CERN for individual component testing
- Dedicated area at CERN's Prevessin site ("EHN1") for full-detector commissioning

| Milestone | Where | When |
|---|---|---|
| Individual component commissioning | CERN labs | July 2020 |
| Detector commissioning | EHN1 | Sept 2020 |
| Installation of magnets | EHN1 | Sept 2020 |
| Surface commissioning – part 1 | EHN1 | Oct 2020 |
| Detector installation – part 1 | TI12 | Nov 2020 |
| Surface commissioning – part 2 | EHN1 | Feb 2021 |
| Detector installation – part 2 | TI12 | March 2021 |
| In-situ dry commissioning | TI12 | During 2021 |

Cosmic data taking



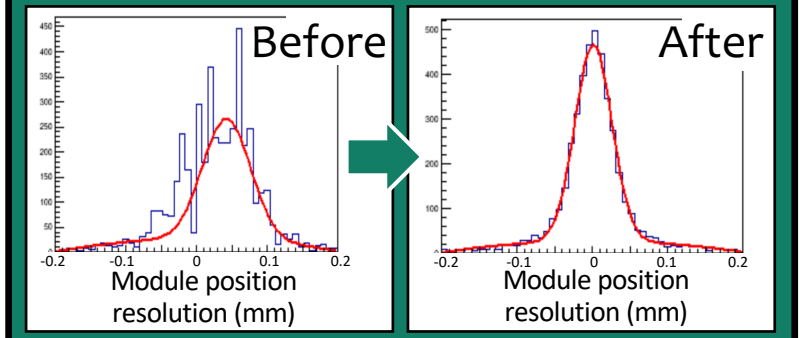
# Commissioning

- Dedicated labs available at CERN for individual component testing
- Dedicated area at CERN's Prevessin site ("EHN1") for full-detector commissioning

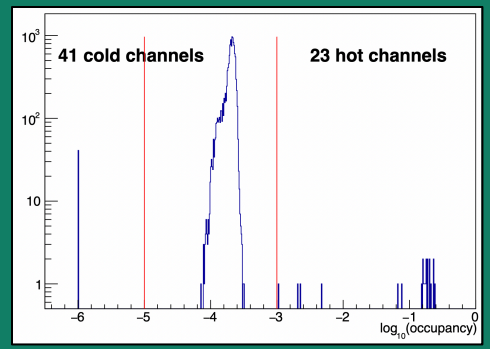
| Milestone | Where | When |
|---|---|---|
| Individual component commissioning | CERN labs | July 2020 |
| Detector commissioning | EHN1 | Sept 2020 |
| Installation of magnets | EHN1 | Sept 2020 |
| Surface commissioning – part 1 | EHN1 | Oct 2020 |
| Detector installation – part 1 | TI12 | Nov 2020 |
| Surface commissioning – part 2 | EHN1 | Feb 2021 |
| Detector installation – part 2 | TI12 | March 2021 |
| In-situ dry commissioning | TI12 | During 2021 |

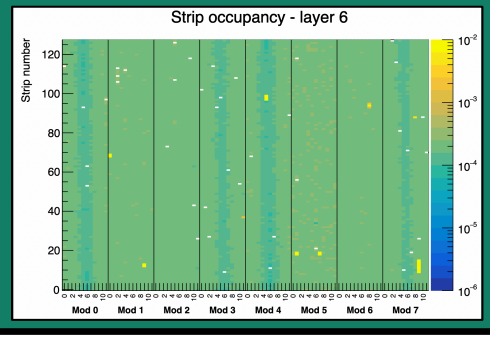
## Cosmic data taking

### First alignment efforts




### Noisy/dead strips in modules

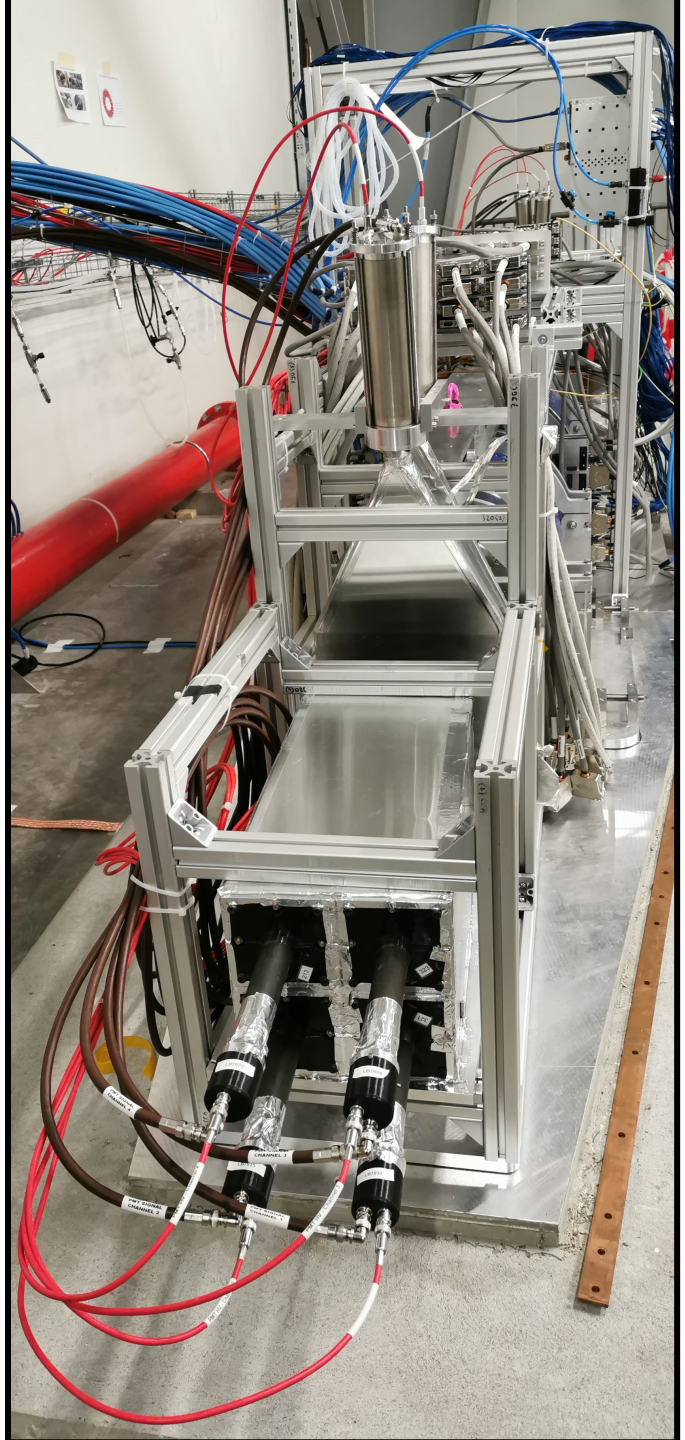


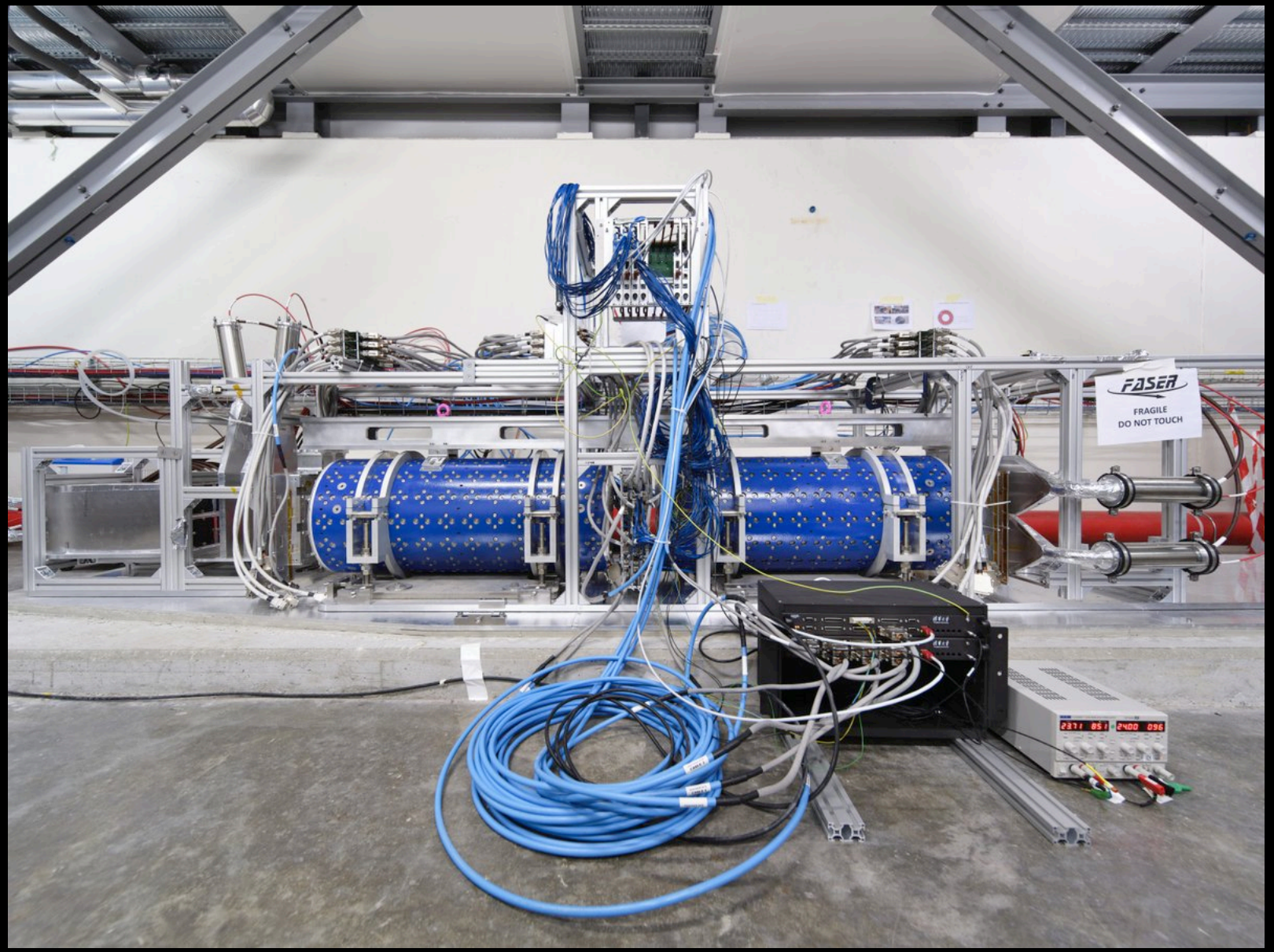



# Commissioning

- Dedicated labs available at CERN for individual component testing
- Dedicated area at CERN's Prevessin site ("EHN1") for full-detector commissioning

| Milestone | Where | When |
|---|---|---|
| Individual component commissioning | CERN labs | July 2020 |
| Detector commissioning | EHN1 | Sept 2020 |
| Installation of magnets | EHN1 | Sept 2020 |
| Surface commissioning – part 1 | EHN1 | Oct 2020 |
| Detector installation – part 1 | TI12 | Nov 2020 |
| Surface commissioning – part 2 | EHN1 | Feb 2021 |
| Detector installation – part 2 | TI12 | March 2021 |
| In-situ dry commissioning | TI12 | During 2021 |




FASER
FRAGILE
DO NOT TOUCH

# Installation to TI12

**First phase complete**


# Installation to TI12


**Second phase in progress**


FASER

# Huge flux of high-energy neutrinos

- Why not exploit FASER to also measure properties of neutrinos at the highest man-made energies ever recorded!

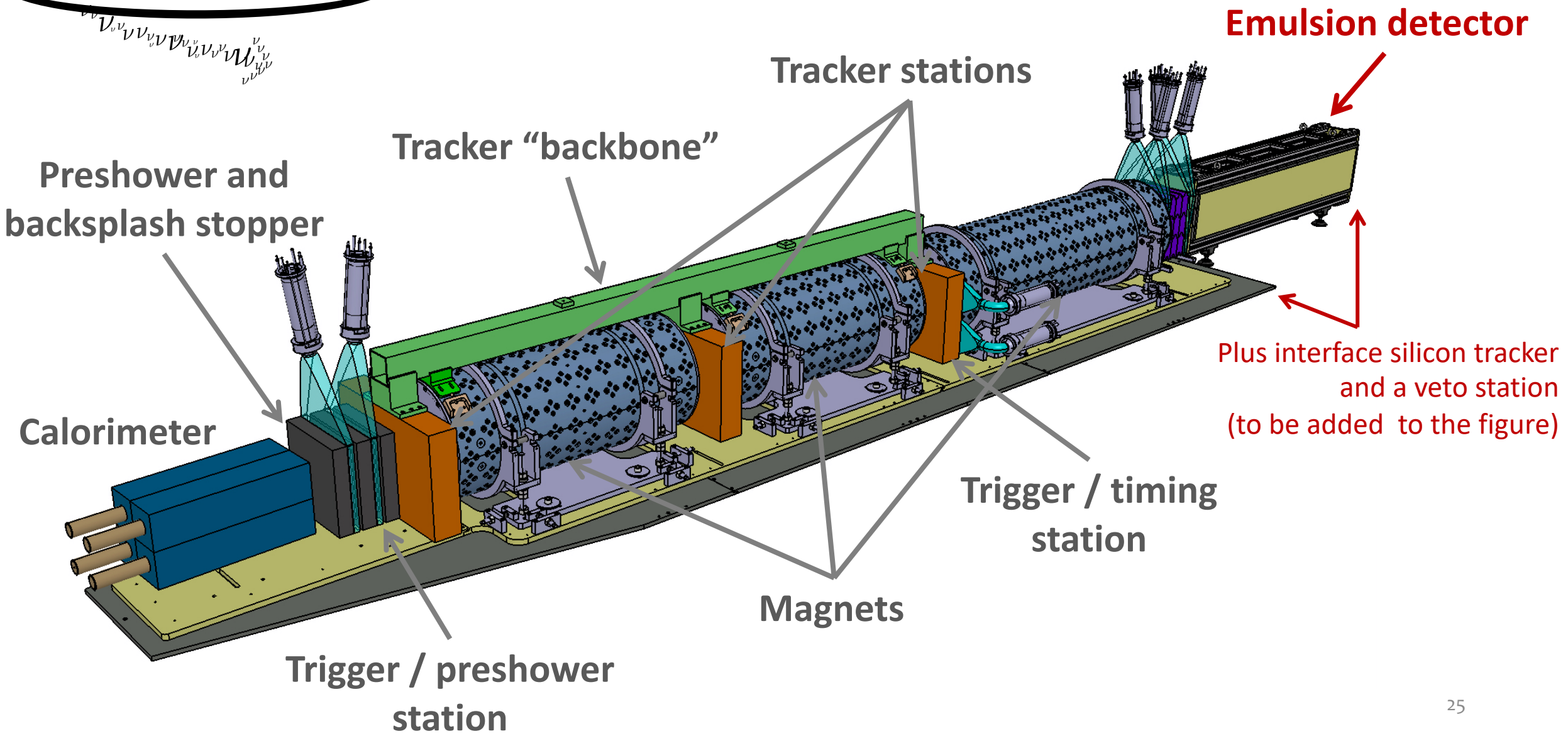
**A bit of history**

**Experiments to study collider neutrinos have been proposed since the 80s, e.g.:**

- A. De Rujula and R. Ruckl, "**Neutrino and muon physics in the collider mode of future accelerators**" ECFA-CERN Workshop on large hadron collider in the LEP tunnel, pp. 571–596, **1984**.
- Klaus Winter, **"Observing tau neutrinos at the LHC"**, LHC workshop, **1990**.

**Other recent concrete experiment proposals include XSEN and SND@LHC.**

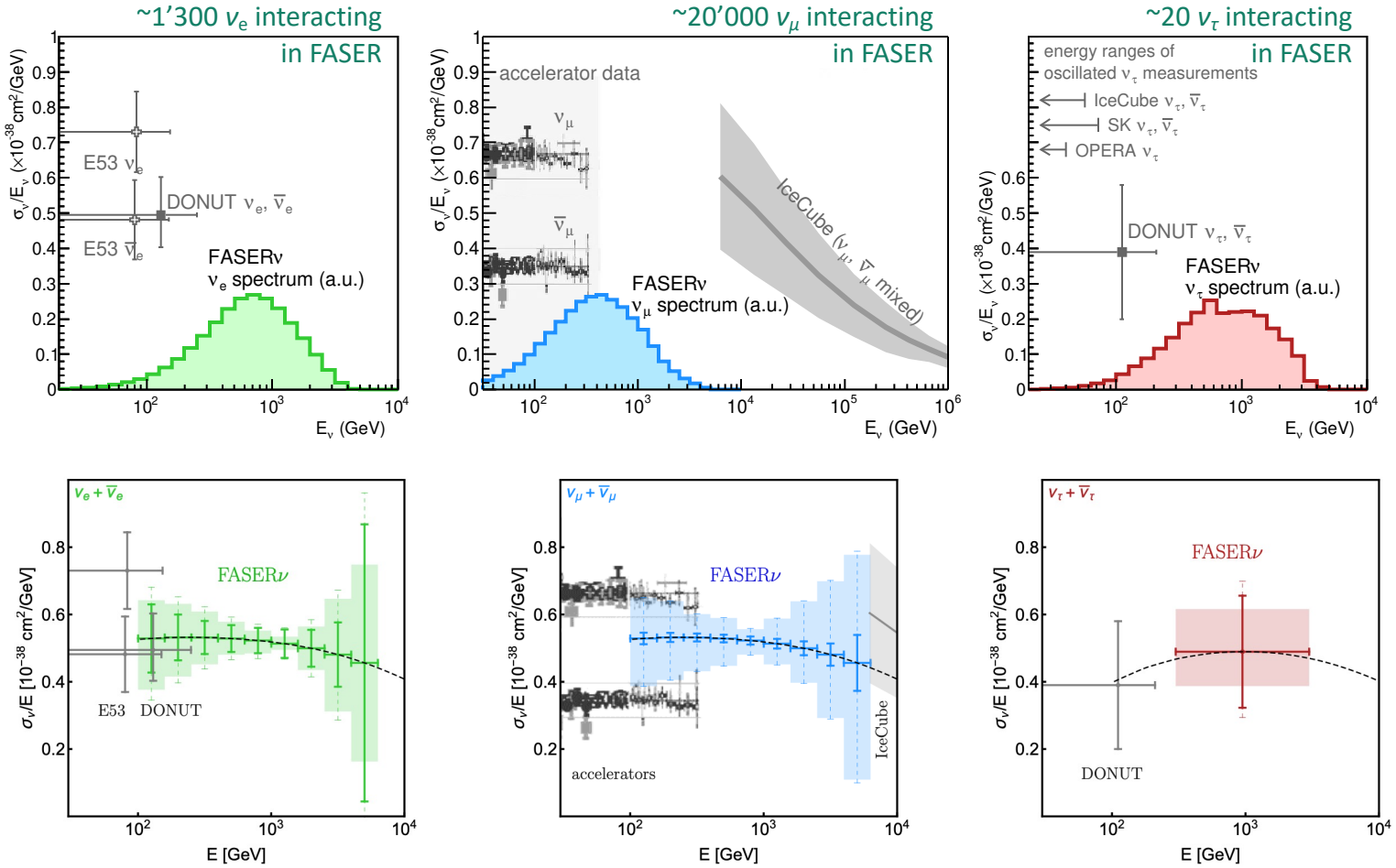
# FASER Detector



# Huge flux of high-energy neutrinos

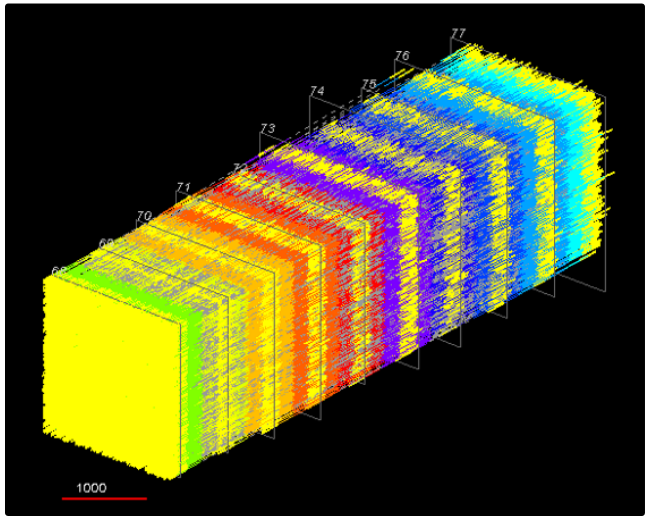
- Why not exploit FASER to also measure properties of neutrinos at the highest man-made energies ever recorded!

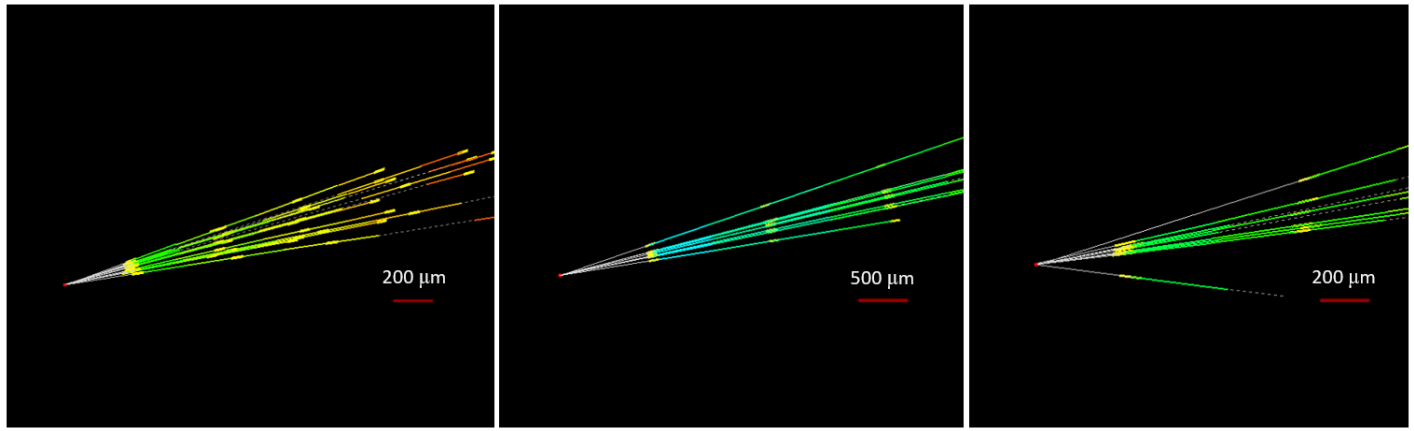
  - Expected spectra: complementary to existing experiments
  - Expected cross section reach: extends current measurements already with 150/fb
  - Uncertainty from neutrino production important
  - Neutrino energy with 30% resolution (simu)



# Pilot run in 2018

- A 30 kg detector at TI18
- Collected ~ 13/fb
- About 7 neutrino interactions expected to have occurred, 2.5 after selections
- Data reconstruction and analysis ongoing
  - a testbed for physics data

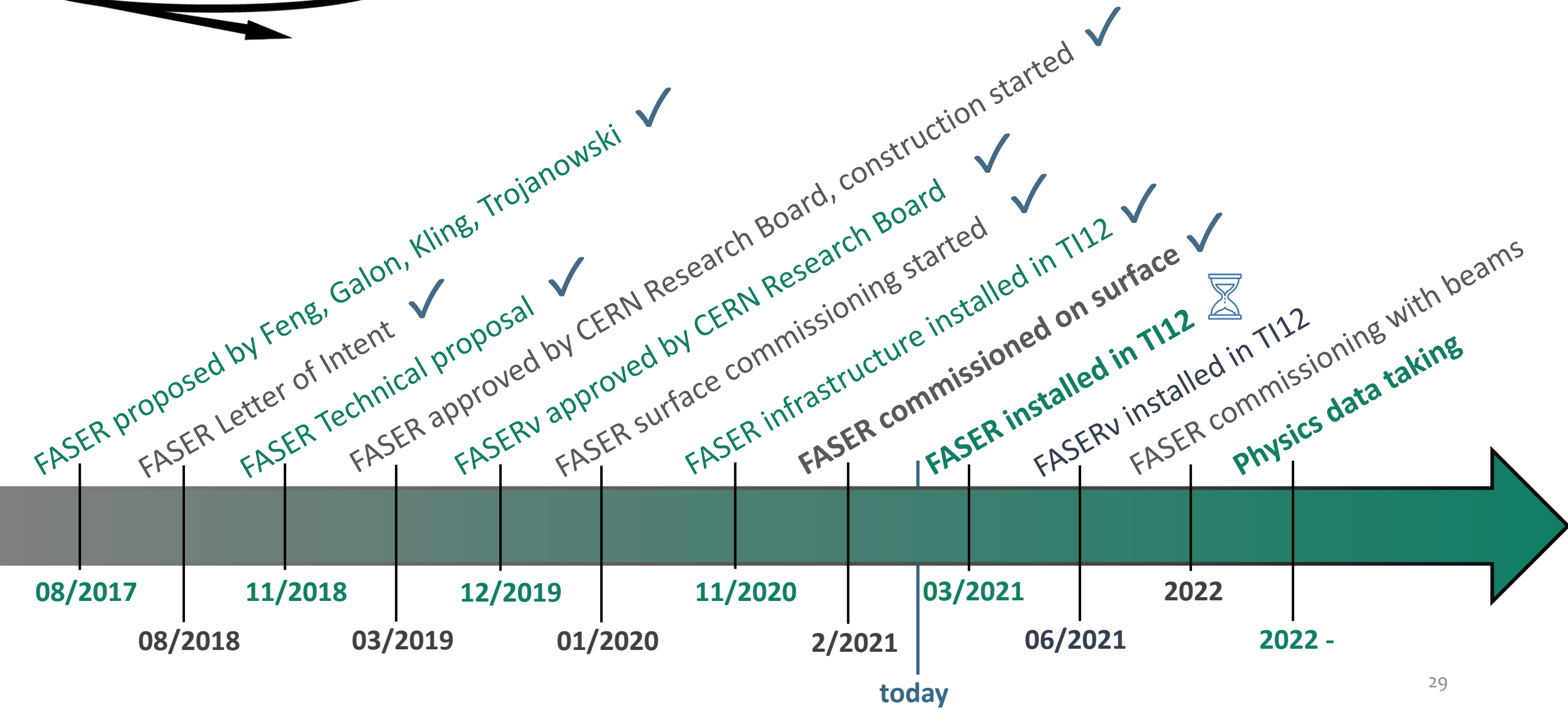




Reconstructed neutral vertices in the prototype dataset

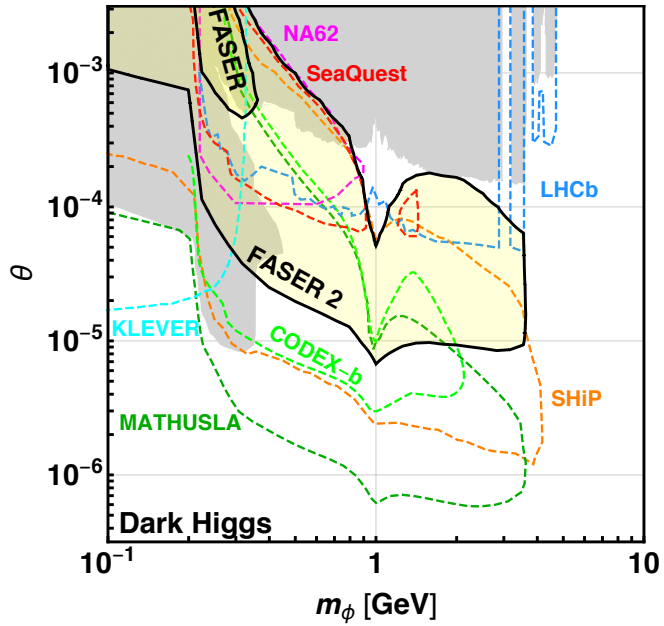

# Timeline

# Global timeline



# Beyond FASER ? FASER2

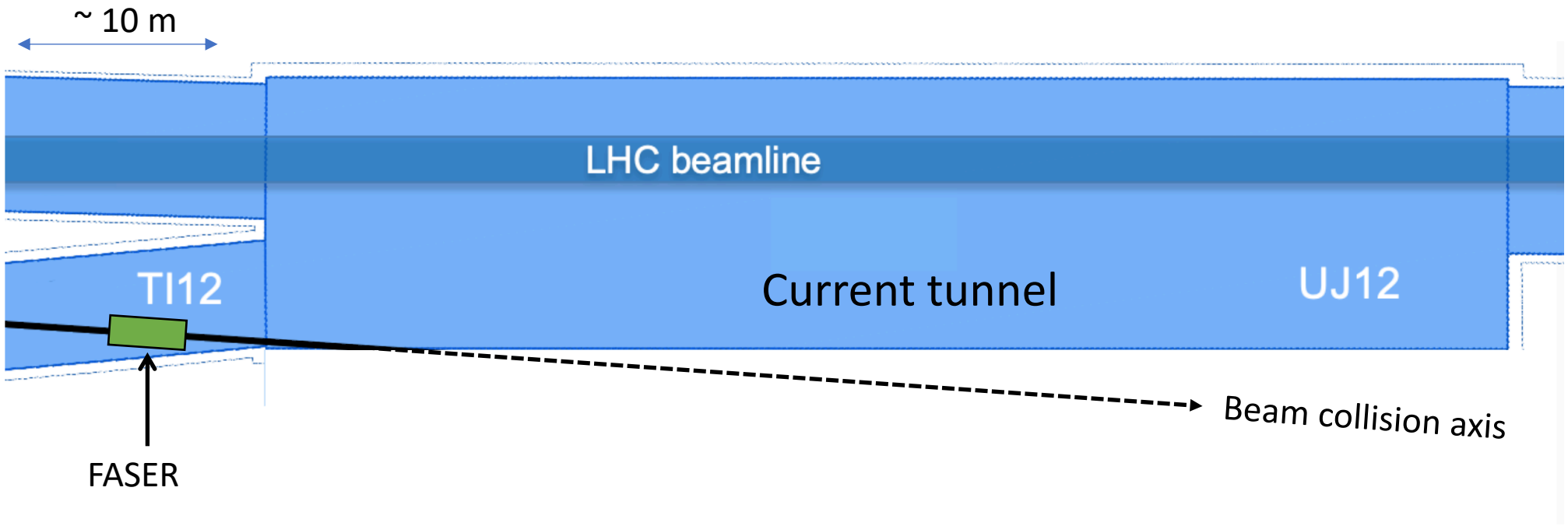
| Benchmark model | Label | Section | PBC | Refs. | FASER | FASER 2 |
|---|---|---|---|---|---|---|
| Dark photons | V1 | IV A | BC1 | [7] | ✓ | ✓ |
| $B-L$ gauge bosons | V2 | IV B | ··· | [30] | ✓ | ✓ |
| $L_i-L_j$ gauge bosons | V3 | IV C | ··· | [30] | ··· | ··· |
| Dark Higgs bosons | S1 | V A | BC4 | [26,27] | ··· | ✓ |
| Dark Higgs bosons with $hSS$ | S2 | V B | BC5 | [26] | ··· | ✓ |
| HNLs with $e$ | F1 | VI | BC6 | [28,29] | ··· | ✓ |
| HNLs with $\mu$ | F2 | VI | BC7 | [28,29] | ··· | ✓ |
| HNLs with $\tau$ | F3 | VI | BC8 | [28,29] | ✓ | ✓ |
| ALPs with photon | A1 | VII A | BC9 | [32] | ✓ | ✓ |
| ALPs with fermion | A2 | VII B | BC10 | ··· | ··· | ✓ |
| ALPs with gluon | A3 | VII C | BC11 | ··· | ✓ | ✓ |
| Dark pseudoscalars | P1 | VIII | ··· | [36] | ··· | ✓ |




- Increased detector radius to 1 m allows sensitivity to particles produced in heavy meson (B, D) decays increasing physics case beyond just increased luminosity

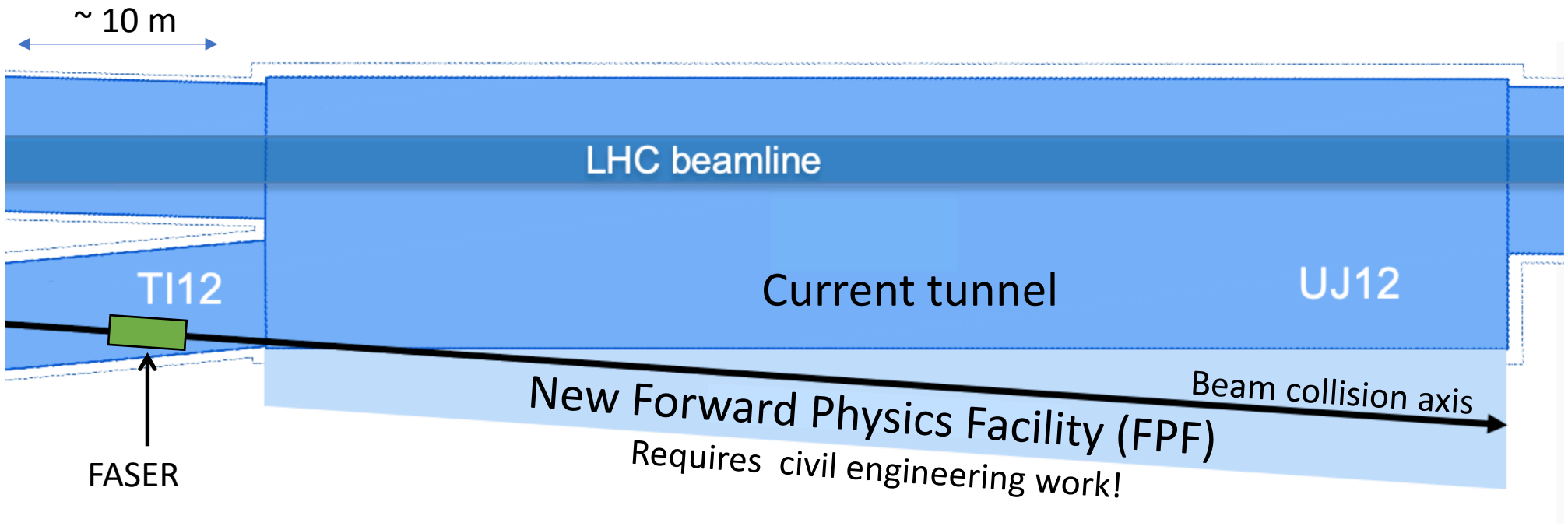
More: https://arxiv.org/abs/1811.12522

# Beyond FASER ? A teaser for the proposed Forward Physics Facility



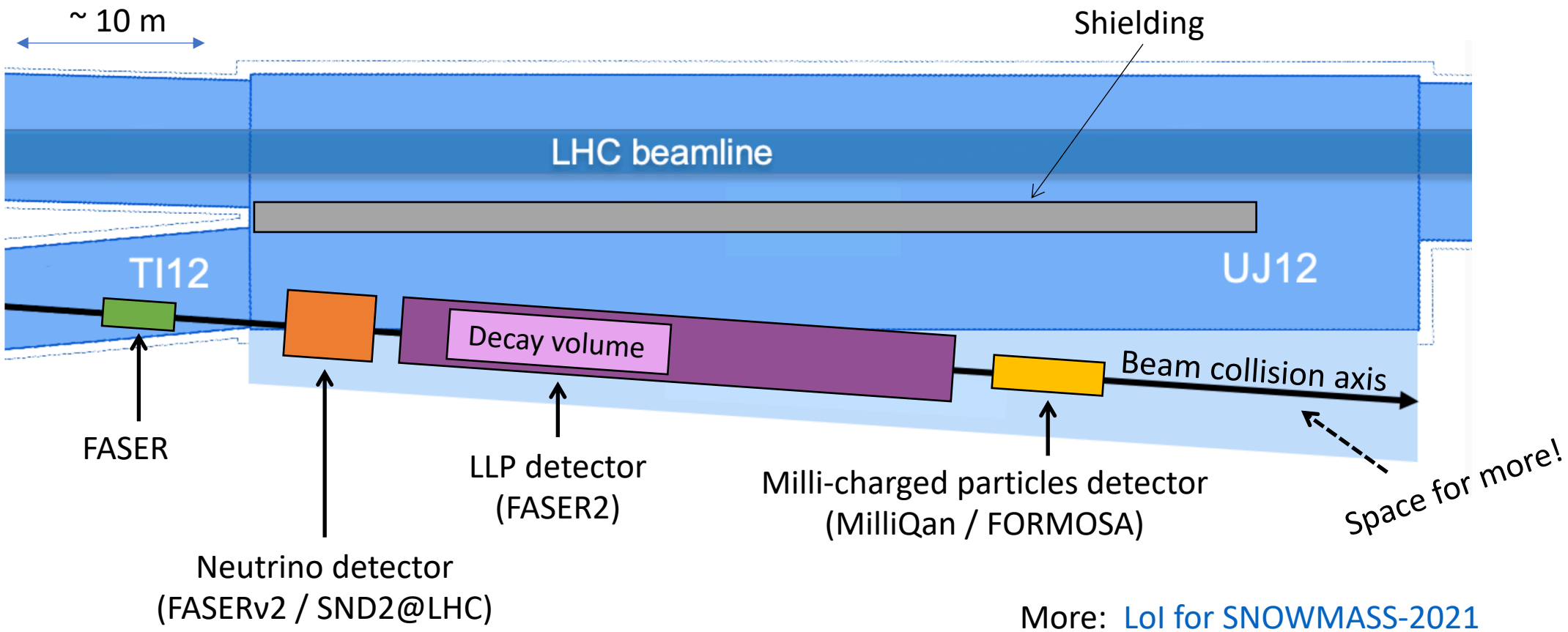

More: LoI for SNOWMASS-2021
FPF – Kickoff workshop

# Beyond FASER ? A teaser for the proposed Forward Physics Facility




More: [LoI for SNOWMASS-2021]
[FPF – Kickoff workshop]

# Beyond FASER ? A teaser for the proposed Forward Physics Facility




More: LoI for SNOWMASS-2021
FPF – Kickoff workshop

# Outlook

- The FASER experiment introduces **a novel approach** to exploit LHC collisions, to:
  - either make **a new discovery** or **constrain parts of phase-space which no current experiment has access to**; and
  - make the first **collider-originated neutrino measurements**
- Collaboration (& CERN technical teams) worked feverishly to construct, commission and install the detector over the current Long Shutdown
- **Goal: get ready for data taking with the start of Run3!**
- Have started planning upgrades, and thinking about FASER2 & a future facility to further exploit forward production in LHC collisions!
- **Lots of exciting physics ahead!**

Stay in touch:

https://faser.web.cern.ch/

@FASERexperiment

# FASER Thanks!

- Many thanks to my collaborators for providing material & great pictures from testing & installation!
- And to the Heising-Simons foundation, Simons foundation and CERN for their financial support

FASER Collaboration: 8 countries, 19 institutes, about 70 members


FNSNF
Swiss National Science Foundation

UNIVERSITÉ DE GENÈVE
FACULTY OF SCIENCE

HEISING-SIMONS FOUNDATION

SIMONS FOUNDATION

CERN

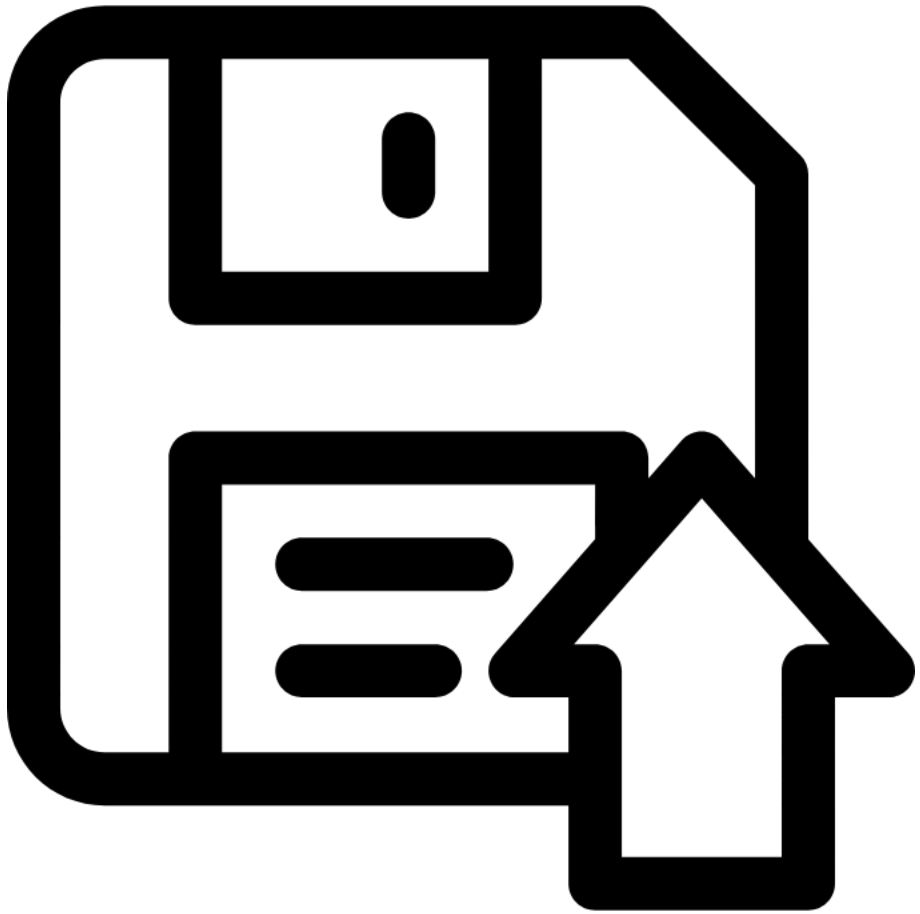
# References

**FASER collaboration:**

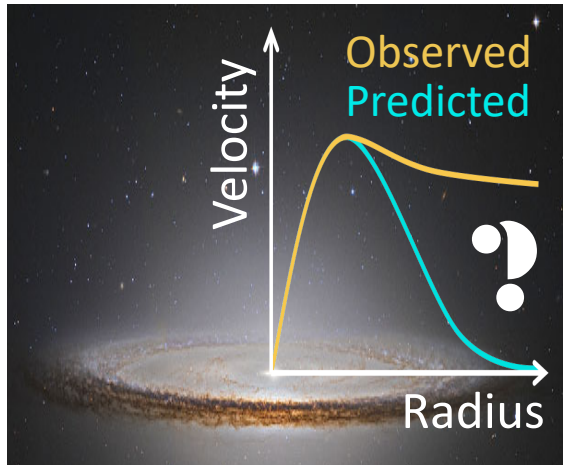
- Letter of Intent arXiv:1811.10243
- Technical Proposal arXiv:1812.09139
- FASER's Physics Reach for Long-Lived arXiv:1811.12522
- Input to the European Strategy for Particle Physics Update arXiv:1901.04468
- Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC arXiv:1908.02310
- Technical Proposal of FASERν neutrino detector arXiv: 2001.03073
- Forward Physics Facility Snowmass LoI

**Plus several theory papers**

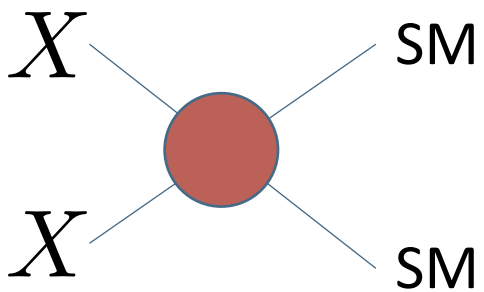
**More information:** https://faser.web.cern.ch/physics/publications



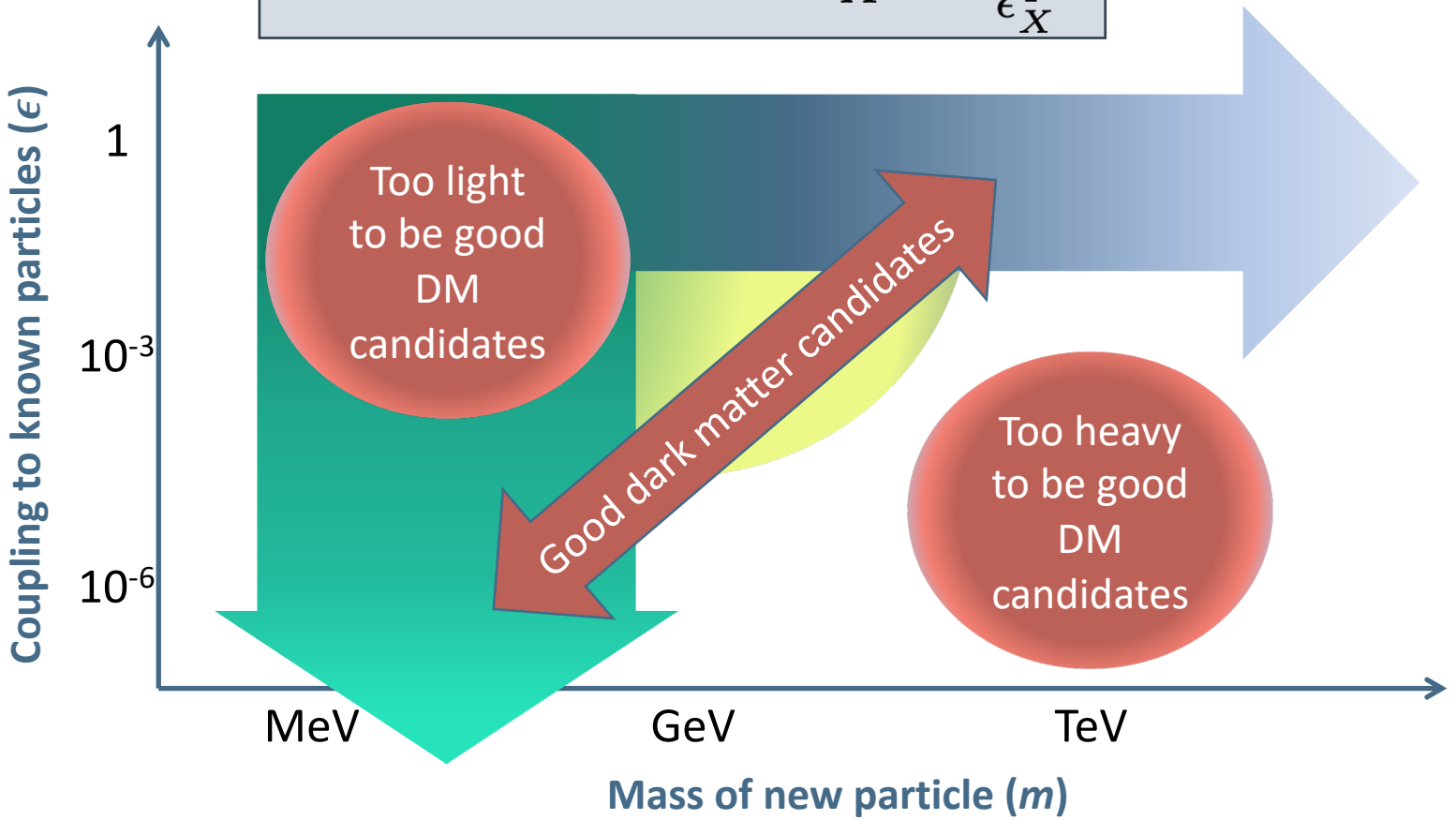
# The landscape of new particles @ colliders




- Simple mechanism for DM generation: "freeze out"



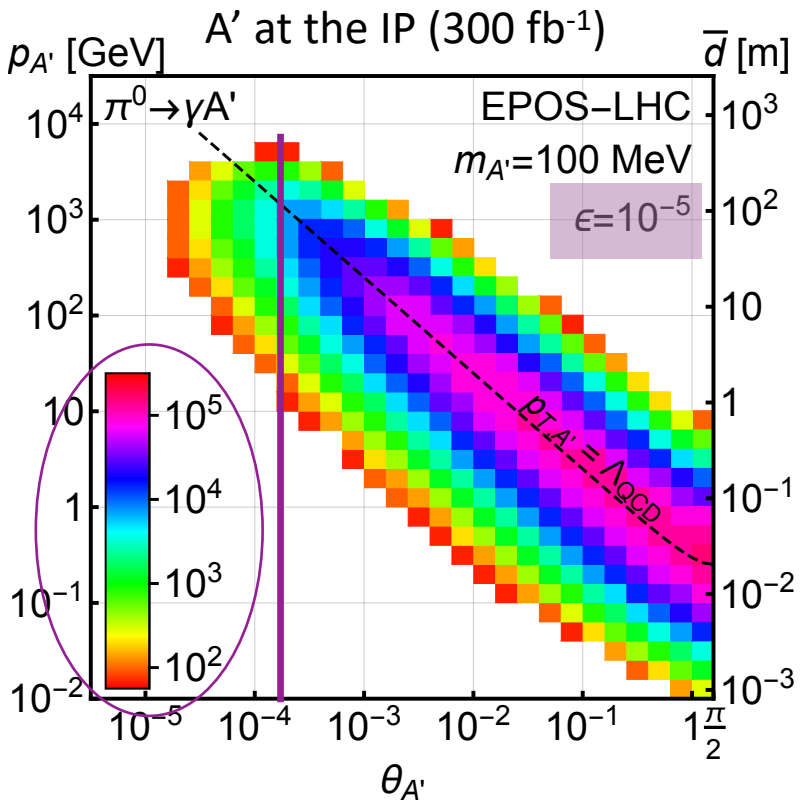

Surviving DM density: $\Omega_X \propto \frac{m_X^2}{\epsilon_X^4}$

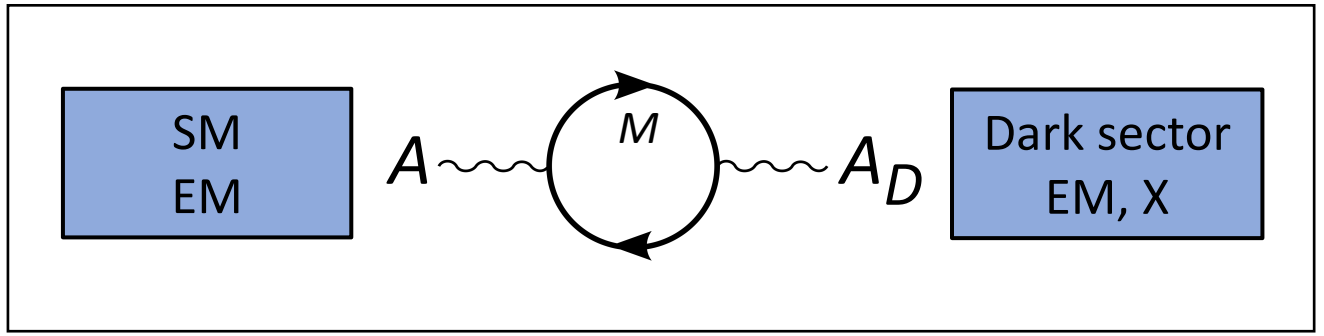


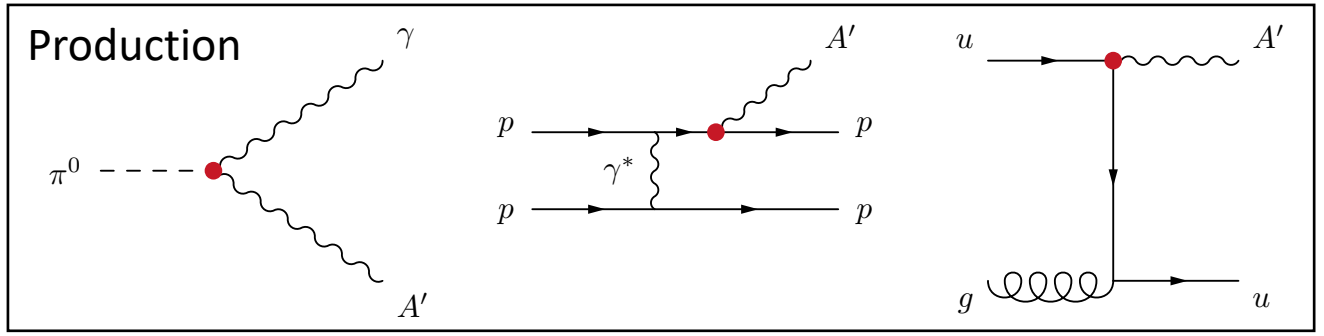

Feng, Kumar - PRL 101, 231301 (2008)

# An example physics case: Dark Photon $A'$

- New massive gauge boson in a dark sector with dark matter candidate X
- Spin 1, couples weakly to SM fermions ($\varepsilon Q_f$ coupling, small $\varepsilon$) through mixing with the photon
  - Will be searched for via its **decay to an electron-positron pair**
- For $m_{A'}$=100 MeV, $\varepsilon \sim 10^{-5}$ and E~TeV, can travel long distance before decay



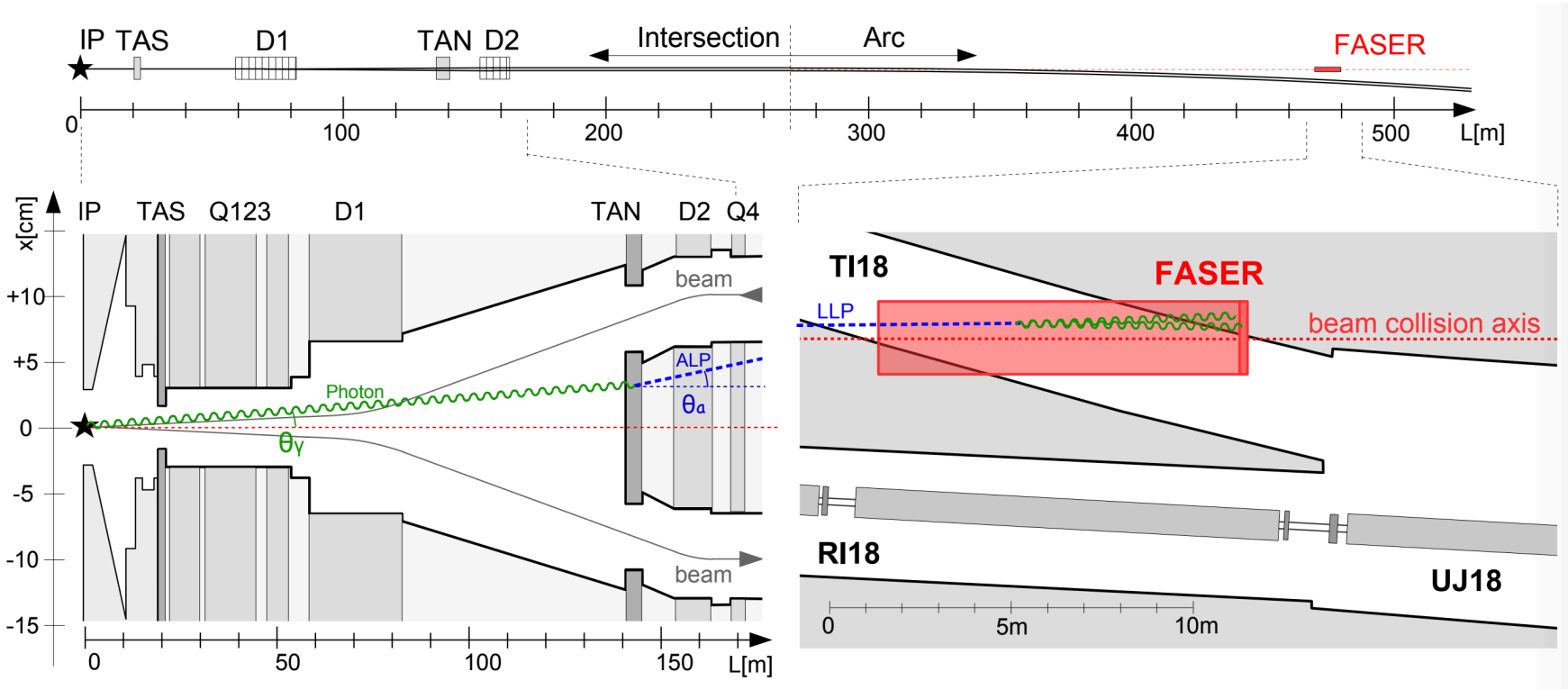



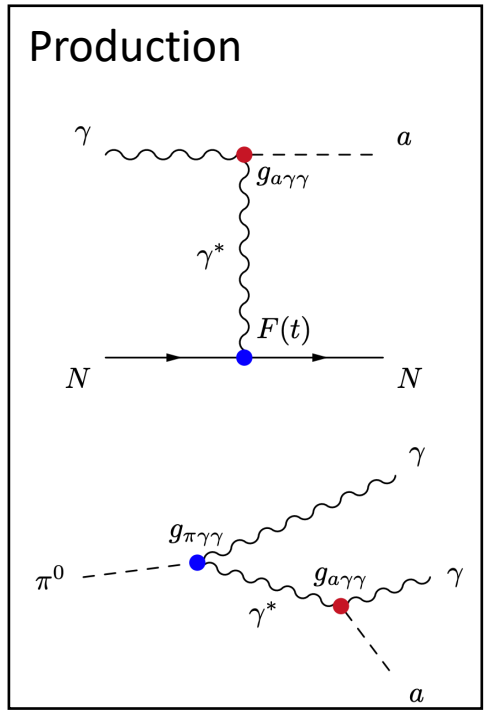



# Another example: Axion-like particles (ALPs)

Qualitatively different: “High-energy photon beam dump experiment”

- Pseudoscalar SM-singlets; can appear in theories with broken global symmetries
- Photons from IP travel 140 m, collide with neutral particle absorber (TAN) and create ALPs
- Low mass particles with suppressed couplings to SM, predominantly **decaying to photons**

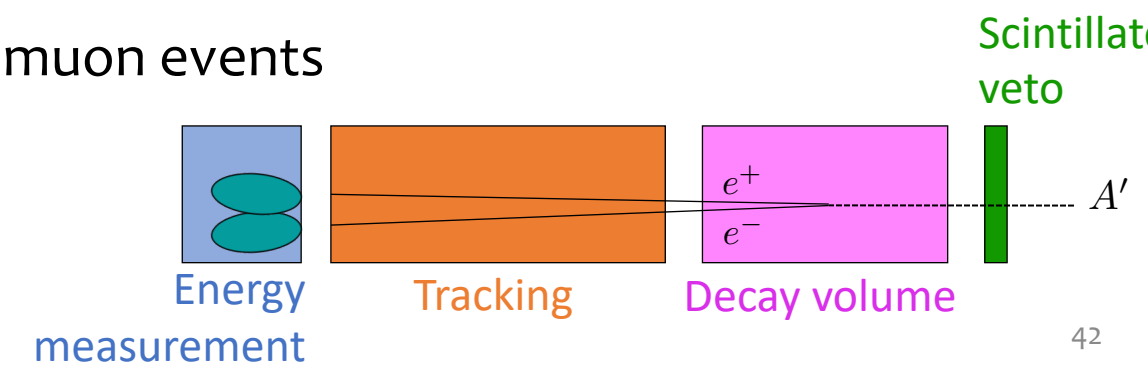


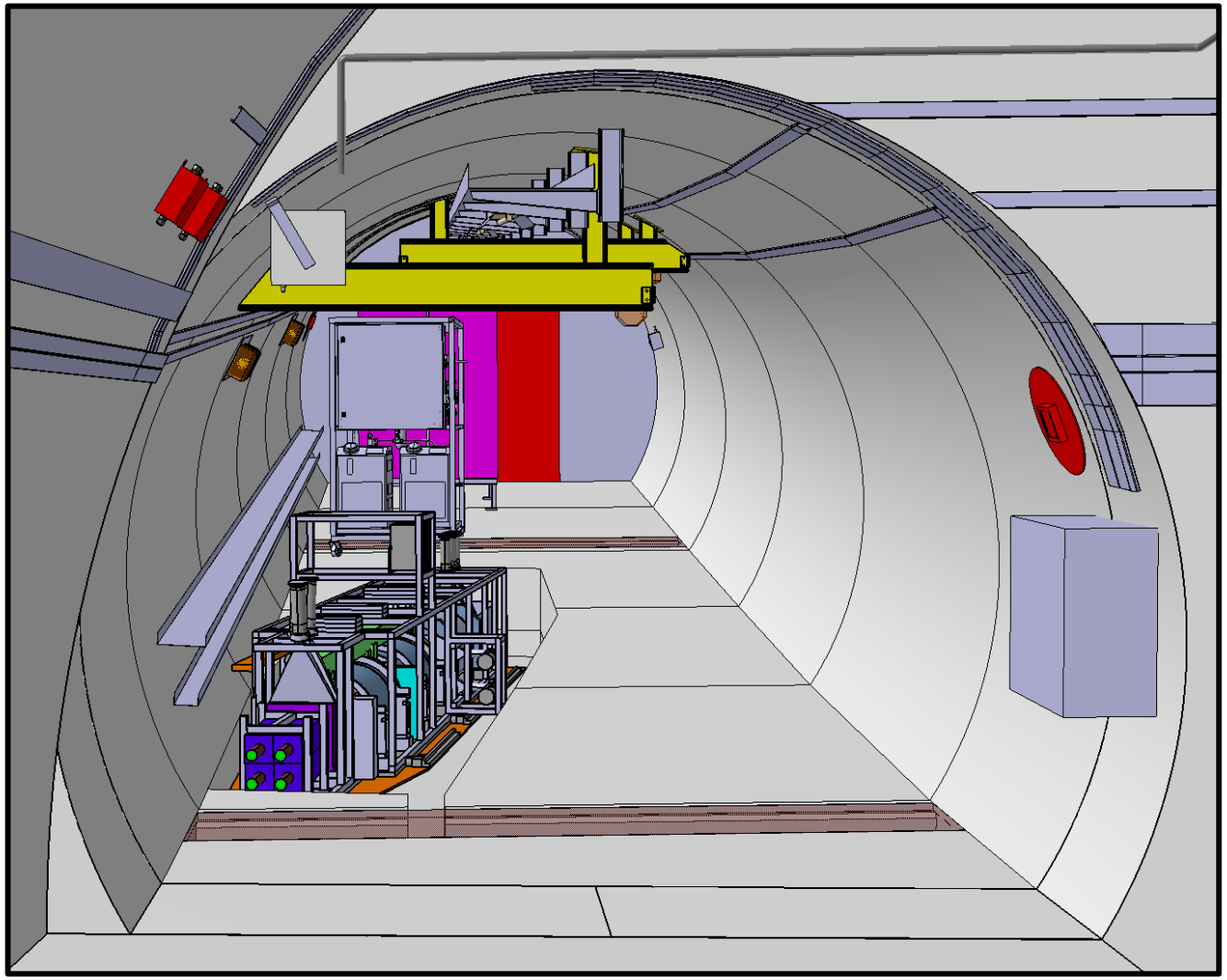

Feng, Galon, Kling, Trojanowski – Phys. Rev. D 98, 055021 (2018)

# Detector concept

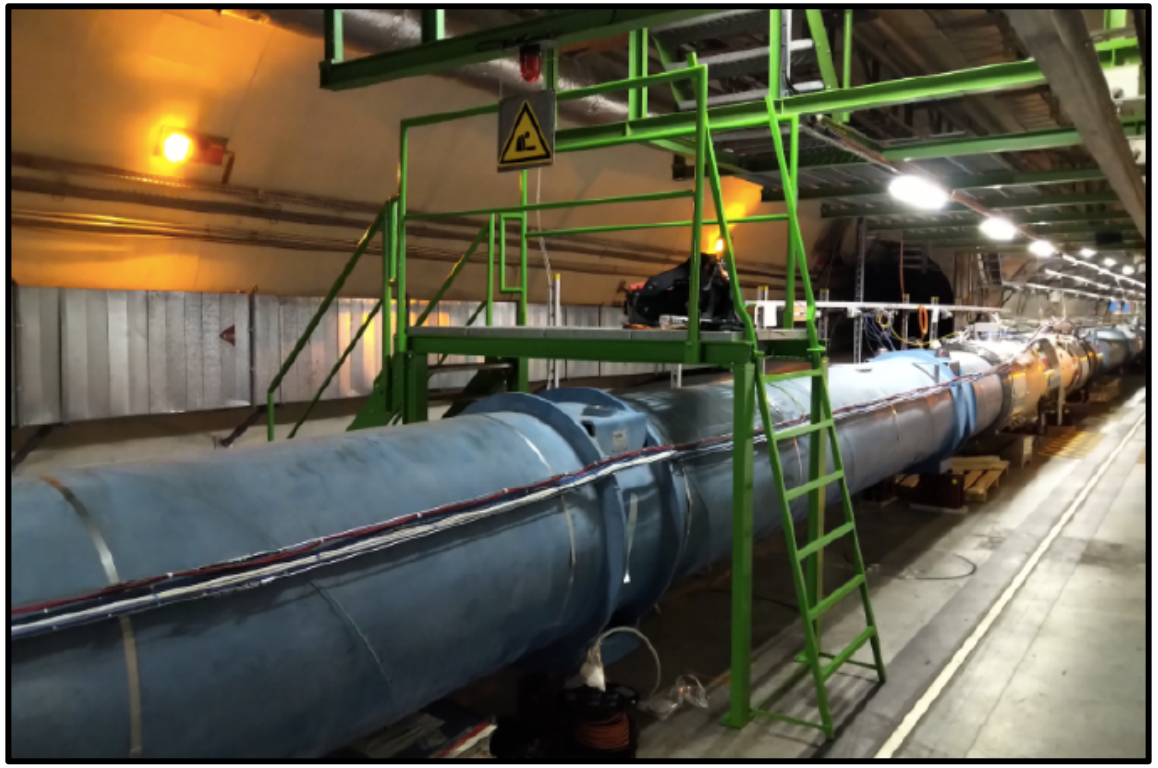
- **Drivers for choices:** Tight timeline between experiment approval and installation & the limited budget.
  - Detector that can be constructed and installed ***quickly & cheaply***
  - Have tried to re-use existing detector components where possible
  - Aimed for a simple, robust detector (access difficult)
  - Tried to minimize the services to simplify the installation and operations
- **Many challenges of the large LHC experiments not there for FASER:**
  - trigger rate O(500Hz) – mostly single muon events
  - low radiation
  - low occupancy / event size



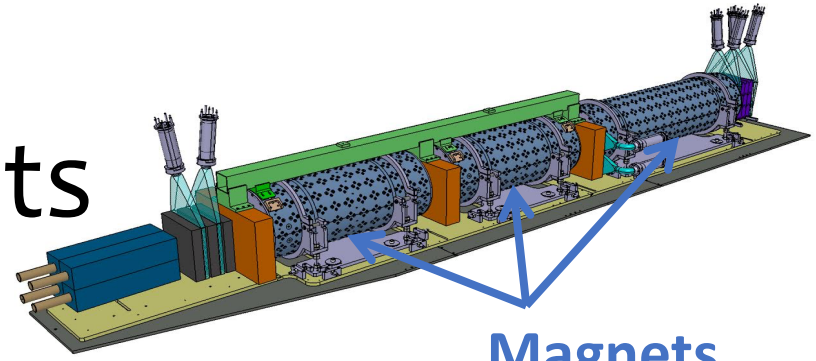
# Access tunnel and Infrastructure

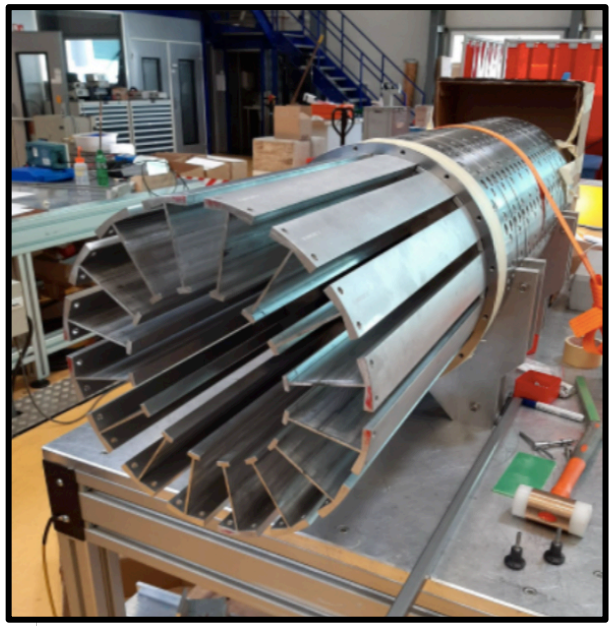


Access to TI12 is over the LHC machine complicates the transport & safety

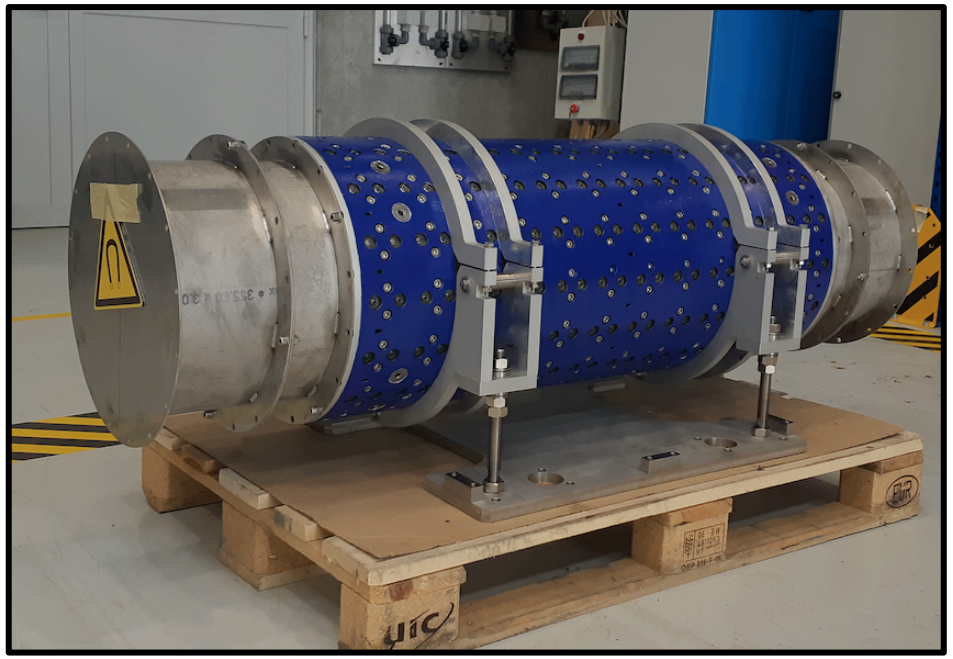


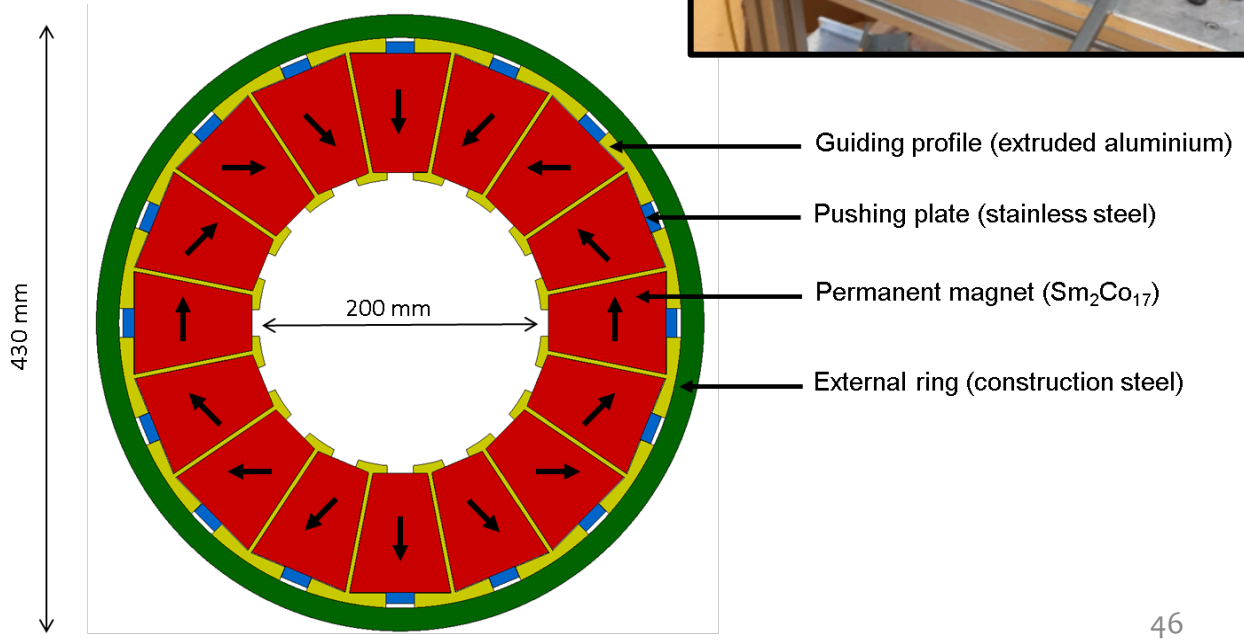
# Magnets



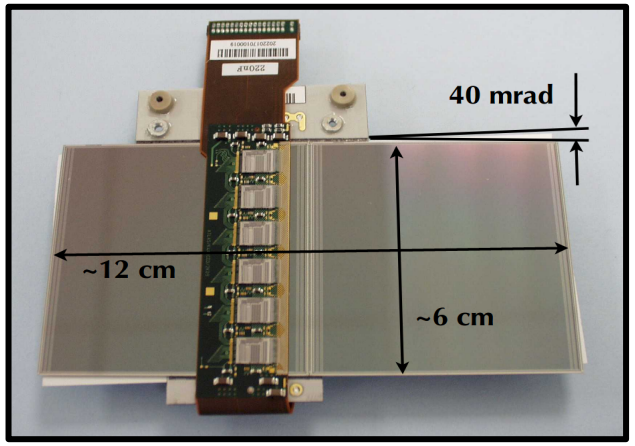
- Field of 0.55 T; permanent dipole
- Halbach array design with fixed-field magnets
  - Maximizes field without need for too much support infrastructure
  - Allows for a compact design, reducing amount of digging





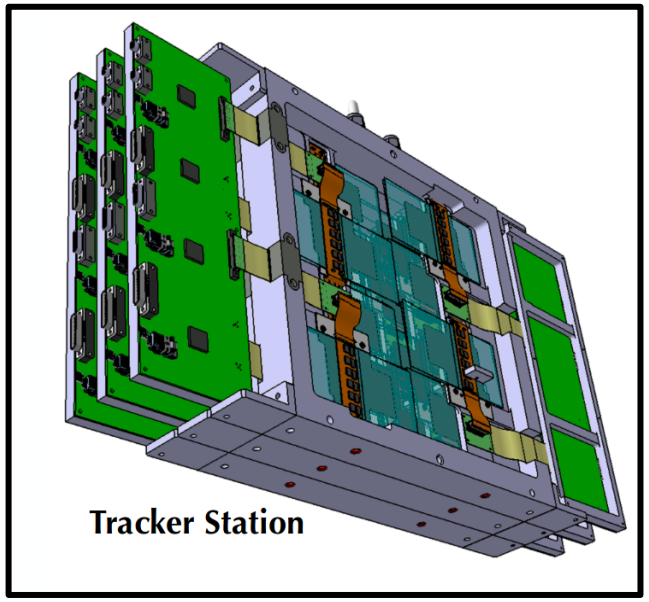
# Tracker

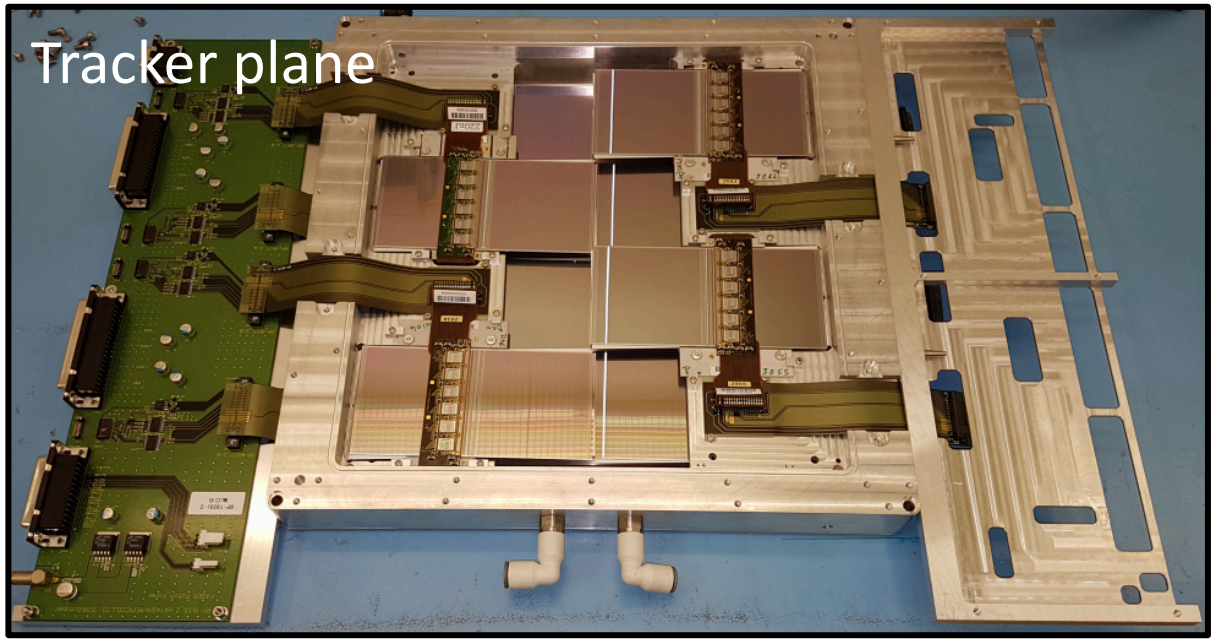
- All individual modules  tested at the lab
- Modules mounted in planes
  - metrology performed
- Planes assembled into stations

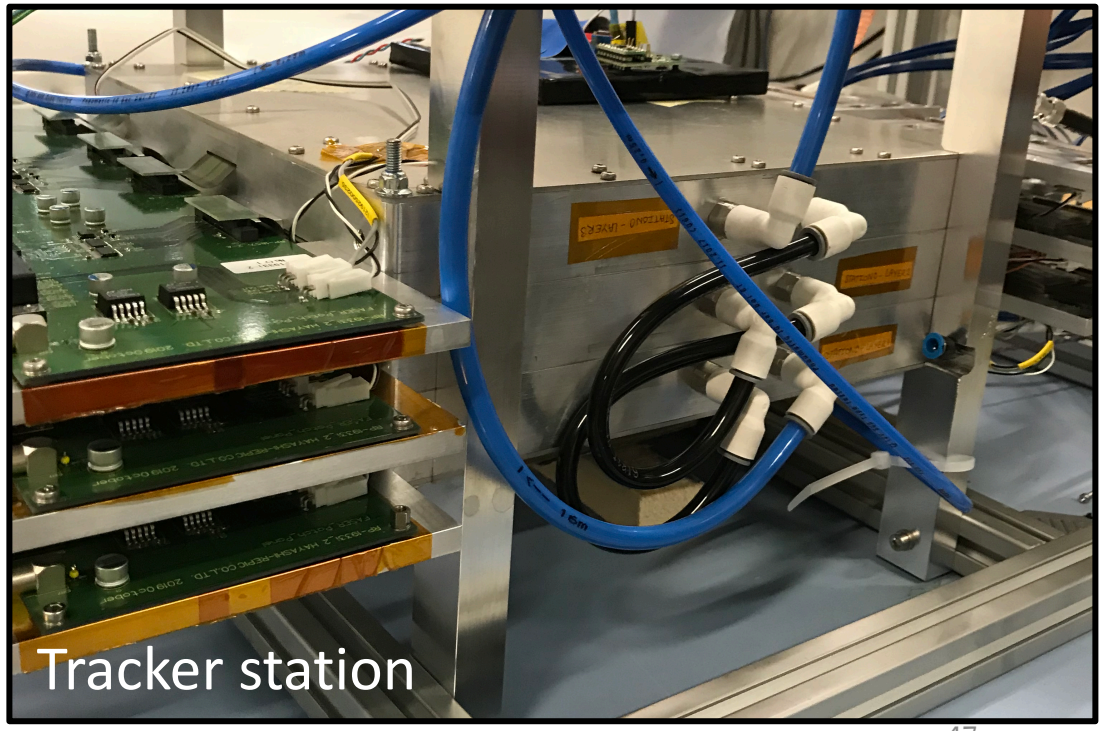



SCT module

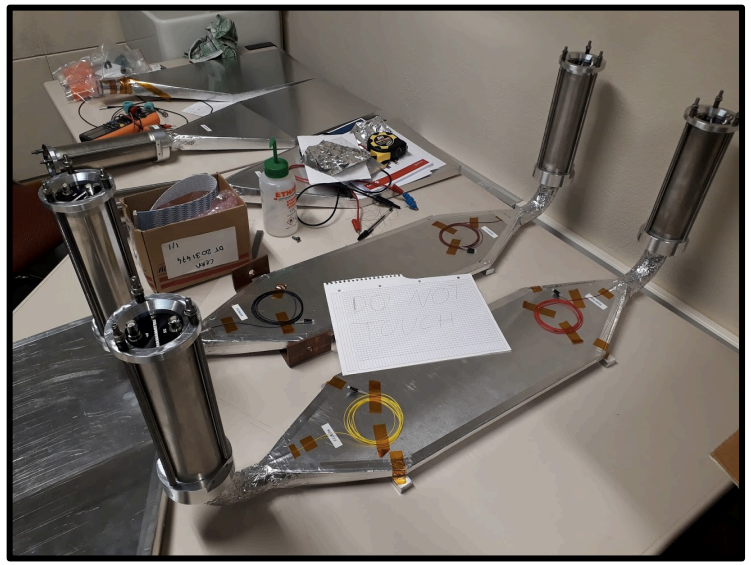
80 µm strip pitch / 40 mrad angle
17 µm / 580 µm track resolution



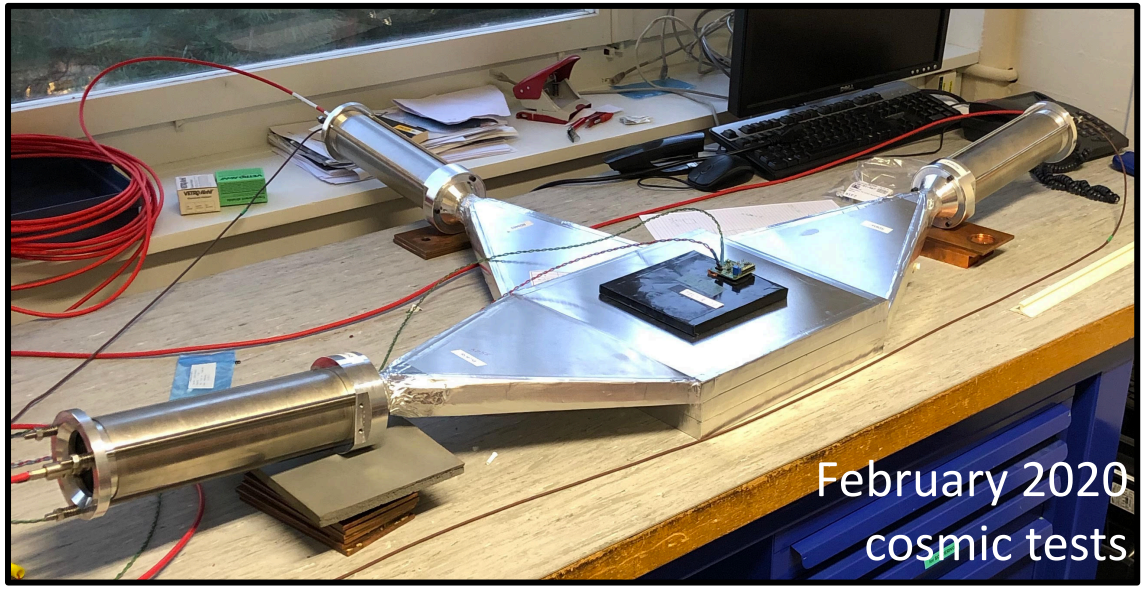



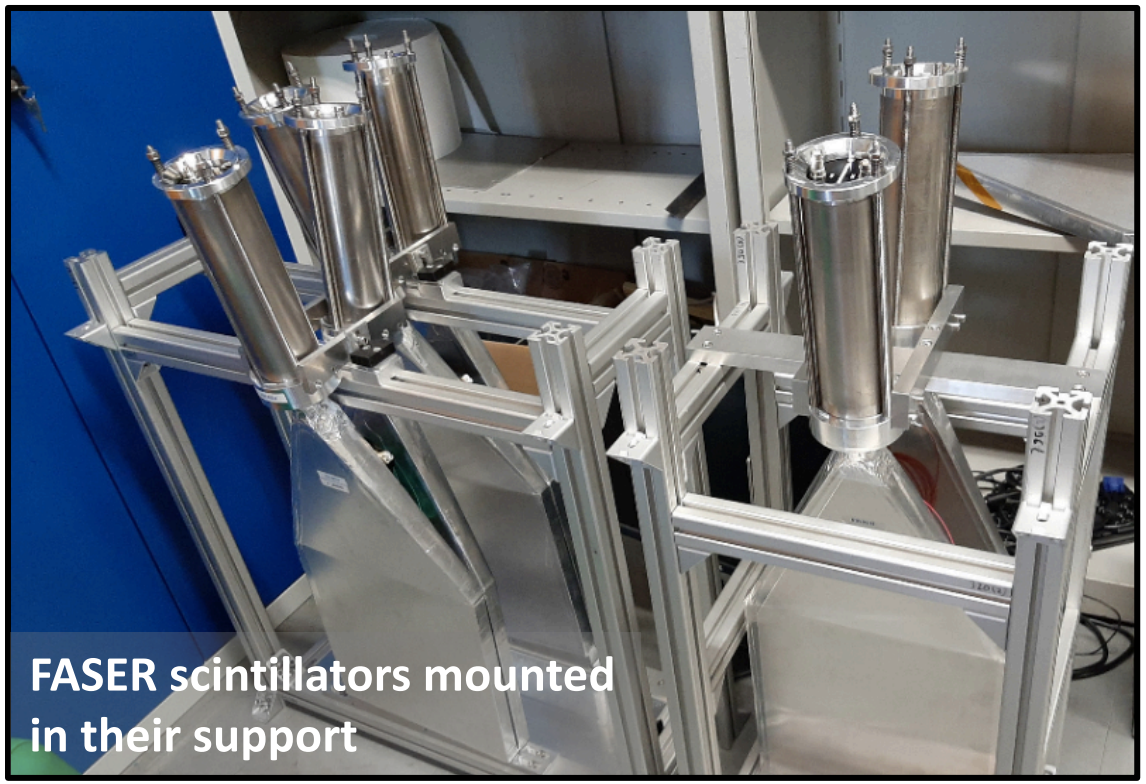



# Scintillators

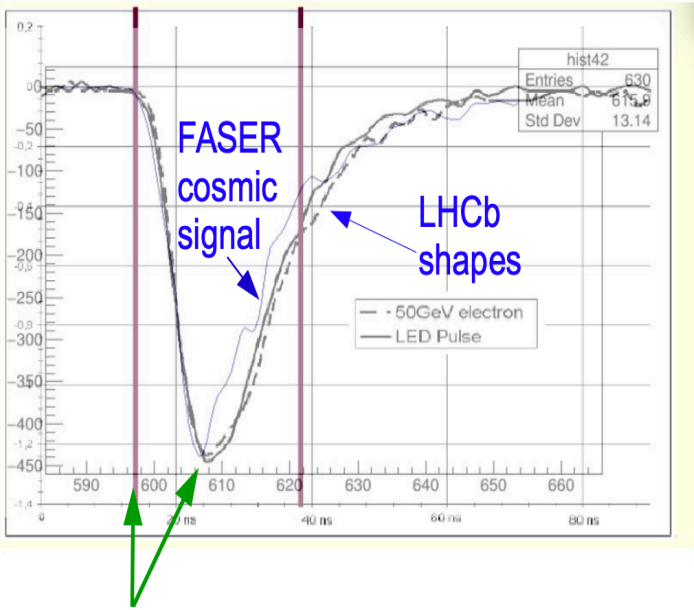


FASER scintillators produced at CERN

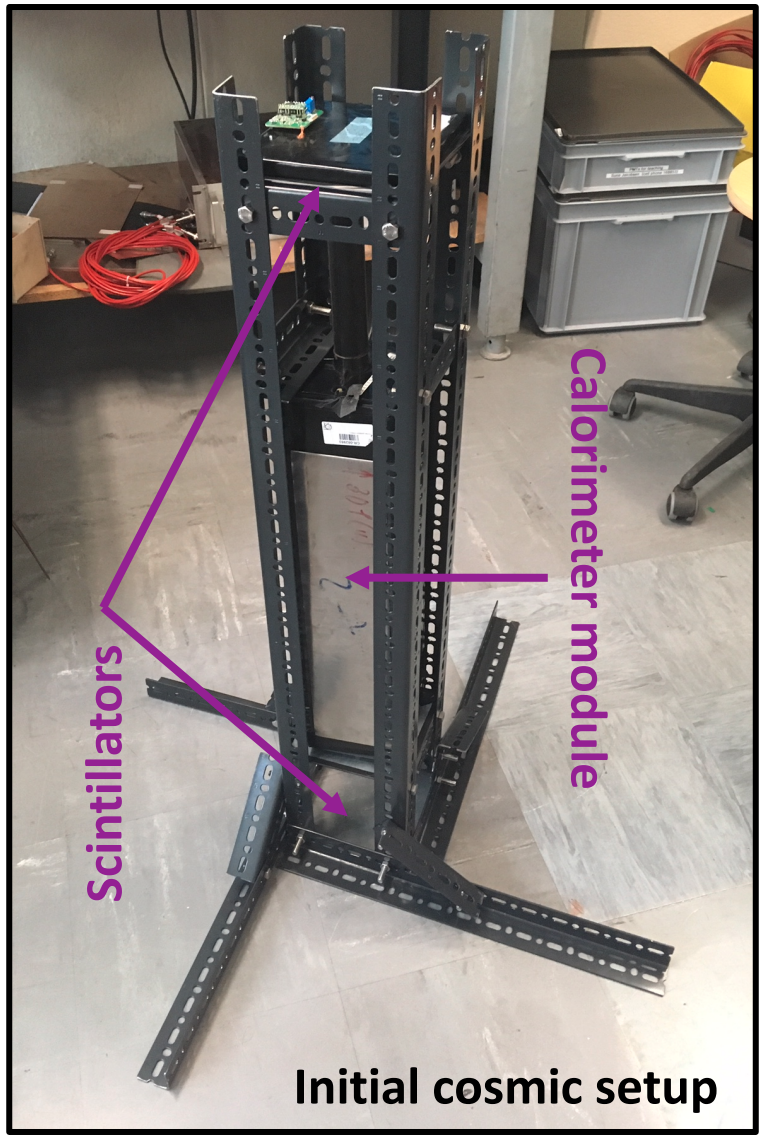


# Calorimeter




~10 ns rise time

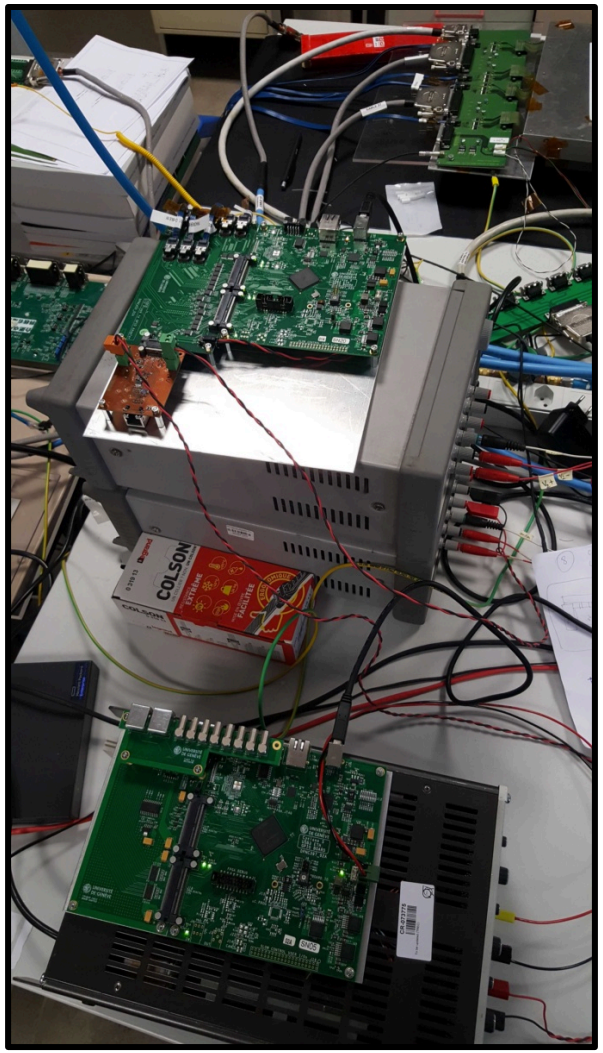




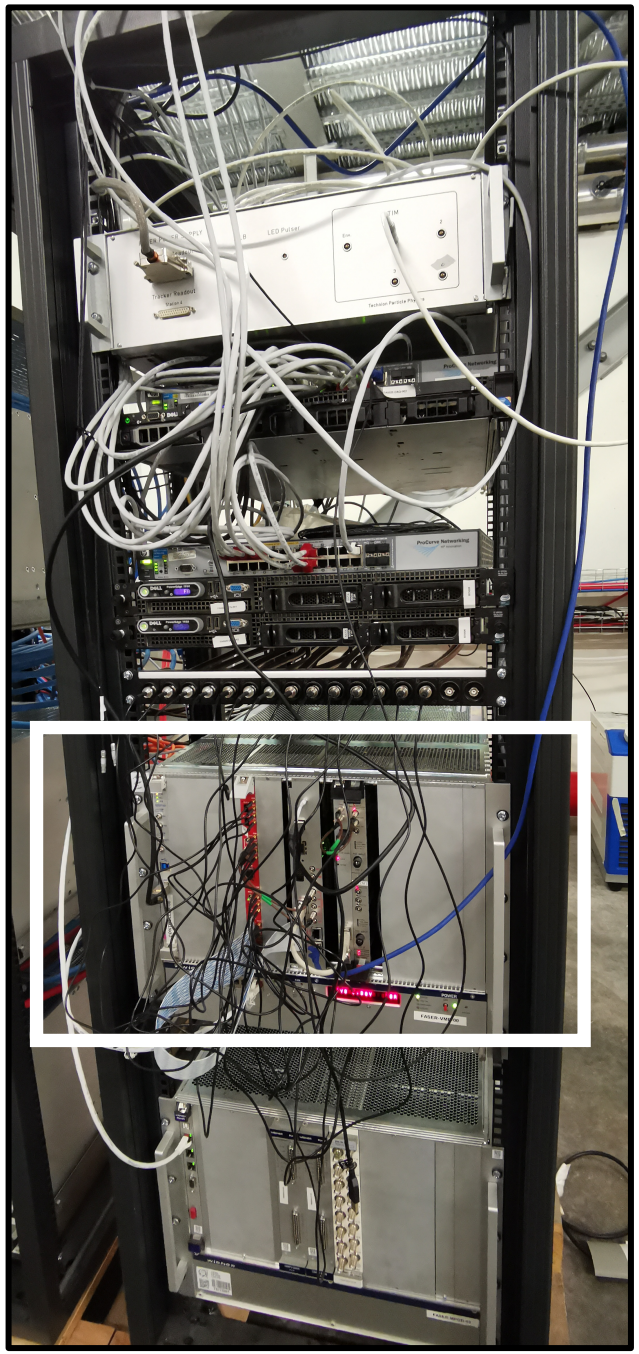
# Trigger & Data acquisition


Initial Run Control application, produced by summer intern

- L1A includes random and software triggers
- Expected **bandwidth** about **15 MB / s**, dominated by PMTs' wide signal (~ 1 µs)
- All TDAQ electronics will be placed in TI12



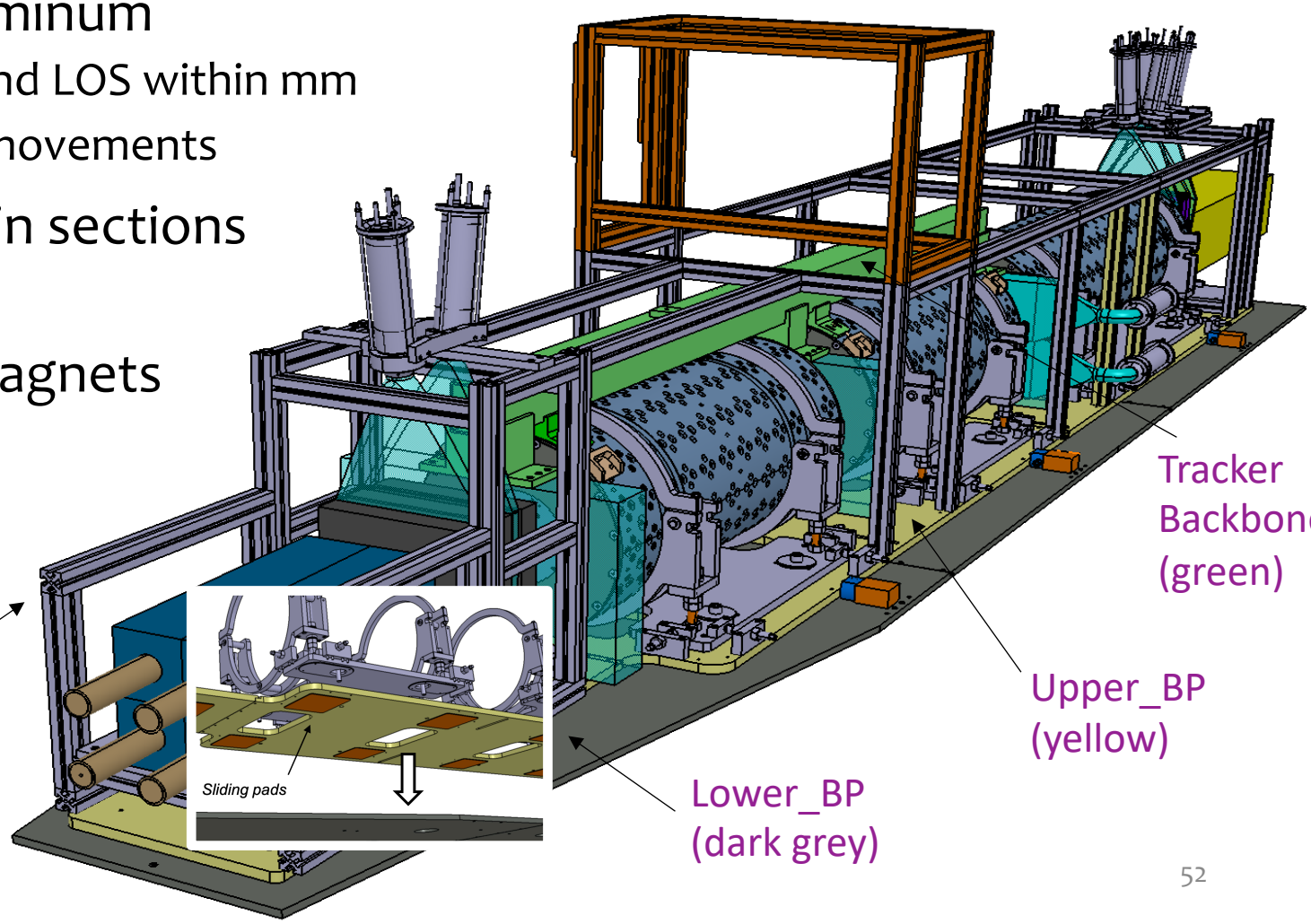
All boards connected together for tests



TDAQ boards in the final VME crate

# Detector support structure

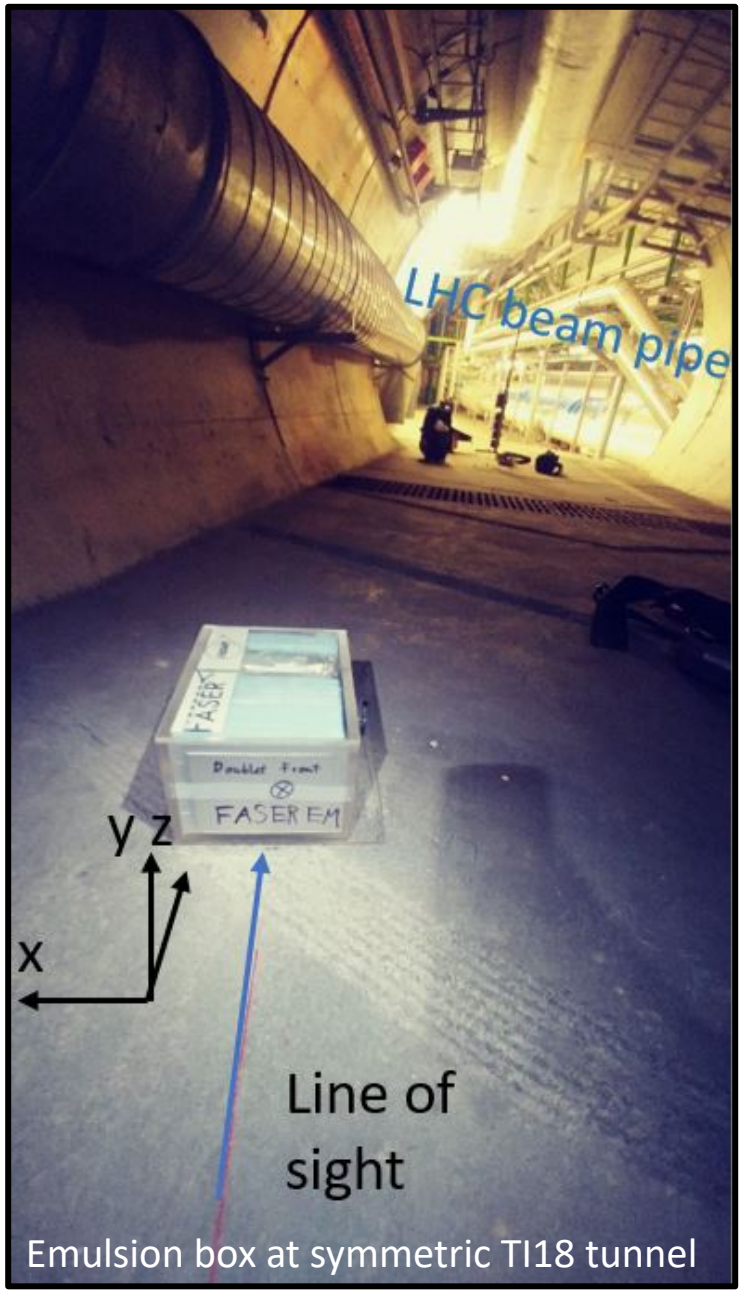
- Two base-plates made of aluminum
  - Align magnets to each other and LOS within mm
  - Allow detector to follow LOS movements
- An upper frame, segmented in sections
  - Align detectors within mm
- Tracker backbone fixed on magnets
  - ensures tracker alignment (<100 µm wrt frame)



# Backgrounds

- **Major background from IP:**
  - Muons and **neutrinos** directly from IP; muons that brem off another particle
  - Veto in scintillators (4 uncorrelated layers) renders muon background negligible; DIS from neutrinos challenging
- **Background from beam:**
  - Beam-gas or diffractive proton losses are found to both be negligible
- Simulation, validated by emulsion-based measurement (recorded ~ **13/fb of data**). CERN beam monitoring also installed
- The radiation level is low ($<10^{-2}$ Gy/year)

⇢ **TI12 very quiet location!**



Emulsion box at symmetric TI18 tunnel

# Huge flux of high-energy neutrinos

- Why not exploit FASER to also measure properties of neutrinos at the highest man-made energies ever recorded!

  - Expected event yields

| 150/fb @14TeV | $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ |
|---|---|---|---|
| Main production source | kaon decay | pion decay | charm decay |
| # traversing FASERnu 25cm x 25cm | O($10^{11}$) | O($10^{12}$) | O($10^{9}$) |
| # interacting in FASERnu (1.2tn Tungsten) | ~1300 | ~20000 | ~20 |