
FASER

# Forward Search Experiment at the LHC

**PHENO2021**

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for the FASER collaboration

# Motivation

- searches for new physics at large LHC experiements focussing mostly on high-$p_T$
- appropriate for heavy, strongly interacting particles

$\sigma$ ~ fb – pb → expectations for Run-3: N ~ $10^2$ – $10^5$, isotropical

- If new particles are instead **light** and **weakly coupling** we might better look for those particles in the forward direction
- LHC is a factory for (SM) particles in forward direction:

$\sigma_{inel}$ ~ 100mb → expecations for Run-3: **N ~ $10^{16}$**, highly forward oriented (**~ mrad**) $\theta \sim \Lambda_{QCD} / E \sim 250$ MeV / TeV

- even extremely rare decays might still be observable in this enourmous forward particle stream
- escapes acceptance of large LHC experiments
- assuming weakly coupling particles as source for BSM physics: valid assumption that newly produced particles will be sufficiently long-lived

FASER

- FASER experiment is placed 480m in the line of sight from LHC IP1 (ATLAS) with an aperture of 20cm targeting this mrad regime ($\eta$>9.1)
- proposed in 2017, approved in 03/2019, installed in 03/2021
- by now: 71 collaborators, 19 institutes, 8 countries

# Physics Case

## Dark photons *(just one example; see arXiv:1811.12522 for many more exampels and details)*

additional terms in SM Lagrangian:

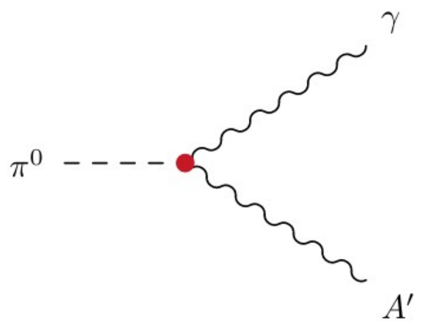
$$\mathcal{L} \supset -\frac{\epsilon'}{2} F_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m'^2 X^2$$ ← new gauge boson

after field redefinition, dark photon A' mass eigenstate:

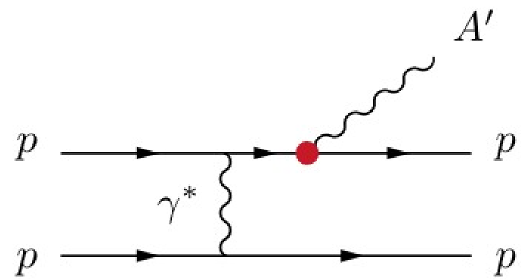
$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon\, e \sum_f q_f \bar{f} \not{A}' f$$

**production**

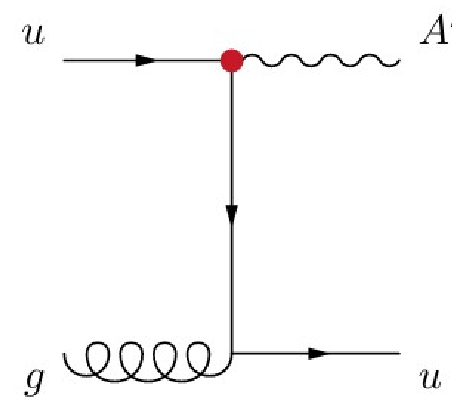
meson decay




dark bremsstrahlung




hard scattering




**decay**

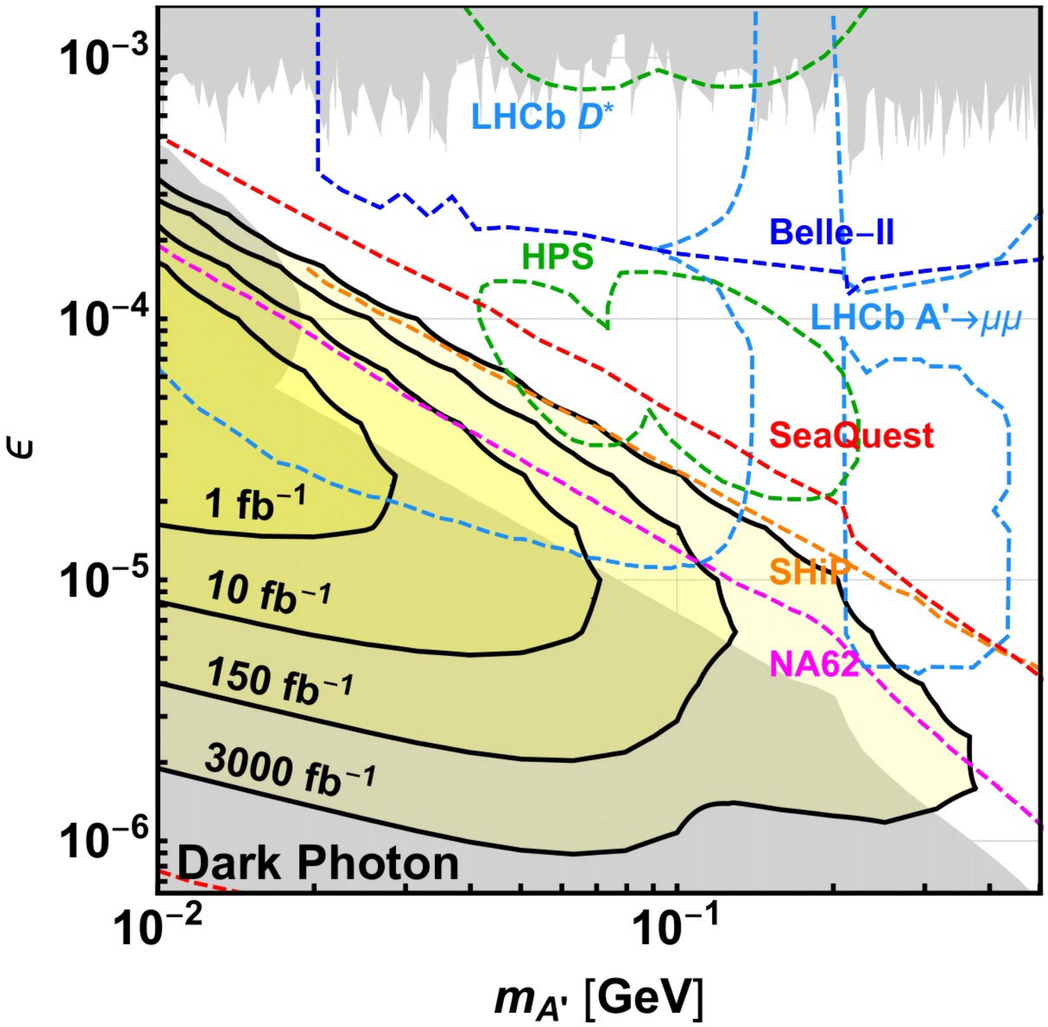
- decay to pair of SM fermions, if kinematically allowed
- for light A': predominantly electron/muon pairs
- suppressed by $\varepsilon^2$: significantly long-lived

signature in FASER:

**A' → $e^+e^-$, $\mu^+\mu^-$, …**

# Physics Case

Dark photons (projected sensitivity)

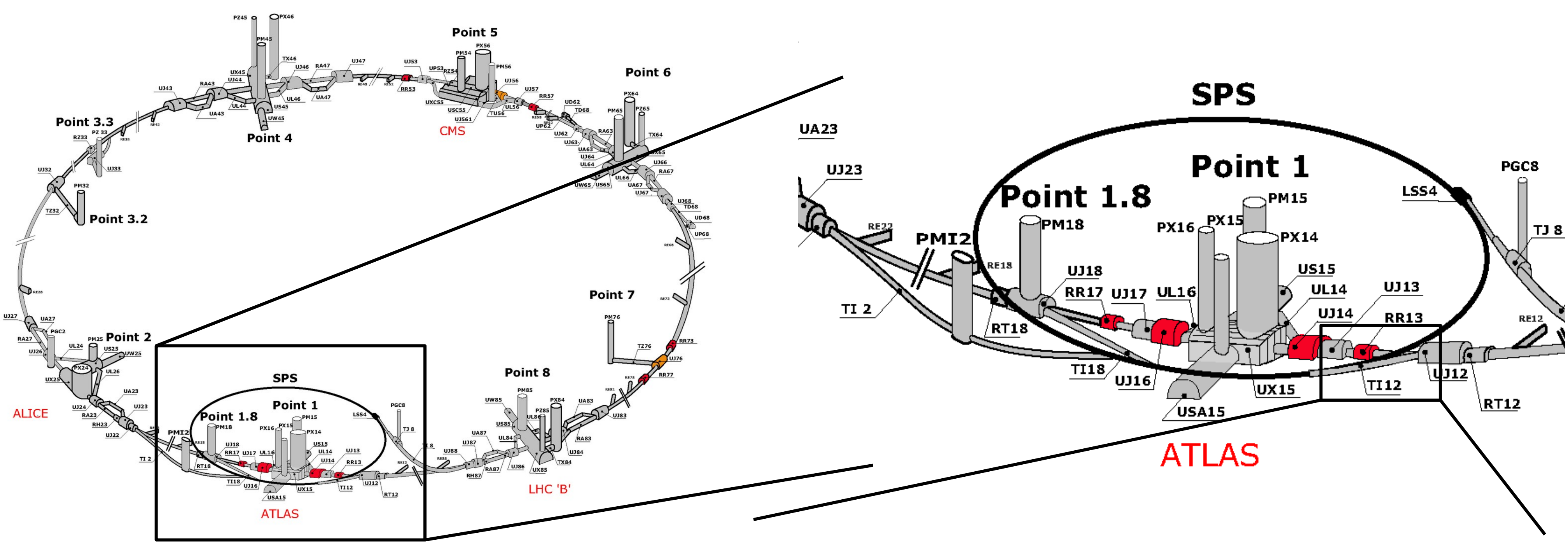


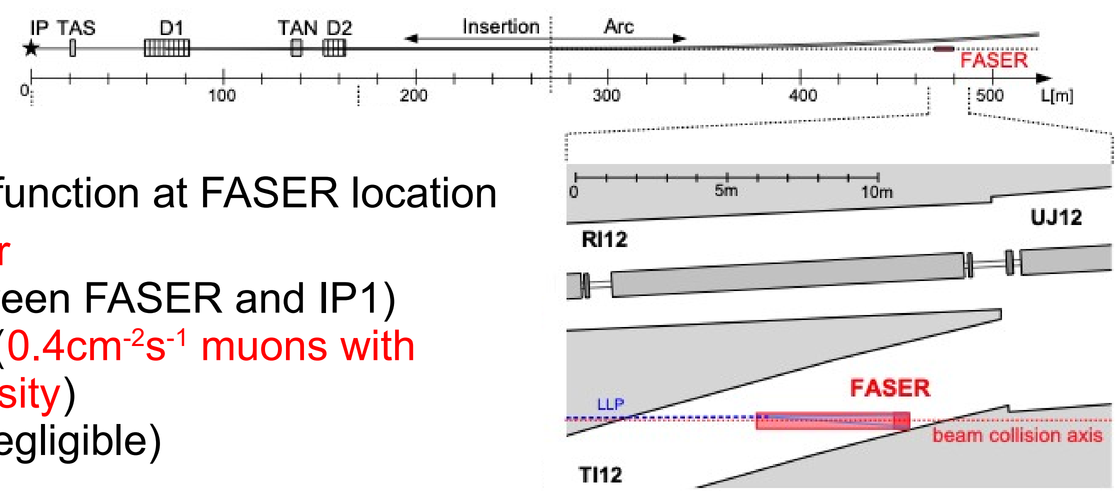

- with already $1fb^{-1}$ starting to explore unconstrained space
- significant discovery potential with $150fb^{-1}$ (expected Run-3 dataset)

- plot assumes 0 background and 100% efficiency
- O(1) inefficiencies have little effect on contour line
- 0-background assumption reasonable

**FASER can complement LHC physics programme significantly wrt searches for weakly coupling light particles**

# Location and Background Considerations




- located 480m away from IP1 (ATLAS)
- placed in old transfer tunnel to SPS on the line of sight of the IP1 collision axis
- extremely low radiation due to low dispersion function at FASER location
  - $<5 \times 10^{-3}$ Gy/year, $<5 \times 10^{7}$ neq@1MeV/year
- extremely low background (100m of rock between FASER and IP1)
  - muons/neutrinos from pp interaction at IP1 ($0.4 cm^{-2}s^{-1}$ muons with $E>10$GeV @ $2 \cdot 10^{34}$ $cm^{-2}s^{-1}$ LHC inst. luminosity)
  - off-orbit protons showering in collimators (negligible)
  - beam gas interactions (negligible)
- FLUKA background model confirmed with in-situ measurements during Run-2

# Detector Concept – Overview

technical proposal:
arXiv: 1812.09139

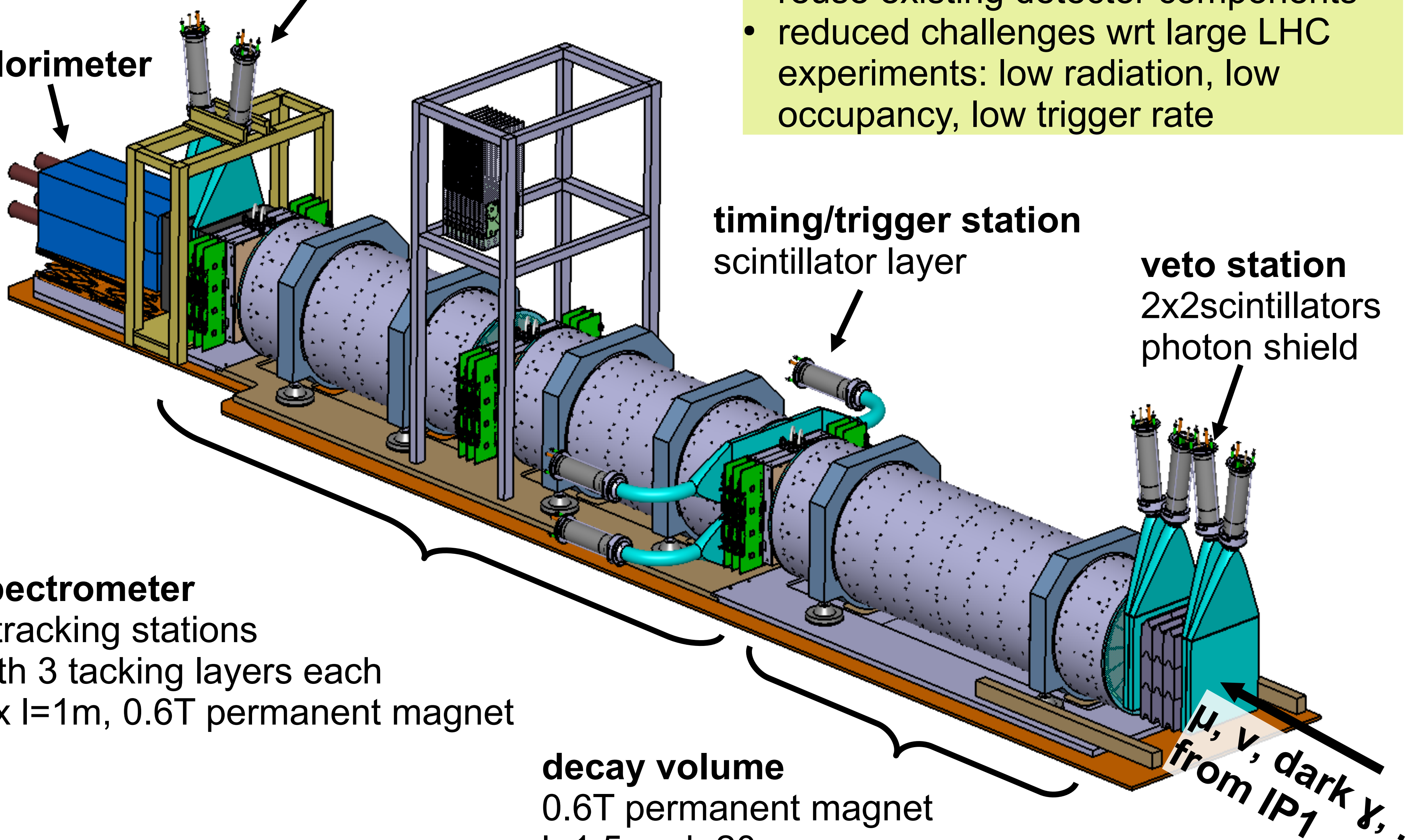
- limited time and budget
- aiming for simple and robust detector
- reuse existing detector components
- reduced challenges wrt large LHC experiments: low radiation, low occupancy, low trigger rate

**preshower/trigger station**
2 scintillator layers

**EM calorimeter**

**timing/trigger station**
scintillator layer

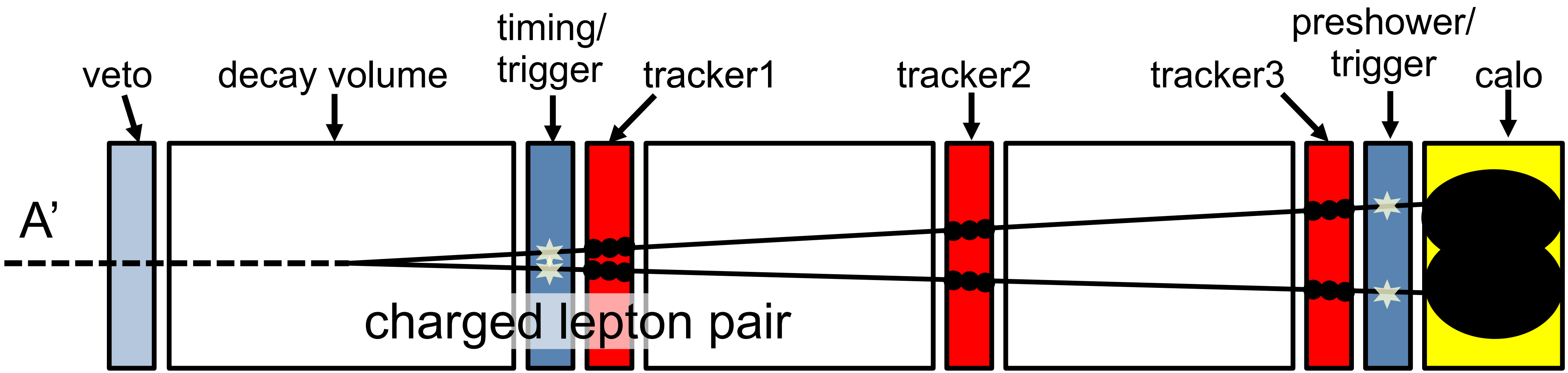
**veto station**
2x2scintillators
photon shield




**spectrometer**
3 tracking stations
with 3 tacking layers each
2 x l=1m, 0.6T permanent magnet

**decay volume**
0.6T permanent magnet
l=1.5m, d=20cm

# Detector Concept – Signal Signature



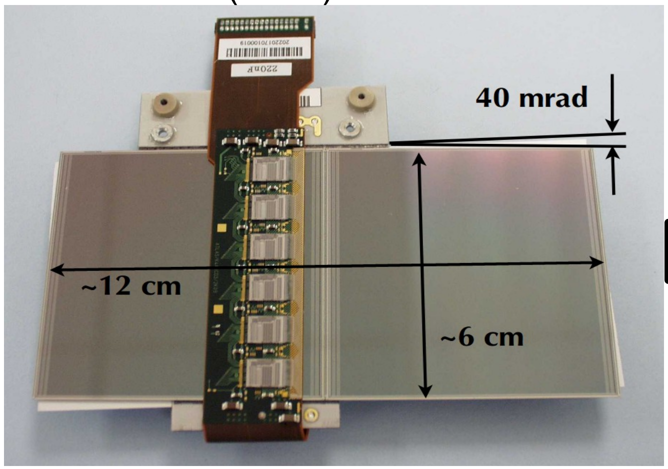

**very clear and clean expected signature**

- no signal in veto station
- signal in all scintillator stations downstream the decay volume
- two lepton tracks starting in the decay volume
- vector sum of tracks pointing back to IP1
  - → strong magnetic field required to separate collimated tracks and measure momentum
- high energy deposition in the calorimeter (no separation possible; only 4 calo blocks)
- no intrinsic irriducible background

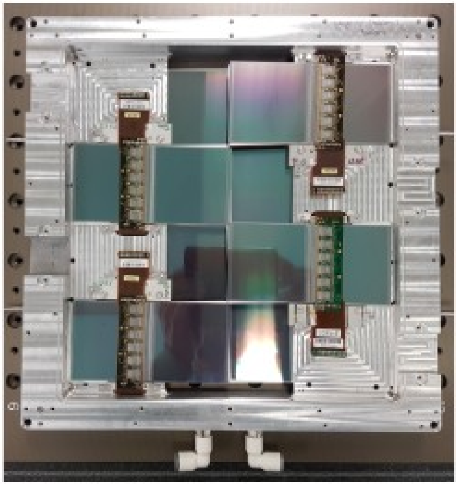
# Detector Components – Tracker

## SCT module

NIM A 568 (2006) 642-671




## Tracker plane



## Tracker station

- using spare ATLAS SCT silicon strip modules
  - *thanks a lot to the ATLAS SCT community!*
- 768 strips per sensor layer with 80µm pitch
- two sensor layers with 40mrad stereo angle

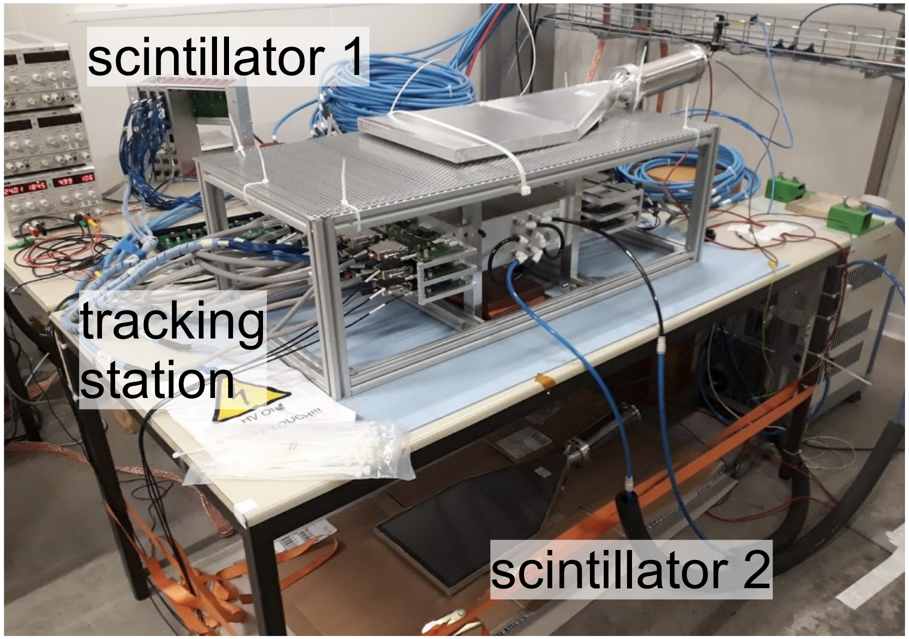
- 2x4 modules per plane
- sensitive area: 24x24cm$^2$ covering full aperture of the magnets
- aluminum frame with integrated cooling channels
- operation at 15degC (no radiation damage)

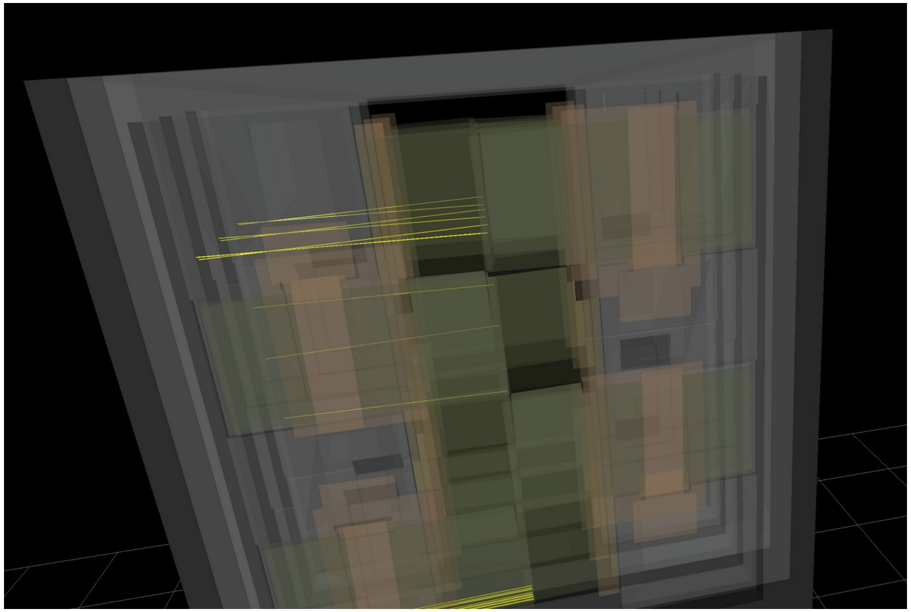
- 3 planes per station
- mechanical frame with carbon fiber entry/exit window to minimize multiple scattering
- careful metrology during assembly

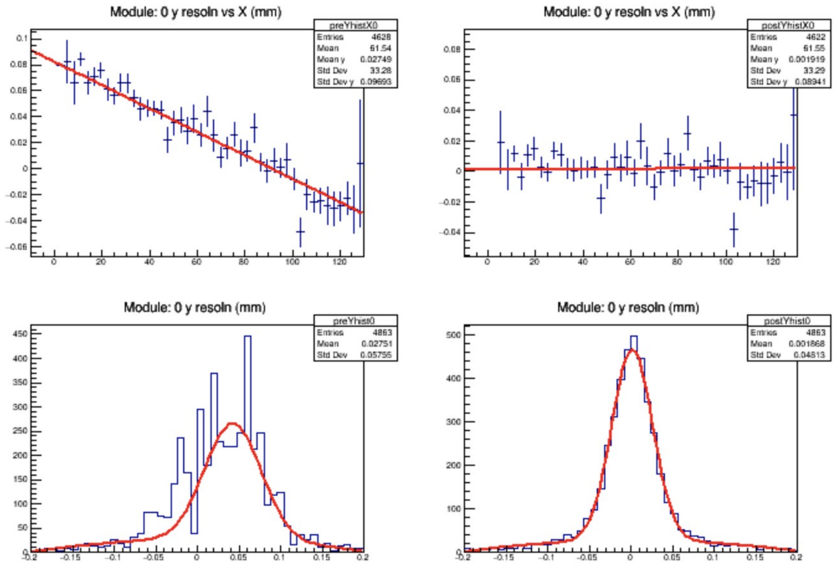
# Detector Components – Tracker

**Cosmic tests with tracker stations on the surface**

- first observation of a cosmics track with the FASER tracker
- very simple intra-station aligement results already in residual resolution (25μm) close to the design expectation
- flawless operation building very strong confidence in overall tracker performance



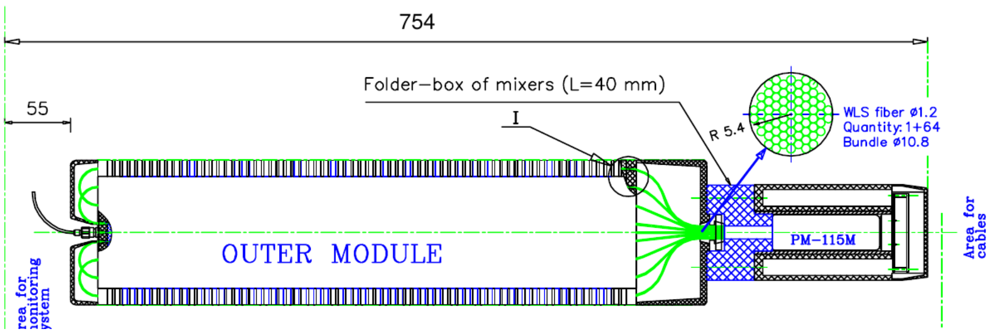



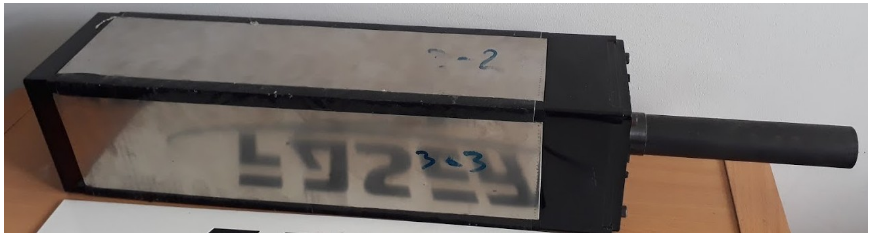


# Detector Components – Calorimeter

## Calorimeter Cell

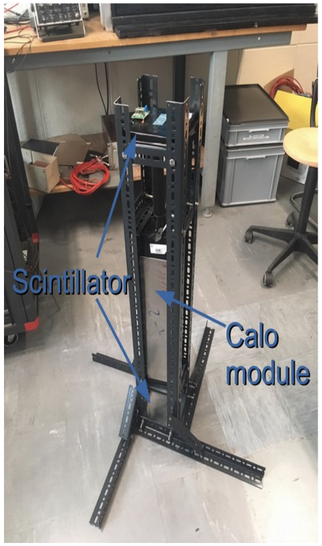
- 6 LHCb outer ECAL modules on permanent loan to FASER, 4 in use in the detector
  - → *thanks a lot to the LHCb ECAL collaboration!*
- Shashlik-calorimeter: 66 layers (2mm lead/ 4mm plastic scintillator)
- total $X_0$=25
- sensitive area of 2x2 cells: ~24x24cm$^2$



## Energy reconstruction

- expected energy resolution for TeV electrons: 1%
- known uncertainty due to leakage: 25$X_0$ might not be sufficient to catch full shower of TeV particles
- SPS testbeam time in July 2021 foreseen for energy calibration using high energy electrons



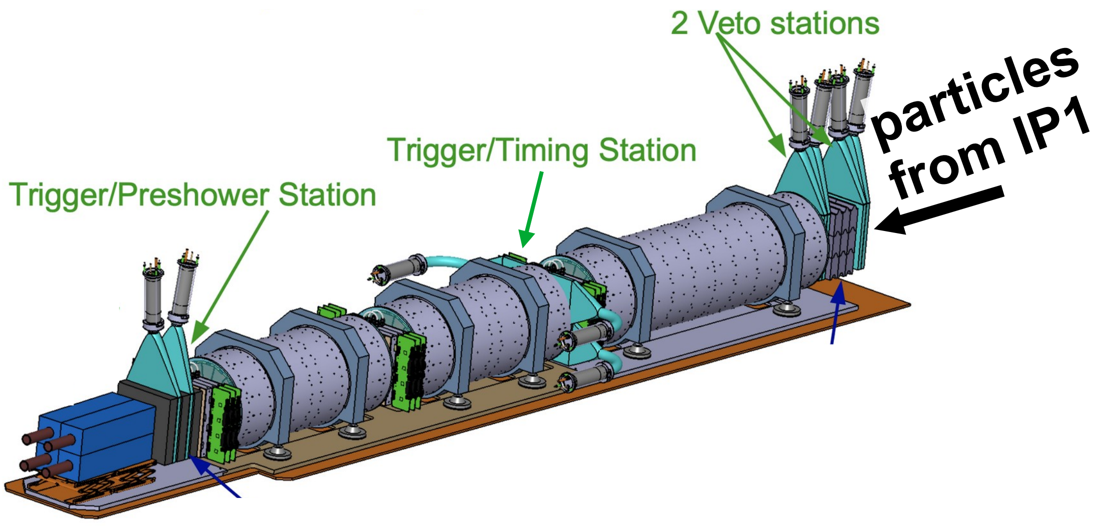

## Cosmics tests in the lab

- excellent results from cosmics tests in the lab proofing good light yield and excellent MIP efficiency (>99.8%)

# Detector Components – Scintillators

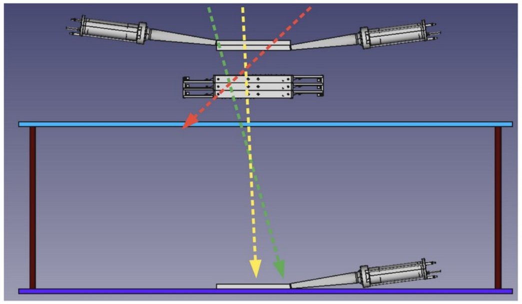
## Scintillator concept

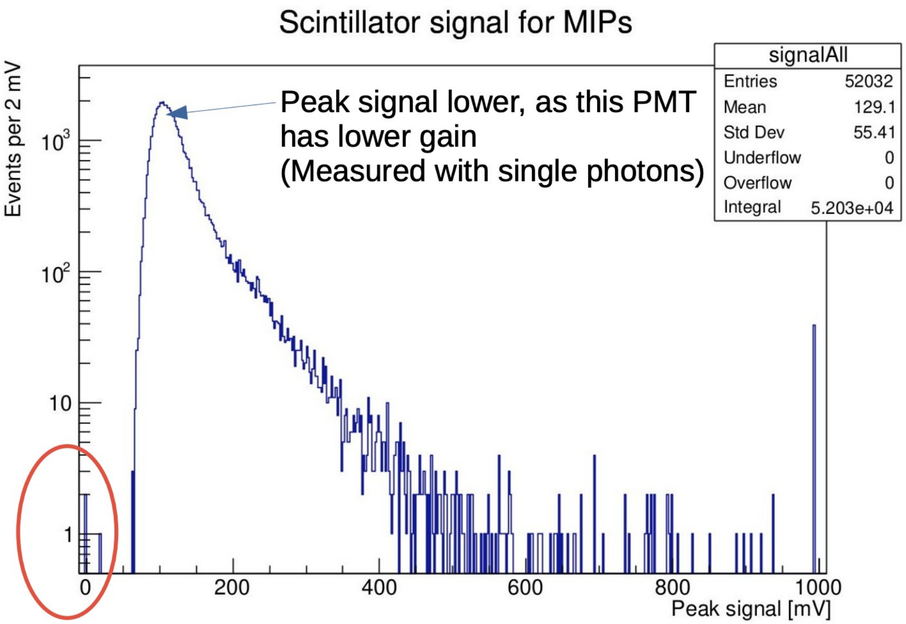
- scintillators used at many different locations serving as:
  - veto
  - trigger
  - timing of event (<1ns resolution)
  - preshower (in combination with absorbe
- scintillator planes produced at CERN



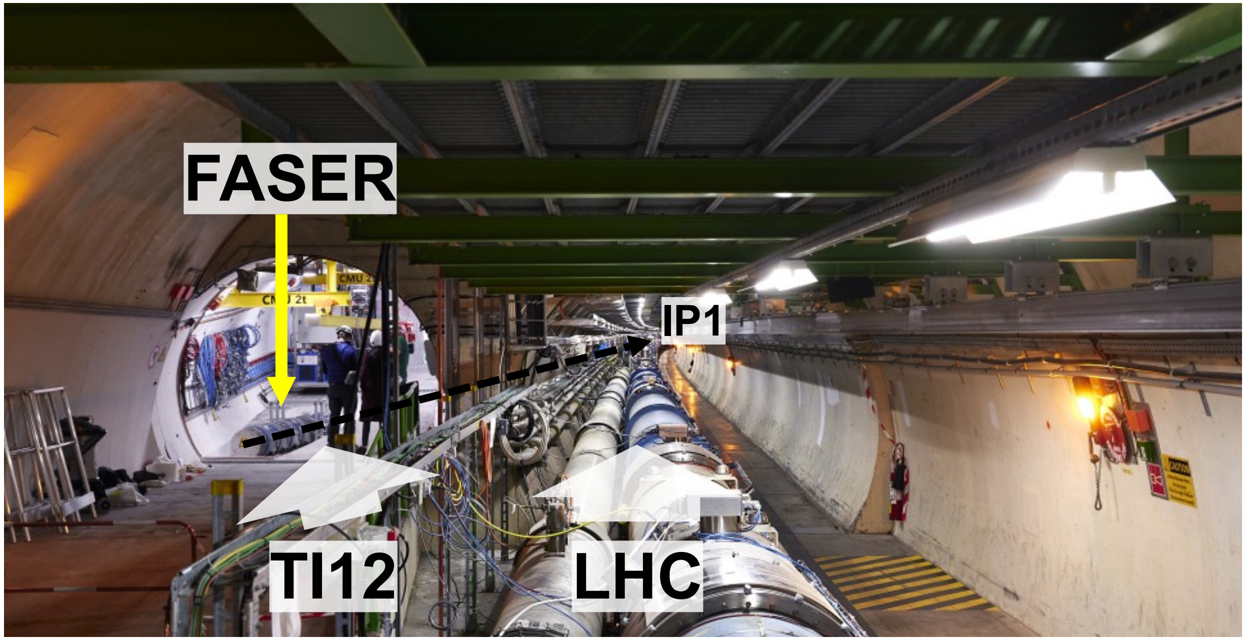

## Cosmics tests in the lab

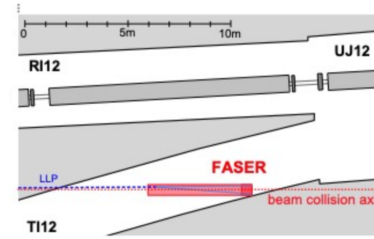
- extremely satisfying performance
- efficiency of "worst" performing veto scintillator >99.99%
- well above the specification (99.9%)





# Installation in the LHC tunnel



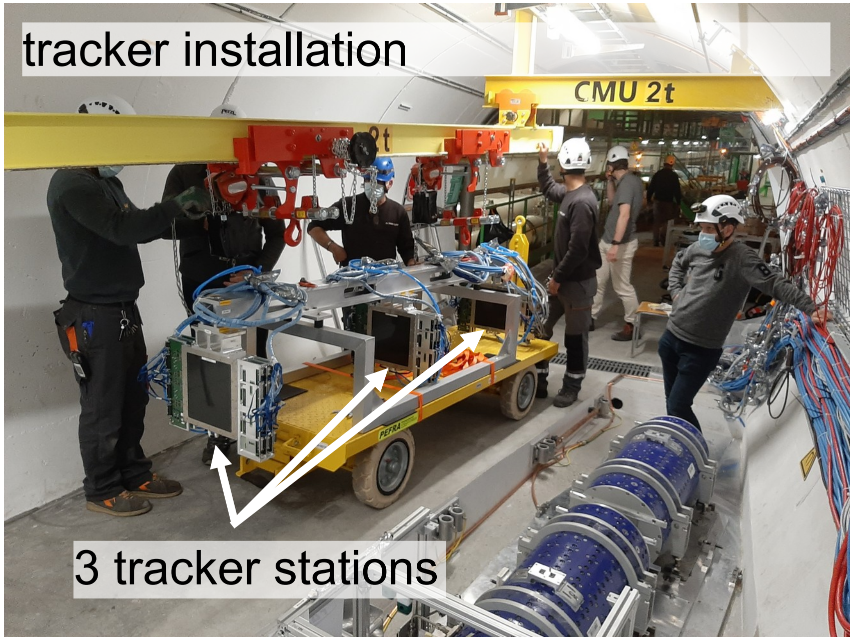


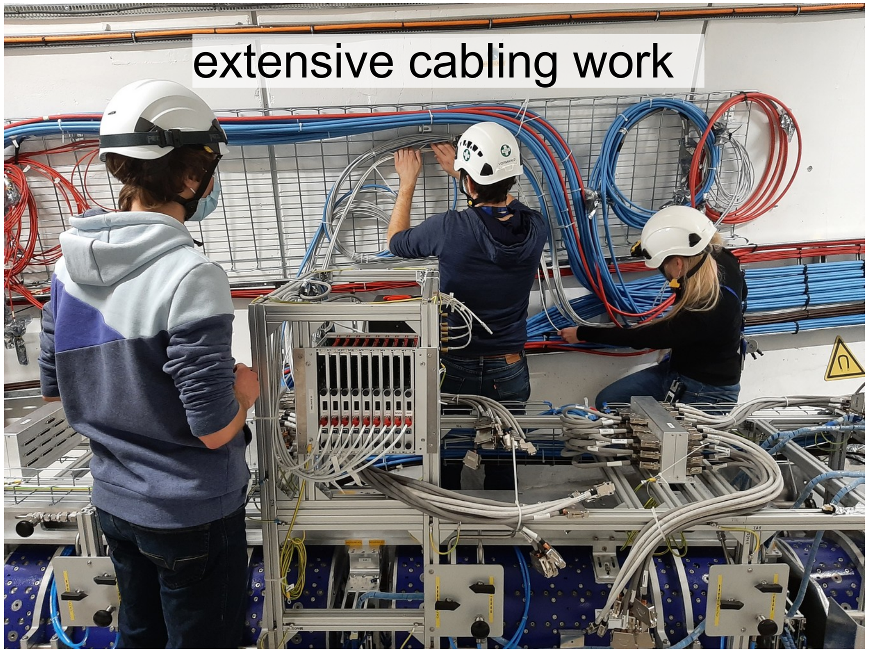
04/2020
modification of the tunnel floor


11/2020
magnets installed


04/2021
FASER detectors in place

# Installation in the LHC tunnel



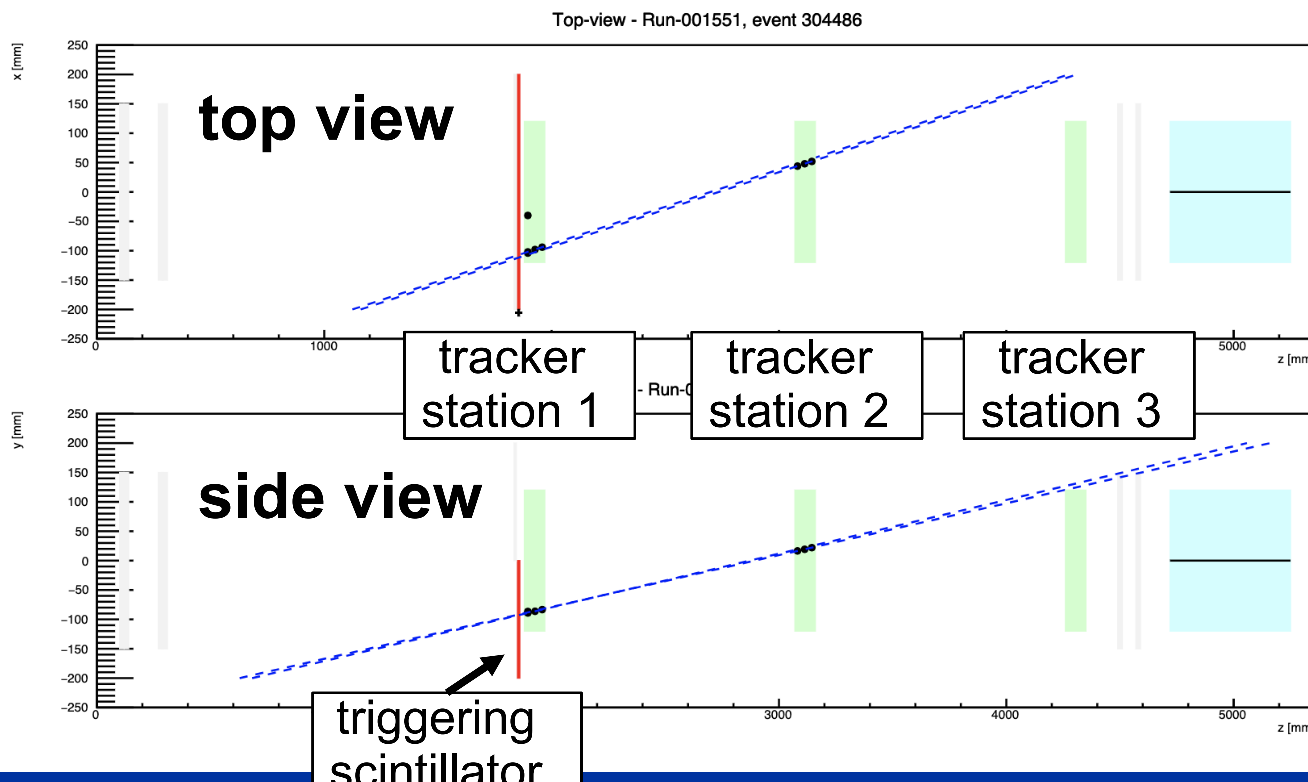





- final installation of FASER subdetectors within 3 weeks in 03/2021
- very smooth thanks to excellent cooperation between CERN transport crew, CERN cooling group and different FASER teams
- no delays or any surprises

# Remote Operation of FASER

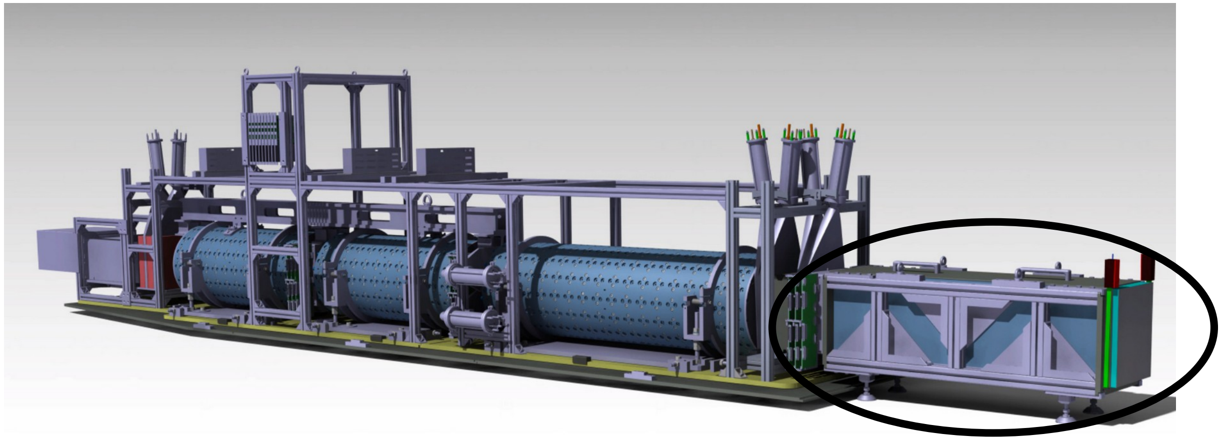
- since end 03/2021 continuous (remote) operation as complete FASER detector system
- DAQ, monitoring and control systems work flawlessly
- in the process of developing a operation model for the data taking period of LHC Run-3


- successful cosmics data taking as complete FASER detector system
- cosmics rate strongly reduced 100m below surface
- nevertheless clear cosmics events reconstructed in FASER
- still waiting for a track hitting all three tracking stations (extremely rare)

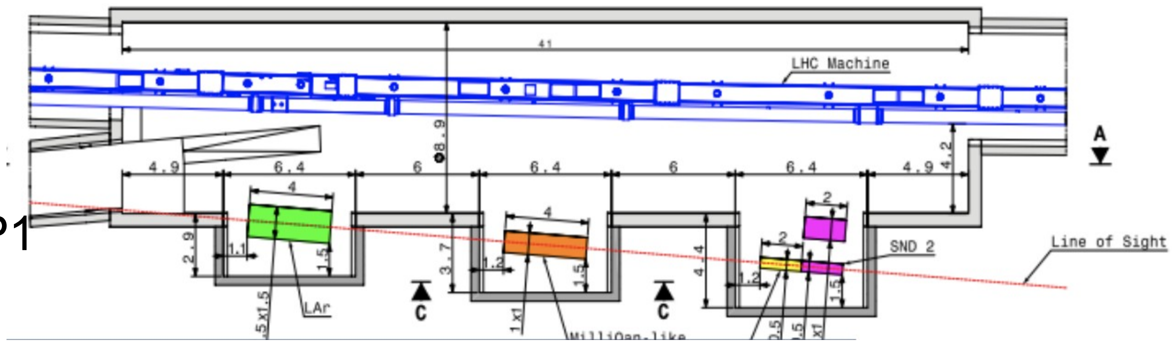
# The Future

**FASERnu**
- 1.3m extension of FASER
- emulsion detector
- sensitive to all flavours of neutrino interactions
- study of collider neutrinos!
- will be installed in October **still for Run-3**



**Detecting and studying high-energy neutrinos with FASERnu at the LHC**
Tomoko Ariga, 26 May 2021, 18:30, neutrino session
https://indico.cern.ch/event/982783/contributions/4365132/

**Forward Physics Facility**
- Ideas about larger FASER (FASER2)
- facility with other forward experiements in line of sight of IP1
- time frame: **HL-LHC**



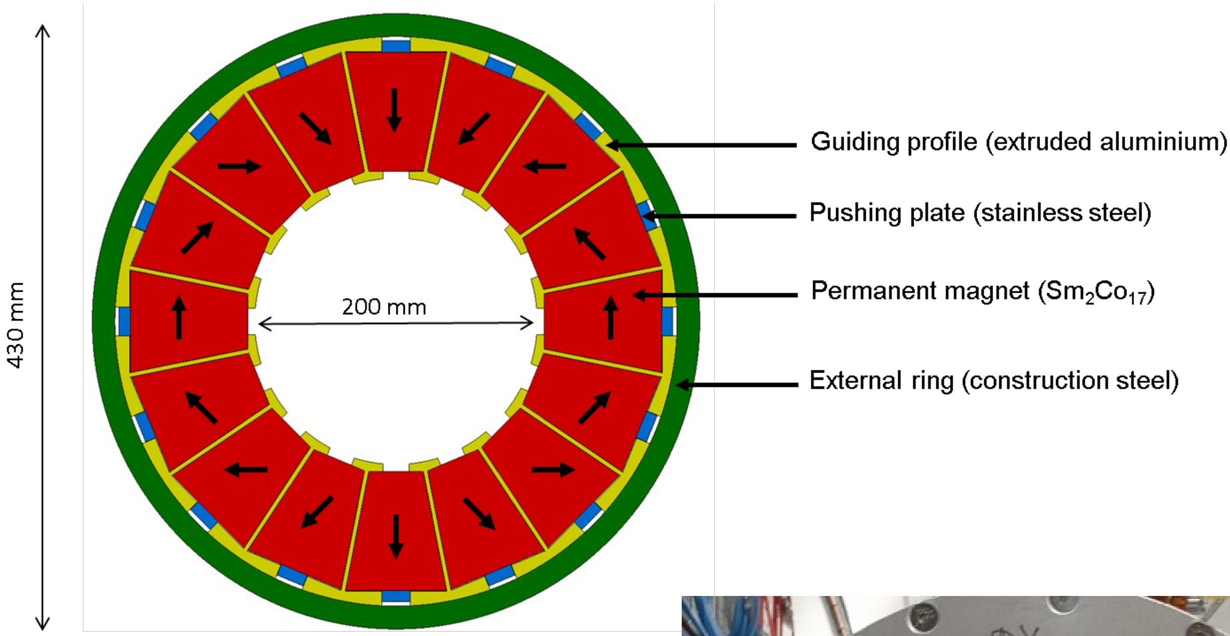

**Forward Physics Facility**
Felix Kling, 25 May 2021, 16:30, BSM session
https://indico.cern.ch/event/982783/contributions/4363954/

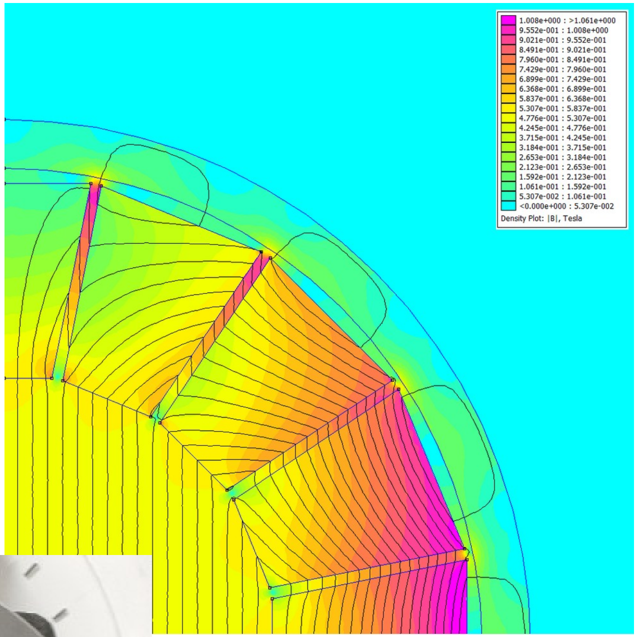
# Conclusions

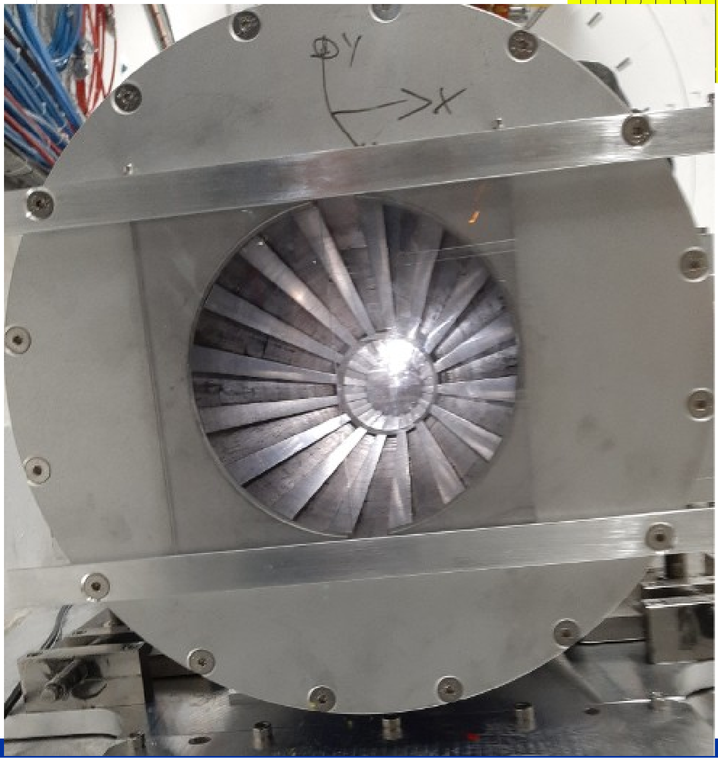
- FASER is a small and cheap experiment exploring the extreme forward direction 480m downstream of IP1
- probing for light, weakling-coupled and long-lived particles
- experiment proposed in 2017 and approved in 2019
- successful detector installation and commissioning in 03/2021
- experience from first 2 months of remote operation show very stable and reliable detector system
- FASERnu detector will be installed in October 2021
- very excited to see first data from FASER and FASERnu from collisions when LHC resumes operation in 2022

# BACKUP

# FASER magnets



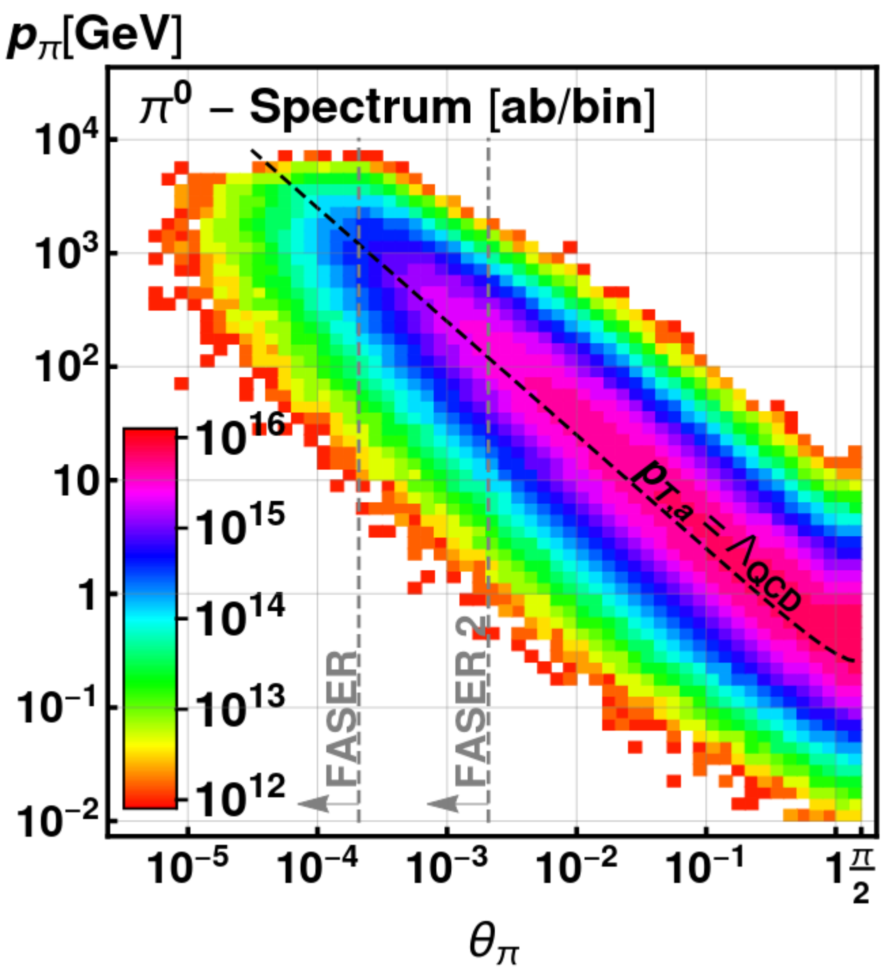





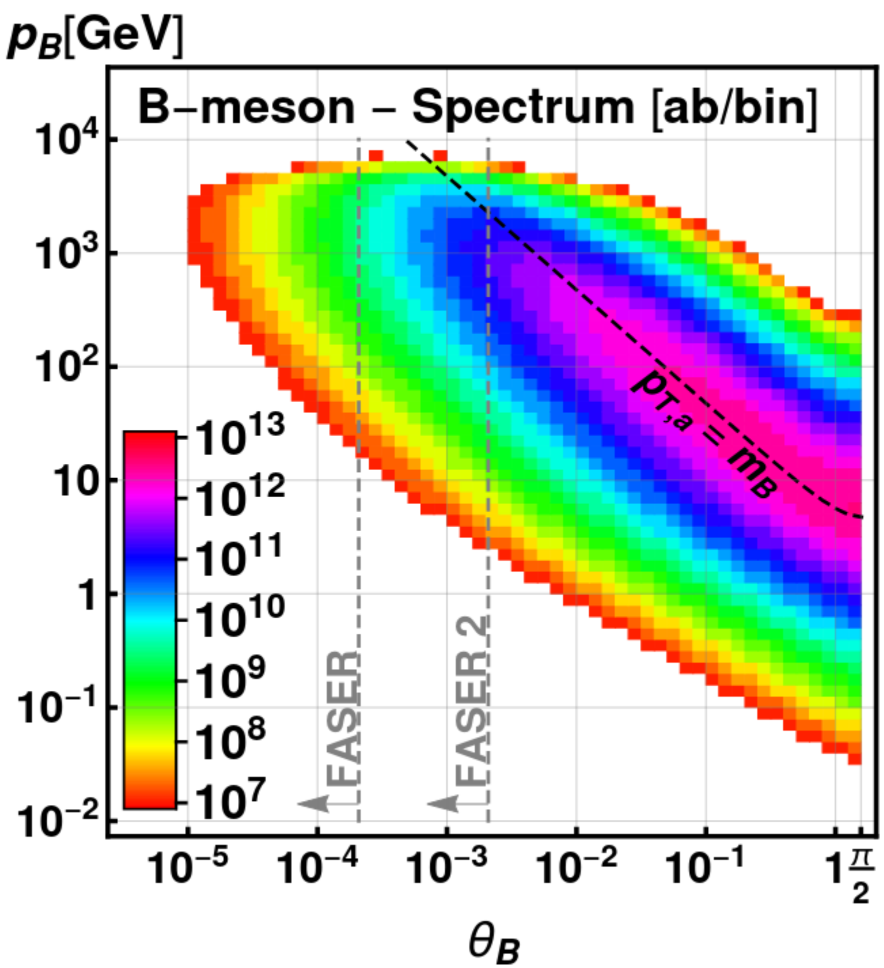
# Differential Meson Production

https://arxiv.org/pdf/1811.12522.pdf

**FASER:** $\Delta = 1.5$ m, $R = 10$ cm, $\mathcal{L} = 150$ fb$^{-1}$
**FASER 2:** $\Delta = 5$ m, $R = 1$ m, $\mathcal{L} = 3$ ab$^{-1}$ .



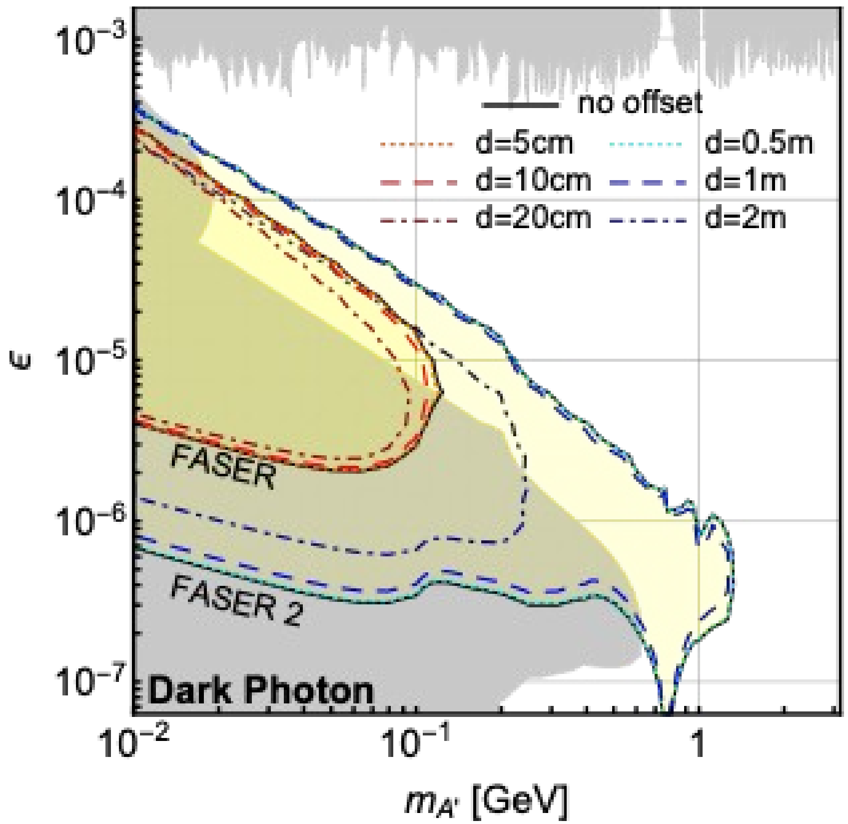

obtained via EPOS-LHC




obtained using FONLL with CTEQ6.6

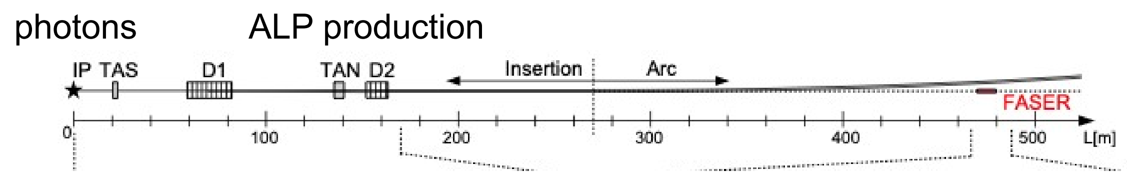
# Effect of Crossing Angle

- to avoid parasitic collisions and beam-beam effects in the common beampipe close to the IP, the LHC runs with a crossing-angle
  - the half crossing angle is ~150μrad, which moves the collision axis by ~7.5cm at the FASER location
  - such a change reduces the signal acceptance in FASER by ~25%
  - leads to very small changes in physics sensitivity

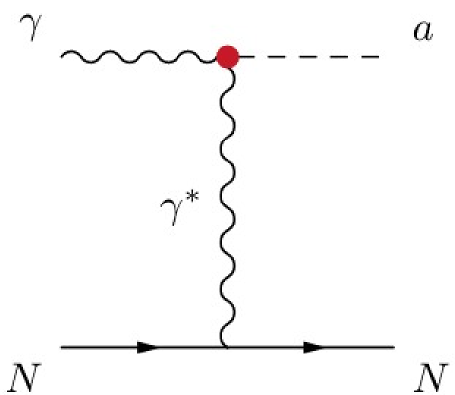


# Physics Case – Axion-like particles

## Axion-like particles



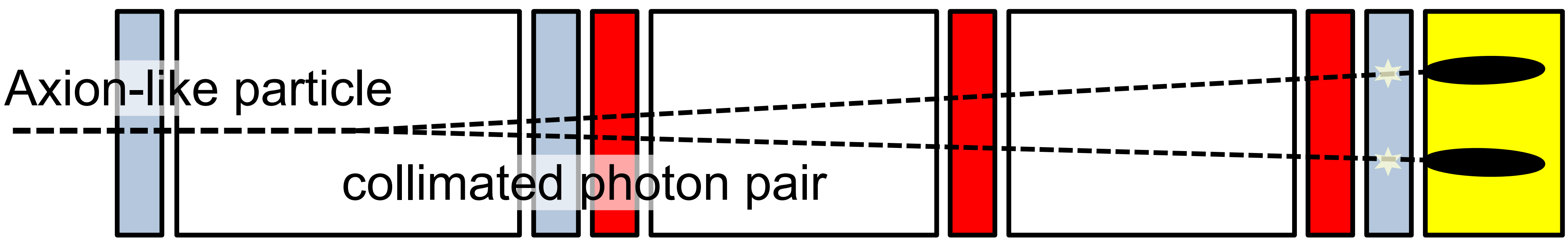

matter interaction in TAN




$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DS} - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \widetilde{F}^{\mu\nu} - \frac{g_s^2}{8} g_{agg} a G^A_{\mu\nu} \widetilde{G}^{A\mu\nu} - i \sum_f g_{aff} \frac{m_f}{v} a \bar{f} \gamma_5 f$$

signature in FASER:

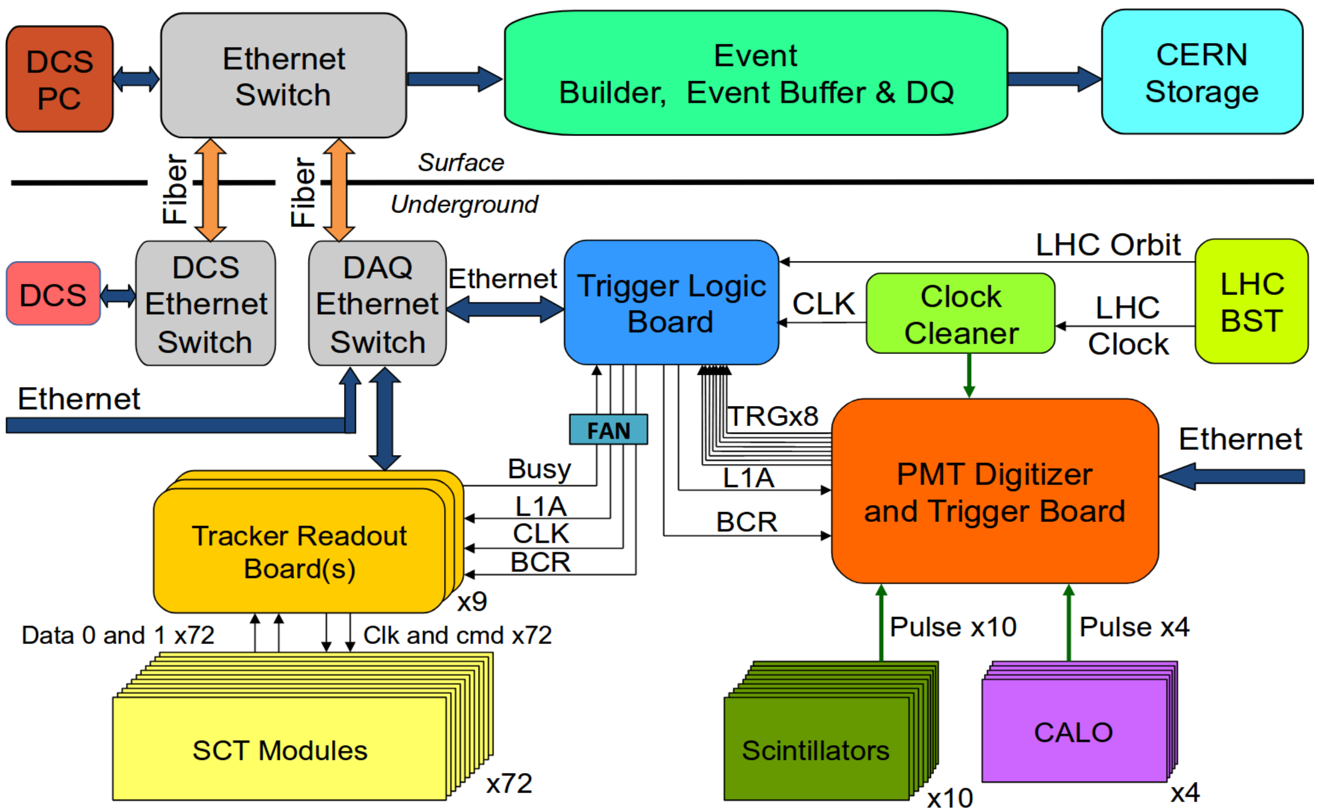
**$a \rightarrow \gamma\gamma$, …**




- very collimated photon pair (no separation due to magnetic field)
- large deposited energy in EM calorimeter with activity in pre-shower
- DIS of neutrino in ECAL potential background (!)
- importance of preshower station (finer segmentation beneficial)

# Detector Components – DAQ

- Trigger an OR of signals from scintillators and calorimeter
- Expected maximum trigger rate ~500Hz from incoming muons
- Expected maximum bandwidth ~15MB/s (evt size ~25kB dominated by PMT waveforms)
- Trigger Logic Board is same general purpose FPGA board as Tracker Readout Board but with different firmware/adapter-card
- Readout and trigger logic electronics in TI12 tunnel
- Event builder and DAQ s/w running on PC on surface (600m away)
- No trigger signals sent/received from ATLAS



# 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 Vormwald (CERN), Di Wang (Tsinghua), Gang Zhang (Tsinghua)