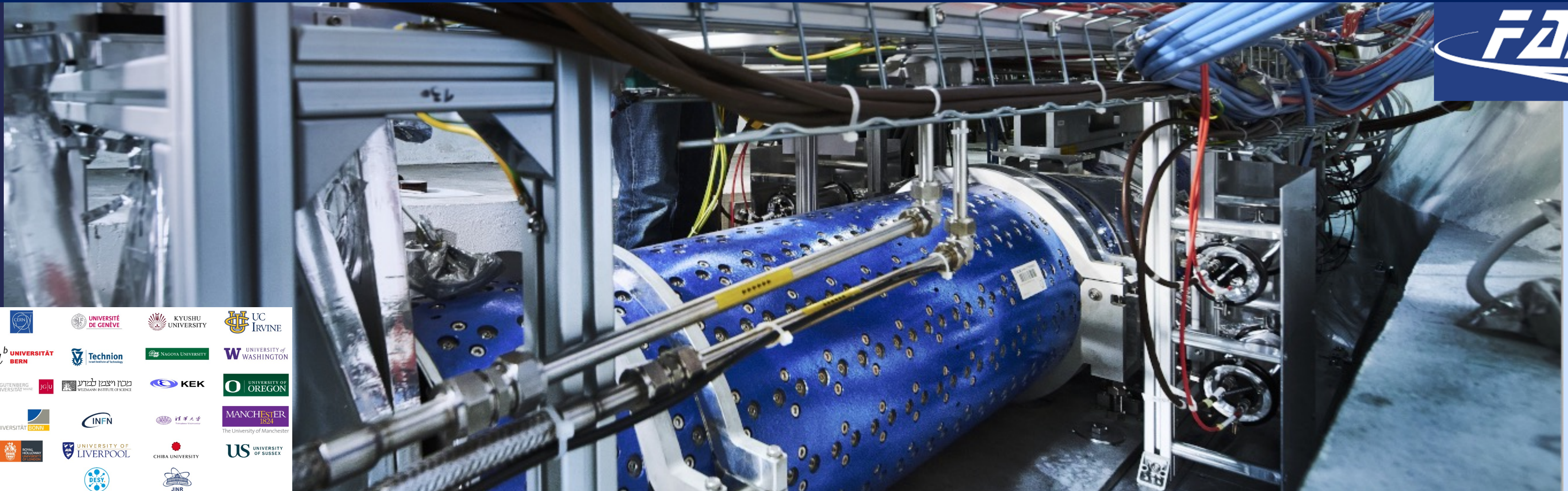
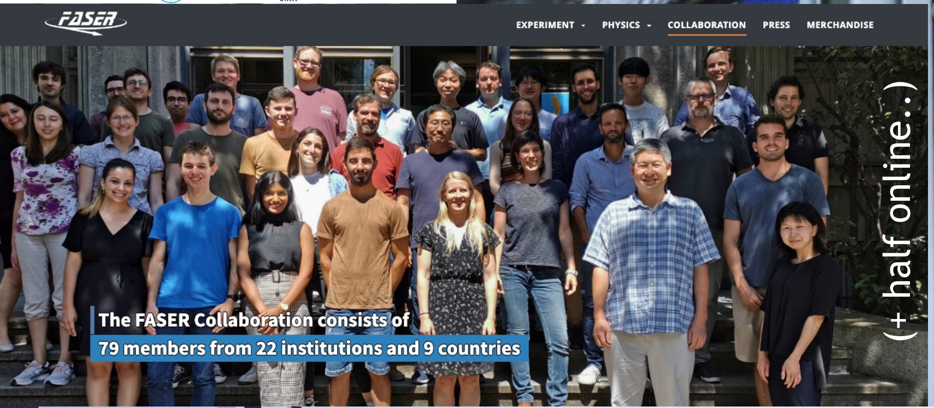
The FASER experiment



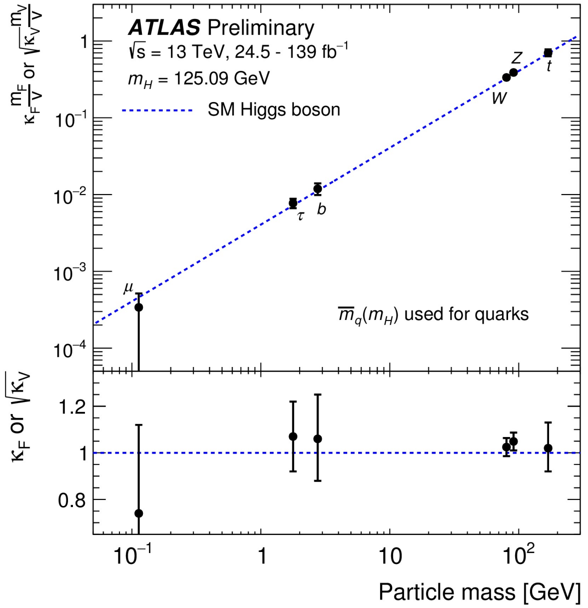


Monica D'Onofrio
University of Liverpool

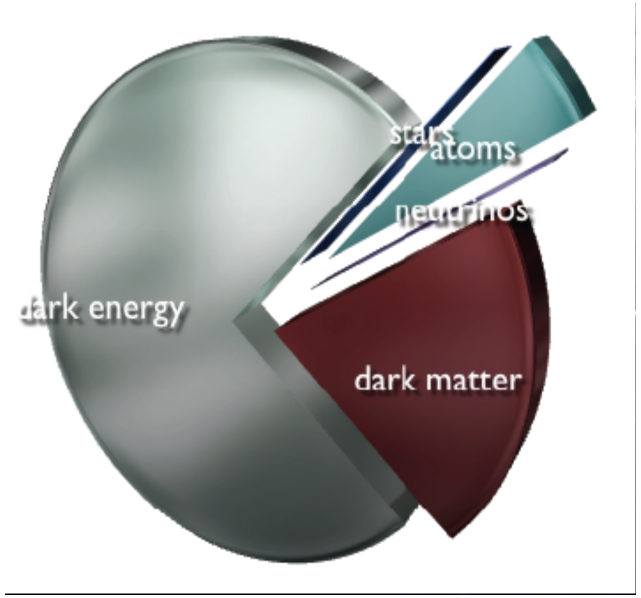
Seminar, Birmingham, 23/11/2022

The Standard Model and its missing bits

- The Standard Model of particle physics is certainly a successful effective theory that describes well our (ewk-scale) world
  - The discovery of the Higgs boson and the precision measurements performed so far have cast a milestone. E.g.
    - Couplings with quarks and leptons
    - (very recently) Evidence of off-shell Higgs production and measurement of total Higgs width $\Gamma_H = 4.6 +2.6{-}2.5$ **MeV**



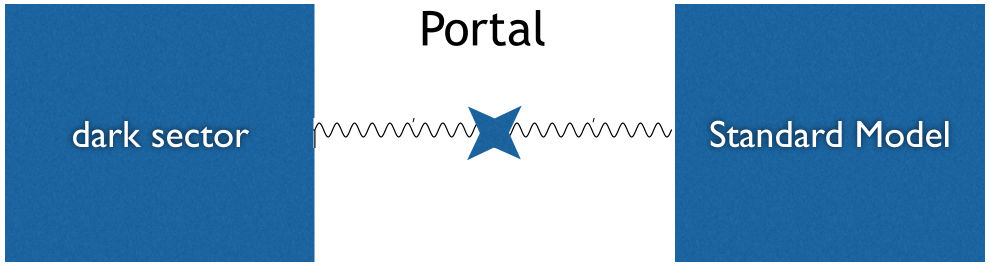
- However, we know that the SM is incomplete
  - No gravity embedded in it
  - No unification of forces at high energies
  - No explanation on Higgs (and other particles) mass(es)
  - No explanation on why we are here as 'matter' (matter-antimatter asymmetry)
  - No explanation of the Universe mass → **dark matter**!



- The nature of Dark Matter (DM) is unknown, so understanding it it is one of the biggest challenges of particle physics nowadays

The quest for a hidden, dark sector

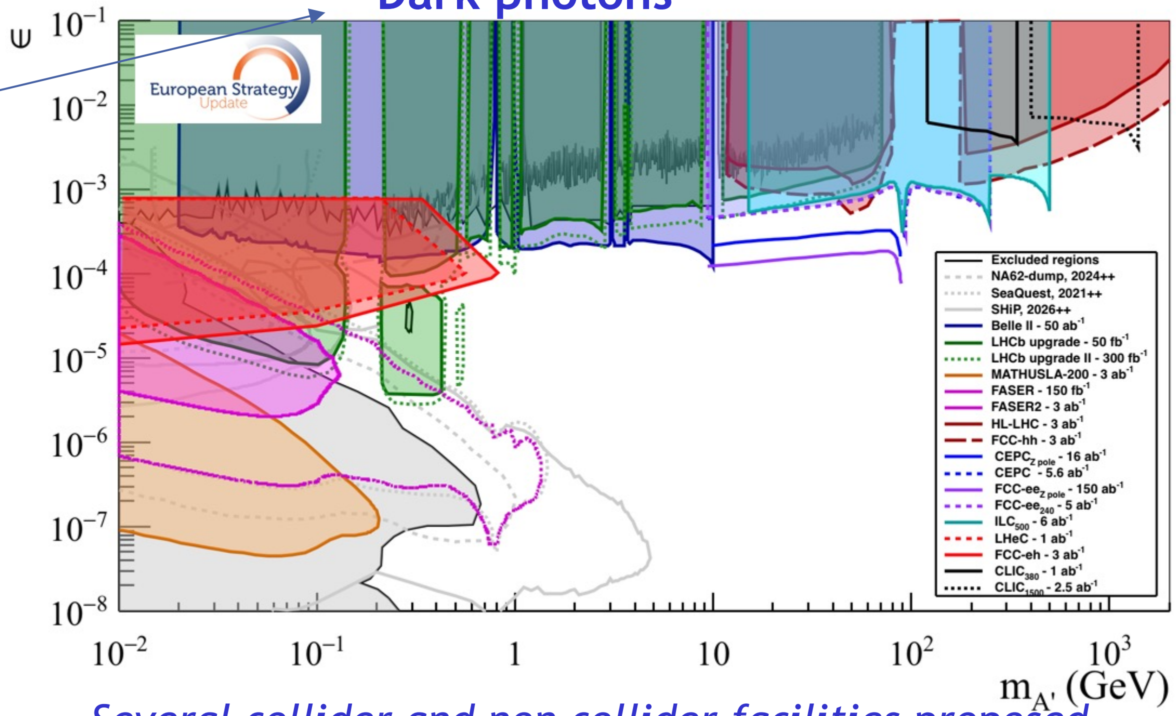
- DM could be just one of the many new particles belonging to a 'hidden' dark sector (DS)



- The mechanism of portals as the lowest canonical-dimension operators that mix new dark-sector states with gauge-invariant combinations of SM fields is often considered, with 4 notable examples (**benchmarks**):

Portal	Coupling
Vector (Dark Photon, A_μ)	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Scalar (Dark Higgs, S)	$(\mu S + \lambda_{HS} S^2) H^\dagger H$
Fermion (Sterile Neutrino, N)	$y_N LHN$
Pseudo-scalar (Axion, a)	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$

Dark photons



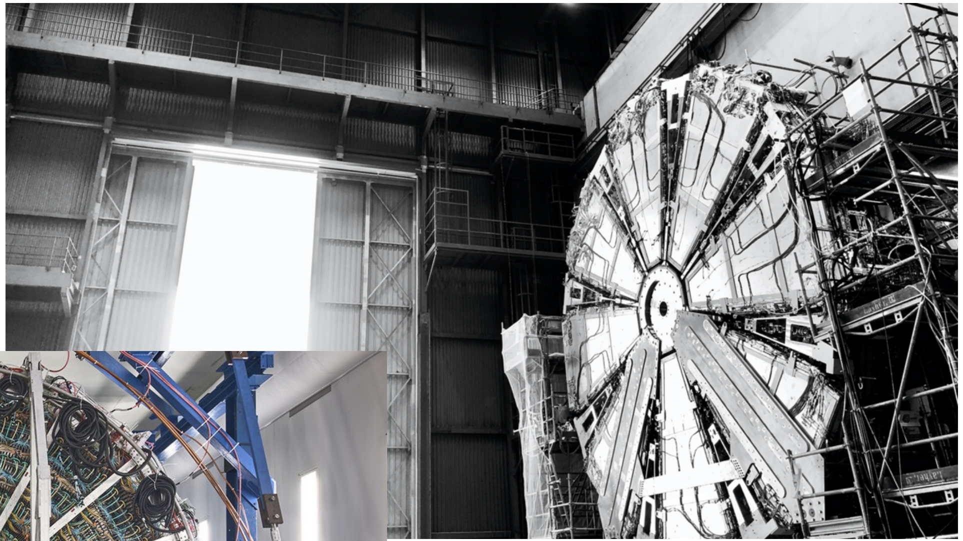
Several collider and non collider facilities proposed, solid lines show were we are…

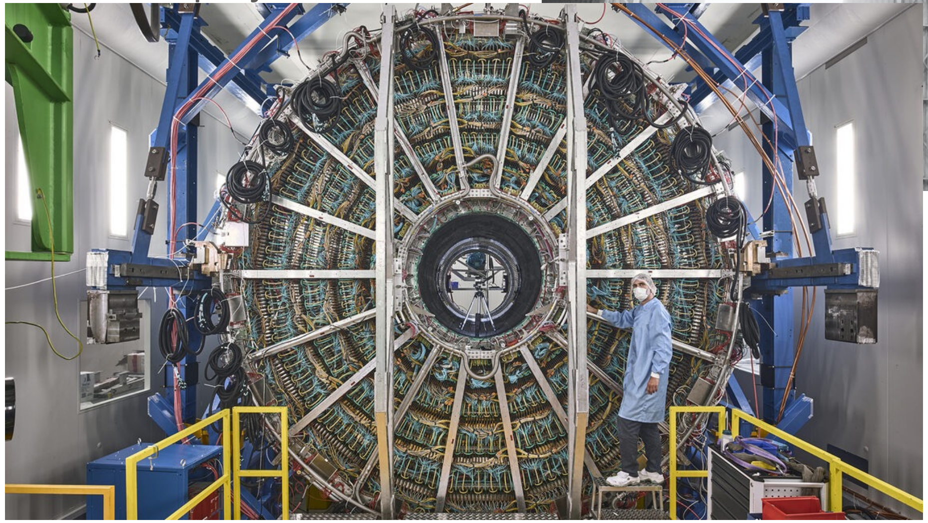
- The resulting new particles could be Long-Lived (LLP)
  - Lifetime related to SM-DS mixing coupling ε
- Targeted searches for these BSM models have been identified as a priority by the European Strategy Updated and the Snowmass process

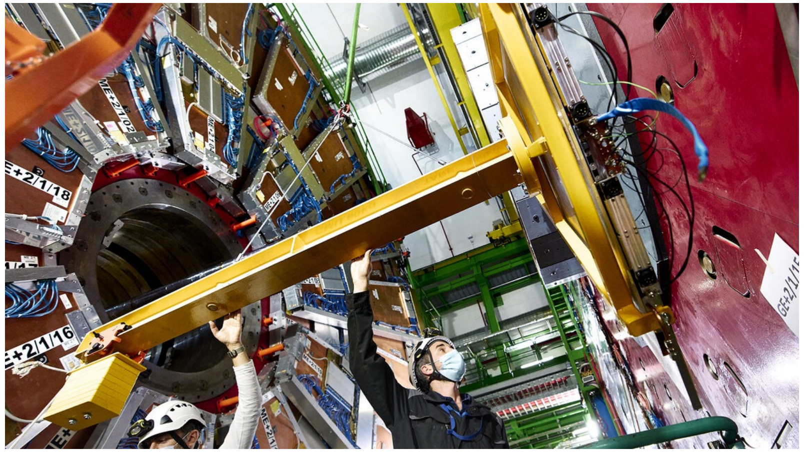
The LHC (main) experiments

- Dark sectors are certainly part of the LHC experiments programmes
- The Run 3 has just started, with exciting opportunities offered by the **upgrade of the accelerator**, leading to an increased centre-of-mass energy (13.6 TeV), **renewed detectors** and **novel triggers**


LHCb's Vertex Locator (VELO)


ATLAS New Small Wheel

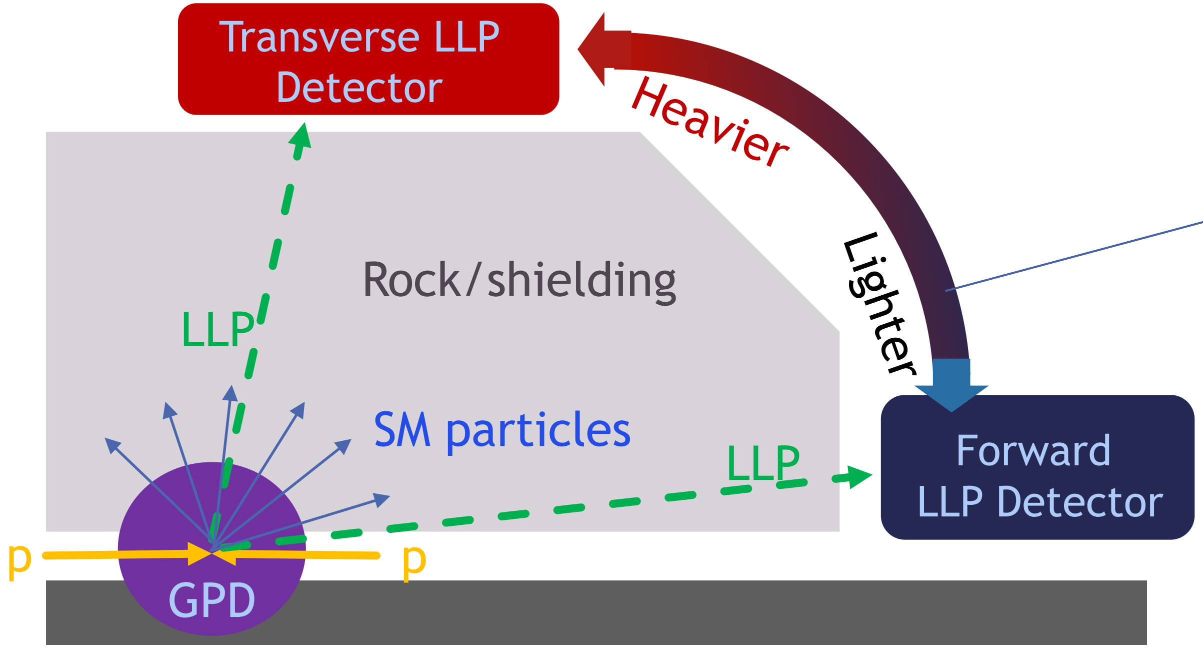
ALICE time-projection chamber


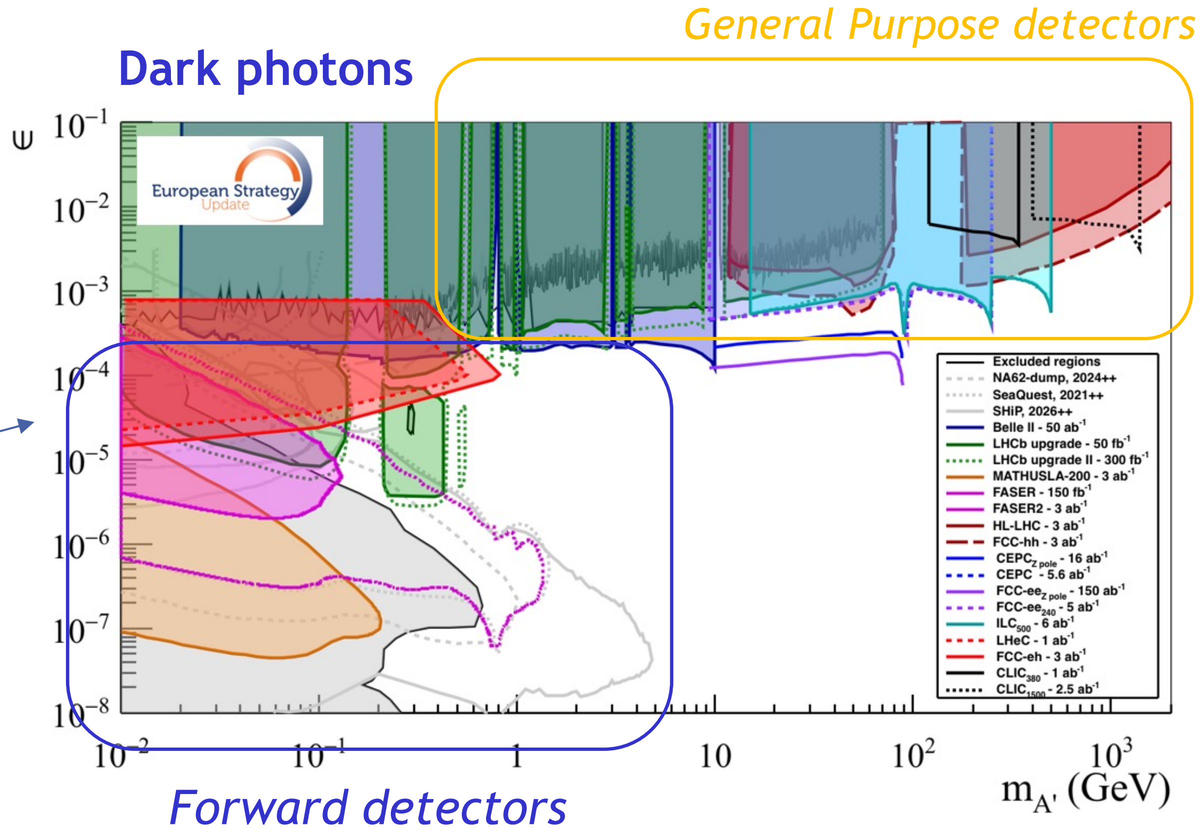
CMS Gas Electron Multiplier


FASER and the DS: Motivation

- **So, why dedicated experiments?** → might complement LHC main experiments in terms of targeted phase space and mitigate issues – notably, large background rates and difficulties in triggering
- Idea of **FASER**: a Forward Detector for low-mass LLPs
  - Background mitigated by rock/shielding
  - Simpler / no triggering needed

Credits to C. Gwilliam





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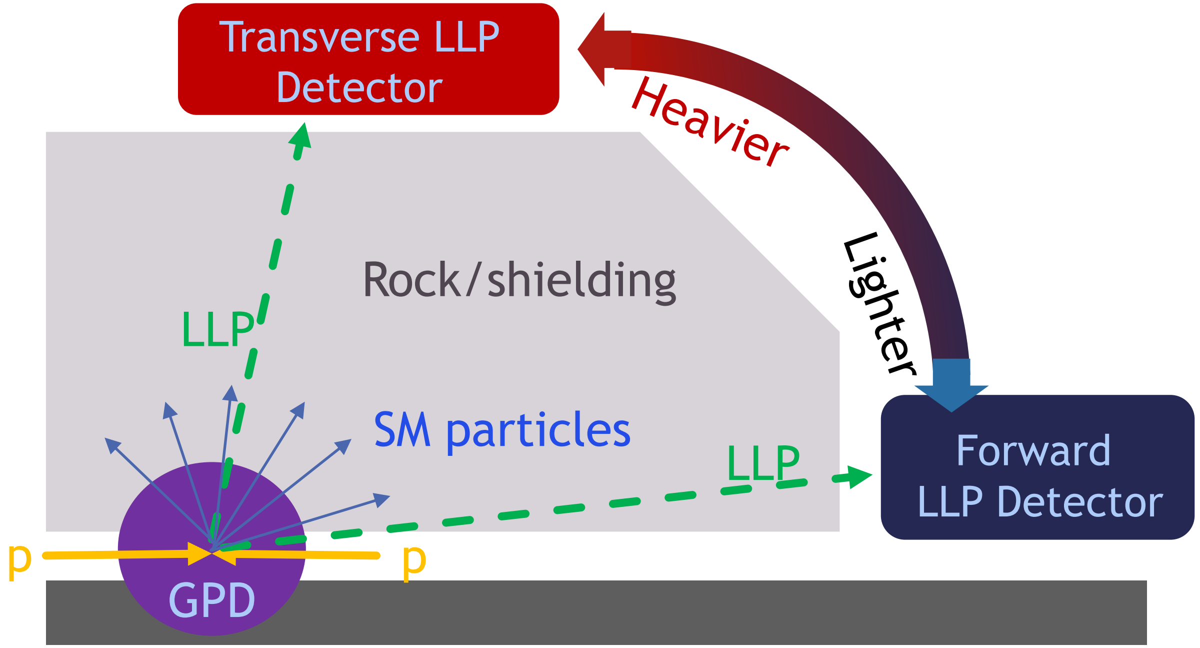
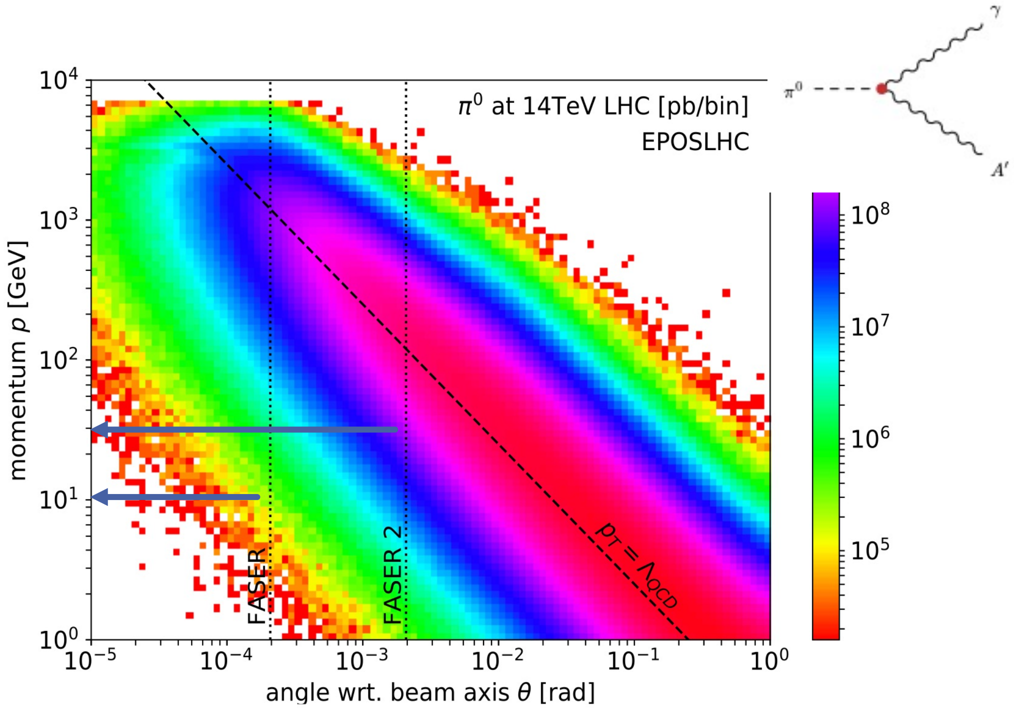


https://arxiv.org/pdf/2105.07077.pdf

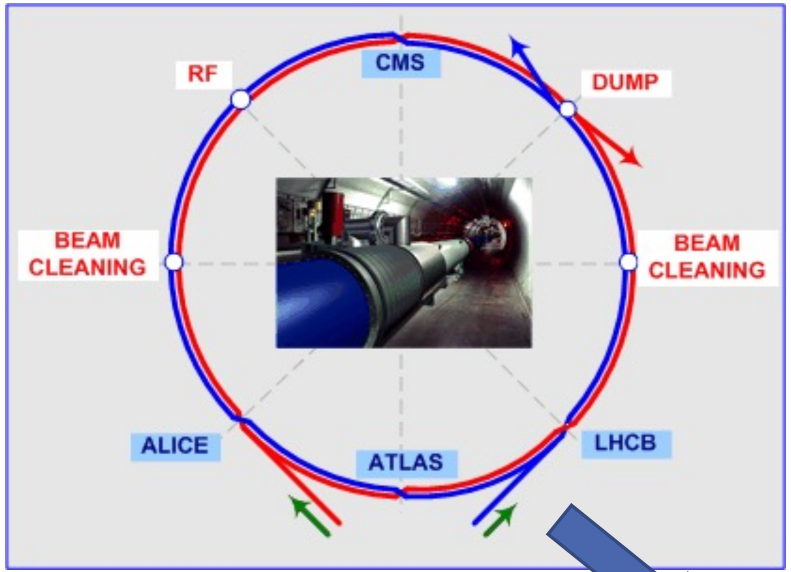


Detector is far from IP → target **long lifetimes**

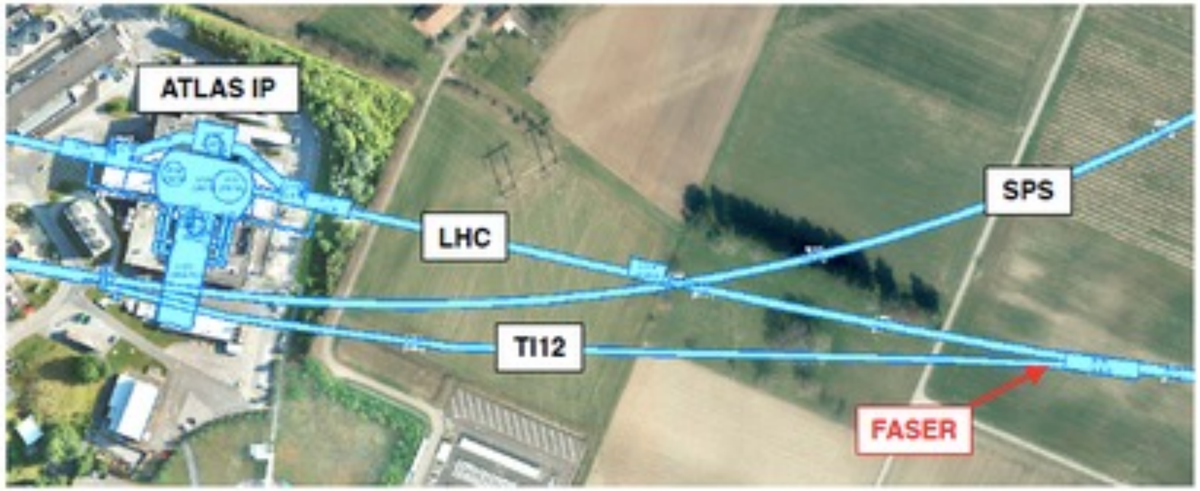
LLPs produced in forward-peaked light hadron decays → e.g. O(10[14]) pions within FASER angular acceptance

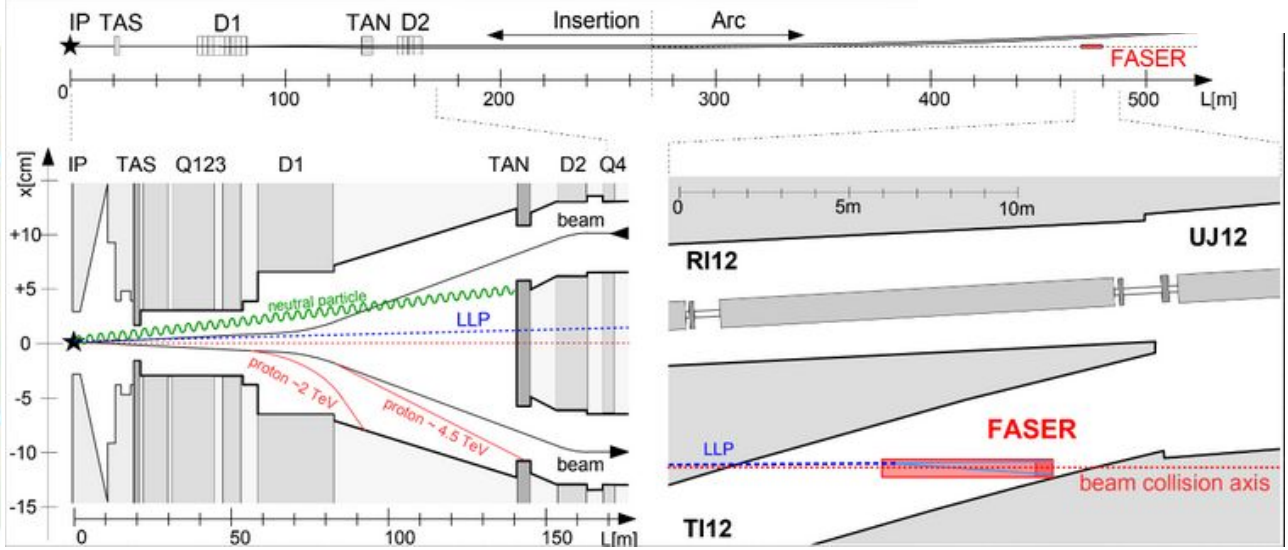
$$\theta \simeq \tan\theta = \frac{p_T}{p} \sim \frac{m}{E} \ll 1$$

FASER location



- FASER is located at ~ 480 m downstream of the ATLAS interaction point (IP) in the TI12 – an unused SPS maintenance tunnel intersecting collision axis
- The beam is highly collimated (mrad diameter) → only a small detector needed, with a magnet aperture of 20cm diameter
- Infrastructure & rock catches most collision products





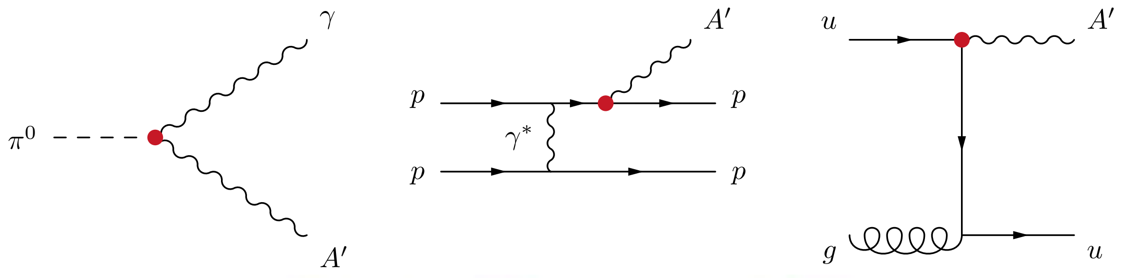
FASER Physics reach

- Designed for events of the kind

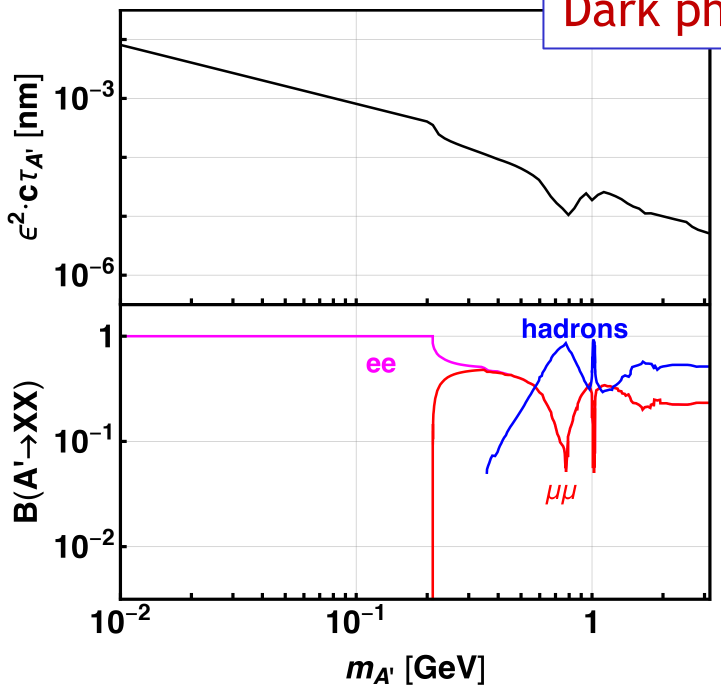
  pp → LLP, LLP travels ~480m, LLP → ee, γγ, μμ, …

- Probes large range of BSM models in regions favoured according to muon g-2, DM hypotheses and anomalies
  - **Dark photons models:**

Dark photon production

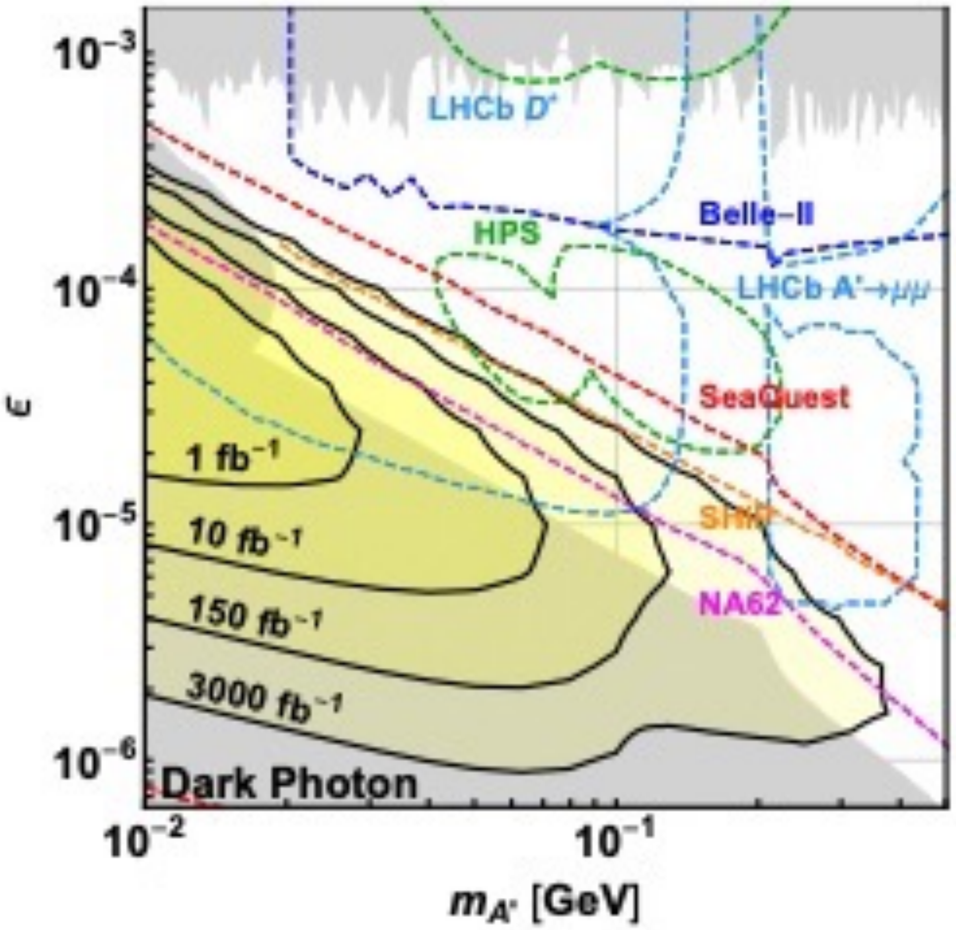


Dark photon decays



$$\tau \propto \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100\ \text{MeV}}{m_{\gamma_d}}\right)$$

Sensitivity to dark photon already with few fb^{-1}



FASER Physics reach (2)

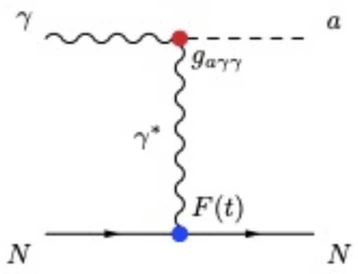
- Also sensitive to axion-like particles (**ALPS**), new particles that can mediate the interactions between the SM and the hidden sector by coupling to **photons**, gluons, W and Z bosons, and fermions.

Still produced and decaying as:

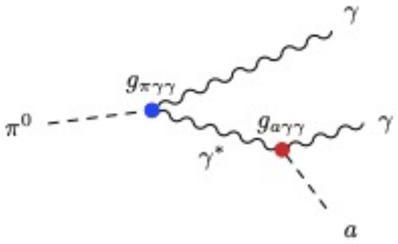
pp → LLP, LLP travels ~480m, LLP → ee, γγ, μμ, …

ALPs production

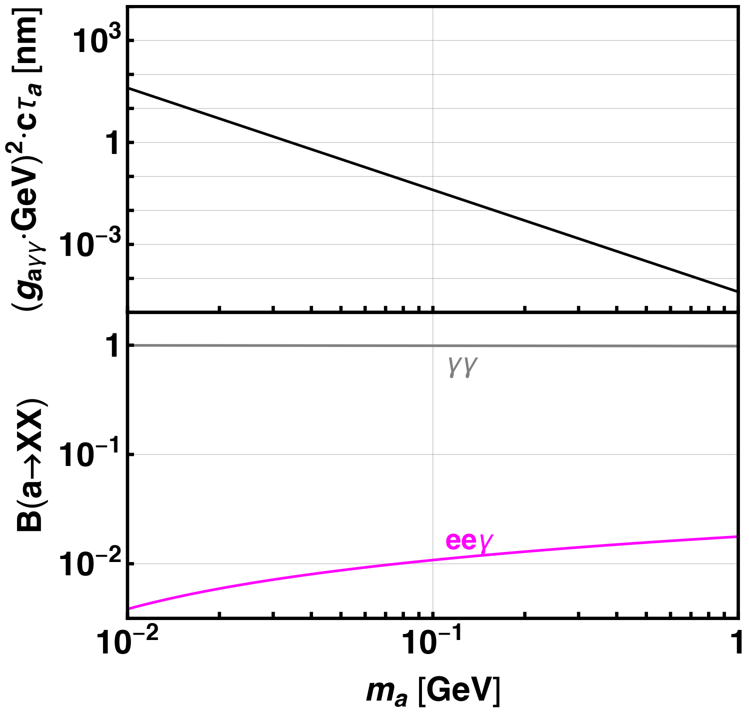
Primakoff process

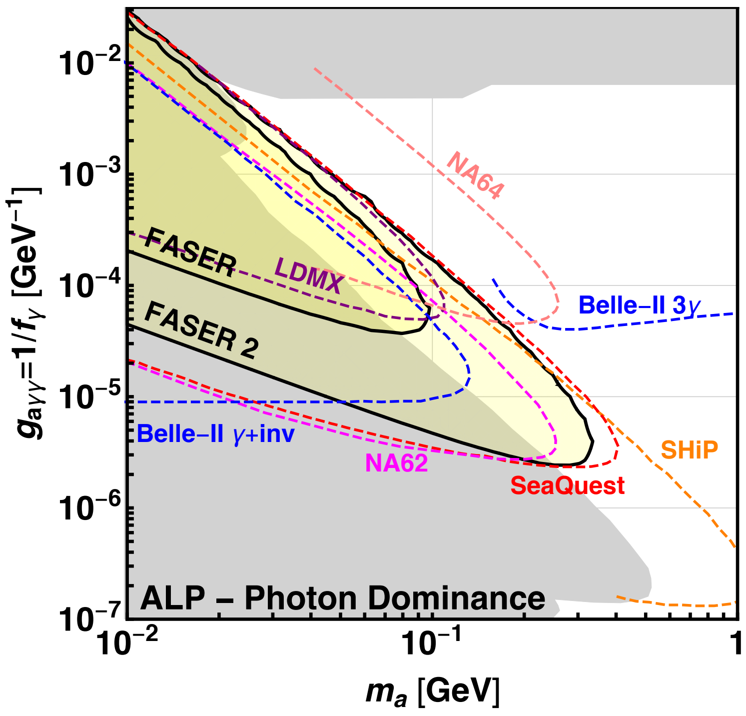


Light meson decays



ALPs decay, e.g. $\Gamma(a \to \gamma\gamma) = \frac{g^2_{a\gamma\gamma} m_a^3}{64\pi}$

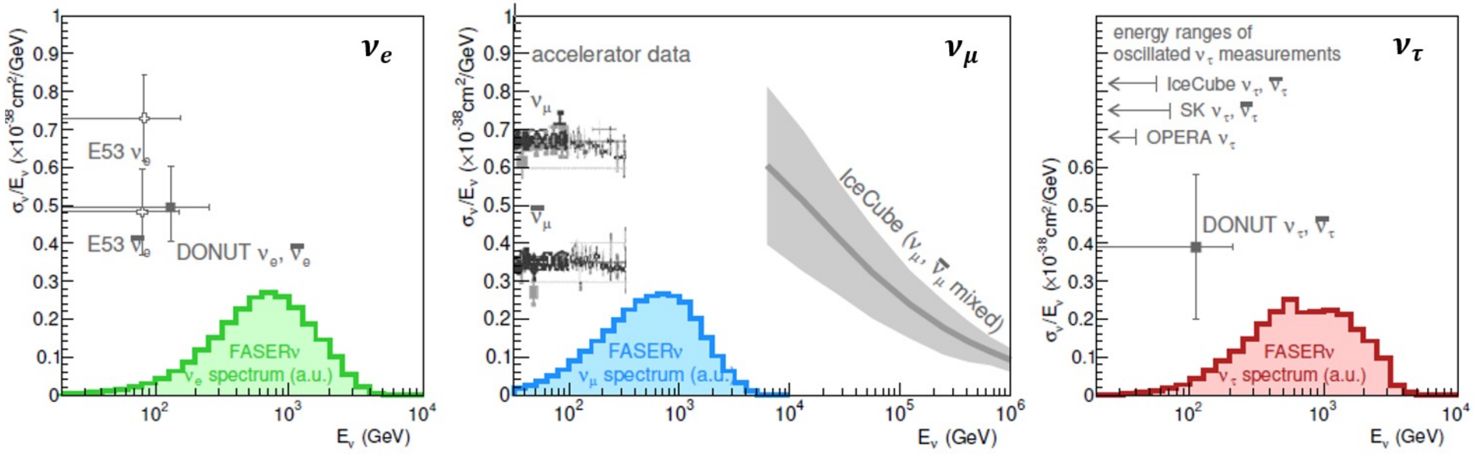




- Other targeted models: Dark Higgses, Heavy Neutral leptons, etc.

FASER ν Physics reach

- FASER is also sensitive to high-energy neutrinos produced along beamline !
    - A dedicated component, **FASERν**, has been added in 2020 to study an uncovered range of energies for ν



Expected number of charged current neutrino interaction events (for 250 fb^{-1})
based on "F. Kling and L.J. Nevay, Forward Neutrino Fluxes at the LHC, Phys. Rev. D 104, 113008"

Generators		FASERν			SND@LHC		
light hadrons	heavy hadrons	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
SIBYLL	SIBYLL	1501	7971	24.5	223	1316	12.6
DPMJET	DPMJET	5761	11813	161	658	1723	31
EPOSLHC	Pythia8 (Hard)	2521	9841	57	445	1871	19.2
QGSJET	Pythia8 (Soft)	1616	8918	26.8	308	1691	12
Combination (all)		2850^{+2910}_{-1348}	9636^{+2176}_{-1663}	67.5^{+94}_{-43}	408^{+248}_{-185}	1651^{+220}_{-333}	$18.8^{+12}_{-6.6}$
Combination (w/o DPMJET)		1880^{+641}_{-378}	8910^{+930}_{-938}	$36^{+20.8}_{-11.5}$	325^{+118}_{-101}	1626^{+243}_{-308}	$14.6^{+4.5}_{-2.5}$

Expected number of charged current neutrino interaction events occurring in FASERν and SND@LHC assuming 250 fb-1 Run 3 lumi.

Predictions from different MC generators differ substantially

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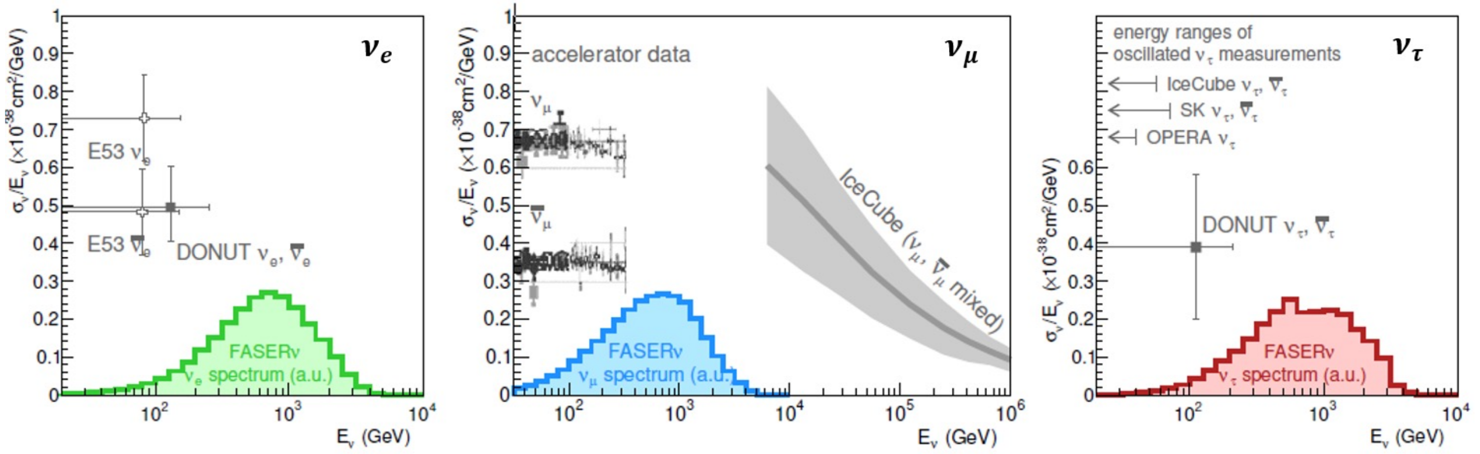
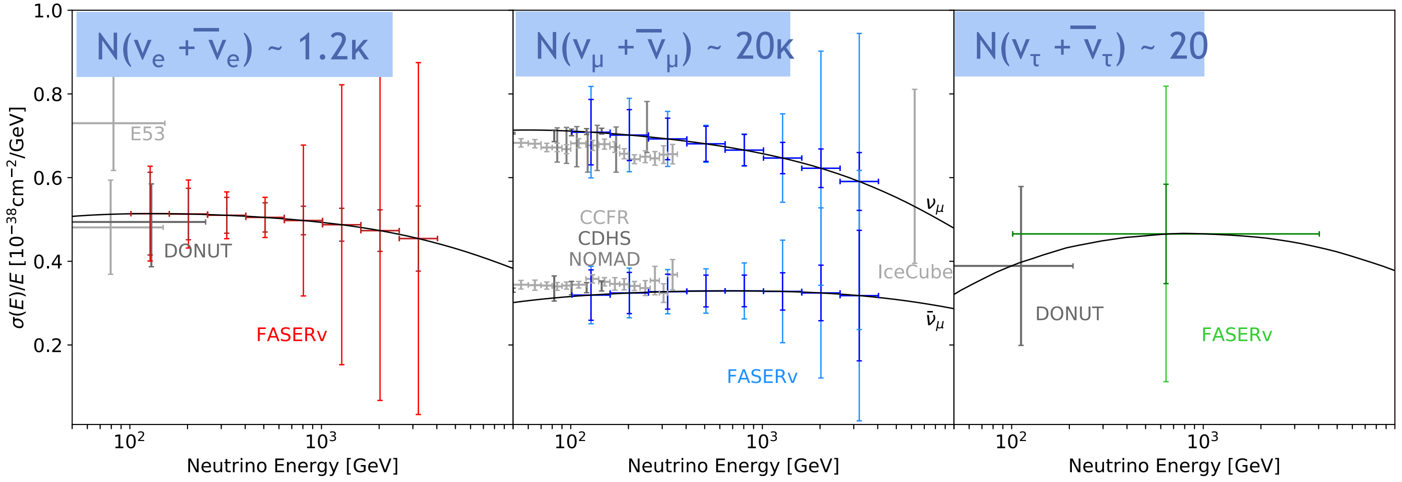


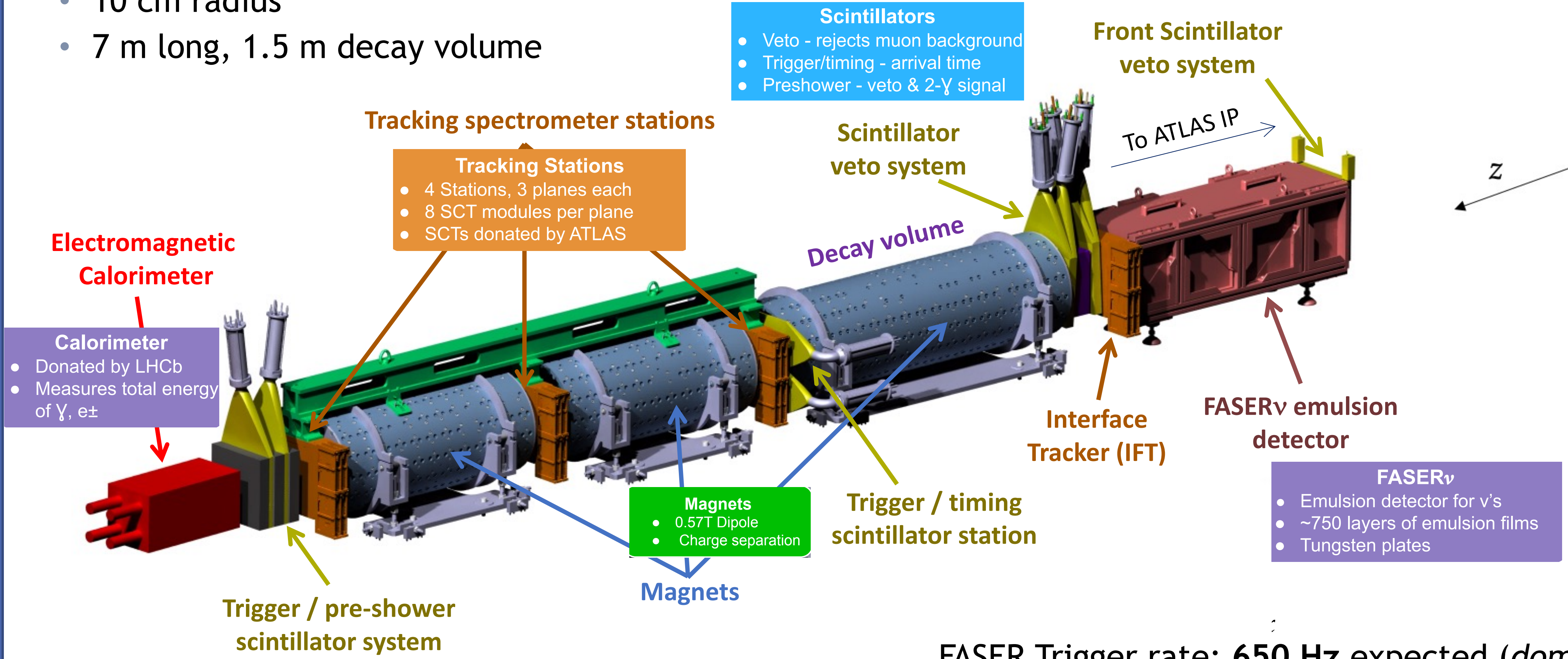
Given the large expected number of charged current neutrino interaction events



- Cross-section measurements possible for all neutrino flavours in E range from ~ 100 GeV to ~1 TeV
  - Unconstrained region of phase space

Overview of the FASER detector

- 10 cm radius
- 7 m long, 1.5 m decay volume



Angular acceptance $|\theta| < 0.21$ mrad region, $\eta > 9.2$

FASERν extends $|\theta|$ to 0.41 mrad and $\eta \sim 8.5$

FASER Trigger rate: **650 Hz** expected (*dominated by muons produced close to the IP*) *2021 JINST 16 P12028*

Very low radiation levels

Detector paper: https://arxiv.org/abs/2207.11427

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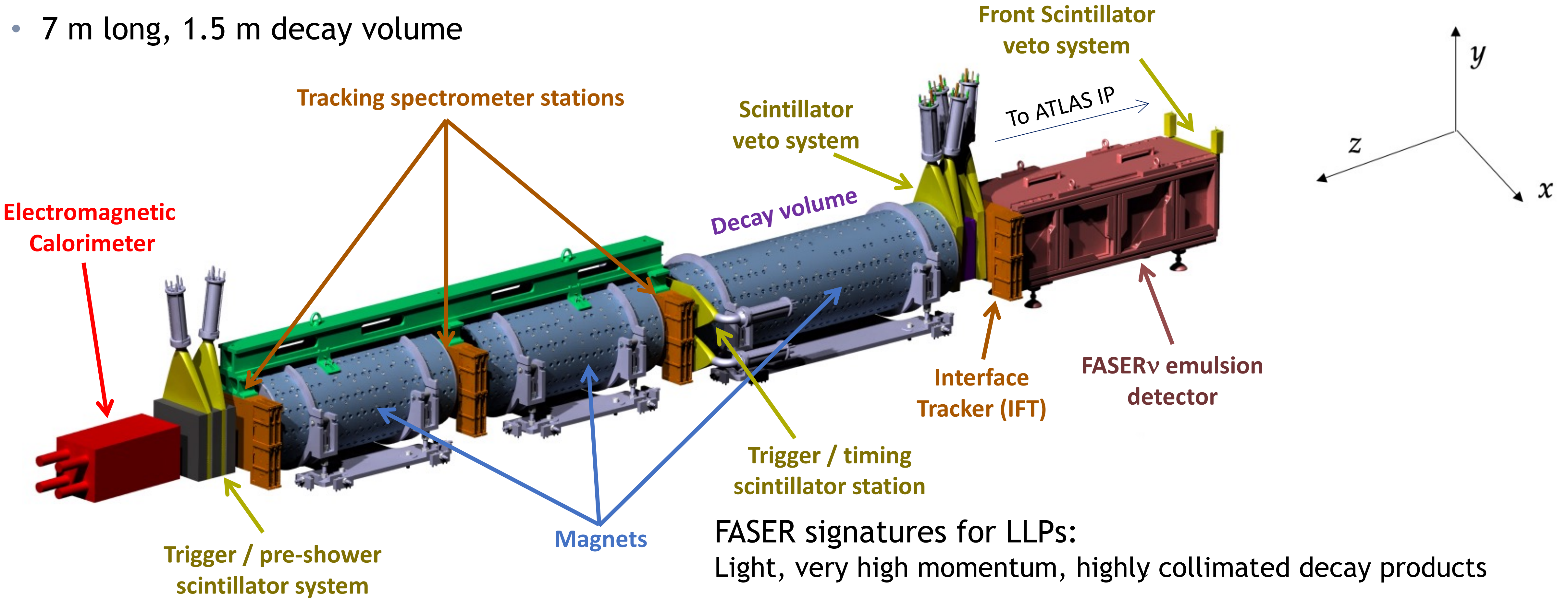
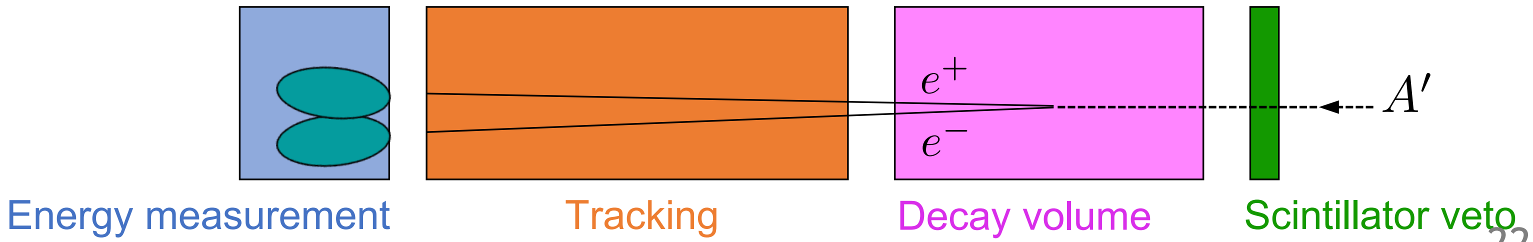


FASER signatures for LLPs:
Light, very high momentum, highly collimated decay products



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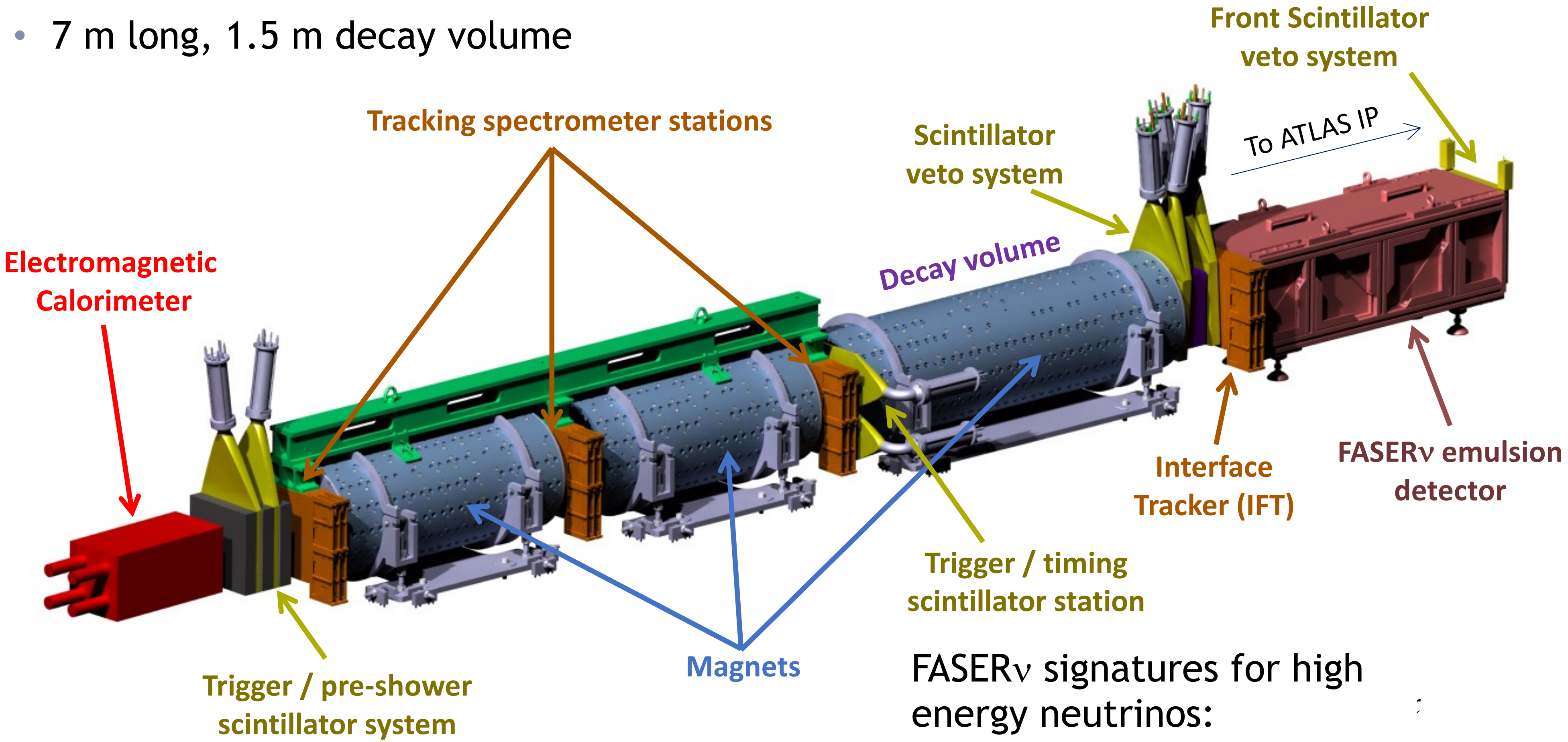
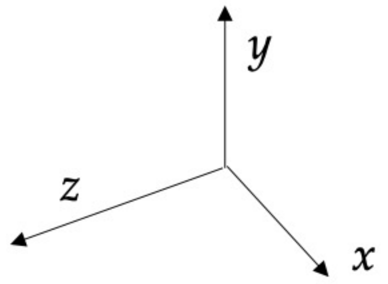
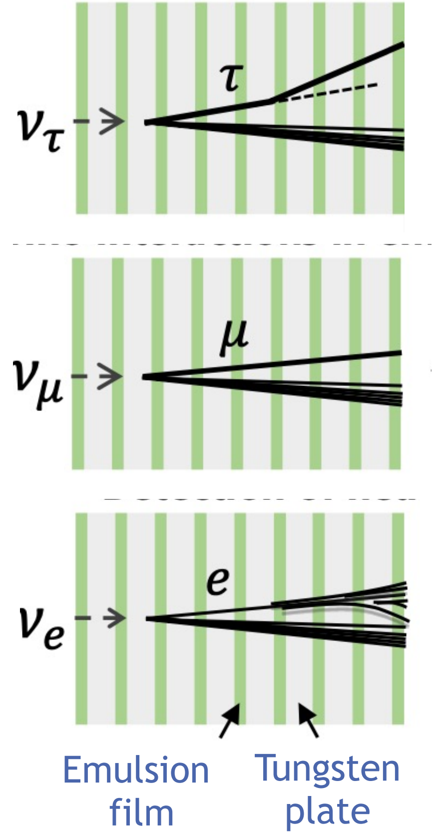
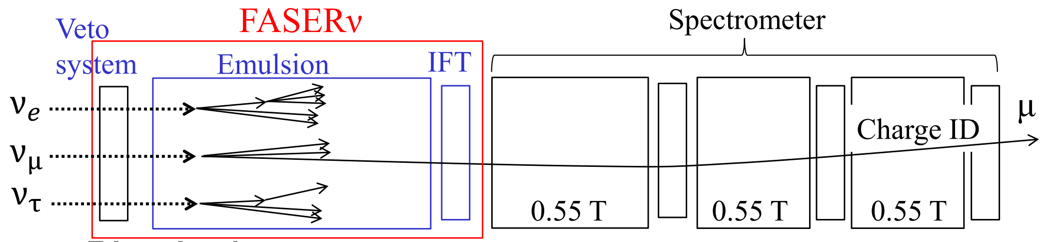




FASERν signatures for high energy neutrinos:





FASER Tracking: components and layout

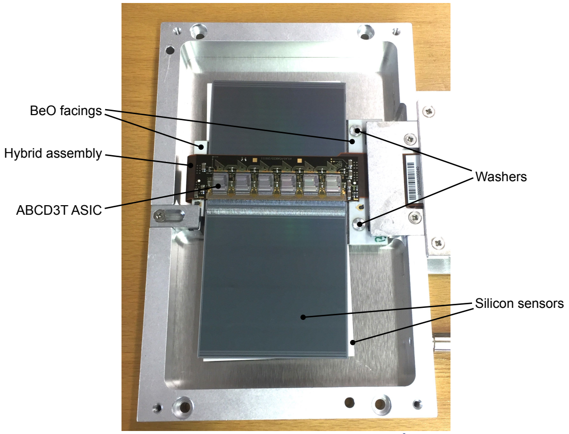
NIMA 166825 (2022)

Composed of two distinct parts: the tracking spectrometer (3 tracking stations) and the Interface Tracker (1 tracking station), placed after the FASERν emulsion detector

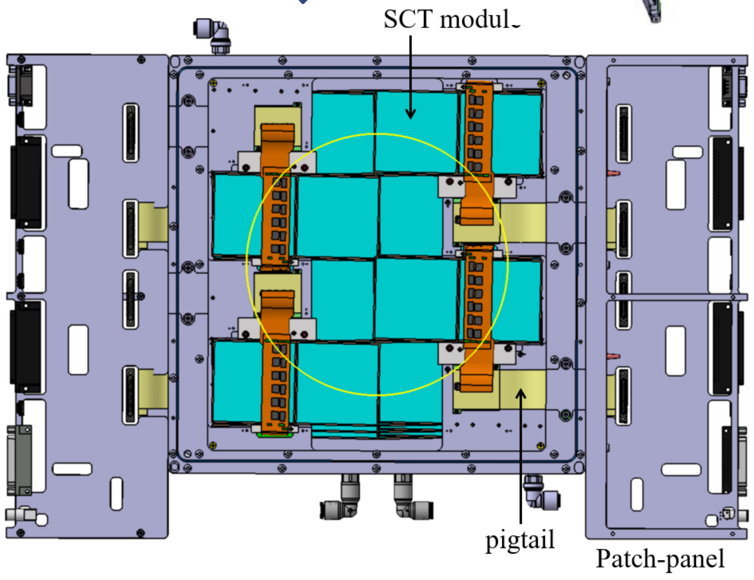
Basic component: **SCT Module**

→ **Strip detector,** pitch 80um and stereo-angle of 40mrad.

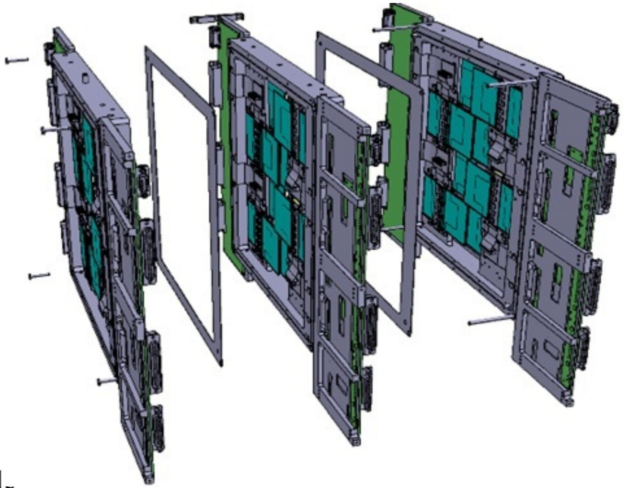
→ 8 modules per tracker plane



Tracker Plane



Tracking Station



3 Tracker planes per station (12 total)

Low material central region: 2.1% radiation length

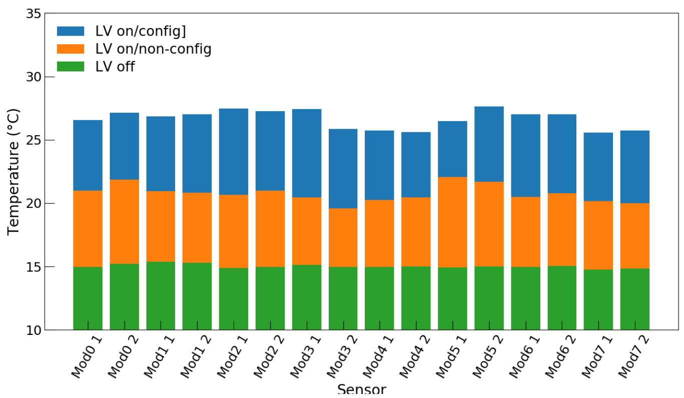
Component	Material	Number / station	X_0 (%) Central region	X_0 (%) Edge region
Silicon sensor	Si	6	1.8%	1.8%
Station Covers	CFRP	2	0.3%	0.3%
SCT module support	TPG	3	-	0.6%
C-C Hybrid	C (based)	3	-	2.2%
ABCD chips	Si	3	-	6.5%
Layer frame	Al	3	-	10.1%
Total / station	**-**	**-**	**2.1%**	**21.5%**

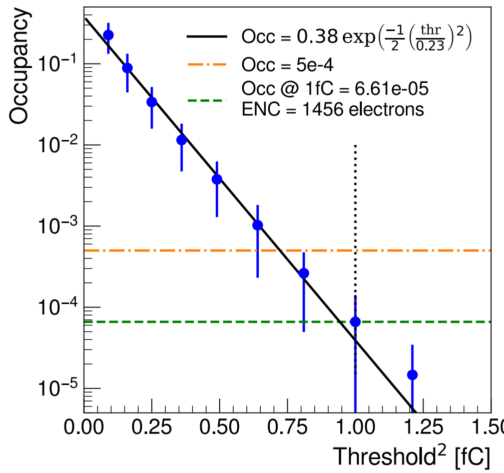
FASER Tracking: tests and performance

NIMA 166825 (2022)

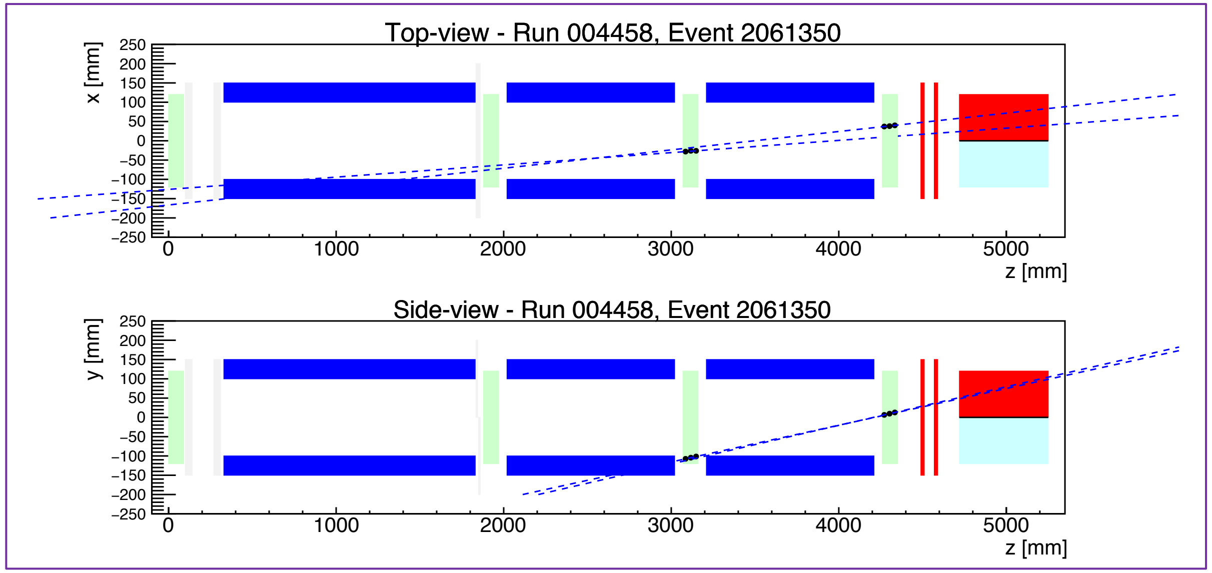
Extensive tests have been carried out to evaluate performance, standalone and after installation:

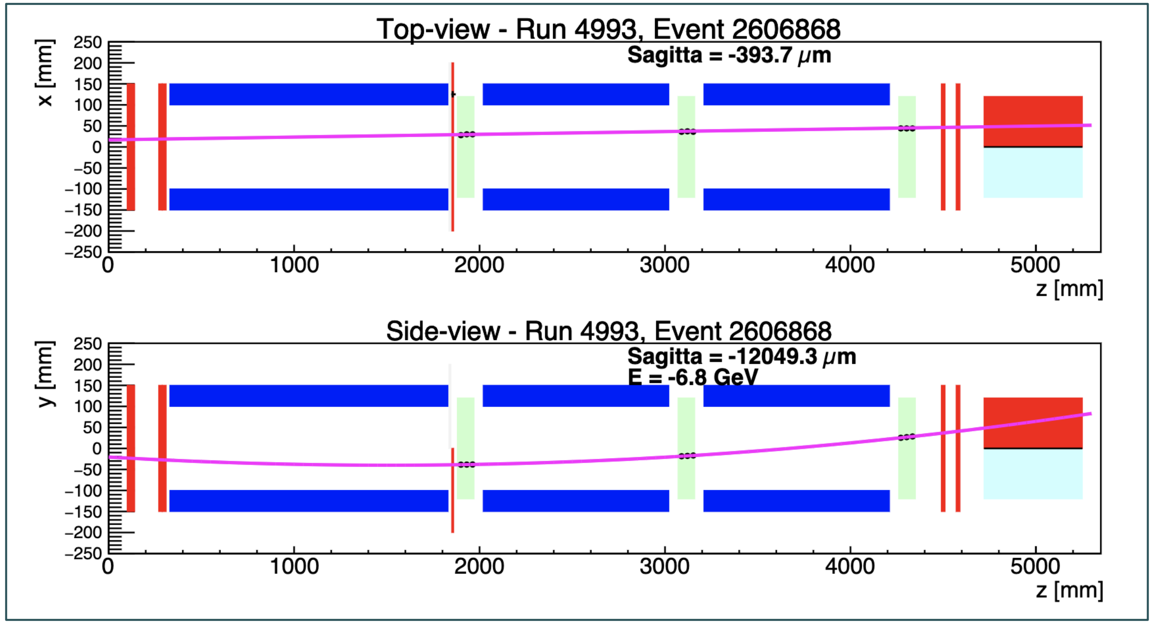
- long-term stability and control checks (temperature, humidity, electronics)
- Quantification of noisy/dead strips
- Alignment and metrology of tracker planes





Commissioning with cosmic rays and LHC pilot run



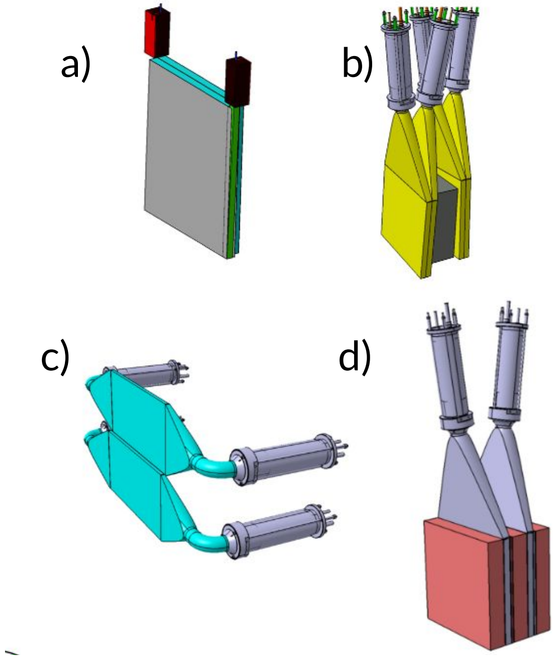


purple line: combined track fit to the hits in the tracking stations during 900 GeV pilot beam

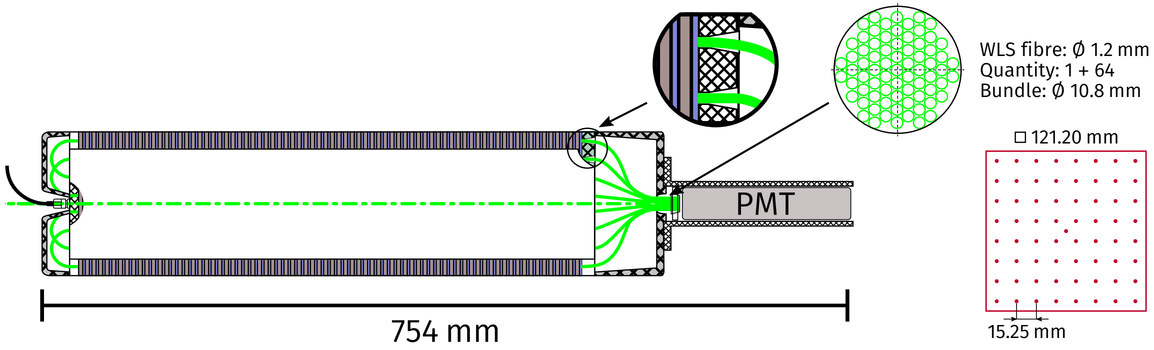
FASER calorimeter, pre-shower and scintillator systems

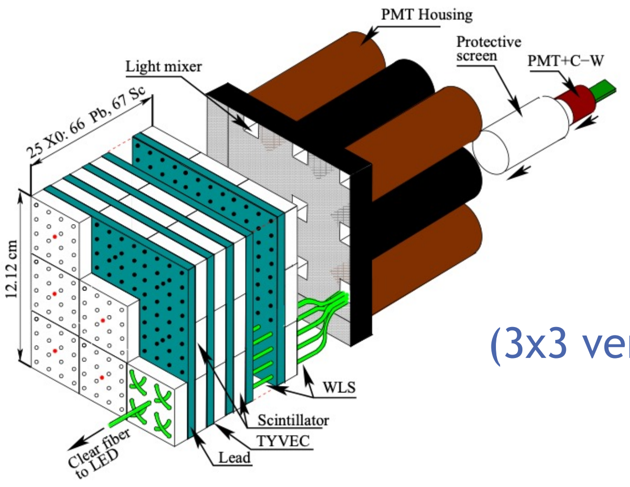
- **Four scintillator stations** with multiple scintillator layers in each station
  - (a) FASERν Veto, (b) Interface Veto, (c) Timing, & (d) Preshower
  - >99.98% efficiency, sufficient to veto all incoming muons
  - photo-multiplier tubes to detect the scintillation signals.

Note: Preshower scintillator to be replaced by silicon pixel detector (tech. proposal) in 2023/2024 To detect 2-photon axion-like particle signals



- **Electromagnetic calorimeter** made of spare LHCb modules
  - 66 layers of lead-scintillator plates read by 2x2 array of PMTs
  - calorimeter readout optimised to measure multi-TeV deposits w/o saturation





LHCb (3x3 version)

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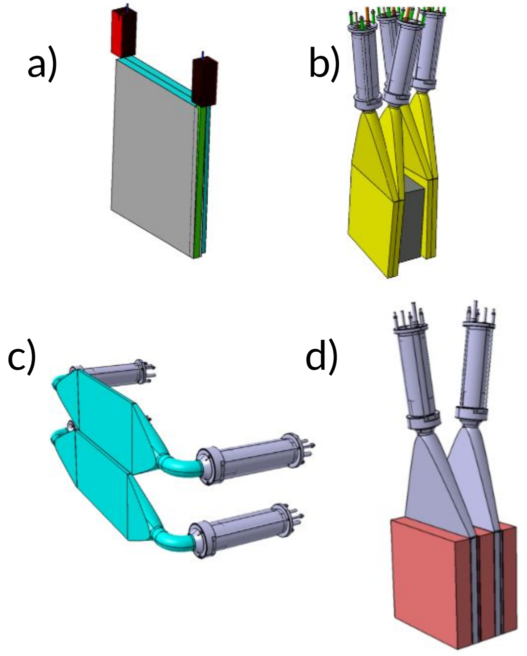

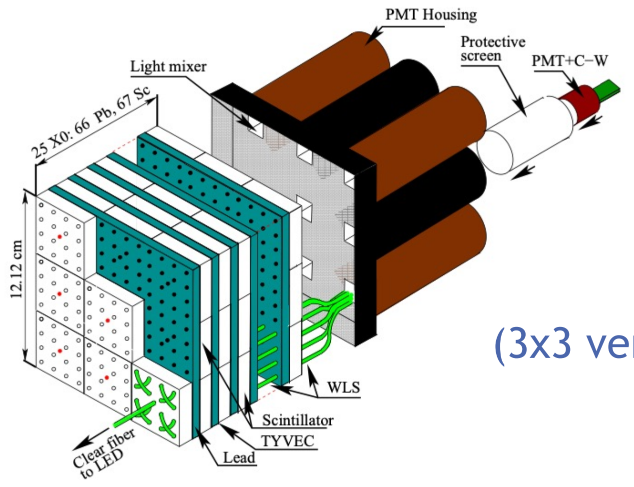

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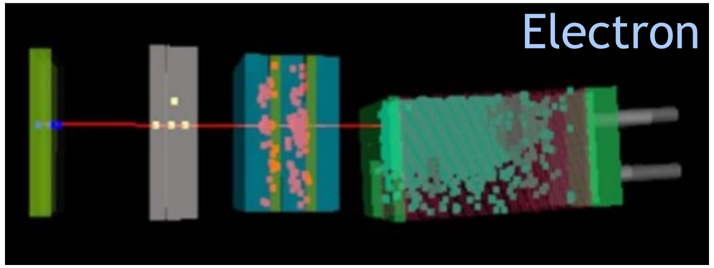

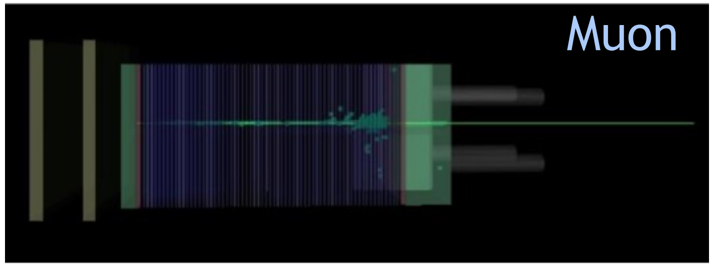

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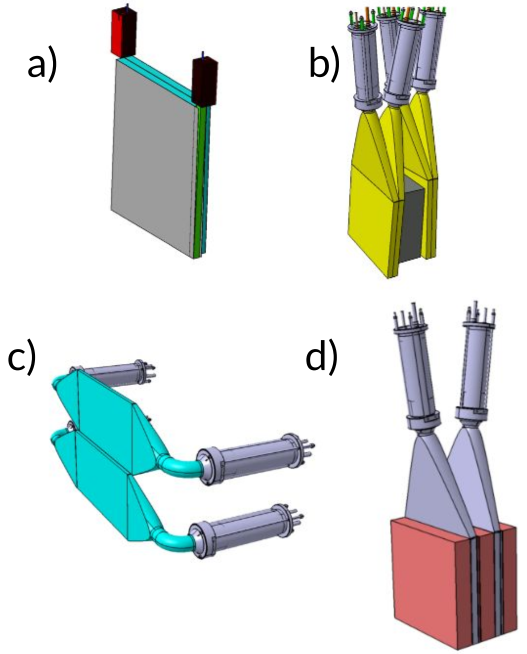
  - photo-multiplier tubes to detect the scintillation signals.

Note: Preshower scintillator to be replaced by silicon pixel detector (tech. proposal) in 2023/2024 To detect 2-photon axion-like particle signals



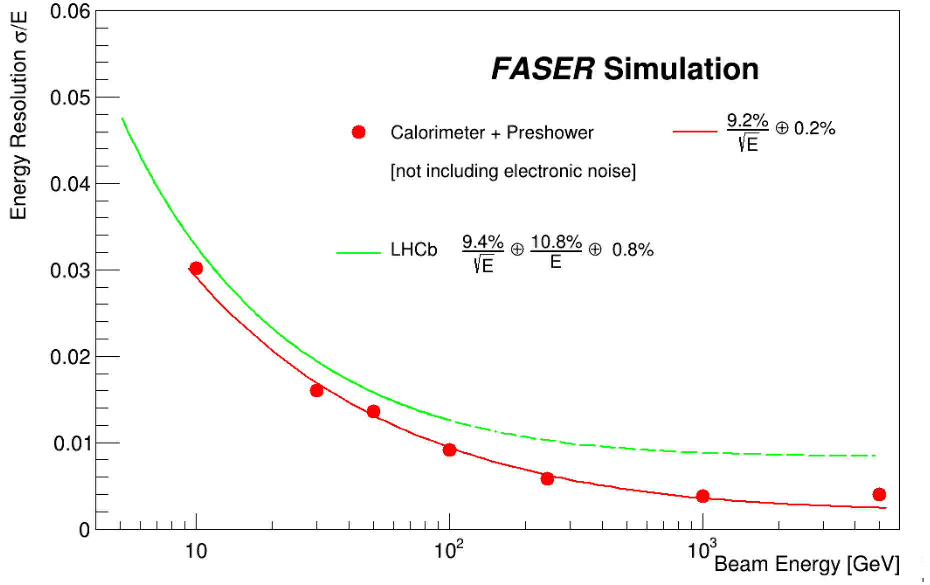
- **Electromagnetic calorimeter** made of spare LHCb modules
  - 66 layers of lead-scintillator plates read by 2x2 array of PMTs
  - calorimeter readout optimised to measure multi-TeV deposits

w/o saturation

$$\frac{\sigma_E}{E} = \frac{9.2\%}{\sqrt{E}} \oplus 0.2\%$$

+ expected 1% constant term

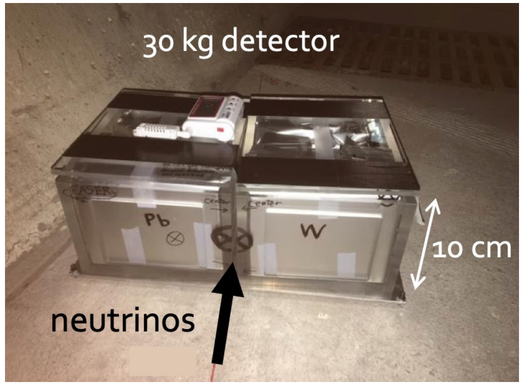
At 1 TeV, about 1.6% of electrons are expected to leak more than 3% of their energy

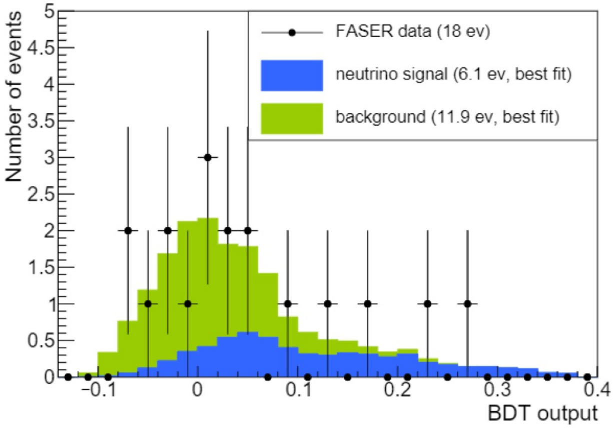


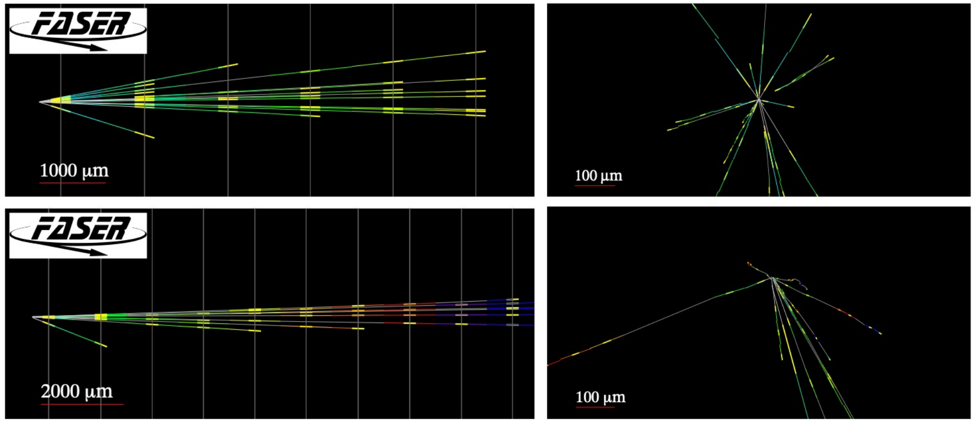
FASERν detector

- 700 layers of an emulsion film and 1.1 mm tungsten plate: 25 cm×30 cm×1.1 m, 1.1 tons, 220 X_0
- Pilot detector (30 kg) exposed in FASER location for 1 month
  - Observed (**2.7σ**) first collider ν candidates!
- FASERν will be exchanged frequently during Run 3
  - First full detector (TS1): 26th July – 13th Sept
  - Second detector (TS2): 13th Sept – 8th Nov
- Frequently exchanged (~ every 3 months) to keep a manageable detector occupancy. **Procedure:**

Phys. ReV. D 1004, L091101







Emulsion Film Production → Detector Assembly → Exposure → Development → Full Area Readout → Reconstruction

Ship to CERN | Install in Ti12 | Disassemble | Ship to Japan

Replacements: ~ 3 times/yr in technical stops, every 30-50 fb^{-1}

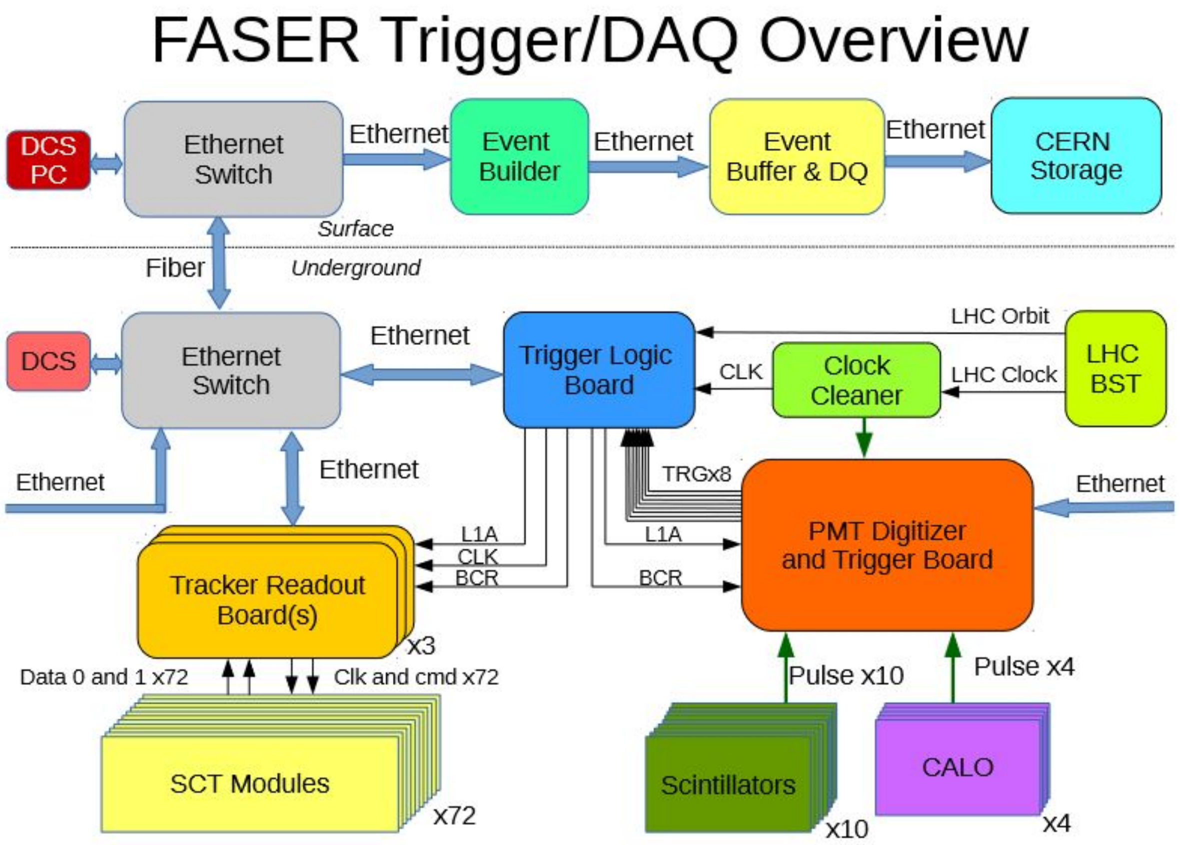
Trigger and DAQ

2021 JINST 16 P12028

FASER Trigger rate: **650 Hz** expected (*dominated by muons*)

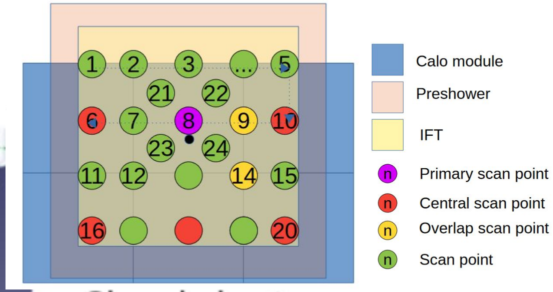
- PMTs from scintillators and calorimeter provide trigger signals
- Trigger system run synchronously to the 40.08 MHz LHC clock
- Data Acquisition (DAQ): Configuration & readout
- Monitoring: checking data flow, detector conditions, and data quality to spot/resolve problems

Data Control & Safety (DCS): powers detector and protects it from unusual conditions

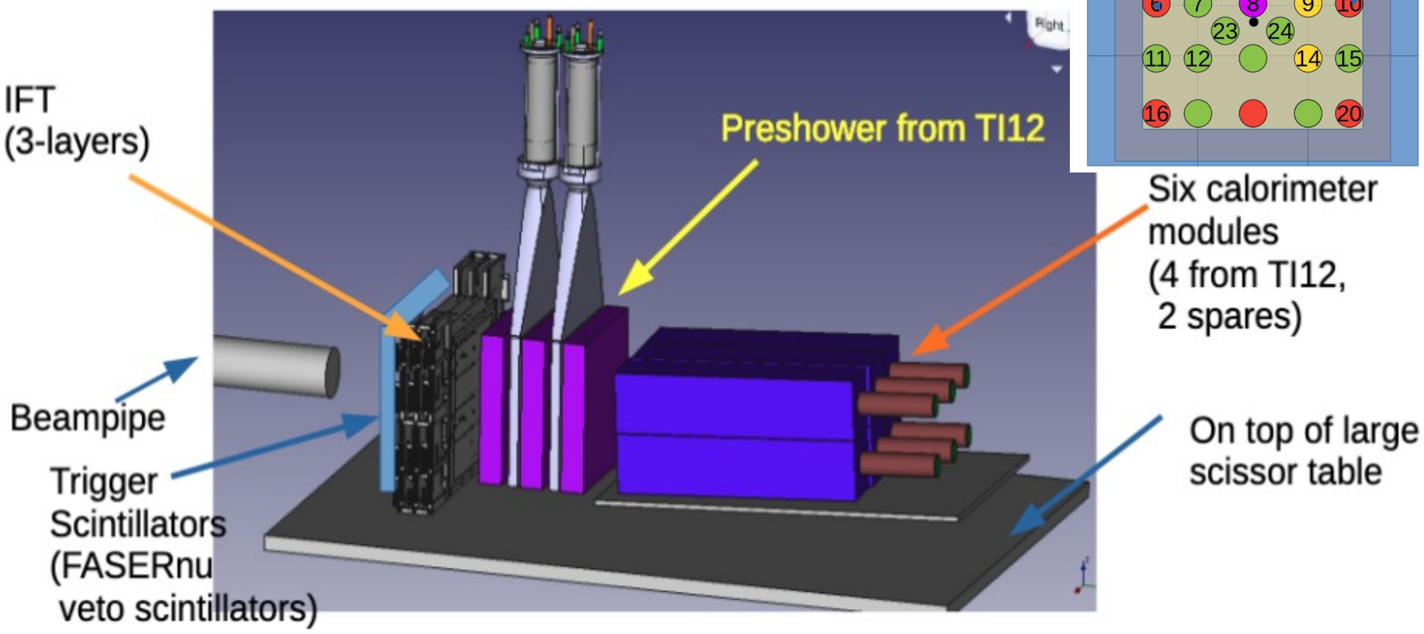


FASER Test Beam

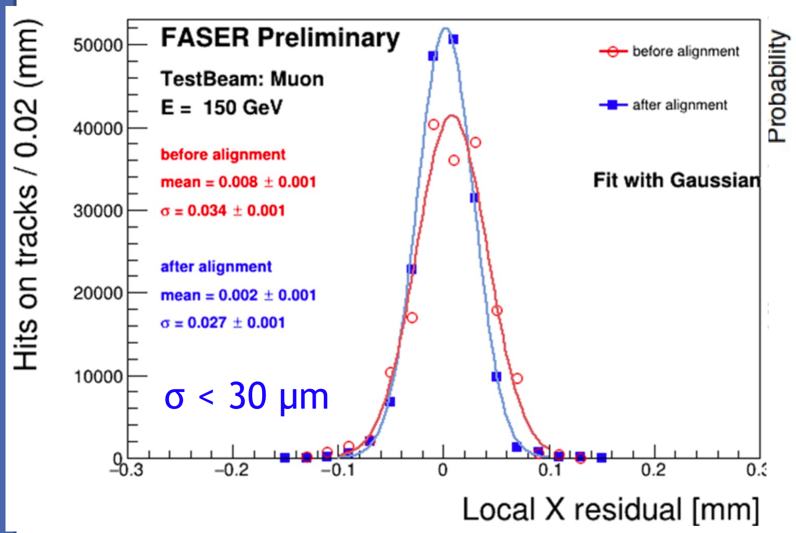
Paper in progress!



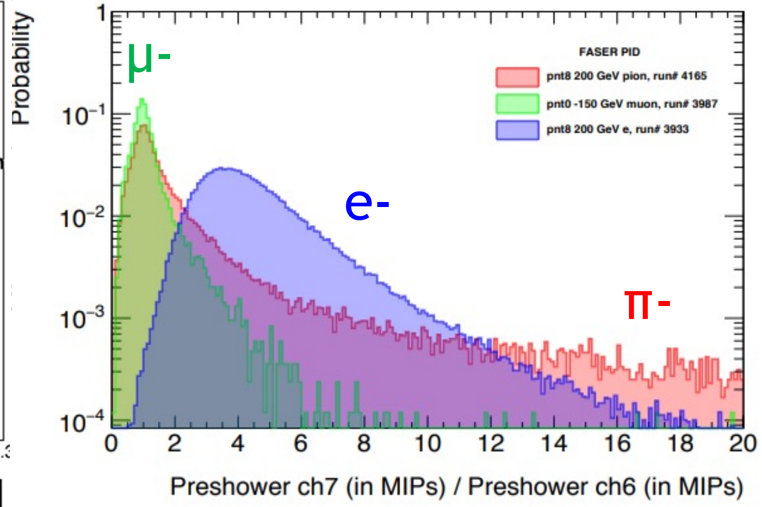
- TB @ CERN H2 beam (summer '21)
  - Electrons (5-300 GeV), muons (200 GeV) and pions (200 GeV)
- 6 ECAL modules (inc. spares)
  - Along with IFT and preshower
- Also used for tracking performance studies
  - Tracker cluster efficiency measured: 99.86 ± 0.04 % , agreeing well with MC and ATLAS (99.74±0.04 %)



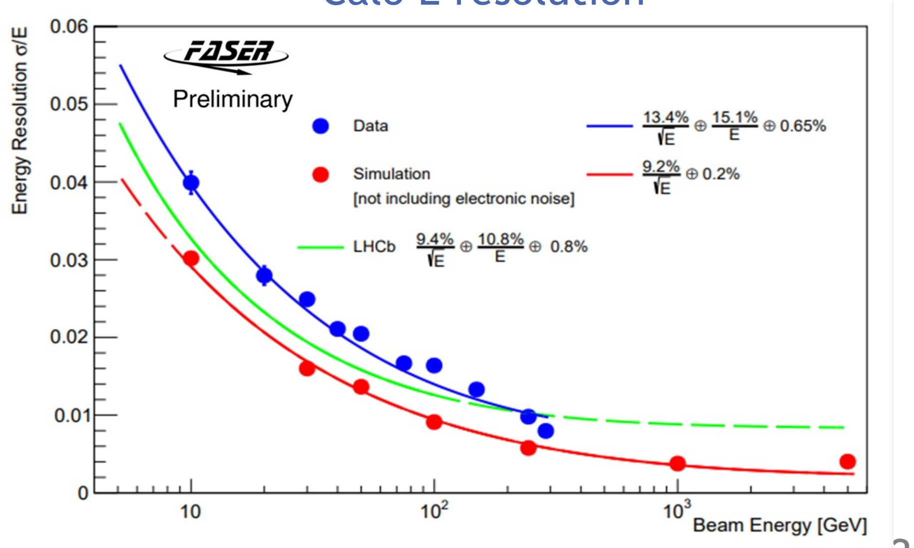
Tracking resolution



Preshower Particle Identification

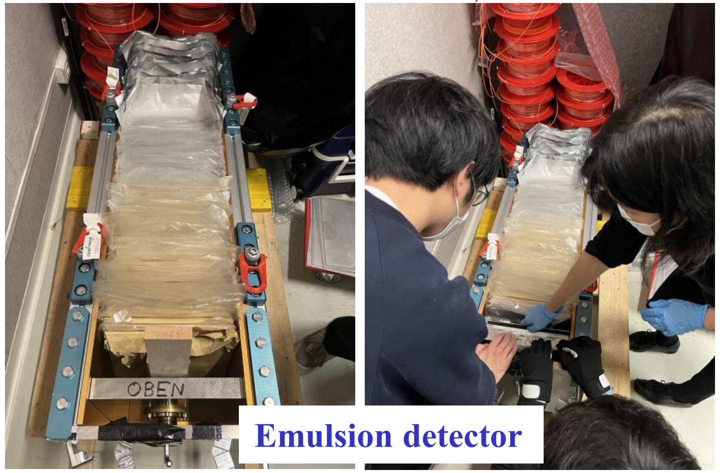


Calo E resolution

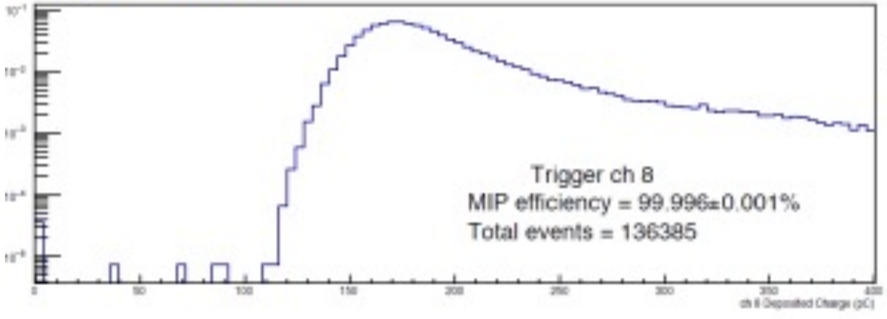


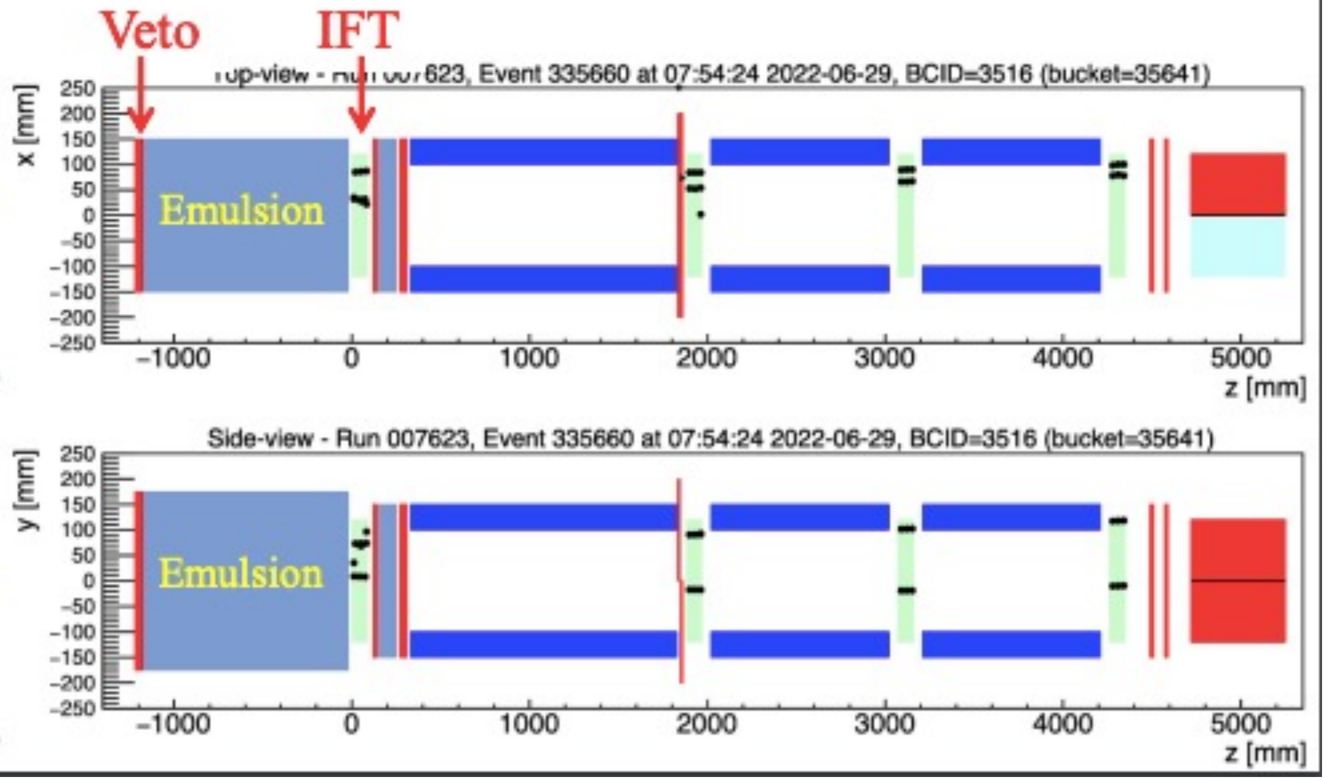
FASERν detector commissioning

- ~30% of the full emulsion for commissioning
- MIP efficiency of the veto system was also measured in the test beam
- Better performance than the requirement (>99.98%) obtained.



Charge deposit in veto system @Testbeam



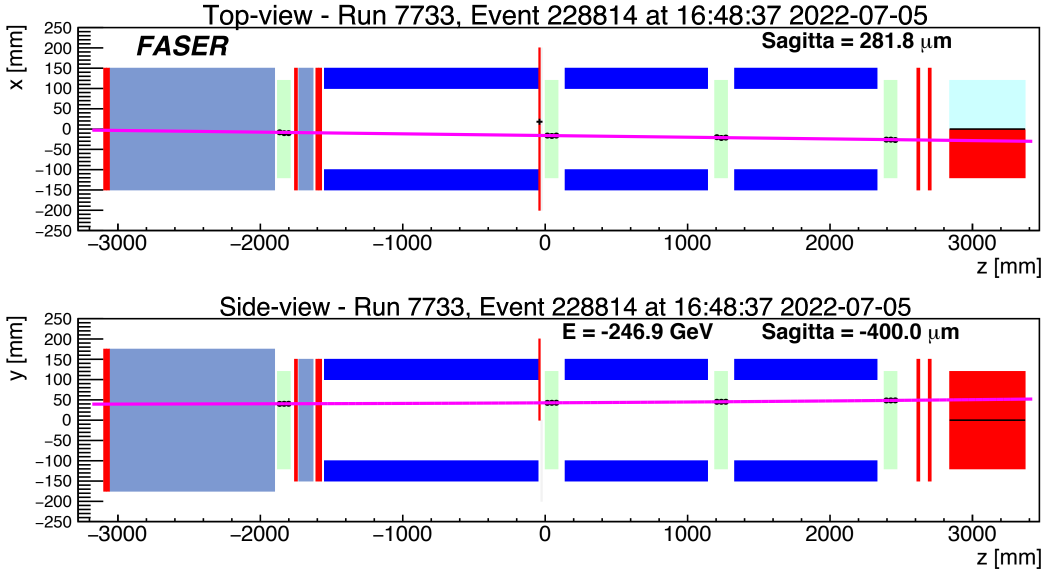


Full detector installed

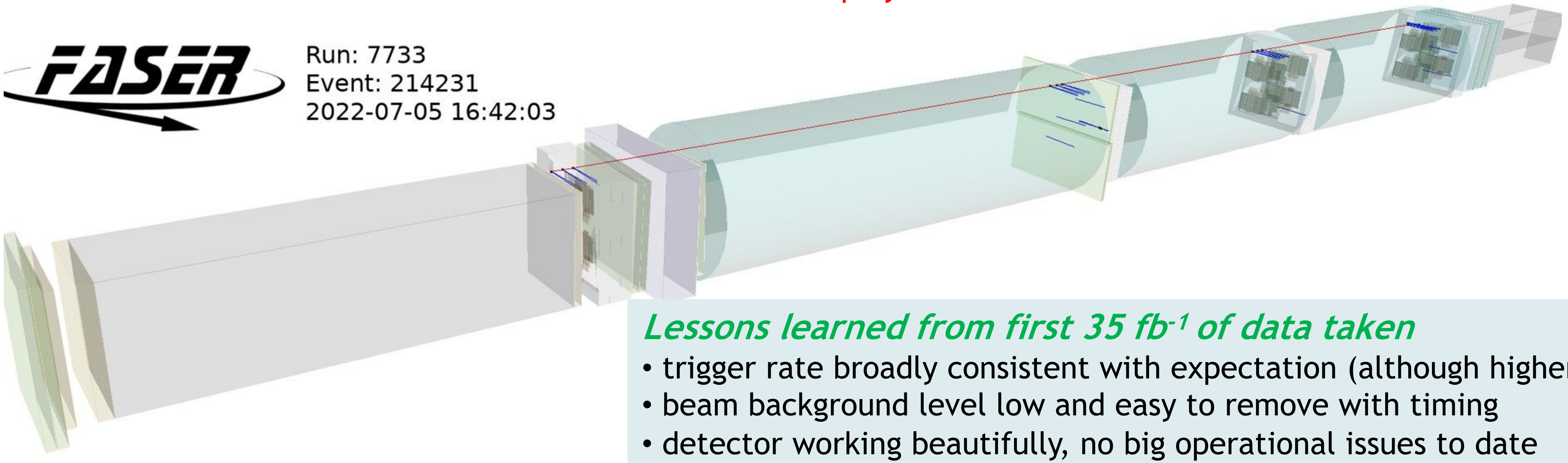
After further commissioning tests, the detector was ready to see first data on July 5th!

First data !

- Thousands of events were already collected with charged particle tracks traversing the detector even prior to official start on 5th of July
  - Great for performance studies, optimizing operation procedures, & commissioning reconstruction software.
- With 13.6 TeV beams, good events seen in the detector consistent with coming from collisions.



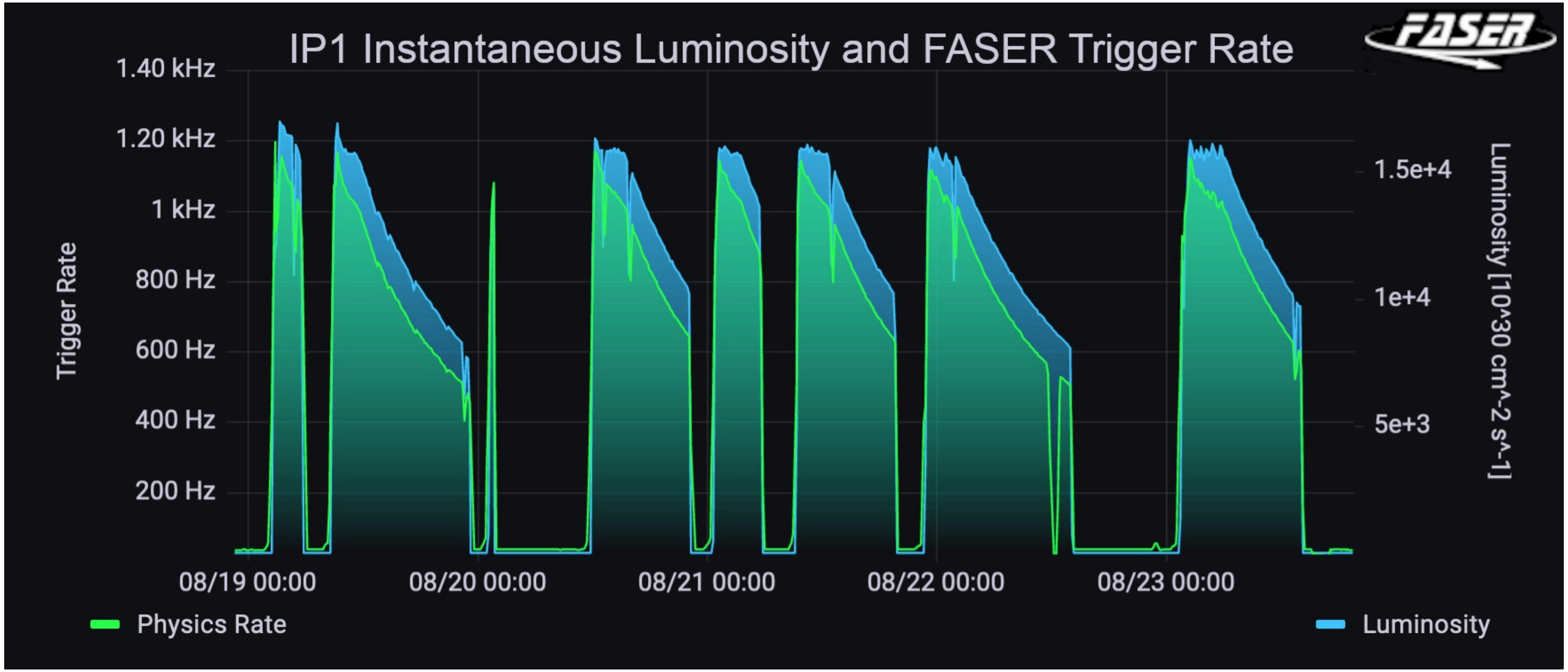
One of first event displays from collisions



Lessons learned from first 35 fb^{-1} of data taken
- trigger rate broadly consistent with expectation (although higher)
- beam background level low and easy to remove with timing
- detector working beautifully, no big operational issues to date

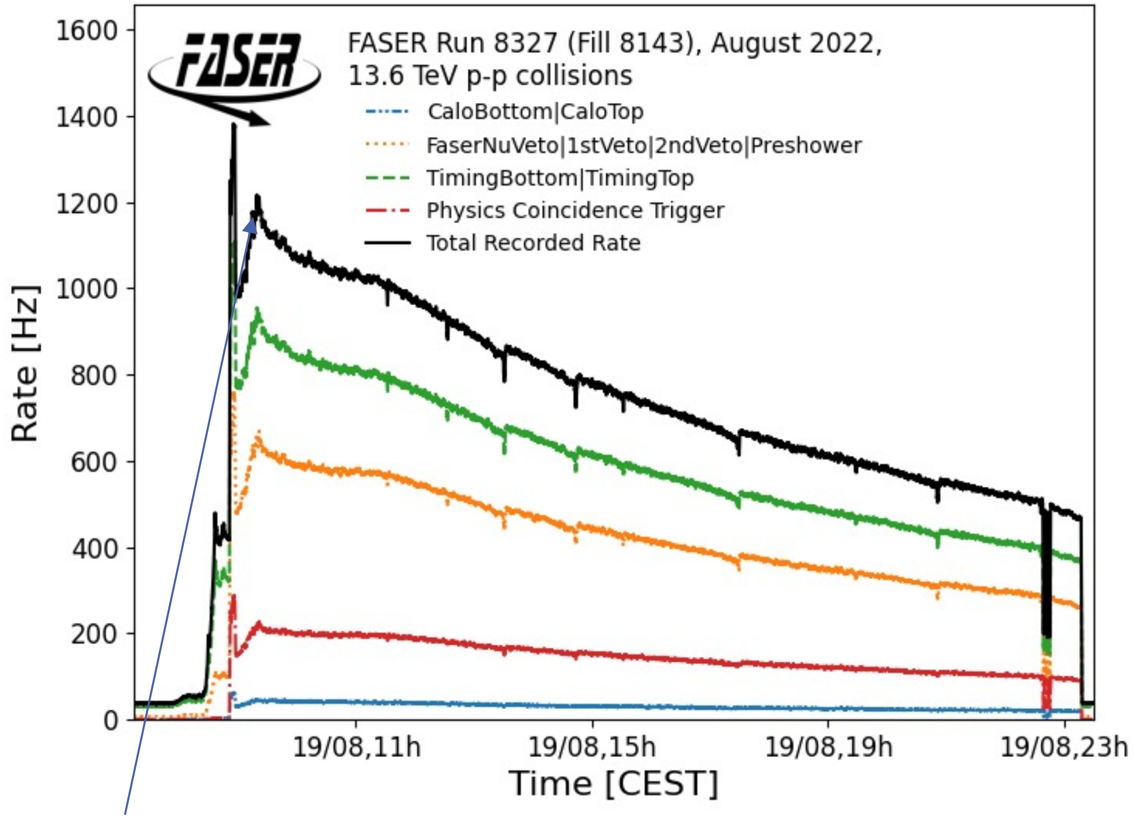
Data-taking

- Instantaneous luminosity measured at IP1 and the FASER total trigger recorded rate for 8 LHC fills between August 19th to 23rd, 2022:
  - The trigger rate trend generally follows the luminosity trend but falls off more strongly at the beginning of fills → higher beam losses at the beginning of fills. Overall very good performance and small issues well understood



Recorded rate very similar to triggered rate, efficient data taking (< 2% physics deadtime)

Rates and trigger efficiency

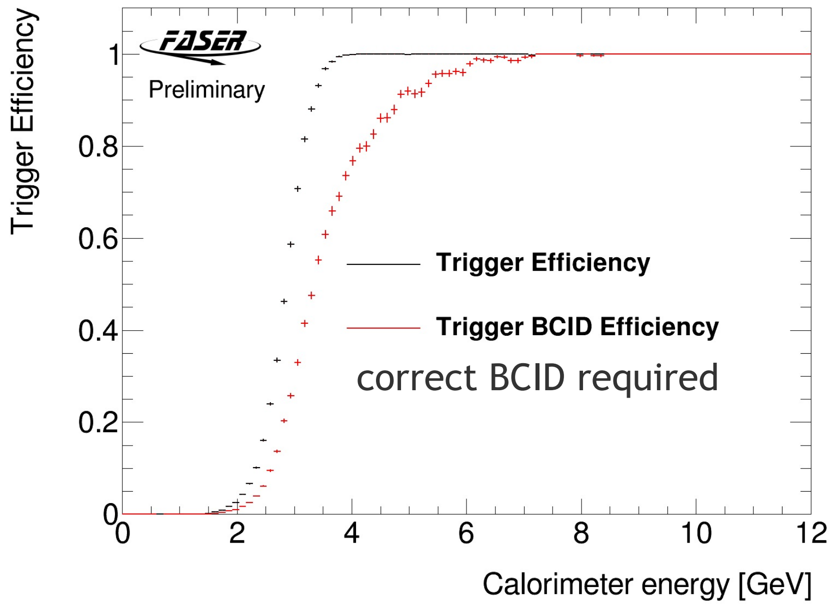


High rate at the beginning of the fill

FASER has 4 physics trigger items (partially overlapping, not prescaled):

- calorimeter (lowest rate, ~ 50 Hz)
- Veto-scintillator or preshower scintillator
- Time scintillator station (highest rate, ~ 800 Hz here)
- Coincidence trigger

Trigger efficiency of the calorimeter

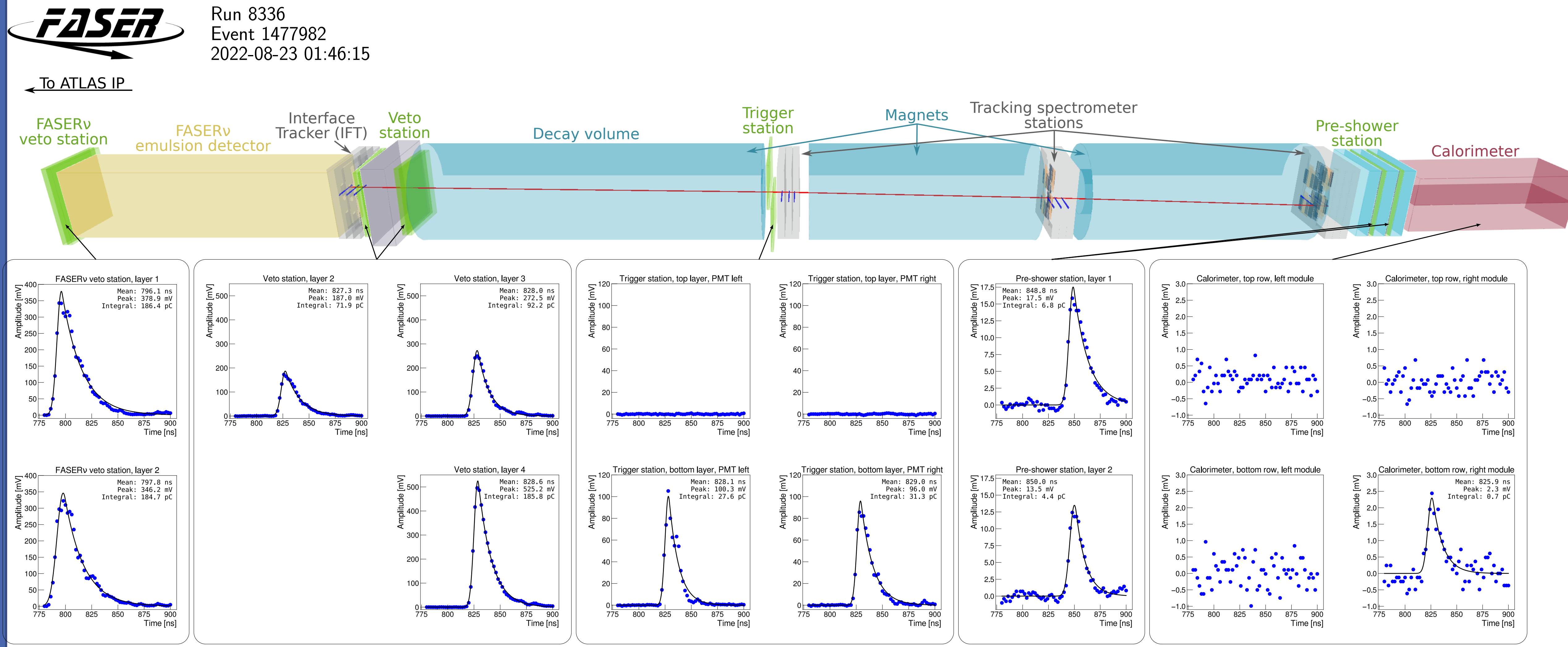


[calibrated using MIP response, MIP eq. 330 MeV EM particle]

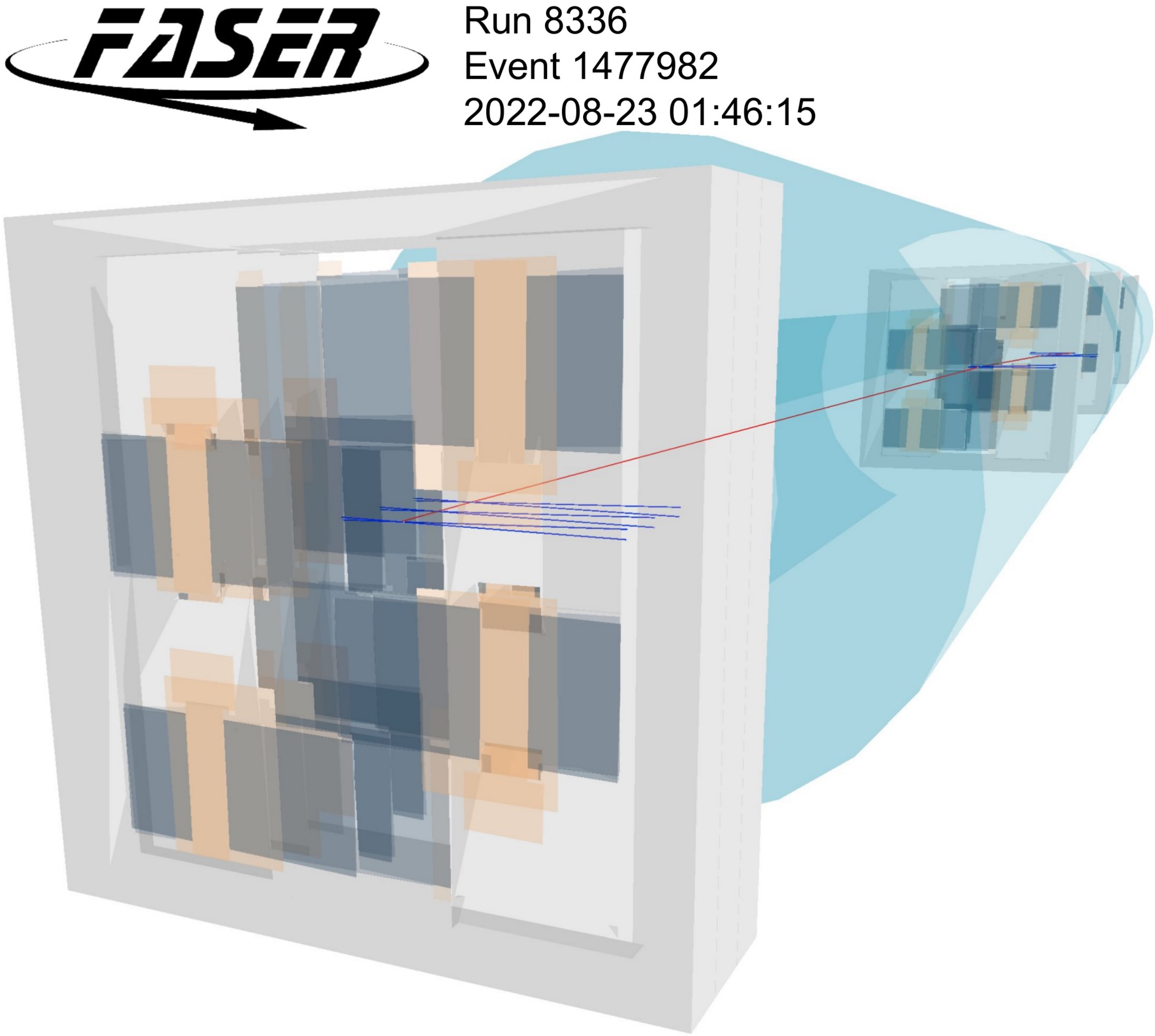
Higher than expected trigger rate in general
~1.3 kHz at L=2×10^{34} cm^{-2} s^{-1}
Dominated by IP1 muon flux, not problematic for physics

Run 3 events

- Collision event with a muon traversing FASER. The measured track momentum is 21.9 GeV. The waveforms are shown for signals in scintillator counters and calorimeter modules and are fitted using a Crystal Ball function.



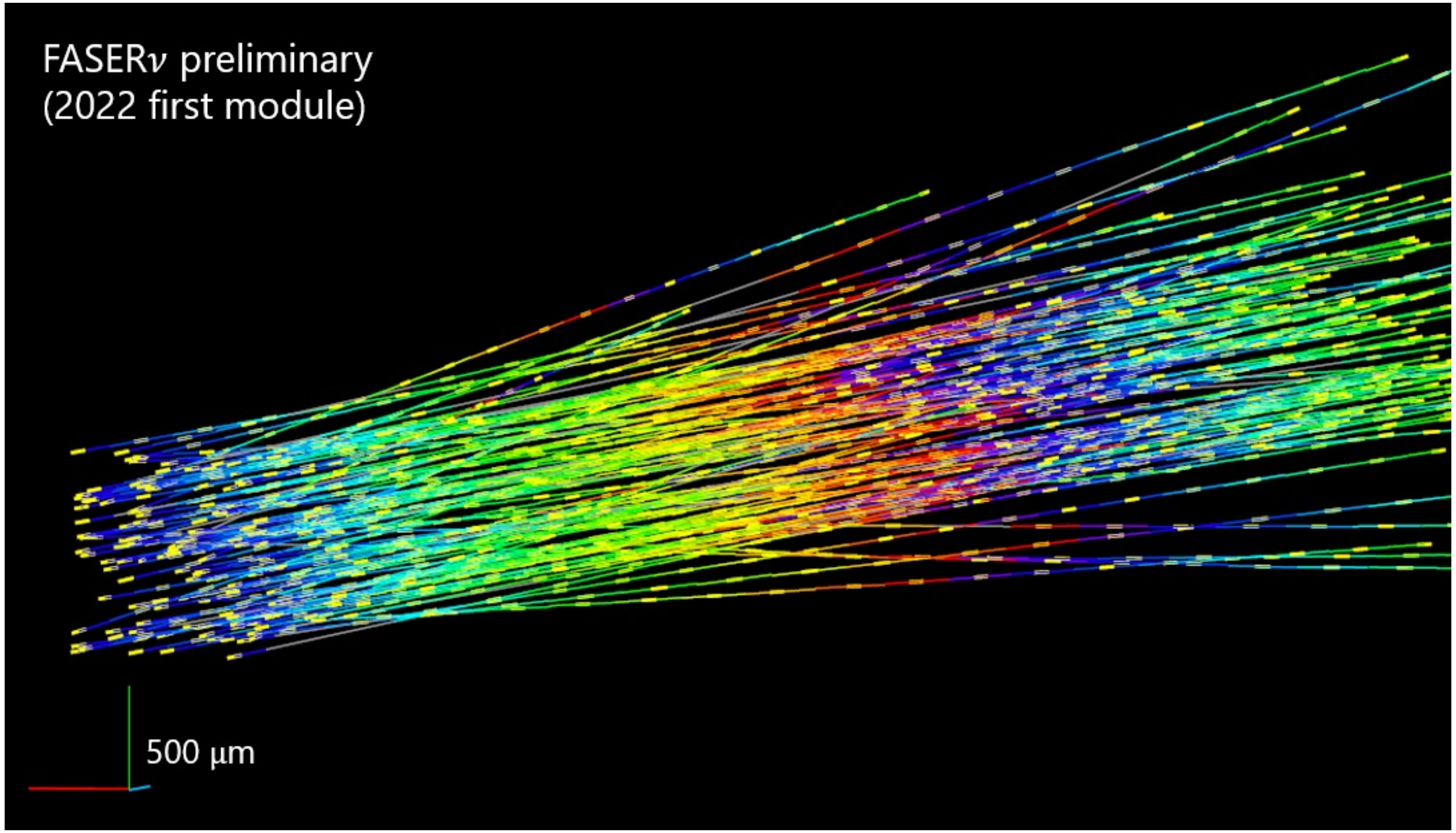
More event displays showing tracking system



- event triggered by modules in the scintillator systems
- magnets are shown as light blue cylinders
- tracking stations as grey cuboids
- In each tracking station, the silicon sensors facing forward are shown in dark blue and the readout electronics in orange.
- The detected hits in the semiconductor tracker modules are shown with blue lines
- The reconstructed track is shown with a red line.

More from the Run 3

- Reconstructed tracks (above ~1 GeV) in 1 mm ~ 1 mm ~ 20 emulsion films from the 2022 first module of the FASERν detector, which collected 0.5 fb^{-1} of data.
- The yellow line segments show the trajectories of charged particles in the emulsion films, others are interpolations, with colours changing depending on the depth in the detector.

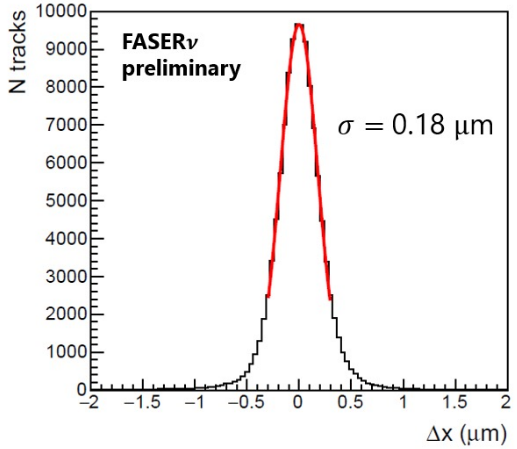


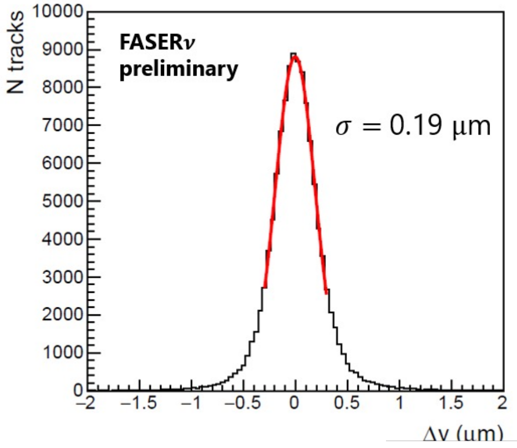
Tracks from the first FASERν emulsion films

The track density is around 2.3~$10^4/cm^2/fb^{-1}$.

Distributions of position and angular distributions

- Distributions of the position deviation between the track hits and the straight-line fits to reconstructed tracks. measured in the 2022 first module of FASERnu

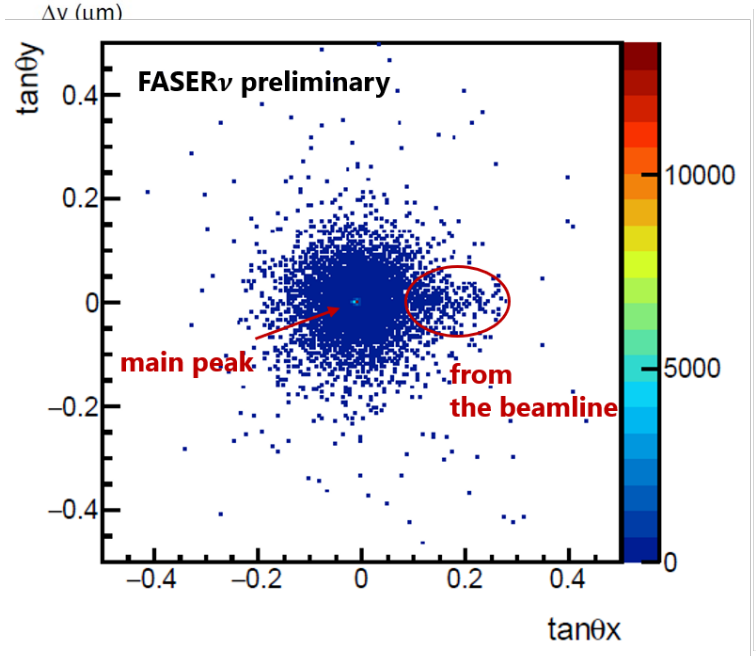


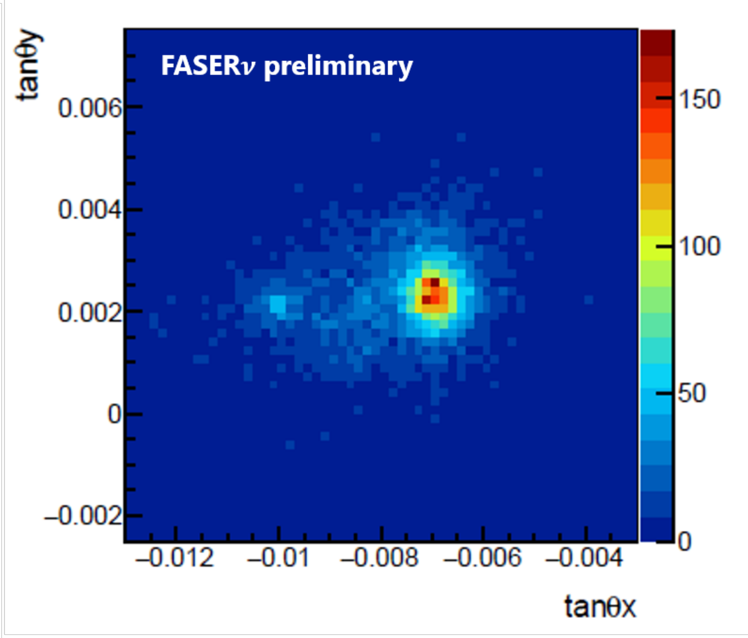


- Position resolutions of ~0.2 μm (transverse plane)
- Dedicated alignment is applied to 10 emulsion films.

Angular coordinates (0, 0) roughly corresponds to the LOS

- Large angle tracks cosmic rays accumulated on surface.
- Peaks consistent with particles arriving from the beam line in the vertical plane.

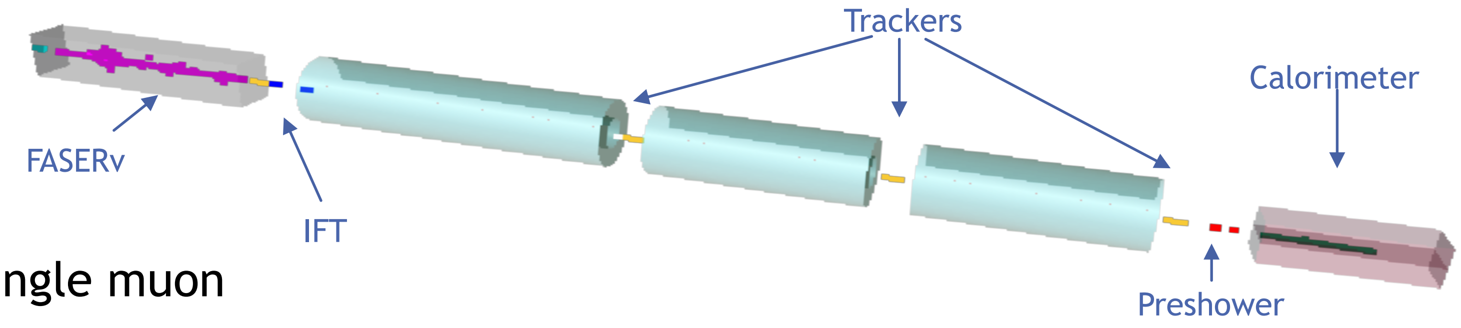




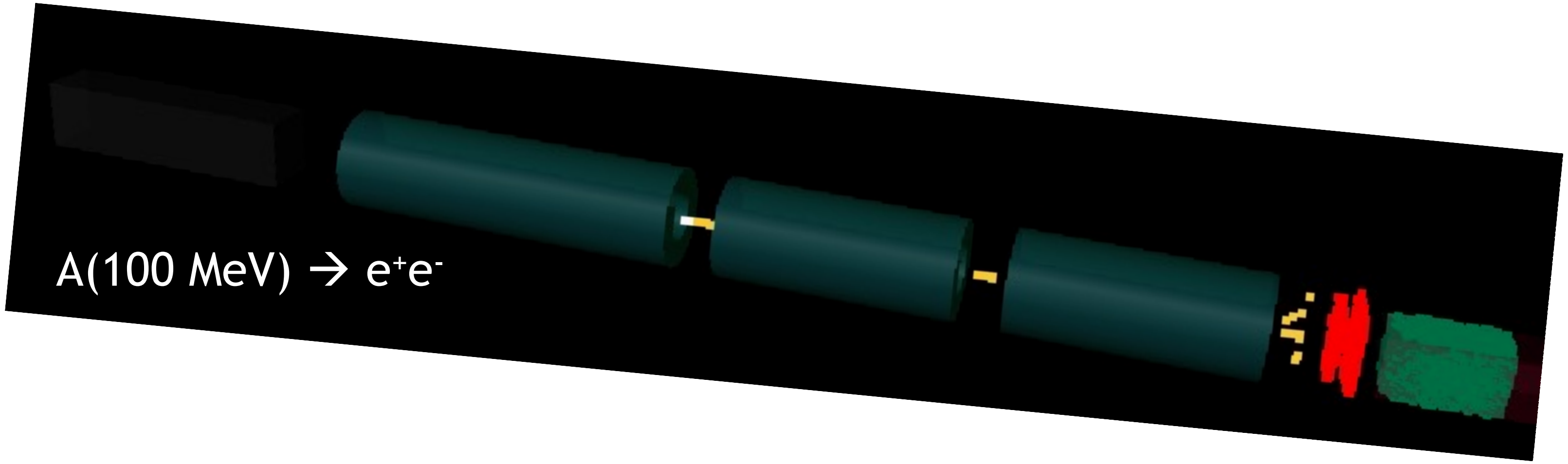
Data analysis readiness

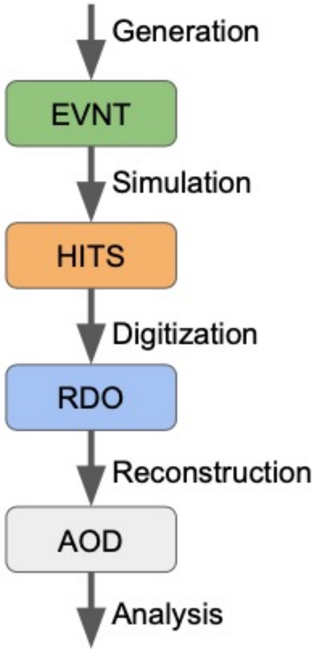
First results for Spring 2023!

- On-going tests on full production chain from generation all the way through to analysis
- Representative background and signal processes have been produced
  - Full FASER detector geometry implemented and validated in offline software
    - **Calypso** software package based on ATLAS framework (Gaudi and Athena)
  - Genie & FLUKA used for neutrinos studies and muon-induced background



Single muon





Good tests for track reconstruction methods, momentum resolution and calorimeter deposits measurements

Data analysis readiness

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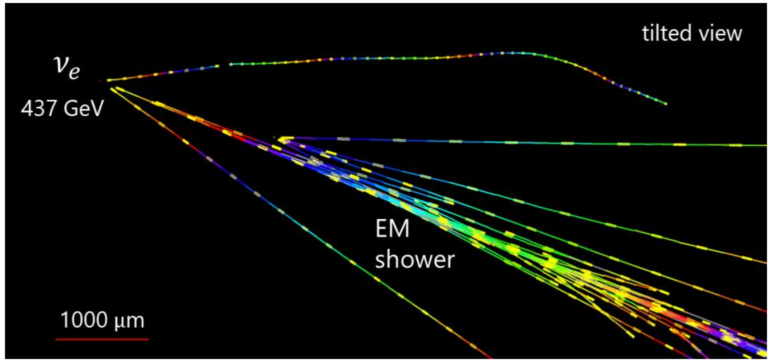
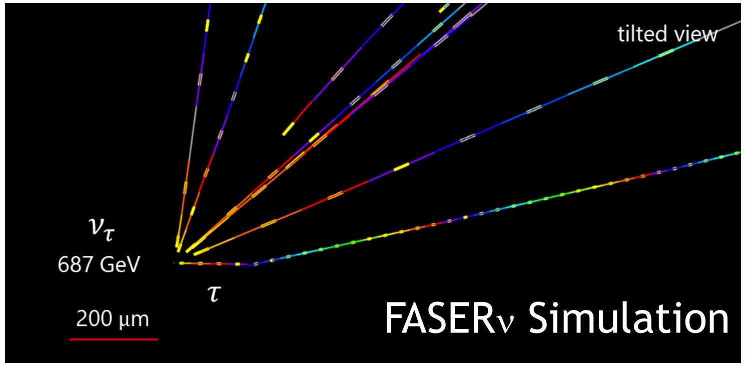
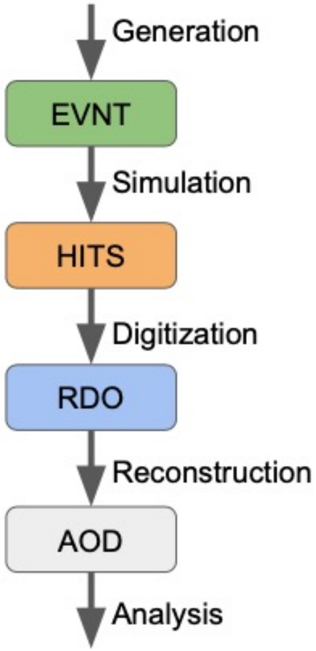
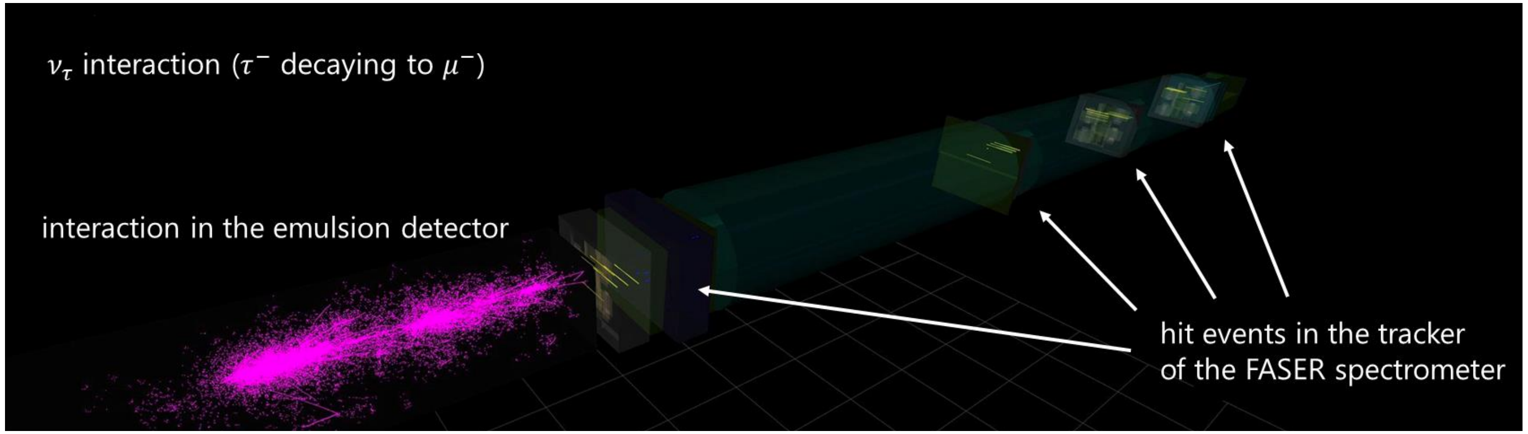








Neutrino events simulation also fully ready

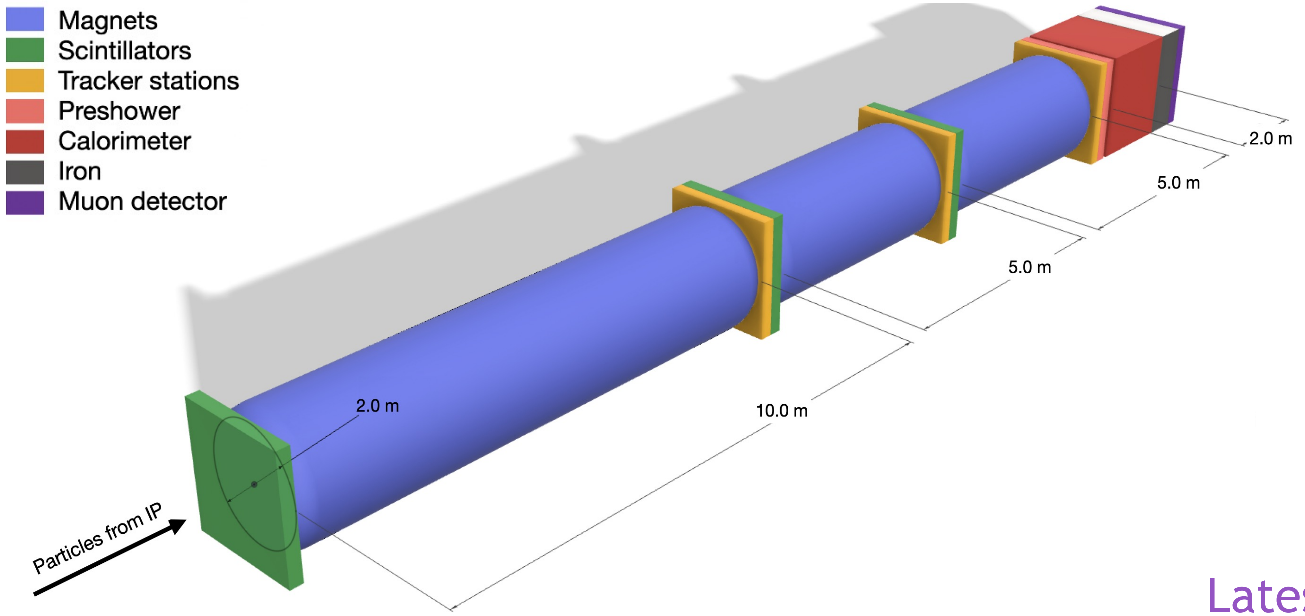
The forward future: FASER(ν)2

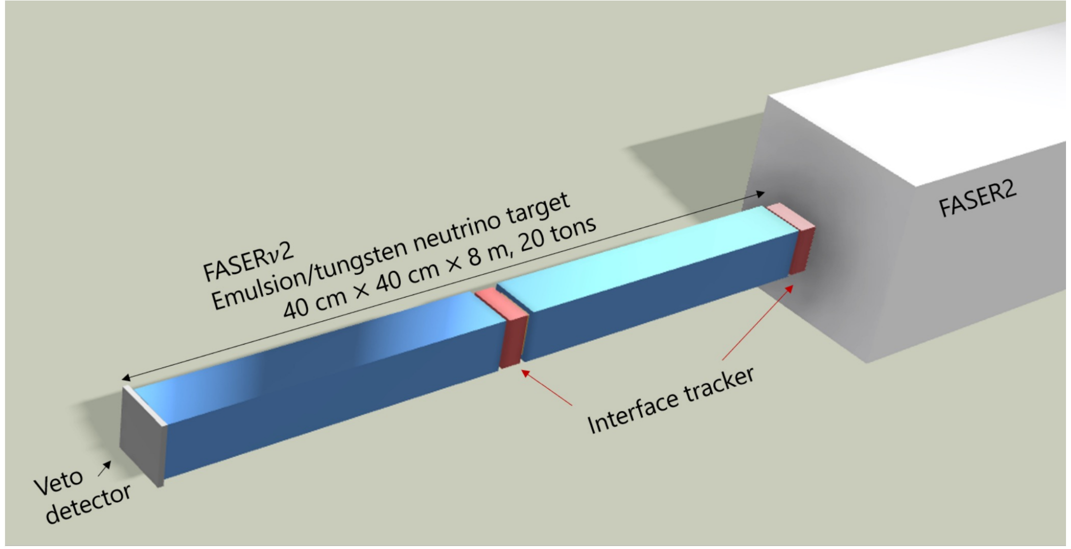
- We must think ahead!
- It could be that we do not see LLPs or NP in Run 3:
  - Extended coverage needs a bigger detector!
- Envisaging a scaled-up version of FASER with ~100 x active area
  - Magnets: Superconducting w/ B = 1 T
  - Tracker: much larger using e.g. SiFI/SiPM
  - Calo/Muon: enhanced PID & position resol.

	FASER	FASER2
R [m]	0.1	1
DV [m}	1.5	10
TS [m]	2.6	10

FASERν2: Focus on ν_τ

~20t emulsion + tungsten detector





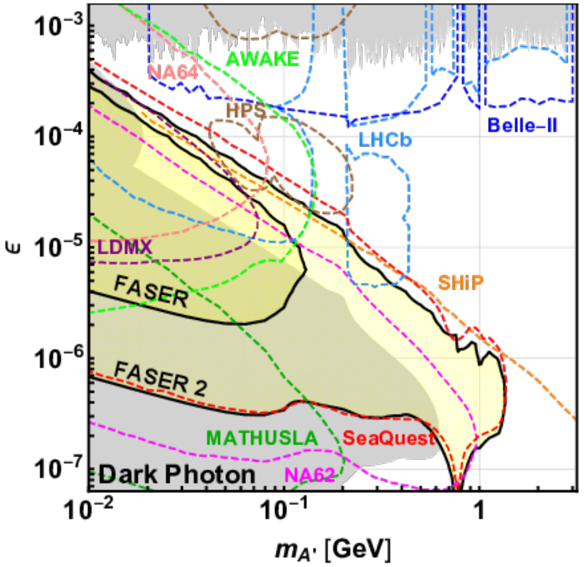
Latest updates: https://indico.cern.ch/event/1196506/

The forward future: FASER(ν)2

- Substantial increase in sensitivity for LLPs from B, D hadrons decays (e.g. Dark Higgs) thanks to larger radius, broader scope including QCD physics

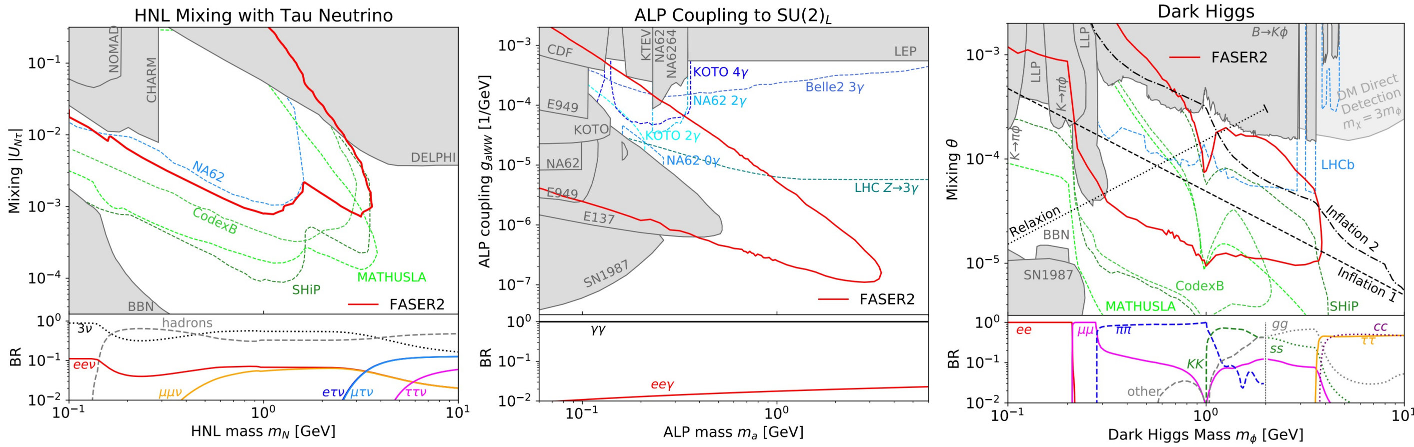
Benchmark Model	FASER	FASER 2
Dark Photons	√	√
$B-L$ Gauge Bosons	√	√
$L_i - L_j$ Gauge Bosons	—	—
Dark Higgs Bosons	—	√
Dark Higgs Bosons with hSS	—	√
HNLs with e	—	√
HNLs with μ	—	√
HNLs with τ	√	√
ALPs with Photon	√	√
ALPs with Fermion	—	√
ALPs with Gluon	√	√
Dark Pseudoscalars	—	√

Probing up to higher mass



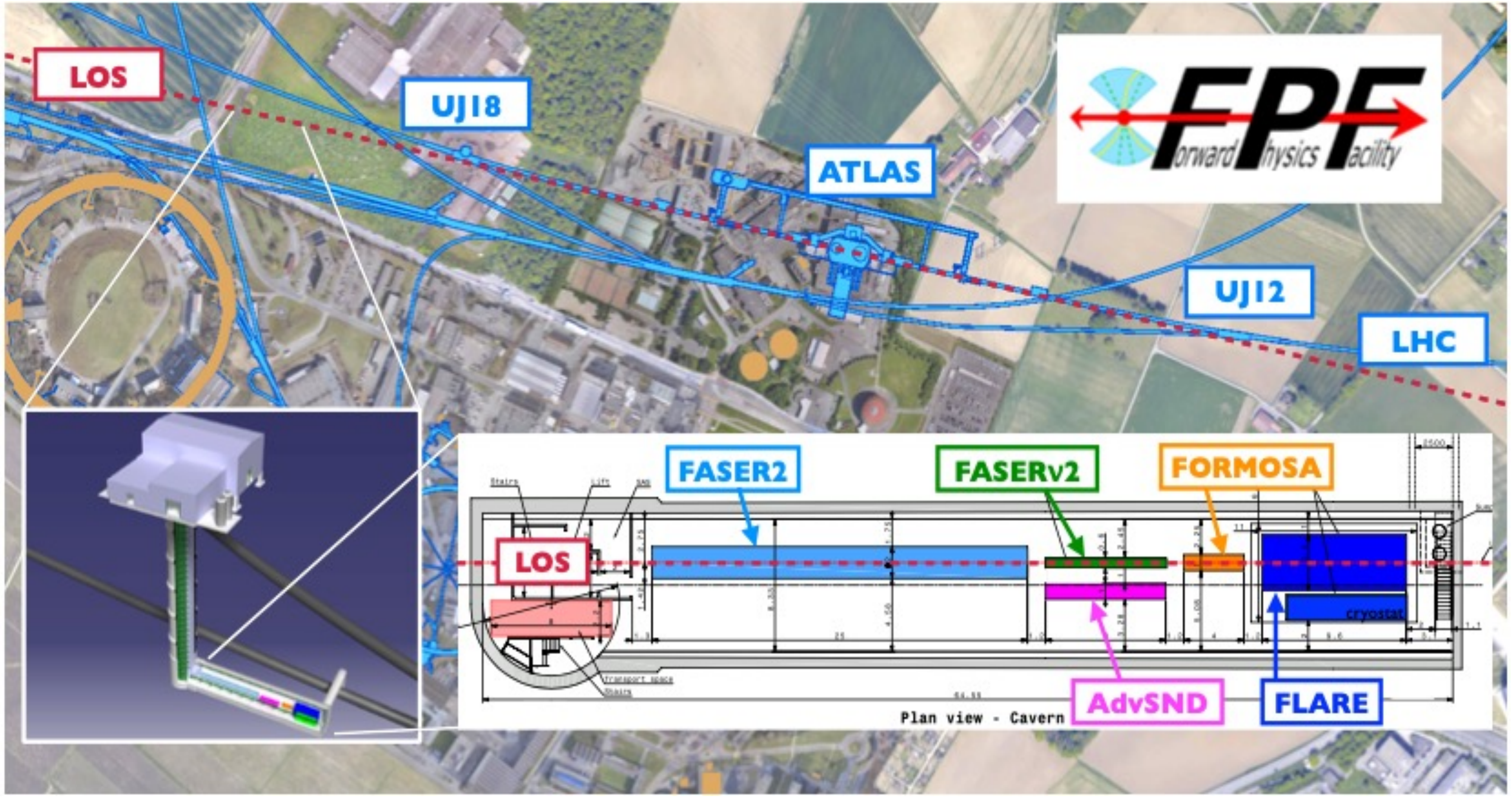
Sensitivity to Dark Higges and HNL Mixing to Tau neutrinos

Systematic studies on-going to establish the layout compromising costs and new physics sensitivity



Where? The Forward Physics Facility (FPF)

- Proposal to build a new dedicated forward physics facility
  - Hosting a suite of far-forward experiments at the HL-LHC



Detailed (429pp) paper submitted as part of Snowmass: https://arxiv.org/abs/2203.05090

Current planned detectors

- **FASER2**
  - FASER scaled to r=1m
  - Light dark sector parts.
- **FASERν2**
  - ~20t emulsion + tungsten detector
  - Mainly ν_τ
- AdvSND
  - Off axis ν detector
  - Fwd charm + low-x gluon
- FORMOSA
  - Scintillating bars
  - Millicharged particles
- FLArE
  - ~10t LAr TPC
  - DM + ν physics

Summary

- FASER gives access to light, weakly-interacting particles with significant lifetime, providing sensitivity to a wide range of BSM physics models (dark γ, ALPS and more) complementary to GPDs; FASERν can measure high energy neutrinos in a previously unconstrained region of phase space
- FASER and FASERν are now fully operational and taking data!
  - Test beam results show excellent tracker cluster efficiency and uniform calorimeter response within a few percent across different beam positions
  - Data collection has started with Run 3! More than **35/fb of data** collected so far…
  - detector working beautifully, no real operational issues to date
- Development of analysis and software tools ongoing
  - First results expected for Spring 2023 – stay tuned!
- A *forward* look: proposal for FPF, a dedicated forward physics facility @ CERN, to take advantage of HL-LHC and build a FASER2
  - Would give a rich and broad physics programme