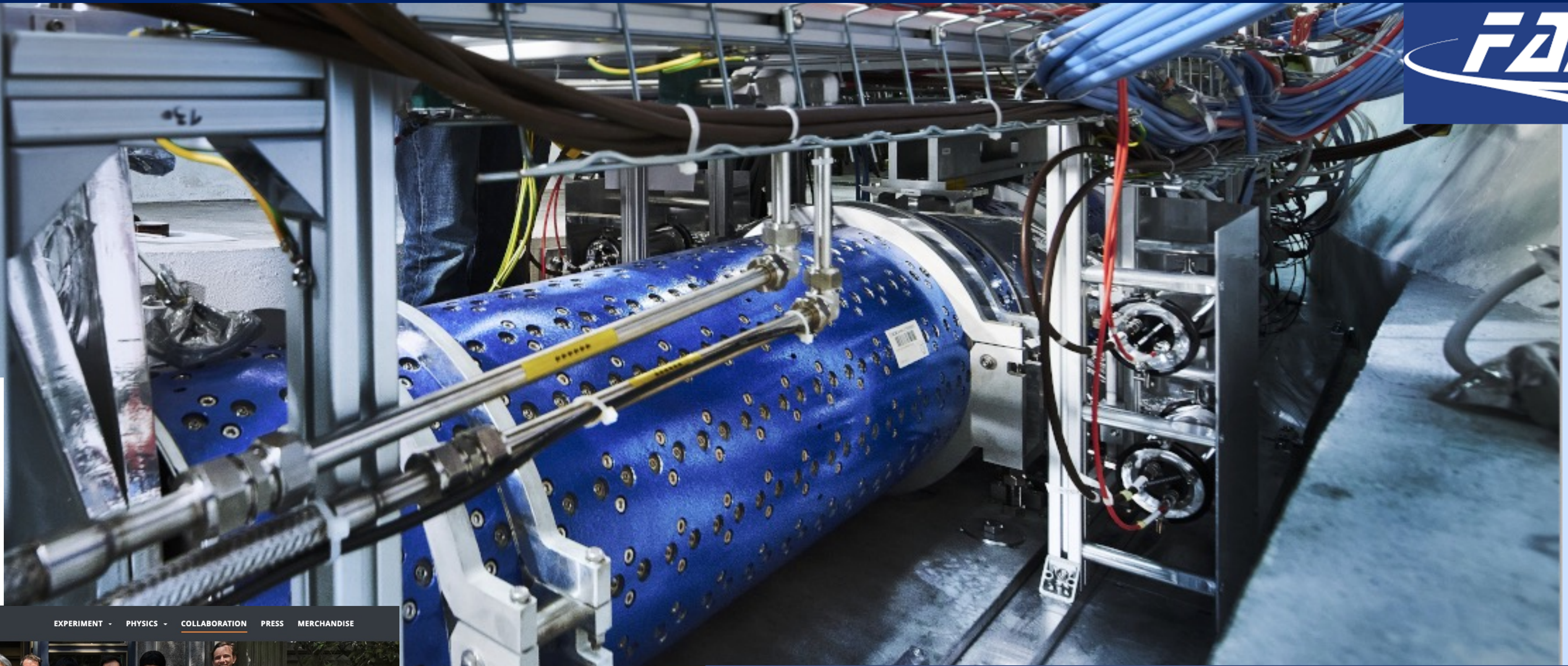
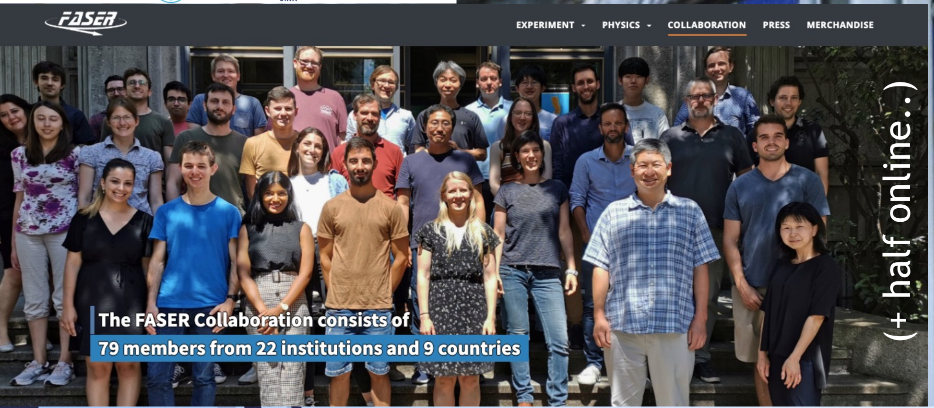
The FASER experiment





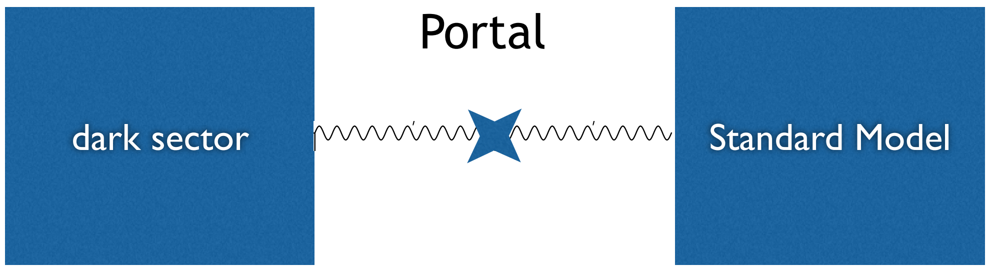
(+ half online..)

Monica D’Onofrio, University of Liverpool
on behalf of the FASER Collaboration

IPA2022 Vienna, 9/9/2022

The quest for a dark sector

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

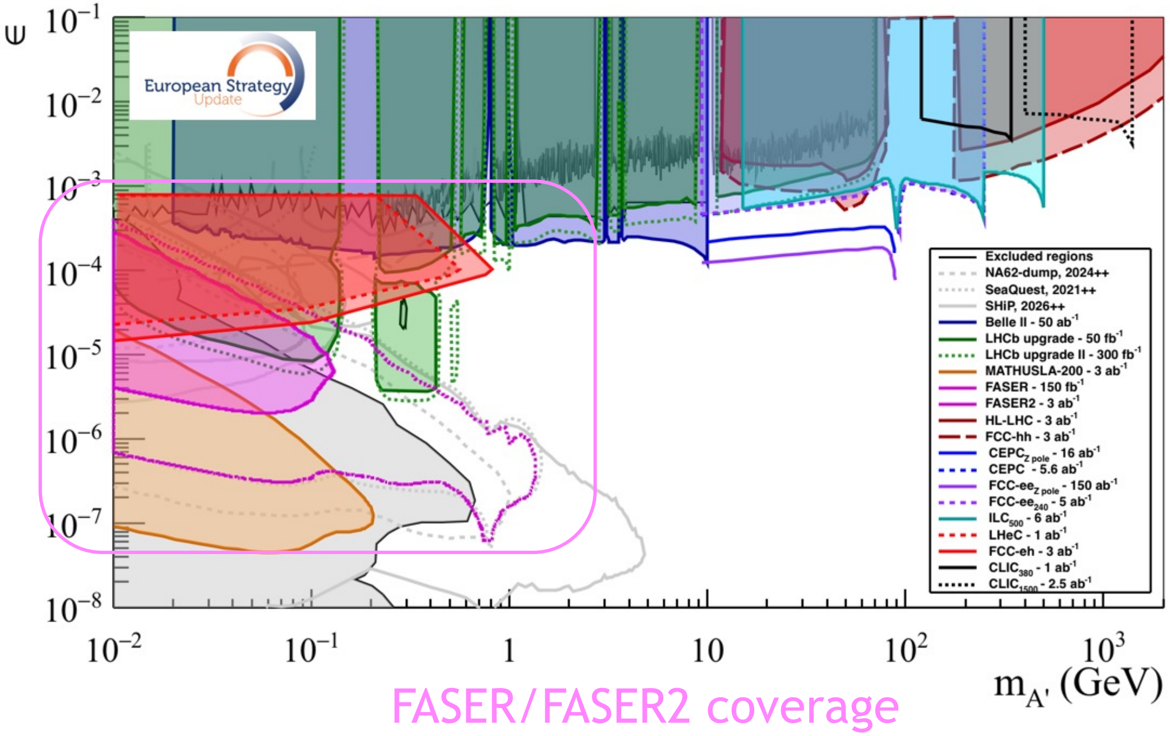


- The mechanism of portals as the lowest canonical-dimension operators that mix new dark-sector states with gauge-invariant combinations of SM fields is often considered, with 4 notable examples:

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)	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$

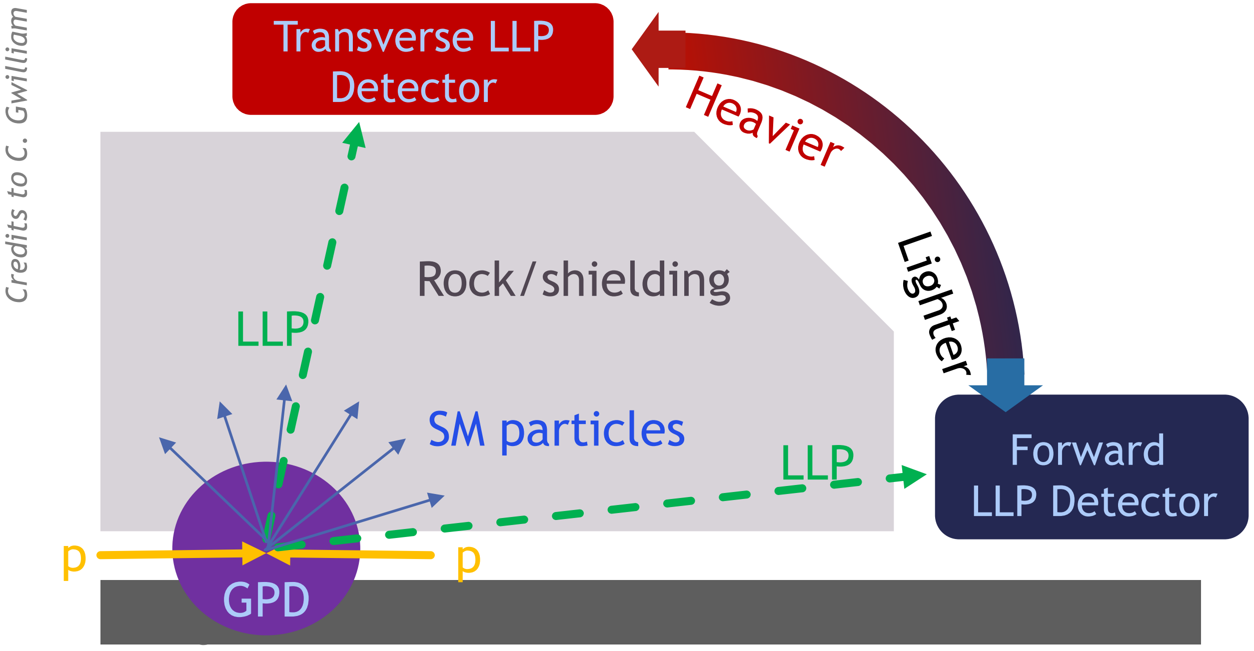
- The resulting new particles could be **Long-Lived** (LLP)

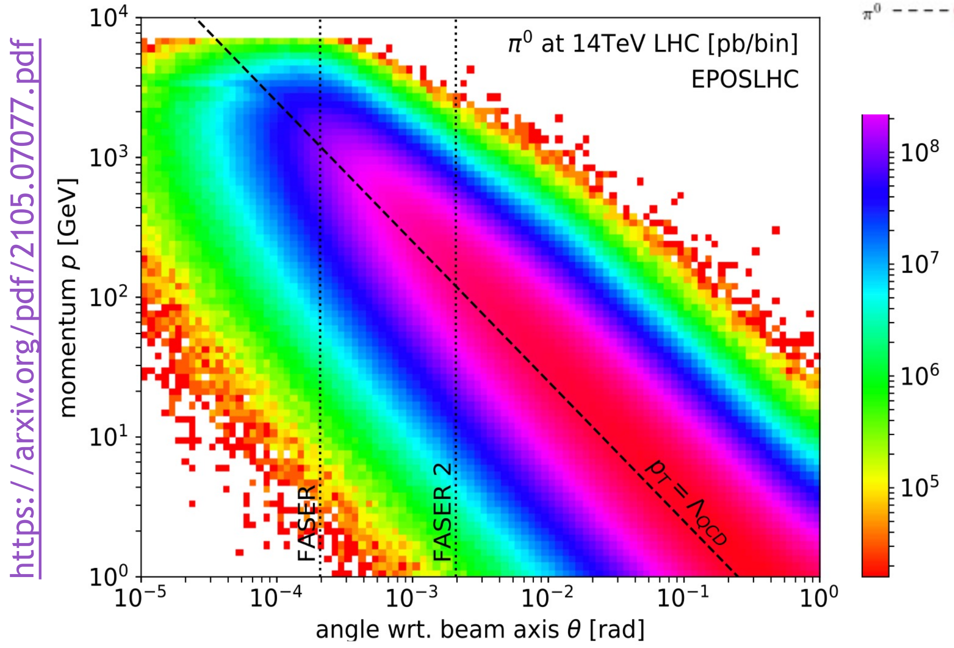
- Targeted searches for these BSM models have been identified as a priority by the European Strategy Update and the Snowmass process

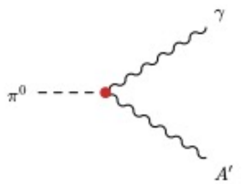


FASER and the DS: Motivation

- ATLAS, CMS (GPDs) and LHCb devote considerable efforts to searches for LLPs
  - Still, dedicated experiments might complement them 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





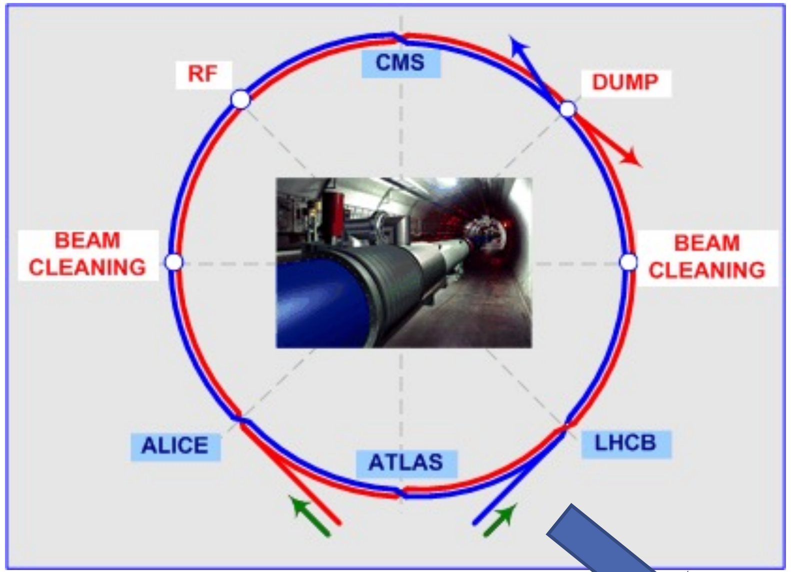


Detector is far from IP → target long lifetimes

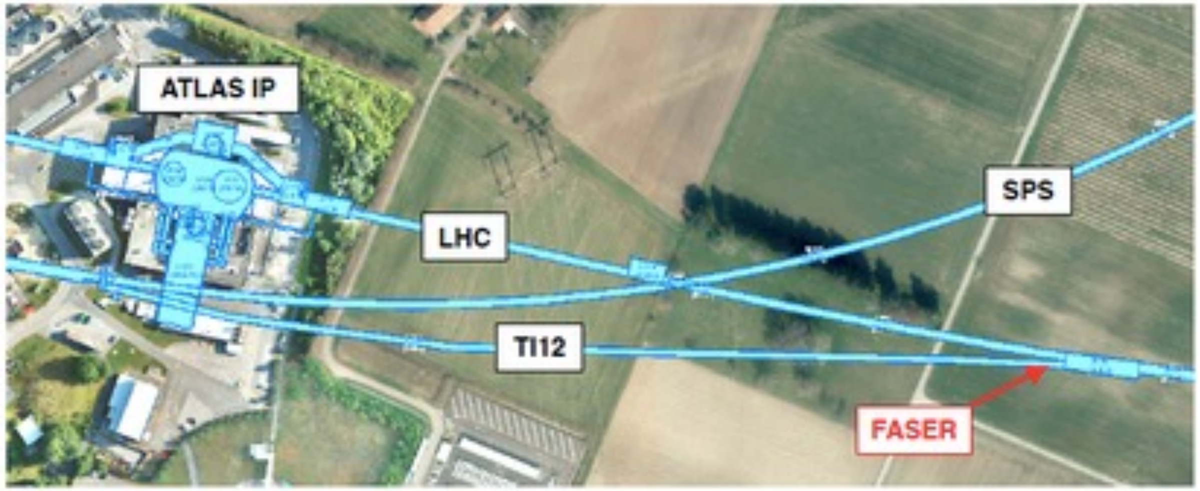
LLPs produced in forward-peaked light hadron decays → e.g. O(10^{14}) pions within FASER angular acceptance

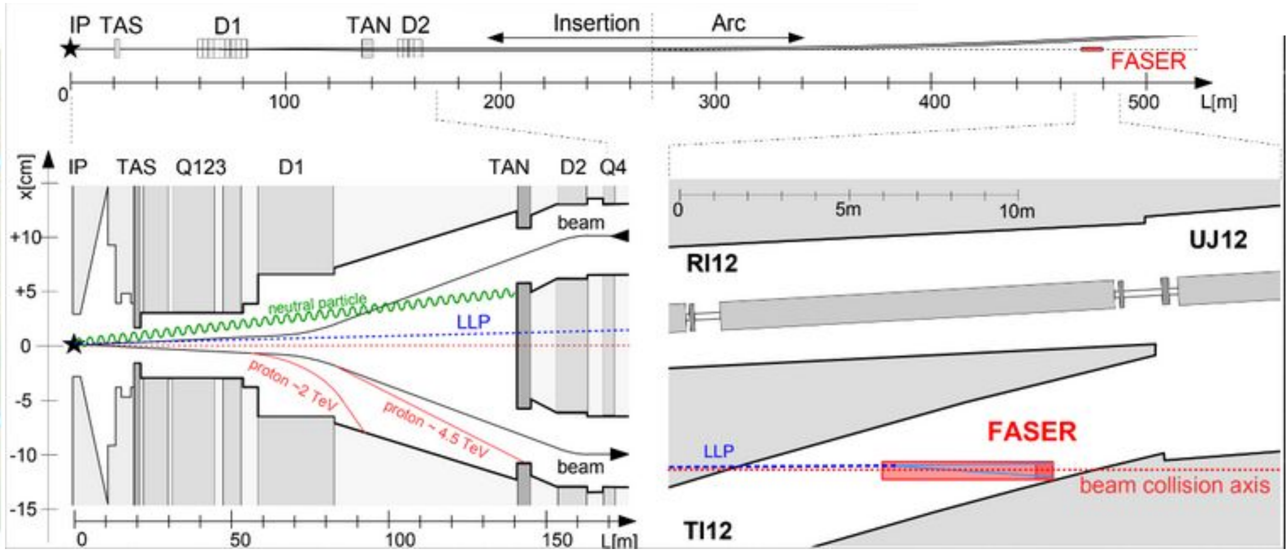
$$\theta \simeq \tan\theta = \frac{p_T}{p} \sim \frac{m}{E} \ll 1$$

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





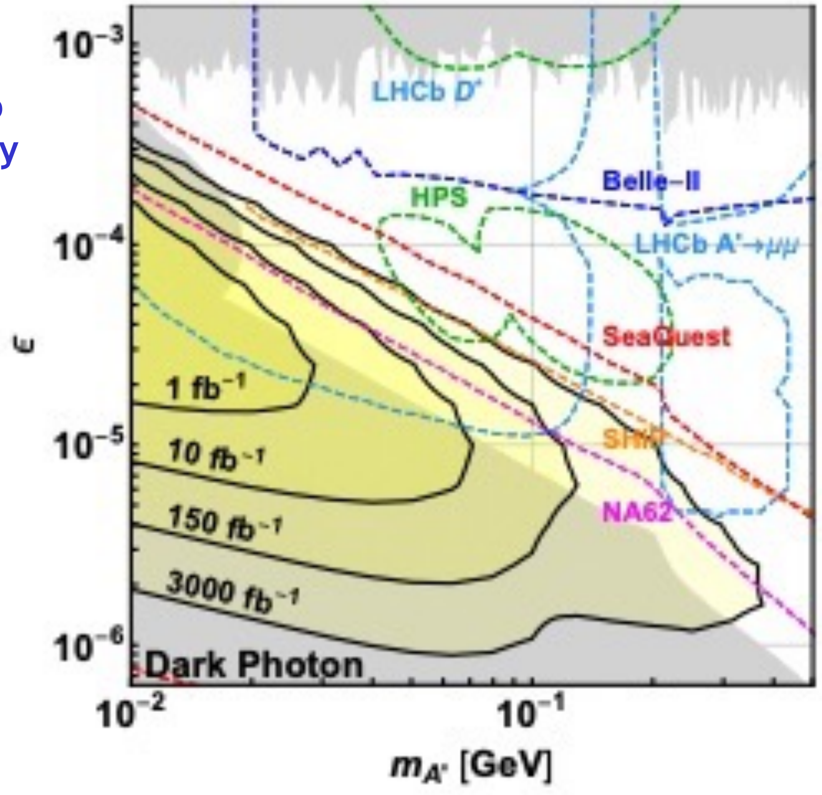
FASER(ν) Physics reach

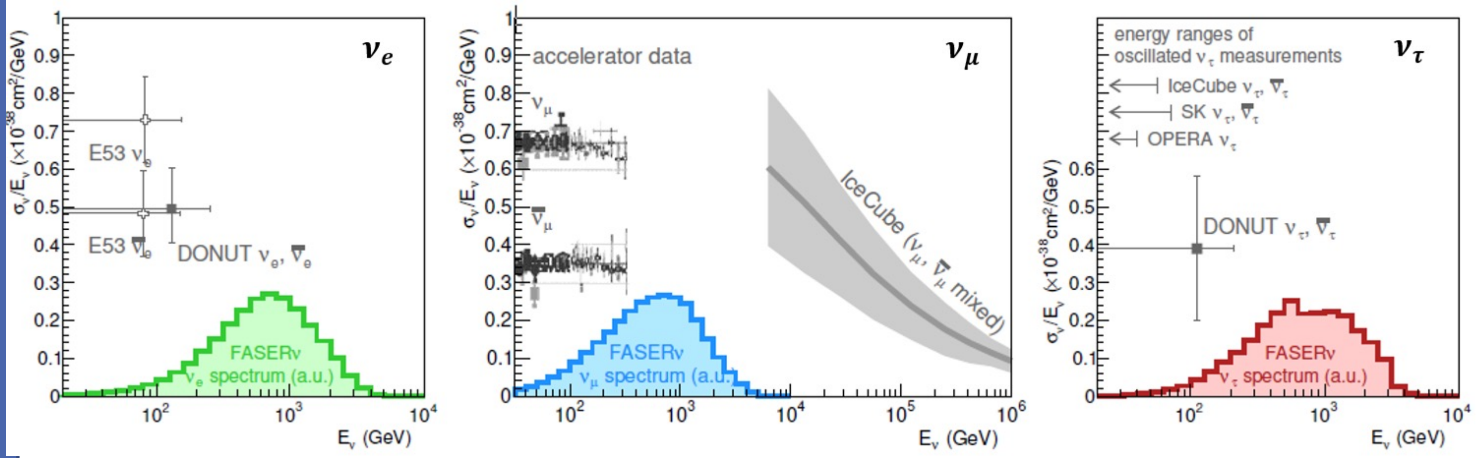
- Designed for events of the kind

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, as well as ALPS, HNL, B-L
- Also sensitive to high-energy neutrinos produced along beamline
  - A dedicated component, FASERν, added in 2020

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





Expected number of CC interactions (150 fb^{-1})

Generators		FASERν		
Light hadrons	Heavy hadrons	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
SIBYLL	SIBYLL	901	4783	14.7
DPMJET	DPMJET	3457	7088	97
EPOSLHC	PYTHIA8 (Hard)	1513	5905	34.2
QGSJET	PYTHIA8 (Soft)	970	5351	16.1
Combination (all)		1710^{+1746}_{-809}	5782^{+1306}_{-998}	$40.5^{+56.6}_{-25.8}$
Combination (w/o DPMJET)		1128^{+385}_{-227}	5346^{+558}_{-563}	$21.6^{+12.5}_{-6.9}$

F. Kling and L. Nevay, Forward Neutrino Fluxes at the LHC, Phys. Rev. D 104, 113008, arXiv:2105.08270

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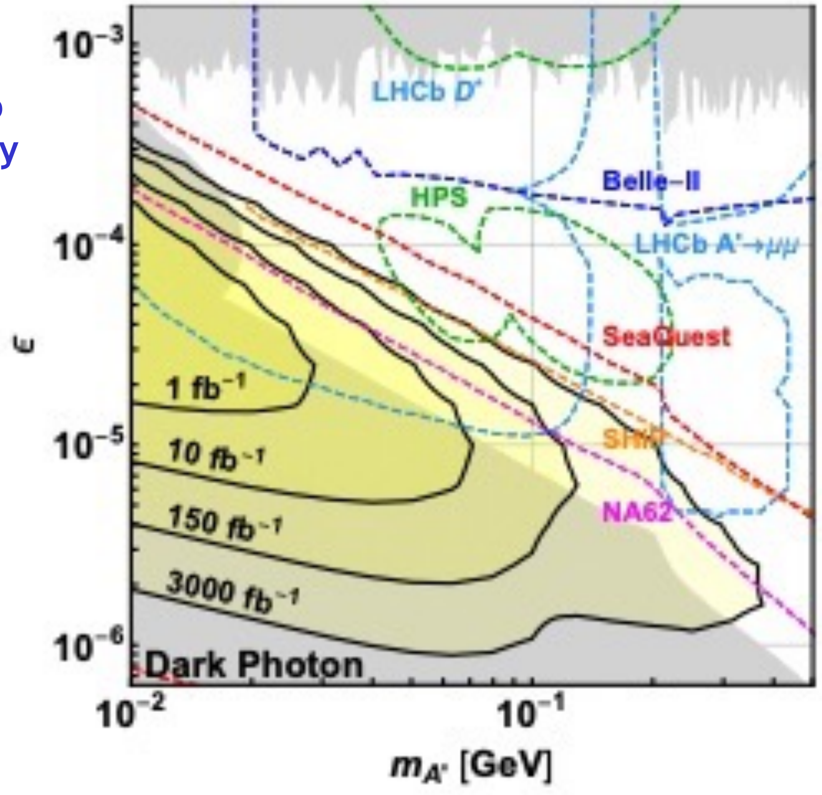
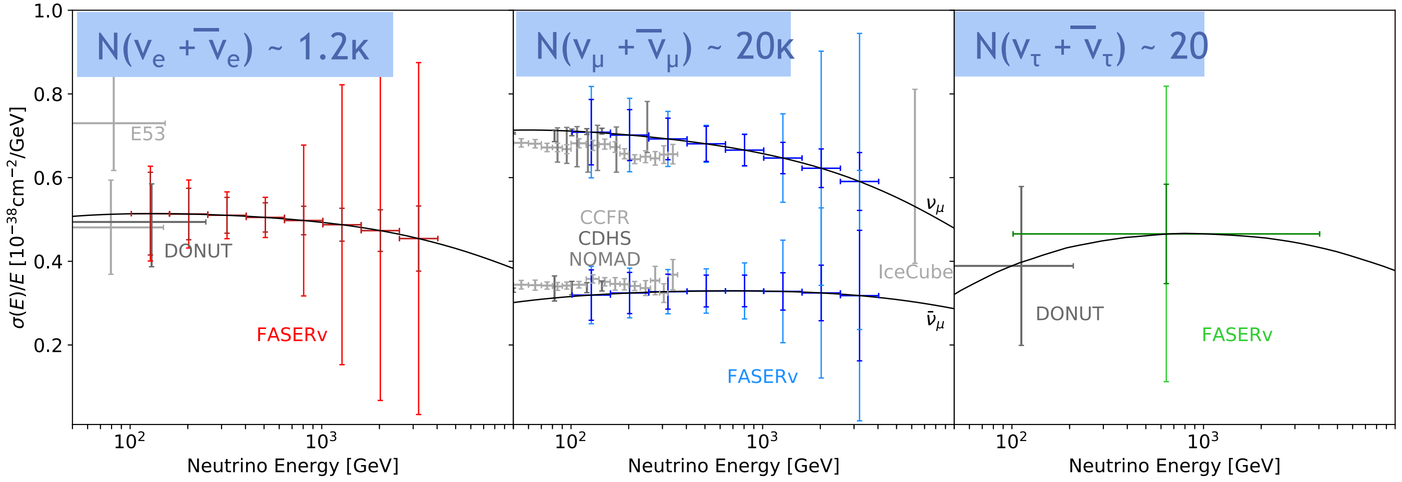
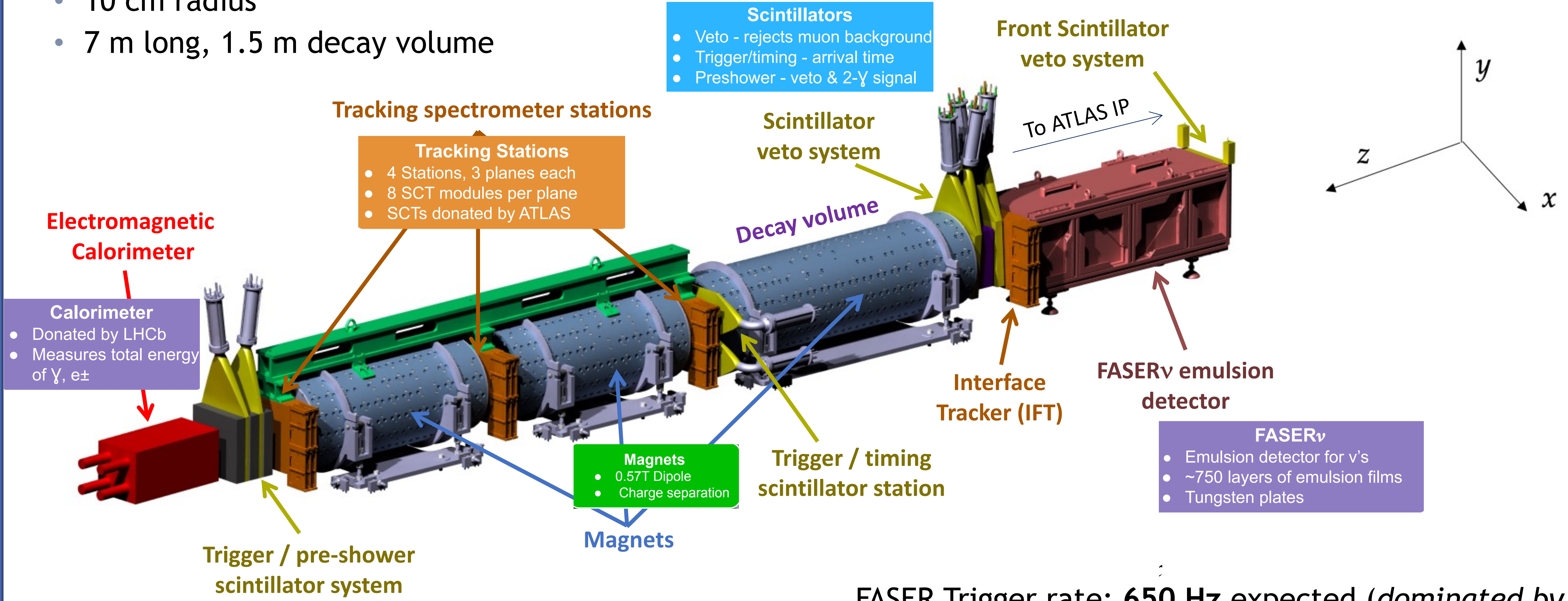




- Cross-section measurements possible for all neutrino flavours in E range from ~ 100 GeV to ~1 TeV
  - Unconstrained region of phase space

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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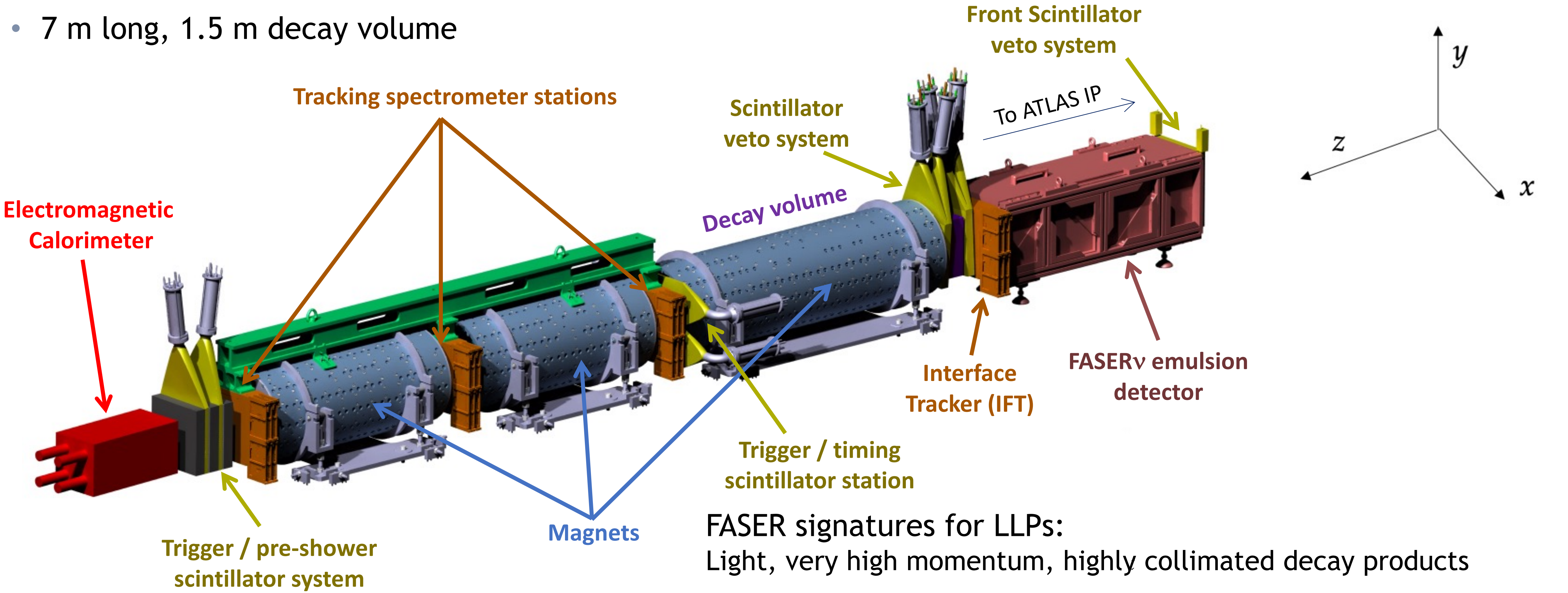
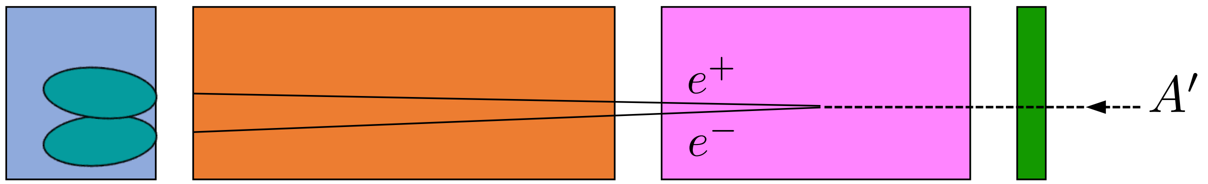


FASER signatures for LLPs:
Light, very high momentum, highly collimated decay products



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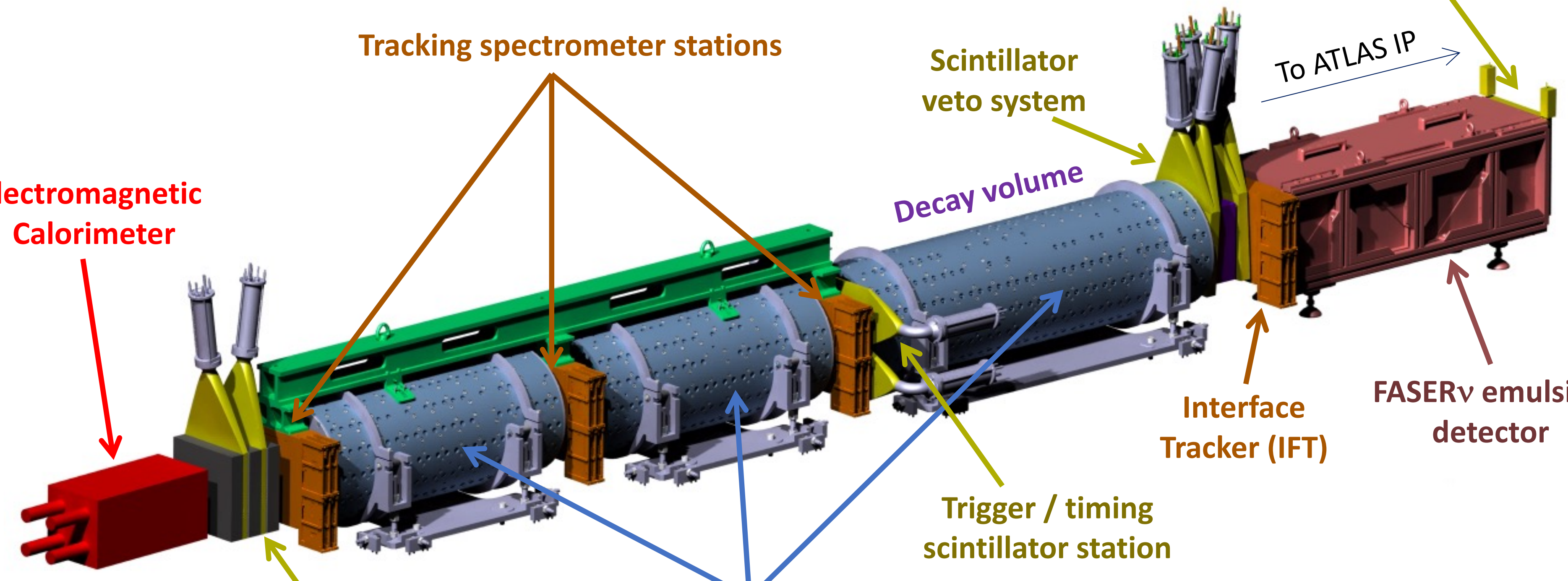
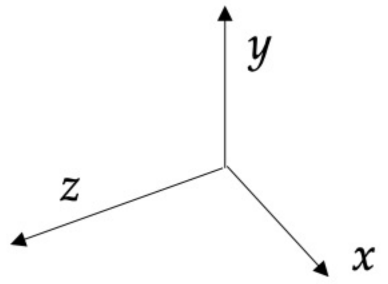
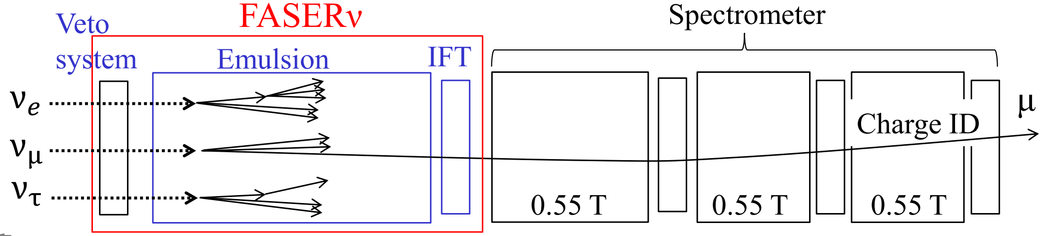
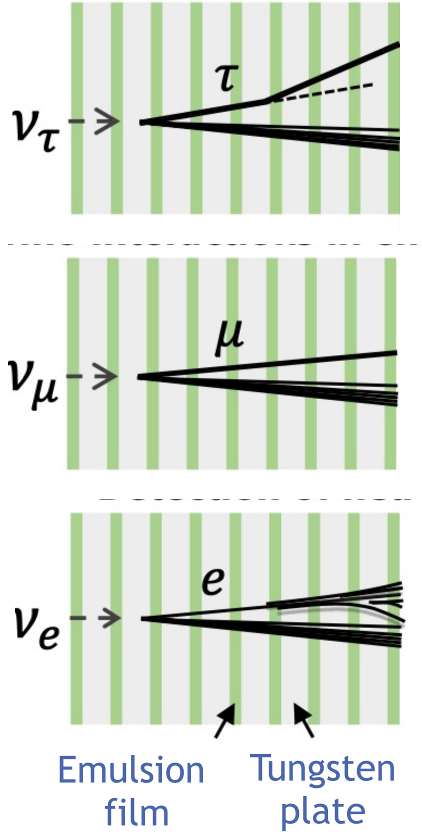




FASERν signatures for high energy neutrinos:



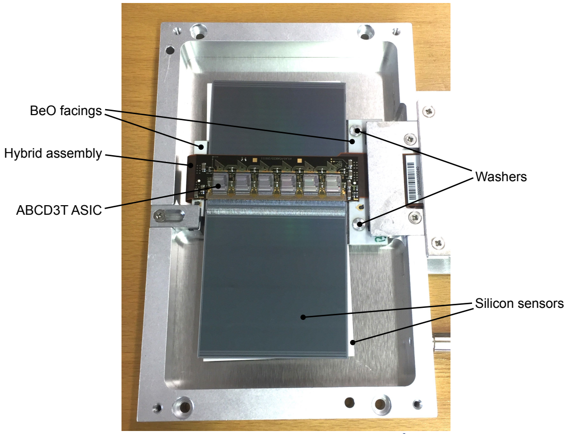


FASER Tracking: components and layout

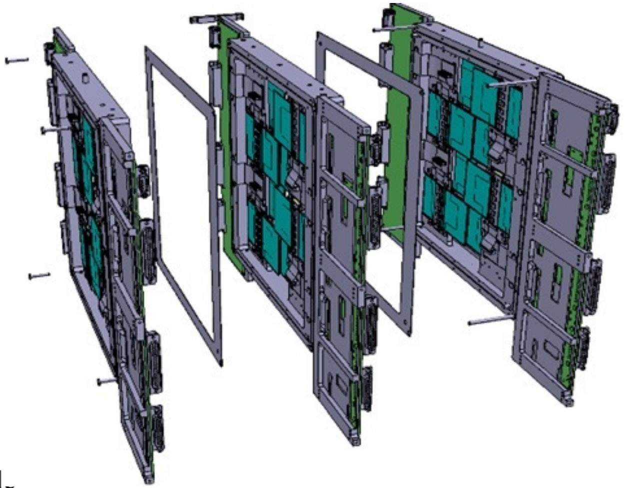
NIMA 166825 (2022)

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

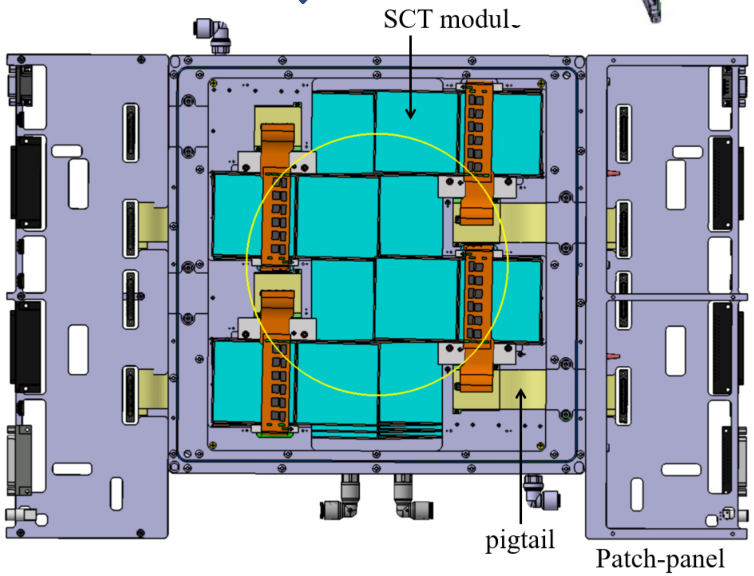
Basic component: SCT Module
→ **Strip detector,** pitch 80um and stereo-angle of 40mrad.
→ 8 modules per tracker plane



Tracking Station



Tracker Plane



3 Tracker planes per station (12 total)

Low material central region: 2.1% radiation length

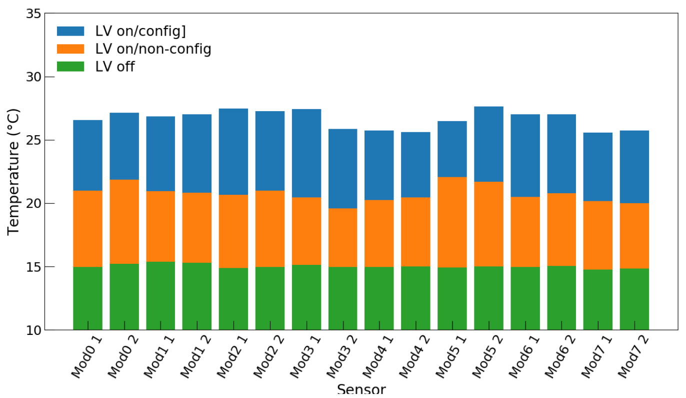
Component	Material	Number / station	X_0 (%) Central region	X_0 (%) Edge region
Silicon sensor	Si	6	1.8%	1.8%
Station Covers	CFRP	2	0.3%	0.3%
SCT module support	TPG	3	-	0.6%
C-C Hybrid	C (based)	3	-	2.2%
ABCD chips	Si	3	-	6.5%
Layer frame	Al	3	-	10.1%
Total / station	**-**	**-**	**2.1%**	**21.5%**

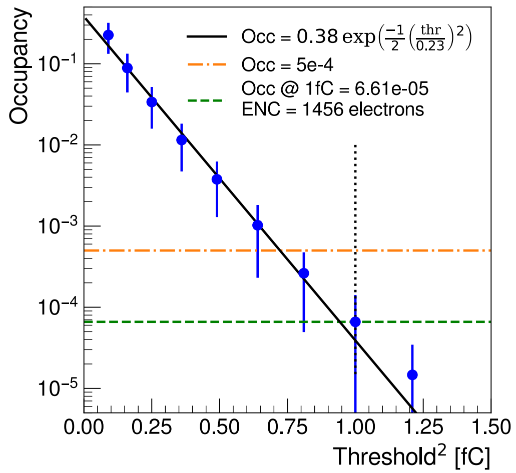
FASER Tracking: tests and performance

NIMA 166825 (2022)

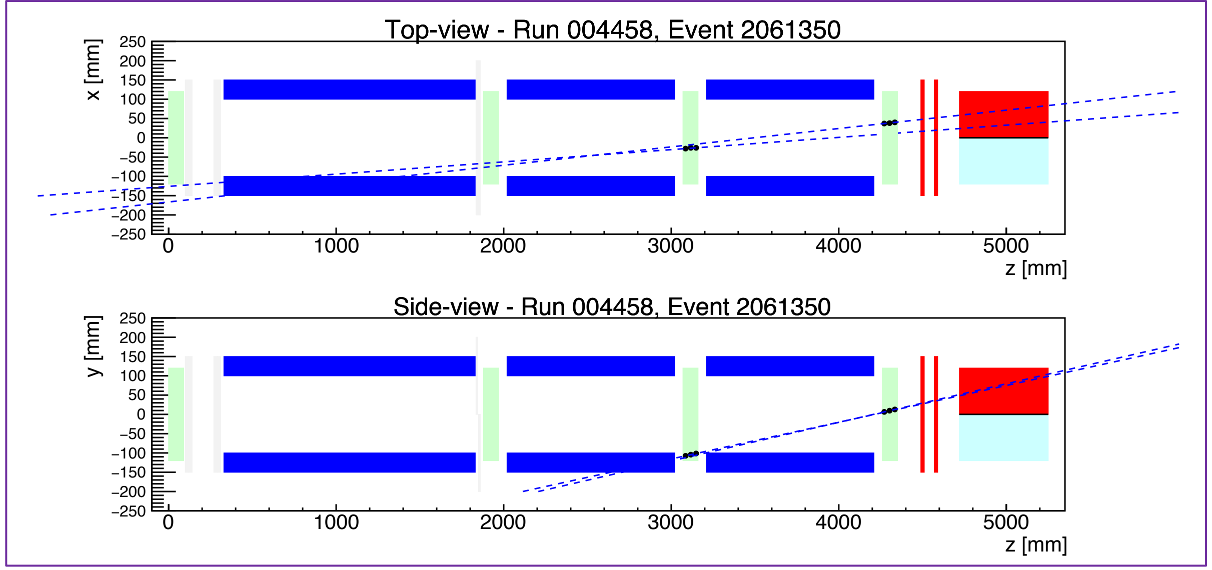
Extensive tests have been carried out to evaluate performance, standalone and after installation:

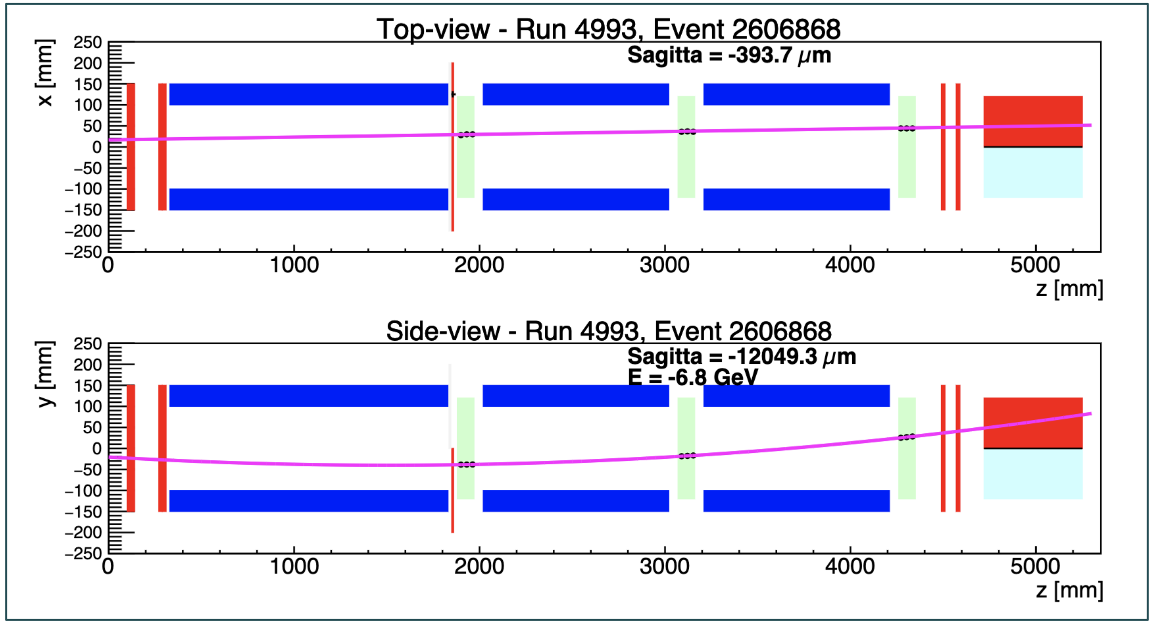
- long-term stability and control checks (temperature, humidity, electronics)
- Quantification of noisy/dead strips
- Alignment and metrology of tracker planes





Commissioning with cosmic rays and LHC pilot run



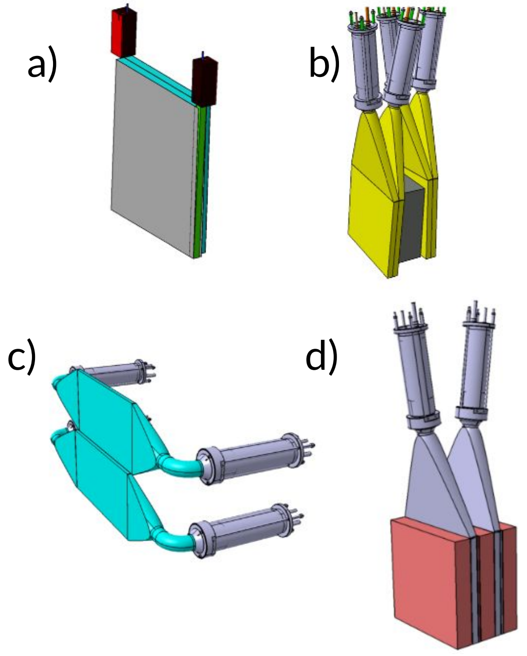


purple line: combined track fit to the hits in the tracking stations during 900 GeV pilot beam

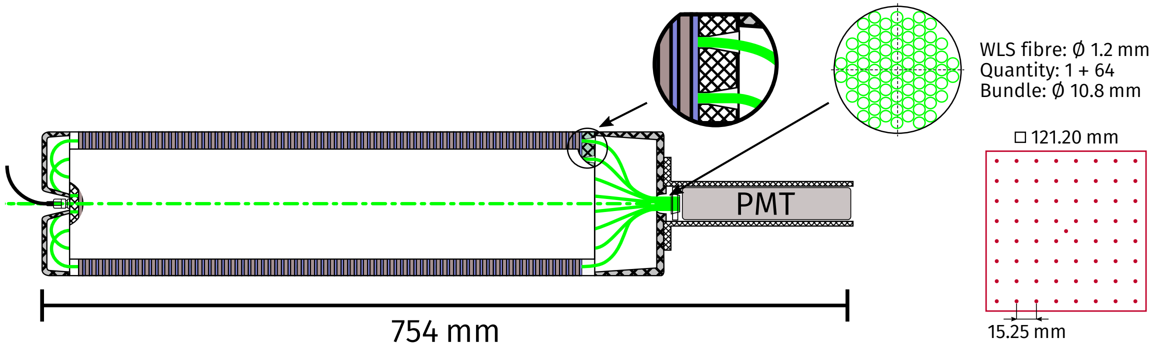
FASER calorimeter, pre-shower and scintillator systems

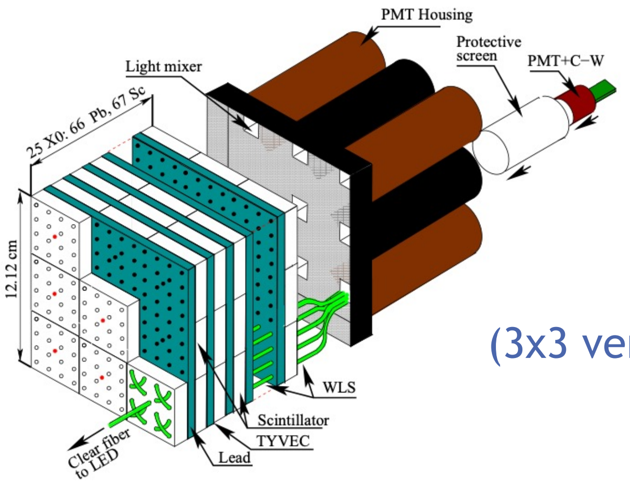
- **Four scintillator stations** with multiple scintillator layers in each station
  - (a) FASERν Veto, (b) Interface Veto, (c) Timing, & (d) Preshower
  - >99.98% efficiency, sufficient to veto all incoming muons
  - photo-multiplier tubes to detect the scintillation signals.

  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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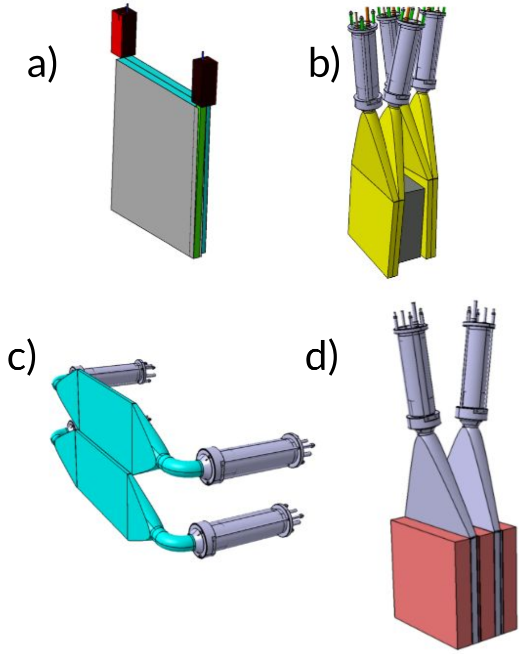

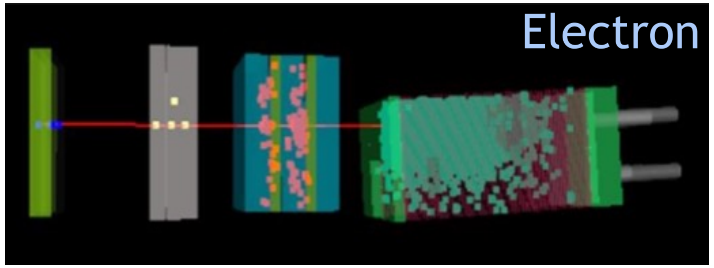

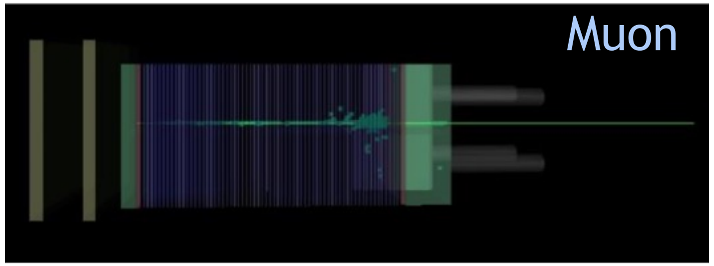

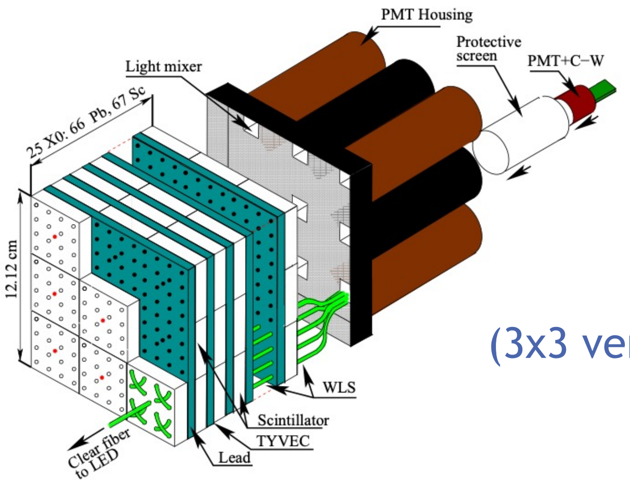

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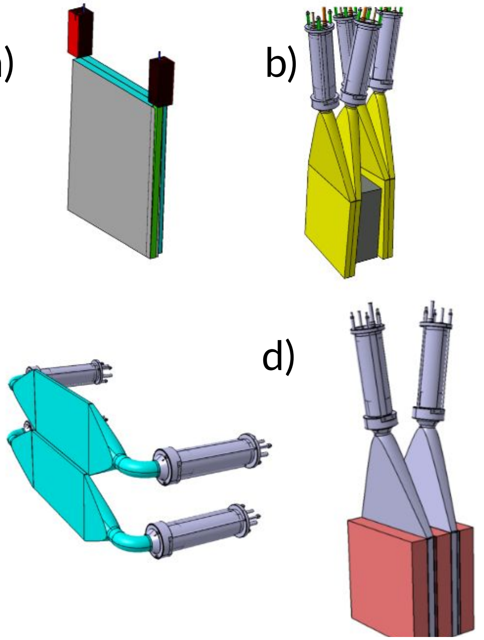

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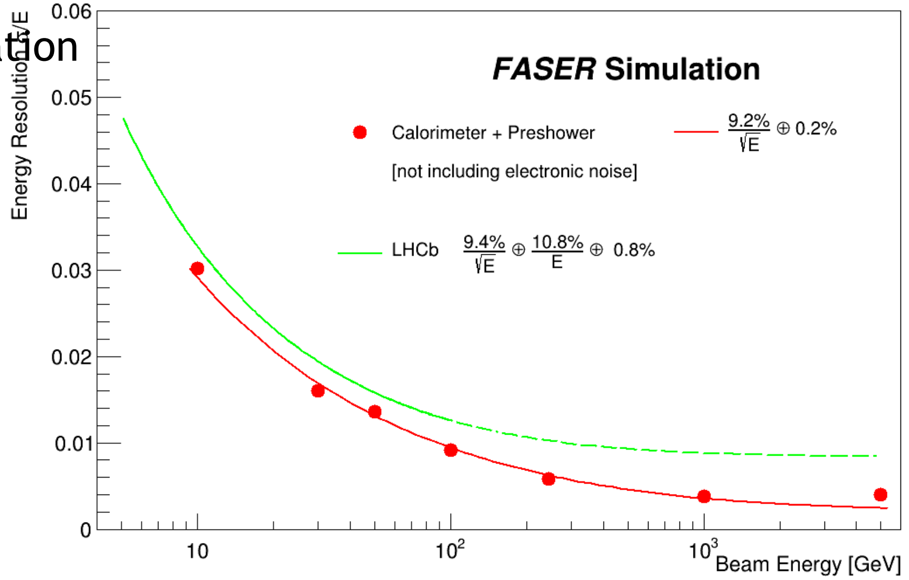


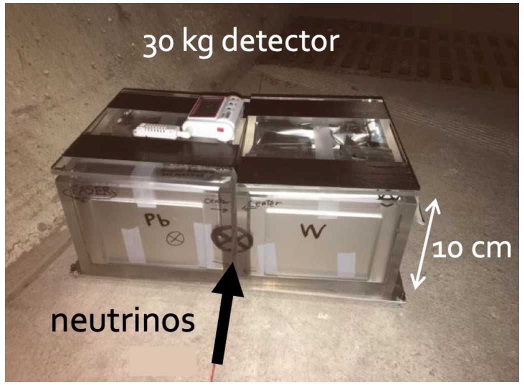
$$\frac{\sigma_E}{E} = \frac{9.2\%}{\sqrt{E}} \oplus 0.2\%$$

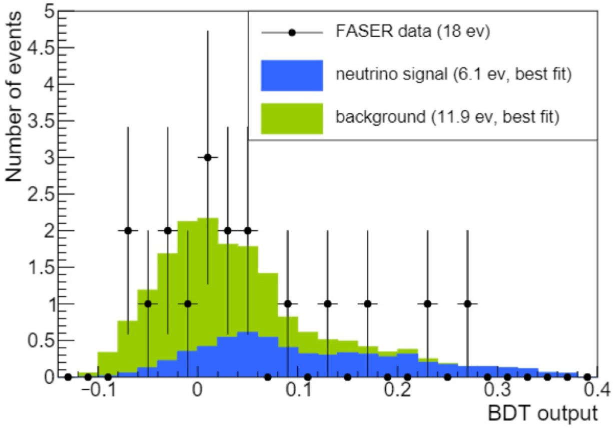
+ expected 1% constant term

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

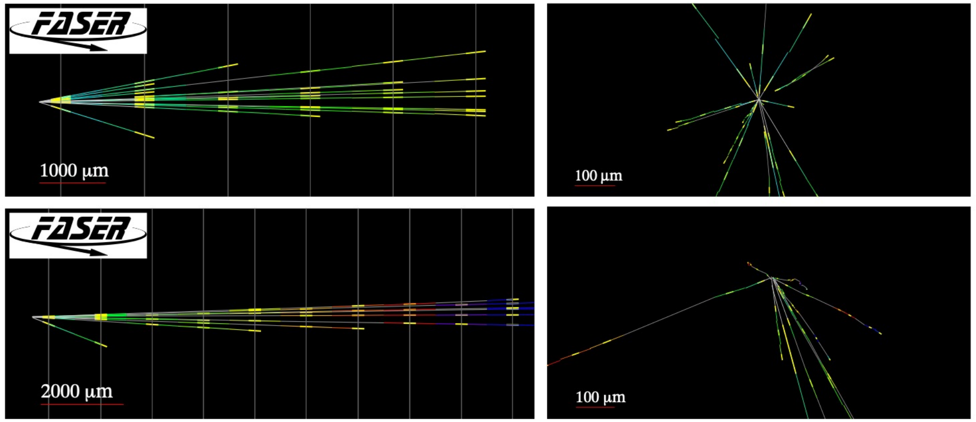
FASERν detector

Phys. ReV. D 1004, L091101





- 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:**



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

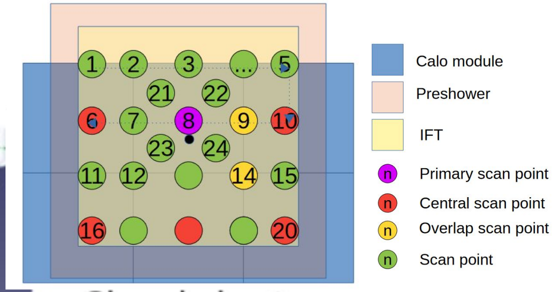
Ship to CERN | Install in Ti12 | Disassemble | Ship to Japan

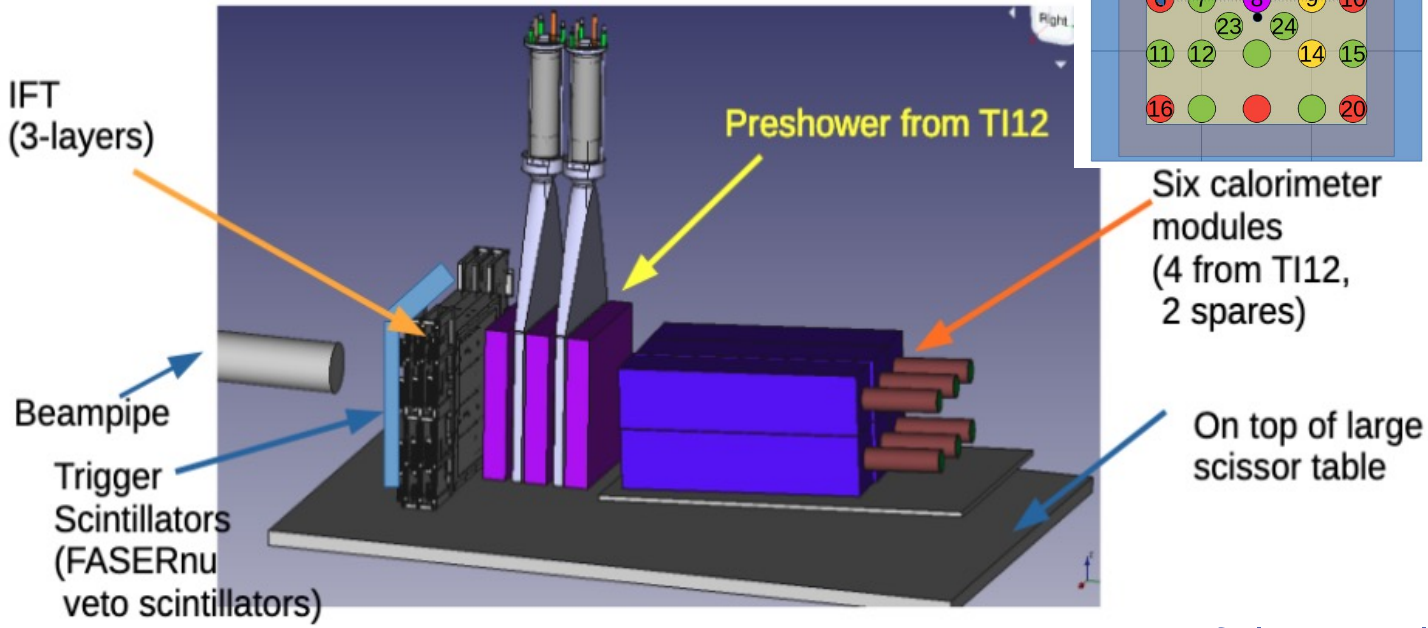
Replacements: ~ 3 times/yr in technical stops, every 30-50 fb^{-1}

FASER Test Beam

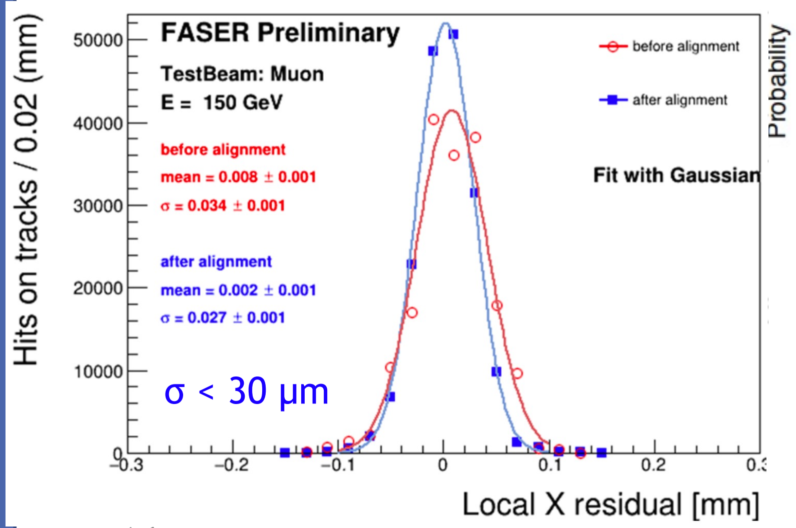
Paper in progress!

- 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 %)

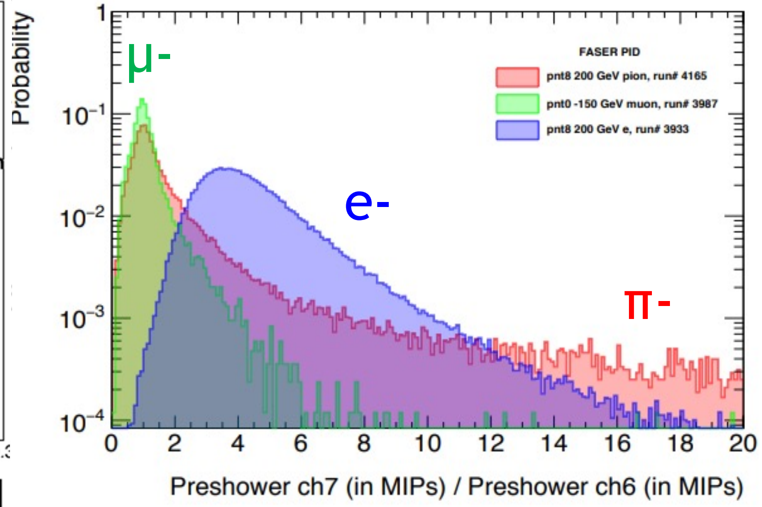




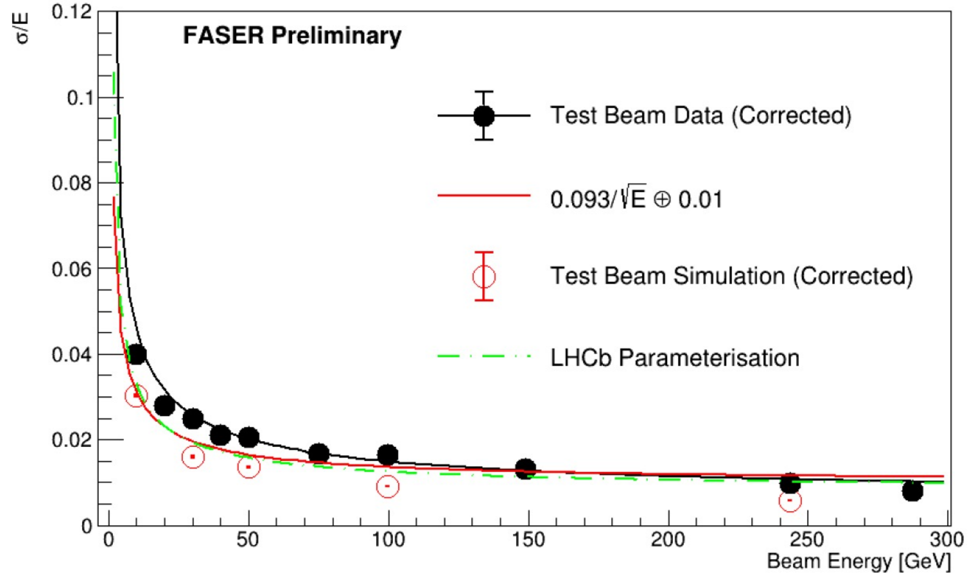
Tracking resolution



Preshower Particle Identification

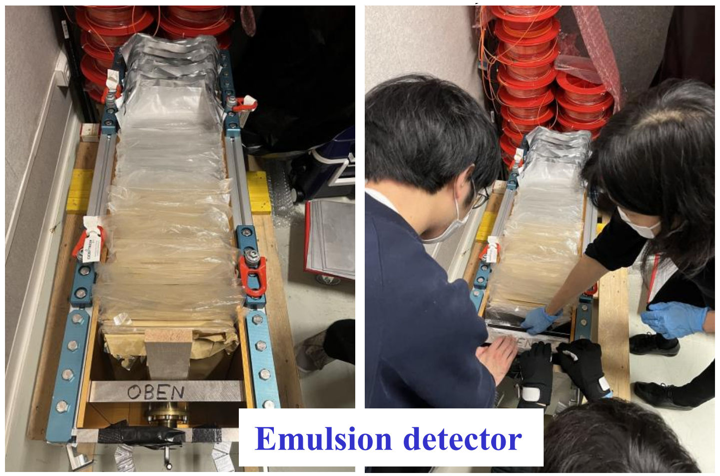


Calo E resolution

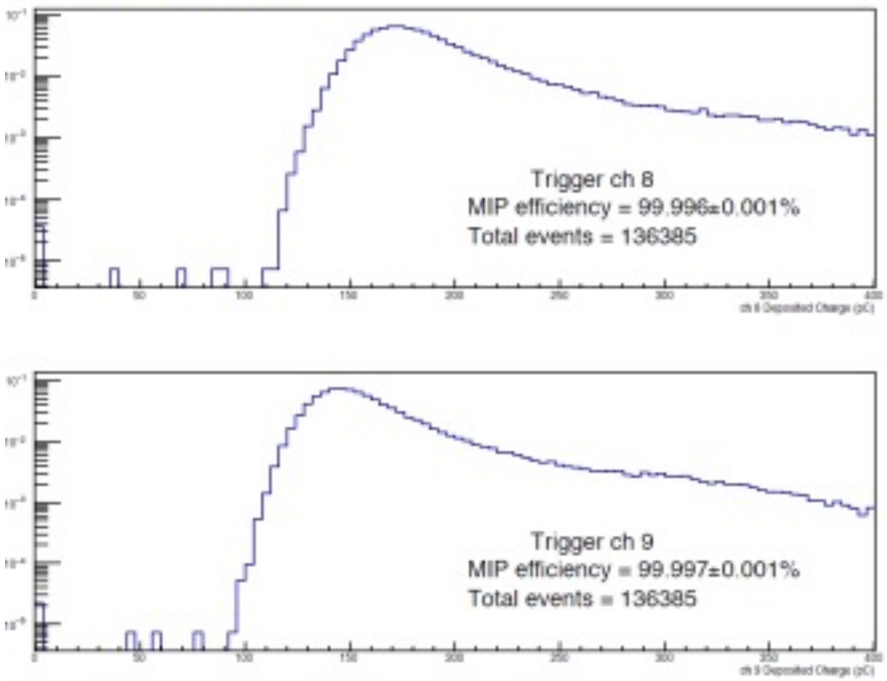


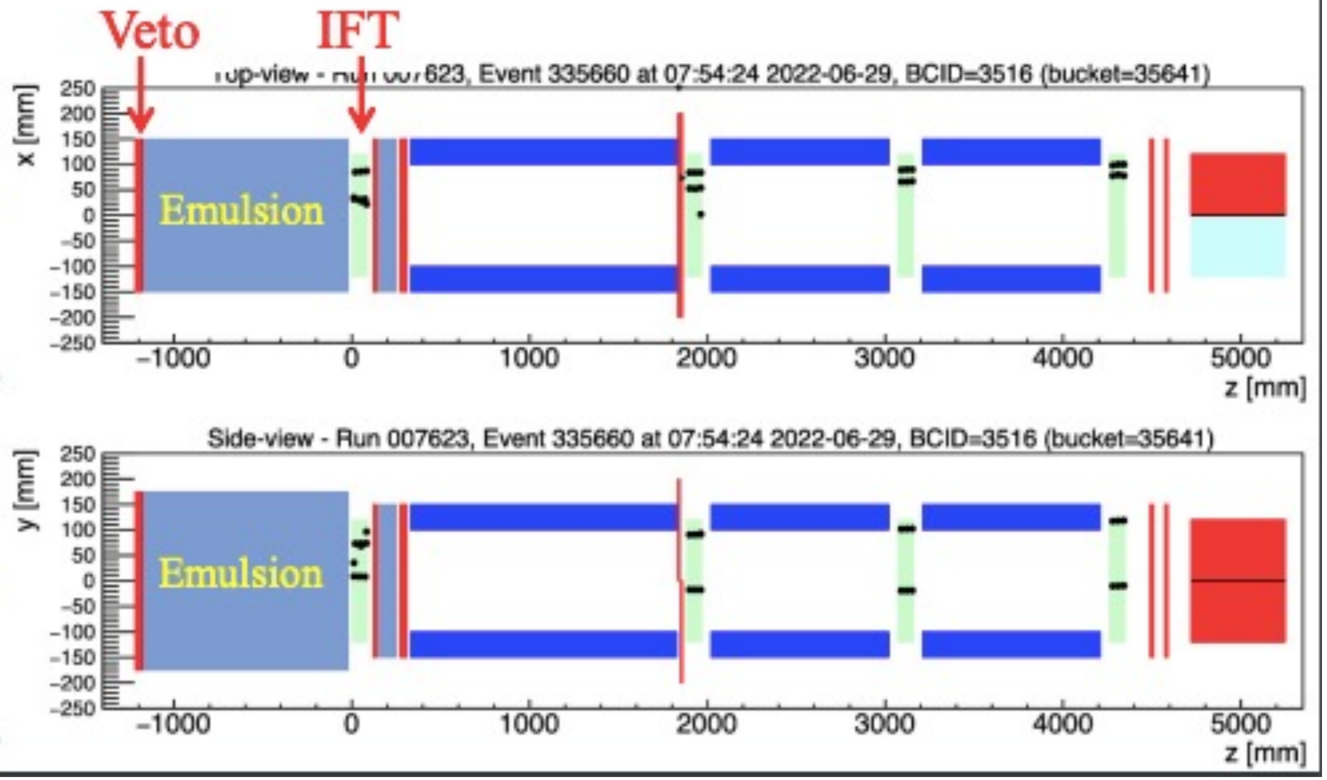
FASERν detector commissioning

- ~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



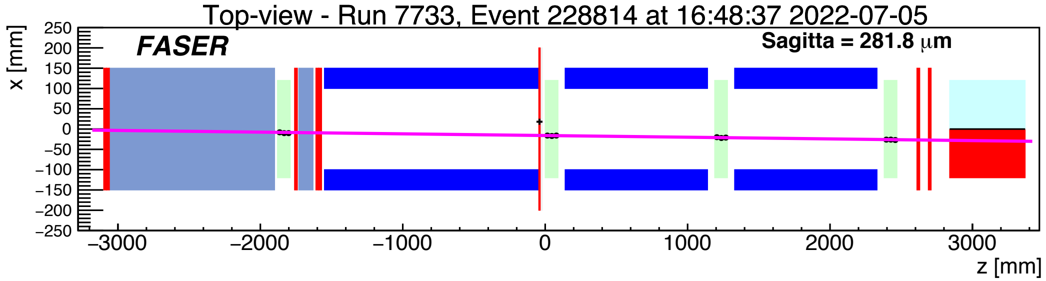


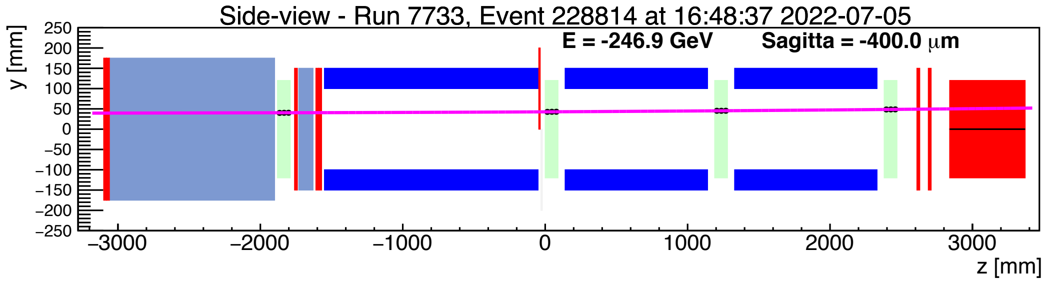
Full detector installed

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

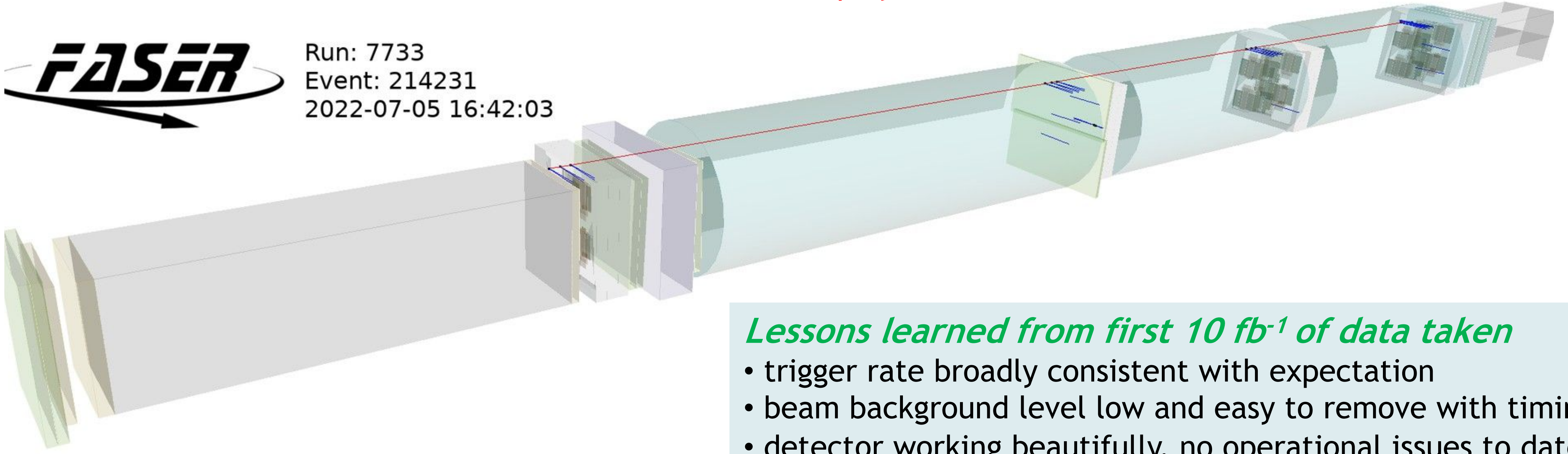
First data !

- 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

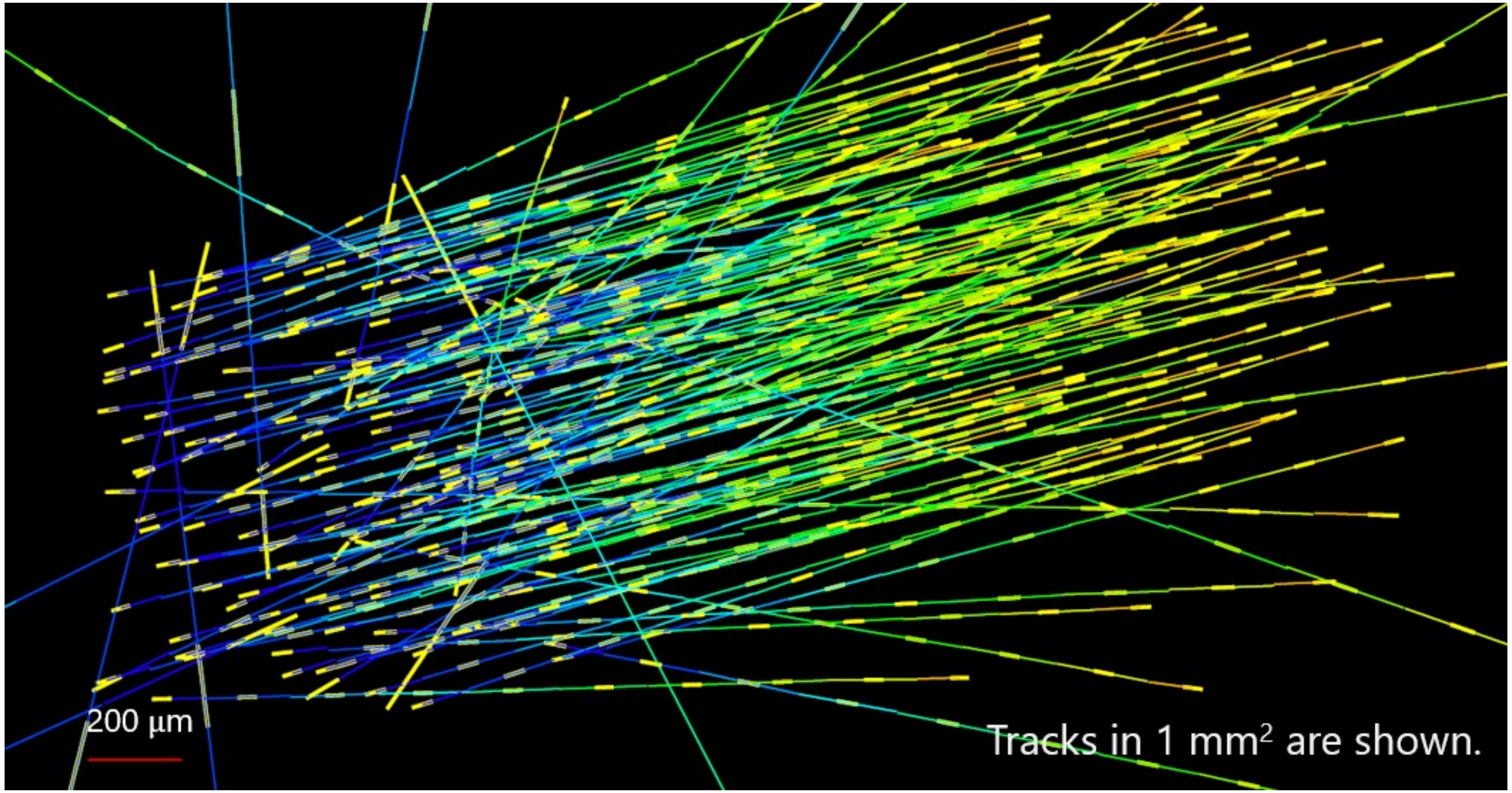


Lessons learned from first 10 fb^{-1} of data taken
- trigger rate broadly consistent with expectation
- beam background level low and easy to remove with timing
- detector working beautifully, no operational issues to date

First data !

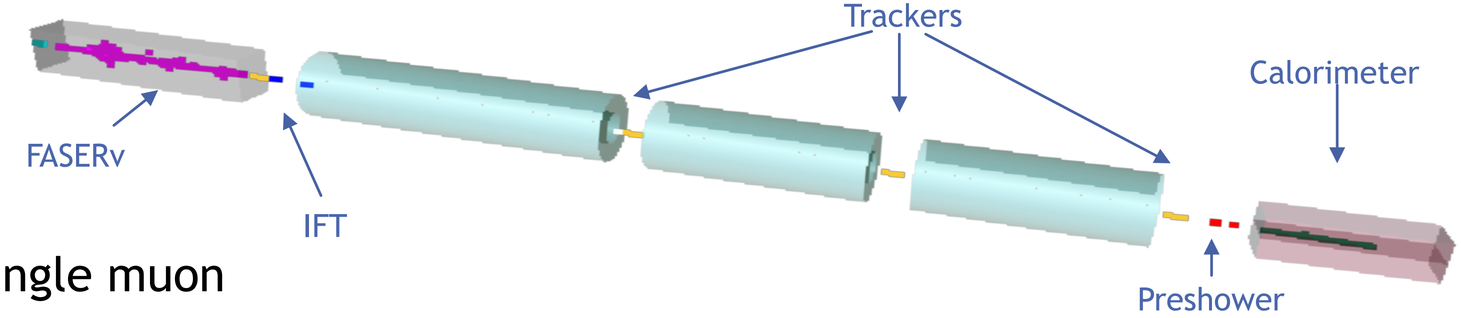
- Thousands of events were already collected with charged particle tracks traversing the detector prior to official start
  - Great for performance studies, optimizing operation procedures, & commissioning reconstruction software.

Tracks from the first FASERν emulsion films

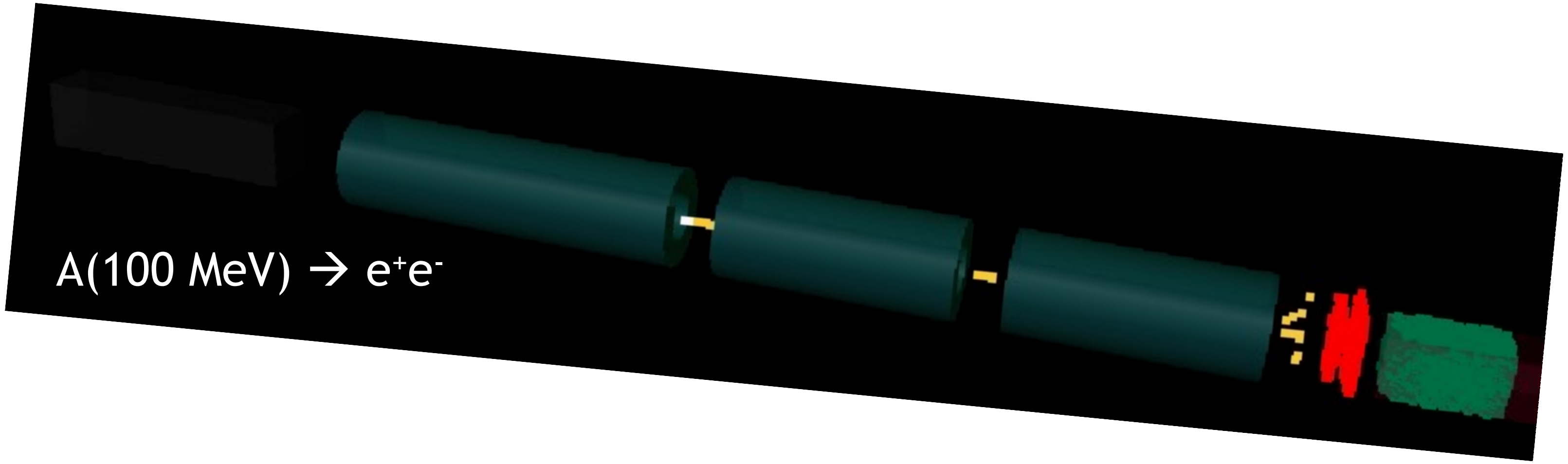


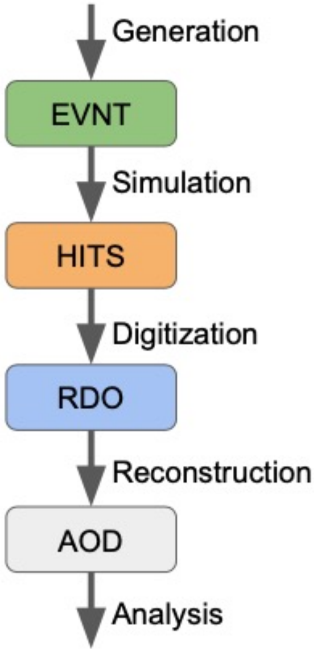
Data analysis readiness

- 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

- On-going tests on full production chain from generation all the way through to analysis
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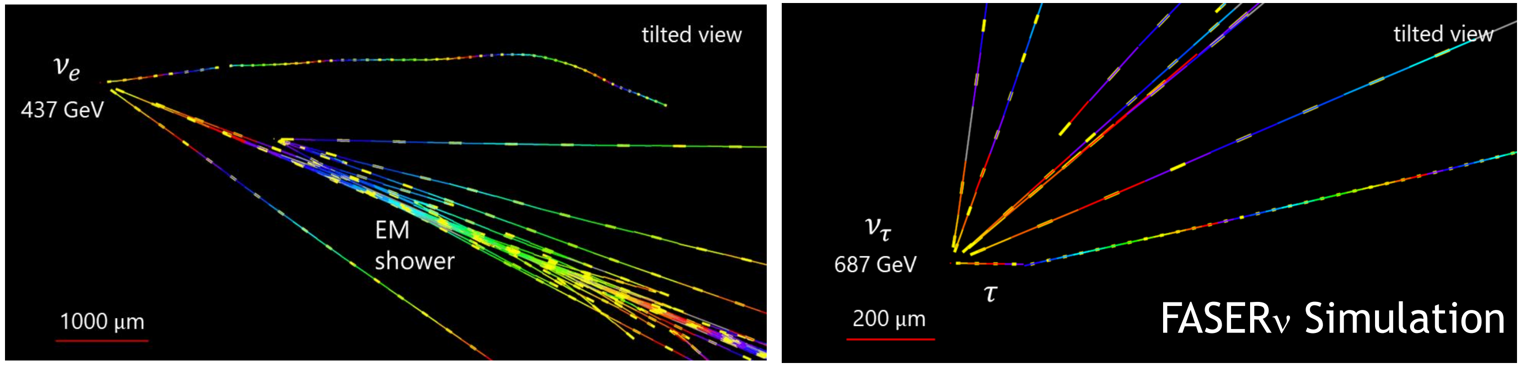
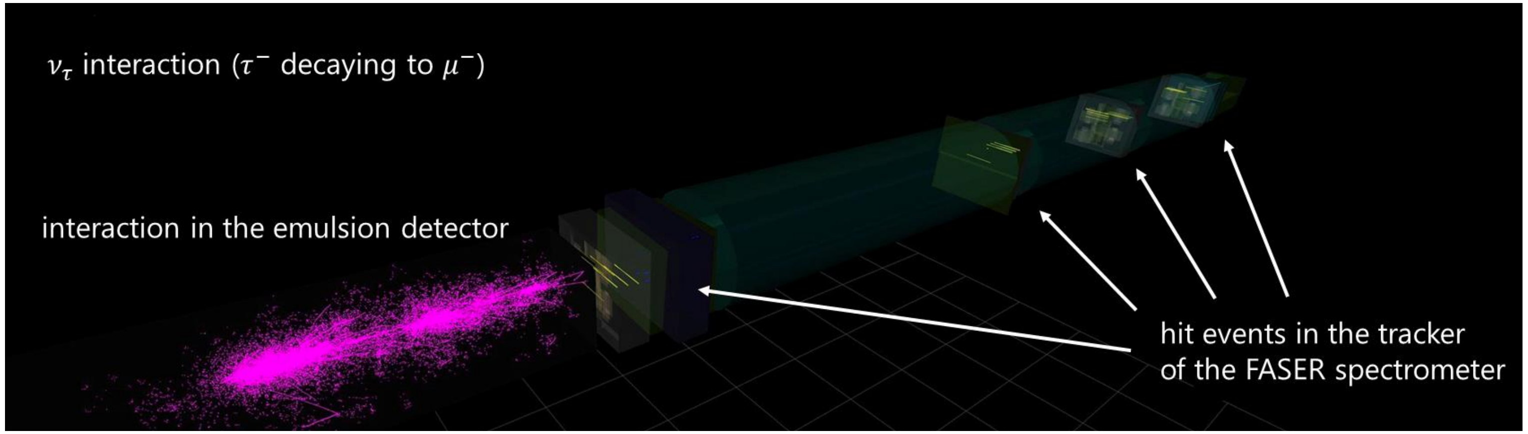
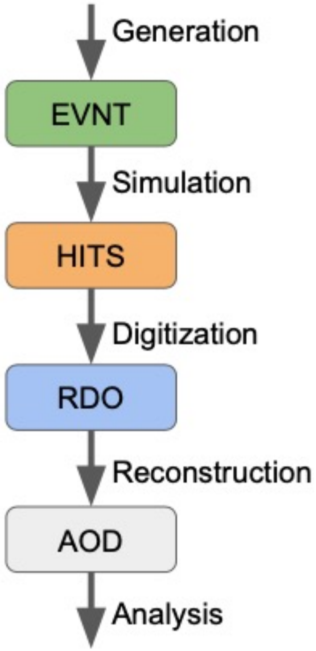




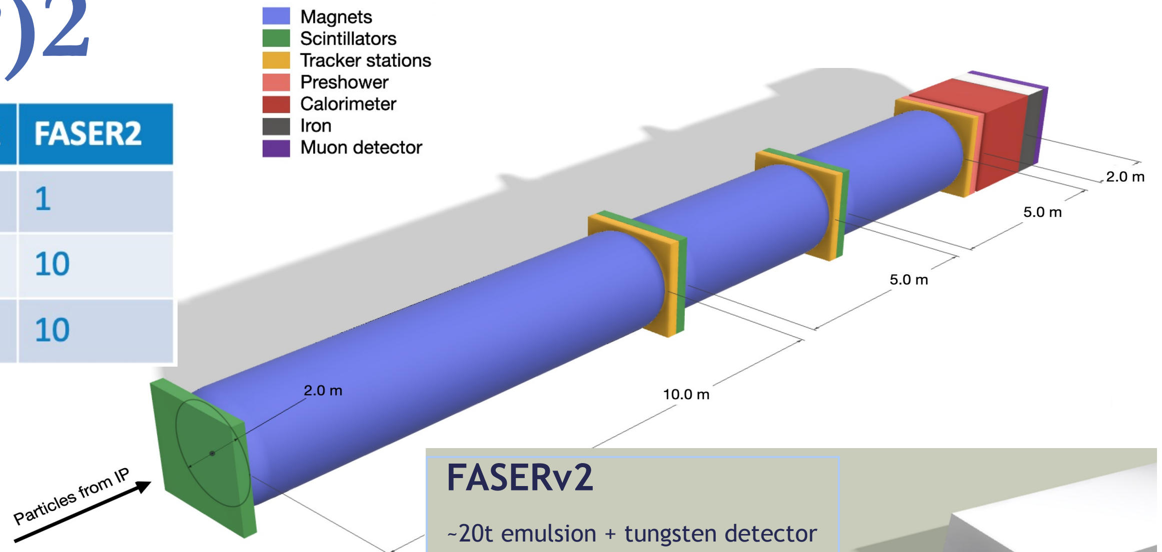


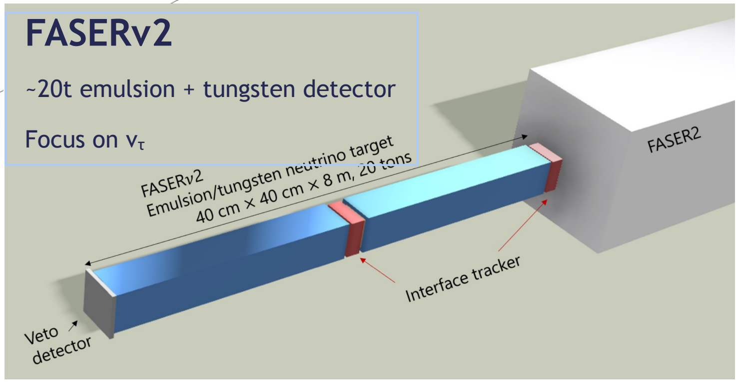
Neutrino events simulation also fully ready

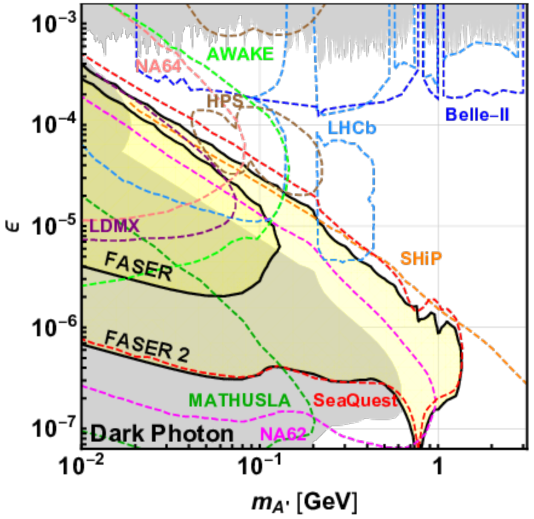
The forward future: FASER(ν)2

- We might not see LLPs or NP in Run 3:
  - Extended coverage needs a bigger detector
- *Thinking ahead*: 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

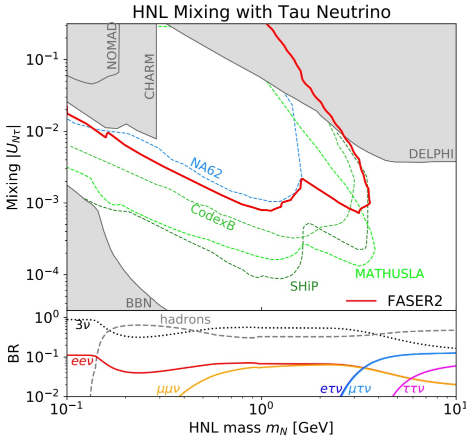


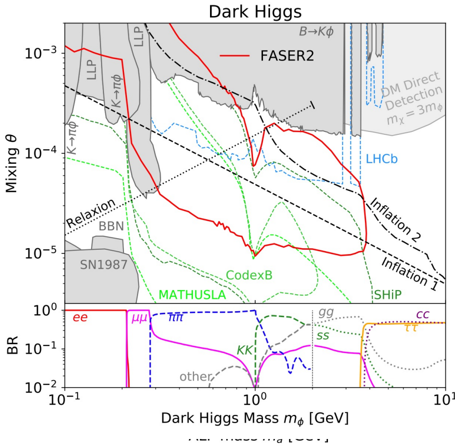




Benchmark Model	FASER	FASER 2
Dark Photons	√	√
$B-L$ Gauge Bosons	√	√
$L_i - L_j$ Gauge Bosons	—	—
Dark Higgs Bosons	—	√
Dark Higgs Bosons with hSS	—	√
HNLs with e	—	√
HNLs with μ	—	√
HNLs with τ	√	√
ALPs with Photon	√	√
ALPs with Fermion	—	√
ALPs with Gluon	√	√
Dark Pseudoscalars	—	√

Probing up to higher mass

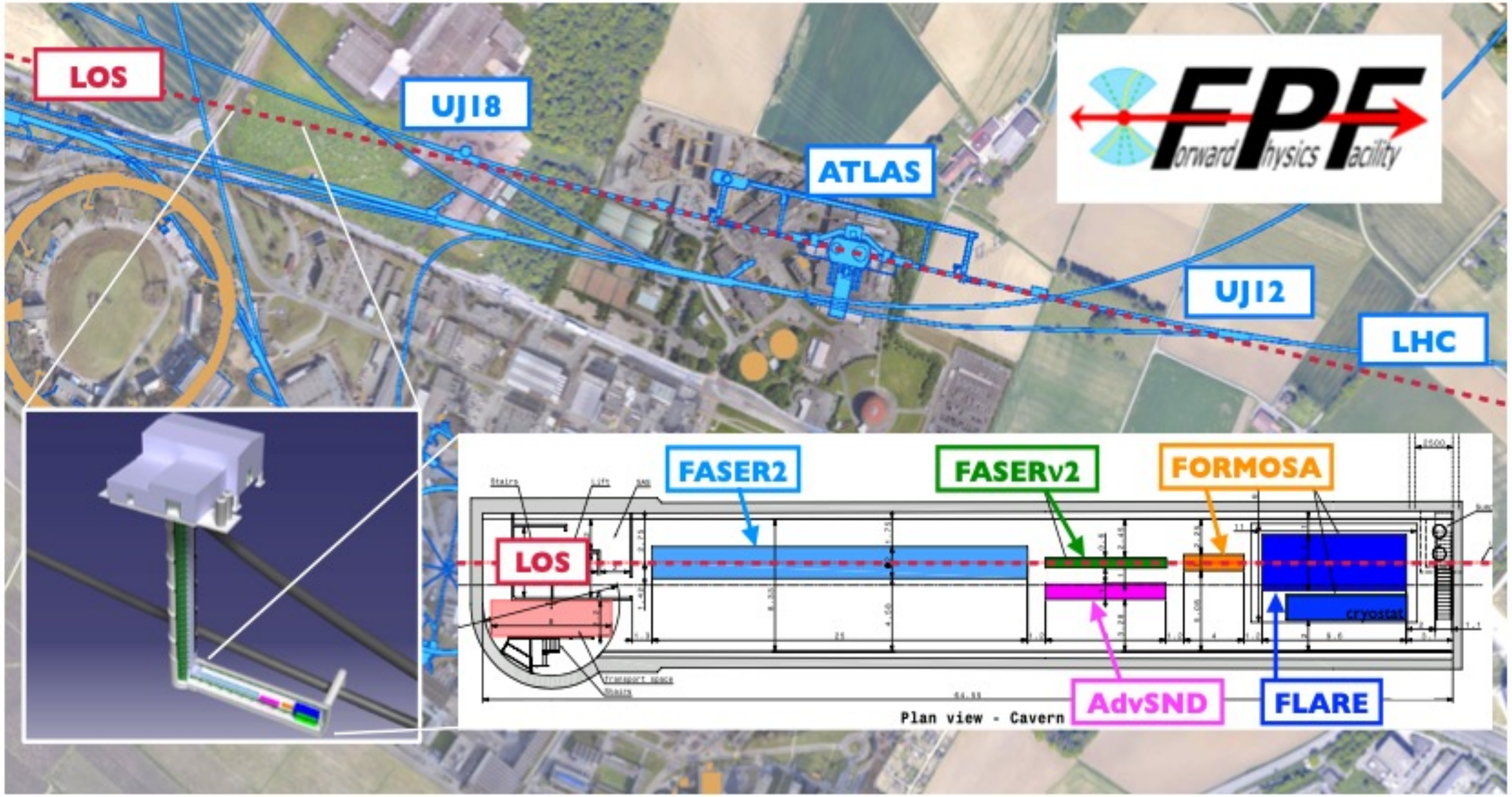




Substantial increase in sensitivity for LLPs from B, D hadrons decays (e.g. Dark Higgs) thanks to larger radius, Broader scope including QCD physics

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



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

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

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 installed and fully operational
  - 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 10/fb of data collected so far…
  - detector working beautifully, no 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

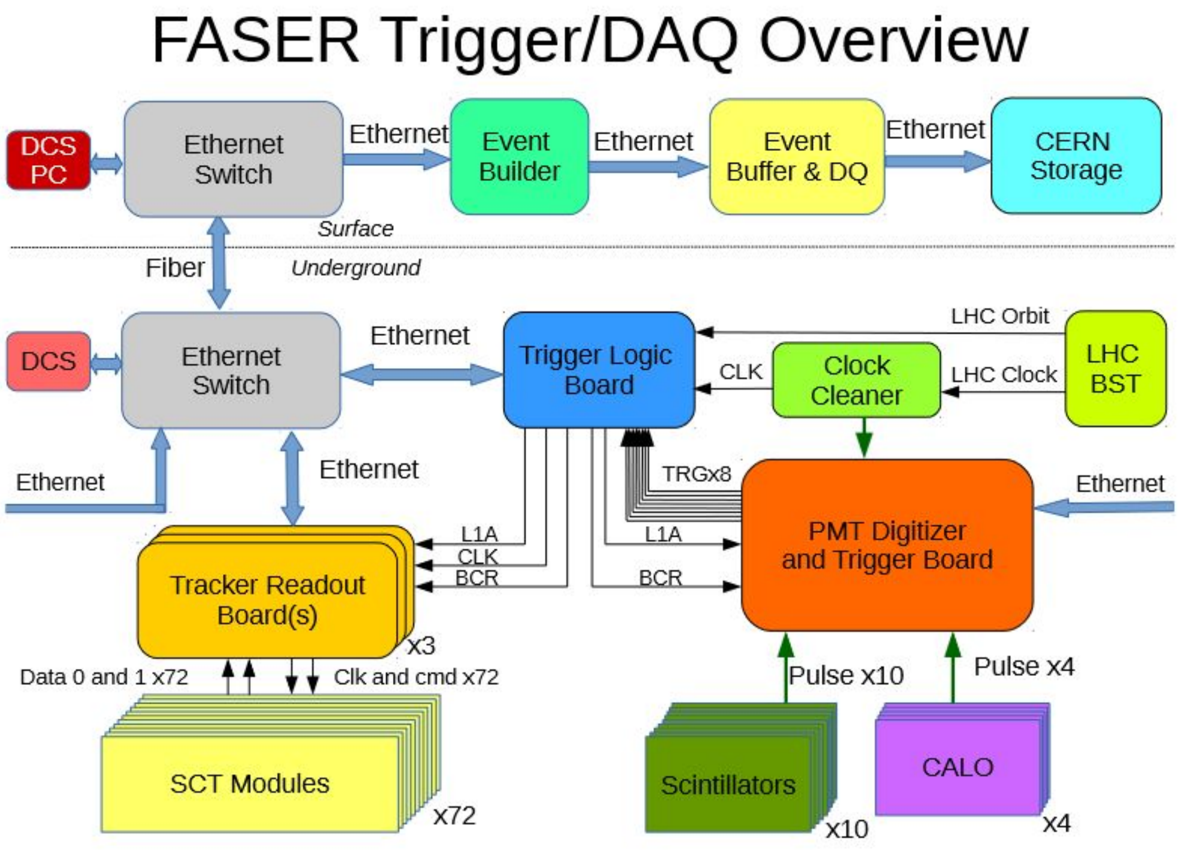
Trigger and DAQ

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



FASERn and SND@LHC

- Comparison of neutrino rates

F. Kling and L. Nevay, Forward Neutrino Fluxes at the LHC, Phys. Rev. D 104, 113008, arXiv:2105.08270

Expected number of CC interactions (150 fb^{-1})

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	901	4783	14.7	134	790	7.6
DPMJET	DPMJET	3457	7088	97	395	1034	18.6
EPOSLHC	PYTHIA8 (Hard)	1513	5905	34.2	267	1123	11.5
QGSJET	PYTHIA8 (Soft)	970	5351	16.1	185	1015	7.2
Combination (all)		1710^{+1746}_{-809}	5782^{+1306}_{-998}	$40.5^{+56.6}_{-25.8}$	245^{+149}_{-111}	991^{+132}_{-200}	$11.3^{+7.3}_{-4.0}$
Combination (w/o DPMJET)		1128^{+385}_{-227}	5346^{+558}_{-563}	$21.6^{+12.5}_{-6.9}$	195^{+71}_{-61}	976^{+146}_{-185}	$8.8^{+2.7}_{-1.5}$