The FASER experiment at the CERN LHC

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

Seminar at CP3, Louvain-La-Neuve
17 June 2020

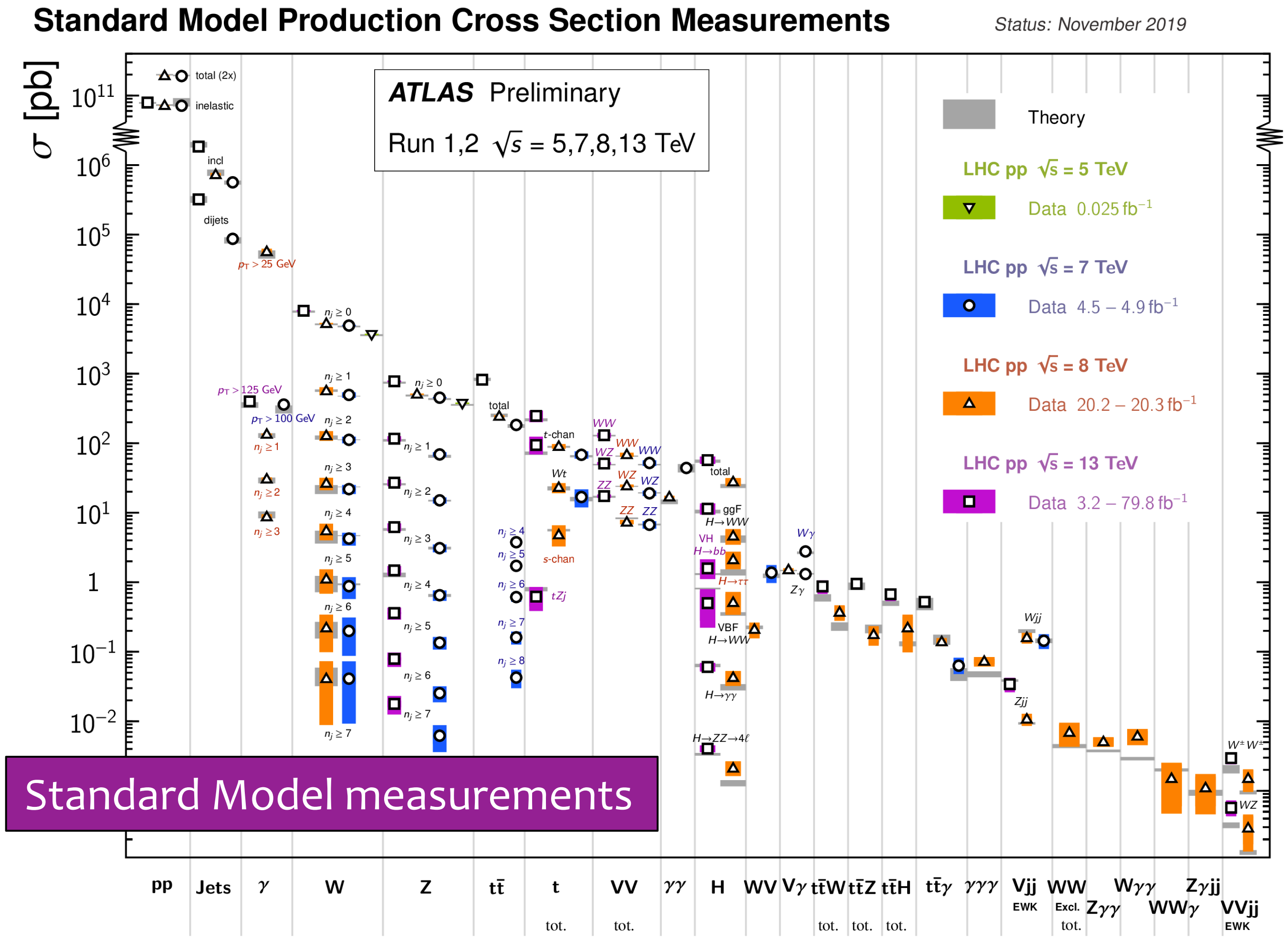
Anna Sfyrla
University of Geneva

UNIVERSITÉ DE GENÈVE
FACULTY OF SCIENCE

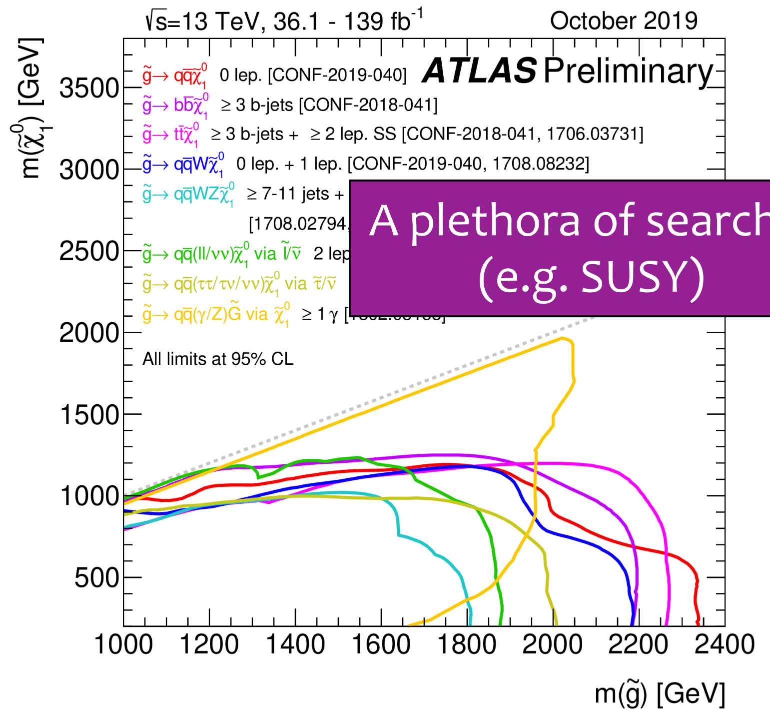
The landscape of new particles @ colliders

The landscape of LHC physics

Consistent among all experiments, here using ATLAS as an example

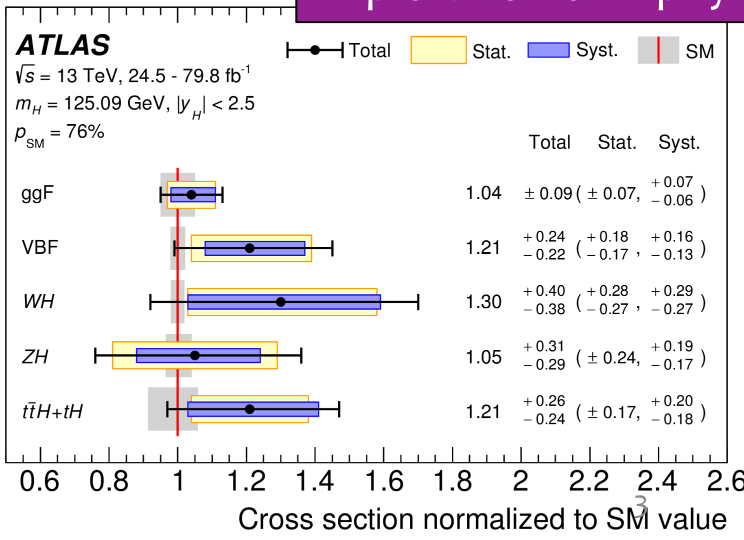


Standard Model measurements



A plethora of searches (e.g. SUSY)

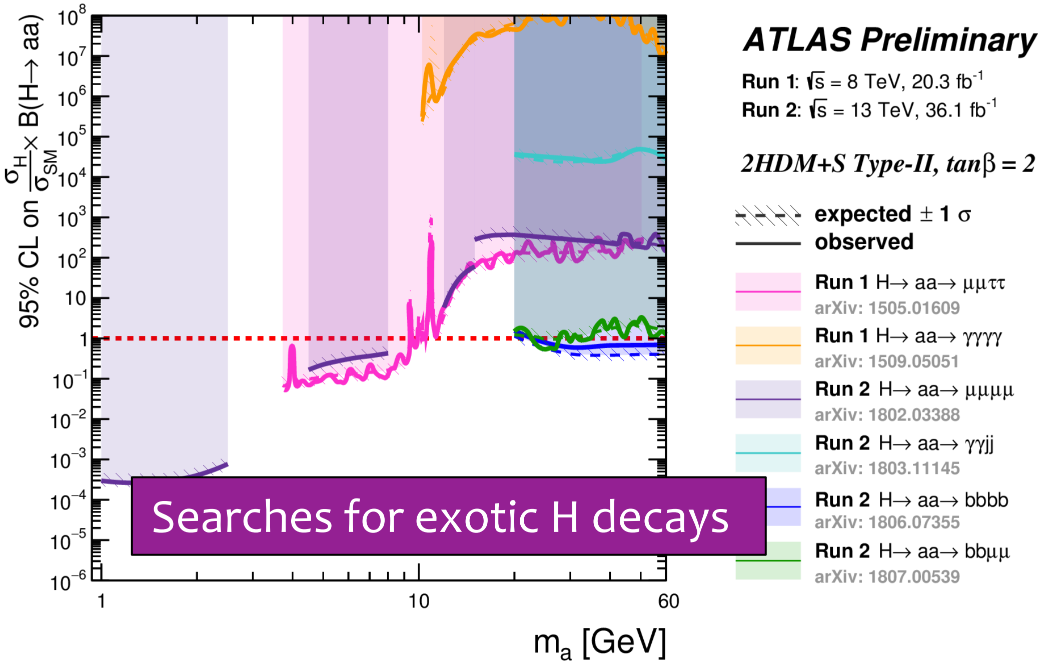
Exploration of H physics



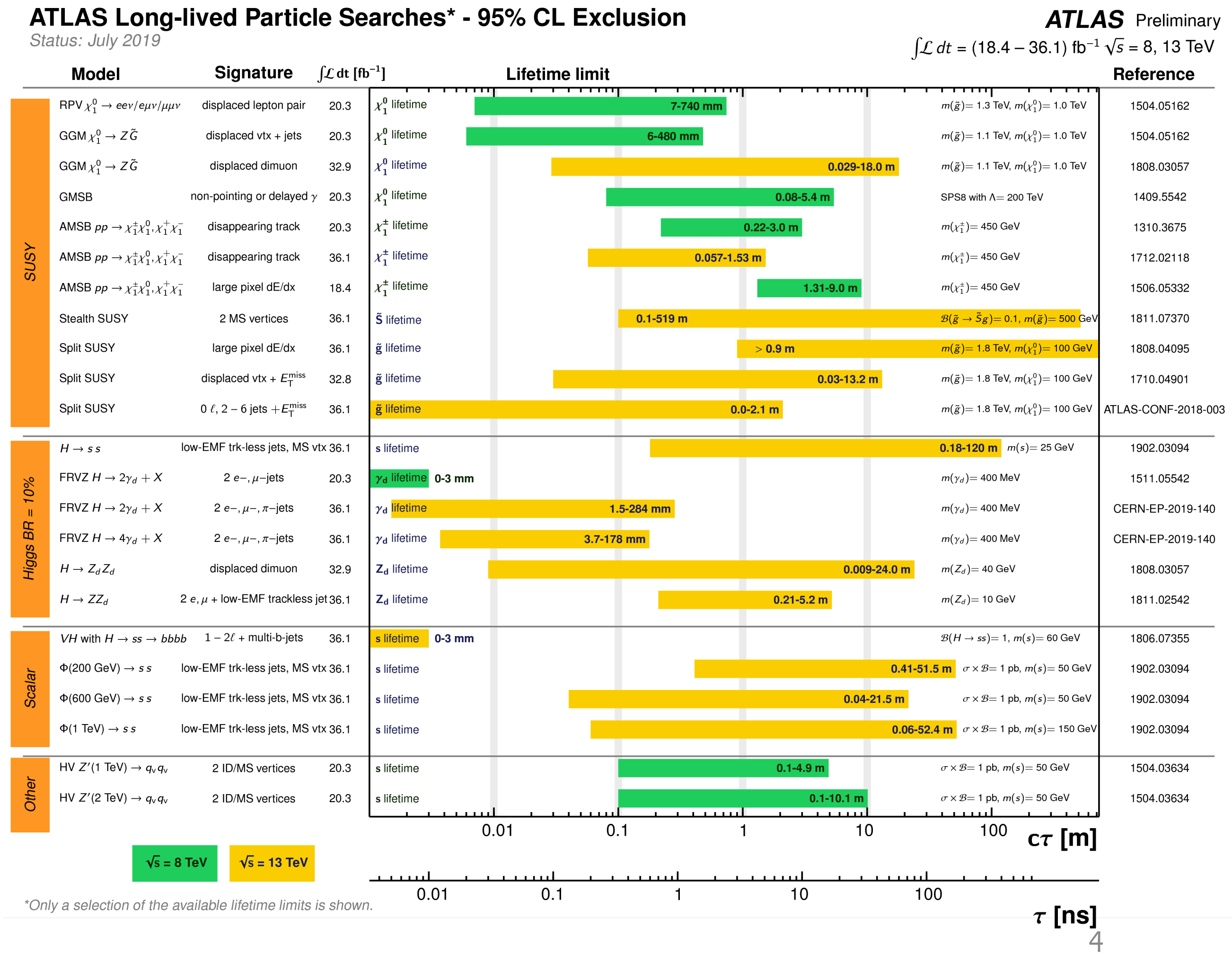
The landscape of LHC physics

Consistent among all experiments, here using ATLAS as an example

Searches for Long-Lived Particles

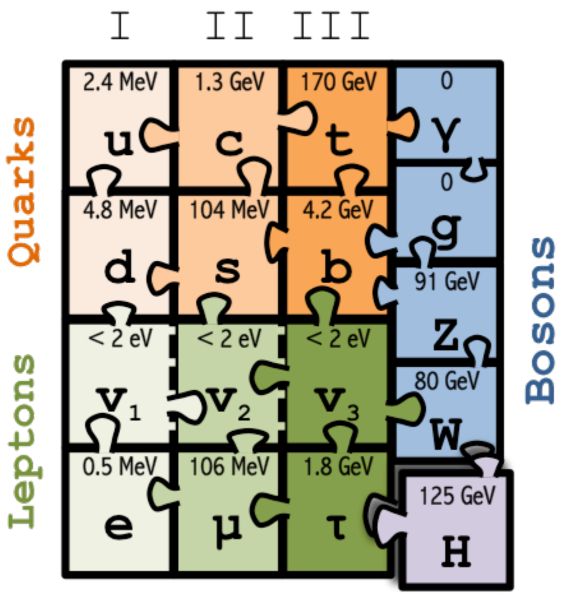


Searches for exotic H decays

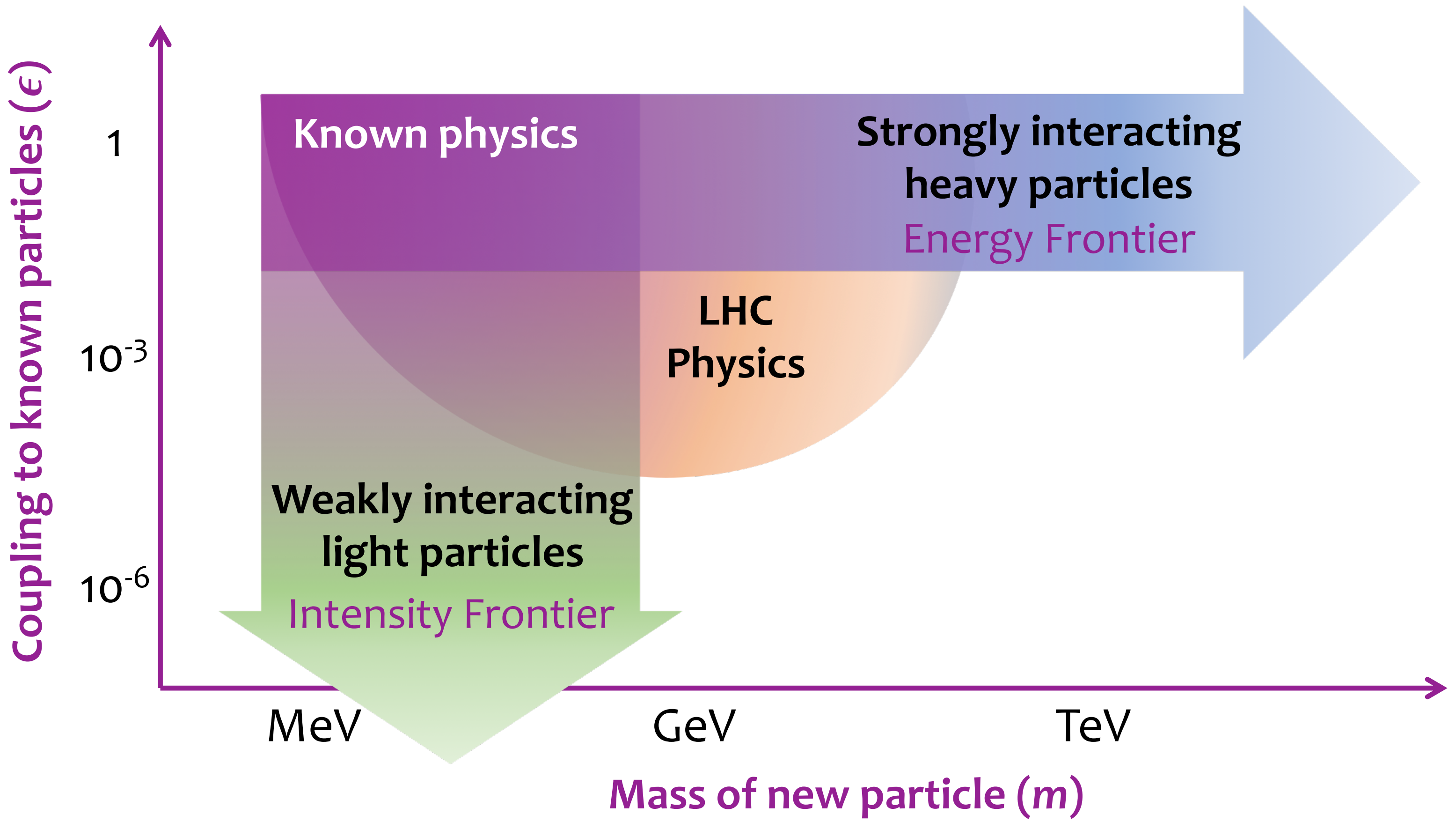


The landscape of new particles @ colliders

- Collider physics: a plethora of measurements and searches

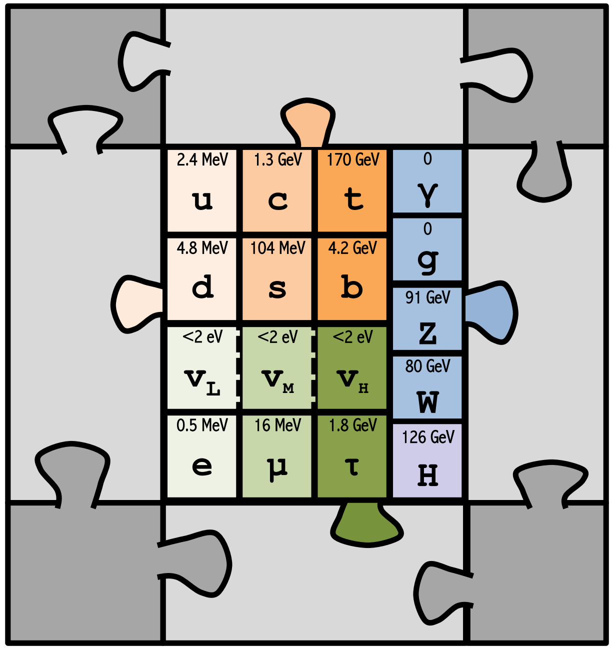


- The Standard Model is complete and confirmed

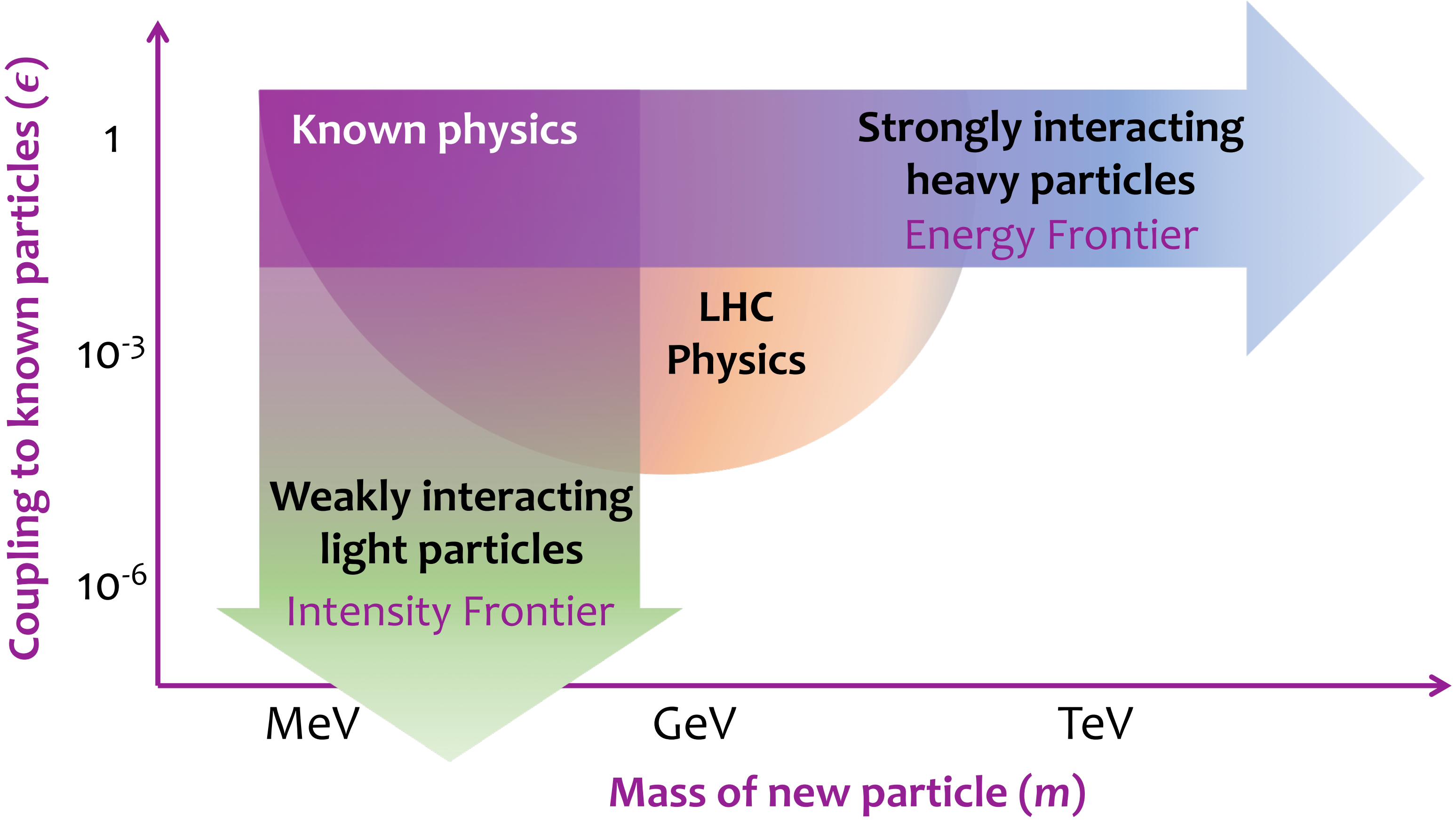


The landscape of new particles @ colliders

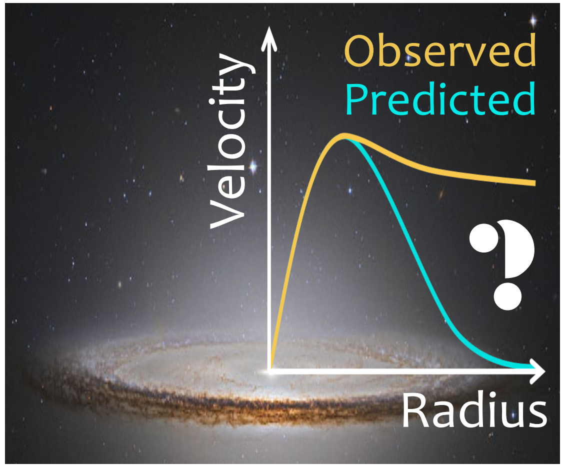
- Collider physics: a plethora of measurements and searches



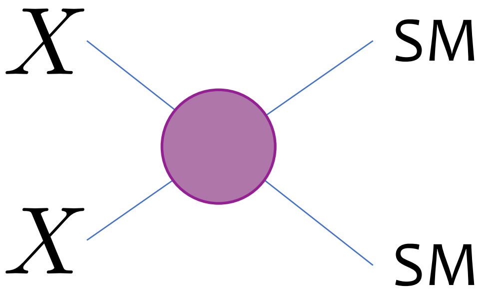
- Burning open questions remain!

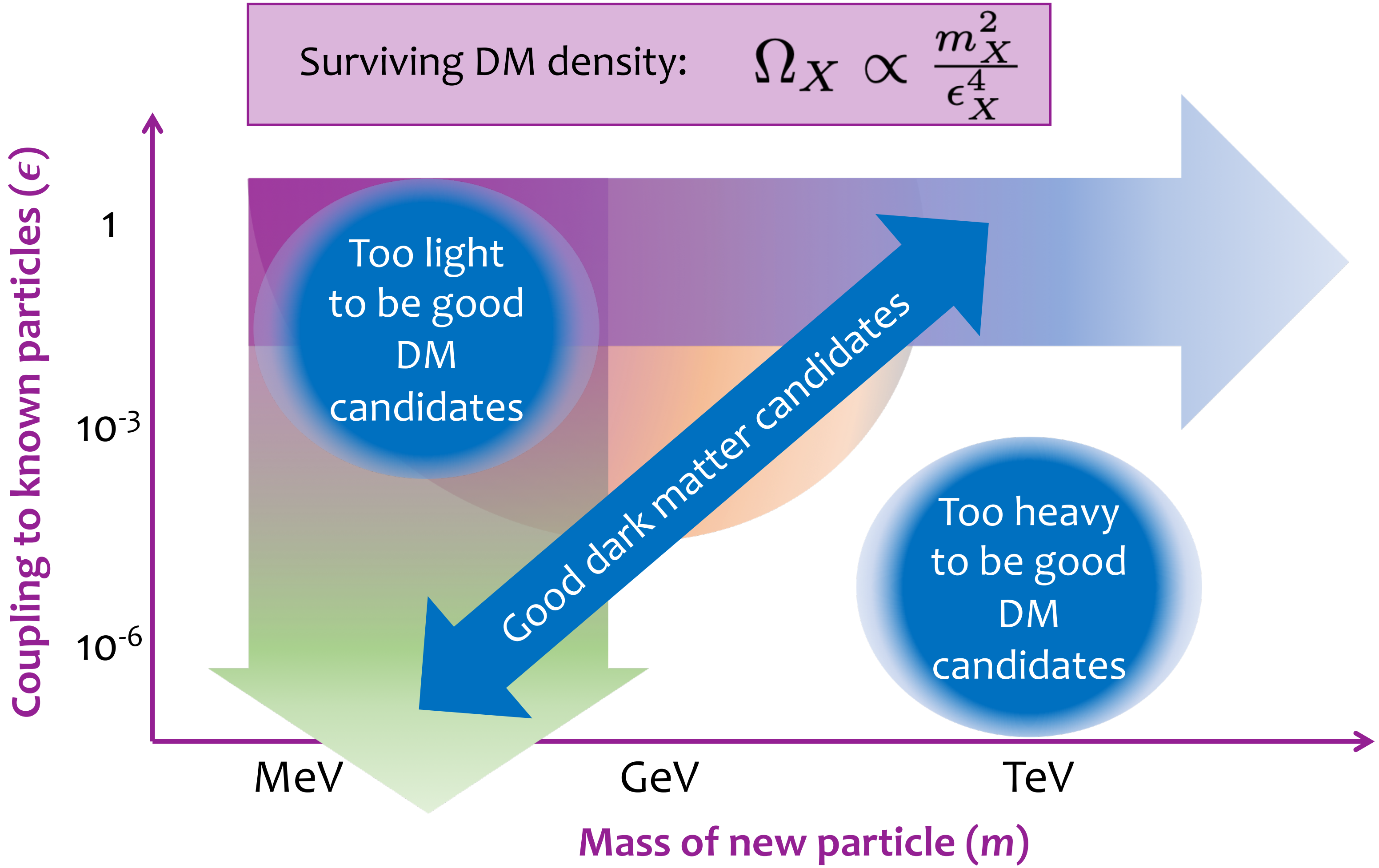


The landscape of new particles @ colliders



- Simple mechanism for DM generation: “freeze out”





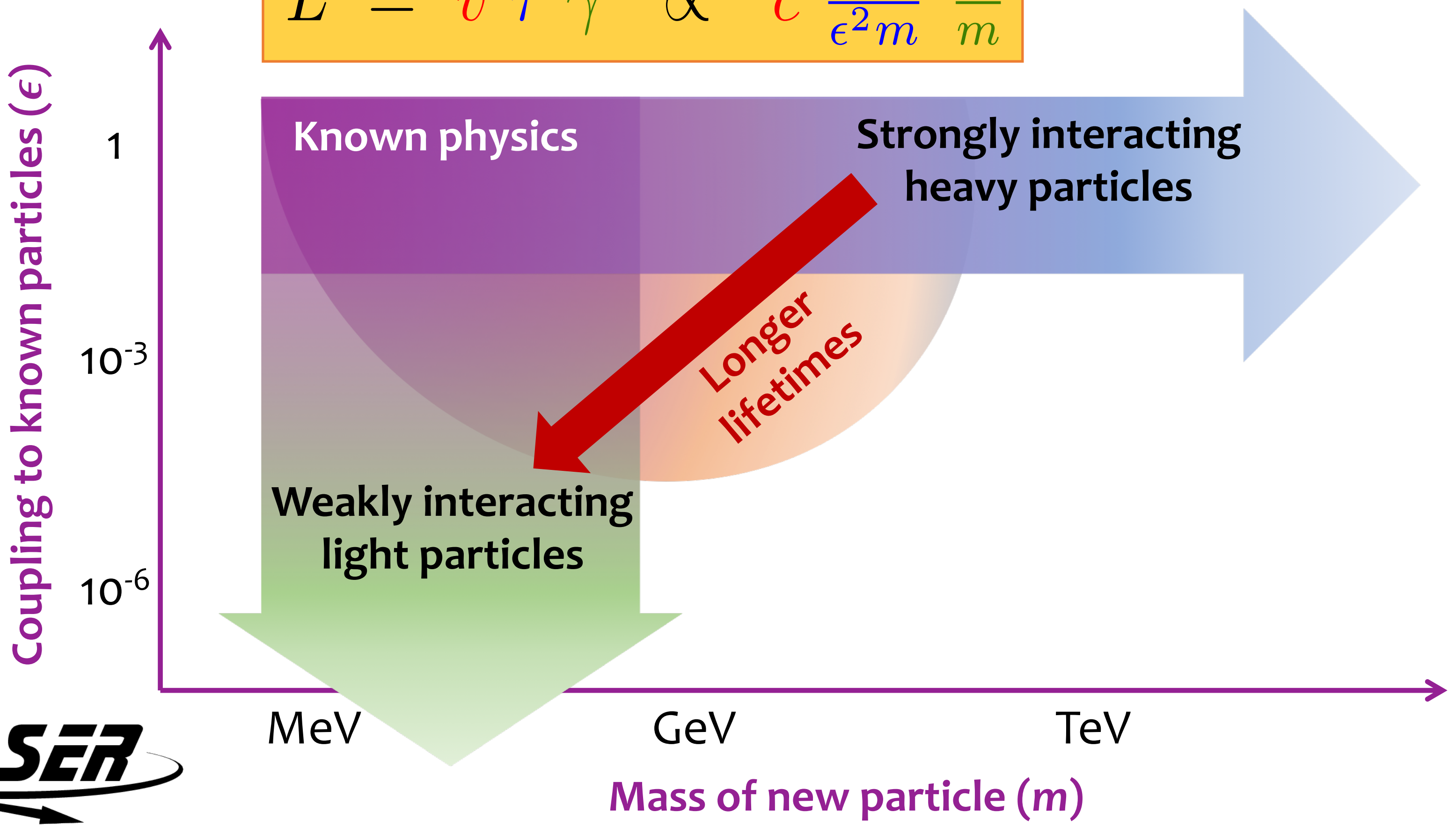
Feng, Kumar - PRL 101, 231301 (2008)

The landscape of new particles @ colliders

- **Lifetime**: a characteristic of weakly interacting light particles
- Distinct signatures, exploited in both general purpose and dedicated experiments
- Most general purpose searches still do target particles that decay promptly
- Opportunity for exploration!
  - Experiments under evaluation: MATHUSLA, milliQan, SHiP, LDMX, …
  - Recently approved: FASER

Distance travelled by particles:

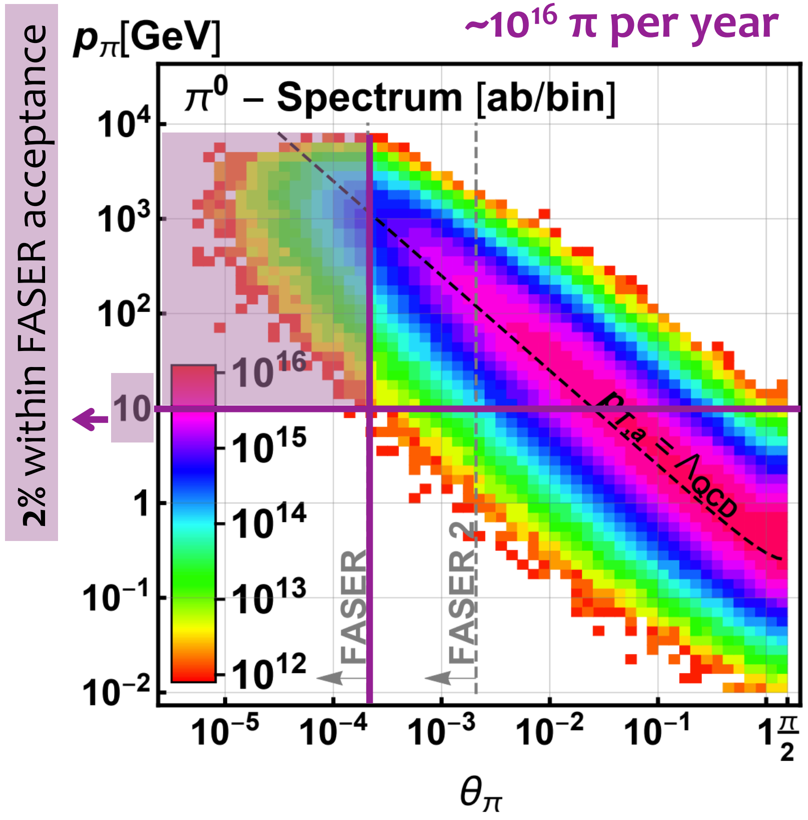
$$L = v\,\tau\,\gamma \quad \propto \quad c\,\frac{1}{\epsilon^2 m}\,\frac{E}{m}$$



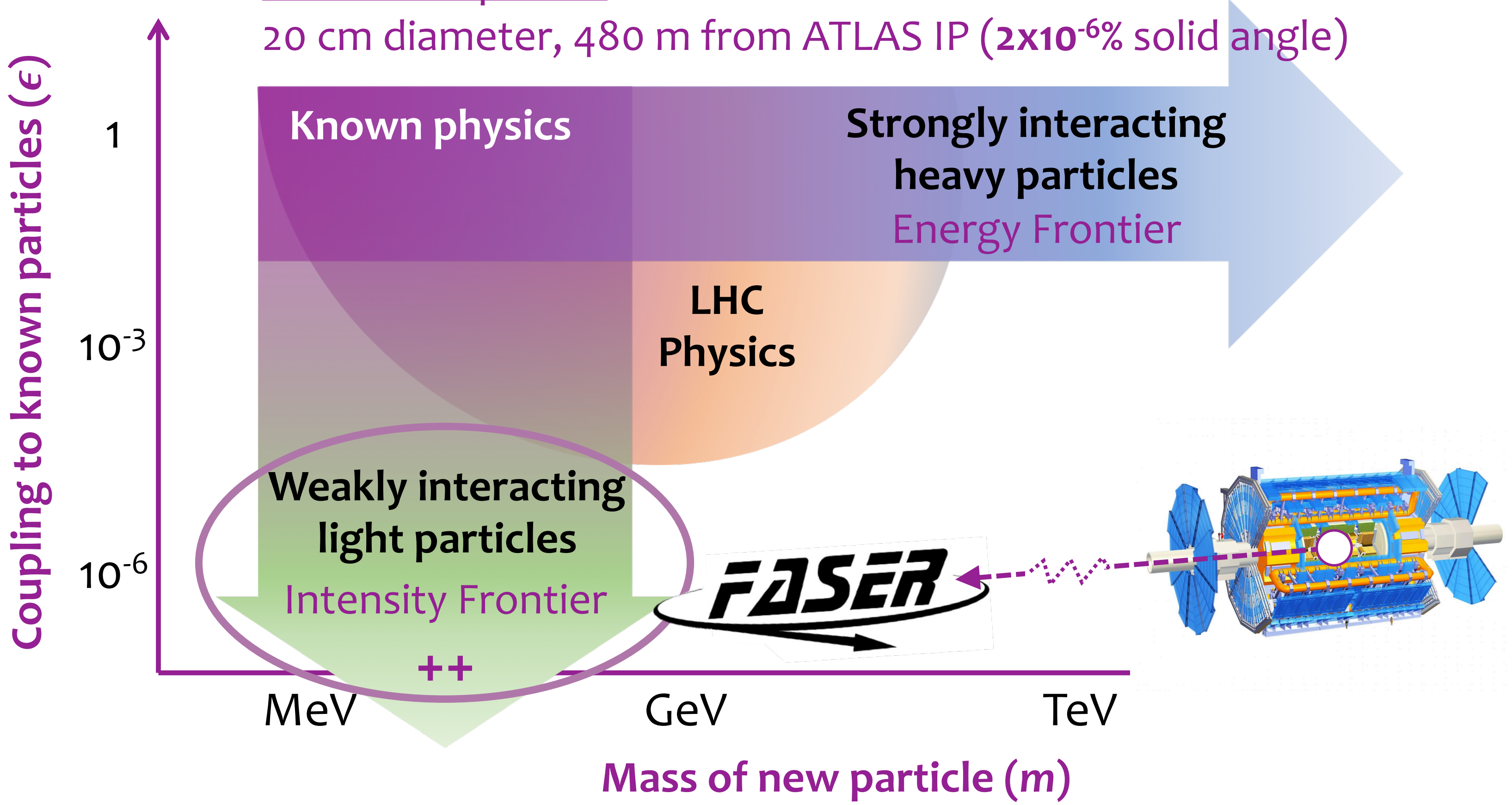
Feng, Galon, Kling, Trojanowski - Phys. Rev. D 97, 035001 (2018)

ForwArd Search ExpeRiment at the LHC

- Searches for new weakly interacting light particles produced in decays of light mesons (e.g. π, K)
- Such light particles are abundantly produced in p-p collisions, primarily in large pseudorapidity

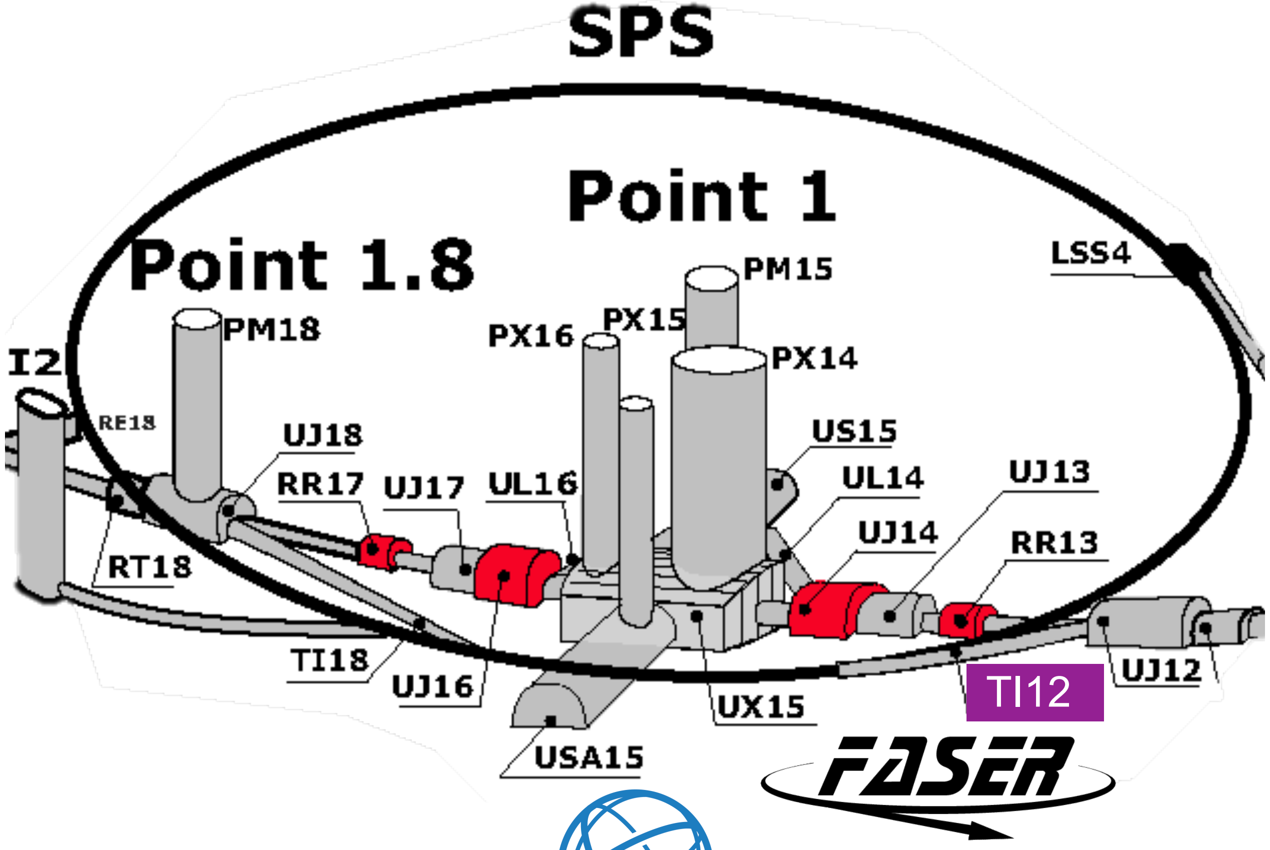


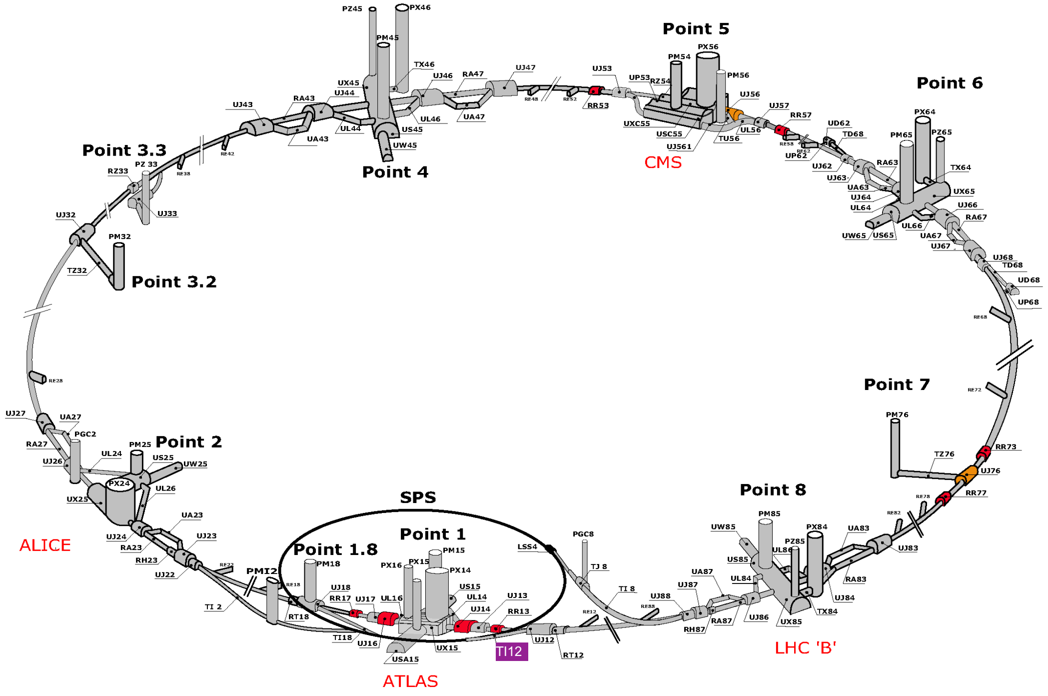
FASER acceptance:
20 cm diameter, 480 m from ATLAS IP (**2x10^{-6}%** solid angle)

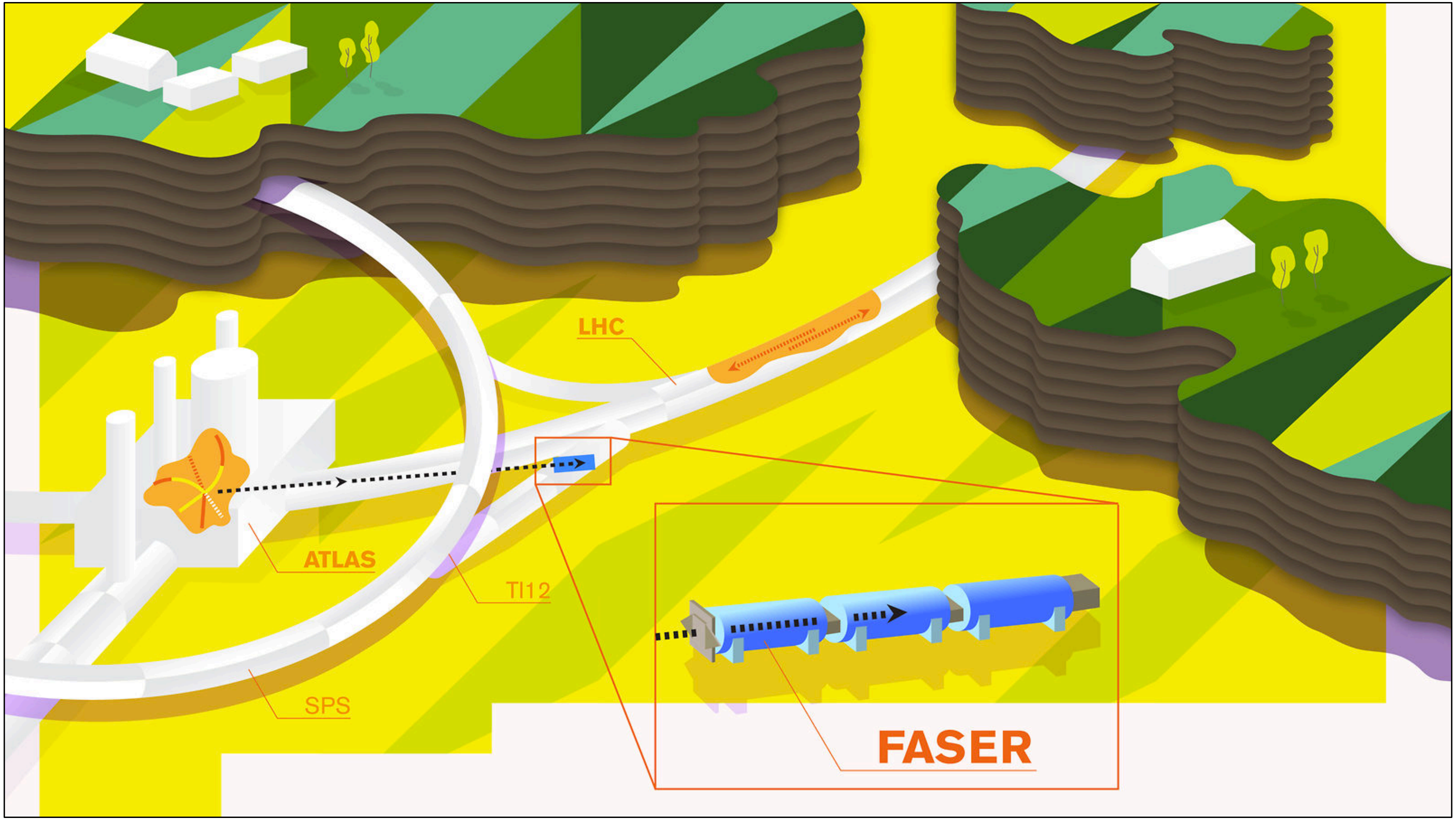


The FASER experiment

FASER Location



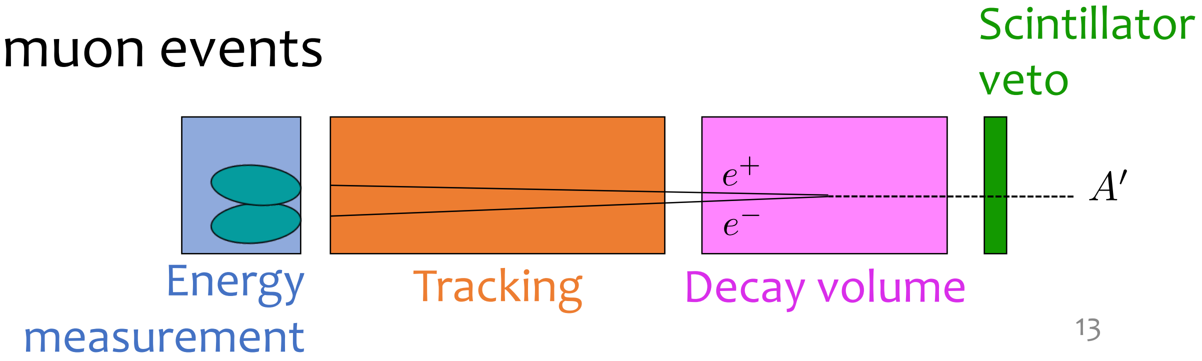




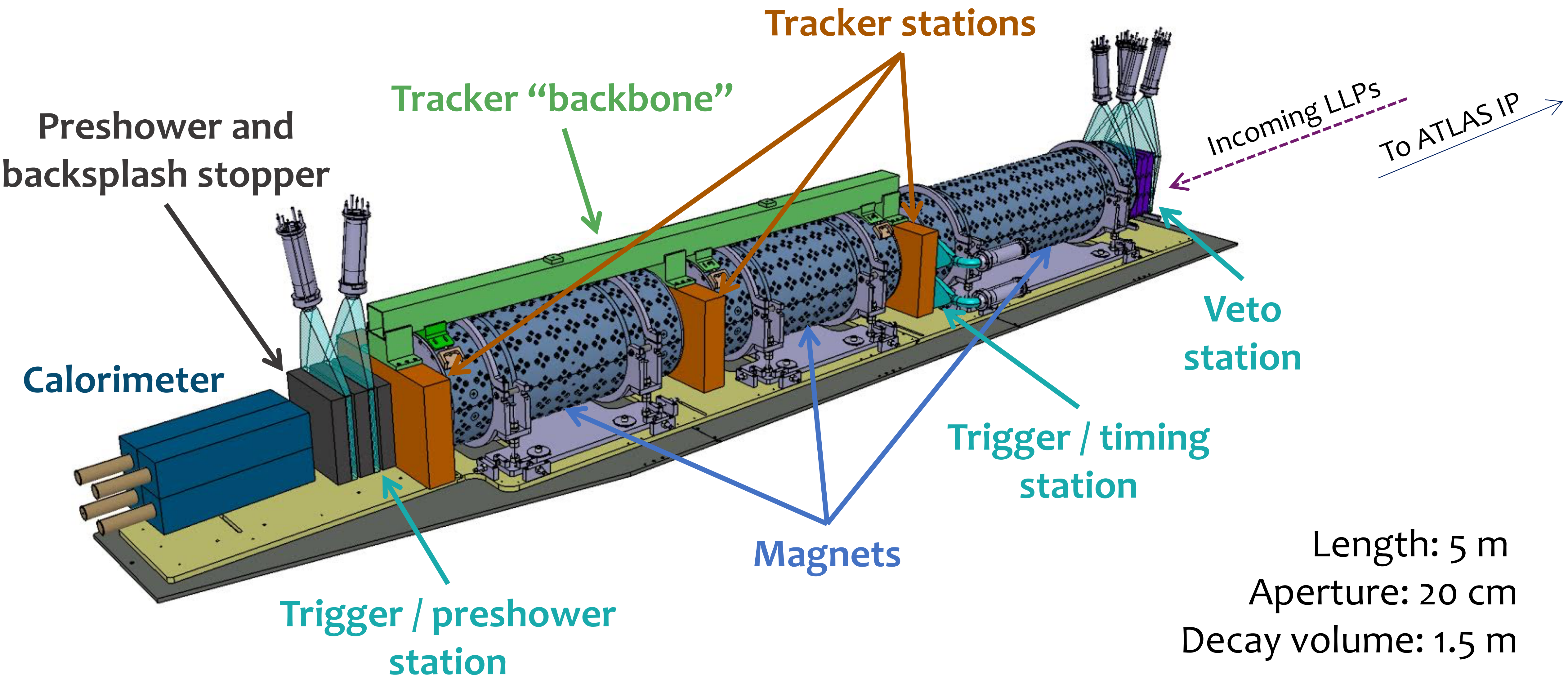
https://www.symmetrymagazine.org/article/a-tiny-new-experiment-at-the-lhc

FASER Detector concept

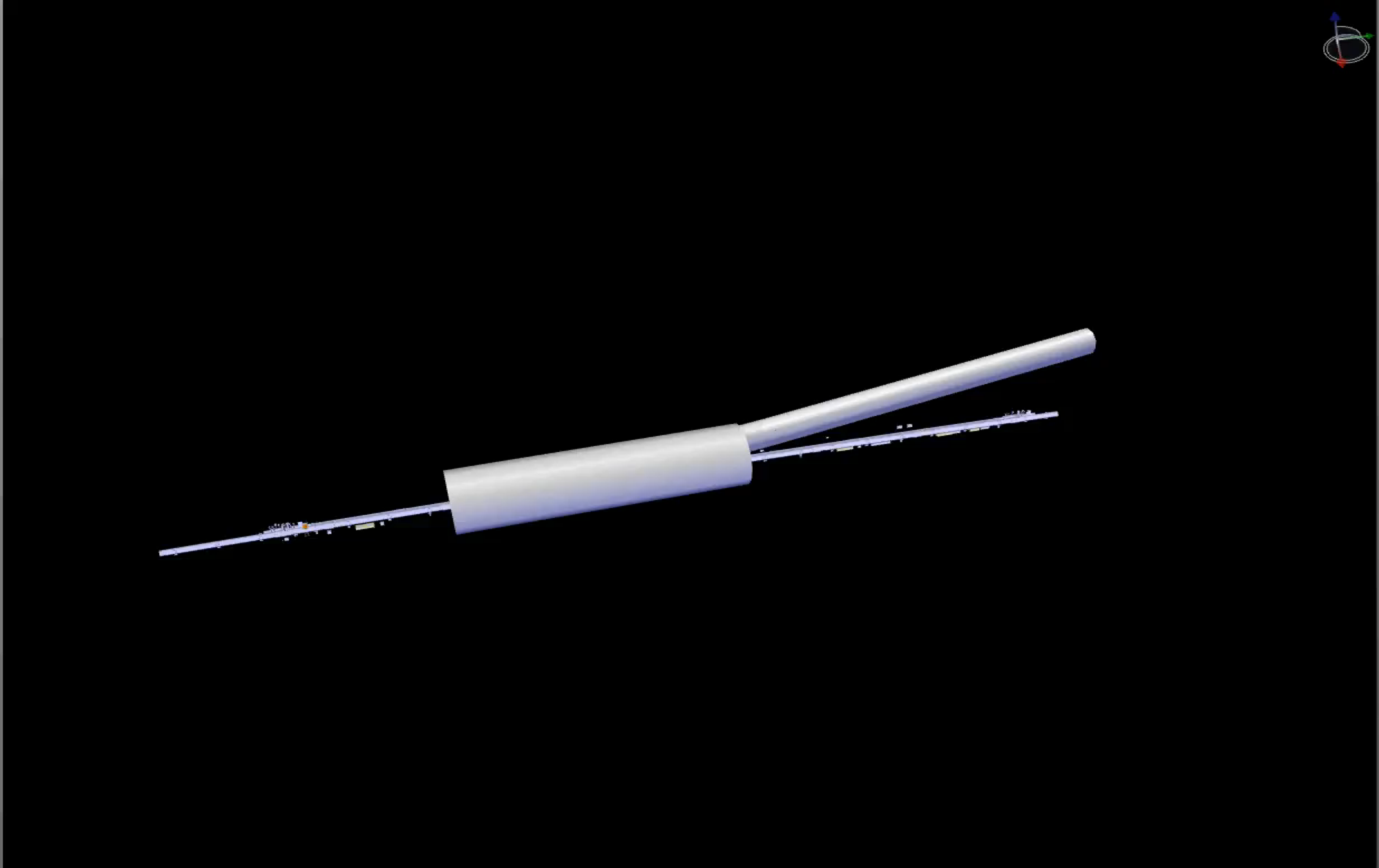
- **Drivers for choices:** Tight timeline between experiment approval and installation & the limited budget.
  - Detector that can be constructed and installed ***quickly & cheaply***
  - Have tried to re-use existing detector components where possible
  - Aimed for a simple, robust detector (access 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



FASER Detector



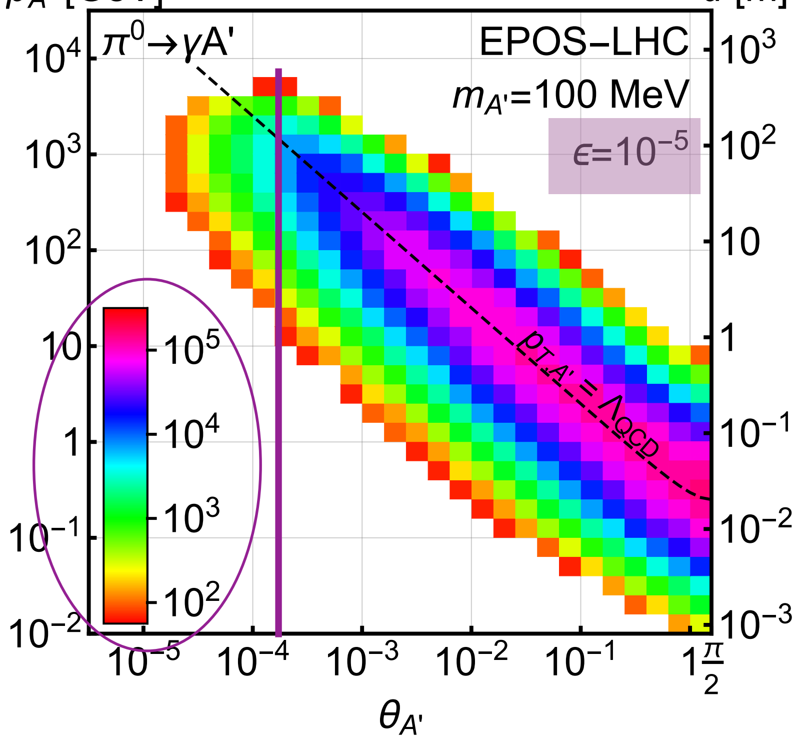
Length: 5 m
Aperture: 20 cm
Decay volume: 1.5 m

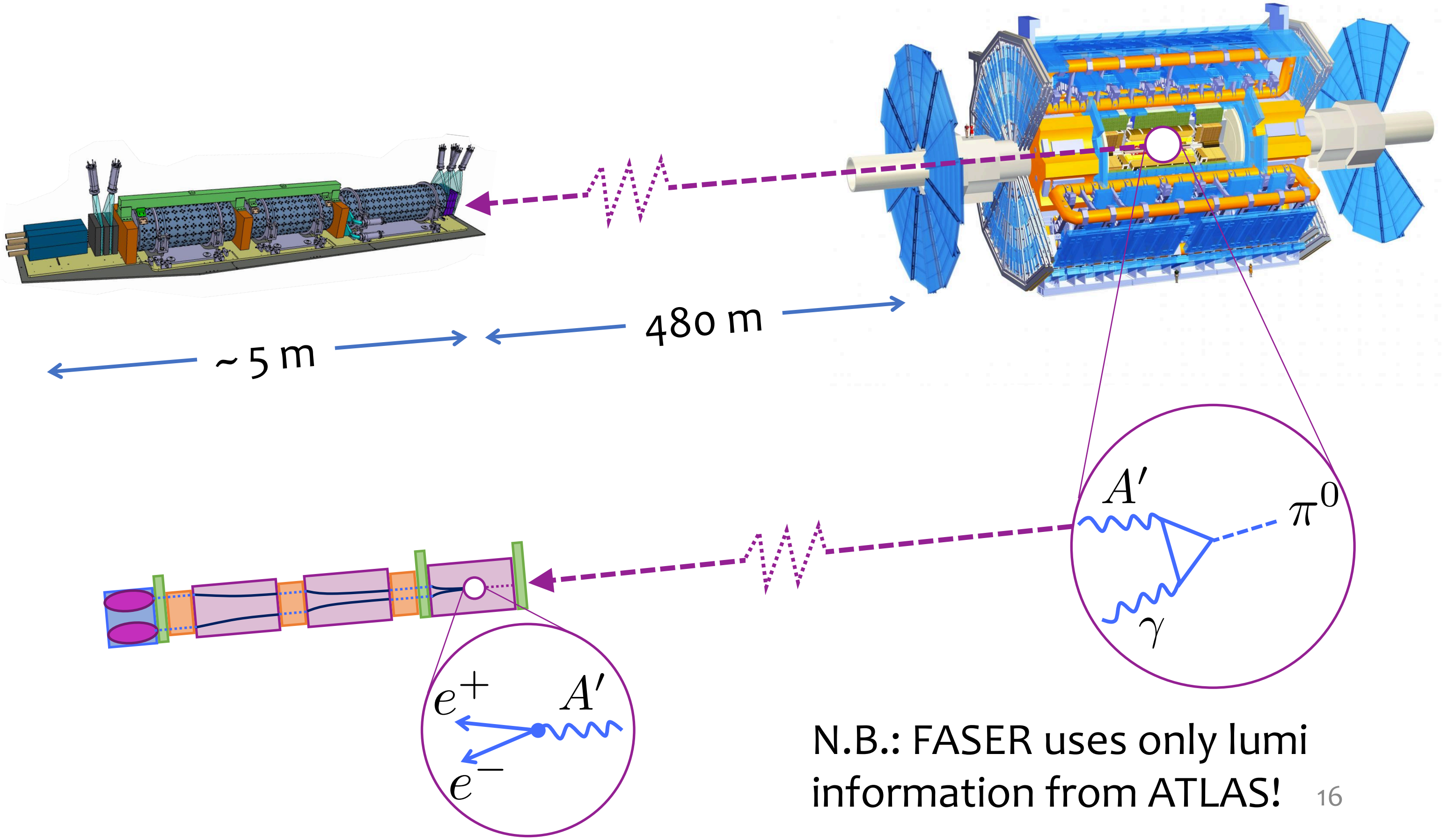


An example physics case: Dark Photon A'

- New massive gauge boson in a dark sector with dark matter candidate X
- Spin 1, couples weakly to SM particles through mixing with the photon
- For $m_{A'}$=100 MeV, $\epsilon \sim 10^{-5}$ and E~TeV, can travel long distance before decay

A' at the IP (300 fb^{-1})

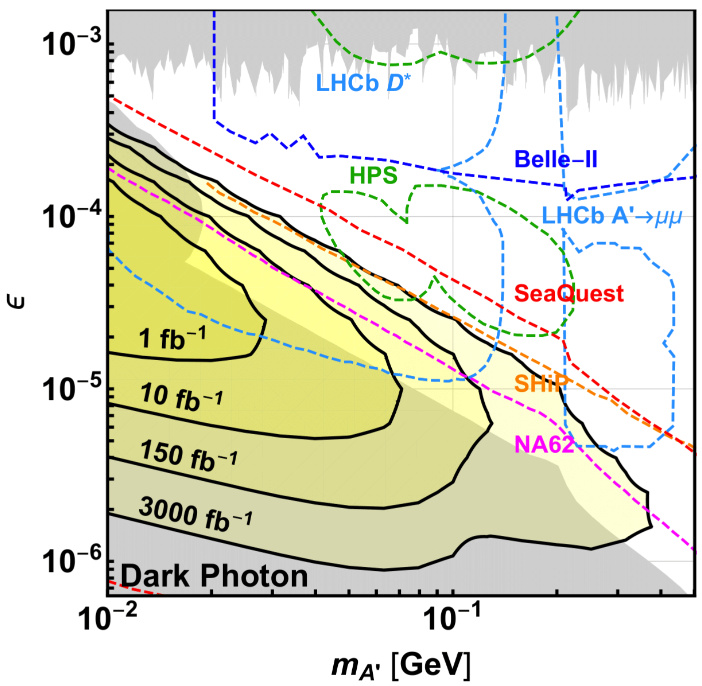


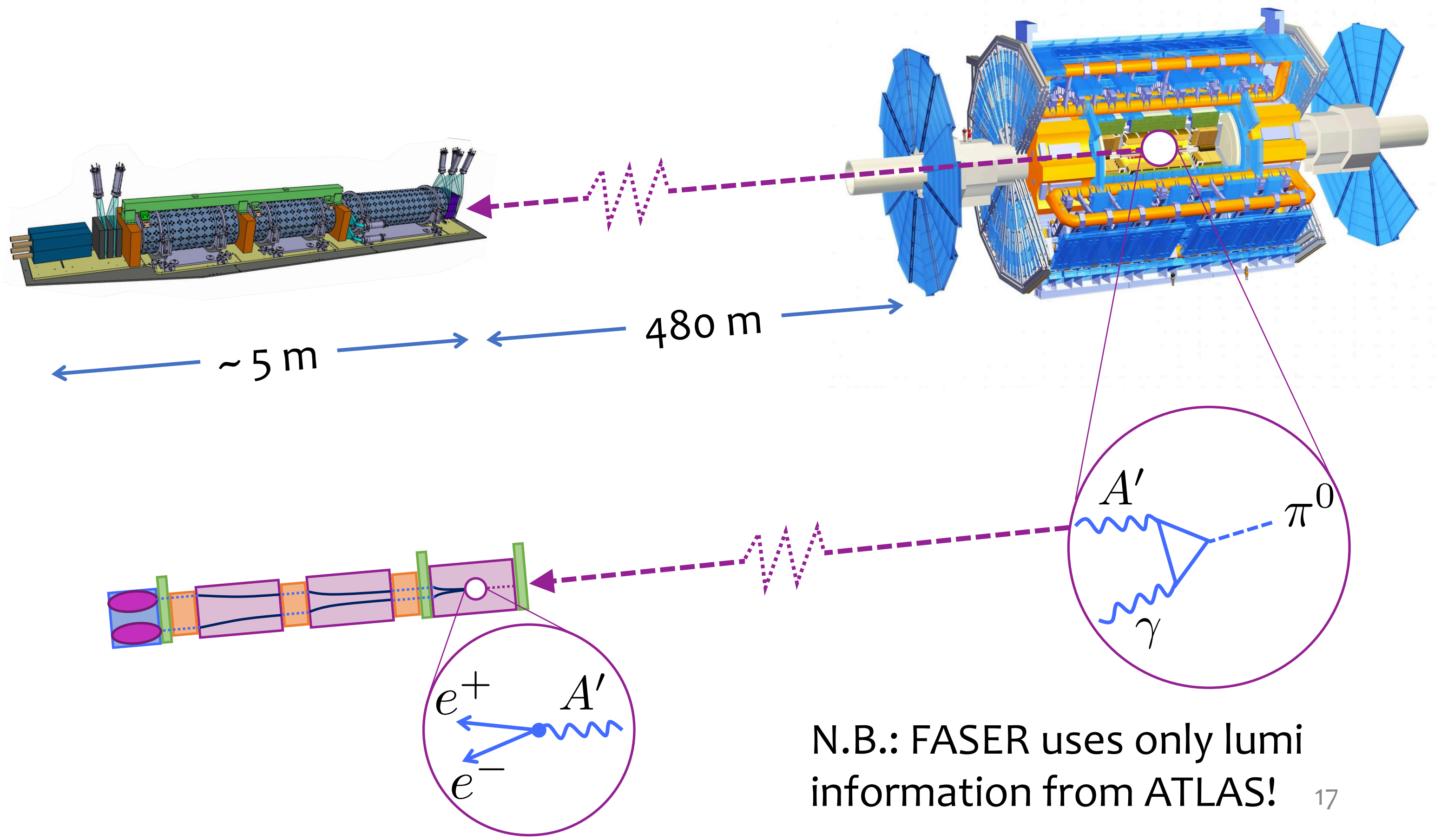


N.B.: FASER uses only lumi information from ATLAS!

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 particles through mixing with the photon
- For $m_{A'}$=100 MeV, $\epsilon \sim 10^{-5}$ and E~TeV, can travel long distance before decay



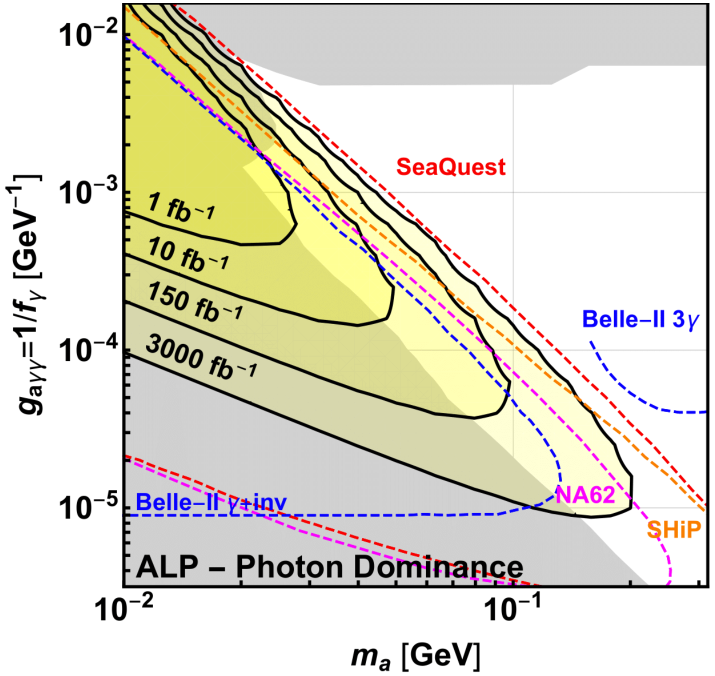


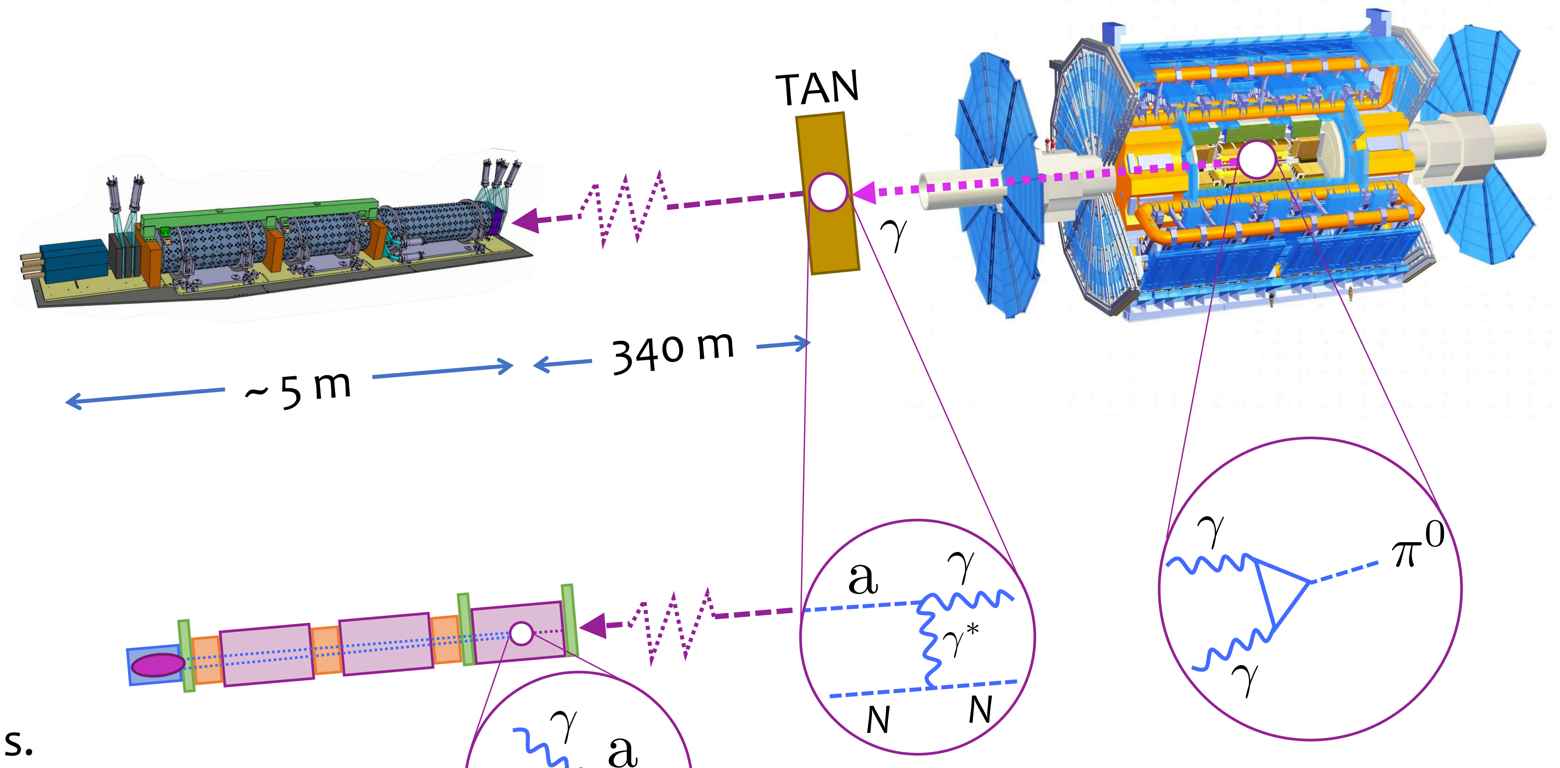
- Discovery contours assume at least 3 signal events, no background.

N.B.: FASER uses only lumi information from ATLAS!

Another example: Axion-like particles (ALPs)

- Photons from IP travel 140 m, collide with neutral particle absorber (TAN) and create ALPs





- Very challenging signature, esp. to distinguish the two close-by photons.
- FASER upgrade proposed to facilitate this.

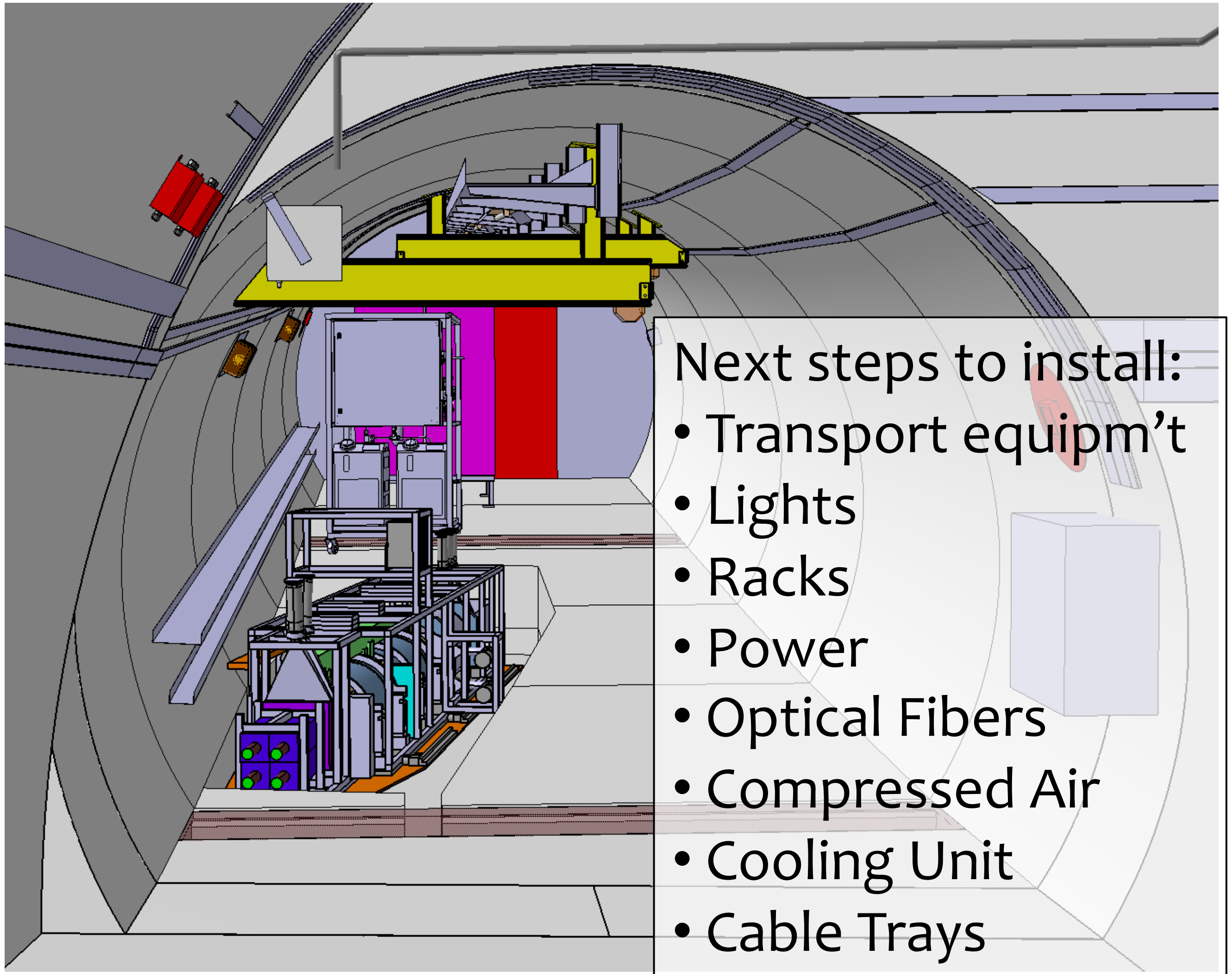
N.B.: FASER uses only lumi information from ATLAS!

FASER experiment construction and commissioning

FASER Location

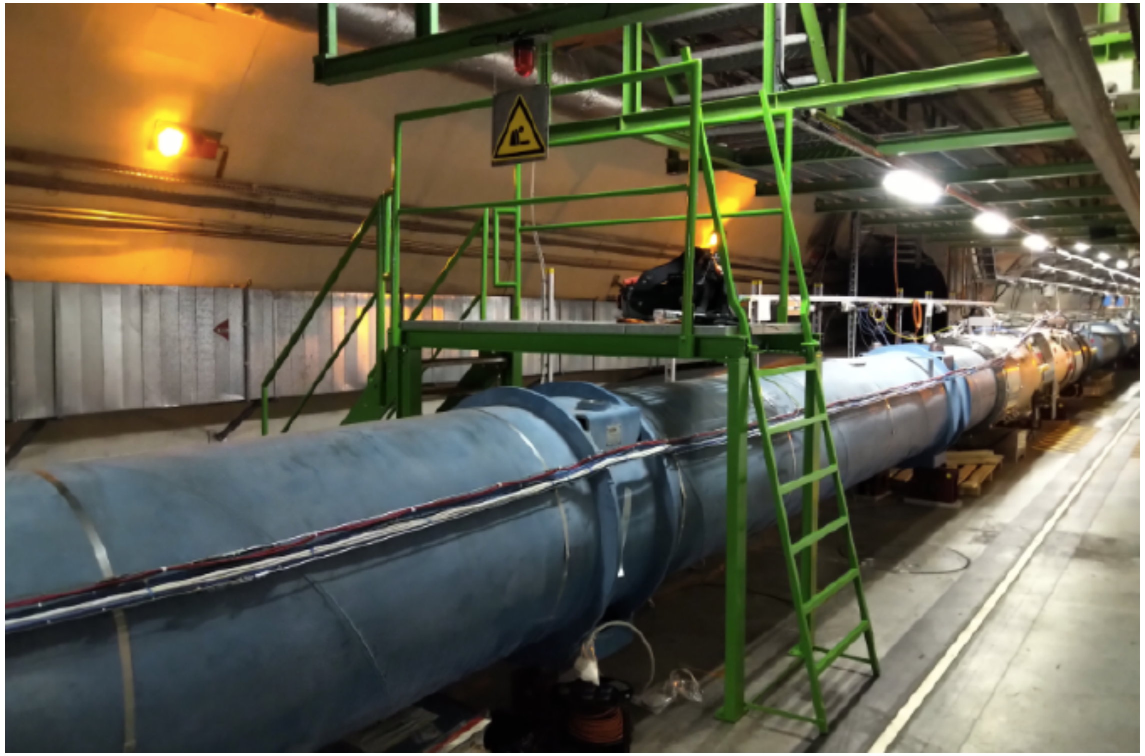
Significant and challenging civil engineering work done by CERN SMB & contractors

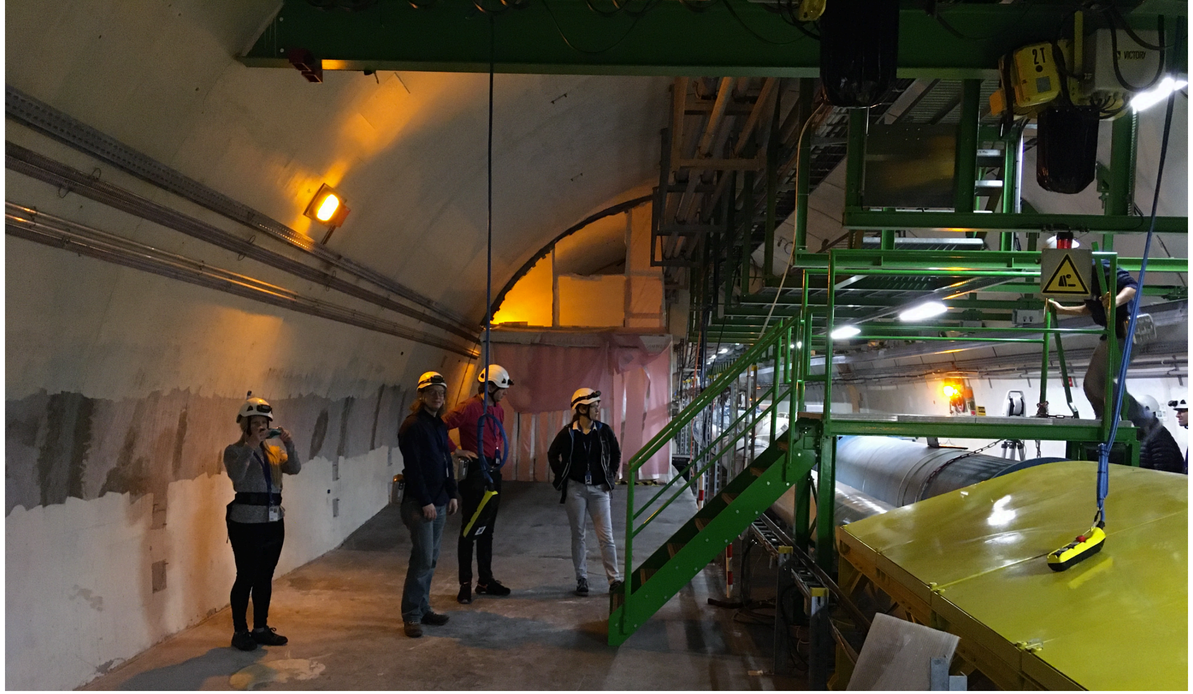
FASER Access tunnel and Infrastructure



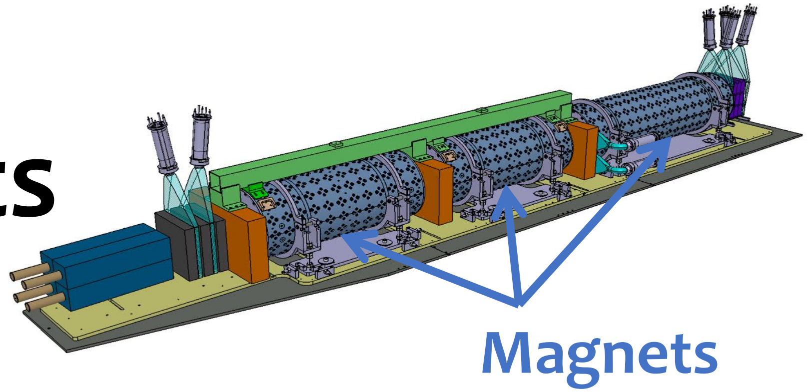
Next steps to install:
- Transport equipm’t
- Lights
- Racks
- Power
- Optical Fibers
- Compressed Air
- Cooling Unit
- Cable Trays

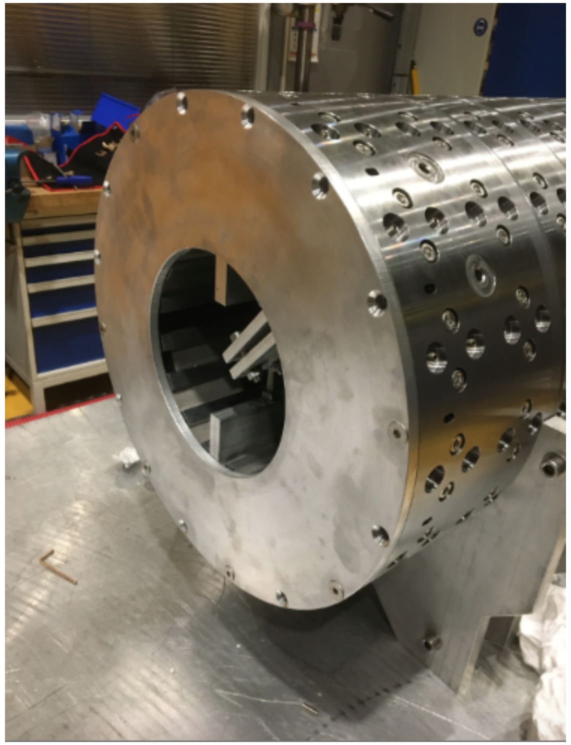
Access to TI12 is over the LHC machine complicates the transport & safety



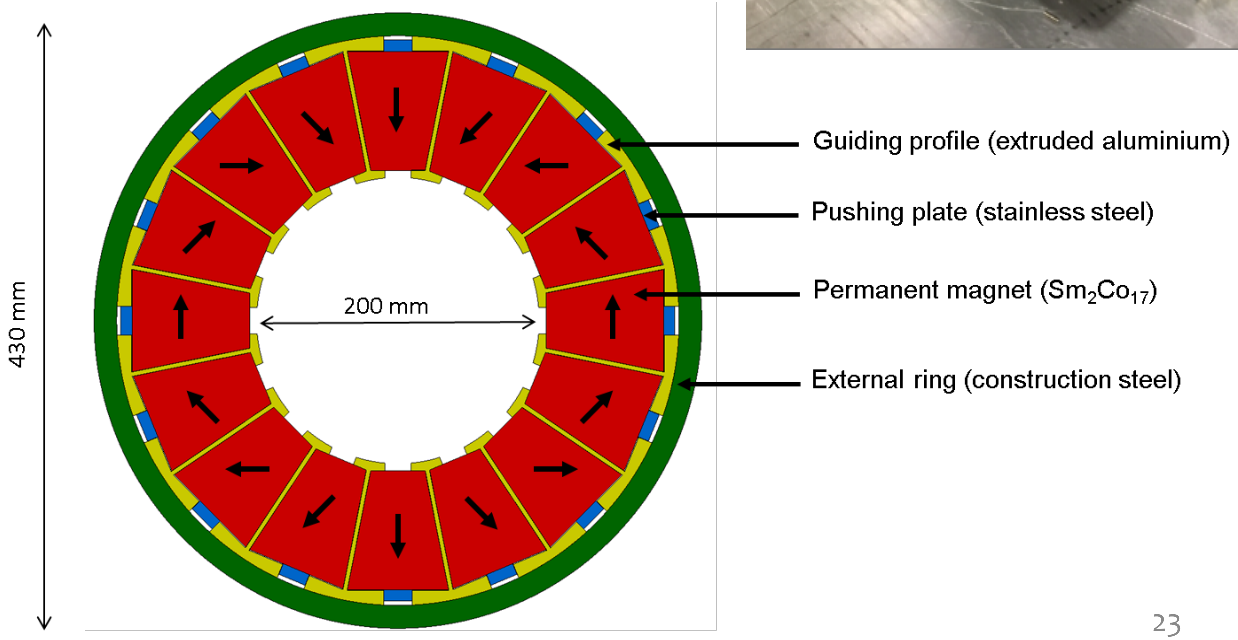




FASER Magnets





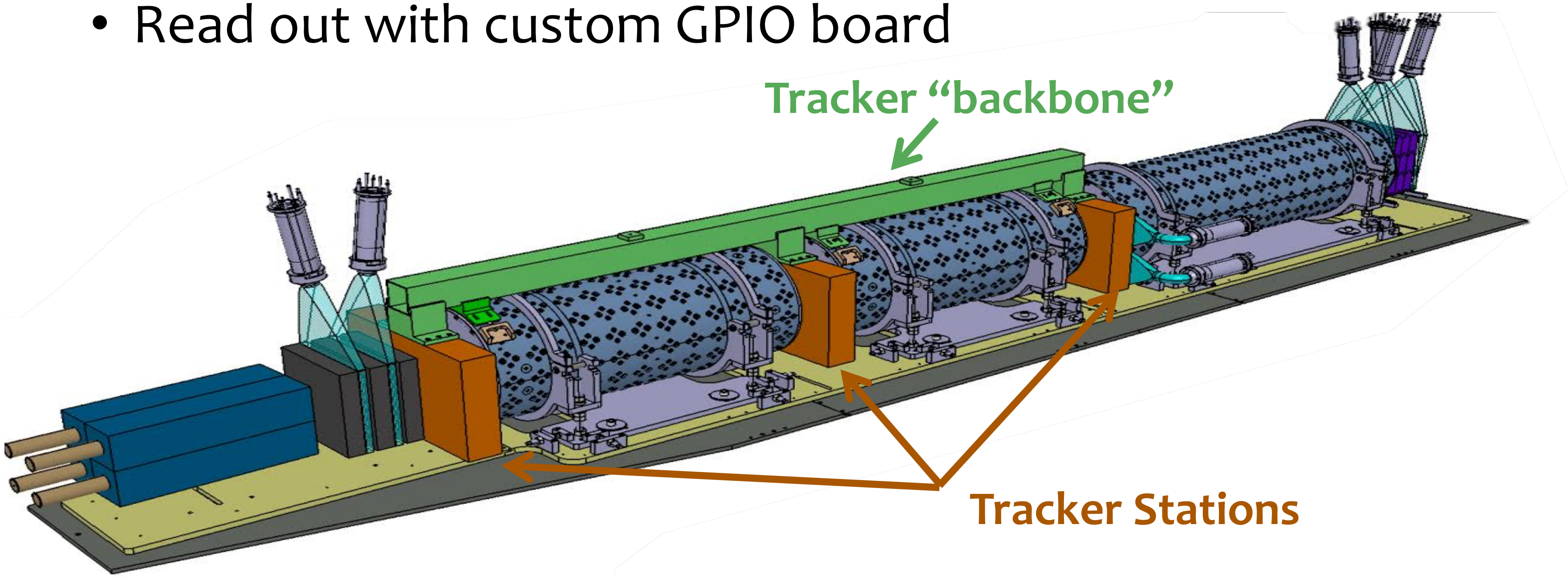
- Field of 0.55 T; permanent dipole
- Halbach array design with fixed-field magnets
  - Maximizes field without need for too much support infrastructure
  - Allows for a compact design, reducing amount of digging
- **Status:**
  - Under construction by the CERN magnet group
  - Part of the first magnet successfully made, production process validated
  - Expecting magnetic block delivery to finalize production

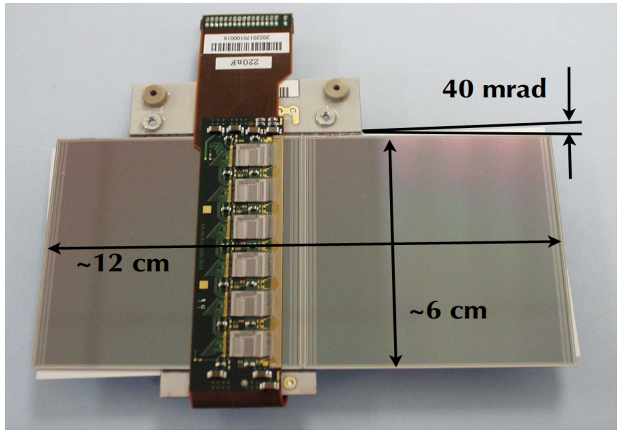


FASER Tracker

THANKS!

- FASER uses ATLAS SCT spare modules
- 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
- Read out with custom GPIO board

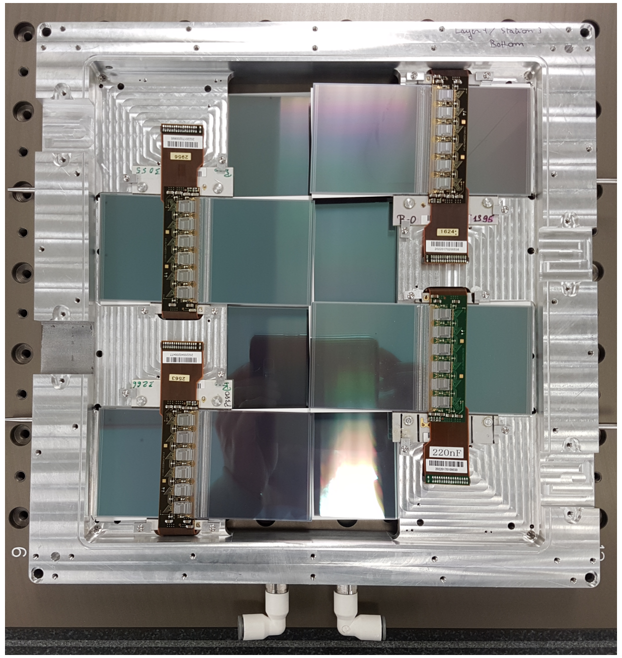




SCT module

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

Tracker layer

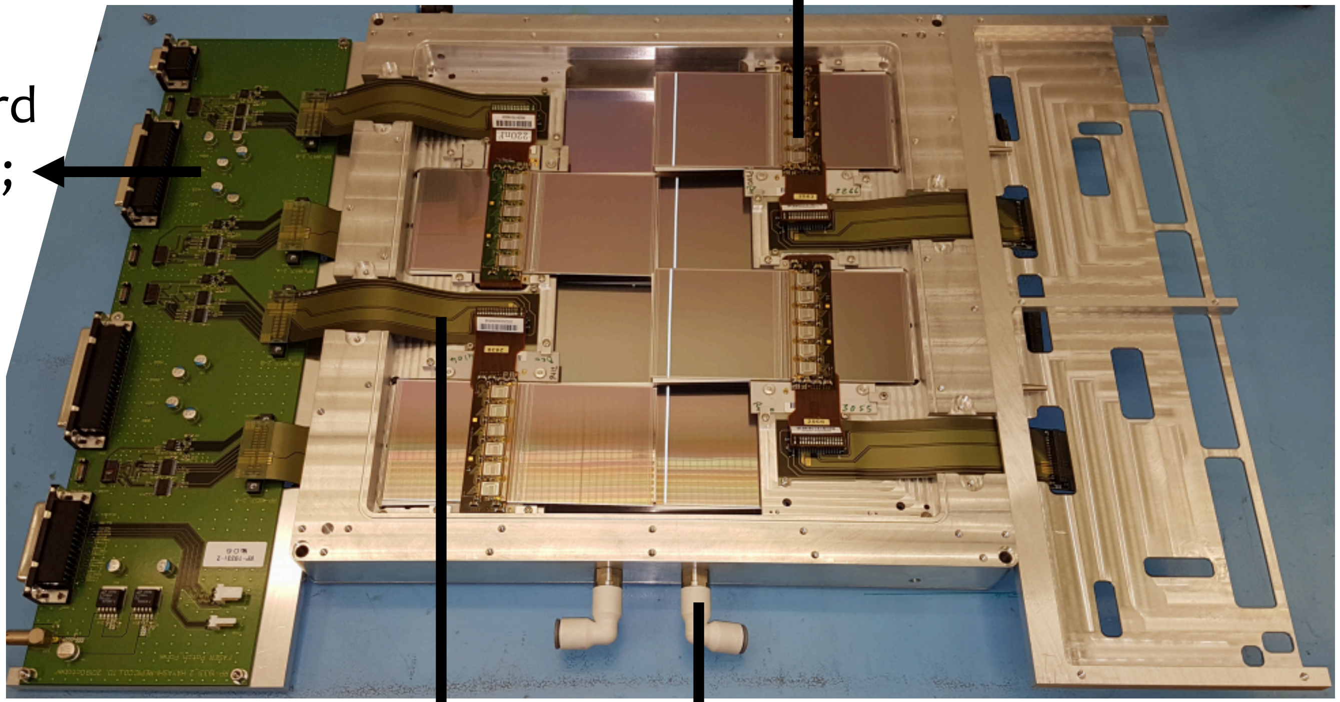


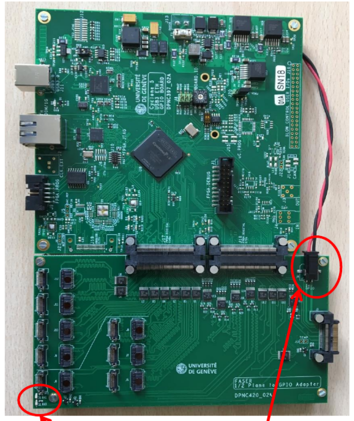
FASER Tracker

SCT module ASICs, require ~ 5 W / module

Low radiation in TI12 and much lower rates than ATLAS allow for simplifications in services and readout.

Patch panel to custom board based on home-made GPIO; Power (HV/LV), monitoring and readout lines.



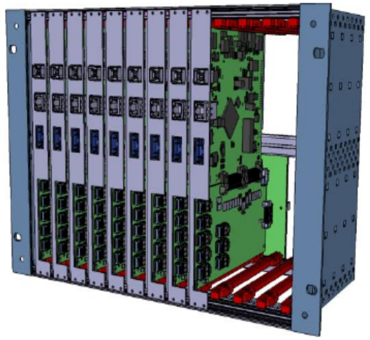


2 front panels LEDs

24V discrete wire to TRB adapter

FLEX cables

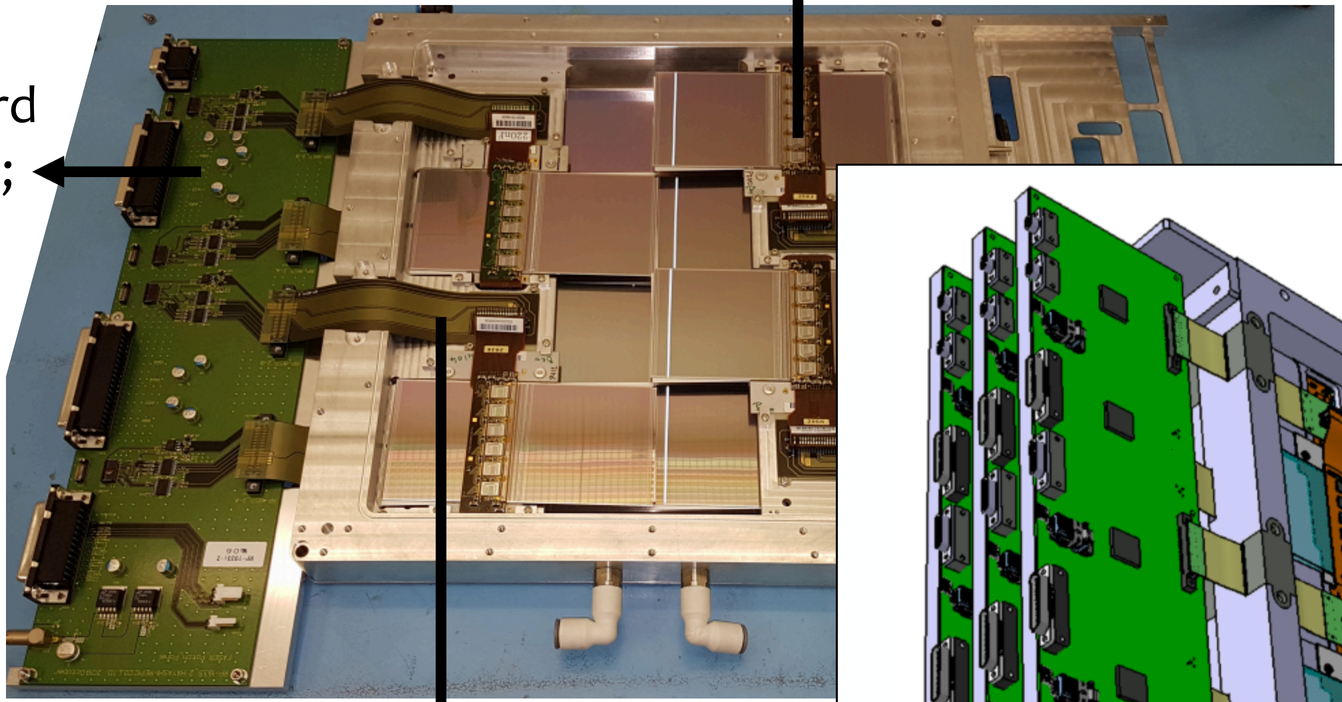
Into custom-made mini-crate



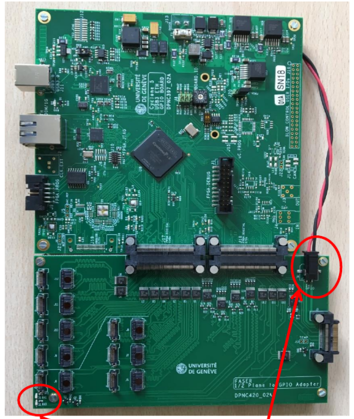
Detector cooling via water chiller operating at 10-15°C

FASER Tracker

SCT module ASICs,
require ~ 5 W / module



Patch panel to custom board based on home-made GPIO; Power (HV/LV), monitoring and readout lines.

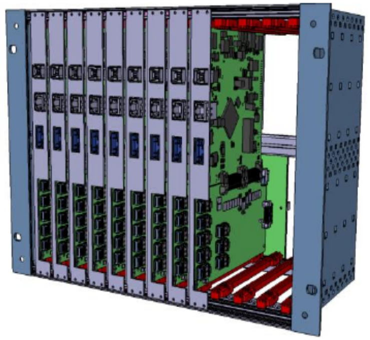


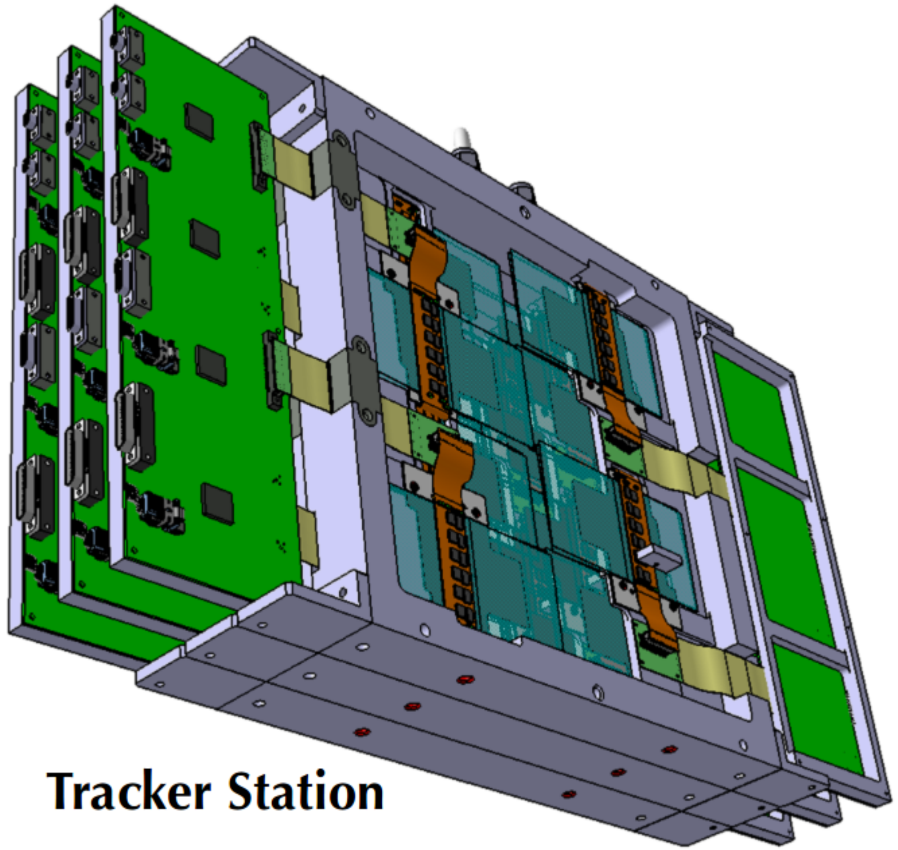
2 front panels LEDs

24V discrete wire to TRB adapter

FLEX cables

Into custom-made mini-crate

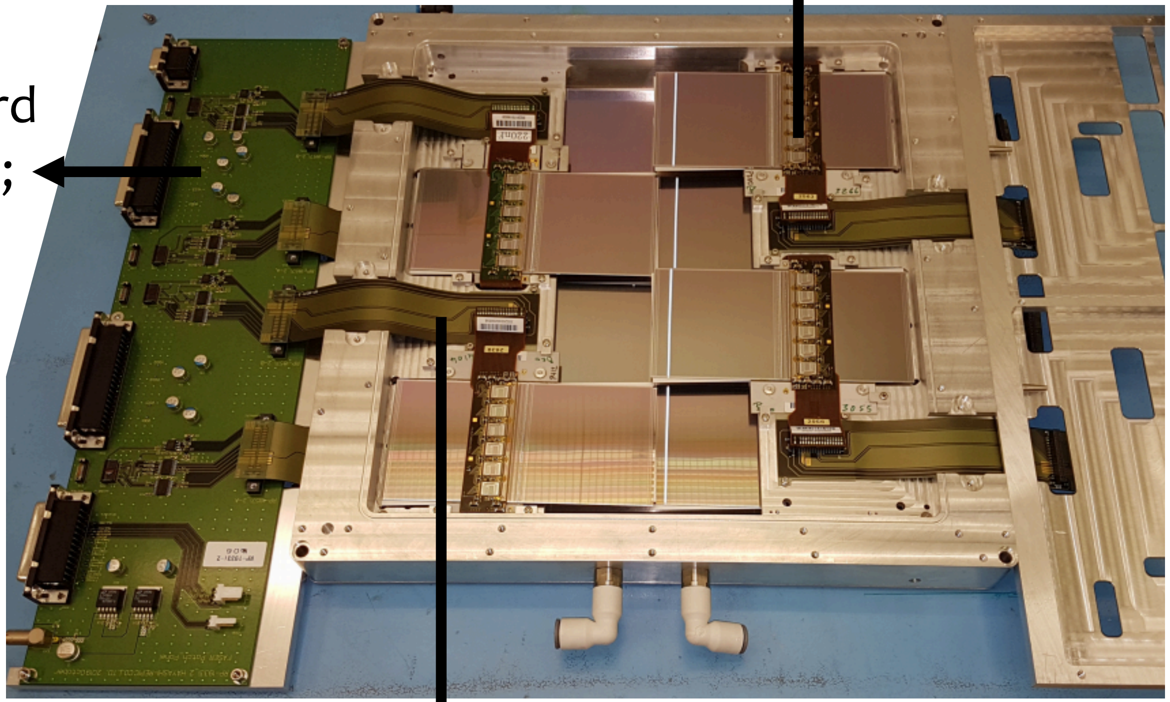




Tracker Station

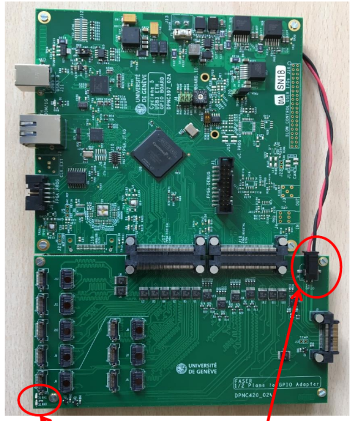
FASER Tracker

SCT module ASICs, require ~ 5 W / module



Patch panel to custom board based on home-made GPIO; Power (HV/LV), monitoring and readout lines.

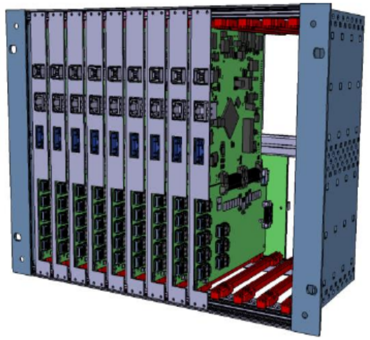
FLEX cables



2 front panels LEDs

24V discrete wire to TRB adapter

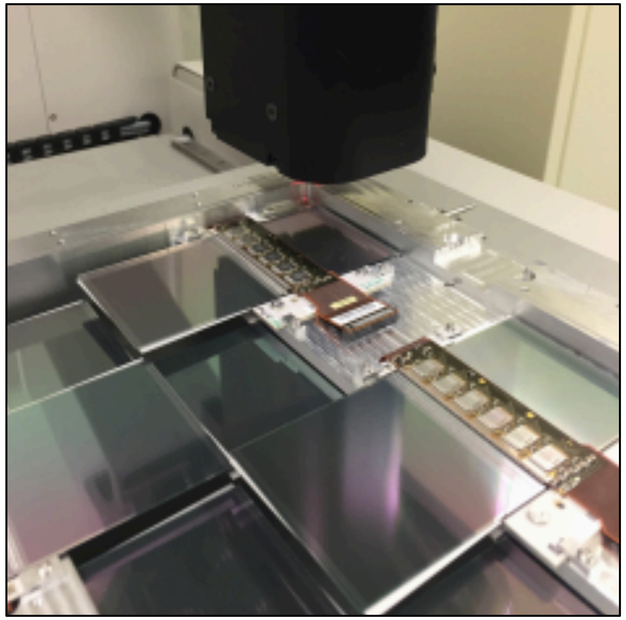
Into custom-made mini-crate



Provides LV and HV

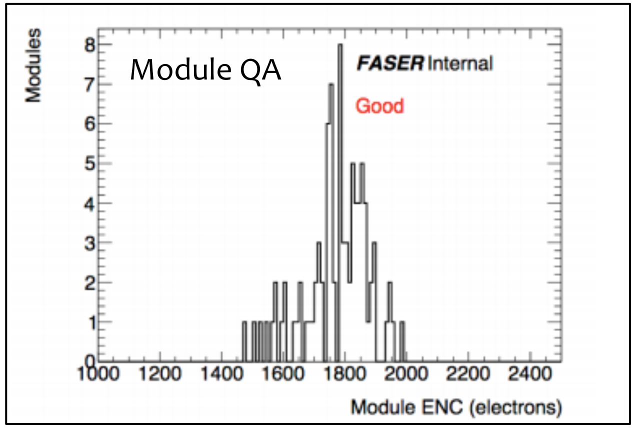
FASER Tracker Status

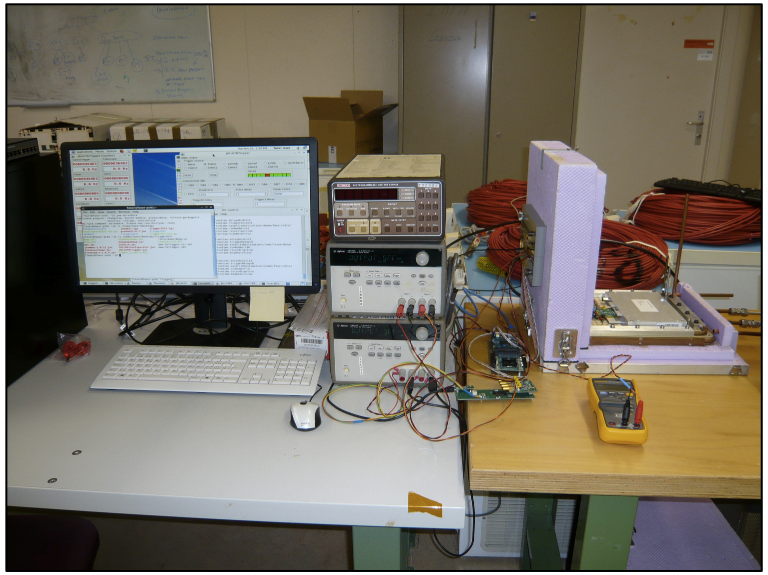
- Prototype layers produced and used for extensive testing (electrical, mechanical and thermal)
- Production planes in progress
- Commissioning started at CERN; well-defined procedure
- Gaining operational experience!



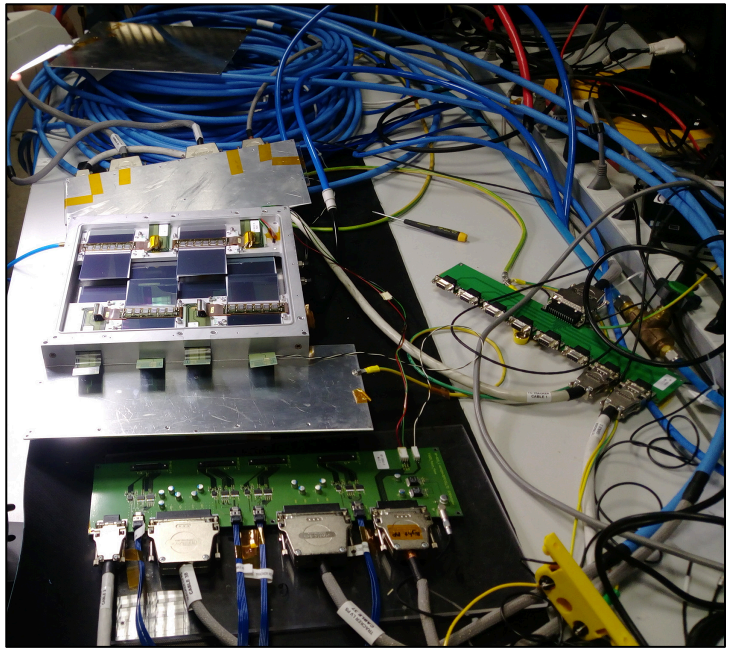
Metrology at the UniGe

- Module QA



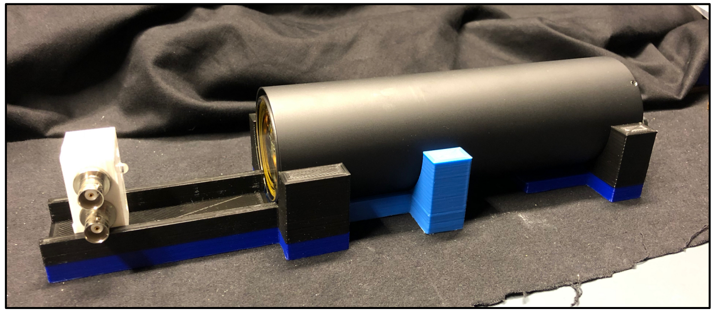


Module QA set up at CERN



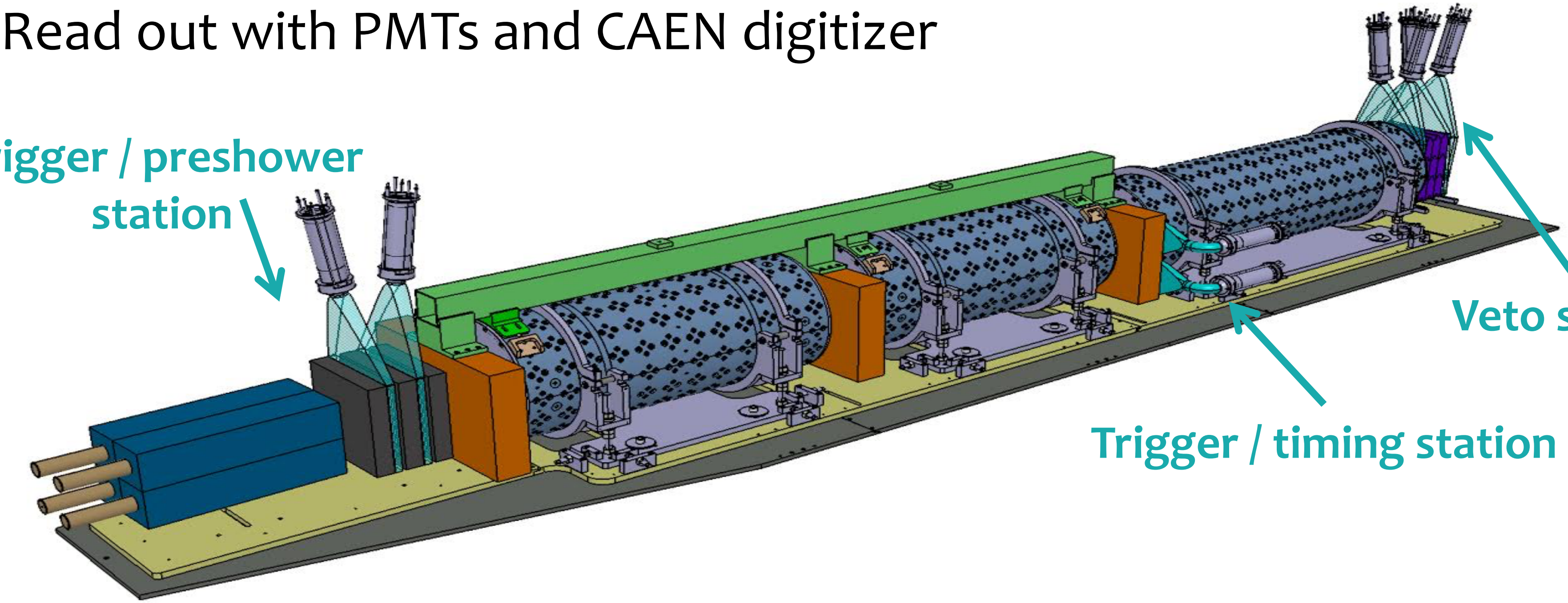
Tracker plane initial testing set up at CERN

FASER Scintillators



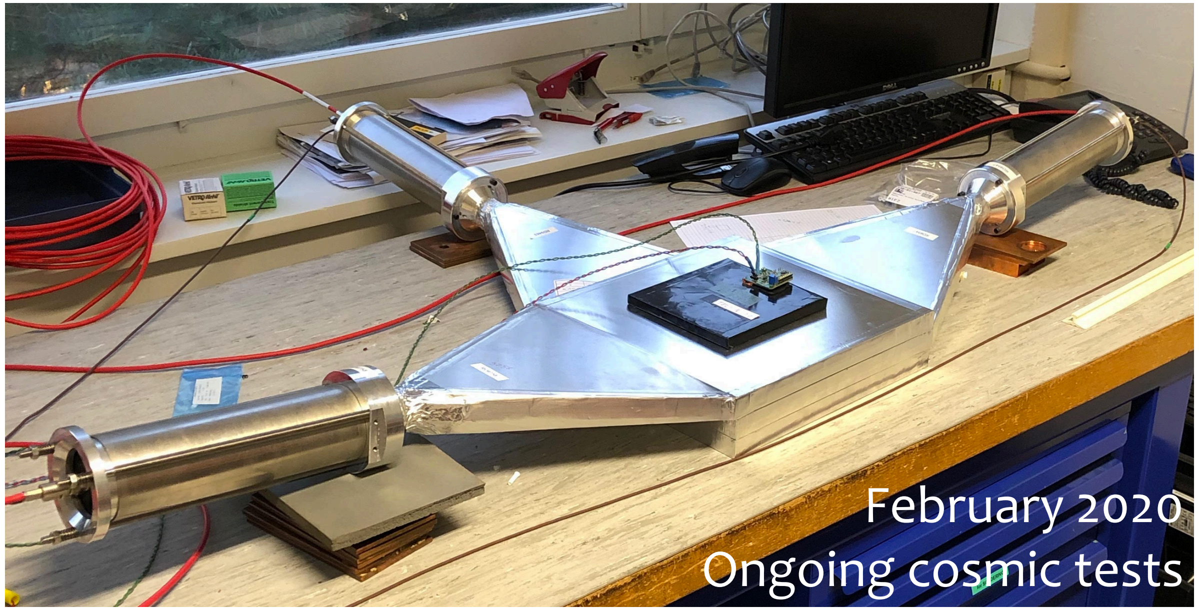
Scintillator PMTs

- Three stations all providing triggering capability:
  - Very high efficiency veto station for incoming charged particles (x4 planes)
  - Timing station; precise timing (~ ns) wrt IP (x1 plane)
  - Preshower station; coincidence with timing station (x2 planes)
- Read out with PMTs and CAEN digitizer

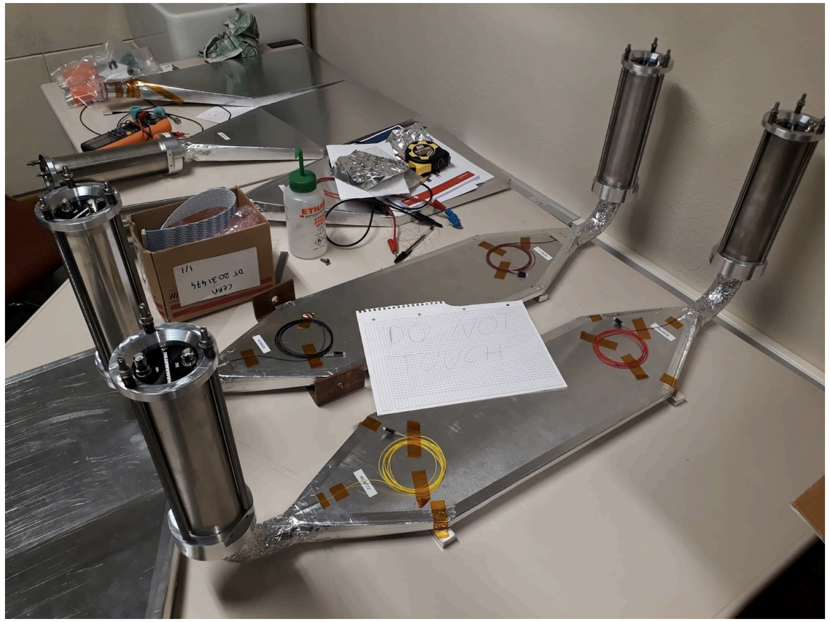


FASER Scintillators Status

- Scintillator planes produced at CERN
- PMTs purchased and studied
- Characterization with cosmics and LEDs
  - First results indicate good light yields (~ 400 photo-electrons/MIP) and high efficiency (> 99.8%)



February 2020
Ongoing cosmic tests



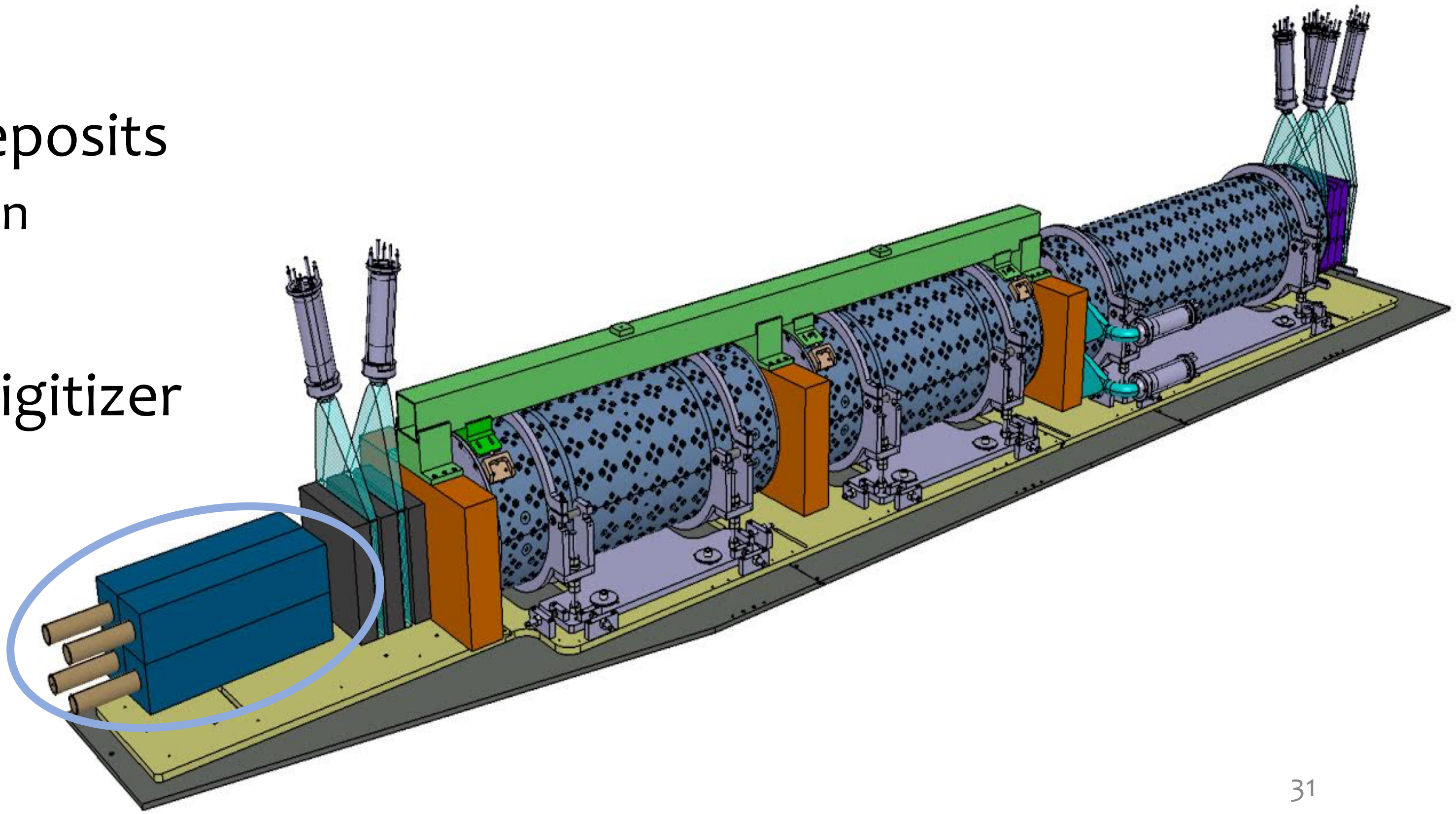
FASER scintillators produced at CERN

FASER Calorimeter

A calorimeter module

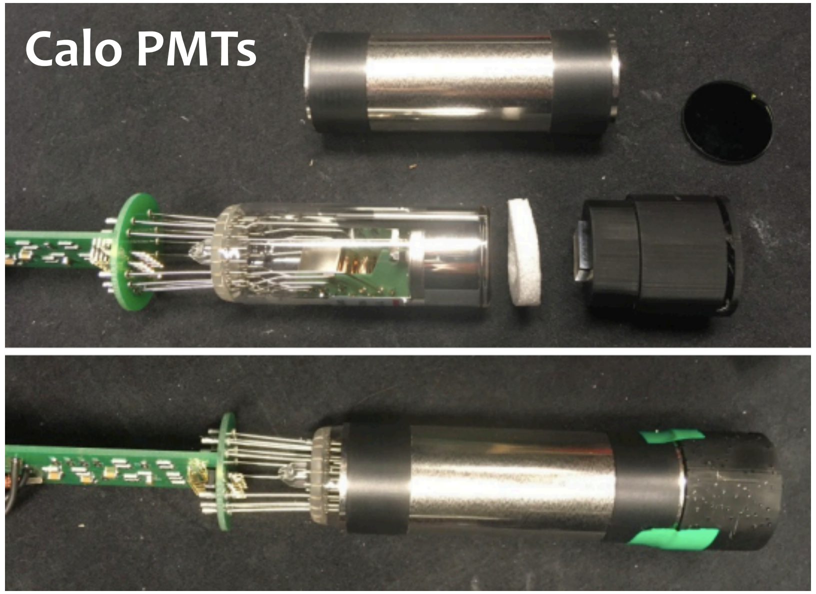
THANKS!

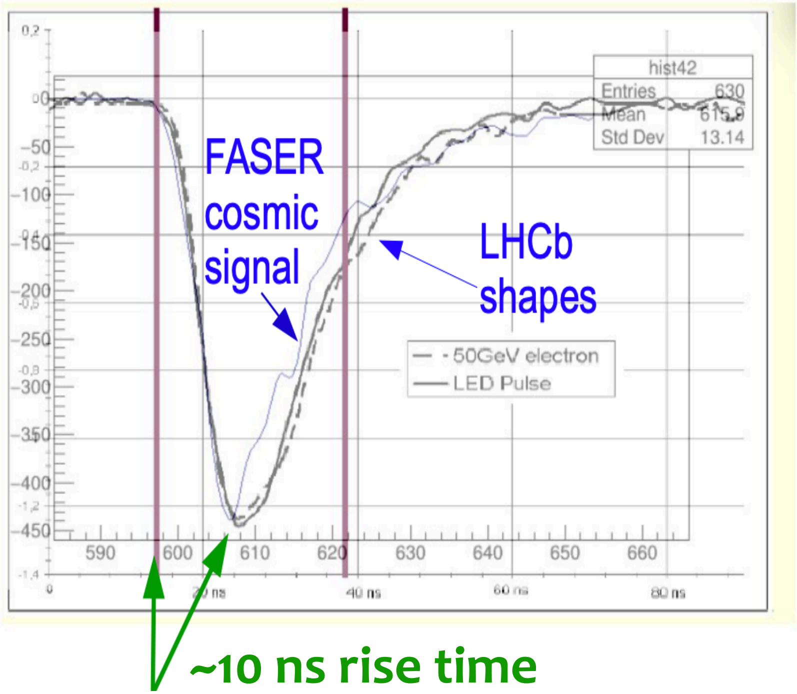
- FASER uses 4 LHCb spare outer ECAL modules
  - 25 radiation lengths long
  - Lead/scintillator calorimeter
- Energy resolution ~ 1% for TeV deposits
  - No longitudinal shower information
- Provides triggering capability
- Read out with PMTs and CAEN digitizer

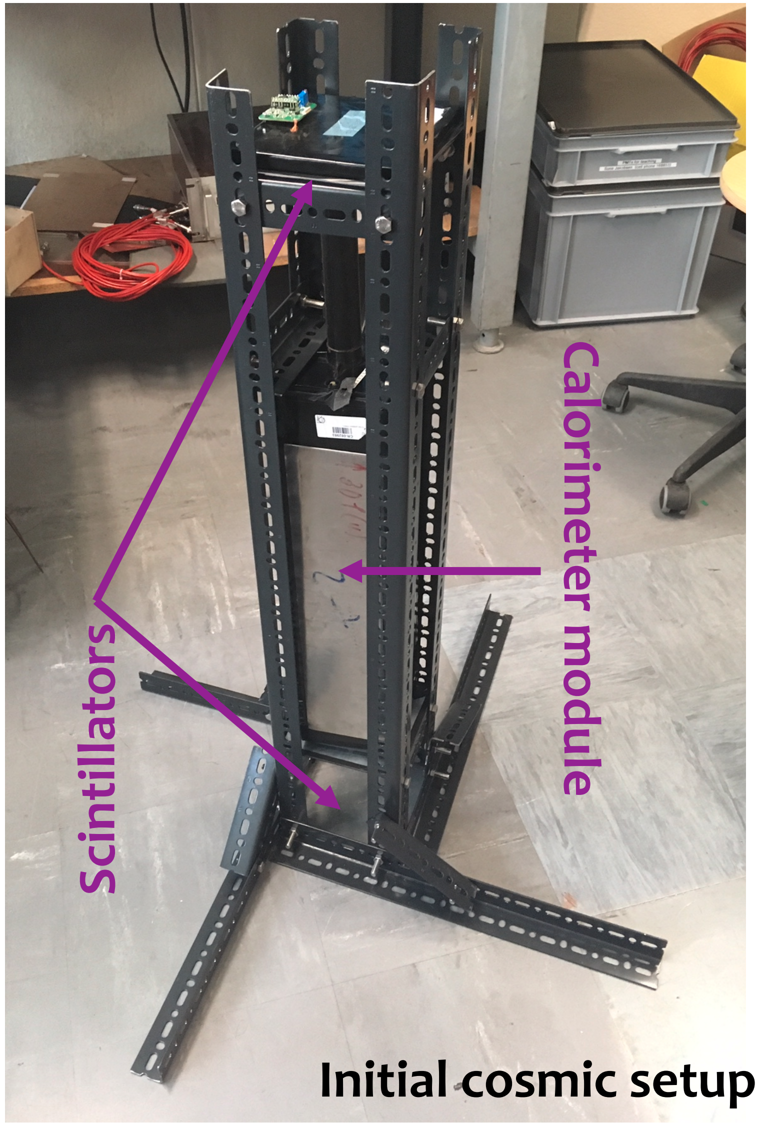


FASER Calorimeter Status

- Calorimeter modules tested; characterization ongoing
- First calibration and linearity measurements with cosmics
  - good agreement with LHCb pulses

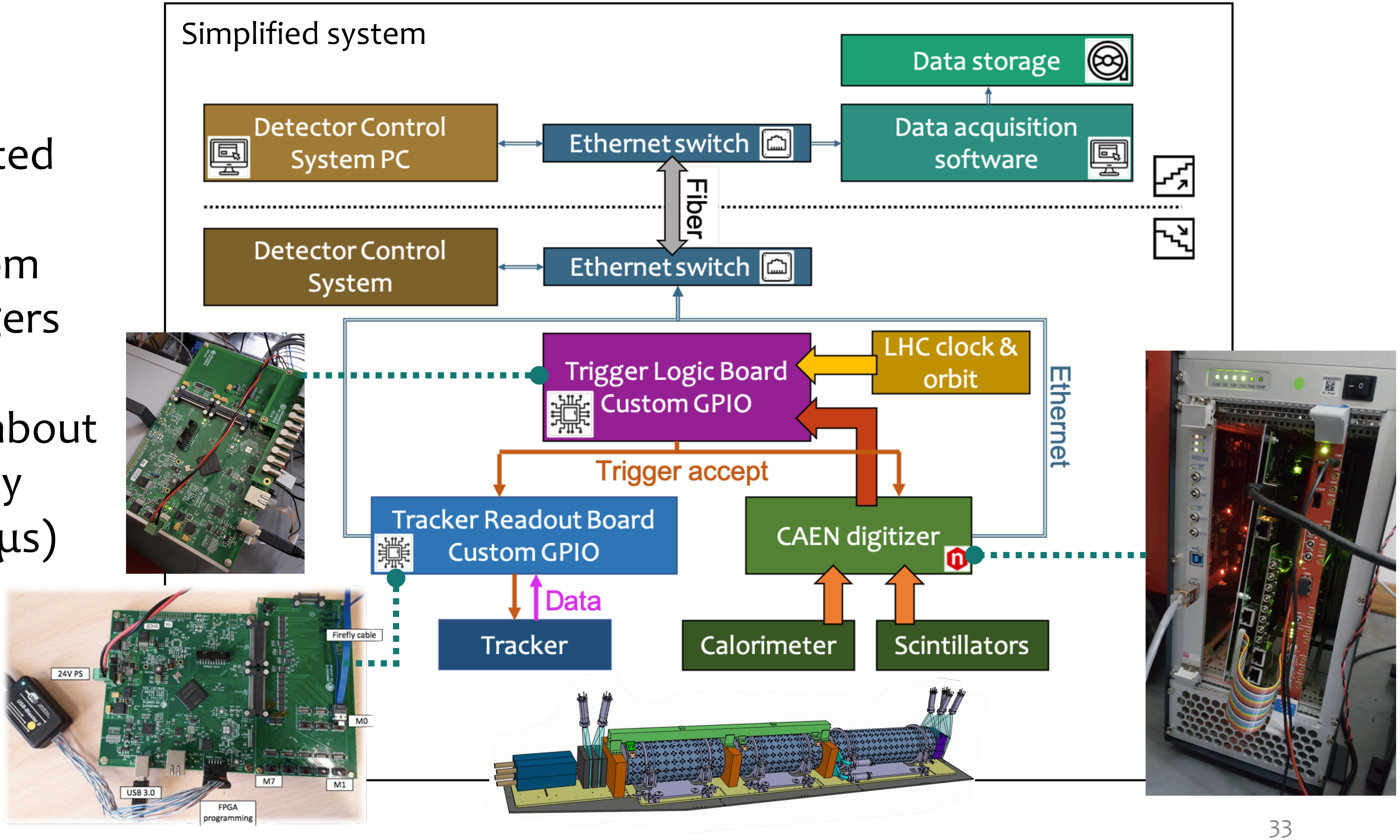






FASER Trigger & Data acquisition

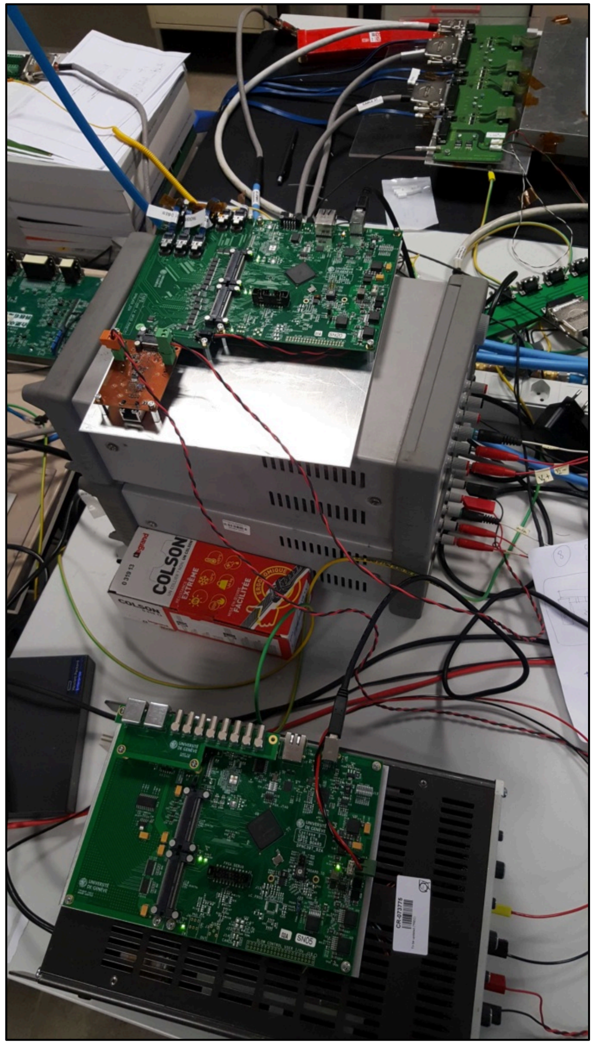
- Expected **trigger rate** about **500 Hz,** dominated by muons from the IP
  - L1A includes random and software triggers
- Expected **bandwidth** about **15 MB / s,** dominated by PMTs' wide signal (~ 1 μs)
- All TDAQ electronics will be placed in TI12



Trigger & Data acquisition **Status**

- **Electronics available and tested**
  - Connected to rack & available online during CERN lockdown for continuing testing
  - Communication tests resumed last week!
- **DAQ SW based on CERN's "DAQling", adapted for FASER**
  - Initial implementations for all detectors in place
  - Includes online monitoring
- **DCS follows CERN practices**

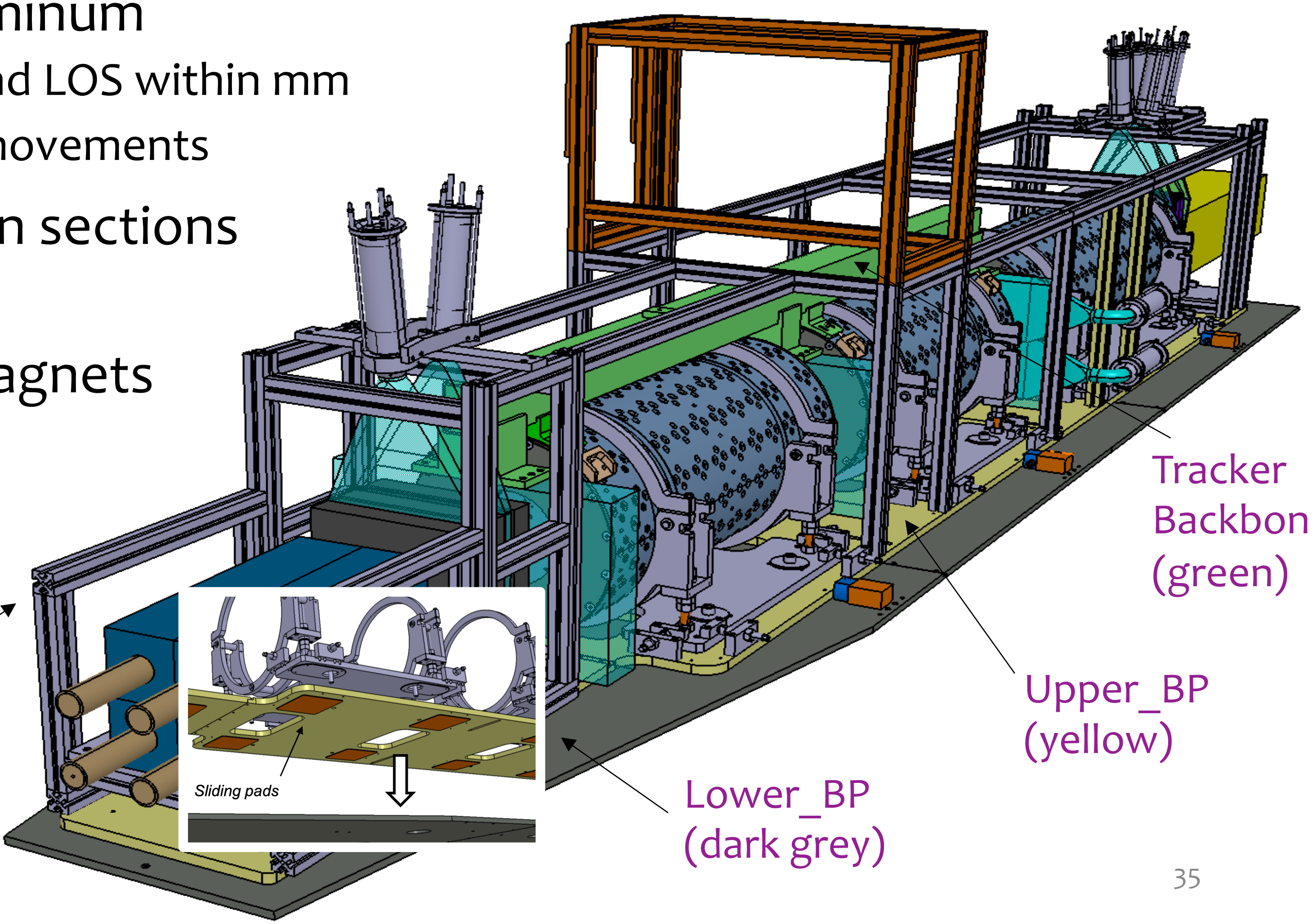
Initial Run Control application, produced by summer intern



All boards connected together for tests

FASER 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)



FASER experiment construction and **commissioning**

FASER Commissioning

- Dedicated labs available at CERN for individual component testing
- Dedicated area at CERN's Prevessin site ("ENH1") for full-detector commissioning

Milestone	Where	When in 2020
Individual component commissioning	CERN labs	July
Detector commissioning	ENH1	September
Installation of magnets	ENH1	September
Complete dry assembly and testing	ENH1	October
Full detector installation	TI12	November
In-situ dry commissioning	TI12	December

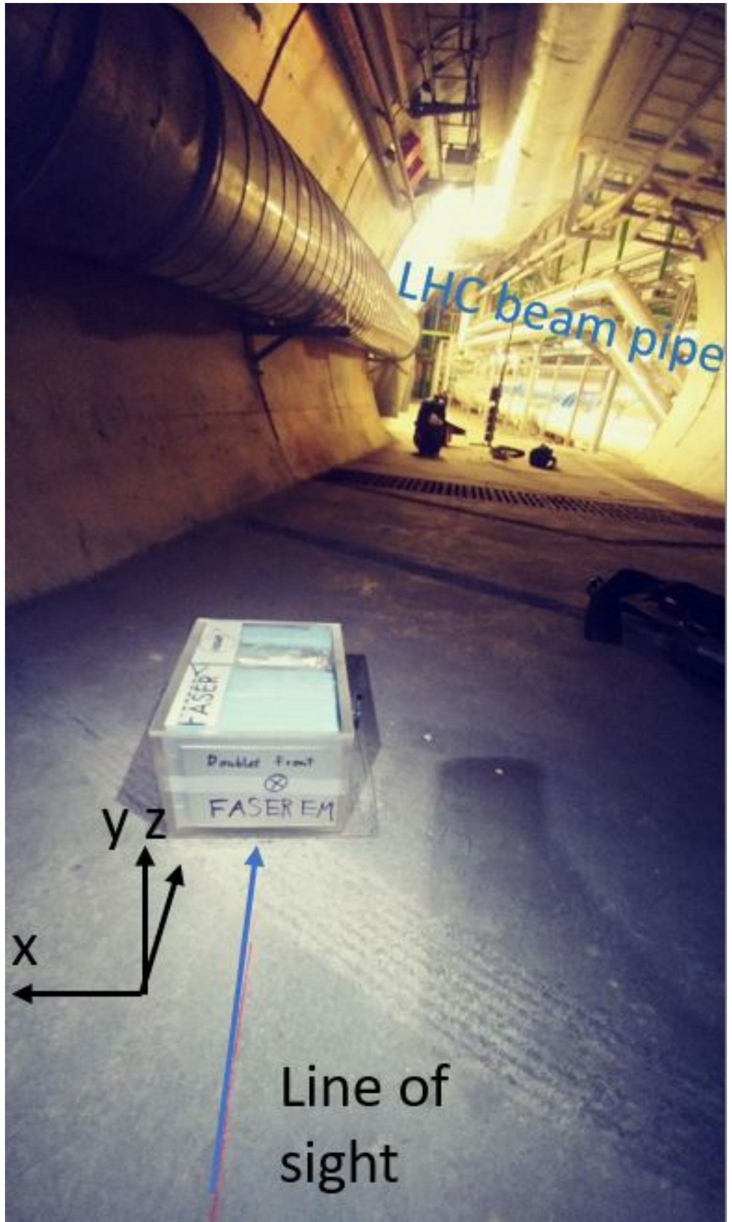
At this point, still some uncertainties in these timescales

Racks and crates at ENH1

FASER Backgrounds

- Major background from IP:
  - Muons and **neutrinos** directly from IP; muons that brem off another particle
  - Veto in scintillators (4 uncorrelated layers) renders this negligible
- 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

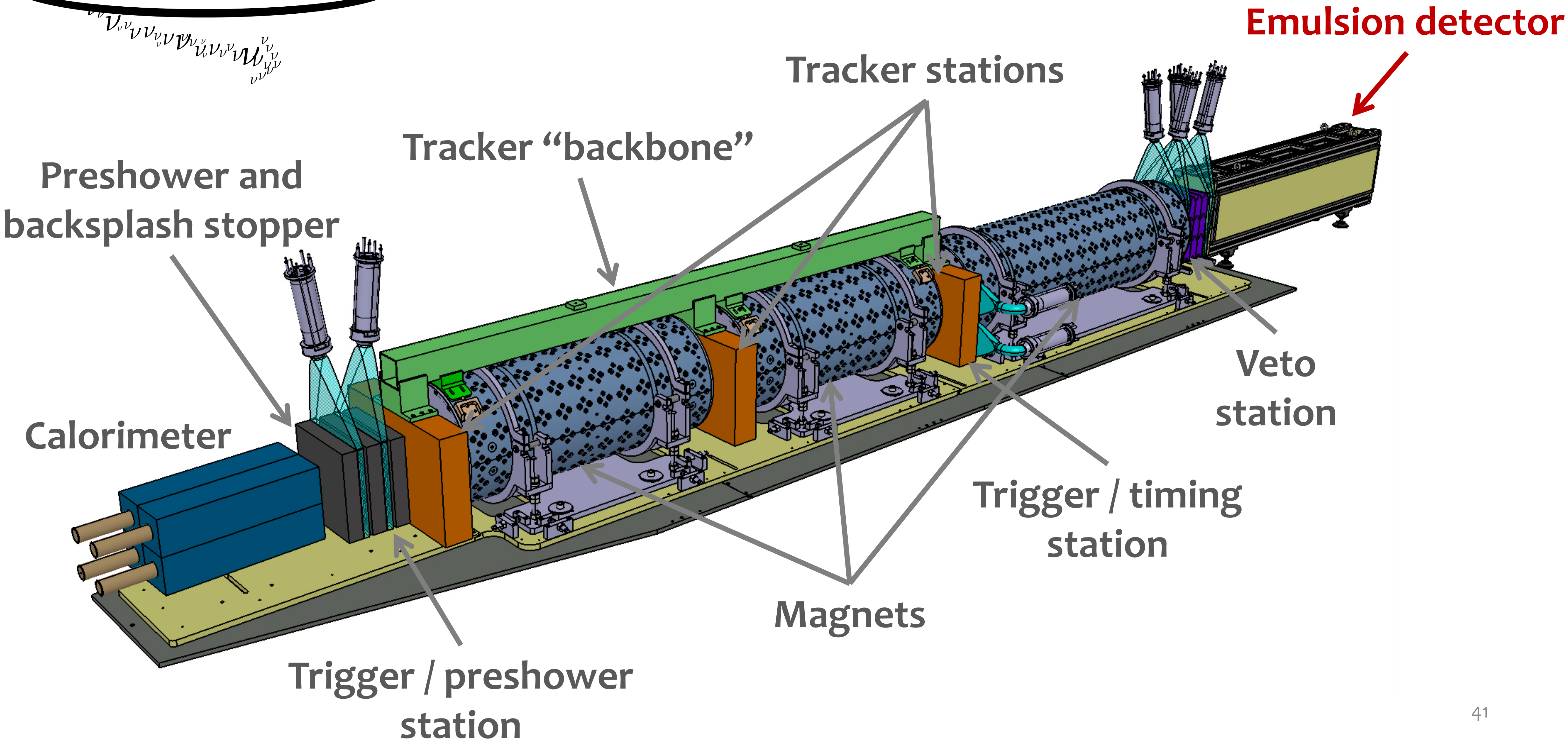
FASER

Huge flux of high-energy neutrinos

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

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"**
Proceedings, ECFA-CERN Workshop on large hadron collider in the LEP tunnel, pp. 571–596, 1984.

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!

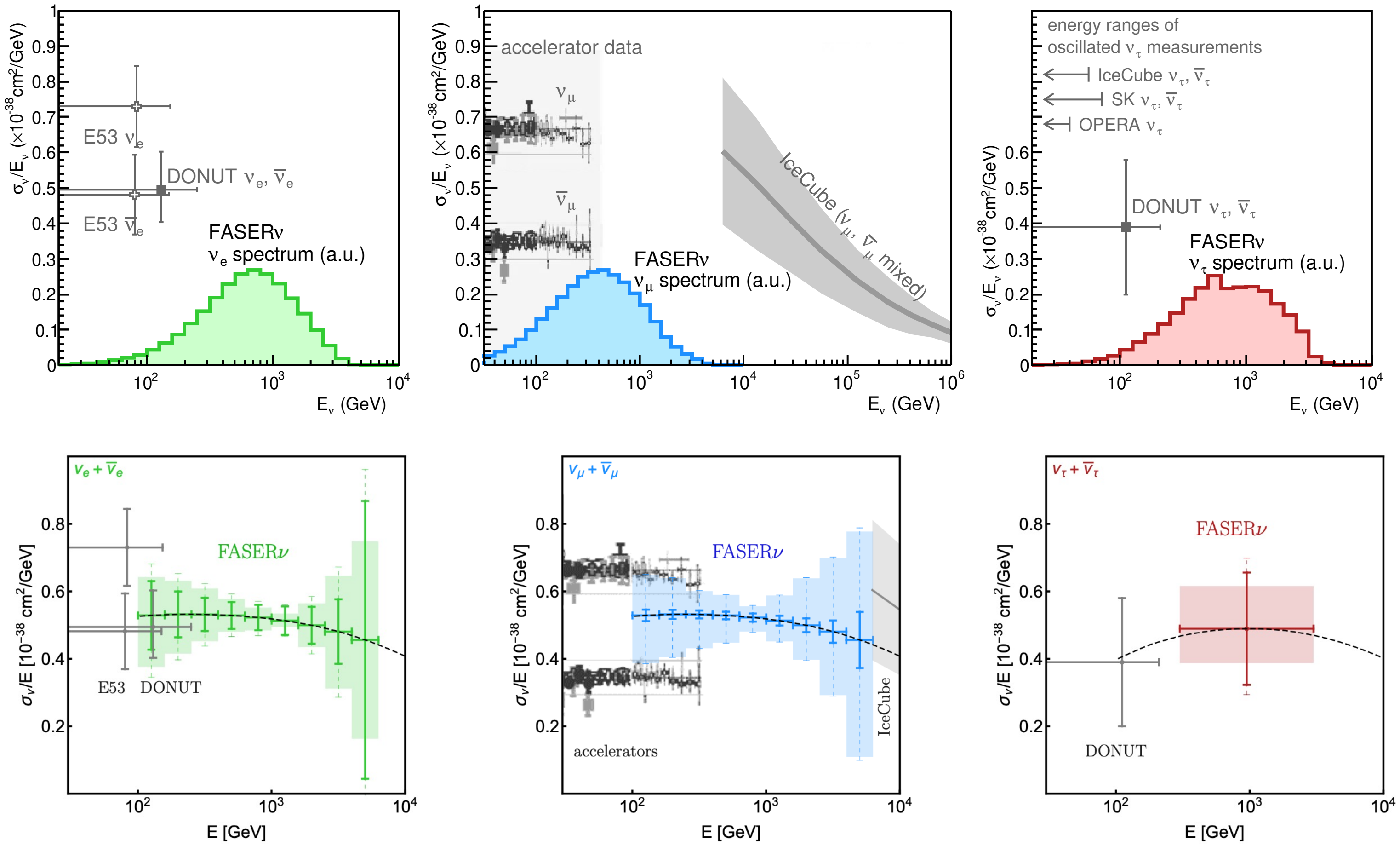
  - Expected event yields

150/fb @14TeV	ν_e	ν_μ	ν_τ
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

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"** Proceedings, ECFA-CERN Workshop on large hadron collider in the LEP tunnel, pp. 571–596, 1984.

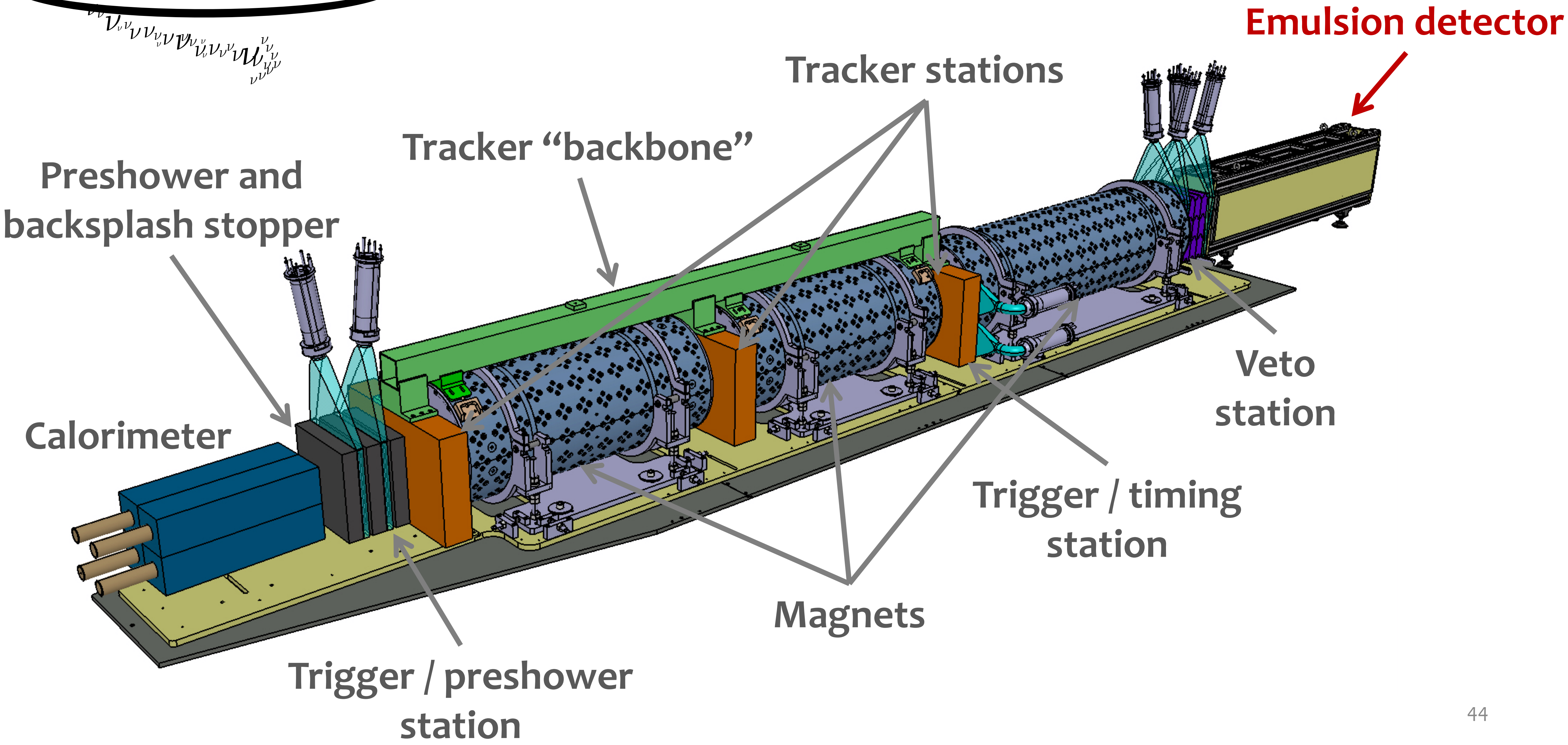
Huge flux of high-energy neutrinos

- 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)



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"** Proceedings, ECFA-CERN Workshop on large hadron collider in the LEP tunnel, pp. 571–596, 1984.

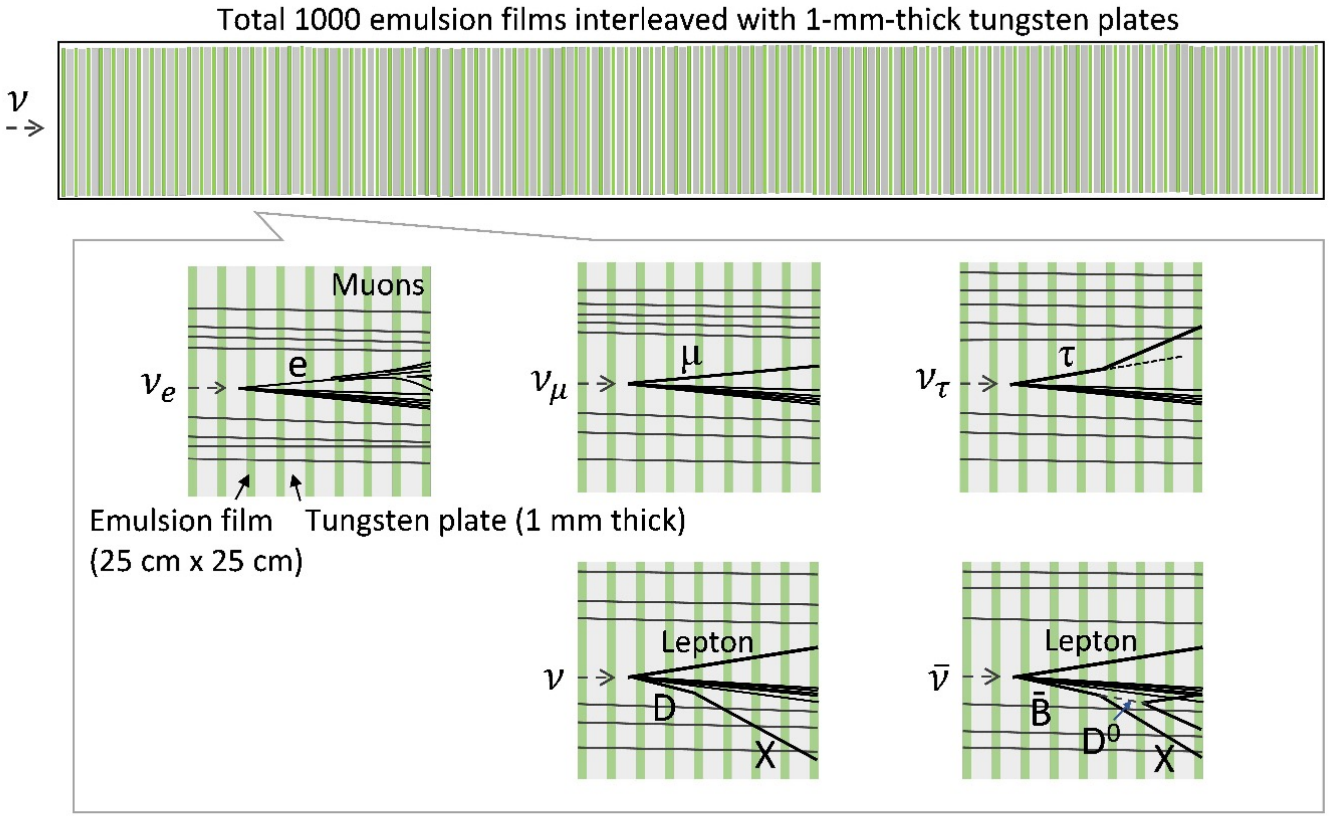
FASER Detector



FASER Detector - emulsion

- Emulsion film detector with tungsten plates; well known neutrino detector technology
- Track position resolution O(50nm), and angular resolution O(0.35mrad). No timing resolution
- Replace every 20-50/fb to maintain manageable track density
- Challenge: replace the 1-ton-scale detector about 3 times/year

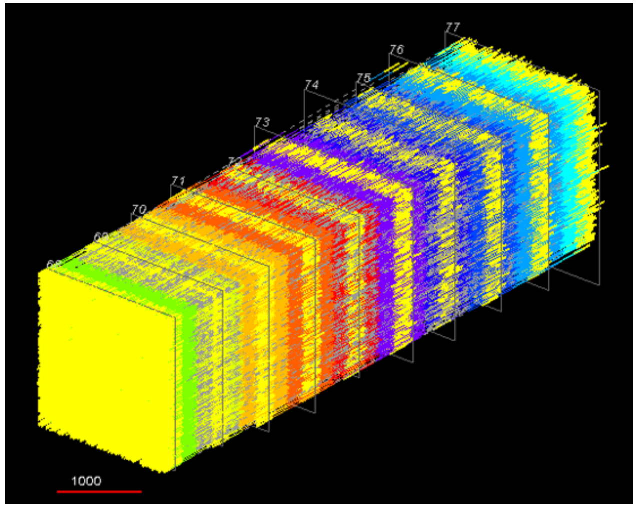
- **Status:**
  - Testing samples of tungsten planes for detector assembly

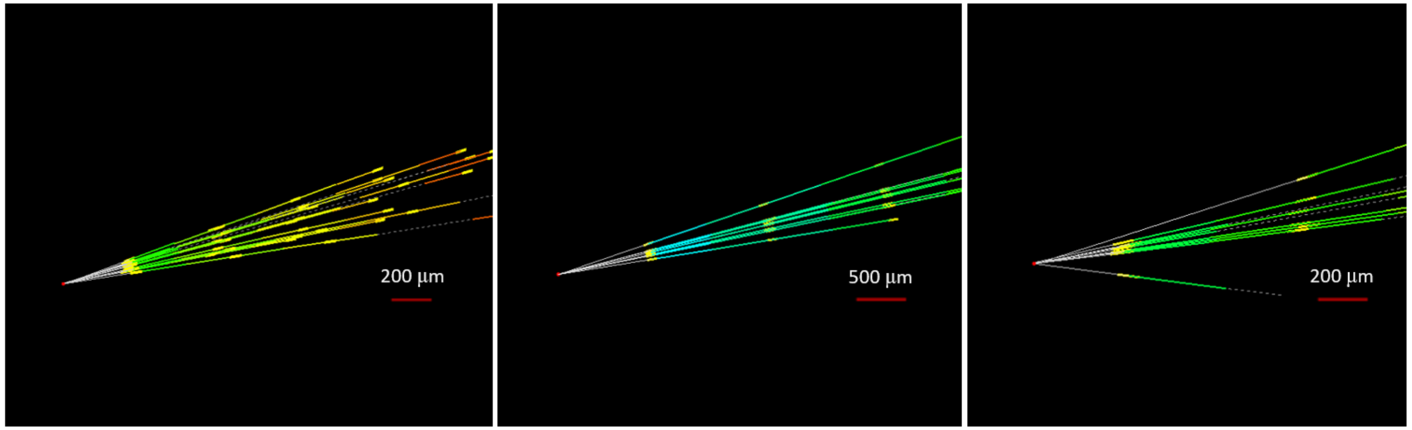


N.B.: Interface tracker for charge ID and improved measurements to be added at a longer timescale

FASER Pilot run in 2018

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

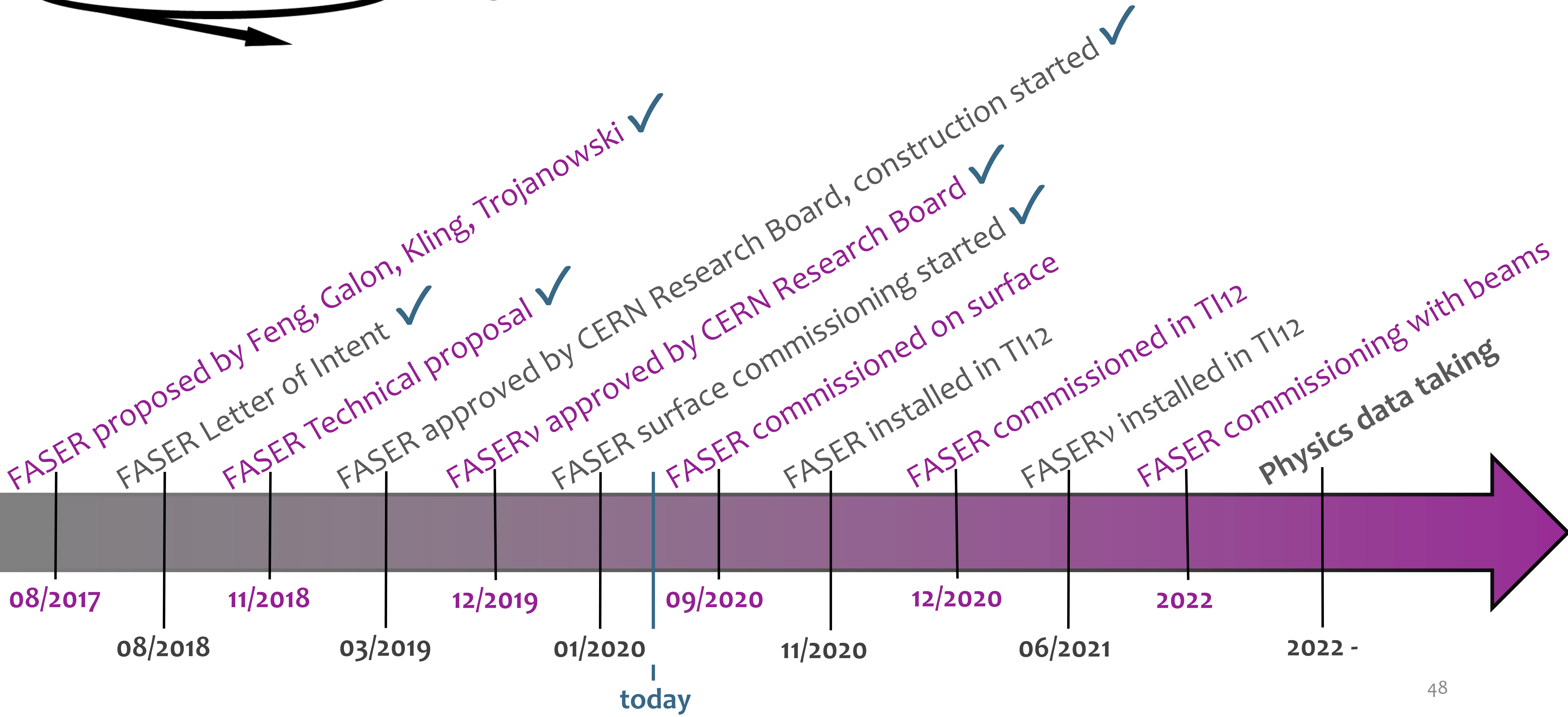




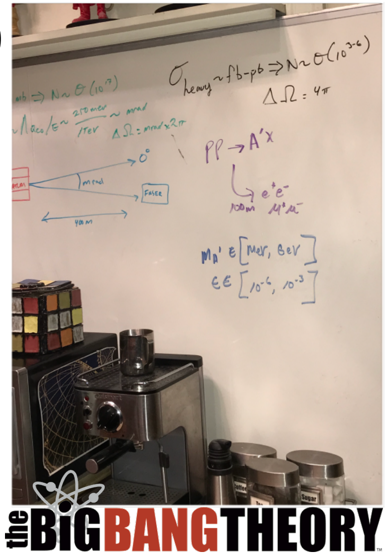
Reconstructed neutral vertices in the prototype dataset

FASER Timeline

FASER Global timeline



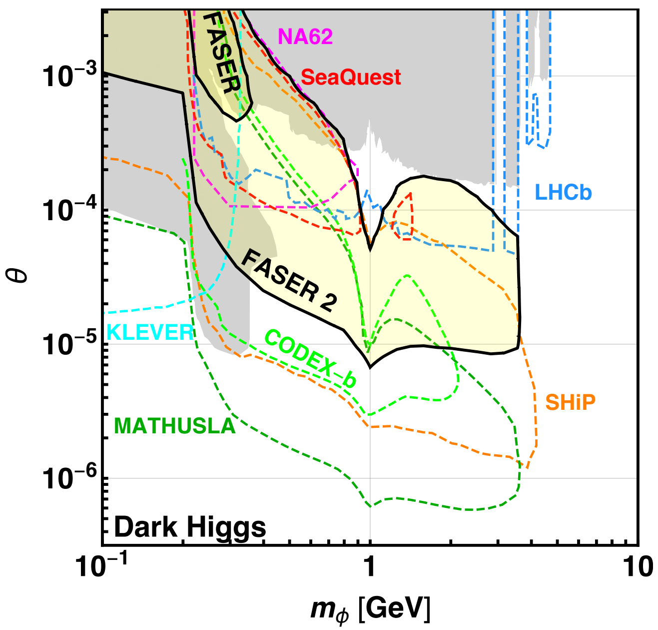
FASER Global timeline

(*) 

- 08/2017 — FASER proposed by Feng, Galon, Kling, Trojanowski (*) ✓
- 08/2018 — FASER Letter of Intent ✓
- 11/2018 — FASER Technical proposal ✓
- 03/2019 — FASER approved by CERN Research Board, construction started ✓
- 12/2019 — FASERν approved by CERN Research Board ✓
- 01/2020 — FASER surface commissioning started ✓
- today
- 09/2020 — FASER commissioned on surface
- 11/2020 — FASER installed in TI12
- 12/2020 — FASER commissioned in TI12
- 06/2021 — FASERν installed in TI12
- 2022 — FASER commissioning with beams
- 2022 - — **Physics data taking**

Beyond FASER?

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 μ	F2	VI	BC7	[28,29]	···	✓
HNLs with τ	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

FASER Outlook

- The collaboration is working feverishly to construct, commission and install the detector over the current Long Shutdown
- CERN teams work on civil engineering, services, magnets, …
- Remarkable progress in all fronts
- Goal: get ready for data taking with the start of Run3!
- Enormous potential to:
  - either make a new discovery or constrain parts of phase-space which no current experiment has access to
  - make the first collider-originated neutrino measurements
- We have started thinking about FASER2!

Stay in touch:

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

@FASERexperiment

FASER 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

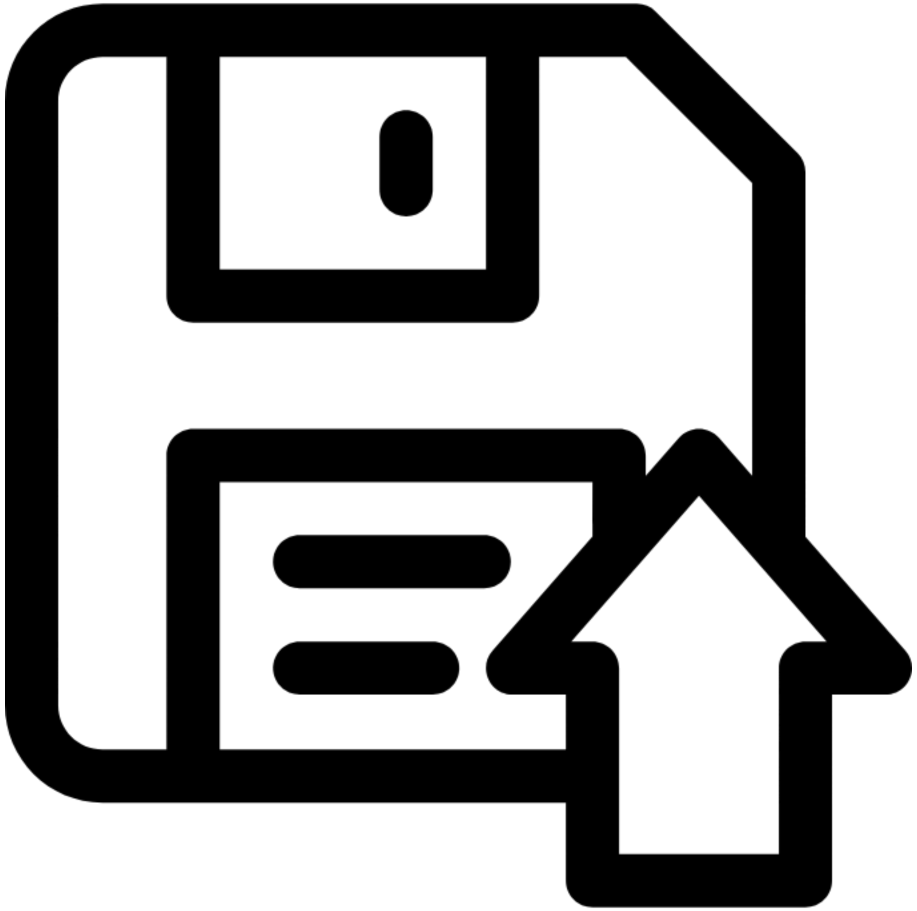
Plus several theory papers

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

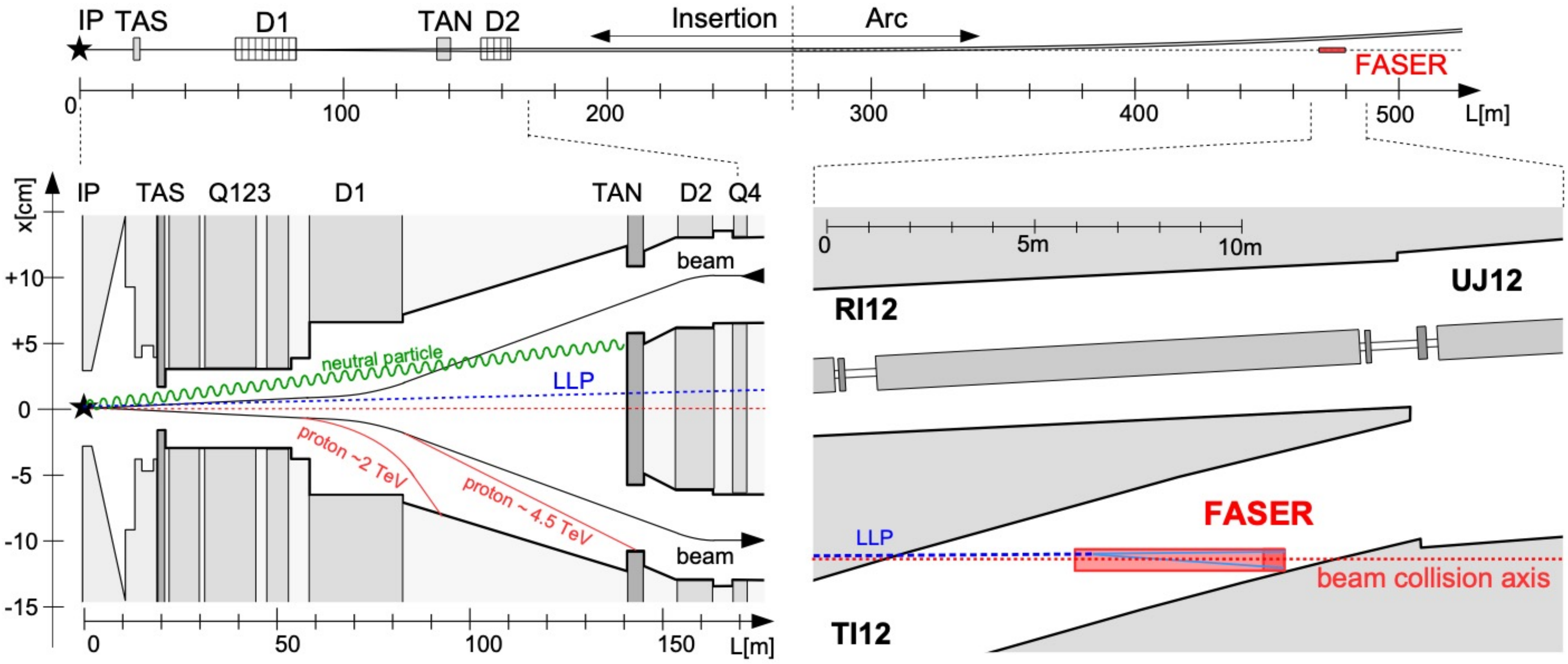
FASER Thanks!

FASER Collaboration: 8 countries, 20 institutes, about 60 members

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

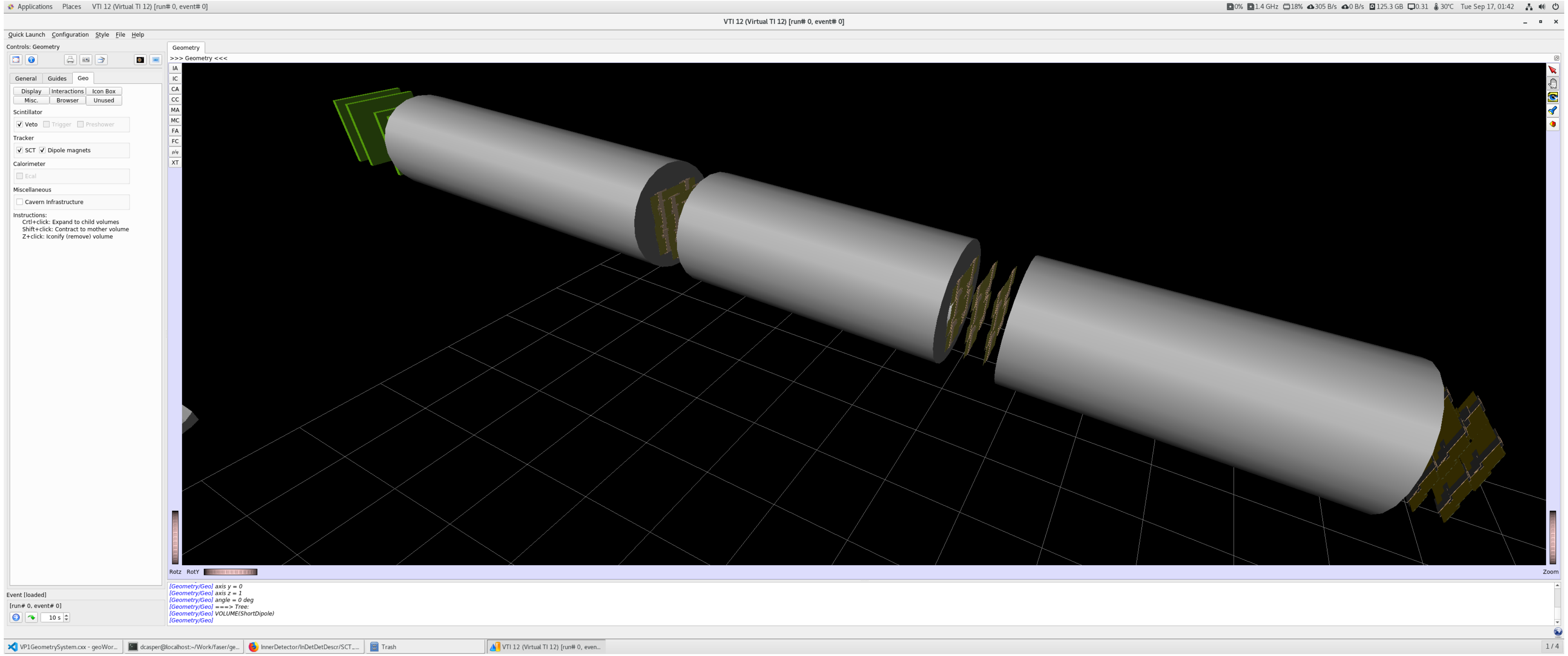


LLP production at ATLAS IP

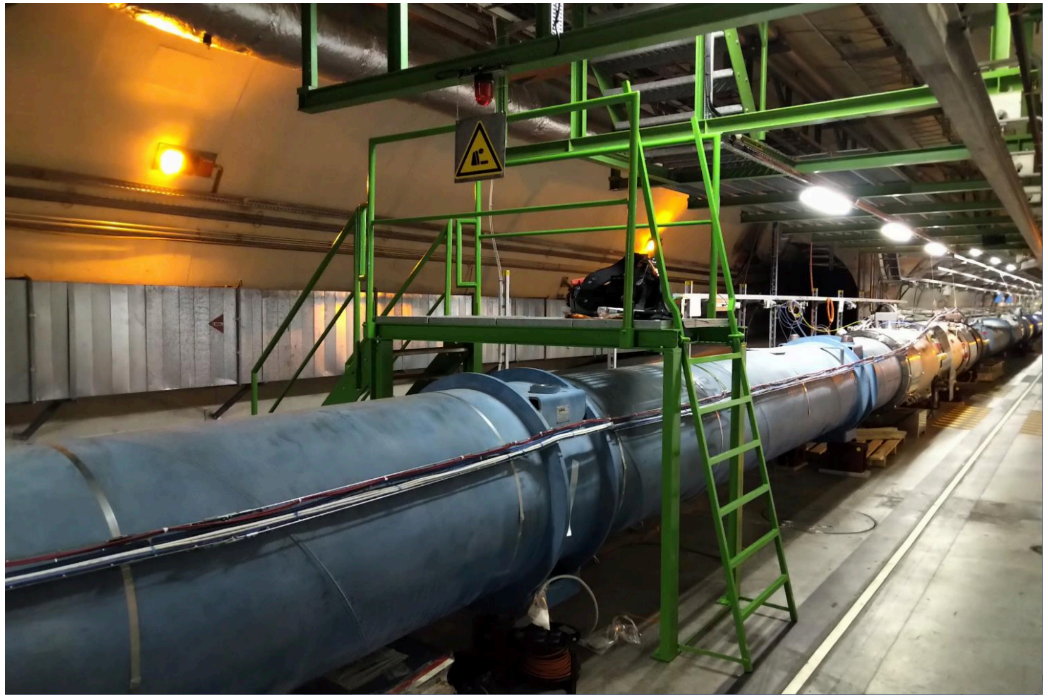


Offline

- Adapt open source ATLAS Athena ("Calypso")
  - First versions of detector description, Geant4 simulation and event display working
- Track reconstruction with “ACTS” under development

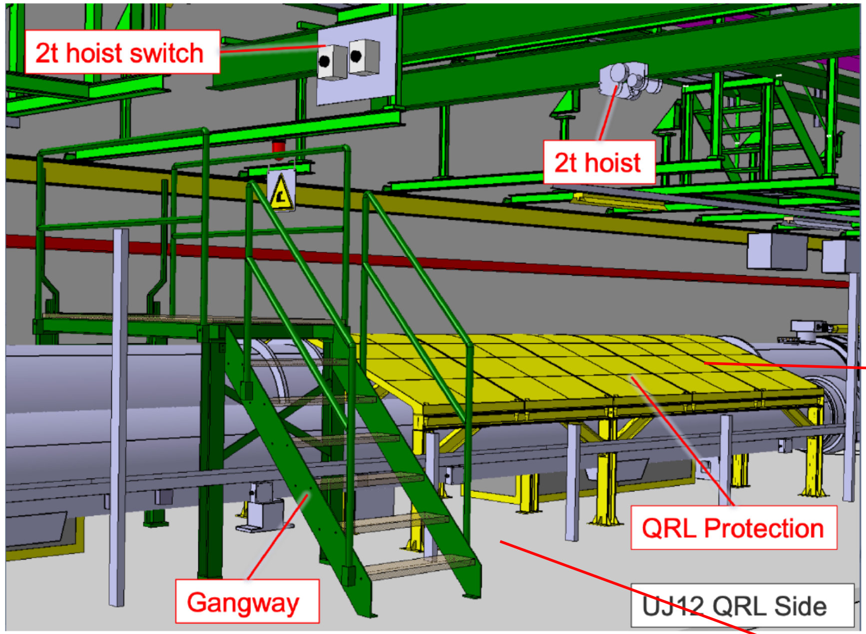


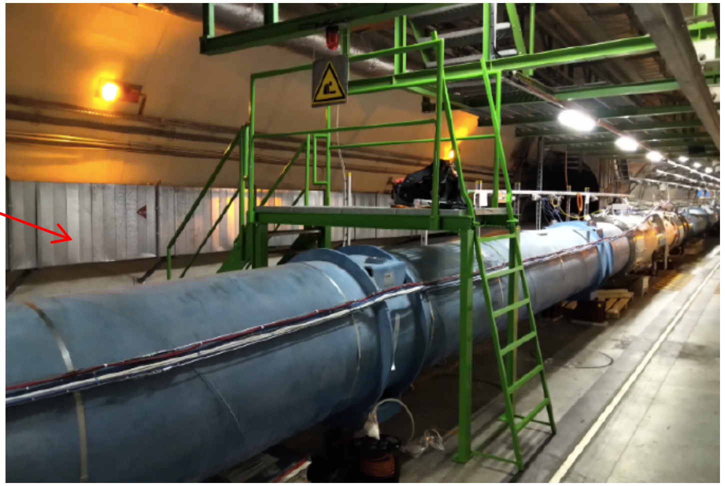
Accessing TI12



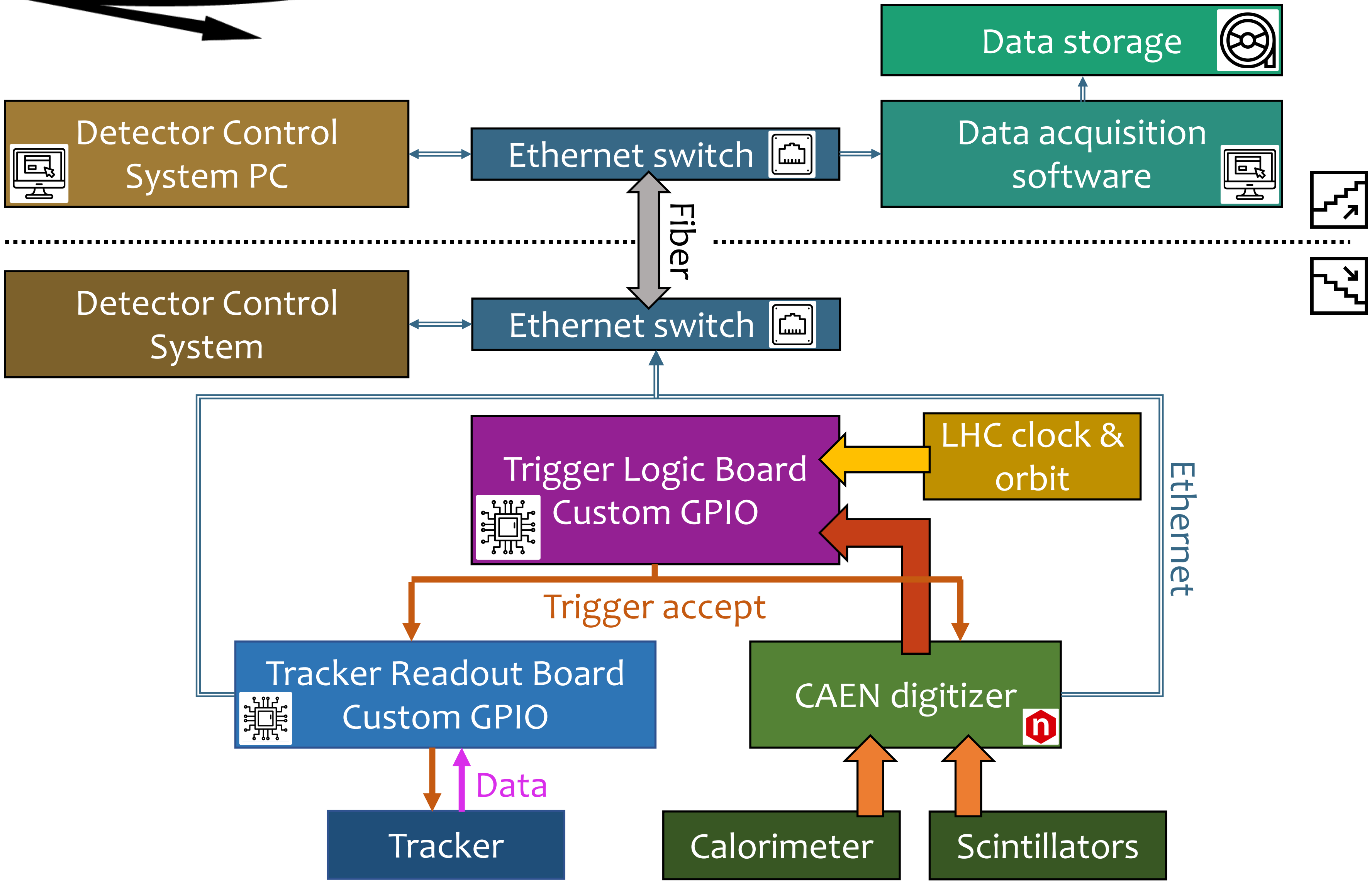
Preparation of TI12

Accessing TI12



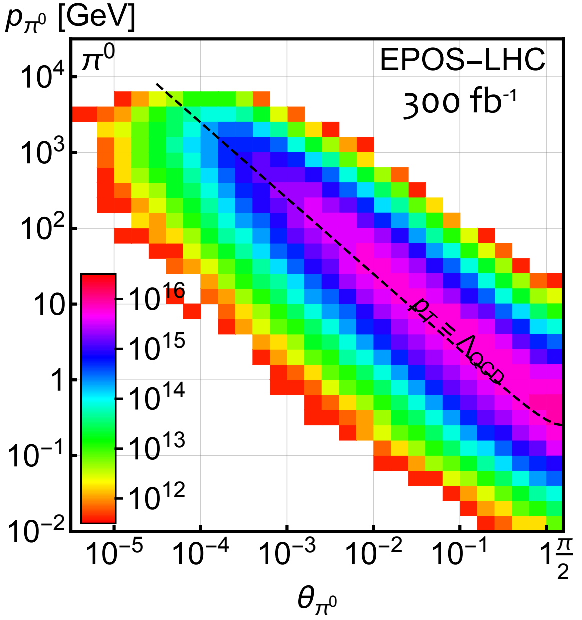


Extremely simplified TDAQ system

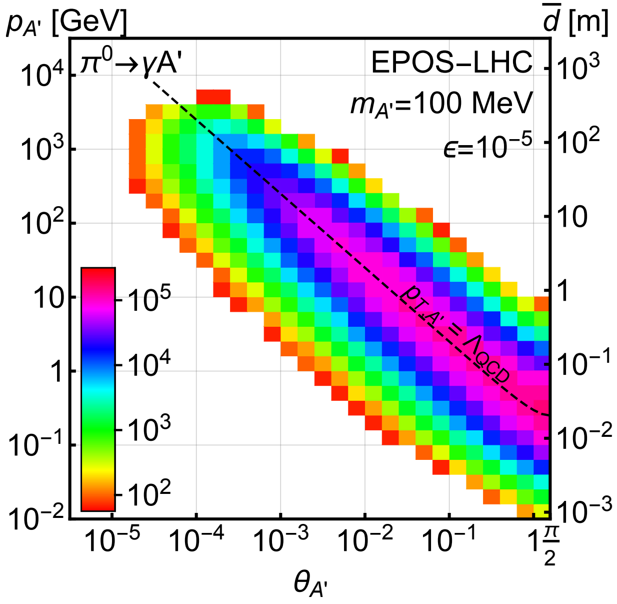


SIGNALS: DARK PHOTONS

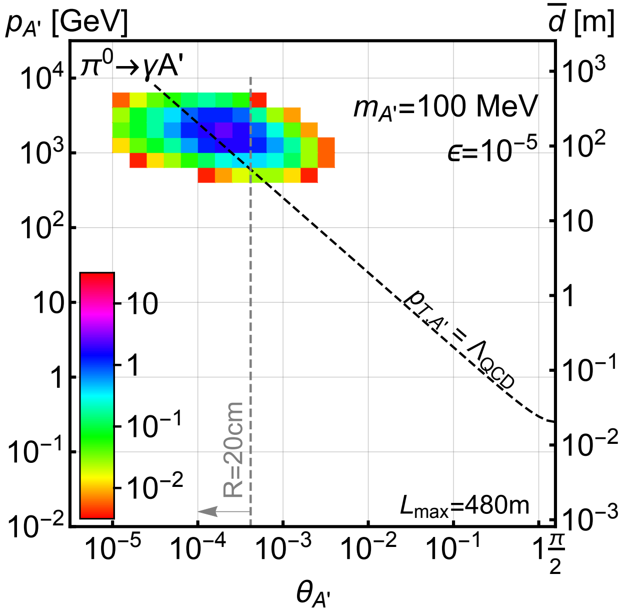
Pions at the IP



A's at the IP



A's decay in FASER



- Enormous event rates: $N_\pi \sim 10^{15}$ per bin
- Production is peaked at low transverse momentum ~250 MeV

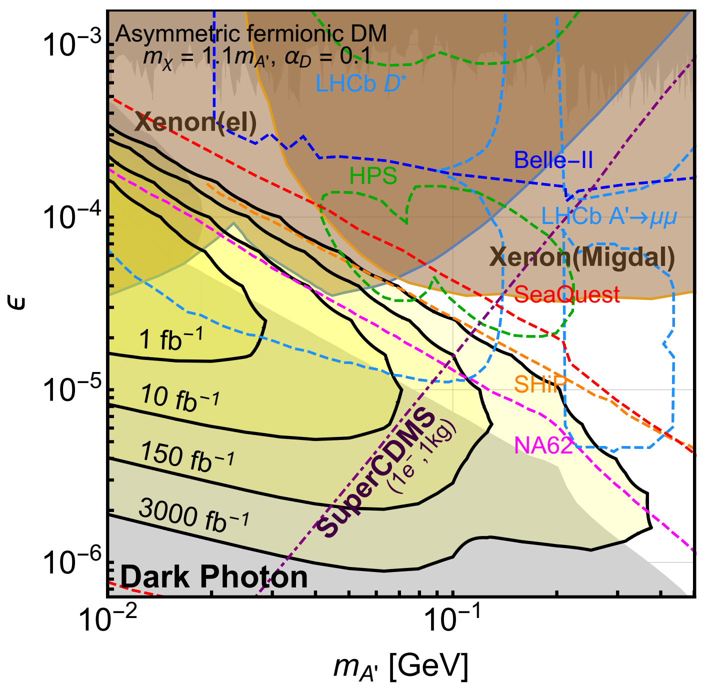
- Rates highly suppressed by $\varepsilon^2 \sim 10^{-10}$
- But still $N_{A'} \sim 10^5$ per bin; LHC is a dark photon factory!

- Rates suppressed again, but still $N_{A'} \sim 100$ signal events
- Signal is E~TeV A's within 20 cm of the line of sight

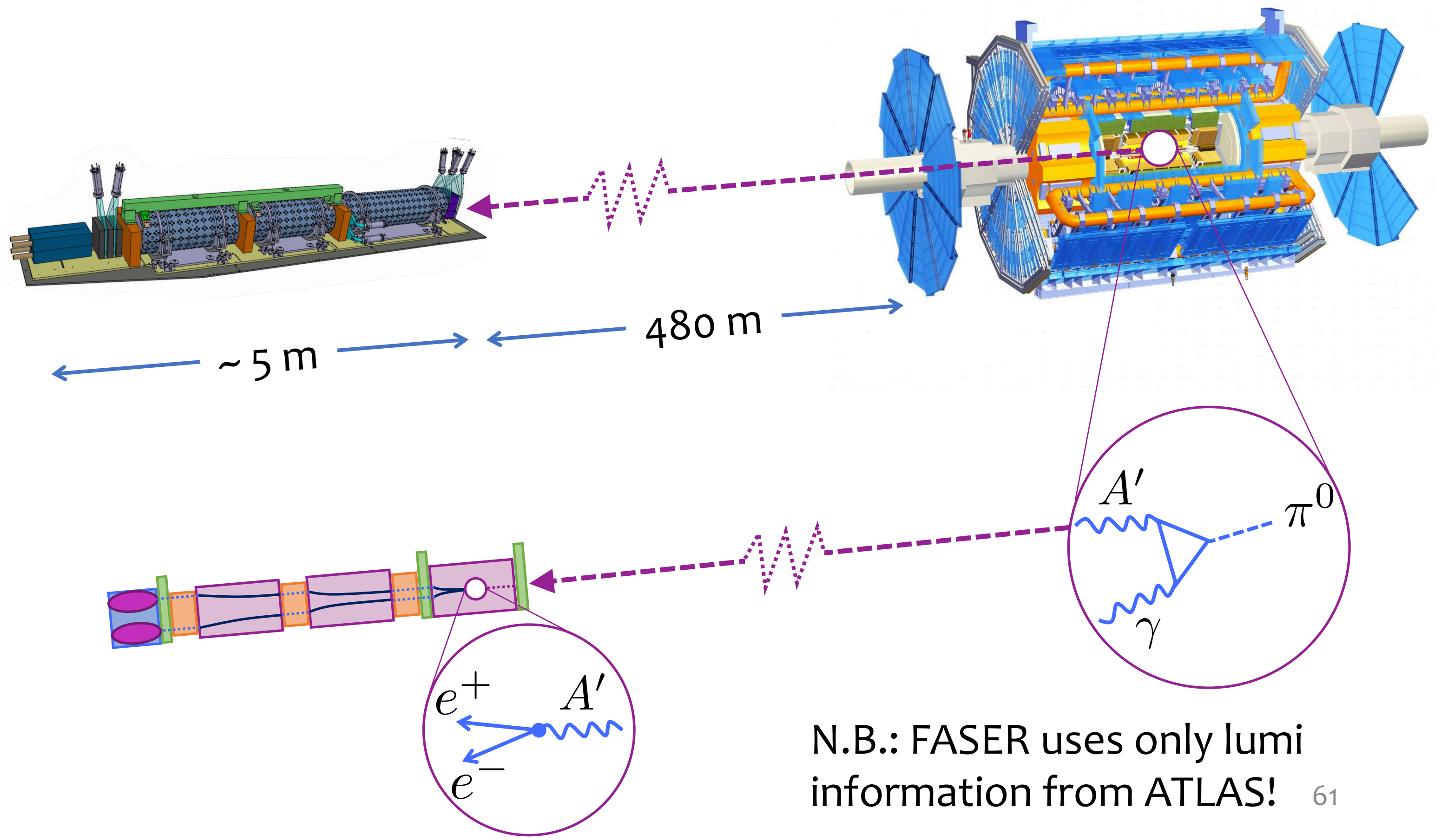
Slide from J. Feng

An example physics case: Dark Photon A'

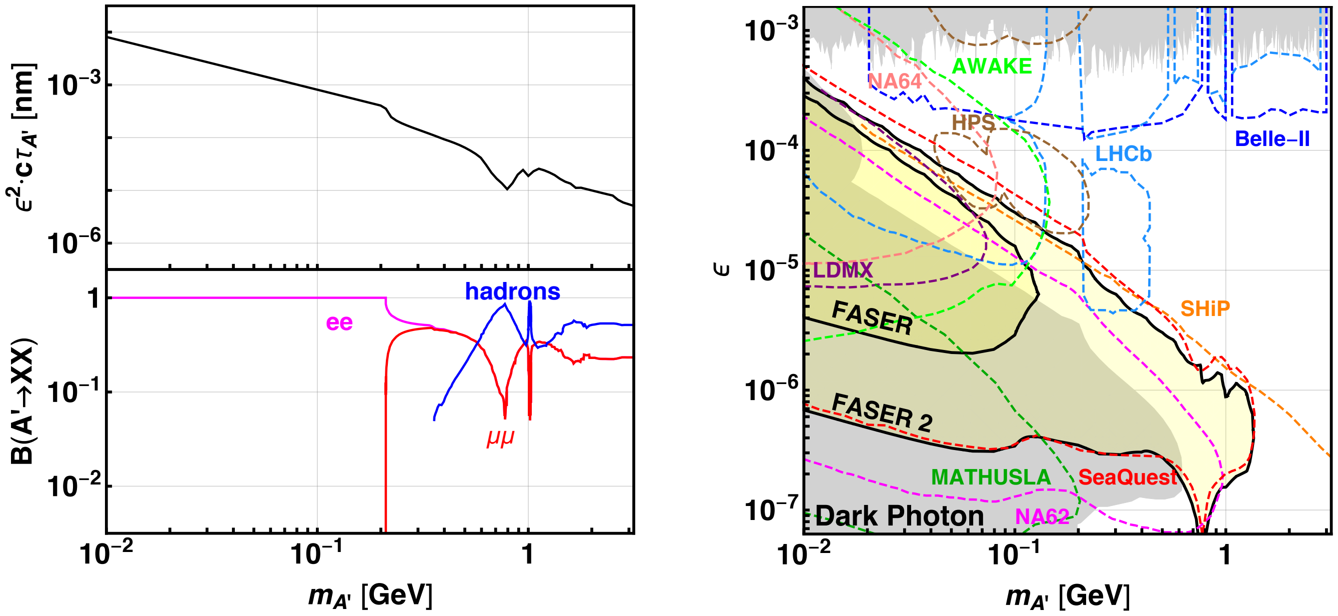
- New massive gauge boson in a dark sector with dark matter candidate X
- Spin 1, couples weakly to SM particles through mixing with the photon
- For $m_{A'}$=100 MeV, $\epsilon \sim 10^{-5}$ and E~TeV, can travel long distance before decay

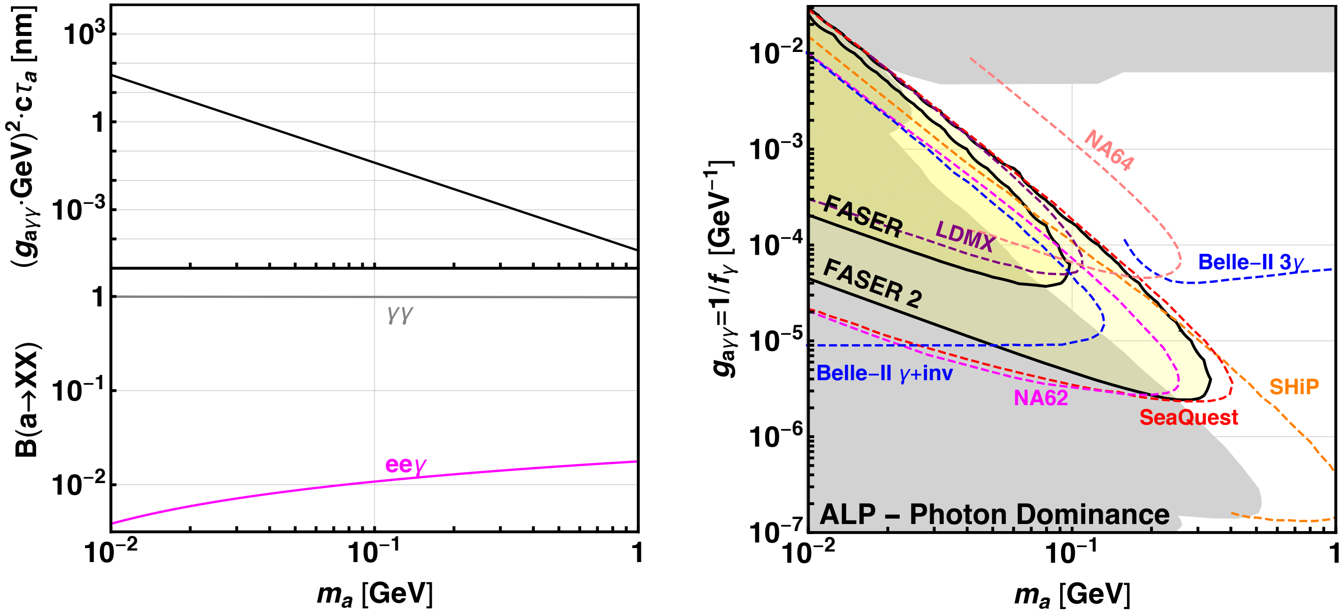


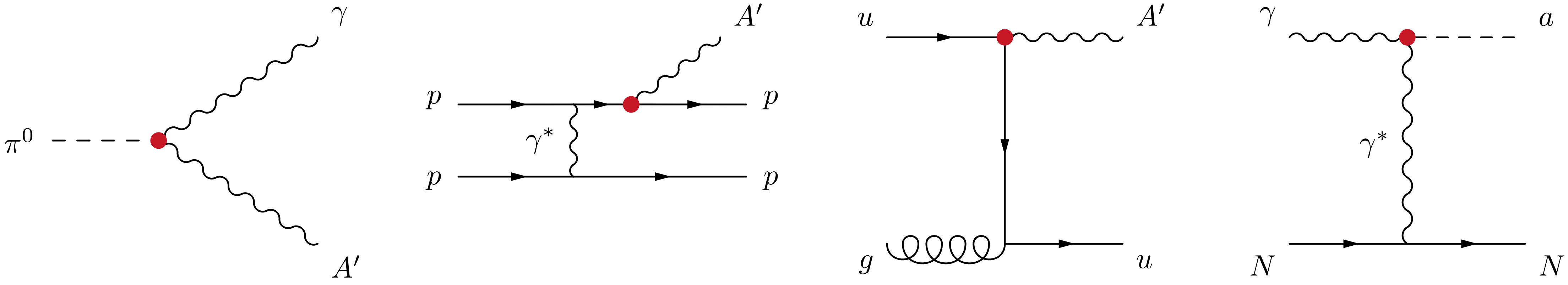
- Discovery contours assume at least 3 signal events, no background.



N.B.: FASER uses only lumi information from ATLAS!


$\epsilon^2 \cdot c\tau_{A'}$ [nm]
B(A'→XX)
ee
hadrons
$\mu\mu$
$m_{A'}$ [GeV]
ϵ
AWAKE
NA64
HPS
LHCb
Belle-II
LDMX
FASER
SHiP
FASER 2
MATHUSLA
SeaQuest
Dark Photon
NA62

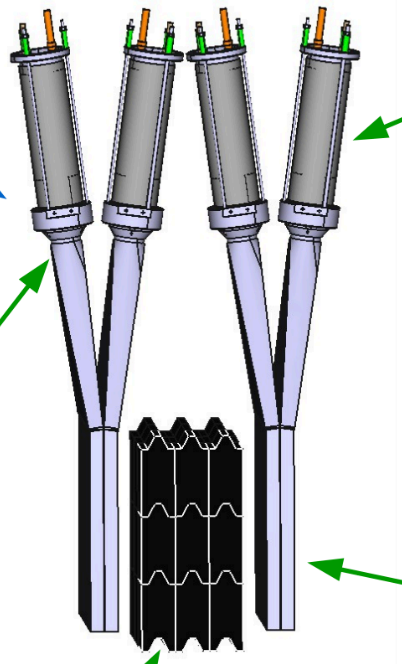

$(g_{a\gamma\gamma} \cdot \text{GeV})^2 \cdot c\tau_a$ [nm]
B(a→XX)
$\gamma\gamma$
$ee\gamma$
m_a [GeV]
$g_{a\gamma\gamma}=1/f_\gamma$ [GeV^{-1}]
NA64
FASER
LDMX
Belle-II 3γ
FASER 2
Belle-II γ+inv
NA62
SeaQuest
SHiP
ALP – Photon Dominance


γ
π^0
A'
A'
p
p
γ^*
p
p
u
A'
g
u
γ
a
γ^*
N
N

FASER Assumptions in sensitivity plots

Results: The projected dark photon sensitivity reaches for FASER at LHC Run 3 with 150 fb^{-1} and FASER 2 at HL-LHC with 3 ab^{-1} are shown in the right panel of Fig. 6. The gray-shaded regions are excluded by current bounds; see Refs. [30, 37] and references therein. For comparison we also show the projected sensitivities of other experiments: NA62 assumes 10^{18} protons on target (POT) while running in a beam dump mode that is being considered for LHC Run 3 [17]; SeaQuest assumes 1.44×10^{18} POT, which could be obtained in two years of parasitic data taking and requires additionally the installation of a calorimeter [19]; the proposed beam dump experiment SHiP assumes $\sim 2 \times 10^{20}$ POT collected in 5 years of operation [20]; the proposed electron fixed-target experiment LDMX during Phase II with a beam energy of 8 GeV and 10^{16} electrons on target (EOT) [25]; Belle-II and LHCb assume the full expected integrated luminosity of 50 ab^{-1} [14] and 15 fb^{-1} [15, 16], respectively; HPS assumes 4 weeks of data at JLab at each of several different beam energies [1, 55]; NA64 [56] corresponds to 5×10^{12} EOT with 100 GeV energy; and AWAKE [57] is assumed to be working as a fixed-target experiment with a 10-m-long decay volume and 10^{16} EOT accelerated in a $50 - 100$ m long plasma cell to the energy $\mathcal{O}(50\ \text{GeV})$.

Scintillators – Veto stations



Final design could be more vertical PMT position

Will have port for LED signal

Light-guides, PMT-holders and assembly to be done at CERN

Interlocking lead bricks

- ~150x300x300mm^3
- exact bricks TBD
- shower/stops photons from upstream muons

Hamamatsu H6410 PMTs

- large diameter (46mm)
- large gain 10^6-10^8

Two independent scintillator layers per station

- 20x300x300mm^3
- EJ-200 from Eljen Tech.

PROPERTIES	EJ-200
Light Output (% Anthracene)	64
Scintillation Efficiency (photons/1 MeV e^-)	10,000
Wavelength of Maximum Emission (nm)	425
Light Attenuation Length (cm)	380
Rise Time (ns)	0.9
Decay Time (ns)	2.1
Pulse Width, FWHM (ns)	2.5

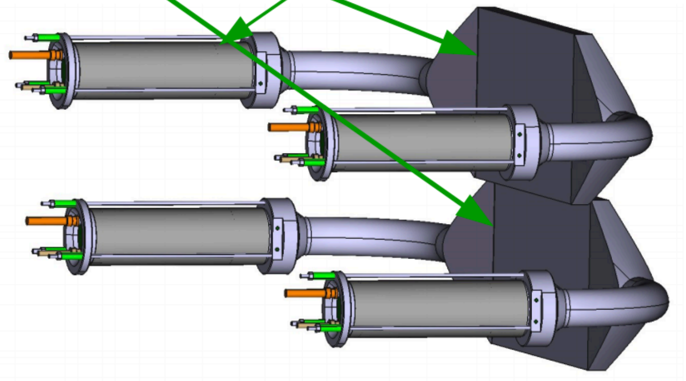
- expect ~200 photo-electrons per MIP

Scintillators – Trigger / Timing

Scintillator layer split in two

- $10X200x400mm^3$
- split reduces vertical time-walk and eases construction
- will have small offset and overlap to avoid gap
- again EJ-200 scintillator
- double sided readout:
  1. allows correction for horizontal time-walk
  2. can reduce noise triggers by requiring coincidence
- expect ~80 photo-electrons per MIP
- timing resolution still to be determined (~ns)

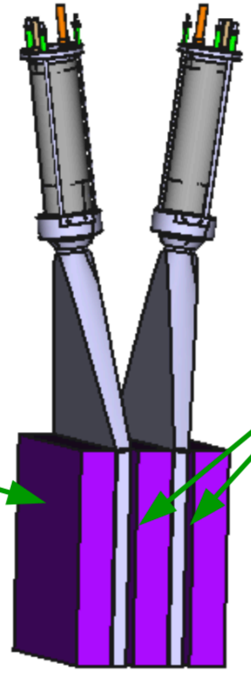
Same H6410 PMTs



Large area to catch muons coming at angle generating showers only seen in last layer/calorimeter, a dominant(?) background for photons-only signal

FASER Scintillators – Trigger / Preshower

Trigger/Preshower station has same scintillator design as veto stations



Carbon fiber (low-Z) blocks between tracker and calorimeter to reduce backsplash from calorimeter

- exact thickness will depend available space after support is designed should be three ~5cm thick blocks

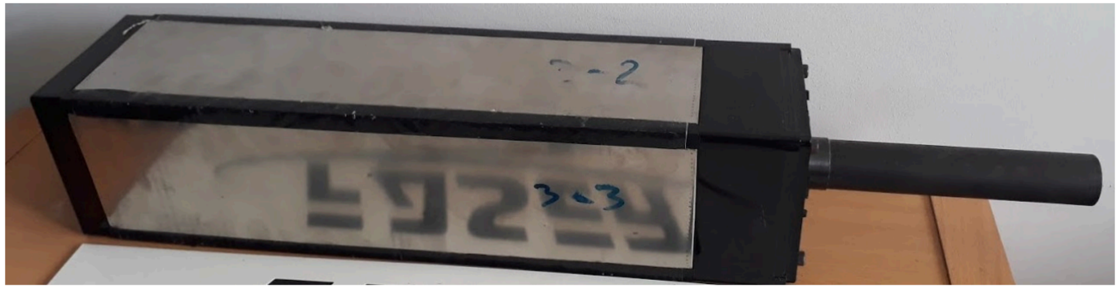
Embed/glue in two 1 radiation length (~5mm) lead plates in front of scintillator layers to start EM shower

- allows to discriminate between incoming di-photon signal and neutrino interactions in calorimeter

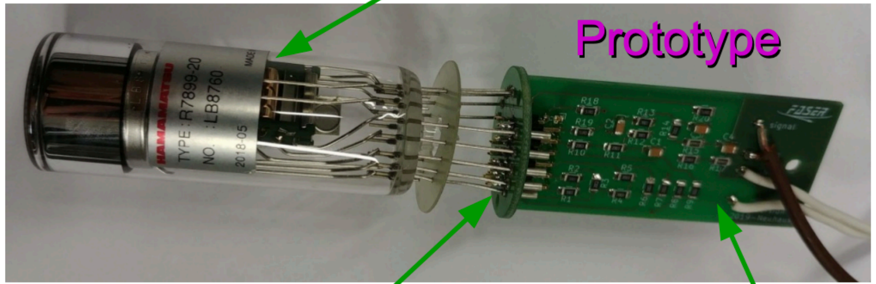
FASER Calorimeter

Using 4 LHCb spare outer ECAL modules for calorimeter (have 8)

Theoretical energy resolution ~1%, but we will be limited by how well we can calibrate and by punch-through



7 R7899-20 Hamamatsu PMT provided by LHCb
- tubes are almost new (from 2018)



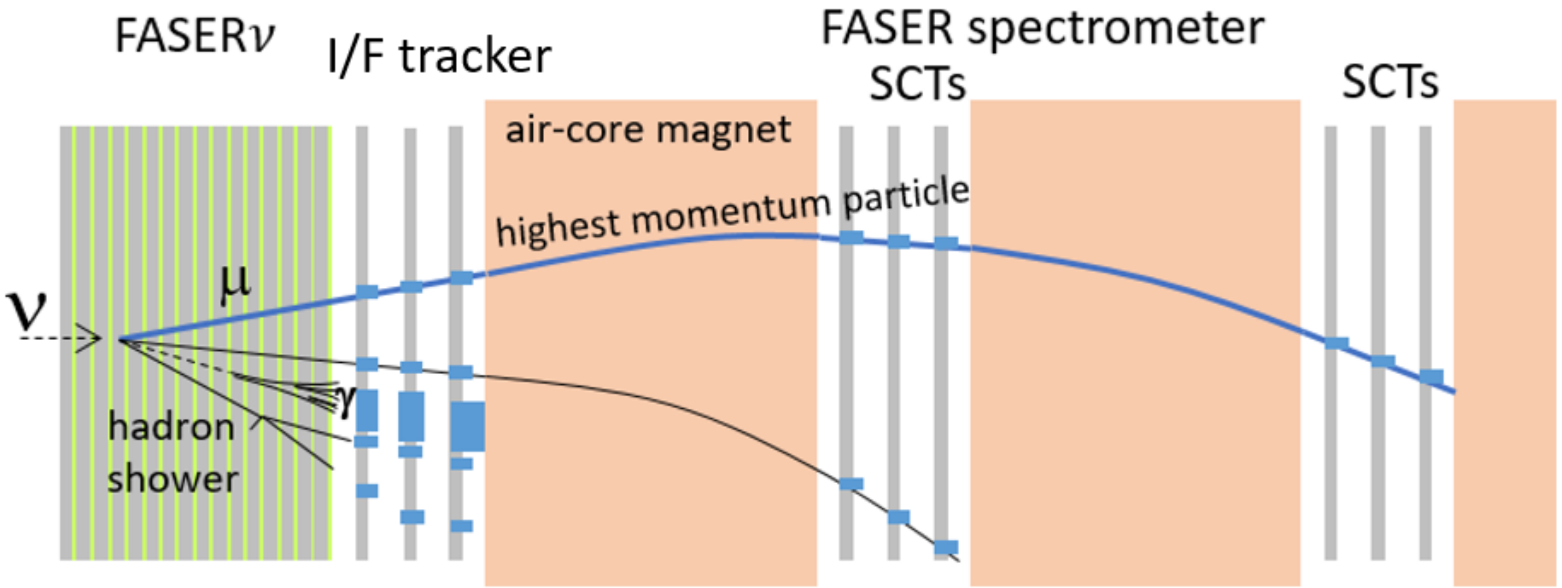
Had to make our own HV base
- done by Friedemann

Have new base with non-solder connection

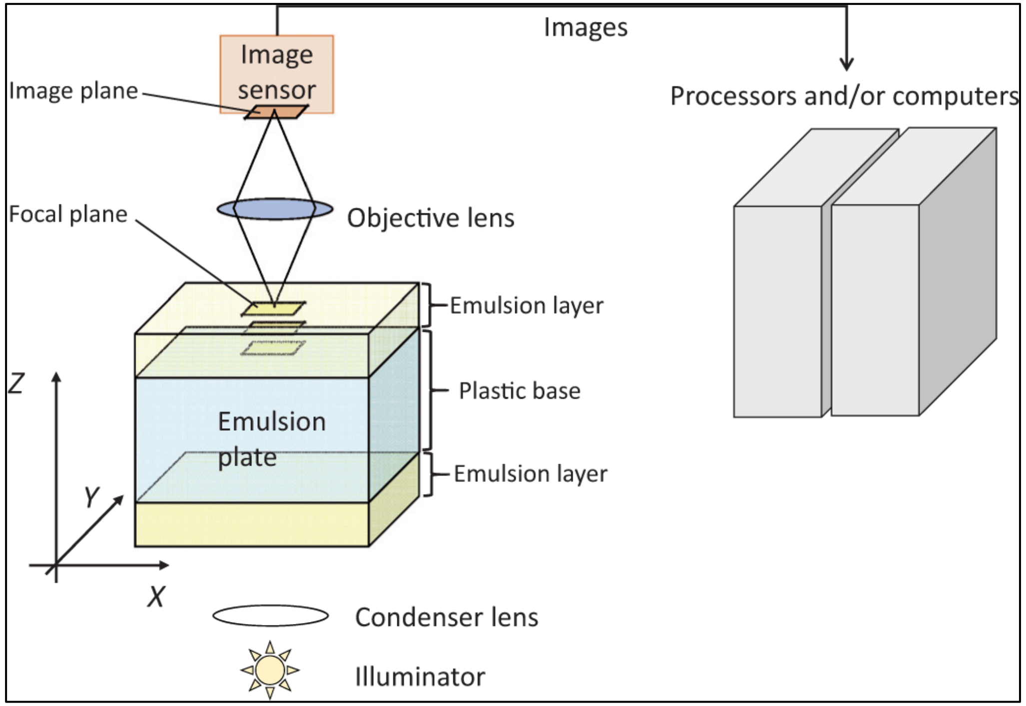
Divider to be shortened to fit in calorimeter tube – waiting for final tests of proto-type

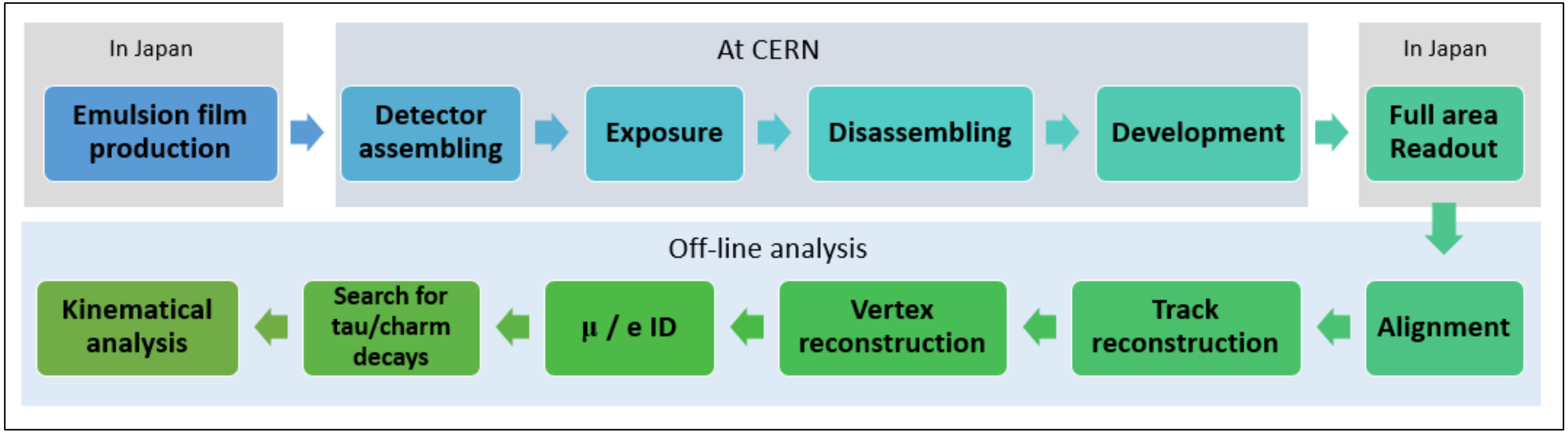
Interface detector

- Possibility to connect FASERν with rest of FASER for:
  - Charge identification, Improved energy resolution, Better background rejection
- Would require interface detector in front of FASER
  - Precision tracker to link FASERν and FASER tracks
  - Most likely a fourth station of spare ATLAS SCT modules
- To not jeopardize FASER schedule, this would be installed in 2021/22 YETS
  - Most data anyway expected after that

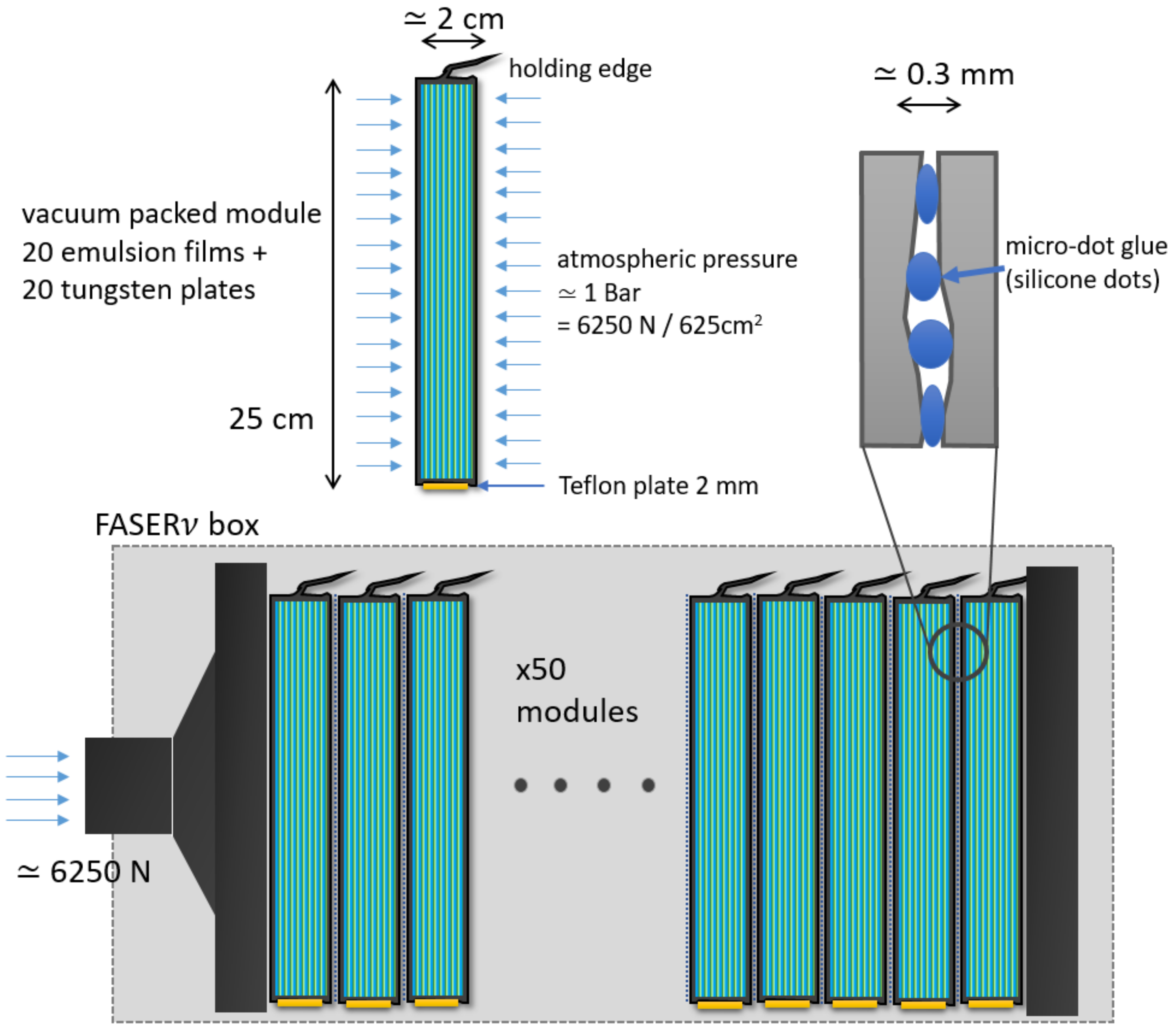


Read-out & Analysis





Module structure



Emulsion

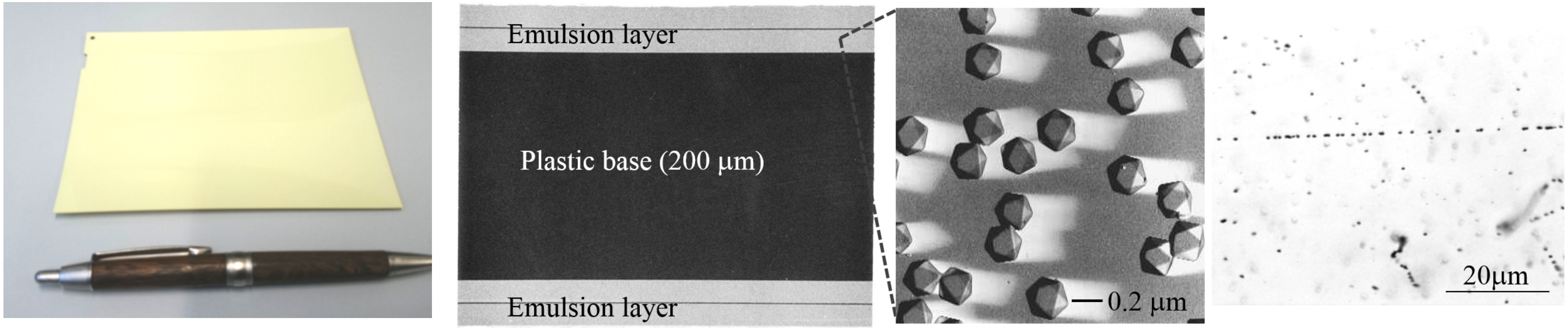


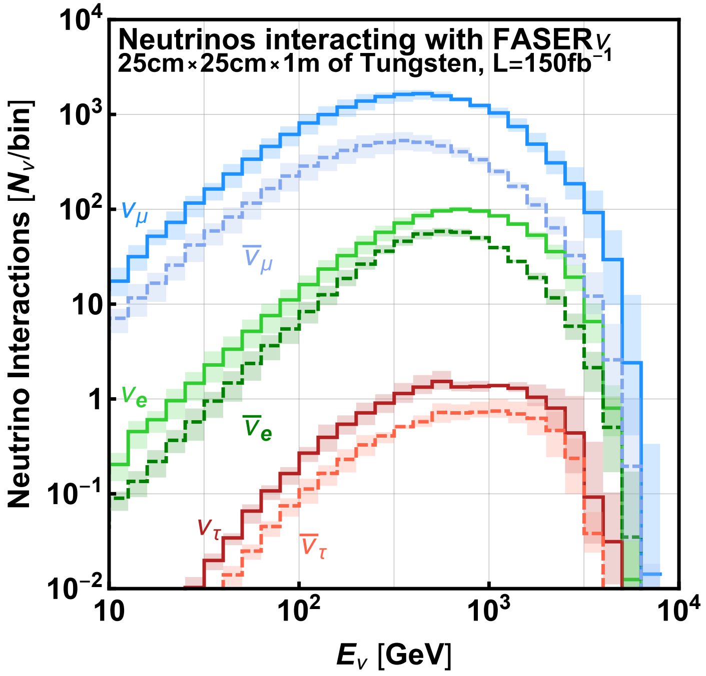
Photo of an emulsion film (left), its cross-sectional view (left center), electron microscope image of the silver halide crystals (right center), and a minimum ionising particle track from a 10 GeV/c π beam (right).

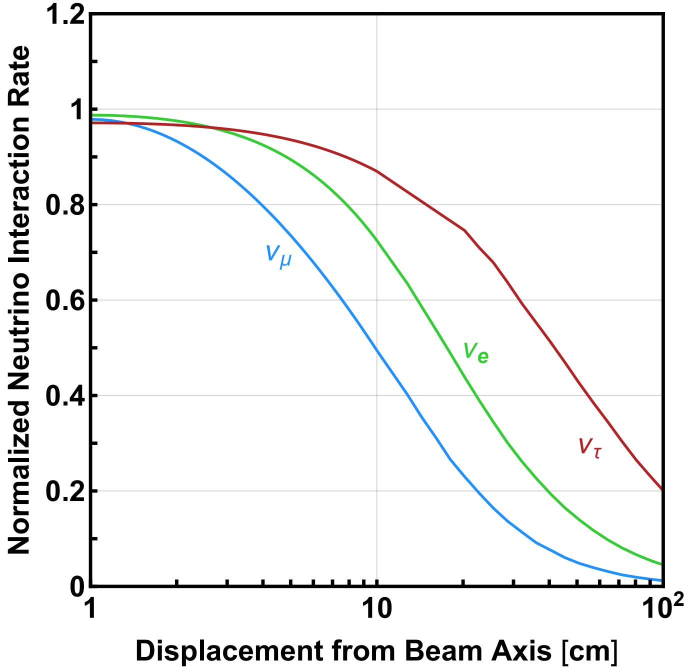
Neutrino production

Type	Particles	Main Decays	E	Q	S	P
Pions	π^+	$\pi^+ \to \mu\nu$	√	√	√	—
Kaons	K^+, K_S, K_L	$K^+ \to \mu\nu$, $K \to \pi\ell\nu$	√	√	√	—
Hyperons	Λ, Σ^+, Σ^-, Ξ^0, Ξ^-, Ω^-	$\Lambda \to p\ell\nu$	√	√	√	—
Charm	D^+, D^0, D_s, Λ_c, Ξ_c^0, Ξ_c^+	$D \to K\ell\nu$, $D_s \to \tau\nu$, $\Lambda_c \to \Lambda\ell\nu$	—	—	√	√
Bottom	B^+, B^0, B_s, Λ_b, ...	$B \to D\ell\nu$, $\Lambda_b \to \Lambda_c\ell\nu$	—	—	—	√

TABLE I. Decays considered for the estimate of forward neutrino production. For each type in the first column, we list the considered particles in the second column and the main decay modes contributing to neutrino production in the third column. In the last four columns we show which generators were used to obtain the meson spectra: EPOS-LHC (E) [59], QGSJET-II-04 (Q) [60], SIBYLL 2.3C (S) [61–64], and PYTHIA 8 (P) [66, 67], using both the MONASH-tune [68] and the minimum bias A2-tune [69].

Neutrino fluxes





The energy spectrum of neutrinos with CC interactions in a 1-ton tungsten detector with dimensions 25 cm × 25 cm × 1 m centered on the beam collision axis at the FASER location at the 14 TeV LHC with 150 fb−1

The neutrino interaction rate per unit area normalized to the prediction at the beam collision axis for a detector with large radius.

Possibility of probing tau neutrino production from the decay of light gauge bosons

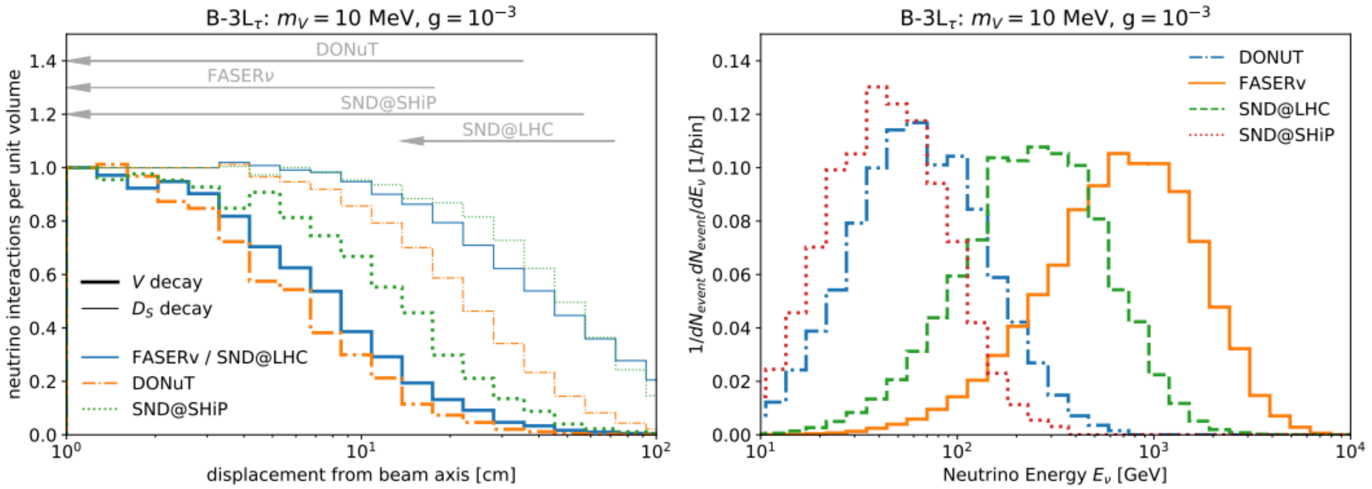
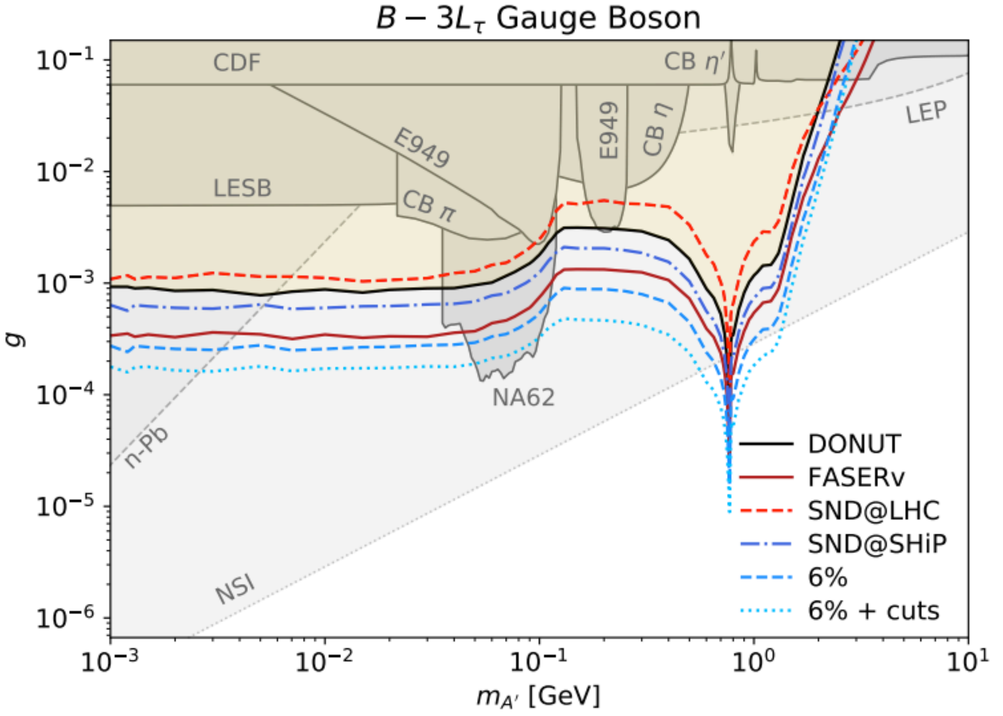


FIG. 1. Kinematic distributions of tau neutrinos produced in the decay of a $U(1)_{B-3L_\tau}$ vector boson with mass $m_V = 10$ MeV and coupling $g = 10^{-3}$ at the considered experiments. The left panel shows the possible rate of neutrino interactions per unit volume, normalized to its value at the beam axis, as a function of the displacement from the beam axis. For comparison, we also show the radial distribution for tau neutrinos from D_s decay. The gray arrows indicate the radial coverage of the considered experiments. The right panel shows the normalized energy distribution for ν_τ's from V decay interacting in the detector.



arXiv:2005.03594

TABLE I. Types of anomaly free gauge groups and corresponding fermion charges q_f.

Gauge Group	q_q	q_e	q_μ	q_τ
$x_e L_e + x_\mu L_\mu - (x_e + x_\mu) L_\tau$	0	x_e	x_μ	$-x_e - x_\mu$
$B + x_e L_e + x_\mu L_\mu - (3 + x_e + x_\mu) L_\tau$	1/3	x_e	x_μ	$-3 - x_e - x_\mu$
$B - L$	1/3	−1	−1	−1
$B - L_\mu - 2L_\tau$	1/3	0	−1	−2
$B - L_e - 2L_\tau$	1/3	−1	0	−2
$B - 3L_\tau$	1/3	0	0	−3

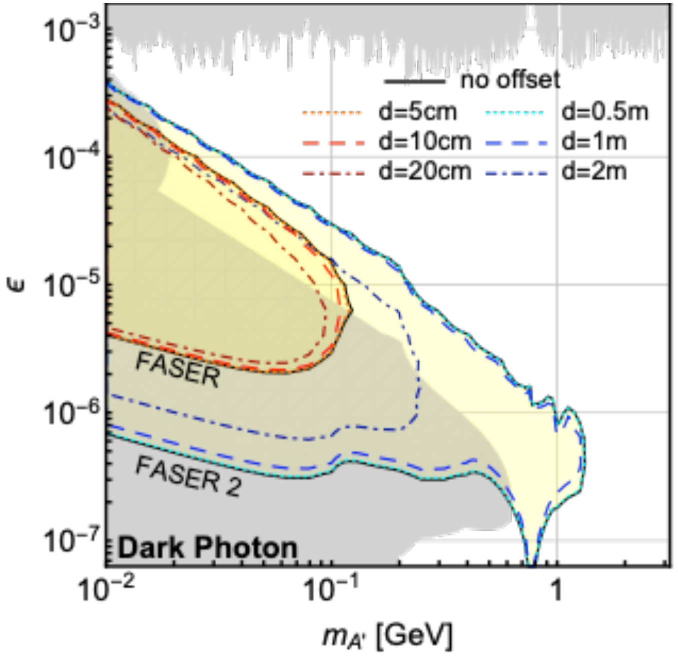
Experimental Setup							SM		$B-3L_\tau$		
Experiment	Status	$\mathcal{L}/N_{POT}$	m_{det}	A_{det}	ϵ_{det}	Ref.	N_{event}	$\langle E_\nu \rangle$	N_{event}	$\langle E_\nu \rangle$	$N_{2\sigma}$
DONuT	completed	$3 \cdot 10^{17}$	0.26 t	50×50 cm^2	0.2	[3]	10 ± 4.6	112 GeV	12	84 GeV	9.1
FASERν	approved	150 fb^{-1}	1.2 t	25×25 cm^2	0.52	[7]	11.6 ± 5.1	965 GeV	96	928 GeV	10
SND@LHC	proposed	150 fb^{-1}	0.85 t	40×40 cm^2	0.5	[9]	4.3 ± 2.5	720 GeV	3.5	382 GeV	5
SND@SHiP	proposed	$2 \cdot 10^{20}$	8 t	80×80 cm^2	0.22	[5]	$(10.9 \pm 3.6) \cdot 10^3$	52 GeV	$2 \cdot 10^4$	54 GeV	7200

Extending the trench for FASERν

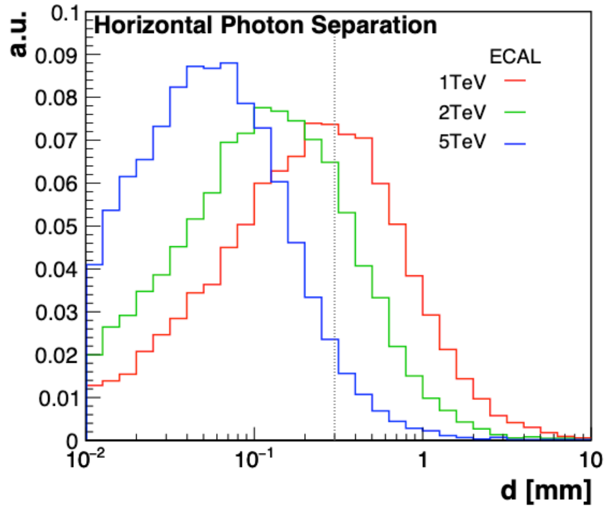
FASER Effect of LHC crossing angle

To avoid parasitic collisions and beam-beam effects in the common beampipe close to the IP, the LHC runs with a crossing-angle

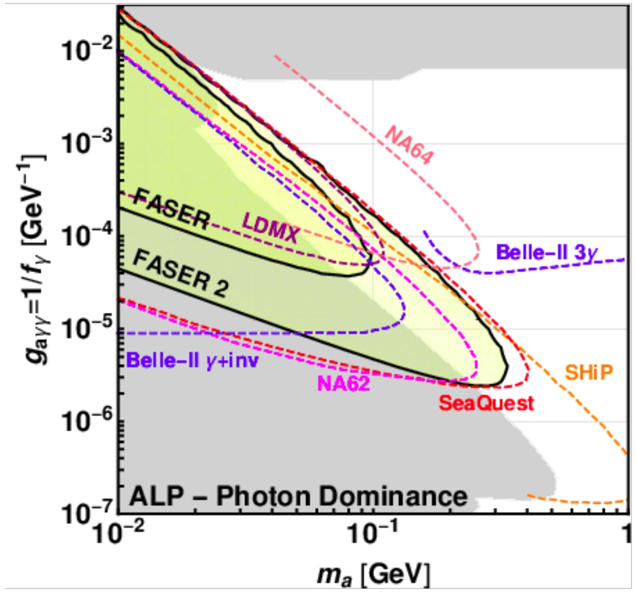
- The half crossing angle is ~150μrad, which moves the collision axis by ~7.5cm at the FASER location
- Such a change reduces the signal acceptance in FASER by ~25%
- Leads to very small changes in physics sensitivity



FASER ALP->γγ performance



- For ALP->γγ decay, magnetic field does not help separate closely spaced decay products
- We investigated calorimeter / pre-shower to allow to be able to resolve closely spaced (~1mm) high energy photons (>500 GeV) - seems very challenging
- Preliminary studies suggest that events with no tracks and a large amount of EM energy in the calorimeter would be ~background free => an ALP signal would be detectable without the need to resolve the 2 photons.
- Further studies show an interesting background would be high energy neutrino's interacting in the calorimeter to give large EM showers
- In longer term investigating installing a fine granularity silicon pre-shower to be able to separate close-by photons.



FASER Cost (estimates from TP)

FASER

Detector component	Cost [kCHF]	Detailed Table
Magnet	420	Table V
Tracker Mechanics	66	Table VI
Tracker Services	105	Table VII
Scintillator Trigger & Veto	52	Table VIII
Calorimeter	13	Table IX
Support structure	60	Table X
Trigger & Data Acquisition	52	Table XIV
Total	**768**	-
Spares	56	-

Biggest single costs:
Magnet
Power Supplies (~100kCHF)

FASERν

Item	Cost [kCHF]
Emulsion gel for 440 m^2	315
Emulsion film production cost for 440 m^2	32
Tungsten plates, 1200 kg (first set)	173
Tungsten plates, 1200 kg (second set)	173
Packing materials	5
Support structure	12
Chemicals for emulsion development	20
Tools for emulsion development	5
Racks for emulsion film storage	5
Computing server	10
Total	**750**
[Emulsion gel for 2024 running]	[135]
[Additional consumables for 2024 running]	[23]
[Total including 2024 running]	**[908]**

Biggest single costs:
Tungsten plates (~350kCHF)
Emulsion Gel (~300kCHF)

Infrastructure

Work	Cost [kCHF]
Civil Engineering	160**
Transport	95**
Optical Fiber & Network Connection	10*
Power Connection	10
Compressed Air Connection	6
Preparation of TI12	10*
Total	291