News from the EXPERIMENT

- Motivation, detector and physics reach
- Operations and initial performance
- Plans beyond 2022

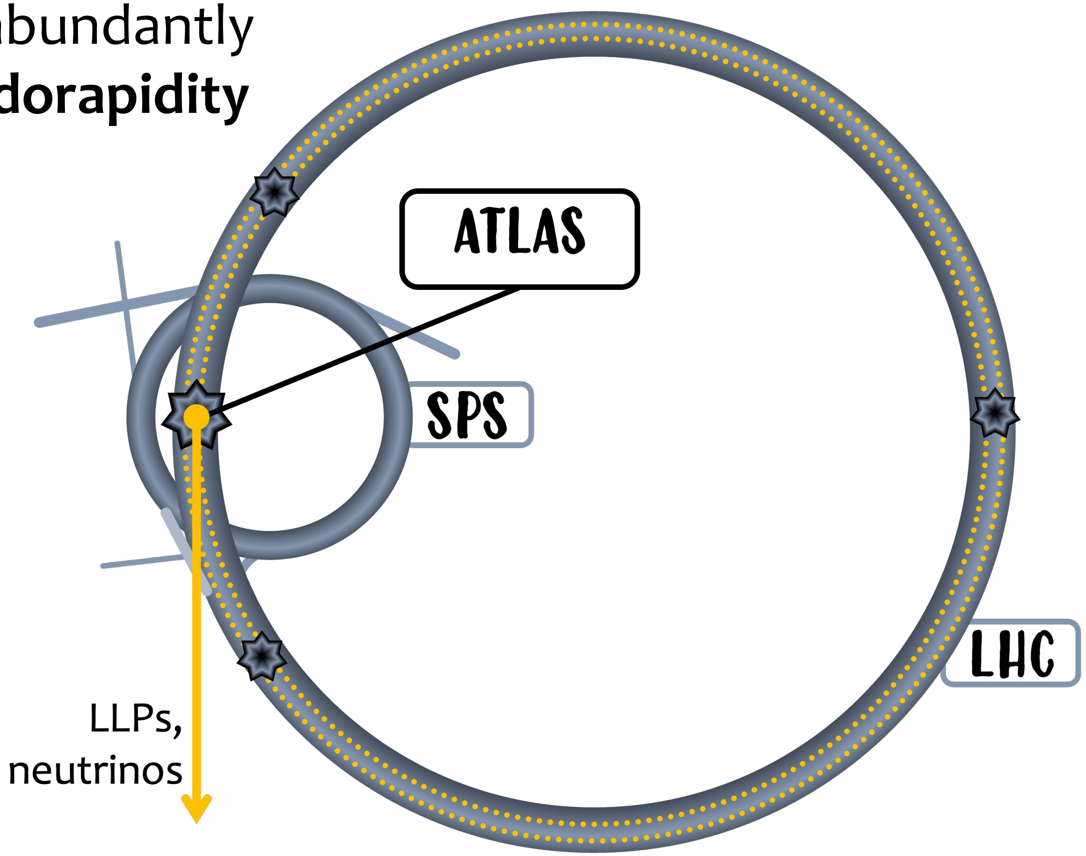
LHCC open session
30 November 2022

Anna Sfyrla
on behalf of the FASER collaboration
UNIVERSITÉ DE GENÈVE
FACULTY OF SCIENCE

Forward Search Experiment at the LHC

Searches for new weakly interacting light particles, coupling to SM via mixing with SM "portal" operator

- Produced in decays of light mesons (e.g. π, K), abundantly present in p-p collisions, **primarily in large pseudorapidity**



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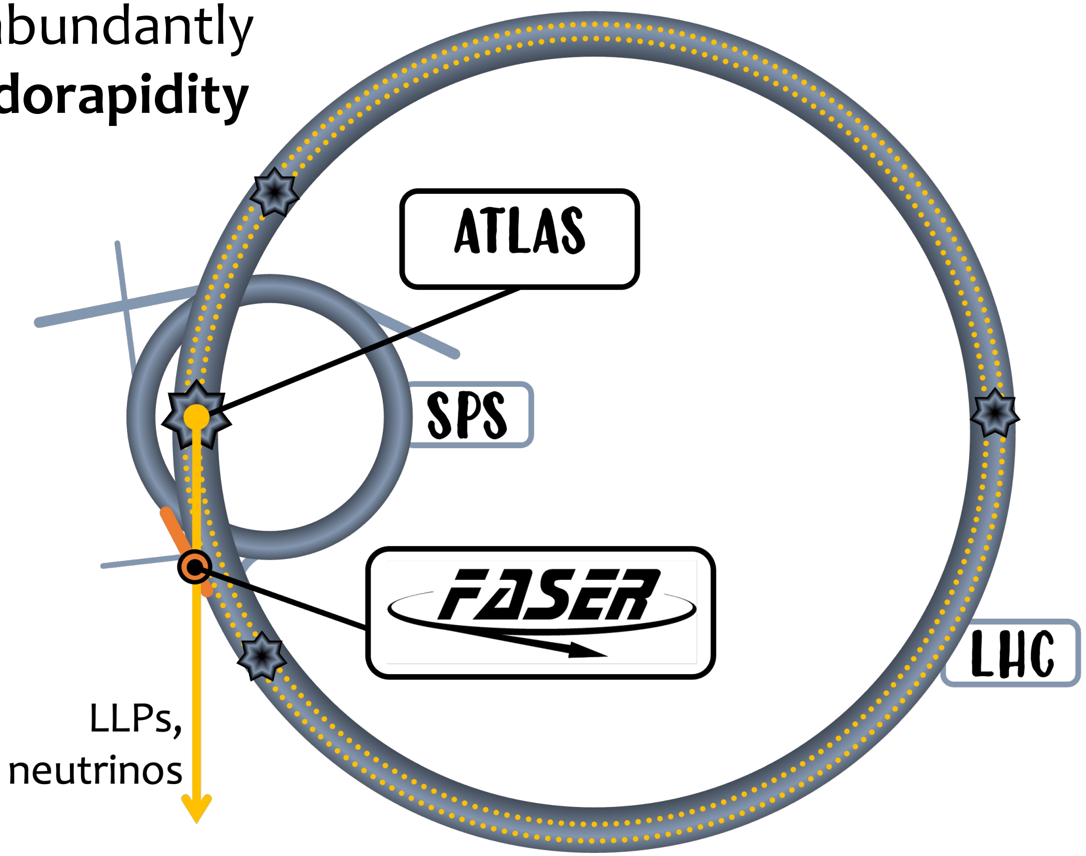

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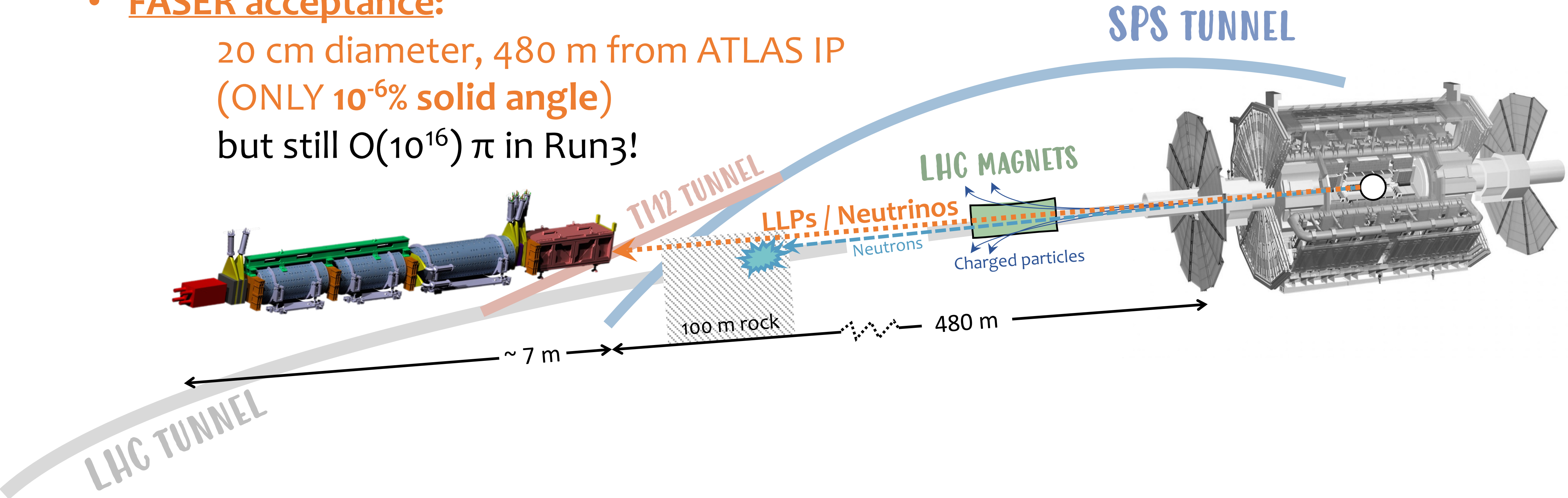
  20 cm diameter, 480 m from ATLAS IP

  (ONLY **10^{-6}% solid angle**)

  but still O(10^{16}) π in Run3!



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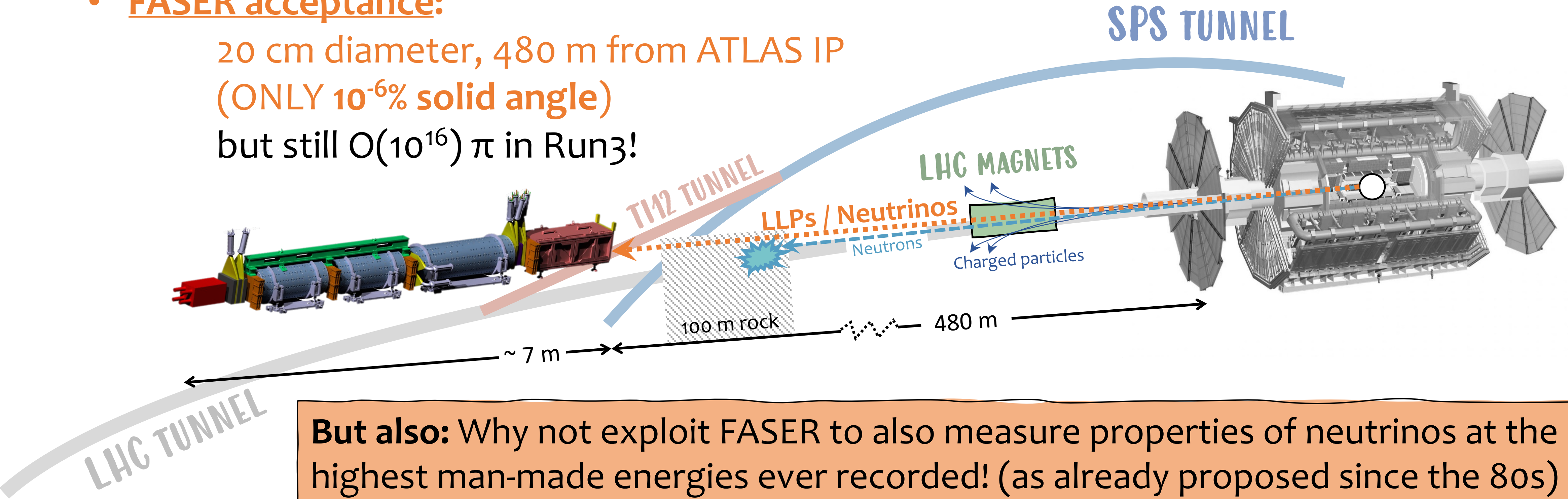
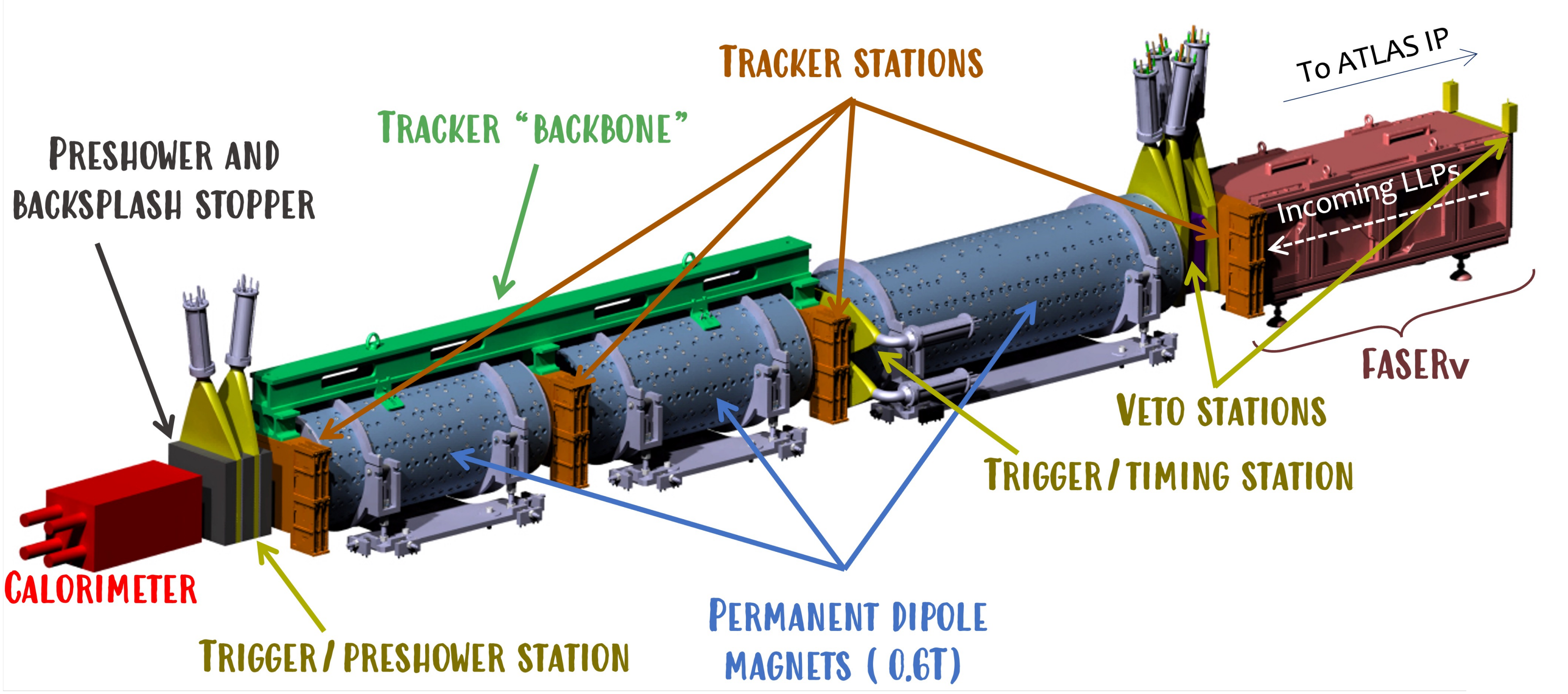


But also: Why not exploit FASER to also measure properties of neutrinos at the highest man-made energies ever recorded! (as already proposed since the 80s)

FASER Detector



Length: 7 m
Aperture: 20 cm
Length of decay volume: 1.5 m

arXiv:2207.11427

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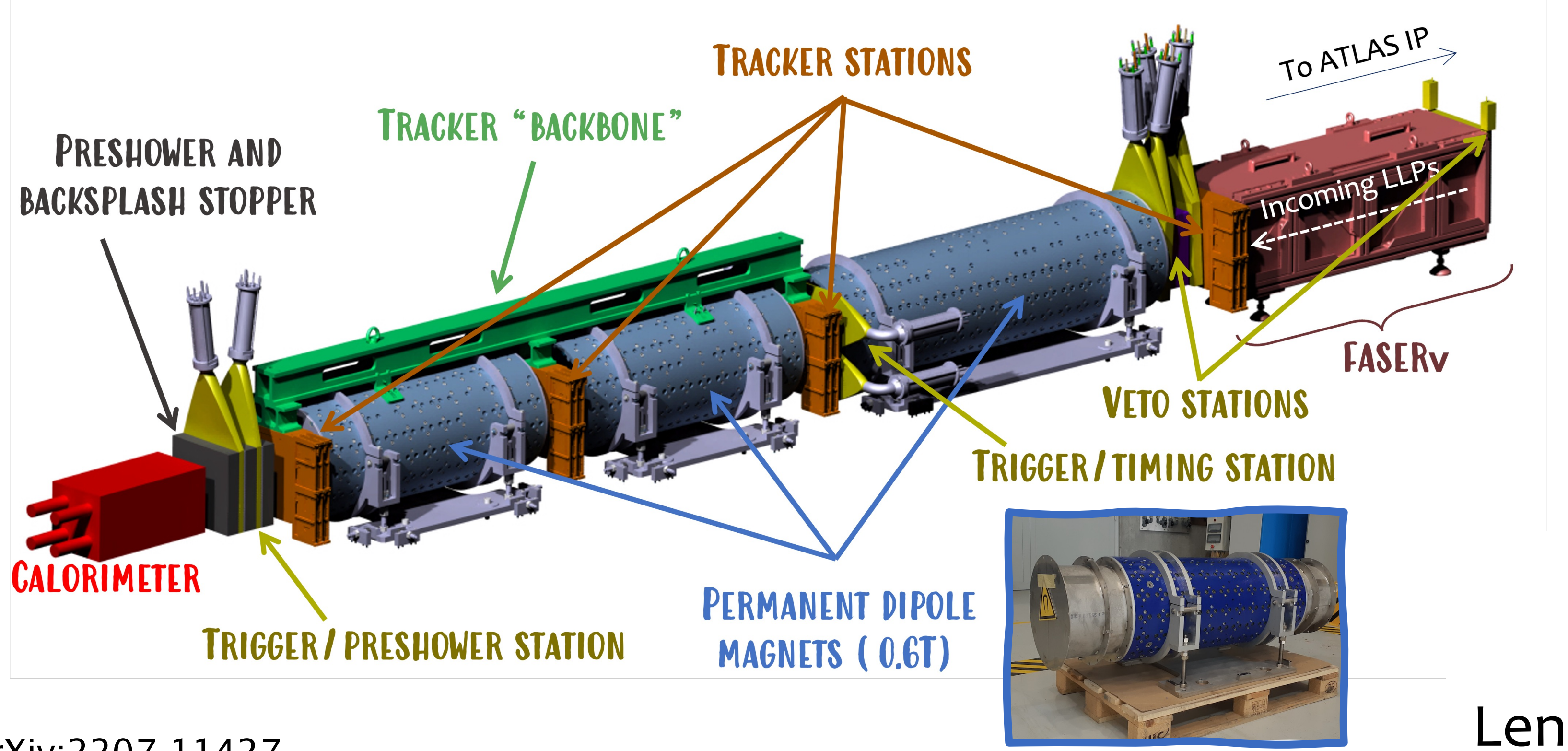

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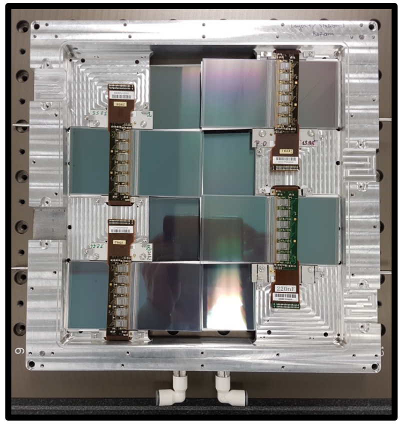
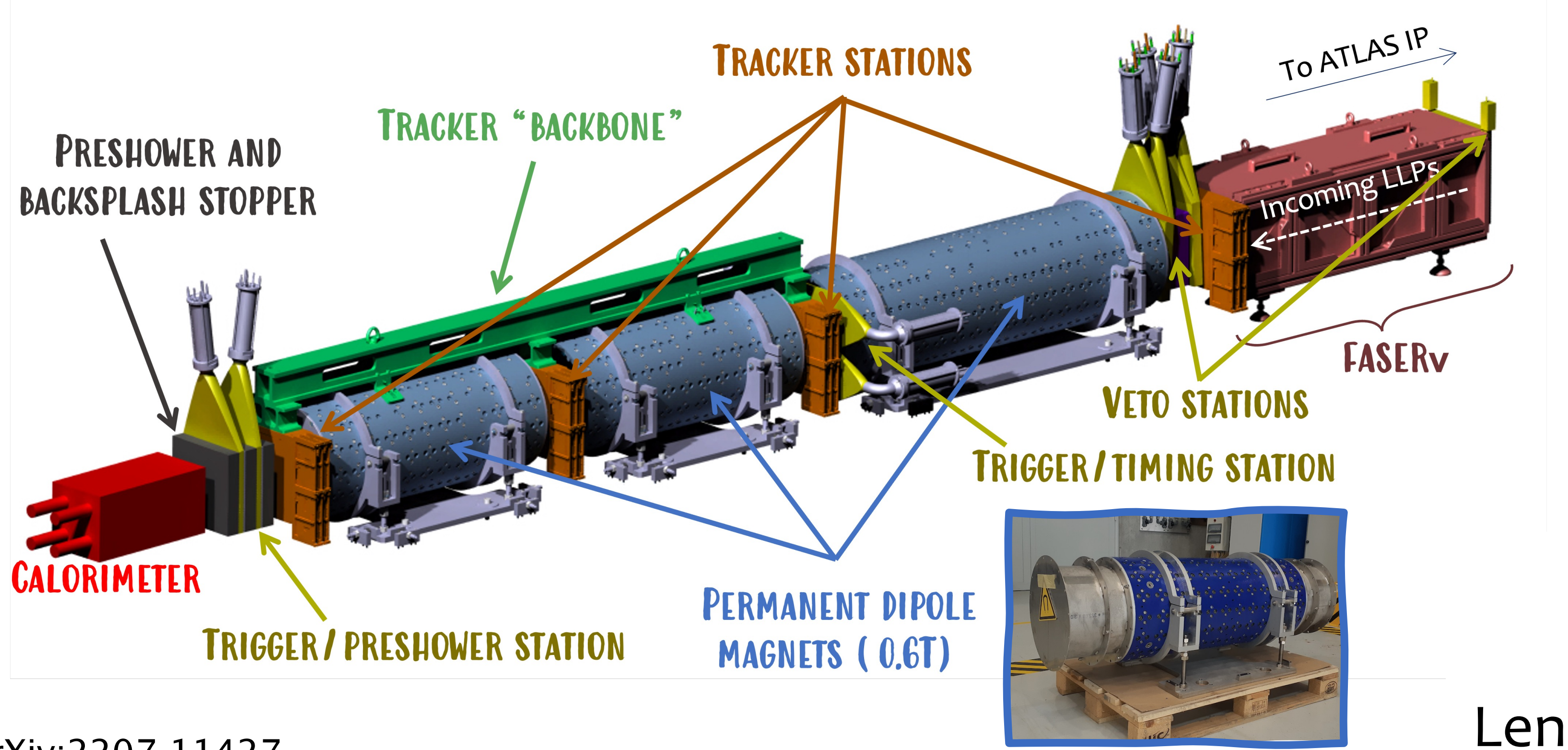


A tracker layer made of ATLAS SCT modules



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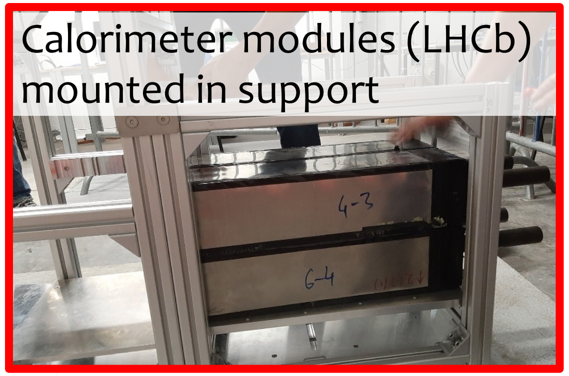
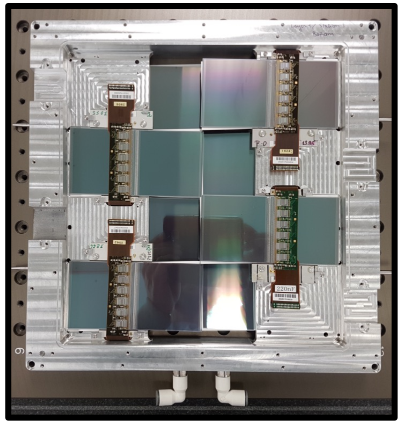


Calorimeter modules (LHCb) mounted in support



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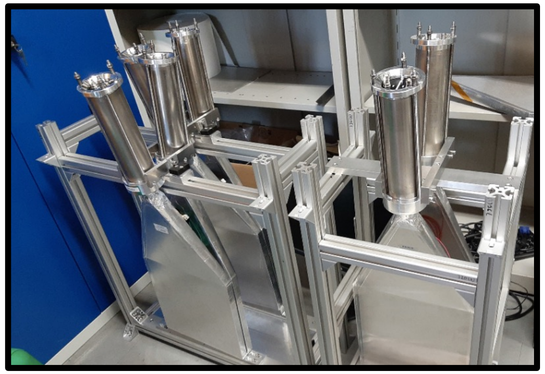
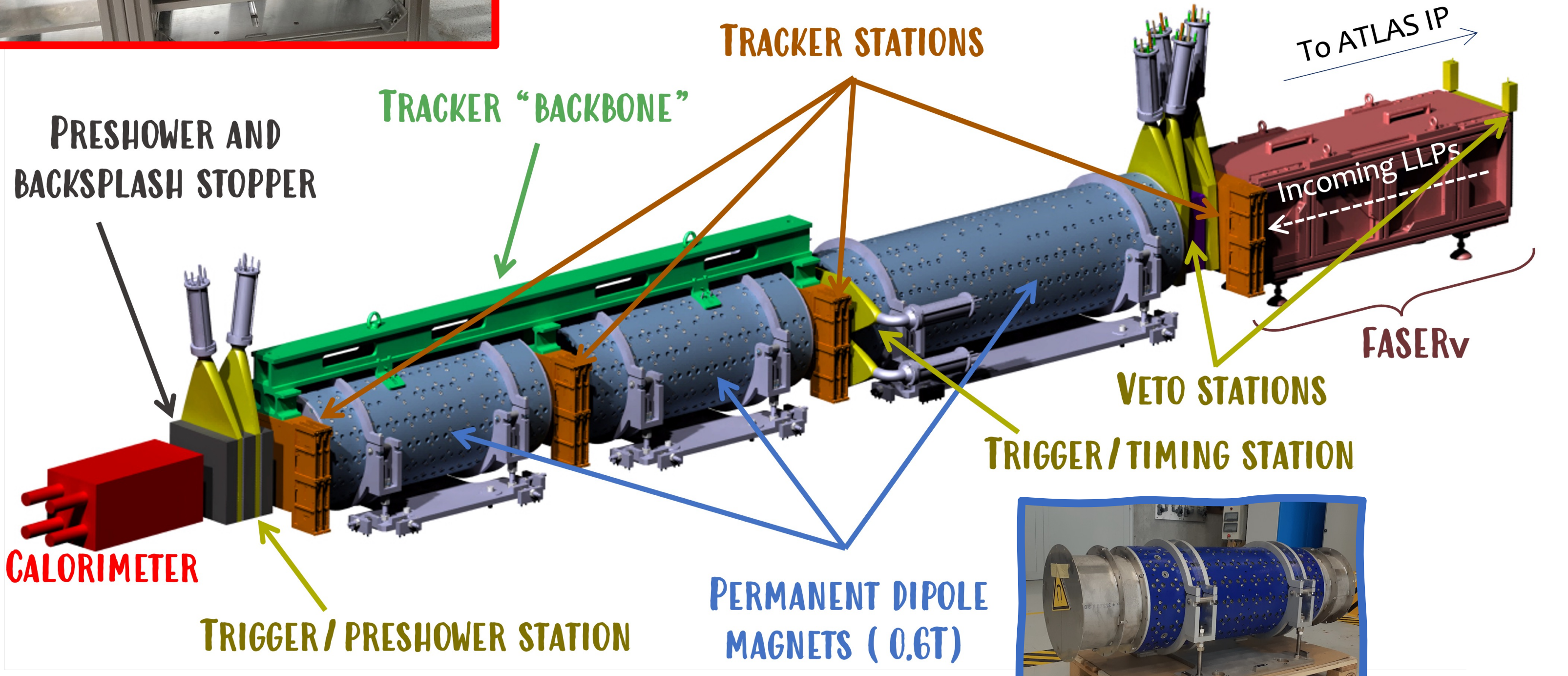


Two stations to veto O(10^9) muons
A timing station, resolution < 1 ns
A preshower station



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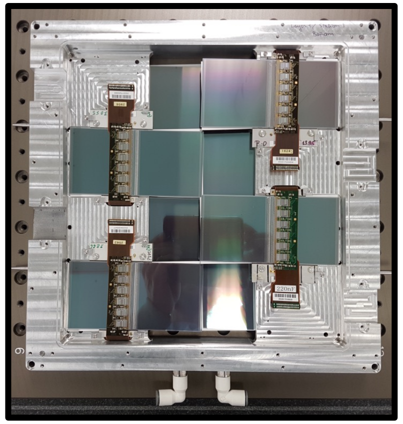
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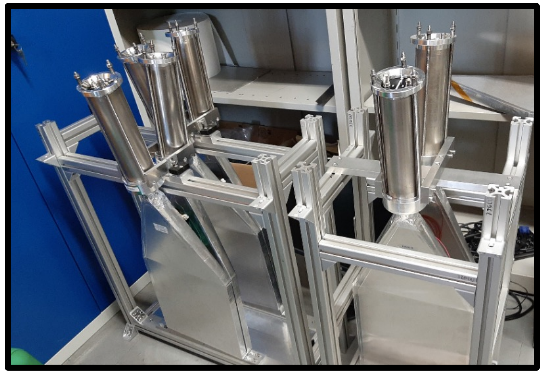
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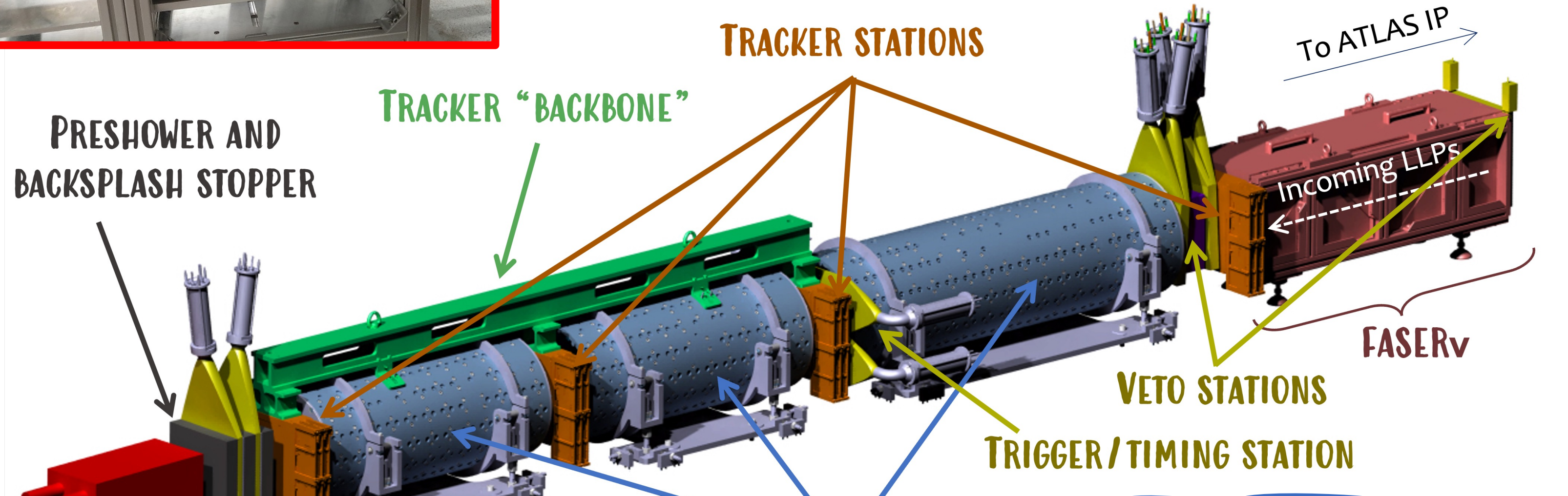

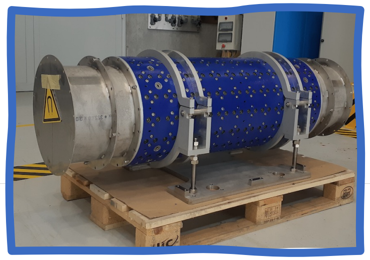


Triggers from scintillators and calorimeter
Expected trigger rate < 1 kHz, dominated by muons from the IP

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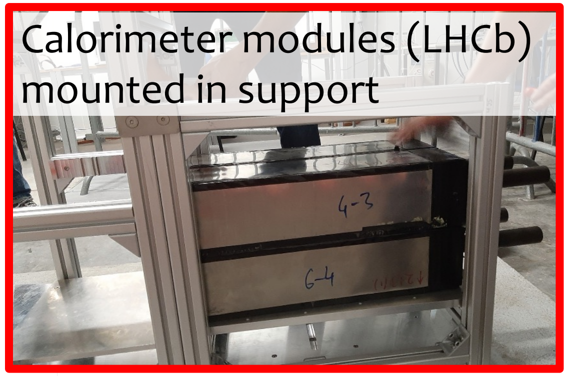
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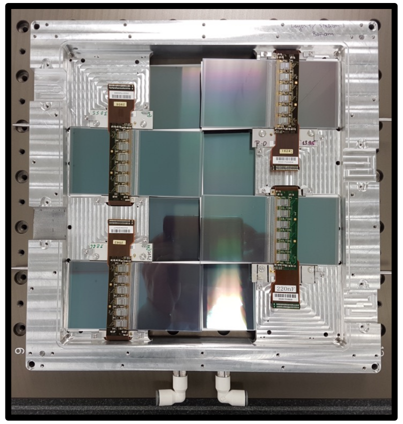
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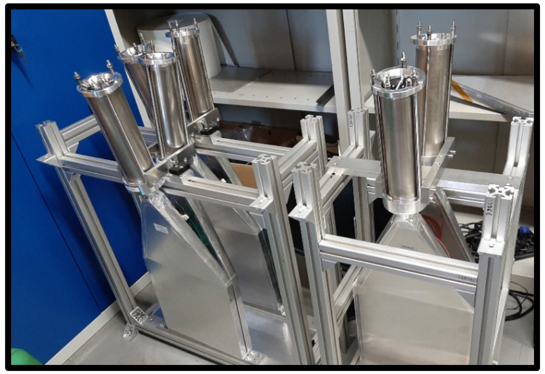
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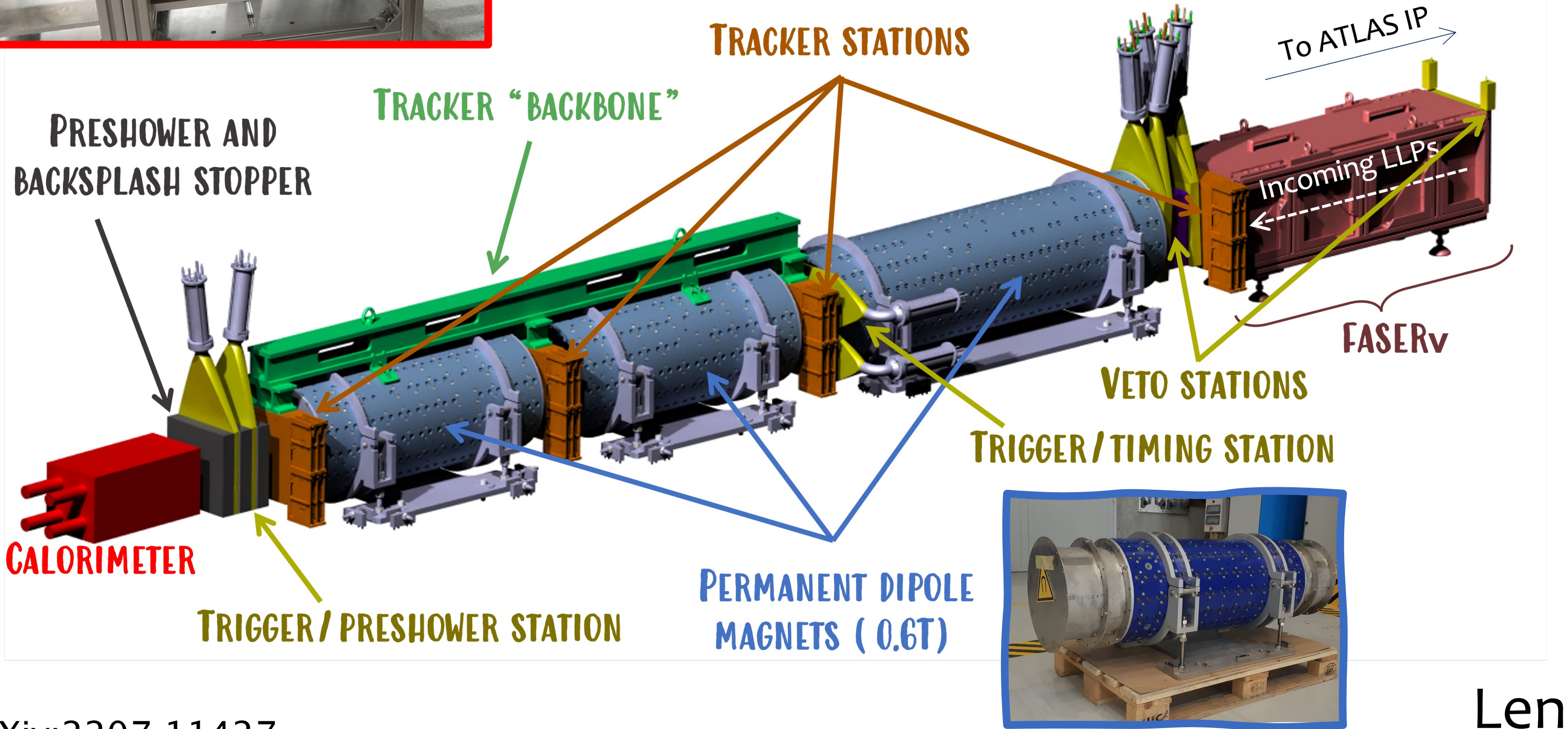


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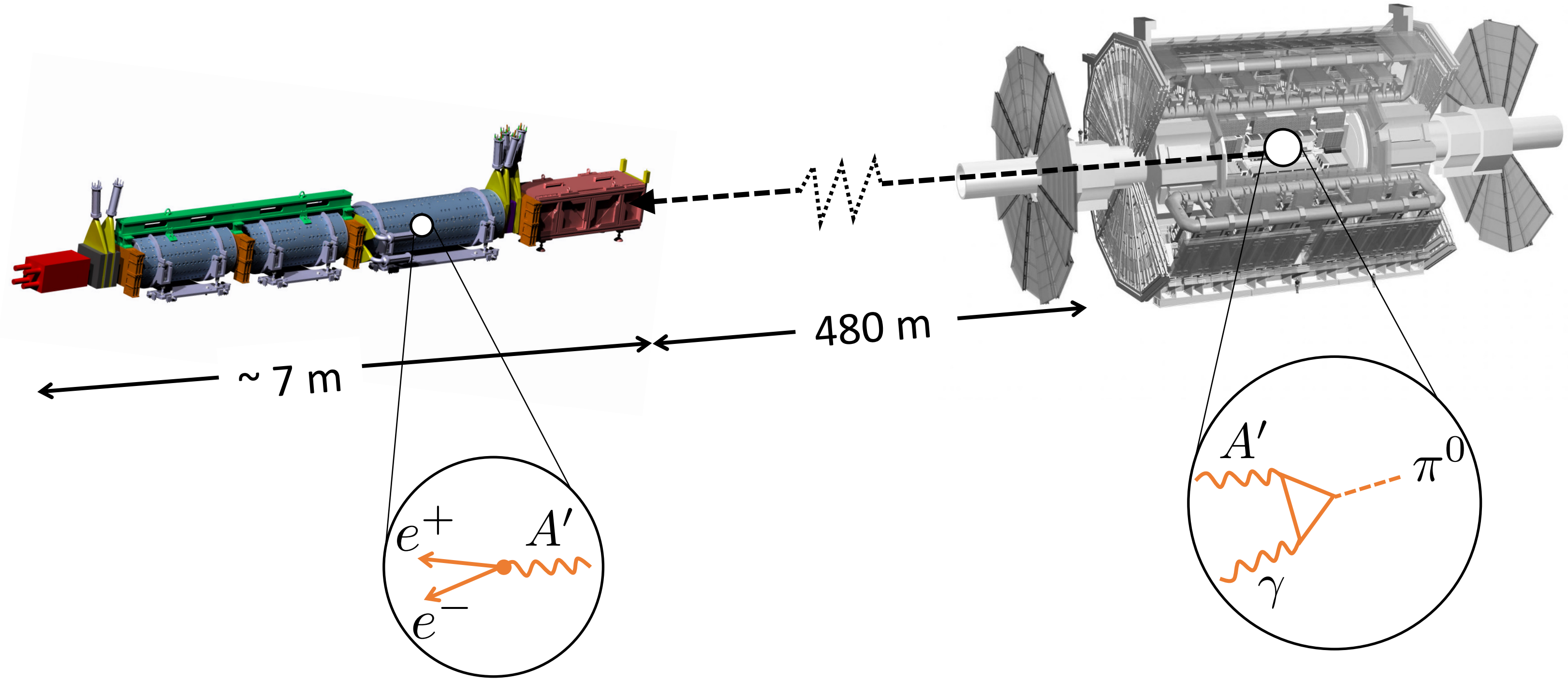
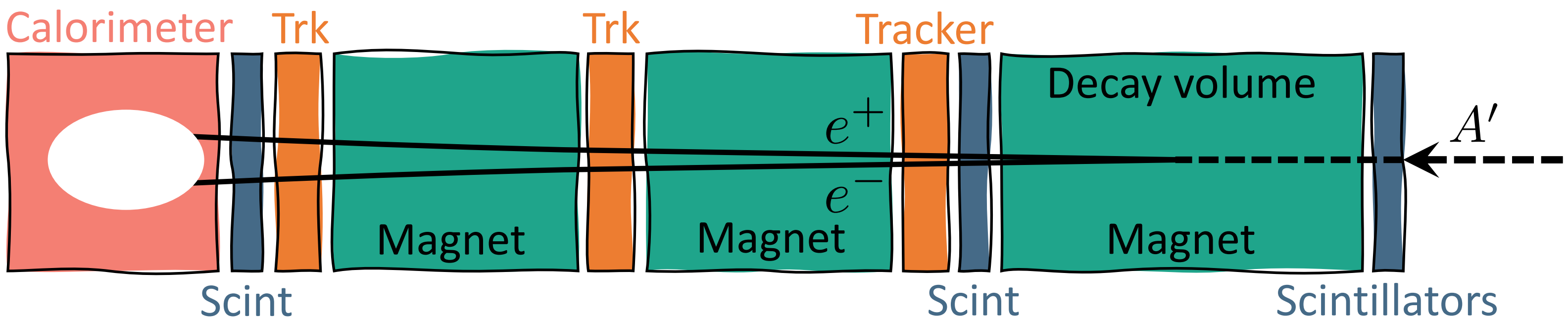
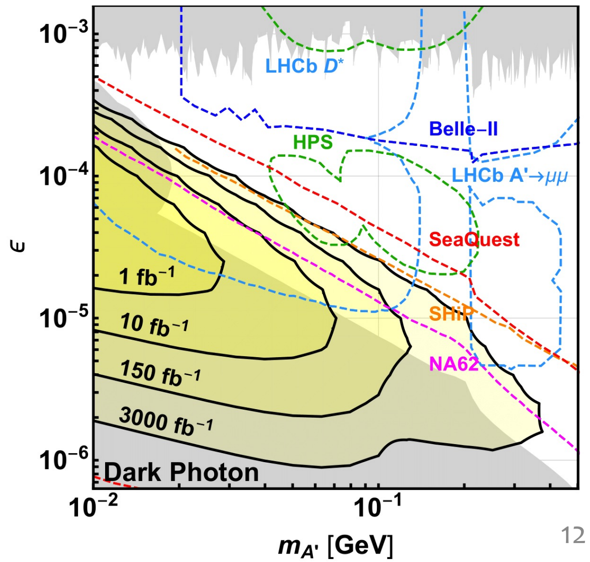
Example Physics signature

Dark photon (A')



Decay products collimated requirements for magnetic field & high-resolution tracker



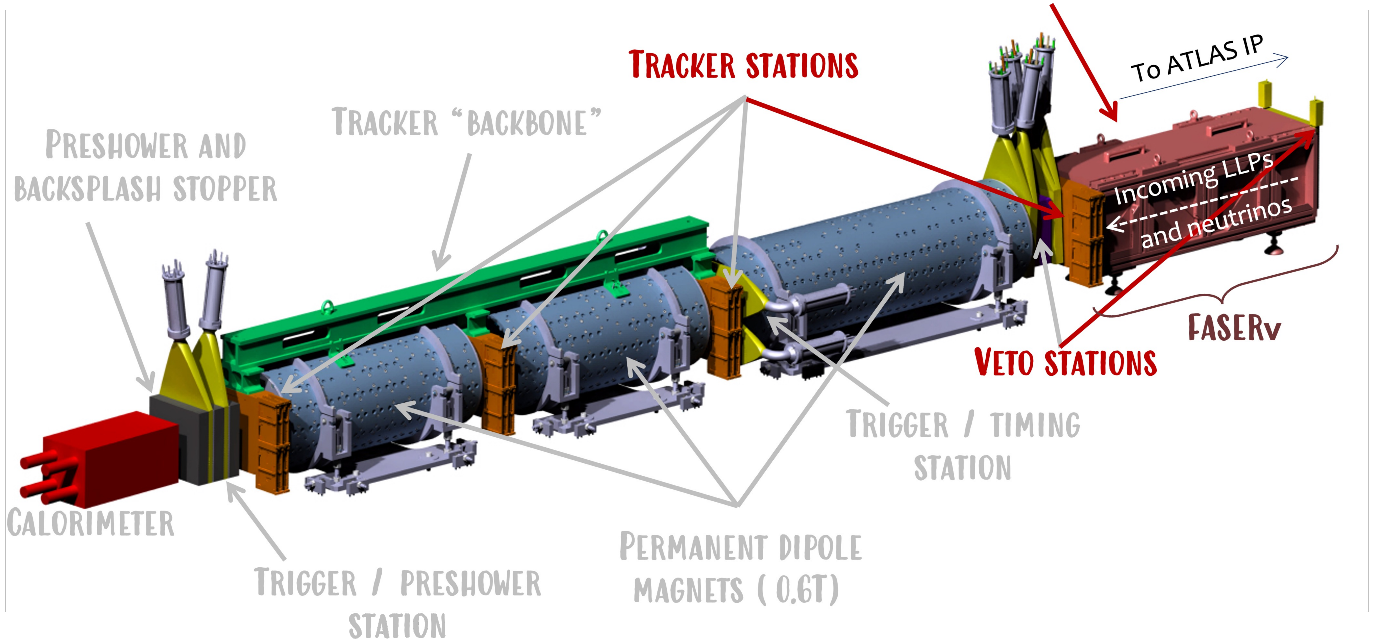


Assuming 3 signal events and no backgrounds

3

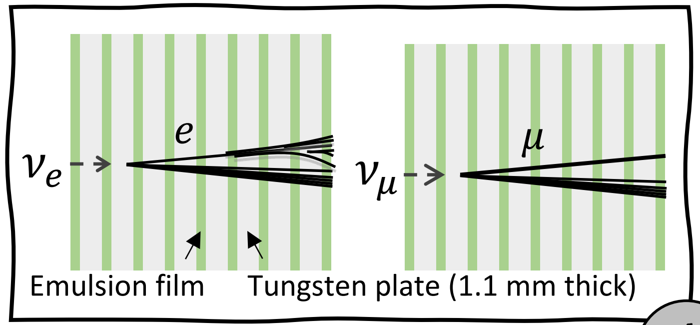
FASER Detector

Total 730 emulsion films interleaved with 1.1-mm-thick tungsten plates



Emulsion detector:

- Excellent track resolution
- No timing resolution
- Replace 3 times/year



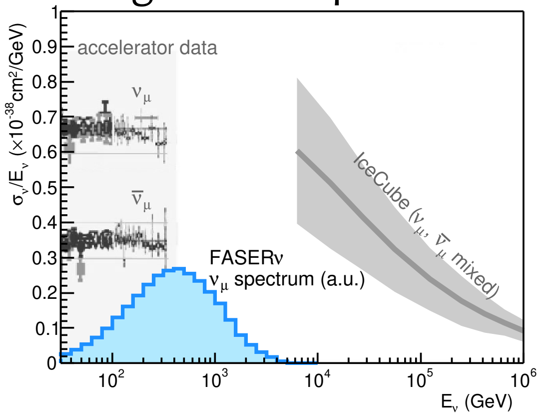
FASER Detector and physics

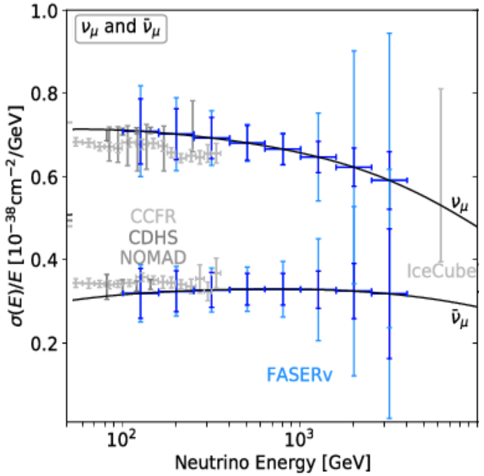
Expected spectra:
- Complementary to existing experiments

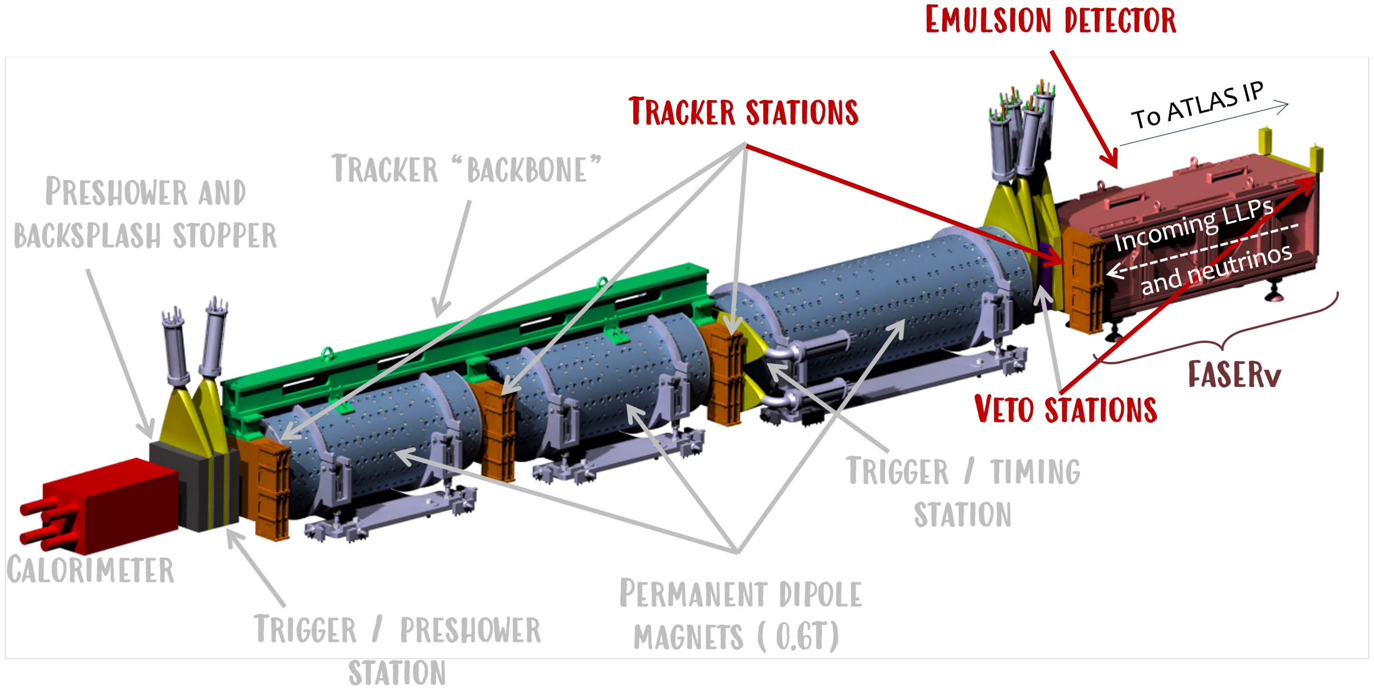
~1'300 ν_e
~20'000 ν_μ
~20 ν_τ
interacting in FASER

Expected cross section reach:
- In unconstrained energy regime with 150/fb

E.g. muon expectations







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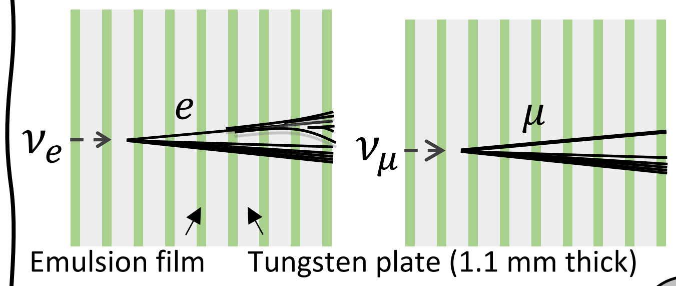

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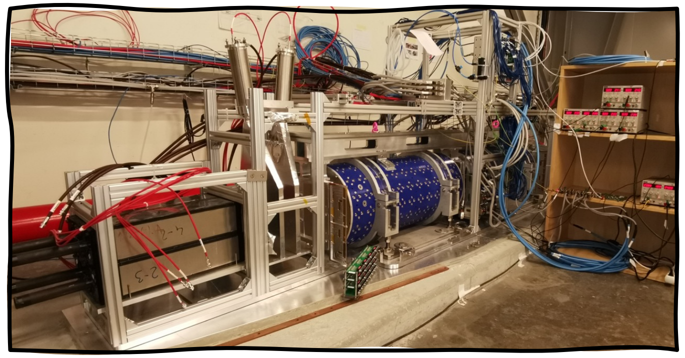
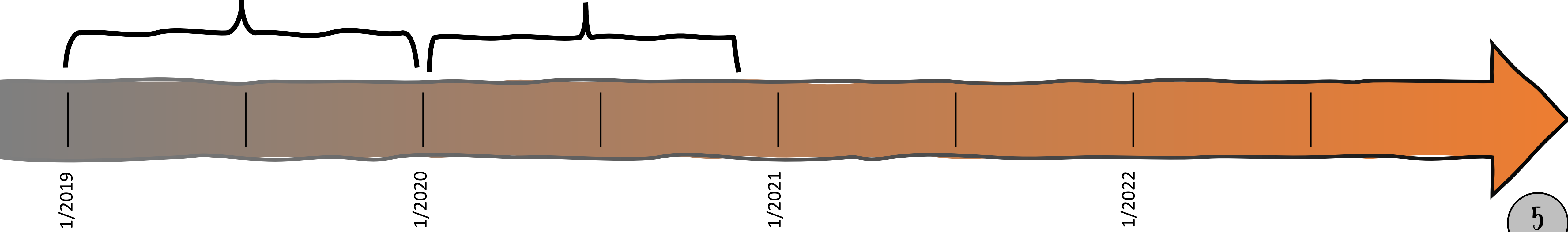
Commissioning

Timeline

Dedicated labs at CERN and UniGe for individual component testing



Dedicated area at CERN's Prevessin site ("EHN1") for full-detector commissioning



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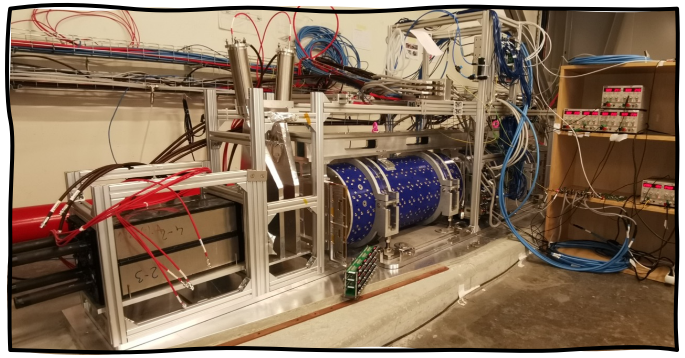

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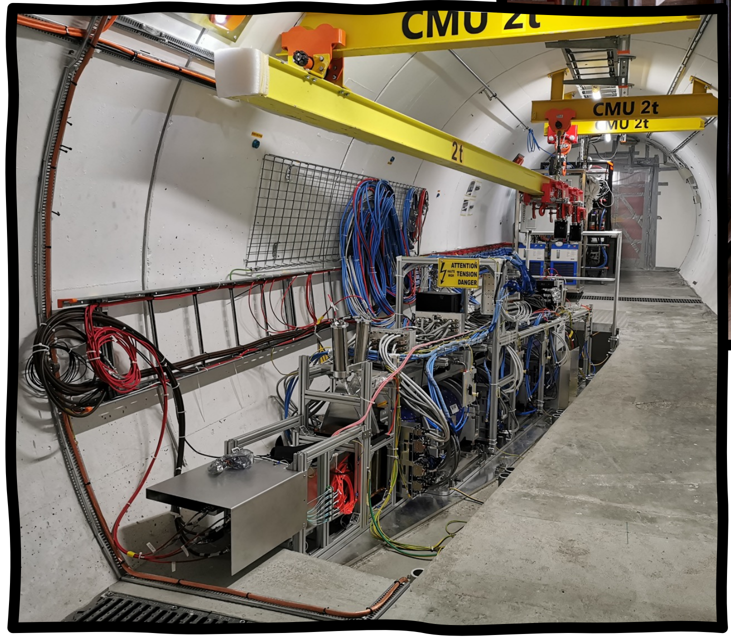

1/2019

1/2020

1/2021

FASER Installation

FASERν Installation

1/2022

Commissioning

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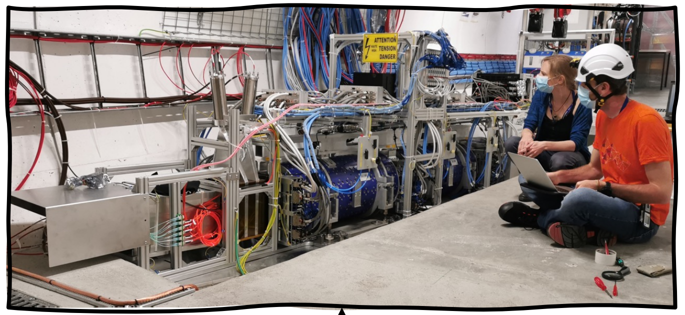

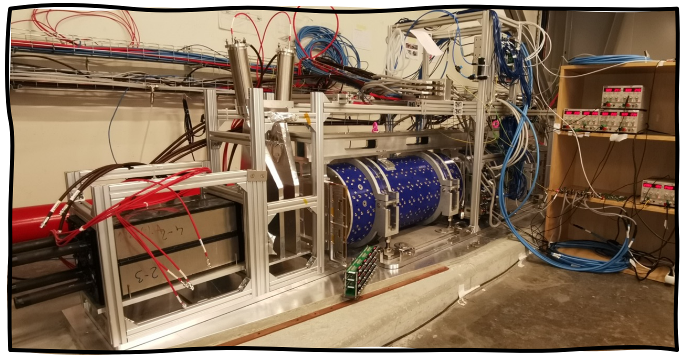

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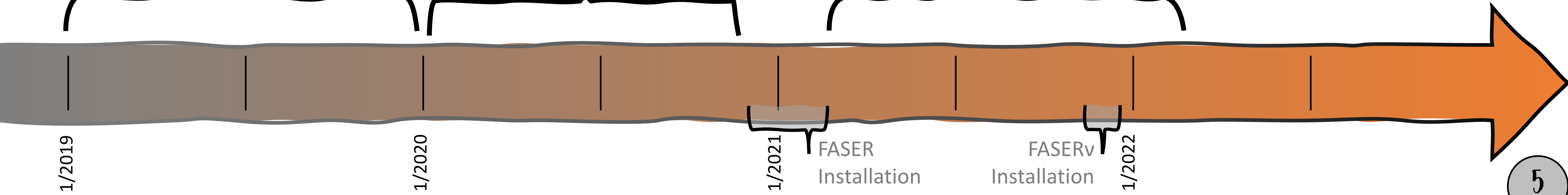
Extensive in-situ commissioning



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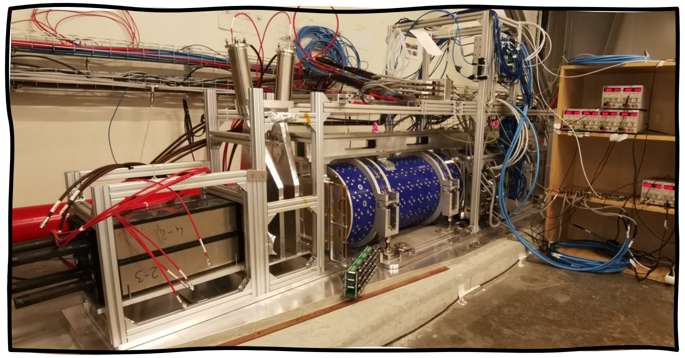

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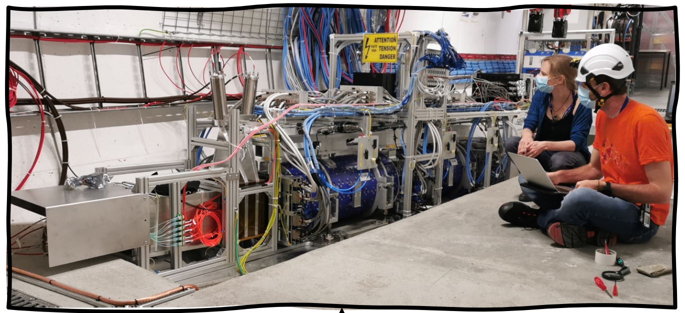

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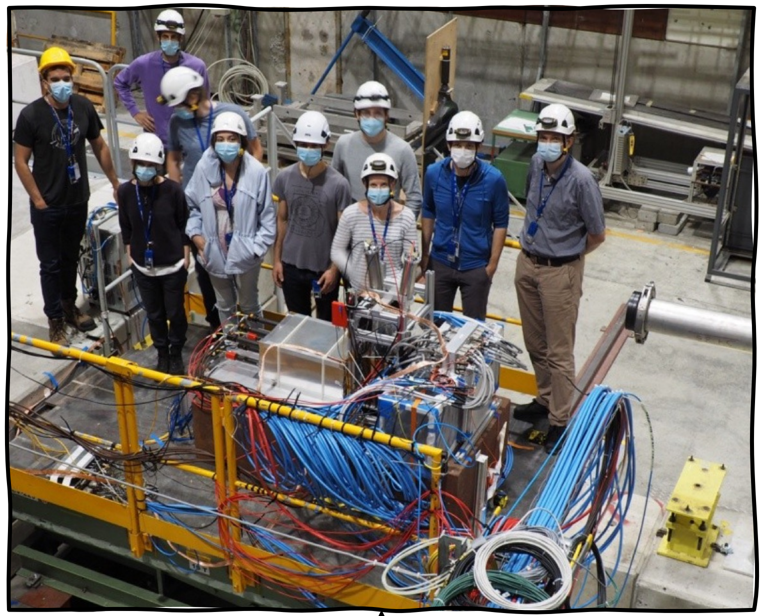


Testbeam

1/2019

1/2020

1/2021

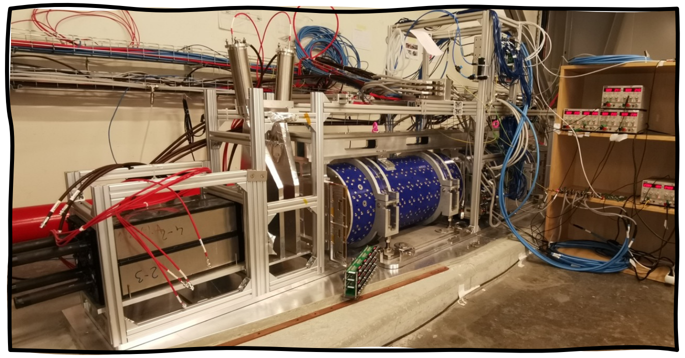
FASER
Installation

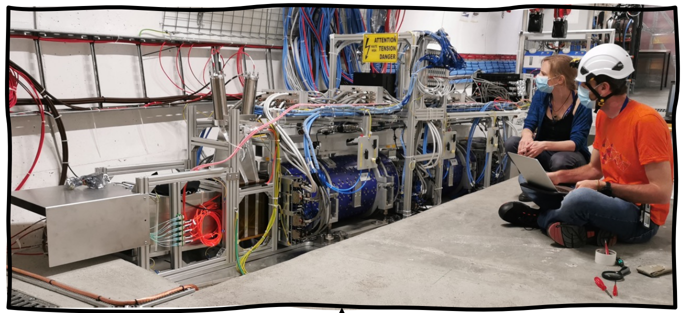
FASERν
Installation

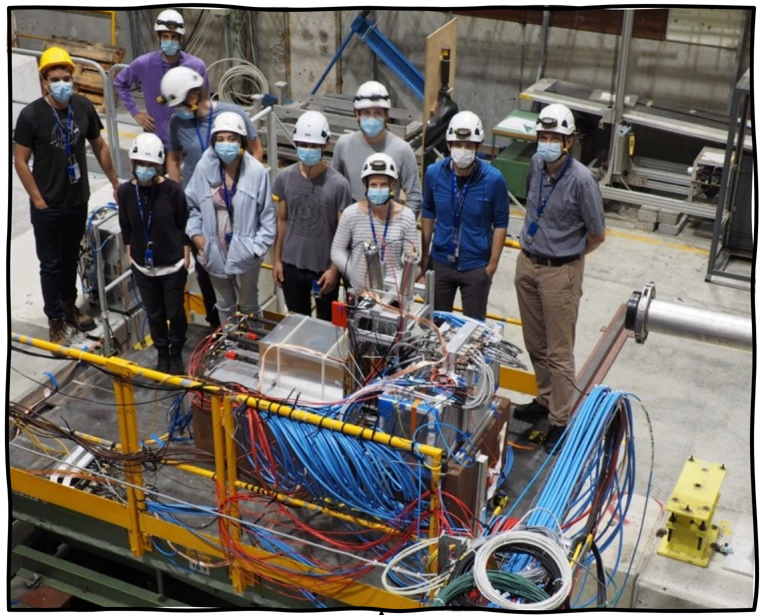
1/2022

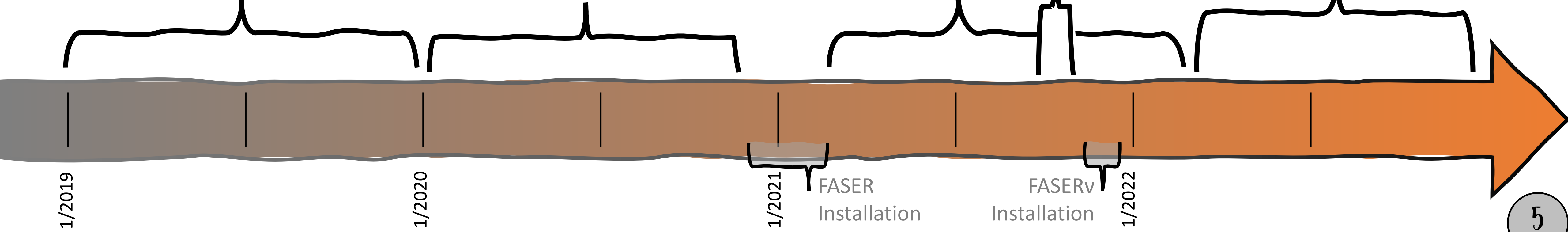
Commissioning

Timeline



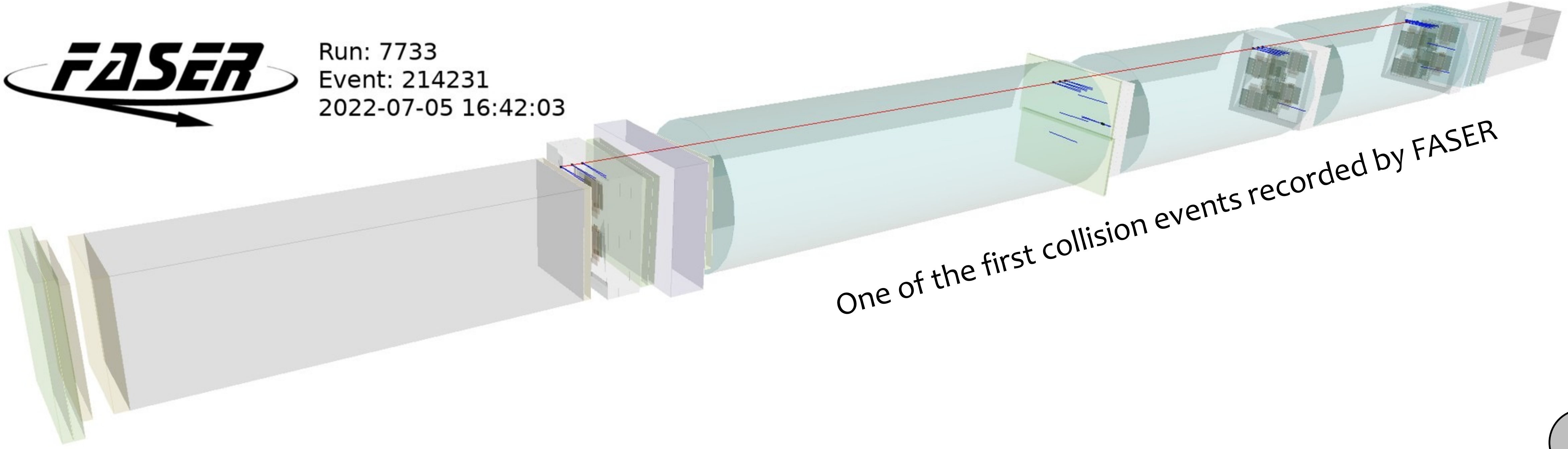






Run3 Data Taking

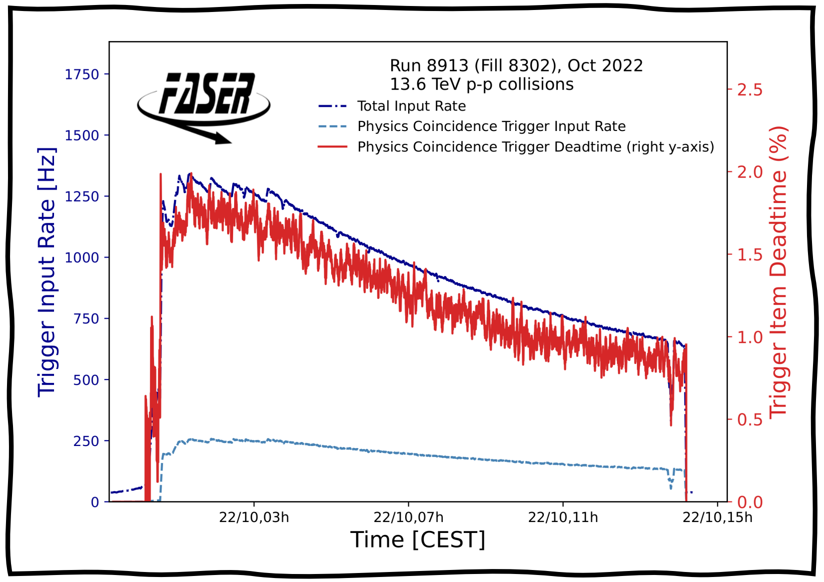
- Have successfully collected 13.6 TeV data
- Initial detector performance being assessed
- Offline and analysis software up and running
- **First analysis results expected in spring 2023**



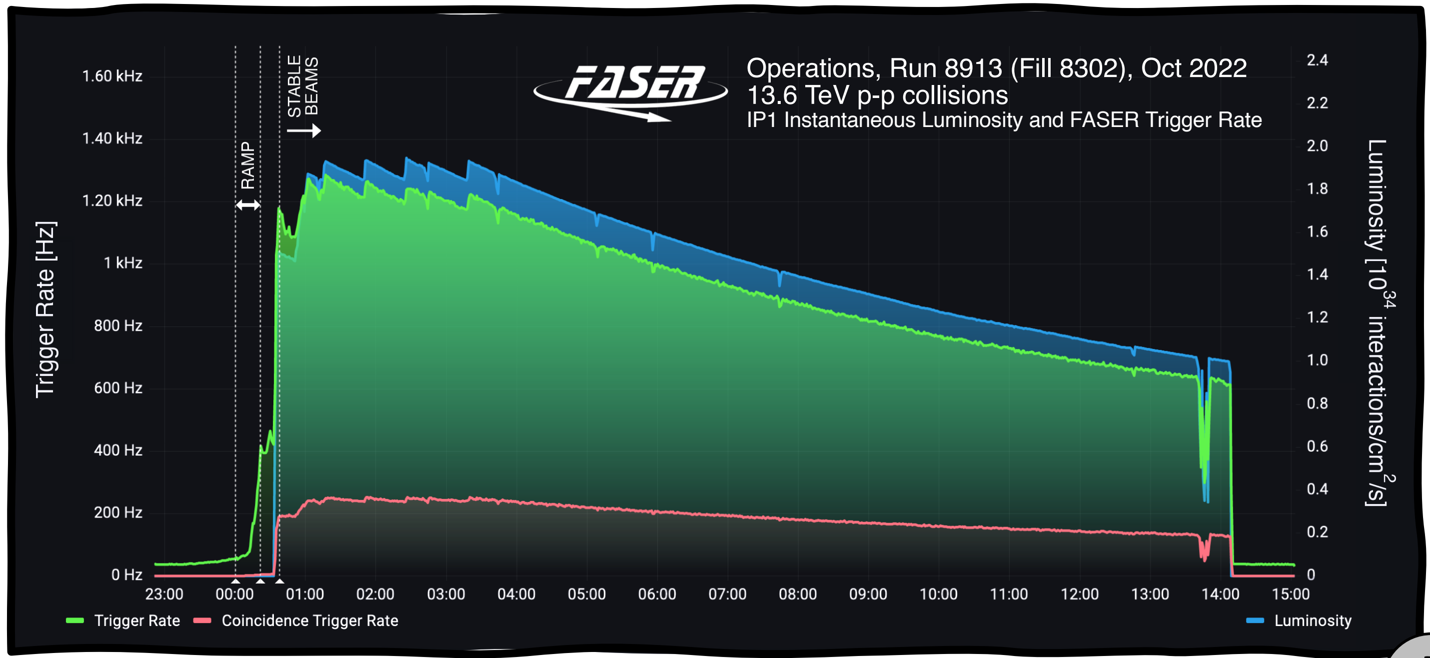
One of the first collision events recorded by FASER

Operating FASER
during Run3 data taking

- Collected ~ 40/fb of data with about 2% data loss due to two specific operational issues
- Trigger rate maximum at 1.2 kHz, same order of magnitude as expectations
- Physics deadtime < 2 %
- First detector performance measurements performed



Luminosity and FASER trigger rate

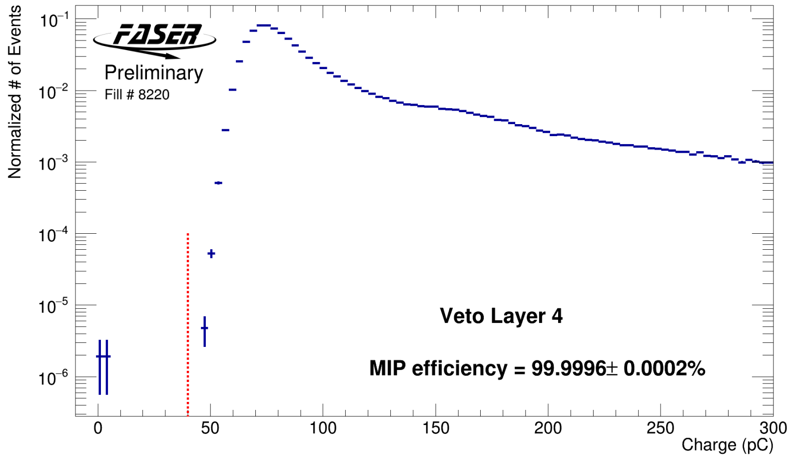


Performance assessment

Veto layer charge distribution

Efficiency > 99.99% per layer

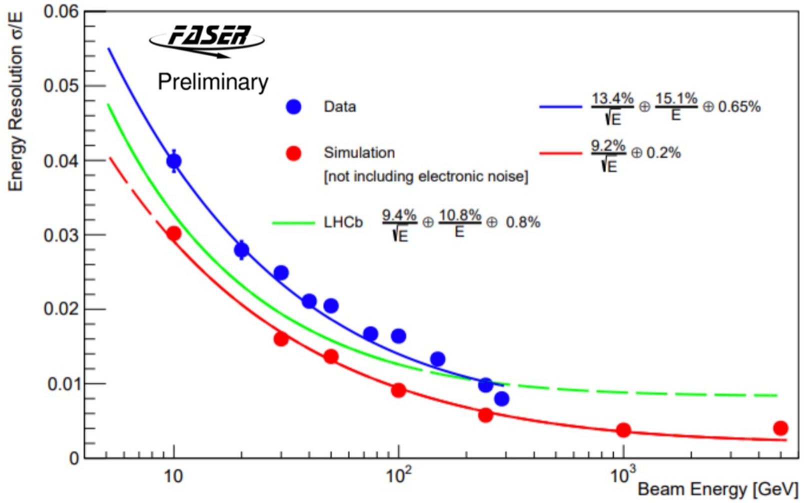
Veto scintillators



Calorimeter calibration at testbeam

Resolution confirmed ~1% for high energy electrons

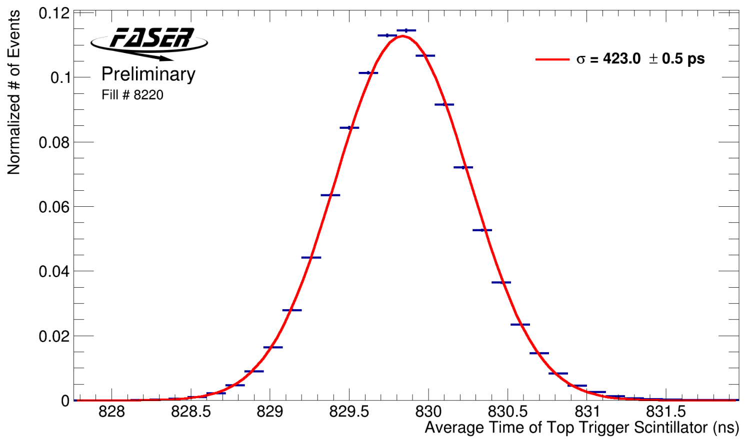
Calorimeter



Timing distribution of top trigger scintillator

Resolution < 0.5 ns

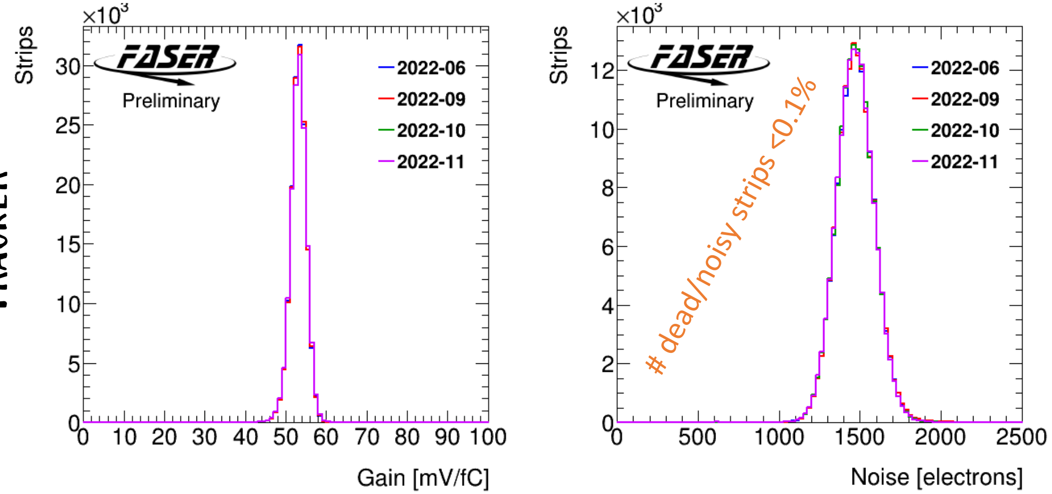
Timing scintillators



Gain and noise distributions of four tracking stations

Confirm stable data taking conditions

Tracker



Studying backgrounds

- Before data taking, expected dominant background source:
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- With first data we see two extra background sources

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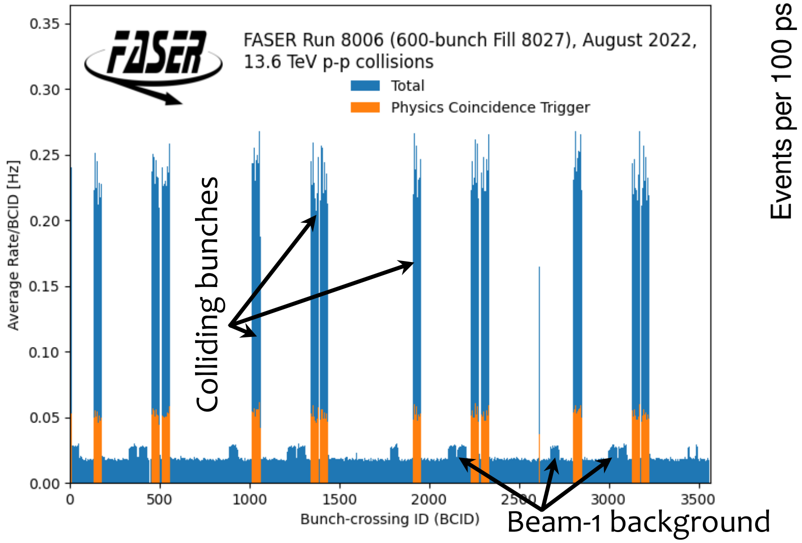
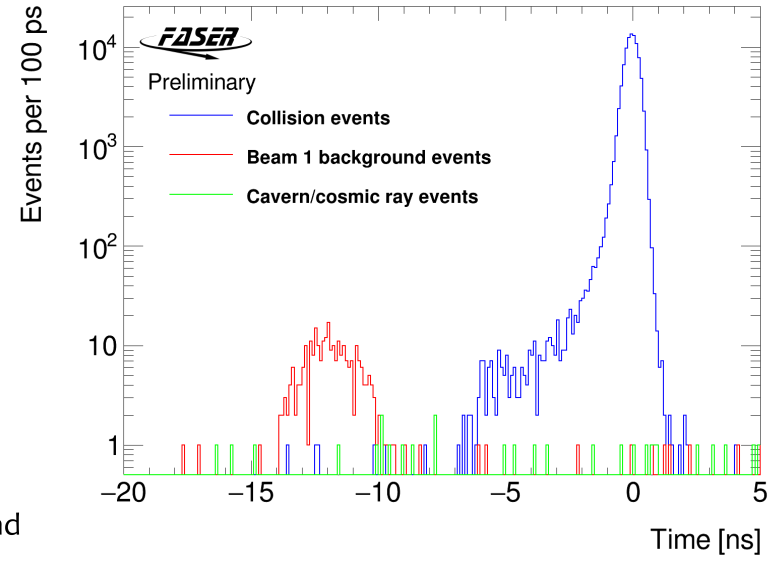
Source A

- Caused by beam-1 on the way to ATLAS passing from the back of FASER
- Early by about 3.2 μs compared to particles from IP
- First observed with pilot beams in Nov 2021
- Concrete shielding installed to reduce it

Average rate per bunch-crossing ID



Calorimeter time separation of collision events and Beam-1 background



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Source B

- Correlated to beam
- Only fires single scintillators
- Likely low energy neutrons

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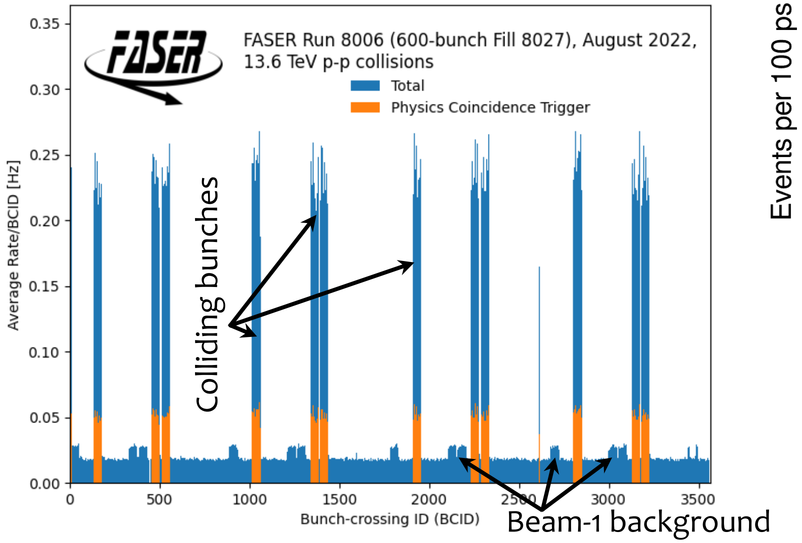

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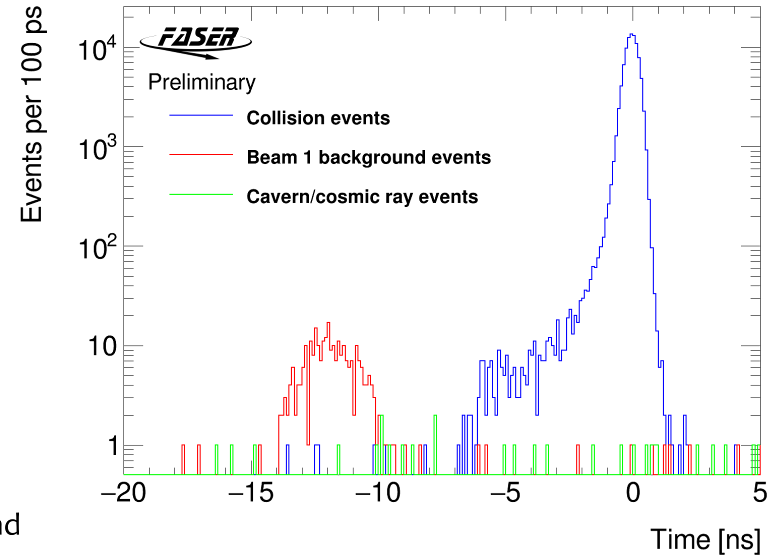

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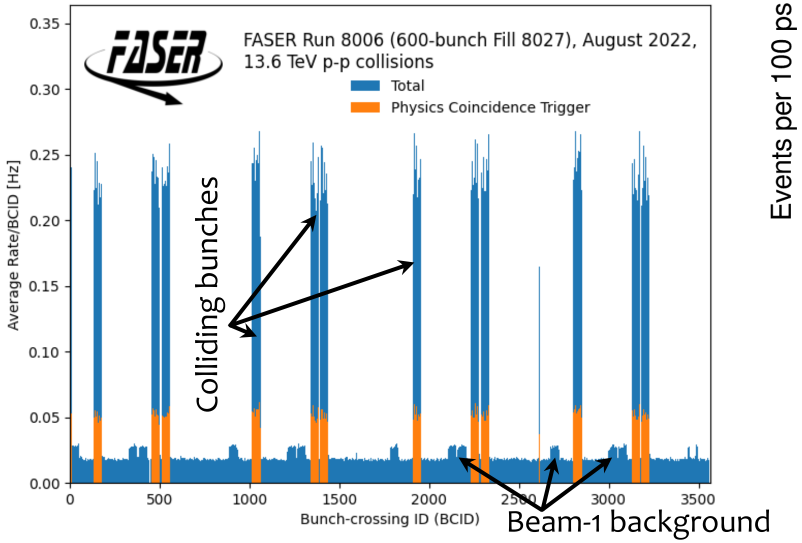

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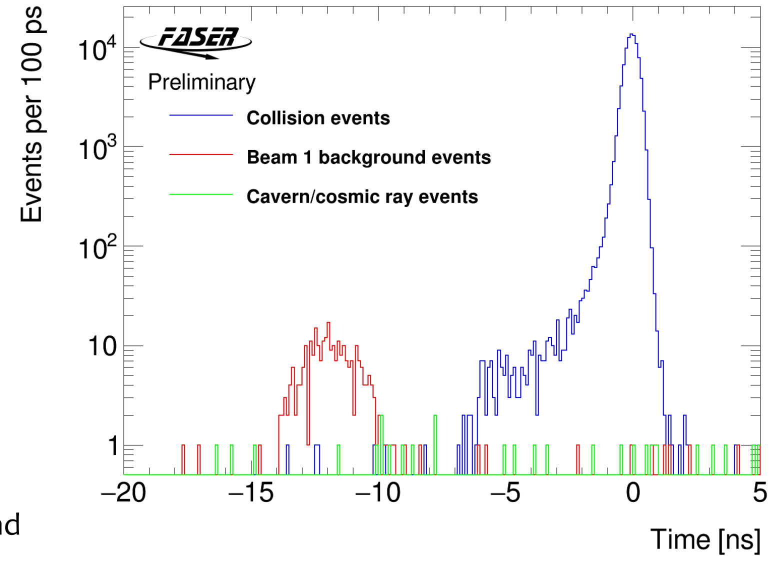

Source B

- Correlated to beam
- Only fires single scintillators
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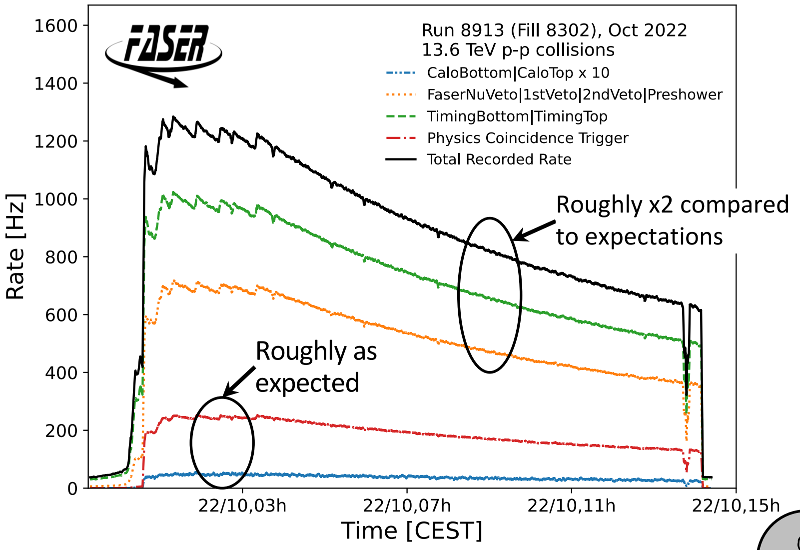
- Additional backgrounds give total trigger rate x2 than expected
- Rate of muons from IP roughly consistent with expectation
- Extra rate not problematic

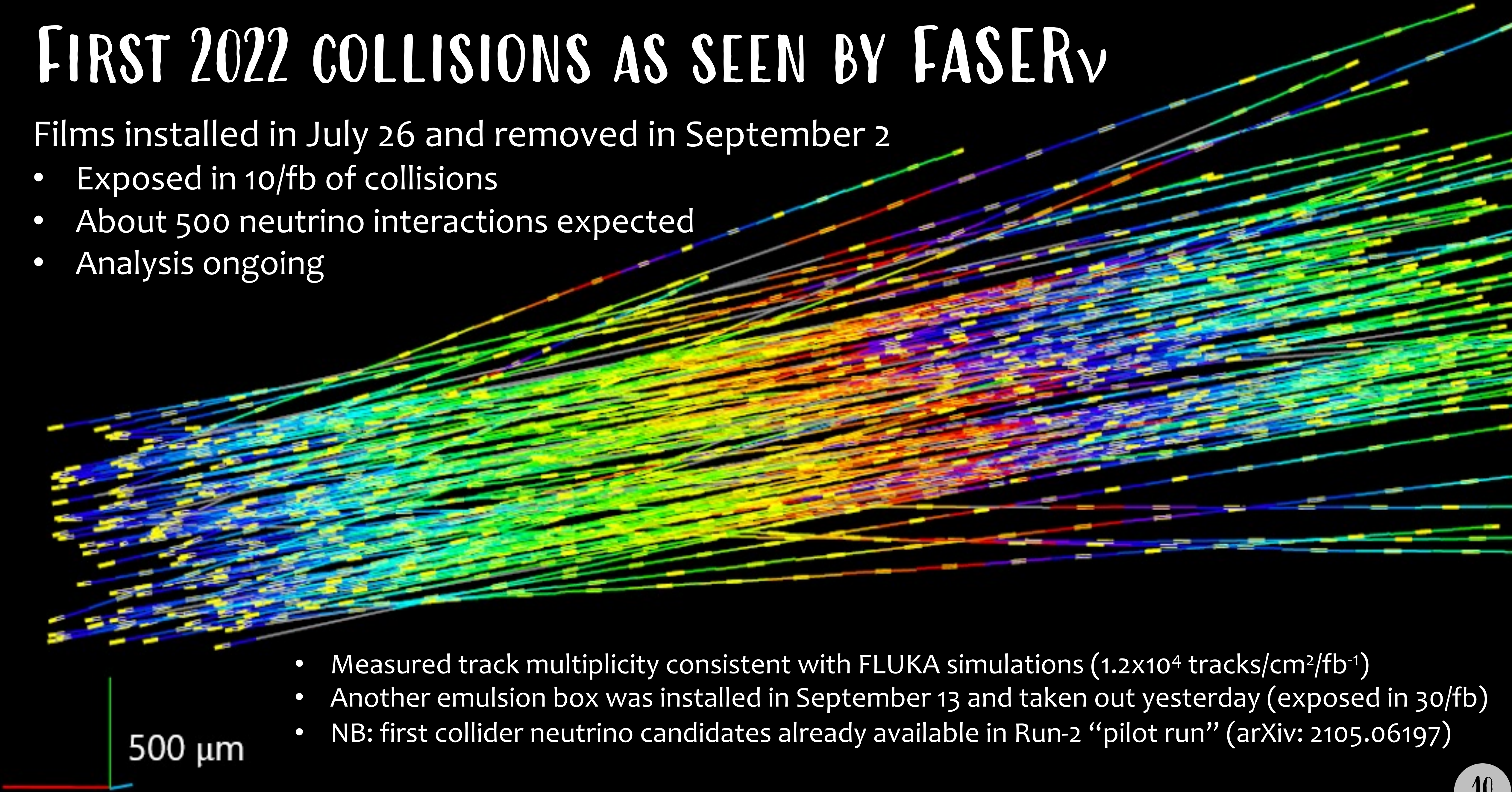
FASER recorded rate per trigger item



First 2022 collisions as seen by FASERν

Films installed in July 26 and removed in September 2

- Exposed in 10/fb of collisions
- About 500 neutrino interactions expected
- Analysis ongoing



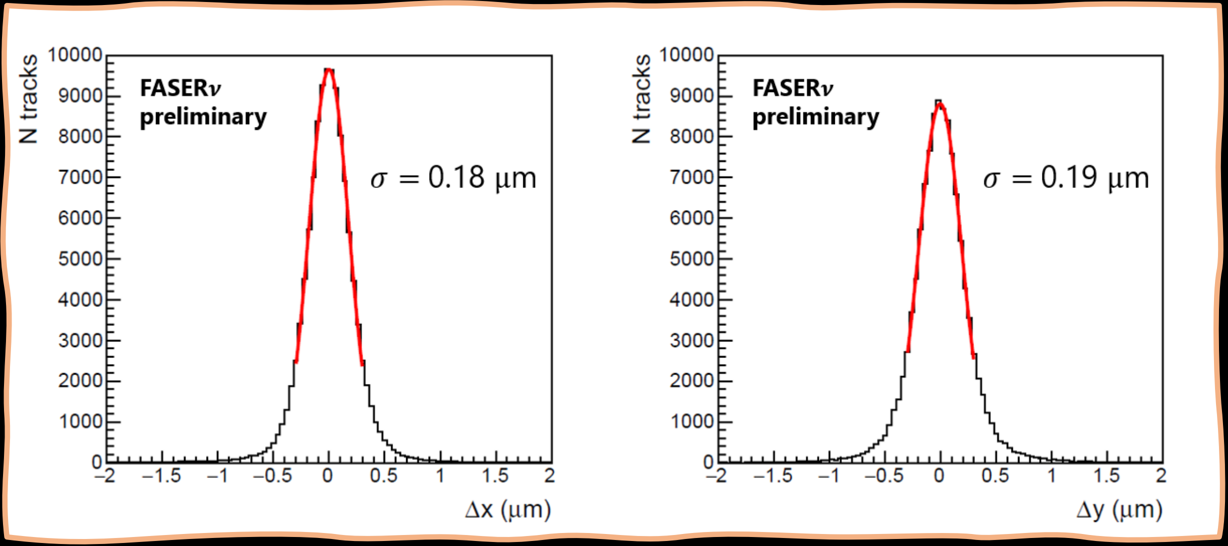
- Measured track multiplicity consistent with FLUKA simulations (1.2×10^4 tracks/cm^2/fb^{-1})
- Another emulsion box was installed in September 13 and taken out yesterday (exposed in 30/fb)
- NB: first collider neutrino candidates already available in Run-2 “pilot run” (arXiv: 2105.06197)

First 2022 collisions as seen by FASERν

Films installed in July 26 and removed in September 2

- Exposed in 10/fb of collisions
- About 500 neutrino interactions expected
- Analysis ongoing

Excellent track resolution measured in first data!



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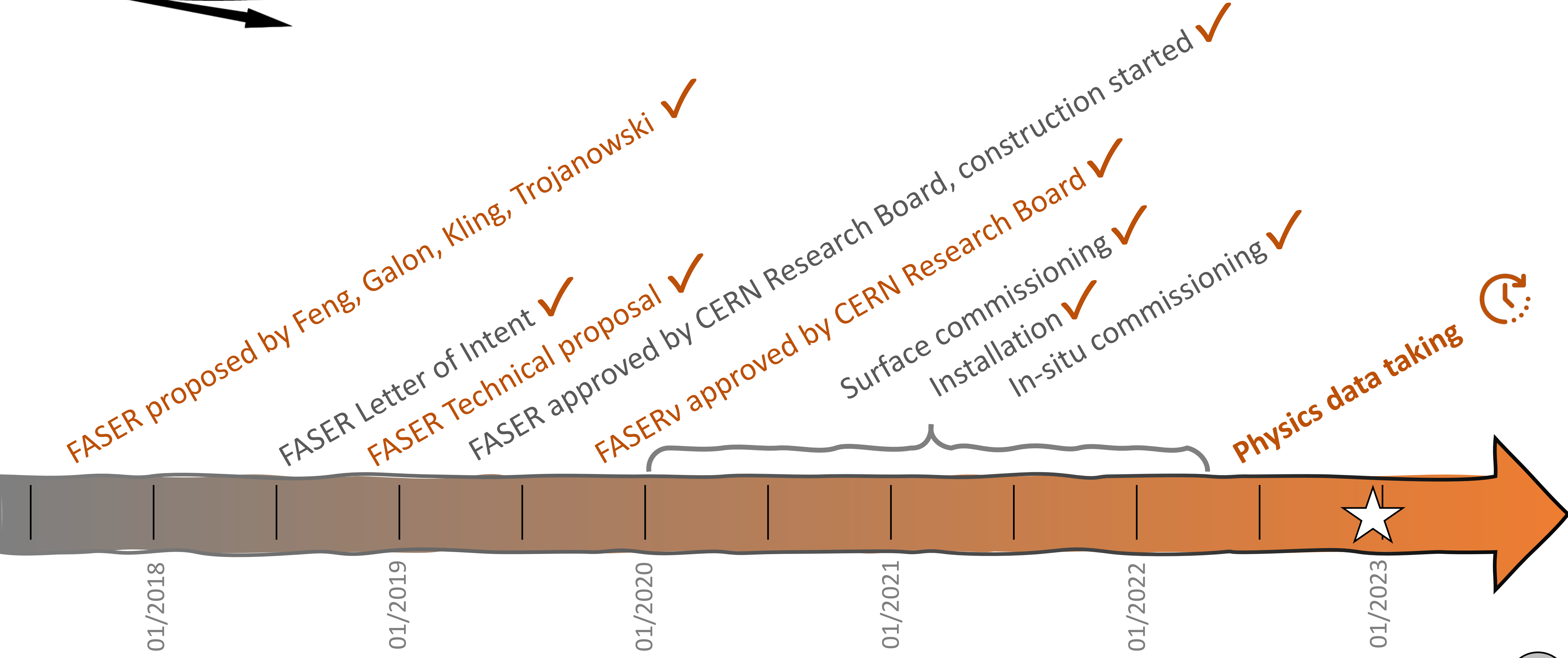
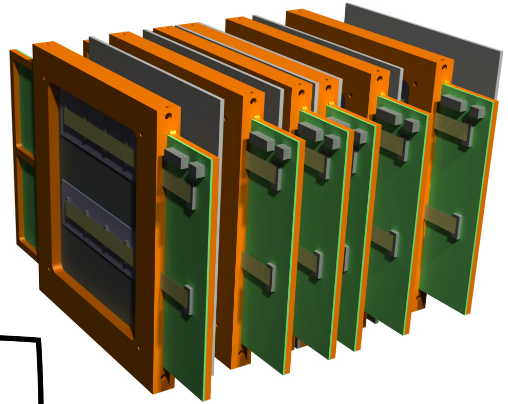
FASER Global timeline



What's beyond 2022?

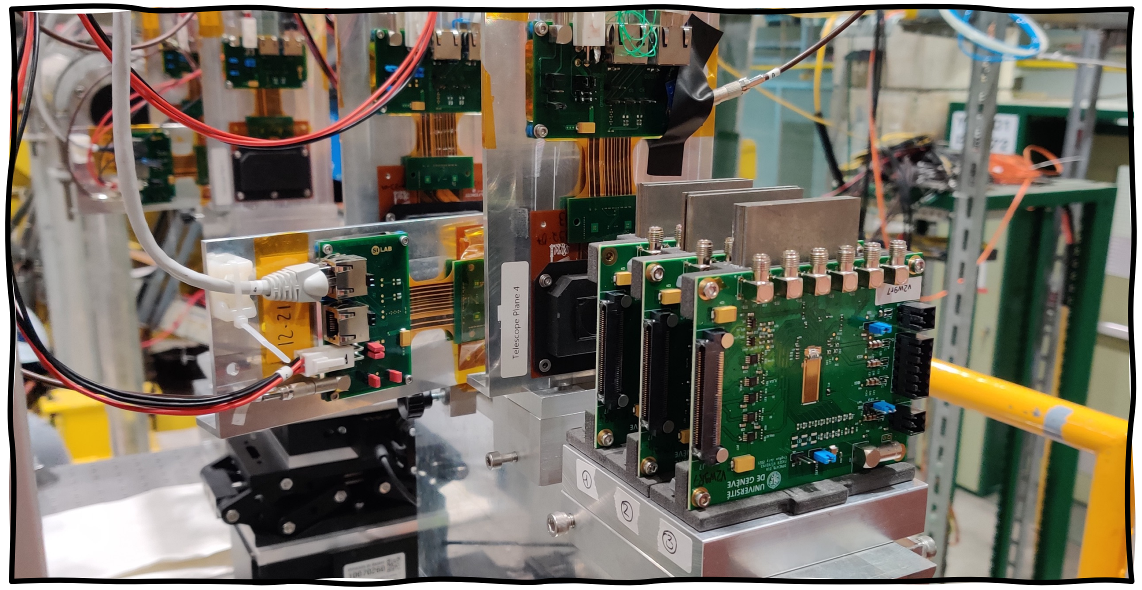


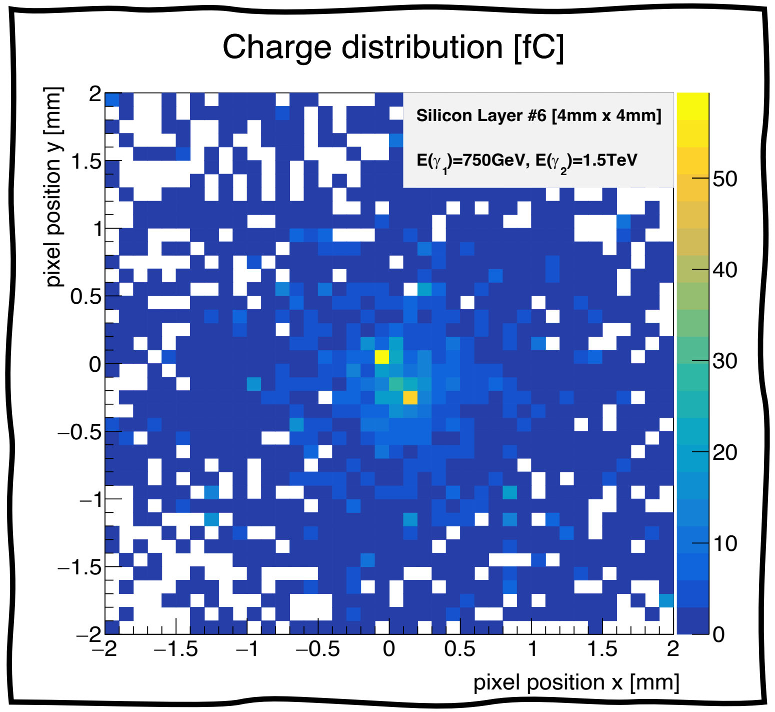
Preshower Upgrade

to enable 2-γ physics

- Existing pre-shower to be replaced with a high-resolution silicon pre-shower detector using monolithic pixel ASICs

Preproduction ASICs in testbeam, Sept 2022





- Distance between two photons: 200 μm
- Distinguishable!

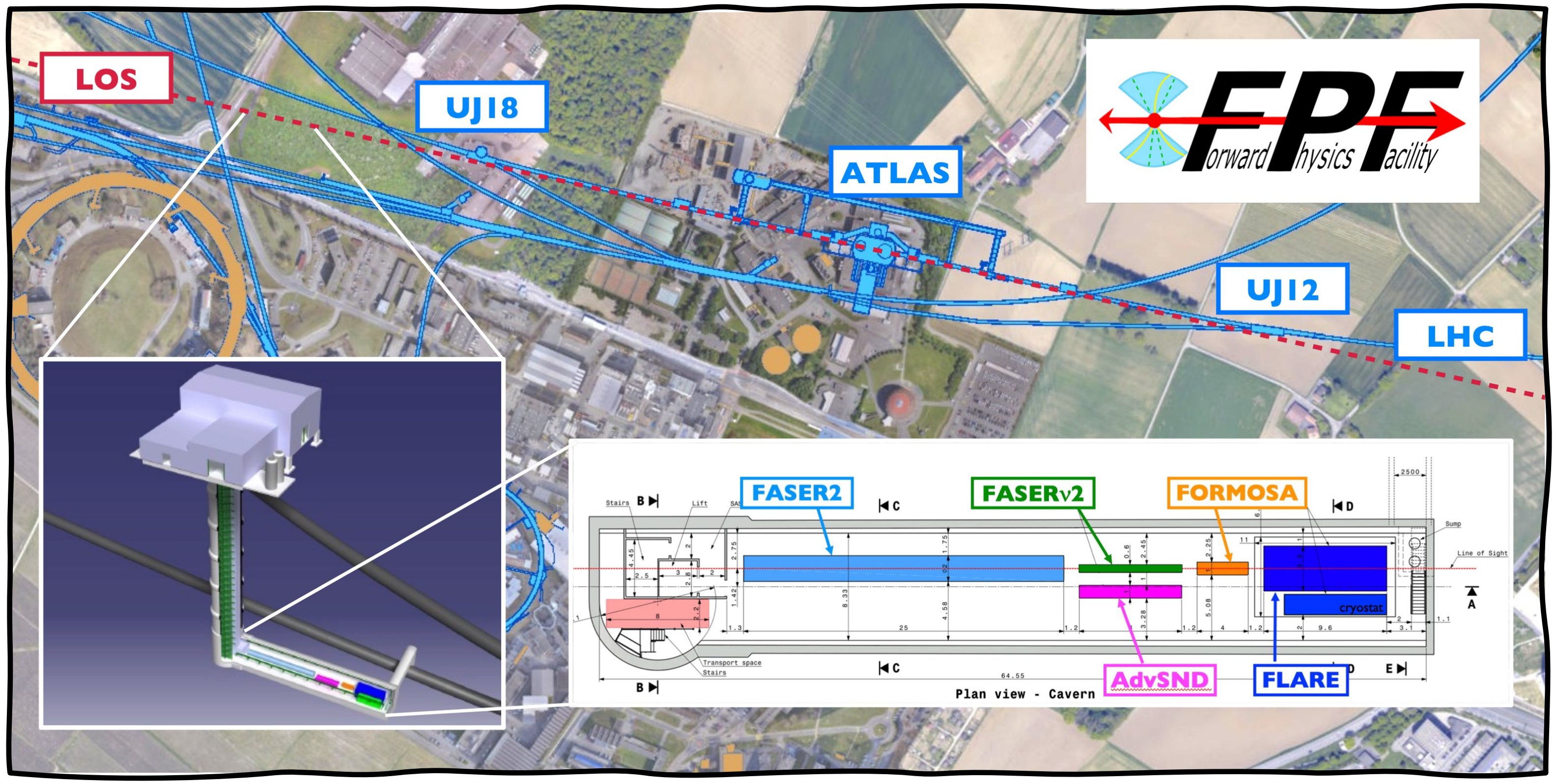
Detector to be used for 2025 data taking

https://cds.cern.ch/record/2803084

What's beyond Run3 ?

Beyond FASER? A teaser for the proposed Forward Physics Facility

FASER2: 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: [LoI for SNOWMASS-2021](#)
[arXiv:2203.05090](#)
[FPF – Kickoff workshop](#)
[FPF – 5th (latest) workshop](#)

Outlook

- The FASER experiment introduces **a novel approach** to exploit LHC collisions, to:
  - either make **a new discovery** or **constrain parts of phase-space which no current experiment has access to**; and
  - make the first **collider-originated neutrino measurements**
- Collaboration (& CERN technical teams) have worked feverishly to construct, install and commission the detector over the Long Shutdown
- **Goal: physics data taking with the start of Run3 and first results around spring 2023**
- Collected good Run3 data, which we are now analysing
  - Thanks to the CERN accelerator teams for the excellent performance!
- Have started upgrades and thinking about FASER2 & a future facility to further exploit forward production in LHC collisions!
- **LOTS OF EXCITING PHYSICS AHEAD!**

Stay in touch:
https://faser.web.cern.ch/
@FASERexperiment

FASER Thanks!

For financial support:

FASER Collaboration: 22 institutes, about 70 members

References

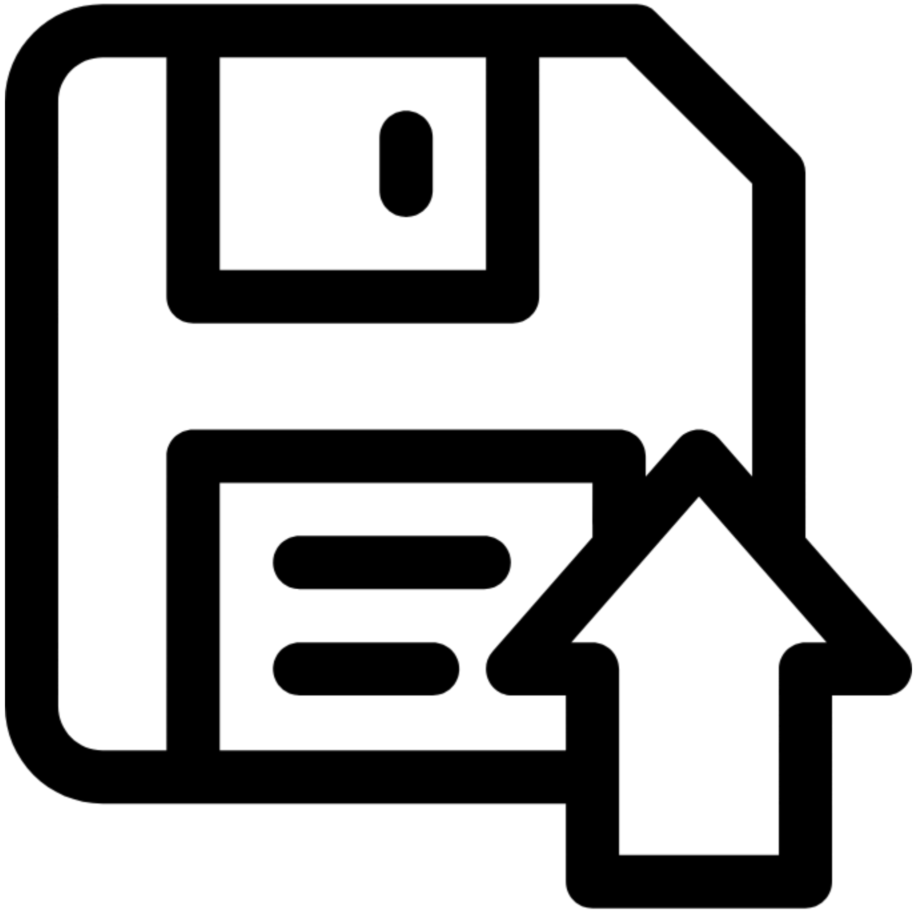
NEW! The FASER detector arXiv:2207.11427

FASER collaboration:

- Letter of Intent arXiv:1811.10243
- Technical Proposal arXiv:1812.09139
- FASER's Physics Reach for Long-Lived arXiv:1811.12522
- Input to the European Strategy for Particle Physics Update arXiv:1901.04468
- Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC arXiv:1908.02310
- Technical Proposal of FASERν neutrino detector arXiv: 2001.03073
- Forward Physics Facility Snowmass LoI
- First neutrino interaction candidates at the LHC arXiv:2105.06197
- The trigger and data acquisition system of the FASER experiment arXiv:2110.15186
- The tracking detector of the FASER experiment arXiv:2112.01116
- The FASER W-Si High Precision Preshower Technical Proposal LHCC-P-023

Plus several theory papers

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

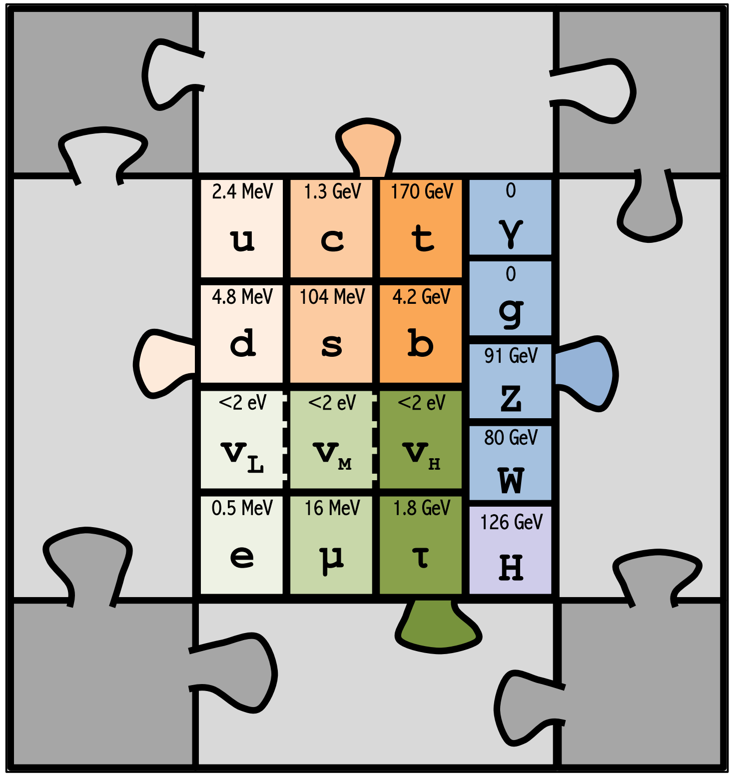


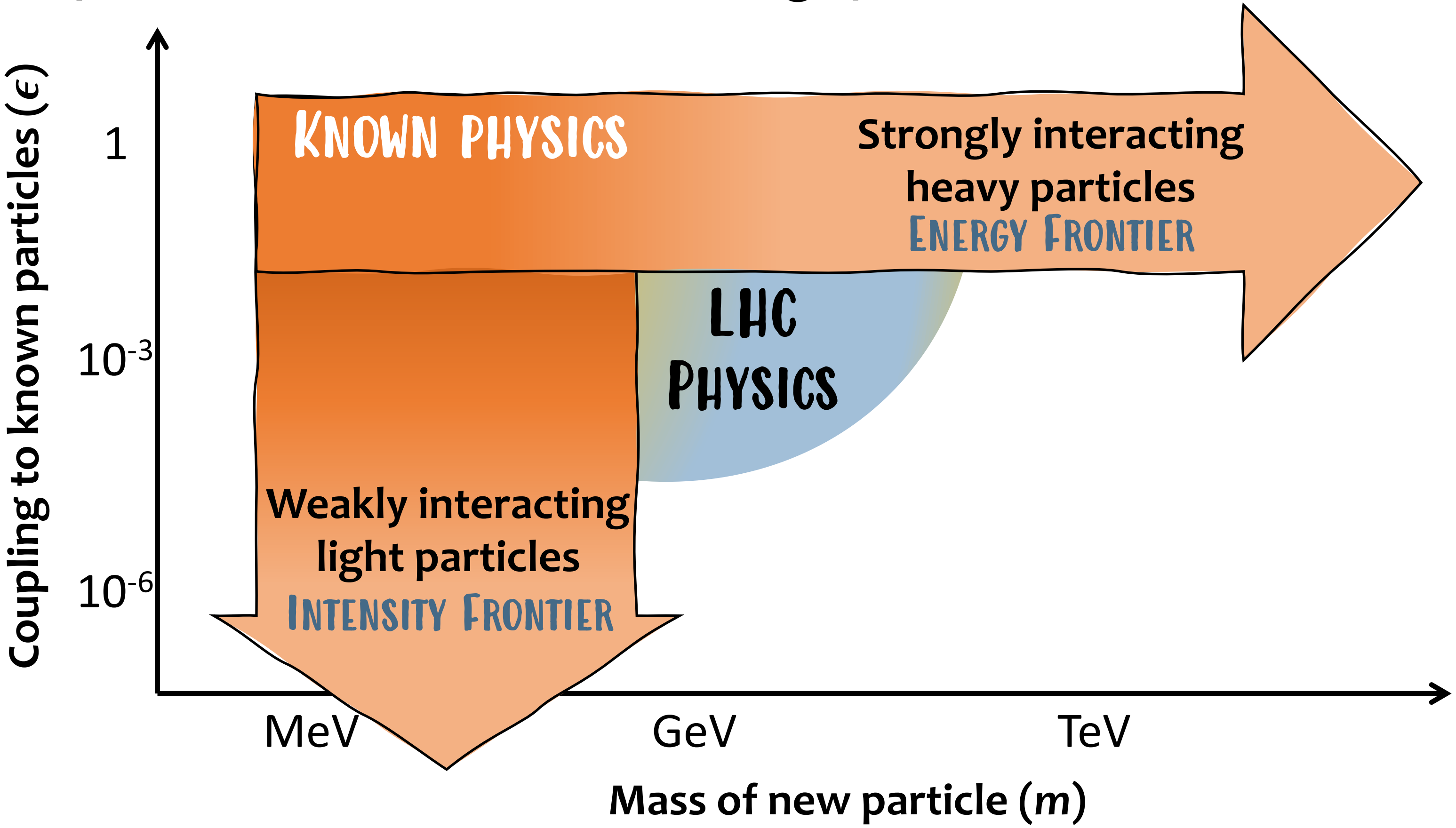
The FASER Experiment

Theory / Intro

The landscape of new particles @ colliders

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





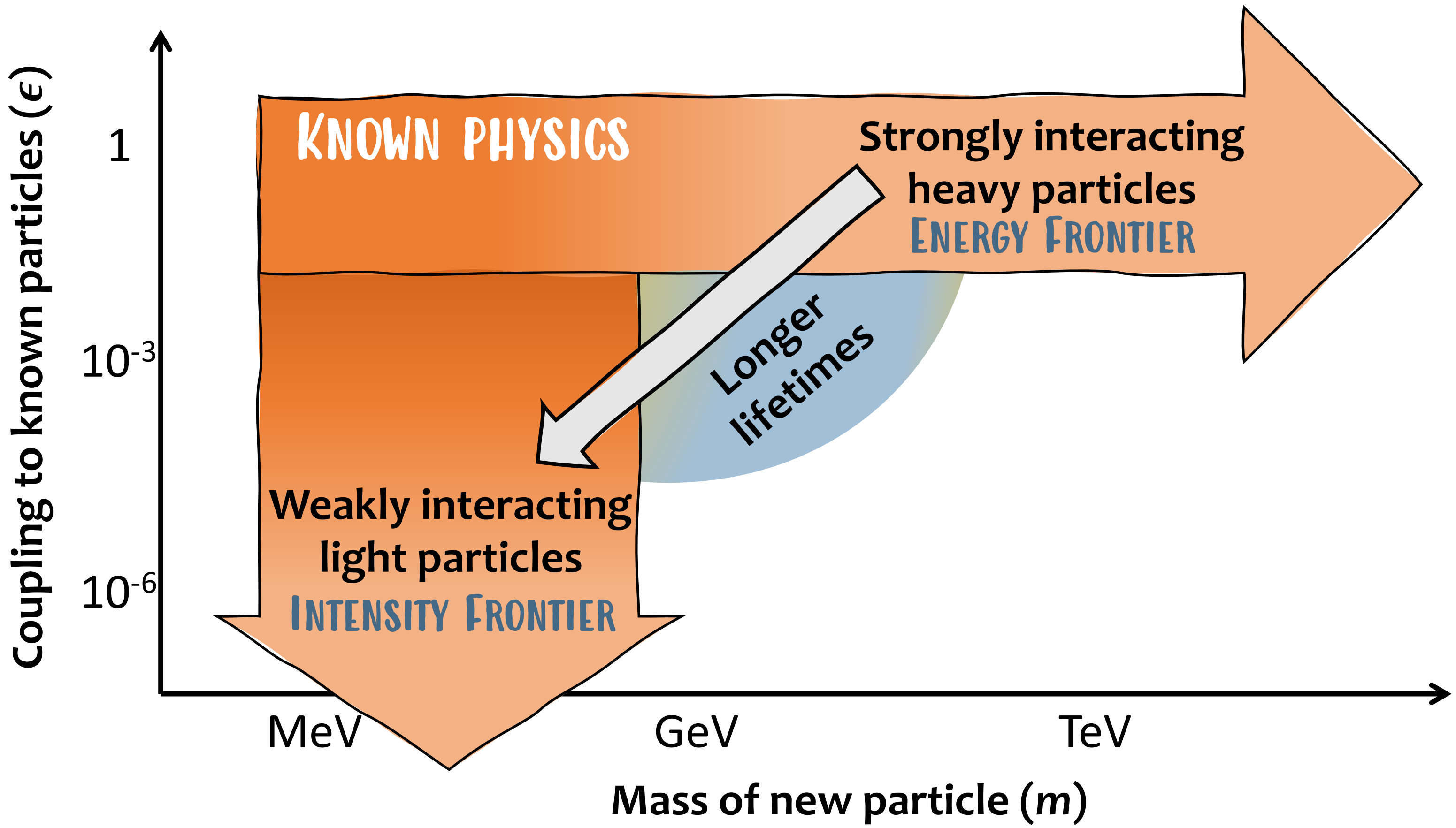
The landscape of new particles @ colliders

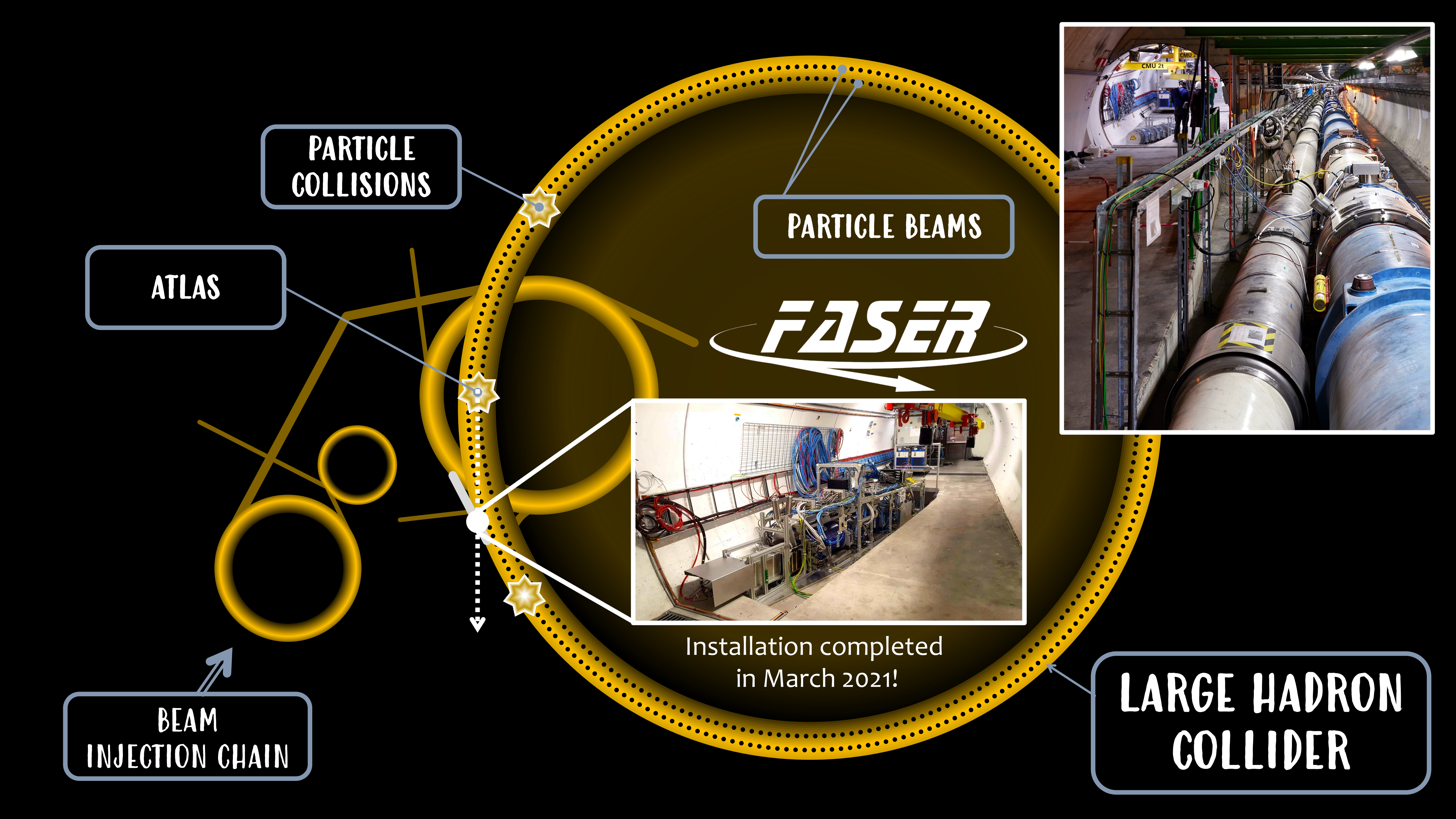
Lifetime

a characteristic of weakly interacting light particles

Distinct signatures

Opportunity for exploration!




PARTICLE COLLISIONS
ATLAS
PARTICLE BEAMS
FASER
Installation completed in March 2021!
BEAM INJECTION CHAIN
LARGE HADRON COLLIDER
CMU 2t

Feebly Interacting Particles (FIPs)

- Due to interacting feebly, they are linked to a "hidden sector"
- Couplings between SM and hidden sector result from "portal" operators
- Large number of specific models; can be simplified to the following:

SM Higgs *h* — h ----- $(\mu S + \lambda S^2) H^\dagger H$ ----- S — Dark Higgs *S*

New scalar: **Dark Higgs**; couplings to SM μ, λ

SM EM *A* — A ∿∿ $-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} F_Y^{\mu\nu}$ ∿∿ A_D — Dark EM A_D

New vector: **Dark photon**; coupling to SM $\propto \epsilon Q$

SM 2γ or $2f$ — 2γ --- $\frac{\alpha}{f_\alpha} F_{\mu\nu} \tilde{F}^{\mu\nu}$; $2f$ --- $\frac{\partial_\mu \alpha}{f_\alpha} \bar{\psi} \gamma^\mu \gamma^5 \psi$ ----- α — ALP α

New pseudo-scalar: **ALP**; coupling to SM suppressed

(Axion Like Particle)

SM LH ν — ν —— $y_N h L \psi_D$ —— N — HNL N

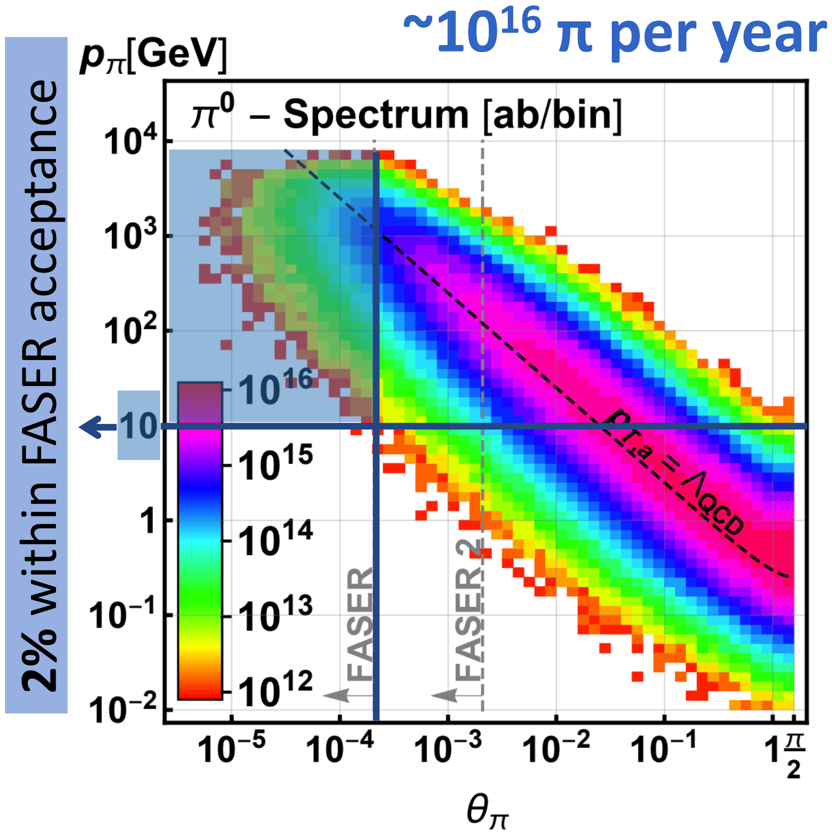
New fermion: **HNL**; coupling to LH SM and h $\propto y_N$

(Heavy Neutral Lepton)

- The masses of the new particles can span several orders of magnitude

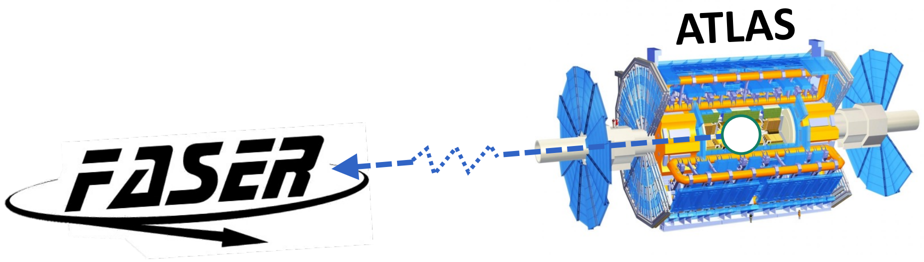
ForwArd Search ExpeRiment at the LHC

Searches for new weakly interacting light particles, coupling to SM via mixing with SM “portal” operator



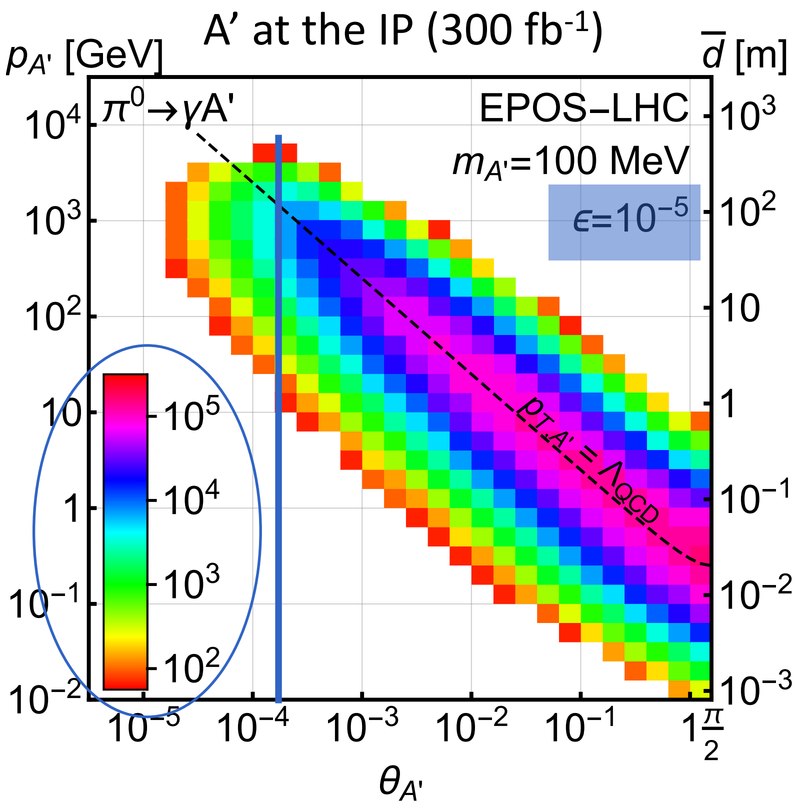
- Produced in decays of light mesons (e.g. π, K), abundantly present in p-p collisions, primarily in large pseudorapidity
- FASER acceptance:

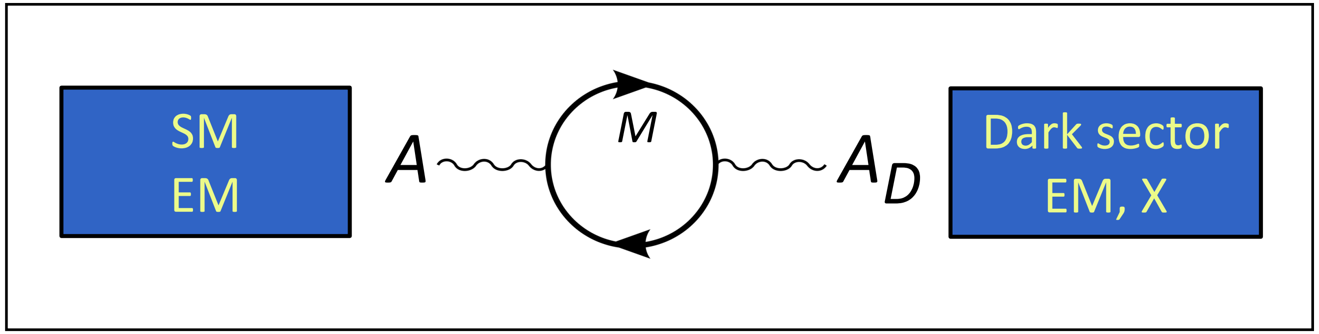
  20 cm diameter, 480 m from ATLAS IP (ONLY **10^{-6}% solid angle**)

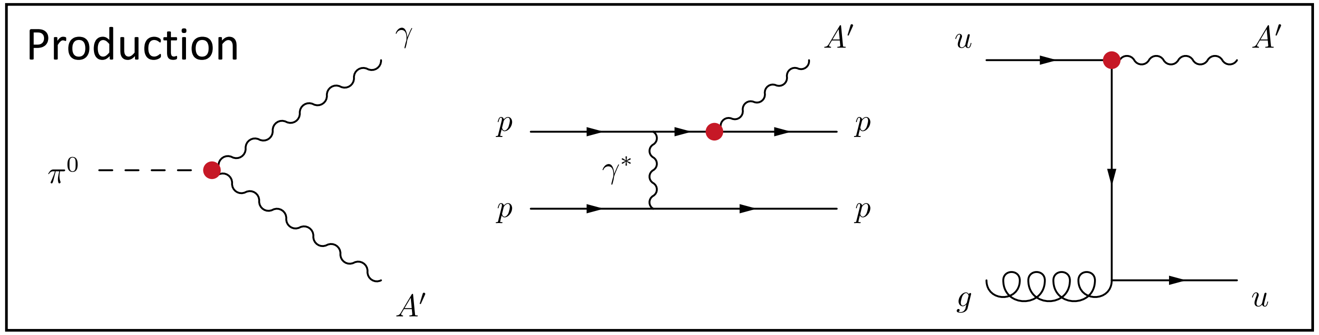


An example physics case: Dark Photon A'

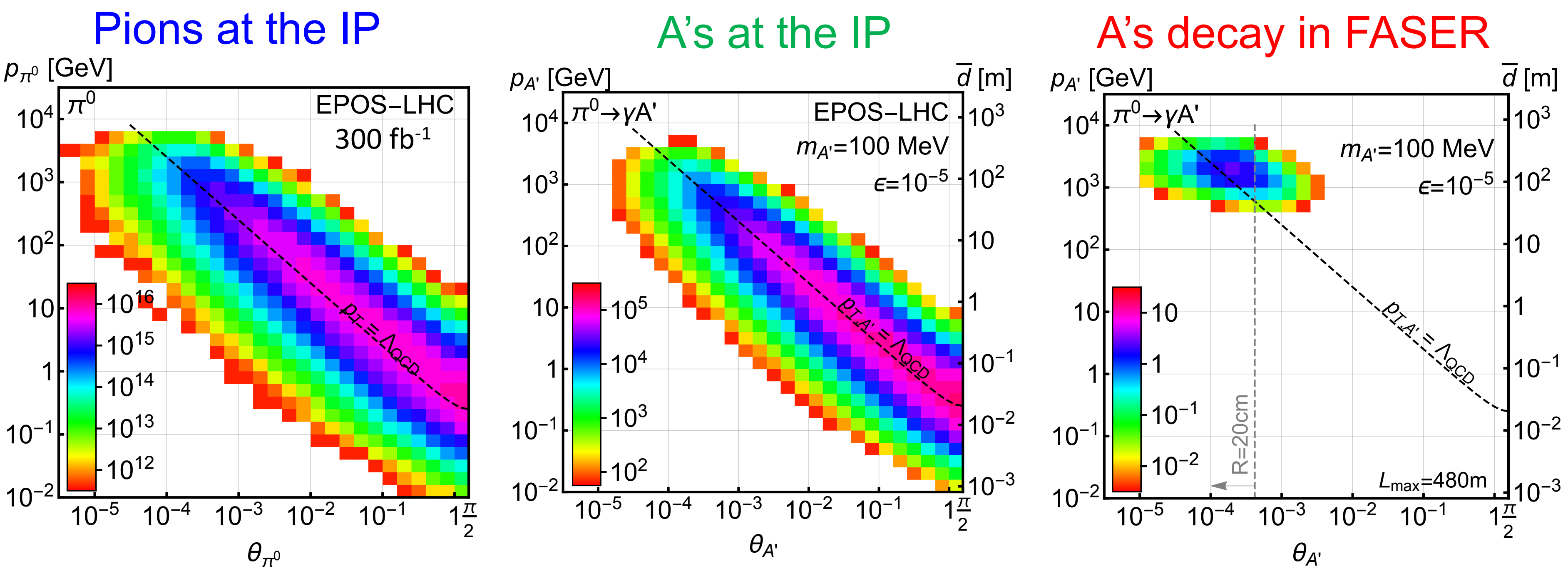
- New **massive** gauge boson in a dark sector with dark matter candidate X
- Spin 1, couples weakly to SM fermions (εQ_f coupling, small ε) through mixing with the photon
  - Will be searched for via its **decay to an electron-positron pair**
- For $m_{A'}$=100 MeV, $\varepsilon \sim 10^{-5}$ and E~TeV,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







SIGNALS: DARK PHOTONS



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

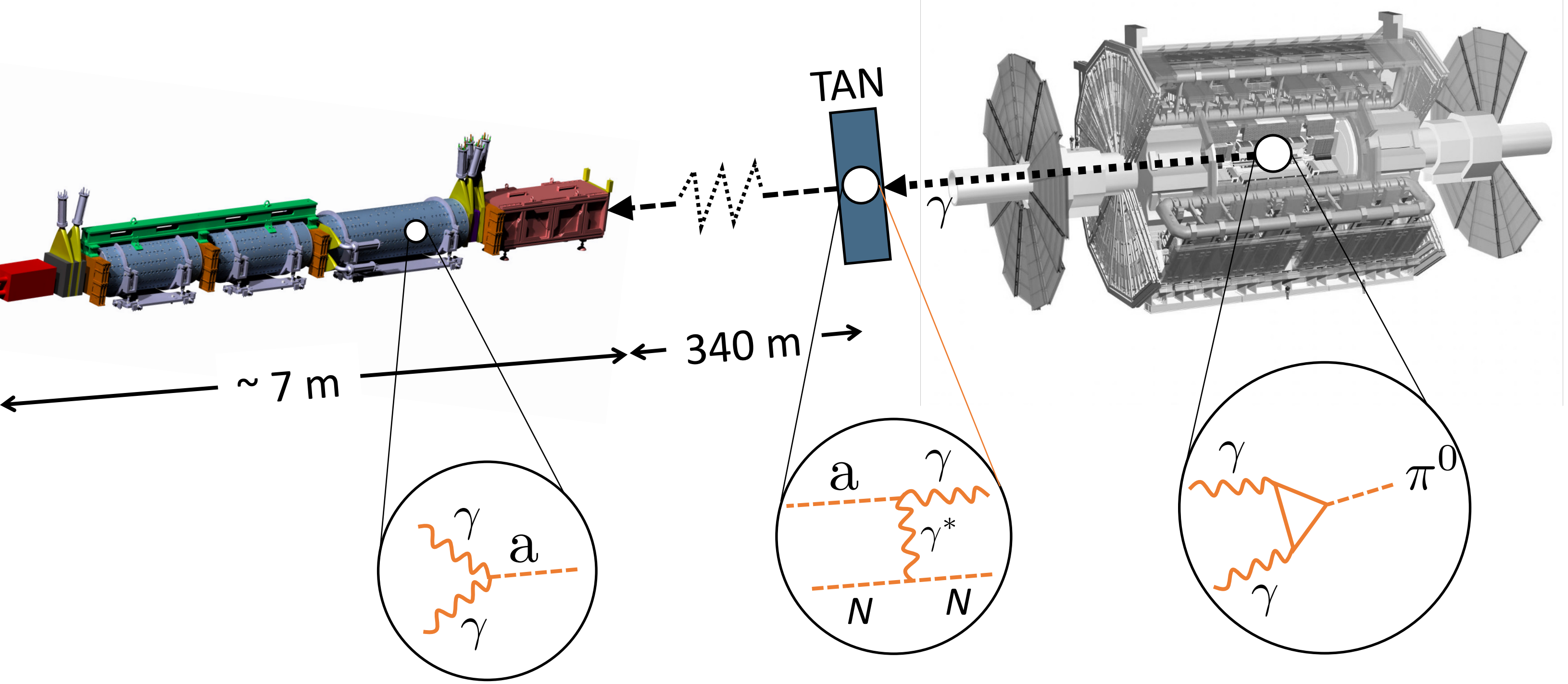
- Rates highly suppressed by $\varepsilon^2 \sim 10^{-10}$
- But still $N_{A'} \sim 10^5$ per bin; LHC is a dark photon factory!

- 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

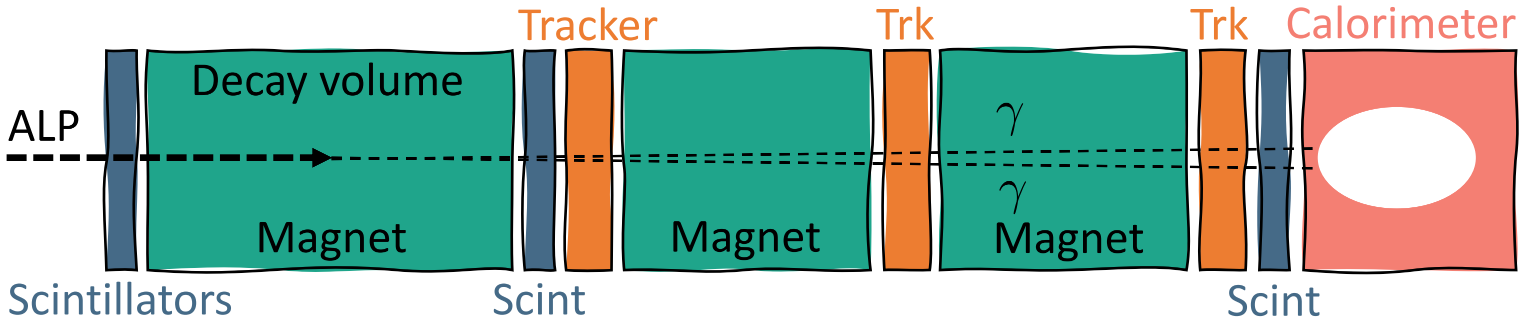
Key signatures

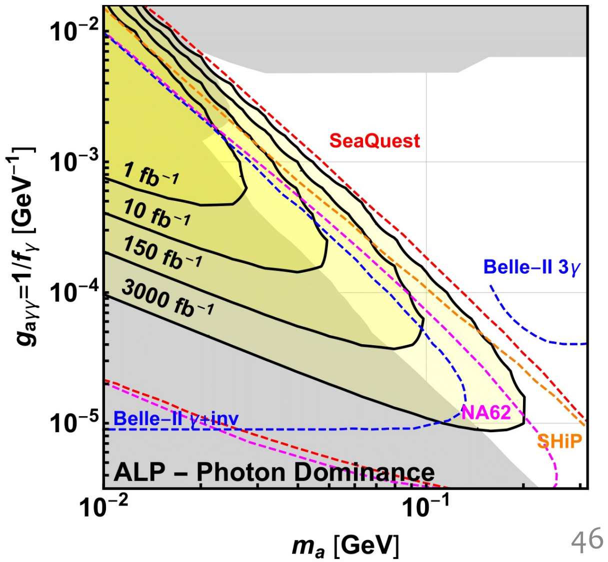
Axion-like particle (ALP, a)



Decay products collimated

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

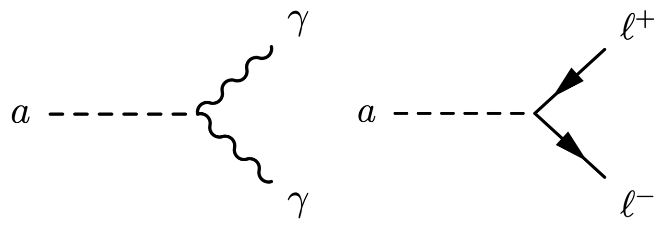


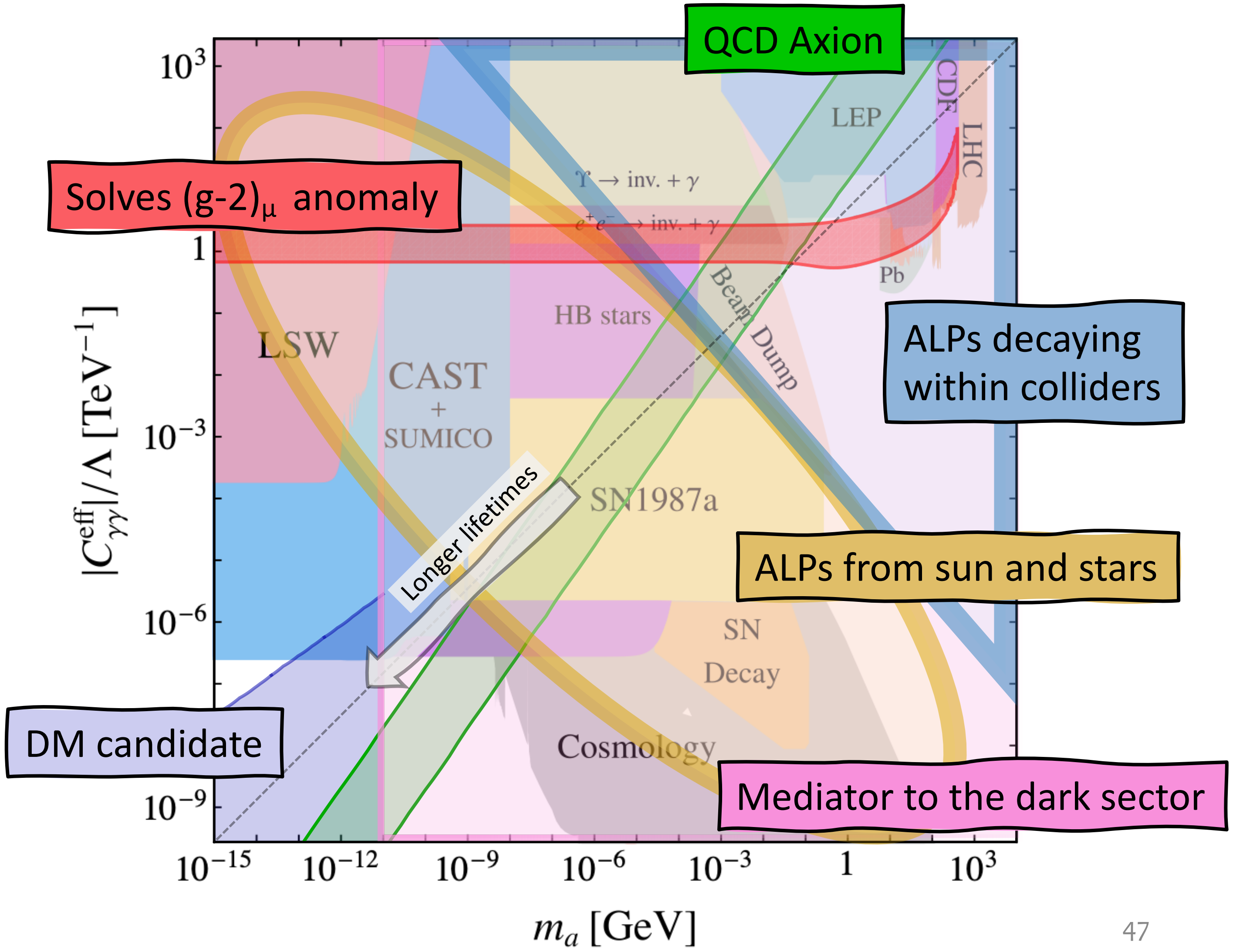


Assuming 3 signal events and no backgrounds

Pseudoscalar portal – ALPs

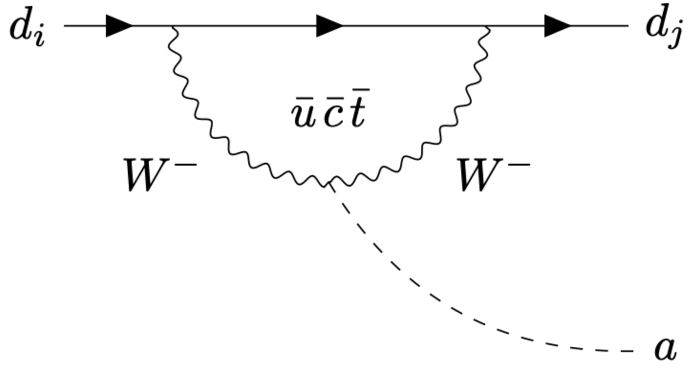
- Pseudoscalar SM-singlets; can appear in theories with broken global symmetries
- "Low" mass particles with suppressed couplings to SM
- BR to SM particles depends on their mass

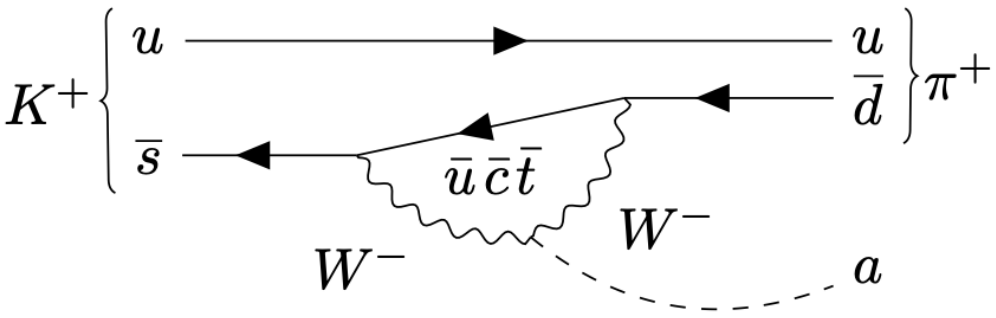


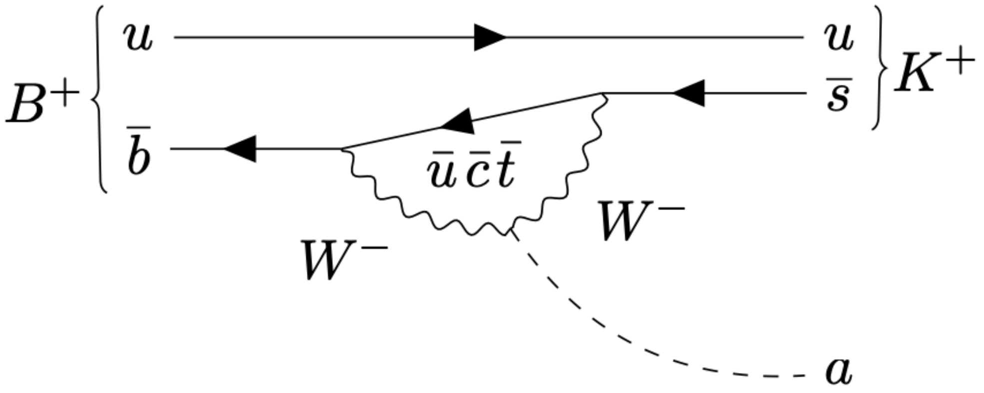


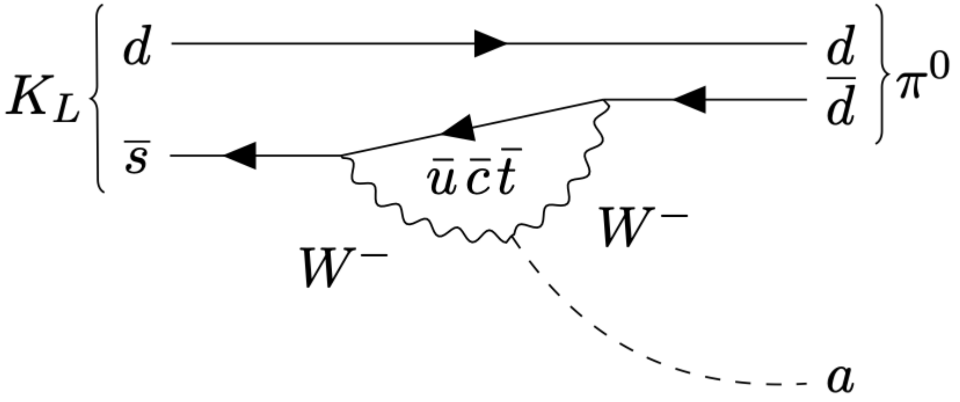
Thanks to Andrea Thamm for the figure!

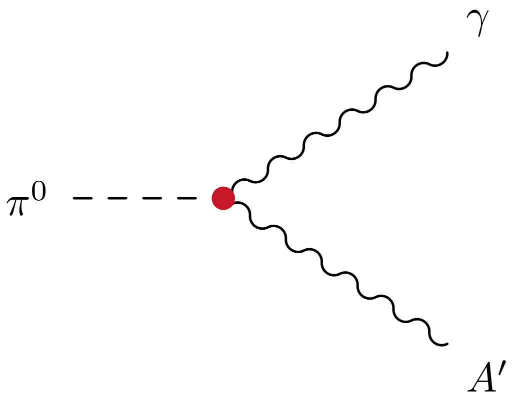
ALP production beyond primakoff

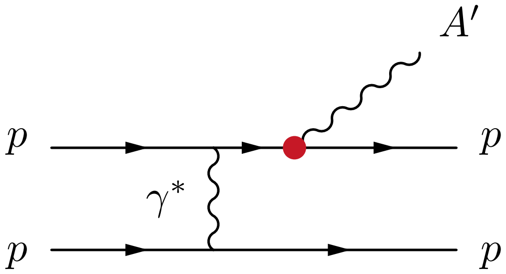


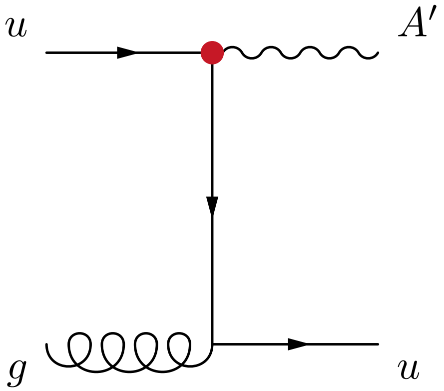


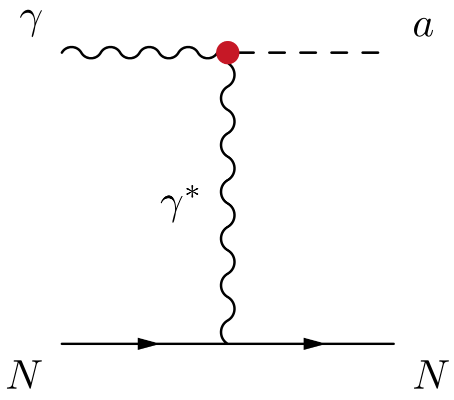


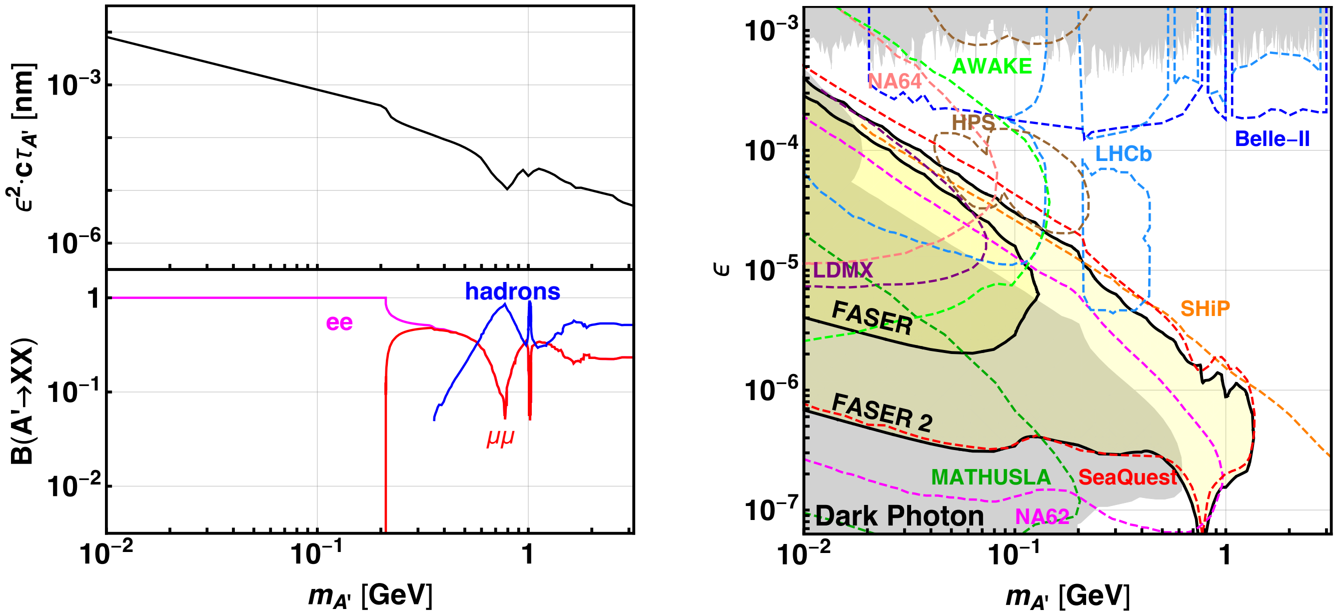


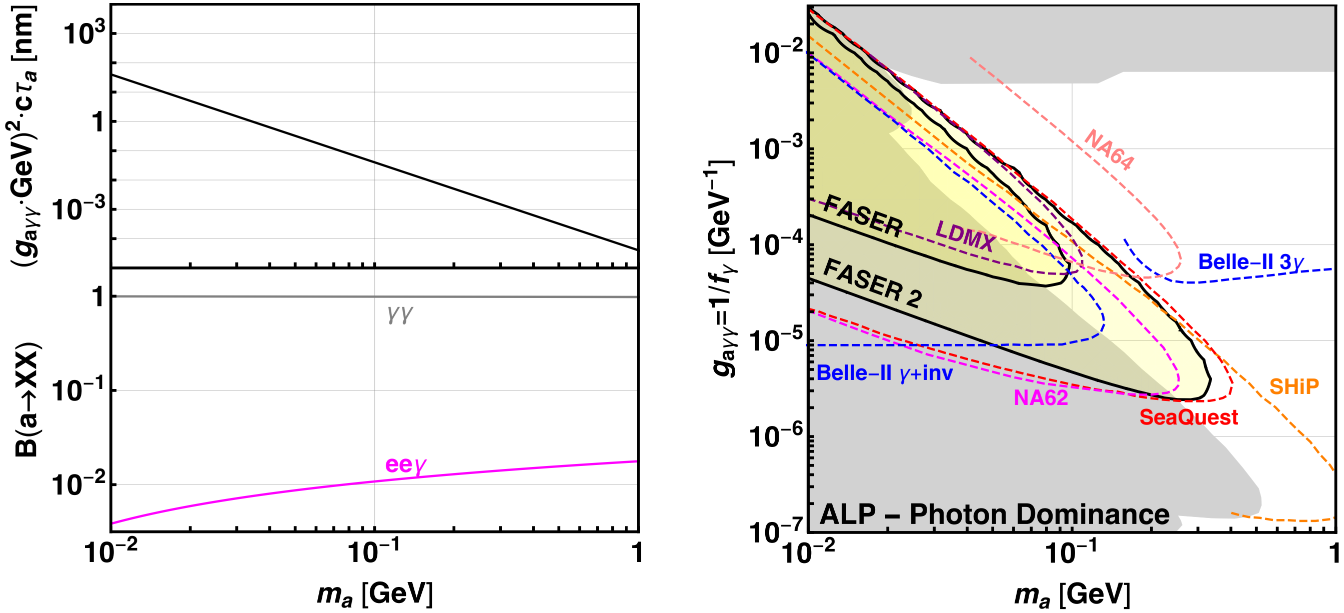

π^0
γ
A'


A'
p
p
γ^*
p
p


u
A'
g
u


γ
a
γ^*
N
N


$\epsilon^2 \cdot c\tau_{A'}$ [nm]
B(A'→XX)
ee
hadrons
μμ
$m_{A'}$ [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)
γγ
eeγ
m_a [GeV]
$g_{a\gamma\gamma} = 1/f_\gamma$ [GeV^{-1}]
NA64
FASER
LDMX
FASER 2
Belle–II 3γ
Belle–II γ+inv
NA62
SeaQuest
SHiP
ALP – Photon Dominance

Reach for Heavy Neutral Leptons

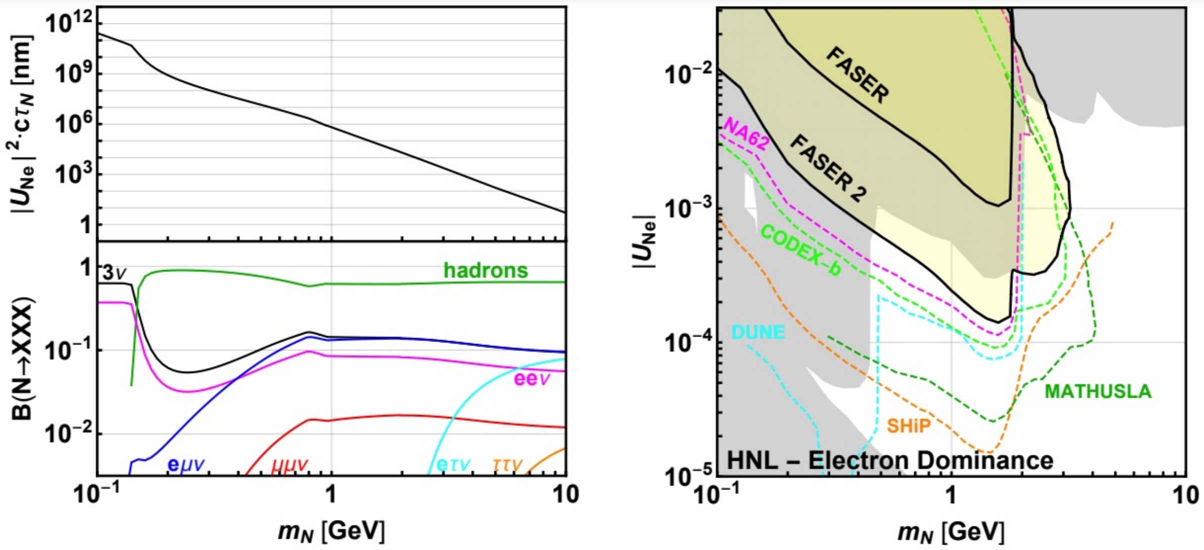


FIG. 12. **Benchmark Model F1.** The decay length (top left panel), decay branching fractions (bottom left panel), and FASER's reach (right panel) for the HNL that mixes only with the electron neutrino ν_e. The gray shaded regions are excluded by current limits, and the colored contours are the projected sensitivities for other proposed experiments. See the text for details.

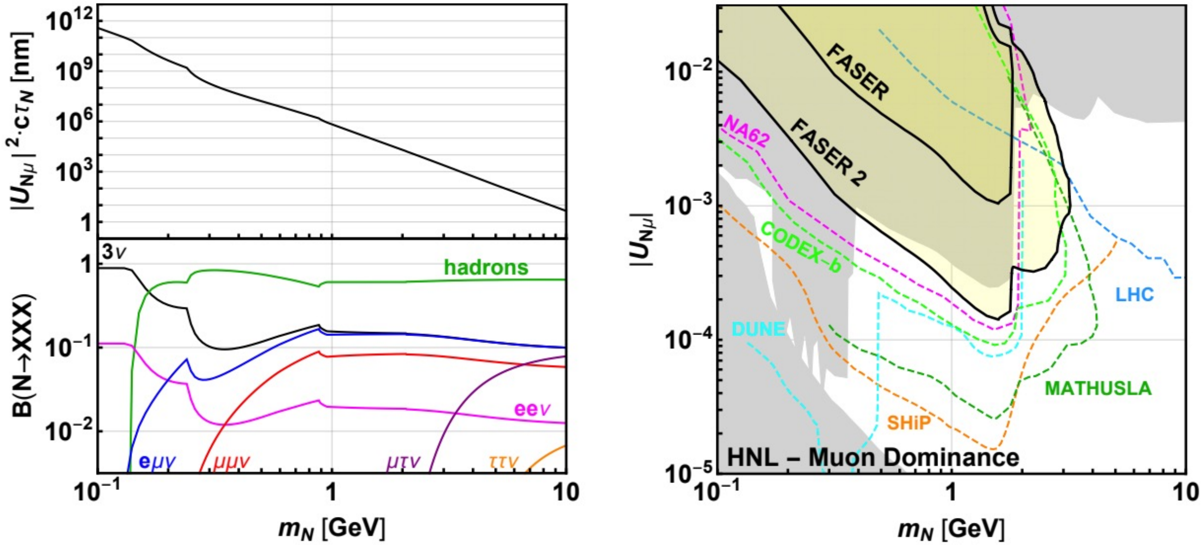


FIG. 13. **Benchmark Model F2.** As in Fig. 12, but for an HNL that only mixes with ν_μ.

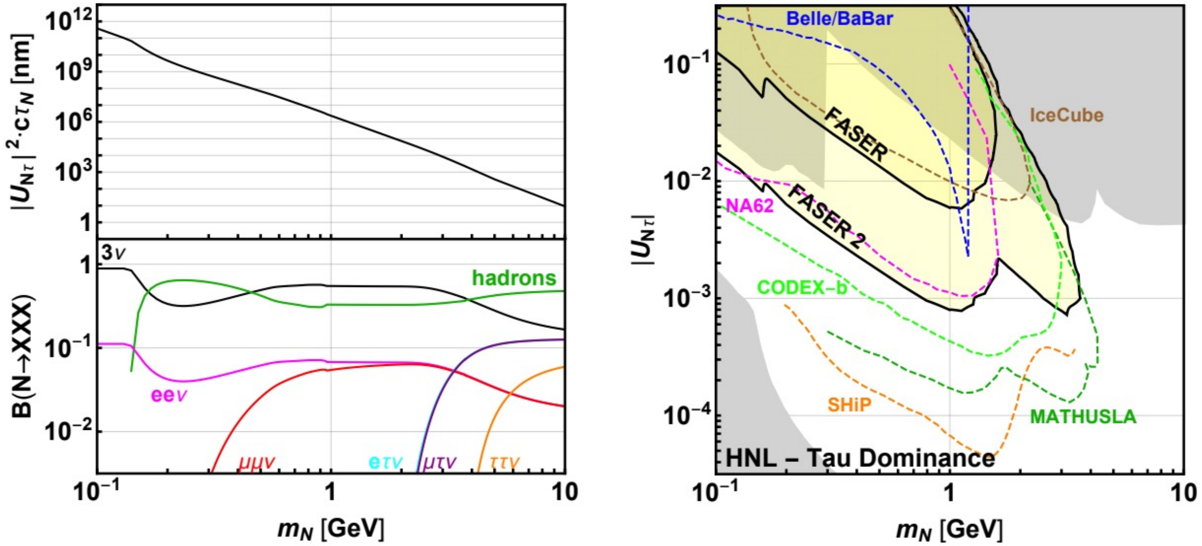
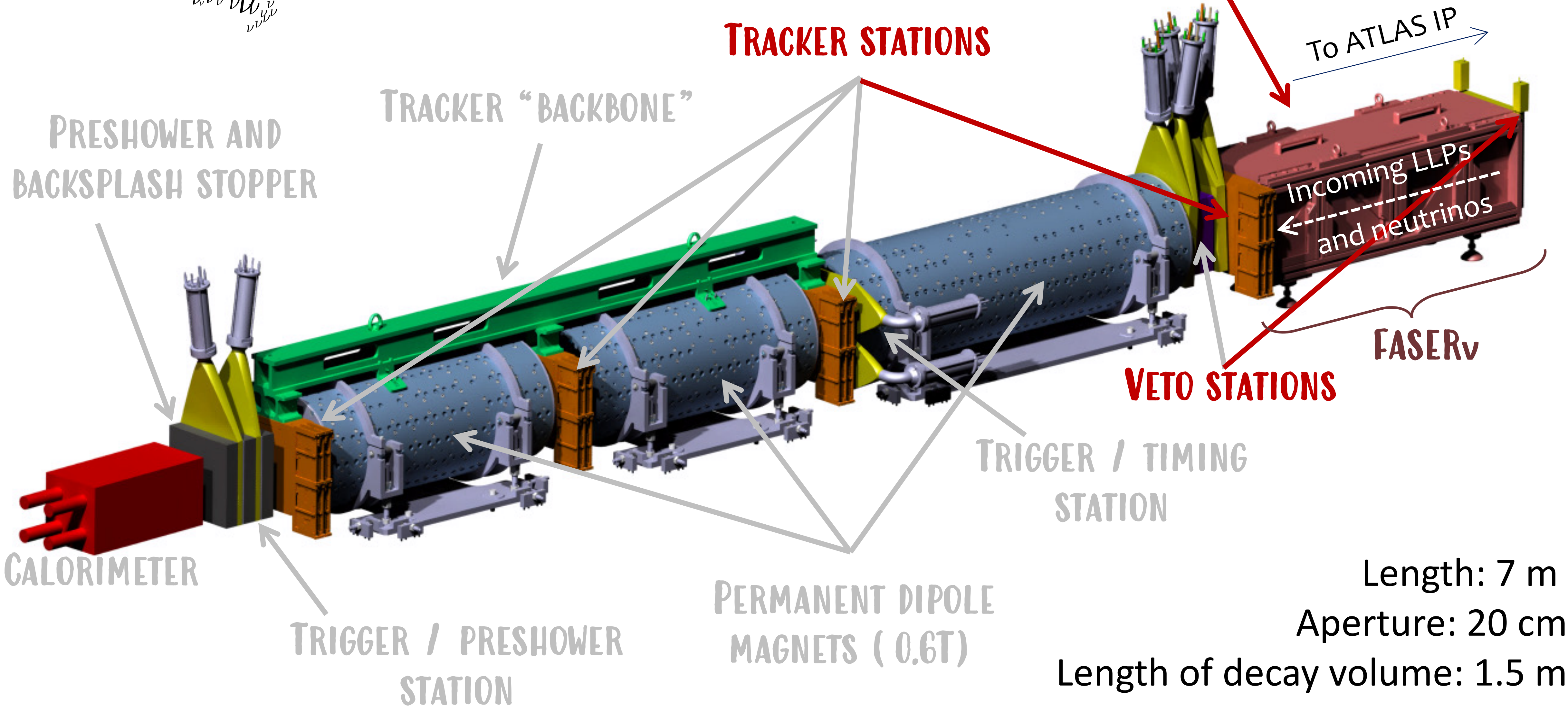


FIG. 14. **Benchmark Model F3.** As in Fig. 12, but for an HNL that only mixes with ν_τ.

The FASER Detector

FASER Detector



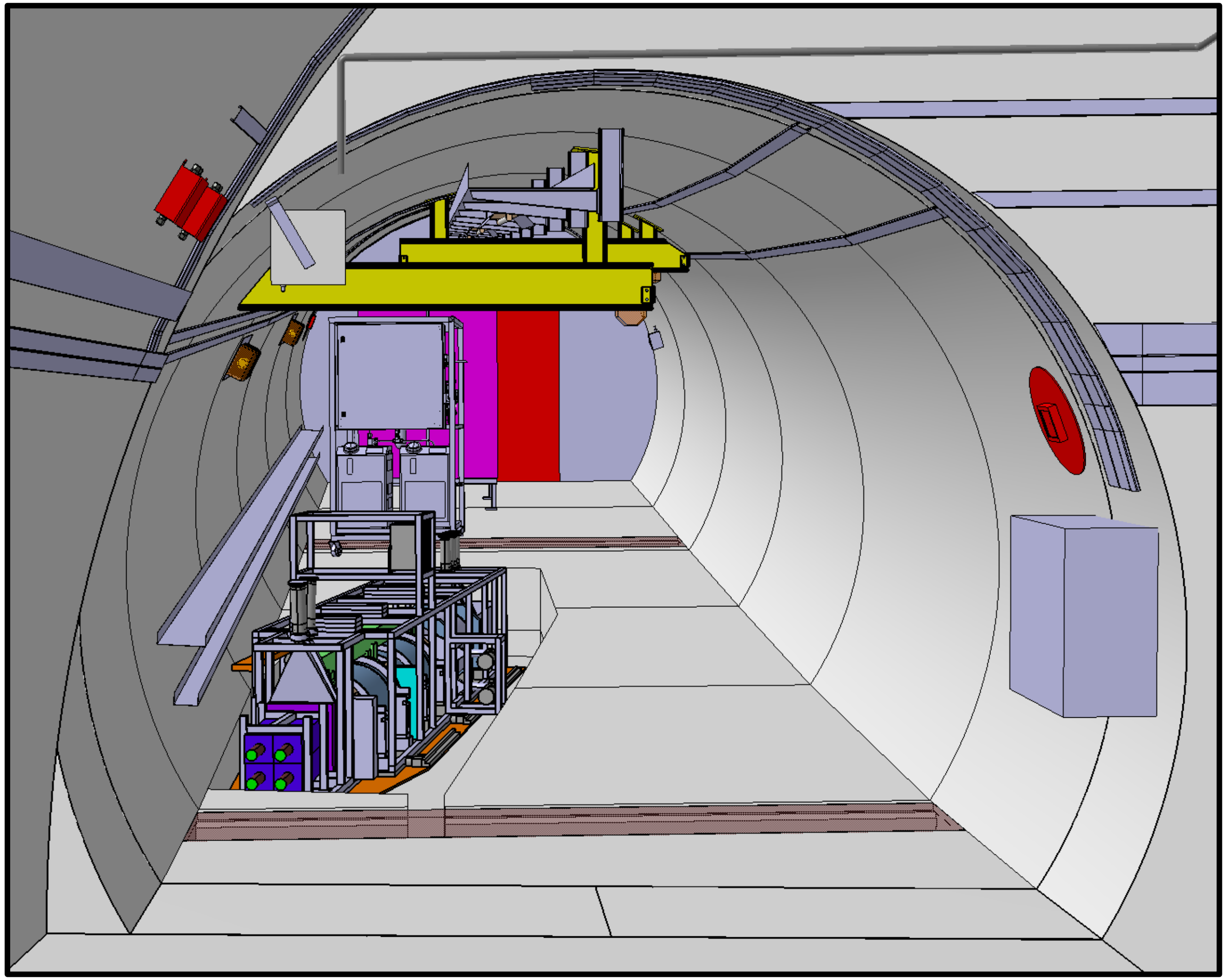
Length: 7 m
Aperture: 20 cm
Length of decay volume: 1.5 m

NEW! The FASER detector arXiv:2207.11427

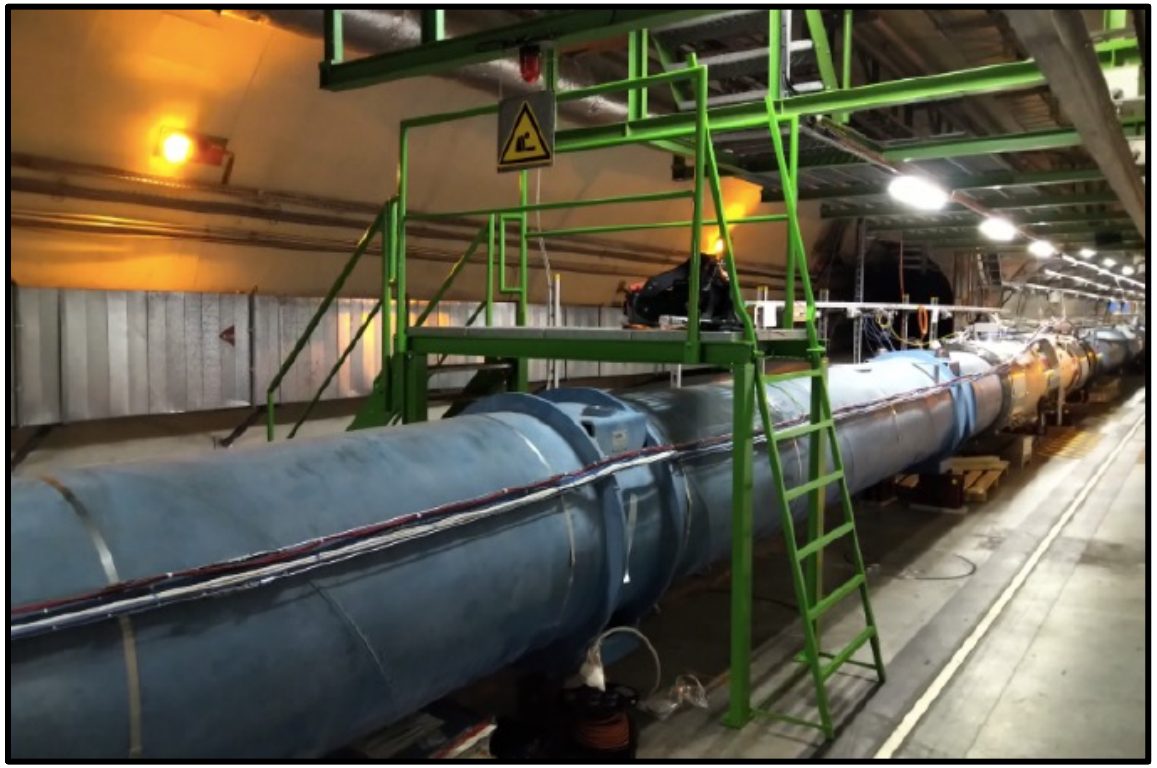
Location

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

Access tunnel and Infrastructure



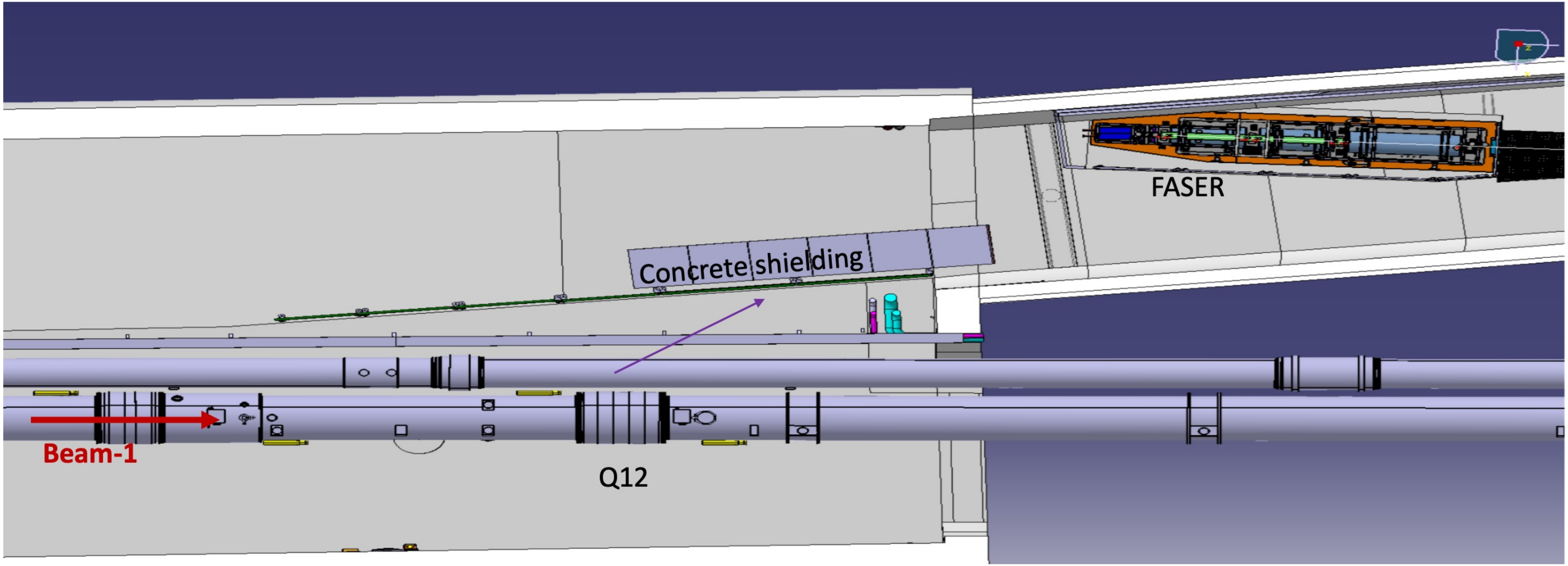
Access to TI12 is over the LHC machine complicates the transport & safety



Slide from Jamie Boyd

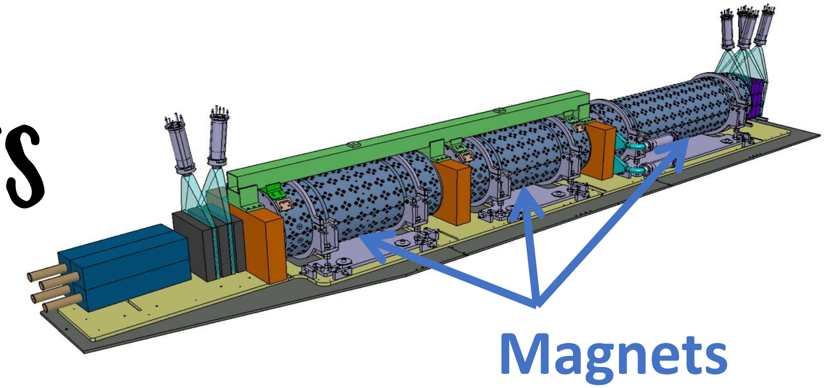
Beam-1 background

- **Reminder**: When beam-1 bunches pass the back of FASER (on way to ATLAS) they can lead to background in FASER (mostly at the back). This background is ~127 BCIDs too early compared to particles coming from IP1 to FASER
  - Concrete shielding installed at back of FASER to reduce this background

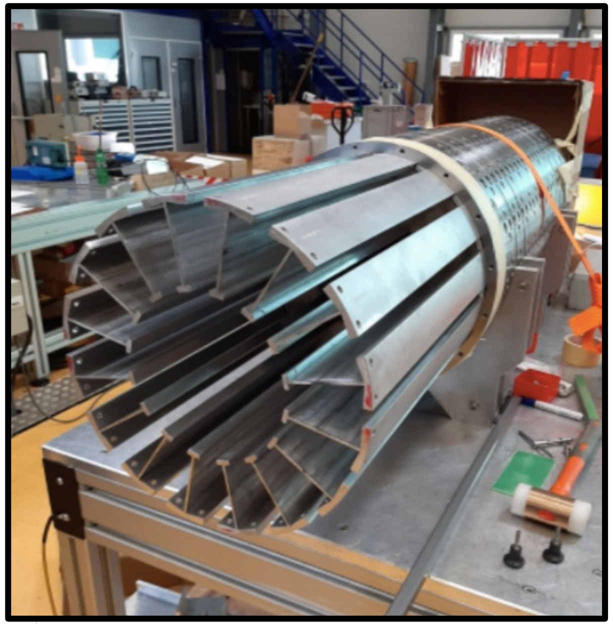


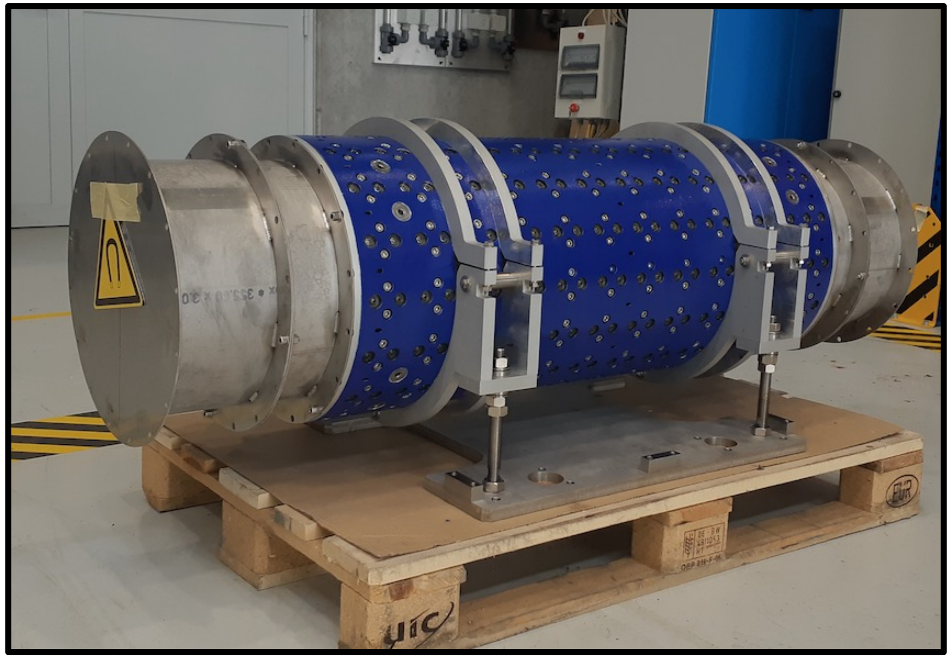
Beam-1 interactions in Q12 magnet can lead to background particles in FASER

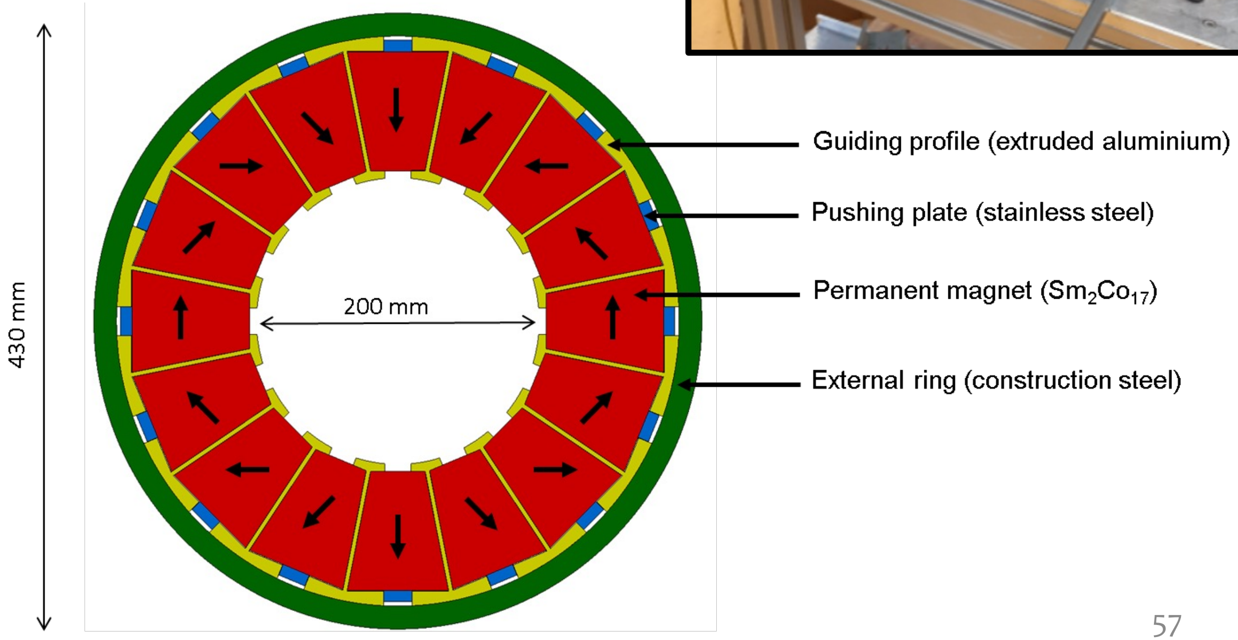
Magnets



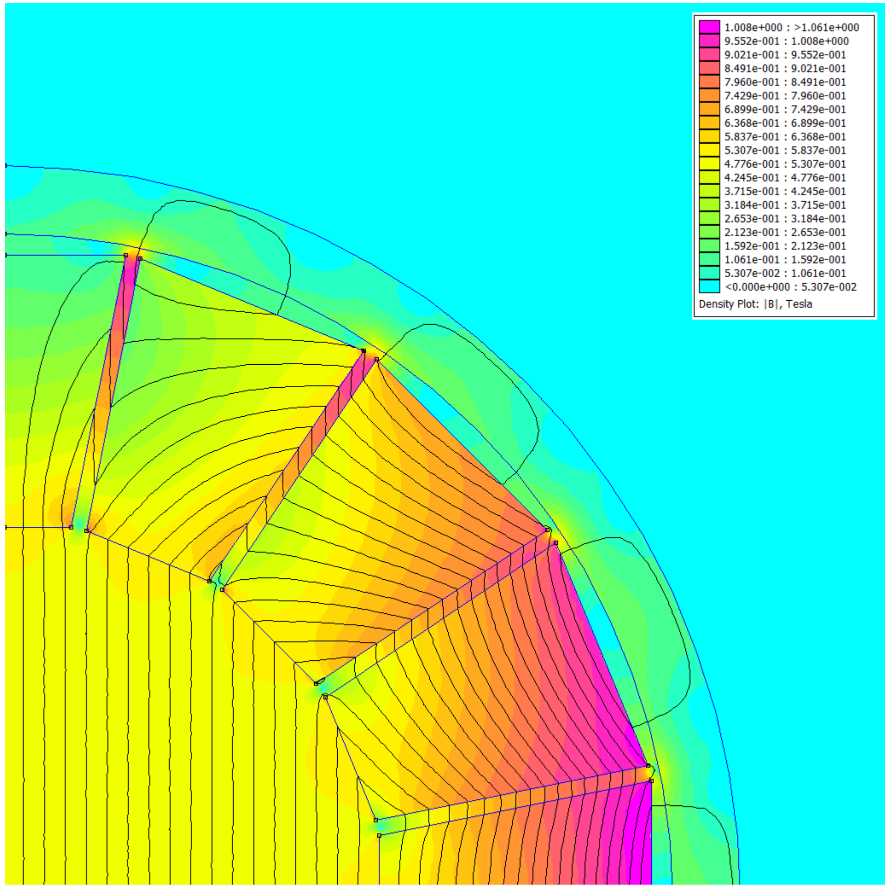
- Field of 0.55 T; permanent dipole
- Halbach array design with fixed-field magnets
  - Maximizes field without need for too much support infrastructure
  - Allows for a compact design, reducing amount of digging

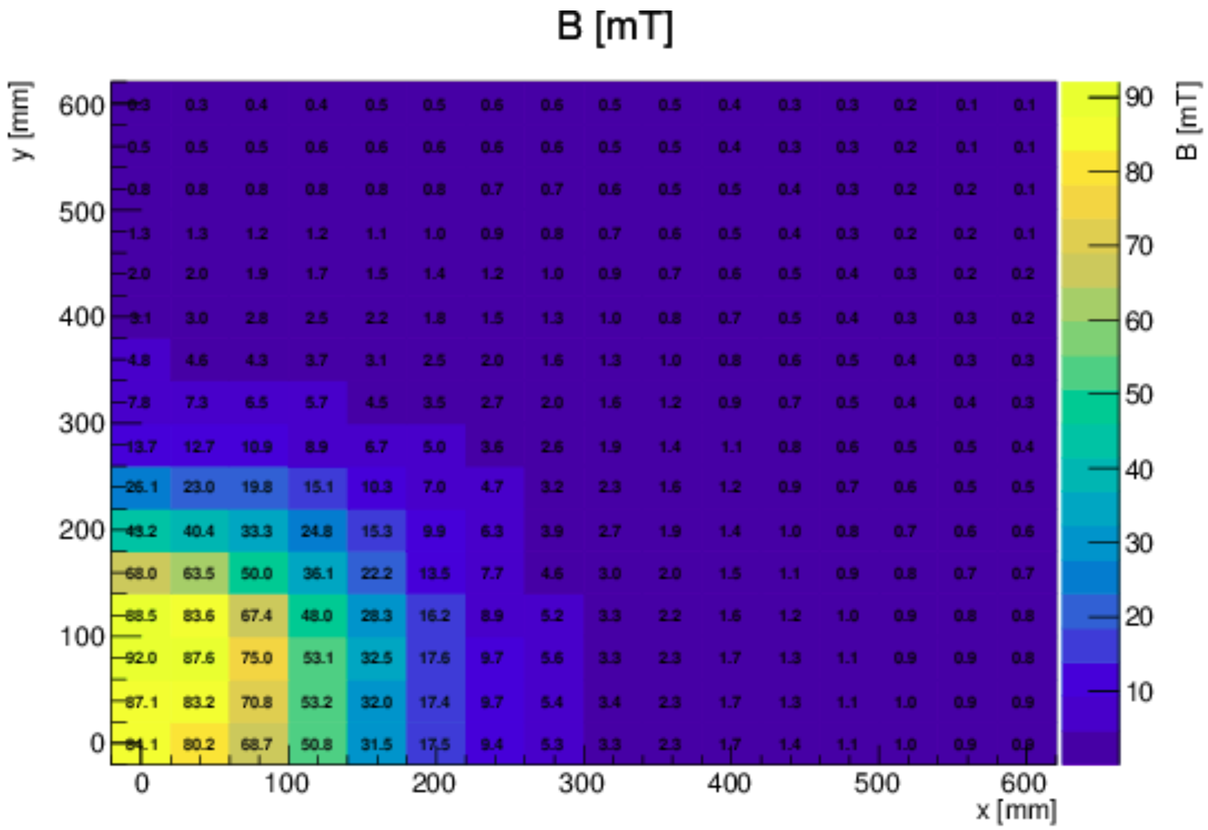






Magnets

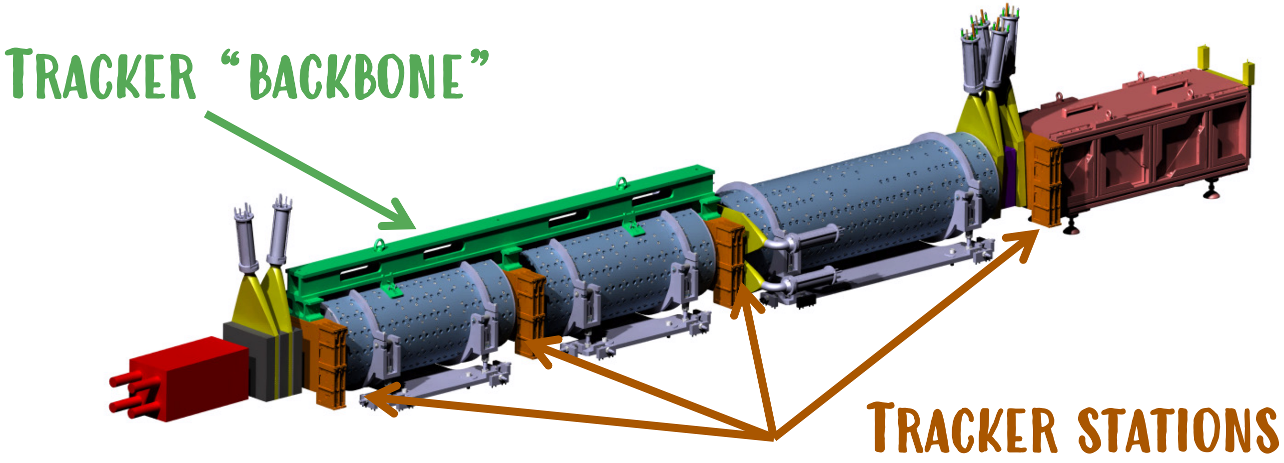

1.008e+000 : >1.061e+000
9.552e-001 : 1.008e+000
9.021e-001 : 9.552e-001
8.491e-001 : 9.021e-001
7.960e-001 : 8.491e-001
7.429e-001 : 7.960e-001
6.899e-001 : 7.429e-001
6.368e-001 : 6.899e-001
5.837e-001 : 6.368e-001
5.307e-001 : 5.837e-001
4.776e-001 : 5.307e-001
4.245e-001 : 4.776e-001
3.715e-001 : 4.245e-001
3.184e-001 : 3.715e-001
2.653e-001 : 3.184e-001
2.123e-001 : 2.653e-001
1.592e-001 : 2.123e-001
1.061e-001 : 1.592e-001
5.307e-002 : 1.061e-001
<0.000e+000 : 5.307e-002
Density Plot: |B|, Tesla

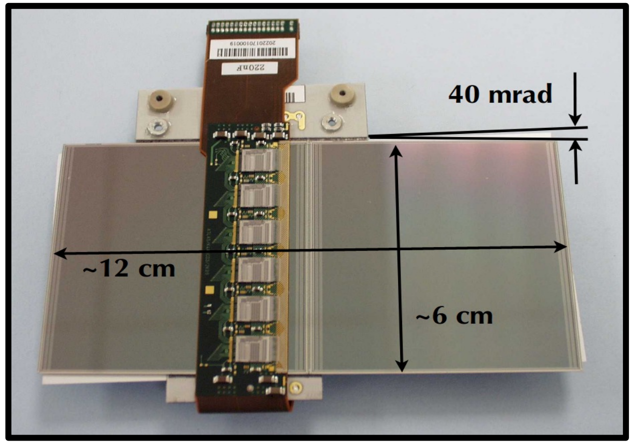

B [mT]
y [mm]
600
500
400
300
200
100
0
0
100
200
300
400
500
600
x [mm]
90
80
70
60
50
40
30
20
10
B [mT]

TRACKER

THANKS!

- FASER uses ATLAS SCT spare modules
- 4 tracker stations x 3 tracker layers x 8 modules
  - 96 modules and $O(10^5)$ channels in total
- Mechanical stability by “backbone” fixed on magnets
- Read out with custom GPIO board

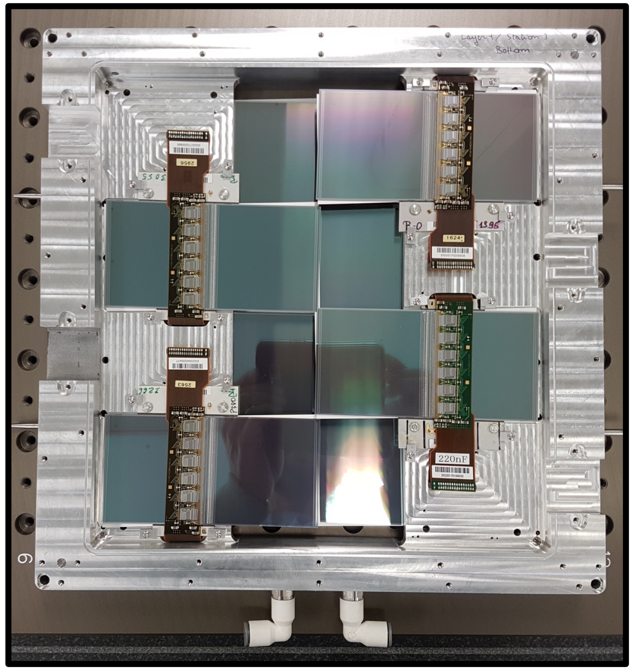




SCT module

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

Tracker layer

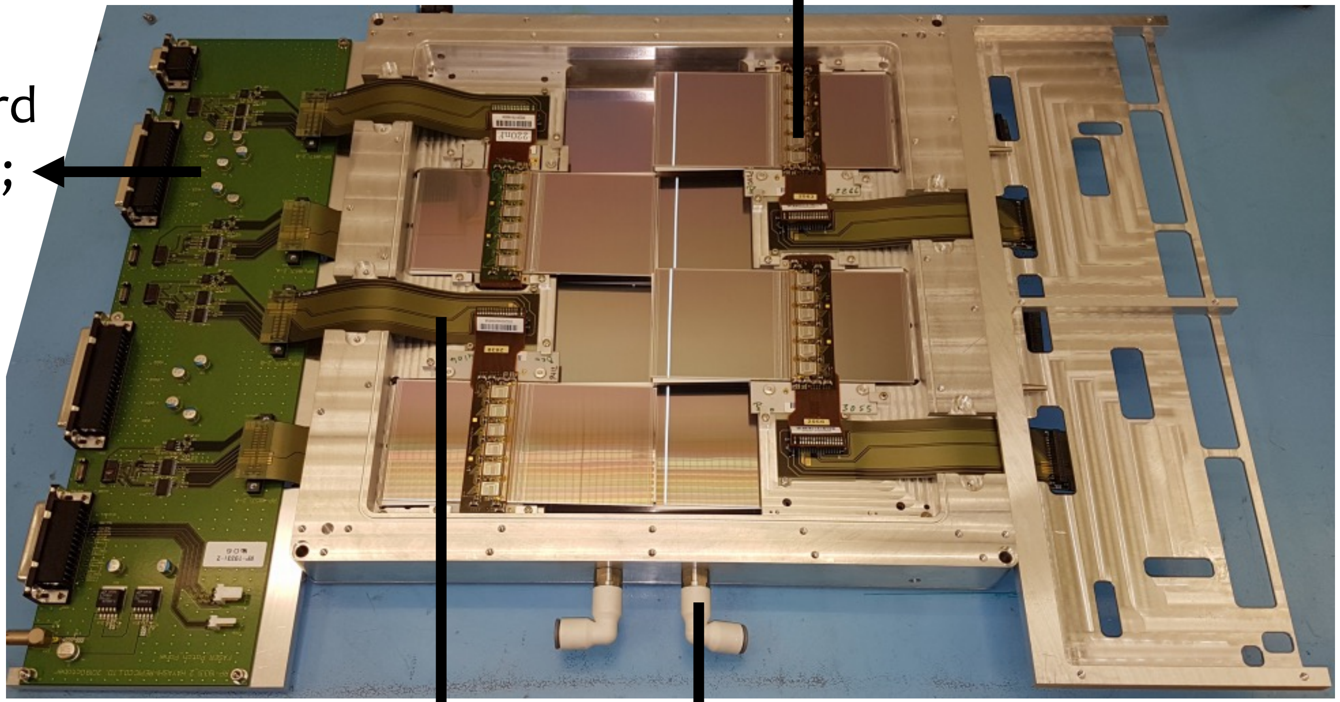


arXiv: 2112.01116

Tracker

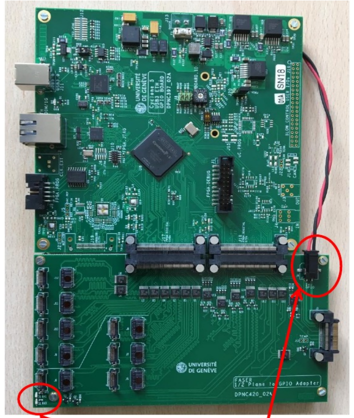
SCT module ASICs, require ~ 5 W / module

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



FLEX cables

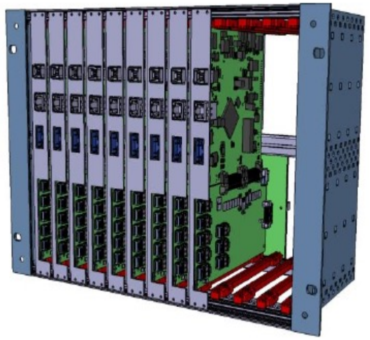
Detector cooling via water chiller operating at 10-15^{o}C



2 front panels LEDs

24V discrete wire to TRB adapter

Into custom-made mini-crate



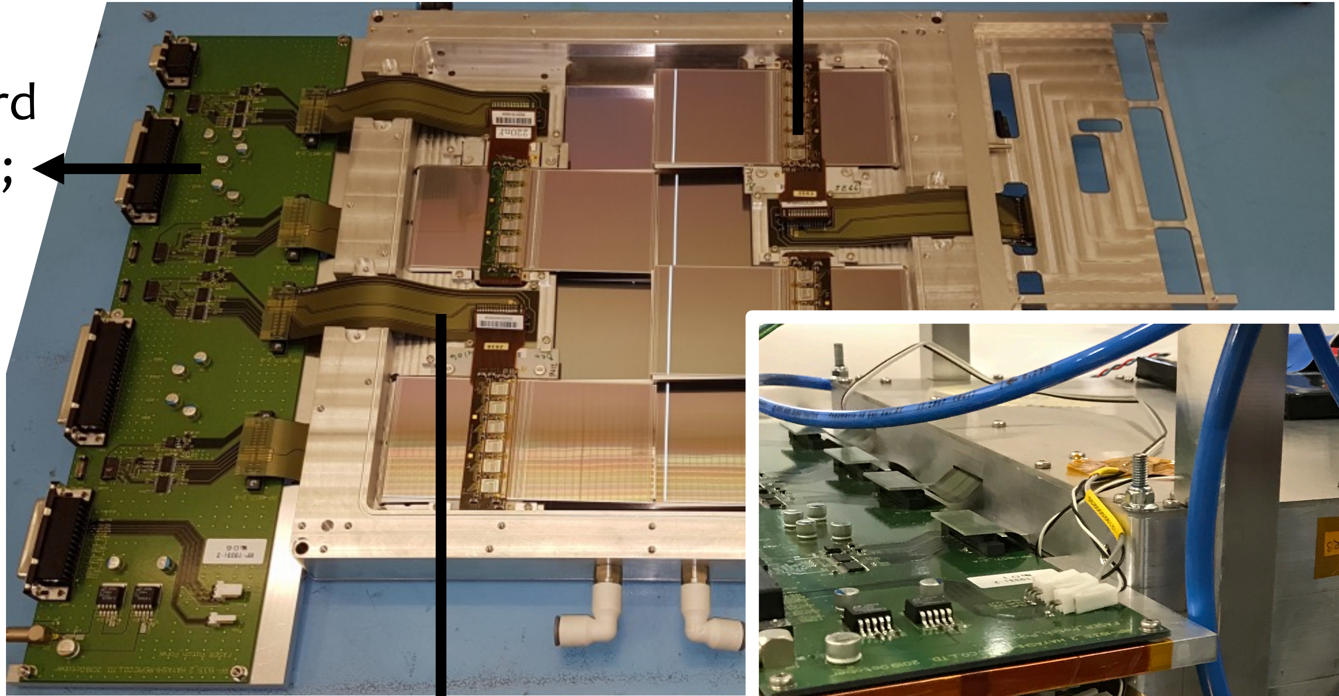
Low radiation in TI12 and much lower rates than ATLAS allow for simplifications in services and readout.

arXiv: 2112.01116

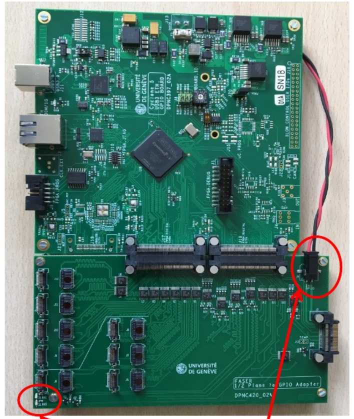
Tracker

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



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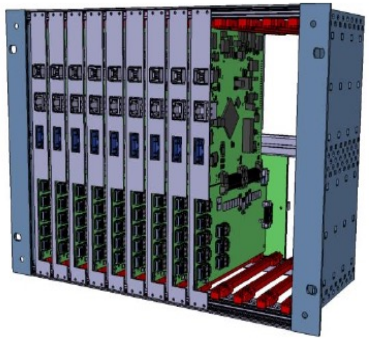
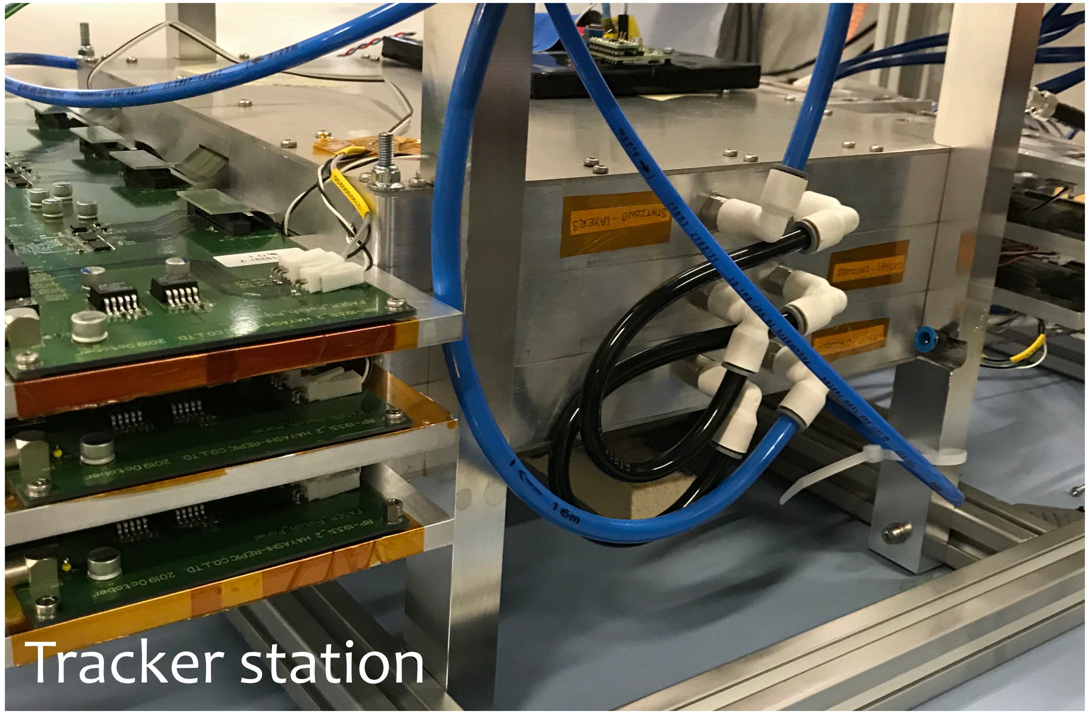
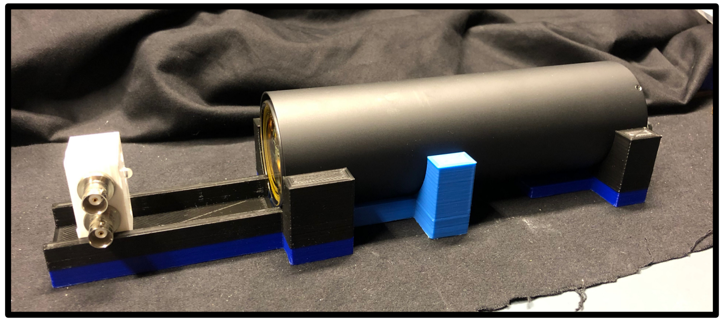




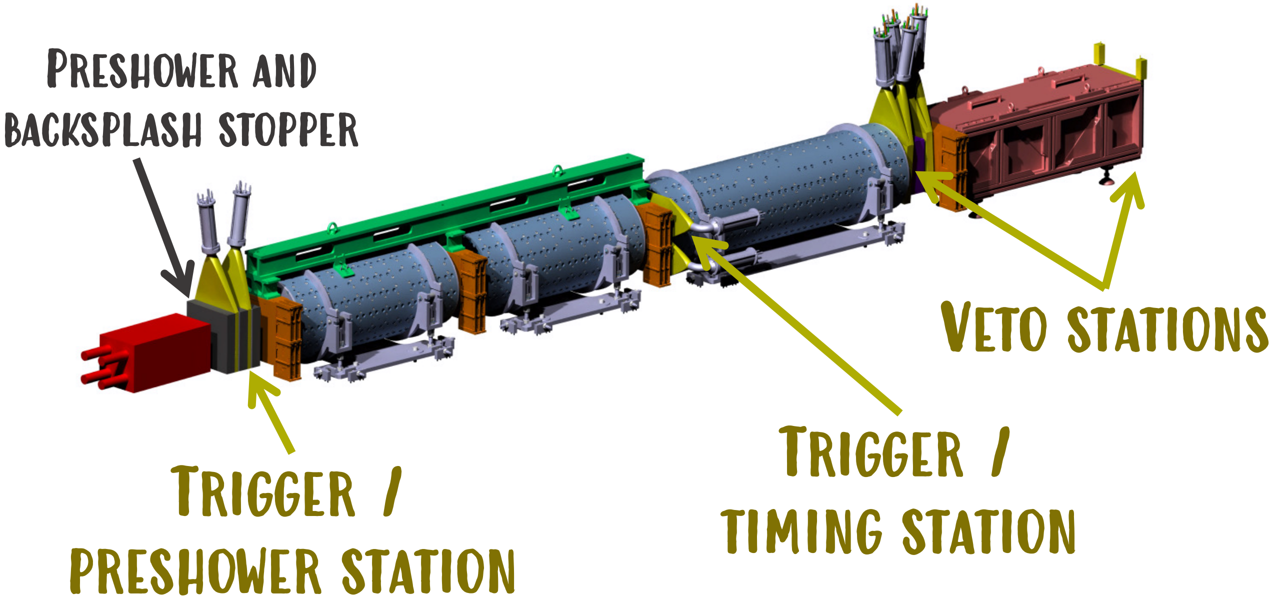
arXiv: 2112.01116

Scintillators



Scintillator PMTs

- Three stations all providing triggering capability:
  - Very high efficiency veto station for incoming charged particles (x6 planes)
  - Timing station; precise timing (~ ns) wrt IP (x1 plane)
  - Pre-shower station; coincidence with timing station (x2 planes)
- Read out with PMTs and CAEN digitizer

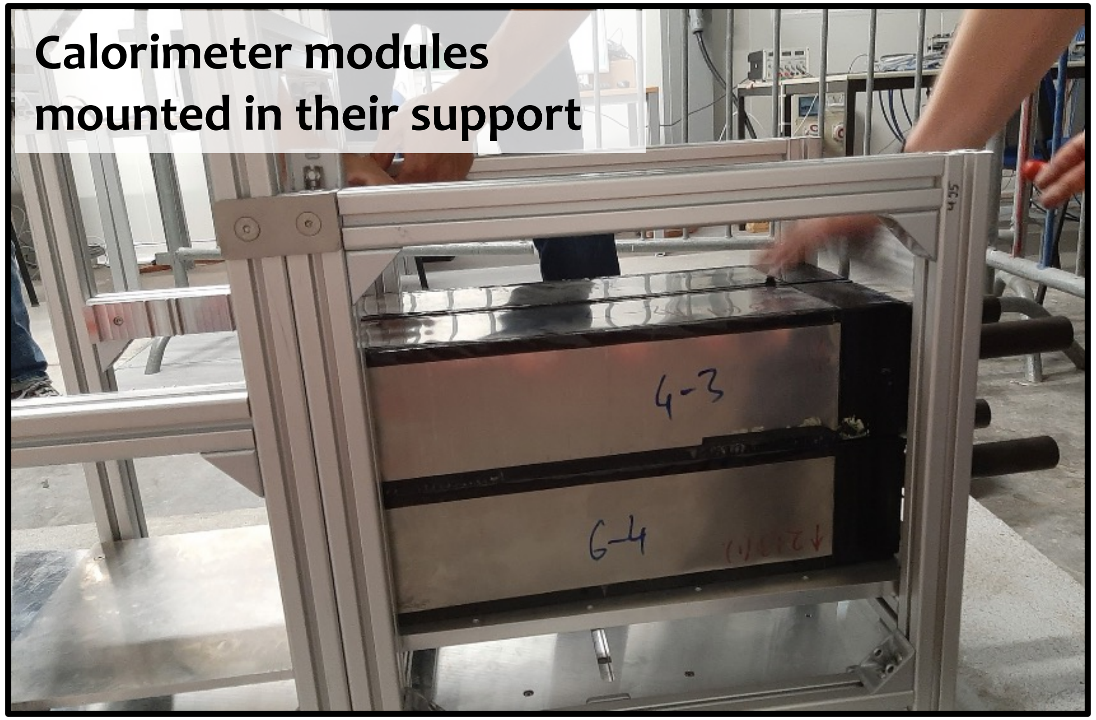


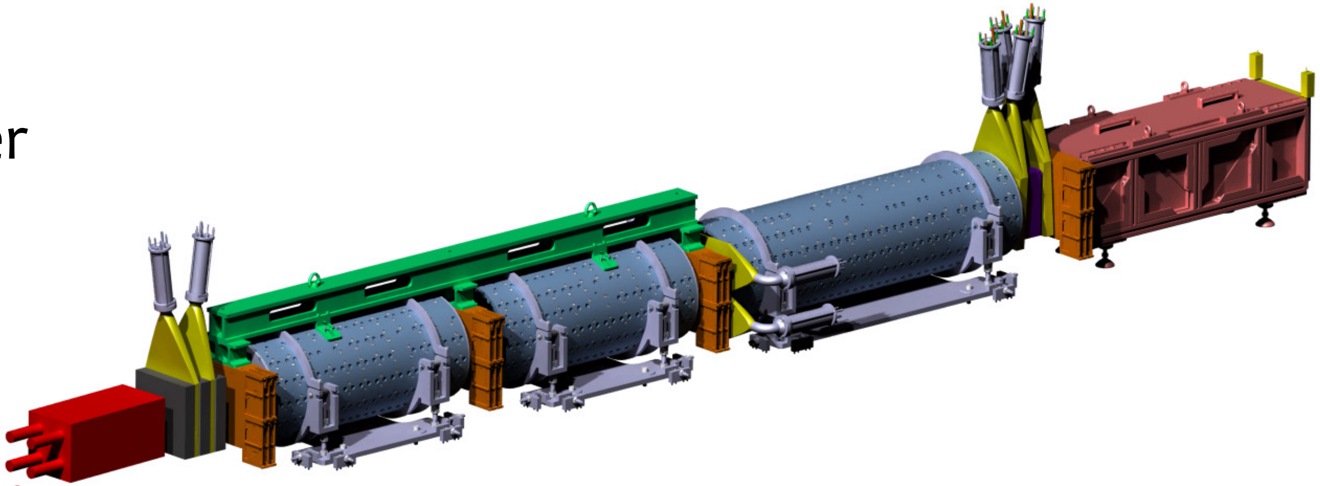
FASER scintillators mounted in their support

Calorimeter

THANKS!

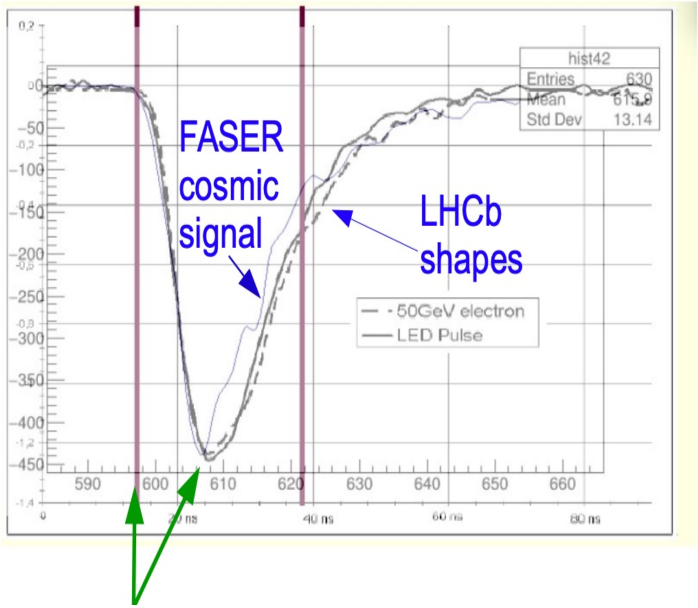
- FASER uses 4 LHCb spare outer ECAL modules
  - 25 radiation lengths long
  - Lead/scintillator calorimeter
- Energy resolution ~ 1% for TeV deposits
  - No longitudinal shower information
- Provides triggering capability
- Read out with PMTs and CAEN digitizer



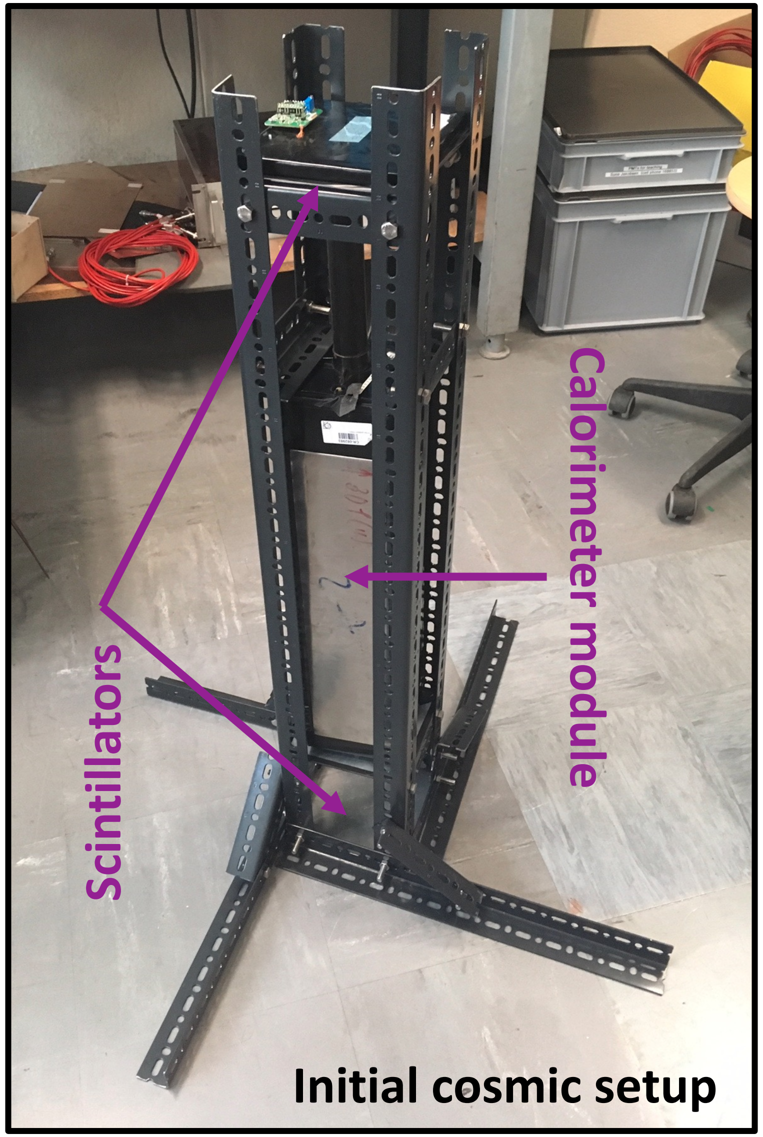


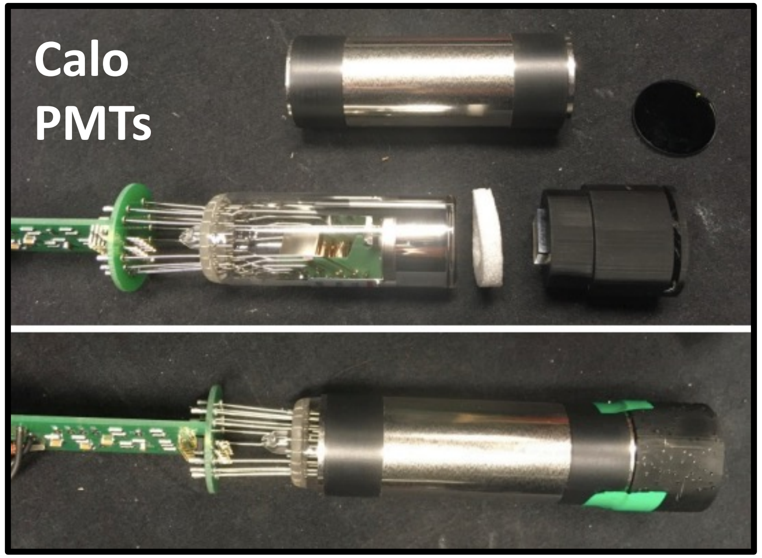
CALORIMETER

Calorimeter



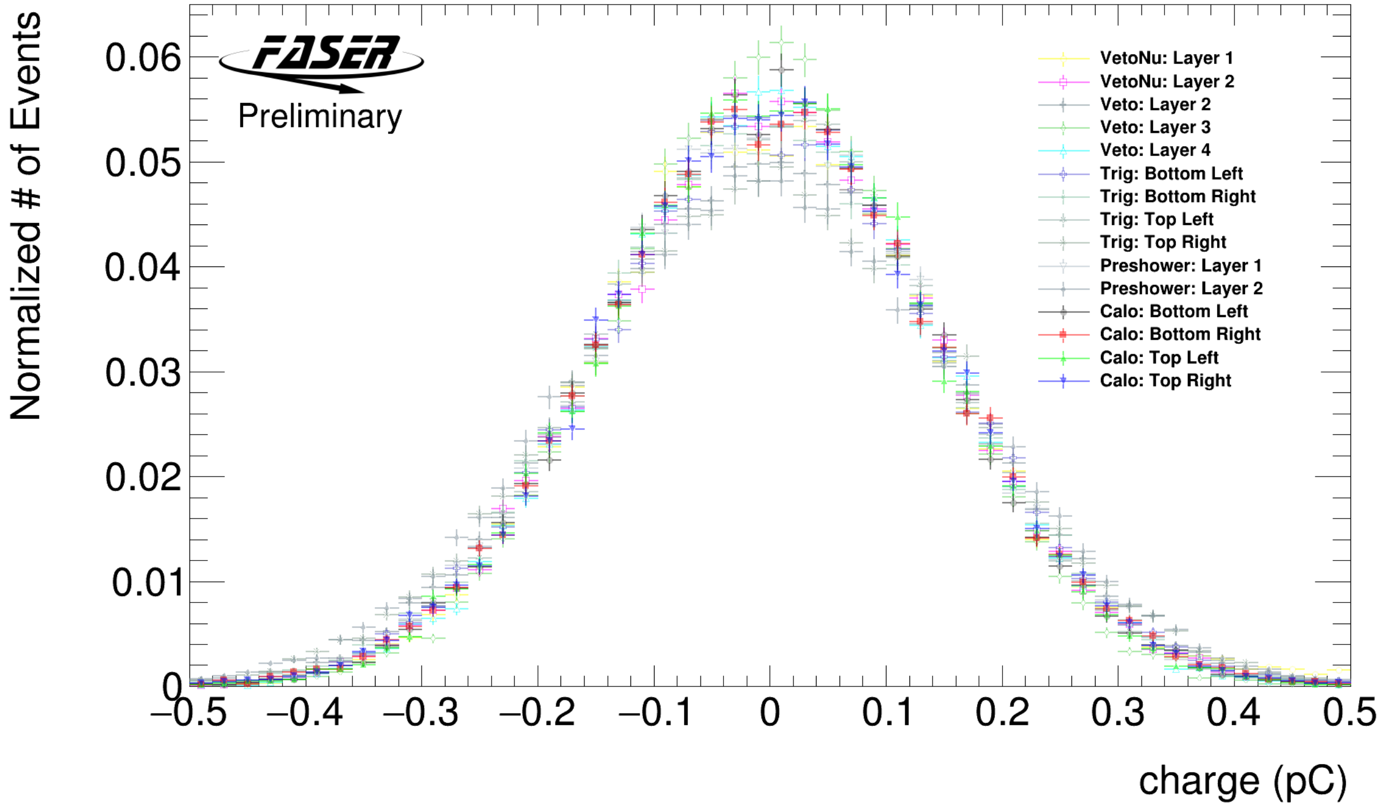
~10 ns rise time





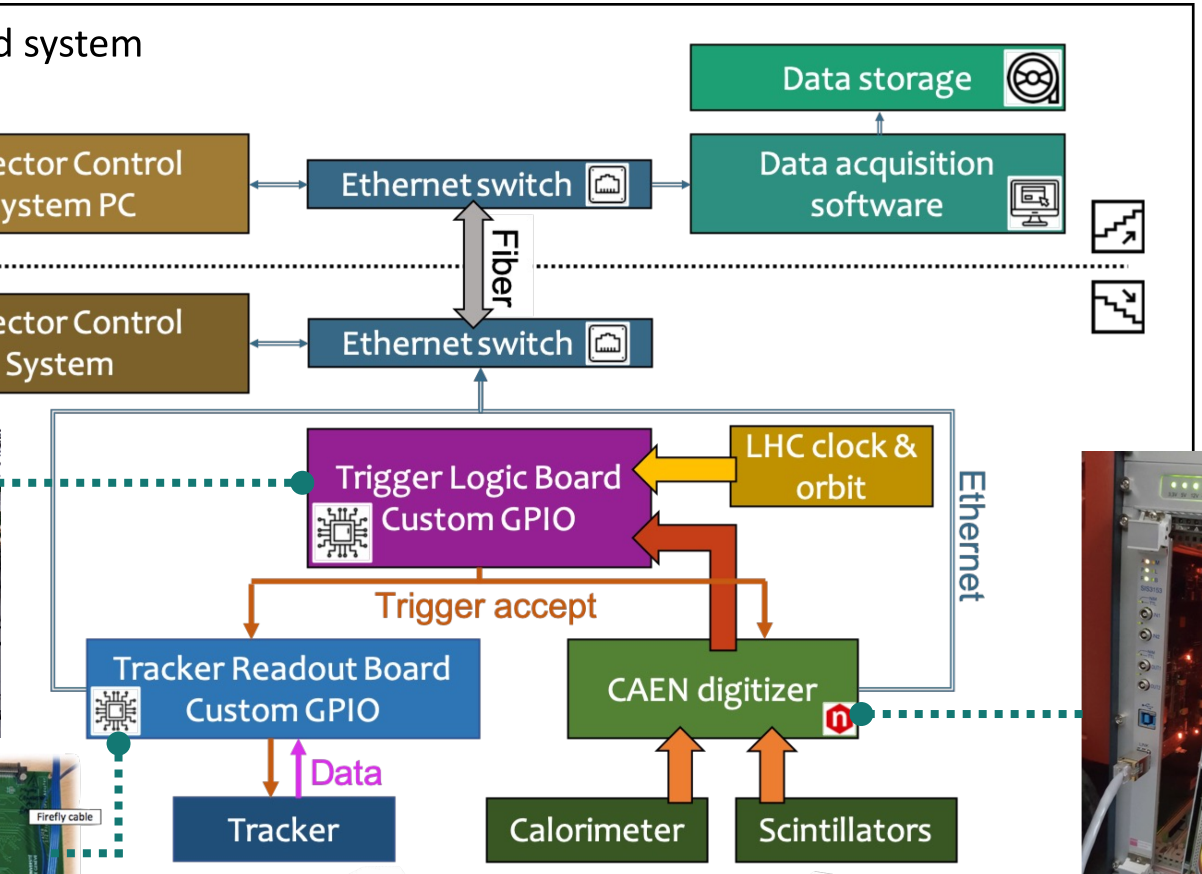
Noise distributions for all scintillator and calo channels

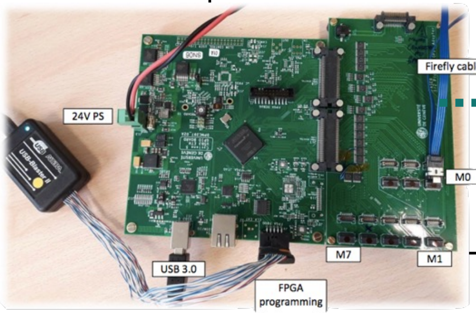
- The pedestal subtracted charge distributions of randomly triggered events are shown for all scintillators and calorimeter modules. The charge is derived from the integration of the waveform over the standard 120 ns reconstruction window. Normalization of the distributions are done by dividing by the total number of events. The plot shows that the noise levels are similar across all scintillators and calorimeter channels, regardless of different PMT types and HV settings. Dominated by the digitizer noise, the total noise of each sub detector falls within the range of 0.15 ± 0.02 pC.

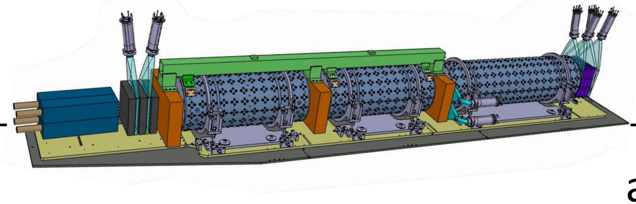


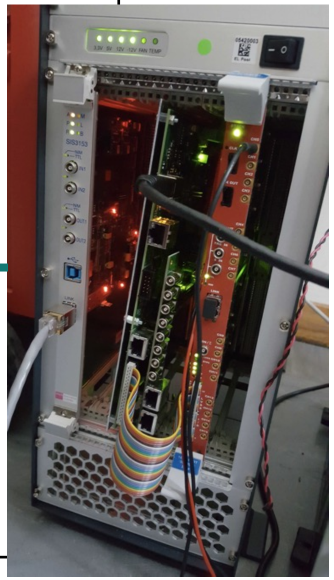
Trigger & Data acquisition

- 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 are placed in TI12







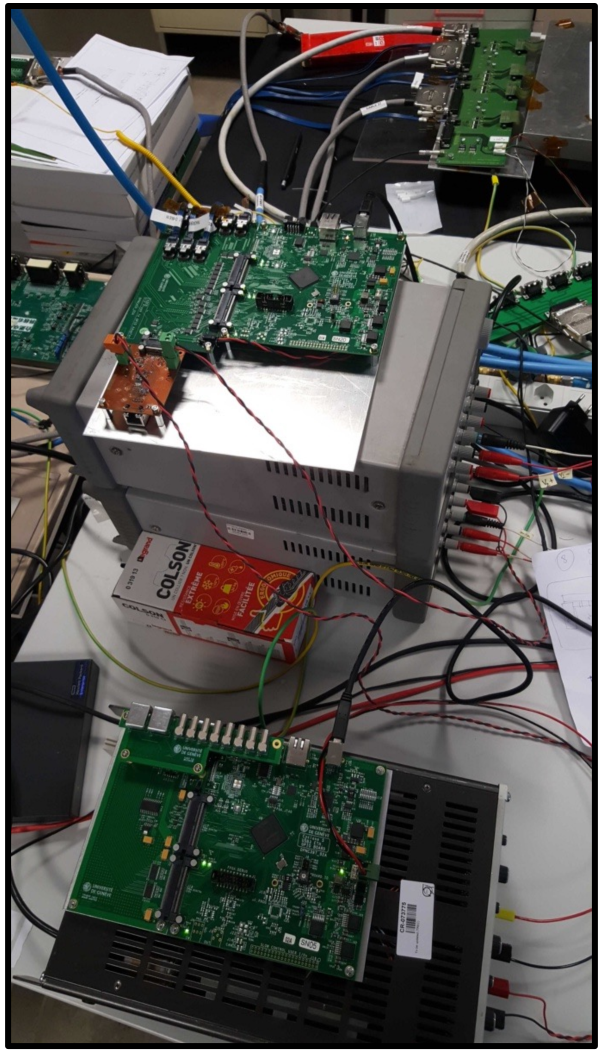


arXiv: 2110.15186

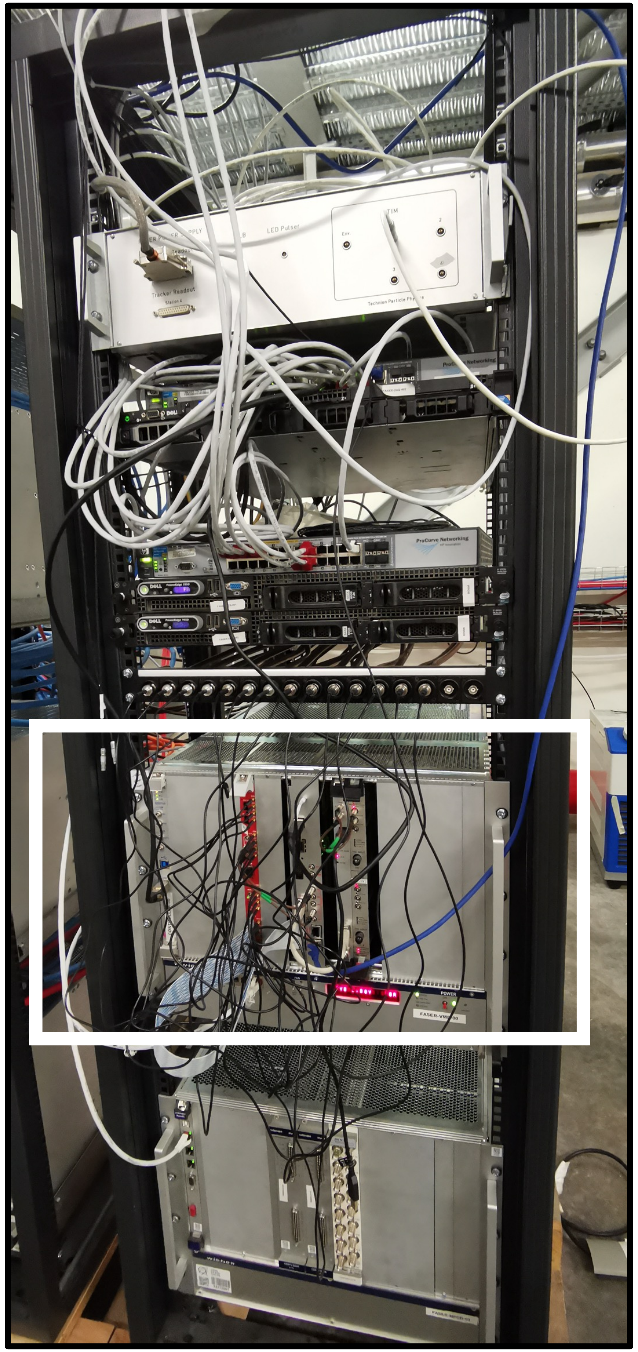
FASER Trigger & Data acquisition

Initial Run Control application, produced by summer intern

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

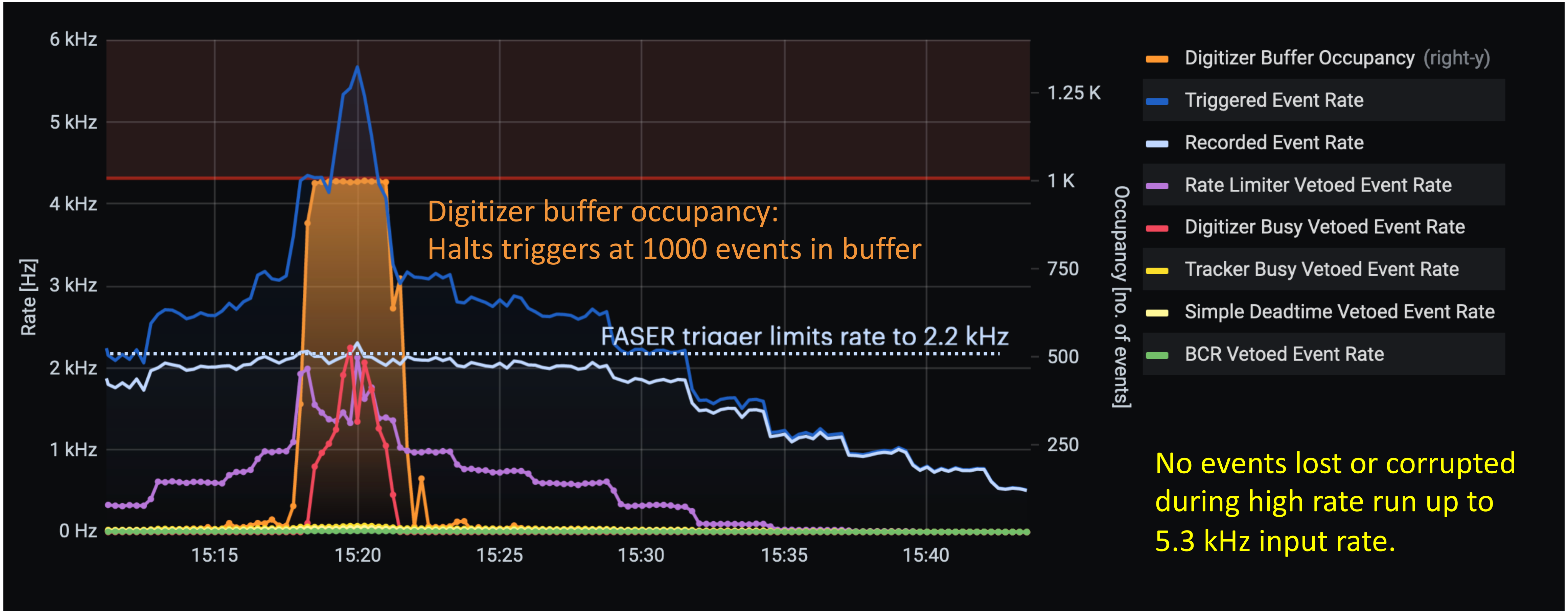


All boards connected together for tests



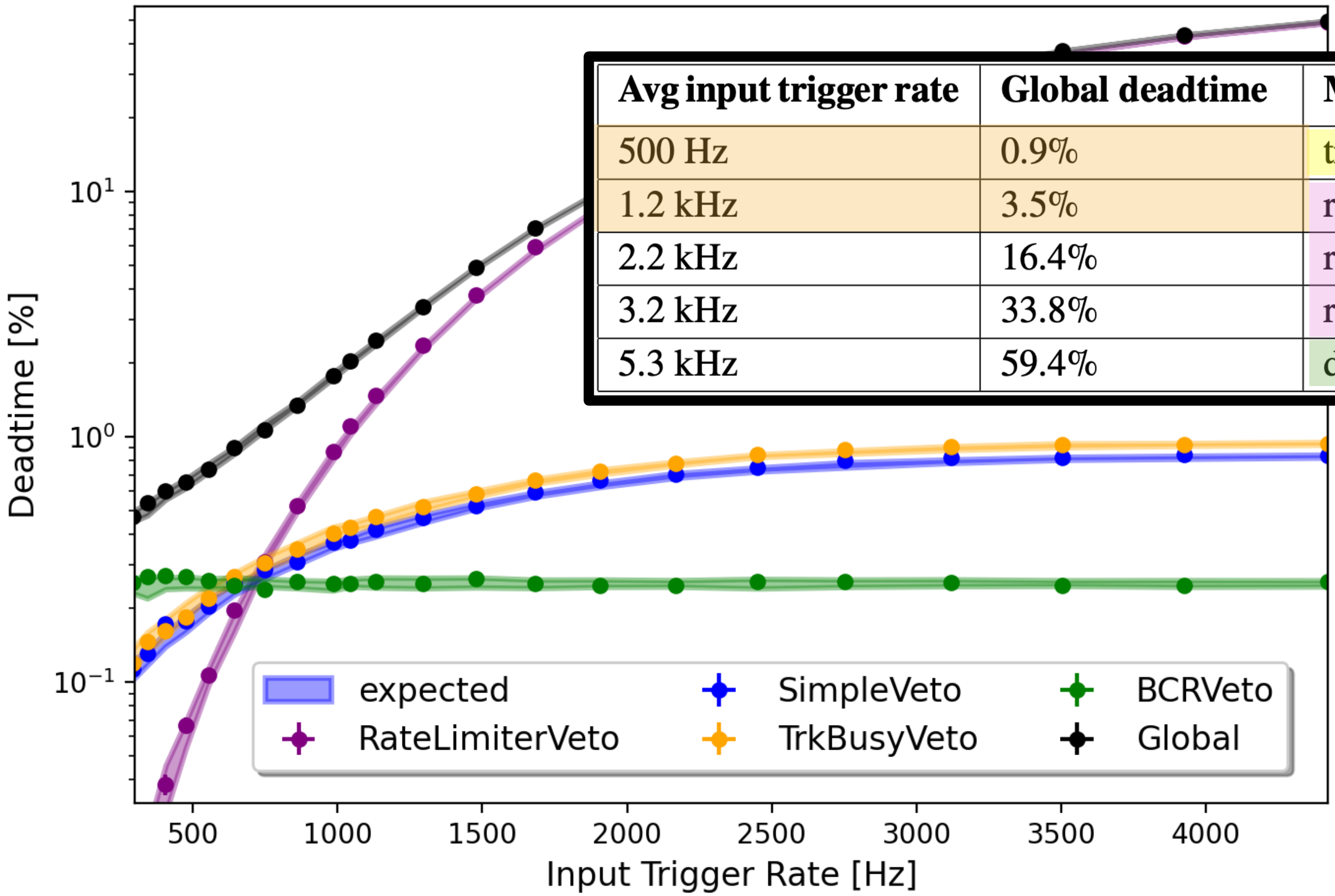
TDAQ boards in the final VME crate

High rate tests



NEW! arXiv: 2110.15186

Precise deadtime measurements



Avg input trigger rate	Global deadtime	Max deadtime source	Data throughput
500 Hz	0.9%	tracker	10 MBytes/s
1.2 kHz	3.5%	rate limiter	26 MBytes/s
2.2 kHz	16.4%	rate limiter	47 MBytes/s
3.2 kHz	33.8%	rate limiter	47 MBytes/s
5.3 kHz	59.4%	digitizer	47 MBytes/s

Expected Run3 rates

Tracker only reads out one event at a time

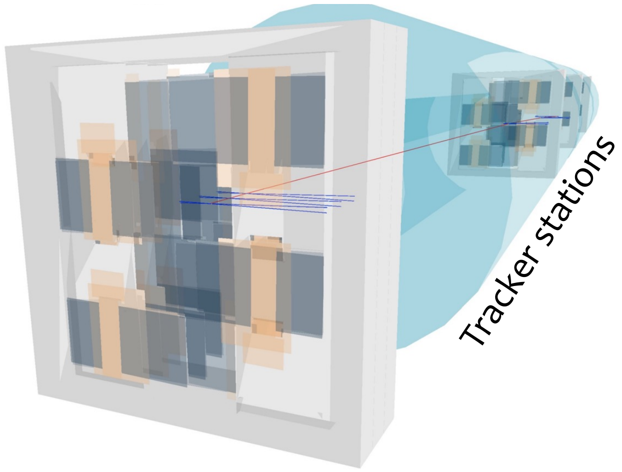
Rate is limited to 2.2 kHz

Digitizer read-out limitations

At 500 Hz,
deadtime expected to be < 1 %

NEW! arXiv: 2110.15186

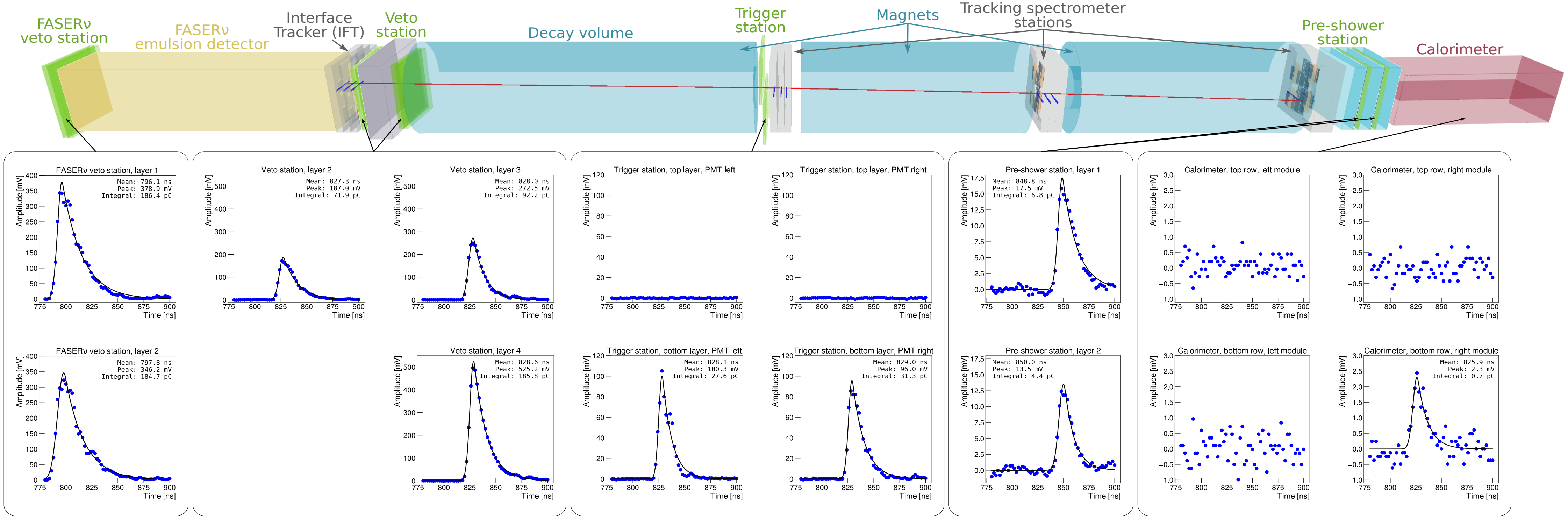
Example Typical event: muon



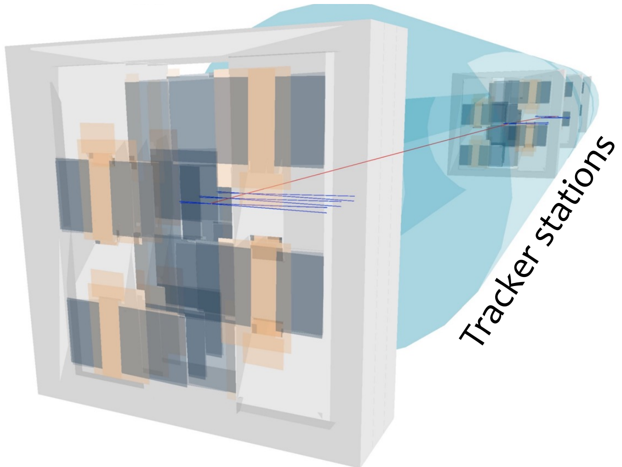
Run 8336
Event 1477982
2022-08-23 01:46:15

Collision event with muon traversing FASER

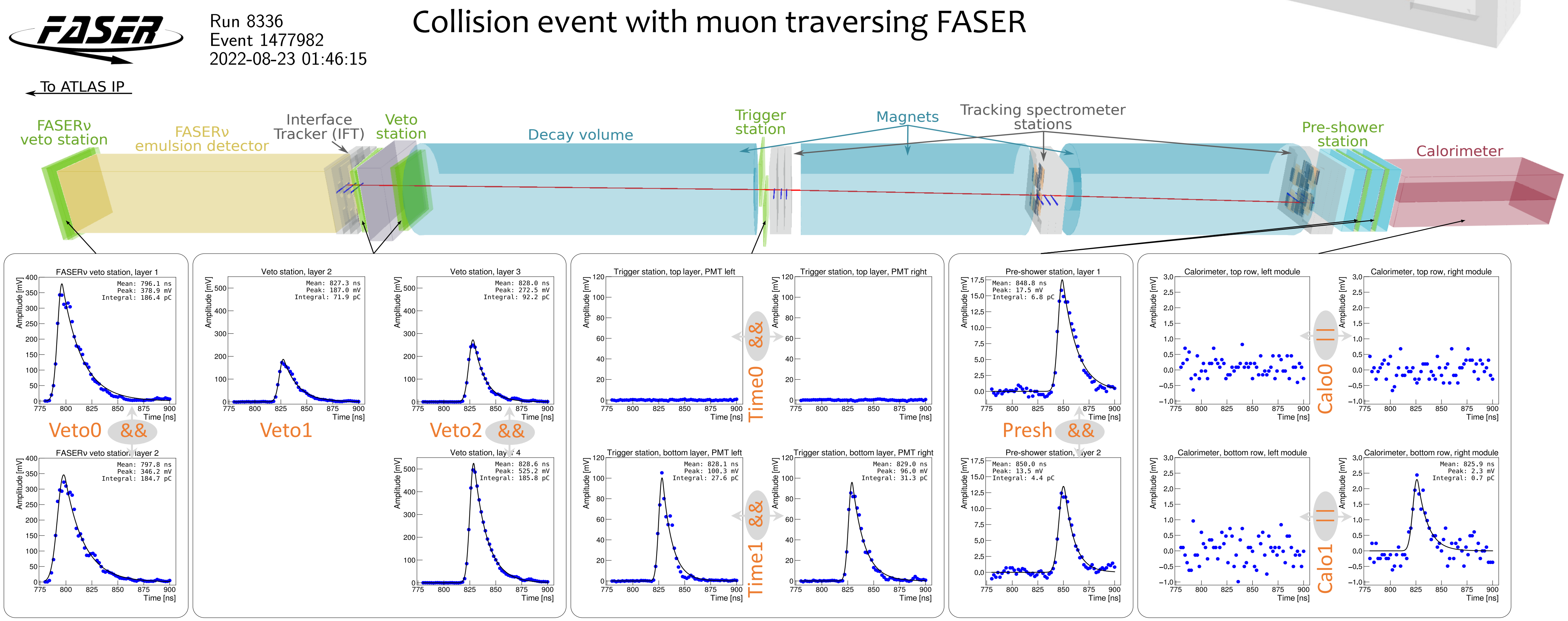
To ATLAS IP



Example Typical event: muon



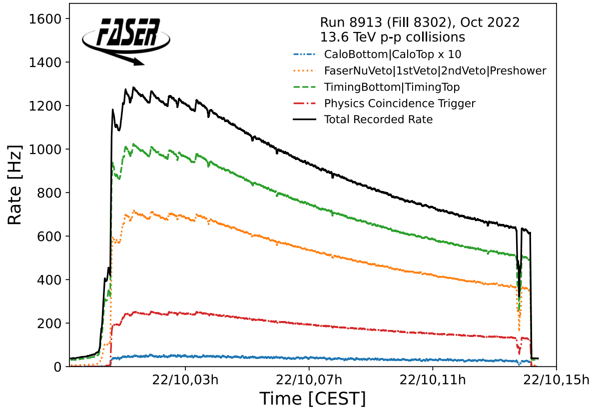
Collision event with muon traversing FASER

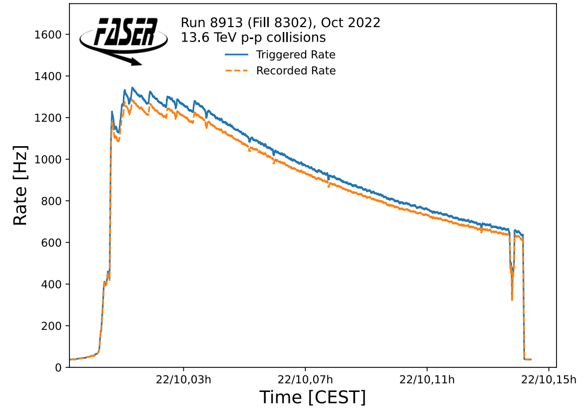


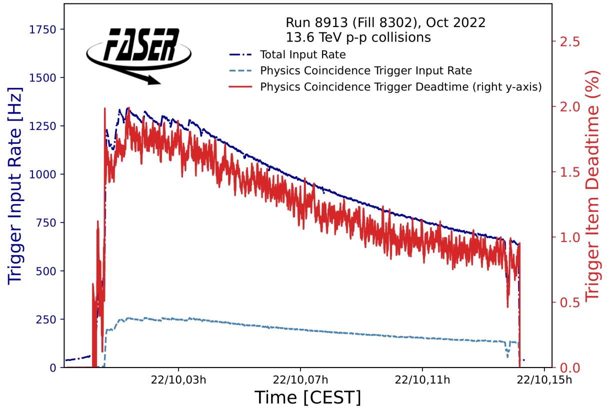
Trigger bits combined to trigger items -- e.g. "coincidence trigger" (incoming muons): (Veto0 || Veto2) && Presh

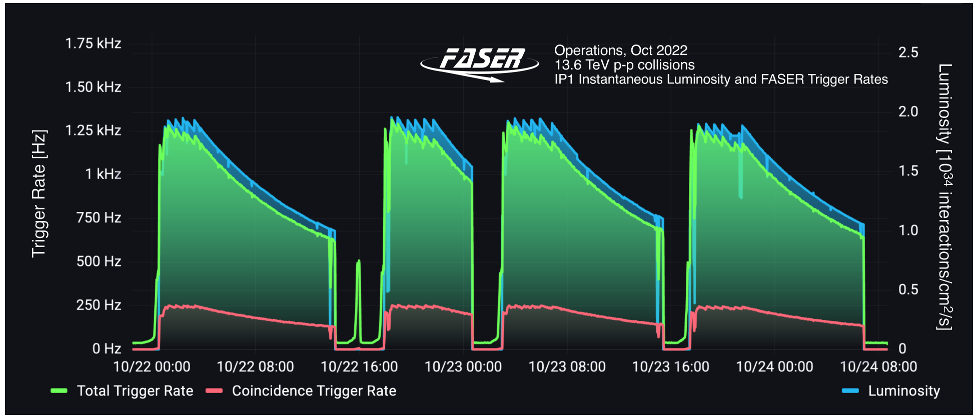
TDAQ Ops

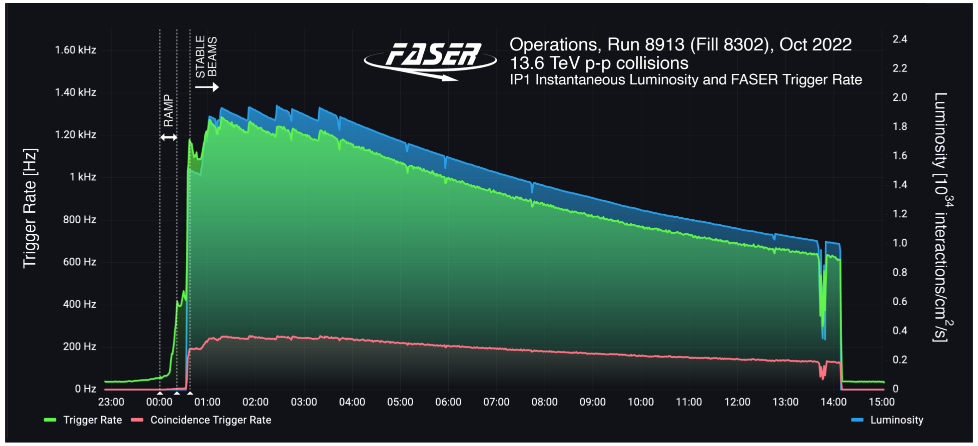
The rate of a coincidence trigger (requiring a signal in the veto scintillators at the front and the preshower scintillator layer at the back of FASER, likely signifying the passage of an energetic muon from the direction of IP1) is shown in red. The trigger rate trend generally follows the luminosity trend but it is evident that the trigger rate falls off more strongly at the beginning of fills than the luminosity. This is due to higher beam-induced backgrounds at the beginning of the fill. The dip in rate towards the end of the fill is due to an emittance scan at IP1.

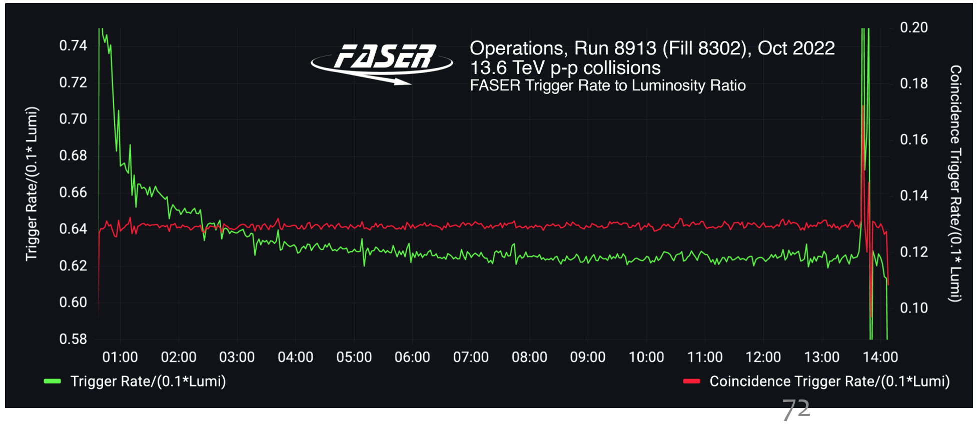










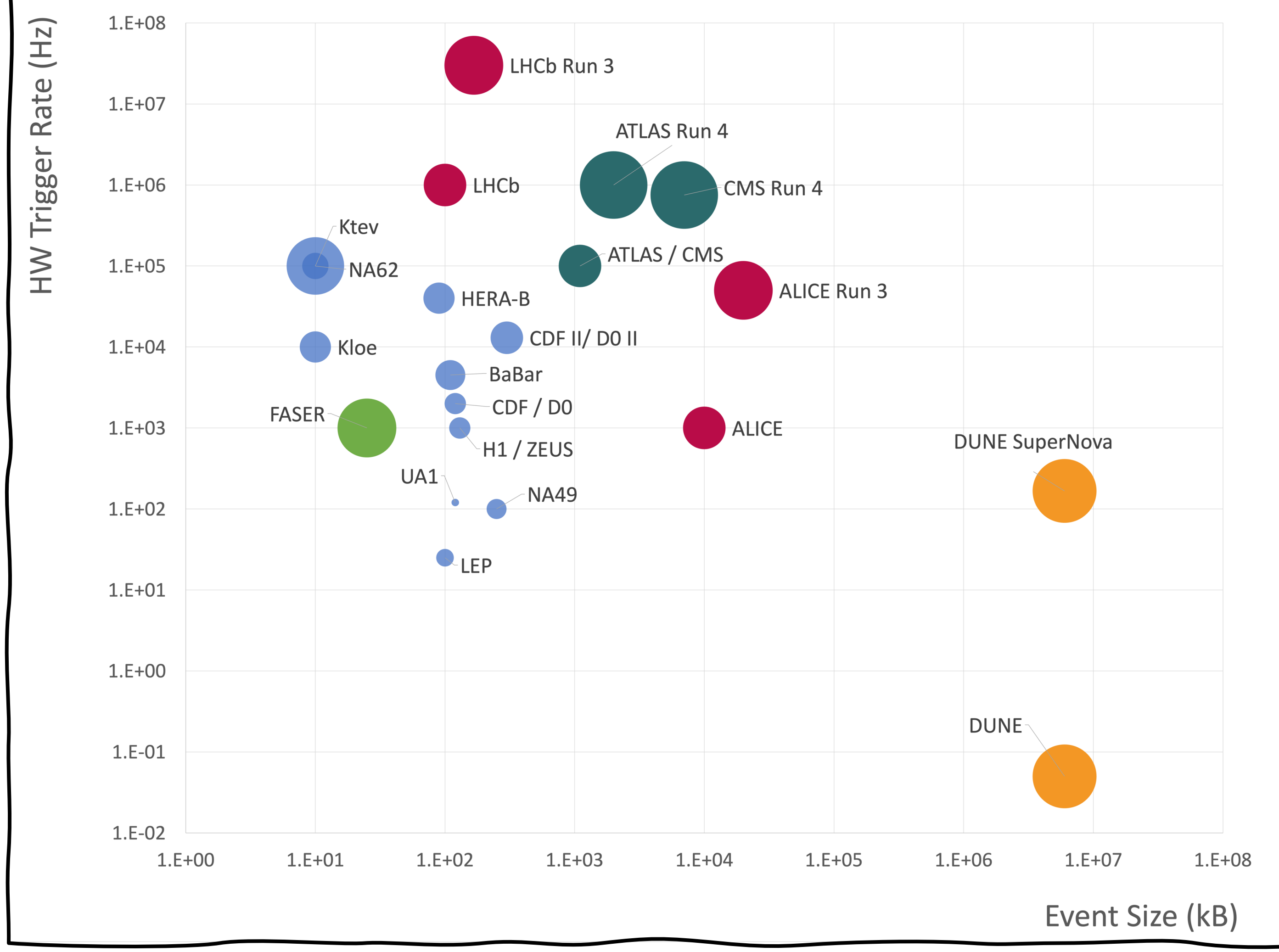


New Run Control

A snapshot of the FASER Run Control GUI, showing the control buttons for the DAQ FSM, the control tree of added DAQ modules (data receivers, monitoring modules, event builder and file writer) and a main monitoring panel showing the current run information and current rates.

...WHY THIS ARCHITECTURE?

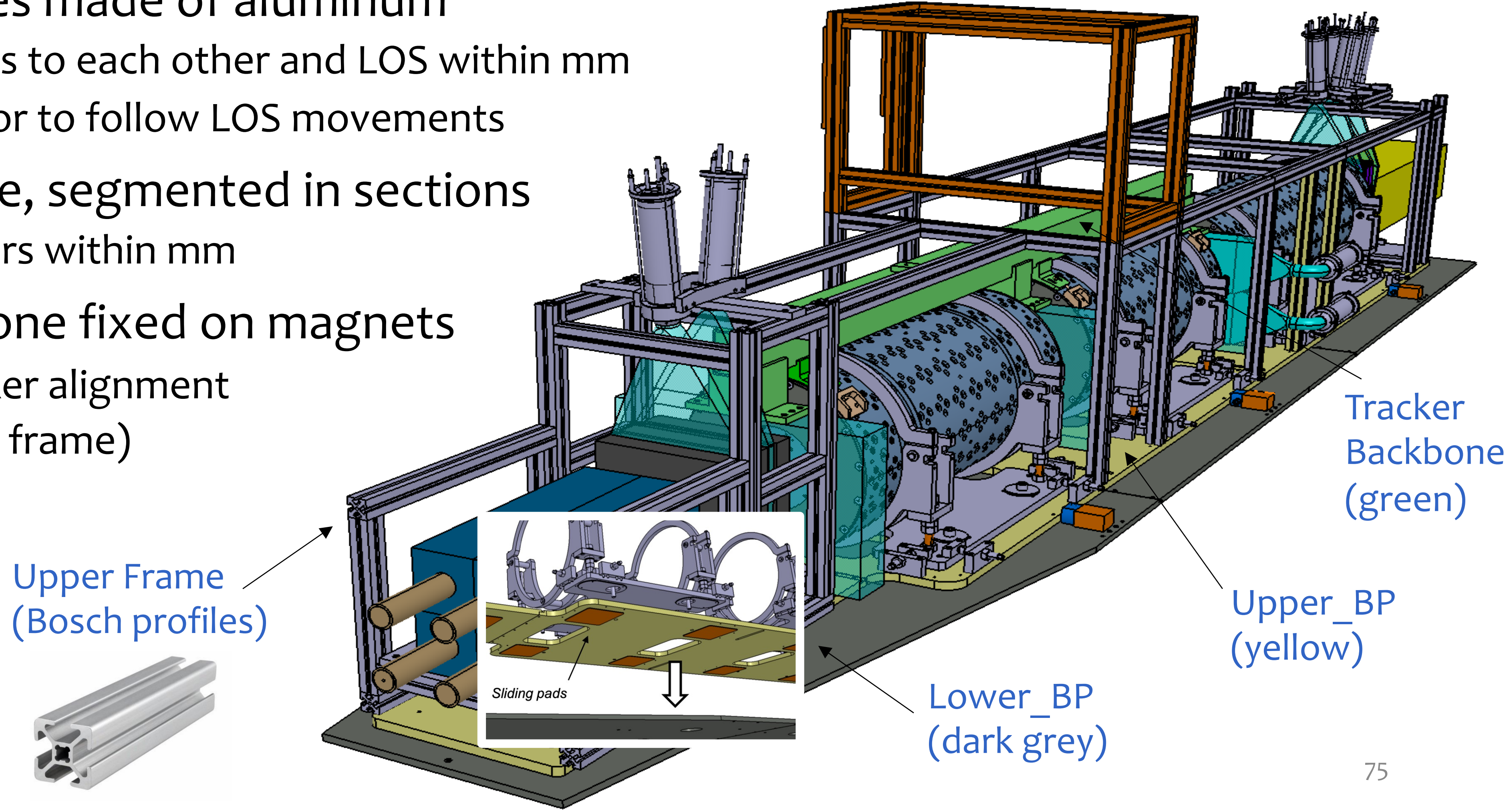
- Compare trigger rate and event size to other LHC experiments!



Plot from Alex Cerri

Detector support structure

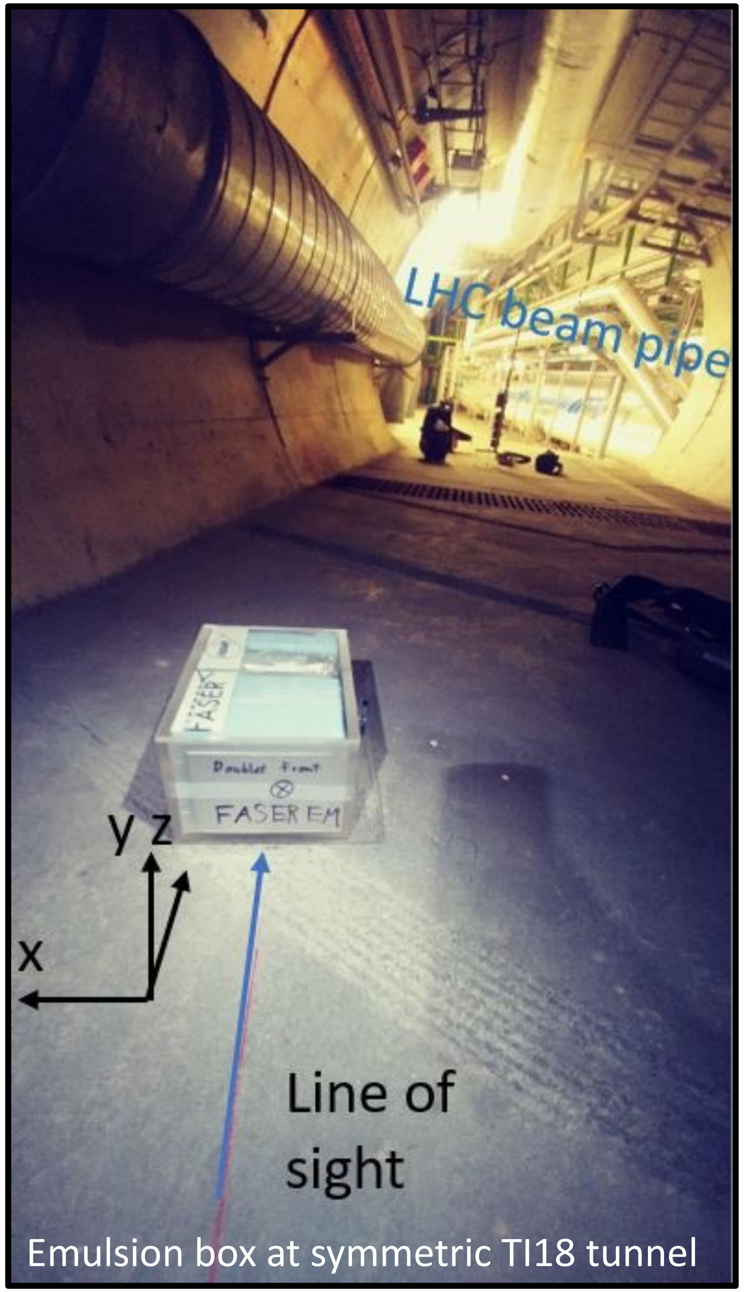
- Two base-plates made of aluminum
  - Align magnets to each other and LOS within mm
  - Allow detector to follow LOS movements
- An upper frame, segmented in sections
  - Align detectors within mm
- Tracker backbone fixed on magnets
  - ensures tracker alignment (<100 µm wrt frame)



Backgrounds

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

⇢ **TI12 very quiet location!**



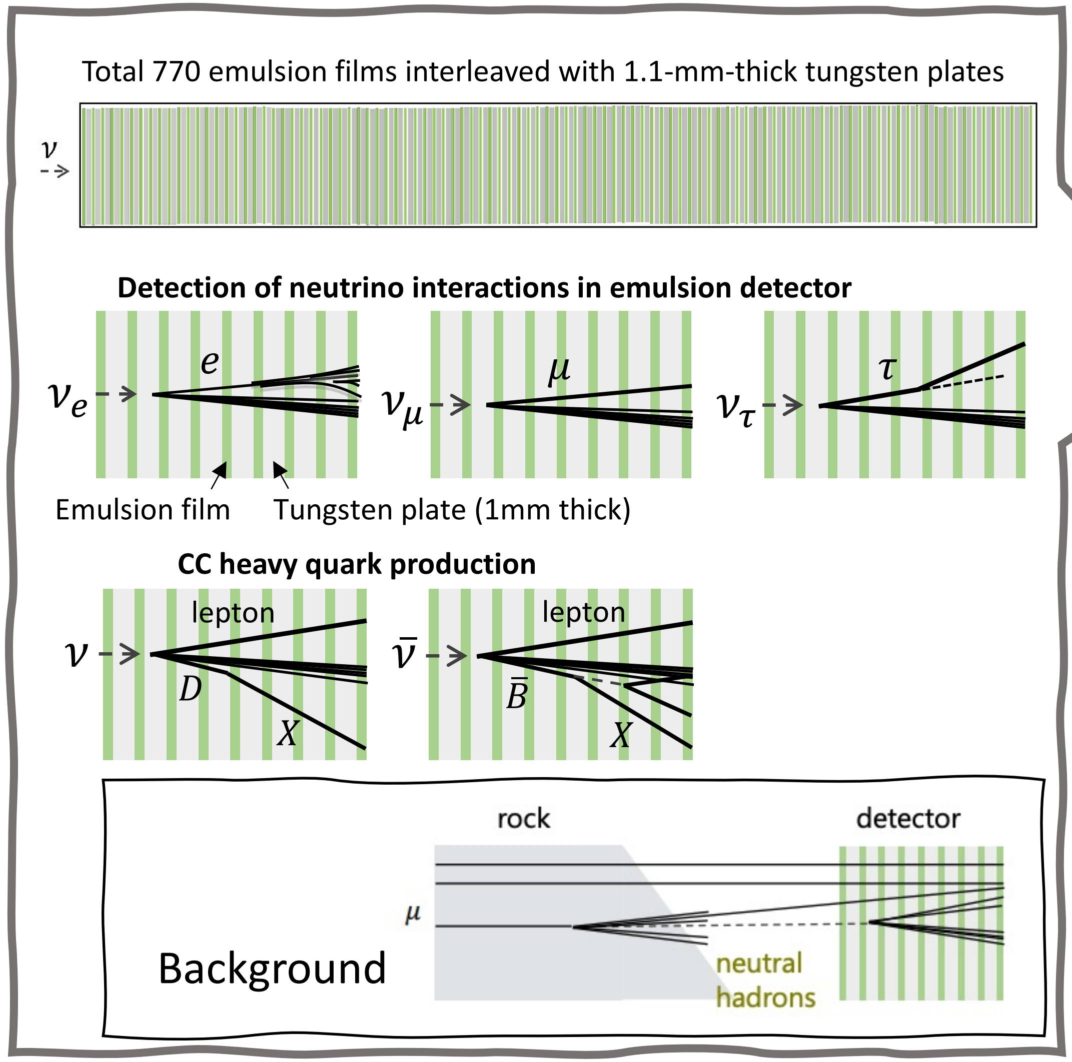
Emulsion box at symmetric TI18 tunnel

FASER Detector

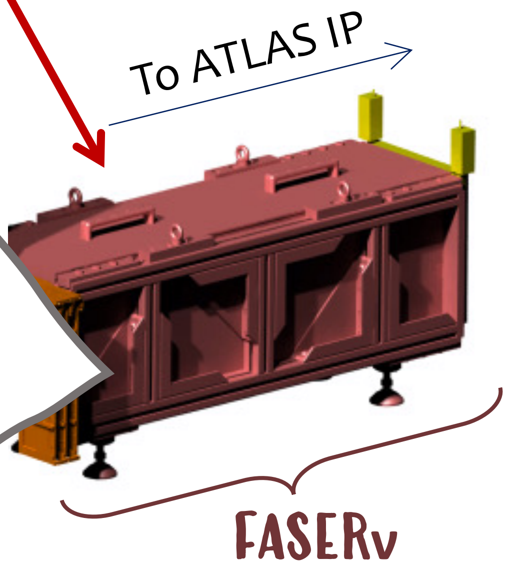
Track position resolution O(50nm), and angular resolution O(0.35mrad).
No timing resolution

Challenges:

- Replace the 1-ton-scale detector about 3 times/year (20-50/fb) to maintain manageable track density
- Read-out of emulsion films quite a demanding procedure!



Emulsion detector



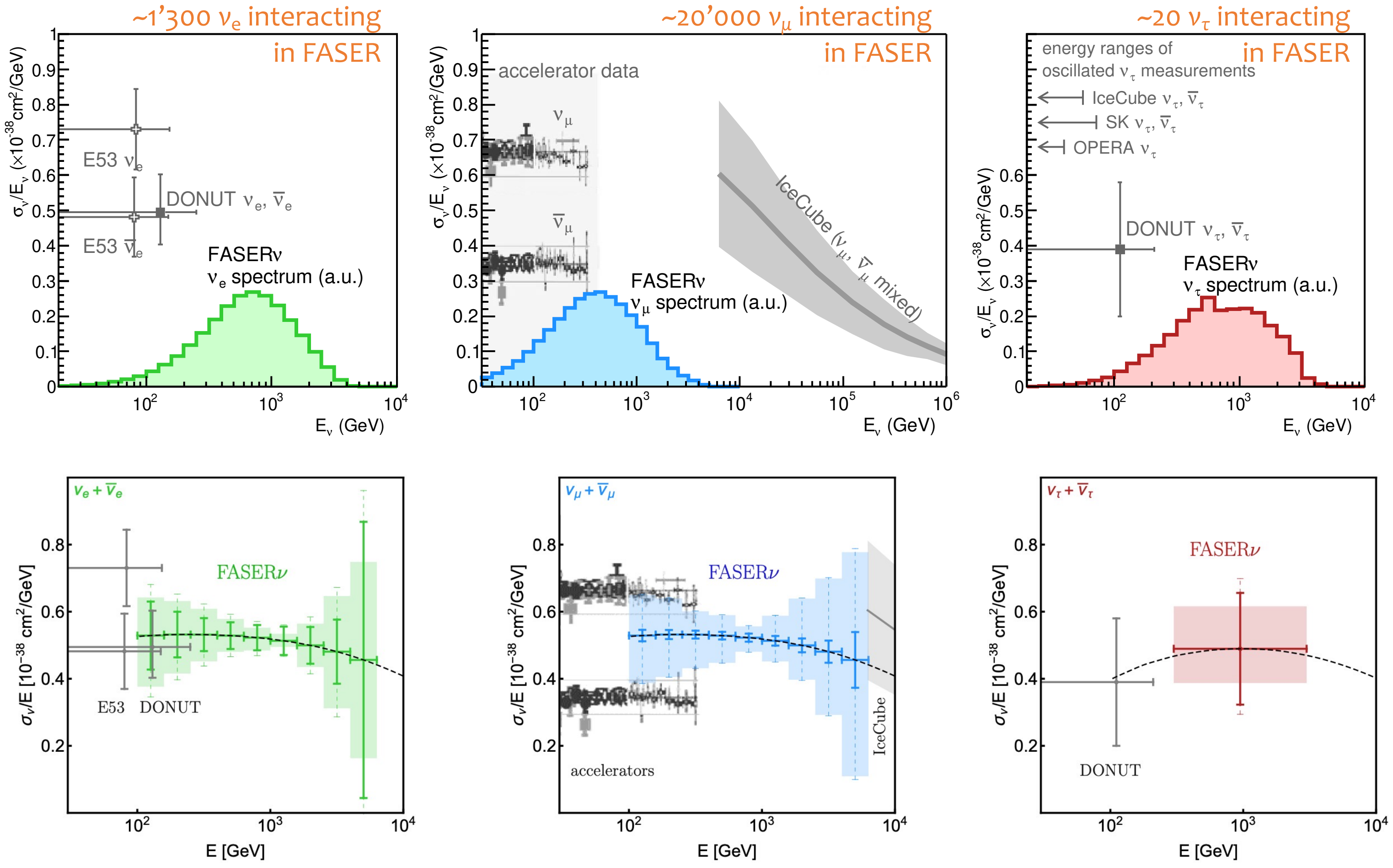
Measurements of high-energy neutrinos

Expected spectra:

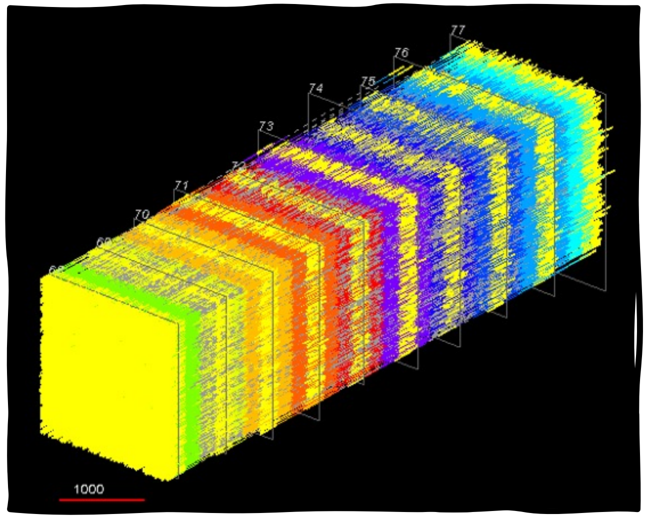
- complementary to existing experiments

Expected cross section reach:

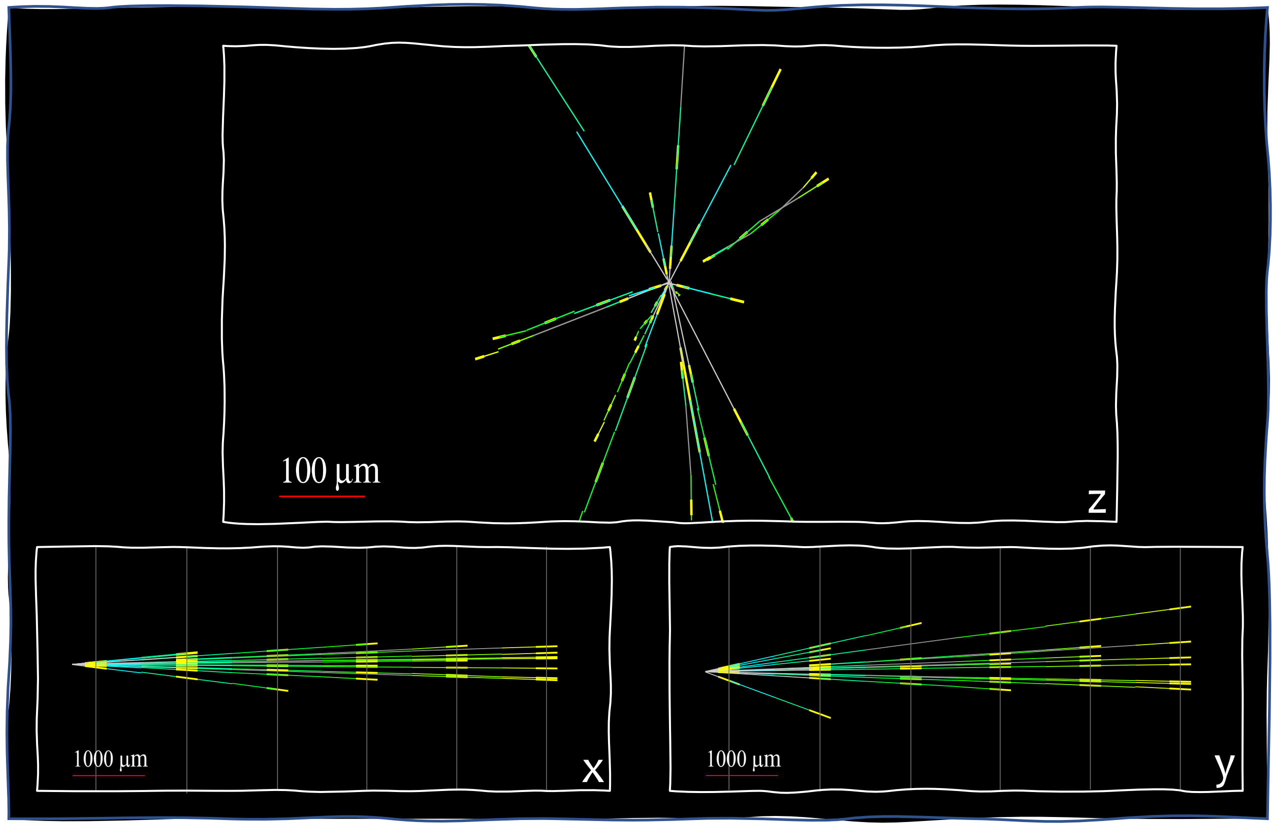
- extends current measurements already with 150/fb

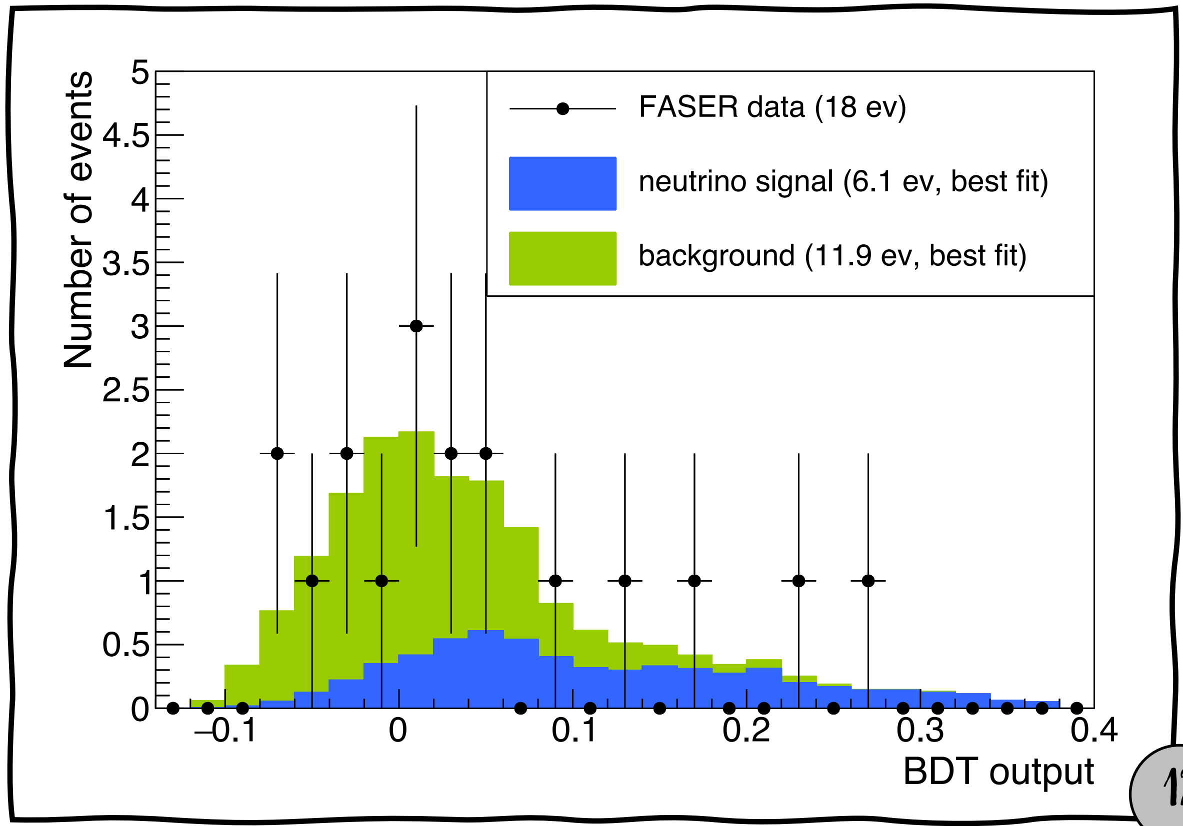


FASER Pilot run in 2018



First candidate **collider neutrino** interactions!



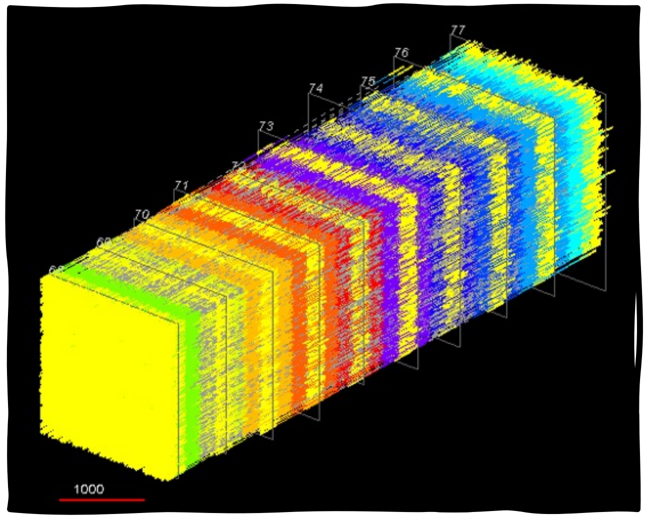


arXiv: 2105.06197

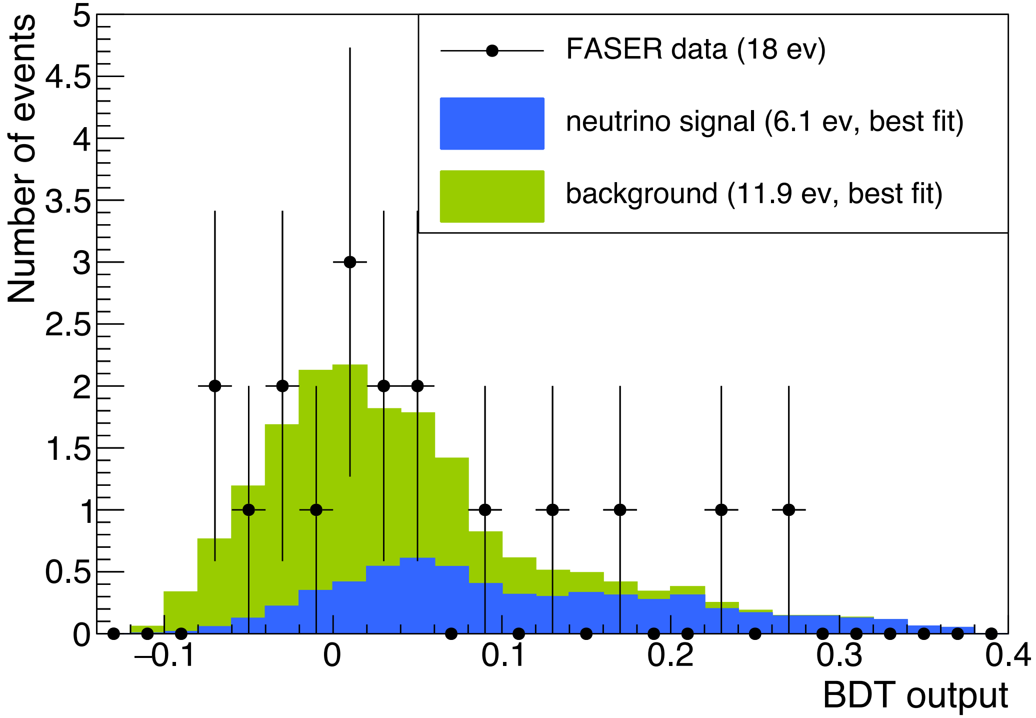
FASER Pilot run in 2018

First candidate **collider neutrino** interactions!

- A 11 kg detector collected ~ 12/fb

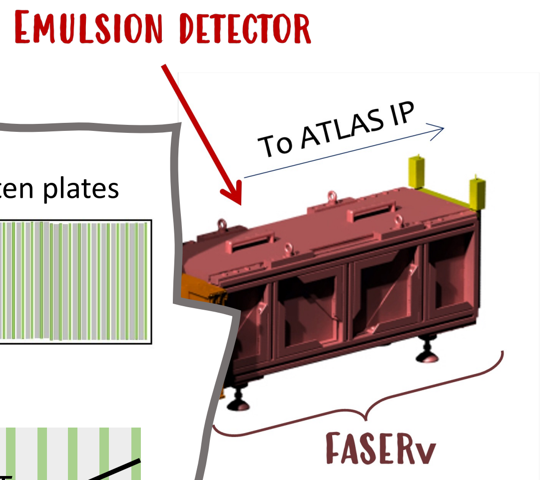


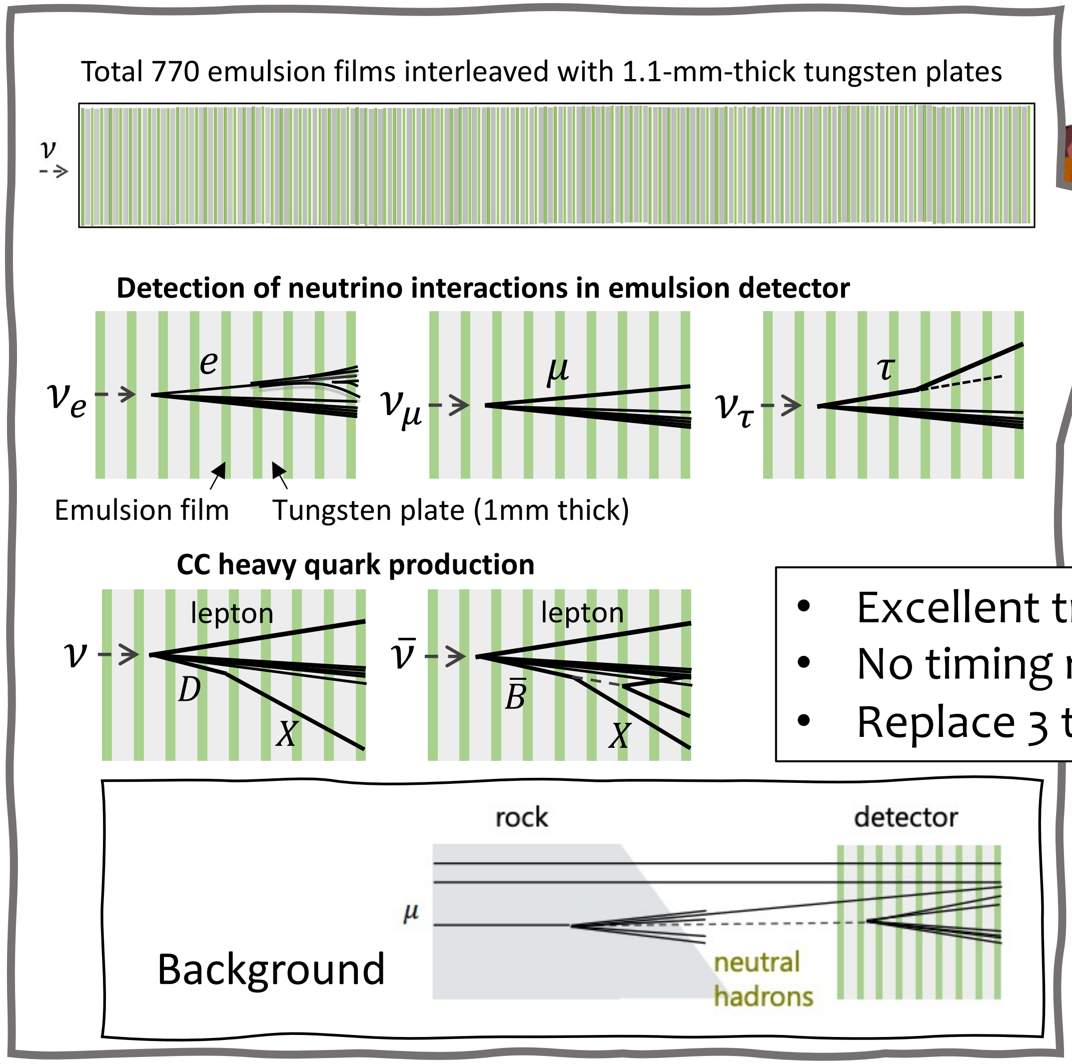
- About 3.3 neutrino interactions expected to have occurred after selections
- BDT developed to distinguish neutrino signal from neutral hadron background
  - The background-only hypothesis is rejected with significance of 2.7σ
- Excellent testbed for future data analysis



arXiv: 2105.06197

FASER Detector





- Excellent track resolution
- No timing resolution
- Replace 3 times/year

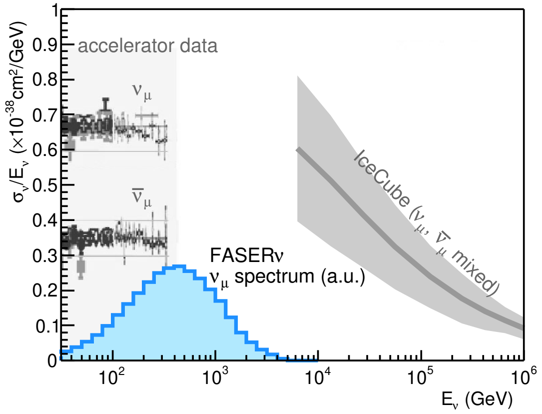
arXiv:2207.11427

FASER Detector and physics

Expected spectra:

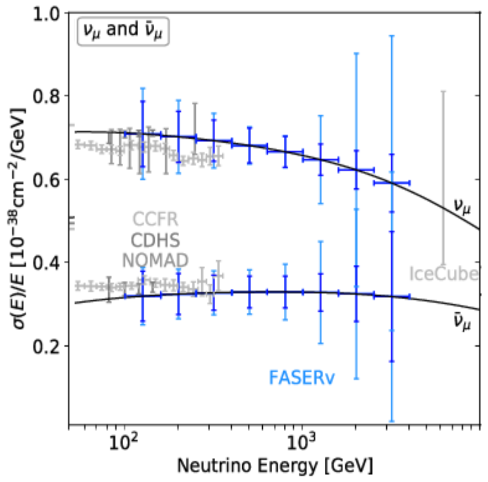
- complementary to existing experiments

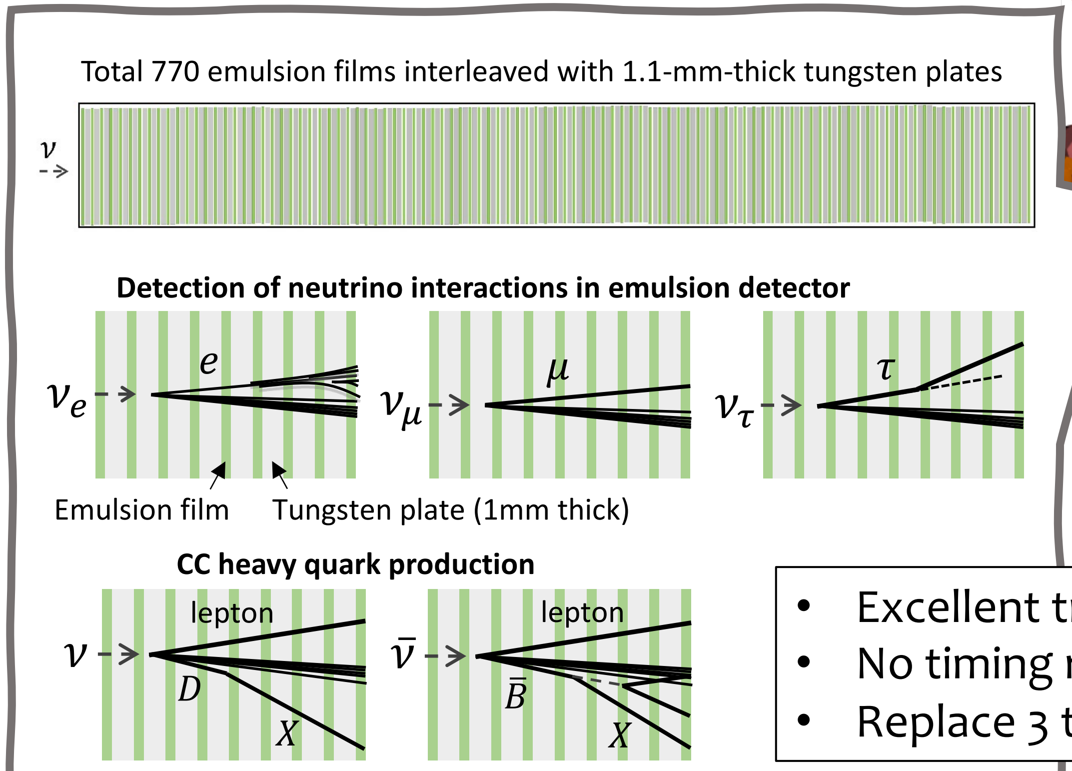
~1'300 ν_e
~20'000 ν_μ
~20 ν_τ
interacting in FASER



Expected cross section reach:

- extends current measurements already with 150/fb





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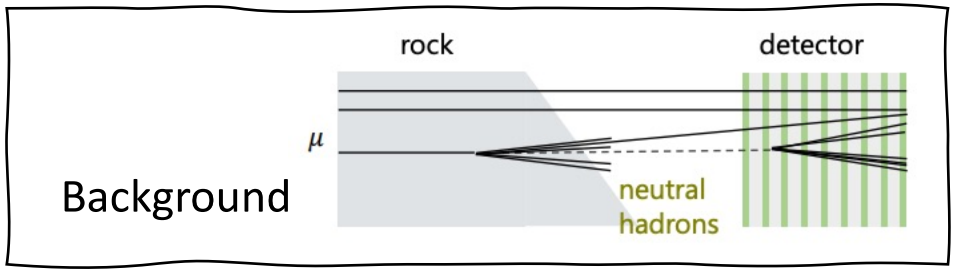
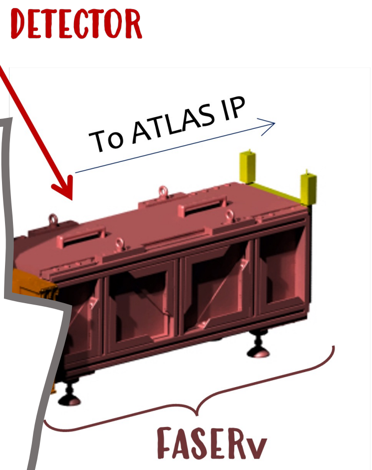
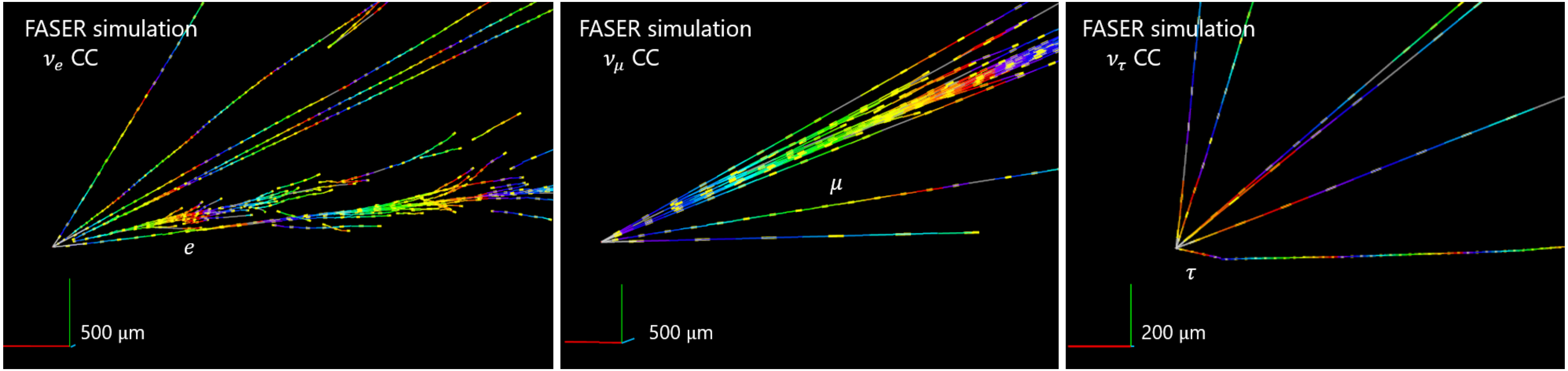




Event displays of simulated neutrino interaction vertices

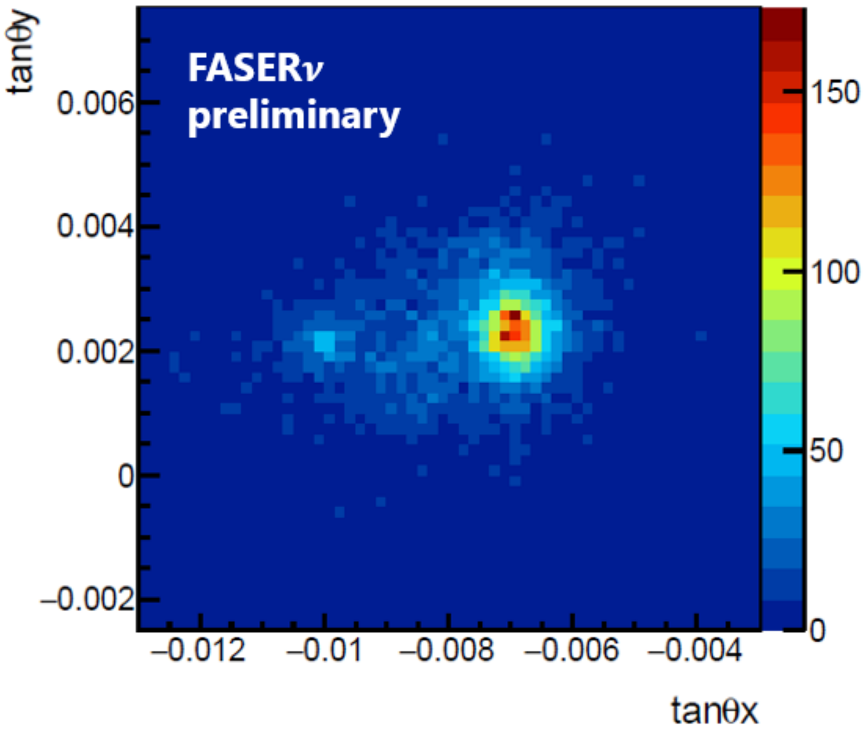


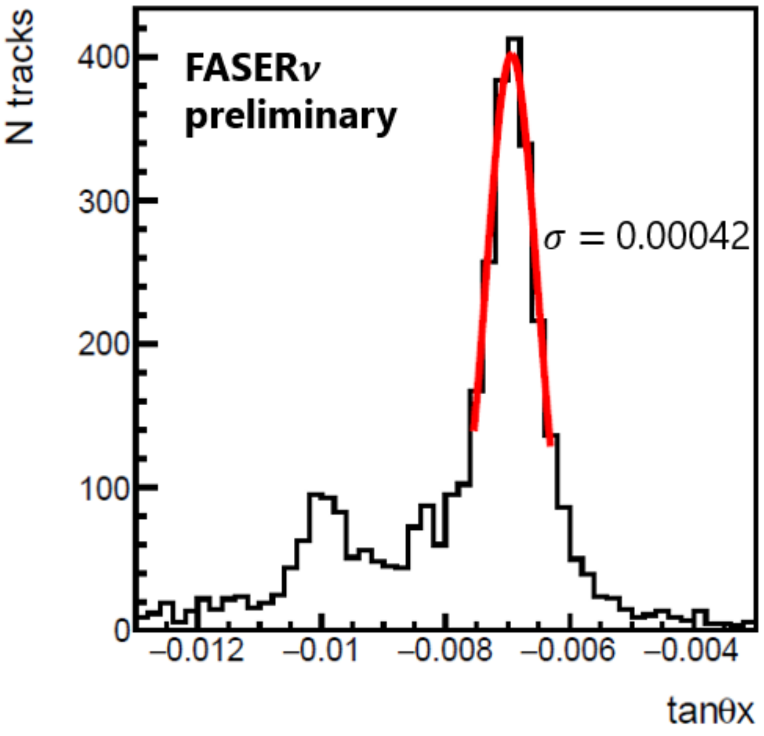
Event displays of simulated neutrino interaction vertices for 433 GeV nue CC, 664 GeV numu CC, and 831 GeV nutau CC. Yellow line segments show the trajectories of charged particles in the emulsion films. The other colored lines are extrapolations of the track hits to the neighboring tungsten plates, and the colors change depending on the depth in the detector.

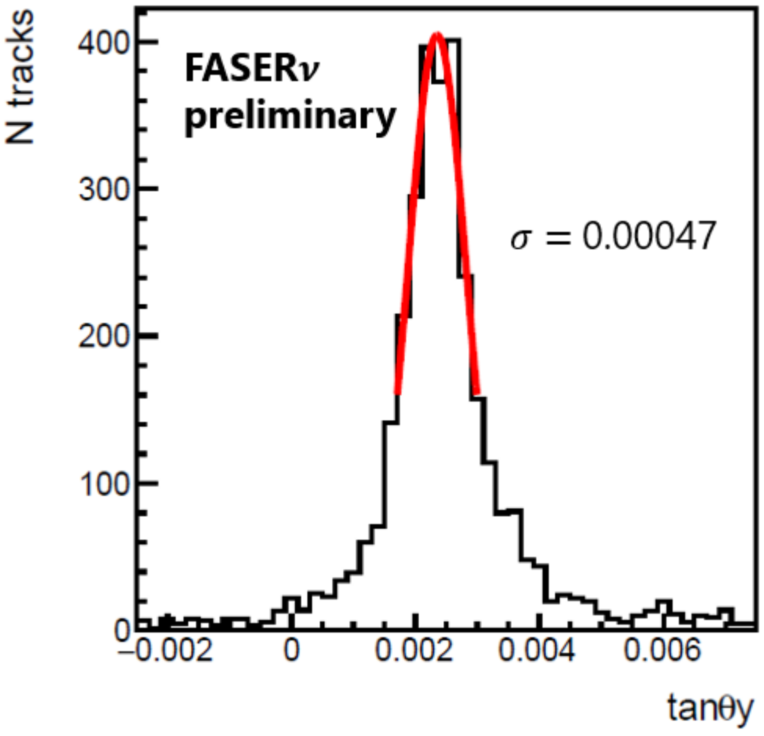
2022 emulsion boxes

(from Jamie)

		Integrated luminosity per module (fb^{-1})	N ν int. expected
2022 1st module	Mar 15 – Jul 26	0.5	~7
2022 2nd module	Jul 26 – Sep 13	10.6	~530
2022 3rd module	Sep 13 – Nov 29	(~30)	(~1500)





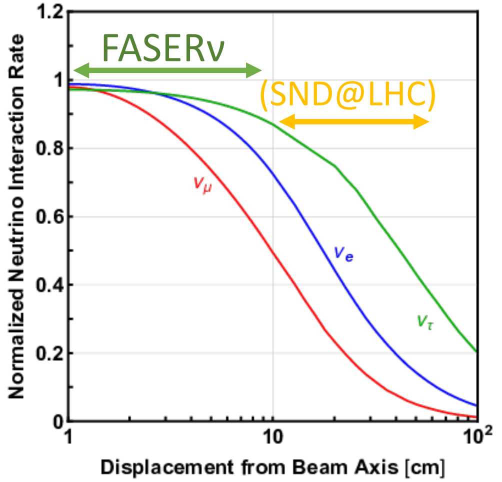


Angular spreads

Angular distributions observed in the 2022 first module of the FASERnu detector. The right figures are projections of the left one. The angular spreads of the peaks are ~0.5 mrad, mainly due to the multiple Coulomb scattering through 100 m of rock.

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 FASERnu and SND@LHC during LHC Run 3 with 250 fb-1 integrated luminosity. Predictions from different MC generators are provided.

Huge flux of high-energy neutrinos

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

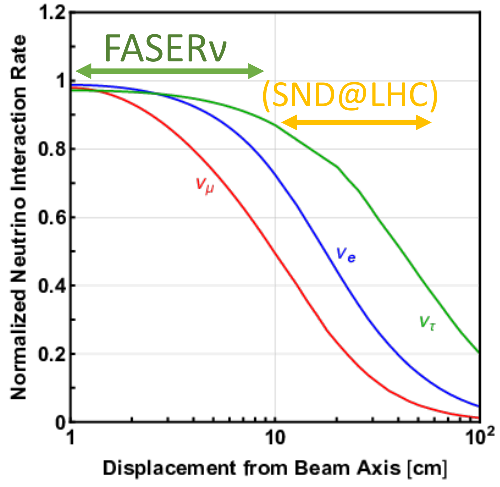
A bit of history

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

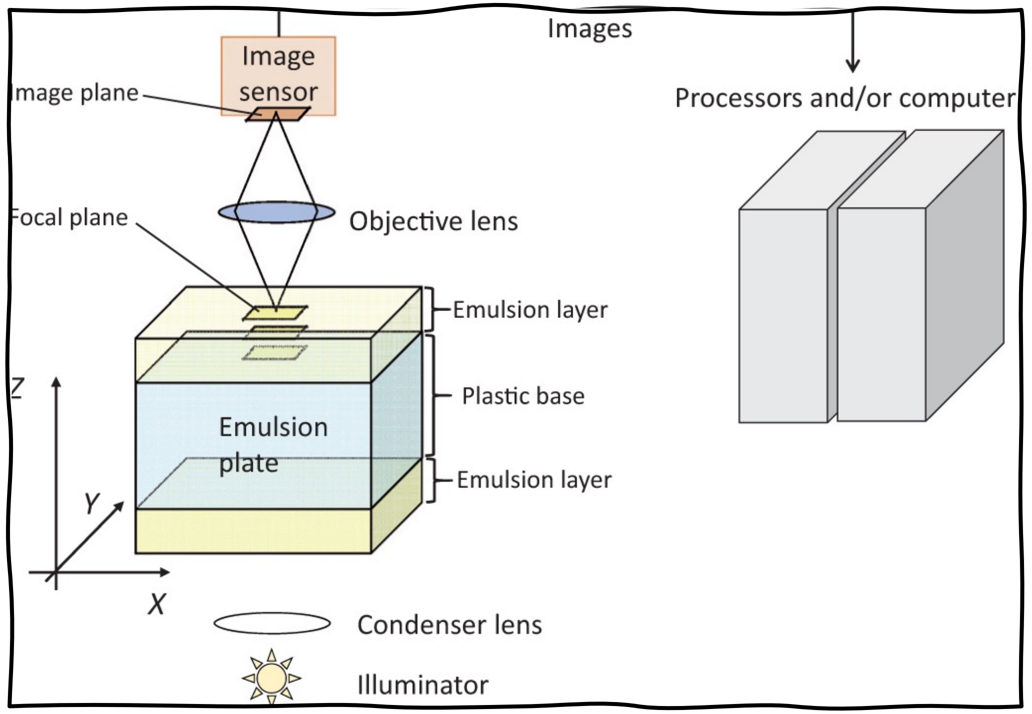
- A. De Rujula and R. Ruckl, "**Neutrino and muon physics in the collider mode of future accelerators**" ECFA-CERN Workshop on large hadron collider in the LEP tunnel, pp. 571–596, **1984**.
- Klaus Winter, **"Observing tau neutrinos at the LHC"**, LHC workshop, **1990**.

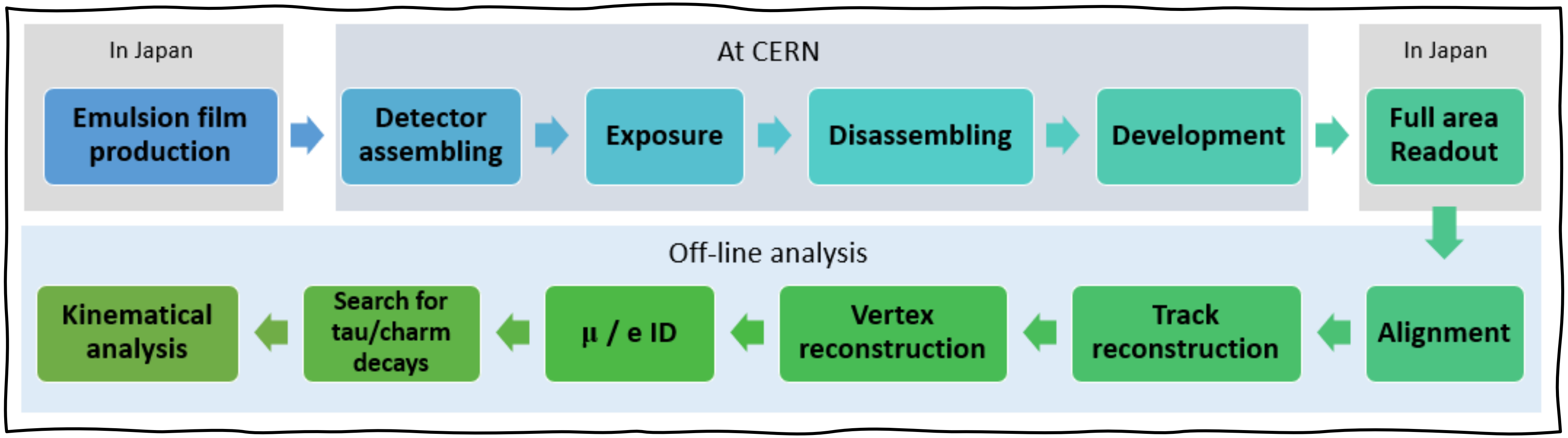
Other recent concrete experiment proposals include XSEN and SND@LHC.

SND@LHC recently approved.



Read-out & Analysis



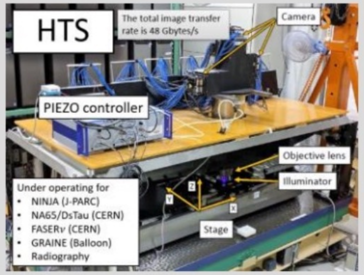


FASERν

Workflow





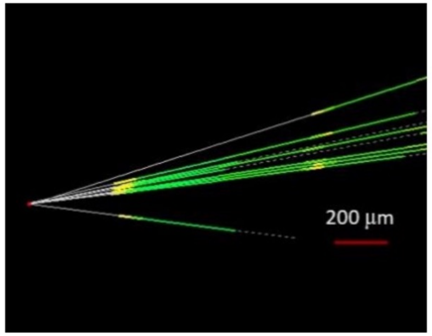


In Japan: **Emulsion film production** → At CERN: **Detector assembling** → **Exposure** → **Disassembling** → **Development** → In Japan: **Full area readout**

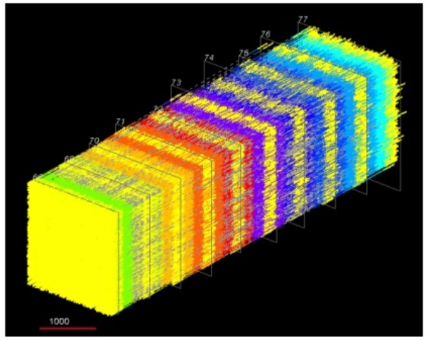
Off-line analysis: Alignment → Track reconstruction → Vertex reconstruction → μ / e ID → Search for tau/charm decays → Kinematical analysis

Interface tracker data

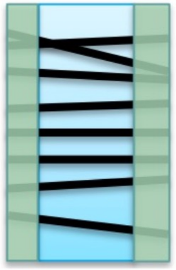
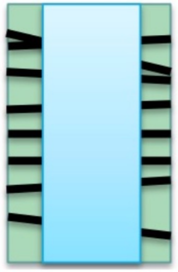
Spectrometer data



500-1000 TB/Run3



~500 TB/Run3

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

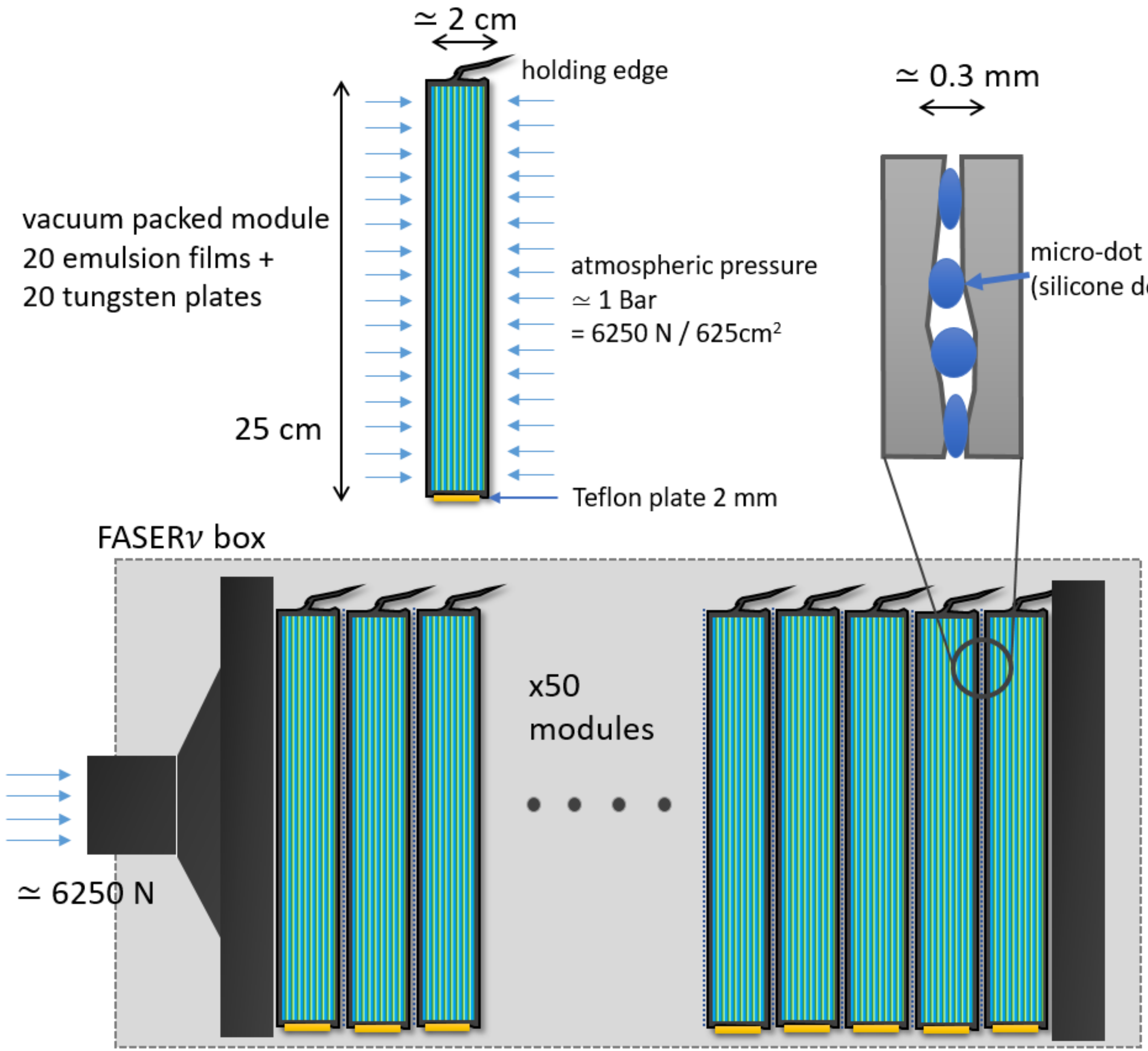
150/fb @14TeV	ν_e	ν_μ	ν_τ
Main production source	kaon decay	pion decay	charm decay
# traversing FASERnu 25cm x 25cm	$O(10^{11})$	$O(10^{12})$	$O(10^{9})$
# interacting in FASERnu (1.2tn Tungsten)	~1300	~20000	~20

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].

Module structure



Emulsion

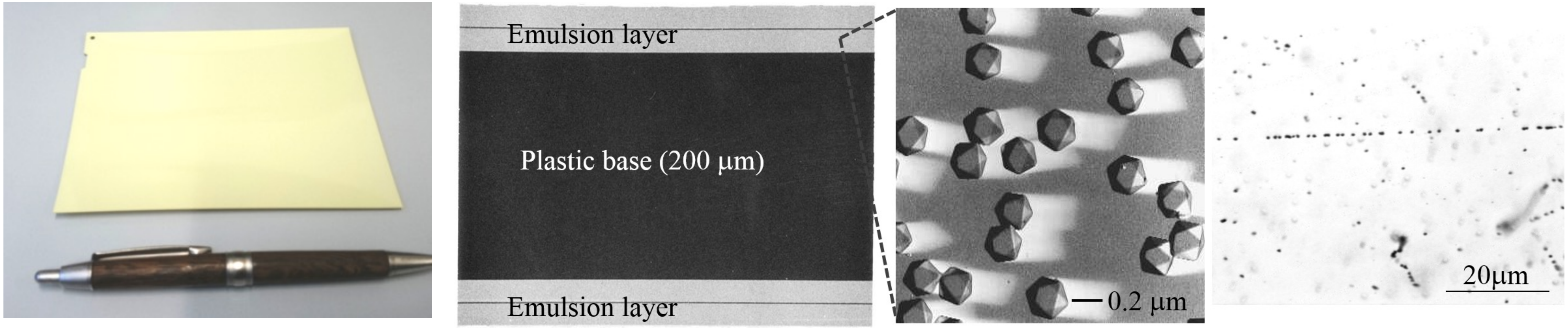
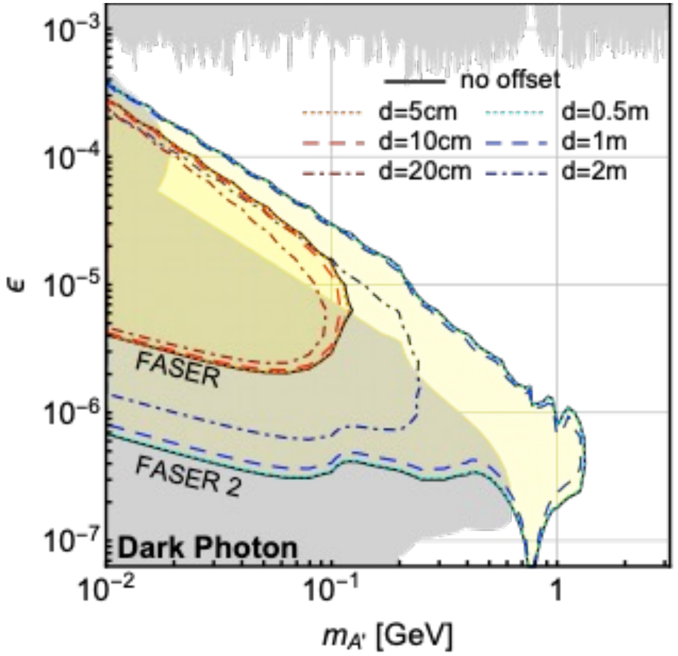


Photo of an emulsion film (left), its cross-sectional view (left center), electron microscope image of the silver halide crystals (right center), and a minimum ionising particle track from a 10 GeV/c π beam (right).

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

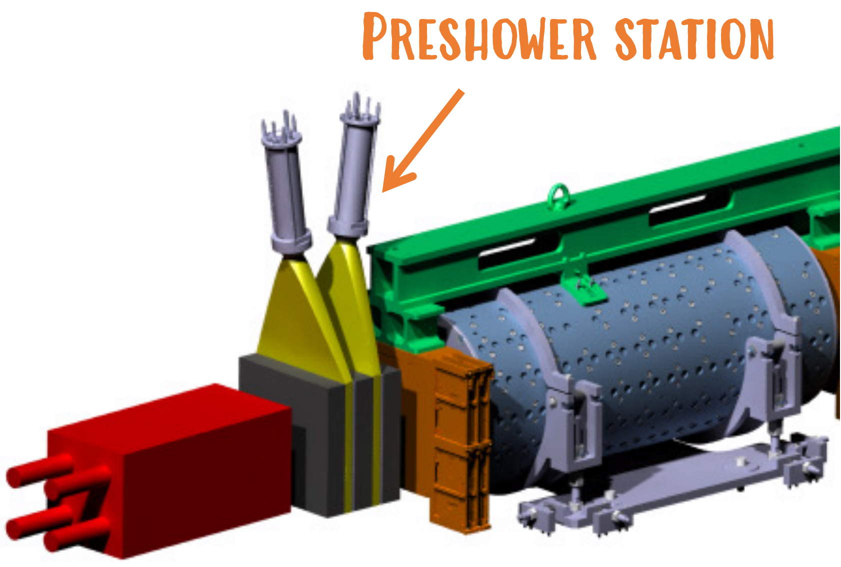
- The half crossing angle is ~150 μrad, which moves the collision axis by ~7.5 cm at the FASER location
- Such a change reduces the signal acceptance in FASER by ~25%
- Leads to very small changes in physics sensitivity



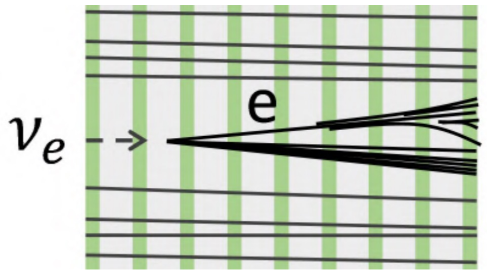
The FASER Detector

Preshower upgrade

Current detector limitation



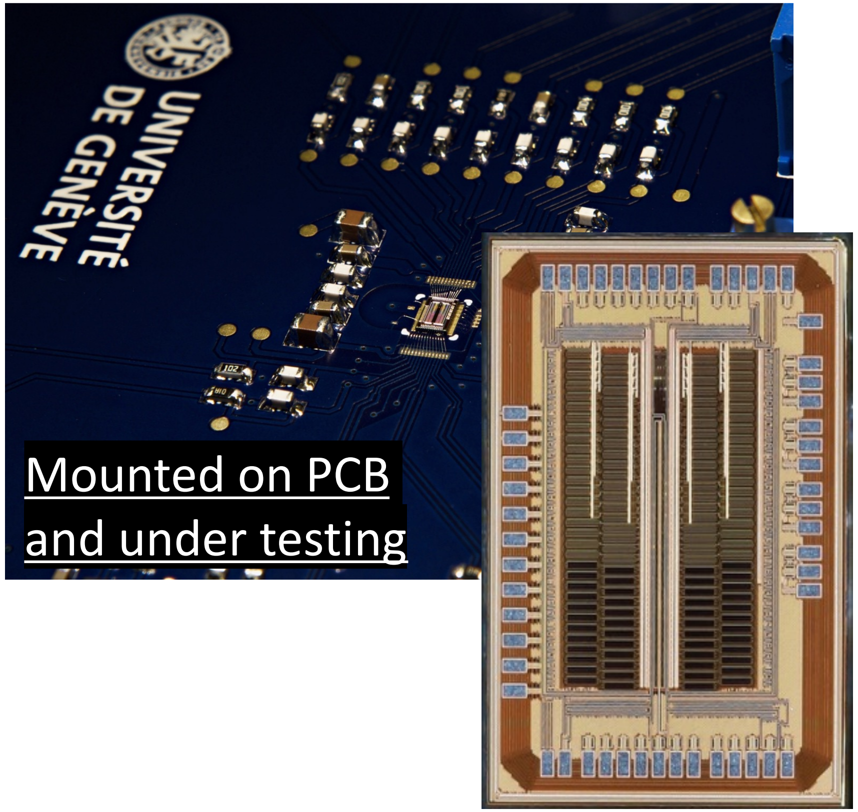
- Current FASER pre-shower
  - two layers of scintillators, each preceded by a 1X0 lead-radiator plane
  - will create a photon shower to help distinguish photons from electrons coming from deep inelastic scattering (DIS) of very energetic neutrinos in the calorimeter.
- Limitations
  - **no information about the multiplicity of the photons or the topology of the event**
  - **neutrino DIS events produced in the 2 X0 lead of the present pre-shower will be undistinguishable from a photon (LLP) signature**
    - About 10 such events expected in 150/fb



Cartoon of ν_e DIS in FASERν

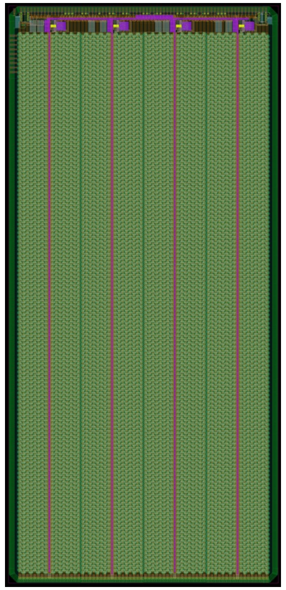
From pixels to layers of modules

Prototype ASIC available end 2020

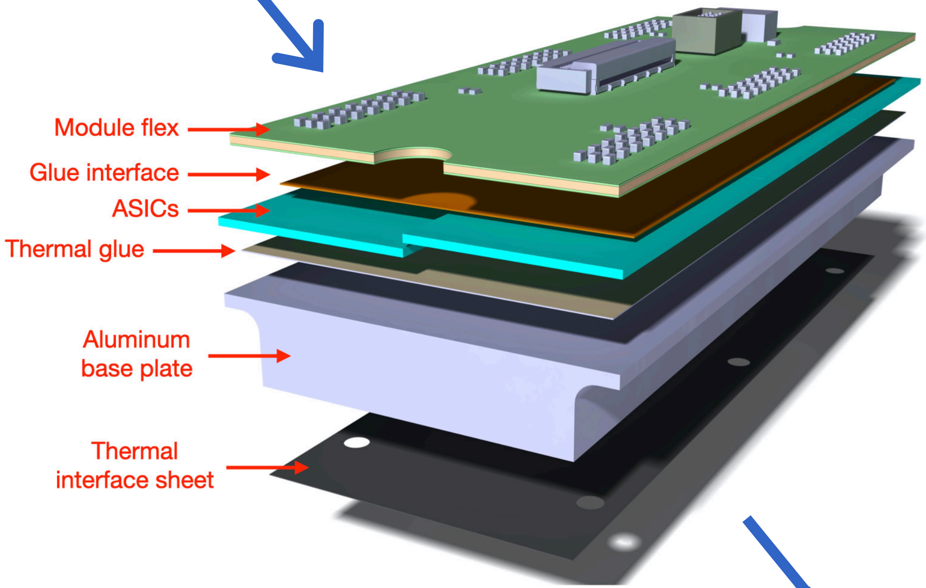


Mounted on PCB and under testing

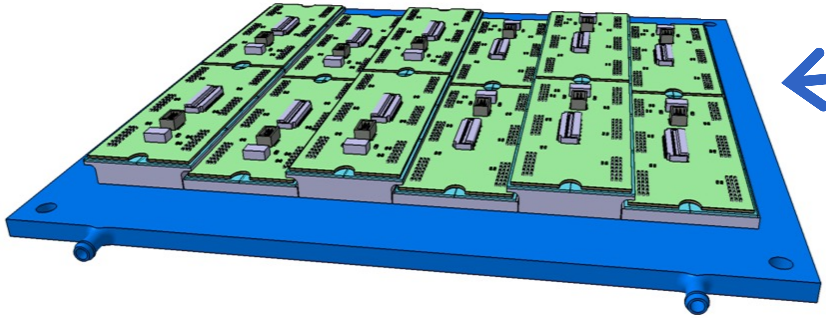
Pixel chips into sensor wafers



…into modules of pixels



…into layers of modules



Proposed layout of 1 layer with 12 modules.

Upgraded Pre-Shower

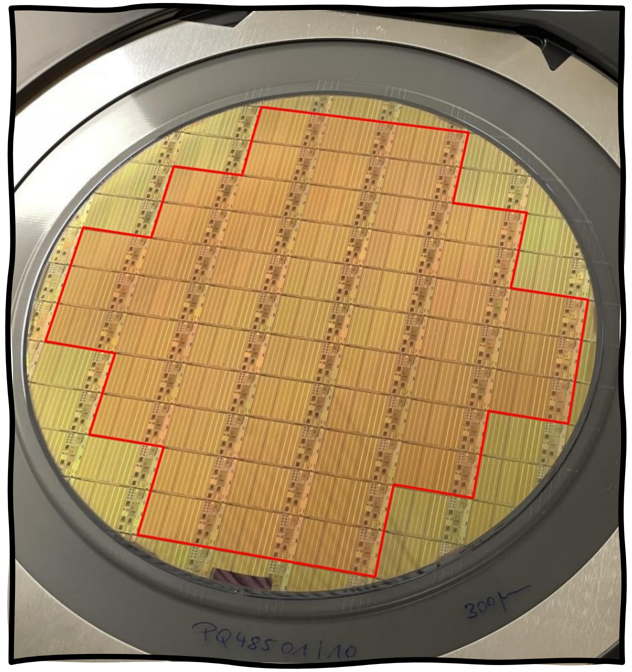
Status:

- Technical proposal approved in March ‘21
- Pre-production ASICs back from foundry
- Design of modules, planes, mechanics, read-out in progress
- Testbeam just last week!
- Simulation and reconstruction in progress

Plan:

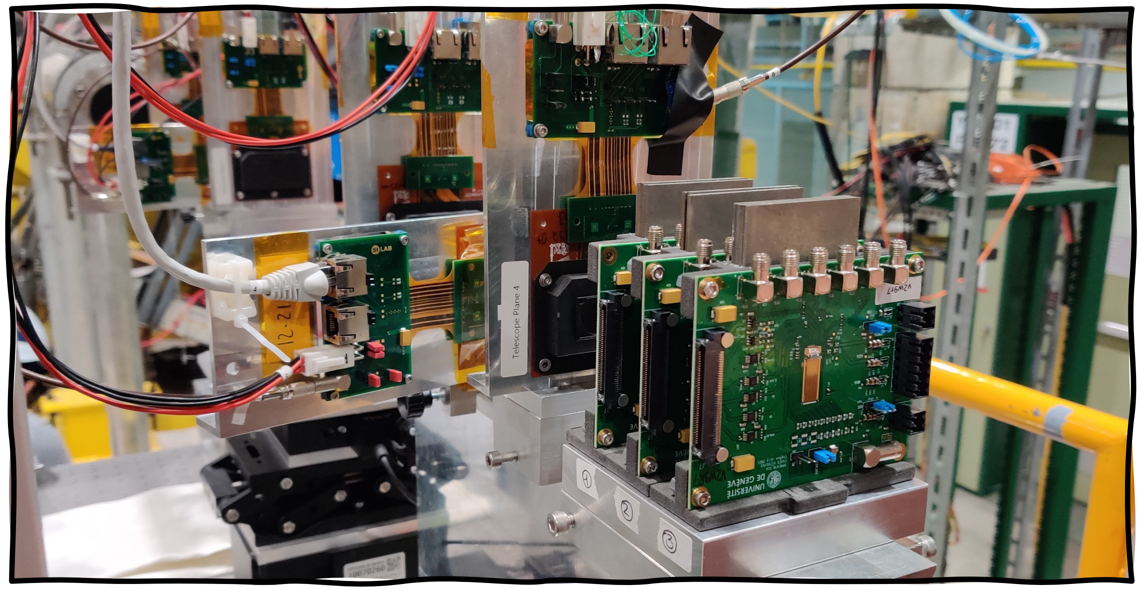
- Install the detector end of 2023 for data taking in 2024 and the rest of Run3

More: https://cds.cern.ch/record/2803084

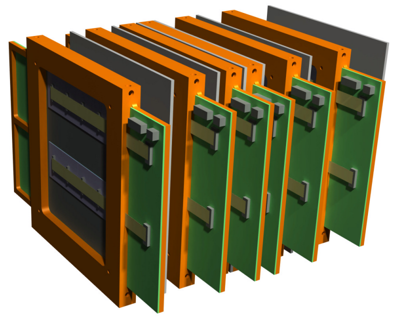


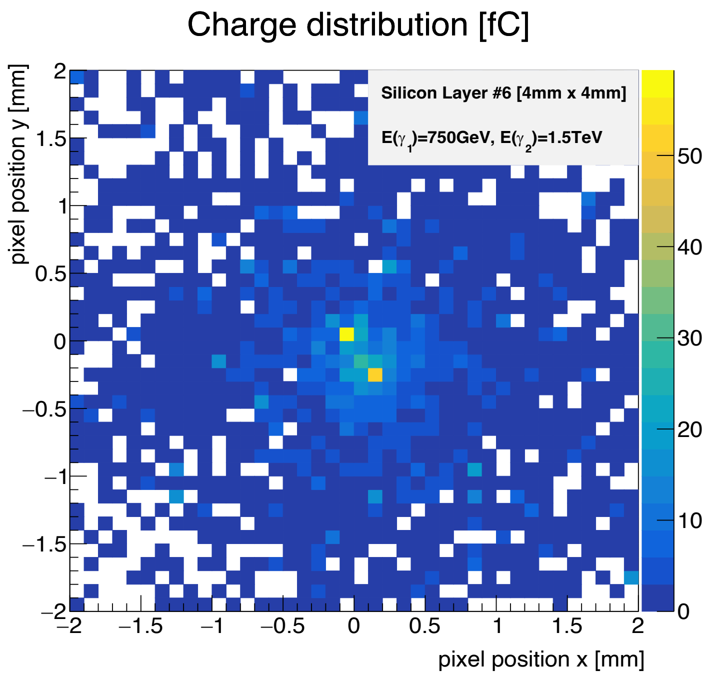
Preproduction ASICs received end of June

Preproduction ASICs in testbeam, Sept 2022



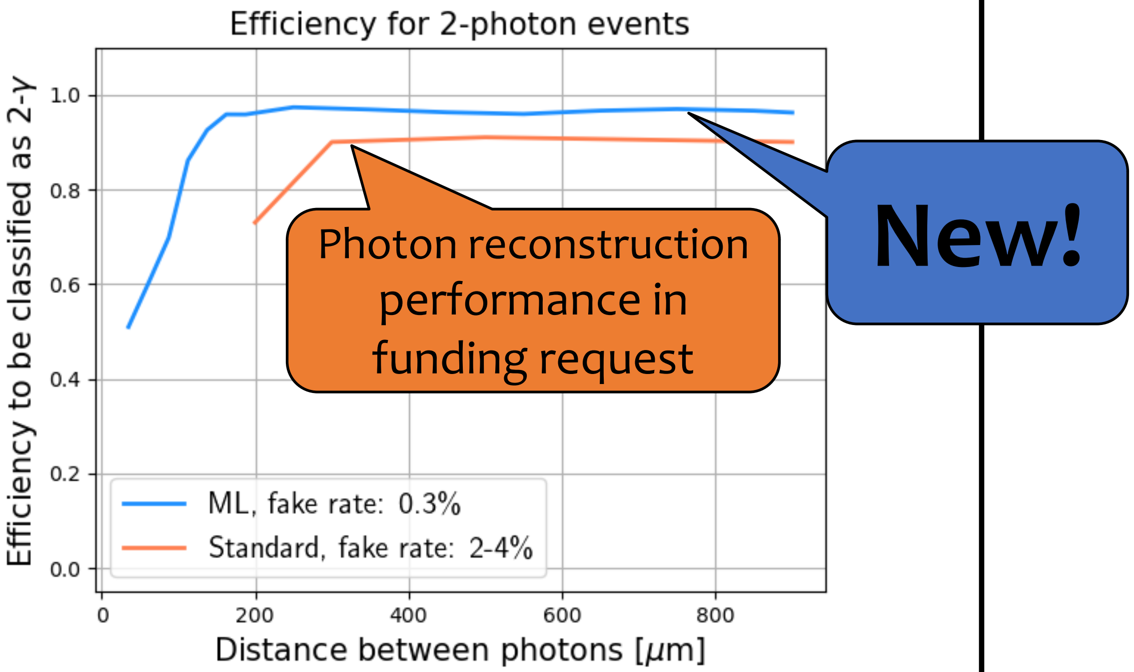
Expected performance





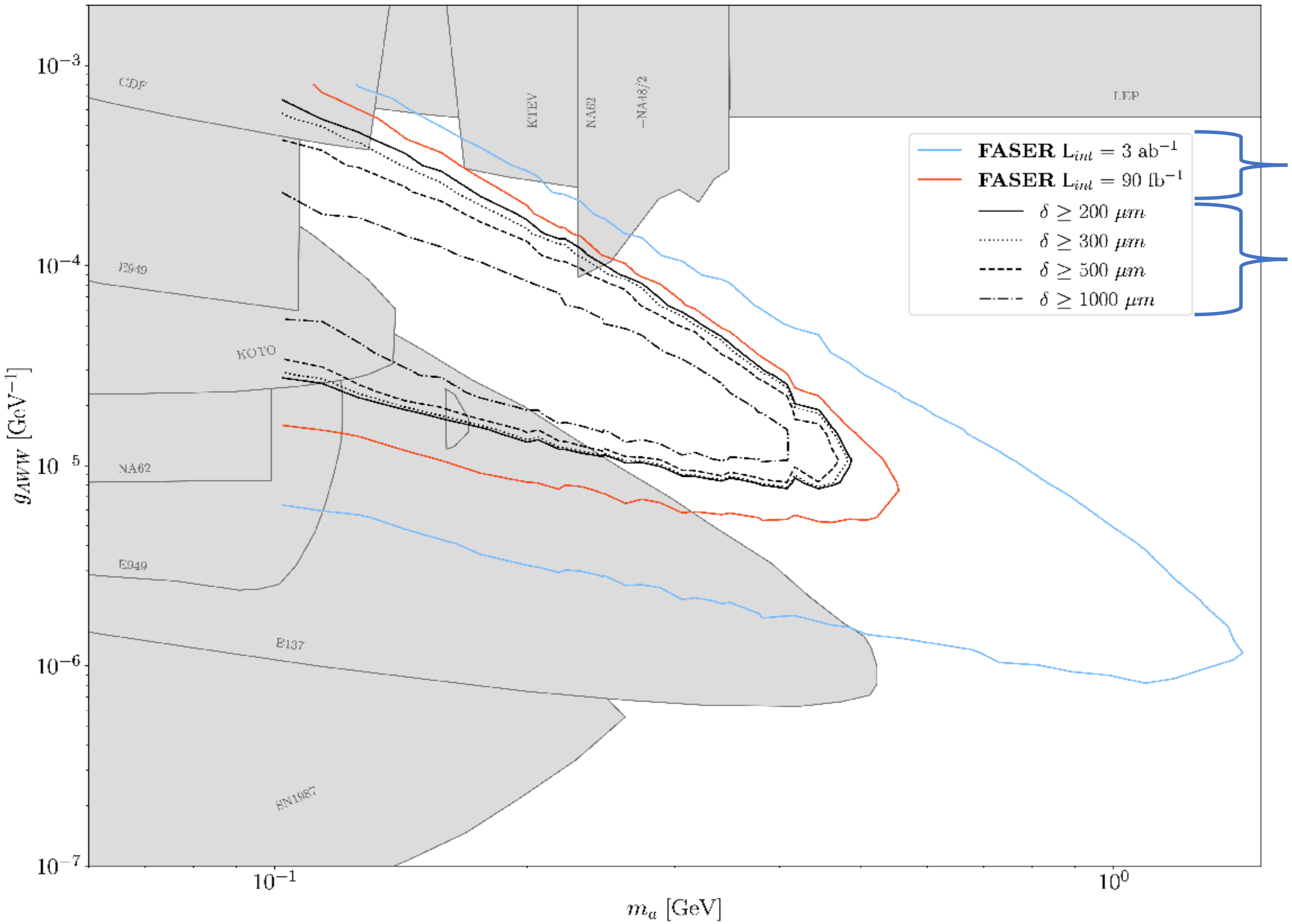
- Distance(2γ): 200 µm
- Distinguishable – because of the 100 µm pixel pitch

- Trained CNN to improve di-γ identification



Already achieved 95% di-γ identification efficiency and < 0.5% fake rate

Reach for ALPs



2-photon pairs with
E>250 GeV and $\delta_{\gamma\gamma}$ > 0.2mm
Zero background events assumed

Ideal detector (100% efficiency)

Realistic detector
(65-75% efficiency for a $\delta_{\gamma\gamma}$ = 0.2 mm, 85-90% efficiency for $\delta_{\gamma\gamma} \geq$ 0.3 mm)

→ 2-photon pairs can be resolved and studied!

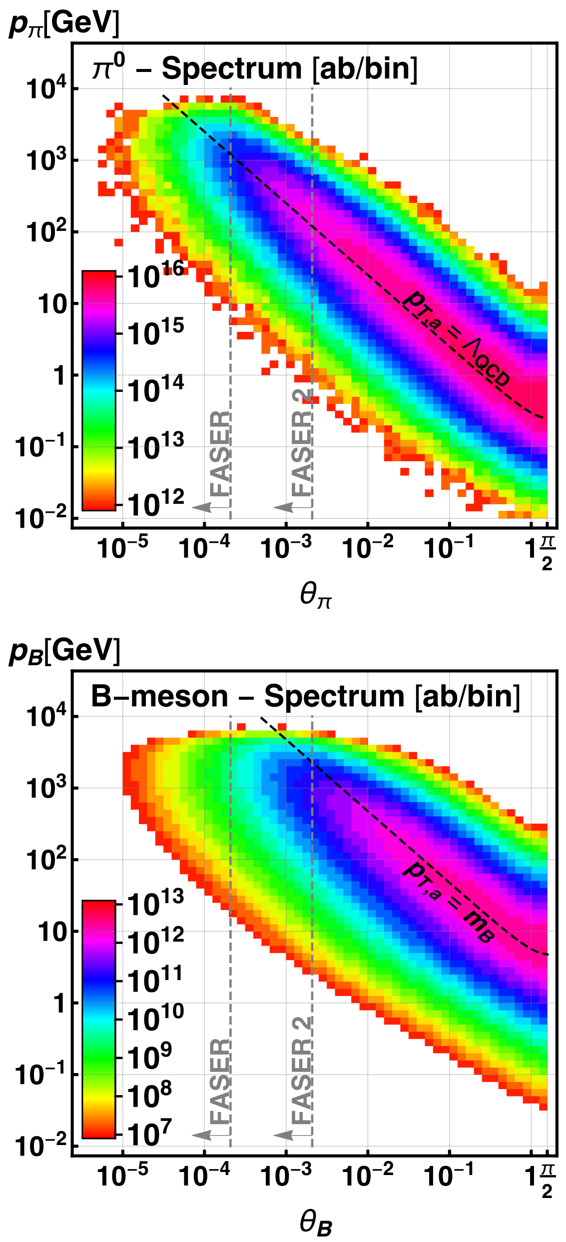
Otherwise: Indistinguishable from background

FASER2 and beyond...

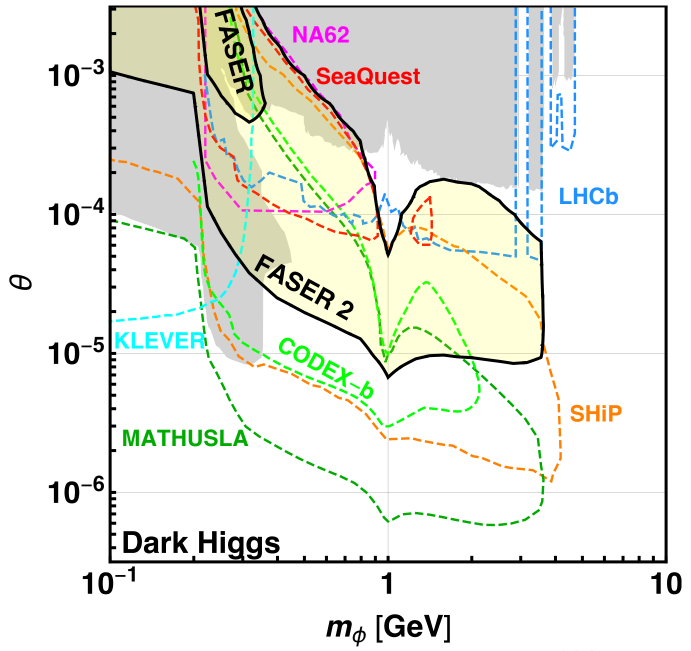
Beyond FASER? FASER2

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	···	✓

[More: https://arxiv.org/abs/1811.12522](https://arxiv.org/abs/1811.12522)

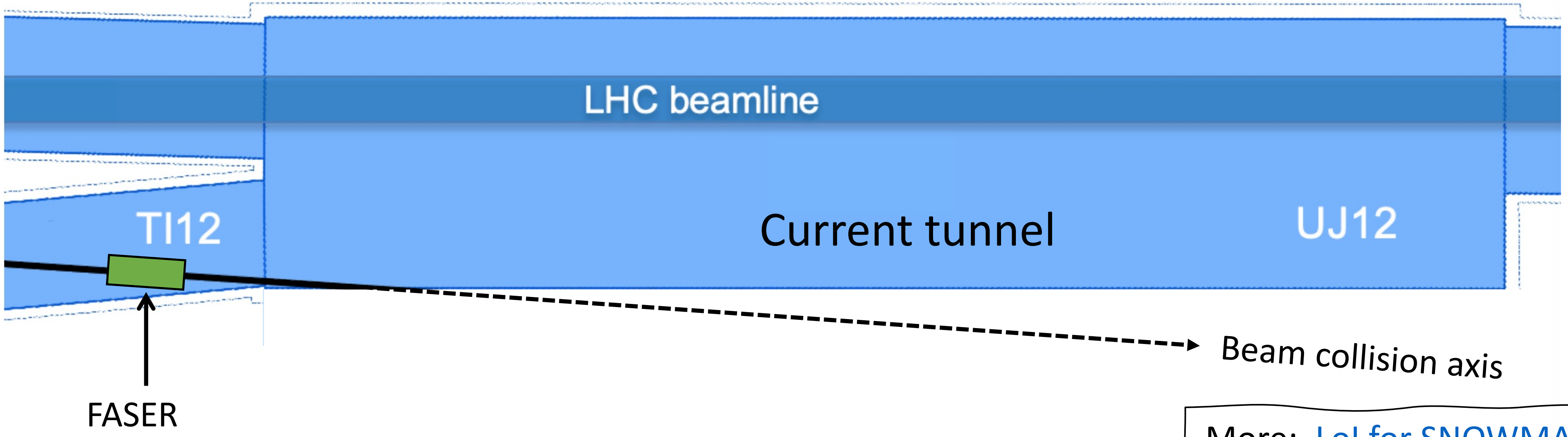


Increased detector radius to 1 m allows sensitivity to particles produced in heavy meson (B, D) decays increasing physics case beyond just increased luminosity



Beyond FASER? A teaser for the proposed Forward Physics Facility

FASER2: Increased detector radius to 1 m allows sensitivity to particles produced in heavy meson (B, D) decays increasing physics case beyond just increased luminosity

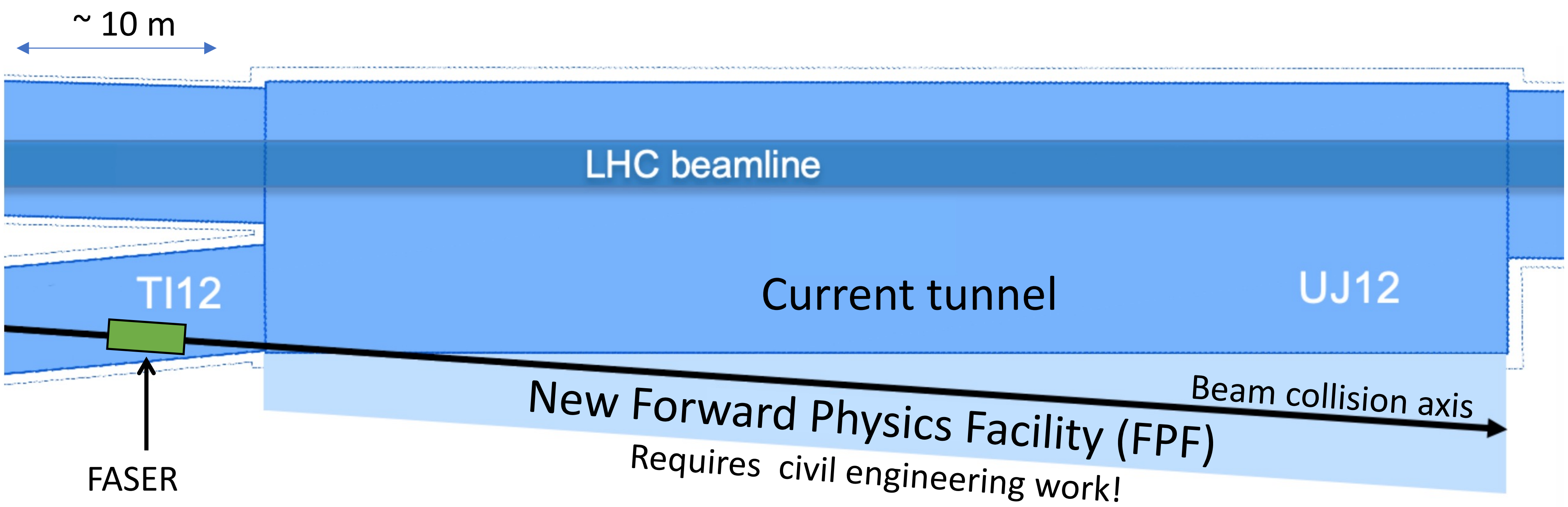


More: LoI for SNOWMASS-2021
arXiv:2203.05090
FPF – Kickoff workshop
FPF – 5th (latest) workshop

Beyond FASER?

A teaser for the proposed

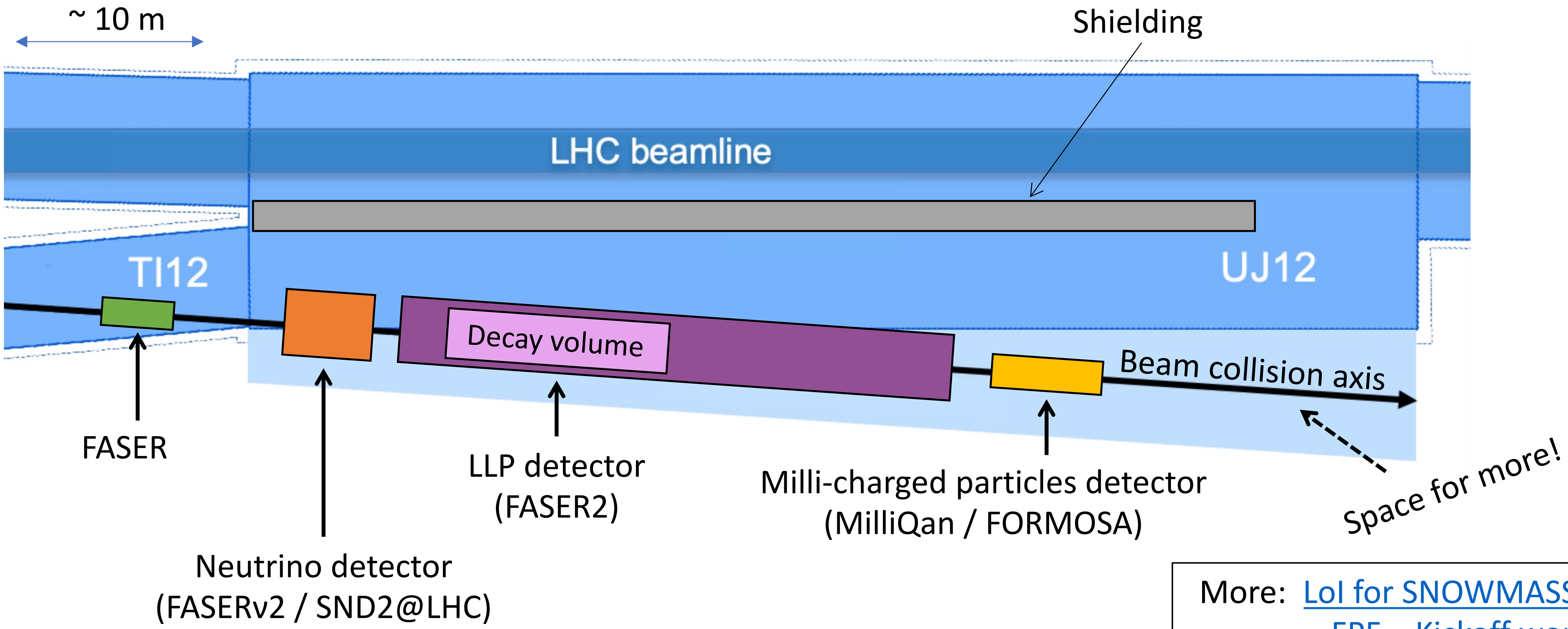
Forward Physics Facility



More: LoI for SNOWMASS-2021
FPF – Kickoff workshop
FPF – 4th (latest) workshop

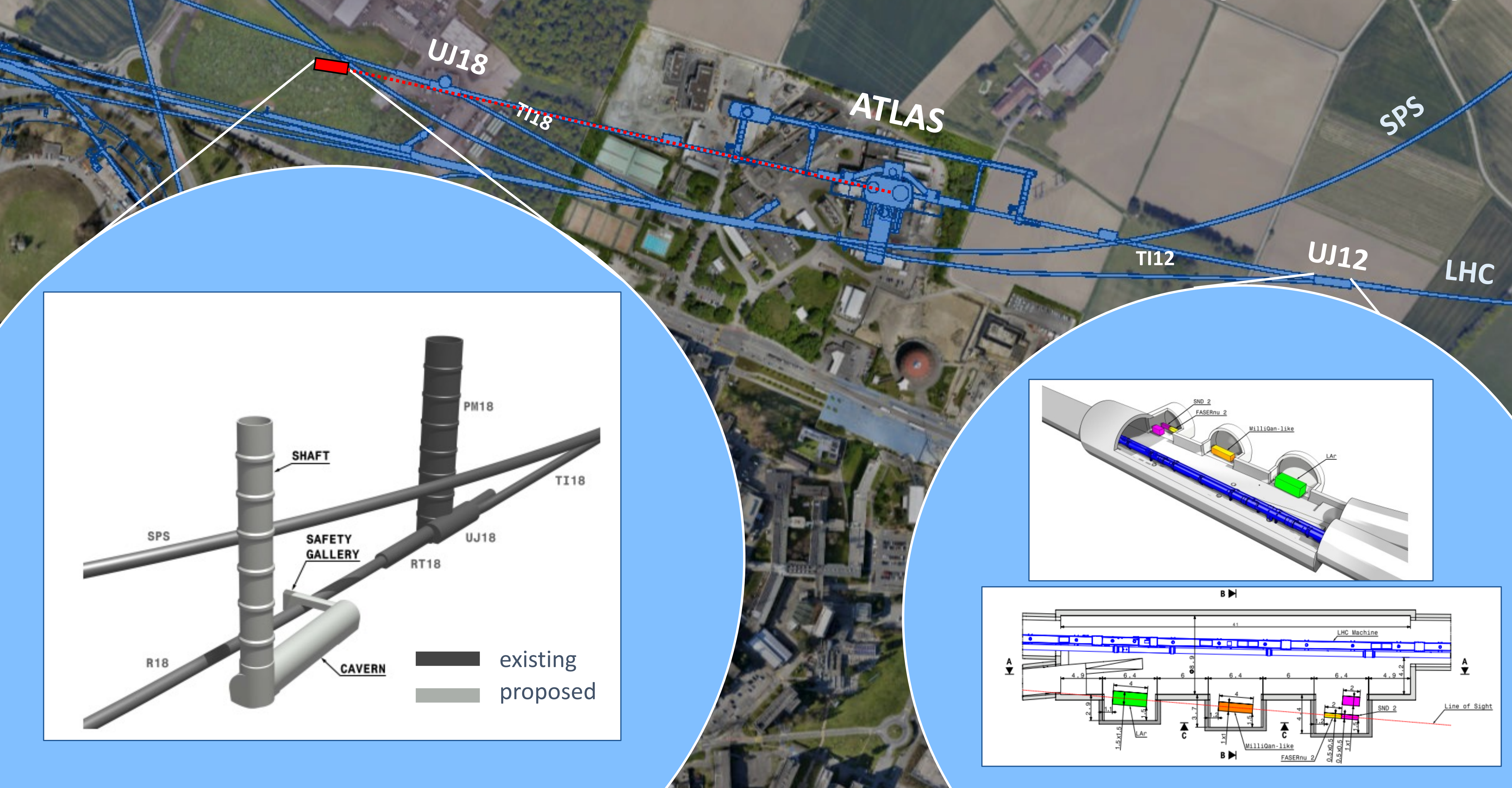
Beyond FASER?

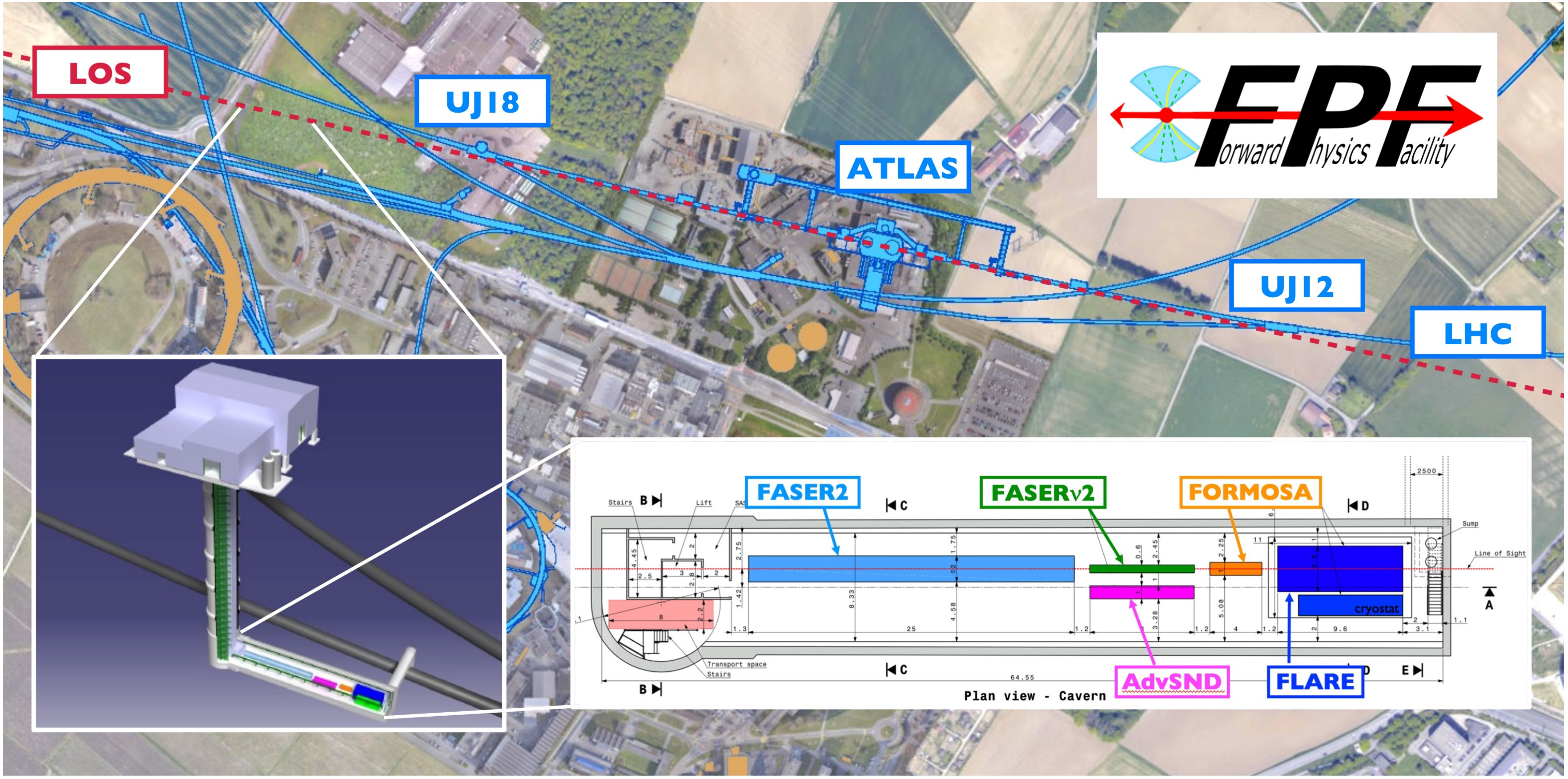
A teaser for the proposed Forward Physics Facility



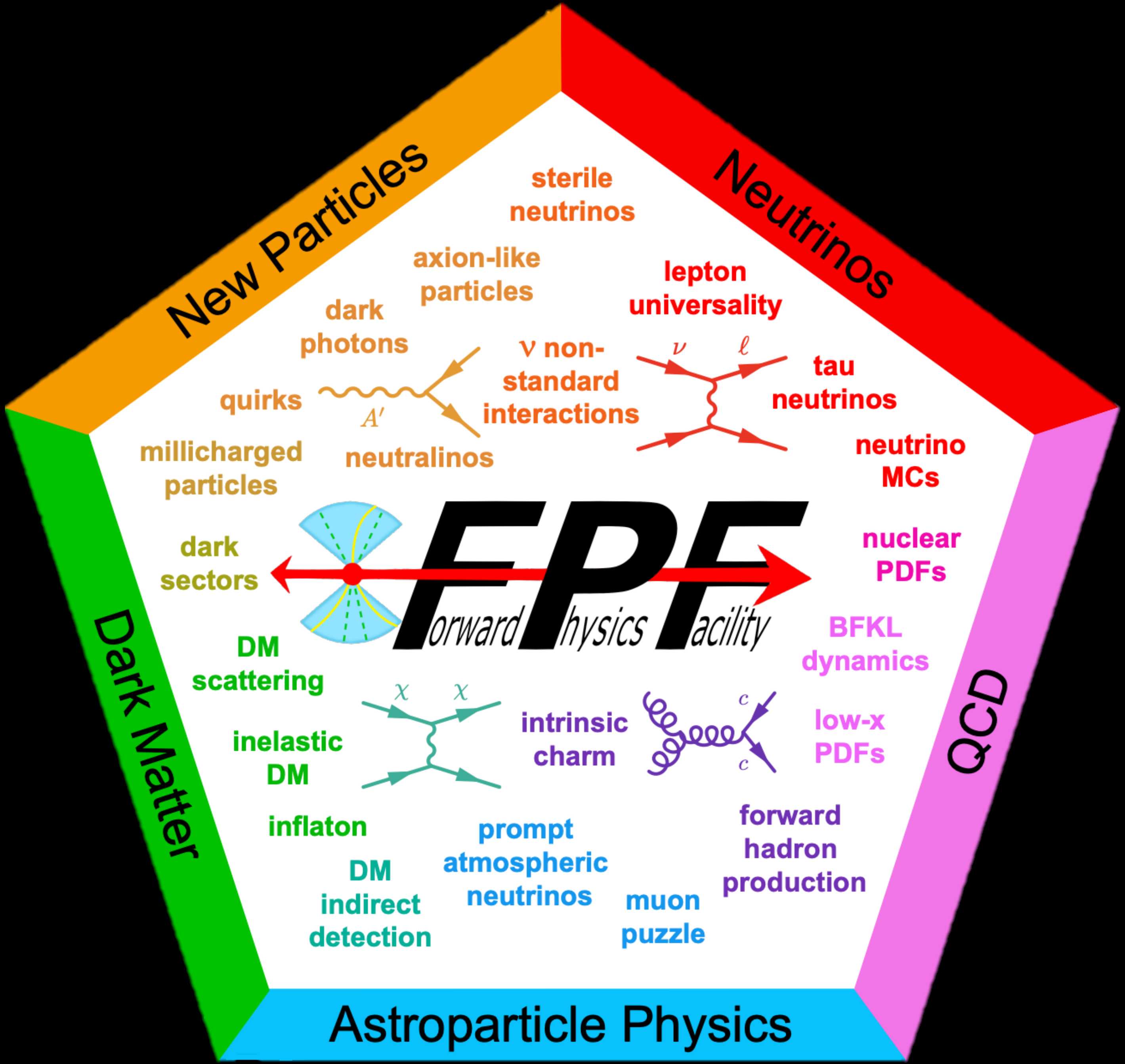
More: LoI for SNOWMASS-2021
FPF – Kickoff workshop
FPF – 4th (latest) workshop

Possibilities for the Forward Physics Facility





arXiv:2203.05090

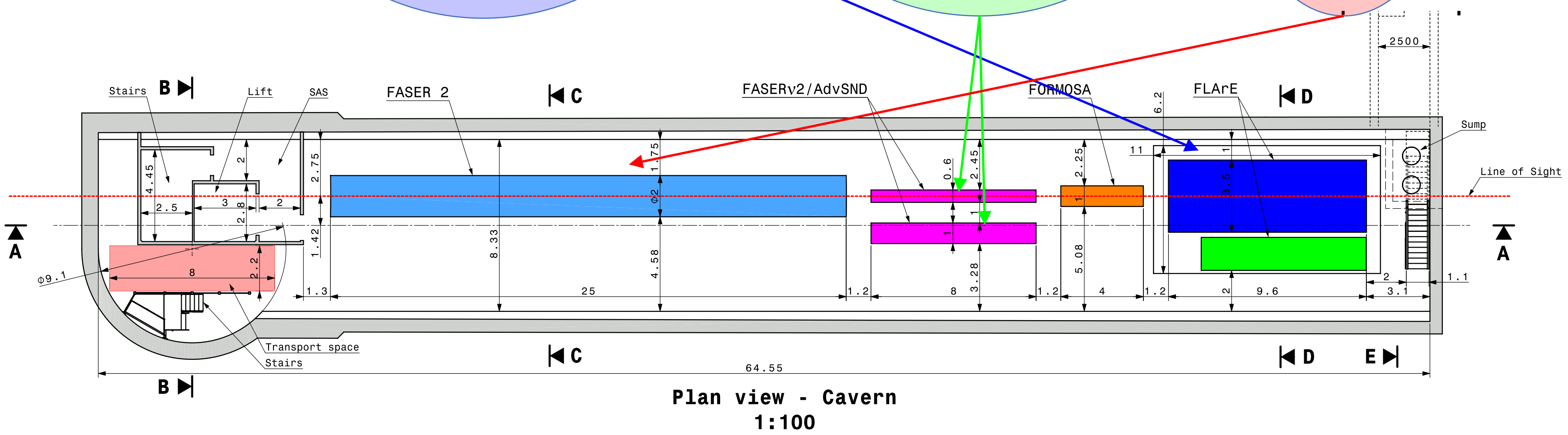


arXiv:2203.05090

SIGNATURES FOR OTHER FPF EXPERIMENTS

Slide from J. Feng

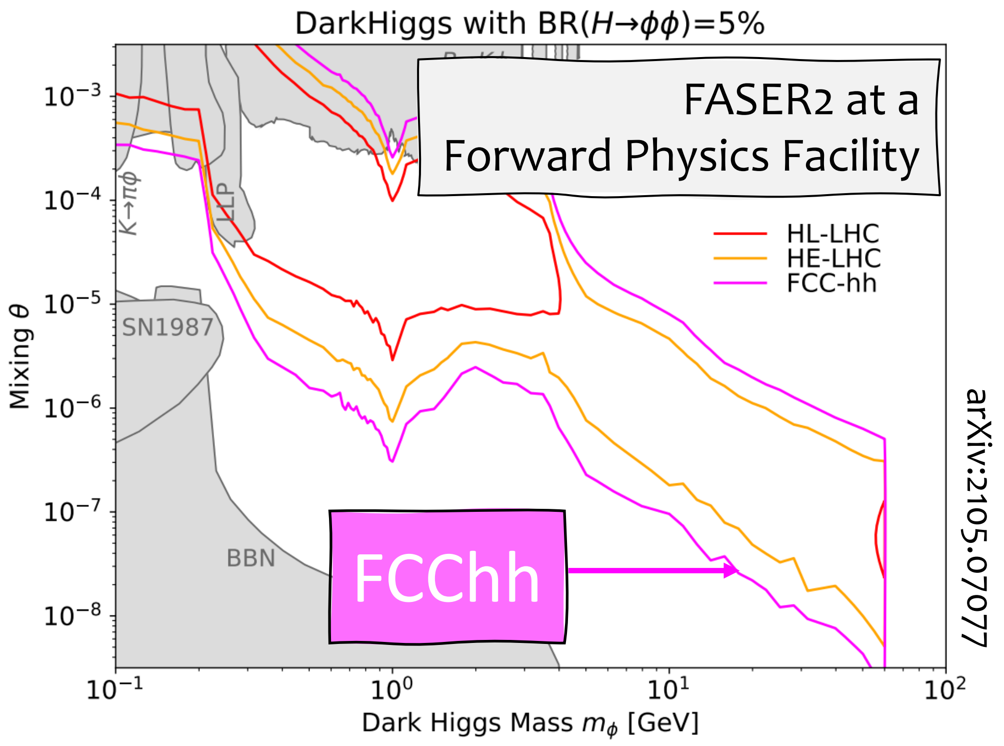
Signature	DM DIS	DM Elastic	ν NC DIS	ν_τ CC DIS	LLP decays
Models	$U(1)_B$, $U(1)_{B-3\tau}$	$U(1)_B$, $U(1)_{B-3\tau}$	$U(1)_{B-3\tau}$	$U(1)_{B-3\tau}$	$U(1)_B$, $U(1)_{B-3\tau}$
Production	$pp \to V \to \chi\chi$	$pp \to V \to \chi\chi$	$pp \to D_s \to \nu_\tau$	$pp \to V \to \nu_\tau\bar{\nu}_\tau$	$pp \to V$
Detection	$\chi N \to \chi X$	$\chi p \to \chi p$	$\nu_\tau N \to \nu_\tau X$	$\nu_\tau N \to \tau X$	$V \to$ hadrons



Batell, Feng, Fieg, Ismail, Kling, Abraham, Trojanowski, 2111.10343

Opportunities for FIPs at FCC

At FCChh



Significant opportunities open up, beyond what can be done with conventional collider detectors!
Essential to account for them since the beginning, to minimize overheads later on.