

Taking physics forward with



15 November 2023

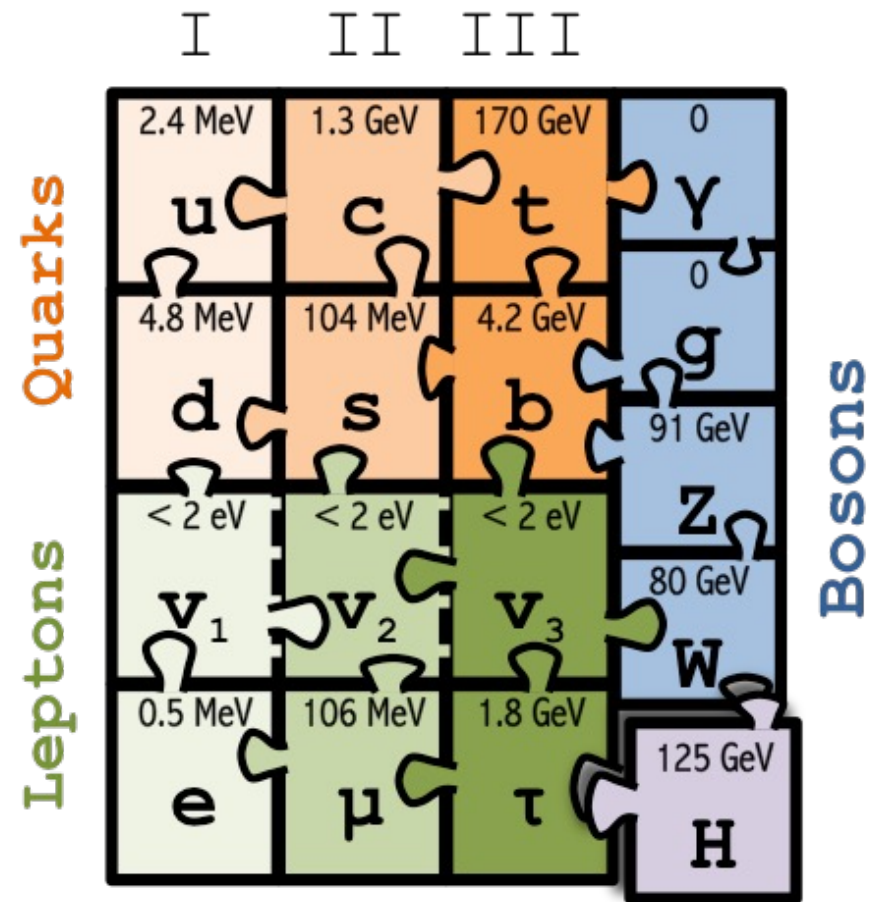
Anna Sfyrla



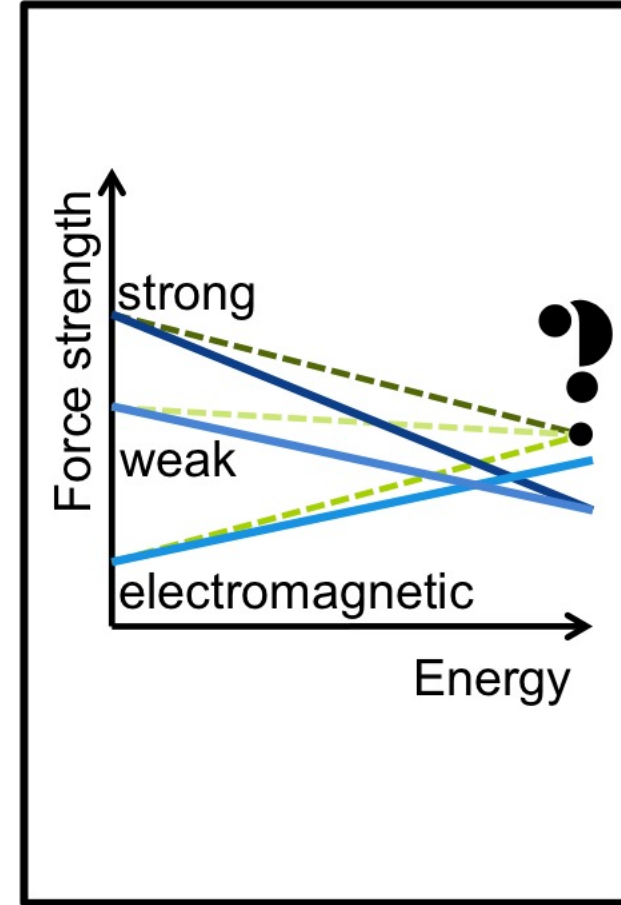
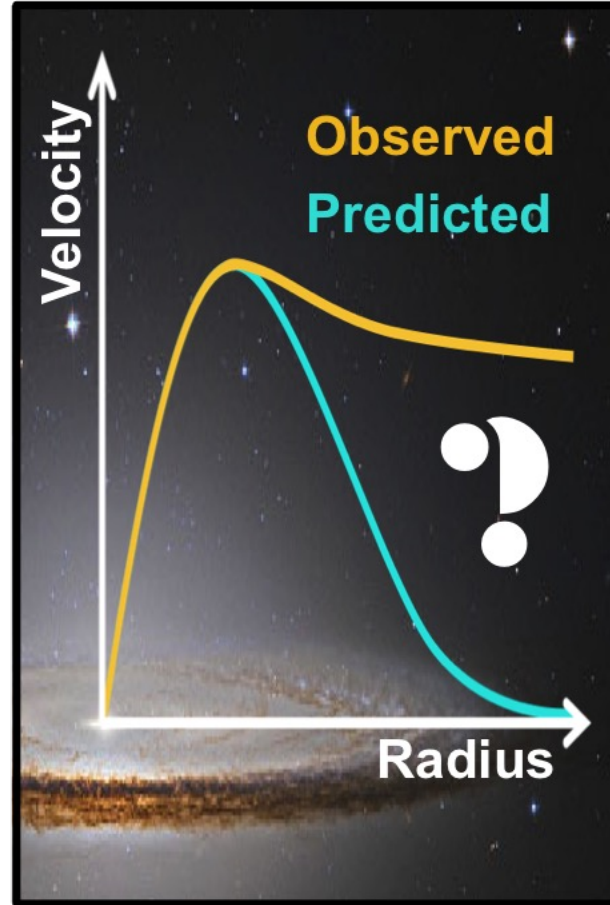
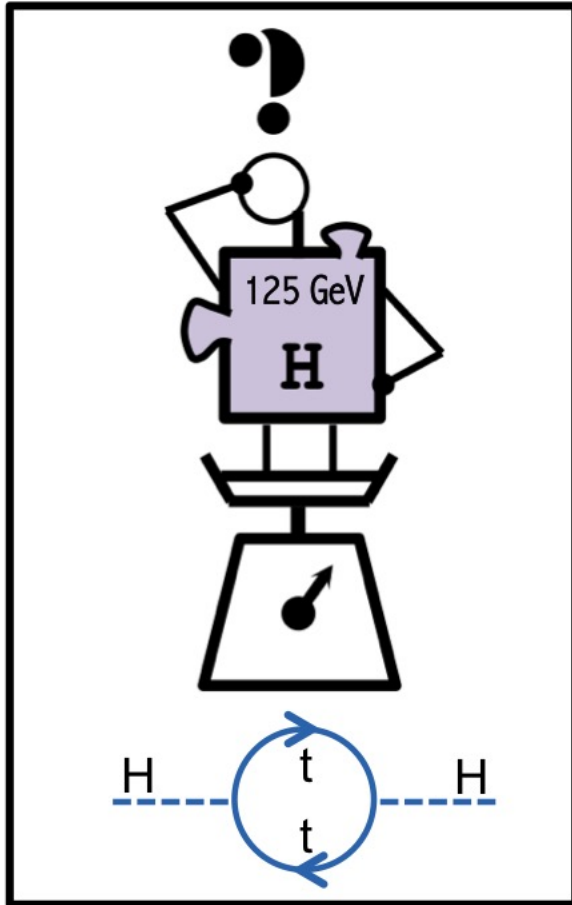
**UNIVERSITÉ
DE GENÈVE**

FACULTY OF SCIENCE

THE STANDARD MODEL



...ITS BIGGEST OPEN QUESTIONS ...



...AND ITS MORE SUBTLE ONES!

Why does QCD preserve CP symmetry?

Within the SM, the QCD vacuum structure introduces a CP violating term in the Lagrangian:

$$L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

while [measurements](#) require that the vacuum angle θ is tiny!

The non-zero angle θ implies non-zero neutron electric dipole moment (EDM)

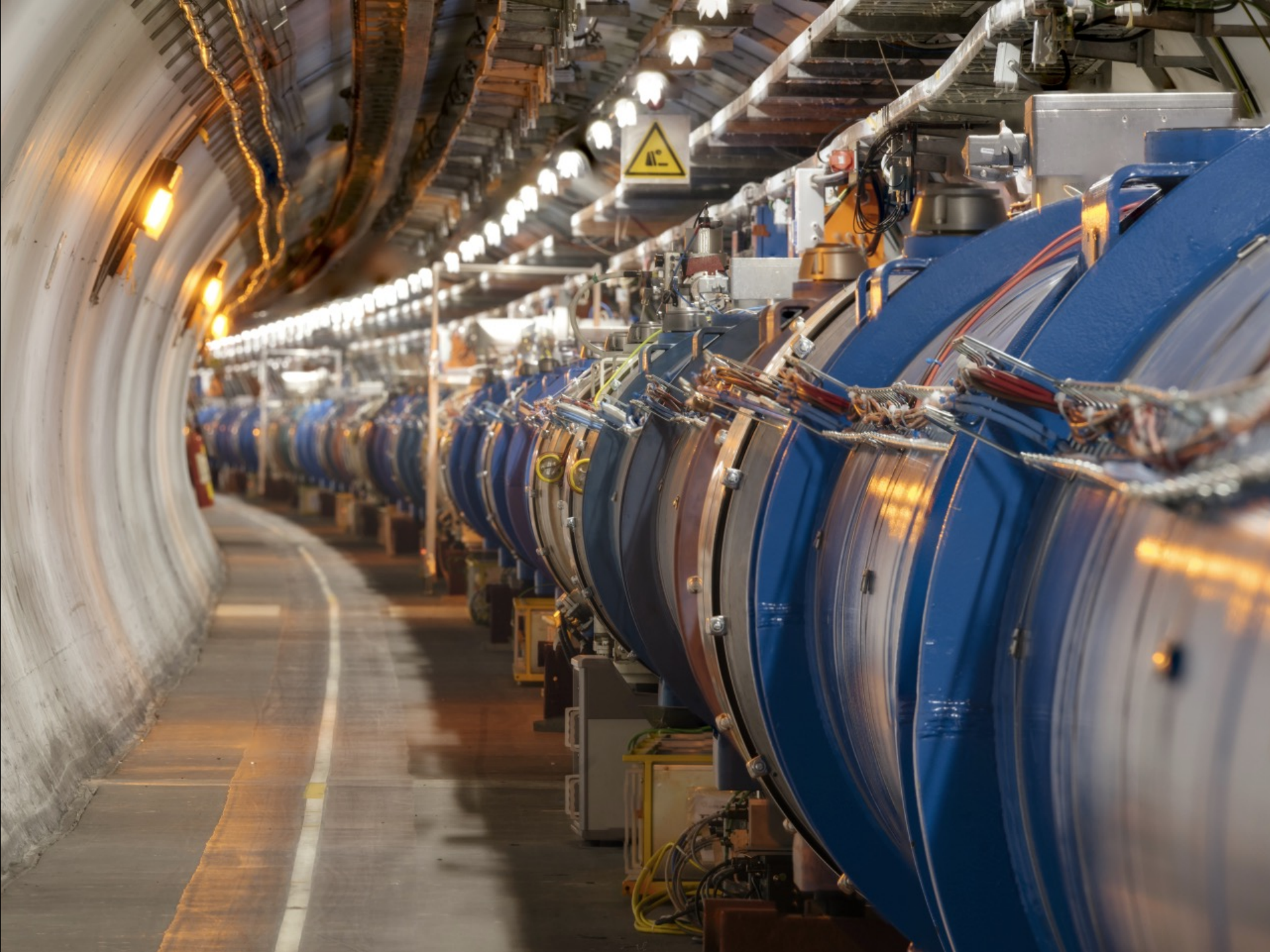
The angle is stringently constrained by neutron EDM measurements

Most sensitive measurement on the neutron EDM to date achieved by the **PSI** experiment **nEDM**:

$$d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-26} \text{ e}\cdot\text{cm}.$$

In other words,

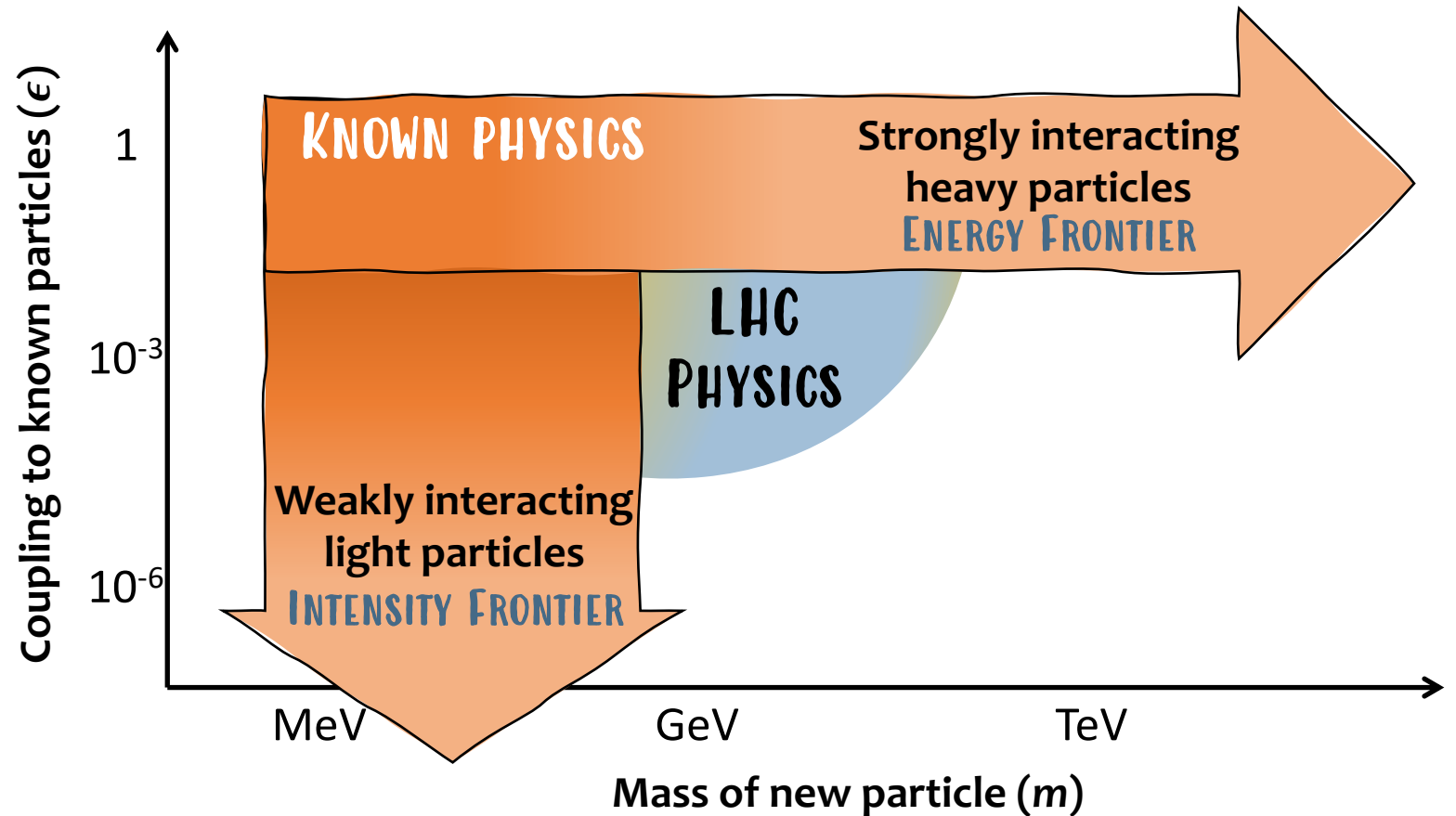
The “**strong CP problem**”: Why no measurable neutron EDM?



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!

	2.4 MeV	1.3 GeV	170 GeV	0
	u	c	t	γ
	4.8 MeV	104 MeV	4.2 GeV	0
	d	s	b	g
	<2 eV	<2 eV	<2 eV	91 GeV
	ν_L	ν_M	ν_H	Z
	0.5 MeV	16 MeV	1.8 GeV	80 GeV
	e	μ	τ	W
				126 GeV
				H



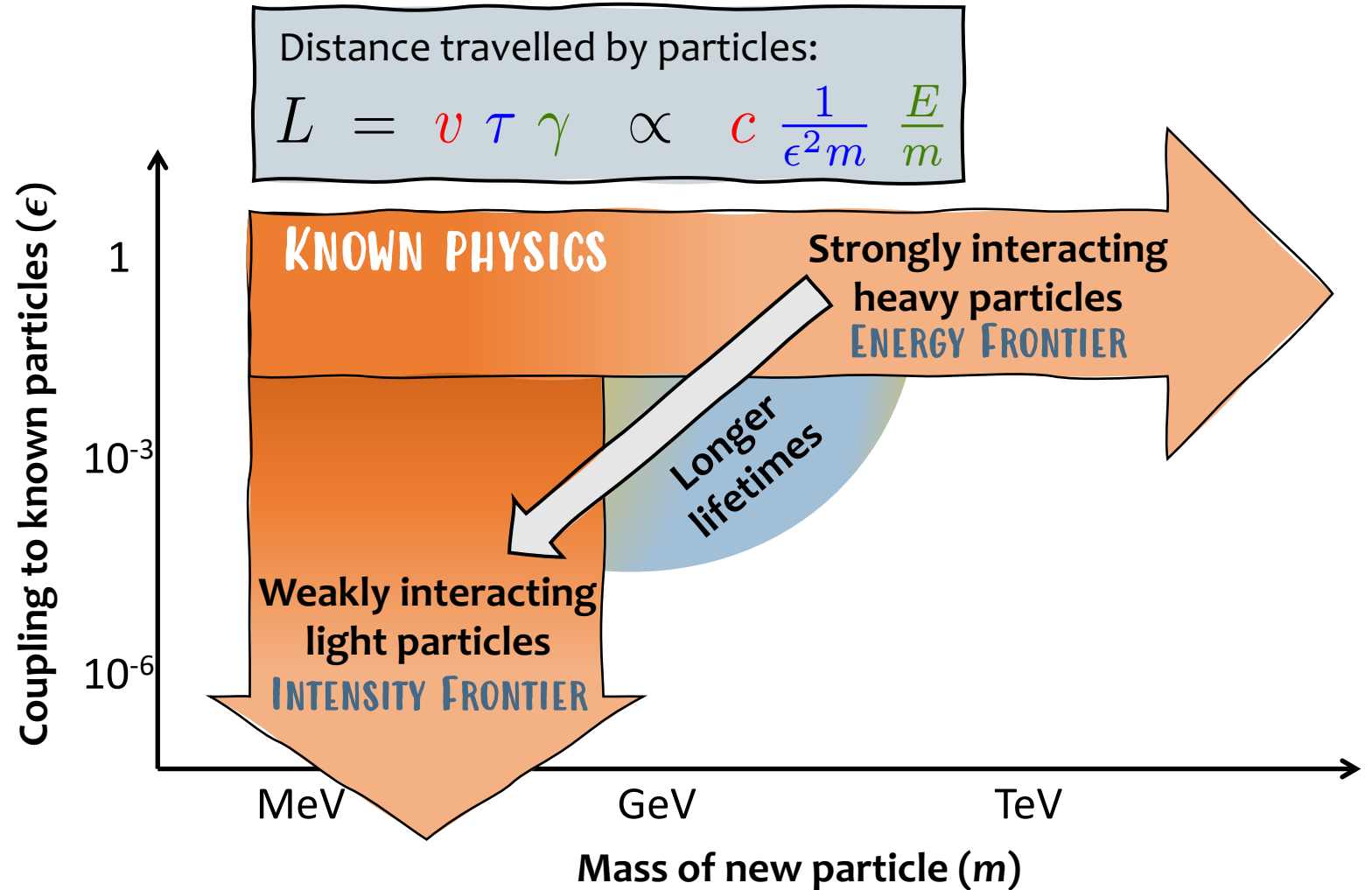
THE LANDSCAPE OF NEW PARTICLES @ COLLIDERS

Lifetime

a characteristic of weakly interacting light particles

Distinct signatures

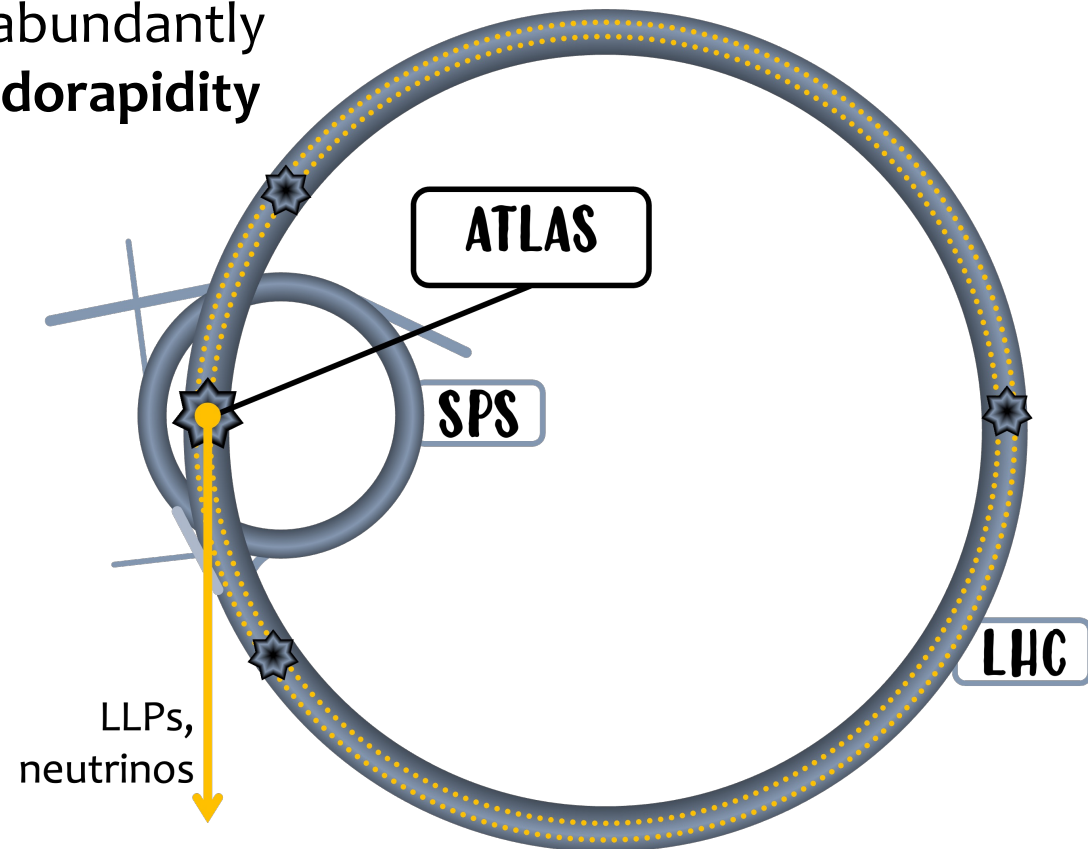
Opportunity for exploration!



FORWARD SEARCH EXPERIMENT AT THE LHC

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

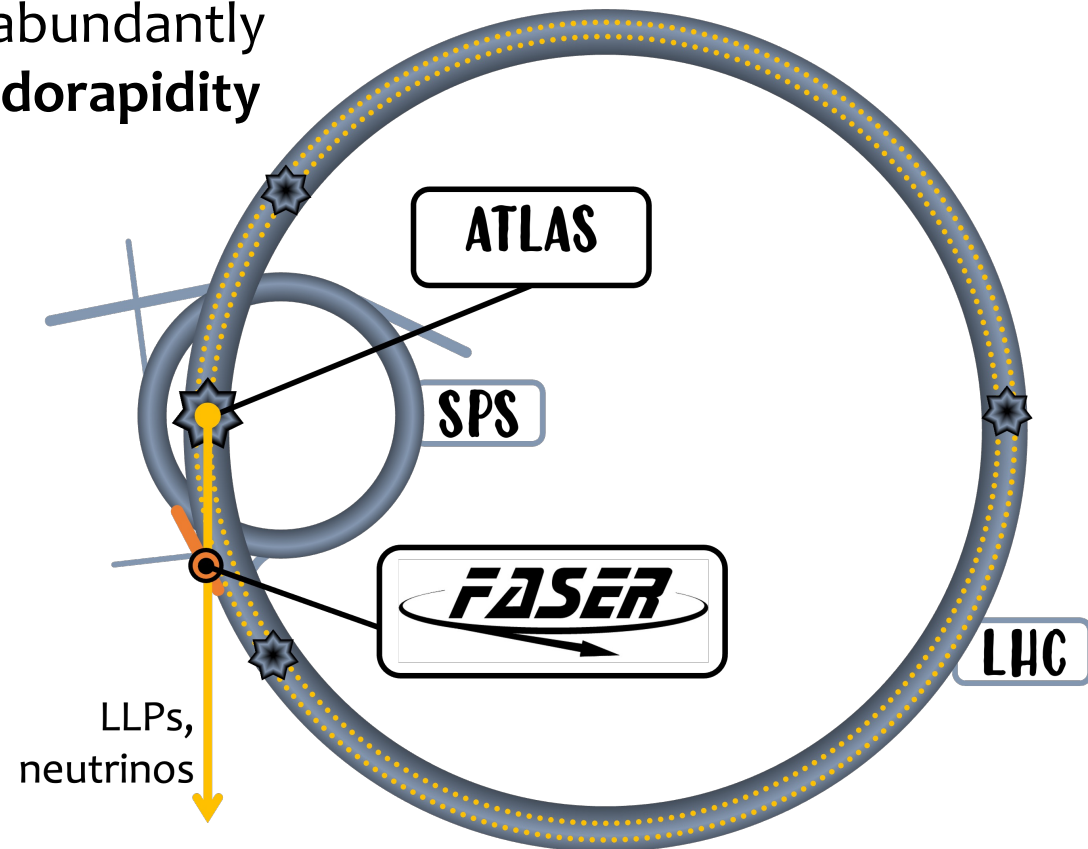
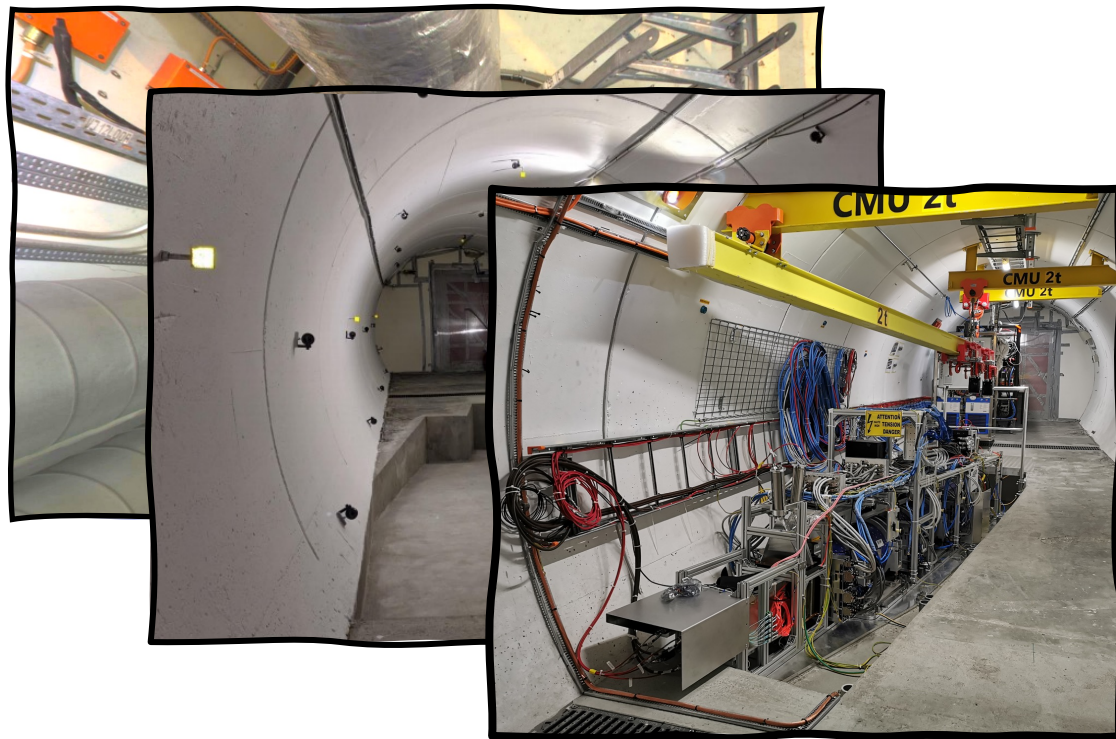
- Produced in decays of light mesons (e.g. π , K), abundantly present in p-p collisions, **primarily in large pseudorapidity**



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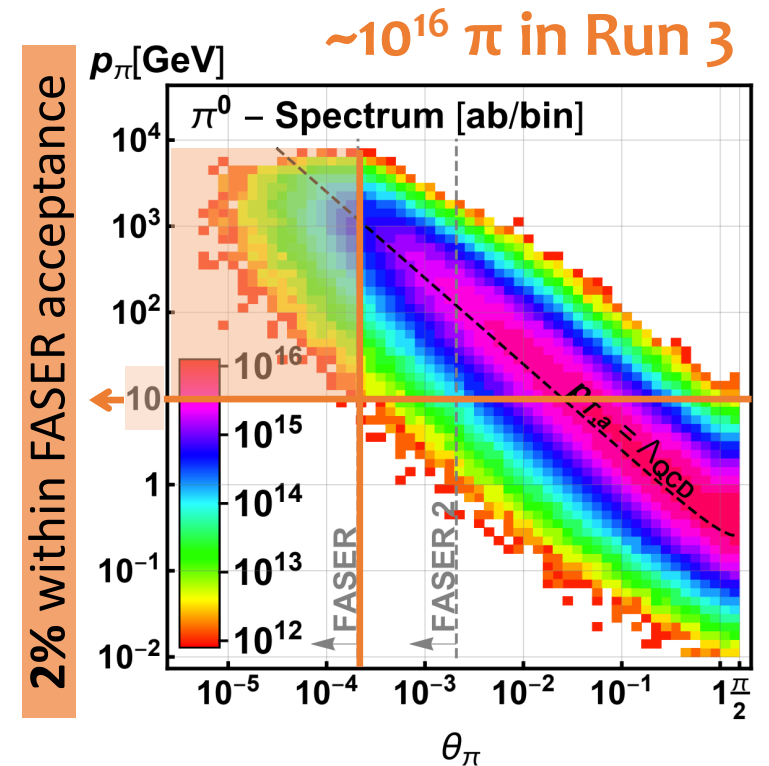
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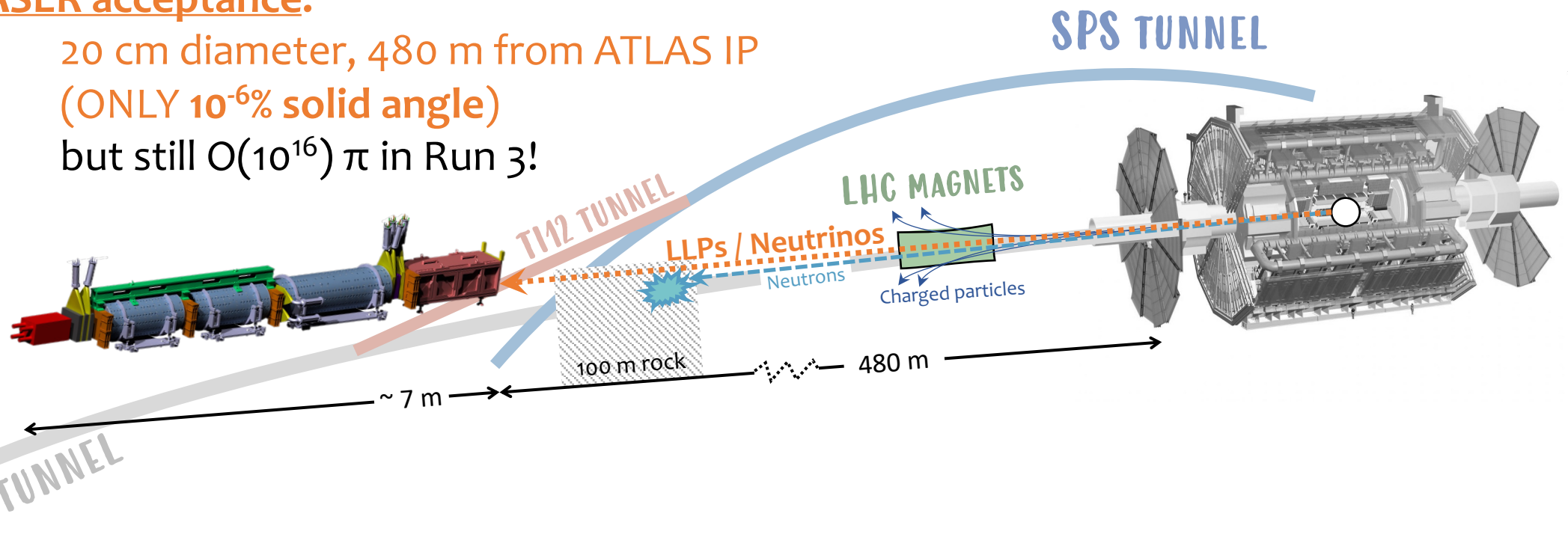
- Produced in decays of light mesons (e.g. π , K), abundantly present in p-p collisions, **primarily in large pseudorapidity**
- FASER acceptance:**
 - 20 cm diameter, 480 m from ATLAS IP (ONLY $10^{-6}\%$ solid angle)
 - but still $O(10^{16}) \pi$ in Run 3!



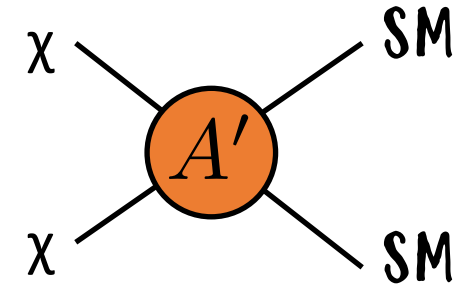
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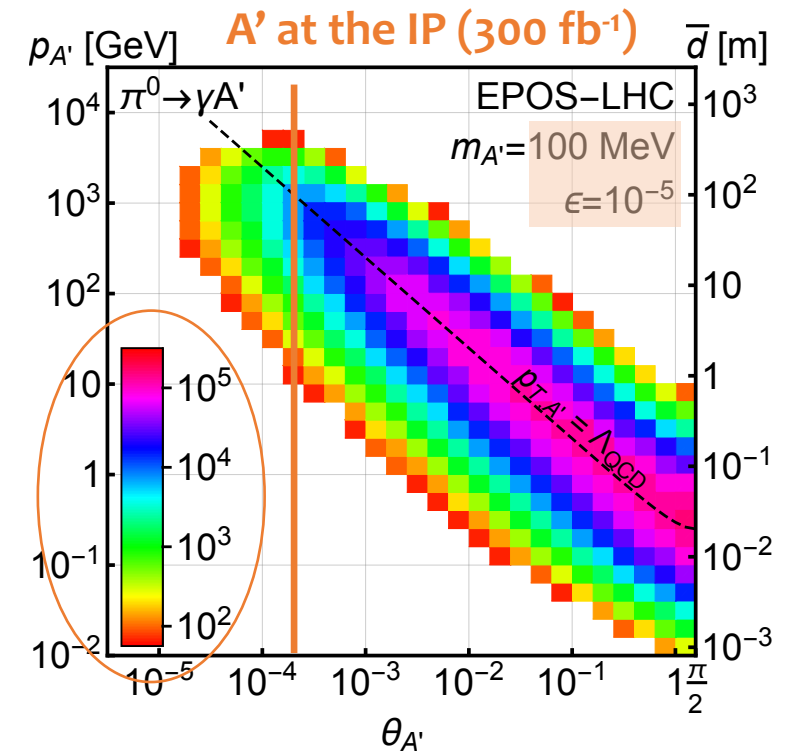
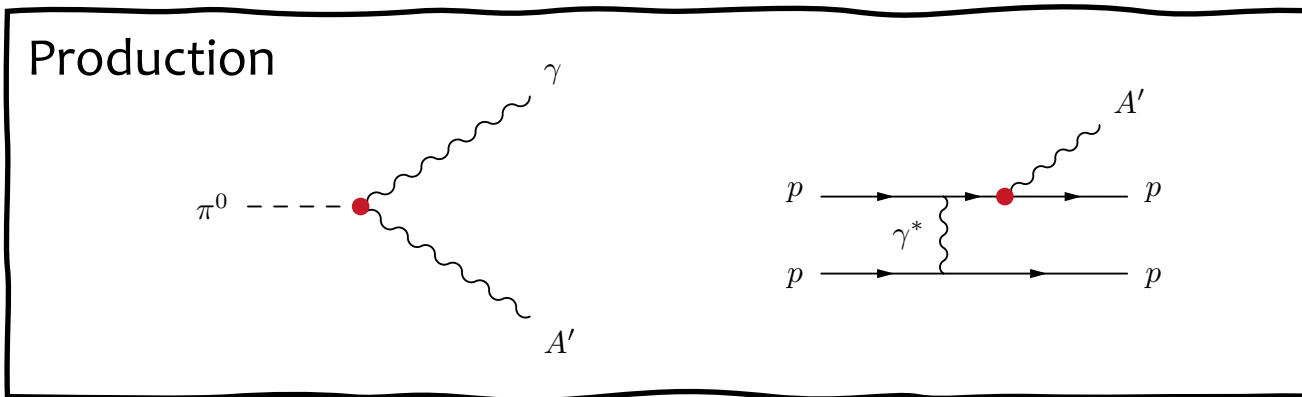
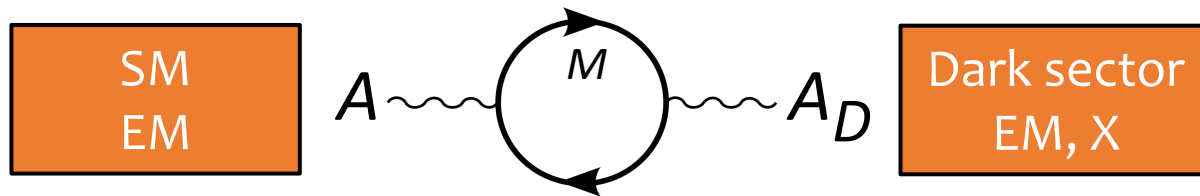
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AN EXAMPLE PHYSICS CASE: DARK PHOTON



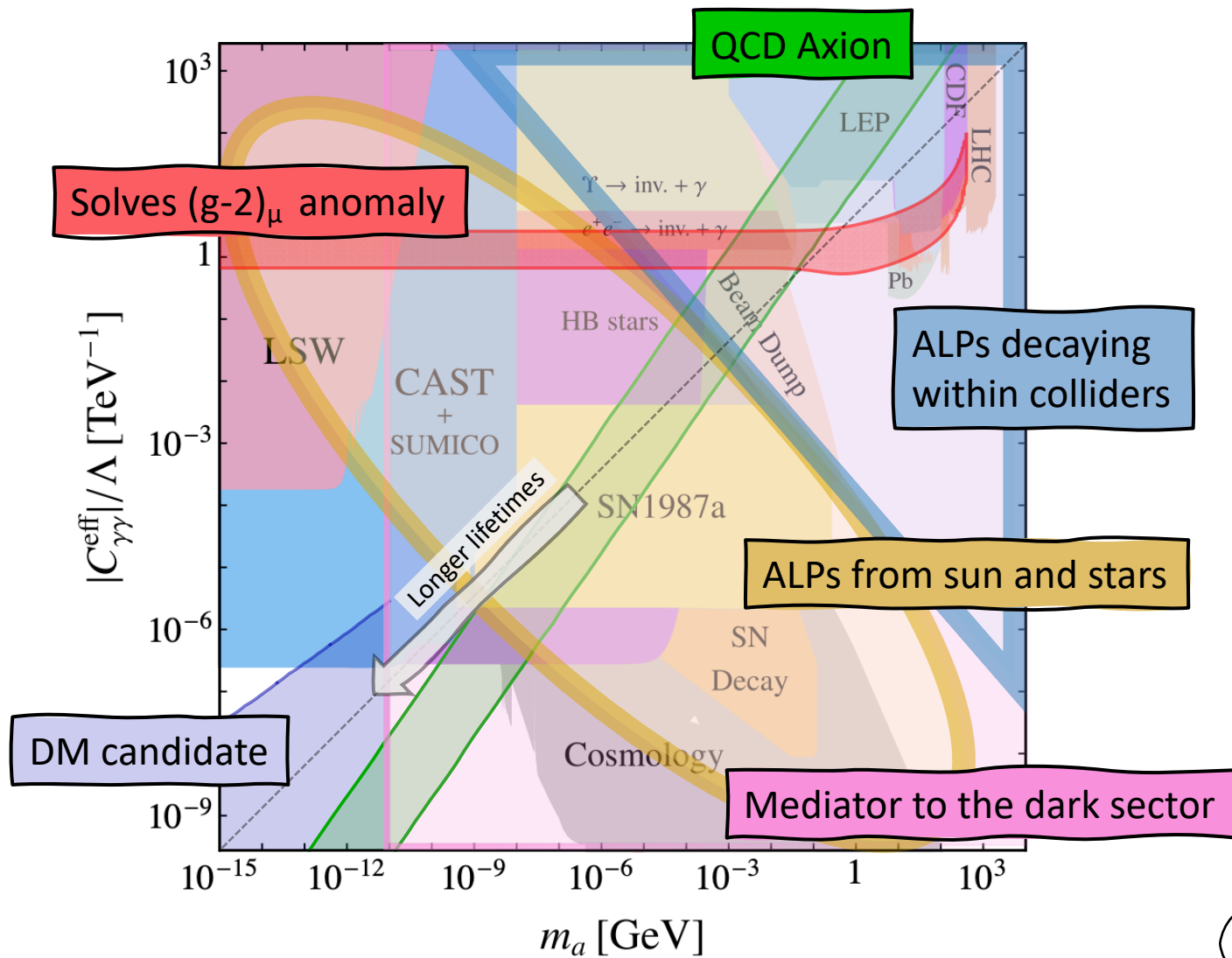
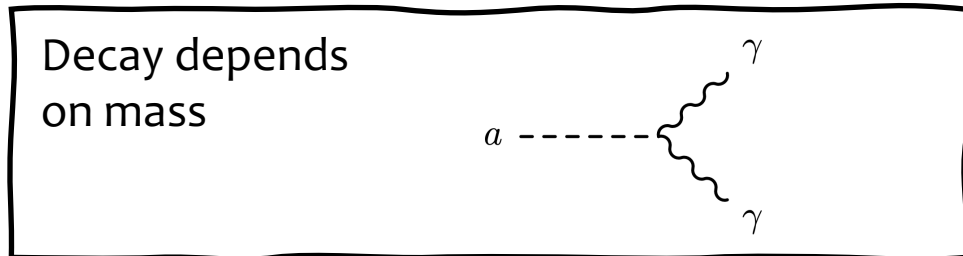
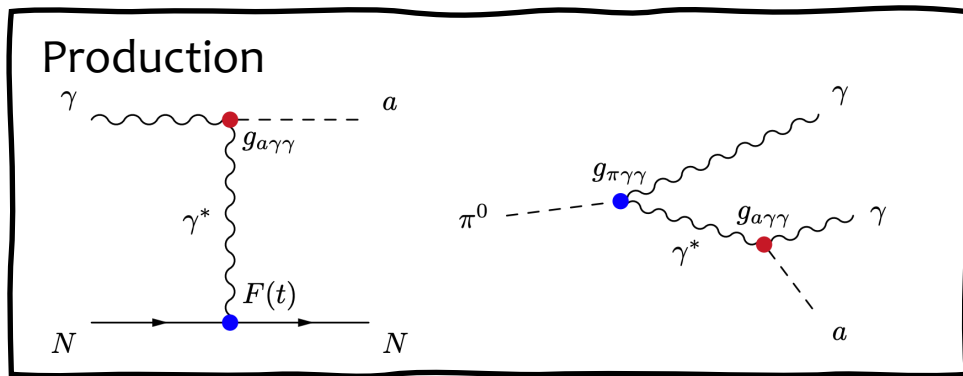
- New **massive** gauge boson in a dark sector with dark matter candidate X
- Spin 1, **couples weakly to SM fermions** (ϵQ_f coupling, small ϵ) through mixing with the photon
 - Will be searched for via its **decay to an electron-positron pair**
- For $m_{A'}=100$ MeV, $\epsilon \sim 10^{-5}$ and $E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



ANOTHER EXAMPLE: AXION-LIKE PARTICLES (ALPs)

Qualitatively different: “High-energy photon beam dump experiment”

- Pseudoscalar SM-singlets; can appear in theories with broken global symmetries
- Low mass particles with suppressed couplings to SM



Thanks to Andrea Thamm for the figure!

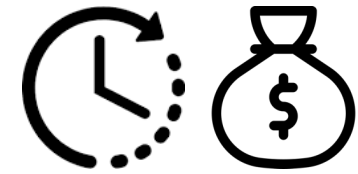
THE



EXPERIMENT

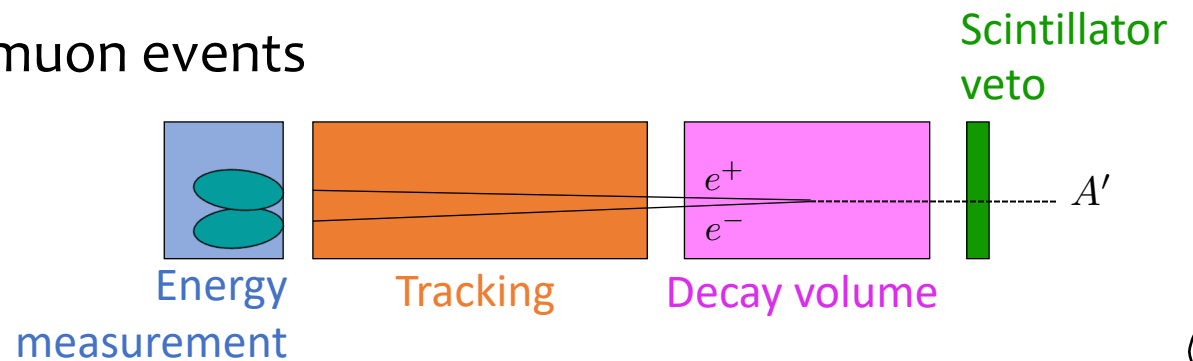
DETECTOR CONCEPT

- **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

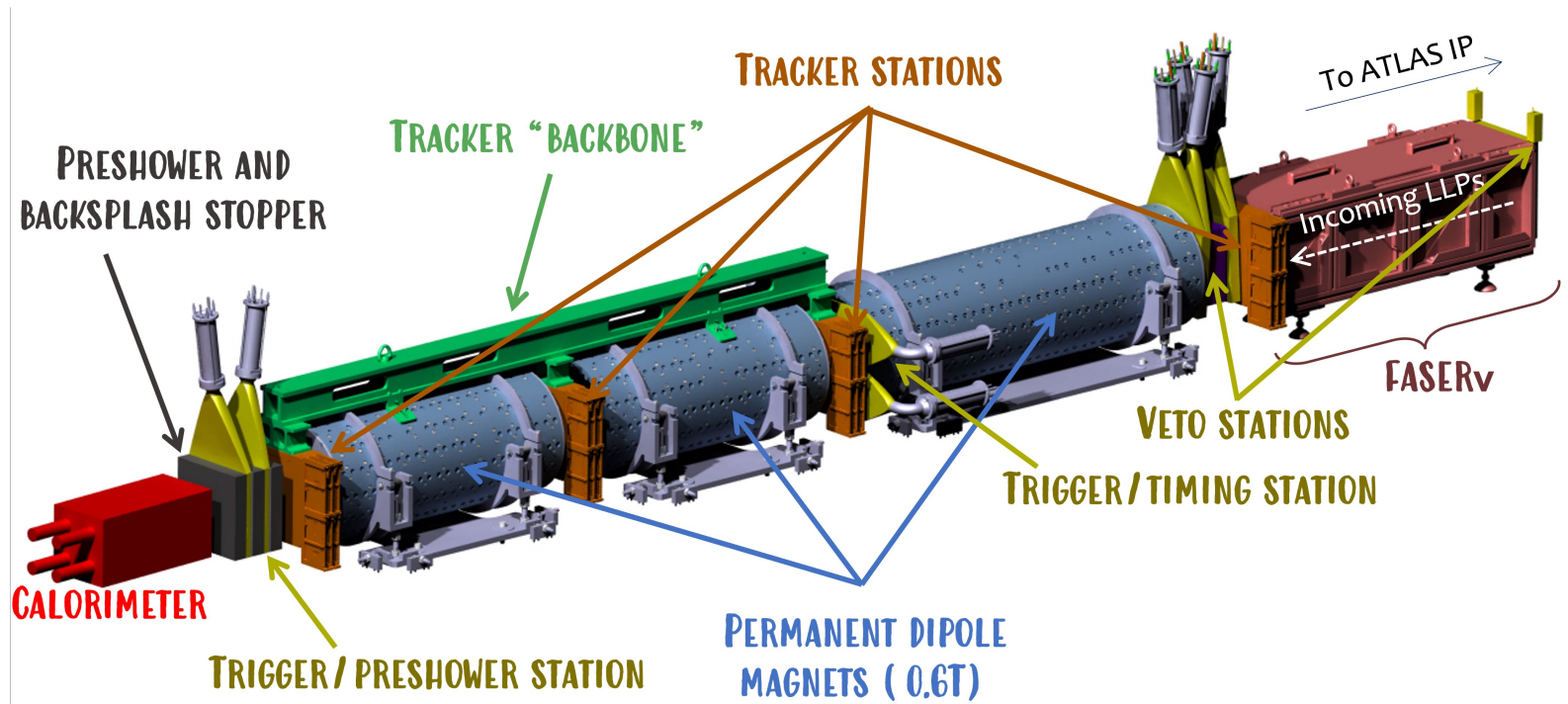


- **Many challenges of the large LHC experiments not there for FASER:**

- trigger rate $O(500\text{Hz})$ – mostly single muon events
- low radiation
- low occupancy / event size



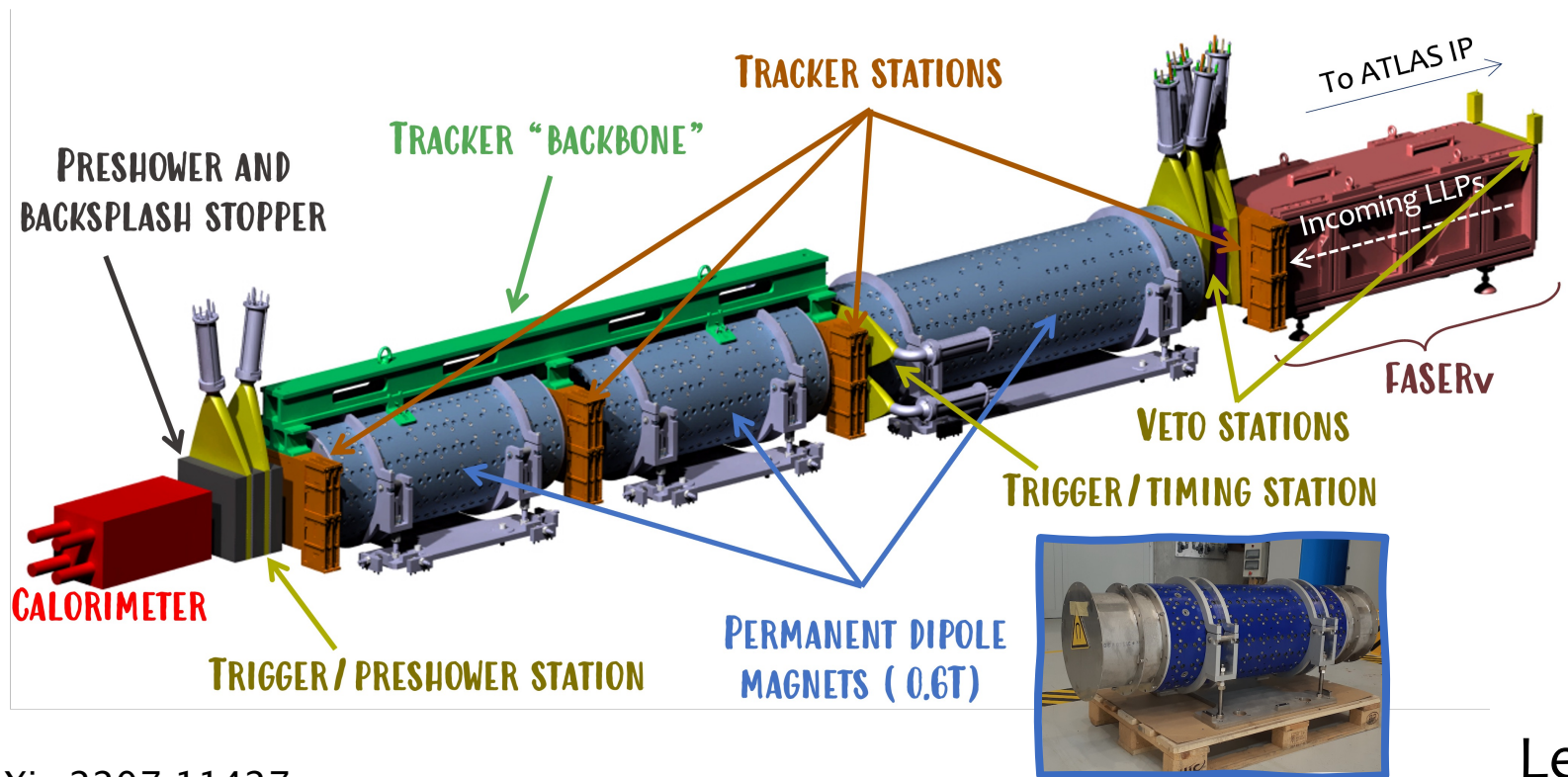
FASER DETECTOR



Length: 7 m
Aperture: 20 cm

Length of decay volume: 1.5 m

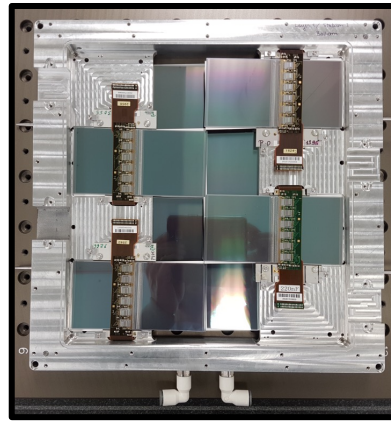
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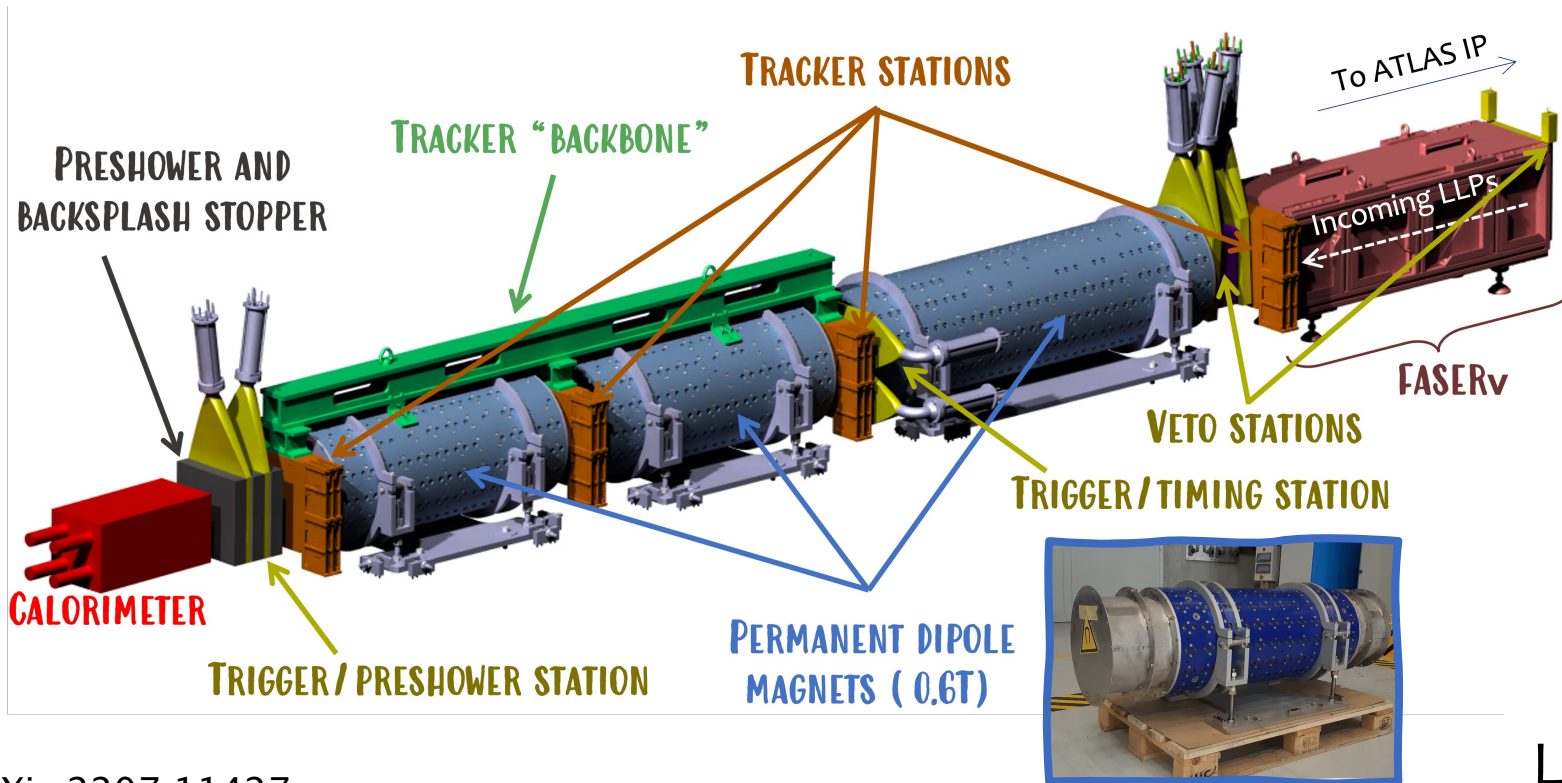
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FASER DETECTOR



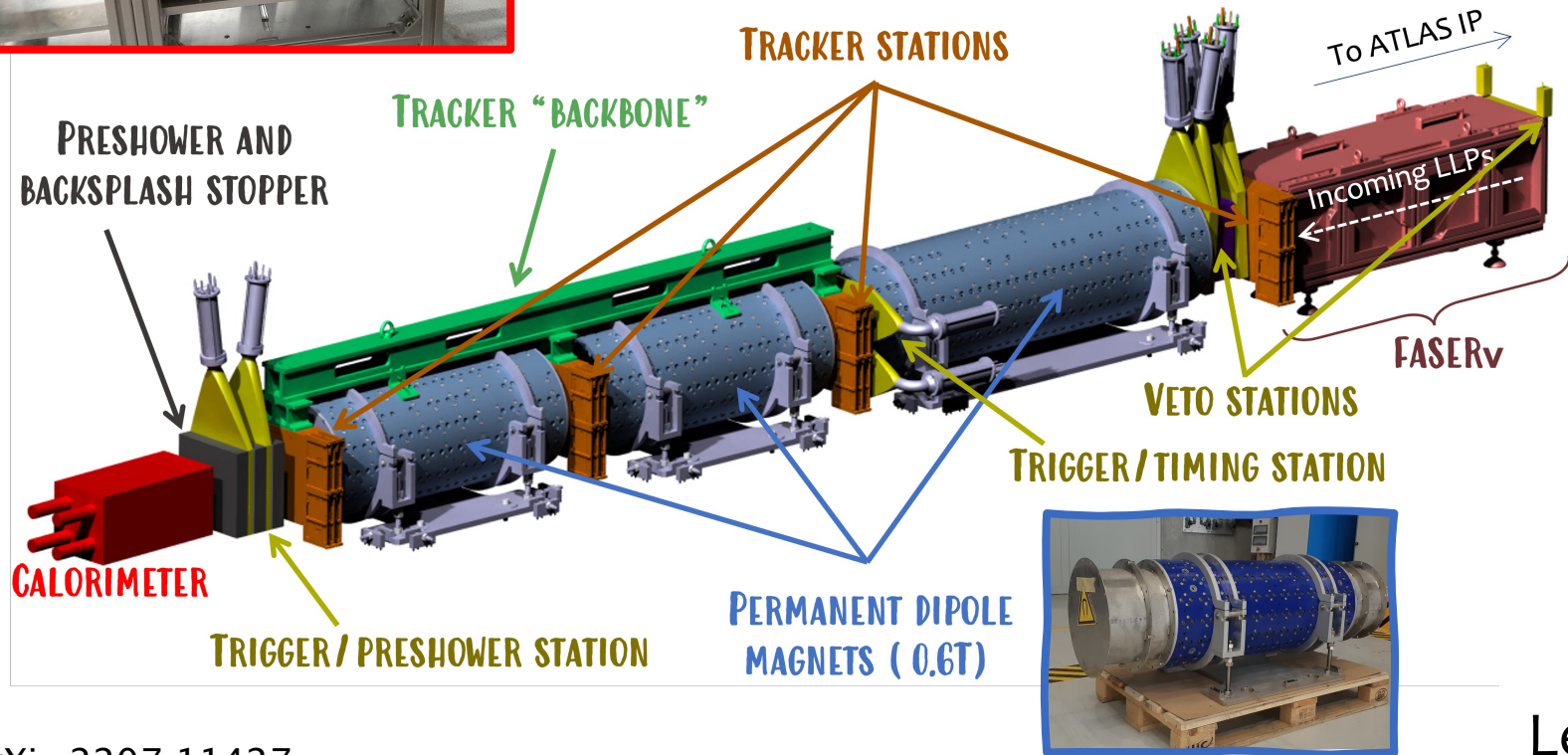
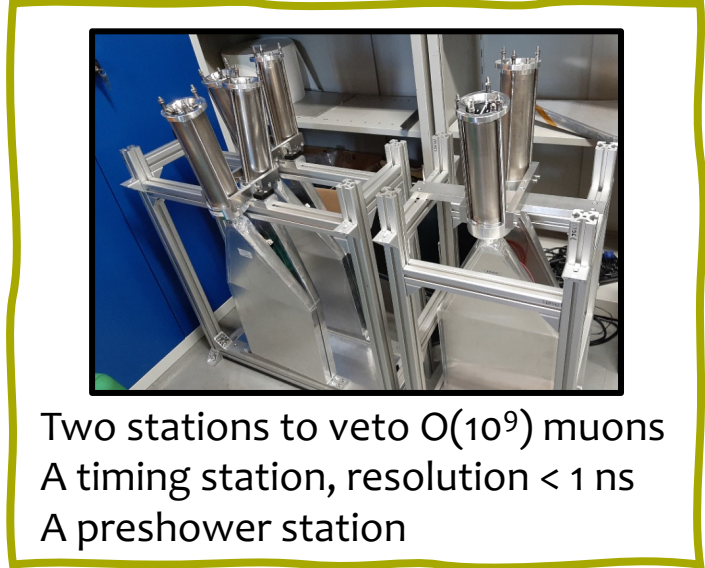
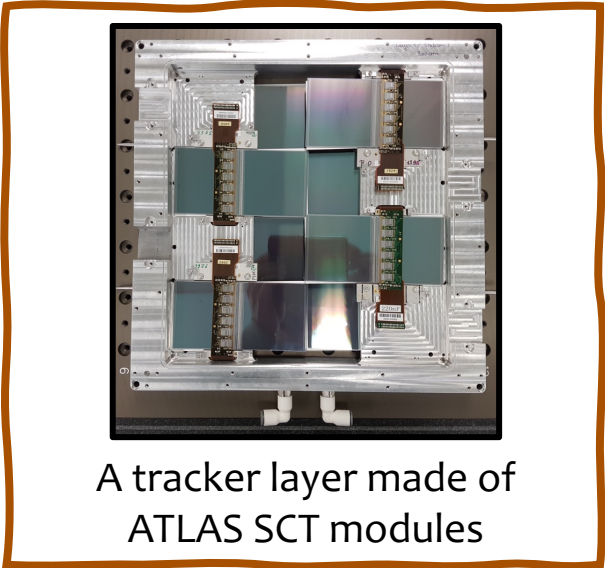
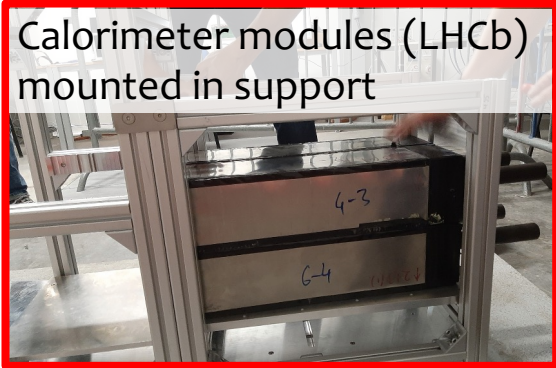
A tracker layer made of ATLAS SCT modules



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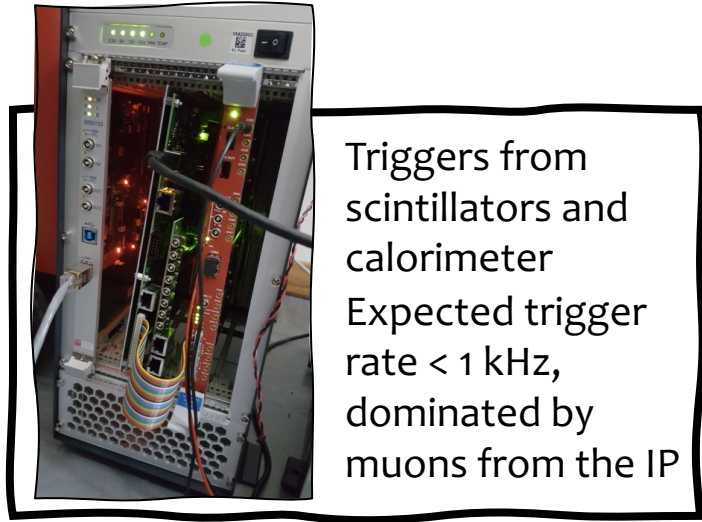
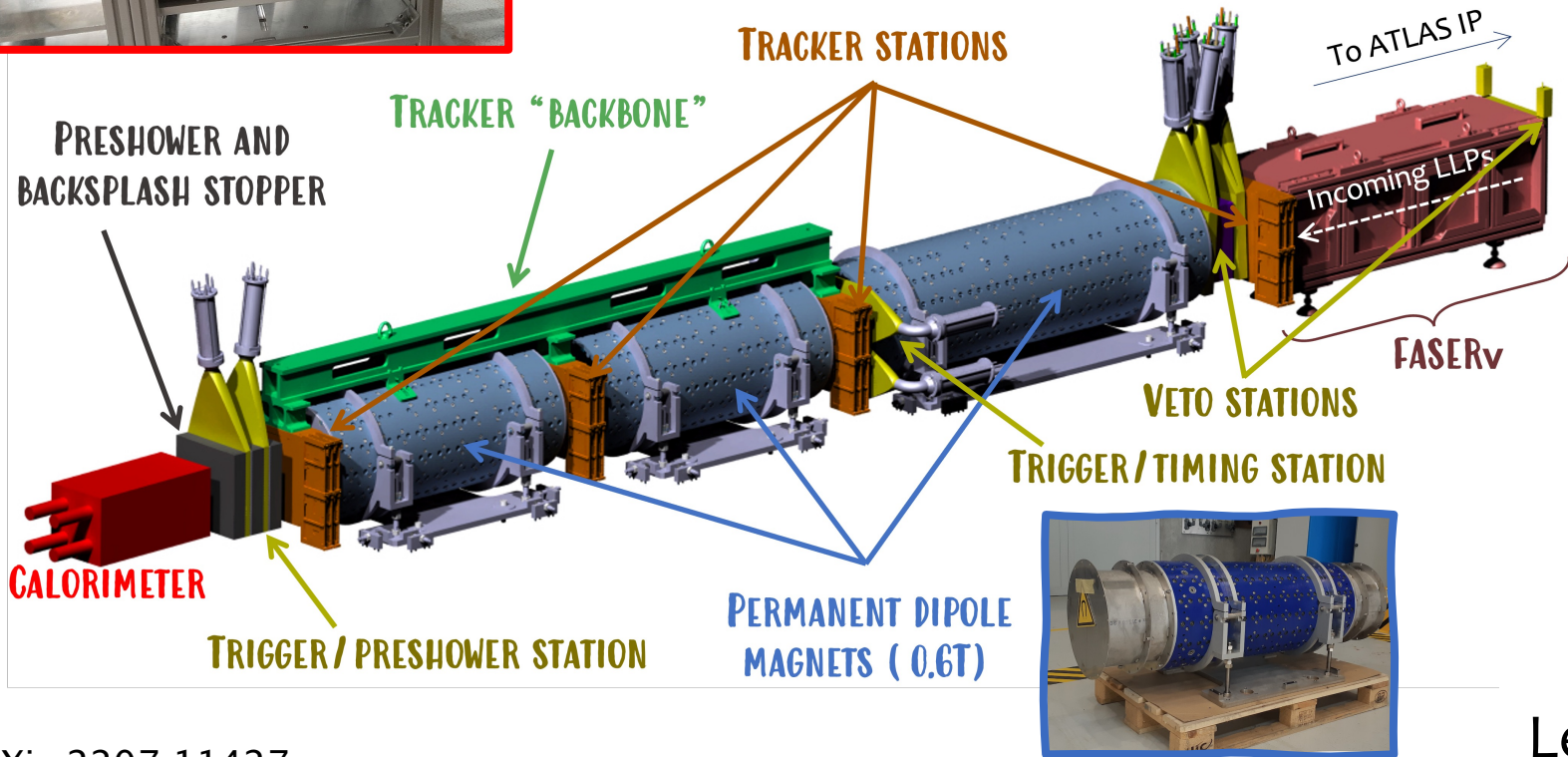
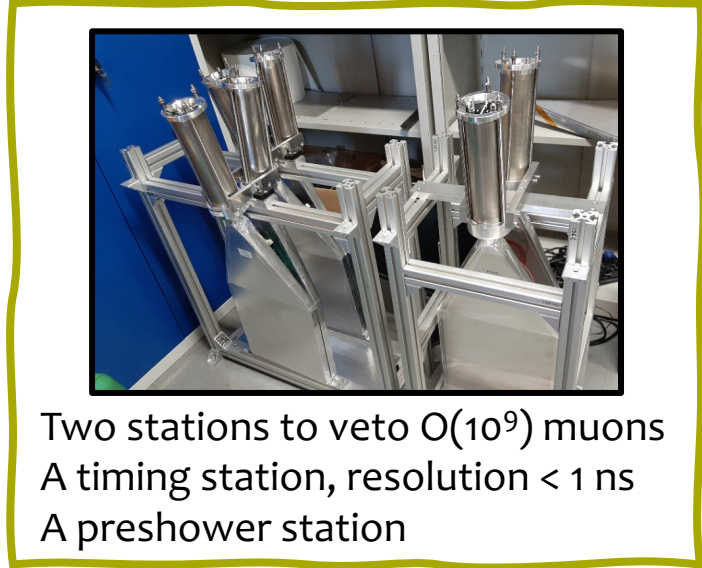
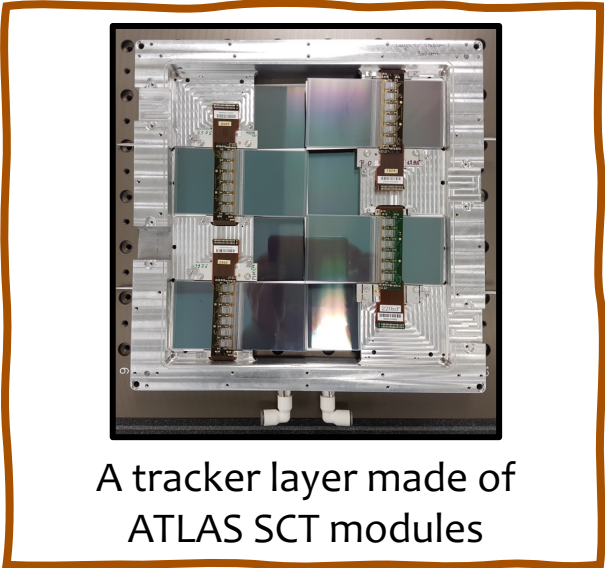
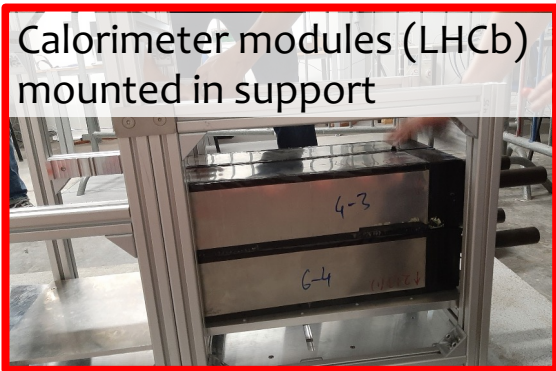
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FASER DETECTOR



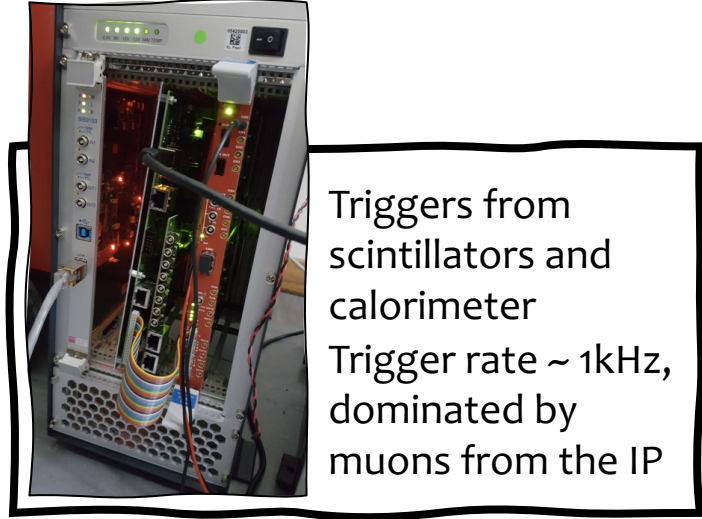
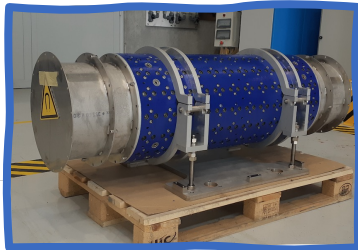
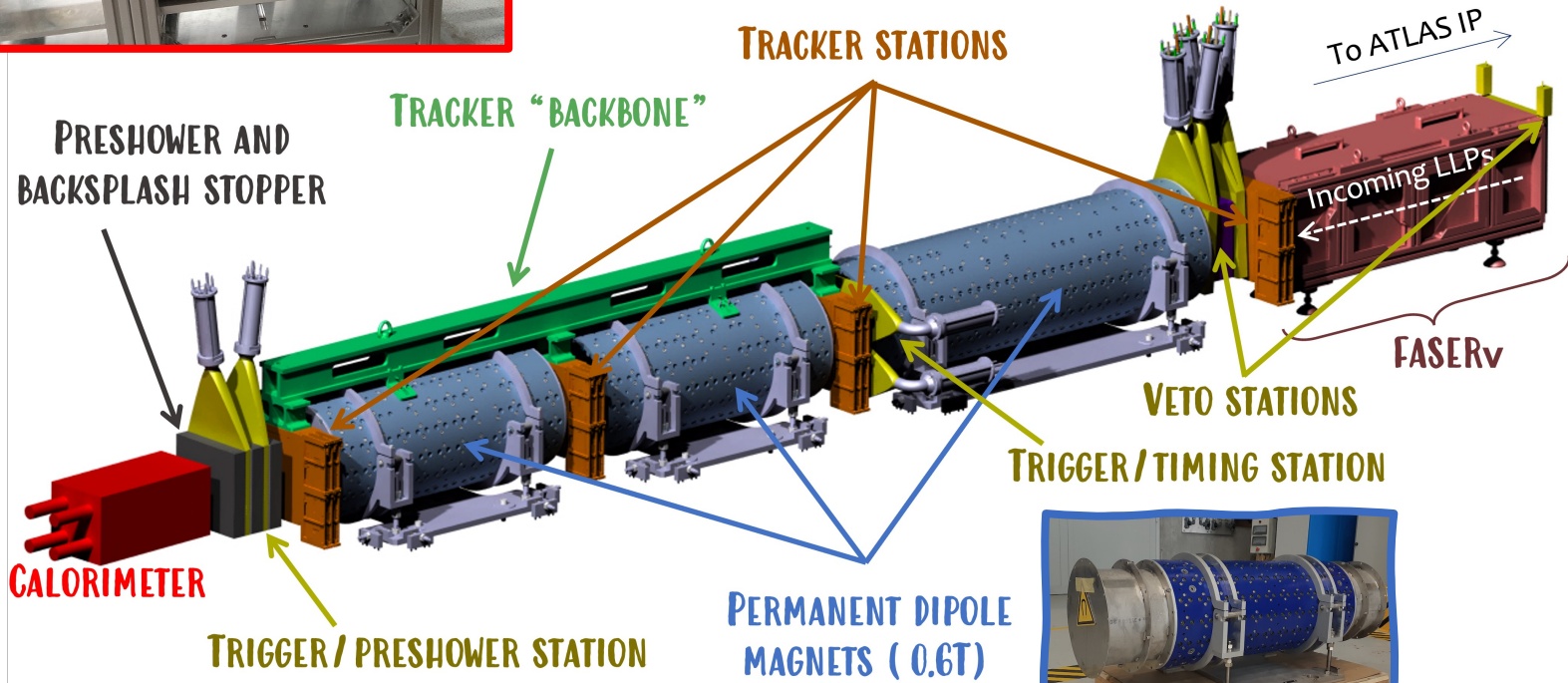
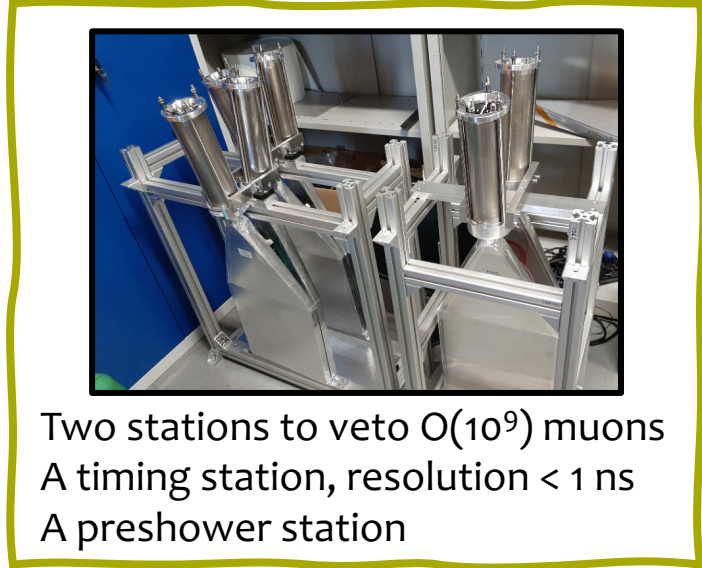
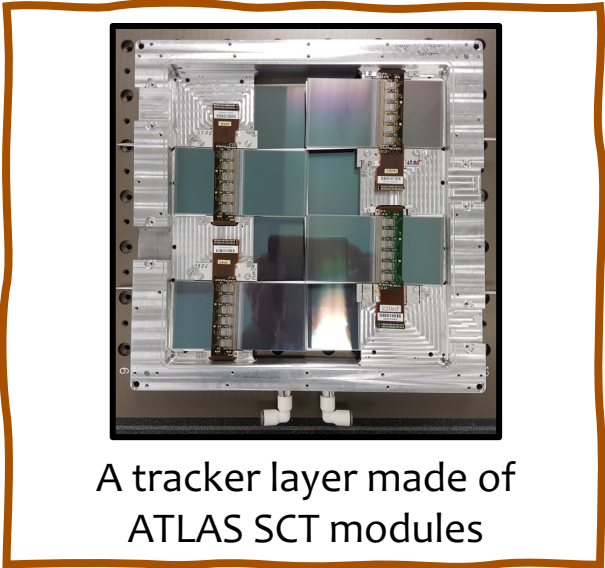
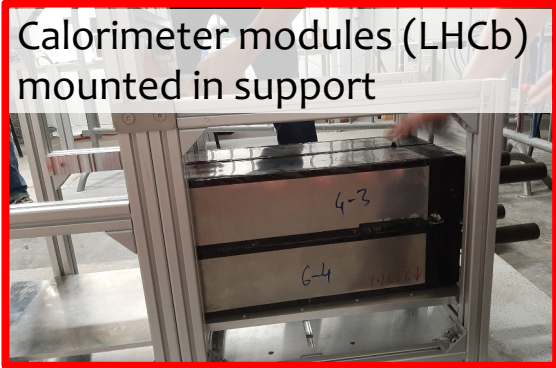
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FASER DETECTOR



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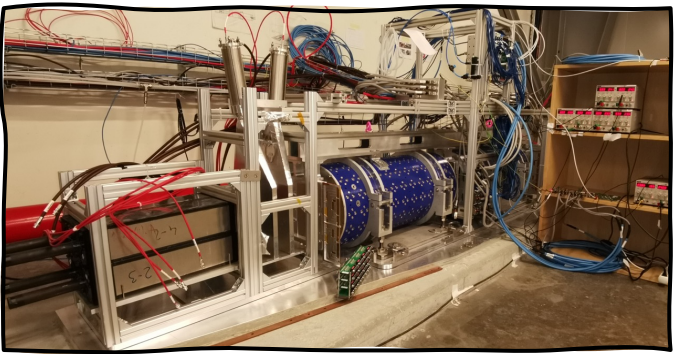
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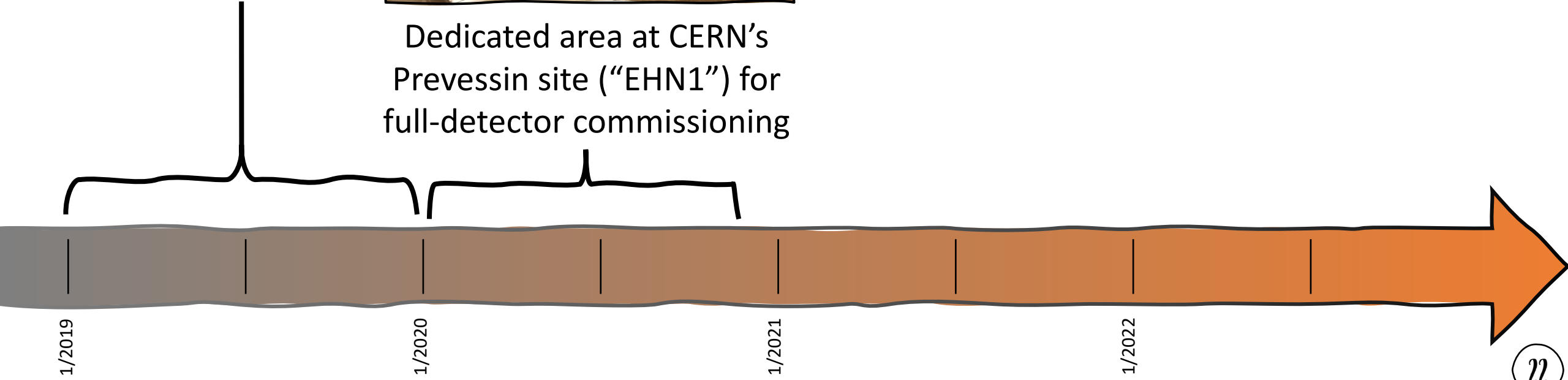
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COMMISSIONING TIMELINE

Dedicated labs at
CERN and UniGe
for individual
component testing

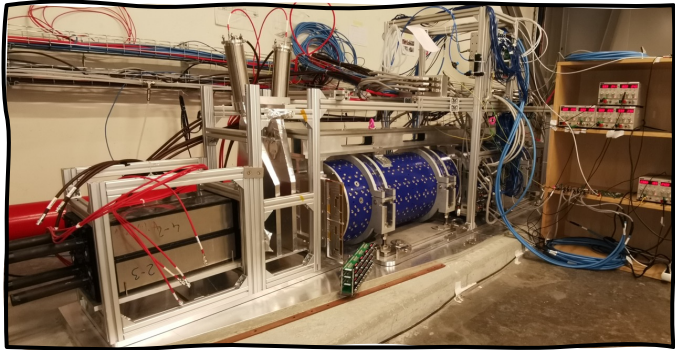


Dedicated area at CERN's
Prevezin site ("EHN1") for
full-detector commissioning

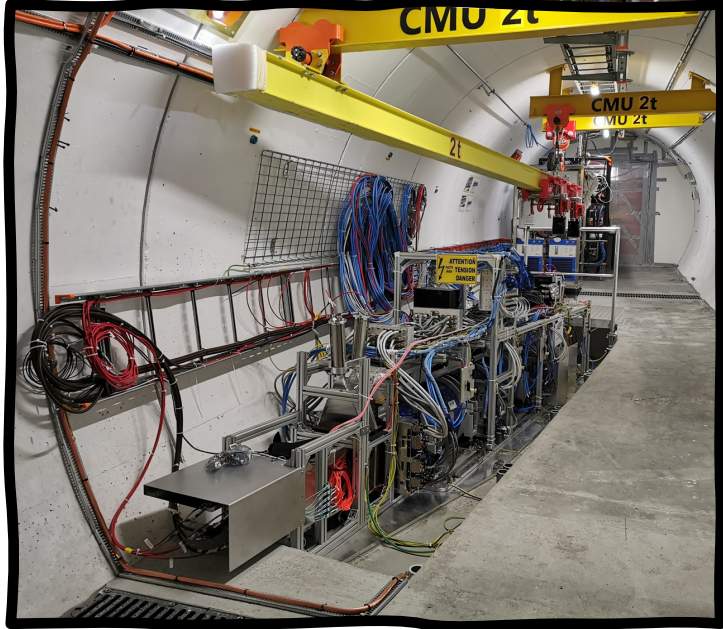


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1/2019

1/2020

1/2021

FASER
Installation

1/2022



CMU 2t

CMU 2t

ATTENTION
HAUTE TENSION
DANGER

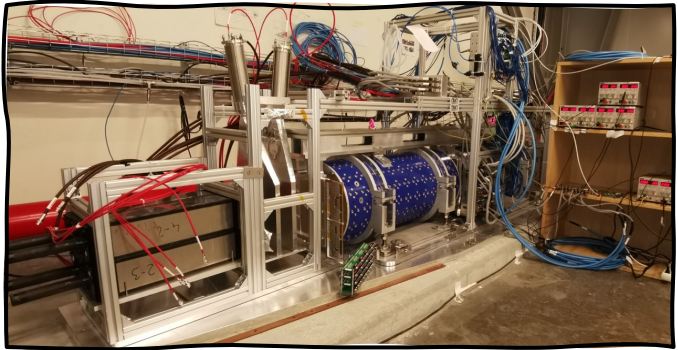


FA SER

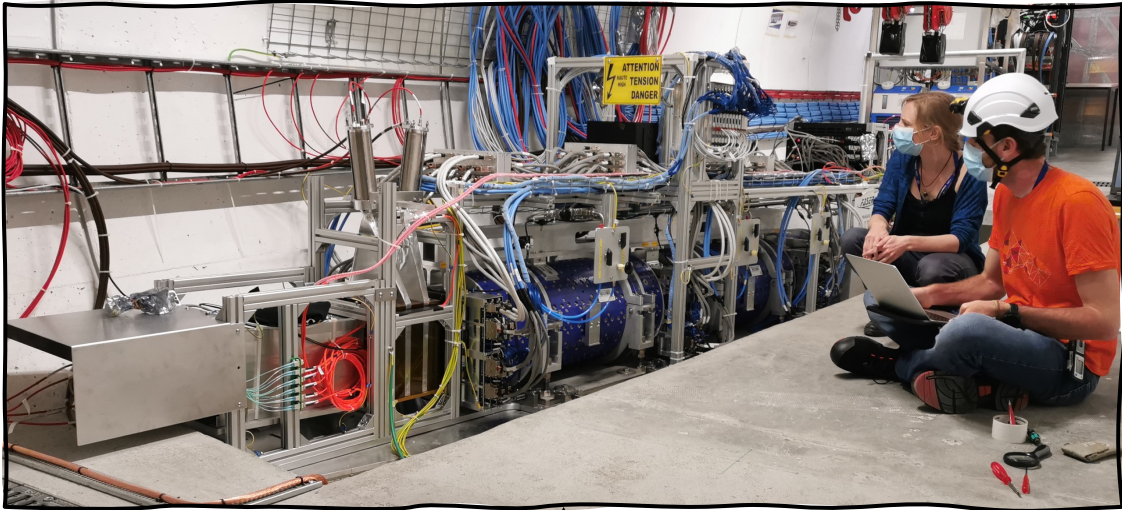
FA SER

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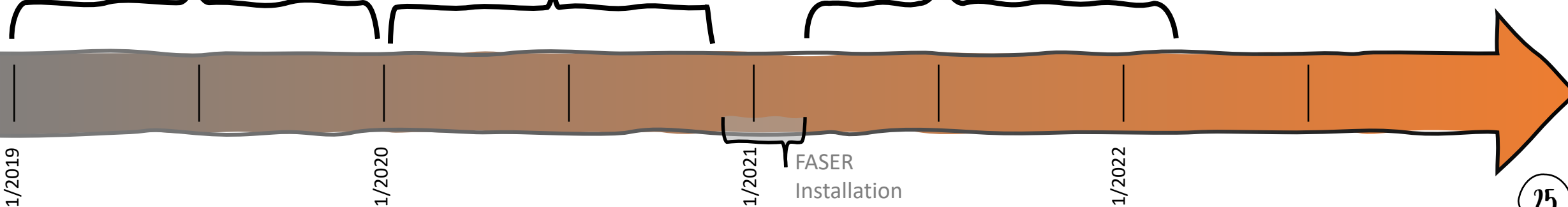
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Extensive in-situ
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1/2019

1/2020

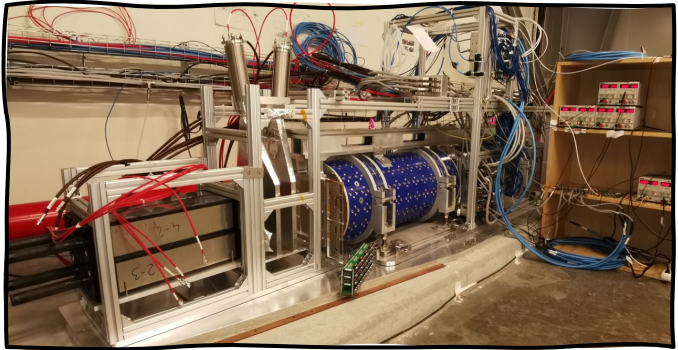
1/2021

FASER
Installation

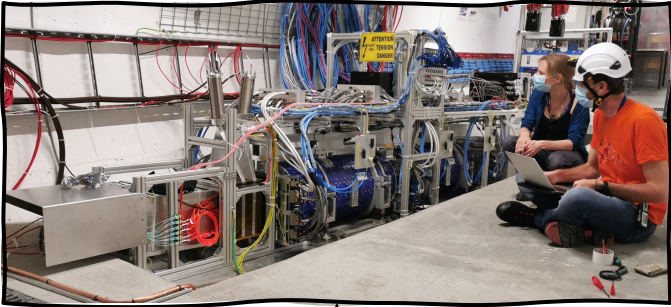
1/2022

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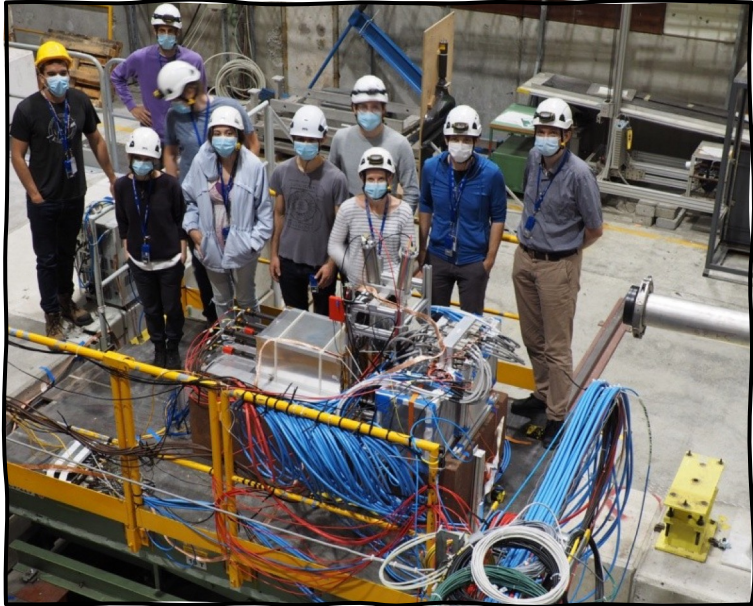
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Testbeam

1/2019

1/2020

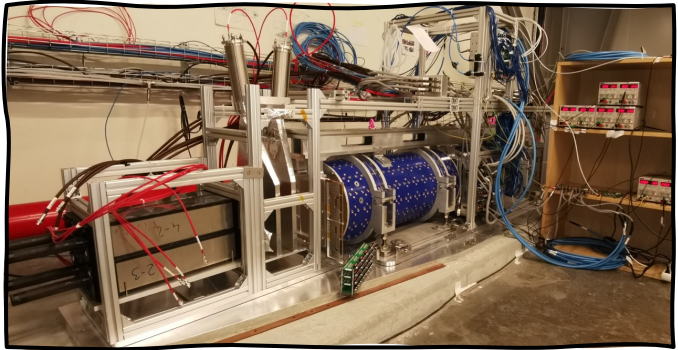
1/2021

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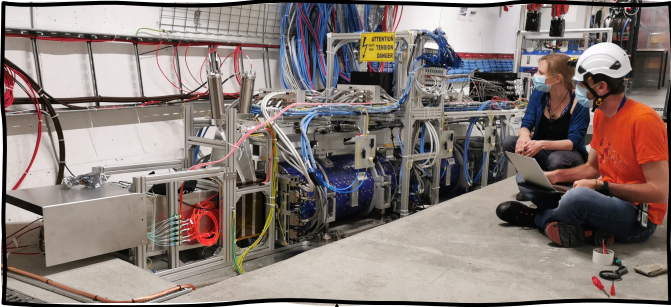
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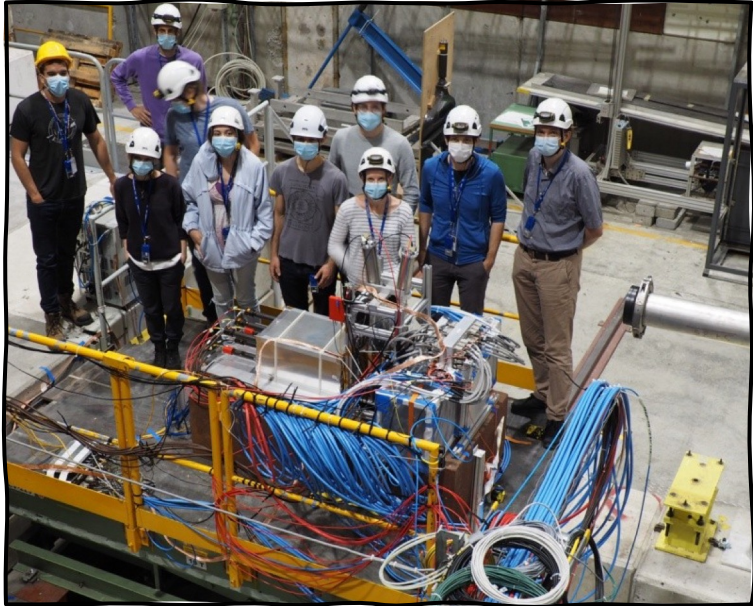
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1/2019

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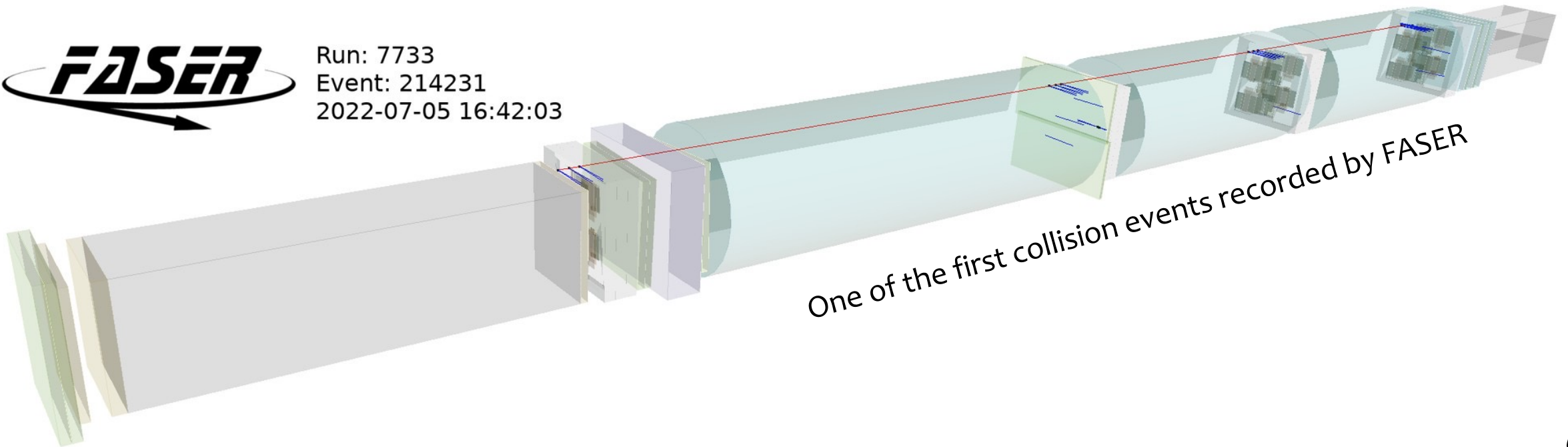
1/2022

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 produced for spring 2023 conferences**



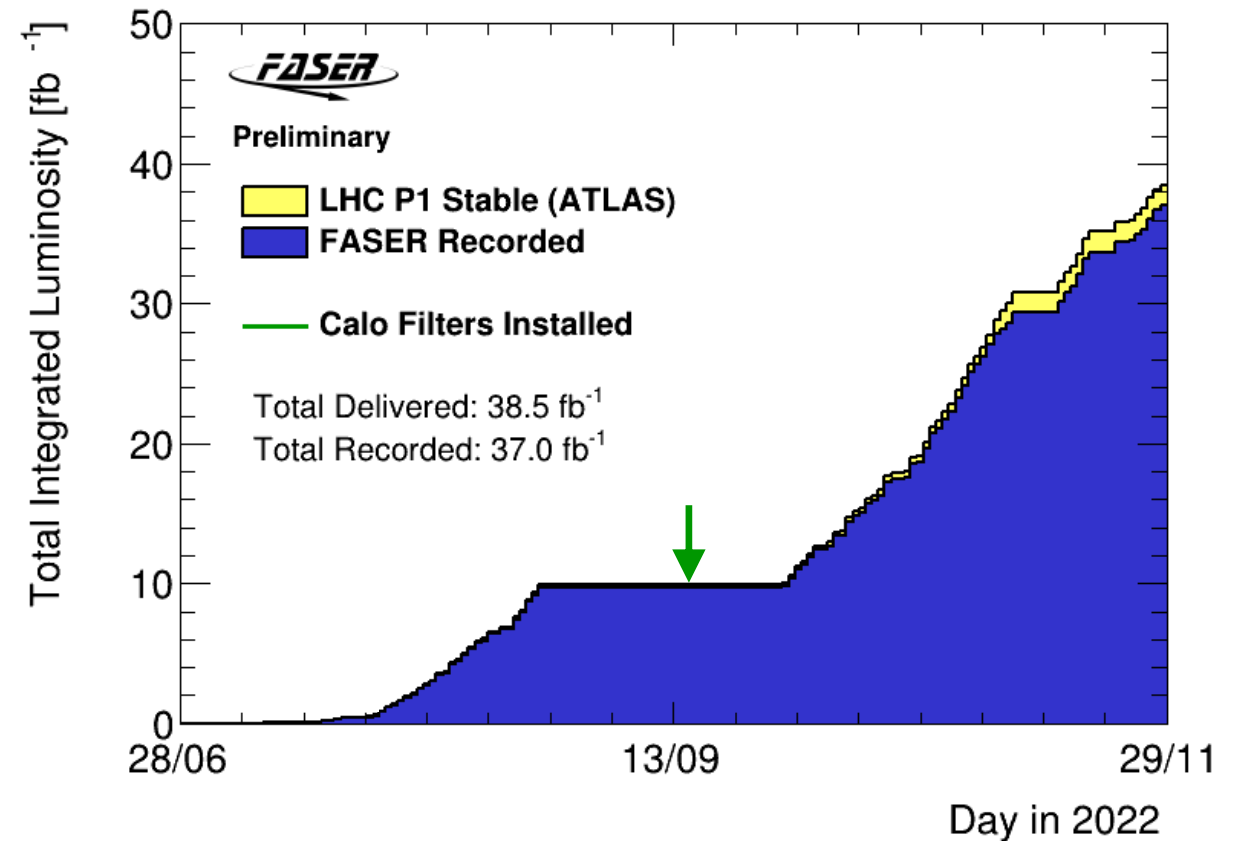
Run: 7733
Event: 214231
2022-07-05 16:42:03



One of the first collision events recorded by FASER

FASER OPERATIONS

- Recorded 96.1% of delivered lumi
- Dead-time of $< 2\%$
- About 2% data loss due to two specific operational issues
- Calorimeter gain optimised for
 - low E (< 300 GeV) initially
 - high E later in the run

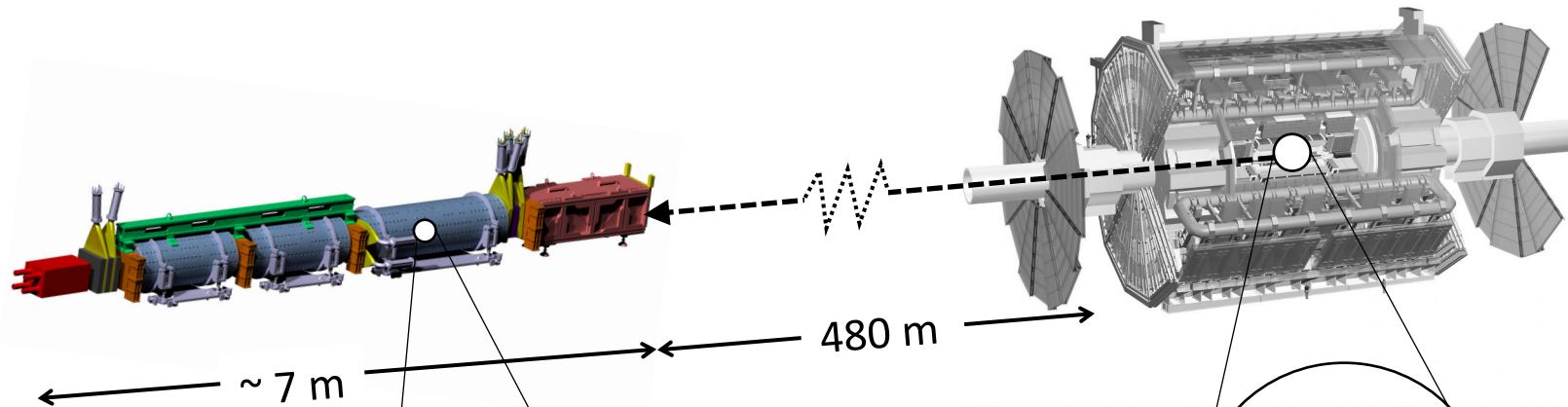


Analyses produced use 27/fb or 35.4/fb of 2022 data

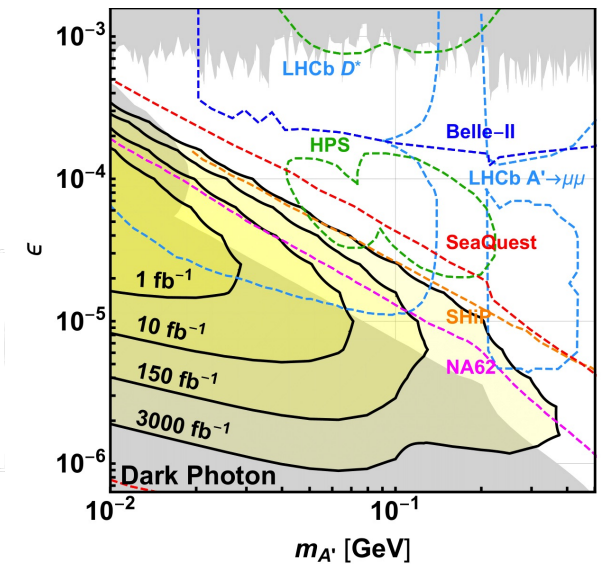
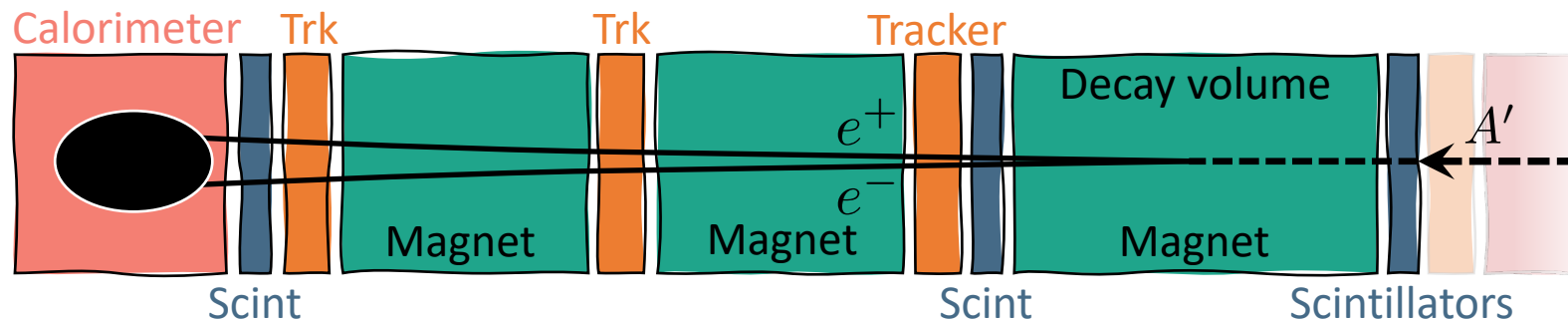
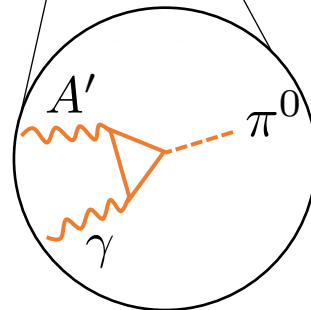
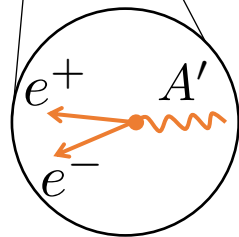
FIRST DARK PHOTON SEARCH WITH *FASER*

A KEY SIGNATURE

Dark photon (A')



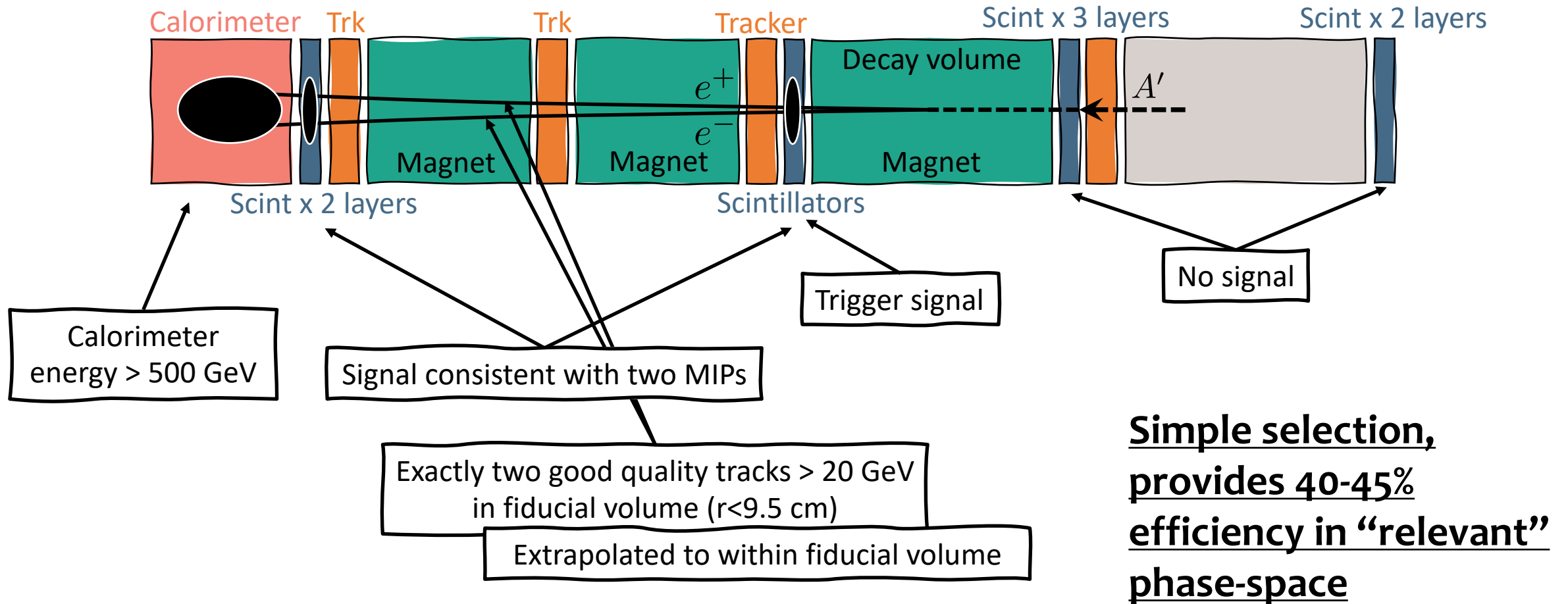
Decay products collimated requirements for magnetic field & high-resolution tracker



Assuming 3 signal events and no backgrounds

SIGNAL SELECTION

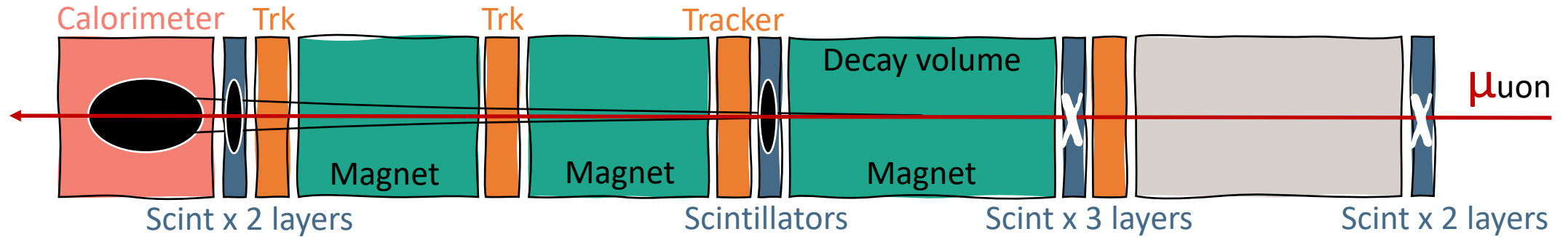
Dark photon (A')



BACKGROUNDS

Dark photon (A')

1. Muons that are not vetoed by any of the 5 scintillator layers



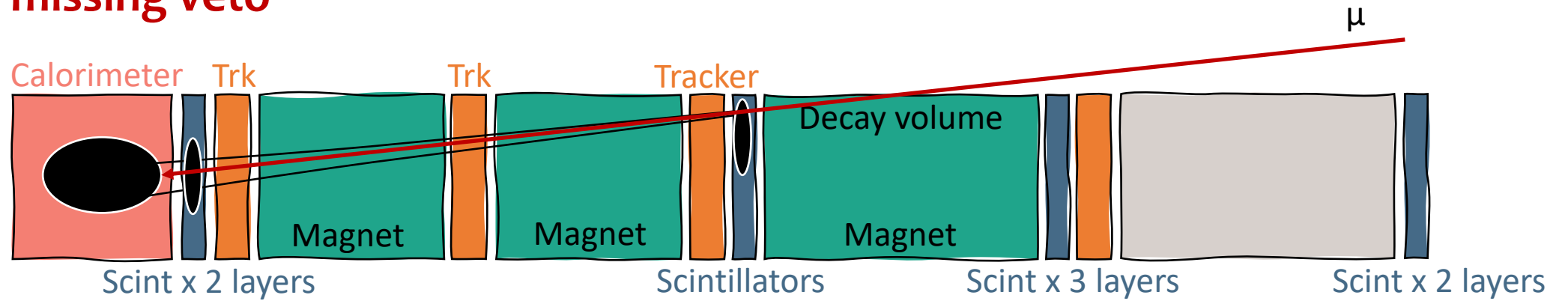
Scintillator	Efficiency
NuVeto-0	0.9999805(5)
NuVeto-1	0.9999810(5)
Veto-0	0.9999985(1)
Veto-1	0.9999984(1)
Veto-2	0.9999986(1)

- Total scintillator inefficiency $< 10^{-20}$
- Even with $O(10^8)$ muons (2022):
 - **zero** probability that one won't be vetoed

BACKGROUNDS

Dark photon (A')

2. Muons missing veto

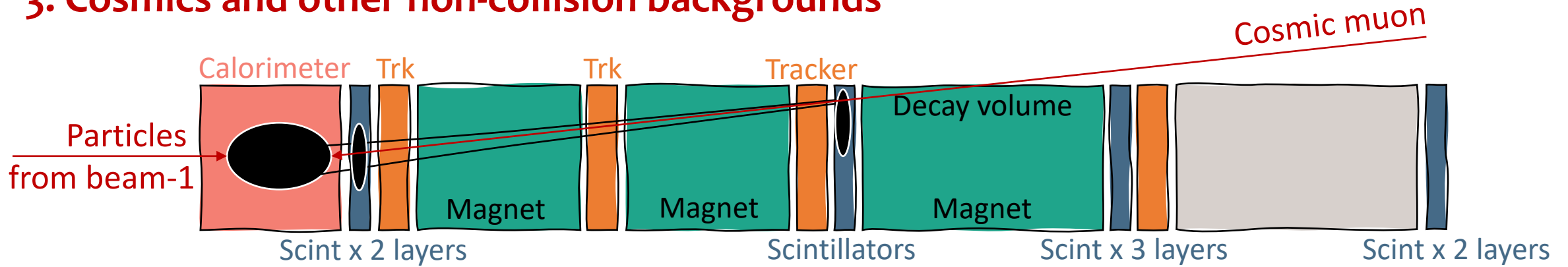


- Evaluated using MC
- **Zero** background

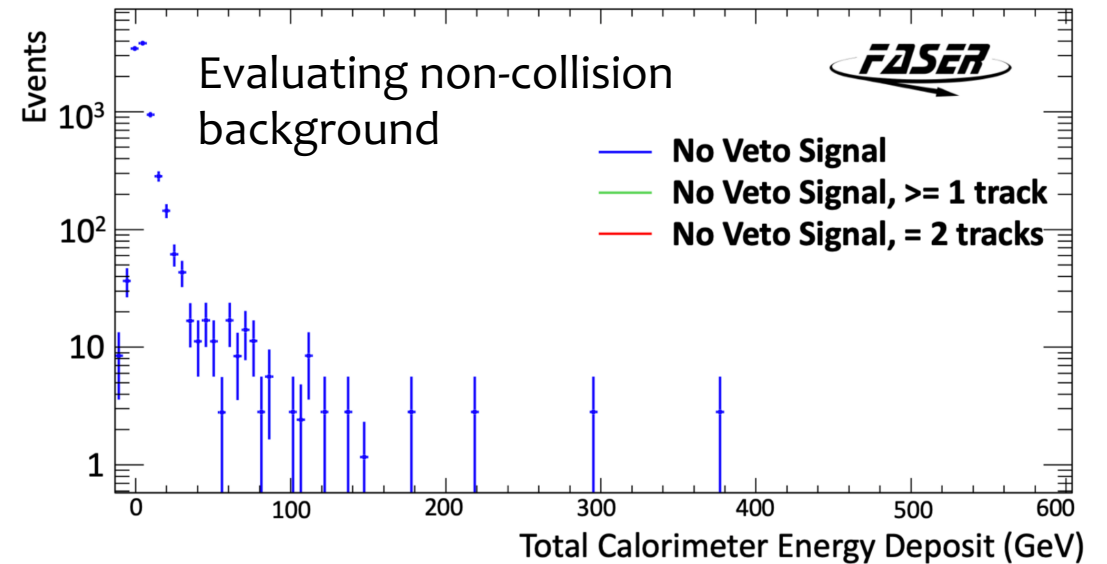
BACKGROUNDS

Dark photon (A')

3. Cosmics and other non-collision backgrounds



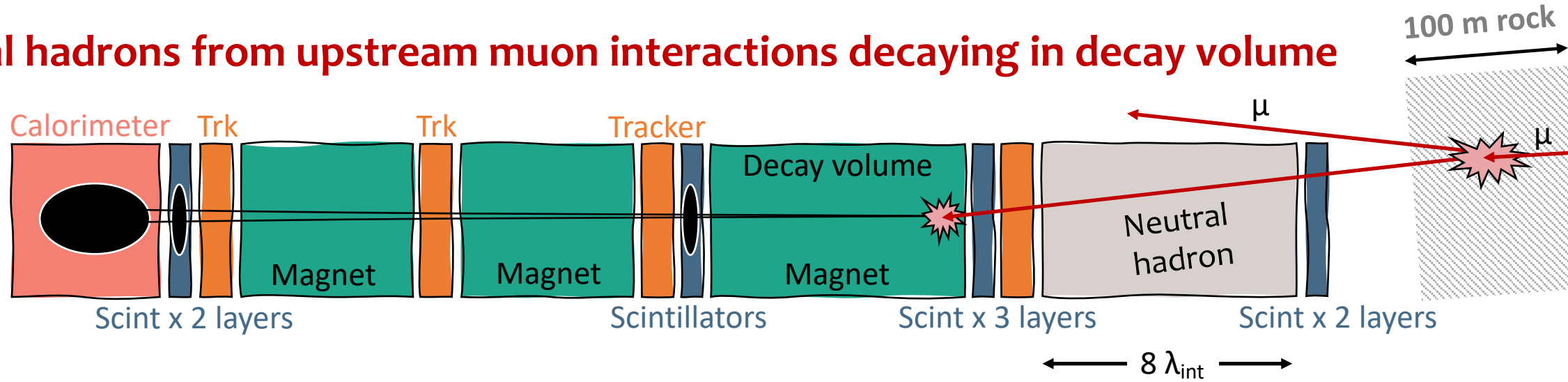
- Evaluated in non-colliding bunches and runs without beam
- **Zero** background



BACKGROUNDS

Dark photon (A')

4. Neutral hadrons from upstream muon interactions decaying in decay volume



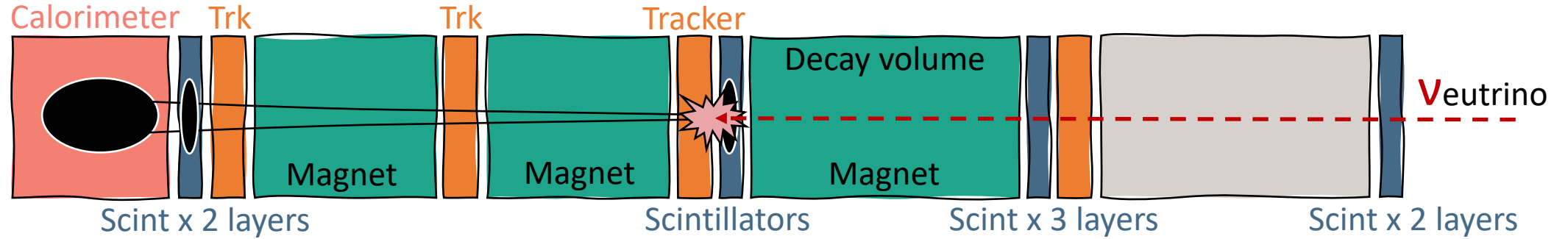
- Evaluated using three-track events, extrapolating from low energy to high energy and from loose to nominal veto requirements

- Estimated background: $(2.2 \pm 3.1)10^{-4}$ events

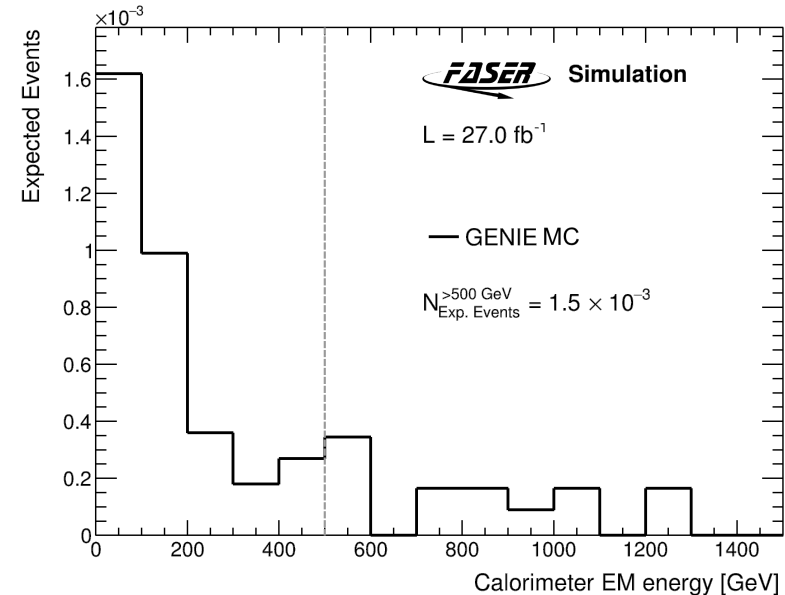
BACKGROUNDS

Dark photon (A')

5. Neutrino interactions

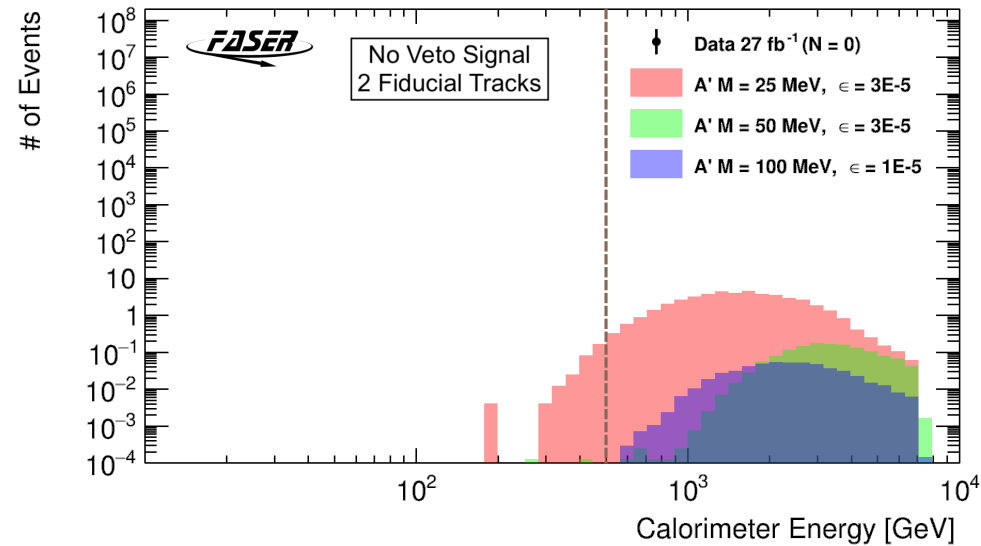
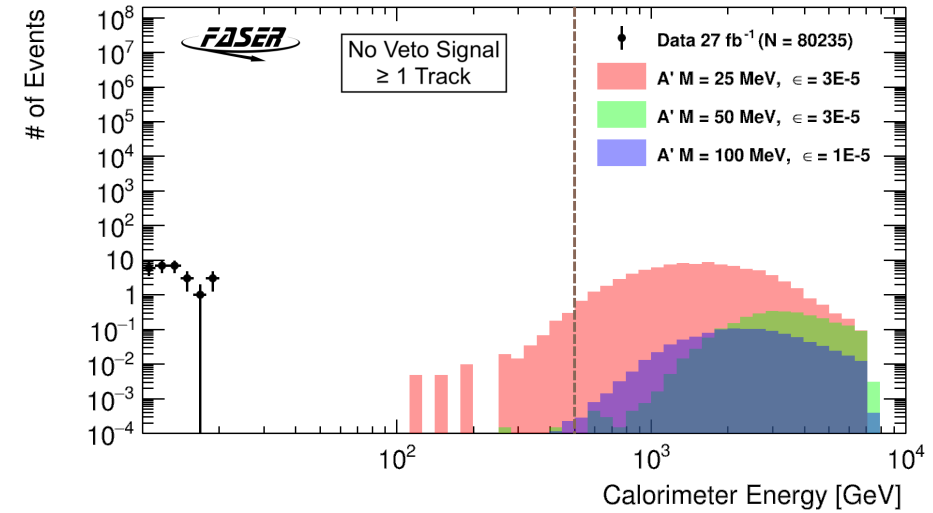
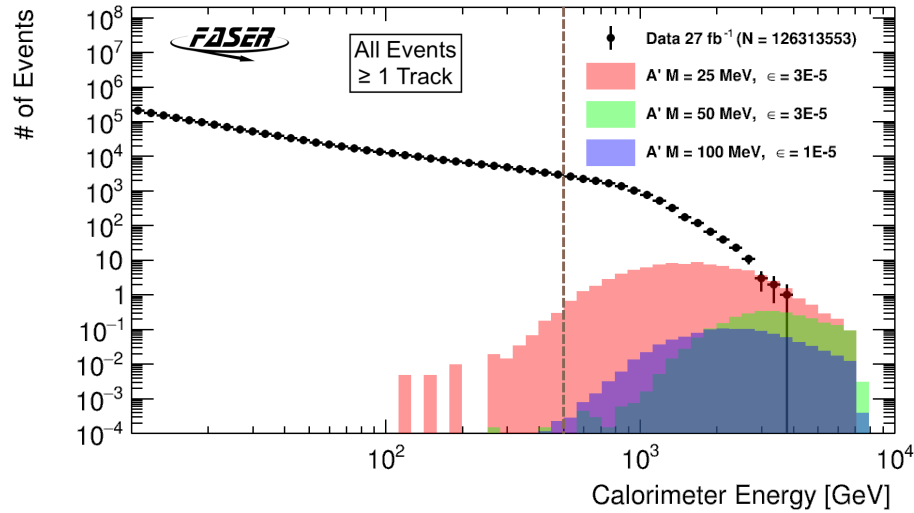


- Evaluated using MC
 - GENIE generator
 - 300/ab
- Estimated background:
 $(1.8 \pm 2.4)10^{-3}$ events



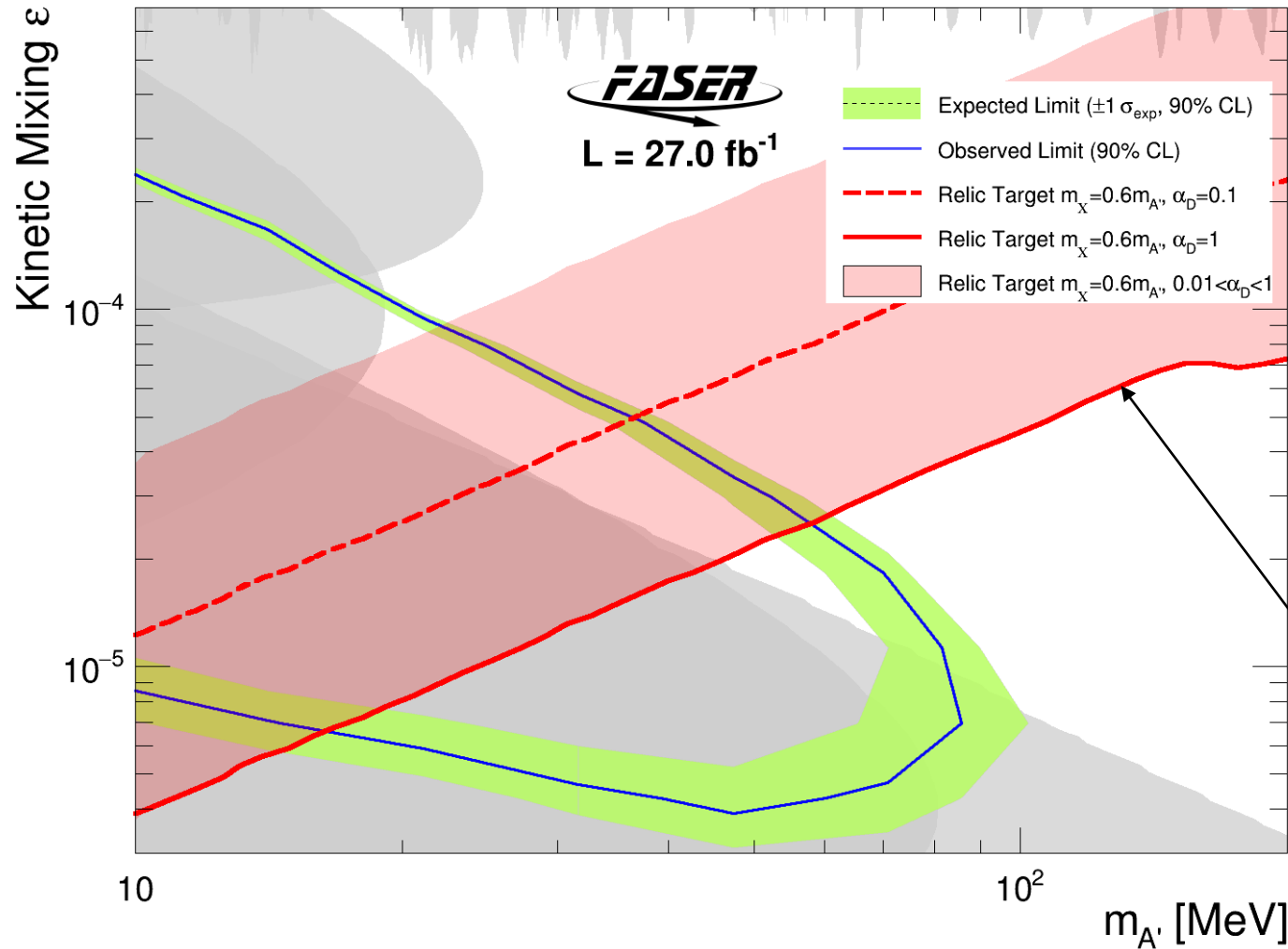
LOOKING IN DATA

Total background: (0.0020 ± 0.0024) events
No events seen in unblinded signal region



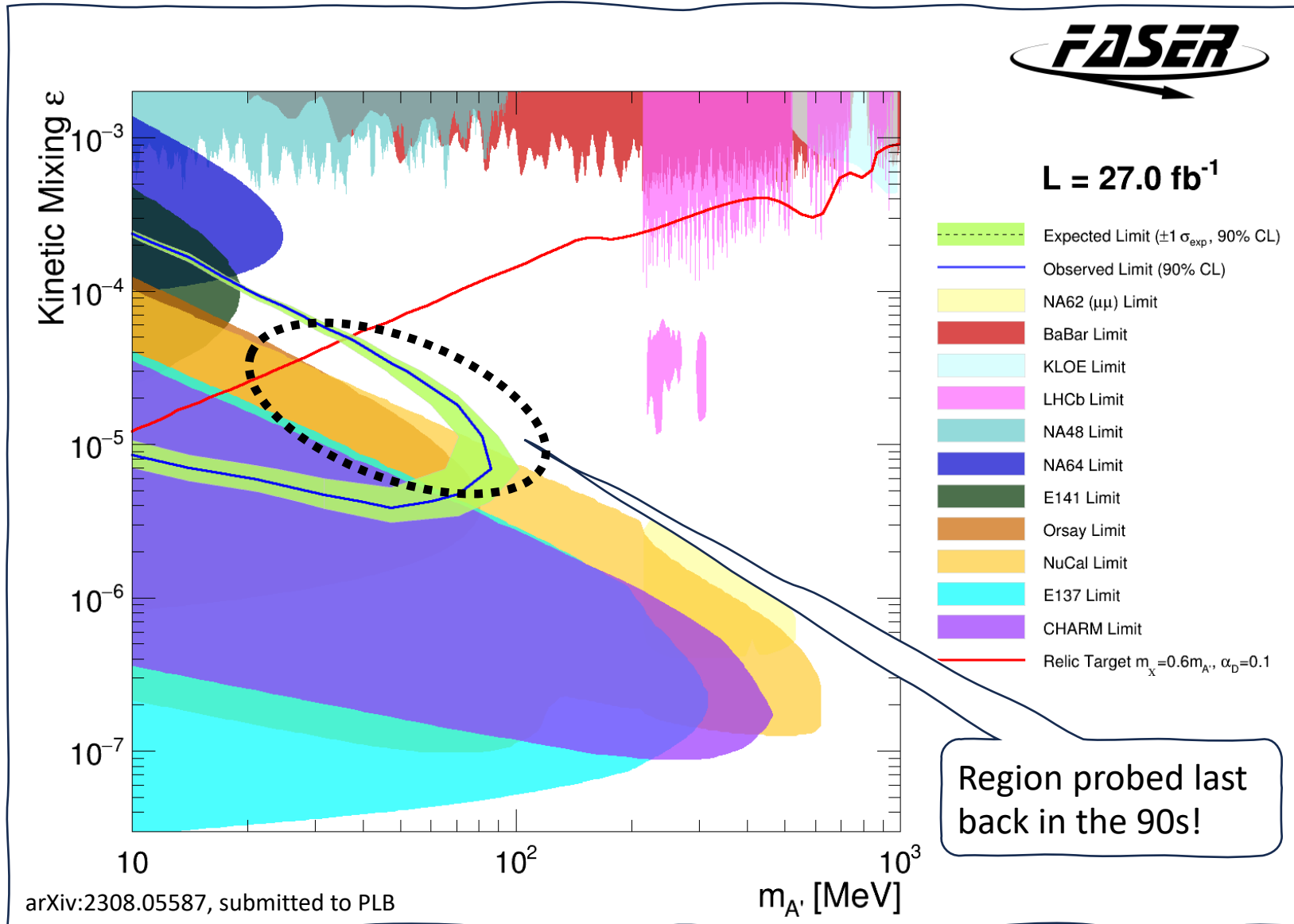
EXCLUSION REACH

On previously unexplored phase-space



- Parameters for which DM χ annihilates via $\chi\chi \rightarrow A' \rightarrow ff$
- Model dependent *line*, but region favoured by DM relic density

SEARCHES FOR DARK PHOTONS



FÄSER



HUGE FLUX OF HIGH-ENERGY NEUTRINOS

u^b UNIVERSITÄT BERN
a main player in this
proposal & developments!

- 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.:

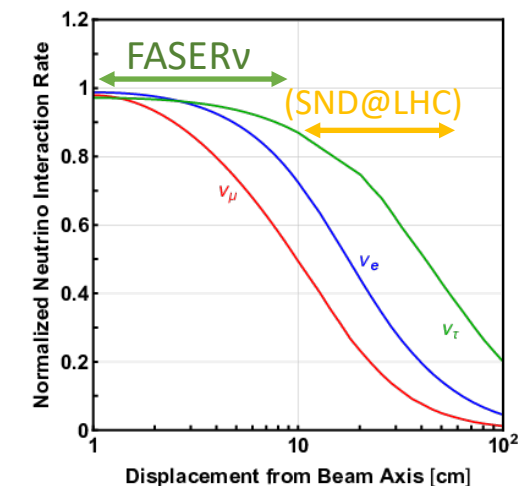
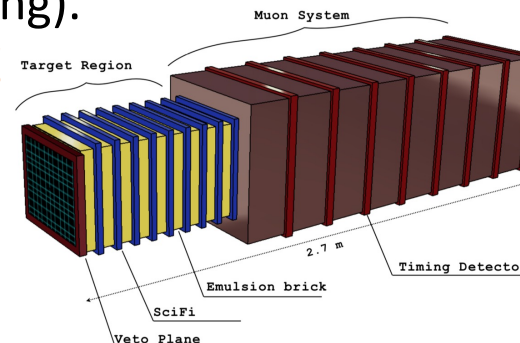
- A. De Rujula and R. Ruckl, “Neutrino and muon physics in the collider mode of future accelerators” ECFA-CERN Workshop on large hadron collider in the LEP tunnel, pp. 571–596, **1984**.
- Klaus Winter, “Observing tau neutrinos at the LHC”, LHC workshop, **1990**.

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

SND@LHC approved for Run 3 data taking (and is running).

FASERv was the first such experiment to be approved!

More on FASERv in what follows...

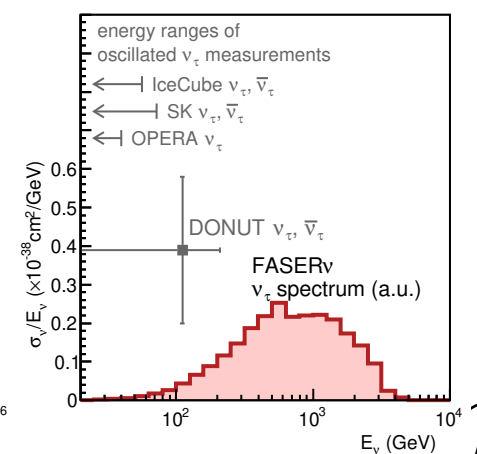
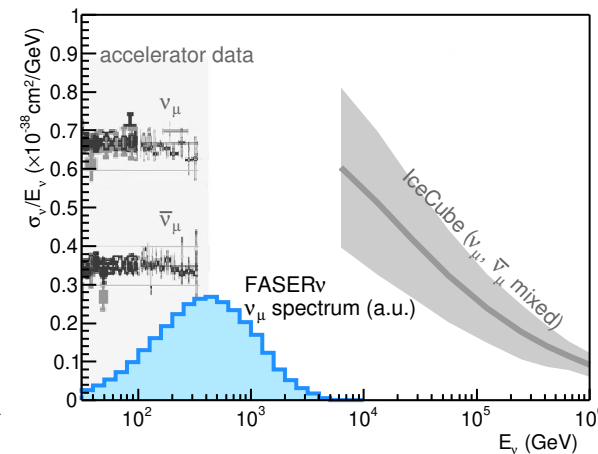
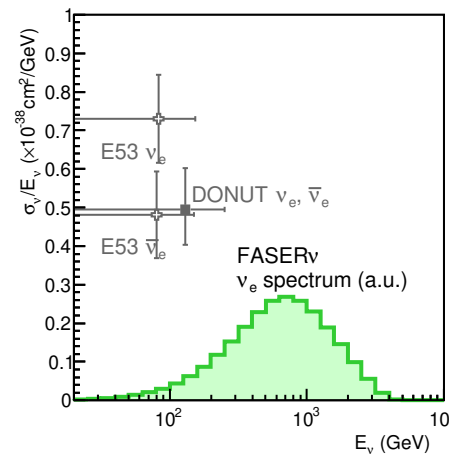


HUGE FLUX OF HIGH-ENERGY NEUTRINOS

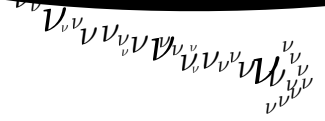
- Why not exploit FASER to also measure properties of neutrinos at the highest man-made energies ever recorded!

- **Expected spectra:** complementary to existing experiments
- **Expected cross section reach:** extends current measurements already with 150/fb
- **Rich QCD physics explorations**
- **Refine simulations that currently vary greatly** (EPOS-LHC, QGSJET, DPMJET, SIBYLL, PYTHIA, ...)

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 tn Tungsten)	~ 1000	~ 20000	~ 10



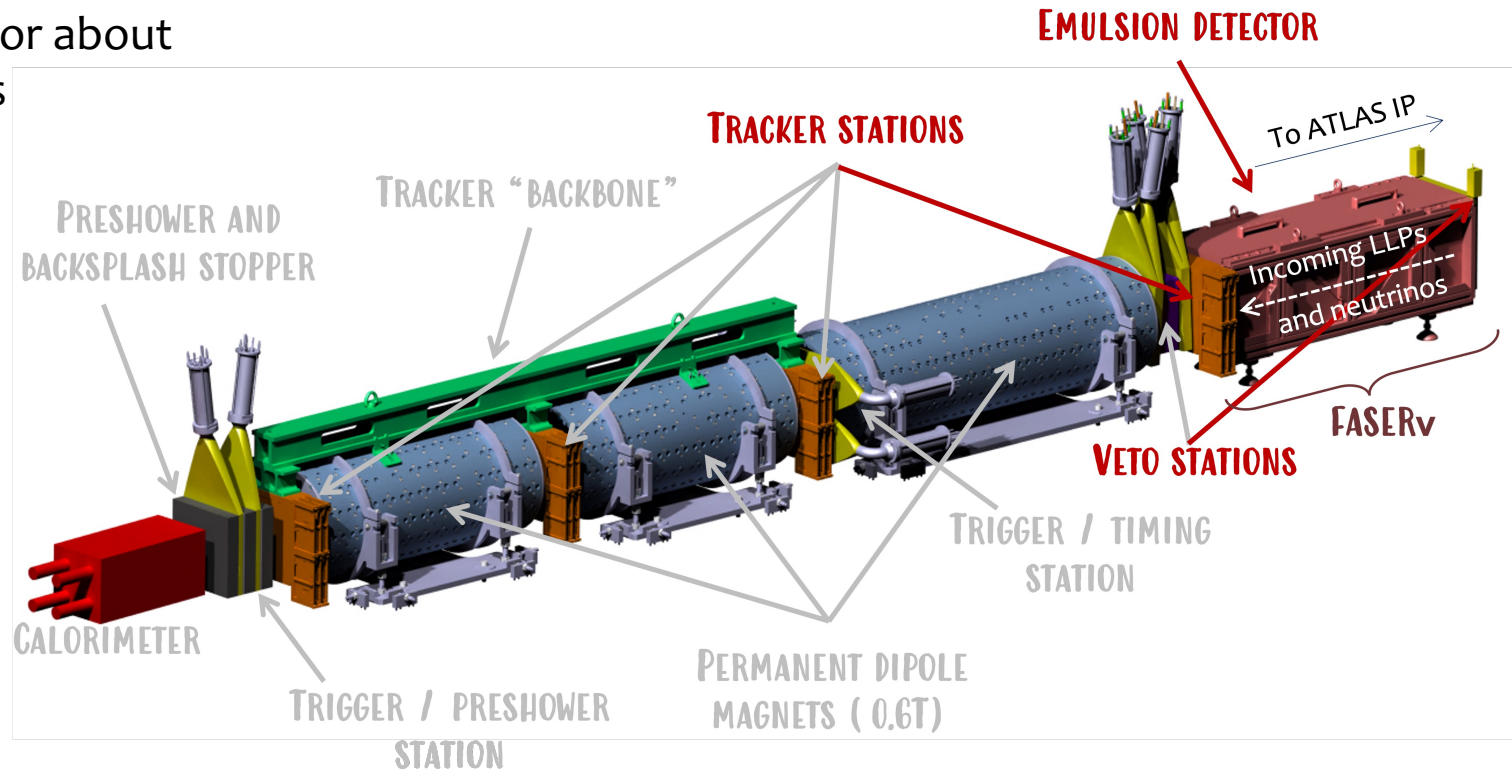
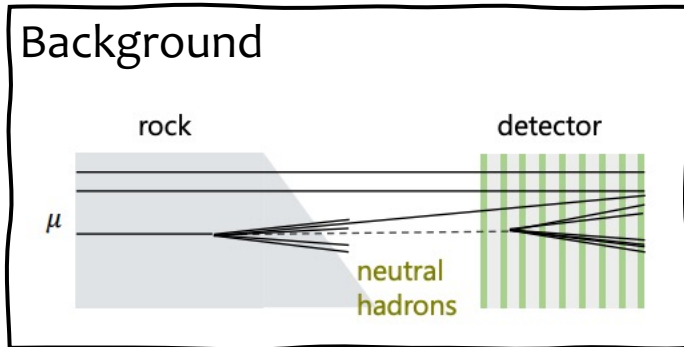
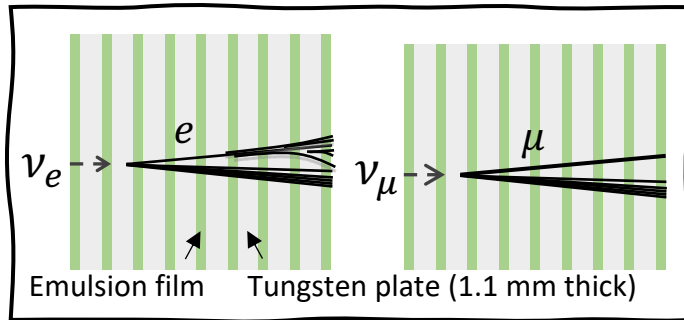
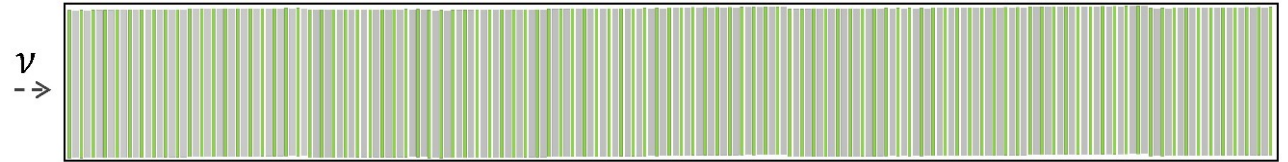
FASER DETECTOR



Emulsion detector:

- Excellent track resolution
- No timing resolution
- **Challenges:** replace the 1-ton-scale detector about 3 times/year & **develop** the emulsion films

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

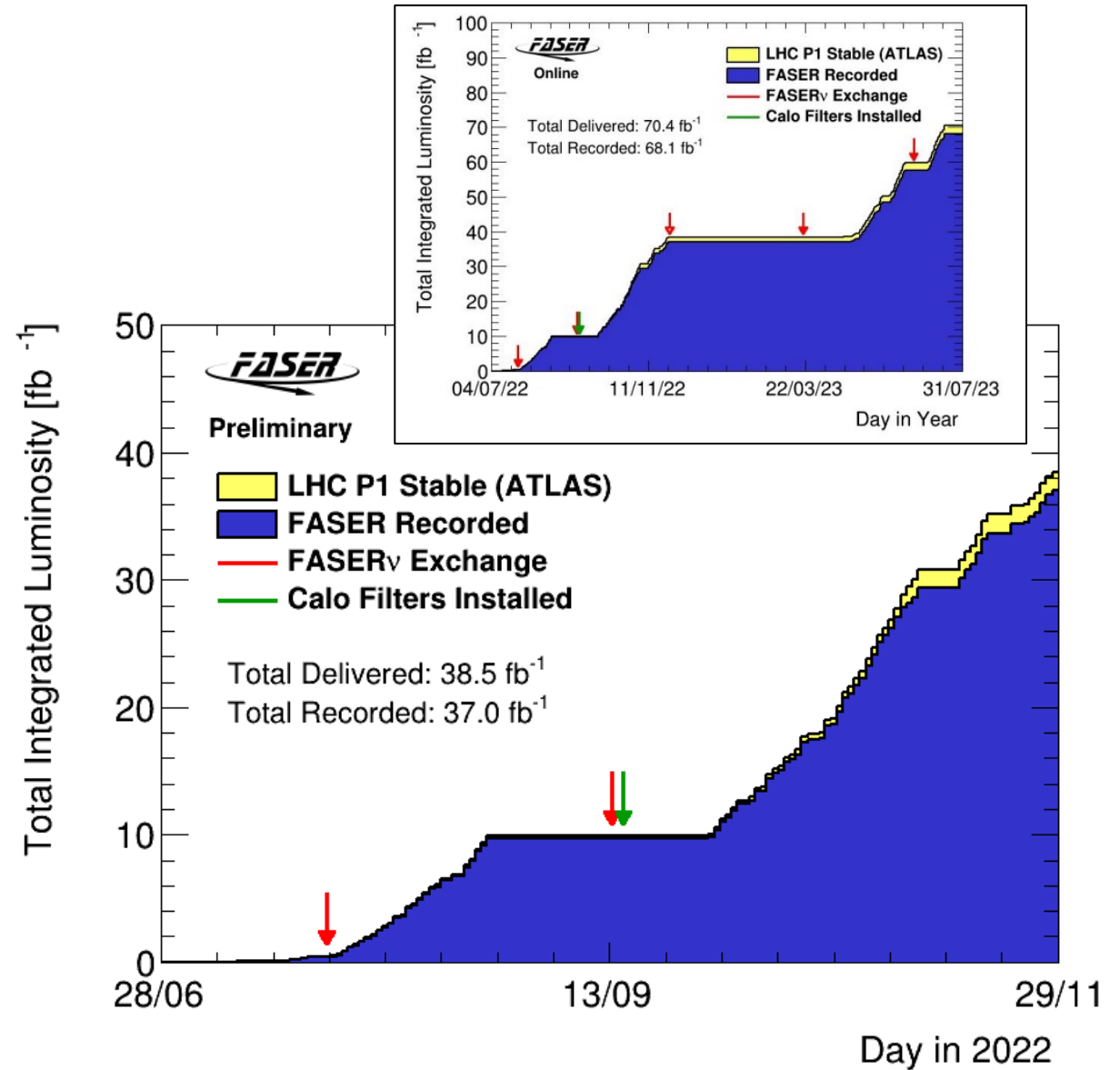


FASER DETECTOR

Emulsion detector:

- Excellent track resolution
- No timing resolution
- **Challenges:** replace the 1-ton-scale detector about 3 times/year & **develop** the emulsion films

→ The first FASER neutrino detection is based the “electronic” part of the detector.



FIRST DIRECT NEUTRINO DETECTION IN A HADRON COLLIDER

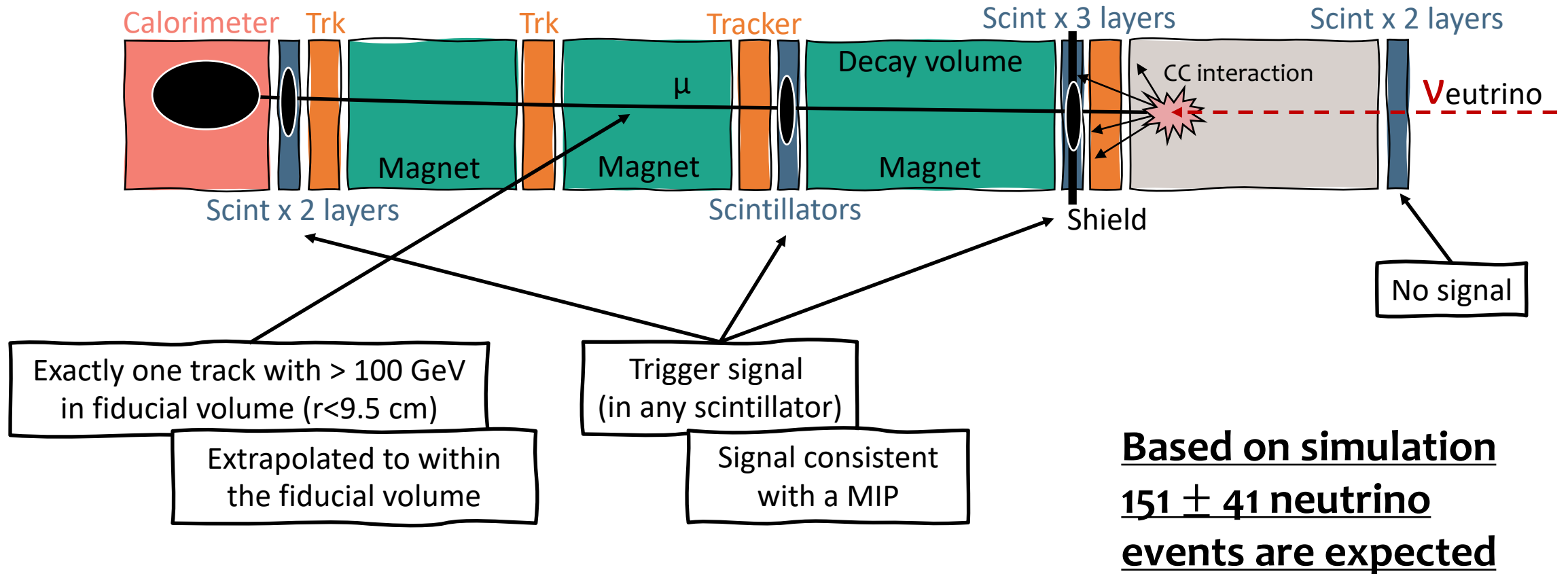
WITH



arXiv:2303.14185

SIGNAL SELECTION

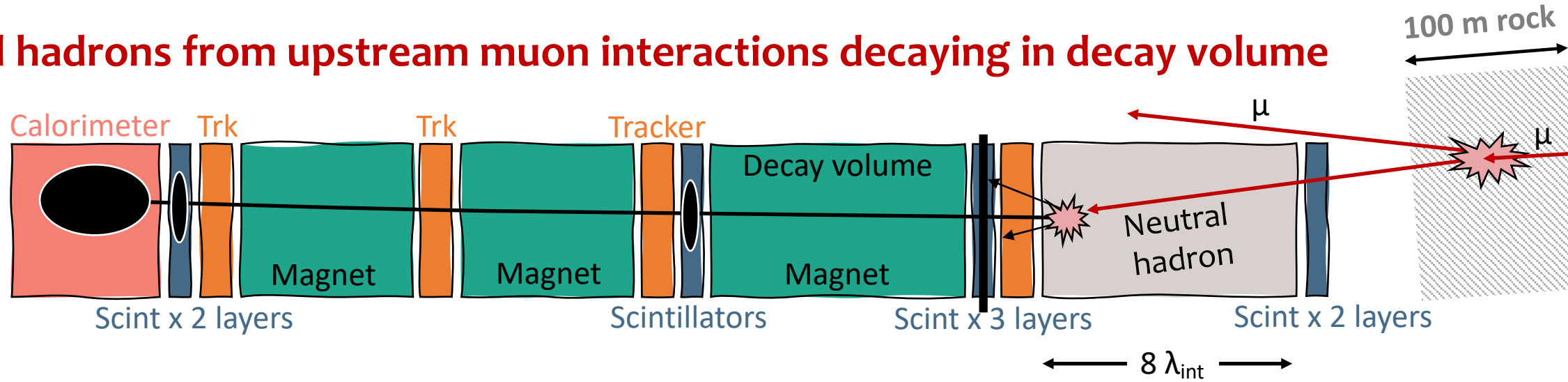
Neutrinos in FASER



BACKGROUNDS

Neutrinos in FASER

1. Neutral hadrons from upstream muon interactions decaying in decay volume

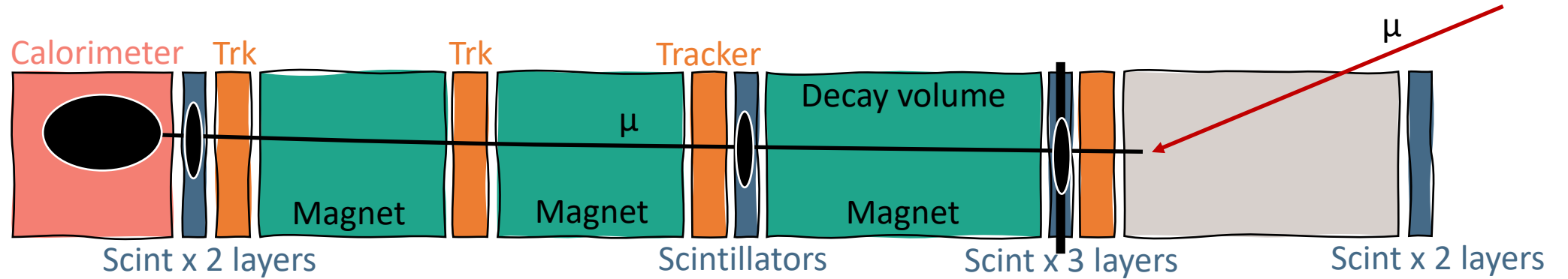


- Evaluated using two-step simulation
 - $O(300)$ neutral hadrons with $E > 100$ GeV would reach FASER
 - Most of them absorbed in tungsten
- Estimated background: **(0.11 ± 0.06) events**

BACKGROUNDS

Neutrinos in FASER

2. Scattered muons

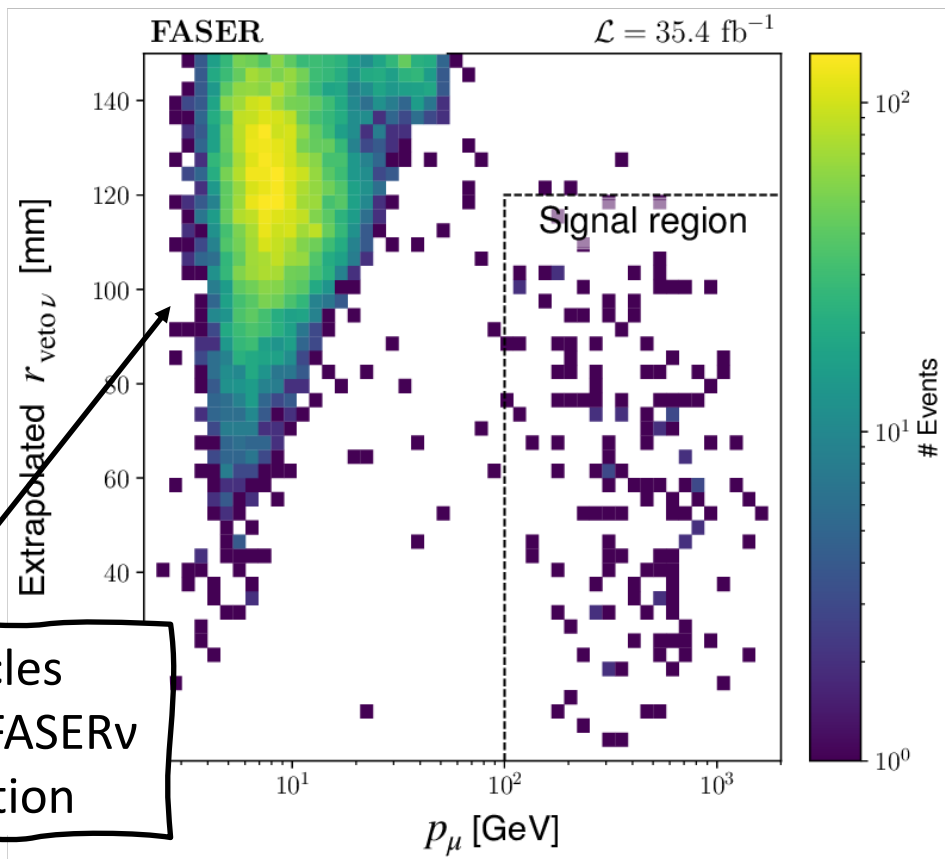


- Estimated from events with single track just outside the fiducial region
- Estimated background: **(0.08 ± 1.83) events**

LOOKING IN DATA

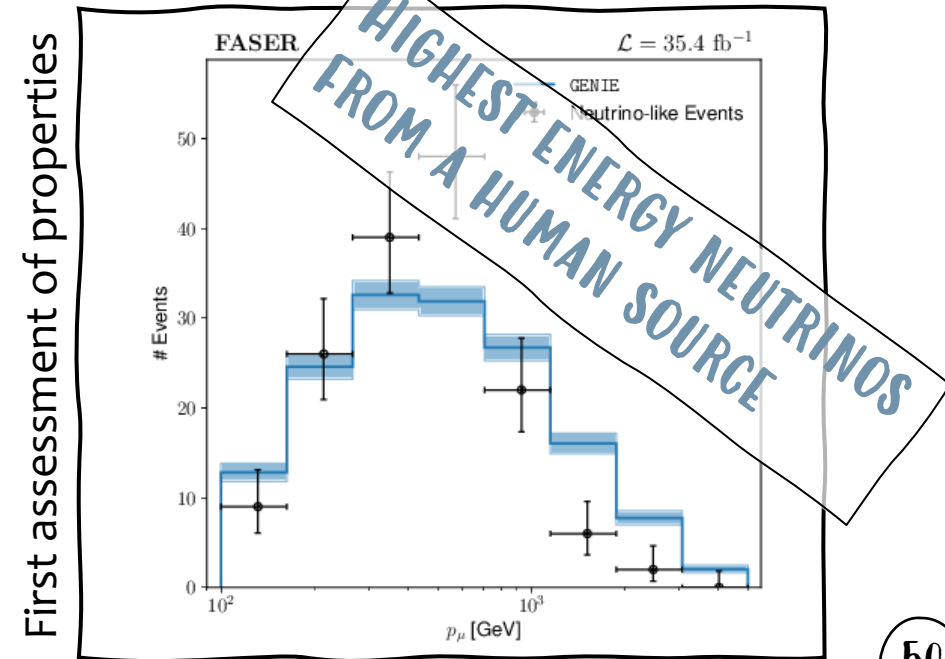
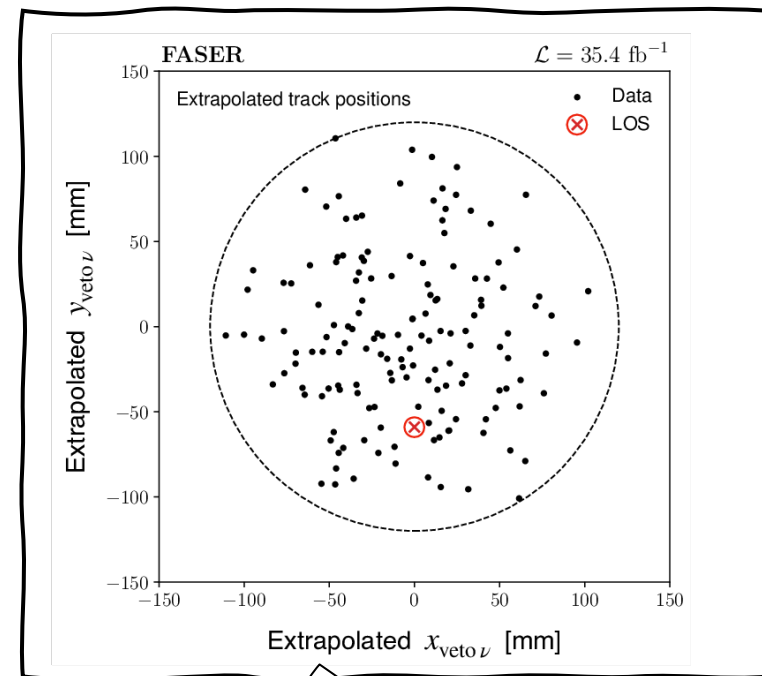
153_{-13}^{+12} events $\Rightarrow \gg 5\sigma$ significance

FIRST DIRECT OBSERVATION OF COLLIDER NEUTRINOS!



Charged particles that miss the FASERv scintillator station

N.B.: SND@LHC also had a collider neutrino observation with 8 signal events and ~ 0.1 background events (arXiv:2305.09383)



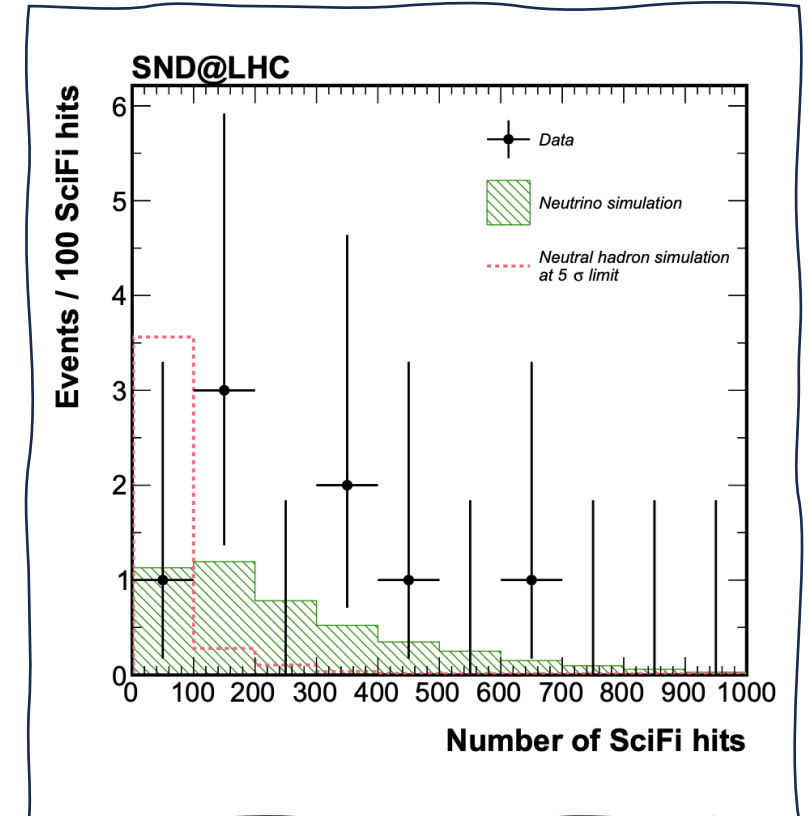
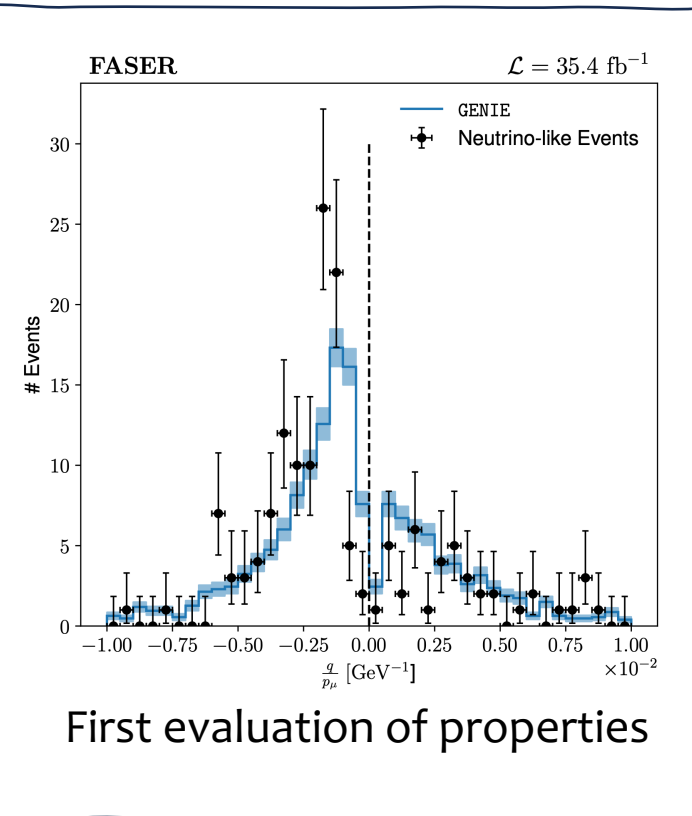
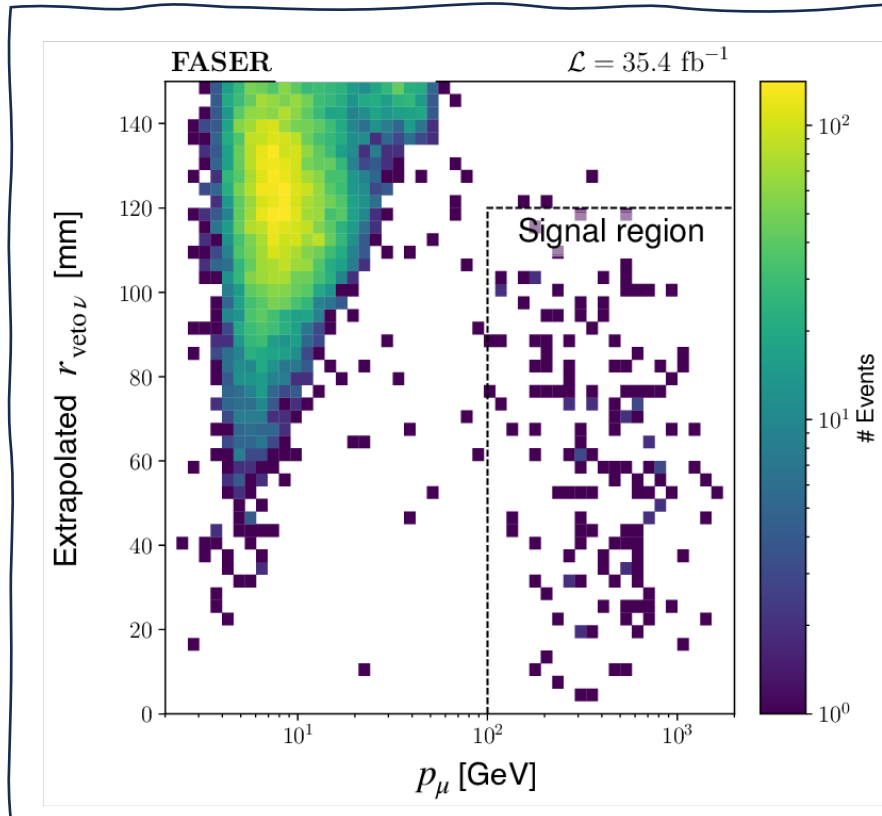
FIRST DIRECT DETECTION OF COLLIDER NEUTRINOS

FASER

153 events $\Rightarrow \gg 5\sigma$ significance
Background ~ 0.2 events



8 events $\Rightarrow > 5\sigma$ significance
Background < 0.1 events



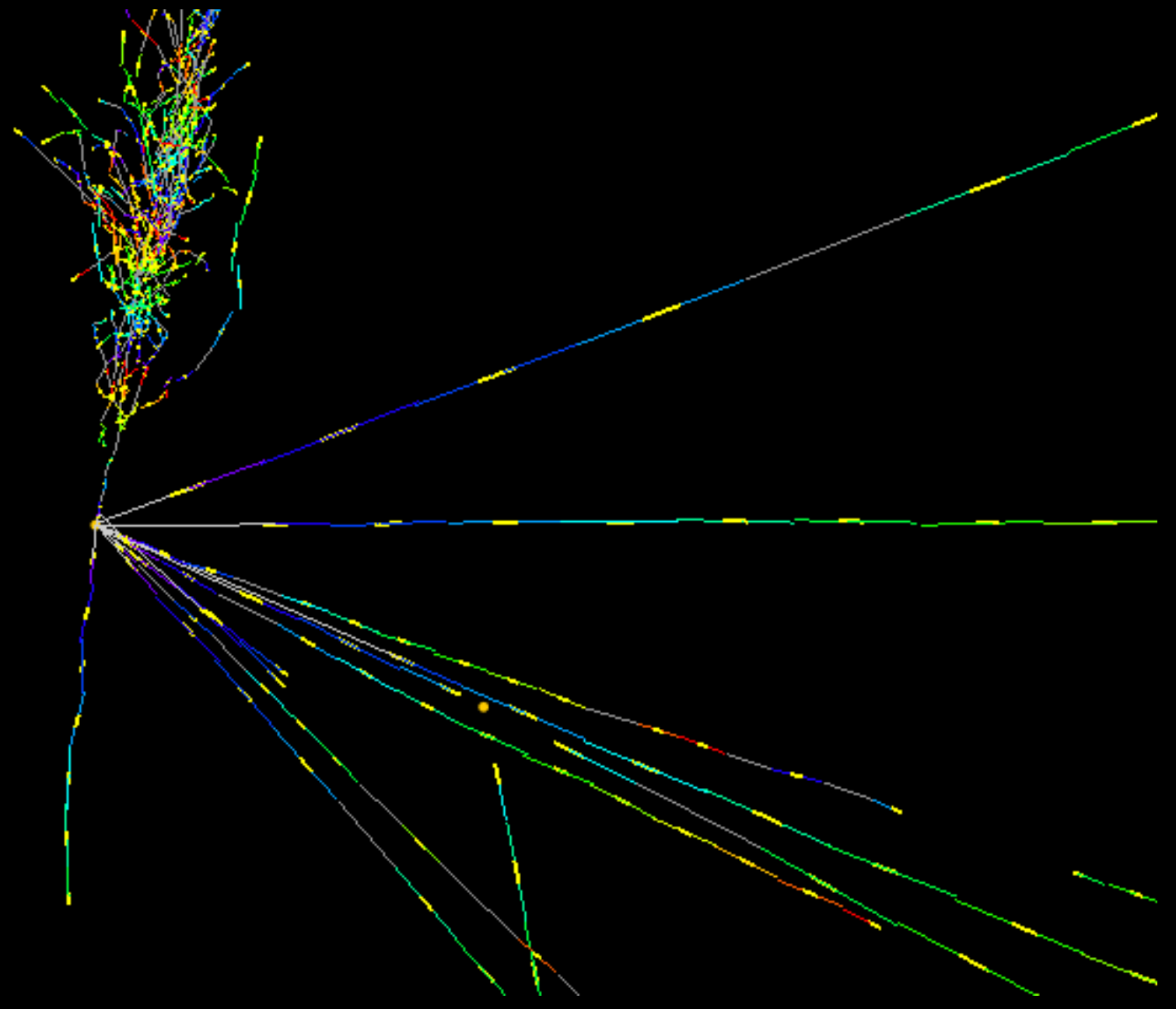
FASER

LHC Fill 8315, Event 47032829,
2022-10-27 08:52:45

↑↑
57 clusters

$p_{\mu} \approx 850$ GeV, negative charge

100



Emulsion detector data

Candidates available, including ν_e events

Discovery of ν_e established using emulsion data

[CERN-FASER-CONF-2023-002](#)

This specific event:

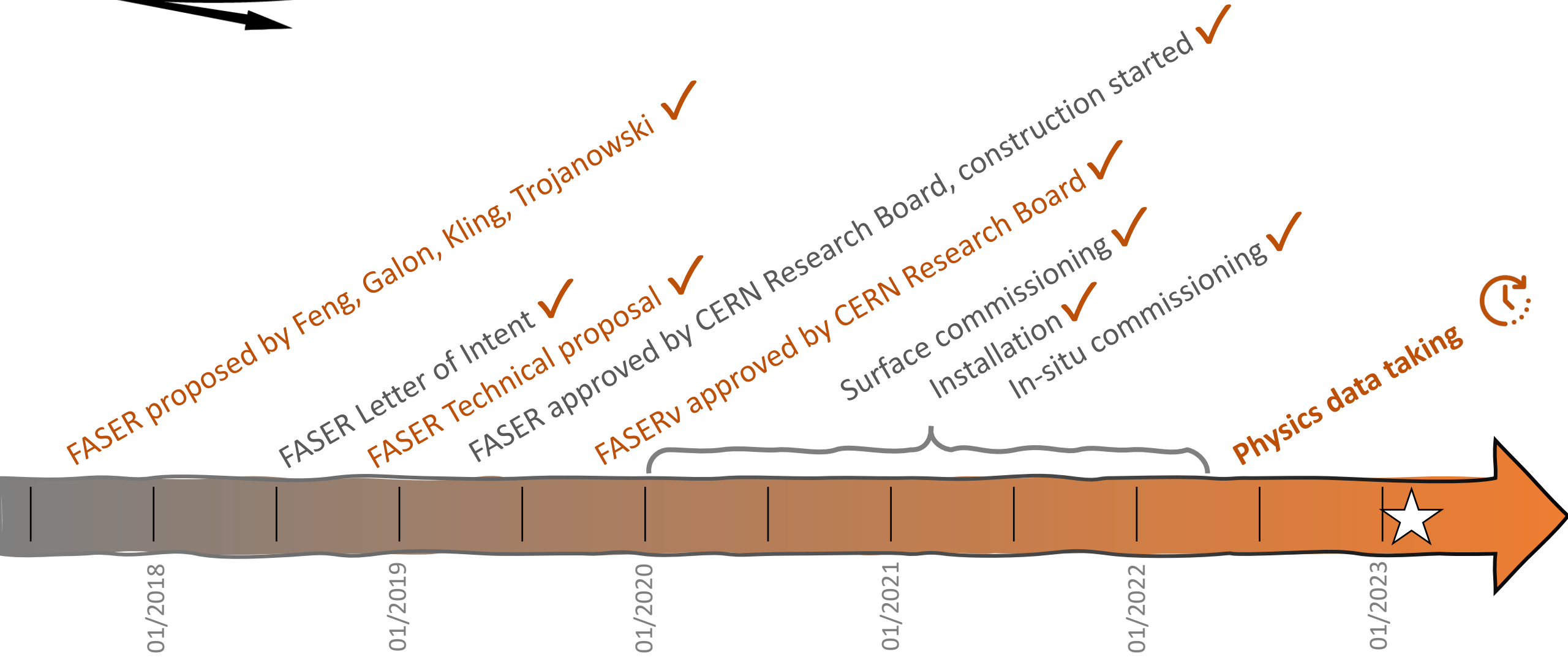
- A very clean high-energy ν_e candidate
- Energy of electron ~ 1.5 TeV



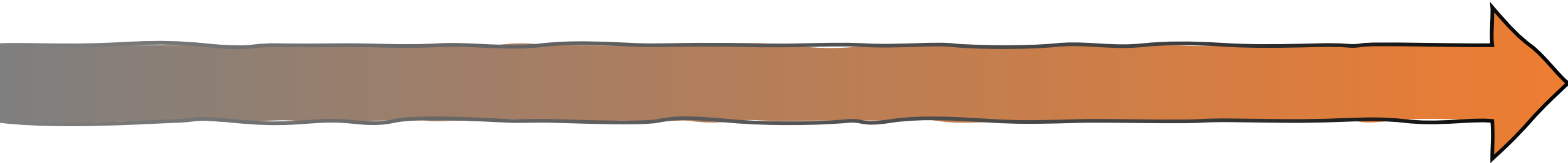
100 μm



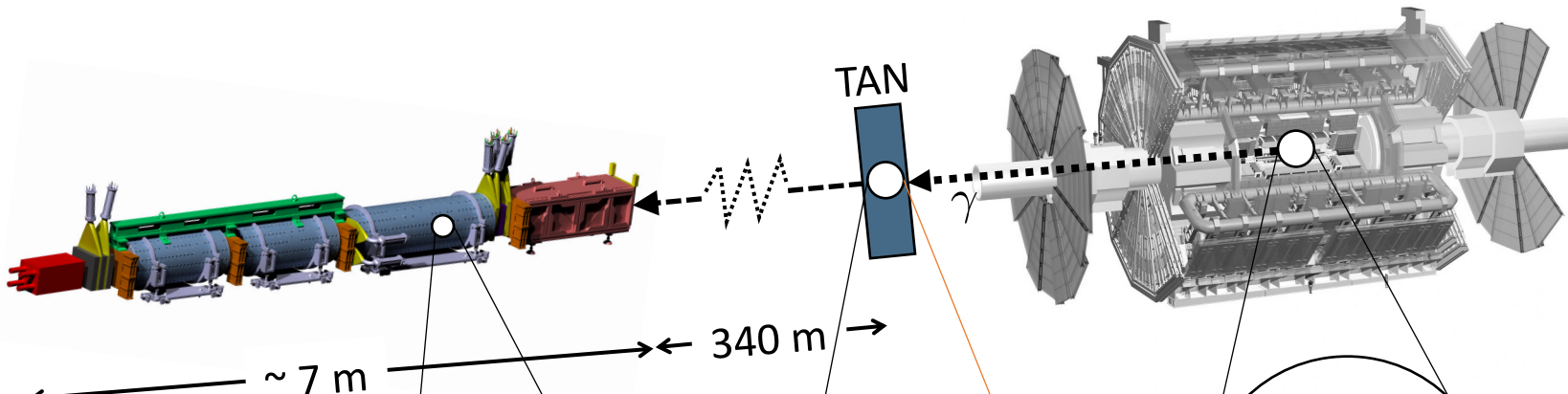
GLOBAL TIMELINE



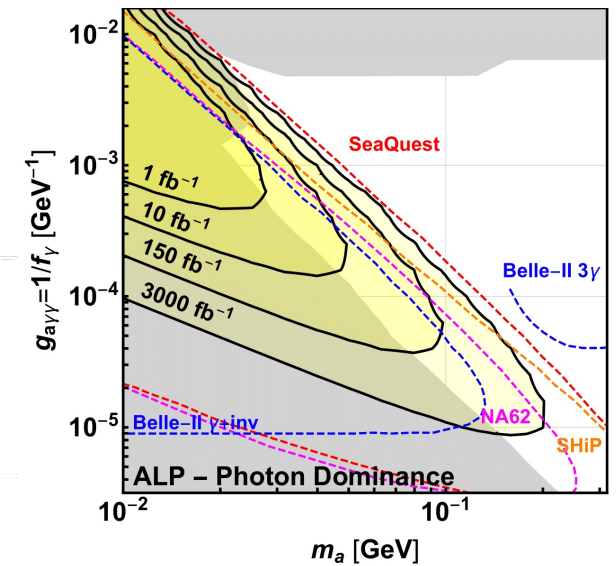
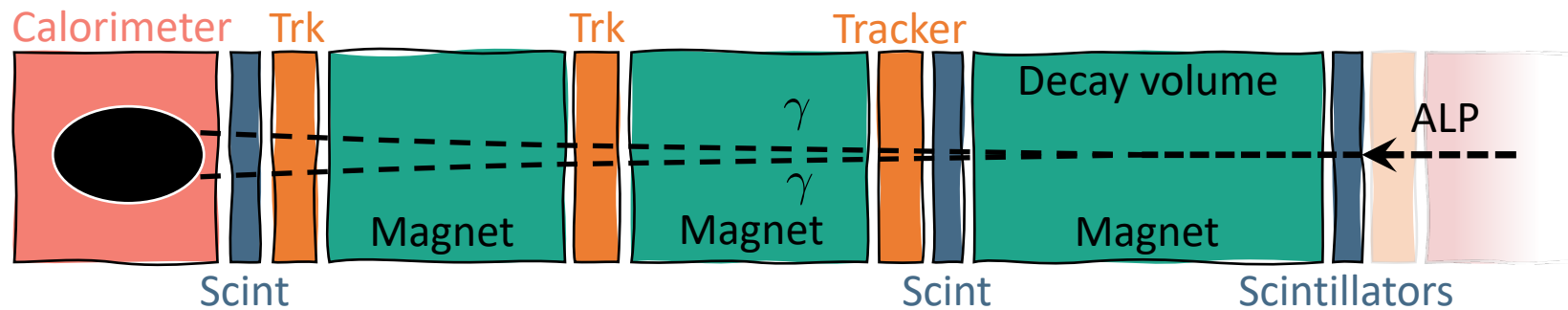
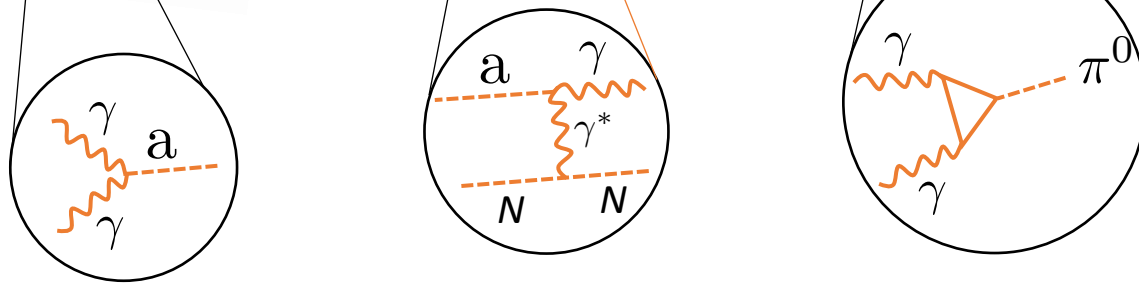
WHAT'S BEYOND 2023 ?



ANOTHER PHYSICS EXAMPLE Axion-like particle (ALP, a)



Decay products collimated
 2- γ signature can't be resolved
 with present detector: **upgrade**



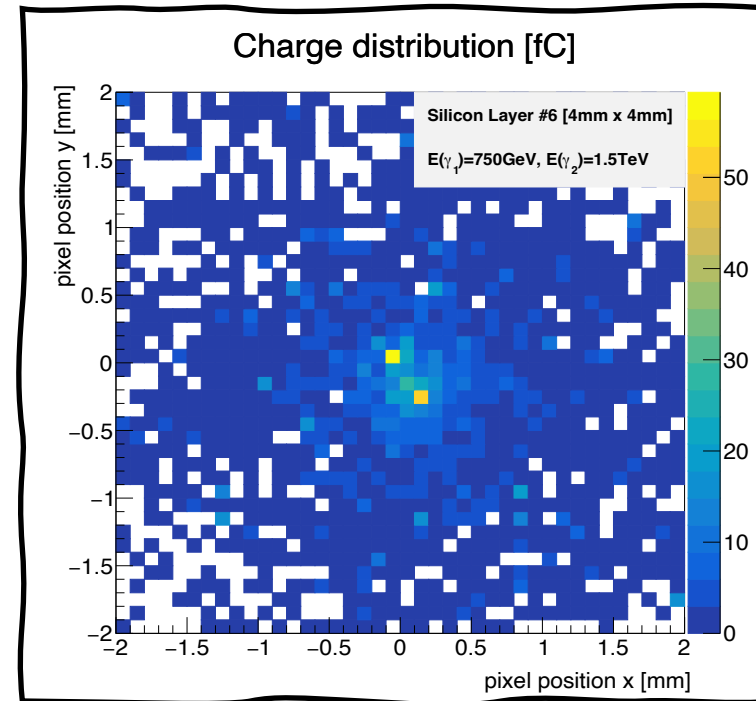
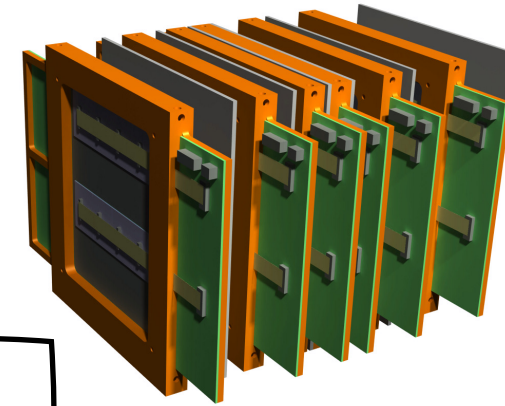
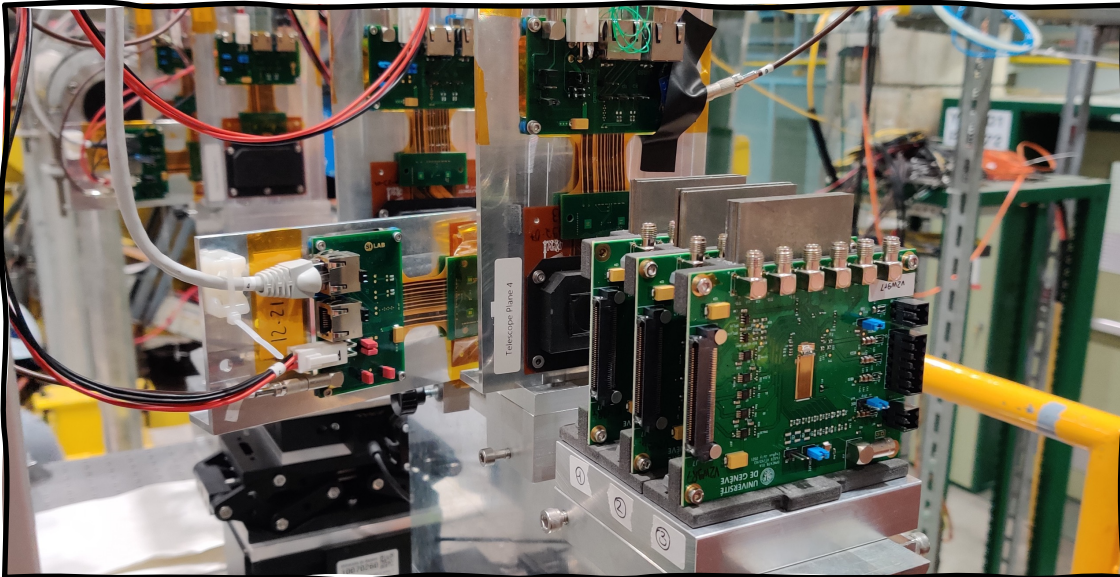
Assuming 3 signal events
 and no backgrounds

PRESHOWER UPGRADE

TO ENABLE $2-\gamma$ PHYSICS

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

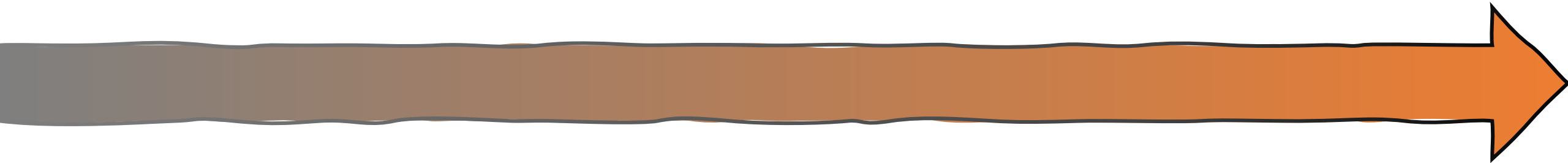
Preproduction ASICs in testbeam, Sept 2022



- Distance between two photons: $200\ \mu\text{m}$
- Distinguishable!

Detector to be used for 2025 data taking

WHAT'S BEYOND RUN 3 ?



NEW PROJECTS IN THE HORIZON

Aligned with the recommendations of recent community studies

The full physics potential of the LHC and the HL-LHC [...] should be exploited.

1st recommendation of the 2020 European Strategy Update



A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world

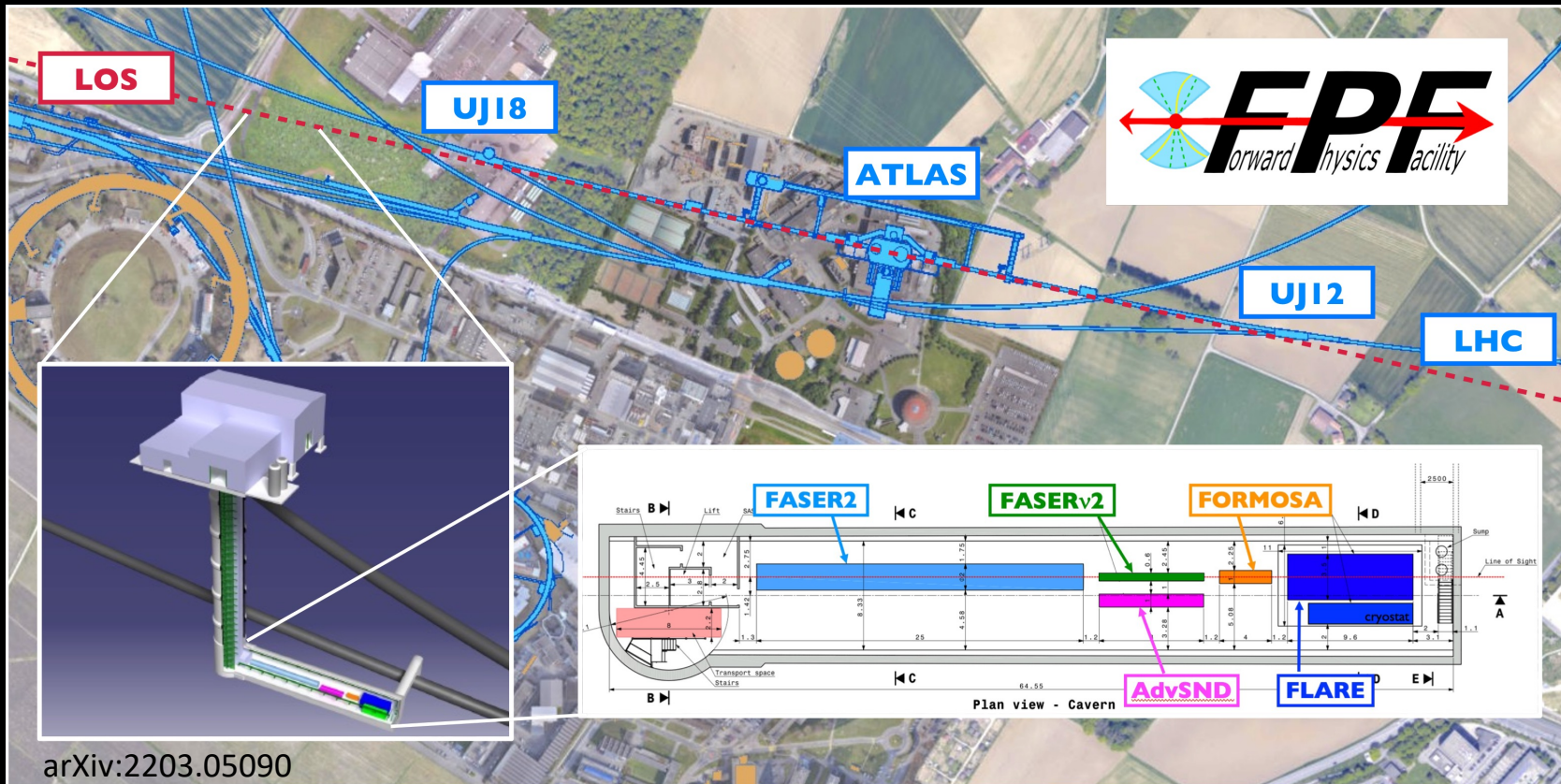
Recommendation of the 2020 European Strategy Update

Our highest immediate priority accelerator and project is the HL-LHC, [...] including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades.

Snowmass 2021 Energy Frontier Report

A TEASER FOR THE PROPOSED FORWARD PHYSICS FACILITY

The rich physics program in the far-forward region strongly motivates creating a dedicated Forward Physics Facility to house far-forward experiments for the HL-LHC era from 2028-2040s



LoI expected by around the beginning of 2024

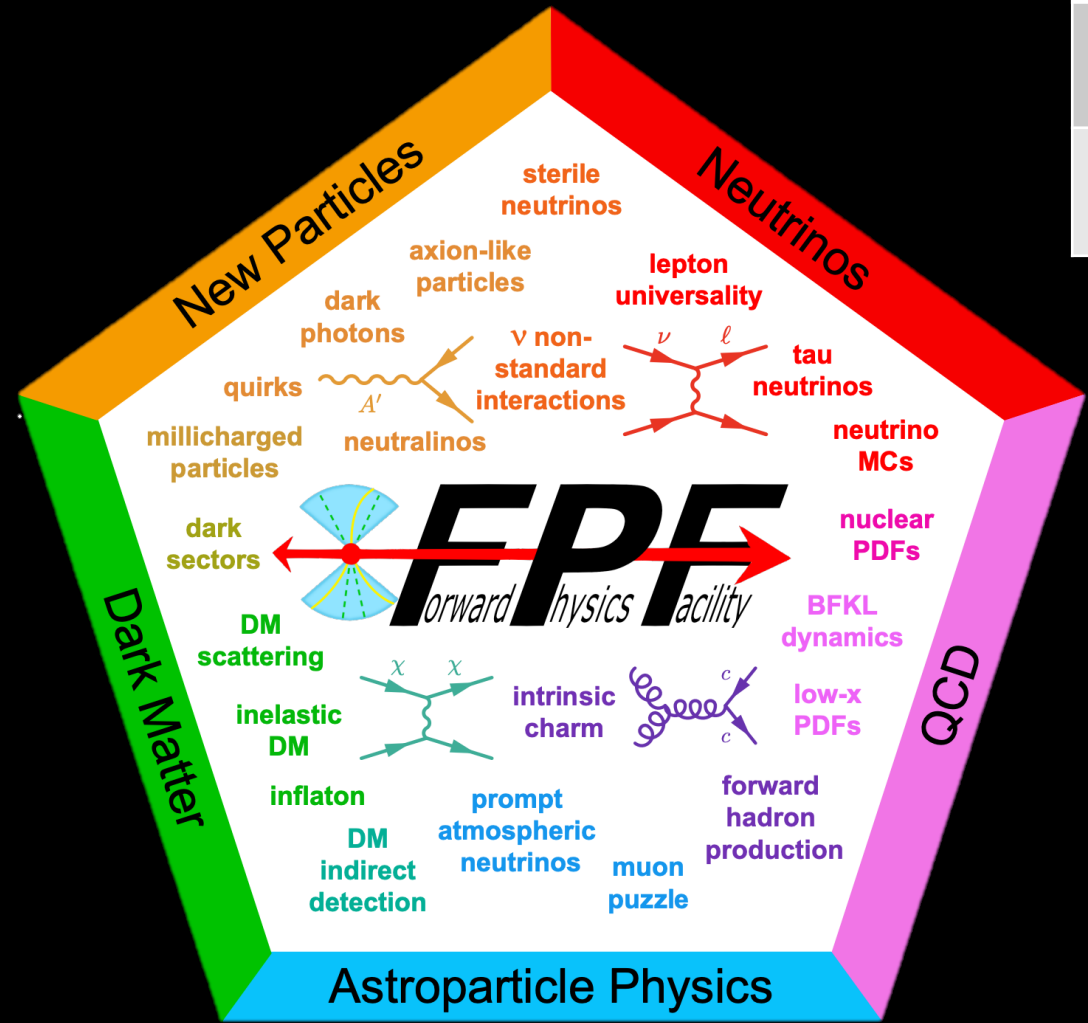
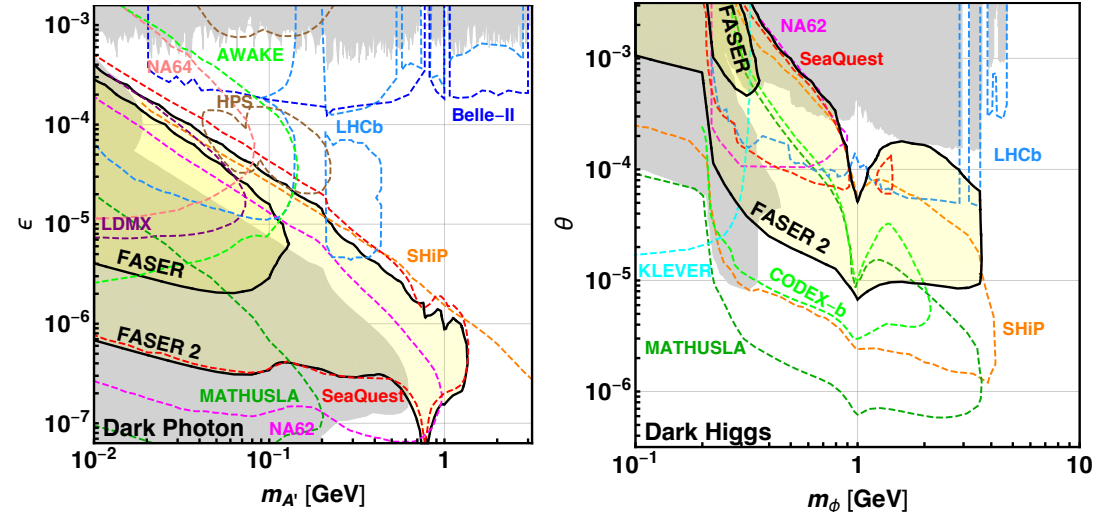
More: [Submitted to P5](#) just in April 2023
[LoI for SNOWMASS-2021](#)
[arXiv:2203.05090](#)
[FPF – Kickoff workshop](#)
[FPF – 5th workshop](#)
[FPF – 6th workshop in June](#)

THE PHYSICS PROGRAMME OF FPF

	Available lumi	Mass of ν detector	ν_e	ν_μ	ν_τ
# interacting in FASERν	150 / fb	1 tn Tungsten	~ 1000	~ 20000	~ 10
# interacting in FASERν2	3000 / fb	10 tn Tungsten	$\sim 10^5$	$\sim 10^6$	$\sim 10^4$

Unprecedented numbers of detectable neutrinos, at energy ranges where there is **currently no available data!**

Increased BSM physics case **beyond** just increased luminosity



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) worked feverishly to construct, install & commission the detector over the Long Shutdown, & successfully collect Run 3 data
- **First FASER results available !**
 - **Dark photon exclusion in interesting thermal relic region**
 - **First collider neutrino direct detection**
- 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:



**HEISING-SIMONS
FOUNDATION**

**SIMONS
FOUNDATION**



**Swiss National
Science Foundation**



**科研費
KAKENHI**

FASER Collaboration: 24 institutes, about 87 members

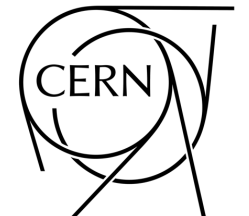


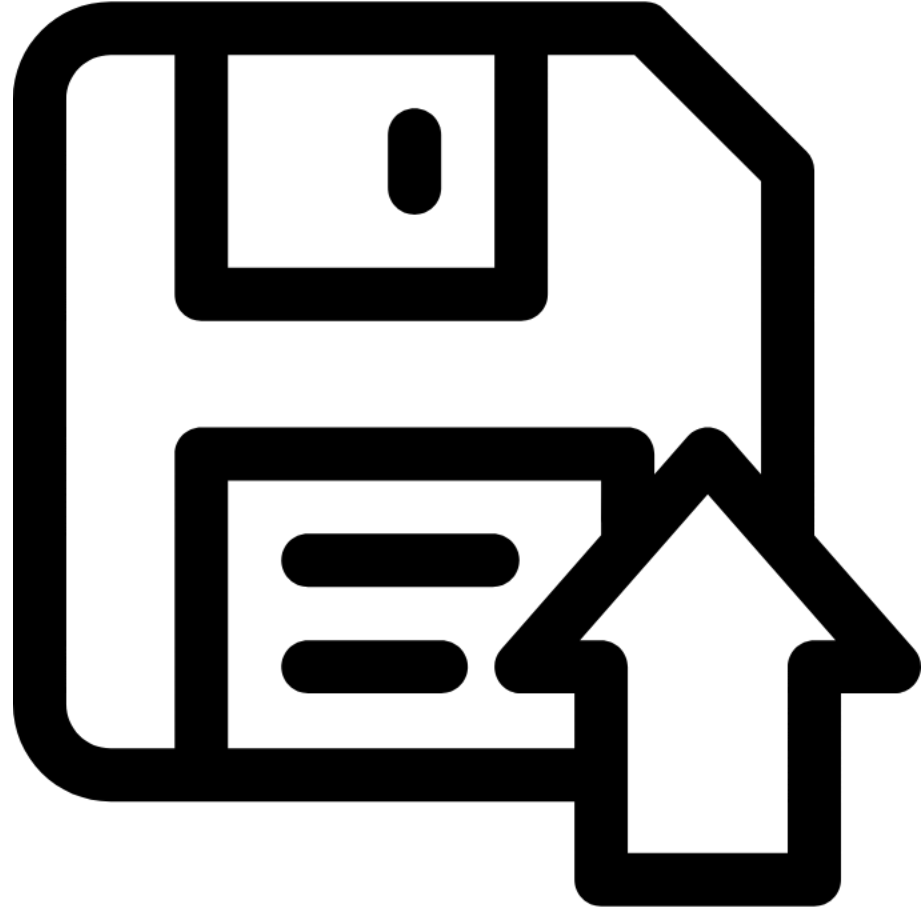
International laboratory
covered by a cooperation
agreement with CERN

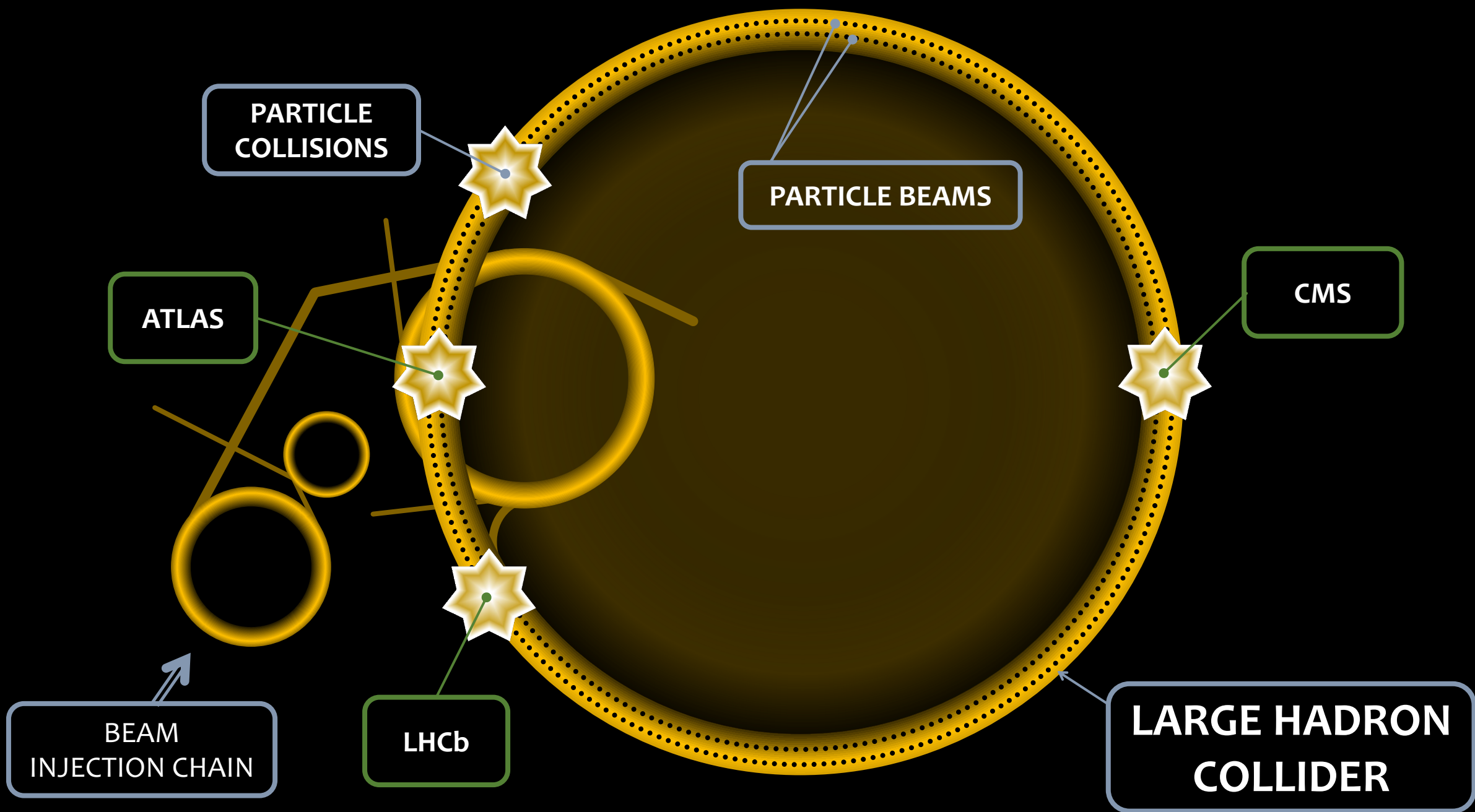


**UNIVERSITÉ
DE GENÈVE**

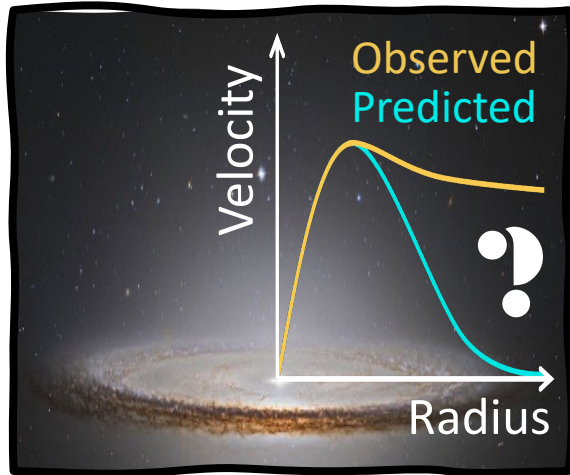
FACULTY OF SCIENCE



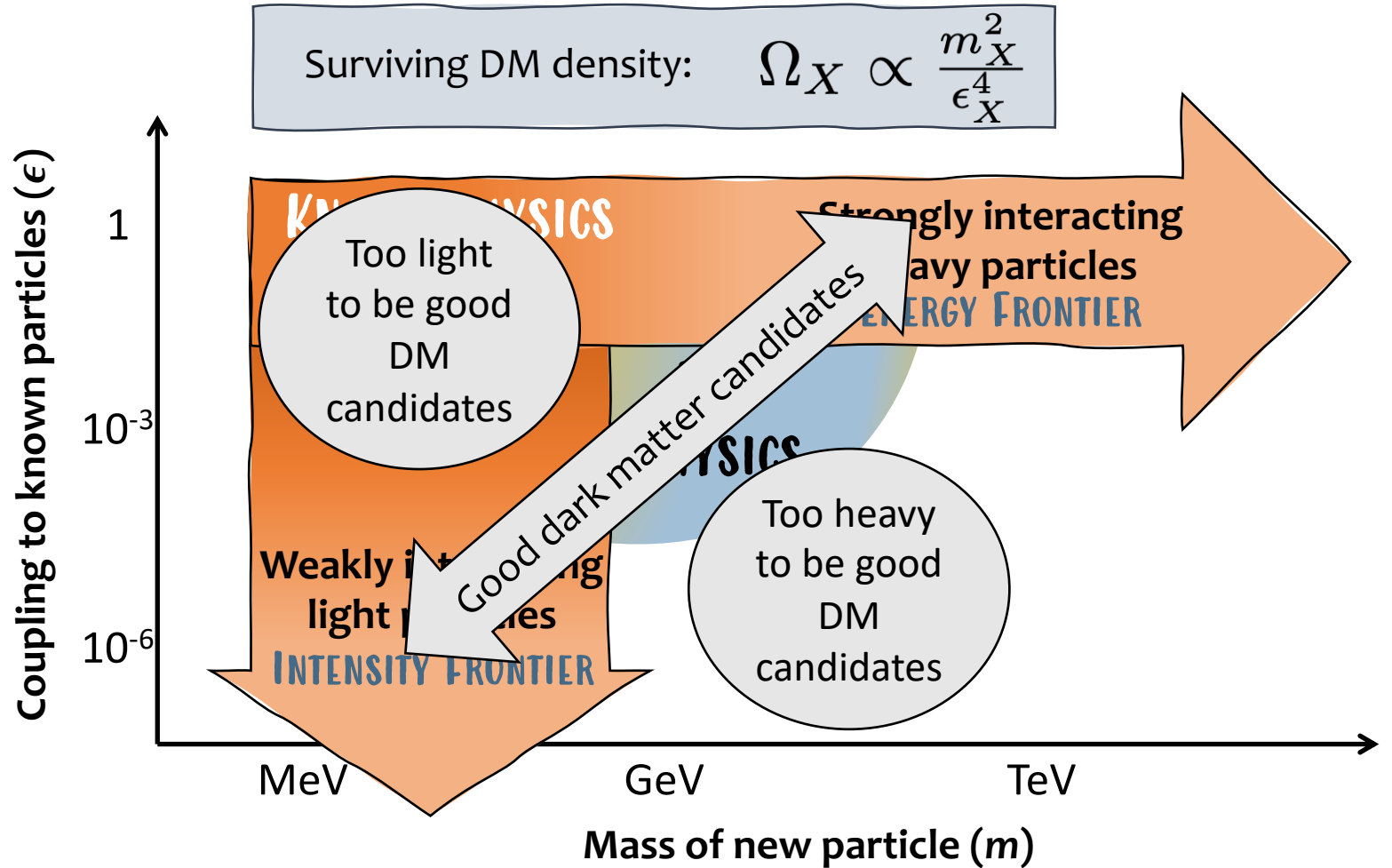
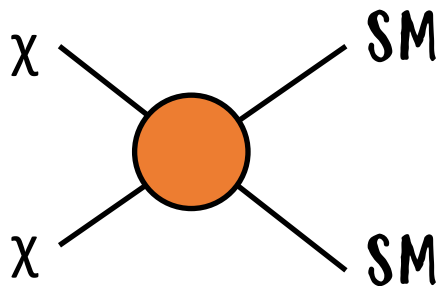




THE LANDSCAPE OF NEW PARTICLES @ COLLIDERS



- Simple mechanism for DM evolution: “freeze out”





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

$h \text{ ----- } (\mu S + \lambda S^2) H^\dagger H \text{ ----- } S$

Dark
Higgs S

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

SM
EM A

$A \rightsquigarrow -\frac{\epsilon}{2 \cos \theta_W} F'_{\mu\nu} F_Y^{\mu\nu} \rightsquigarrow A_D$

Dark
EM A_D

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

SM
 2γ or $2f$

$2\gamma \text{ --- } \frac{\alpha}{f_\alpha} F_{\mu\nu} \tilde{F}^{\mu\nu}$
 $2f \text{ ---- } \frac{\partial_\mu \alpha}{f_\alpha} \bar{\psi} \gamma^\mu \gamma^5 \psi$

ALP
 α

New pseudo-scalar: **ALP**; coupling to SM suppressed
(Axion Like Particle)

SM
LH ν

$\nu \text{ --- } y_N h L \psi_D \text{ --- } N$

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

DARK PHOTON PHYSICS

Dark photon's properties defined through the Lagrangian terms :

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon e \sum_f q_f A'_\mu \bar{f} \gamma^\mu f ,$$

For dark photon masses $2m_e < m_{A'} < 2m_\mu \simeq 211 \text{ MeV}$, dark photons decay to electrons with $B(A' \rightarrow e^+e^-) \approx 100\%$:

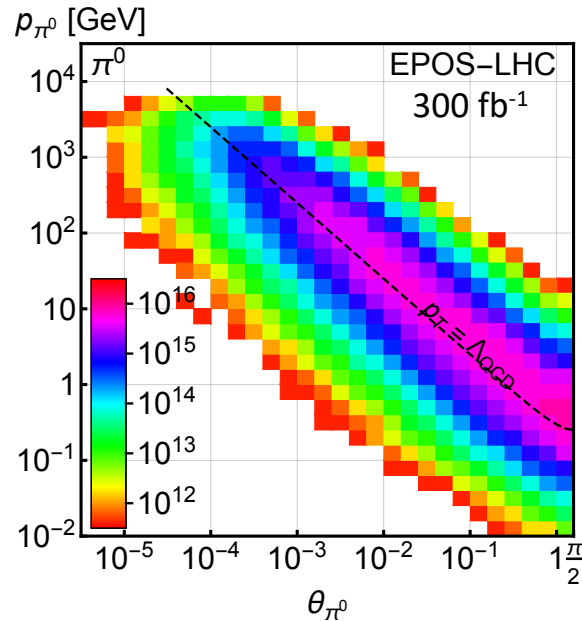
$$\Gamma_e \equiv \Gamma(A' \rightarrow e^+e^-) = \frac{\epsilon^2 e^2 m_{A'}}{12\pi} \left[1 - \left(\frac{2m_e}{m_{A'}} \right)^2 \right]^{1/2} \left[1 + \frac{2m_e^2}{m_{A'}^2} \right] .$$

For $E_{A'} \gg m_{A'} \gg m_e$, the dark photon decay length :

$$L = c\beta\tau\gamma \approx (80 \text{ m}) \left[\frac{10^{-5}}{\epsilon} \right]^2 \left[\frac{E_{A'}}{\text{TeV}} \right] \left[\frac{100 \text{ MeV}}{m_{A'}} \right]^2$$

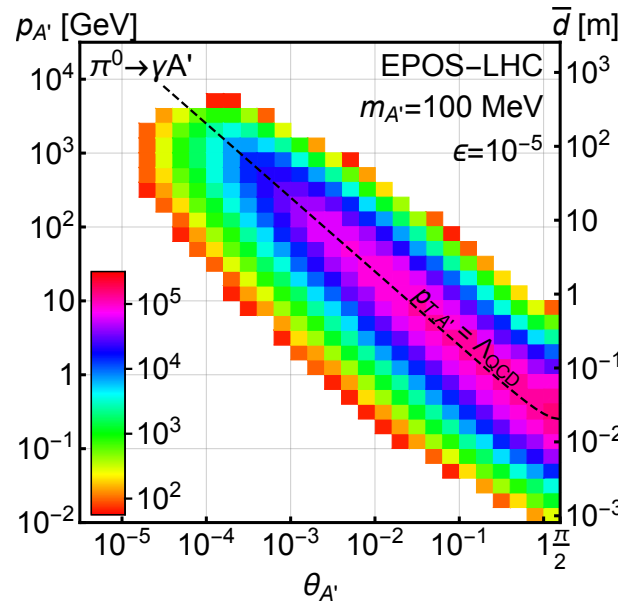
SIGNALS: DARK PHOTONS

Pions at the IP



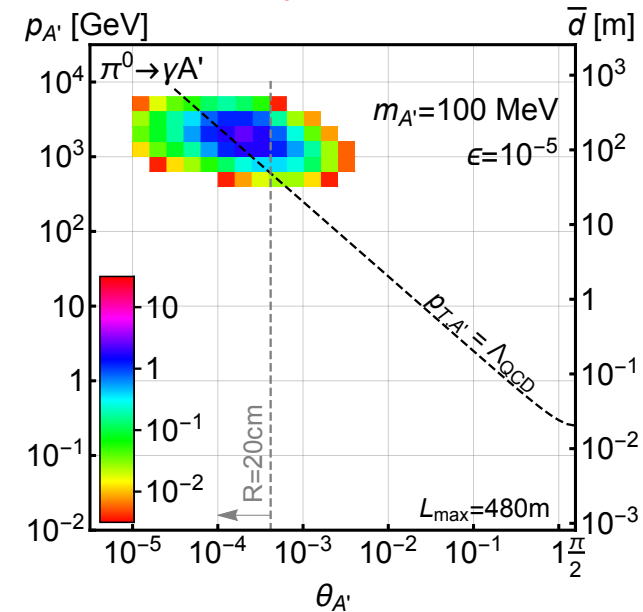
- Enormous event rates: $N_{\pi} \sim 10^{15}$ per bin
- Production is peaked at low transverse momentum ~ 250 MeV

A's at the IP



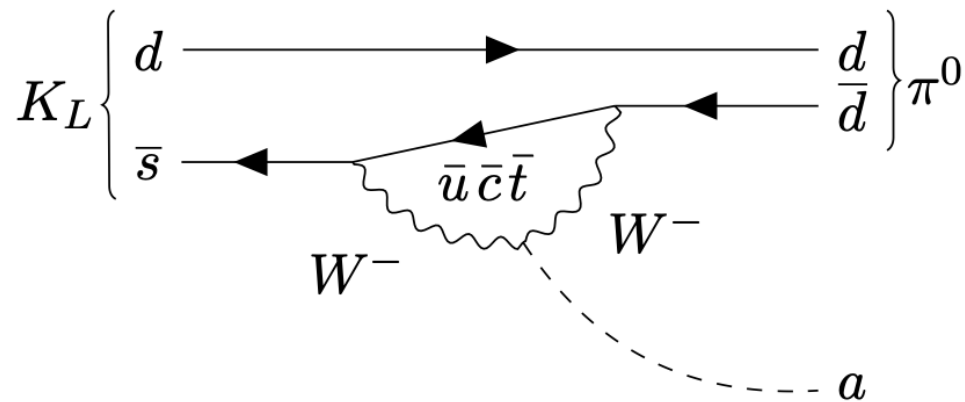
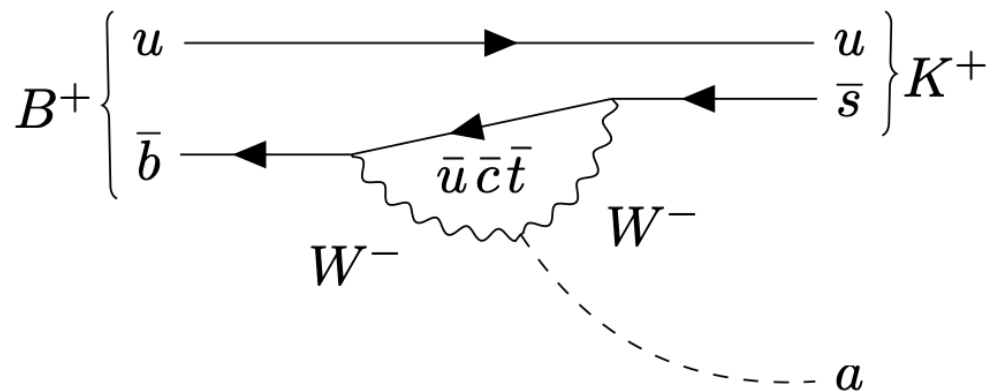
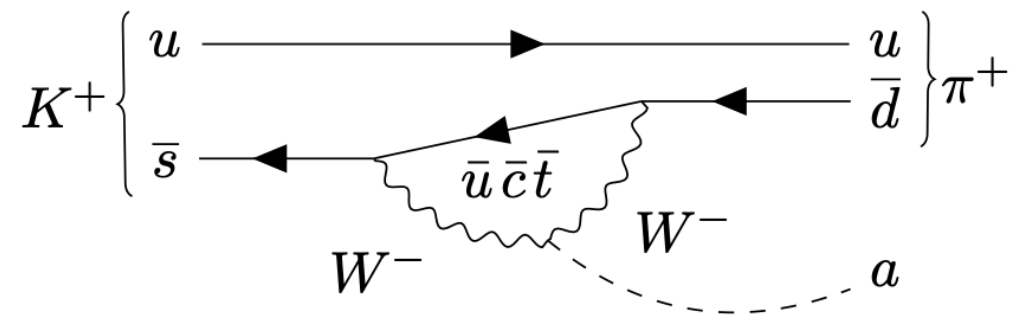
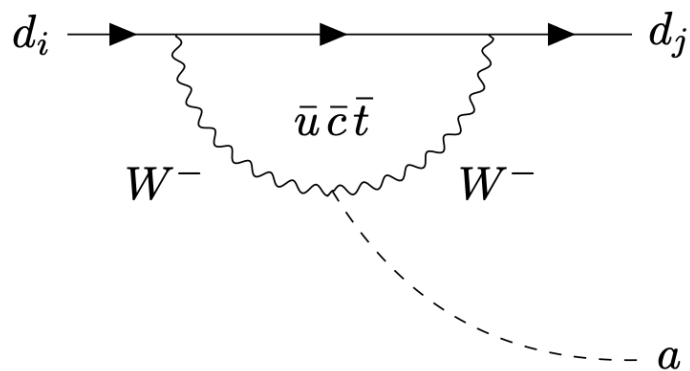
- Rates highly suppressed by $\epsilon^2 \sim 10^{-10}$
- But still $N_{A'} \sim 10^5$ per bin; LHC is a dark photon factory!

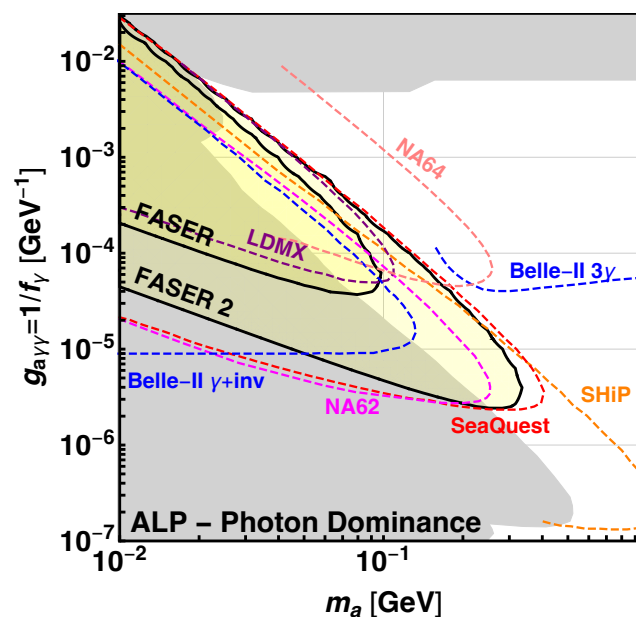
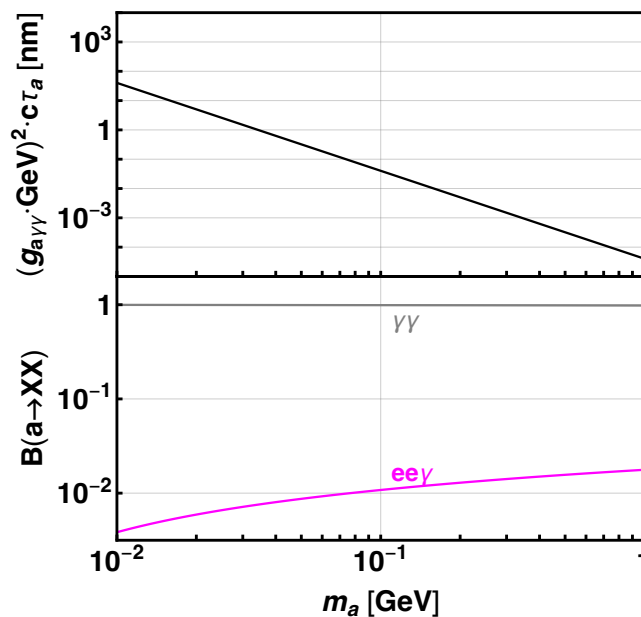
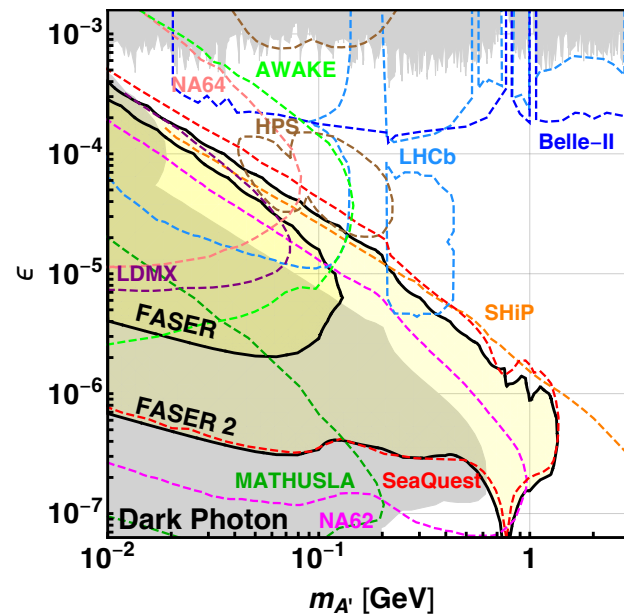
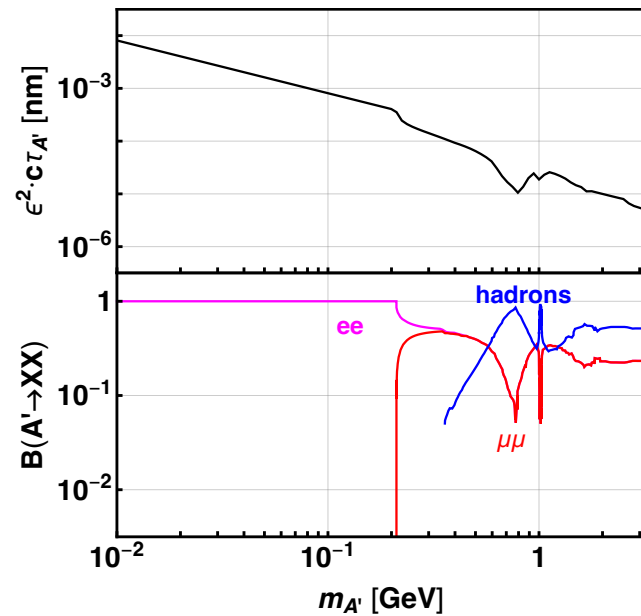
A's decay in FASER



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

ALP production beyond primakoff





Reach for Heavy Neutral Leptons

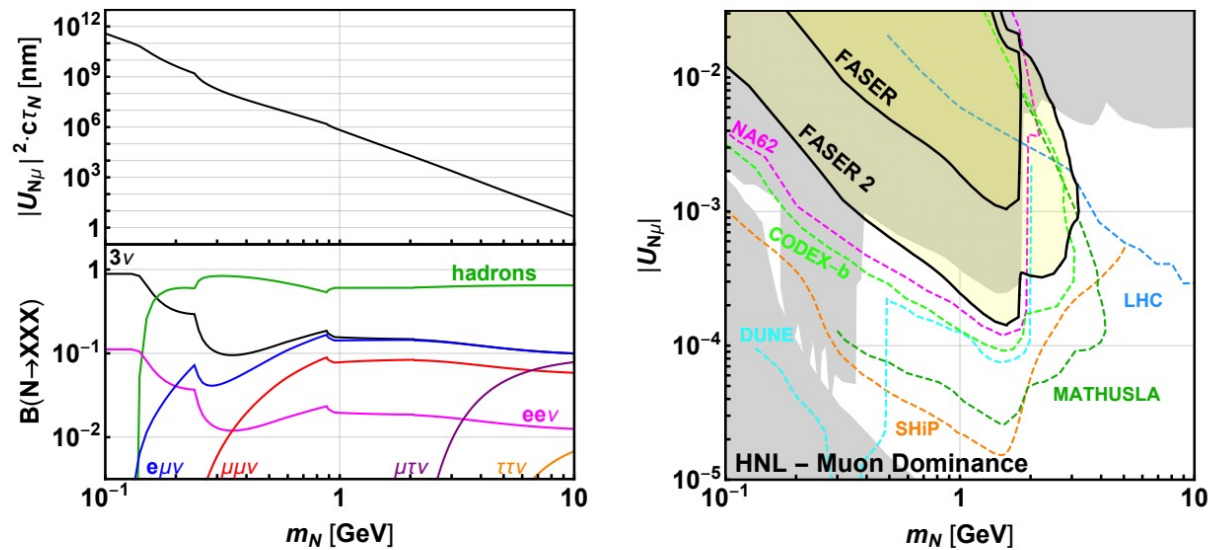


FIG. 13. **Benchmark Model F2.** As in Fig. 12, but for an HNL that only mixes with ν_μ .

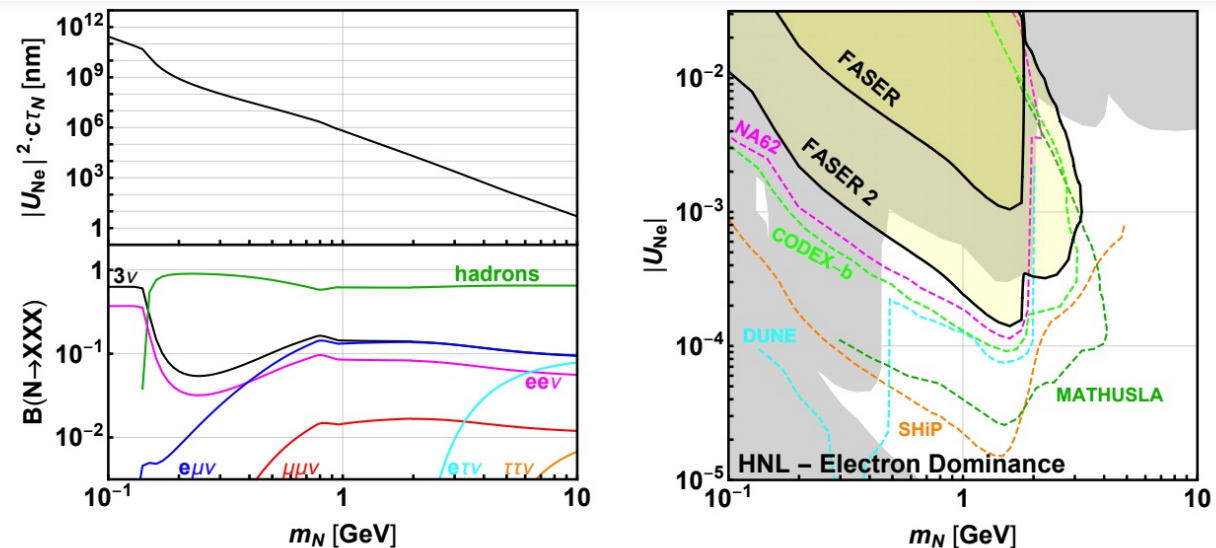


FIG. 12. **Benchmark Model F1.** The decay length (top left panel), decay branching fractions (bottom left panel), and **FASER's reach** (right panel) for the HNL that mixes only with the electron neutrino ν_e . The gray shaded regions are excluded by current limits, and the colored contours are the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

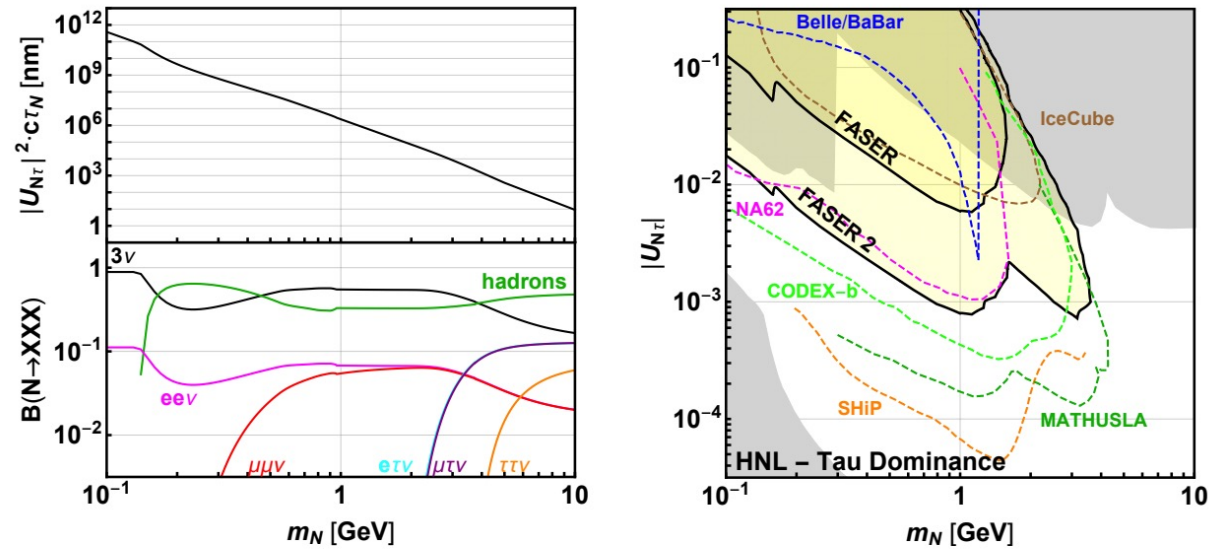
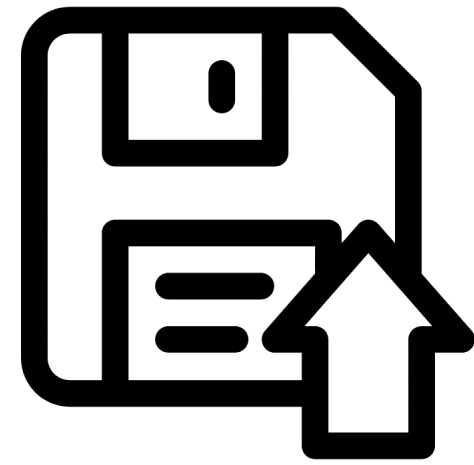
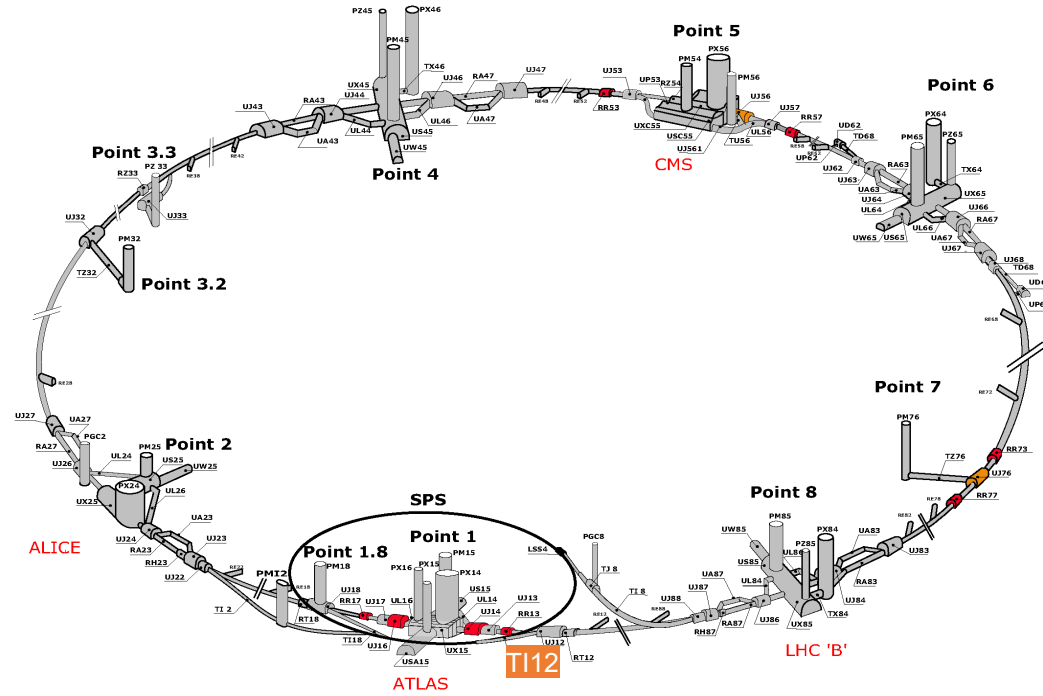


FIG. 14. **Benchmark Model F3.** As in Fig. 12, but for an HNL that only mixes with ν_τ .

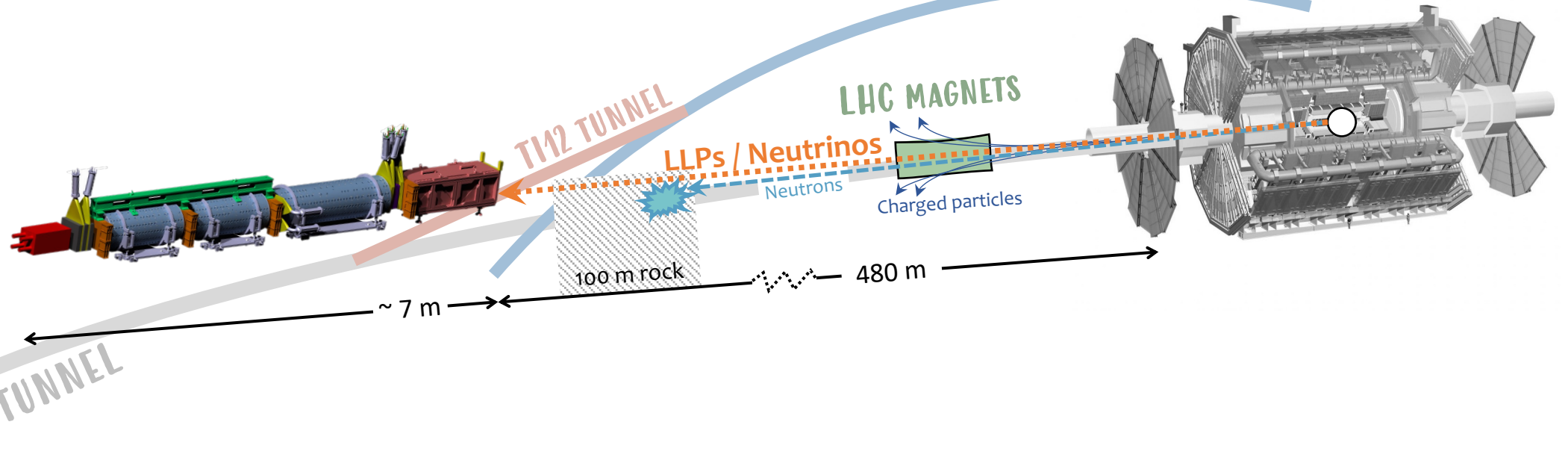


THE *FASER* DETECTOR

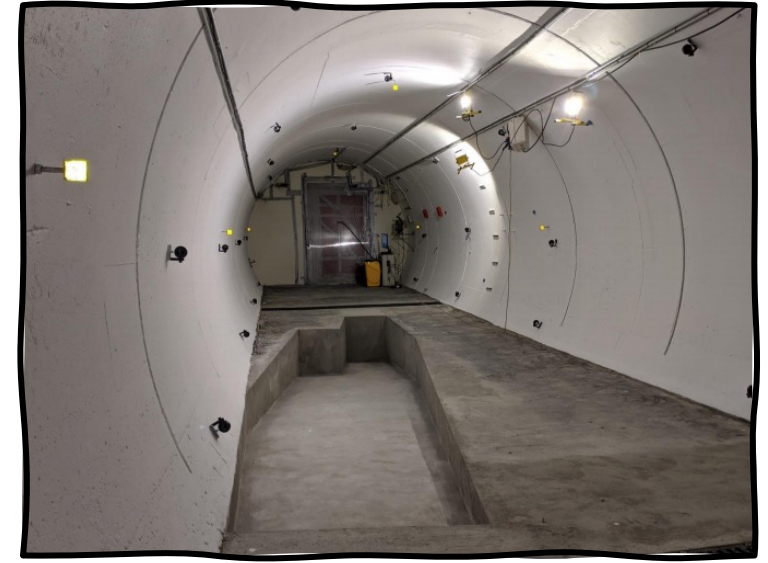
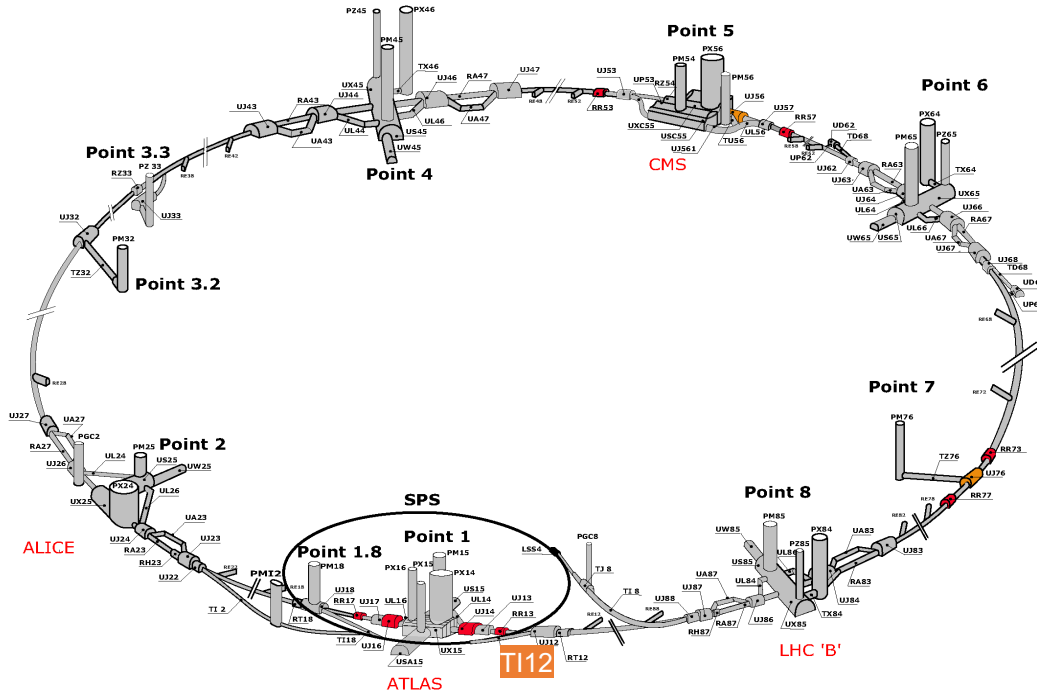
LOCATION



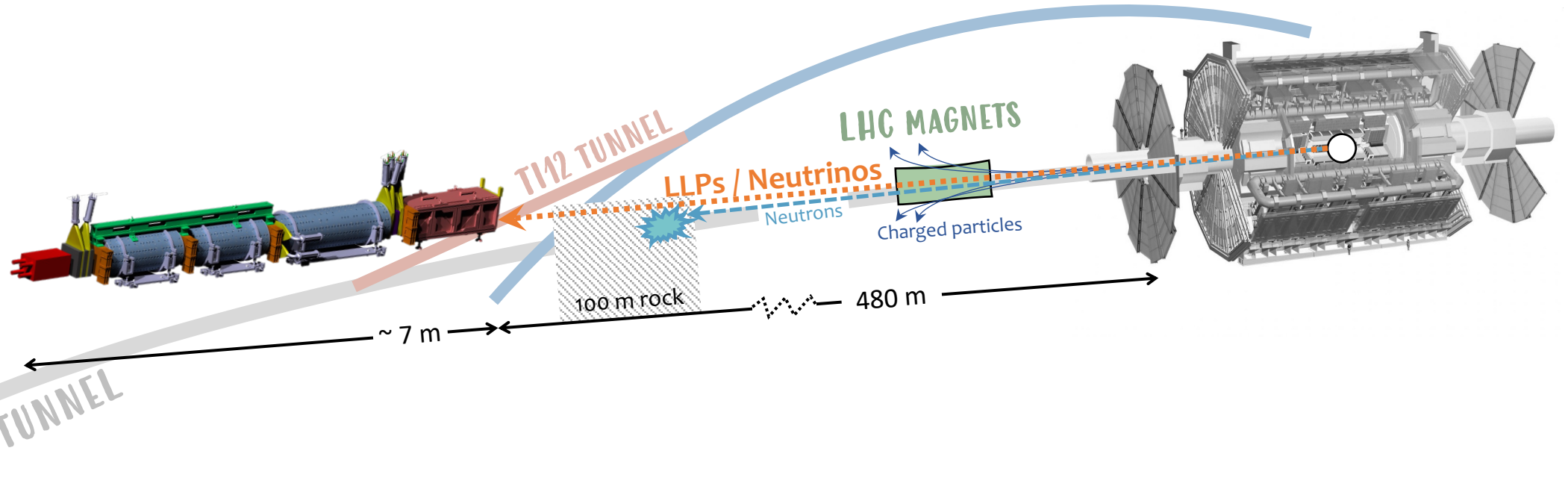
SPS TUNNEL



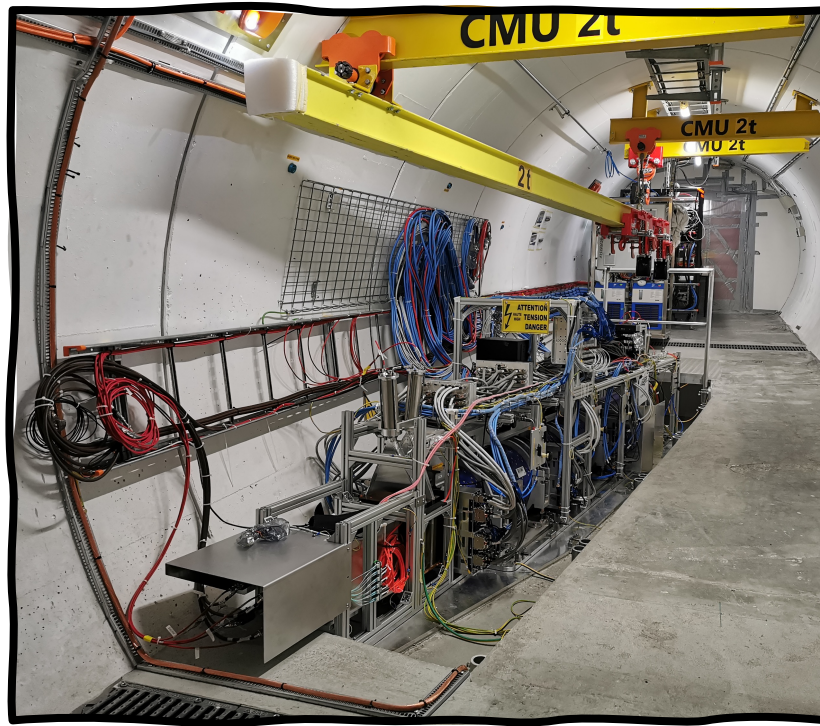
LOCATION



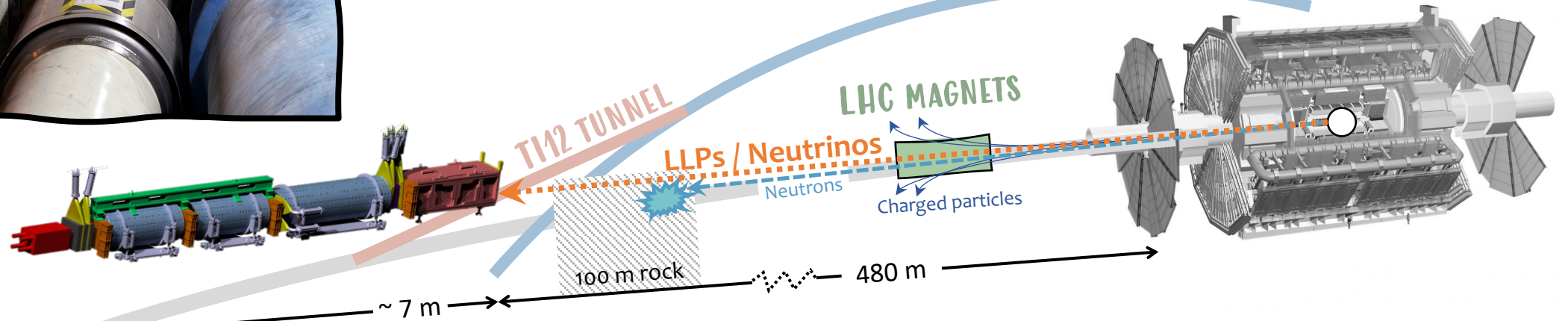
SPS TUNNEL



LOCATION



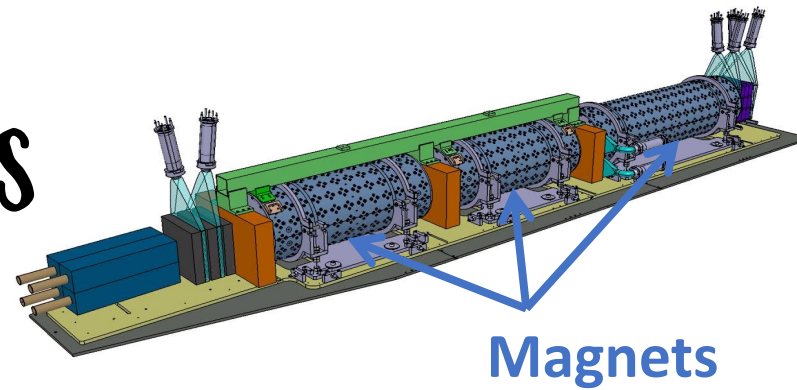
SPS TUNNEL



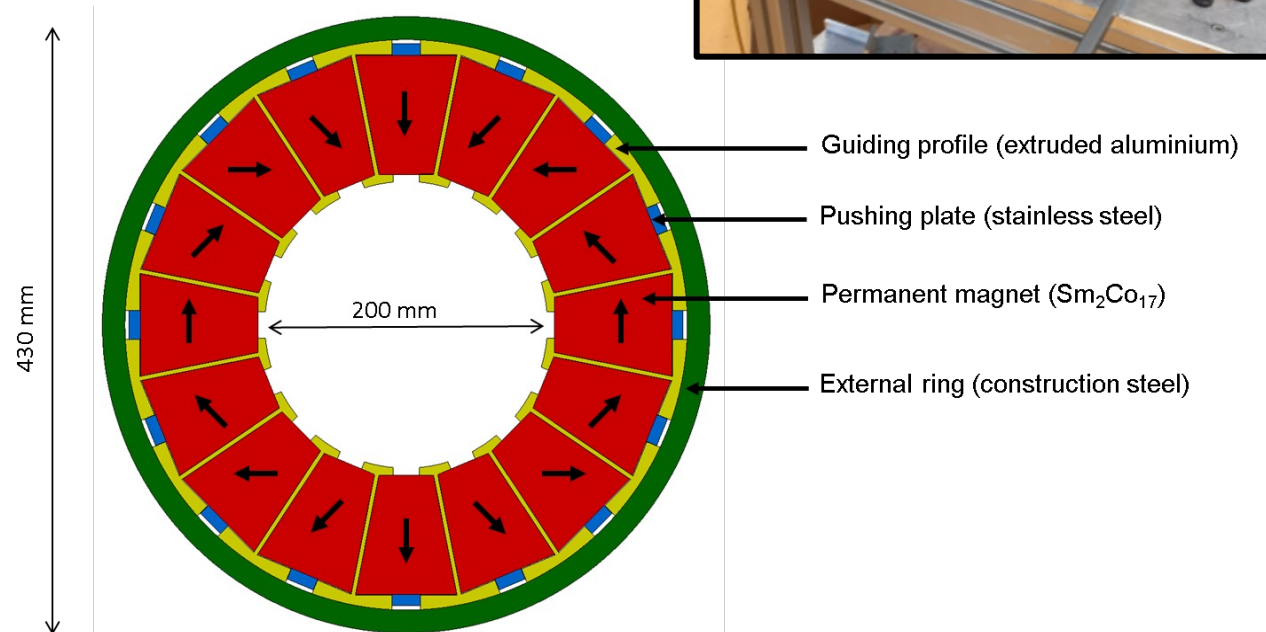
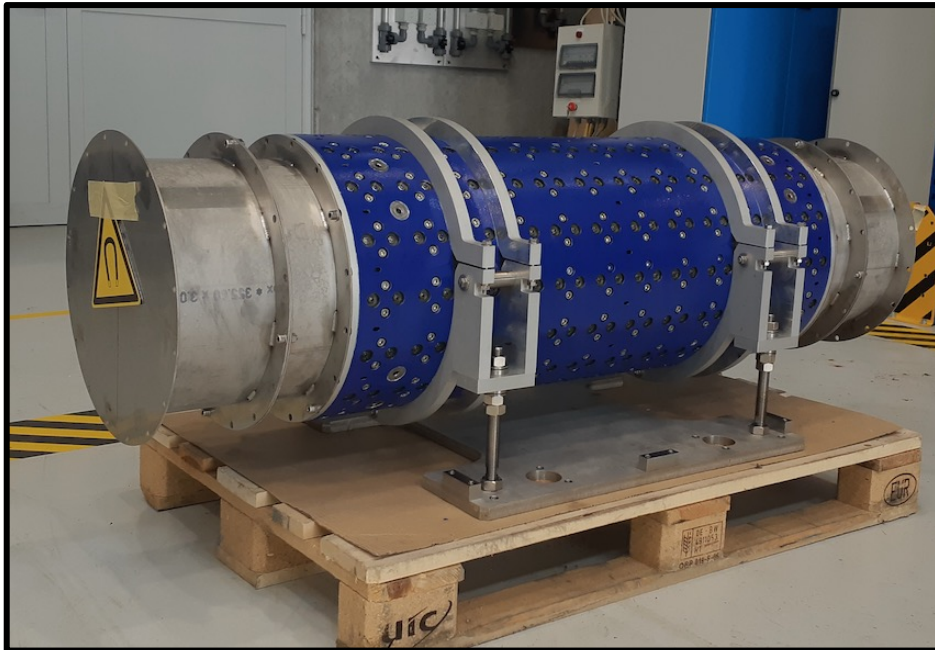
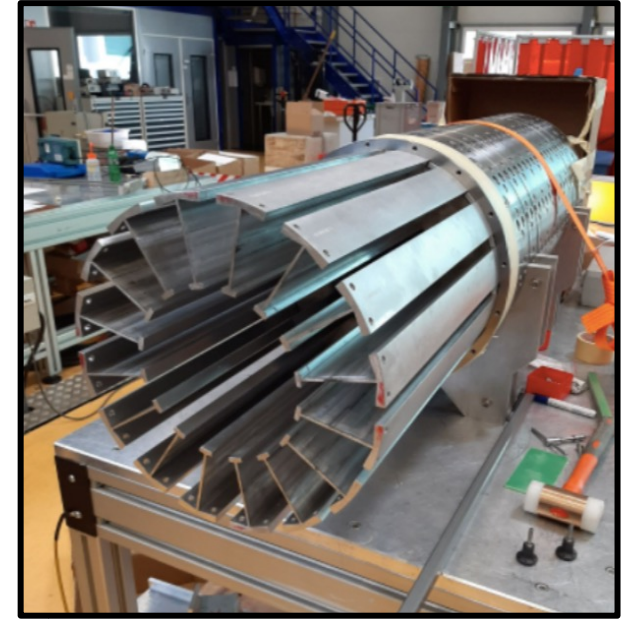
LHC TUNNEL



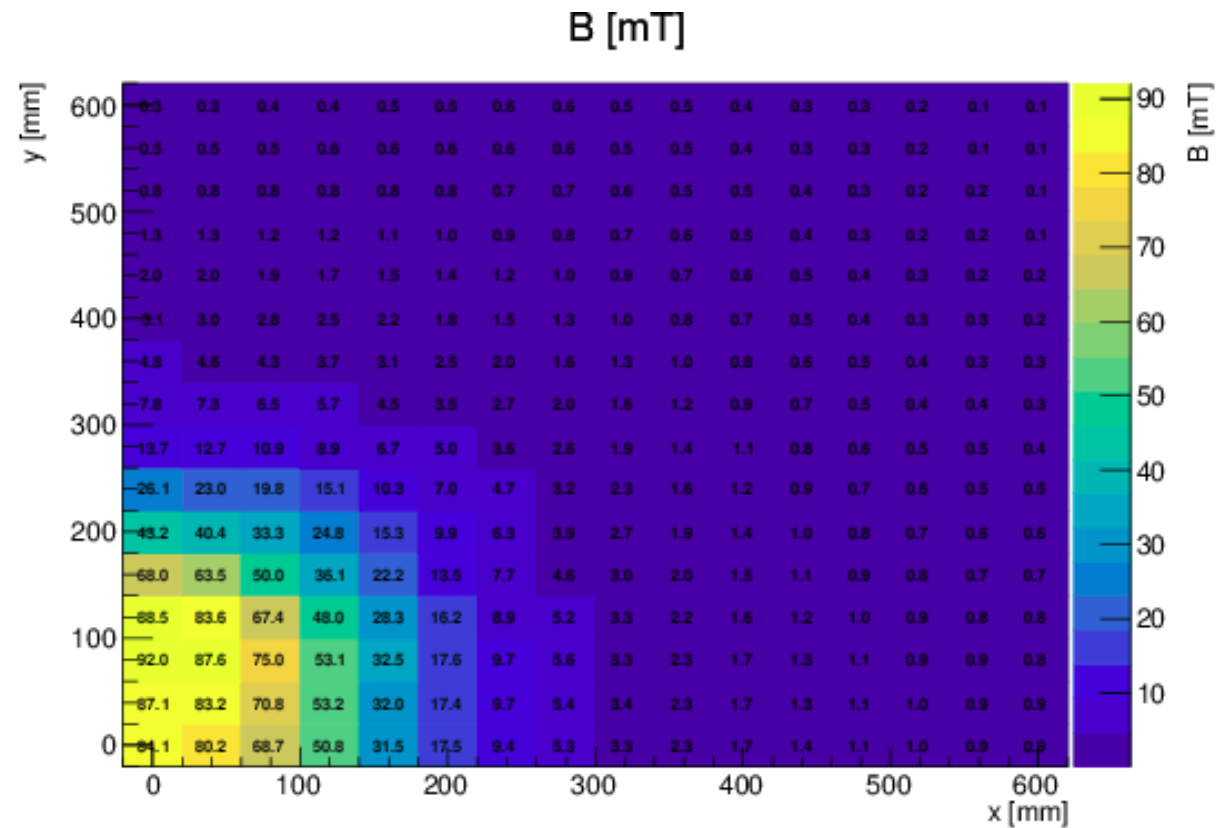
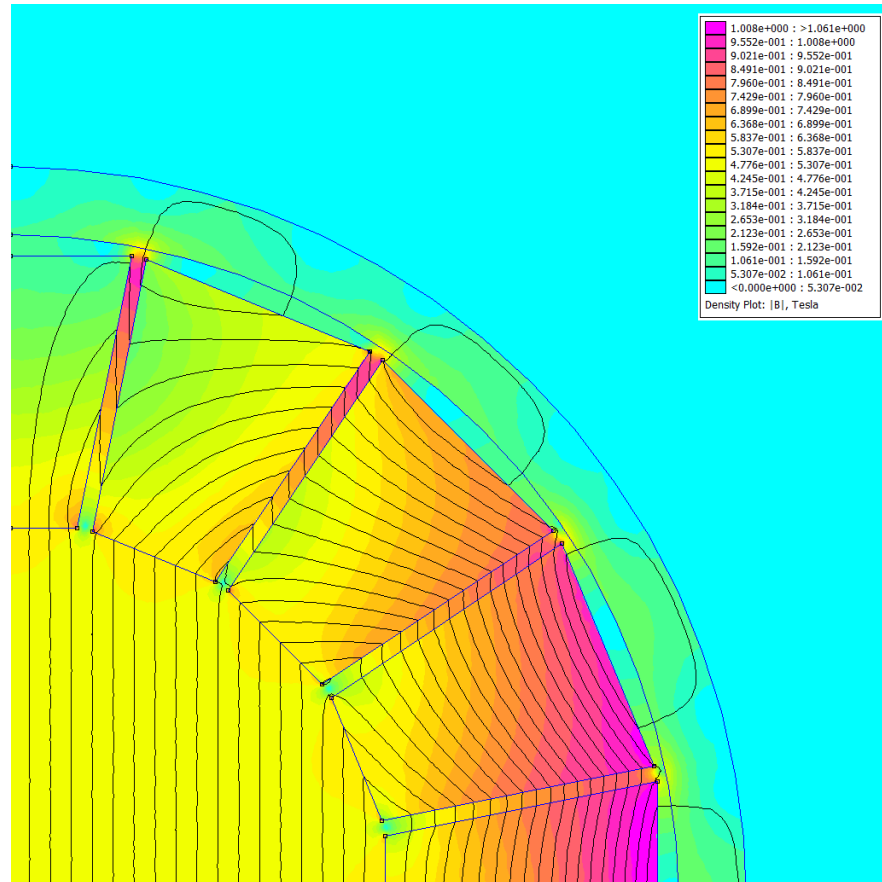
MAGNETS



- 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

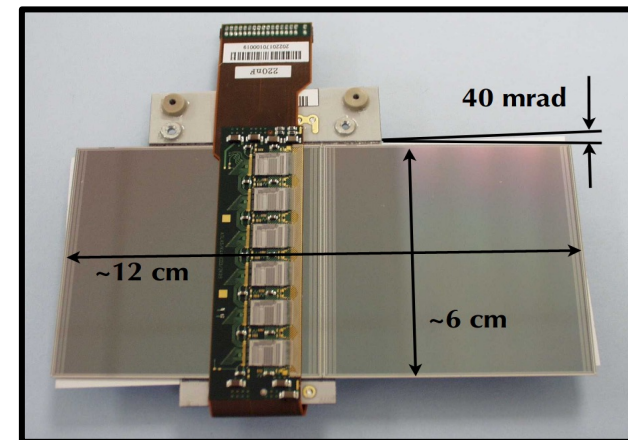
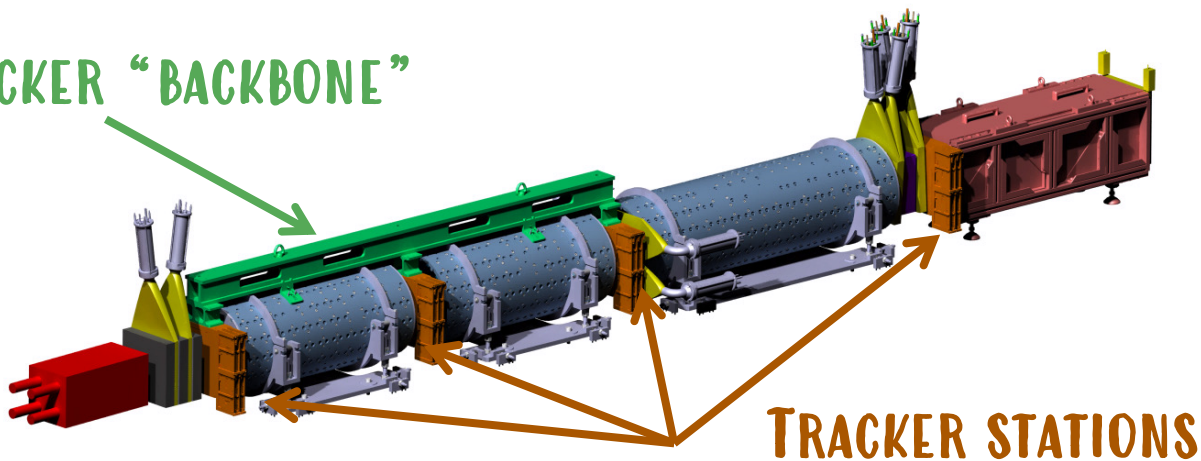


TRACKER

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

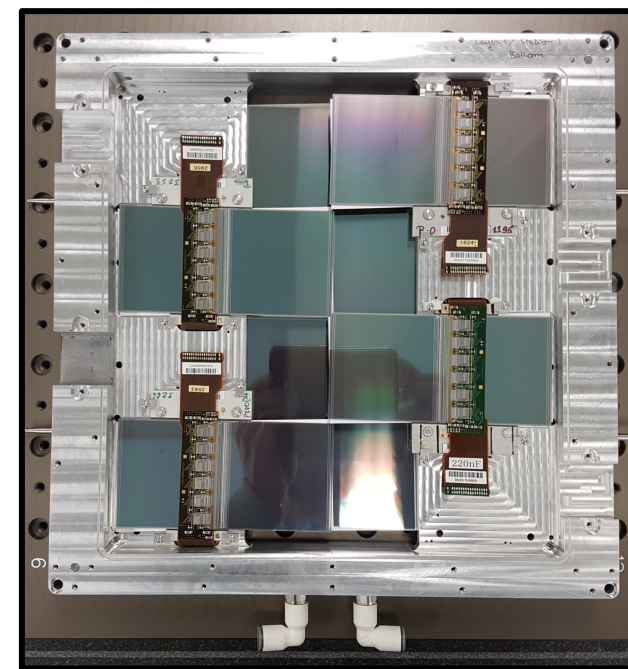
TRACKER “BACKBONE”



SCT module

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

Tracker layer

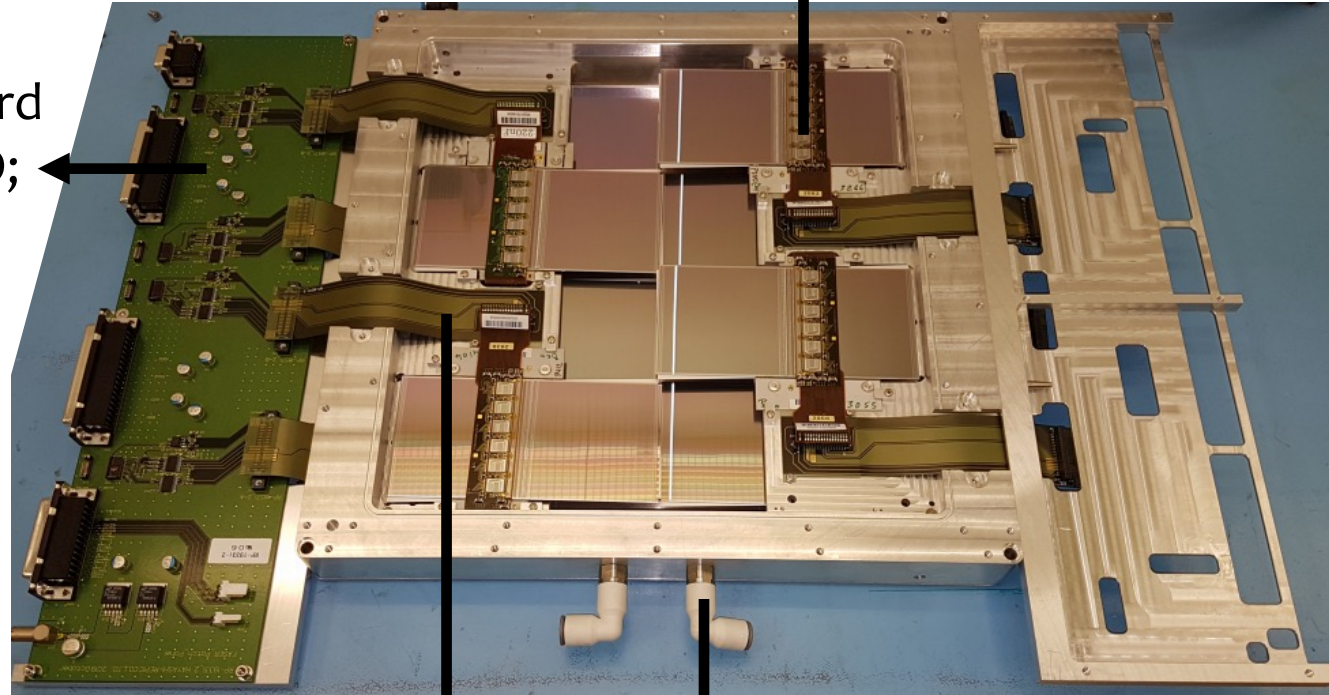


TRACKER

SCT module ASICs,
require $\sim 5 \text{ W / module}$

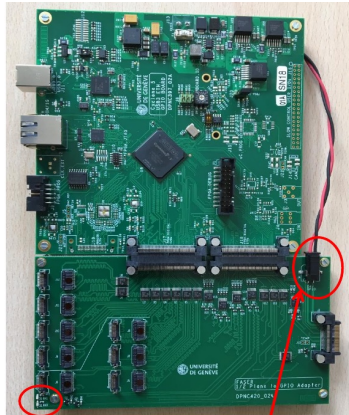
Low radiation in
TI12 and much
lower rates
than ATLAS
allow for
simplifications
in services and
readout.

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

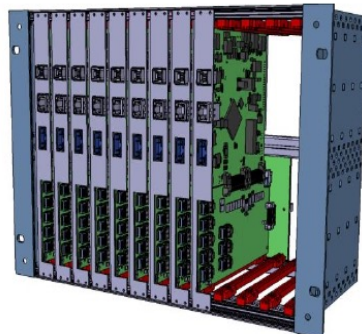


FLEX cables

Detector cooling via water
chiller operating at $10\text{-}15^\circ\text{C}$



2 front panels LEDs
24V discrete wire to
TRB adapter

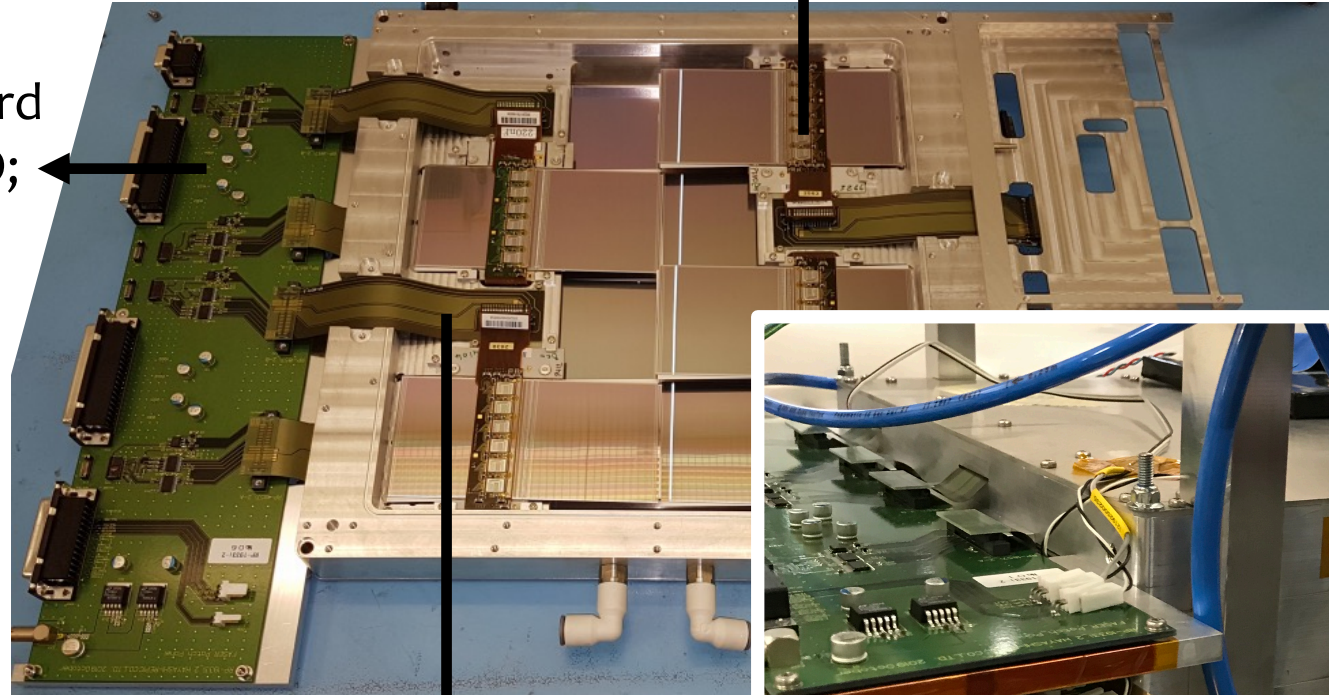


Into
custom-made
mini-crate

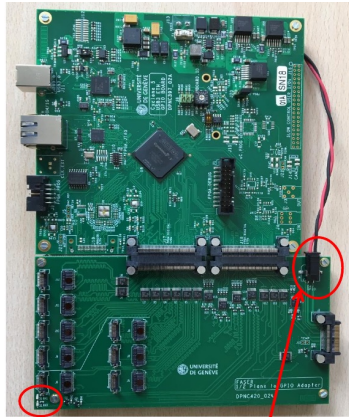
TRACKER

SCT module ASICs,
require ~ 5 W / module

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

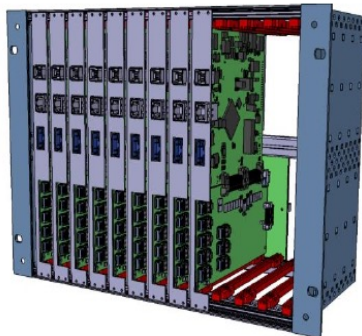


FLEX cables

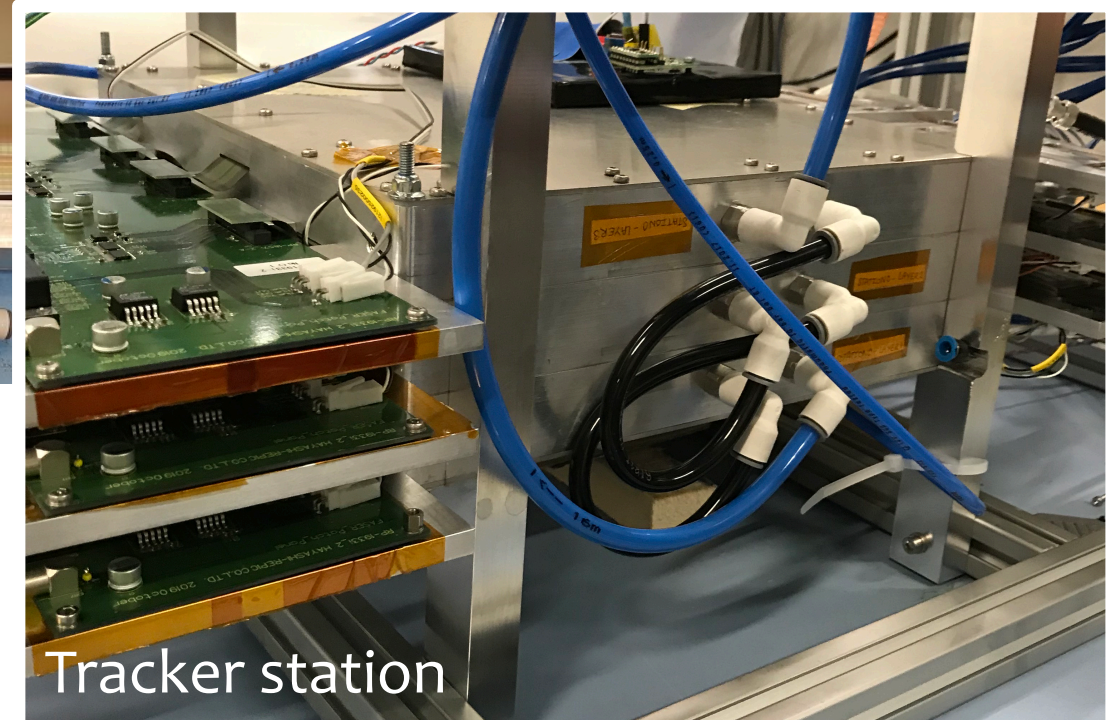


2 front panels LEDs

24V discrete wire to
TRB adapter

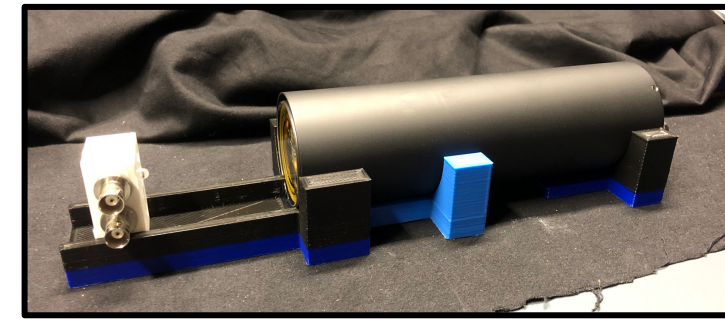


Into
custom-made
mini-crate



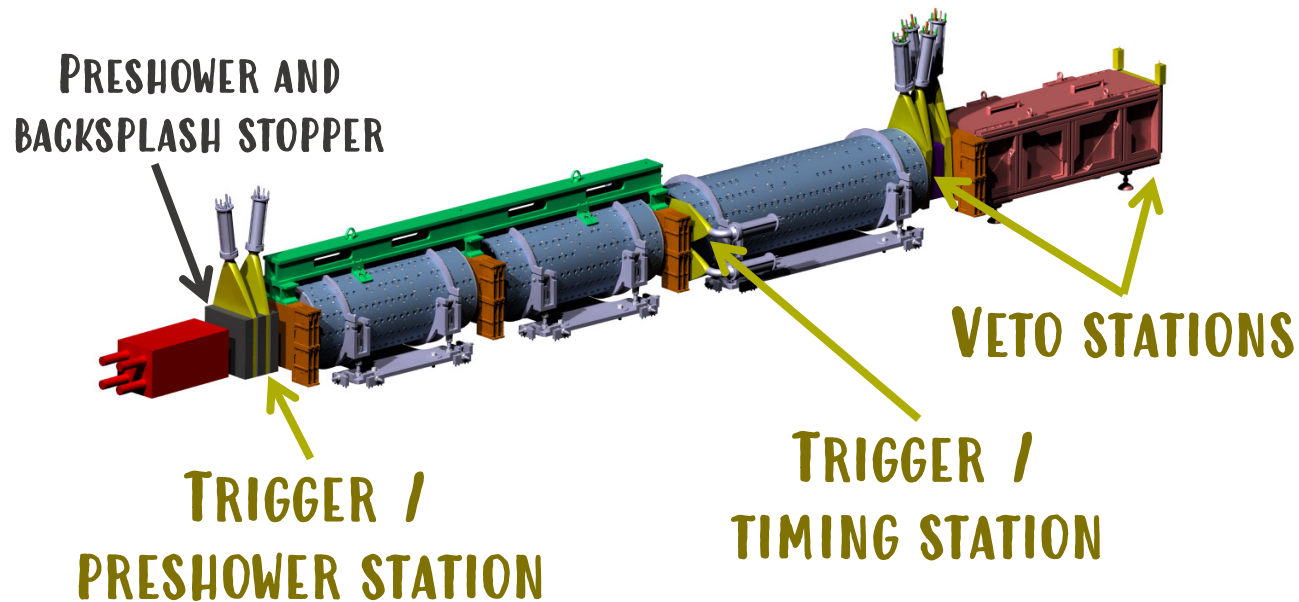
Tracker station

SCINTILLATORS



Scintillator PMTs

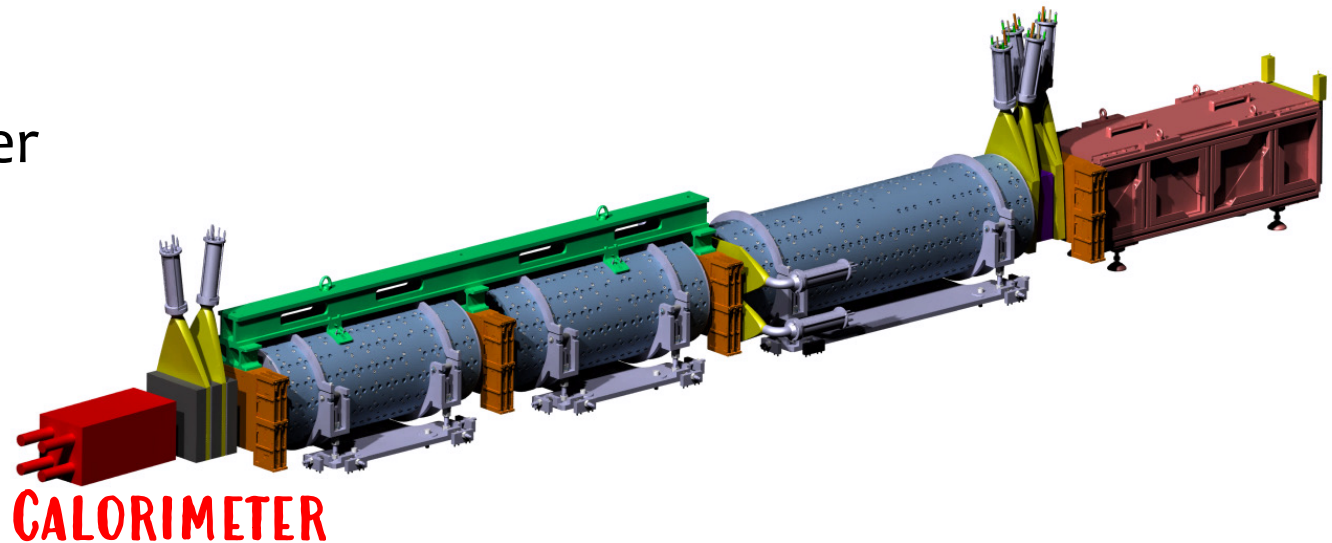
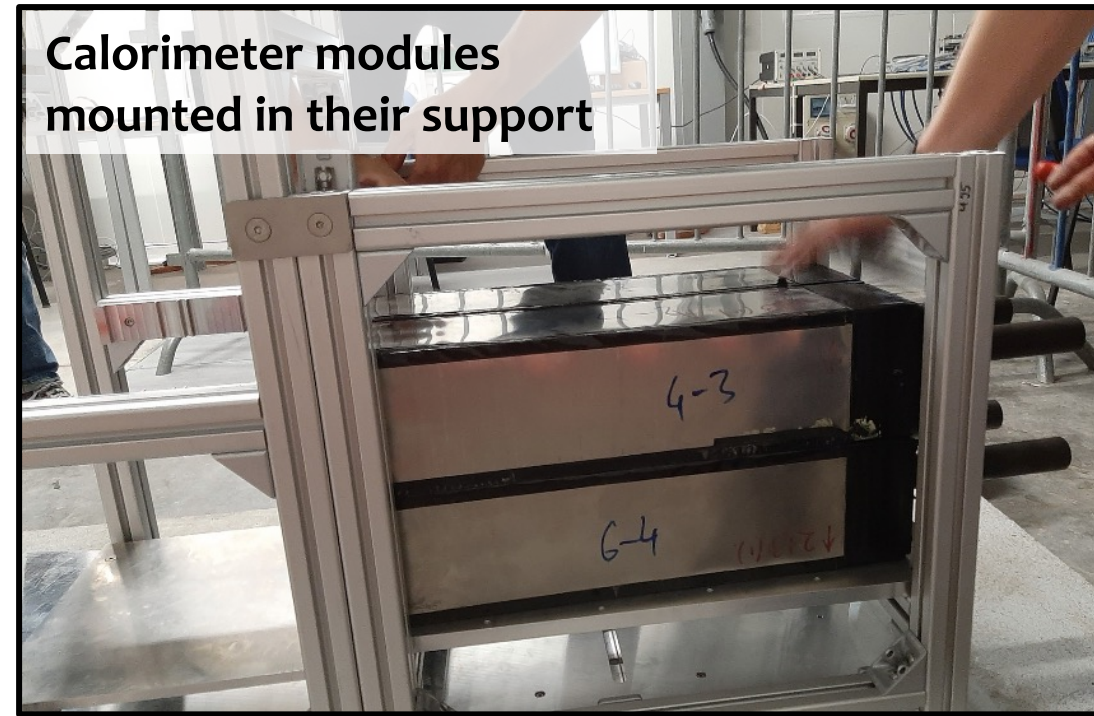
- Three stations all providing triggering capability:
 - Very high efficiency veto station for incoming charged particles (x6 planes)
 - Timing station; precise timing (\sim ns) wrt IP (x1 plane)
 - Pre-shower station; coincidence with timing station (x2 planes)
- Read out with PMTs and CAEN digitizer



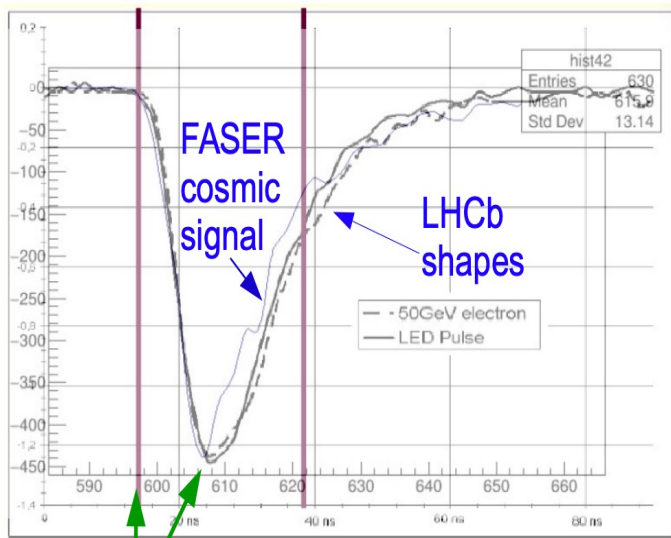
CALORIMETER

THANKS!

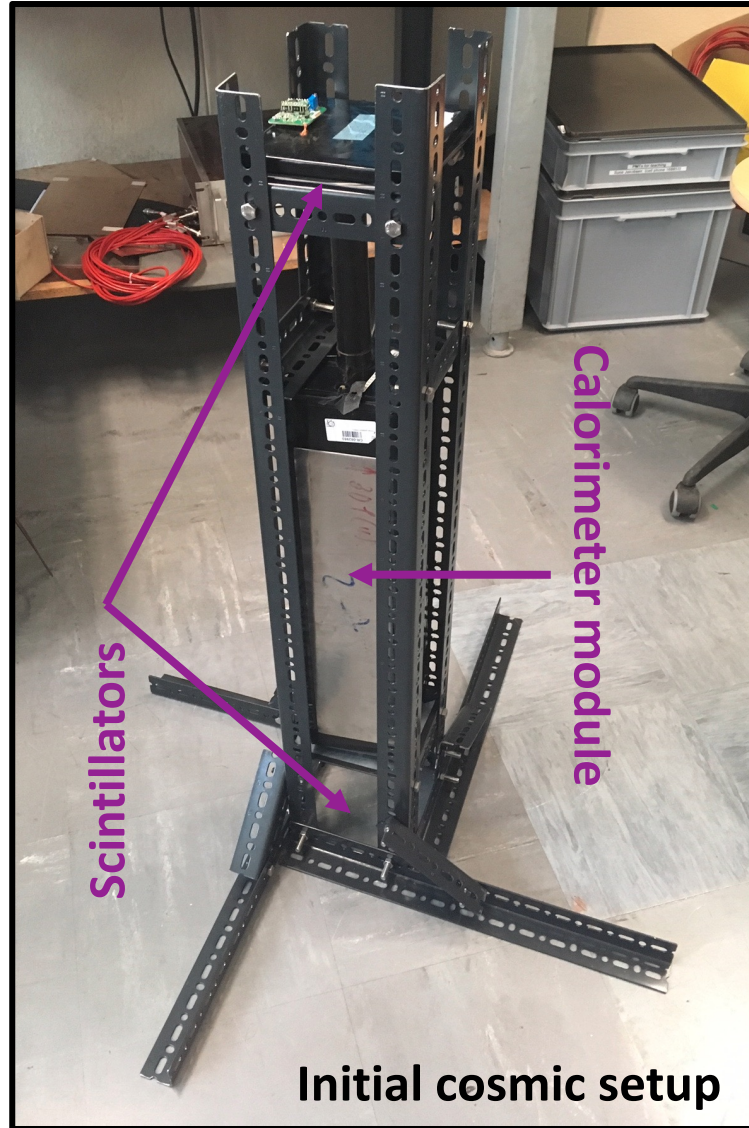
- FASER uses 4 LHCb spare outer ECAL modules
 - 25 radiation lengths long
 - Lead/scintillator calorimeter
- Energy resolution $\sim 1\%$ for TeV deposits
 - No longitudinal shower information
- Provides triggering capability
- Read out with PMTs and CAEN digitizer



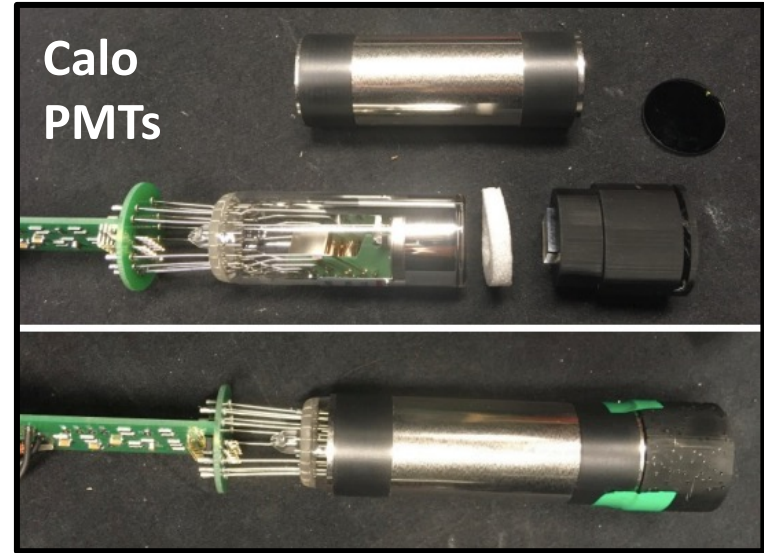
Calorimeter



~10 ns rise time

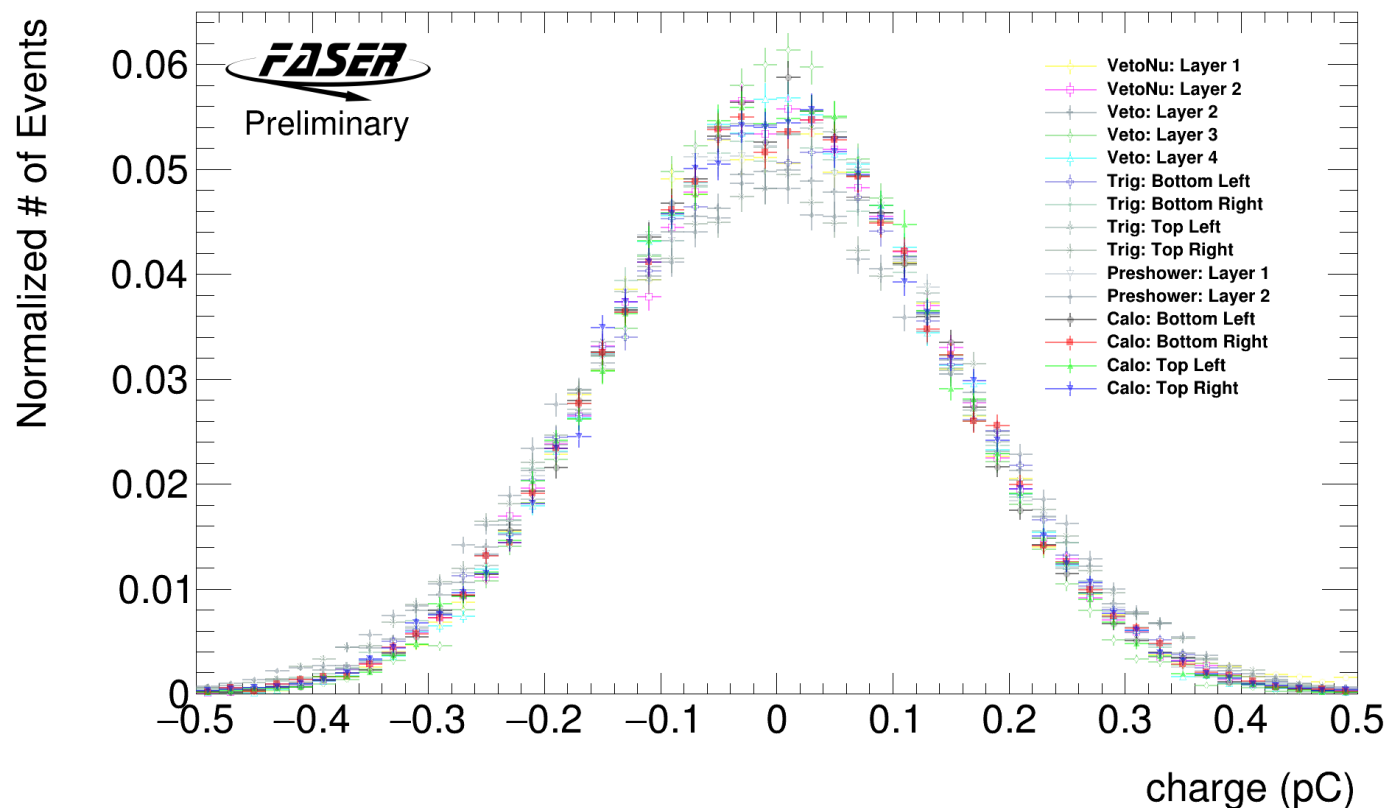


Initial cosmic setup



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.

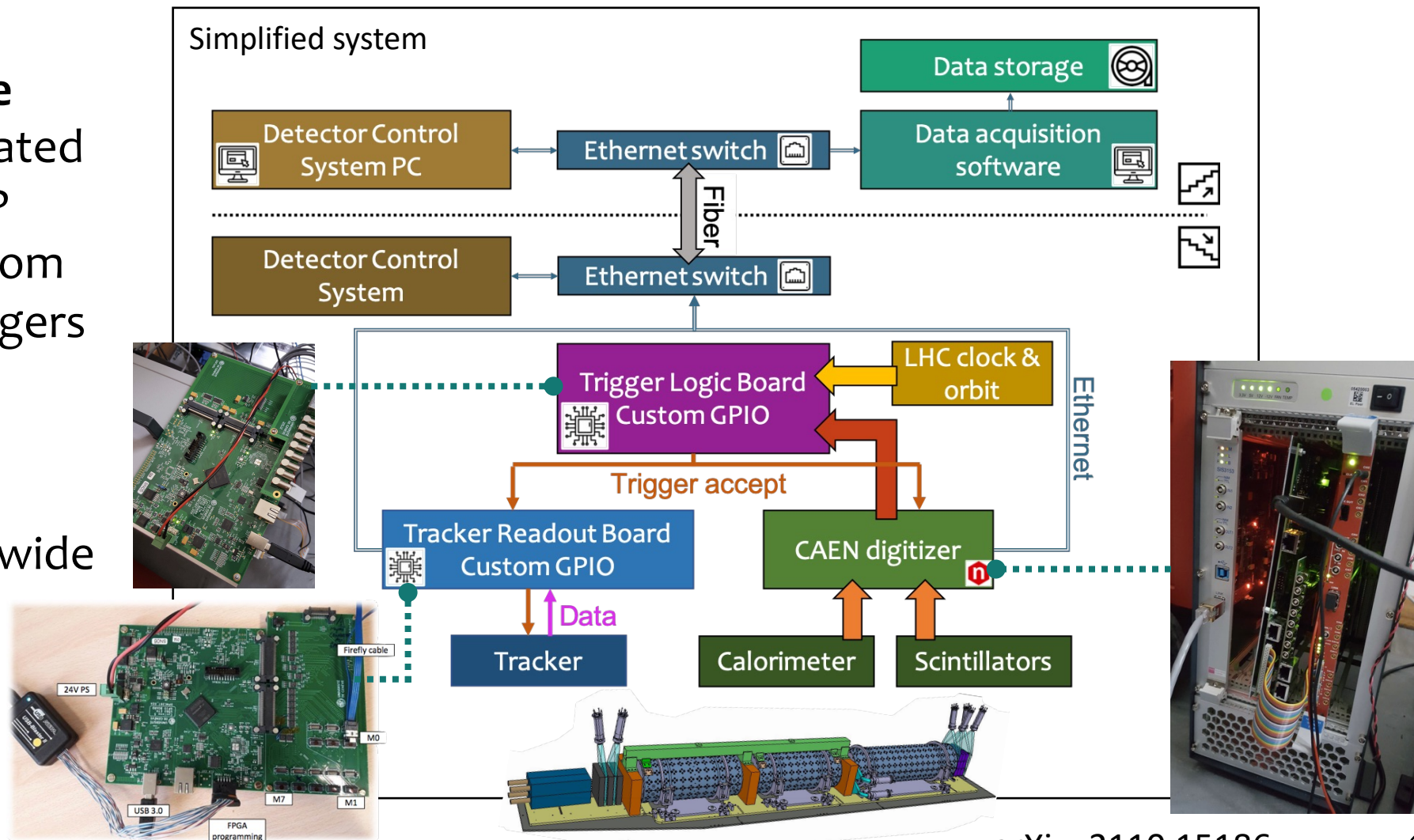


TRIGGER & DATA ACQUISITION

- 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 ($\sim 1 \mu\text{s}$)

- All TDAQ electronics are placed in T12





Trigger & Data acquisition

The screenshot shows the 'Monitoring Link' DAQ software interface. It features a 'Configuration' panel with a list of JSON files, a 'CONTROLS' panel with 'INITIALISE', 'START', 'STOP', and 'SHUTDOWN' buttons, and a 'RUN INFORMATION' table. The 'RUN INFORMATION' table shows the following data:

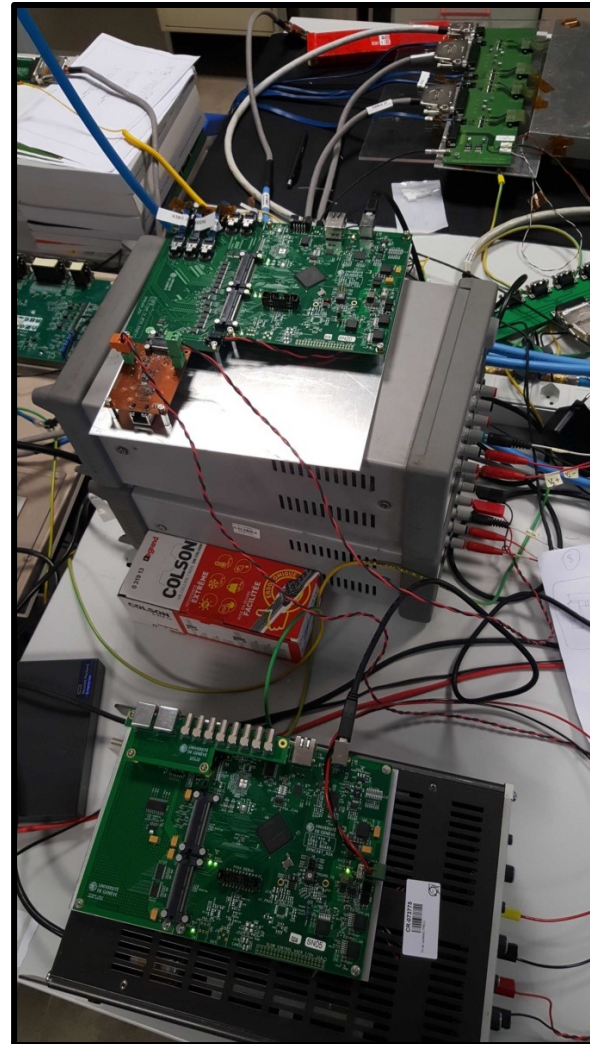
Run	number: 100	Starting Time: 8/23/2019 18:35:41
Physics	573 events	21 Hz
Monitoring	35 events	1 Hz
Calibration	0 events	0 Hz

Below the table is a line graph of 'PhysicsRate' over time. To the right is a 'STATUS AND SETTINGS' table:

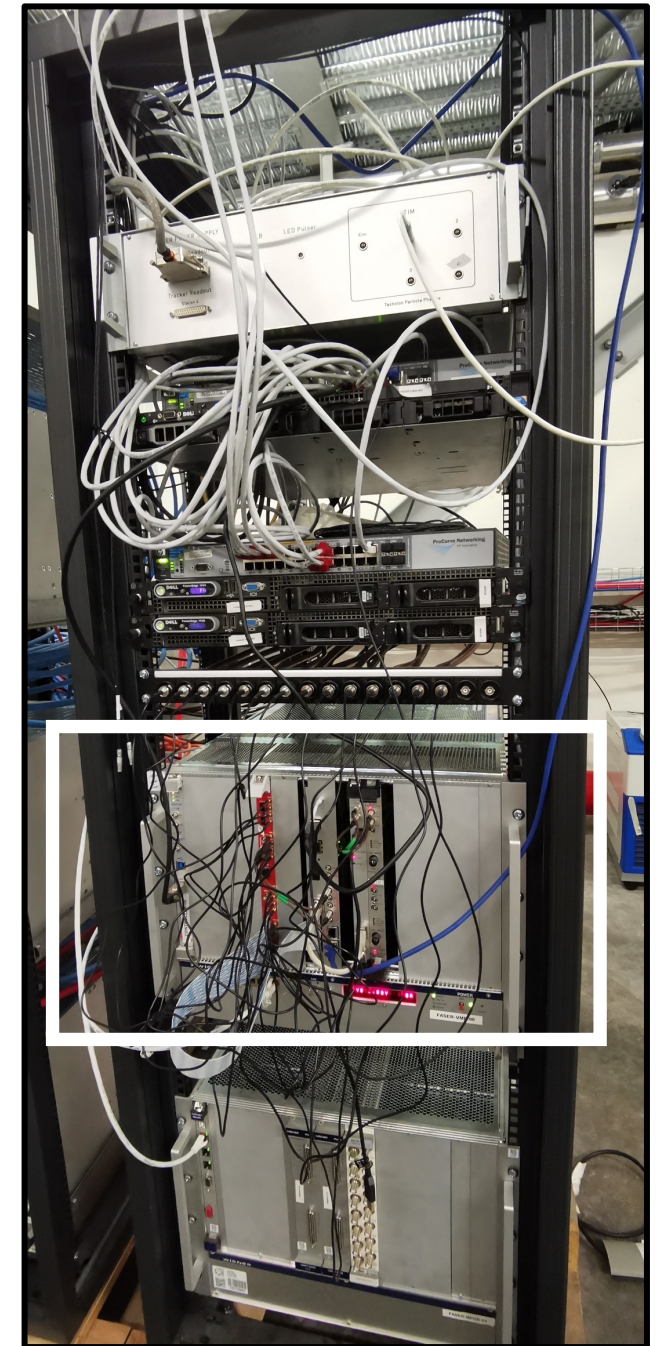
Component	CONFIG	LOG	INFO	RUN
triggergenerator	CONFIG	LOG	INFO	RUN
frontendemulator01	CONFIG	LOG	INFO	RUN
frontendemulator02	CONFIG	LOG	INFO	RUN
frontendreceiver01	CONFIG	LOG	INFO	RUN
frontendreceiver02	CONFIG	LOG	INFO	RUN
eventbuilder01	CONFIG	LOG	INFO	RUN
datalogger01	CONFIG	LOG	INFO	RUN
trackermonitor01	CONFIG	LOG	INFO	RUN
tibmonitor01	CONFIG	LOG	INFO	RUN
eventmonitor01	CONFIG	LOG	INFO	RUN

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 ($\sim 1 \mu\text{s}$)
- All TDAQ electronics will be placed in TI12

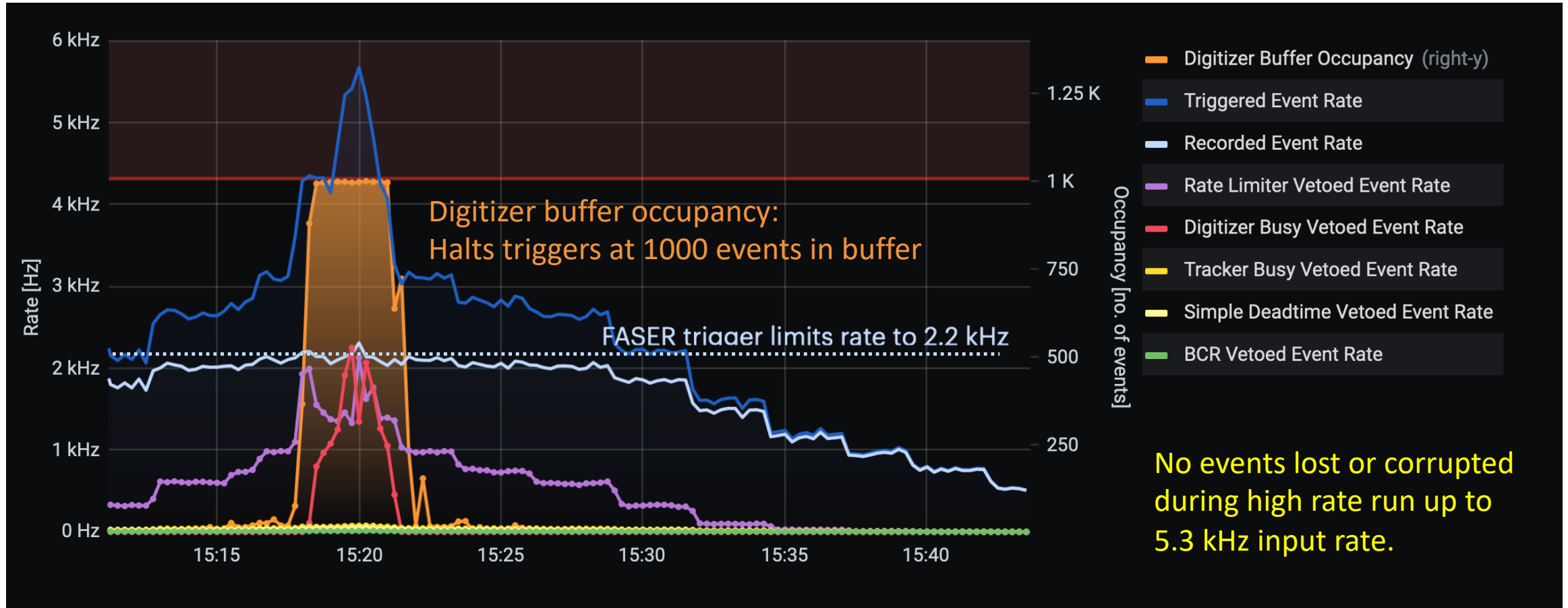


All boards connected together for tests

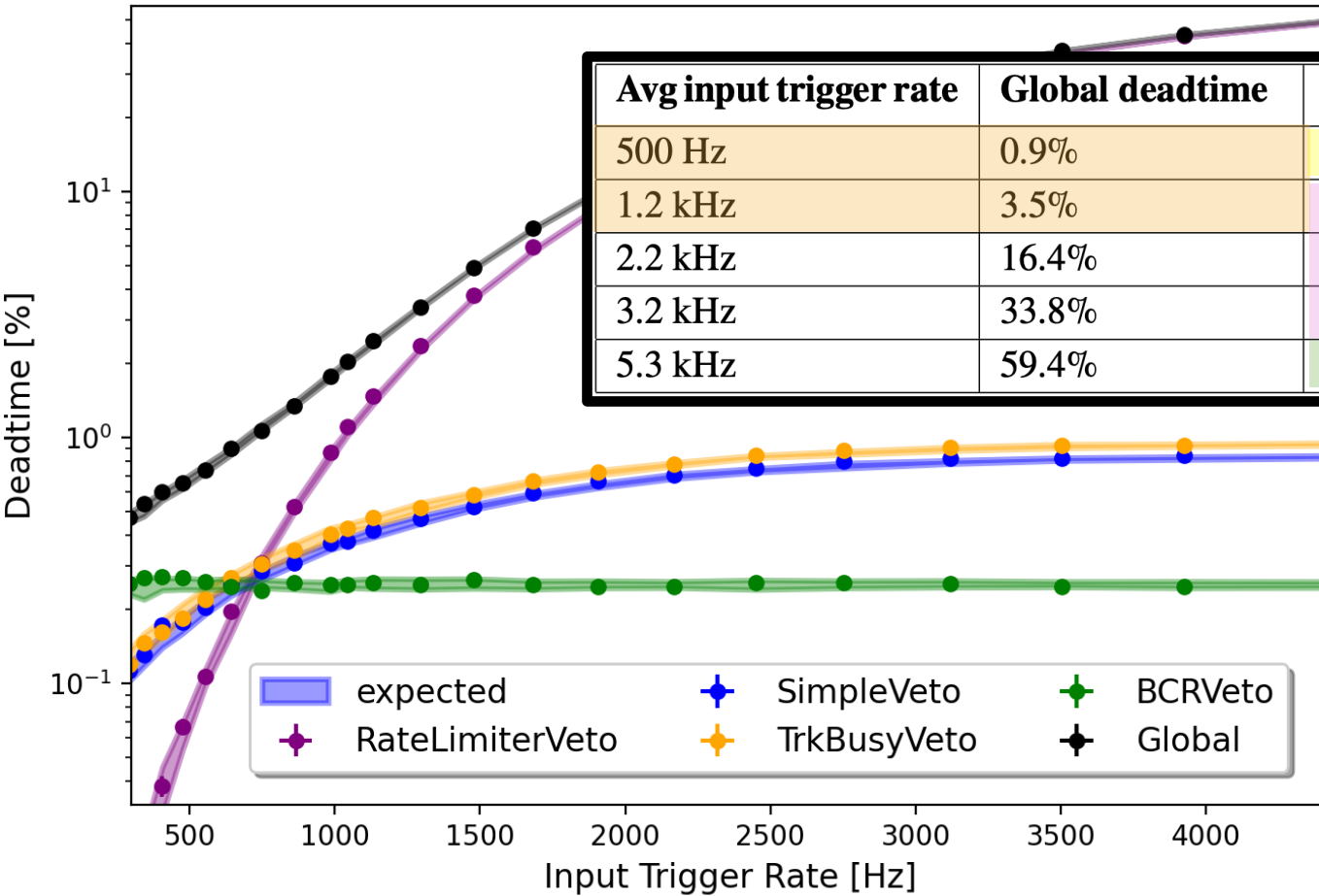


TDAQ boards in the final VME crate

High rate tests



Precise deadtime measurements



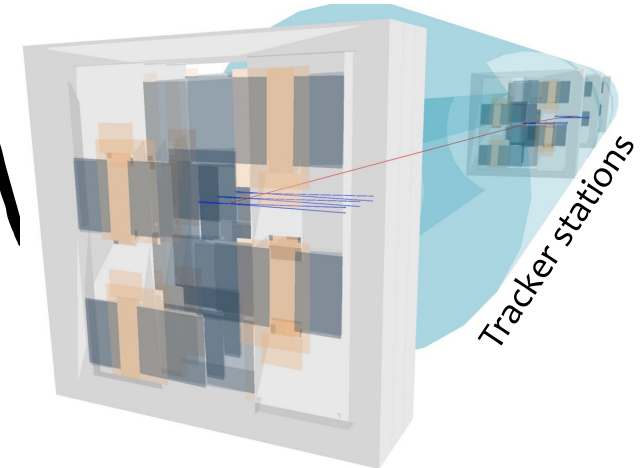
Avg input trigger rate	Global deadtime	Max deadtime source	Data throughput
500 Hz	0.9%	tracker	10 MBytes/s
1.2 kHz	3.5%	rate limiter	26 MBytes/s
2.2 kHz	16.4%	rate limiter	47 MBytes/s
3.2 kHz	33.8%	rate limiter	47 MBytes/s
5.3 kHz	59.4%	digitizer	47 MBytes/s

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 %

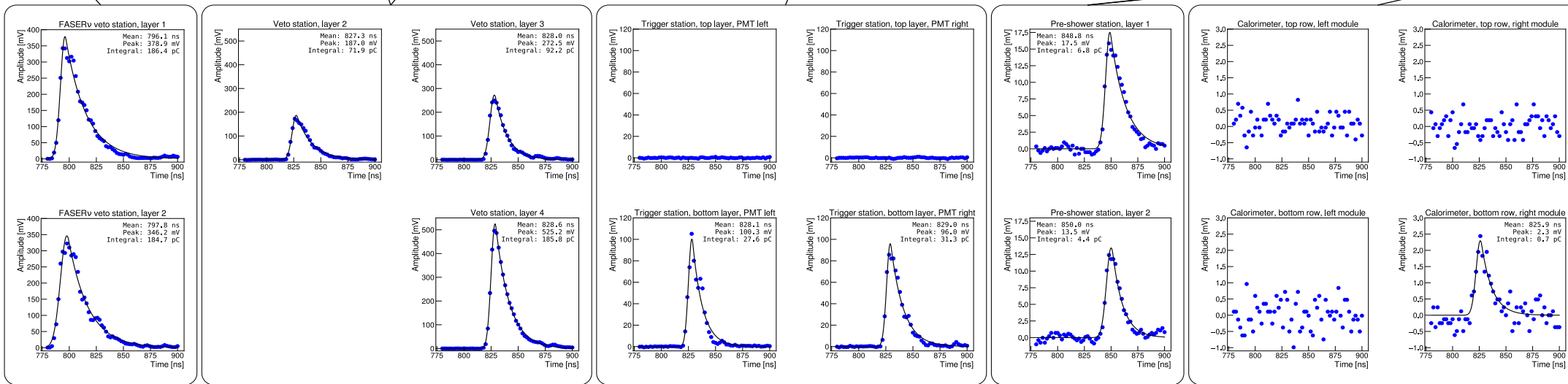
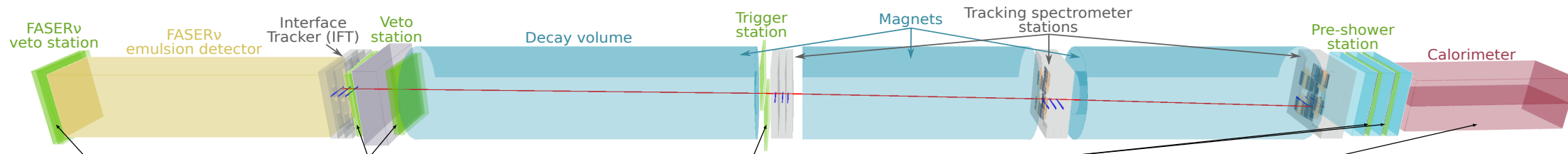
EXAMPLE TYPICAL EVENT: MUON



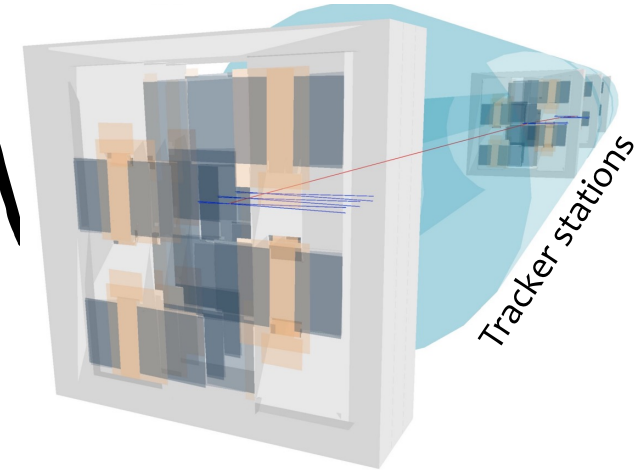
Run 8336
Event 1477982
2022-08-23 01:46:15

Collision event with muon traversing FASER

← To ATLAS IP



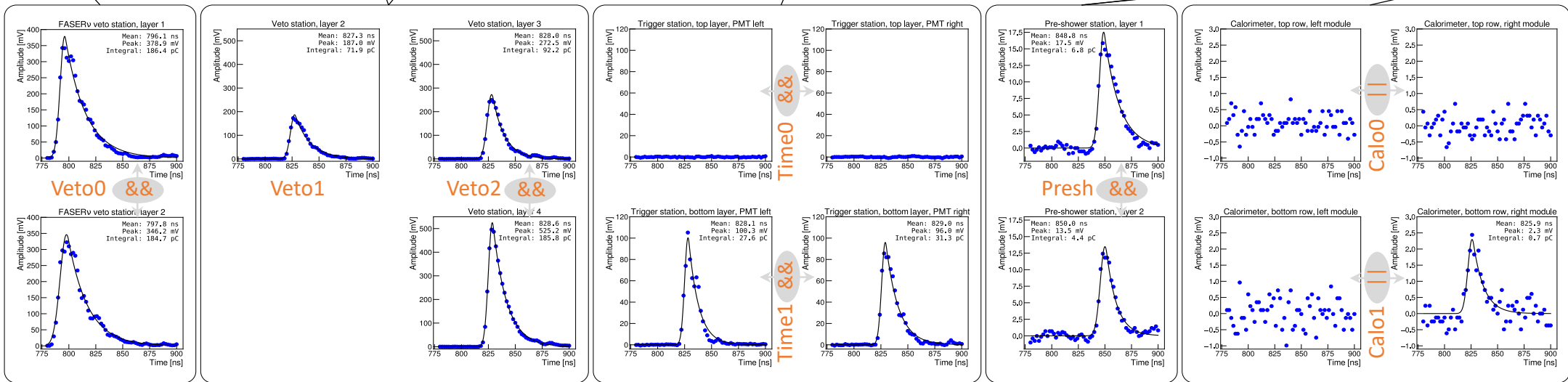
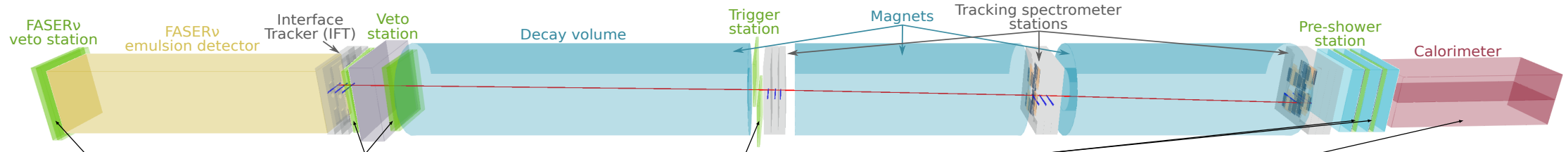
EXAMPLE TYPICAL EVENT: MUON



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

Collision event with muon traversing FASER

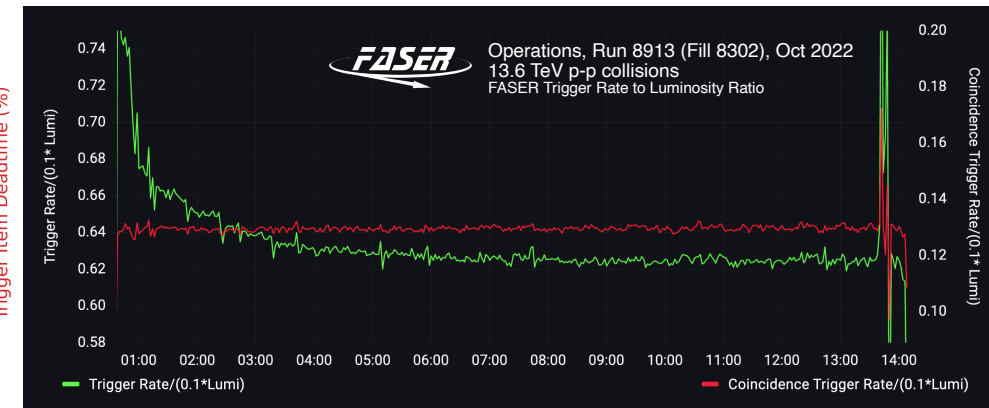
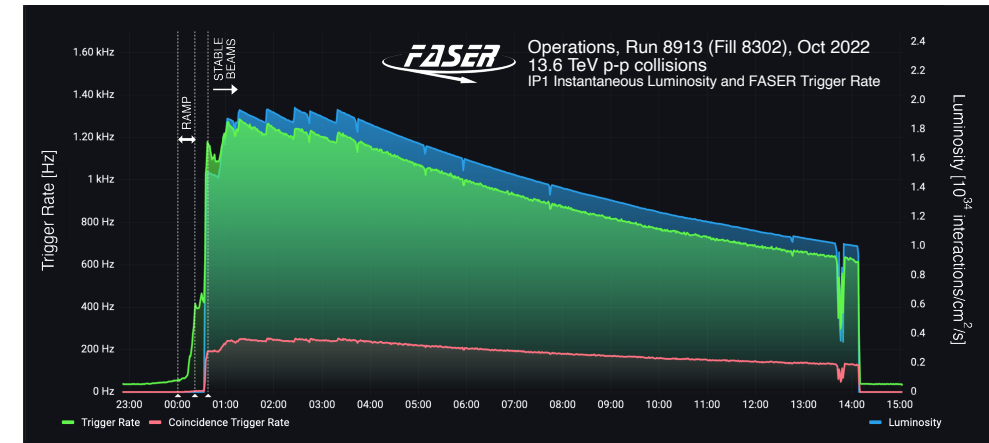
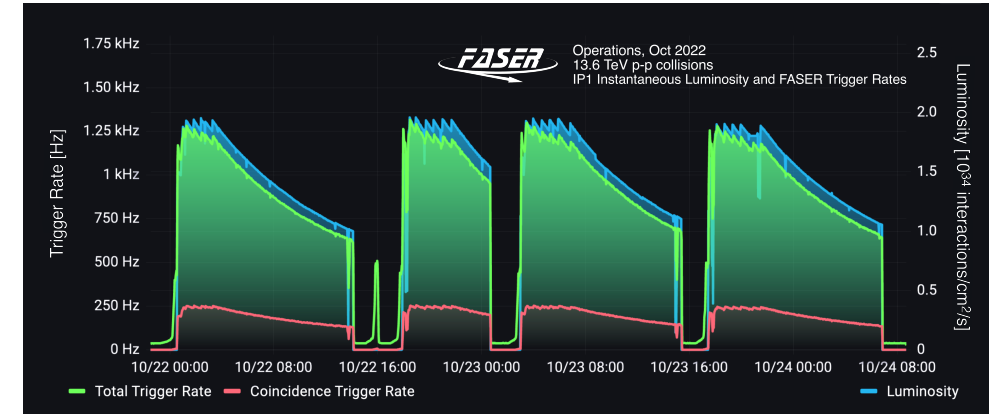
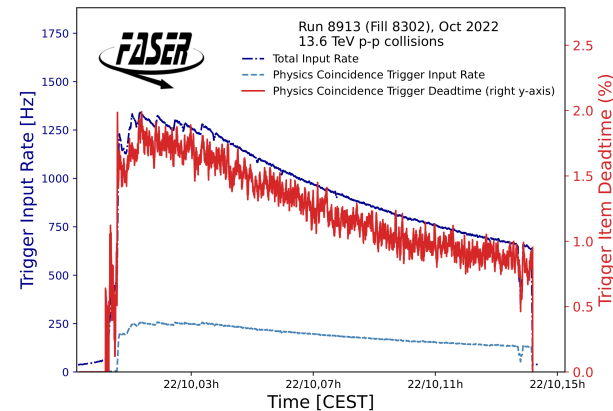
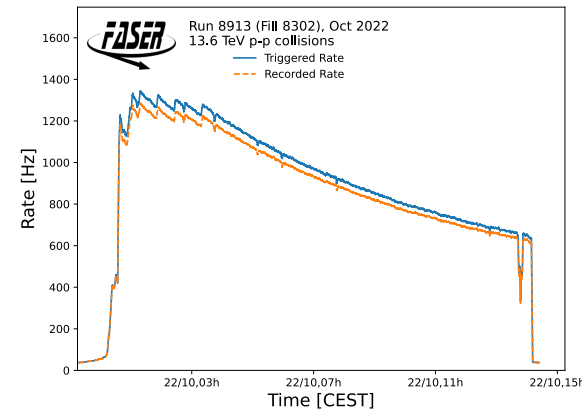
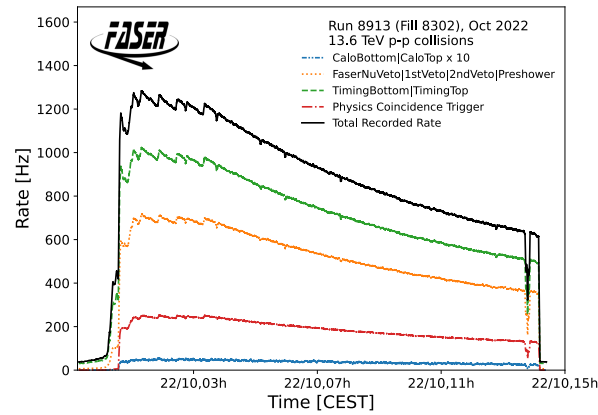
← To ATLAS IP



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

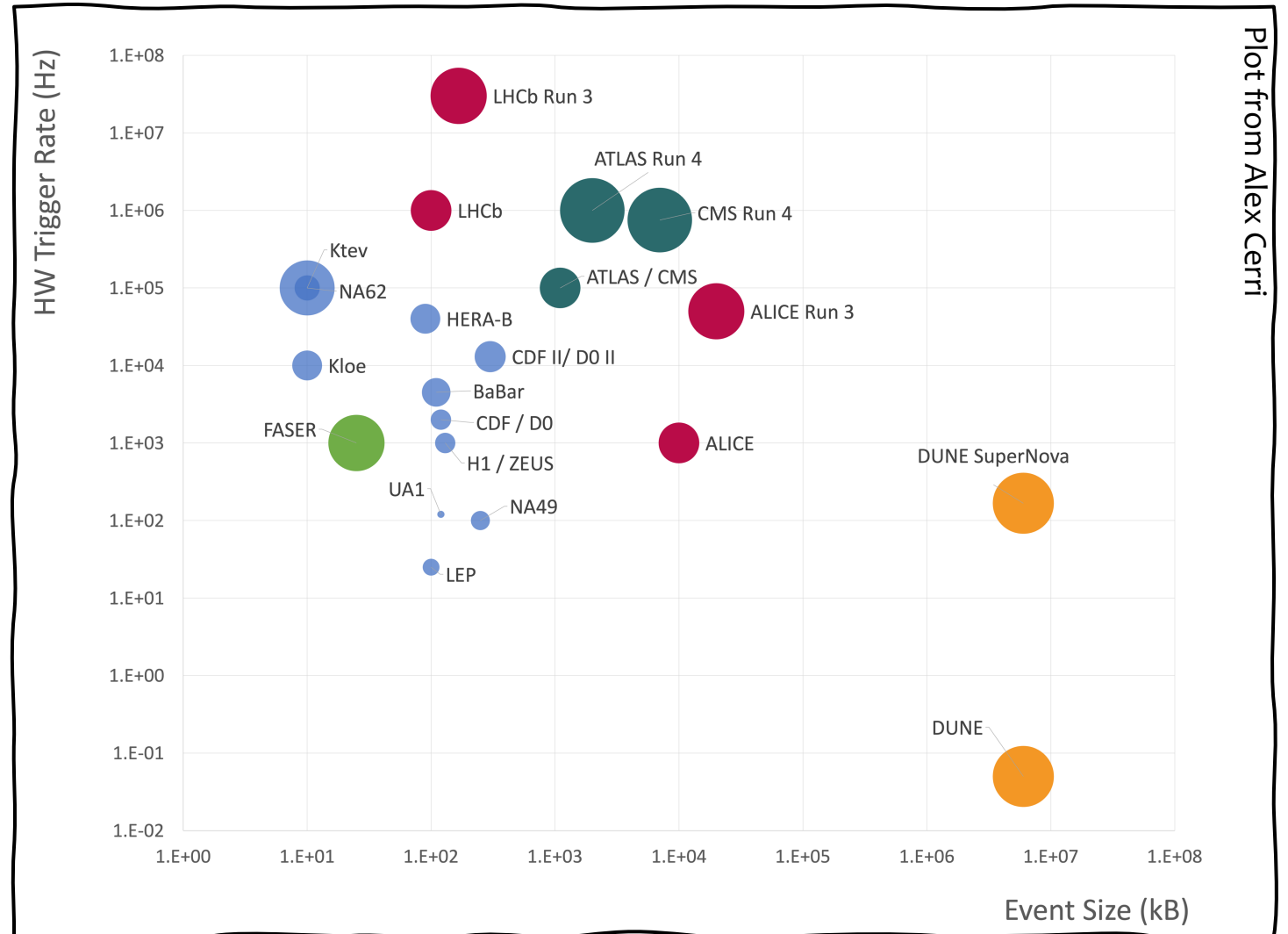
TDAQ OPS

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.



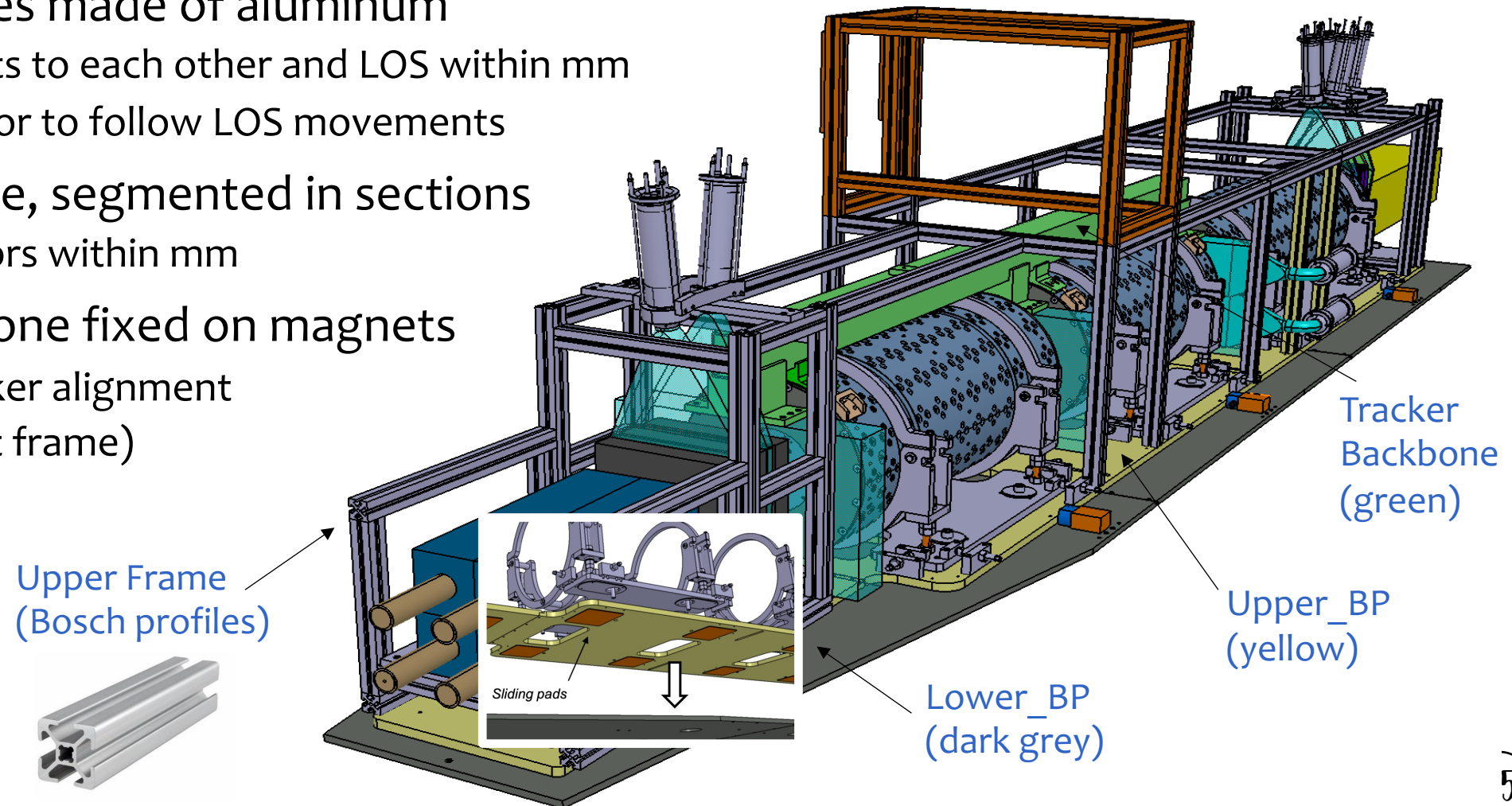
...WHY THIS ARCHITECTURE?

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



DETECTOR SUPPORT STRUCTURE

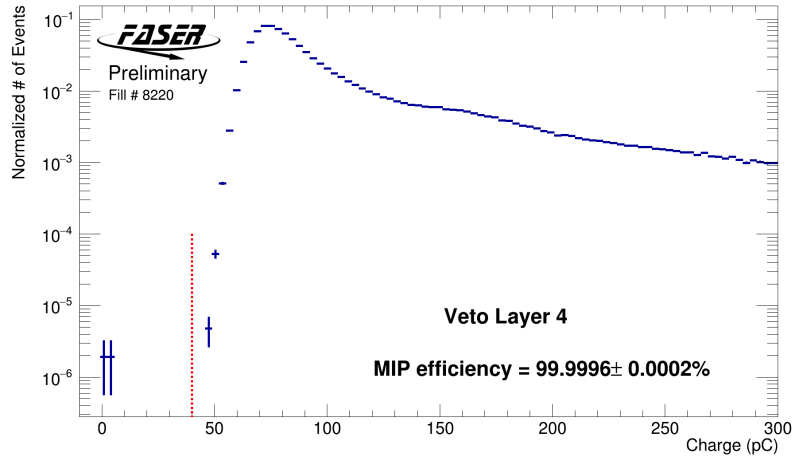
- Two base-plates made of aluminum
 - Align magnets to each other and LOS within mm
 - Allow detector to follow LOS movements
- An upper frame, segmented in sections
 - Align detectors within mm
- Tracker backbone fixed on magnets
 - ensures tracker alignment ($<100 \mu\text{m}$ wrt frame)



PERFORMANCE ASSESSMENT

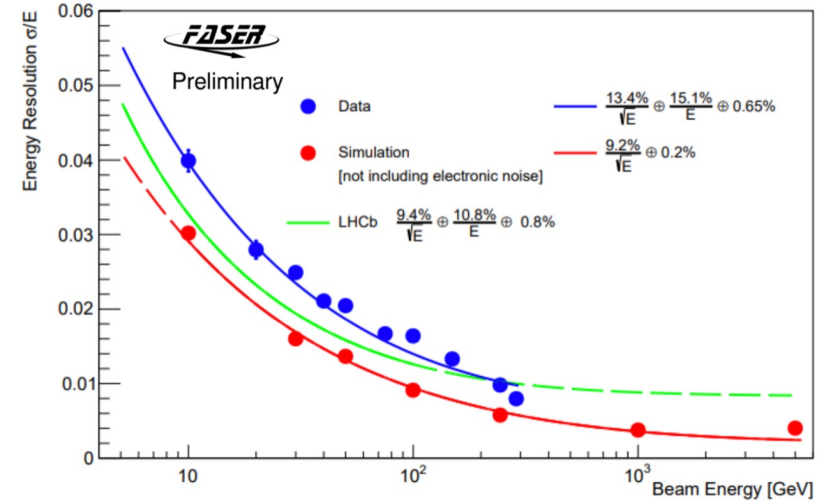
Veto layer charge distribution Efficiency > 99.99% per layer

VETO SCINTILLATORS



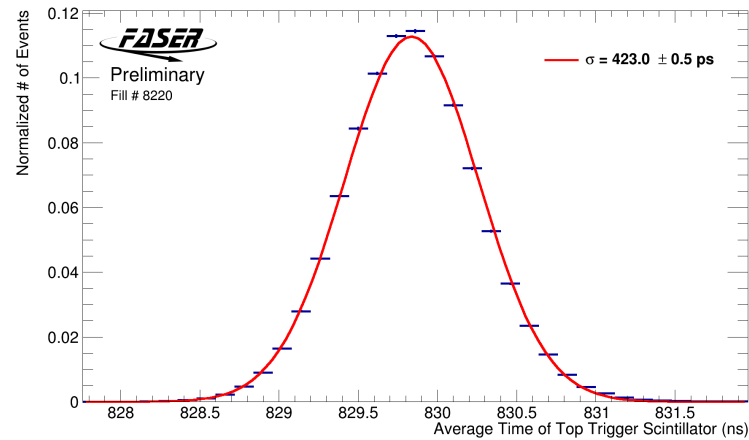
Calorimeter calibration at testbeam Resolution confirmed ~1% for high energy electrons

CALORIMETER



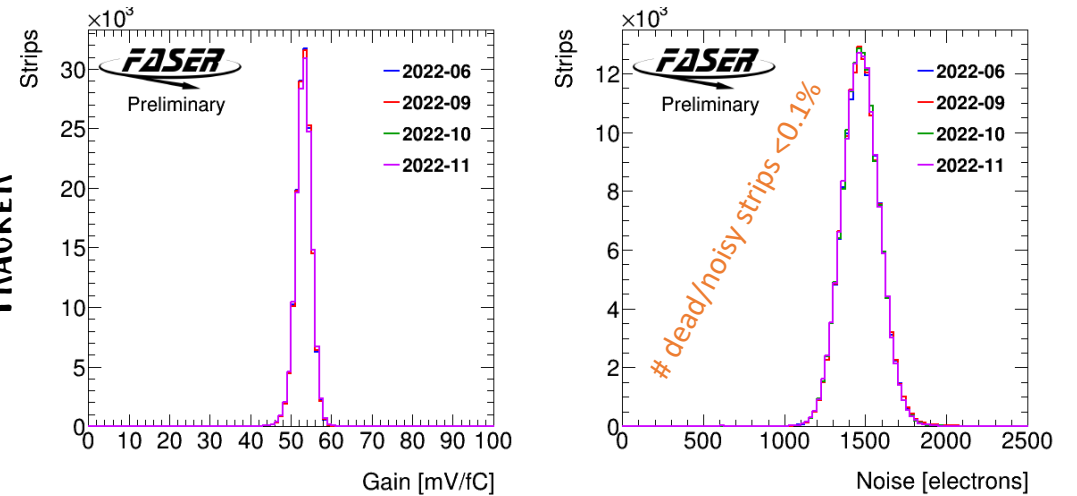
Timing distribution of top trigger scintillator Resolution < 0.5 ns

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:
 - high energy muons from IP
- With first data we see two extra background sources

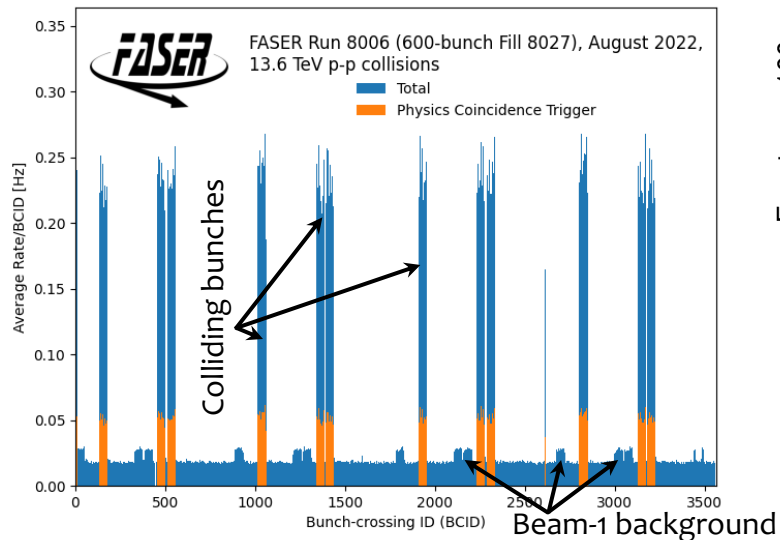
STUDYING BACKGROUNDS

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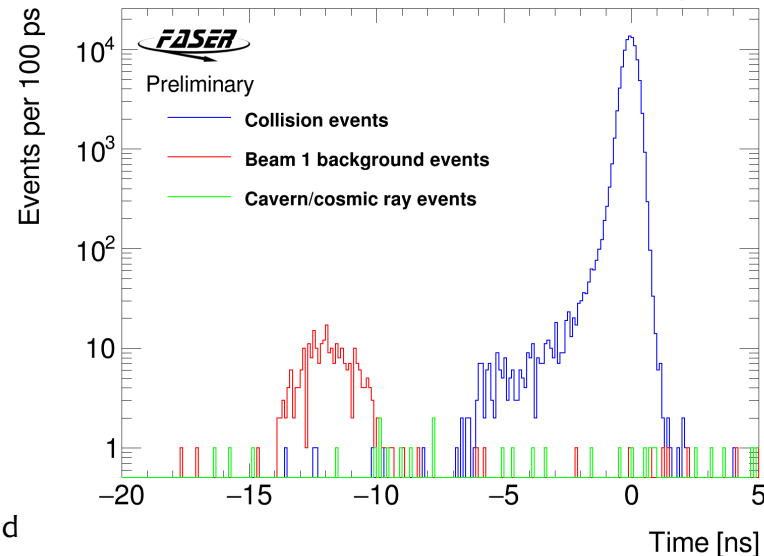
SOURCE A

- Caused by beam-1 on the way to ATLAS passing from the back of FASER
- Early by about $3.2 \mu\text{s}$ 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



STUDYING BACKGROUNDS

- Before data taking, expected dominant background source:
 - high energy muons from IP
- With first data we see two extra background sources

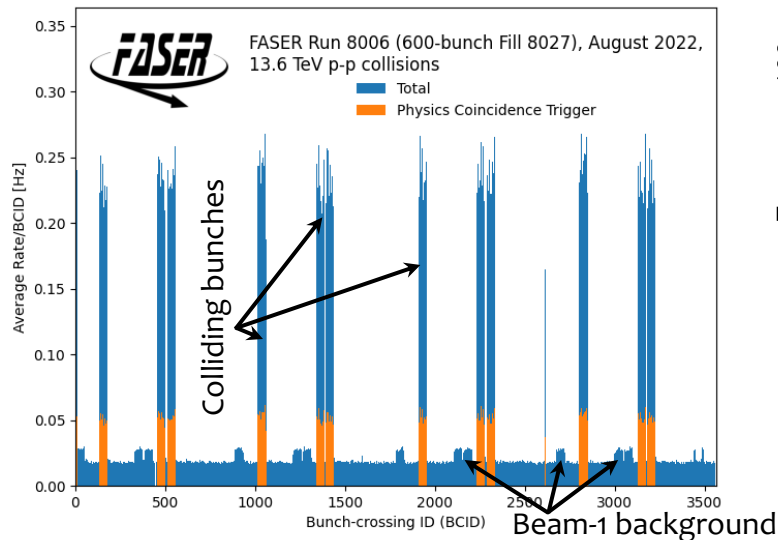
SOURCE B

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

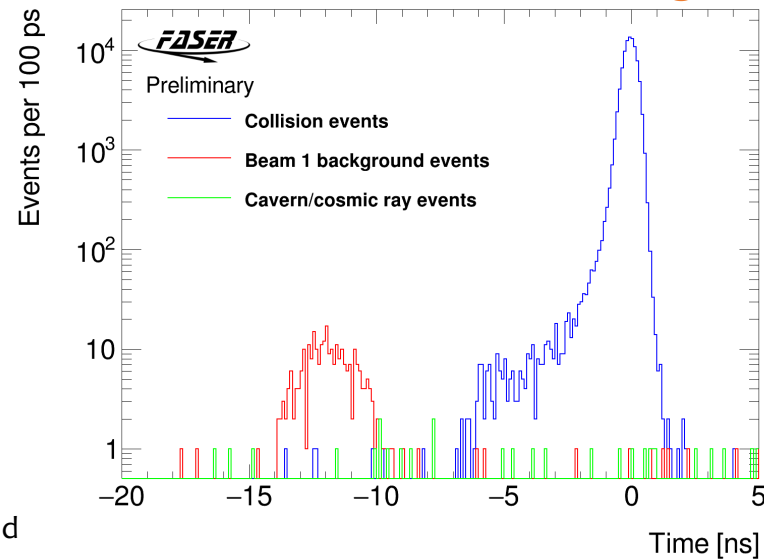
SOURCE A

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- Early by about $3.2 \mu\text{s}$ 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



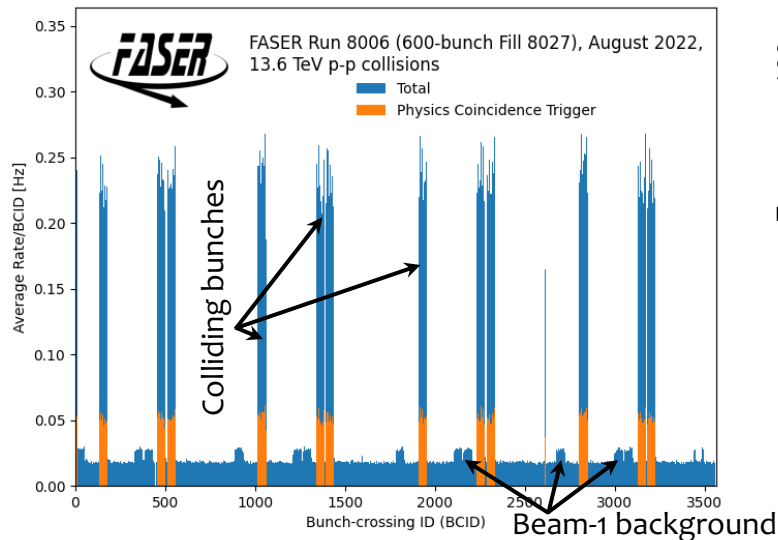
STUDYING BACKGROUNDS

- Before data taking, expected dominant background source:
 - high energy muons from IP
- With first data we see two extra background sources

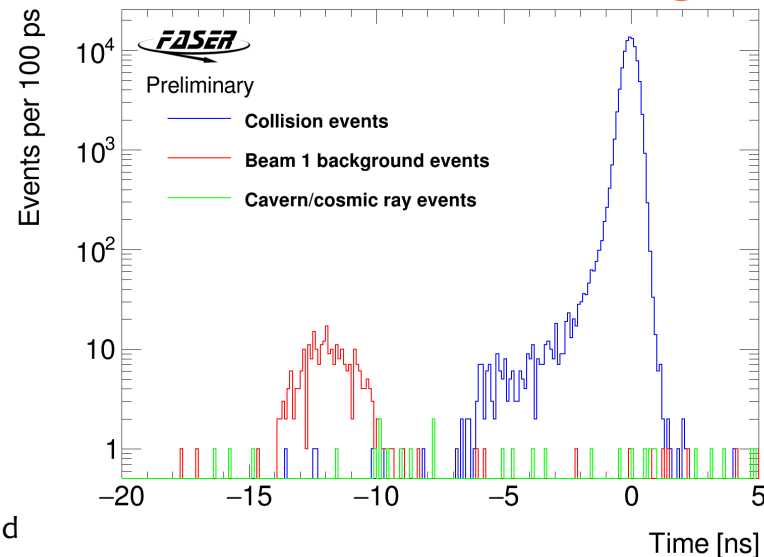
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- Early by about $3.2 \mu\text{s}$ compared to particles from IP
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Calorimeter time separation of collision events and Beam-1 background

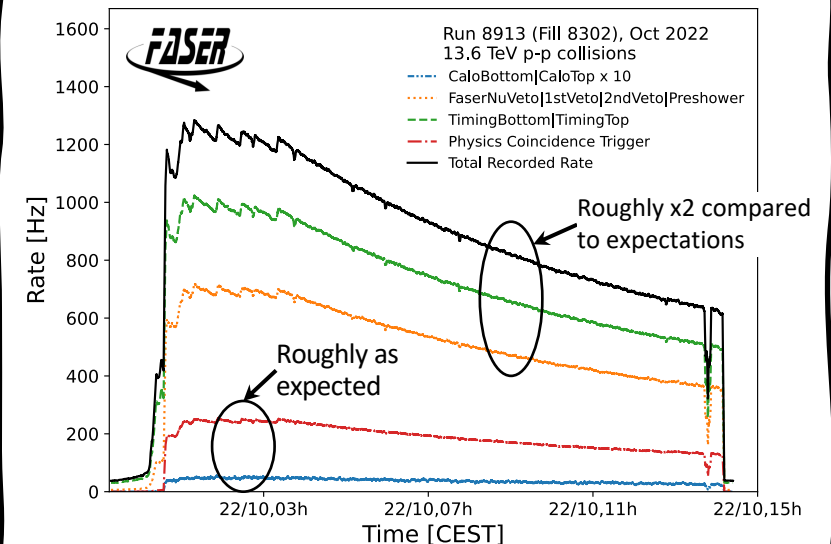


SOURCE B

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

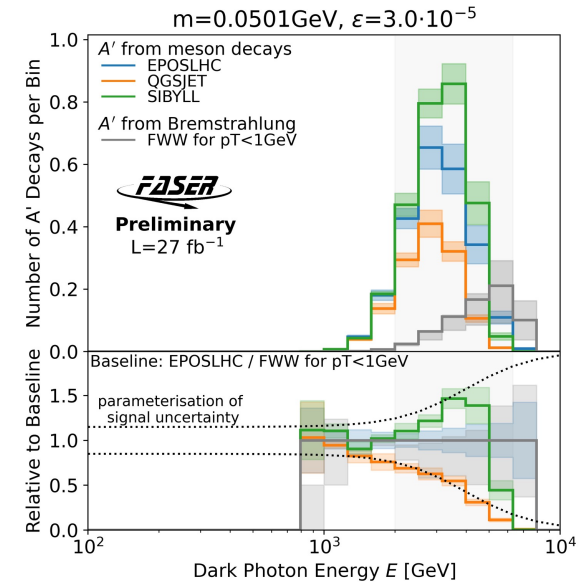
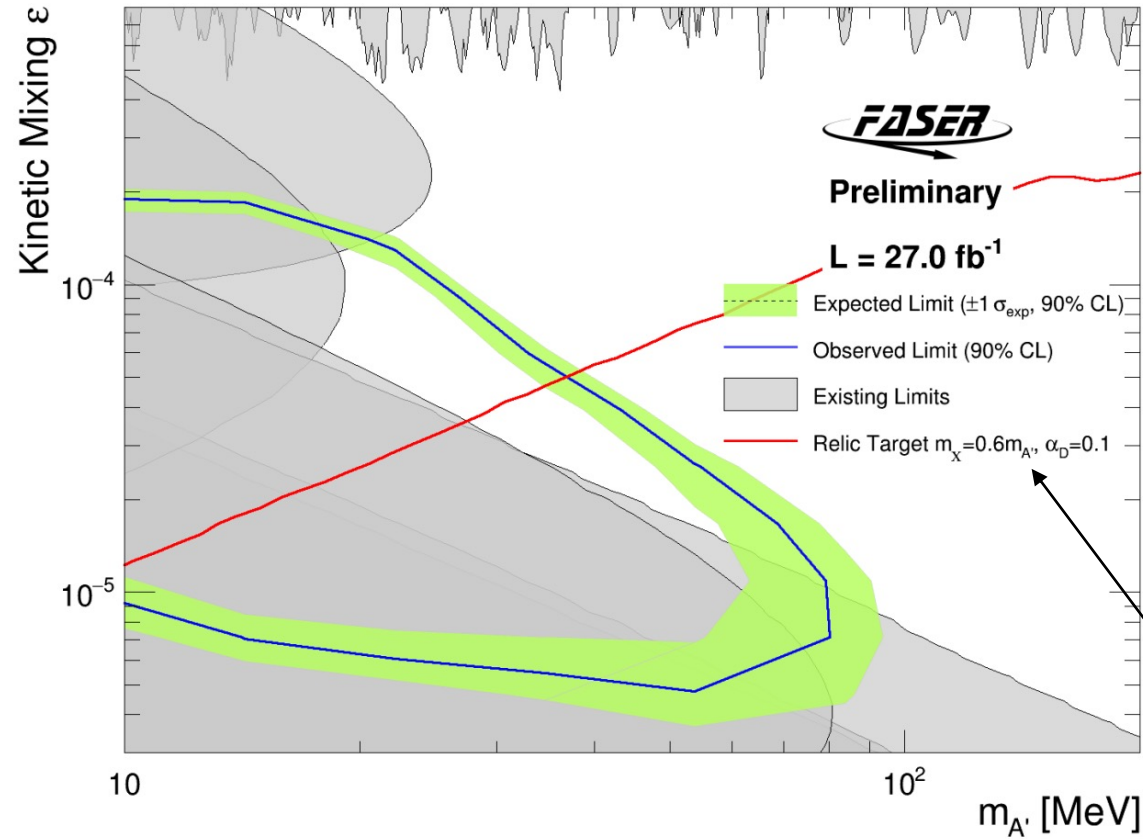
- Additional backgrounds give total trigger rate x2 than expected
- Rate of muons from IP roughly consistent with expectation
- Extra rate not problematic

FASER recorded rate per trigger item

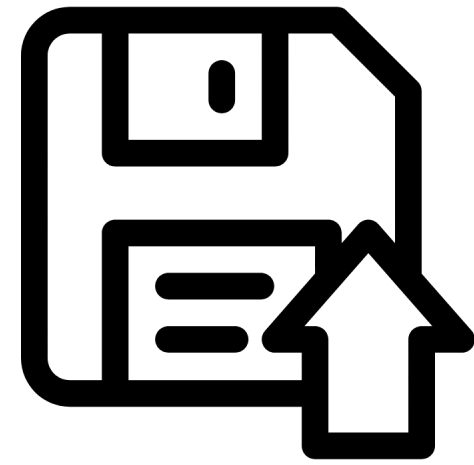


EXCLUSION REACH

On previously unexplored phase-space



- Parameters for which DM χ annihilates via $\chi\chi \rightarrow A' \rightarrow ff$
- Model dependent **line**, but region favoured by DM relic density



THE *FAZER* DETECTOR

Preshower upgrade

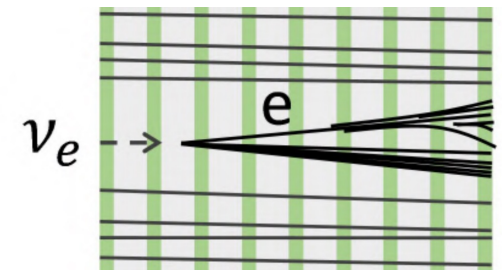
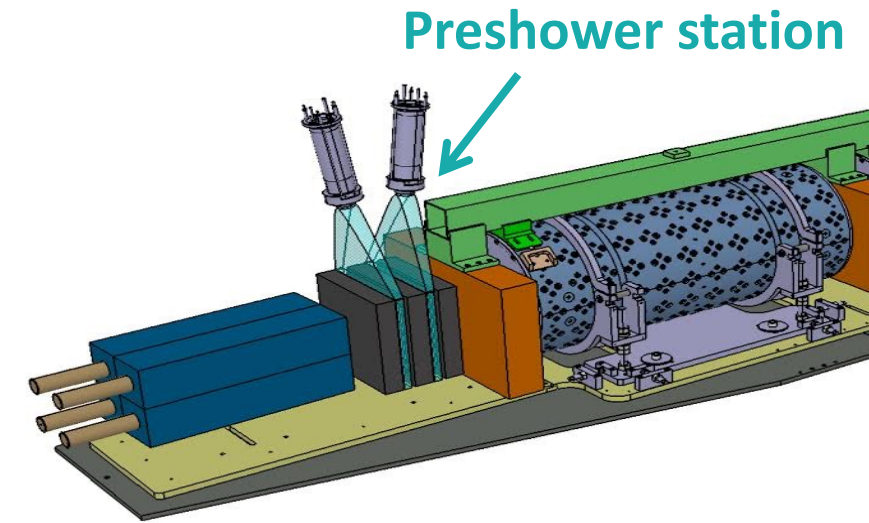
CURRENT DETECTOR LIMITATION

- **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.

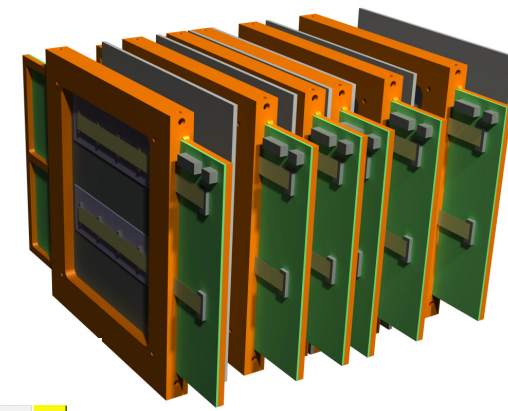
- **Limitations:**

- 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

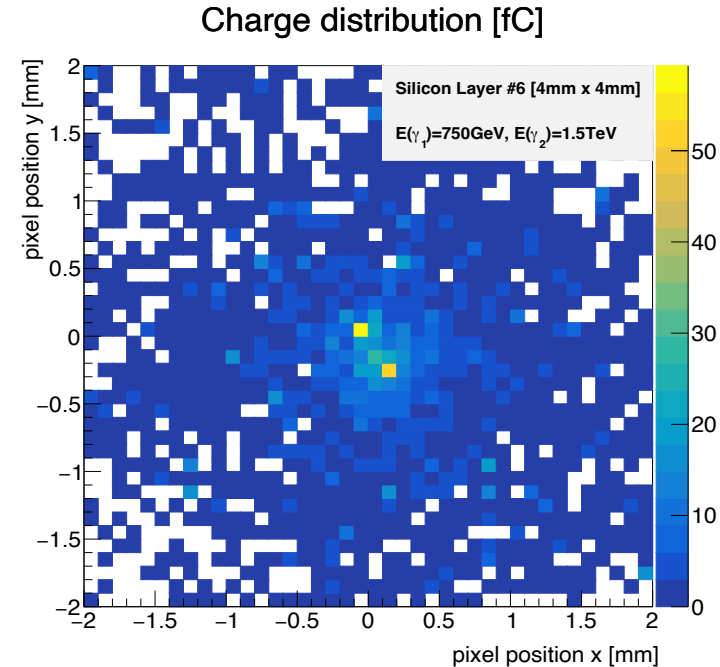
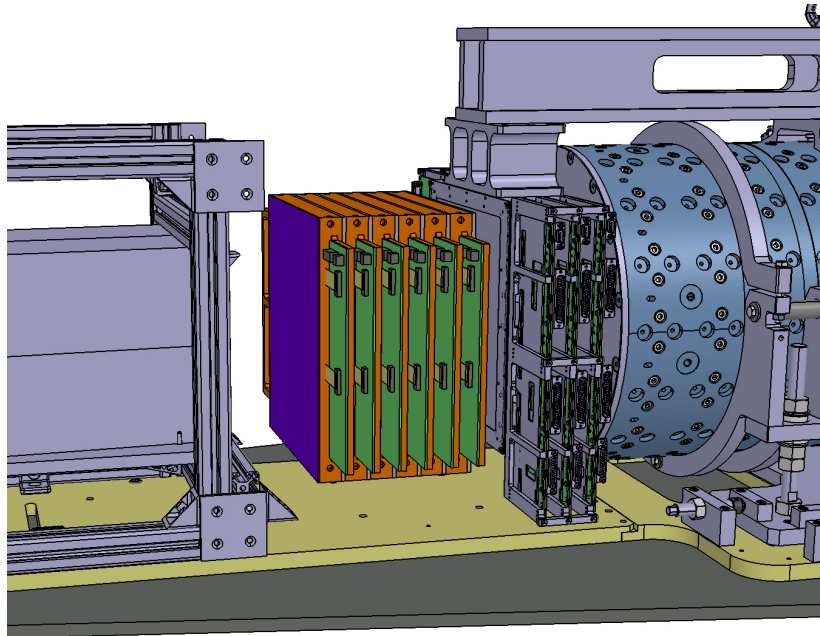


Cartoon of ν_e DIS
in FASERv

UPGRADE TO ENABLE $2-\gamma$ PHYSICS



- Existing pre-shower to be replaced with a high-resolution silicon pre-shower detector using monolithic pixel ASICs
 - hexagonal pixels of $65\ \mu\text{m}$ side

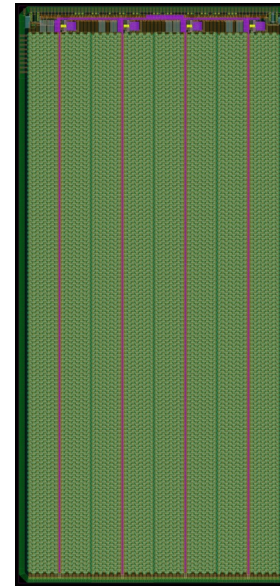
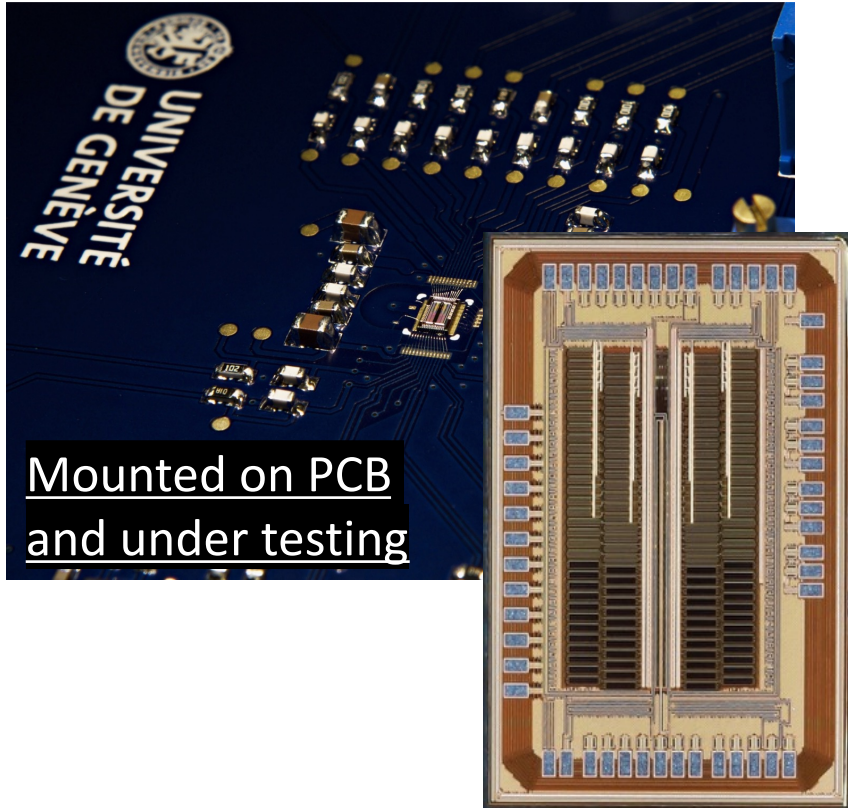


- Distance between two photons: $200\ \mu\text{m}$
- Distinguishable!

Detector to be used for
2024 & 2025 data taking
(70% of Run3 data)

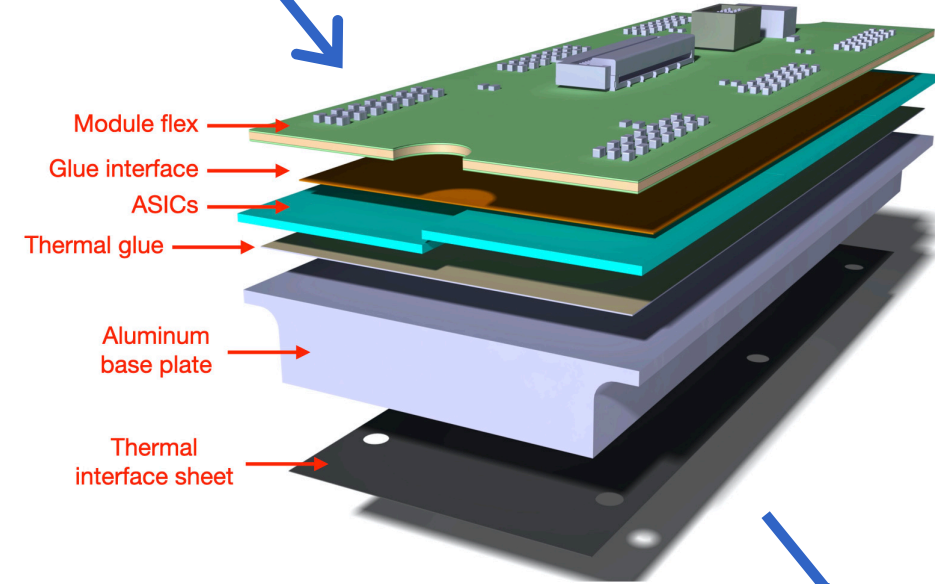
FROM PIXELS TO LAYERS OF MODULES

Prototype ASIC available end 2020

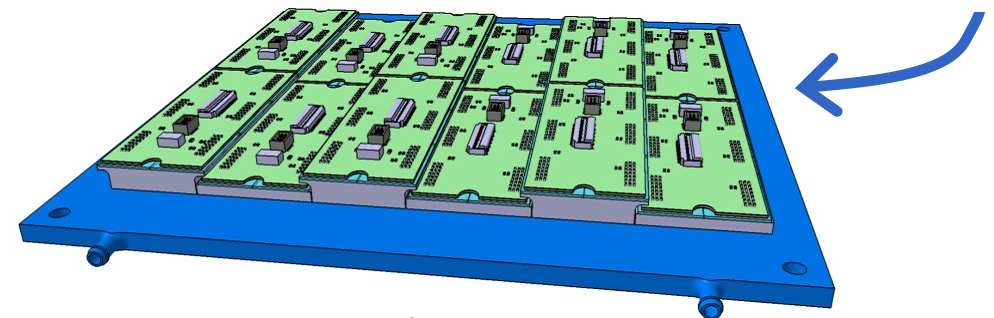


Pixel chips into sensor wafers

...into modules of pixels



...into layers of modules



Proposed layout of 1 layer with 12 modules.

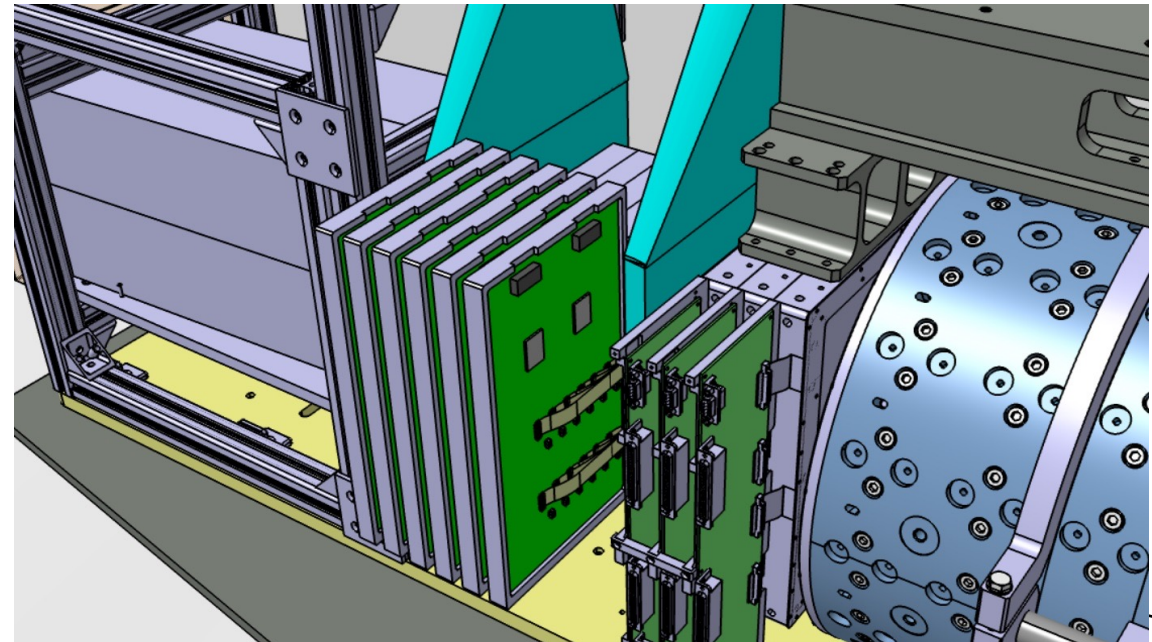
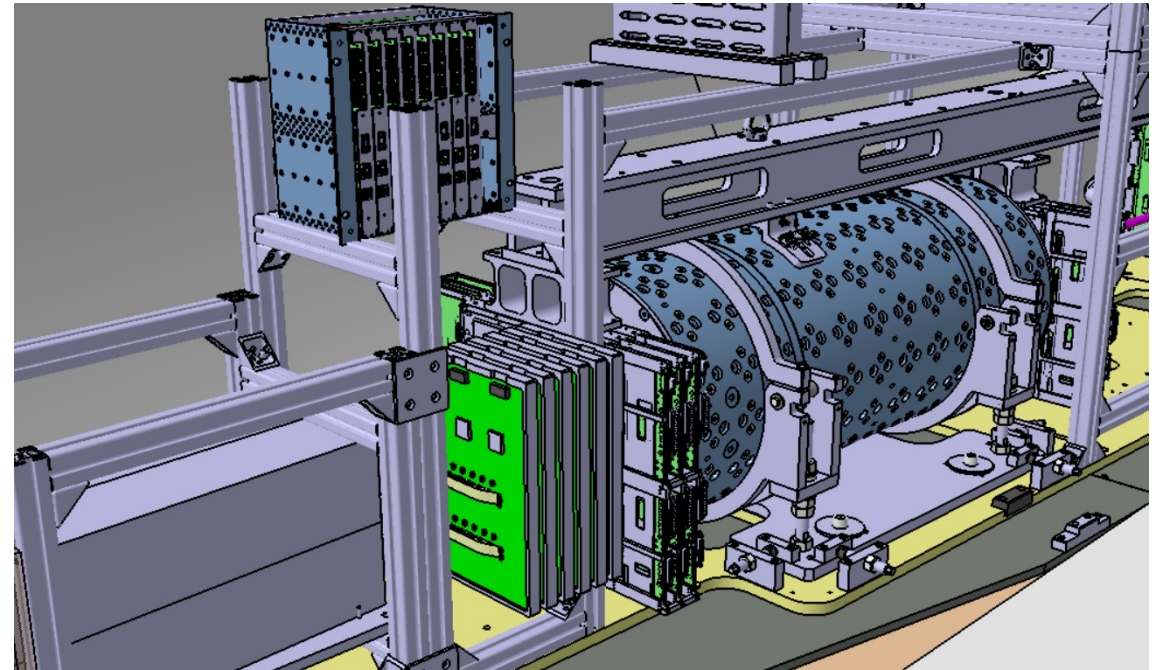
UPGRADED PRE-SHOWER

Status:

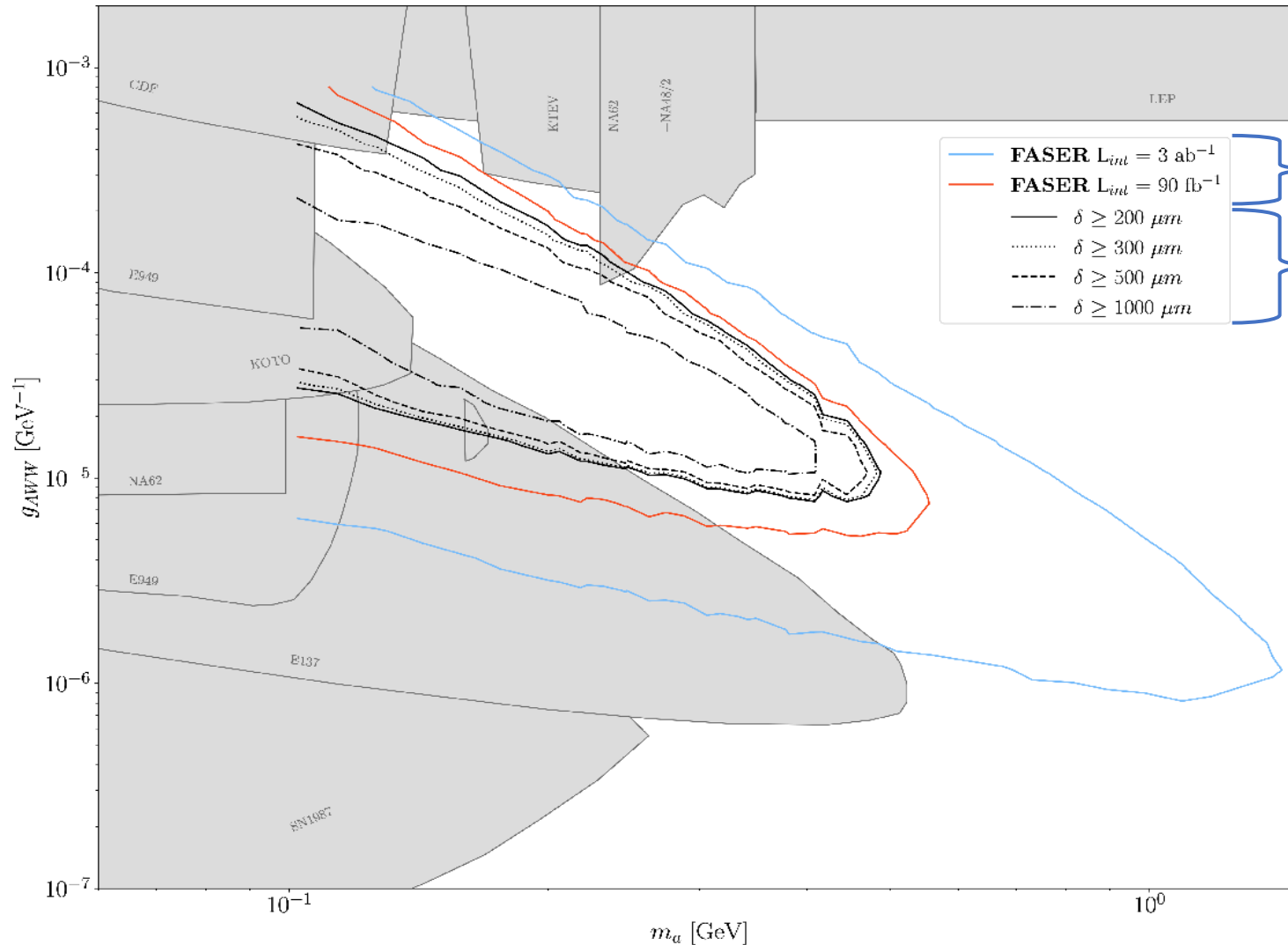
- Preparing the detailed technical proposal
- Pre-production ASICs in foundry, expected ~ March
- Design of modules, planes, mechanics, read-out in progress
- Simulation and reconstruction in progress

Plan:

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



REACH FOR ALPS



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

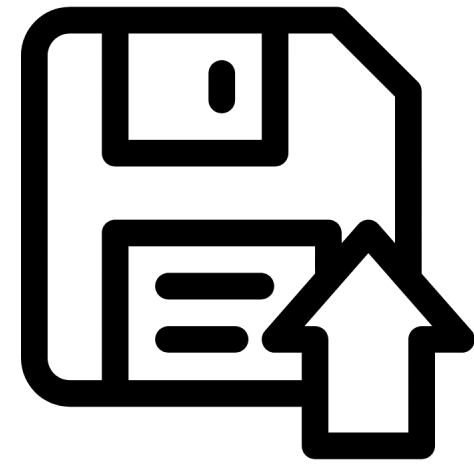
Ideal detector (100% efficiency)

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!

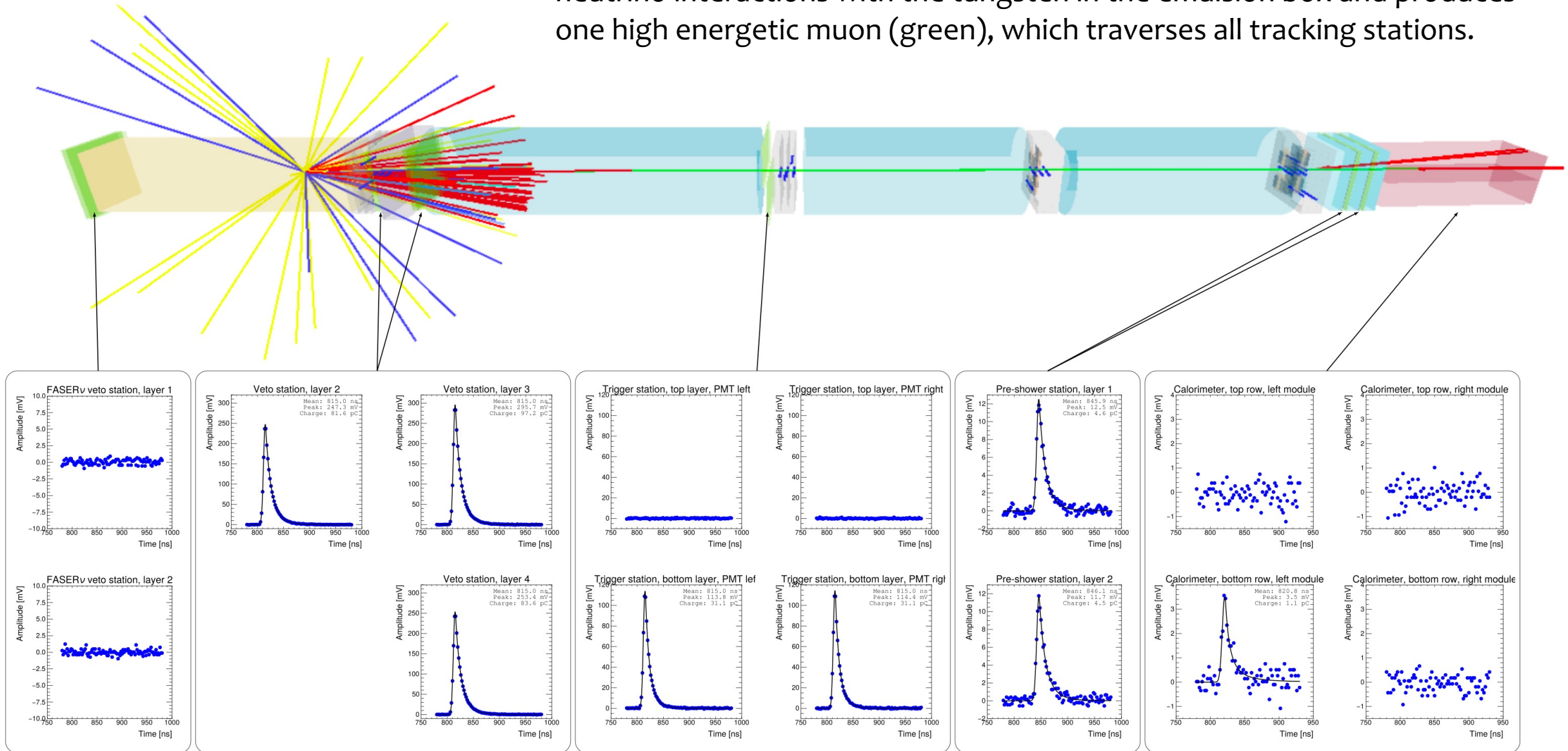
**Otherwise: Indistinguishable
 from background**



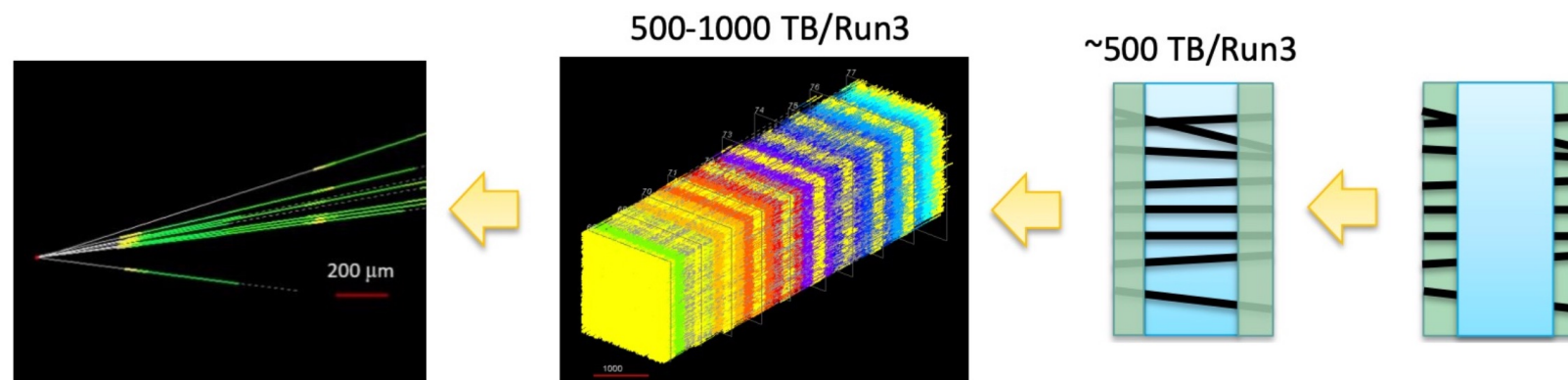
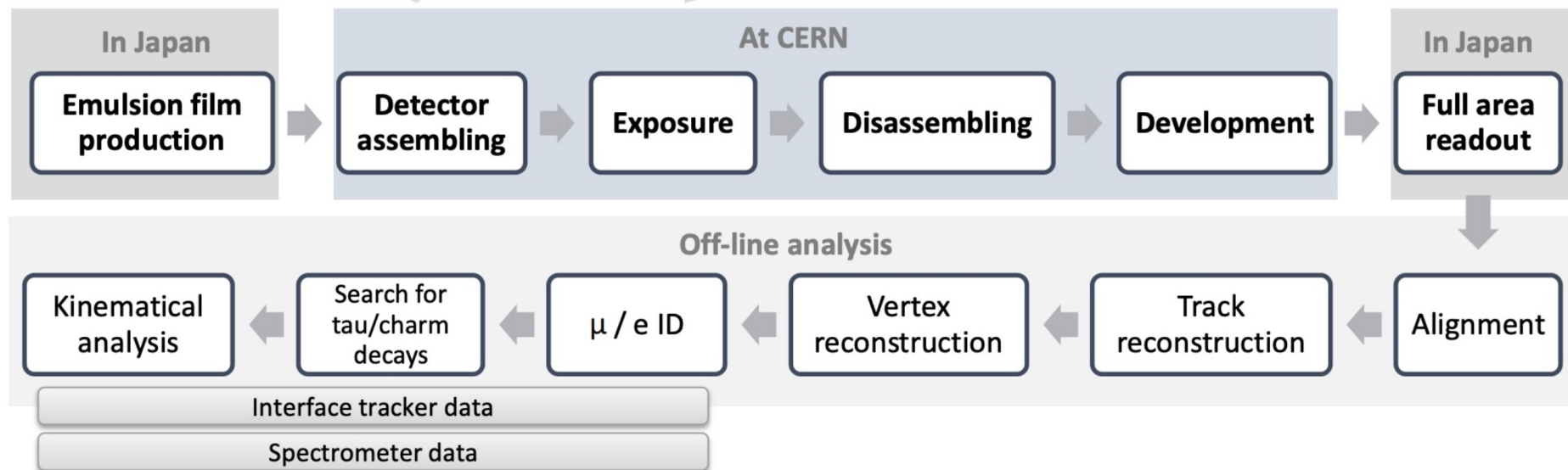
FAZER

FAZERmu

Event display for a typical charged current interaction where a muon neutrino interactions with the tungsten in the emulsion box and produces one high energetic muon (green), which traverses all tracking stations.



FASERv Workflow





EMULSION

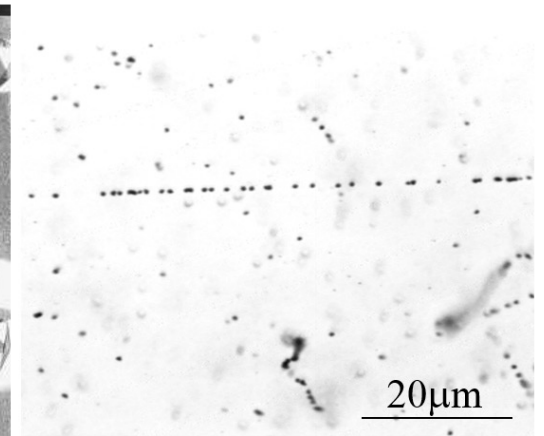
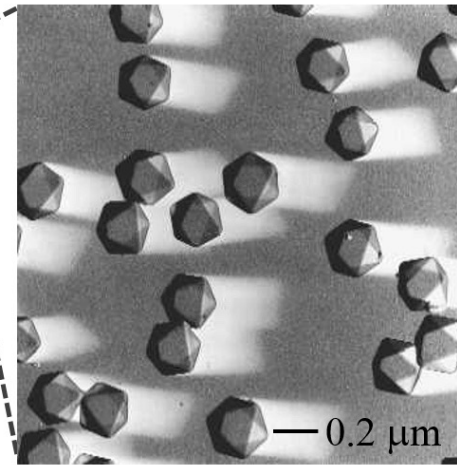
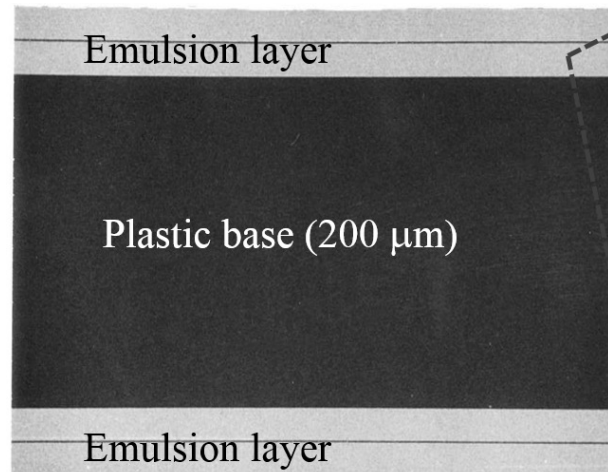


Photo of an emulsion film (left), its cross-sectional view (left center), electron microscope image of the silver halide crystals (right center), and a minimum ionising particle track from a 10 GeV/c π beam (right).

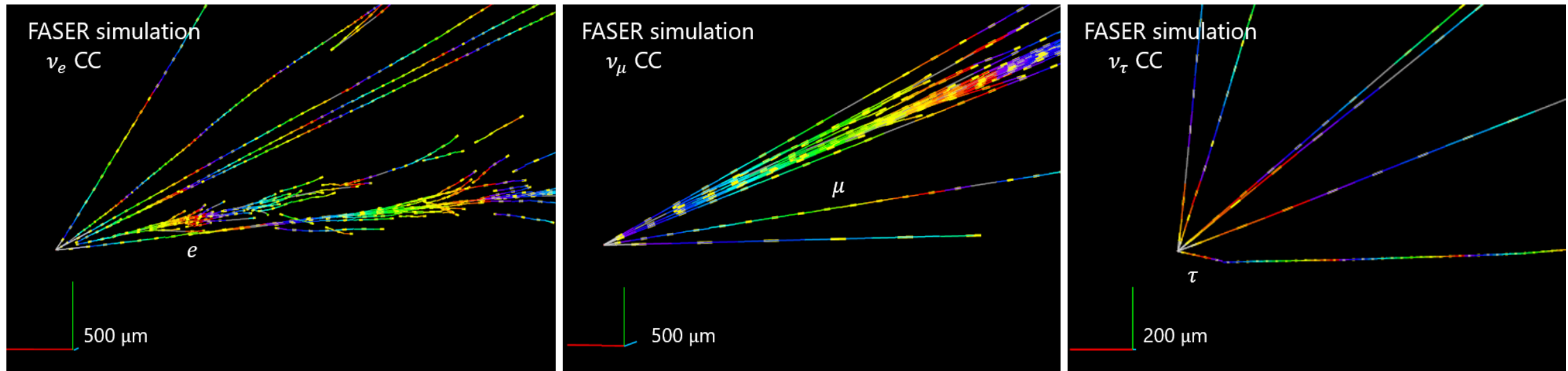


NEUTRINO PRODUCTION

Type	Particles	Main Decays	E	Q	S	P
Pions	π^+	$\pi^+ \rightarrow \mu\nu$	✓	✓	✓	—
Kaons	K^+, K_S, K_L	$K^+ \rightarrow \mu\nu, K \rightarrow \pi l\nu$	✓	✓	✓	—
Hyperons	$\Lambda, \Sigma^+, \Sigma^-, \Xi^0, \Xi^-, \Omega^-$	$\Lambda \rightarrow p l\nu$	✓	✓	✓	—
Charm	$D^+, D^0, D_s, \Lambda_c, \Xi_c^0, \Xi_c^+$	$D \rightarrow K l\nu, D_s \rightarrow \tau\nu, \Lambda_c \rightarrow \Lambda l\nu$	—	—	✓	✓
Bottom	$B^+, B^0, B_s, \Lambda_b, \dots$	$B \rightarrow D l\nu, \Lambda_b \rightarrow \Lambda_c l\nu$	—	—	—	✓

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].

EVENT DISPLAYS OF SIMULATED NEUTRINO INTERACTION VERTICES

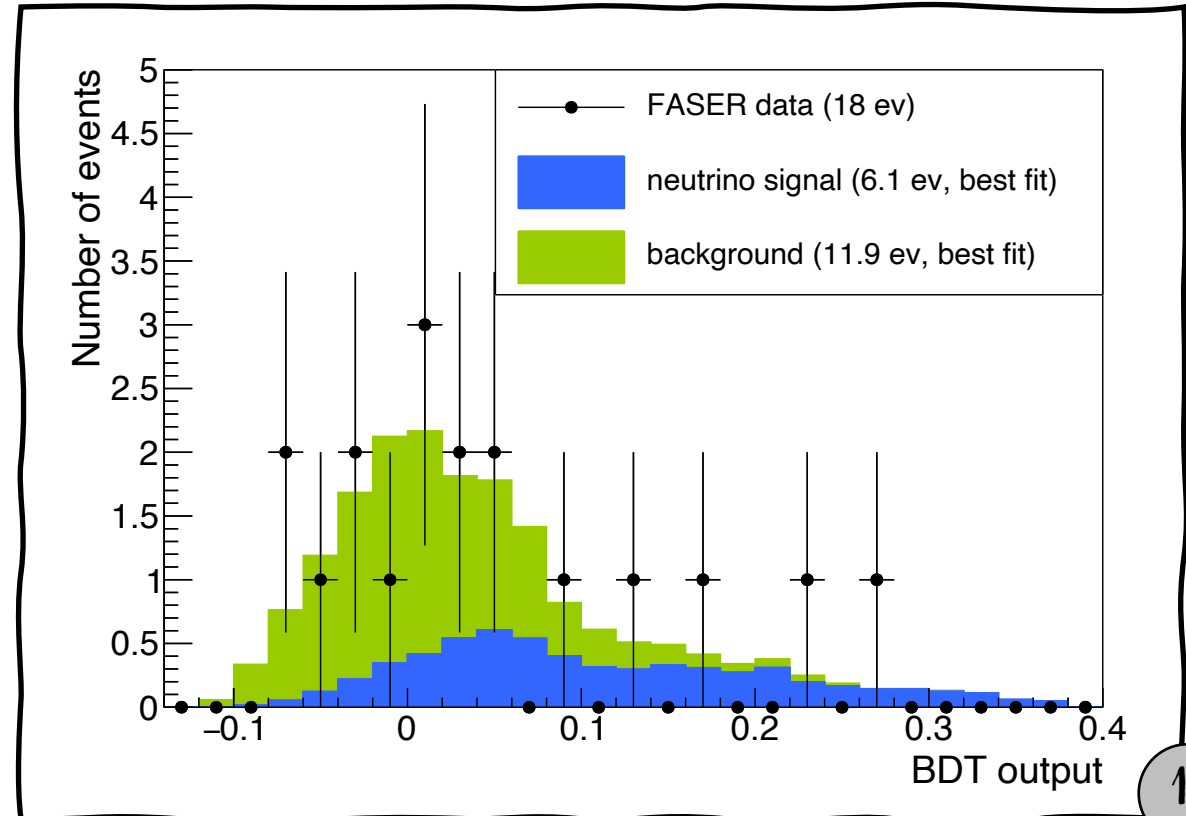
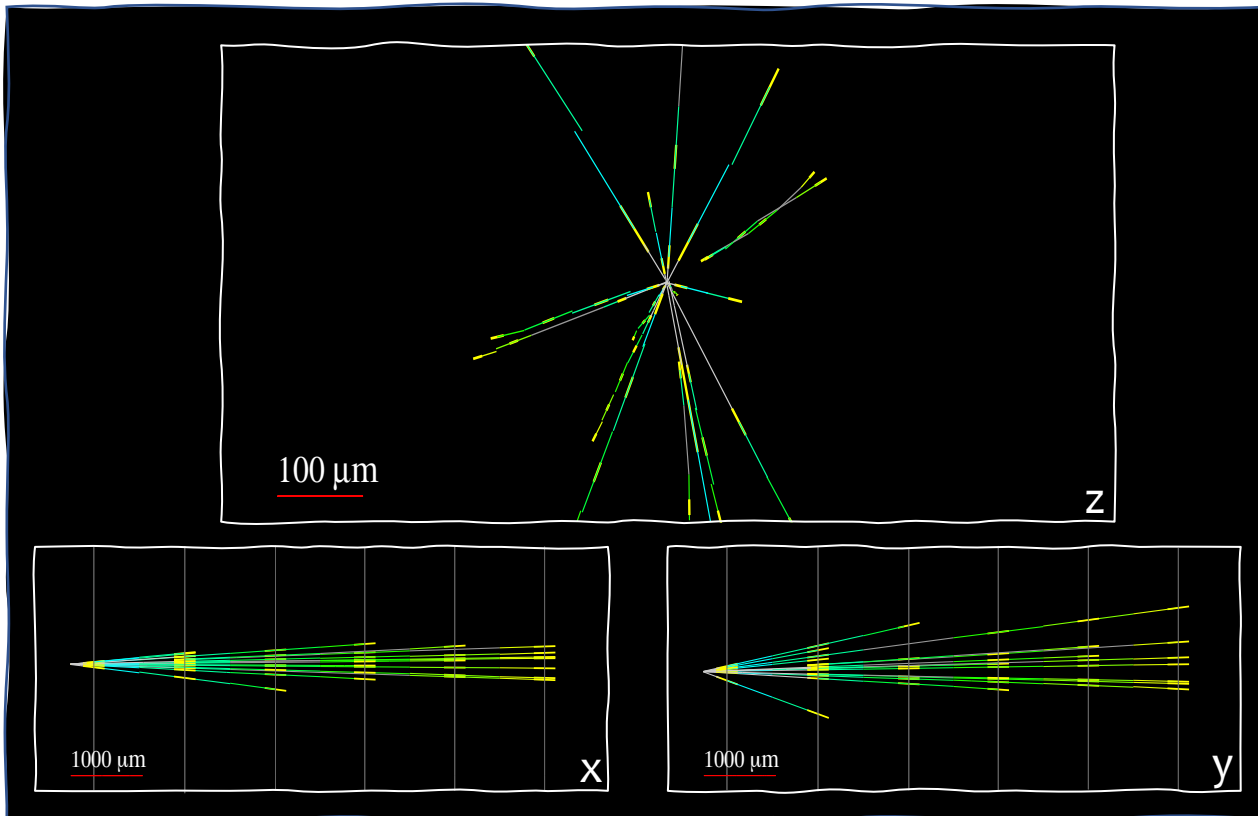
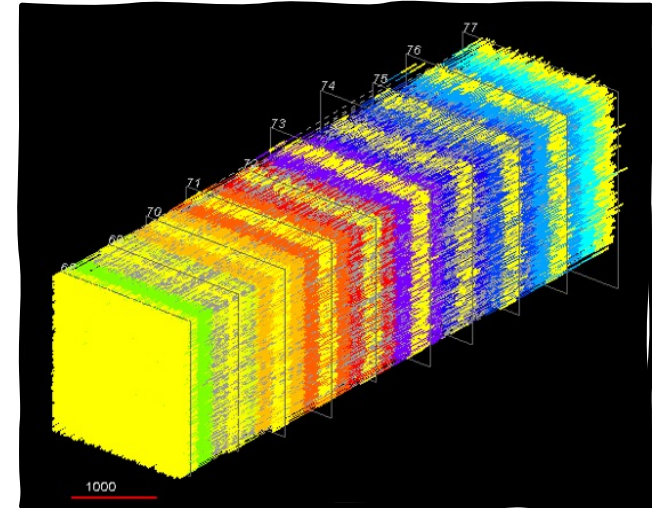


Event displays of simulated neutrino interaction vertices for 433 GeV ν_e CC, 664 GeV ν_μ CC, and 831 GeV ν_τ CC. Yellow line segments show the trajectories of charged particles in the emulsion films. The other colored lines are extrapolations of the track hits to the neighboring tungsten plates, and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



PILOT RUN IN 2018

First candidate **collider neutrino** interactions!

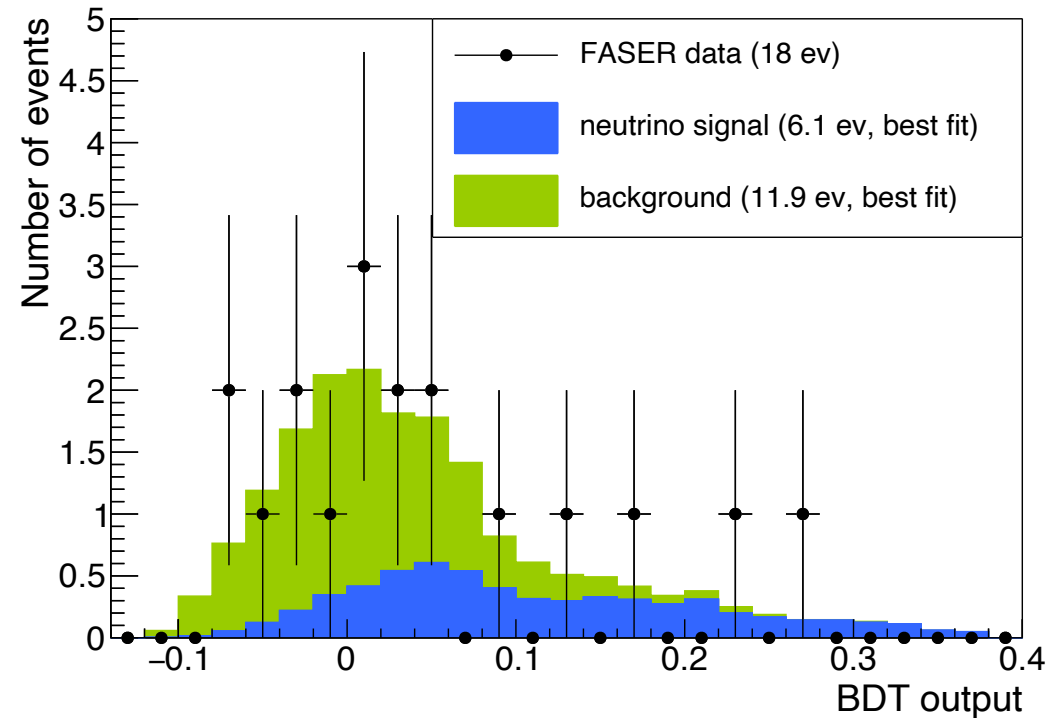
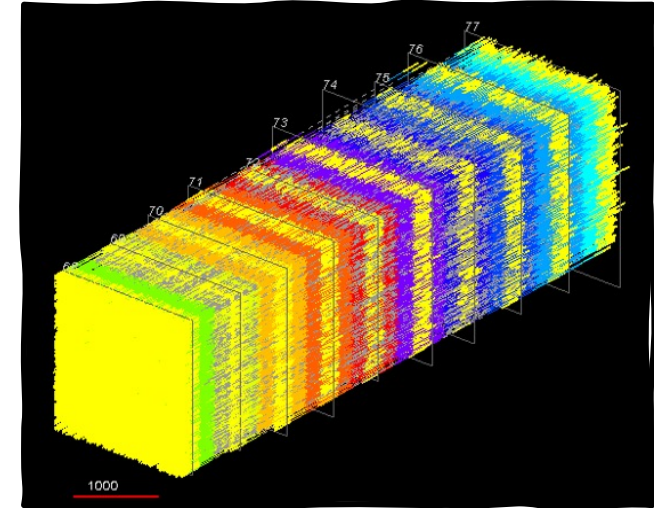


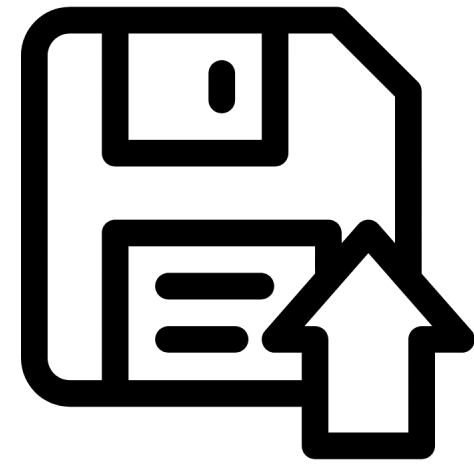


PILOT RUN IN 2018

First candidate **collider neutrino** interactions!

- A 11 kg detector collected $\sim 12/\text{fb}$
- 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





FASER

RESULTS

Neutrinos

STATISTICAL ANALYSIS FOR SIGNIFICANCE ESTIMATION

Besides the signal category, we select:

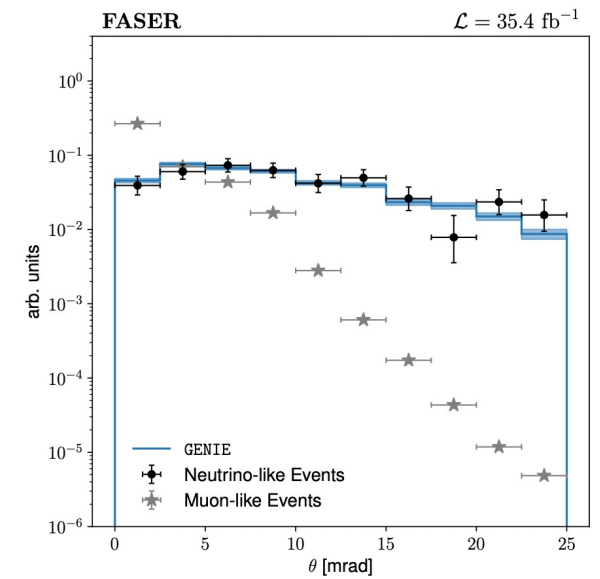
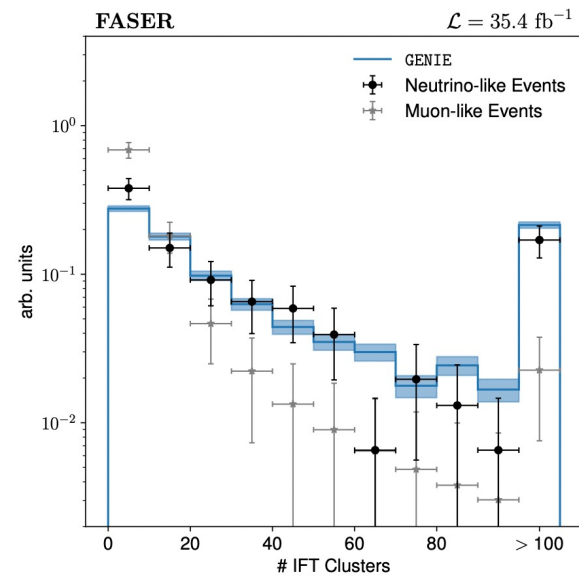
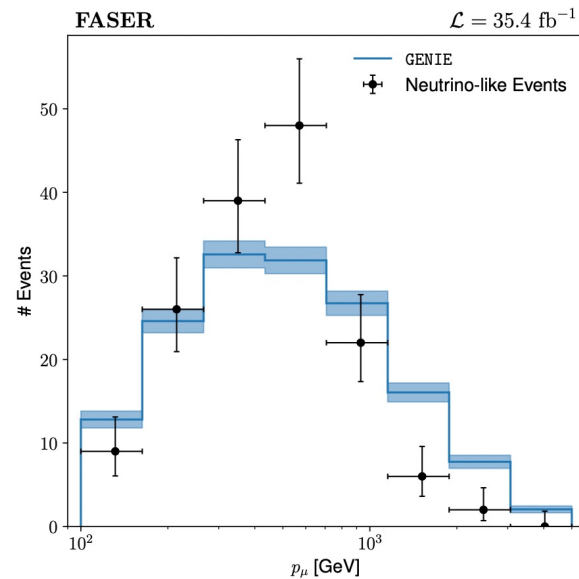
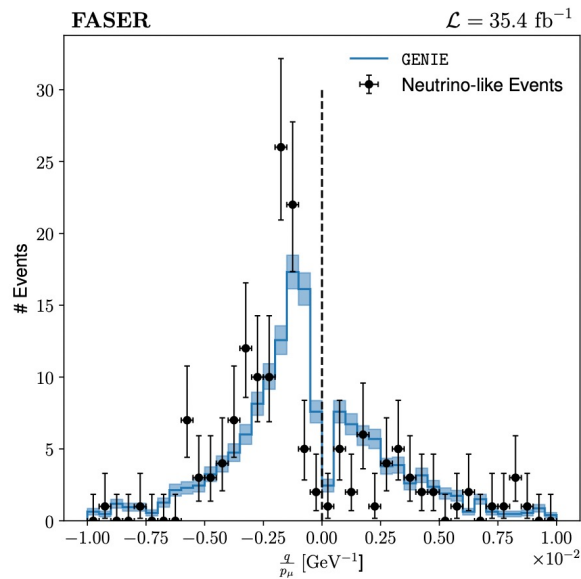
- n_{10} : Events for which the first layer of the FASER ν scintillator produces a charge of >40 pC in the PMT, but no signal with sufficient charge is seen in the second layer.
- n_{01} : Analogous events for which more than 40 pC in the PMT was observed in the second layer, but not in the first layer.
- n_2 : Events for which both layers observe more than 40 pC of charge.

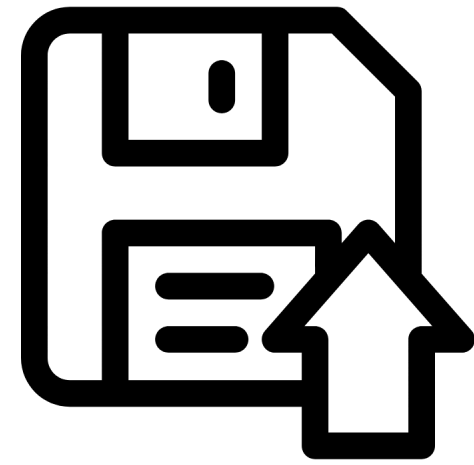
tor response and selection. The determined inefficiencies of the two FASER ν scintillators are $p_1 = (6_{-3}^{+4}) \times 10^{-8}$ and $p_2 = (9_{-3}^{+4}) \times 10^{-8}$, showing values close to the expected performance [25].

Category	Events	Expectation
Signal	153	$n_\nu + n_b \cdot p_1 \cdot p_2 + n_{\text{had}} + n_{\text{geo}} \cdot f_{\text{geo}}$
n_{10}	4	$n_b \cdot (1 - p_1) \cdot p_2$
n_{01}	6	$n_b \cdot p_1 \cdot (1 - p_2)$
n_2	64014695	$n_b \cdot (1 - p_1) \cdot (1 - p_2)$

TABLE I. Observed event yields in 35.4 fb^{-1} of collision data and their relation to neutrino and background events.

PROPERTIES OF OBSERVED EVENTS





FASER

RESULTS

Dark Photon

EXPECTED DARK PHOTON PHASE-SPACE

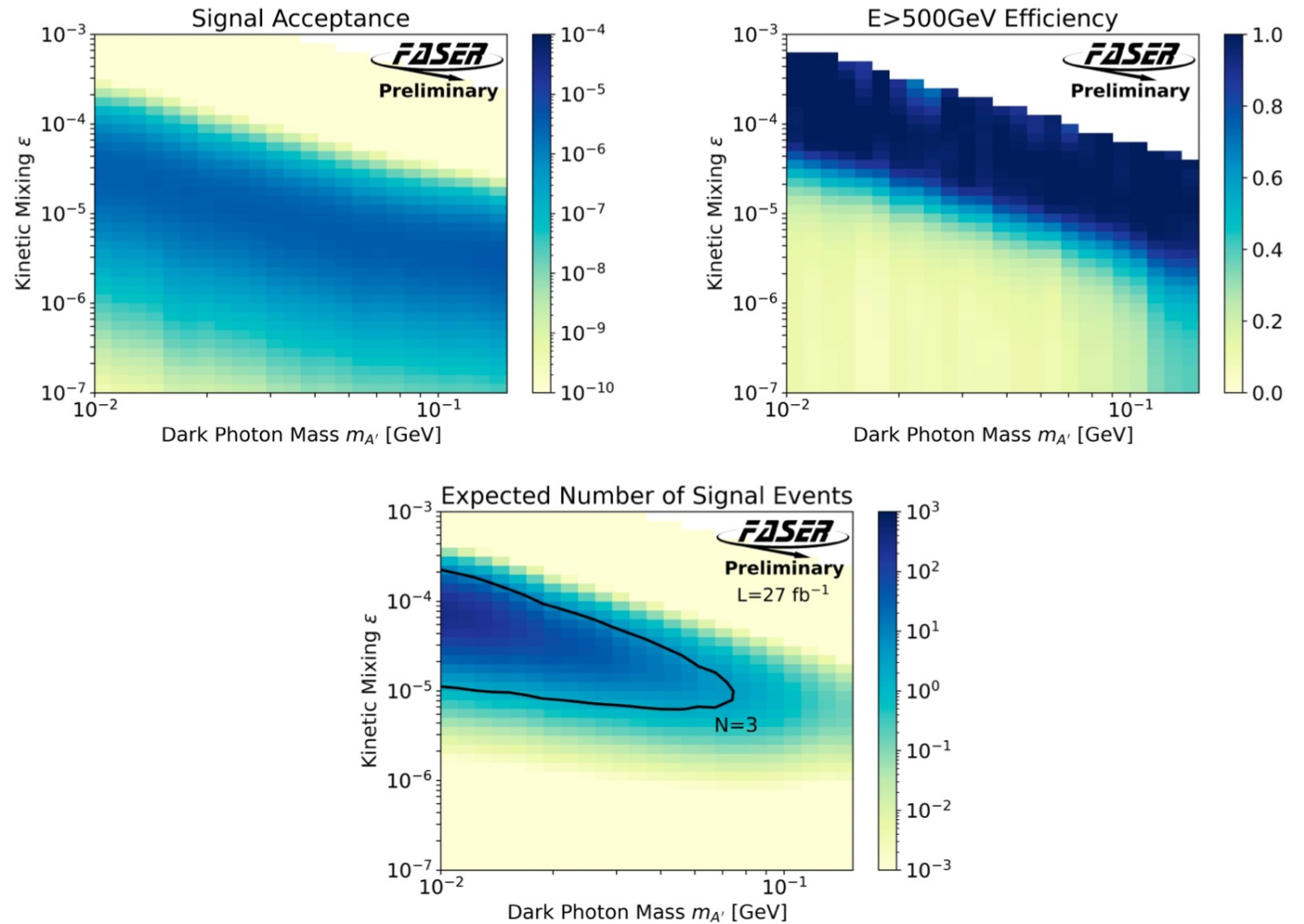
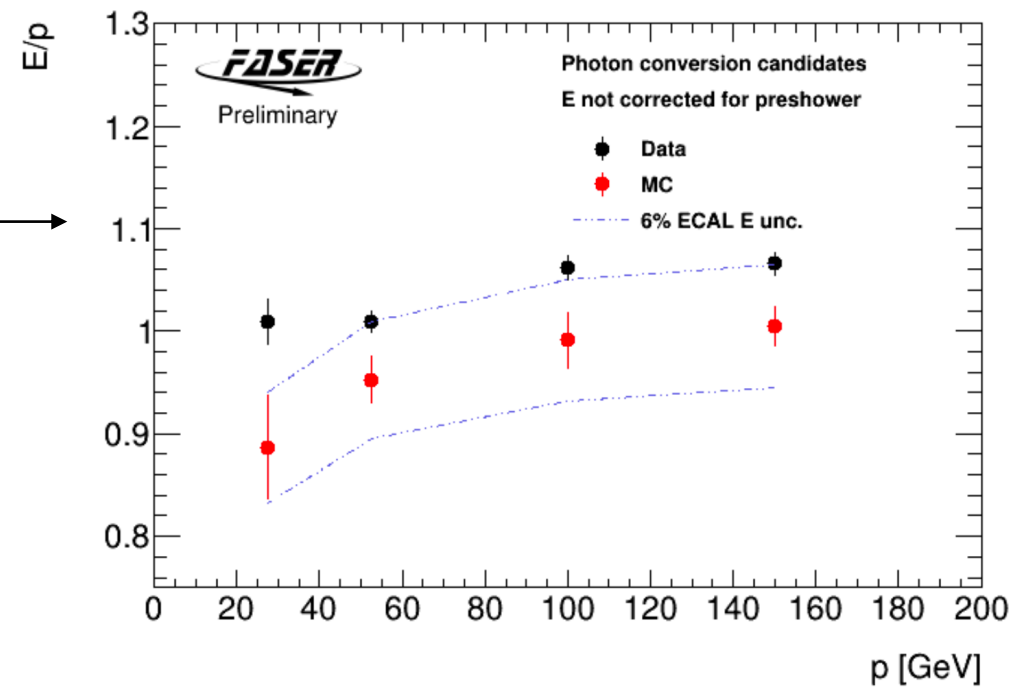
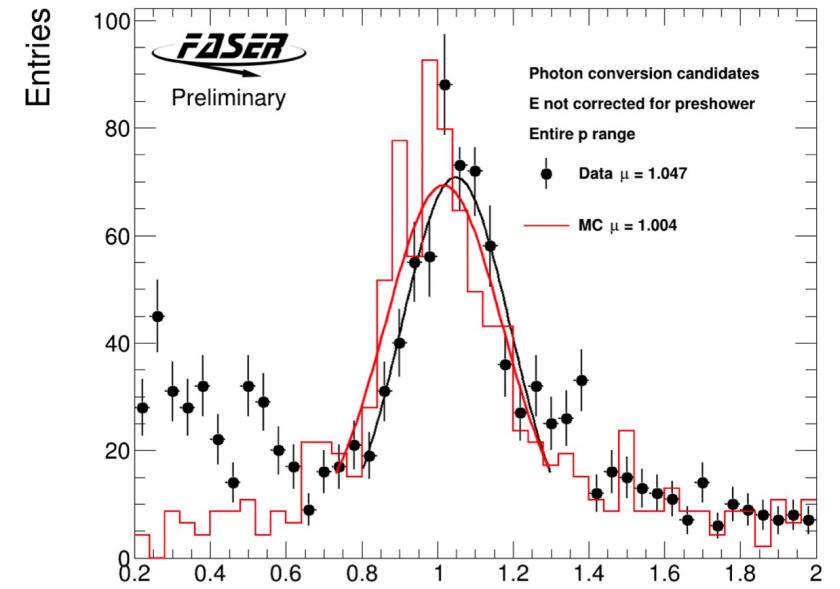
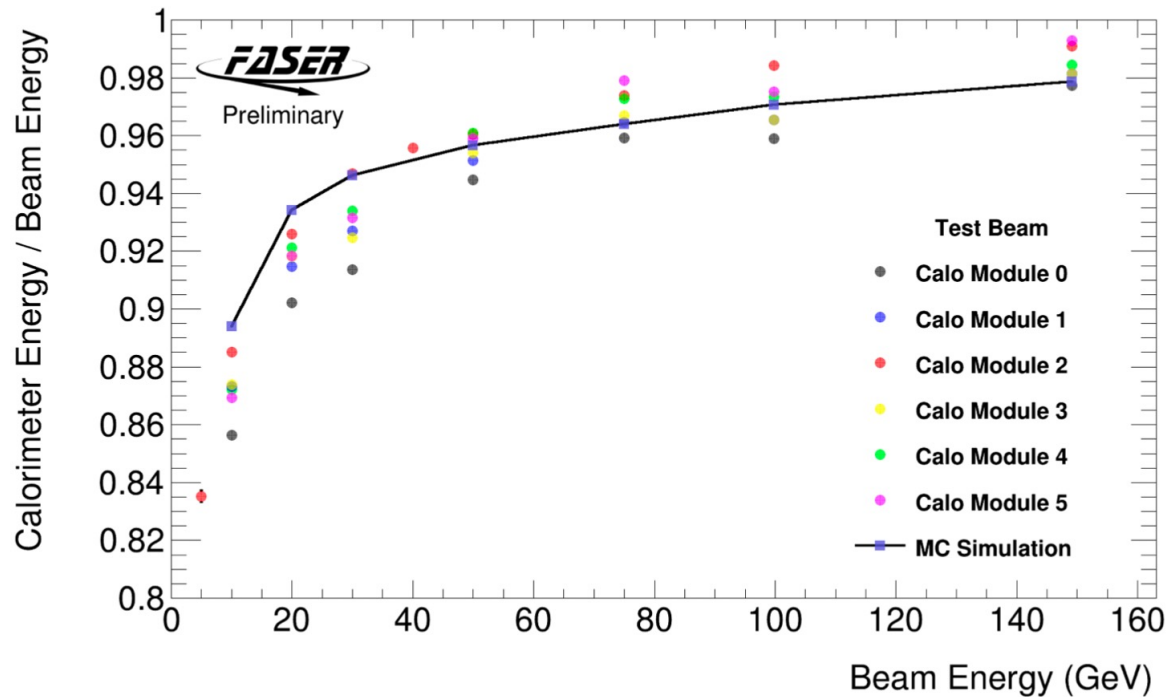


FIG. 1. Top left: The acceptance for dark photons to decay inside the FASER decay volume. Top right: The fraction of dark photons decaying inside the FASER decay volume that have energy greater than 500 GeV. Bottom: The expected number of dark photon events in FASER for 27.0 fb^{-1} of data, assuming a 50% signal efficiency, on top of the requirement that the A' energy is greater than 500 GeV.

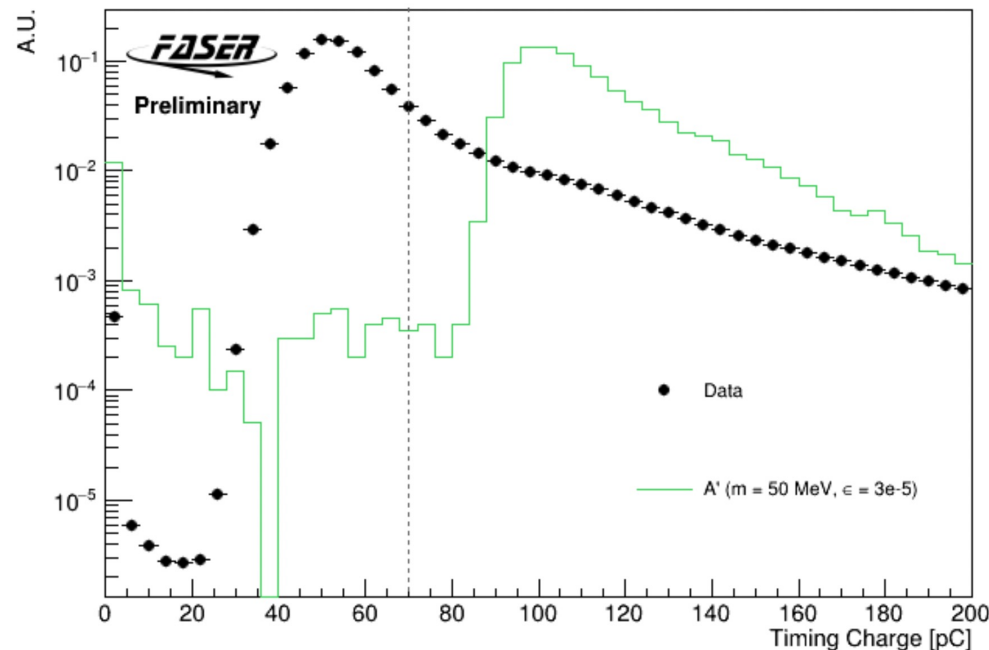
CALO-RELATED PERFORMANCE ASSESSMENT

- Calorimeter energy scale and uncertainty estimated based on test beam data and in situ MIP calibration
- Validated using conversion events (μ with $e+e-$ pair)
- E/p in data/MC agrees within 6%



SELECTION IN TIMING LAYER

Selecting events with more than 70pC in timing layer is $\sim 100\%$ efficient for signal, while also suppressing a large fraction of single track events

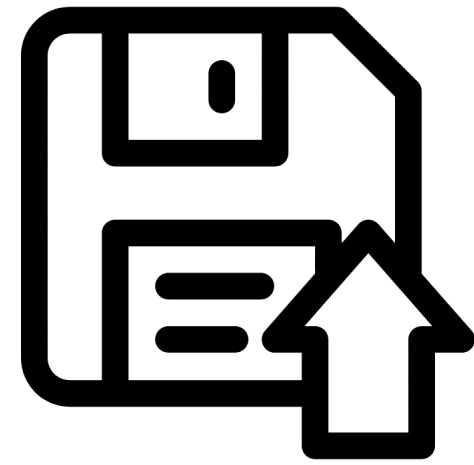


SYSTEMATICS

Source	Value	Effect on signal yield
Theory, Statistics and Luminosity		
Dark photon cross-section	$\frac{0.15+(E_{A'}/4\text{TeV})^3}{1+(E_{A'}/4\text{TeV})^3}$	15-65% (15-45%)
Luminosity	2.2%	2.2%
MC Statistics	$\sqrt{\sum W^2}$	1-3% (1-2%)
Tracking		
Momentum Scale	5%	< 0.5%
Momentum Resolution	5%	< 0.5%
Single Track Efficiency	3%	3%
Two-track Efficiency	15%	15%
Calorimetry		
Calo E scale	6%	0-8% (< 1%)

YIELDS

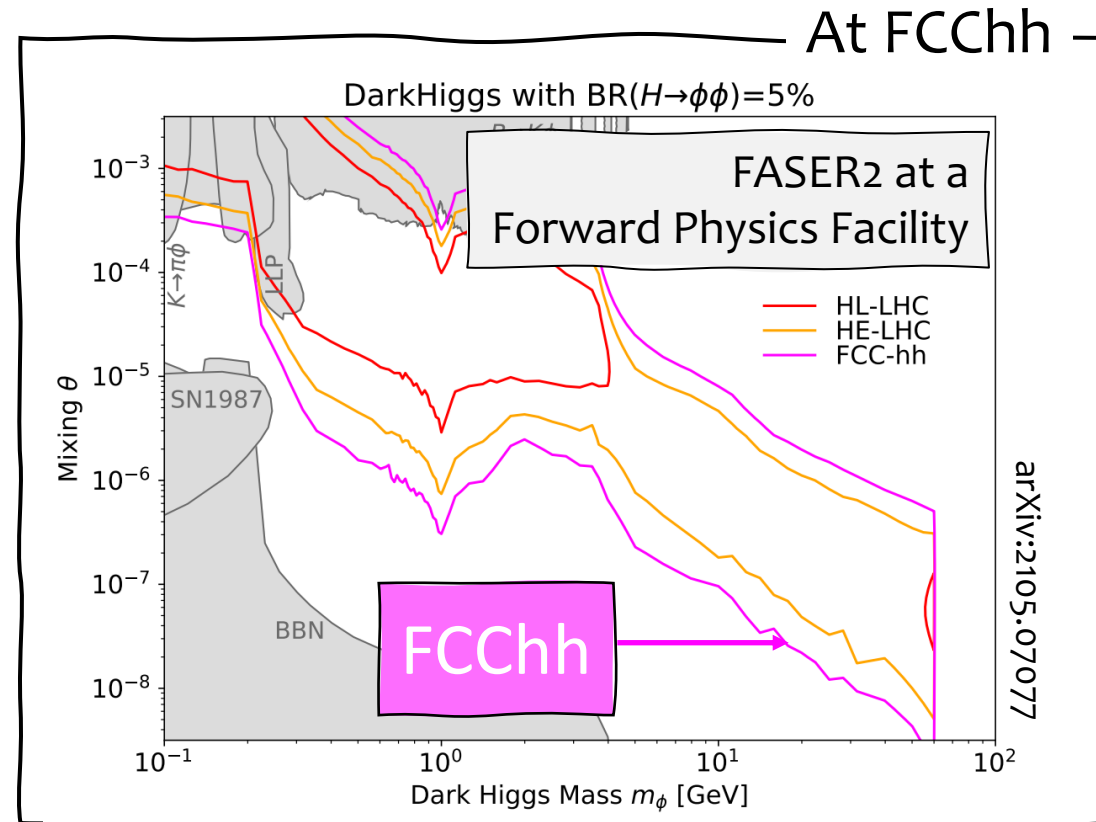
Cut	Data	
	Events	Efficiency
Good collision event	151750788	—
No Veto Signal	1235830	0.814%
Timing/Preshower Signal	313988	0.207%
≥ 1 good track	21329	0.014%
= 2 good tracks	0	0.000%
Track radius < 95 mm	0	0.000%
Calo energy > 500 GeV	0	0.000%



BEYOND

FASER

OPPORTUNITIES FOR FIPs AT FCC



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.

BEYOND FASER?

A TEASER FOR THE PROPOSED

FORWARD PHYSICS FACILITY

The rich physics program in the far-forward region strongly motivates creating a dedicated Forward Physics Facility to house far-forward experiments for the HL-LHC era from 2028-2040s

Well aligned with the recommendations of recent community studies

The full physics potential of the LHC and the HL-LHC [...] should be exploited.

1st recommendation of the 2020 European Strategy Update

Our highest immediate priority accelerator and project is the HL-LHC, [...] including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades.

Snowmass 2021 Energy Frontier Report

More: [Submitted to P5](#) just in April 2023

[LoI for SNOWMASS-2021](#)

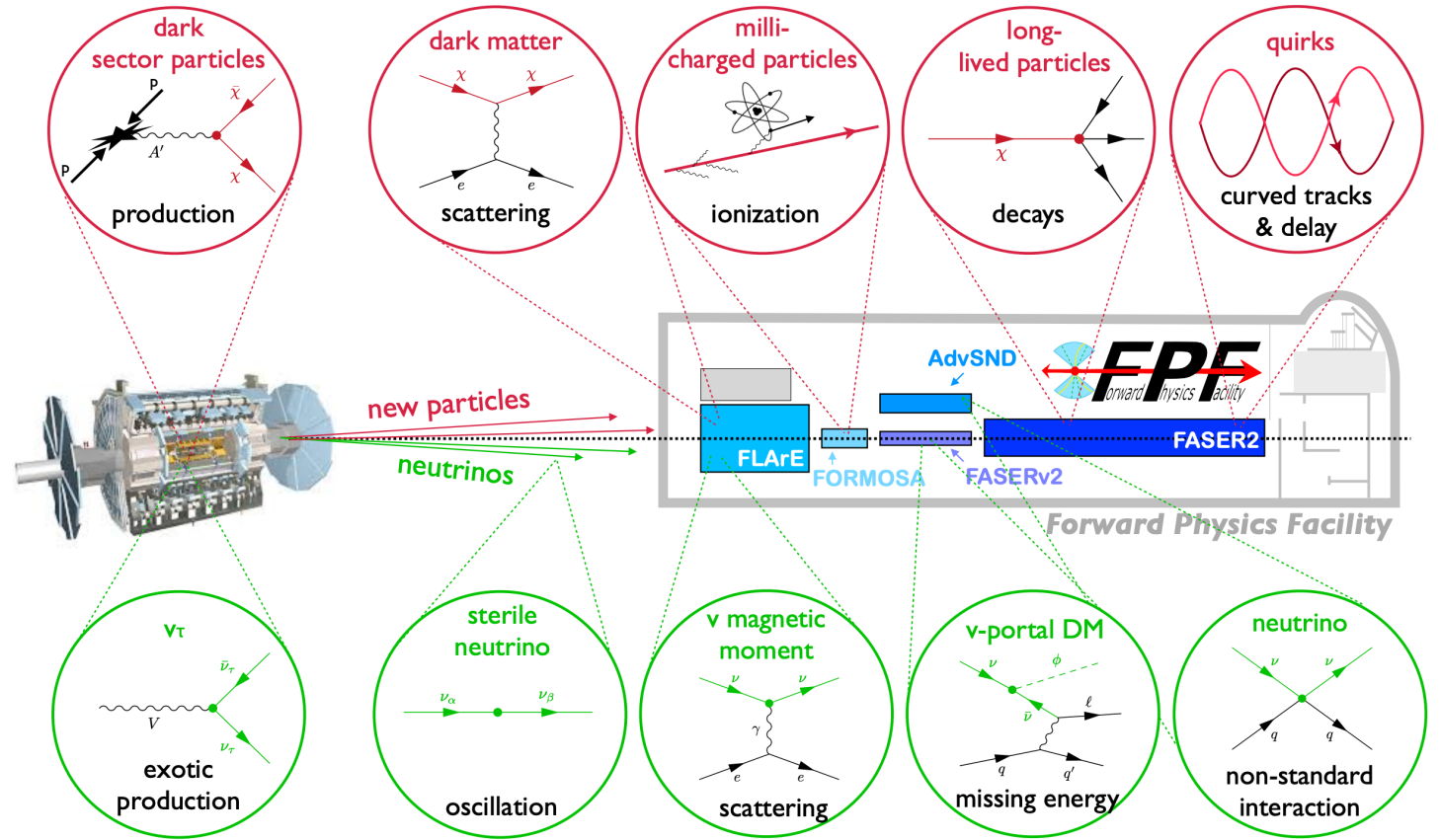
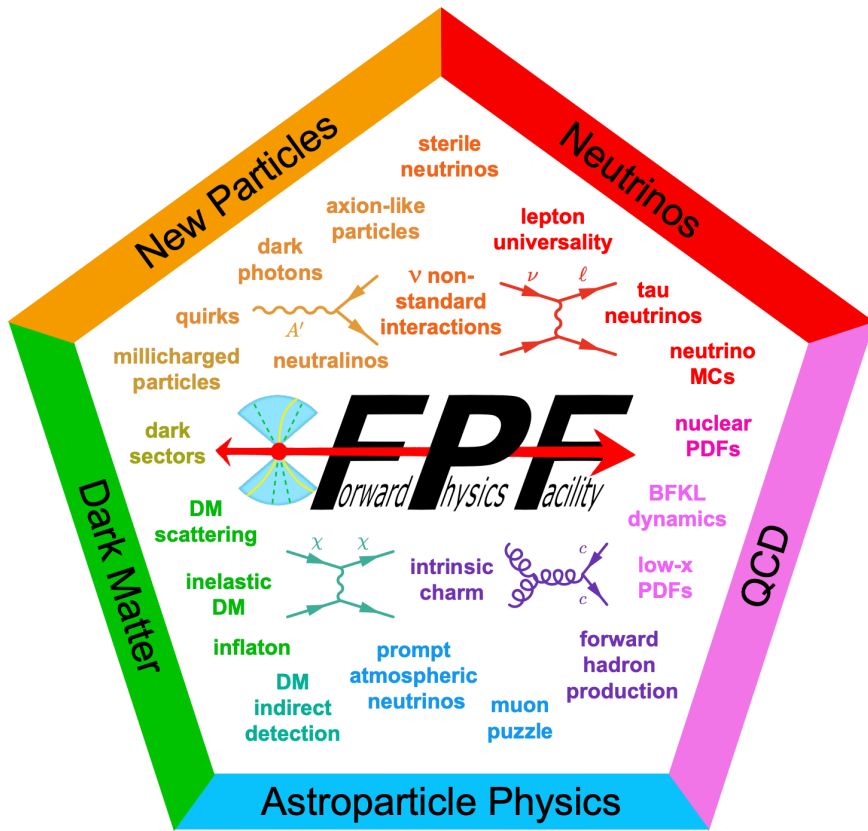
[arXiv:2203.05090](#)

[FPF – Kickoff workshop](#)

[FPF – 5th \(latest\) workshop](#)

[FPF – 6th workshop coming up next week!](#)

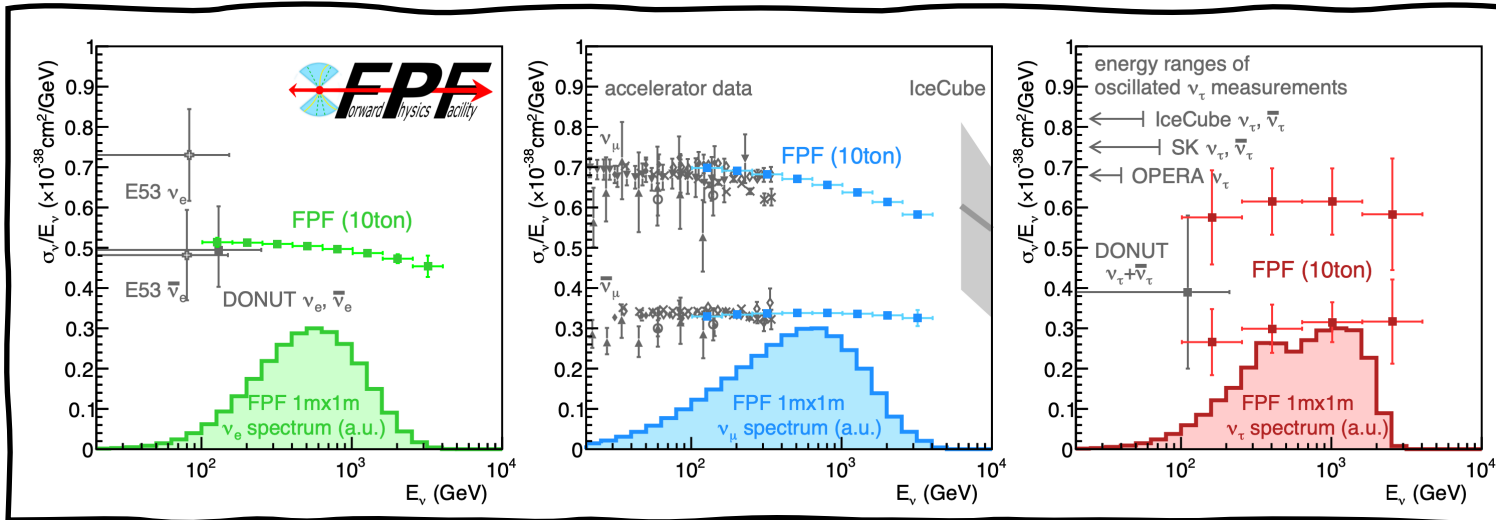
THE PHYSICS PROGRAMME OF FPF



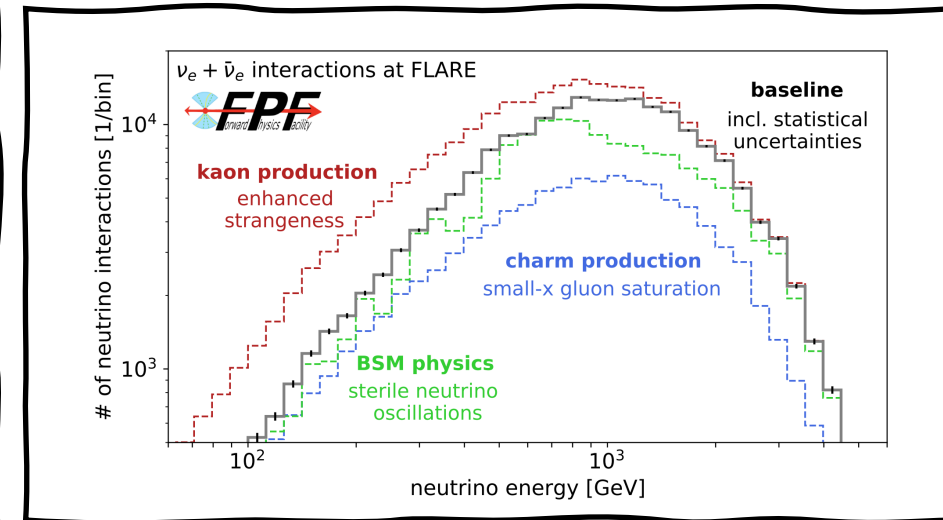
A RICH NEUTRINO PROGRAMME

	Available lumi	Mass of ν detector	ν_e	ν_μ	ν_τ
Main production source			kaon decay	pion decay	charm decay
# interacting in FASERv	150 / fb	1 tn Tungsten	~ 1000	~ 20000	~ 10
# interacting in FASERv2	3000 / fb	10 tn Tungsten	$\sim 10^5$	$\sim 10^6$	$\sim 10^4$

Unprecedented numbers of detectable neutrinos, at energy ranges where there is currently no available data!



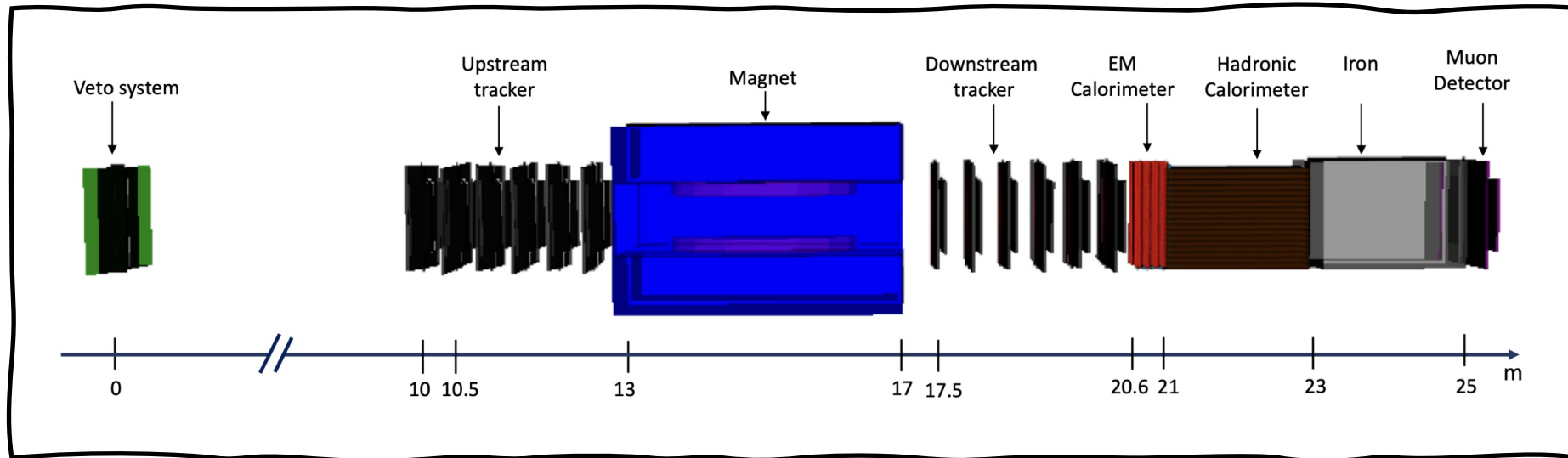
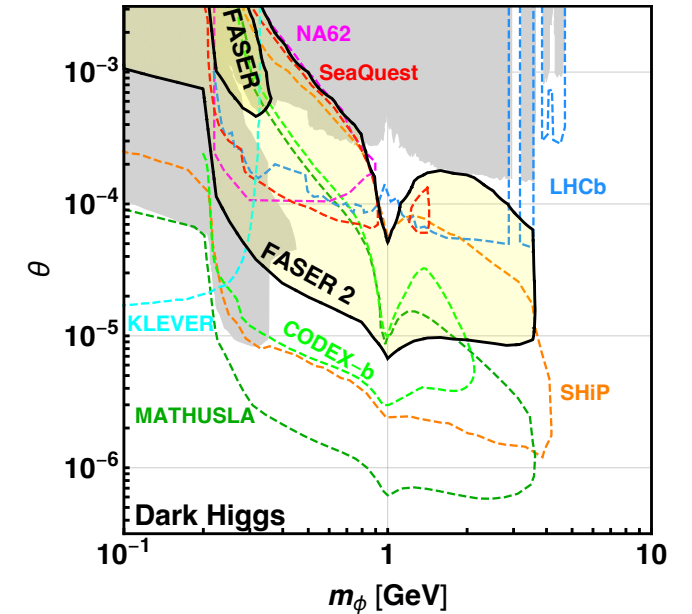
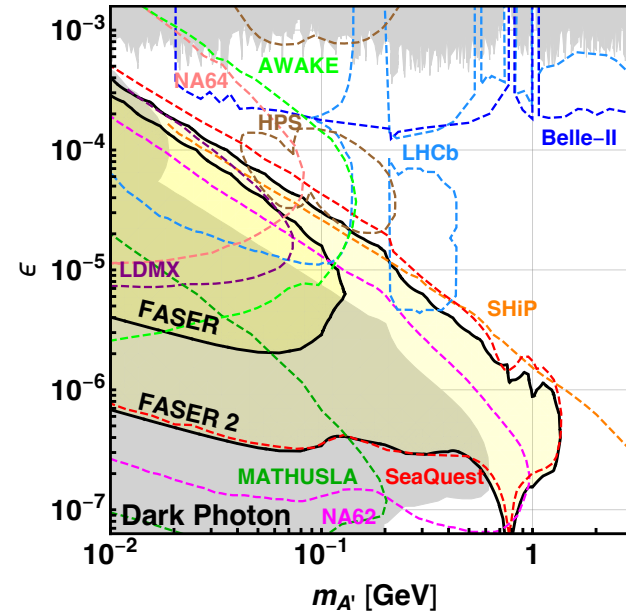
Expected precision of FPF measurements of the neutrino interaction cross section with nucleons



Coloured lines: three examples of physics that can change the expected flux, all probed at FPF

BSM & 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



Possible FASER2 layout

NORTH AREA HIGH INTENSITY BEAMS – ECN3



A number of proposals requiring **higher intensities** (factor 6 to 12 in p/spill – factor 6 to >20 in p.o.t./year) in the **ECN3** underground cavern **post-LS3**:

- **HIKE** (High intensity Kaon Experiment)
 - **Ultra Rare Kaon decay studies**
 - search for FIP visible decays **on axis**
- **SHADOWS** (Search for Hidden And Dark Objects With the SPS)
 - search for **FIP visible decays off-axis**. Running in parallel to HIKE when operated in Beam-Dump mode
- **SHiP** (Search for Hidden Particle)
 - comprehensive investigation of the Hidden Sector in the O(GeV) domain
- A programme going **beyond HL-LHC (~15 years of operation)**

Strong support from SPSC for the High Intensity Upgrade of ECN3

Final recommendation / decision on which experiment to host (SPSC & RB November/December 2023)

Possible start of the TDR phase in 2024

RUNNING EXPERIMENTS

Machine	Experiment	Beam	Lumi / Yields	Running up to...
LHC	ATLAS / CMS	pp – up to 14TeV	Up to 3 / ab	2042
	LHCb		Up to 300 / fb	
	FASER / SND		Up to 300 / fb	2025
SPS	NA62	K ⁺ – 75 GeV p – 400 GeV	10 ¹³ Kaon decays 10 ¹⁸ POT	2025
	NA64	e ⁺ /e ⁻ – 100 GeV μ ⁺ /μ ⁻ – 160 GeV	10 ¹³ e ⁺ /e ⁻ 10 ¹³ μ ⁺ /μ ⁻	2032



PROPOSED EXPERIMENTS

Machine	Experiment	Beam	Lumi / Yields	Running during...	Where?
SPS	HIKE	K ⁺ – 75 GeV K _L – 40 GeV	10 ¹⁴ Kaon decays 10 ¹⁴ Kaon decays	Run 4 – Run 5 Run 6	NA62 hall - the two running in parallel
	SHADOWS	p – 400 GeV	5x10 ¹⁹ POT	Run 4 – Run 5	
	SHiP	p – 400 GeV	2x10 ²⁰ POT	Run 4 – Run 5	NA62 hall
LHC	FASER(ν) 2	pp – 14 teV	3 / ab	Run 4 – Run 6	New forward physics facility (FPF)
	FORMOSA				
	advSND@LHC				
	FLARE				

RUN1, RUN2, RUN3 AND BEYOND

