ForwArd Search ExpeRiment at the LHC

https://twiki.cern.ch/twiki/bin/view/FASER/
Technical Proposal: arXiv:1811.12522

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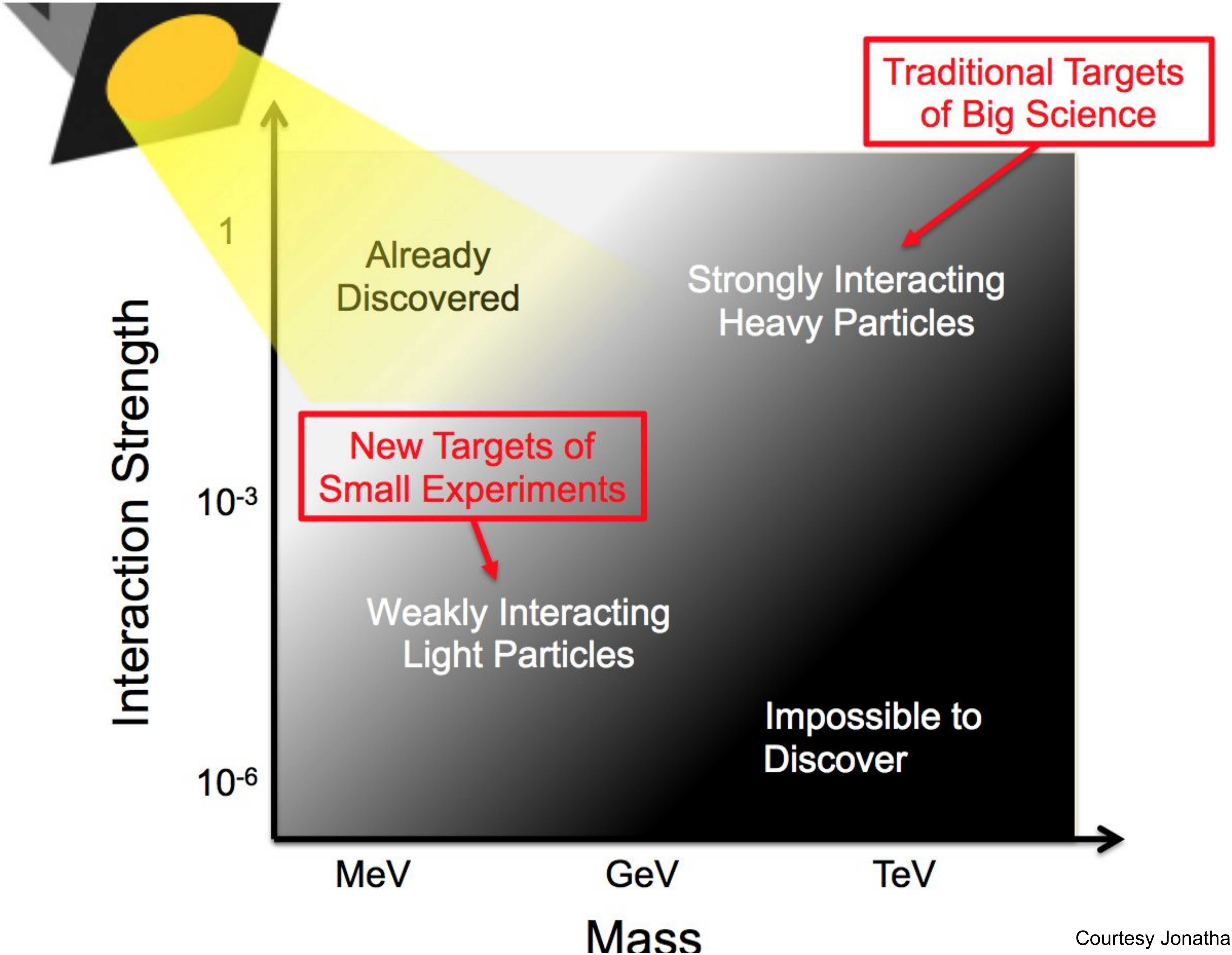
University of Washington
On behalf of the FASER Collaboration

Jan 23rd 2019, IAS HEP, HKUST

HEISING-SIMONS FOUNDATION
SIMONS FOUNDATION

The Lamppost Landscape



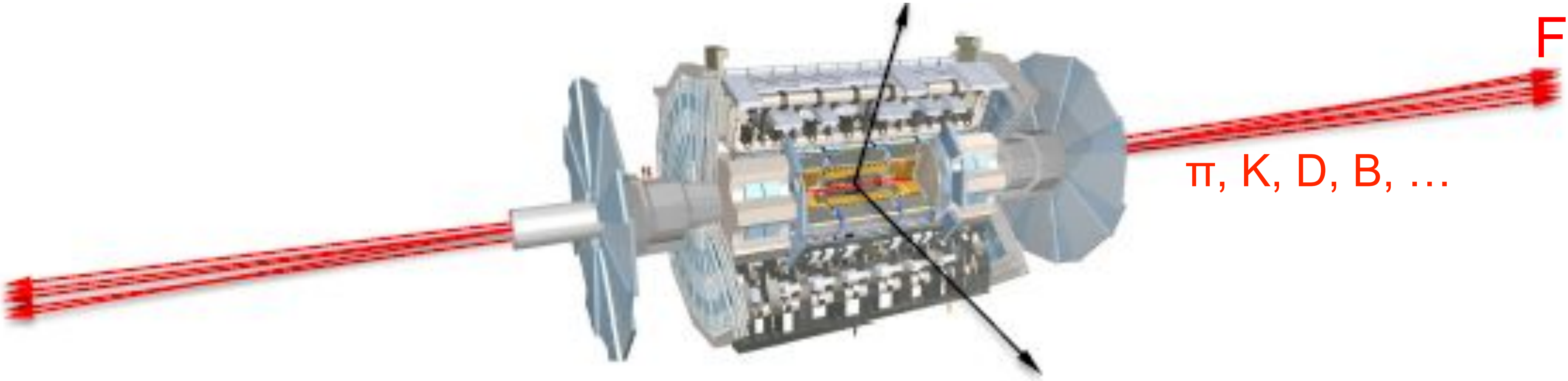
Courtesy Jonathan Feng

The idea

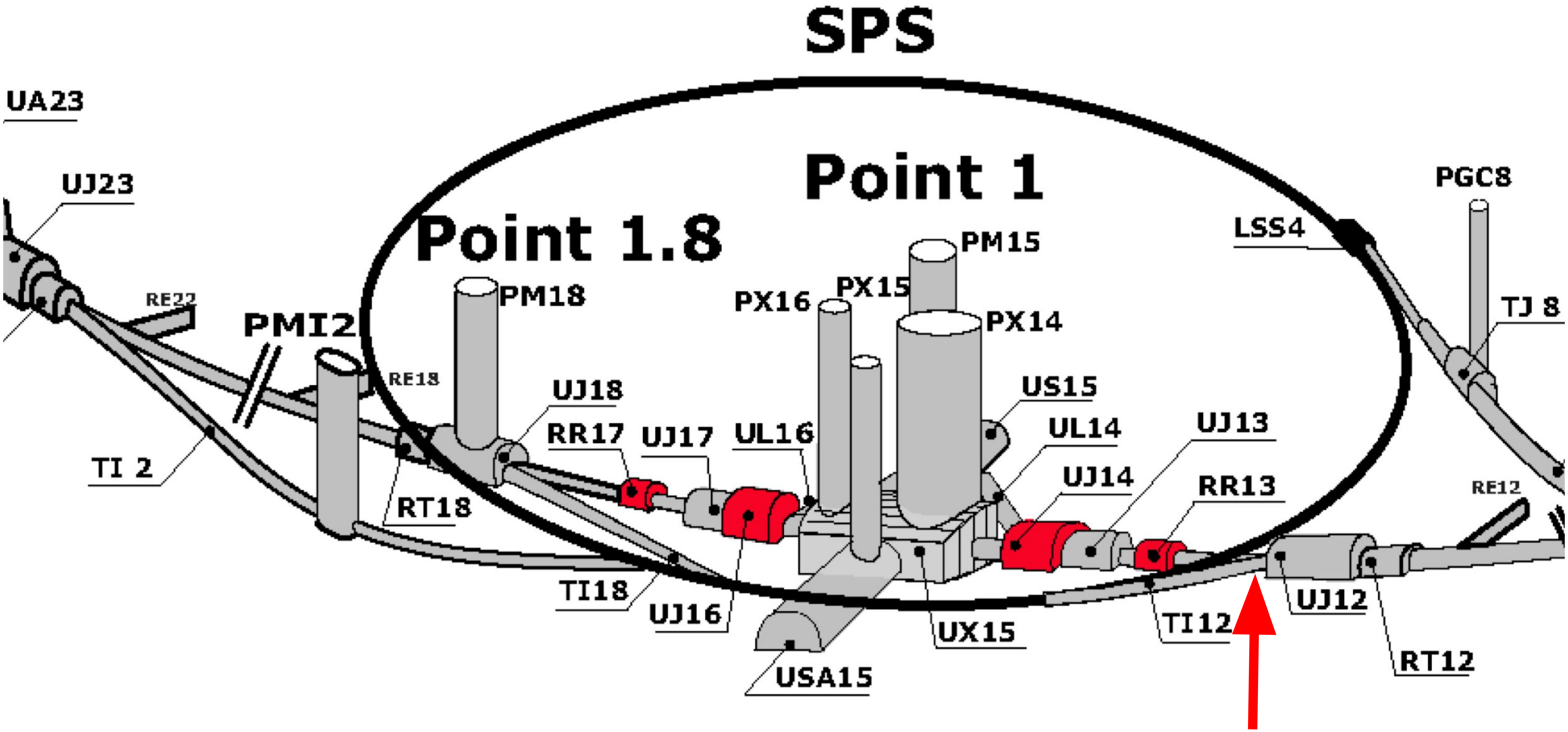
- New physics searches at the LHC have traditionally focused on high pT. This is appropriate for heavy, strongly-interacting particles
  - $\sigma \sim$ fb to pb → $N_\pi \sim 10^3 - 10^6$ in 3 ab^{-1} produced ~isotropically

- However, if new particles are light and weakly interacting, this may be completely misguided. Instead should exploit
  - $\sigma_{inel} \sim 100$ mb → $N_\pi \sim 10^{17}$, $\theta_{\text{beam axis}} \sim m_\pi$ / TeV ~ 0.1 mrad

- These light, weakly-interacting particles are long-lived and collimated. This motivates a small (~0.1 m^3) and inexpensive (~1M CHF) experiment placed in the very forward region of ATLAS (480 m downstream).



FASER location

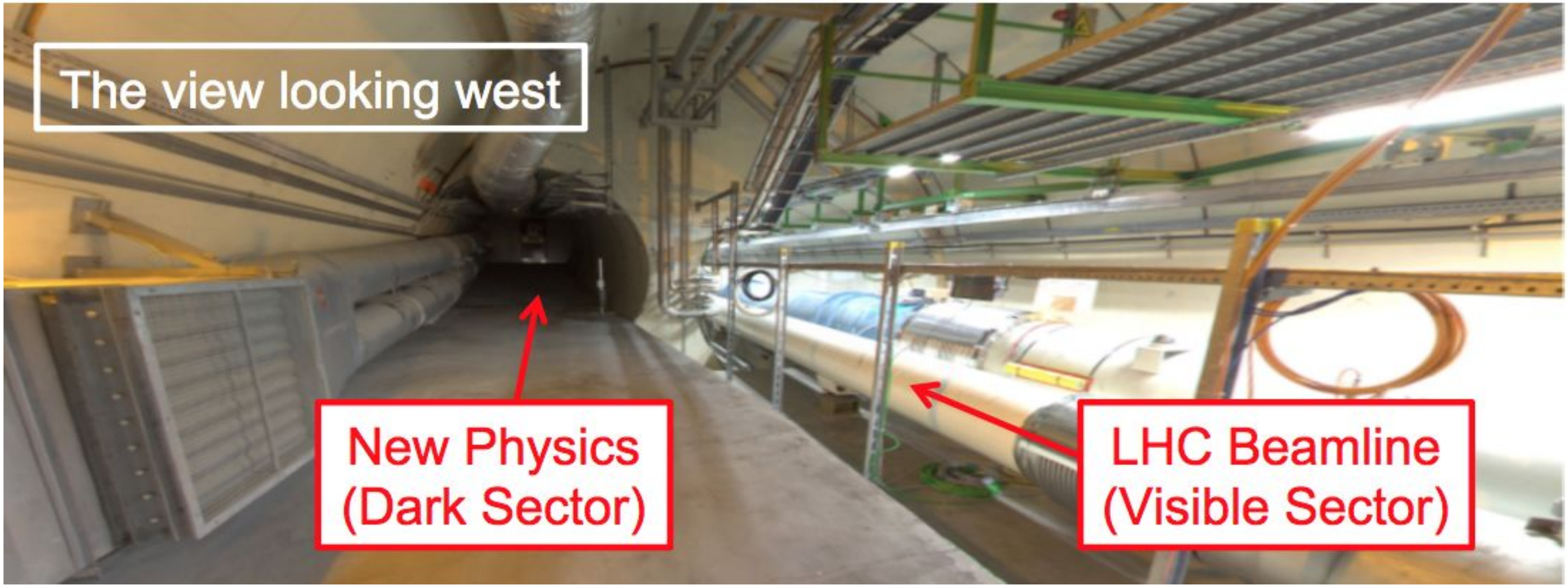


ATLAS

FASER

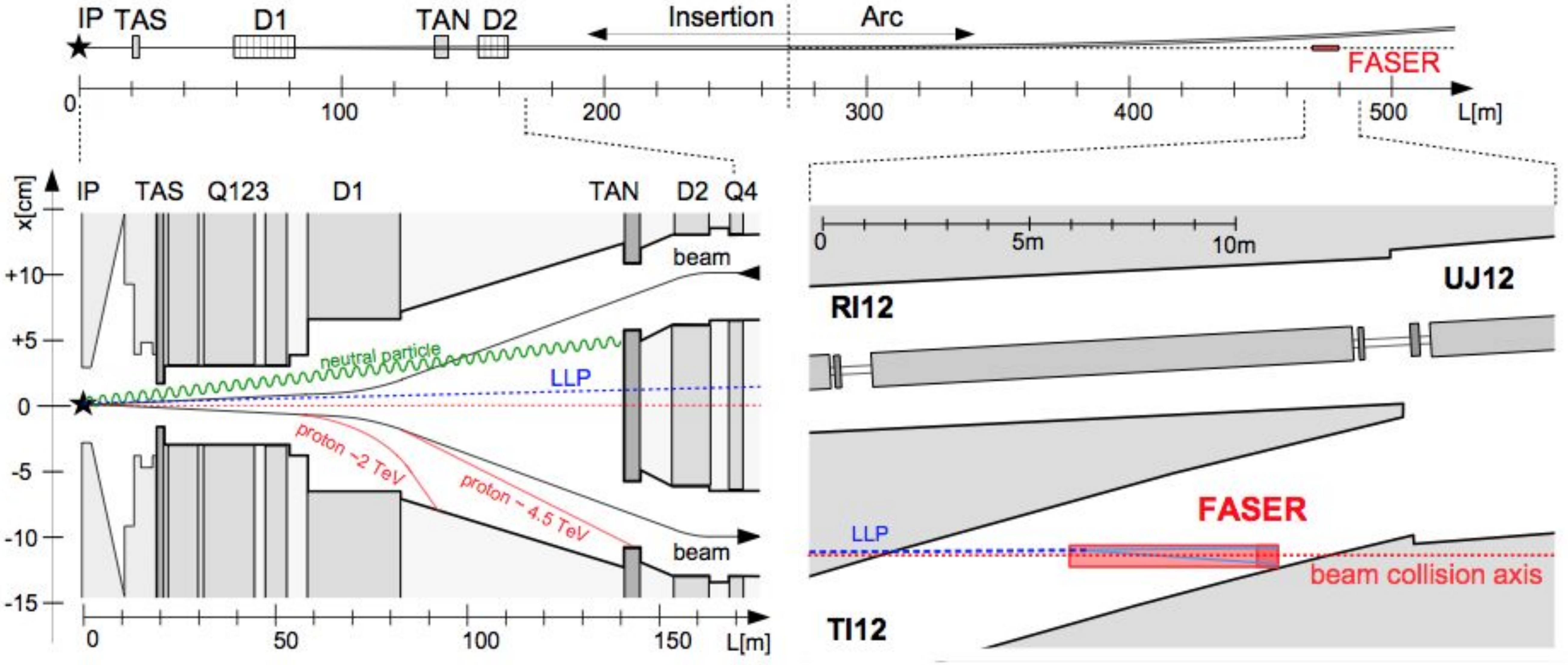
Fit 5m long detector but less service supports.

FASER location



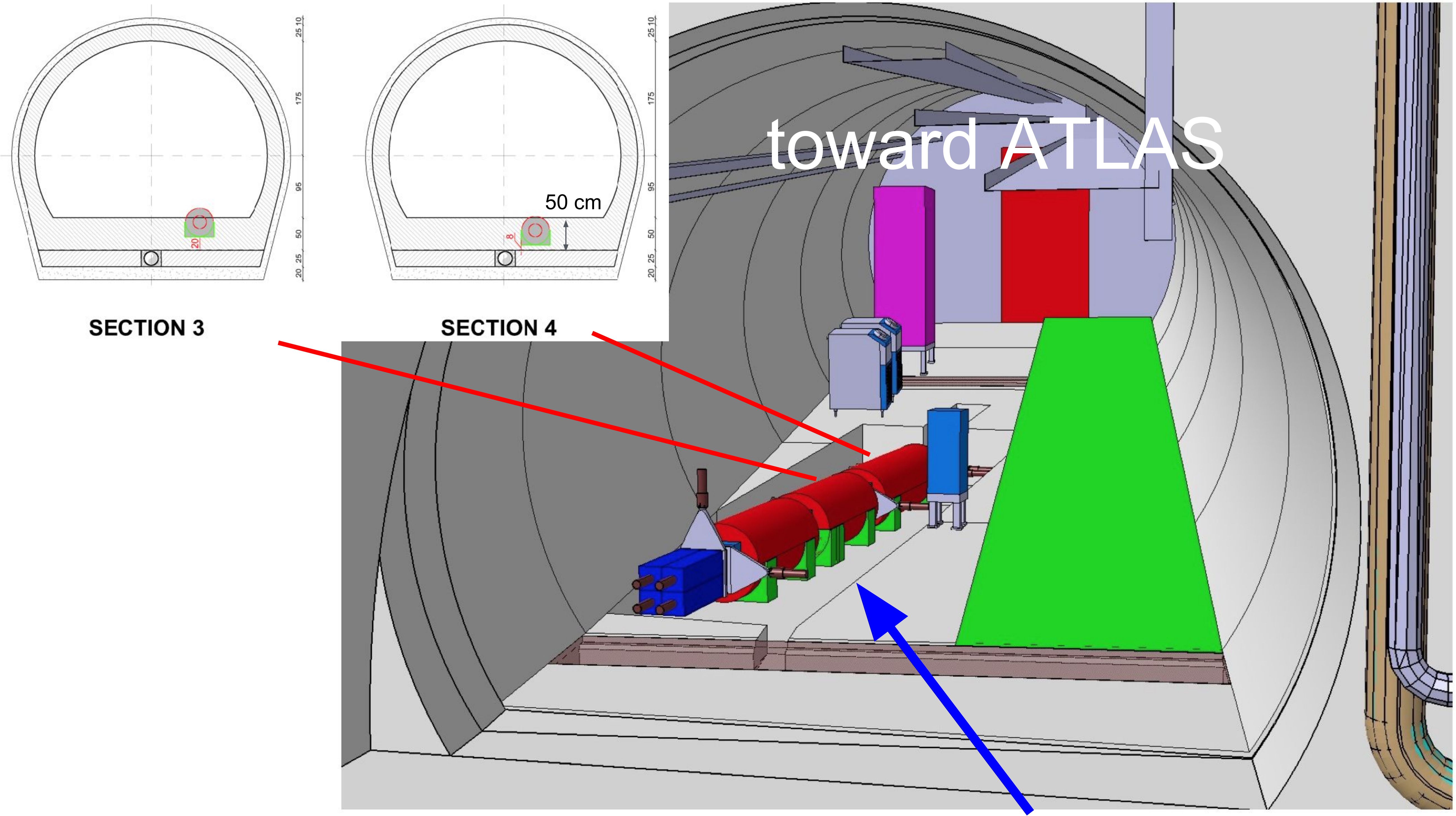
Long-lived particles in FASER

LLP starts at IP, travels through Target Absorber Neutral (TAN) and other very forward infrastructure, then leaves the LHC tunnel, travels through 100 m of rock, decays to two highly energetic (~TeV) charged tracks in FASER



FASER in TI12

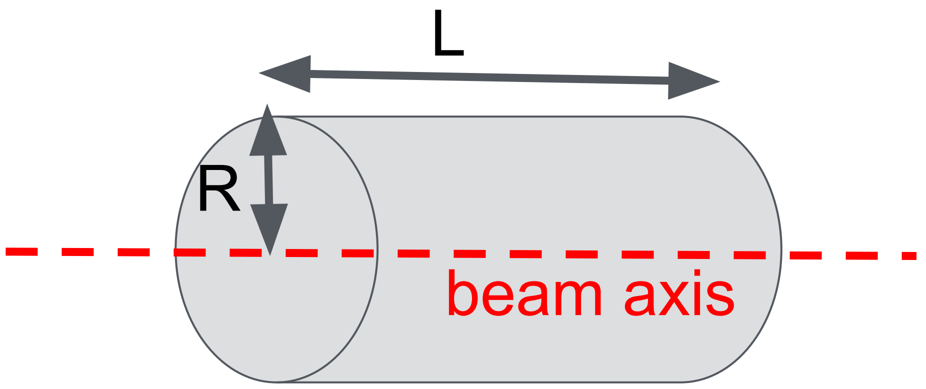
- FASER will be placed on the beam collision axis (“on-axis”) within mm accuracy. A little digging is required to lower the floor by 45 cm



- The beam crossing angle also matters: with 285 (590) μrad, the “on axis” location at FRASER shifts by 6 (12) cm

Dark Photon Discovery Potential

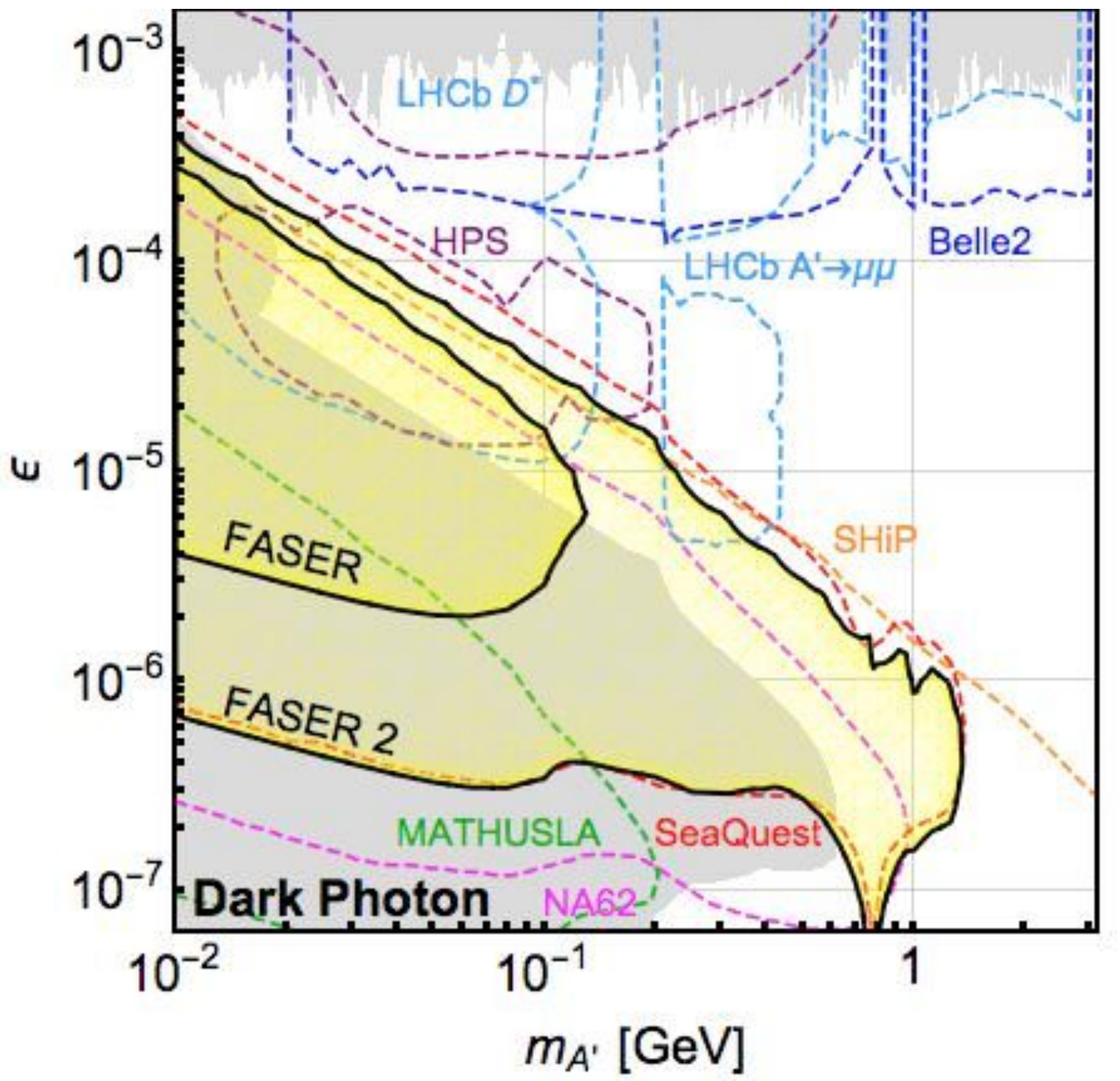
- FASER
  - Collect data during Run 3 (150 fb^{-1})
  - Decay volume: R=10 cm, L=1.5 m
- FASER 2
  - Collect data during HL-LHC (3 ab^{-1})
  - Decay volume: R=1 m, L=5 m



Decay Volume

FASER is complementary to other proposed experiments. FASER covers more parameter space for new particles produced in pion decays

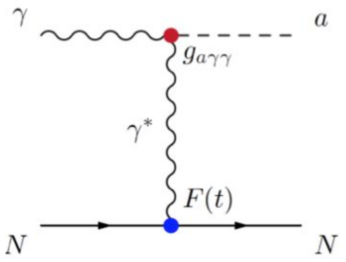
A' as a DM-SM mediator

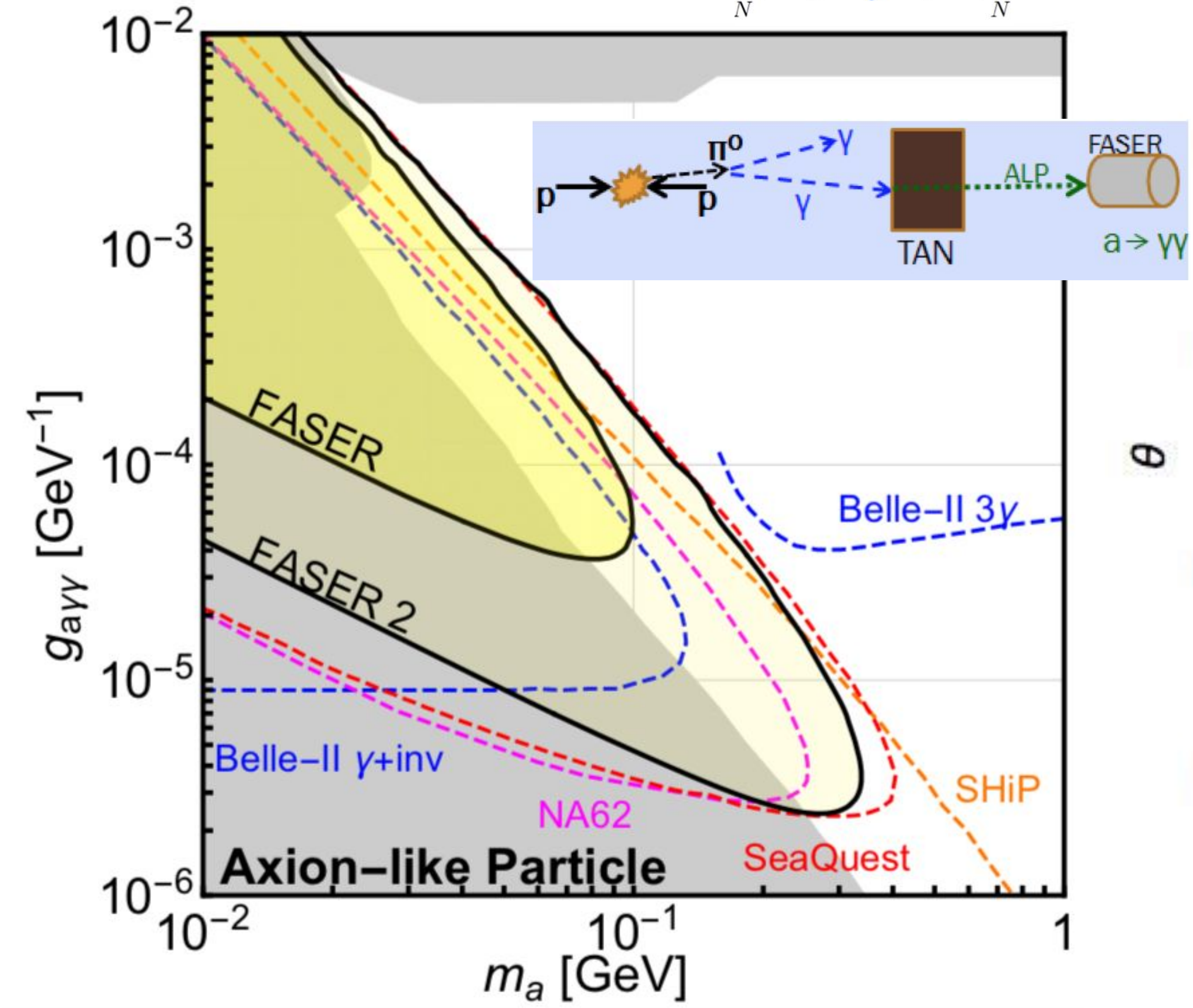


$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 + \epsilon\, e j^\mu_{EM} A'_\mu$$

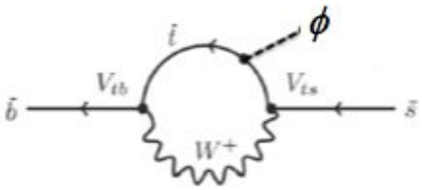
Axion-Like Particle and Dark Higgs

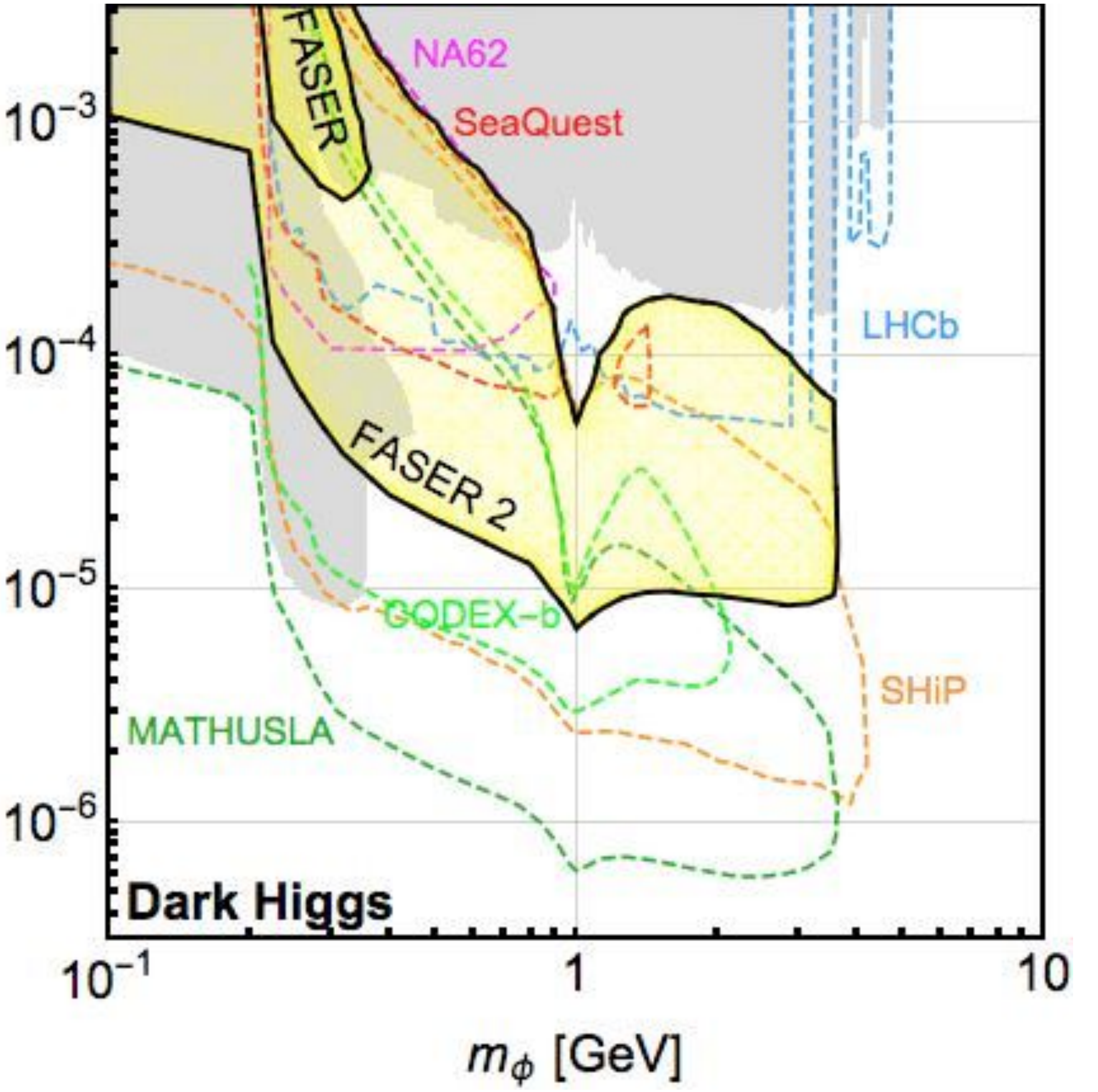
Similar to QCD axion





Dark Higgs-DM portal





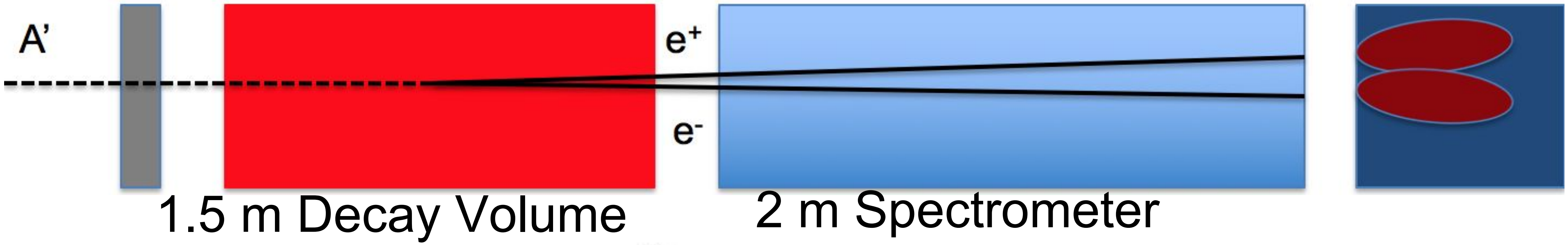
$$\mathcal{L} \supset \frac{1}{2} m_a^2 a^2 + g_{a\gamma\gamma}\, a F^{\mu\nu} \widetilde{F}_{\mu\nu}$$

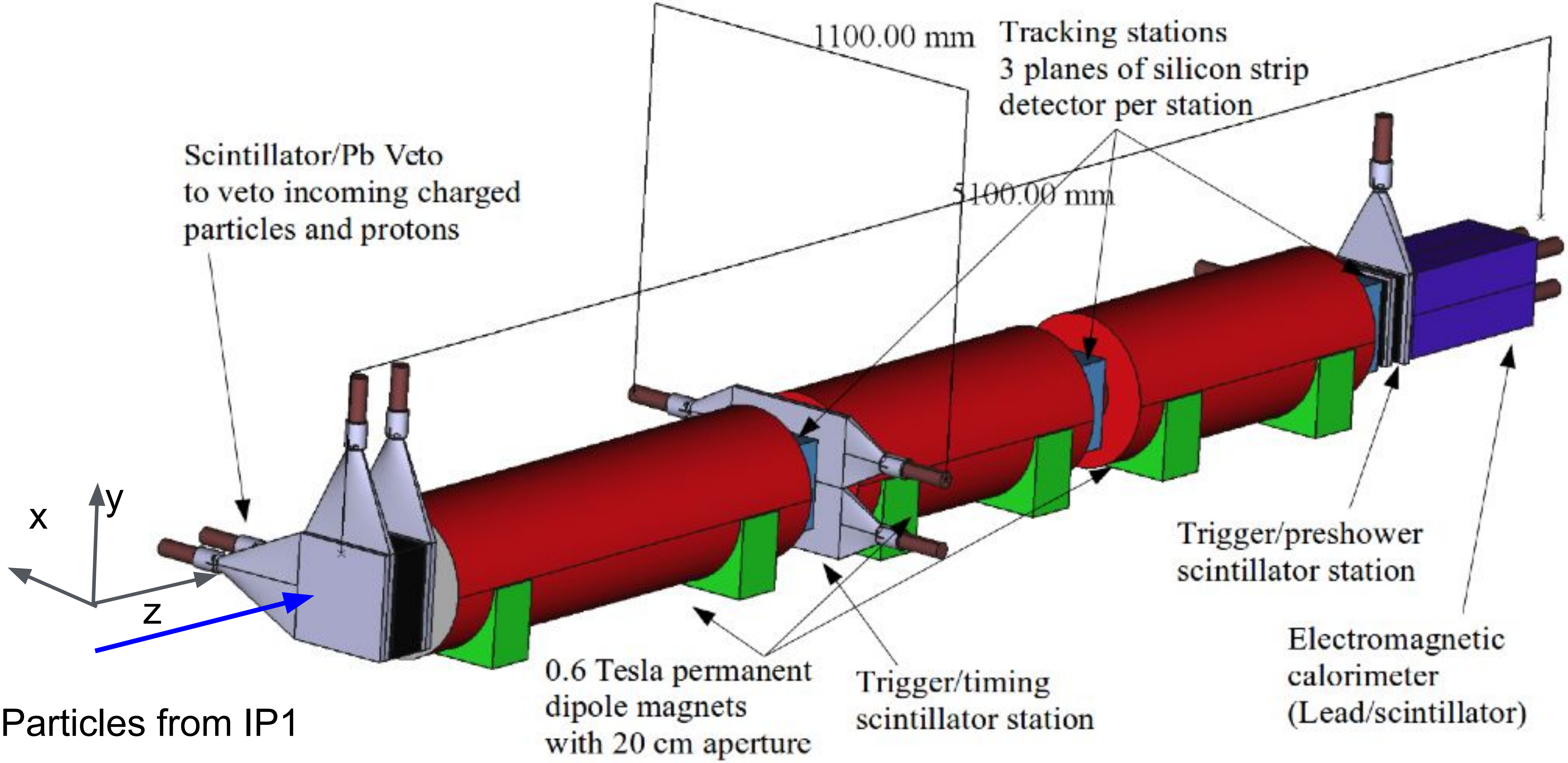
$$\mathcal{L} \supset -m_\phi^2\, \phi^2 - \sin\theta \frac{m_f}{v}\, \phi \bar{f} f - \lambda v h \phi\phi$$

Produced through Primakoff process (γN→aN)

Produced in B decay to probe h-ϕ mixing and h$\phi\phi$ trilinear coupling

Detector Layout





Tracking stations
3 planes of silicon strip
detector per station

Scintillator/Pb Veto
to veto incoming charged
particles and protons

Trigger/preshower
scintillator station

Electromagnetic
calorimeter
(Lead/scintillator)

0.6 Tesla permanent
dipole magnets
with 20 cm aperture

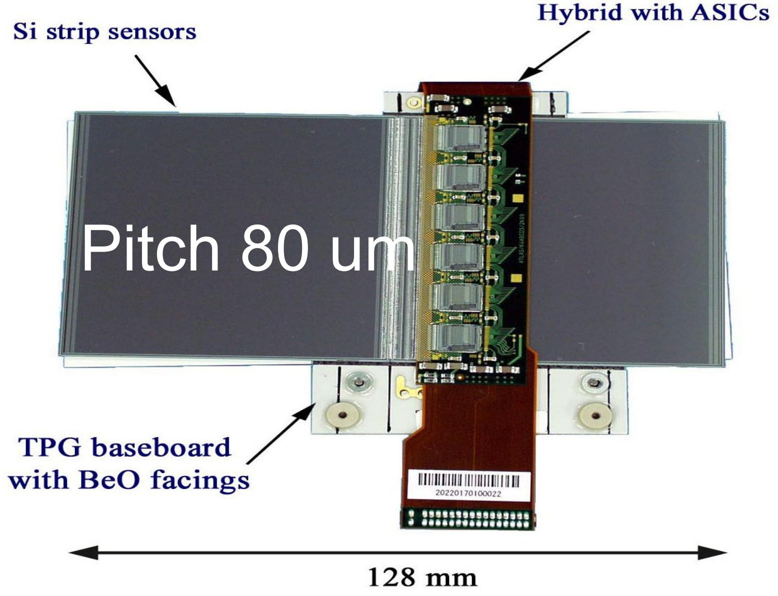
Trigger/timing
scintillator station

Particles from IP1

Detector Technology

ATLAS SCT module

10% mom resolution @ 1TeV muon



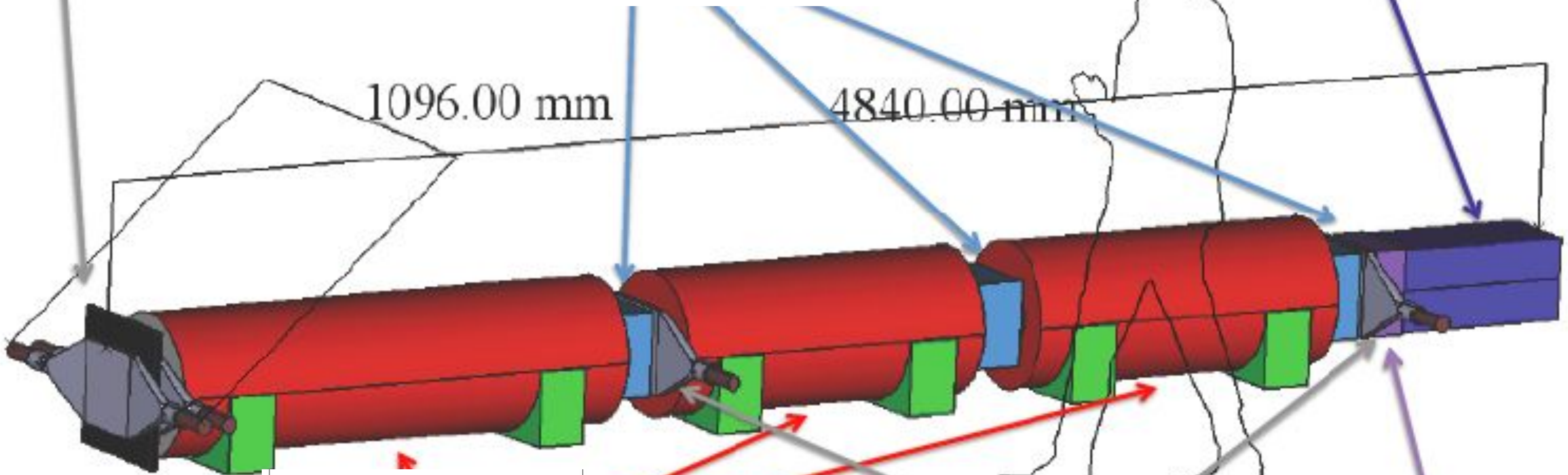
Pitch 80 um

LHCb ECAL module 25 X_0

1% energy resolution @ 1TeV electron

$$\sigma_E/E \approx \frac{10\%}{\sqrt{E}} \oplus 1\%$$

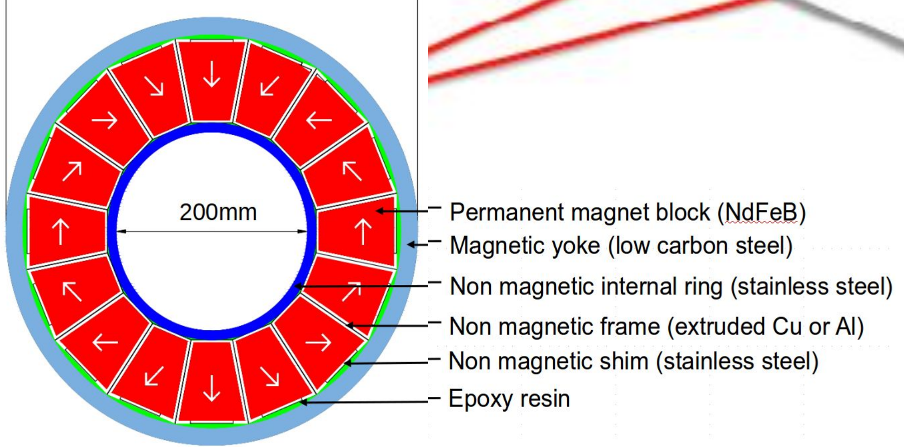
Scintillator/Pb Veto
to veto incoming charged



Scintilator planes
for trigger/timing

Pre-sampler
(to be dropped)

CERN made permanent dipole magnet to minimize services



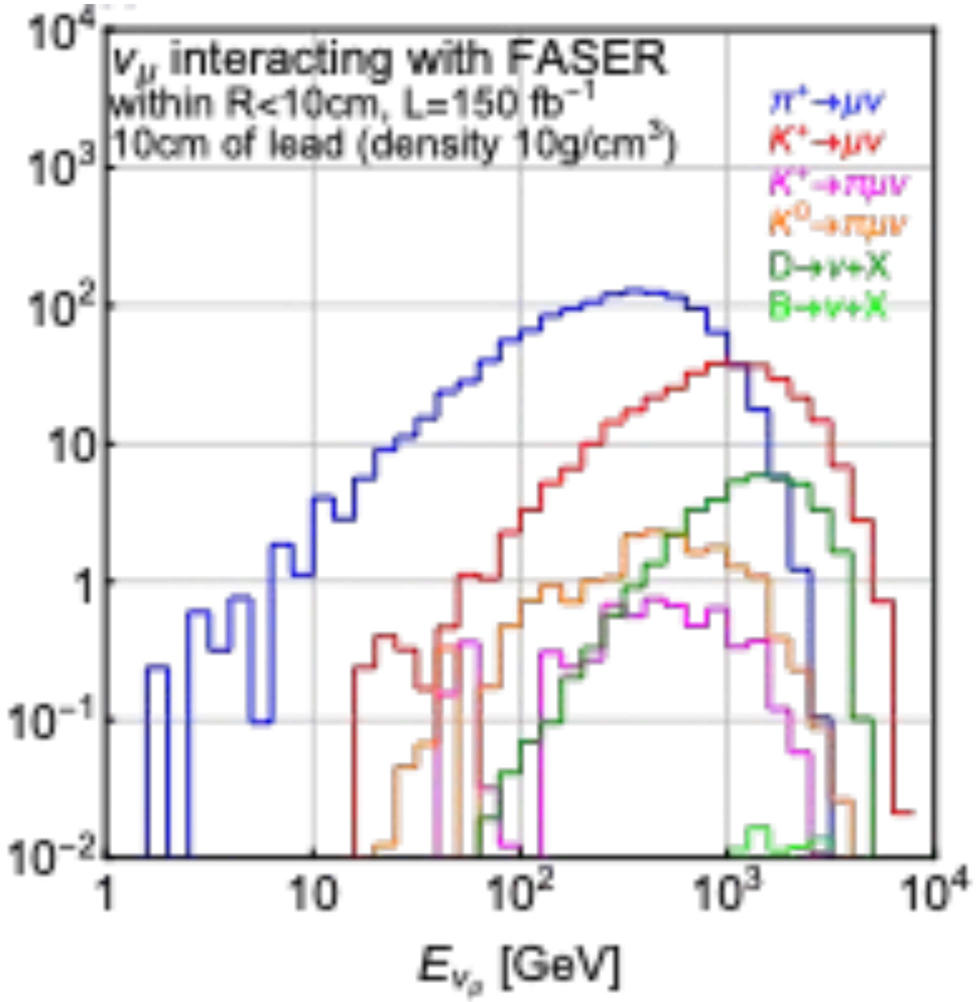
Background - FLUKA simulation

- **Muons coming from IP**

EPOS+theory with FLUKA simulation
70 Hz (>100 GeV) at L=2x10^{34}cm^{-2}s^{-1}

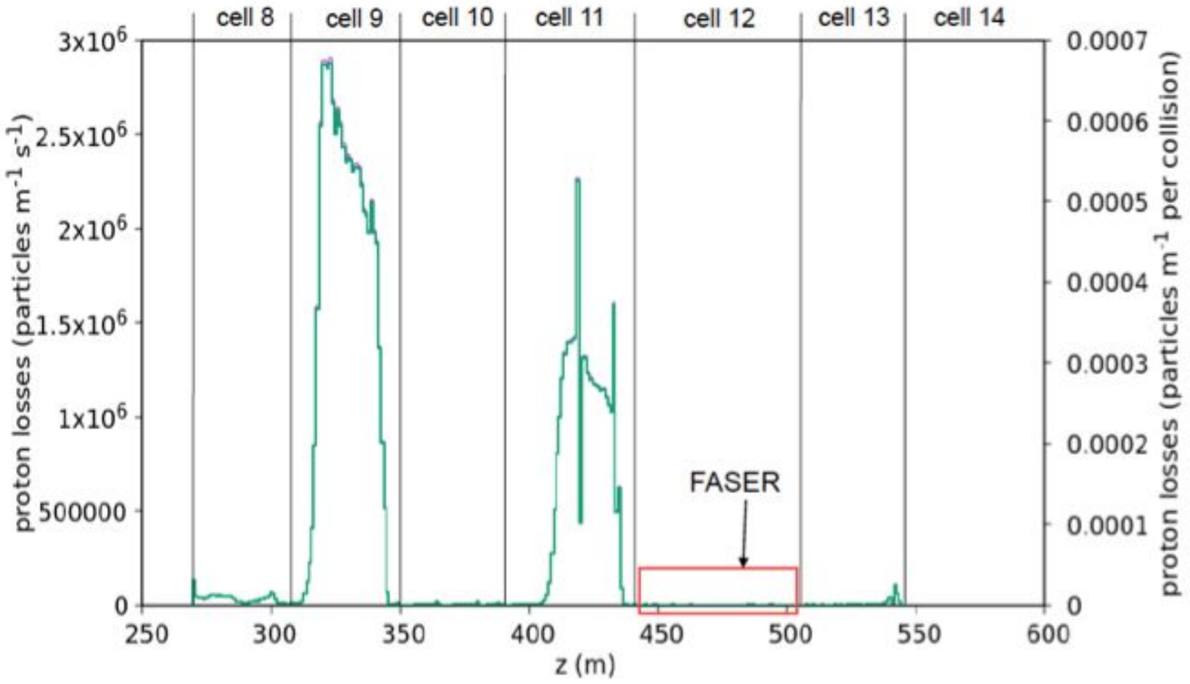
- **Neutrino-induced events: low rate**

a few ~100 GeV events at 150 fb^{-1}

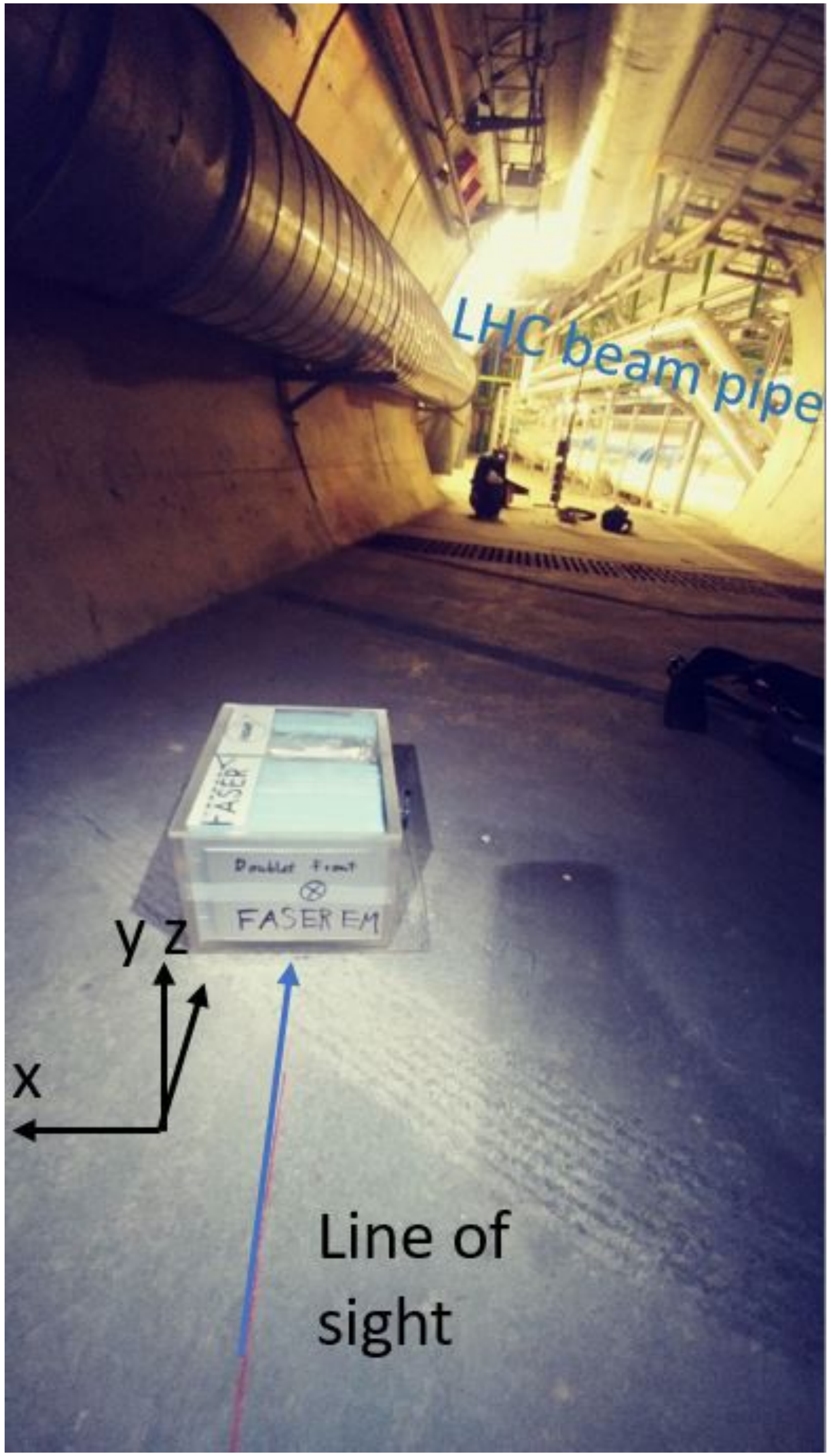


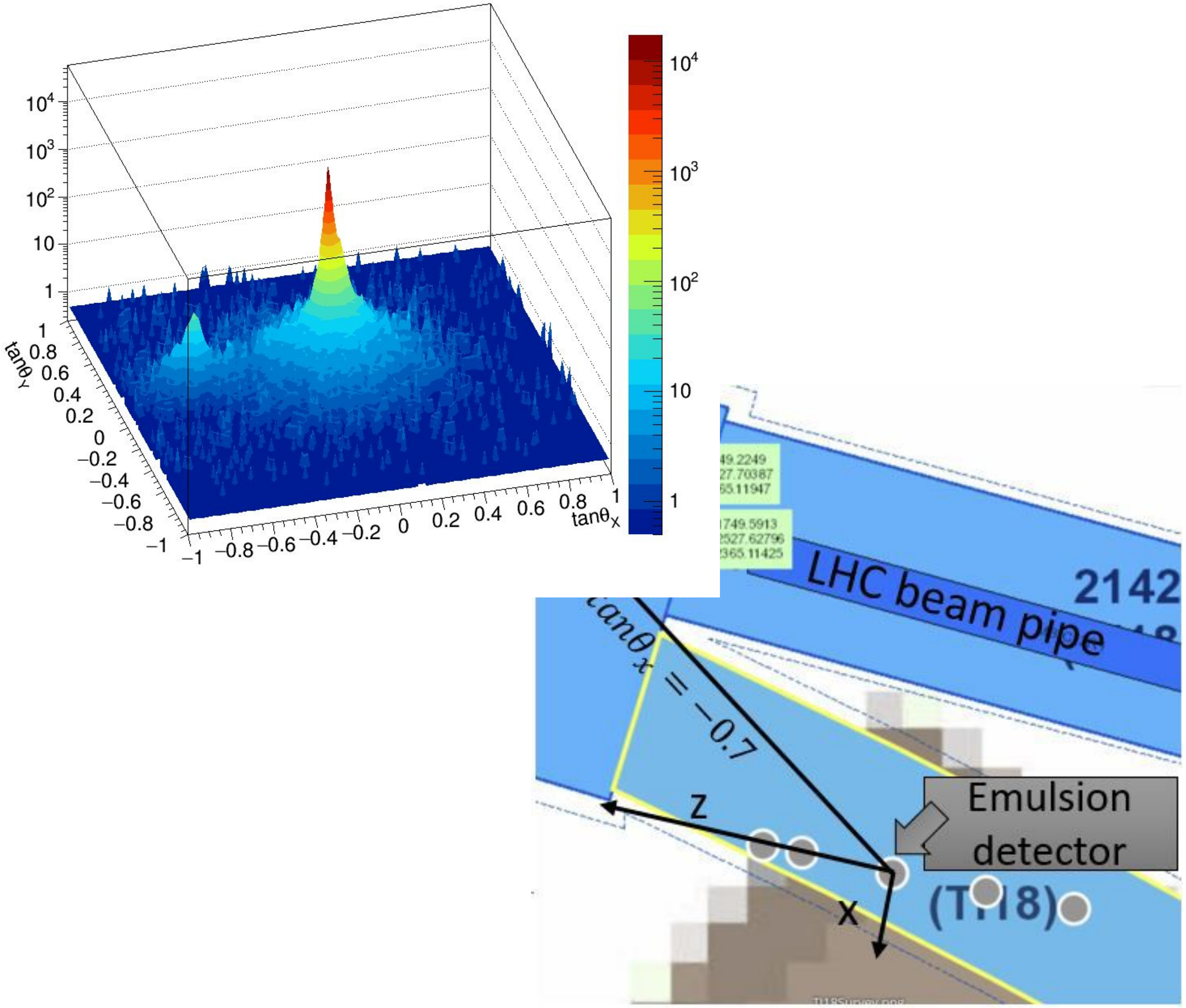
- The FLUKA study also finds that proton showers in dispersion suppressor and beam-gas background (from “beam 2”) are also negligible.
- The radiation level is low (<10^{-2} Gy/year), which is encouraging for detector electronics.

Sabate-Gilarte, Cerutti, Tsinganis (2018)



In-situ background measurements in TI18





- First measurements already performed
  - Emulsion detectors
  - BatMon (Battery-operated radiation monitor)
- First results promising - consistent with FLUKA
- Data analysis and TI12 measurements on-going

The FASER Collaboration

The FASER collaboration: 27 collaborators, 17 institutions, 8 countries

Akitaka Ariga,[1] Tomoko Ariga,[1,2] Jamie Boyd,[3,*] Franck Cadoux,[4] David W. Casper,[5] Francesco Cerutti,[3] Salvatore Danzeca,[3] Liam Dougherty,[3] Yannick Favre,[4] Jonathan L. Feng,[5,†] Didier Ferrere,[4] Jonathan Gall,[3] Iftah Galon,[6] Sergio Gonzalez-Sevilla,[4] Shih-Chieh Hsu,[7] Giuseppe Iacobucci,[4] Enrique Kajomovitz,[8] Felix Kling,[5] Susanne Kuehn,[3] Mike Lamont,[3] Lorne Levinson,[9] Hidetoshi Otono,[2] John Osborne,[3] Brian Petersen,[3] Osamu Sato,[10] Marta Sabaté-Gilarte,[3,11] Matthias Schott,[12] Anna Sfyrla,[4] Jordan Smolinsky,[5] Aaron M. Soffa,[5] Yosuke Takubo,[13] Pierre Thonet,[3] Eric Torrence,[14] Sebastian Trojanowski,[15,16] and Gang Zhang[17]

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九州大学
KYUSHU UNIVERSITY

UNIVERSITY OF OREGON

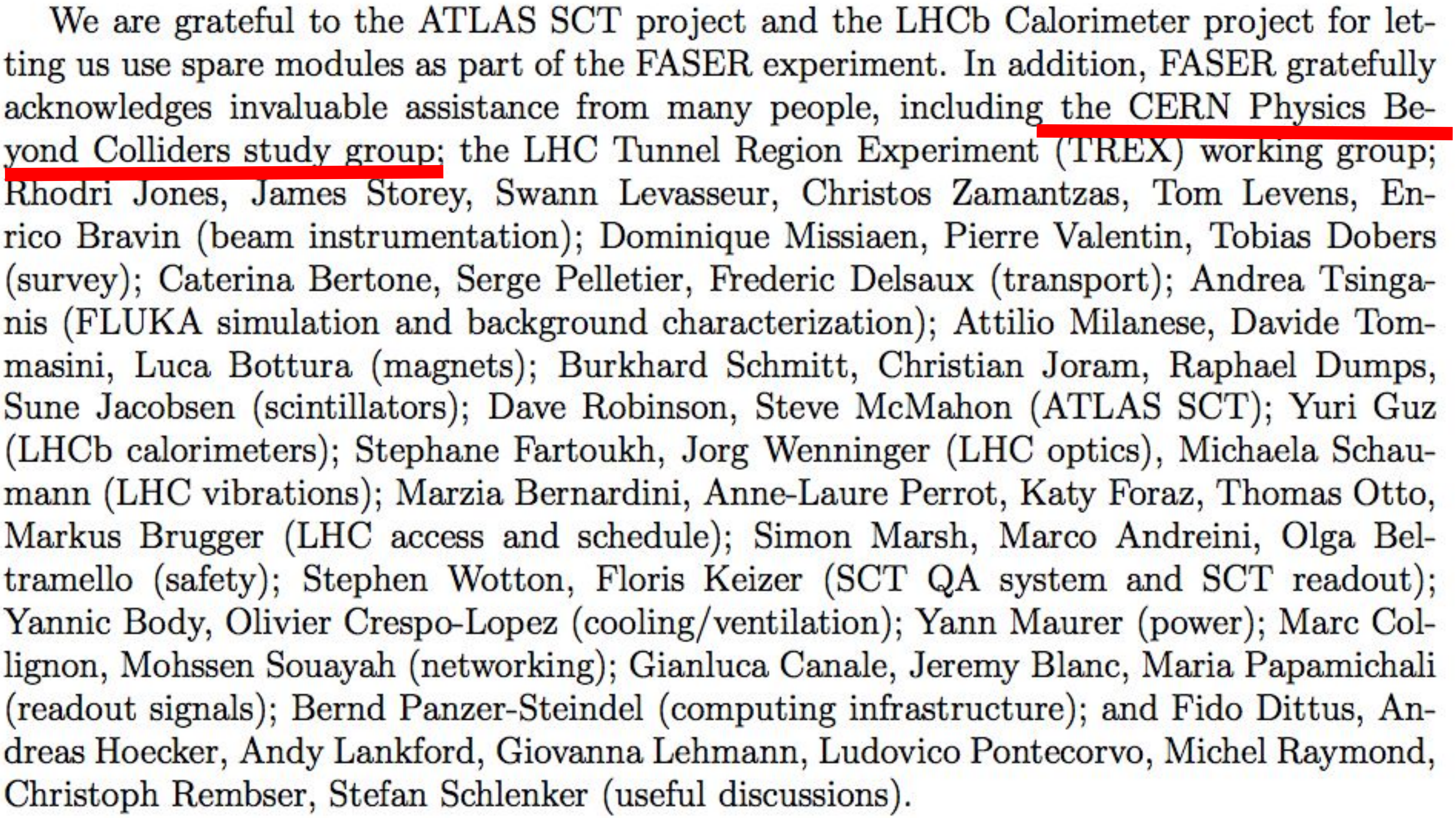
CERN

Weizmann Institute of Science

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

The University Of Sheffield.

Acknowlegement



We are grateful to the ATLAS SCT project and the LHCb Calorimeter project for letting us use spare modules as part of the FASER experiment. In addition, FASER gratefully acknowledges invaluable assistance from many people, including the CERN Physics Beyond Colliders study group; the LHC Tunnel Region Experiment (TREX) working group; Rhodri Jones, James Storey, Swann Levasseur, Christos Zamantzas, Tom Levens, Enrico Bravin (beam instrumentation); Dominique Missiaen, Pierre Valentin, Tobias Dobers (survey); Caterina Bertone, Serge Pelletier, Frederic Delsaux (transport); Andrea Tsinganis (FLUKA simulation and background characterization); Attilio Milanese, Davide Tommasini, Luca Bottura (magnets); Burkhard Schmitt, Christian Joram, Raphael Dumps, Sune Jacobsen (scintillators); Dave Robinson, Steve McMahon (ATLAS SCT); Yuri Guz (LHCb calorimeters); Stephane Fartoukh, Jorg Wenninger (LHC optics), Michaela Schaumann (LHC vibrations); Marzia Bernardini, Anne-Laure Perrot, Katy Foraz, Thomas Otto, Markus Brugger (LHC access and schedule); Simon Marsh, Marco Andreini, Olga Beltramello (safety); Stephen Wotton, Floris Keizer (SCT QA system and SCT readout); Yannic Body, Olivier Crespo-Lopez (cooling/ventilation); Yann Maurer (power); Marc Collignon, Mohssen Souayah (networking); Gianluca Canale, Jeremy Blanc, Maria Papamichali (readout signals); Bernd Panzer-Steindel (computing infrastructure); and Fido Dittus, Andreas Hoecker, Andy Lankford, Giovanna Lehmann, Ludovico Pontecorvo, Michel Raymond, Christoph Rembser, Stefan Schlenker (useful discussions).

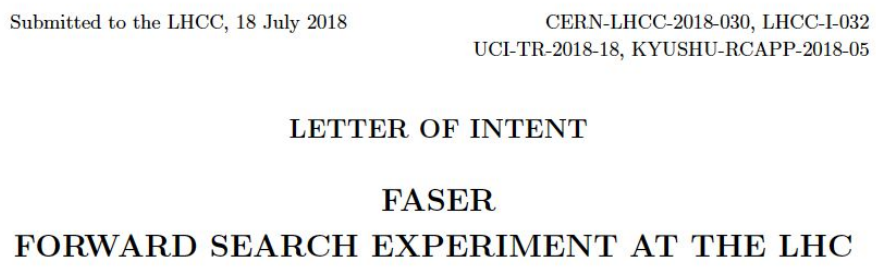
Document

First proposal:

J. Feng, I. Galon, F. Kling, S. Trojanowski [Phys. Rev. D 97, 035001 (2018)]

Letter of Intent

https://arxiv.org/abs/1811.10243



Submitted to the LHCC, 18 July 2018

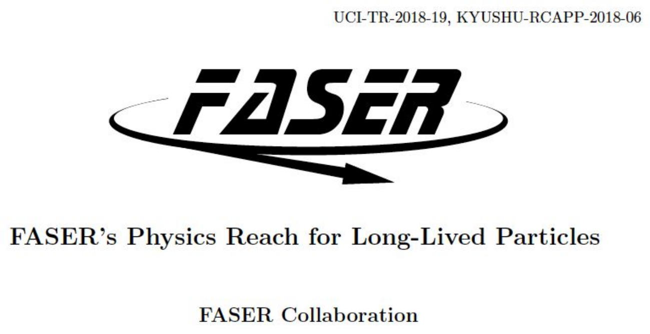
CERN-LHCC-2018-030, LHCC-I-032
UCI-TR-2018-18, KYUSHU-RCAPP-2018-05

LETTER OF INTENT

FASER
FORWARD SEARCH EXPERIMENT AT THE LHC

Physics White paper

https://arxiv.org/abs/1811.12522



UCI-TR-2018-19, KYUSHU-RCAPP-2018-06

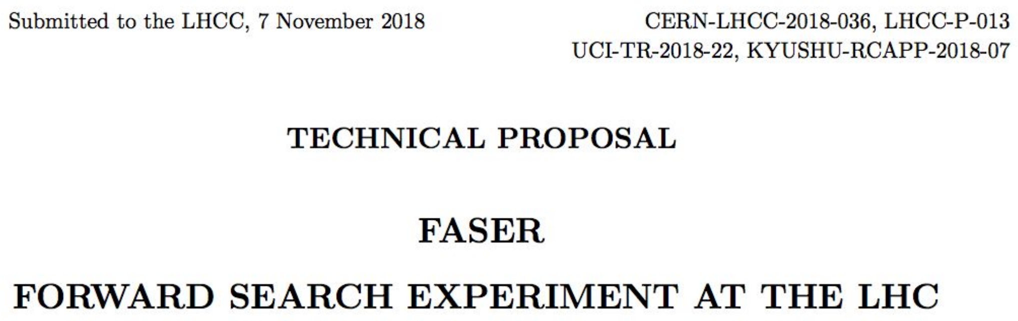
FASER

FASER's Physics Reach for Long-Lived Particles

FASER Collaboration

Technical Proposal

https://arxiv.org/abs/1811.12522



Submitted to the LHCC, 7 November 2018

CERN-LHCC-2018-036, LHCC-P-013
UCI-TR-2018-22, KYUSHU-RCAPP-2018-07

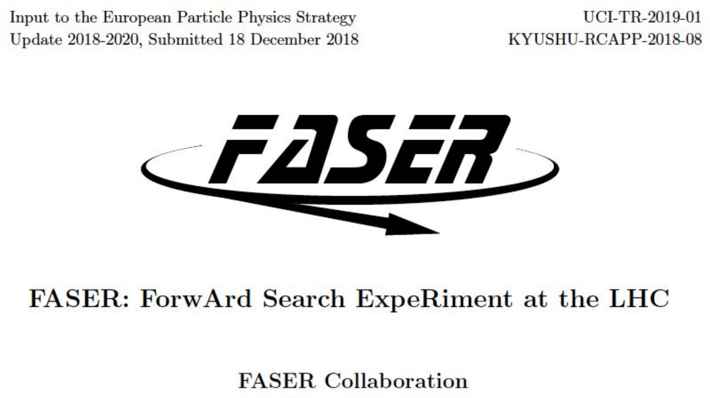
TECHNICAL PROPOSAL

FASER

FORWARD SEARCH EXPERIMENT AT THE LHC

European Strategy

https://arxiv.org/abs/1901.04468



Input to the European Particle Physics Strategy
Update 2018-2020, Submitted 18 December 2018

UCI-TR-2019-01
KYUSHU-RCAPP-2018-08

FASER

FASER: ForwArd Search ExpeRiment at the LHC

FASER Collaboration

Timeline

- Currently Approval Process
  - LOI July 2018 supported by LHCC
  - TP Nov 2018 recommended by LHCC
  - CERN research board approval in Jan 2019
  - Pursuing full approval by LS2 schedule committee by March
  - Magnet construction started soon
  - Procurement, Finalization of Engineering Design, Construction by Spring 2020
  - Installation, Commission starting from Aut 2020
  - Data taking in April **2021** - ready for Run III

- Funding from Simons and Heinsing-Simones
  - 1M CHF from each
  - 420k CHF for Magnet construction
  - 300k CHF for the rest of detectors
  - 300k CHF for Civil Engineering, Transportation, Powering
  - The rest is to support students

Summary

- FASER is an opportunity for a small and inexpensive experiment to search for a full range of light and weakly-interacting particles, complementing other experiments.

- If successful, a possible timeline and plan is
    - Install FASER in LS2 (2019-20) for Run 3 (150 fb^{-1})
        - Decay volume R = 10 cm, L = 1.5 m, requires lowering floor by 50cm
        - Target dark photons, ALPs, etc.
    - Install FASER 2 in LS3 (2023-25) for HL-LHC (3 ab^{-1})
        - Decay volume R = 1 m, L = 5 m, requires some extension of existing tunnel
        - Full physics program: dark photons, B-L gauge boson, ALPs, dark Higgs, HNLs, etc.

DARK MATTER @ LHC 2019

13~16 August

University of Washington

Seattle

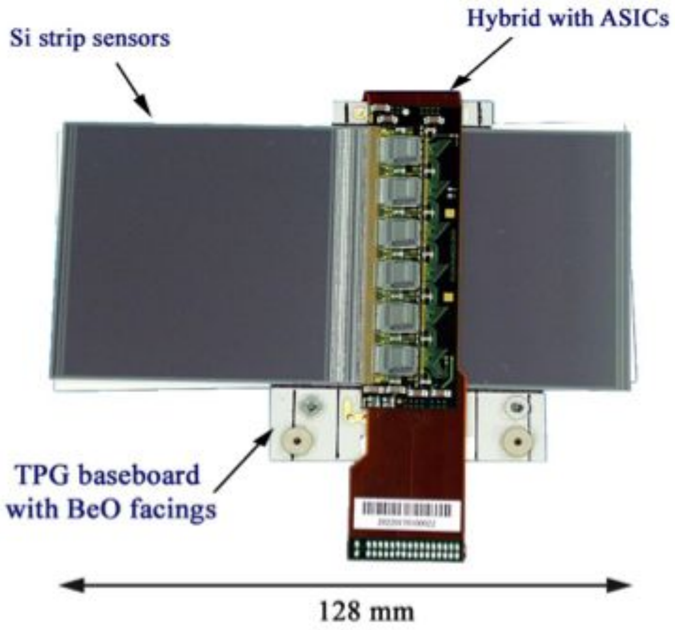
https://indico.cern.ch/event/dmlhc2019

Backup

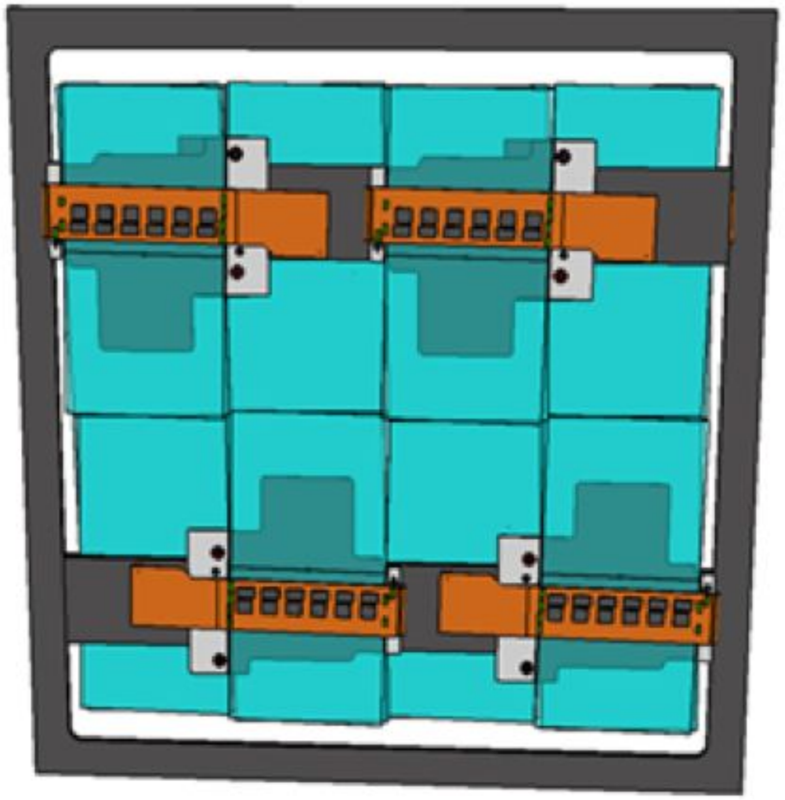
FASER Tracker

- The FASER tracker is composed of spare SCT modules from ATLAS. About 350 spares were prepared. They were not needed, and the ATLAS SCT collaboration has now kindly allowed us to use 80 of them.

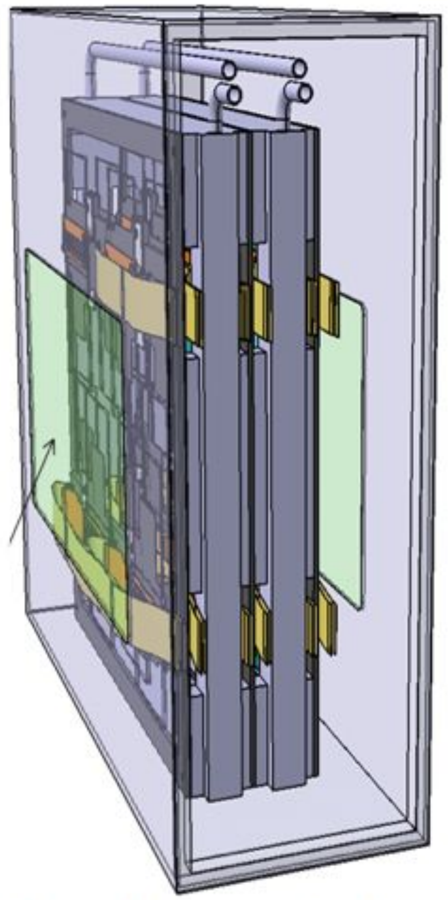
- 8 SCT modules make up a 24cm x 24cm tracking layer, 3 layers make up a tracking station, and FASER has 3 tracking stations.



SCT module

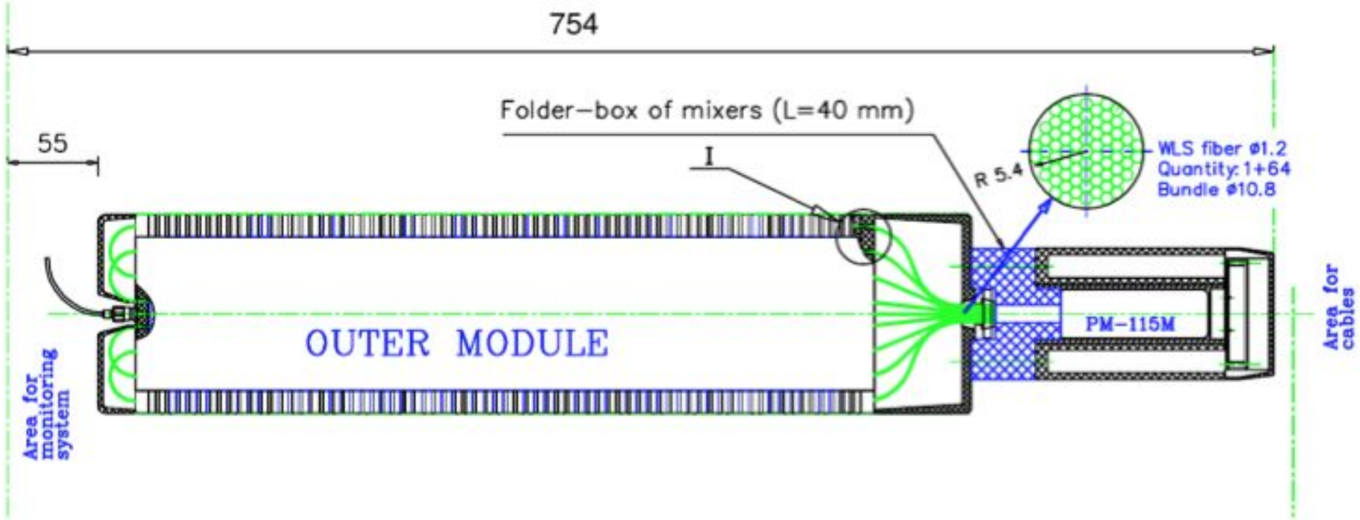


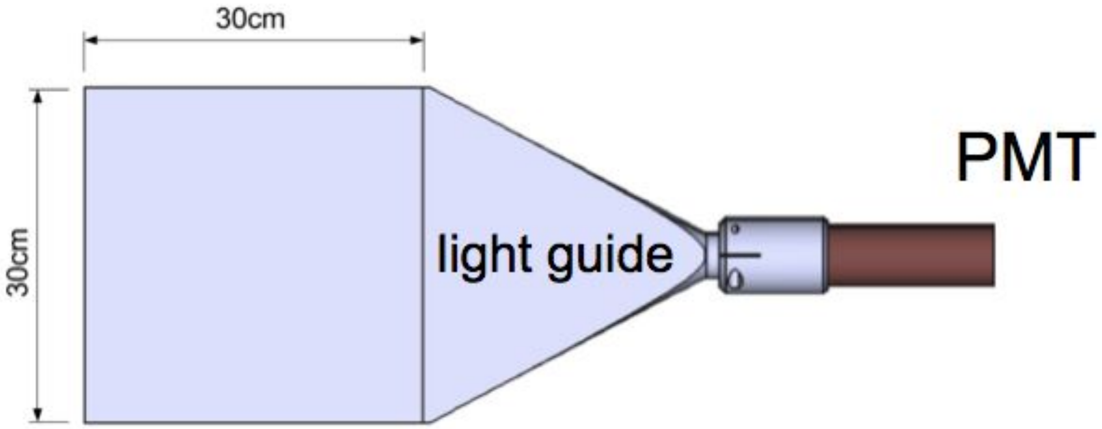
Tracking layer



Tracking station

FASER Calorimeter and Scintillator

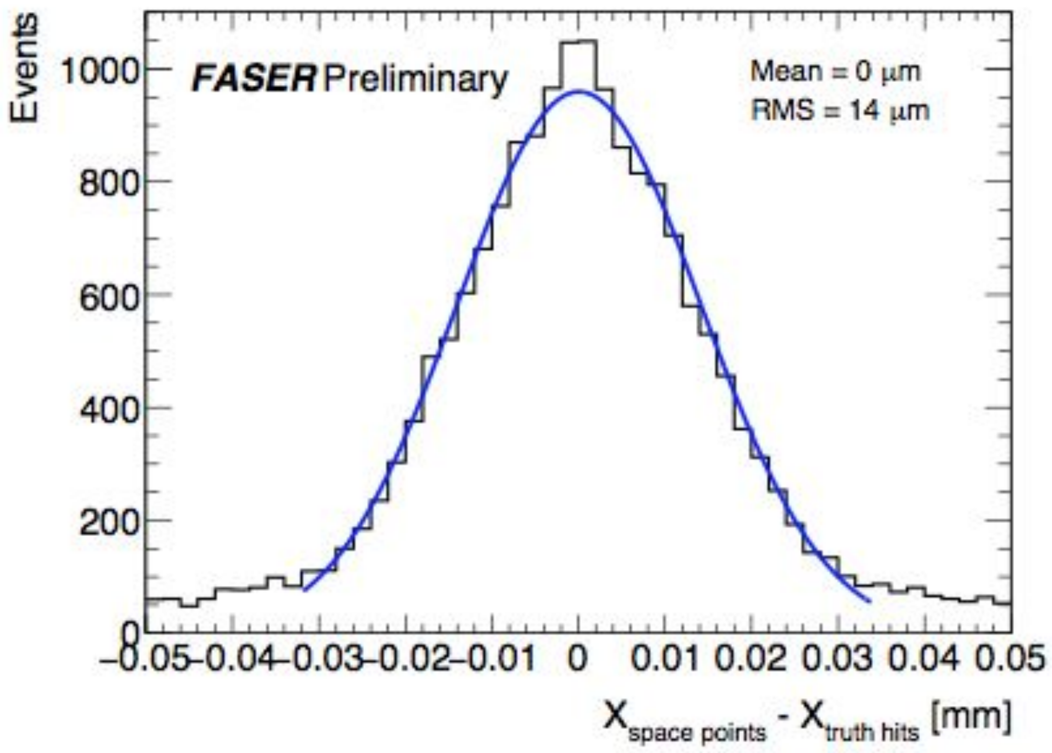


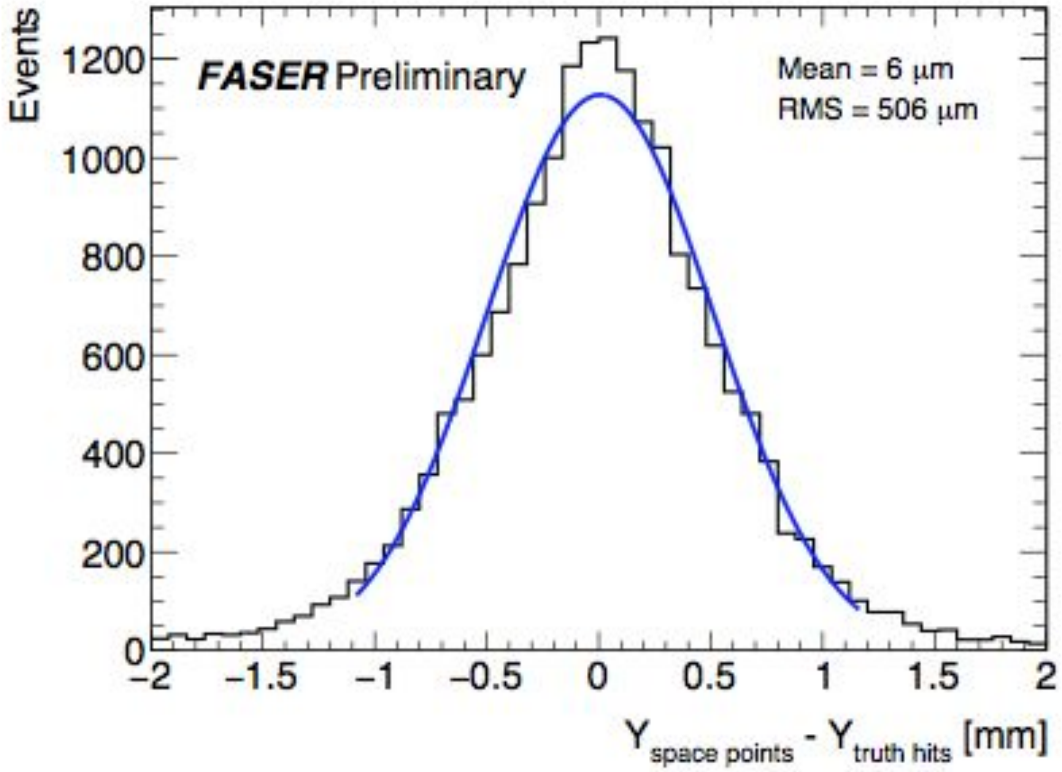


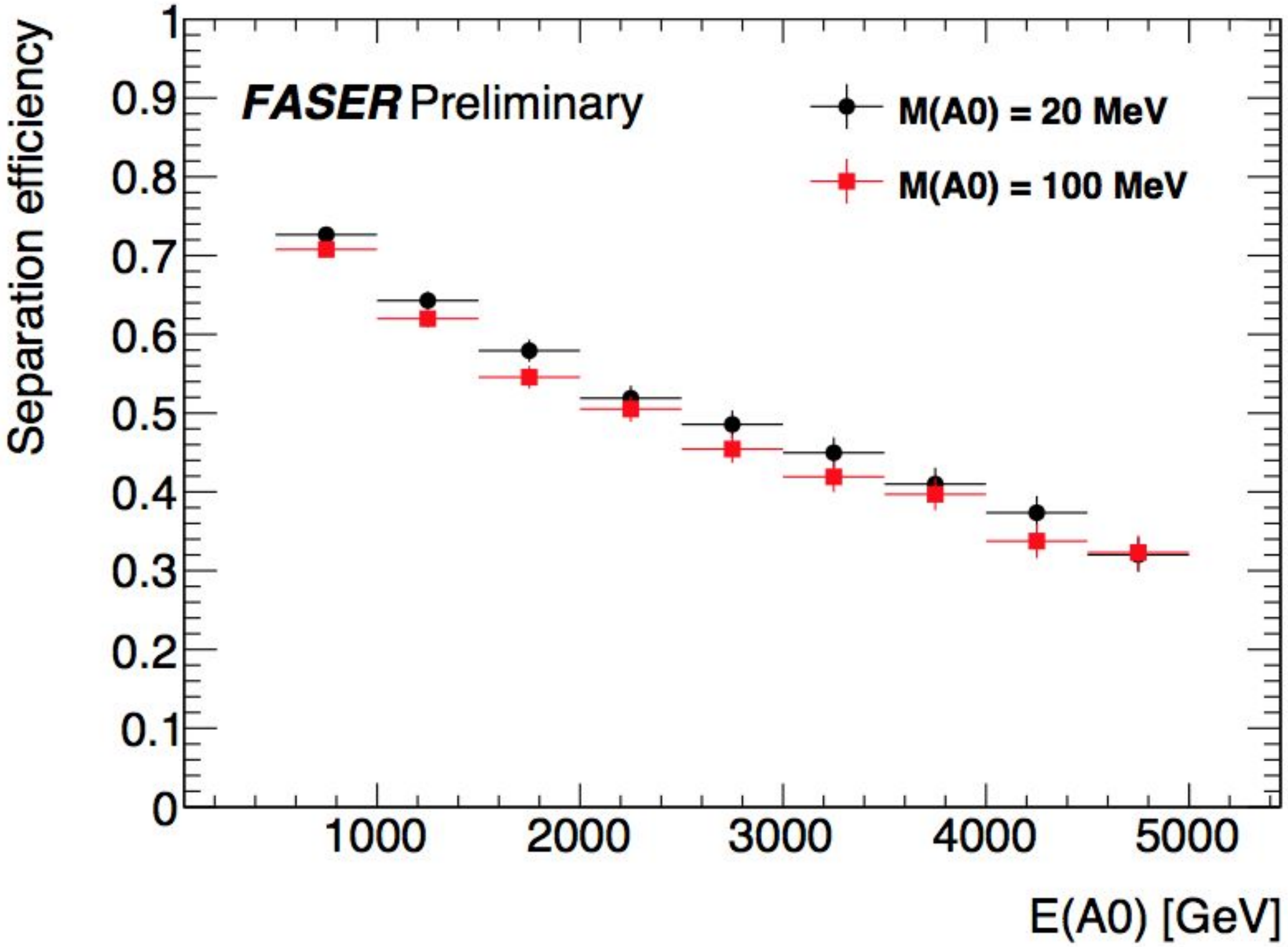
- The FASER ECAL will consist of spare LHCb outer ECAL modules, which the LHCb Collaboration has kindly allowed us to use.
    - Dimensions: 12cm x 12cm – 75cm long (including PMT)
    - 66 layers of lead/scintillator, light out by wavelength shifting fibres, and readout by PMT (no longitudinal shower information)
    - 25 radiation lengths long
    - Provides ~1% energy resolution for 1 TeV electrons

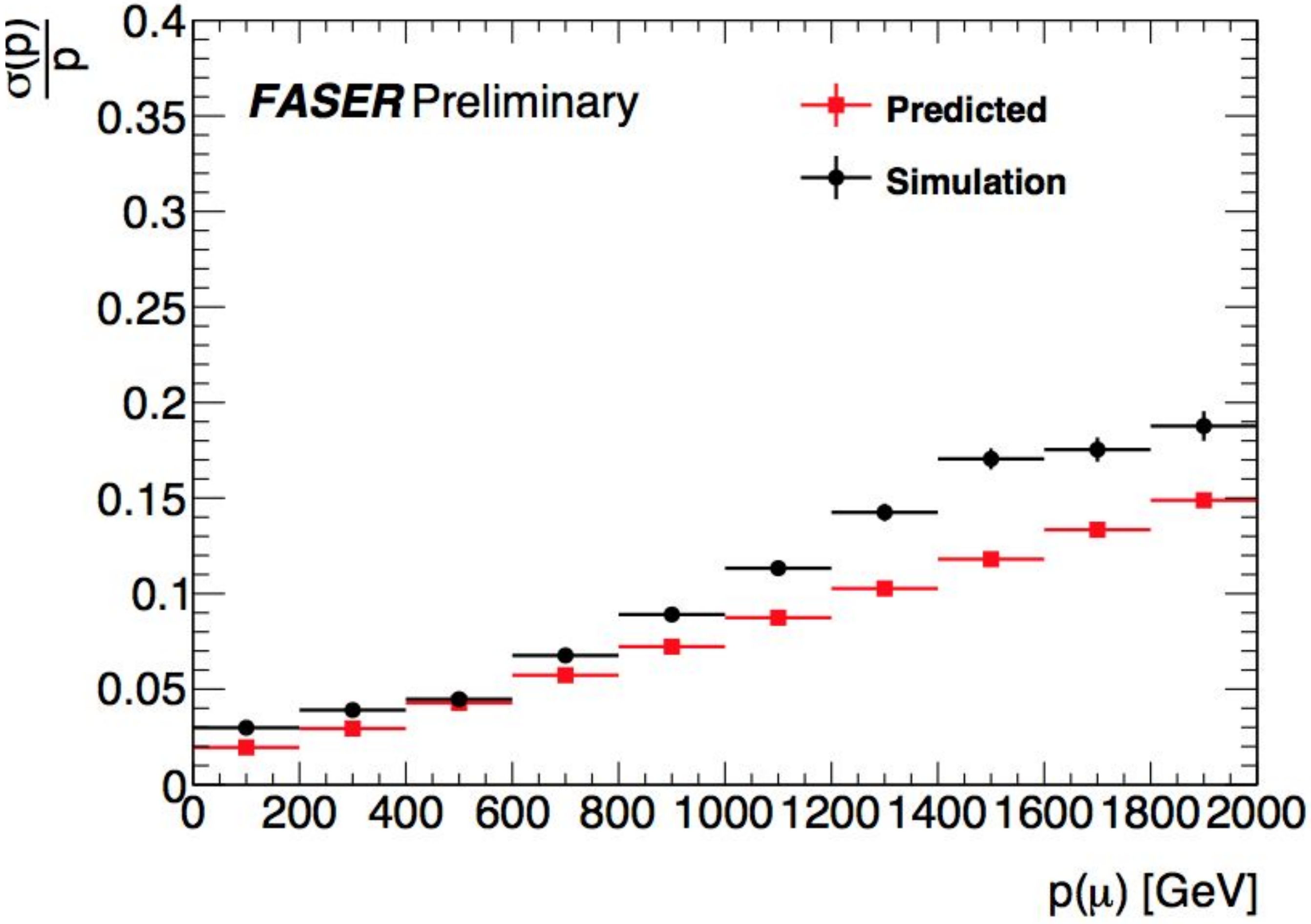
- Scintillators used for vetoing charged particles entering the decay volume and for triggering, to be produced by the CERN scintillator lab

FASER Tracker Performance



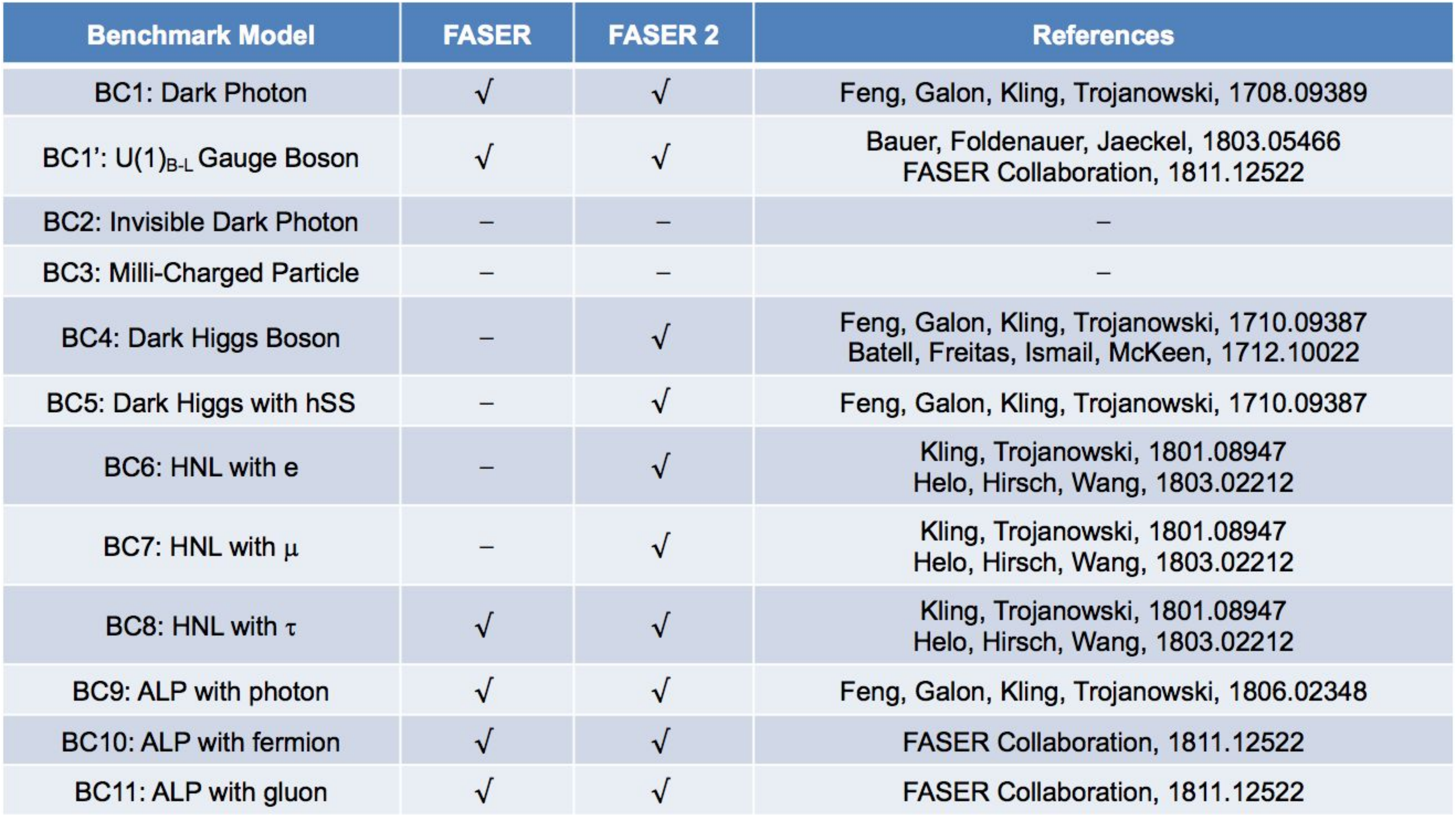






FASER Physics Summary

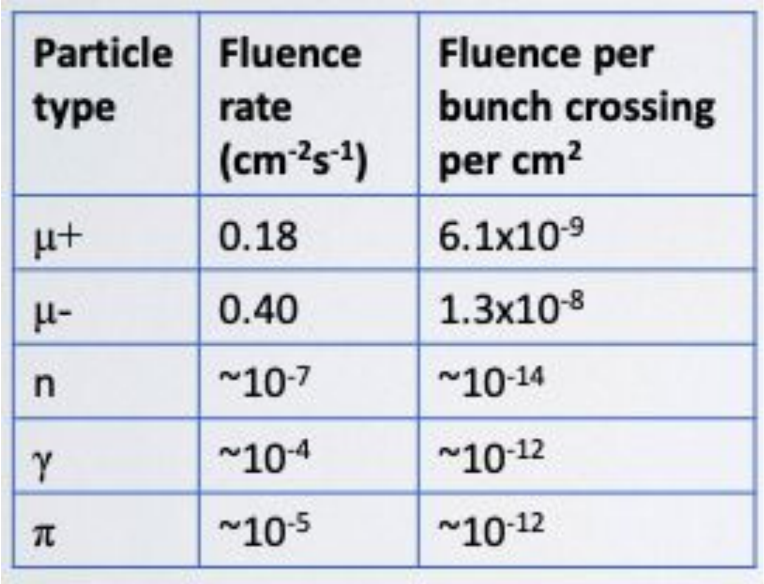
FASER has a full physics program: can discover all candidates with renormalizable couplings (dark photon, dark Higgs, HNL); ALPs with all types of couplings (g, f, g); and many other examples.



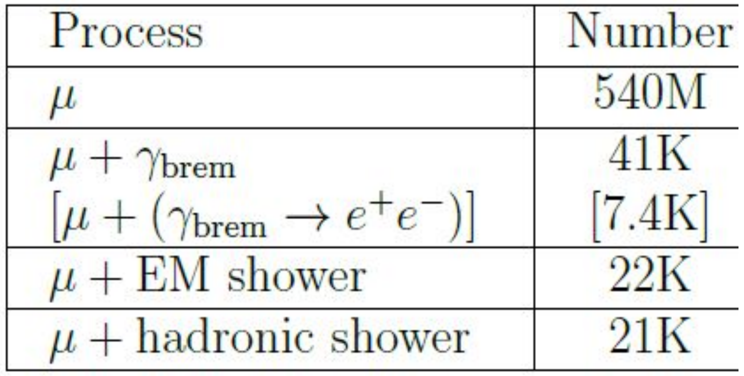
Benchmark Model	FASER	FASER 2	References
BC1: Dark Photon	√	√	Feng, Galon, Kling, Trojanowski, 1708.09389
BC1': U(1)$_{B-L}$ Gauge Boson	√	√	Bauer, Foldenauer, Jaeckel, 1803.05466 FASER Collaboration, 1811.12522
BC2: Invisible Dark Photon	–	–	–
BC3: Milli-Charged Particle	–	–	–
BC4: Dark Higgs Boson	–	√	Feng, Galon, Kling, Trojanowski, 1710.09387 Batell, Freitas, Ismail, McKeen, 1712.10022
BC5: Dark Higgs with hSS	–	√	Feng, Galon, Kling, Trojanowski, 1710.09387
BC6: HNL with e	–	√	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
BC7: HNL with μ	–	√	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
BC8: HNL with τ	√	√	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
BC9: ALP with photon	√	√	Feng, Galon, Kling, Trojanowski, 1806.02348
BC10: ALP with fermion	√	√	FASER Collaboration, 1811.12522
BC11: ALP with gluon	√	√	FASER Collaboration, 1811.12522

FLUKA Simulation

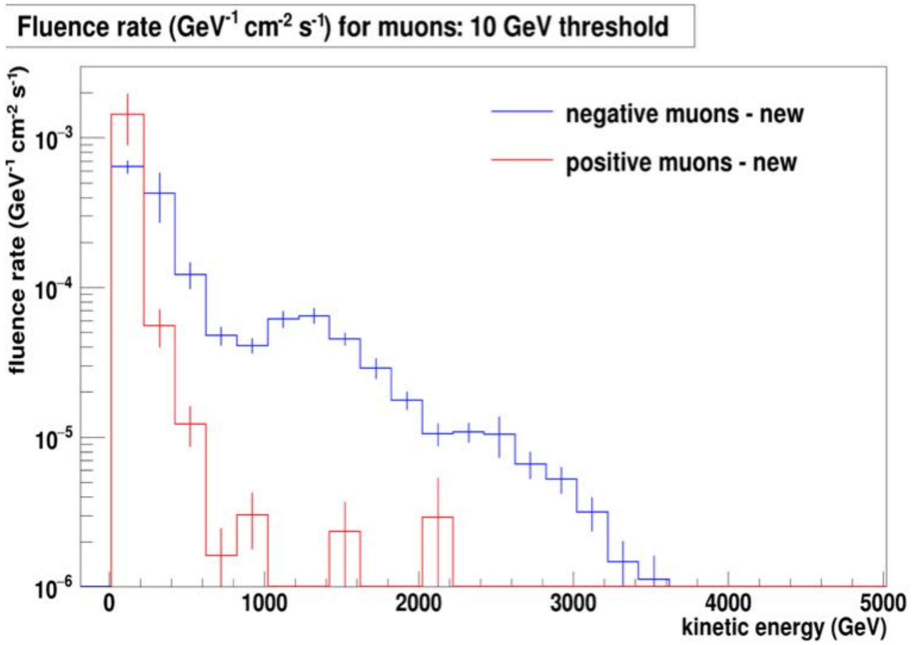
- For HL-LHC conditions Luminosity: 5×10^{34} cm^{-2}s^{-1} Cross section p-p collision: 85 mb Pile-up: 140 events/bunch crossing
- A high-energy muon that brems off a photon or an EM or hadronic jet is a leading background if the incoming muon is not vetoed.

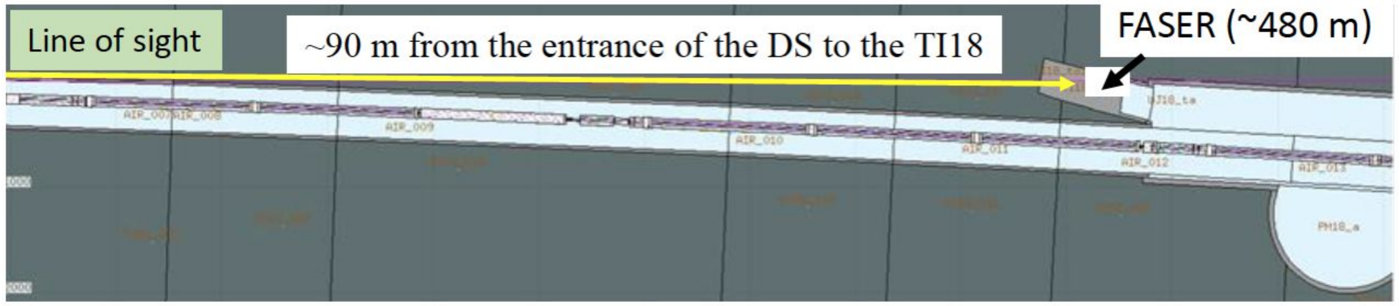


Particle type	Fluence rate (cm^{-2}s^{-1})	Fluence per bunch crossing per cm^2
μ+	0.18	6.1×10^{-9}
μ-	0.40	1.3×10^{-8}
n	~10^{-7}	~10^{-14}
γ	~10^{-4}	~10^{-12}
π	~10^{-5}	~10^{-12}

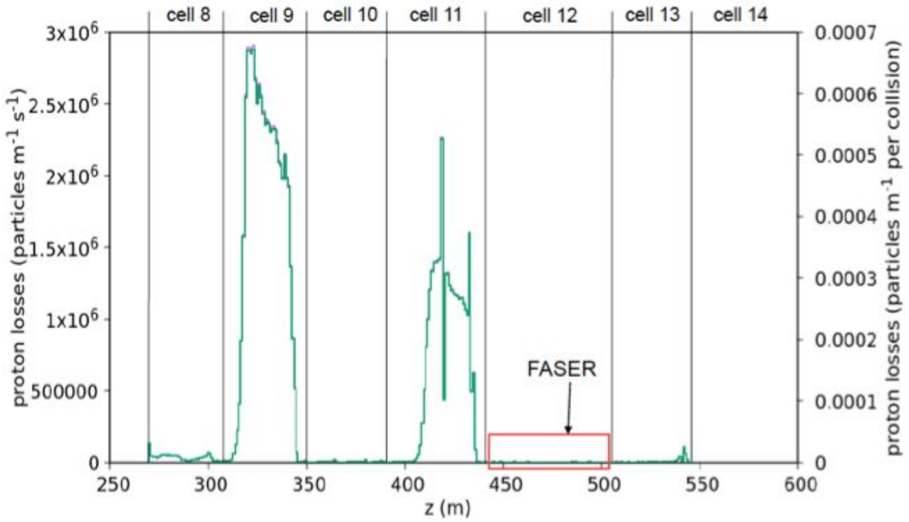


Process	Number
μ	540M
$\mu + \gamma_{\text{brem}}$ $[\mu + (\gamma_{\text{brem}} \to e^+e^-)]$	41K [7.4K]
$\mu +$ EM shower	22K
$\mu +$ hadronic shower	21K



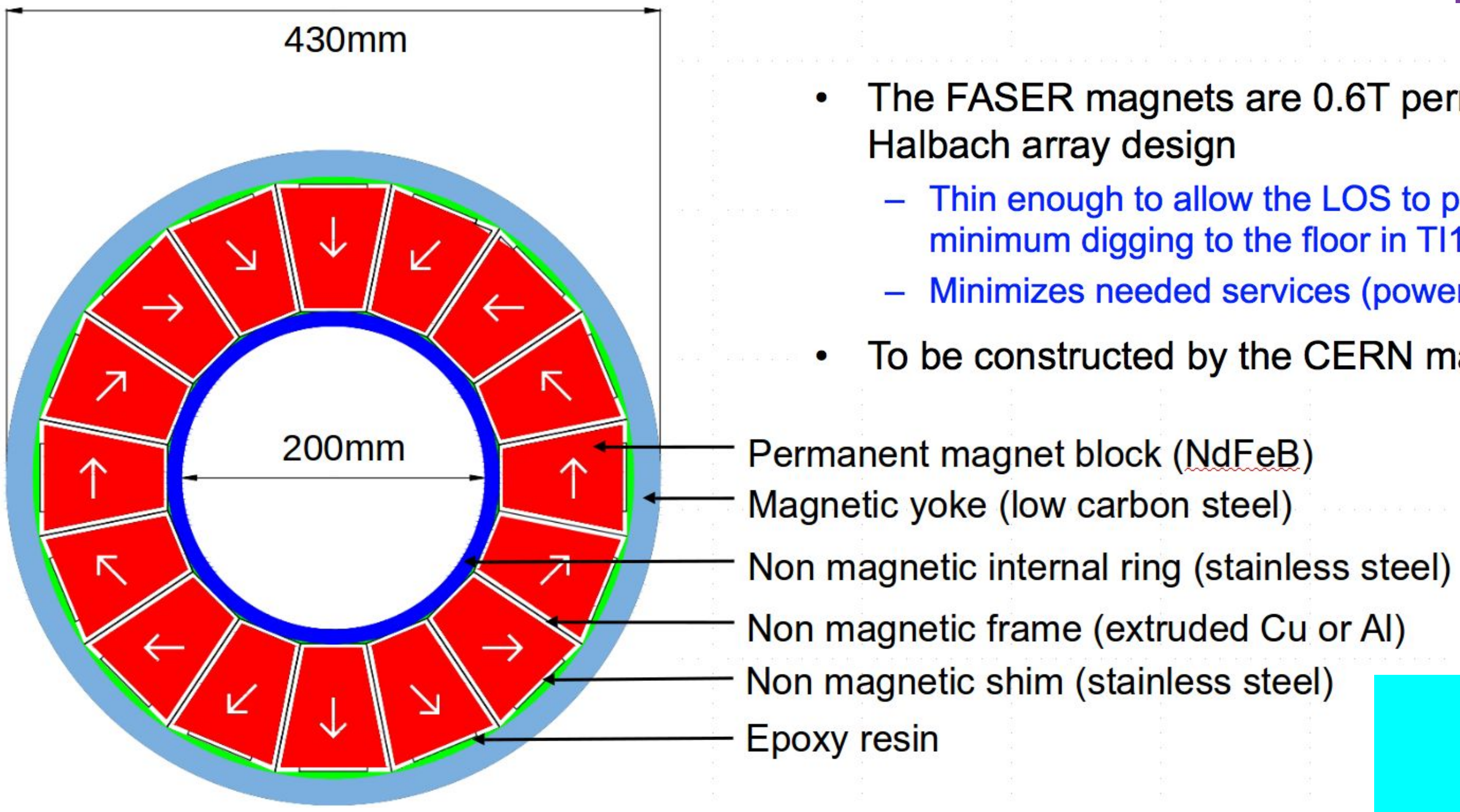


proton showers in dispersion suppressor and beam-gas background (from "beam 2") are also negligible. The radiation level is low (<10^{-2} Gy/year), which is encouraging for ddetector electronics.

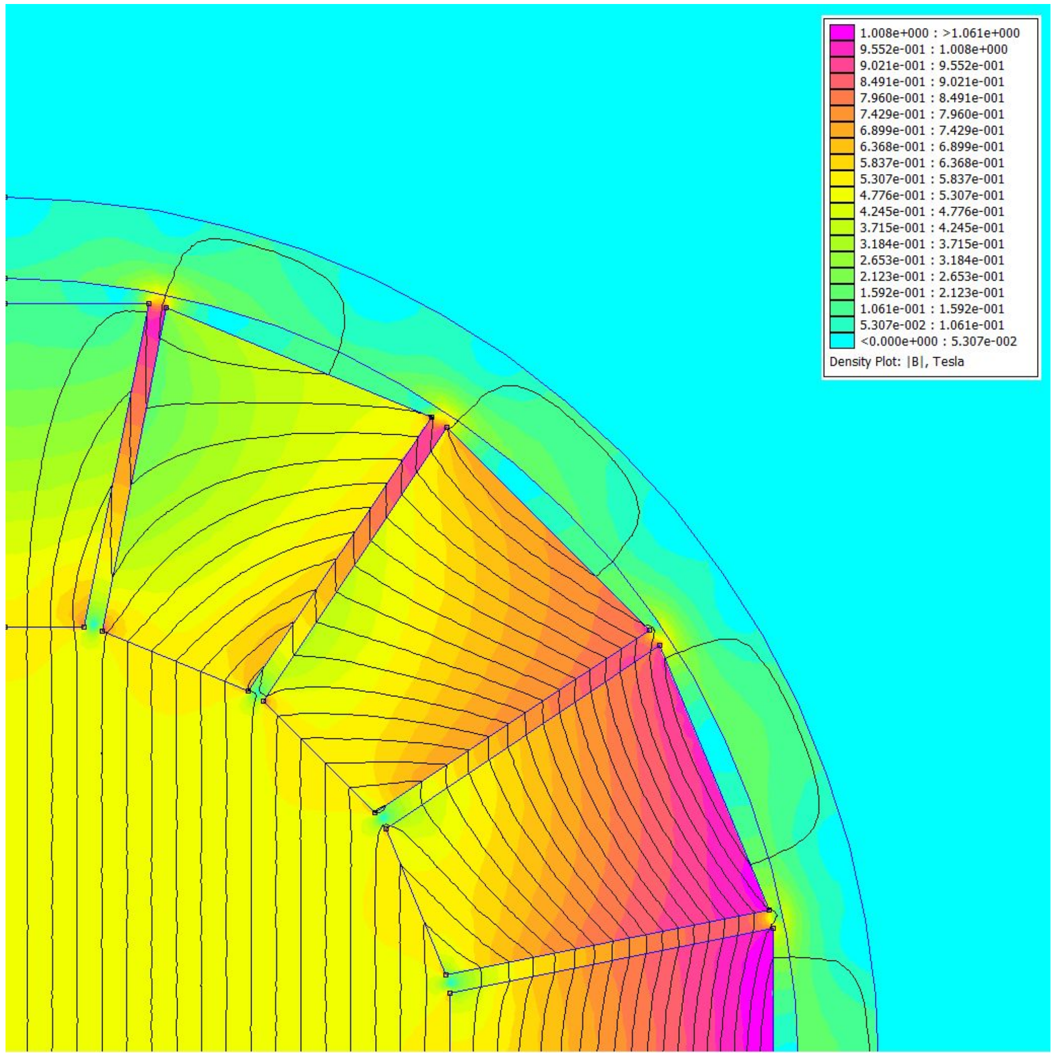


Magnet

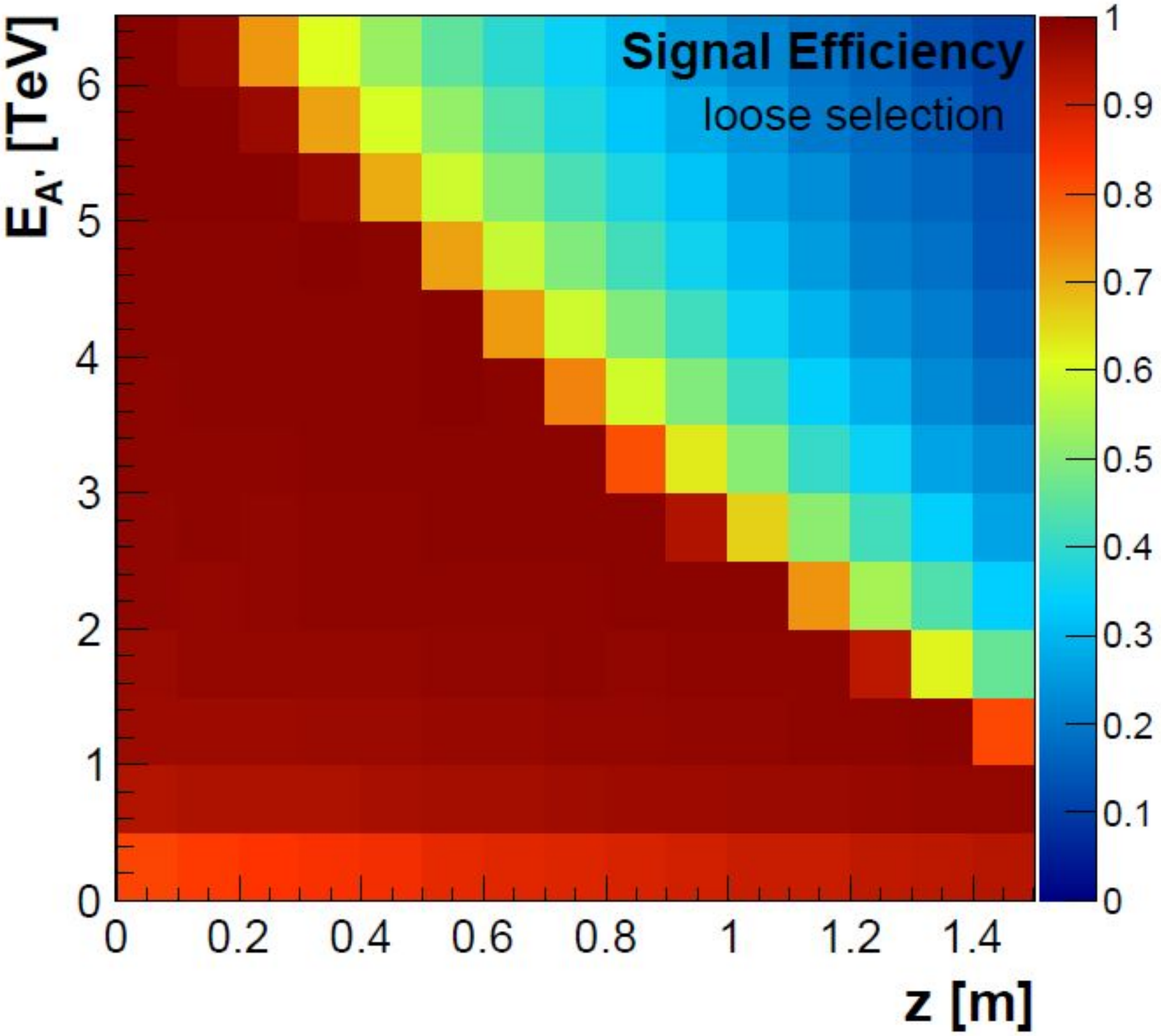
- The FASER magnets are 0.6T permanent dipole magnets based on the Halbach array design
  - Thin enough to allow the LOS to pass through the magnet center with minimum digging to the floor in TI12
  - Minimizes needed services (power, cooling etc..)
- To be constructed by the CERN magnet group

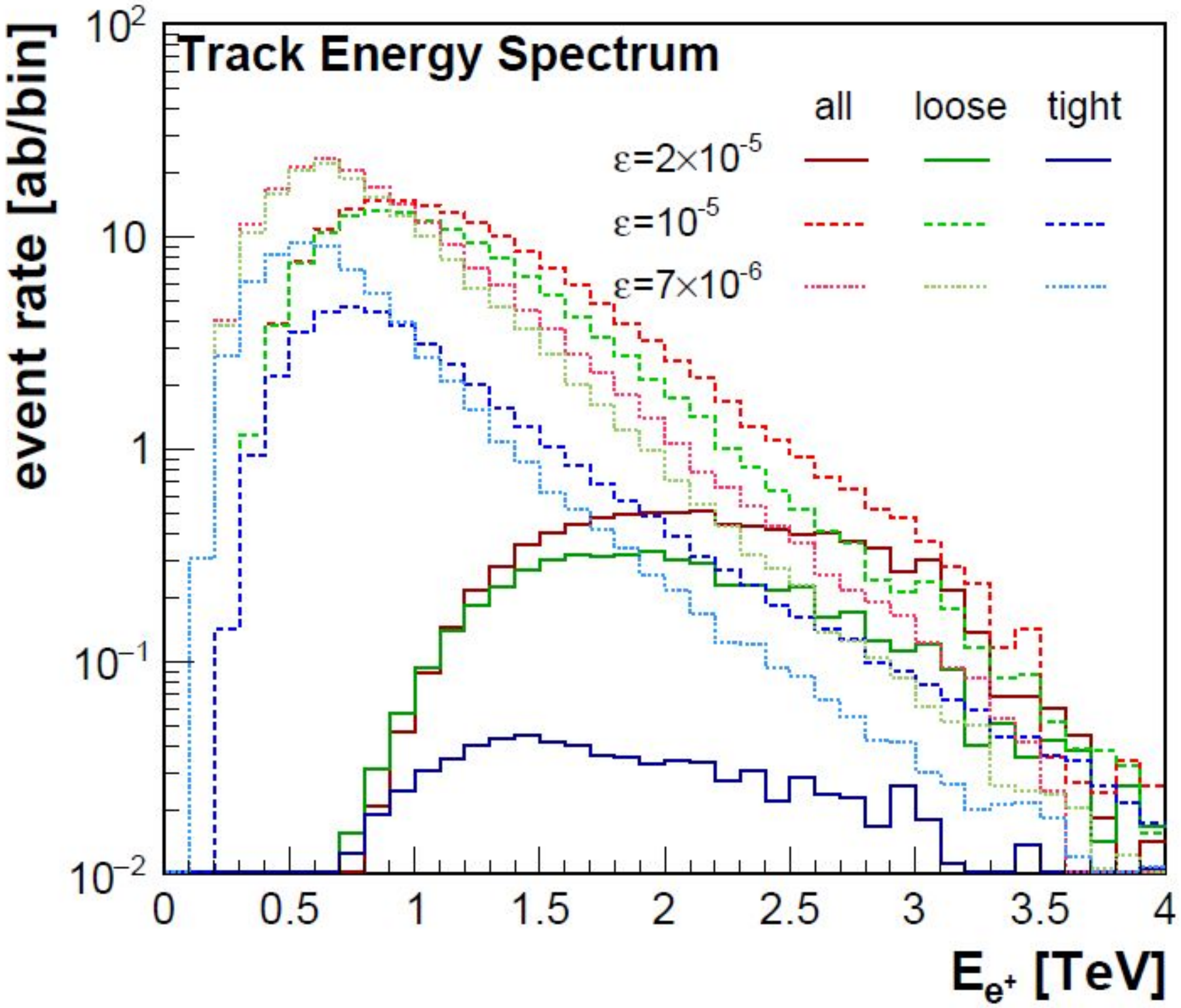


Parameter	Value	Unit
Magnetic material	NdFeB	
Central Field	0.6	T
Aperture	200	mm
Outer diameter	430	mm
Field homogeneity	±2	%
Temperature dependence	-0.12	%/K
Weight / meter	≈1000	kg/m

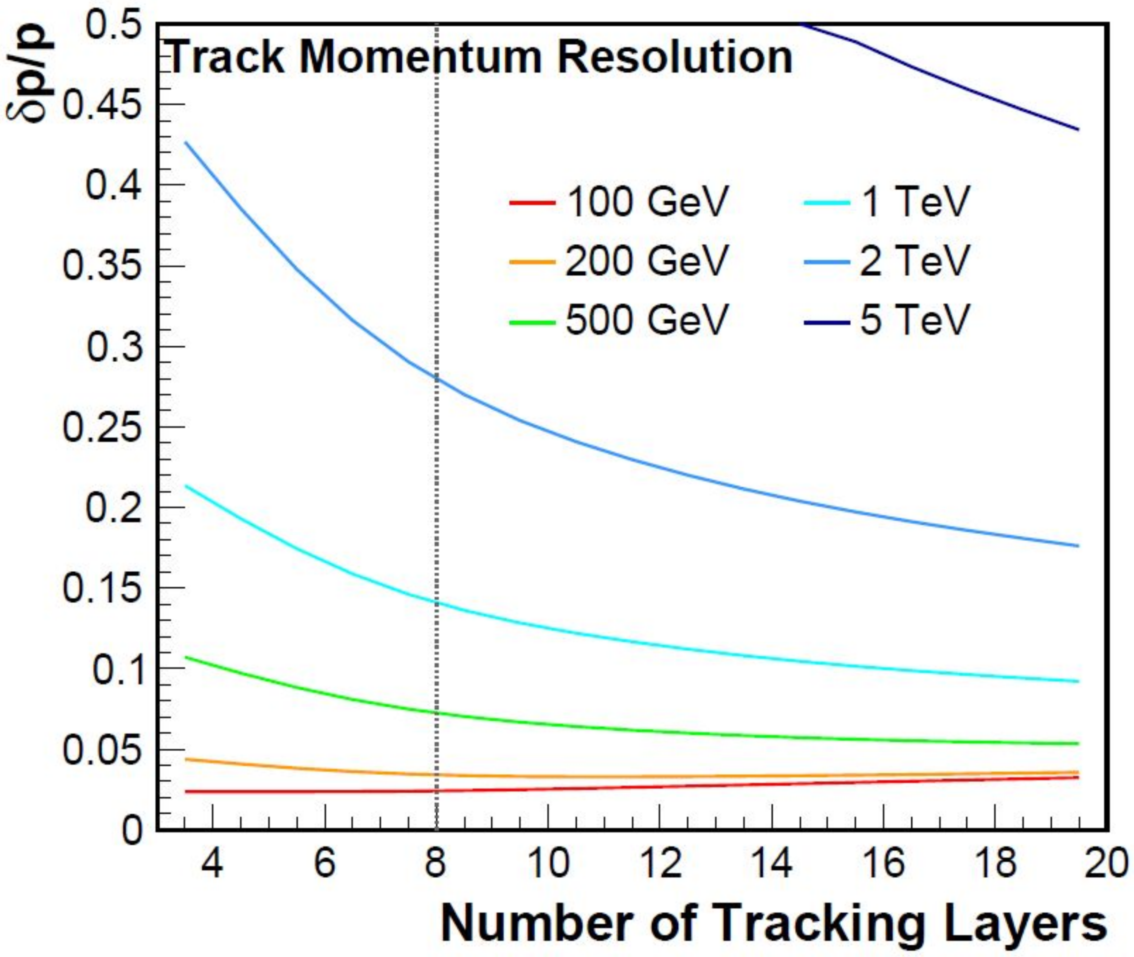


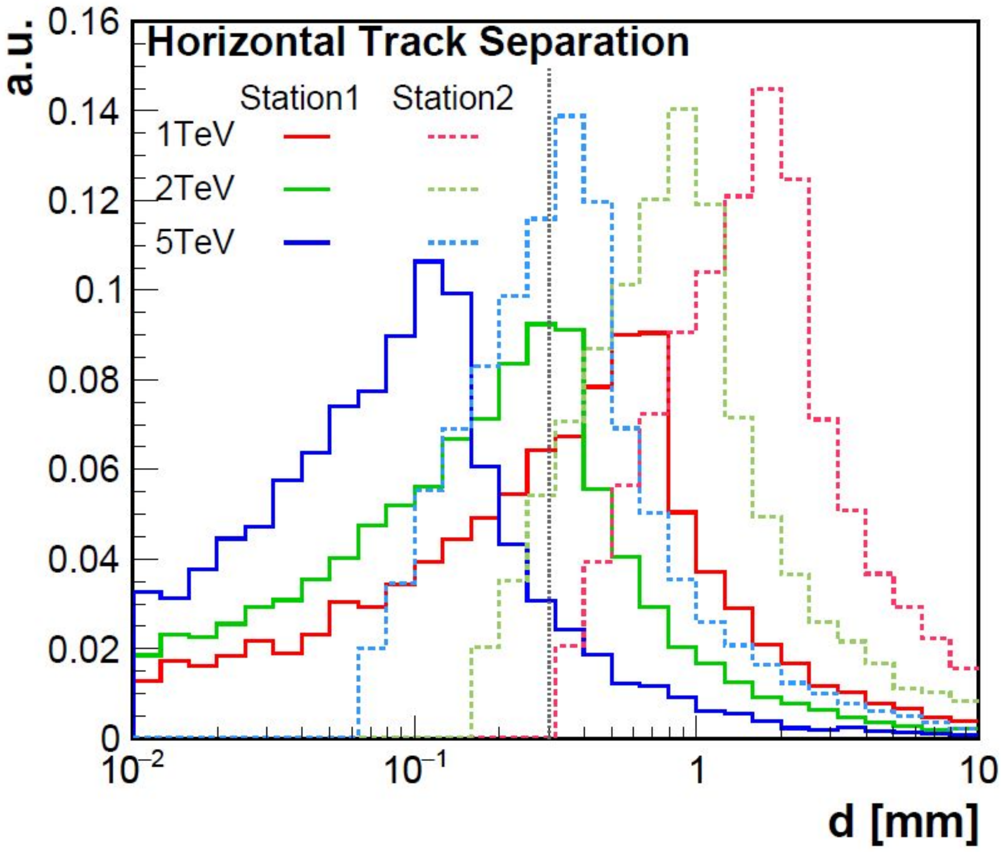
Tracking Spectrum



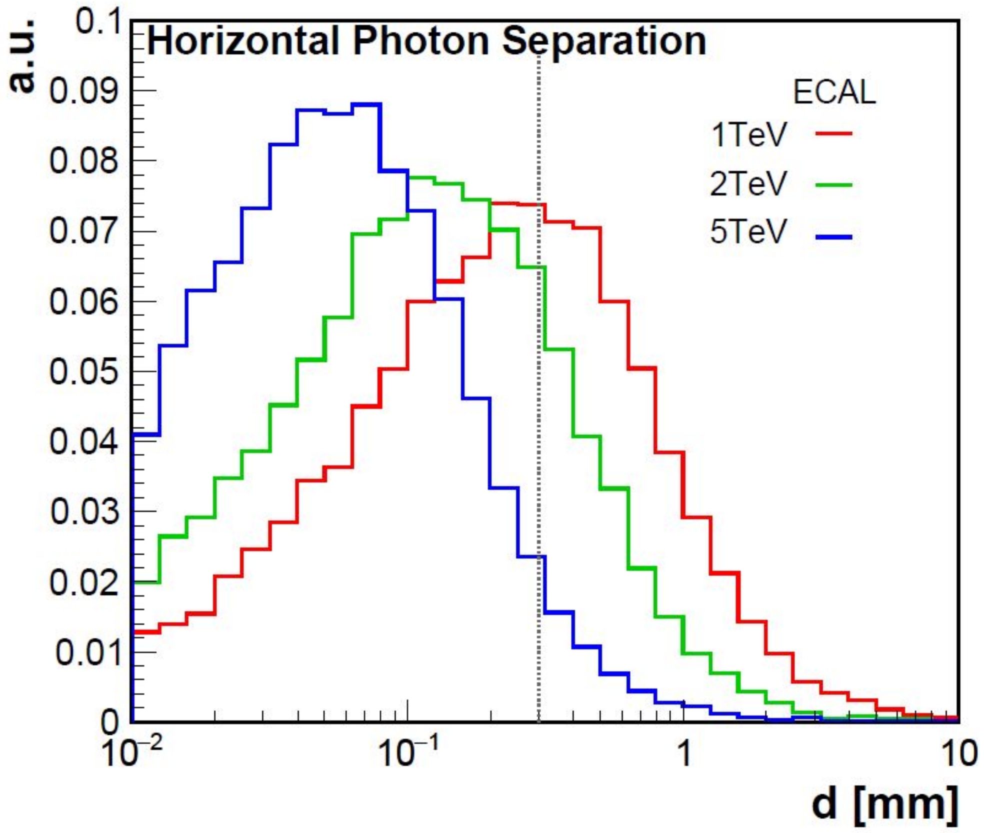


Track separation and momentum resolution

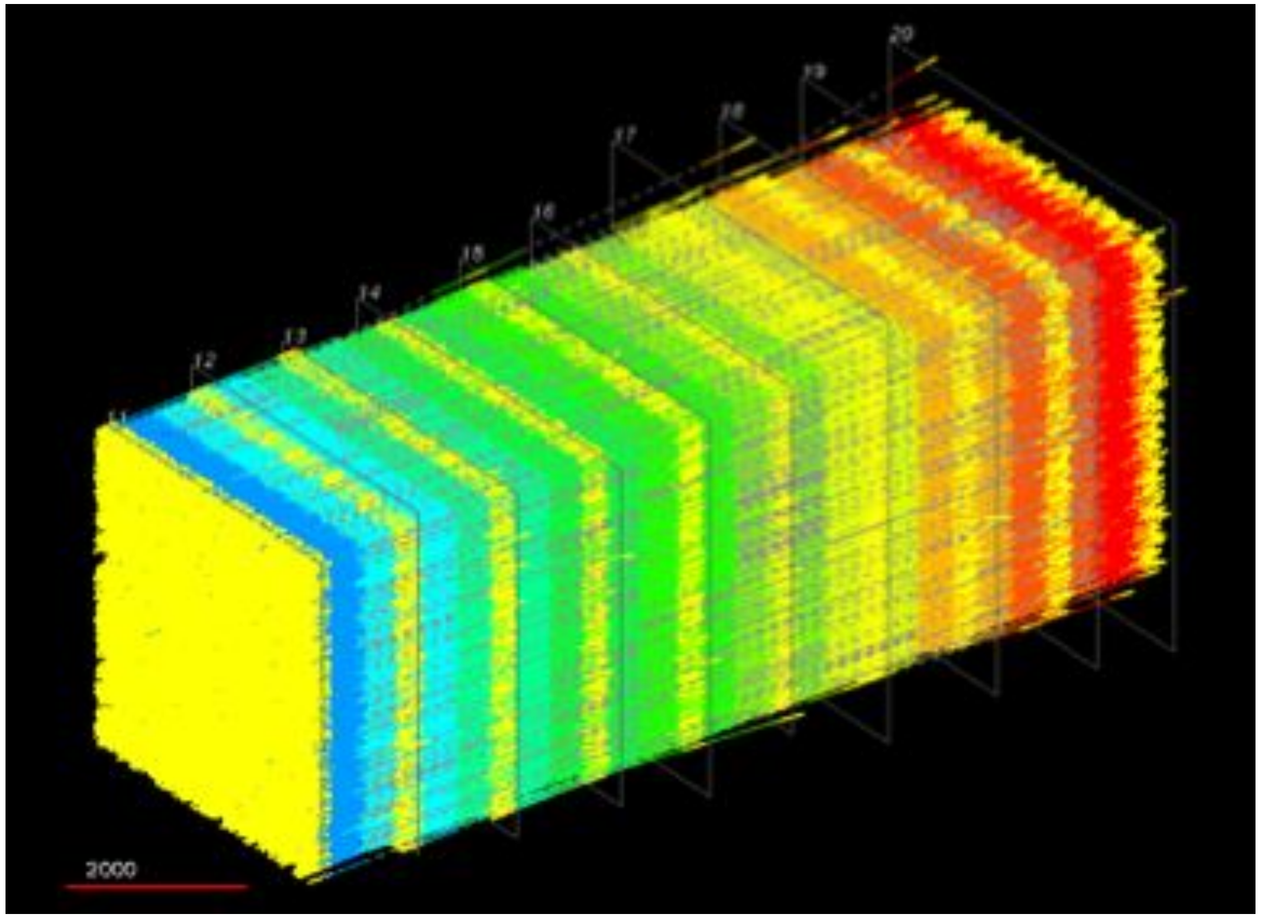


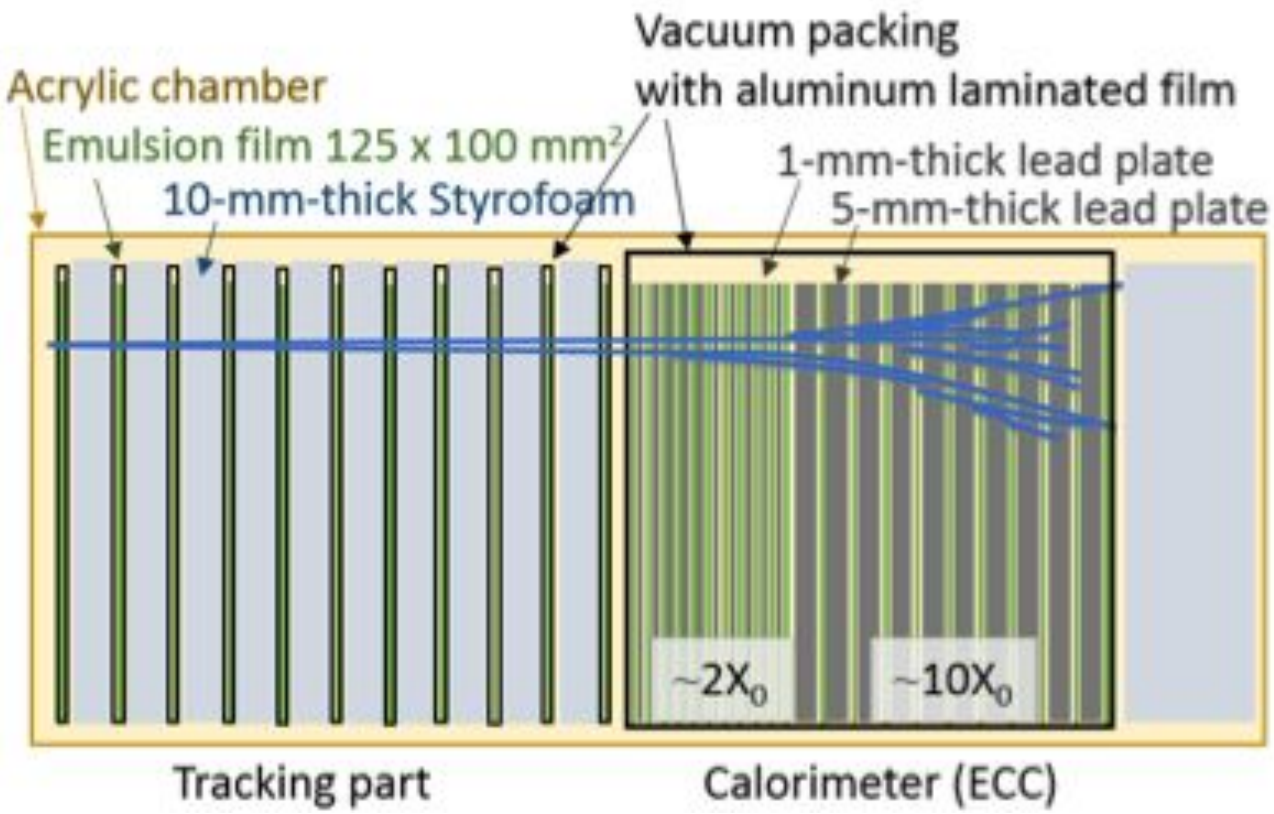


A conservative estimate of the separation required to FASER's choice create isolated clusters in a silicon strip detector



FASER Emulsion





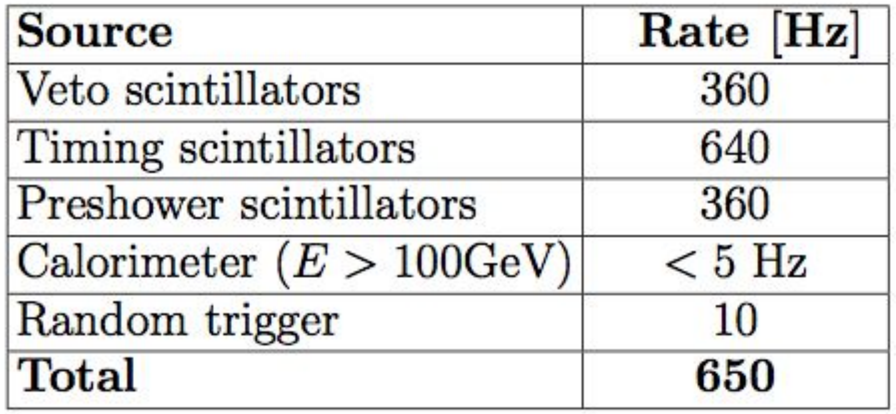
	Energy cutoff	Flux / 14 fb^{-1}
Emulsion	E > 0.5 GeV	1.8×10^5 /cm^2
FLUKA	E > 100 GeV	1.4×10^5 /cm^2

FASER TDAQ

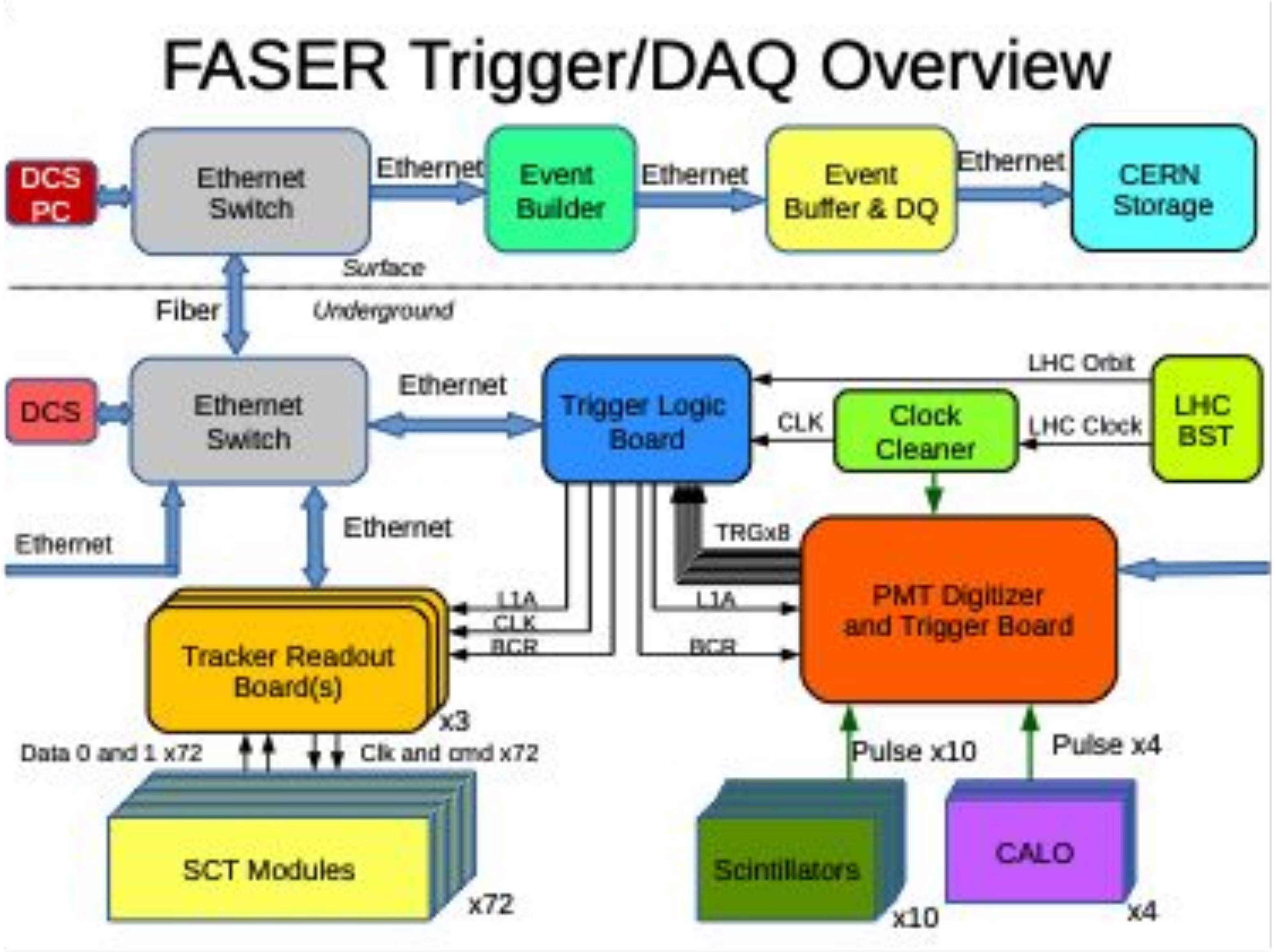
40MHz synchronous to LHC

Event size 25 kB

650 Hz Trigger Rate (dominant by high energy muon) at $L = 2$ x 10^{34} cm^{-2} s^{-1}

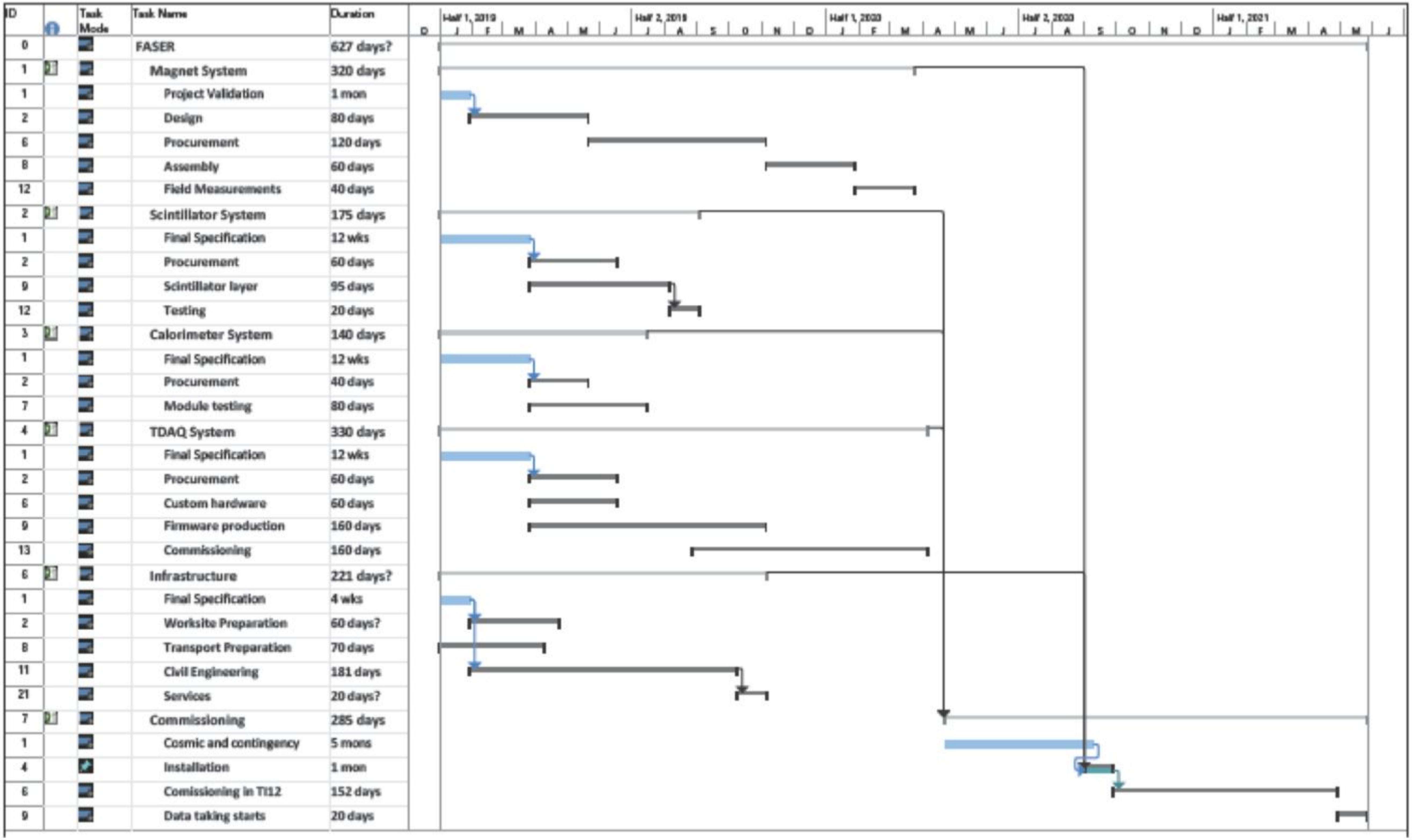


Source	**Rate [Hz]**
Veto scintillators	360
Timing scintillators	640
Preshower scintillators	360
Calorimeter ($E > 100$GeV)	< 5 Hz
Random trigger	10
Total	**650**



FASER Trigger/DAQ Overview

Schedule



ID		Task Mode	Task Name	Duration
0			FASER	627 days?
1			Magnet System	320 days
1			Project Validation	1 mon
2			Design	80 days
6			Procurement	120 days
8			Assembly	60 days
12			Field Measurements	40 days
2			Scintillator System	175 days
1			Final Specification	12 wks
2			Procurement	60 days
9			Scintillator layer	95 days
12			Testing	20 days
3			Calorimeter System	140 days
1			Final Specification	12 wks
2			Procurement	40 days
7			Module testing	80 days
4			TDAQ System	330 days
1			Final Specification	12 wks
2			Procurement	60 days
6			Custom hardware	60 days
9			Firmware production	160 days
13			Commissioning	160 days
6			Infrastructure	221 days?
1			Final Specification	4 wks
2			Worksite Preparation	60 days?
8			Transport Preparation	70 days
11			Civil Engineering	181 days
21			Services	20 days?
7			Commissioning	285 days
1			Cosmic and contingency	5 mons
4			Installation	1 mon
6			Comissioning in TI12	152 days
9			Data taking starts	20 days