Far Detector Experiments for LHC Run III and beyond

Stephen Gibson
on behalf of ***the FASER Collaboration***

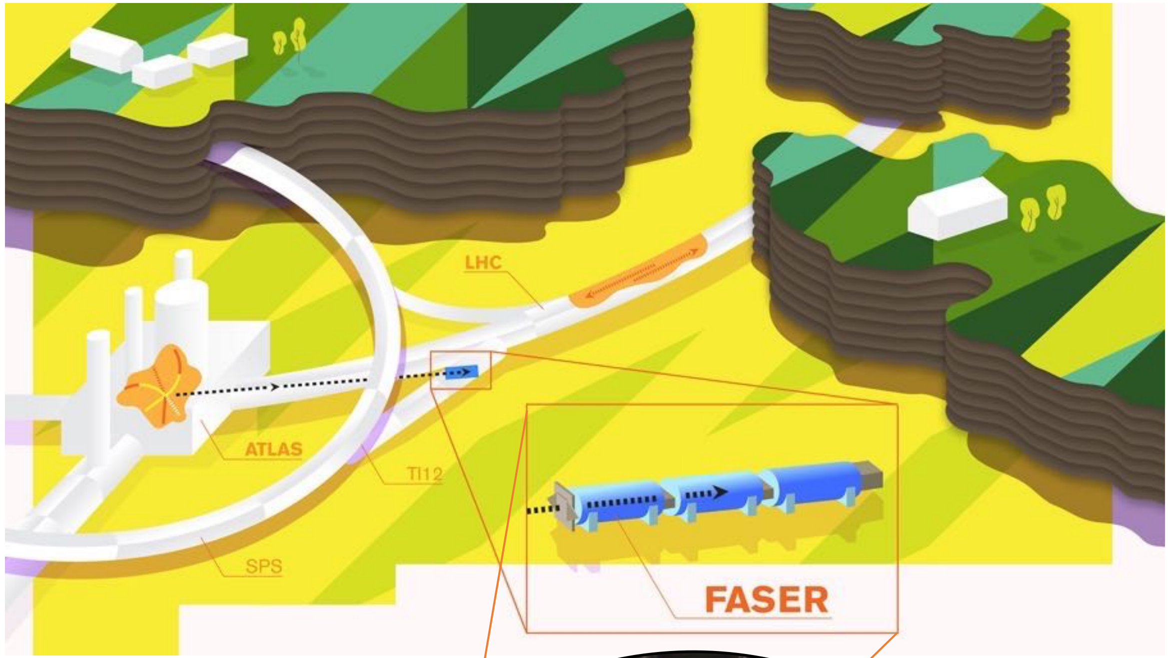
with thanks to

Jim Brooke & Joel Goldstein
for ***the MilliQan Collaboration***

John Adams Institute for Accelerator Science
Royal Holloway University of London
University of Bristol

Overview

- ***Motivation for far detectors***
- ***The ForwArd Search ExpeRiment***
  - *Pilot run & first candidate neutrinos*
  - *Detector installation and commissioning*
  - *Physics prospects for Run-III and beyond*
- ***Scattering and Neutrino Detector @LHC***
  - *SND@LHC complementary to FASER ν*
- ***The milliQan experiment***
  - *Searching for milli-charged particles*
- ***Future proposals:***
  - *ANUBIS, CODEX-b, FORMOSA, Mathusla, FASER2…*
  - *Forward Physics facility*

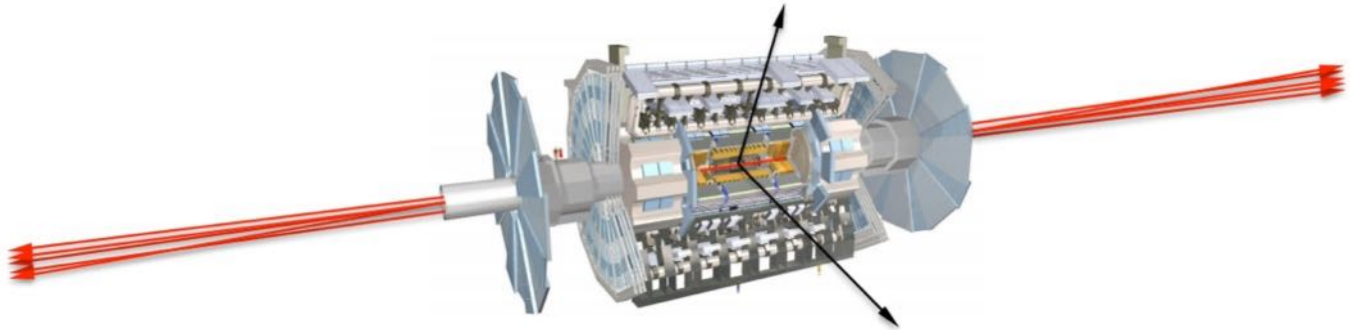


Symmetry magazine

Why place a tiny detector 0.5 km away from the collision point?

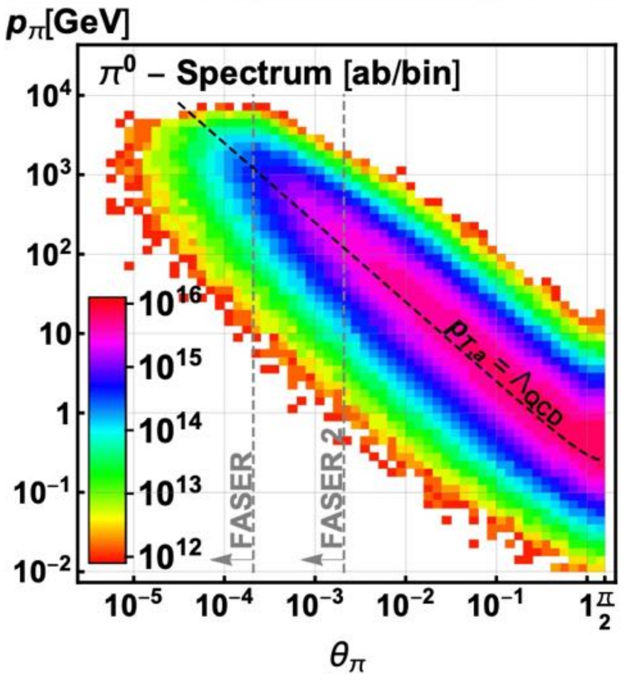
Motivation for far detectors

- ***An alternative search strategy for BSM Physics:***
  - *Heavy (TeV scale), strongly interacting new particles are sought by their high p_T decays in the established detectors at LHC, albeit with relatively low production rates.*
  - *Light (MeV to GeV), feebly-interacting and long lived particles, however, currently evade detection along the beam axis, despite the enormous inelastic cross section:*
    - ***~75mb => 1.1 x 10^{16} collisions with 150 fb^{-1} at 13 TeV, giving high meson production rates.***
  - *By plugging the gap in the far-forward region we can be potentially sensitive to very weak couplings!*



$\theta \sim \Lambda_{QCD}/E$

m_B/E



- **Low p_T blind spot from inelastic collisions:**
  - *Highly boosted new particles produced in pion or B meson decays are well collimated:*
  - *At 500m downstream the transverse spread is 10cm – 1m*

→ *only need* ***small, inexpensive far-detector(s)***

Motivation 1: LLPs, e.g. Dark Photons

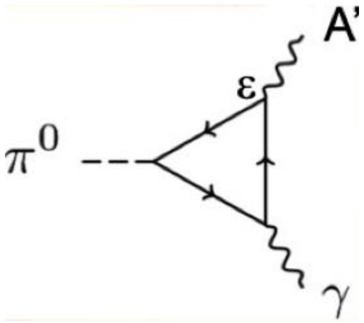
- *Astrophysical observations motive terrestrial searches for long lived DM particles at LHC, e.g. Dark Sector mediator:*
  - *U(1) extensions give rise to a new gauge boson of mass $m_{A'}$ that couples weakly to SM fermions*

$$\mathcal{L} \supset -\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} - \frac{1}{2} m_{A'}^2 A'^2 - m_\chi^2 \chi^2 - i g_D A' \chi^2$$

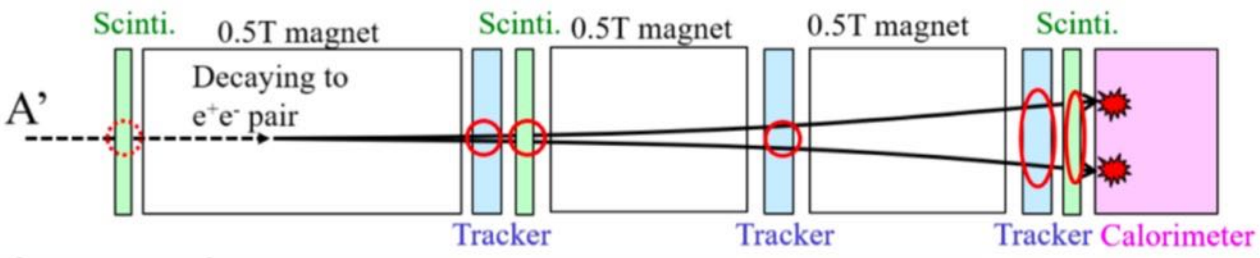
  - *If $m_{A'} < 2\, m_\chi$: A' can only decay to SM and becomes* ***long lived****.*

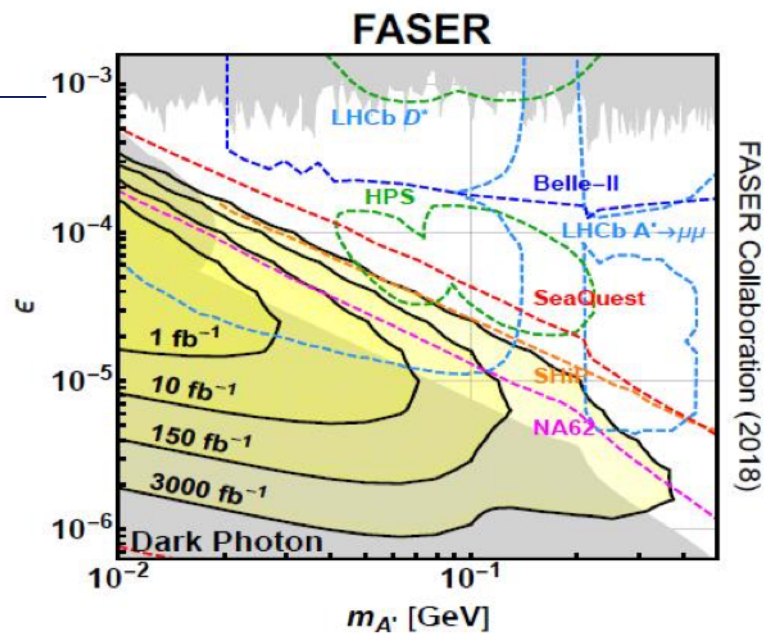
$$\Gamma(A' \rightarrow ee) \sim \varepsilon^2 m_{A'}$$

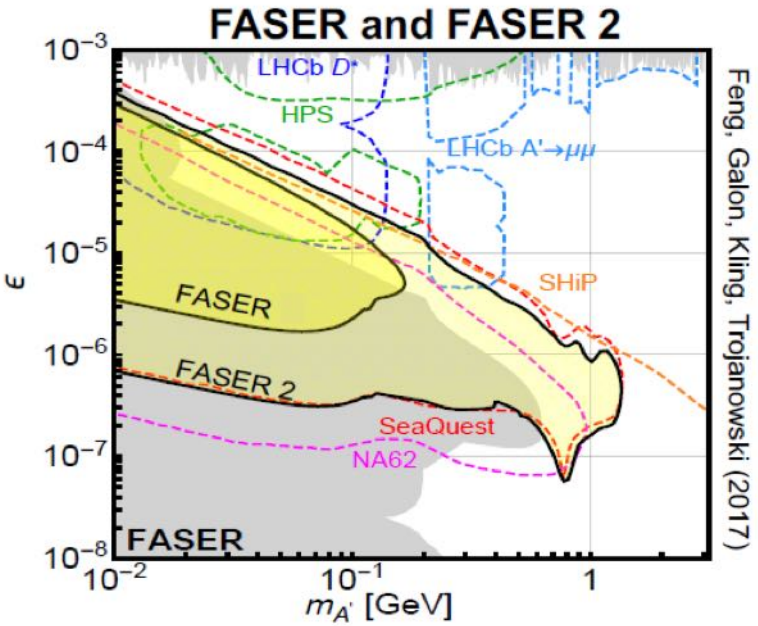
  - *Loop suppressed A' production is more than compensated by the huge meson rate in TeV inelastic collisions: is LHC a Dark Photon factory?*



Characteristic e^+e^-, $\mu^+\mu^-$ decay signatures:

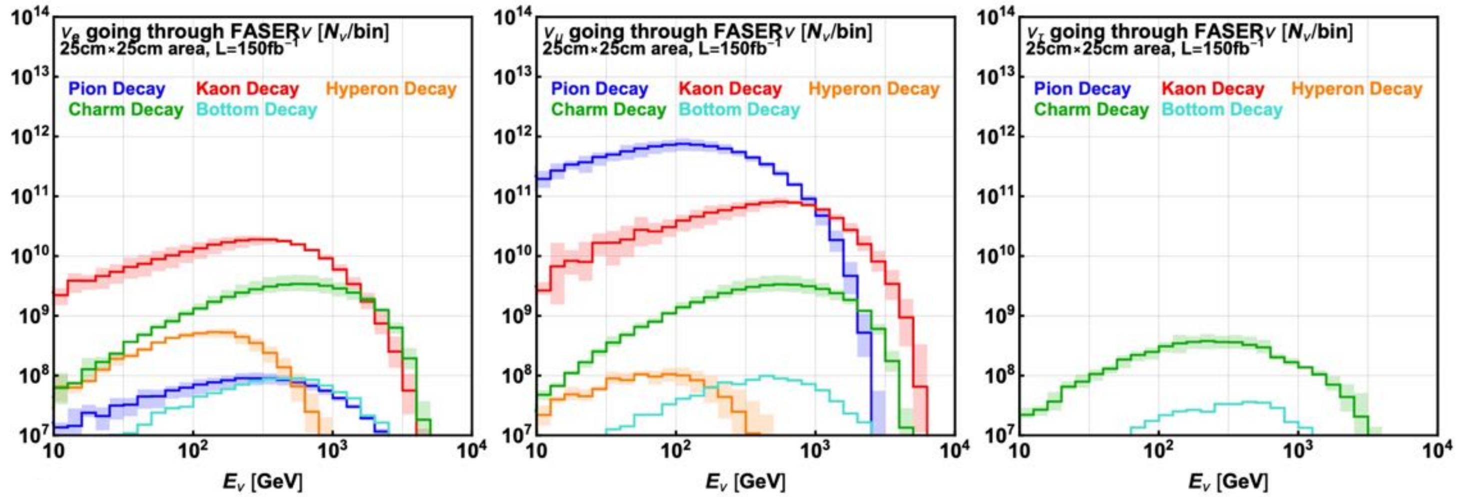






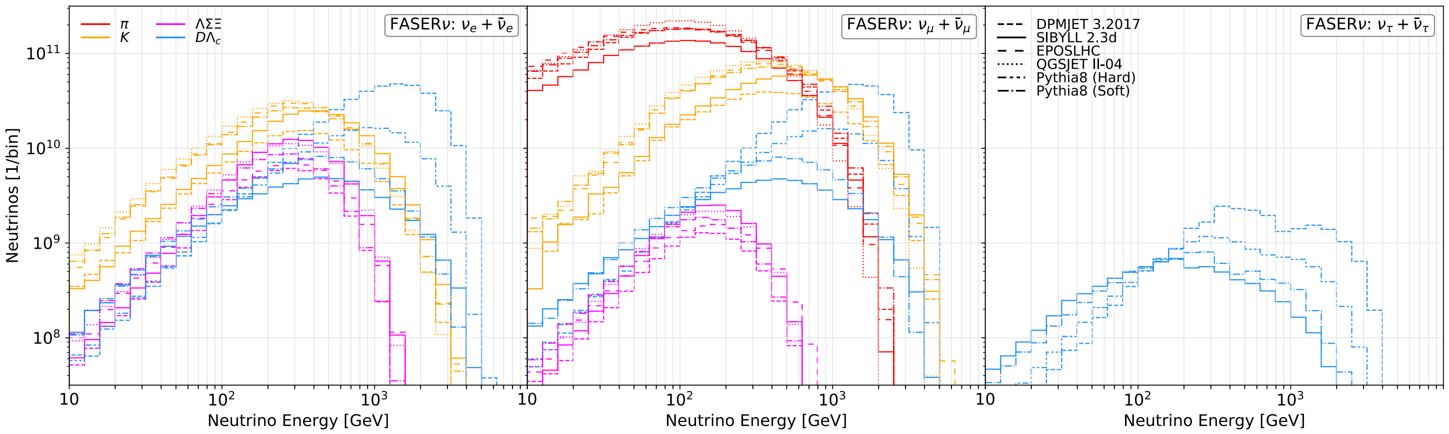
Motivation 2: First detection of collider-produced neutrinos

- *Incredible rates of forward neutrinos are expected at LHC:*
  - *High energy (TeV) neutrino flux is concentrated in far-forward region*
  - *Aim at cross-section measurements of different flavours in an unexplored energy range.*
  - *For 150 fb^{-1} in Run-III*



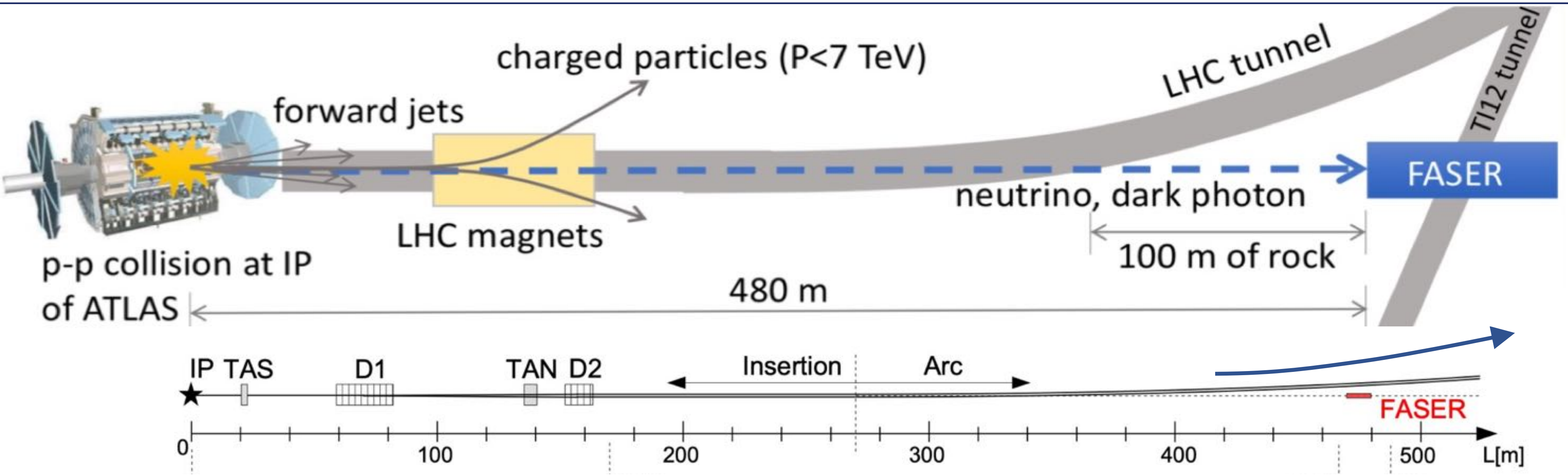
Generators		FASERν		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	1343	6072	21.2
DPMJET	DPMJET	4614	9198	131
EPOSLHC	Pythia8 (Hard)	2109	7763	48.9
QGSJET	Pythia8 (Soft)	1437	7162	24.5
Combination (all)		2376^{+2238}_{-1032}	7549^{+1649}_{-1476}	$56.4^{+74.5}_{-35.1}$
Combination (w/o DPMJET)		1630^{+479}_{-286}	7000^{+763}_{-926}	$31.5^{+17.3}_{-10.3}$

FASER Collaboration: 2105.08270



FASER Collaboration: Eur. Phys. J. C80 (2020) no.1, 61

The ForwAard Search ExpeRiment



FASER

Generously funded by:

77 collaborators, 21 institutes, 9 countries

- The FASER experiment is installed 480m from IP1, directly in the line-of-sight and low p_T blind spot of ATLAS.
  - The detector is housed in a disused side-tunnel, TI12, just after the start of the LHC dipole arc.
  - Most charged particle backgrounds are swept aside by the accelerator lattice magnets, while LLPs and neutrinos reach FASER.
  - ~100m of rock provides additional shielding.

The phases of FASER

Run II

- ***FASER Pilot***
  - *Test run in 2018, 12.2 fb^{-1} recorded: 30 kg Pb/W emulsion detector*
  - *First collider neutrino candidates and background measurement*

Letter of Intent
1811.10243

Result 2105.06197 PRD

Run III

- ***FASER** – new particle searches*
  - *Approved in March 2019 and installed by March 2021 in TI12*
  - *Ready for data-taking in Run III, from 2022 (>150 fb^{-1})*
  - *Decay volume: R=0.1 m and L = 1.5m*

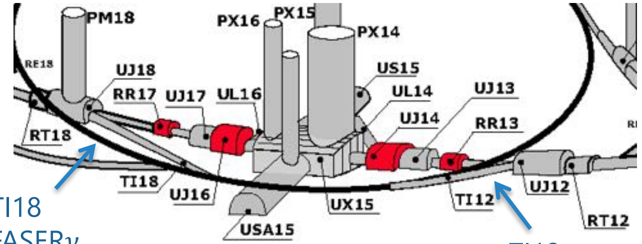
FASER technical proposal
CDS 1812.09139
& Physics Reach for LLPs
PhysRevD.99.095011

***FASER ν** – first neutrino measurements*
  - *Approved Dec 2019 for Run-III & funded by HSF, ERC, JSPS and Mitsubishi Foundation.*
  - *25 x 30 cm^2, 1.1 t tungsten / emulsion detector, interface silicon tracker, and veto station placed in front of the main FASER spectrometer.*

FASERν technical proposal
CDS 2001.03073
& neutrino physics EPJC

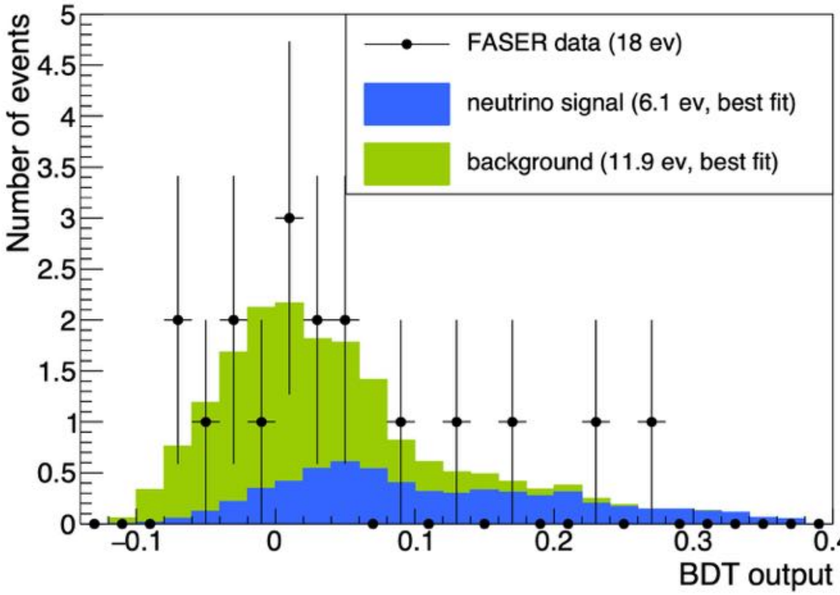
Run IV +

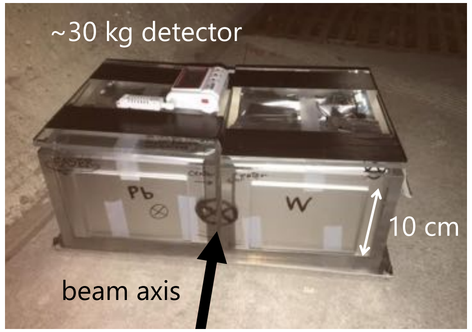
- ***FASER2***
  - *Potential upgrade for the HL-LHC era (3 ab^{-1})*
  - *Decay volume: R=1 m and L = 5m*

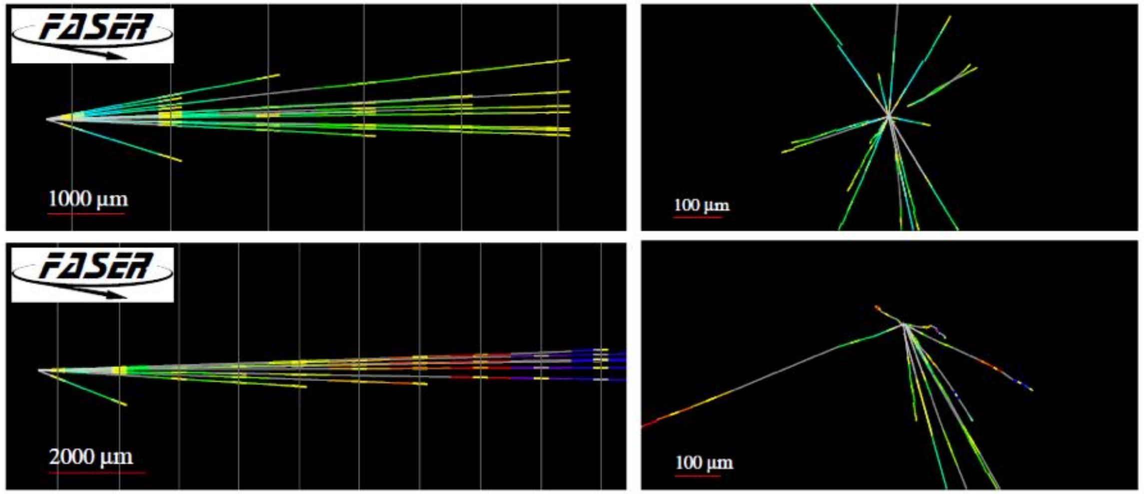


FASER Pilot run

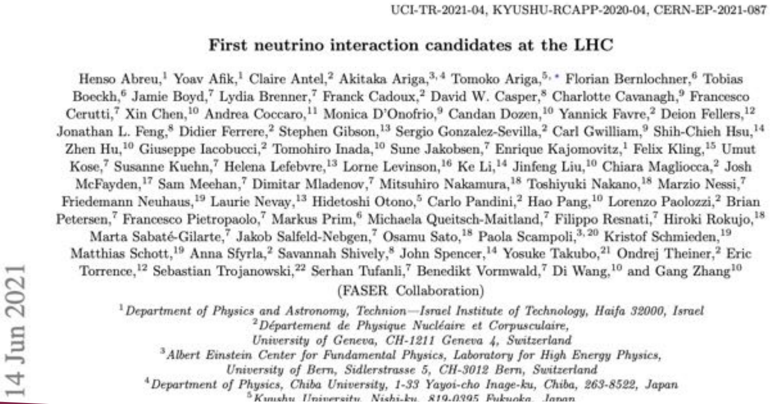
- ***Run II data recorded by pilot detector in TI18 tunnel, symmetric to FASER location.***
  - *2 halves: Pb (1mm x 100 layers) + W Blank (0.5mm x 120 layers).*
  - *12.2 fb^{-1} data collected in 1.5 months during Sep/Oct 2018.*
  - *Neutral hadron background arises from muon decays in rock.*
  - *BDT discriminates signal and background using 5 input variables.*
  - *18 neutral vertices were identified in a 11kg target mass; 6.1 signal events (2.7σ) obtained from the fit, while $3.3^{+1.7}_{-0.9}$ expected.*
  - ➢ ***Detection of first neutrino interaction candidates at the LHC.***







FASER Collaboration: [2105.06197](2105.06197) accepted in PRD



UCI-TR-2021-04, KYUSHU-RCAPP-2020-04, CERN-EP-2021-087

First neutrino interaction candidates at the LHC

Henso Abreu,[1] Yoav Afik,[1] Claire Antel,[2] Akitaka Ariga,[3,4] Tomoko Ariga,[5,*] Florian Bernlochner,[6] Tobias Boeckh,[6] Jamie Boyd,[7] Lydia Brenner,[7] Franck Cadoux,[2] David W. Casper,[8] Charlotte Cavanagh,[9] Francesco Cerutti,[7] Xin Chen,[10] Andrea Coccaro,[11] Monica D'Onofrio,[9] Candan Dozen,[10] Yannick Favre,[2] Deion Fellers,[12] Jonathan L. Feng,[8] Didier Ferrere,[2] Stephen Gibson,[13] Sergio Gonzalez-Sevilla,[2] Carl Gwilliam,[9] Shih-Chieh Hsu,[14] Zhen Hu,[10] Giuseppe Iacobucci,[2] Tomohiro Inada,[10] Sune Jakobsen,[7] Enrique Kajomovitz,[1] Felix Kling,[15] Umut Kose,[7] Susanne Kuehn,[7] Helena Lefebvre,[13] Lorne Levinson,[16] Ke Li,[14] Jinfeng Liu,[10] Chiara Magliocca,[2] Josh McFayden,[17] Sam Meehan,[7] Dimitar Mladenov,[7] Mitsuhiro Nakamura,[18] Toshiyuki Nakano,[18] Marzio Nessi,[7] Friedemann Neuhaus,[19] Laurie Nevay,[13] Hidetoshi Otono,[5] Carlo Pandini,[2] Hao Pang,[10] Lorenzo Paolozzi,[2] Brian Petersen,[7] Francesco Pietropaolo,[7] Markus Prim,[6] Michaela Queitsch-Maitland,[7] Filippo Resnati,[7] Hiroki Rokujo,[18] Marta Sabaté-Gilarte,[7] Jakob Salfeld-Nebgen,[7] Osamu Sato,[18] Paola Scampoli,[3,20] Kristof Schmieden,[19] Matthias Schott,[19] Anna Sfyrla,[2] Savannah Shively,[8] John Spencer,[14] Yosuke Takubo,[21] Ondrej Theiner,[2] Eric Torrence,[12] Sebastian Trojanowski,[22] Serhan Tufanli,[7] Benedikt Vormwald,[7] Di Wang,[10] and Gang Zhang[10]

(FASER Collaboration)

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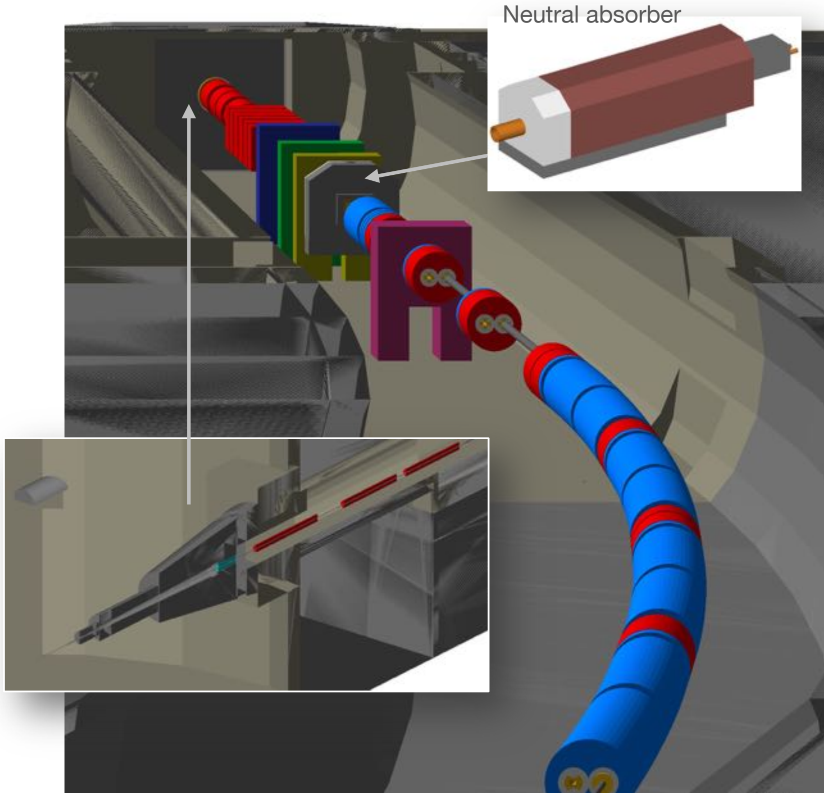
[3] Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland
[4] Department of Physics, Chiba University, 1-33 Yayoi-cho Inage-ku, Chiba, 263-8522, Japan

14 Jun 2021

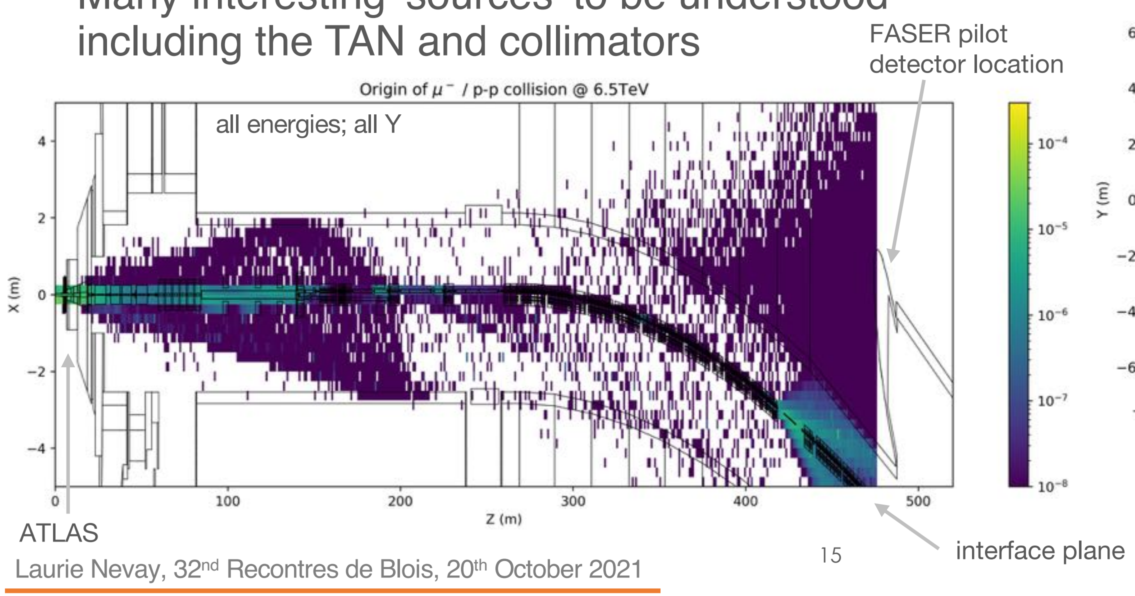
Accelerator modelling

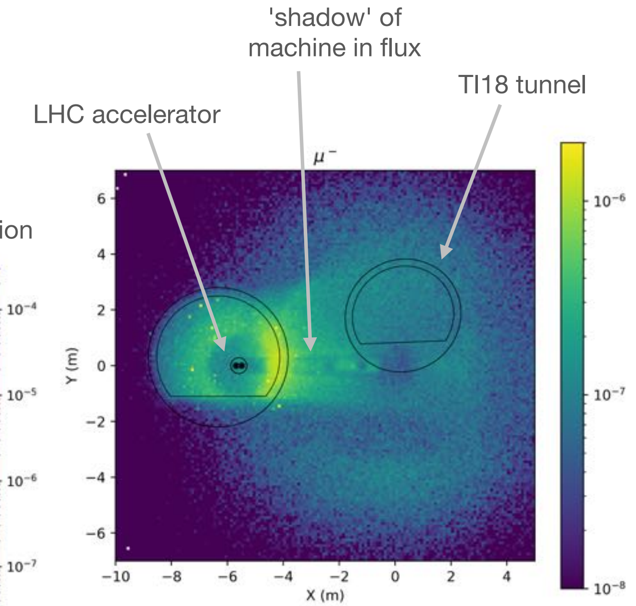
- ***A full Geant4 model from IP1 to the FASER detector (pilot shown here) developed in BDSIM***
  - *Aim to understand propagation of the signal through accelerator optics, assess contributions from secondary showers, and identify the source of backgrounds:*



Model of accelerator components with magnetic fields for particle tracking, and material interactions.

- The majority of muons come from < 150 m and along the beam line axis
- Many interesting 'sources' to be understood including the TAN and collimators

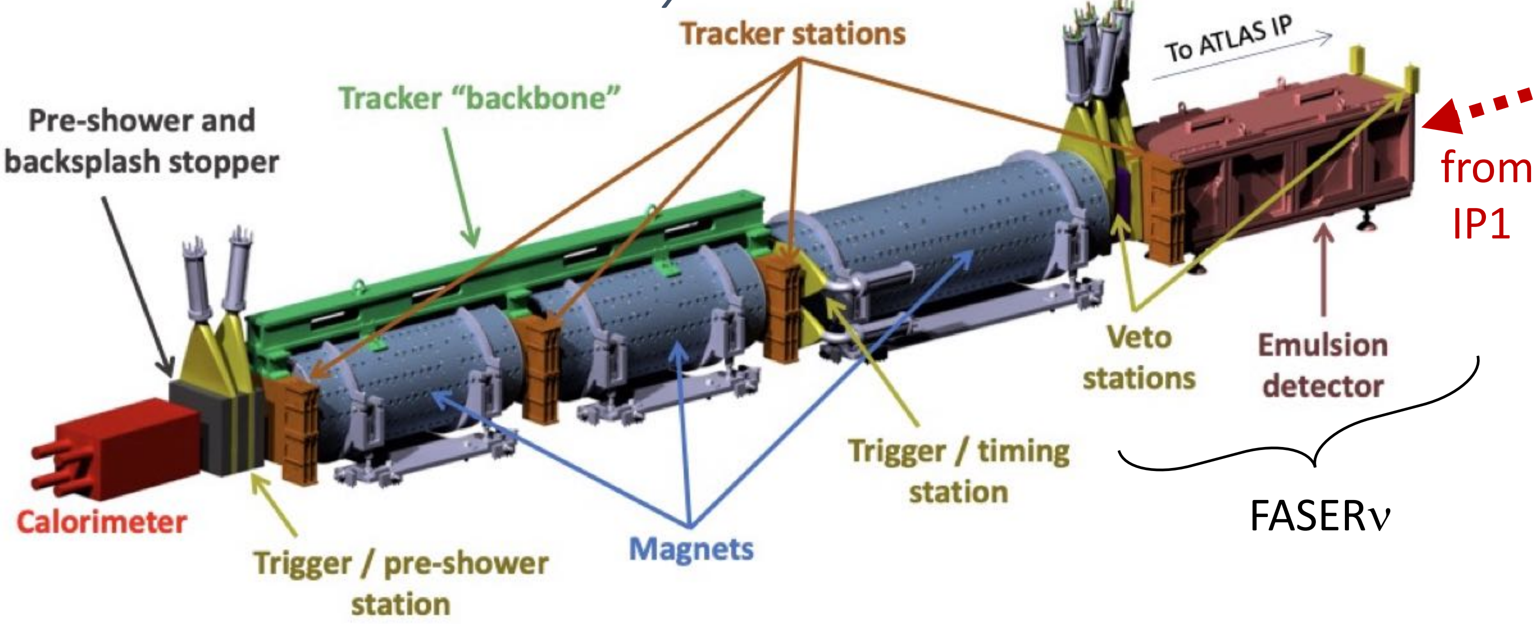


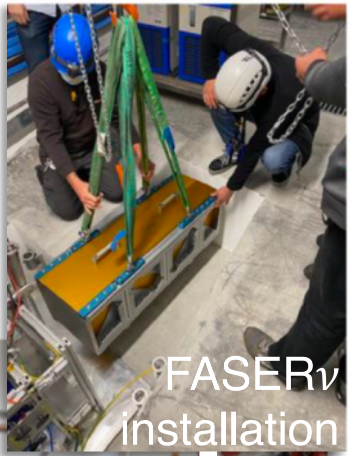


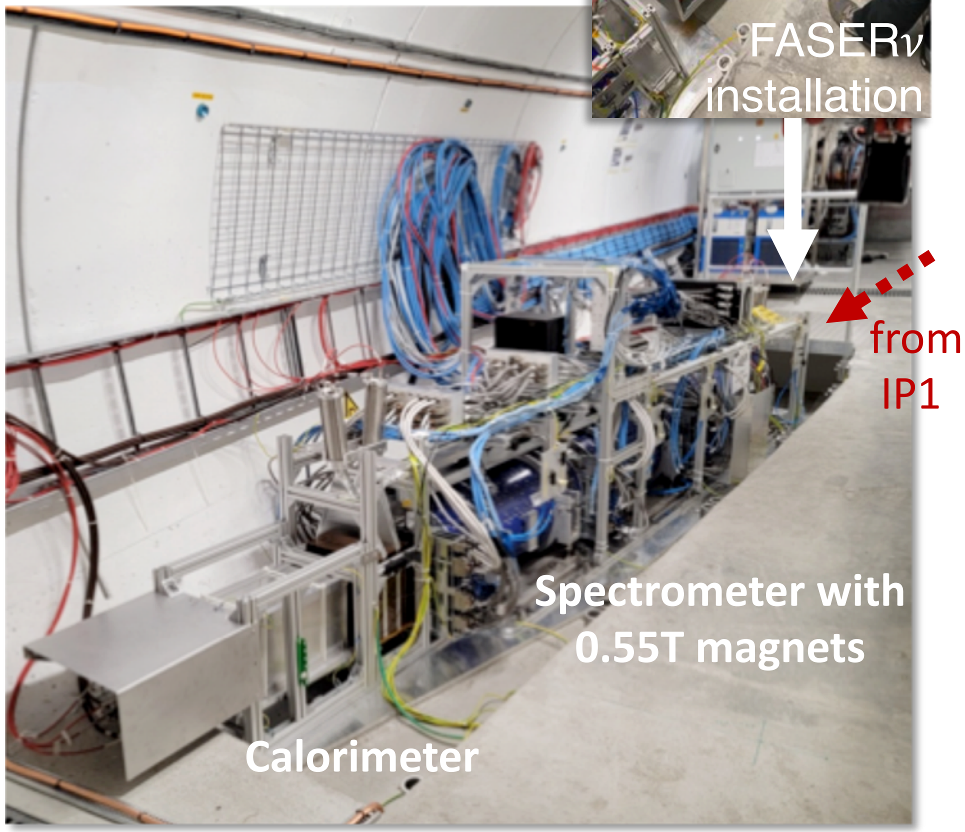
TI18 pilot detector plane simulated μ^- distribution per p-p collision at 6.5 TeV

FASER detector layout and installation

- ***Combined FASER and FASERν detectors prepared for Run-III***
  - *Rapid development possible thanks to spares donated by ATLAS and LHCb*
  - *20cm aperture, 1.5m long magnetised decay volume + 2x 1m spectrometer magnets*
  - *4 x 3-plane tracker stations, each plane using 8 ATLAS SCT modules*
  - *Scintillator veto of charged particles*
  - *Calorimeter donated by LHCb*

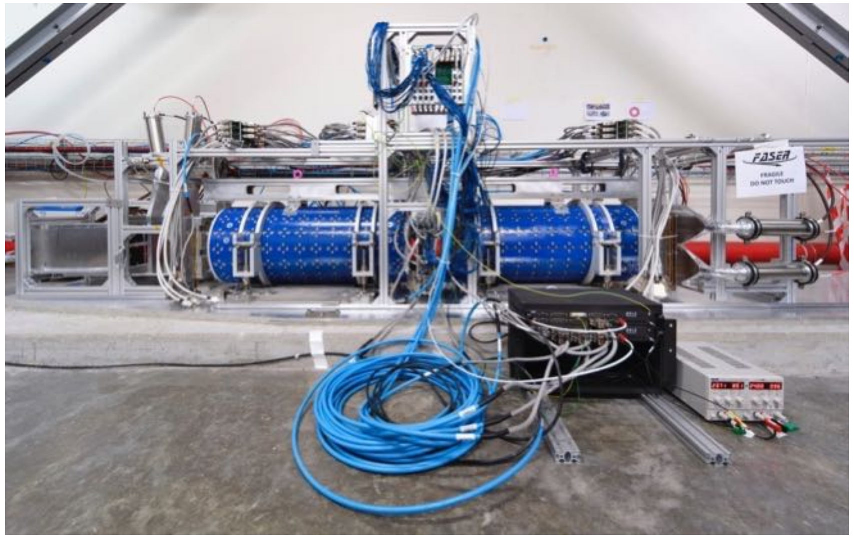


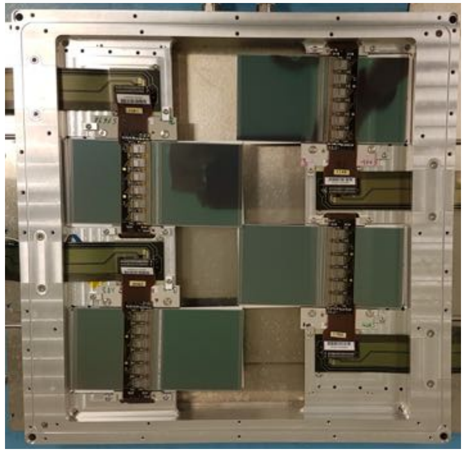


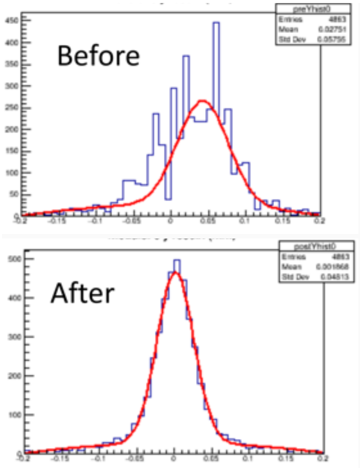


Detector commissioning prior to installation

Oct 2020: assembly and system test in Prévessin







Nov 2020 begin installation in TI12

Si strip tracker stations

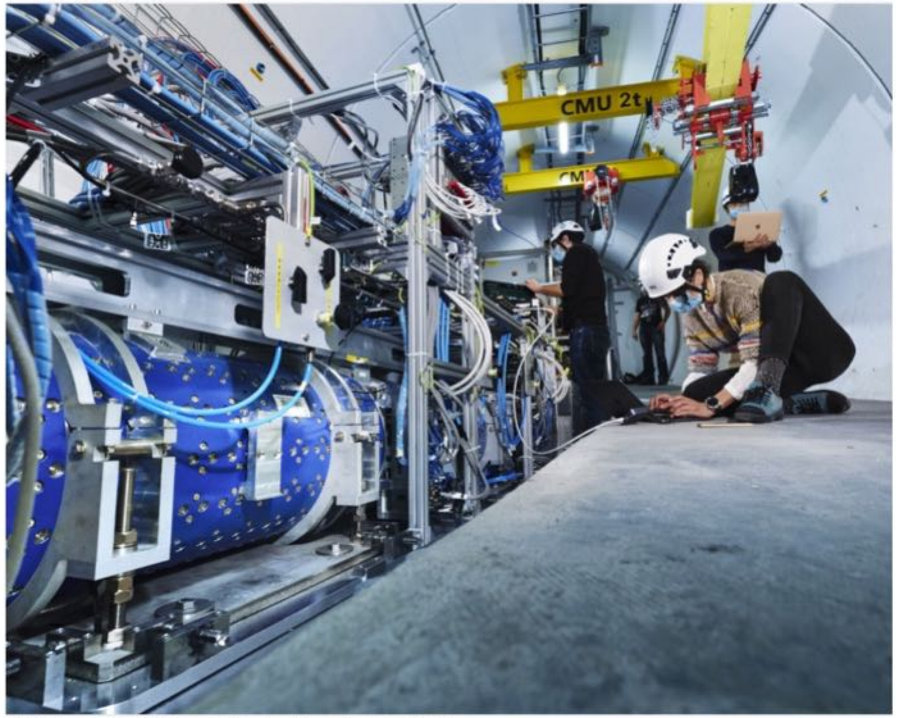
- Surface cosmic studies achieved 25μm resolution with simple corrections

Completed by March 2021, CERN Courier:

LS2 Report: FASER is born

FASER, the Forward Search Experiment, has been installed in the LHC tunnel during Long Shutdown 2. It is currently being tested and will start taking data next year

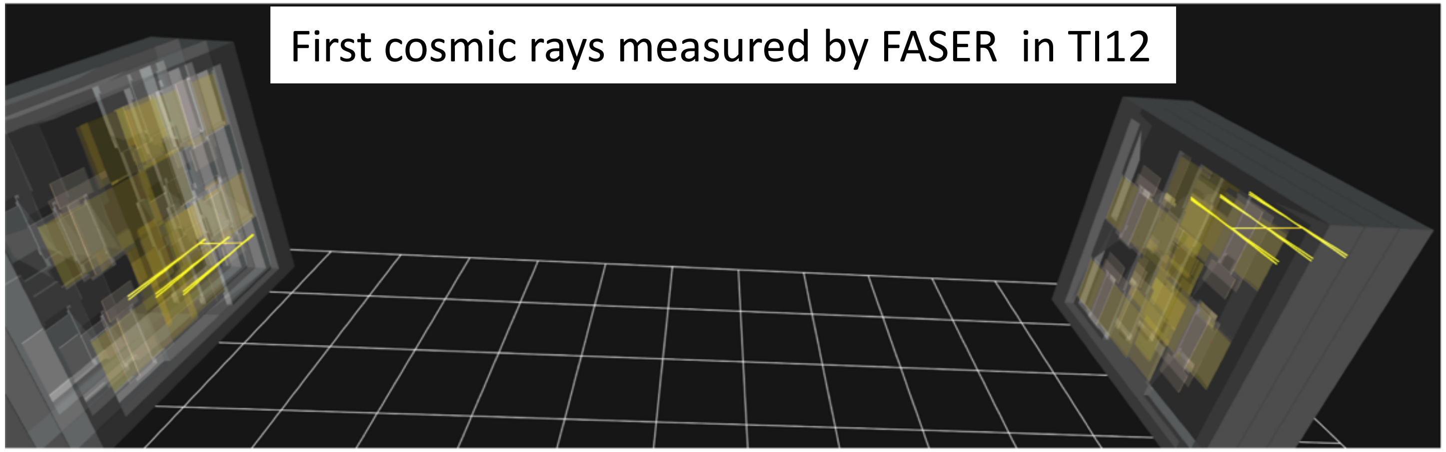
24 MARCH, 2021 | By Anaïs Schaeffer



The final elements of FASER were put into place this month. (Image: CERN)

FASER* (Forward Search Experiment), CERN's newest experiment, is now in place in the LHC tunnel, only two years after its approval by CERN's Research Board in March 2019. FASER is designed to study the interactions of high-energy neutrinos and search for new, as-yet-undiscovered light and weakly interacting particles. Such particles are dominantly produced along the beam collision axis and may be long-lived particles, travelling

In situ commissioning: first cosmics + tracks from LHC events!



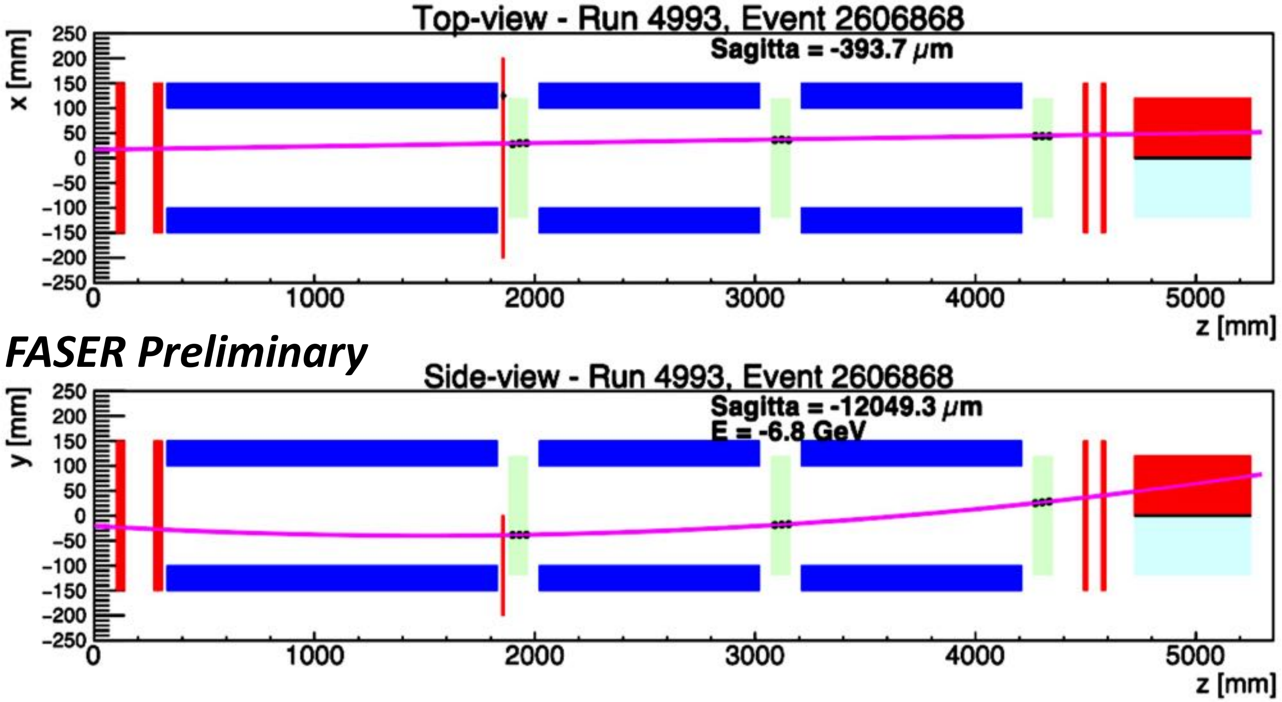
FASER

Looking forward to new physics

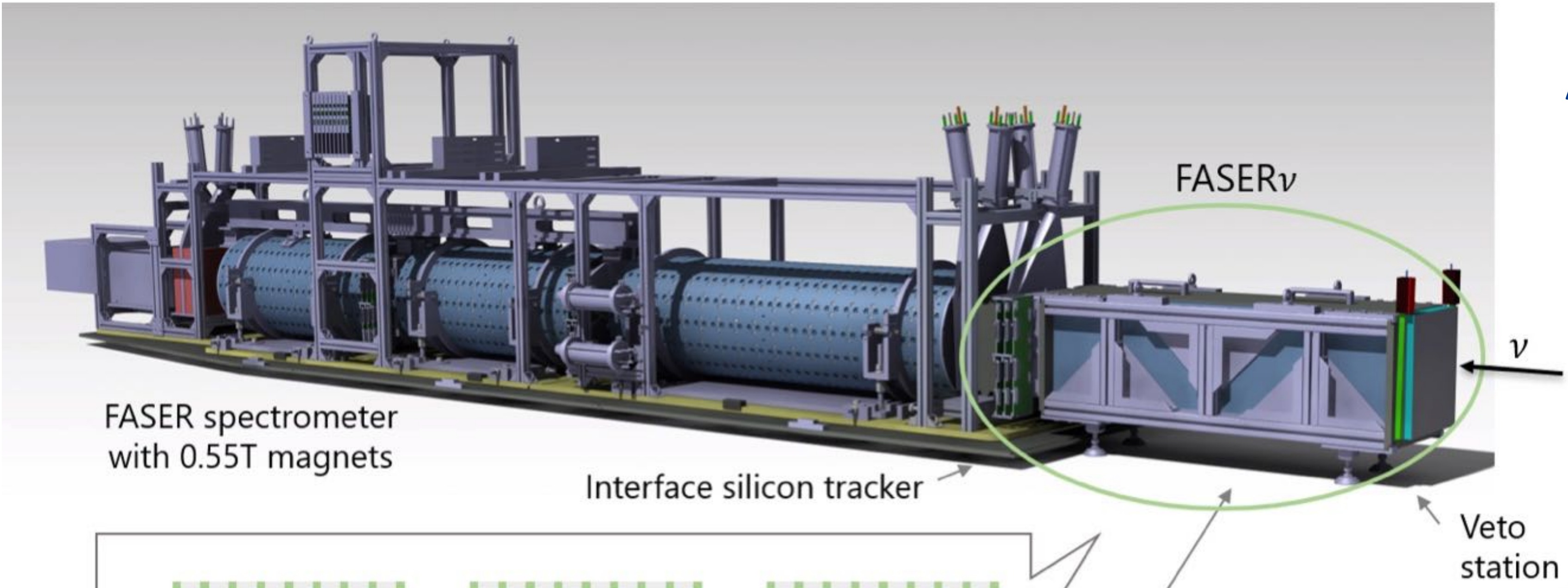
Commissioning data recorded from 12 days of beam operations in the LHC, 20 Oct – 1 November:

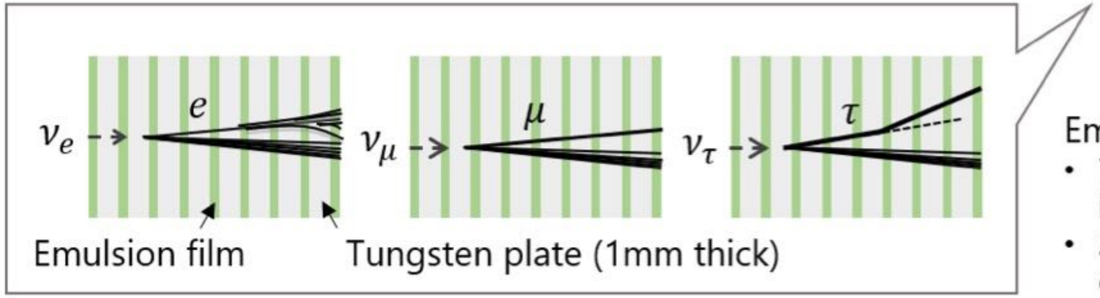
- ***During automatic alignment of the LHC collimators on 27th October 2021:***
  - *Trigger rate increase in FASER; observed 500 events.*
  - *Lower energy events show track curvature in magnetic field.*

Event displays thanks to Brian Petersen & Jamie Boyd



FASERν physics potential

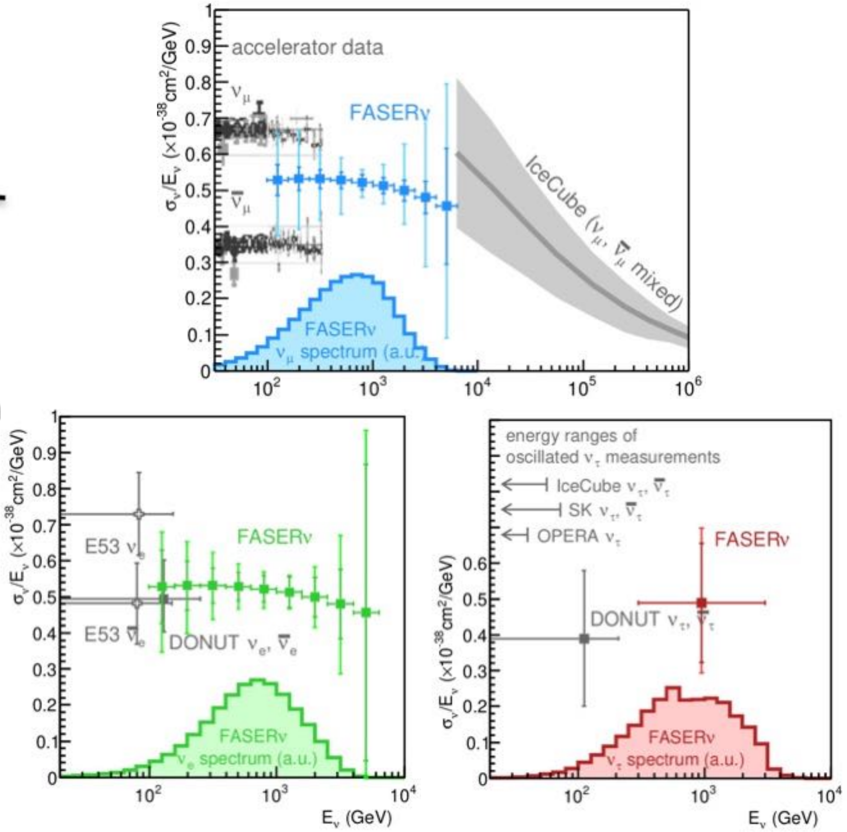




Emulsion/tungsten detector

- 770 1-mm-thick tungsten plates, interleaved with emulsion films
- 25x30 cm^2, 1.1 m long, 1.1 tons detector (220X_0)

Aim for cross-section measurements in an unexplored energy regime.



FASER Collaboration: Eur. Phys. J. C80 (2020) no.1, 61

All neutrino flavours can be distinguished

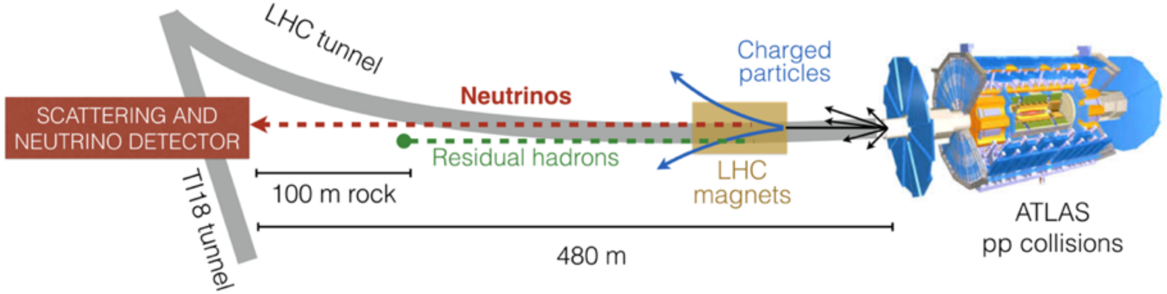
- Muons identified by track length ($8\lambda_{int}$) and charge in FASER spectrometer
- Neutrino energy with ANN by combining topological and kinematical variables

Funded by the Heising-Simons Foundation, ERC, JSPS and the Mitsubishi Foundation.

Scattering and Neutrino Detector at LHC

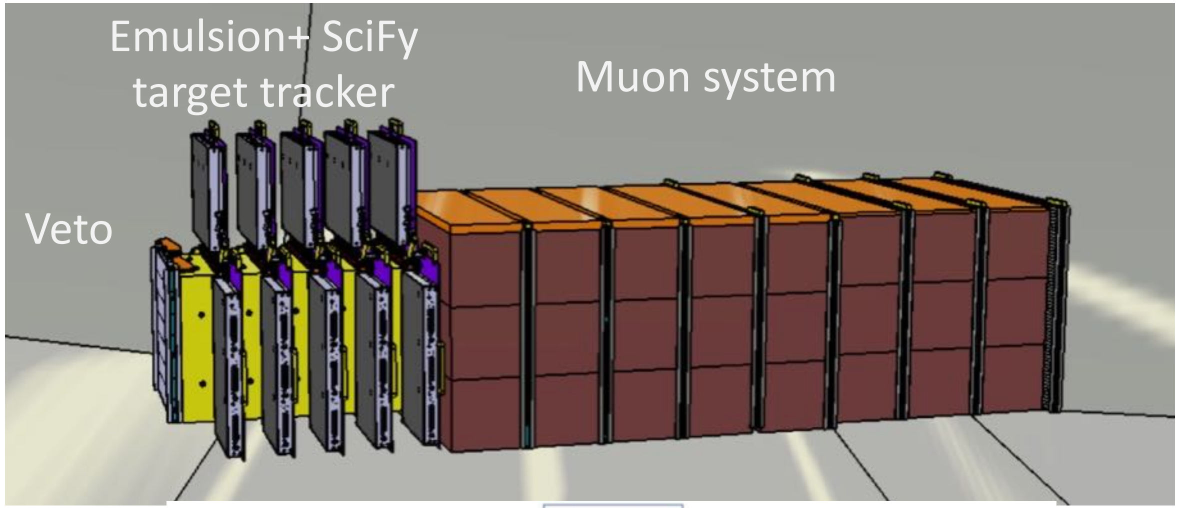
Full details see ***C. Betancourt, SND@LHC, 32nd Recontres de Blois 2021***

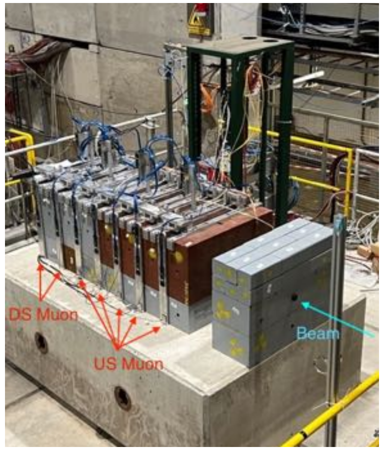
- ***A standalone experiment to probe neutrino production at the LHC in the forward direction***
  - *Approved 17 March 2021 by CERN.*
  - *24 institutes from 13 countries*
  - *To be installed in TI18 tunnel (symmetric to FASER)*

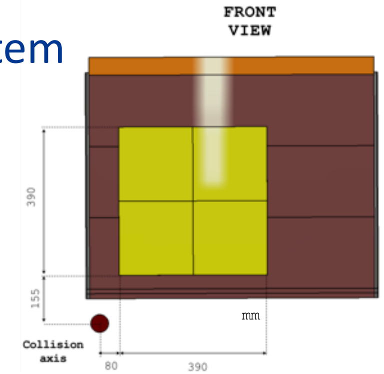


- **Off-axis location**
  - Probes region: $7.2 < \eta < 8.6$
  - Tungsten target in cold box
  - Passive iron in muon system

Complementary to on-axis FASERν

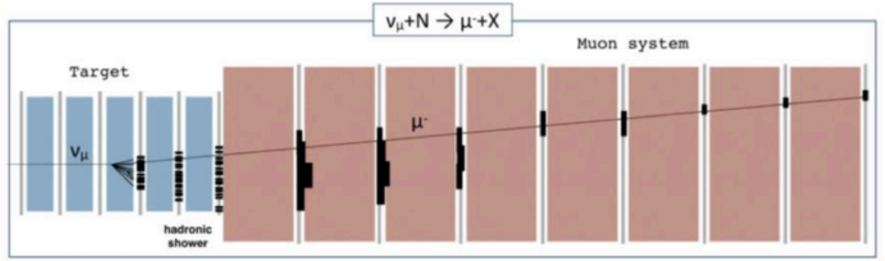






from IP1

H8 Beam tests in Sept 1-5 & Oct 1-6

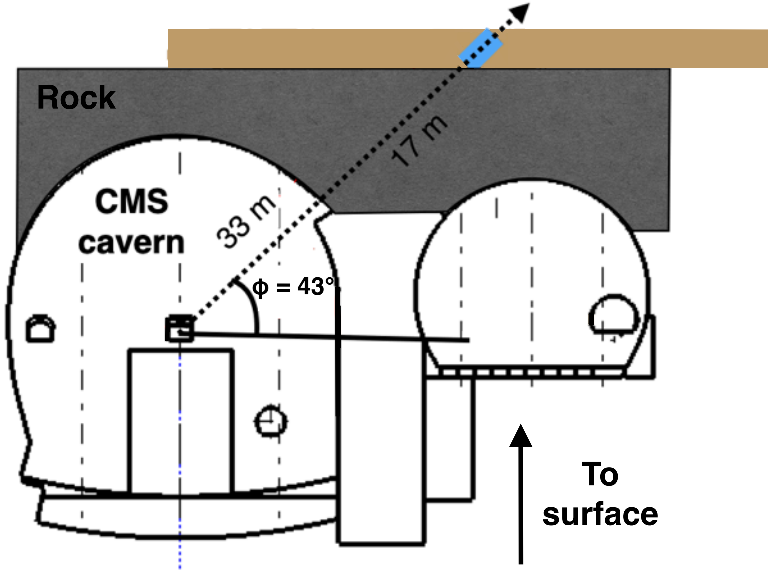


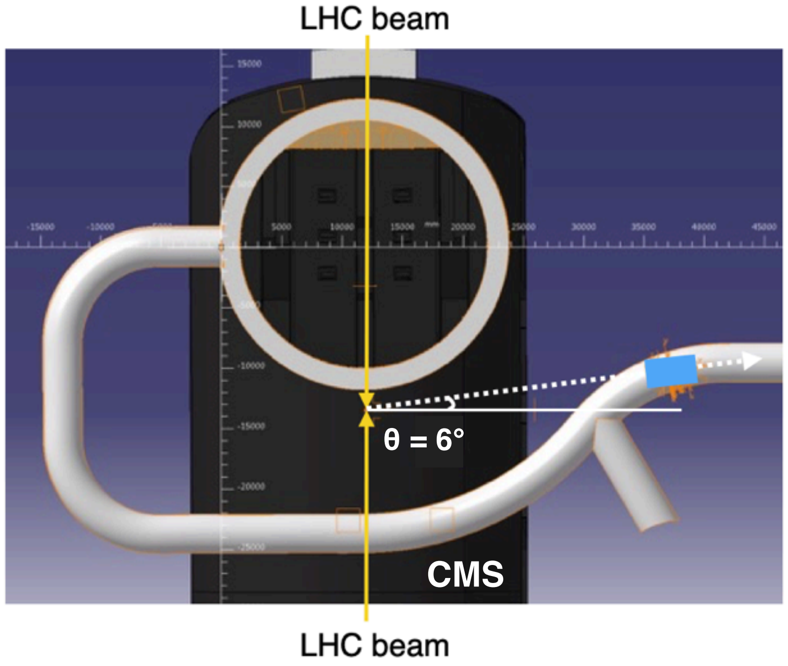
CMS & THE MILLIQAN sub-detector

Slides thanks to Jim Brooke & Joel Goldstein

The Ohio State University, New York University, UC-Santa Barbara, UC-Irvine, University of Chicago, University of Nebraska, University of Bristol, The Lebanese University, Vrije Universiteit Brussel

- ***A search for millicharged particles:***
  - *Uses a simple detector shielded by large depth of rock from the LHC IP.*
  - *1% scale demonstrator operated in Run 2 and used to extract physics.*





Run 3 detector

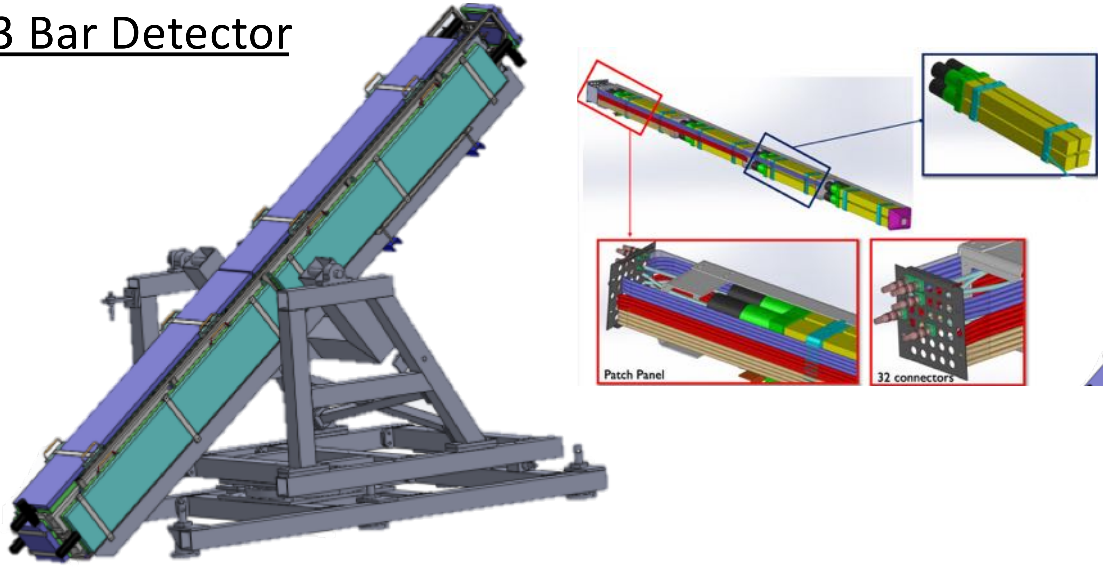
THE MILLIQAN sub-detector

- ***Proposal to LHCC (last week) that MilliQan become a sub-detector of CMS***
- ***Add "slab detector" to existing bar detector design***
  - *Complementary physics coverage*
- ***Re-use of R878 PMTs from decommissioned LANL neutrino expt reduced cost***
  - *Run 3 detectors fully funded*

Run 3 Slab Detector

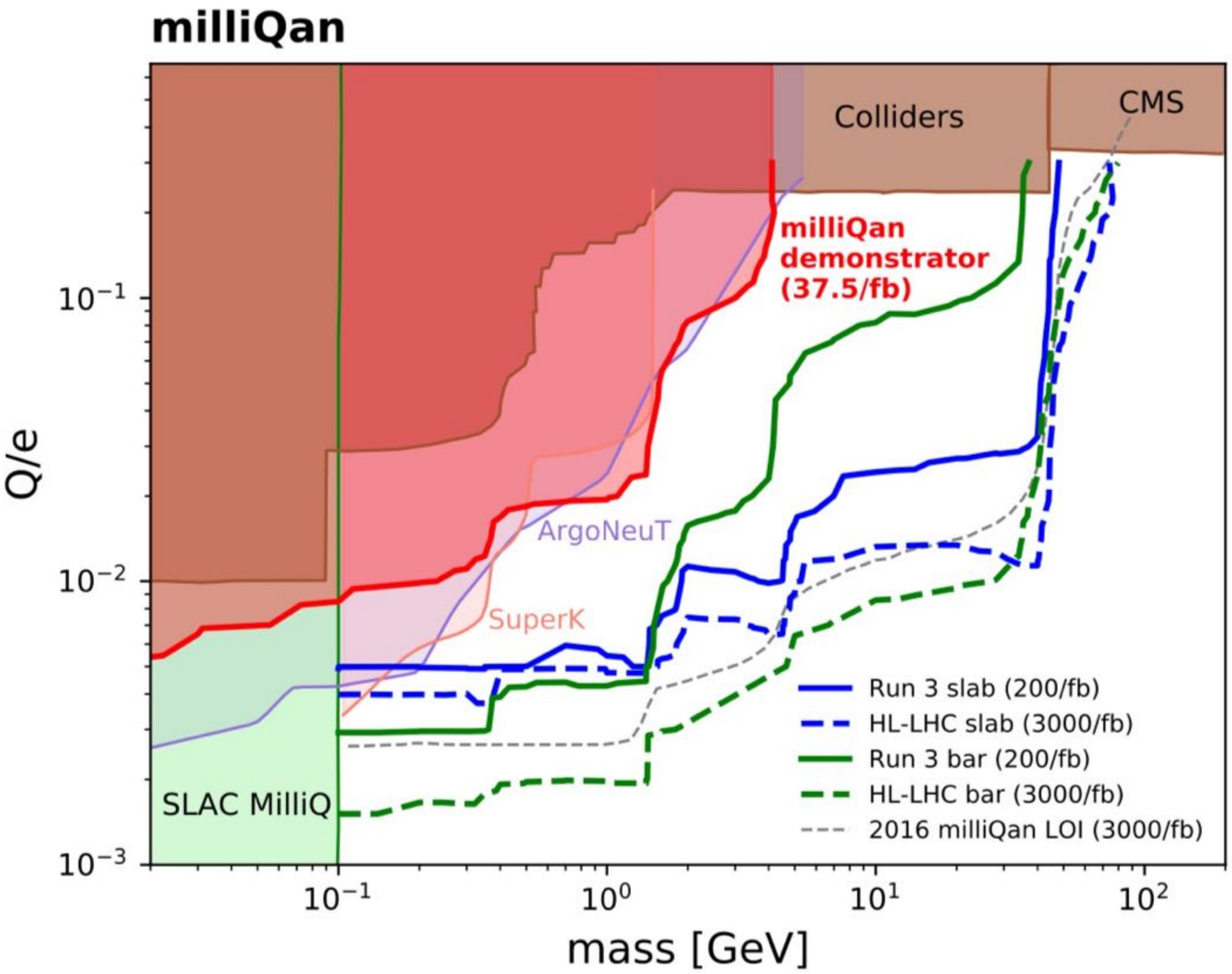
3

Run 3 Bar Detector



Sensitivity

- ***MilliQan Run 2 result in red***
  - *arXiv:2005.06518*
- ***Run 3 sensitivity in green/blue***
  - *arXiv:2104.07151*
- ***Original bar detector***
  - *High mCP flux / low efficiency*
- ***New slab detector***
  - *Low flux / high efficiency*



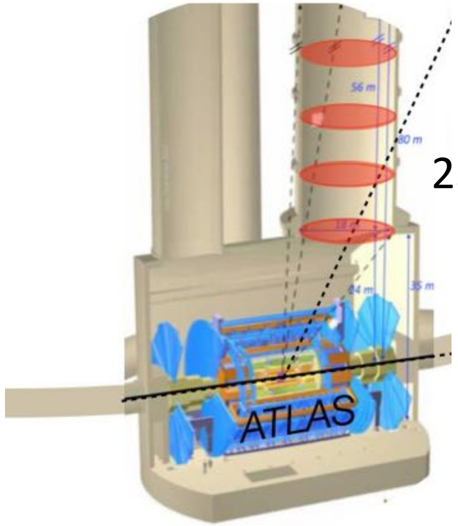
Related proposed experiments

- ***ANUBIS***
  - *an ambitious chandelier in the ATLAS service shaft*

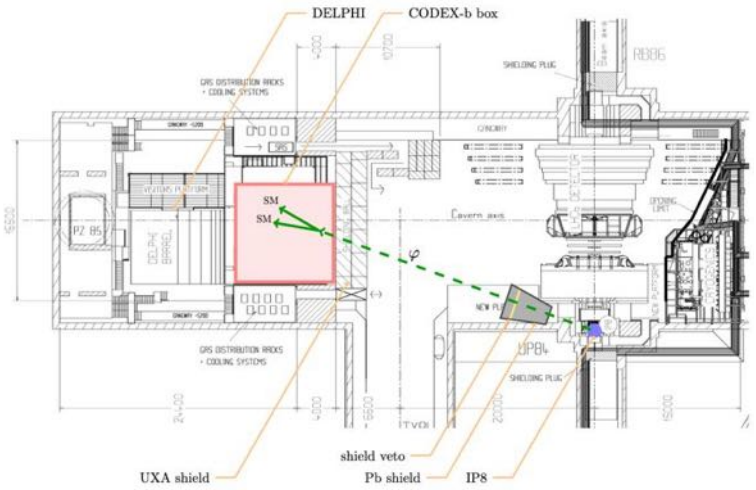
Idea [1909.13022]

hep.phy.cam.ac.uk/ANUBIS

Oleg Brandt et al



4x 230m^2



- ***CODEX-b***
  - *In LHCb cavern*

Idea 1708.09395
EOI 1911.00481

FORMOSA: **FOR**ward **M**icr**O**charge **S**e**A**rch
Recently proposed for UJ12 or TI12 tunnel
PhysRevD.104.035014

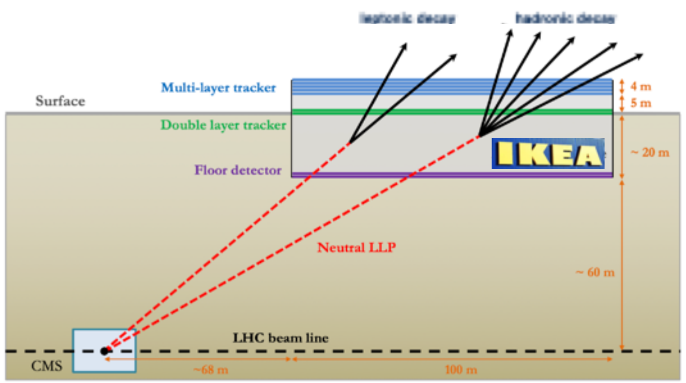
MATHUSLA

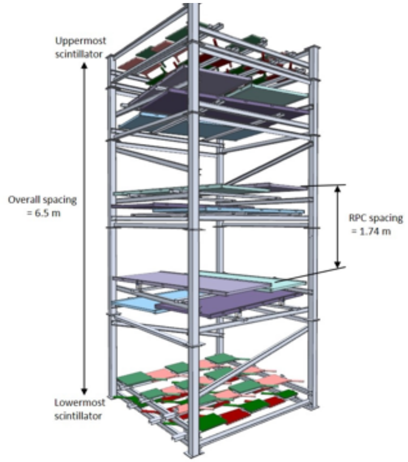
***MA**ssive **T**iming **H**odoscope for **U**ltra-**S**table neutra**L** p**A**rticles*

100 × 100 m^2 large detector proposed above GPDs:

Build an IKEA near ATLAS or CMS and put trackers in the ceiling. LLPs that stop to buy furniture will be reconstructed as displaced vertices.

D. Curtain





IKEA-like probe of the lifetime frontier

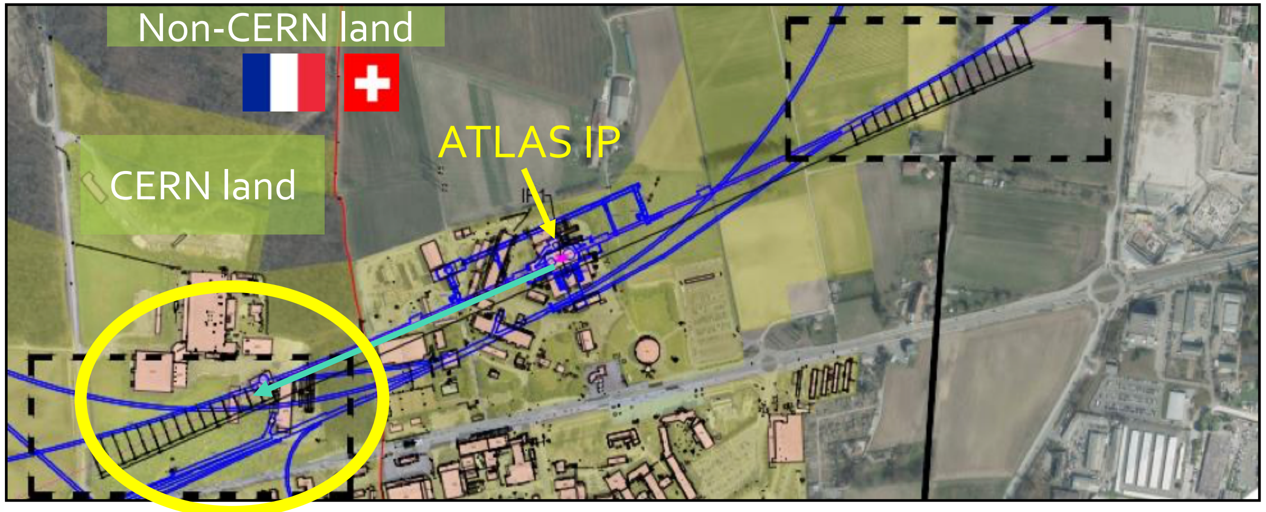
1901.04040

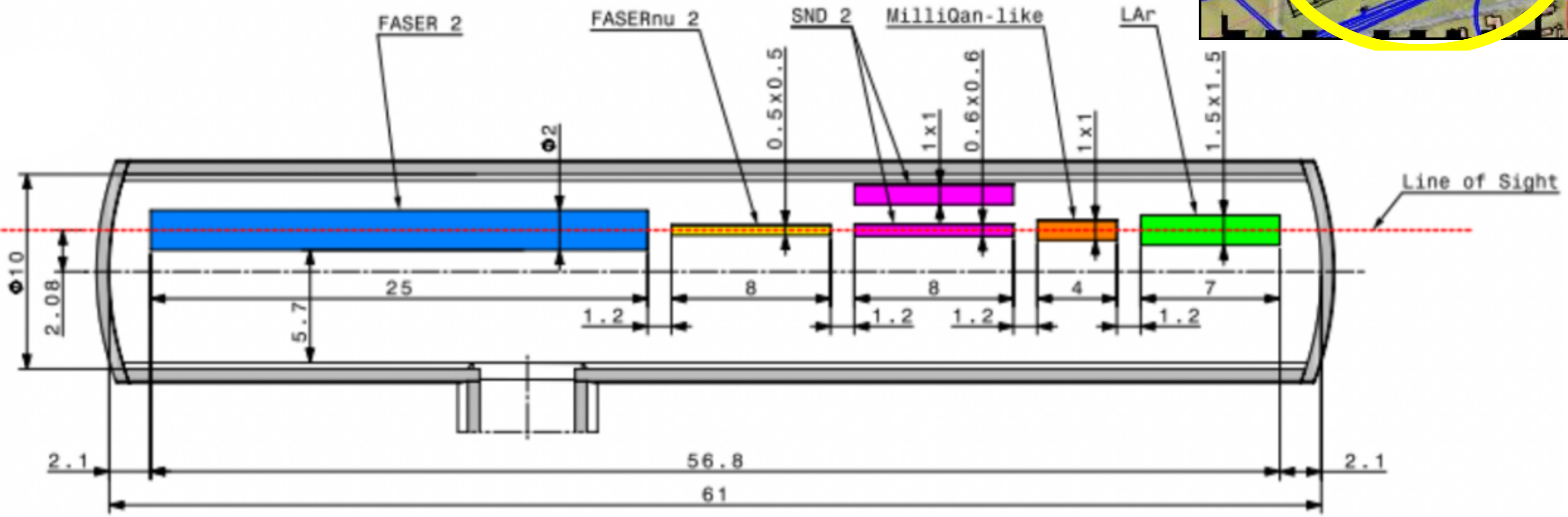
Mathusla test stand

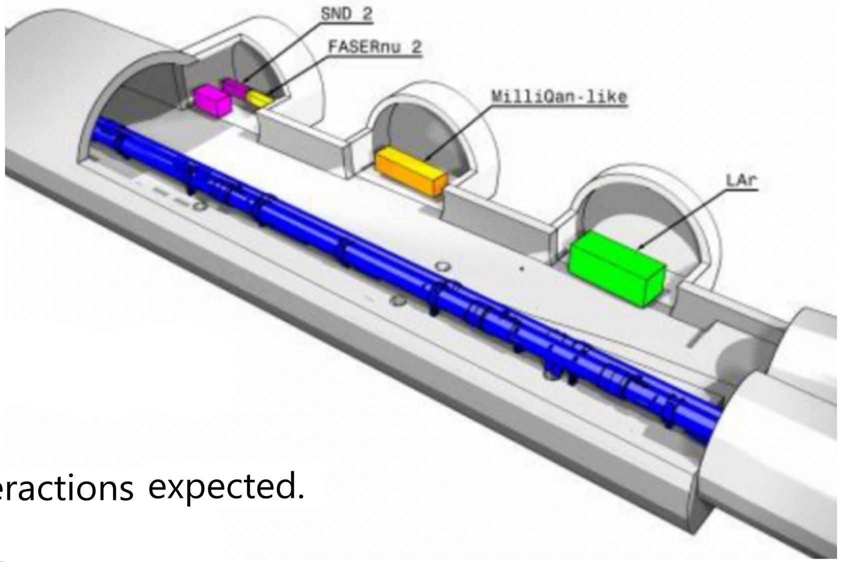
2005.02018

Potential Forward Physics Facility (FPF)

- ***Physics reach would benefit from larger detectors than can fit in the existing infrastructure.***
- ***Community would profit from a dedicated forward physics facility***
- ***Two options considered:***
  - *Alcoves in UJ12*
  - *Dedicated new cavern behind UJ18*







FASERν2: ~2300 (SIBYLL) / ~20000 (DPMJET) ν_τ interactions expected.

Summary

- ***A range of agile, small detectors are being developed to complement searches at the established LHC detectors and probe the unexplored forward intensity frontier.***
- ***Such detectors can be rapidly developed, thanks to spare hardware from the main experiments.***
- ***Run-III experiments should enable major advances:***
  - ***First detection of first collider neutrinos in a new energy regime***
  - ***Searches for long lived, feebly-interacting particles that may be abundant in the far forward region***
- ***Exciting new ideas in development, including a Forward Physics Facility for the HL-LHC era.***

FASER

Looking forward to new physics

Thanks to the UK HEP organisers and all colleagues who contributed slides!