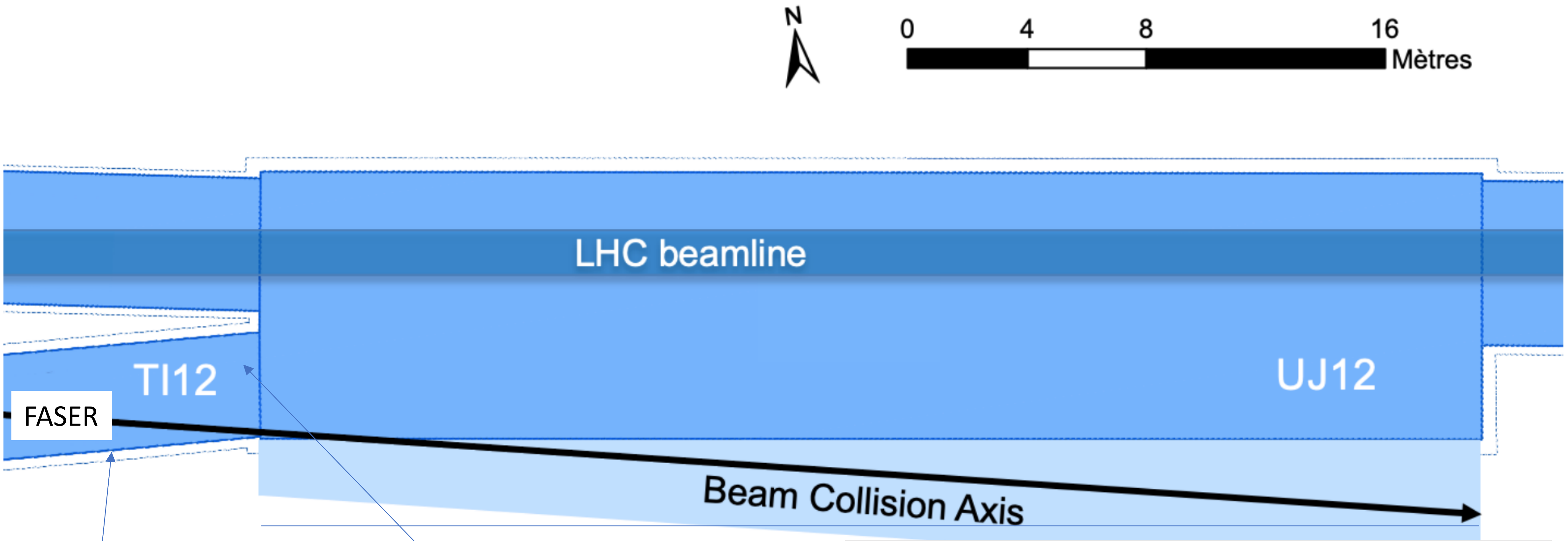
Forward Physics Facility: Environment and Services

Jamie Boyd (CERN)

Overview

- In preparation for the FASER experiment which is being installed in TI12 in Long Shutdown 2 (2019-2021) we made measurements and produced simulations to give us an overview of the environment in TI12
  - Particle flux
  - Radiation
  - Temperature / humidity
- Most of these results are public in the FASER Technical Proposal (arxiv:1812.09139)

Where are measurements have been made



Emulsion and TimePix measurements made here (both for TI12 and TI18)

Radiation measurements made here (both in TI12 and TI18)

Would expect high energy particle flux from IP to be the same along the LOS in the FPF area.
However radiation and low energy background particle flux could be significantly different from FASER measurements

Particle flux

- Particle flux measurements made with emulsion detectors installed into TI18 and TI12 during 2018 LHC running
- Luminosity dependence measured using a TimePix Beam Loss Monitor (BLM) installed by the CERN Beam Instrumentation group in 2018 running
    - BLM not properly calibrated so absolute flux measurement was not possible, but rate changes compared to luminosity in IP1
- FLUKA simulations run by CERN STI group are used to estimate expected particle fluxes from different sources
    - Collision products
    - Showers from off-momentum protons hitting the beam pipe apperture close to FASER
    - Beam-gas interactions

Particle flux

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All measurements made using the LHC optics (2018 version), for HL-LHC there will be quite some changes to the optics and to the HL insertions (magnets around ATLAS) including:

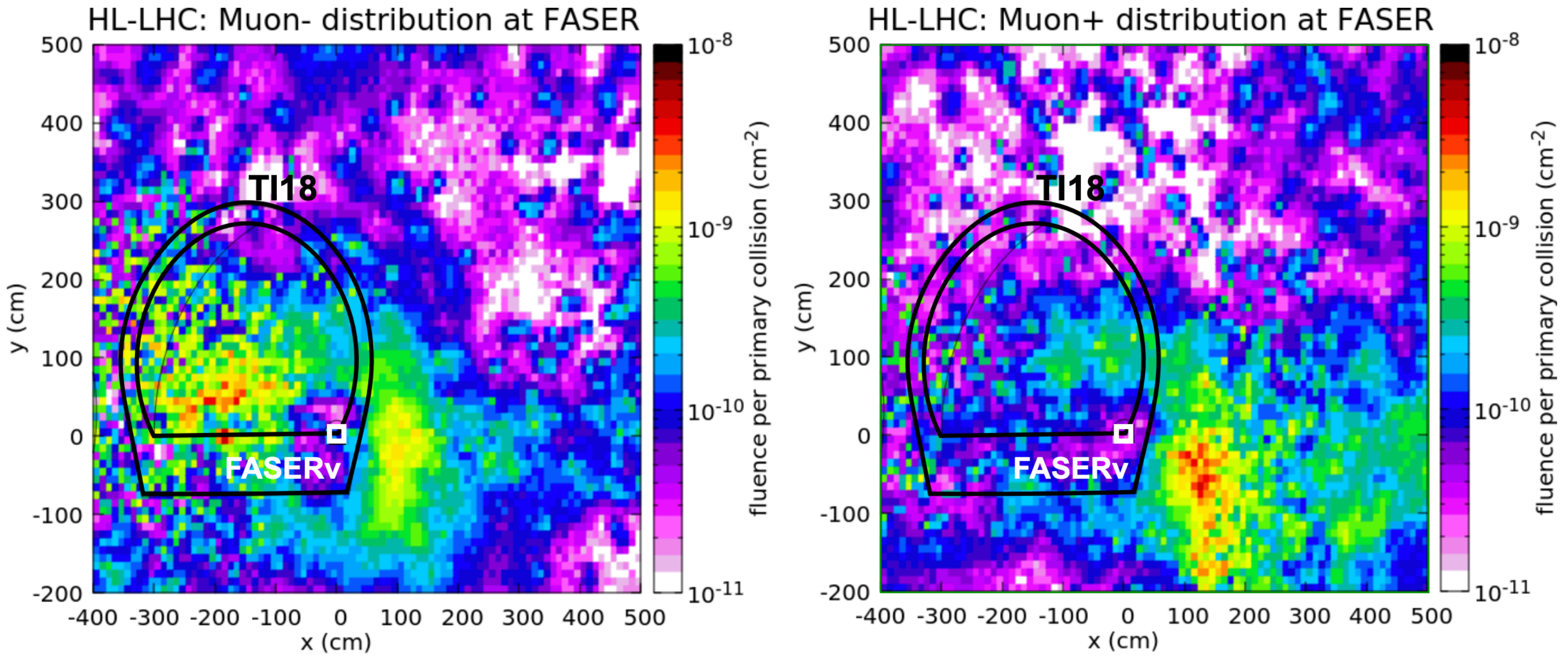
- β* levelling down to 15cm, (probably) larger variation in half crossing angle (to maximum of 200 urad)
- Crab cavities, different separation magnets (D1 and D2) etc…
- As well as beam energy (13 -> 14 TeV)

The effect of these changes on the particle flux at FASER and FPF can be estimated with simulations, but without direct measurements become less reliable…

Particle flux: FLUKA

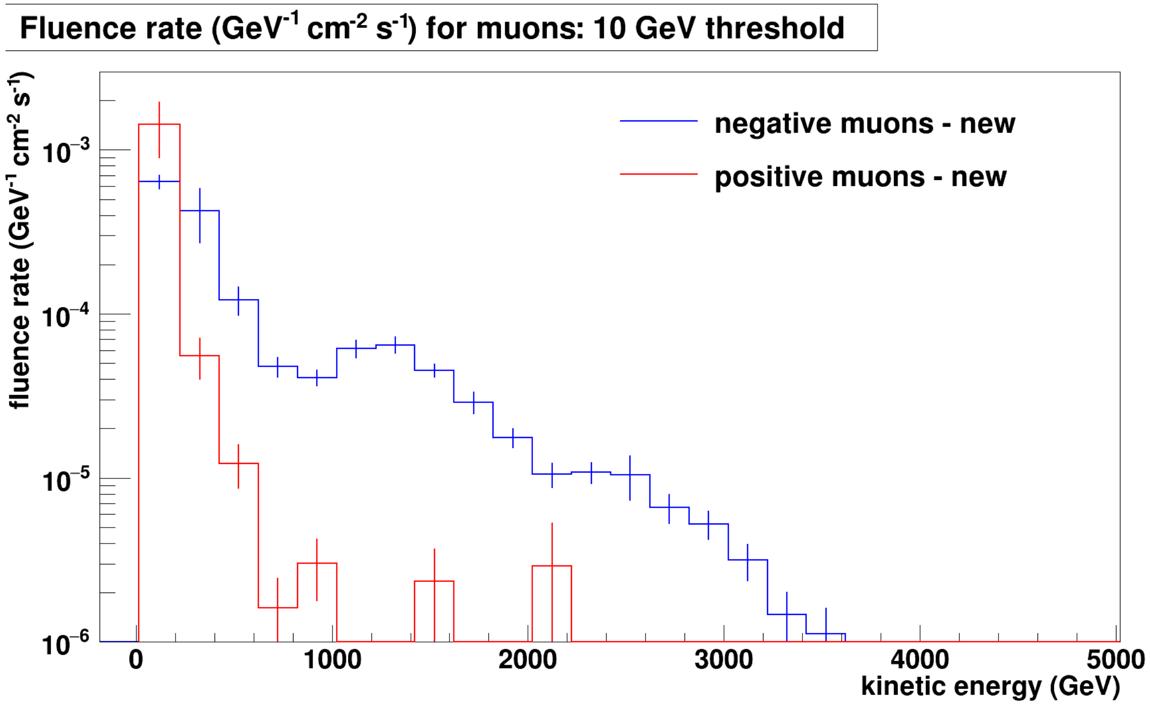
- FLUKA simulations show that the only high energy particles that reach FASER are muons and neutrinos
- For high energy particles these come from collisions at IP1
  - Either directly from collision product decay
  - Or high energy forward neutral particles produced in the collisions causing showers when they hit the TAN, which leads to muons in FASER
  - These particles need to travel through ~100m of rock to reach FASER
  - Of course muons can produce secondary particles through interactions in the rock
- Simulation studies show we do not expect high energy particles from LHC proton losses near FASER
  - Either beam-gas interactions or off-momentum protons hitting the beam pipe apperture

Muon flux: FLUKA



Muon flux in transverse plane at FASER location, separated by charge.
Shows minimum flux on LOS (due to bending in D1/D2 separation/recombination magnets).
Flux increases significantly when moving ~2-3m away from LOS.

Muon flux: FLUKA

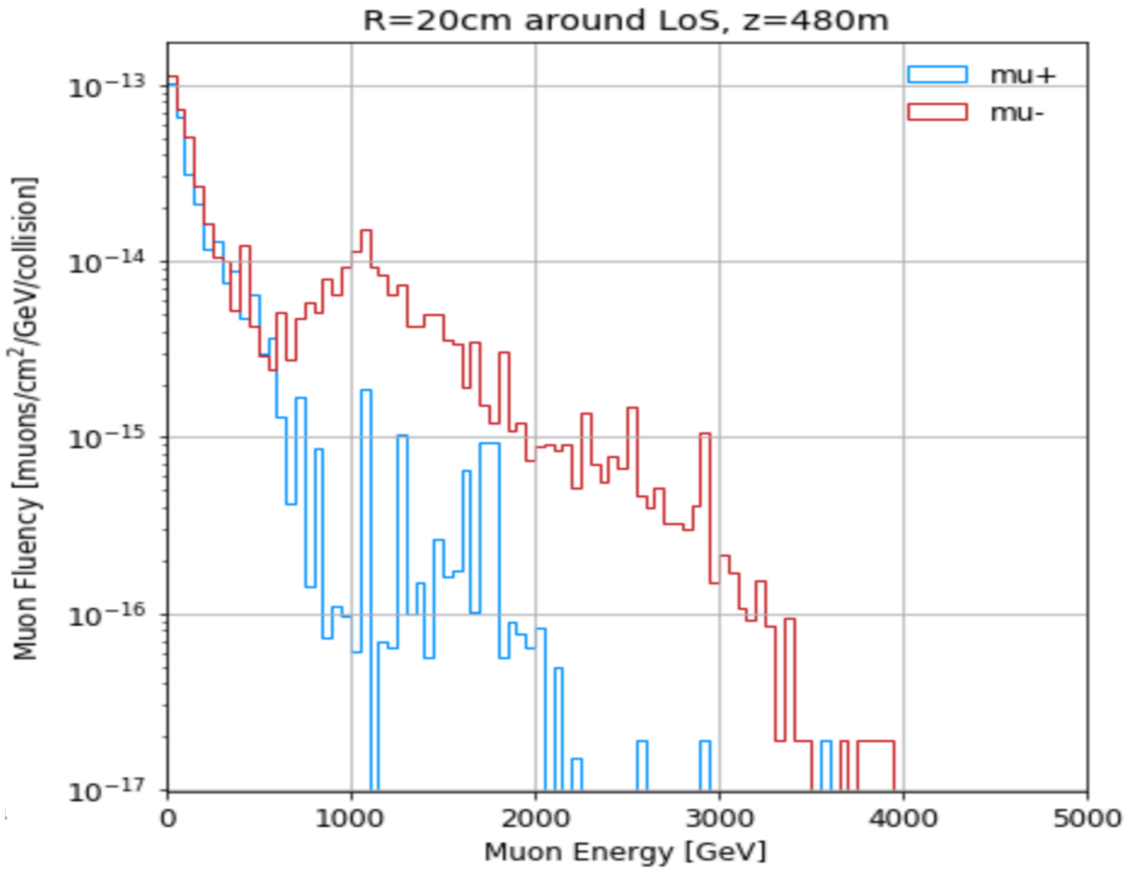


Energy spetra of muons at FASER (in R=20cm region around the LOS) show large difference between negative/positive muons.
Spectrum suffers from large statistical uncertainties.

Energy threshold [GeV]	Charged particle flux [cm^{-2} s^{-1}]
10	0.40
100	0.20
1000	0.06

Expected charged particle rate for different energy thresholds (at a luminosity of 2e34$cm^{-2}s^{-1}$)

Muon flux: FLUKA

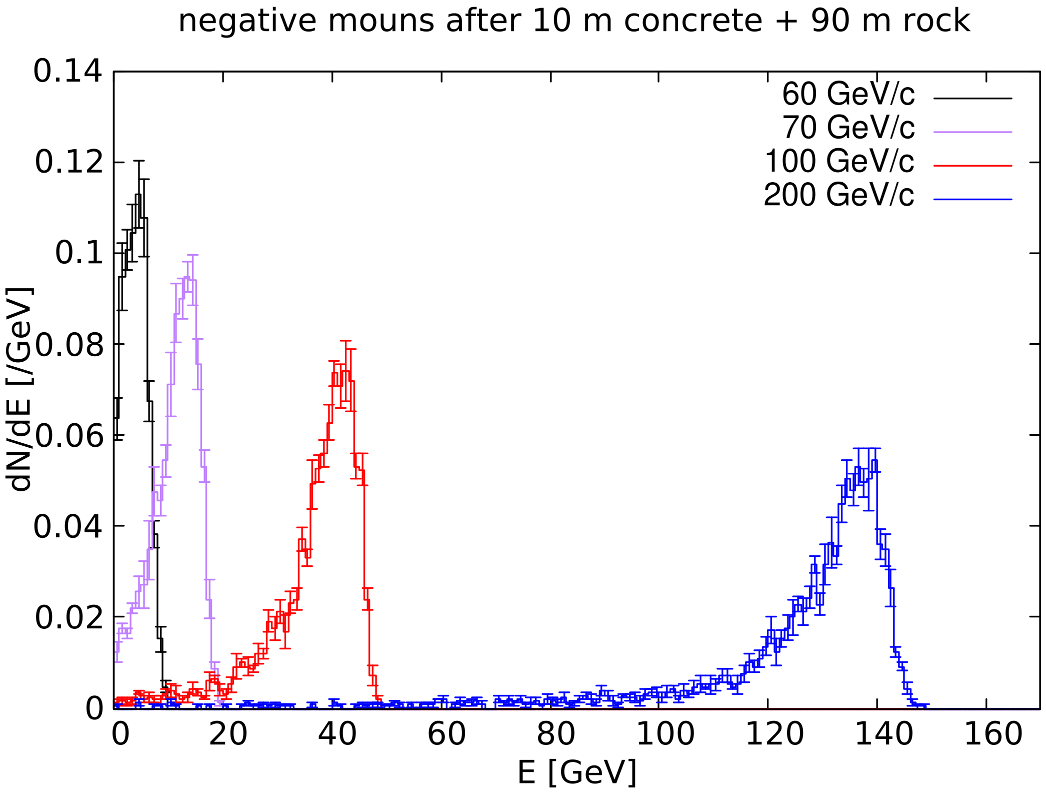


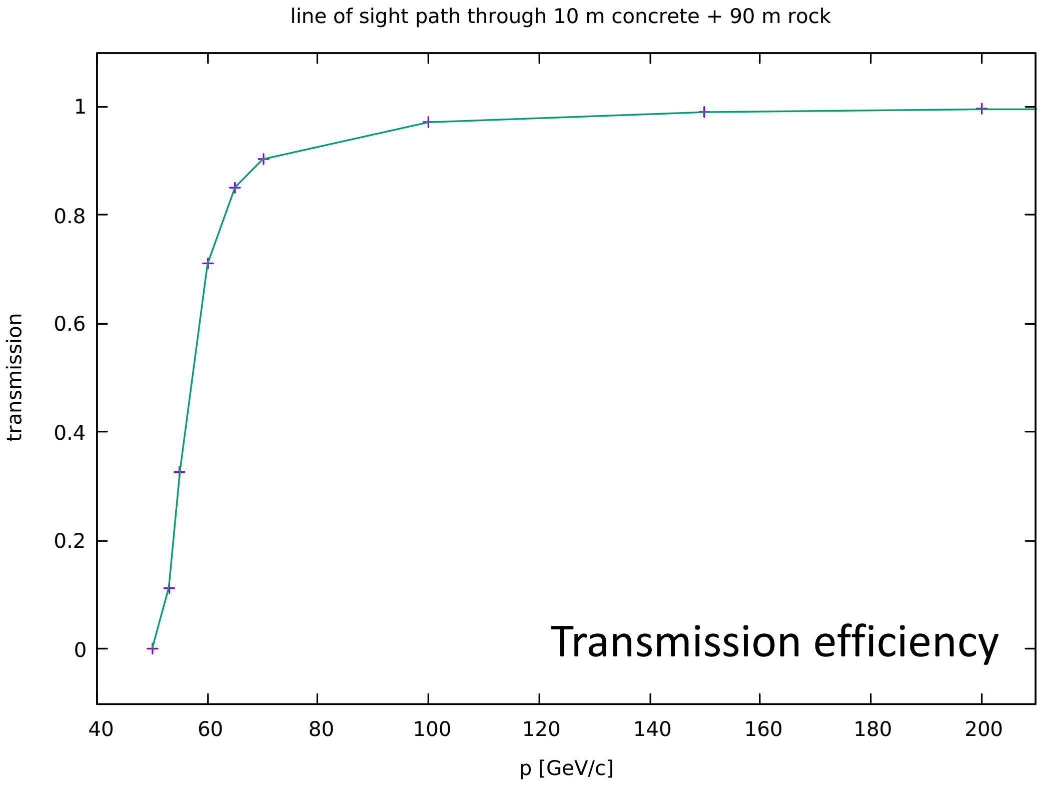
Recently the FLUKA team have updated the flux estimates with more statistics.
The mu- curve is consistent with the previous result but with much better statistics, the mu+ curve seems different (due to better statistics).

Energy Threshold [GeV]	Muon flux (old sim) [fb/cm^2]	Muon flux (new sim) [fb/cm^2]
10	2.0	2.5
100	1.0	1.3

Muon propagation through rock

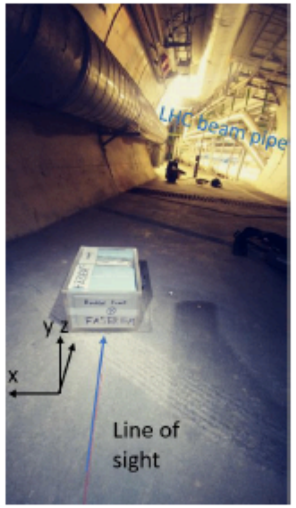
Particles travelling on the LOS to FASER pass through ~10m of concrete and 90m of rock.
Most probable energy loss for a muon traversing the LOS is ~60 GeV.
Of course there is a tail to larger energy loss values.
Plots below from FLUKA studies on this.

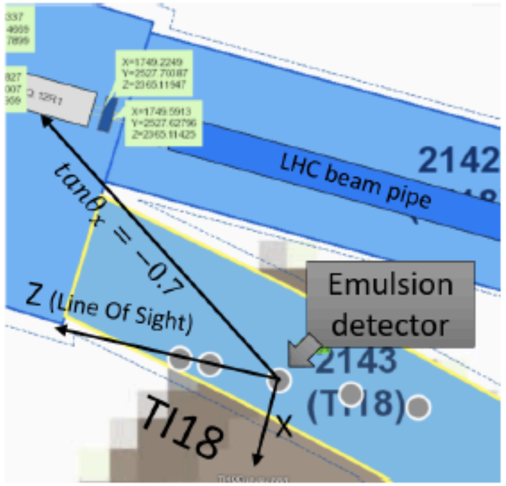


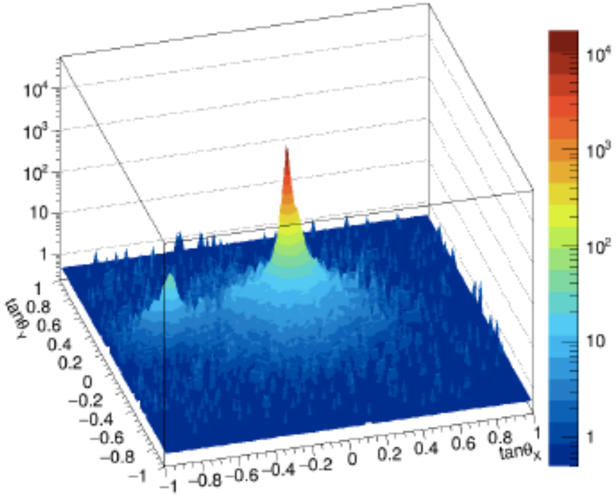


Particle flux: Measurements

Measurements using emulsion detectors installed in TI12 / TI18 in 2018 running confirm expected particle flux

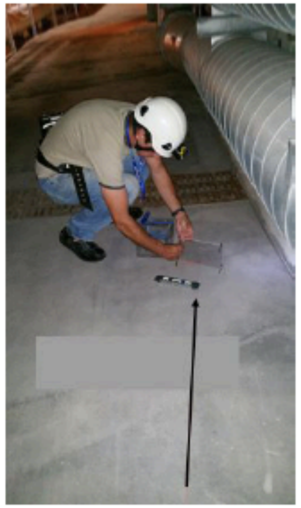


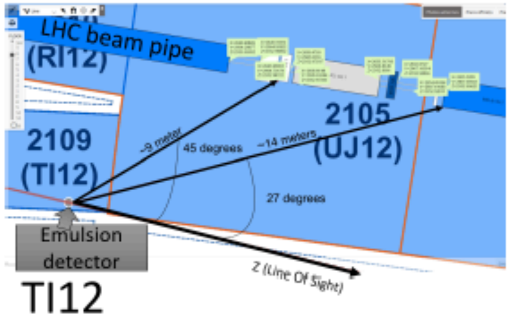


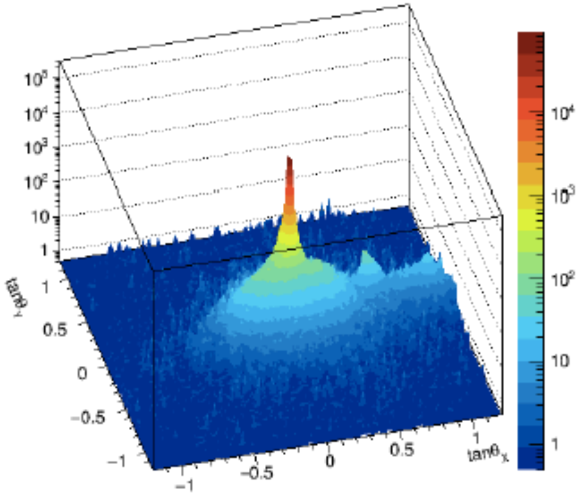


Sharp peak in angular space consistent with high energy particles from the IP.

Small secondary peak consistent with particles coming from beamline.





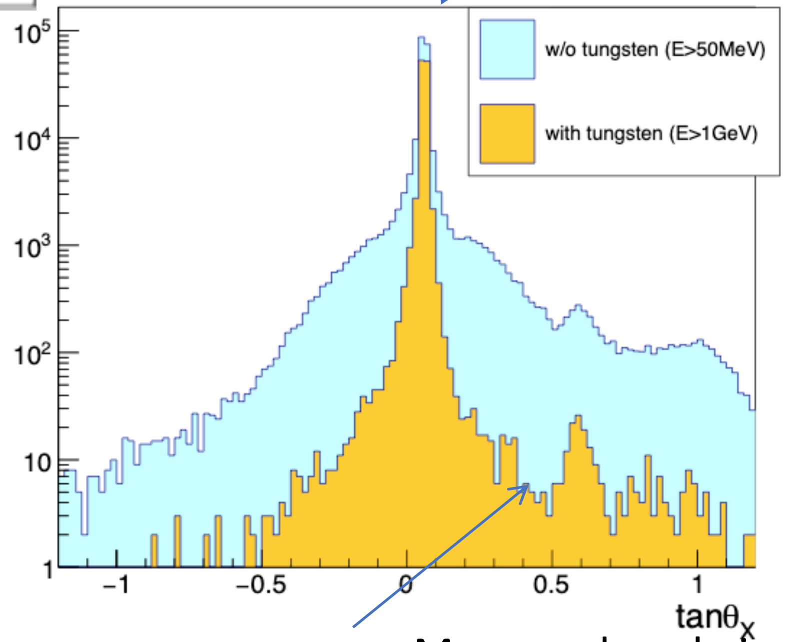


Particle flux: Measurements

Measurements using emulsion detectors installed in TI12 / TI18 in 2018 running confirm expected particle flux

	beam $[fb^{-1}]$	observed tracks $[cm^{-2}]$	efficiency	normalized flux, all $[fb\ cm^{-2}]$	normalized flux, main peak $[fb\ cm^{-2}]$
TI18	2.86	18407	0.25	$(2.6 \pm 0.7) \times 10^4$	$(1.2 \pm 0.4) \times 10^4$
TI12	7.07	174208	0.80	$(3.0 \pm 0.3) \times 10^4$	$(1.9 \pm 0.2) \times 10^4$
FLUKA simulation, E>100 GeV				1×10^4	

particles from IP1



particles from LHC beam line

Measured angle in emulsion detector

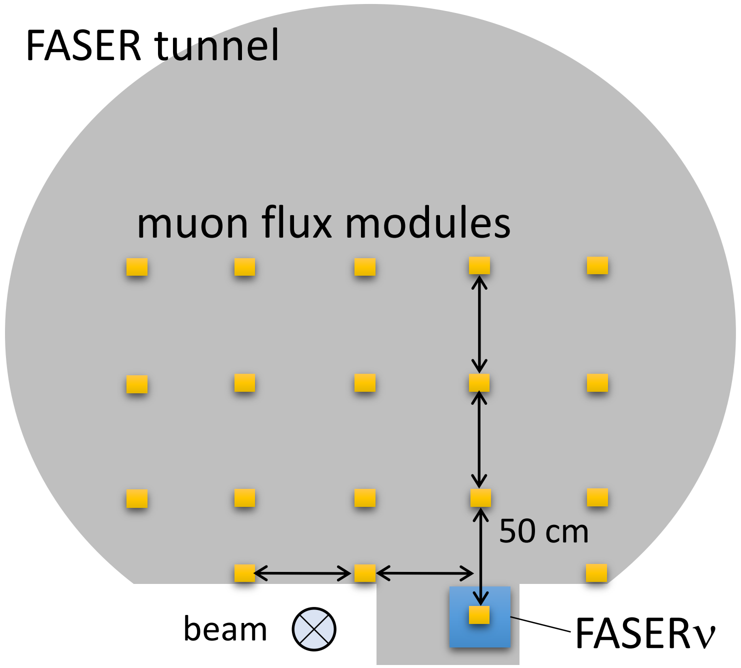
Measured width of peak of 2mrad consistent with angular resolution of detector. Suggests particles are high energy (>250 GeV) as otherwise multiple scattering in rock should smear out the peak.

Good agreement observed between measurement and simulation:
Data: (1.2 – 1.9) x 10^4 fb cm^{-2} (main uncertainty related to emulsion efficiency)
FLUKA: 2.5 x10^4 fb cm^{-2} (For E>10GeV) (large uncertainties due to statistics)

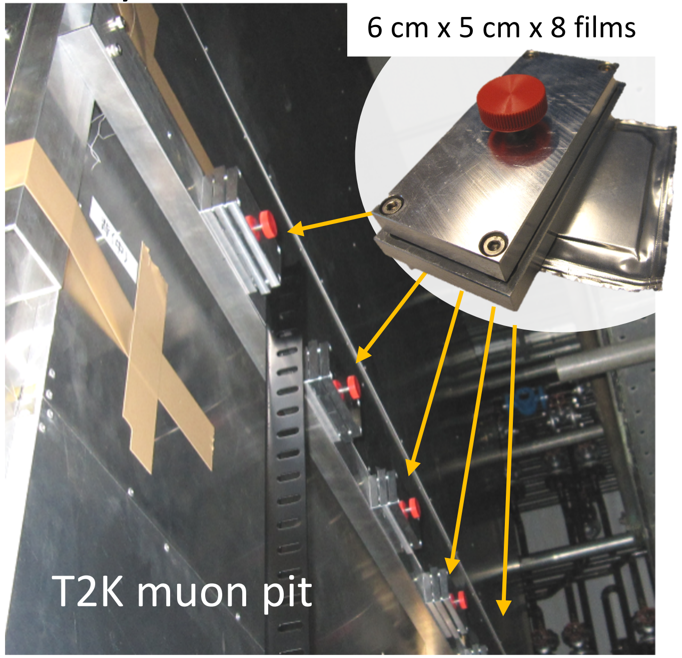
Further muon flux measurements in Run 3

- It would be useful to make more flux measurements in this region in early Run 3 (2022) to help prepare for future experiments
- FASER will be able to make muon momentum measurements on the LOS
- But plan to also make emulsion based measurements further from LOS

Emulsion-based beam monitor, used in T2K and FASER, can be used for these measurents purpose.
[10.1093/ptep/ptv054, arXiv:1812.09139]



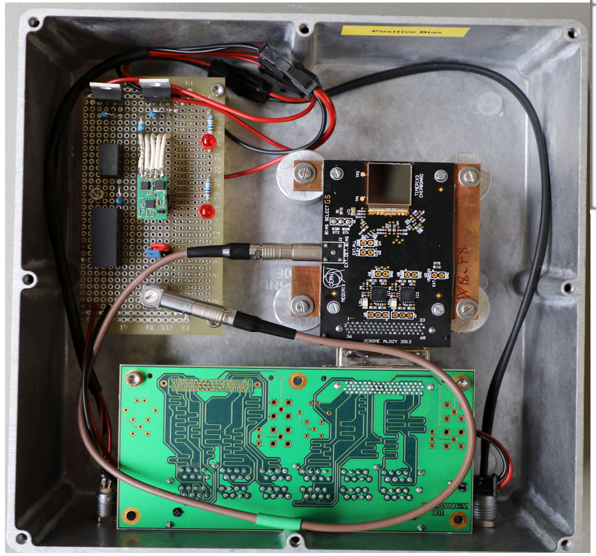
an array of emulsion modules in T2K



Particle flux: Measurements

Since the emulsion measurement has no time granularity, the flux measured can not be correlated with the instantaneous luminosity in IP1 (to show the particles are coming from luminosity debris).
The CERN Beam Instrumentation group installed a TimePix BLM in TI18 to allow such a time dependent measurement.
BLM not properly calibrated so absolute flux measurement not possible, but rate changes compared to luminosity in IP1.

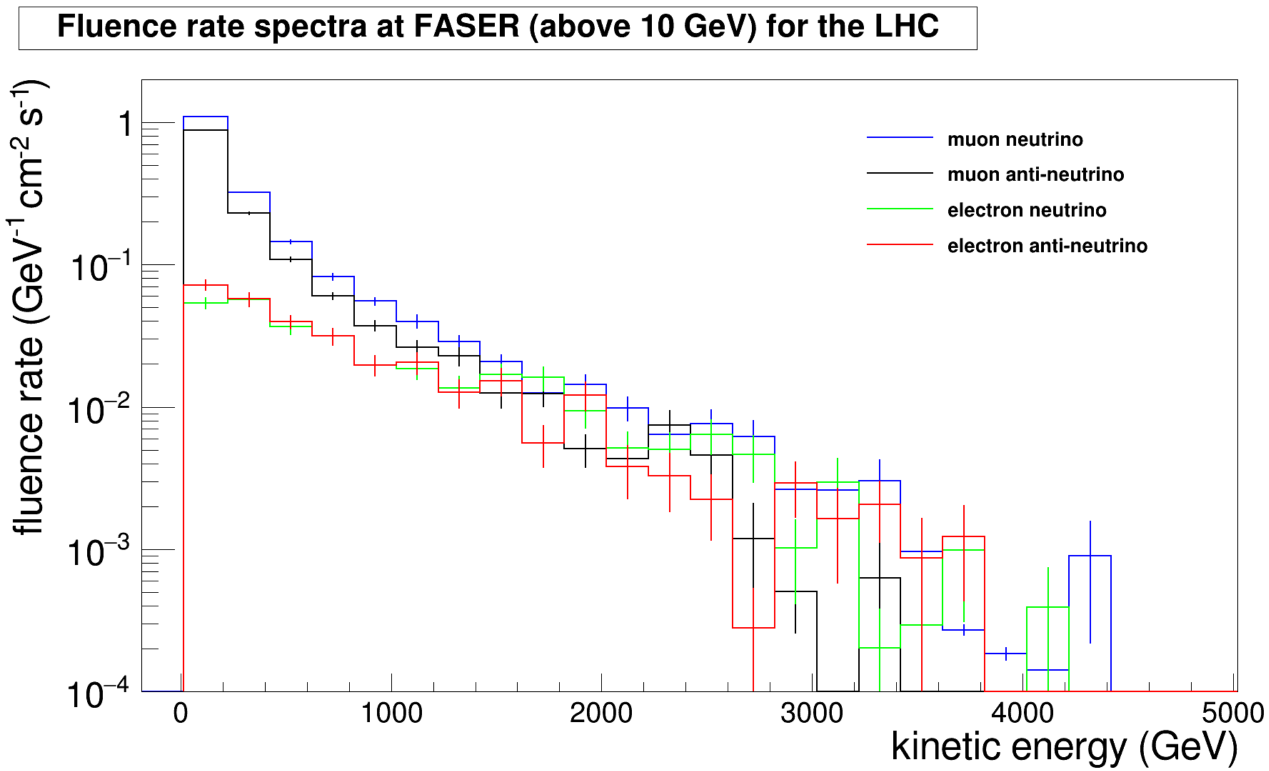
1.4cm^2 pixel detector

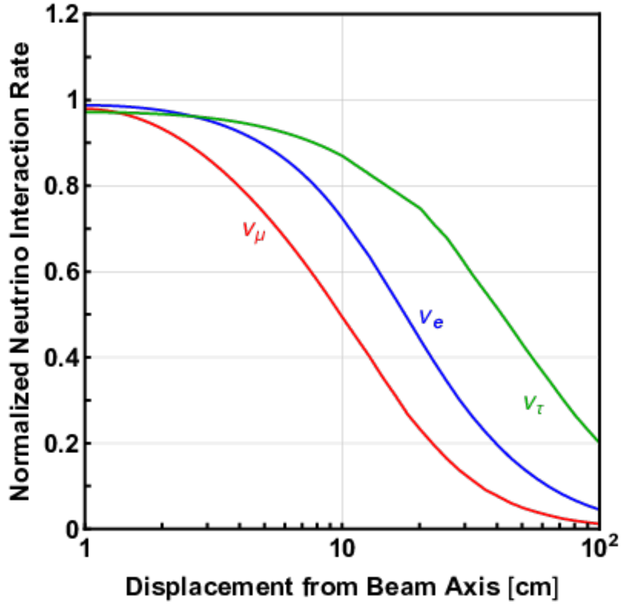


Period	Luminosity $[10^{34}\ s^{-1}\ cm^{-2}]$	Counting Rate $[s^{-1}]$	Counting Rate/Luminosity $[10^{-34}\ cm^2]$
No beam	-	0.16	-
Beam (no collisions)	-	0.55	-
Collisions	1.8	7.0	4.0
Collisions	1.3	4.8	3.8
Collisions	0.8	3.3	4.2
Collisions	0.6	2.7	4.3
Collisions	0.5	2.2	4.1

Rate higher with beam (no collisions) than pedestal, means some particles coming from beamline.
But rate much higher when beams colliding – and proportional to luminsoity as expected from FLUKA.

FLUKA: Neutrino flux





Neutrino production depends on flavour and energy:
- Electron neutrinos mostly kaon decay (charm at high E)
- Muon neutrinos mostly pion decay
- Tau neutrinos mostly charm decays

The angular spread of the neutrino flux around the LOS depends on the production.

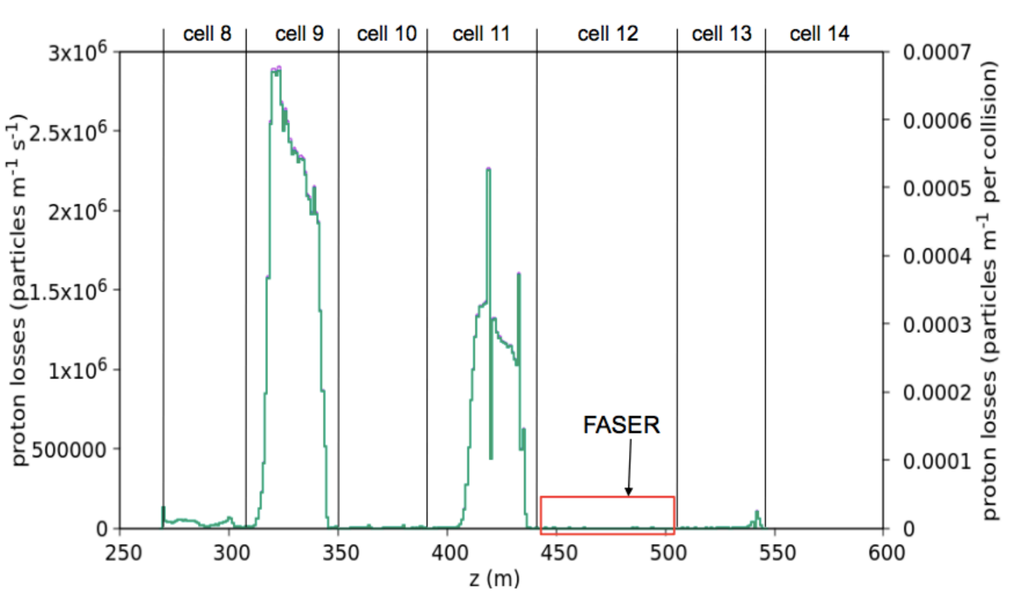
Huge flux of high energy neutrinos along LOS.
Physics opportunity, but also can act as a background (in FASER we expect neutrino interactions in the calorimeter can be a background for BSM searches – possibly the first time neutrinos are a background at a collider experiment!).
Note forward heavy flavour production not well validated in DPMJet (used as generator for FLUKA) – tau neutrino flux likely significantly over estimated in FLUKA.
There is an ongoing effort in the FASERnu team to come up with the best neutrino flux estimates.

Radiation Level and Beam Losses

- FLUKA studies show that the radiation level in TI12/TI18 arises from showers close to FASER
  - This is usually coming from protons hitting the beam apperture, but due to the beam dispersion near FASER this is sub-dominant
  - So in the case of FASER beam-gas interactions are dominant. Mostly for the incoming beam (due to the orientation of the tunnels)
    - The very good vacuum in the LHC arcs means this is still very low
- FLUKA expectations:
  - less than 5 x 10^{-3} Gy/year
  - less than 5 x 10^{7} 1 MeV neutron equivalent fluence / cm^{2} / year
- Generally low radiation but still at the level where it could effect electronics
  - In FASER we pushed our electronics as far from the LHC as possible to reduce radiation effects (~1 order of magnitude reduction in dose)
  - For FPF we would probably want some shielding for experiments electronics

Beam Losses around FASER

Due to the dispersion function of the LHC around the FASER/FPF location, the beam losses from off-momentum protons (following diffractive processes at IP1) has a distinct pattern.
This shows very low losses at Q12, with much higher losses in Q11 and higher in Q13. This is good for FASER/FPF.
This feature is related to the dispersion suppresor lattice, and will not change for HL-LHC.



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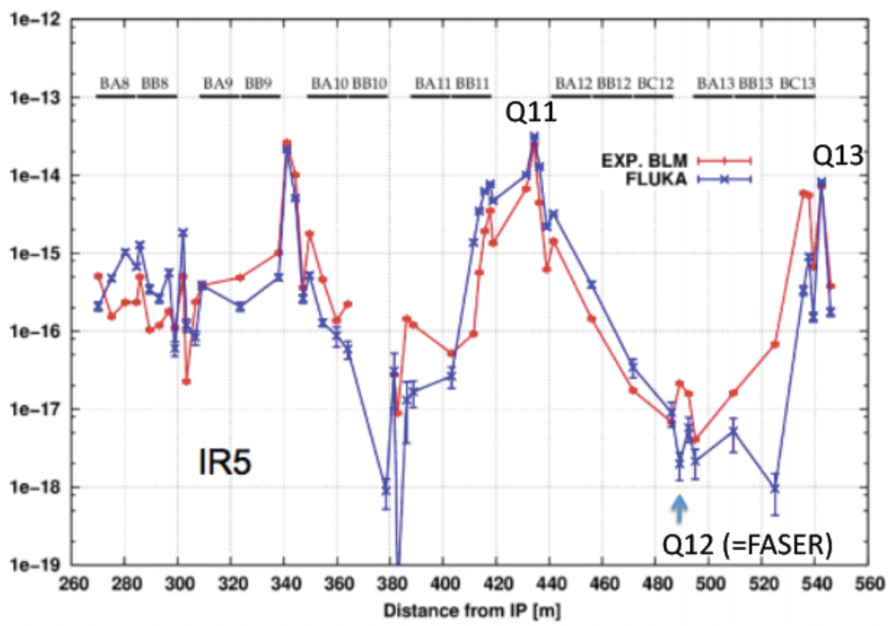
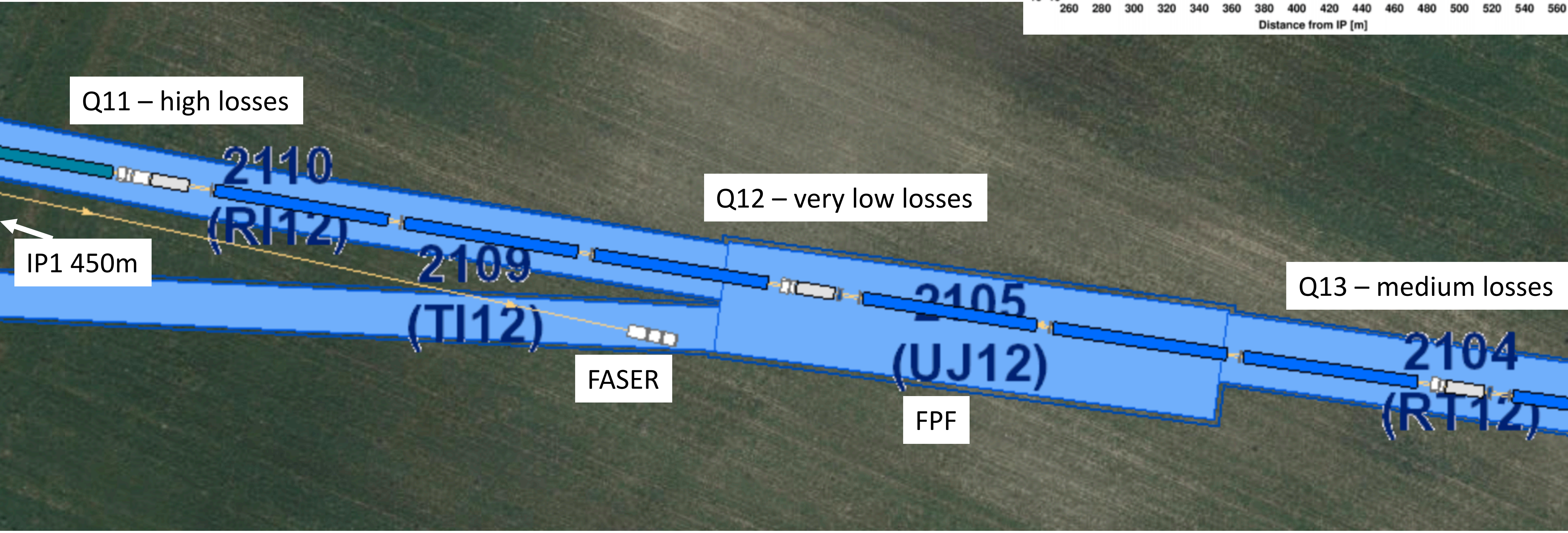
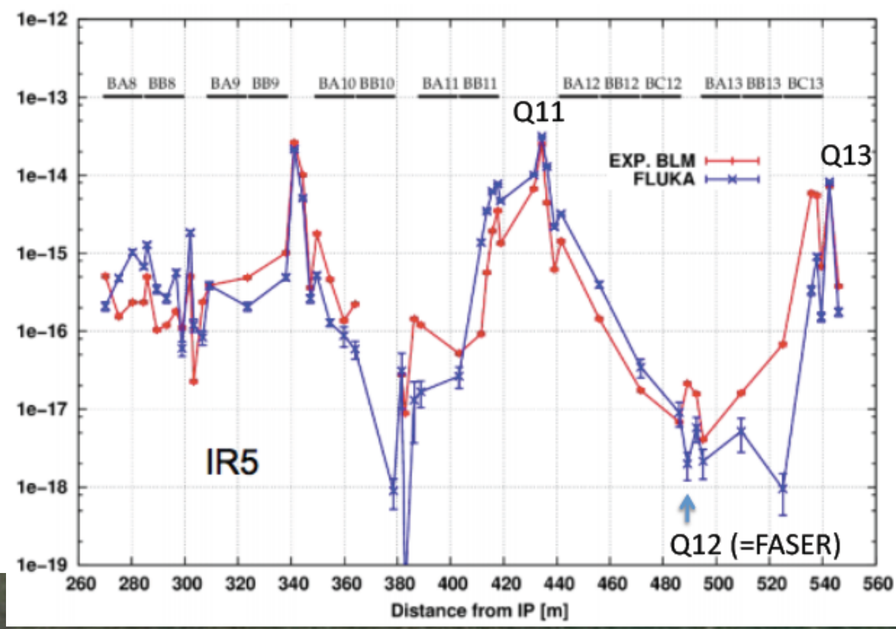




Beam Losses around FPF



Would expect more radiation from beam loss induced showers in FPF than in FASER, due to lack of shielding, and being closer to Q13 (at back of FPF). Still particles would need to back scatter from Q13 losses to get to FPF.

Would be important to take radiatoin measurements along the UJ12/UJ18 wall during 2022 LHC running. Can consider to install shielding between LHC and FPF if needed.

Beam Losses around FPF

Example shielding wall ~0.5m thick to protect electronics in RR in the LHC.

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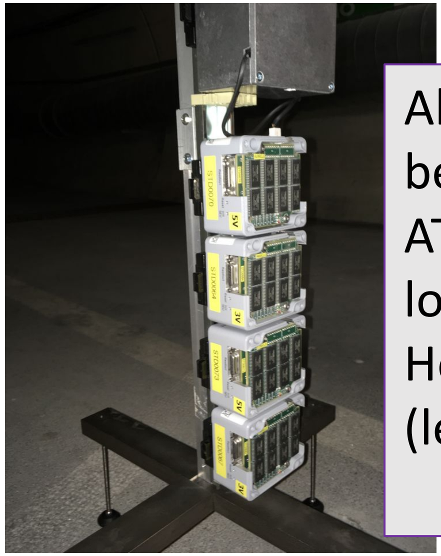
Radiation Level and Beam Losses

- Radiation measurements performed in TI12 and TI18 using BatMon radiation monitors during 2018 LHC operations
- The measurements showed that the high energy hadron fluence was below the device sensitivity of 10^6 cm^{-2} which is completely consistent with the FLUKA estimate
- The measured thermal neutron flux was $4x10^6$ cm^{-2} within a factor of 1.5 of the FLUKA estimate of $6x\ 10^6$ cm^{-2}
  - This is normalized to an integrated proton intensity of $3x10^{20}$ p s (corresponding to ~1month of running 2018)
- Measurements validate well the FLUKA estimates
- Given the radiation will be higher and vary across the UJ12/UJ18 caverns, it would be good to make measurements during Run-3 operations

Note for HL-LHC the expected 1MeV neutron equivalent fluence is above 10^{15} cm^{-2}/yr for the most exposed detector areas (this is a factor 10^8 higher fluence than in TI12).

Radiation Level and Beam Losses



All measurements made using the LHC optics (2018 version), for HL-LHC there will be quite some changes to the optics and to the HL insertions (magnets around ATLAS). However the dispersion in this region of the LHC will not change, so the losses at Q12 will remain very low.
However with higher bunch current the beam-gas rate will increase.
(less than factor of 2 from LHC -> HL-LHC).

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the FLUKA

~1month of

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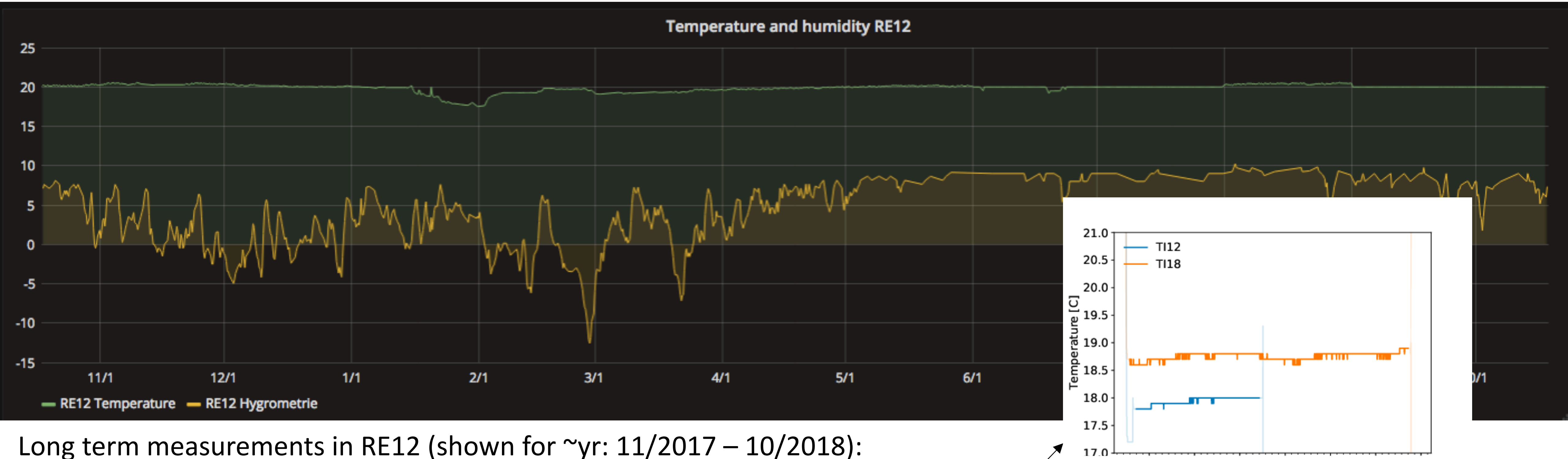
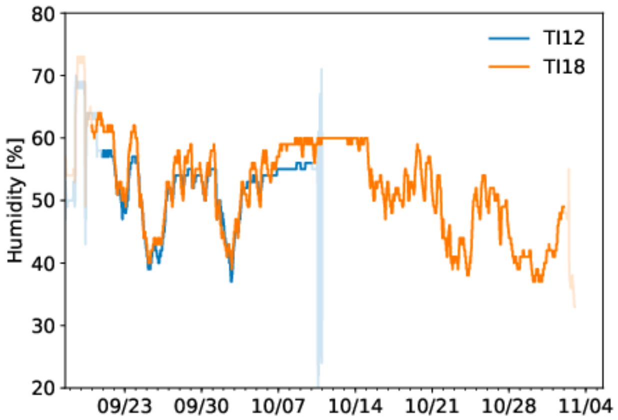
Temperature & Humidity



Long term measurements in RE12 (shown for ~yr: 11/2017 – 10/2018):

- Temperature very stable around 20 degrees
- Humidity varies, but due point never above 10 degrees

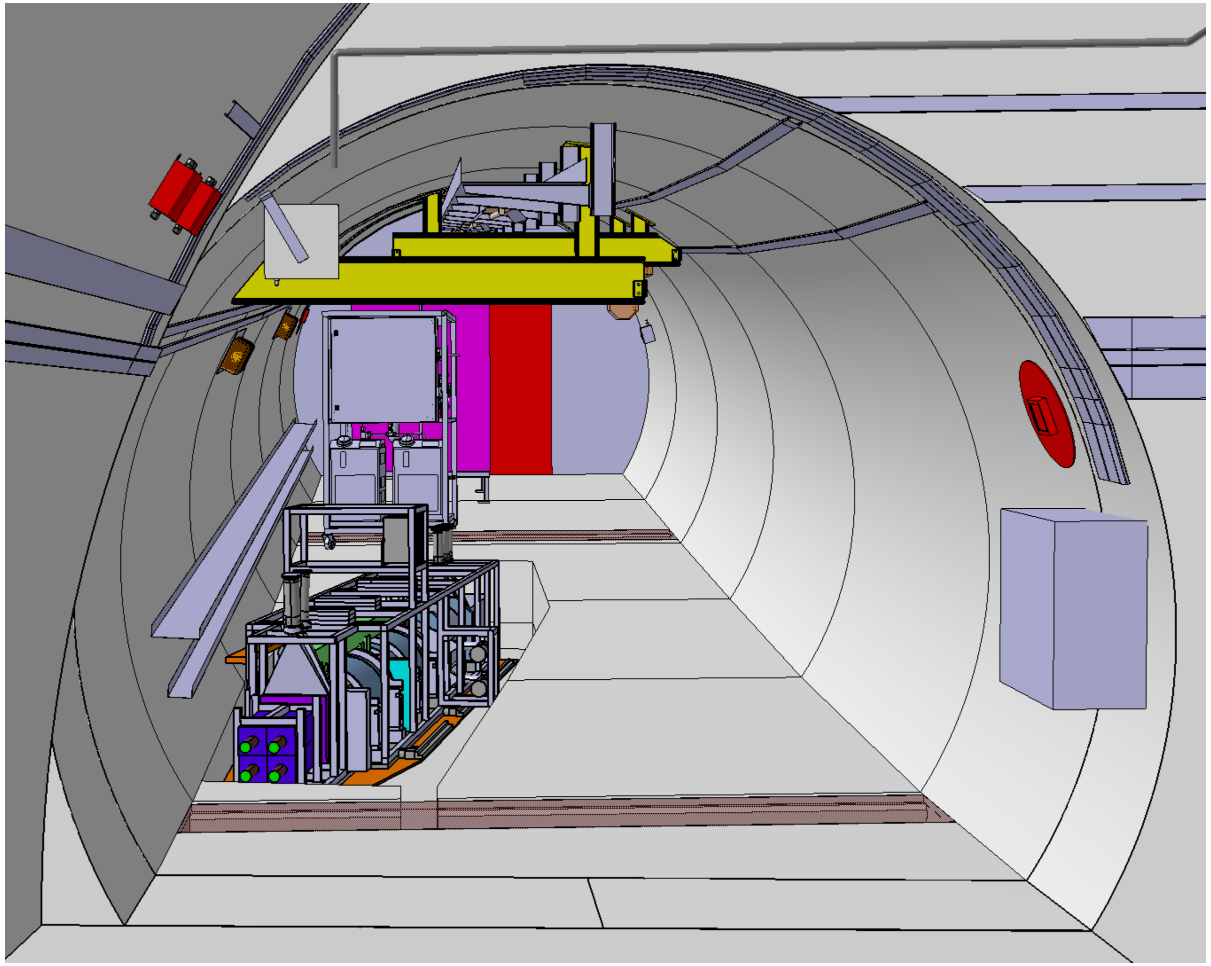


Measurements taken when emulsion detector installed in TI12.
Shows ~1month of data:

- Temperature very stable ~19degrees (TI18), ~18degrees (TI12)
- Humidity varying quite a lot…

One slide on Experiment Services

- For FASER we have installed:
  - Power
    - 16A x 400V + UPS
  - Optical fibers
    - (detector readout and control, including clock and LHC information)
  - Compressed Air
  - Handling equipment
- It is a lot of work to install these services and one of the big advantages of the FPF is that the services could be provided to serve all the experiments in the facility together
  - With more diverse and sophisticated experiments cryogenics maybe needed



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Effect of beam configuration on FPF physics

- Crossing angle (& direction) in HL-LHC
  - ~200-250urad half crossing
  - Will move the LOS about 10cm from nominal position
  - Most likely configuration for HL-LHC at IP1 will move it horizontal AWAY from LHC
  - Likely that the crossing angle will change during the fills at the level of moving the LOS by a few cm in the fill
- Divergence
  - The divergence is the transverse spread of the collision system from the squeezing of the beam
  - It has the effect of smearing out the LOS
  - The size of the divergence is ~4-5 times smaller than the half crossing angle given above, so the LOS is smeared with a width of O(2cm). This should not have any real effect for physics at the FPF.

Summary

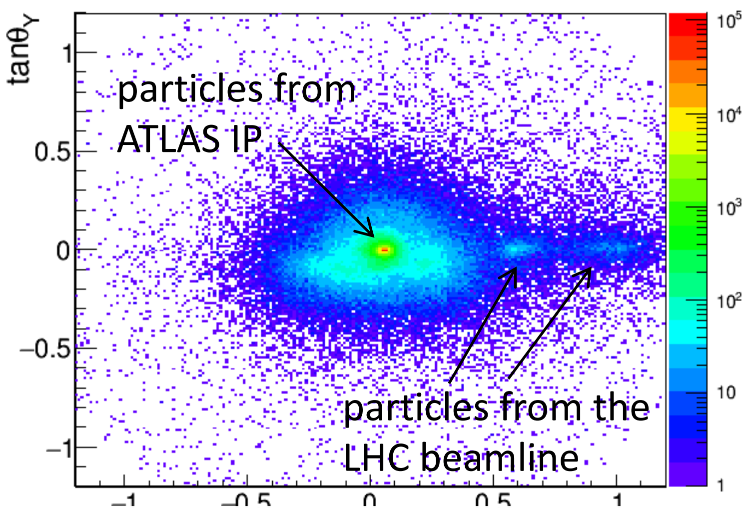
- In preparation for FASER we have studied particle flux, and radiation in TI12/TI18 with simulations and measurements:
  - In general particle flux is low dominated by muons with a rate of ~0.5Hz/cm^2 at 2x10^{34} (would scale to 1.25Hz/cm^2 @ HL-LHC)
  - Radiation generally low and dominated by beam-gas interactions (due to local dispersion function)
- In this sense TI12 / TI18 are ideal to place experiments – and the FPF in UJ12 / UJ18 would likely be similar, although shielding from the LHC would likely be needed
  - Additional measurements should be made in 2022 running to confirm the radiation levels across the UJ caverns, and particle flux away from the LOS
- The installation of common services for the FPF would be a big advantage for preparing the experiments

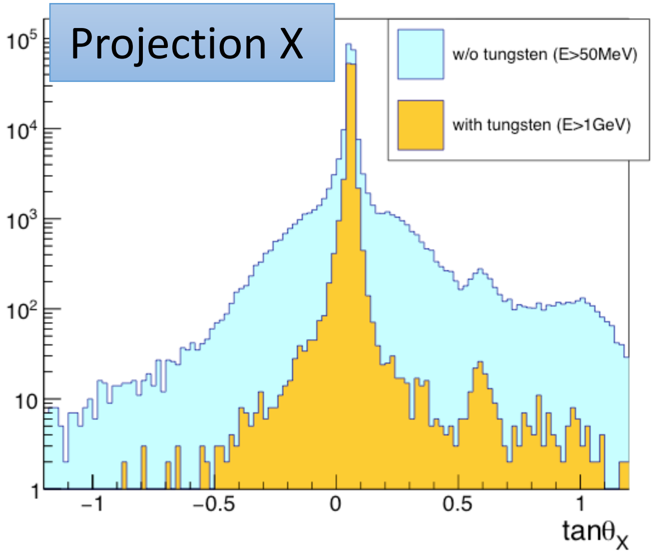
References

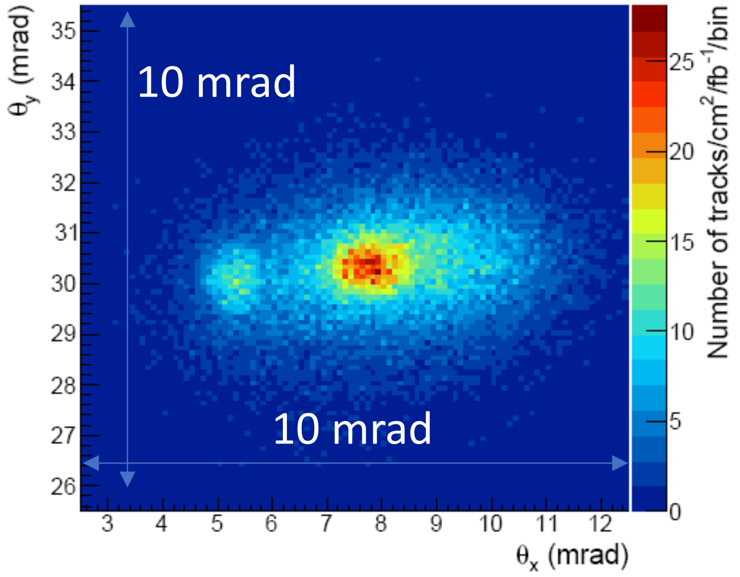
- FASER Technical Proposal: https://arxiv.org/abs/1812.09139
- FASERnu Technical Proposal: https://arxiv.org/abs/2001.03073

Backup…

Angular distributions of muons







There are two peaks in the main peak. Particles traveled through 100 m of rock, nevertheless the angular spread is very small. The fitted sigma is less than 1 mrad, corresponding to P>500 GeV

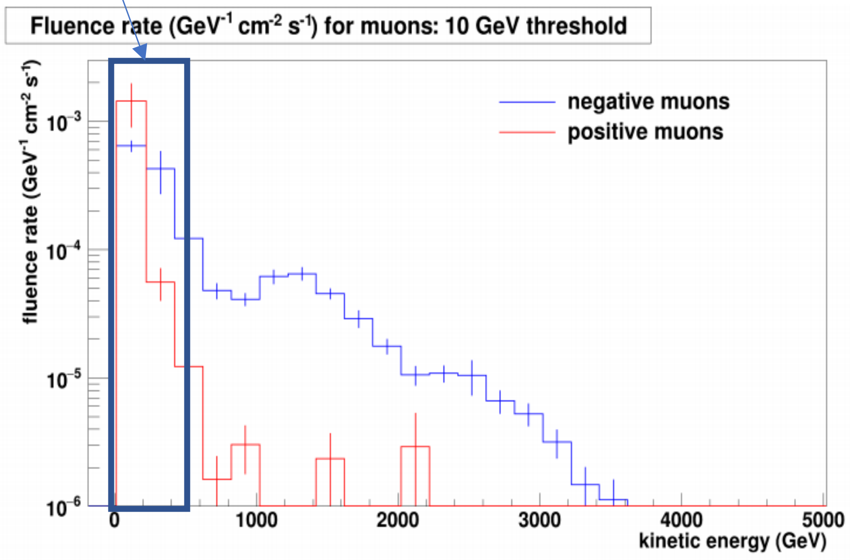
	beam $[\mathrm{fb}^{-1}]$	normalized flux, all $[\mathrm{fb\ cm}^{-2}]$	normalized flux, main peak $[\mathrm{fb\ cm}^{-2}]$
TI18	2.86	$(2.6 \pm 0.7) \times 10^4$	$(1.2 \pm 0.4) \times 10^4$
TI12	7.07	$(3.0 \pm 0.3) \times 10^4$	$(1.9 \pm 0.2) \times 10^4$
FLUKA, E>10 GeV		2×10^4 (uncertainty 100%)	

Data and the FLUKA prediction agrees within their uncertainty.

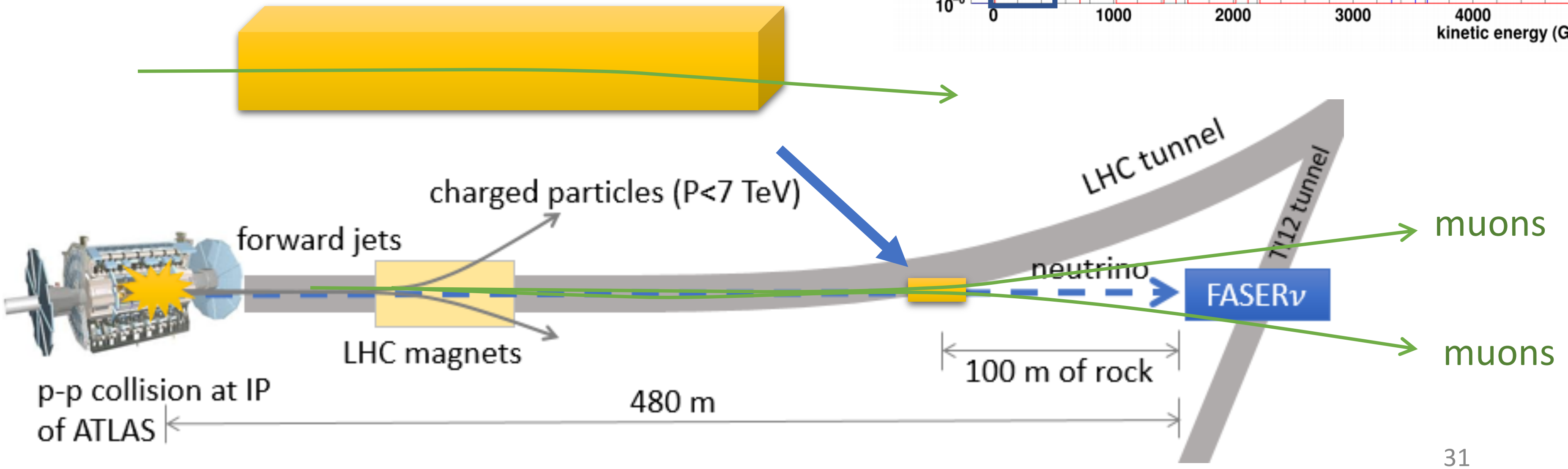
Key issue: Muon background

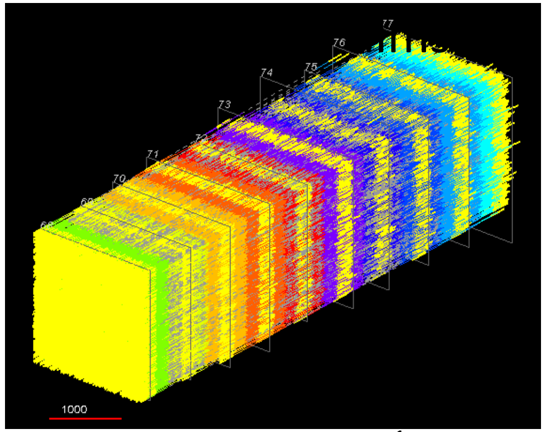
- Density of muons limits the duration of each data taking with emulsion detectors
- HL-LHC would increase muon rate by a factor of 5 → Problem!!
- **Can we suppress 80-90% of muon background?**
- Let's sweep muons by a magnet upstream of the rock shielding
  - To bend 500 GeV particle by 4 mrad → 6.7 $T \cdot m$ is required

90% of muons are expected to be P<500 GeV



1-Tesla x 7-m-long x 40-cm-wide permanent magnet with a proper yoke (not to affect the LHC)





with 12.5 fb^{-1}