FASER

FORWARD SEARCH EXPERIMENT AT THE LHC

PITT-PACC Workshop: BSM Circa 2020

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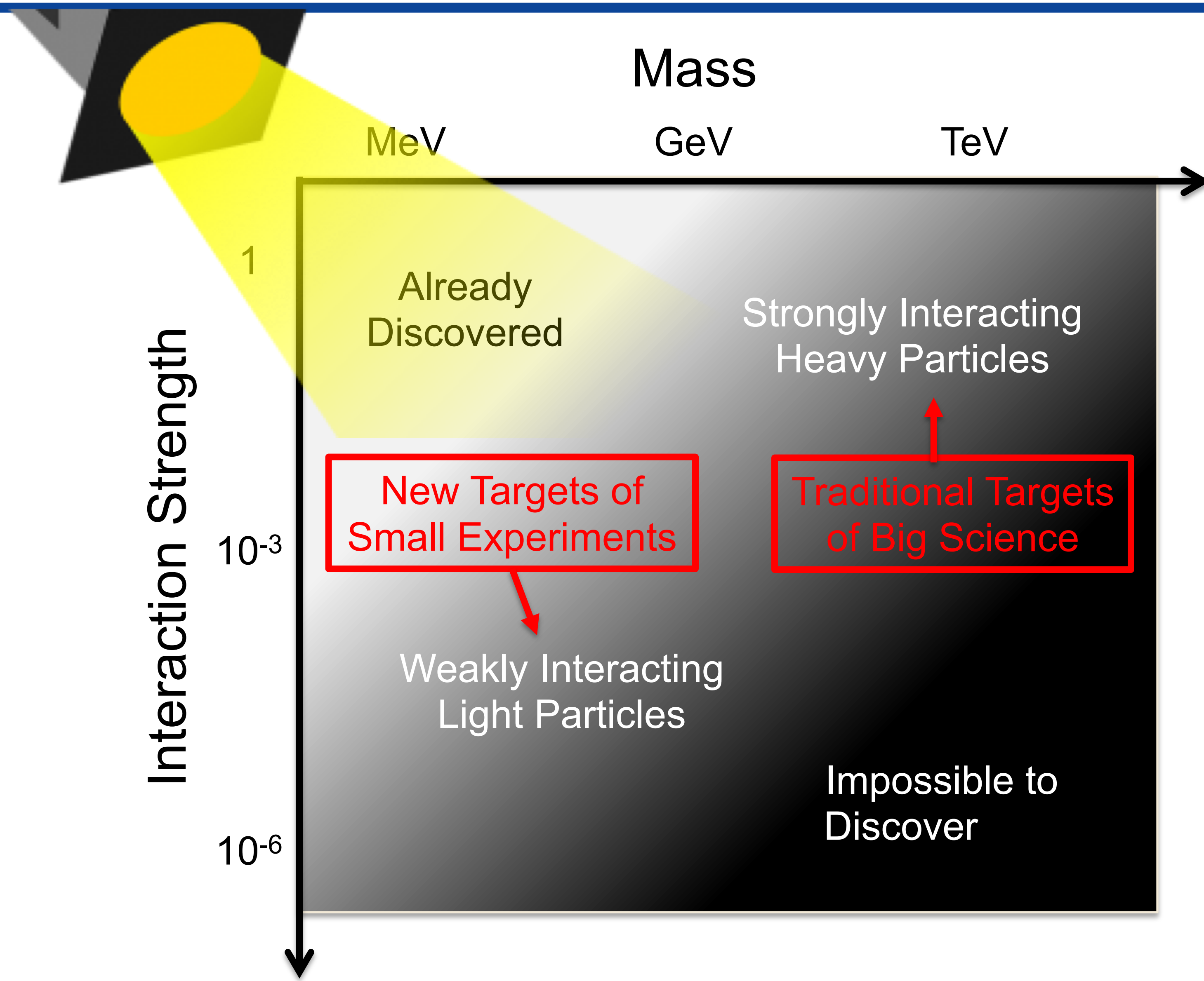
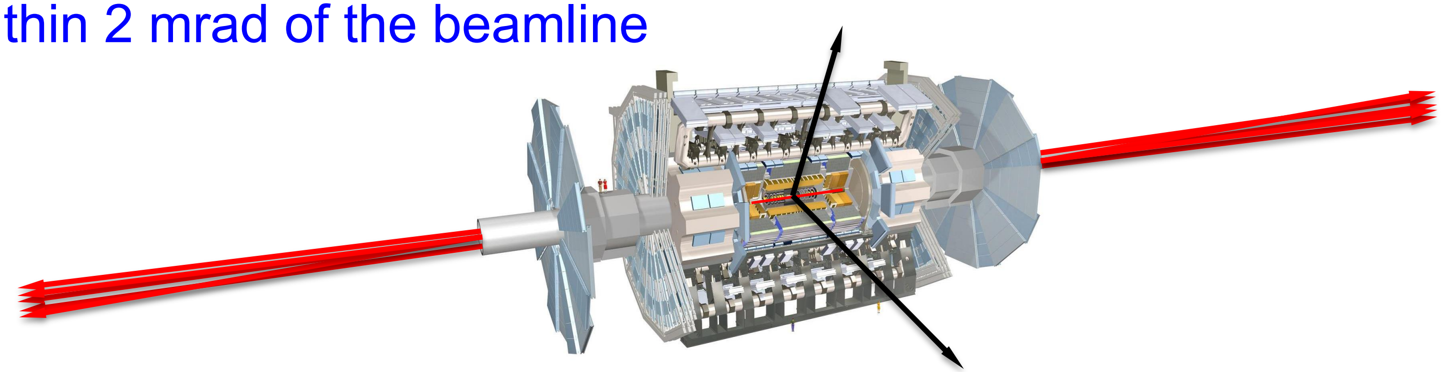
1 March 2019

THE LAMPPOST LANDSCAPE



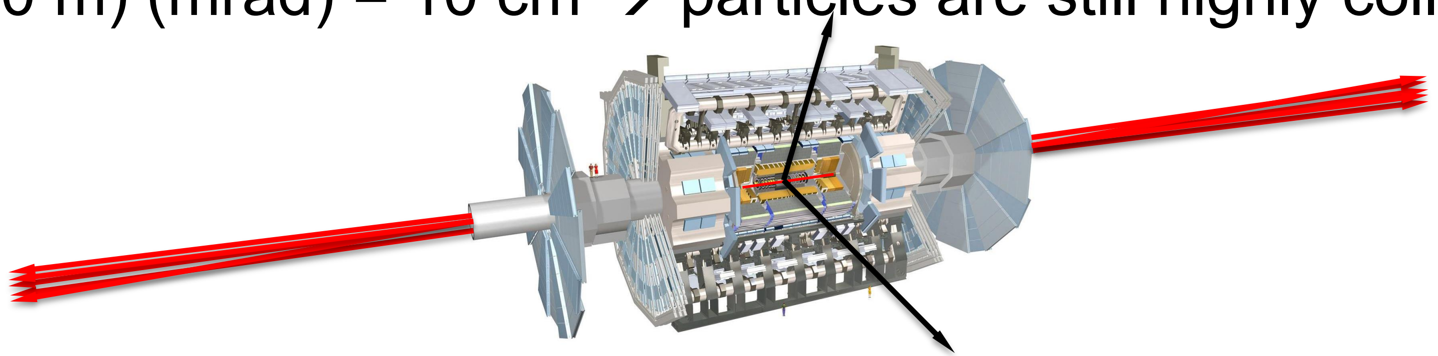
THE IDEA

- New physics searches at the LHC focus on high p_T. This is appropriate for heavy, strongly interacting particles
  - σ ~ fb to pb → N_{events} ~ $10^3 - 10^6$, produced ~isotropically
- However, if new particles are light and weakly interacting, this may be completely misguided
  - Light → we can produce them in π, *K*, *D*, *B* decays
  - Weakly-interacting → need extremely large SM event rate to see them
- Conclusion: we should go where the pions are: at low p_T along the beamline
  - σ_{inel} ~ 100 mb → N_{events} ~ 10^{17}, and 10% of the pions are produced within 2 mrad of the beamline



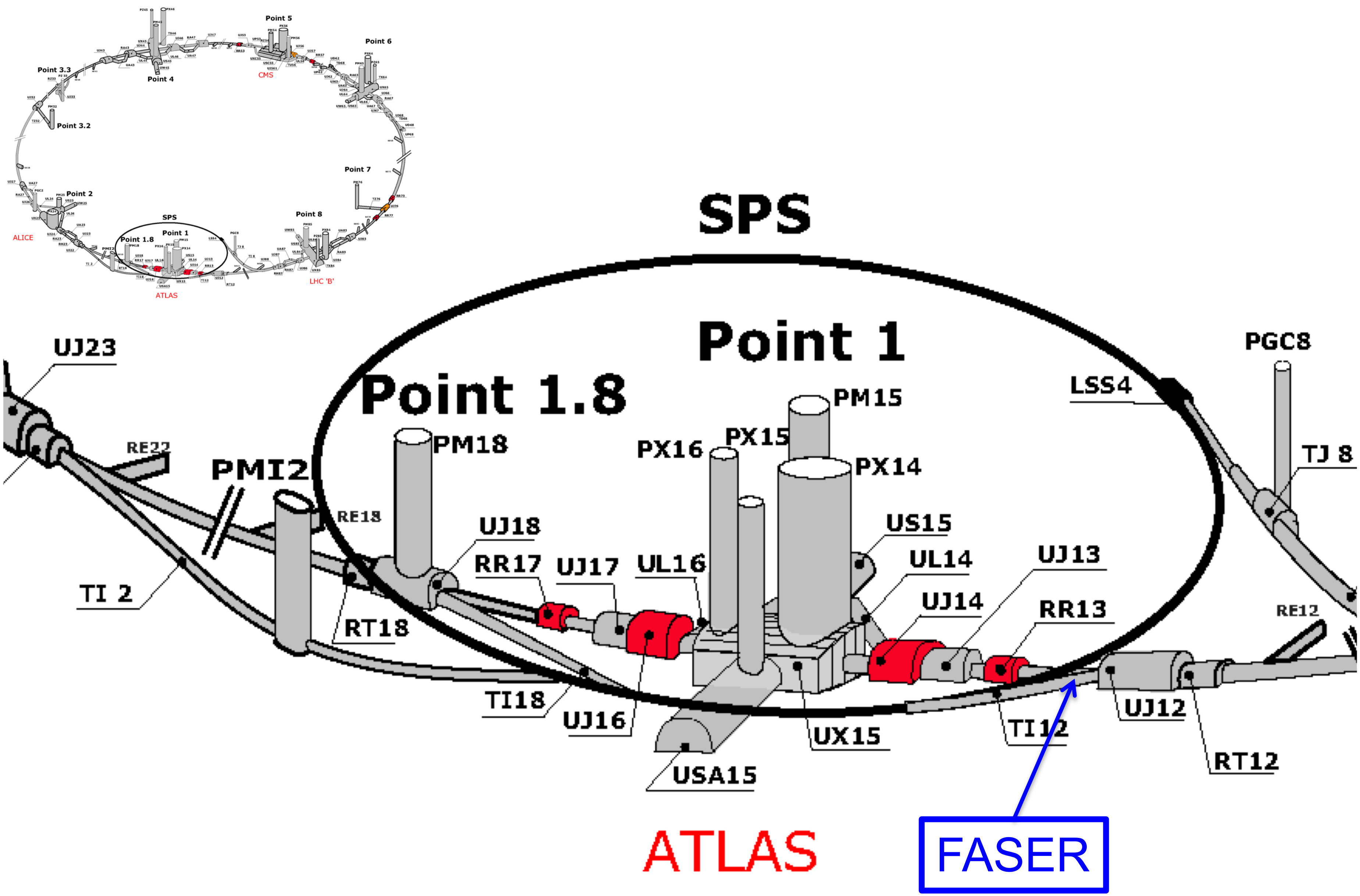
THE IDEA

- Of course, we can't put a reasonably-sized detector on the beamline near the IP – it would block the proton beams
- However, weakly-interacting particles are also typically long-lived, so we can place the detector O(100) m away, after the beam curves away
- (100 m) (mrad) = 10 cm → particles are still highly collimated

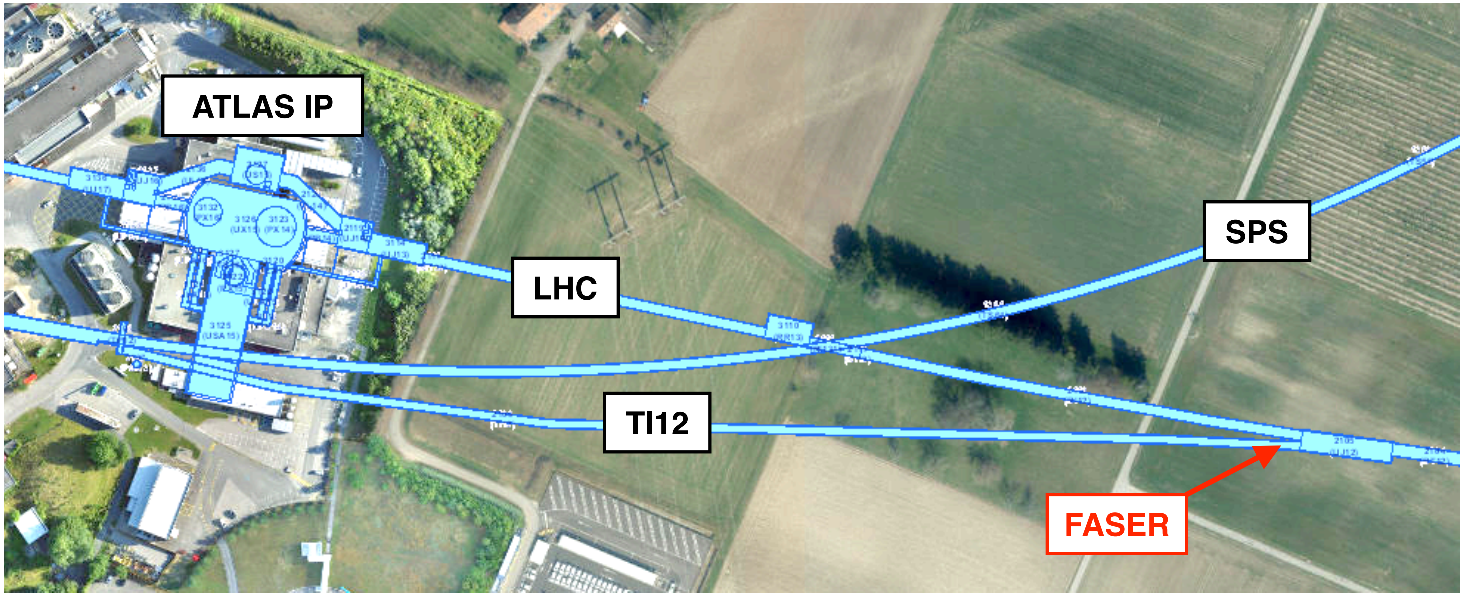


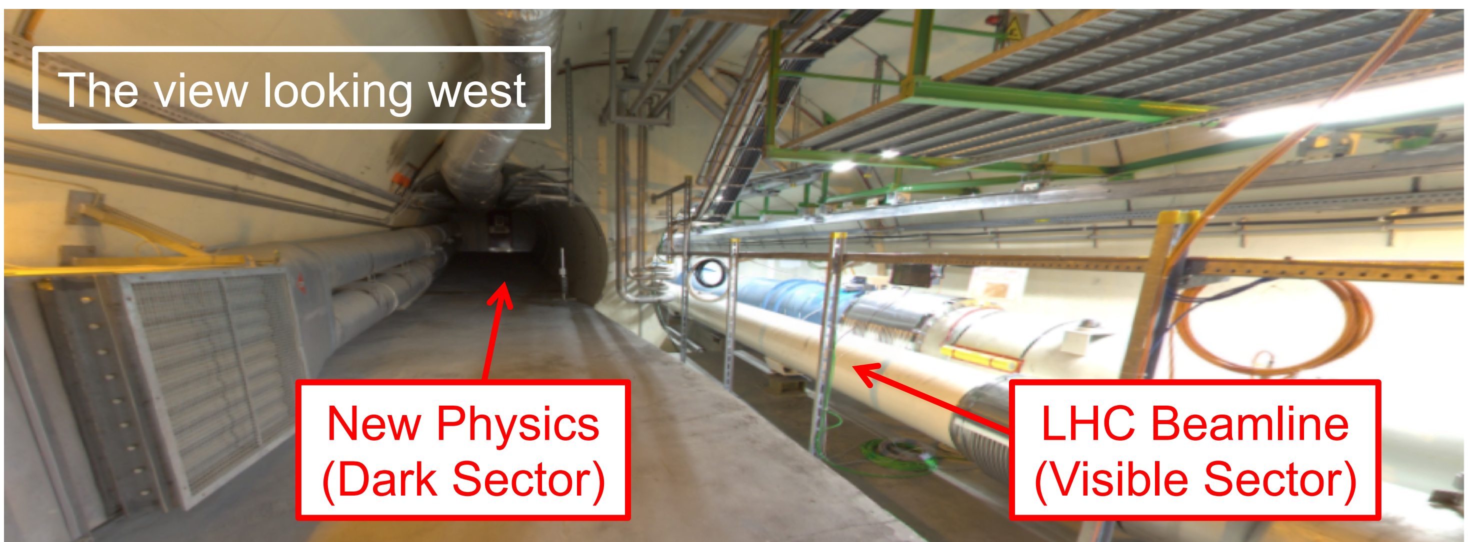
- These general considerations motivate a small, fast, inexpensive experiment placed in the very forward region of ATLAS/CMS, a few 100m downstream: FASER, the Forward Search Experiment at the LHC.

FASER LOCATION



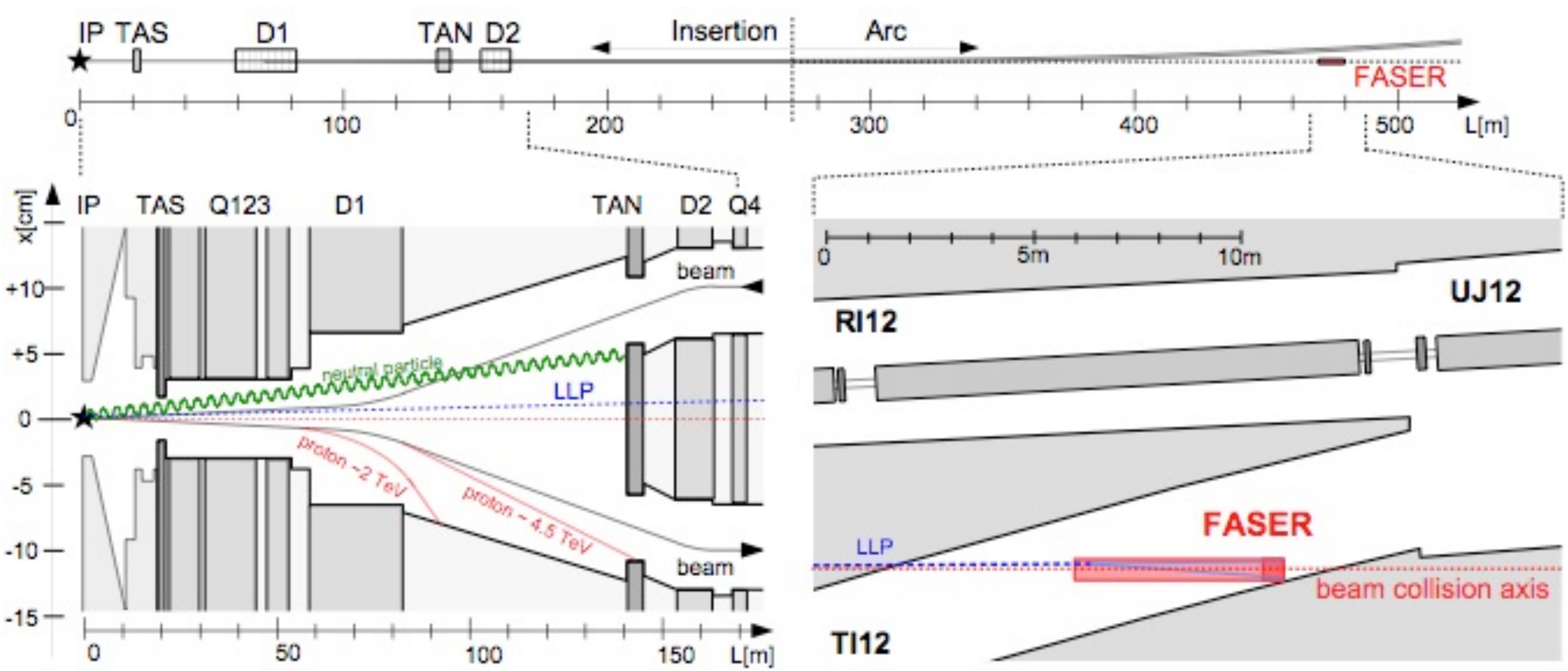
FASER LOCATION





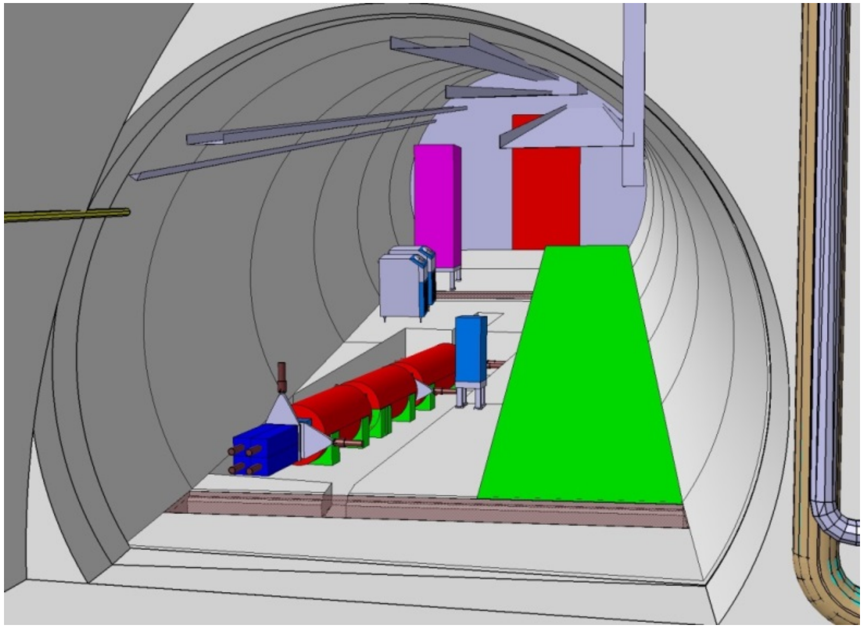
LONG LIVED PARTICLES IN FASER

- Typical FASER event: LLP produced at IP, travels 380 m, leaves LHC tunnel, passes through 100 m of concrete and rock, enters TI12, decays to two charged particles in FASER.



FASER IN TUNNEL TI12

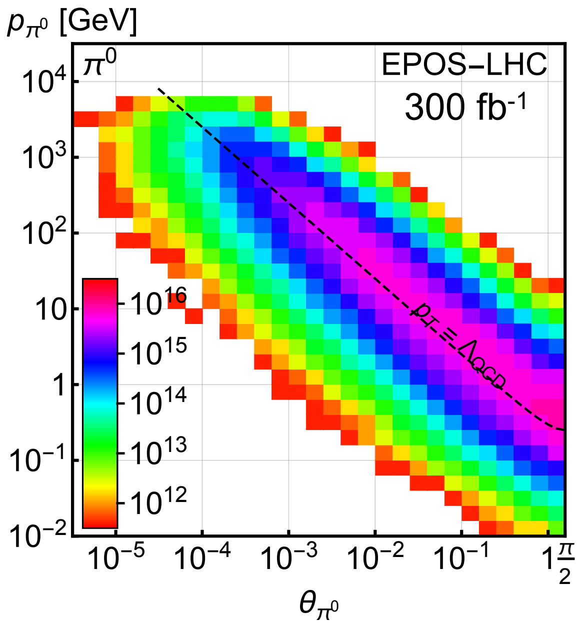
- The beam collision axis has been located to mm accuracy by the CERN survey department. To place FASER on this axis, a little digging is required to lower the floor by 46 cm.



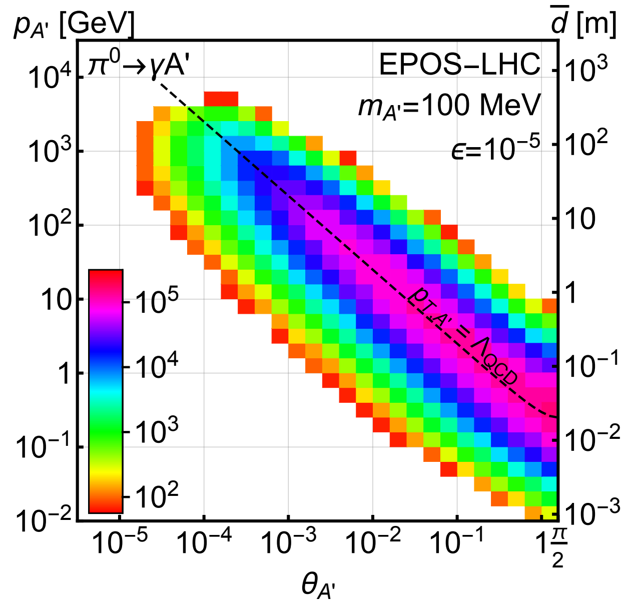
- The beam crossing angle also matters: if 285 (590) μrad, the "on axis" location at FASER shifts by 6 (12) cm.

PHYSICS EXAMPLE: DARK PHOTONS

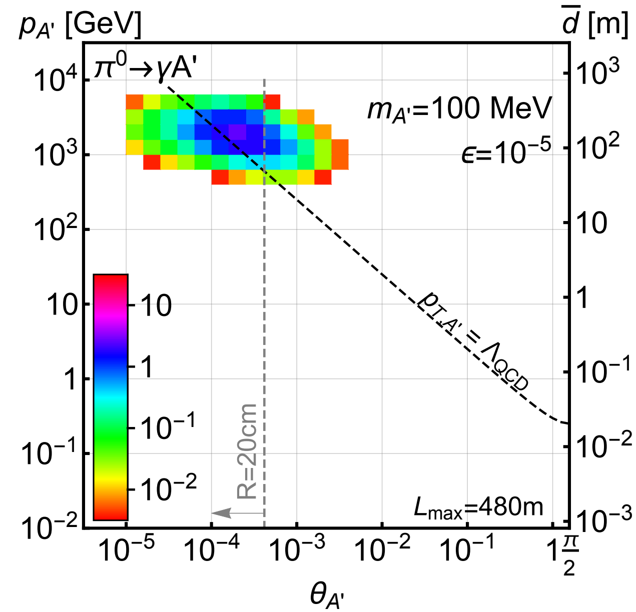
Pions at the IP



A's at the IP



A's decay in [480m, 483m]

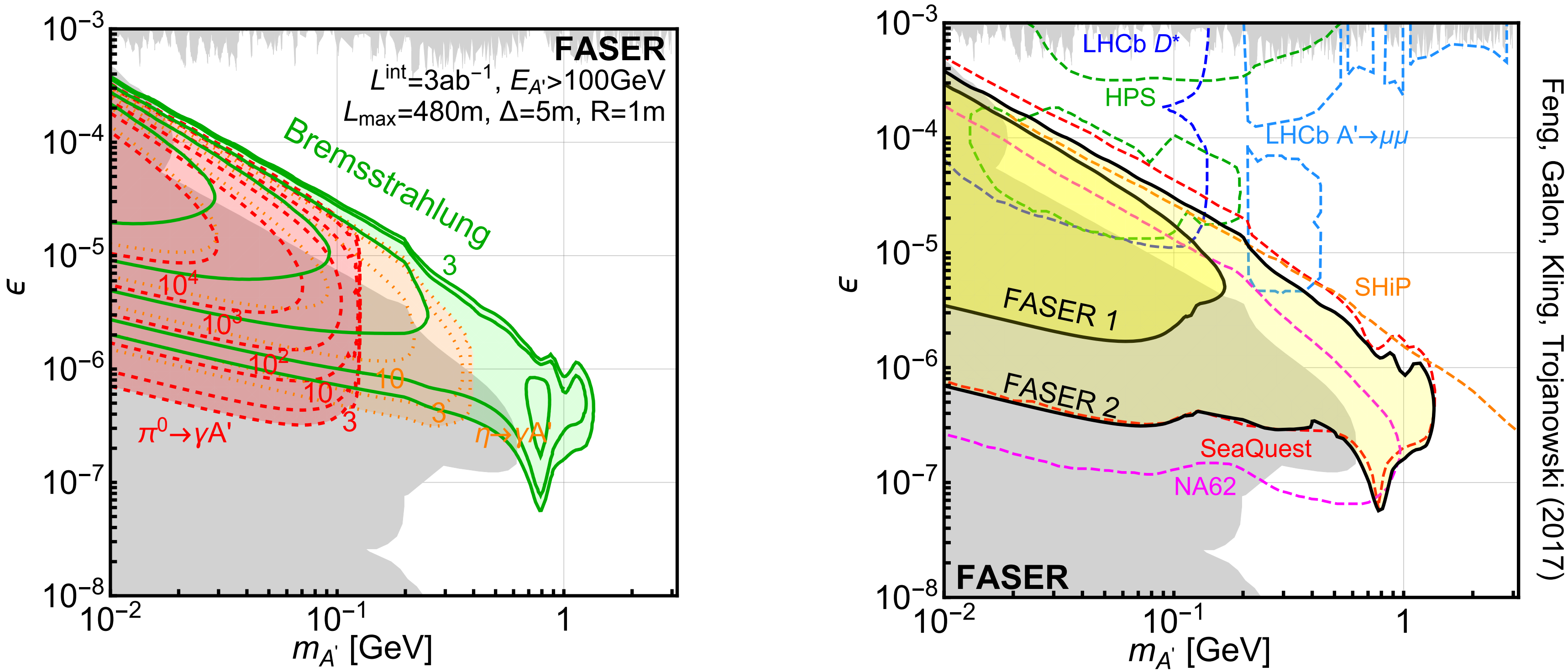


- Simulations greatly refined by LHC data
- Production is peaked at $p_T \sim \Lambda_{QCD} \sim 250$ MeV
- Enormous event rates: $N_\pi \sim 10^{15}$ per bin

- Production is peaked at $p_T \sim \Lambda_{QCD} \sim 250$ MeV
- Rates highly suppressed by $\varepsilon^2 \sim 10^{-10}$
- But still $N_{A'} \sim 10^5$ per bin

- Only highly boosted ~TeV A's decay in FASER
- Rates again suppressed by decay requirement
- But still $N_{A'} \sim 100$ signal events, and almost all are within 20 cm of "on axis"

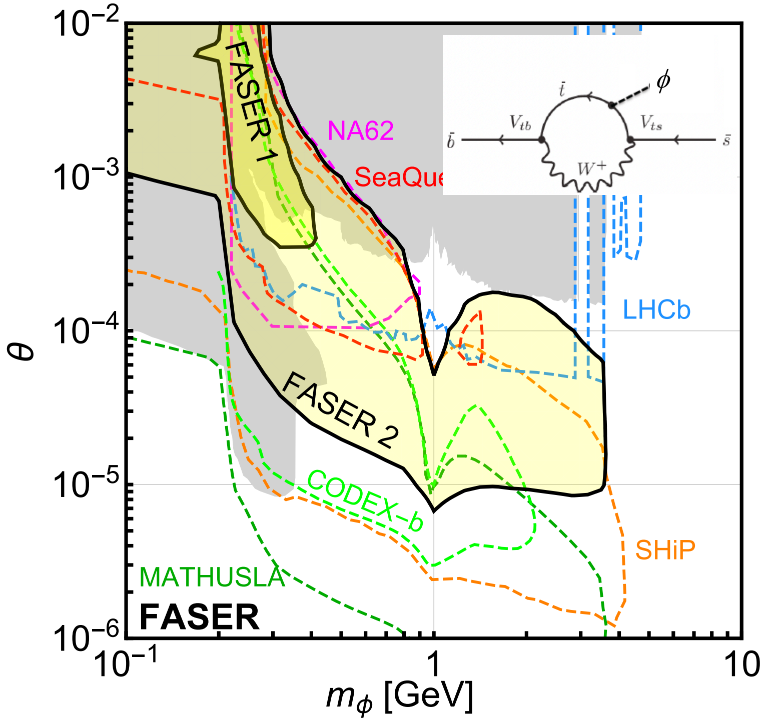
DARK PHOTON SENSITIVITY REACH



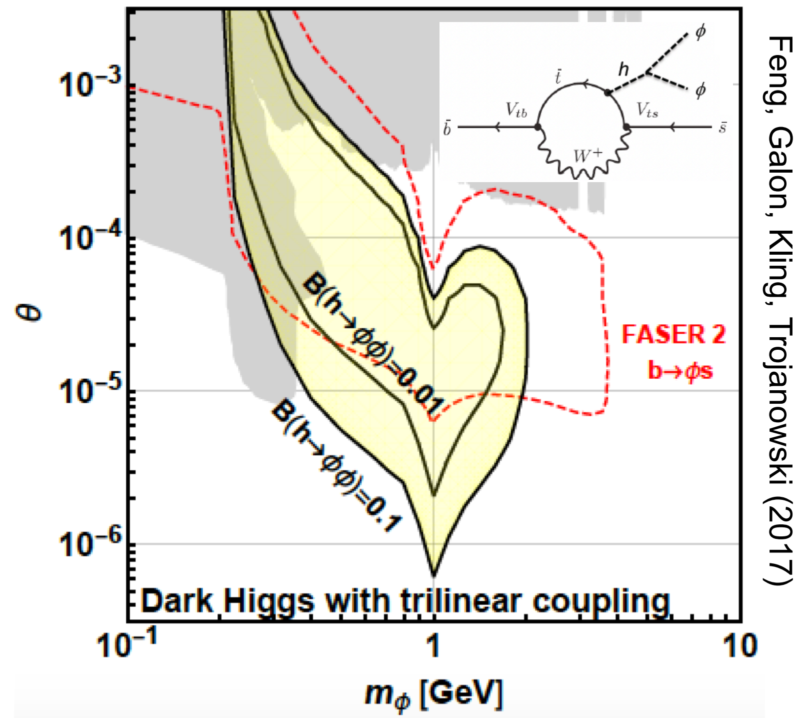
- FASER 1: R=10cm, L=1.5 m, Run 3;   FASER 2: R=1m, L=5m, HL-LHC
- For low ε, FASER is not competitive with SHiP.
- For high ε, FASER may have world-leading sensitivity. Note: contours are very closely spaced: ~50% signal efficiency, N=3 vs.10, e^+e^- vs. e^+e^- + $\mu^+\mu^-$, L=3m vs. 5m, … each lead to nearly imperceptible shifts in reach.

PHYSICS EXAMPLE: DARK HIGGS BOSONS

- **SINGLE PRODUCTION**



- **DOUBLE PRODUCTION**

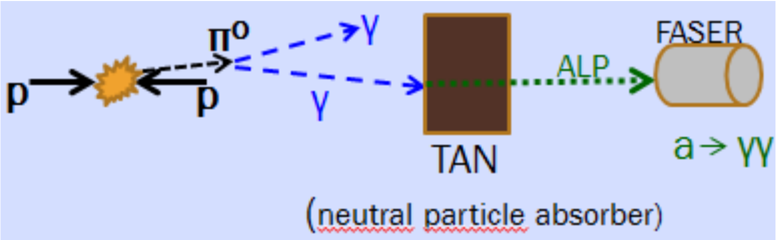


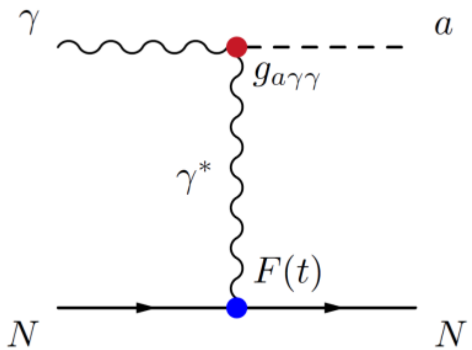
- Dark Higgs produced in B decays. $N_B/N_\pi \sim 10^{-2}$ at FASER ($N_B/N_\pi \sim 10^{-7}$ at beam dumps)
- Probes h-ϕ mixing, reach is complementary to other experiments
- Probes $h\phi\phi$ trilinear coupling
- Complementary to probes of exotic Higgs decays $h \rightarrow \phi\phi$
- FASER probes SM Higgs properties!

PHYSICS EXAMPLE: ALPS COUPLED TO PHOTONS

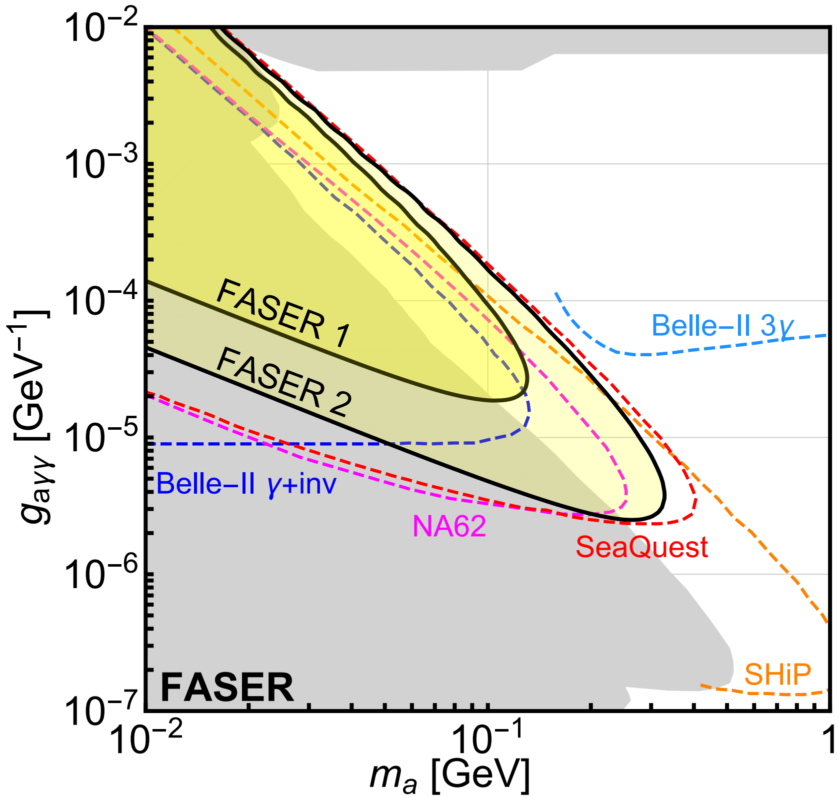
- **PRODUCTION THROUGH PRIMAKOFF PROCESS**

- ALP not produced at IP: ~TeV photon from IP collides with TA(X)N, creates ALP through Primakoff, and a → γγ in FASER
- "Photon beam dump" or "light shining through walls"





- **ALPS WITH PHOTON**



Feng, Galon, Kling, Trojanowski (2018)

- Requires calorimeter

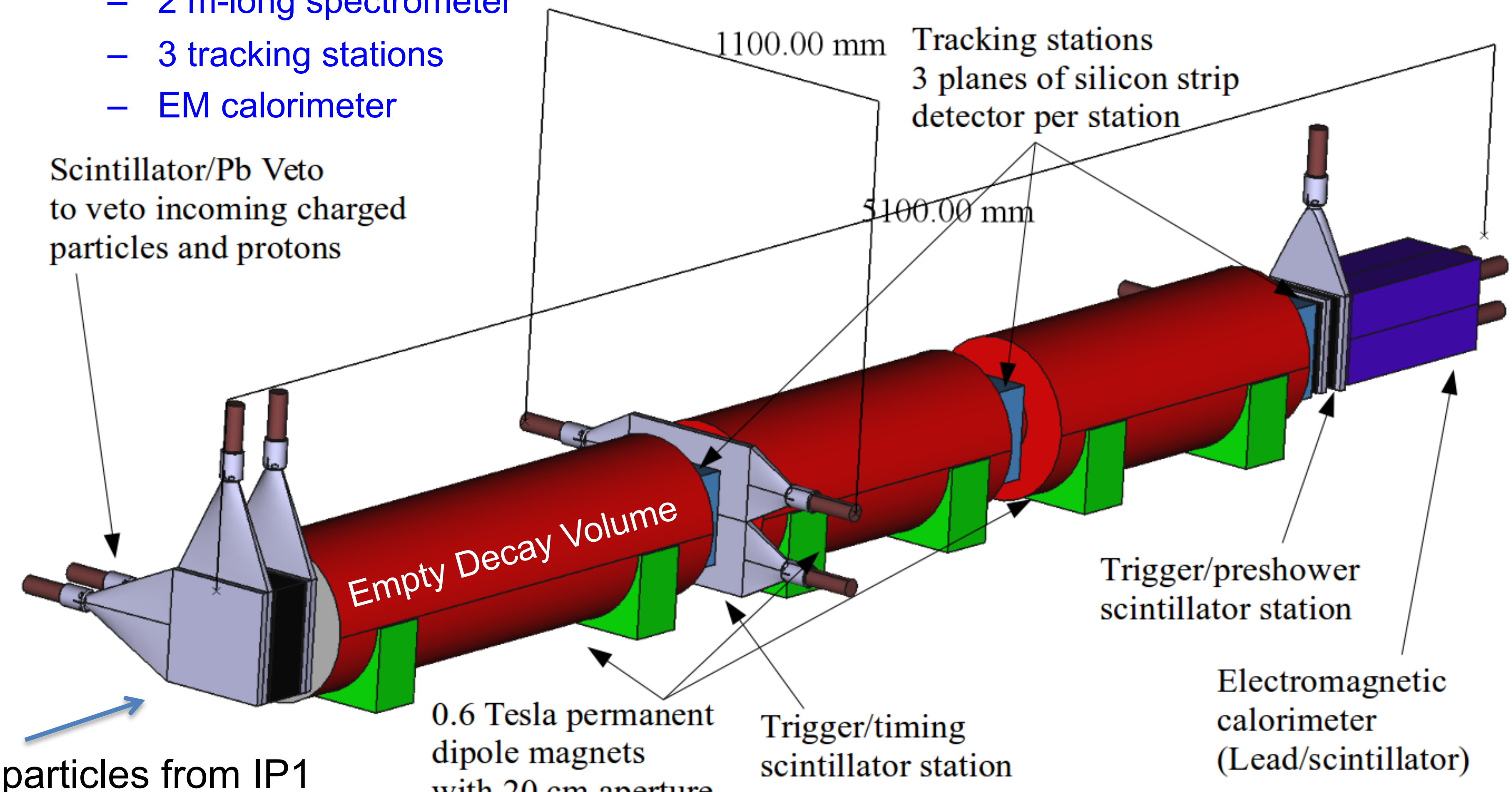
PHYSICS SUMMARY

- FASER has a full physics program: can discover all candidates with renormalizable couplings (dark photon, dark Higgs, HNL); ALPs with all types of couplings (γ, 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

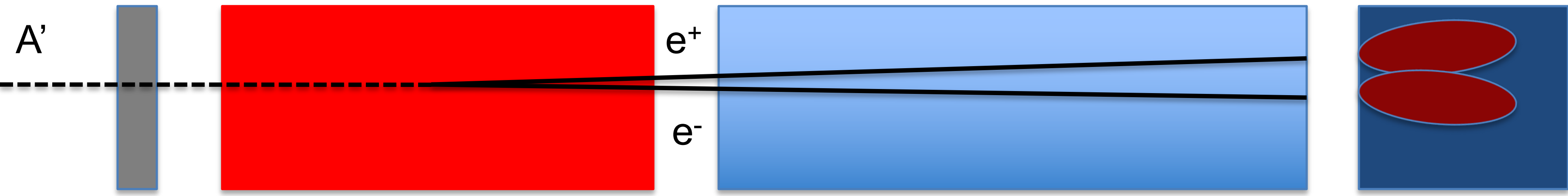
THE FASER DETECTOR

- The detector consists of
  - Scintillator veto
  - 1.5 m-long decay volume
  - 2 m-long spectrometer
  - 3 tracking stations
  - EM calorimeter



THE FASER DETECTOR

- Signal Signature



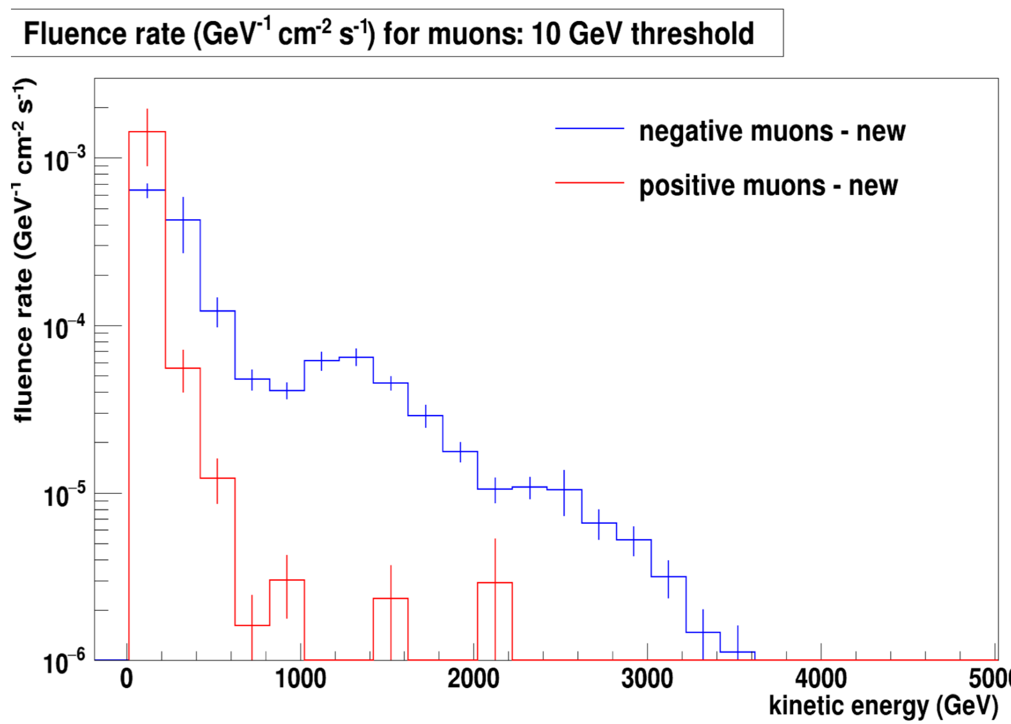
  - No signal in the veto scintillator
  - 2 high-energy, oppositely charged tracks consistent with originating from a common vertex in the decay volume and with a combined momentum pointing back to the IP
  - For e^+e^- signature, also get a large EM deposit in the calorimeter
  - Magnets are needed to separate the 2 charged tracks sufficiently to resolve them in the tracker

BACKGROUNDS

- FASER's location is very quiet – the only SM particles that get through from the IP are muons and neutrinos.

- 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.

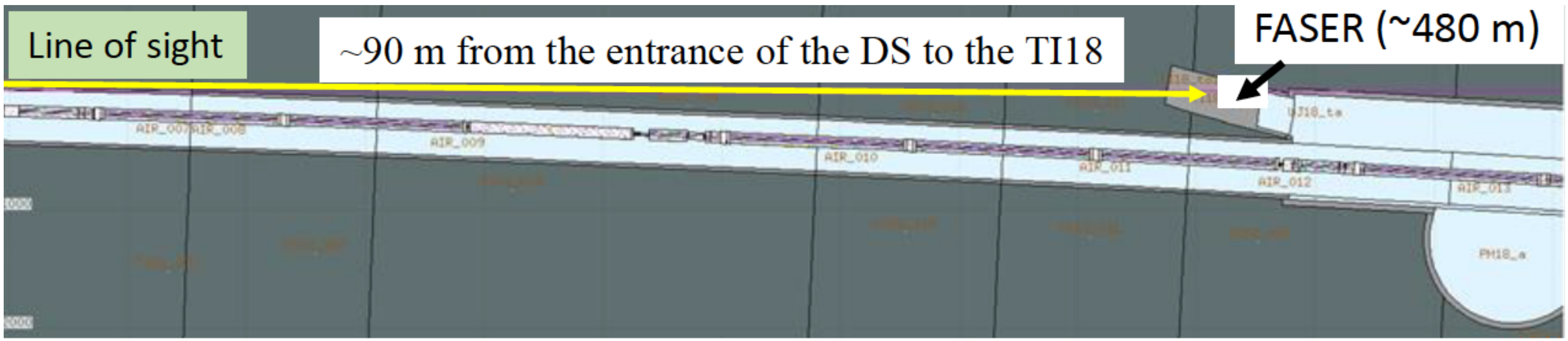
- The muon event rate has been estimated by EPOS+theory and a FLUKA study, yielding consistent results. Assuming each scintillator layer gives an uncorrelated 10^{-4} veto suppression for muons entering the detector, the resulting backgrounds appear to be negligible.



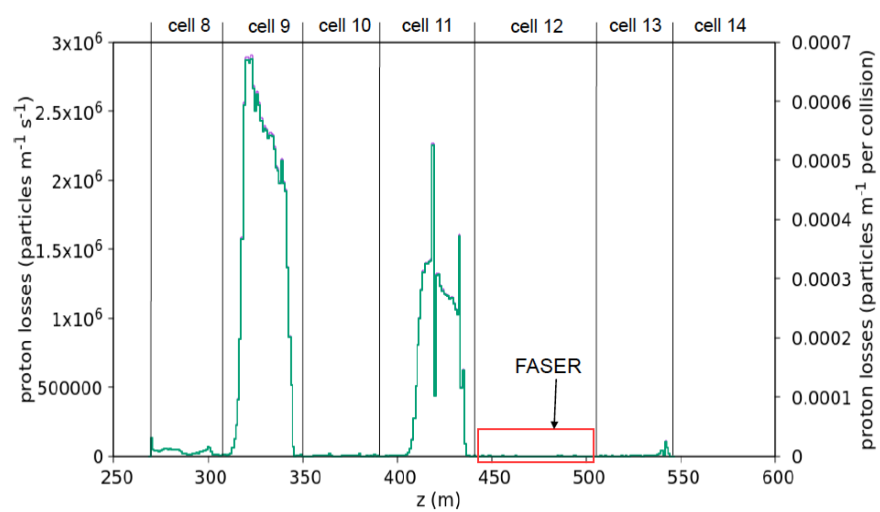
FLUKA study: Sabate-Gilarte, Cerutti, Tsinganis (2018)

MORE BACKGROUNDS

- The FLUKA study also finds that proton showers in dispersion suppressor and beam-gas background (from “beam 2”) are also negligible.



Proton-loss map in the DS

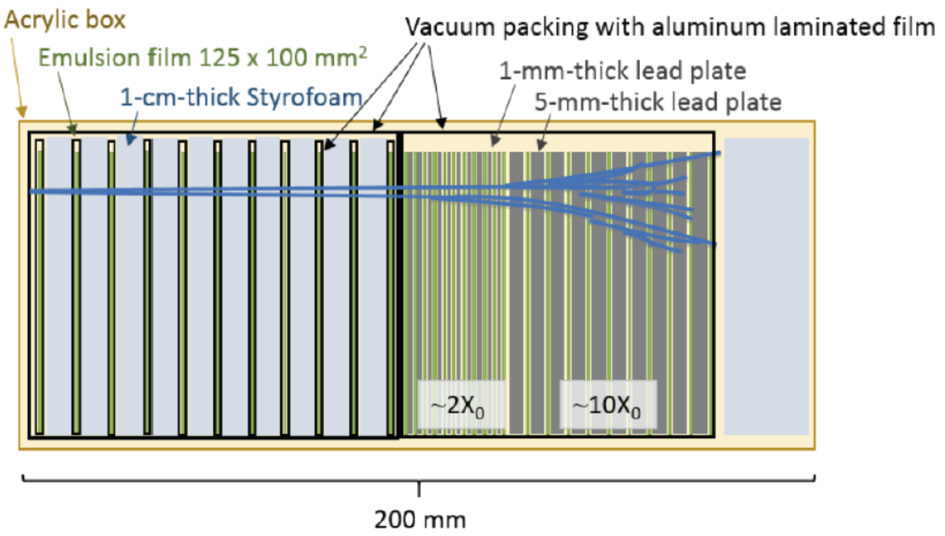


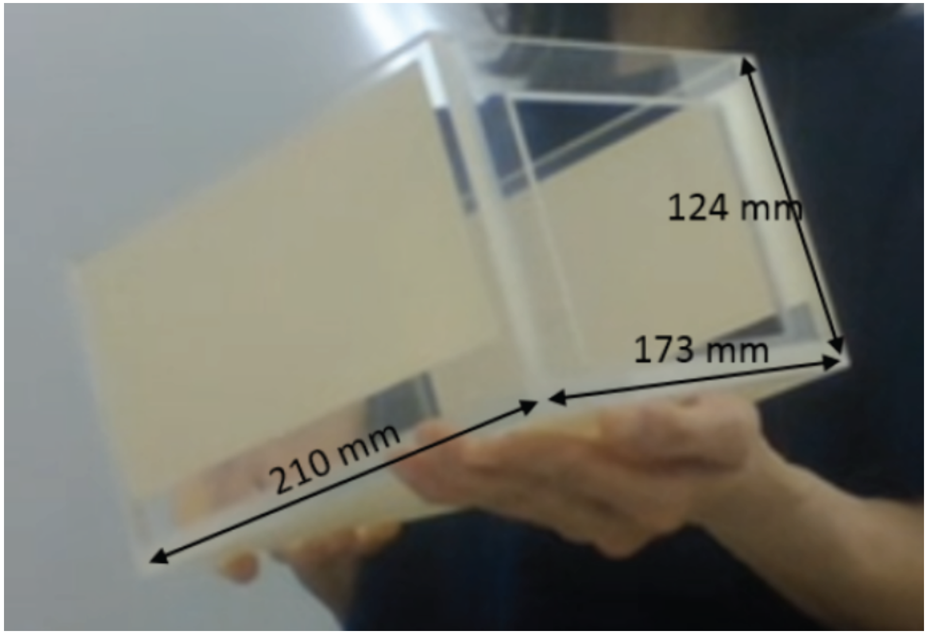
Sabate-Gilarte, Cerutti, Tsinganis (2018)

- The dispersion of the machine means activity close to FASER from diffractive proton losses is very small. It would be orders of magnitude higher 50m along LHC in either direction. The radiation level is low ($<10^{-2}$ Gy/year), which is encouraging for detector electronics.

IN SITU MEASUREMENTS

- To validate the FLUKA background study, in 2018 we installed detectors in Technical Stops 1 and 2 to provide the first in situ measurements at the FASER site.
- An emulsion detector was prepared and placed at the FASER location.
- A BatMon (battery-operated radiation monitor) was also installed.





IN SITU MEASUREMENTS

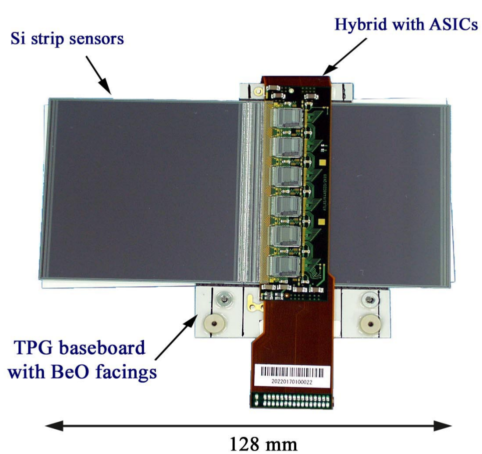
- The emulsion detector results are within measurement accuracy (factor of 2) of FLUKA predictions.

- BatMon results for low-energy radiation are also promisingly low.

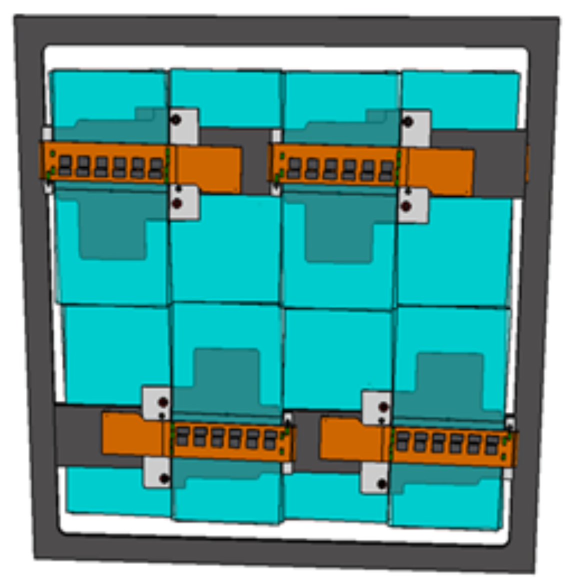
FASER TRACKER

- 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. QA now underway.

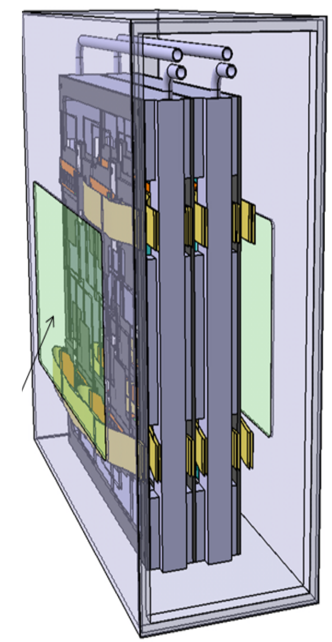
- 8 SCT modules make up a 24cm x 24cm tracking layer, 3 layers make up a tracking station, and FASER has 3 tracking stations.



SCT module

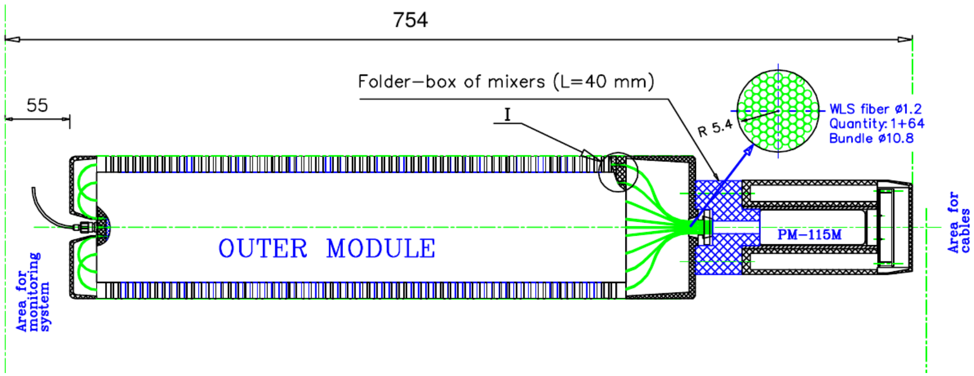


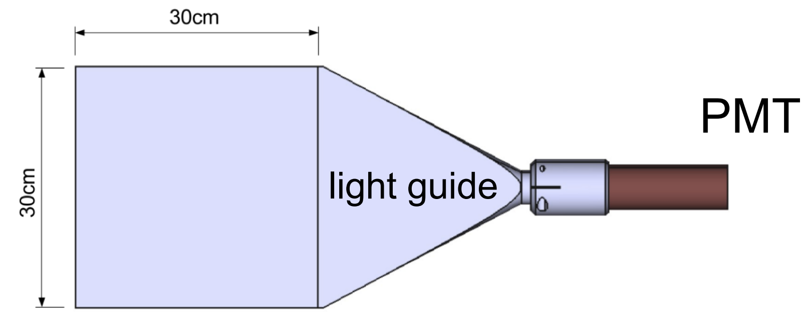
Tracking layer



Tracking station

FASER CALORIMETER / SCINTILLATORS

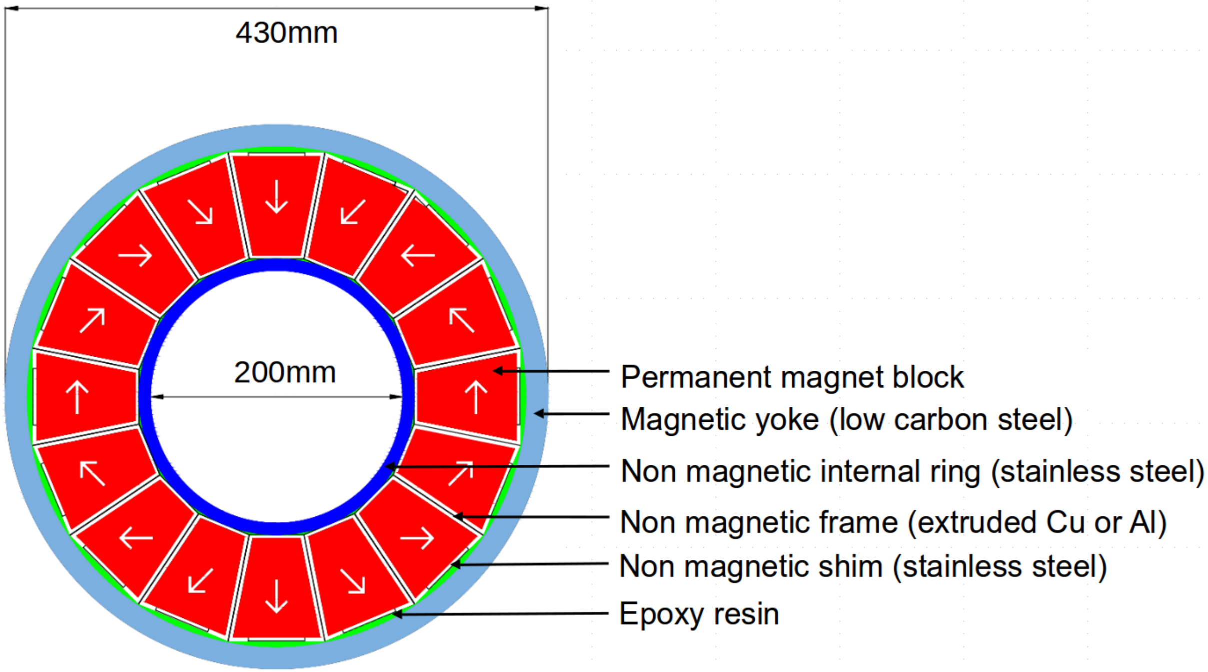


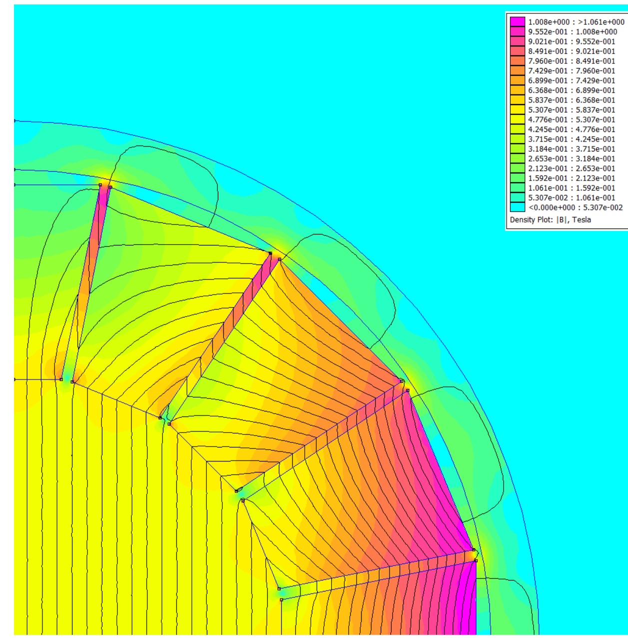


- The FASER ECAL will consist of spare LHCb outer ECAL modules, which the LHCb Collaboration has kindly allowed us to use.
  - Dimensions: 12cm x 12cm – 75cm long (including PMT)
  - 66 layers of lead/scintillator, light out by wavelength shifting fibres, and readout by PMT (no longitudinal shower information)
  - 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 MAGNETS





- The FASER magnets are 0.55T SmCo 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..)
- Design and construction by the CERN magnet group.

CURRENT STATUS

- The FASER Collaboration: 32 collaborators, 16 institutions, 8 countries

Akitaka Ariga (Bern), Tomoko Ariga (Kyushu/Bern), Jamie Boyd (CERN), Dave Casper (UC Irvine), Franck Cadoux (Geneva), Xin Chen (Tsinghua), Andrea Coccaro (Genova), Yannick Favre (Geneva), Jonathan Feng (UC Irvine), Didier Ferrere (Geneva), Iftah Galon (Rutgers), Sergio Gonzalez-Sevilla (Geneva), Shih-Chieh Hsu (Washington), Zhen Hu (Tsinghua), Peppe Iacobucci (Geneva), Enrique Kajomovitz (Technion), Felix Kling (UC Irvine), Susanne Kuehn (CERN), Lorne Levinson (Weizmann), Josh McFayden (CERN), Friedemann Neuhaus (Mainz), Hidetoshi Otono (Kyushu), Brian Petersen (CERN), Osamu Sato (Nagoya), Matthias Schott (Mainz), Anna Sfyrla (Geneva), Jordan Smolinsky (UC Irvine), Aaron Soffa (UC Irvine), Yosuke Takubo (KEK), Eric Torrence (Oregon), Sebastian Trojanowski (Sheffield), Gang Zhang (Tsinghua)

ACKNOWLEDGEMENTS

Many others have also played essential roles in supporting FASER

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, 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); Gianluca Canale, Jeremy Blanc (readout signals); and Ludovico Pontecorvo, Christoph Rembser (general support).

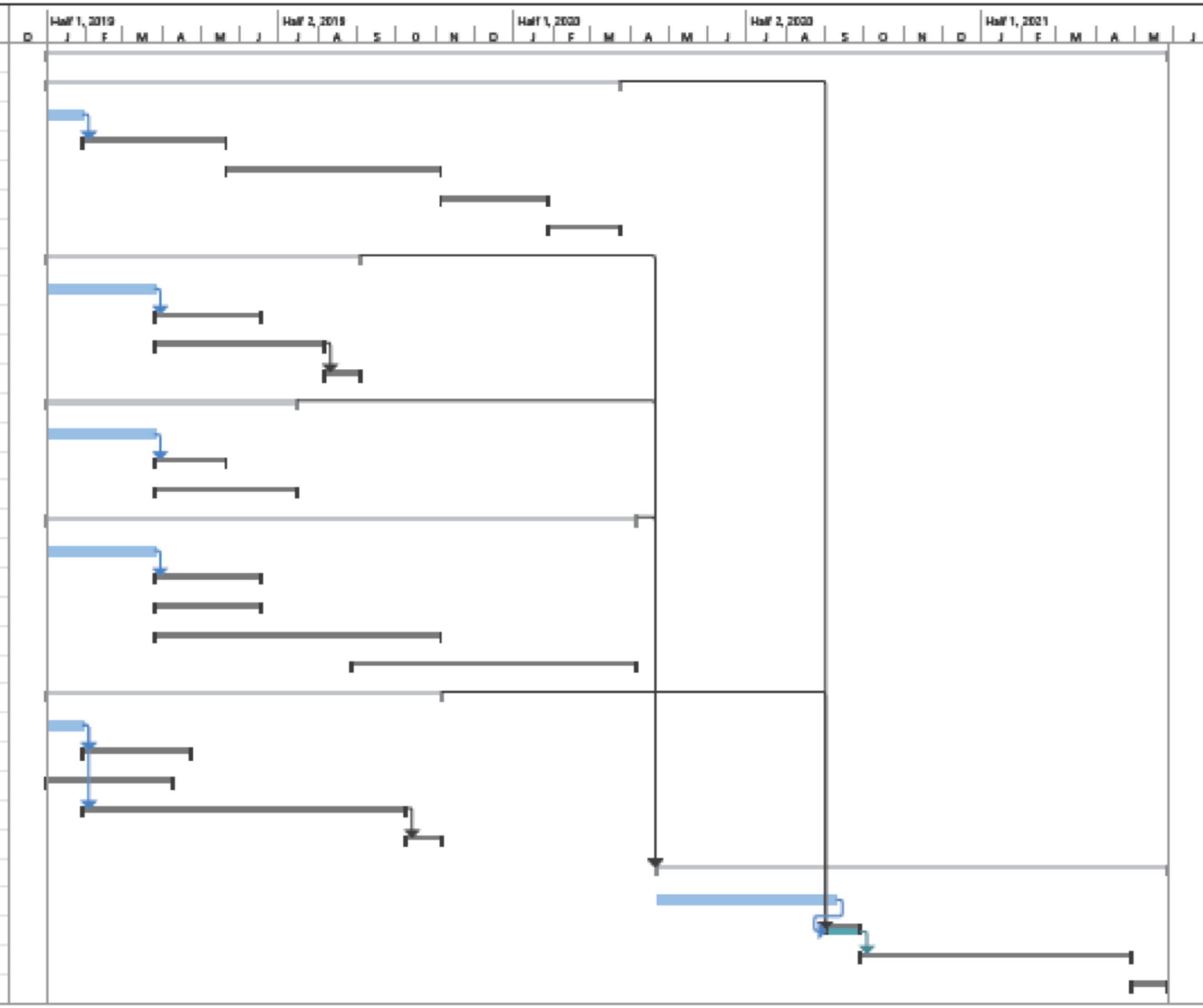
TIMELINE

- CERN Approval Process
  - Submitted LOI to LHCC in July 2018. This was received favorably and we were invited to submit a Technical Proposal.
  - Submitted Technical Proposal in November, this was also received favorably, LHCC recommended approval to the CERN Research Board.
  - The Research Board asked us to obtain approval from LMC and LS2C. We have now done this. We therefore anticipate that the Research Board will fully approve FASER on 5 March 2019.

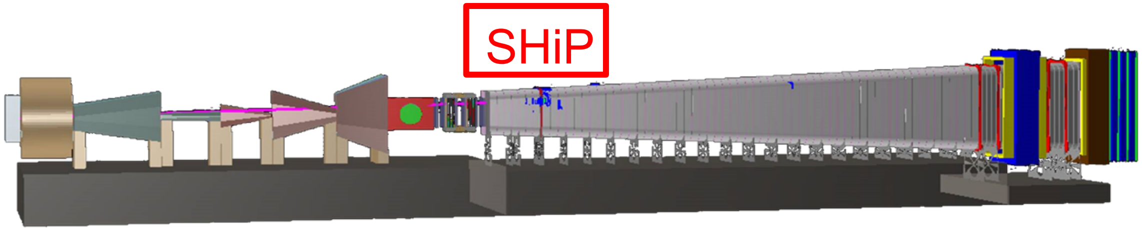
- Funding
  - FASER's construction and some research costs are fully supported by the Heising-Simons and Simons Foundations through grants for ~$2M. Cost to be borne by CERN is ~$300 kCHF.

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

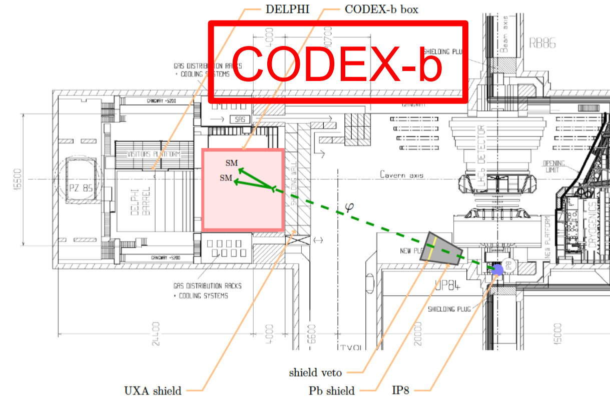


COMPLEMENTARY PROPOSED EXPERIMENTS



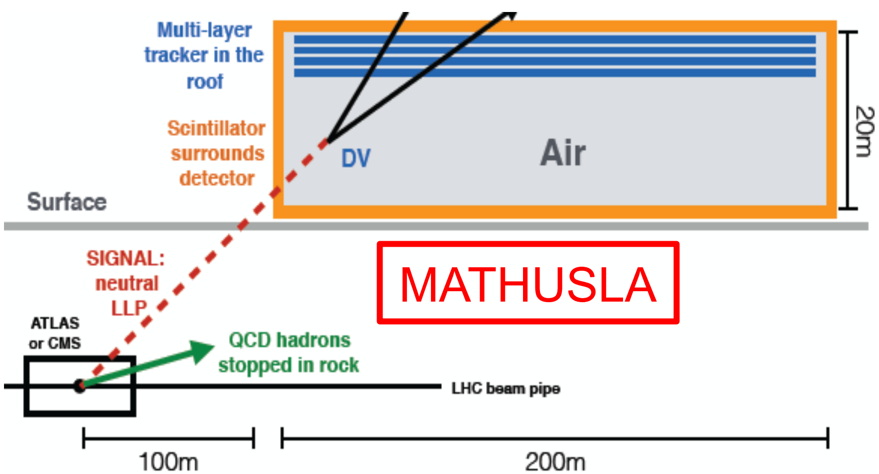
~1000 m^3, ~100M CHF + beam

Alekhin et al. (2015)



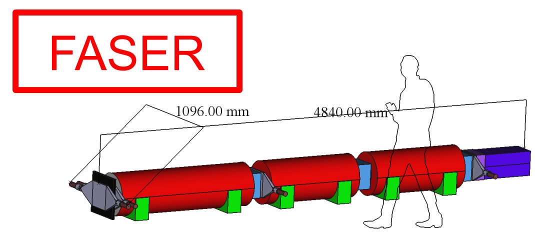
~1000 m^3 ~ 1 mIKEAs

Gligorov, Knapen, Papucci, Robinson (2017)



~800,000 m^3 ~ 1 IKEA, ~$50M

Chou, Curtin, Lubatti (2016)



~1 m^3 ~ 1 μIKEAs

Feng, Galon, Kling, Trojanowski (2017)

SUMMARY AND OUTLOOK

- 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. FASER collects data when ATLAS collects data, but is independent (requires only bunch crossing timing).

- Currently in advanced stage of CERN approval process. If successful:

  Install FASER 1 in LS2 (2019-20) for Run 3 (2021-23, 150 fb^{-1})
  - Decay volume: R = 10 cm, L = 1.5 m. Total length < 5 m, requires lowering floor by 46 cm in existing tunnel.
  - Discovery prospects for dark photons, B-L gauge bosons, ALPs, etc.

  After successful operation of FASER, FASER 2 could be installed in LS3 (2023-25) for HL-LHC (2026-35, 3 ab^{-1})
  - Decay volume: R = 1 m, L = 5 m. Requires extension of existing tunnel (widening of UJ12 or UJ18 areas).
  - Full physics program: dark photons, B-L, ALPs, dark Higgs, HNLs, etc.

- More info: https://twiki.cern.ch/twiki/bin/viewauth/FASER/WebHome.