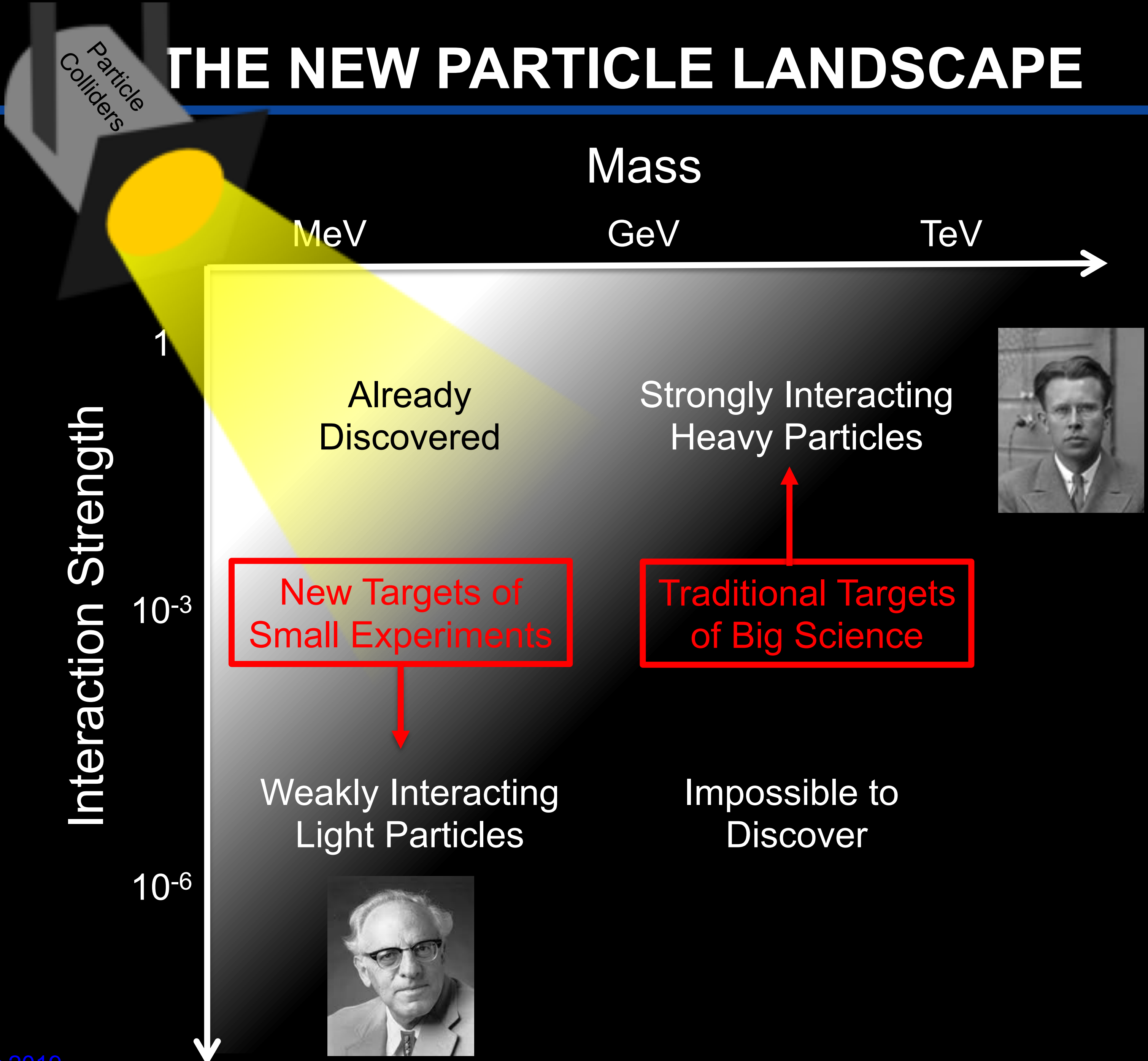
FASER

SUSY2019, Texas A&M Corpus Christi, 22 May 2019

Jonathan Feng (UC Irvine) for the FASER Collaboration

NSF
HEISING-SIMONS FOUNDATION
SIMONS FOUNDATION

THE NEW PARTICLE LANDSCAPE



Particle Colliders

Mass

MeV

GeV

TeV

Interaction Strength

1

10^{-3}

10^{-6}

Already Discovered

Strongly Interacting Heavy Particles

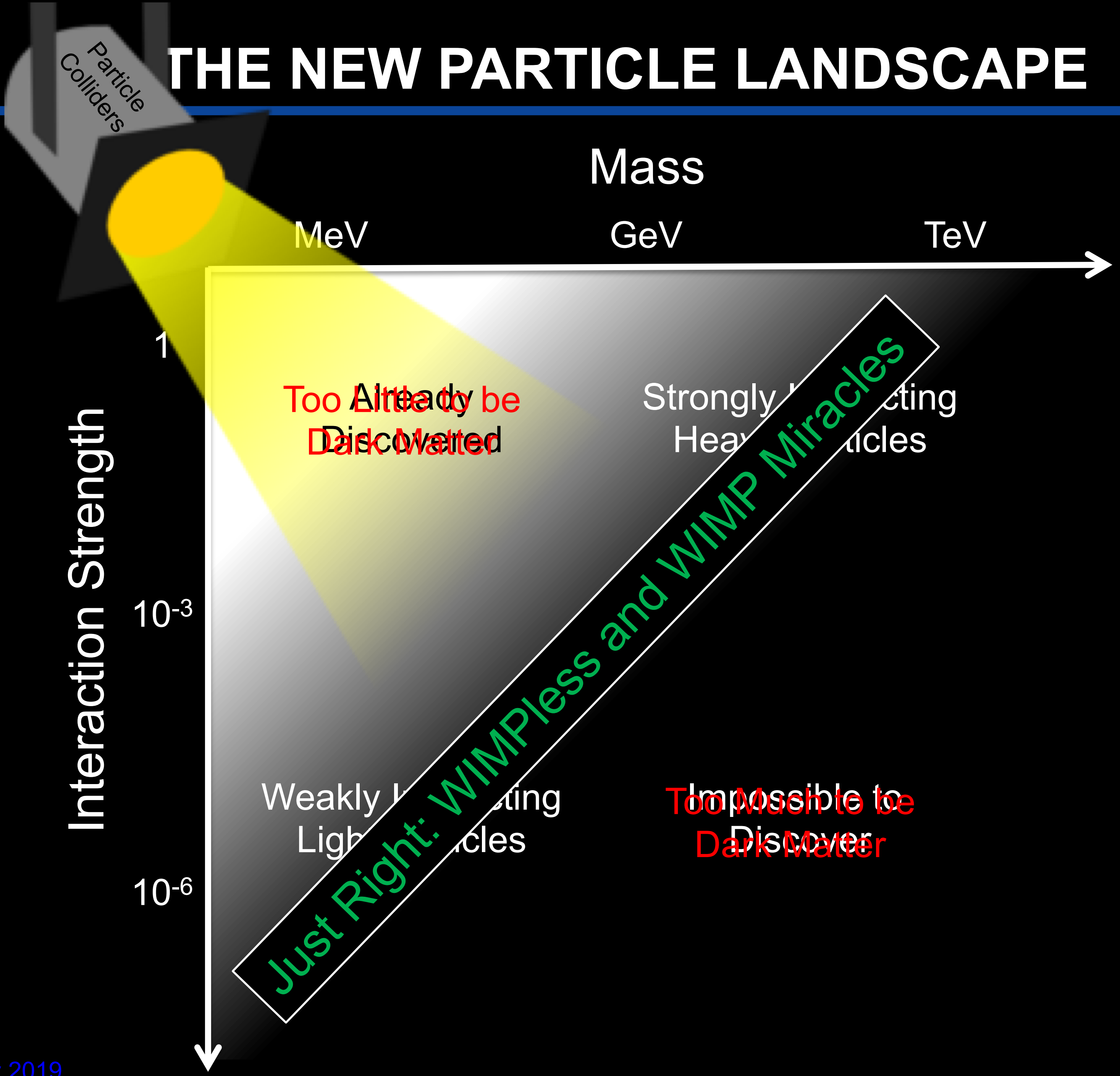
New Targets of Small Experiments

Traditional Targets of Big Science

Weakly Interacting Light Particles

Impossible to Discover

THE NEW PARTICLE LANDSCAPE



LOTS OF ACTIVITY

LLPs at LHC (1903.00497)

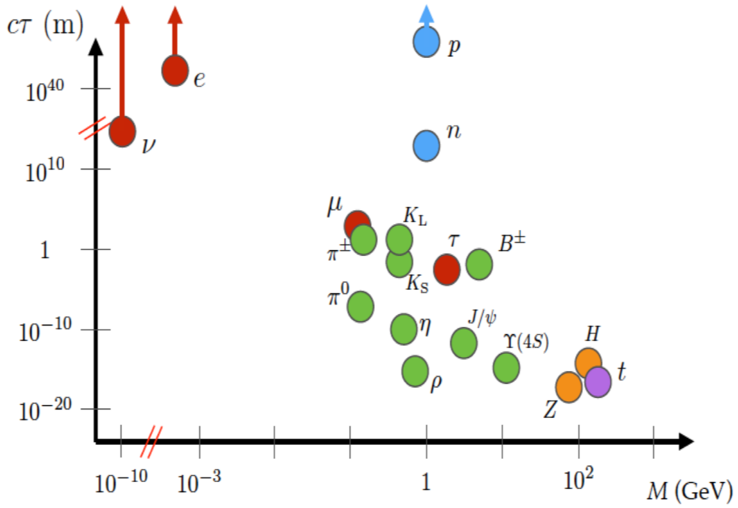
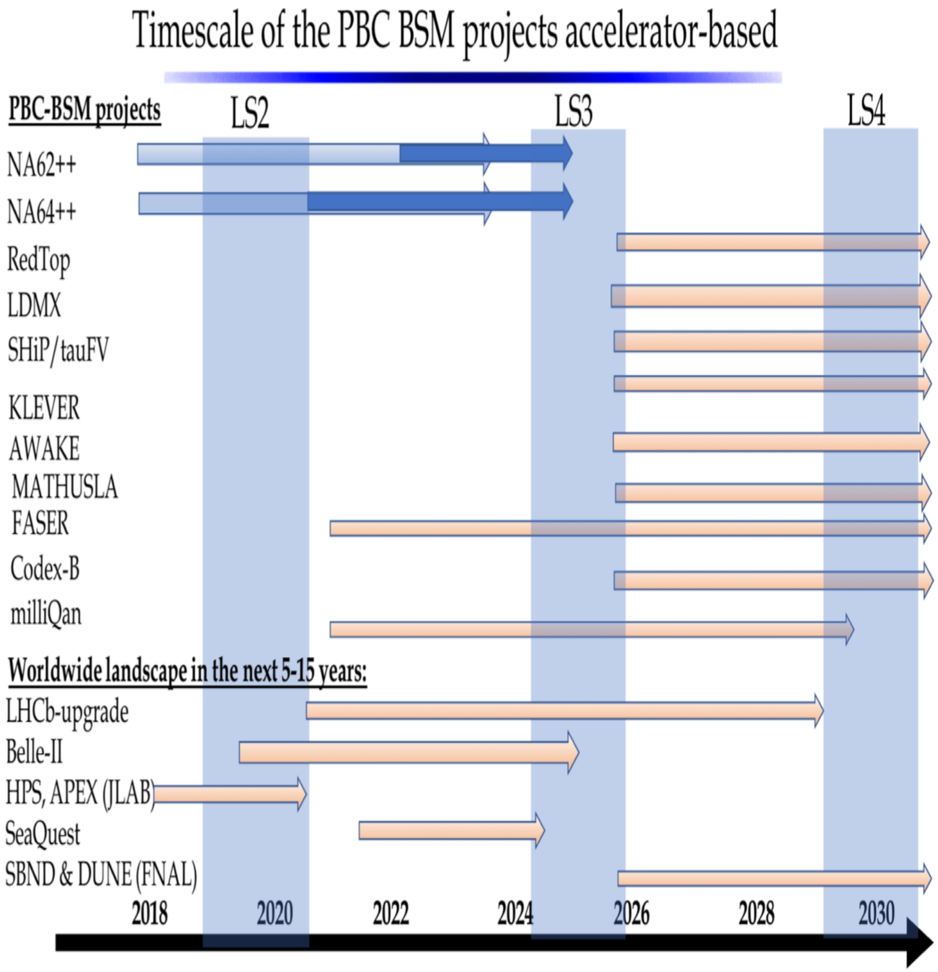


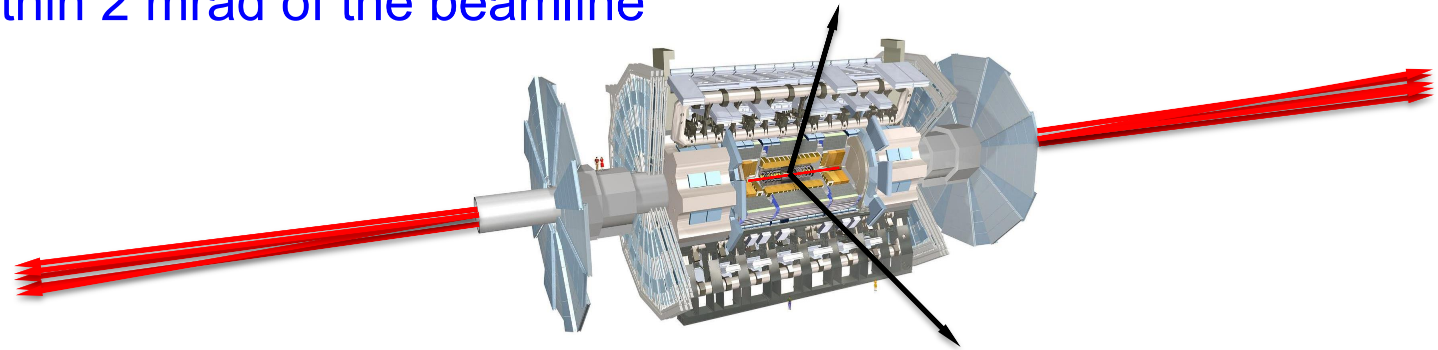
Figure 1.1: Particle lifetime $c\tau$, expressed in meters, as a function of particle mass, expressed in GeV, for a variety of particles in the Standard Model [1].

Physics Beyond Colliders (1901.09966)



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

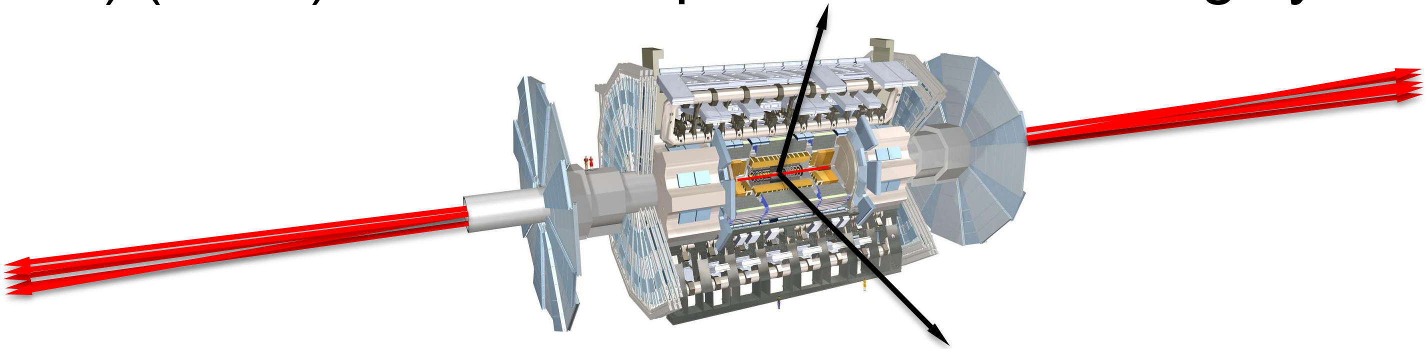


THE IDEA

- 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 also do not interact with matter and are long-lived, so we can place the detector O(100) m away along the “line of sight” after the beams curve

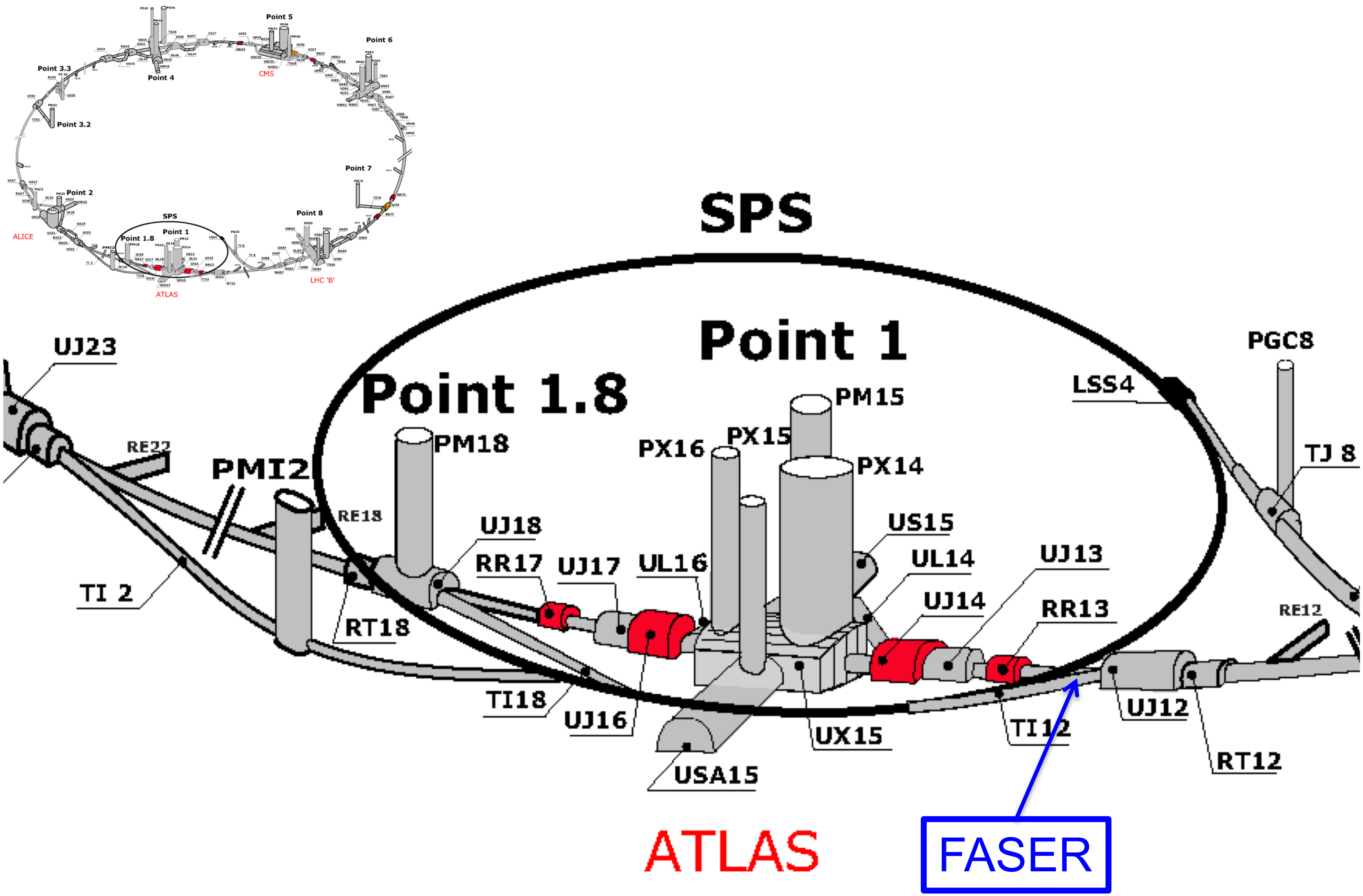
- (100 m) (mrad) = 10 cm → particles are still highly collimated.



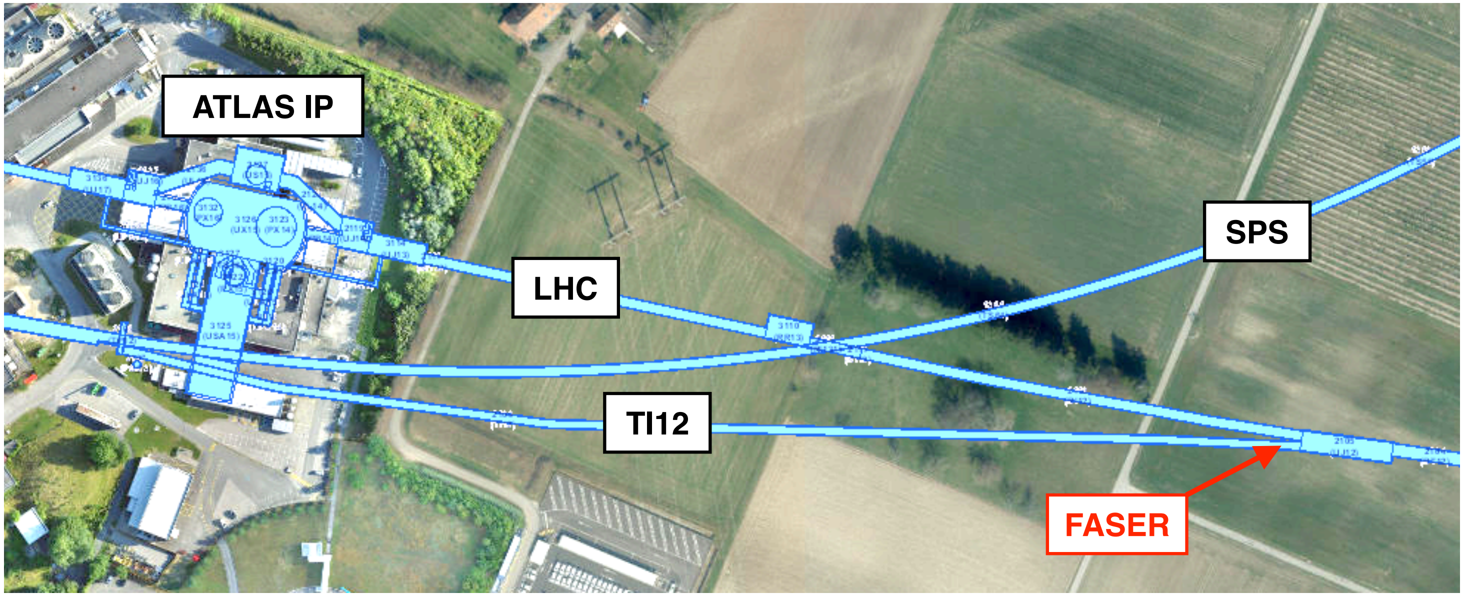
- These simple considerations motivate a small, fast, cheap experiment placed a few 100 m downstream of ATLAS/CMS: FASER, the ForwArd Search ExpeRiment at the LHC.

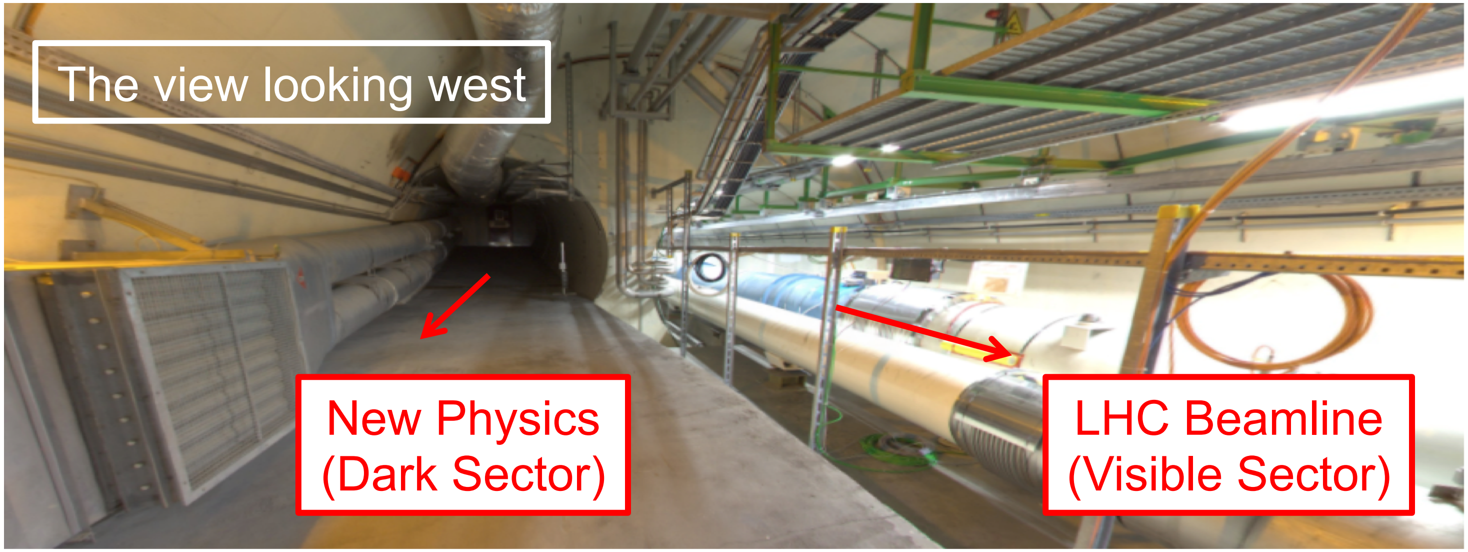
Feng, Kling, Galon, Trojanowski (2017)

FASER LOCATION



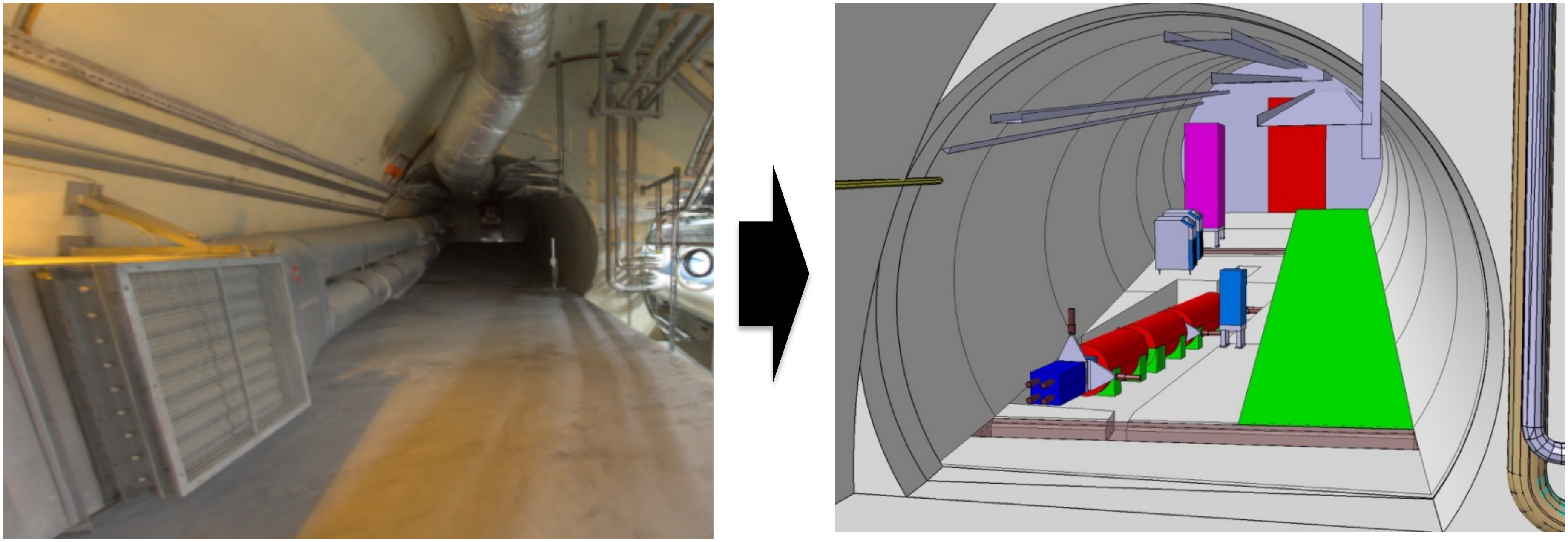
FASER LOCATION





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.

FASER LOCATION

Dougherty, CERN Integration (2019)

FASER TIMELINE

- September 2017: First theory paper
- July 2018: Submitted LOI to CERN LHCC
- October 2018: Approval from ATLAS SCT and LHCb Collaborations for use of spare detector modules – thank you!
- November 2018: Submitted Technical Proposal to LHCC
- November – December 2018: Construction fully funded by the Heising-Simons and Simons Foundations
- March 2019: FASER fully approved by CERN Research Board along with support for infrastructure costs
- April 2019: 1st FASER Collaboration Meeting
- 2019-20: Install FASER in Long Shutdown 2
- 2021-23: Collect data in Run 3 with the potential to discover new particles starting with the first fb^{-1} of luminosity

FASER COLLABORATION

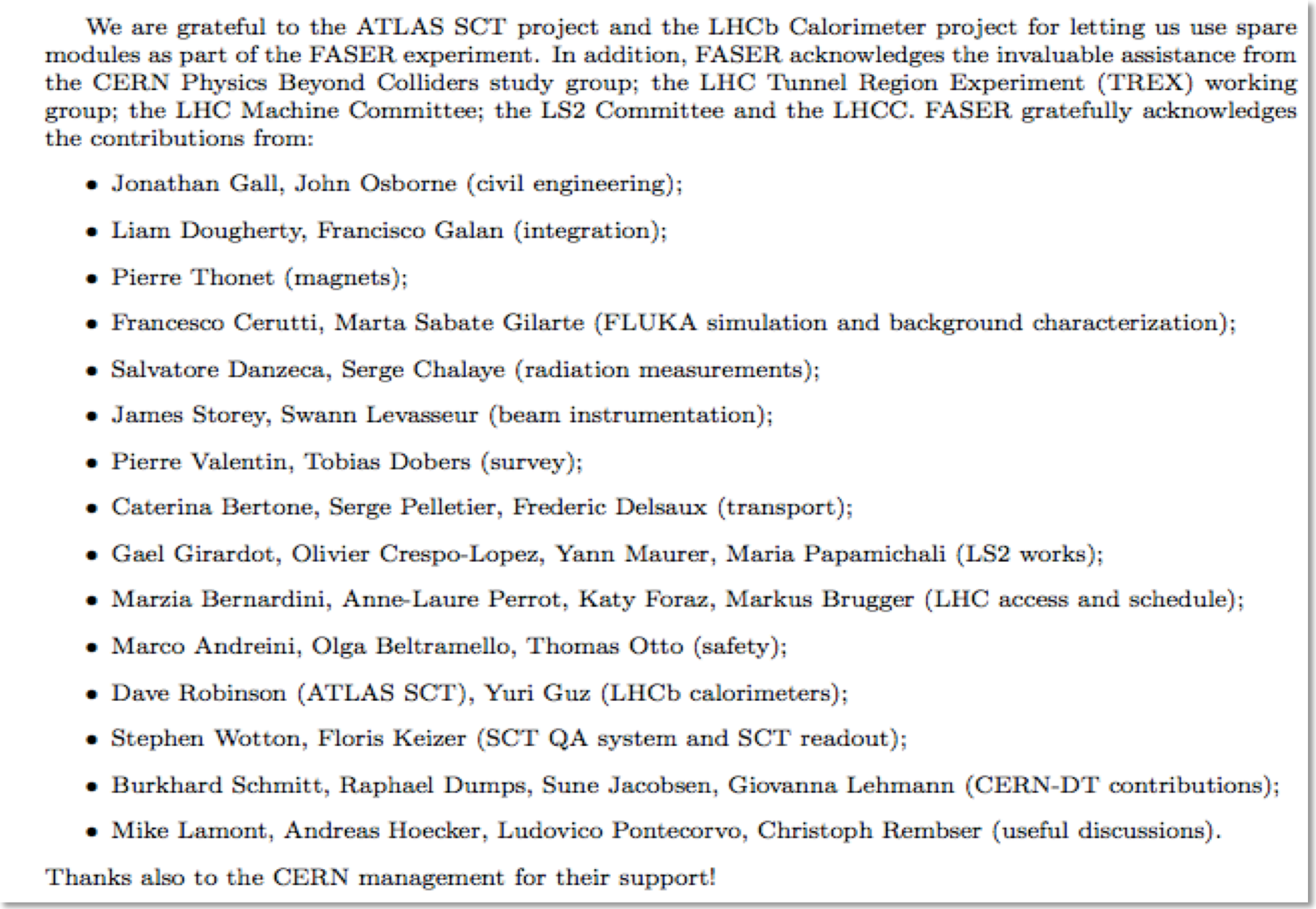
- The FASER Collaboration: 39 collaborators, 16 institutions, 8 countries

Henso Abreu (Technion), Claire Antel (Geneva), Akitaka Ariga (Bern), Tomoko Ariga (Kyushu/Bern), Jamie Boyd* (CERN), Dave Casper (UC Irvine), Franck Cadoux (Geneva), Xin Chen (Tsinghua), Andrea Coccaro (INFN), Candan Dozen (Tsinghua), 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), Sune Jakobsen (CERN), Roland Jansky (Geneva), Enrique Kajomovitz (Technion), Felix Kling (UC Irvine), Susanne Kuehn (CERN), Lorne Levinson (Weizmann), Josh McFayden (CERN), Sam Meehan (CERN), Friedemann Neuhaus (Mainz), Hidetoshi Otono (Kyushu), Lorenzo Paolozzi (Geneva), 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)

FIRST FASER COLLABORATION MEETING

ACKNOWLEDGEMENTS

The FASER Collaboration has also received essential support from many others



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 acknowledges the invaluable assistance from the CERN Physics Beyond Colliders study group; the LHC Tunnel Region Experiment (TREX) working group; the LHC Machine Committee; the LS2 Committee and the LHCC. FASER gratefully acknowledges the contributions from:

- Jonathan Gall, John Osborne (civil engineering);
- Liam Dougherty, Francisco Galan (integration);
- Pierre Thonet (magnets);
- Francesco Cerutti, Marta Sabate Gilarte (FLUKA simulation and background characterization);
- Salvatore Danzeca, Serge Chalaye (radiation measurements);
- James Storey, Swann Levasseur (beam instrumentation);
- Pierre Valentin, Tobias Dobers (survey);
- Caterina Bertone, Serge Pelletier, Frederic Delsaux (transport);
- Gael Girardot, Olivier Crespo-Lopez, Yann Maurer, Maria Papamichali (LS2 works);
- Marzia Bernardini, Anne-Laure Perrot, Katy Foraz, Markus Brugger (LHC access and schedule);
- Marco Andreini, Olga Beltramello, Thomas Otto (safety);
- Dave Robinson (ATLAS SCT), Yuri Guz (LHCb calorimeters);
- Stephen Wotton, Floris Keizer (SCT QA system and SCT readout);
- Burkhard Schmitt, Raphael Dumps, Sune Jacobsen, Giovanna Lehmann (CERN-DT contributions);
- Mike Lamont, Andreas Hoecker, Ludovico Pontecorvo, Christoph Rembser (useful discussions).

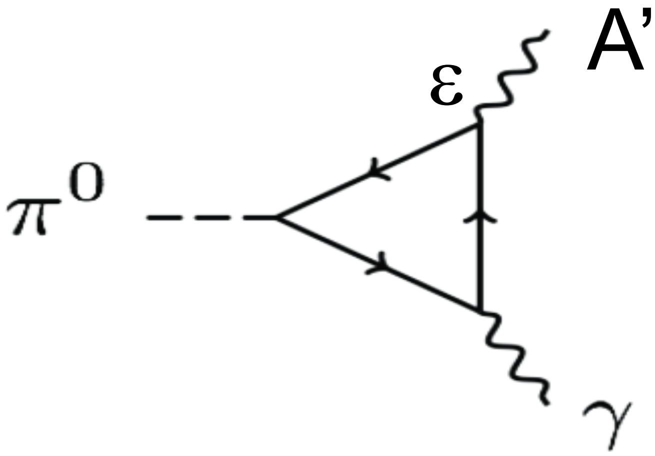
Thanks also to the CERN management for their support!

AN EXAMPLE: DARK PHOTONS

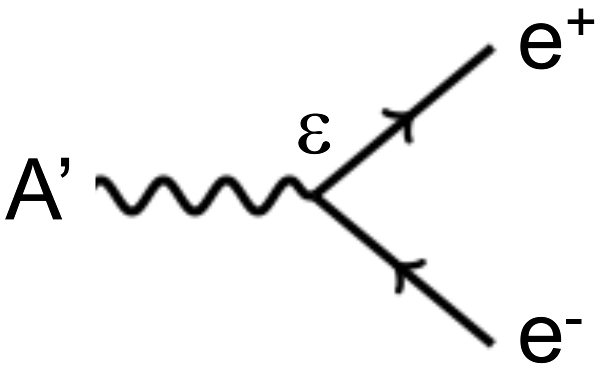
Fayet (1980); Okun (1982); Galison, Manohar (1984); Holdom (1986)

- The dark photon is like the standard photon, but
  - It is massive, with a mass $m_{A'}$
  - Its couplings to SM particles are suppressed by a small coupling ε

- It can be produced, for example, in pion decay:

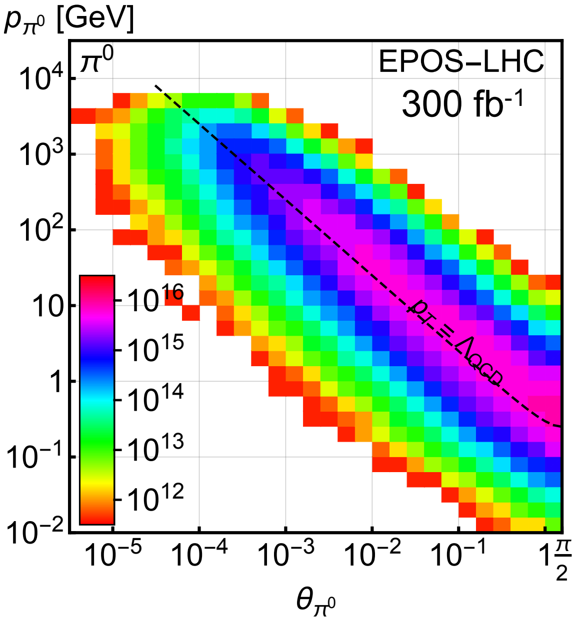


- It can decay to particle/anti-particle pairs:



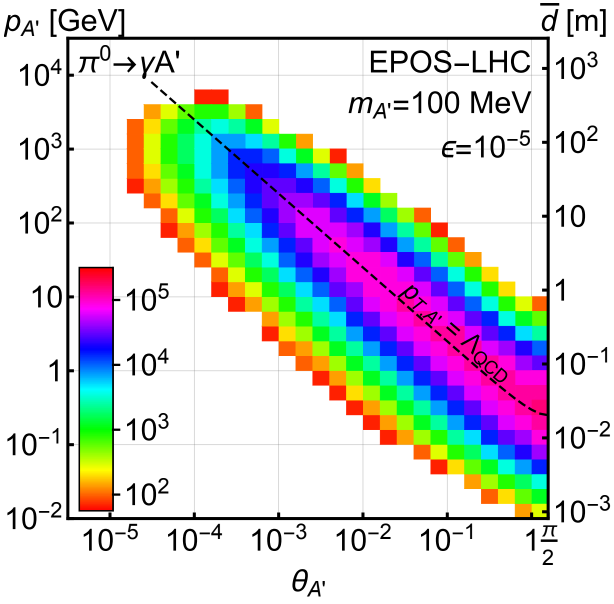
DARK PHOTON SIGNAL RATES

Pions at the IP



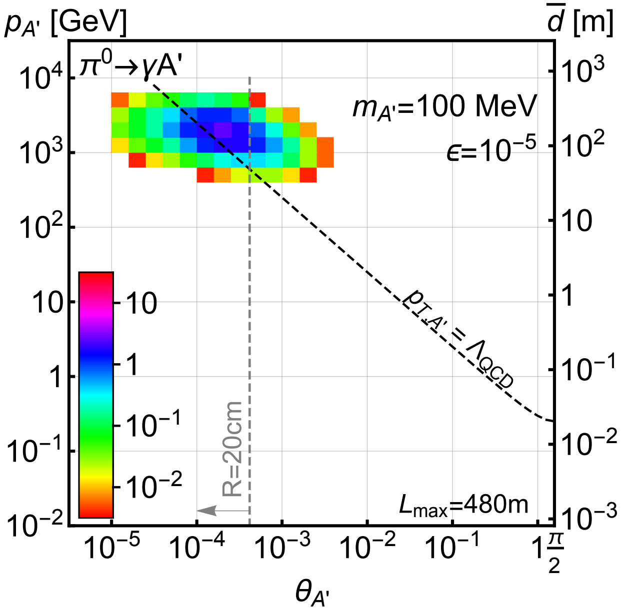
- Simulations now grounded in LHC data
- Production is peaked at $p_T \sim \Lambda_{QCD} \sim 250$ MeV
- Enormous event rates: $N_\pi \sim 10^{15}$ per bin

A's at the IP



- 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, LHC can be a dark photon factory!

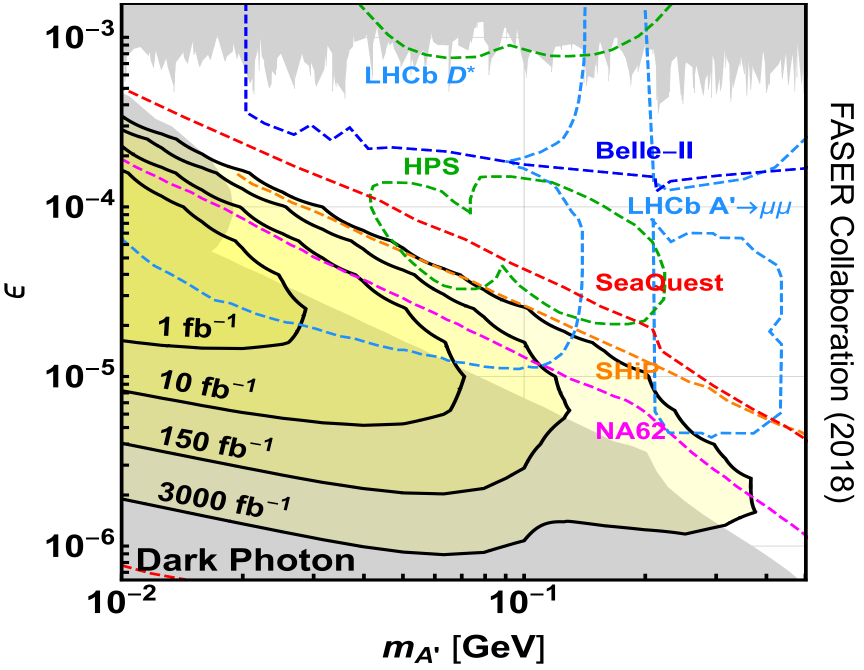
A's decay in [480m, 483m]



- 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"

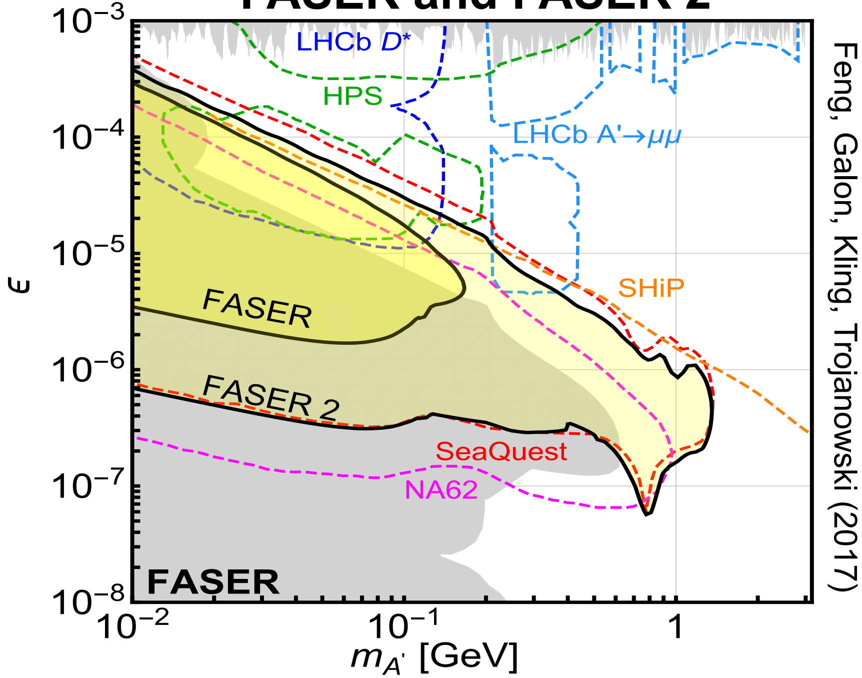
DARK PHOTON SENSITIVITY REACH

- Combine $\pi,\eta \rightarrow A'\gamma$, $qq \rightarrow qqA'$, etc., plot N_S=3 (10 makes little difference)
- FASER: R=10cm, L=1.5m, Run 3; FASER 2: R=1m, L=5m, HL-LHC



FASER

FASER Collaboration (2018)

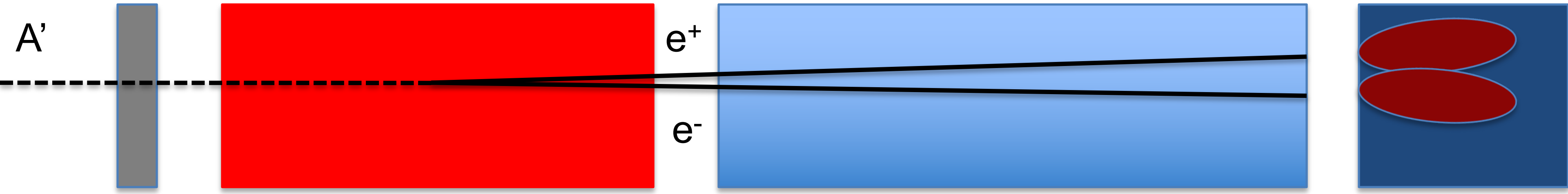


FASER and FASER 2

Feng, Galon, Kling, Trojanowski (2017)

- FASER probes new parameter space with just 1 fb^{-1} starting in 2021
- Without upgrade, HL-LHC extends (L*Volume) by factor of 3000; with possible upgrade to FASER 2, HL-LHC extends (L*Volume) by ~10^6

THE SIGNAL



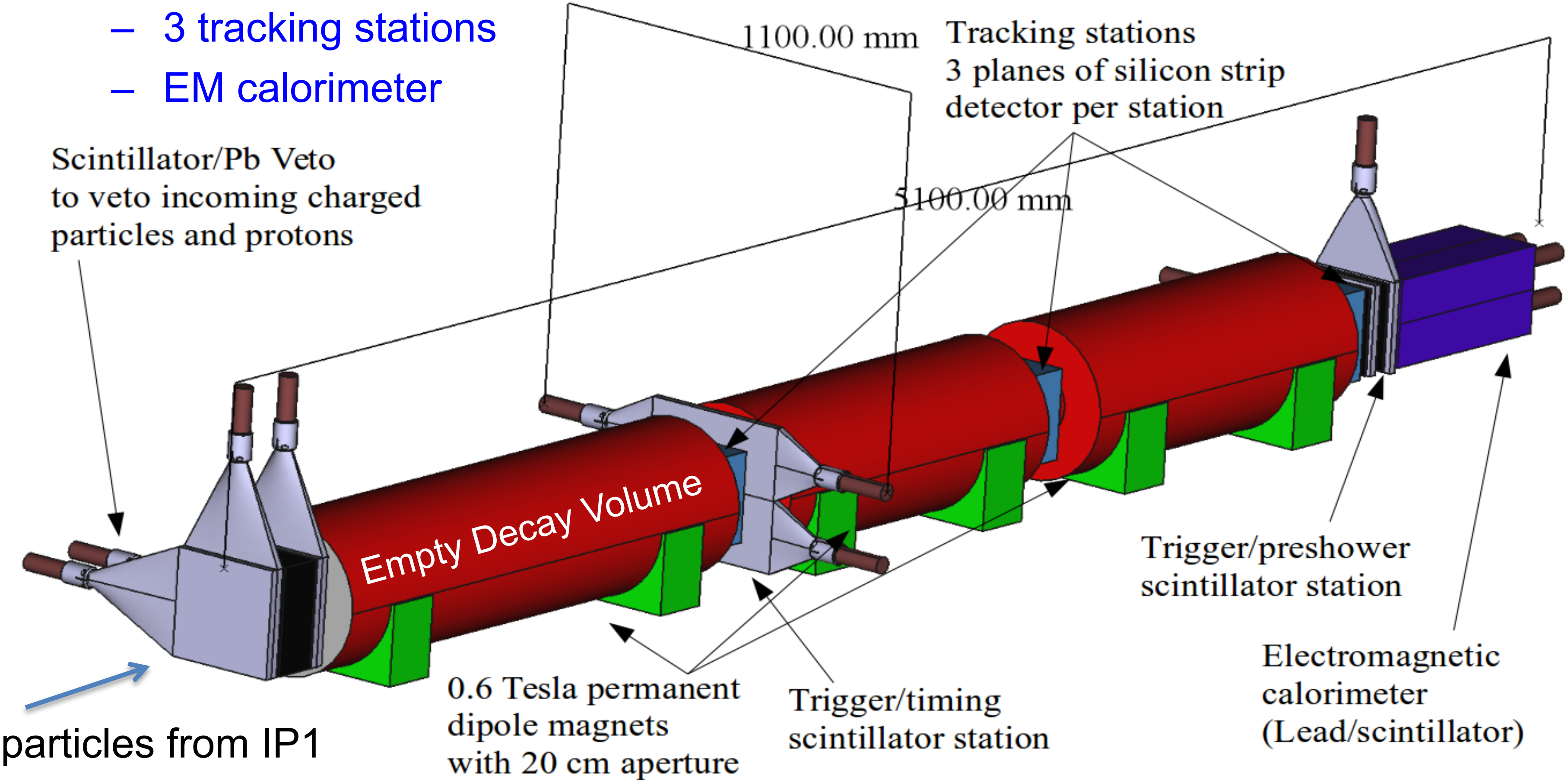
- The signal is spectacular: 2 ~TeV-energy, oppositely-charged tracks originating in the decay volume and pointing back to IP
- Initial scintillators: veto entering tracks
- Tracker: detect charged tracks
- Magnets: separate the 2 charged tracks sufficiently to resolve them in the tracker

$$h_B \approx \frac{ec\ell^2}{E} B = 2 \text{ mm} \left[\frac{1 \text{ TeV}}{E}\right] \left[\frac{\ell}{3 \text{ m}}\right]^2 \left[\frac{B}{0.6 \text{ T}}\right]$$

- Calorimeter: differentiate e from μ, detect γ, measure energy

THE FASER DETECTOR

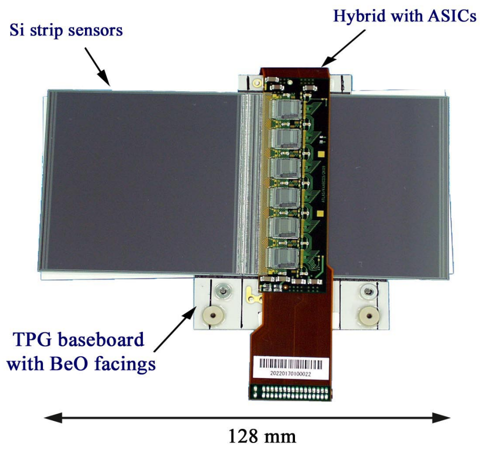
- The entire detector is 5.5 m long. It consists of
  - Scintillator veto
  - 1.5 m-long decay volume
  - 2 m-long spectrometer
  - 3 tracking stations
  - EM calorimeter



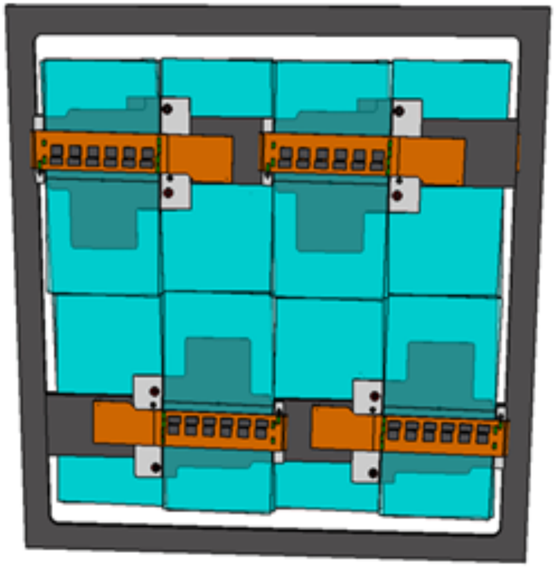
FASER TRACKER

- 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 generously allowed us to use 80 of them. QA now completed.

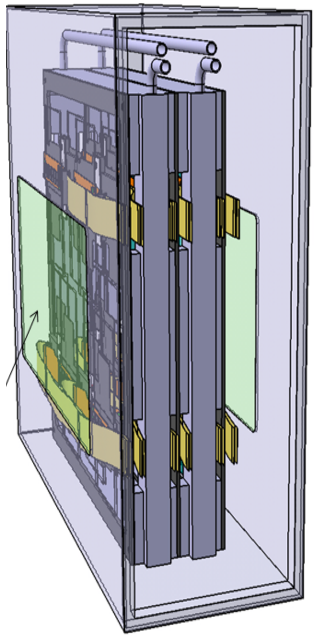
- 8 SCT modules make up a 24cm x 24cm tracking layer, 3 layers make up a tracking station, and FASER has 3 tracking stations.



SCT module

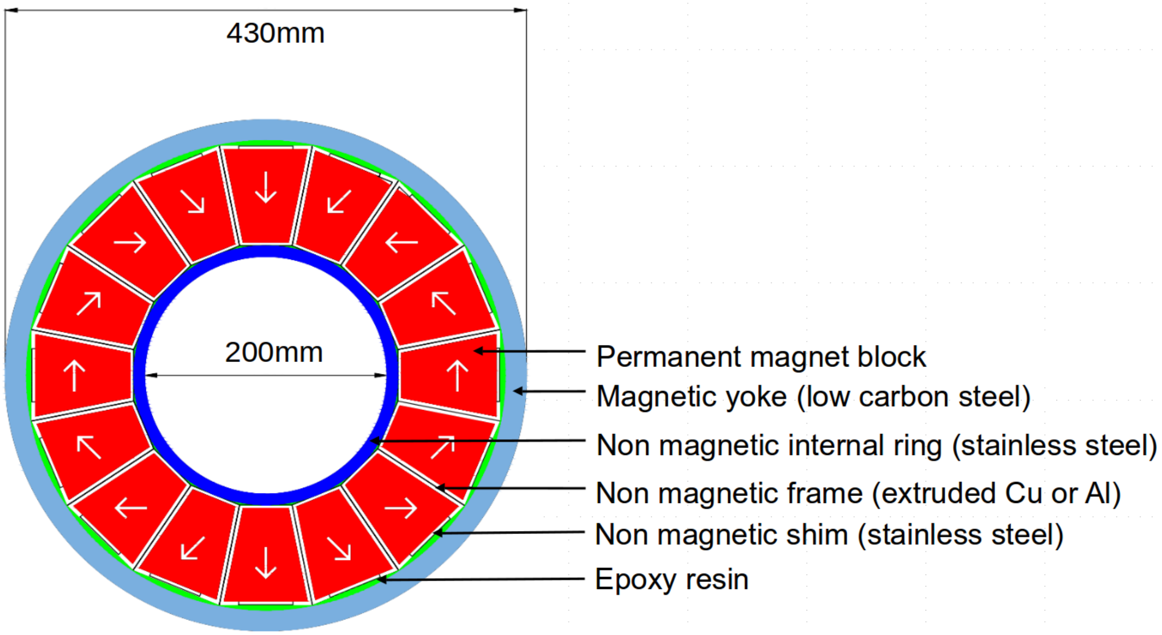


Tracking layer

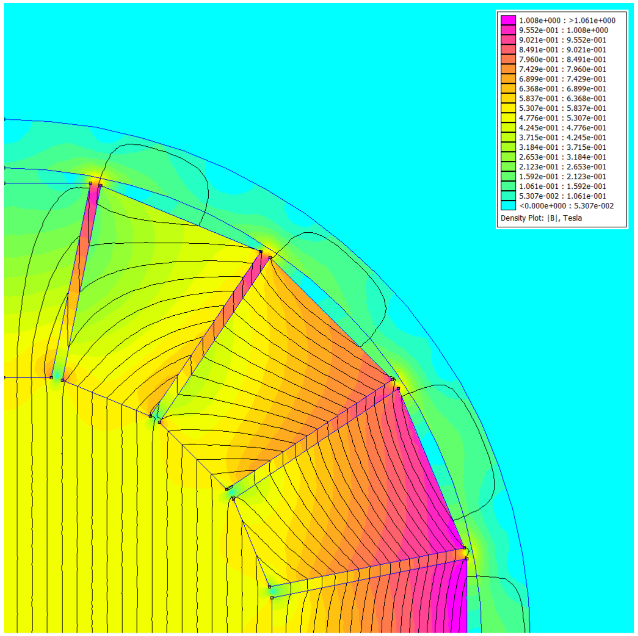


Tracking station

FASER MAGNETS

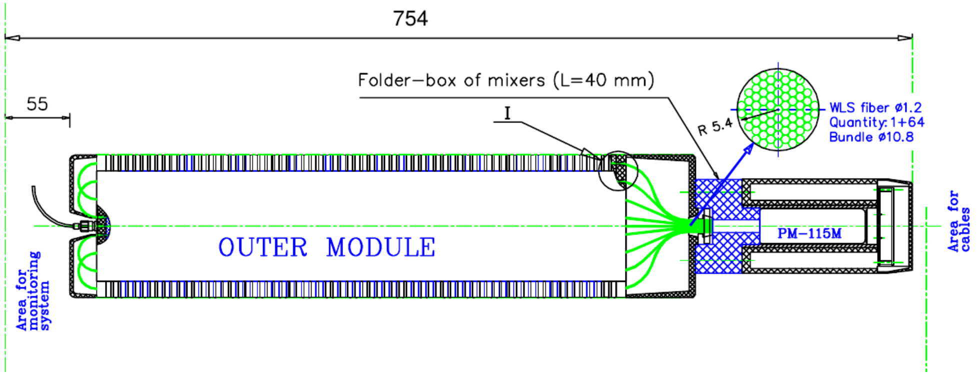


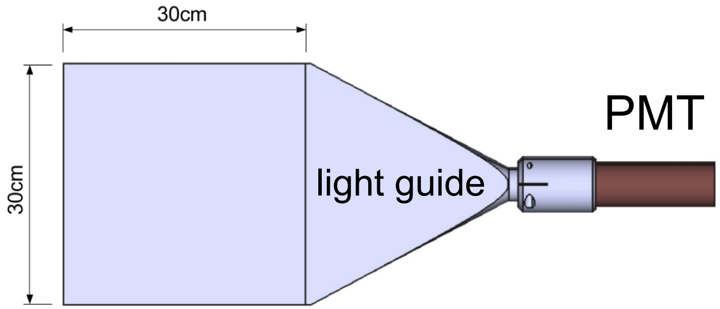
Permanent magnet block
Magnetic yoke (low carbon steel)
Non magnetic internal ring (stainless steel)
Non magnetic frame (extruded Cu or Al)
Non magnetic shim (stainless steel)
Epoxy resin



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

FASER CALORIMETER / SCINTILLATORS

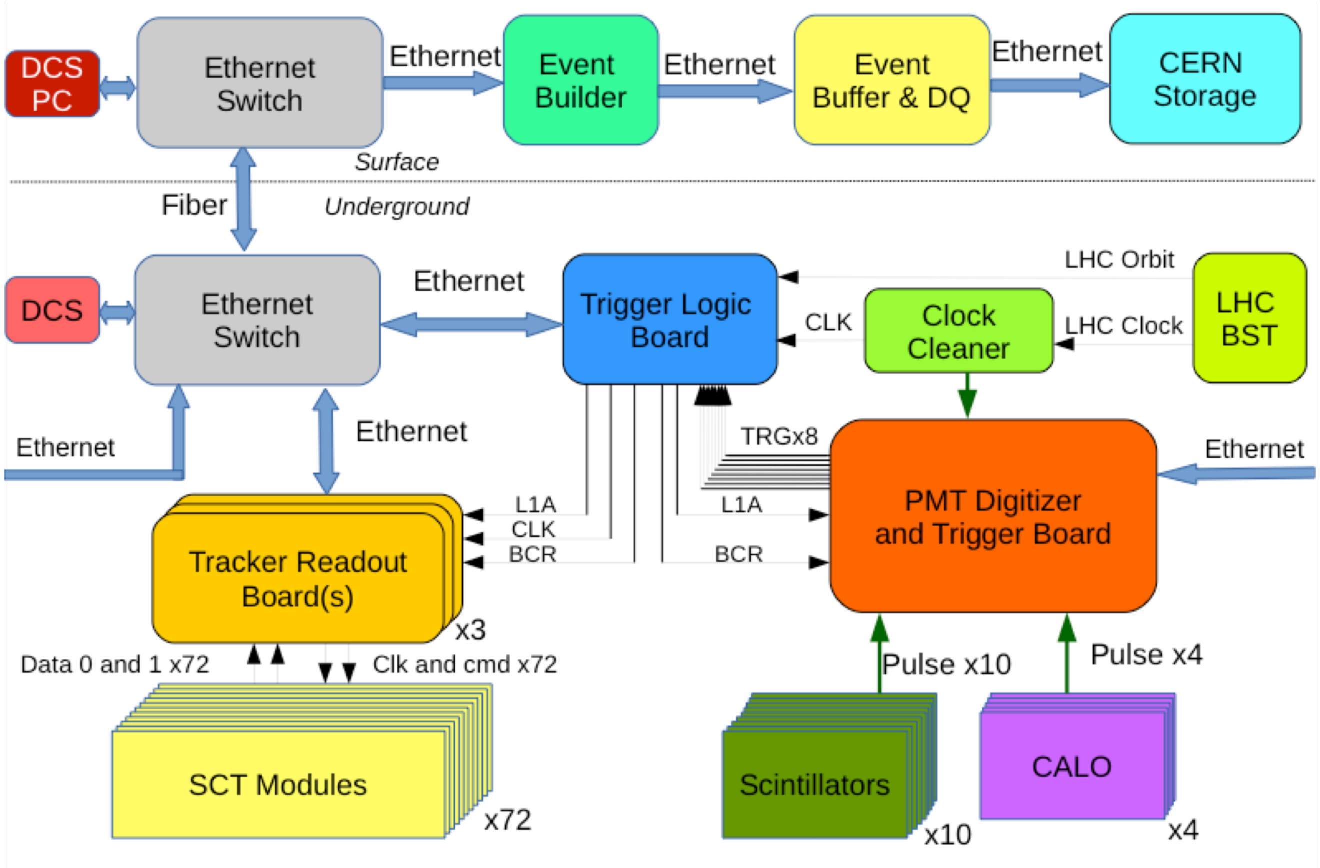




- The FASER ECAL consists of spare LHCb outer ECAL modules, which the LHCb Collaboration generously allowed us to use.
  - Dimensions: 12cm x 12cm – 75cm long (25 radiation lengths)
  - 66 layers of lead/scintillator, light out by wavelength shifting fibres, and read out by PMT (no longitudinal shower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

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

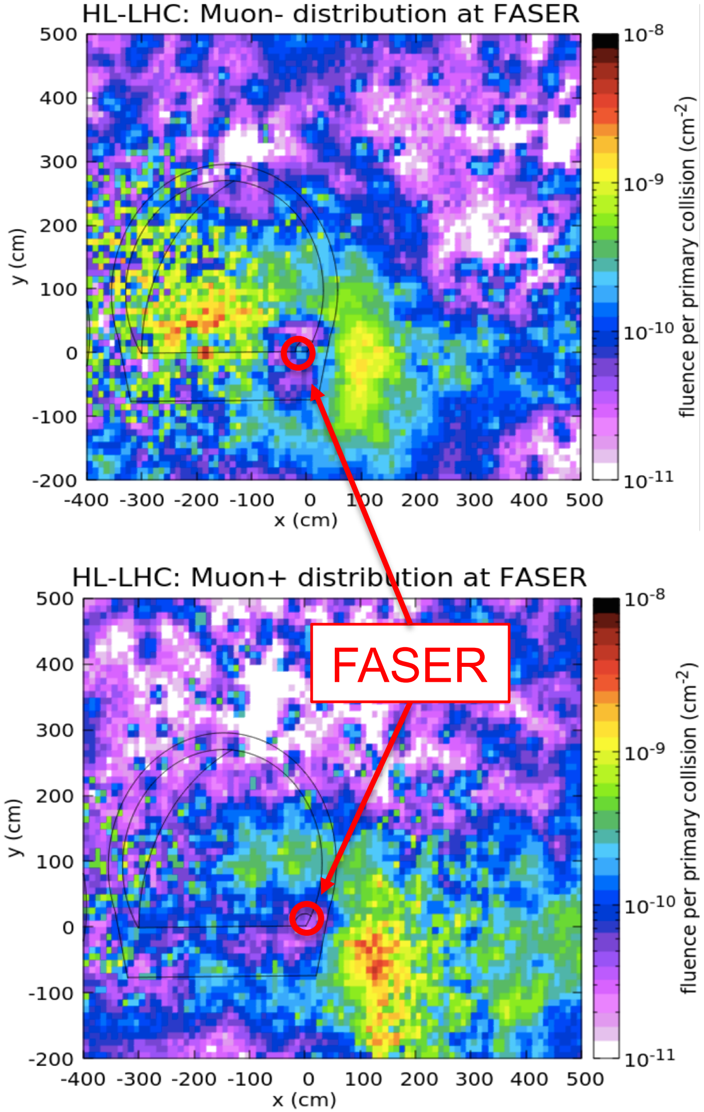
FASER TDAQ



- Trigger rate expected to be ~600 Hz, dominated by muons from IP.
- Trigger will be an OR of triggers from scintillators and from the ECAL.
- Largely independent of ATLAS; only need to know bunch crossing time and ATLAS luminosity for off-line analysis.

BACKGROUNDS

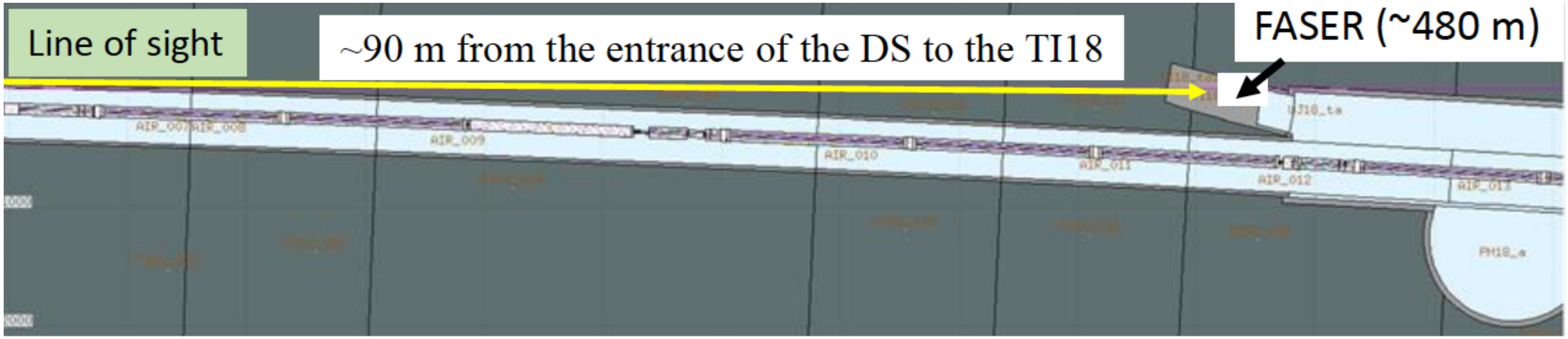
- FASER's location is very quiet – the only SM particles that get through from the IP are muons and neutrinos, and FASER is (fortuitously) in a remarkably quiet spot for muons.
- A high-energy muon that brems off a photon or an EM or hadronic jet is a leading background if the incoming muon is not vetoed.
- But assuming each of 4 scintillator layers gives an uncorrelated 10^{-2} veto suppression for muons entering the detector, the resulting backgrounds are negligible.



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

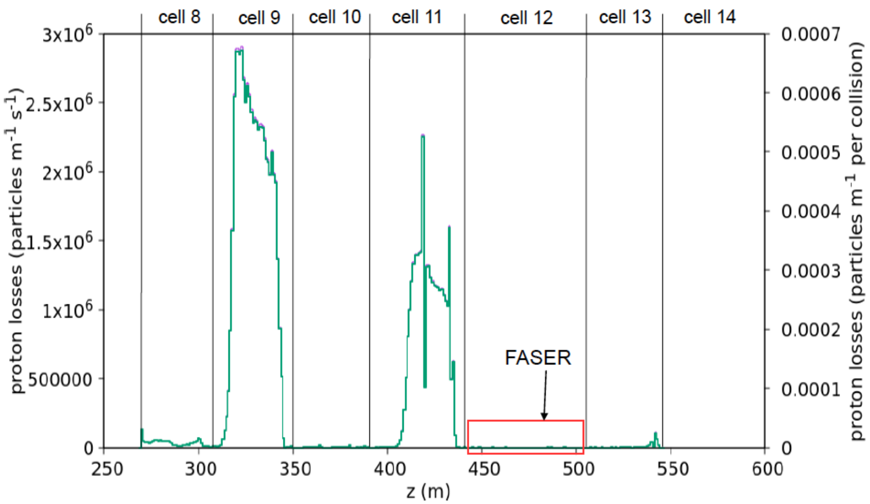
MORE BACKGROUNDS

- The FLUKA study also finds that beam-gas background (from “beam 2” traveling in the other direction) is also negligible.



Proton-loss map in the DS

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



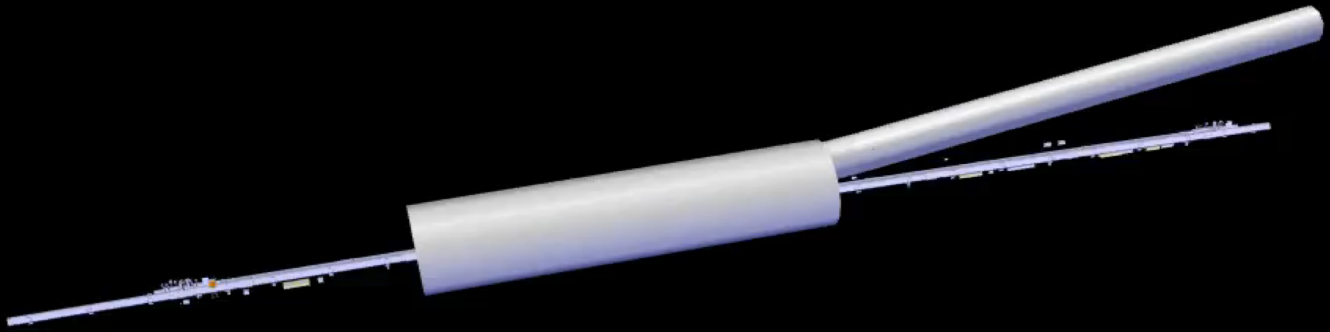
Sabate-Gilarte, Cerutti, Tsinganis (2018)

IN SITU MEASUREMENTS

- To validate the FLUKA study, in 2018 we installed emulsion detectors in (weeklong) Technical Stops 1 and 2 to provide the first *in situ* measurements at the FASER site.
- The emulsion detector results are within measurement accuracy (factor of 2) of the FLUKA predictions.
- A BatMon (battery-operated radiation monitor) was also installed. Results for low-energy radiation are also promisingly low.

FASER INSTALLATION

Dougherty, CERN Integration (2019)

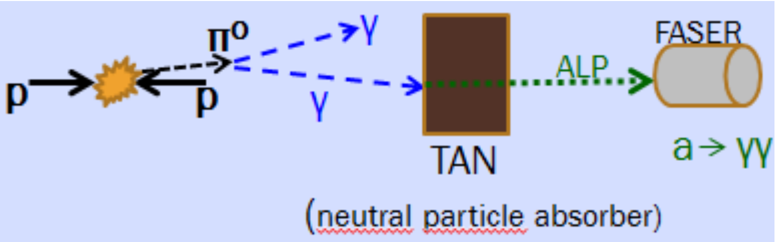


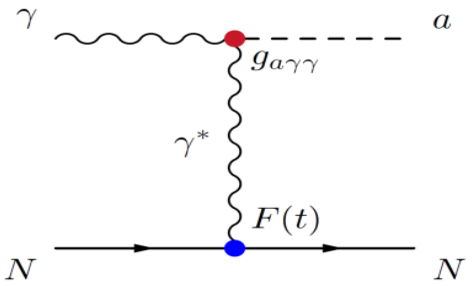
MORE FASER PHYSICS: ALPS WITH PHOTONS

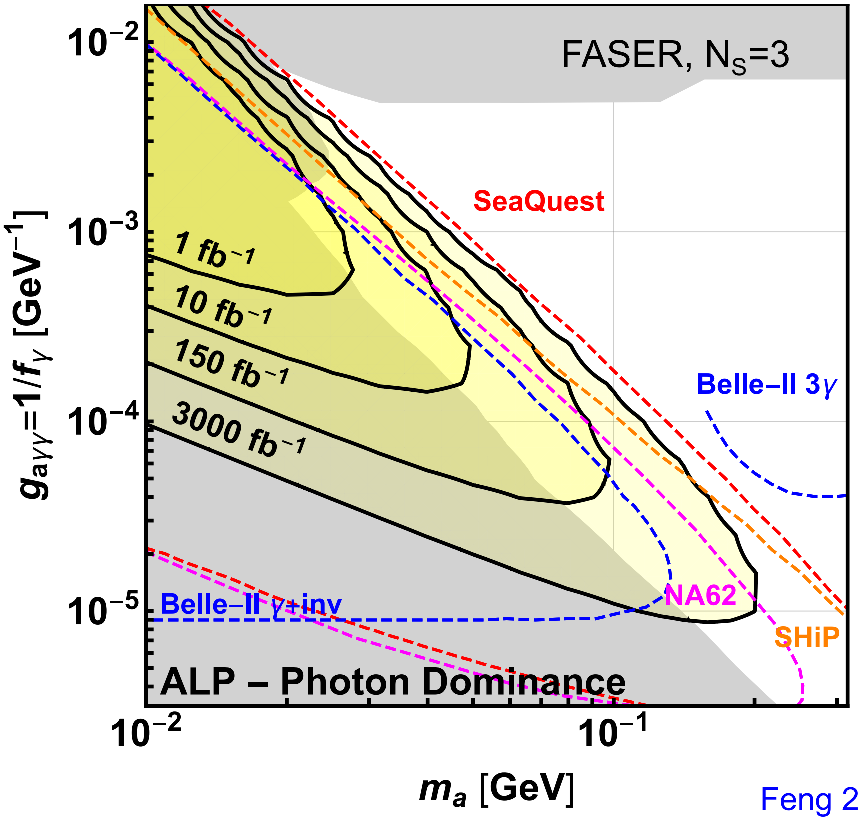
- FASER can also discover ALPs and other LLPs produced not at the IP, but further downstream

- For example: ~TeV photon from IP collides with TA(X)N ~140 m downstream (between beams), creates Axion-Like Particle, which decays through a → $\gamma\gamma$, detected in FASER calorimeters

- "Photon beam dump" or "light shining through walls"

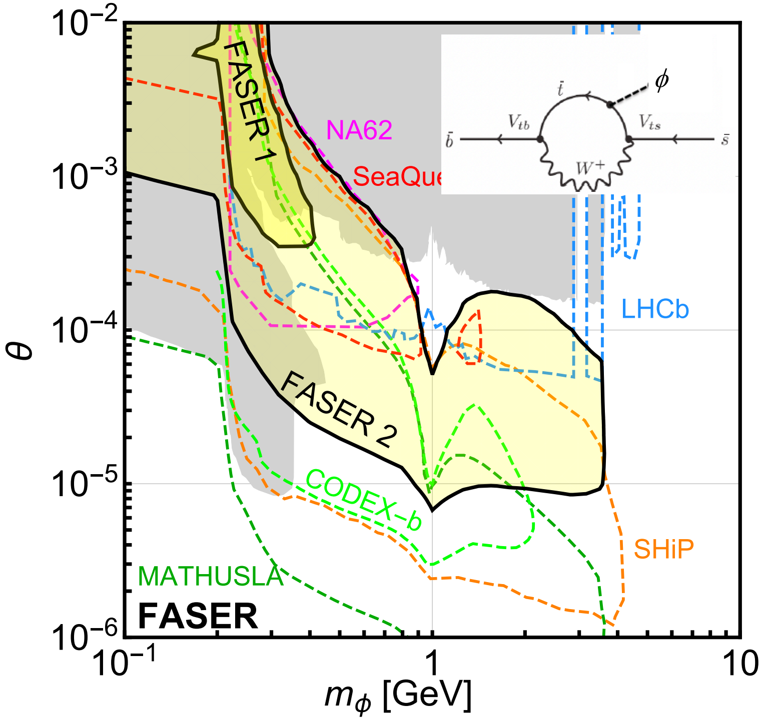




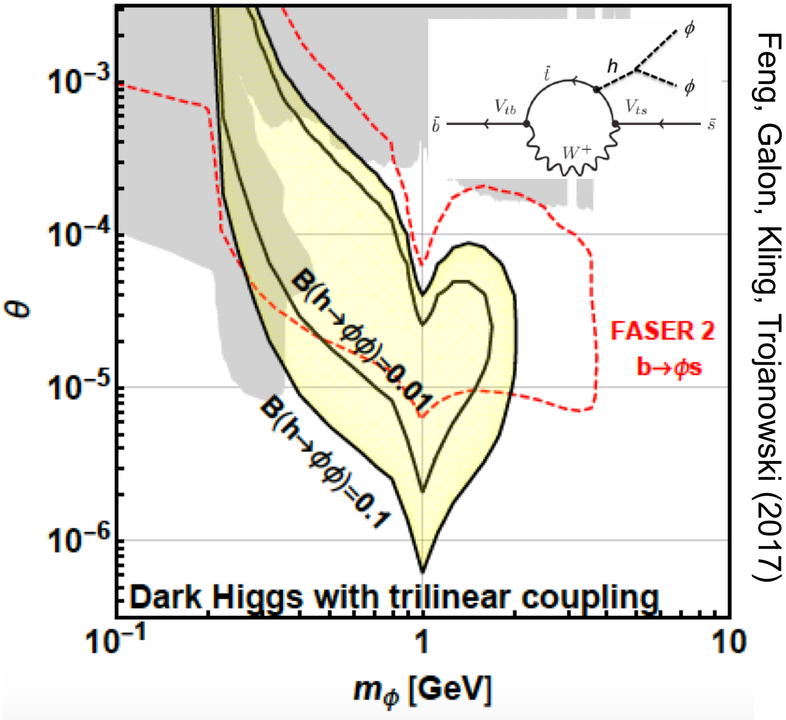


MORE FASER PHYSICS: DARK HIGGS BOSONS

- **SINGLE PRODUCTION**



- **DOUBLE PRODUCTION**

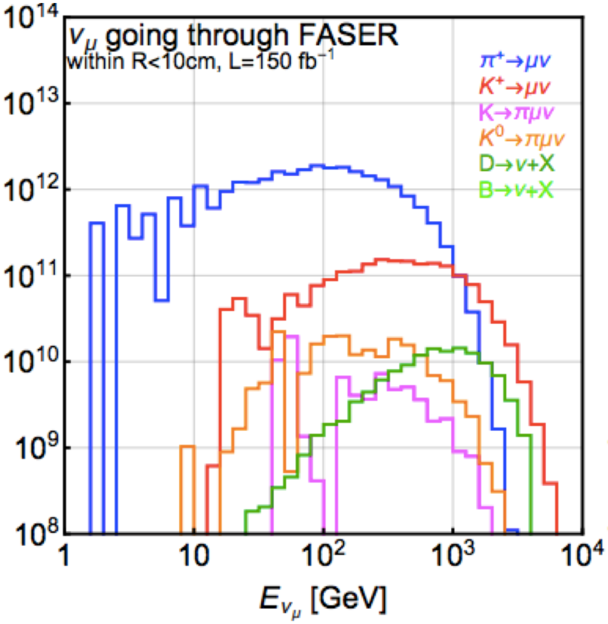


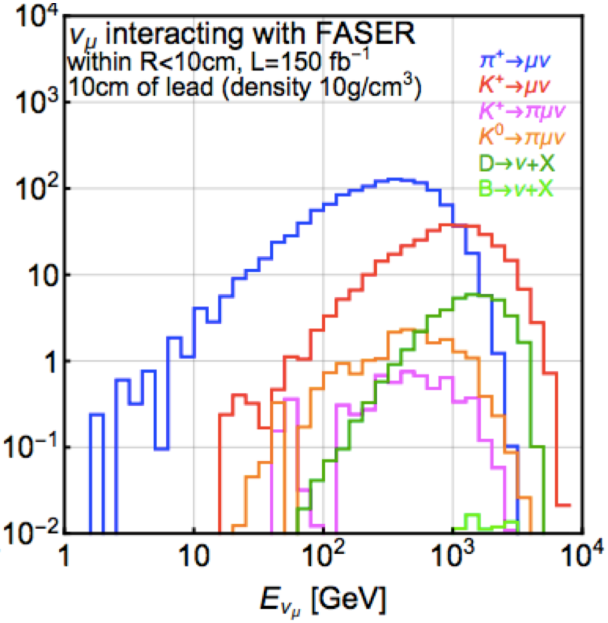
Feng, Galon, Kling, Trojanowski (2017)

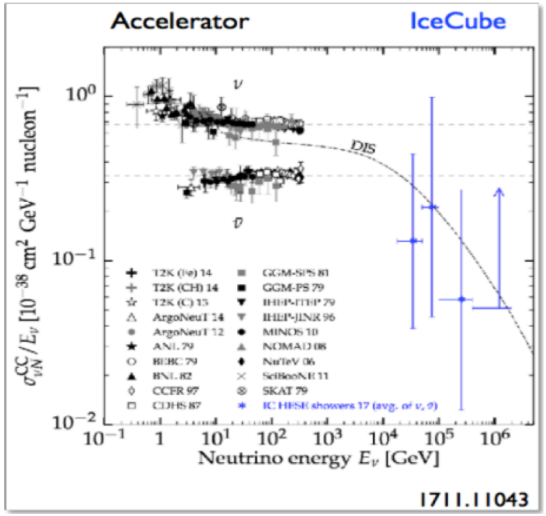
- Dark Higgs produced in B decays. $N_B/N_\pi \sim 10^{-2}$ at FASER
(cf. $N_B/N_\pi \sim 10^{-7}$ at beam dumps)
- Reach is complementary to other experiments

- Probes $h\phi\phi$ trilinear coupling
- Complementary to probes of exotic Higgs decays $h \rightarrow \phi\phi$
- FASER probes SM Higgs properties, exotic decays!

MORE FASER PHYSICS: NEUTRINO PHYSICS







1711.11043

- Huge flux of high-energy neutrinos through FASER could allow for the 1st detection of an LHC neutrino and other interesting measurements.

- E.g., ν_μ CC cross section in unexplored region E>400 GeV, ν_τ events.

- In fact, we are already looking for neutrino interactions in the 30 kg emulsion detectors installed in TI12 in 2018. In 12.8 fb^{-1} of data, we expect ~10 ν_μ events.

PHYSICS SUMMARY

- FASER and FASER 2 have full physics programs: 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

SUMMARY AND OUTLOOK

- The possibility of new light and weakly-interacting particles opens up exciting opportunities for small, cheap, and fast search experiments.

- FASER: “Tabletop” experiment, ~$2M, 18 months from idea to beginning of construction

- Current: Install FASER in LS2 (2019-20) for Run 3 (2021-23, 150 fb^{-1})
  - Decay volume: R = 10 cm, L = 1.5 m. Total length is 5.5 m.
  - Discovery potential starting with the 1st fb^{-1} of luminosity in 2021.

- Future: Install FASER 2 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).
  - Extends FASER’s initial 1 fb^{-1} sensitivity (L*Vol) by factor of ~10^6, probes full physics program: dark photons, B-L, ALPs, dark Higgs, HNLs, SM neutrinos, etc.

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