Looking forward to new Physics with FASER

Felix Kling

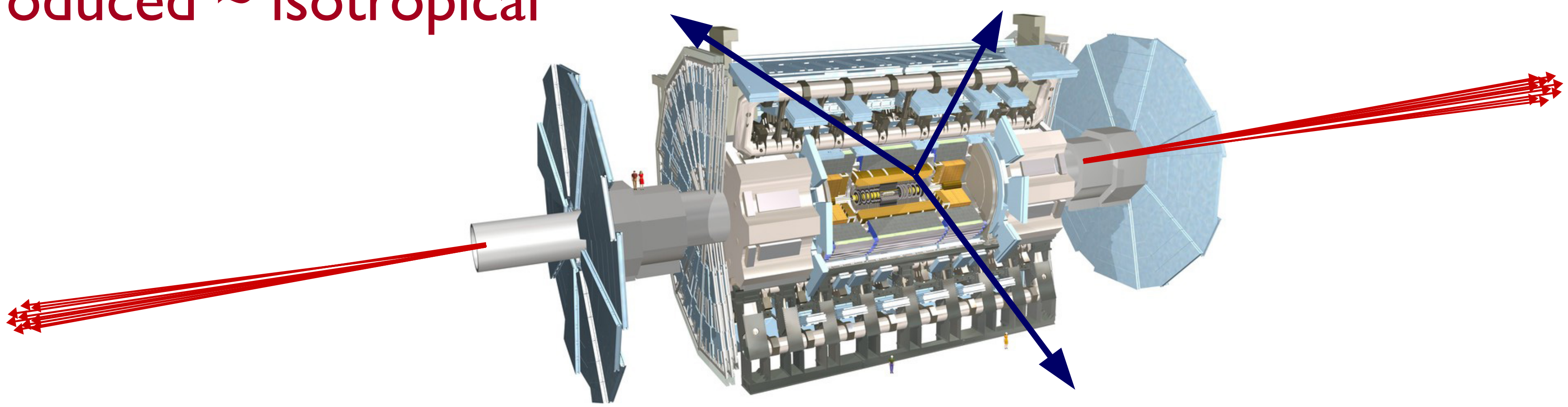
April 16th 2020
Forward Spectrometer Meeting

FASER is a forward spectrometer

SLAC NATIONAL ACCELERATOR LABORATORY
HEISING-SIMONS FOUNDATION
SIMONS FOUNDATION

FASER: Motivation and Idea

- LHC searches/experiments focus on **central region**, which is motivated by heavy, strongly interacting particles
  * small rates: $\sigma \sim$ fb - pb or 10^7 Higgs Bosons during LHC Run3
  * high pT, produced ~ isotropical



- For light and weakly interacting particles, 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

- We should go where the pions are: **forward region** along the beam line
  * enormous event rates: $\sigma_{inel} \sim$ 100mb or 10^{17} Higgs Bosons during LHC Run3
  * highly energetic beam remnants: E ~ TeV
  * low pT ~ Λ_{QCD} → particles are collimated $\theta \sim \Lambda_{QCD}/E \sim$ mrad

- We can't place a reasonably-sized detector on the beam line near the IP
  * blocks the proton beams, subject to large radiation

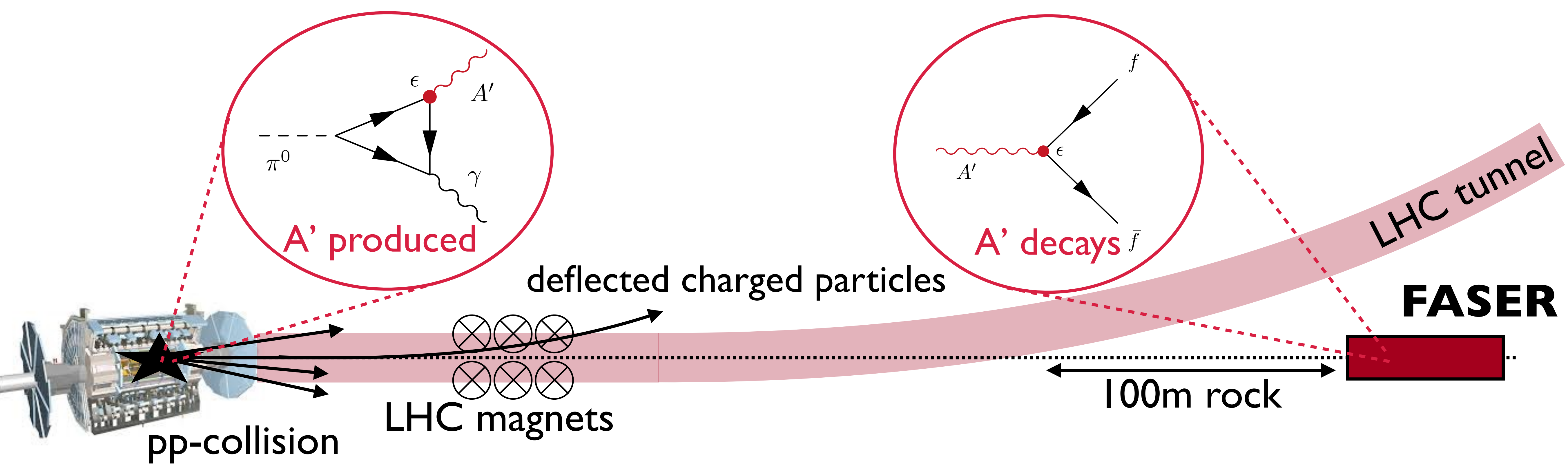
- However, weakly-interacting particles are long-lived and do not interact with matter
  → place detector few 100m away along the "collision axis" after beam curves
  * LHC infrastructure acts and rock act as shielding

- At this location, particles are still highly collimated
  * 100m x mrad ~ 10cm spread in transverse plane

- This motivates small, fast and cheap inexpensive detector

FASER: ForwArd Search ExpeRiment

[Feng, Galon, FK, Trojanowski 1708.09389]

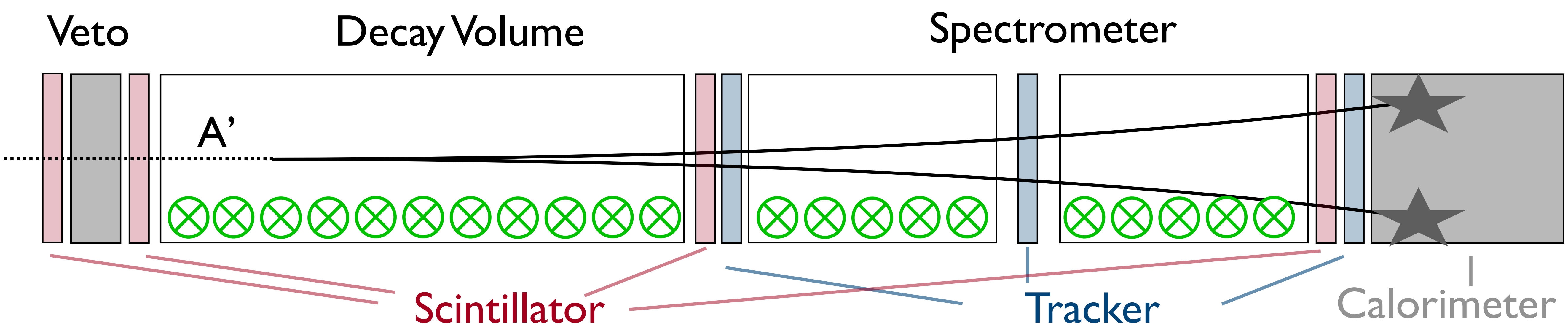


pp→A' + X   A' travels ~ 480m   A'→electrons

FASER: Motivation and Idea

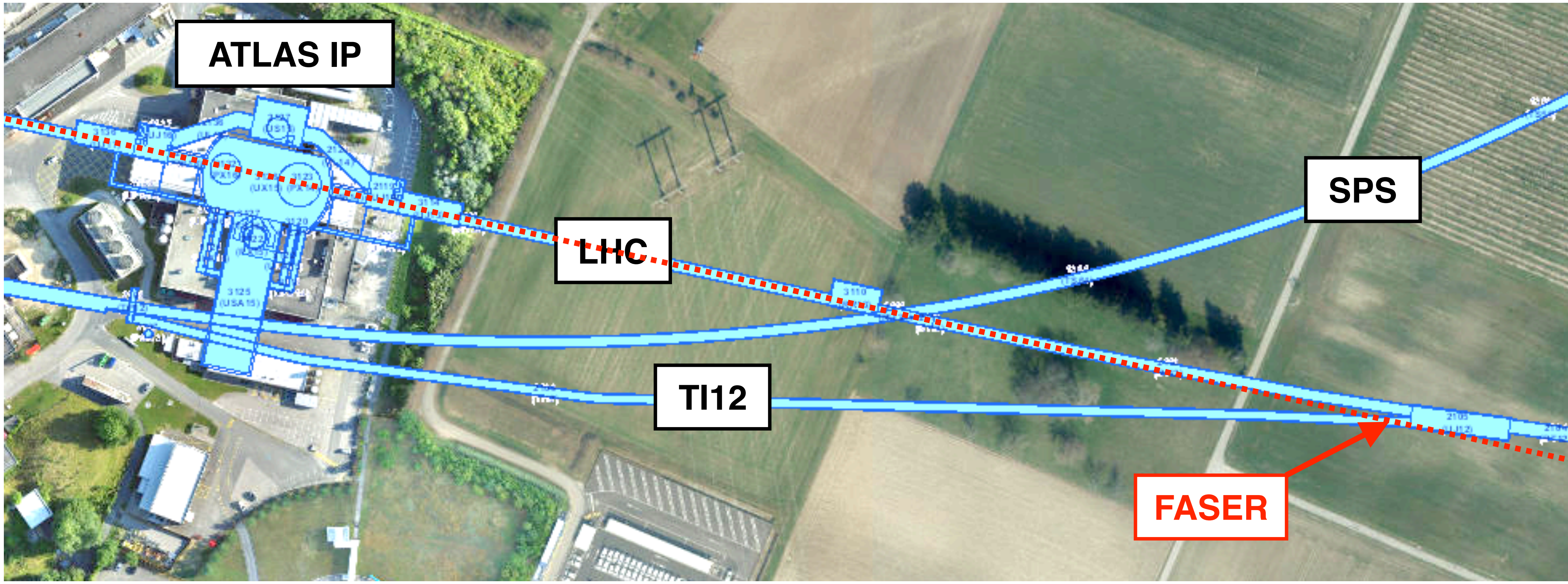
- Signal is striking
  * two oppositely charged, high energy electrons (E > 500 GeV)
  * originate from a common vertex in a small, empty decay volume
  * point back to ATLAS through ~100 m of rock

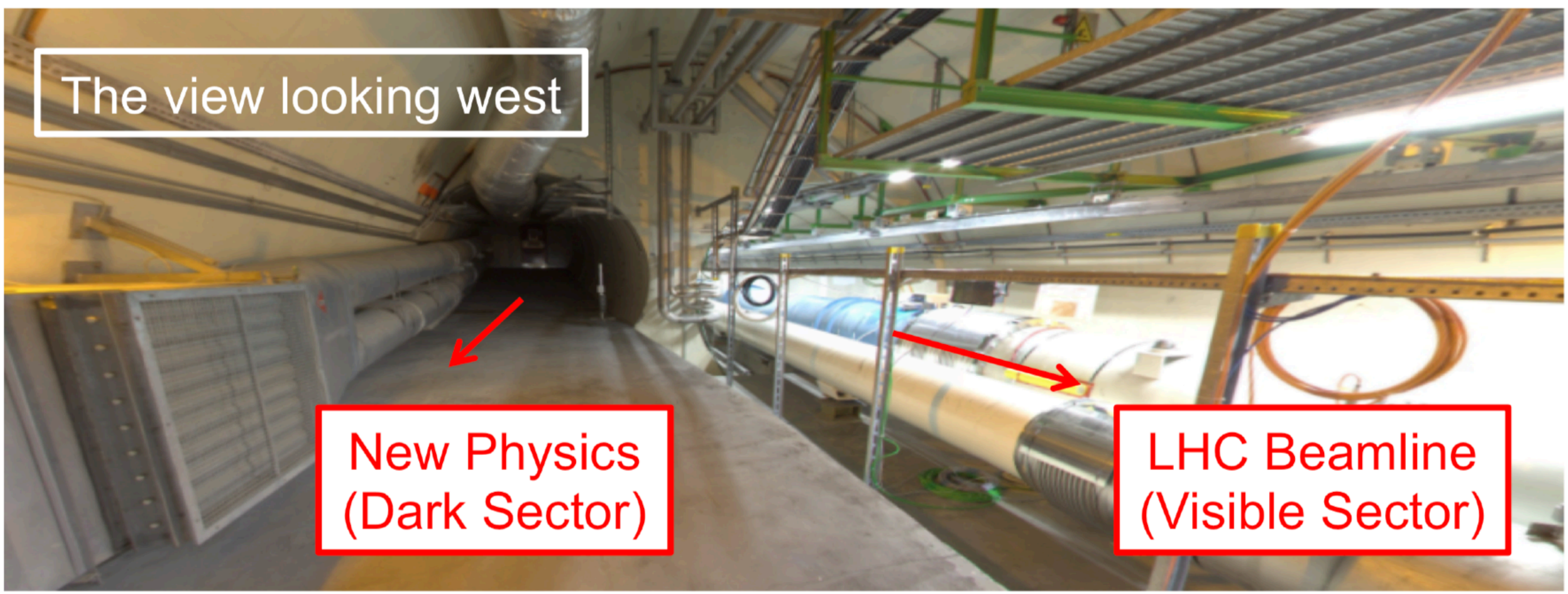
- Proposed detector design:
  * FASER needs tracking, charge identification, rough energy estimate, timing
    → tracking based technology, with a magnet, scintillators and a calorimeter



- Background considerations
  * only neutrino and muons can travel through 100 m of rock
  * neutrino interactions are rare and look different
  * incoming muons can be identified using scintillators

FASER Location

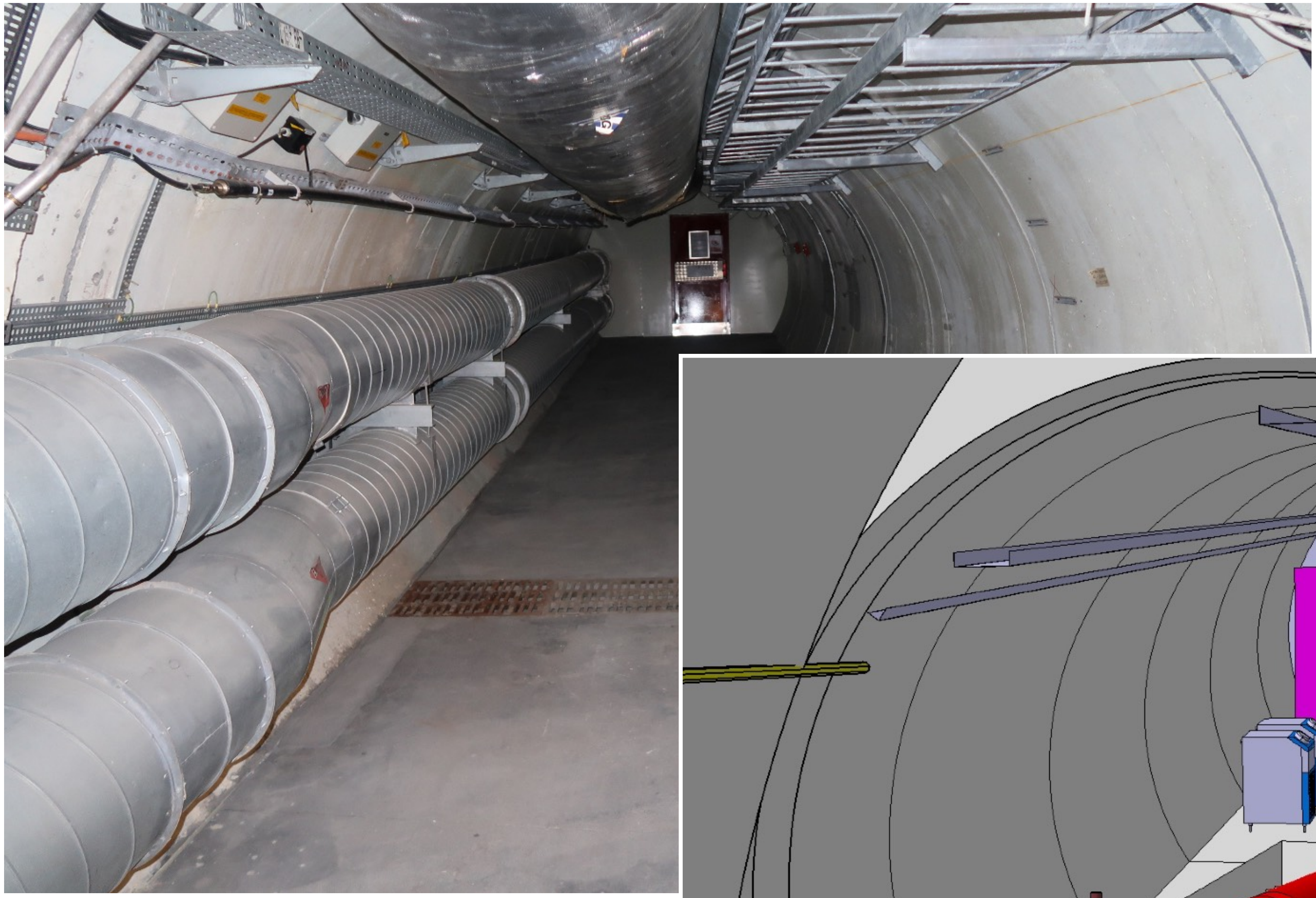




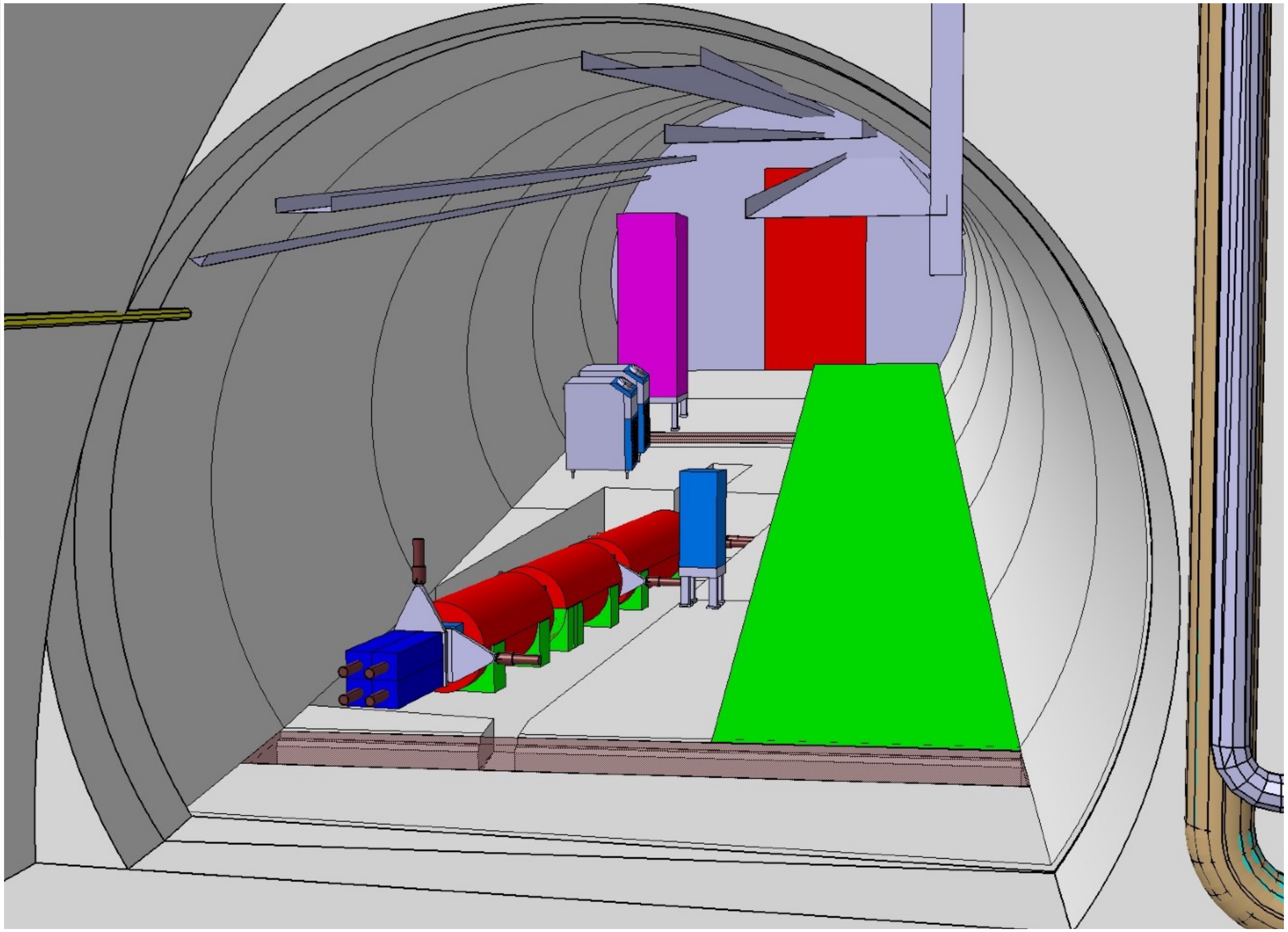
FASER Location

T112 last summer

FASER Location

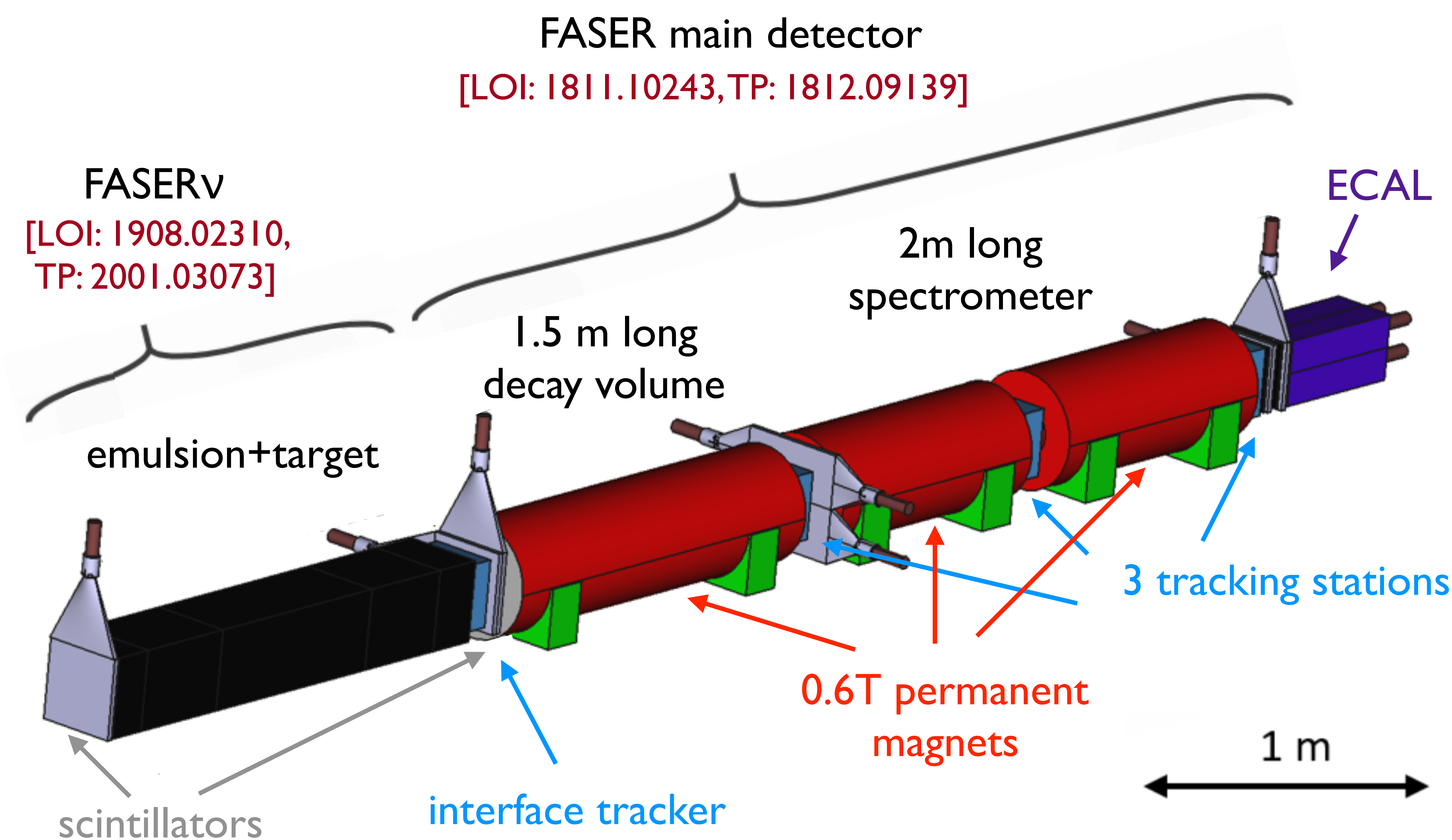


T112 last summer



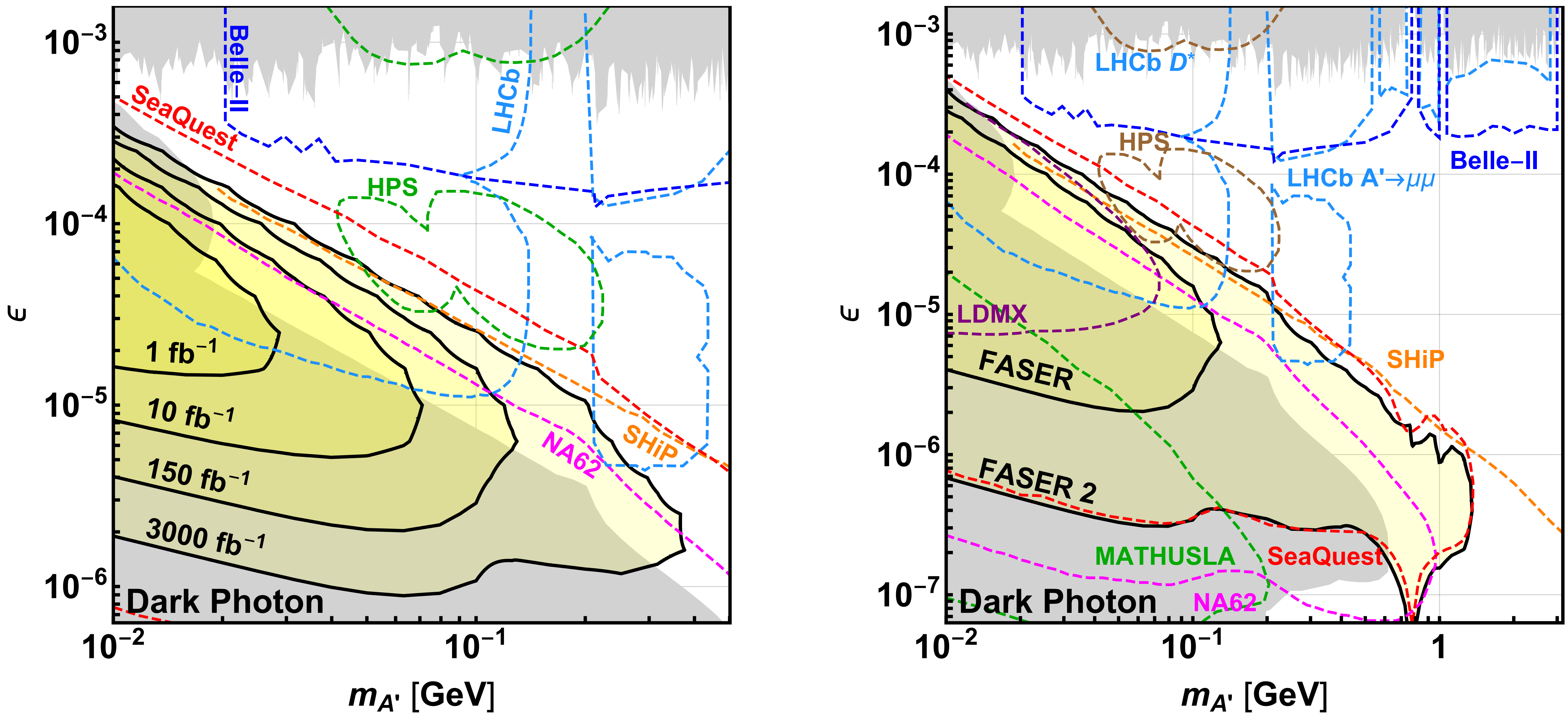
FASER in T112 (Technical Proposal)

FASER Detector



FASER LLP Physics Reach

- we estimated the expected physics potential
  * FASER is a qualitatively new approach: quick progress expected
  * discover possible after 1 week of running in 2021
  * possible FASER 2 upgrade in 2025 with larger volume (R=1m, L=5m)



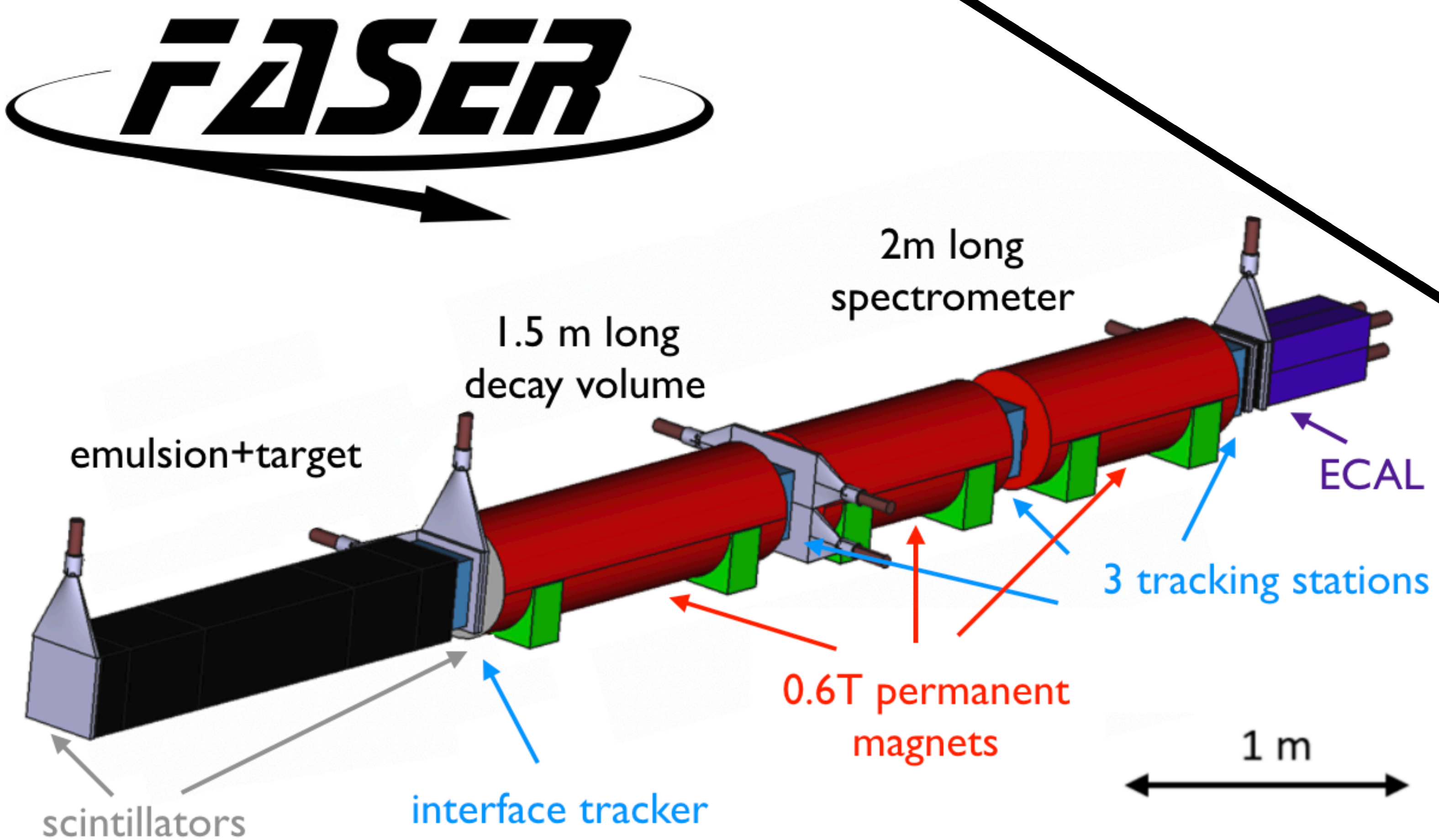
* reach for many more models, see FASER Physics Case: arXiv:1811.12522

FASER Status and Outlook

09/2017 - original FASER idea paper arXiv:1708.09389

spring 2018 - FASER collaboration forms

07/2018 - Letter of Intent arXiv:1811.10243



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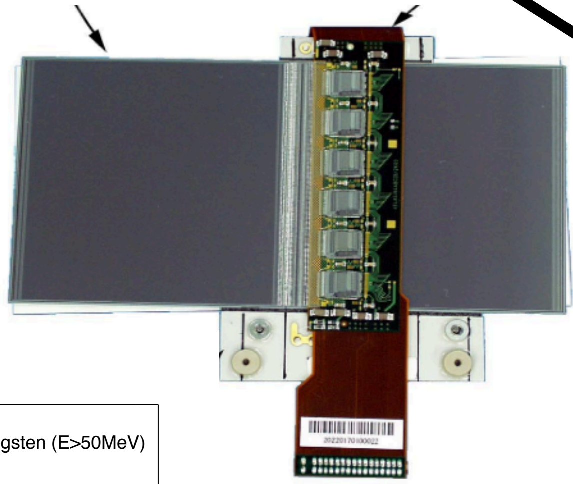

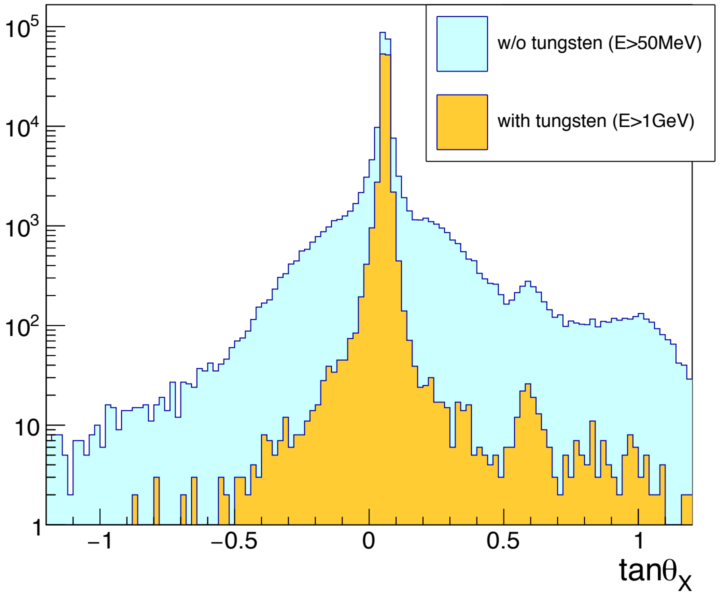

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12/2018 - funding

03/2019 - approval by CERN

FASER: CERN approves new experiment to look for long-lived, exotic particles

The experiment, which will complement existing searches for dark matter at the LHC, will be operational in 2021

7 MARCH, 2019 | By Cristina Agrigoroae

Benchmark Model	Label	Section	PBC	Refs	FASER	FASER 2
Dark Photons	V1	IV A	BC1	[7]	√	√
$B-L$ Gauge Bosons	V2	IV B	—	[30]	√	√
$L_i - L_j$ Gauge Bosons	V3	IV C	—	[30]	—	—
Dark Higgs Bosons	S1	V A	BC4	[26, 27]	—	√
Dark Higgs Bosons with hSS	S2	V B	BC5	[26]	—	√
HNLs with e	F1	VI	BC6	[28, 29]	—	√
HNLs with μ	F2	VI	BC7	[28, 29]	—	√
HNLs with τ	F3	VI	BC8	[28, 29]	√	√
ALPs with Photon	A1	VII A	BC9	[32]	√	√
ALPs with Fermion	A2	VII B	BC10	—	—	√
ALPs with Gluon	A3	VII C	BC11	—	√	√
Dark Pseudoscalars	P1	VIII	—	[36]	—	√

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11/2019 - FASERν TP arXiv: 2001.03073

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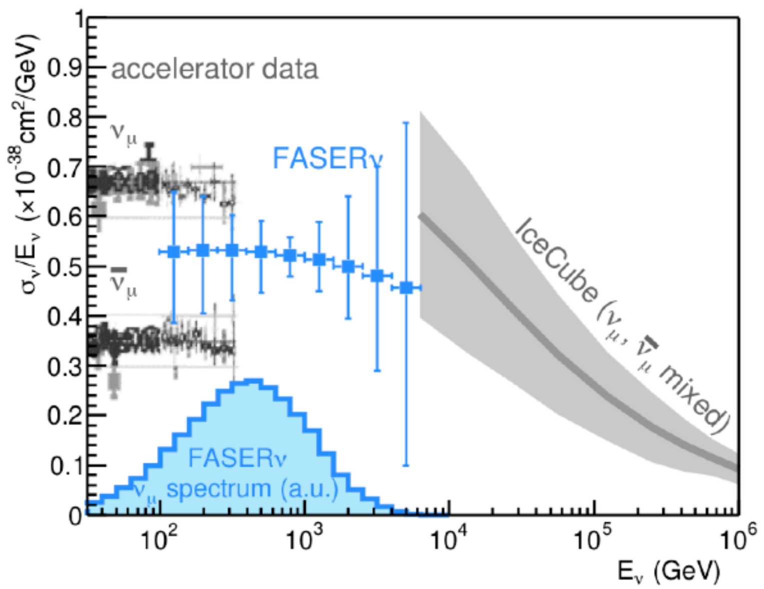

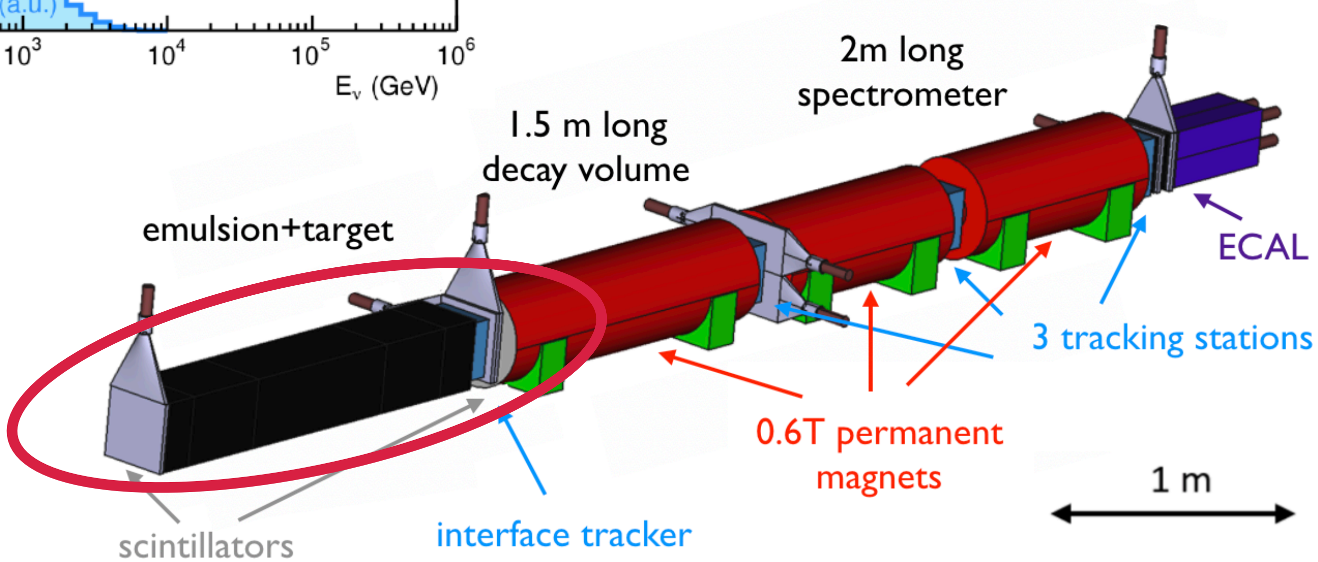

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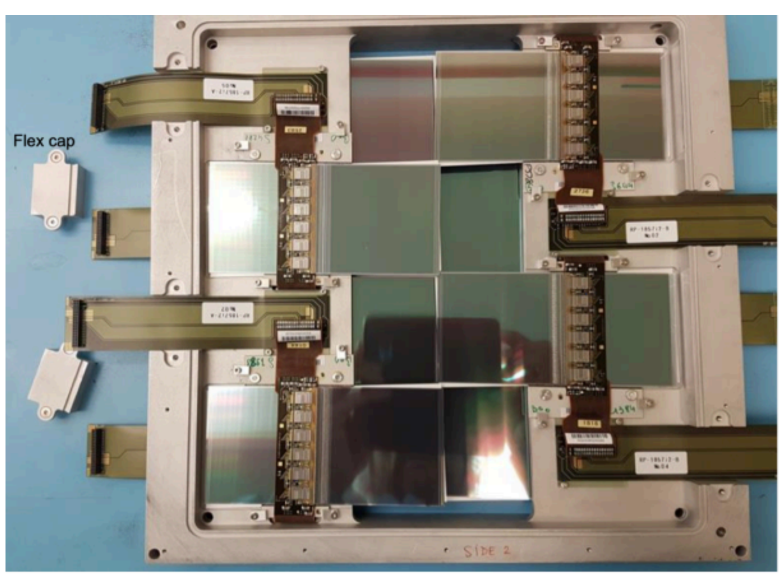
2019/2020 - preparation of FASER location

2019/2020 - detector construction



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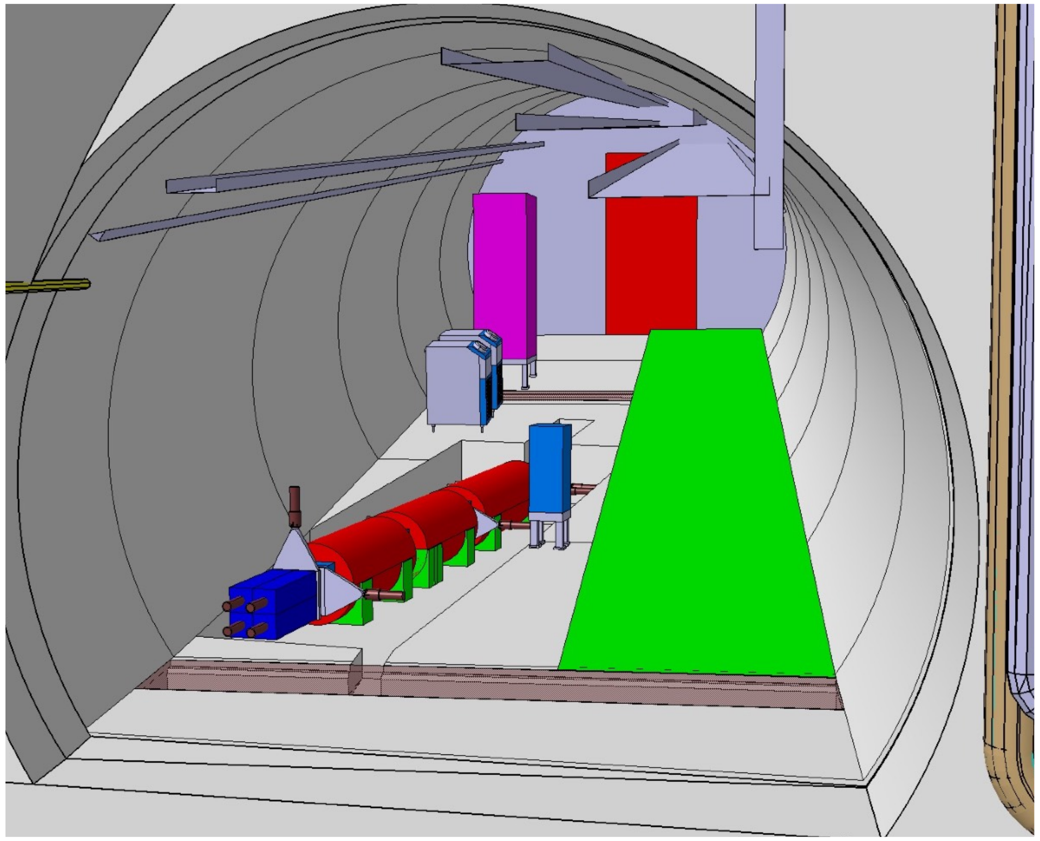
FASER installation- **07/2020**

data collection - **2021-2023**

FASER 2 Upgrade - **HL-LHC era**



The FASER collaboration: 64 collaborators, 20 institutions, 8 countries

Henso Abreu (Technion), Yoav Afik (Technion), Claire Antel (Geneva), Akitaka Ariga (Bern), Tomoko Ariga (Kyushu/Bern), Florian Bernlochner (Bonn), Jamie Boyd (CERN), Lydia Brenner (CERN), Dave Casper (UC Irvine), Franck Cadoux (Geneva), Xin Chen (Tsinghua), Andrea Coccaro (INFN), Candan Dozen (Tsinghua), Yannick Favre (Geneva), Deion Fellers (Oregon), Jonathan Feng (UC Irvine), Didier Ferrere (Geneva), Iftah Galon (Rutgers), Stephen Gibson (Royal Holloway), Sergio Gonzalez-Sevilla (Geneva), Shih-Chieh Hsu (Washington), Zhen Hu (Tsinghua), Peppe Iacobucci (Geneva), Sune Jakobsen (CERN), Enrique Kajomovitz (Technion), Felix Kling (SLAC), Umut Kose (CERN), Susanne Kuehn (CERN), Helena Lefebvre (Royal Holloway), Lorne Levinson (Weizmann), Ke Li (Washington), Jinfeng Liu (Tsinghua), Chiara Magliocca (Geneva), Josh McFayden (CERN), Sam Meehan (CERN), Dimitar Mladenov (CERN), Mitsuhiro Nakamura (Nagoya), Toshiyuki Nakano (Nagoya), Marzio Nessi (CERN), Friedemann Neuhaus (Mainz), Hidetoshi Otono (Kyushu), Carlo Pandini (Geneva), Hao Pang (Tsinghua), Brian Petersen (CERN), Francesco Pietropaolo (CERN), Michaela Queitsch-Maitland (CERN), Filippo Resnati (CERN), Jakob Salfeld-Nebgen (CERN), Osamu Sato (Nagoya), Paola Scampoli (Bern), Kristof Schmieden (CERN), Matthias Schott (Mainz), Anna Sfyrla (Geneva), Savannah Shively (UC Irvine), Jordan Smolinsky (Florida), Yosuke Takubo (KEK), Ondrej Theiner (Geneva), Eric Torrence (Oregon), Sebastian Trojanowski (Sheffield), Serhan Tufanli (CERN), Dengfeng Zhang (Tsinghua), Gang Zhang (Tsinghua)

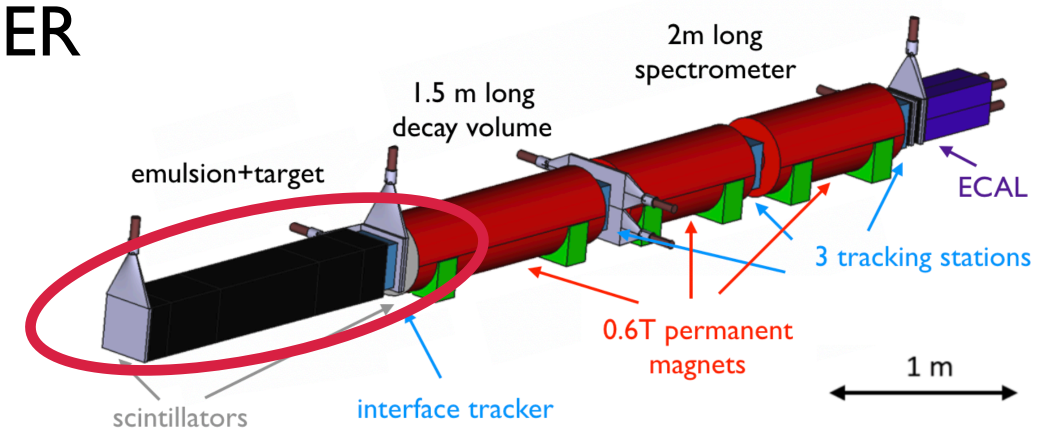
CERN · The University Of Sheffield. · KYUSHU UNIVERSITY · UC IRVINE · UNIVERSITÄT BERN · Technion Israel Institute of Technology · NAGOYA UNIVERSITY · RUTGERS THE STATE UNIVERSITY OF NEW JERSEY · UNIVERSITÉ DE GENÈVE · מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE · KEK · UNIVERSITY of WASHINGTON · JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U · INFN · 清華大学 Tsinghua University · UNIVERSITY OF OREGON · UNIVERSITÄT BONN · ROYAL HOLLOWAY UNIVERSITY OF LONDON · SLAC NATIONAL ACCELERATOR LABORATORY · UF UNIVERSITY of FLORIDA

FASERν Detector

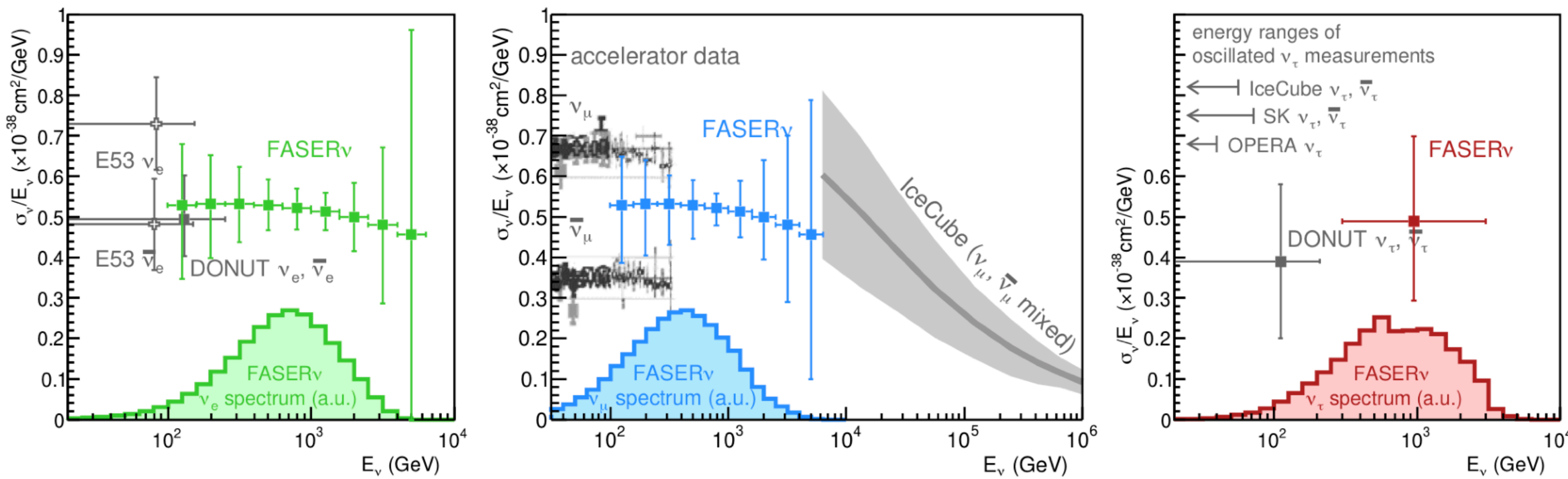
- neutrinos detected from many sources, but not from colliders

- many neutrinos at LHC produced in π, K, D meson decay
  → ATLAS provides intense energetic collimated neutrino beam towards FASER
  * ~10^{12} neutrino in LHC Run 3 * E~TeV. * θ ~ mrad

- dedicated FASERν neutrino detector in front of FASER
  * 25cm x 25cm x 1.3m emulsion detector
  * tungsten target with 1.2 ton mass
  * ~ 20000 ν_μ, ~ 2000 ν_e, ~ 20 ν_τ



- TeV energy range currently unconstrained
  * this allows to probe neutrino cross sections at TeV for all 3 flavors

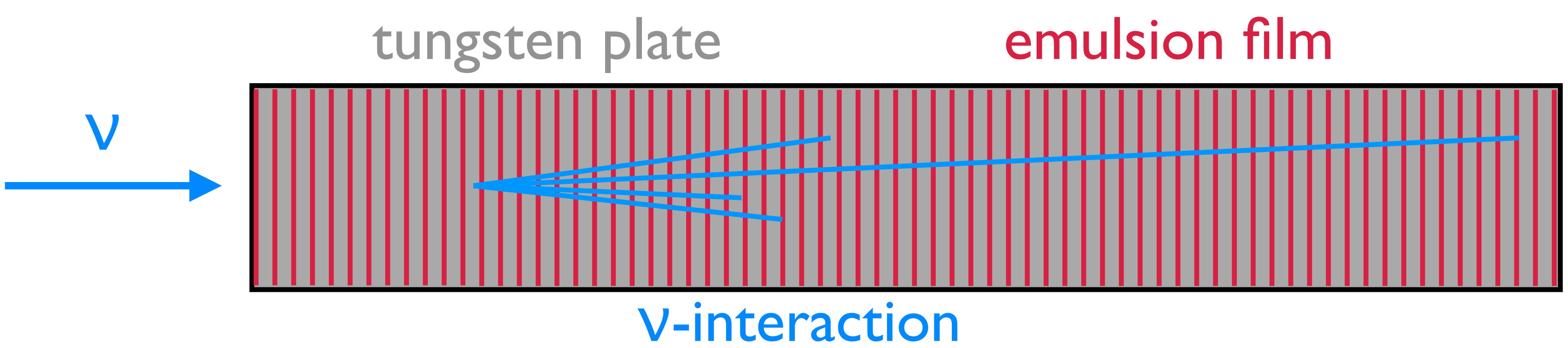


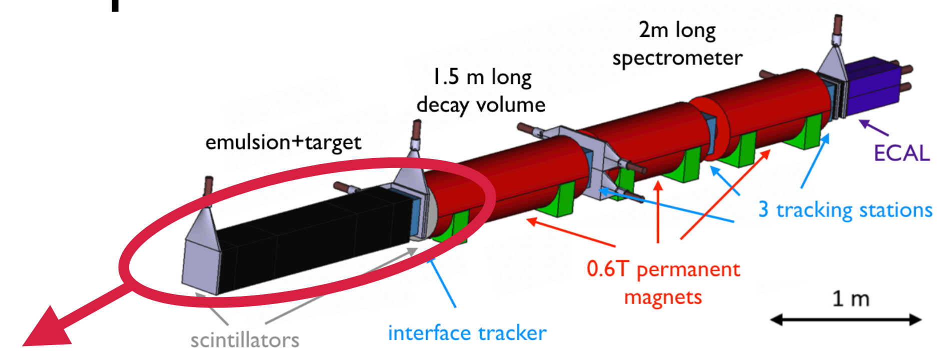
FASERν Detector

FASERν: Detecting and Studying High-Energy Collider Neutrinos

[FASER Collaboration, 1708.09389], [FASER Collaboration, 2001.03073]

- FASERν: 1000 emulsion films interleaved with 1mm tungsten plates
  * sensitive to neutrino interactions

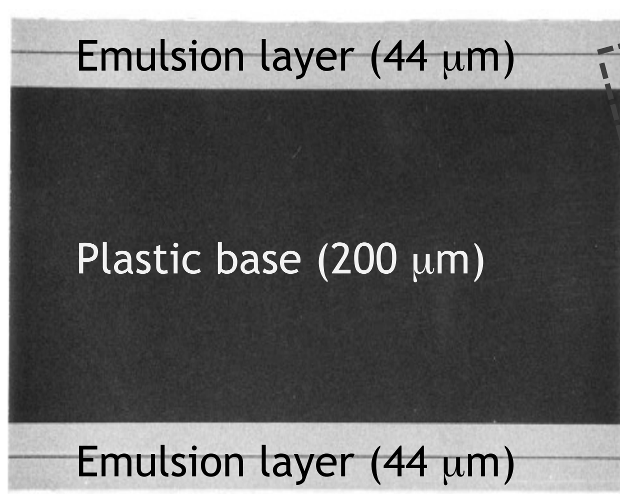




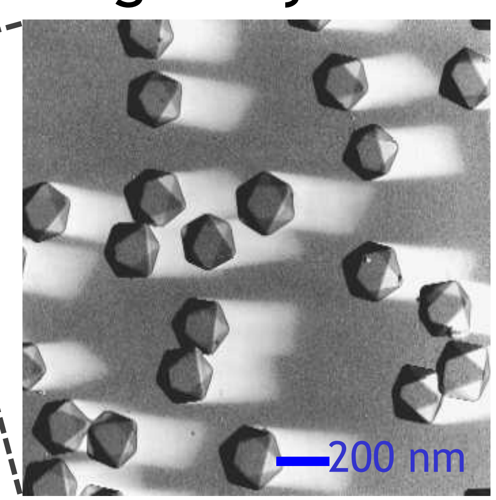
- emulsion detectors are 3D tracking devices with 50 nm spatial precision
  * used by many other neutrino experiments: CHORUS, DONUT, OPERA,

Emulsion film

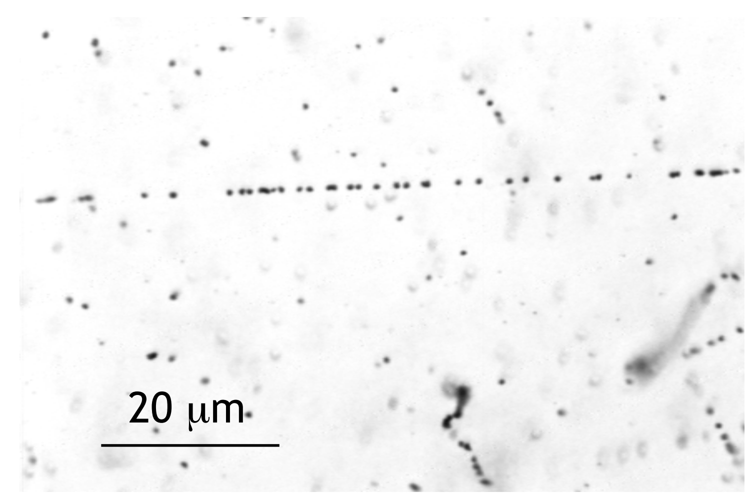
Cross-sectional view



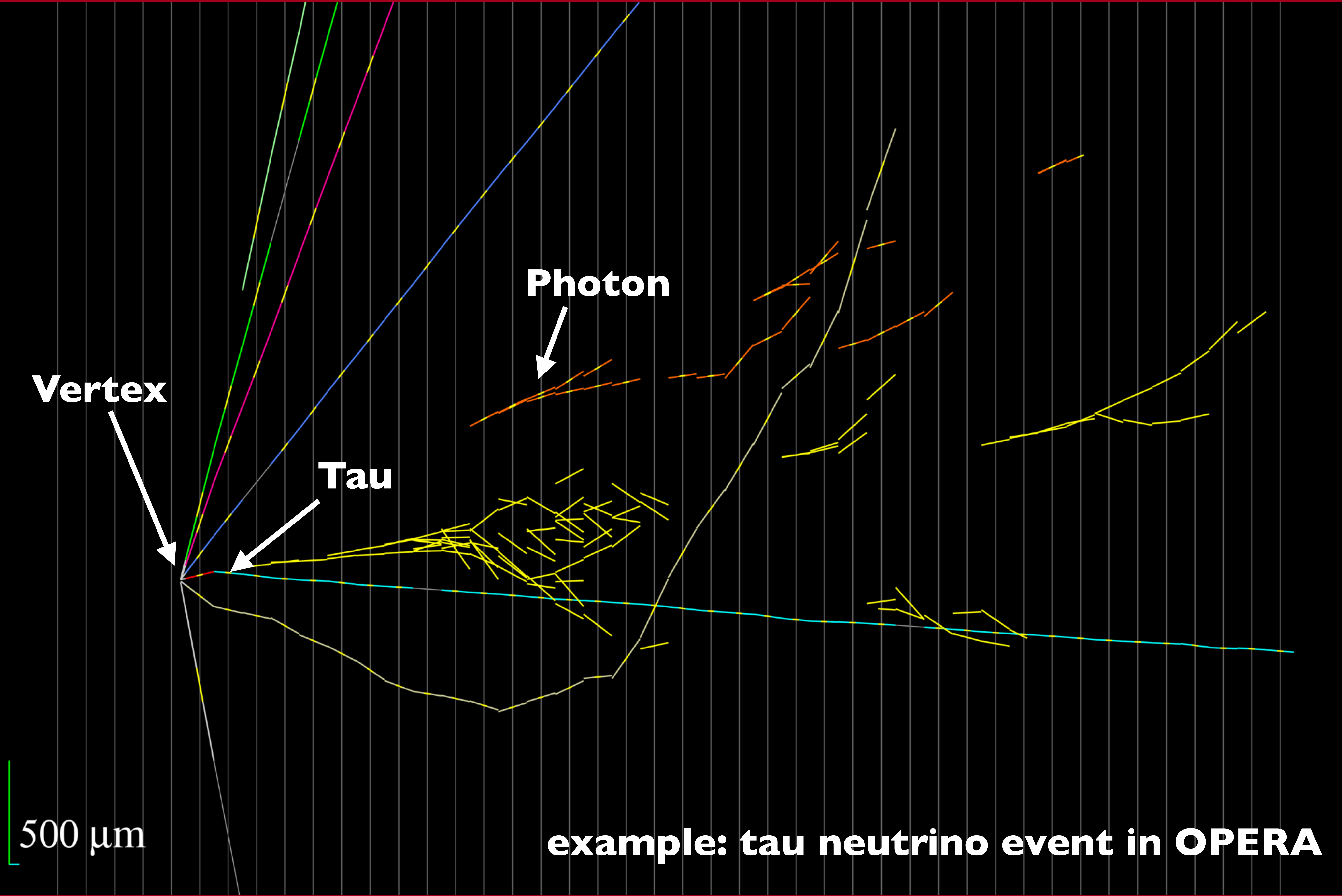
AgBr crystal



Track in emulsion film

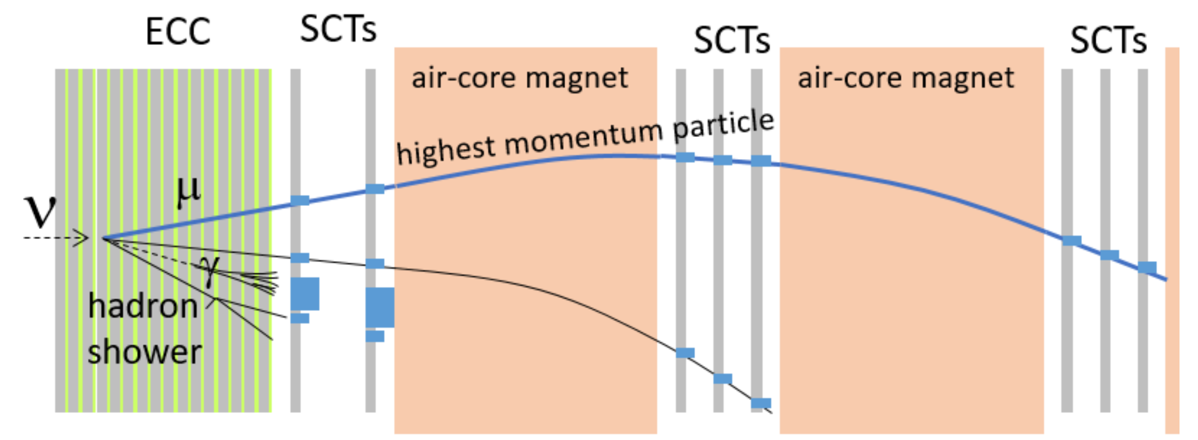


FASERν Detector



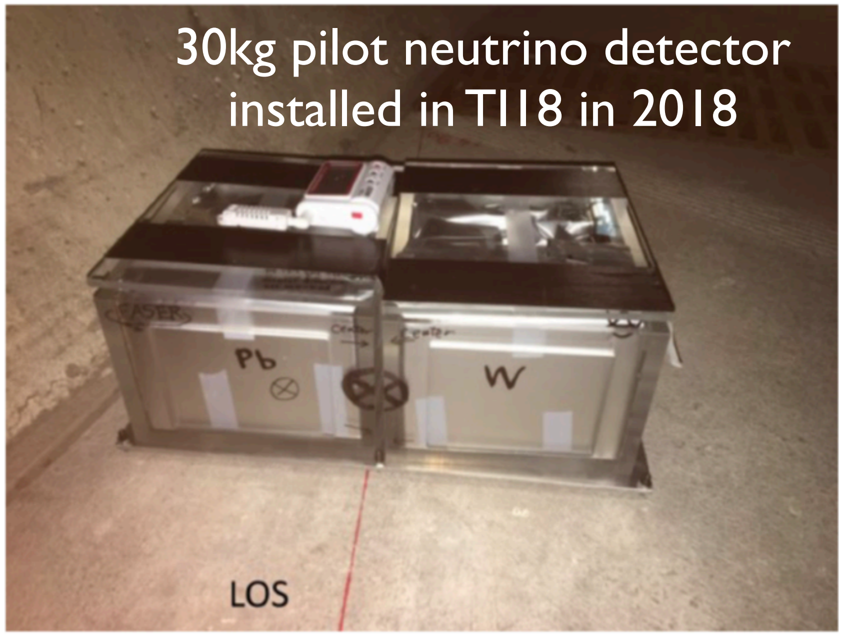
FASERν Detector

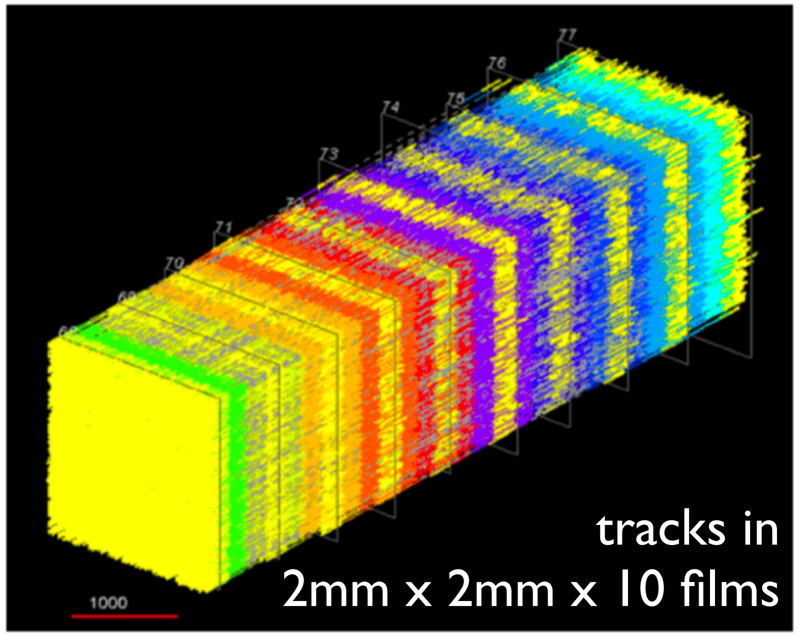
- detector performance has been studied
  * flavor identification
  * vertex finding efficiency: ~80%
  * energy resolution: ~30%

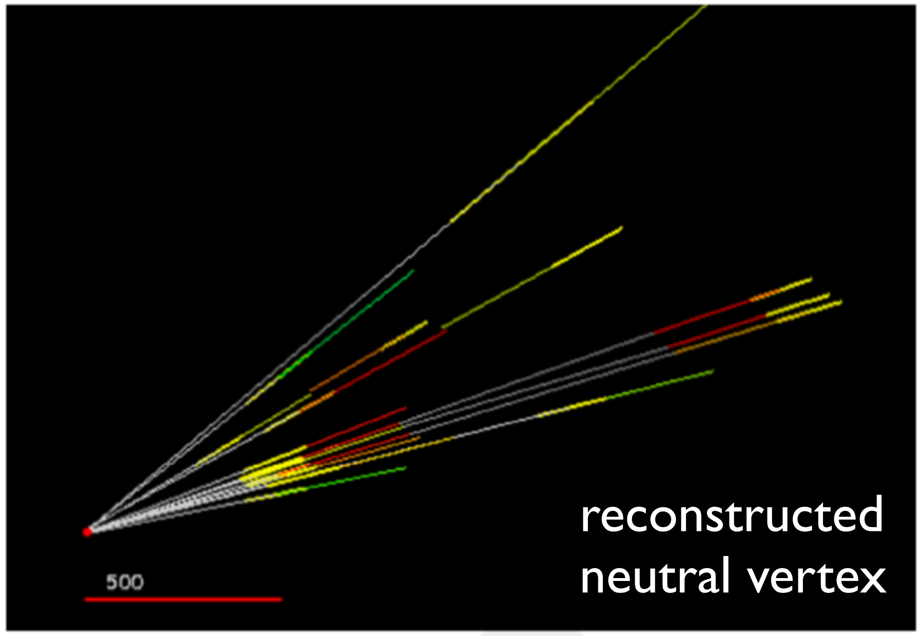


- global reconstruction with the FASER detector
  * distinguish neutrino / anti-neutrino
  * improve neutrino energy reconstruction
  * background rejection

- pilot detector data is currently analyzed
  * 30 kg detector was installed in TI18, 12.5 fb^{-1} of data collected 2018
  * goal: first neutrino detection at the LHC







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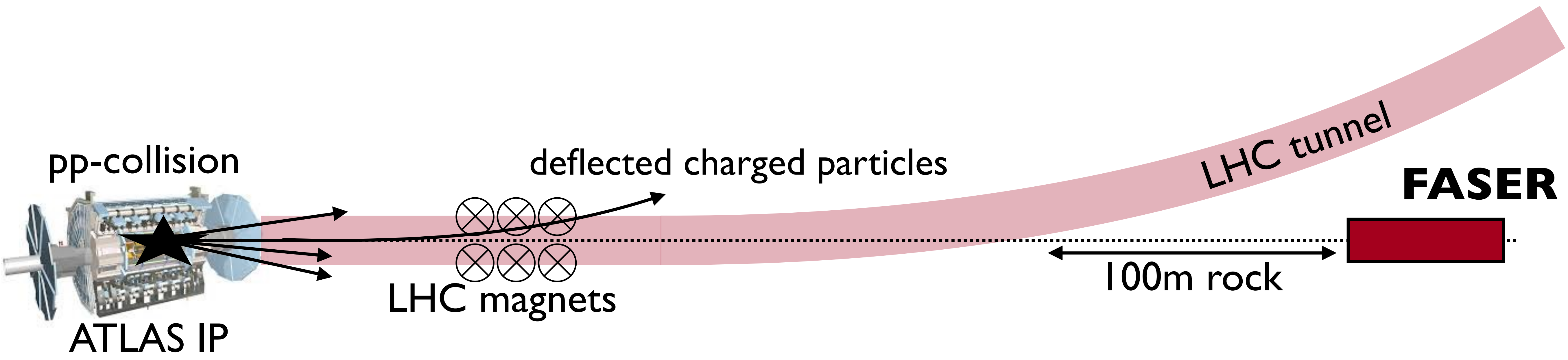


neutrino production

validation of hadronic interaction models

parton distribution functions

atmospheric neutrino background at neutrino telescopes

neutrino propagation

sterile neutrino oscillations

Physics potential studies have just started.

neutrino interactions

neutrino cross section measurements

events shapes and kinematics

heavy flavor associated neutrino interactions

Forward Flux Estimates

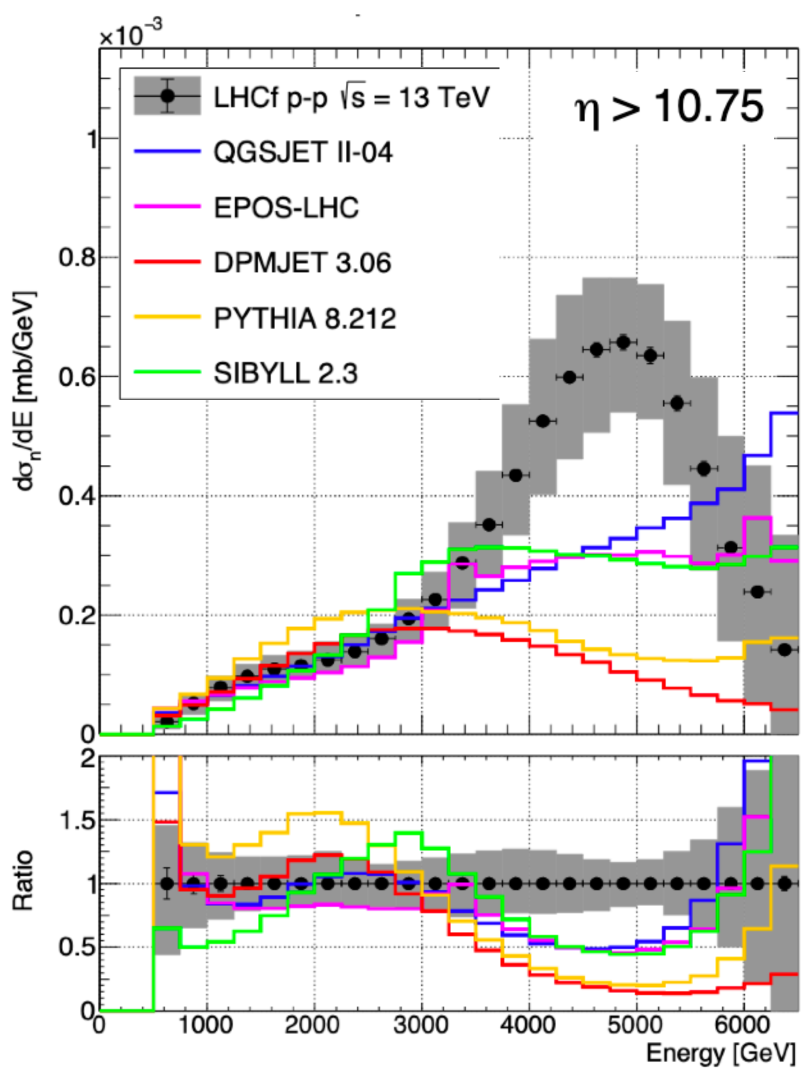
- cross section measurements are limited by neutrino flux uncertainty
  * we need to quantify and reduce these uncertainties

- forward particle production is not described by perturbative QCD, but soft physics
  * use hadronic interaction models

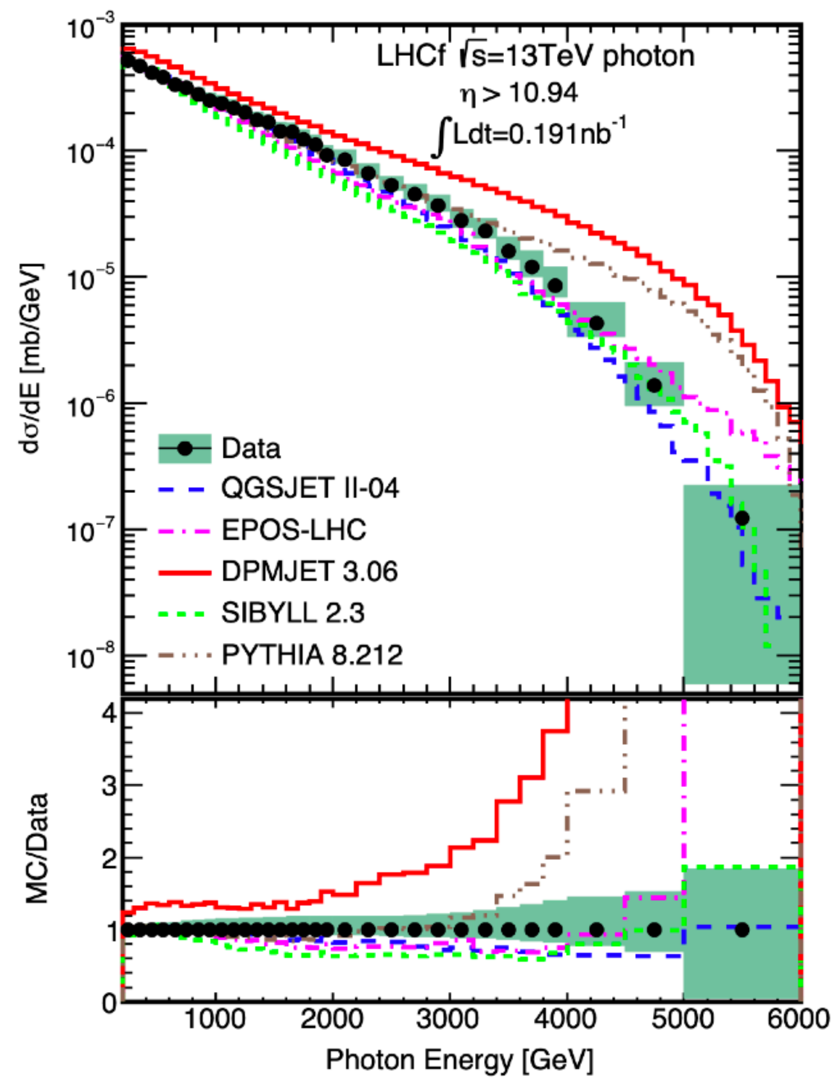
- simulators are based on sophisticated modeling of microscopic physics
  * phenomenological parameters need to be tuned
  * include tuning uncertainties (similar to PDFs)

→ develop dedicated forward physics tune using forward data

FASER measurements might help to better constrain these models



[LHCf: 2003.02192]



[LHCf: 1703.07678]

Summary and Outlook

FASER
- newest experiment at the LHC
- quick, small and inexpensive
- funded and approved

Envisioned Timeline
- build/install FASER in LS2 (2019-20)
- take data during Run 3 (2021-23, 150 fb^{-1})
- upgrade to FASER 2 in LS3 for HL-LHC

Physics:
- search for light long-lived particles at LHC
- neutrino measurements at TeV energies
- and more unexplored opportunities …

SIMONS FOUNDATION

HEISING-SIMONS FOUNDATION

Many thanks to the Heising-Simons Foundation, the Simons Foundation, and to CERN for invaluable support

For more information, see
https://twiki.cern.ch/twiki/bin/view/FASER/WebHome

We look forward to feedback and suggestions

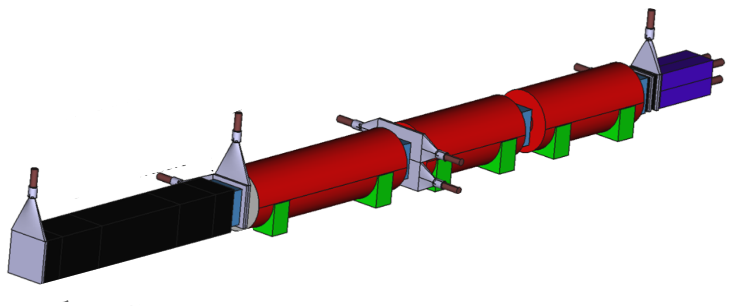
Acknowledgements

The FASER Collaboration gratefully acknowledges the contributions of many people.

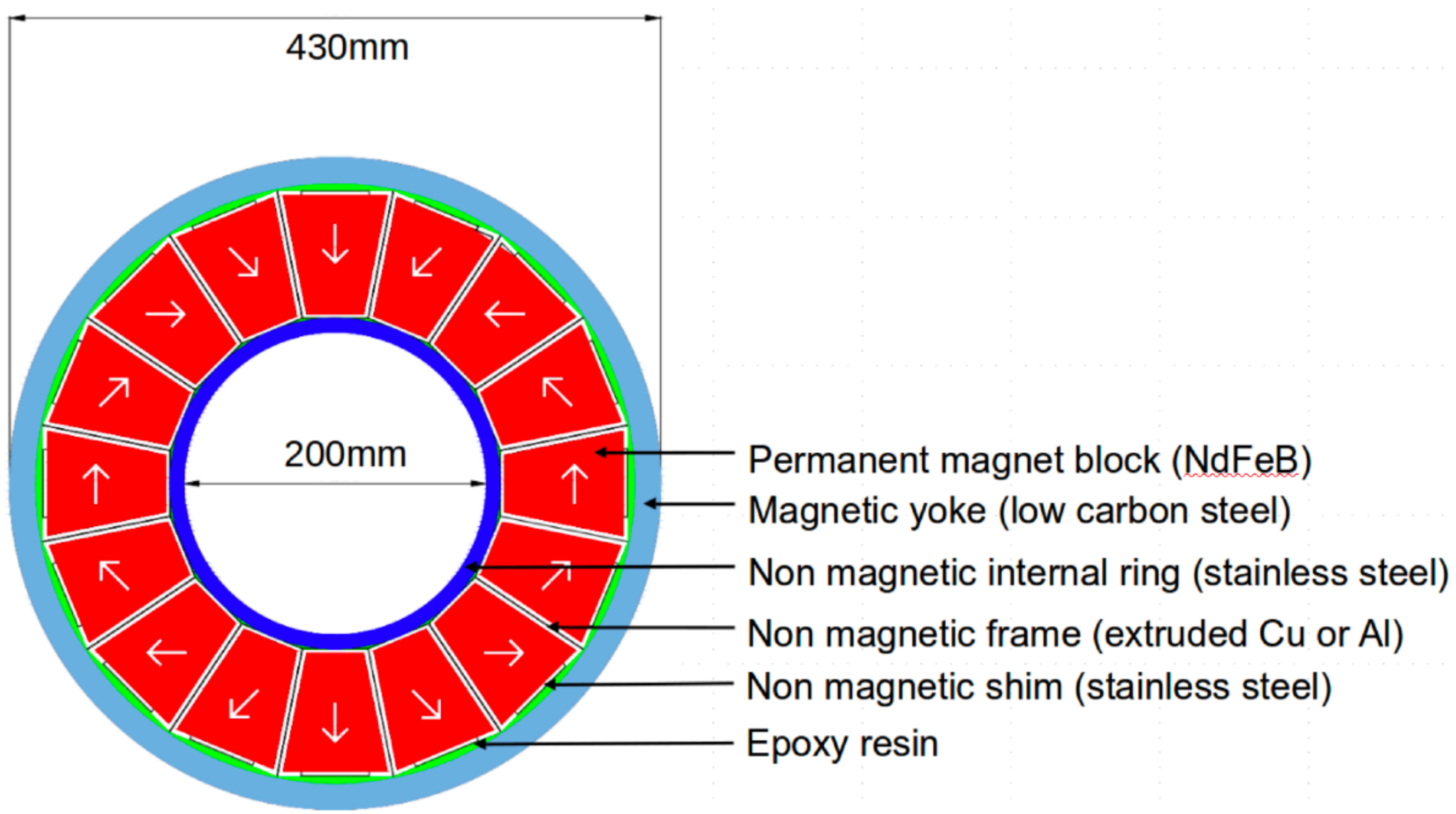
We are grateful to the ATLAS SCT project and the LHCb Calorimeter project for letting us use spare modules as part of the FASER experiment. In addition, FASER gratefully acknowledges invaluable assistance from many people, including the CERN Physics Beyond Colliders study group; the LHC Tunnel Region 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); Jonathan Gall, John Osborne (civil engineering); Caterina Bertone, Serge Pelletier, Frederic Delsaux (transport); Francesco Cerutti, Marta Sabaté-Gilarte, Andrea Tsinganis (FLUKA simulation and background characterization);Pierre Thonet, 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); Salvatore Danzeca (Radiation Monitoring);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); Liam Dougherty (integration);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 Mike Lamont, Fido Dittus, Andreas Hoecker, Andy Lankford, Ludovico Pontecorvo, Michel Raymond, Christoph Rembser, Stefan Schlenker (useful discussions).

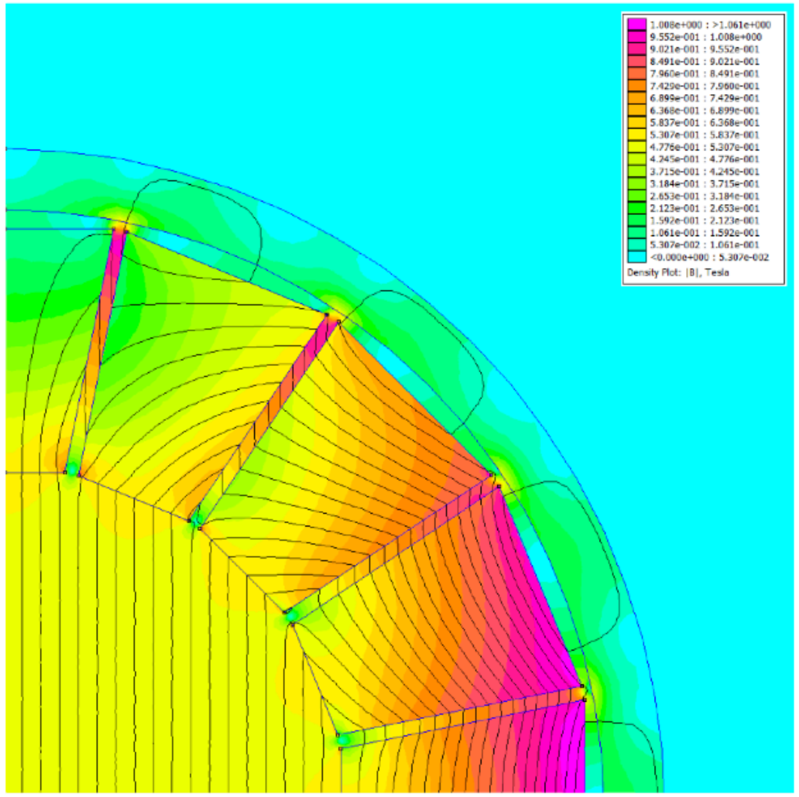
Backup

FASER Magnet

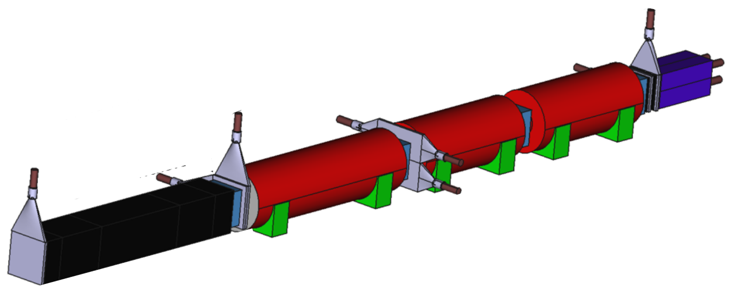


- 0.6T permanent dipole magnets
- Halbach array design
  - LOS to passes through the magnet center
  - minimum digging to the floor in TI12
  - minimized needed services (power, cooling etc..)
- to be constructed by the CERN magnet group

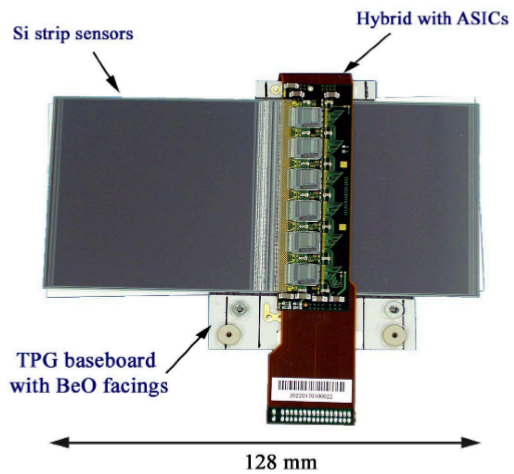




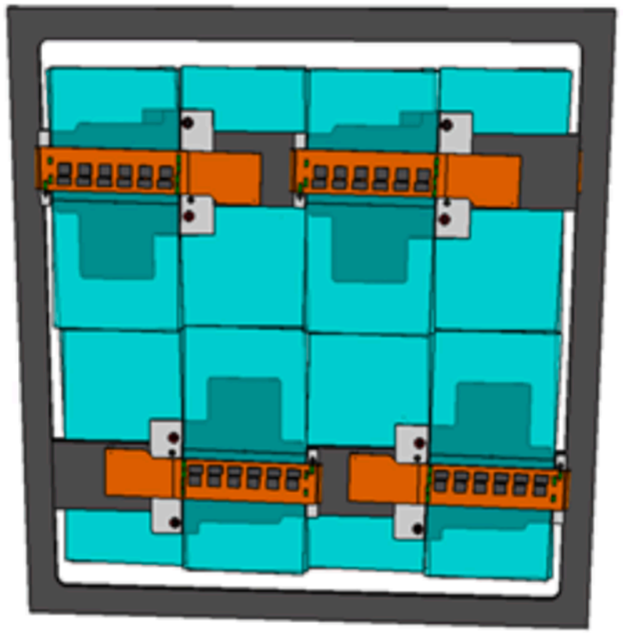
FASER Tracker



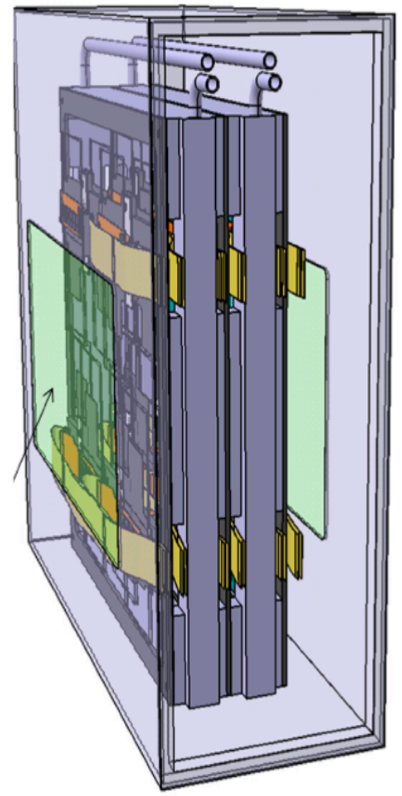
- 3 tracking stations, each with 3 tracking layers
- double sided silicon micro-strip detectors
- ATLAS SCT spare modules will be used
  - 80µm strip pitch, 40mrad stereo angle
  - many thanks to the ATLAS SCT collaboration!
  - 72 SCT modules for the full tracker



SCT module

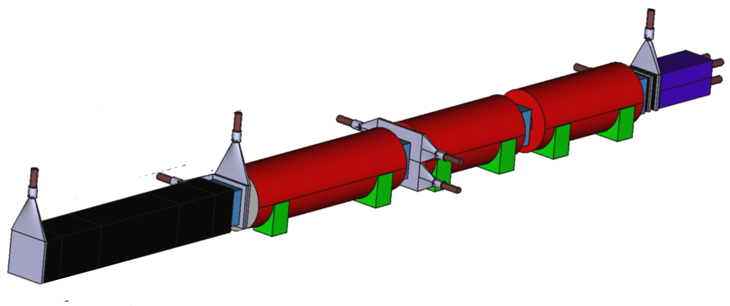


Tracking layer



Tracking station

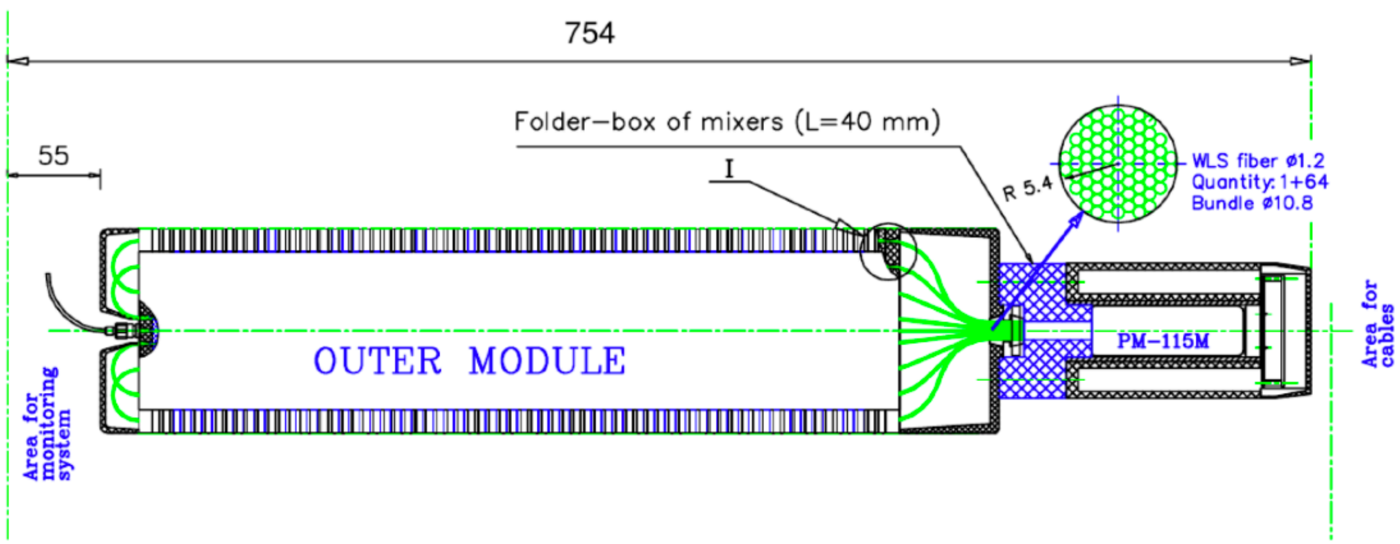
FASER ECAL

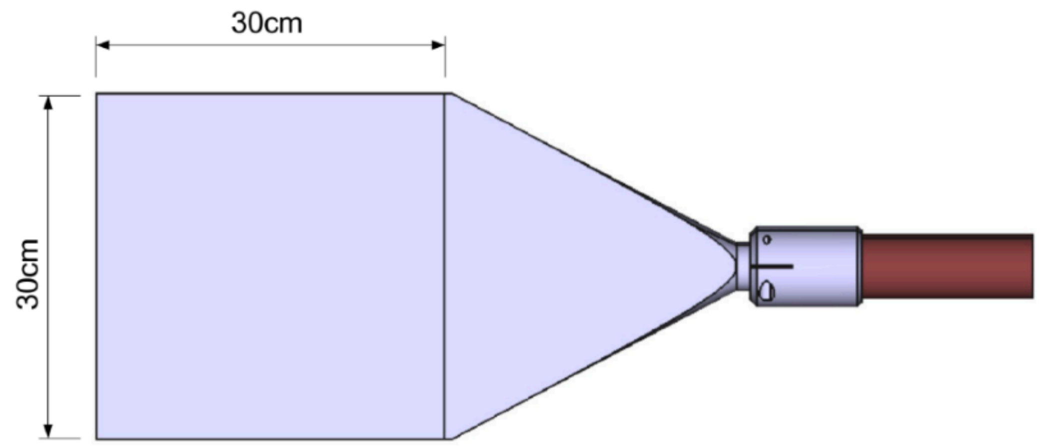


- EM energy measuring / triggering / electron/photon identification
- FASER will use spare LHCb outer ECAL modules
  - ~1% energy resolution for 1 TeV electrons
  - Many thanks for LHCb for allowing us to use these!

FASER Scintillators

- vetoing charged particles entering the decay volume / triggering
- to be produced at CERN scintillator lab

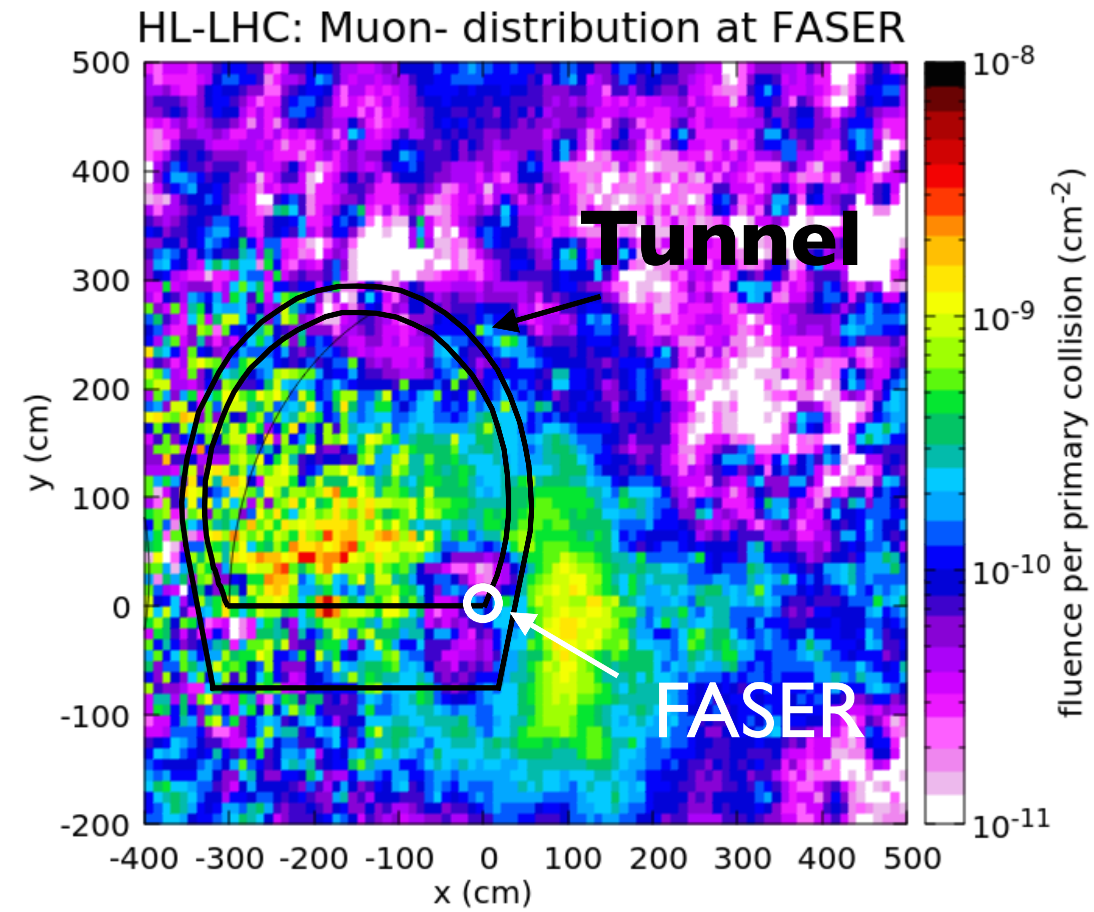




General Considerations

- LLP/neutrino signals have TeV energies, come from ATLAS IP
- shielding: natural (rock) and LHC infrastructure (magnets, absorbers)
- only muons/neutrino can transport TeV energies through ~100m rock

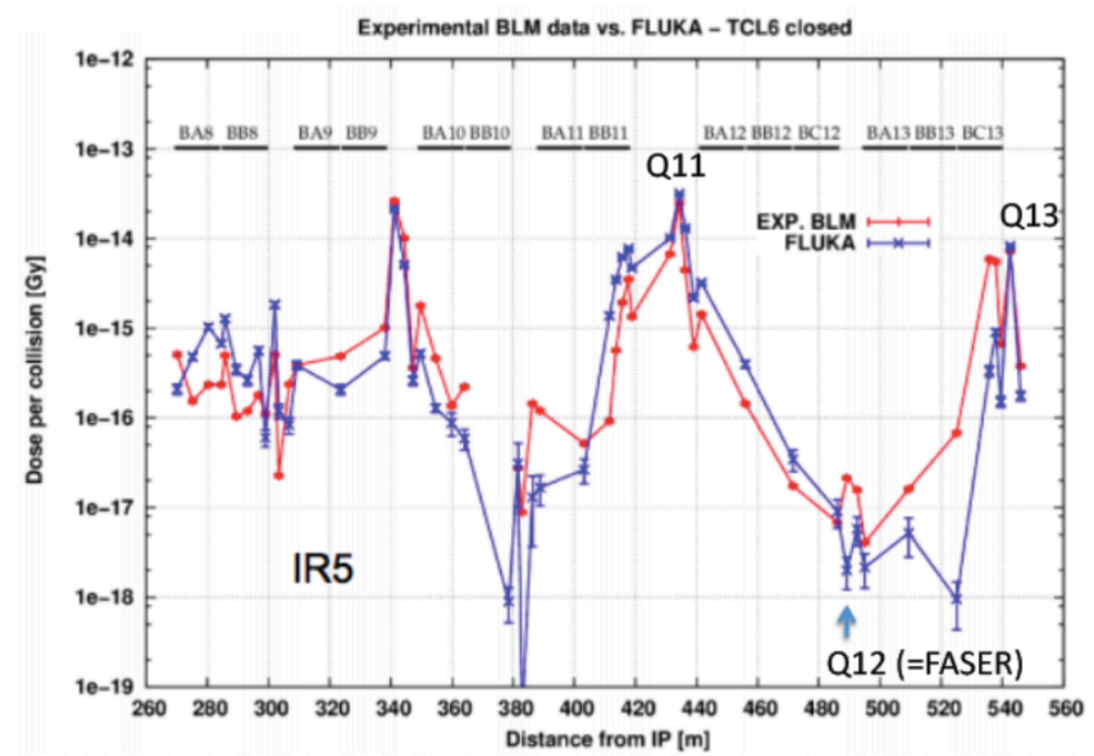
→ FASER's location is very quiet



FLUKA simulation (by CERN STI group)

- FASER in remarkable quite spot
- estimated muon flux from IP: $2{\cdot}10^4$ fb/cm^2
- HE particles from beam-gas collisions and proton losses near FASER are negligible
- other HE particles produced in muon radiative processes

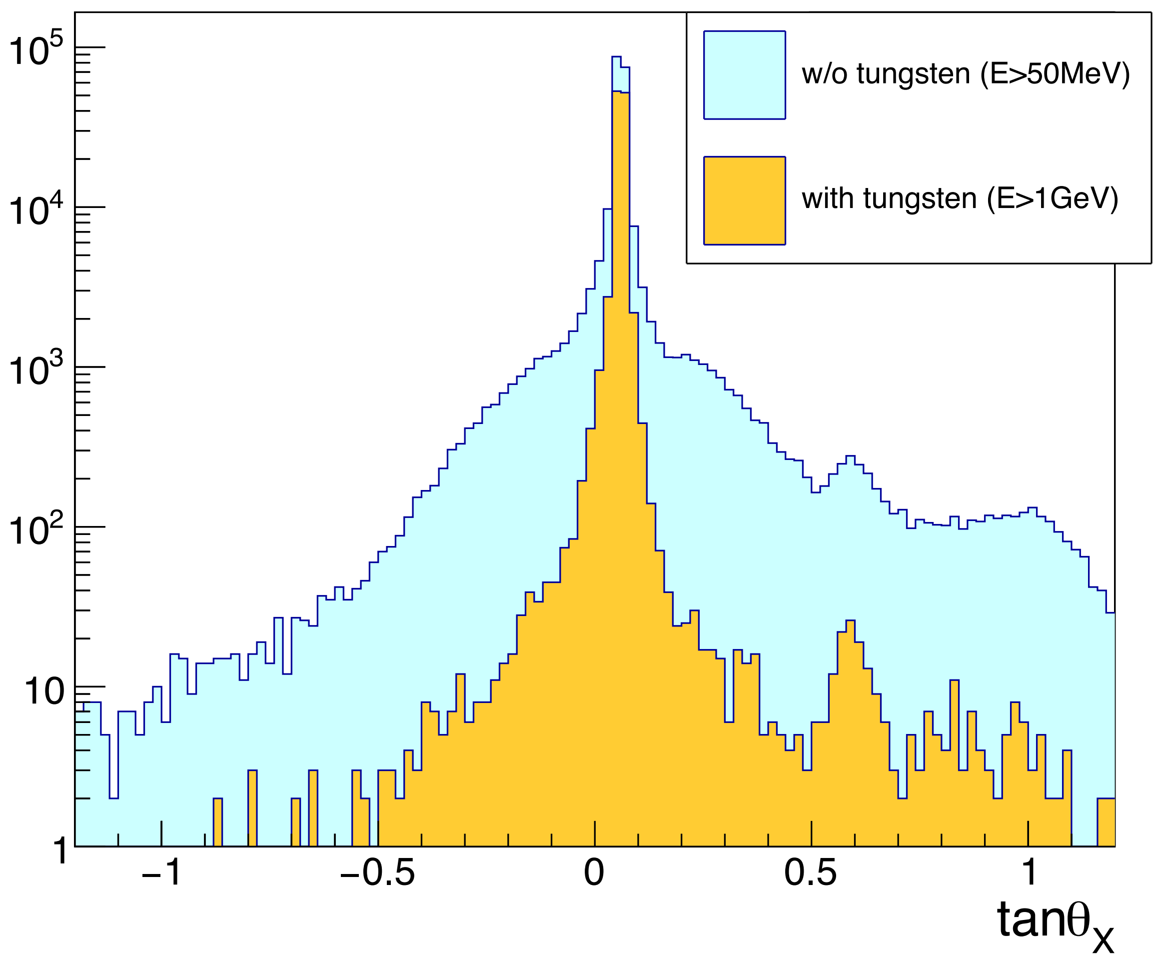
→ use scintillator to veto muons for LLP searches



Sabate-Gilarte, Cerutti, Tsinganis (2018)

In-Situ Measurements

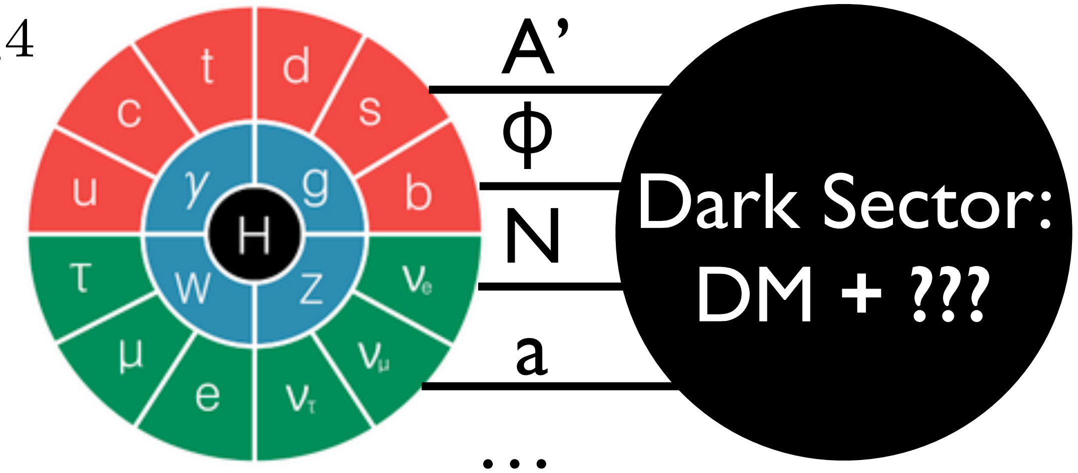
- BatMon radiation monitor:
  * low-energy radiation levels are promisingly low
- emulsion detector installed in 2018 in both TI18 and TI12
  * consistent with FLUKA simulations
  * more data analysis on-going



Backup: Dark Photons

Motivation

- Dark matter solid evidence for new particles
  * thermal freeze out: $\Omega_{DM} \sim 1/\langle\sigma v\rangle \sim m^2/g^4$
  * WIMP miracle: $m \sim m_{weak},\ g \sim g_{weak}$
  * light DM (m~GeV) requires new mediators
    → $m < m_{weak},\ g < g_{weak}$
    → light weakly coupled particles
- Anomalies: muon g-2, Be-8



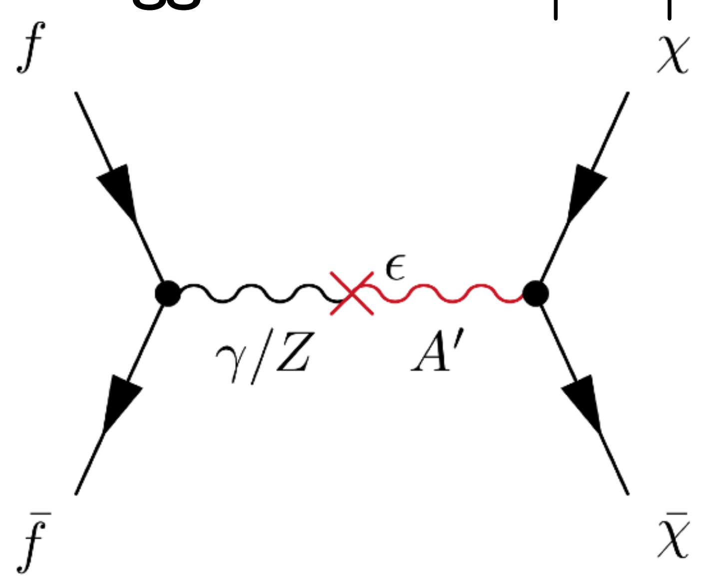
Prominent examples

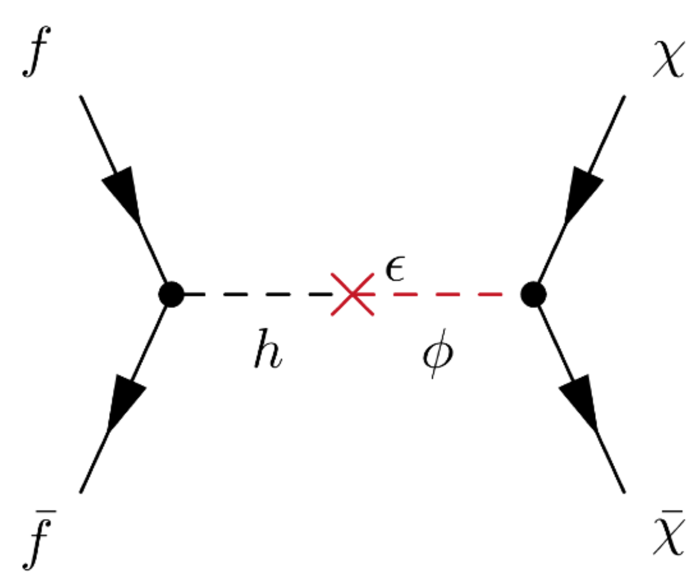
Dark Photon Portal: $\epsilon F^{\mu\nu} F'_{\mu\nu}$

Dark Higgs Portal: $\epsilon |H|^2 \phi^2$

Neutrino Portal: $yLHN$

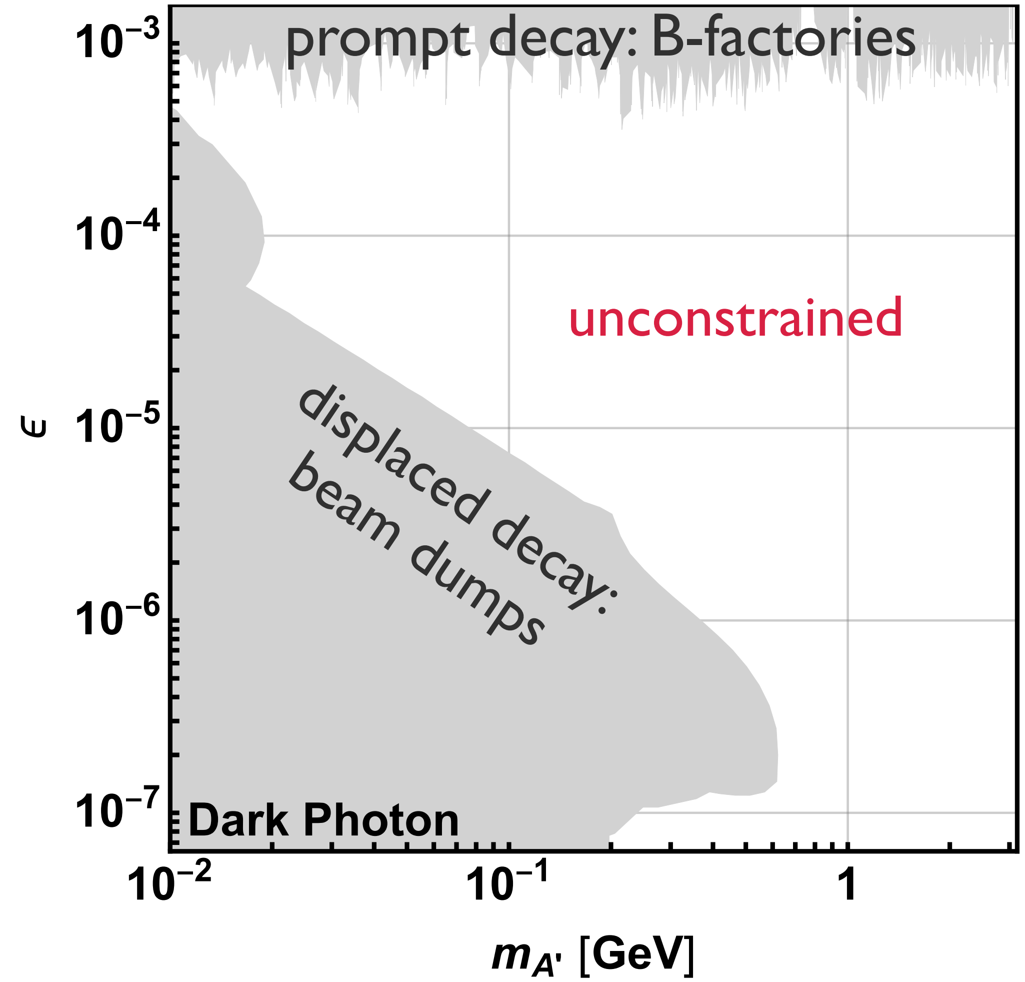
Axion Portal: $gaF^{\mu\nu}\tilde{F}_{\mu\nu}$





Long Lived Particles

- if $m_{A'} < 2 m_{DM}$
  - → Mediator decays to SM
  - → Long Lived Particle



Dark Photons

- (broken) dark U(1) gauge group mixing with the SM photon

$$\mathcal{L} \subset \epsilon F_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{A'}{}^2 A'_\mu A'^\mu$$

- after field re-definition:

$$\mathcal{L} \subset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{A'}{}^2 A'_\mu A'^\mu + \sum \bar{f}(i \not{\partial} - \epsilon e q_f \not{A}') f$$

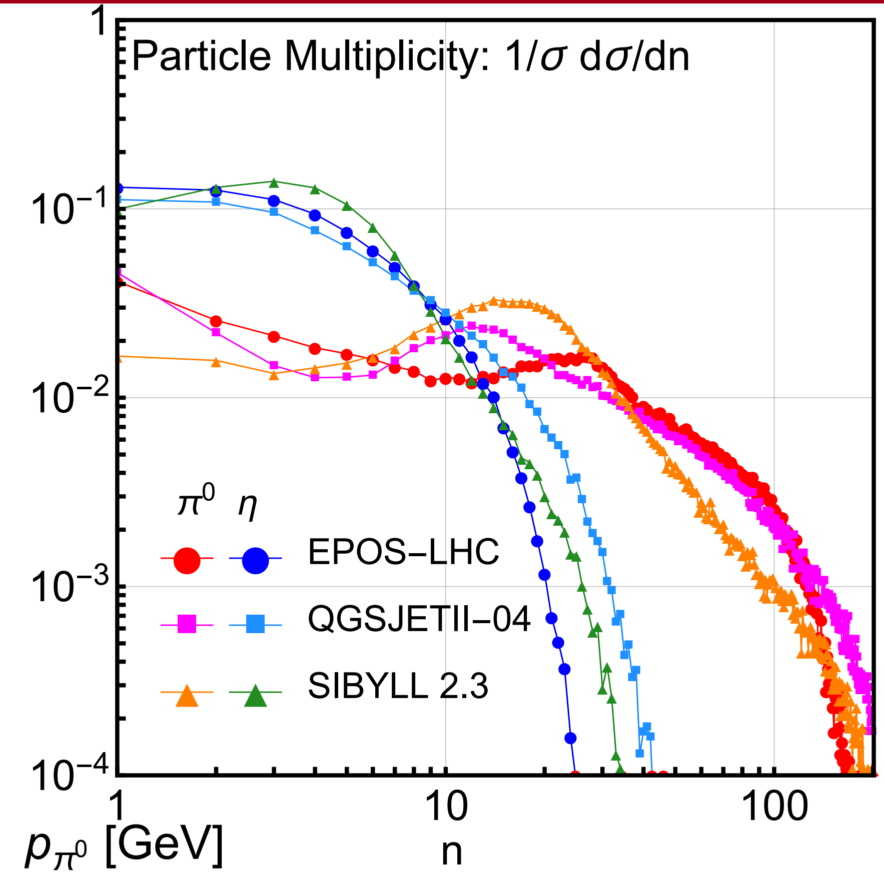
- FASER aims to probe $m_{A'} \sim 10 - 500 \text{ MeV}$ and $\epsilon \sim 10^{-6} - 10^{-4}$

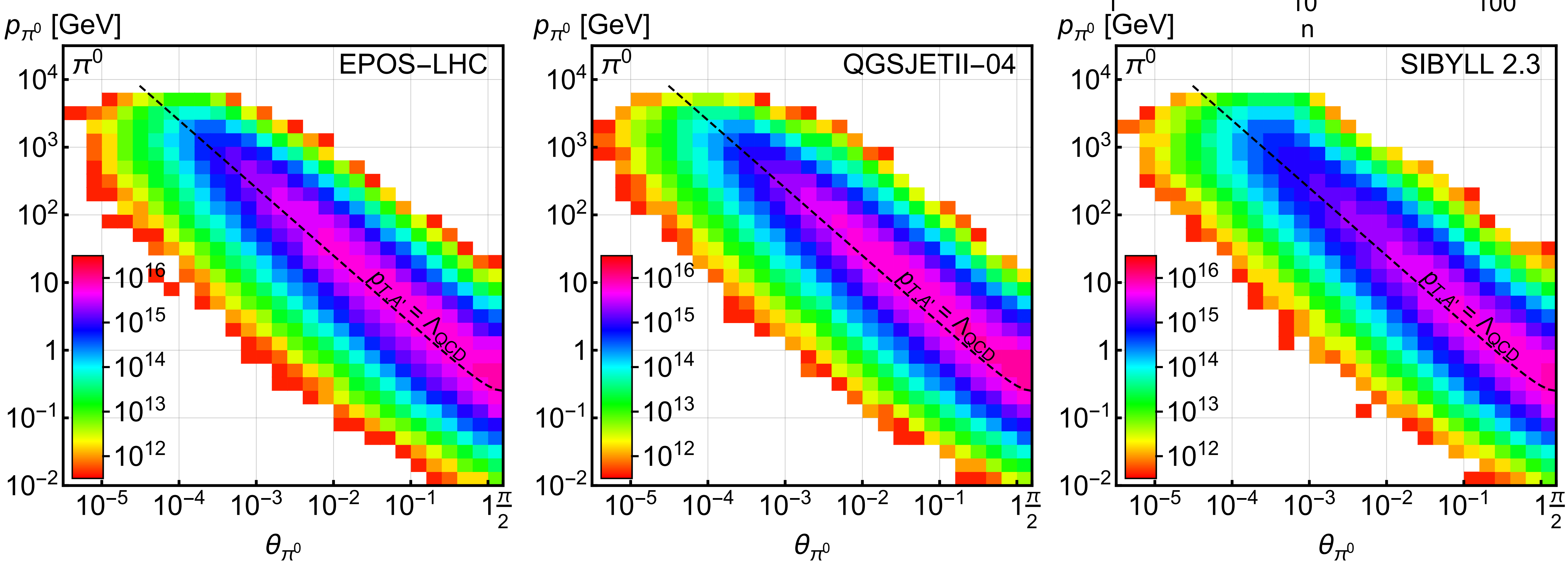
Production Modes

- meson decays: mainly $\pi^0 \to \gamma A'$, $\eta \to \gamma A'$
- proton Bremsstrahlung: $pp \to p A' X$
- (direct production): $q\bar{q} \to g A'$, $qg \to q A'$

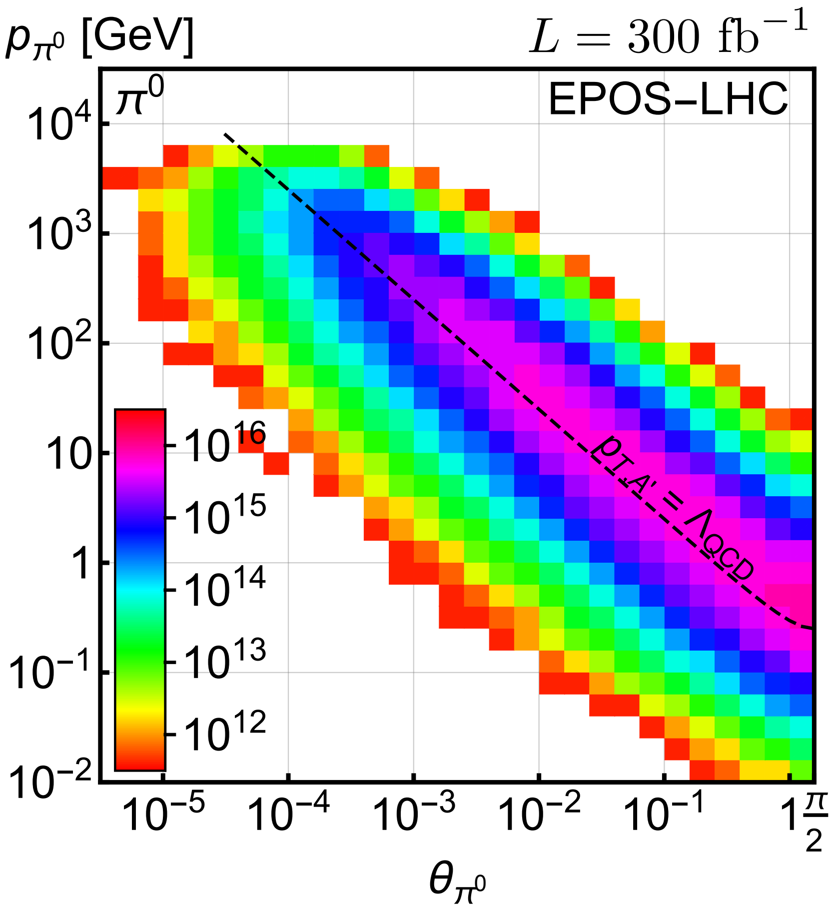
Comparison of Forward Physics Models

- traditionally relied on data from ultra-high-energy cosmic-ray experiments
- new models are tuned to match LHC data (LHCf, ALFA)
- predictions are consistent



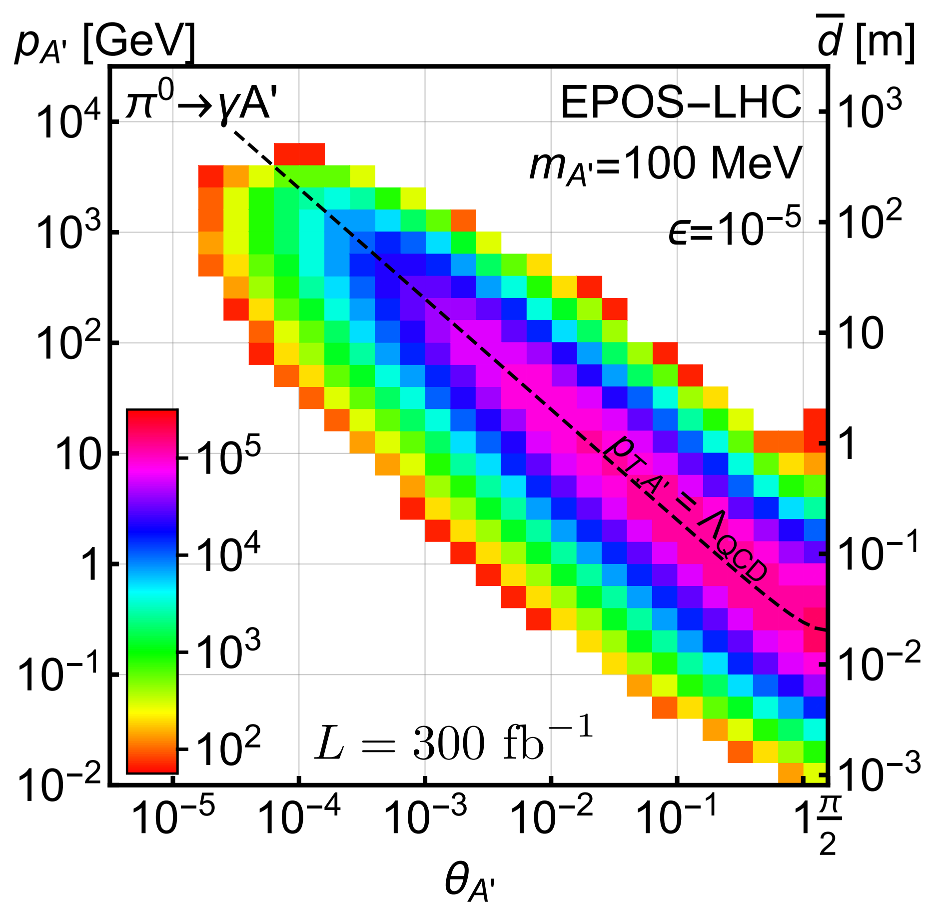


Pions at IP



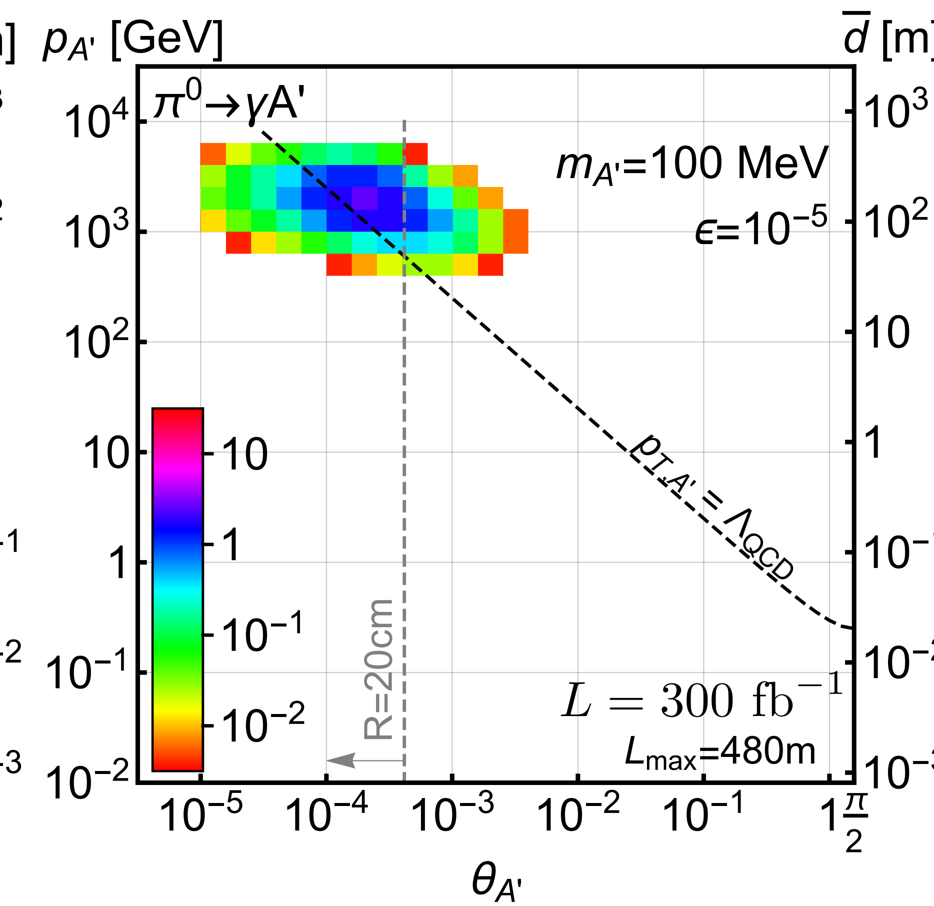
- dedicated hadronic interaction models, grounded on LHC data
- production peaks at pT~ Λ_{QCD}
- enormous event rates N ~ 10^{15} per bin

A' at IP



- production peaks at pT~ Λ_{QCD}
- rates highly suppressed by ε^2 ~ 10^{-10}
- still rates N~10^5 per bin: LHC could be dark a photon factory

A' decay at FASER

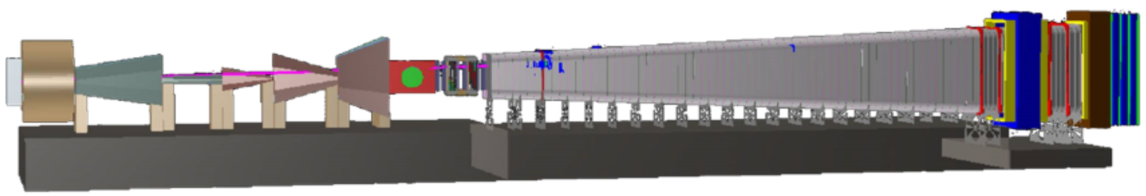


- only highly boosted ~TeV A' arrive at FASER
- rates suppressed by decay requirements
- still rates N~100 signal events within 20cm of beam collision axis

Backup: Other Experiments

Other proposed Experiments for Long Lived Particles

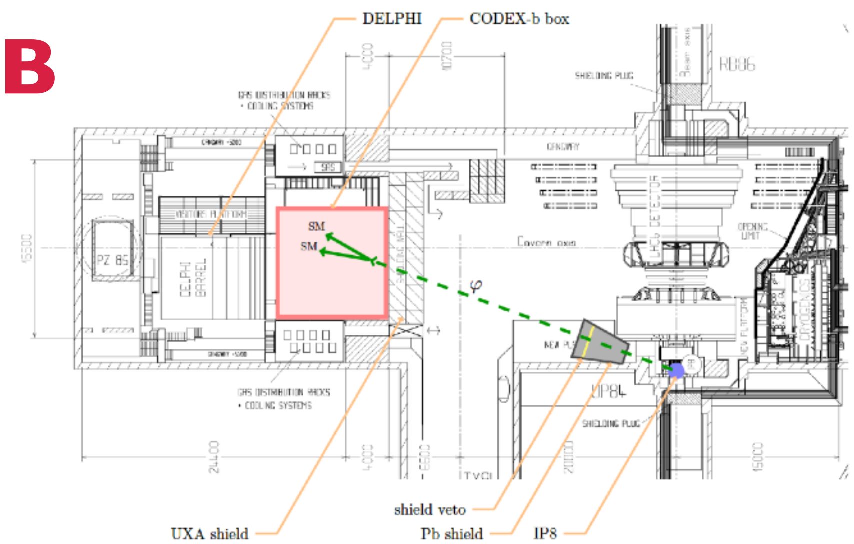
SHiP



~1000 m³, ~$500M

Alekhin et al. (2015)

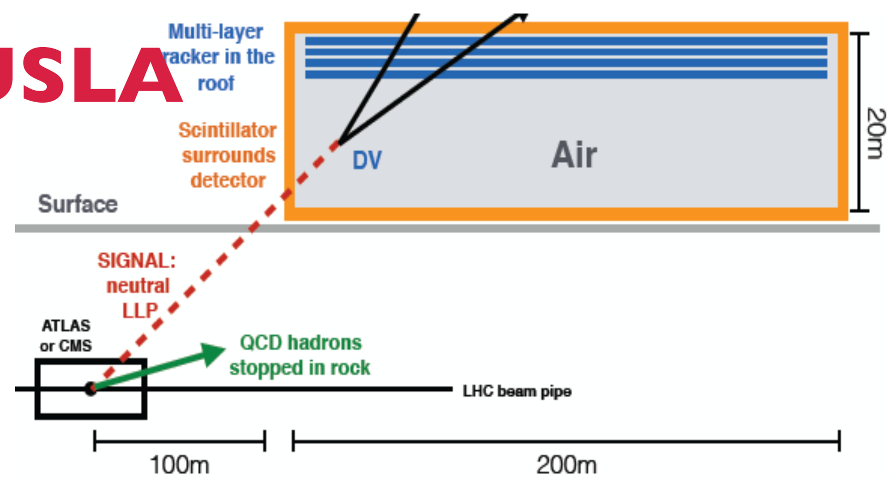
Codex-B



~1000 m³

Gligorov, Knapen, Papucci, Robinson (2016)

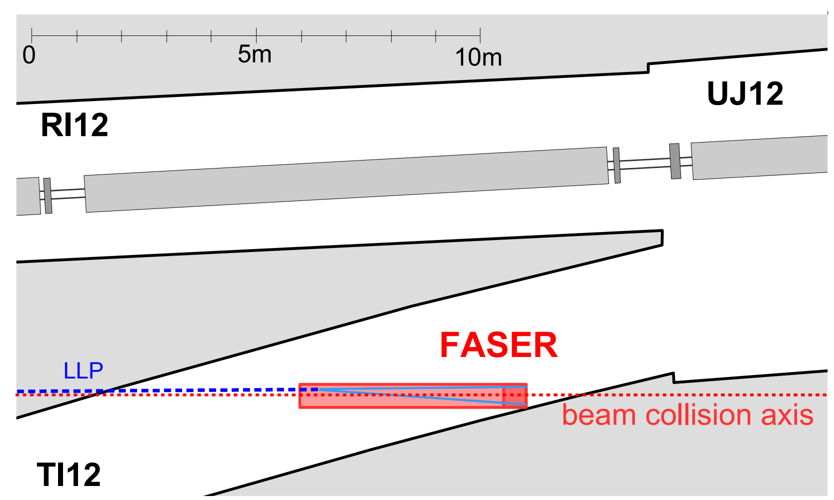
MATHUSLA



~2 10^5 m³ ~ 1 IKEA, ~$100M

Chou, Curtin, Lubatti (2016)

FASER



~1 m³ ~ µIKEA, ~$2M

Feng, Galon, Kling, Trojanowski (2017)