

ForwArd Search ExpeRiment at the LHC

Jamie Boyd (CERN) on behalf of the FASER Collaboration

CERN Seminar

16/4/2019

Supported by:

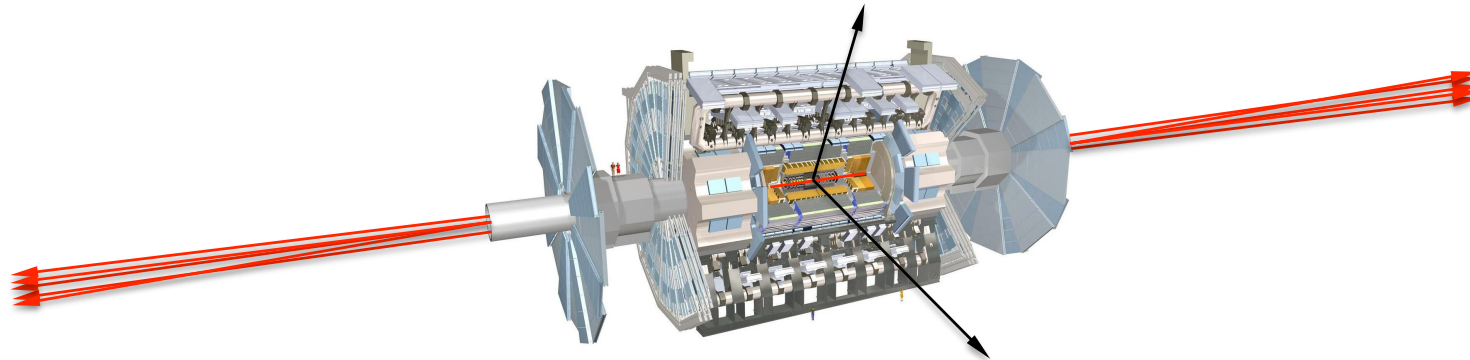


FASER website:

<https://twiki.cern.ch/twiki/bin/view/FASER/WebHome>

FASER: THE IDEA

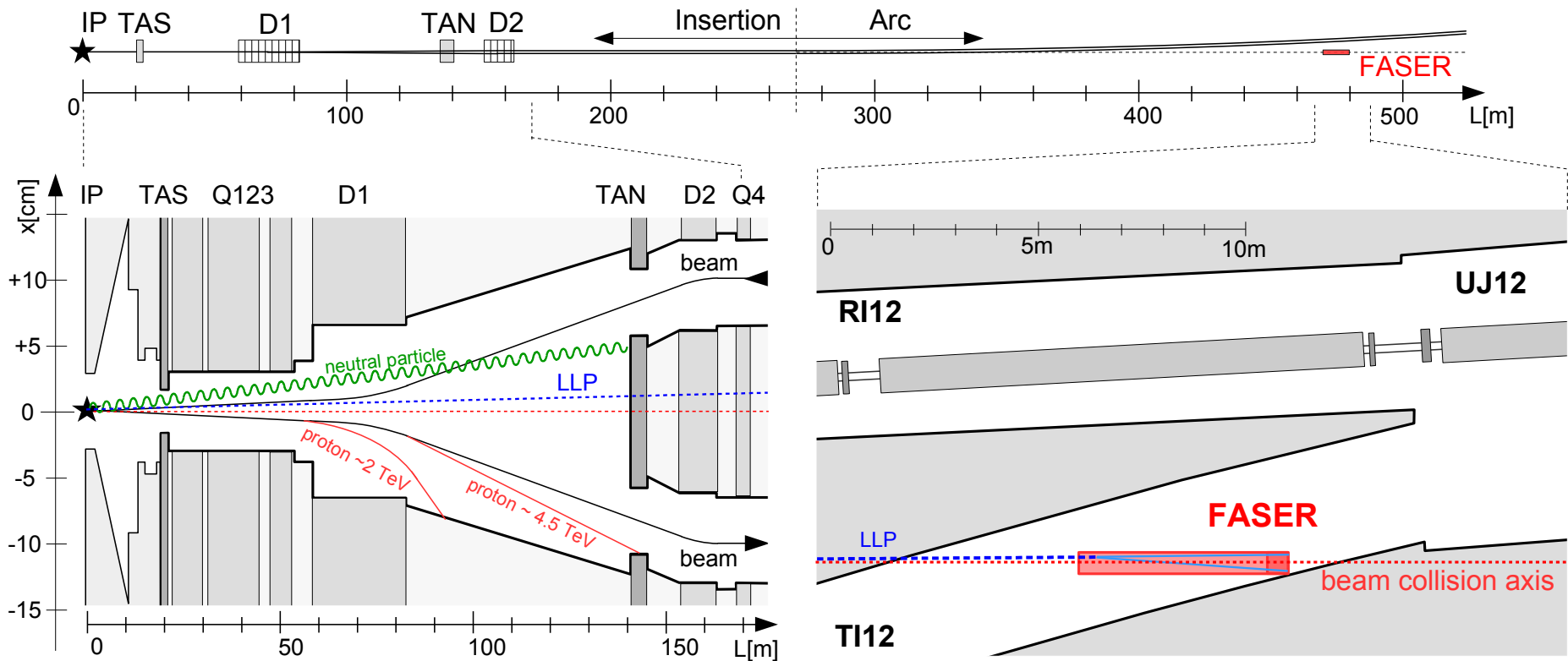
- New physics searches at the LHC focus on high p_T . This is appropriate for heavy, strongly interacting particles
 - $\sigma \sim \text{fb to pb} \rightarrow$ In Run-3 $N \sim 10^2 - 10^5$, produced \sim isotropically
- However, if new particles are light and weakly interacting, this may be completely misguided. Instead can exploit
 - $\sigma_{\text{inel}} \sim 100 \text{ mb} \rightarrow$ In Run-3 $N \sim 10^{16}$, $\theta \sim \Lambda_{\text{QCD}} / E \sim 250 \text{ MeV} / \text{TeV} \sim \text{mrad}$



- FASER is a proposed experiment designed to cover this scenario at the LHC
- Detector to be placed 480m from IP1 directly on the beam collision axis line of sight (LOS) with transverse radius of only 10cm covering the mrad regime

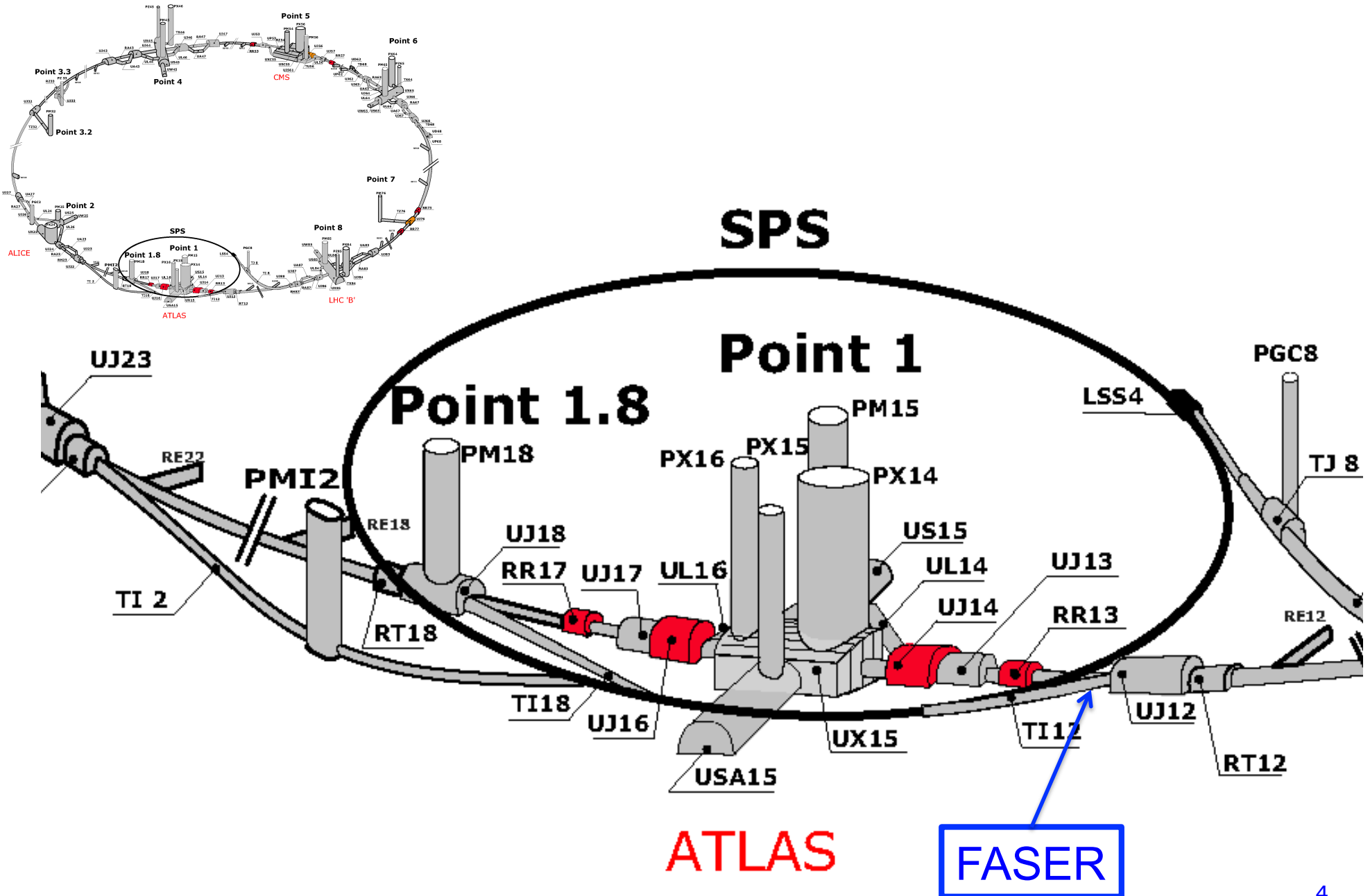
FASER LOCATION

- FASER will be situated along the beam *collision* axis line of sight (LOS)
 - ~480 m from IP
 - after beams start to bend
 - a few meters from the LHC beamline



TI12 unused tunnel, that intersects LOS 480m from IP1

FASER LOCATION: TI12



THE TI12 TUNNEL

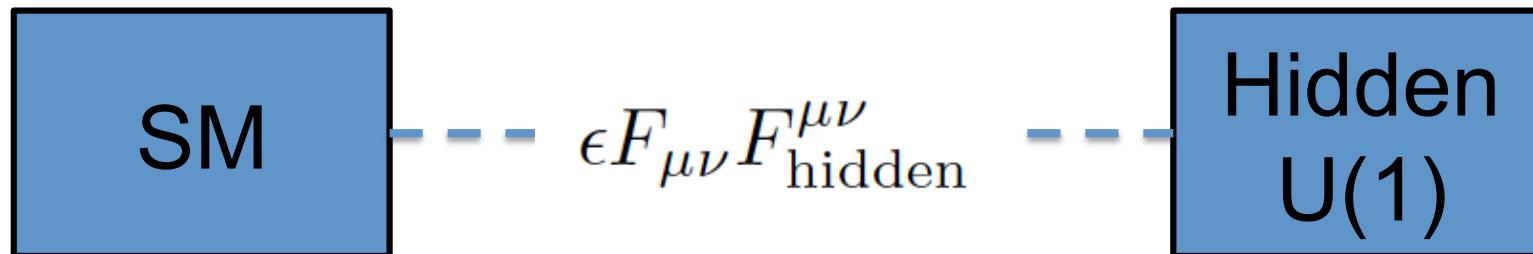


FASER would be situated at the bottom of the TI12 tunnel close to the LHC. TI12 was the old injection line for LEP, and is now unused. TI12 slopes upwards, and the LOS emerges from the tunnel floor. In order to install the FASER detector on the LOS a small amount of civil engineering work needs to be done, to lower the floor of the tunnel (50cm maximum). After such digging a 5m long detector can be situated along the LOS.

EXAMPLE PHYSICS CASE (DARK PHOTONS)

DARK PHOTONS

- Dark matter is our most solid evidence for new particles. In recent years, the idea of dark matter has been generalized to dark sectors
- Dark sectors motivate light, weakly coupled particles (WIMPlless miracle, SIMP miracle, small-scale structure, ..)
- A prominent example: vector portal, leading to dark photons

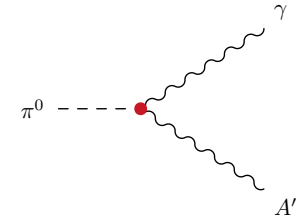


- The resulting theory contains a new gauge boson A' with mass $m_{A'}$ and ϵQ_f couplings to SM fermions f

DARK PHOTON PROPERTIES

- Produced in meson decays, e.g.,

$$B(\pi^0 \rightarrow A' \gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \rightarrow \gamma\gamma),$$



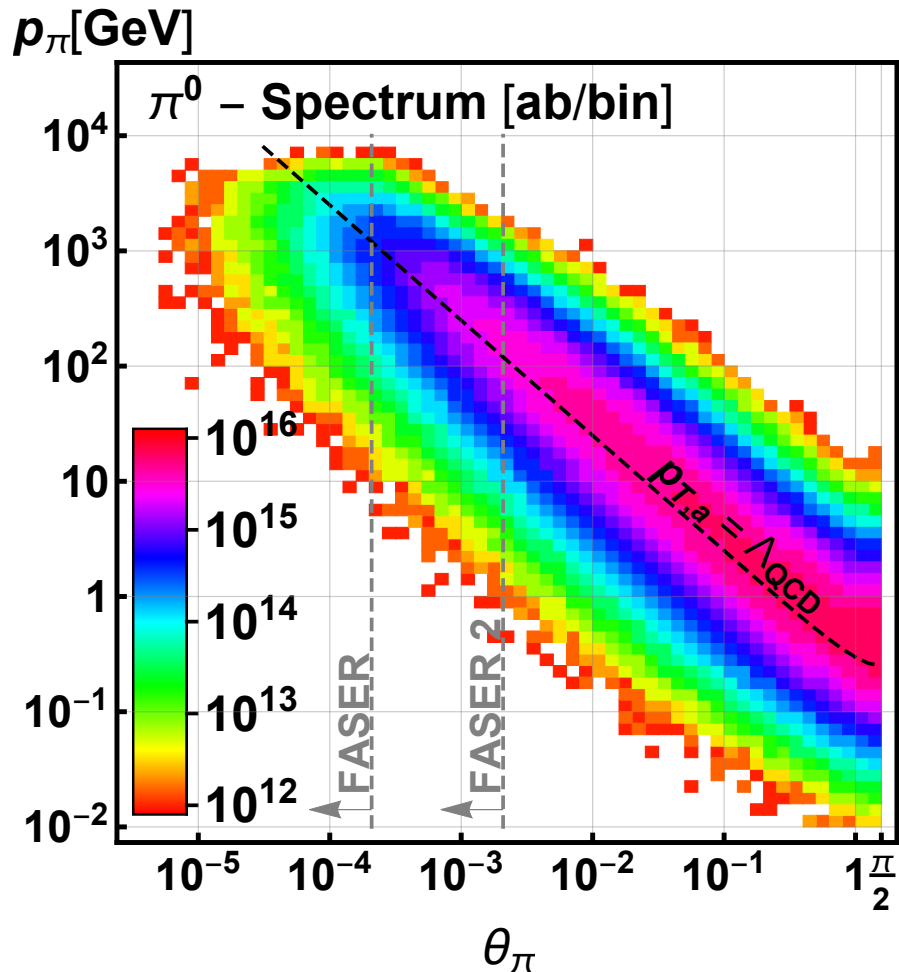
and also through other processes

- Travels long distances through matter without interacting, decays to e^+e^- , $\mu^+\mu^-$ for $m_{A'} > 2 m_\mu$, other charged pairs

$$\bar{d} = c \frac{1}{\Gamma_{A'}} \gamma_{A'} \beta_{A'} \approx (80 \text{ m}) B_e \left[\frac{10^{-5}}{\epsilon} \right]^2 \left[\frac{E_{A'}}{\text{TeV}} \right] \quad E_{A'} \gg m_{A'} \gg m_e$$

- TeV energies at the LHC \rightarrow huge boost, decay lengths of ~ 100 m are possible for viable and interesting parameters

PRODUCTION AT LHC

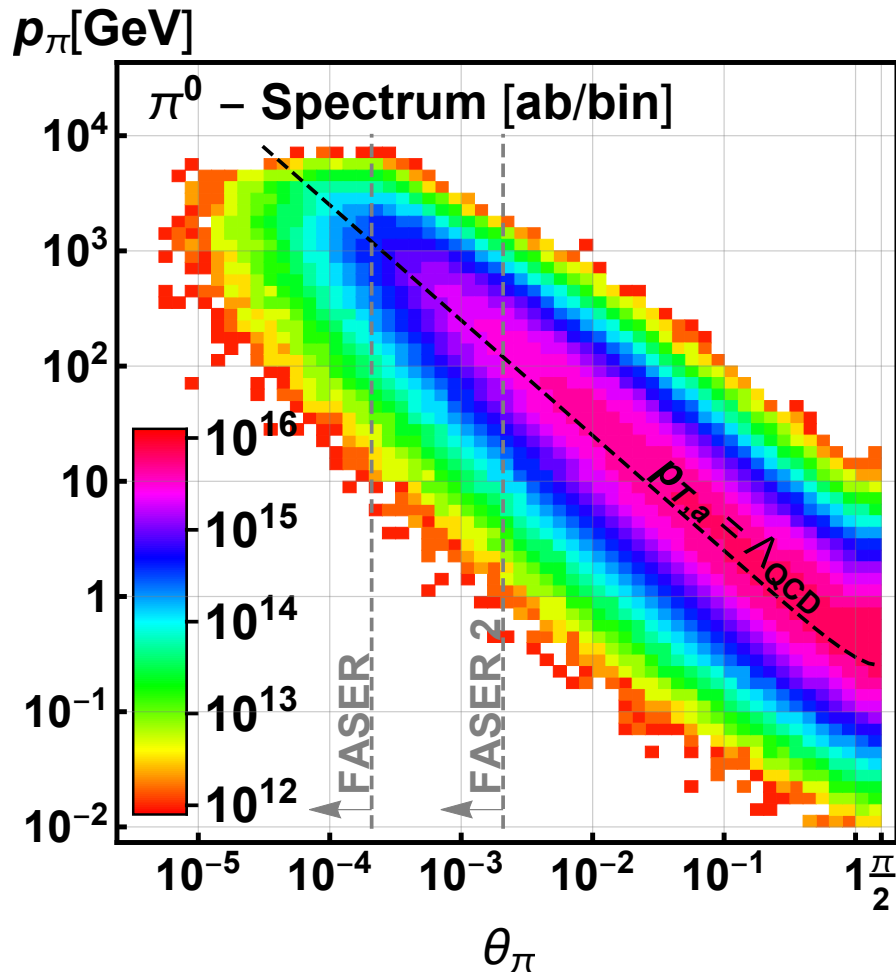


FASER takes advantage of the the huge number of light mesons (π^0, η, \dots) that are produced at the LHC, predominantly in the very forward direction.

For example for $E(\pi^0) \geq 10$ GeV,

- 2% of π^0 s fall in FASER acceptance;
- whereas the FASER acceptance covers just $(2 \times 10^{-6})\%$ of the solid angle.

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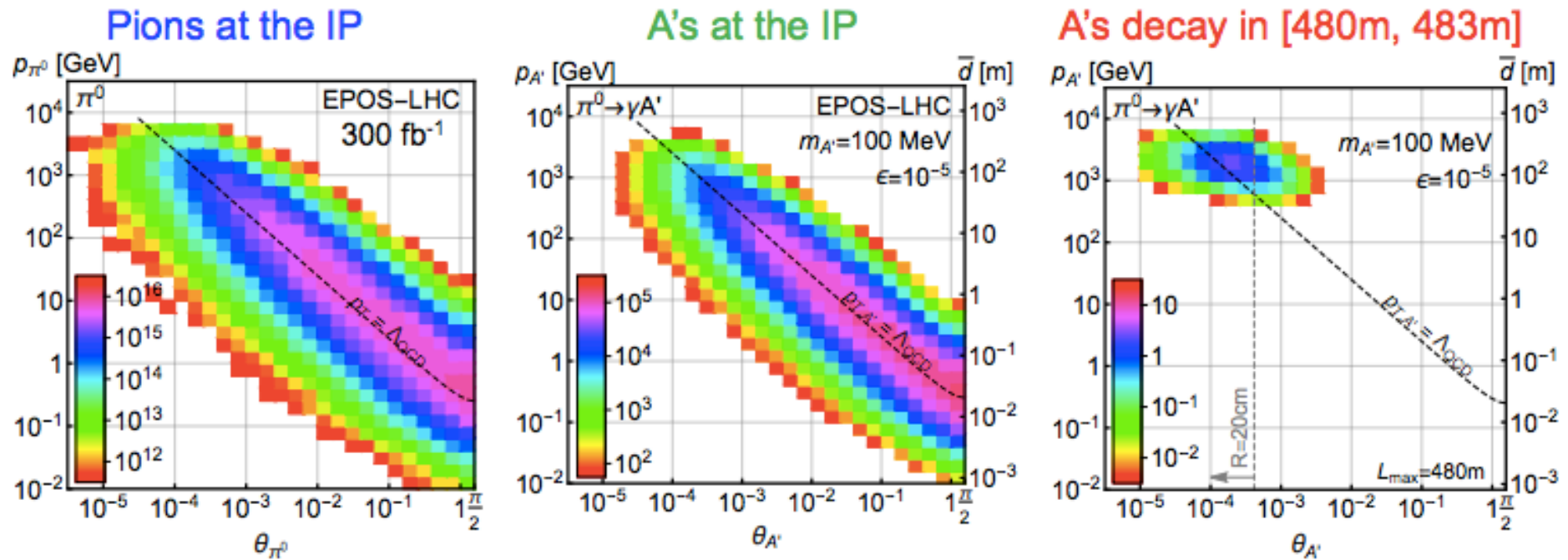
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Run-3 (0.15/ab) will produce a huge number of π^0 s in FASER angular acceptance. Even with large suppression ($\varepsilon^2 \sim 10^{-8} - 10^{-10}$ for relevant region of phase space) can still have very large number of dark photons produced.

LHC can be a dark photon factory!

DARK PHOTONS IN FASER



- Simulations greatly refined by LHC data
- Production is peaked at $p_T \sim \Lambda_{\text{QCD}} \sim 250$ MeV
- Enormous event rates: $N_{\pi} \sim 10^{15}$ per bin
- Production is peaked at $p_T \sim \Lambda_{\text{QCD}} \sim 250$ MeV
- Rates highly suppressed by $\epsilon^2 \sim 10^{-10}$
- But still $N_{A'} \sim 10^5$ per bin
- Only highly boosted \sim 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"

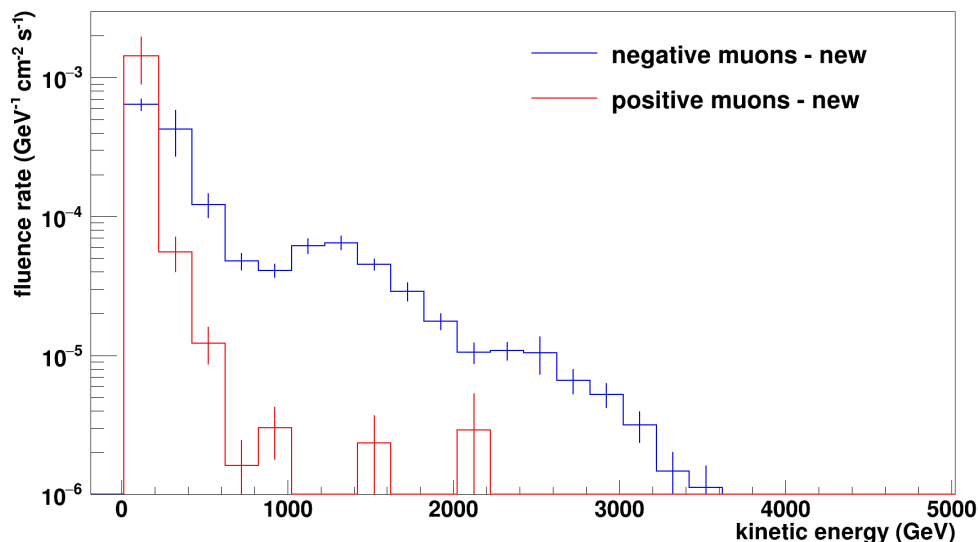
note this is an old slide, and FASER volume $R=10$ cm now!

THE TI12 ENVIRONMENT

BEAM BACKGROUNDS

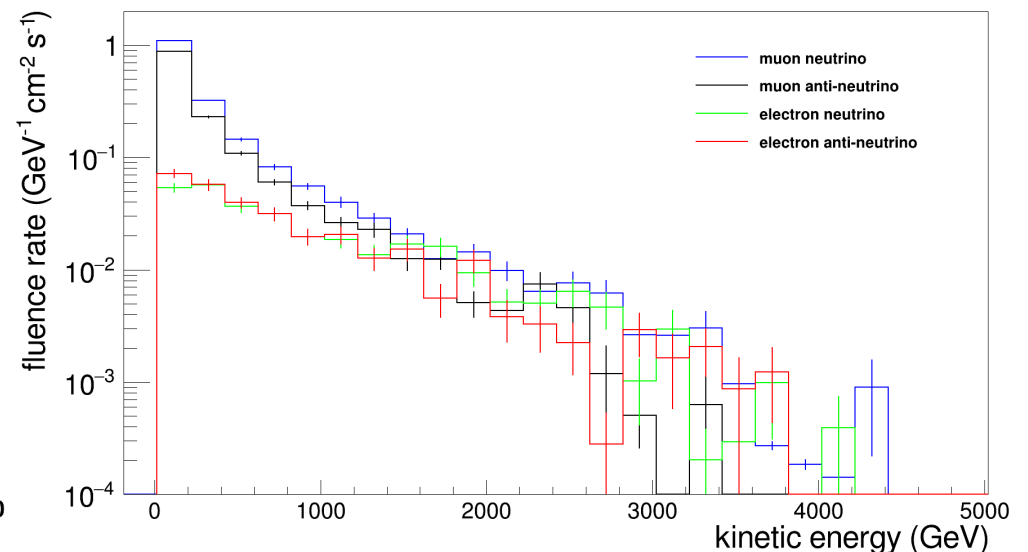
- FLUKA simulations and *in situ* measurements have been used to assess the backgrounds expected in FASER
- FLUKA simulations studied particles entering FASER from:
 - IP1 collisions (shielded by 100m of rock)
 - off-orbit protons hitting beam pipe aperture in dispersion suppressor (close to FASER) (following diffractive interactions in IP1)
 - beam-gas interactions
- Expect a flux of high energy muons ($E > 10$ GeV) of $0.4 \text{ cm}^{-2} \text{ s}^{-1}$ at FASER for $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ luminosity from IP1 collisions

Fluence rate ($\text{GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$) for muons: 10 GeV threshold



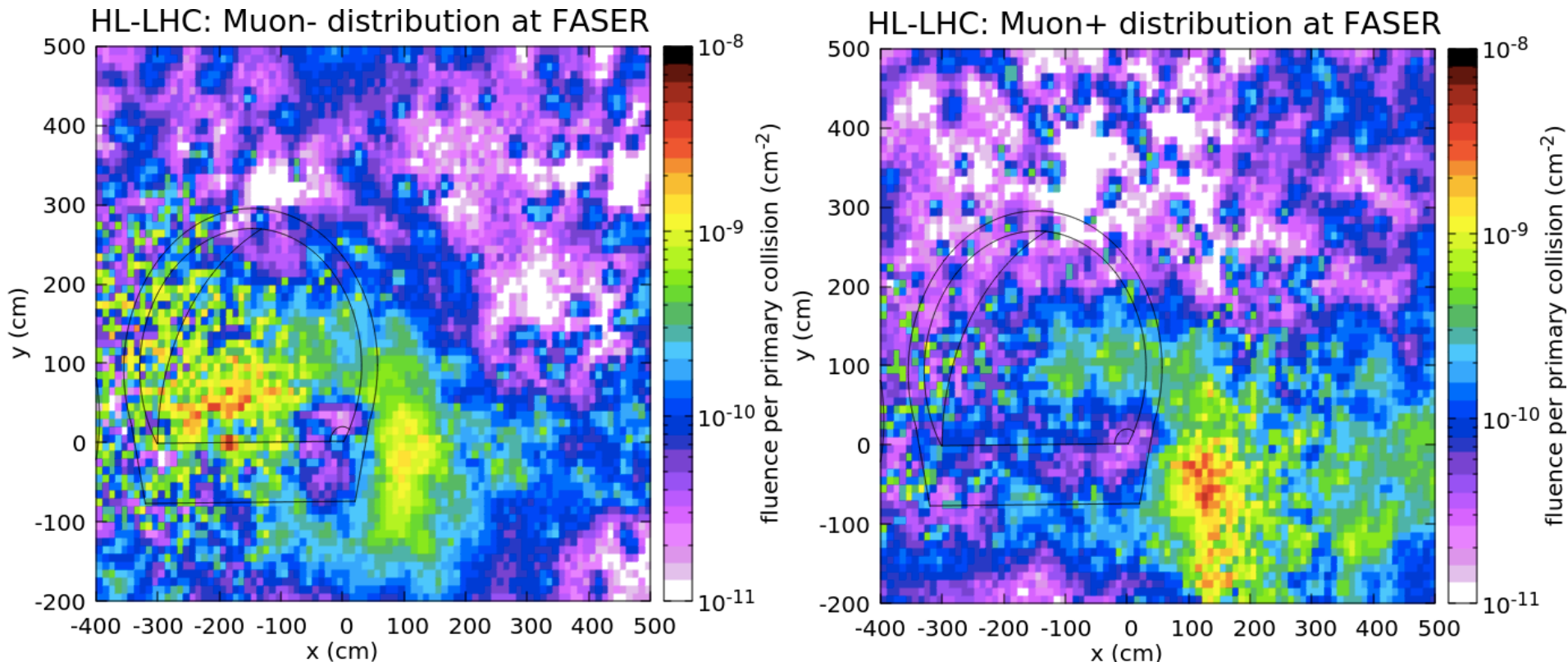
Large muon charge asymmetry at FASER due to LHC bending magnets

Fluence rate spectra at FASER (above 10 GeV) for the LHC



Huge flux of high energy neutrinos

FLUKA SIMULATIONS: MUON MAP



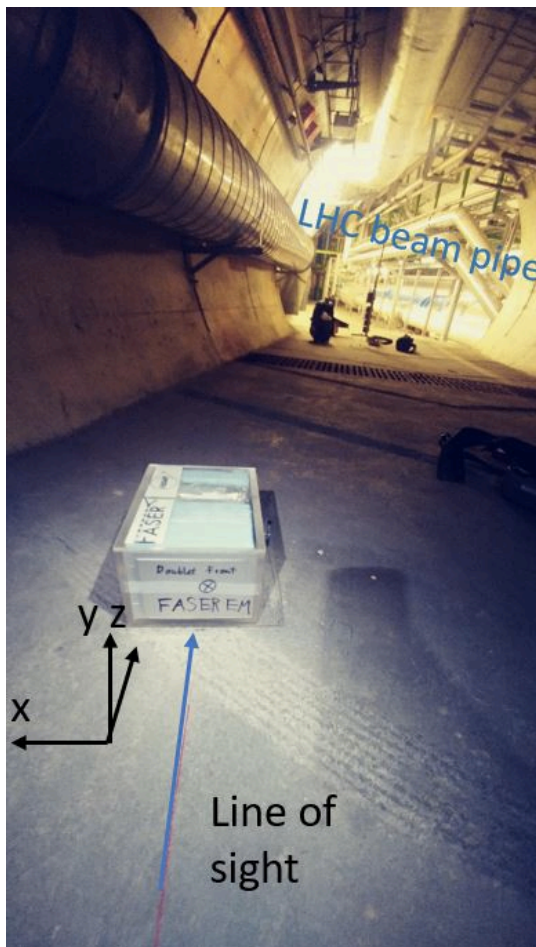
Due to bending from LHC magnets, muon flux on LOS is reduced:
 μ^- tend to be bent to the left, μ^+ to the right of FASER.

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

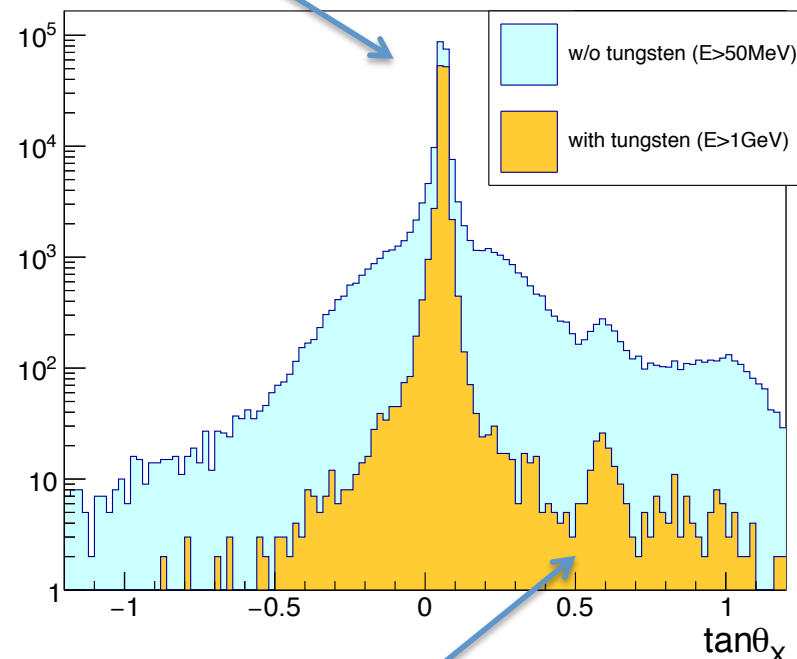
Expected charged particle rate for different energy thresholds ($2e34\text{cm}^{-2}\text{s}^{-1}$)

BEAM BACKGROUNDS

- Measurements using emulsion detectors installed in TI12 in 2018 running confirm expected particle flux
- Measurements using TimePix BLM in TI12 confirm that particle flux is correlated with luminosity in IP1



particles from IP1

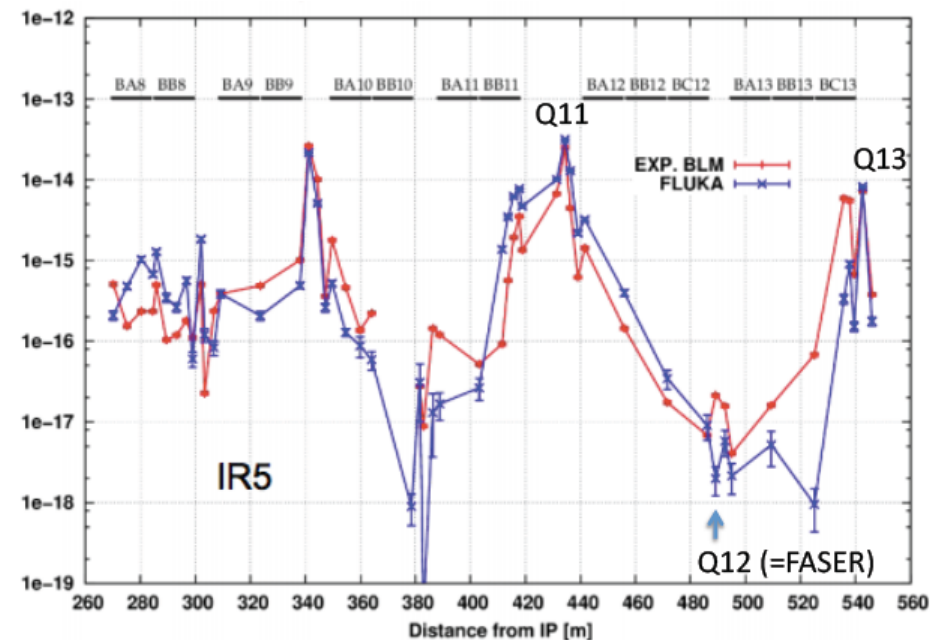
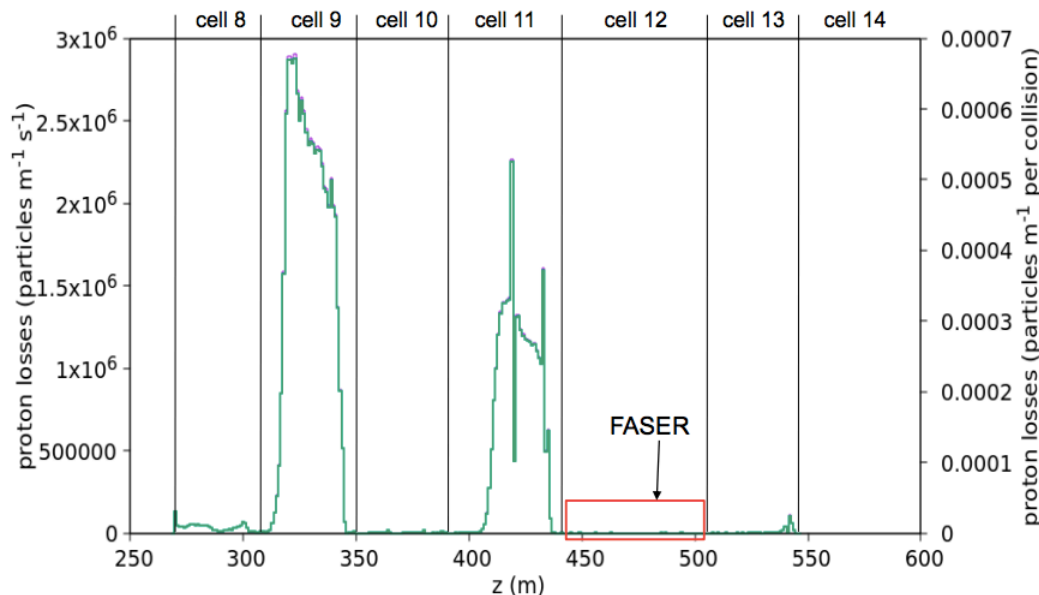


particles from LHC beam line

Measured angle in emulsion detector

TI12 RADIATION LEVEL

- Radiation level predicted to be very low in TI12 due to dispersion function of LHC at this location
 - Radiation comes from off-momentum protons (following diffractive processes in IP1) hitting beam aperture, and causing showers
 - Dispersion function defines where this happens – FASER location one of the quietest!
- Measurements by BatMon radiation monitor in 2018 running confirm FLUKA expectations of:
 - less than 5×10^{-3} Gy/year
 - less than 5×10^7 1 MeV neutron equivalent fluence / year
- FASER detector does not need radiation hard electronics

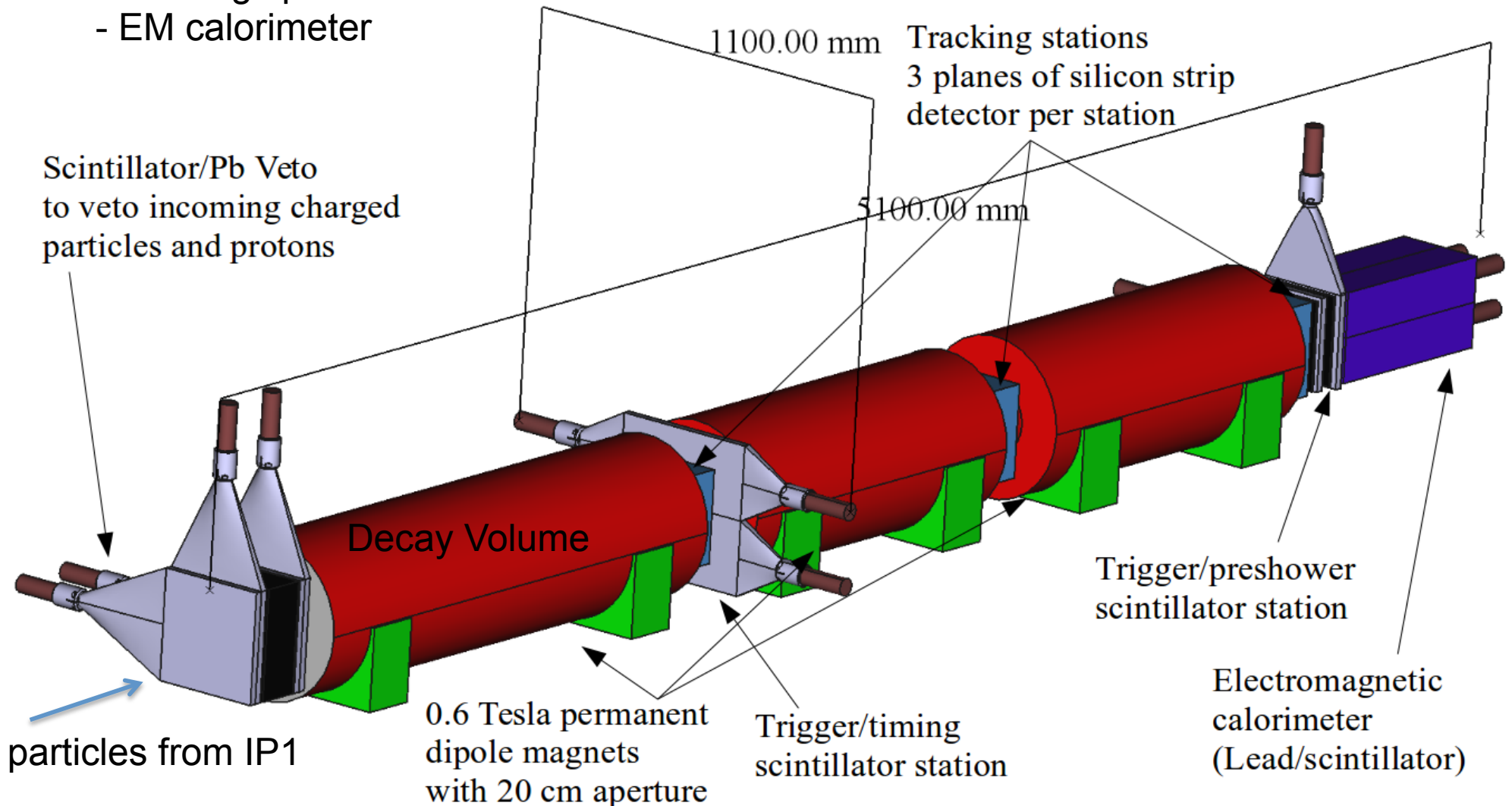


THE FASER DETECTOR

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The detector consists of:

- Scintillator veto
- 1.5m long decay volume
- 2m long spectrometer
- EM calorimeter

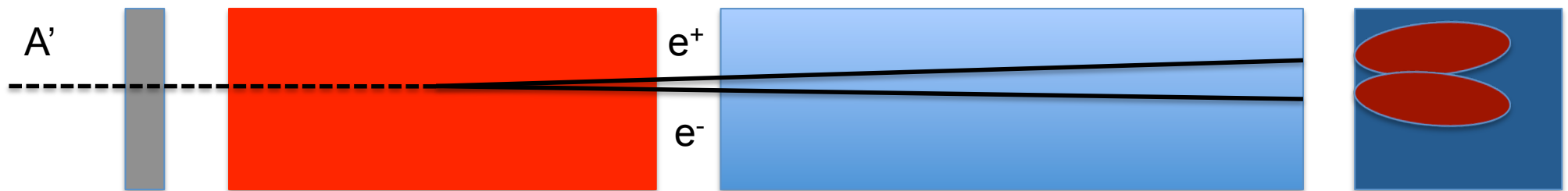


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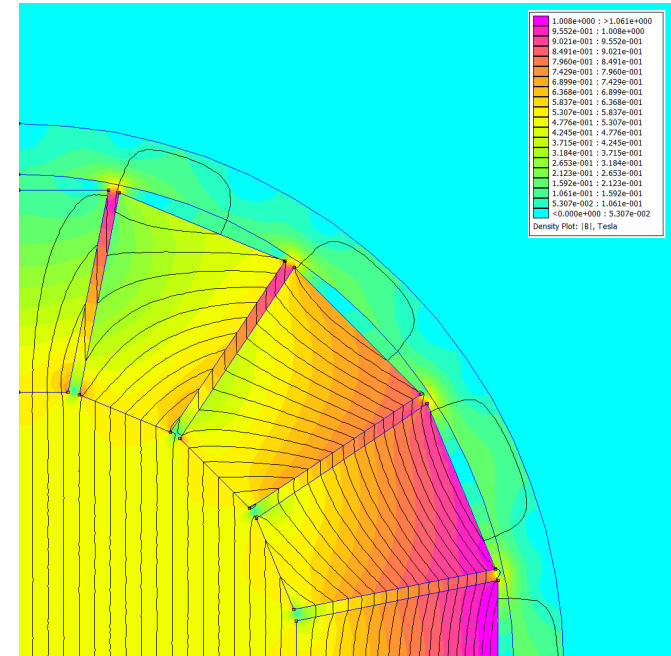
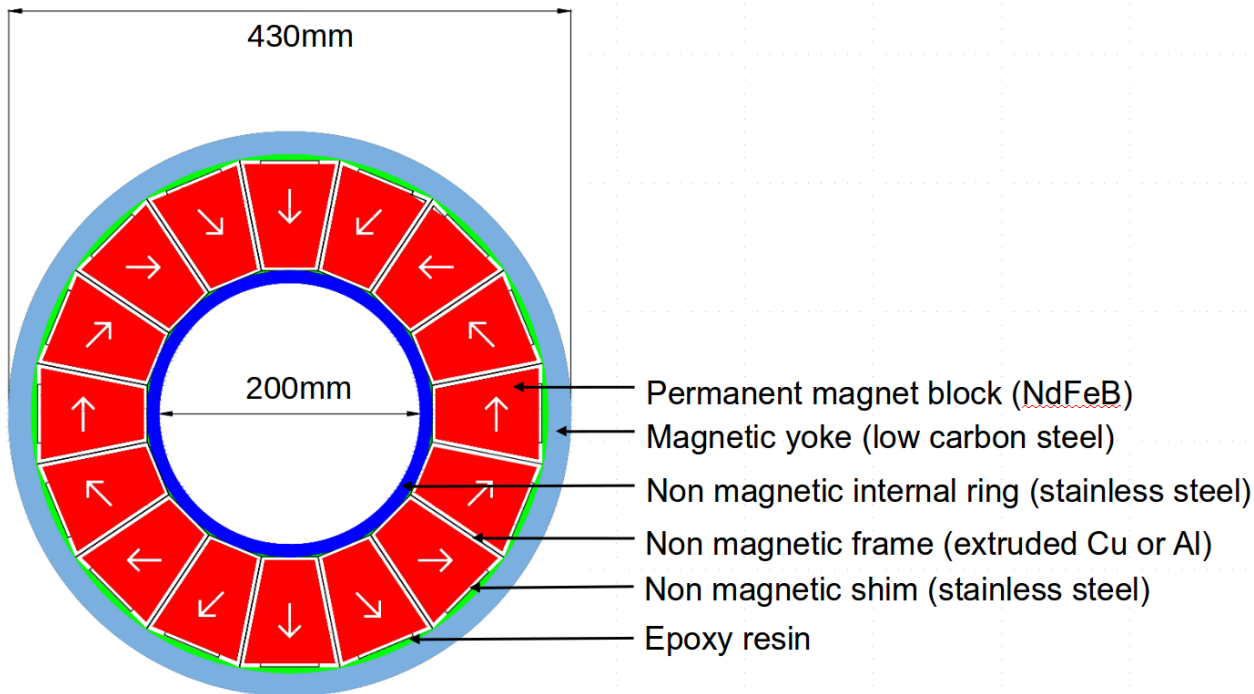
Signal signature



1. No signal in the veto scintillator;
2. Two 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;
3. For $A' \rightarrow ee$ decay: Large EM energy in calorimeter. EM showers too close to be resolved.

Magnets needed to separate the A' decay products sufficiently to be able to be resolved in tracker

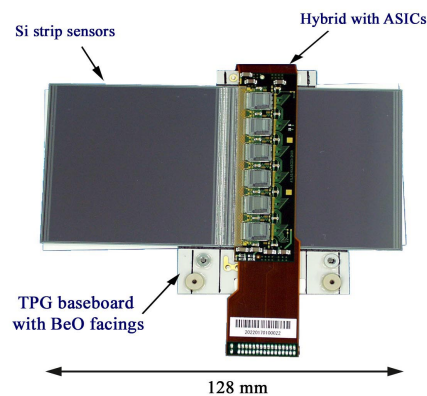
FASER MAGNETS



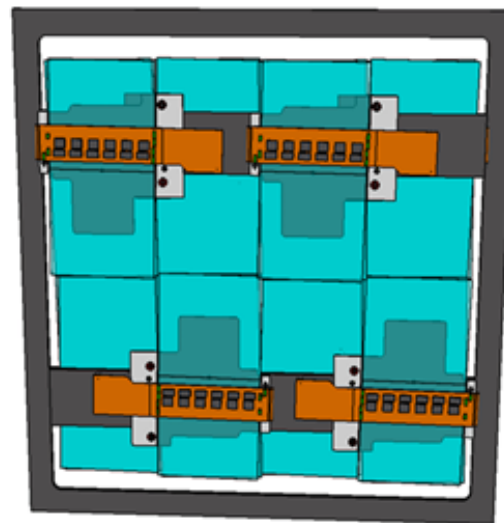
- The FASER magnets are 0.6T permanent dipole magnets based on the Halbach array design
 - Thin enough to allow the LOS to pass through the magnet center with minimum digging to the floor in T112
 - Minimized needed services (power, cooling etc..)
- To be constructed by the CERN magnet group

FASER TRACKER

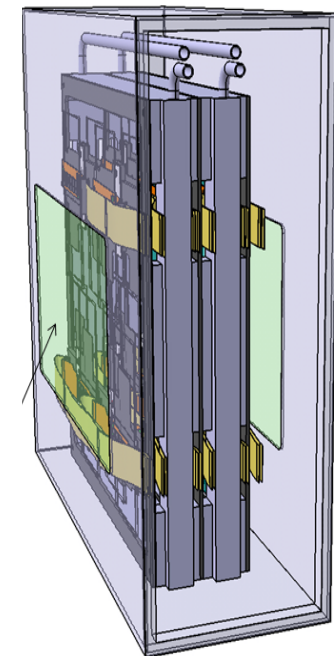
- The FASER Tracker will be made up of 3 tracking stations
- Each containing 3 layers of double sided silicon micro-strip detectors
 - Spare ATLAS SCT modules will be used
 - 80 μ m strip pitch, 40mrad stereo angle
 - Many thanks to the ATLAS SCT collaboration!
- 8 SCT modules give a 24cm x 24cm tracking layer
- 9 layers (3/station, 3 stations) => 72 SCT modules needed for the full tracker
 - 10⁵ channels in total



SCT module

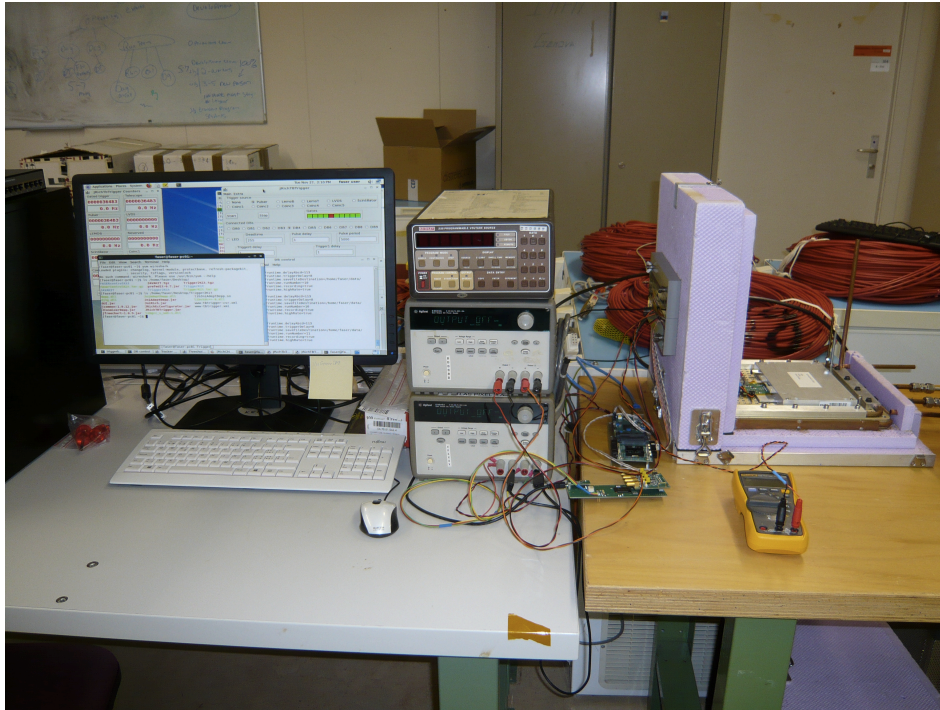


Tracking layer



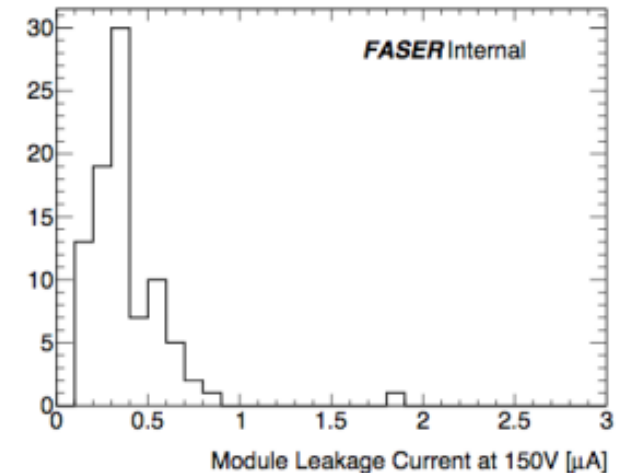
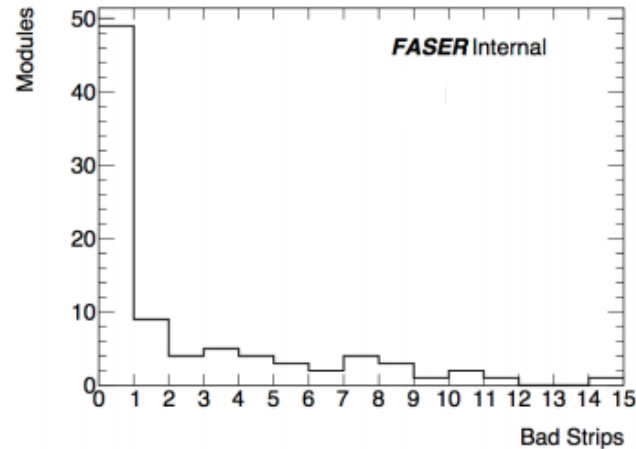
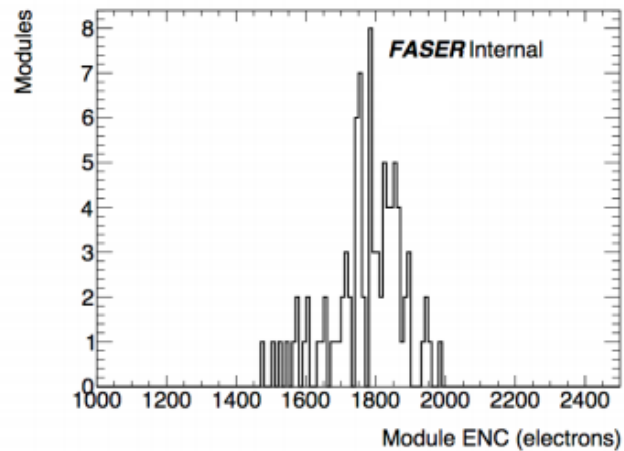
Tracking station 21

FASER TRACKER- MODULE QA



SCT module QA at CERN in March. Identified > 80 good spare modules – more than enough for FASER needs.

Many thanks to Steve Wotton & Floris Keizer for allowing us to use their readout system for these QA test.



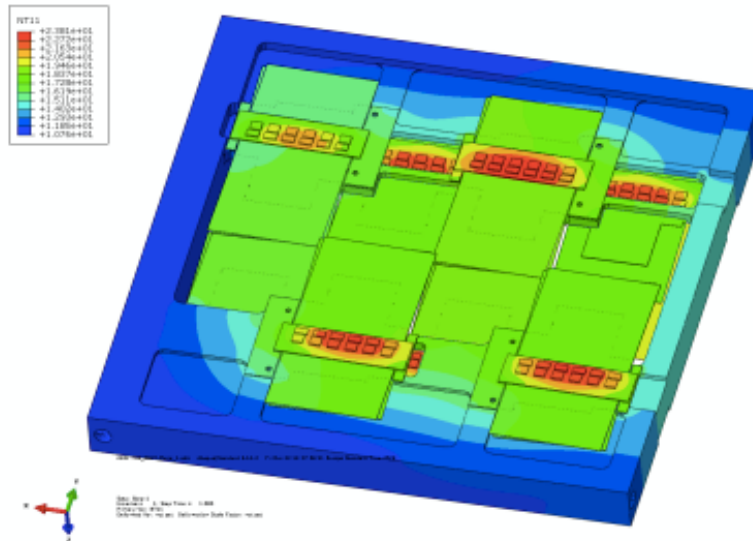
TRACKER COOLING & READOUT

- Due to the low radiation in T112 the silicon can be operated at room temperature, but the detector needs to be cooled to remove heat from the on-detector ASICs
- Design of tracking layer ongoing to give sufficient thermal and mechanical properties, whilst minimizing material in tracking volume
- Plan to use simple water chiller with inlet temperature $<10^{\circ}\text{C}$
- Need to fill tracking station with dry air to avoid condensation problems

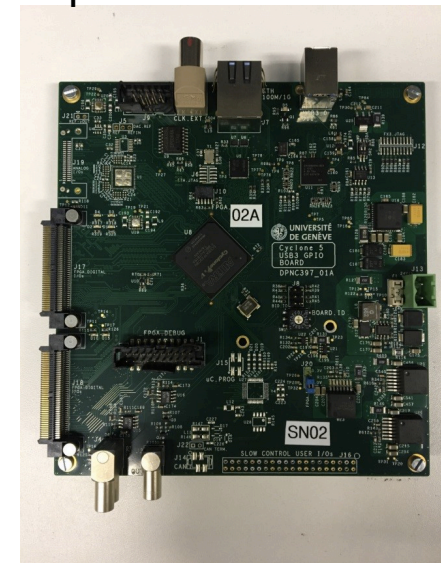
Proposed chiller to be used:



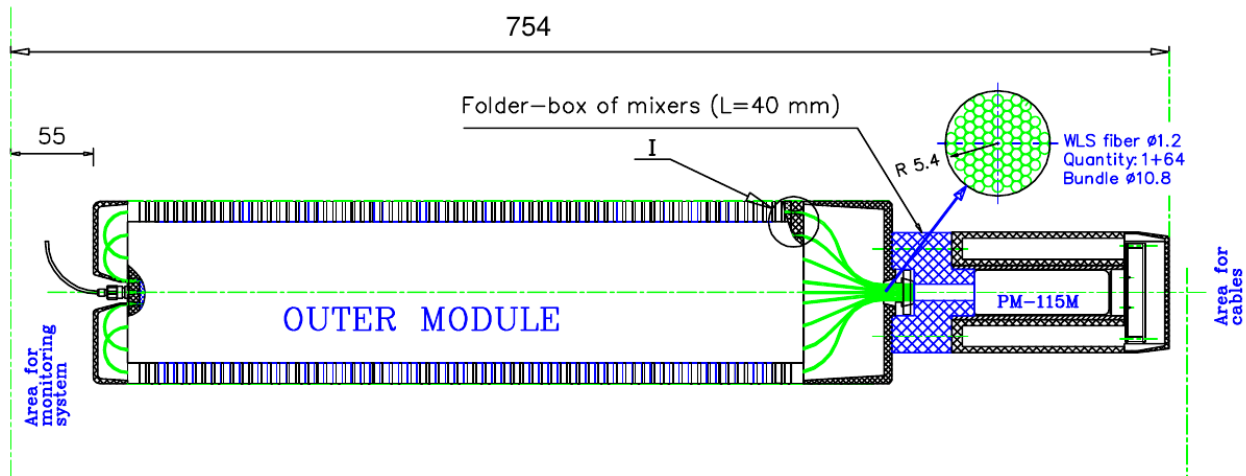
Example FEA analysis in tracker design:



Custom readout of SCT modules using existing GPIO board (from University of Geneva). Simplifies readout chain compared to ATLAS:

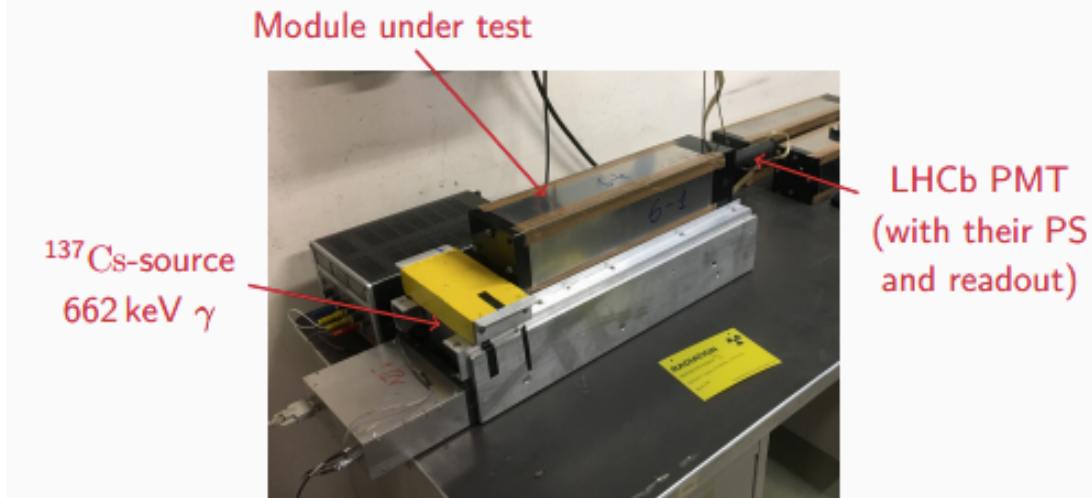


CALORIMETER

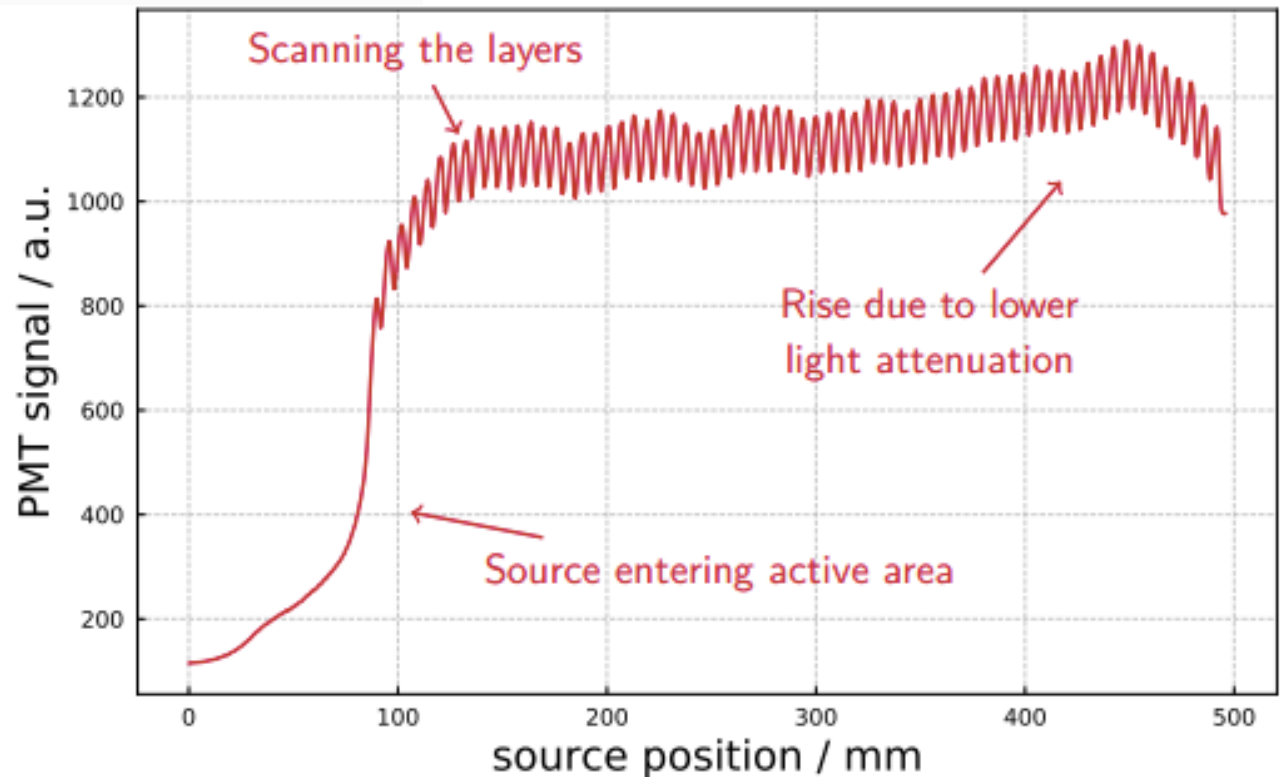


- FASER EM calorimeter for:
 - Measuring the EM energy in the event
 - Electron/photon identification
 - Triggering
- Will use 4 spare LHCb outer ECAL modules
 - Many thanks to LHCb for allowing us to use these!
 - 66 layers of lead/scintillator, light out by wavelength shifting fibers
 - 25 radiation lengths long
 - Readout by PMT (no longitudinal shower information)
 - dimensions: 12cmx12cm – 75cm long (including PMT)
 - Provides ~1% energy resolution for 1 TeV electrons
 - Resolution will degrade at higher energy due to not containing full shower in calorimeter

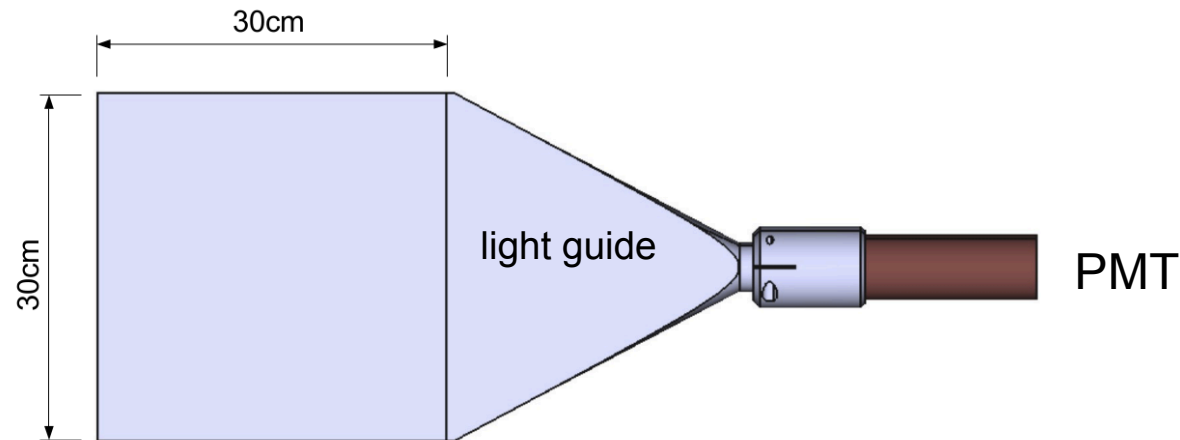
CALORIMETER



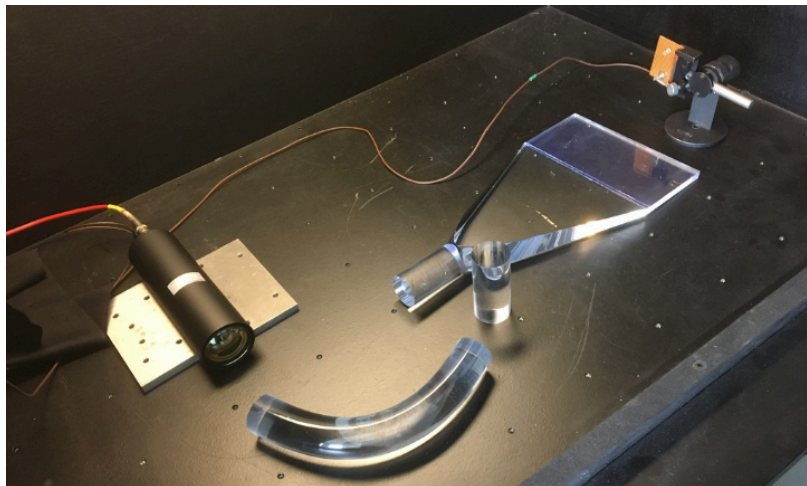
Testing of calorimeter modules at CERN in March showed expected response in all modules tested. Many thanks to Yuri Guz for his help with these tests!



SCINTILLATORS

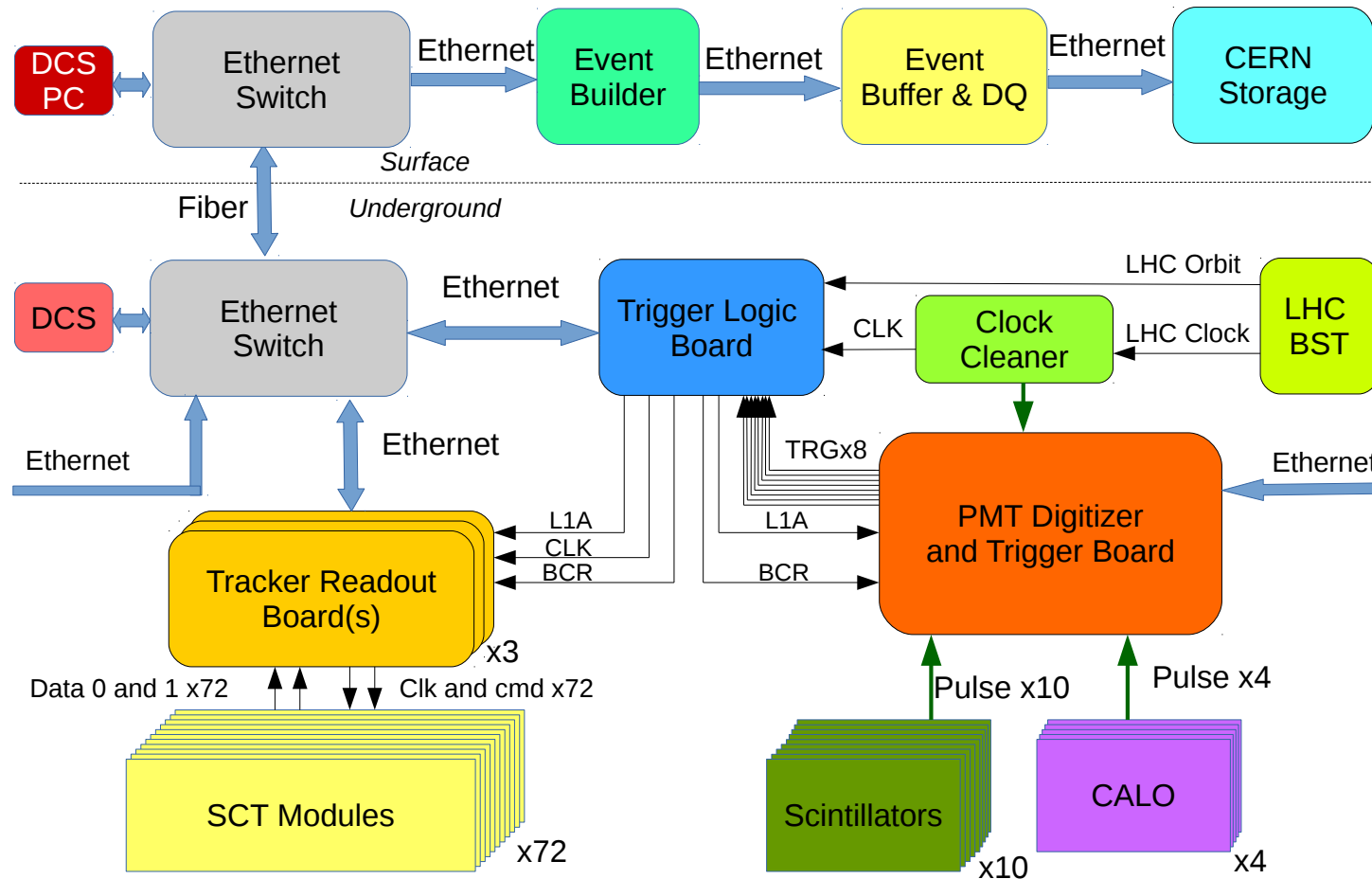


- Scintillators used for vetoing charged particles entering the decay volume, and for triggering
 - To be produced at CERN scintillator lab
 - PMT readout
 - Require extremely efficient charged particle veto ($\text{eff} > 99.99\%$)
 - Achievable with the current design



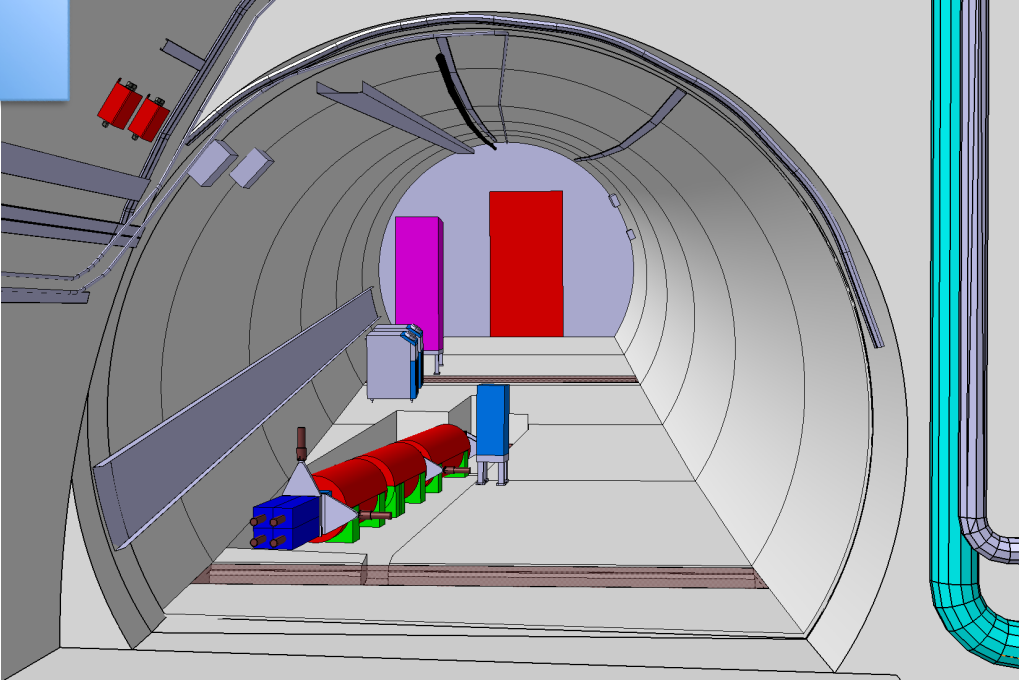
Tests started on light guide and PMT performance

TDAQ OVERVIEW

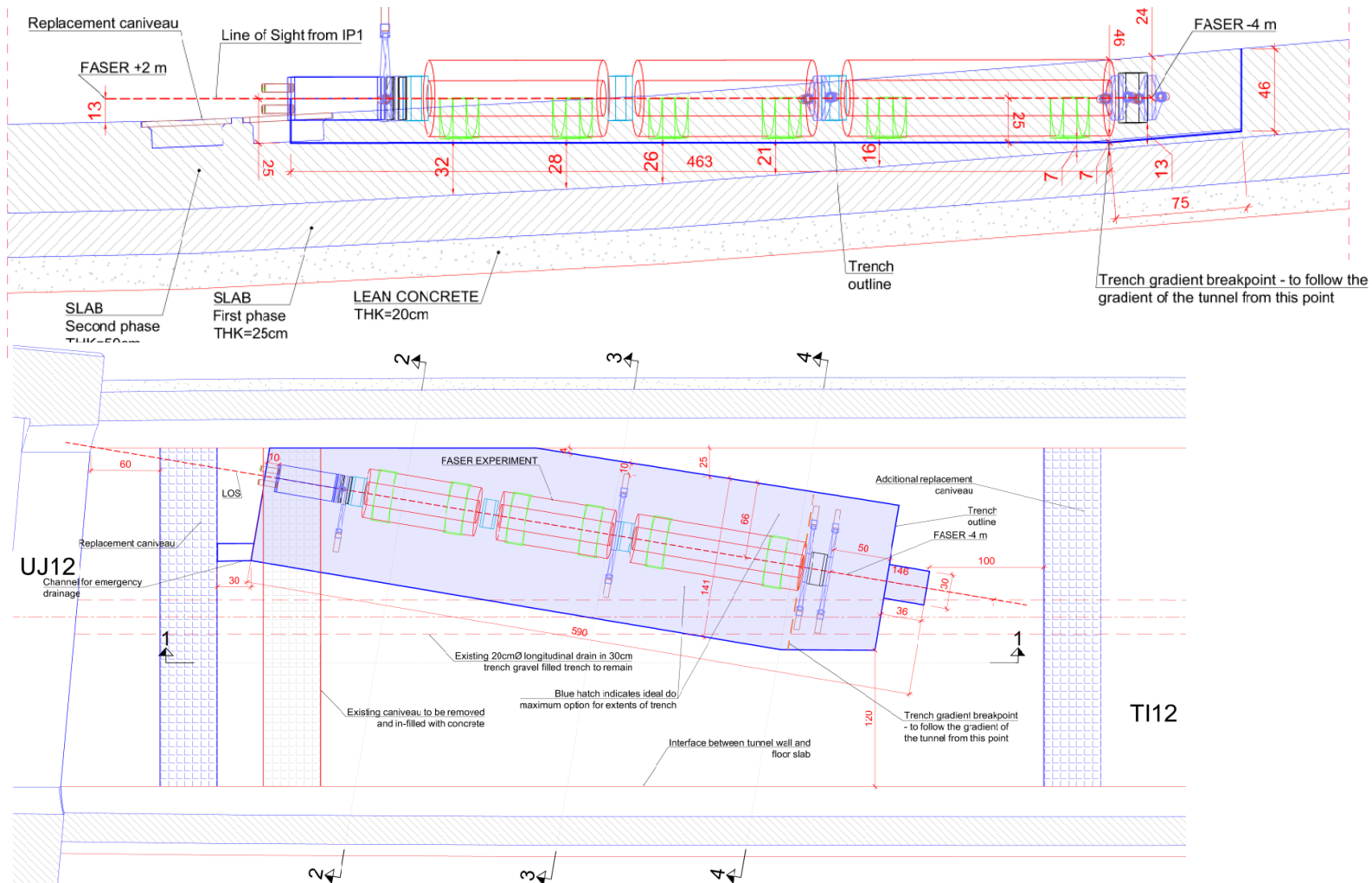


Trigger rate expected to be ~ 600 Hz dominated by muons from IP.
 Trigger will be an OR of triggers from scintillators and from the ECAL.
 No signals shared with ATLAS, need LHC orbit and clock signals, and for offline analysis ATLAS luminosity.
 Readout and trigger logic needs to be in TI12 tunnel, as not sufficient time to send signals to surface and back. Event builder on surface (in SR1)

INSTALLATION IN TI12

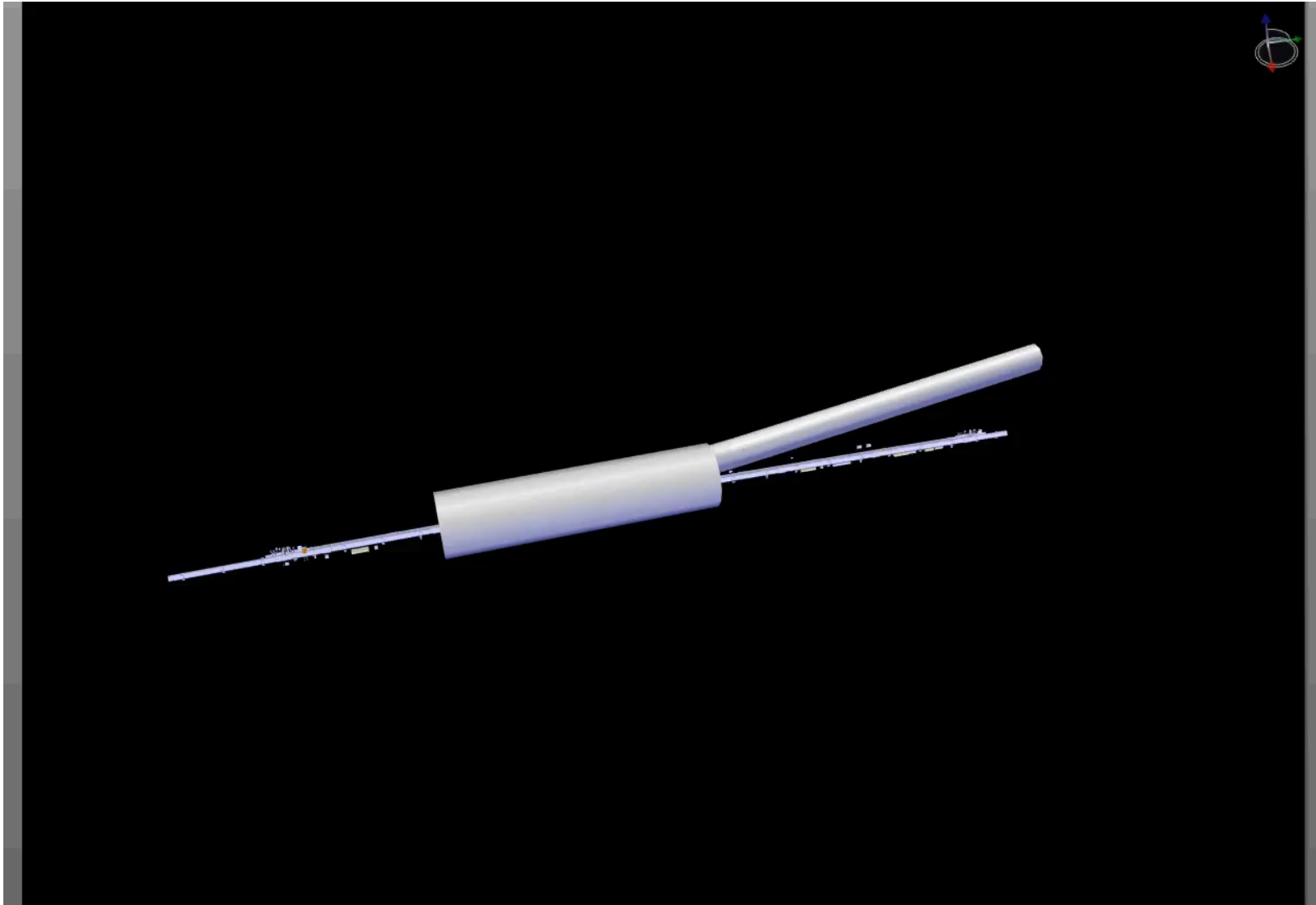


CIVIL ENGINEERING WORK



Maximum digging depth ~50cm - to avoid drainage membrane.
 Detailed study by CERN civil engineering department.
 With this design can fit ~5m long detector centered on LOS.
 Some local strengthening needed (steel frame) to ensure tunnel stability.
 Dust suppression critical for such work in the LHC tunnel.

FASER INTEGRATION MODEL

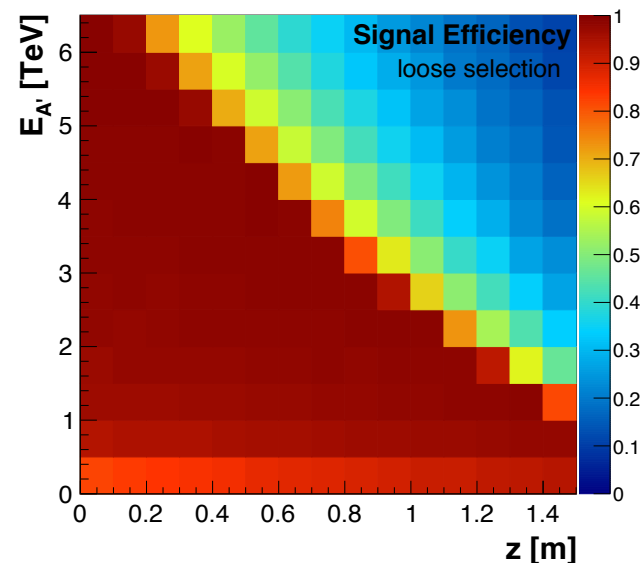
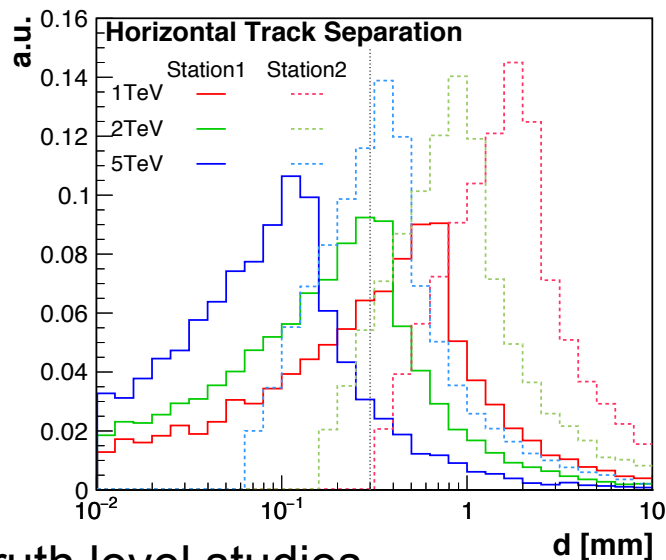


L. Dougherty (CERN)

PHYSICS PERFORMANCE

EXPECTED PERFORMANCE – Track signature

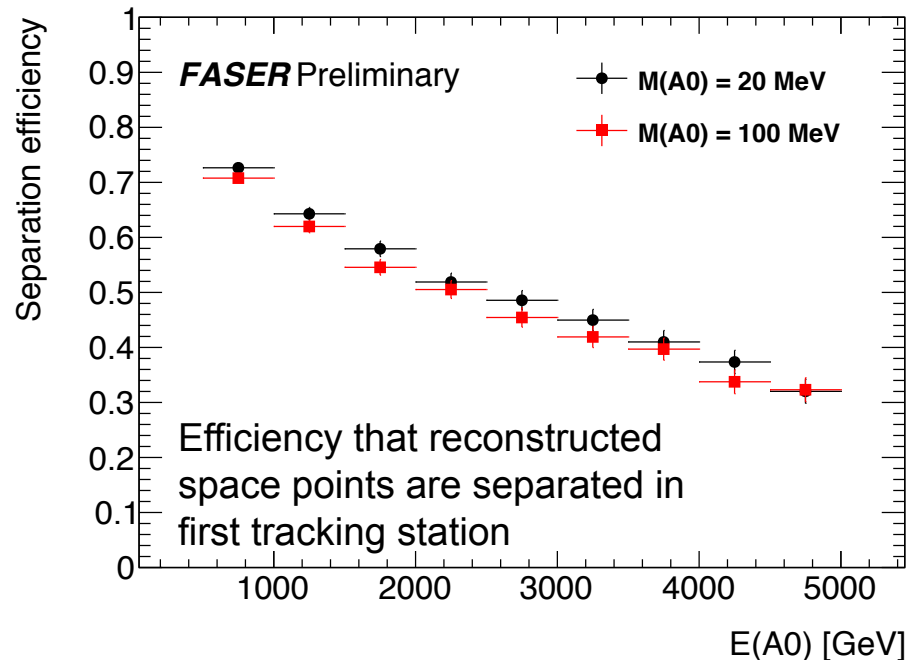
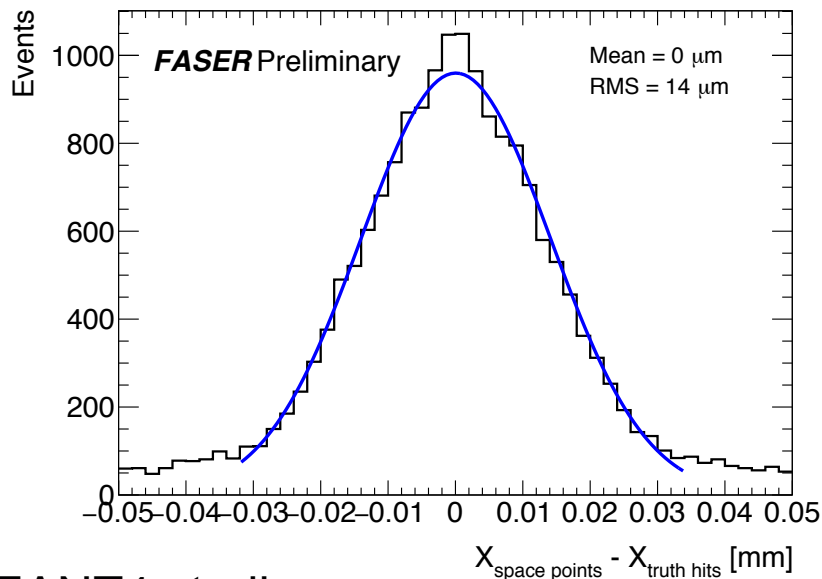
- Main backgrounds radiative processes associated with high energy muons entering the detector from the IP
 - All can be vetoed by scintillator at front of detector
- Potential small backgrounds from neutrino interactions inside the detector
 - Very low rate, and give different detector signature allowing to reject events
- Efficiency for separating very closely spaced tracks important for very high energy signals



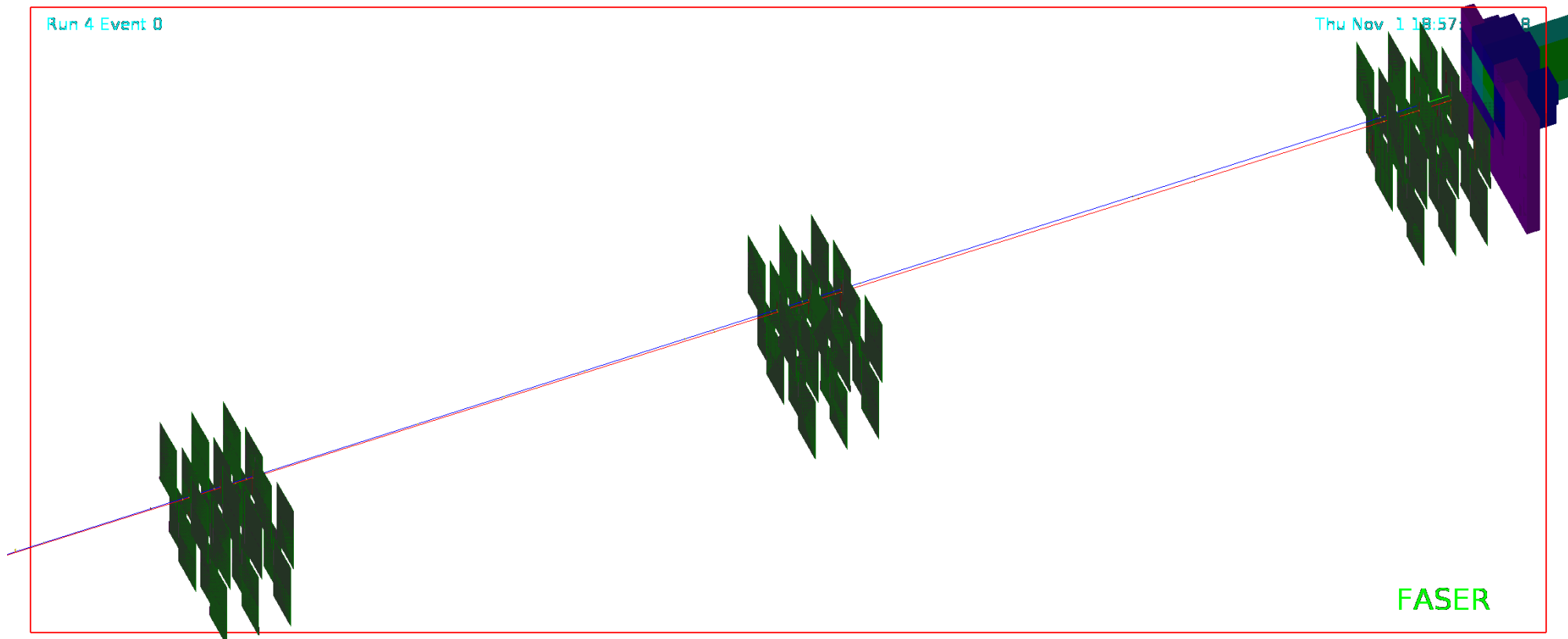
efficiency that
signal tracks
are separated
by >0.3 mm in
2nd / 3rd tracking
stations

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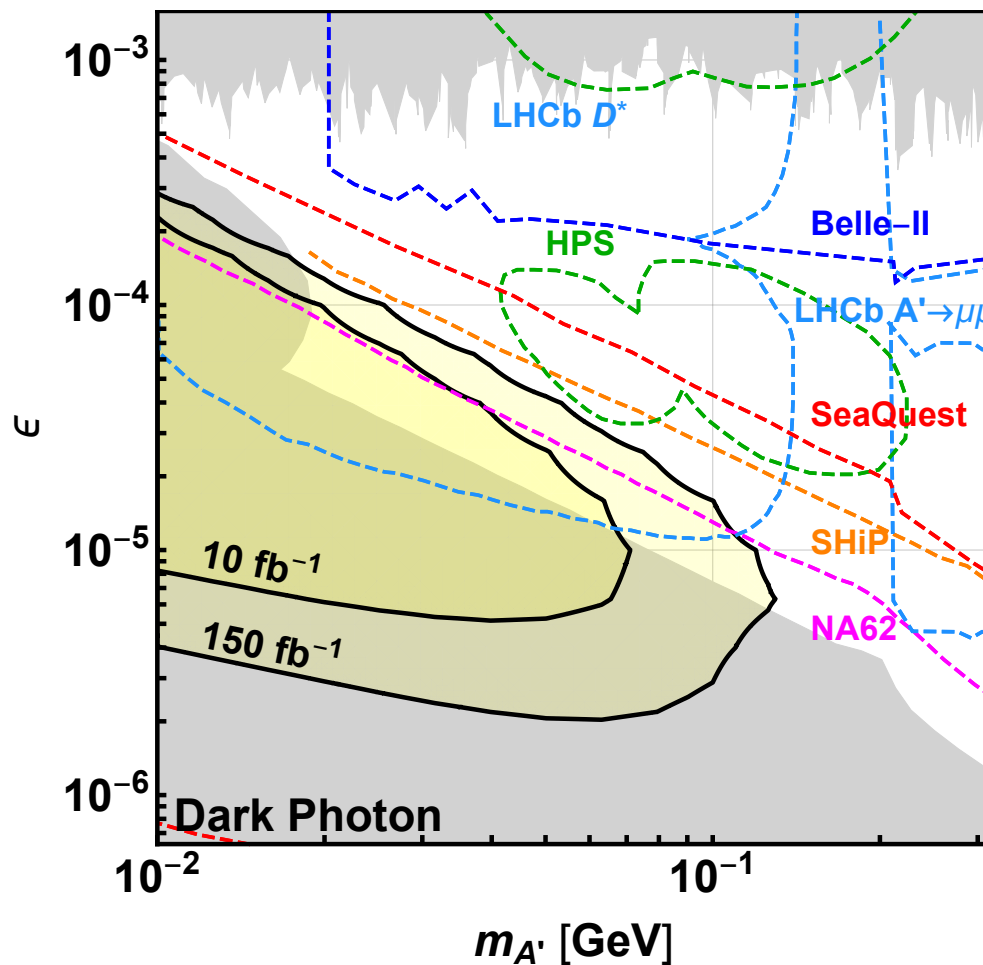
SIGNAL EVENT



G4 simulation of a signal dark photon decay to e^+e^-
Simulation in development

EXPECTED SENSITIVITY

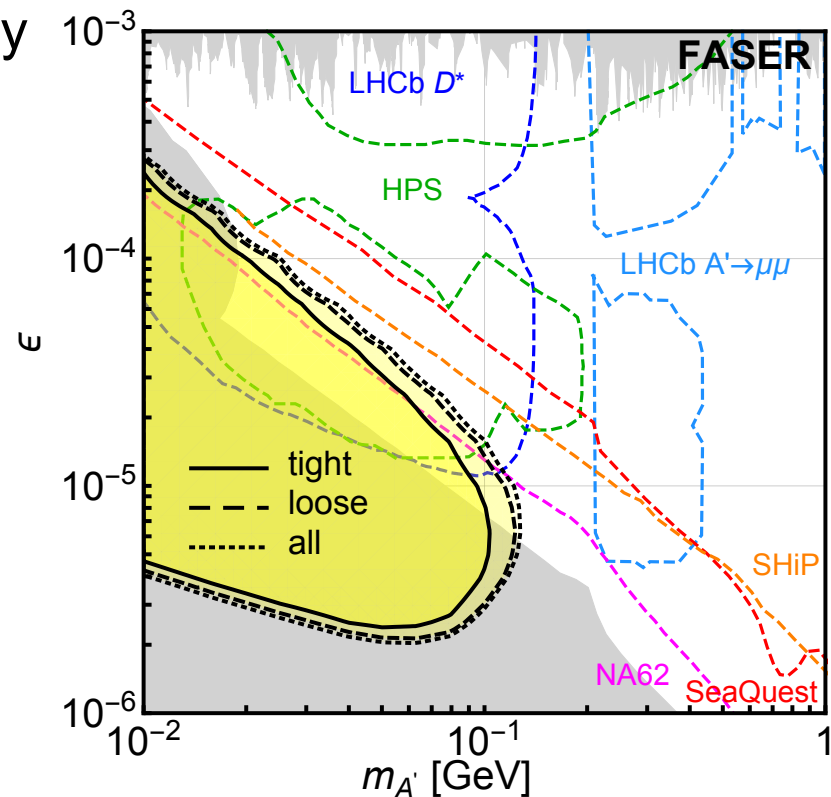
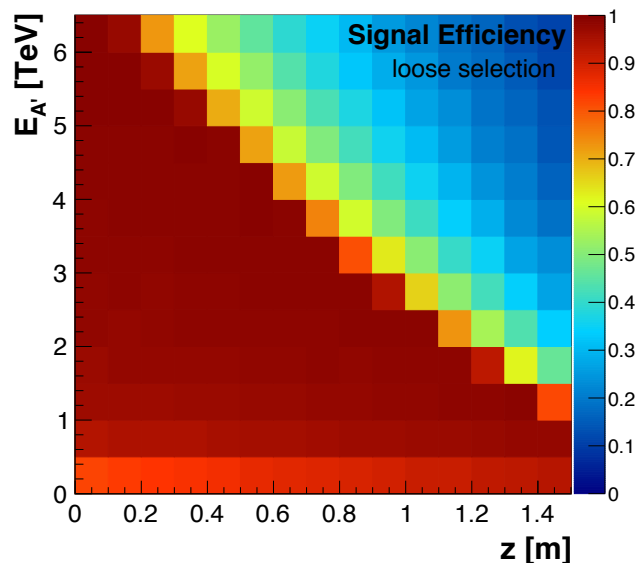
- Sensitivity for dark photons
 - Assuming no background and 100% signal efficiency
 - Curves only slightly effected by $O(1)$ changes in efficiency



Even with 10/fb (to be collected by end of 2021?) have sensitivity to uncharted territory.
With full Run 3 dataset (150/fb) significant discovery potential.

EFFECT OF SELECTION EFFICIENCY

- To take into account an inefficiency due to the analysis selections
 - Defined loose selection: signal tracks separated by $>0.3\text{mm}$ in 2nd and 3rd tracking stations
 - Defined tight selection: signal tracks separated by $>0.3\text{mm}$ in all tracking stations
- Sensitivity basically unchanged for loose selection
- Tight selection loose some sensitivity



EXPECTED PERFORMANCE – 2 photon signature

- FASER can be sensitive to ALPs produced at the LHC (1806.02348)
- For ALP- $\rightarrow\gamma\gamma$ decay, magnetic field does not help separate closely spaced decay products
- We investigated calorimeter / pre-shower to allow to be able to resolve closely spaced ($\sim 1\text{mm}$) high energy photons ($>500\text{ GeV}$) - seems very challenging

Preliminary studies suggest that events with no tracks and a large amount of EM energy in the calorimeter would be \sim background free \Rightarrow an ALP signal would be detectable without the need to resolve the 2 photons.

Further studies show an interesting background would be high energy neutrino's interacting in the calorimeter to give large EM showers

- either muon neutrinos leading to hadronic showers with π^0 ,
- or (more rarely) electron neutrinos interacting to give electrons

First time I have heard of neutrino interactions in the detector being a background for a collider search!

We are considering to have a scintillator pre-shower to give a small amount of longitudinal information which could be used to veto such neutrino interaction events.

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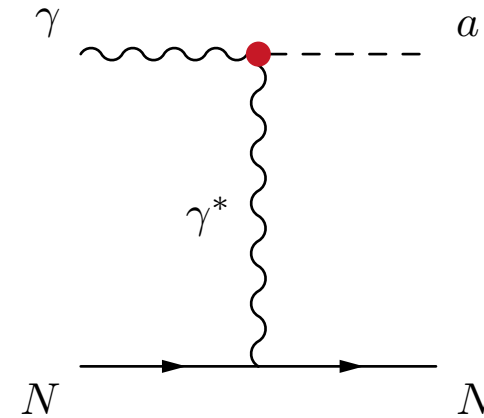
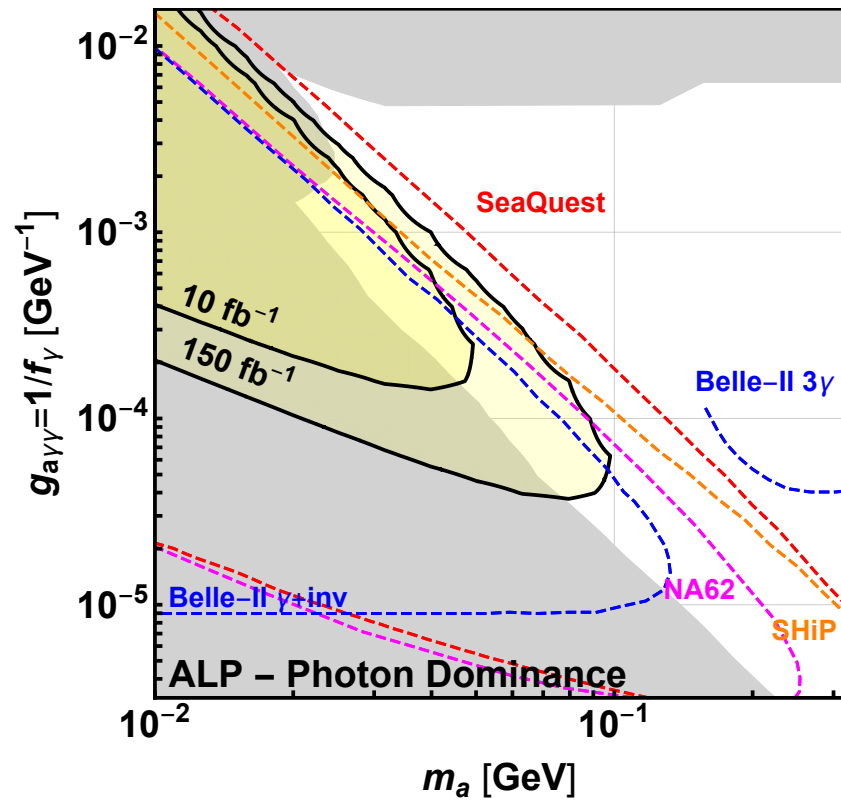
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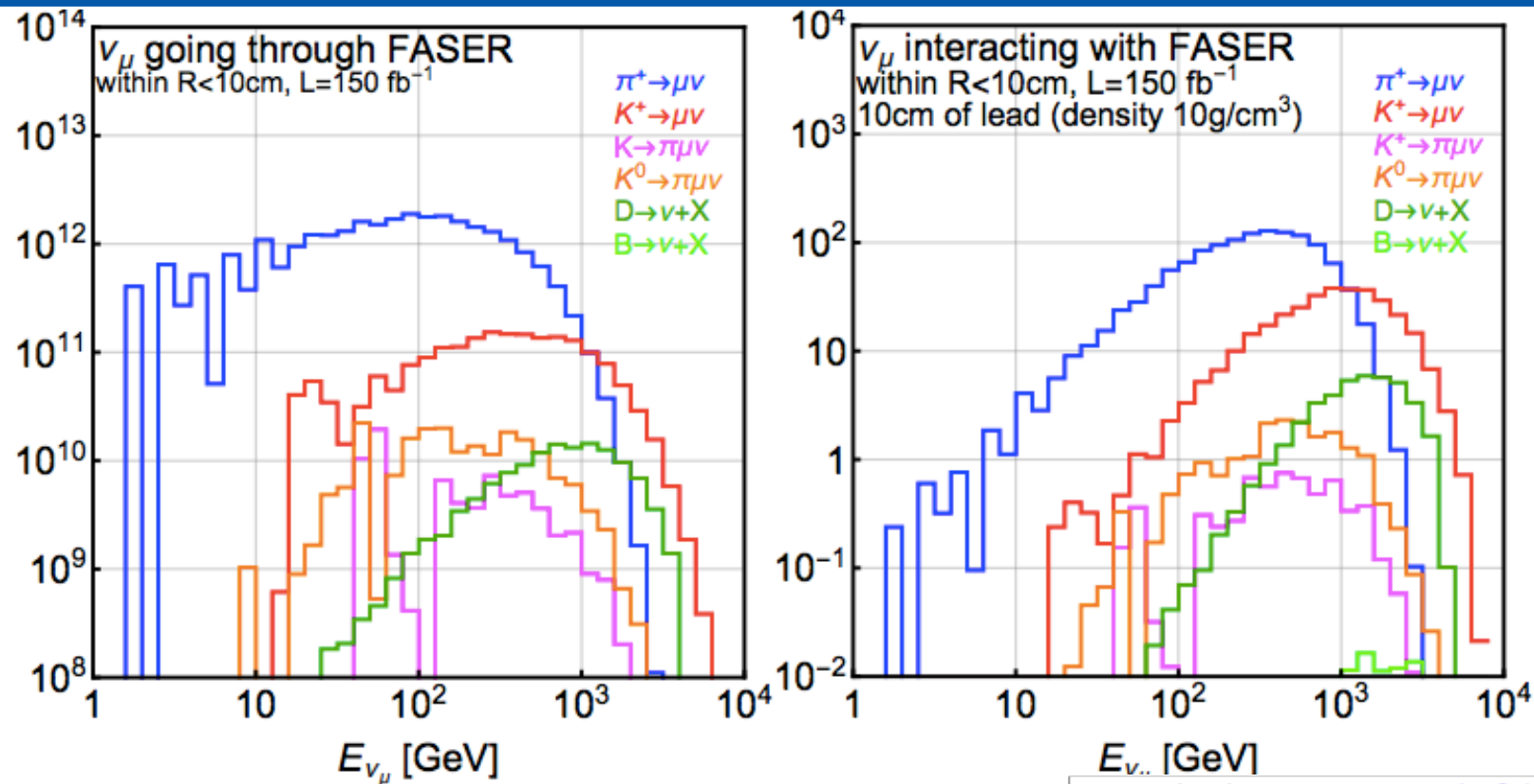
In longer term investigating installing a fine granularity silicon pre-shower to be able to separate close-by photons.

AXION LIKE PARTICLES (ALPs)

- Assuming background free single-photon like search for ALPs sensitivity for 10/fb and 150/fb

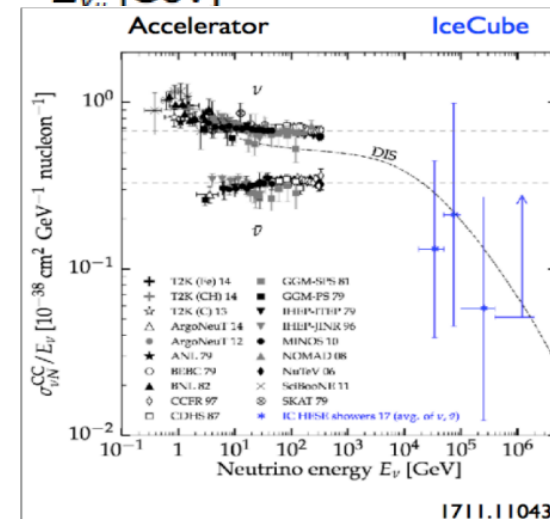


POSSIBLE NEUTRINO MEASUREMENTS



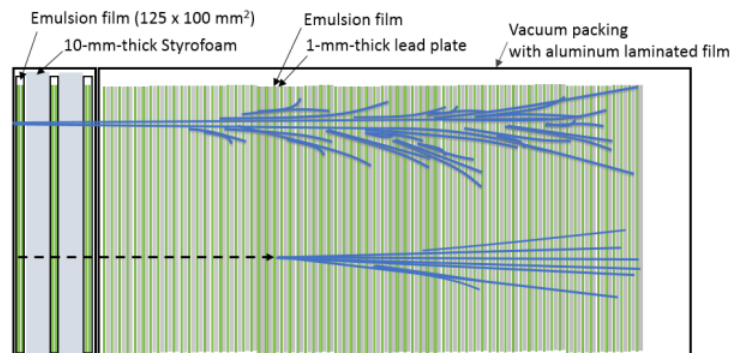
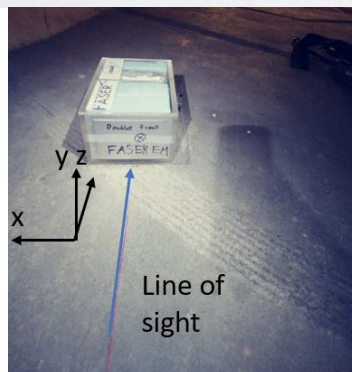
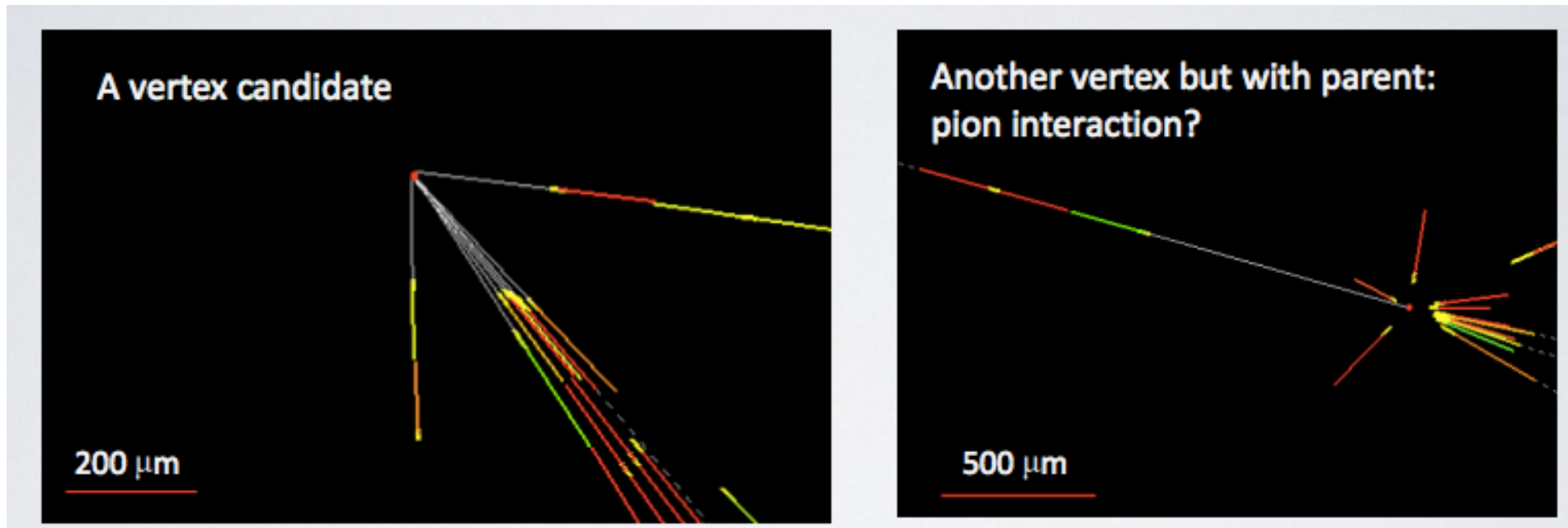
Huge flux of neutrinos through FASER could allow for interesting neutrino measurements e.g. ν_μ CC cross section in unexplored region $E > 400\text{ GeV}$.

There could also be interesting possibilities for ν_τ measurements at the FASER location (e.g. using emulsion detectors)



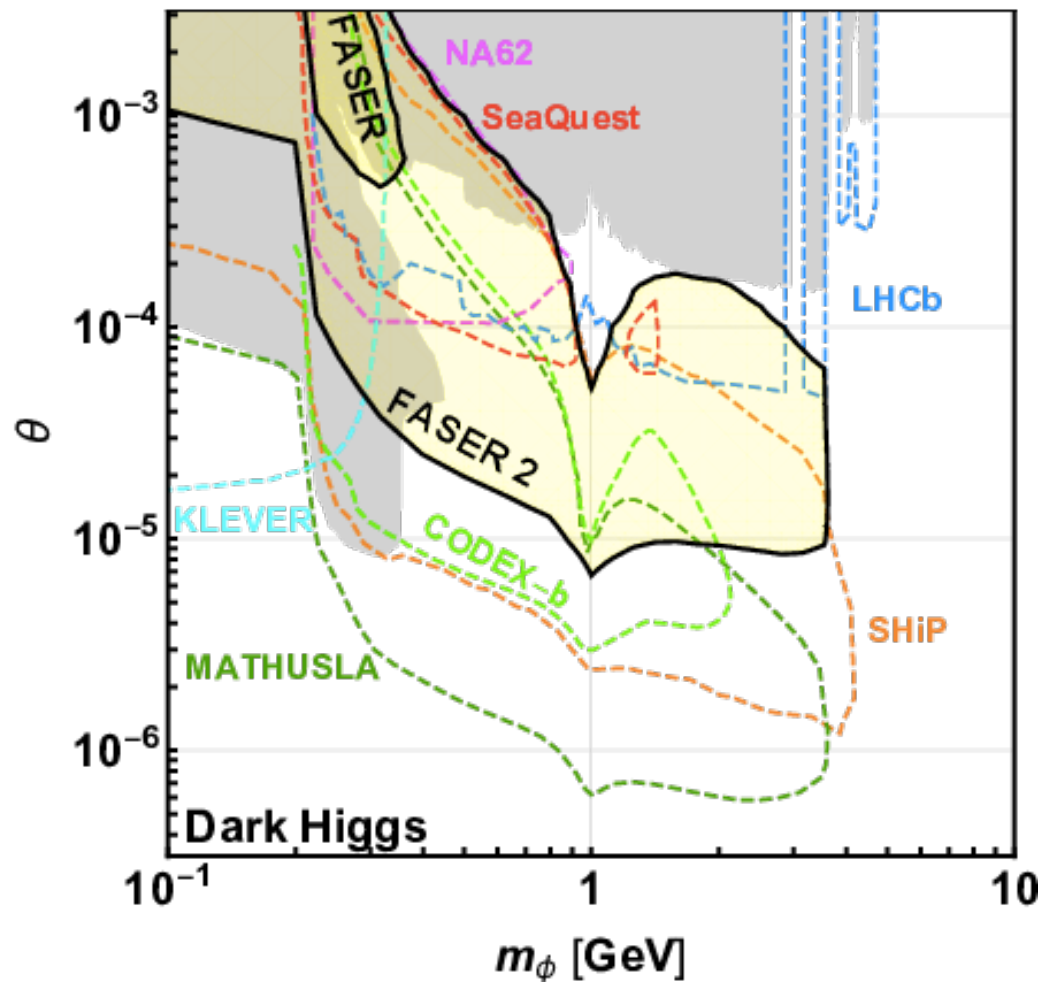
POSSIBLE NEUTRINO MEASUREMENTS

We are already looking for neutrino interactions in the emulsion detectors installed in T112 in 2018. This corresponded to 30 kg detector for 12.8/fb of data. First analysis has identified a few multi-track vertices. Further analysis needed to distinguish neutron interactions from neutrino interactions – expect a handful of muon neutrino interactions in this data.

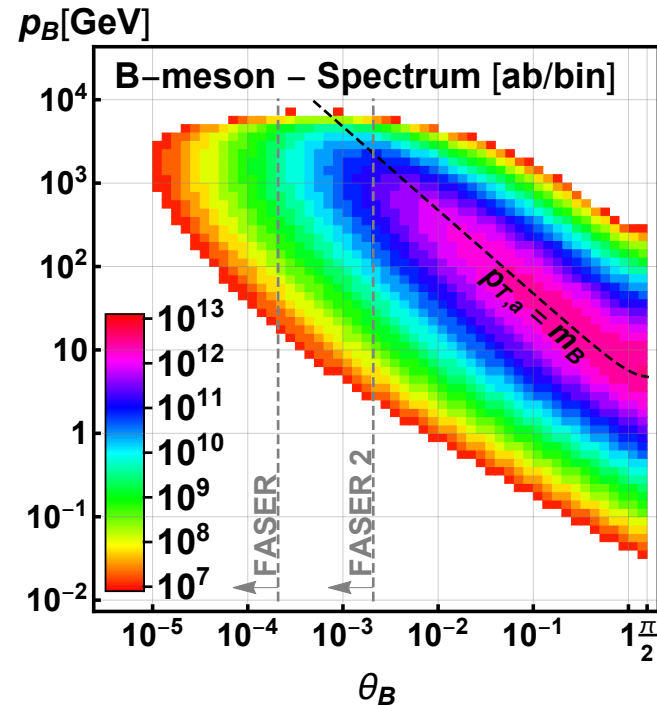


POSSIBLE FUTURE UPGRADE - FASER 2

- A potential upgraded detector for HL-LHC running, would increase sensitivity further
- Increasing detector radius to 1m would allow sensitivity to new physics produced in heavy meson (B, D) decays increasing the physics case beyond just the increased luminosity



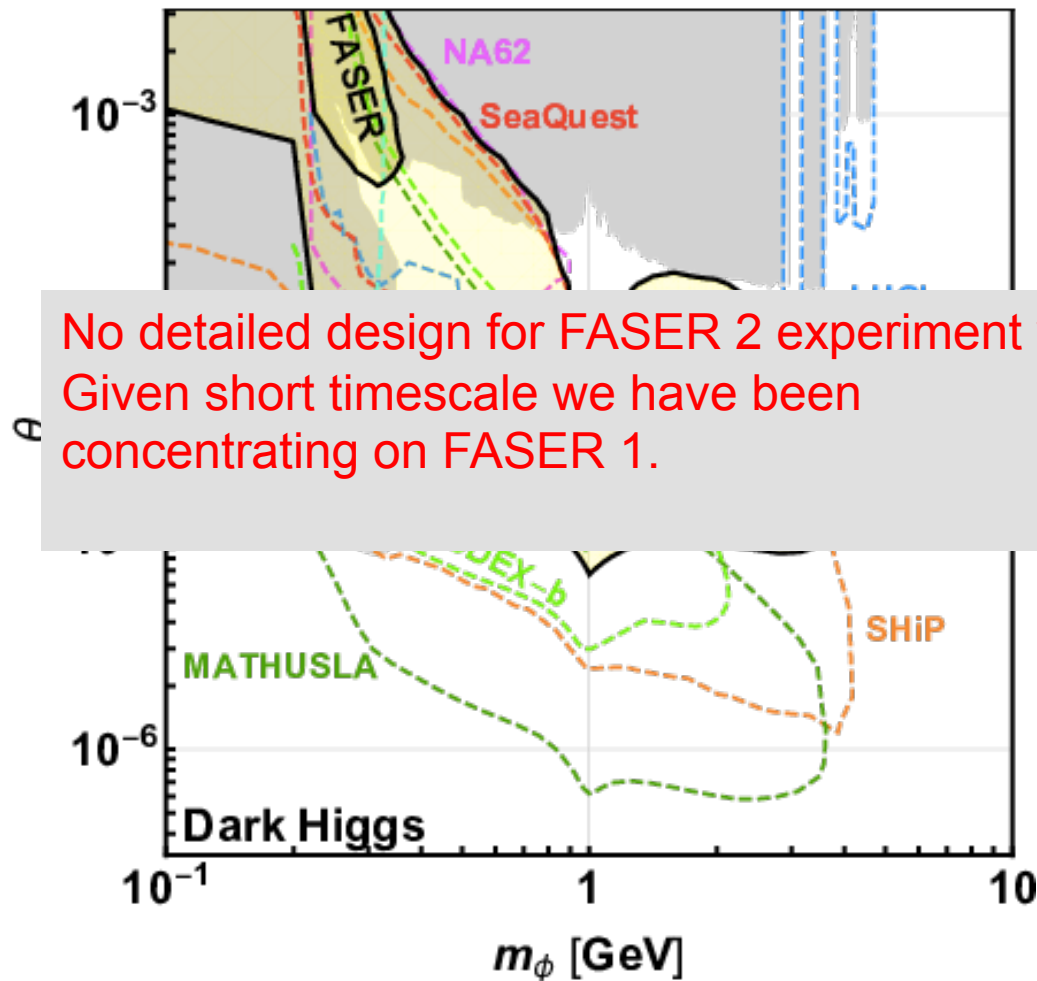
FASER 2 therefore becomes very strong compared to low energy experiments for certain models (dark Higgs), due to large B/D production rates at LHC:
 $N_B/N_\pi \sim 10^{-2}$ ($\sim 10^{-7}$ at beam dump expts)



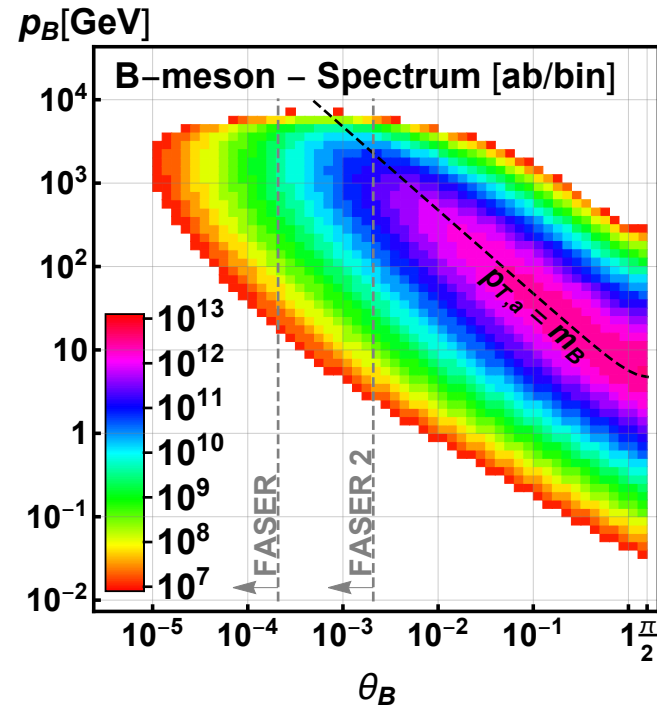
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FASER 2 therefore becomes very strong compared to low energy experiments for certain models (dark Higgs), due to large B/D production rates at LHC:
 $N_B/N_\pi \sim 10^{-2}$ ($\sim 10^{-7}$ at beam dump expts)



No detailed design for FASER 2 experiment yet. Given short timescale we have been concentrating on FASER 1.



PBC BENCHMARK 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 examples that are not PBC benchmarks.

| Benchmark Model | FASER 1 | FASER 2 | References |
|--------------------------------|---------|---------|--|
| BC1: Dark Photon | √ | √ | Feng, Galon, Kling, Trojanowski, 1708.09389 |
| BC1': $U(1)_{B-L}$ Gauge Boson | √ | √ | Bauer, Foldenauer, Jaeckel, 1803.05466; 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 | √ | √ | 1811.12522 |
| BC11: ALP with gluon | √ | √ | 1811.12522 |

CURRENT STATUS

- FASER Letter of Intent submitted to the LHCC in July 2018
 - arXiv:1811.10243
- Technical Proposal submitted to LHCC in November 2018
 - arXiv:1812.09139
- Experiment formally approved by CERN at the Research Board on March 5th 2019
- Detector designed to be affordable and fast to construct and install
 - Utilizing spare modules from existing experiments
 - Minimizing services needed where possible
 - Total detector cost <1MCHF (including contingency)
 - Host-Lab costs to be borne by CERN (civil engineering, transport, services)
- Funding for detector construction/operation secured from Simons Foundation and Heising-Simons Foundation
 - Installation in LS2, data-taking in Run 3
 - Schedule very tight!

SUMMARY AND OUTLOOK

- FASER is a proposed small, fast and cheap experiment to be installed in the LHC during LS2, to take data in Run 3
 - Taking advantage of already existing tunnel infrastructure and using spare detector parts from existing experiments
- It targets light, weakly-coupled new particles at low p_T , runs simultaneously with, and is complementary to, ATLAS/CMS, allowing to fill a possible hole in the current LHC new physics search programme
 - FASER has significant discovery potential for dark photons and other light, weakly coupled, new physics particles
- A possible upgrade FASER 2, with a bigger detector (radius = 1m) in LS3 would allow sensitivity to additional scenarios, including new particles produced in heavy meson decays
- Many thanks for the support from CERN:
 - Physics Beyond Colliders, EN/TE/BE Technical teams, EP dep. and CERN management (& LHCC reviewers)

THE FASER COLLABORATION

- The FASER Collaboration: 35 collaborators, 16 institutions, 8 countries

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 (Genova), 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), Roland Jansky (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)



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Dave C
(Genov
Ferrere
(Washin
Kajom
(Weizm
Brian P
Jordan
(Oregon



Part of the Collaboration

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orrence



ACKNOWLEDGEMENTS

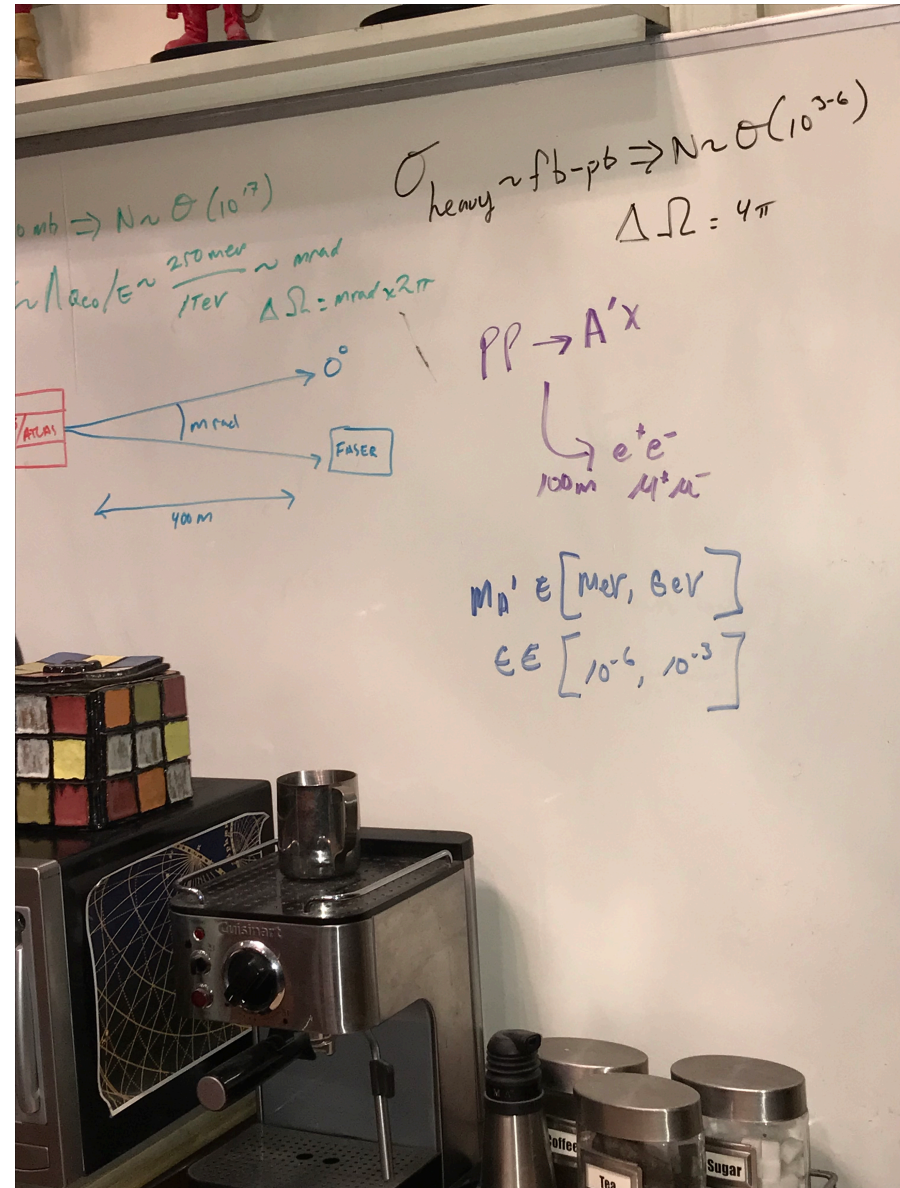
The FASER Collaboration gratefully acknowledges the contributions of many people

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

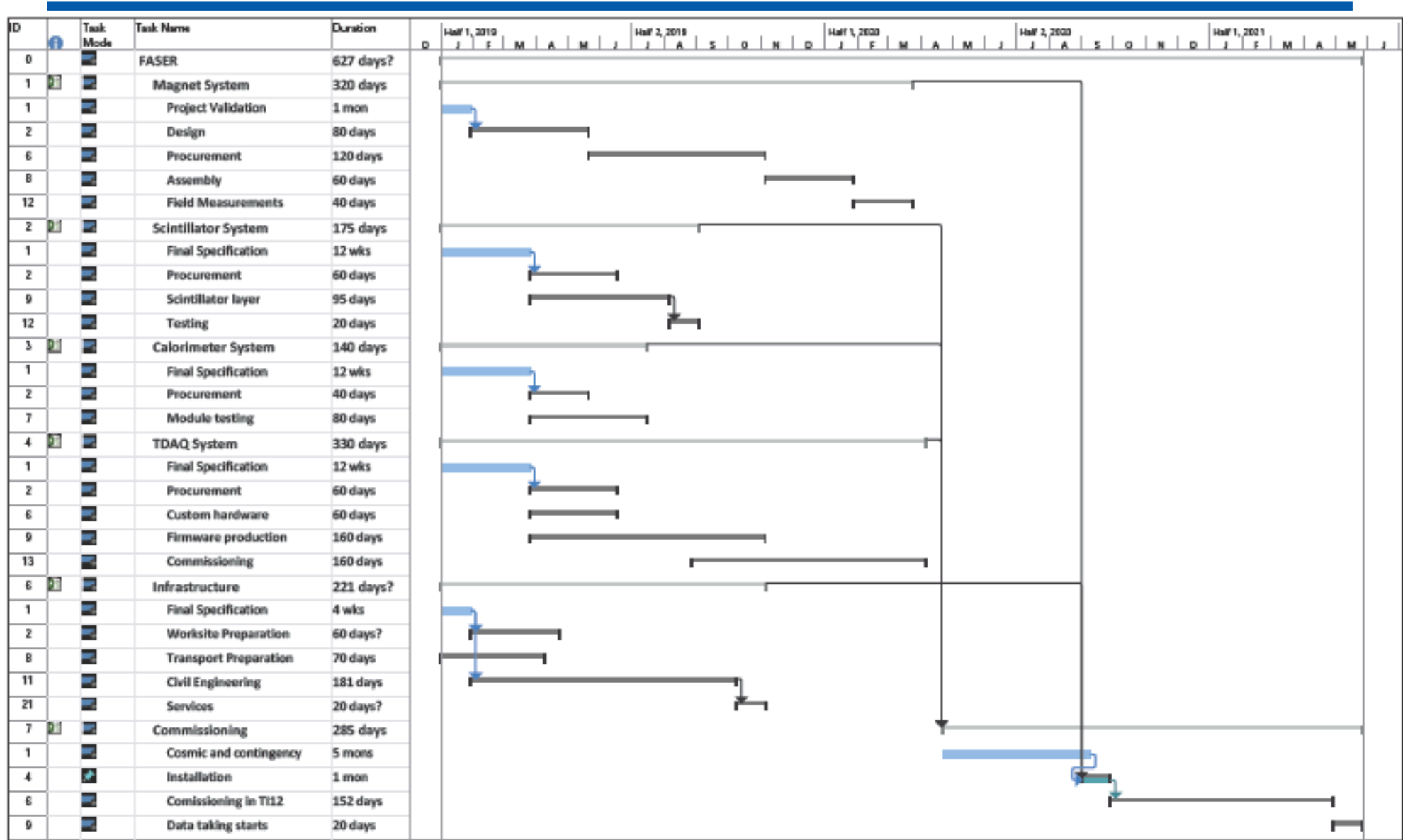
- Jonathan Gall, John Osborne (civil engineering);
- Liam Dougherty, Francisco Galan (integration);
- Pierre Thonet (magnets);
- Francesco Cerutti, Marta Sabate Gilarte (FLUKA simulation and background characterization);
- Salvatore Danzeca, Serge Chalaye (radiation measurements);
- James Storey, Swann 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!

BACK UP



Schedule

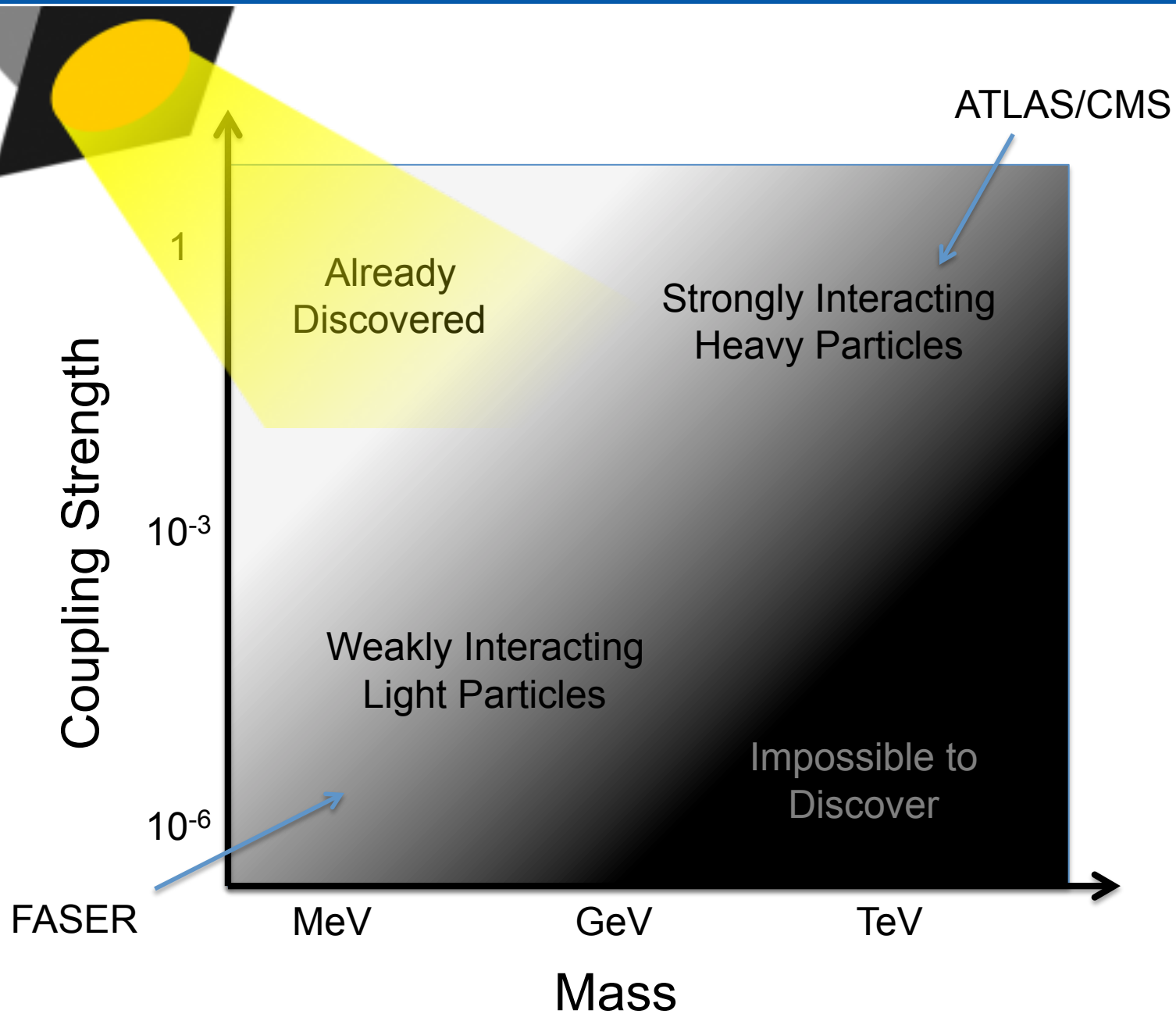


Note fitting work into LS2 schedule very complex.

No dust allowed in LHC tunnel in 2019 due to diode consolidation (means no digging)

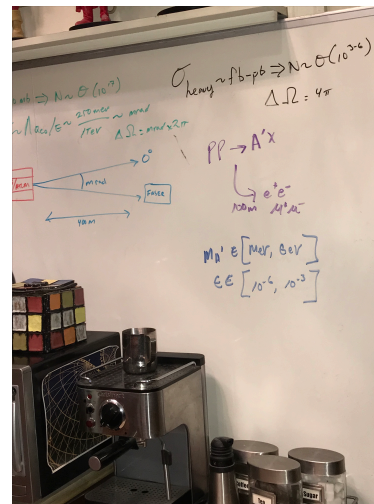
Need to transport FASER to TI12 before the machine is cooled (mid-June 2020)

LAMPPOST LANDSCAPE



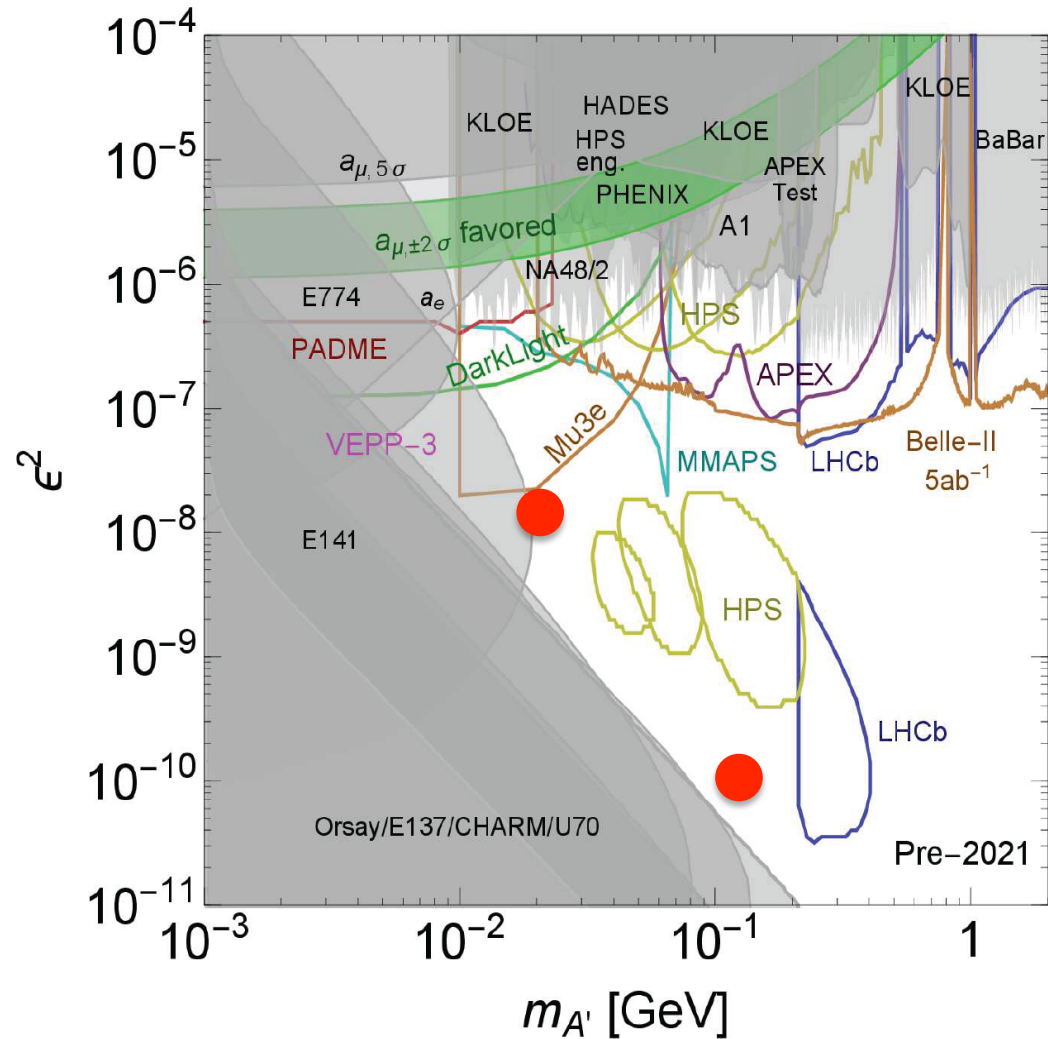
THE LIFETIME FRONTIER

- Very popular, many interesting experiments: LHCb, Belle-II, NA62, SHiP, SeaQuest, MilliQan, MATHUSLA, Codex-b, and many others
- FASER: **F**orw**A**rd **S**earch **E**xpe**R**iment. “The acronym recalls another marvelous instrument that harnessed highly collimated particles and was used to explore strange new worlds.”



DARK PHOTON STATUS

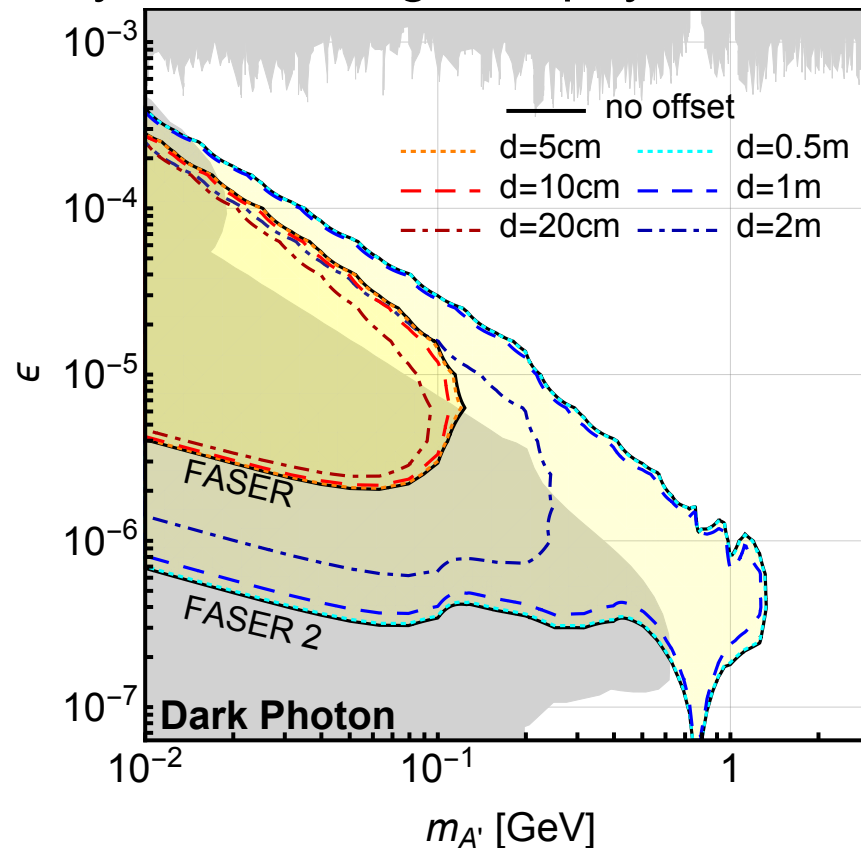
- Low $\varepsilon \rightarrow$ fixed target constraints, high $\varepsilon \rightarrow$ collider, precision constraints
- But still lots of open parameter space with
 - $m_{A'} > 10 \text{ MeV}$
 - $\varepsilon \sim 10^{-6} - 10^{-3}$
- E.g., 2 representative model points: $(m_{A'}, \varepsilon) =$
 - $(20 \text{ MeV}, 10^{-4})$
 - $(100 \text{ MeV}, 10^{-5})$



Cosmic Visions White Paper (2017)

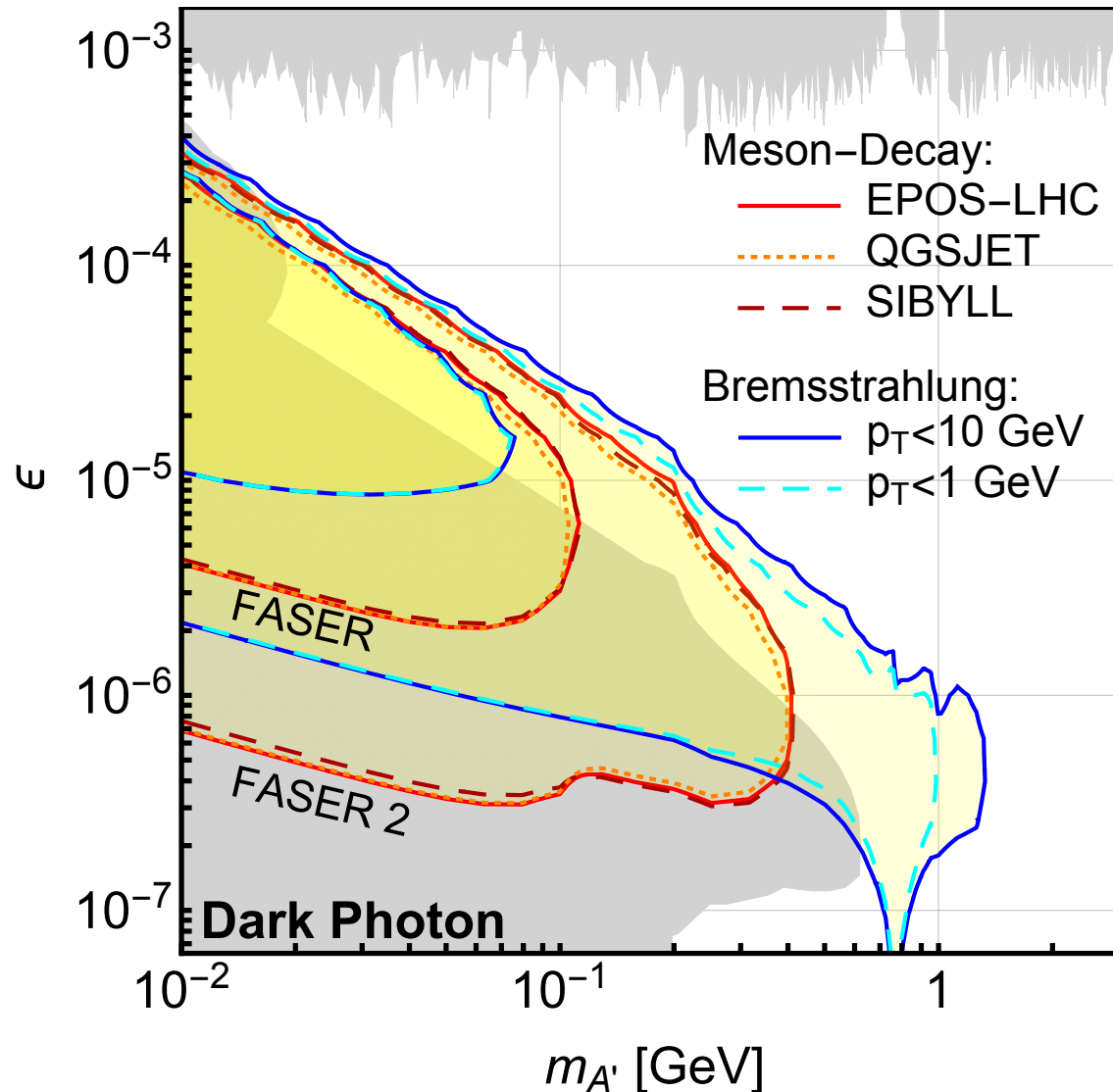
EFFECT OF LHC CROSSING ANGLE

- To avoid parasitic collisions and beam-beam effects in the common beampipe close to the IP, the LHC runs with a crossing-angle
 - The half crossing angle is $\sim 150\mu\text{rad}$, which moves the collision axis by $\sim 7.5\text{cm}$ at the FASER location
 - Such a change reduces the signal acceptance in FASER by $\sim 25\%$
 - Leads to very small changes in physics sensitivity



GENERATOR/SCALE DEPENDENCE

- Sensitivity basically unchanged when comparing production with different generators, and scale choices



FASER LHCC DOCUMENTS

Version: 14:25 (GMT) on Wednesday 7th November, 2018
DRAFT: LHCC, 7 November 2018

TECHNICAL PROPOSAL

FASER

FORWARD SEARCH EXPERIMENT AT THE LHC

Akitaki Ariga,¹ Tomoko Ariga,^{1,2} Jamie Boyd,^{3,*} Franck Cadoux,⁴ David W. Casper,⁵
Francesco Cerutti,³ Salvatore Danzeca,³ Liam Dougherty,³ Yannick Favre,⁴
Jonathan L. Feng,^{6,†} Didier Ferrere,⁴ Jonathan Gall,³ Iftah Galon,⁶ Sergio
Gonzalez-Sevilla,⁴ Shih-Chieh Hsu,⁷ Giuseppe Iacobucci,⁴ Enrique Kajomovitz,⁸ Felix
Kling,⁵ Susanne Kuehn,² Mike Lamont,² Lorne Levinson,⁹ Hidetoshi Otono,² John
Osborne,³ Brian Petersen,³ Osamu Sato,¹⁰ Marta Sabaté-Gilarte,^{3,11} Matthias
Schott,¹² Anna Sfyra,⁴ Jordan Smolinsky,³ Aaron M. Soffa,³ Yosuke Takubo,¹³
Pierre Thonet,³ Eric Terrence,¹⁴ Sebastian Trojanowski,¹⁵ and Gang Zhang¹⁶

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²Kyushu University, Nishi-ku, 819-0395 Fukuoka, Japan

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⁸Technion—Israel Institute of Technology, Haifa 32000, Israel

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¹⁰Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8602, Japan

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¹⁶Tsinghua University, Beijing, China

Submitted to the LHCC, 18 July 2018

CERN-LHCC-2018-030, LHCC-I-032
UCI-TR-2018-18, KYUSHU-RCAPP-2018-05

LETTER OF INTENT

FASER

FORWARD SEARCH EXPERIMENT AT THE LHC

Akitaki Ariga,¹ Tomoko Ariga,^{1,2} Jamie Boyd,^{3,*} David W. Casper,⁴ Jonathan L. Feng,^{4,†}
Iftah Galon,⁵ Shih-Chieh Hsu,⁶ Felix Kling,⁴ Hidetoshi Otono,² Brian Petersen,³
Osamu Sato,⁷ Aaron M. Soffa,⁴ Jeffrey R. Swaney,⁴ and Sebastian Trojanowski⁸

¹Universität Bern, Stälerstrasse 5, CH-3012 Bern, Switzerland

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⁸National Centre for Nuclear Research, Hoza 69, 00-681 Warsaw, Poland

Executive Summary

FASER is a proposed small and inexpensive experiment designed to search for light, weakly-interacting particles at the LHC. Such particles are dominantly produced along the beam collision axis and may be long-lived, traveling hundreds of meters before decaying. To exploit both of these properties, FASER is to be located along the beam collision axis, 480 m downstream from the ATLAS interaction point, in the unused service tunnel T118. We propose that FASER be installed in T118 in Long Shutdown 2 in time to collect data from 2021-23 during Run 3 of the 14 TeV LHC. FASER will detect new particles that decay within a cylindrical volume with radius $R = 10$ cm and length $L = 1.5$ m. With these small dimensions, FASER will complement the LHC's existing physics program, extending its discovery potential to a host of new particles, including dark photons, axion-like particles, and other CP-odd scalars. A FLUKA simulation and analytical estimates have confirmed that numerous potential backgrounds are highly suppressed at the FASER location, and the first *in situ* measurements are currently underway. We describe FASER's location and discovery potential, its target signals and backgrounds, the detector's layout and components, and the experiment's preliminary cost estimate, funding, and timeline.

* Contact email: Jamie.Boyd@cern.ch

† Contact email: jlf@uci.edu

arXiv:1811.10243v1 [physics.ins-det] 26 Nov 2018

ASSUMPTIONS FOR OTHER EXPTS LIMITS

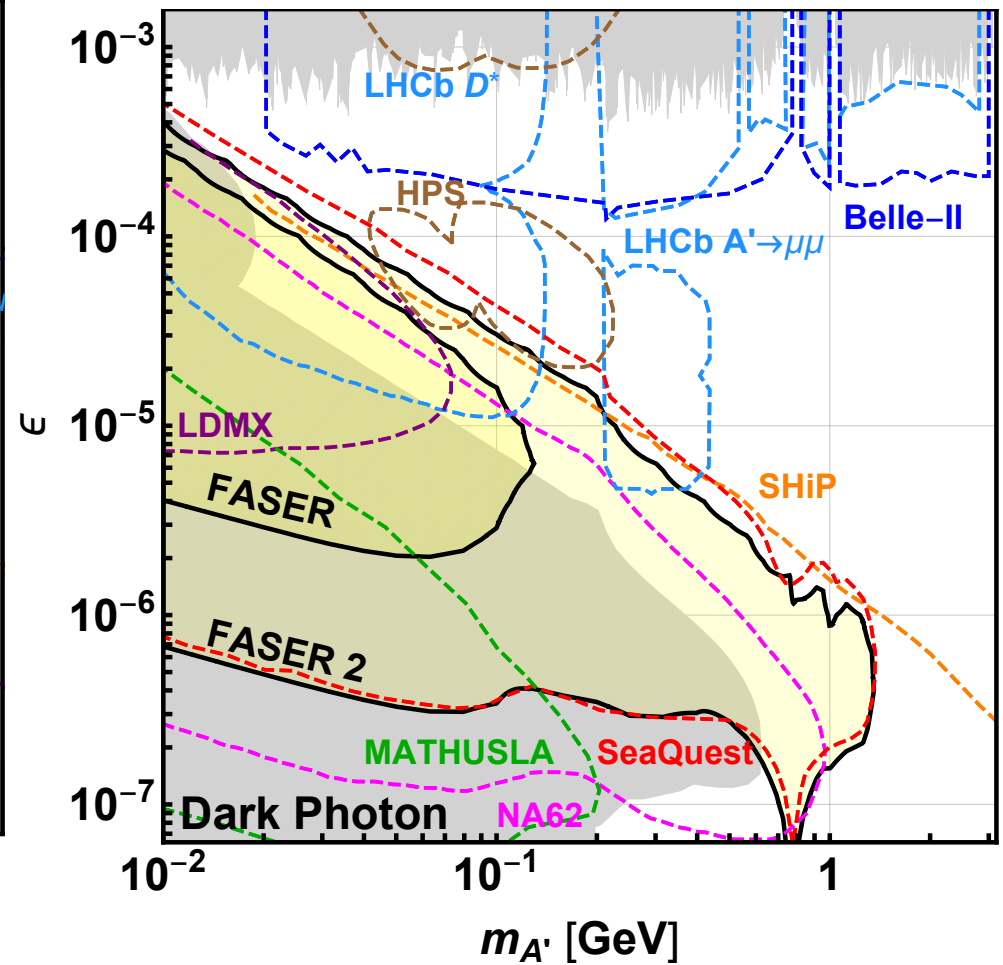
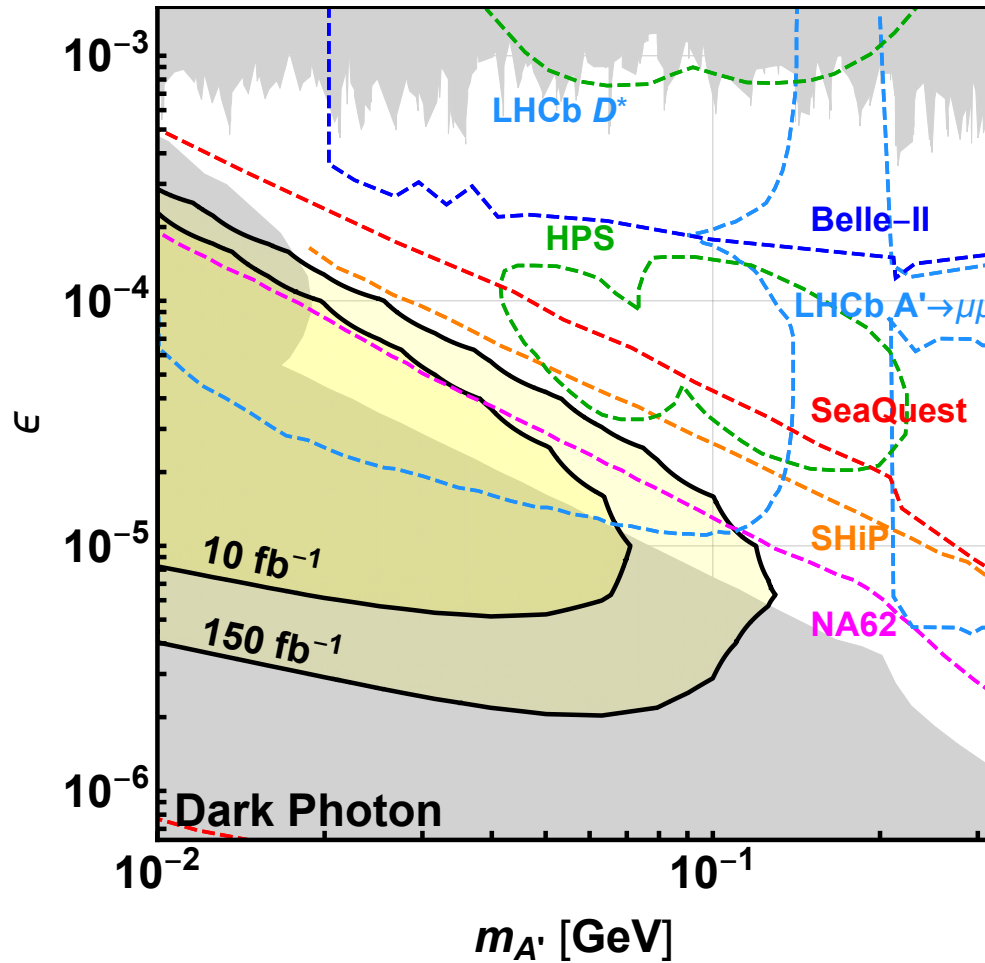
NA62 assumes 3.9×10^{17} protons on target (POT) while running in a beam dump mode that is being considered for LHC Run 3 [16]; SeaQuest assumes 1.44×10^{18} POT, which could be obtained in two years of parasitic data taking and requires additionally the installation of a calorimeter [12, 17]; the proposed beam dump experiment SHiP assumes $\sim 2 \times 10^{20}$ POT collected in 5 years of operation [16, 18]; Belle-II and LHCb assume the full expected integrated luminosity of 50 ab^{-1} [19] and 300 fb^{-1} [20, 21], respectively;

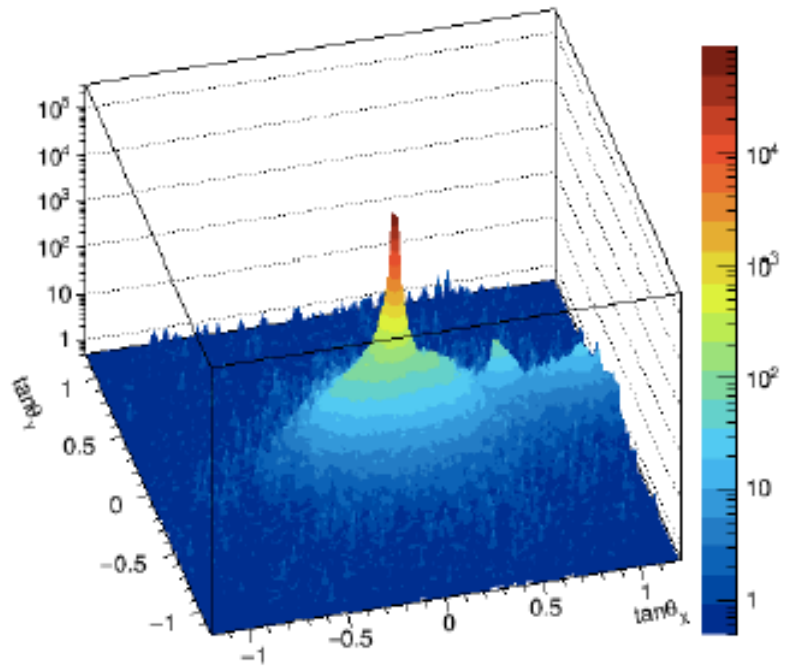
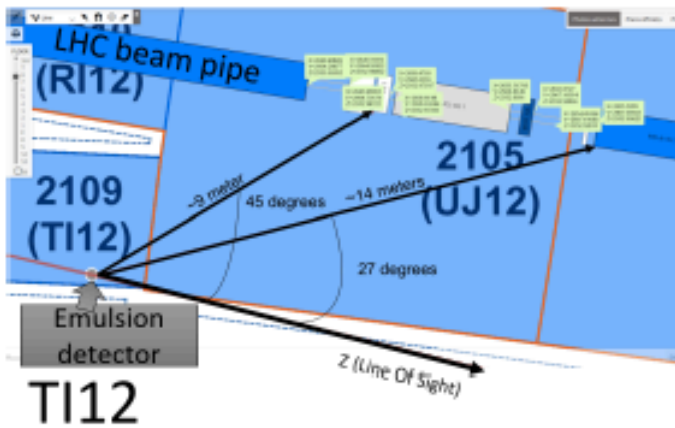
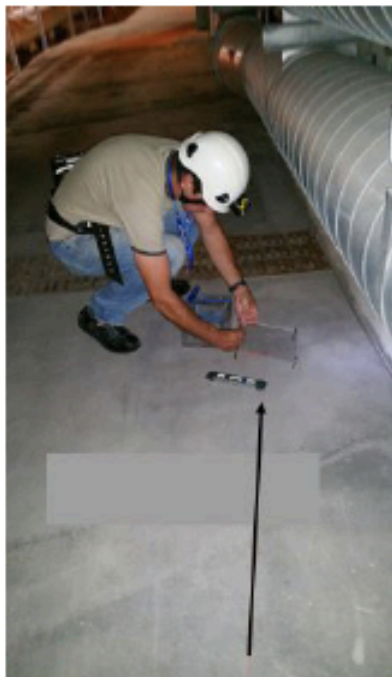
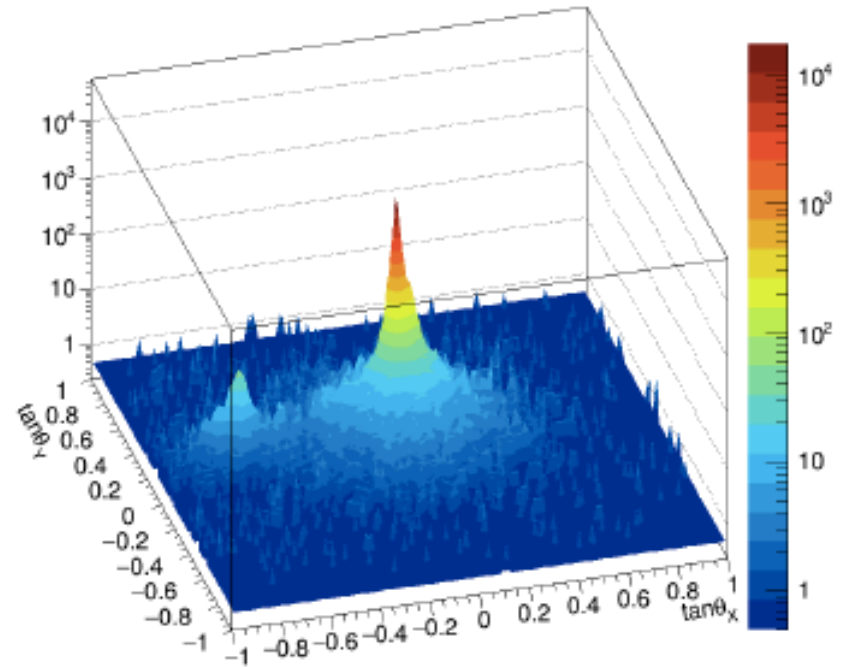
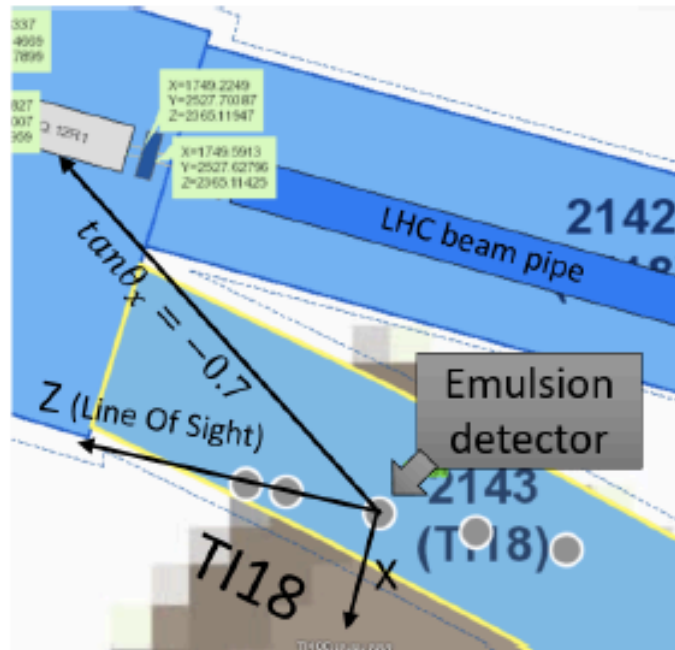
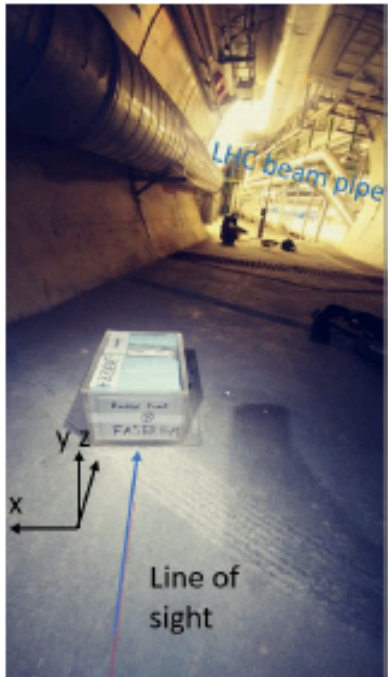
- [12] M. Bauer, P. Foldenauer, and J. Jaeckel, “Hunting All the Hidden Photons,” *JHEP* **07** (2018) 094, [arXiv:1803.05466 \[hep-ph\]](#).
- [16] B. Döbrich, J. Jaeckel, F. Kahlhoefer, A. Ringwald, and K. Schmidt-Hoberg, “ALPtraum: ALP production in proton beam dump experiments,” *JHEP* **02** (2016) 018, [arXiv:1512.03069 \[hep-ph\]](#). [JHEP02,018(2016)].
- [17] A. Berlin, S. Gori, P. Schuster, and N. Toro, “Dark Sectors at the Fermilab SeaQuest Experiment,” *Phys. Rev. D* **98** no. 3, (2018) 035011, [arXiv:1804.00661 \[hep-ph\]](#).
- [18] S. Alekhin *et al.*, “A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case,” *Rept. Prog. Phys.* **79** (2016) 124201, [arXiv:1504.04855 \[hep-ph\]](#).
- [19] M. J. Dolan, T. Ferber, C. Heartv, F. Kahlhoefer, and K. Schmidt-Hoberg, “Revised constraints and Belle II sensitivity for visible and invisible axion-like particles,” *JHEP* **12** (2017) 094, [arXiv:1709.00009 \[hep-ph\]](#).
- [20] P. Ilten, J. Thaler, M. Williams, and W. Xue, “Dark photons from charm mesons at LHCb,” *Phys. Rev. D* **92** (2015) 115017, [arXiv:1509.06765 \[hep-ph\]](#).
- [21] P. Ilten, Y. Soreq, J. Thaler, M. Williams, and W. Xue, “Proposed Inclusive Dark Photon Search at LHCb,” *Phys. Rev. Lett.* **116** (2016) 251803, [arXiv:1603.08926 \[hep-ph\]](#).

HPS limits taken from talk:

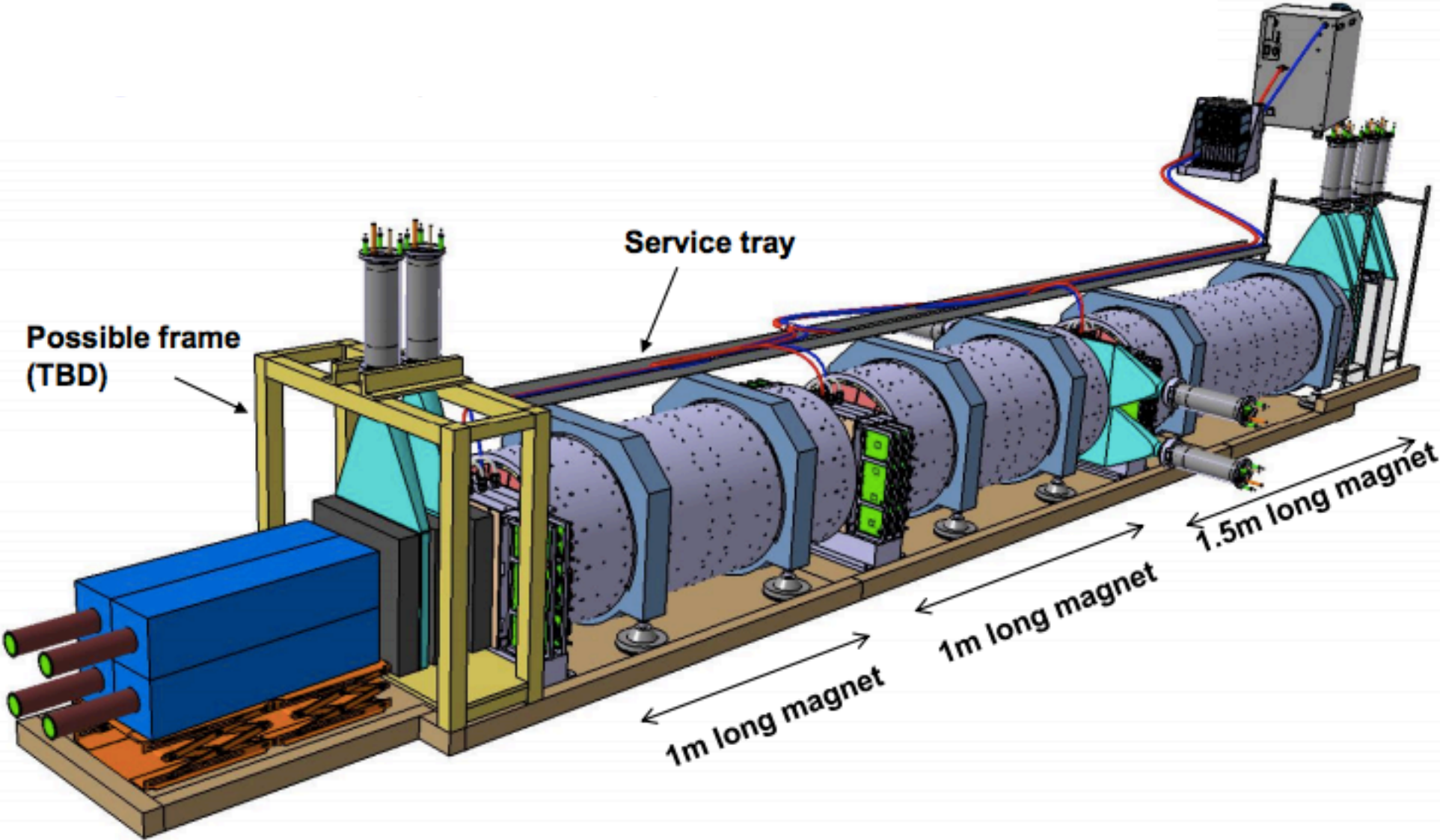
‘First Results from the Heavy Photon Search Experiment’ at ICHEP 2018

ASSUMPTIONS FOR OTHER EXPTS LIMITS





Detector Support



Tracker alignment issues

Momentum resolution will be limited by the relative alignment of the 3 tracking stations in the bending plane.

Significant rate of muons going through FASER tracker, but since we don't know their momentum they can not be used to constrain this alignment (no standard candles (Z, J/psi etc..) in FASER.

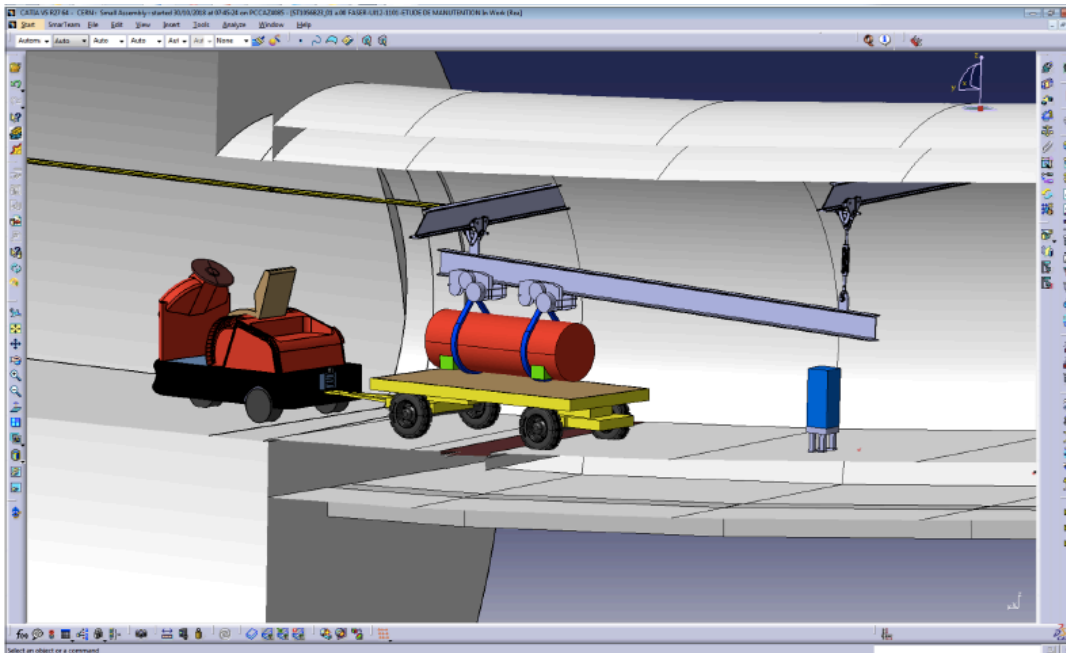
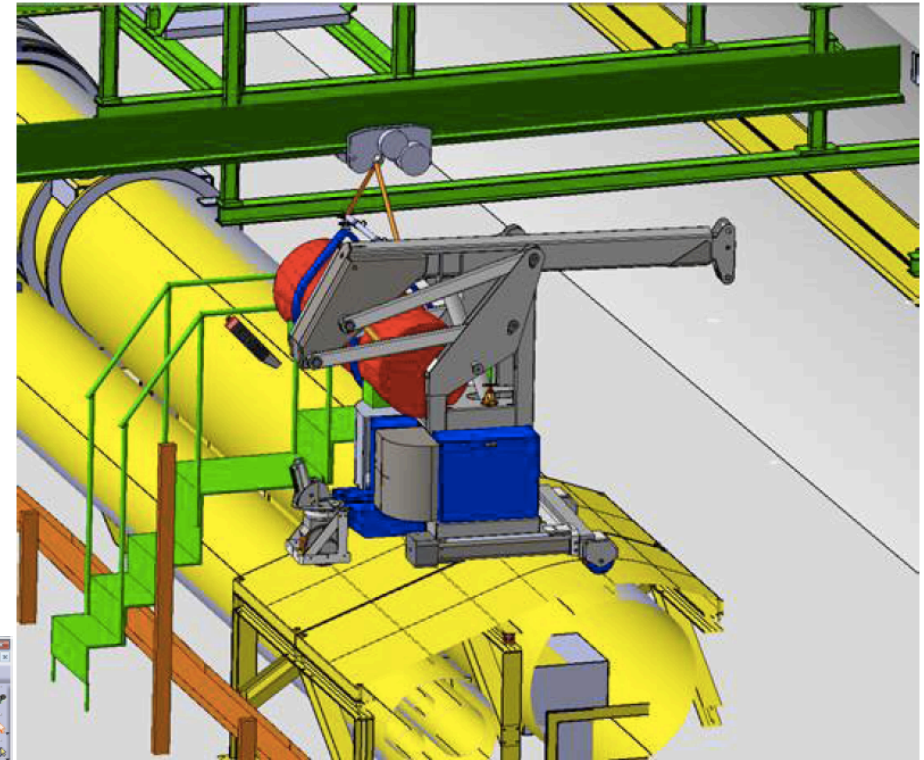
Since we use a permanent magnet we cannot use the trick (used in ATLAS MS) of taking straight track data with the field off to constrain the alignment.

A 100um precision of the relative position of the tracking stations in the bending plane, leads to 100% uncertainty on the momentum for track momenta above ~650 GeV.

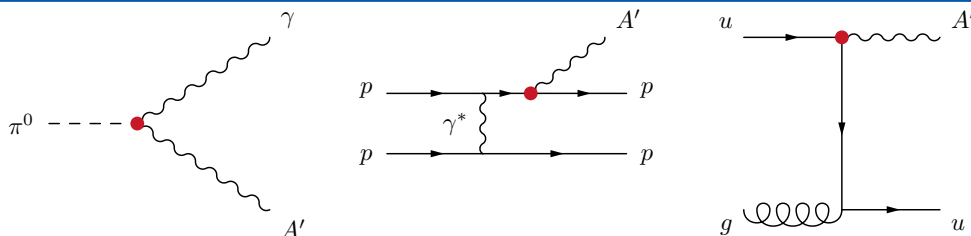
For FASER physics good track momentum resolution not needed, but of course for many reasons (background measurements, auxiliary physics measurements etc..) we want as good resolution as possible.

Transport / Installation issues

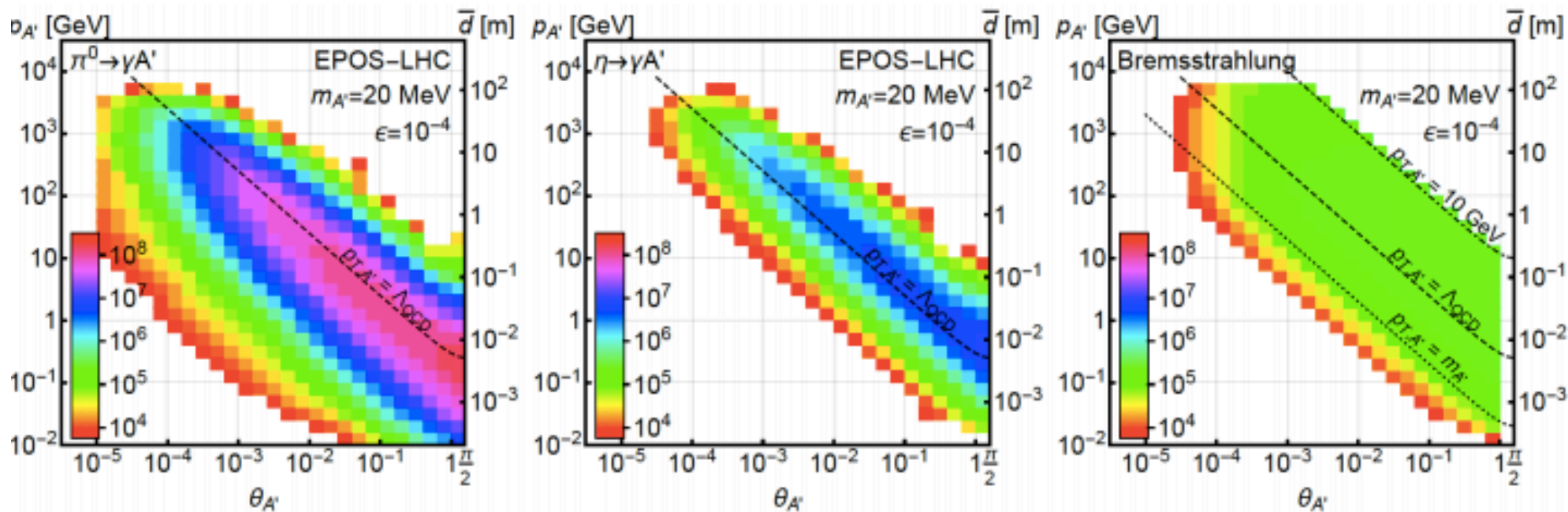
FASER components need to be carried over the LHC machine, and the QRL He cryo line, to get to TI12. Limits when this can be done, and requires installing protection.



OTHER PRODUCTION MECHANISMS



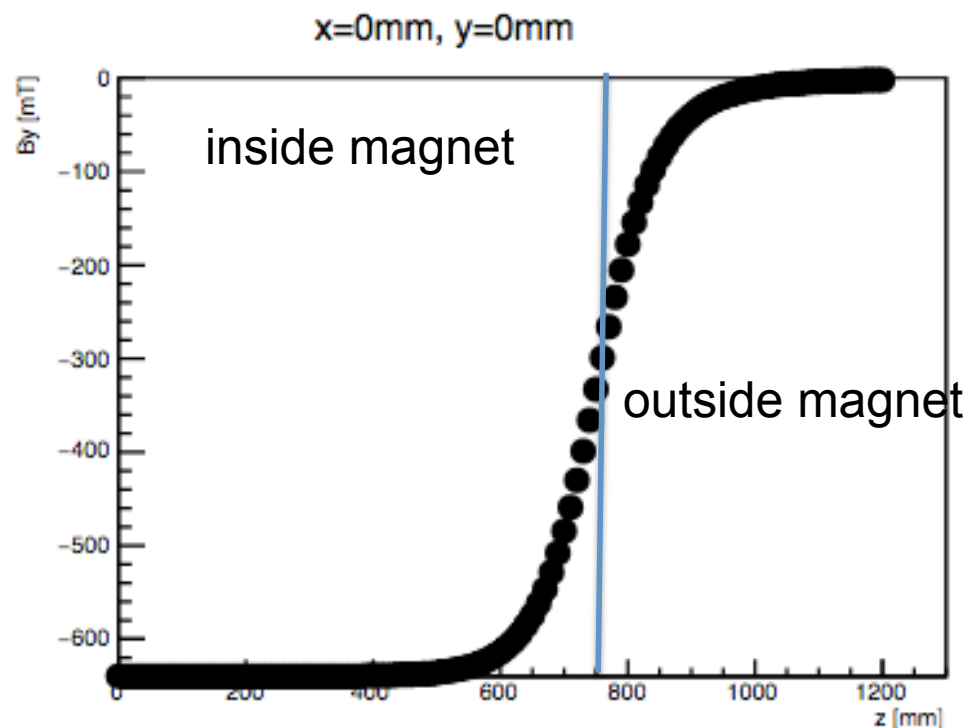
- Consider π^0 decay, η decay, dark bremsstrahlung
- Results for 1st model point: $(m_{A'}, \epsilon) = (20 \text{ MeV}, 10^{-4})$



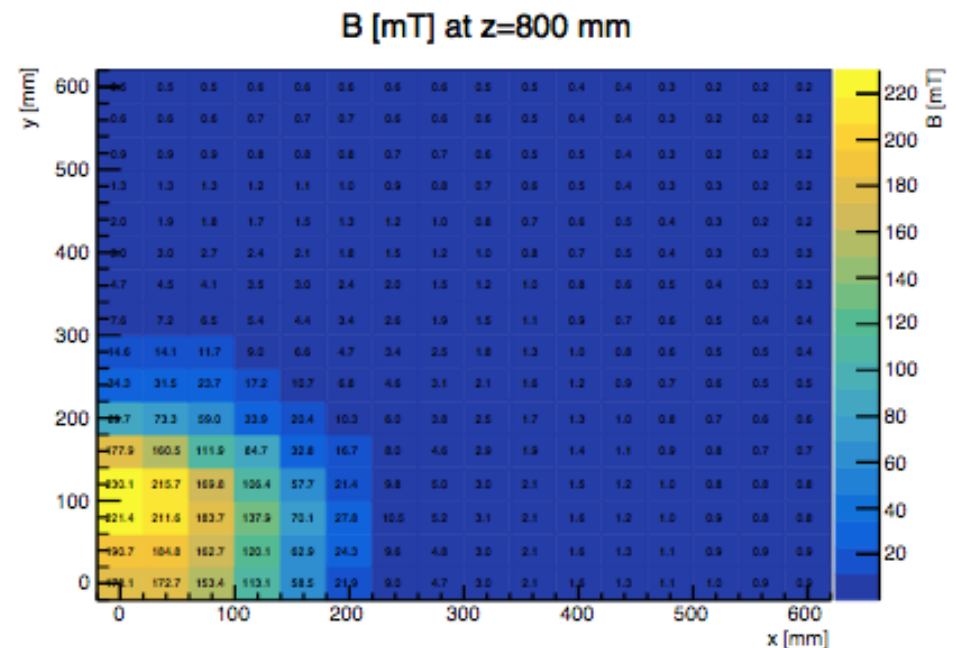
- From $\pi^0 \rightarrow \gamma A'$, $E_{A'} \sim E_\pi / 2$ (no surprise)
- But note rates: even after ϵ^2 suppression, $N_{A'} \sim 10^8$;

STRAY MAGNETIC FIELD

- More detailed calculation of stray field, also going to larger distance
 - 3mT limit (for signage at CERN) always within 50cm of magnet centre (so enclosed in trench, does not impact access)



5cm outside magnet opening



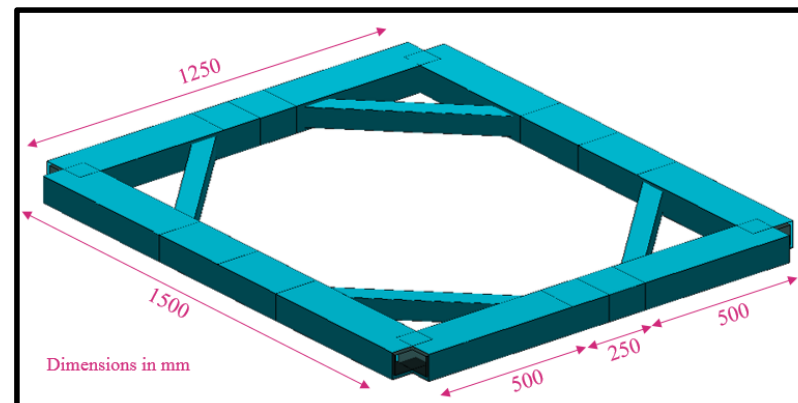
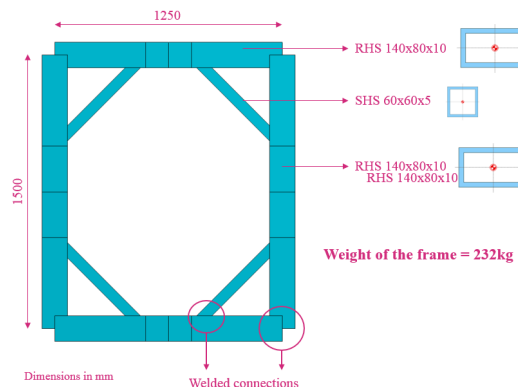
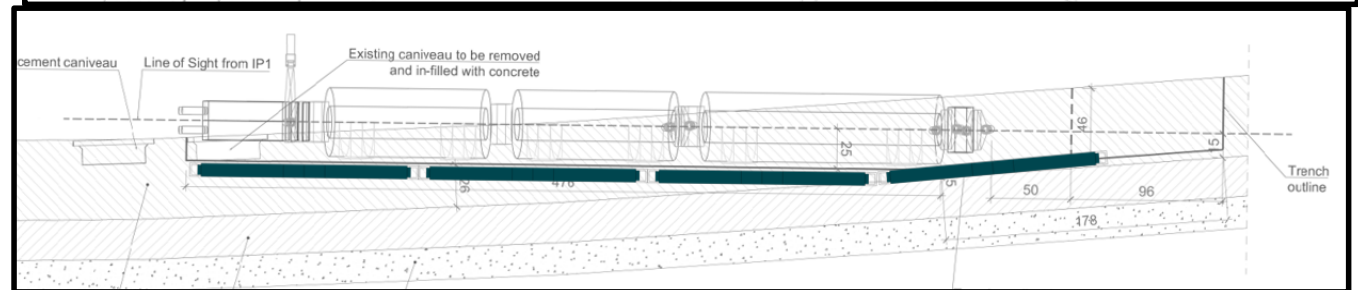
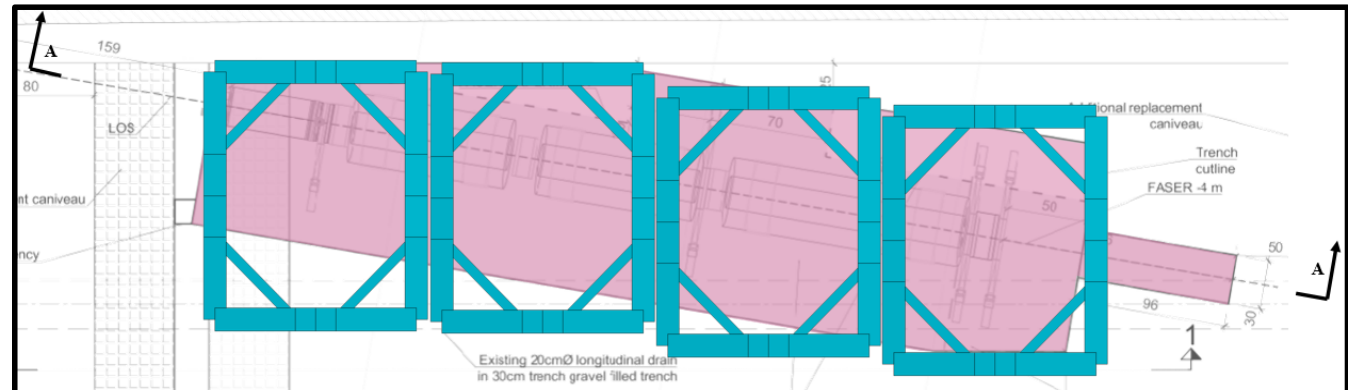
1mT field 50cm from magnet centre

Magnets: Parameter Table

| Magnet | Short model | Long model | Unit |
|-------------------------------------|----------------------------------|----------------------------------|------|
| Type | Dipole | Dipole | |
| Aperture diameter | 200 | 200 | mm |
| Length | 1000 | 1500 | mm |
| Outer diameter | 430 | 430 | mm |
| Mass (including support) | 914 | 1331 | kg |
| Yoke | | | |
| Steel type | Construction steel | Construction steel | |
| Iron length | 1000 | 1500 | mm |
| Permanent magnets | | | |
| Permanent magnet material | Sm ₂ Co ₁₇ | Sm ₂ Co ₁₇ | |
| BH max | 32 | 32 | MGOe |
| Mass of permanent magnet | 606 | 909 | kg |
| Magnetic field | | | |
| Nominal field at the centre | 0.576 | 0.576 | T |
| Nominal integrated field | 0.584 | 0.87 | T.m |
| Magnetic length | 1014 | 1510 | mm |
| GFR radius | 100 | 100 | mm |
| Integrated field homogeneity in GFR | ≤ ± 3 | ≤ ± 3 | % |
| Integral field error (rms) | ≤ ± 2 | ≤ ± 2 | % |

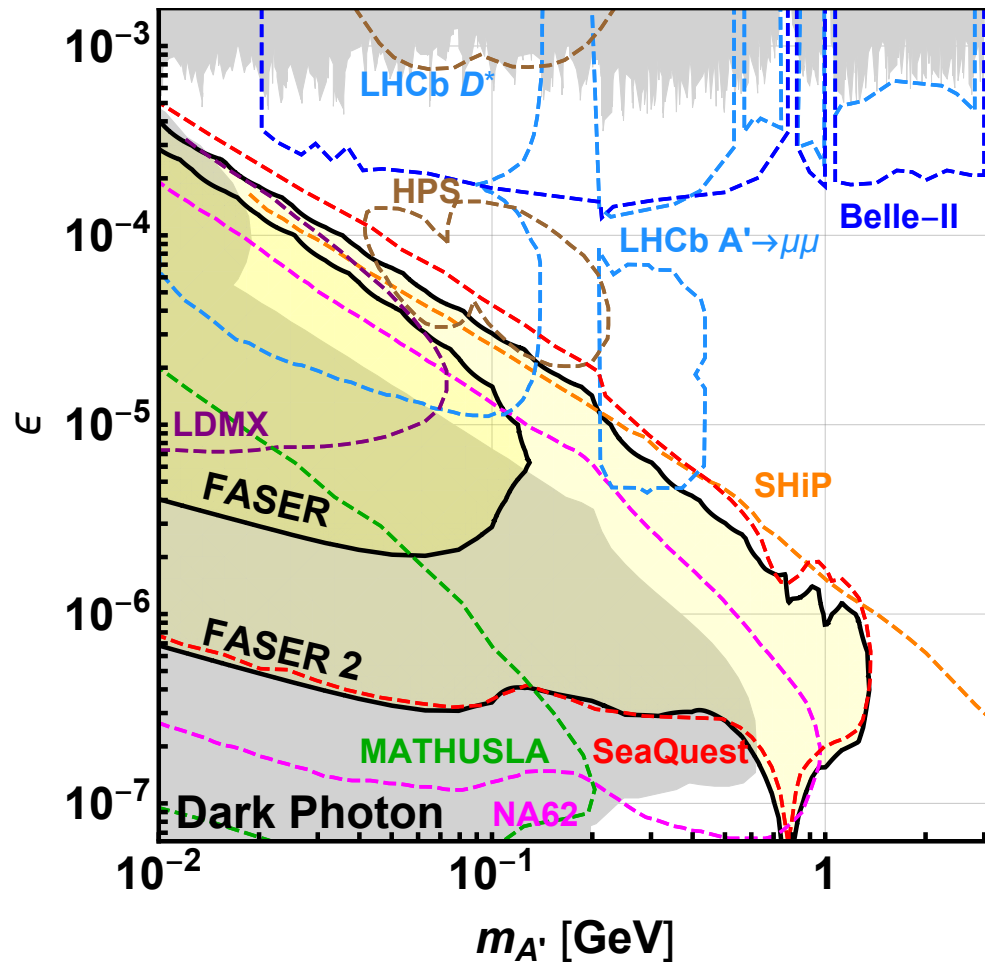
CE works: Strengthening Concept

- Modular design of four stainless steel frames
- Assembled at surface
- Frames within transport parameters
- Installation in stages
- Flexible

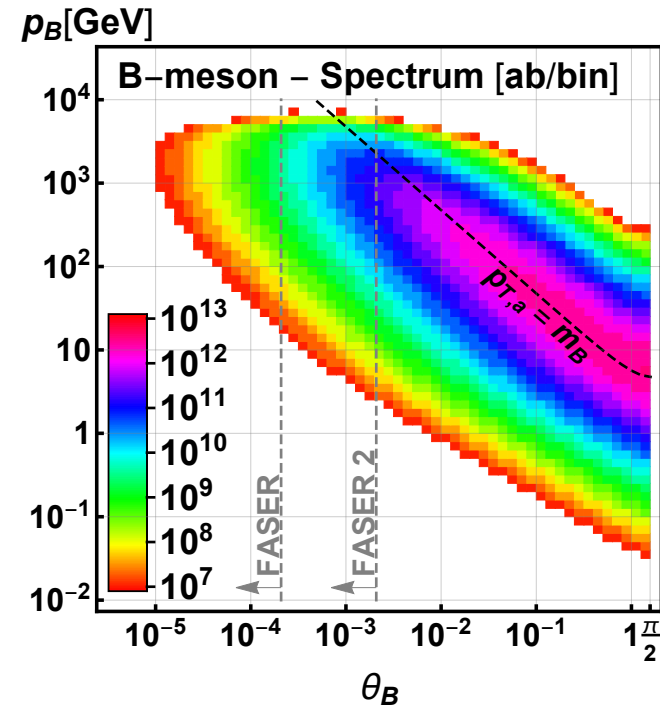


POSSIBLE FUTURE UPGRADE - FASER 2

- A potential upgraded detector for HL-LHC running, would increase sensitivity further
- Increasing detector radius to 1m would allow sensitivity to new physics produced in heavy meson (B, D) decays increasing the physics case beyond just the increased luminosity



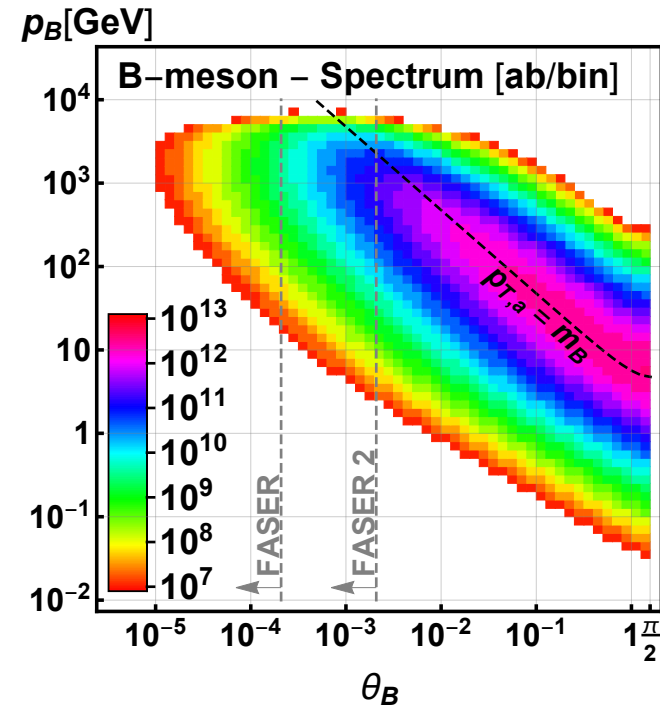
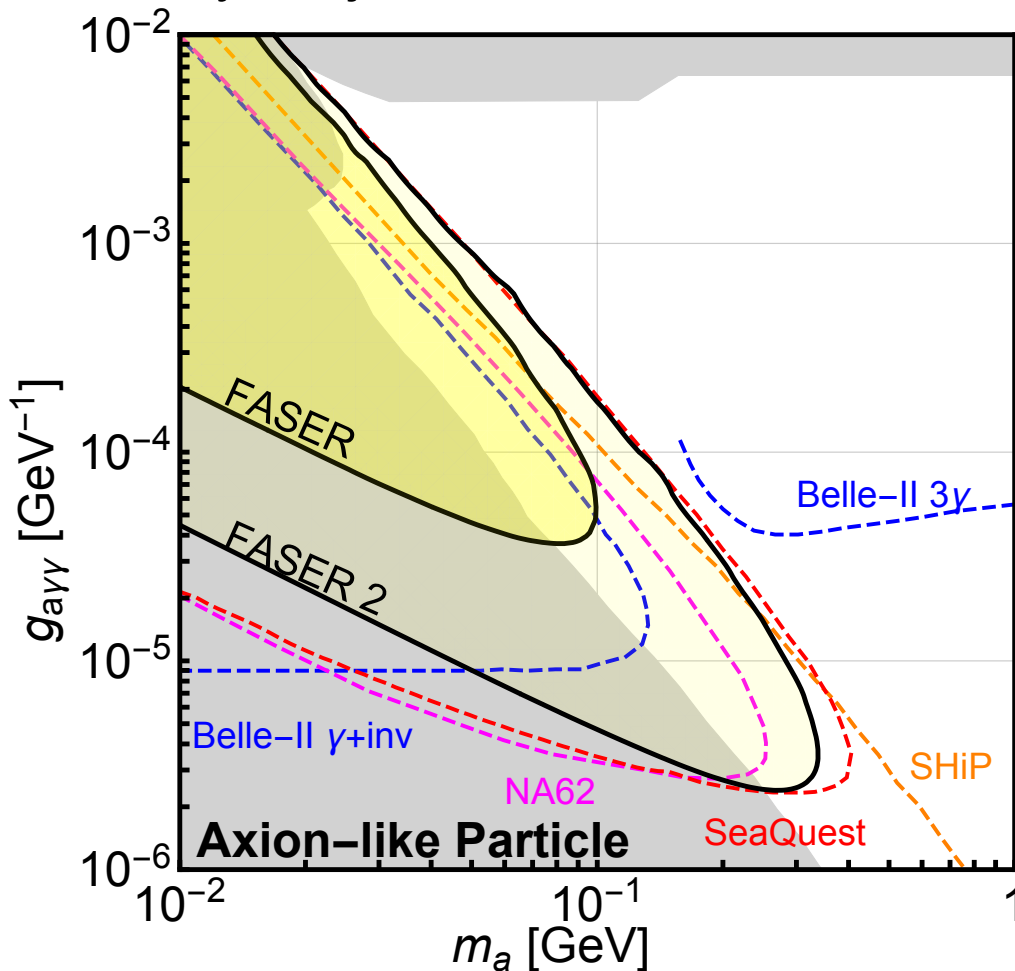
FASER 2 therefore becomes very strong compared to low energy experiments for certain models (dark Higgs), due to large B/D production rates at LHC:
 $N_B/N_\pi \sim 10^{-2}$ ($\sim 10^{-7}$ at beam dump expts)



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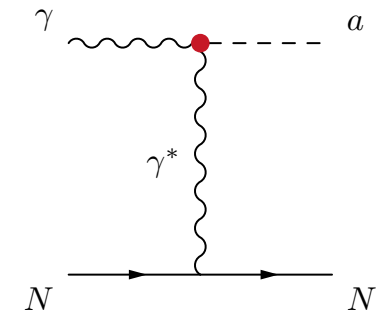


ANOTHER EXAMPLE: Axion-Like-Particles (ALPs)

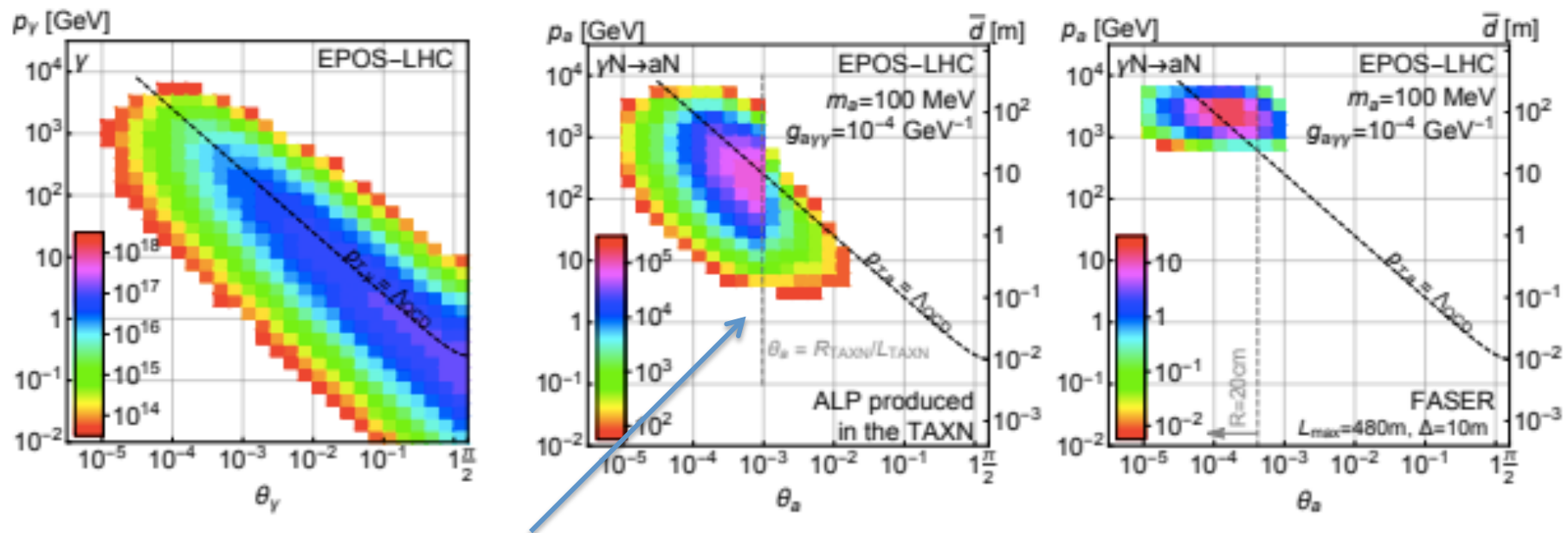
ALP production using the LHC as a beam-dump experiment.

Very high energy photons produced in LHC collisions, interacting with material in the **TAN** can produce ALPs.

The ALPs (with \sim TeV energy) then propagate in a straight line, and can decay inside FASER (480-140 = 340m from their production point).



ALP production via the Primakoff process from photons scattering in the TAN



Assuming angular coverage of TAN is < 1 mrad

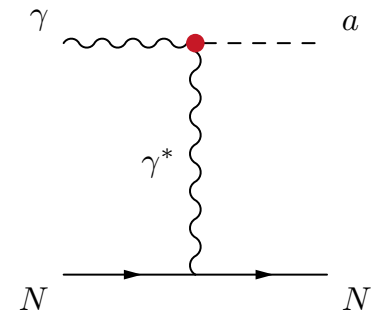
note this old plots, and FASER volume $R=10$ cm and decay length 1.5m now! 70

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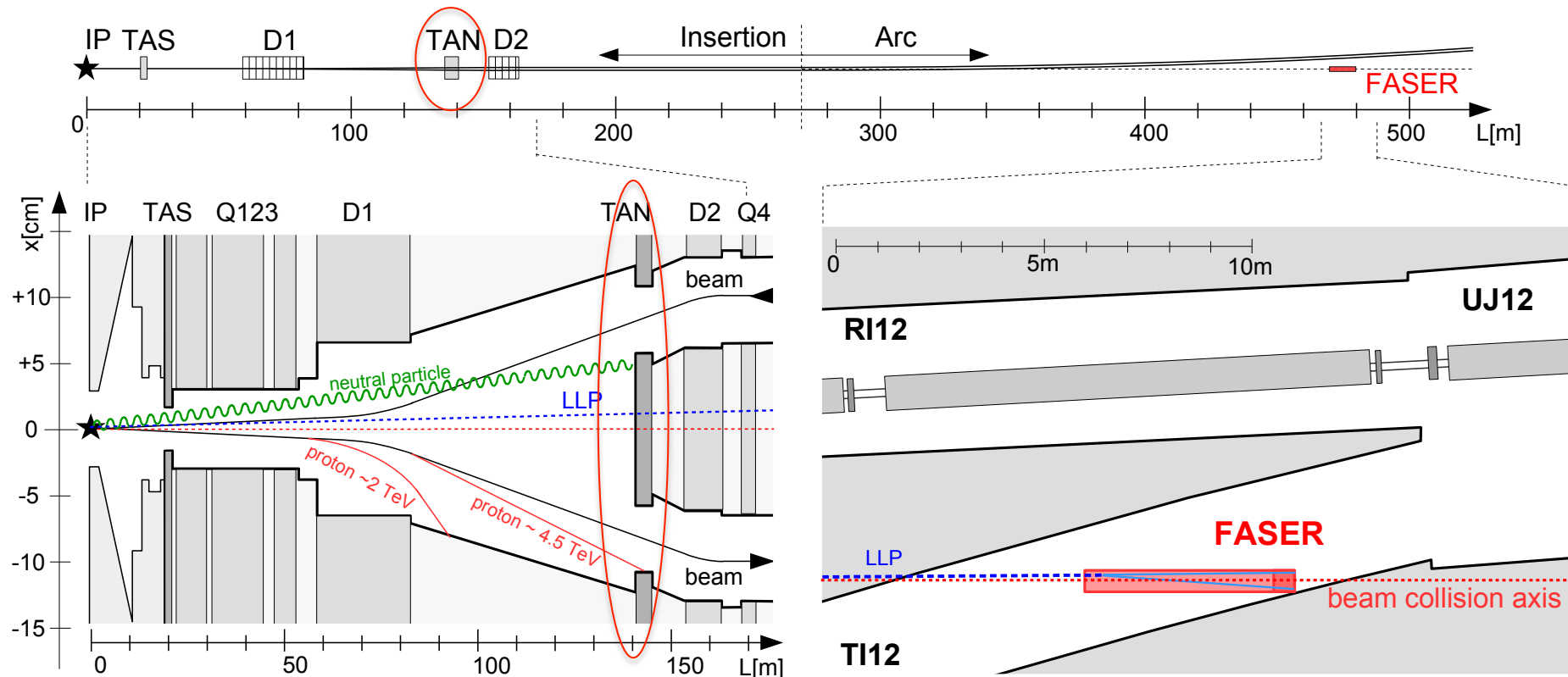
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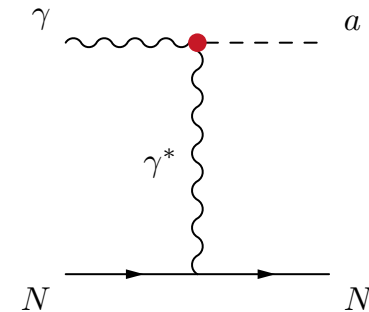
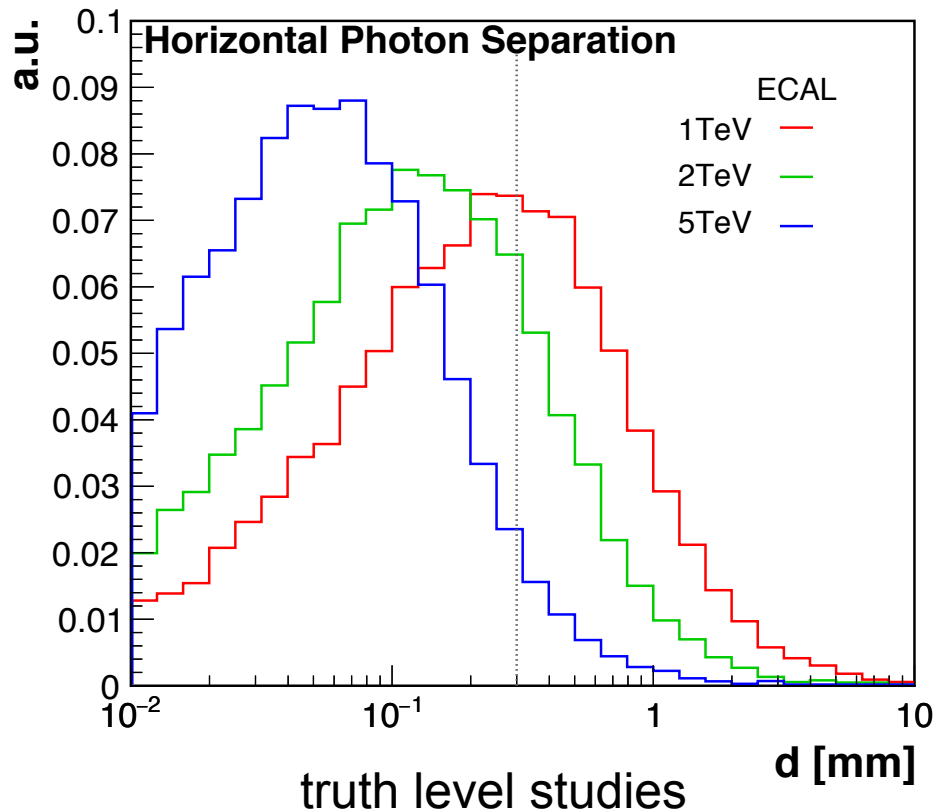


ALP production via the Primakoff process from photons scattering in the TAN



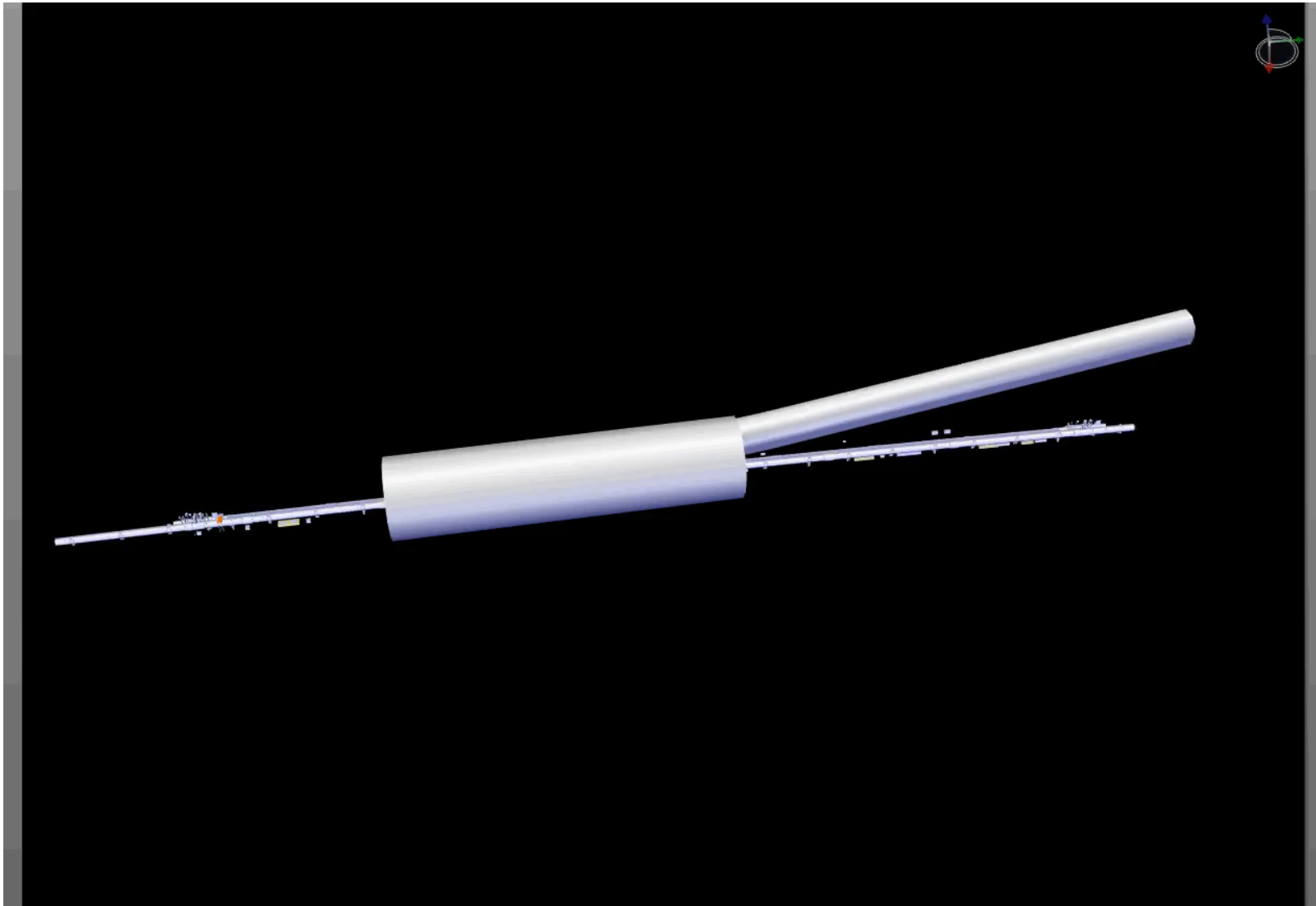
EXPECTED PERFORMANCE – 2 photon signature

- For ALP- $\rightarrow\gamma\gamma$ decay, magnetic field does not help separate closely spaced decay products
- We investigated calorimeter / pre-shower to allow to be able to resolve closely spaced ($\sim 1\text{mm}$) high energy photons ($>500\text{ GeV}$) - seems very challenging



ALP production via the Primakoff process from photons scattering in the LHC infrastructure material (TAN)

EXISTING SITUATION



L. Dougherty (CERN)