ForwArd Search ExpeRiment at the LHC

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Seminar at the University of Geneva

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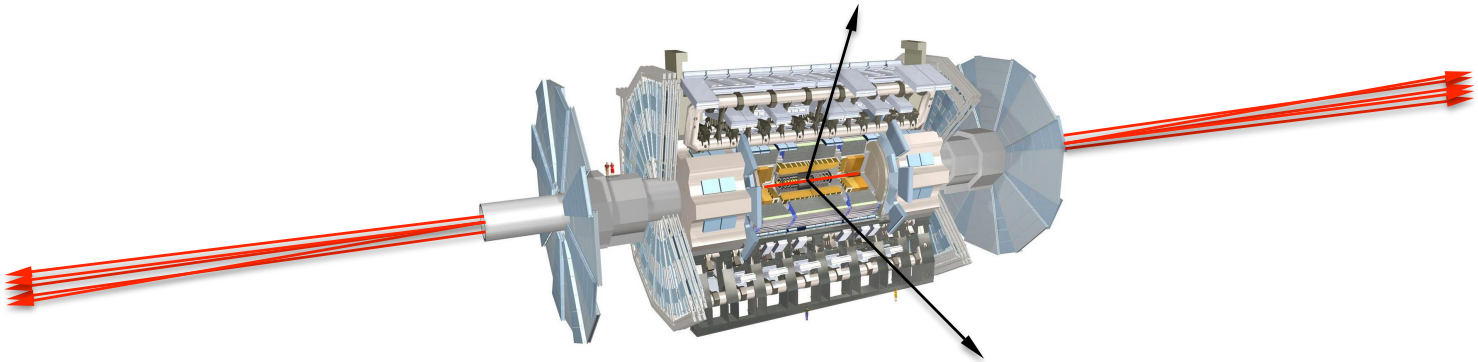
FASER website:
https://twiki.cern.ch/twiki/bin/view/FASER/WebHome

arXiv:1708.09389

FASER: 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 → In Run-3 N ~ 10^2 – 10^5, produced ~isotropically

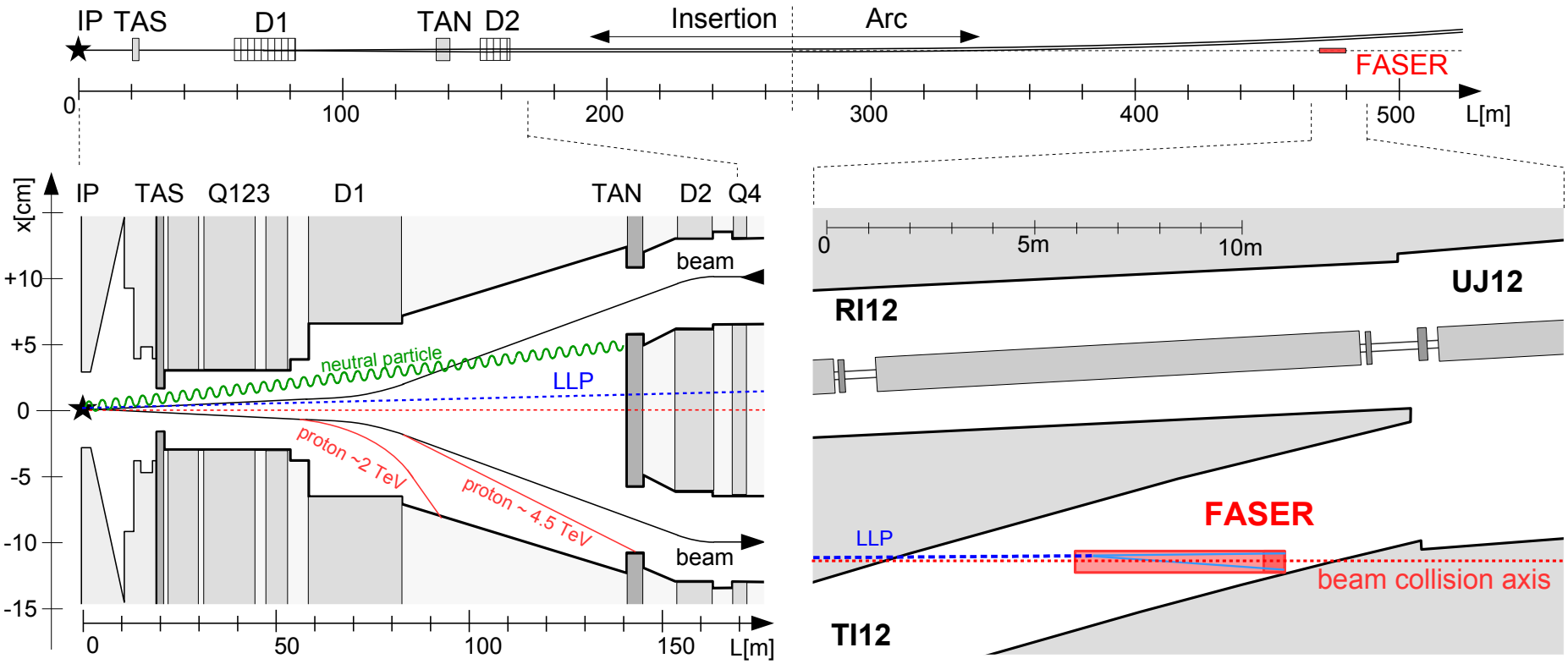
- However, if new particles are light and weakly interacting, this may be completely misguided. Instead can exploit
  - σ_{inel} ~ 100 mb → In Run-3 N ~ 10^{16}, θ ~ Λ_{QCD} / E ~ 250 MeV / TeV ~ mrad



- 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

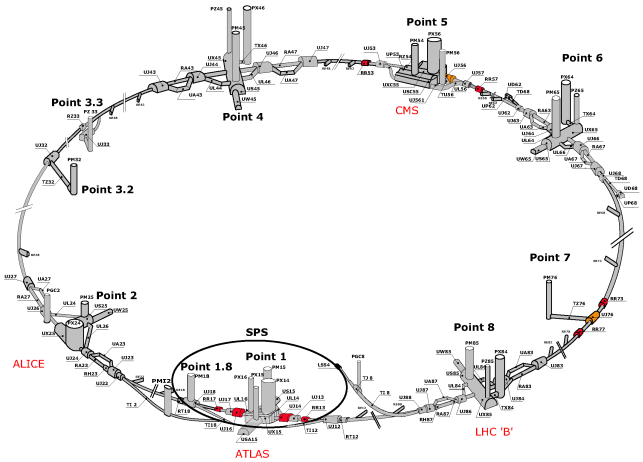
FASER LOCATION

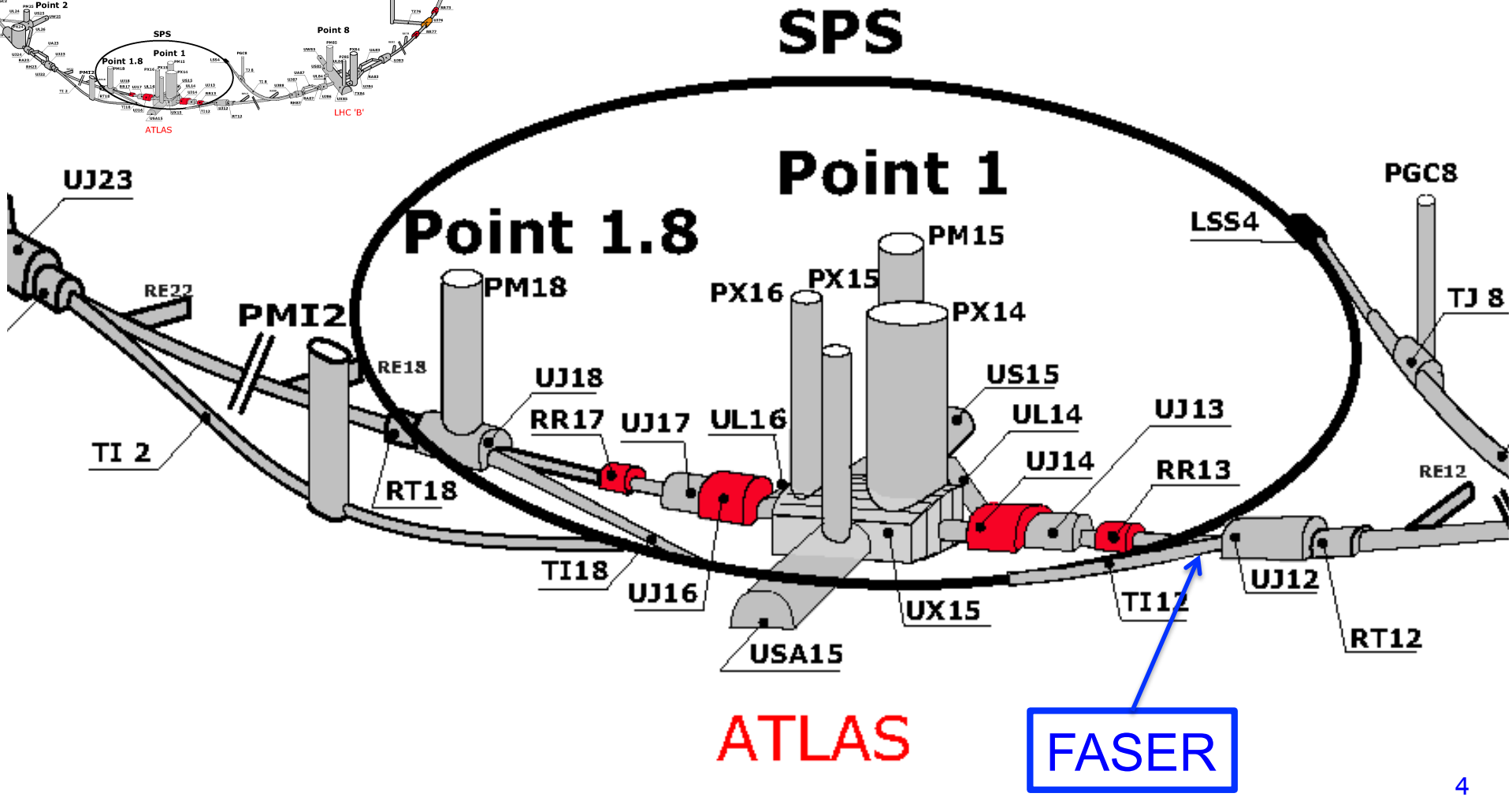
- FASER will be situated along the beam *collision* axis line of sight (LOS)
  - ~480 m from IP
  - after beams start to bend
  - a few meters from the LHC beamline



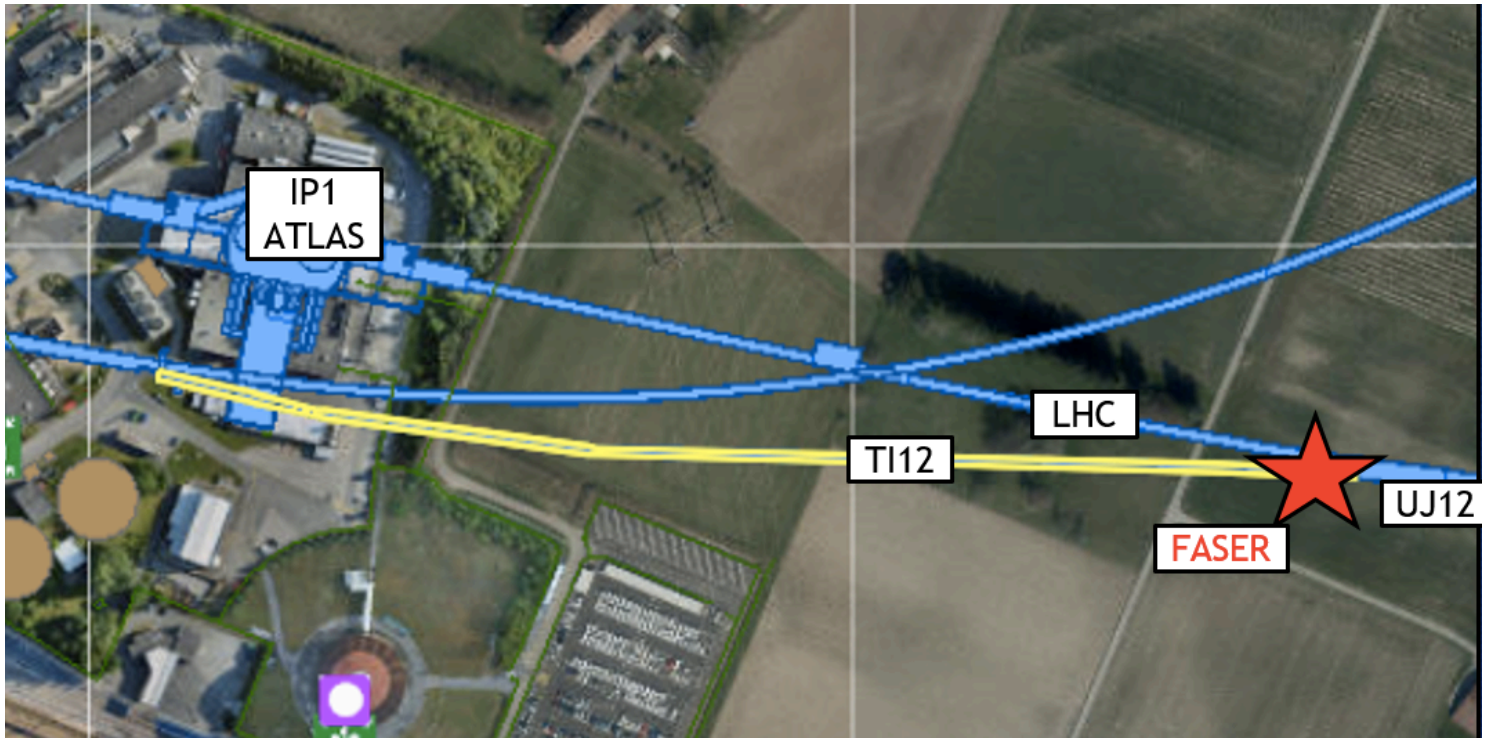
TI12 unused tunnel, that intersects LOS 480m from IP1

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.

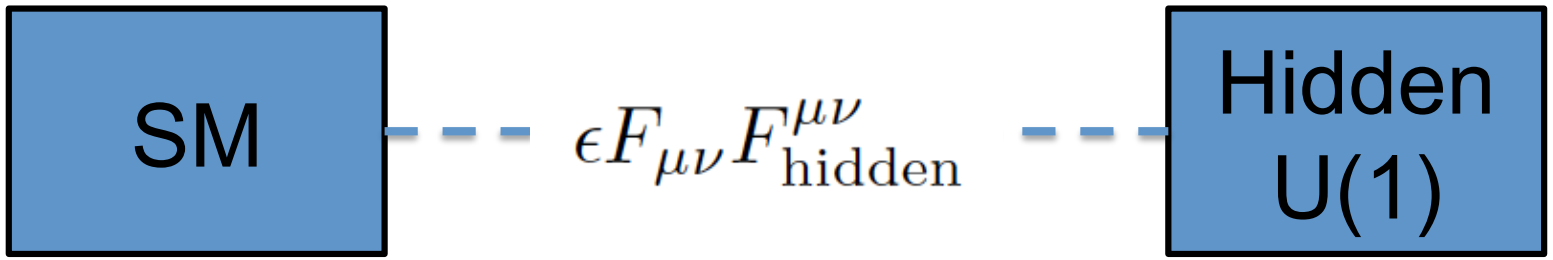
EXAMPLE PHYSICS CASE (DARK PHOTONS)

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 (WIMPless miracle, SIMP miracle, small-scale structure, ..)

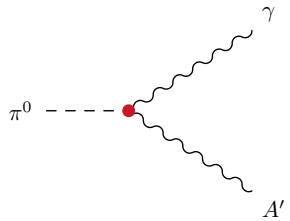
- A prominent example: vector portal, leading to dark photons



- 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.,



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

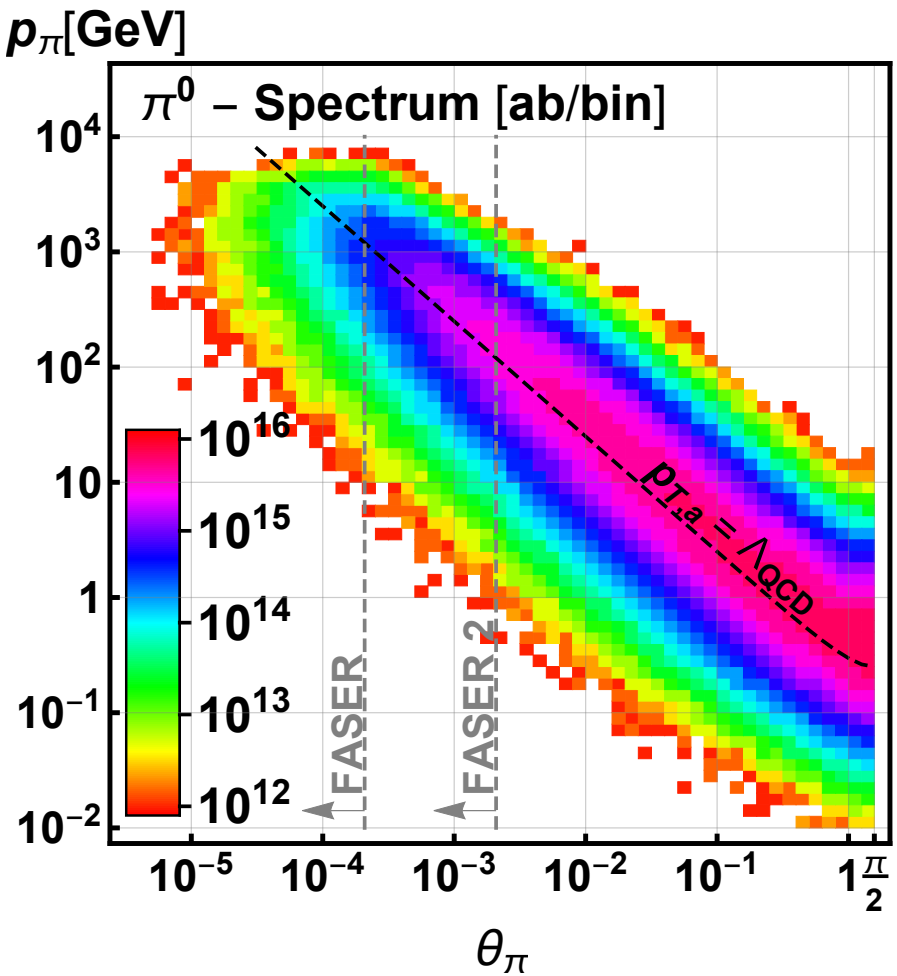
and also through other processes

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

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

- TeV energies at the LHC → 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,..) that are produced at the LHC, predominantly in the very forward direction.

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

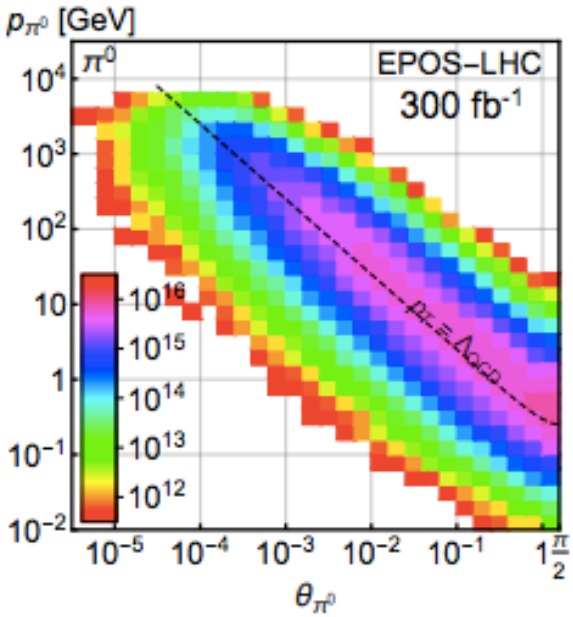
- 2% of π^0s fall in FASER acceptance;
- whereas the FASER acceptance covers just (2×10^{-6})% of the solid angle.

Run-3 (0.15/ab) will produce a huge number of π^0s 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!

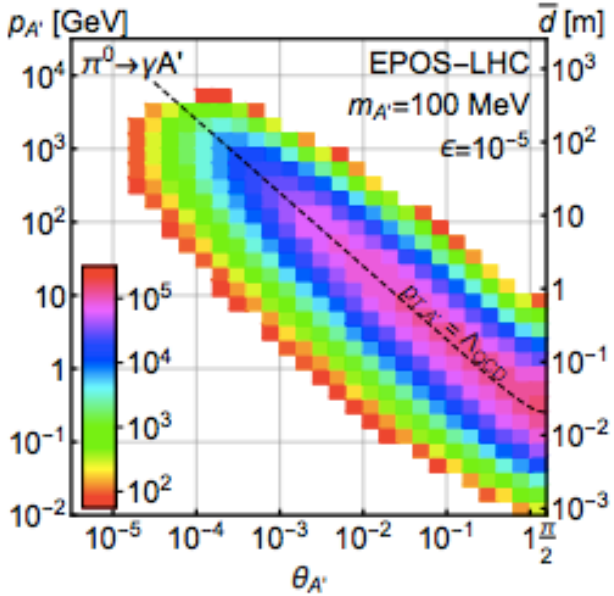
DARK PHOTONS IN FASER

Pions at the IP



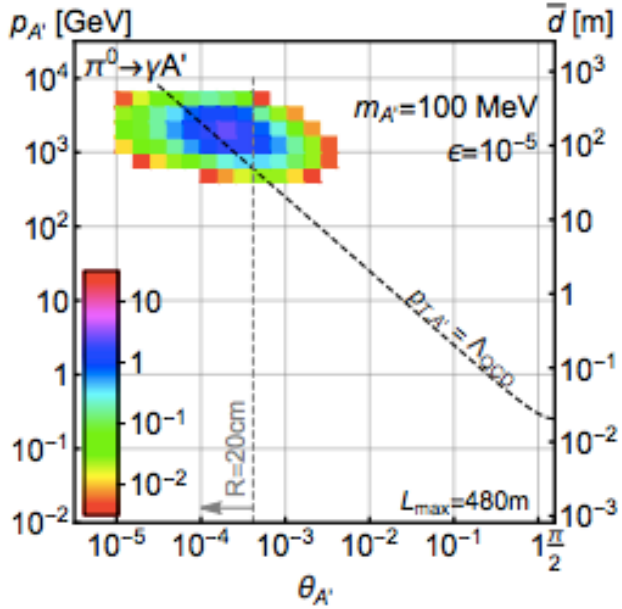
- Simulations greatly refined by LHC data
- Production is peaked at $p_T \sim \Lambda_{QCD} \sim 250$ MeV
- Enormous event rates: $N_\pi \sim 10^{15}$ per bin

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

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



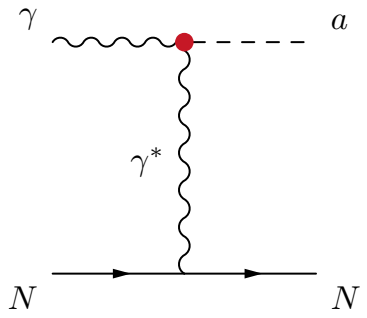
- Only highly boosted ~TeV A's decay in FASER
- Rates again suppressed by decay requirement
- But still $N_{A'} \sim 100$ signal events, and almost all are within 20 cm of "on axis"

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

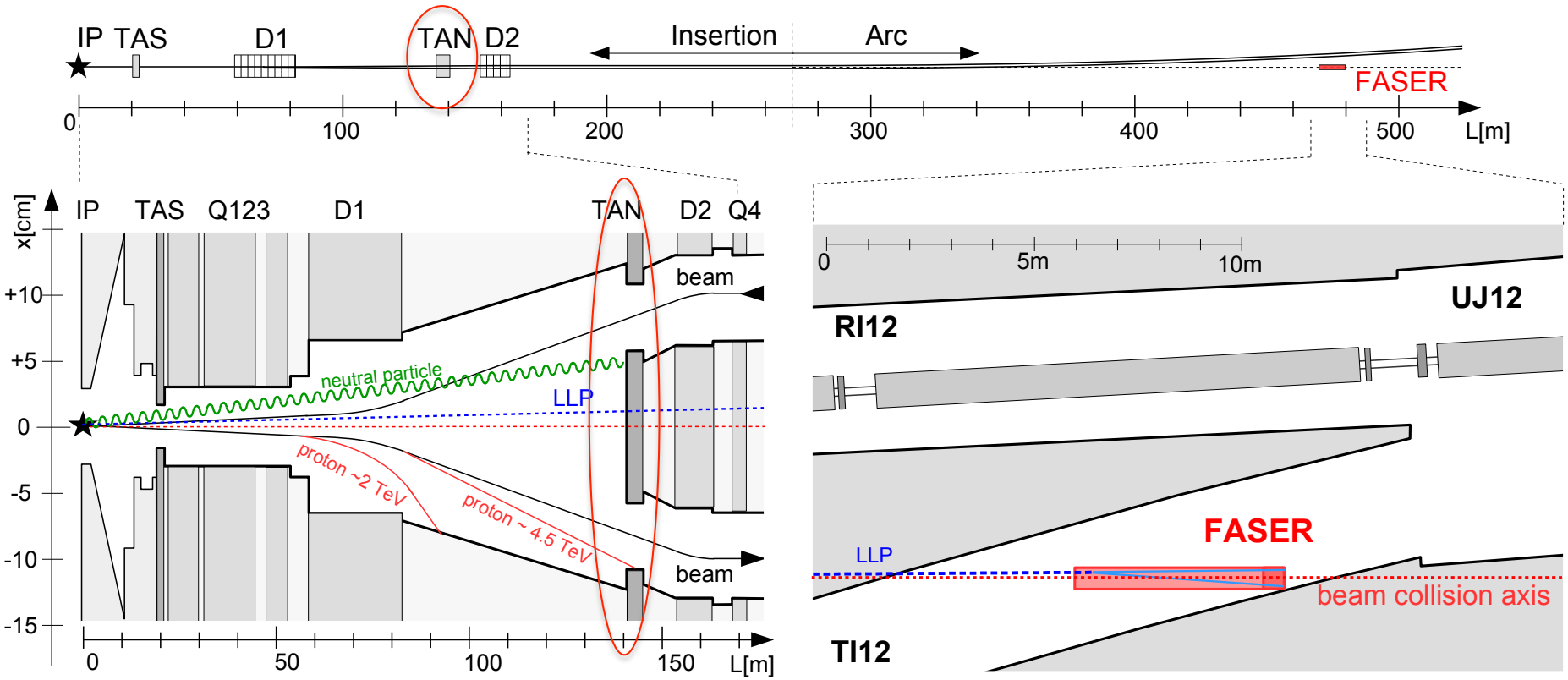
1806.02348

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 ~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



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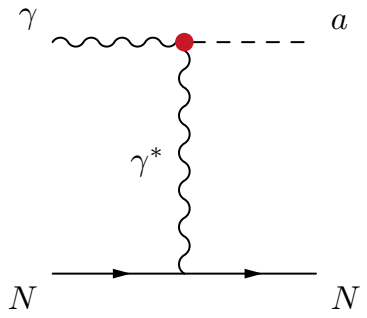

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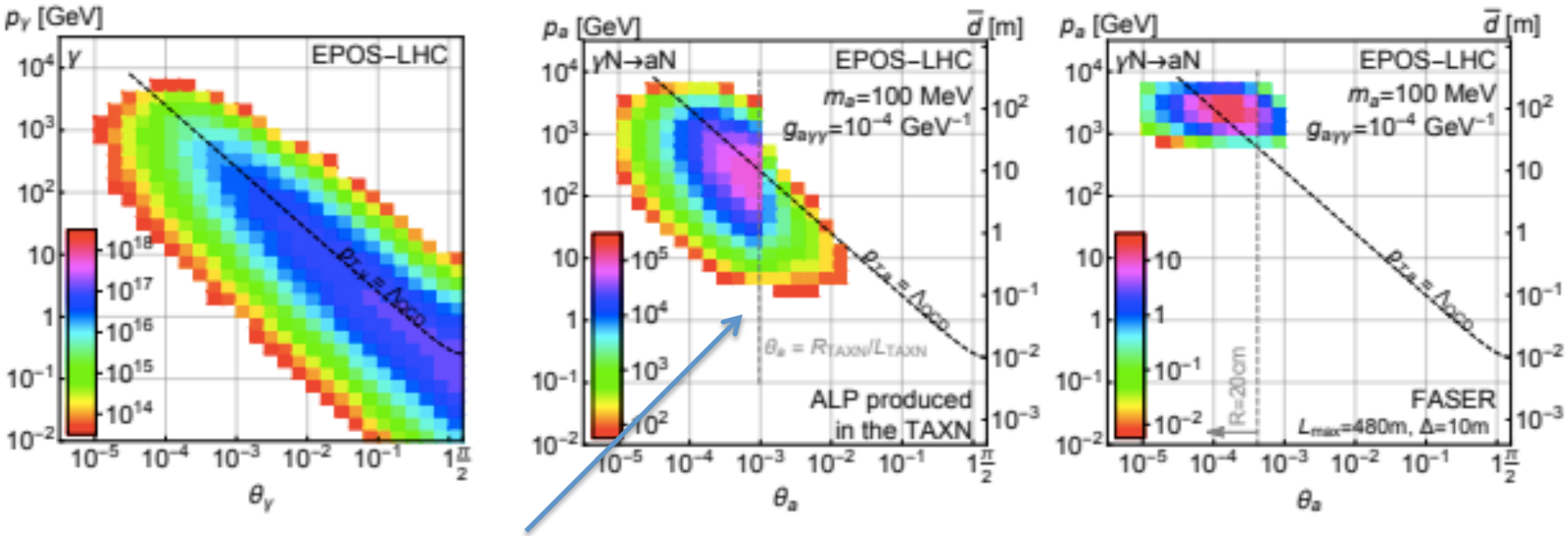


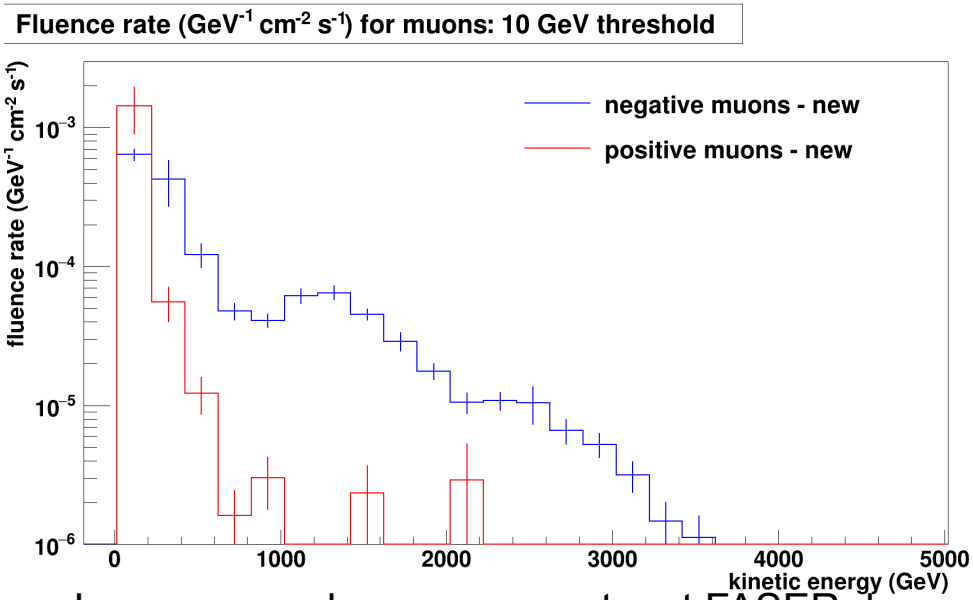
Assuming angular coverage of TAN is <1mrad

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

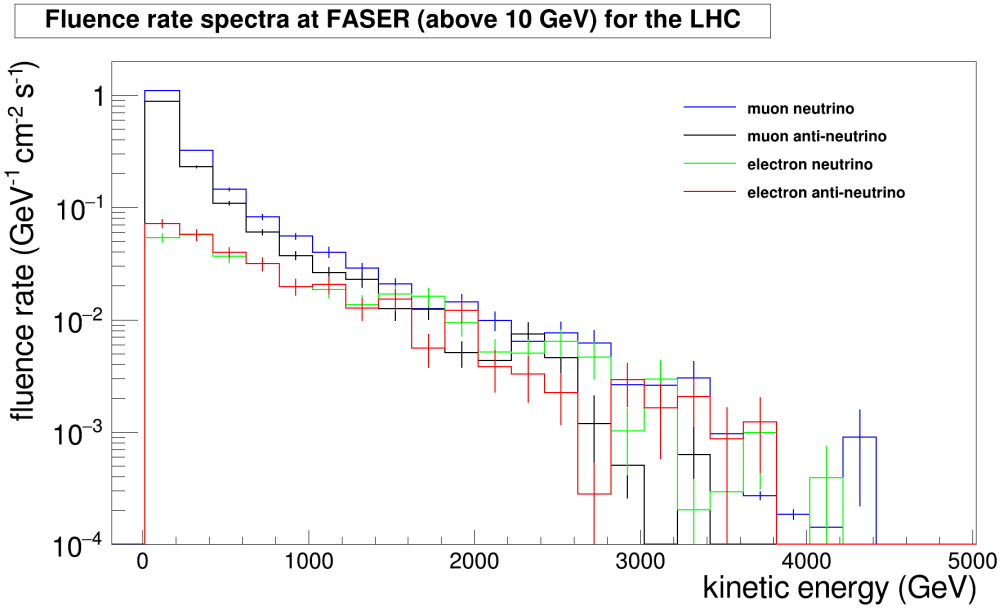
THE TI12 ENVIRONMENT

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 0.4cm^{-2}s^{-1} at FASER for 2e34cm^{-2}s^{-1} luminosity from IP1 collisions

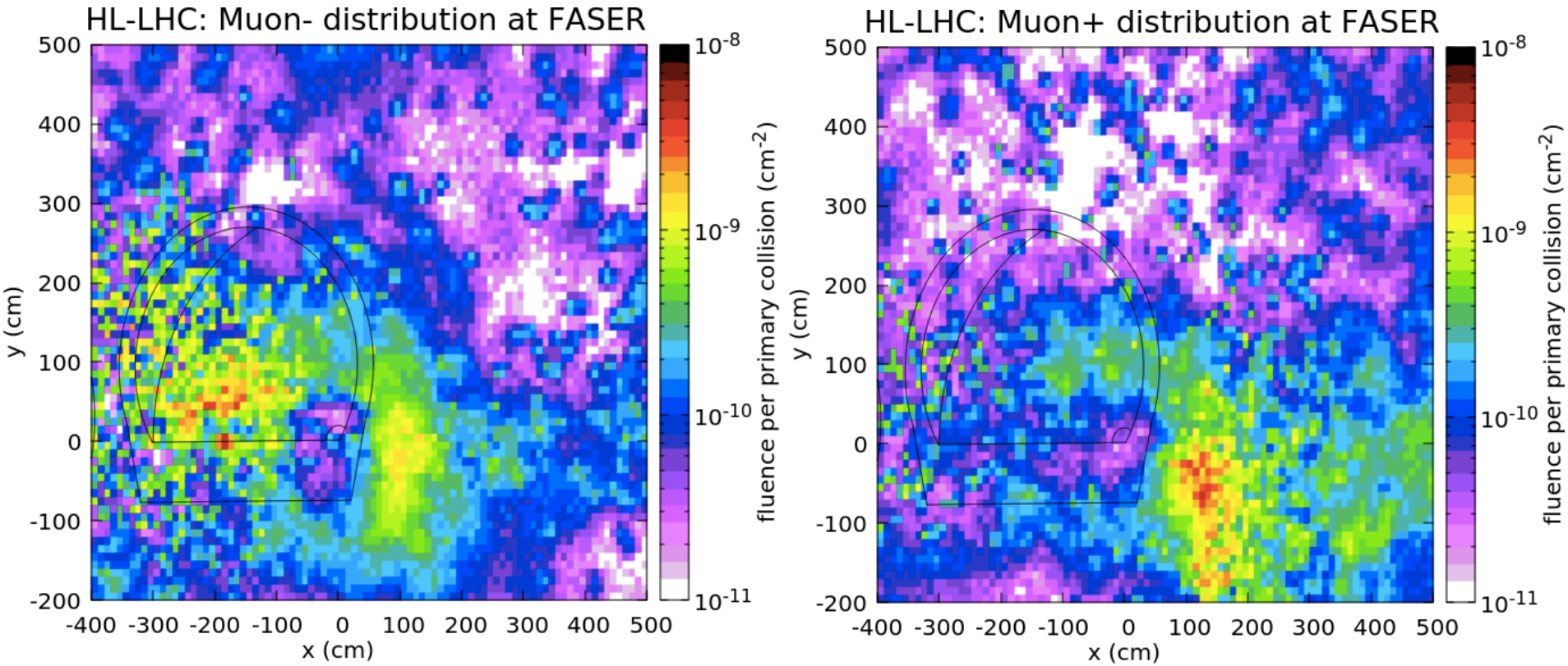


Large muon charge asymmetry at FASER due to LHC bending magnets



Huge flux of high energy neutrinos

FLUKA SIMULATIONS: MUON MAP



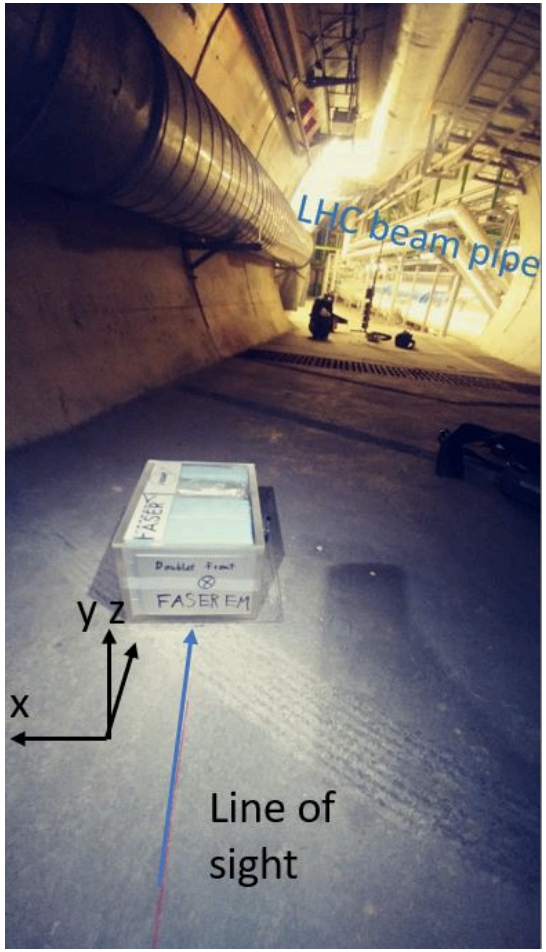
Due to bending from LHC magnets, muon flux on LOS is reduced:
μ^- tend to be bent to the left, μ^+ to the right of FASER.

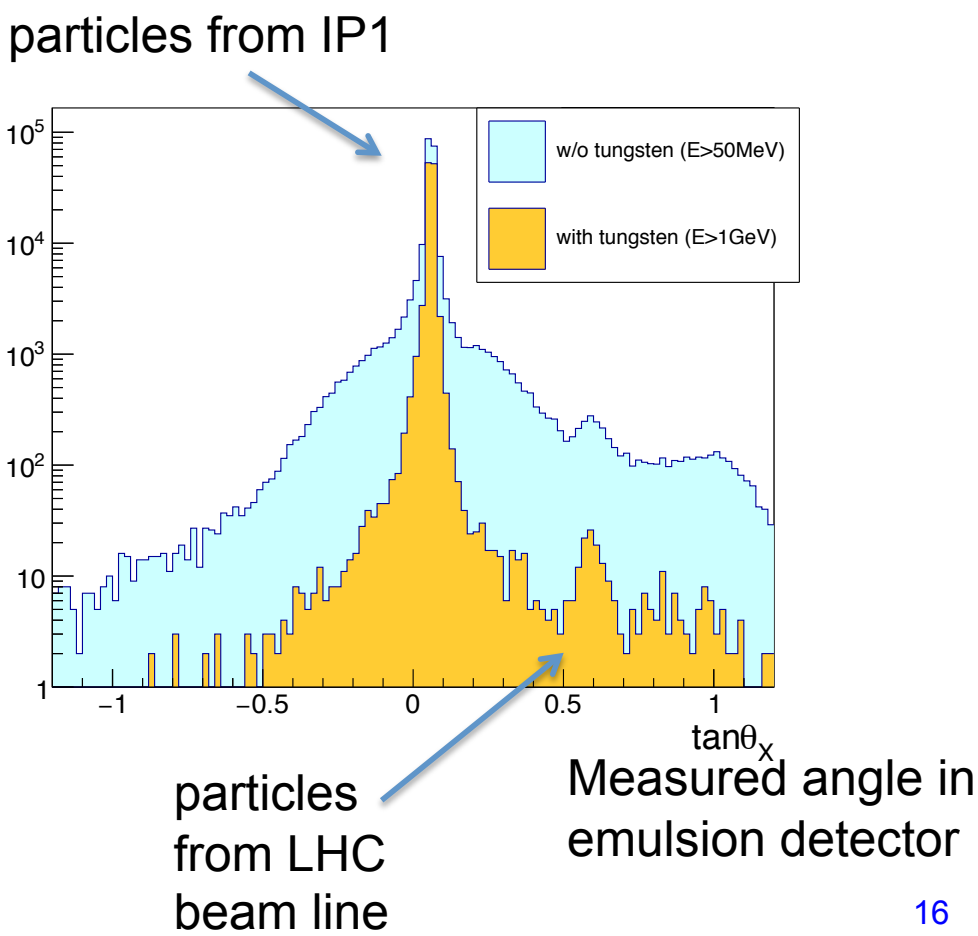
Energy threshold [GeV]	Charged particle flux [cm^{-2} s^{-1}]
10	0.40
100	0.20
1000	0.06

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

BEAM BACKGROUNDS

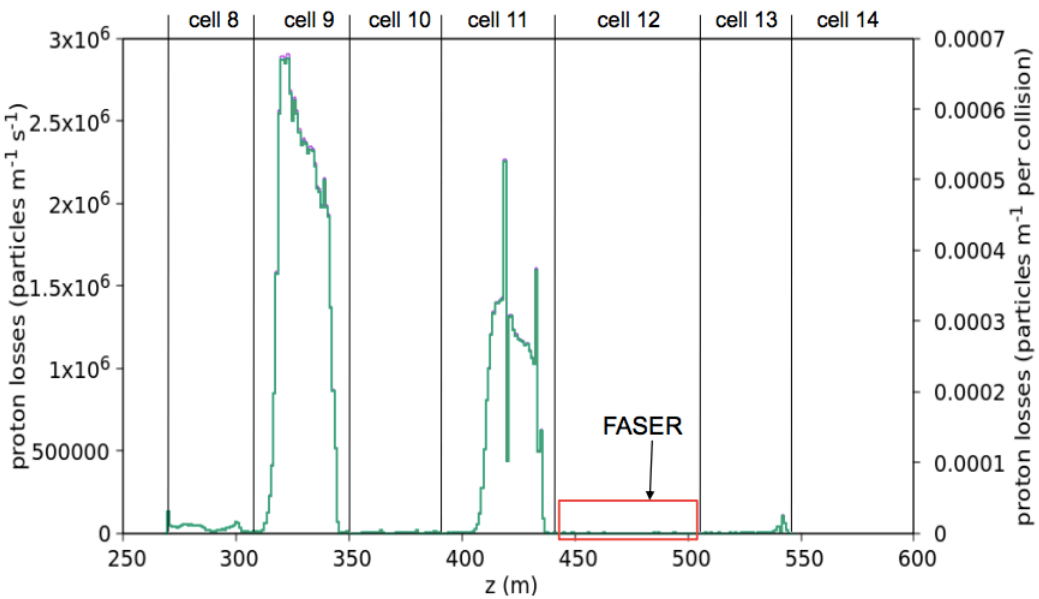
- Measurements using emulsion detectors installed in TI12 in 2018 running confirm expected particle flux
- Measurements using TimePix BLM in TI12 confirm that particle flux is correlated with luminosity in IP1

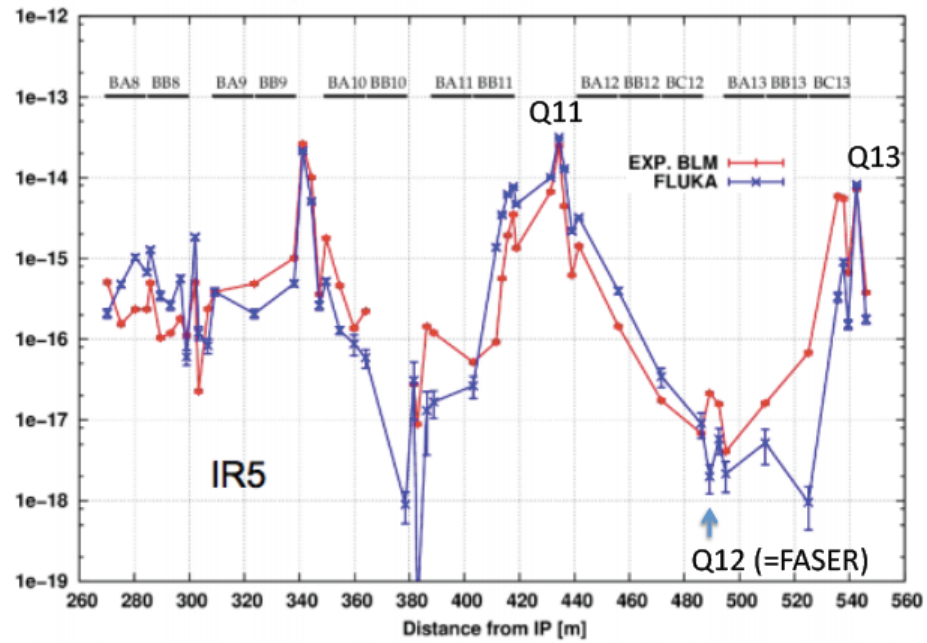




TI12 RADIATION LEVEL

- 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 x 10^{-3} Gy/year
  - less than 5 x 10^{7} 1 MeV neutron equivalent fluence / year
- FASER detector does not need radiation hard electronics



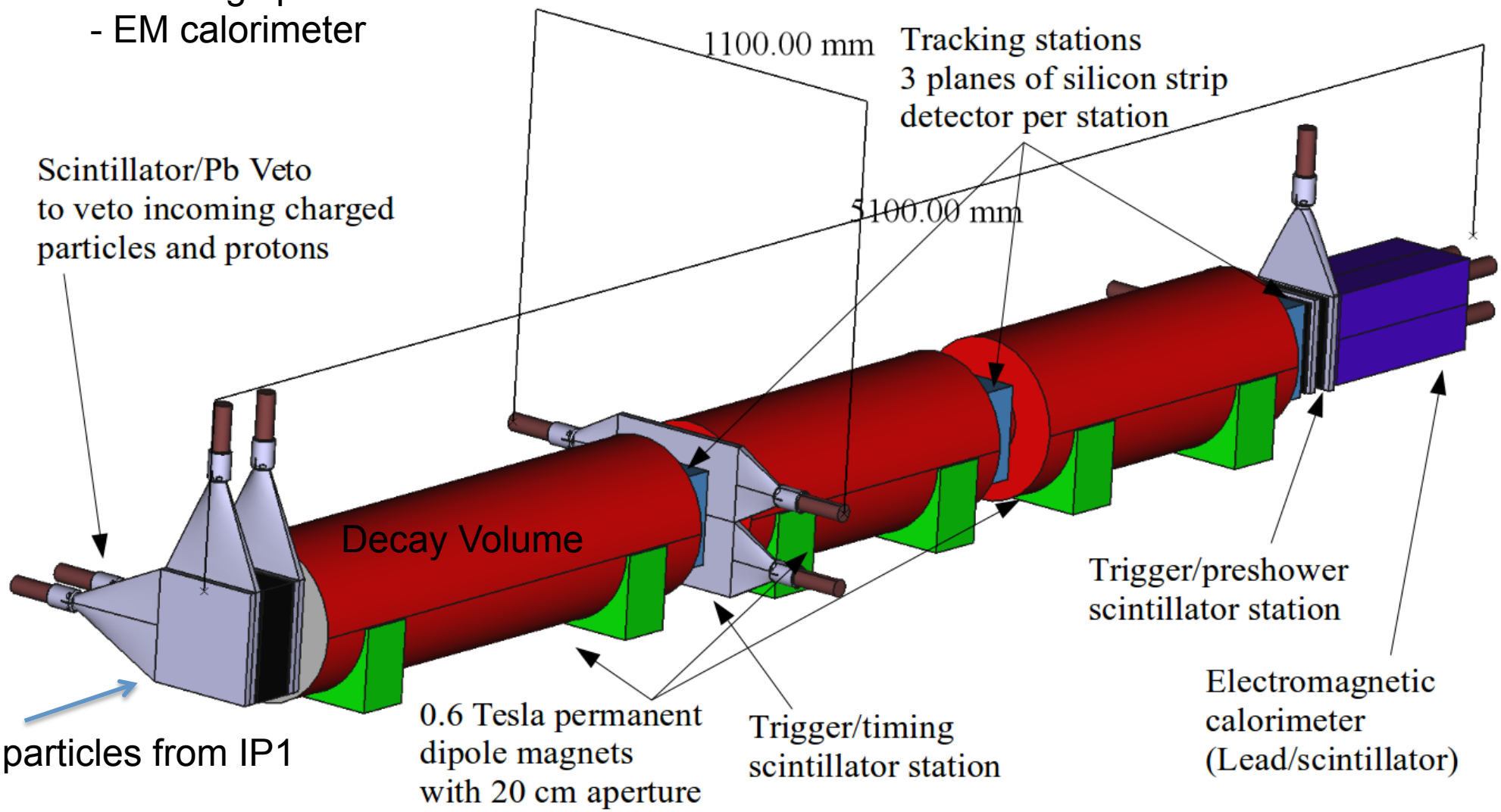


THE FASER DETECTOR

THE FASER DETECTOR

The detector consists of:

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



THE FASER DETECTOR

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- Scintillator veto
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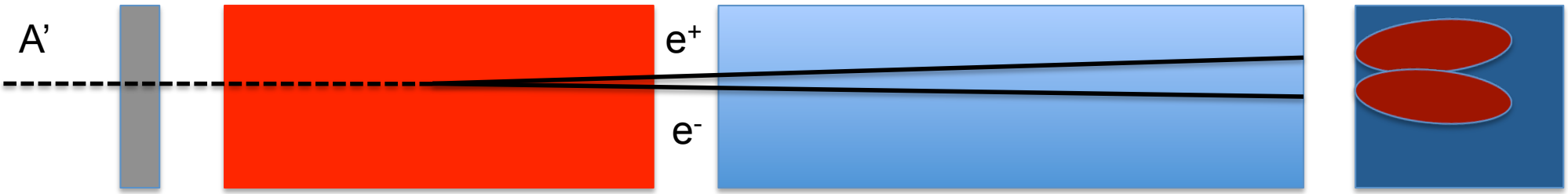
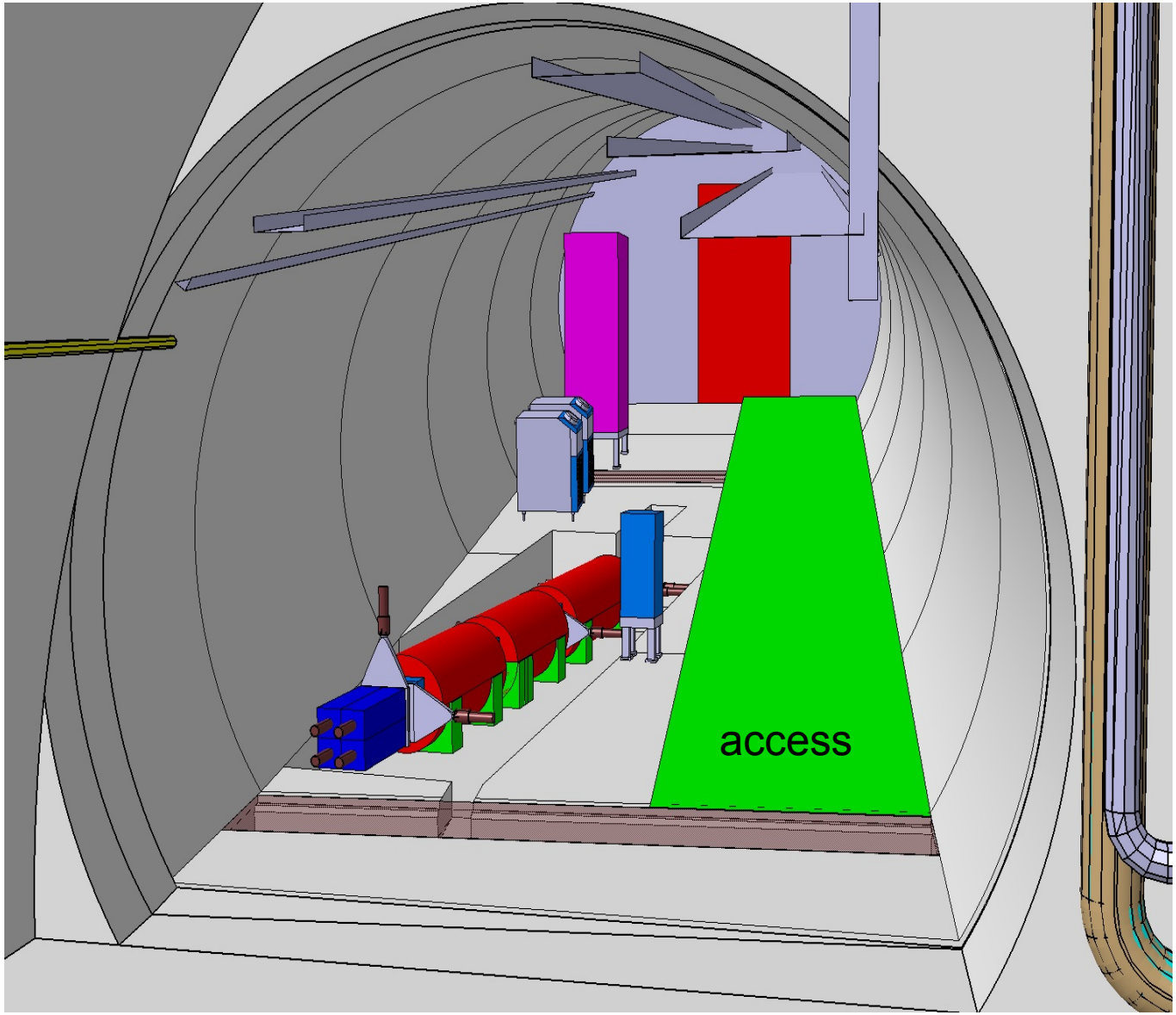
Signal signature



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'->ee decay: Large EM energy in calorimeter. EM showers too close to be resolved.

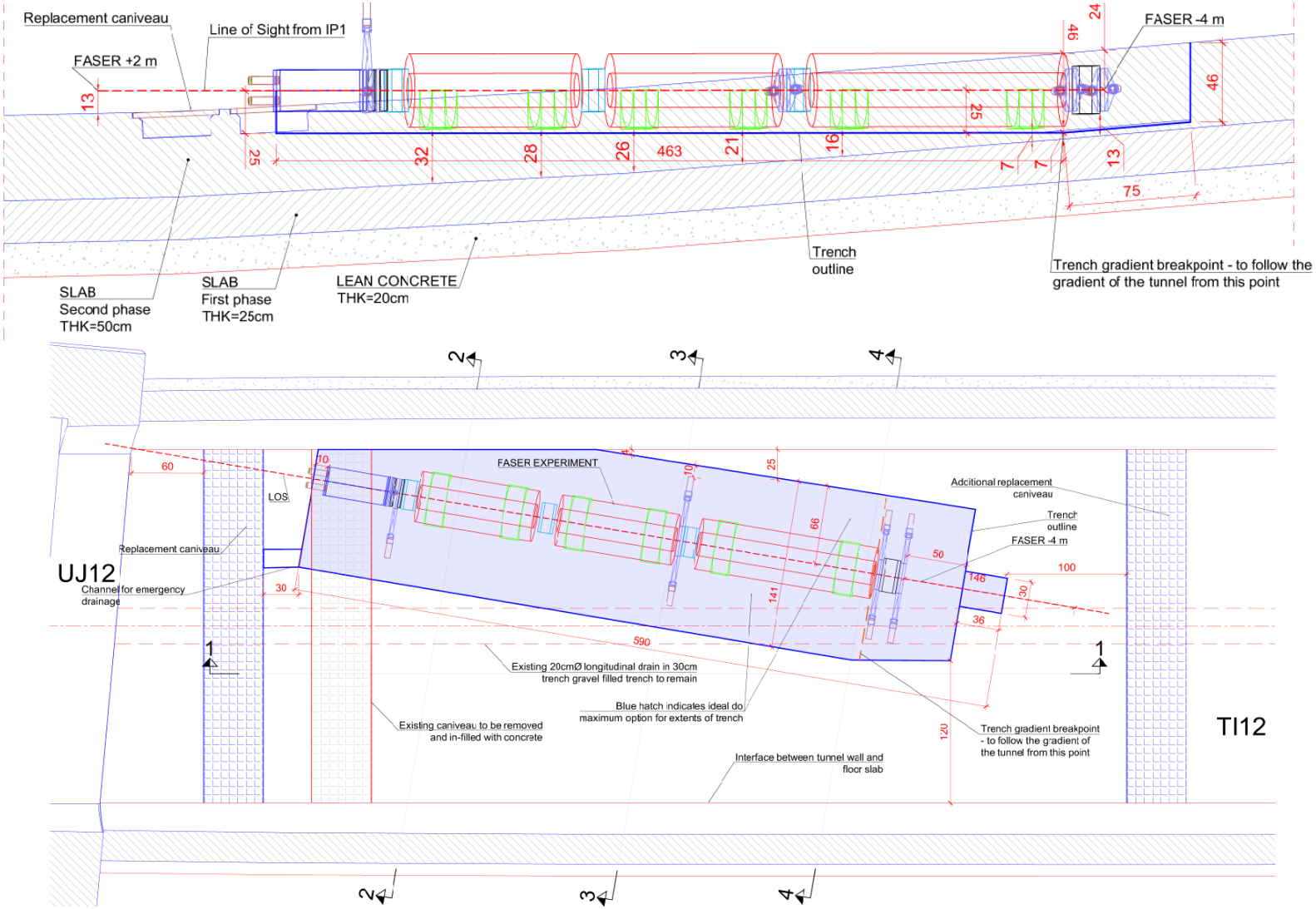
Magnets needed to separate the A' decay products sufficiently to be able to be resolved in tracker

FASER IN TI12



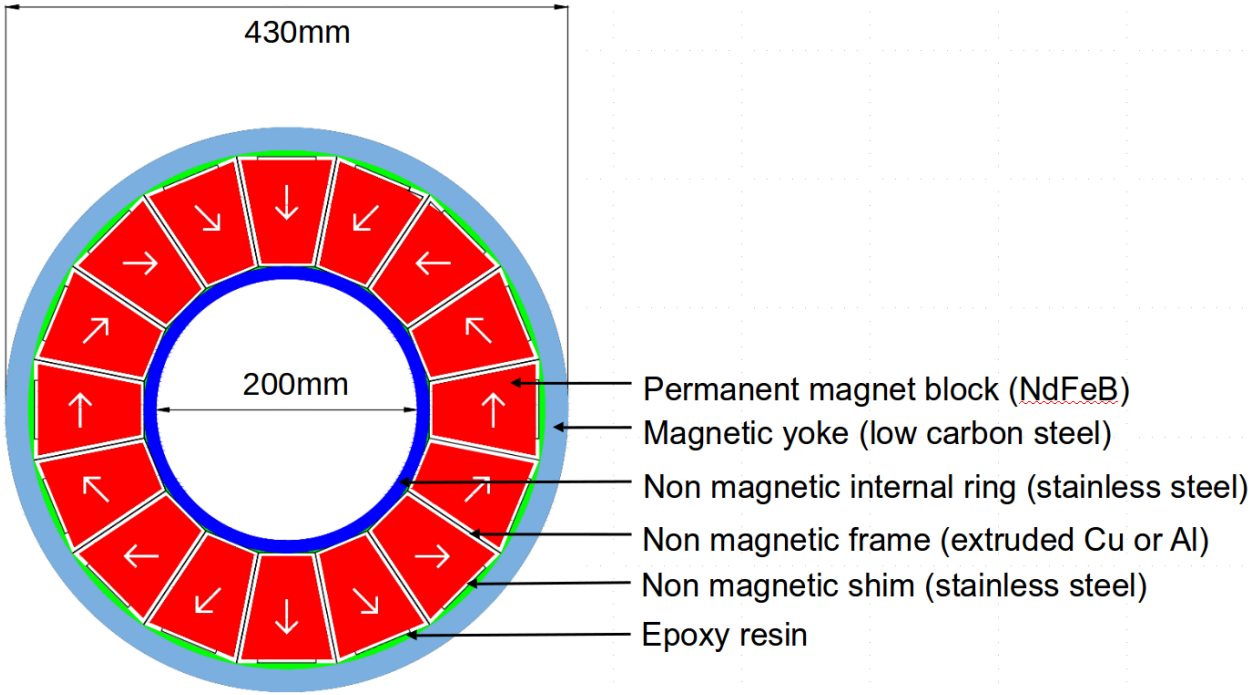
For detector to be situated on LOS, require small amount of digging in TI12 tunnel

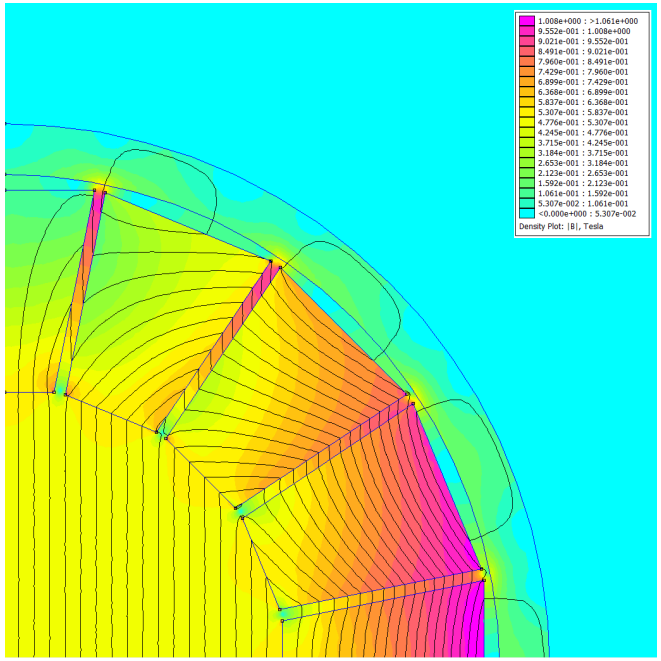
CIVIL ENGINEERING WORK



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.

FASER MAGNETS

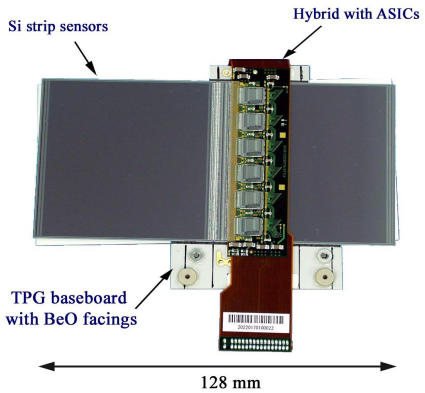




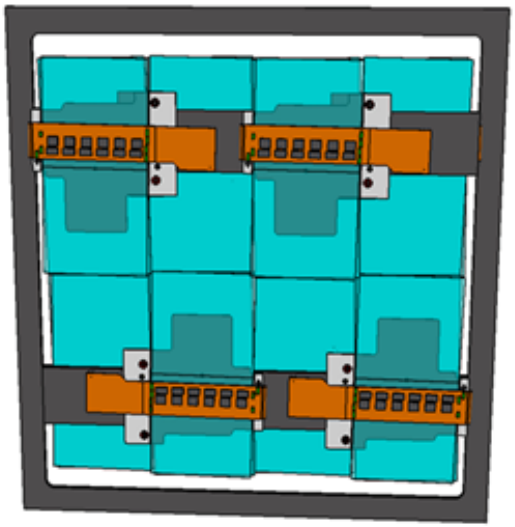
- The FASER magnets are 0.6T permanent dipole magnets based on the Halbach array design
  - Thin enough to allow the LOS to pass through the magnet center with minimum digging to the floor in TI12
  - Minimized needed services (power, cooling etc..)
- To be constructed by the CERN magnet group
  - Cost 450kCHF

FASER TRACKER

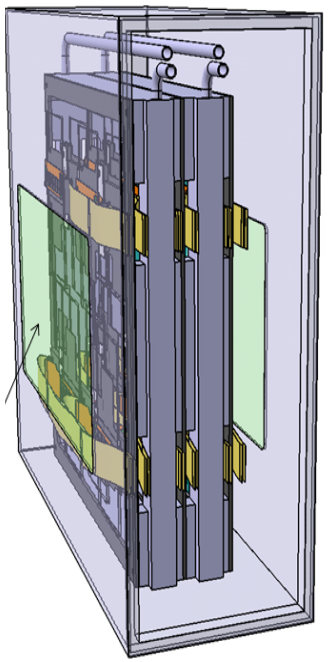
- The FASER Tracker will be made up of 3 tracking stations
- Each containing 3 layers of double sided silicon micro-strip detectors
  - Spare ATLAS SCT modules will be used
    - 80μm strip pitch, 40mrad stereo angle
    - Many thanks to the ATLAS SCT collaboration!
- 8 SCT modules give a 24cm x 24cm tracking layer
- 9 layers (3/station, 3 stations) => 72 SCT modules needed for the full tracker
  - 10^5 channels in total



SCT module



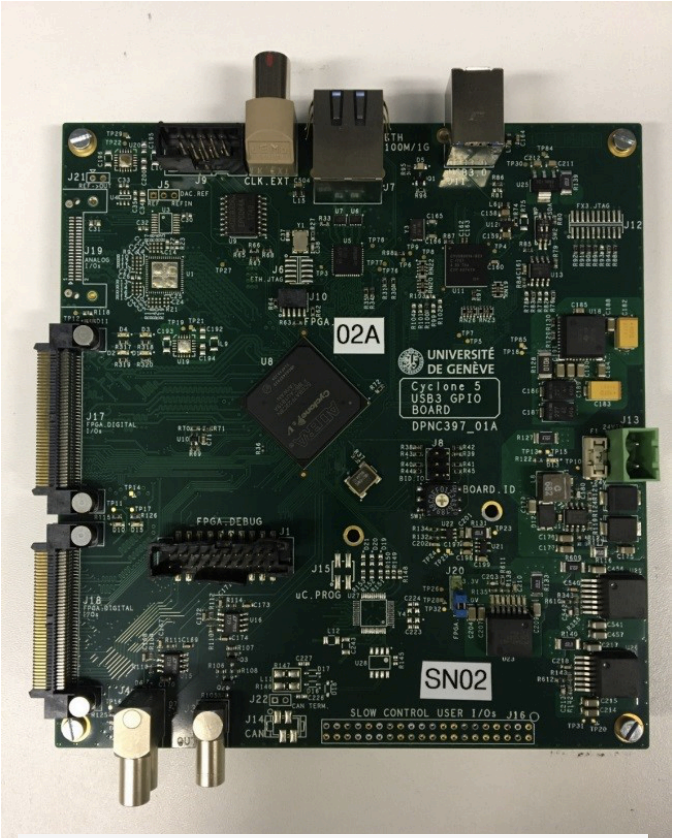
Tracking layer



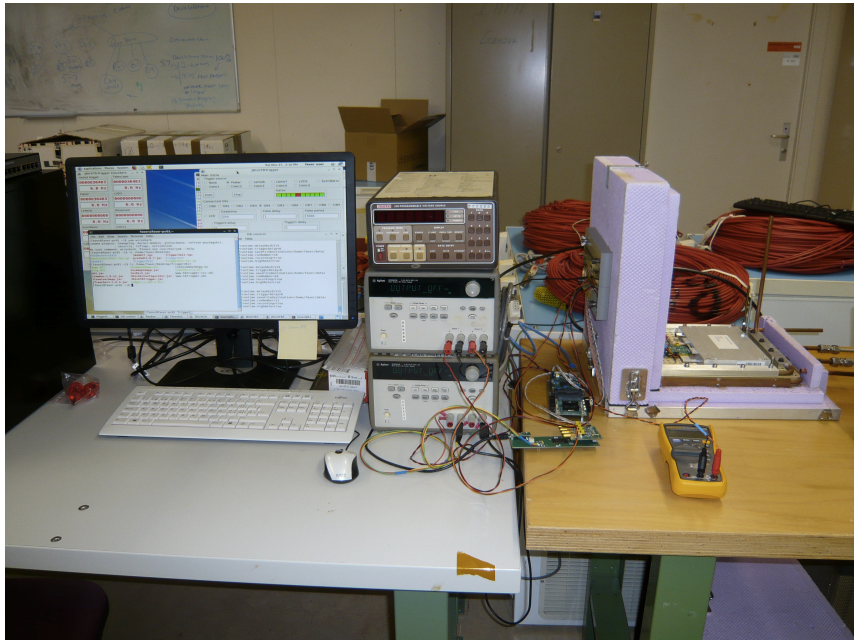
Tracking station

FASER TRACKER

University of Geneva(DPNC) taking large responsibility in the FASER Tracker:
- Tracking mechanics, being designed and built by DPNC mechanics team
- Tracker readout design and FW by the DPNC electronics team, using existing GPIO board



1 GPIO board per tracking layer (9 in total)



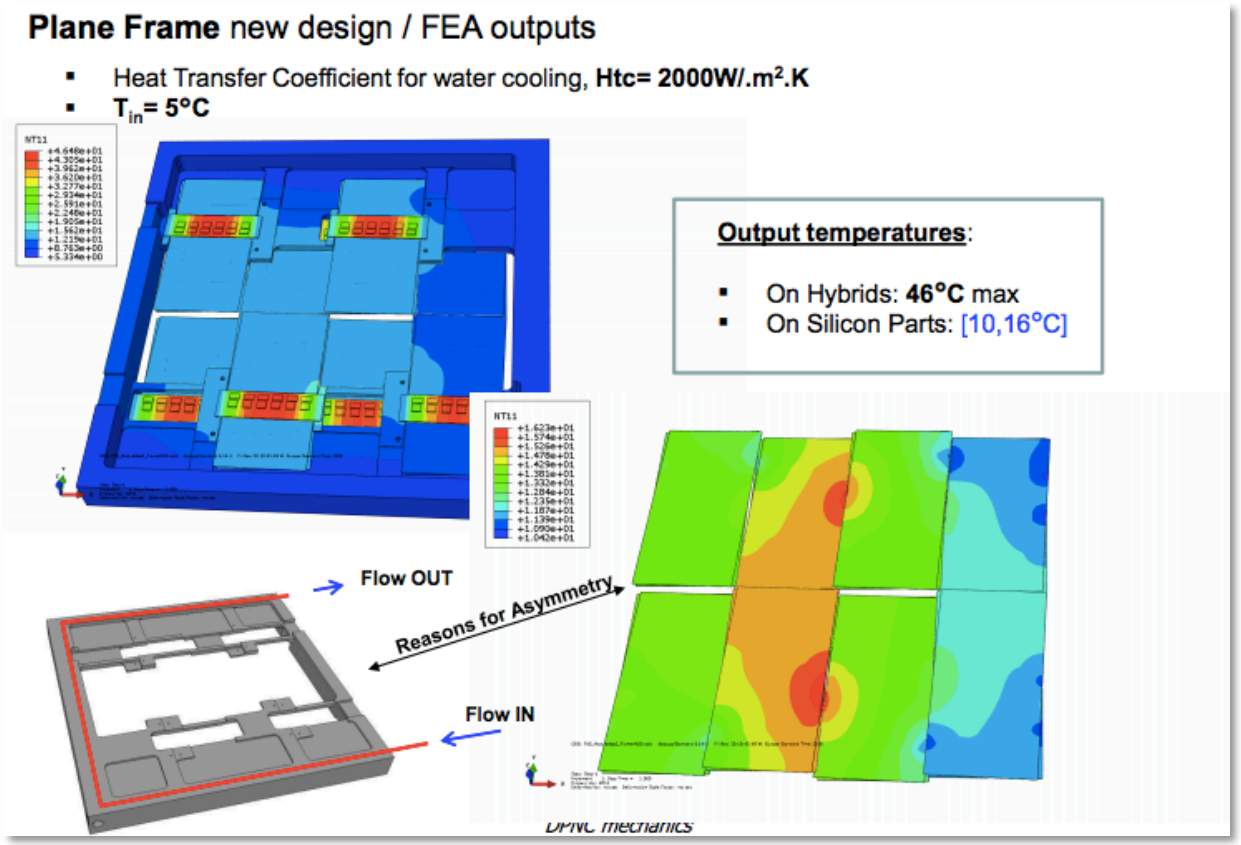
SCT module QA currently ongoing at CERN to identify 80 good spare modules – this is using non-final readout

TRACKER COOLING

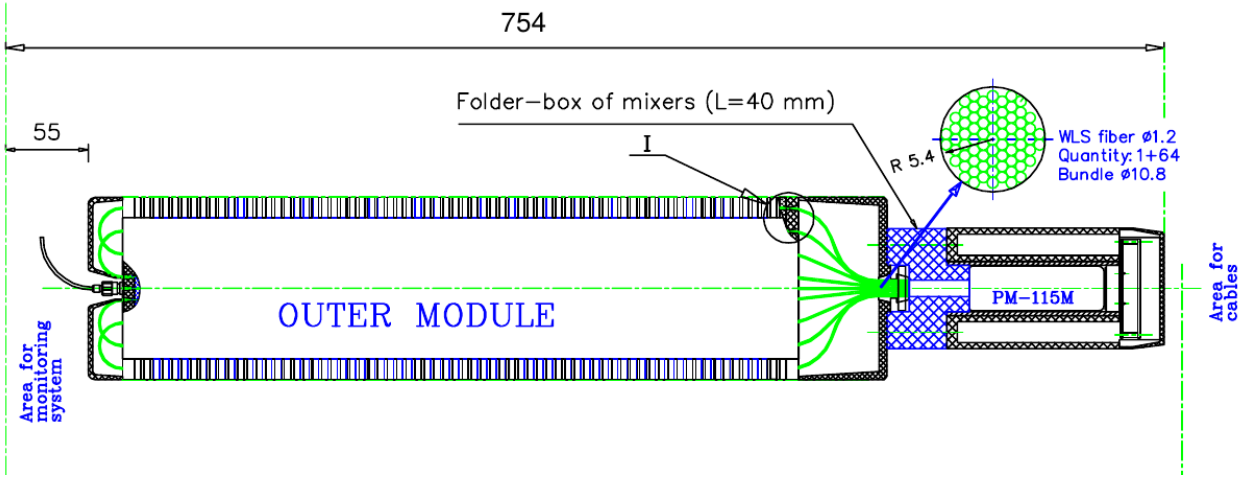
- Due to the low radiation in TI12 the silicon can be operated at room temperature, but the detector needs to be cooled to remove heat from the on-detector ASICs.
- Design of tracking layer ongoing to give sufficient thermal and mechanical properties, whilst minimizing material in tracking volume.
- Plan to use simple water chiller with inlet temperature <10degrees.

Dry air to be provided by CERN CV group.
Will need DCS and interlock to turn off tracker if cooling or humidity control fails.

Example FEA analysis in tracer design:

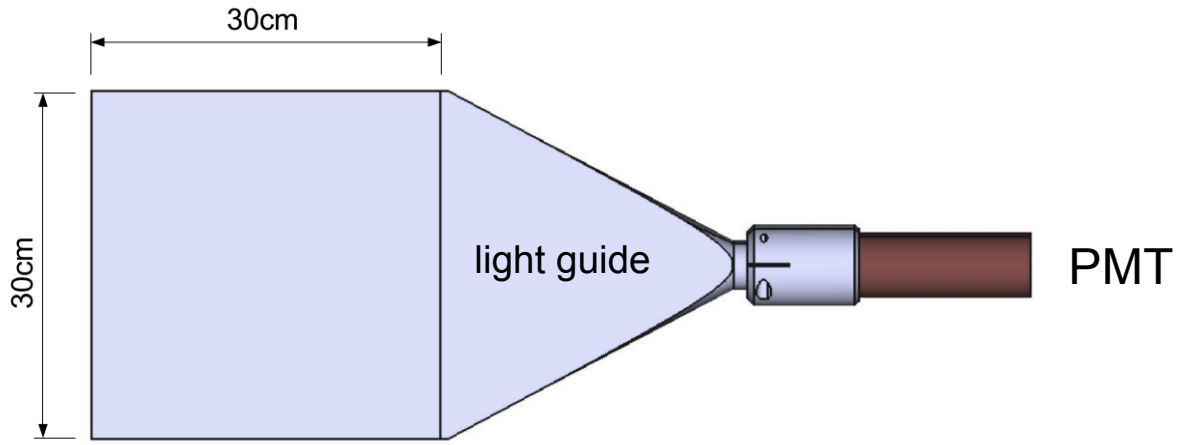


CALORIMETER



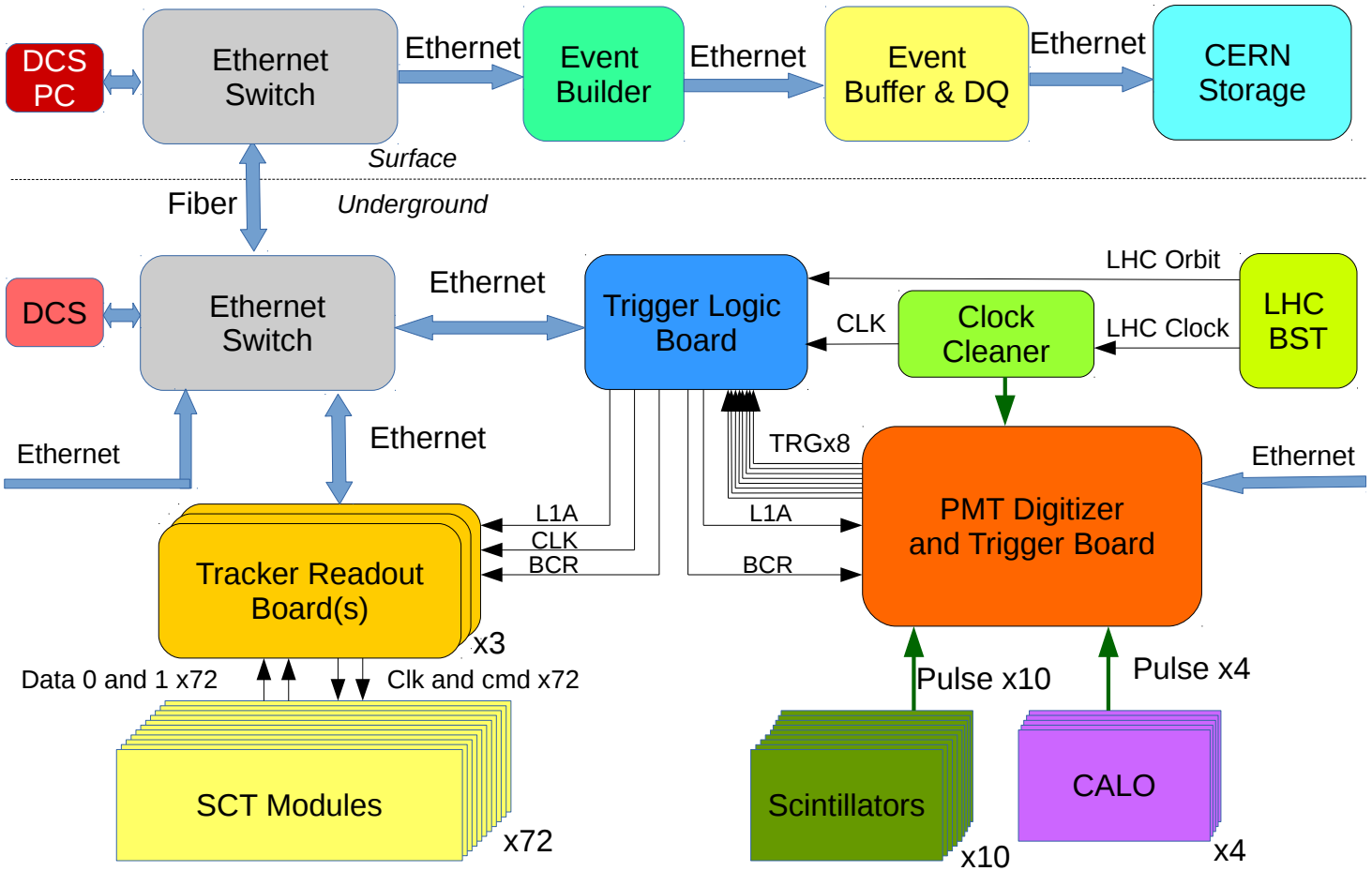
- FASER EM calorimeter for:
  - Measuring the EM energy in the event
  - Electron/photon identification
  - Triggering
- Will use 4 spare LHCb outer ECAL modules
  - Many thanks to LHCb for allowing us to use these!
  - 66 layers of lead/scintillator, light out by wavelength shifting fibers
    - 25 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

SCINTILLATORS



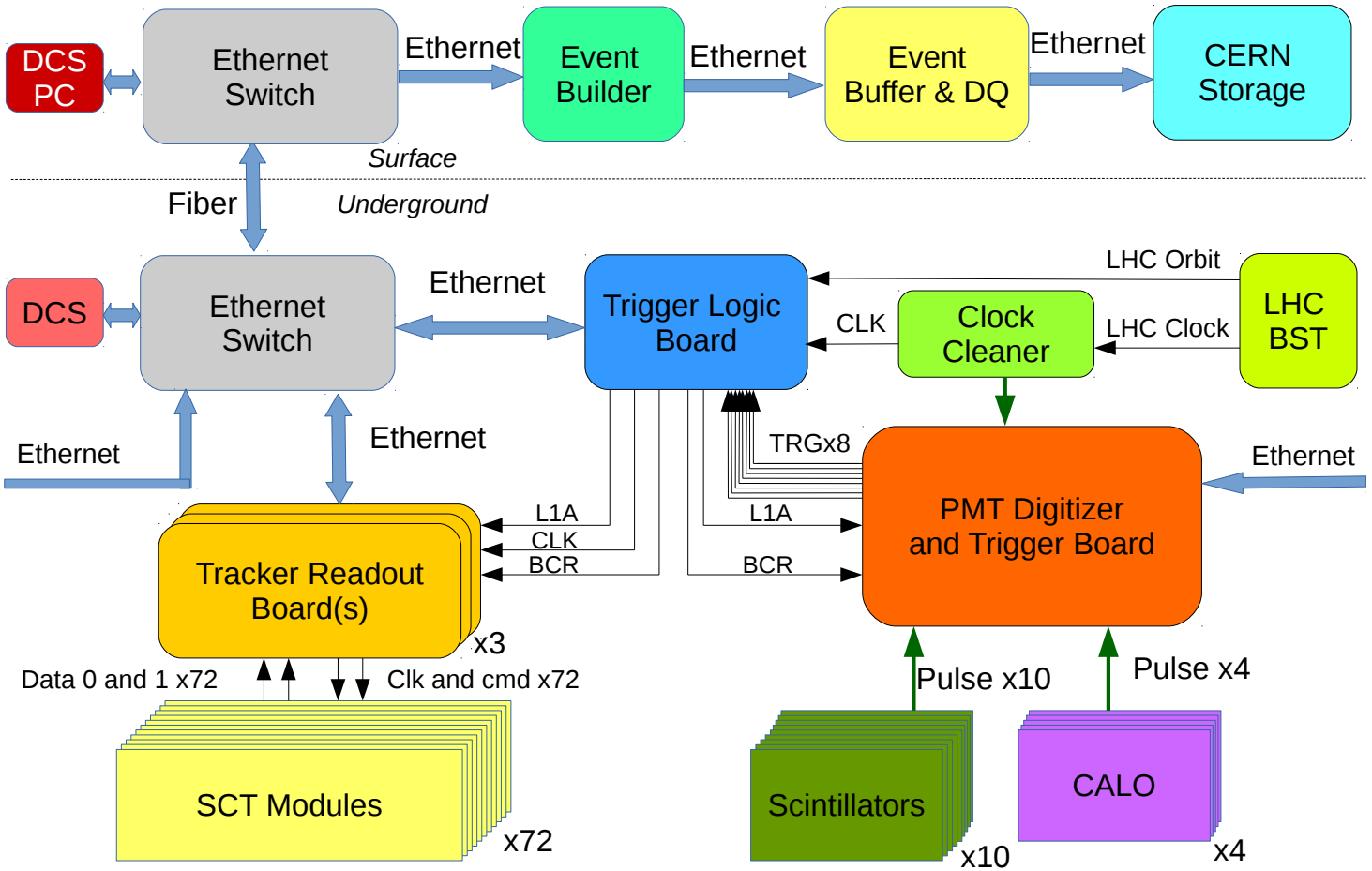
- Scintillators used for vetoing charged particles entering the decay volume, and for triggering
  - To be produced at CERN scintillator lab
  - PMT readout
  - Require extremely efficient charged particle veto (eff>99.99%)
    - Achievable with the current design

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)

TDAQ OVERVIEW

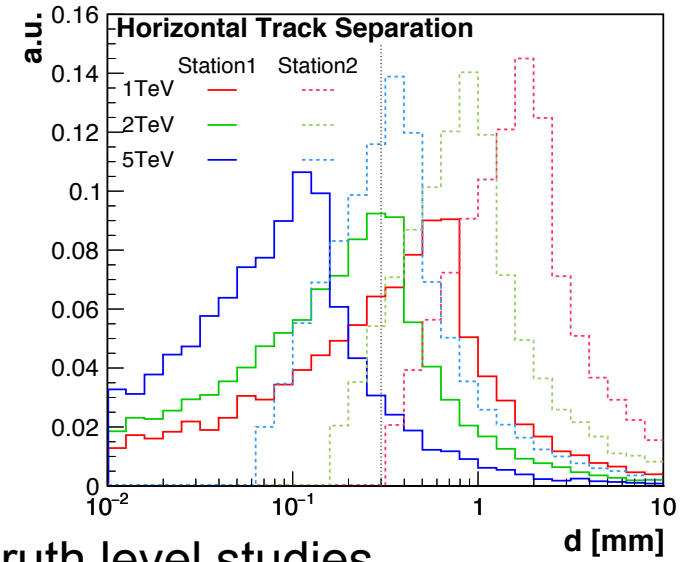


DPNC making large contributions to the TDAQ. Trigger Logic Board is same GPIO board used for tracker readout, with dedicated firmware to be written by DPNC electronics team.

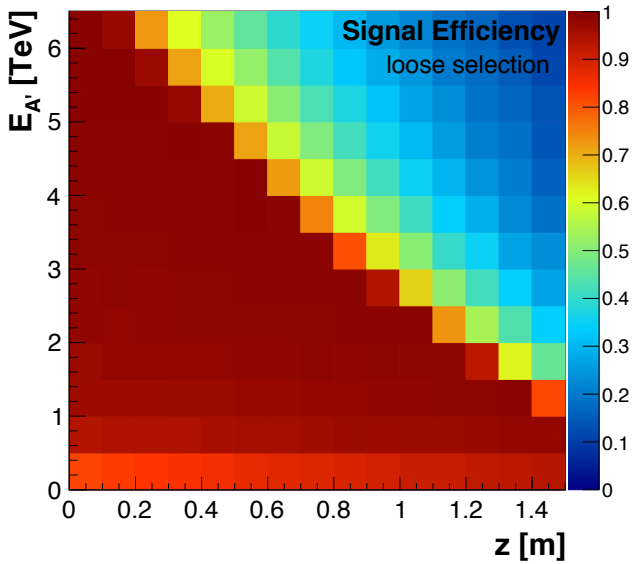
PHYSICS PERFORMANCE

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



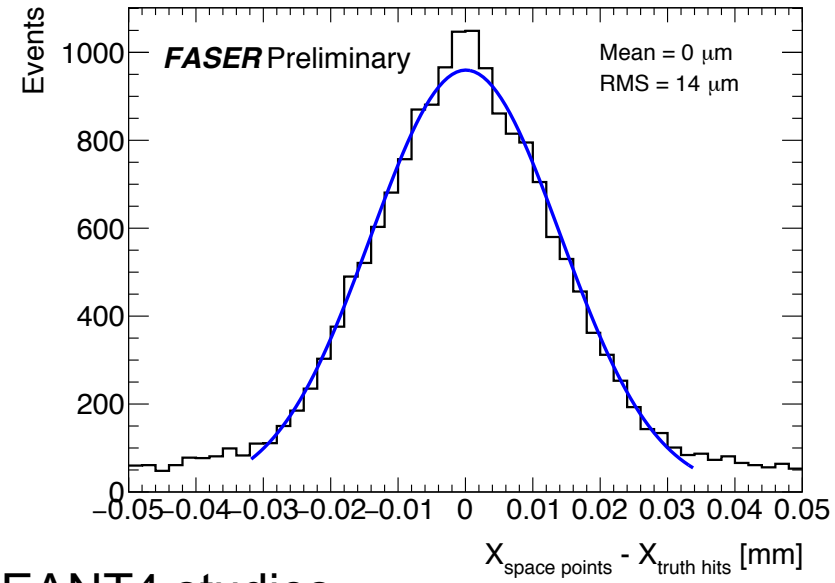
truth level studies

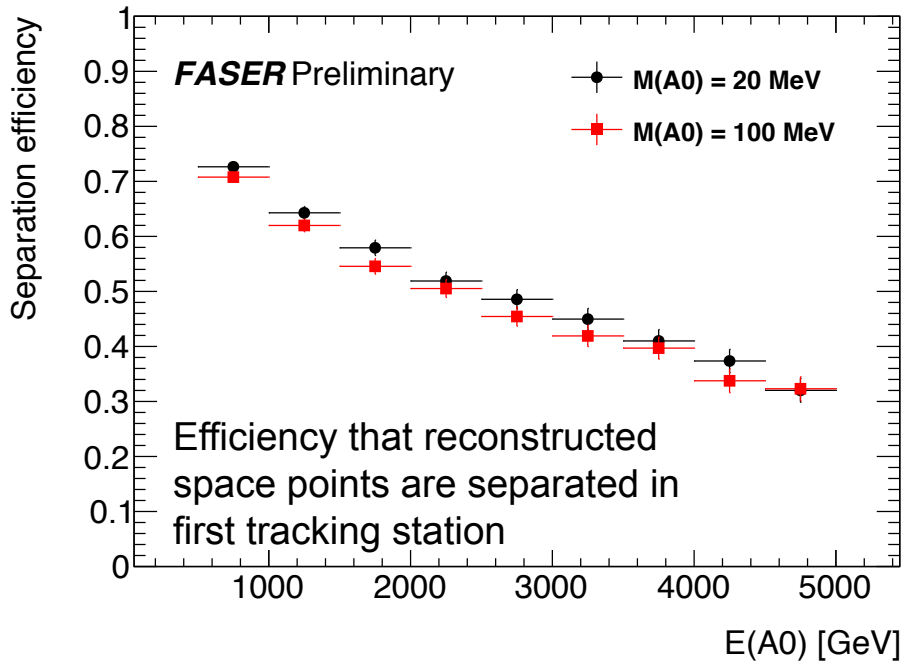


efficiency that signal tracks are separated by >0.3mm in 2nd / 3rd tracking stations

EXPECTED PERFORMANCE – Track signature

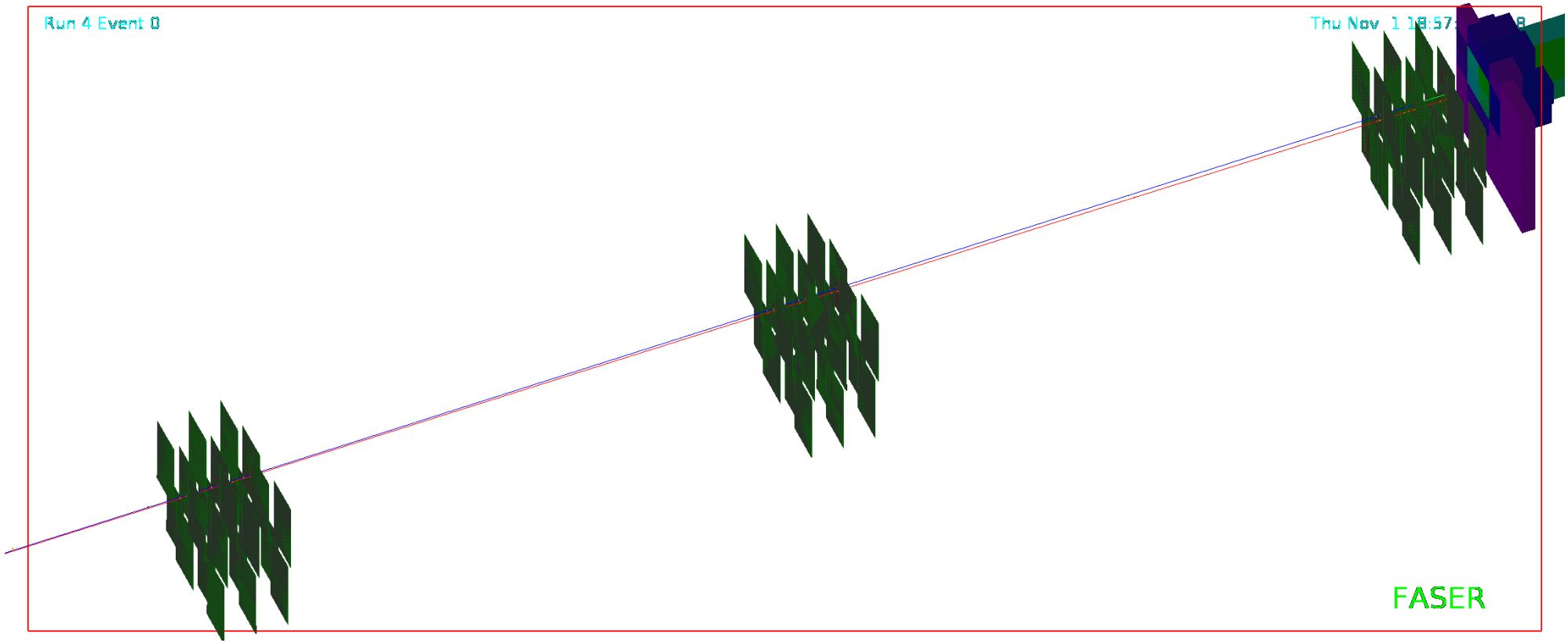
- Main backgrounds radiative processes associated with high energy muons entering the detector from the IP
  - All can be vetoed by scintillator at front of detector
- Potential small backgrounds from neutrino interactions inside the detector
  - Very low rate, and give different detector signature allowing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





GEANT4 studies

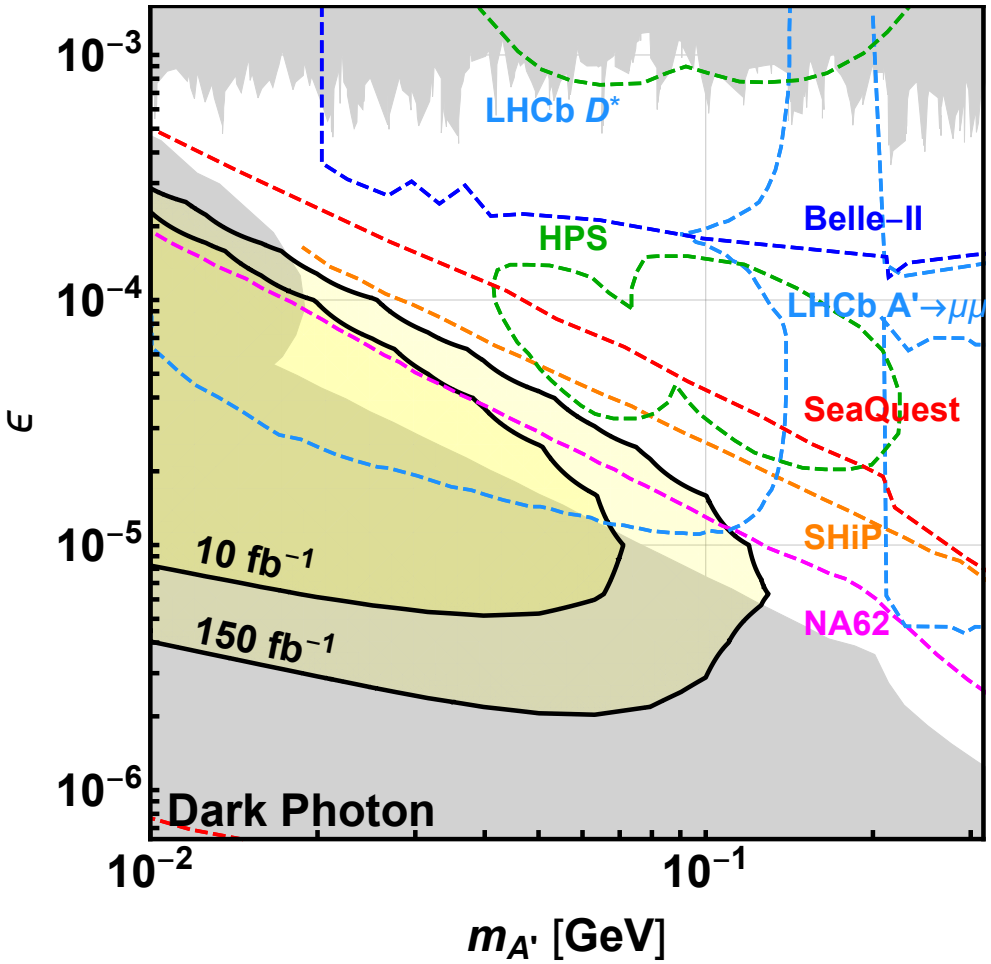
SIGNAL EVENT



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

EXPECTED SENSITIVITY

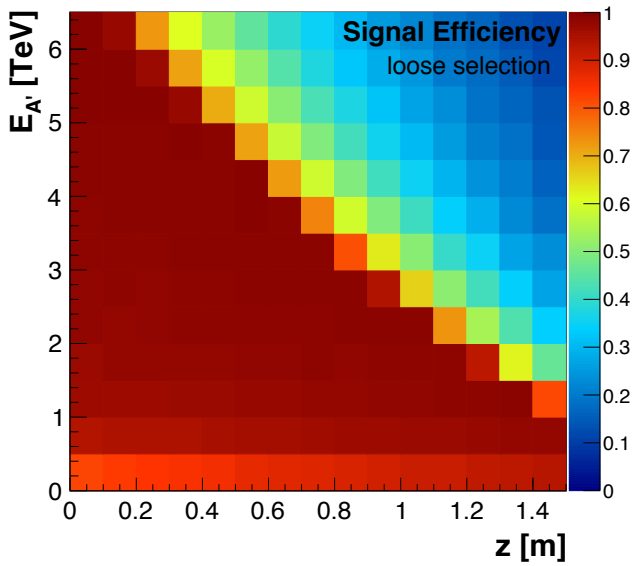
- Sensitivity for dark photons
  - Assuming no background and 100% signal efficiency
  - Curves only slightly effected by O(1) changes in efficiency

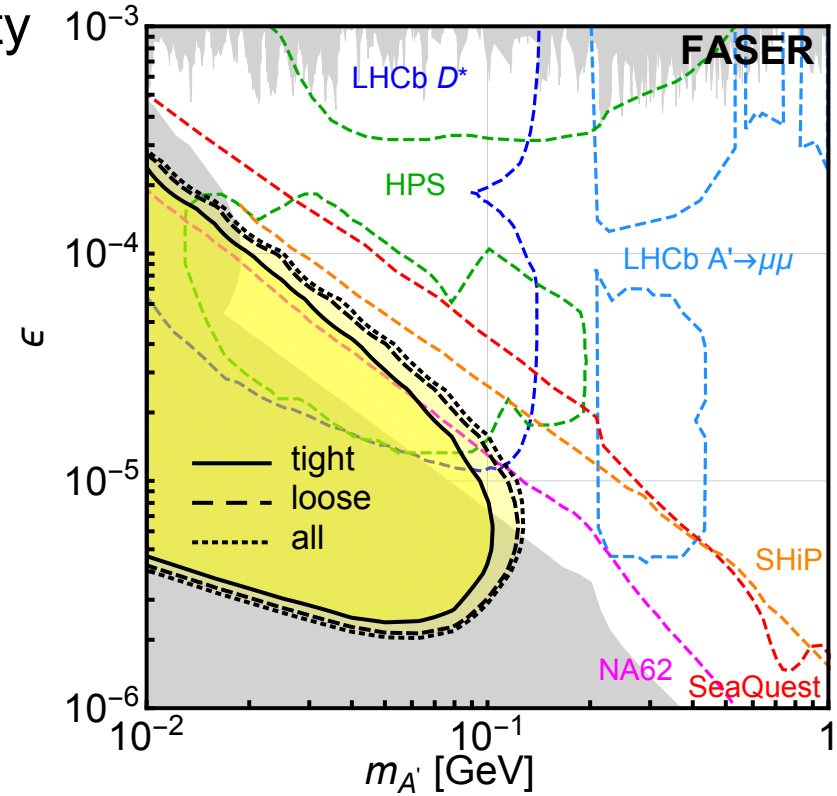


Even with 10/fb (to be collected by end of 2021?) have sensitivity to uncharted territory.
With full Run 3 dataset (150/fb) significant discovery potential.

EFFECT OF SELECTION EFFICIENCY

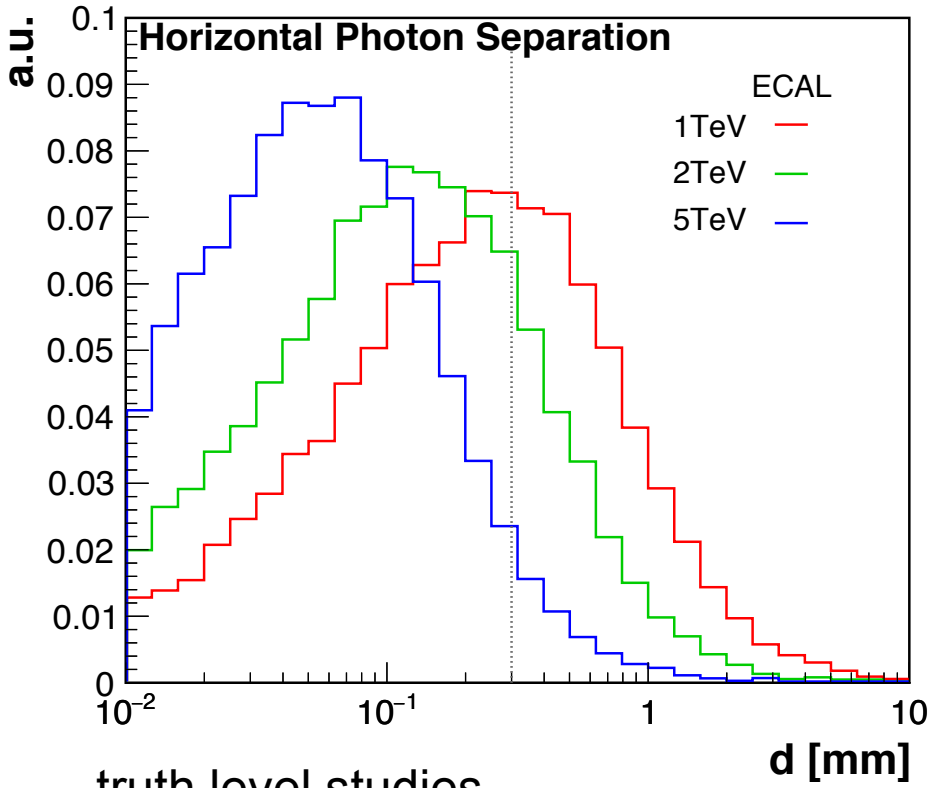
- To take into account an inefficiency due to the analysis selections
  - Defined loose selection: signal tracks separated by >0.3mm in 2nd and 3rd tracking stations
  - Defined tight selection: signal tracks separated by >0.3mm in all tracking stations
- Sensitivity basically unchanged for loose selection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





EXPECTED PERFORMANCE – 2 photon signature

- For ALP->γγ 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 (~1mm) high energy photons (>500 GeV) - seems very challenging



truth level studies

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Preliminary studies suggest that events with no tracks and a large amount of EM energy in the calorimeter would be ~background free => 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 pi0,
- 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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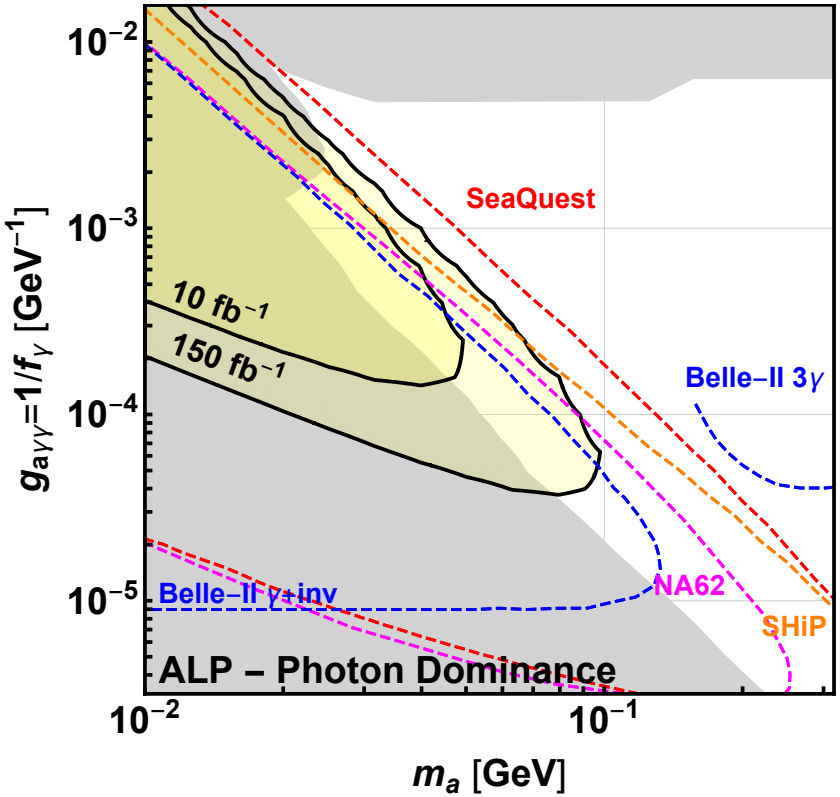
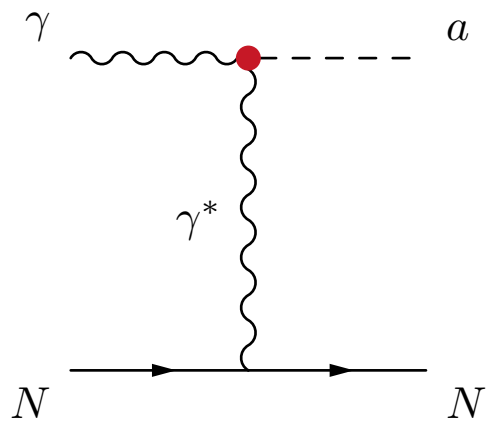
In longer term investigating installing a fine granularity silicon pre-shower to be able to separate close-by photons. Under investigation at University of Geneva.

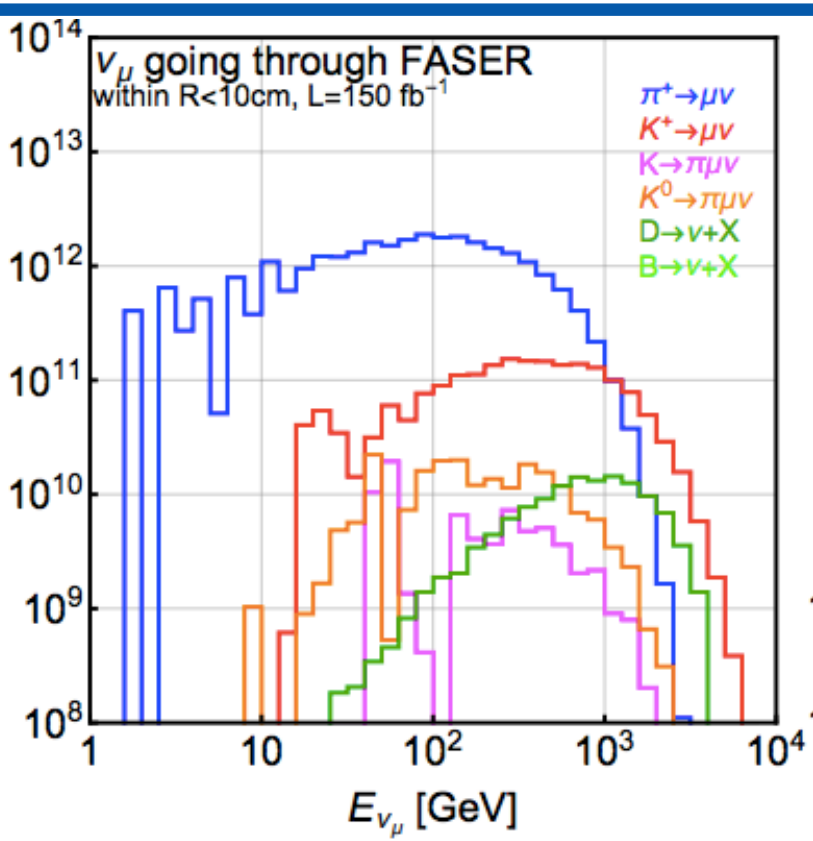
AXION LIKE PARTICLES (ALPs)

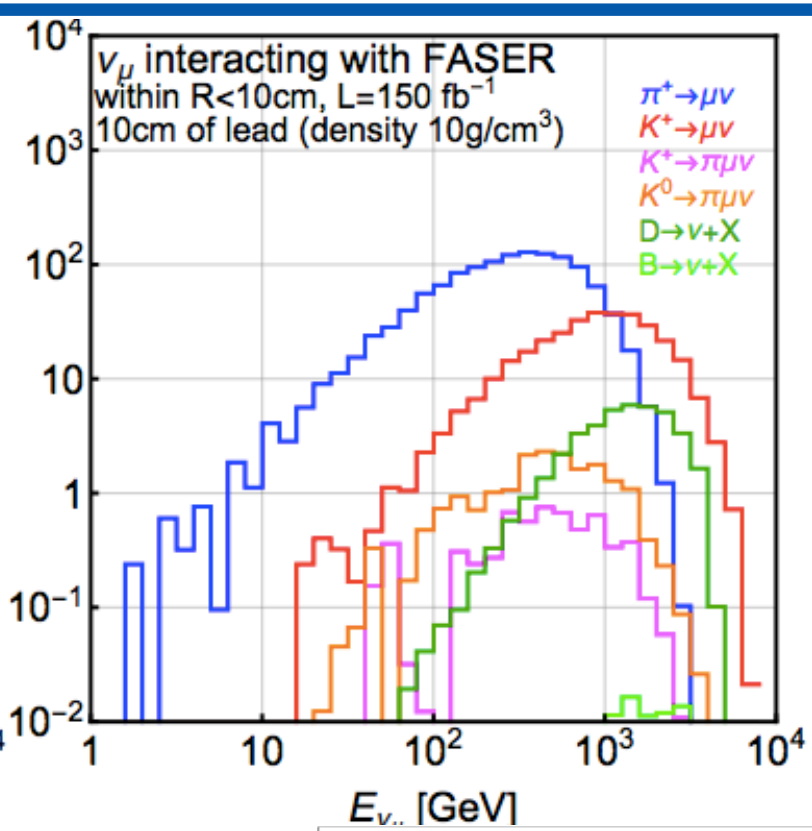
- Assuming background free single-photon like search for ALPs sensitivity for 10/fb and 150/fb





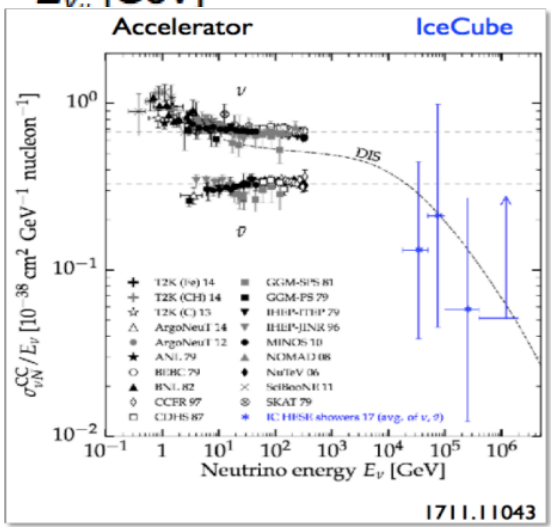
POSSIBLE NEUTRINO MEASUREMENTS





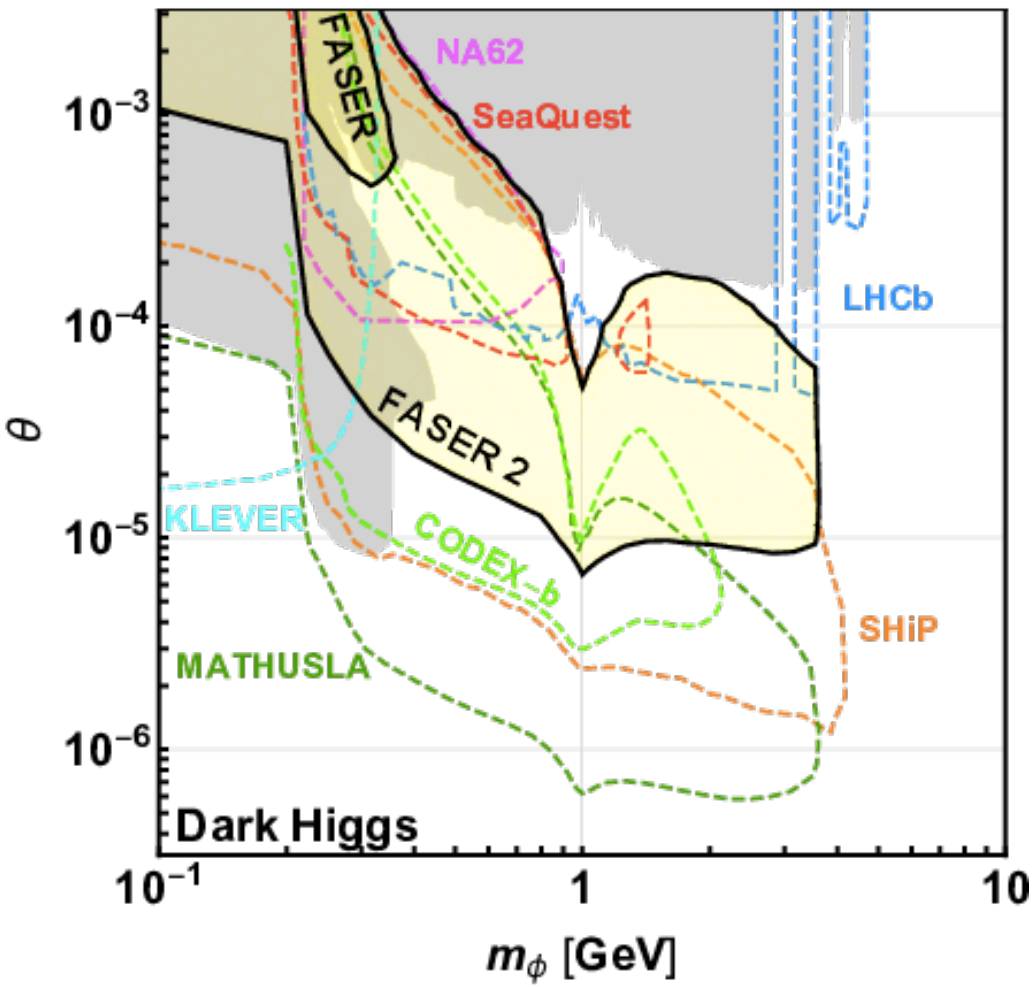
Huge flux of neutrinos through FASER could allow for interesting neutrino measurements e.g. ν_μ CC cross section in unexplored region E>400 GeV.

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

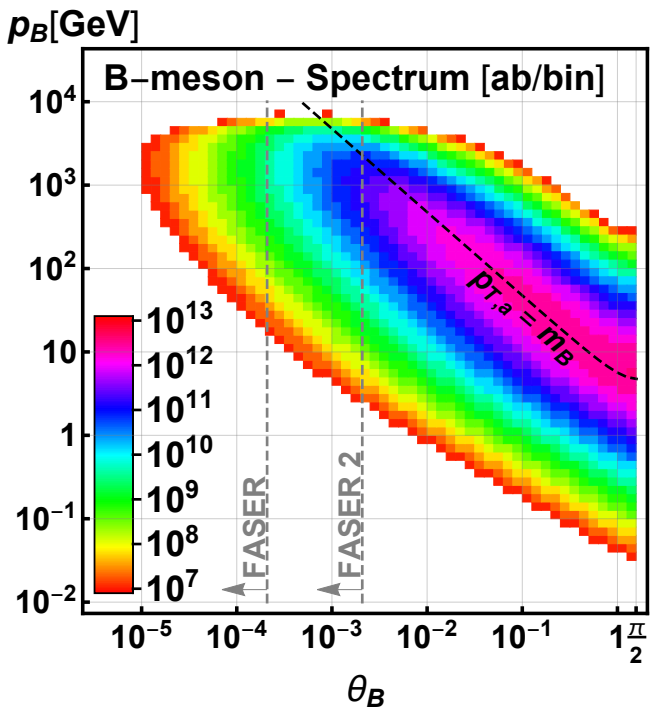


POSSIBLE FUTURE UPGRADE - FASER 2

- 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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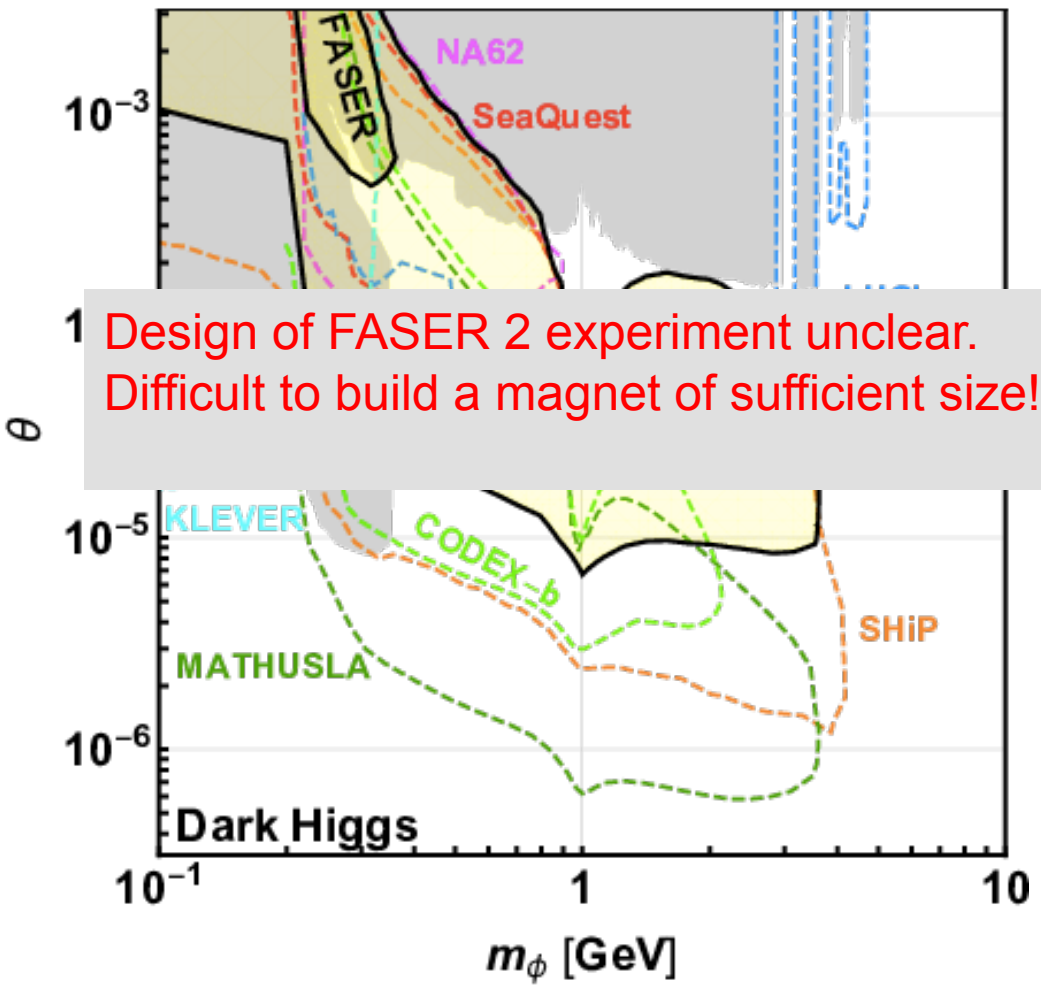

Design of FASER 2 experiment unclear.
Difficult to build a magnet of sufficient size!

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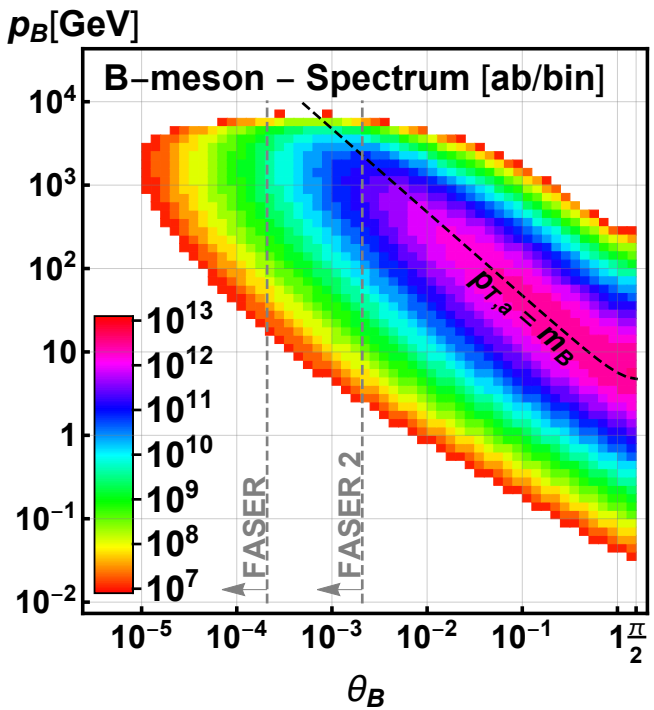


1811.12522

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
  - arXiv:1811.10243
- Technical Proposal submitted to LHCC in November
  - arXiv:1812.09139
- LHCC recommended experiment to be approved
- CERN Research Board positive about FASER, but postponed approval to March to allow FASER LS2 work to be integrated into LS2 schedule
- 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)
  - Cost to be borne by CERN (civil engineering, transport, services)
- Funding for detector construction/operation secured from Simons Foundation and Heising-Simons Foundation, contingent on CERN approval
  - Installation in LS2, data-taking in Run 3

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

- The University of Geneva is making critical contributions to FASER!

THE FASER COLLABORATION

Akitaki Ariga,[1] Tomoko Ariga,[1,2] Jamie Boyd,[3] Franck Cadoux,[4] David W. Casper,[5] Yannick Favre,[4] Jonathan L. Feng,[5] Didier Ferrere,[4] Iftah Galon,[6] Sergio Gonzalez-Sevilla,[4] Shih-Chieh Hsu,[7] Giuseppe Iacobucci,[4] Enrique Kajomovitz,[8] Felix Kling,[5] Susanne Kuehn,[3] Lorne Levinson,[9] Hidetoshi Otono,[2] Brian Petersen,[3] Osamu Sato,[10] Matthias Schott,[11] Anna Sfyrla,[4] Jordan Smolinsky,[5] Aaron M. Soffa,[5] Yosuke Takubo,[12] Eric Torrence,[13] Sebastian Trojanowski,[14,15] and Gang Zhang[16]

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

UNIVERSITÀ DEGLI STUDI DI GENOVA

清華大學 Tsinghua University

UNIVERSITY OF OREGON

Supported by:

HEISING-SIMONS FOUNDATION

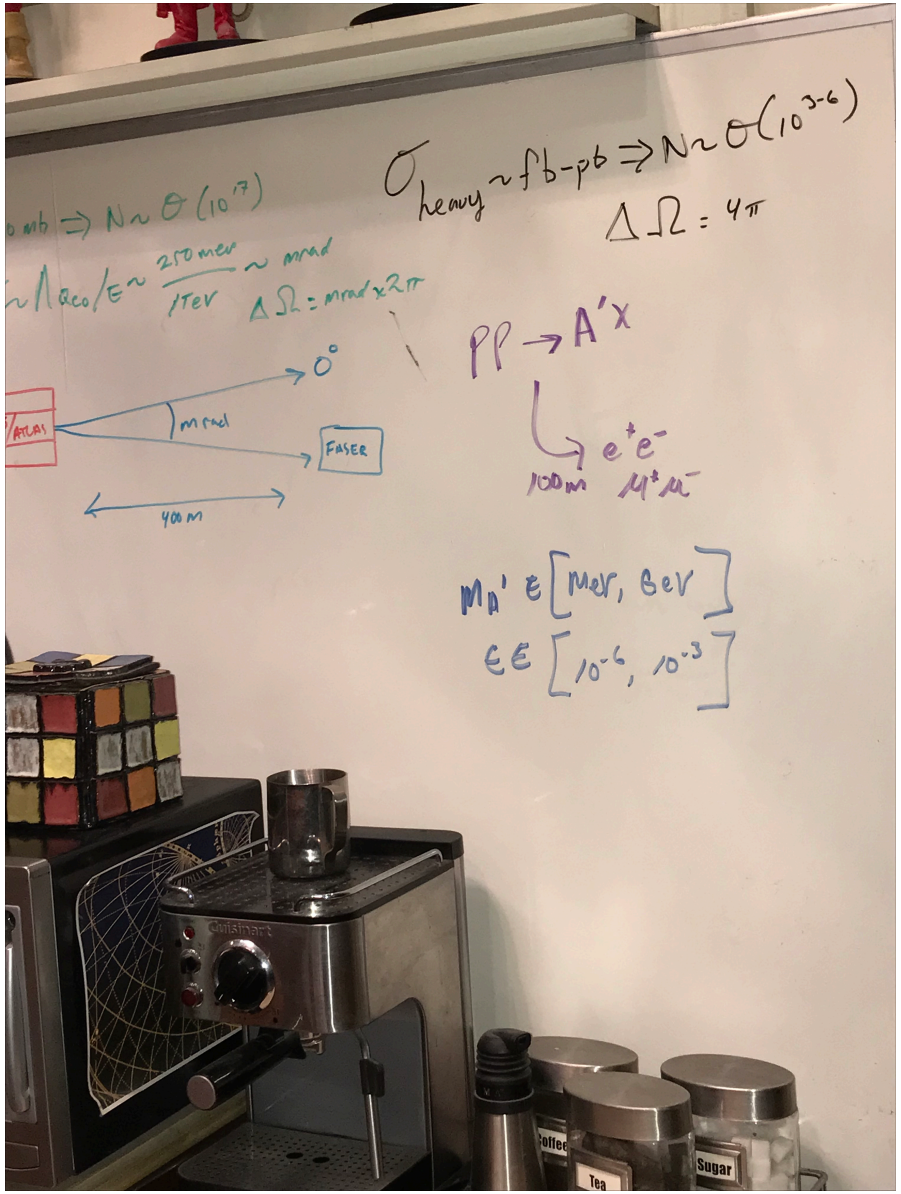
SIMONS FOUNDATION

ACKNOWLEDGEMENTS

The FASER Collaboration gratefully acknowledges the contributions of many people

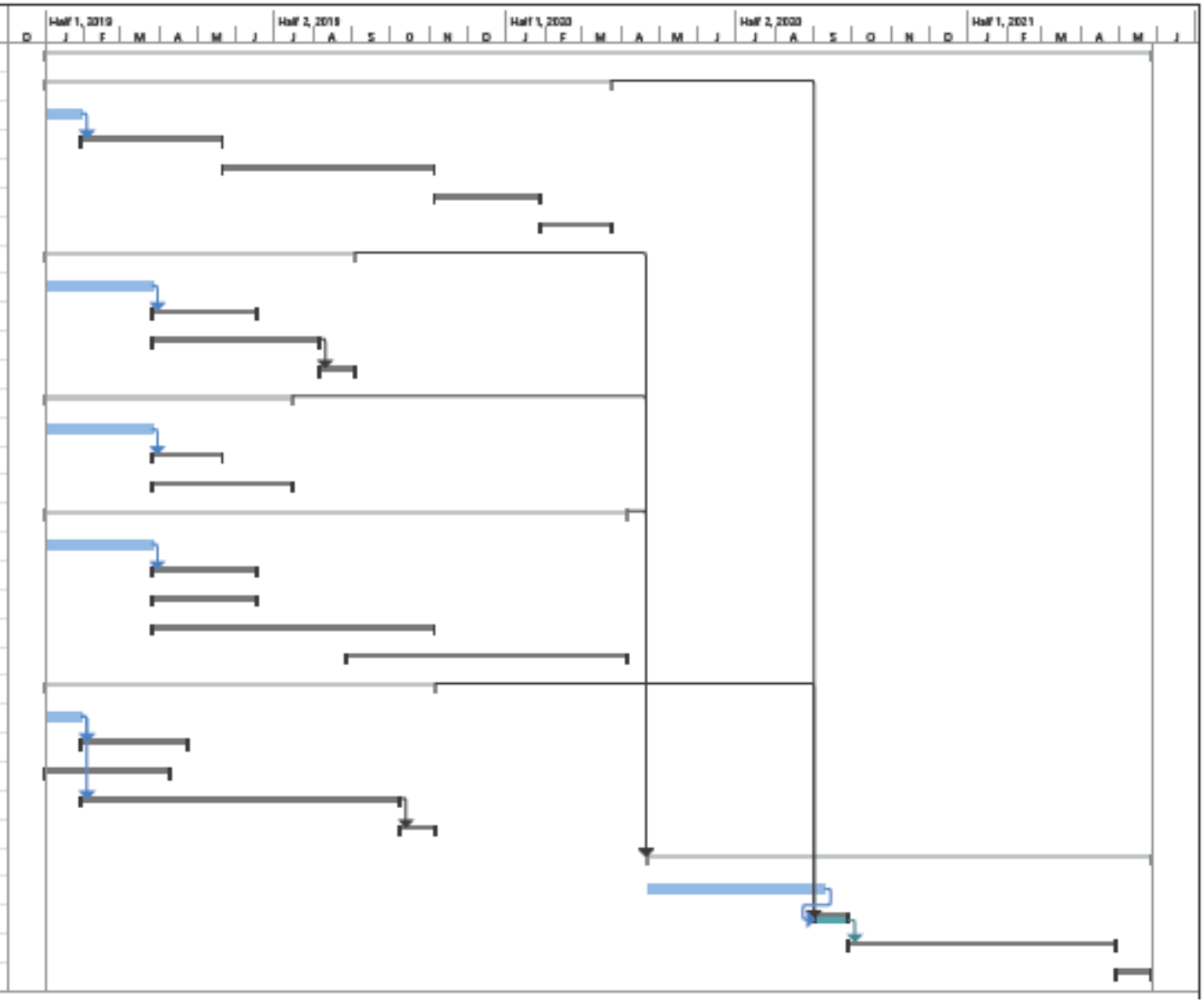
We are grateful to the ATLAS SCT project and the LHCb Calorimeter project for letting us use spare modules as part of the FASER experiment. In addition, FASER gratefully acknowledges invaluable assistance from many people, including the CERN Physics Beyond Colliders study group; the LHC Tunnel Region 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).

BACK UP


$\sigma_{heavy} \sim fb\text{-}pb \Rightarrow N \sim \mathcal{O}(10^{3\text{-}6})$
$\Delta\Omega = 4\pi$
$\Rightarrow N \sim \mathcal{O}(10^{17})$
$\sim \Lambda_{QCD}/E \sim \frac{250\,MeV}{1\,TeV} \sim mrad$
$\Delta\Omega = mrad \times 2\pi$
0°
mrad
ATLAS
FASER
400 m
$pp \to A'X$
e^+e^-
100 m
$\mu^+\mu^-$
$m_{A'} \in [MeV, GeV]$
$\epsilon \in [10^{-6}, 10^{-3}]$
Coffee
Tea
Sugar

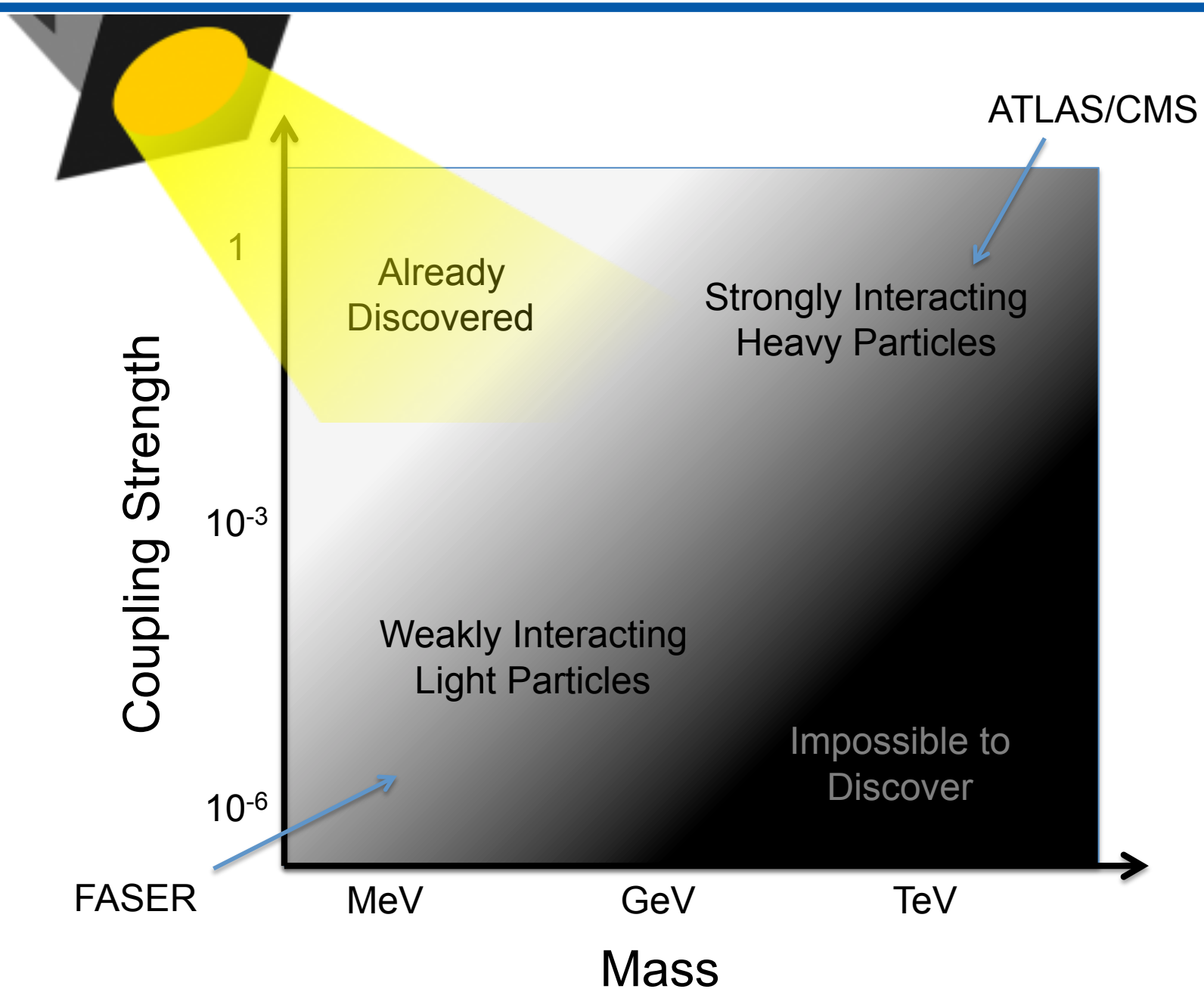
Schedule

ID	Task Mode	Task Name	Duration
0		FASER	627 days?
1		Magnet System	320 days
1		Project Validation	1 mon
2		Design	80 days
6		Procurement	120 days
8		Assembly	60 days
12		Field Measurements	40 days
2		Scintillator System	175 days
1		Final Specification	12 wks
2		Procurement	60 days
9		Scintillator layer	95 days
12		Testing	20 days
3		Calorimeter System	140 days
1		Final Specification	12 wks
2		Procurement	40 days
7		Module testing	80 days
4		TDAQ System	330 days
1		Final Specification	12 wks
2		Procurement	60 days
6		Custom hardware	60 days
9		Firmware production	160 days
13		Commissioning	160 days
6		Infrastructure	221 days?
1		Final Specification	4 wks
2		Worksite Preparation	60 days?
8		Transport Preparation	70 days
11		Civil Engineering	181 days
21		Services	20 days?
7		Commissioning	285 days
1		Cosmic and contingency	5 mons
4		Installation	1 mon
6		Comissioning in TI12	152 days
9		Data taking starts	20 days



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)

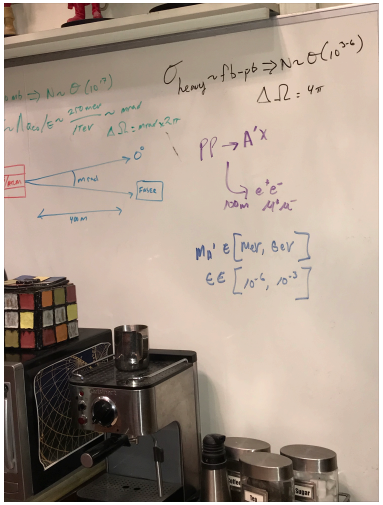
LAMPPOST LANDSCAPE



THE LIFETIME FRONTIER

- Very popular, many interesting experiments: LHCb, Belle-II, NA62, SHiP, SeaQuest, MilliQan, MATHUSLA, Codex-b, and many others

- FASER: ForwArd Search ExpeRiment. “The acronym recalls another marvelous instrument that harnessed highly collimated particles and was used to explore strange new worlds.”



DARK PHOTON STATUS

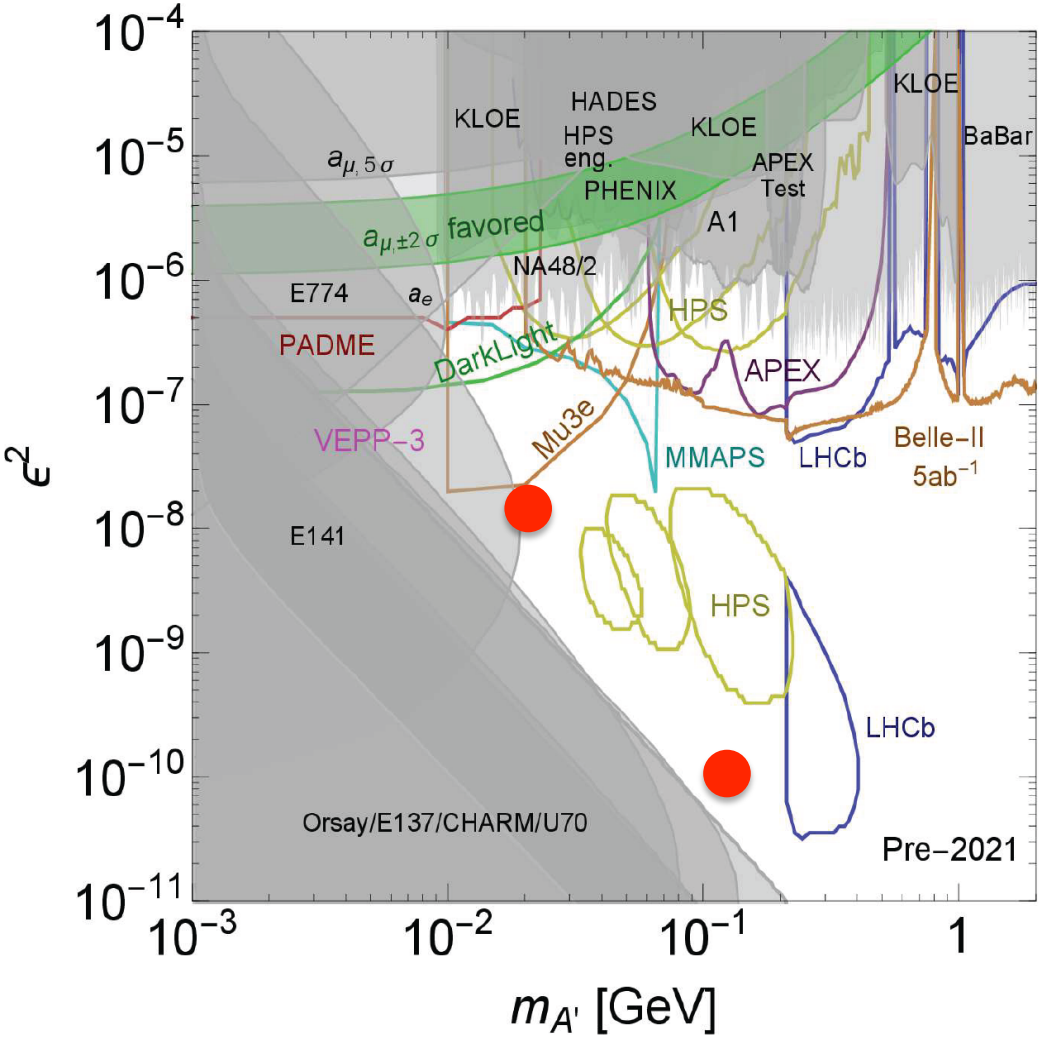
- Low ε → fixed target constraints, high ε → collider, precision constraints
- But still lots of open parameter space with

  $m_{A'} > 10$ MeV

  $\varepsilon \sim 10^{-6} - 10^{-3}$
- E.g., 2 representative model points: $(m_{A'}, \varepsilon)$ =

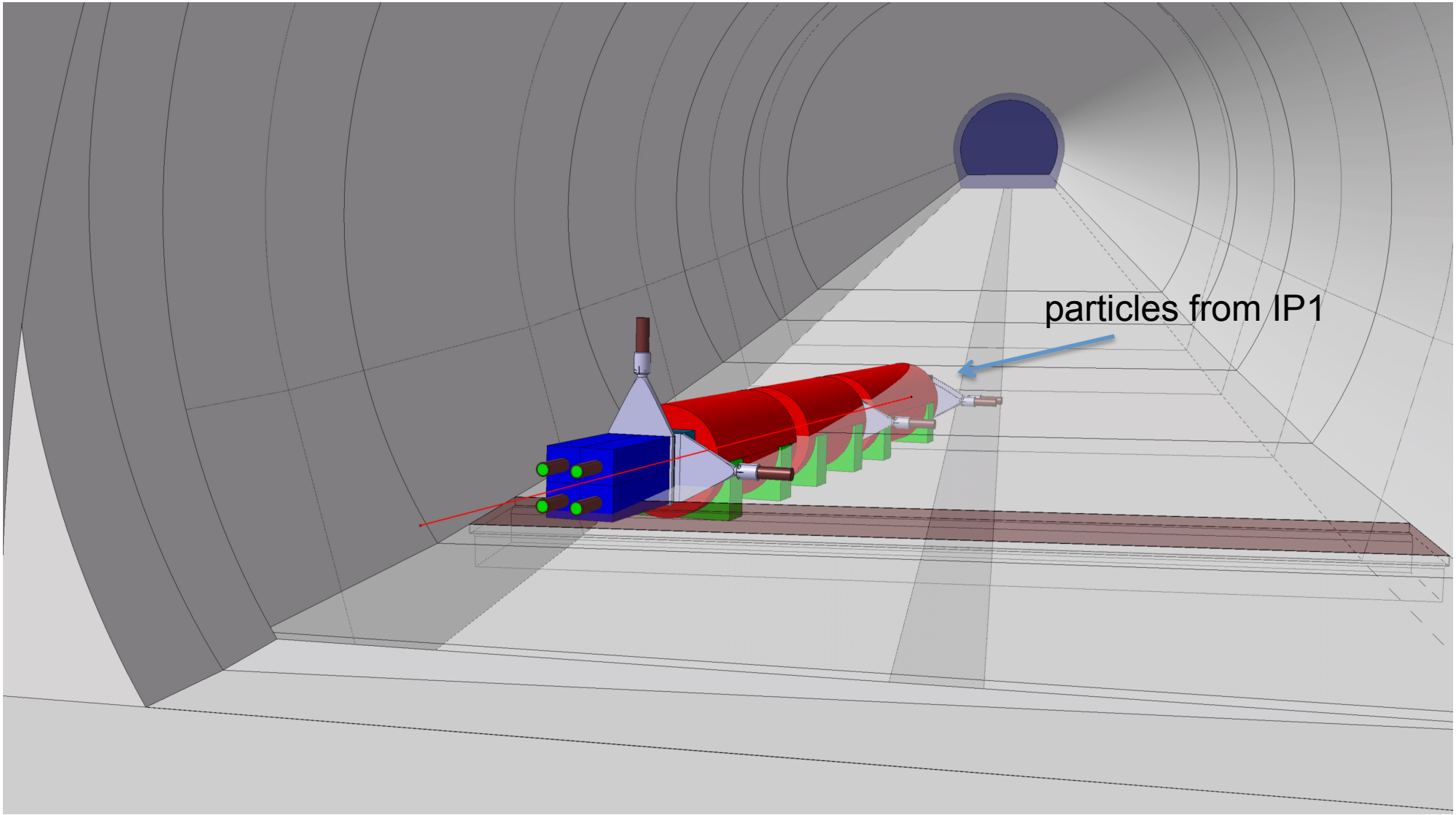
  (20 MeV, 10^{-4})

  (100 MeV, 10^{-5})



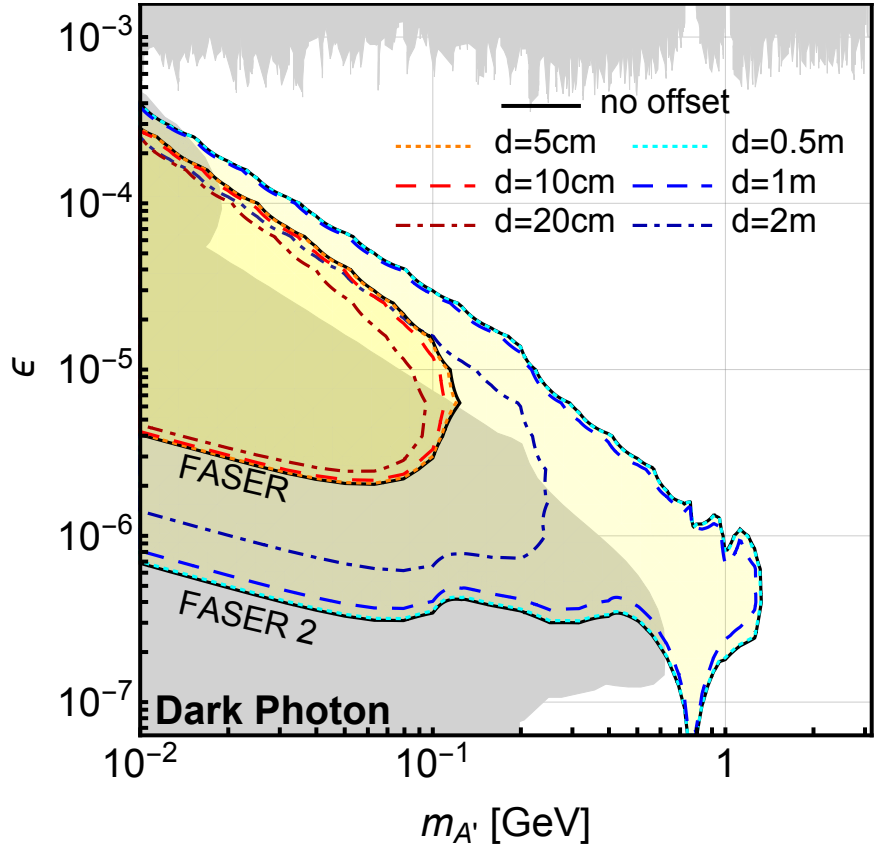
Cosmic Visions White Paper (2017)

FASER IN SITU



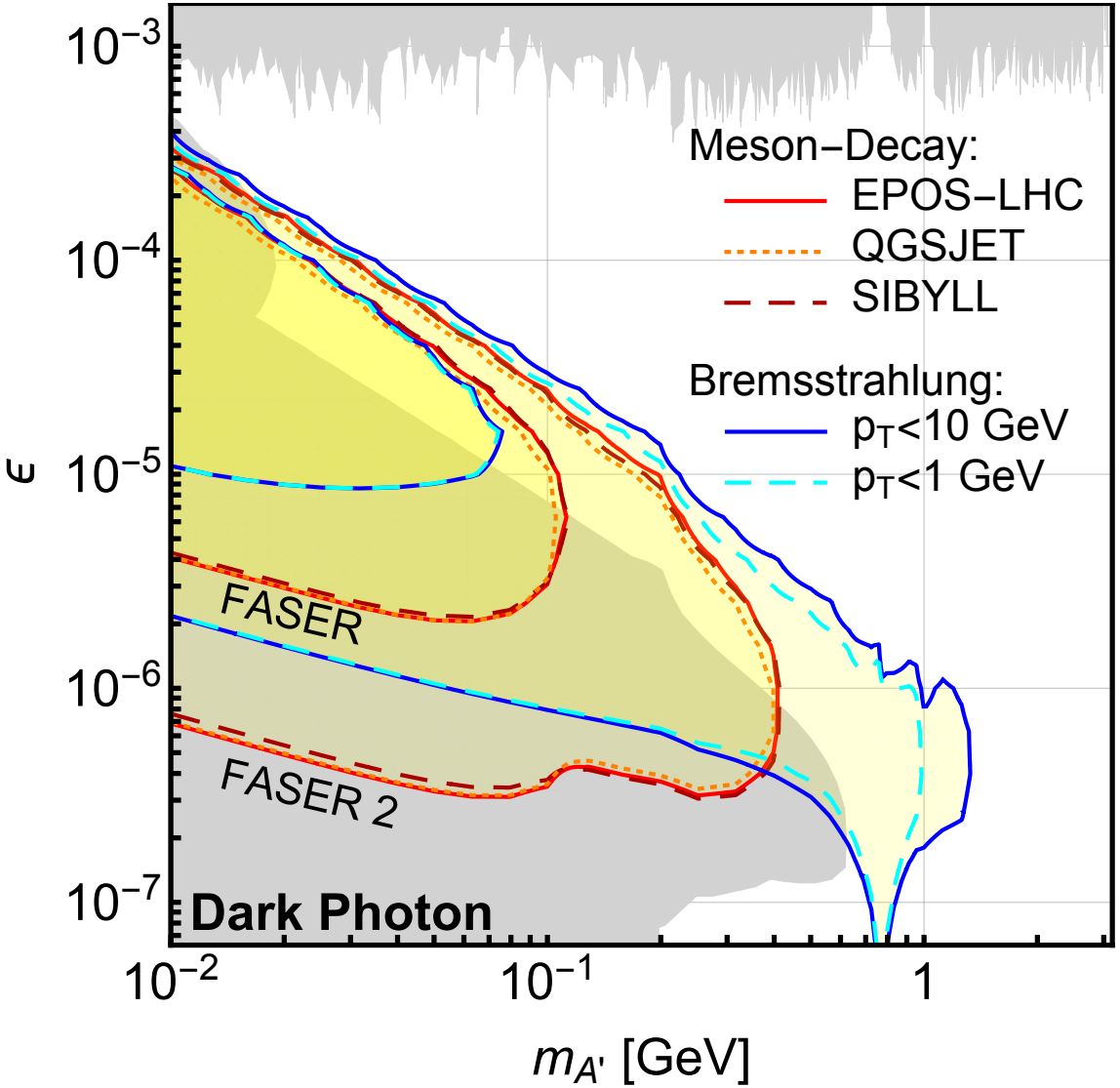
EFFECT OF LHC CROSSING ANGLE

- 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 ~150μrad, which moves the collision axis by ~7.5cm at the FASER location
  - Such a change reduces the signal acceptance in FASER by ~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,[5,†] 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,[3] Mike Lamont,[3] Lorne Levinson,[9] Hidetoshi Otono,[2] John Osborne,[3] Brian Petersen,[3] Osamu Sato,[10] Marta Sabaté-Gilarte,[3,11] Matthias Schott,[12] Anna Sfyrla,[4] Jordan Smolinsky,[5] Aaron M. Soffa,[5] Yosuke Takubo,[13] Pierre Thonet,[3] Eric Torrence,[14] Sebastian Trojanowski,[15] and Gang Zhang[16]

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LETTER OF INTENT

FASER
FORWARD SEARCH EXPERIMENT AT THE LHC

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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 TI18. We propose that FASER be installed in TI18 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.

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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.* **D98** 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].

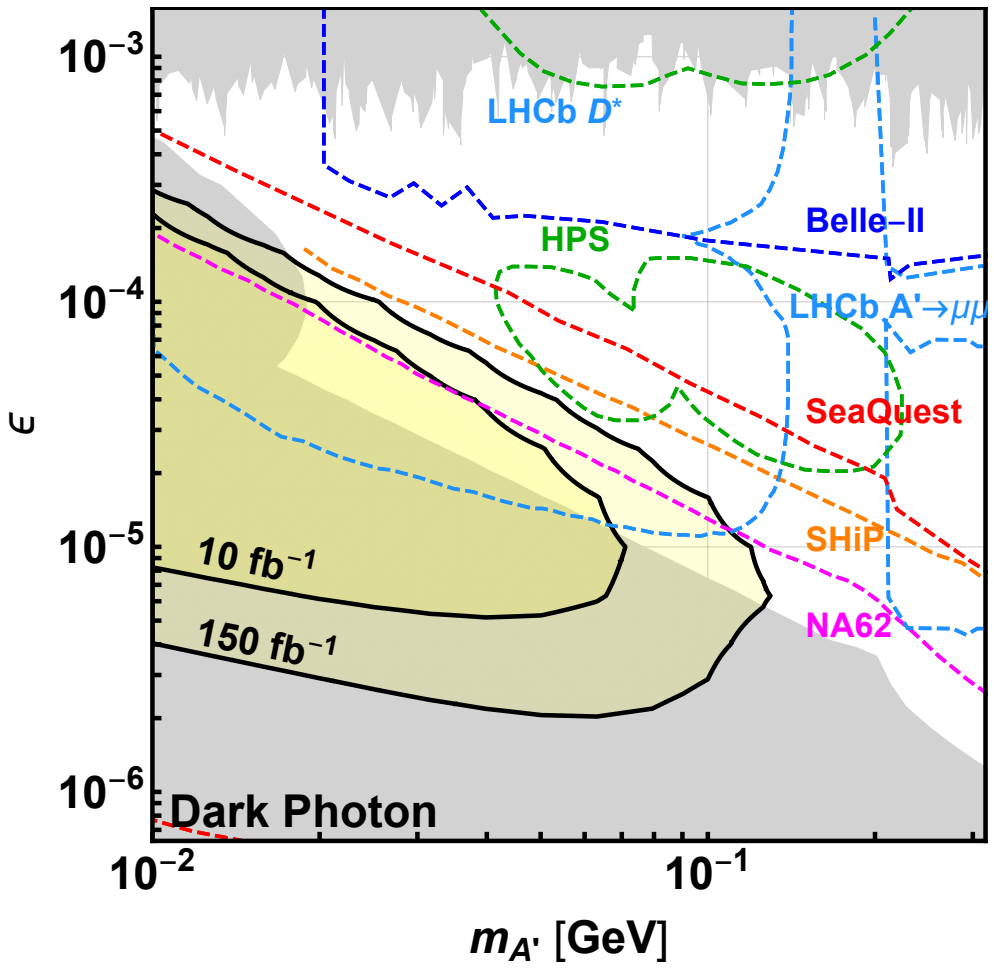
[19] M. J. Dolan, T. Ferber, C. Hearty, F. Kahlhoefer, and K. Schmidt-Hoberg, "Revised constraints and Belle II sensitivity for visible and invisible axion-like particles," *JHEP* **12** (2017) 094, arXiv:1709.00009 [hep-ph].

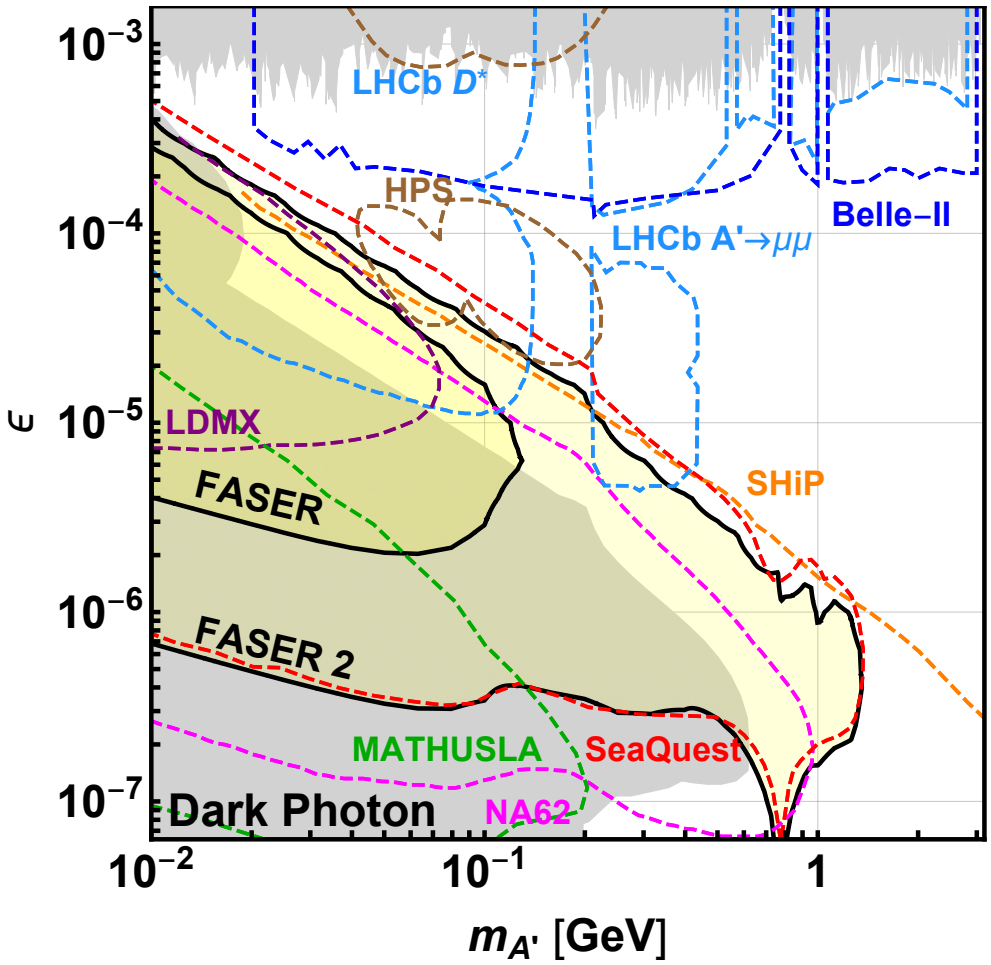
[20] P. Ilten, J. Thaler, M. Williams, and W. Xue, "Dark photons from charm mesons at LHCb," *Phys. Rev.* **D92** (2015) 115017, arXiv:1509.06765 [hep-ph].

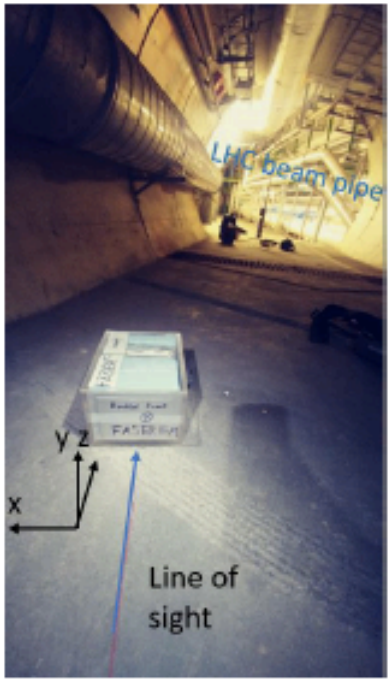
[21] P. Ilten, Y. Soreq, J. Thaler, M. Williams, and W. Xue, "Proposed Inclusive Dark Photon Search at LHCb," *Phys. Rev. Lett.* **116** (2016) 251803, arXiv:1603.08926 [hep-ph].

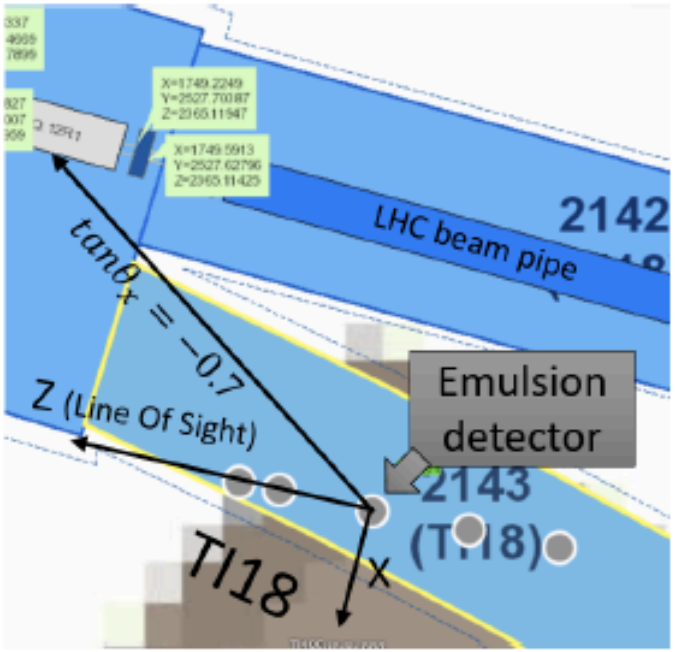
HPS limits taken from talk:
'First Results from the Heavy Photon Search Experiment' at ICHEP 2018

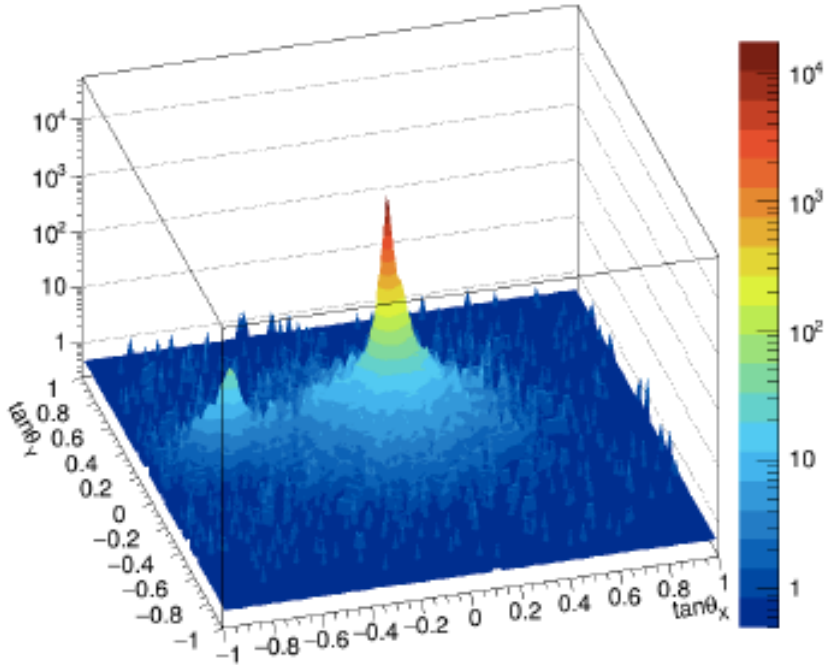
ASSUMPTIONS FOR OTHER EXPTS LIMITS

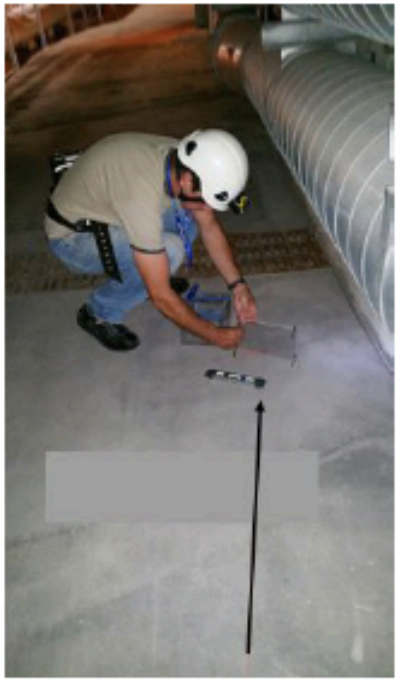


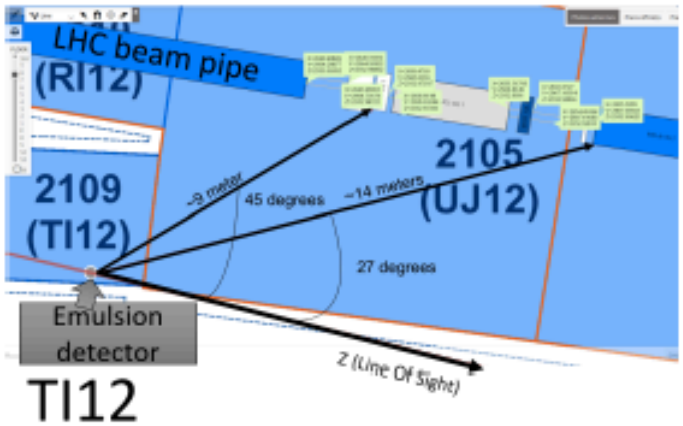


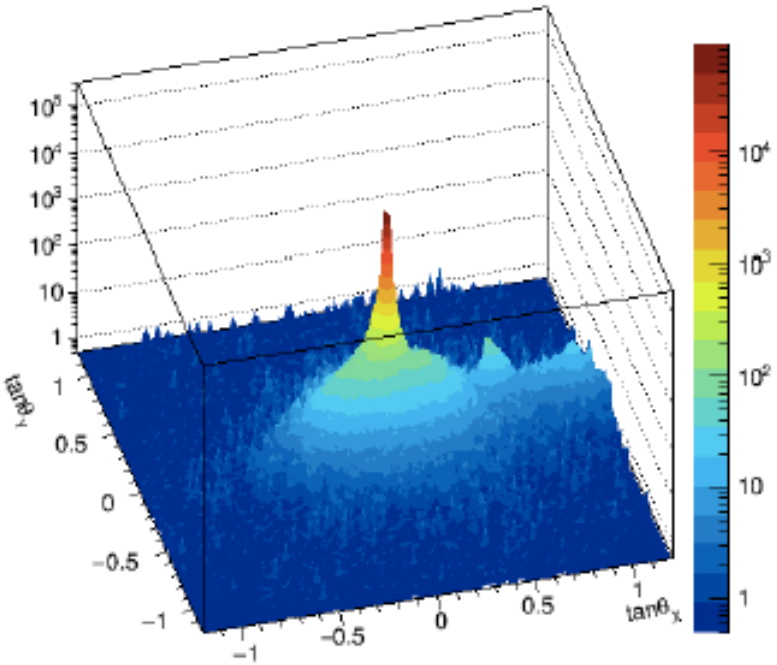

LHC beam pipe
y z
x
Line of
sight


LHC beam pipe
2142
tanθ_x = −0.7
Z (Line Of Sight)
Emulsion
detector
2143
(TI8)
TI18
x


tanθ_y
tanθ_x

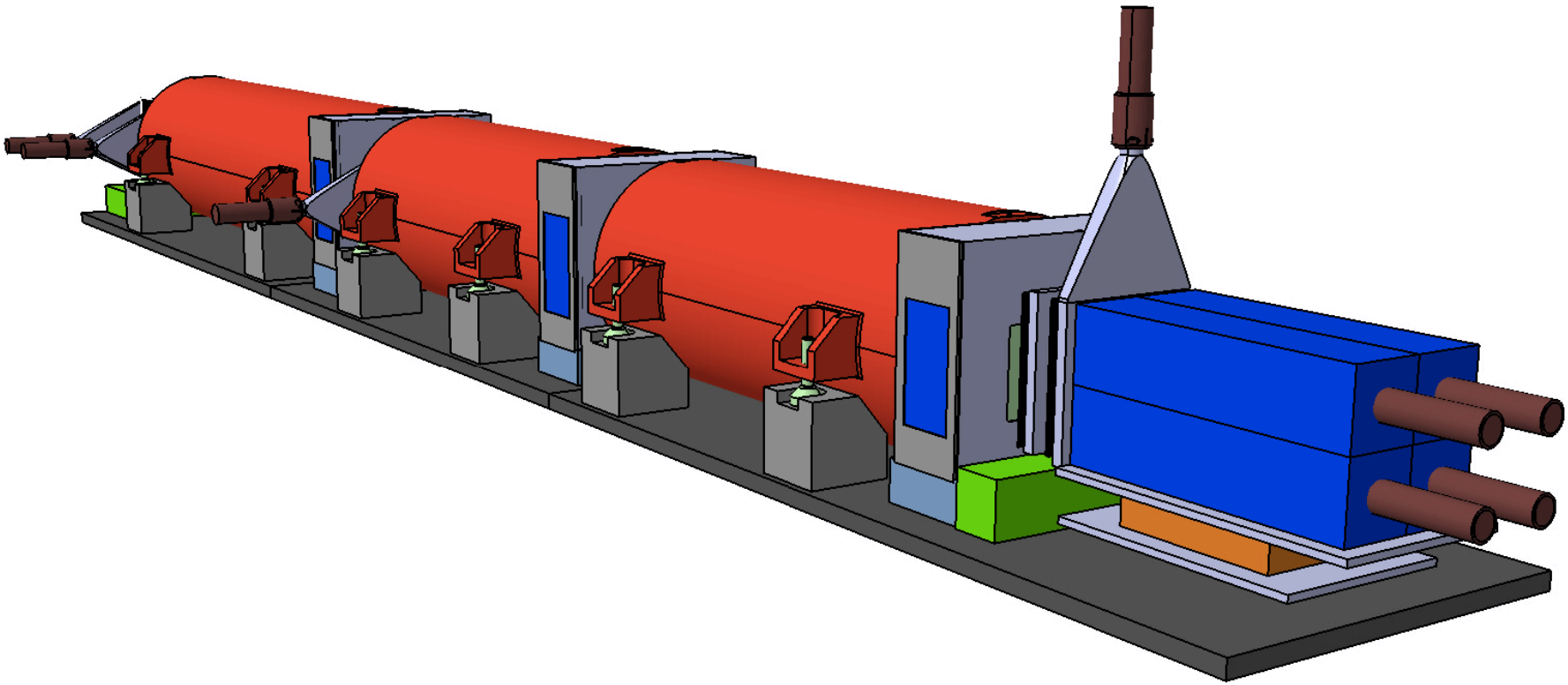



LHC beam pipe
(RI12)
2109
(TI12)
2105
(UJ12)
45 degrees
27 degrees
Emulsion
detector
Z (Line Of Sight)
TI12


tanθ_y
tanθ_x

Detector Support

Preliminary conceptual design:



Design/construction by DPNC mechanics team

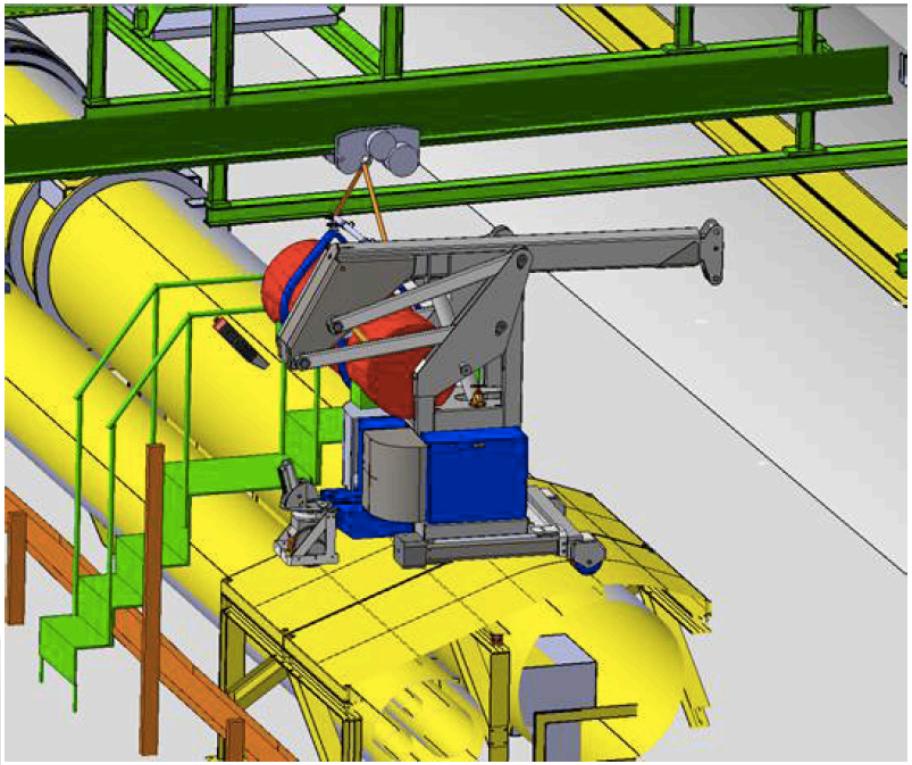
Tracker alignment issues

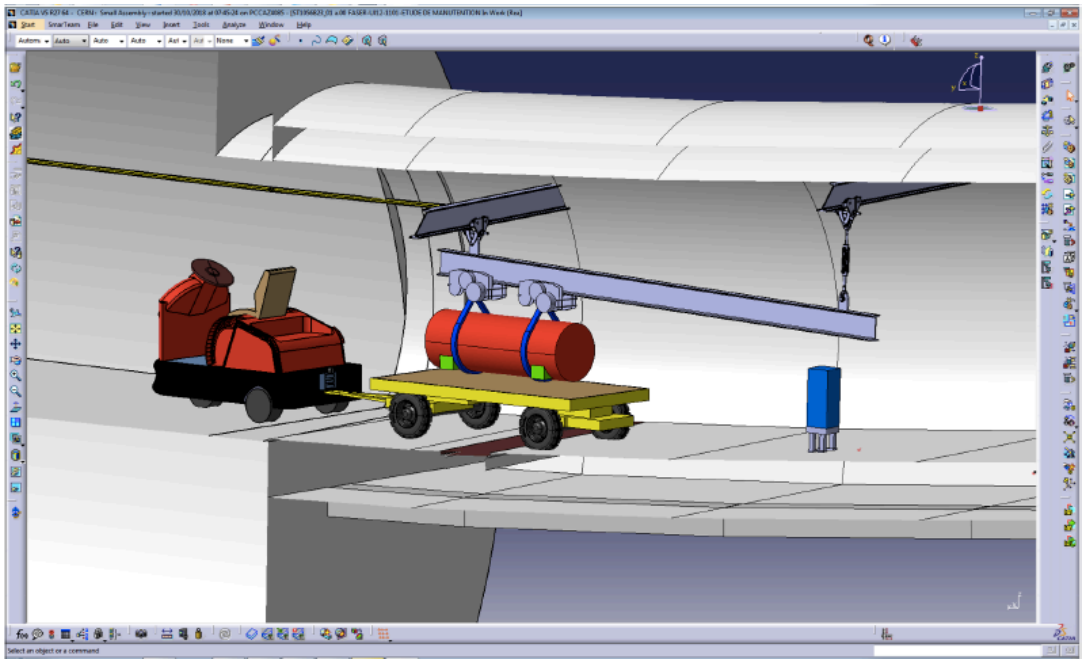
Momentum resolution will be limited by the relative alignment of the 3 tracking stations in the bending plane.
Significant rate of muons going through FASER tracker, but since we don't know their momentum they can not be used to constrain this alignment (no standard candles (Z, J/psi etc..) in FASER.
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.

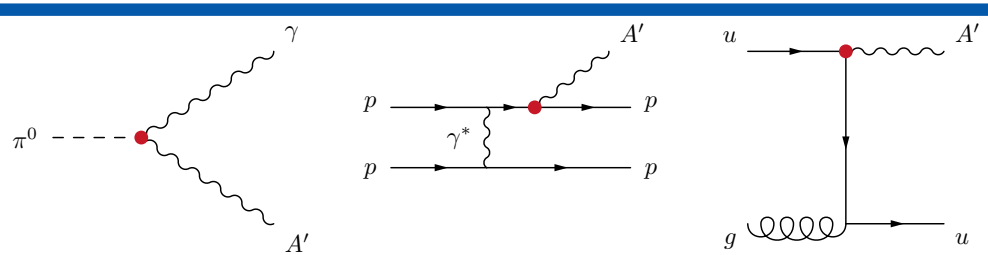
Transport / Installation issues

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.

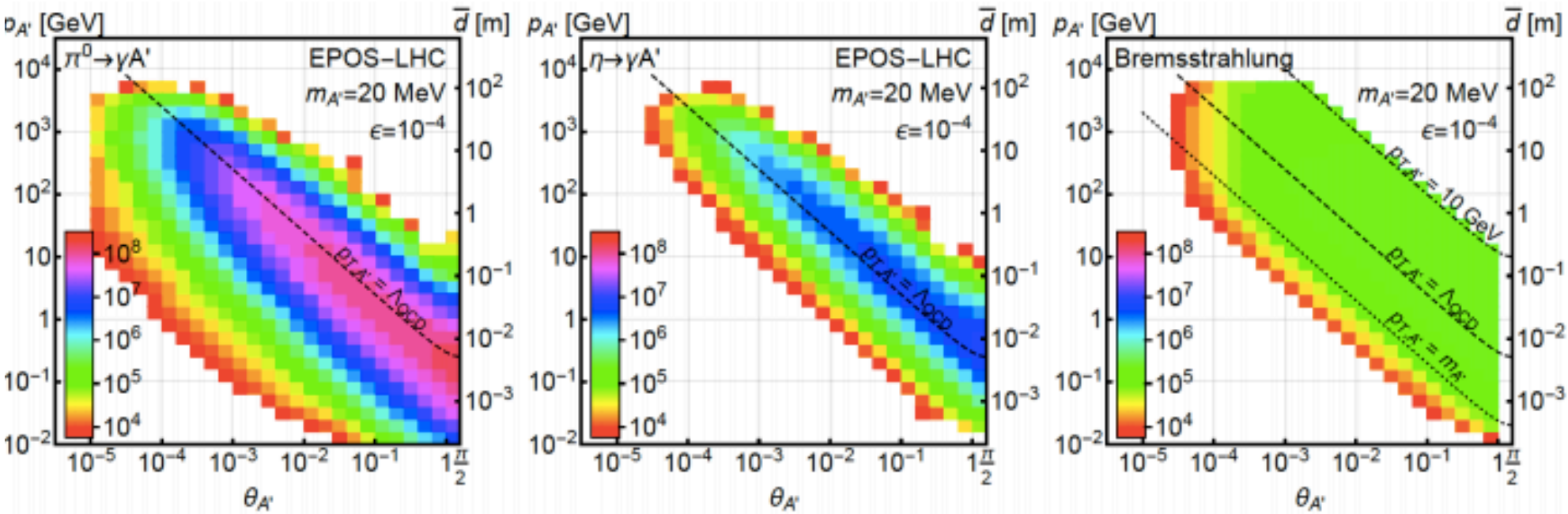




OTHER PRODUCTION MECHANISMS



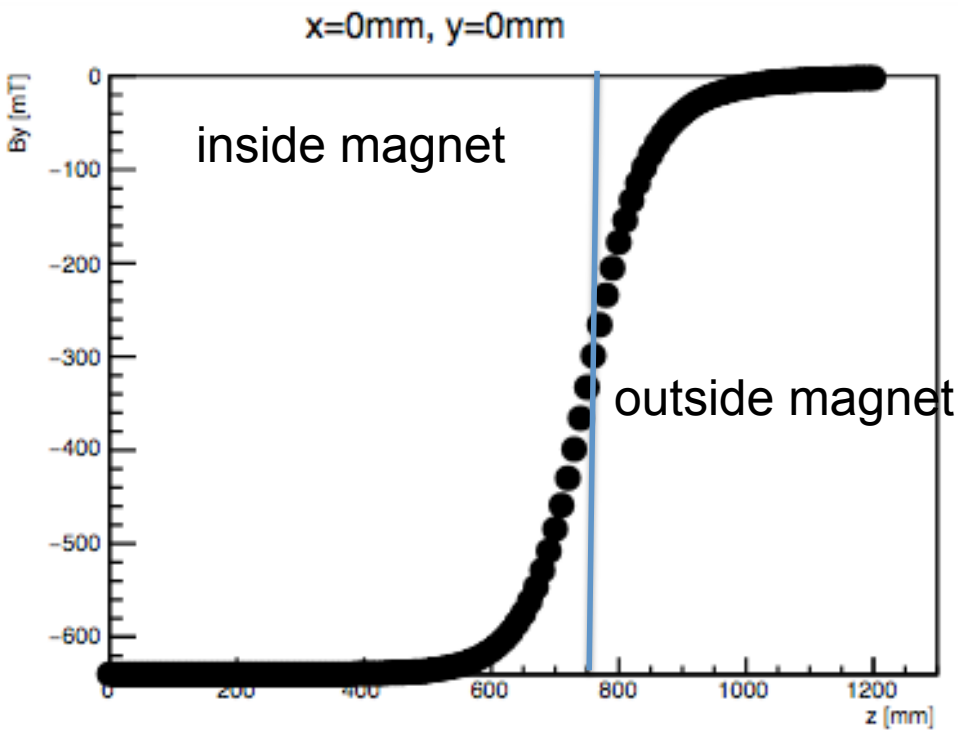
- Consider π^0 decay, η decay, dark bremsstrahlung
- Results for 1st model point: $(m_{A'}, \varepsilon) = (20\ \text{MeV}, 10^{-4})$



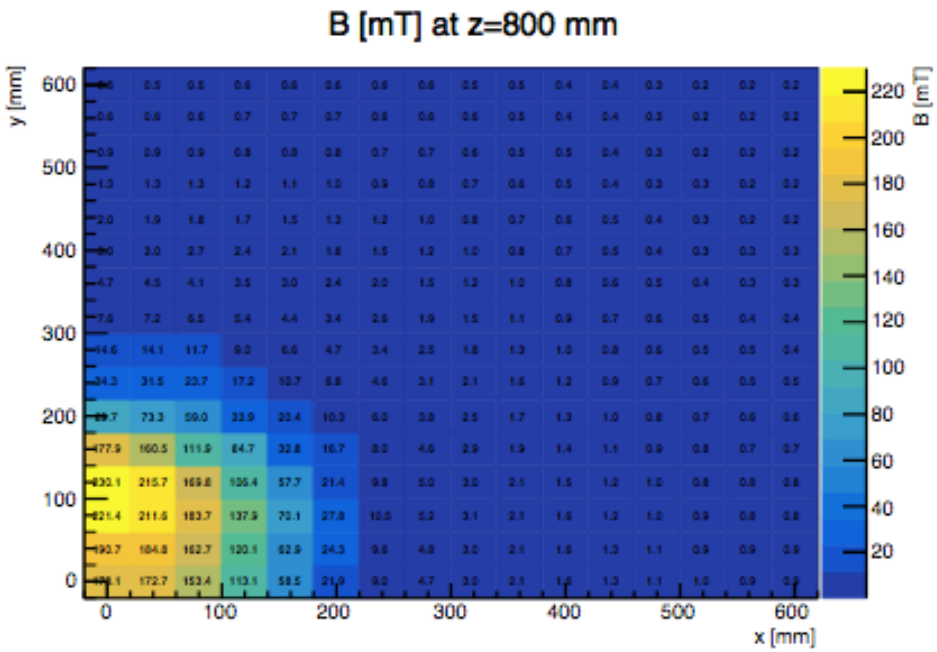
- From $\pi^0 \rightarrow \gamma A'$, $E_{A'} \sim E_\pi / 2$ (no surprise)
- But note rates: even after ε^2 suppression, $N_{A'} \sim 10^8$;

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)



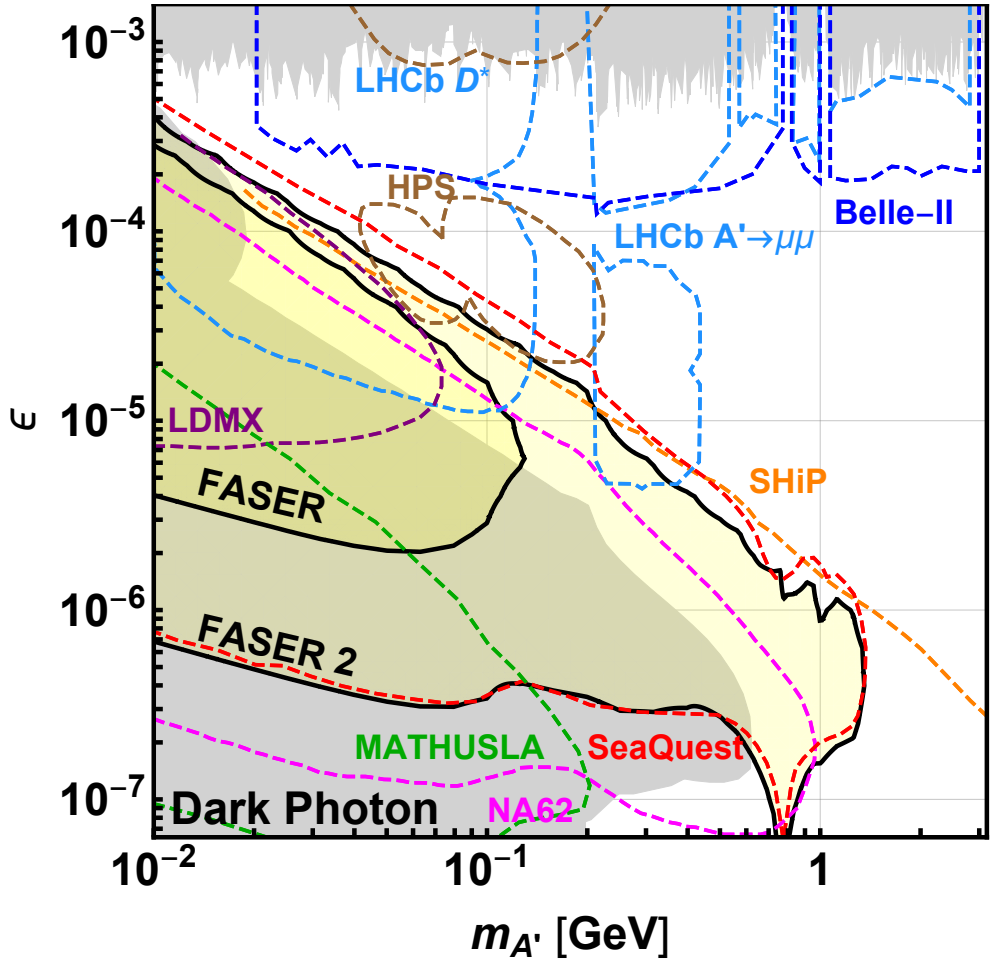
5cm outside magnet opening



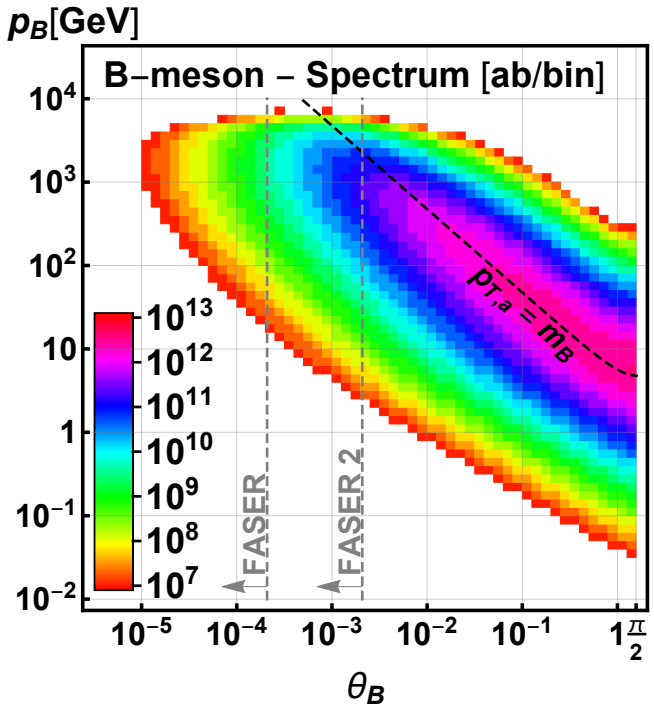
1mT field 50cm from magnet centre

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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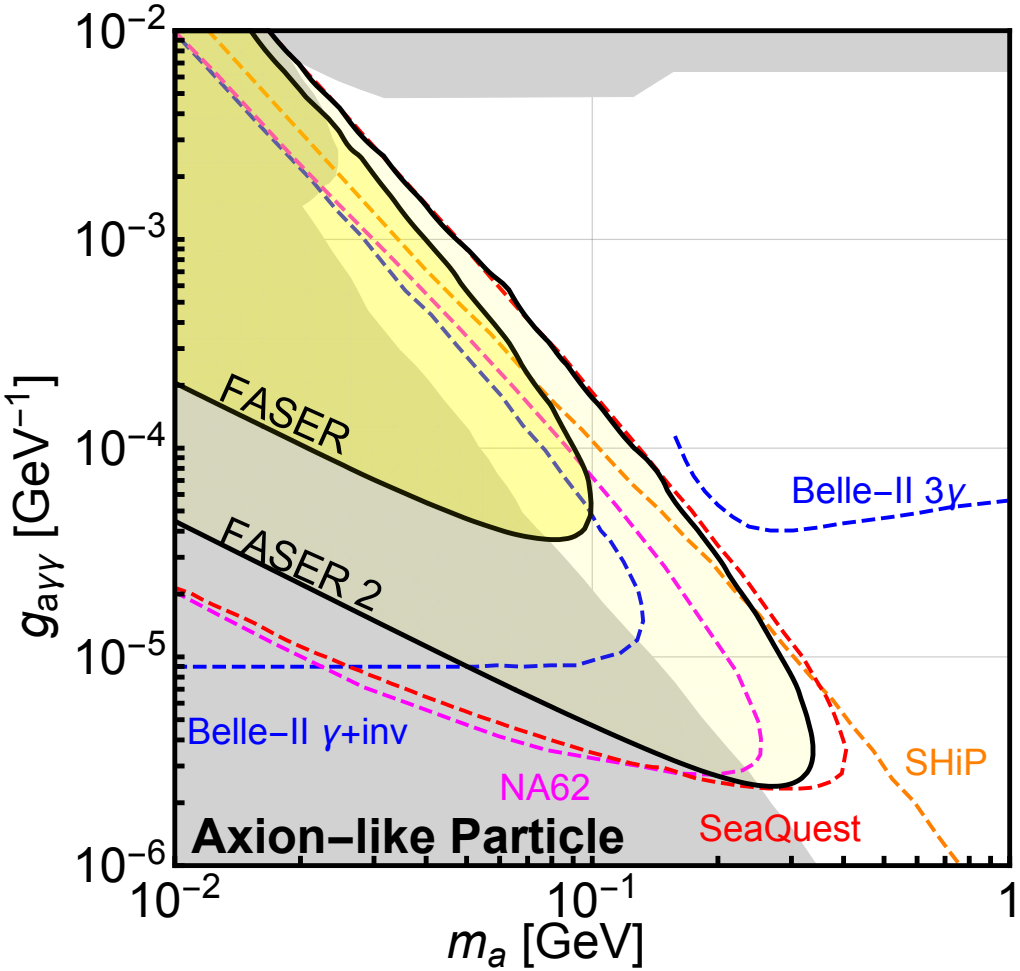

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