The (proposed) FASER experiment
(ForwArd Search ExpeRiment)

LHC LLP Workshop, CERN

Jamie Boyd (CERN) for the FASER team

based on slides from: Jonathan Feng (UC Irvine)

1708.09389

FASER: ForwArd Search ExpeRiment at the LHC

Jonathan L. Feng,[1,*] Iftah Galon,[1,†] Felix Kling,[1,‡] and Sebastian Trojanowski[1,2,§]

[1]*Department of Physics and Astronomy, University of California, Irvine, CA 92697-4575 USA*

[2]*National Centre for Nuclear Research, Hoża 69, 00-681 Warsaw, Poland*

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Abstract

New physics has traditionally been expected in the high-p_T region at high-energy collider experiments. If new particles are light and weakly-coupled, however, this focus may be completely misguided: light particles are typically highly concentrated within a few mrad of the beam line, allowing sensitive searches with small detectors, and even extremely weakly-coupled particles may be produced in large numbers there. We propose a new experiment, **F**orw**A**rd **S**earch **E**xpe**R**iment, or FASER, which would be placed downstream of the ATLAS or CMS interaction point (IP) in the very forward region and operated concurrently there. Two representative on-axis locations are studied: a far location, 400 m from the IP and just off the beam tunnel, and a near location, just 150 m from the IP and right behind the TAN neutral particle absorber. For each location, we examine leading neutrino- and beam-induced backgrounds. As a concrete example of light, weakly-coupled particles, we consider dark photons produced through light meson decay and proton bremsstrahlung. We find that even a relatively small and inexpensive cylindrical detector, with a radius of ~ 10 cm and length of $5-10$ m, depending on the location, can discover dark photons in a large and unprobed region of parameter space with dark photon mass $m_{A'} \sim 10-500$ MeV and kinetic mixing parameter $\epsilon \sim 10^{-6}-10^{-3}$. FASER will clearly also be sensitive to many other forms of new physics. We conclude with a discussion of topics for further study that will be essential for understanding FASER's feasibility, optimizing its design, and realizing its discovery potential.

* Electronic address: jlf@uci.edu
† Electronic address: iftachg@uci.edu
‡ Electronic address: fkling@uci.edu
§ Electronic address: strojano@uci.edu

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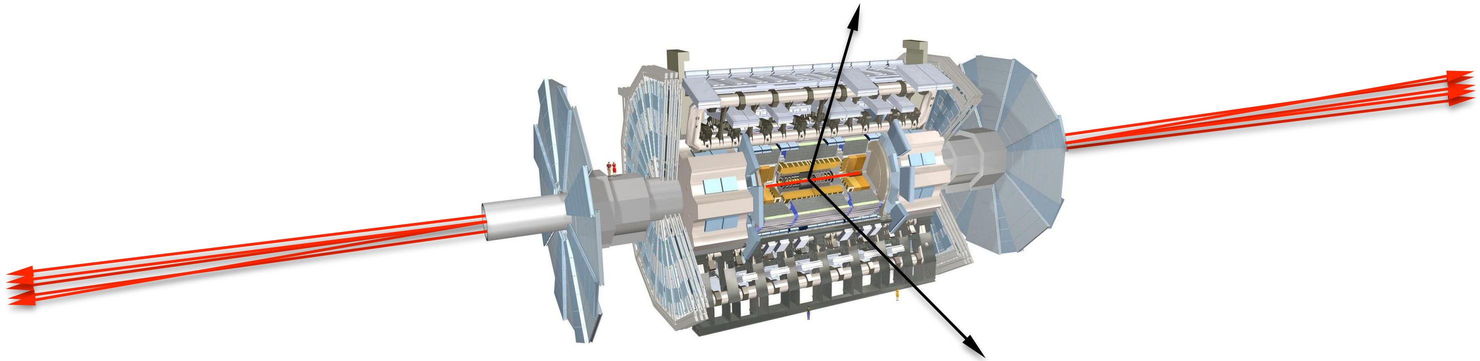
18 May 2018

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

FASER: THE IDEA

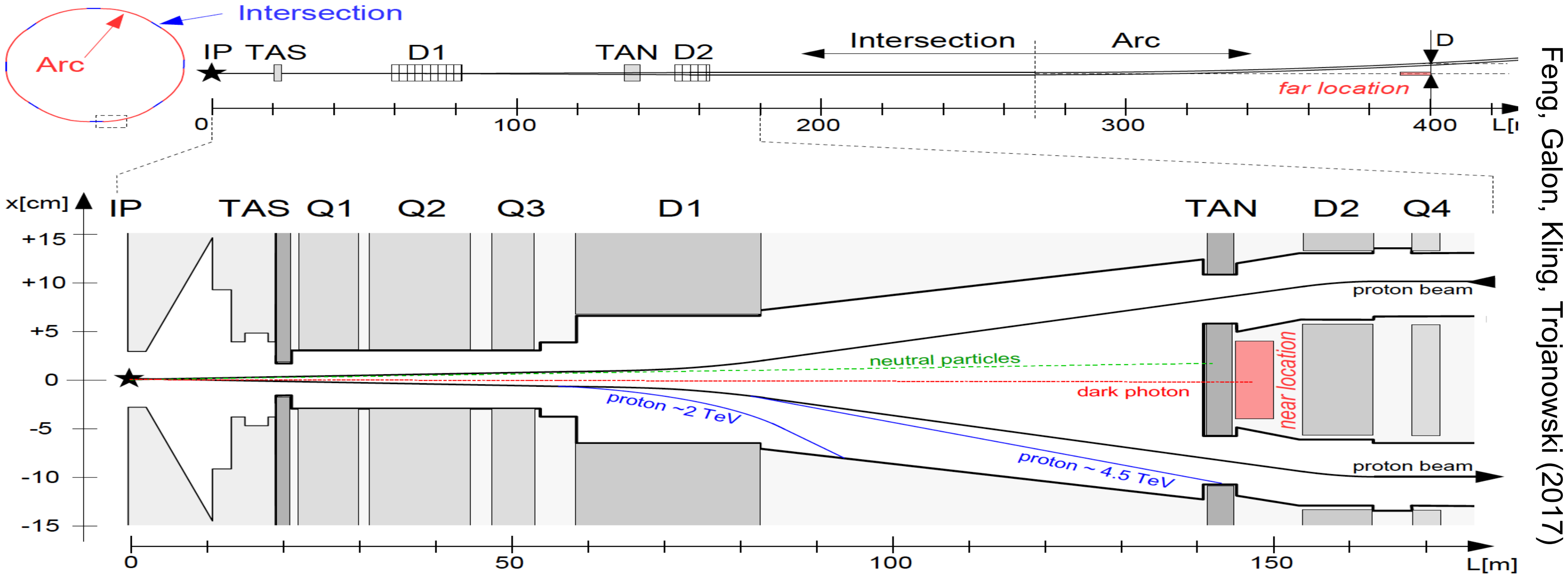
- New physics searches at the LHC focus on high p_T. This is appropriate for heavy, strongly interacting particles
  - σ ~ fb to pb → N ~ 10^3 – 10^6, produced ~isotropically
- However, if new particles are light and weakly interacting, this may be completely misguided. Instead should exploit
  - σ_{inel} ~ 100 mb → N ~ 10^{17}, $\theta \sim \Lambda_{QCD}$ / E ~ 250 MeV / TeV ~ mrad



- We propose a small, inexpensive experiment, FASER, to be placed in the very forward region of ATLAS/CMS, a few 100m downstream of the IP, and analyze its discovery potential

FASER LOCATION

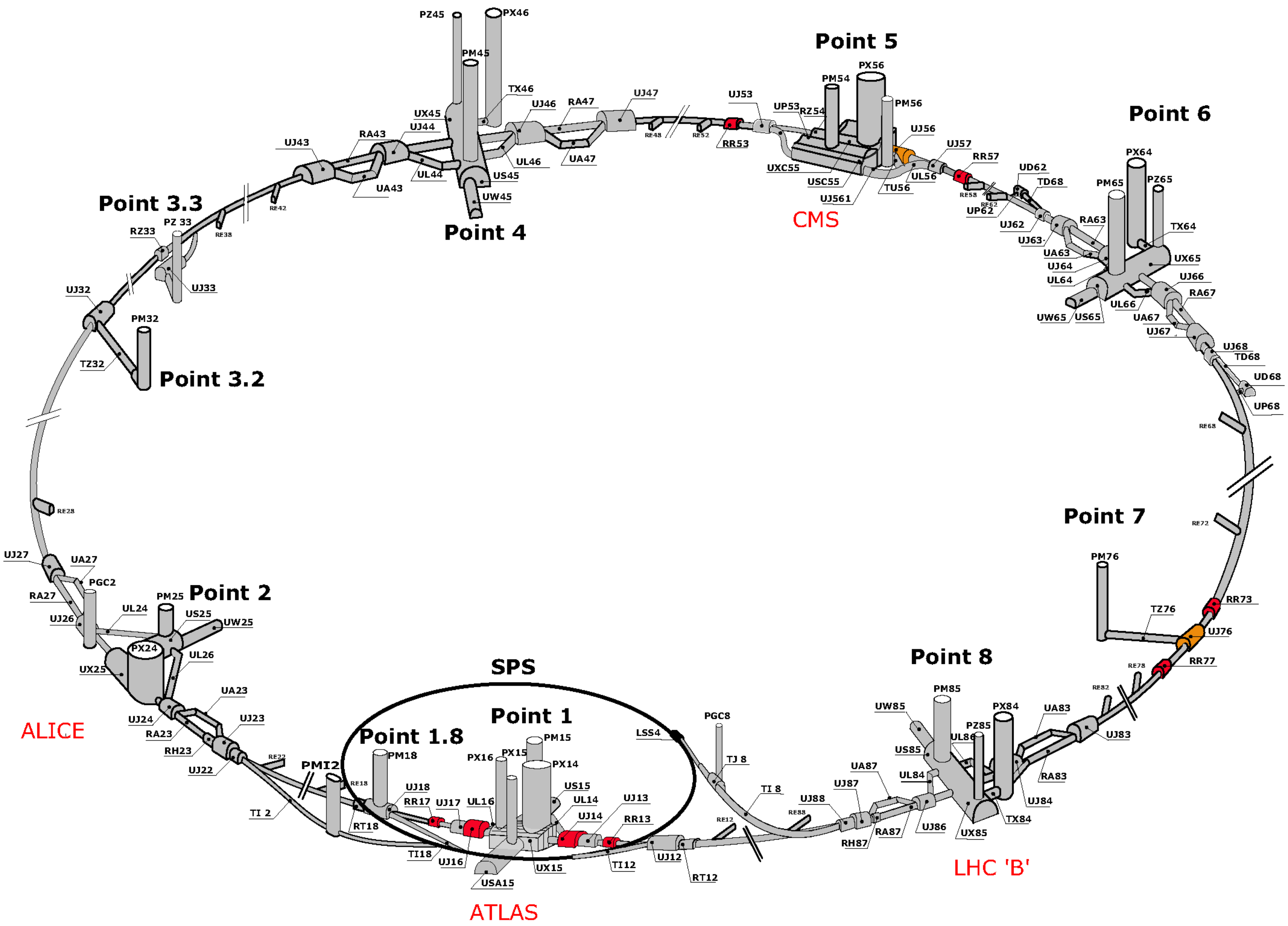
- We want to place FASER along the beam *collision* axis
  - Location: ~400 m from IP, after beams curve, ~3 m from the beams



Here assume FASER is exactly on-axis

- If ATLAS/CMS beams cross at 285 (590) μrad in vertical/ horizontal plane, far location shifts by 6 (12) cm

LHC RING



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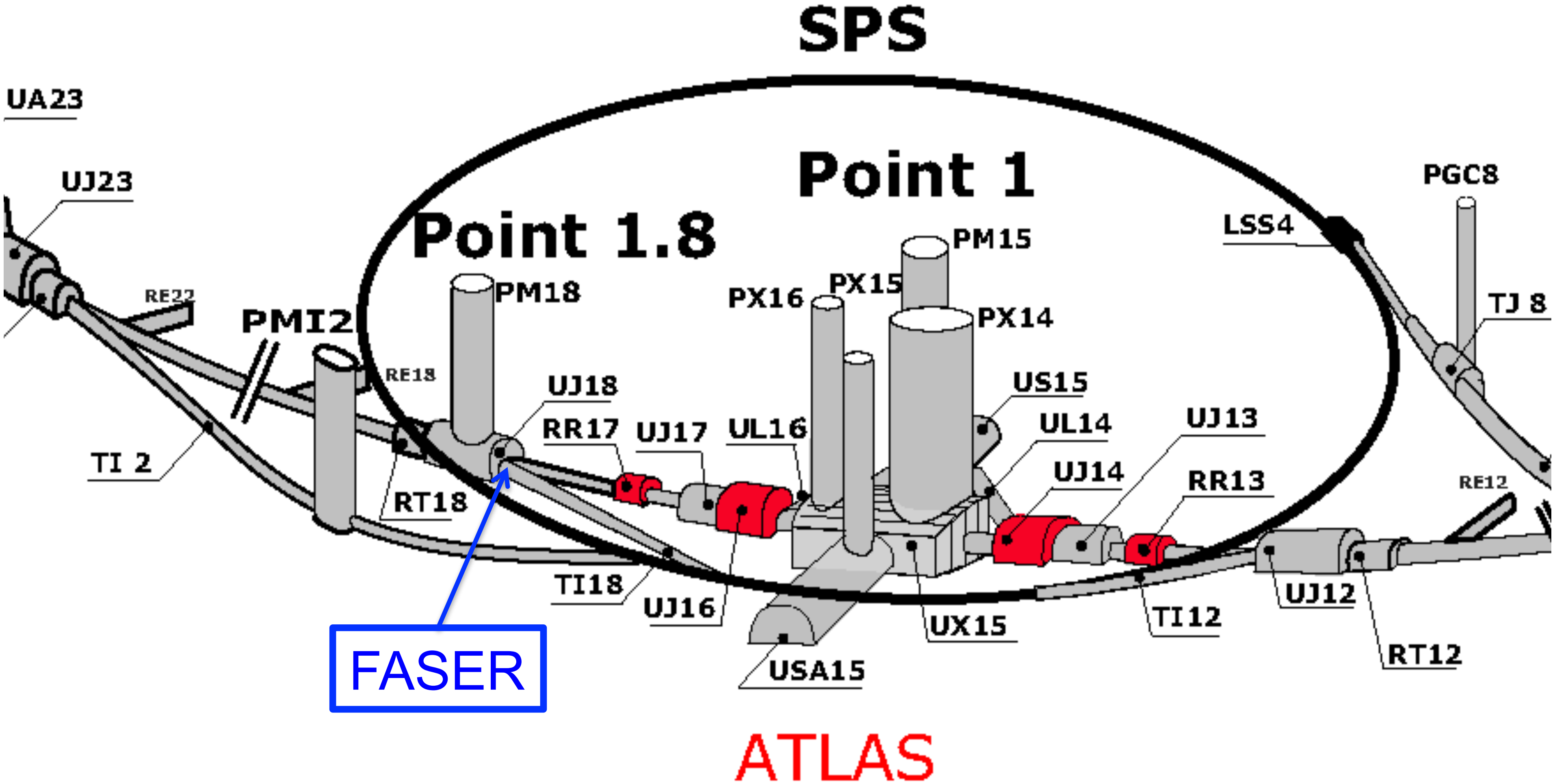
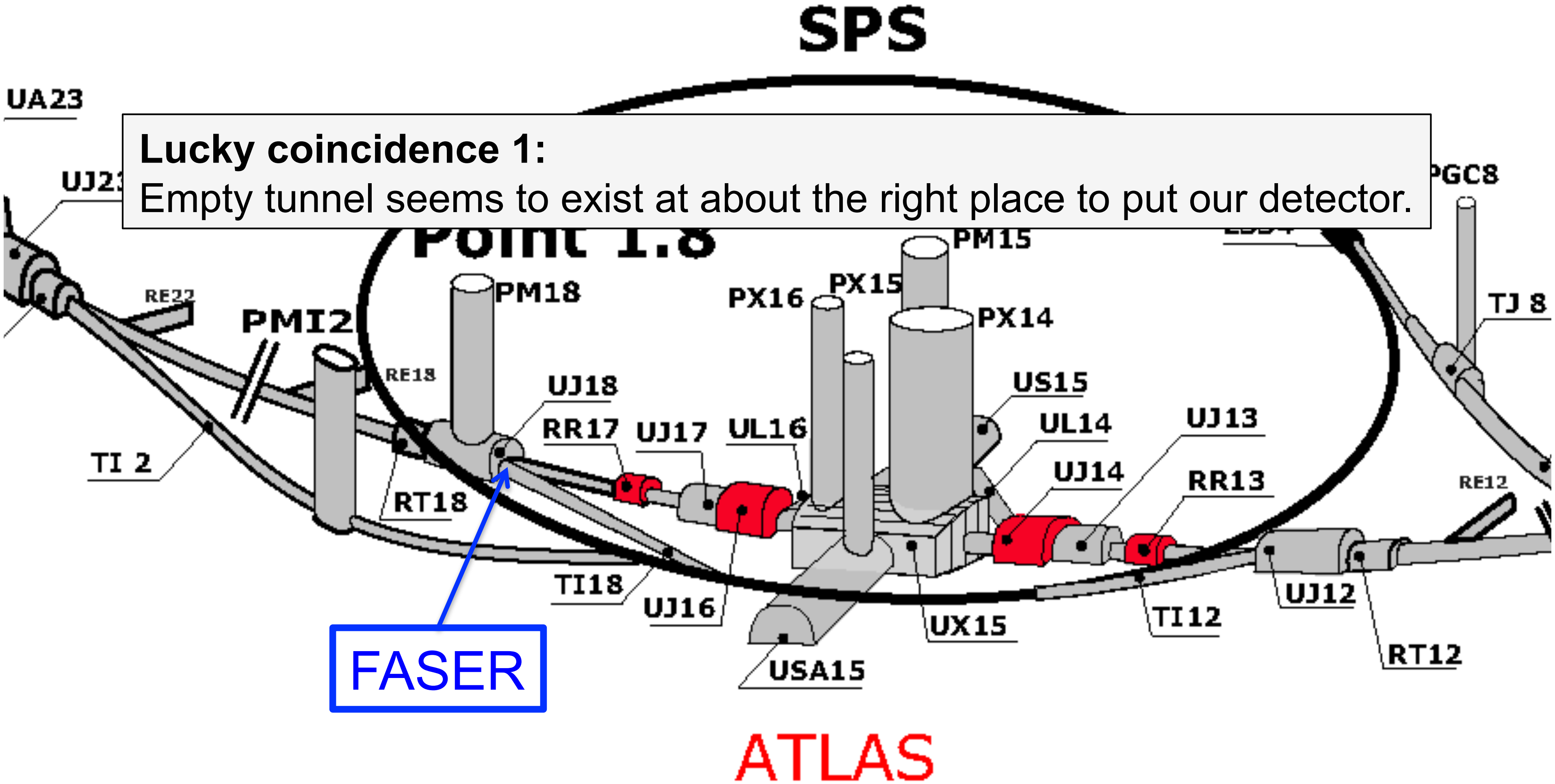
LHC 'B'

SERVICE TUNNEL TI18



SERVICE TUNNEL TI18

Lucky coincidence 1:
Empty tunnel seems to exist at about the right place to put our detector.



Example physics case (dark photons)

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 dark bremsstrahlung pp → p A' X and direct QCD processes qq → A' X (requires pdfs at low Q^2, x)

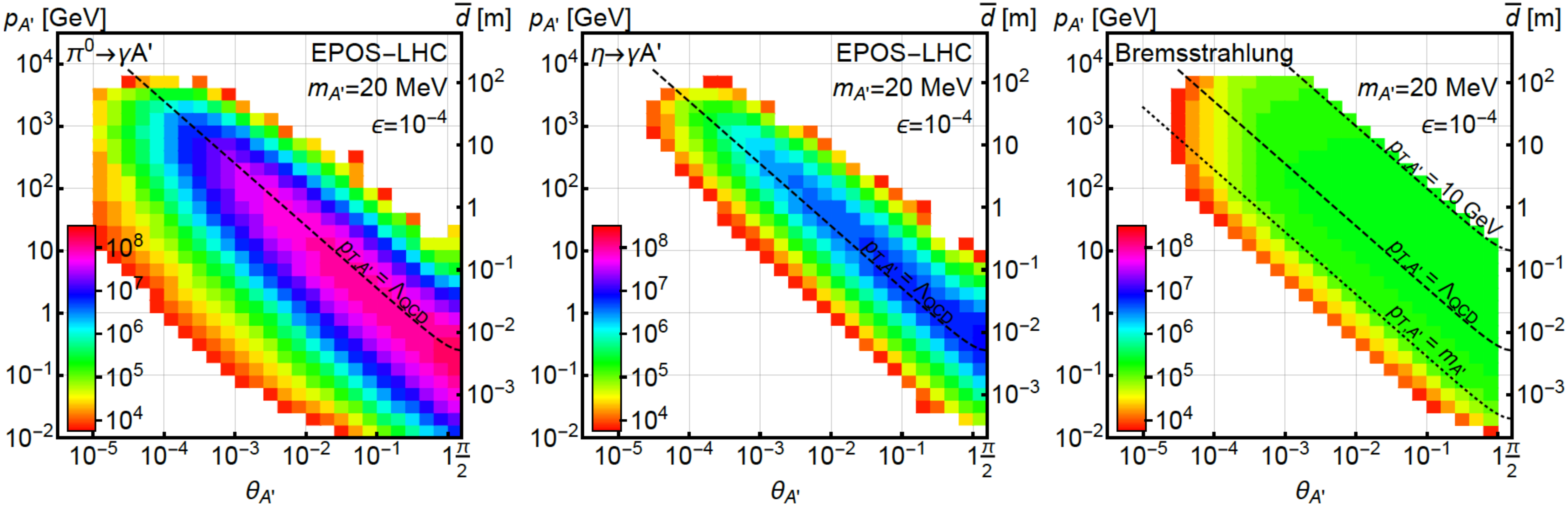
- Travels long distances through matter without interacting, decays to e^+e^- , $\mu^+\mu^-$ for $m_{A'} > 2\ m_\mu$, other charged pairs

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

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

DARK PHOTON PRODUCTION

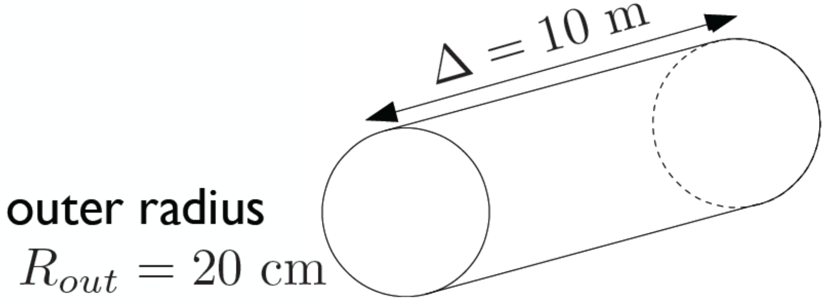
- Consider π^0 decay, η decay, dark bremsstrahlung
- Results for 1st model point: $(m_{A'}, \varepsilon) = (20\text{ MeV}, 10^{-4})$

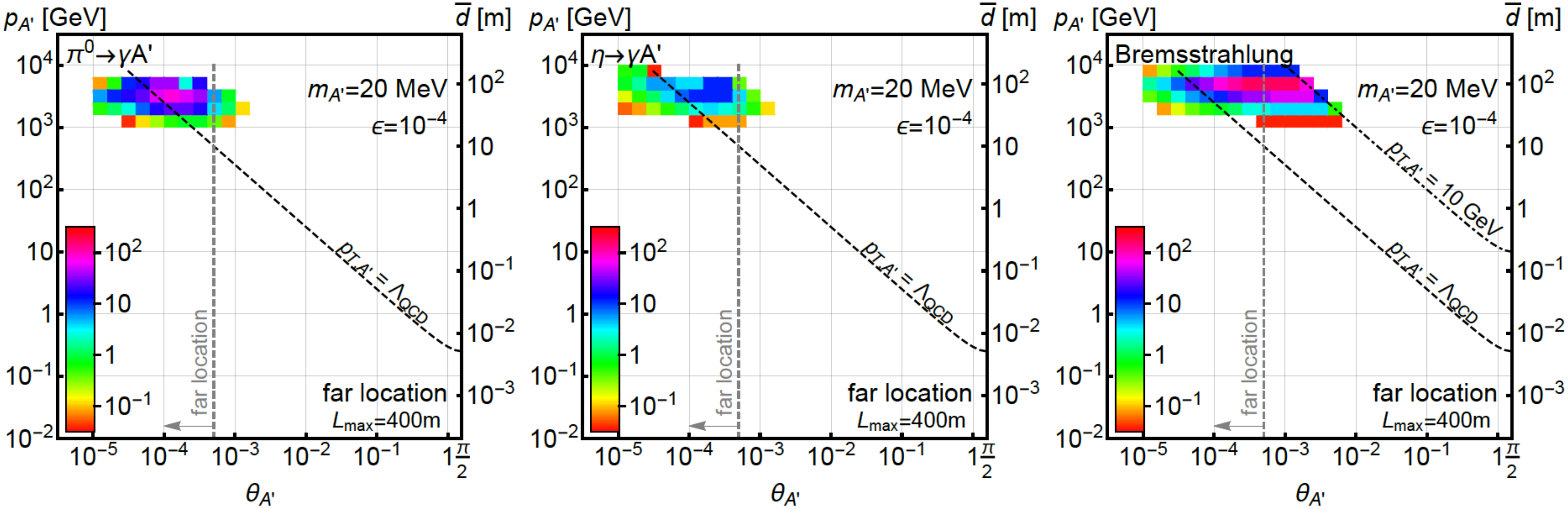


- From $\pi^0 \to \gamma A'$, $E_{A'} \sim E_\pi / 2$ (no surprise)
- But note rates: even after ε^2 suppression, $N_{A'} \sim 10^8$; LHC may be a dark photon factory!

DARK PHOTONS IN FASER

- Now require dark photons to decay in FASER: consider cylindrical detector with volume ~1 m^3





- Only the highest energy A's survive, but there are still many of them, and they are highly collimated
- Studies show 20cm radius detector capture nearly all of the dark-photon signal

BACKGROUNDS

- The signal is two simultaneous, opposite-sign, highly-energetic (E > 500 GeV) charged particles that start in the detector at a vertex and point back to IP → a tracker-based technology

- The opening angle is $\theta_{ee} \sim m_{A'} / E \sim 10\ \mu\text{rad}$. After traveling ~1 m, this leads to 10 μm separation, too small to resolve, so we need a small magnetic field

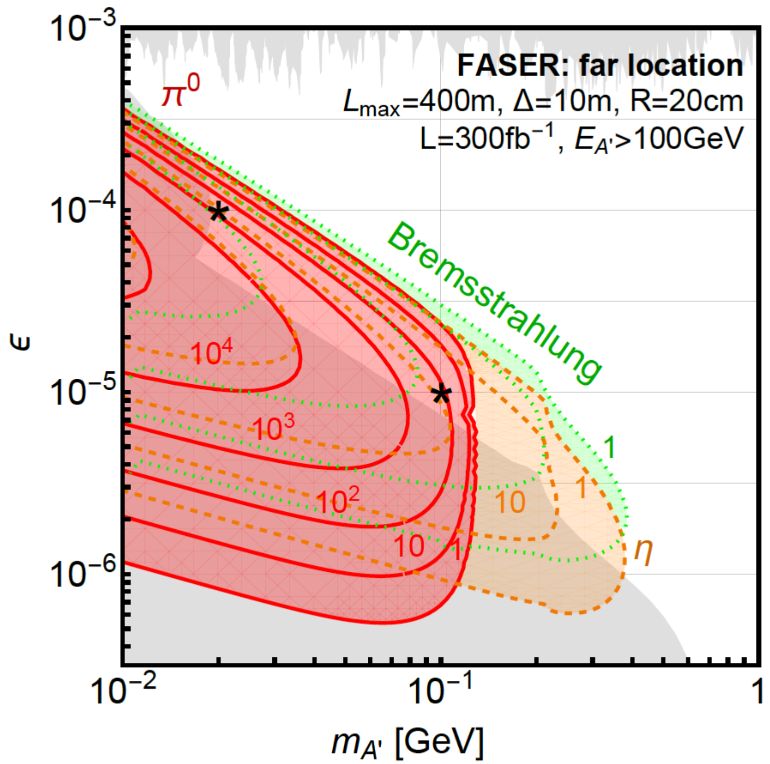
$$h_B \approx \frac{ec\ell^2}{E} B = 3\ \text{mm} \left[\frac{1\ \text{TeV}}{E}\right] \left[\frac{\ell}{10\ \text{m}}\right]^2 \left[\frac{B}{0.1\ \text{T}}\right]$$

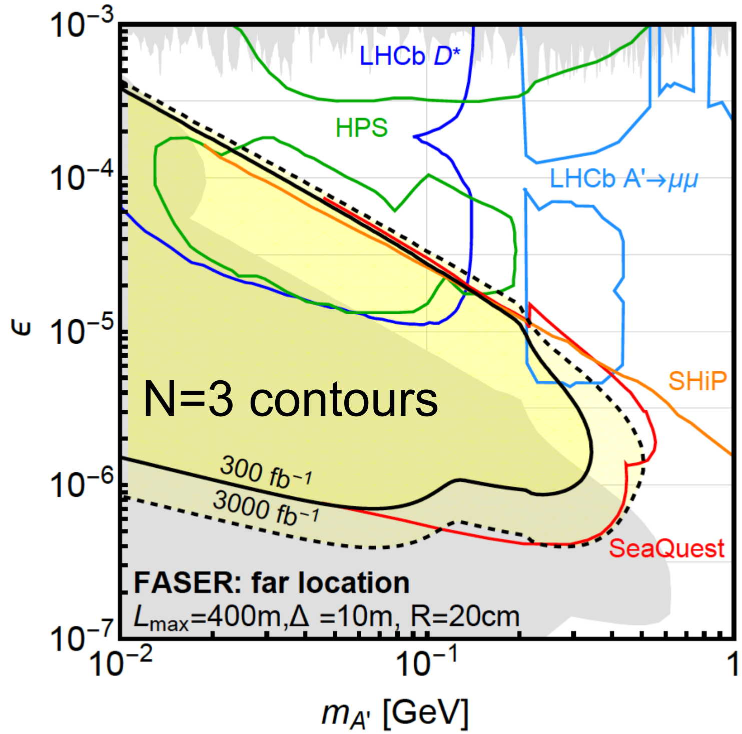
- Many backgrounds are eliminated simply by virtue of FASER's location. Particles from IP must pass through ~50 m of matter to get to FASER. Cosmic ray background is negligible, charged particles from IP are bent away by D1 magnet

- Leading backgrounds: neutrino-induced backgrounds and beam-induced backgrounds

DARK PHOTON EVENT RATES AND REACH

- Up to 10^5 dark photons decay in FASER in 300 fb^{-1} in parameter regions with $m_{A'}$ ~ 10 - 500 MeV, $\varepsilon \sim 10^{-6} - 10^{-3}$





- Note that at upper ε boundary, rates are extremely sensitive to ε and the reach is quite insensitive to background, provided it is known

Other interesting signal models

- Other weakly coupled new physics scenarios considered – e.g. see:

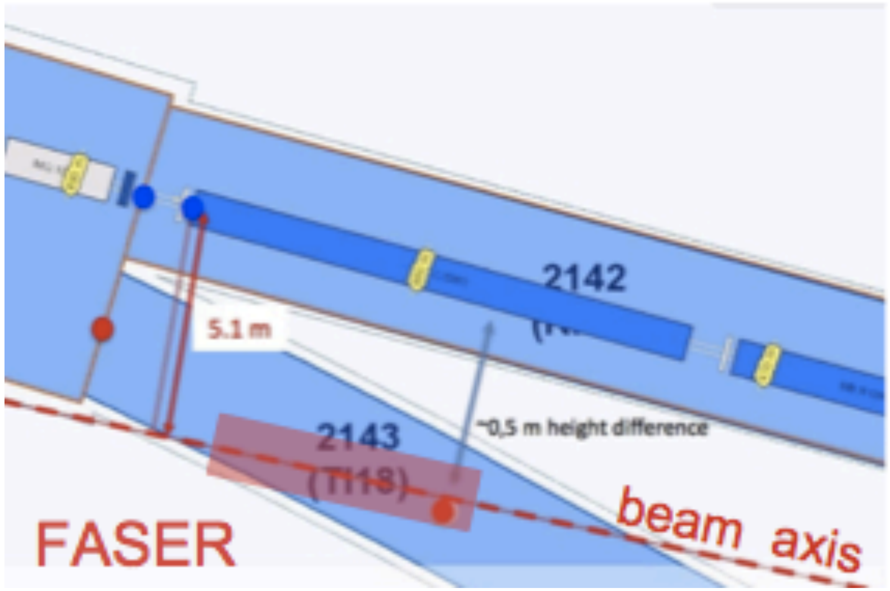
  - Dark Higgs Bosons at FASER, arxiv:1710.09387, Jonathan L. Feng, Iftah Galon, Felix Kling, Sebastian Trojanowski
  - Flavor-Specific Scalar Mediators, arxiv:1712.10022, Brian Batell, Ayres Freitas, Ahmed Ismail, David McKeen
  - Heavy Neutral Leptons at FASER, arxiv:1801.08947, Felix Kling, Sebastian Trojanowski
  - Heavy Neutral Fermions at the High-Luminosity LHC, arxiv:1803.02212, Juan Carlos Helo, Martin Hirsch, Zeren Simon Wang
  - Hunting All the Hidden Photons, arxiv:1803.05466, Martin Bauer, Patrick Foldenauer, Joerg Jaeckel

+ Axion-like-particles (produced in collision of LHC decay products with material in forward region of LHC (TAN) - paper in preparation

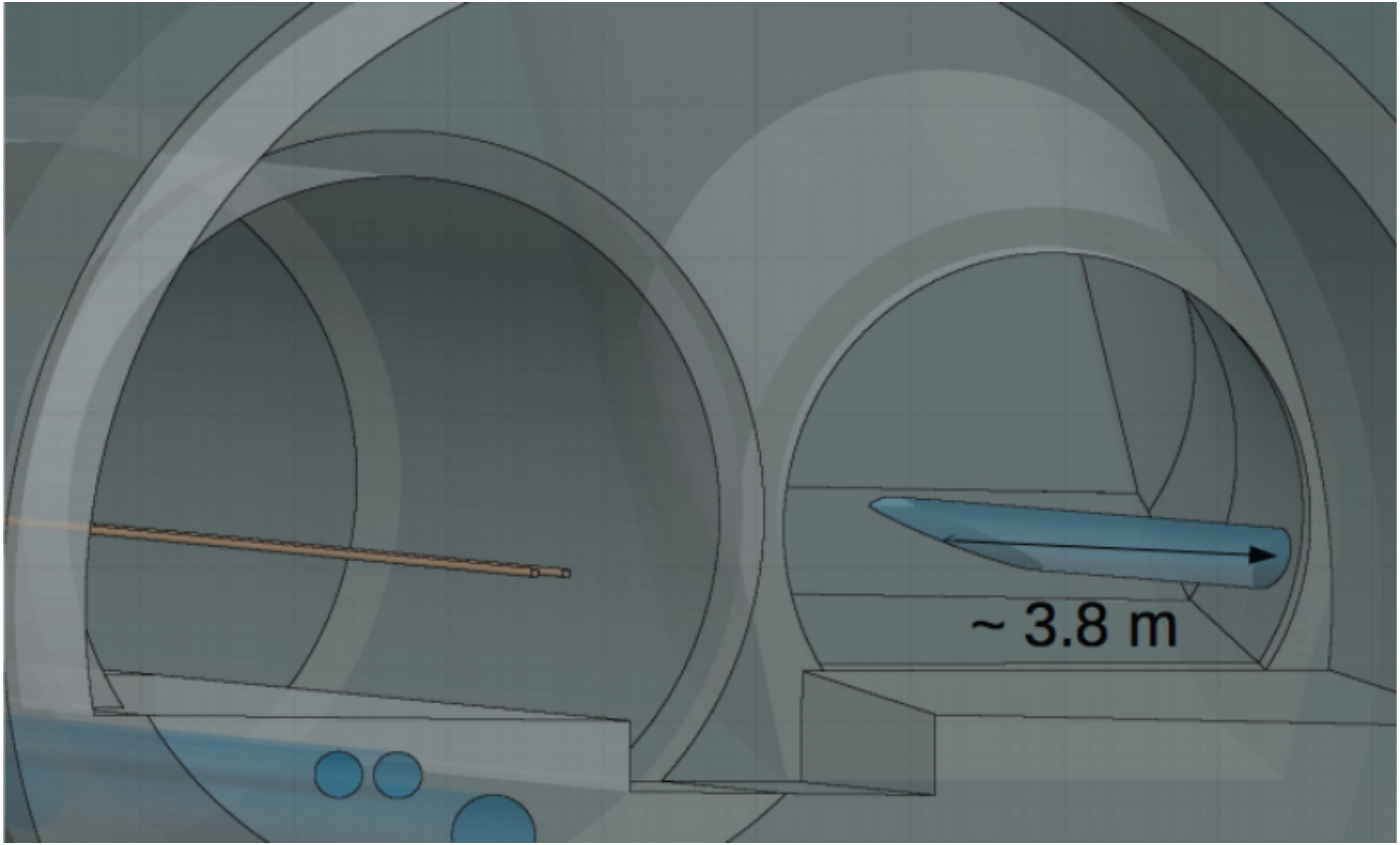
- Some differences in optimal detector for these
  - Dark higgs coming from b-hadron decays
    - Need a larger radius detector to capture most of the signal e.g. 20cm -> 50cm
    - Even bigger detector (R~1m) preferred for HNL searches
  - ALP decays to 2 photons (very close together)
    - Need calorimeter with excellent position resolution to resolve two ~500 GeV photons separated by ~1mm

Experimental status

FASER: LOCATION



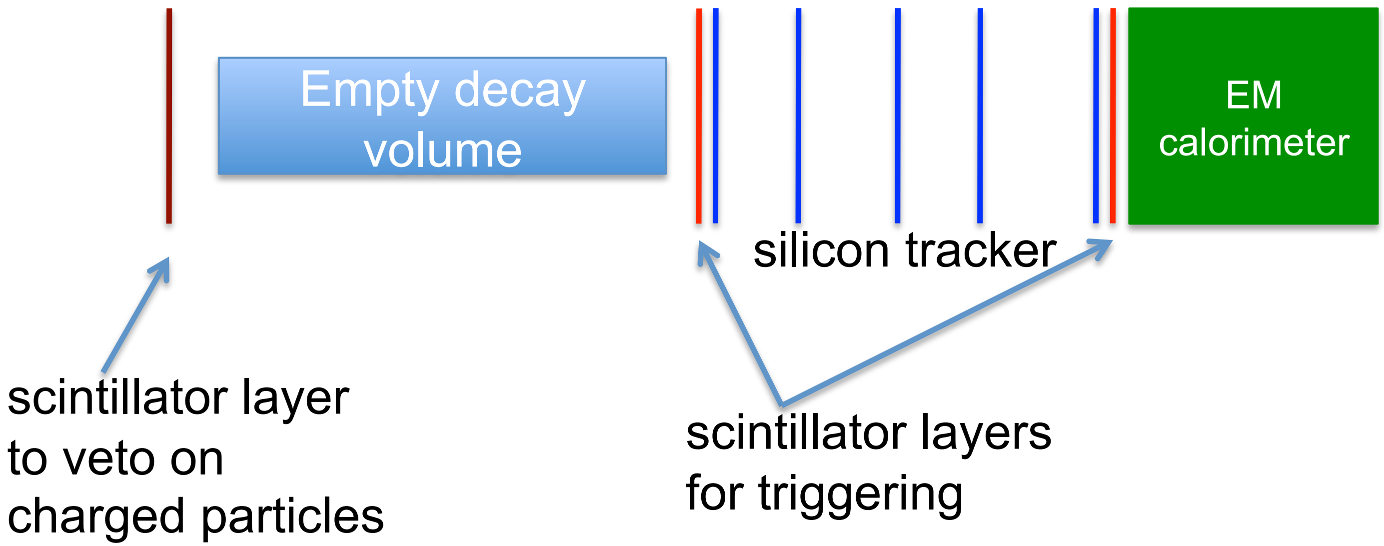
FASER: LOCATION



FASER: Detector considerations

- Currently have in mind an initial veto layer, followed by ~5 tracking layers and EM calorimeter, with volume largely empty and a magnetic field.

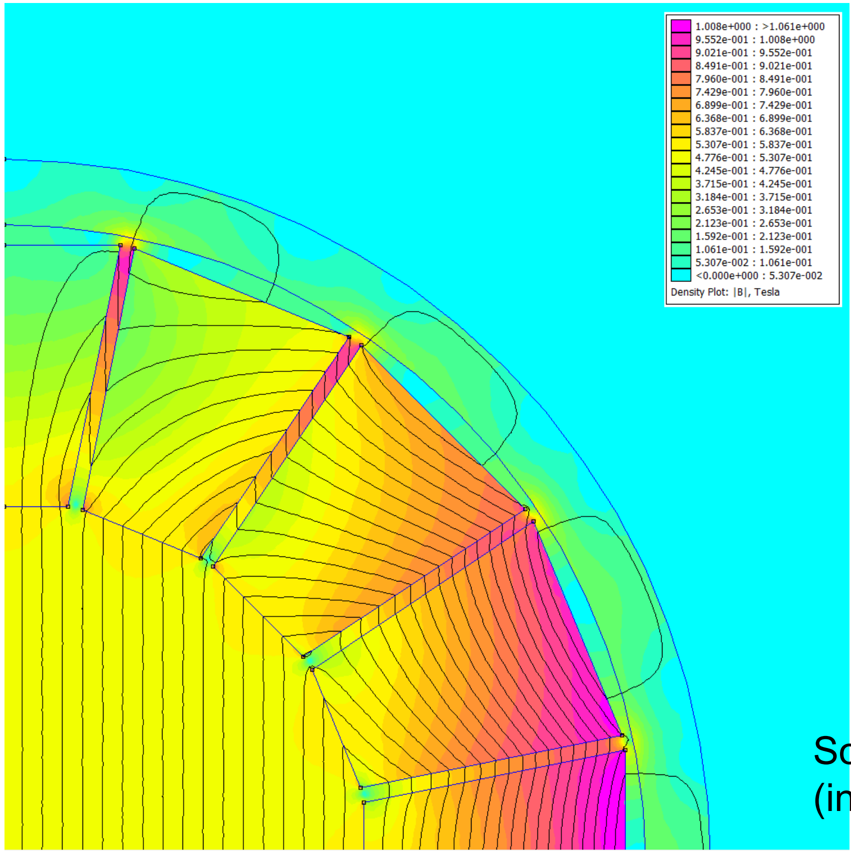
sketch:



Currently optimizing the detector layout also based on re-using parts / spare-parts of existing detectors (e.g. for tracker).
Looking at different options for calorimeter.
Considering a permanent dipole magnet (suggested by CERN experts).
Detector needs to sit very close to the floor of the tunnel to lie on the line-of-sight, and needs to fit in available length (~4m, depends on crossing angle and possible digging).

FASER: Detector considerations

- Currently have in mind an initial veto layer, followed by ~5 tracking layers and EM calorimeter, with volume largely empty and a magnetic field.

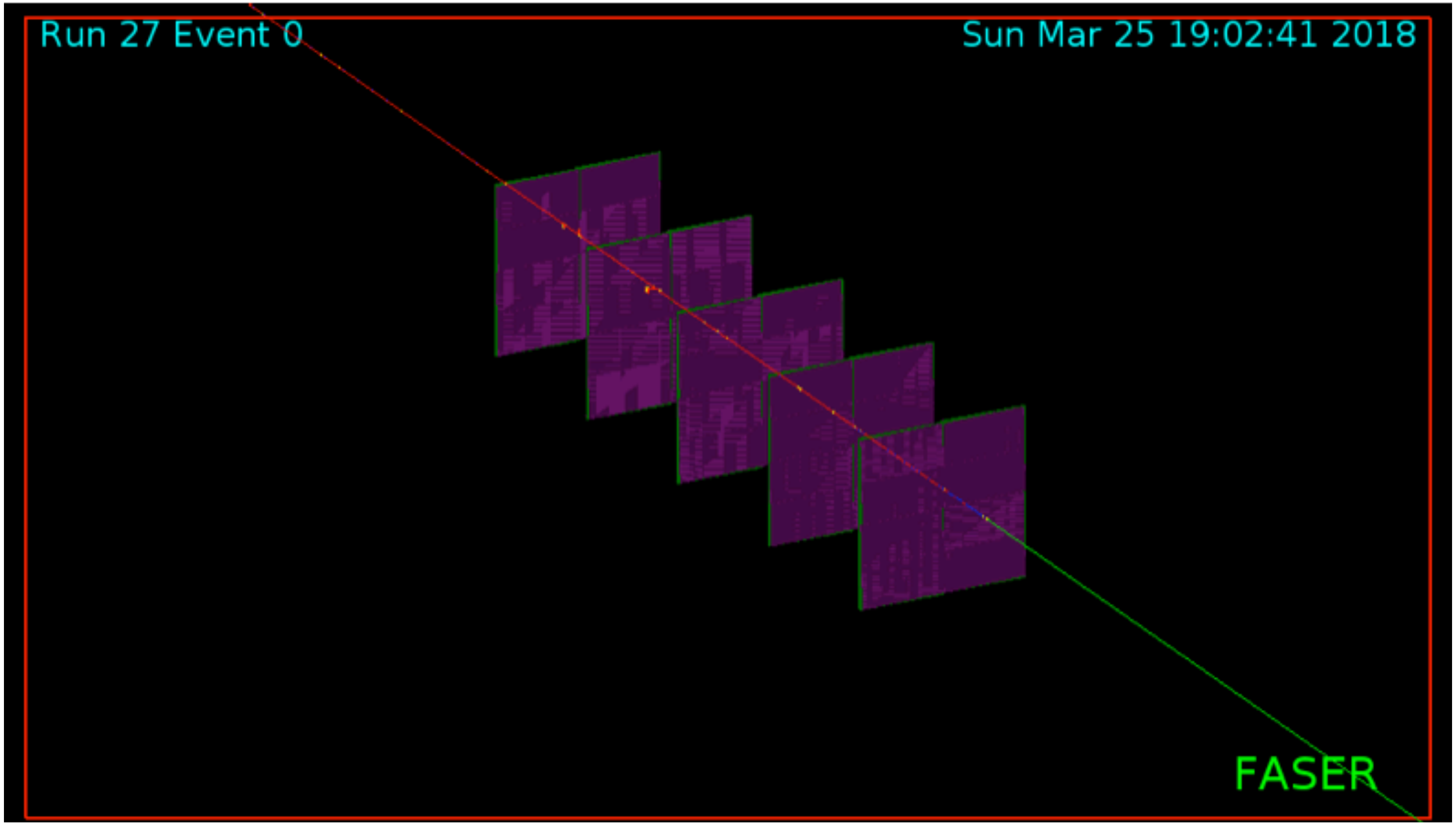


Parameter	Value	Unit
Central field	0.52	T
Integrated field	0.67	T.m
Good field region	Ø 200	mm
Field homogeneity	+/- 2	%
Free aperture	Ø 200	mm
Outside diameter	430	mm
Magnet length	1300	mm
Magnet weight	1200	kg

Some idea of a permanent dipole magnet we could use
(informal discussion with Attilio Milanese of CERN magnet group)

FASER: GEANT STUDY UNDERWAY

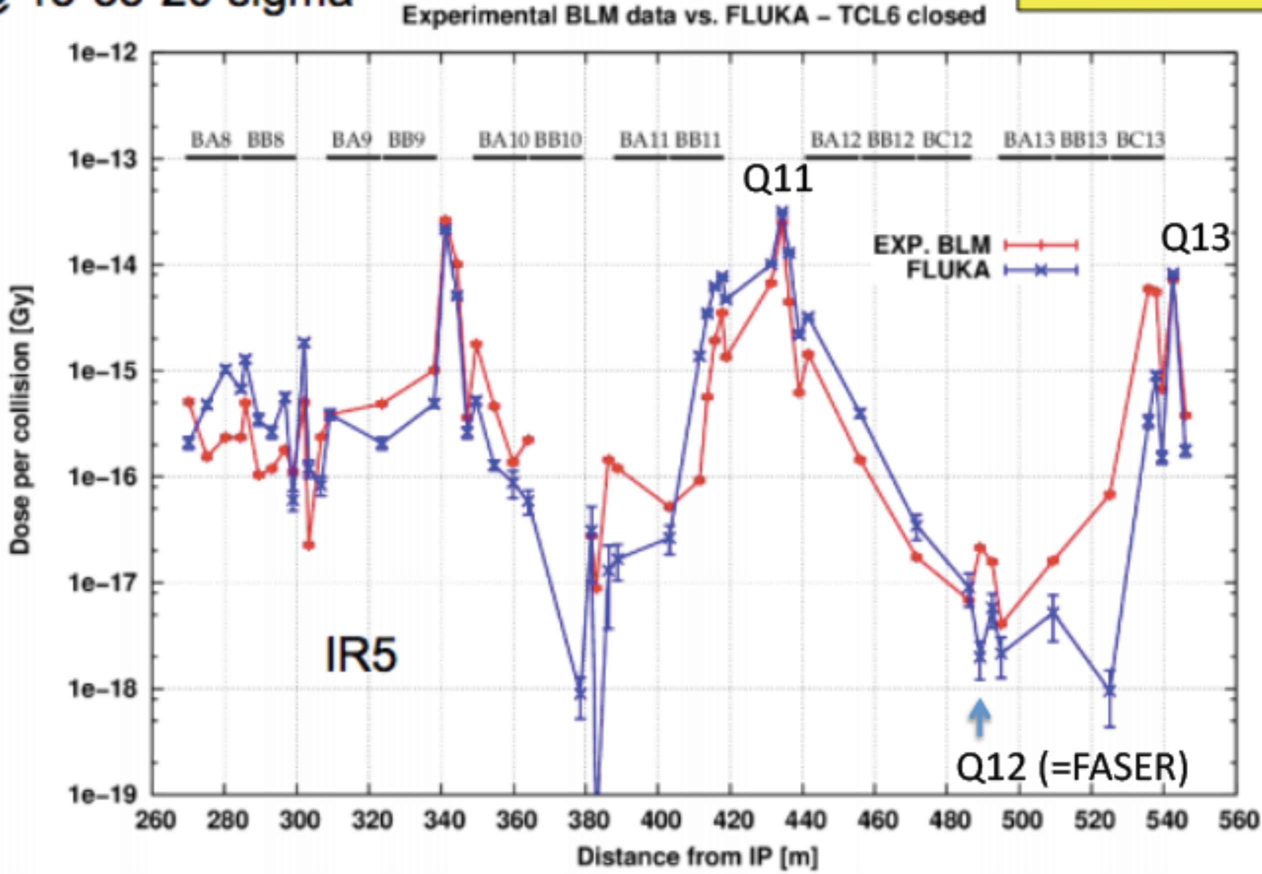
- Currently have in mind an initial veto layer, followed by ~5 tracking layers and EM calorimeter, with volume largely empty and a magnetic field.



FASER: FLUKA STUDY UNDERWAY

Fill #5401 (October 2016)
TCLs @ 15-35-20 sigma

6.5 TeV beams



Plot from F. Cerutti's talk at Chamonix 2018.
Comparing FLUKA and BLM data for 2015 fill (reasonable agreement).
FASER location close to Q12 – lucky low background from collision debris, background peaks at Q11/Q13 due to dispersion at these points (these are +/-~50m along ring from FASER location). (In theory this depends on the optics, but should also be valid for HL-LHC)

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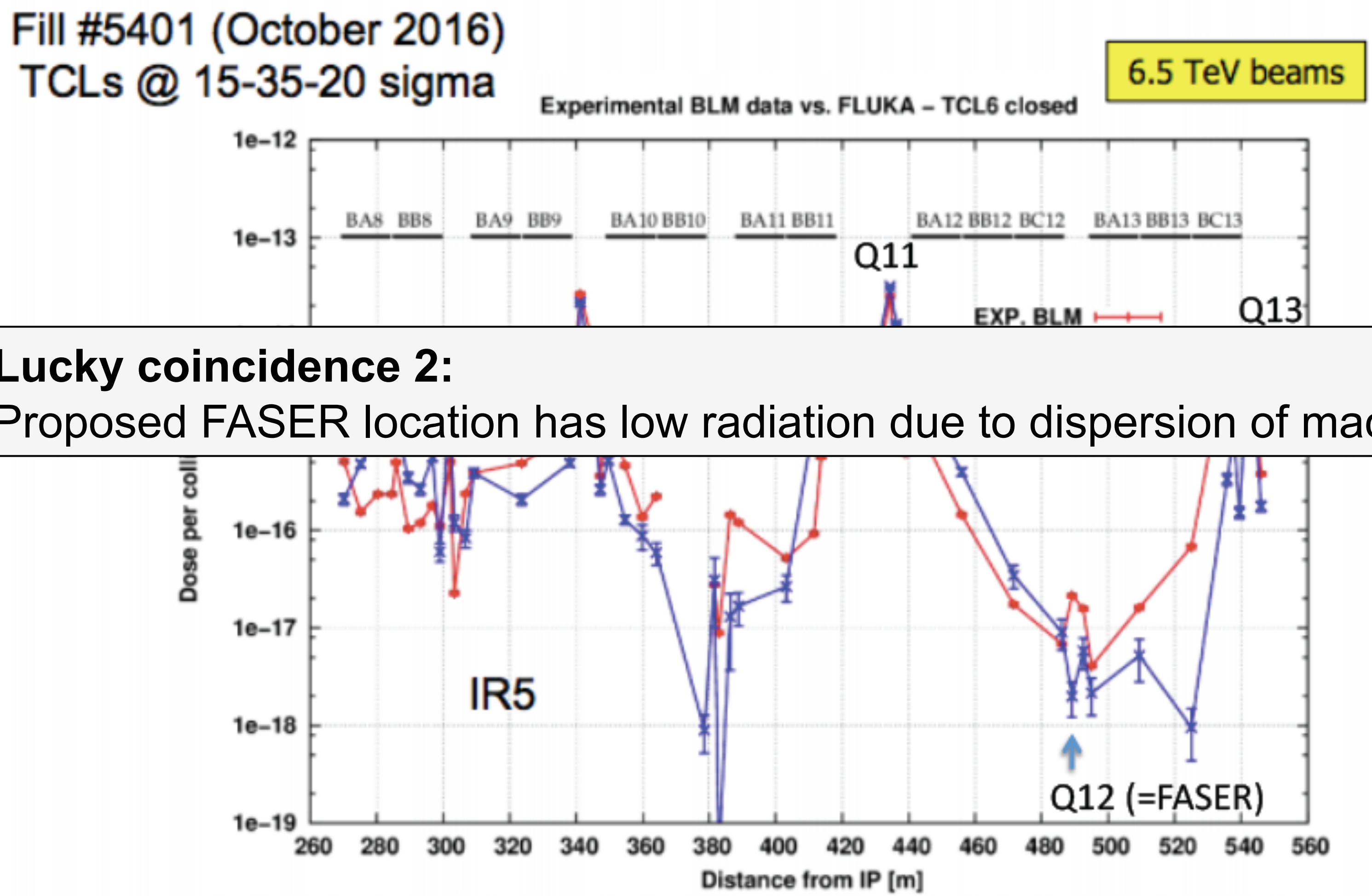
FASER: FLUKA STUDY UNDERWAY



Lucky coincidence 2:
Proposed FASER location has low radiation due to dispersion of machine!

Plot from F. Cerutti's talk at Chamonix 2018.
Comparing FLUKA and BLM data for 2015 fill (reasonable agreement).
FASER location close to Q12 – lucky low background from collision debris, background peaks at Q11/Q13 due to dispersion at these points (these are +/-~50m along ring from FASER location). (In theory this depends on the optics, but should also be valid for HL-LHC) 2

SUMMARY AND OUTLOOK

- The LHC has seen no new physics. Adding supplementary detectors to improve discovery prospects is a good idea, and there are many proposals targeting the lifetime frontier.

- FASER targets light, weakly-coupled new particles at low p_T, runs simultaneously with ATLAS/CMS, is small, fast, and cheap.

- FASER has significant discovery potential for dark photons dark Higgs bosons, heavy neutral leptons (sterile neutrinos), ALPs, other gauge bosons, and many other new particles.

- Possible timeline: install prototype in LS2 (2019-20) for Run 3 (150 fb^{-1}) with R~10cm, install full detector in LS3 (2023-25) for HL-LHC (3 ab^{-1}).
  - Currently assessing options for detector, and studying backgrounds (FLUKA simulations, and installing monitors in FASER location in upcoming LHC technical stop (TS1))

FASER team

Current team:

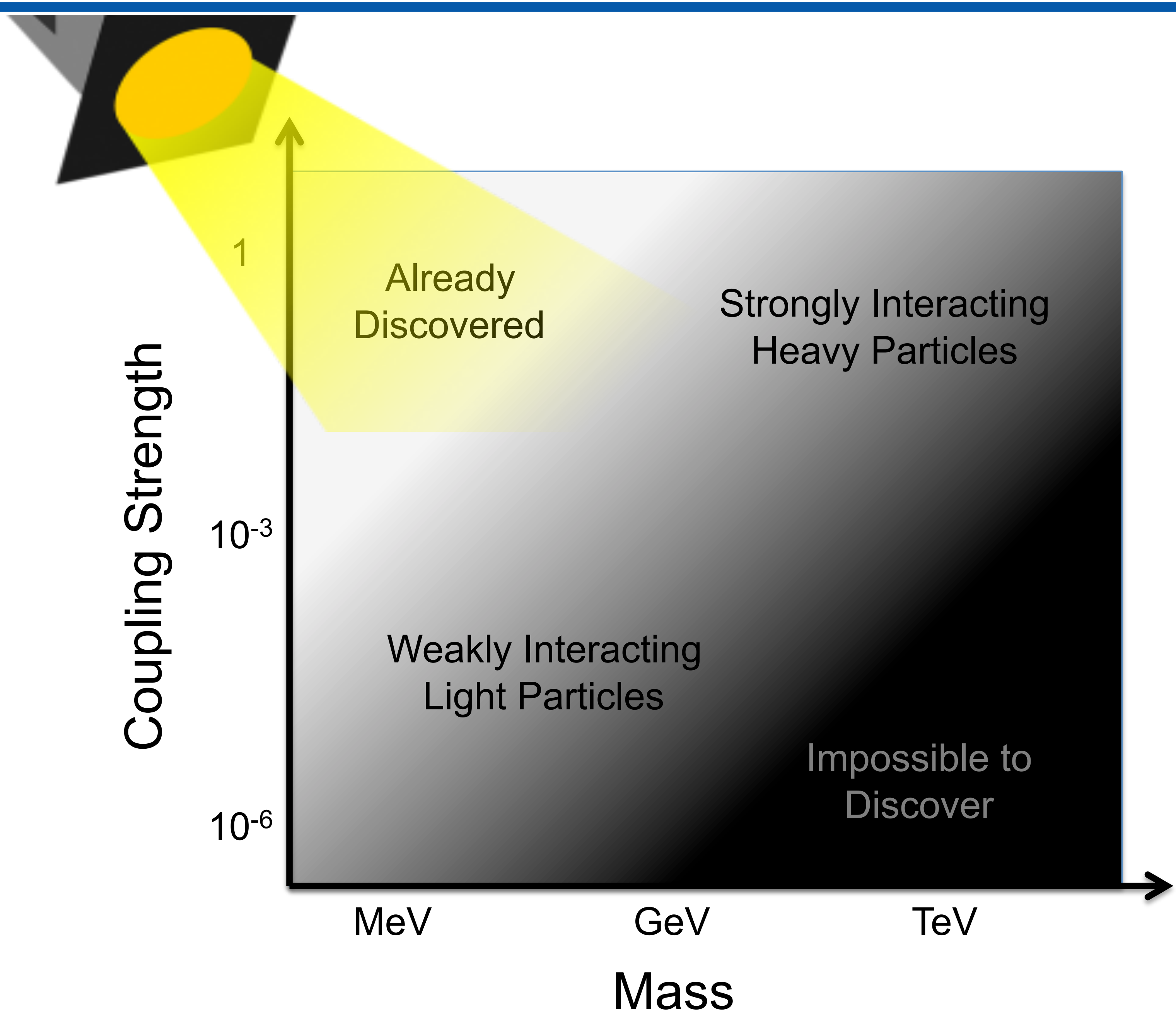
FASER e-group is: faser-all@cern.ch Active members:

- Jonathan Feng (UCI, theorist) (contact with PBC BSM group)
- Iftah Galon (Rutgers, theorist)
- Sebastian Trojanowski (UCI, theorist)
- Felix Kling (UCI, theorist)
- Dave Casper (UCI, experimentalist)
- Jamie Boyd (CERN, experimentalist) (contact with PBC accelerator group)
- Brian Petersen (CERN, experimentalist)
- Shih-Chieh Hsu (Washington, experimentalist)
- Hidetoshi Otono (Kyushu, experimentalist)
- Aaron Soffa (UCI, experimentalist)
- Akitaka Ariga (Kyushu, experimentalist)
- Tomoko Ariga(Kyushu/Bern, experimentalist)
- Osamu Sato (Nagoya, experimentalist)

With great help from various CERN teams, contact via physics beyond colliders study group (contact: Mike Lamont).
We are looking at various detector options based on existing detectors to use in FASER prototype to be installed in LS2.

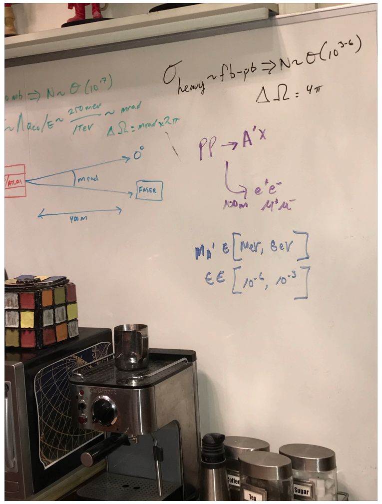
Back Up

LAMPPOST LANDSCAPE



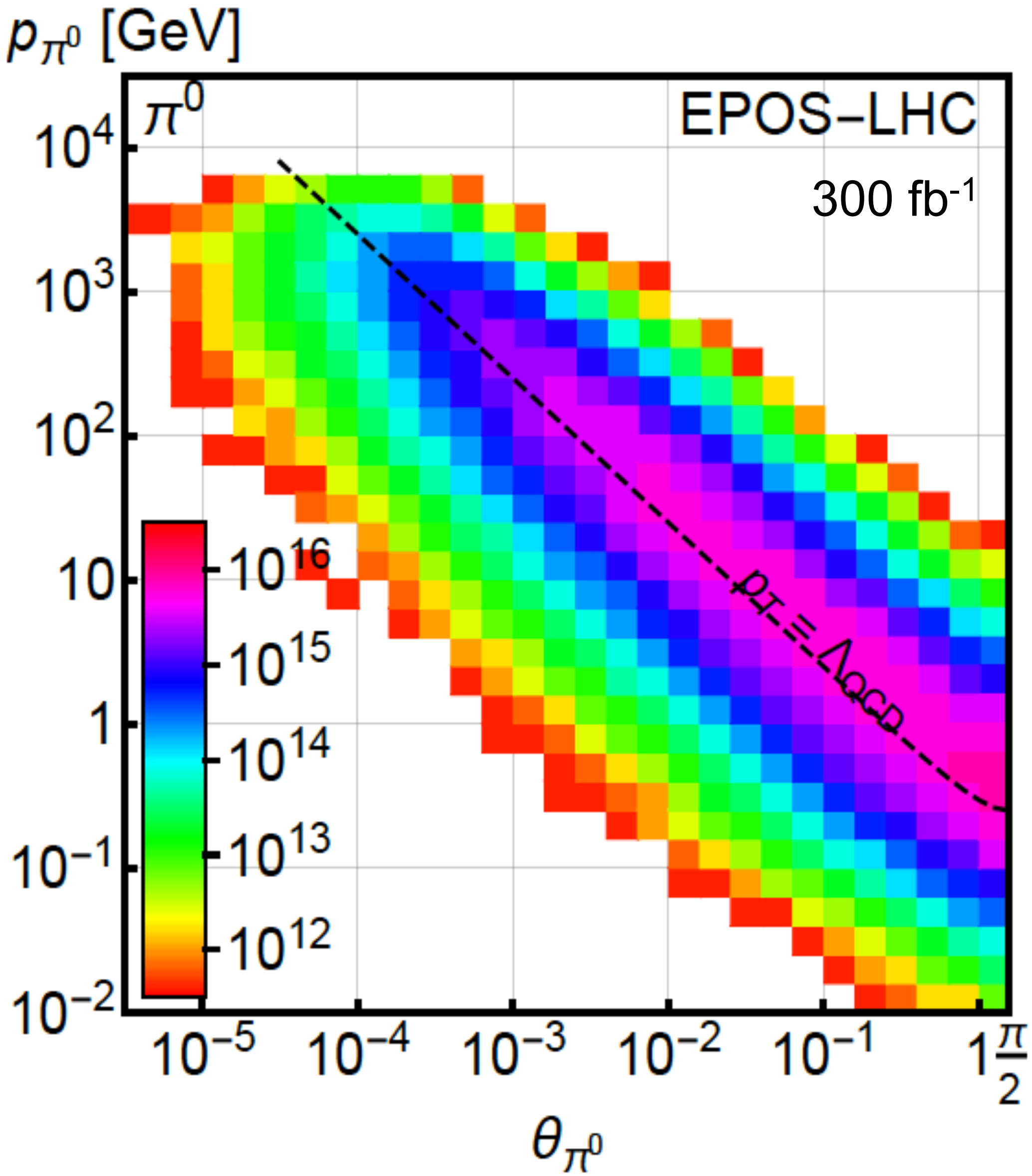
THE LIFETIME FRONTIER

- 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.”



PION PRODUCTION AT THE LHC

- Forward particle production simulations and models have been greatly constrained by LHC data
- EPOS-LHC, SIBYLL 2.3, QGSJETII-04 agree very well
- Enormous event rates (σ_{inel}~70 mb, N_{inel}~10^{17}), production is peaked at $p_T \sim \Lambda_{QCD}$



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

SM $\;\text{- - -}\;$ $\epsilon F_{\mu\nu} F^{\mu\nu}_{\text{hidden}}$ $\;\text{- - -}\;$ Hidden U(1)

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

DARK PHOTON STATUS

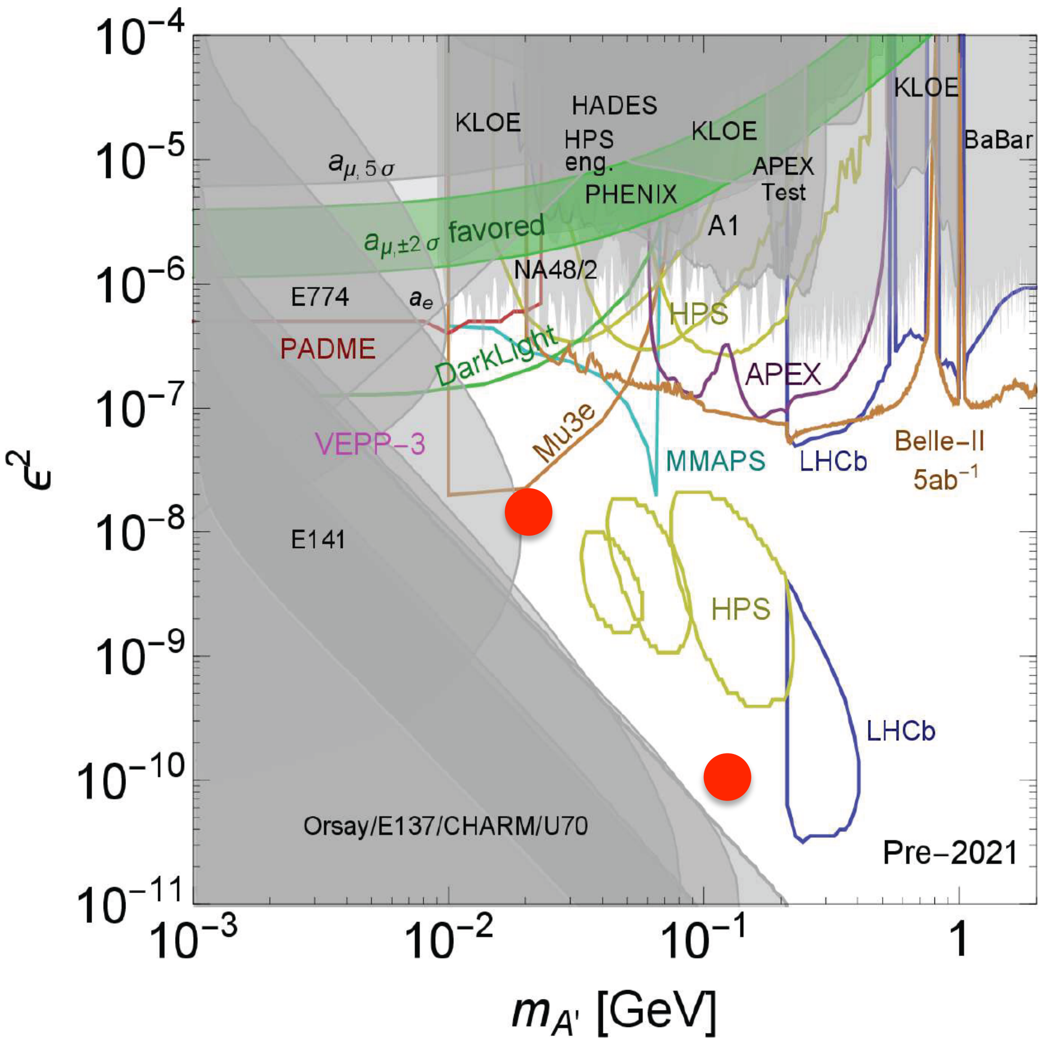
- Low ε → fixed target constraints, high ε → collider, precision constraints
- But still lots of open parameter space with

  $m_{A'} > 10$ MeV

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

  (20 MeV, 10^{-4})

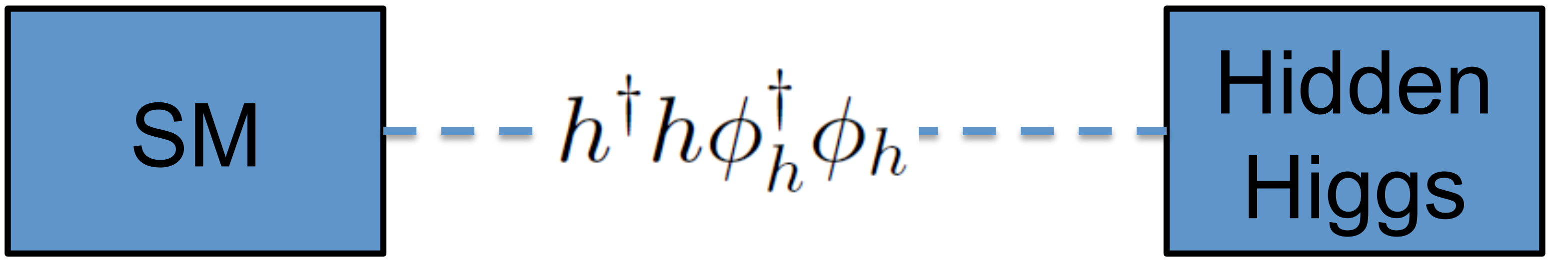
  (100 MeV, 10^{-5})



Cosmic Visions White Paper (2017)

DARK HIGGS BOSONS

- Another renormalizable coupling: Higgs portal



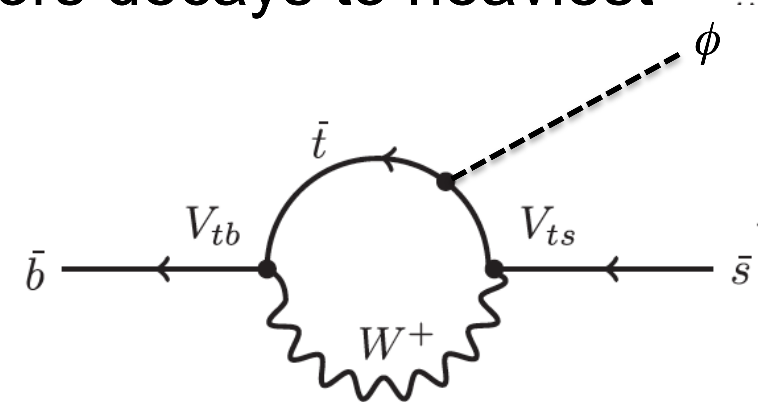
- The resulting theory contains a new scalar boson ϕ with mass m_ϕ , Higgs-like couplings suppressed by $\sin\theta$, and a trilinear coupling λ

$$\mathcal{L} = -m_\phi^2 \phi^2 - \sin\theta \, \frac{m_f}{v} \, \phi \bar{f} f - \lambda v h \phi \phi + \ldots$$

DARK HIGGS PROPERTIES

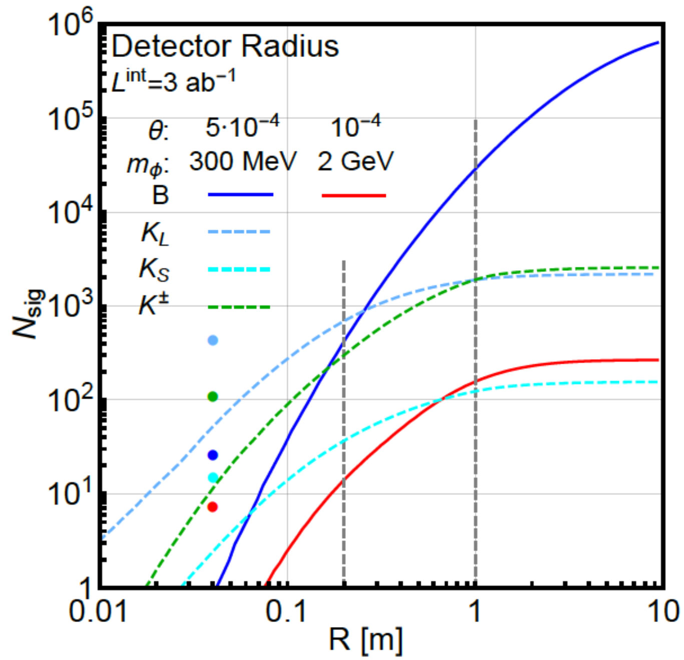
- Dark Higgs couples to mass, so favors decays to heaviest possible states

$$B(B \to \phi) \gg B(K \to \phi) \gg B(\eta, \pi \to \phi)$$



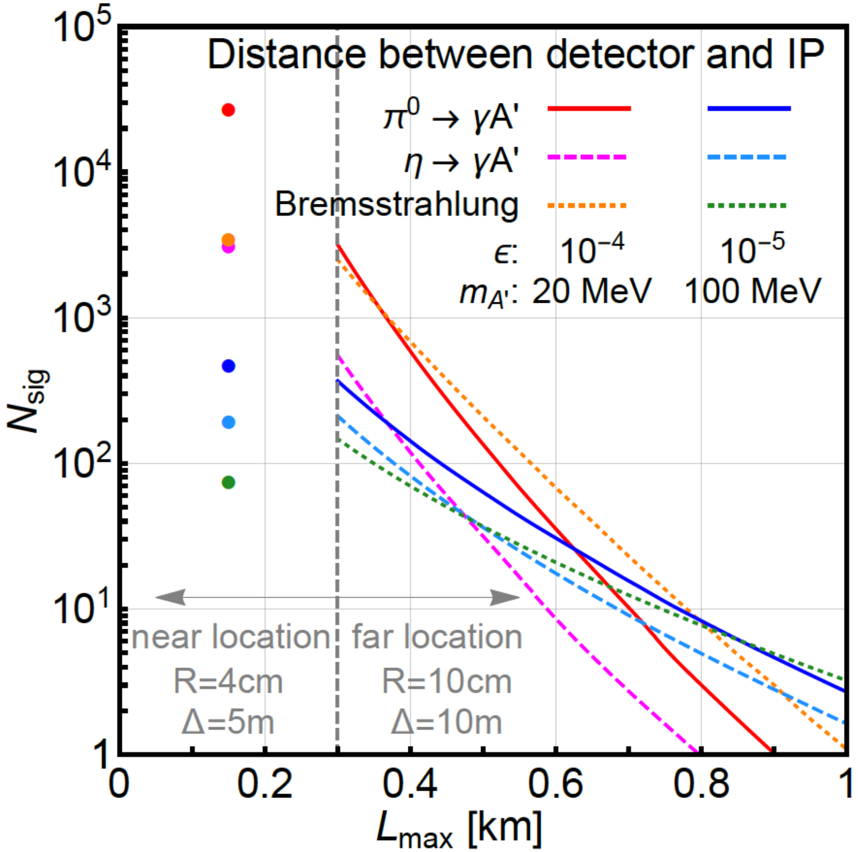
- In contrast to fixed target experiments, lots of COM energy to produce ~10^{15} B mesons, excellent probe of new physics that couples to 3rd generation

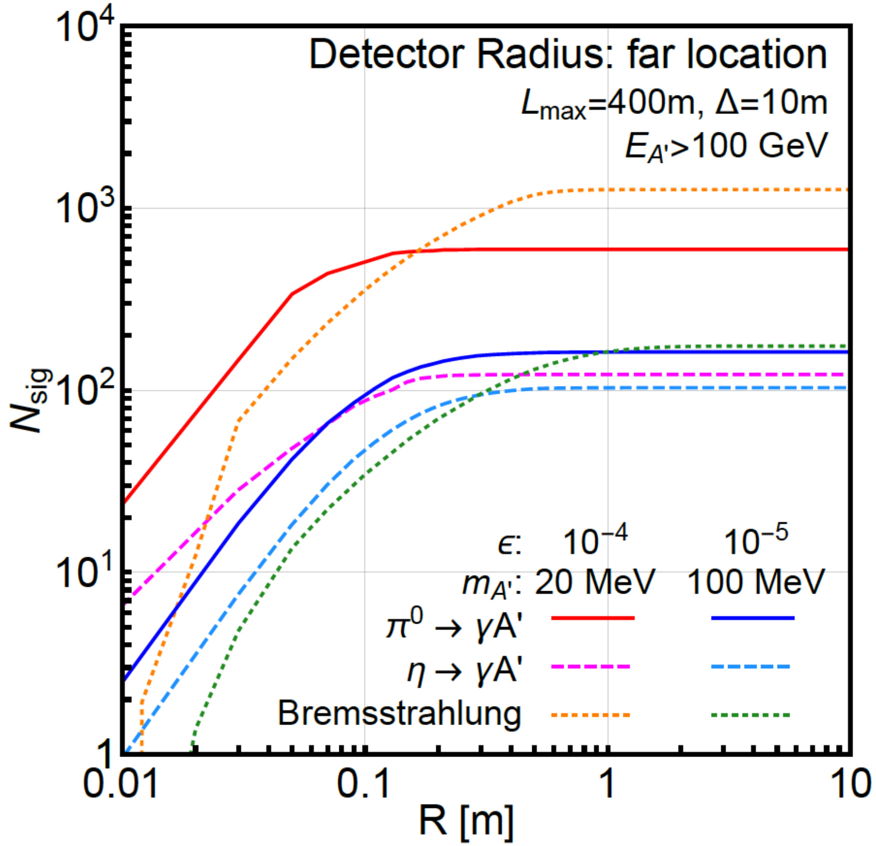
- In B decays, $p_T \sim m_B$, dark Higgs bosons are less collimated than dark photons



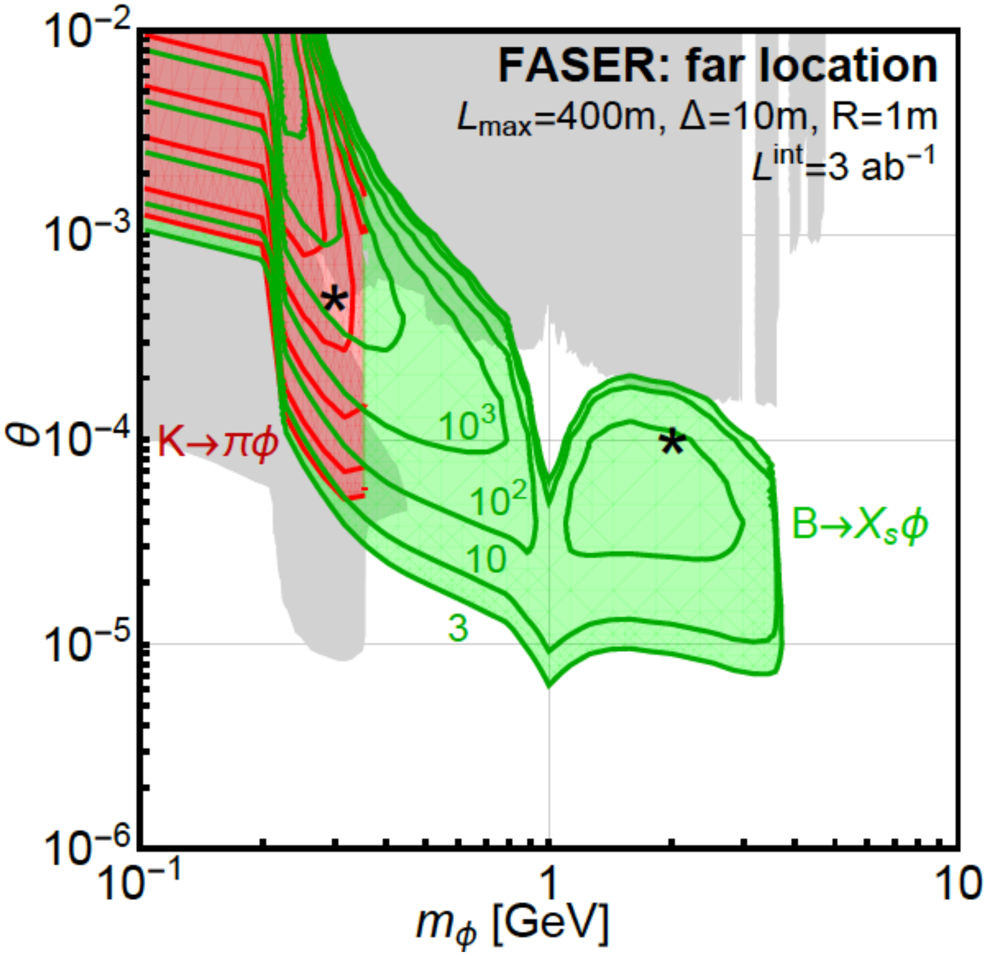
SIGNAL DEPENDENCE ON DETECTOR SPECS

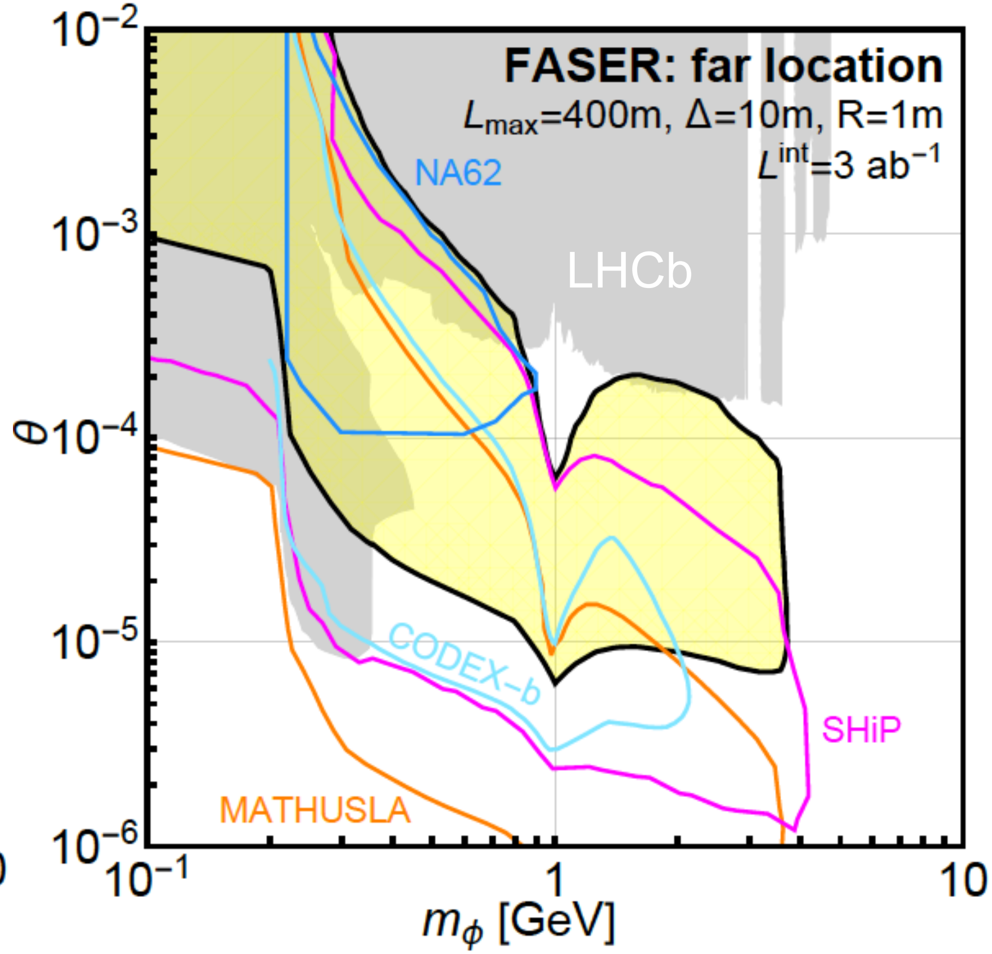
- For dark photons, moving the detector closer helps
- At the far location, R = 20 cm captures almost all the A'





DARK HIGGS EVENT RATES AND REACH



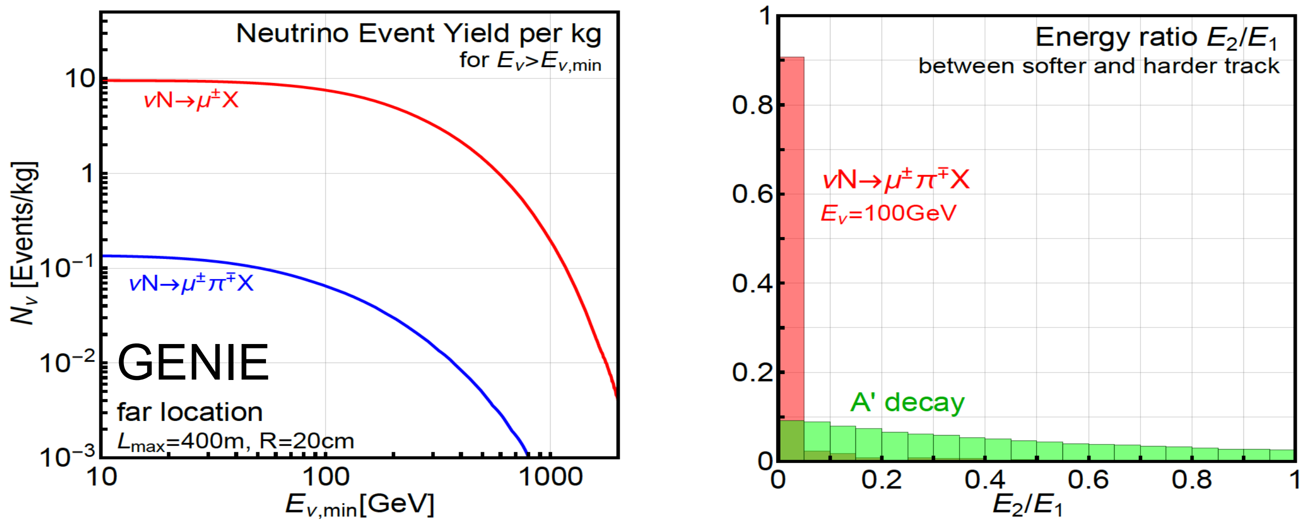


- FASER probes a large swath of new parameter space and is complementary to other current and proposed experiments

BACKGROUNDS

- If $\pi^+ \rightarrow \mu\nu$ before D1 magnet, neutrinos can propagate into FASER, produce charged tracks through CC interactions

$$\nu_\ell N \rightarrow \ell X \qquad \nu N \rightarrow \mu^\pm \pi^\mp X$$



- Coincident single tracks that fake double tracks are negligible; second process eliminated by requiring no other activity, tracks start in the detector and have high and symmetric energies

- Beam-induced backgrounds currently being investigated by CERN FLUKA study

Emulsion detector

- Considering possibility of using an emulsion detector to help find signal
- Incredible charged particle position resolution (~50nm!), but integrates over large timescale (~3months between TSs)
- Hoping to install a small 10cm x 10cm x 10cm prototype in TS1 (mid-June 2018) to see background level