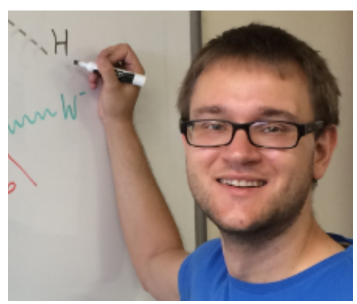
FASER AND OTHER OUTPOSTS ON THE LIFETIME FRONTIER

New Probes for Physics Beyond the Standard Model, KITP, Santa Barbara

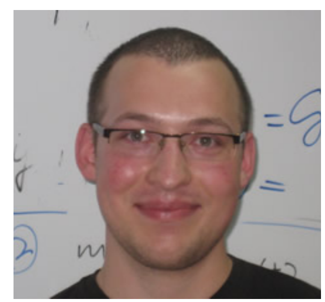
Jonathan Feng, UC Irvine

Based on 1708.09389 and 1710.09387 with

Iftah Galon



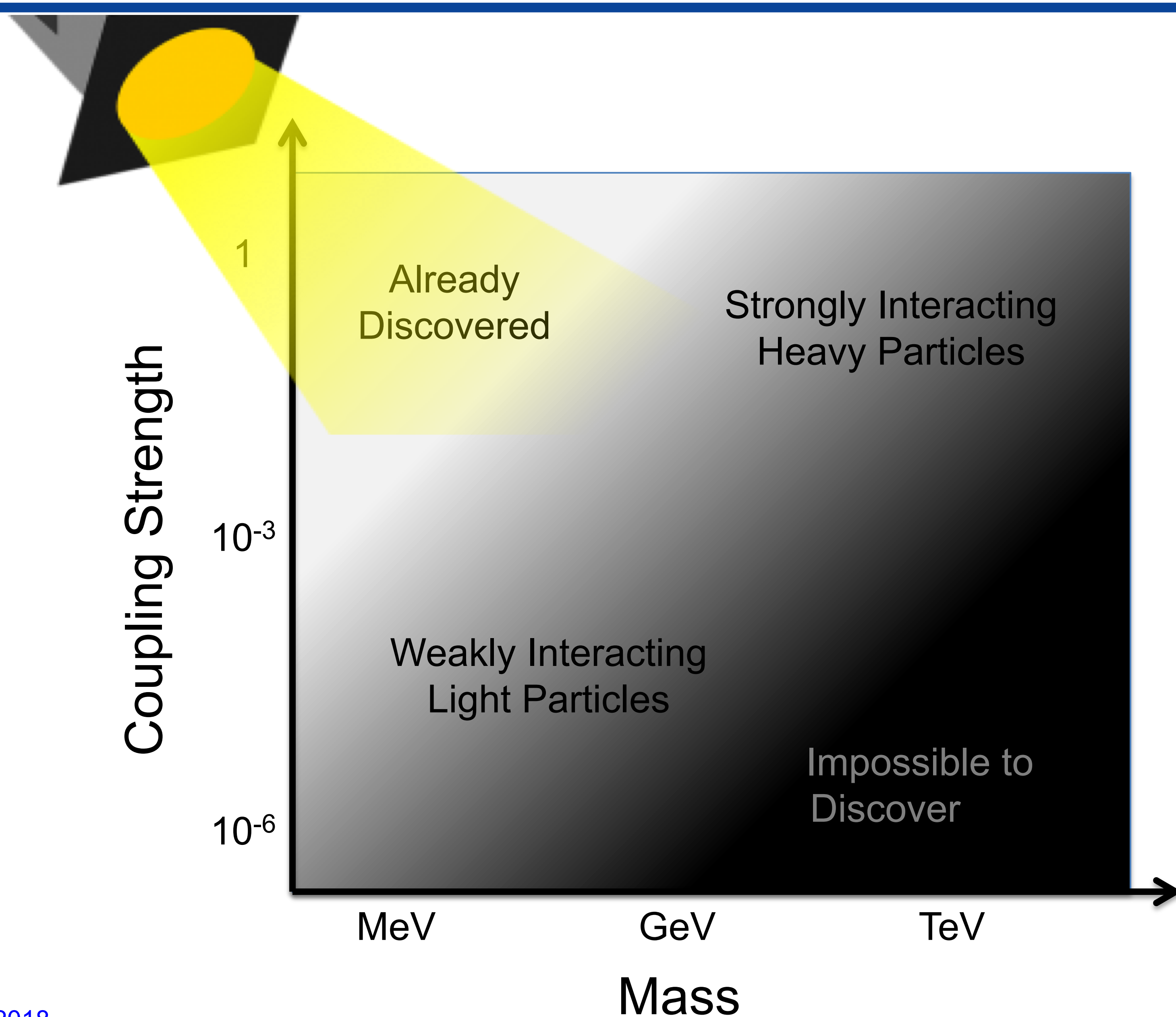
Felix Kling



Sebastian Trojanowski

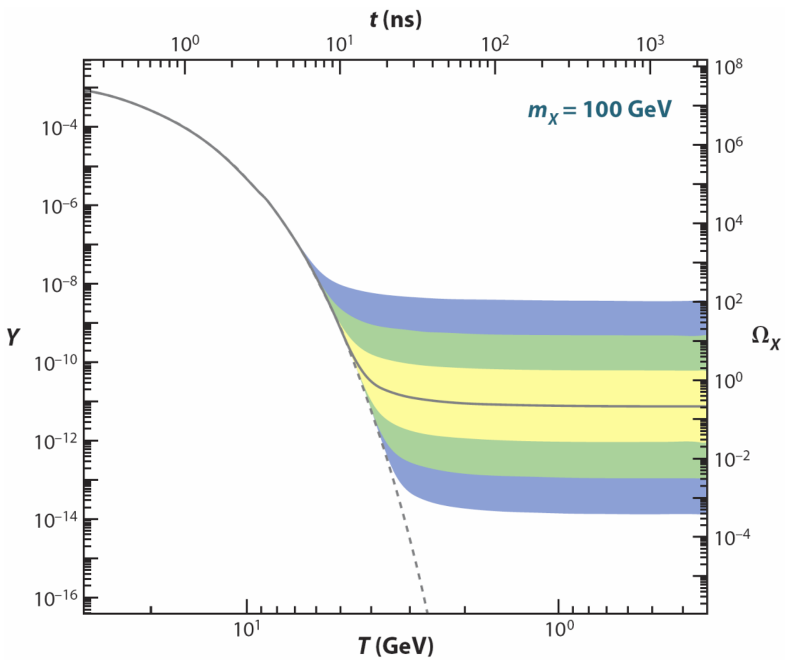
9 April 2018

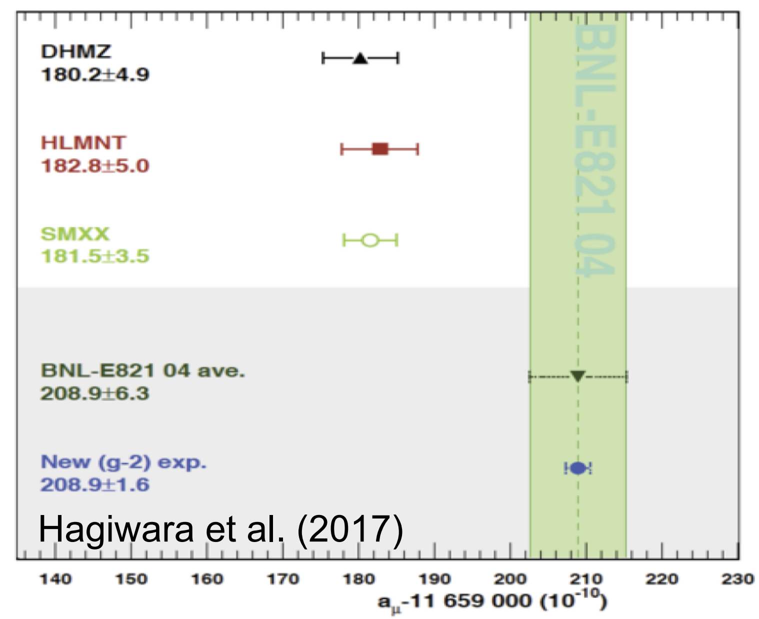
LAMPPOST LANDSCAPE

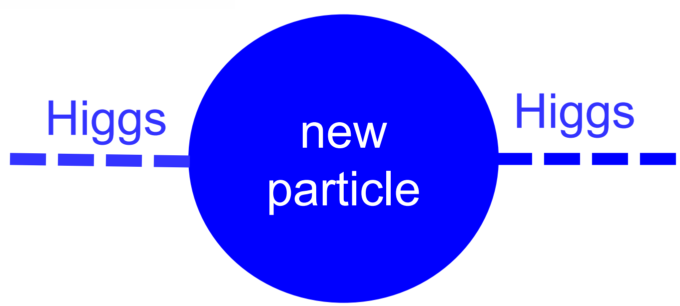


STRONGLY INTERACTING, HEAVY PARTICLES

- The traditional target for new physics searches: the high energy frontier
- Motivations: WIMP miracle, gauge hierarchy, anomalies (muon g-2, ...)

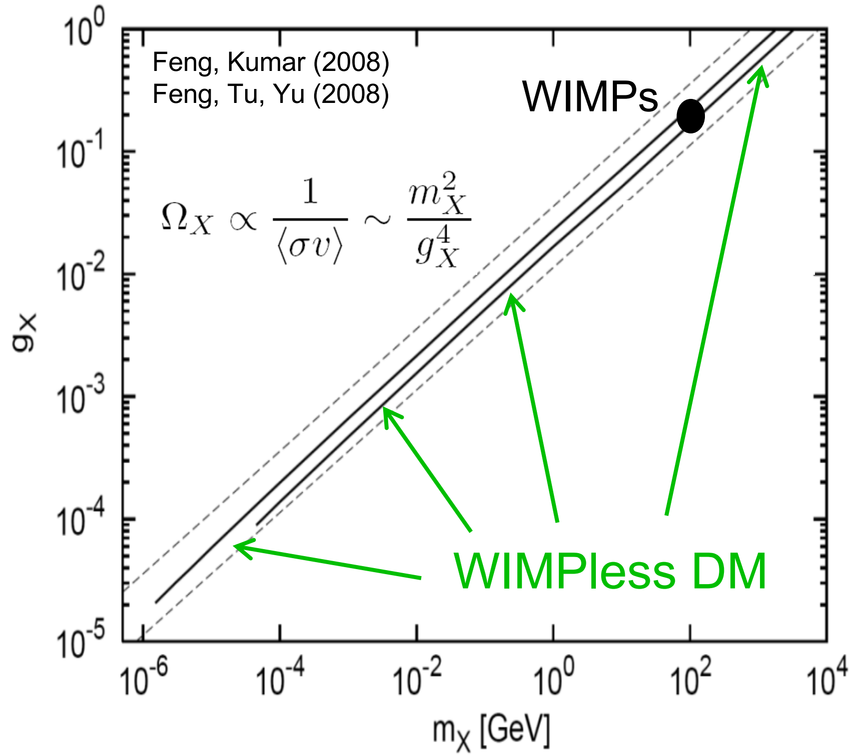


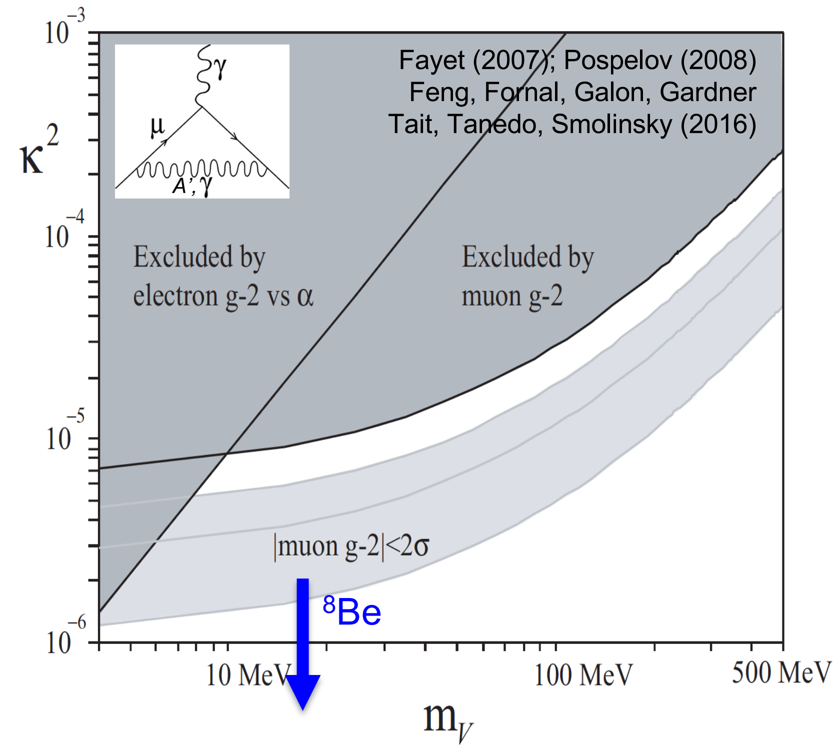




WEAKLY INTERACTING, LIGHT PARTICLES

- A new target for new physics searches
- Similar motivations: WIMPless miracle, anomalies (muon g-2, ^{8}Be, ...)



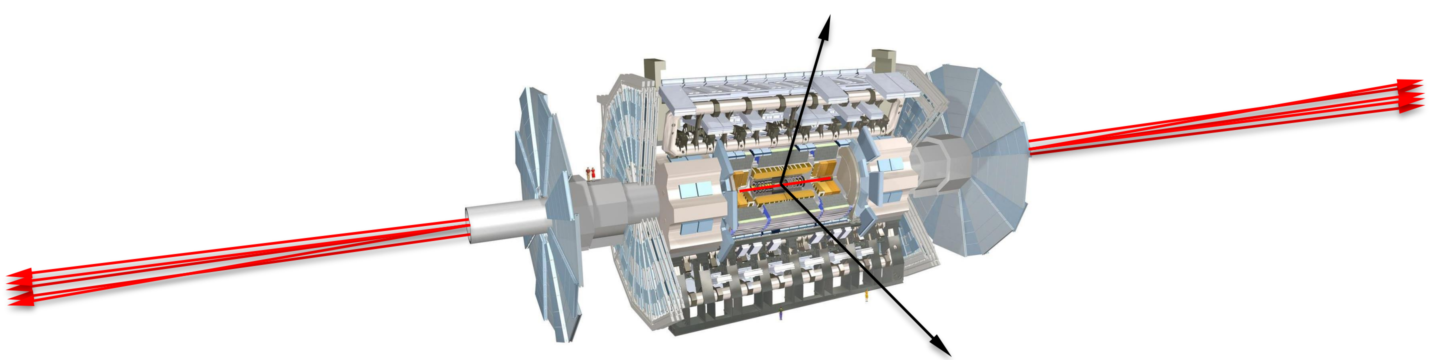


- Weakly interacting, light particles can be thermal relic dark matter, resolve existing anomalies, open new possibilities for experimental detection

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

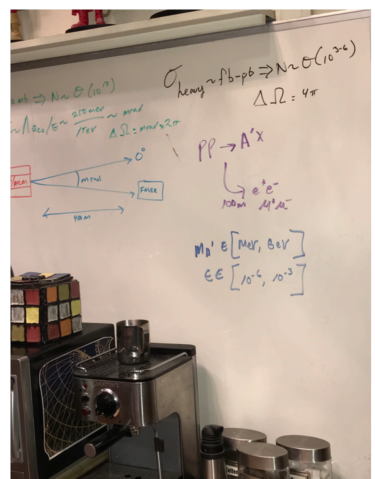


- We propose a small, inexpensive experiment, FASER, to be placed in the very forward region of ATLAS/CMS, a few 100m downstream of the IP, and analyze its discovery potential

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."

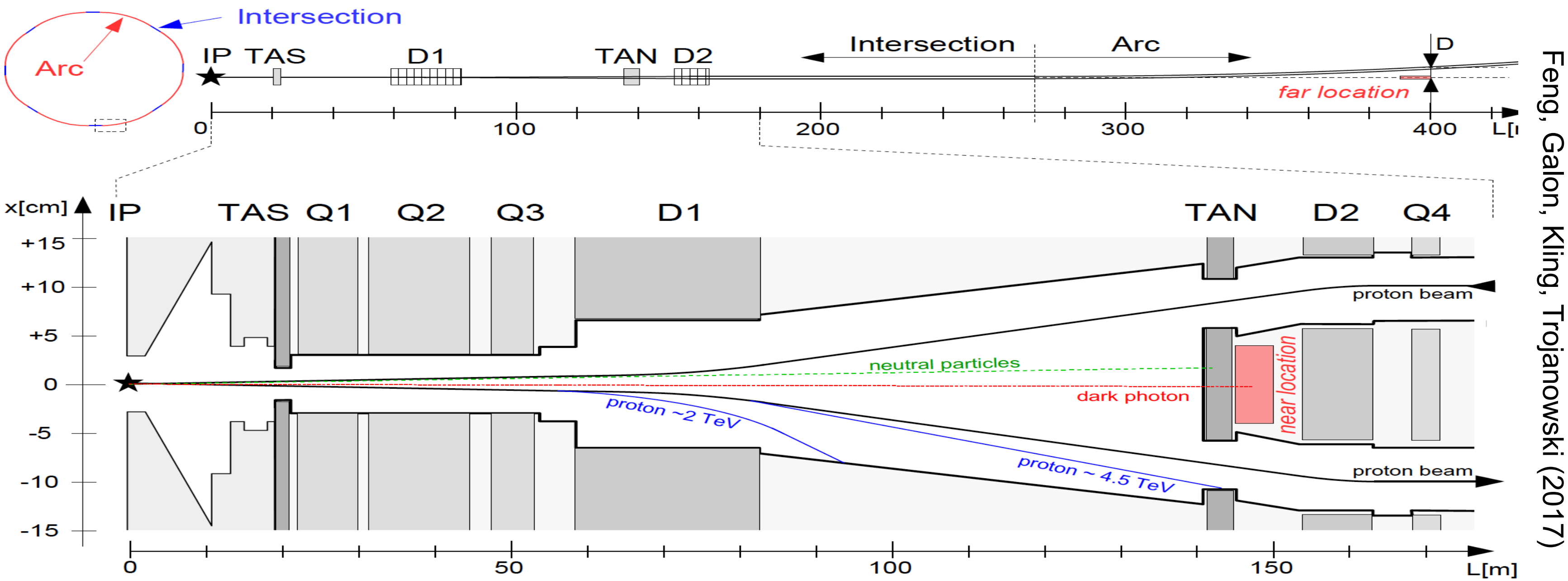


OUTLINE

- Very Forward Region Infrastructure
- New Physics Example: Dark Photons
- Signal and Backgrounds
- Event Rates and Reach
- New Physics Example: Dark Higgs Bosons
- Recent Progress
- Summary and Outlook

FASER LOCATION

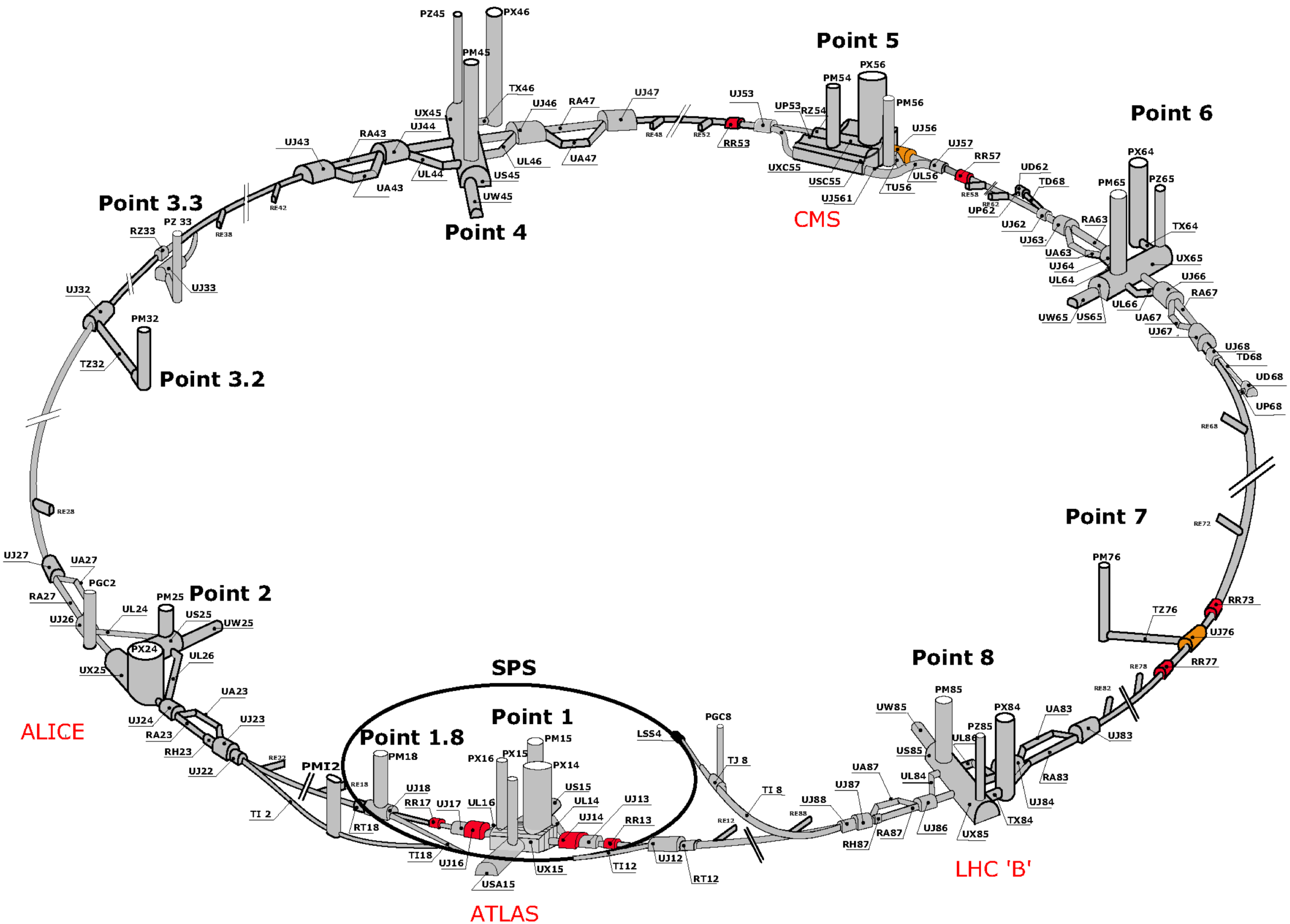
- We want to place FASER along the beam *collision* axis
  - Far location: ~400 m from IP, after beams curve, ~3 m from the beams
  - Near location: 150 m, after TAN, between the beams



- Here, focus on far location, assume FASER is exactly on-axis

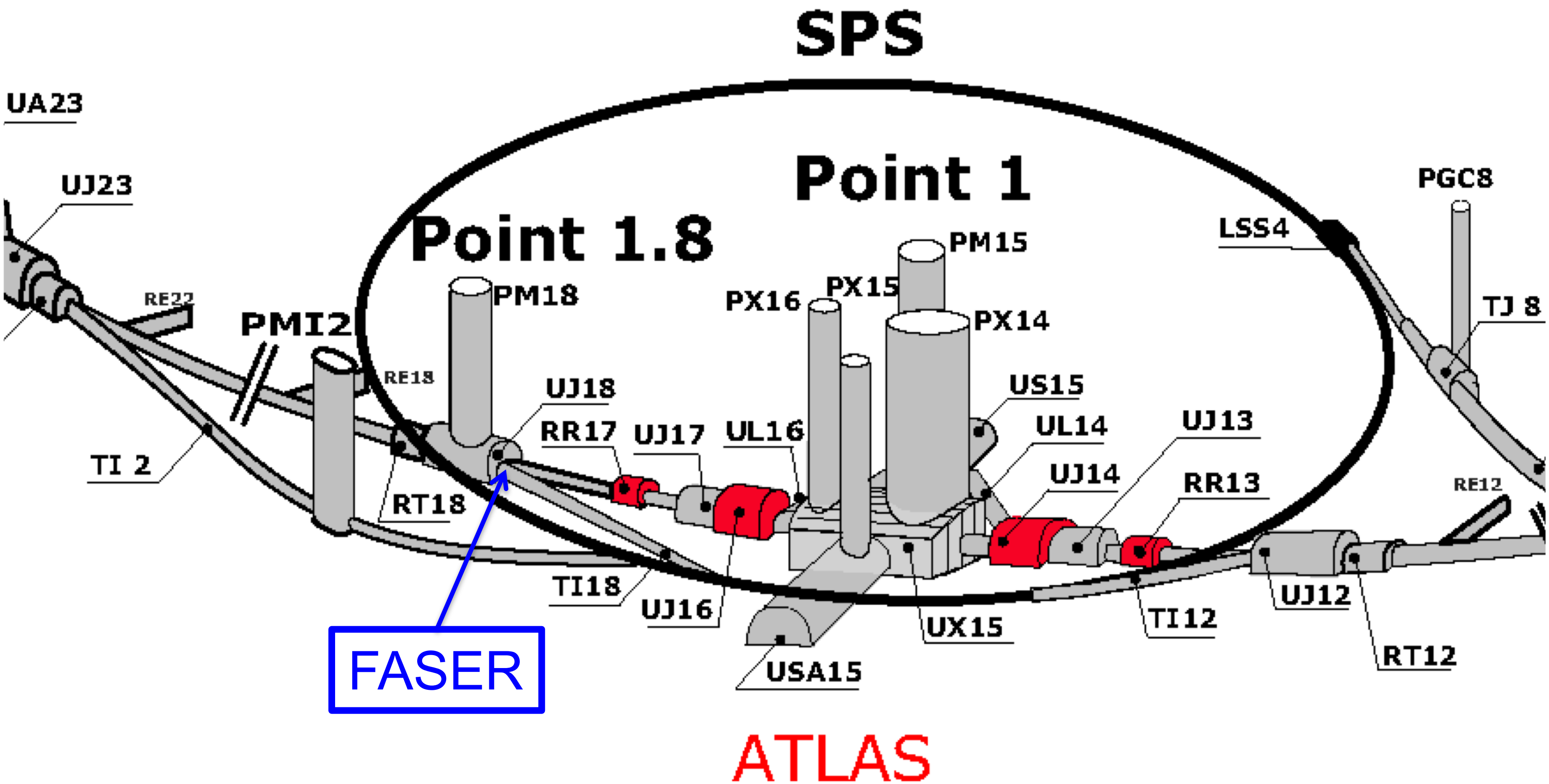
- If ATLAS/CMS beams cross at 285 (590) μrad in vertical/horizontal plane, far location shifts by 6 (12) cm

LHC RING



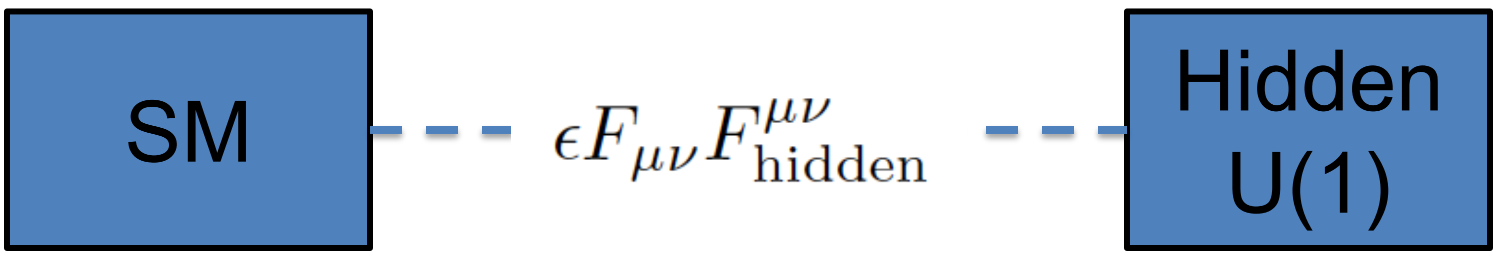
Point 1
Point 1.8
Point 2
Point 3.2
Point 3.3
Point 4
Point 5
Point 6
Point 7
Point 8
SPS
ALICE
CMS
ATLAS
LHC 'B'

SERVICE TUNNEL TI18



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

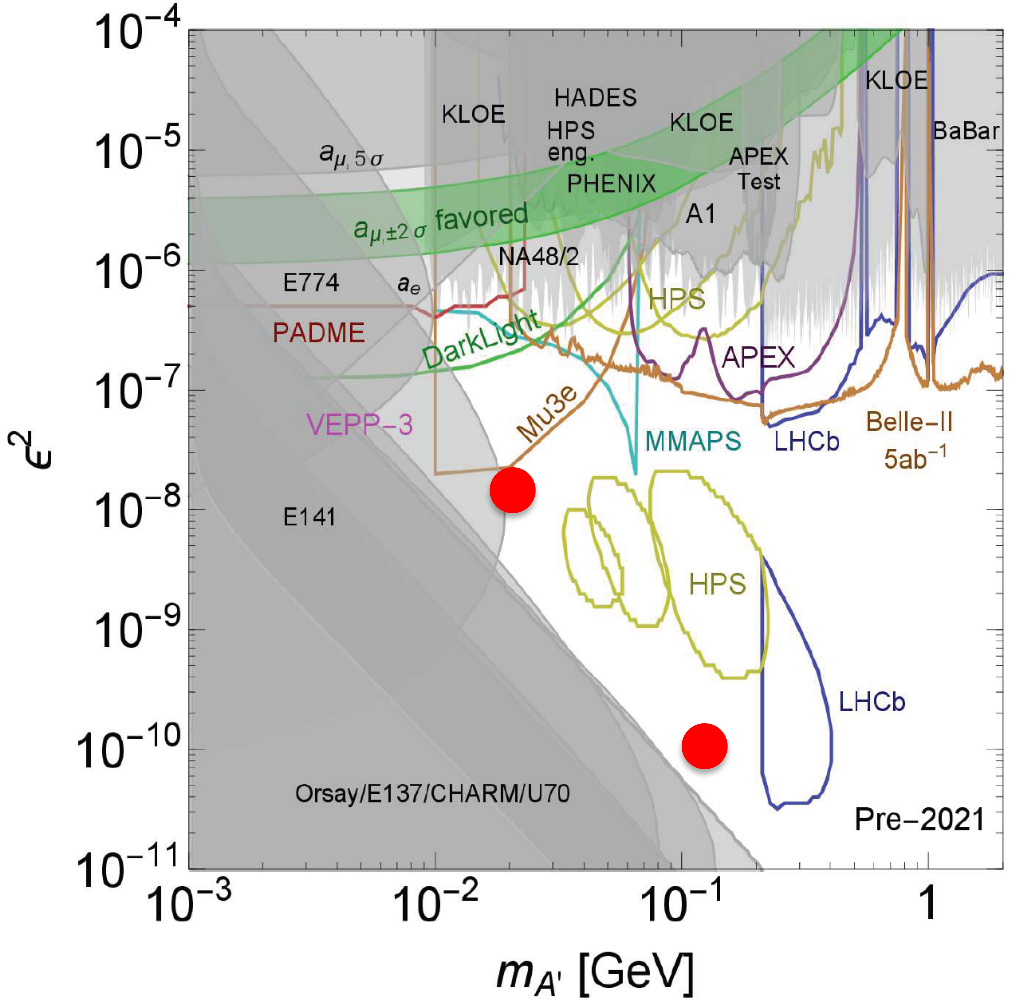
- Travels long distances through matter without interacting, decays to e^+e^- , $\mu^+\mu^-$ for $m_{A'} > 2\ m_\mu$, other charged pairs

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

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

DARK PHOTON STATUS

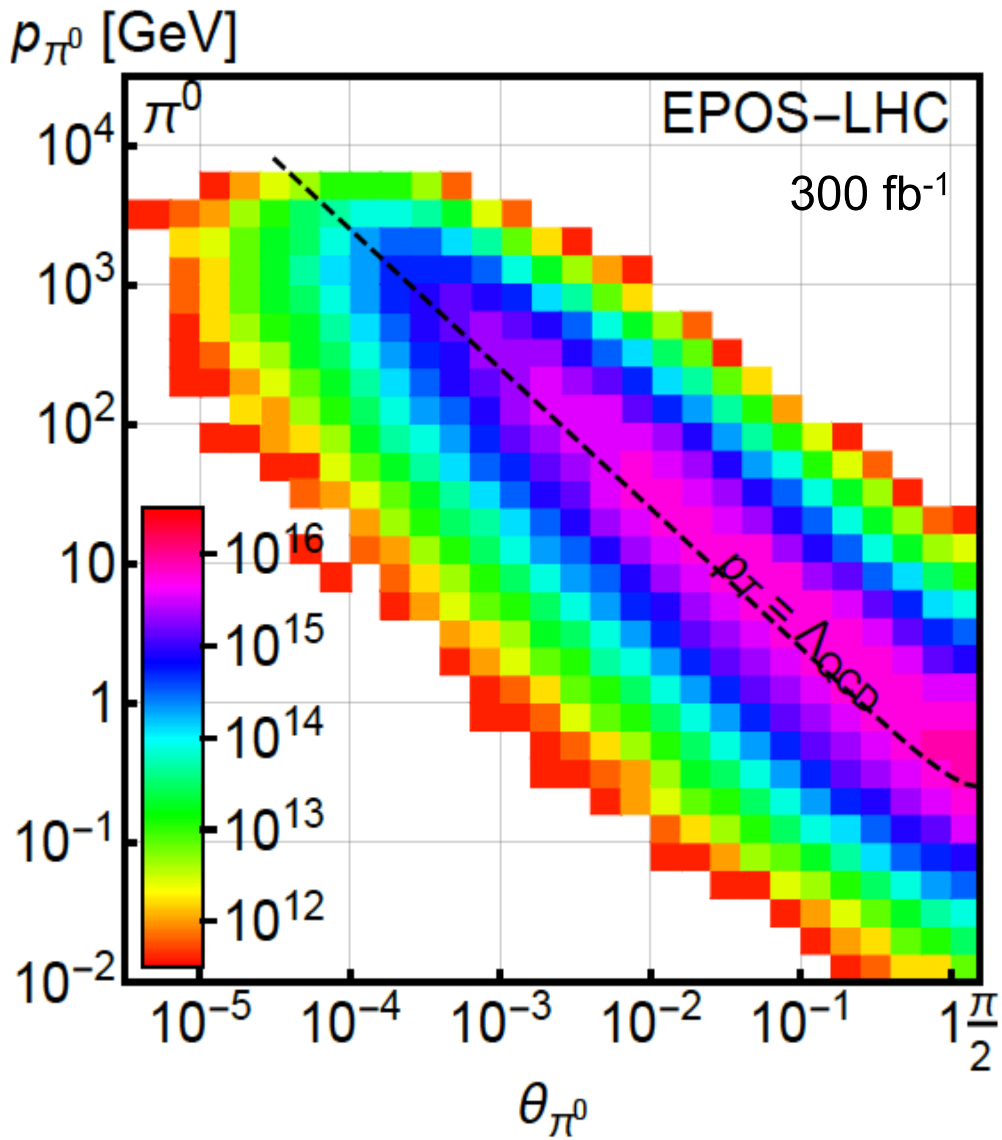
- Low $\varepsilon \rightarrow$ fixed target constraints, high $\varepsilon \rightarrow$ collider, precision constraints
- But still lots of open parameter space with
  $m_{A'} > 10$ MeV
  $\varepsilon \sim 10^{-6} - 10^{-3}$
- E.g., 2 representative model points: $(m_{A'}, \varepsilon)$ =
  (20 MeV,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



Cosmic Visions White Paper (2017)

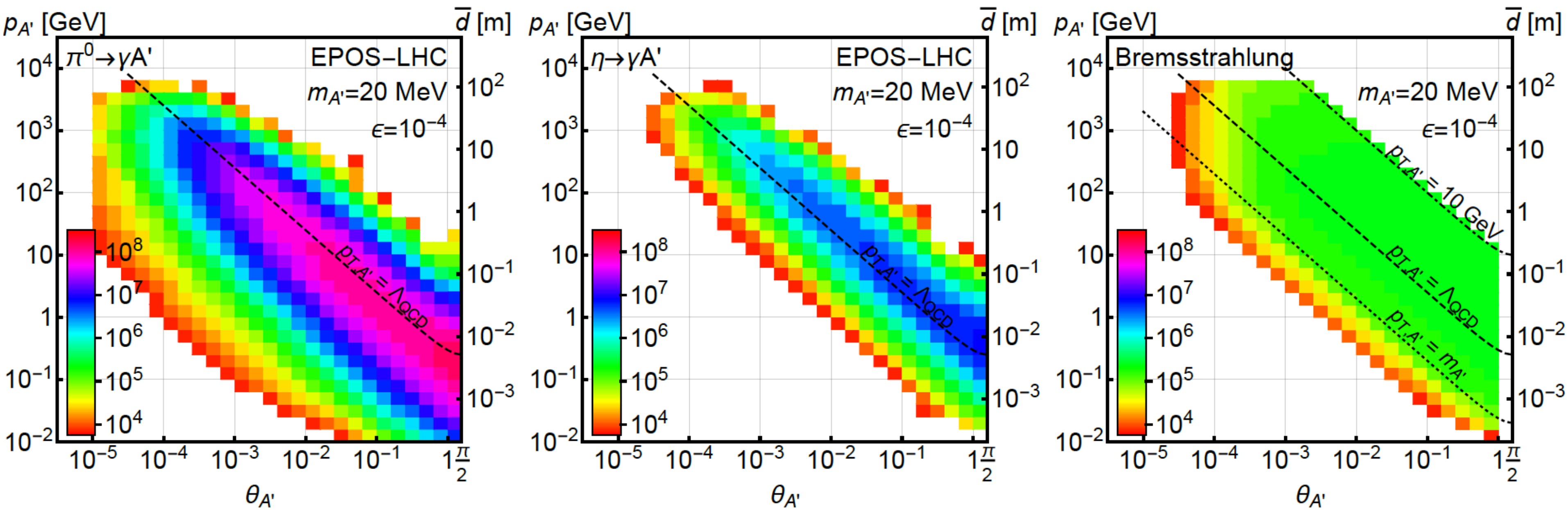
PION PRODUCTION AT THE LHC

- 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 PHOTON PRODUCTION

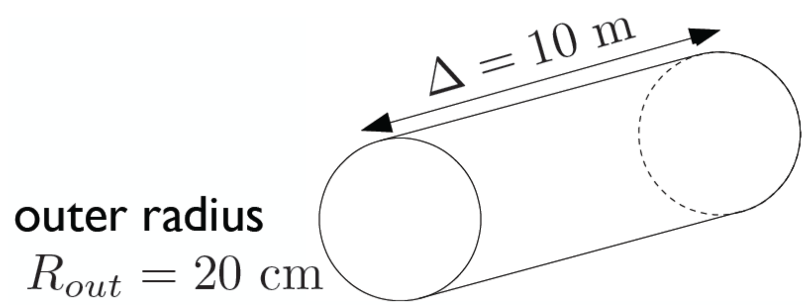
- Consider π^0 decay, η decay, dark bremsstrahlung
- Results for 1st model point: $(m_{A'}, \varepsilon) = (20\text{ MeV}, 10^{-4})$

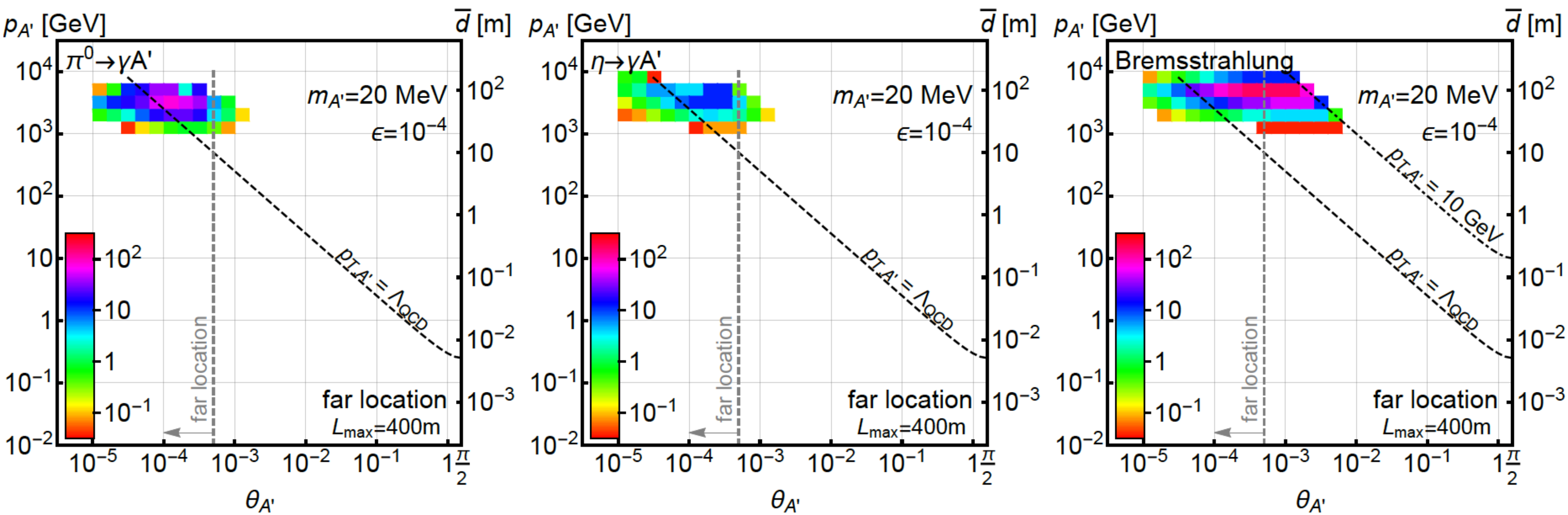


- From $\pi^0 \rightarrow \gamma A'$, $E_{A'} \sim E_\pi / 2$ (no surprise)
- But note rates: even after ε^2 suppression, $N_{A'} \sim 10^8$; LHC may be a dark photon factory!

DARK PHOTONS IN FASER

- Now require dark photons to decay in FASER: consider cylindrical detector with volume ~1 m^2

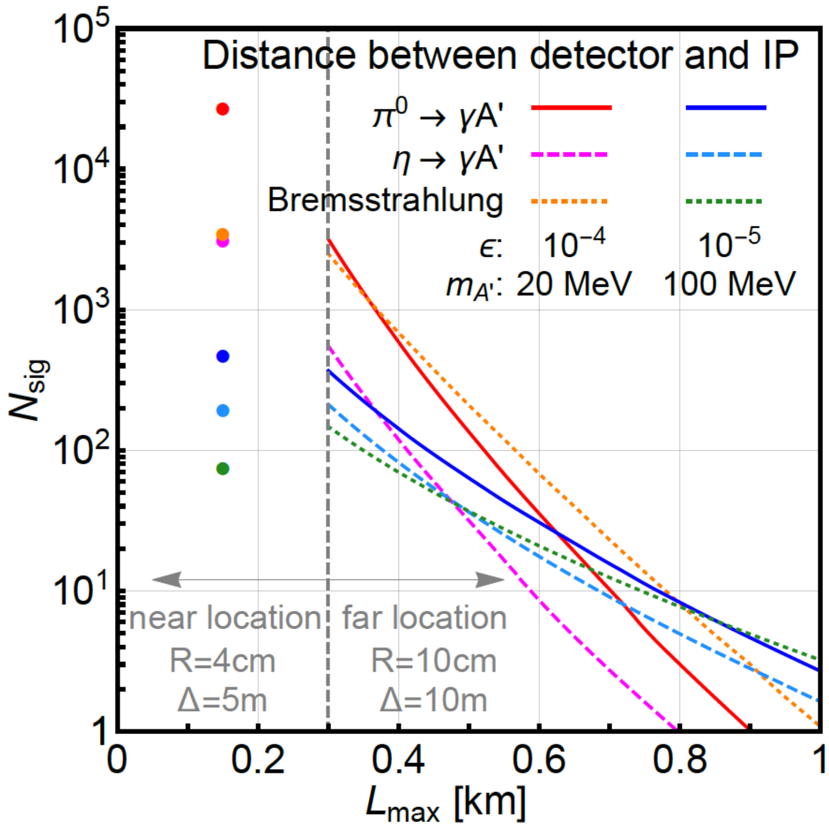


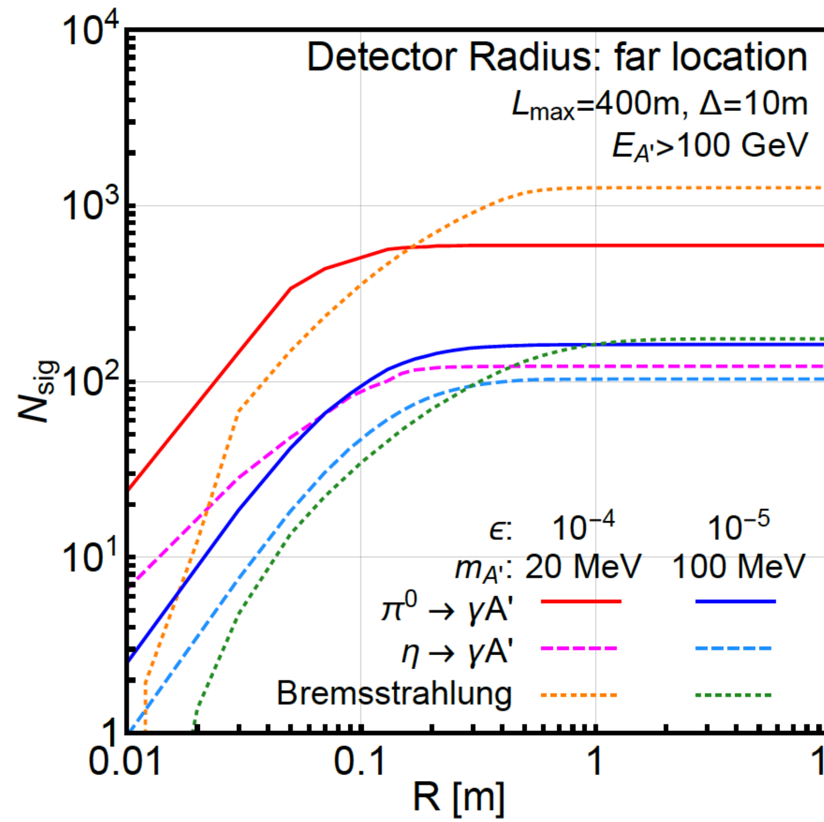


- Only the highest energy A's survive, but there are still many of them, and they are highly collimated

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'





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

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

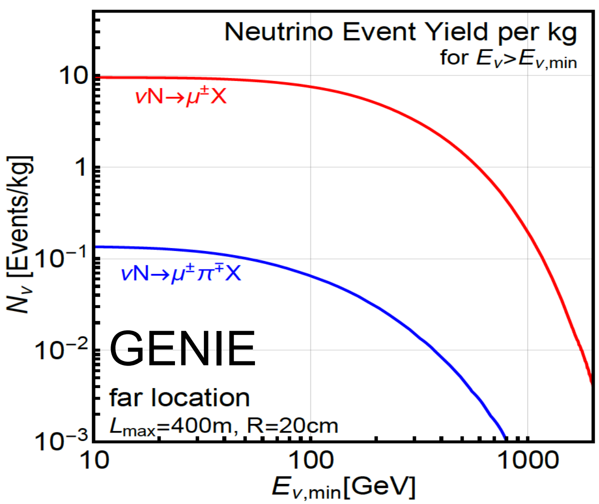
- Many backgrounds are eliminated simply by virtue of FASER's location. Particles from IP must pass through ~50 m of matter to get to FASER. Cosmic ray background is negligible, charged particles from IP are bent away by D1 magnet

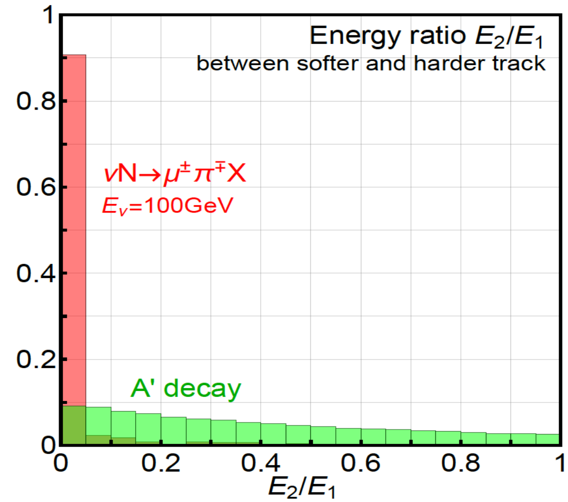
- Leading backgrounds: neutrino-induced backgrounds and beam-induced backgrounds

BACKGROUNDS

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

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



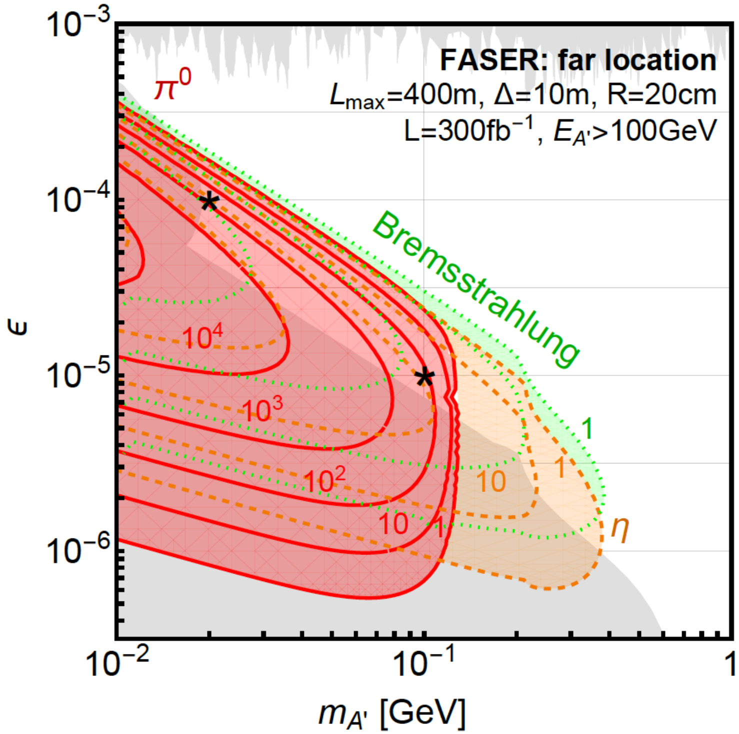


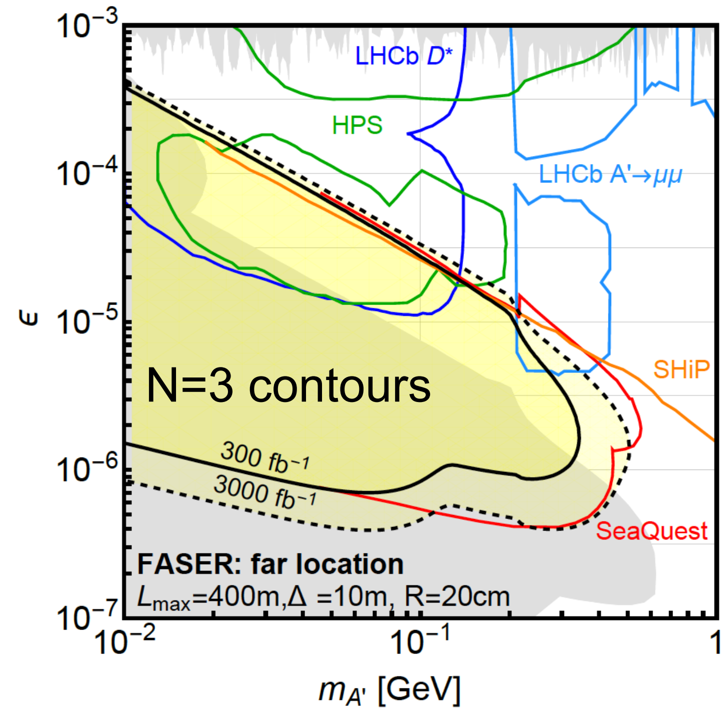
- Coincident single tracks that fake double tracks are negligible; second process eliminated by requiring no other activity, tracks start in the detector and have high and symmetric energies

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

DARK PHOTON EVENT RATES AND REACH

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

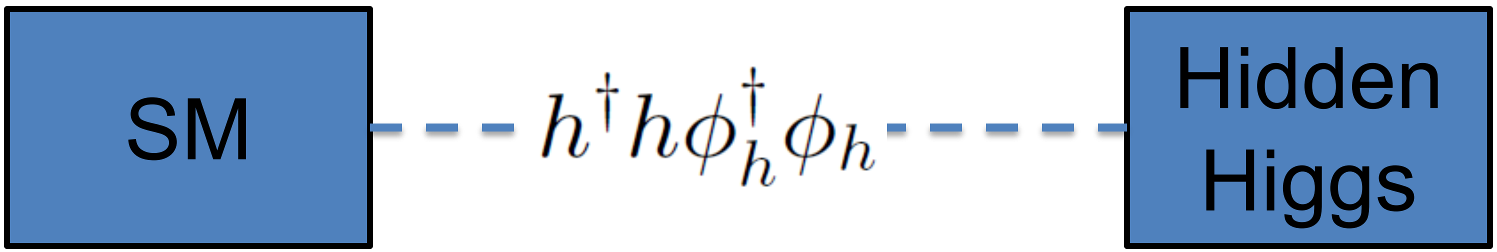




- Note that at upper ε boundary, rates are extremely sensitive to ε and the reach is quite insensitive to background, provided it is known

DARK HIGGS BOSONS

- Another renormalizable coupling: Higgs portal



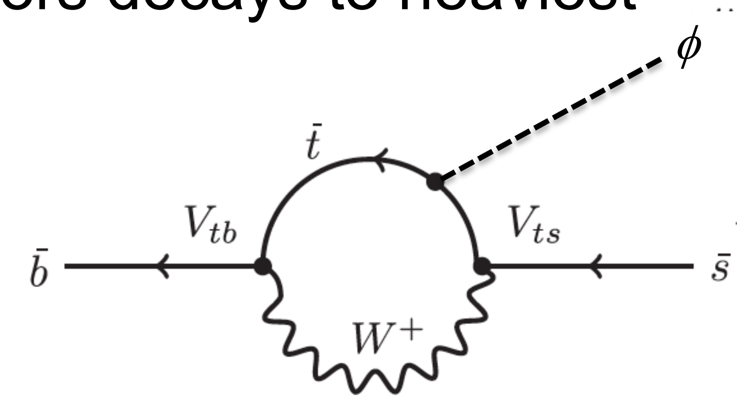
- The resulting theory contains a new scalar boson ϕ with mass m_ϕ , Higgs-like couplings suppressed by $\sin\theta$, and a trilinear coupling λ

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

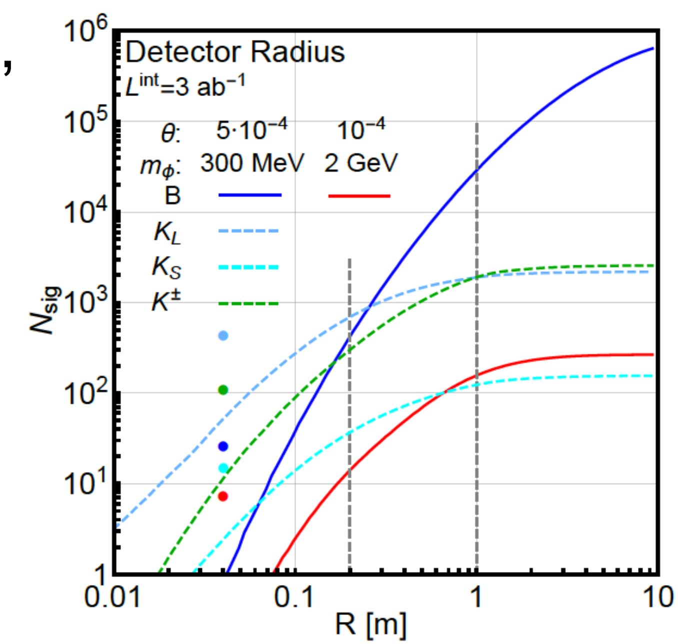
DARK HIGGS PROPERTIES

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

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

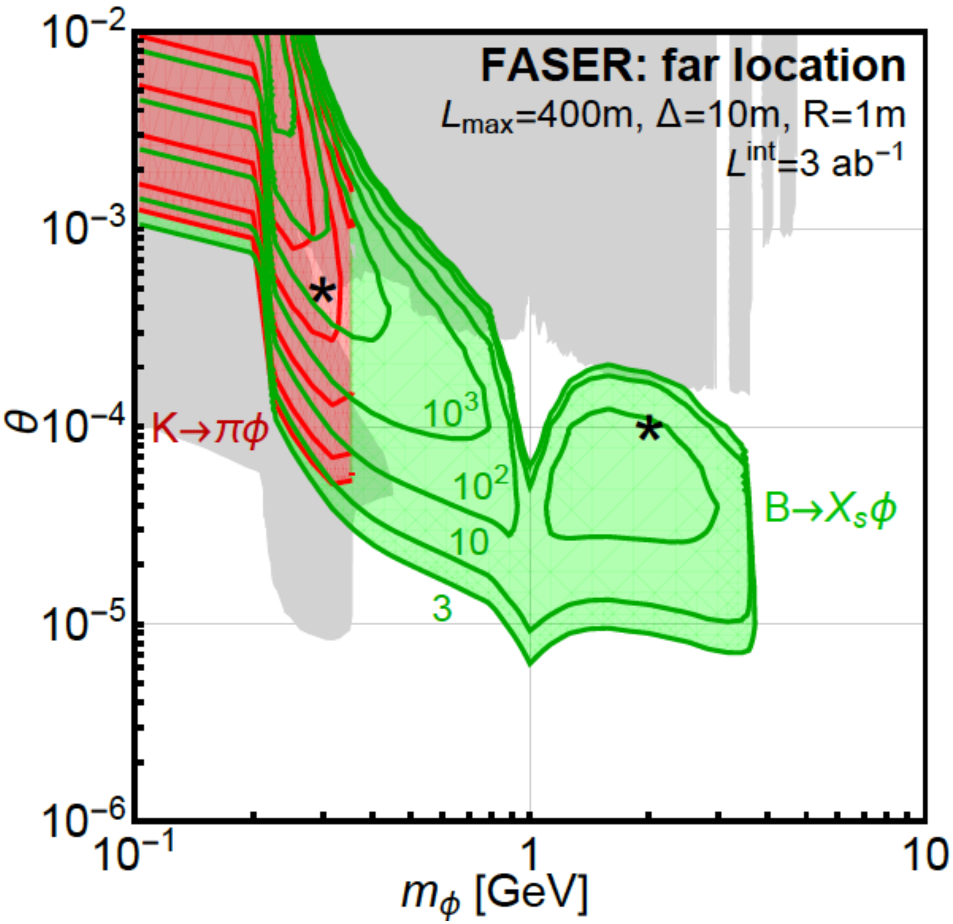


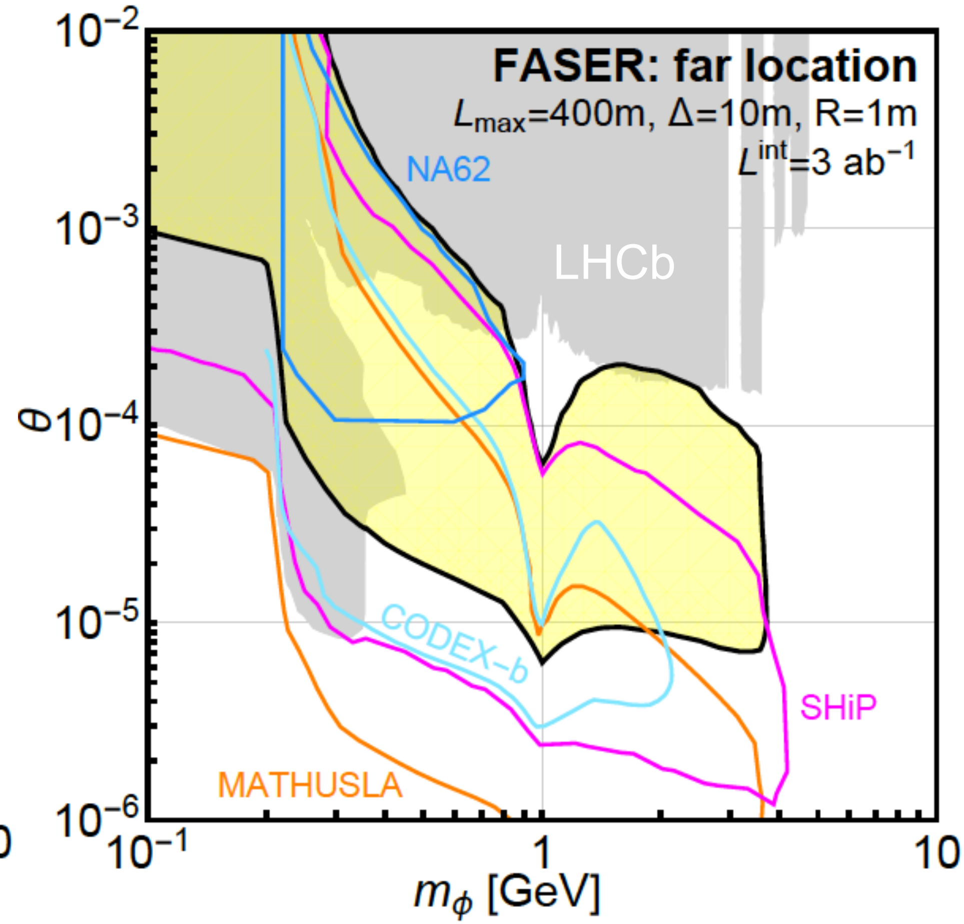
- In contrast to fixed target experiments, lots of COM energy to produce ~10^{15} B mesons, excellent probe of new physics that couples to 3rd generation



- In B decays, p_T ~ m_B, dark Higgs bosons are less collimated than dark photons

DARK HIGGS EVENT RATES AND REACH

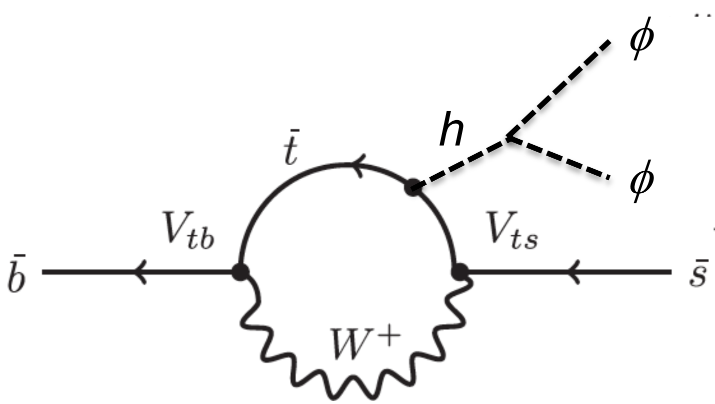


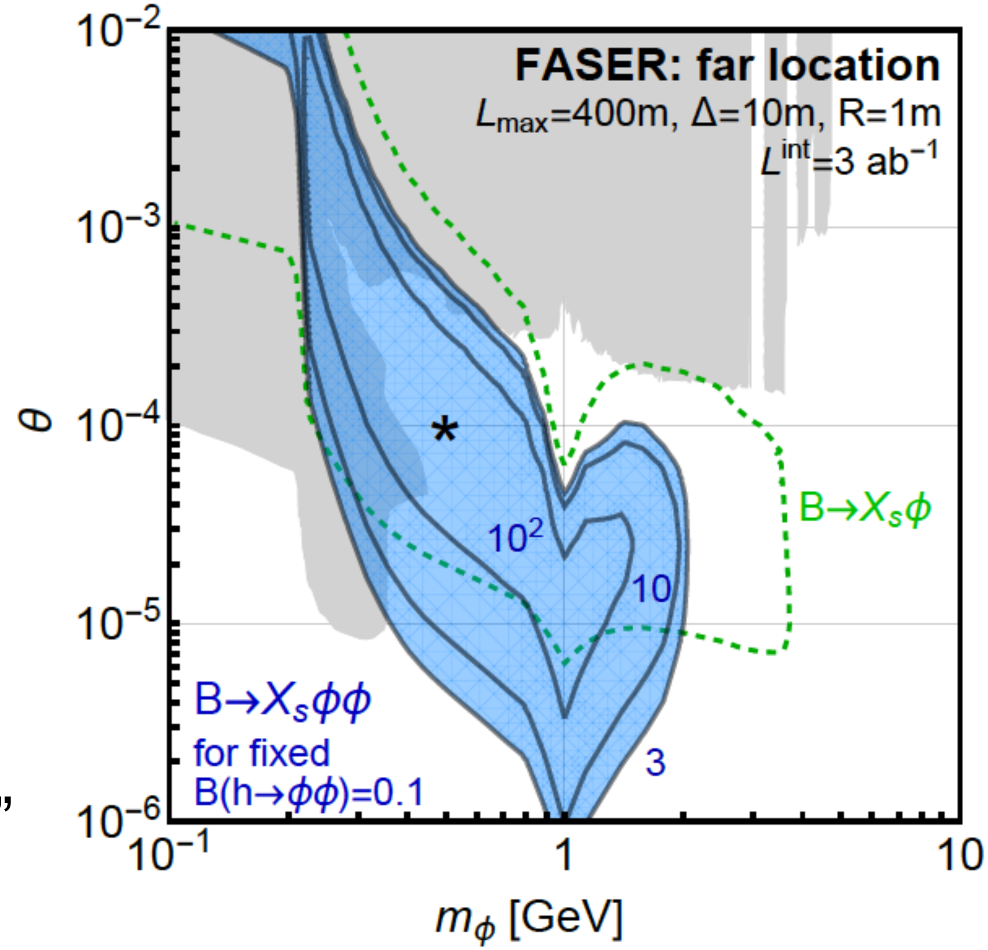


- FASER probes a large swath of new parameter space and is complementary to other current and proposed experiments

TRILINEAR COUPLINGS REACH

- FASER can also probe the trilinear couplings through

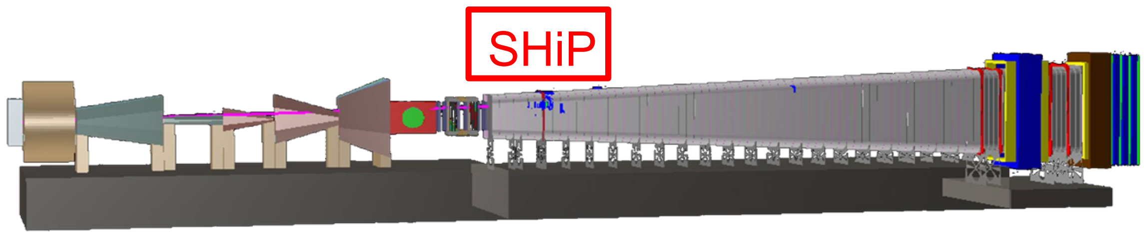




- This competes with
  h → ϕϕ (invisible)

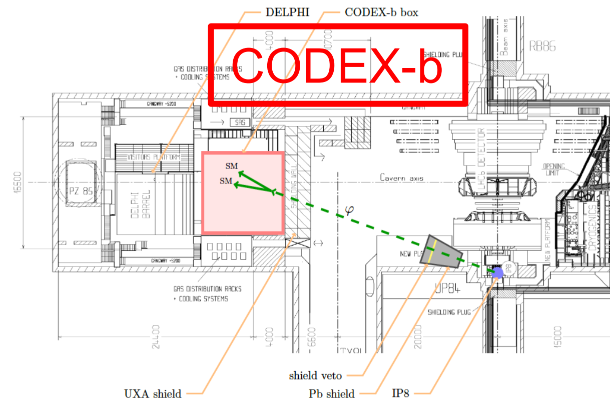
- Can get 100s of events from "double dark Higgs" production

COMPLEMENTARY PROPOSED EXPERIMENTS



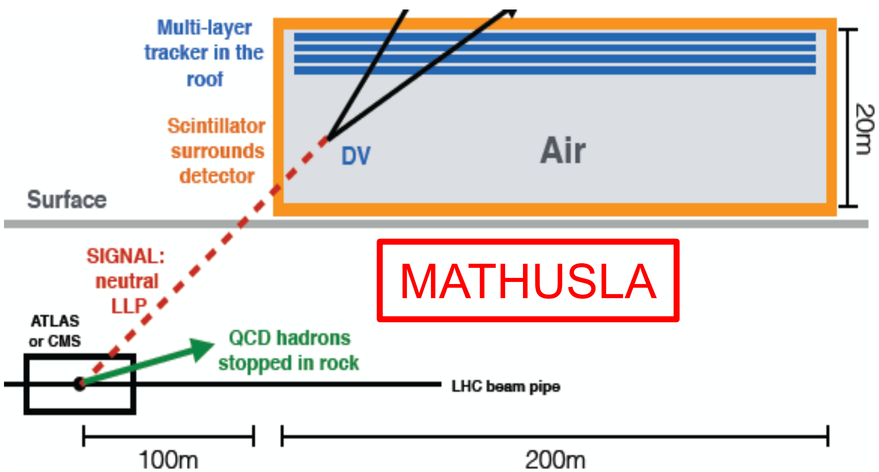
~1000 m^3, ~100M CHF + beam

Alekhin et al. (2015)



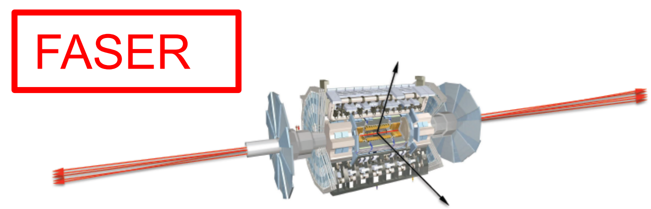
~1000 m^3

Gligorov, Knapen, Papucci, Robinson (2017)



~200,000 m^3 ~ 1 IKEA, ~$50M

Chou, Curtin, Lubatti (2016)



~1 m^3 ~ 5 μIKEAs

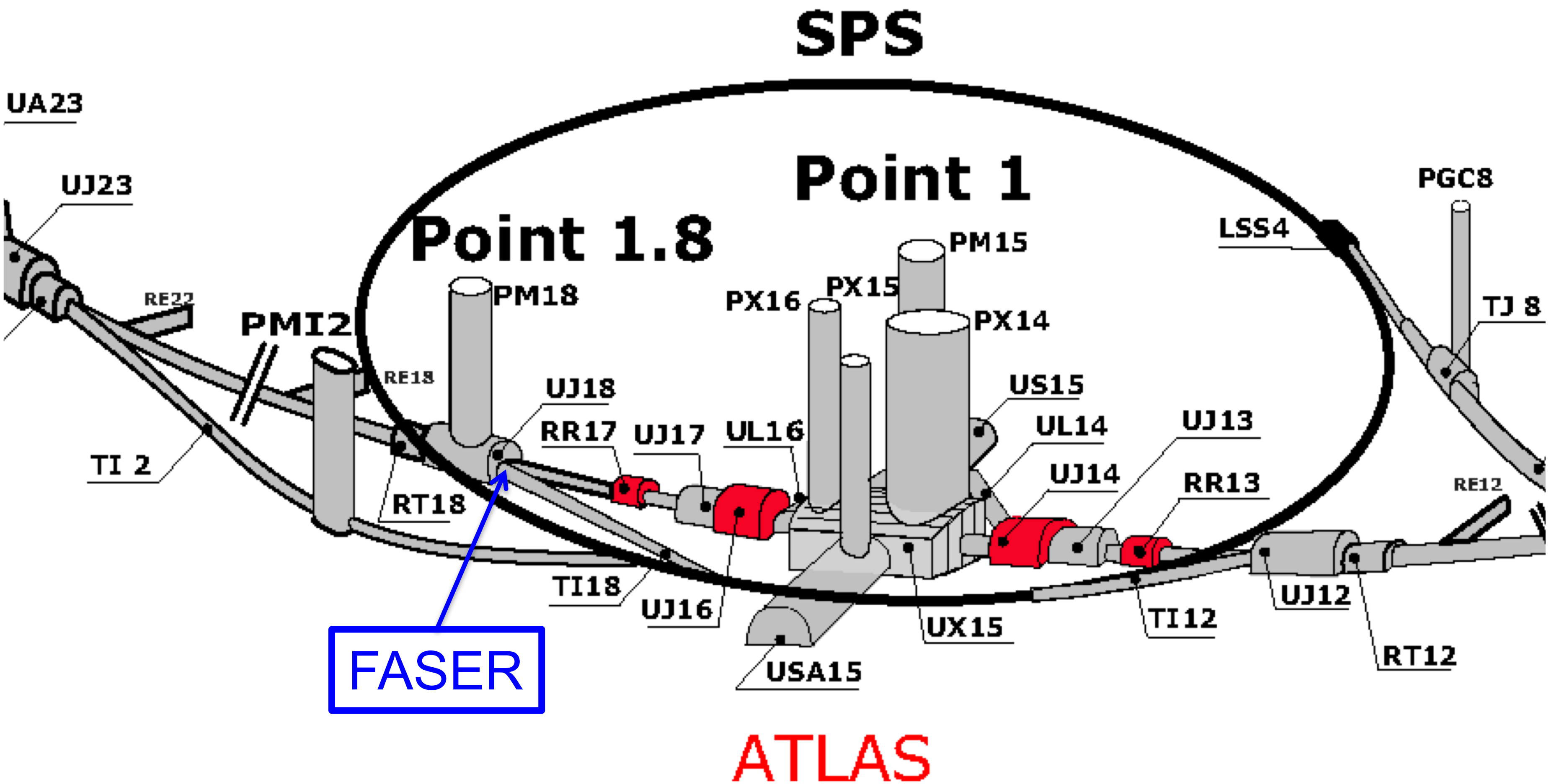
Feng, Galon, Kling, Trojanowski (2017)

RECENT PROGRESS

- Theory: see also studies of flavor-specific scalar mediators (Batell, Freitas, Ismail, McKeen, 1712.10022), HNLs (heavy neutral leptons, sterile neutrinos) (Kling, Trojanowski, 1801.08947; Helo, Hirsch, Wang, 1803.02212), other gauge bosons (Bauer, Foldenauer, Jaeckel, 1803.05466), ALPs (axion-like particles) and other models in progress

- Experiment: FASER, MATHUSLA, CODEX-b, MilliQan have joined the CERN Physics Beyond Collider study. A few examples of recent progress follow. Thanks to Jamie Boyd, Dave Casper, Francesco Cerrutti and FLUKA team, Paolo Fessia, Shih-Chieh Hsu, and Mike Lamont.

FASER: LOCATION



FASER: LOCATION

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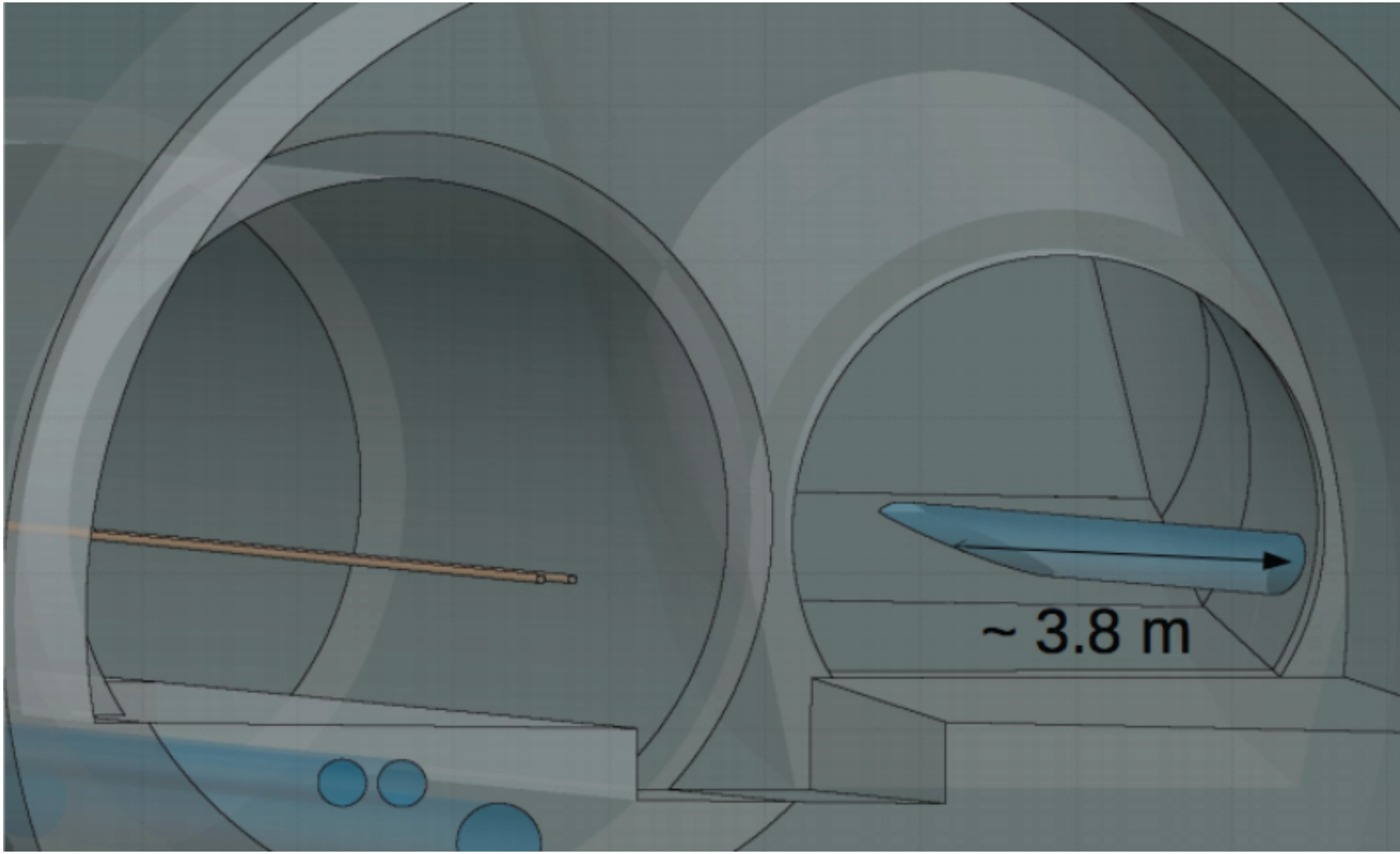
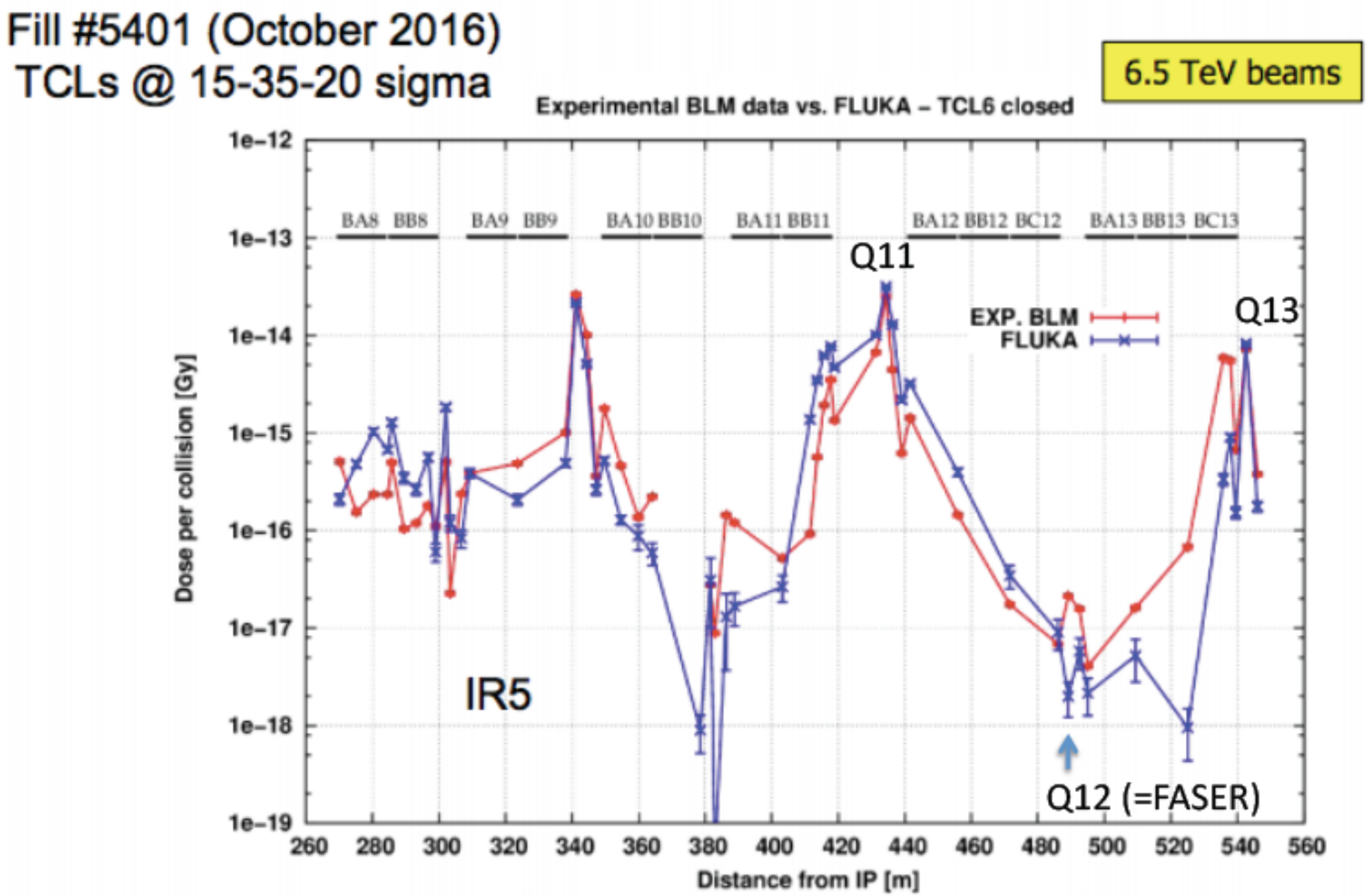


FASER: GEANT STUDY UNDERWAY

- 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



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 (150-300 fb^{-1}), install full detector in LS3 (2023-25) for HL-LHC (3 ab^{-1}).