FASER:
FORWARD SEARCH EXPERIMENT AT THE LHC

UCLA

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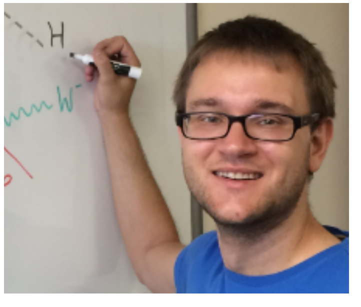
Based on 1708.09389 and 1710.09387 with

Iftah Galon

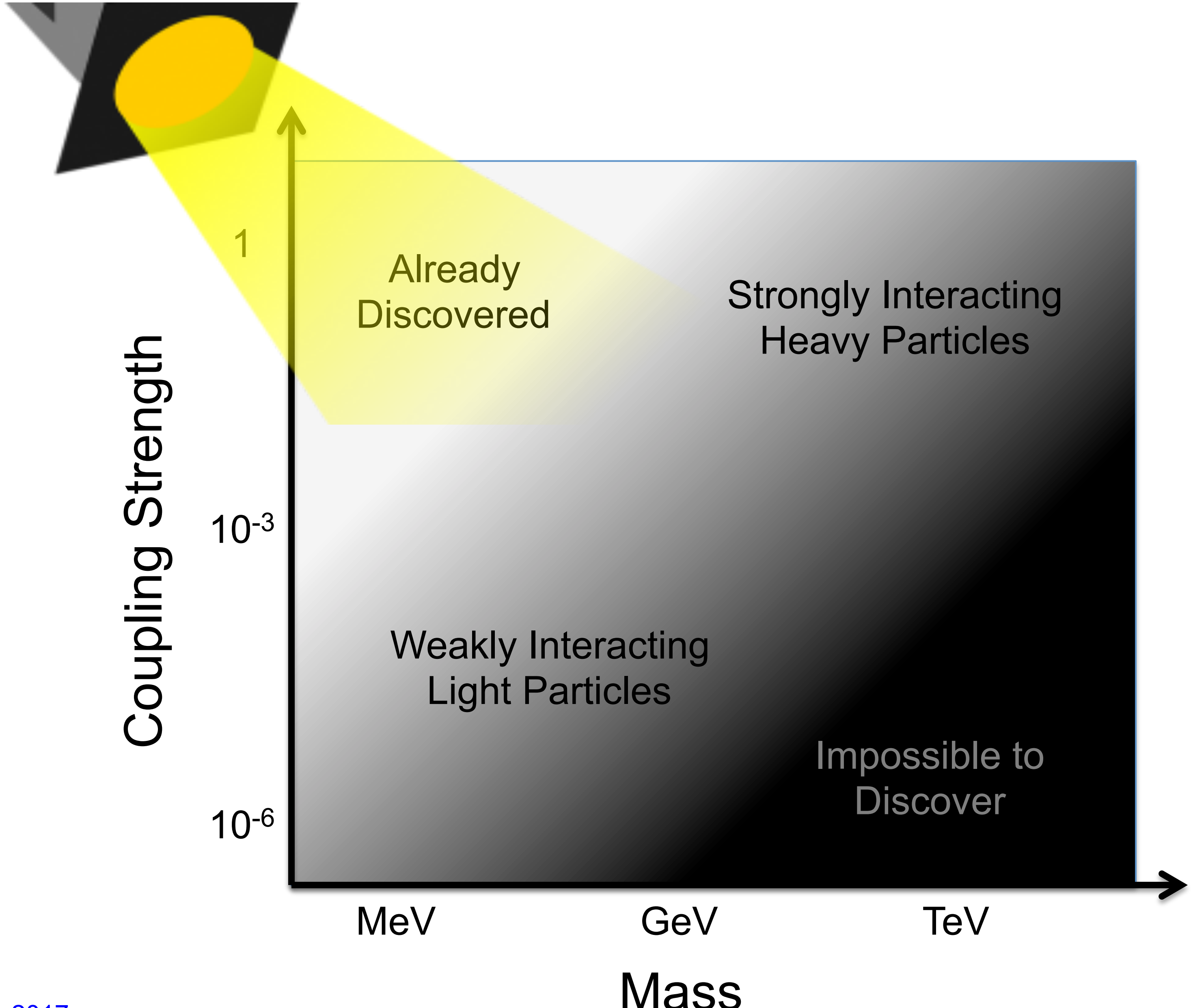


Felix Kling

Sebastian Trojanowski

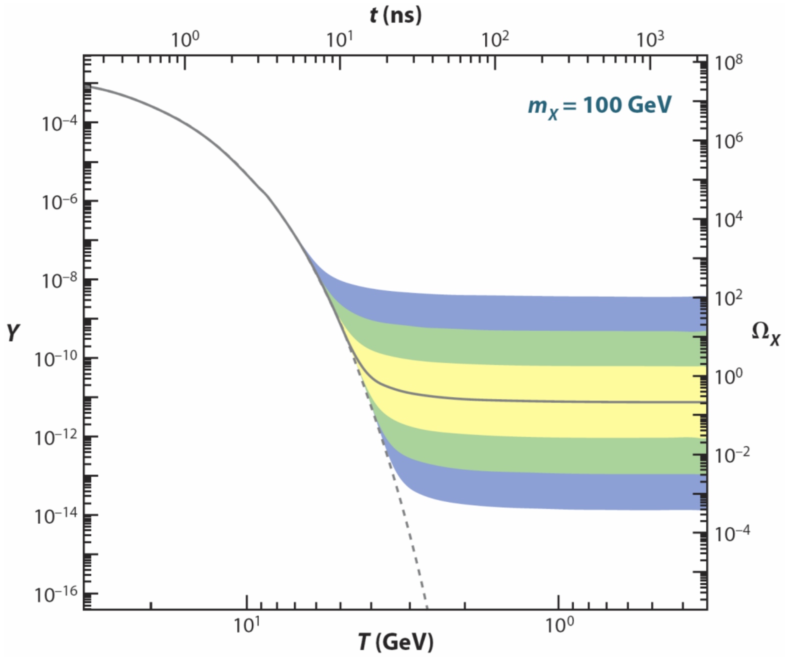
21 November 2017

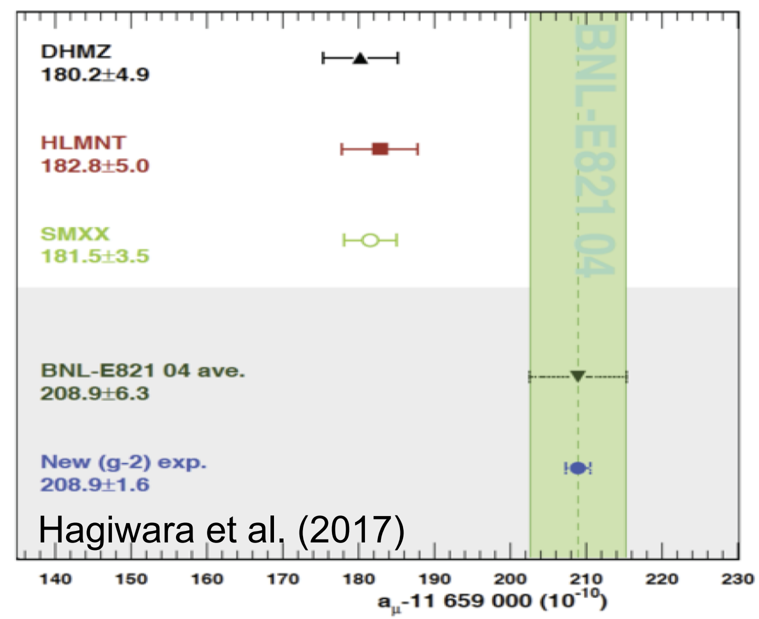
LAMPPOST LANDSCAPE

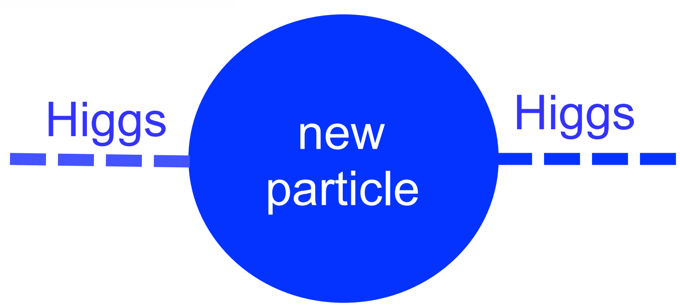


STRONGLY INTERACTING, HEAVY PARTICLES

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

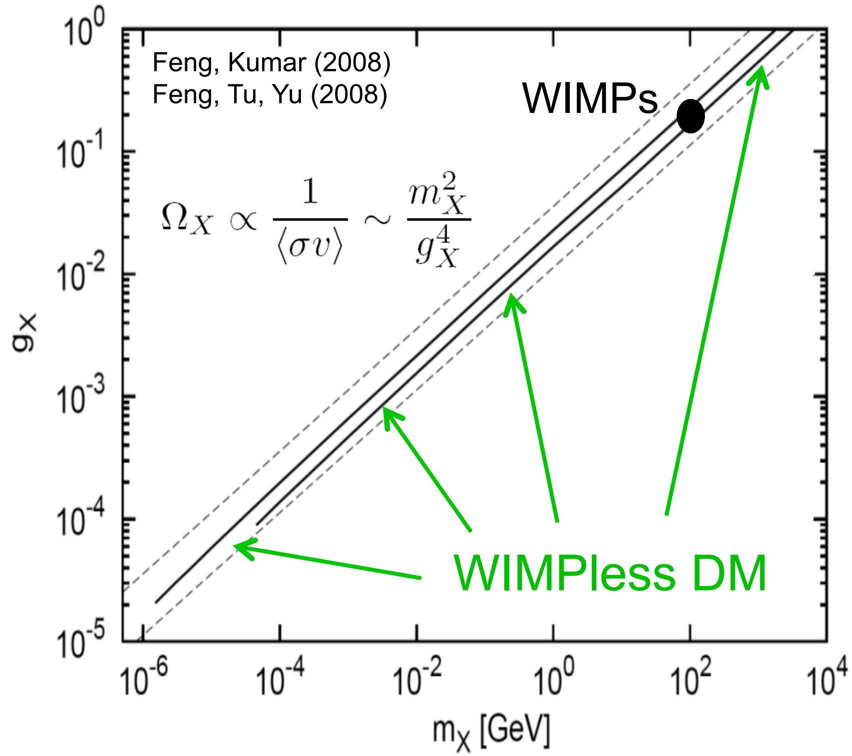


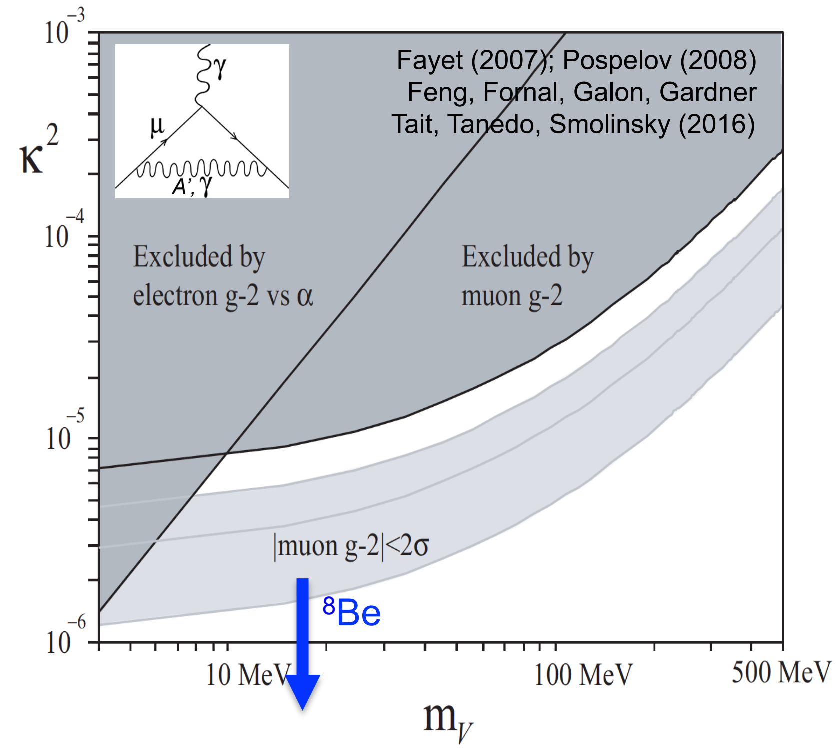




WEAKLY INTERACTING, LIGHT PARTICLES

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

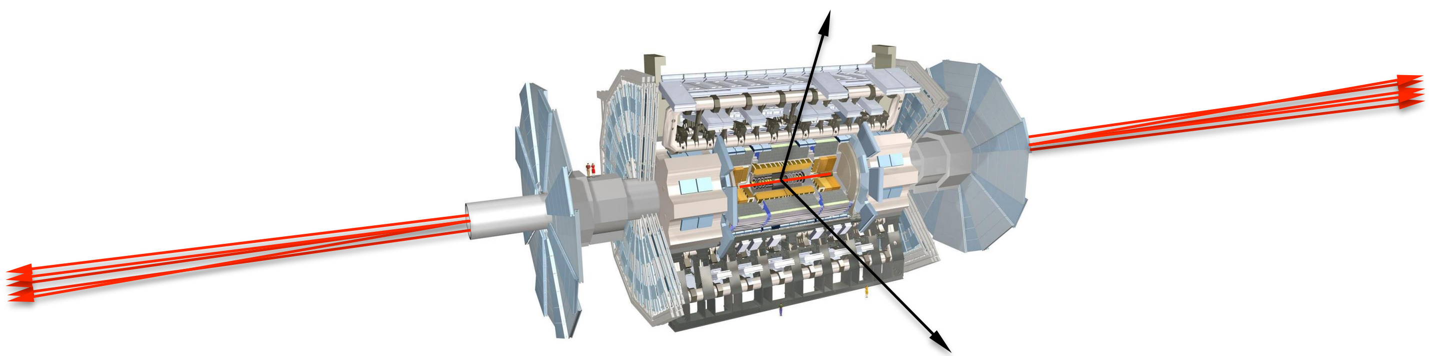




- Weakly interacting, light particles can be thermal relic dark matter, resolve anomalies, open new possibilities for experimental detection

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



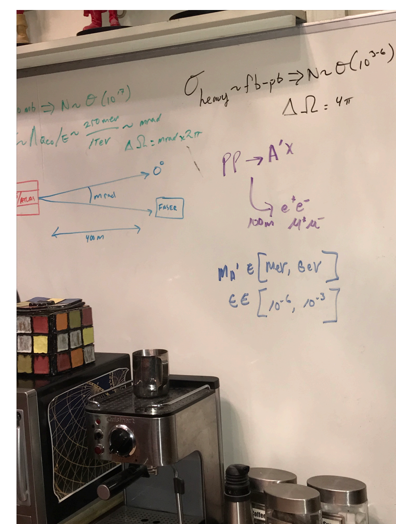
- We propose a small, inexpensive experiment, FASER, to be placed in the very forward region of ATLAS/CMS, a few 100m downstream of the IP, and analyze its discovery potential

THE LIFETIME FRONTIER

Increasing worldwide interest. At CERN: LHCb, NA62, SHiP, MilliQan, MATHUSLA, Codex-b, ...

FASER: "The acronym recalls another marvelous instrument that harnessed highly collimated particles and was used to explore strange new worlds."

the BIG BANG THEORY



OUTLINE

- Very Forward Region Infrastructure
- New Physics Example: Dark Photons
- Signal
- Backgrounds
- Results
- New Physics Example: Dark Higgs Bosons
- Summary and Outlook

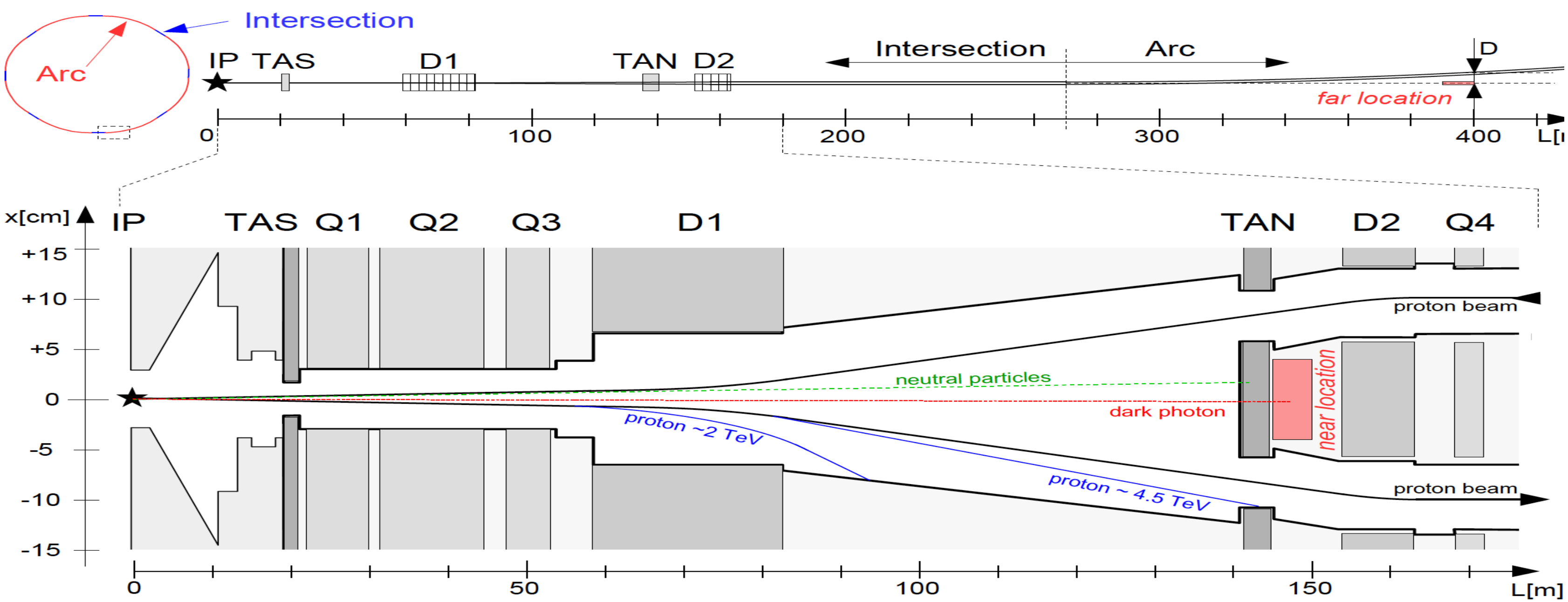
VERY FORWARD REGION INFRASTRUCTURE

- LHC ring consists of 8 straight 545 m intersections and 8 curved arcs. The infrastructure common to IP1 and IP5 (also have CASTOR, LHCf, ALFA, TOTEM, etc.):

TAS: front quadrupole absorbers (θ > 0.85 mrad)

D1: dipole magnet, splits beams, deflects μ, p, ...

TAN: neutral target absorbers (n, γ)

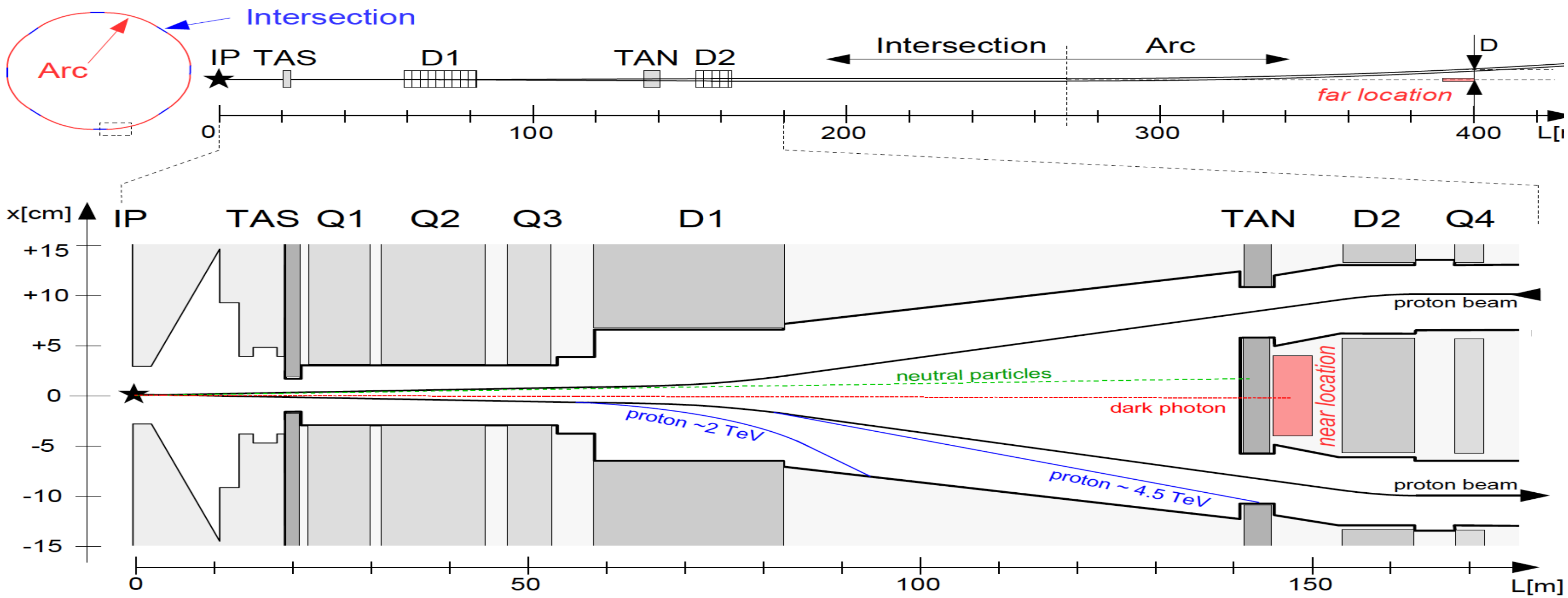


Feng, Galon, Kling, Trojanowski (2017)

Note the extreme difference in longitudinal and transverse scales

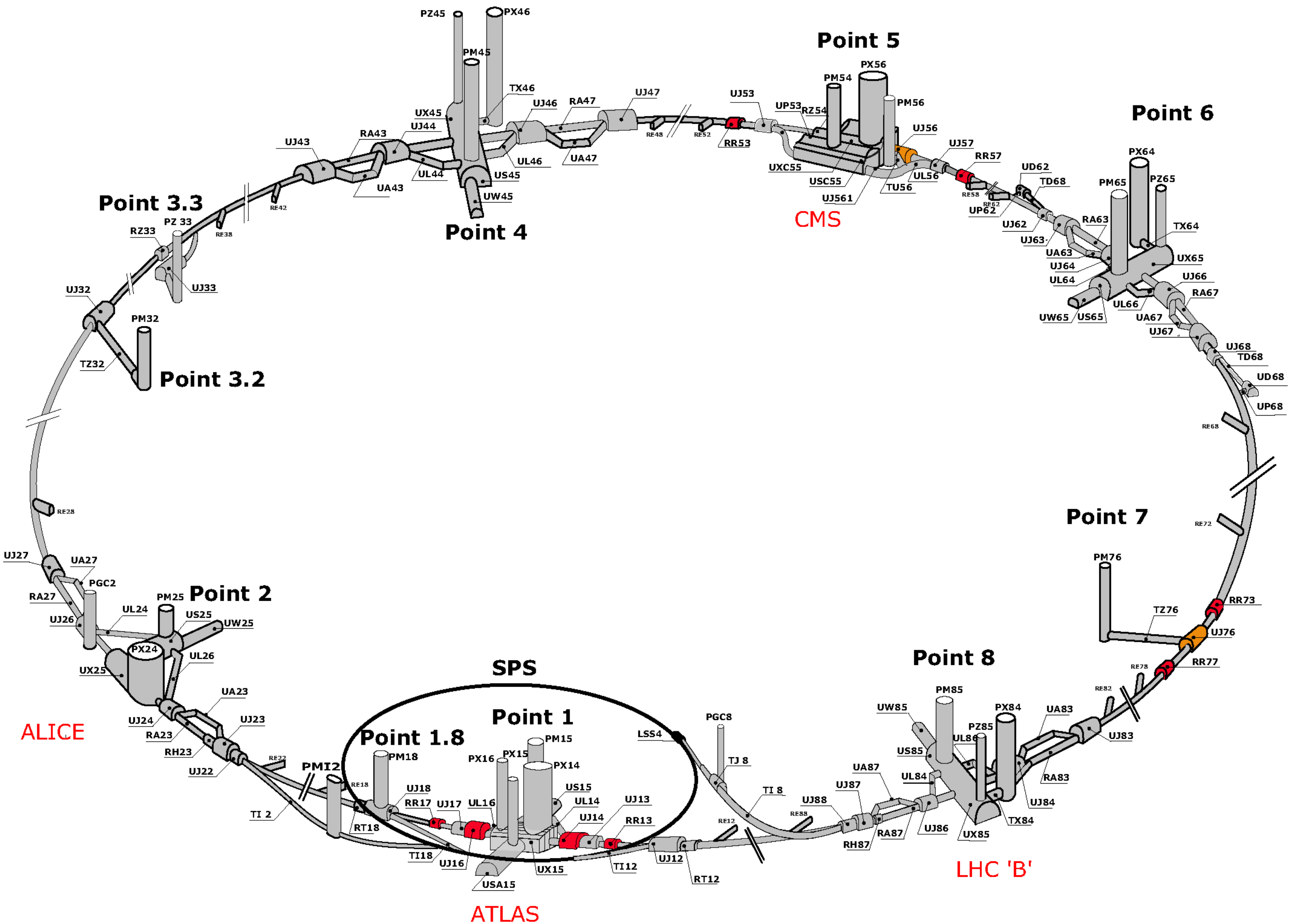
FASER LOCATIONS

- We want to place FASER along the beam *collision* axis
  - Far location: 400 m from IP, after beams curve, 2.6 m from the beams
  - Near location: 150 m, after TAN, between the beams



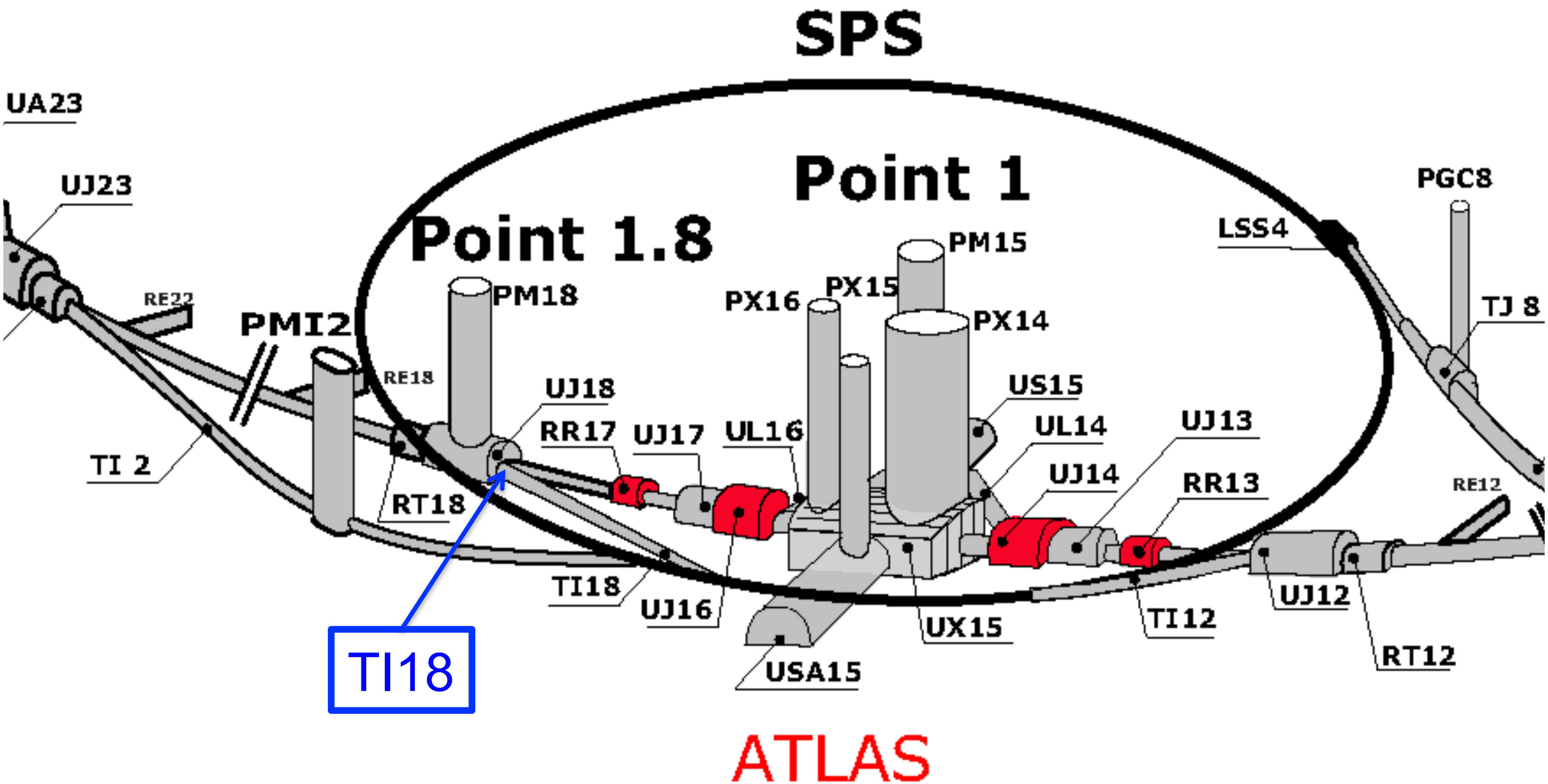
- ATLAS/CMS beams cross at 285 μrad in vertical/horizontal plane → shifts far (near) location by 5.7 (2.1) cm
- HL-LHC: 285→590 μrad, TAN→TAXN moves forward 10 m,... We assume current parameters, FASER is exactly on-axis

LHC RING



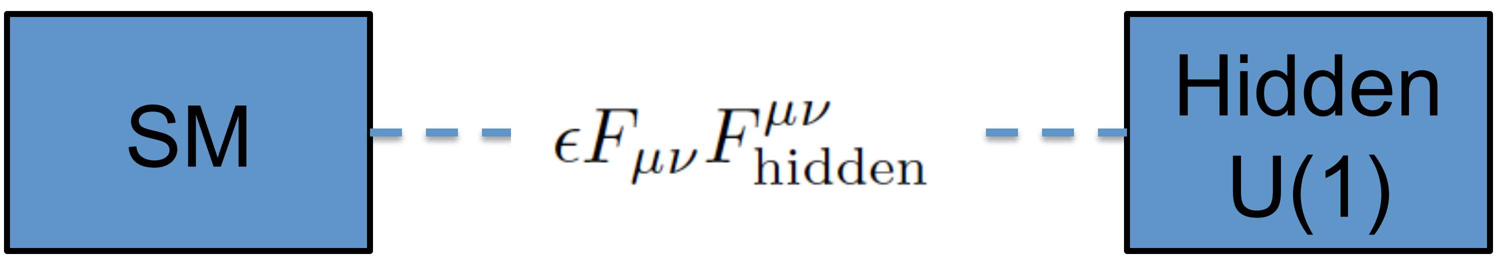
Point 1
Point 1.8
Point 2
Point 3.2
Point 3.3
Point 4
Point 5
Point 6
Point 7
Point 8
SPS
ATLAS
ALICE
CMS
LHC 'B'

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 mainly to e^+e^- (and $\mu^+\mu^-$ for $m_{A'} > 2\, m_\mu$)

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

- The essential tension: low ε → low event rate, high ε → decays too fast. Is there a happy middle ground?

DARK PHOTON STATUS

- Lots of unconstrained parameter space with

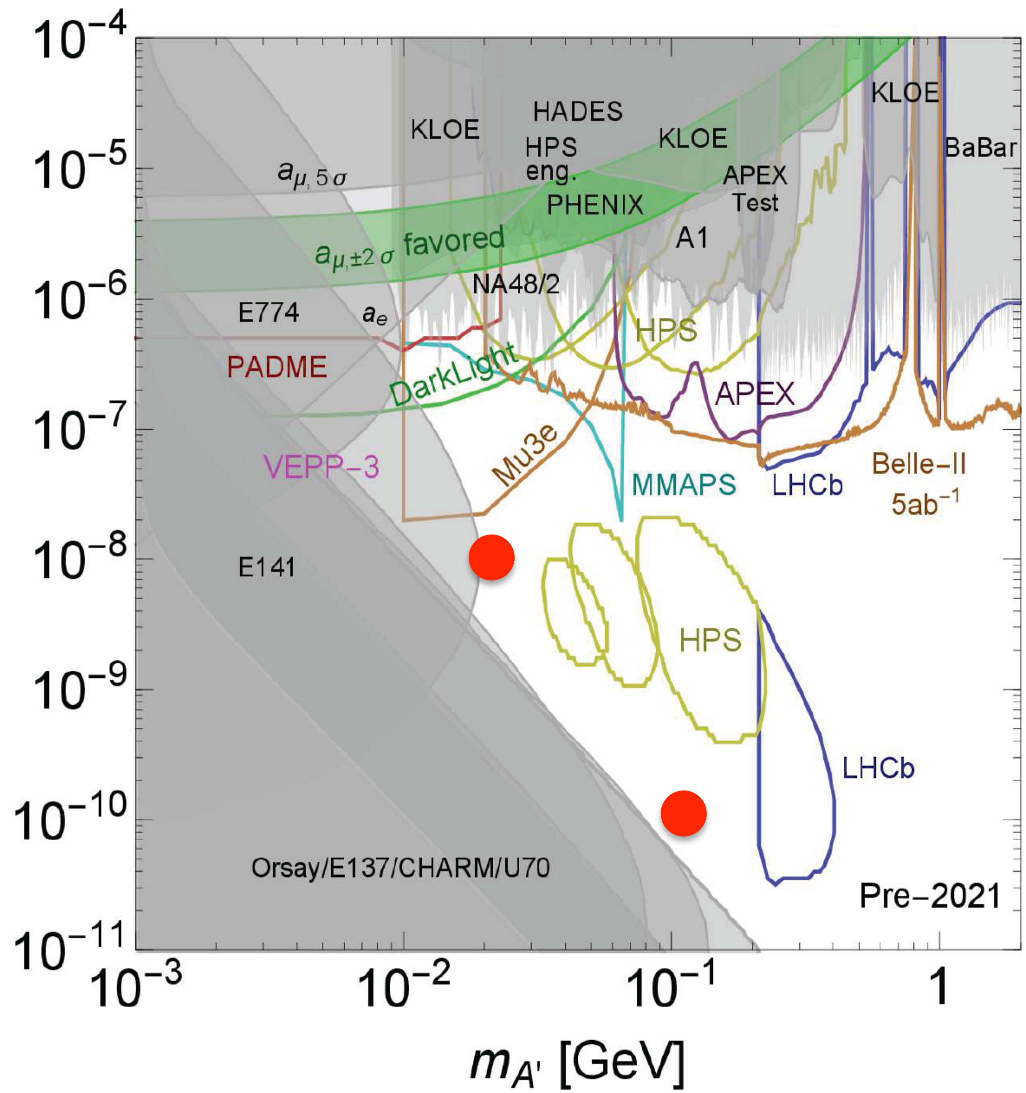
  $m_{A'} > 10$ MeV

  $\varepsilon \sim 10^{-6} - 10^{-3}$

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

  $(20\ \text{MeV}, 10^{-4})$

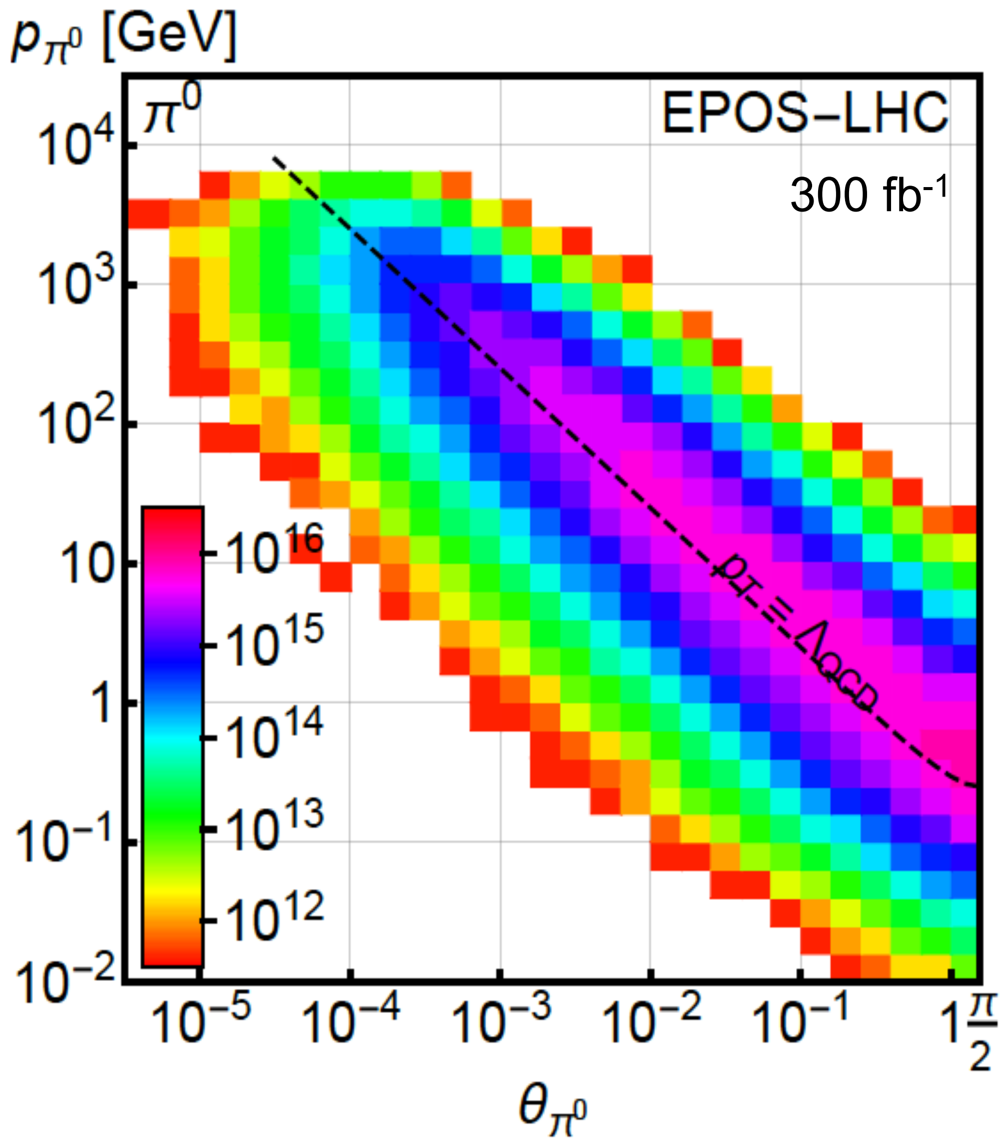
  $(100\ \text{MeV}, 10^{-5})$



Cosmic Visions White Paper (2017)

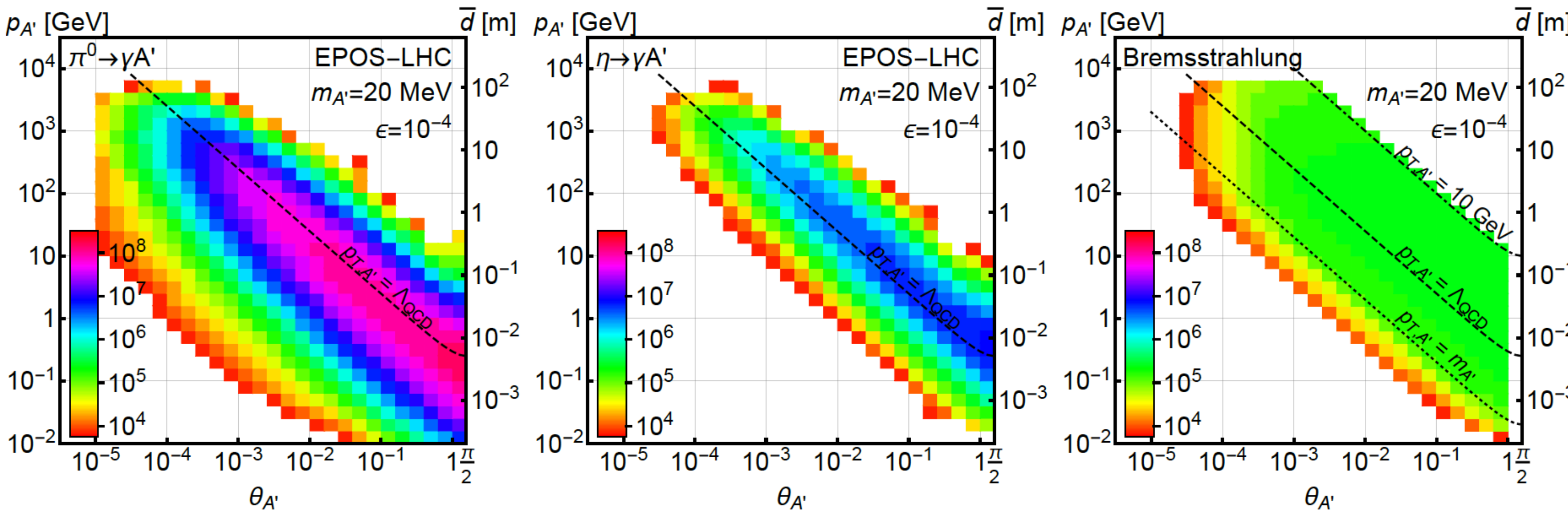
PION PRODUCTION AT THE LHC

- 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 $p_T \sim \Lambda_{QCD}$, but with significant width



DARK PHOTON PRODUCTION

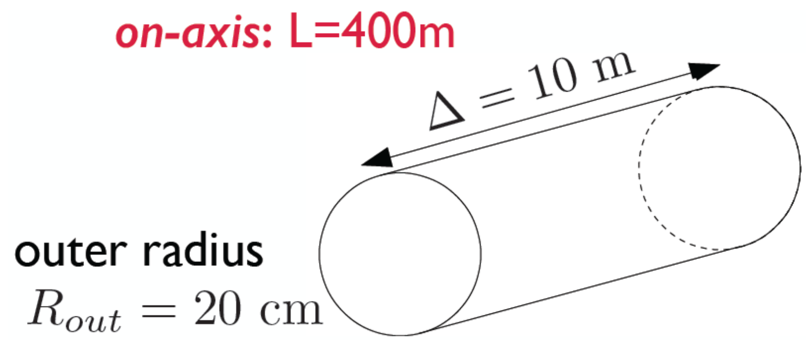
- Consider π^0 decay, η decay, dark bremsstrahlung
- Results for 1st model point: $(m_{A'}, \varepsilon) = (20\ \text{MeV}, 10^{-4})$

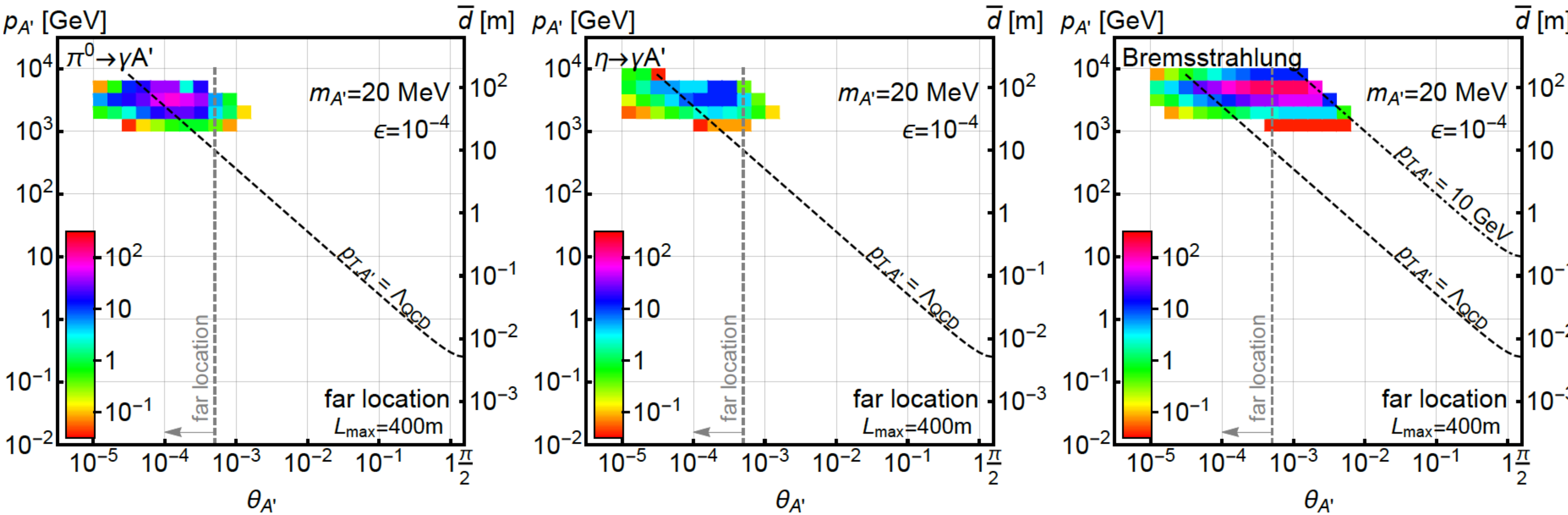


- From $\pi^0 \to \gamma A'$, $E_{A'} \sim E_\pi / 2$ (no surprise)
- But note rates: even after ε^2 suppression, $N_{A'} \sim 10^8$; LHC may be a dark photon factory!

DARK PHOTONS IN THE FAR DETECTOR

- Now require dark photons to decay in the far detector: consider cylindrical detector with volume ~1 m²

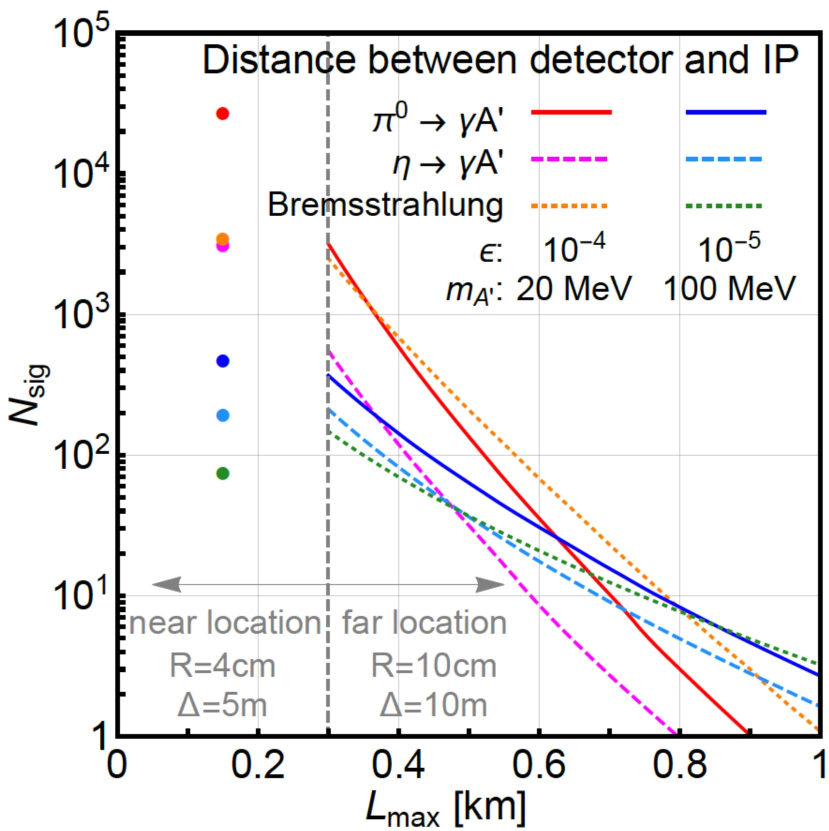


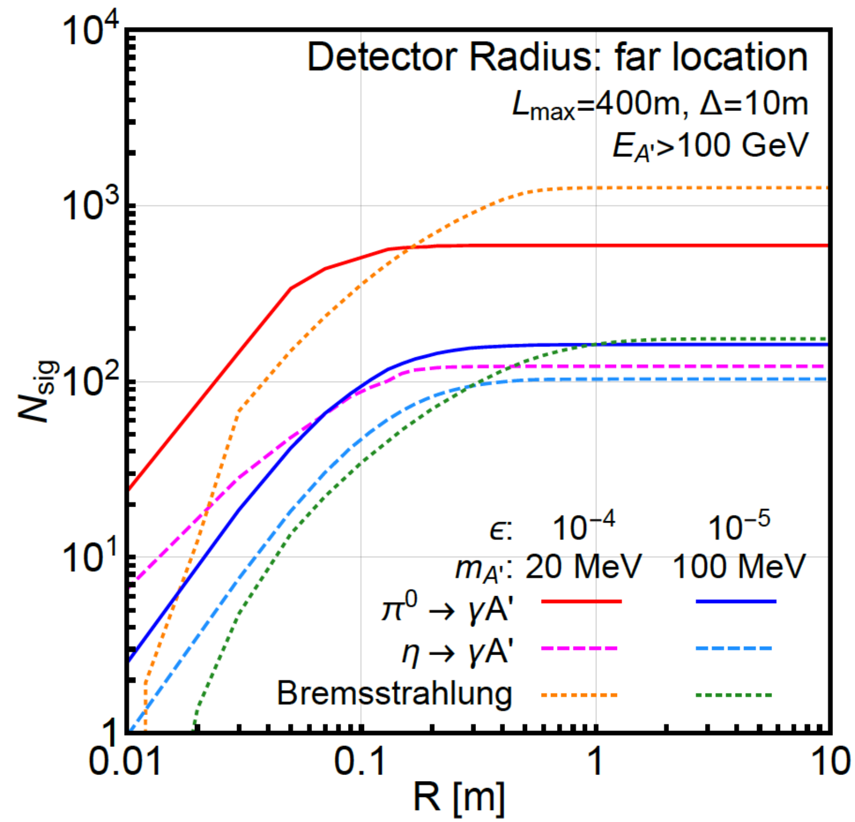


- Only the highest energy A's survive, but there are still many of them, and they are highly collimated

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'

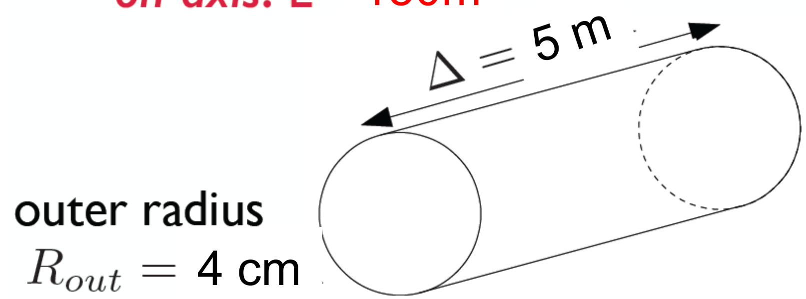


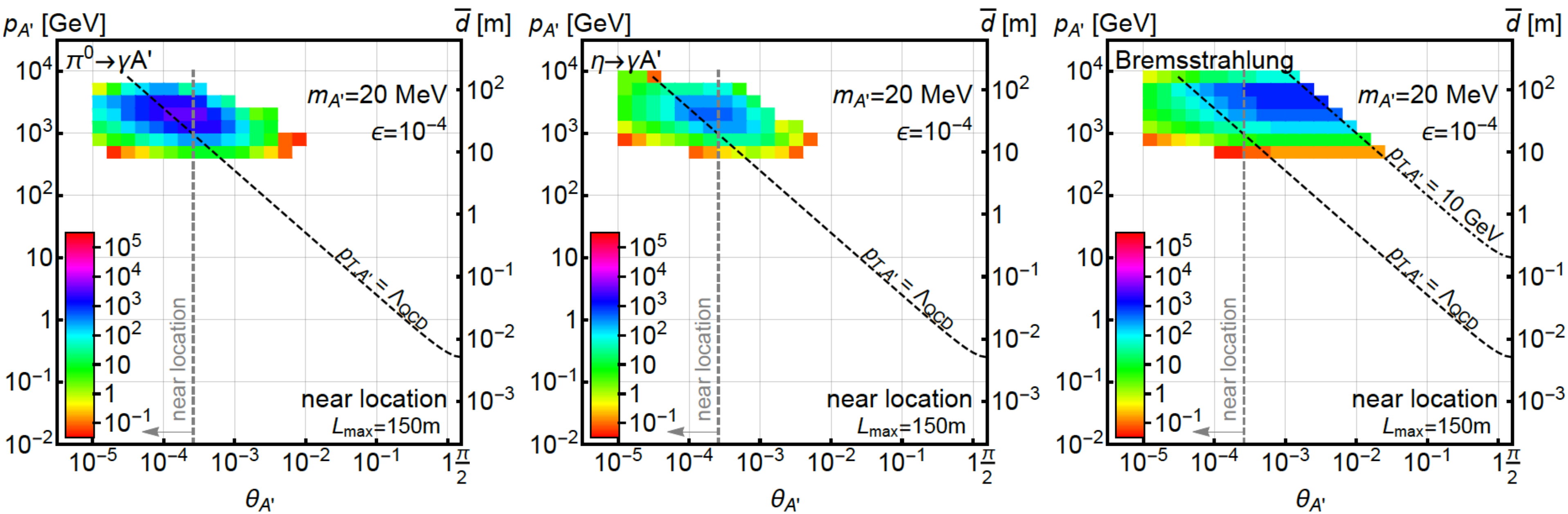


DARK PHOTONS IN THE NEAR DETECTOR

- Now require dark photons to decay in the near detector: detector volume only ~0.1 m^2 !

on-axis: L= 150m





- Moving the detector closer → more dark photons decay in the detector, even though the near detector is much smaller

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

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

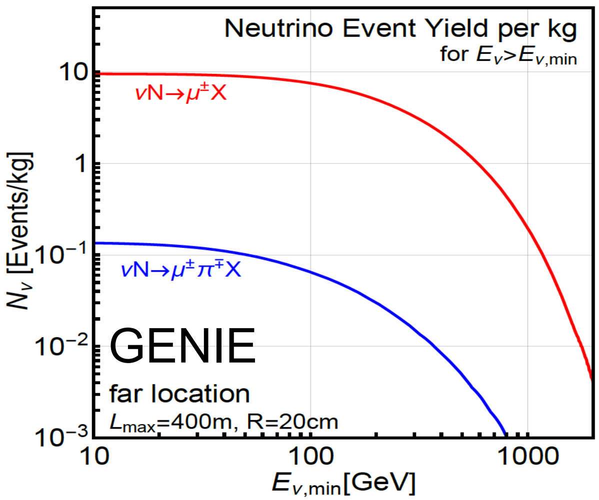
- Many backgrounds are eliminated simply by virtue of FASER's location. Cosmic ray background is negligible, charged particles from IP are bent away by D1 magnet

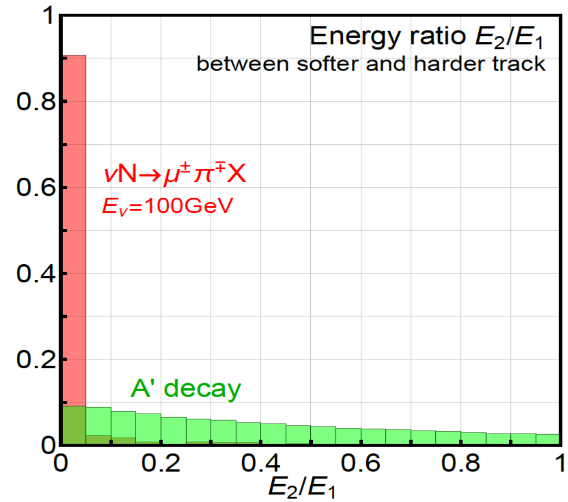
- Leading backgrounds: neutrino-induced backgrounds and beam-induced backgrounds

NEUTRINO-INDUCED BACKGROUNDS

- If $\pi^+ \rightarrow \mu\nu$ before D1 magnet, resulting neutrinos can propagate into FASER, interact through

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





- Coincident single tracks that fake double tracks: negligible
- Second process eliminated by requiring no other activity, tracks start in the detector and have high and symmetric energies
- $\nu \rightarrow K_{S,L} \rightarrow$ 2 charged tracks also negligible with same cuts

BEAM-INDUCED BACKGROUNDS: FAR LOCATION

- Depends on exact configuration. At 400m, line of sight is 2.6 m from beam, outside tunnel. With sufficient shielding, hadrons, electrons are stopped, only muons are relevant

- A 2013 ATLAS study based on 2011 data can be used to determine muon background at far location. Requiring E_μ > 100 GeV, the flux is

$$\Phi \sim 10^{-3} \text{ Hz cm}^{-2}$$

- The muon arrival times correspond to bunch crossings. Accounting for the bunch structure and assuming a timing resolution of 100 (10) ps, get ~0.1 (~0.01) coincident $\mu^+\mu^-$ pairs in 1 LHC year

- No significant backgrounds identified for far location

BEAM-INDUCED BACKGROUNDS: NEAR LOCATION

- Far more challenging environment
- Dedicated simulation using MARS/FLUKA/etc. should be used, but we can use published results to get an estimate

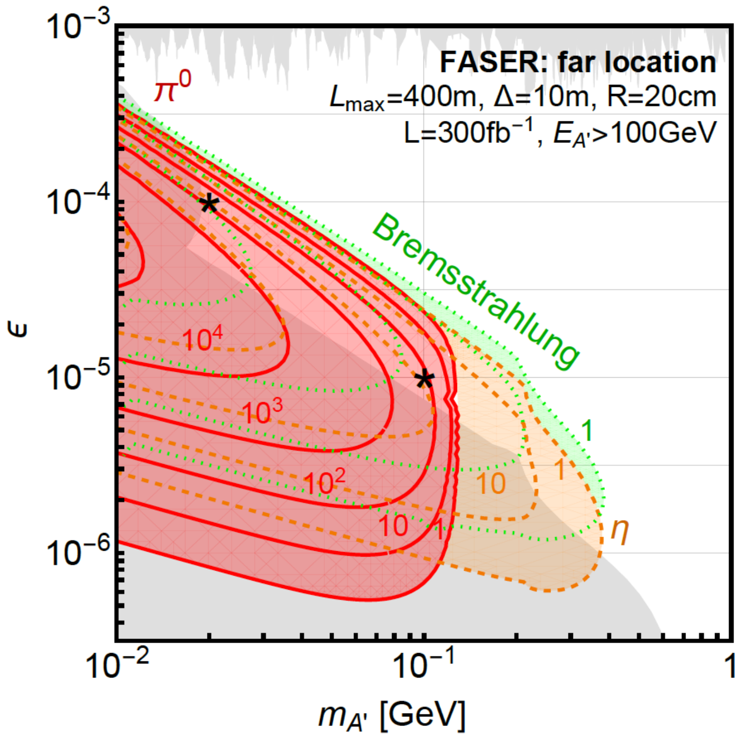
Mokhov, Rakhno, Kerby, Strait (2003)

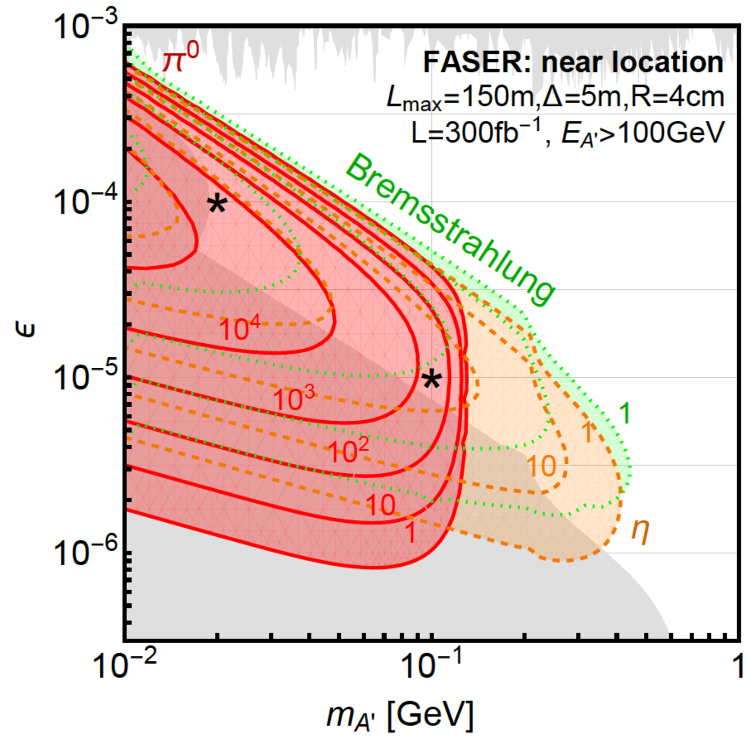
- Hadrons and electrons absorbed in the TAN
- Coincident muon background ~10^8 per LHC year. Can be greatly suppressed by requiring tracks to start in the detector and reconstruct a vertex, and requiring high and symmetric energies
- Electron background greatly reduced if electrons can be distinguished from muons

DARK PHOTON EVENT RATES

- Up to 10^5 dark photons arrive in FASER in 300 fb^{-1} in currently unconstrained regions of dark photon parameter space

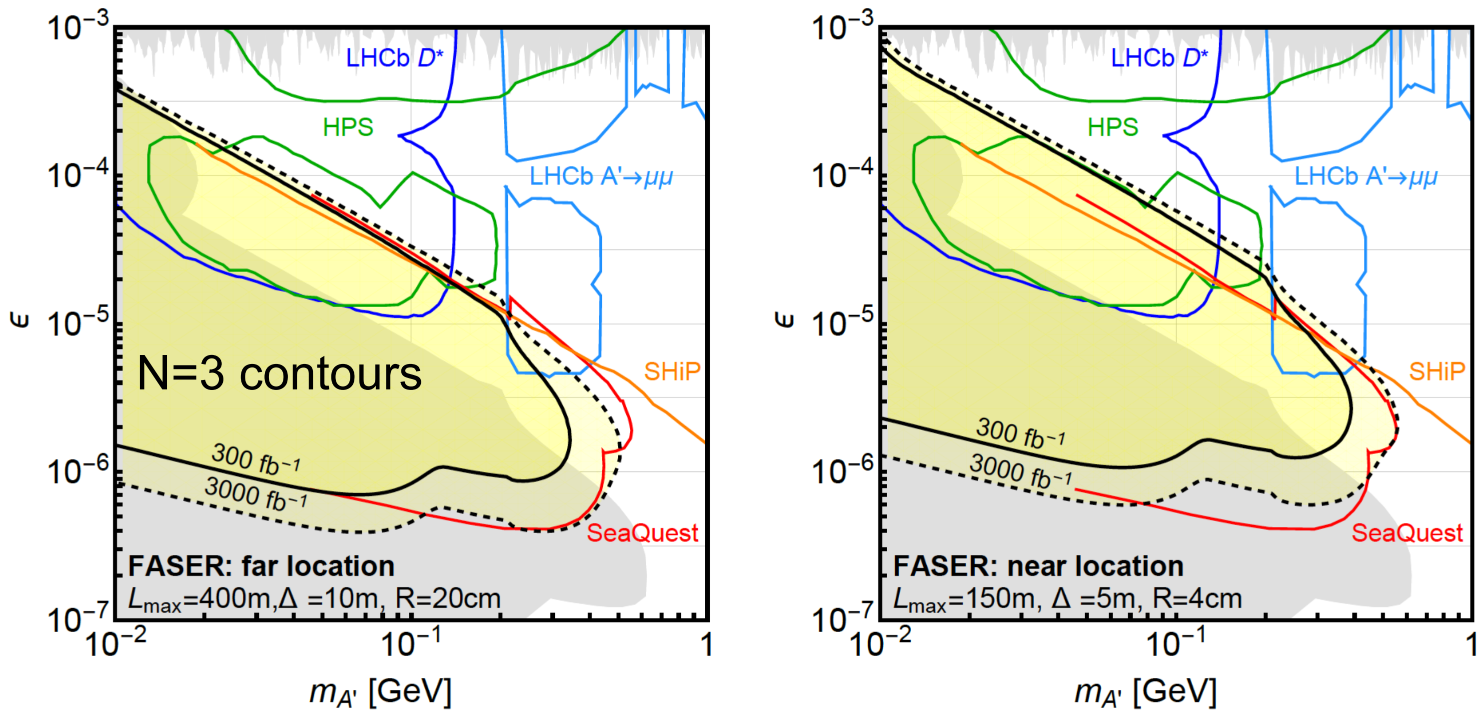
$$pp \to A' X \,, \quad A' \text{ travels } \sim \mathcal{O}(100) \text{ m} \,, \quad A' \to e^+e^-, \, \mu^+\mu^-$$





DARK PHOTON REACH

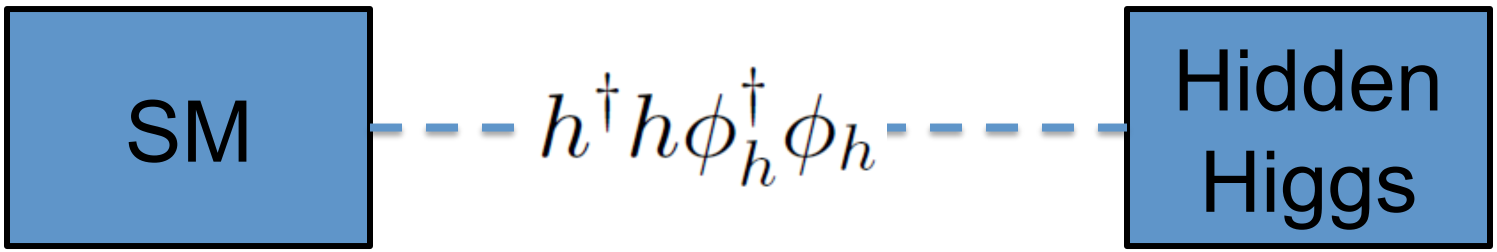
- Assuming negligible background, FASER may probe parameter space with $m_{A'} \sim 10$ - 500 MeV, $\varepsilon \sim 10^{-6} - 10^{-3}$



- SHiP much more sensitive at very low ε, but much of this is excluded already. SHiP reach at high $m_{A'}$ is from direct QCD production, which we have neglected

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

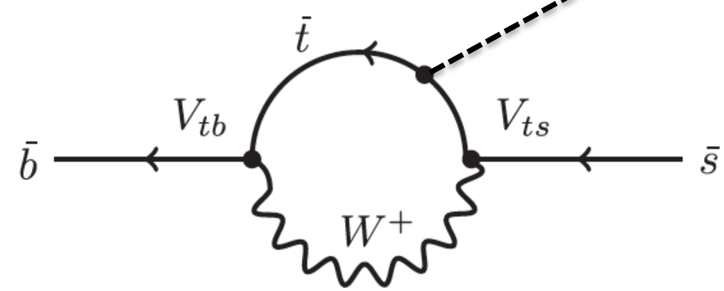
$$\mathcal{L} = -m_\phi^2 \phi^2 - \sin\theta \, \frac{m_f}{v} \, \phi \bar{f} f - \lambda v h \phi \phi + \ldots$$

DARK HIGGS PROPERTIES

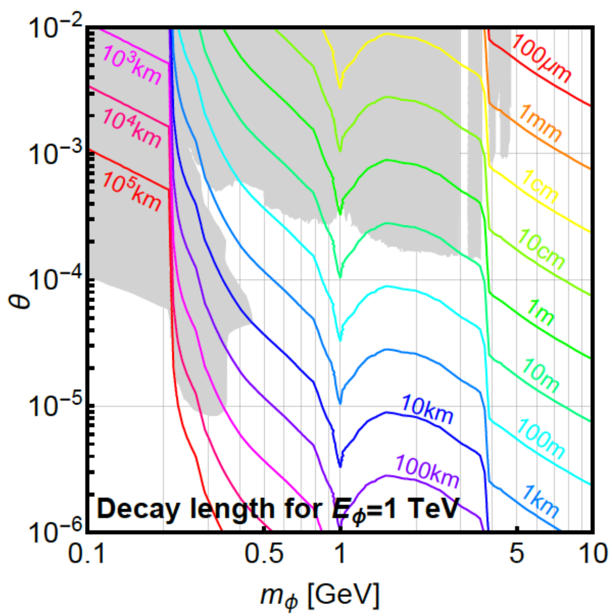
- $N_B << N_K \sim N_\pi$, but dark Higgs couples to mass, so

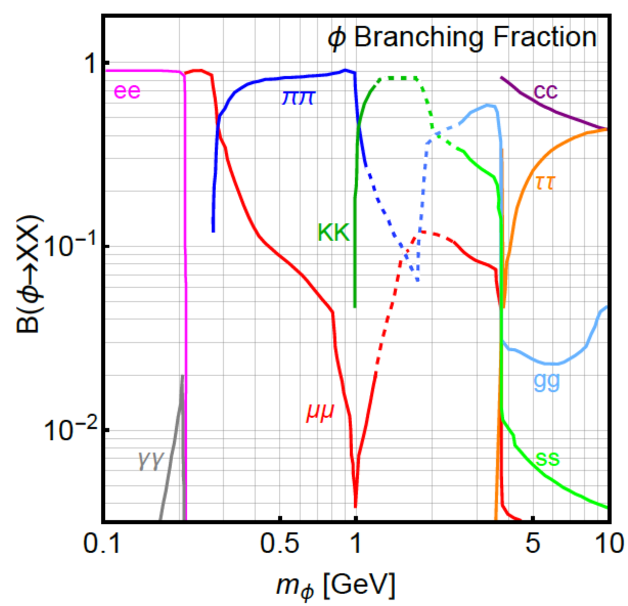
$$B(B \to \phi) \gg B(K \to \phi) \gg B(\eta, \pi \to \phi)$$

Turns out B and K are similar and the dominant sources of dark Higgses

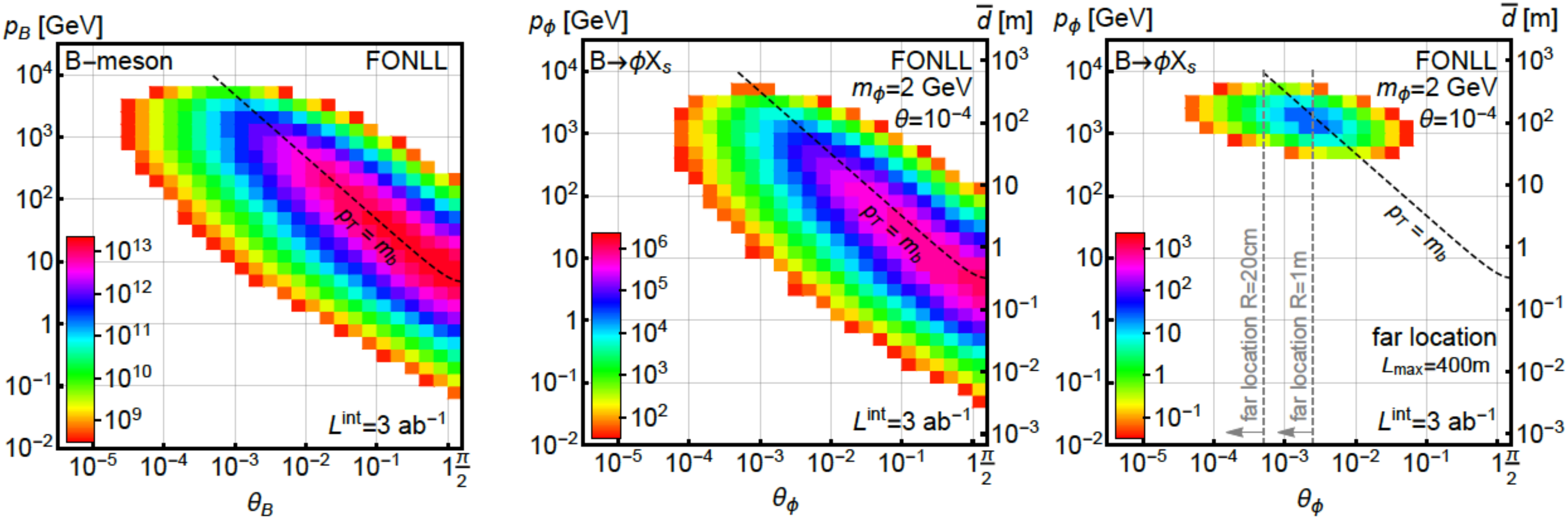


- Decays to heaviest possible states

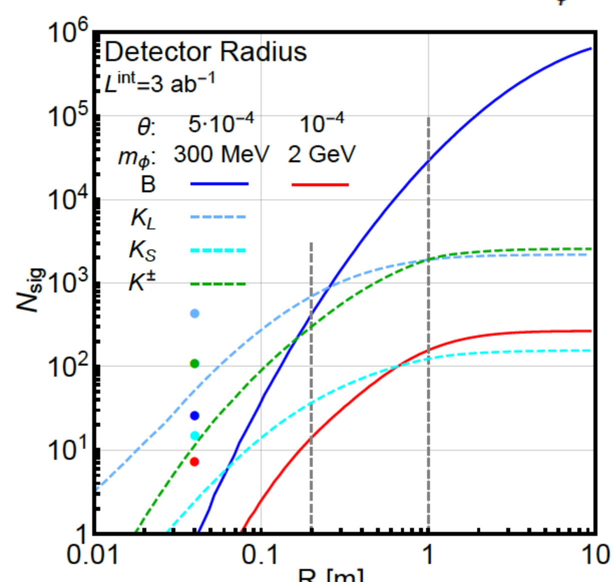




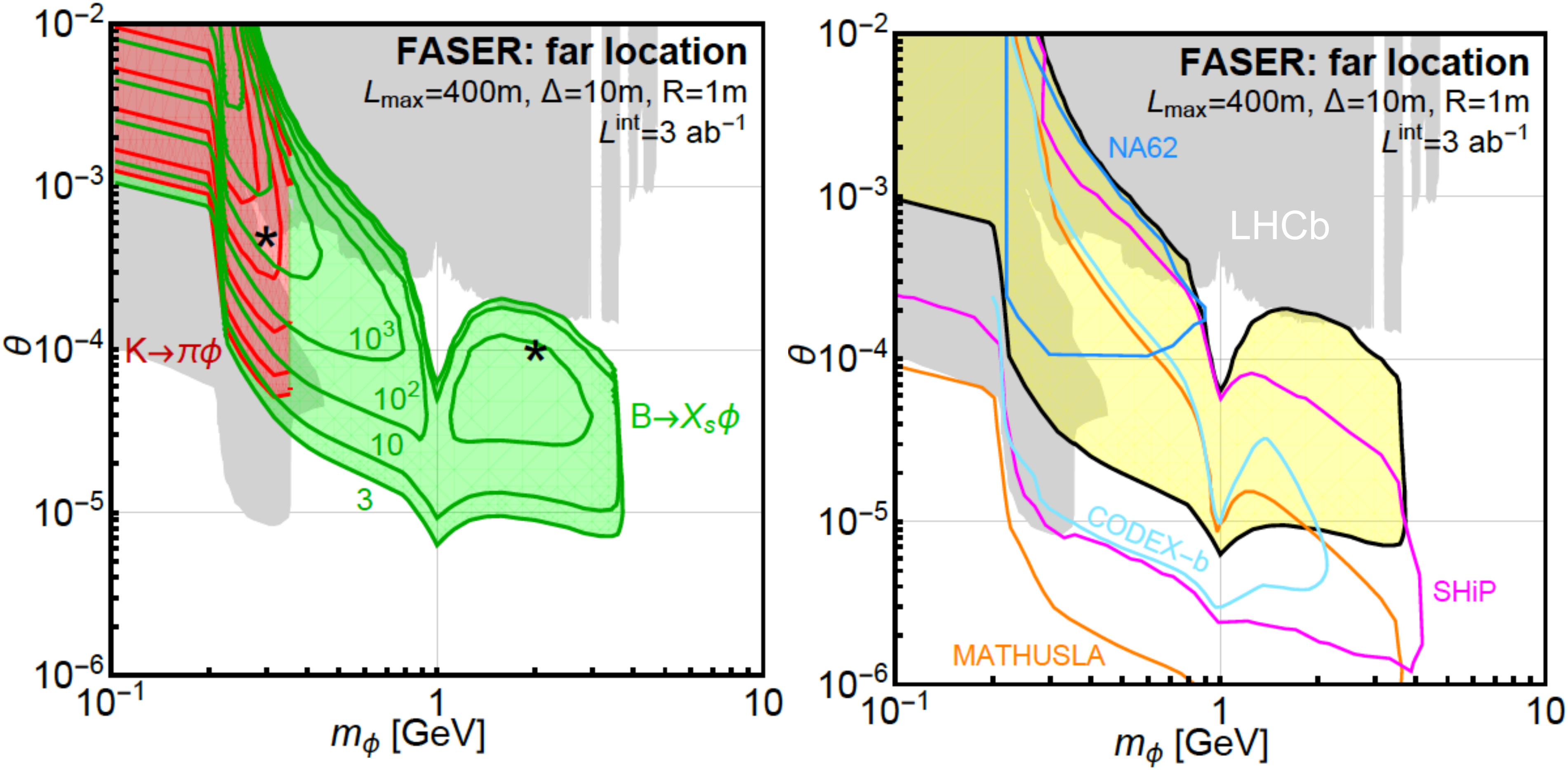
B MESON AND DARK HIGGS PRODUCTION



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



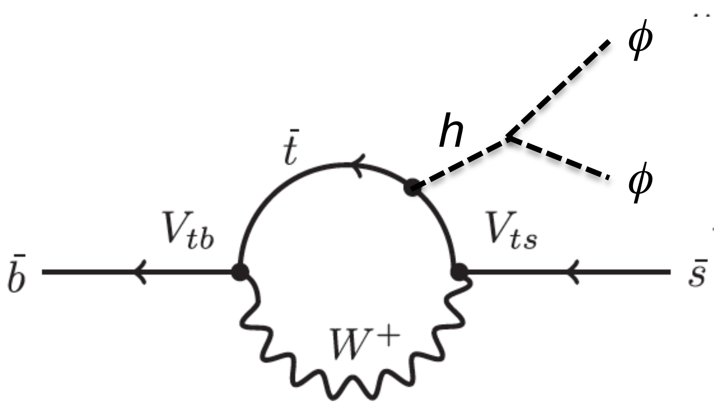
DARK HIGGS EVENT RATES AND REACH

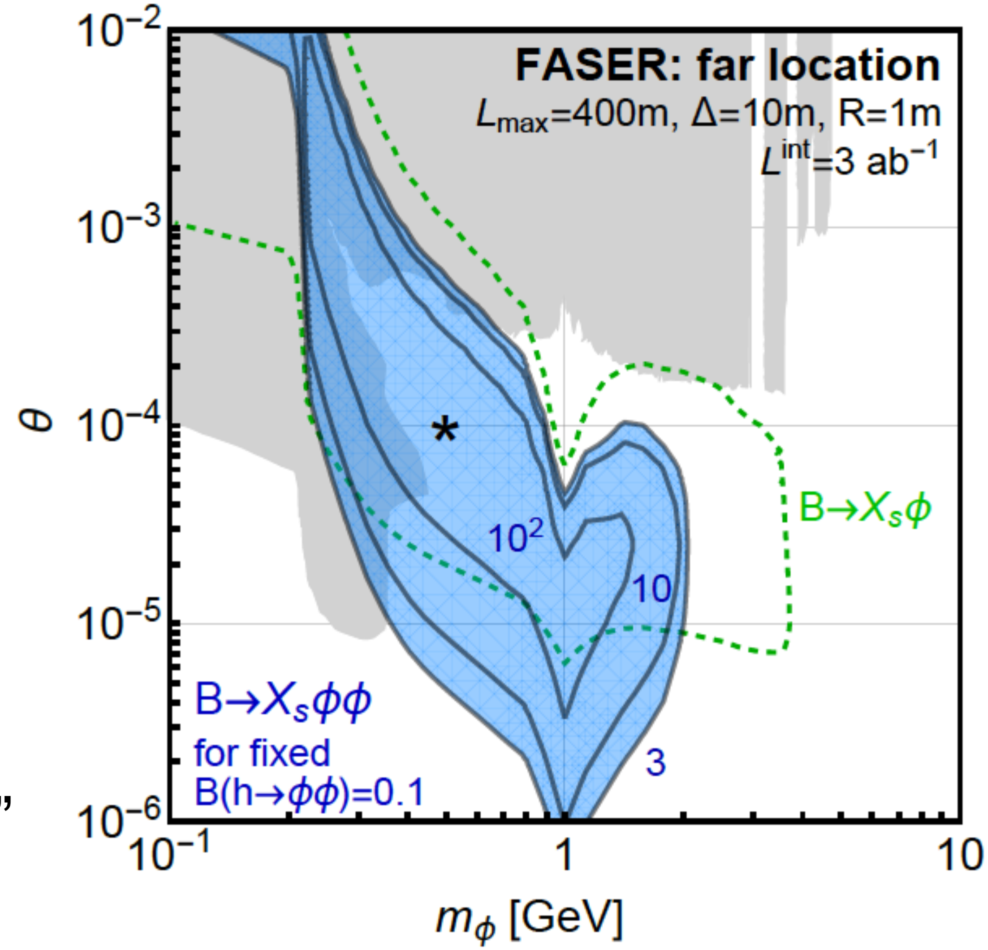


- FASER probes a large swath of new parameter space and is complementary to other current and proposed experiments

TRILINEAR COUPLINGS REACH

- FASER can also probe the trilinear couplings through



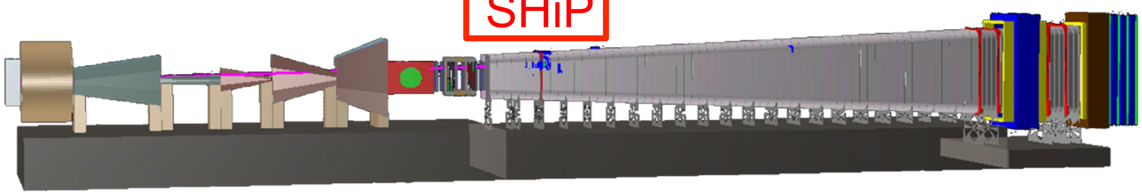


- This competes with
  h → ϕϕ (invisible)

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

COMPLEMENTARY PROPOSED EXPERIMENTS

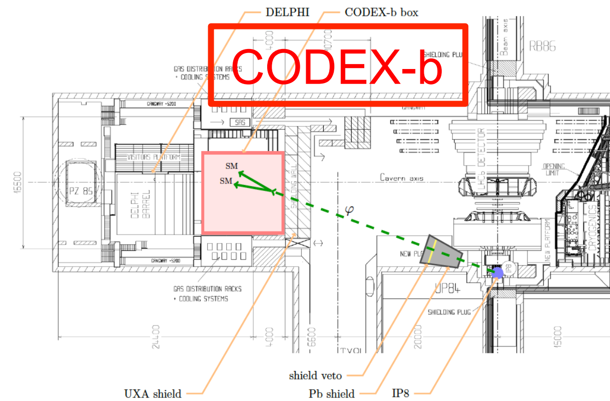
SHiP



~1000 m^3, ~100M CHF

Alekhin et al. (2015)

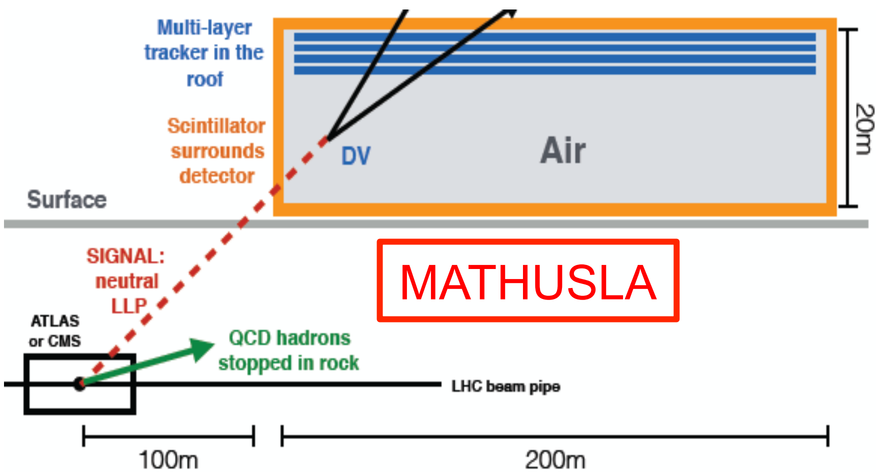
CODEX-b



~1000 m^3

Gligorov, Knapen, Papucci, Robinson (2017)

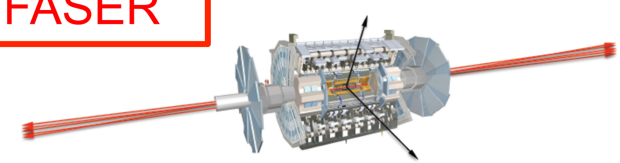
MATHUSLA



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

Chou, Curtin, Lubatti (2016)

FASER



~1 m^3 ~ 5 μIKEAs

Feng, Galon, Kling, Trojanowski (2017)

SUMMARY AND OUTLOOK

- The LHC has seen no new physics. Adding inexpensive, small detectors to improve discovery prospects is a good idea
- FASER: targets light, weakly-coupled new particles at low p_T, runs simultaneously with ATLAS/CMS, and is small and inexpensive
- No significant backgrounds identified for the far location; near location requires more study
- FASER will probe significant new regions of dark photon and dark Higgs parameter space. Other models?
- Much work to do. Possible timeline: install prototype in LS2, install full detector in LS3 in time for the HL-LHC era