FASER

FORWARD SEARCH EXPERIMENT AT THE LHC

International Workshop on WIMP Dark Matter and Beyond

Shanghai Jiao Tong University

Jonathan Feng, UC Irvine

[based on 1708.09389 with Iftah Galon, Felix Kling, Sebastian Trojanowski]

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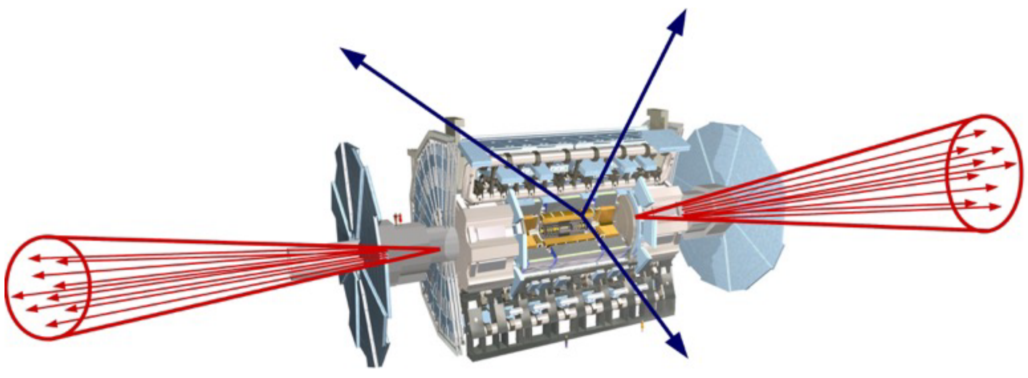
SUMMARY

- New physics searches at the LHC focus on high p_T. This is appropriate for heavy, strongly coupled particles
  - σ ~ fb to pb → N ~ 10^3 – 10^6, produced isotropically
- However, if new particles are light and weakly coupled, 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, ~150-400 m downstream of the IP, and analyze its discovery potential

OUTLINE

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

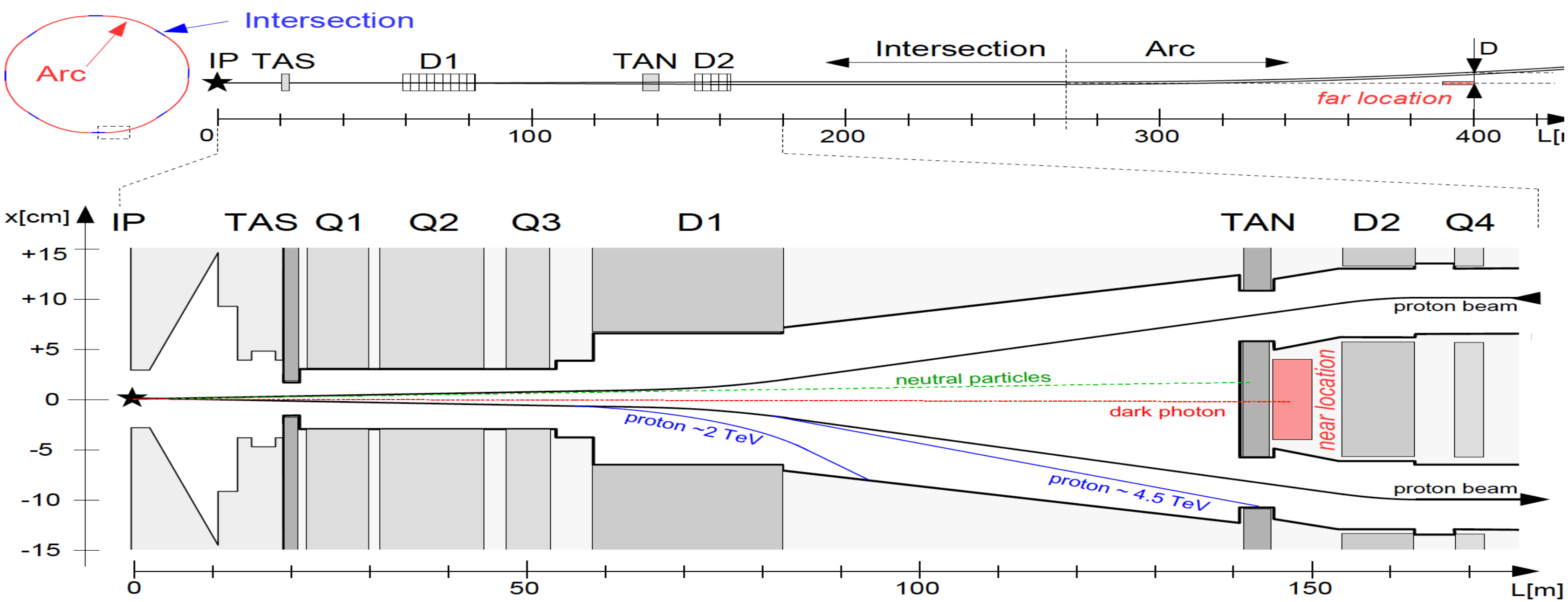
VERY FORWARD REGION INFRASTRUCTURE

- LHC ring consists of 8 straight 545 m intersections and 8 curved arcs. The infrastructure common to IP1 and IP4 (also have ALFA, CASTOR, LHCf, TOTEM, etc.):

TAS: front quadrupole absorbers (θ > 0.85 mrad)

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

TAN: neutral target absorbers (n, γ)

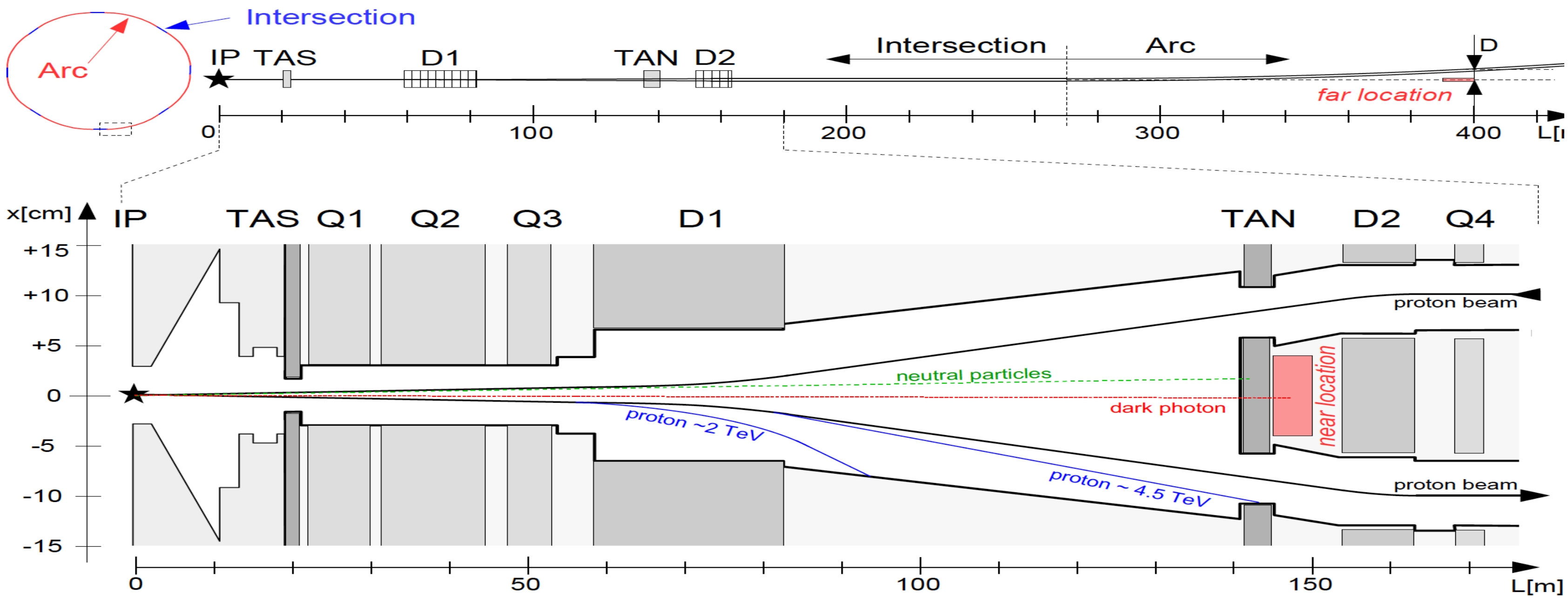


Feng, Galon, Kling, Trojanowski (2017)

Note the extreme difference in longitudinal and transverse scales

ON-AXIS LOCATIONS

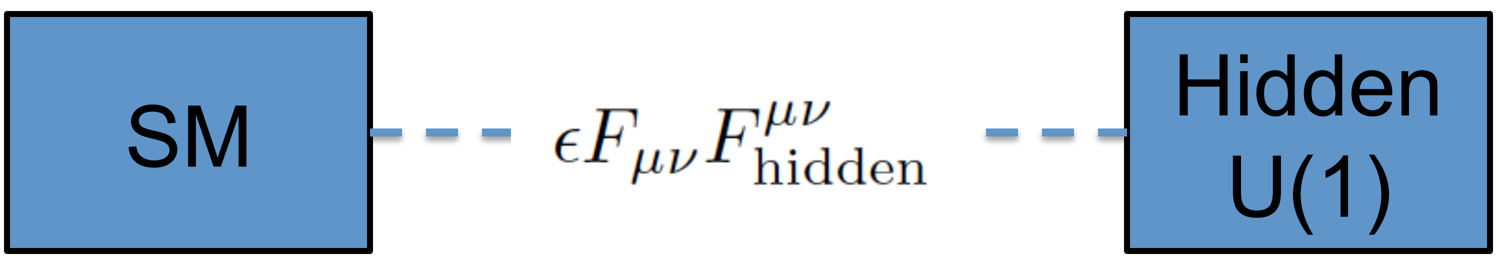
- We want to place FASER along the beam *collision* axis
  - Far location: 400 m from IP, after beams curve, 2.6 m from the beams
  - Near location: 150 m, after TAN, between the beams



- 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

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: 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

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

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

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

- 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

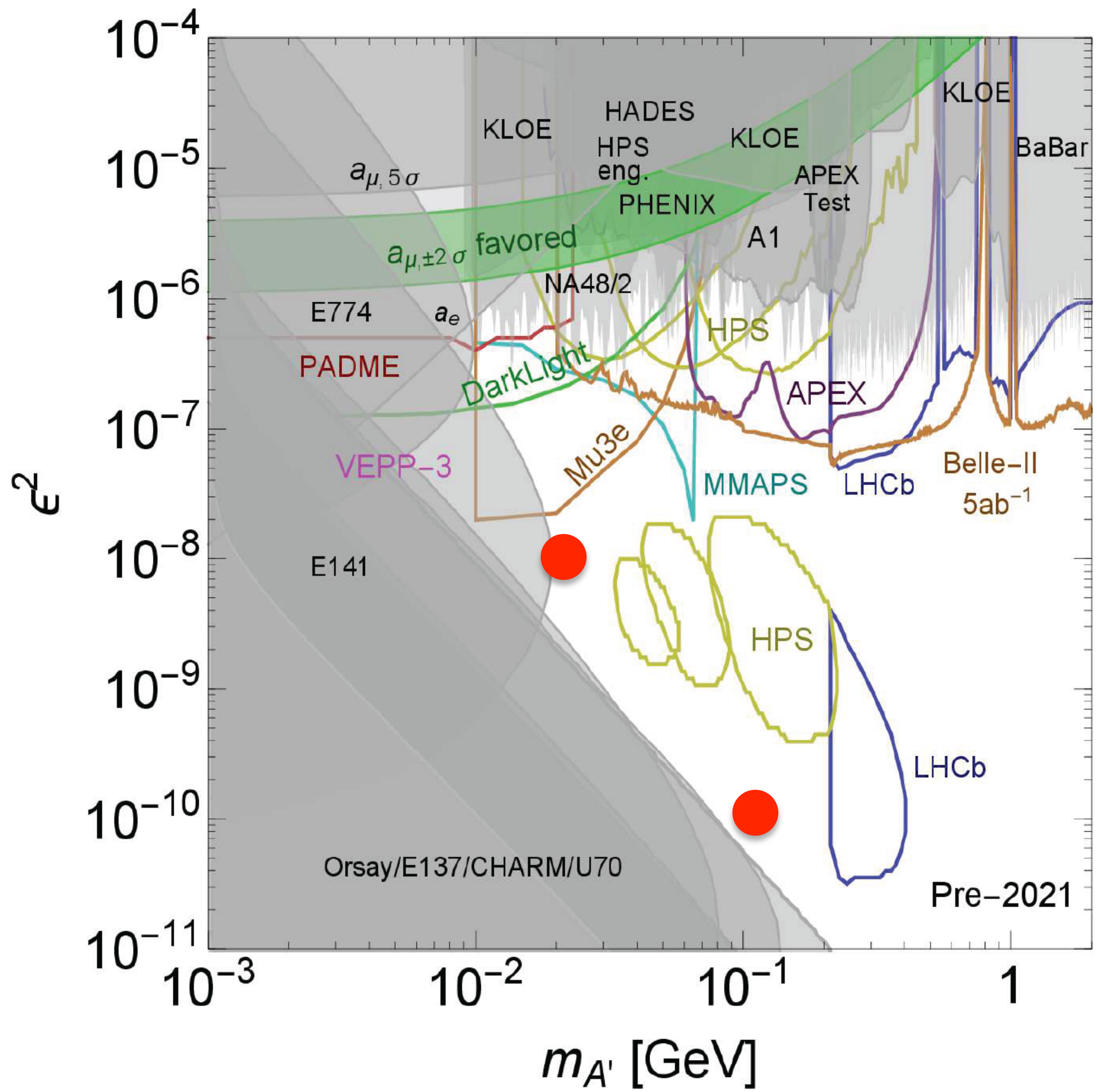
  $m_{A'} > 10$ MeV

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

- We will present results for 2 representative model points: $(m_{A'}, \varepsilon)$ =

  (20 MeV, 10^{-4})

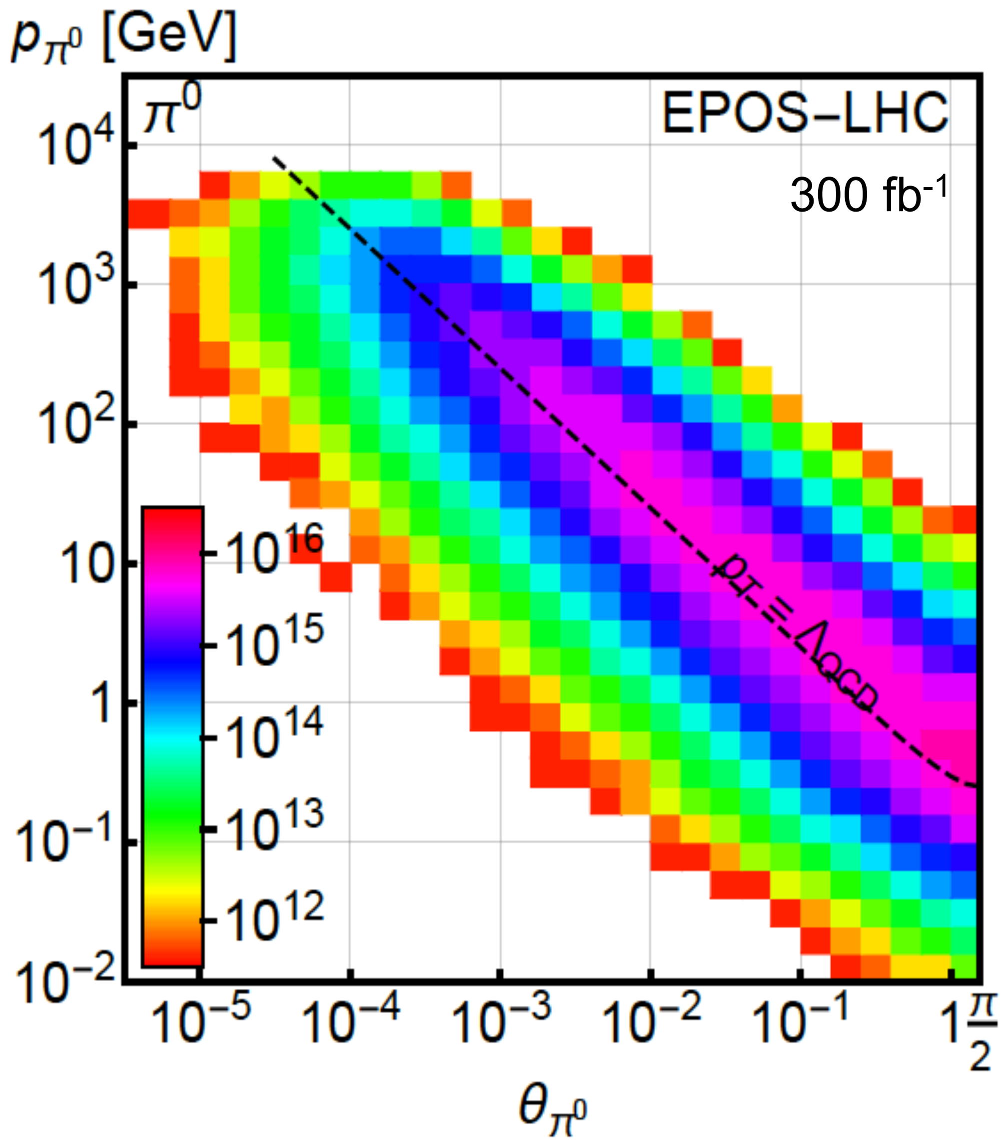
  (100 MeV, 10^{-5})



Cosmic Visions White Paper (2017)

PION PRODUCTION AT THE LHC

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

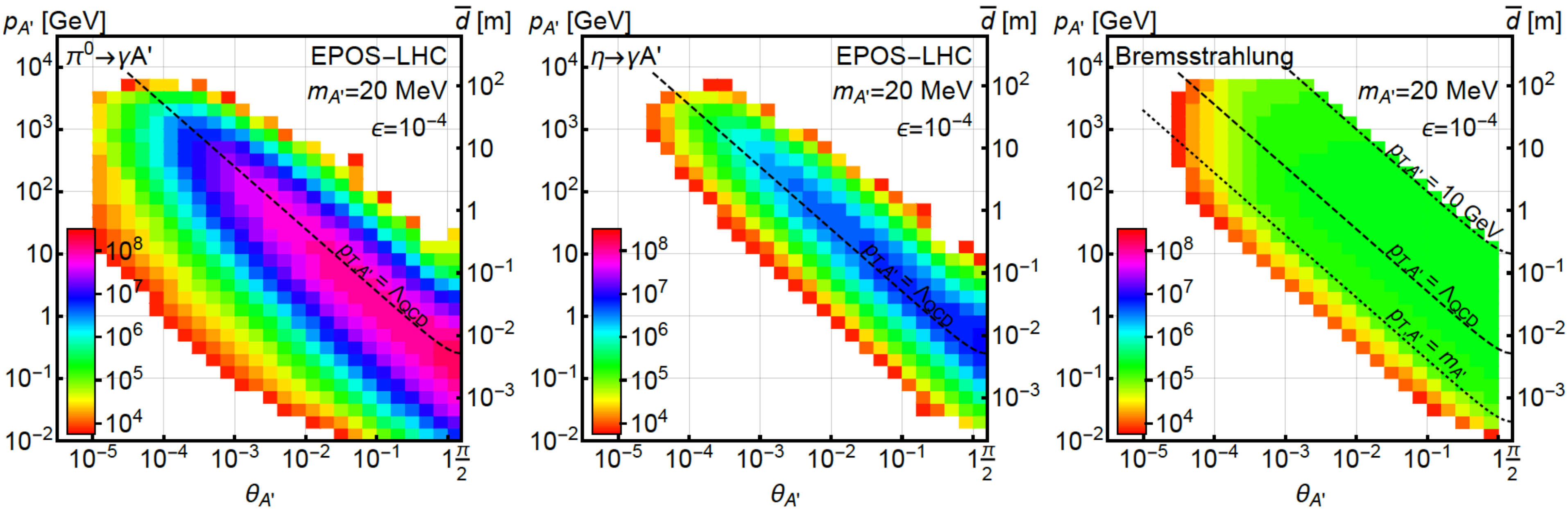


DARK PHOTON PRODUCTION

- Consider π^0 decay, η decay, dark bremsstrahlung

- Results for 1st representative model point:

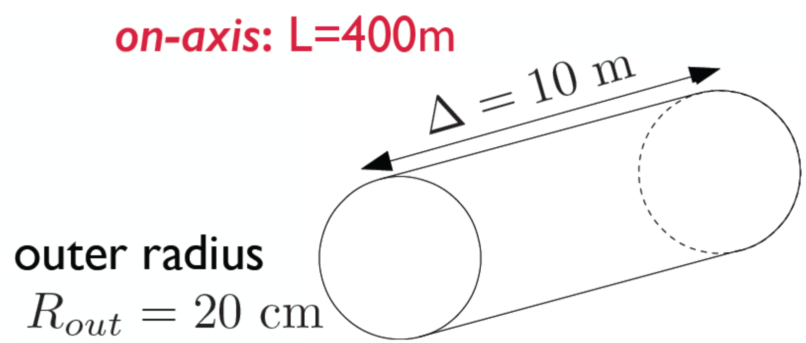
$$(m_{A'}, \varepsilon) = (20 \text{ MeV}, 10^{-4})$$

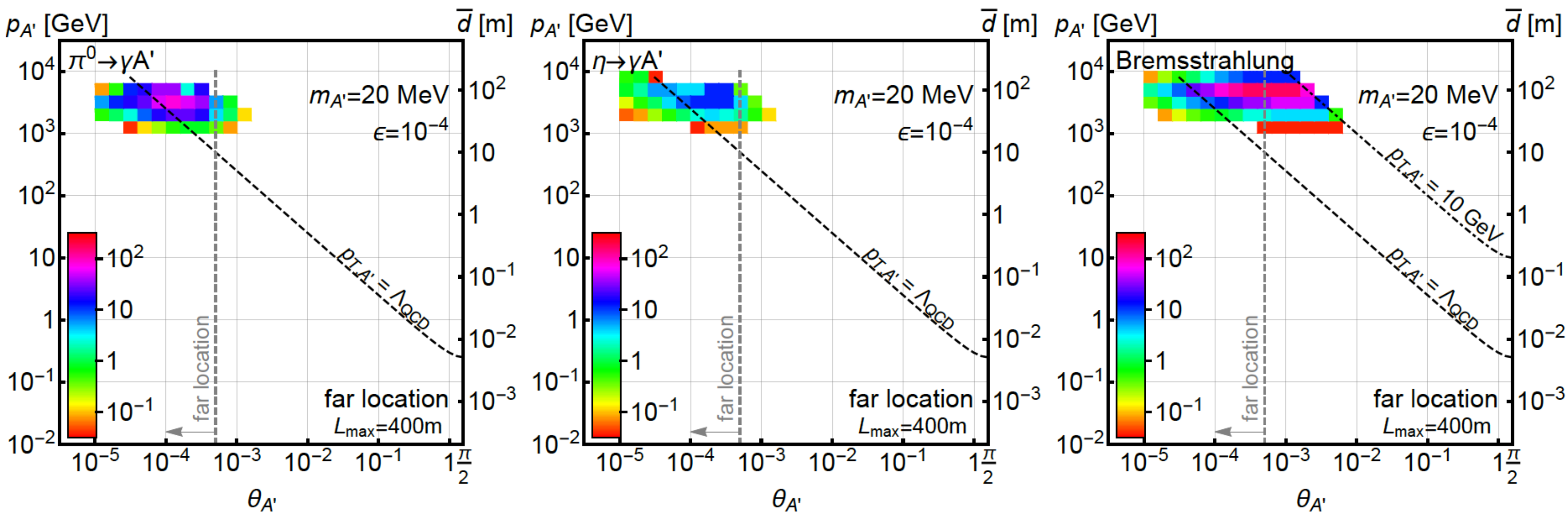


- Nothing surprising: in $\pi^0 \to A' \gamma$, relative to pion distributions, rates suppressed by ε^2, energies reduced by factor of ~2

DARK PHOTONS IN THE FAR DETECTOR

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

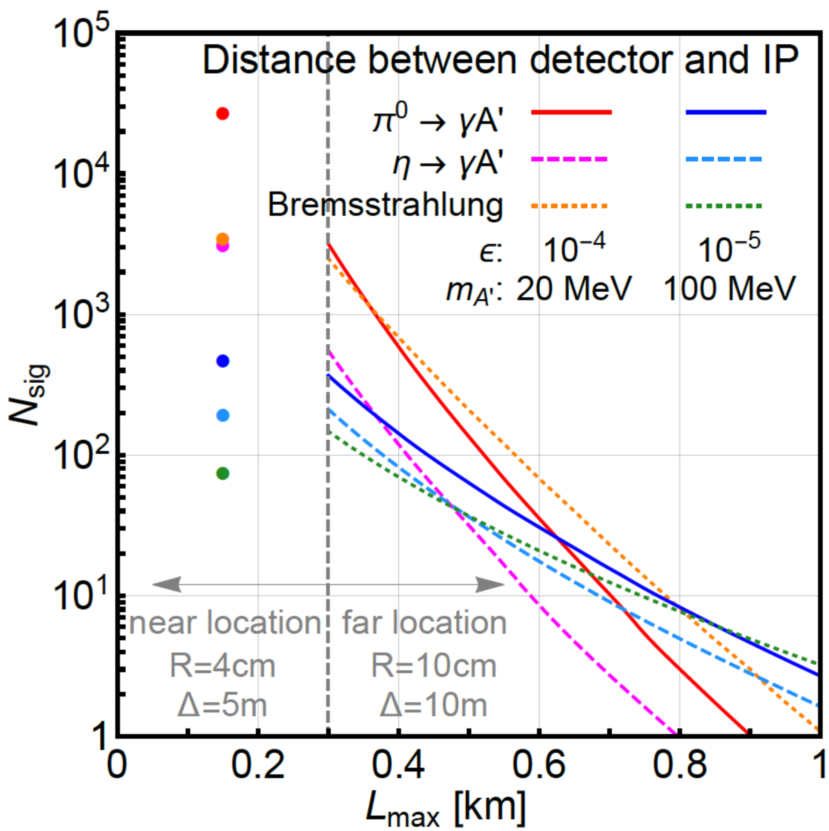




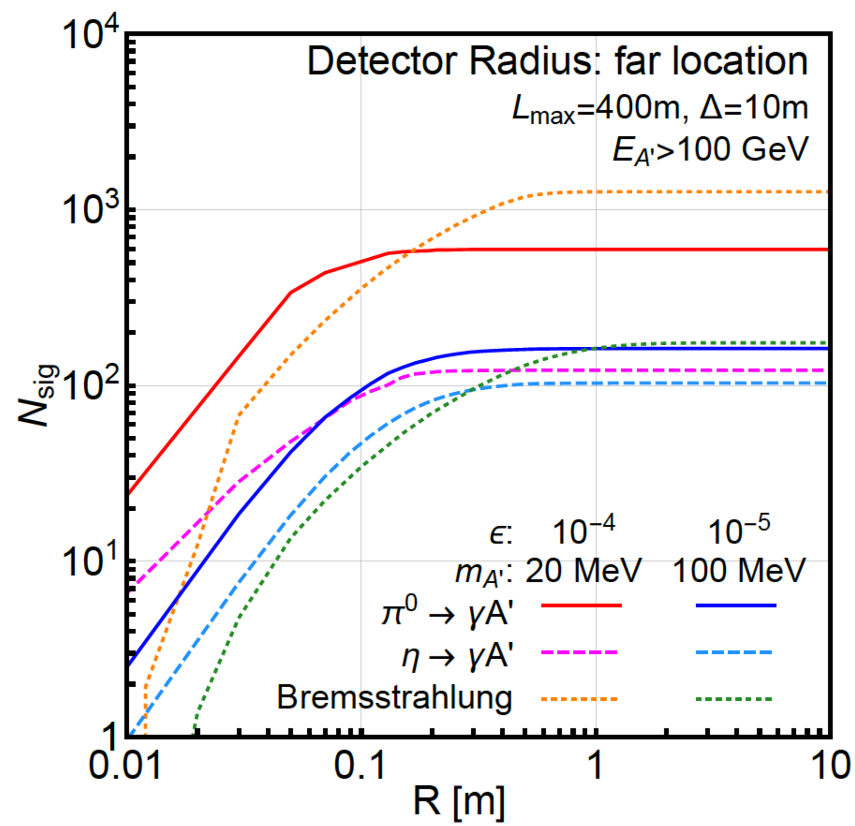
- Only the highest energy A's survive, but there are still many of them, and they are highly collimated

SIGNAL DEPENDENCE ON DETECTOR SPECS

- Moving the detector closer helps

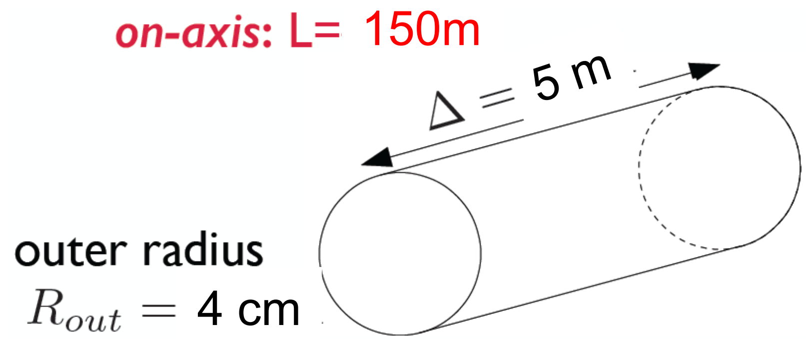


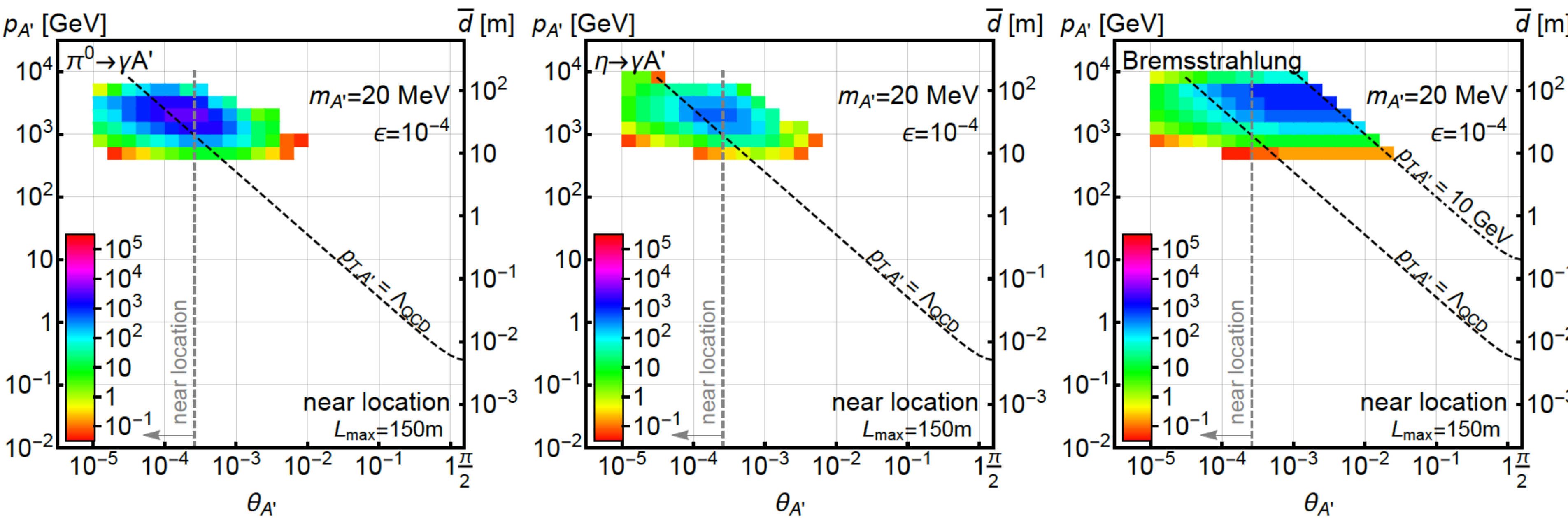
- At the far location, R = 20 cm captures almost all the A'



DARK PHOTONS IN THE NEAR DETECTOR

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





- Moving the detector closer → more dark photons decay in the detector, even though the after-TAN location is crowded

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 $\theta_{ee} \sim m_{A'} / E \sim 10$ μrad. After traveling ~ 1 m, this leads to 10 μm separation, too small to resolve → 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

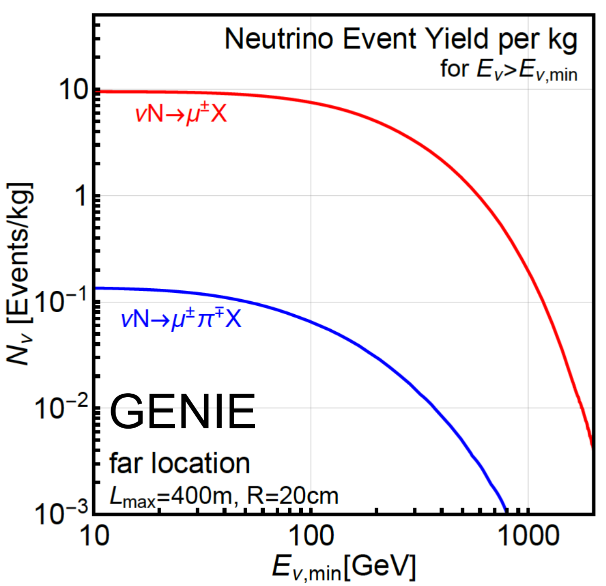
- Leading backgrounds are neutrino-induced and beam-induced backgrounds

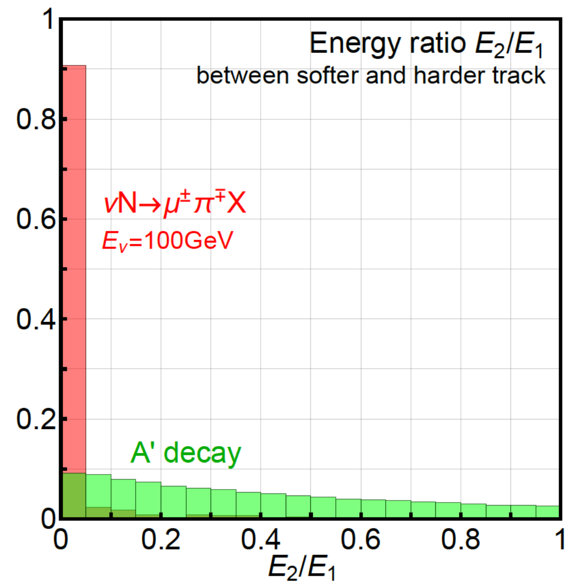
NEUTRINO-INDUCED BACKGROUNDS

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

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

- 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

- Particles from IP must pass through ~ 50 m of matter. Hadrons, electrons are stopped, only muons are relevant
- Muon background from 2011 ATLAS study can be used to determine muon background at far location. Requiring E_μ > 100 GeV, the flux is

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

- 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
- Far location appears to be background-free

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

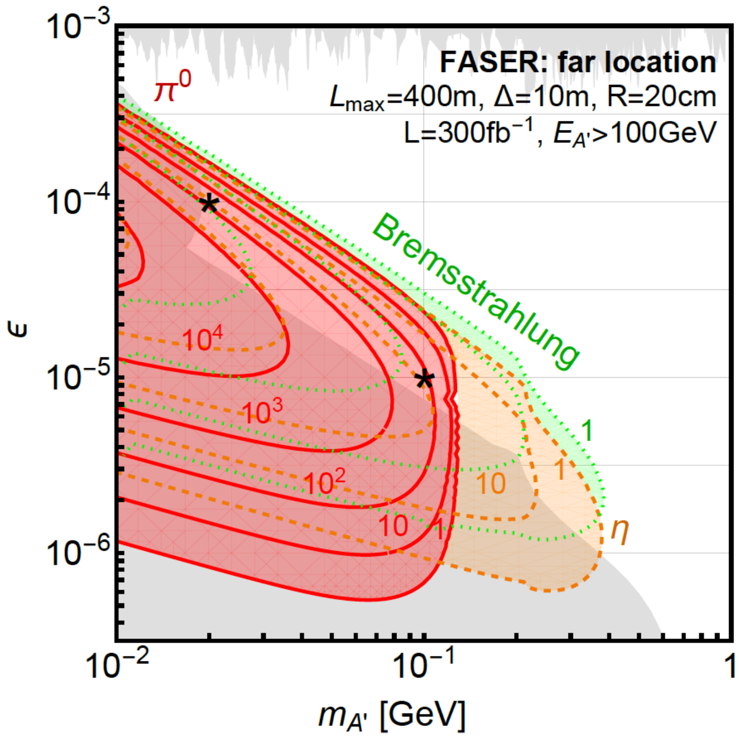
Mokhov, Rakhno, Kerby, Strait (2003)

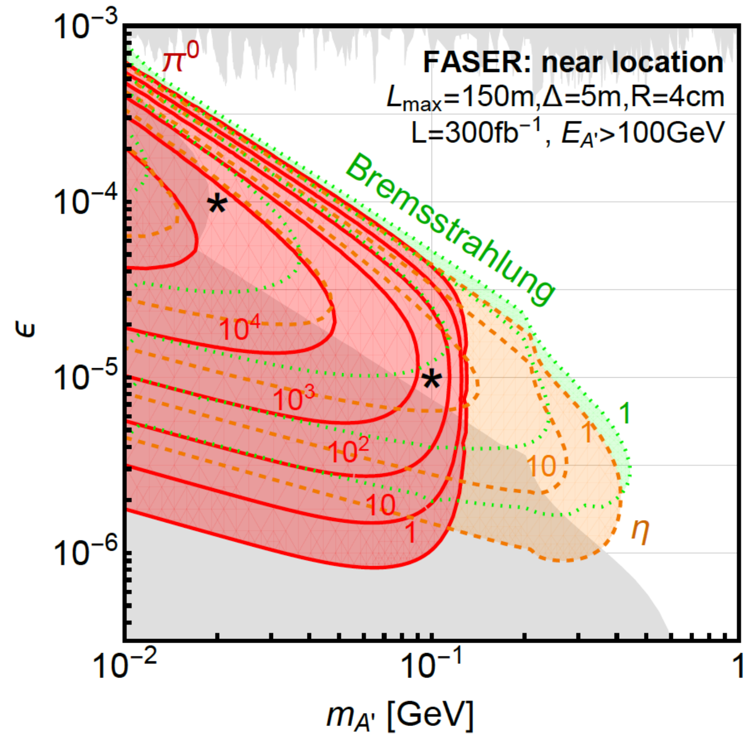
- Hadrons and electrons absorbed in the TAN
- Coincident muon background ~10^8 per LHC year. Can be greatly suppressed by requiring tracks to start in the detector and reconstruct a vertex, and requiring high and symmetric energies
- Electron signal is clean if electrons can be distinguished from muons

RESULTS: EVENT RATES

- Up to 10^4 dark photons arrive in FASER in 300 fb^{-1} in currently unconstrained regions of dark photon parameter space

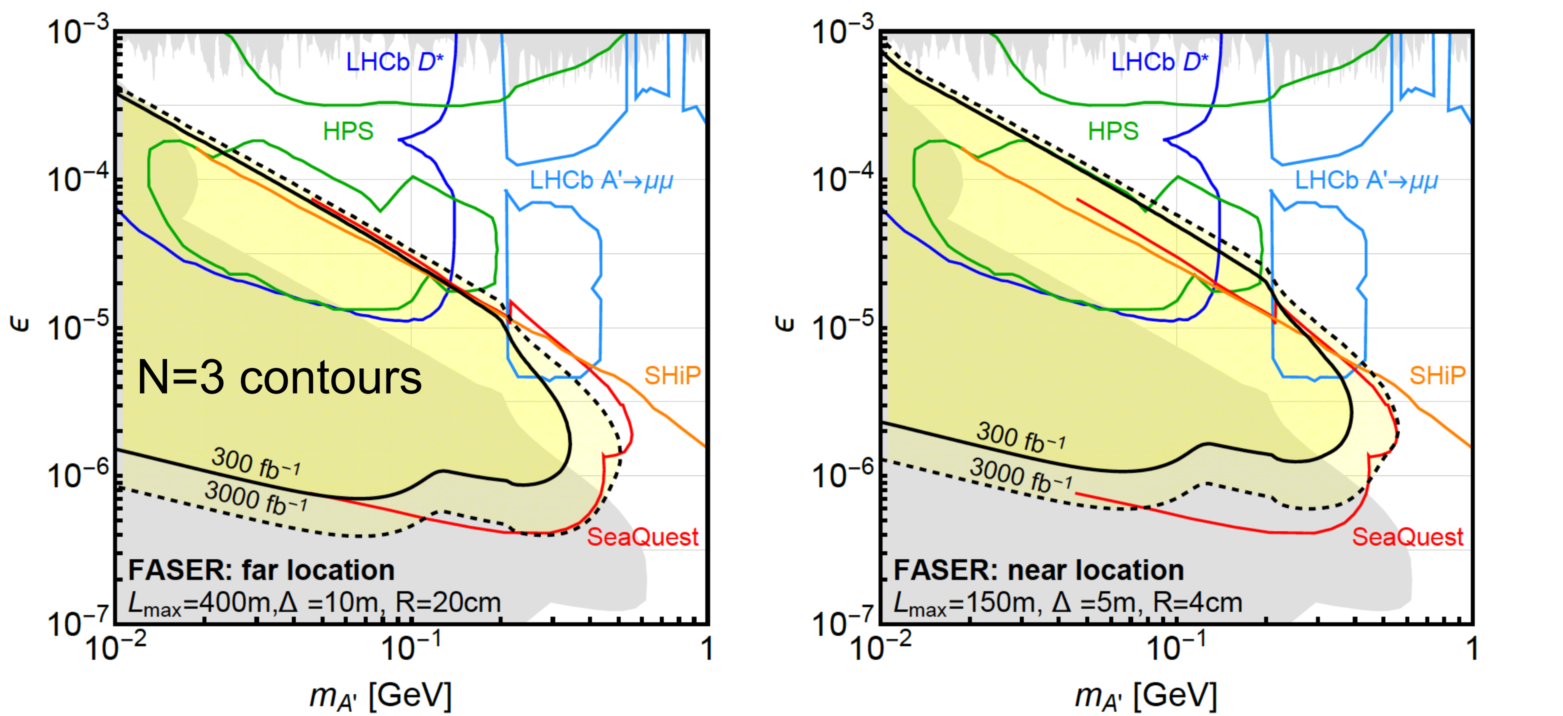
$$pp \to A' X\,, \quad A' \text{ travels } \sim \mathcal{O}(100) \text{ m}\,, \quad A' \to e^+e^-, \mu^+\mu^-$$





RESULTS: REACH

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



- SHiP probes much greater region at low ε, but this is mostly excluded already. SHiP reach at high $m_{A'}$ is from direct QCD production, which we have neglected

SUMMARY AND OUTLOOK

- The LHC has seen nothing yet. Adding a small, inexpensive detector to improve LHC's discovery prospects seems like a good idea

- Related ideas: old proposals for long-lived particles; new ideas, like MATHUSLA and MilliQan; beam dump experiments, like SeaQuest and SHiP; very forward experiments, like CT-PPS

  Feng, Smith (2004); Hamaguchi, Kun, Makaya, Nojiri (2004); De Roeck, Ellis, Gianotti, Moortgat, Olive, Pape (2004); Chou, Curtin, Lubatti (2016); Ball et al. (2016); Alekhin et al. (2016); Aidala et al. (2017); Albrow (2015)

- FASER is unique in that it and targets light, weakly-coupled new particles at low p_T , runs simultaneously with the LHC program, and should be very small and inexpensive

SUMMARY AND OUTLOOK

- Far location: appears to be background free. A small 20cm x 20cm x 10m detector ~400m from the IP would provide world-leading sensitivity to dark photons
- Near location: a far more challenging environment, but if backgrounds can be controlled, a tiny 4cm x 4cm x 5m detector can do even better
- Work to do: We've considered dark photons. A multitude of other new physics ideas are also worth considering
- Work to do: simulate near detector beam-induced backgrounds, specify detector design, integrate into LHC beam infrastructure, ...