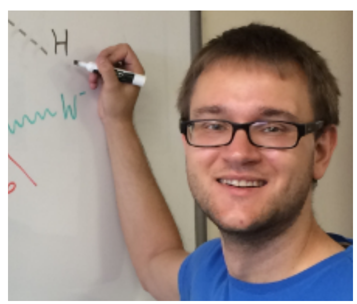
LIFETIME FRONTIER EXPERIMENTS AT THE LHC

Simons Symposium: Illuminating Dark Matter

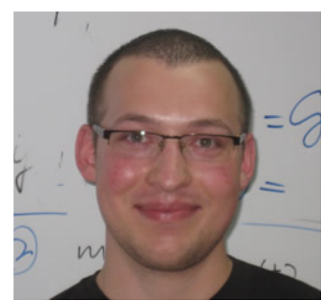
Jonathan Feng, UC Irvine

Much of talk based on 1708.09389, 1710.09387, and work in progress with

Iftah Galon



Felix Kling



Sebastian Trojanowski

16 May 2018

THE PLAN

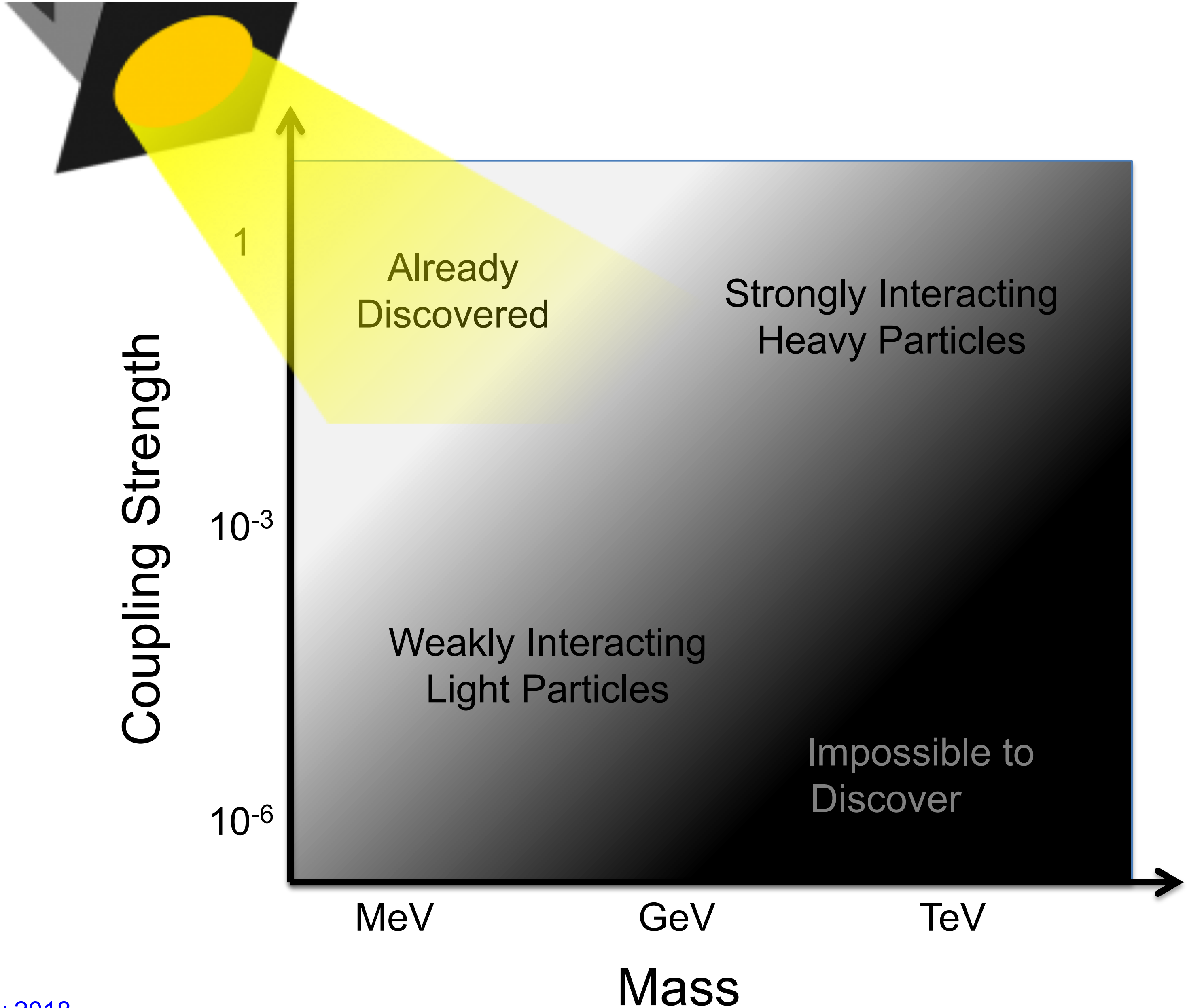
- This is an area of rapid progress, even in the last year. This is in stark contrast to the usual time it takes to mount an LHC experiment (~ decades).

- The goal of this talk is to give a flavor of this progress by discussing
  - Motivations
  - Properties of new particles at the lifetime frontier
  - FASER, one of the proposed experiments

- Tomer: "Nowadays you are not a theorist unless you are working on an experiment." I'm glad I just barely made the cut!

MOTIVATIONS

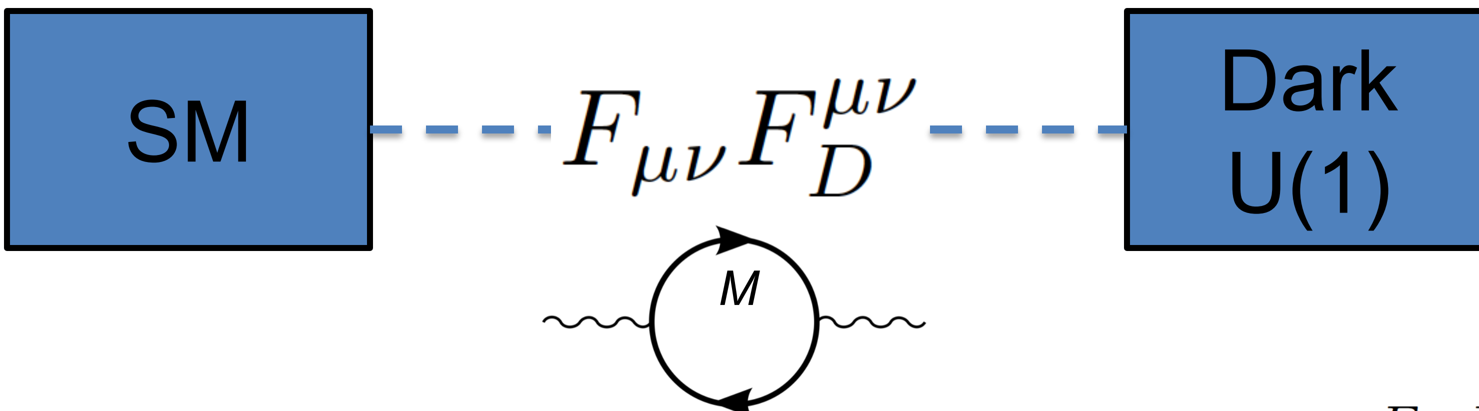
PARTICLE PHYSICS: THE LAMPPOST LANDSCAPE



COSMOLOGY: DARK SECTORS

- In recent years, dark matter → dark sectors. What are the "most likely" non-gravitational interactions?

- Suppose the dark sector has U(1) electromagnetism. There are infinitely many possible SM-dark sector interactions, but only one is induced by arbitrarily heavy mediators:



$$F_{\mu\nu} F_D^{\mu\nu}$$

- It is "most likely" because it is non-decoupling. Cf. $\dfrac{F_{\mu\nu} F_D^{\nu\alpha} F_\alpha^\mu}{M^2}$

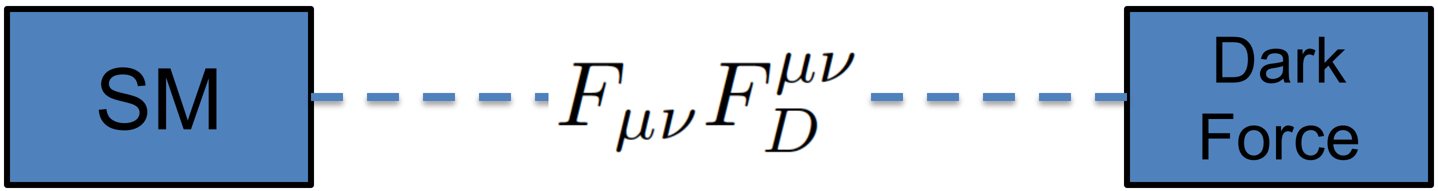
- It is also naturally small, since it is induced by a loop.

Okun (1982), Galison, Manohar (1984), Holdom (1986)

DARK PHOTON, DARK HIGGS, STERILE NUS

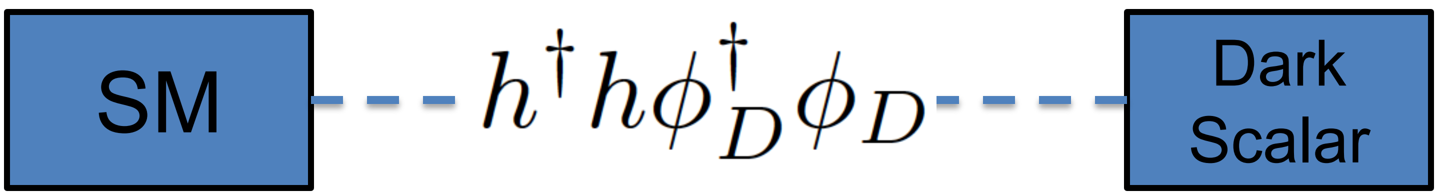
- This provides an organizing principle that motivates specific examples of new, weakly interacting light particles. There are just a few options:

- Spin 1



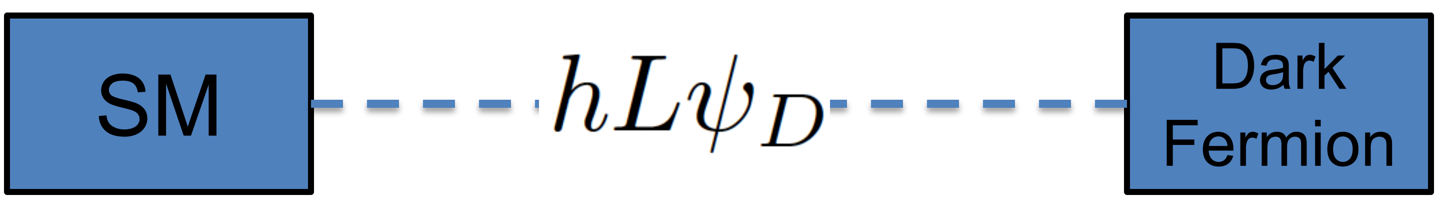
→ dark photon, couples to SM fermions with suppressed couplings proportional to charge: εq_f.

- Spin 0



→ dark Higgs boson, couples to SM fermions with suppressed coupling proportional to mass: $\sin\theta\, m_f$.

- Spin 1/2



→ sterile neutrino, mixes with SM neutrinos with suppressed mixing $\sin\theta$.

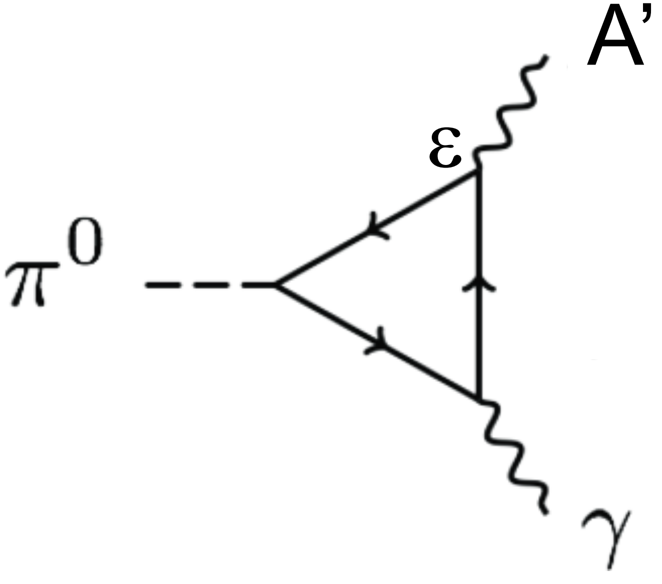
PROPERTIES OF NEW PARTICLES AT THE LIFETIME FRONTIER

BASIC PROPERTIES

- How do we find these particles?
- E.g. dark photons with some “typical” parameters:

$$m_{A'} = 100 \text{ MeV}, \varepsilon = 10^{-5}.$$

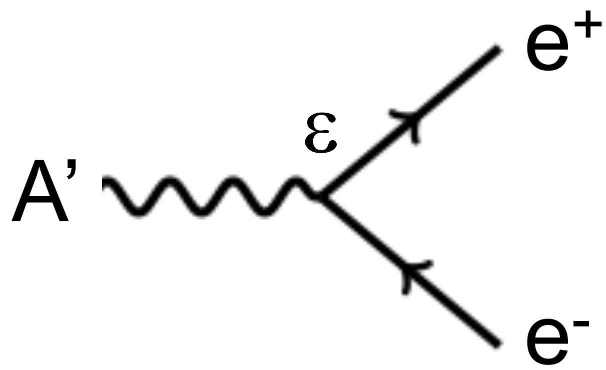
- Production: for example, pion decay:



- Branching ratio suppressed by $\varepsilon^2 = 10^{-10}$. Need lots of pions!

BASIC PROPERTIES

- Decay



$$\bar{d} = c\,\frac{1}{\Gamma_{A'}}\,\gamma_{A'}\beta_{A'} \approx (80\ \mathrm{m})\ B_e \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\mathrm{TeV}}\right] \left[\frac{100\ \mathrm{MeV}}{m_{A'}}\right]^2$$

- Decay length is long, typically decays after leaving detector. (Note that the interaction length is even longer: ~10^{11} cm!)

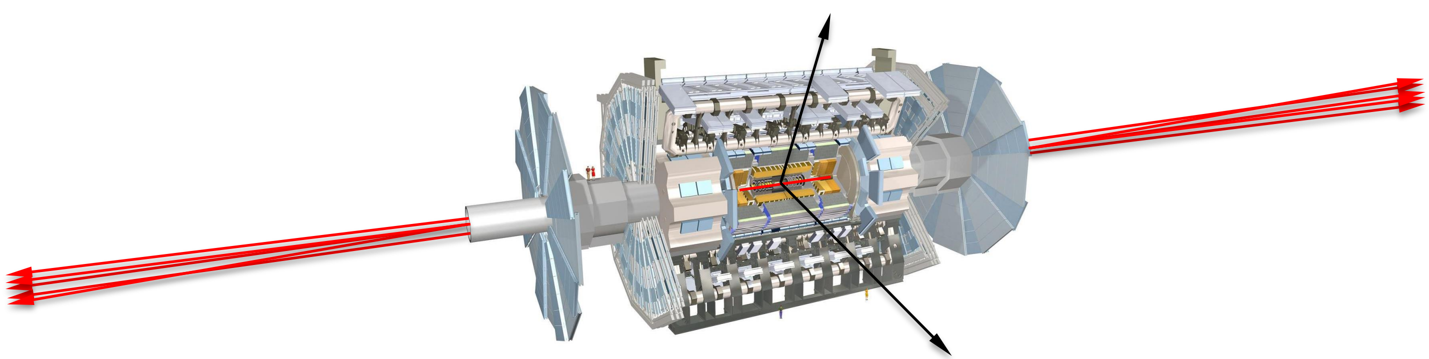
- Motivates new analyses, new experiments at the lifetime frontier: LDMX, PADME, NA62, LHCb, Belle-II, SeaQuest, SHiP, HPS, MATHUSLA, FASER, Codex-b, and many others.

FASER

FASER

- 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

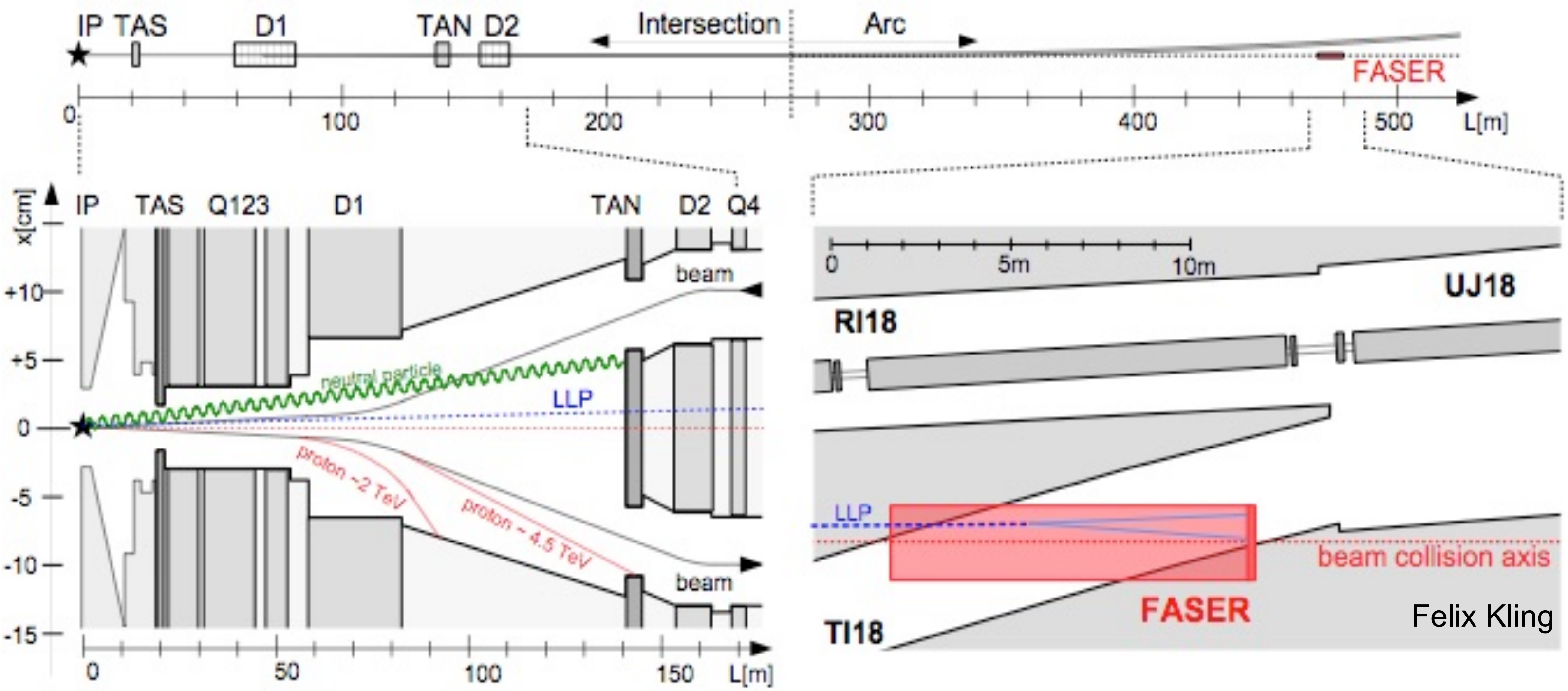
- However, if new particles are light and weakly interacting, this may be completely misguided. Instead should go where the pions are: at low p_T along the beamline
  - σ_{inel} ~ 100 mb → N ~ 10^{17}, $\theta \sim \Lambda_{QCD} / E$ ~ 250 MeV / TeV ~ mrad



- Since the long-lived particles are extremely collimated, they motivate a small, fast, inexpensive experiment placed in the very forward region of ATLAS/CMS, a few 100m downstream

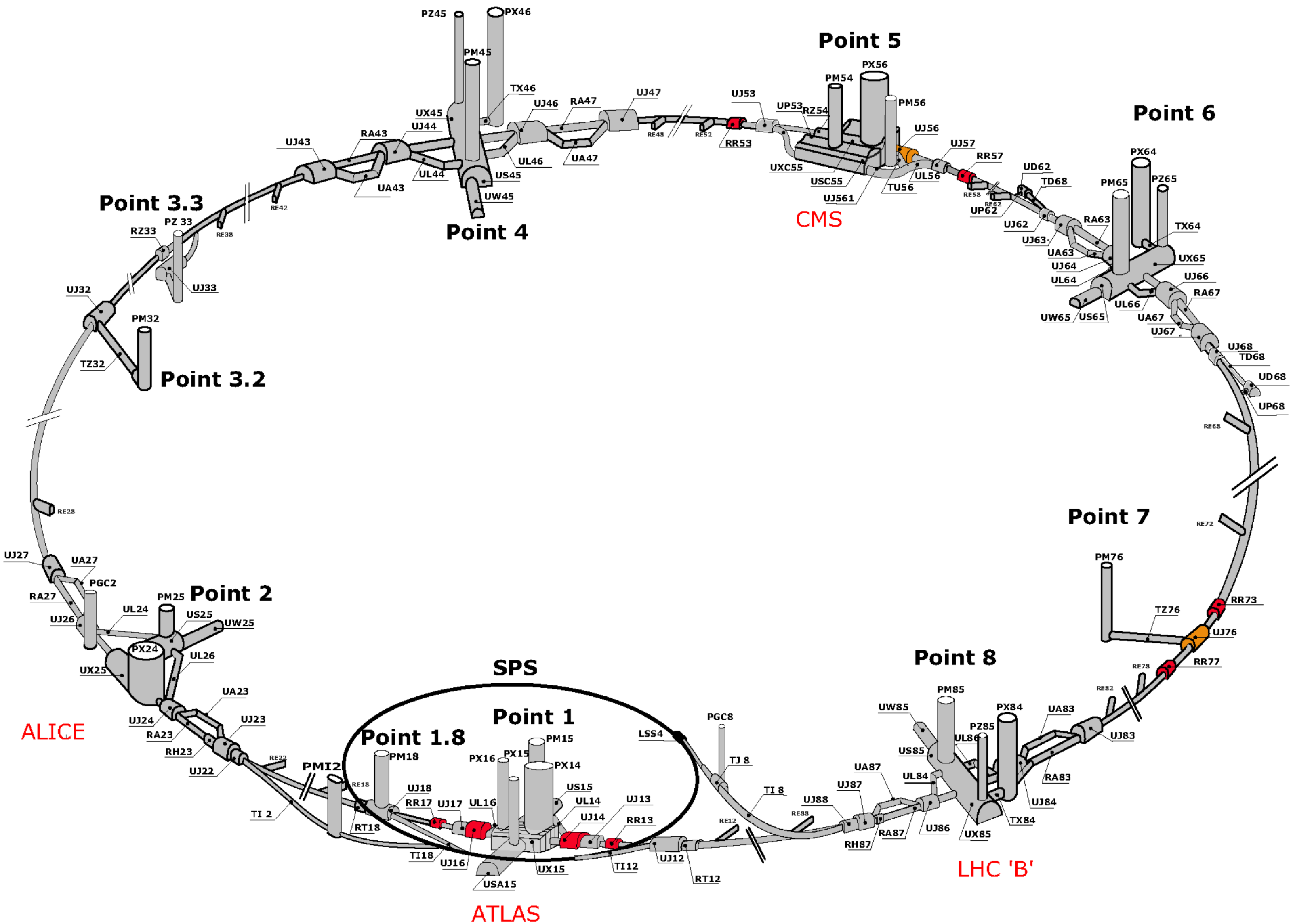
LONG LIVED PARTICLES IN FASER

- LLP produced at IP, travels ~480 m, decays in FASER

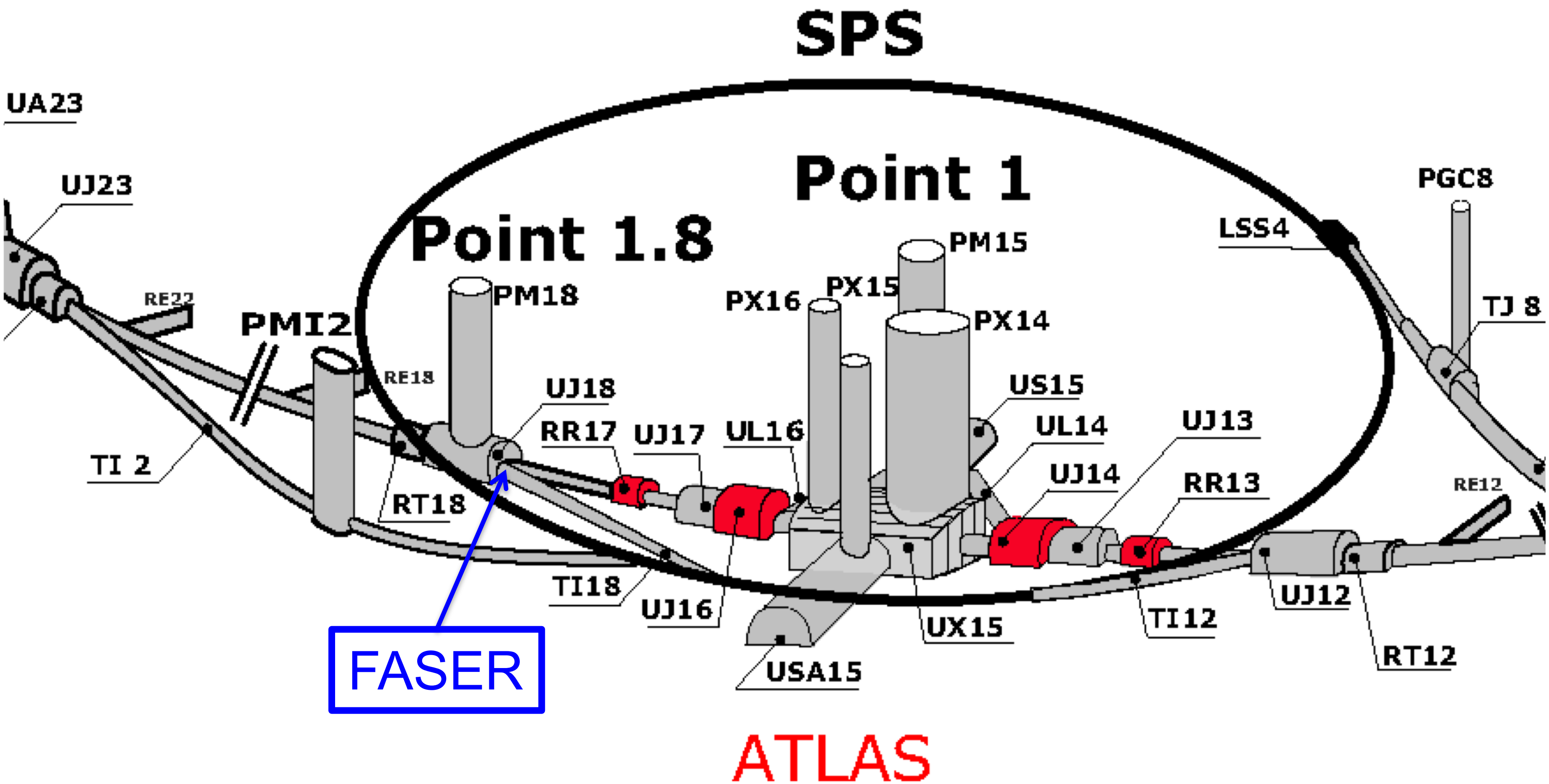


- If beam crossing angle = 285 (590) μrad in vertical/horizontal plane, the "on axis" location at FASER shifts by 6 (12) cm

FASER LOCATION

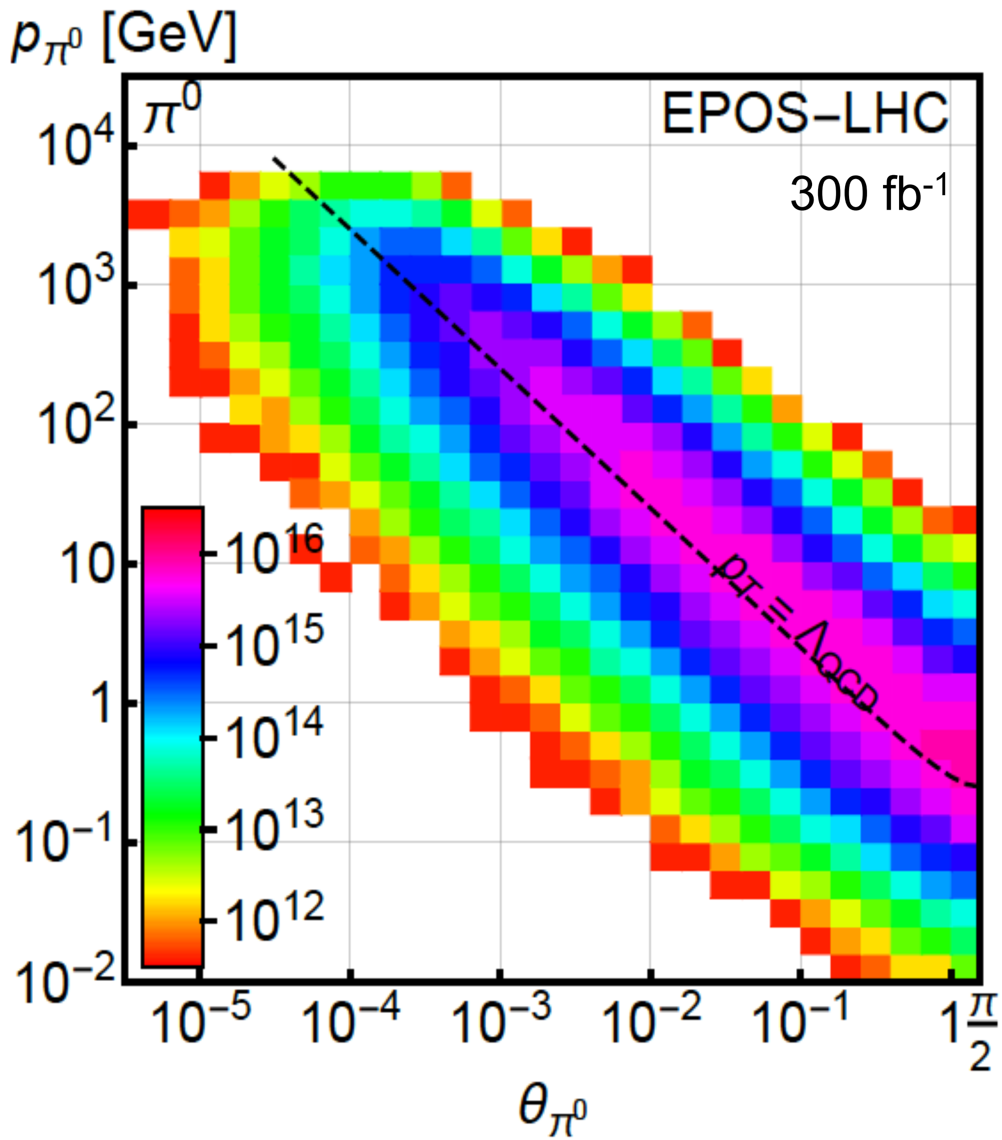


FASER: LOCATION



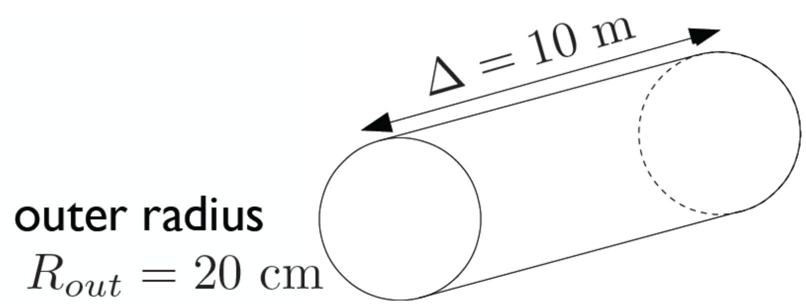
PION PRODUCTION AT THE LHC

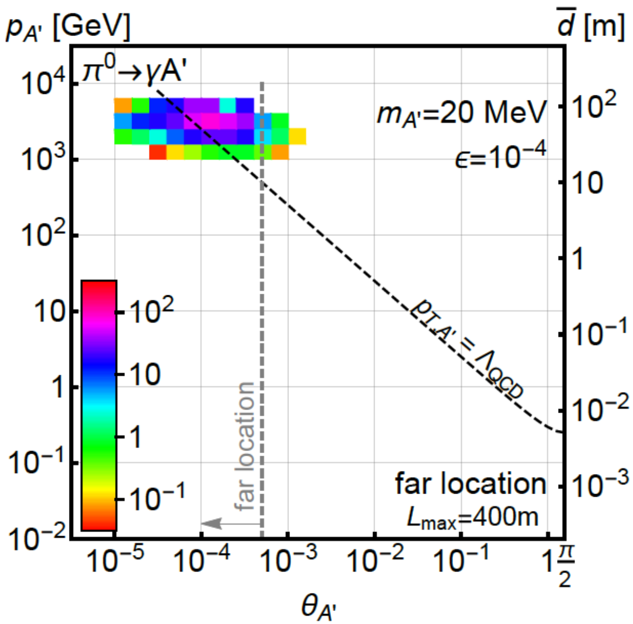
- Forward particle production simulations and models have been greatly constrained by LHC data
- EPOS-LHC, SIBYLL 2.3, QGSJETII-04 agree very well
- Enormous event rates (σ_{inel}~70 mb, N_{inel}~10^{17}), production is peaked at $p_T \sim \Lambda_{QCD}$

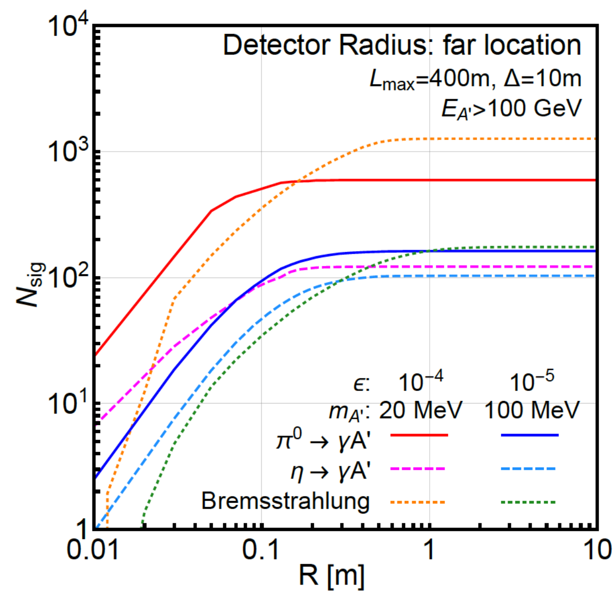


DARK PHOTONS IN FASER

- Now require $\pi^0 \rightarrow A' \gamma$, $A' \rightarrow e^+e^-$ in FASER: consider cylindrical detector with volume ~1 m^2



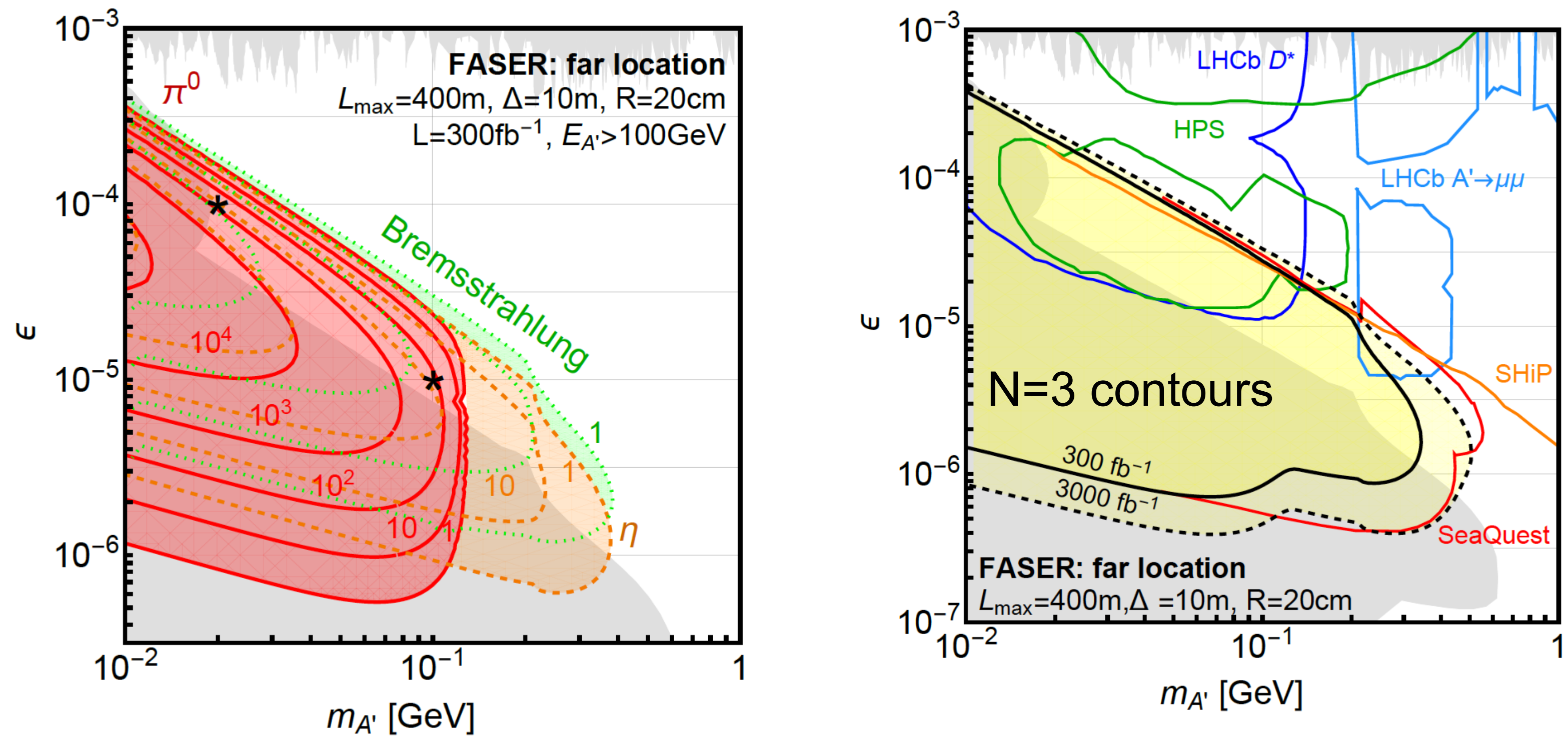




- Only the TeV A's survive, but there are still many of them, and they are highly collimated within 20 cm of beam axis

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



- At the upper ε boundary, rates are extremely sensitive to ε, reach is insensitive to background, provided it is known

SIGNAL AND BACKGROUND

- 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

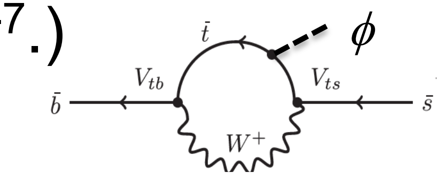
$$h_B \approx \frac{ec\ell^2}{E} B = 3 \text{ mm} \left[\frac{1 \text{ TeV}}{E}\right] \left[\frac{\ell}{10 \text{ m}}\right]^2 \left[\frac{B}{0.1 \text{ T}}\right]$$

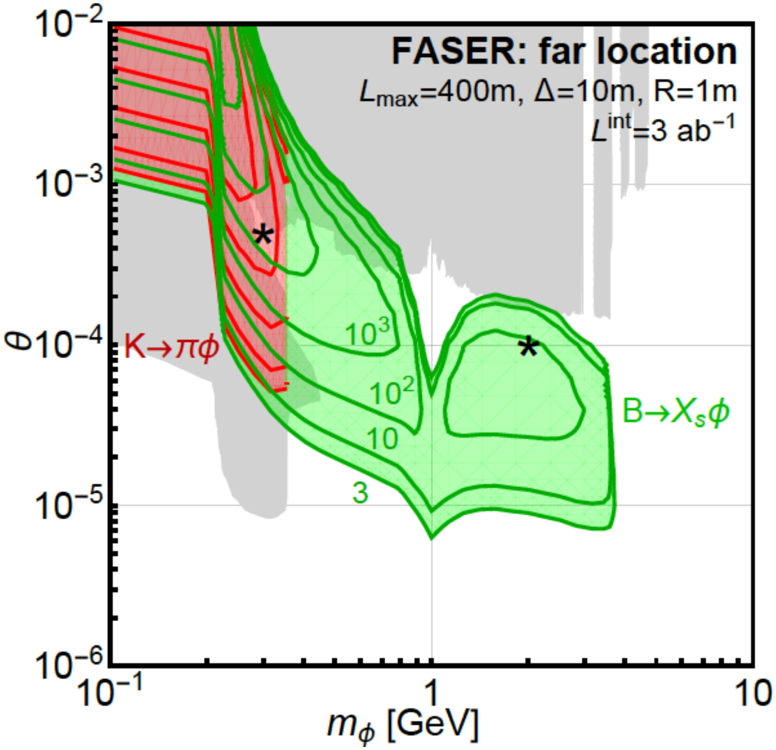
- Many backgrounds are eliminated simply by virtue of FASER's location. Particles from IP must pass through ~50 m of matter to get to FASER. Cosmic ray background is negligible, charged particles from IP are bent away by D1 magnet

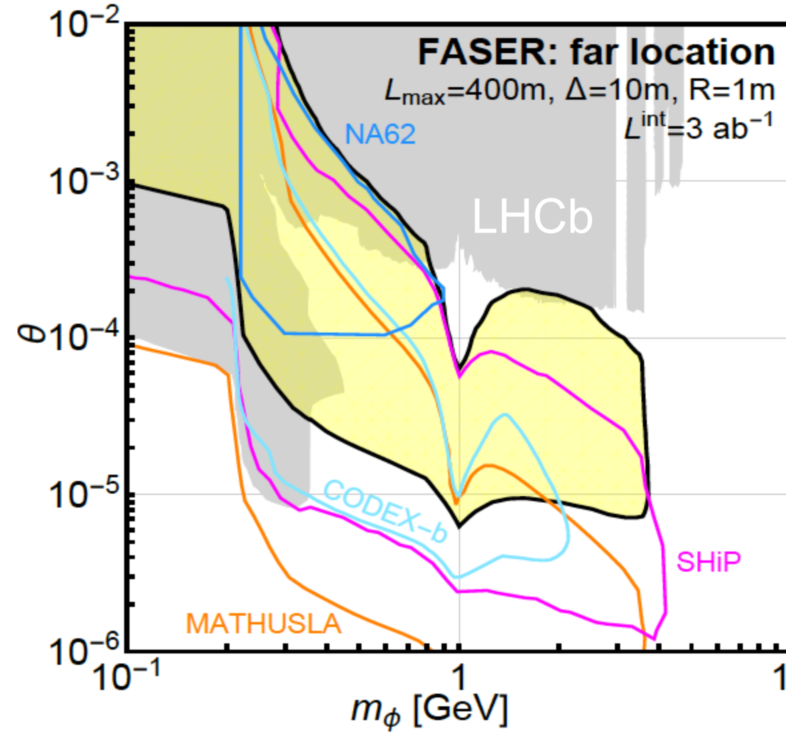
- Leading backgrounds: neutrino-induced backgrounds are very small, beam-induced backgrounds (see FLUKA study).

DARK HIGGS EVENT RATES AND REACH

- FASER is especially good at probing LLPs from B decays: FASER: $N_B/N_\pi \sim 10^{-2}$. (Cf. SHiP: $N_B/N_\pi \sim 10^{-7}$.)



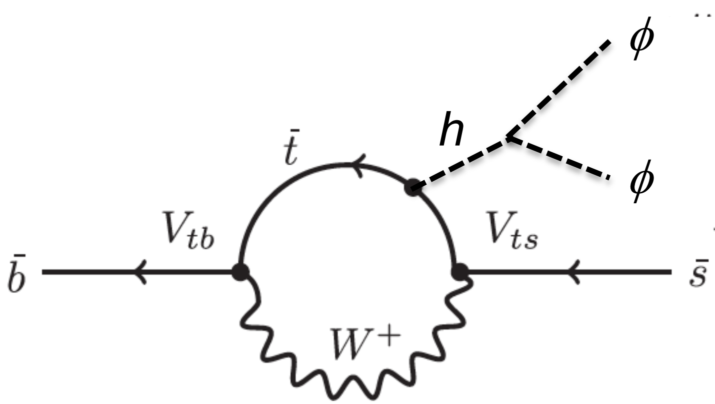


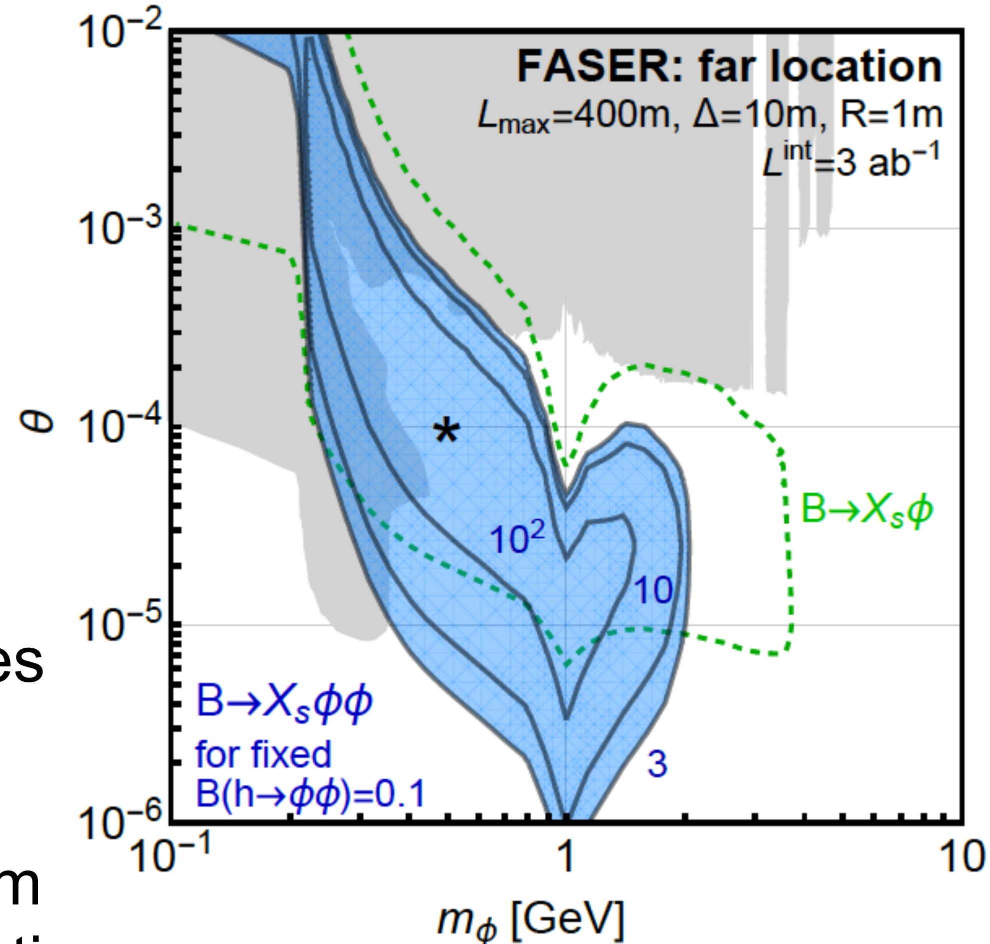


- FASER with 1m x 1m cross section probes a large swath of new parameter space, is complementary to other experiments

TRILINEAR COUPLINGS REACH

- FASER can also probe the trilinear couplings through



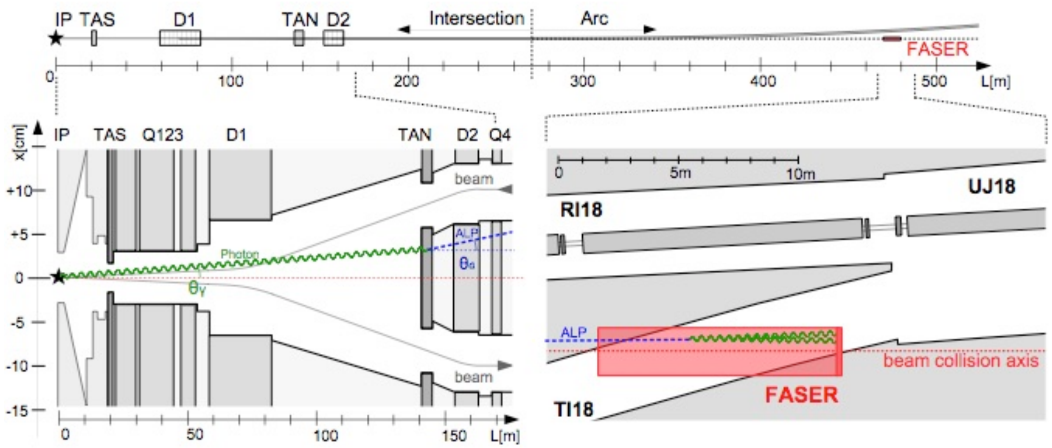


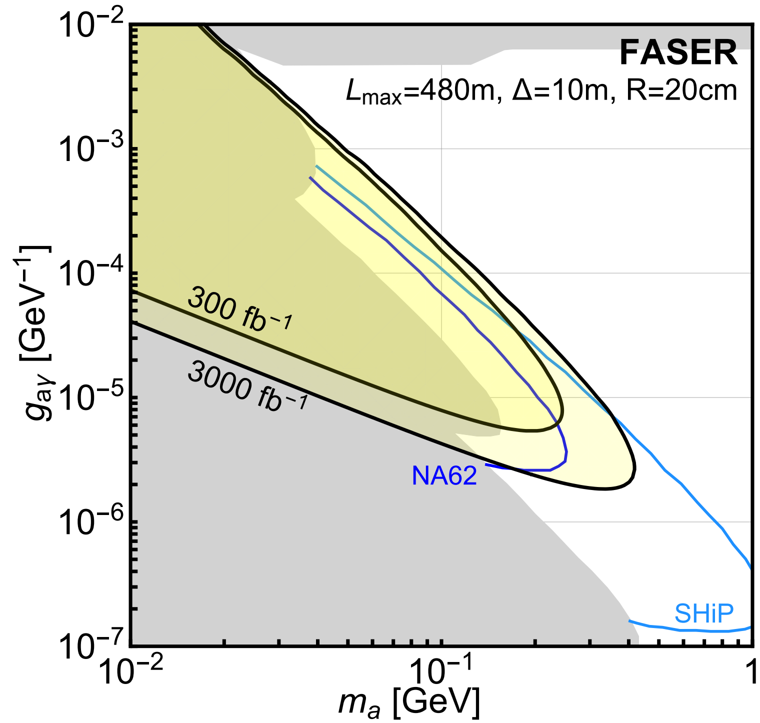
- This competes with
  h → ϕϕ (ATLAS, CMS)
  h → ϕϕ → charged particles (MATHUSLA)

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

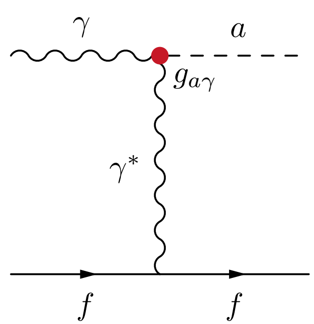
ALPS EVENT RATES AND REACH

- FASER can probe ALPs as a high-energy photon beam dump





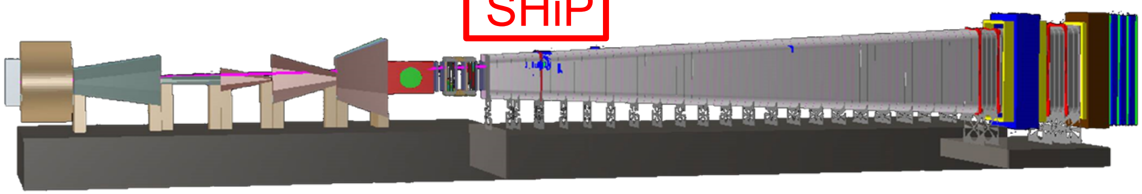
- Primakoff production in TA(X)N



- FASER probes a large swath of new parameter space

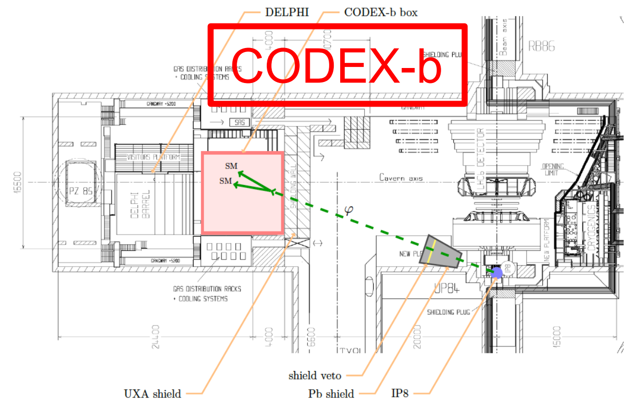
COMPLEMENTARY PROPOSED EXPERIMENTS

SHiP



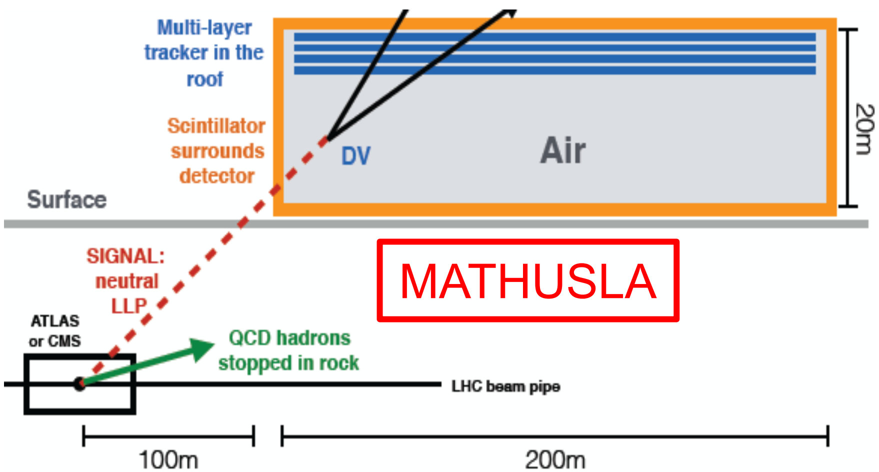
~1000 m^3, ~100M CHF + beam

Alekhin et al. (2015)



~1000 m^3 ~ 1 mIKEAs

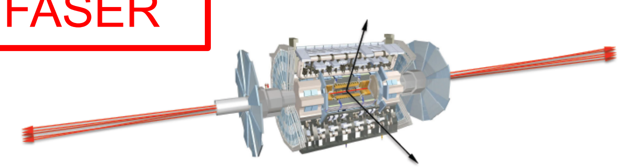
Gligorov, Knapen, Papucci, Robinson (2017)



~800,000 m^3 ~ 1 IKEA, ~$50M

Chou, Curtin, Lubatti (2016)

FASER



~1 m^3 ~ 1 μIKEAs

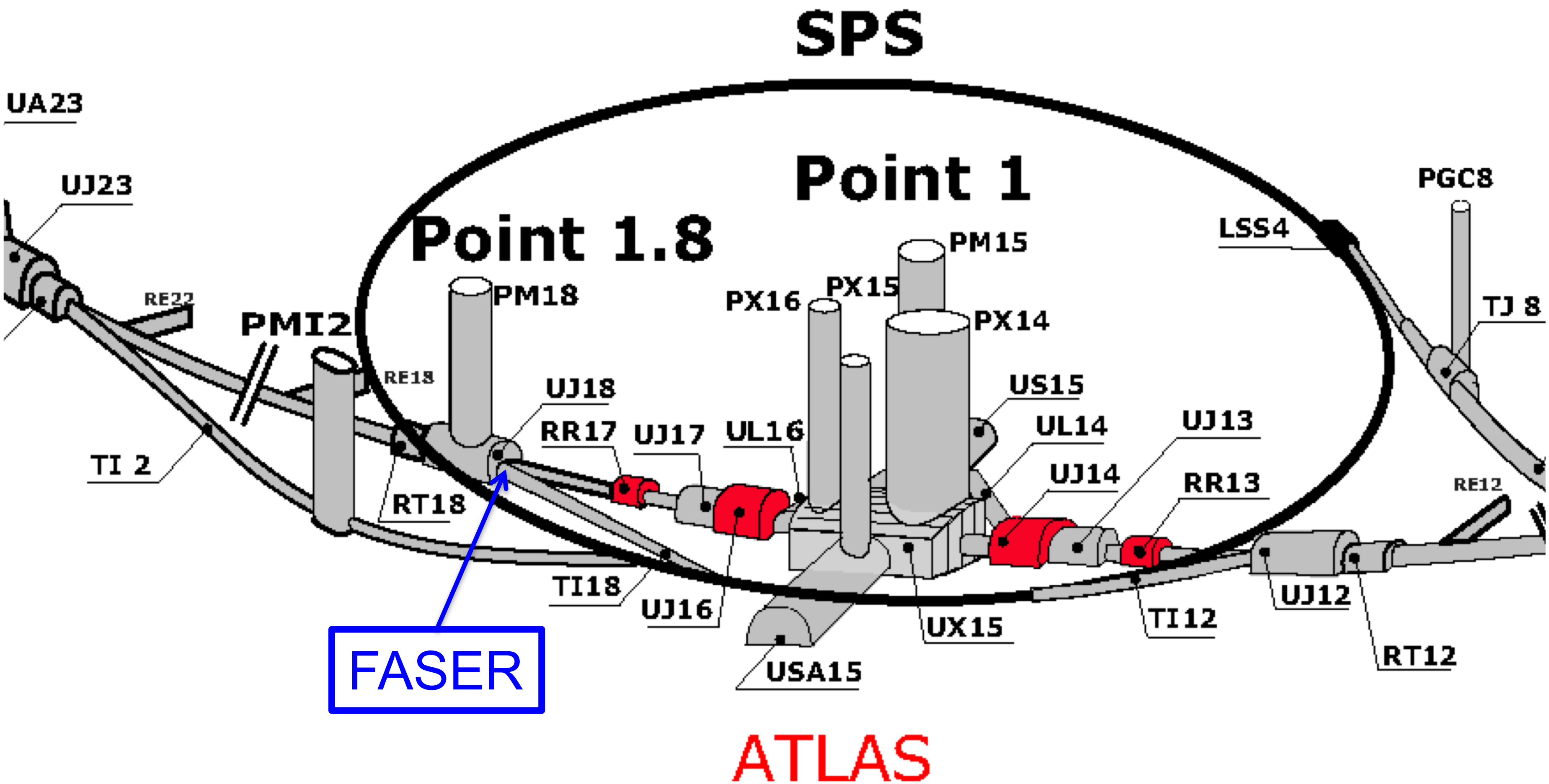
Feng, Galon, Kling, Trojanowski (2017)

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 Aki Ariga, Tomoko Ariga, Jamie Boyd, Dave Casper, Francesco Cerrutti and FLUKA team, Paolo Fessia, Shih-Chieh Hsu, Mike Lamont, Hide Otono, Brian Petersen, Osamu Sato, …

FASER: LOCATION



FASER: LOCATION

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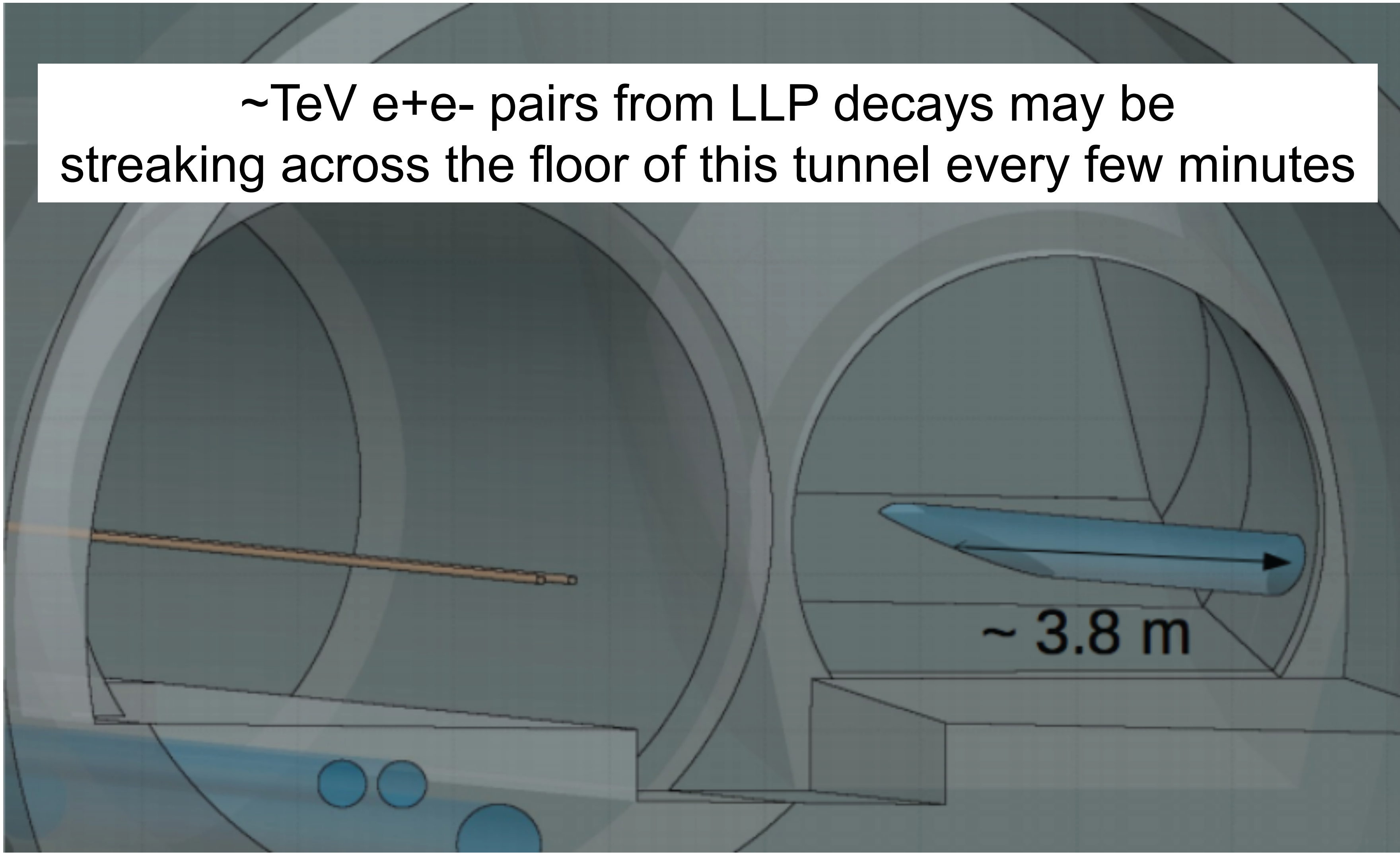
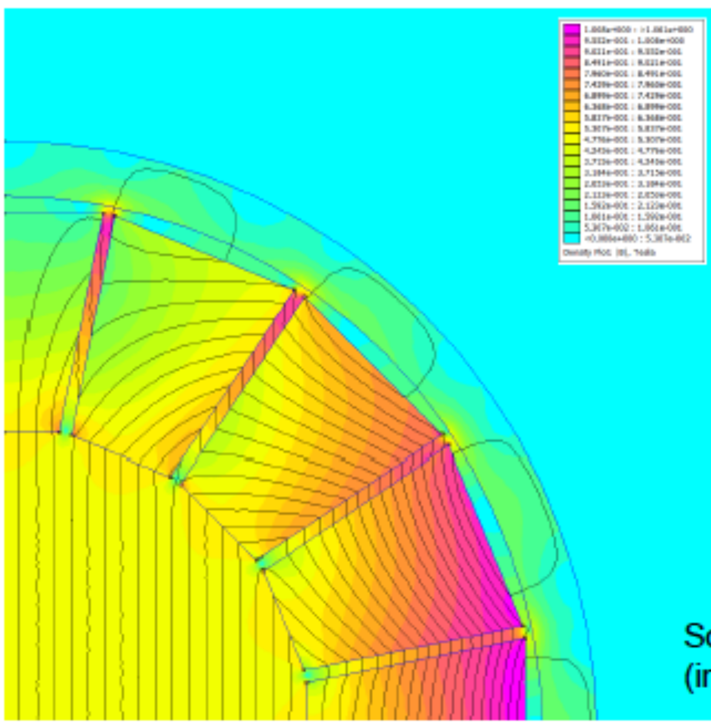


DETECTOR DESIGN

- GENAT study underway. Current design has an initial veto layer, followed by 3 tracking layers and EM calorimeter, with some of the volume in a 0.35 T permanent dipole magnet.

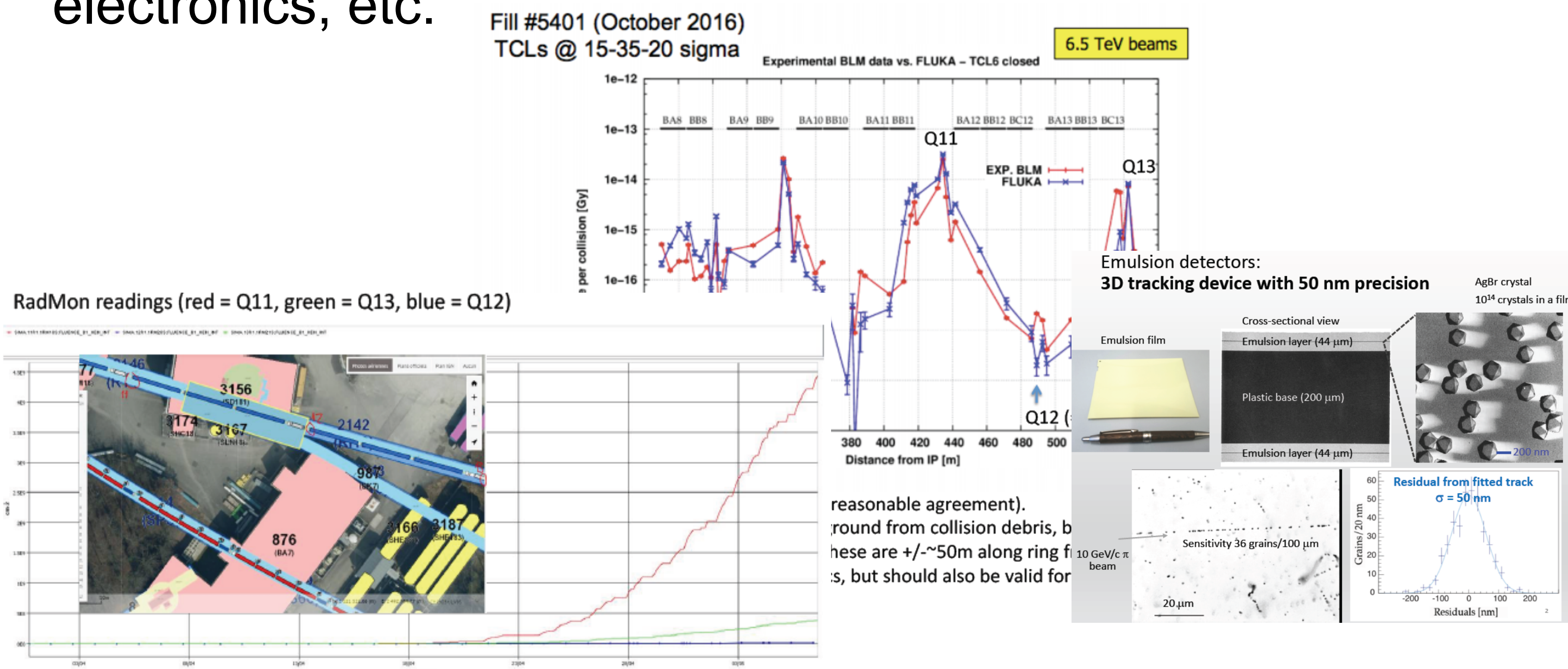


Parameter	Value	Unit
Central field	0.52	T
Integrated field	0.67	T.m
Good field region	Ø 200	mm
Field homogeneity	+/- 2	%
Free aperture	Ø 200	mm
Outside diameter	430	mm
Magnet length	1300	mm
Magnet weight	1200	kg

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

BACKGROUND SIMULATION AND MEASUREMENT

- Initial FLUKA study shows very low backgrounds at FASER location. Details expected soon.
- Hope to put RadMon and emulsion detector in TS1 (June 15) to validate FLUKA simulation, understand radiation levels for electronics, etc.



SUMMARY AND OUTLOOK

- The LHC has seen no new physics. Adding supplementary detectors is a good idea, and there are many proposals targeting the lifetime frontier.
- All have significant discover prospects for “dark” particles: dark photons, dark Higgs bosons, HNLs, ALPs, …
- Possible timeline for FASER: install FASER 1 (20 cm x 20 cm) in LS2 (2019-20) for Run 3 (150-300 fb^{-1}), install FASER 2 (1m x 1m) in LS3 (2023-25) for HL-LHC (3 ab^{-1}).

https://twiki.cern.ch/twiki/bin/viewauth/FASER/WebHome