FASER

# MOTIVATIONS AND SIGNALS

1st FASER Collaboration Meeting, CERN

Jonathan Feng, UC Irvine

1 April 2019

# PHYSICS SESSION

**11:20** → 12:30 **FASER Physics: Long-Lived Particles**

**Convener**: Jonathan Lee Feng (University of California Irvine (US))

- 11:20 **Motivations and Signals** ¶
  **Speaker**: Jonathan Lee Feng (University of California Irvine (US))
- 12:00 **Backgrounds**
  **Speaker**: Iftah Galon (Rutgers University)

**12:30** → 12:40 **Collaboration Photo!**

**12:40** → 14:00 **Lunch Break**

**14:00** → 14:45 **FASER Physics: Neutrinos**

**Convener**: Jonathan Lee Feng (University of California Irvine (US))

- 14:00 **Neutrino Signals**
  **Speaker**: Felix Kling (University of California, Irvine)
- 14:20 **Neutrino Detection**
  **Speaker**: Tomoko Ariga (Kyushu University)

# OUTLINE

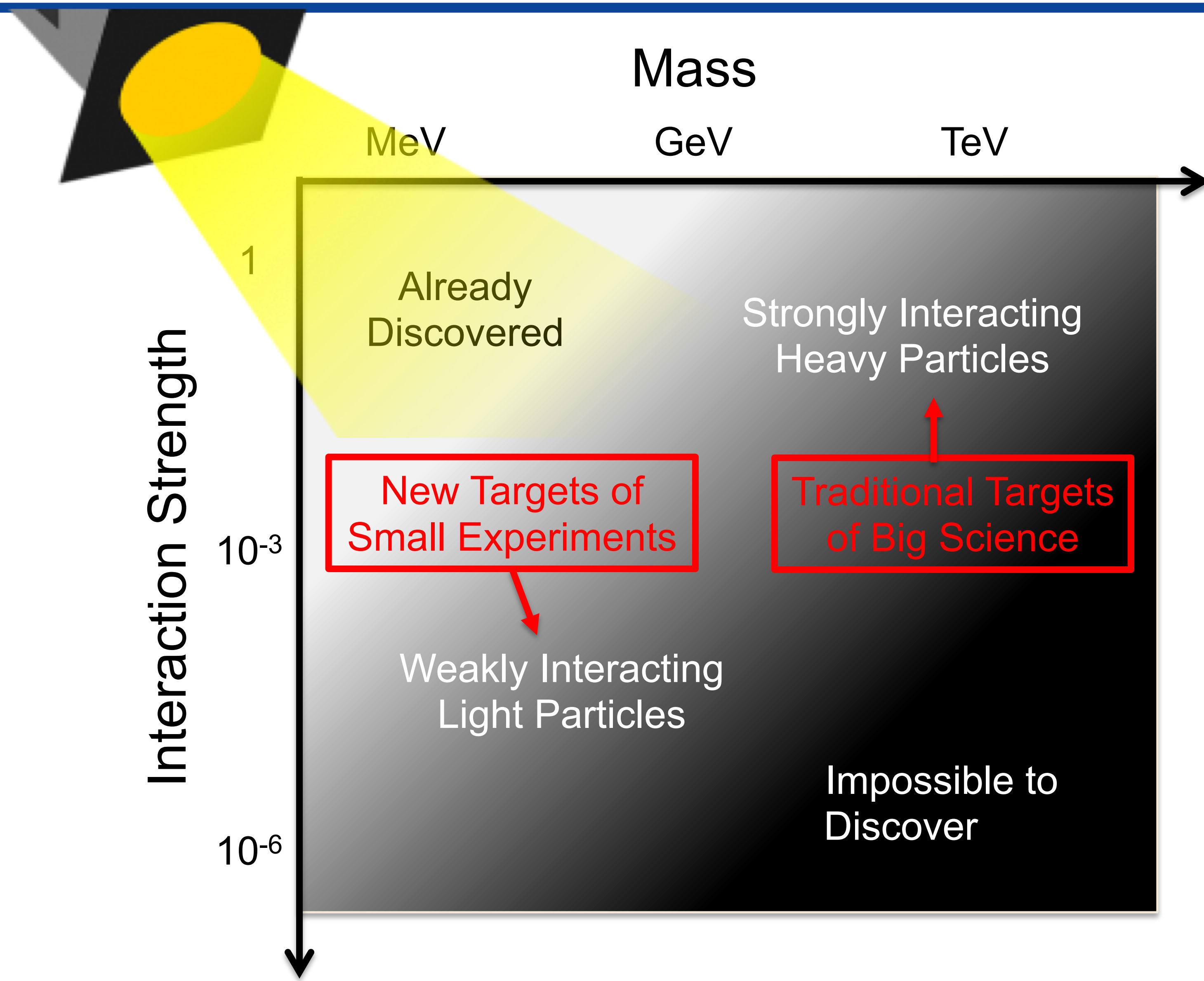
Motivations

- Particle Physics
- Cosmology

Signals

- Concrete Models
- Dark Photons
- Dark Higgs Bosons
- Axion-Like Particles

# MOTIVATIONS: PARTICLE PHYSICS

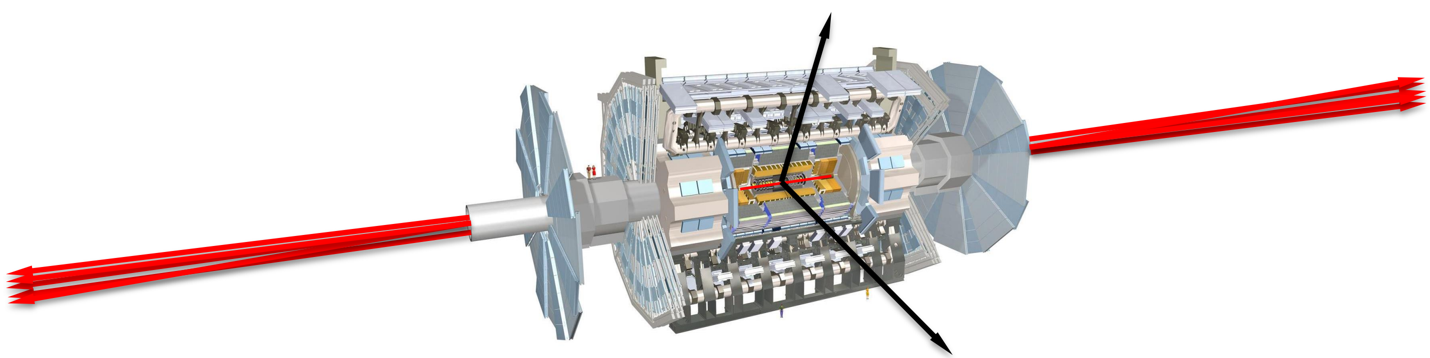


# NEW PHYSICS SEARCHES AT THE LHC

- The traditional targets are heavy, strongly interacting particles
  - $\sigma$ ~ fb to pb → $N_{Run3}$ ~ $10^2$–$10^5$, produced ~isotropically →high $p_T$

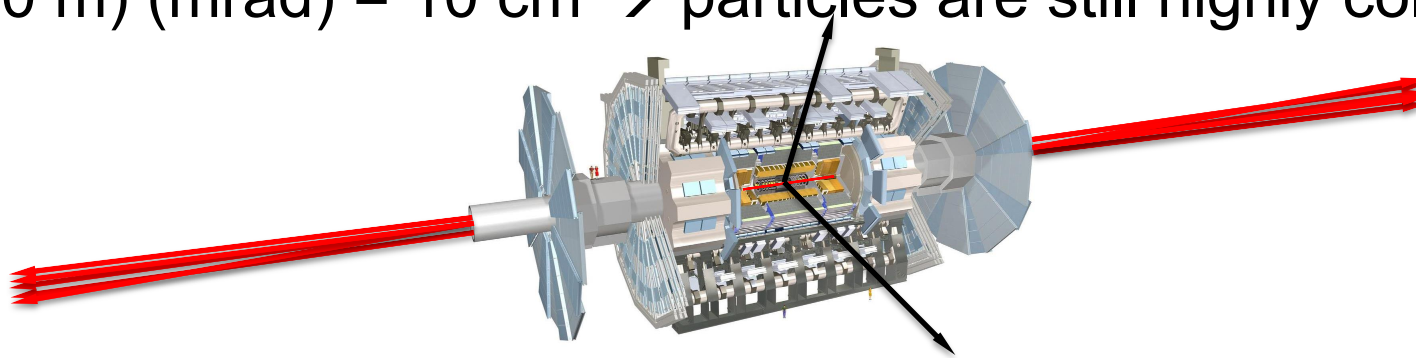
- However, if new particles are light and weakly interacting, this may be completely misguided
  - Light → they may be produced in $\pi$, *K*, *D*, *B* decays…
  - Weakly-interacting → …but extremely rarely in $\pi$, *K*, *D*, *B* decays

- More promising to look where most of the pions (and other mesons) are: along the beamline at low $p_T$
  - $\sigma_{inel}$ ~ 100 mb → $N_{Run3}$ ~ $10^{16}$, and 10% of the pions are produced within 2 mrad of the beamline ($\eta$ > 7)



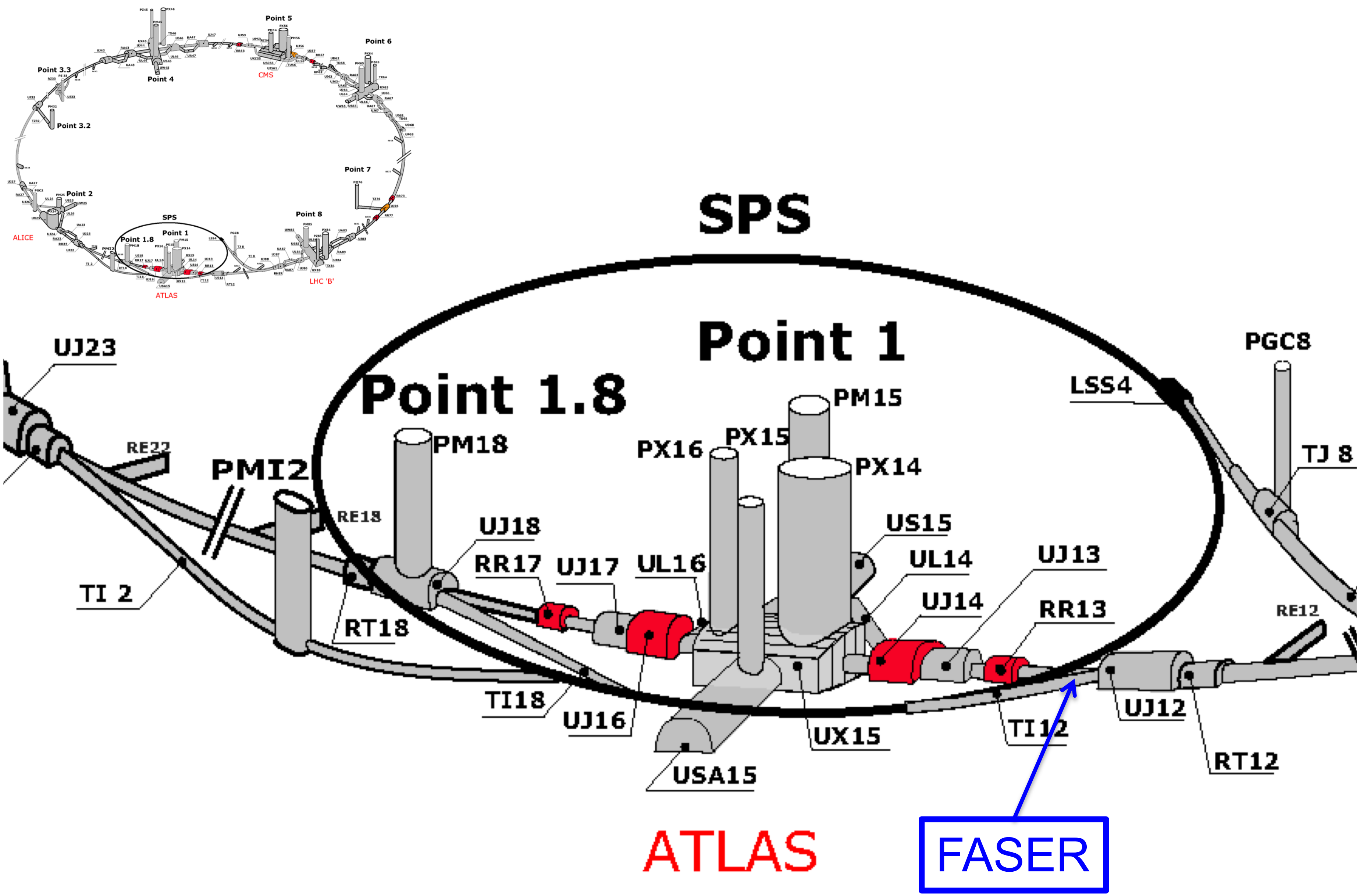
# THE IDEA

- Of course, we can't put a reasonably-sized detector on the beamline near the IP – it would block the proton beams
- However, weakly-interacting particles are also typically long-lived, so we can place the detector O(100) m away, after the beam curves away
- (100 m) (mrad) = 10 cm → particles are still highly collimated

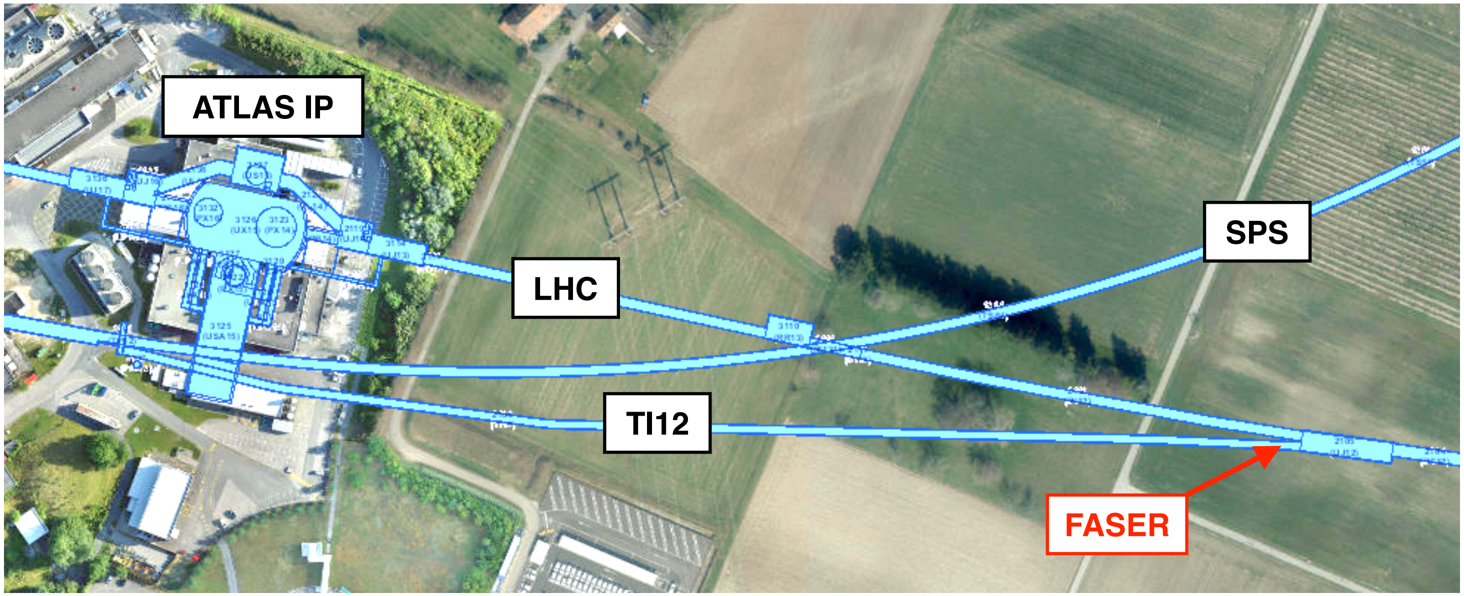


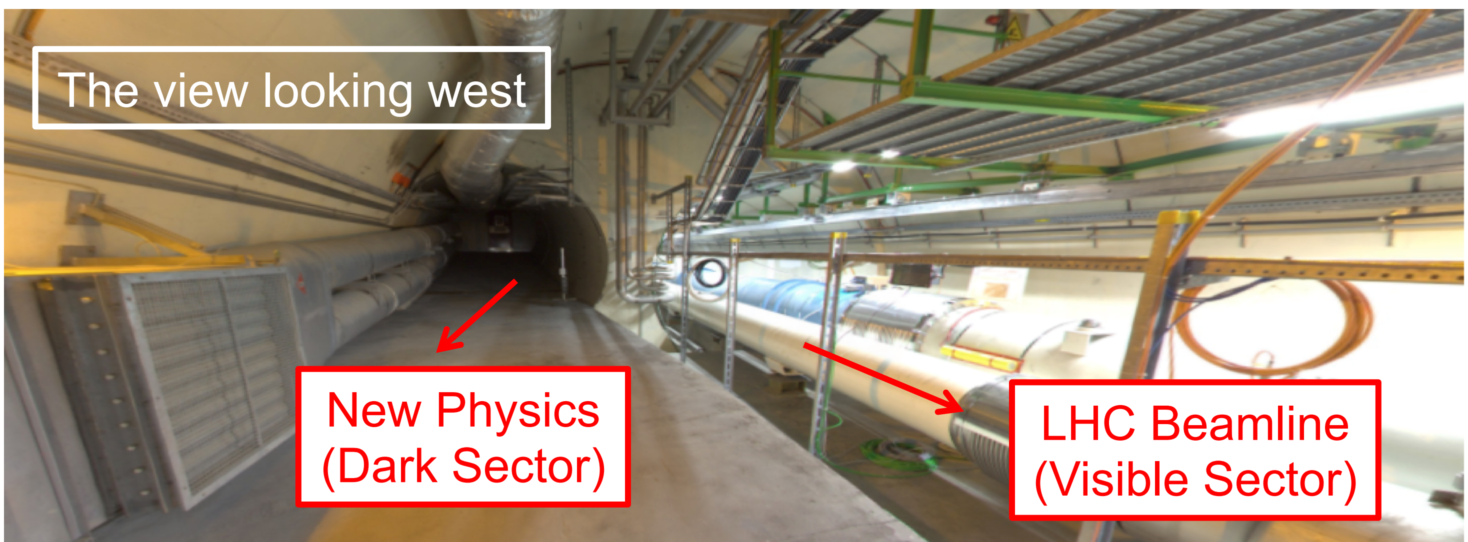
- These general considerations motivate a small, fast, inexpensive experiment placed in the very forward region of ATLAS/CMS, a few 100m downstream: FASER, the Forward Search Experiment at the LHC.

# FASER LOCATION



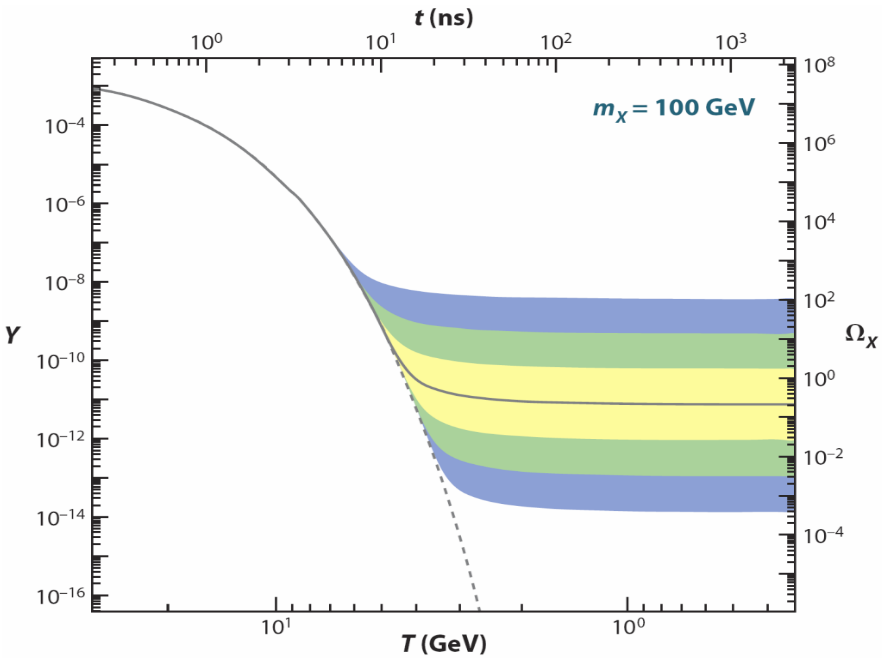
# FASER LOCATION

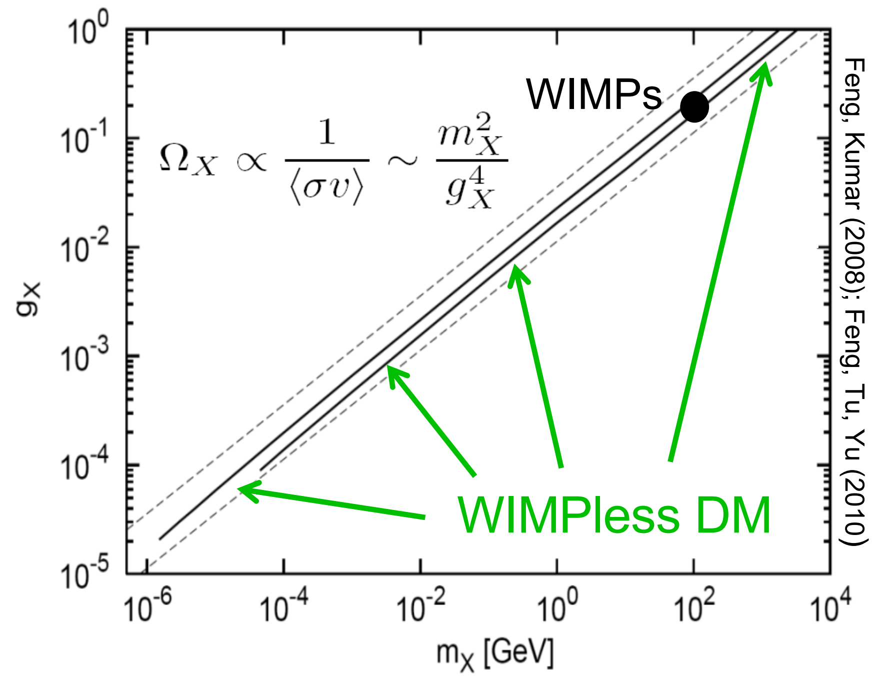


# MOTIVATIONS: COSMOLOGY

- Thermal freezeout is a simple mechanism for generating dark matter in the early universe
- The WIMP Miracle: 100 GeV - TeV mass particles with weak interaction couplings to the SM freezeout with the right thermal relic density

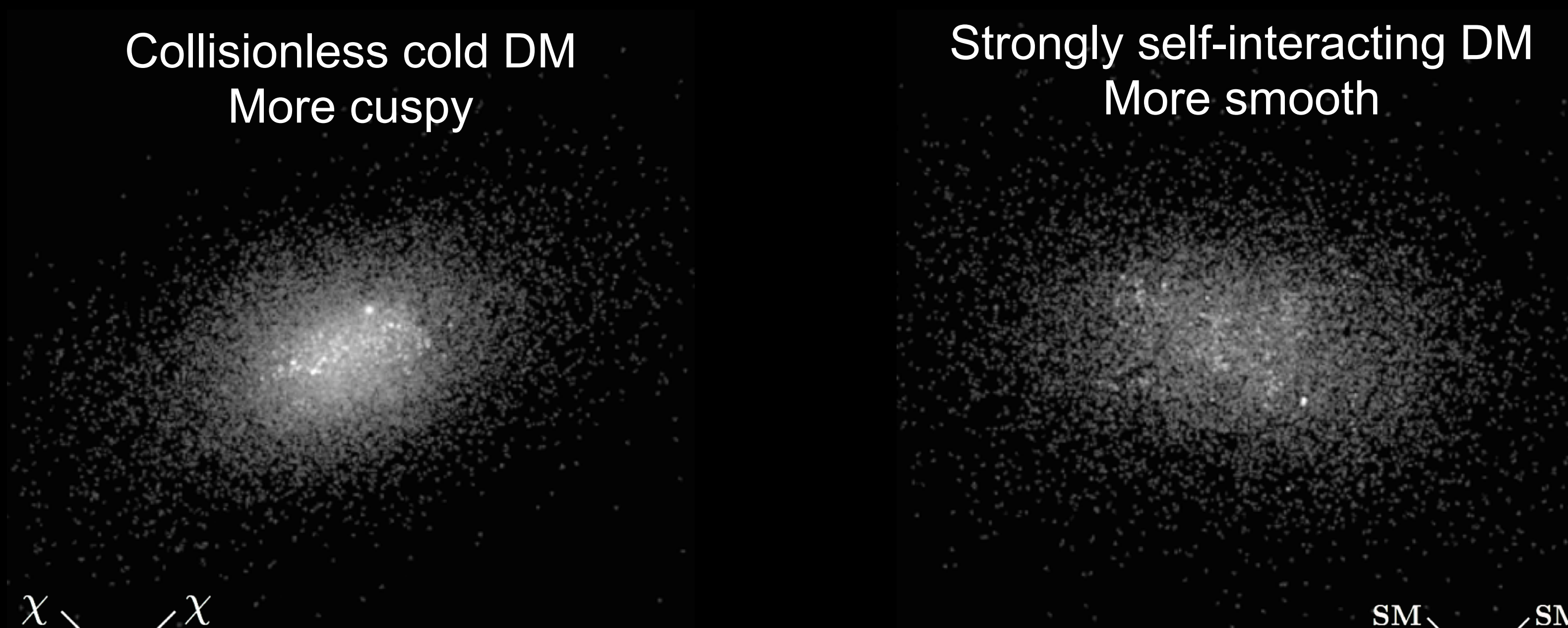


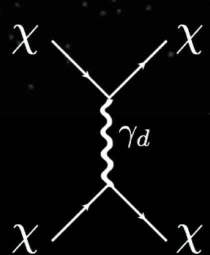

- The WIMPless Miracle: lighter particles with even weaker interactions with the SM can also freezeout with the right thermal relic density, providing a cosmological motivation that enhances the particle physics motivation

# DARK MATTER

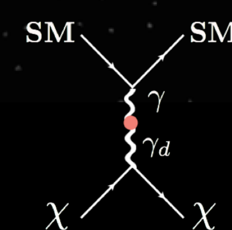
- There are even tentative indications that there is a new "mediator" particle with mass 10 – 100 MeV that mediates large DM-DM self-interactions




Brooks et al. (2017)




$$\frac{\sigma}{m_{\rm DM}} \sim 1\ \frac{\rm barn}{\rm GeV} \left(\frac{\alpha_D}{\alpha_{\rm EM}}\right)^2 \left(\frac{m_{\rm DM}}{5\ {\rm GeV}}\right) \left(\frac{10\ {\rm MeV}}{m_{\rm mediator}}\right)^4$$

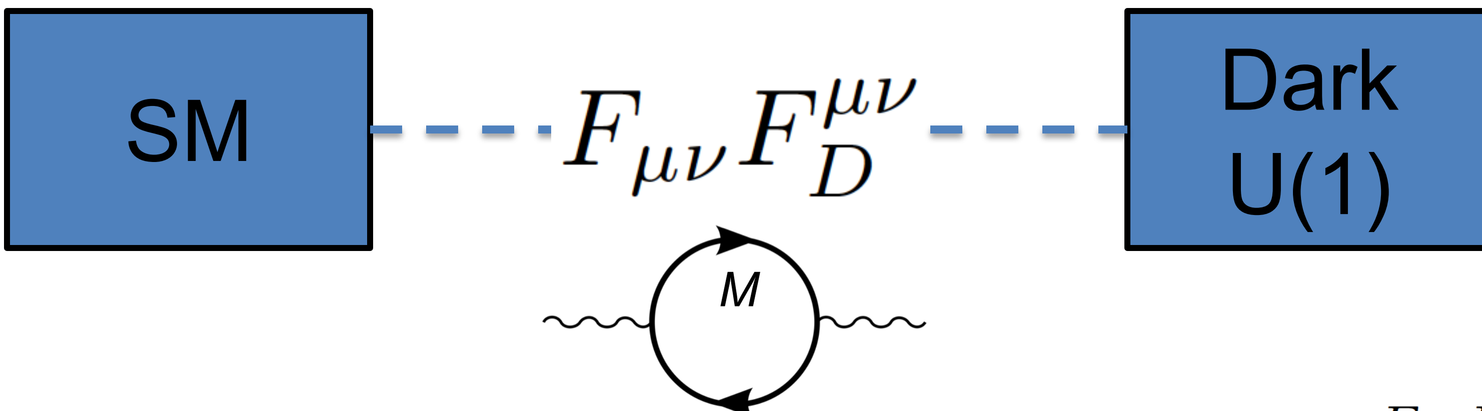



- Such scenarios predict a 10-100 MeV weakly-interacting particle

# SIGNALS: CONCRETE MODELS

- We want to determine signals, FASER's potential in concrete models. Seems like a Pandora's box of possibilities.

- But suppose there is a dark sector with its own $U(1)_{EM}$. There are infinitely many possible SM-dark sector interactions, but only one is induced by arbitrarily heavy mediators:




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

- 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 — SM - - - - $F_{\mu\nu}F_D^{\mu\nu}$ - - - - Dark Force

→ dark photon, couples to SM fermions with suppressed couplings proportional to charge: $\varepsilon q_f$.

- Spin 0 — SM - - - - $h^\dagger h \phi_D^\dagger \phi_D$ - - - - Dark Scalar

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

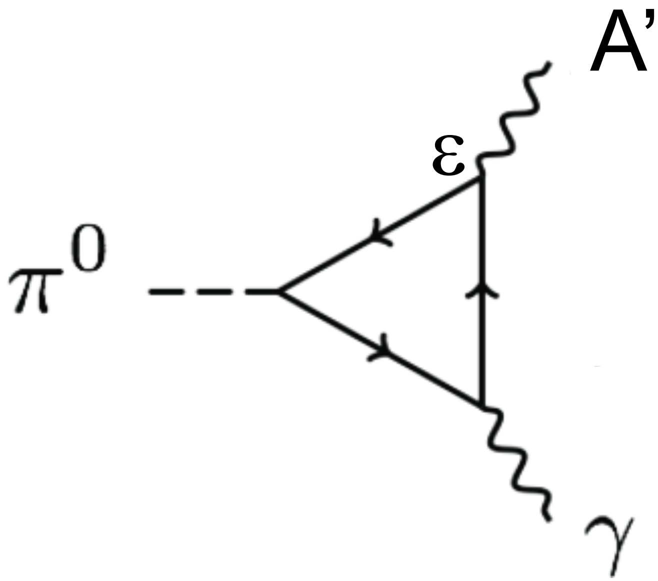
- Spin 1/2 — SM - - - - $hL\psi_D$ - - - - Dark Fermion

→ Heavy neutral lepton, mixes with SM $\nu$s with suppressed mixing $\sin\theta$.

# SIGNALS: DARK PHOTONS

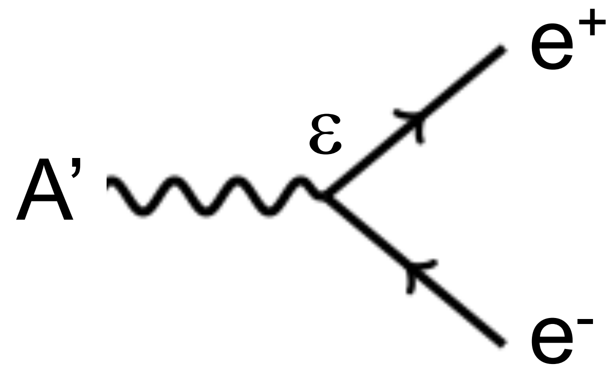
- Consider some “typical” parameters: $m_{A'}$ = 100 MeV, $\varepsilon = 10^{-5}$.

- Production: for example, pion decay:




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

- Decay

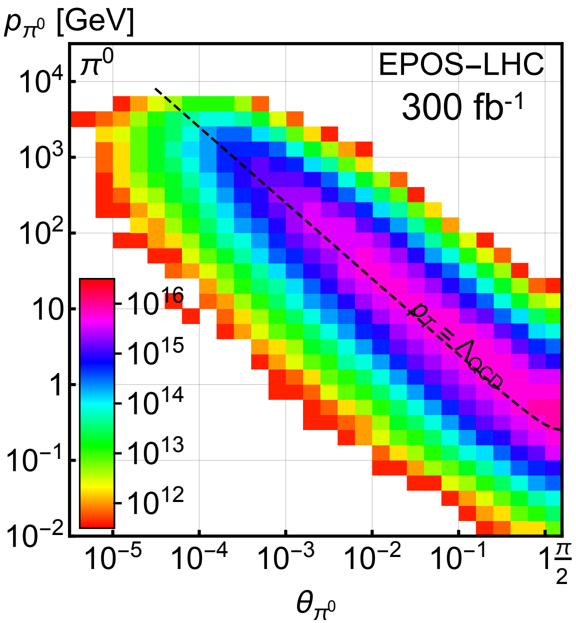



$$\bar{d} = c \frac{1}{\Gamma_{A'}} \gamma_{A'} \beta_{A'} \approx (80 \text{ m}) \ B_e \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\text{TeV}}\right] \left[\frac{100 \text{ MeV}}{m_{A'}}\right]^2$$

- Decay lengths of ~100 m

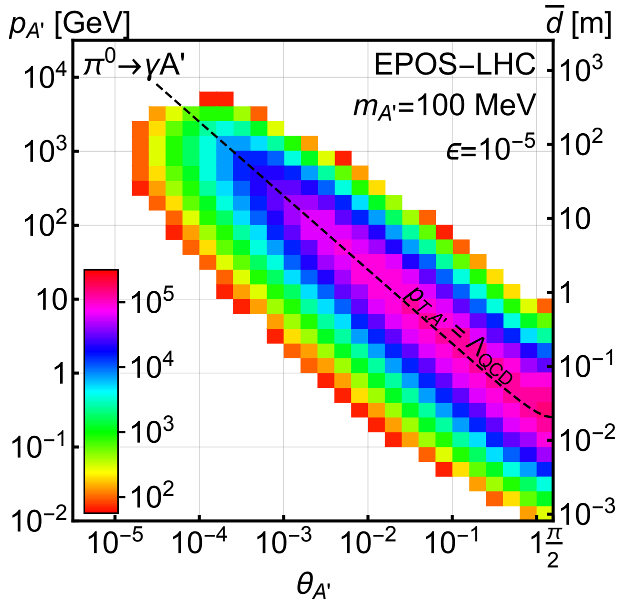
# SIGNALS: DARK PHOTONS

## Pions at the IP



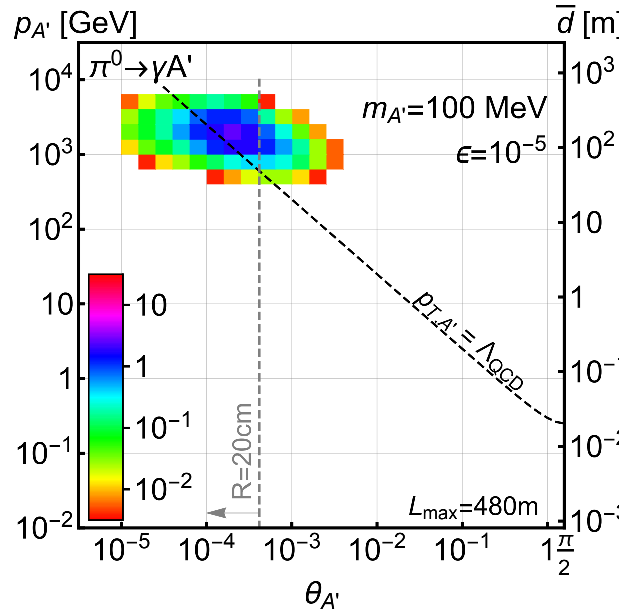

- Simulations greatly refined by LHC data
- Production is peaked at $p_T \sim \Lambda_{QCD} \sim 250$ MeV
- Enormous event rates: $N_\pi \sim 10^{15}$ per bin

## A's at the IP



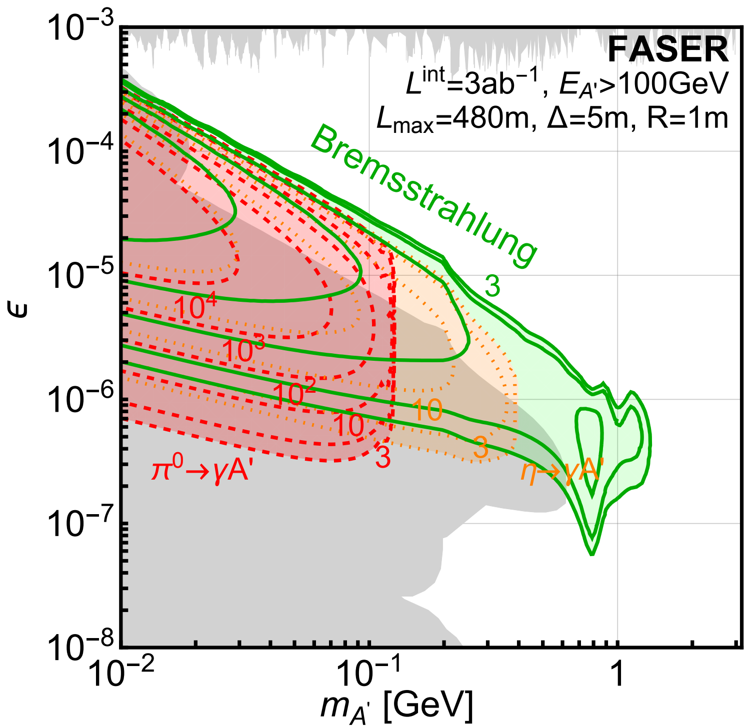

- Production is peaked at $p_T \sim \Lambda_{QCD} \sim 250$ MeV
- Rates highly suppressed by $\varepsilon^2 \sim 10^{-10}$
- But still $N_{A'} \sim 10^5$ per bin

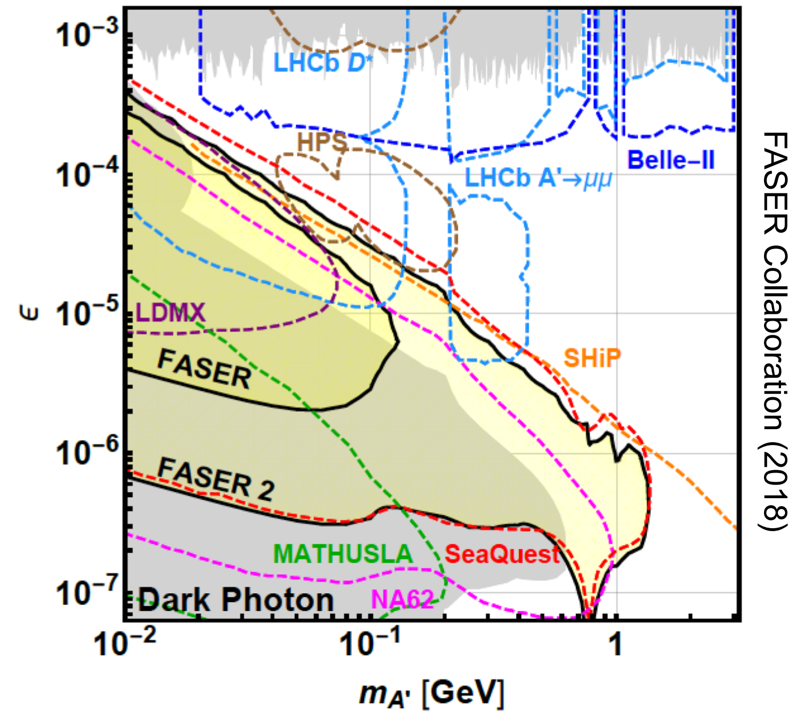
## A's decay in [480m, 483m]




- Only highly boosted ~TeV A's decay in FASER
- Rates again suppressed by decay requirement
- But still $N_{A'} \sim 100$ $e^+e^-$ signal events, most within 20 cm of “on axis”

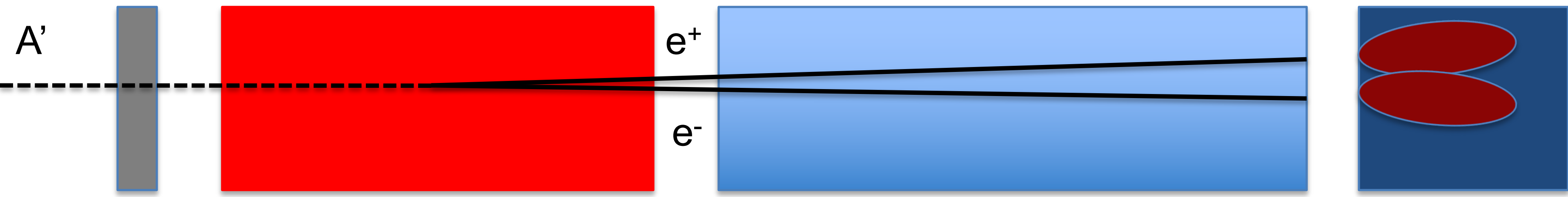
# DARK PHOTON SENSITIVITY REACH




- FASER 1: R=10cm, L=1.5 m, Run 3; FASER 2: R=1m, L=5m, HL-LHC
- For low ε, FASER is not competitive with SHiP.
- For high ε, FASER may have world-leading sensitivity.
- Discovery contours assume no background. But note: signal contours are very closely spaced: ~50% signal efficiency, N=3 vs.10, $e^+e^-$ vs. $e^+e^- + \mu^+\mu^-$, L=3m vs. 5m, … each lead to nearly imperceptible shifts in reach.

# THE DARK PHOTON SIGNAL

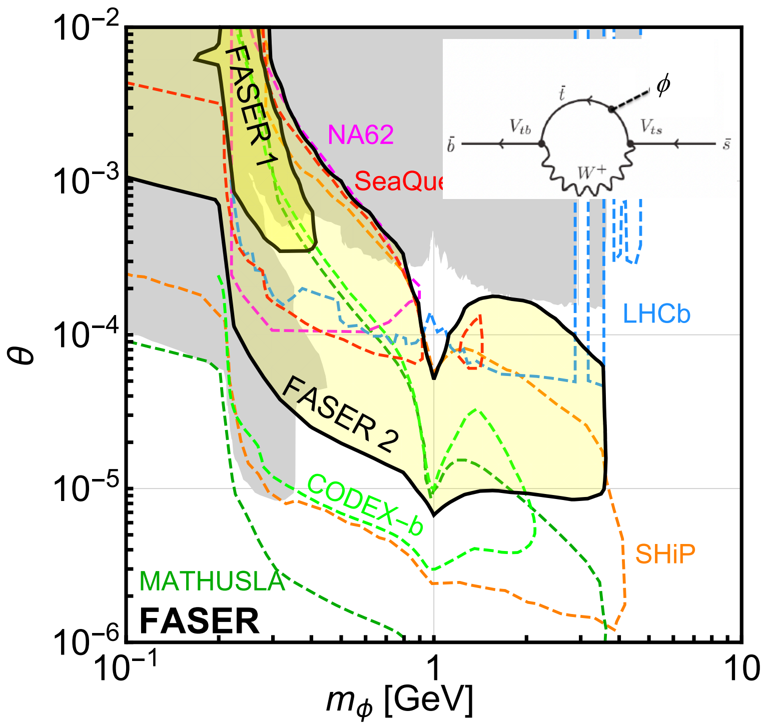



- No signal in the veto scintillator
- 2 high-energy, oppositely charged tracks consistent with originating from a common vertex in the decay volume and with a combined momentum pointing back to the IP
- For $e^+e^-$ signature, also get a large EM deposit in the calorimeter
- Magnets are needed to separate the 2 charged tracks sufficiently to resolve them in the tracker

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

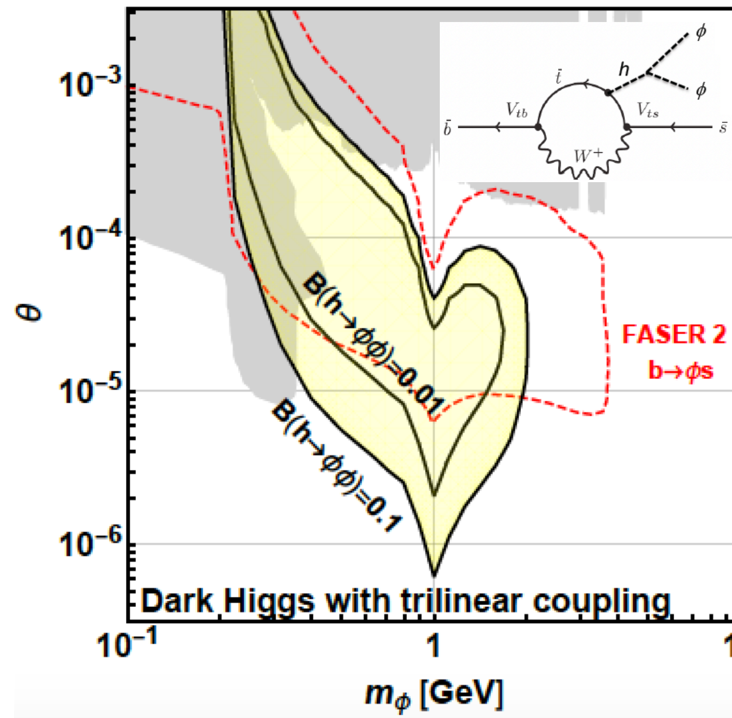
# SIGNALS: DARK HIGGS BOSONS

- **SINGLE PRODUCTION**




- Dark Higgs produced in B decays. $N_B/N_\pi \sim 10^{-2}$ at FASER ($N_B/N_\pi \sim 10^{-7}$ at beam dumps)
- Signal is $\mu^+\mu^-$, $\pi^+\pi^-$, $K^+K^-$
- Probes h-$\phi$ mixing, reach is complementary to other experiments

- **DOUBLE PRODUCTION**

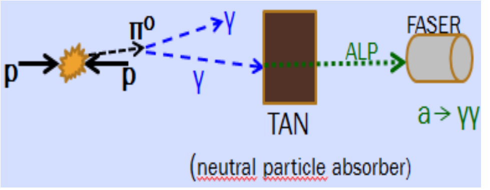



Feng, Galon, Kling, Trojanowski (2017)

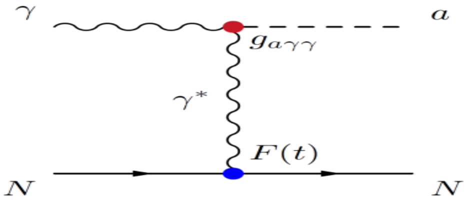
- Probes $h\phi\phi$ trilinear coupling
- Complementary to probes of exotic Higgs decays $h \rightarrow \phi\phi$
- FASER probes SM Higgs properties!

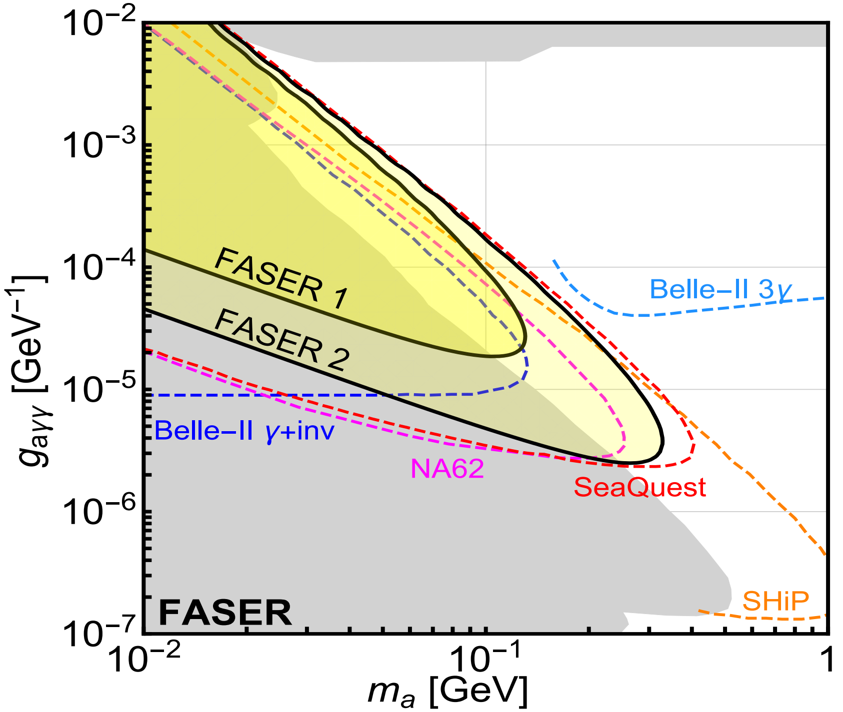
# SIGNALS: ALPS COUPLED TO PHOTONS

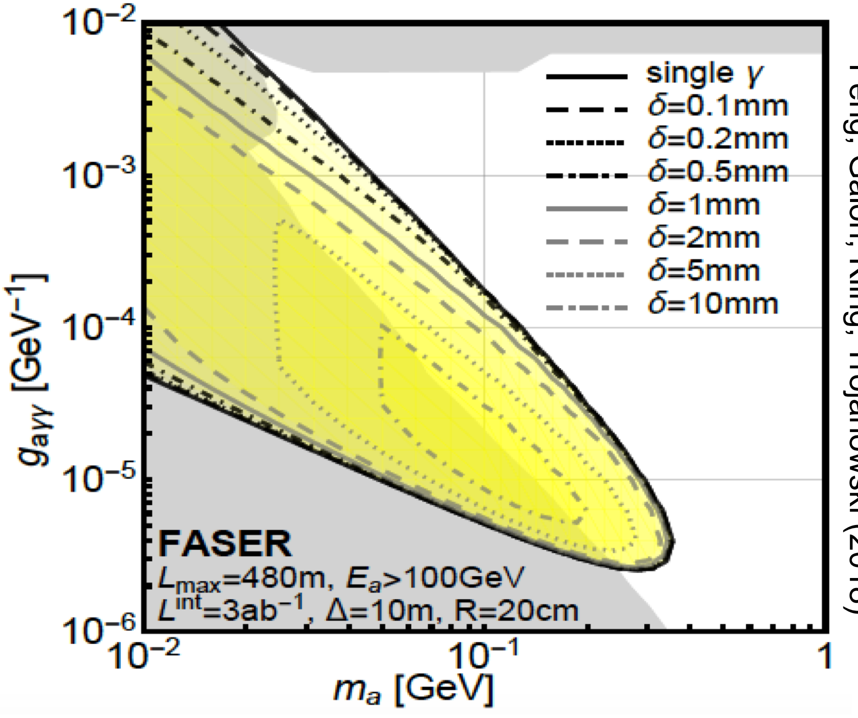
- ~TeV photon from IP collides with TA(X)N, creates ALP through Primakoff process and a → γγ in FASER. "light shining through (100 m) wall expt"




- Signal is 2 photons separated by 0.1 – few mm. Distinguishing 2 photons is very challenging, but already some FASER upgrades proposed



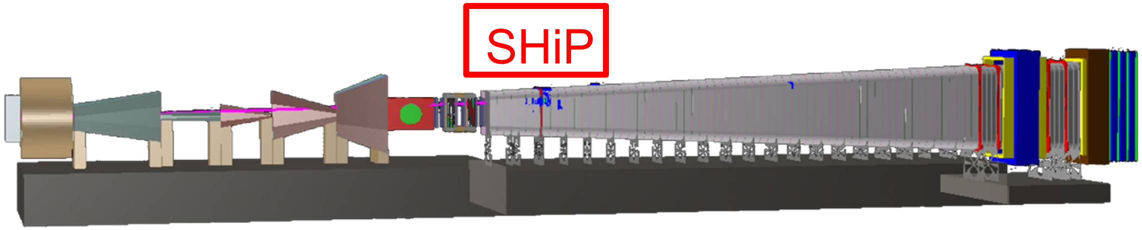

Feng, Galon, Kling, Trojanowski (2018)

# PHYSICS SUMMARY

- FASER has a full physics program: can discover all candidates with renormalizable couplings (dark photon, dark Higgs, HNL); ALPs with all types of couplings ($\gamma$, f, g); and many other examples; see FASER's Physics Reach for LLPs, 1811.12522.

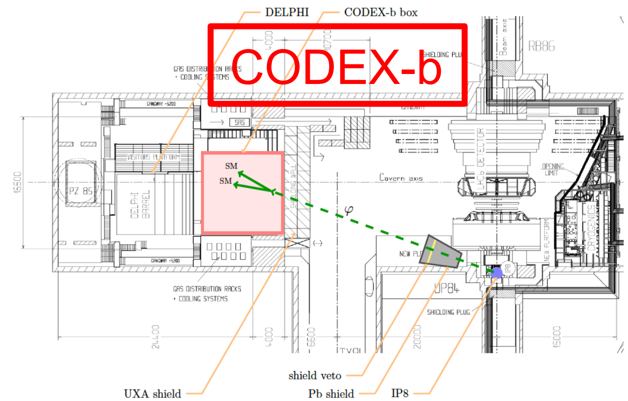
| Benchmark Model | FASER | FASER 2 | References |
|---|---|---|---|
| V1/BC1: Dark Photon | √ | √ | Feng, Galon, Kling, Trojanowski, 1708.09389 |
| V2/BC1': $U(1)_{B-L}$ Gauge Boson | √ | √ | Bauer, Foldenauer, Jaeckel, 1803.05466<br>FASER Collaboration, 1811.12522 |
| BC2: Invisible Dark Photon | – | – | – |
| BC3: Milli-Charged Particle | – | – | – |
| S1/BC4: Dark Higgs Boson | – | √ | Feng, Galon, Kling, Trojanowski, 1710.09387<br>Batell, Freitas, Ismail, McKeen, 1712.10022 |
| S2/BC5: Dark Higgs with hSS | – | √ | Feng, Galon, Kling, Trojanowski, 1710.09387 |
| F1/BC6: HNL with e | – | √ | Kling, Trojanowski, 1801.08947<br>Helo, Hirsch, Wang, 1803.02212 |
| F2/BC7: HNL with $\mu$ | – | √ | Kling, Trojanowski, 1801.08947<br>Helo, Hirsch, Wang, 1803.02212 |
| F3/BC8: HNL with $\tau$ | √ | √ | Kling, Trojanowski, 1801.08947<br>Helo, Hirsch, Wang, 1803.02212 |
| A1/BC9: ALP with photon | √ | √ | Feng, Galon, Kling, Trojanowski, 1806.02348 |
| A2/BC10: ALP with fermion | √ | √ | FASER Collaboration, 1811.12522 |
| A3/BC11: ALP with gluon | √ | √ | FASER Collaboration, 1811.12522 |

# COMPLEMENTARY PROPOSED EXPERIMENTS



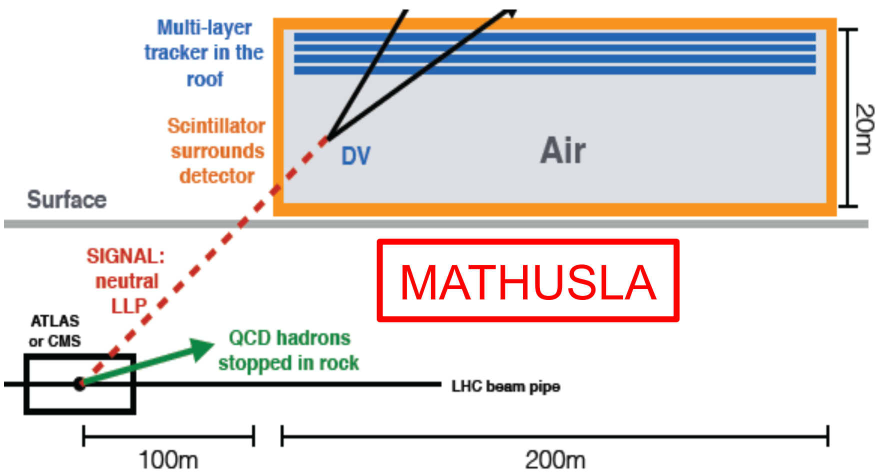

~1000 m$^3$, ~100M CHF + beam

Alekhin et al. (2015)



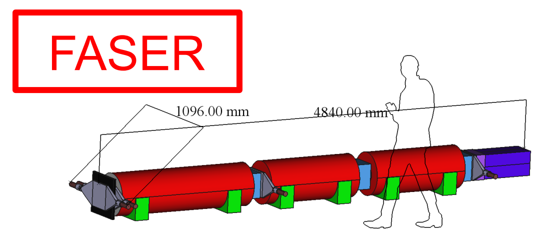

~1000 m$^3$ ~ 1 mIKEAs

Gligorov, Knapen, Papucci, Robinson (2017)




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

Chou, Curtin, Lubatti (2016)




~1 m$^3$ ~ 1 μIKEAs

Feng, Galon, Kling, Trojanowski (2017)

# SUMMARY AND SEARCH PROSPECTS

- FASER is an opportunity for a small and inexpensive experiment to search for light and weakly-interacting particles, complementing other experiments and extending the discovery prospects of the LHC.

- Discovery prospects for LLPs

  Install FASER in LS2 (2019-20) for Run 3 (2021-23, 150 $fb^{-1}$)
  - Decay volume: R = 10 cm, L = 1.5 m.
  - Discovery prospects for dark photons, B-L gauge bosons, ALPs, etc.

  After successful operation of FASER, FASER 2 could be installed in LS3 (2023-25) for HL-LHC (2026-35, 3 $ab^{-1}$)
  - Decay volume: R = 1 m, L = 5 m. Requires extension of existing tunnel (widening of UJ12 or UJ18 areas).
  - Full physics program: dark photons, B-L, ALPs, dark Higgs, HNLs, etc.

- Also interesting prospects for detecting the first LHC neutrinos, measuring their properties.